Dark Matter: Particle Properties I

Tim M.P. Tait
University of California, Irvine

Grenoble
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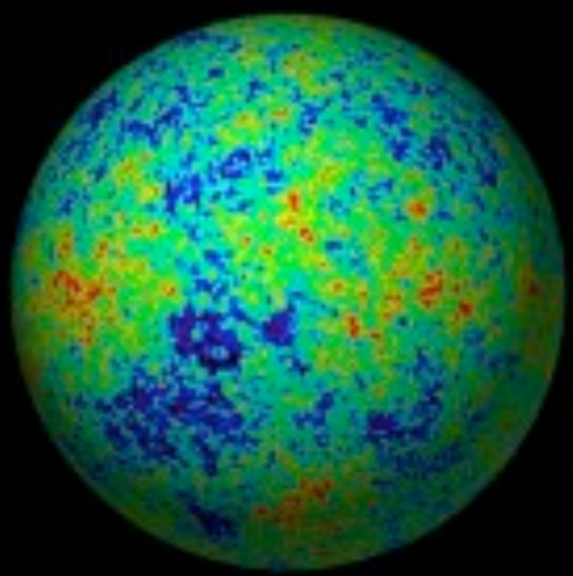
Outline of Lecture 2

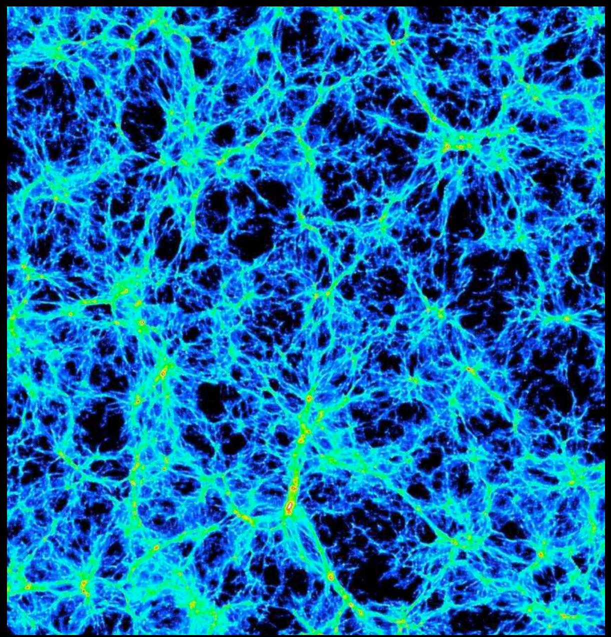
- Characteristics of a Dark Matter Candidate Particle
  - Stabilization
  - Relic Density
- WIMPs
  - R-parity: The SUSY WIMP
    - Relic Density
    - Indirect Signals
    - Direct Detection
    - Colliders

Dark Matter

CMB



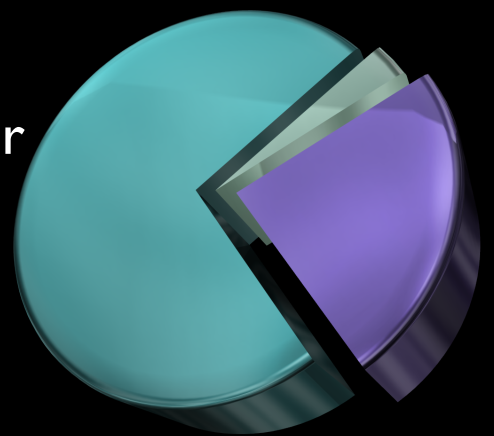
Supernova

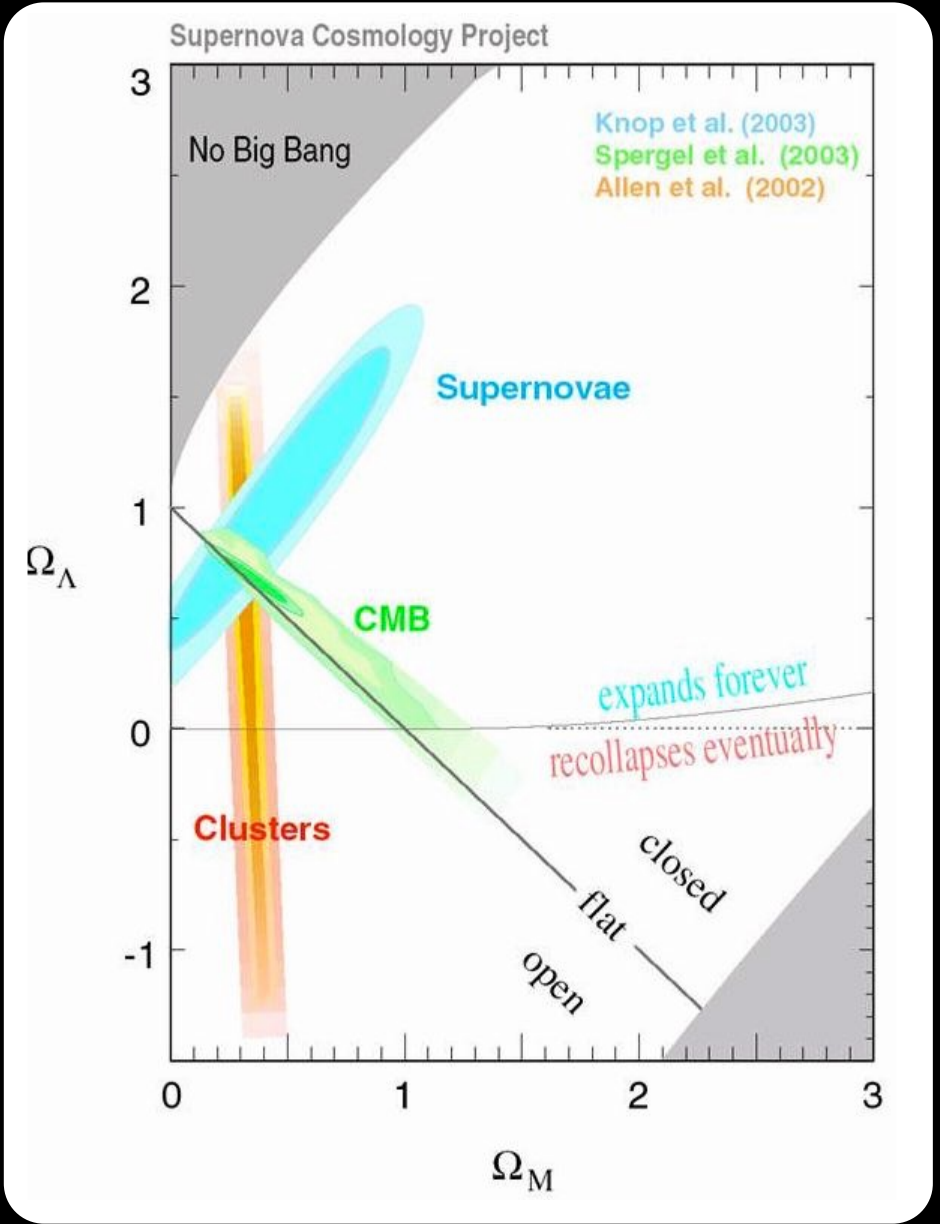


Structure

Lensing

- Ordinary Matter
- Dark Matter
- Dark Energy





Evidence for dark matter is overwhelming…

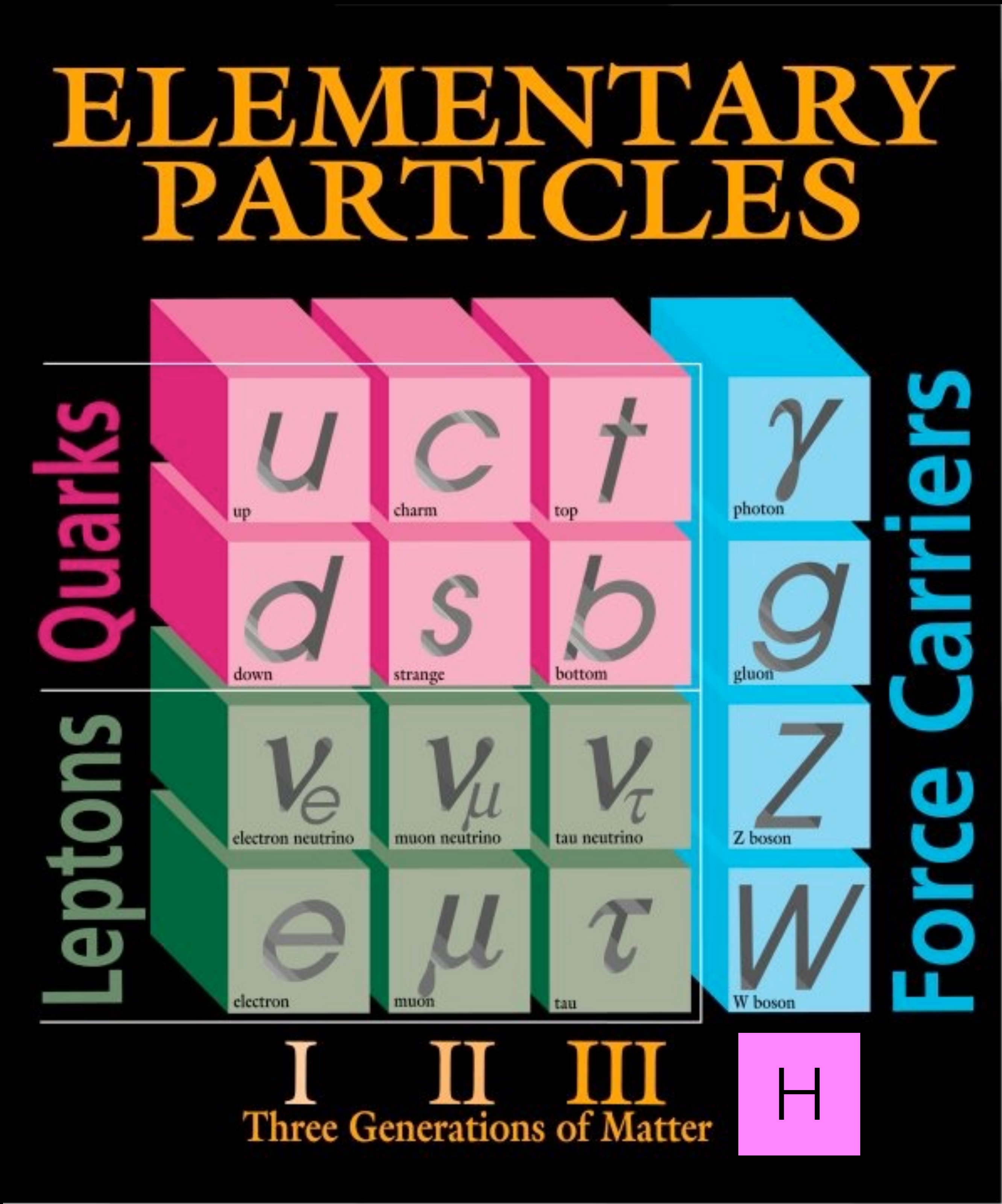
So what is this stuff?

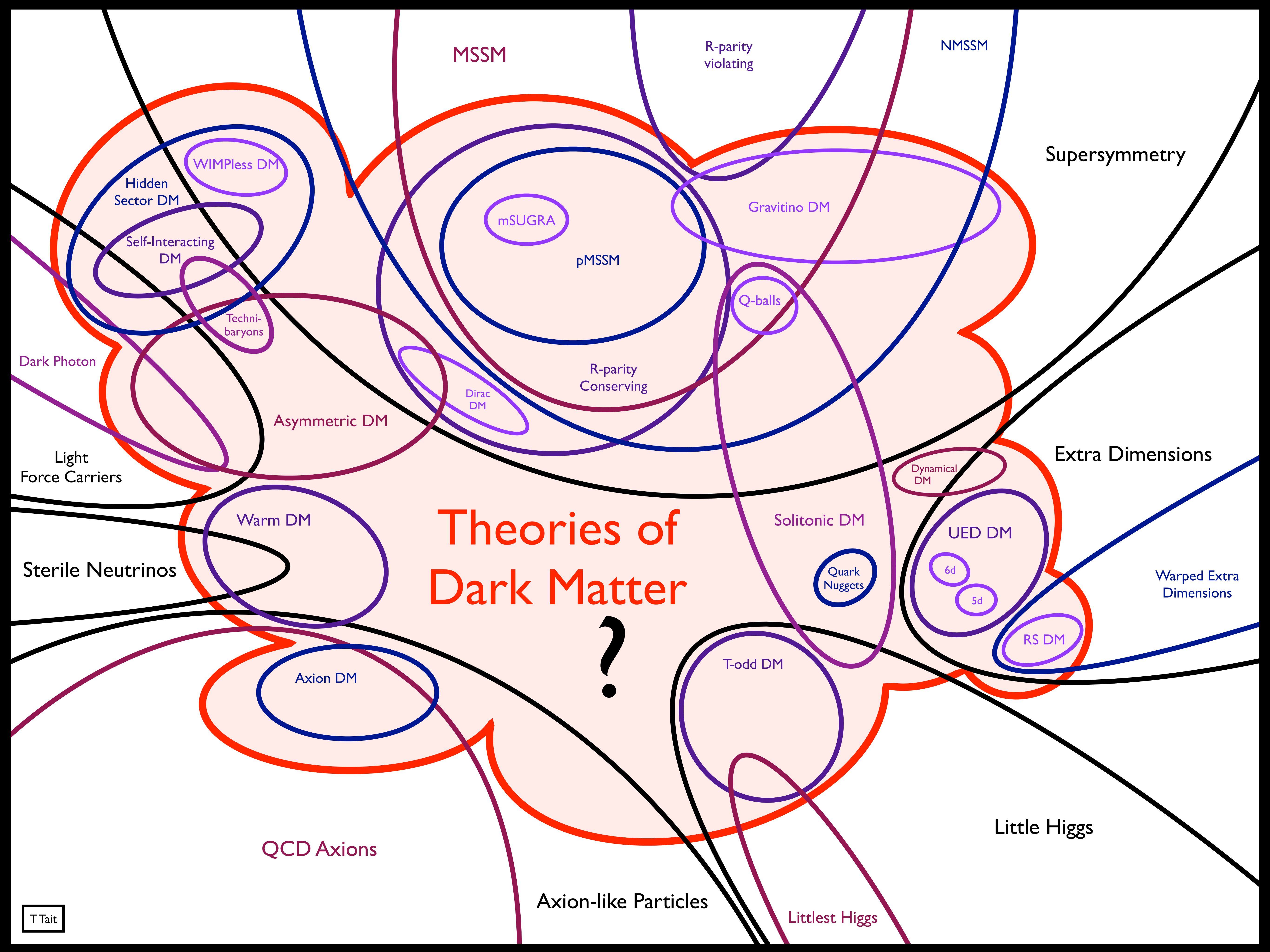
“Cold Dark Matter: An Exploded View” by Cornelia Parker

- As a particle physicist, my job is to explore how dark matter fits into the bigger picture of particles.
- What do we know about dark matter?
  - Dark (neutral)
  - Massive
  - Still around today
  - Stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the Standard Model of particle physics fits the description.

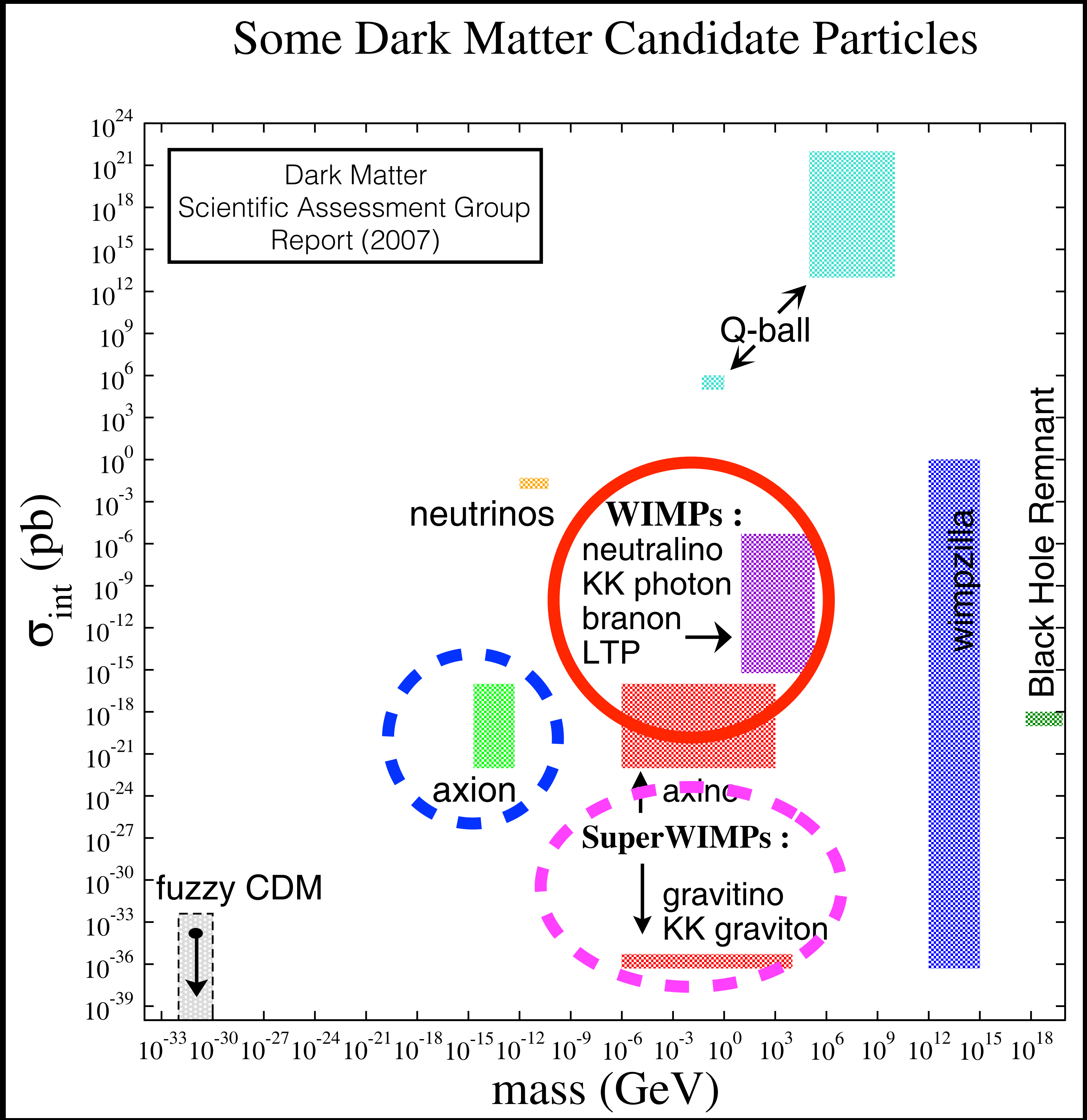
Physics Beyond the SM

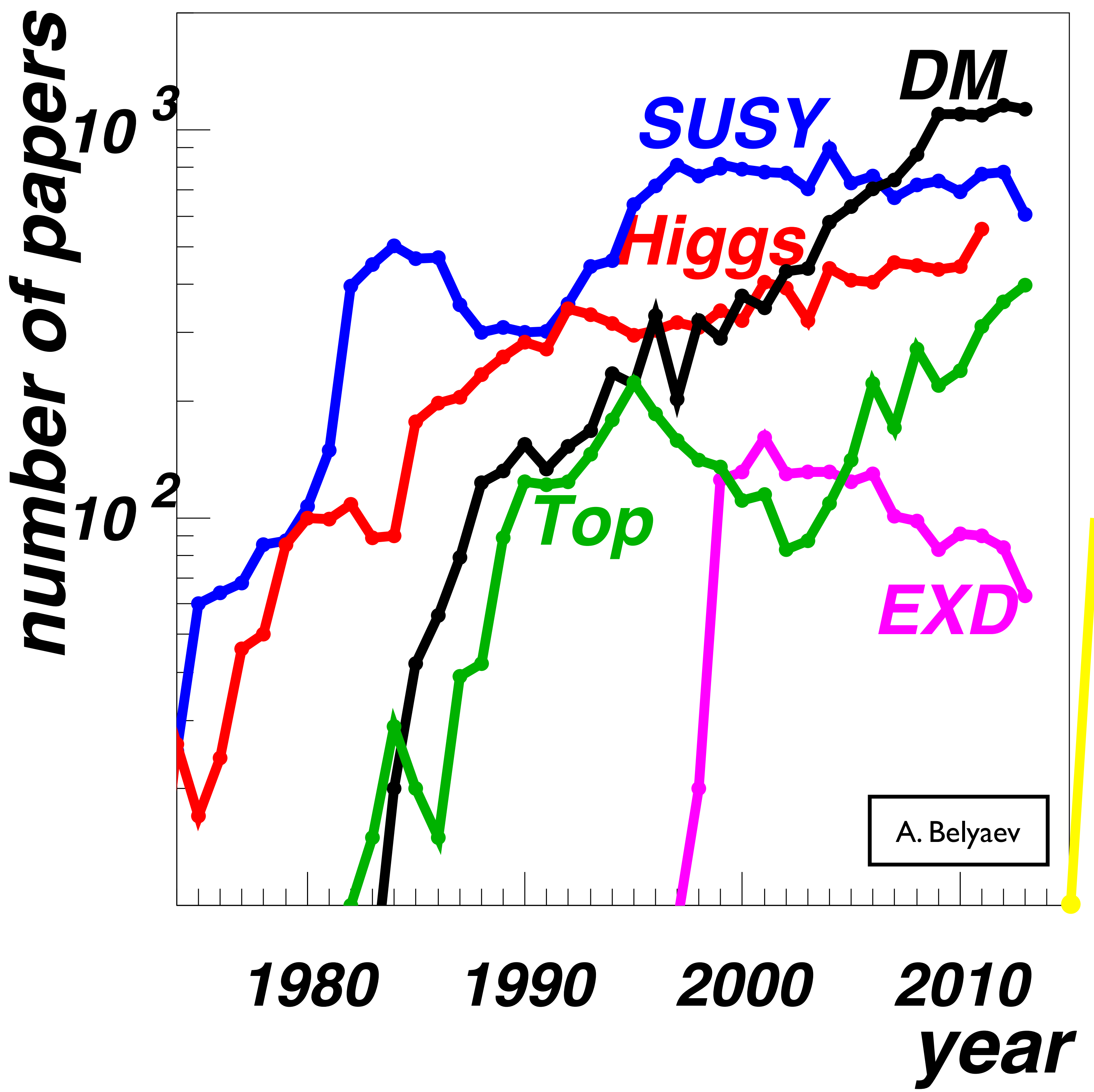
- The Standard Model of particle physics has nothing with the right properties to be dark matter:
  - Photons, leptons, hadrons, and W bosons all shine too brightly.
  - Neutrinos are too light.
  - Z and Higgs bosons are too short-lived.
- Dark matter is a manifestation of physics beyond the Standard Model.
- We have **lots** of ideas for what it *could* be…




MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac
DM
R-parity
Conserving
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Dynamical
DM
Warm DM
Theories of
Dark Matter
?
Solitonic DM
UED DM
6d
5d
Sterile Neutrinos
Quark
Nuggets
Warped Extra
Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Wide Ranging…





number of papers
10^3
10^2
DM
SUSY
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year

The Dark Matter Questionnaire

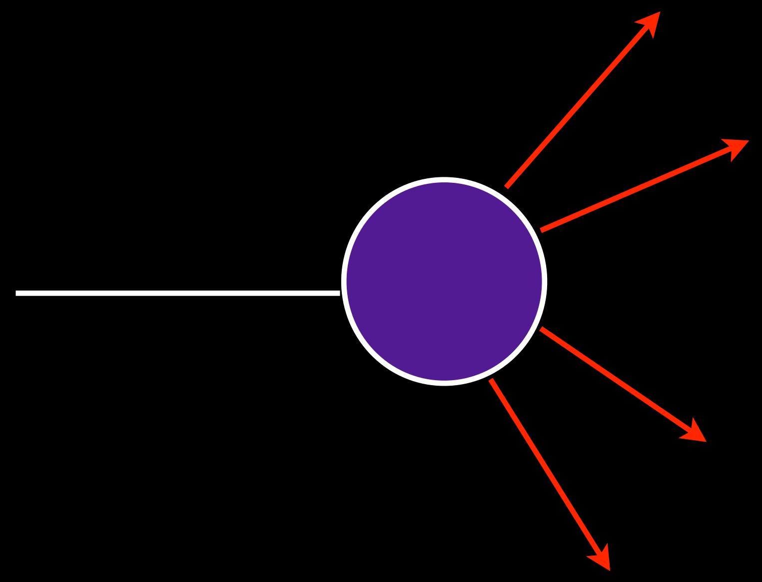
- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

Couplings:

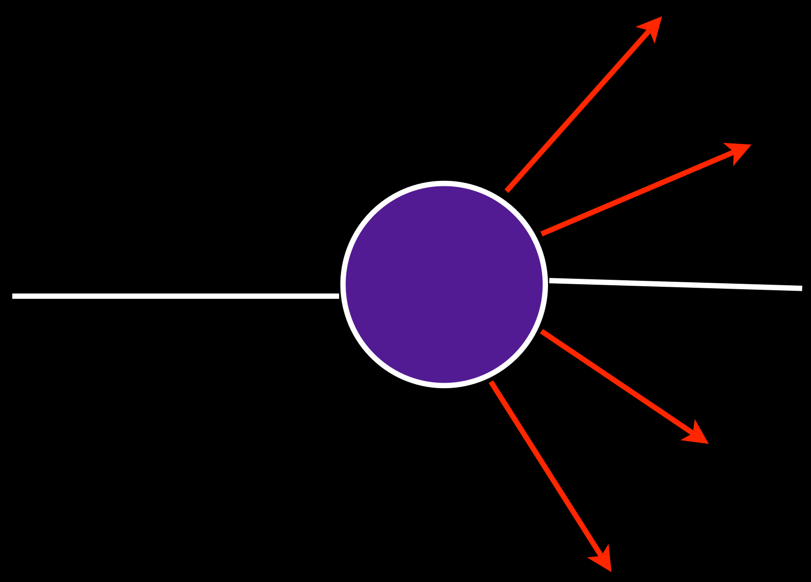
- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?
- ☐ Thermal Relic?
  - ☐ Yes ☐ No

(Quasi) Stable

- One of the mysteries of dark matter is why it is very massive but (at least to very good approximation) stable.
- This is actually telling us something very important about how it can interact with the Standard Model.
    - We need a symmetry (at least approximately) to prevent dark matter particles from decaying.
    - The simplest example is a new kind of parity (a Z_2 discrete symmetry) which forces them to couple in pairs to SM fields.
    - We could explore larger (and continuous) symmetries as well.



χ decays.



The number of χ's is conserved.

WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
    - WIMPs naturally can account for the amount of dark matter we observe in the Universe.
    - WIMPs automatically occur in many models of physics beyond the Standard Model, such as i.e. supersymmetric extensions.
- WIMPs are a vision of dark matter for which we can use particle physics experimental techniques to search very effectively.
    - Are we looking under the lamp post?
- We will classify different WIMPs based on which symmetry allows them to be stable.

$59.99 for 20 servings

Available in Blue Raspberry, Fruit Punch, and Grape flavors....

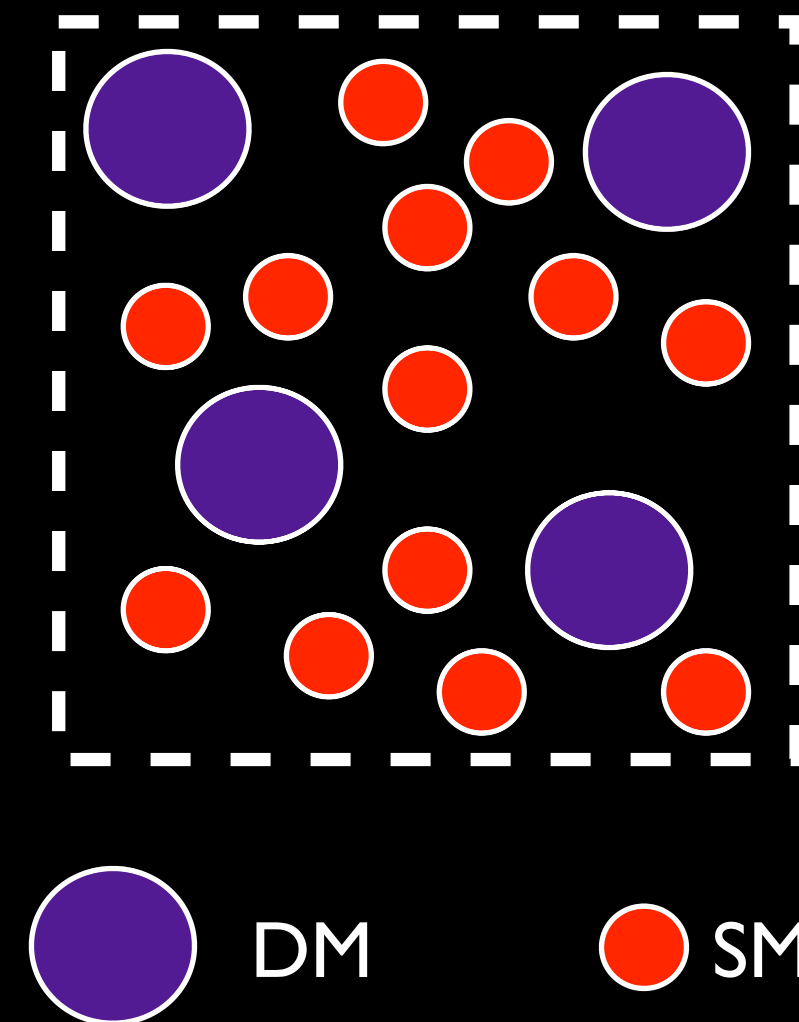
The WIMP Miracle

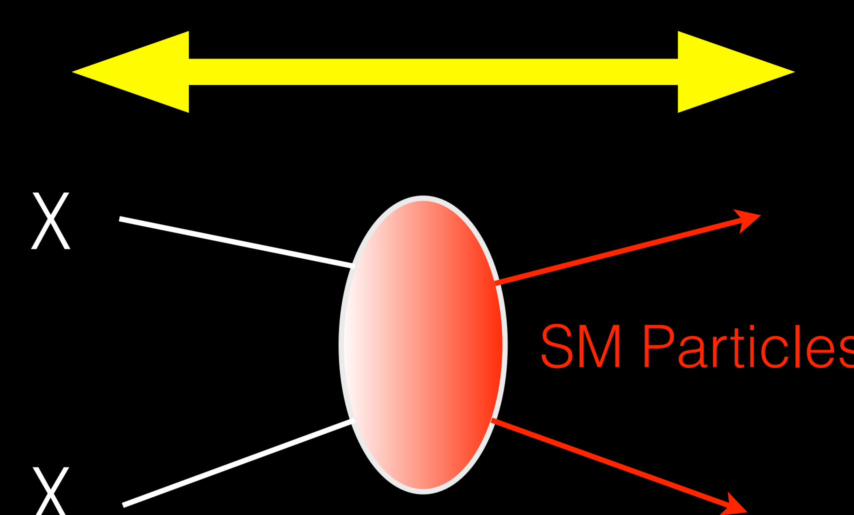
- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.

- While not strictly a requirement for a successful theory of dark matter, this picture is very attractive [meaning: we think it is likely that things work this way], and so it is worth understanding the argument.

- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.

- Equilibrium is maintained by scattering of WIMPs into SM particles, $\chi\chi$ -> SM and vice-versa.

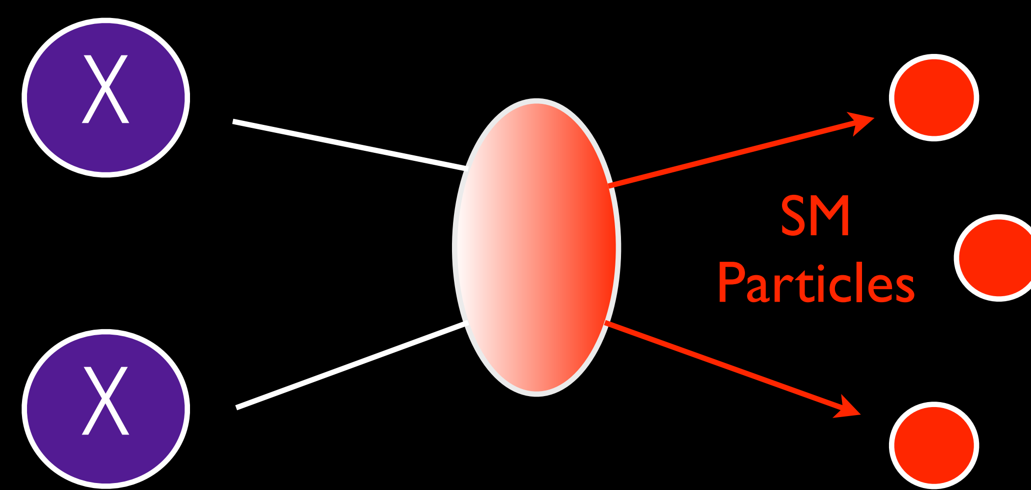




Boltzmann Equation

- The evolution of the dark matter number density (n) is controlled by a Boltzmann equation, which tracks the effect of the expansion of the Universe (H) and the creation and destruction of dark matter.

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right]$$



- A Universe where WIMPs stayed in equilibrium would be pretty boring.
  - As the temperature falls, there will be fewer and fewer WIMPs present, since the fraction of the plasma with enough energy to produce them will become smaller and smaller.
  - (Almost) Nothing would be left!

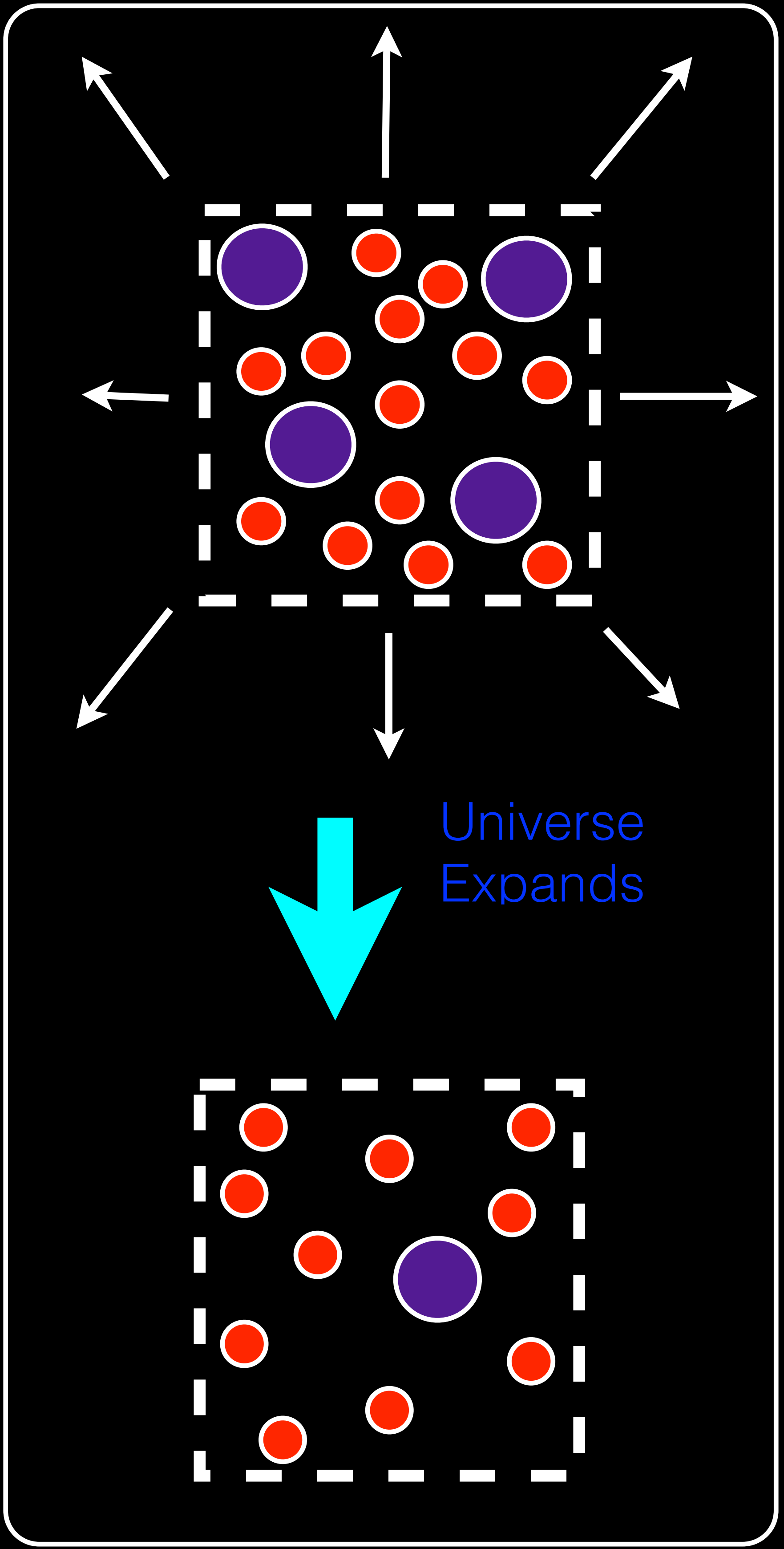
$$n_{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} \mathrm{Exp}\left[-m/T \right]$$

Freeze-Out

- However, the expansion of the Universe eventually results in a loss of equilibrium.

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle \left[n^2 - n_{eq}^2\right]$$

- When (n_{eq} $\langle\sigma v\rangle$) << H, the scattering that maintains equilibrium can't keep up with the expansion.
- The WIMPs become sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- Where they "freeze out" obviously depends on how big $\langle\sigma v\rangle$ is.

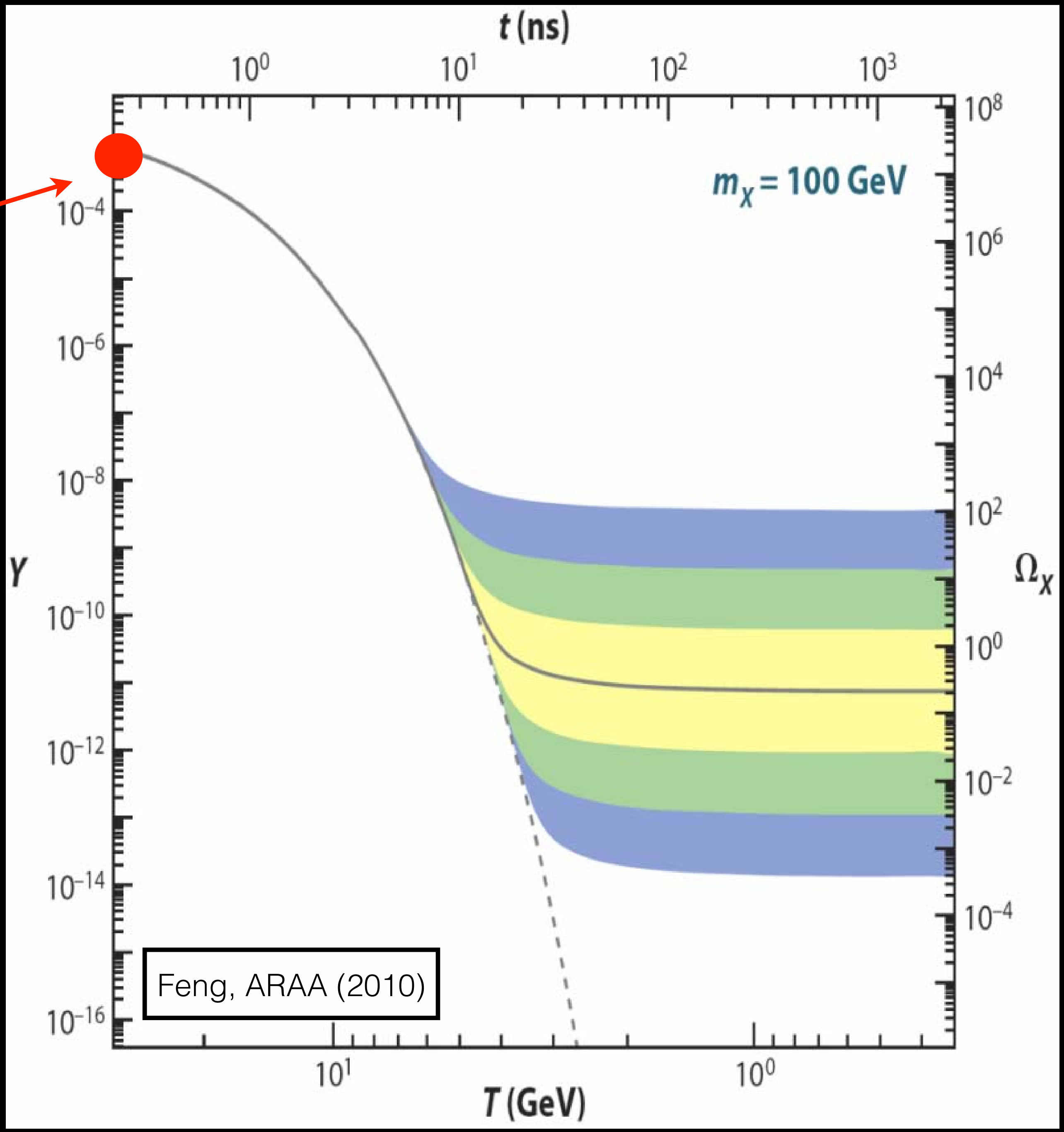


Relic Density

- So the basic picture is:
  - We start out with dark matter in equilibrium with the SM plasma.
  - As the temperature falls, the number of WIMPs does too.
  - We track the equilibrium density until freeze-out:

$$n_{eq}\langle\sigma v\rangle \sim H$$

$$(mT)^{3/2}e^{-m/T} \qquad \frac{g^4}{m^2} \qquad \sim \frac{T^2}{M_{Pl}}$$



$$\frac{m}{T} \sim \log\left[\frac{M_{Pl}}{m}\right] \qquad m \sim 100 \text{ GeV} : \frac{m}{T} \sim 40$$

...and that's how much dark matter we get!

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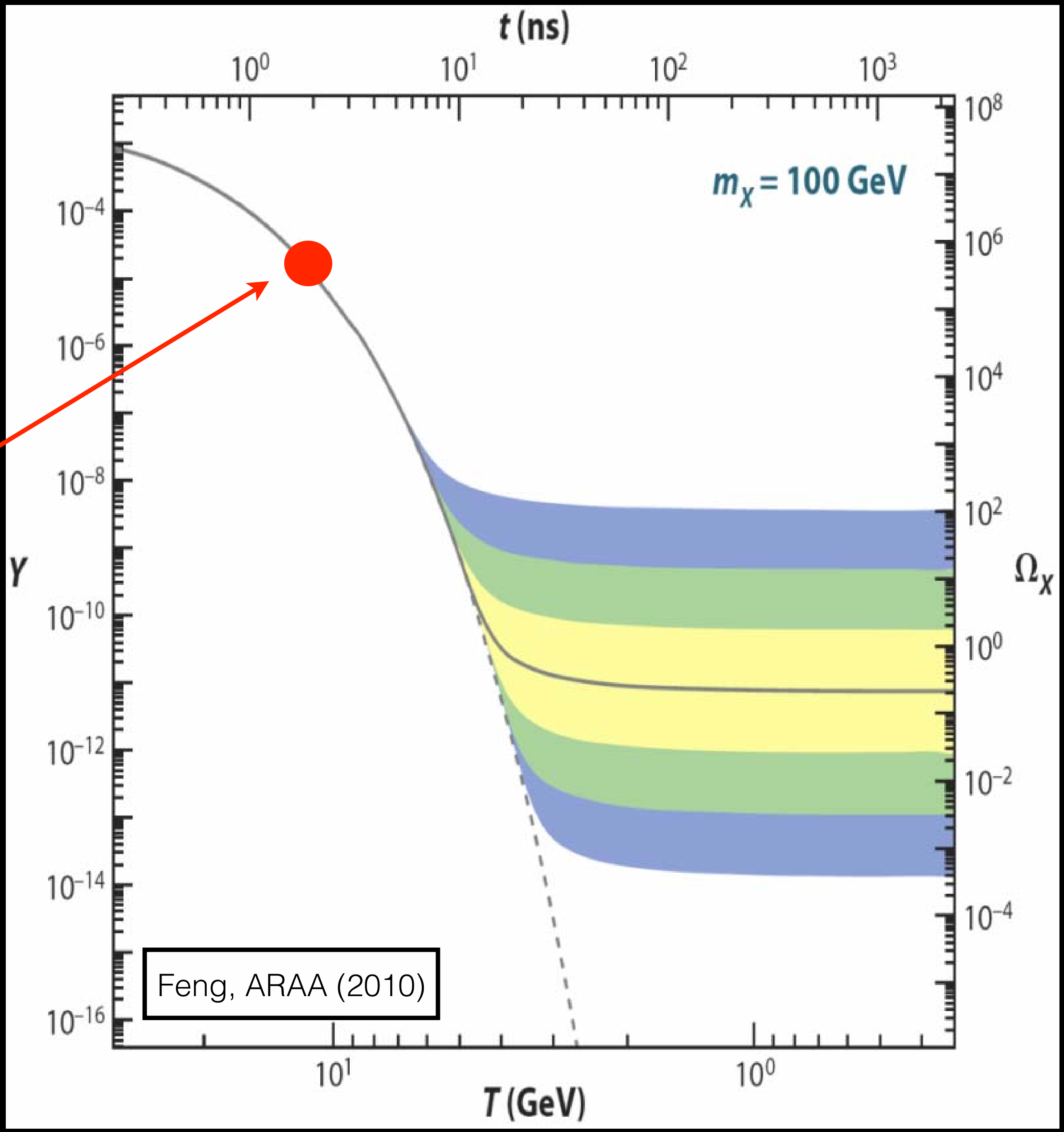

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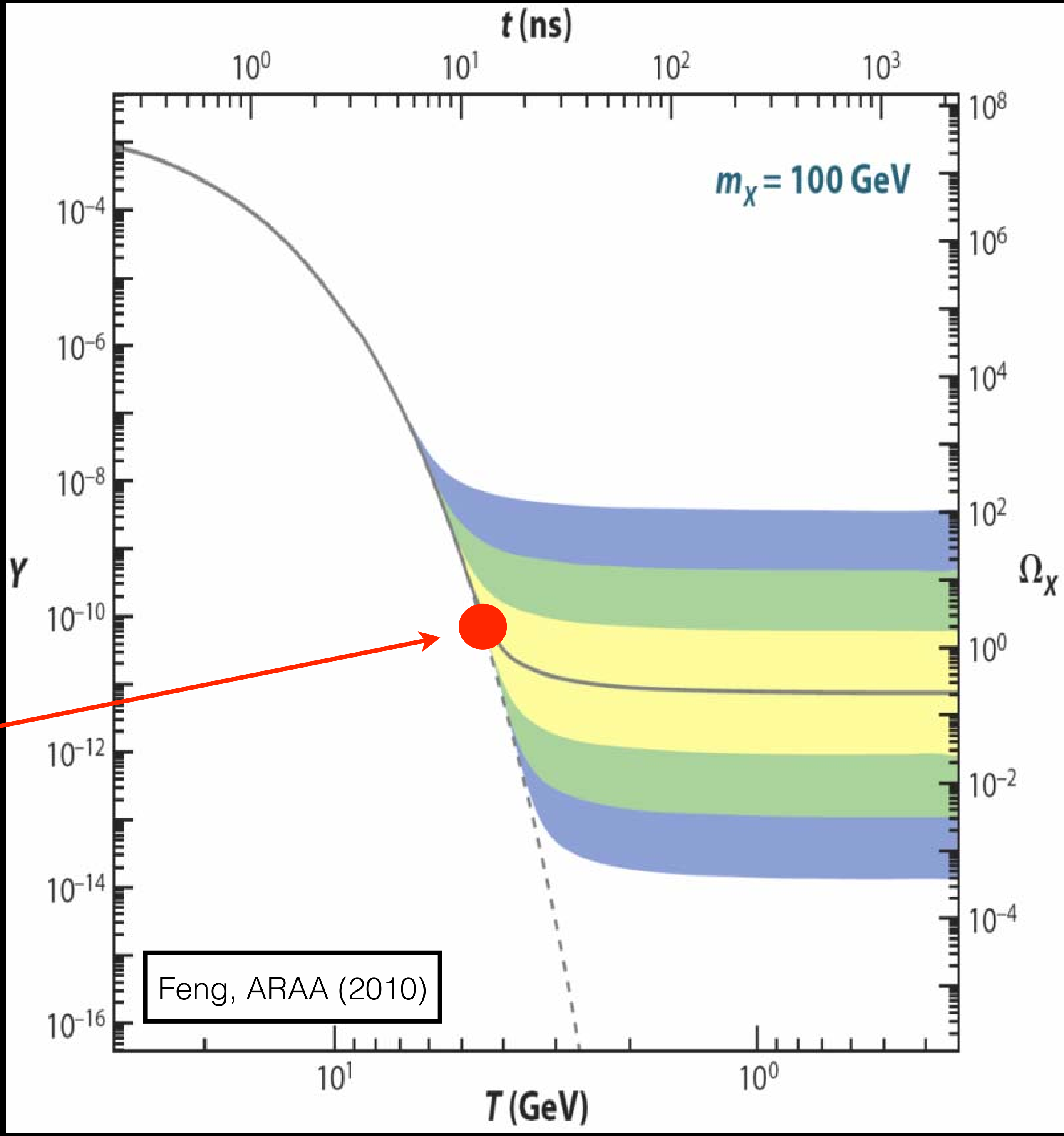

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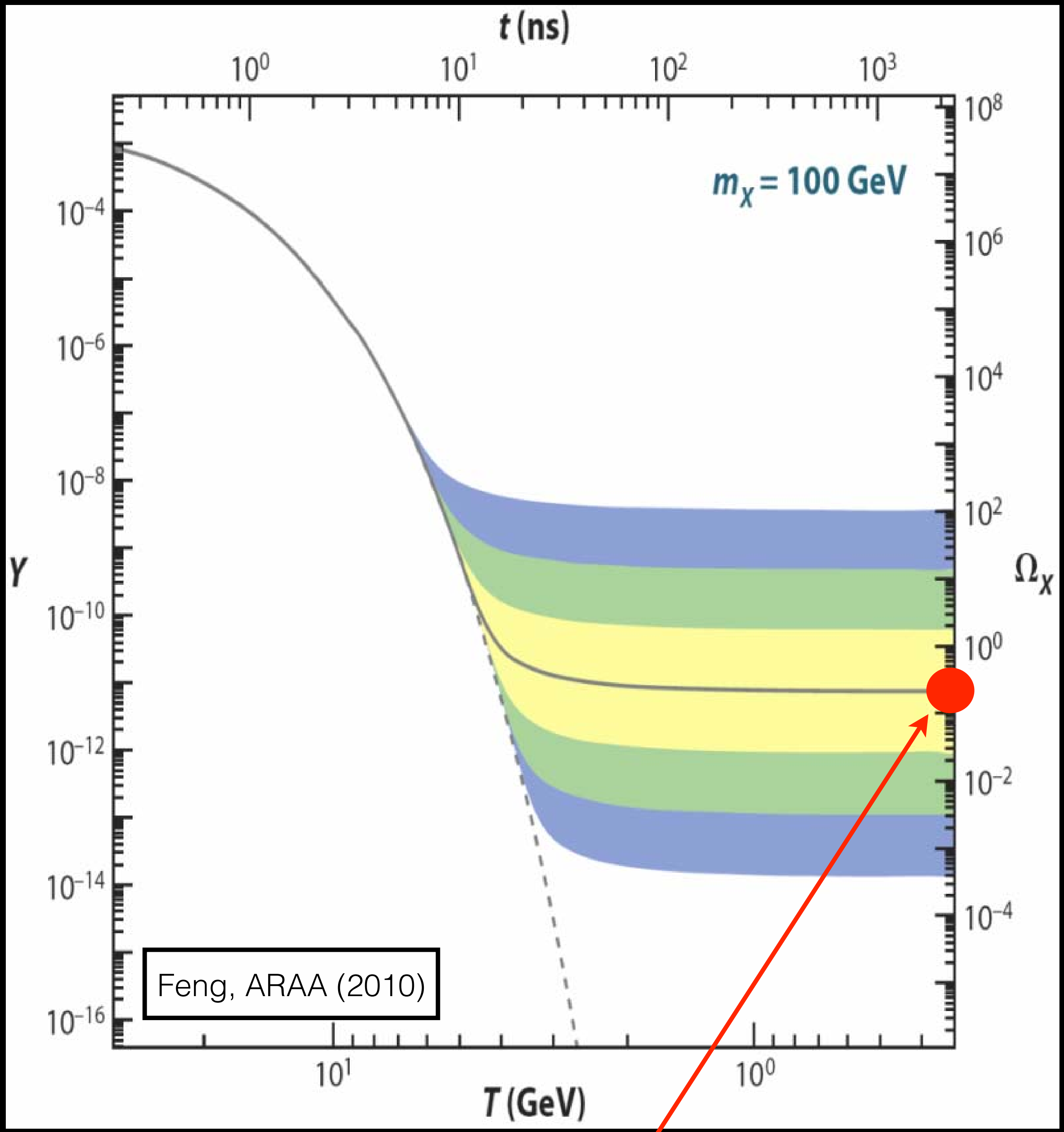

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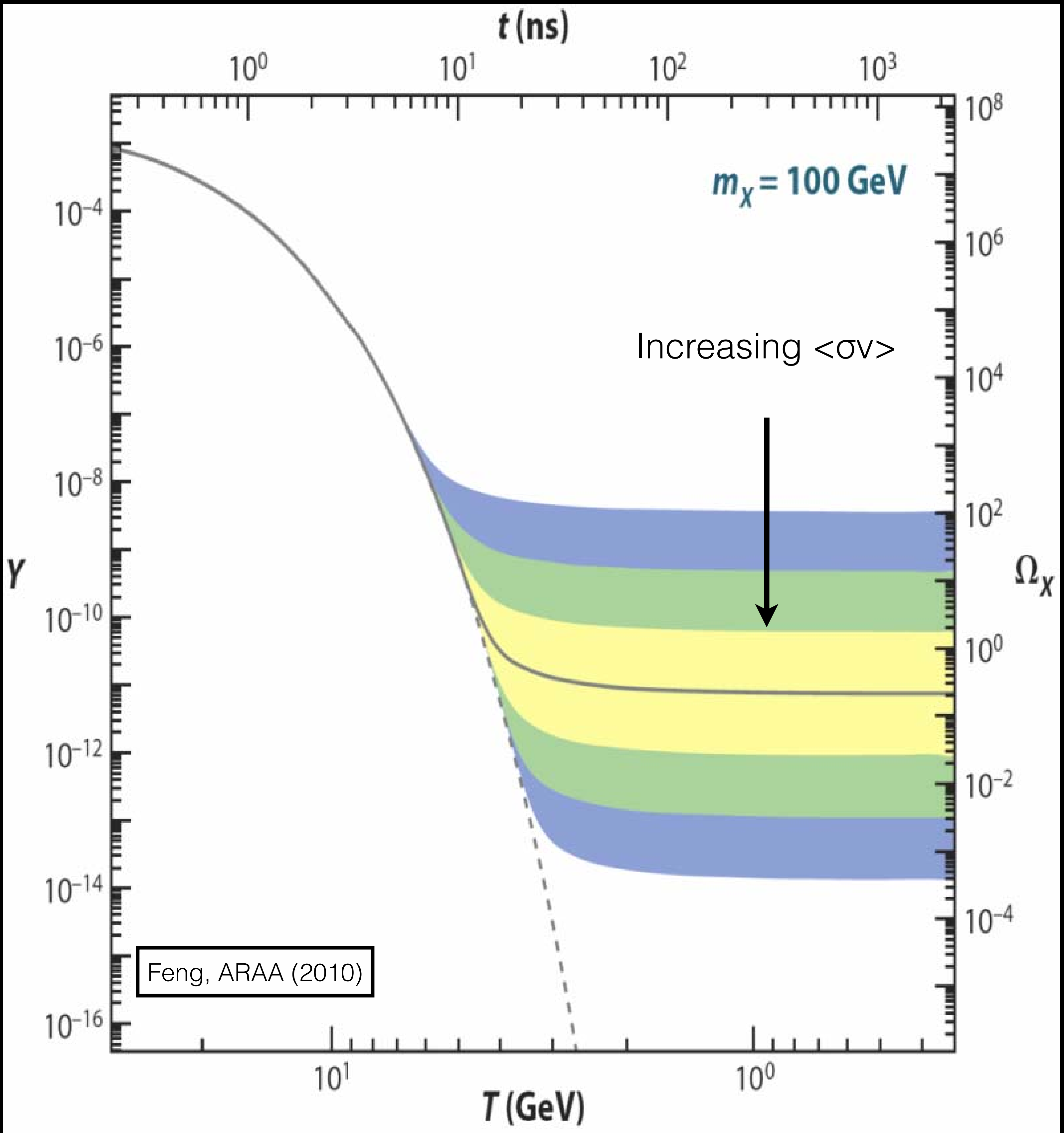
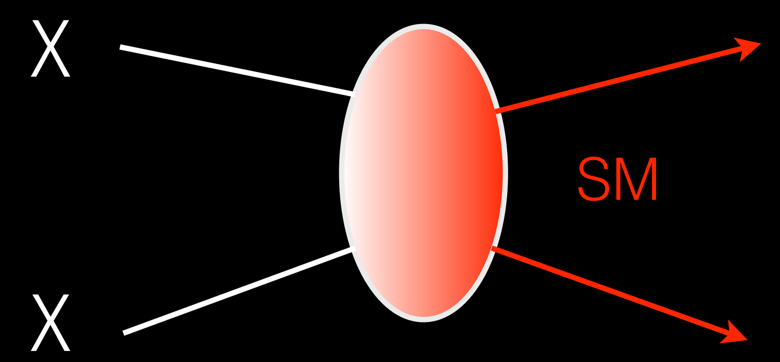
Relic Density



- For a WIMP, once we know its mass and cross section into SM particles, we can predict its relic density.
- I find it remarkable that one simple, reasonable assumption (DM is in equilibrium with the SM at early times) is enough to predict the dark matter density today in terms of the particle physics properties of DM.

WIMP Interactions

- Ideally, we would like to measure WIMP interactions with the Standard Model, allowing us to compute $\sigma(\chi\chi$ -> SM particles) and check the relic density.



  - If our predictions "check out" we have indirect evidence that our extrapolation backward to higher temperatures is working.
  - If not, we will look for signs of new physics to make up the difference.

- The first step is to actually rediscover dark matter by seeing it interact through some force other than gravitational.
- That tells us which SM particles it likes to talk to and in some cases something about its spin, mass, etc.

Thermal Relic?

We all love the WIMP miracle.
We have to admit that this is
really why we love WIMPs.

But what do we *know* about the
history of the Universe?

Thermal Relic?

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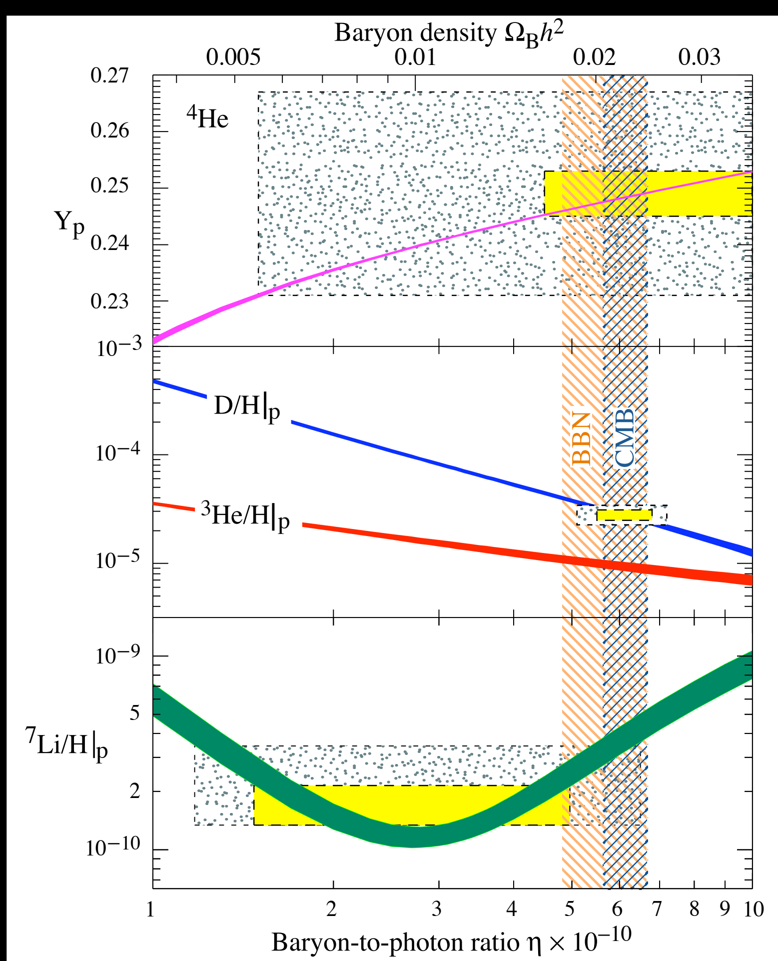
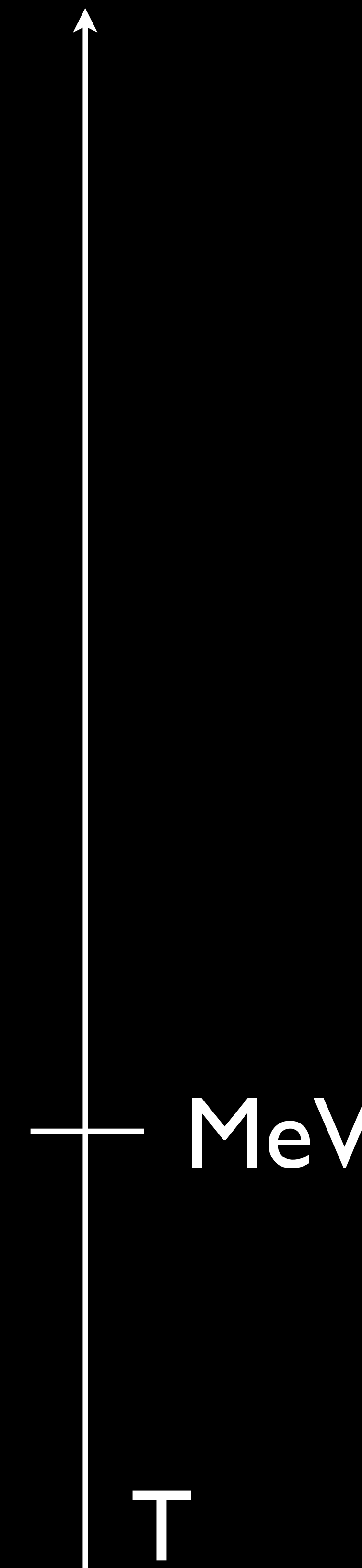


We understand the Universe back to the time of Nucleosynthesis

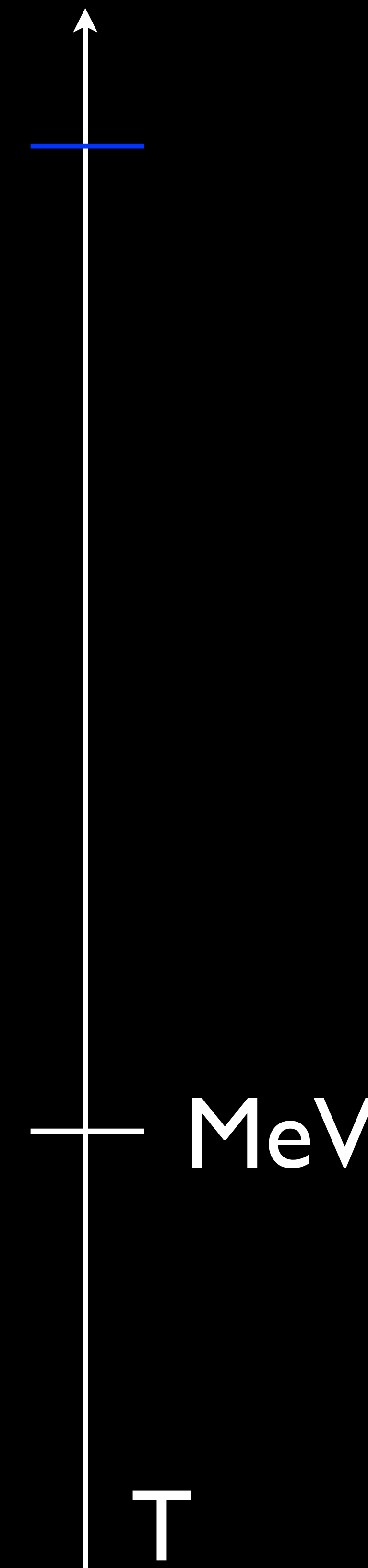


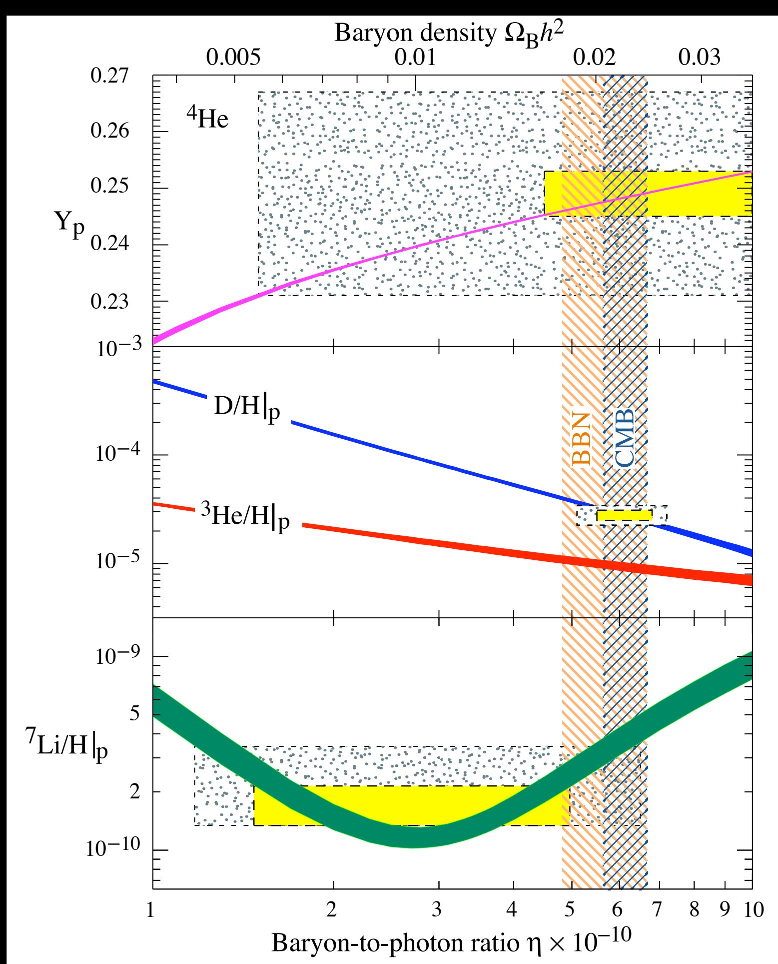
Thermal Relic?

What does that mean for DM?

A typical WIMP had already frozen out through annihilation

We understand the Universe back to the time of Nucleosynthesis





Lots Could Happen

Dark Matter could have a primordial asymmetry

A typical WIMP had already frozen out through annihilation

Some other particle could decay into DM

Some other particle could decay into SM stuff, diluting the dark matter we had.

We understand the Universe back to the time of Nucleosynthesis

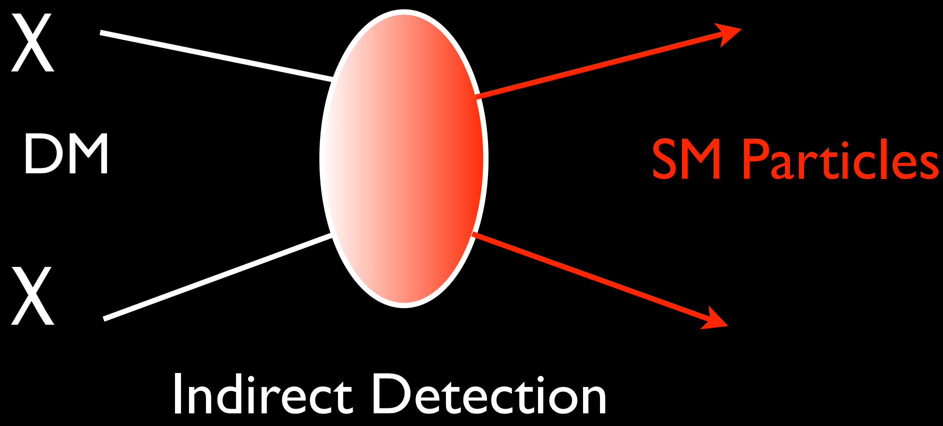
MeV

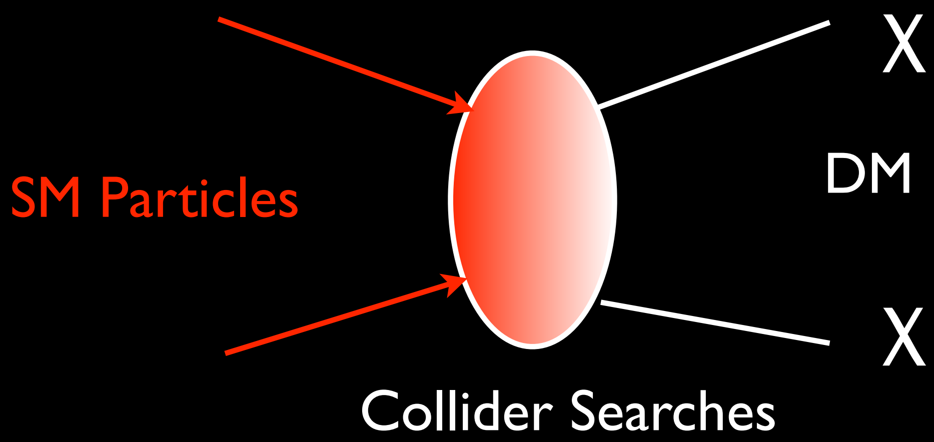
T

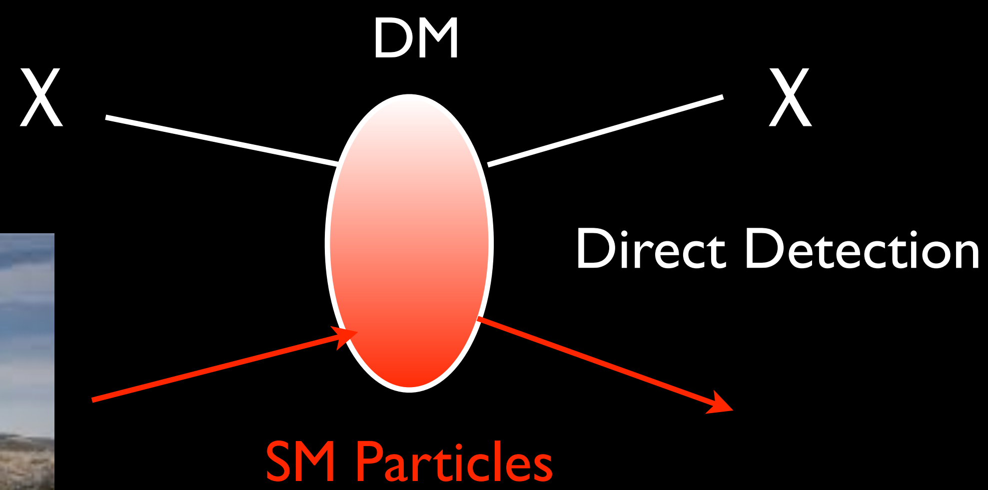
This is a feature!

Understanding the annihilation cross section could verify the WIMP miracle and push back our understanding of the Universe to earlier times.

Particle Probes of WIMPs



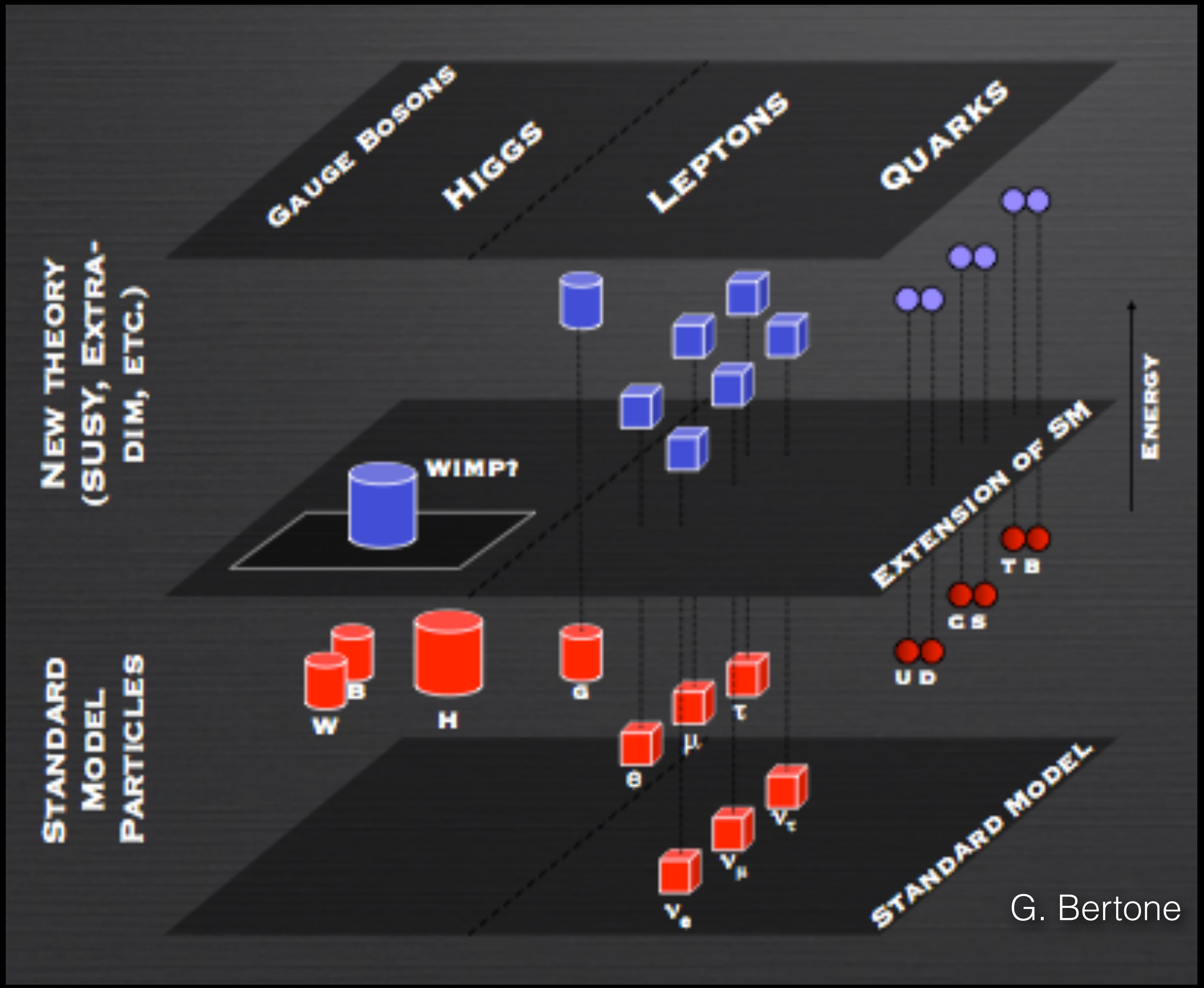




- The common feature of particle searches for WIMPs is that all of them are determined by how it interacts with the Standard Model.

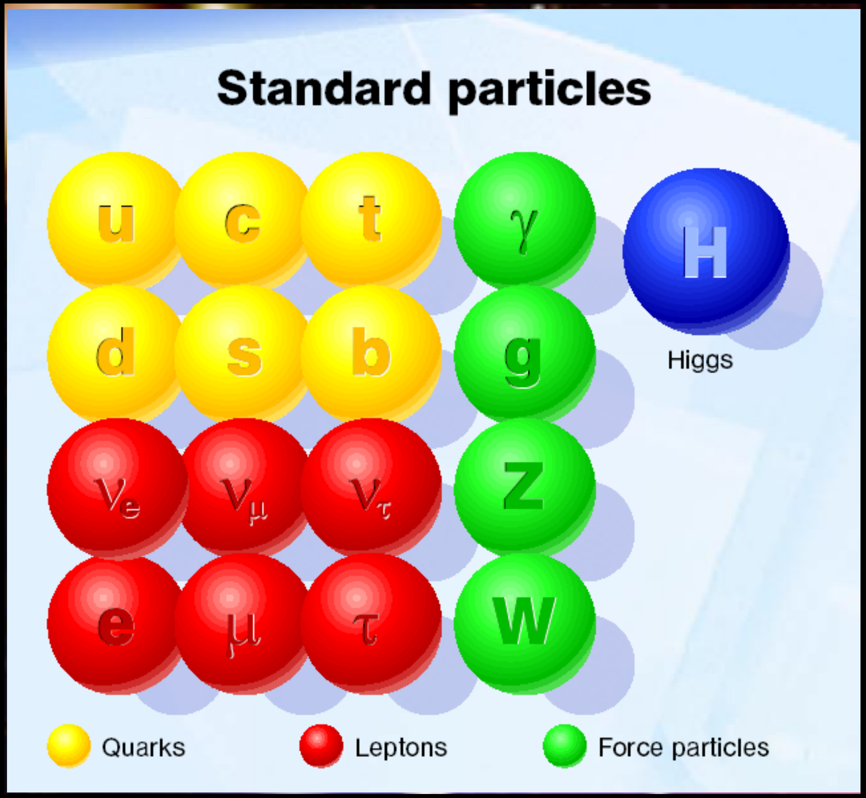
Catalogue of Candidates

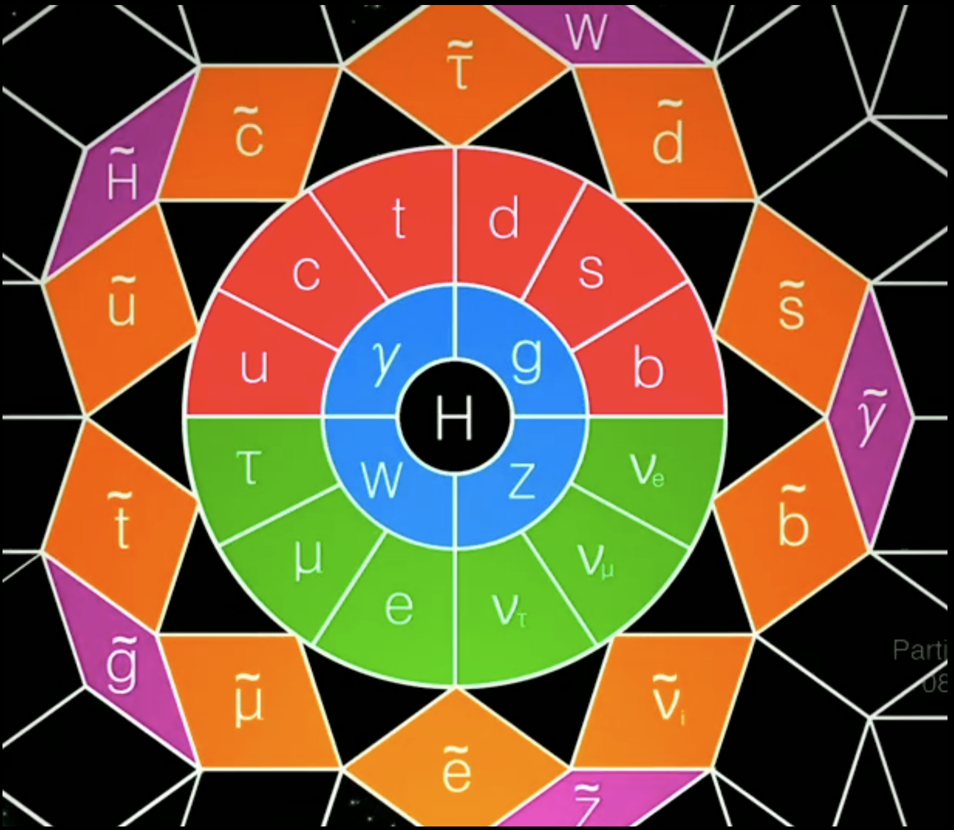
- So here is how we'll catalogue WIMPs:
  - Stability Mechanism
  - How they interact with the SM:
    - Relic density
    - Detection prospects
      - Direct
      - Indirect
      - Collider
- The picture that emerges will be that there are a lot of interesting ideas for DM -- and we can test them!



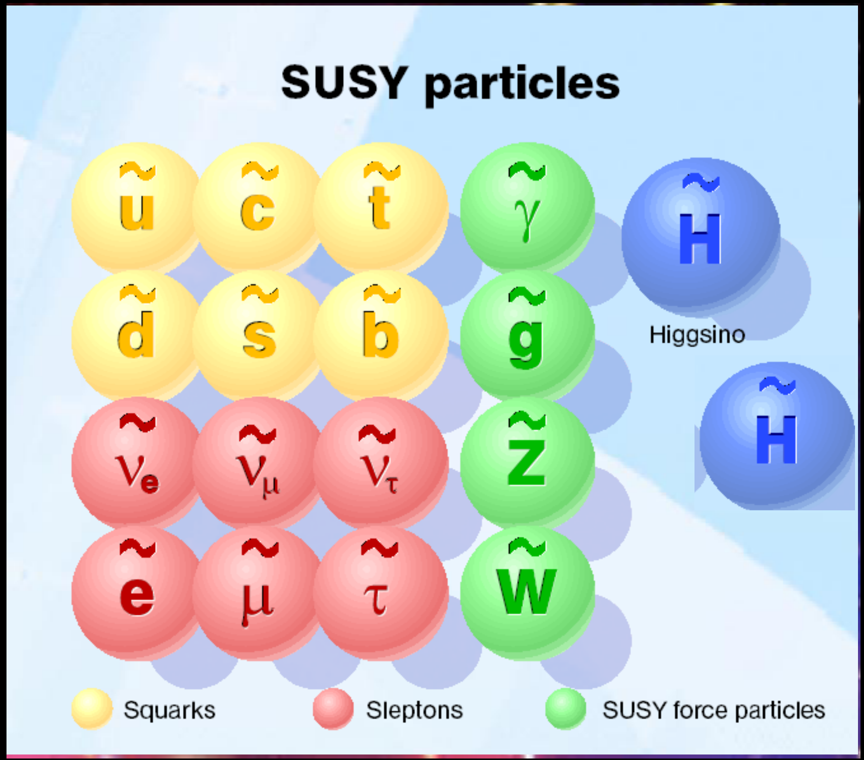
Supersymmetry (SUSY)

- The most famous candidate for dark matter is a supersymmetric particle.
- You are now all experts on SUSY and the MSSM thanks to Yael's lectures.
- I'll focus on how to pick out the features of a supersymmetric theory such as the MSSM that are important to understand how it describes dark matter.



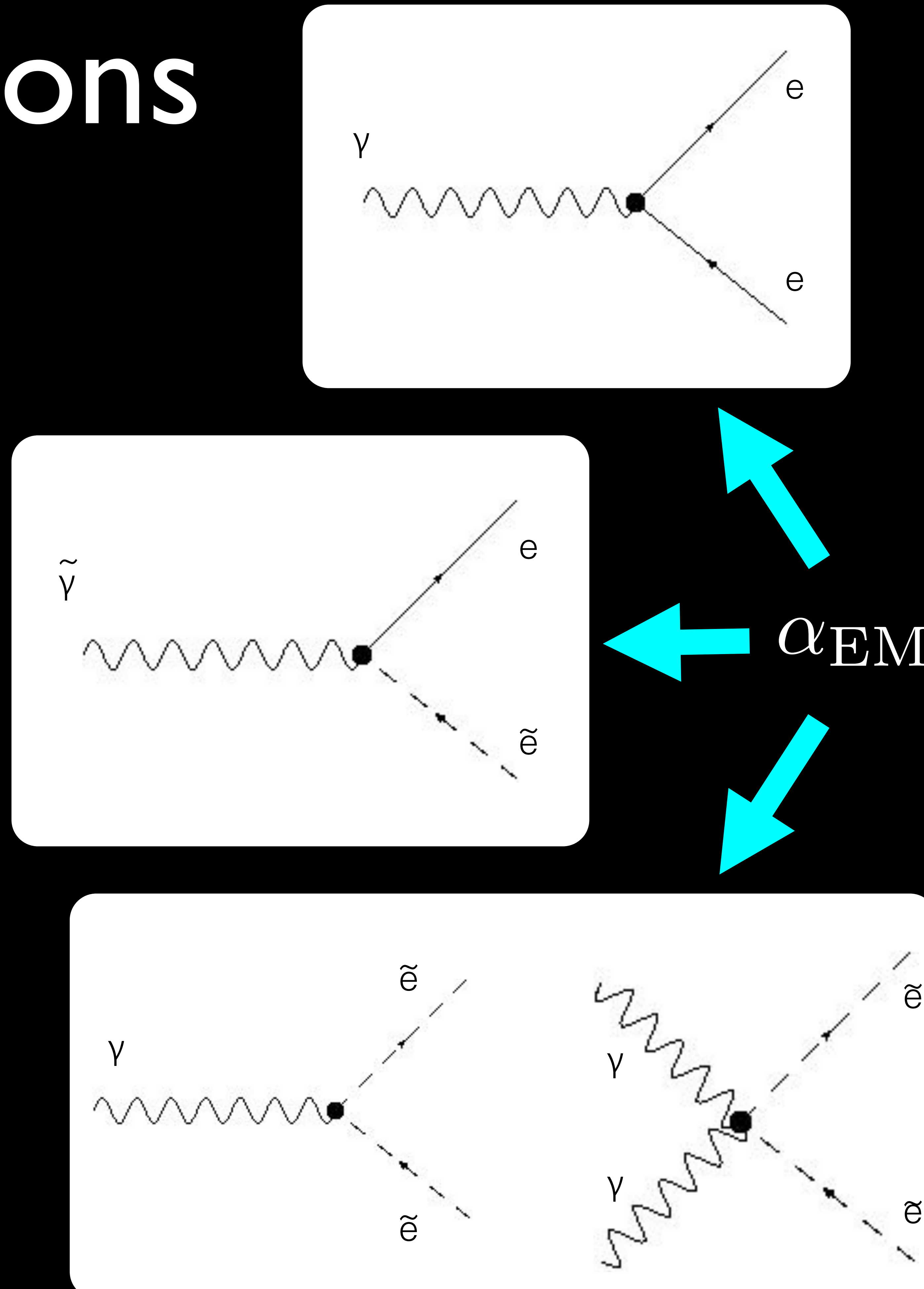


Particle Fever
D.E. Kaplan



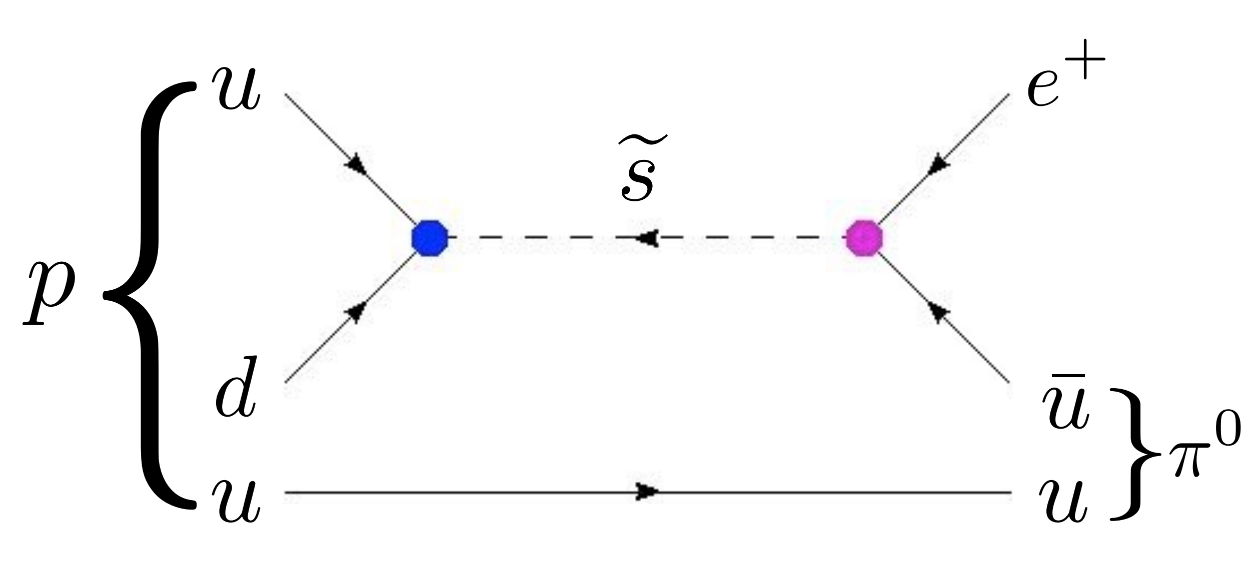
SUSY Interactions

- If we break supersymmetry "softly", the masses of the super-partners will separate, but the interactions remain fixed by supersymmetry.
- Despite having many, many new parameters, SUSY theories inherit a huge structure from the SM.
- This implies that many things can be calculated in supersymmetric theories in terms of the masses of the superpartners.
- See: Yael's lectures or Martin, hep-ph/9709356 for a more complete introduction to SUSY.



R-Parity

- By itself, supersymmetry does not imply a stable massive particle.
- It has interactions which would naively violate baryon and lepton number, and do scary things like make protons decay.
- The usual take on this is to simply forbid all of these interactions by invoking a symmetry: R-parity.
- R-parity insures that the superpartners only couple in pairs to the SM.
  - It produces a stable particle!

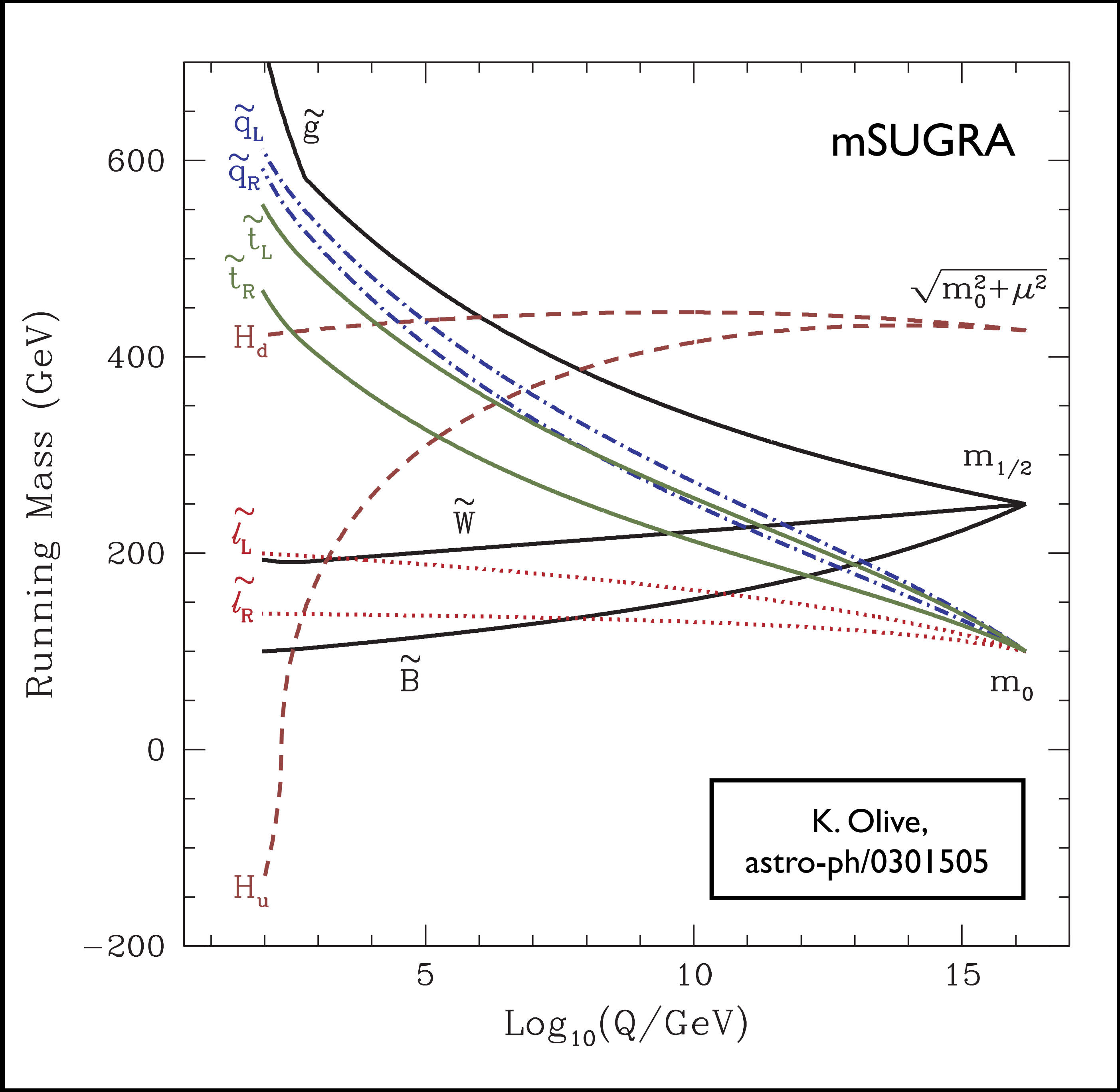


$$R_P \equiv (-1)^{3(B-L)+2S}$$

SM particles: +1
Superpartners: -1

Identity of the LSP

- If the Lightest Supersymmetric Particle is stable, any superpartners present in the early universe will eventually decay into them.
- The LSP had better turn out to be neutral if we would like it to play the role of dark matter.
- For a given model of SUSY breaking, we can calculate the spectrum and determine which particle is the lightest.
- In fact, there are some generic trends that come about from the renormalization group.



Neutralino Dark Matter

- In the MSSM, the 4 neutralinos are Majorana fermions which are mixtures of the superpartners of W_3, B, and the two neutral Higgses.

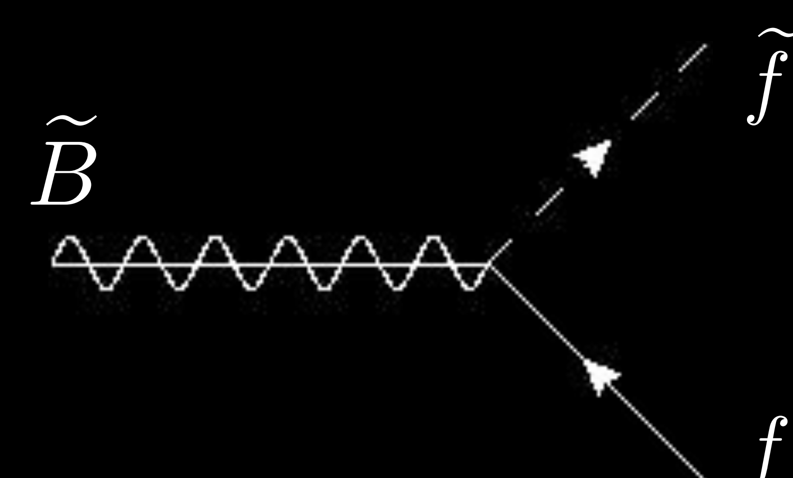
$$\widetilde{\chi}_1^0 = N_{11}\widetilde{B} + N_{12}\widetilde{W}_3 + N_{13}\widetilde{H}_1^0 + N_{14}\widetilde{H}_2^0$$

- As a result, their interactions are a little complicated: it depends on what admixture of each state is present.

- The RGEs typically result in an LSP which is mostly Bino, with a small amount of Higgsino and W3ino.

- Specific models of SUSY breaking may upset these expectations.
  - AMSB: W_3ino WIMP

Bino: Couples to g1 Y
(interactions with the SM
involve the sfermions)



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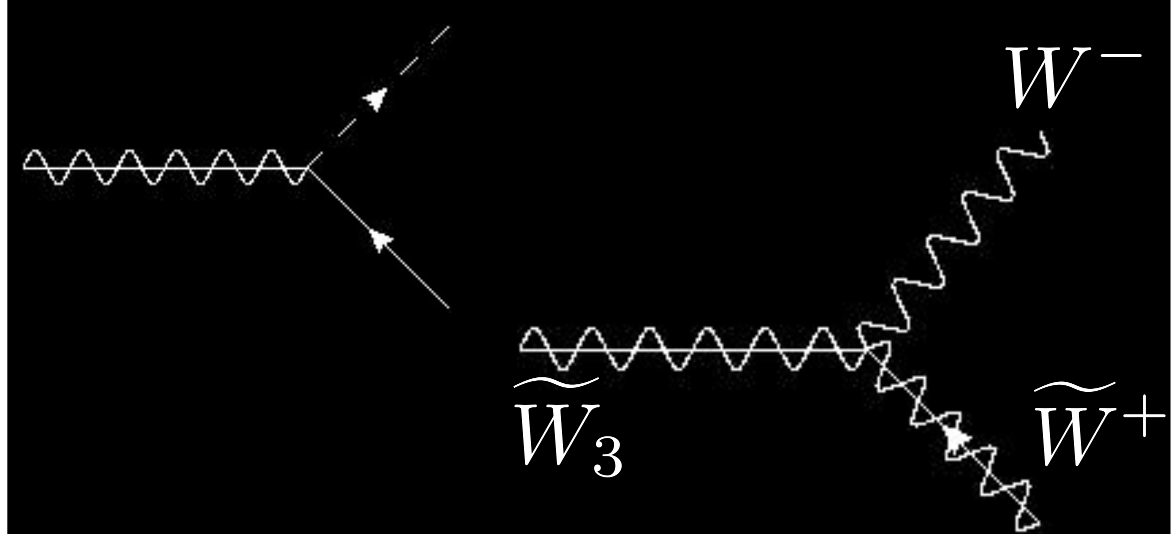
W3ino: Couples to g2 T3 (interactions with sfermions and W -- not Z! -- bosons)



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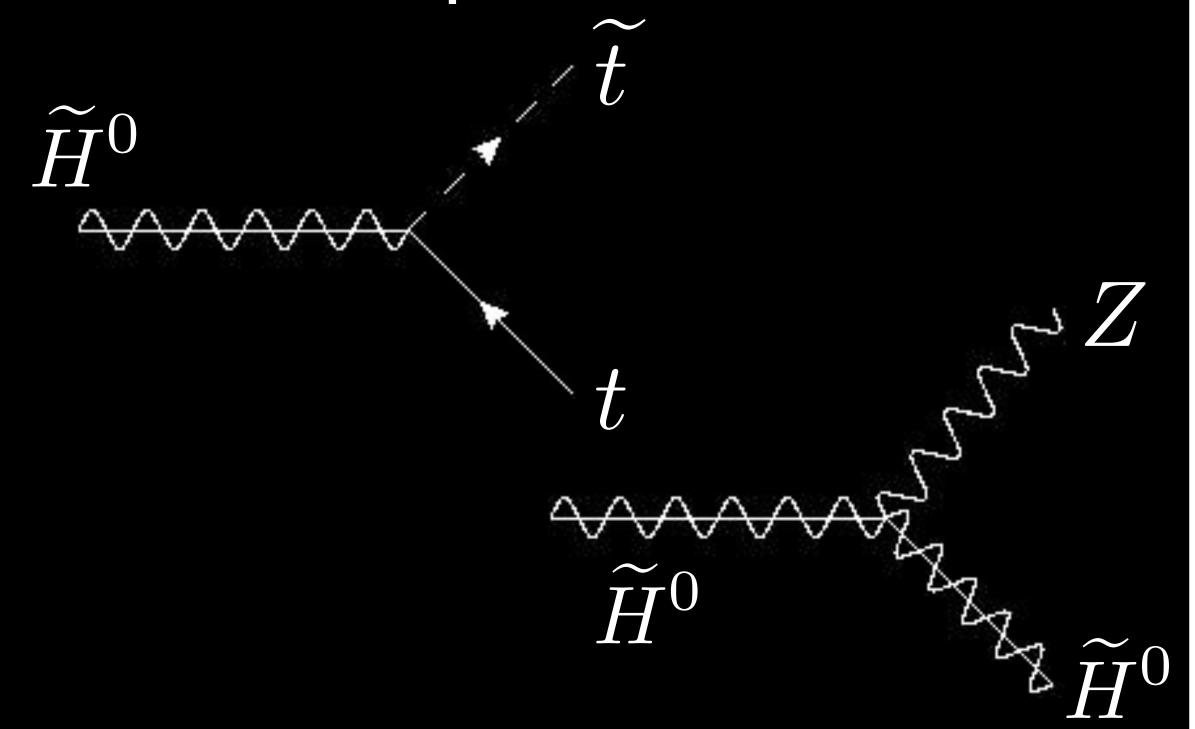
Higgsino: Couples to massive particles



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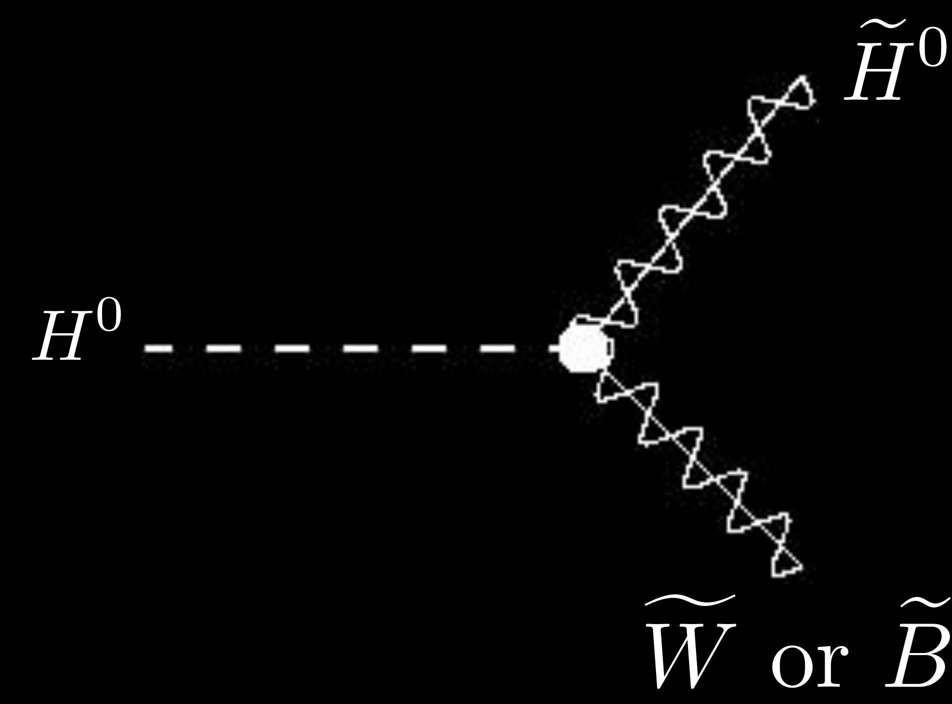
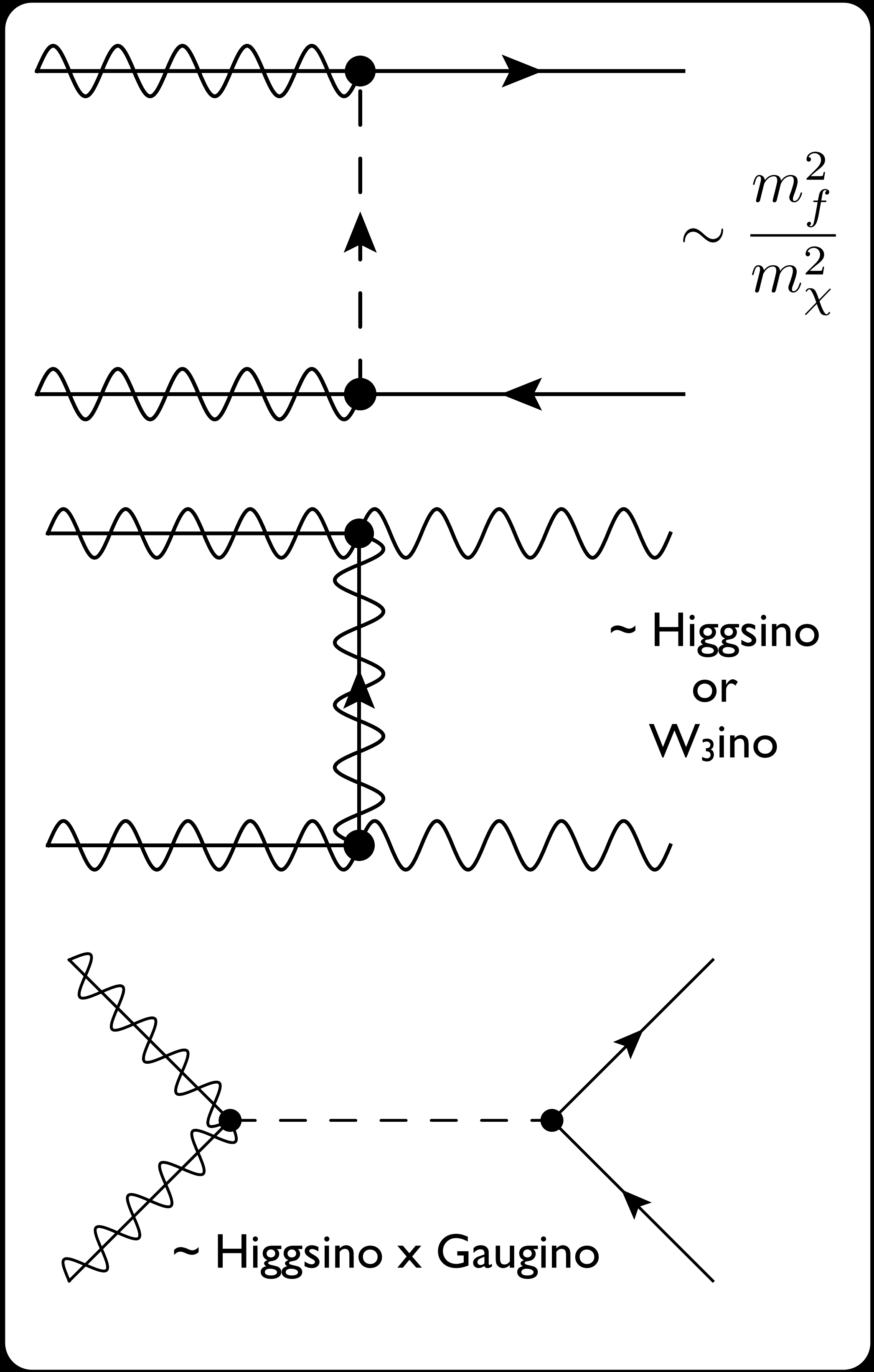
Higgs interactions are hybrids...



Annihilation

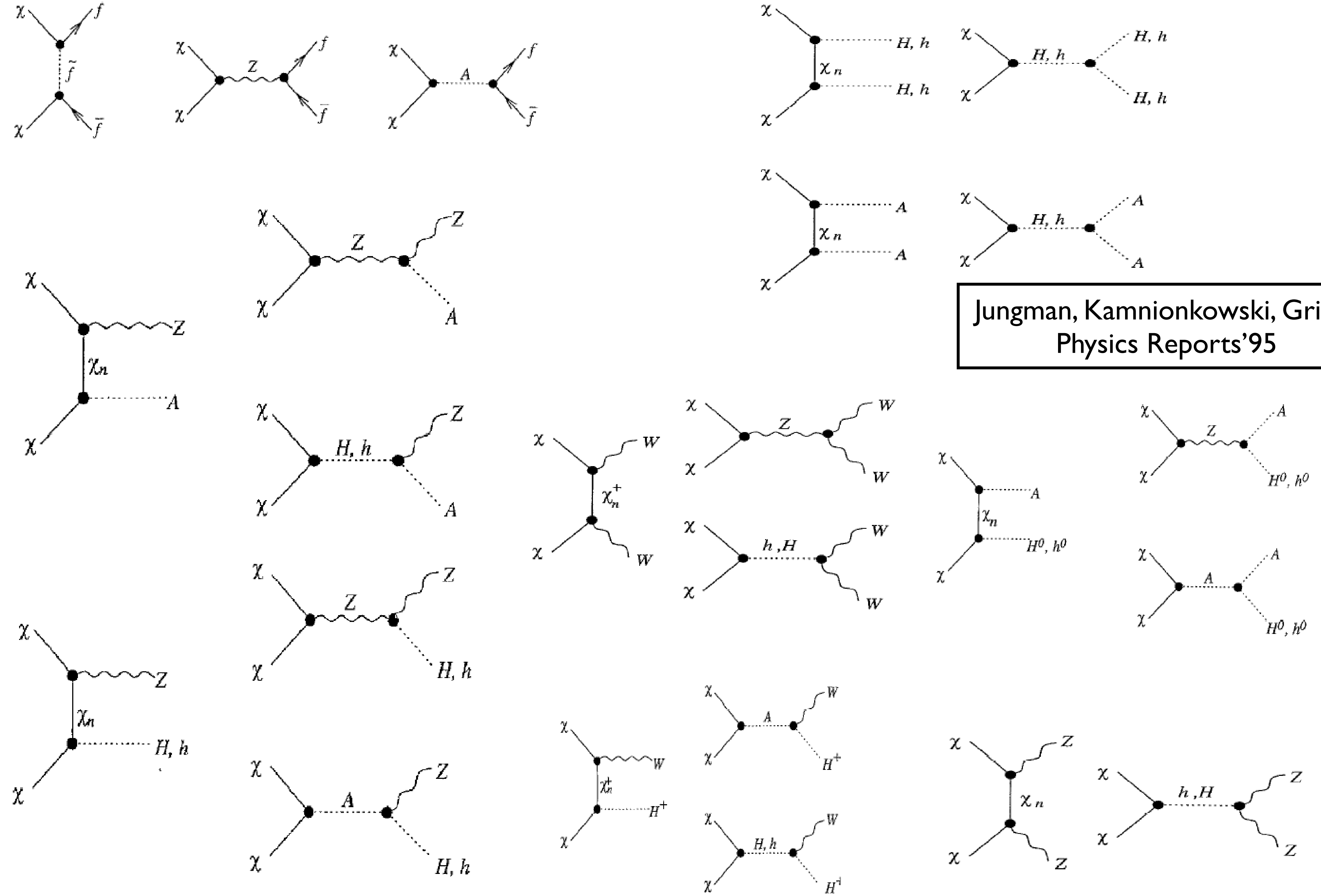
- Now we have everything we need to look at neutralino annihilations. This is a complicated process... but we can understand some general features.

- Neutralinos are Majorana fermions.
  - In the non-relativistic limit, they are Pauli-blocked from an initial S=1 state.
  - No annihilation through an s-channel vector particle.
  - Sfermion exchange likes to produce SM fermions of like-chirality, (S=1) and is suppressed by m_f for an S=0 initial state.



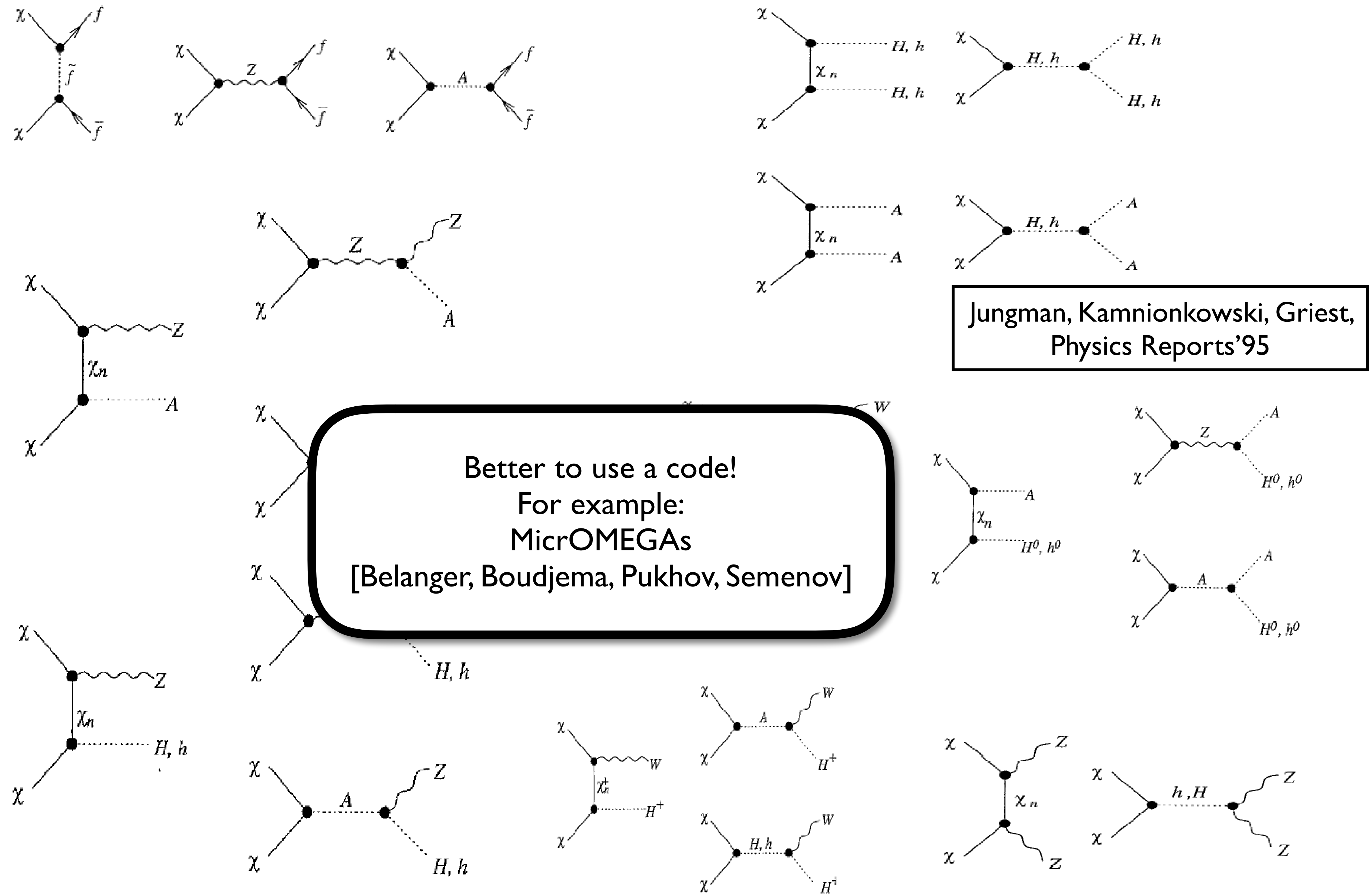
Bottom Line: Suppressed <σ v> leads generically to too many Binos.

A Plethora of Processes



Jungman, Kamnionkowski, Griest, Physics Reports'95

A Plethora of Processes

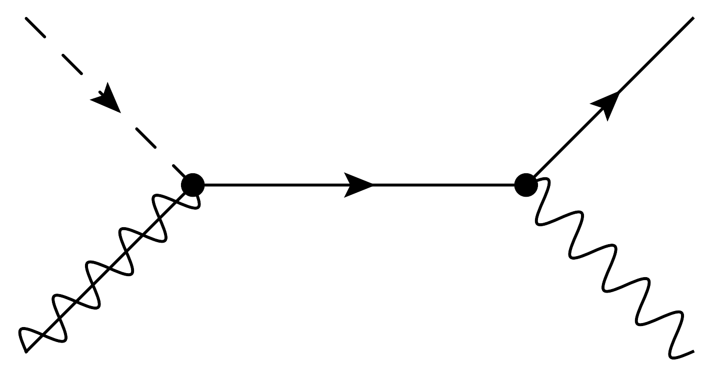


Jungman, Kamnionkowski, Griest,
Physics Reports'95

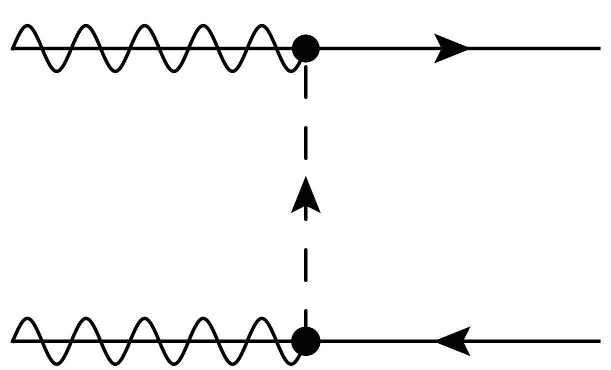
Better to use a code!
For example:
MicrOMEGAs
[Belanger, Boudjema, Pukhov, Semenov]

Relic Density: Small Tan β

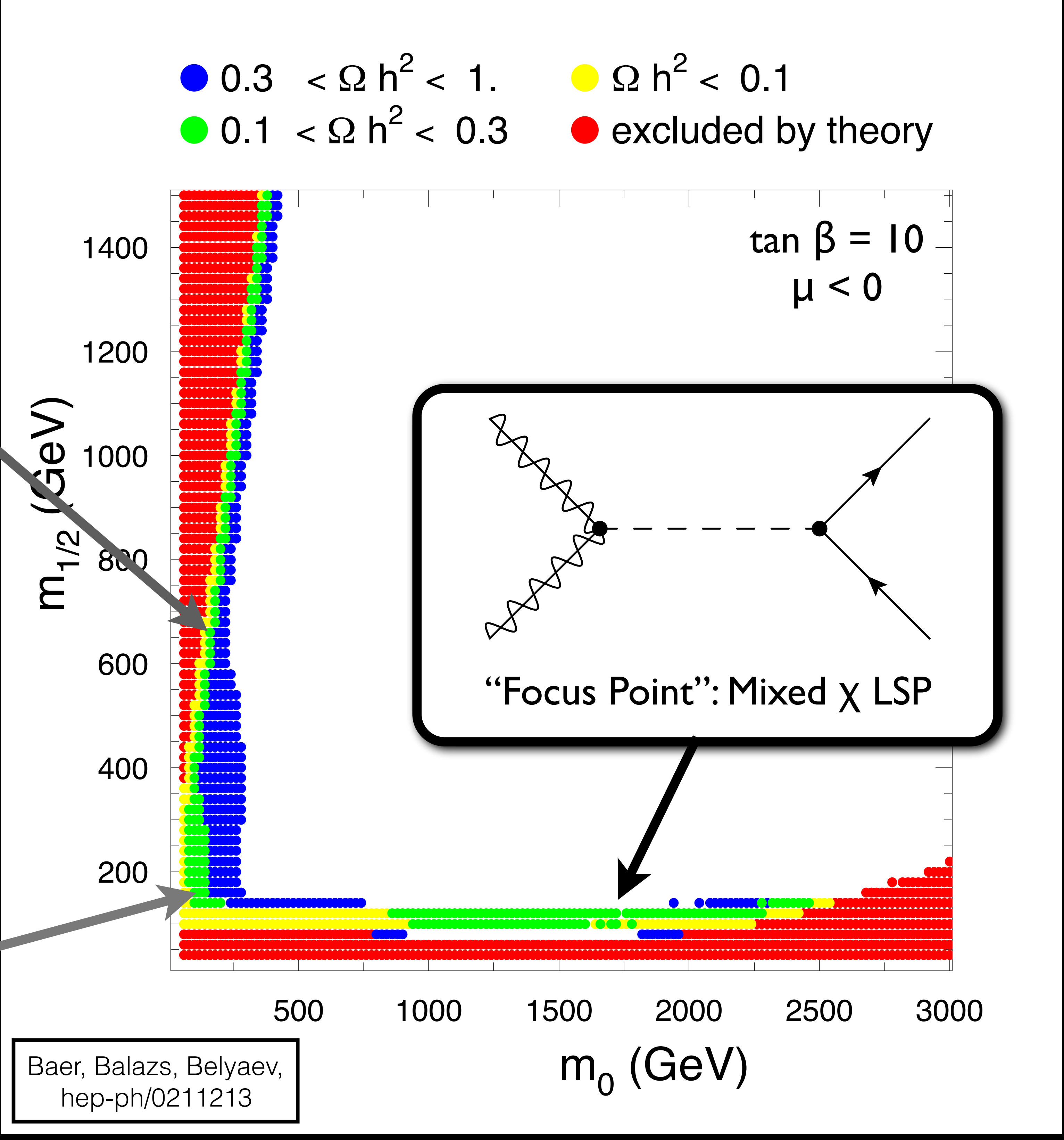
mSUGRA



"Coannihilation Region": Degenerate stau active during freeze-out



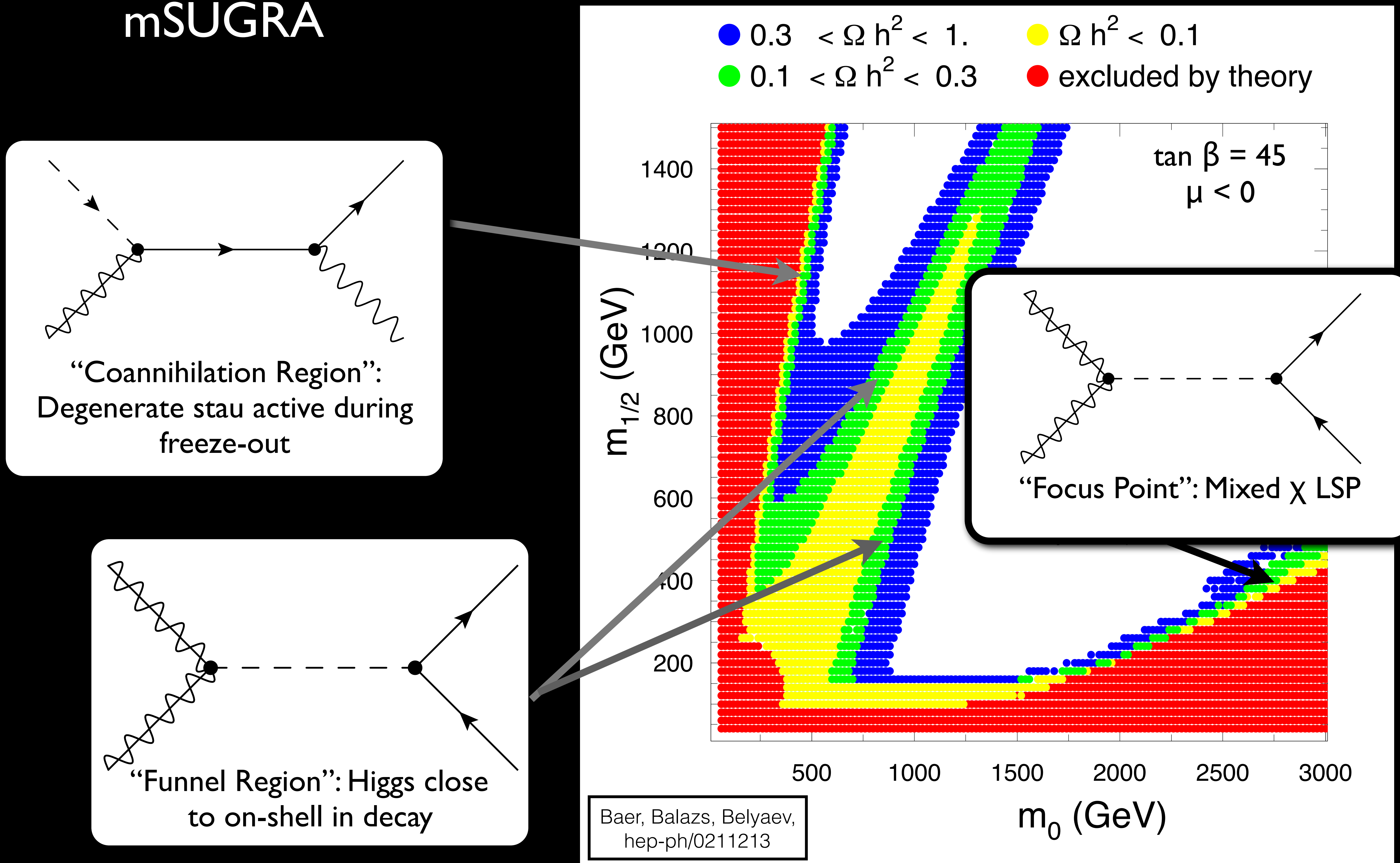
"Bulk Region": Light sfermions (~excluded by LHC)



"Focus Point": Mixed χ LSP

Large Tan β

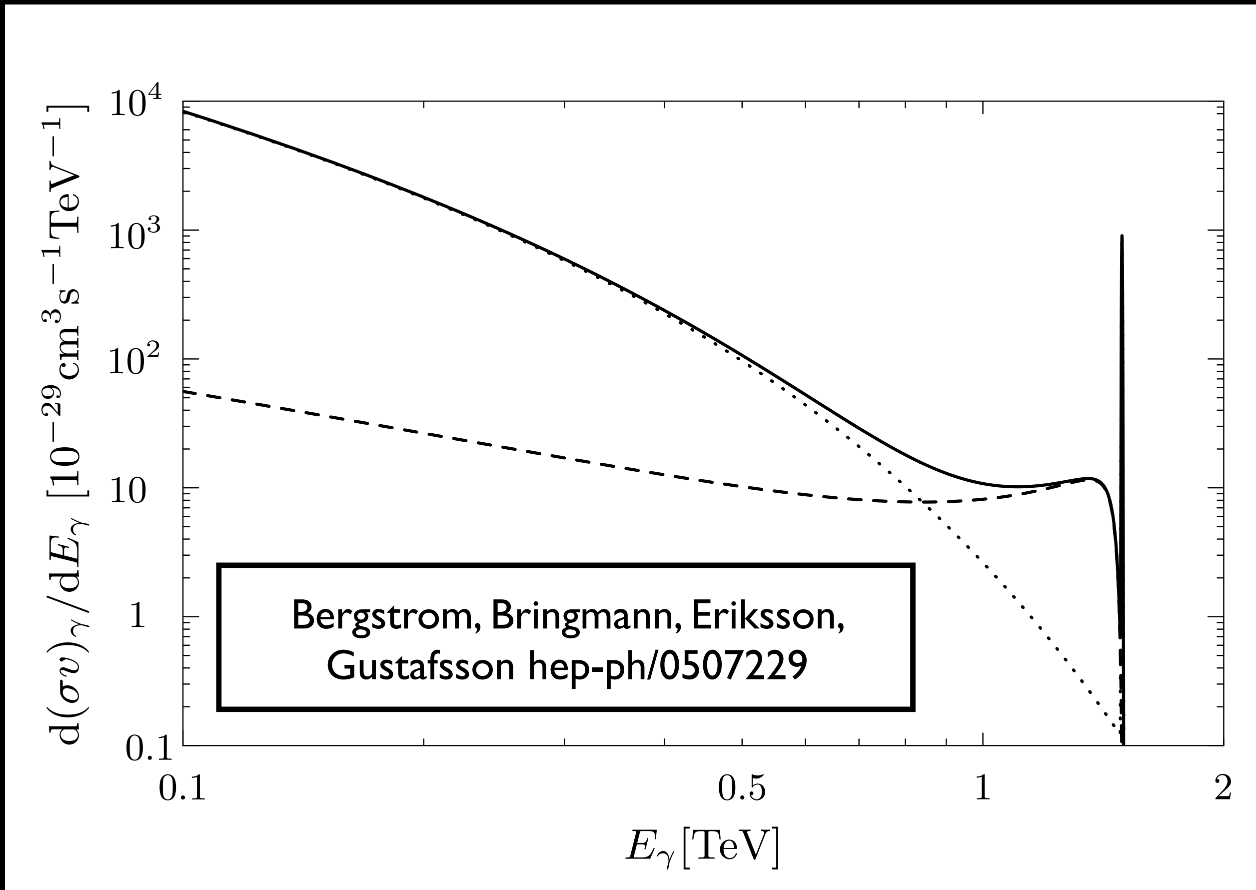
mSUGRA



Cosmic Neutralino Signals

- We've already learned a fair amount about how neutralinos annihilate by studying the relic density.
- The same physics controls the search for them annihilating in the halo.
  - As Majorana particles, they tend to annihilate into heavier fermions and/or W bosons.
    - Fermi searches for bb spectra...
  - Loops of charged particles allow them to annihilate into γγ or γZ.
    - A "smoking gun" signal!

1.5 TeV (Mostly) Higgsino LSP



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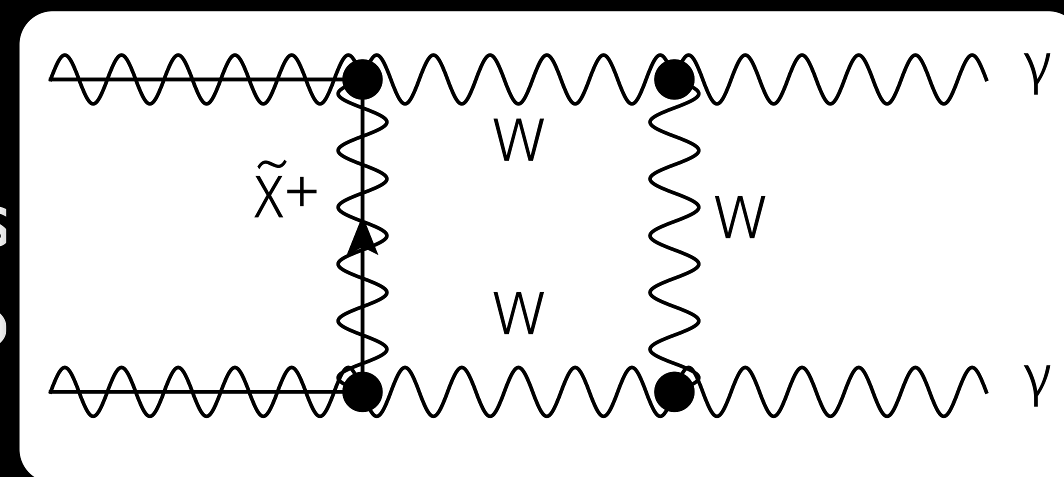

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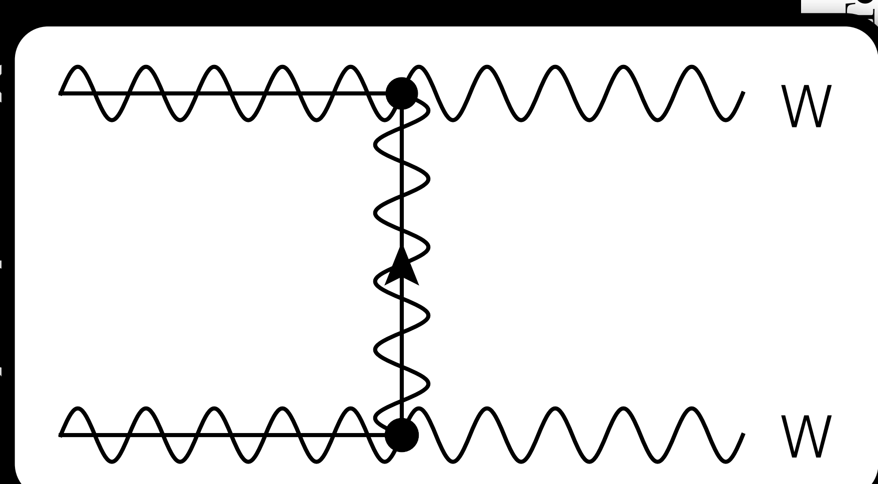
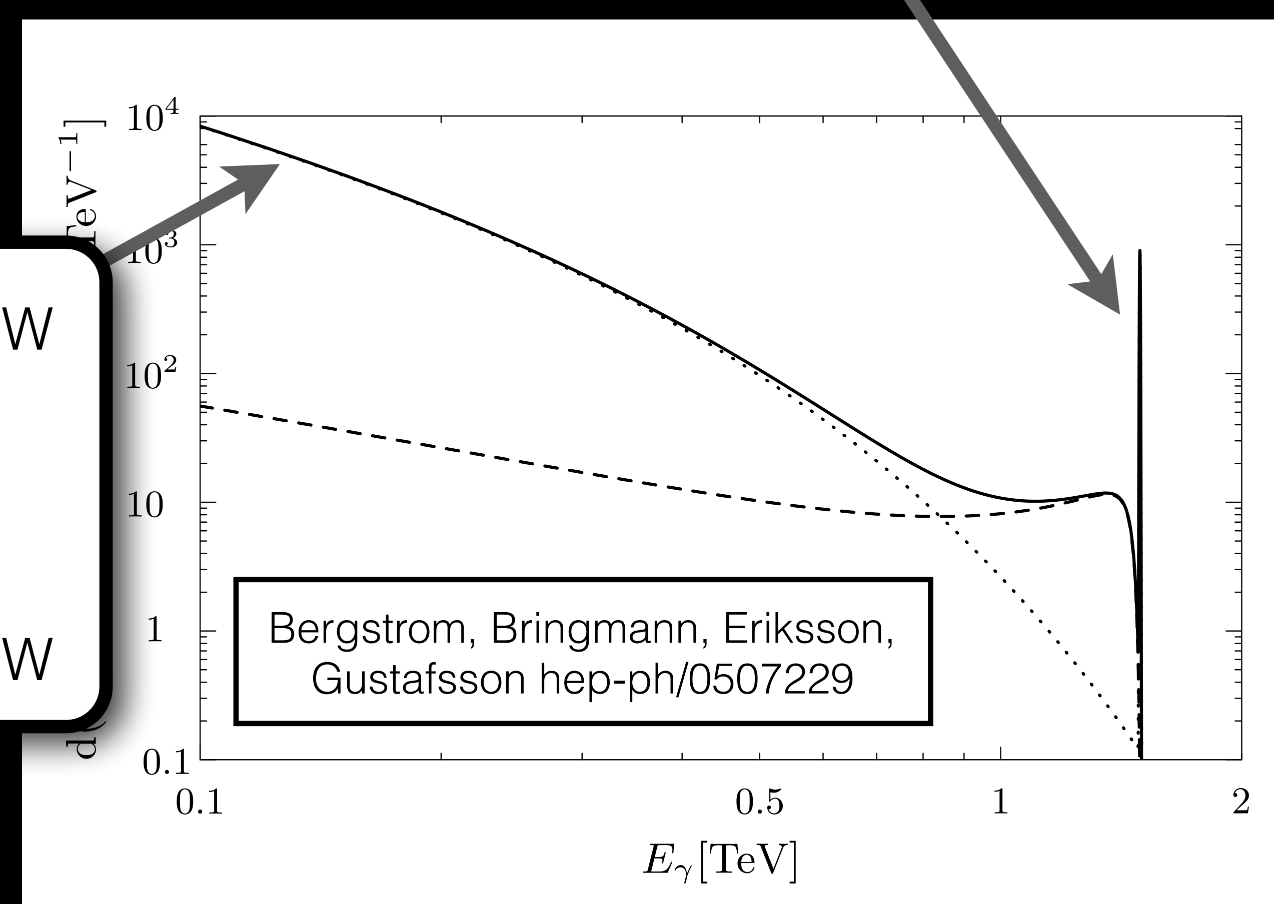
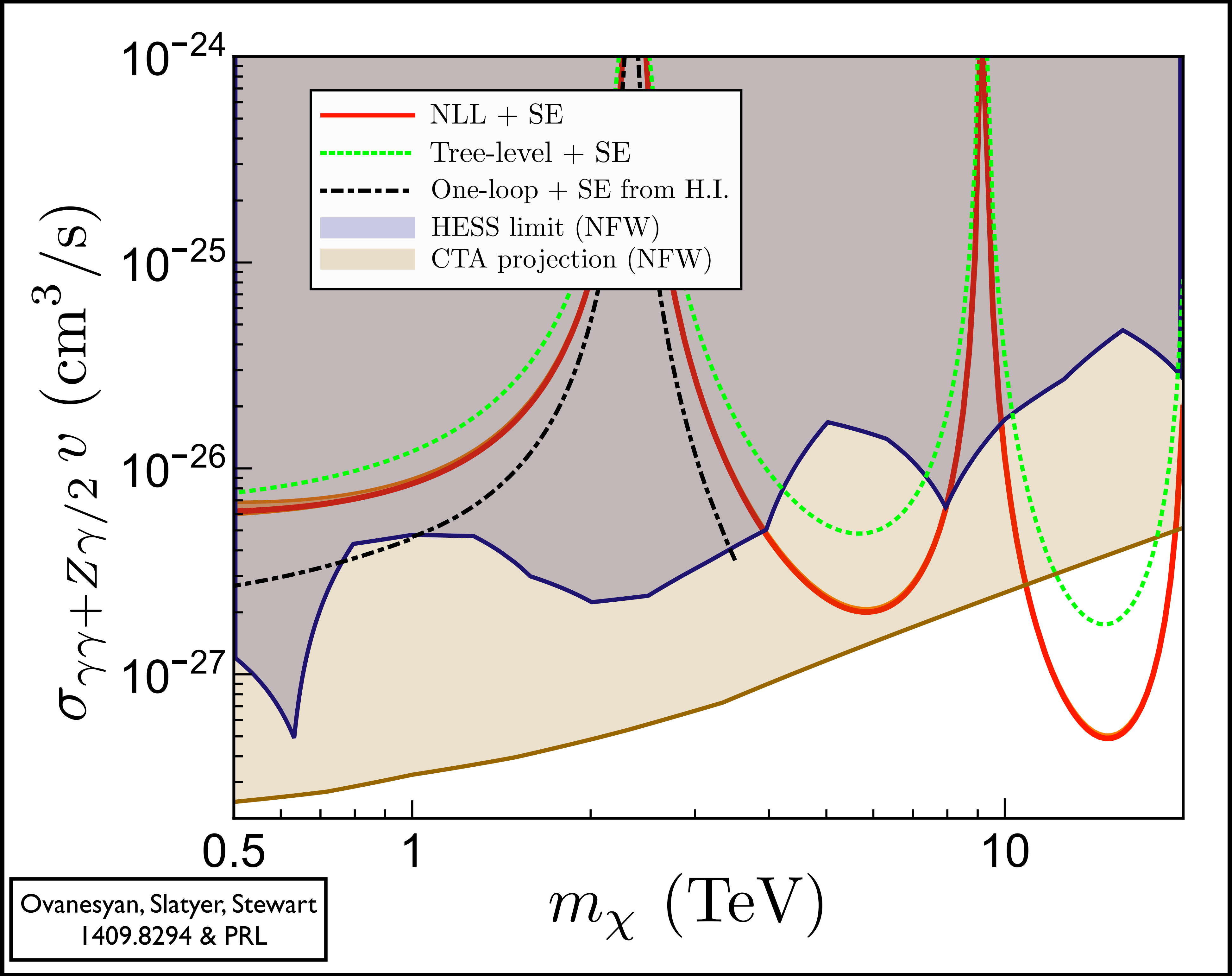




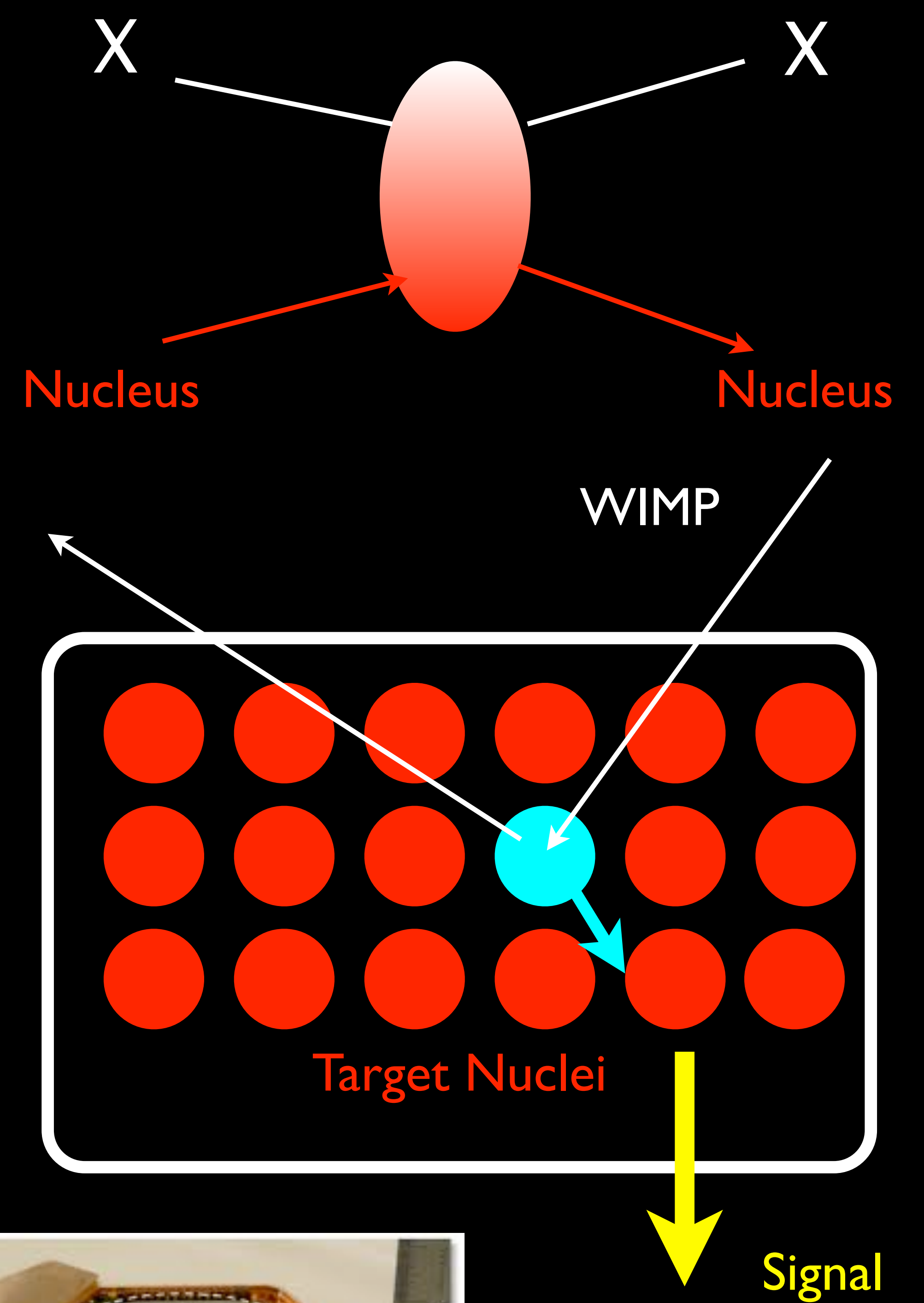
A Window to Winos!

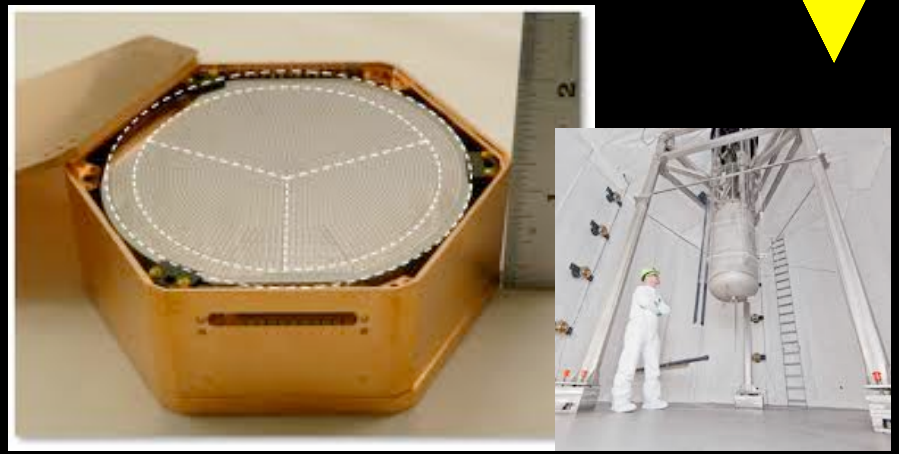


H.E.S.S. limits on the line signal already largely exclude wino dark matter.

Direct Detection

- Before looking at direct detection of neutralinos, let's review some basic features of the searches.
- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when dark matter brushes against it.
- Direct detection looks for the dark matter in our galaxy's halo, and a positive signal would be a direct observation.
- Heavy shielding and secondary characteristics of the interaction, such as scintillation light or timing help filter out backgrounds.
- In the non-relativistic (v -> 0) limit, the DM-nucleon interaction can either be a constant (Spin-Independent scattering) or the dot product of their spins (Spin-Dependent scattering).





Direct Detection

- The rate of a direct detection experiment depends on one power of the WIMP density (close to the Earth).

Nuclear Physics

DM density

$$\frac{dN}{dE} = \sigma_0 \, \frac{\rho}{m} \int dv \, f(v) \, F(E)$$

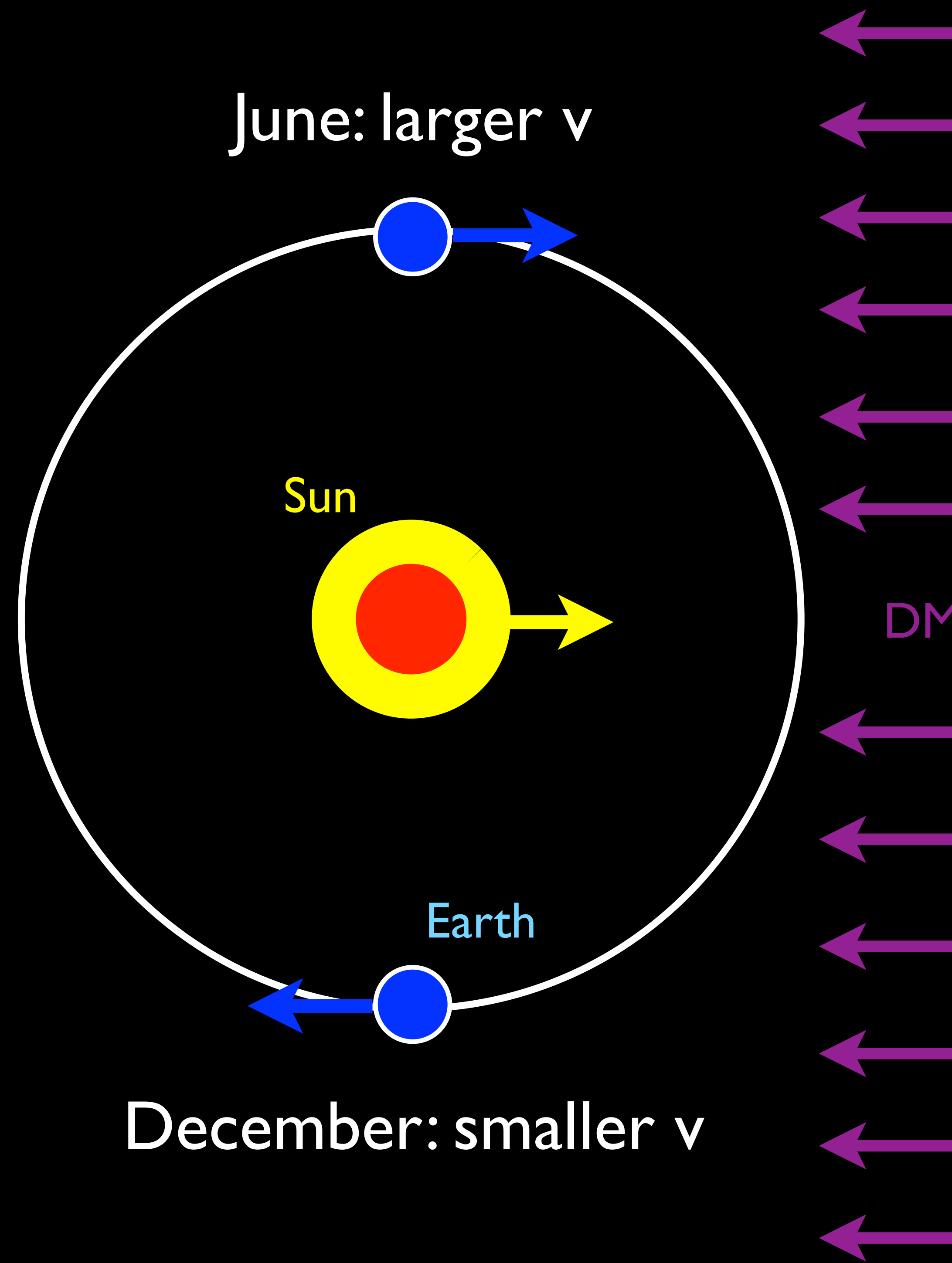
DM velocity distribution

Particle Physics

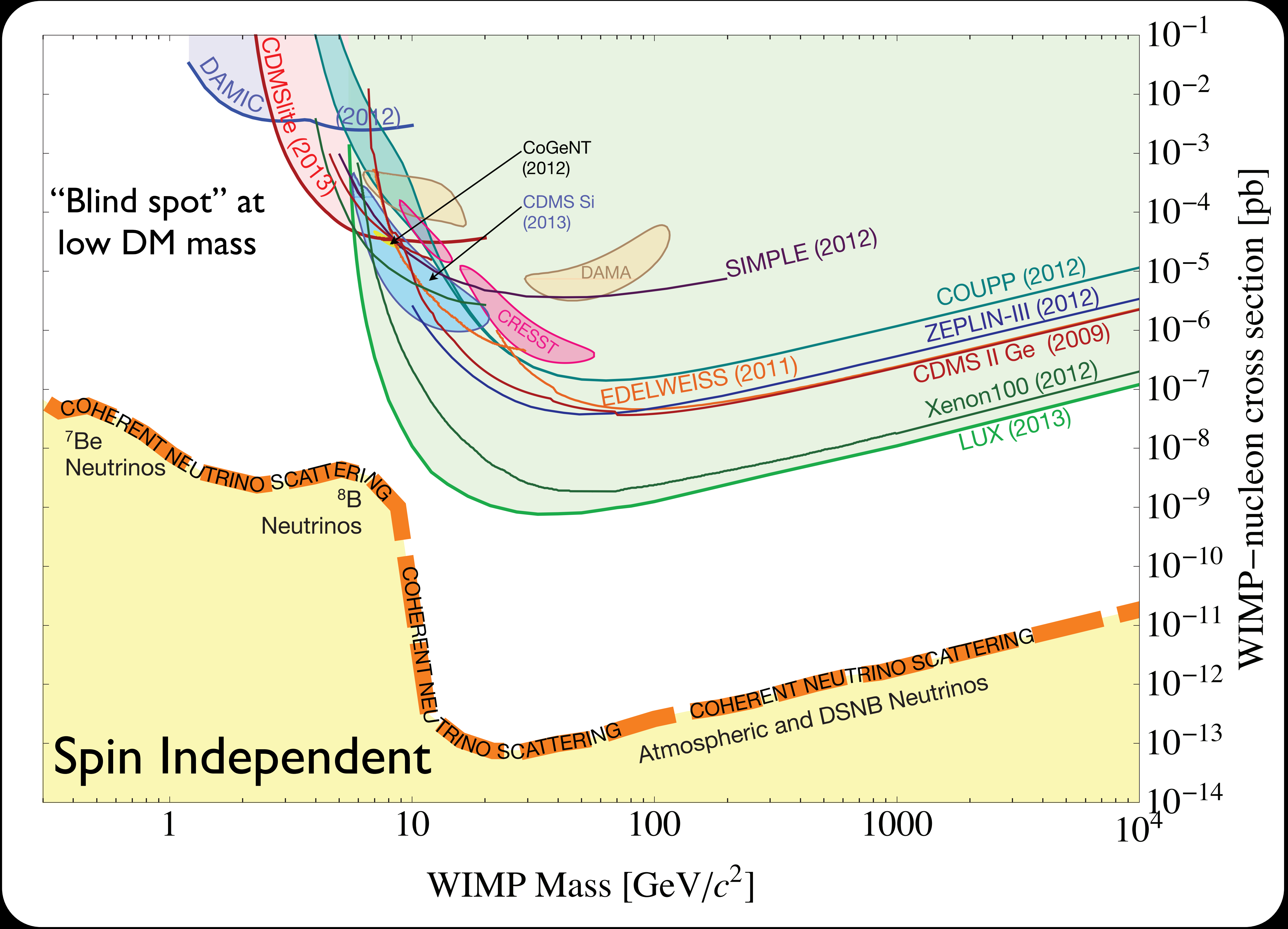
- The energy spectrum of the recoiling nucleus depends on the WIMP mass, its coupling to quarks, and nuclear physics.

- The cross section is dominated by the effective WIMP interactions with quarks and gluons.

- An interesting handle on the signal is an expected annual modulation.



Direct Detection Today

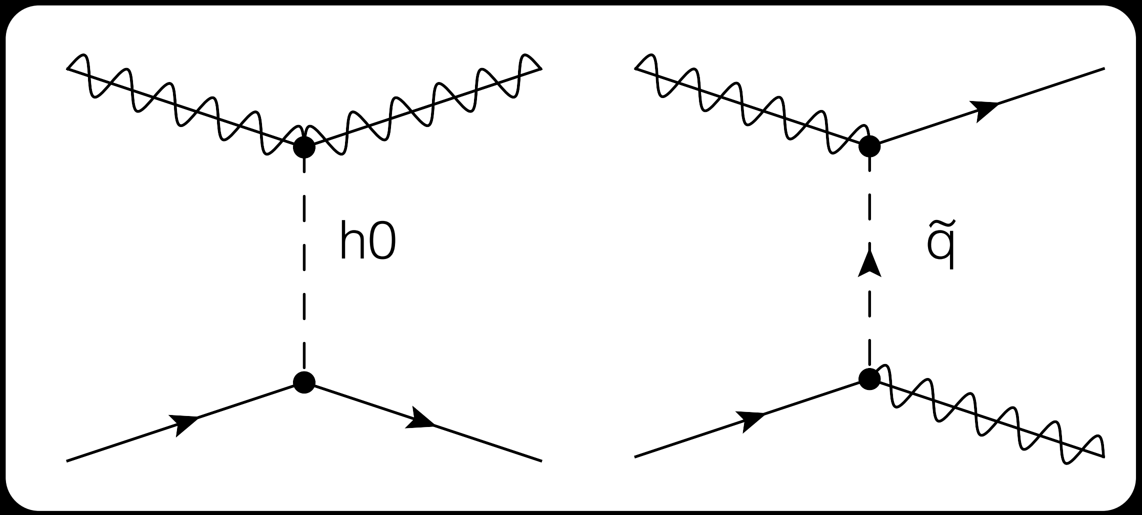


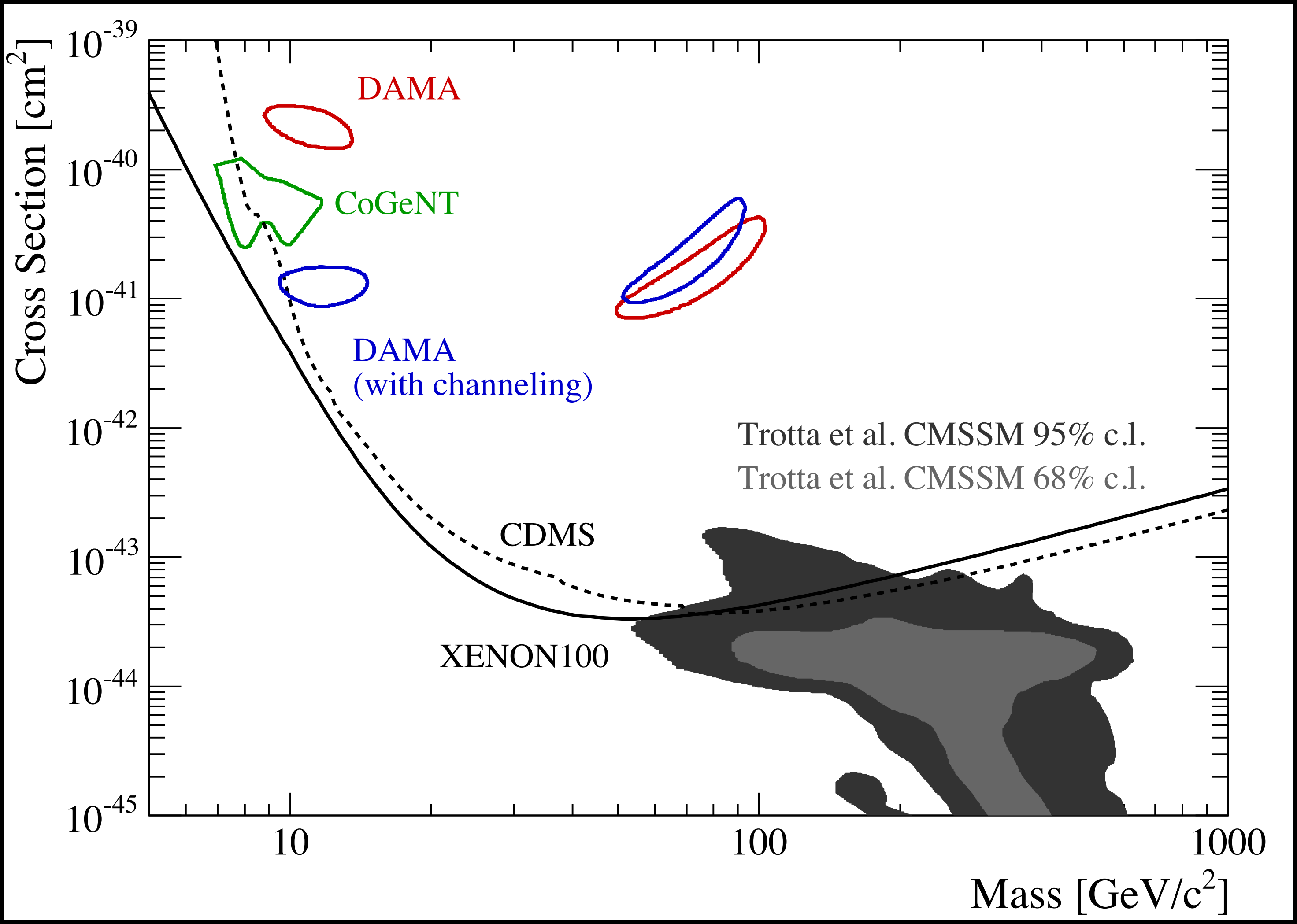
Neutrino "Floor"

Billard, Figueroa-Feliciano, Strigari 1307.5458

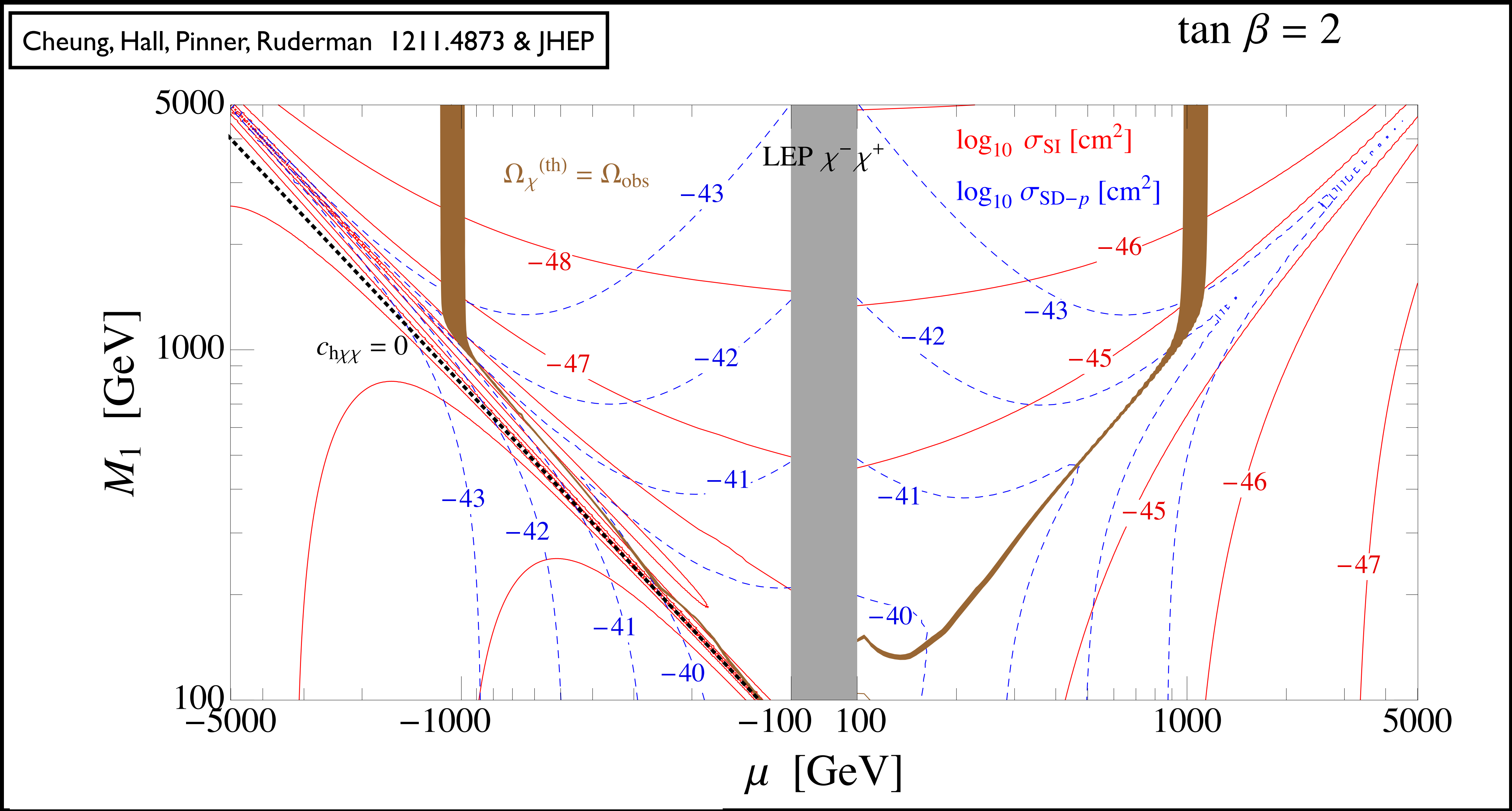
Direct Detection of Neutralinos

- The Majorana character also has important consequences for direct detection.
  - No vector currents imply the Z exchange can only mediate spin-dependent interactions.
  - The Higgs exchange requires both gaugino and higgsino admixture: the rate is very sensitive to the neutralino mixing angles.
  - Direct detection is sensitive to MSSM parameter space!

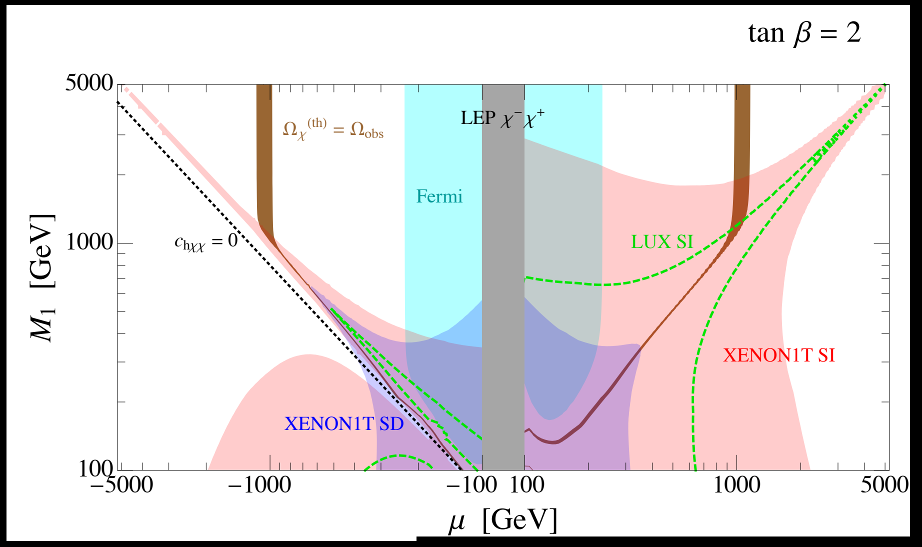




Neutralino Composition

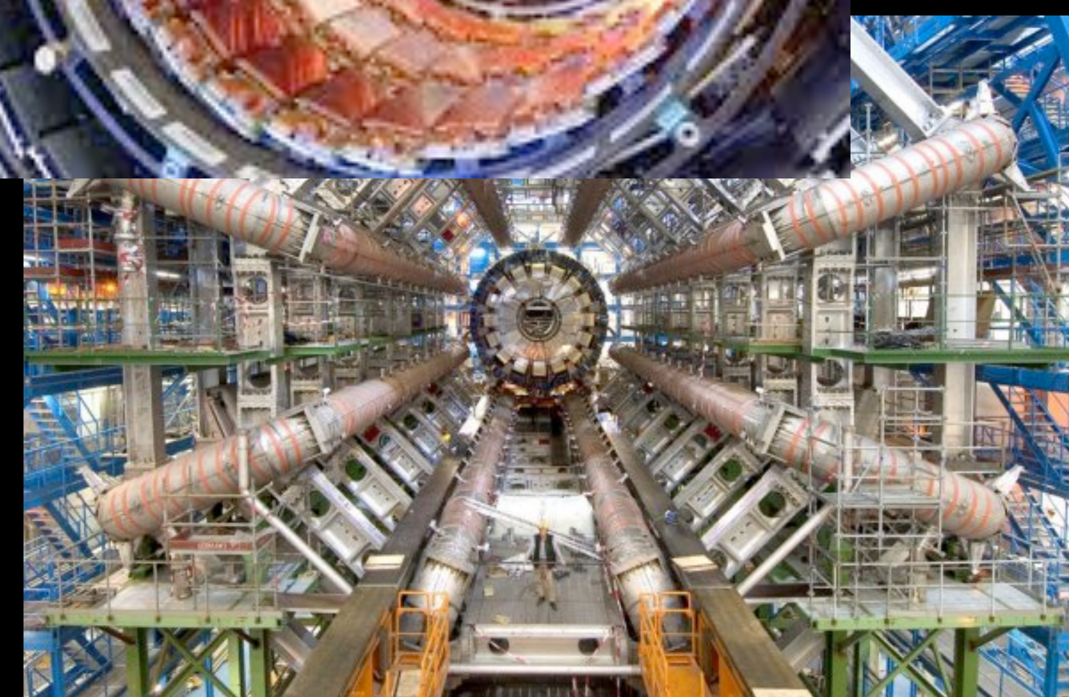


Because of the importance of the coupling to the Higgs, the contours of the SI cross section are highly dependent on the neutralino admixture. A "blind spot" where the neutralino becomes entirely Higgsino occurs for $M_1 + \mu \sin 2\beta = 0$.



Collider Production

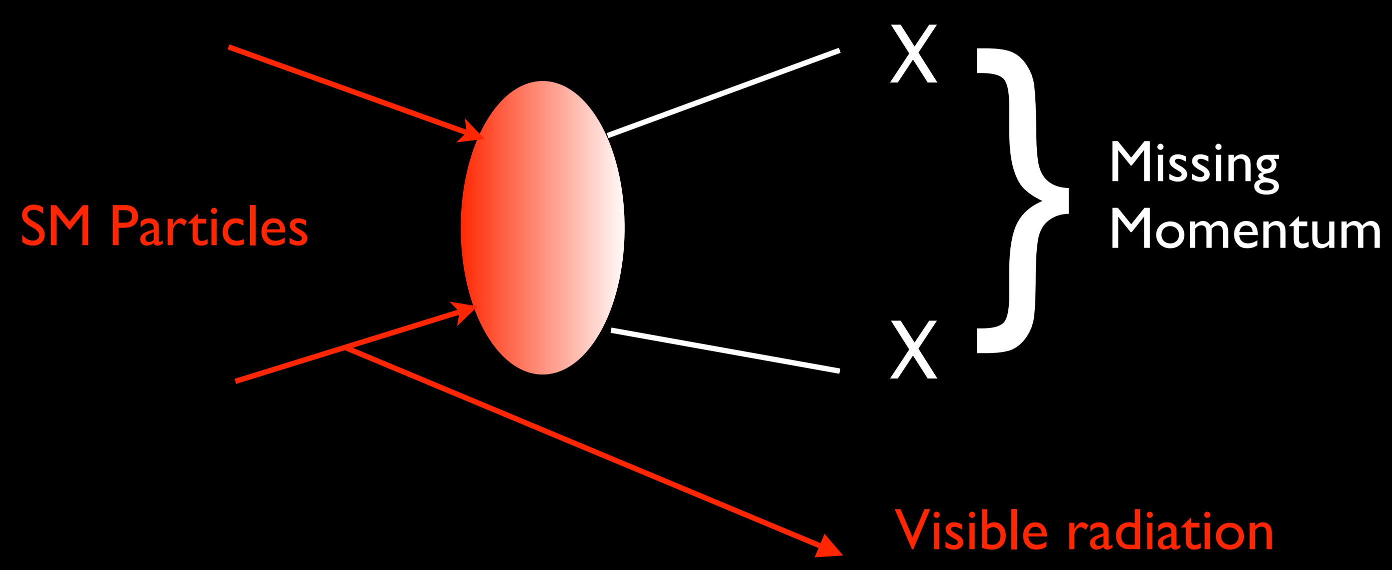
- If WIMPs couple to quarks or gluons, we should also be able to produce them at high energy colliders.
- By studying the production of WIMPs in collisions of SM particles, we are seeing the inverse of the process which kept the WIMPs in equilibrium in the early Universe.
- Provided they have enough energy to produce them, colliders may allow us to study other elements of the "dark sector", which are no longer present in the Universe today.

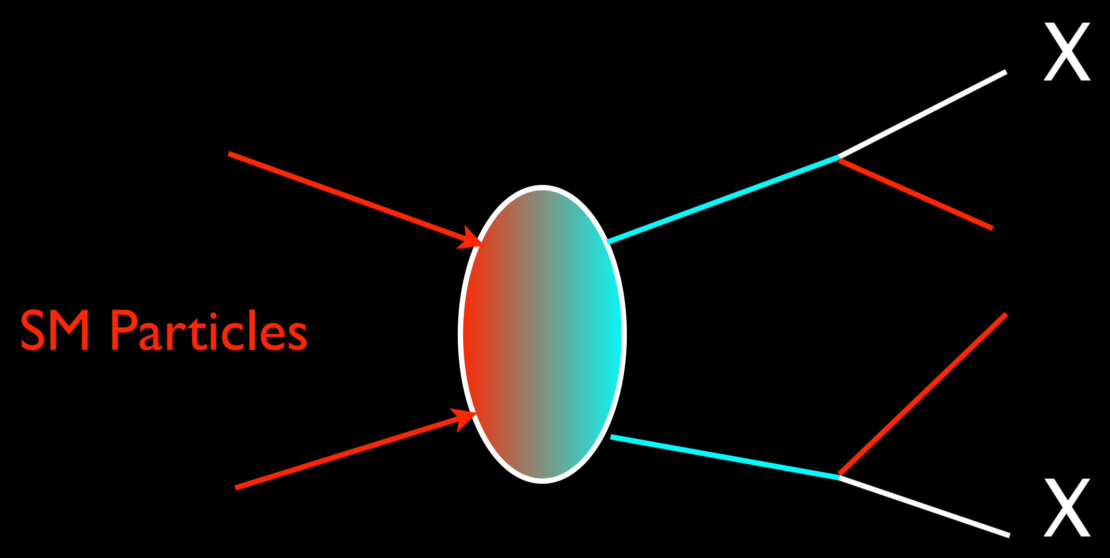


Very sophisticated detectors with many, many (many!) subsystems: But no WIMP detectors.

Seeing the Invisible?

- WIMPs interact so weakly that they are expected to pass through the detector components without any significant interaction, making them effective invisible (much like neutrinos).
- There are two ways we can try to "see" them nonetheless:



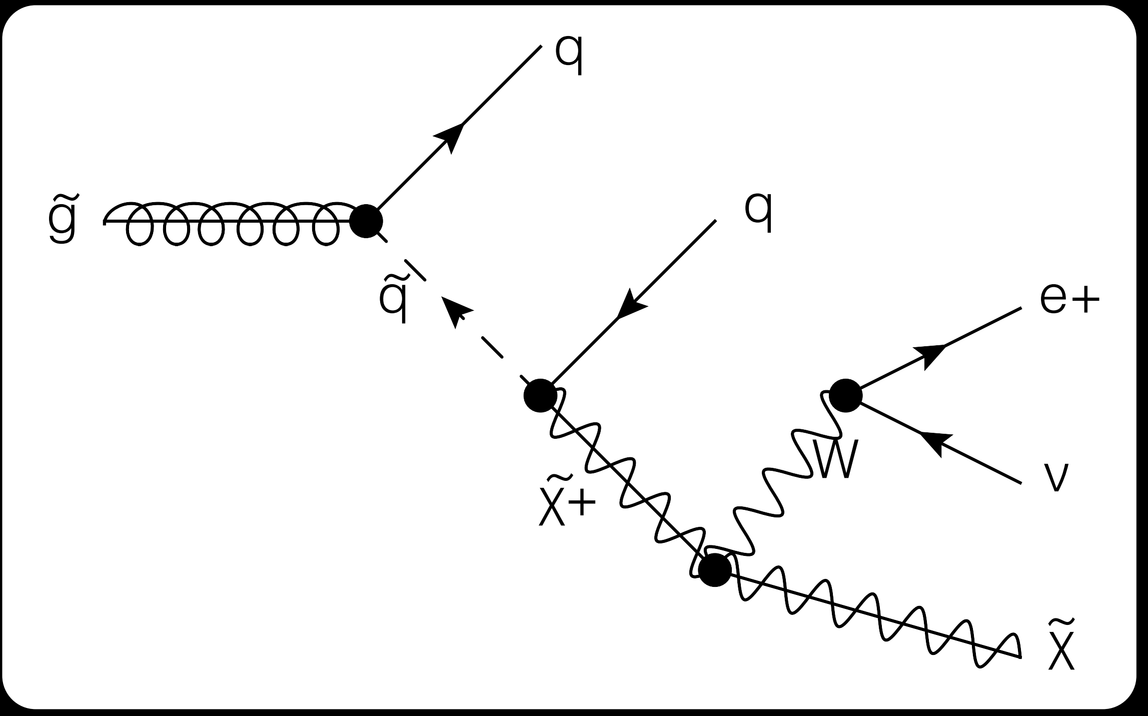


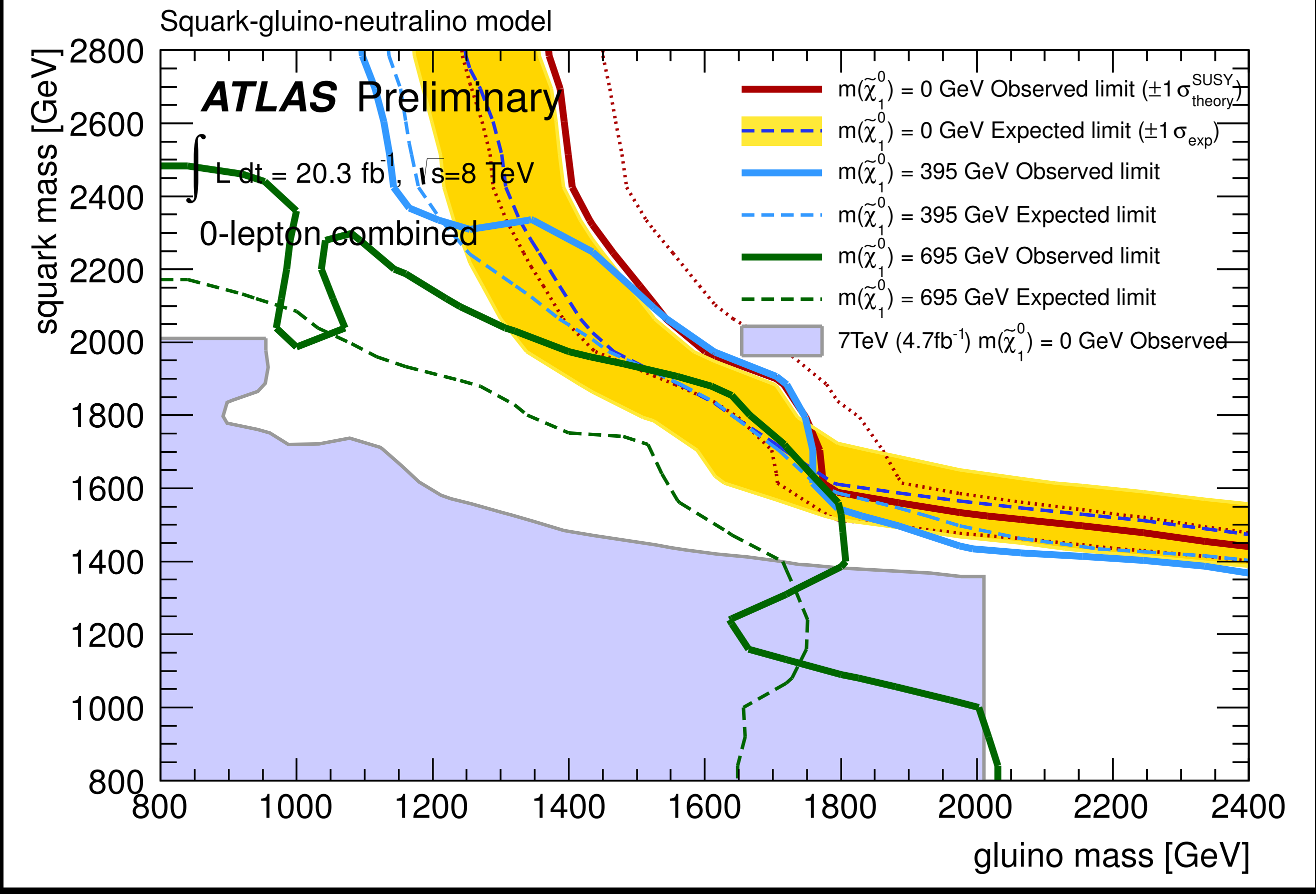
Radiation from the SM side of the reaction.

Production of "partners" which decay into WIMPS + SM particles.

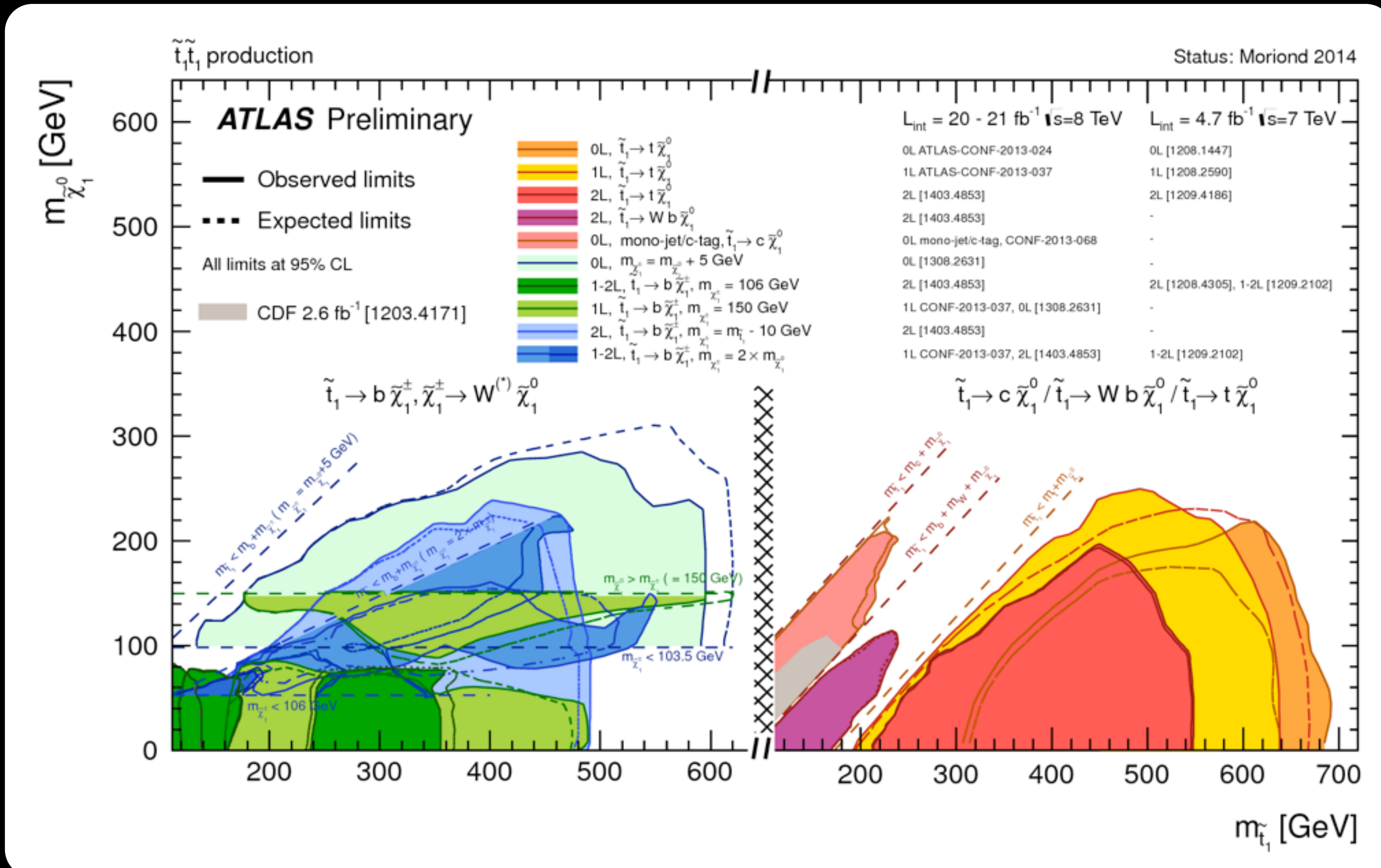
Collider Signals

- At hadron colliders like the LHC, the largest signals tend to come from producing the colored superpartners.
  - There can be "Cascade" decays down to the LSP.
  - The LSP passes through the detector, leading to missing momentum.
  - Hard jets are also present.
  - Depending on the decay chain, there may be hard leptons as well.
  - Often pairs of leptons will have the same charge, a signal with small expected SM backgrounds.





3rd Generation Squarks

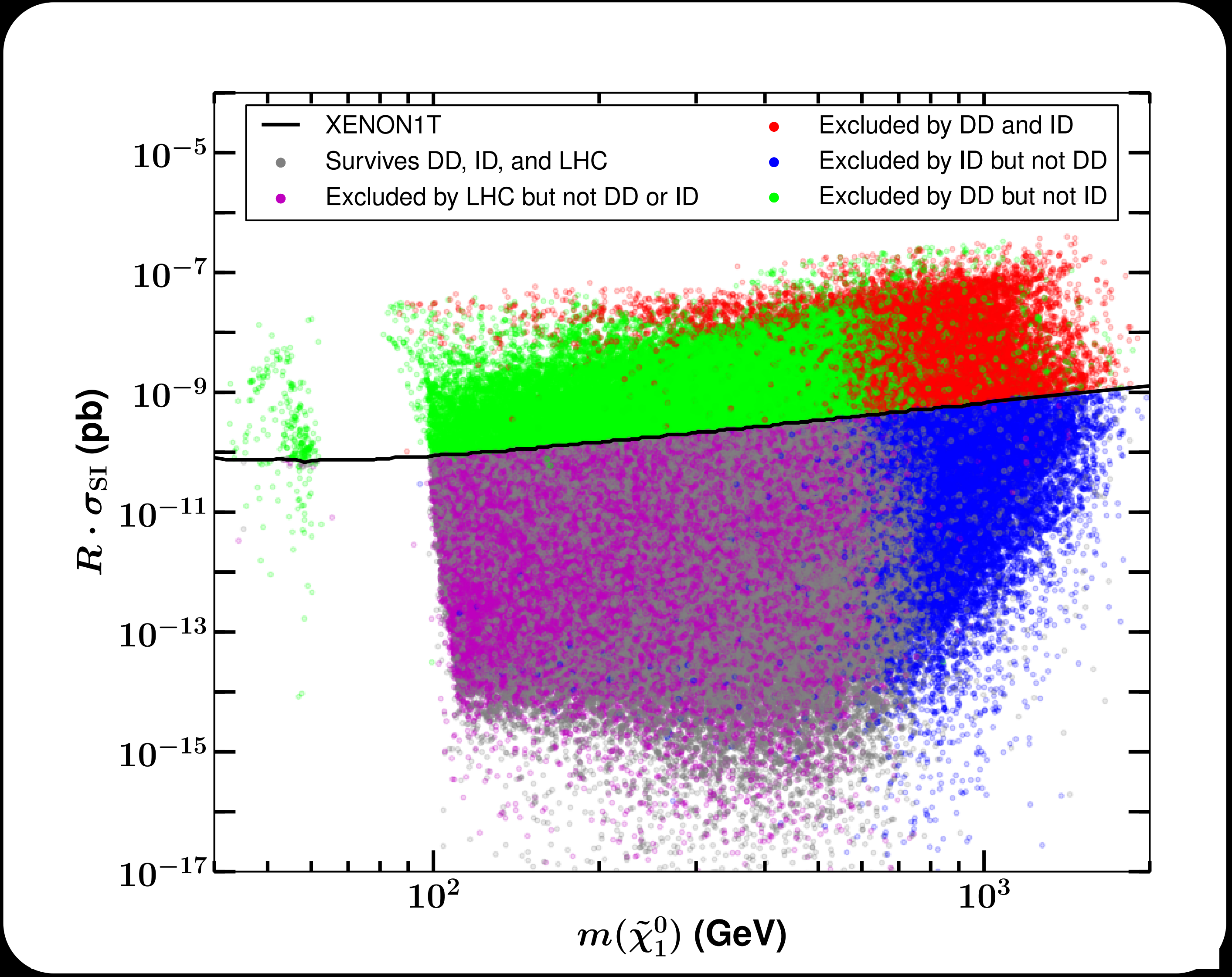


We're also starting to see searches for electroweak superpartners from the LHC.

- Naturalness requires SUSY to have light(ish) stops. This should be balanced by the fact that in the MSSM, the Higgs mass is calculable, suggesting the stops aren't *too* light.
- Searches for stops are starting to reach 600-700 GeV, and carving out the natural regions of supersymmetry!

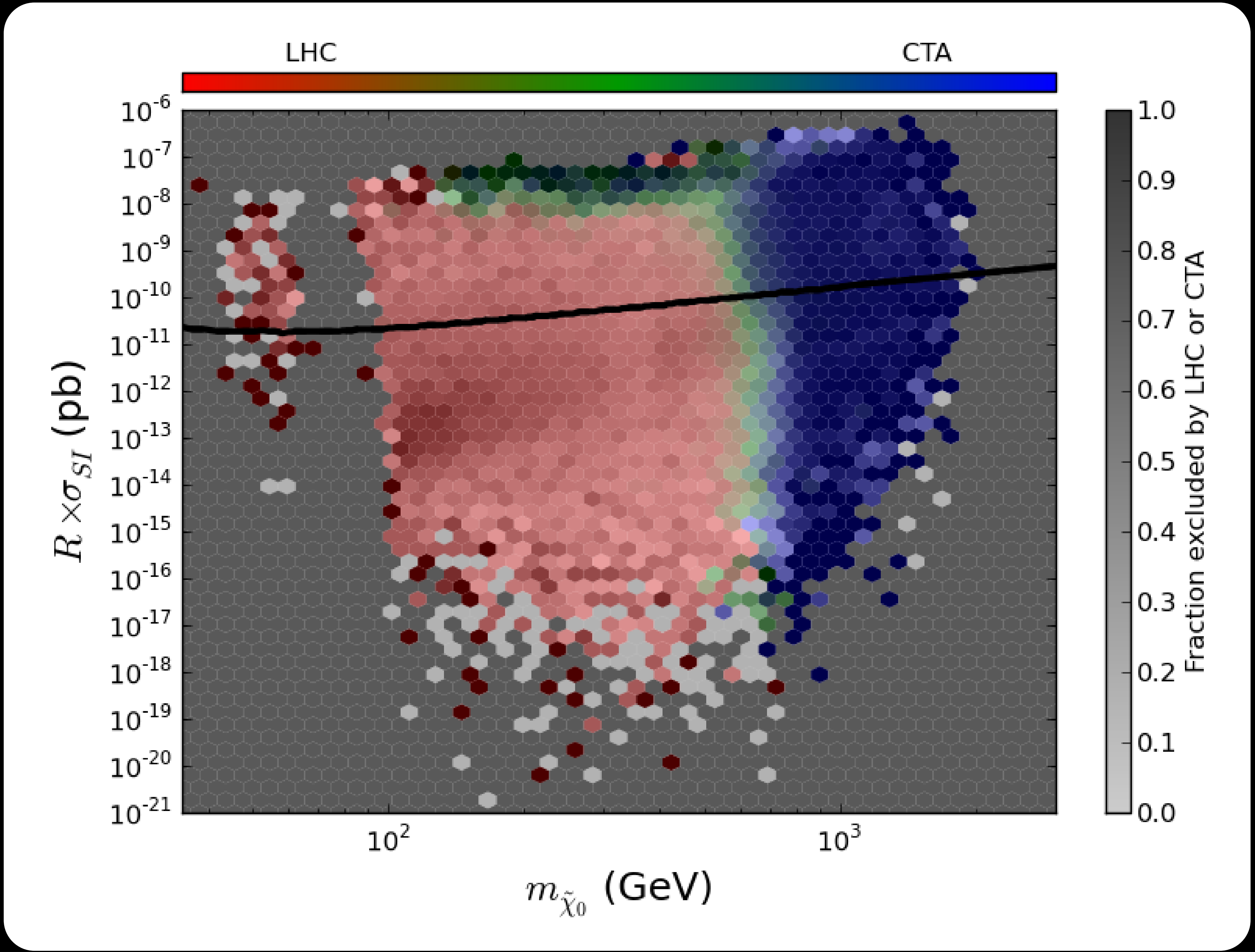
Reconstructing the MSSM

- While we can hope to eventually have many, many signals to measure, the parameter space is also very large.
  - Even simplified versions like the "pMSSM" have ~20 parameters!
  - Mapping from signal to parameter space is very complicated and not generally one to one: there is a complicated inverse problem.
  - The connection to dark matter specifically is often not very clear, leading to statistical approaches based on simulating many (many) model points in the parameter space.



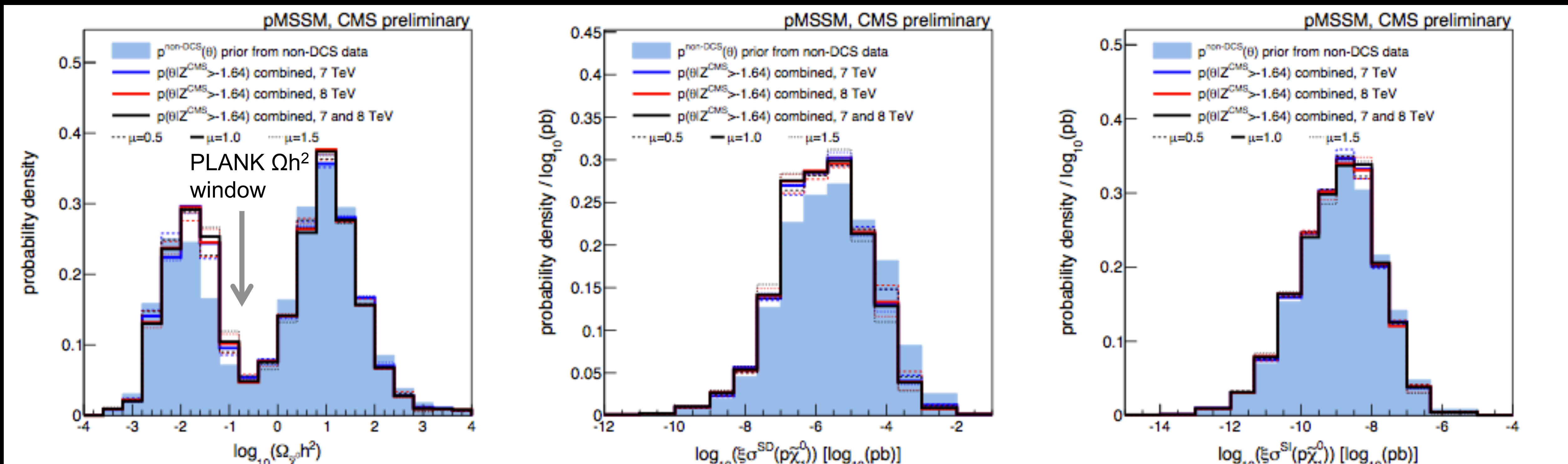
Cahill-Rowley et al, 1305.6921

Coverage Distribution



Cahill-Rowley et al, 1305.6921

pMSSM at the LHC



Neutralino relic density

Spin-dependent direct DM detection cross-section

Spin-independent direct DM cross-section

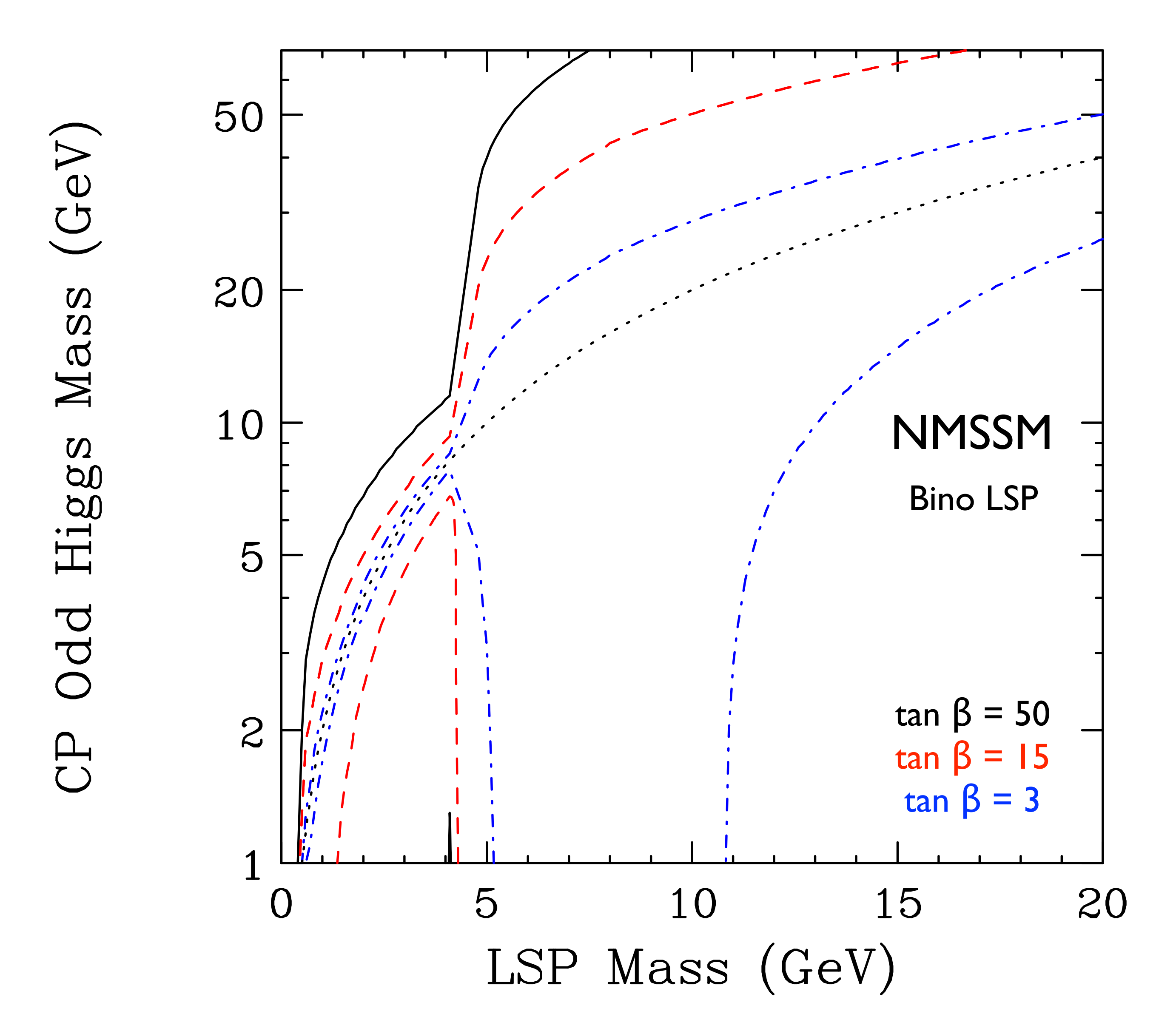
Posterior probabilities give an indication for how dense the coverage is of a given observable.

Note that this depends intimately on the model!

Beyond the MSSM

- As we have seen, the minimal model already contains a lot of interesting physics.
  - But nothing tells us Nature has chosen something minimal!
- Simple extensions such as adding a gauge singlet (i.e. the NMSSM) can have a big impact on the picture of dark matter.
  - New neutralinos
  - New Higgs bosons
  - New couplings
  - New relations between parameters.

Curves of constant $\Omega h^2 = 0.1$



Gunion, Hooper, McElrath, hep-ph/0509024

Recap of Lecture IIa

- There are many ideas for what dark matter could be.
  - Dark, Neutral, and Stable [Symmetry!].
  - WIMPs are a particularly attractive class of dark matter.
    - Their relic density explains the ballpark dark matter abundance.
    - Large interactions give us handles to search for them.
- Supersymmetry is an attractive, representative theory of dark matter.
  - We can explore the features of a Majorana fermion WIMP.
    - Interesting regions with the correct relic density.
    - Distinctive signals of direct, indirect, and collider searches.
    - We'll see contrasting features when we discuss other visions for DM, including Universal Extra Dimensions.

Dark Matter: Particle Properties II

Tim M.P. Tait

University of California, Irvine

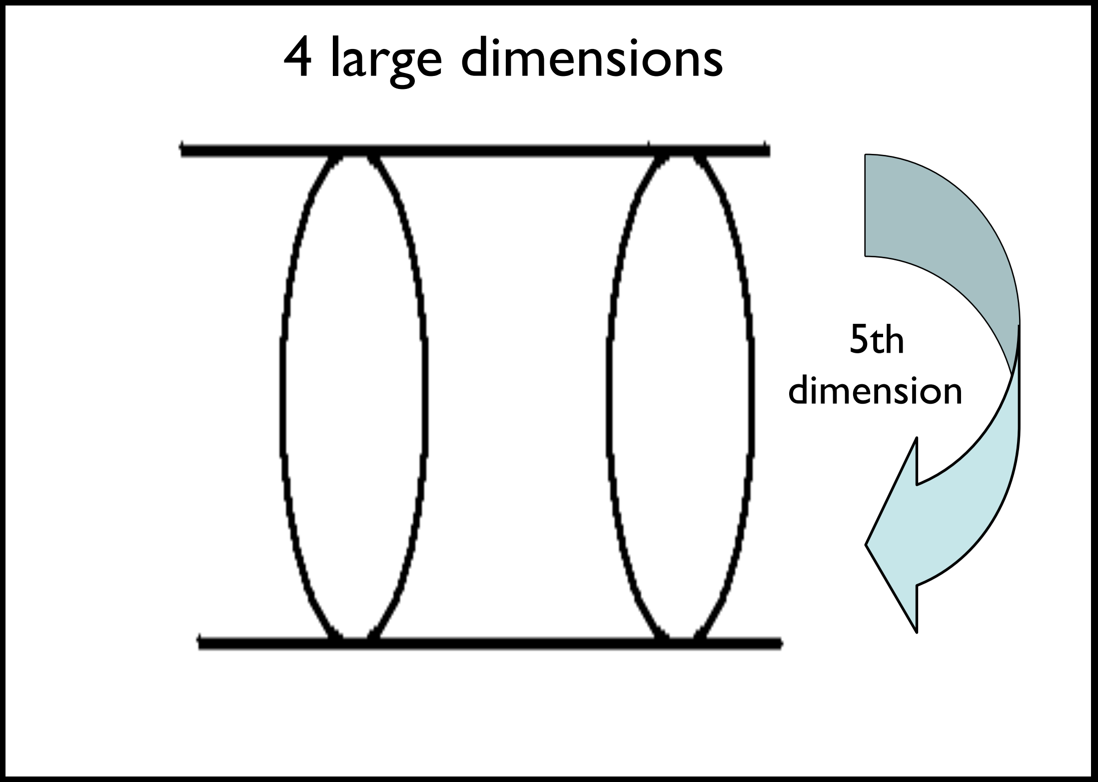
Grenoble
January 21-22, 2016

Outline for Lecture IIb

- KK parity: UED Dark Matter
  - 5d UED Dark Matter
  - The 6d Chiral Square
- T-parity
- Super-WIMPs:
  - Gravitinos,
  - Axions
  - Sterile Neutrinos
- "Designer" Dark Matter
- Complementarity of Searches

Universal Extra Dimensions

- Our next entry in the catalogue has "Universal Extra Dimensions"
- The basic premise is that in addition to the large dimensions we are familiar with, there is one or more small, curled up dimensions.
  - R smaller than (a few hundred GeV)$^{-1}$.
- All of the quantum fields are functions of the four large (ordinary) coordinates x as well as the extra (compact) coordinates y.
- We'll take a look at both 5d and 6d versions.



Field Theory in 5 Dimensions

- To begin with, imagine our extra dimension is a circle (S1), requiring wave functions to be periodic as one traverses the extra dimension.
  - Mathematically, this is the particle-in-a-box problem familiar from basic QM.
  - The 5th component of Momentum (p5) is quantized in units of 1 / R.
- States with p5 different from zero appear massive to an observer who does not realize the extra dimension is there.

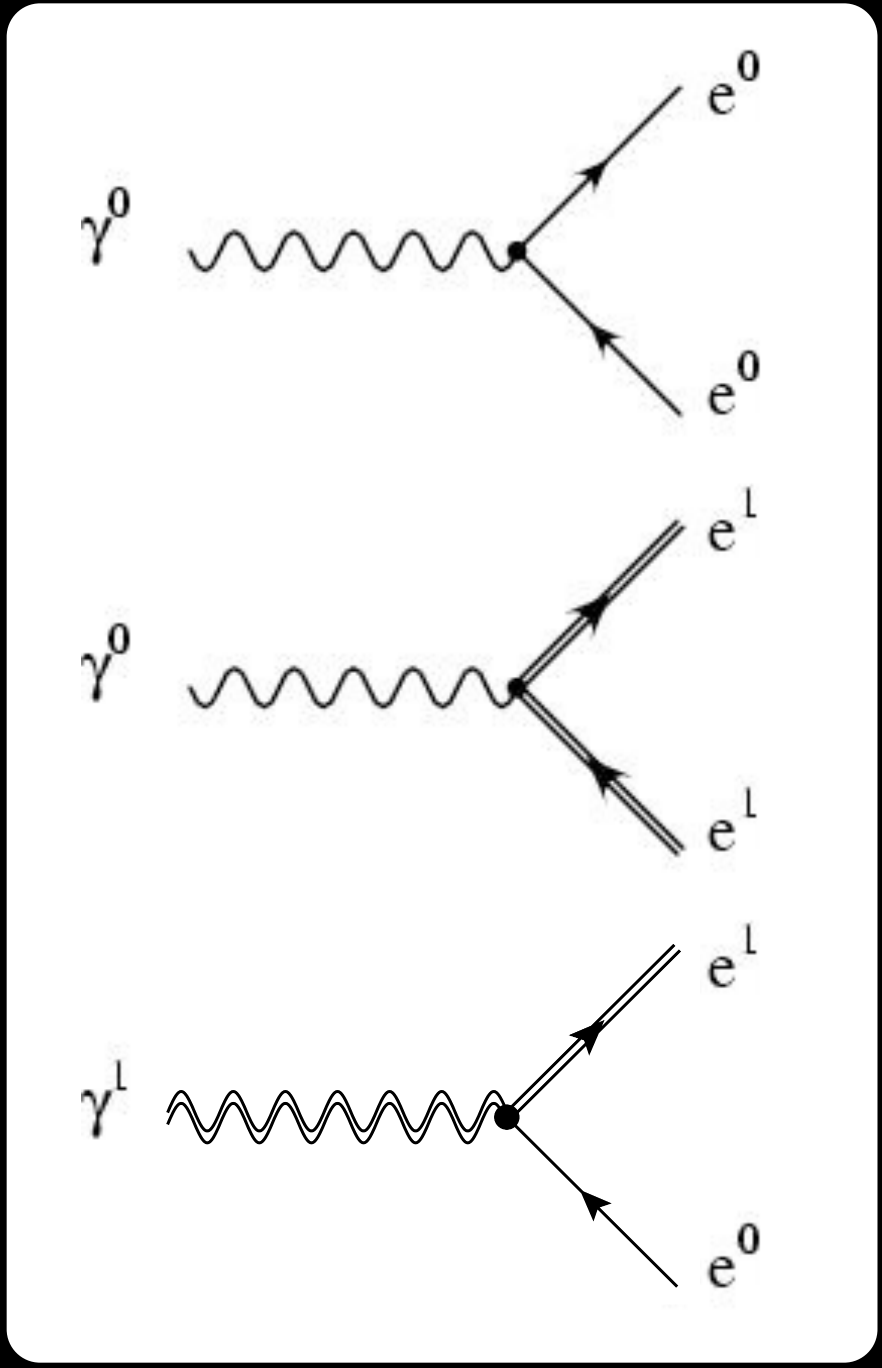
$$p_0^2 - \vec{p}^{\,2} - p_5^2 = 0 \quad \Longrightarrow \quad p_0^2 - \overrightarrow{p}^{\,2} = p_5^2 = m_{eff}^2$$

- We (and all low energy physics) are composed of the lowest (n=0) modes.
- Each SM field comes with a tower of massive states with the same charge and spin as the zero mode, but with masses given by n / R.

Kaluza-Klein Particles

- The translational invariance along the extra dimensional direction implies conservation of p5, or in other words, of KK mode number.
- Clearly, all fields must "live" universally in the extra dimension for there to be translational invariance -- this is not a brane world.
- The conserved KK number implies that the Lightest Kaluza-Klein Particle is stable.
    - Usually the n=1 KK "Photon".
- From the extra dimensional point of view: a photon is massless and cannot be dark matter, but if one is circulating around in a hidden dimension, to an outside observer, it appears to be a massive particle at rest.

Sample Interactions



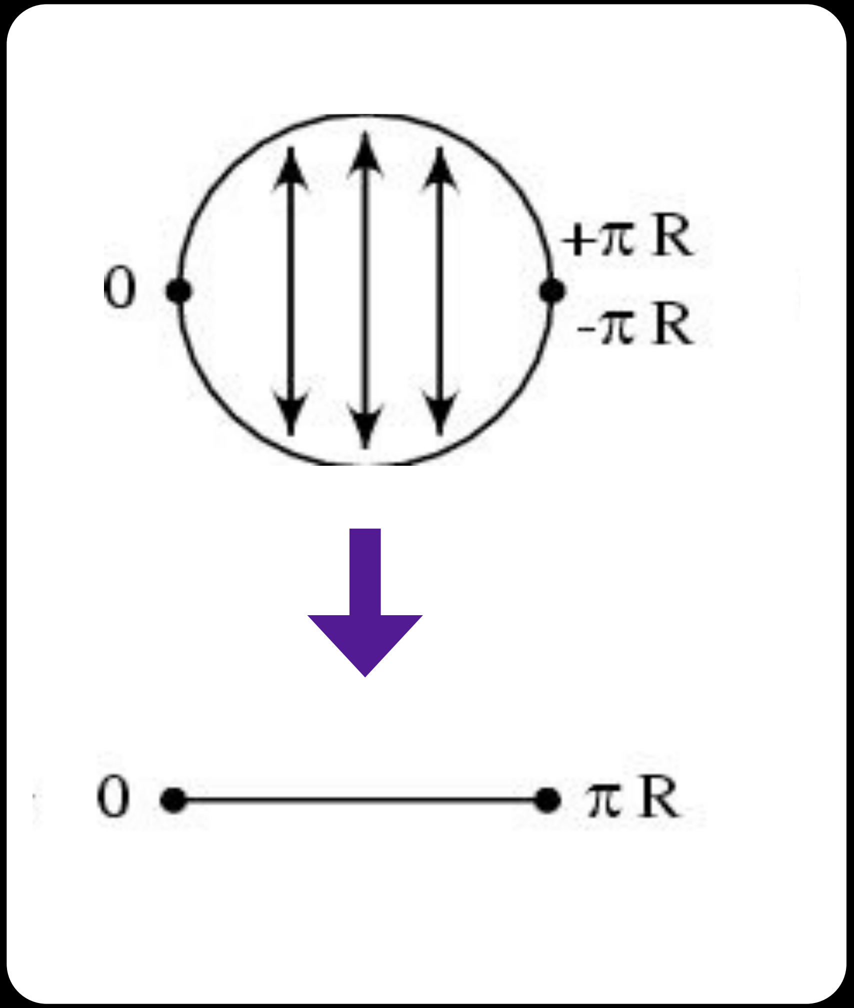
Why Universal Extra Dimensions?

- String Theory:
  - String theories require supersymmetry and extra dimensions to be consistent. So extra dimensions are (from a low energy point of view), the "other half" of stringy phenomenology.
- Number of generations:
  - Cancellation of anomalies in six dimensions requires the number of families to be a multiple of three!
- Dark Matter!

Dobrescu, Poppitz
PRL87, 031801 (2001)

Orbifold

- Our circular extra dimension is not quite realistic. It contains unwanted zero-mode degrees of freedom:
  - 5d vector bosons contain a 4d vector V_μ and scalar V_5.
  - Massless 5d spinors have 4 components, leading to mirror fermions at low energies.
- Orbifold boundary conditions project out the unwanted degrees of freedom:
  - Instead of a circular extra dimension, we fold the circle, identifying y with –y.
  - This results in a line segment, with the points 0 and πR at the end-points.
  - Boundary conditions forbid the unwanted zero modes.



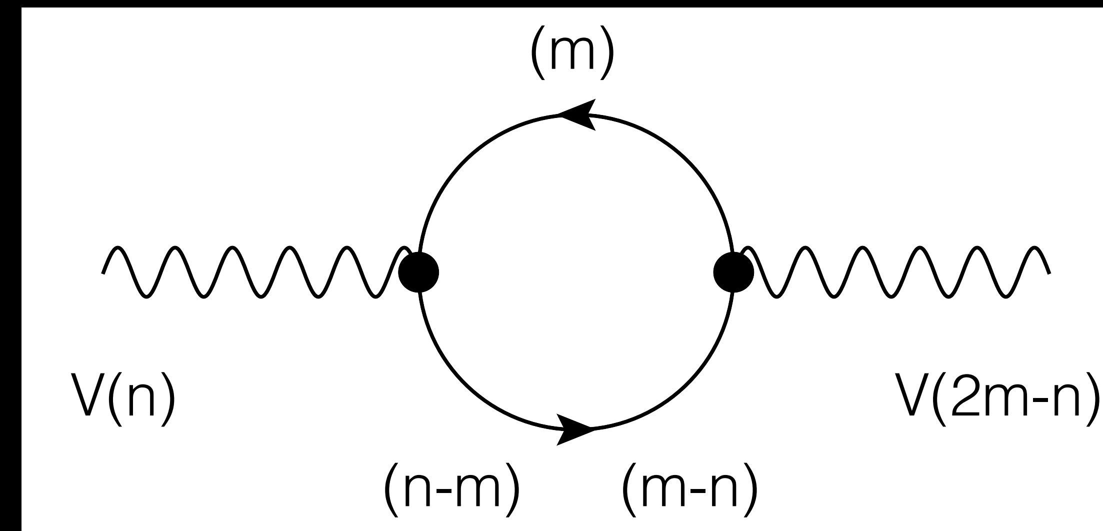
$$V_\mu(-y) = V_\mu(y)$$

$$V_5(-y) = -V_5(y)$$

$$\Psi(-y) = \gamma_5 \Psi(y)$$

Orbifolds are Opaque

- Even theories without localized fields have terms living on their boundaries.
- The orbifold, identifying (y and –y), implies the theory can't tell one direction from another.
- Loops of bulk fields generate p5 non-conserving terms.
- In position space, these are equal size terms living on the boundaries.
- The loops are log-divergent, indicating that they are not calculable -- they are parameters of the effective theory.



Georgi, Grant, Hailu, PLB506, 207 (2001)

$$-\frac{r_c}{4}\left[\delta(y)+\delta(y-L)\right]F_{\mu\nu}F^{\mu\nu}$$

$$r_c : \frac{\alpha_5}{4\pi}\log\left[\frac{\Lambda}{\mu}\right]$$

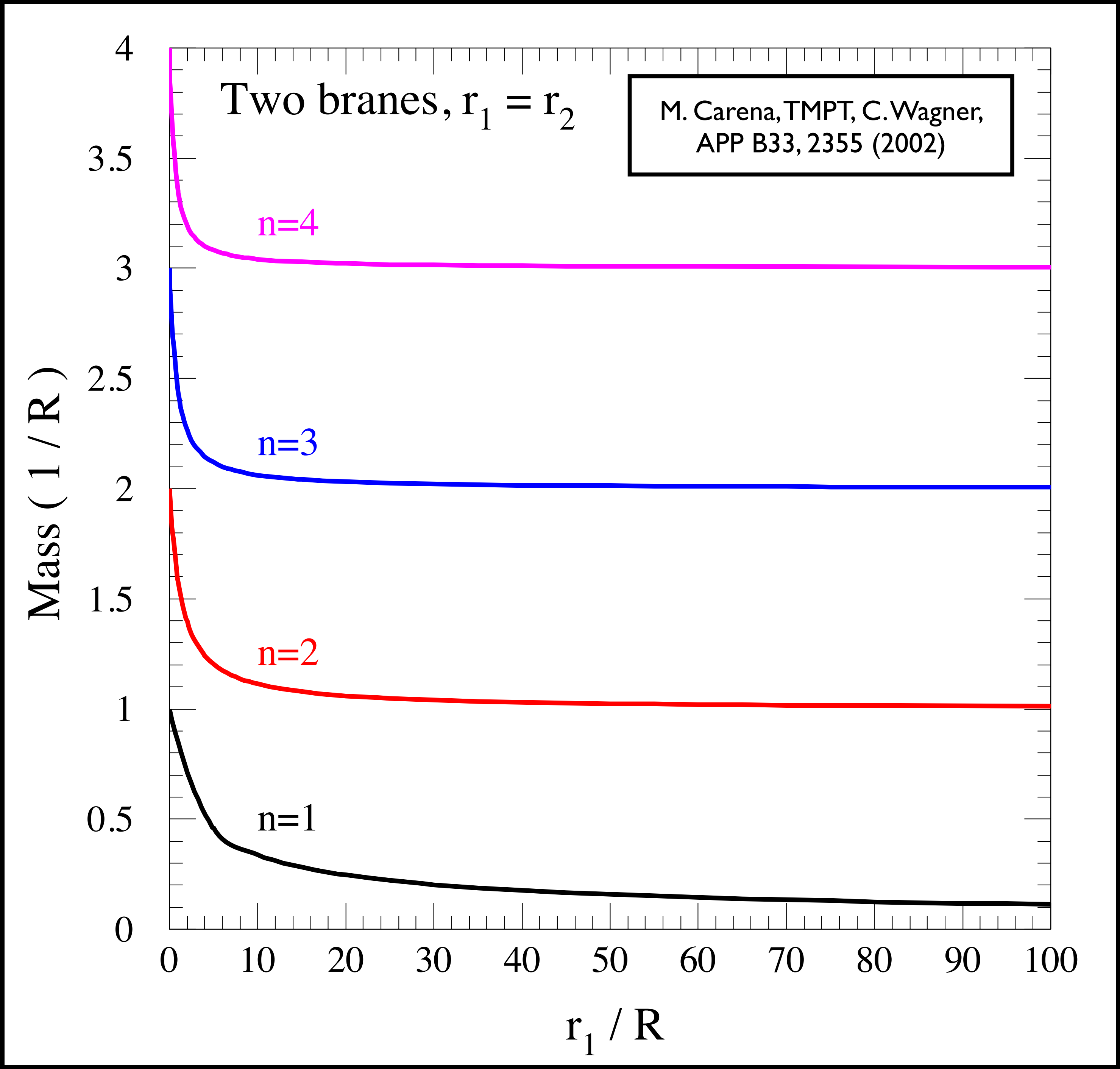
Opaque Orbifolds

The boundary terms modify the KK expansion, reshuffling modes in the expansion.

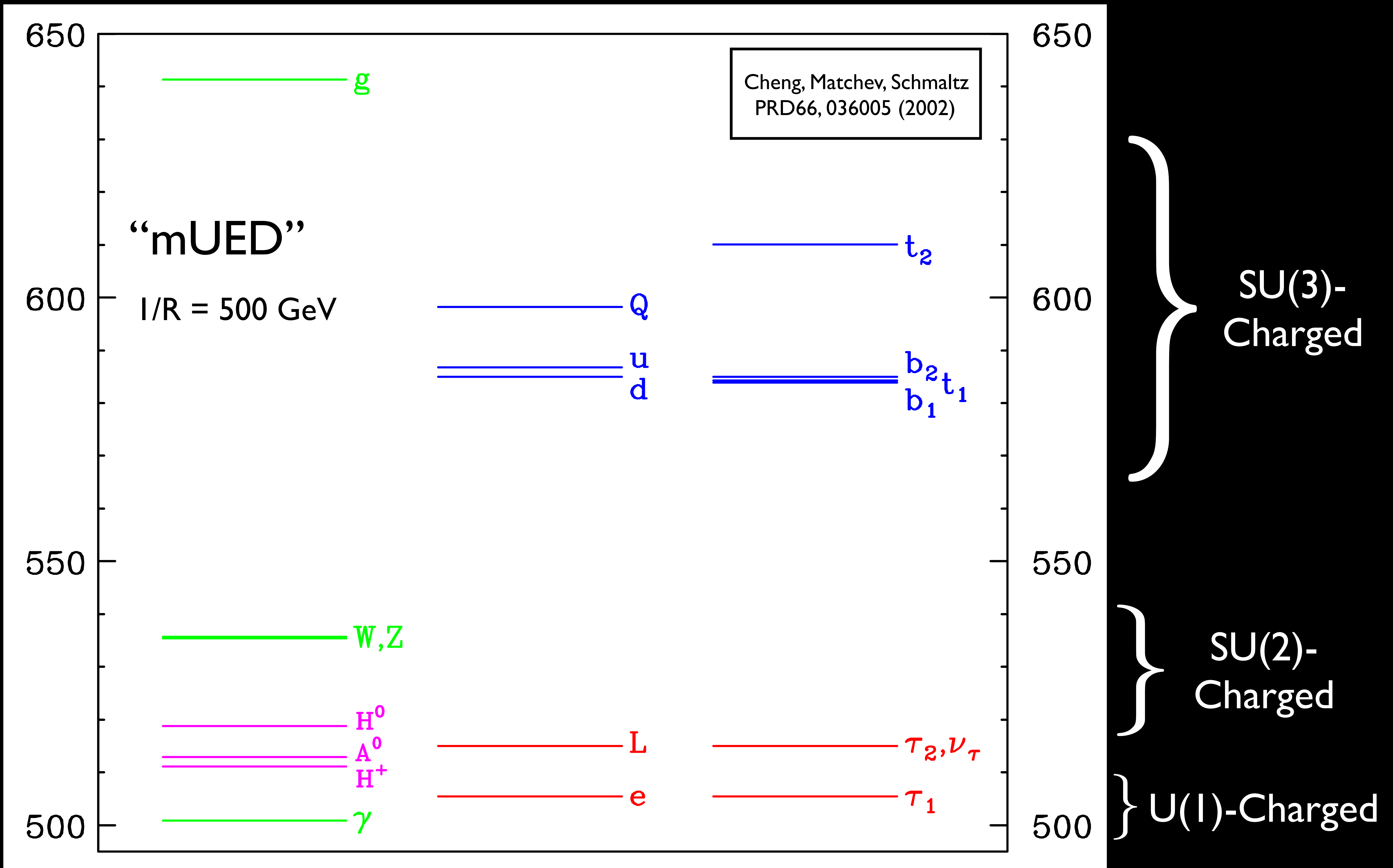
This has the effect of changing the KK mass spectrum.

It breaks conservation of KK number down to a KK parity under which odd KK number modes are odd.

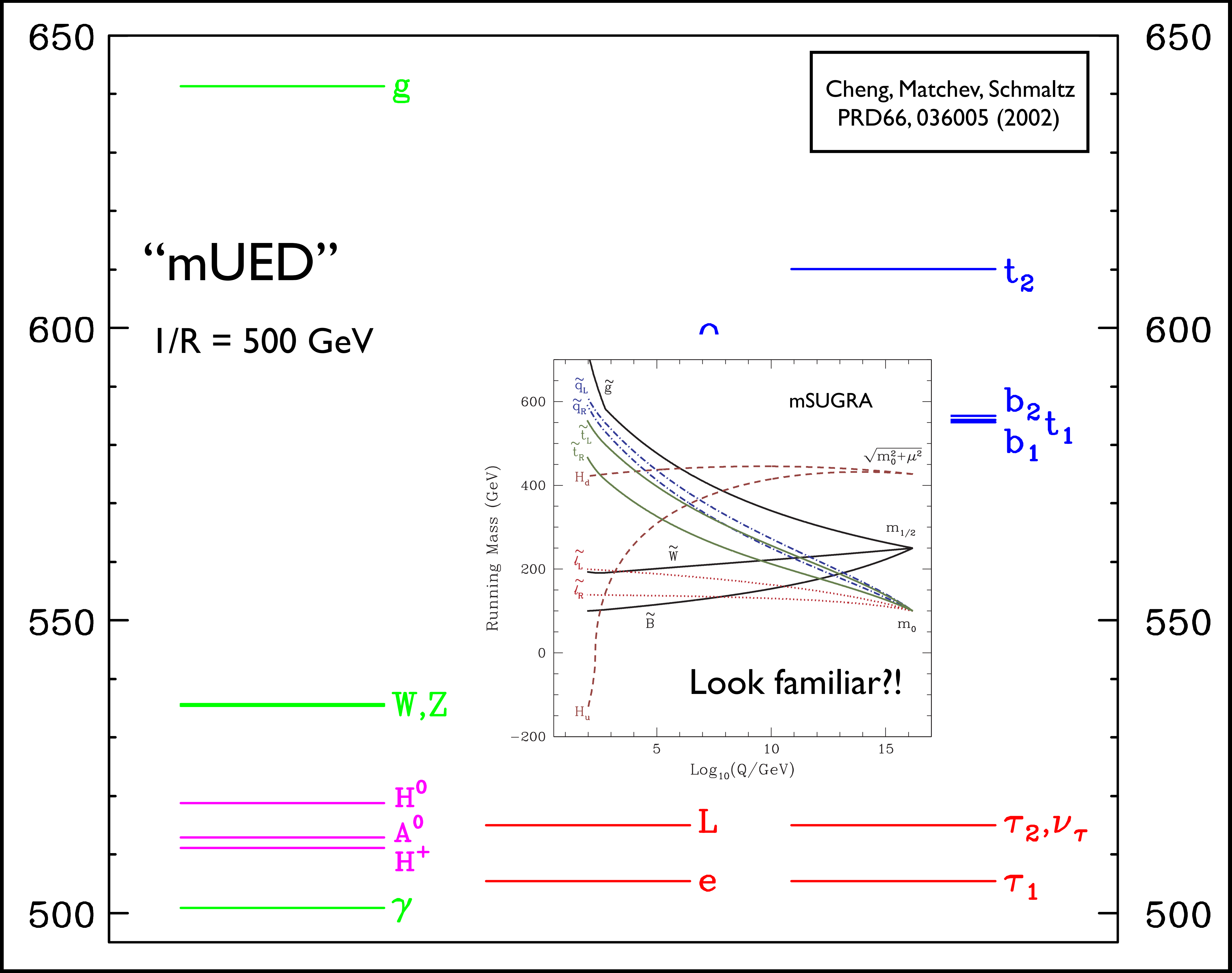
Much like R-parity, the lightest odd mode is stable, and odd modes are produced in pairs.



KK Mode Spectrum



KK Mode Spectrum



SU(3)-Charged

SU(2)-Charged

U(1)-Charged

Identity of the LKP

- Boundary terms play a role similar to SUSY soft masses, determining masses and couplings for the entire KK tower.
- If we imagine the terms are zero at the cut-off, they will be induced at loop size.
- Since α1 << α2 << α3, we imagine the smallest corrections will be to the U(1) gauge boson.
- Since δM ~ 1 / R >> v, the LKP is (almost) purely a KK mode of the U(1) gauge boson, $B_\mu^{(1)}$.
- Following this line of reasoning, the NLKP is the right-handed electron, $e^{(1)}_R$.

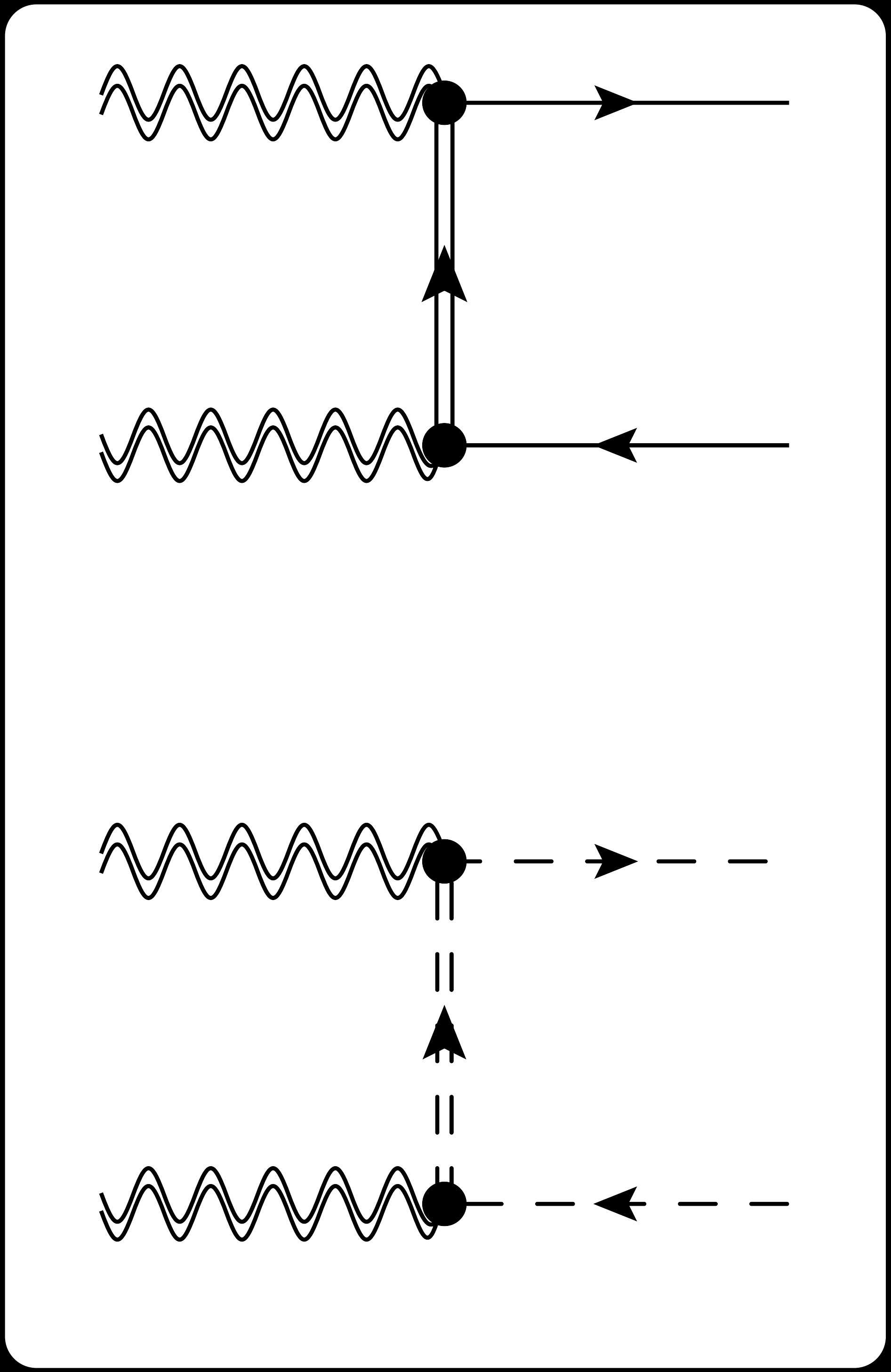
$\boxed{B^{(1)} - W_3^{(1)} \text{ Mass}^2 \text{ matrix}}$

$$\begin{pmatrix} \frac{1}{R^2} + \frac{1}{4} g_1{}^2 v^2 + \delta M_1{}^2 & \frac{1}{4} g_1 g_2 v^2 \\ \frac{1}{4} g_1 g_2 v^2 & \frac{1}{R^2} + \frac{1}{4} g_2{}^2 v^2 + \delta M_2{}^2 \end{pmatrix}$$

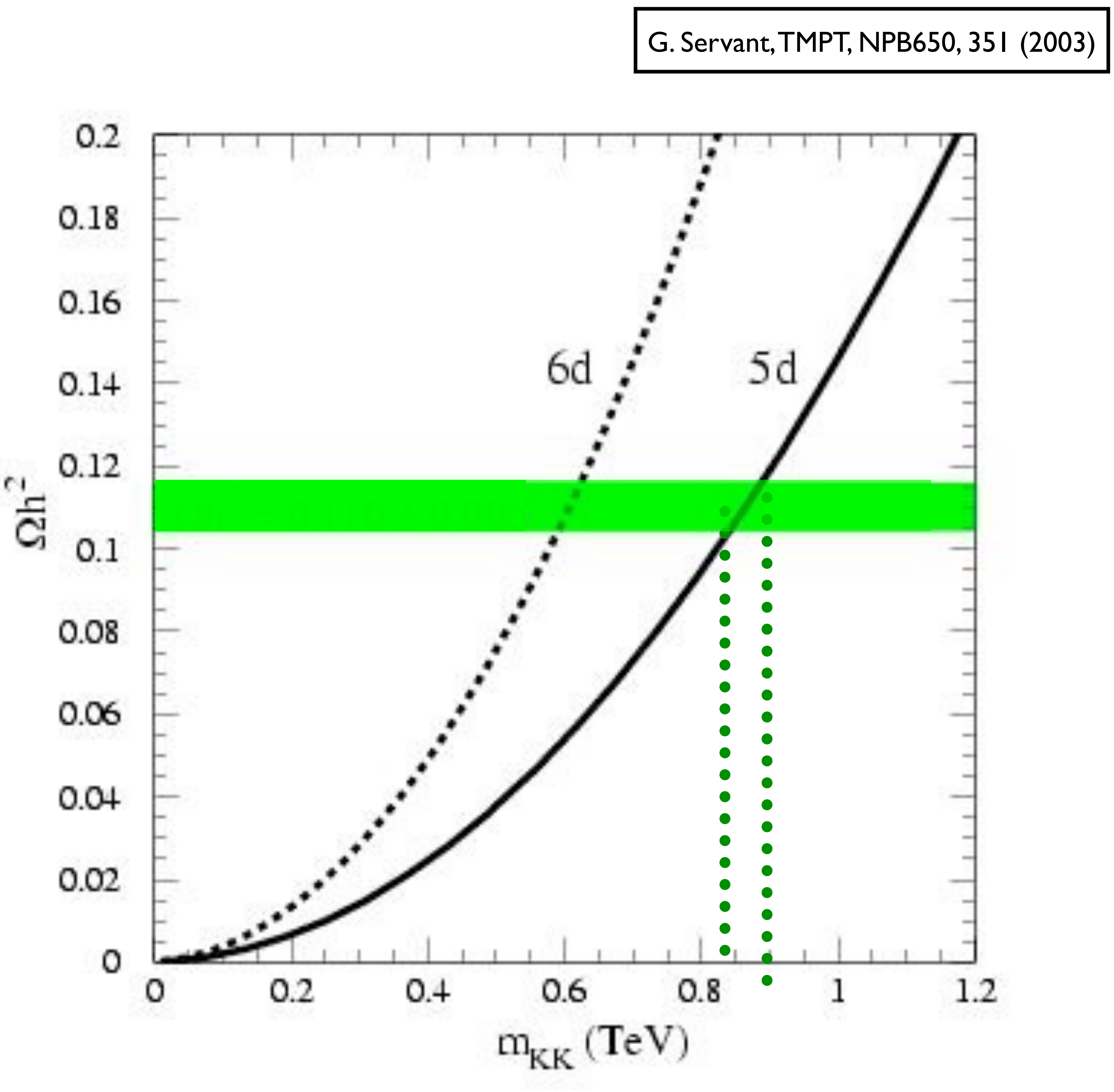
$$\delta M^2 : \frac{1}{R^2} \frac{\alpha}{4\pi} \log(\Lambda R)$$

LKP Annihilations

- For a pure $B^{(1)}$ LKP, we know couplings are controlled by the hypercharges.
- There are annihilations into SM fermions and Higgs bosons.
  - 59% Charged Leptons
  - 35% Hadrons
  - 4% Neutrinos
  - 2% Higgs/Goldstone bosons
- As bosons, there are no restrictions from Fermi statistics: cross sections are generally larger than for SUSY bino WIMPs.

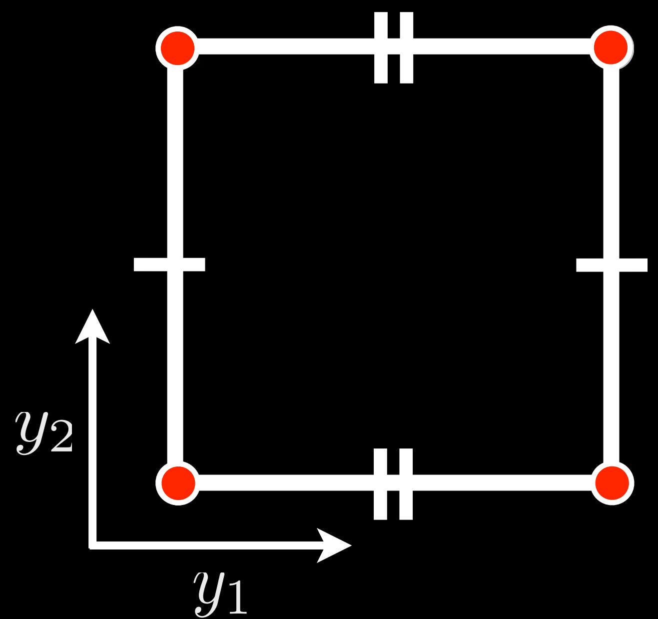


LKP Relic Density



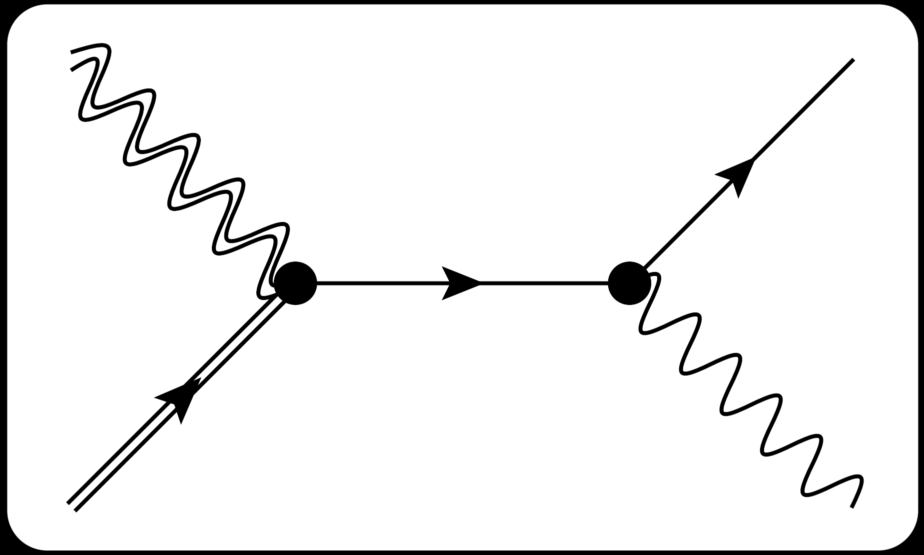
With no helicity suppression for annihilation, the LKP realizes the correct relic density for larger WIMP masses.

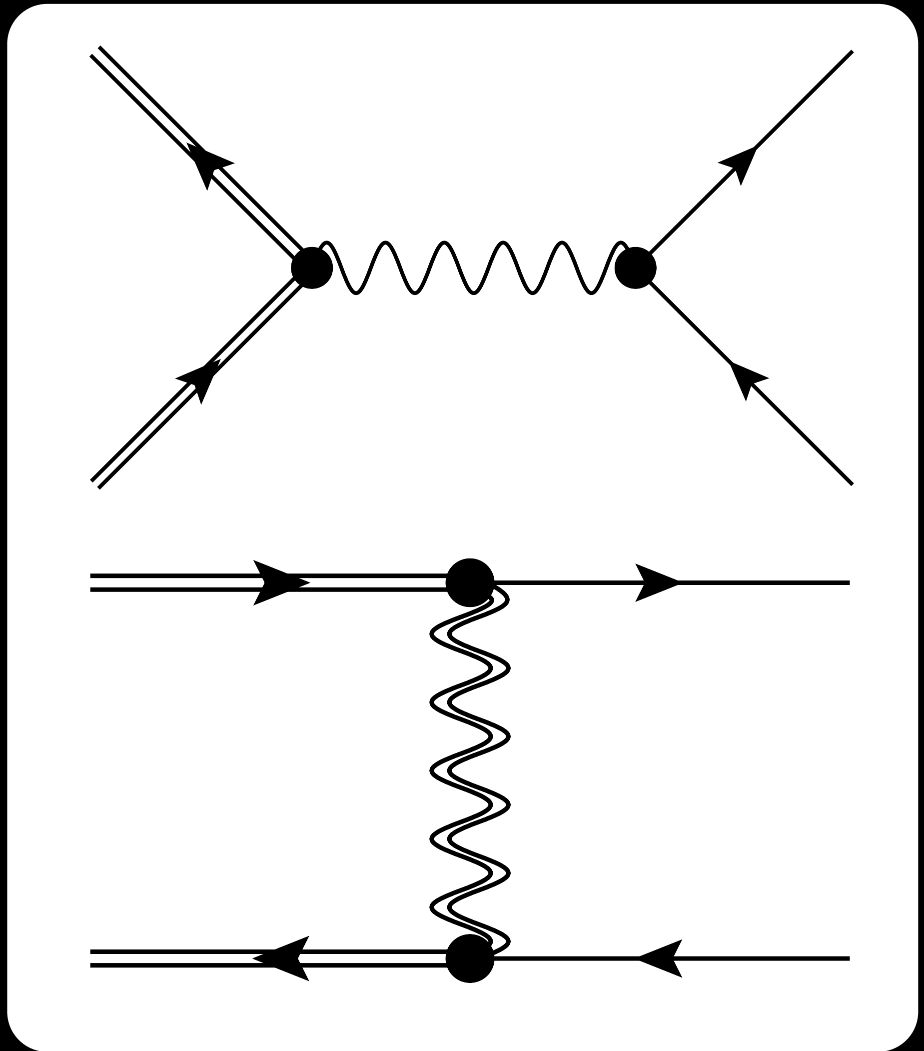
The 6d curve is for a 2-torus with equal radii (2 LKPs):



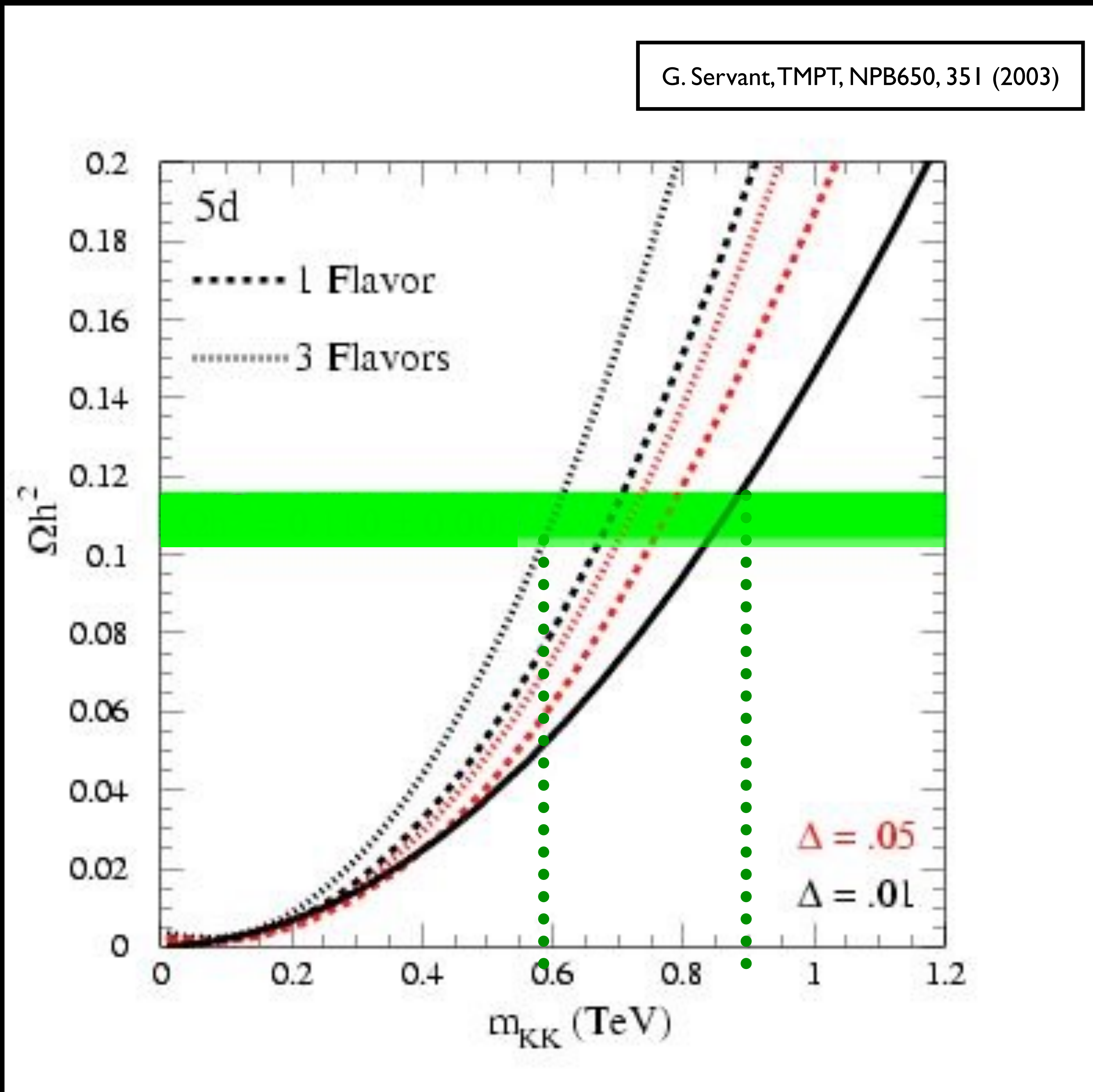
Co-annihilation

- Just like in SUSY, nearby particles can affect the relic density. In particular, we saw that the mass of $e^{(1)}{}_R$ is close to $B^{(1)}$ in mUED.
- However unlike SUSY, both particles interact with roughly with the same cross section, and the freeze-out temperature is basically unchanged,
- Some $e^{(1)}{}_R$ are left over after freeze-out, and eventually decay into $B^{(1)}$ and $e^{(0)}$. The net relic density of $B^{(1)}$ is increased, rather than reduced.





Relic Density with Co-annihilation



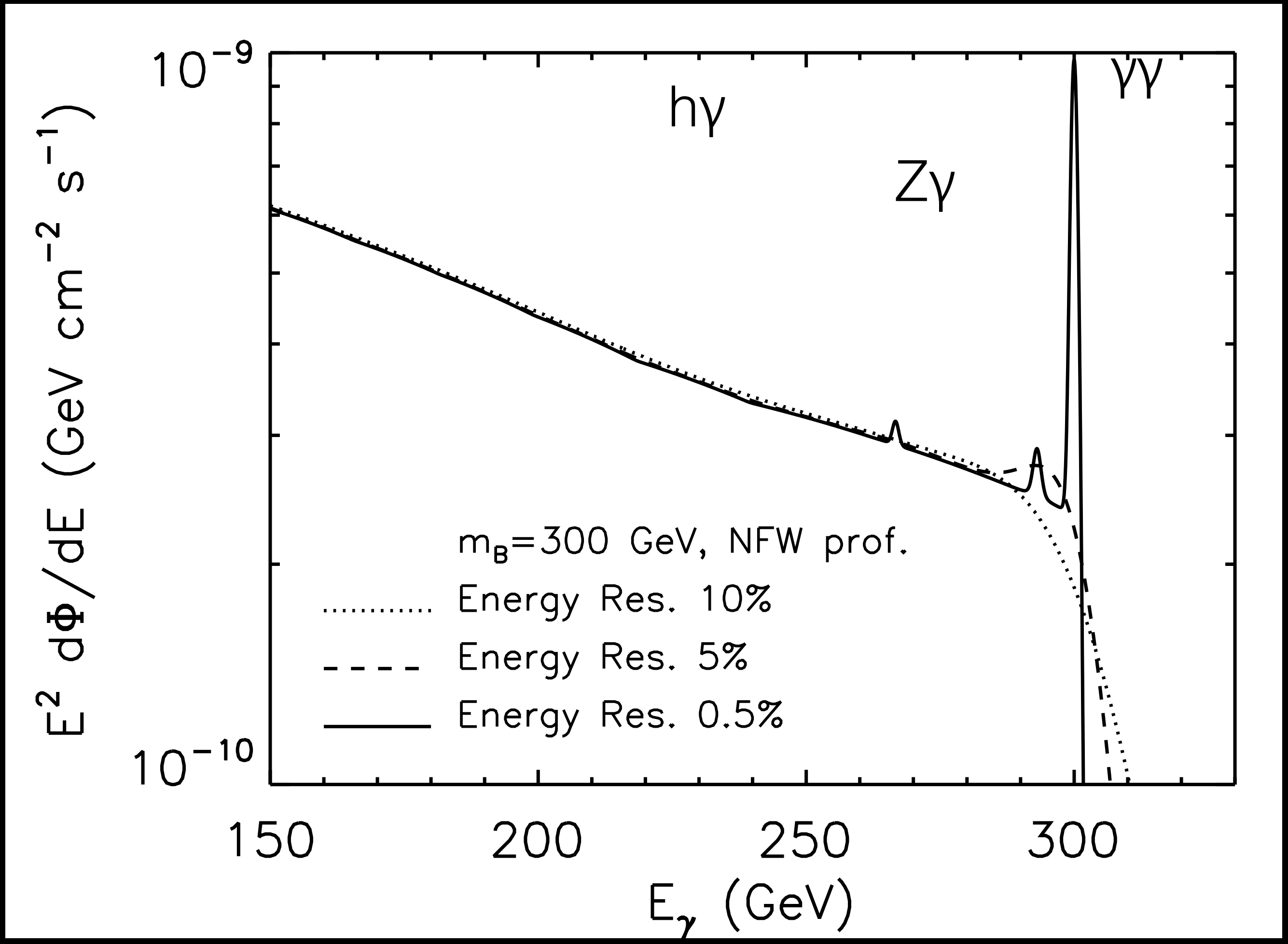
Coannihilation leads to an increase in the number of LKPs after freeze-out. To compensate, we dial down the mass of the LKP so that the correct energy density results.

Δ is the splitting between the $B^{(1)}$ and $e^{(1)}_R$ masses.

$$\Delta \equiv \frac{m_{e_R^{(1)}} - m_{B^{(1)}}}{m_{B^{(1)}}}$$

Gamma Rays from UED

- There is a large rate for continuum γ's with a harder (than, say, SUSY) spectrum, because the LKP likes to annihilate into e^+e^-.
- There are γγ, γZ, and γ Higgs lines.
- Over-all, the lines are relatively faint, and tend to merge into the continuum photons from WIMP annihilations.
- Resolving them is possible for a very light LKP, and would require a next- (or next to next) generation gamma ray observatory.

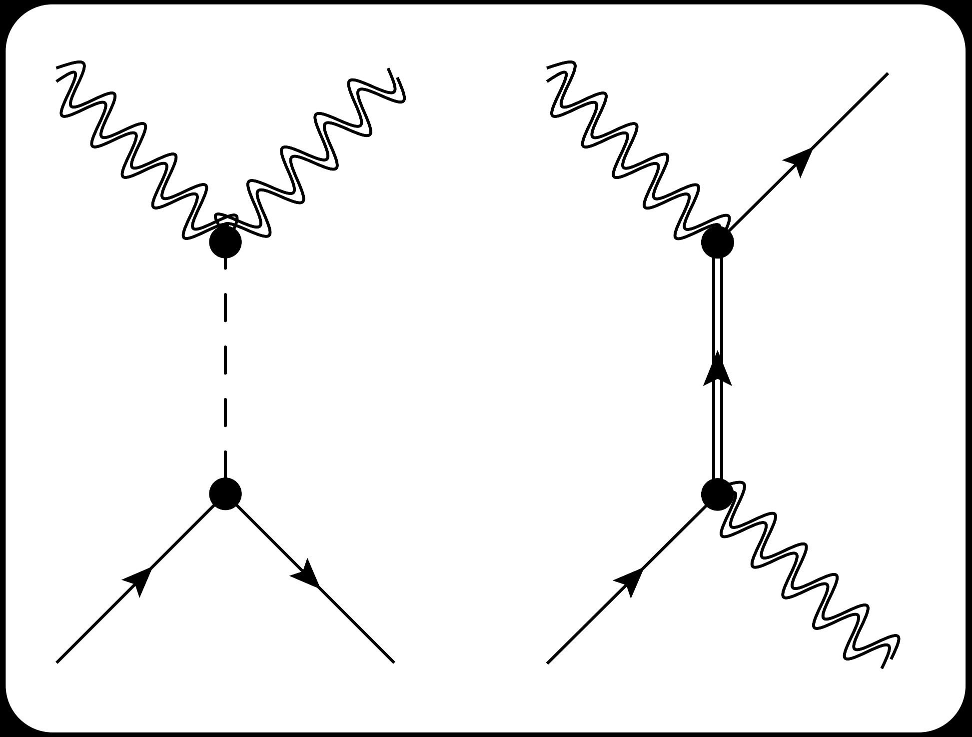


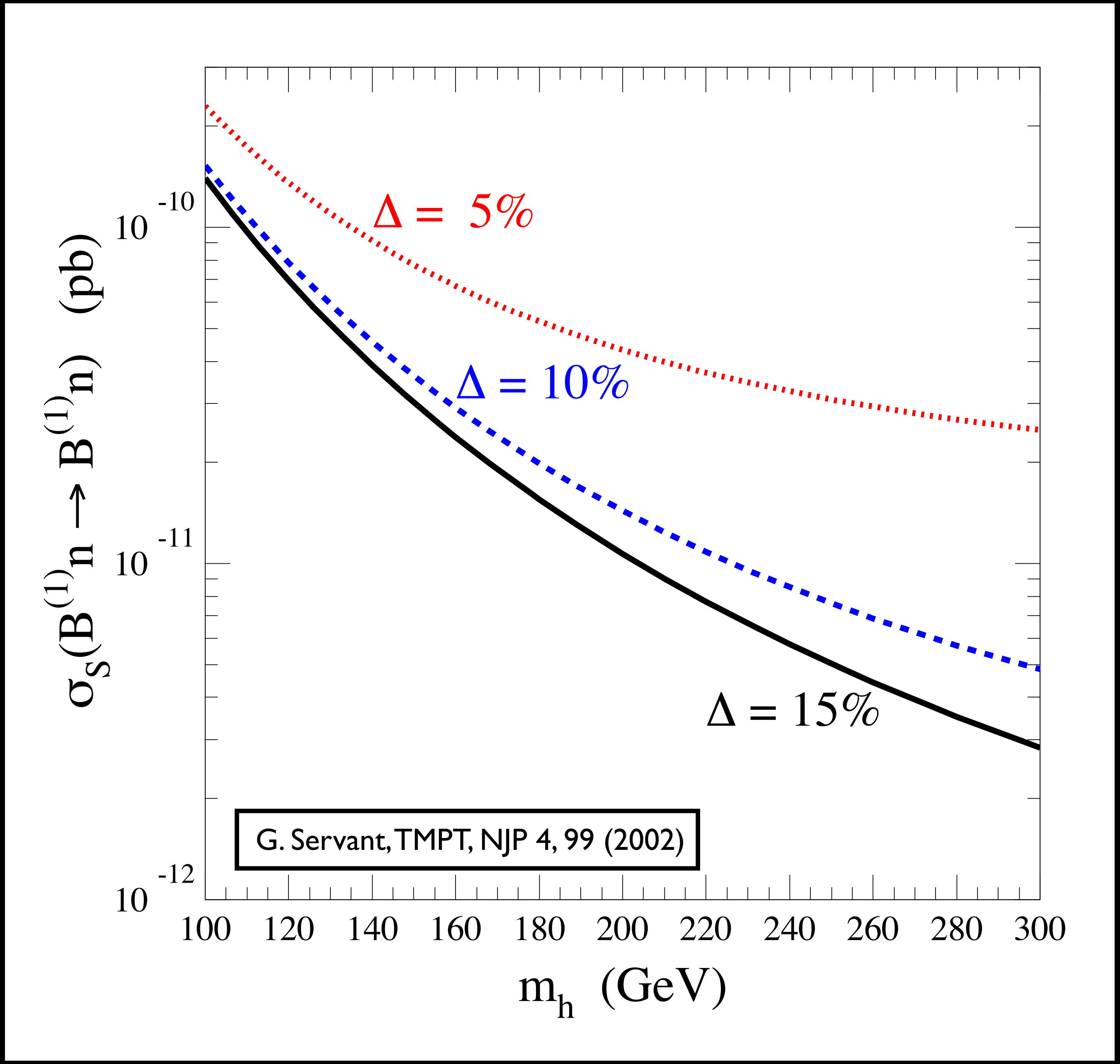
Bertone, Jackson, Shaughnessy, TMPT, Vallinotto 1009.5197

Direct Detection

- Much like the case of SUSY models, UED dark matter interacts with nuclei largely by exchanging Higgs (zero mode) bosons.

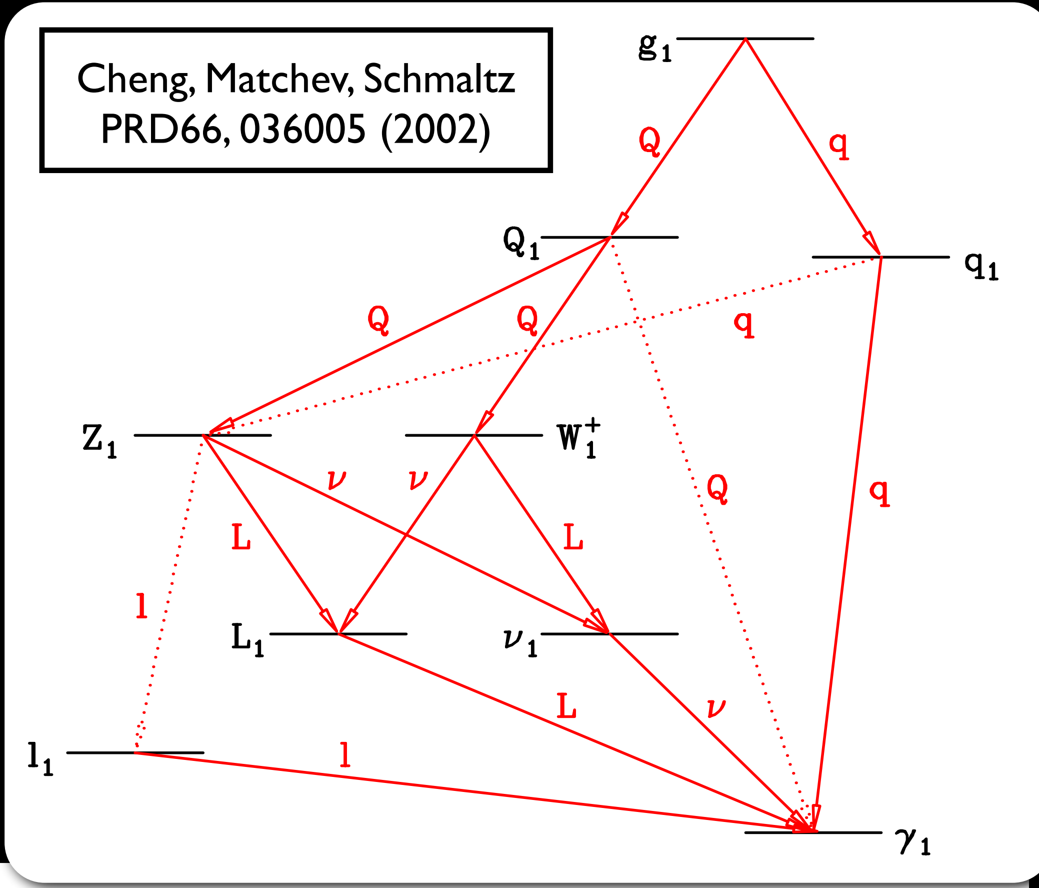
- KK quarks also contribute, but are expected to be heavier and thus less important.

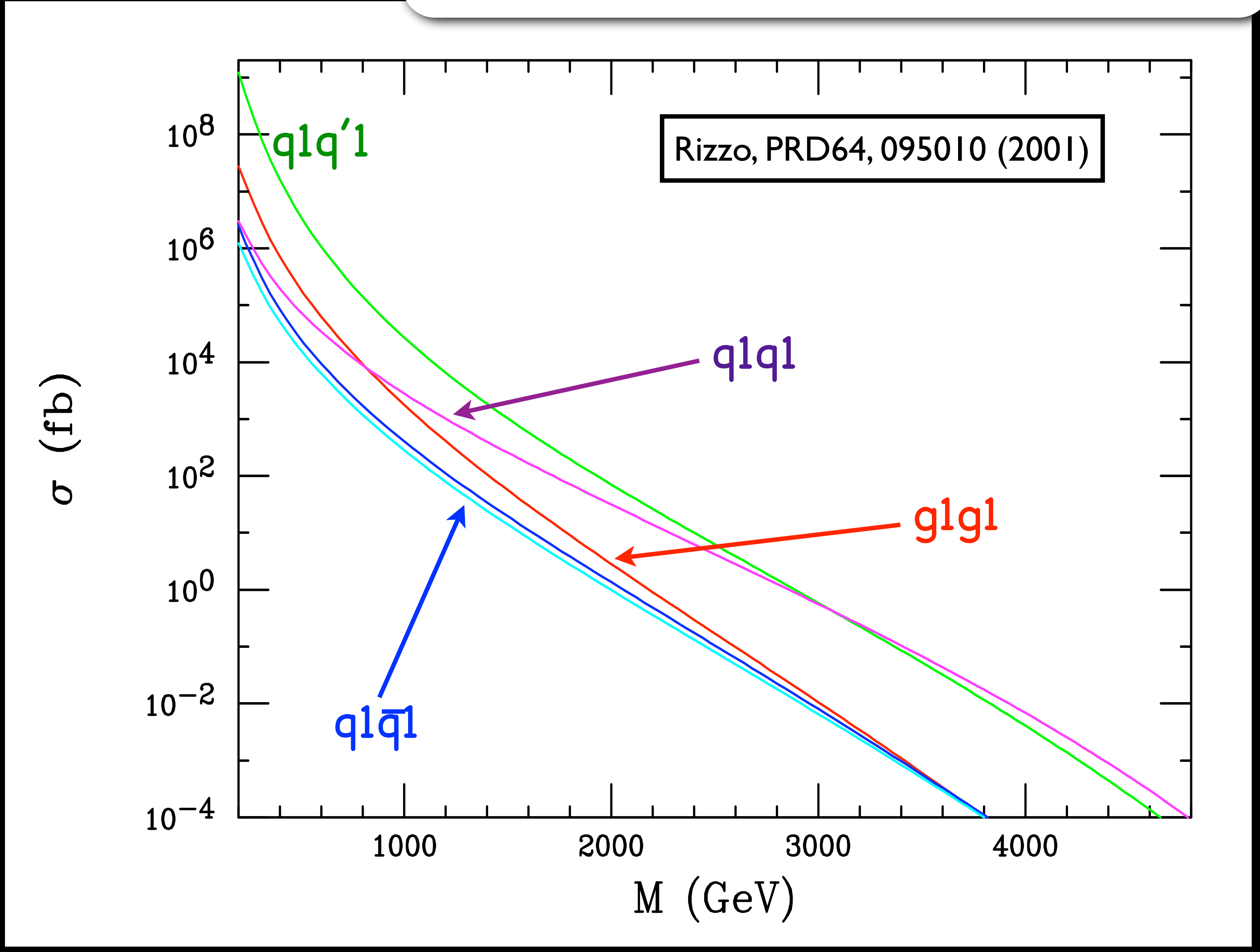




UED at the LHC

- At the LHC, one can expect cascade decays very much like we find in SUSY models, where we produce colored KK particles and they decay down through the weakly interacting ones into the LKP.
- This raises an interesting and important question: how do we measure the spins of particles when we can't observe some of their decay products directly?





6d UED: The Chiral Square

- Let's look at another example of a 6d model. The Chiral Square is a UED theory with two extra dimensions.

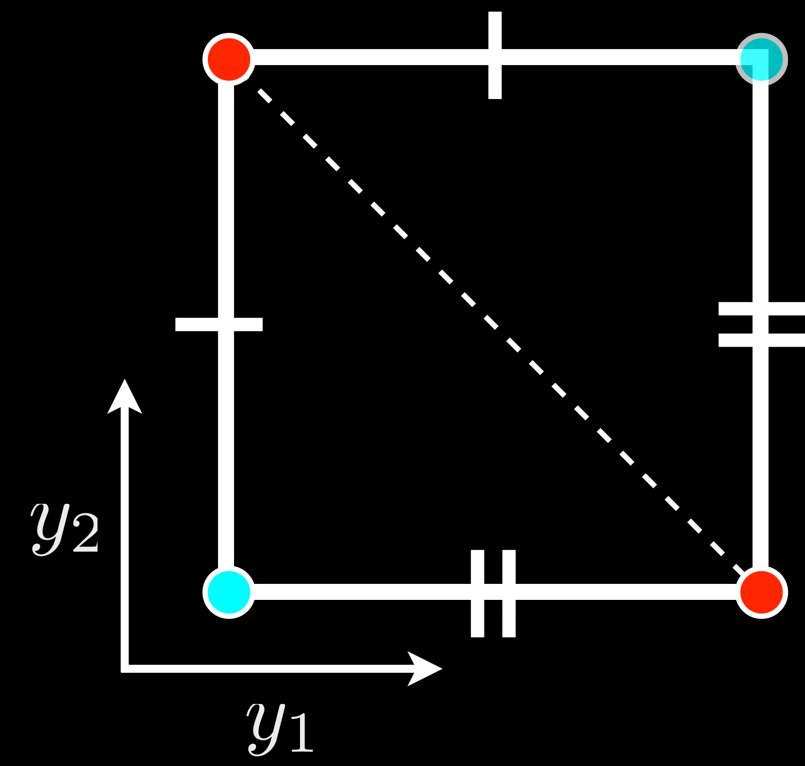
Burdman, Dobrescu, Ponton '04, '05

- The adjacent sides are identified as the same, which can be visualized as a square region folded along a diagonal. This is another orbifold compactification with chiral fermions.

- There are three "fixed points", where boundary terms can live which preserve KK parity.

- I'll follow the usual practice and assume the size of the boundary terms is consistent with their being generated by loops -- ``minimal UED".

Ponton, Wang '06



KK parity requires that two of the boundary terms at (0,R) and (R,0) are equal in size.

KK Decomposition

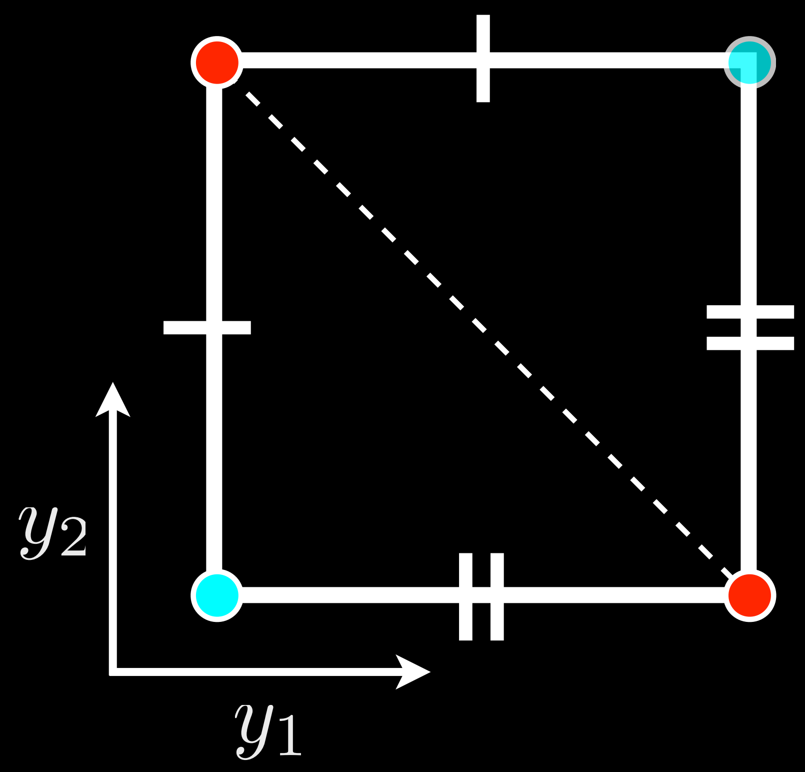
- In the case of a 6d UED model, KK modes are labelled by a pair of integers (j,k) indicating momentum flow in the extra dimensions.

- Masses are given (up to corrections from boundary terms) in terms of (j,k):

$$M^2_{(j,k)} \simeq \frac{1}{L^2}\left(j^2 + k^2\right)$$

- KK parity leaves the lightest of the j+k = odd modes stable, providing our stable WIMP.

- The vector bosons have KK towers corresponding to 4d vector particles (which contain a zero mode) and a combination of the 5 and 6 components which looks like a 4d scalar (without a zero mode).

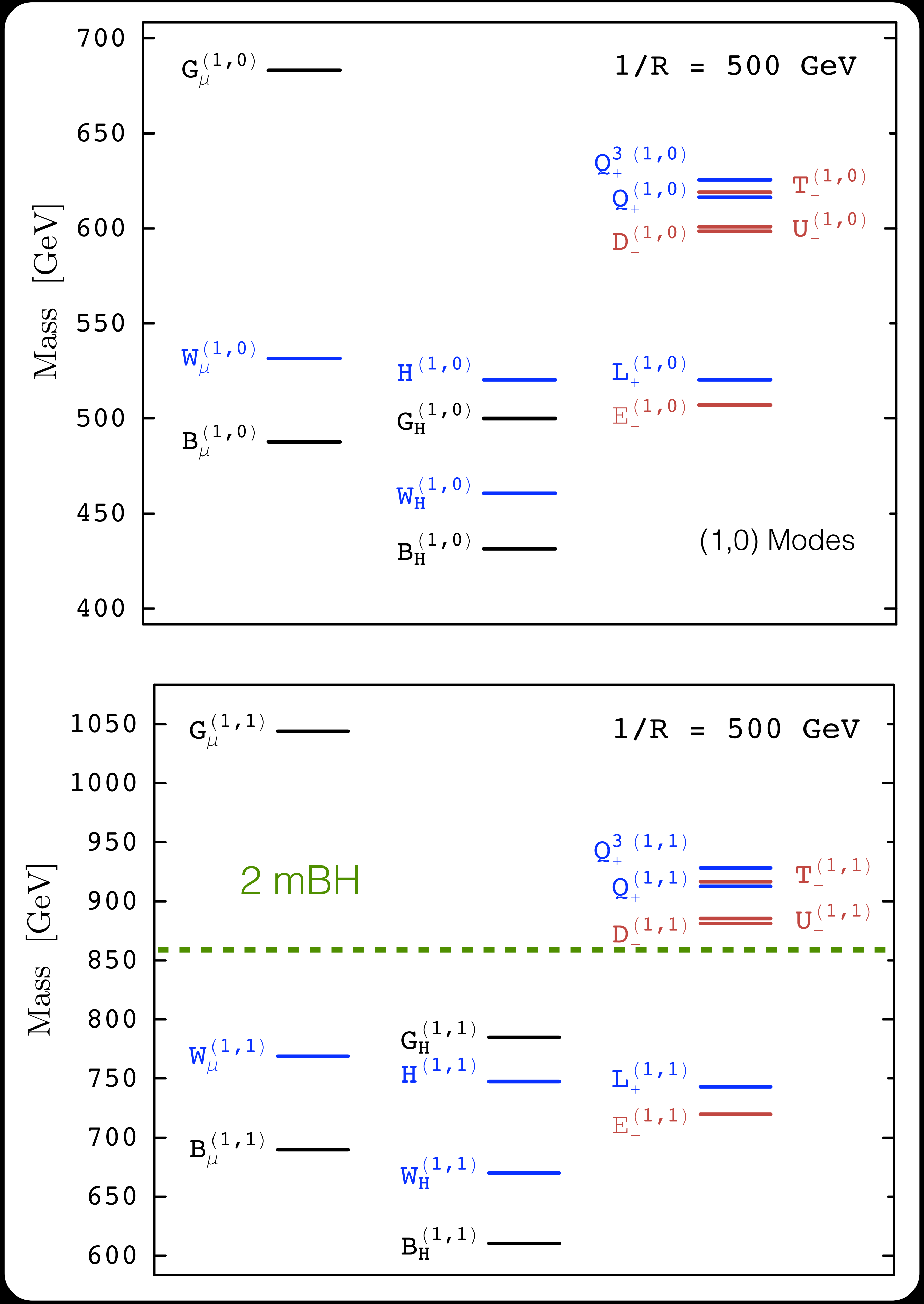


$$V_M \to \{V_\mu, V_5, V_6\}$$

One combination eaten by massive Vμ, the other combination is physical.

Spectrum

- As in the 5d theory, boundary terms modify the masses of the fields at a given (j,k) level.
- The LKP is usually the scalar (1,0) KK mode of the Hypercharge gauge boson, B_H.
    - Colored states are the heaviest of a given (j,k).
- The (1,1) modes are KK even and many have masses above M_B but below 2 x M_B.



BH Annihilations

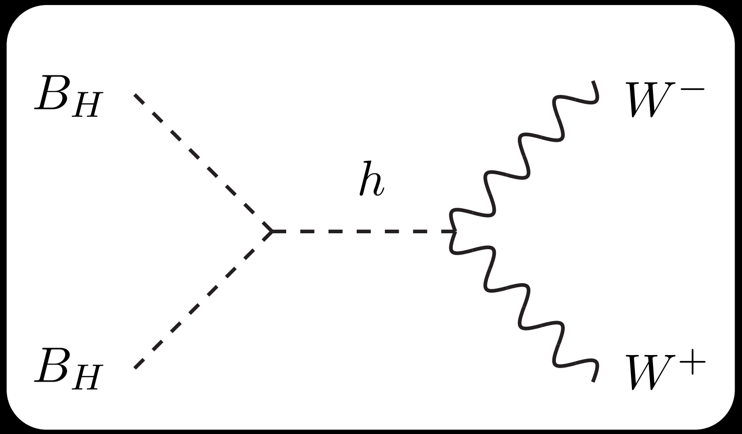
- Both the regions of parameter space and the continuum gamma ray emission spectra and rates are controlled by the tree level LKP annihilation channels.

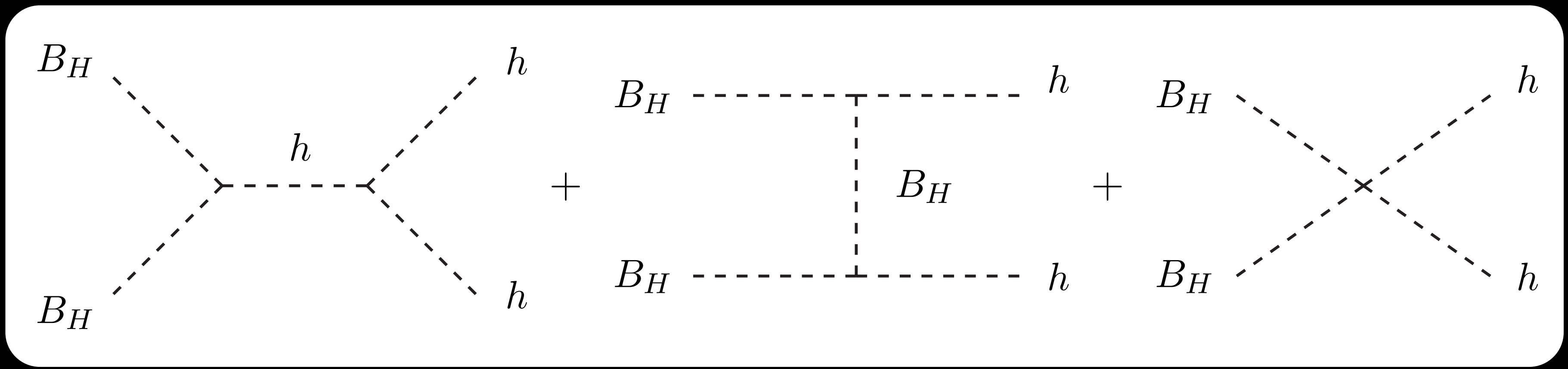
- BH is a real scalar and an electroweak singlet:

  - BH BH into fermions is suppressed by the final state fermion mass (more like what we saw in the MSSM than the 5d UED model).

  - Annihilation into weak boson and Higgs pairs are mediated by the Higgs boson itself.

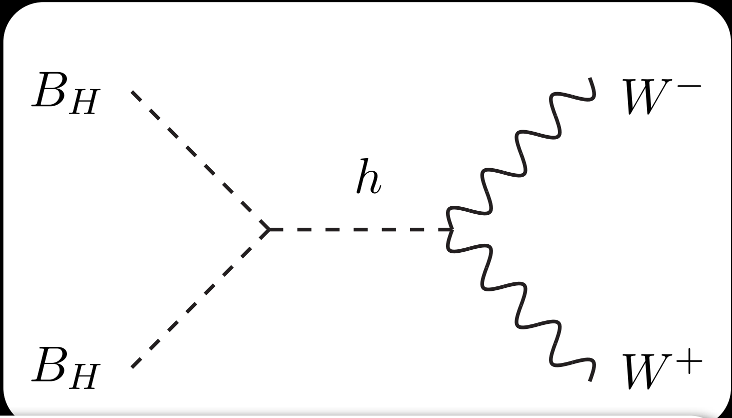
Dobresu, Hooper, Kong, Mahbubani, '07

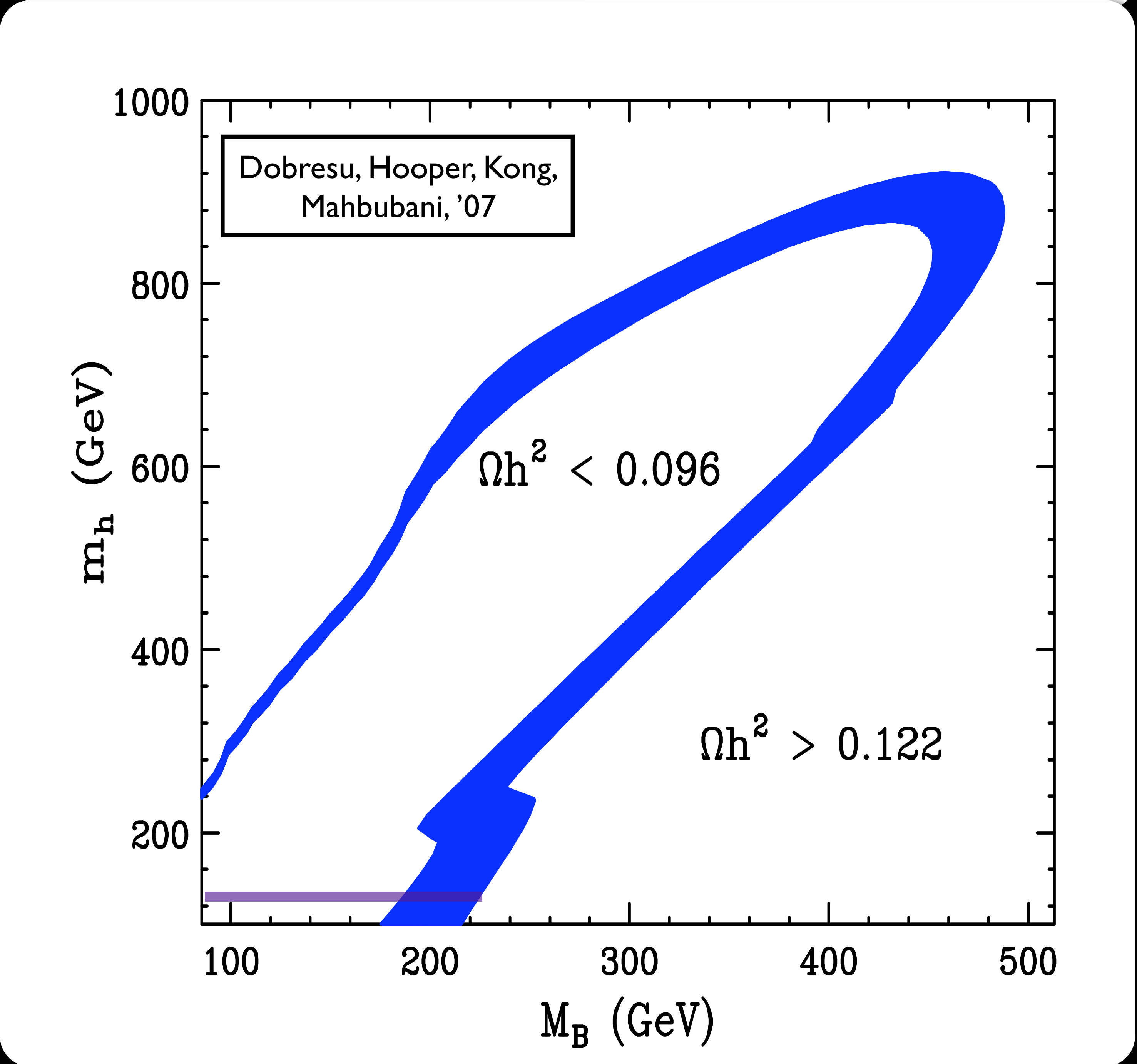




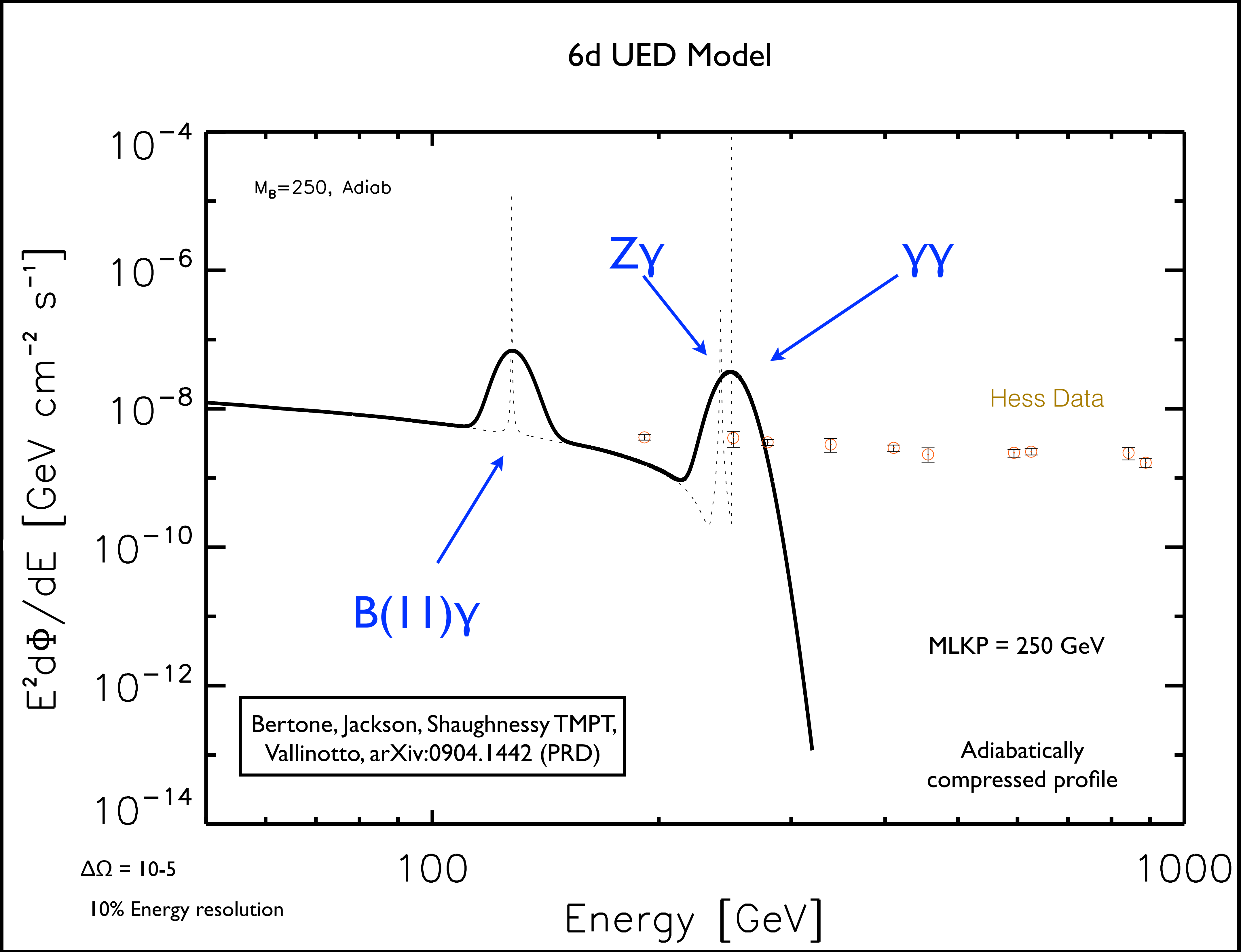
Relic Density

- Because of the s-channel Higgs-mediated graphs, the annihilation cross section is very sensitive to the interplay between the LKP and Higgs masses.
  - This is another example of a funnel region, like the ones we saw in the MSSM.
- The Higgs discovery at the LHC has severely collapsed the parameter space down to LKP masses around 200 GeV.



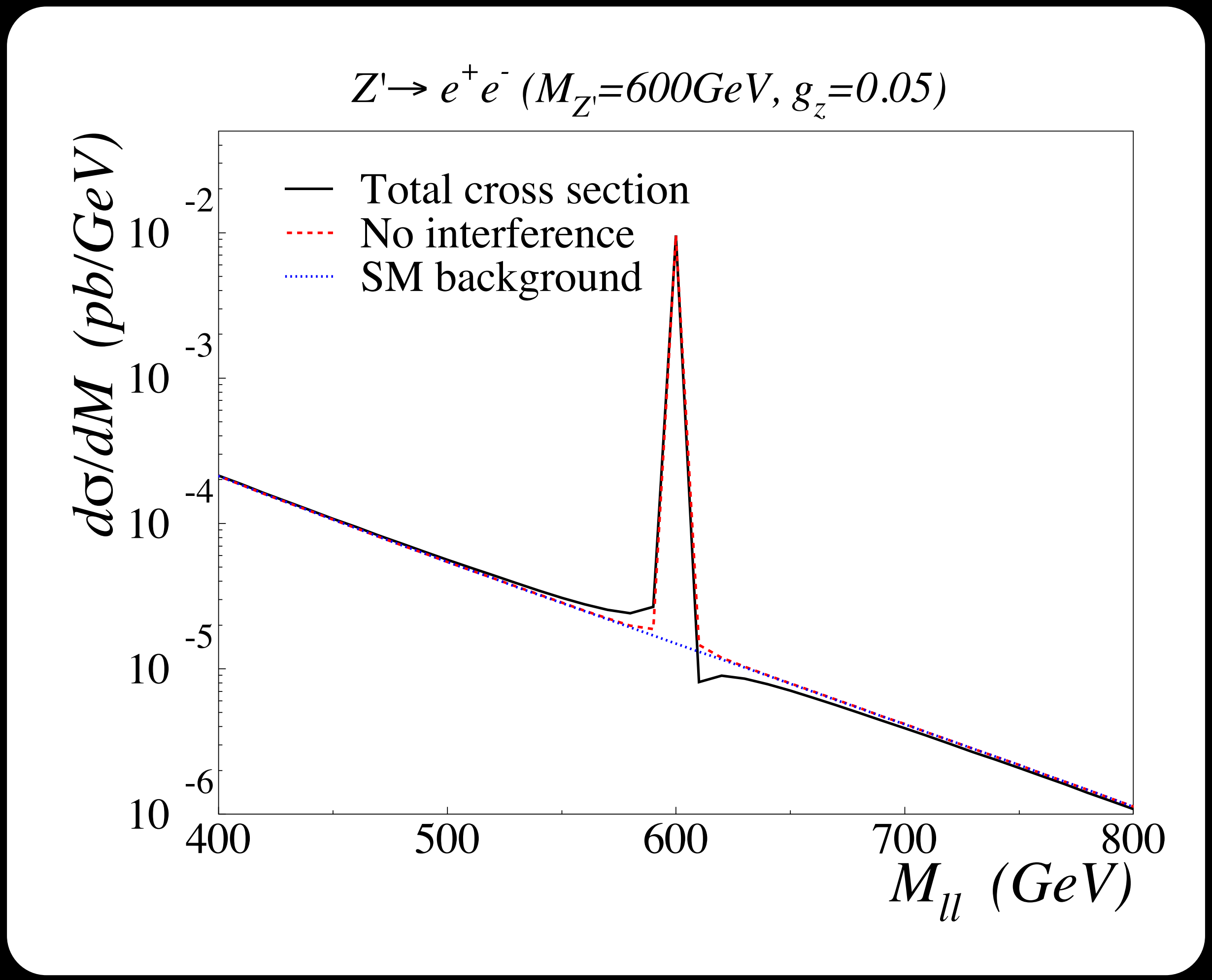


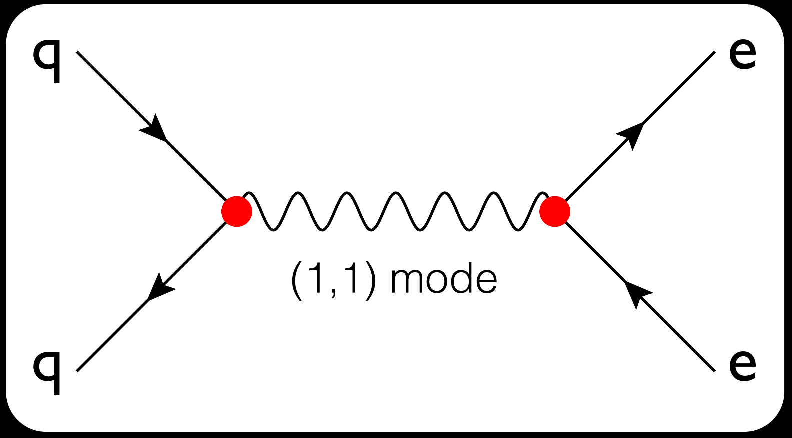
Chiral Square: γ-Rays



B(1,1) at the LHC

- At the LHC, B(1,1), can be produced from a q qbar initial state (with reduced but substantial couplings proportional to hypercharge).
- It decays into ordinary leptons and quarks, providing a classic Z' signature.
- γ-ray observations can observe the secondary line, and measure the mass - telling the LHC where to look.
- LHC data severely constrains the potential size of the brane terms, limiting the coupling of the (1,1) state to zero mode (SM) fermions.





T-Parity

- Another symmetry which can stabilize dark matter is "T-parity".

Cheng, Low hep-ph/0308199

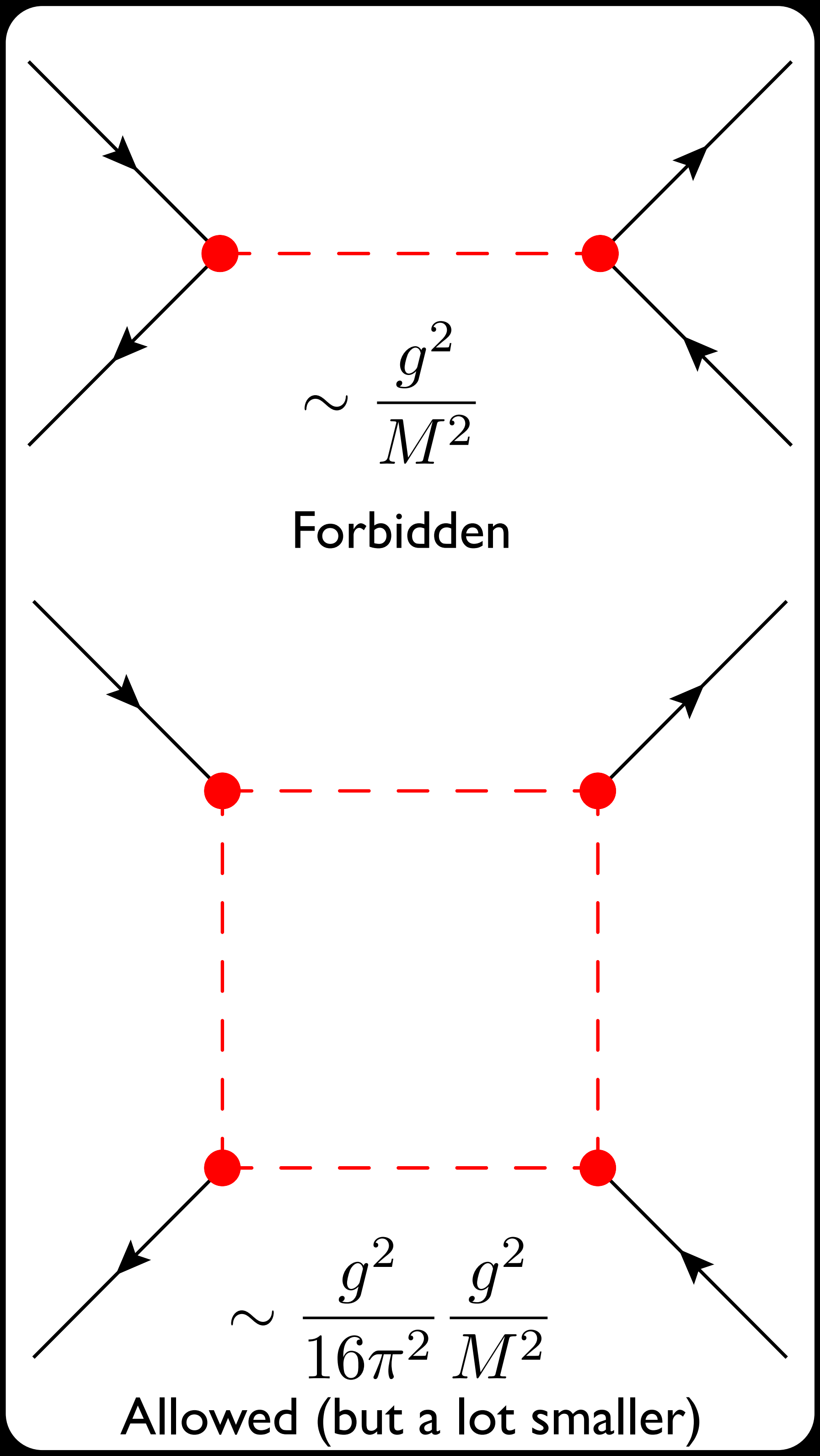
- T-parity is a phenomenological symmetry which can be invoked to protect precision measurements from large contributions from new physics.

- If one requires the new particles to couple in pairs, they can't contribute to SM processes at tree level, and first appear at loop level.

- This implies the lightest new particle is stable.

  - R-parity and KK-parity are both examples!

- We can still address the hierarchy problem which, as you know from Michael's lectures, is a problem with loop diagrams.

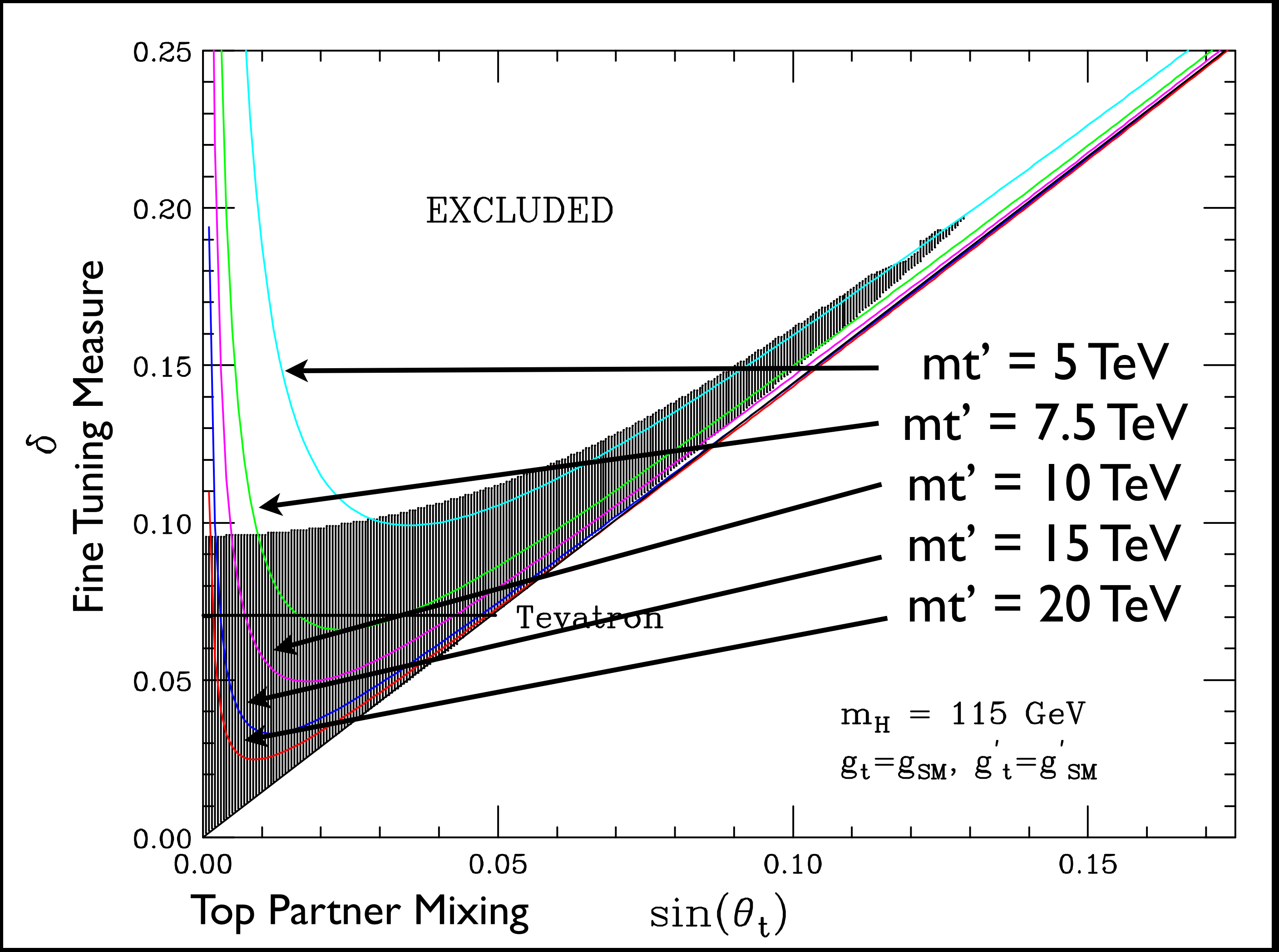


Little Higgs with T-parity

- Little Higgs theories attempt to create a gap between whatever stuff solves the hierarchy problem and the Higgs itself by engineering the Higgs to be a pseudo-Goldstone boson.

- It's a very nice idea, but it faltered in practice when it was found that precision electroweak data made it difficult to realize in practice.

- T-parity allows the extra new particles ("partners") to have light enough masses to make the Little Higgs idea workable.



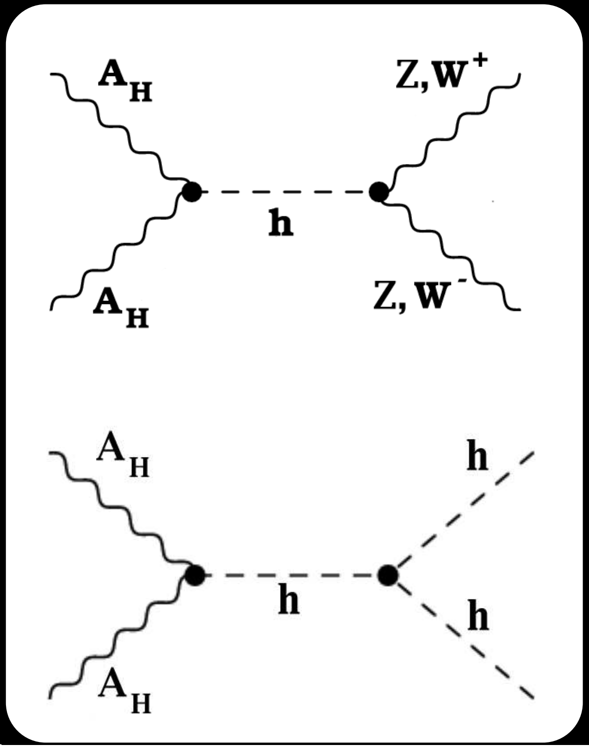
$$\delta \equiv \frac{v}{f}$$

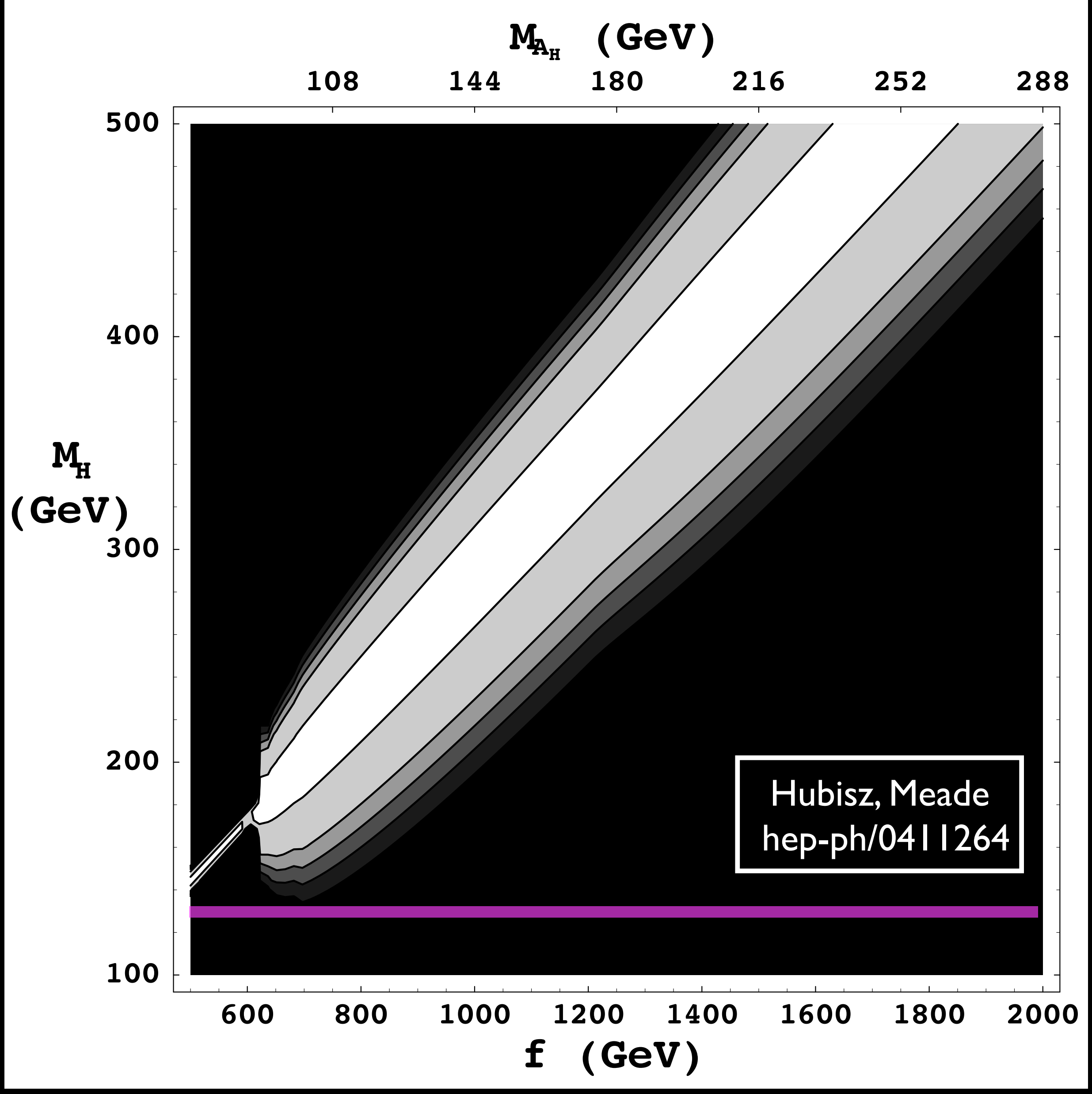
Hewett, Petriello, Rizzo
hep-ph/0211218
See Also: Terning et al
hep-ph/0211124

Less fine-tuned theories result, with new states coupling in pairs -- the Lightest T-odd Particle is DM!

LTP

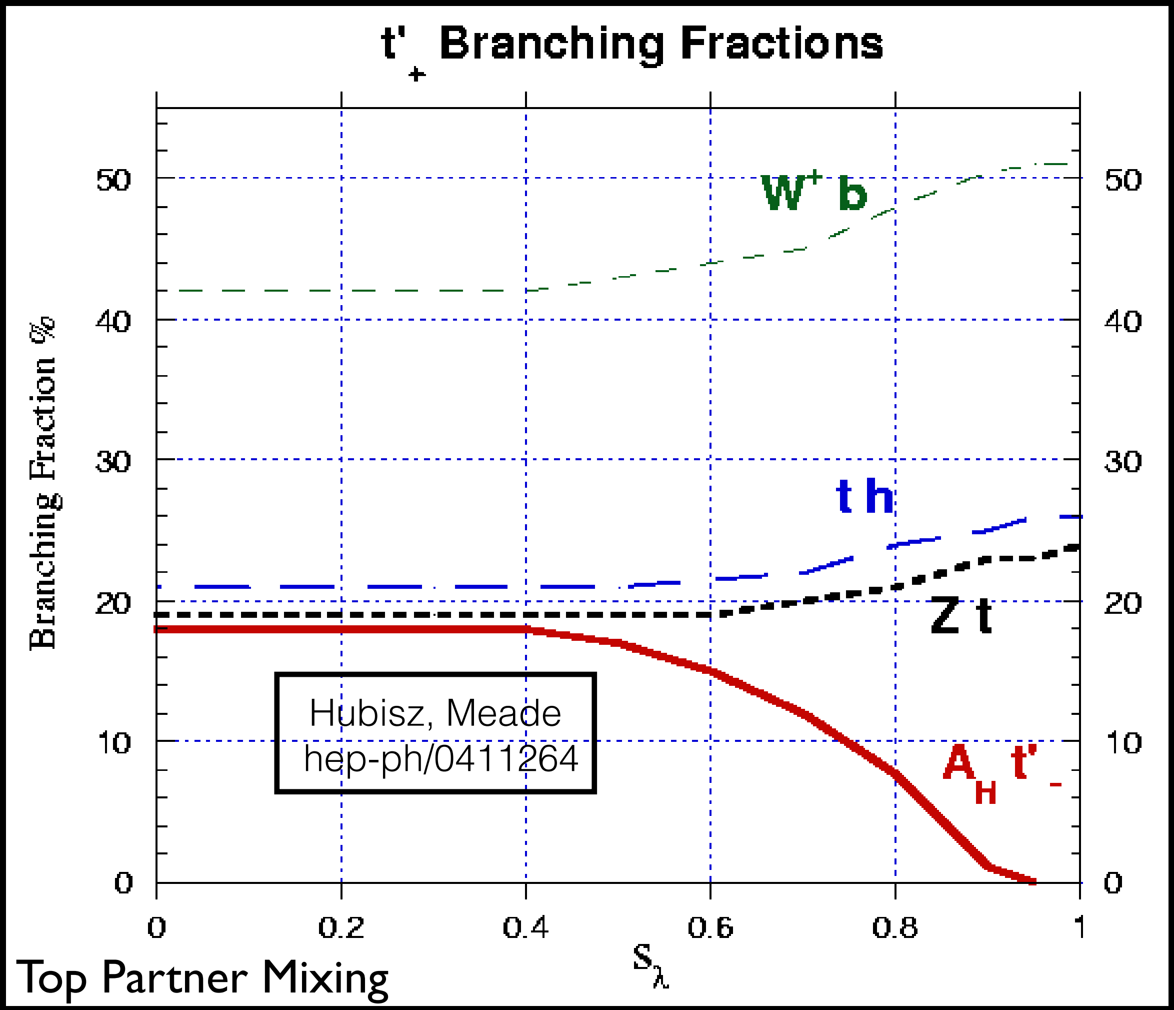
- A simple LH model with dark matter is the "Littlest Higgs with T-parity".
- The lightest particle is often a U(1) gauge boson, very similar to the LKP.
- The key difference is that the model only needs light partners for particles which couple strongly to the SM Higgs.
  - The t, W, Z, h partners are all light.
  - All other partners are assumed very heavy.
  - As a result, the cross section away from the SM Higgs funnel is always way too small to give us the correct relic density for a Standard Cosmology.
- This simplest model is ruled out by the LHC because the SM Higgs is too light.

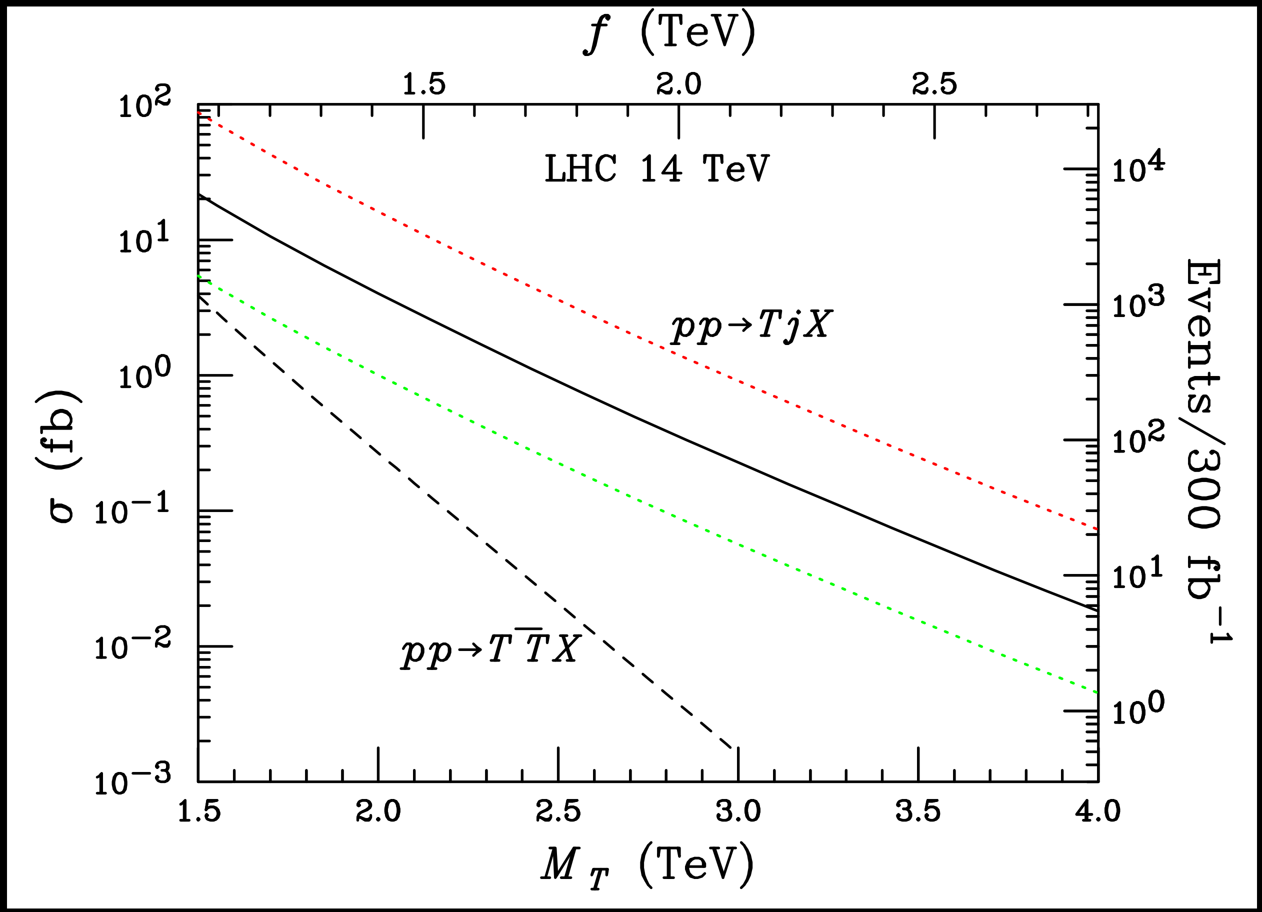




LHC Signals

- The LHC signals are dominated by the light colored partner (the top-partner).
- It turns out there are two:
  - A T-odd one which decays into t + LTP.
  - A T-even one which decays to W + b, Z + t, and/or h + t.
- The cross section for pair production of the top partners is QCD : depends on the mass & αS.
- Single production of the T-even partner can dominate.

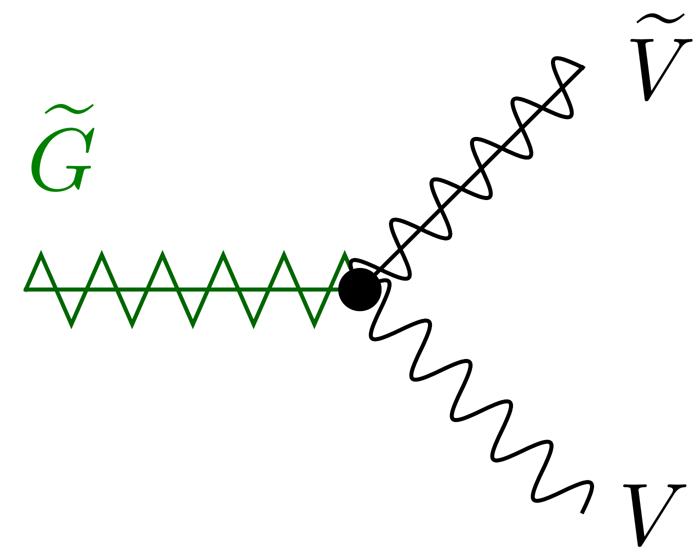




Han, Logan, McElrath, Wang
hep-ph/03o1040

Super-WIMPs

- Dark matter could be super-weakly interacting.
- This gives up the beauty of the WIMP miracle, but is still an interesting possibility.
- In fact, both SUSY and UED theories naturally have a particle which could be dark matter and falls into this category:
    - SUSY: spin 3/2 gravitino
    - UED: spin 2 KK graviton
- I'll focus on the gravitino here, but the generalization to the KK graviton is rather straightforward.



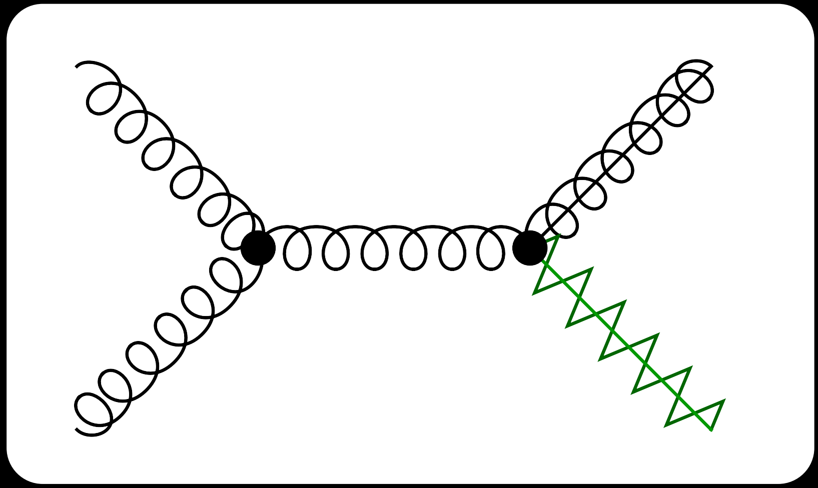
$$\sim \frac{M_{\widetilde{V}}}{F} \sim \frac{M_{\widetilde{V}}}{m_{\widetilde{G}} M_{\rm Pl}}$$

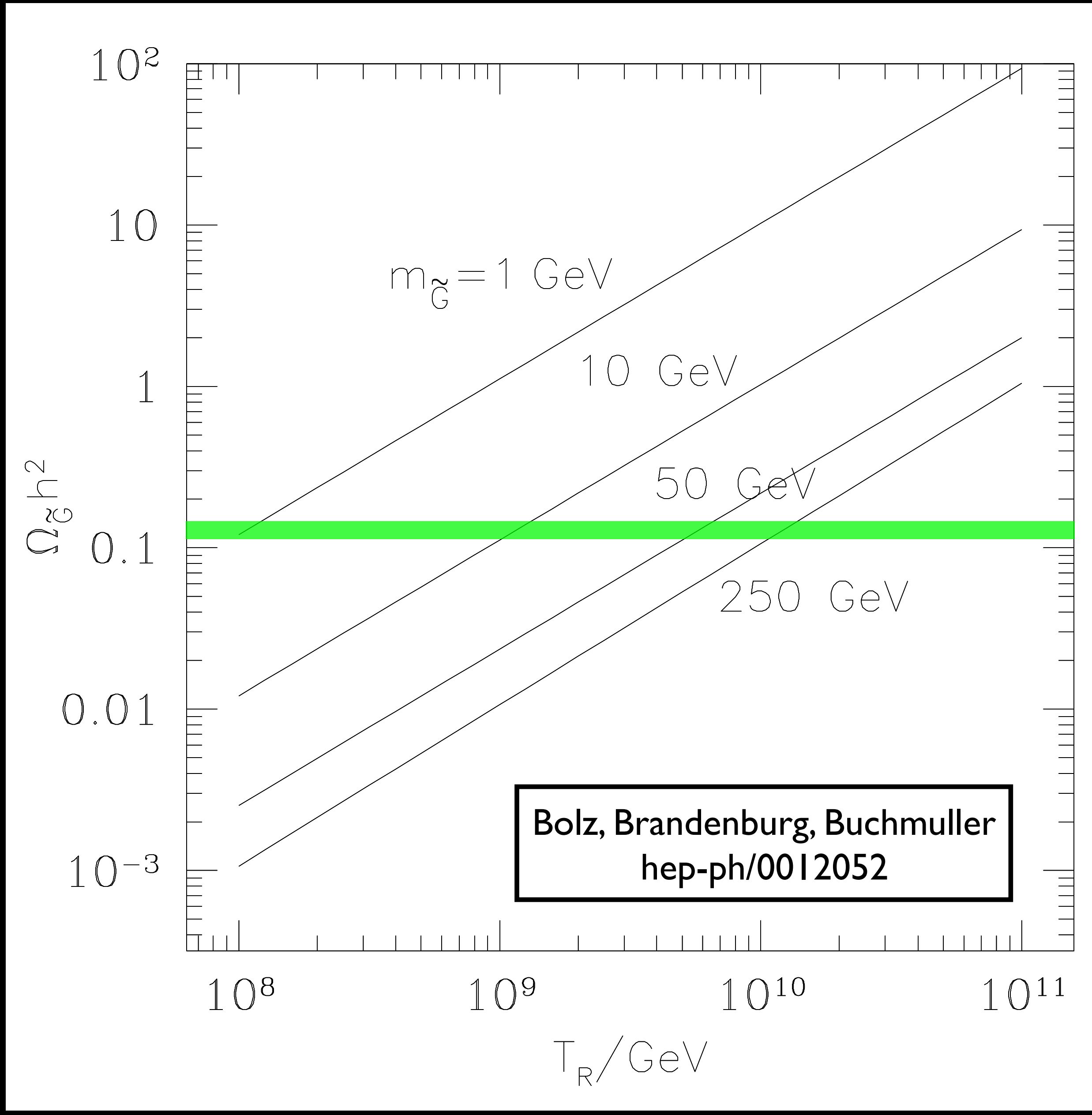
Dominant Coupling through the Goldstino component

For more UED details, see:
Feng, Rajaraman, Takayama
hep-ph/0302215 & 0307375

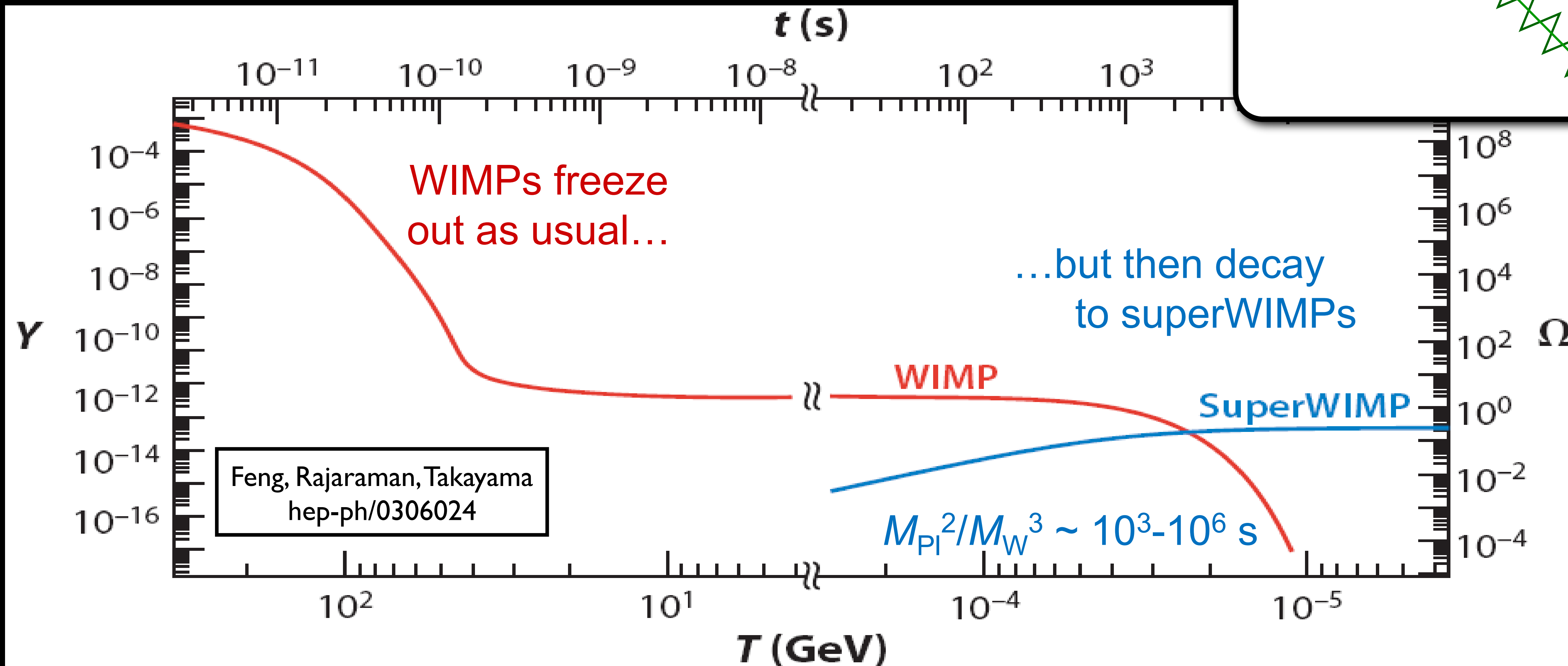
Relic Gravitinos

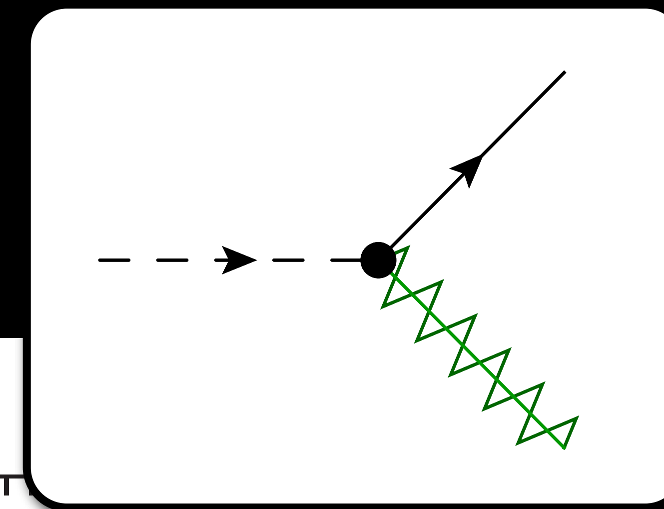
- Though they are never in equilibrium, we can still produce relic gravitinos:
- One mechanism is to have them *freeze-in*.
- Since they fail to reach equilibrium, the quantity generated depends very sensitively on the reheating temperature at the end of inflation.
- This can be a problem -- if they are overproduced, we can end up with too much dark matter, leading to a bound on T_R.
- For just the right T_R, we get Ωh^2 ~0.1.





Late Decay



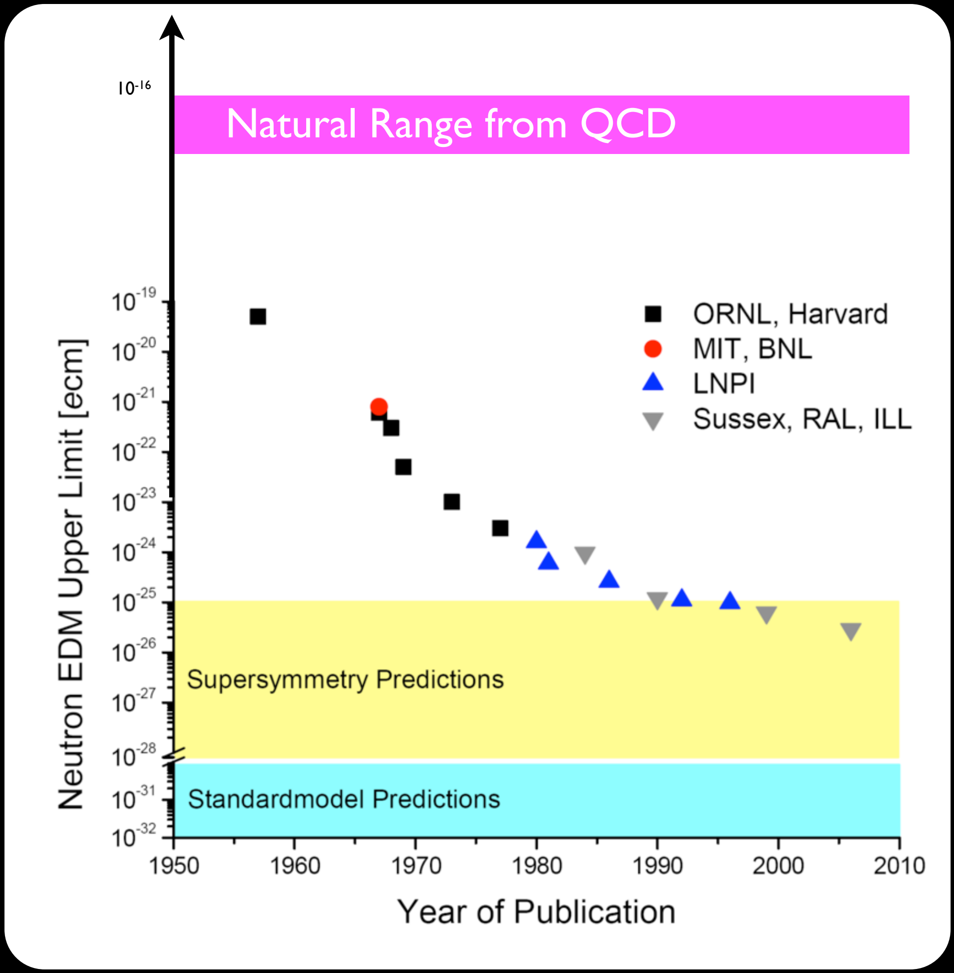


- A gravitino LSP can also be produced by the late decay of a more conventional WIMP, inheriting its relic density.
  - The NLSP need not even be neutral!
- Some care is needed to have the decay not destroy light elements.

Axion Dark Matter

- As we learned from Michael, the axion is motivated by the strong CP-problem, where the QCD θ term is cancelled by introducing a scalar field -- the QCD axion.

Peccei, Quinn '77



- The axion's mass and coupling are determined by virtue of its being a pseudo-Goldstone boson and are characterized by the energy scale $f_a > 10^9$ GeV.

$$m_a \sim f_\pi / f_a \times m_\pi$$

Preskill, Wise, Wilczek '83
Abbott, Sikivie '83
Dine, Fischler '83

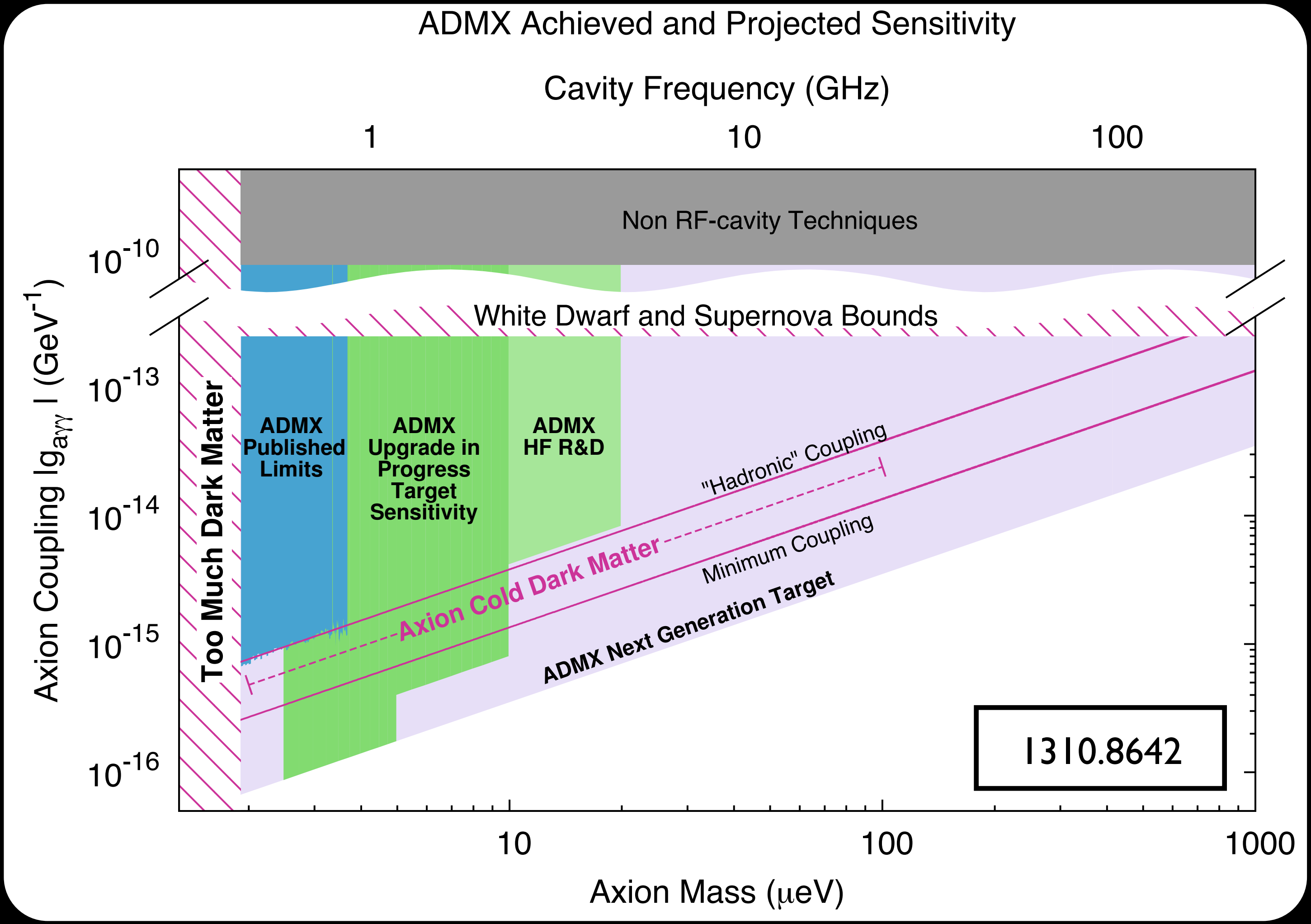
- The axion is unstable, but its tiny mass and weak couplings conspire to predict that for much of the viable parameter space its lifetime is much greater than the age of the Universe itself.

- More generally, string theories often contain axion-like particles which are long-lived and can play the role of dark matter but have less tight correlations between their masses and couplings.

Axion Conversion

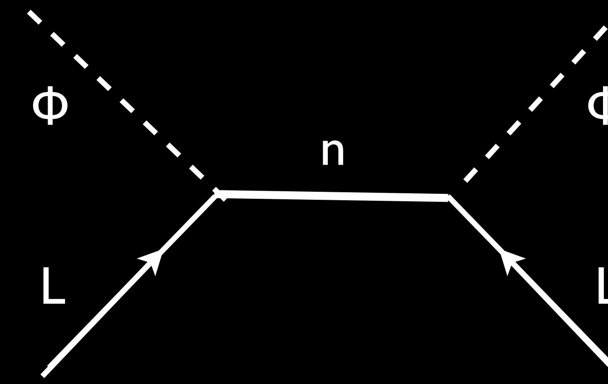
- The axion has a model-dependent coupling to electromagnetic fields that is somewhat smaller than $1 / f_a$.
- There is a rich and varied program of axion searches based on this coupling.
- One particular search looks for ambient axions converting into EM signals in the presence of a strong background magnetic field.
- Other very interesting new ideas are to look for time variation in the neutron EDM or the induced current in an LC circuit.

1306.6088 & 1310.8545

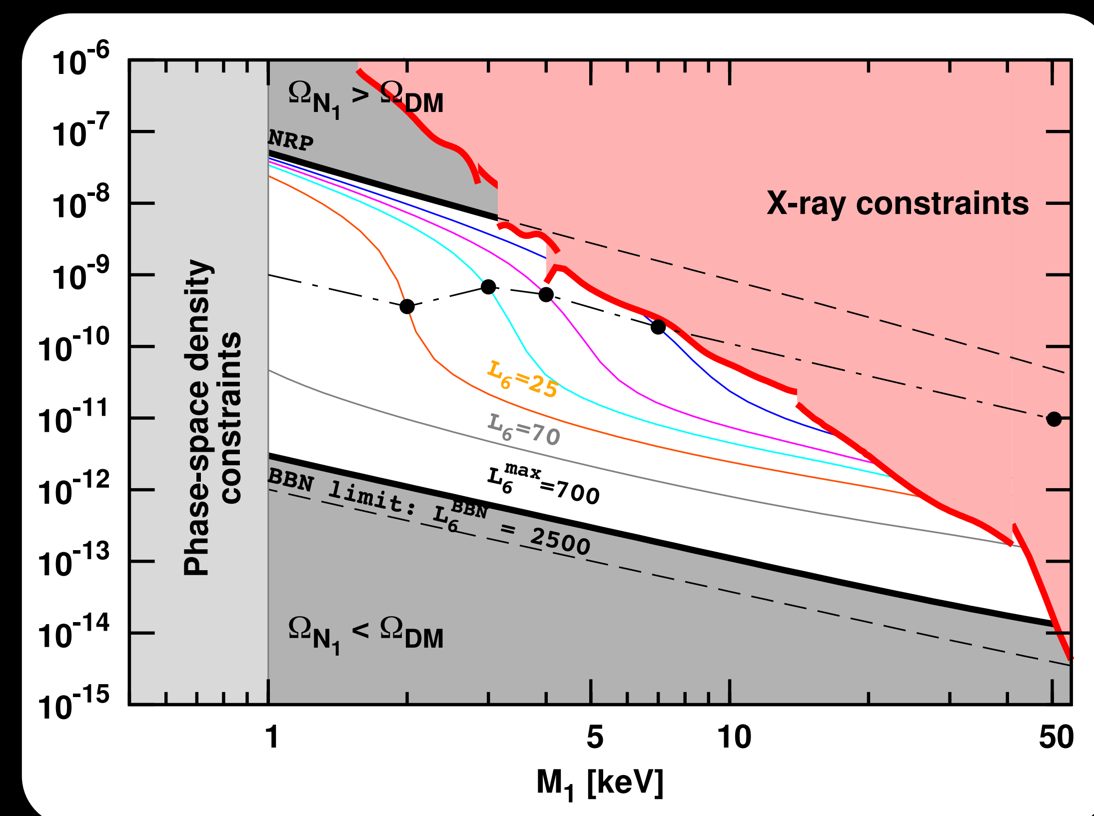


Axion dark matter can be produced by a misalignment mechanism, in which its original value at the time of inflation converts into a particle density once its mass turns on.

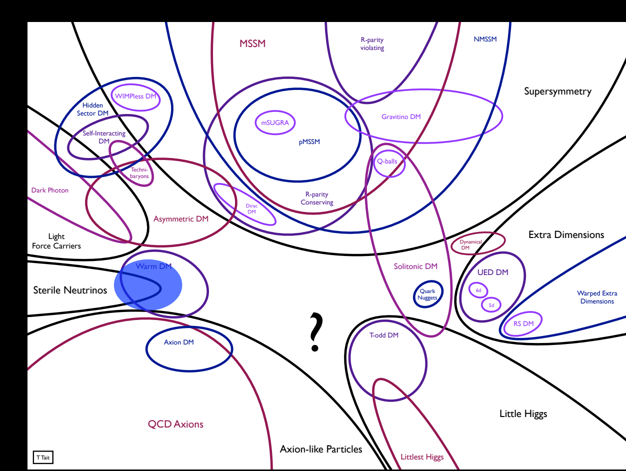
Sterile Neutrino DM



- Dark matter may be connected to one of the other incontrovertible signals of physics beyond the SM: neutrino masses.
- The simplest way to generate neutrino masses in the SM is to add some number of gauge singlet fermions to play the role of the right-handed neutrinos.
- If the additional states are light and not strongly mixed with the active neutrinos (as required by precision electroweak data), they can be stable on the scale of the age of the Universe and play the role of dark matter.
- Arriving at the right amount of dark matter via oscillations typically requires delicately choosing the mass and mixing angle, or invoking some other new physics.



1310.8642

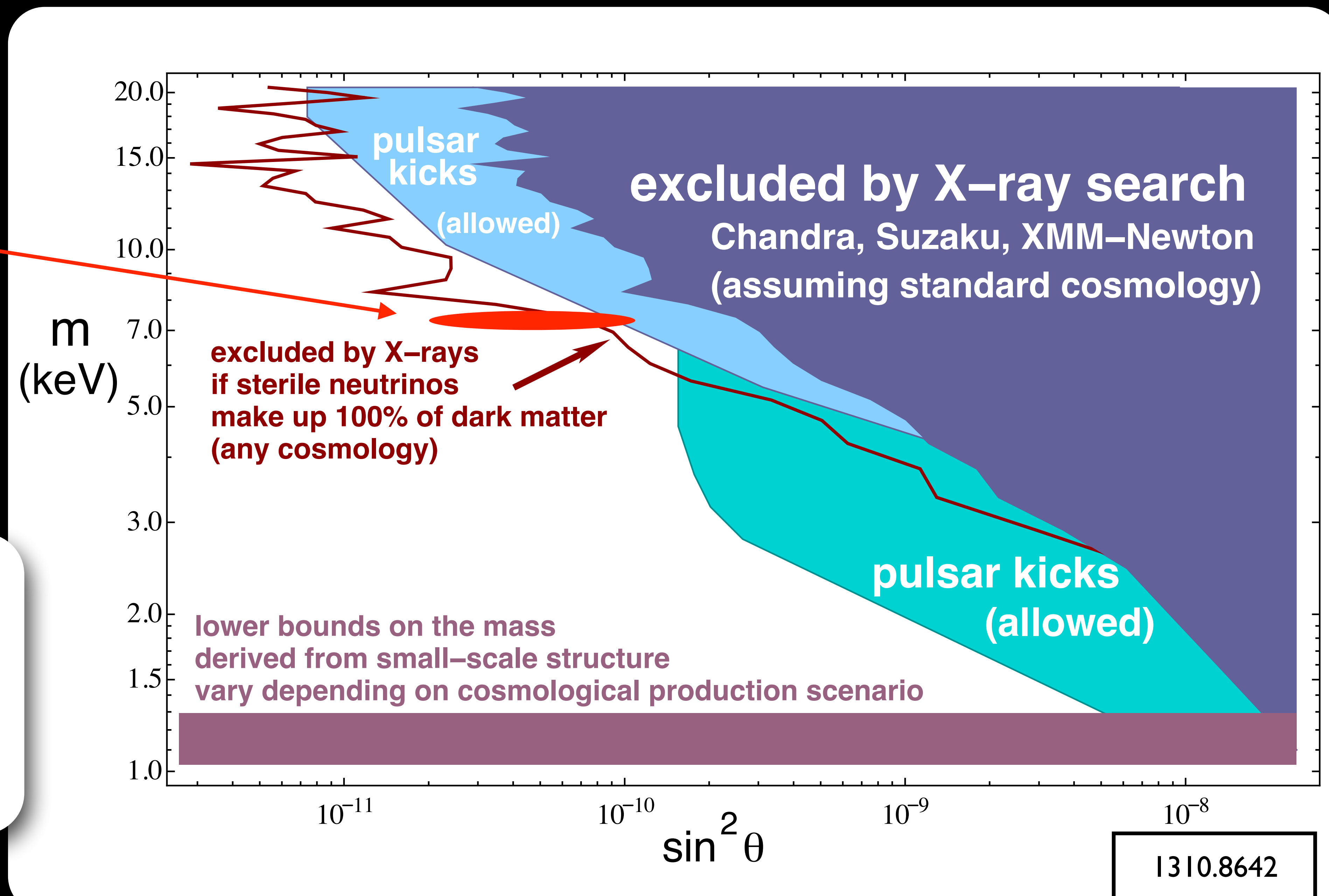


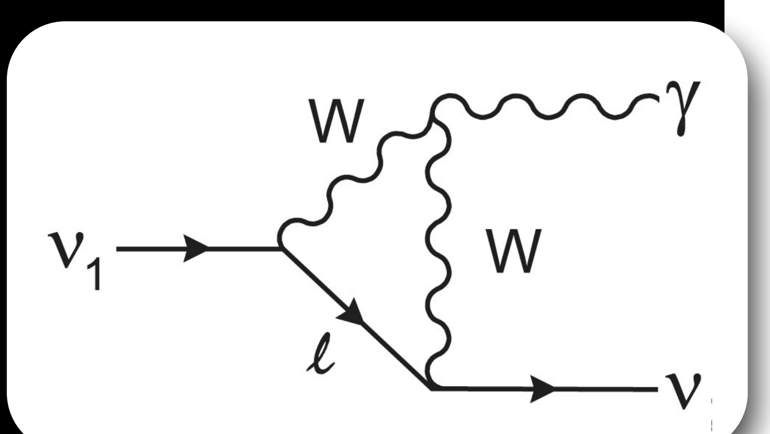
Sterile Neutrino Decay

- Though rare, sterile neutrinos can decay into ordinary neutrinos and a photon, resulting in (mono-energetic) keV energy photons.
- Constraints from the lack of observation of such a signal put limits in the plane of the mass versus the mixing angle.

Possible X-ray Signal
[Bulbul et al 2014]

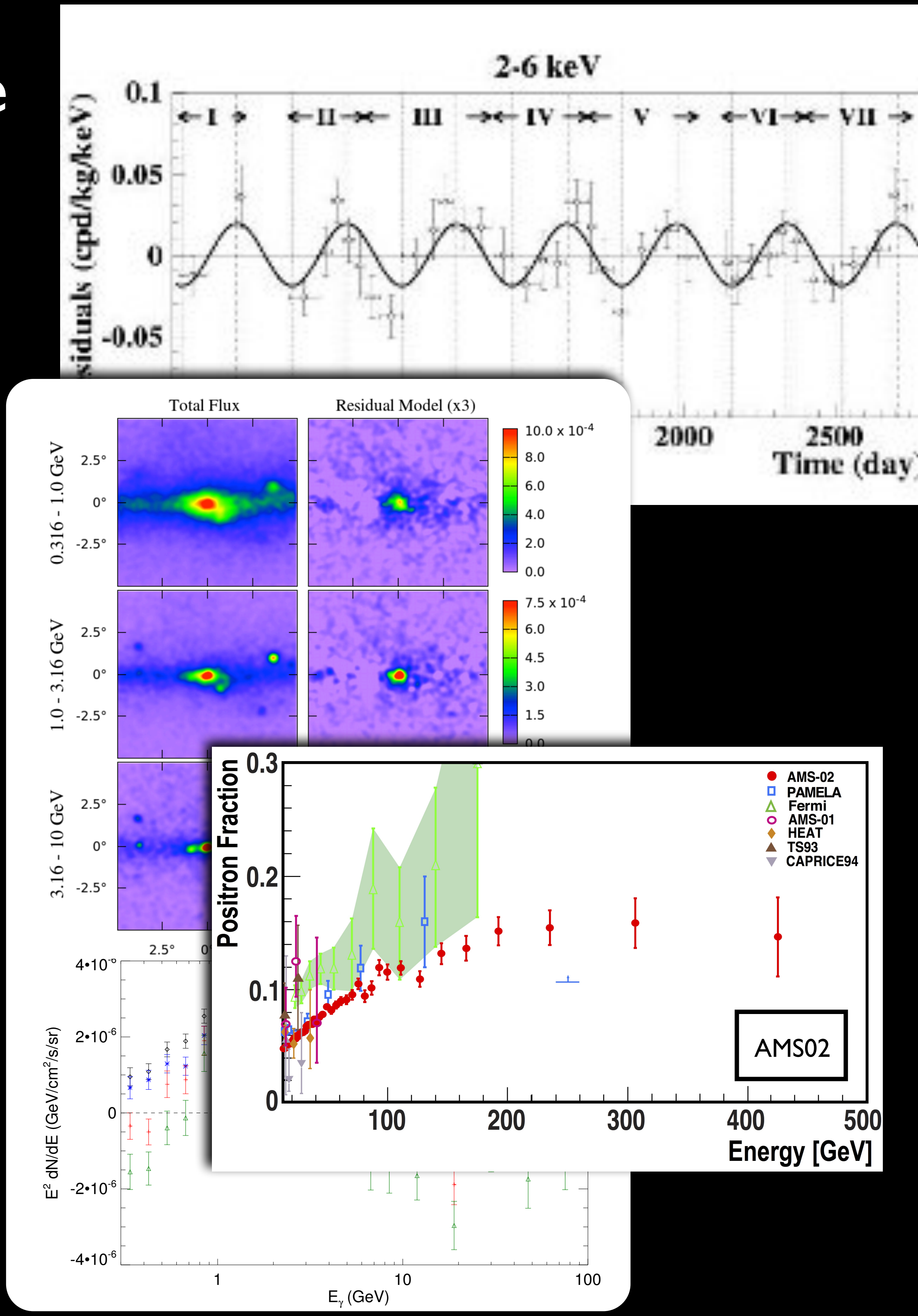
(Extracted from Abazajian 2014)





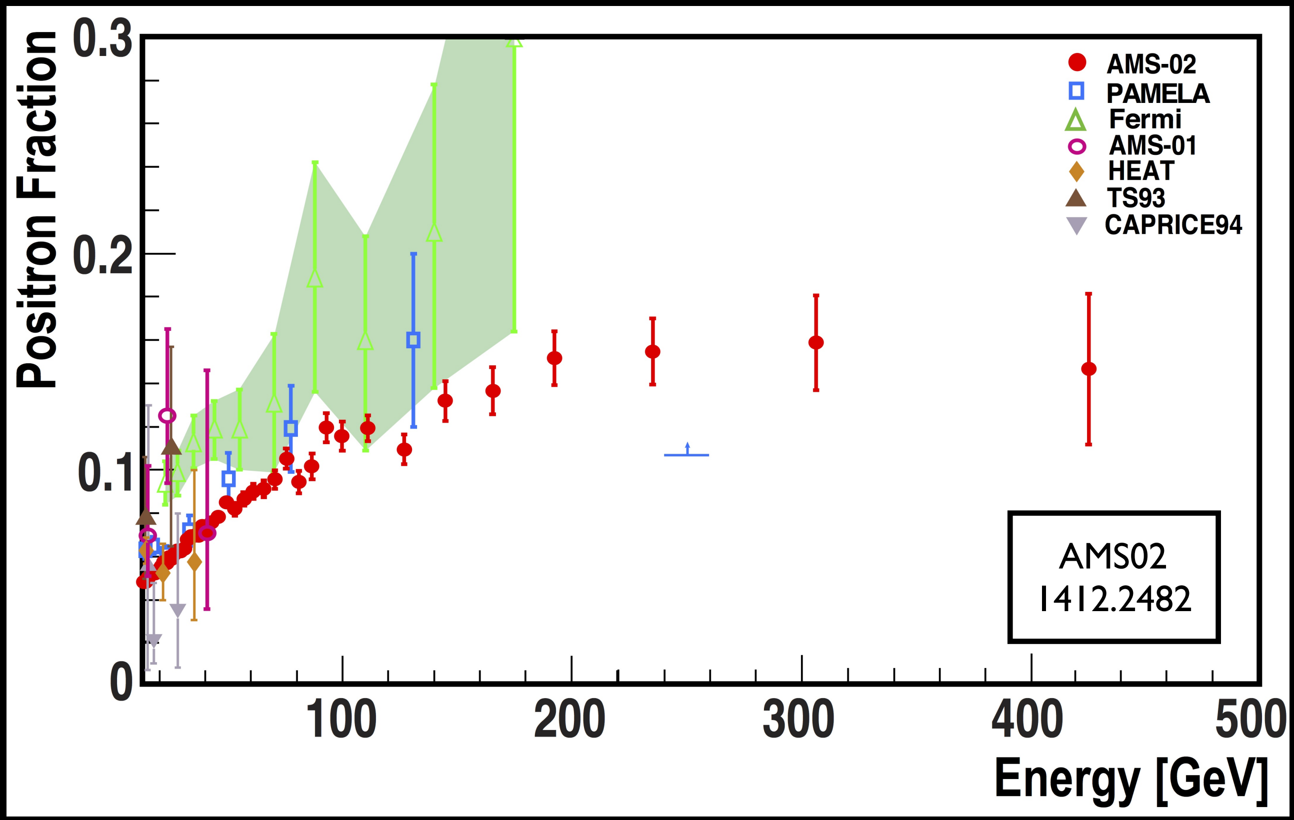
Designer Dark Matter

- As our searches for dark matter mature, we hope to eventually see a hint for a signal.
- There is no completely compelling evidence for an observation, but there are some tantalizing hints for things we don't understand. They might even be WIMPs!
- We can hope to eventually construct a theory of dark matter from observation.
- Even if the hints don't stand the test of time, they may inspire unconventional visions for how dark matter could work. They're still valuable to inspire new experiments and analyses.

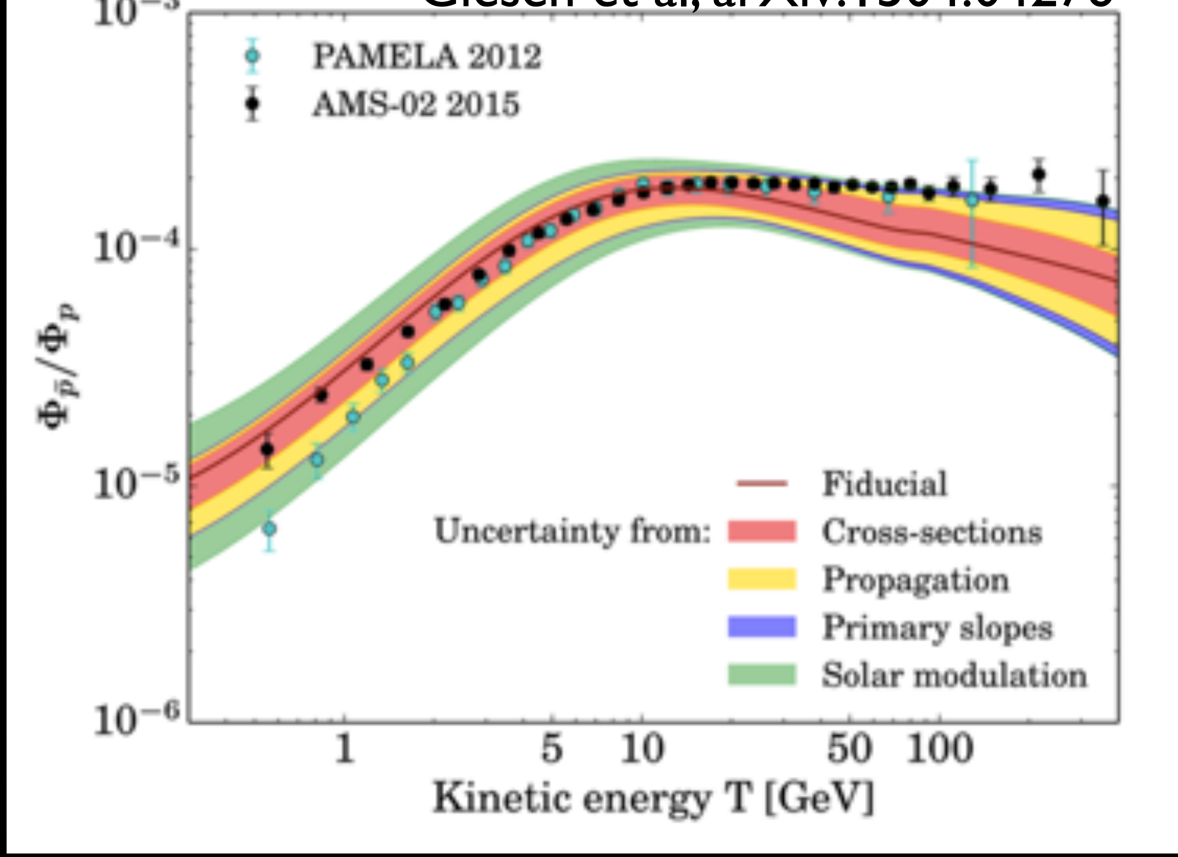


Positron Fraction

- Anti-matter is only rarely produced by astrophysical objects. An excess is a possible signature of dark matter annihilation.
- Somewhat mysteriously, the fraction of positrons increases with energy up to ~500 GeV as measured by AMS-02.
- This could be the output of a nearby pulsar, or it could be a signal of dark matter annihilation.
- If interpreted as dark matter, a cross section that is somewhat shockingly high compared to the thermal one would be required.
- Anti-proton measurements show no excess over expectations.

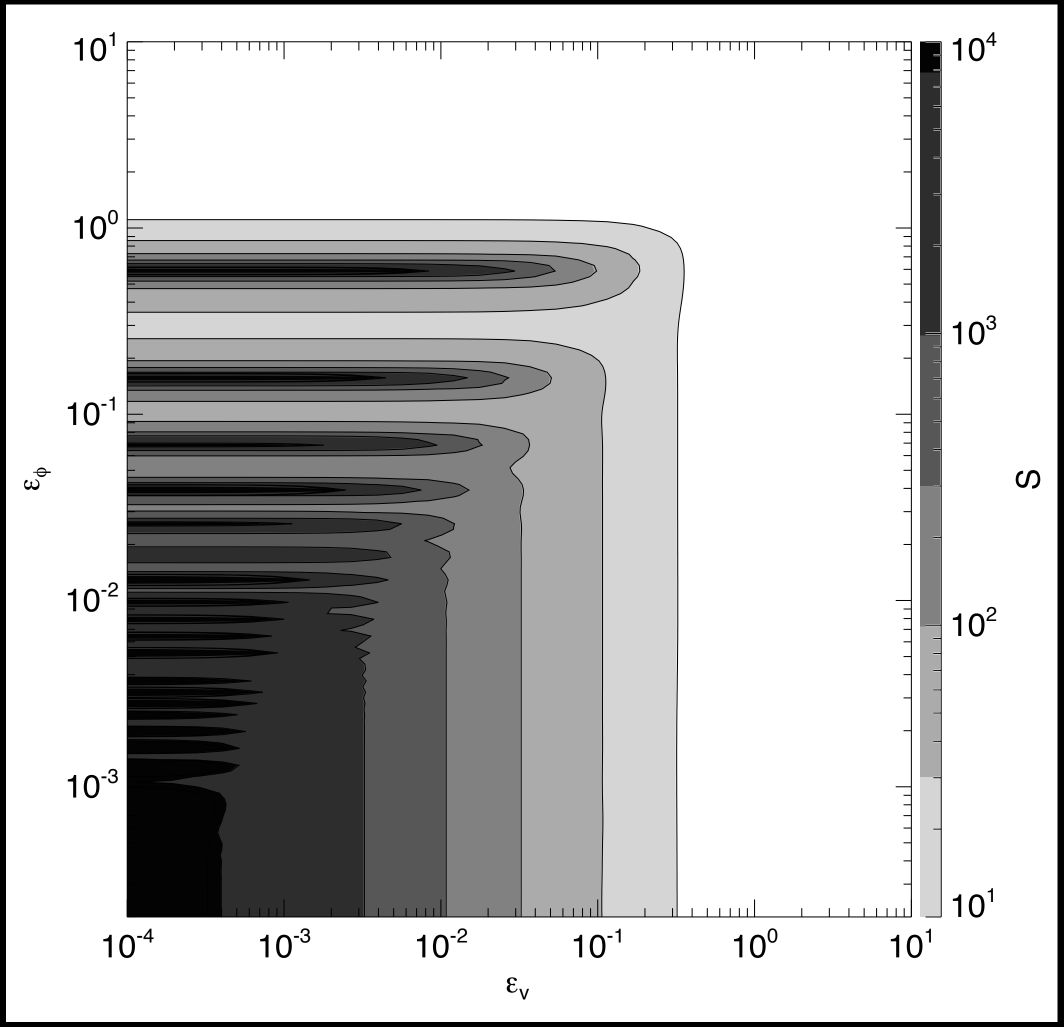


Giesen et al, arXiv:1504.04276



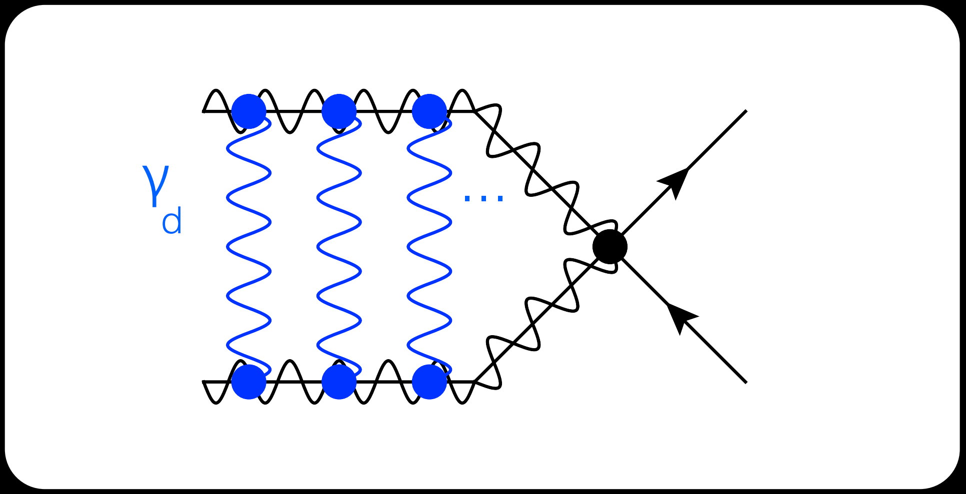
Light Mediators

- The PAMELA (and now Fermi and AMS02) positron excesses are an interesting signal that could be from dark matter annihilation/decay.
- A DM explanation runs into tension between the rate of annihilation required to produce a large enough signal compared with the relic density.
- A popular idea to reconcile the two is to introduce a light mediator (such as a dark photon) to invoke a Sommerfeld-like enhancement at small WIMP velocities.
- Summing up the effect of the mediator on the scattering can lead to a large enhancement factor compared to the leading order annihilation rate.



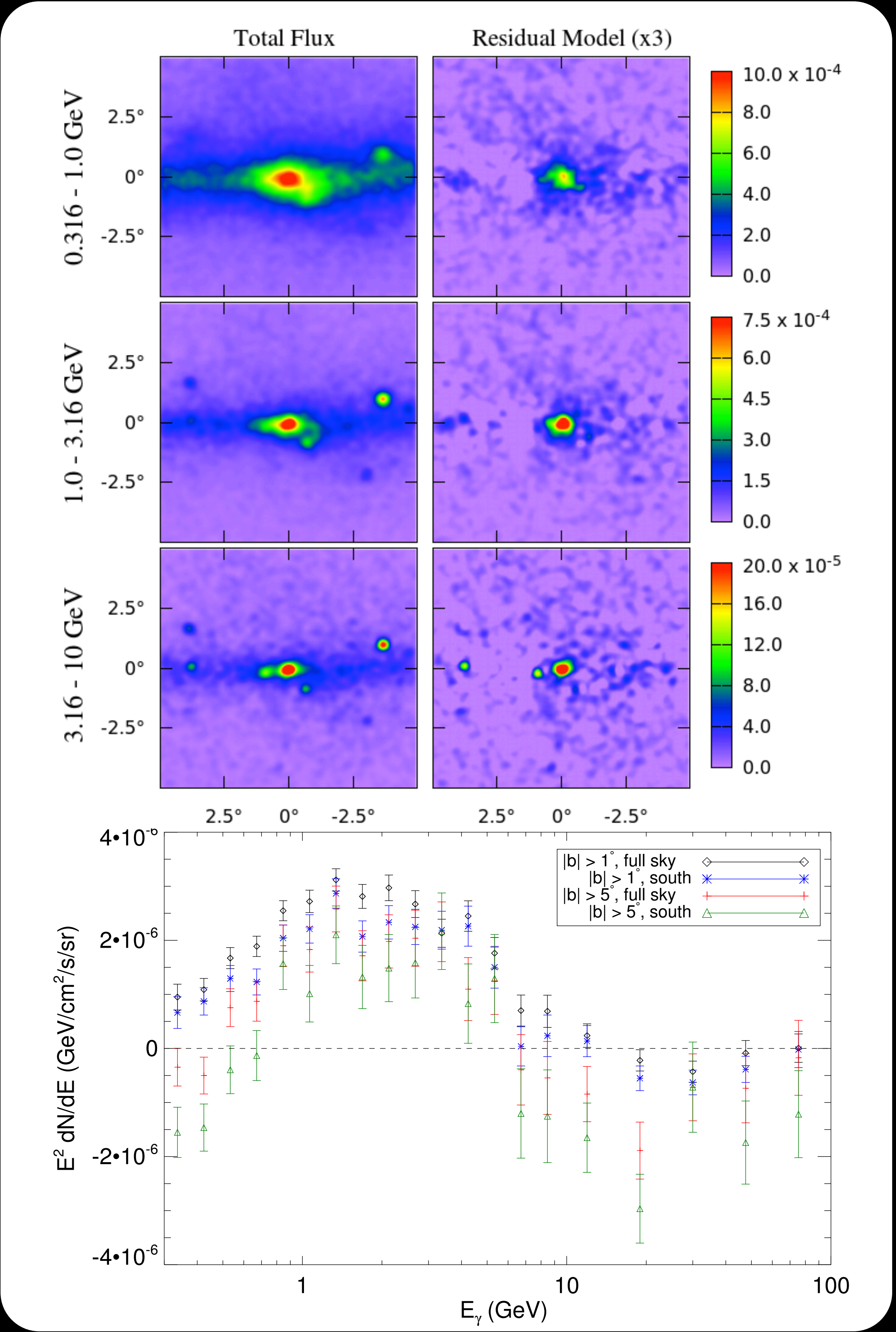
$$\epsilon_\phi \equiv \frac{m}{\alpha M} \qquad \epsilon_v \equiv \frac{v}{\alpha}$$

Cirelli, Kadastik, Raidal, Strumia 0809.2409
Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
...



Gamma Ray GeV Excess

- A simplified model allows us to put a (possible) discovery into context and ask what a theory that could explain it should look like.
- As an example: there are hints for what could be a dark matter signal in the Fermi data from the galactic center.
- After subtracting models of the diffuse gamma ray emission, known point sources, etc, an excess remains with a distribution peaking around a few GeV, consistent with the expectations of a 40 GeV dark matter particle annihilating into bottom quarks.
- This signal is currently the most credible hint for particle dark matter we have!



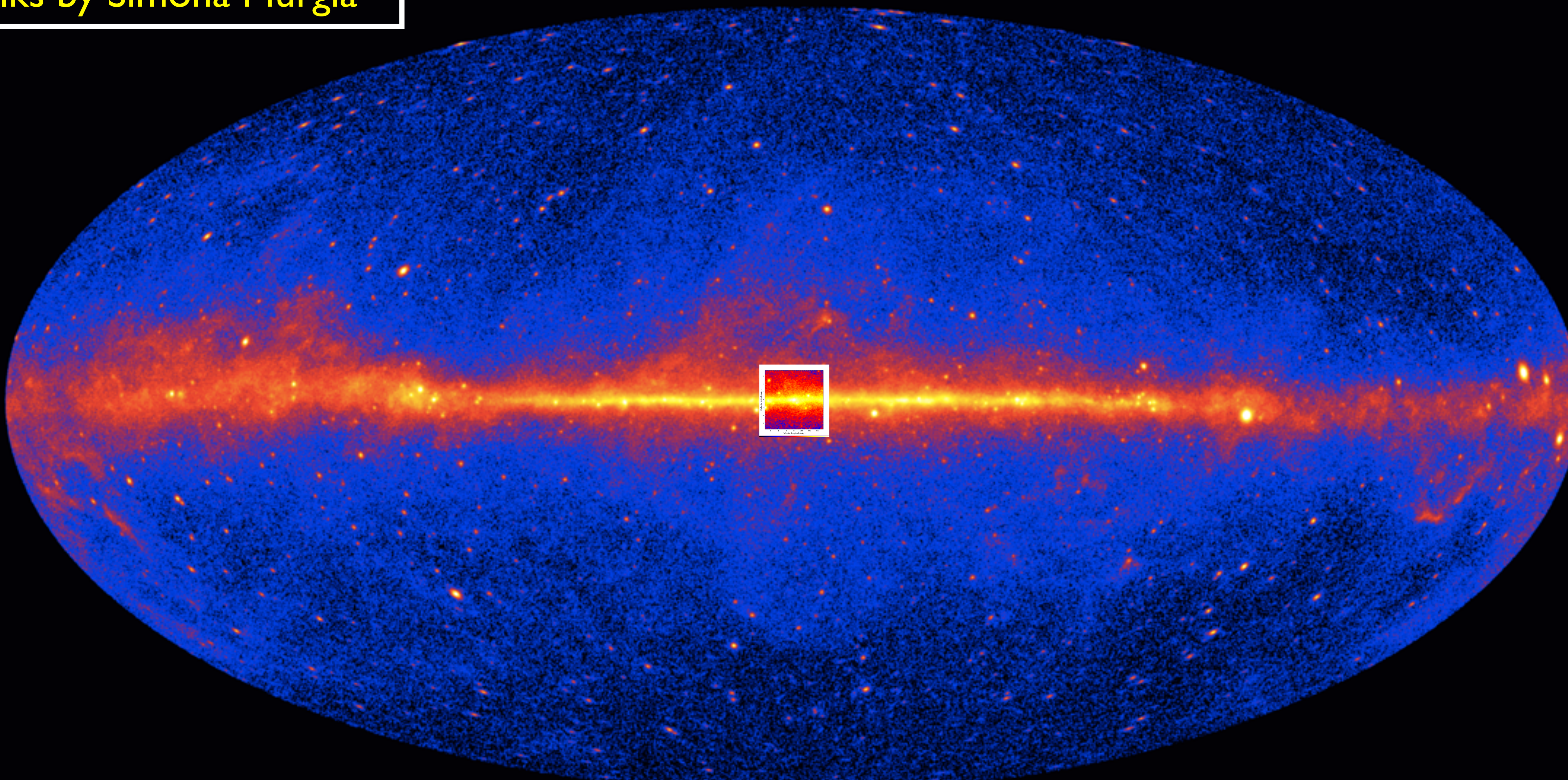
Hooper, Goodenough, 2009 + 2010
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703
see also: Abazajian, Canac, Horiuchi, Kaplinghat; Macias, Gordon

Modeling the Interstellar Emission

- Let's review the approach by Fermi LAT collaboration to develop a set of specialized models for the inner 15°x15° to extract the emission from the innermost ~1 kpc.

These slides adapted from talks by Simona Murgia

Fermi LAT collab. arXiv:1511.02938



Modeling the Interstellar Emission

- Let's review the approach by Fermi LAT collaboration to develop a set of specialized models for the inner 15°x15° to extract the emission from the innermost ~1 kpc.

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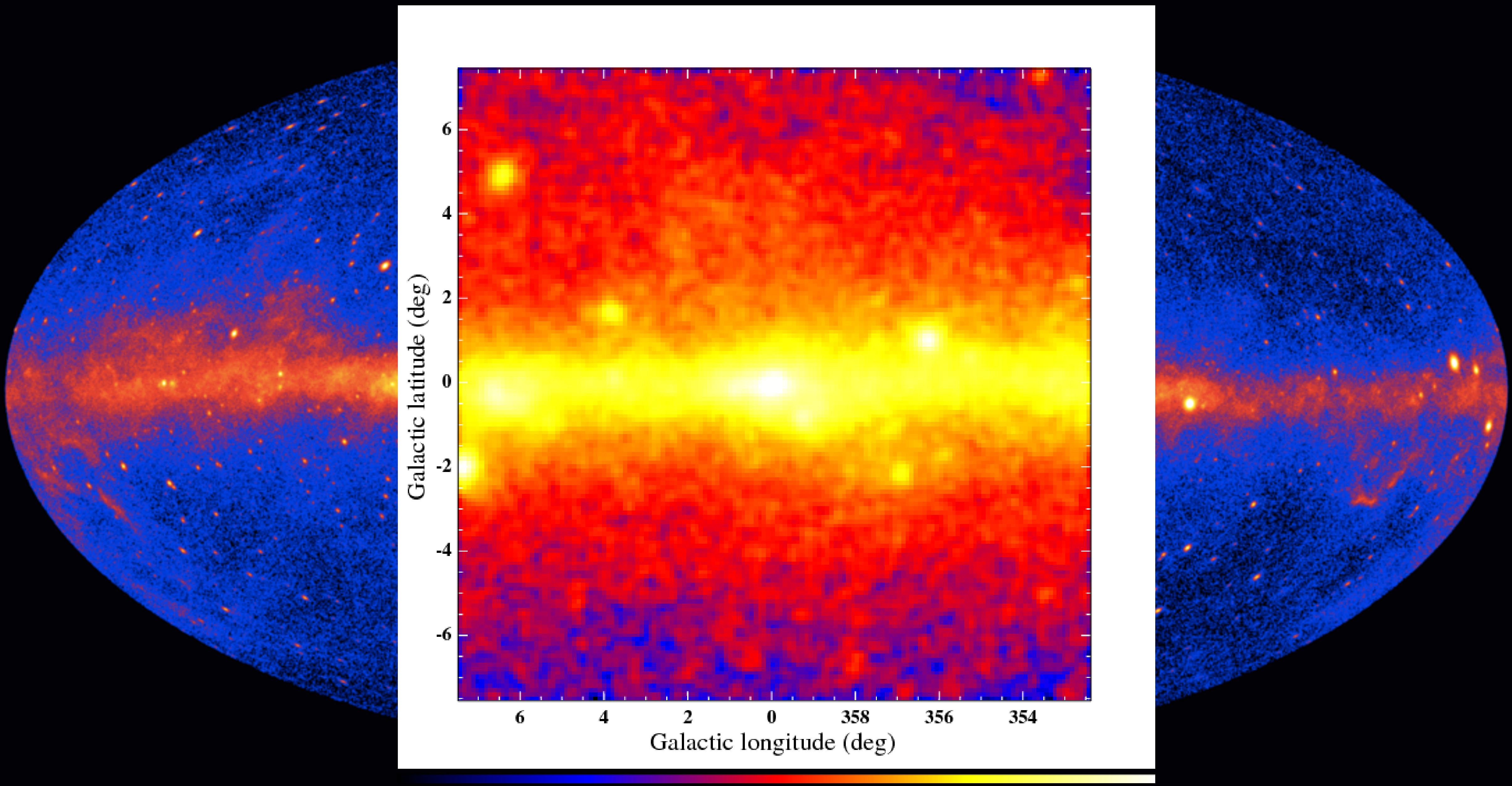
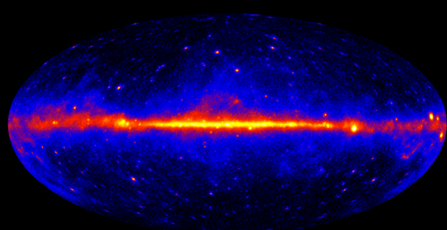


Understanding the Gamma-ray Sky



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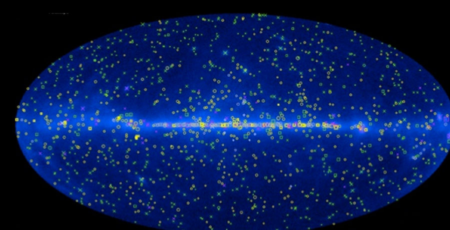

sources

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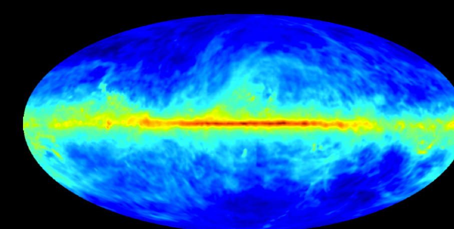

galactic interstellar emission

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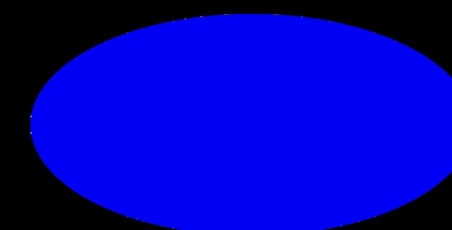
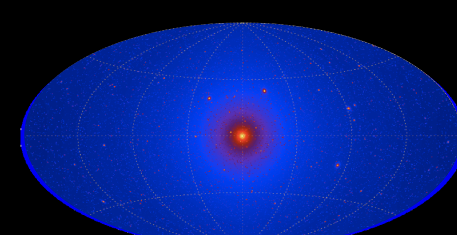


isotropic

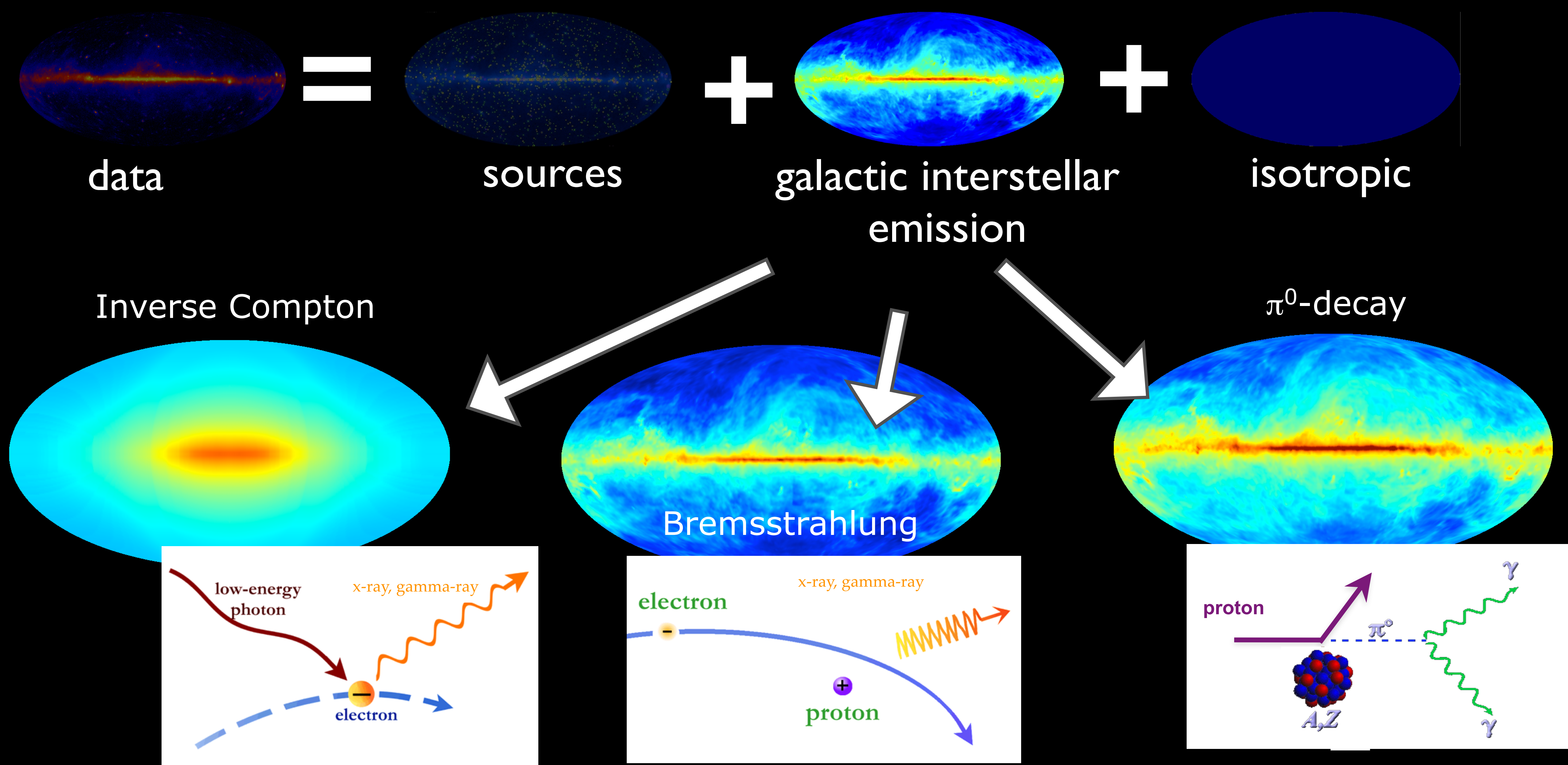
+



dark matter??

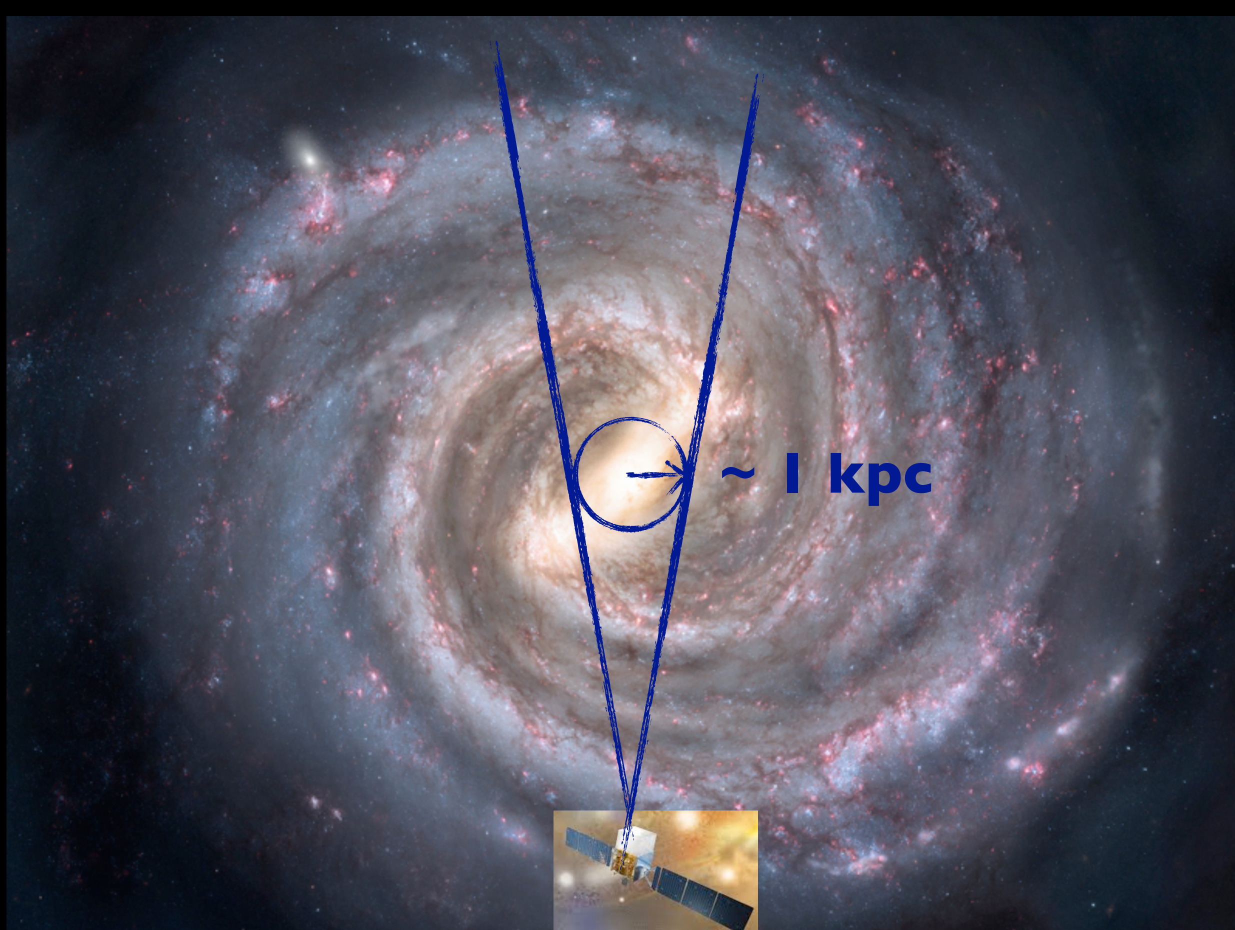
Galactic Gamma-Ray Interstellar Emission

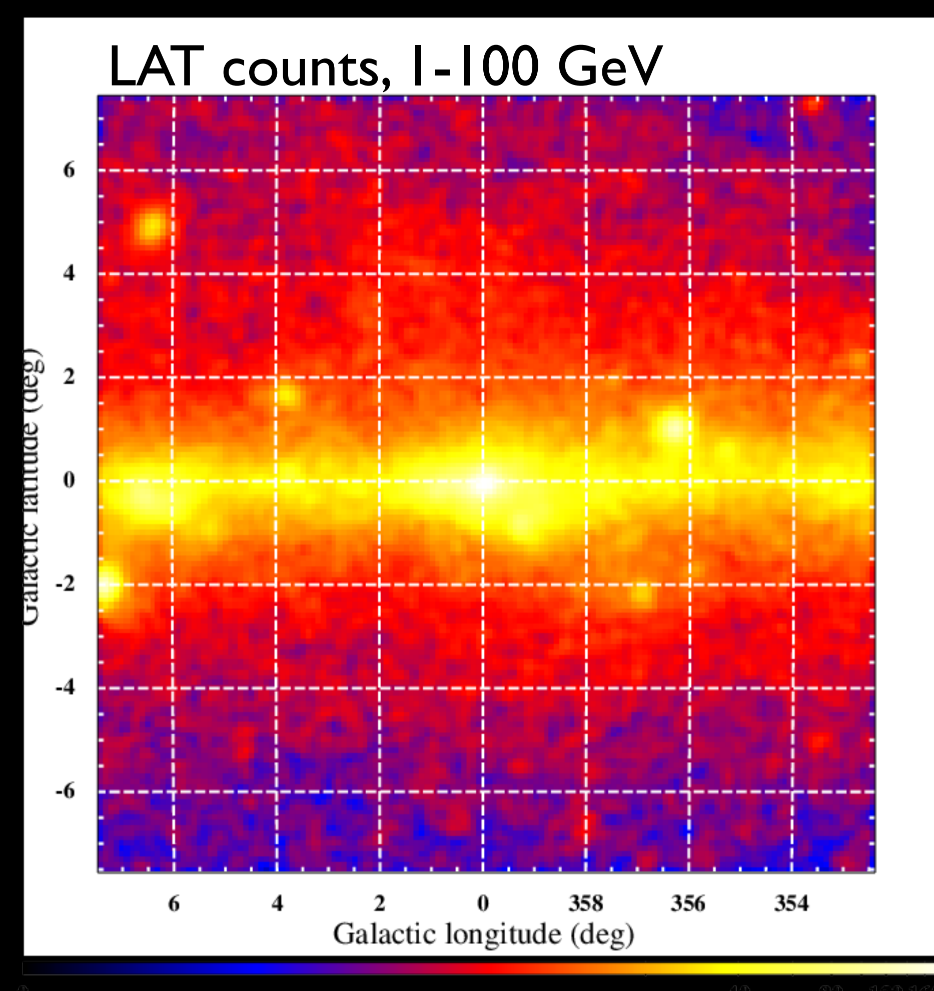
- The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field

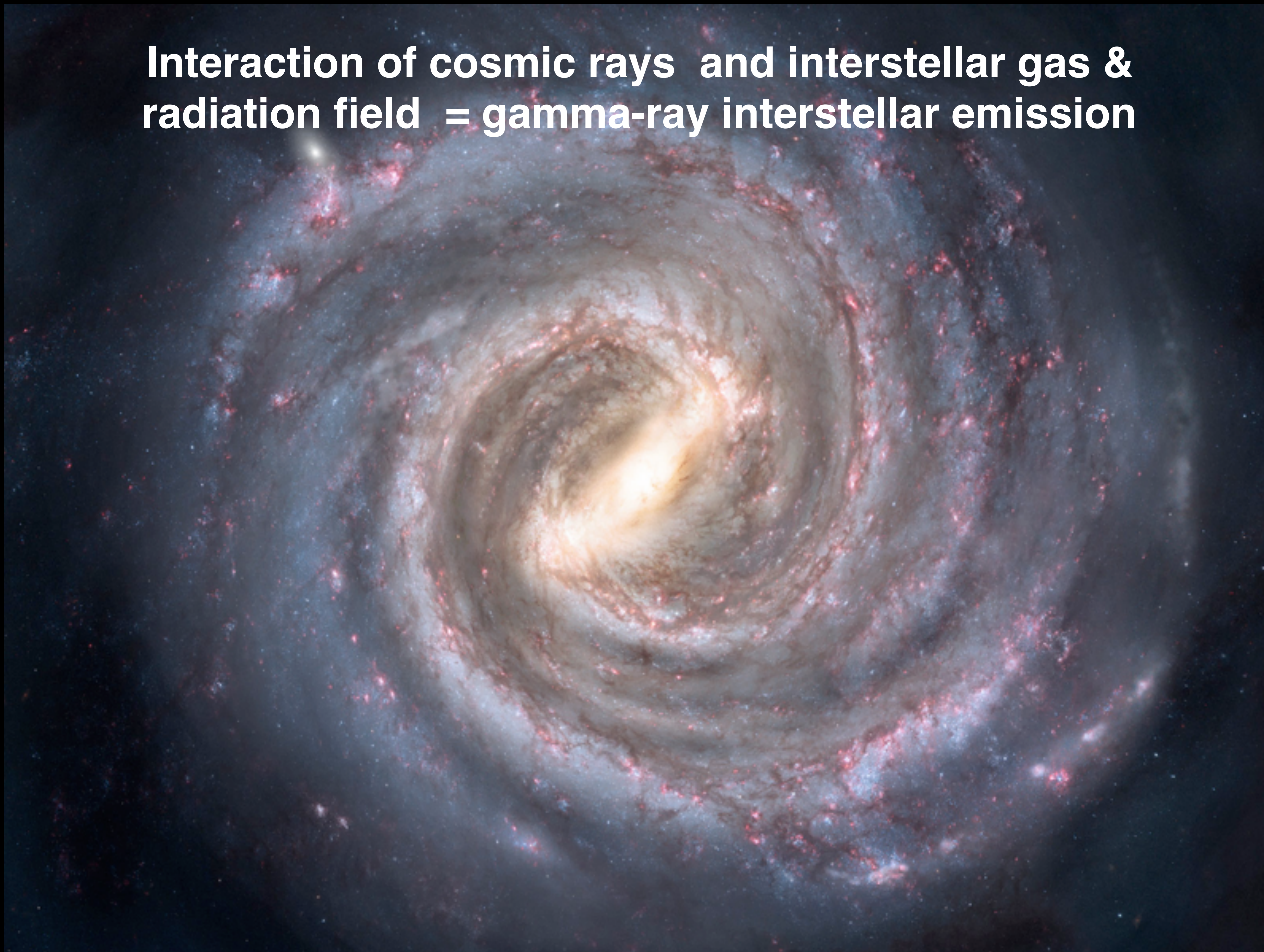


Modeling the Interstellar Emission

- Let's review the approach by Fermi LAT collaboration to develop a set of specialized models for the inner 15°x15° to extract the emission from the innermost ~1 kpc.
- Part of the complication is to extract the gamma rays coming from the galactic center, removing the contamination from the fore- and backgrounds.
- One must also account for the contribution from astrophysical point sources along the line of sight.






Interaction of cosmic rays and interstellar gas &
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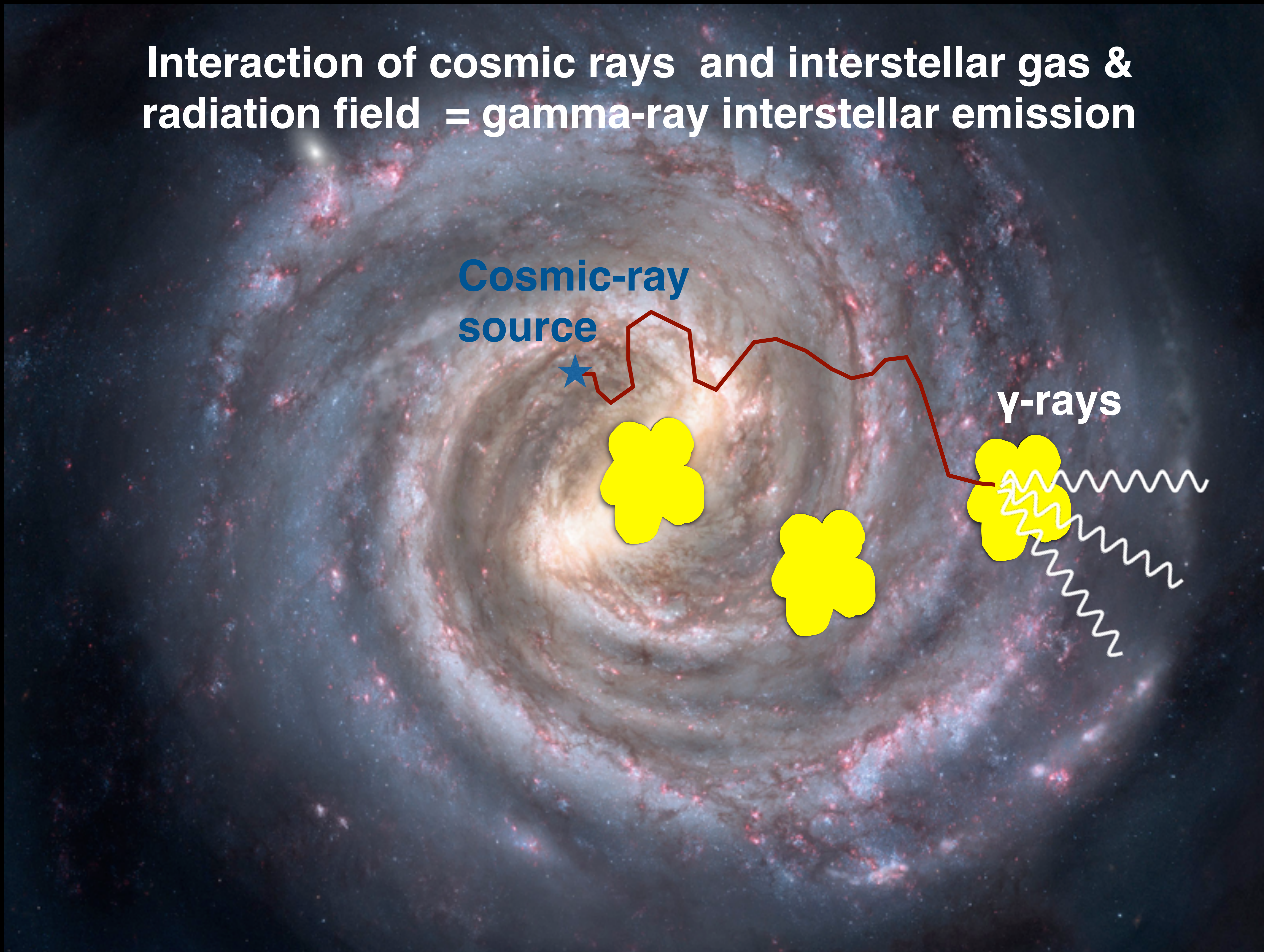

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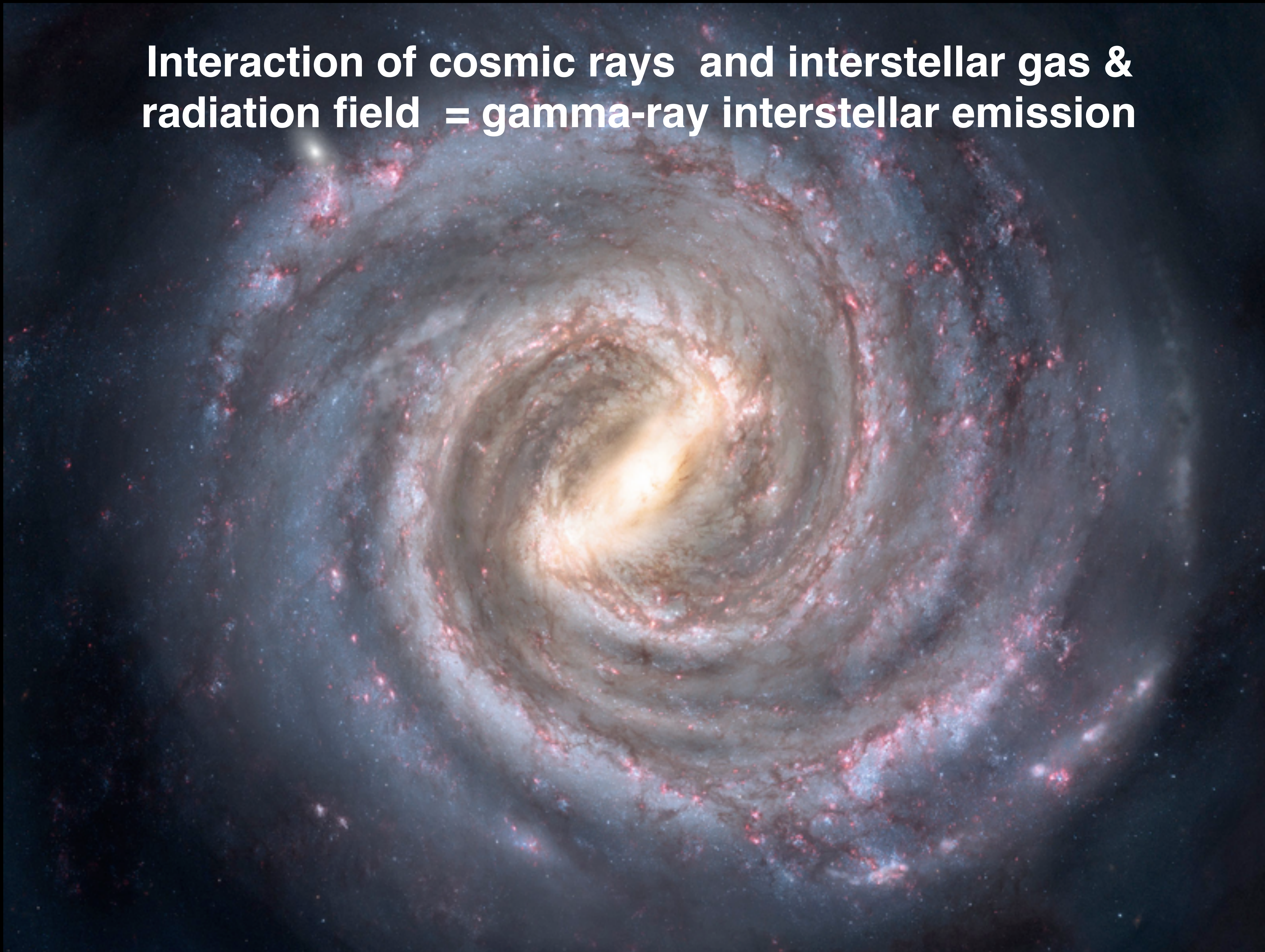

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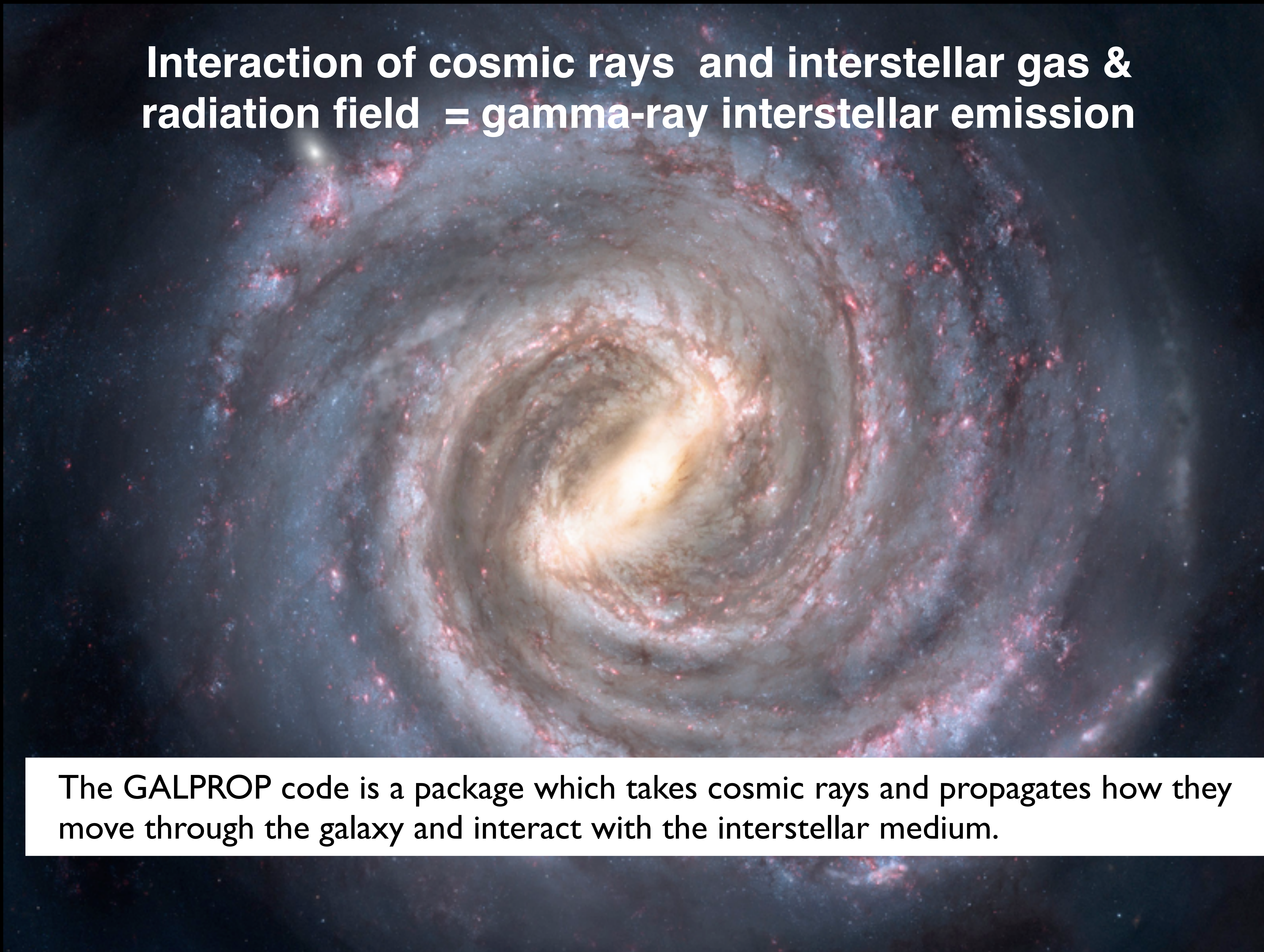
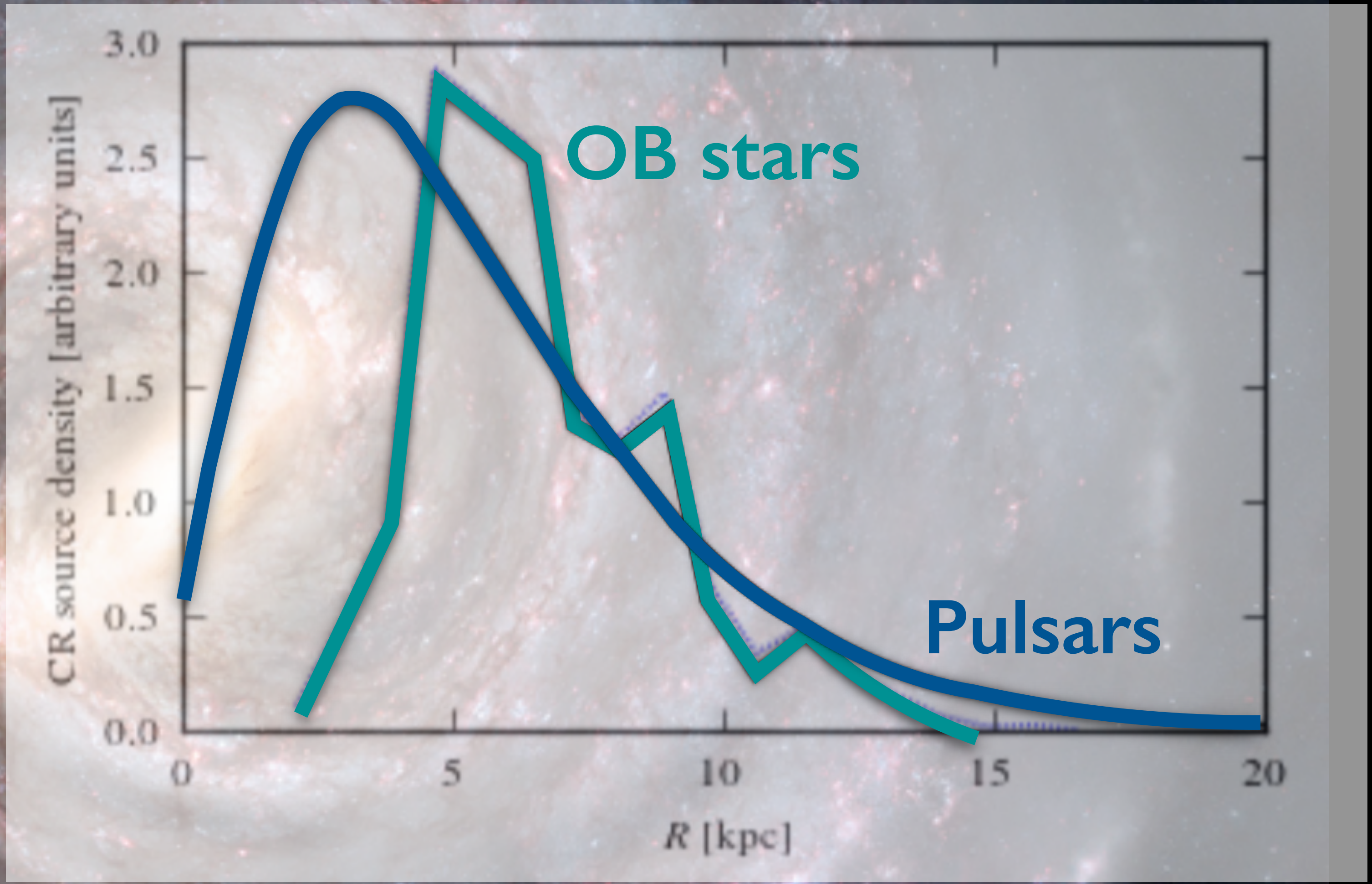


The GALPROP code is a package which takes cosmic rays and propagates how they move through the galaxy and interact with the interstellar medium.

Interaction of cosmic rays and interstellar gas & radiation field = gamma-ray interstellar emission



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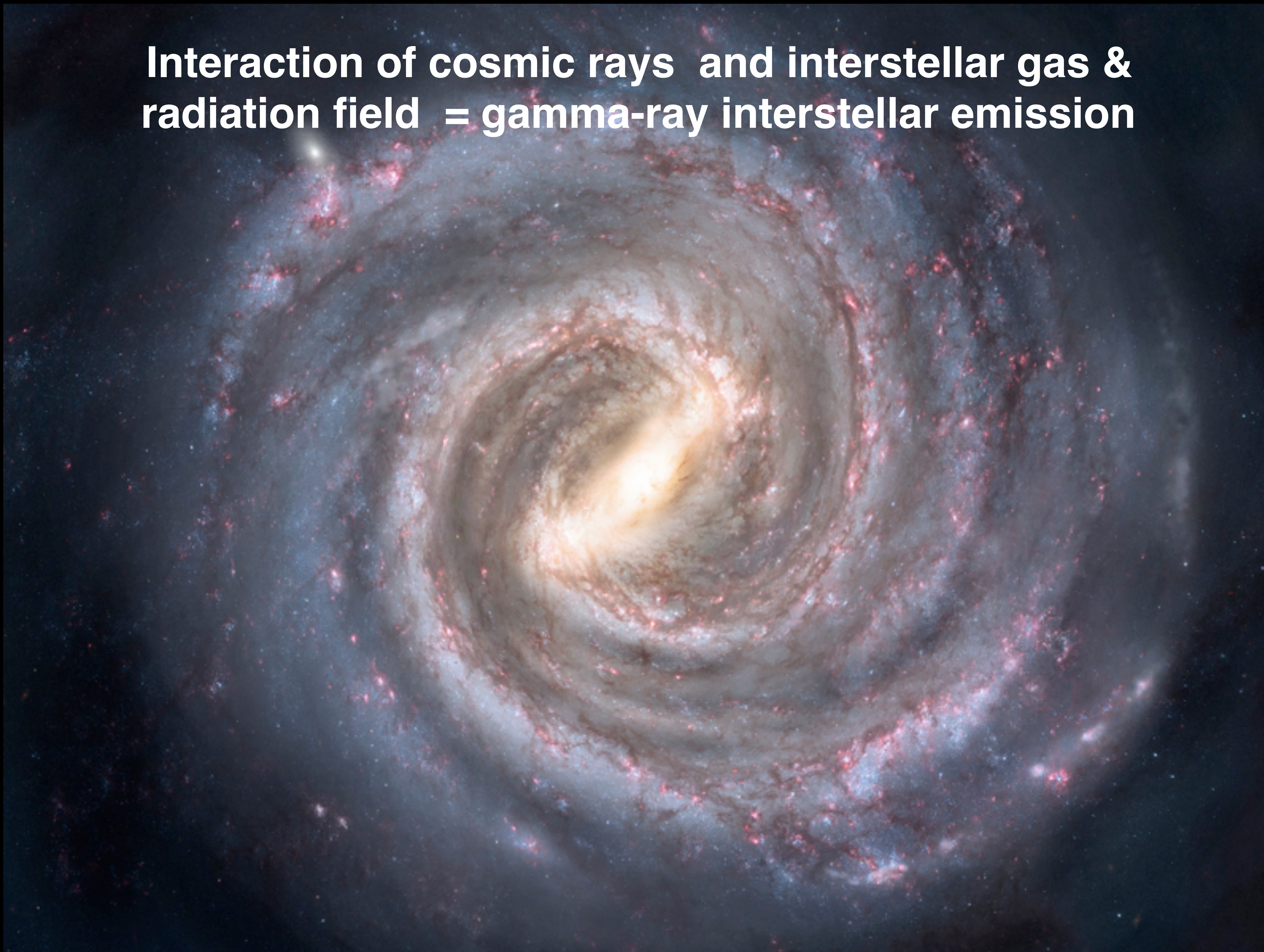
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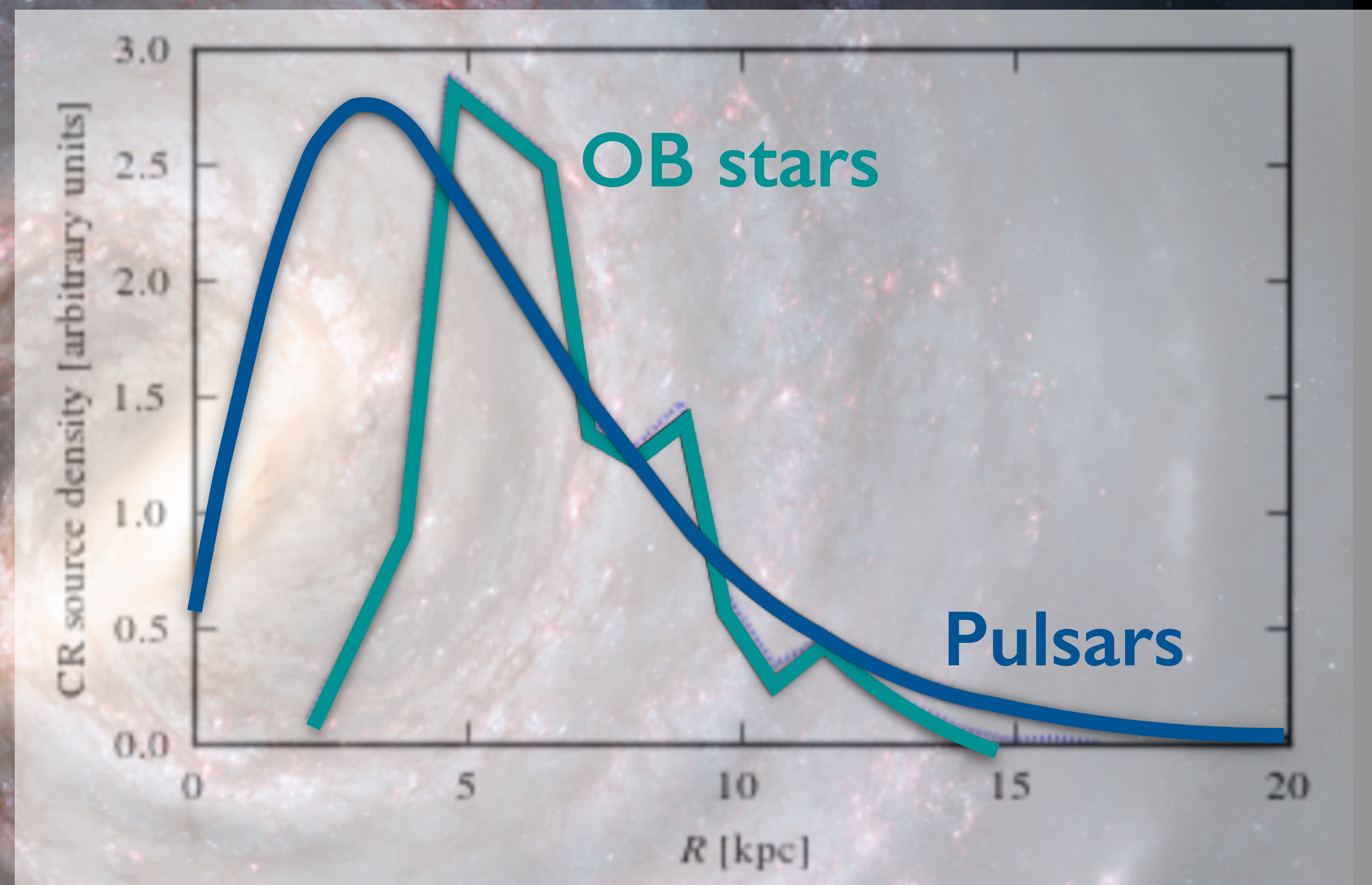

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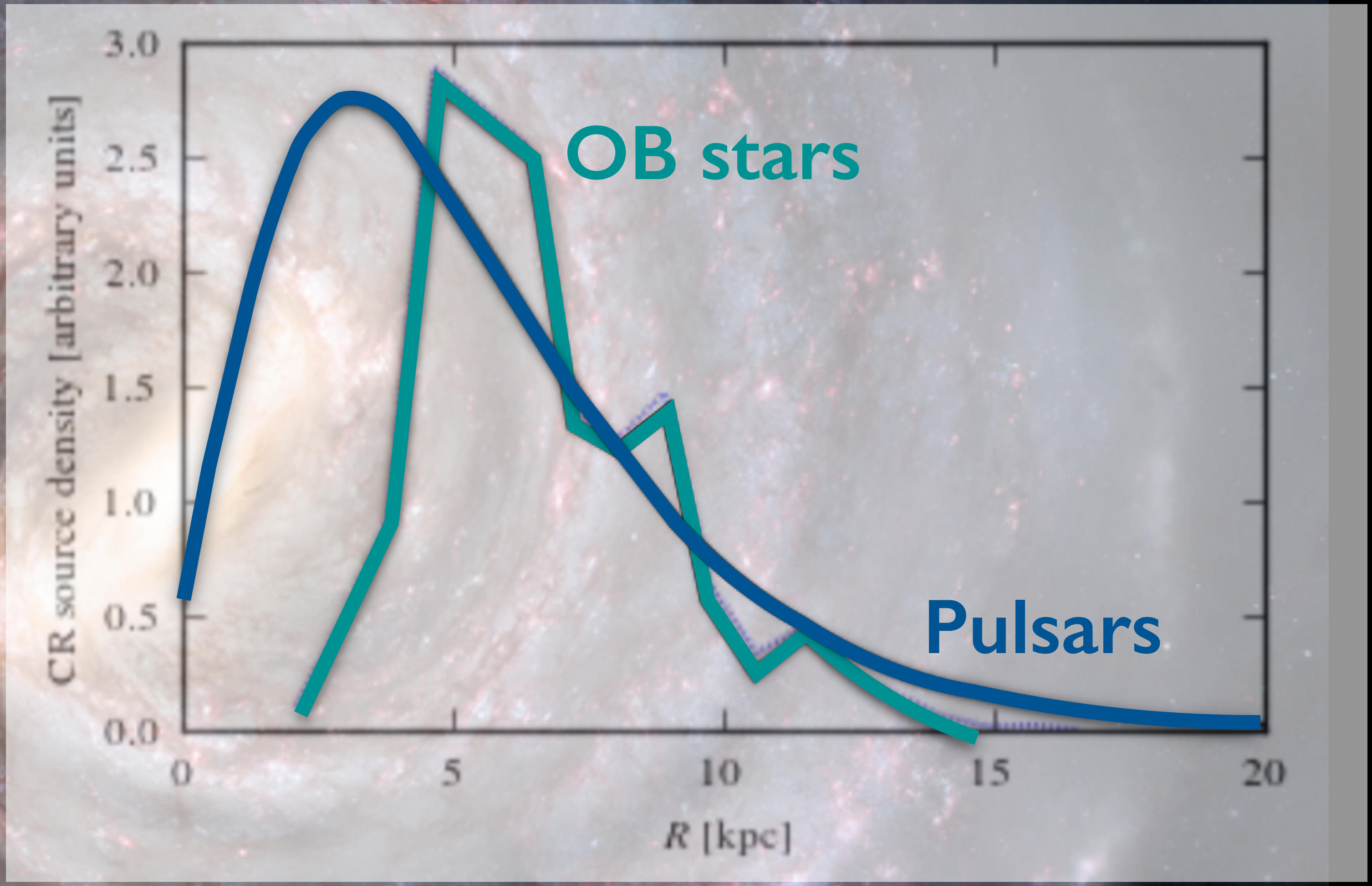

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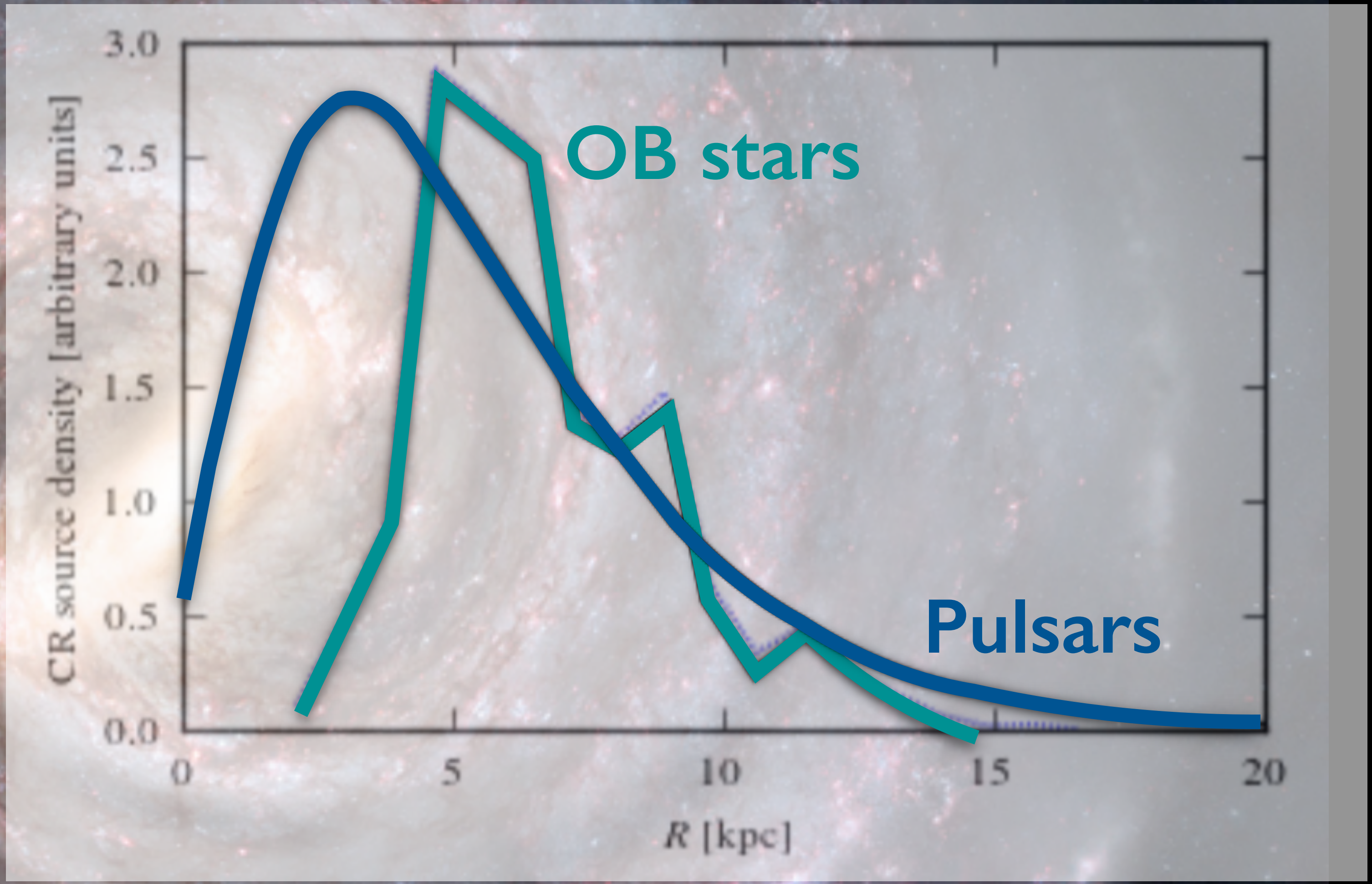

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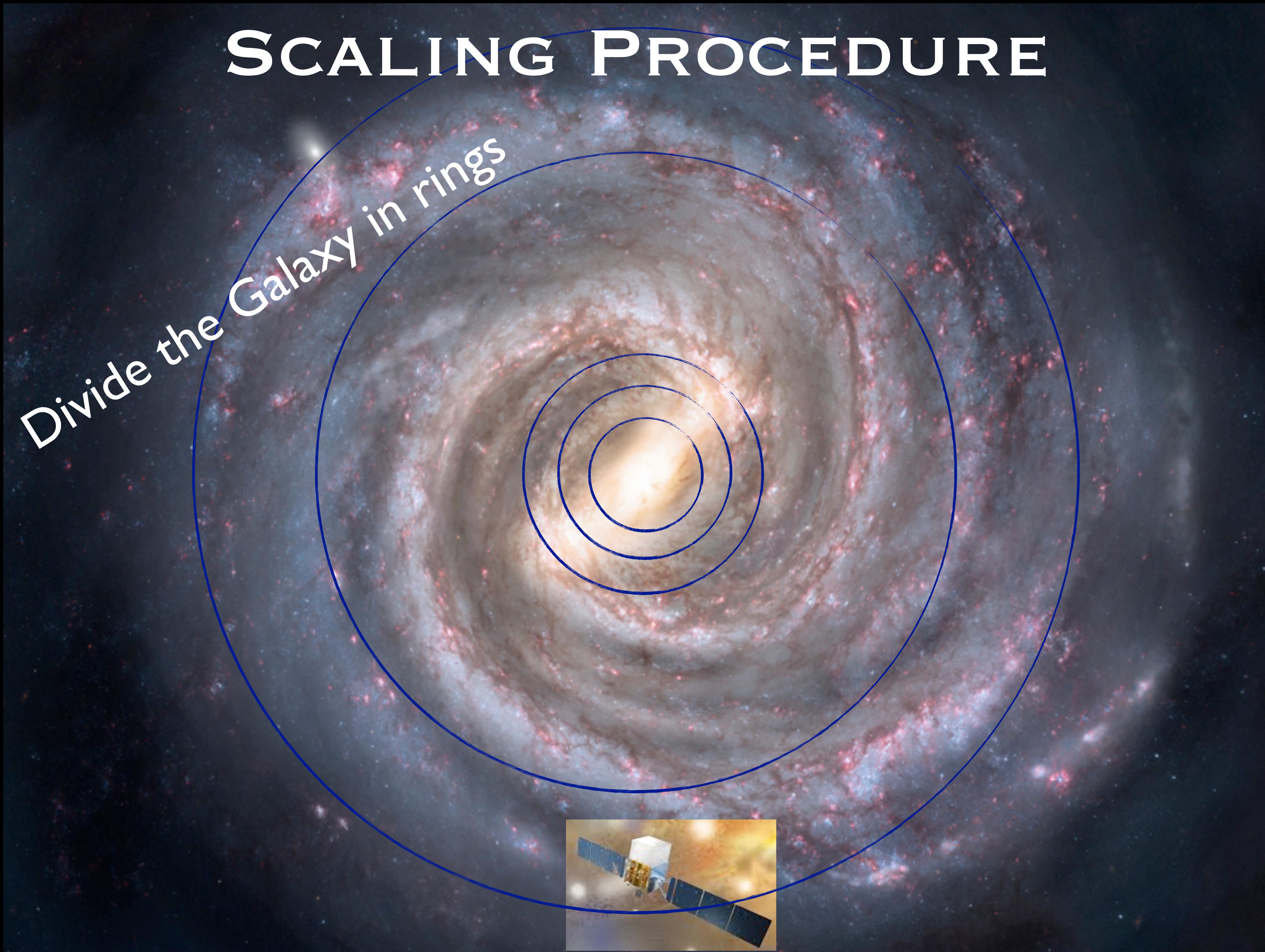
Scaling Procedure



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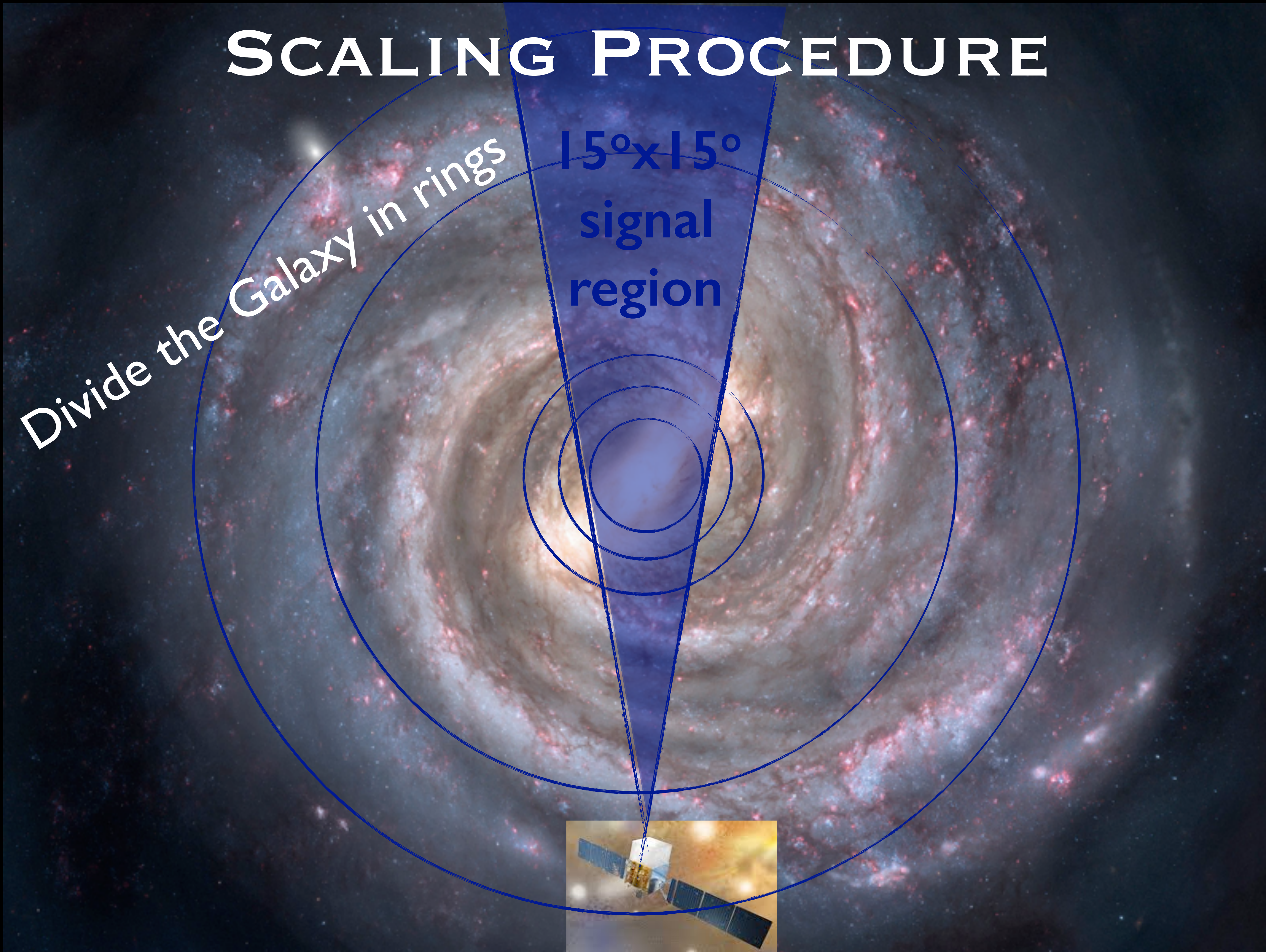
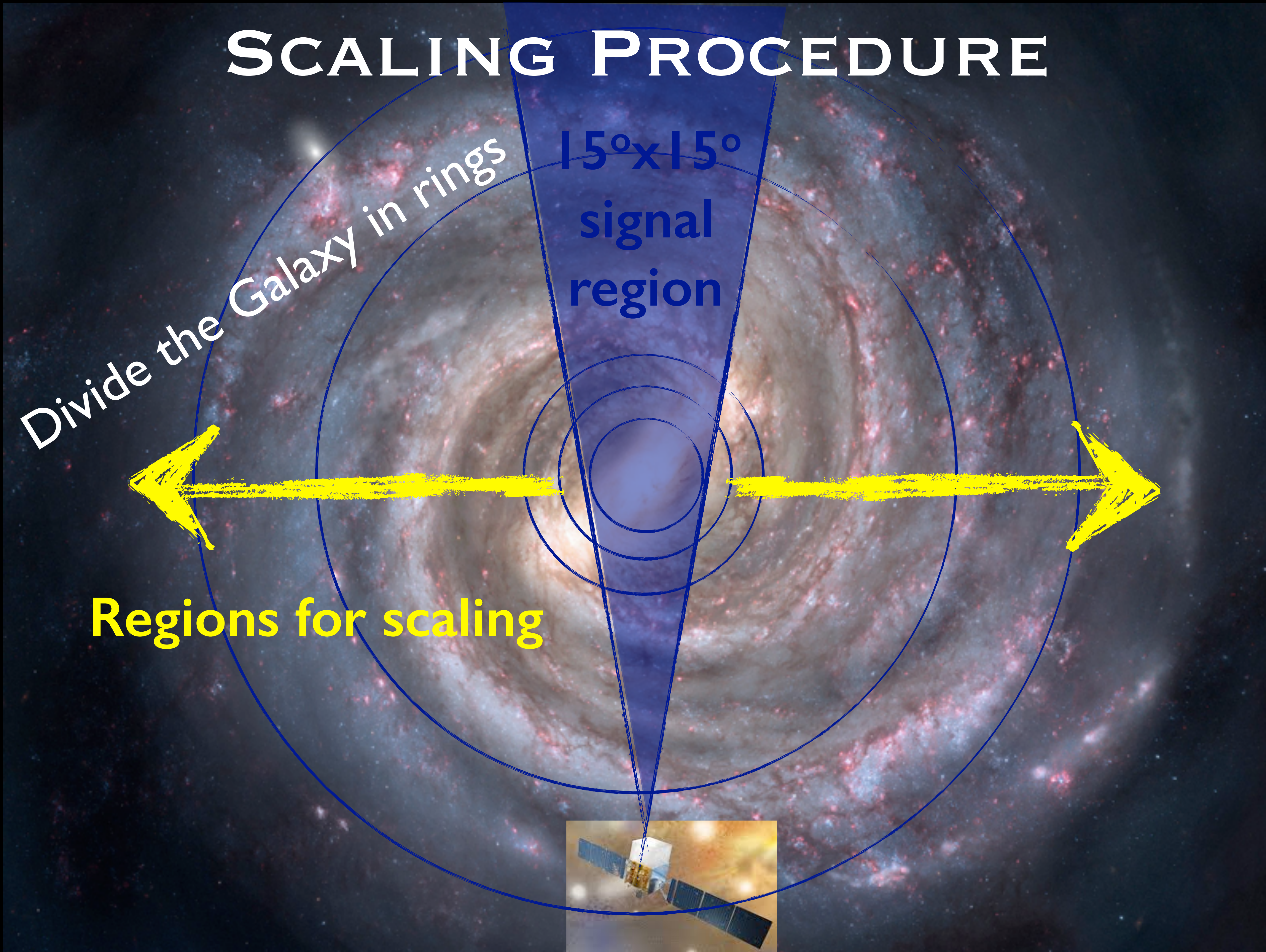
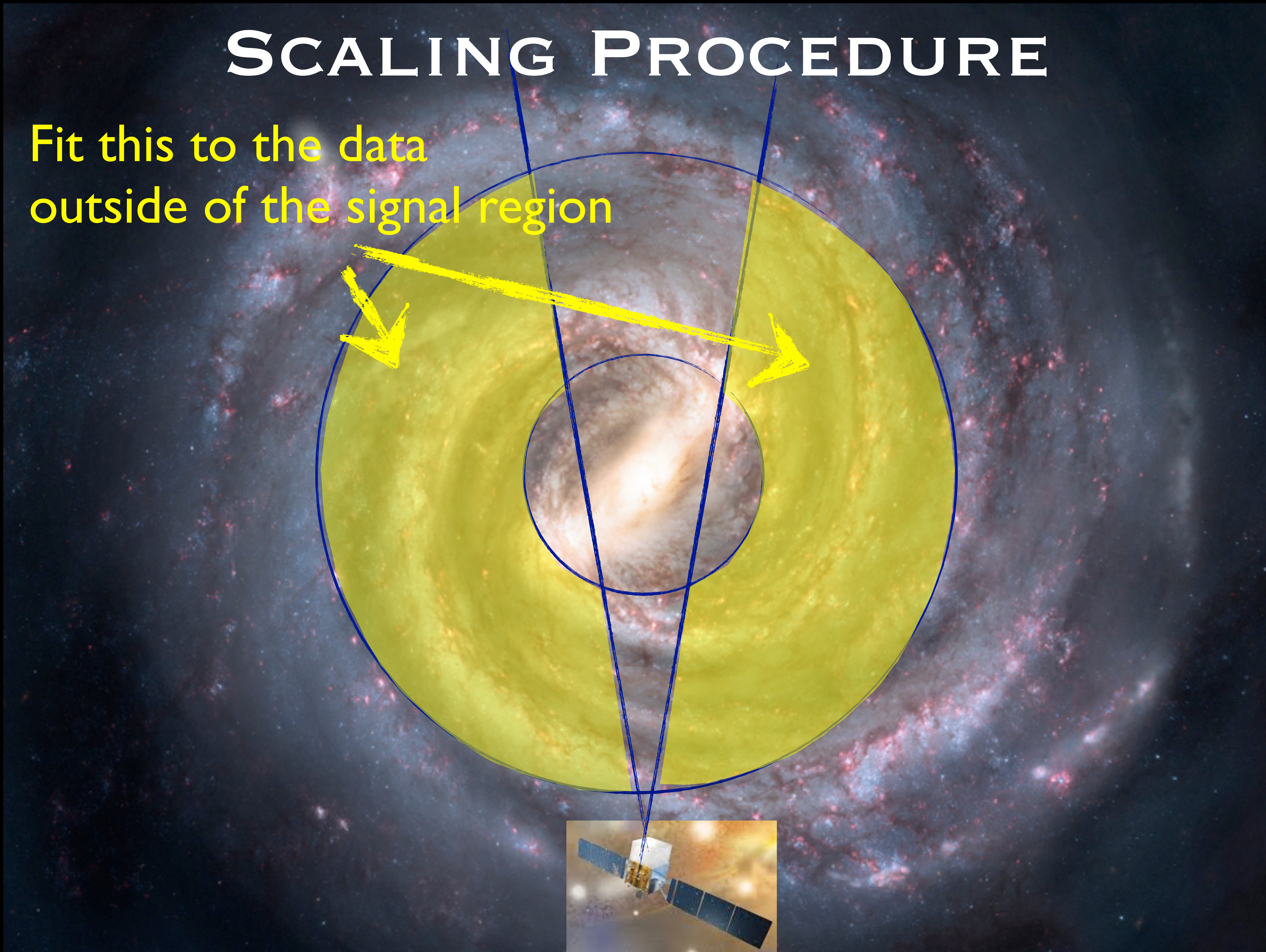
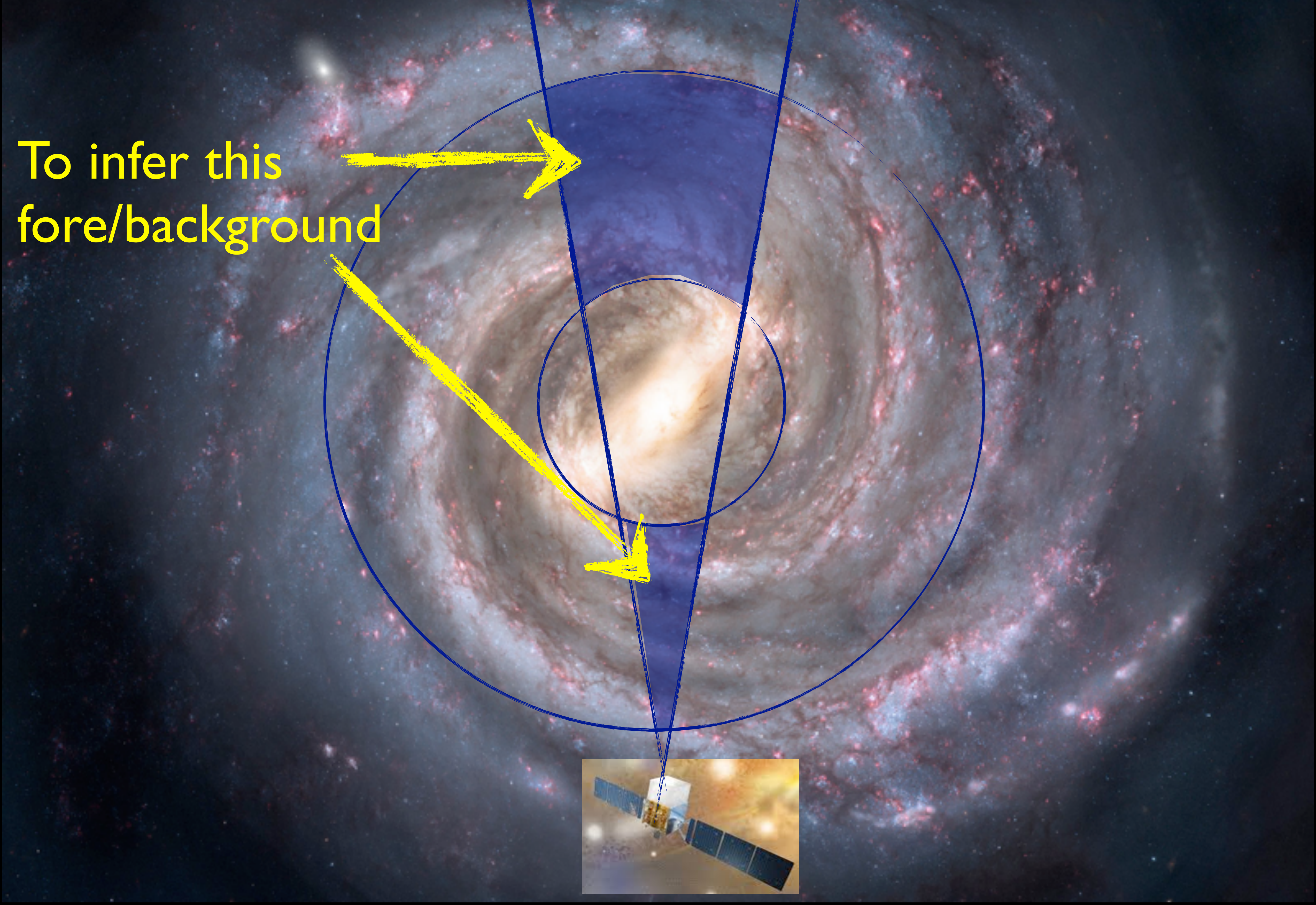



Scaling Procedure
Divide the Galaxy in rings
15°x15°
signal
region
Regions for scaling


Scaling Procedure
Fit this to the data
outside of the signal region

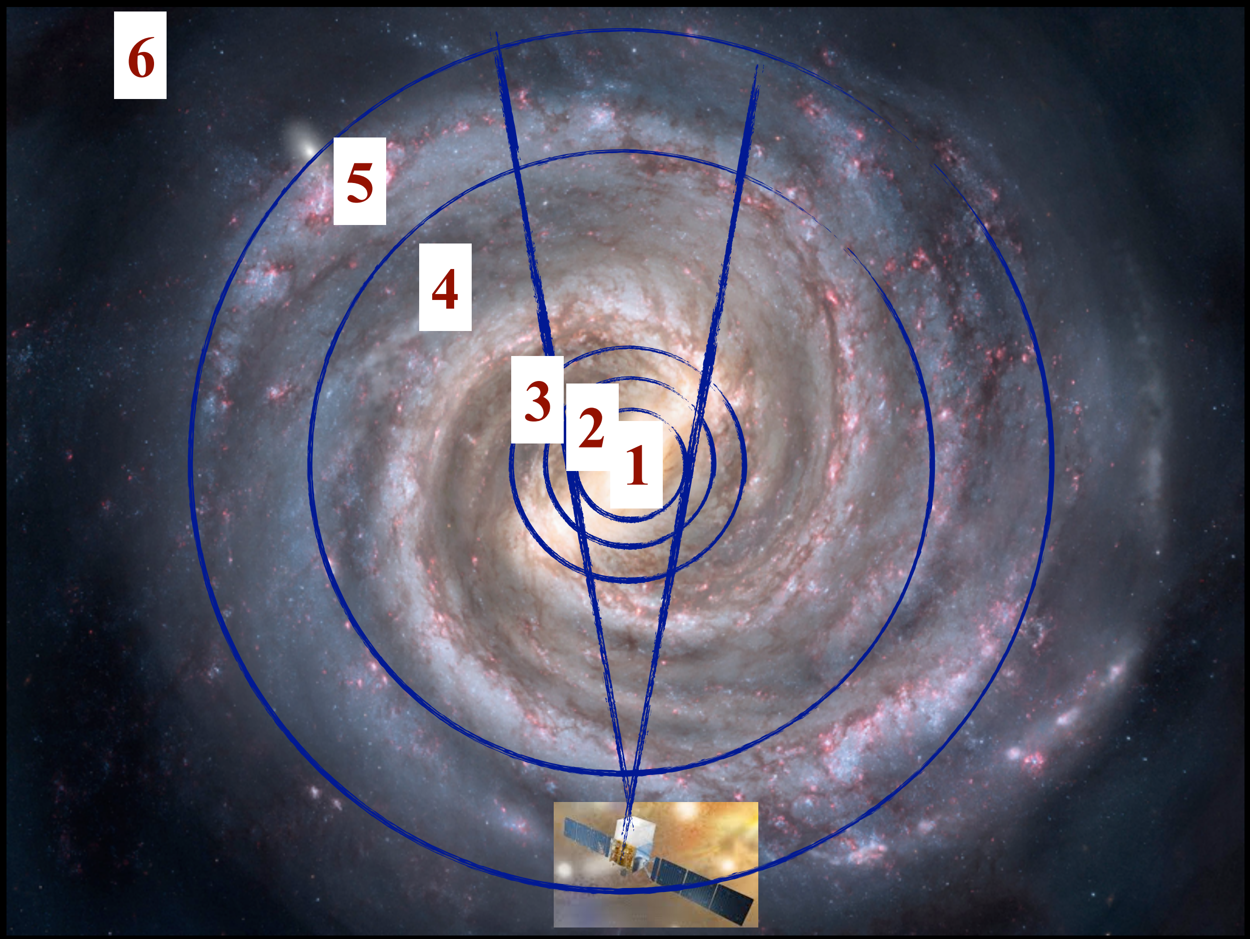
Scaling Procedure



Modeling the Interstellar Emission

- Two scaling procedures: one adjusting intensity of the rings only, the other also allowing spectral adjustment

  ➡ This yields four variants for the fore/background IEM:
    - Pulsars, intensity scaled
    - Pulsars, index scaled
    - OB Stars, intensity scaled
    - OB Stars, index scaled



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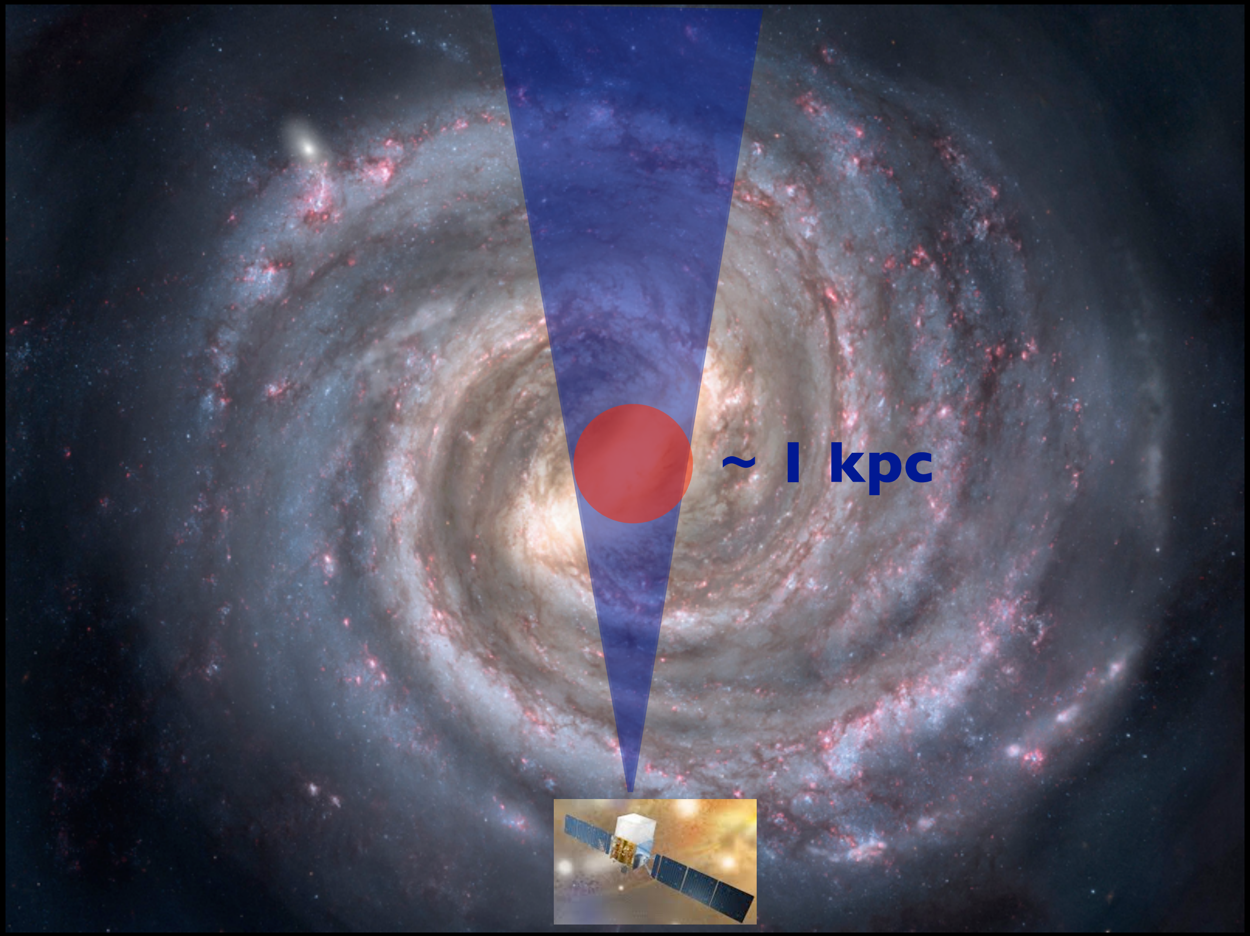
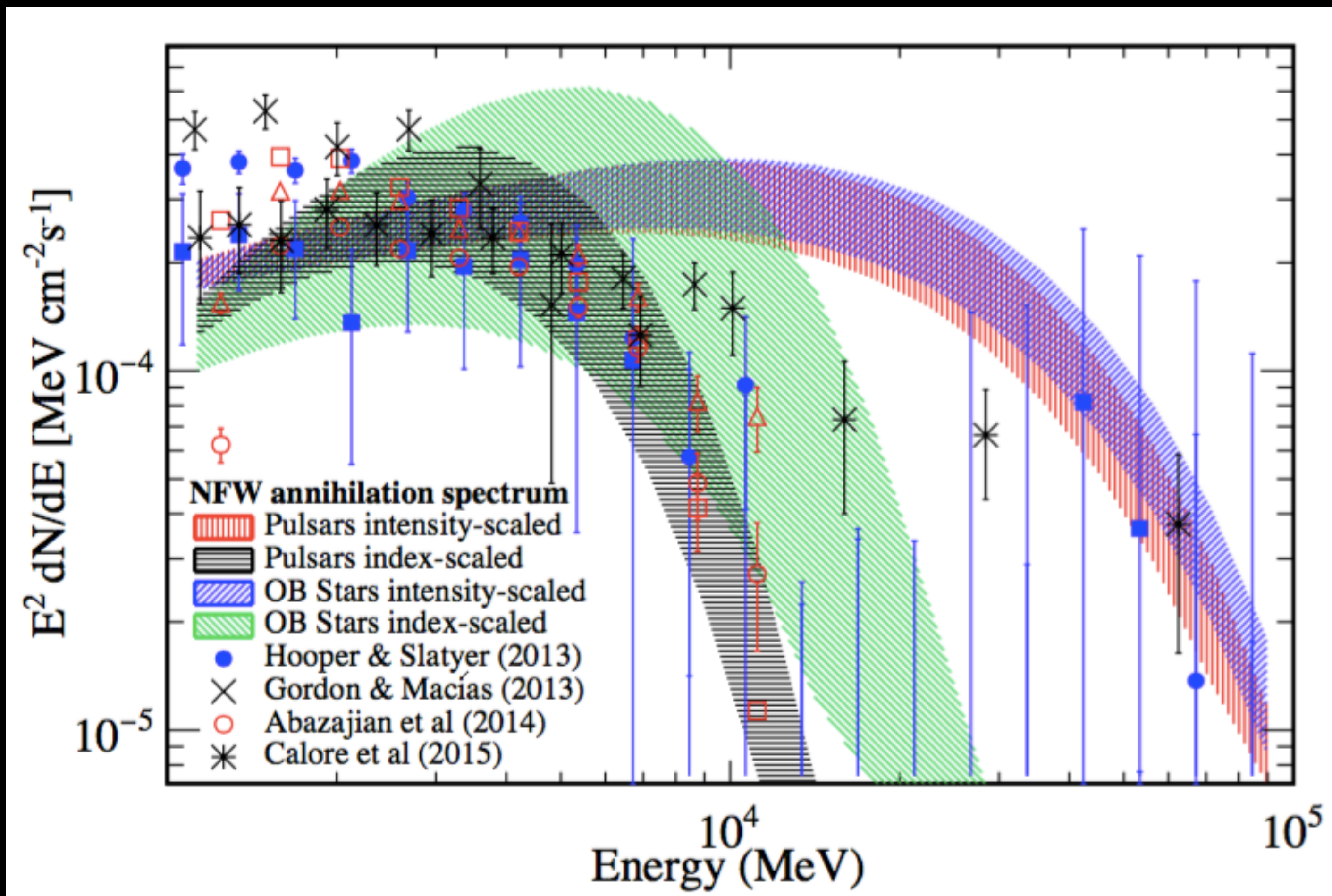
- Determine intensities for the **innermost ring for π^0, and inverse compton** by fitting the data in the 15°x15° region for each of the four **fore/background models** (held constant in the fit)

- Point sources are determined consistently with these background models from the data (rather than using existing catalogues).

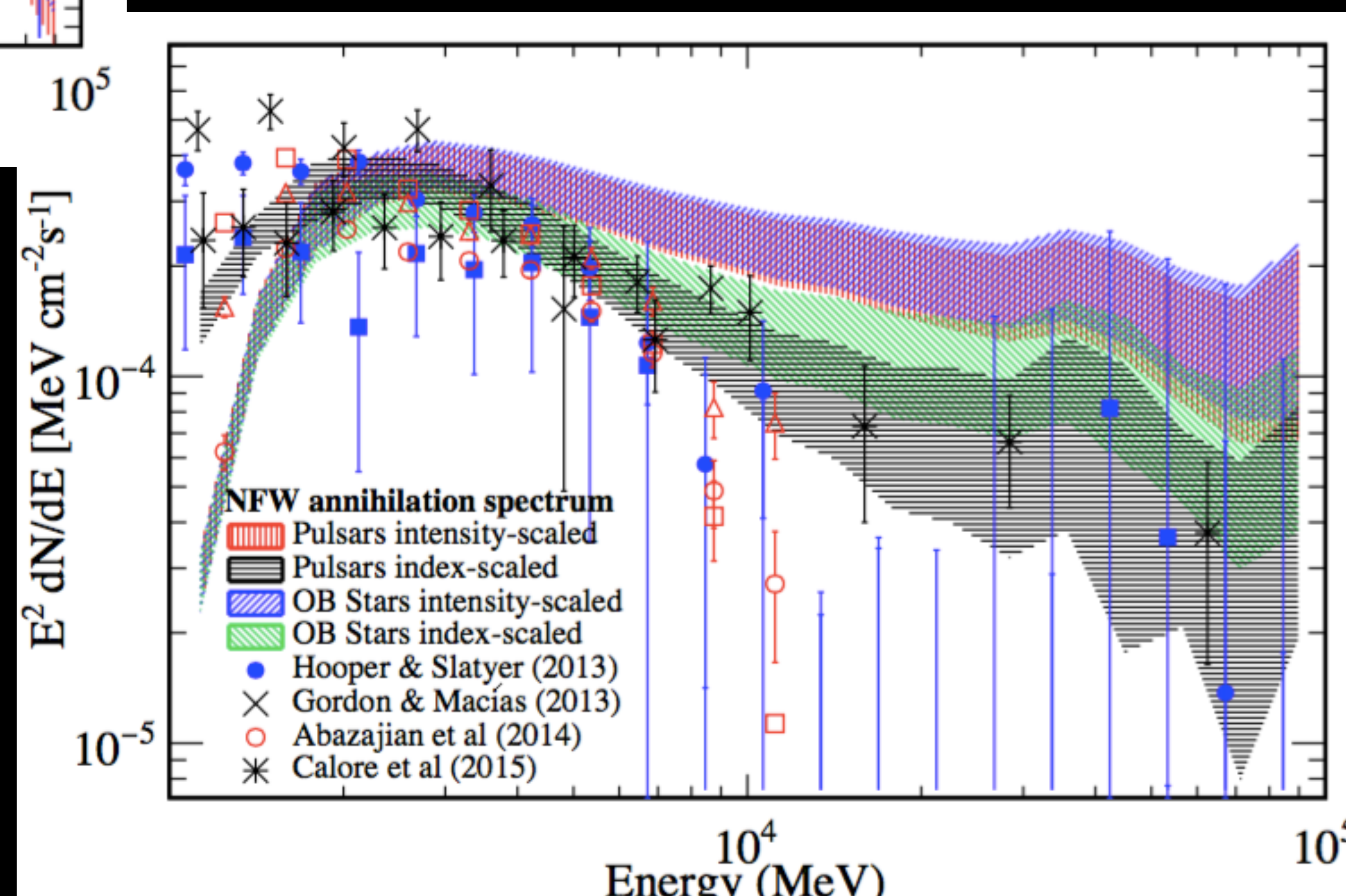


NFW Component Spectrum



Masses favored in the 10s-100s of GeV range

Fermi LAT collab. arXiv:1511.02938

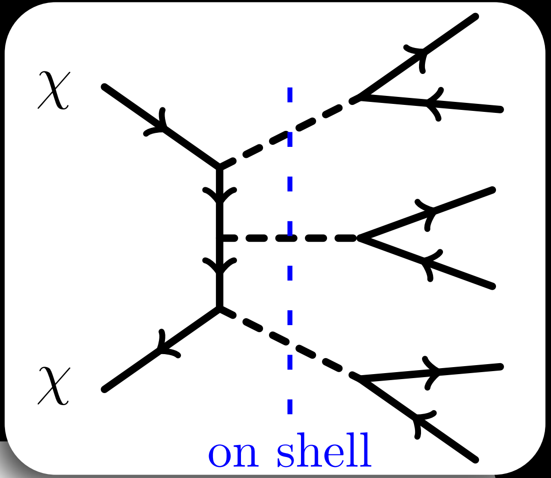


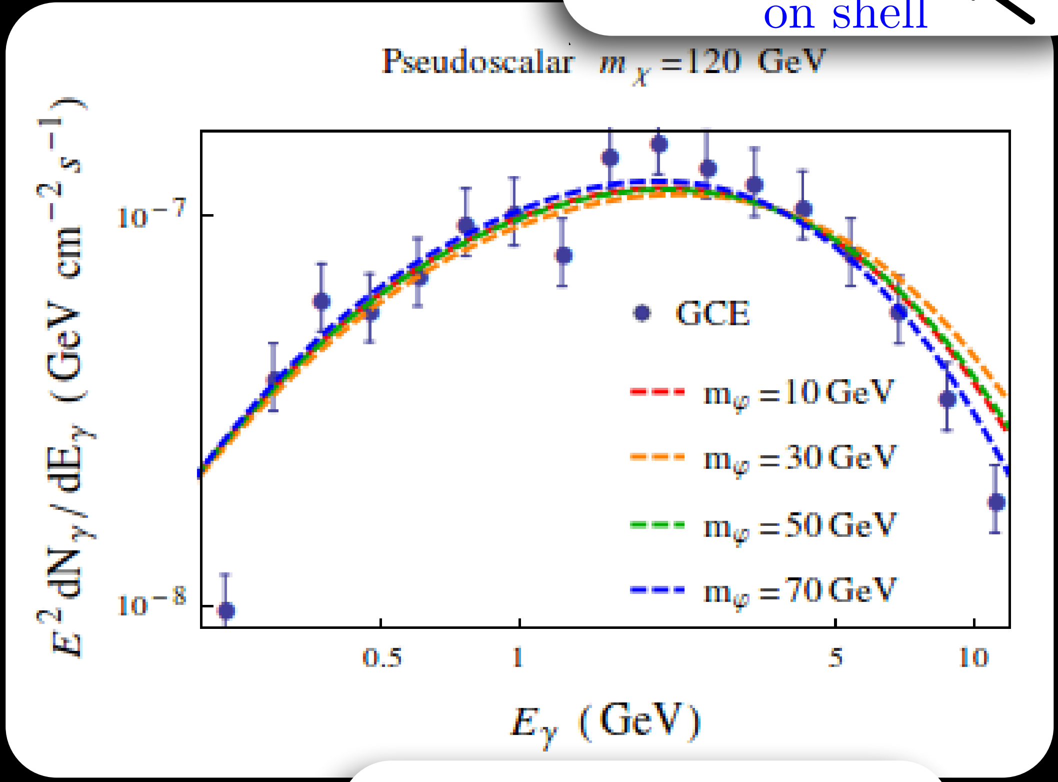
Preferred cross sections turn out to be around the thermal one or a bit smaller.

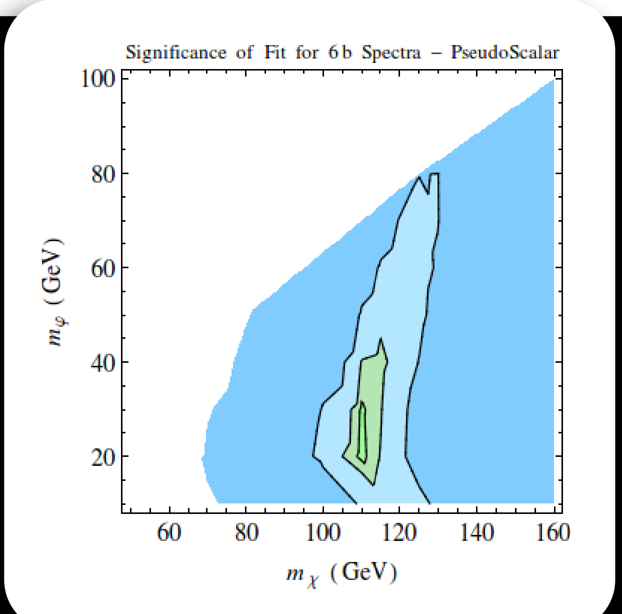
Gamma Ray Excess

- The signal suggests something about the simplified models that could work.
- The signal is large enough that something is going to need to suppress scattering with heavy nuclei.
- For example, the particle communicating between dark matter and the SM could be a pseudoscalar, leading to spin-dependent and velocity suppressed coupling to nuclei.
- Even these tricks won't hide from direct searches forever.
- If the mediating particle is light, the dark matter can decay into on-shell mediators, which further allows weak coupling to the SM particles.

Abdullah, DiFranzo, Rajaraman, TMPT, Tanedo, Wijangco 1404.6528 & PRD

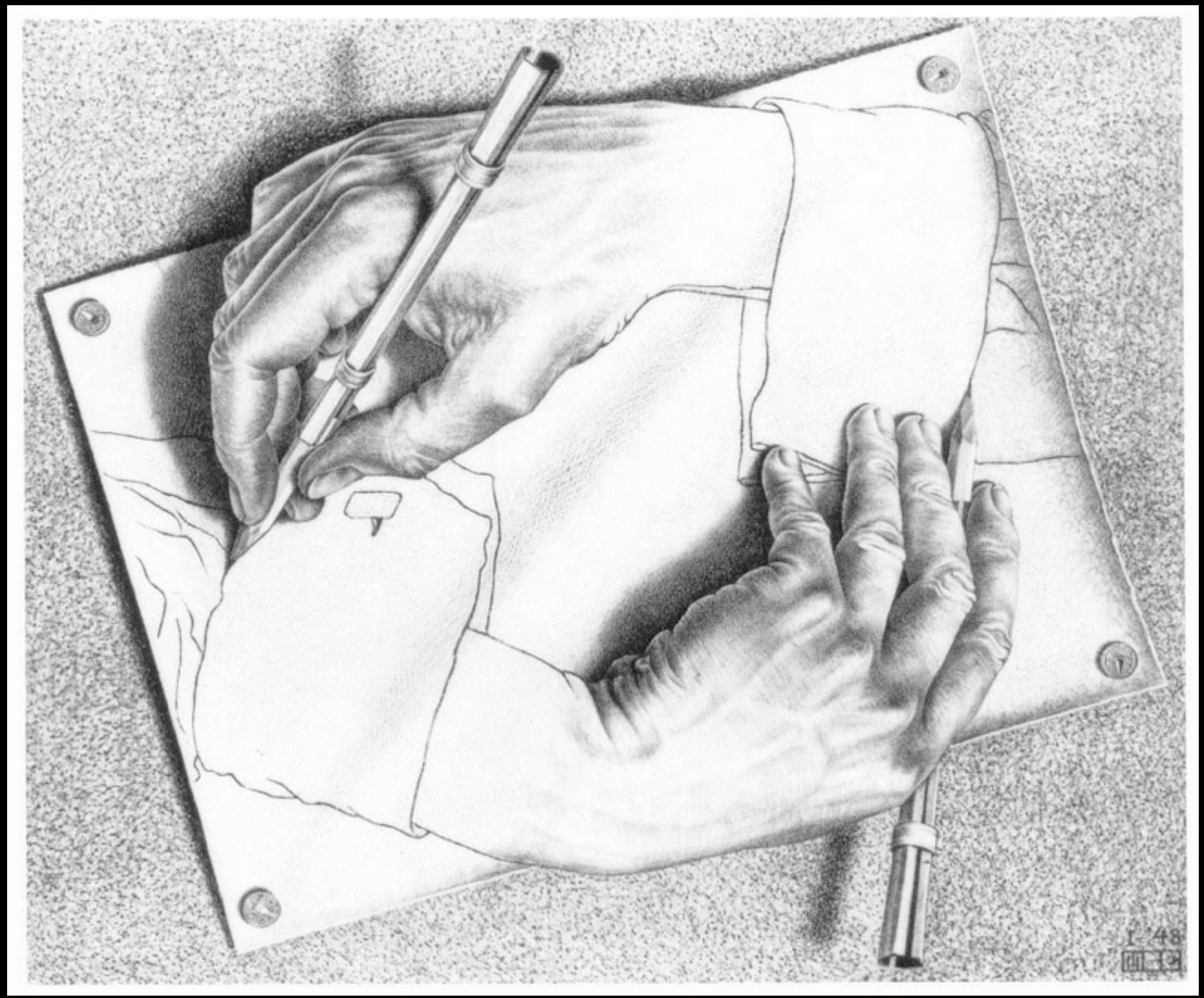




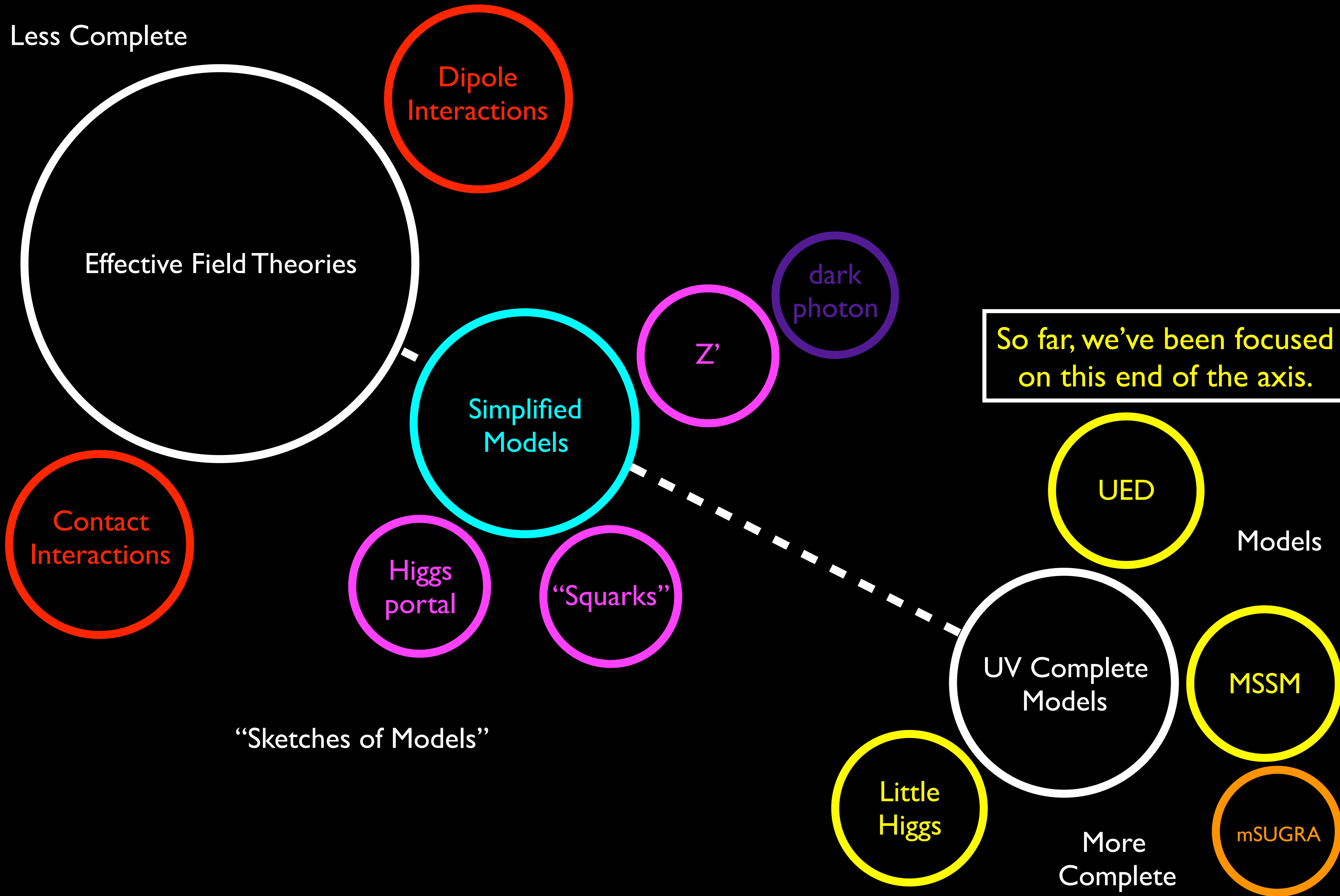


Sketches of Theories

- Another area of wide activity is to try to capture simple features of models of WIMPs that are not inspired by a particular paradigm.
- While perhaps not able to describe the whole story, these simplified models could potentially still capture the most important features of a theory of dark matter.
- We'll see that they are useful to help us piece together what information we get from our different kind of searches, to understand how they complement one another.

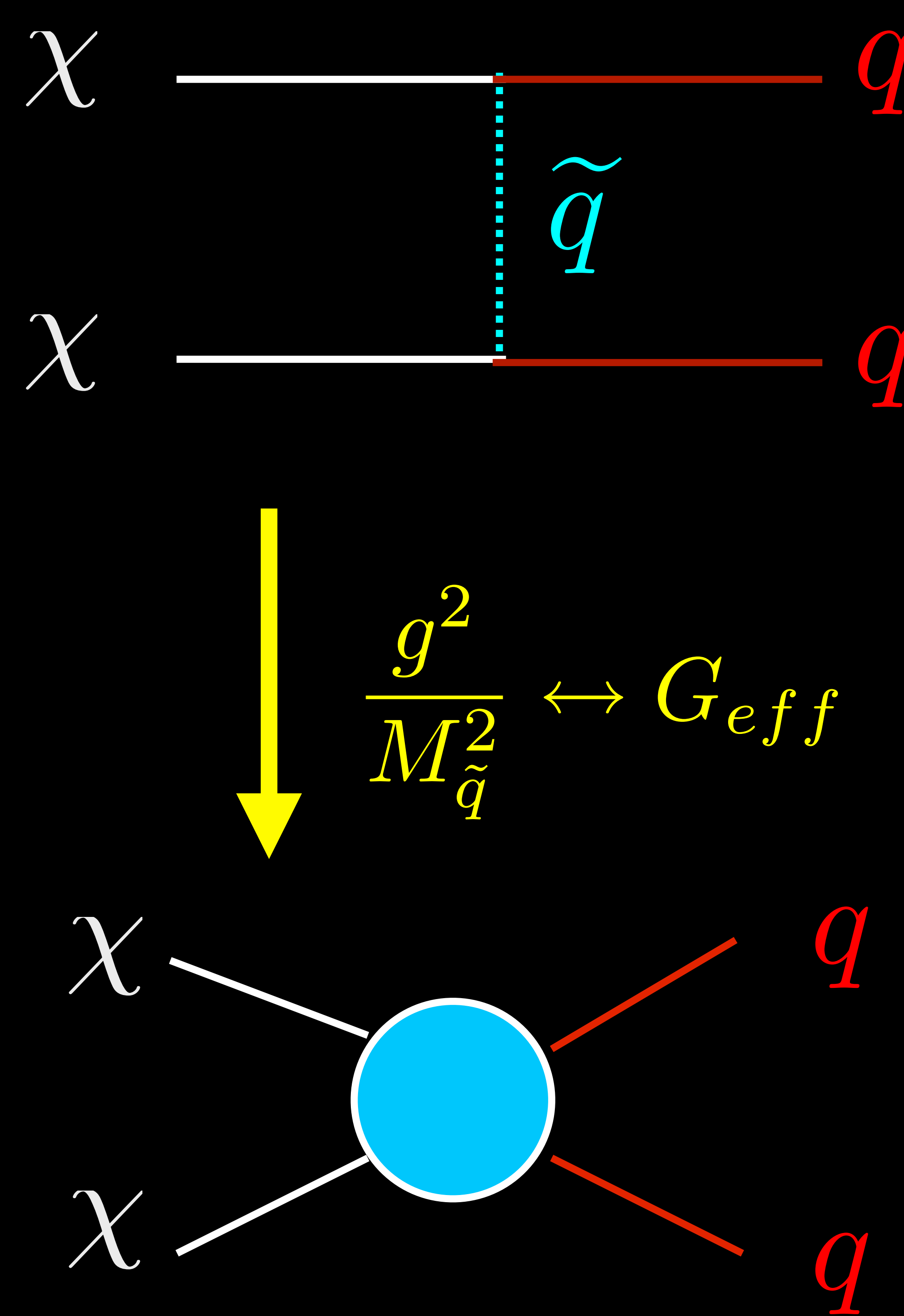


Spectrum of Theory Space



Contact Interactions

- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible to our experiments.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared to the energies involved.
- The drawback to a less complete theory is such a simplified description will undoubtably miss out on correlations between quantities which are obvious in a complete theory.
- And it will fail to describe high energies, where one can produce more of the new particles directly.



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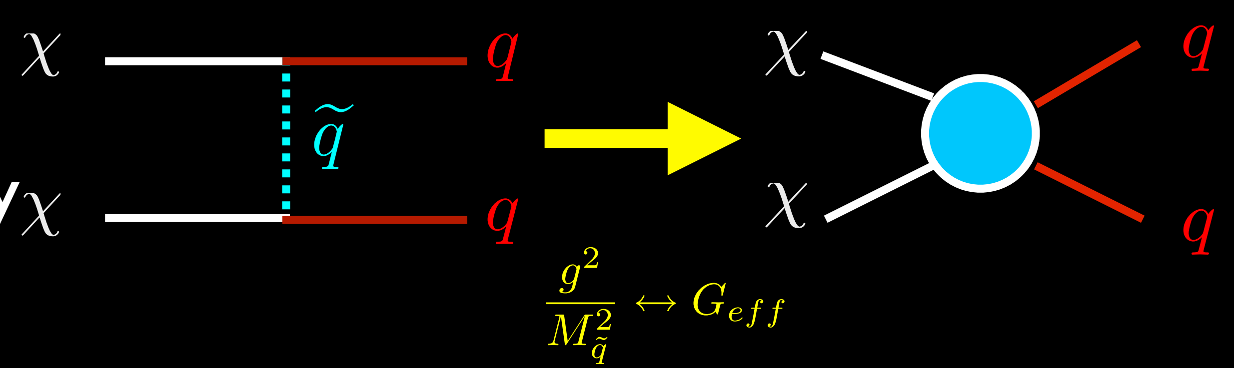

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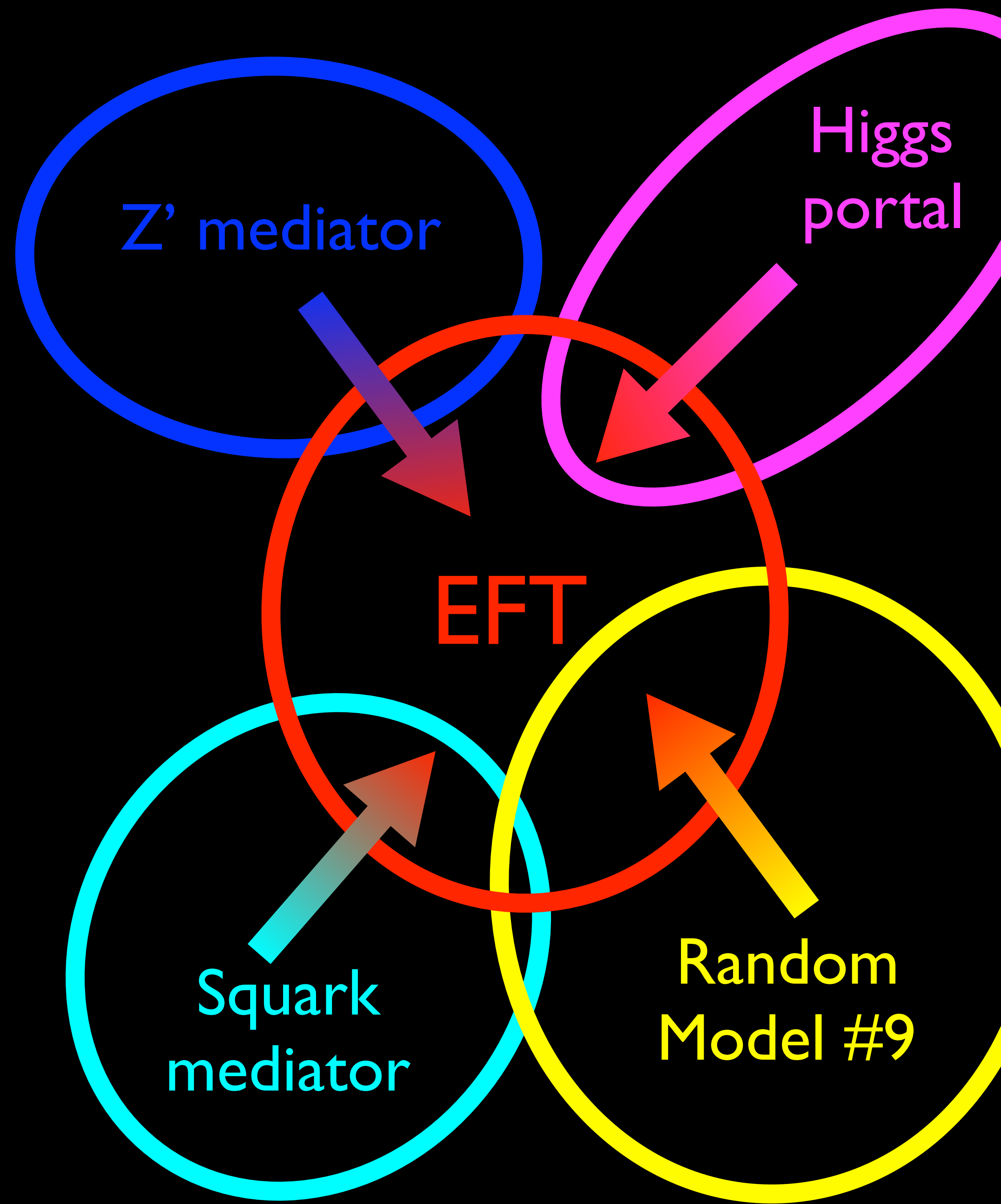
- And it will break down at high energies, where one can produce more of the new particles directly.



Example: Majorana WIMP

- As an example, we can write down the operators of interest for a Majorana WIMP.
- There are 10 leading operators consistent with Lorentz and SU(3) x $U(1)_{EM}$ gauge invariance coupling the WIMP to quarks and gluons.
- Each operator has a (separate) coefficient M_* which parametrizes its strength.
- In principle, a realistic UV theory will turn on some combination of them, with related coefficients.

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
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M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
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$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

Other operators may be rewritten in this form by using Fierz transformations.

Example: Majorana WIMP

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

- The various types of interactions are accessible to different kinds of experiments. (Technically meaning: the observables are unsuppressed by the small dark matter velocity in our halo, v ~ 10^{-3}.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation in the galactic halo
  - Collider Production

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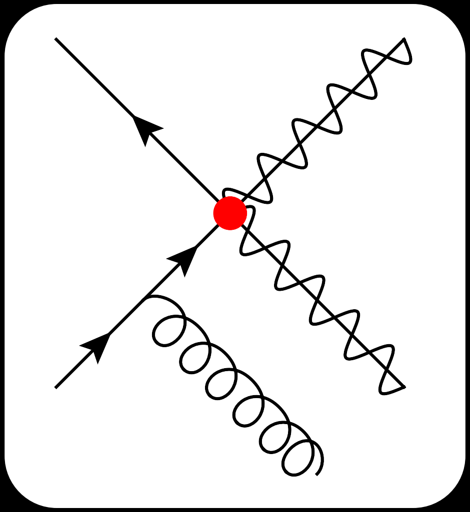
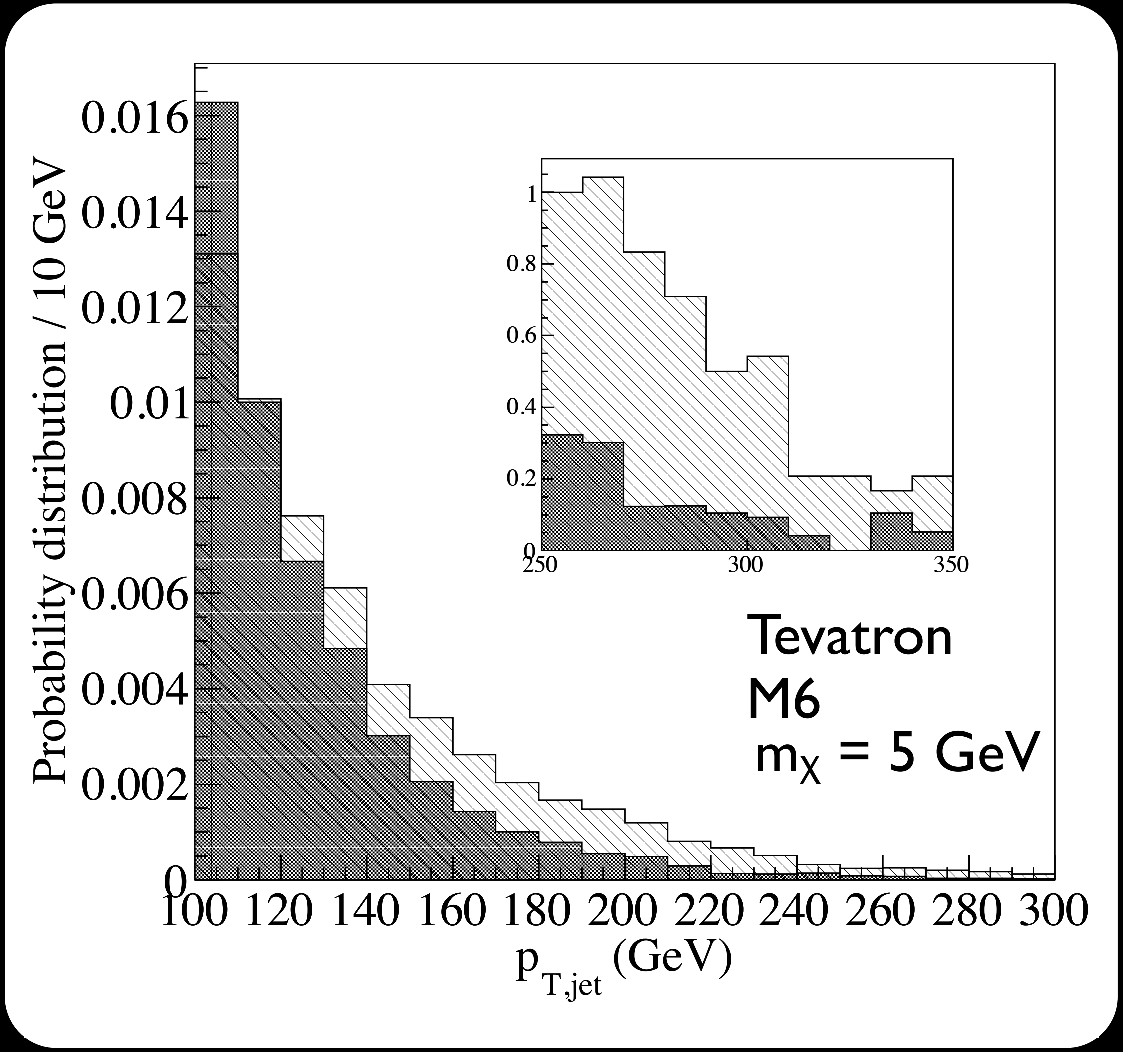
Collider Searches

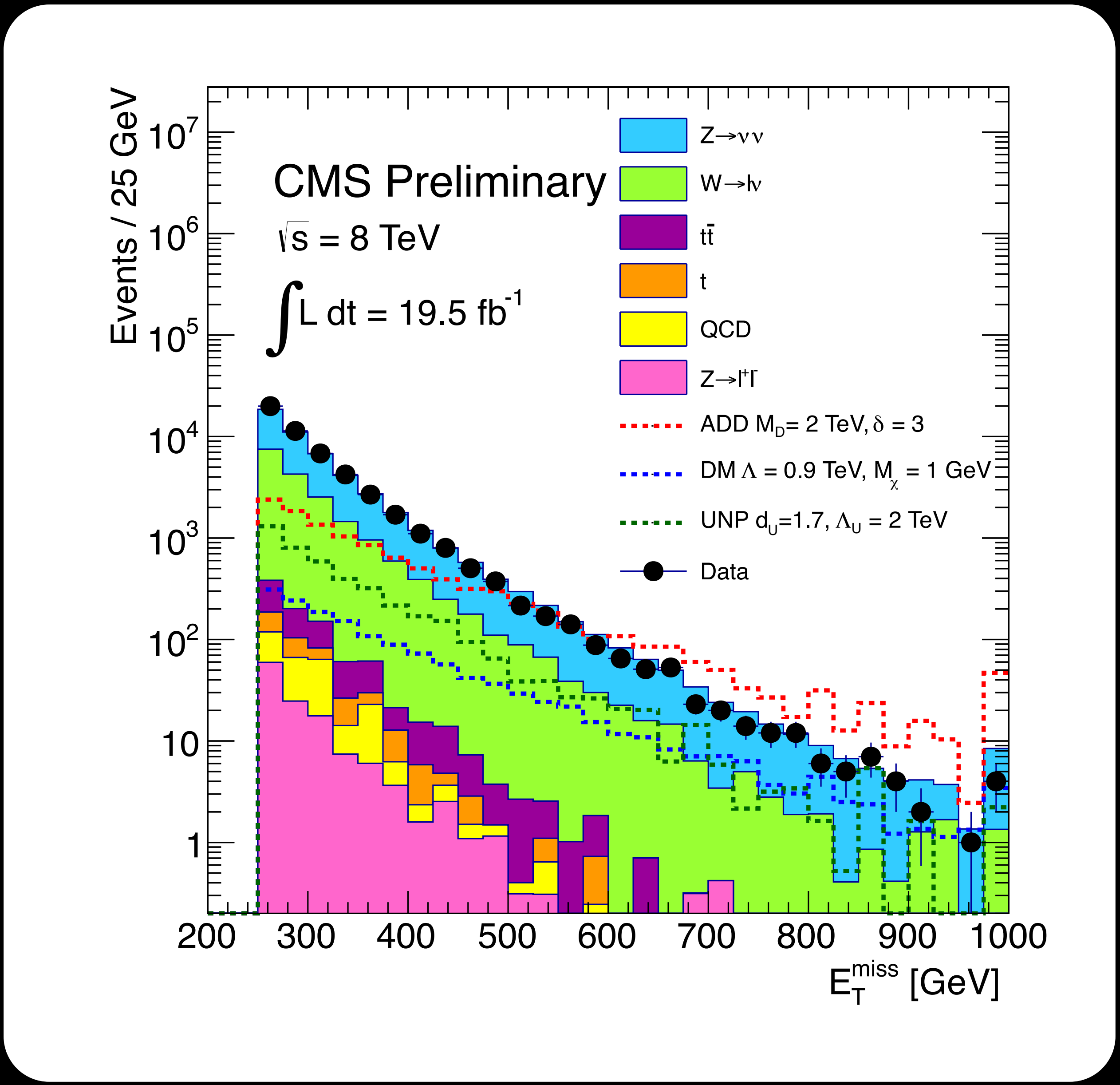
- At colliders, one searches for this type of theory by producing the dark matter directly.
- Since the detector needs something to trigger on, one looks for processes with additional final state particles, and infers the presence of dark matter based on the missing momentum it carries away from the interaction.
- There are the usual SM backgrounds from Z + jets, as well as fake backgrounds from QCD, etc.
- Contact interactions grow with energy, generically leading to a harder MET spectrum than the SM backgrounds.

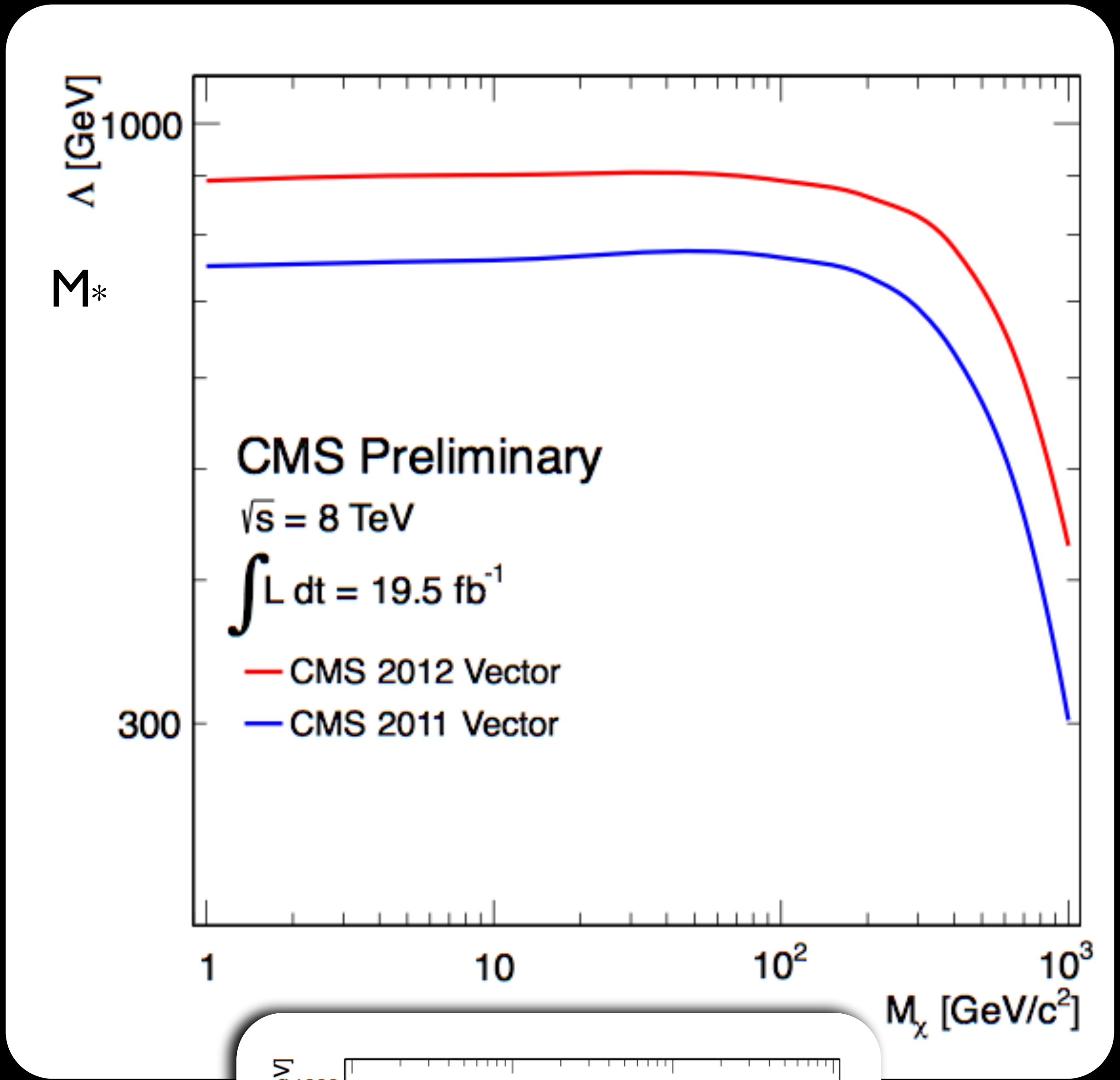


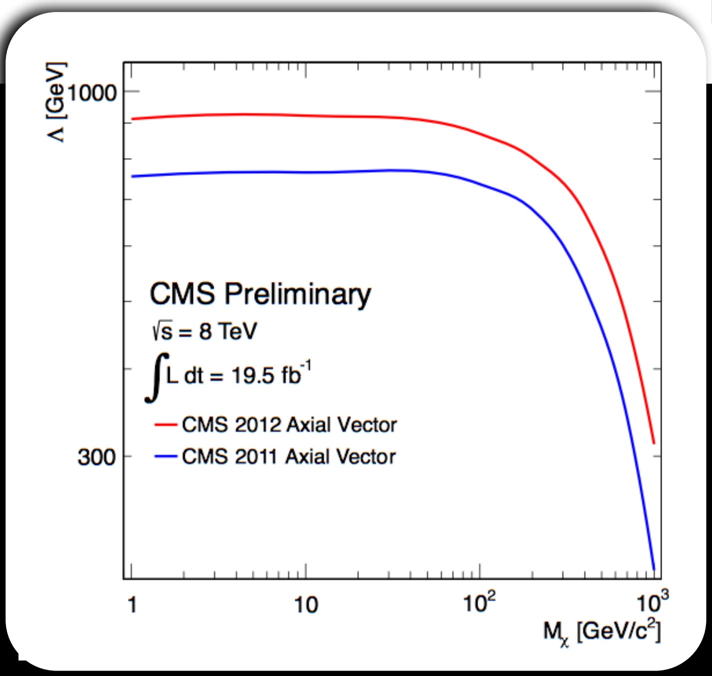
Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137 & JHEP



Collider Results

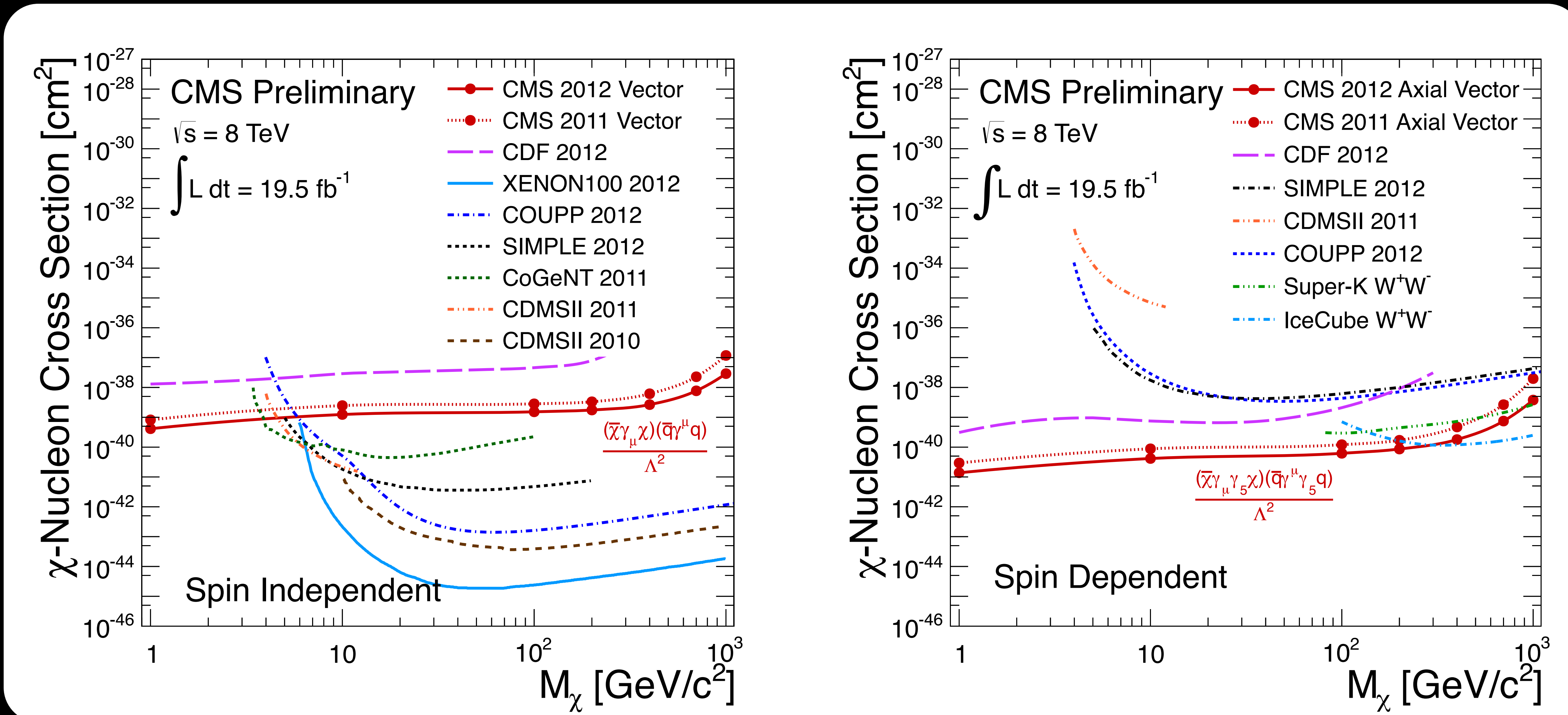






Both CMS and ATLAS have made very nice progress interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

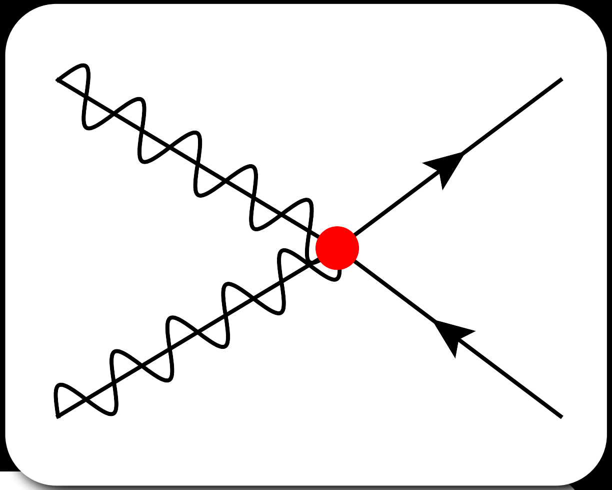
Translation to Elastic Scattering



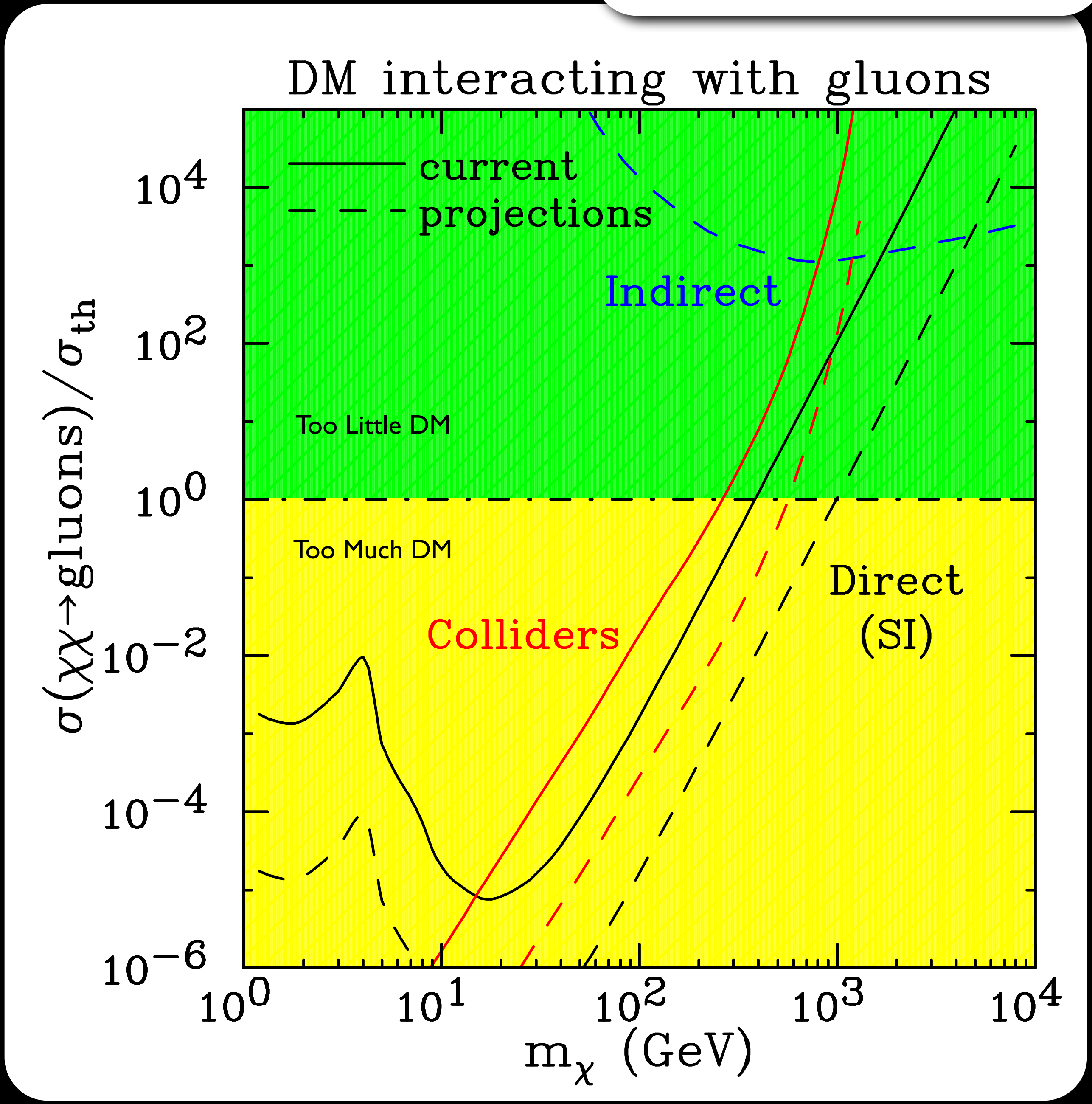
See: Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB; Bai, Fox, Harnik 1005.3797 & JHEP; and lots of other papers…

- Colliders can help fill in a challenging region of low dark matter mass and spin-dependent interactions.
- Since they see individual partons, rather than the nucleus coherently, collider results offer a complementary perspective on DM interactions with hadrons.
- The translation assumes a heavy mediating particle (contact interaction).

Annihilation

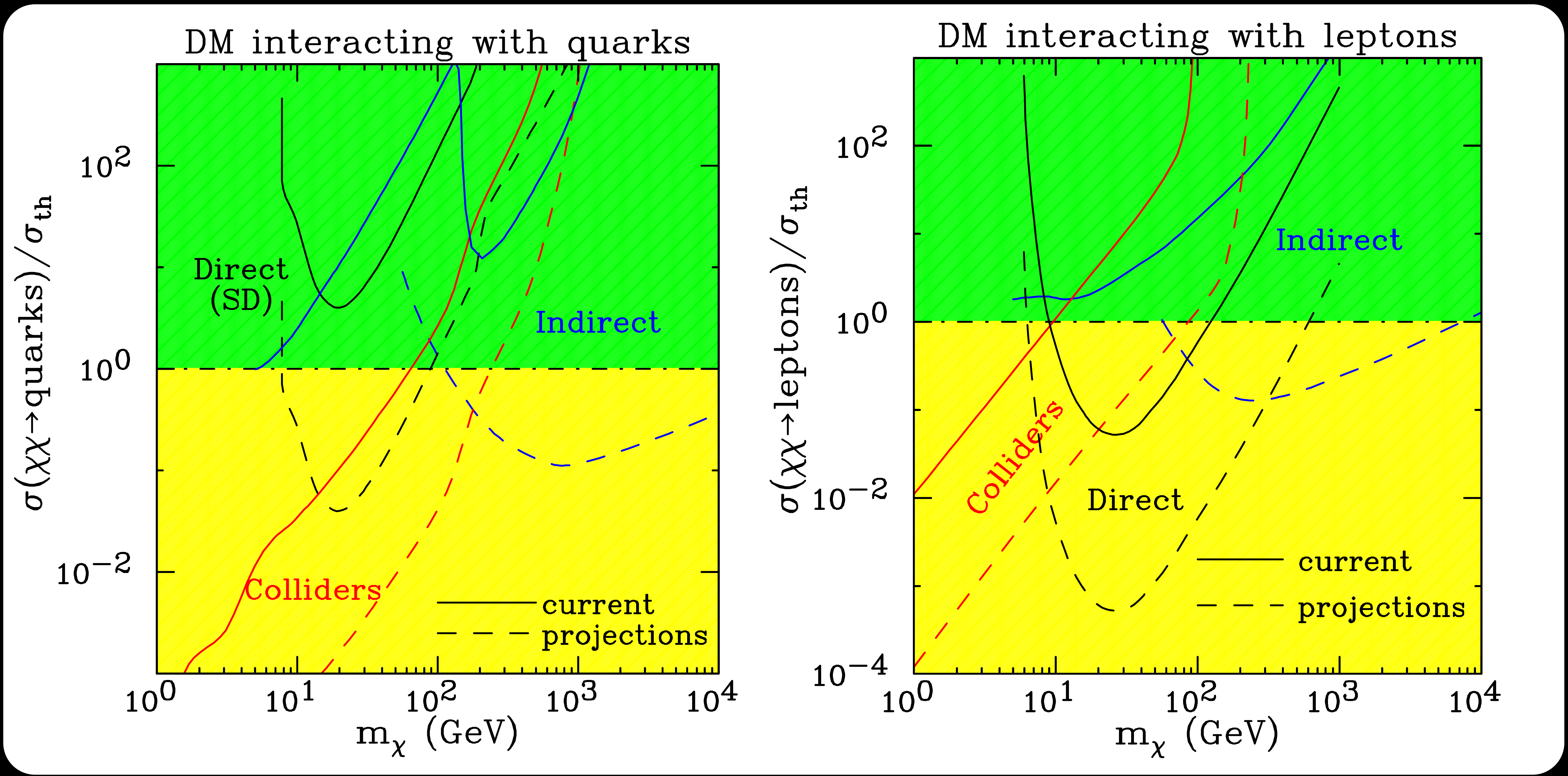


- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- Colliders continue to do better for lighter WIMPs or p-wave annihilations whereas indirect detection is more sensitive to heavy WIMPs.



DM Complementarity, arXiv:1305.1605

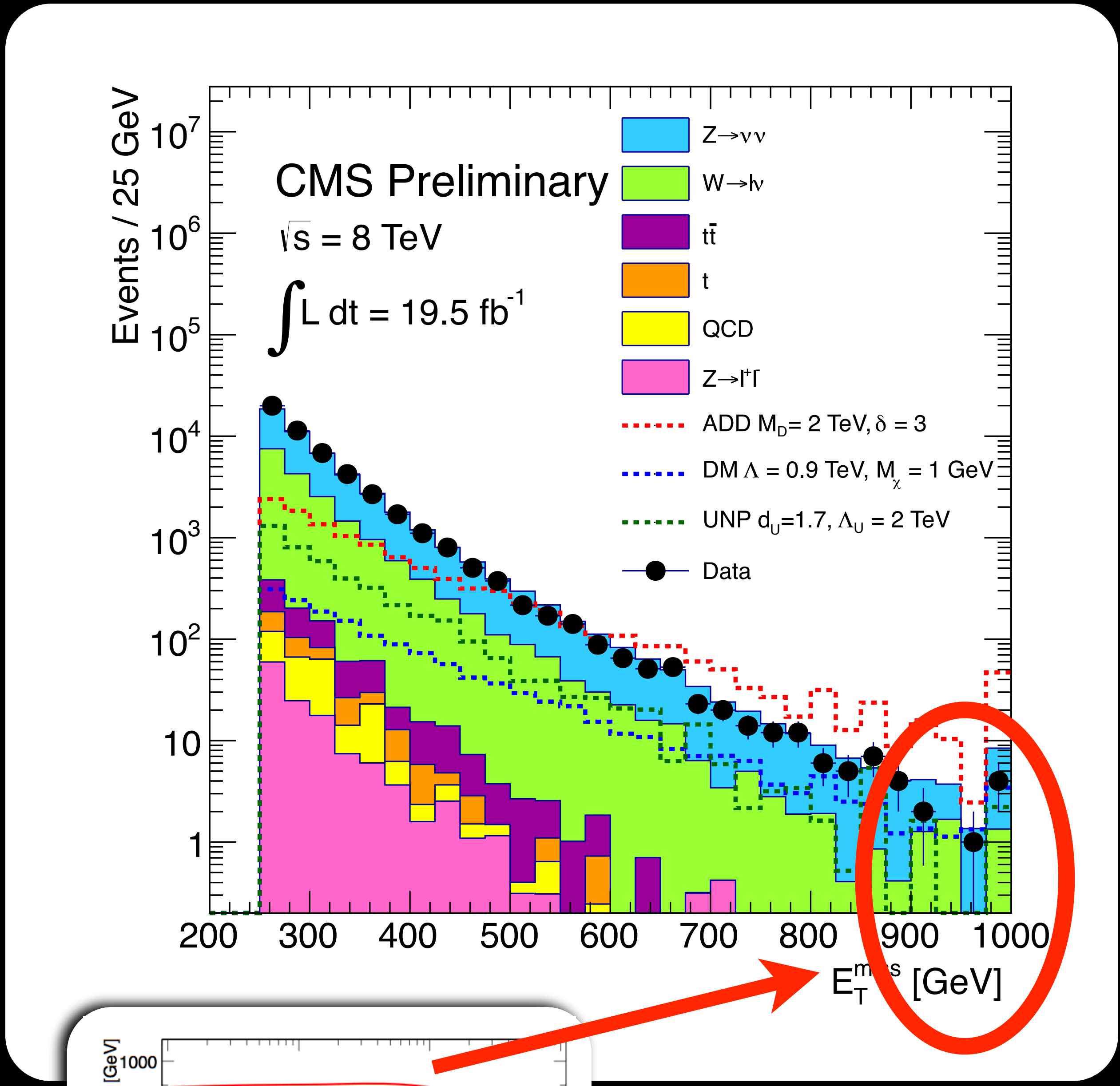
Quarks & Leptons

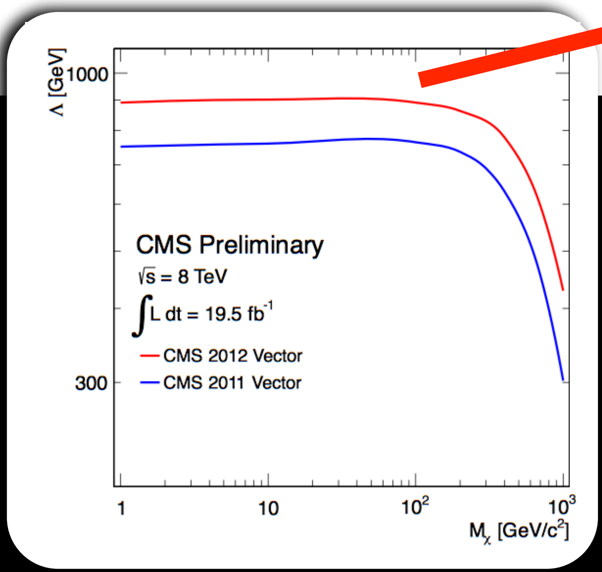


DM Complementarity, arXiv:1305.1605

How Effective a Theory?

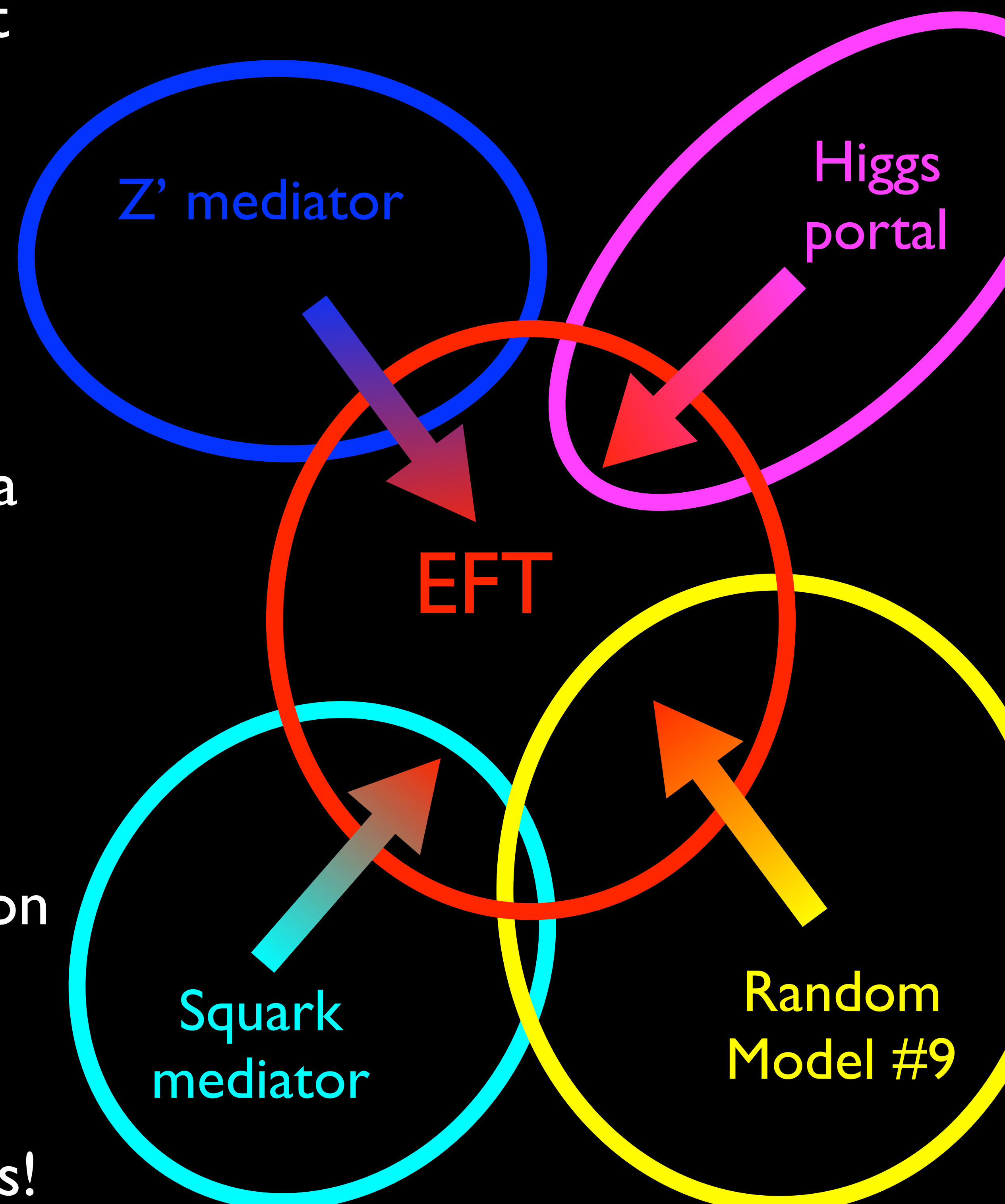
- We should worry a little bit about whether what we are doing makes sense.
- The bounds on the scale of the contact interaction are ~ 1 TeV, and we know that LHC collisions are capable of producing higher energies.
- For the highest energy events, we might be using the wrong theory description.
- It is difficult to be quantitative about precisely where the EFT breaks down, because the energies probed by the LHC depend on the parton distribution functions. [The answer is time-dependent in that sense.]





"EFT Doesn't Work at LHC"

- One sometimes hears the statement that the EFT doesn't work at the LHC.
  - This is inspired to some extent by the fact that the EFT is the universal large mass limit of any simplified model.
  - One should remember that the EFT is a superset of a limit of all simplified models: any one of them does not typically characterize all of them.
  - It is logistically impossible to rule out application of the EFT *in general* based on one *specific* model.
  - Instead, this reminds us that the EFT cannot itself describe all the possibilities!



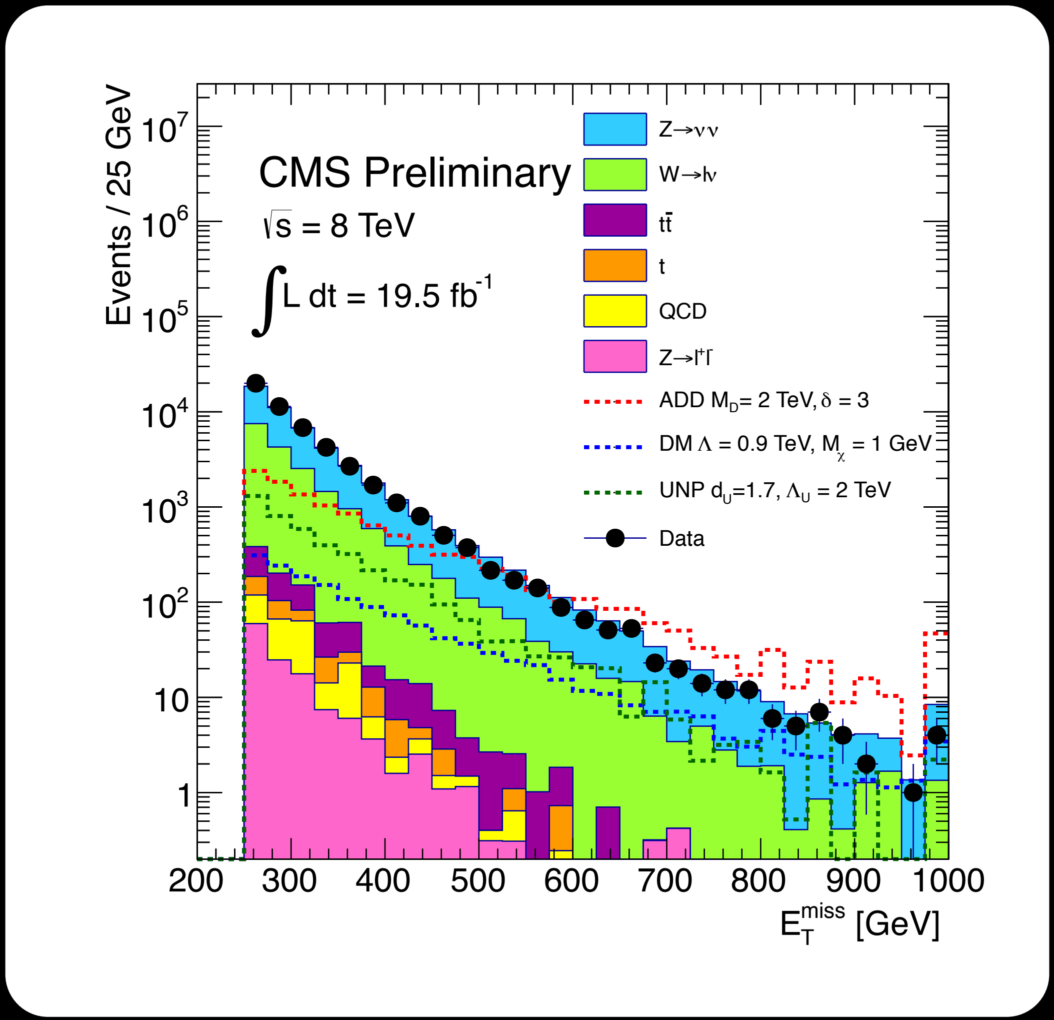
1. “EFT Doesn’t Work at LHC”

- So what can we learn from the EFT itself?
- The EFT is an expansion in energy: E / M*.
  - If E is too large, loop contributions to the observables will contribute as much as the tree level, and the theory ceases to be predictive.
  - Where that happens for fixed M* is somewhere around:

$$E \gtrsim 4\pi \ M_*$$

(We can argue about whether this should be 4π or 2π or some other number. One is as indefensible as another.)

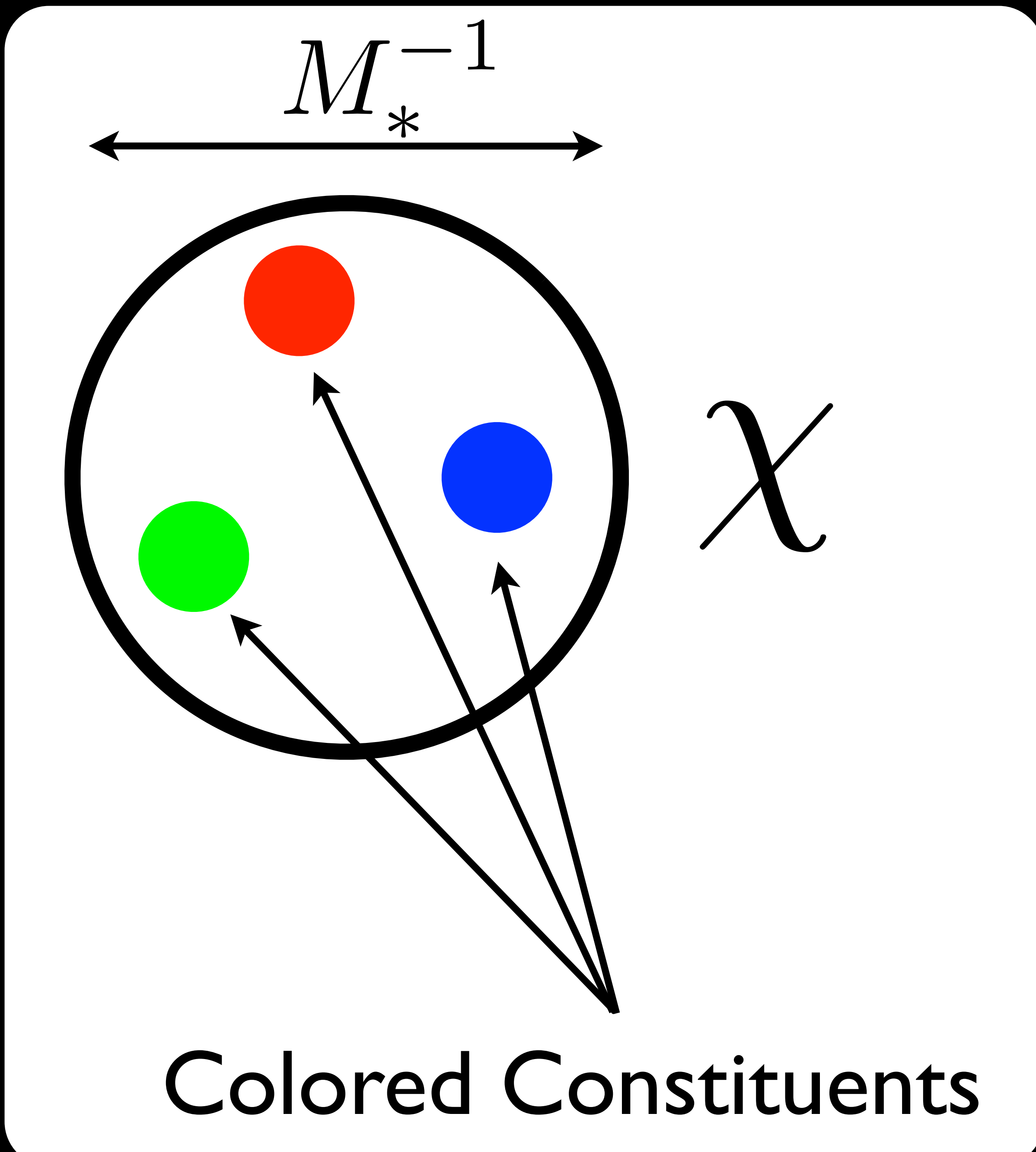
  - For the Run I limits of M* ~ 1 TeV, this forbids us from using events with energies larger than about 10 TeV.



Not a big problem at Run I…

(even in the limit 4π -> ~1!)

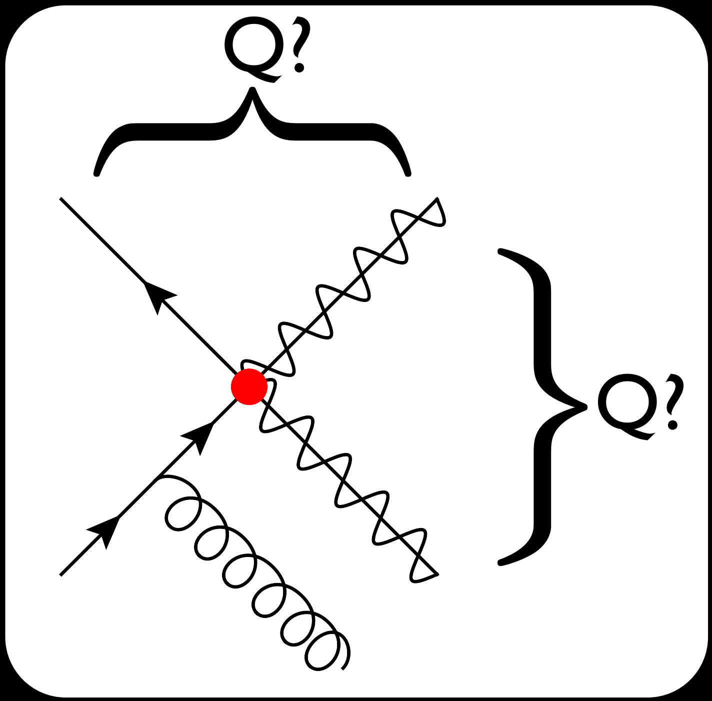
A Composite WIMP?

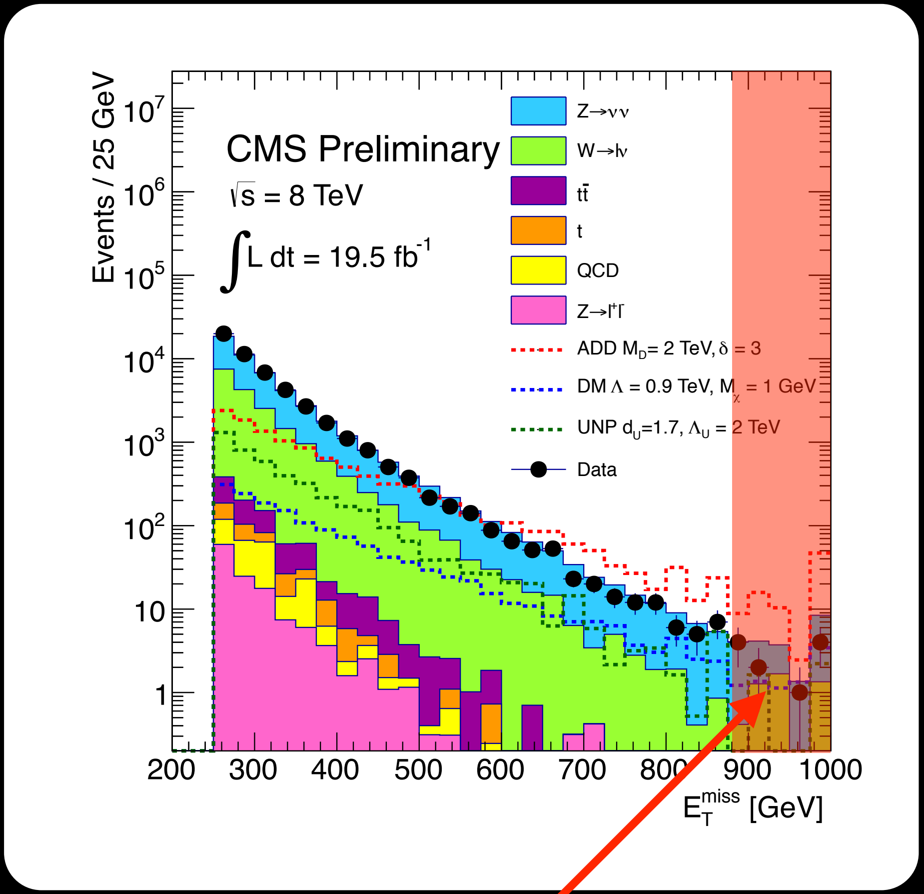


- There are cases where an EFT still says something even when there is no perturbative simplified model that can describe the physics.
- If the dark matter is a (neutral) confined bound state (confined by some dark gauge force, say) of colored constituents, we should expect its coupling to quarks and gluons to be represented by higher dimensional operators whose strength is characterized by the new confinement scale.
- Bounds on EFTs constrain the dark confinement scale -- the "radius" of the dark matter.

Truncation

- A good idea is to present EFT bounds using "truncation".
- The idea is to exclude the events with the largest momentum transfer from the bound, since they are the most likely to be badly modeled by the EFT.
- If one imagines a simple t-channel or s-channel model, two different quantities ("Q") characterize the momentum through the implicit propagator.
  - The EFT can't tell you which one to use.
  - (Neither really can be measured anyway).
- Events with Q larger than some cut value Q_{cut} are excluded from the analysis bounding M_*.

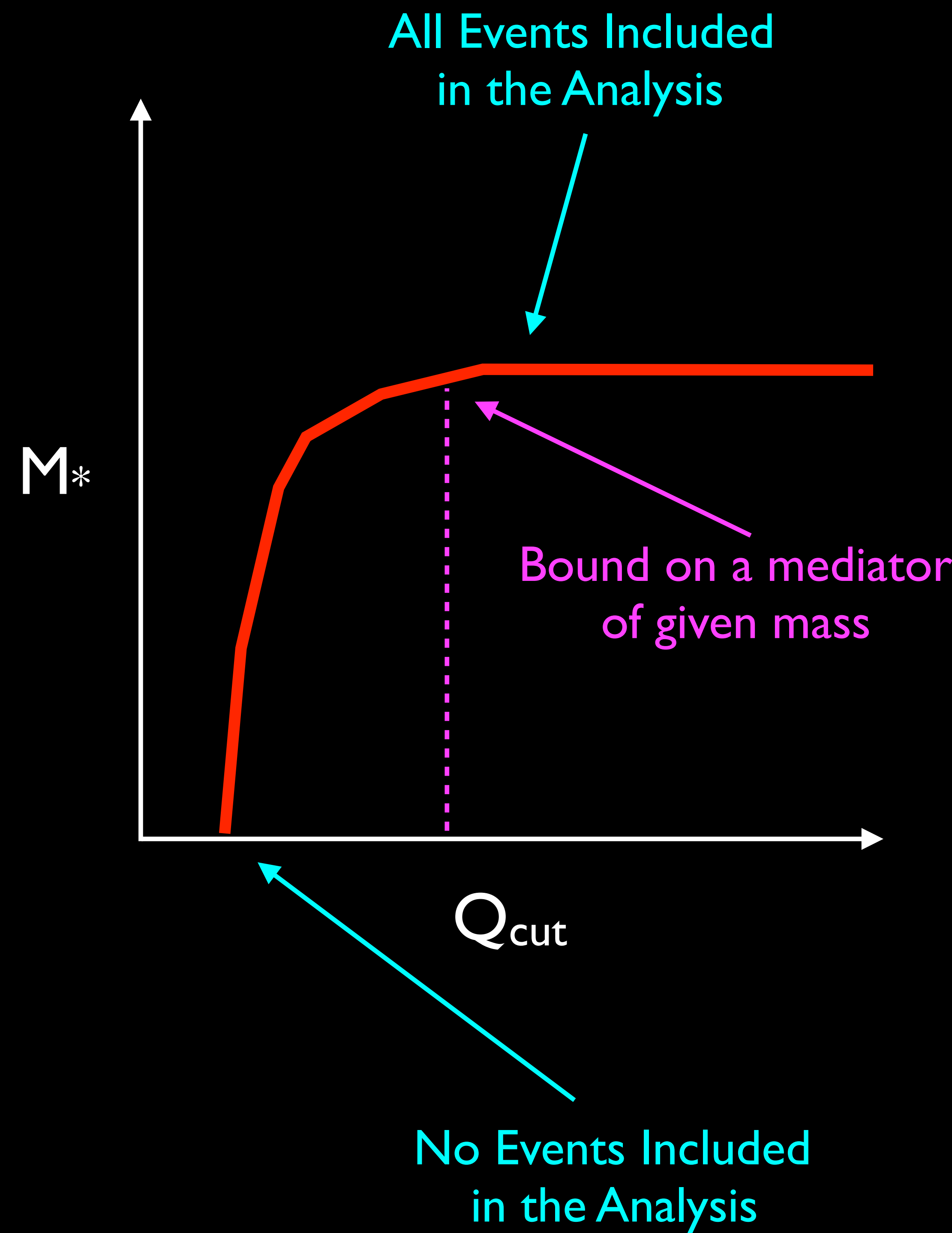




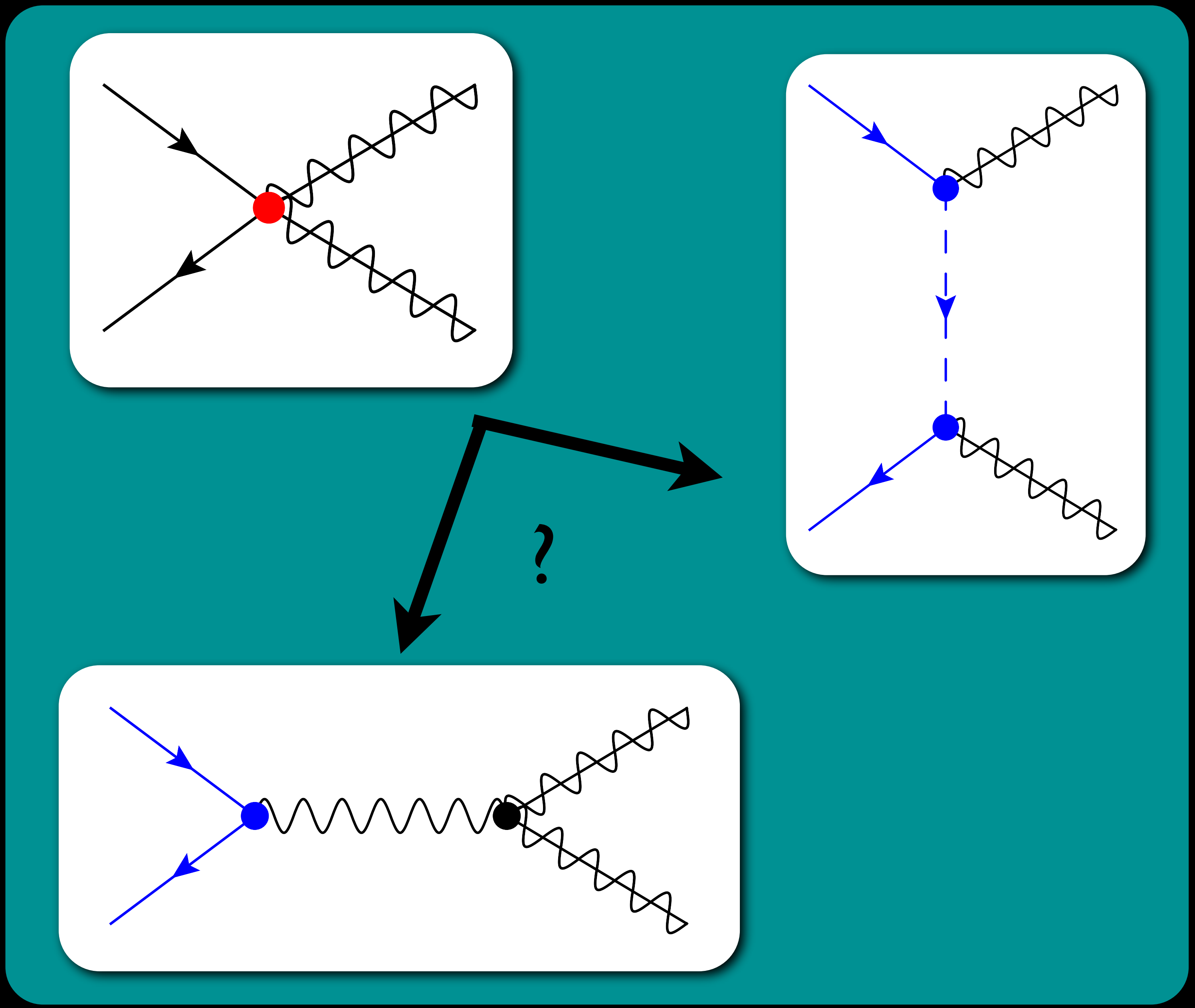
Exclude these Events for Q_{cut} = 900 GeV.

Truncation

- Probably the most useful way to present results would be to show the resulting bound on M_* as a function of Q_{cut}.
- That way, the end user can decide (based on the masses of the particles in her theory) what value of Q_{cut} is appropriate, and find the conservative limit on her model.
- (And of course dedicated searches for mediators will be important, too).
- This the final recommendation made by the "ATLAS/CMS Dark Matter Forum", 1507.00966 for presenting the results in terms of EFT parameterizations.



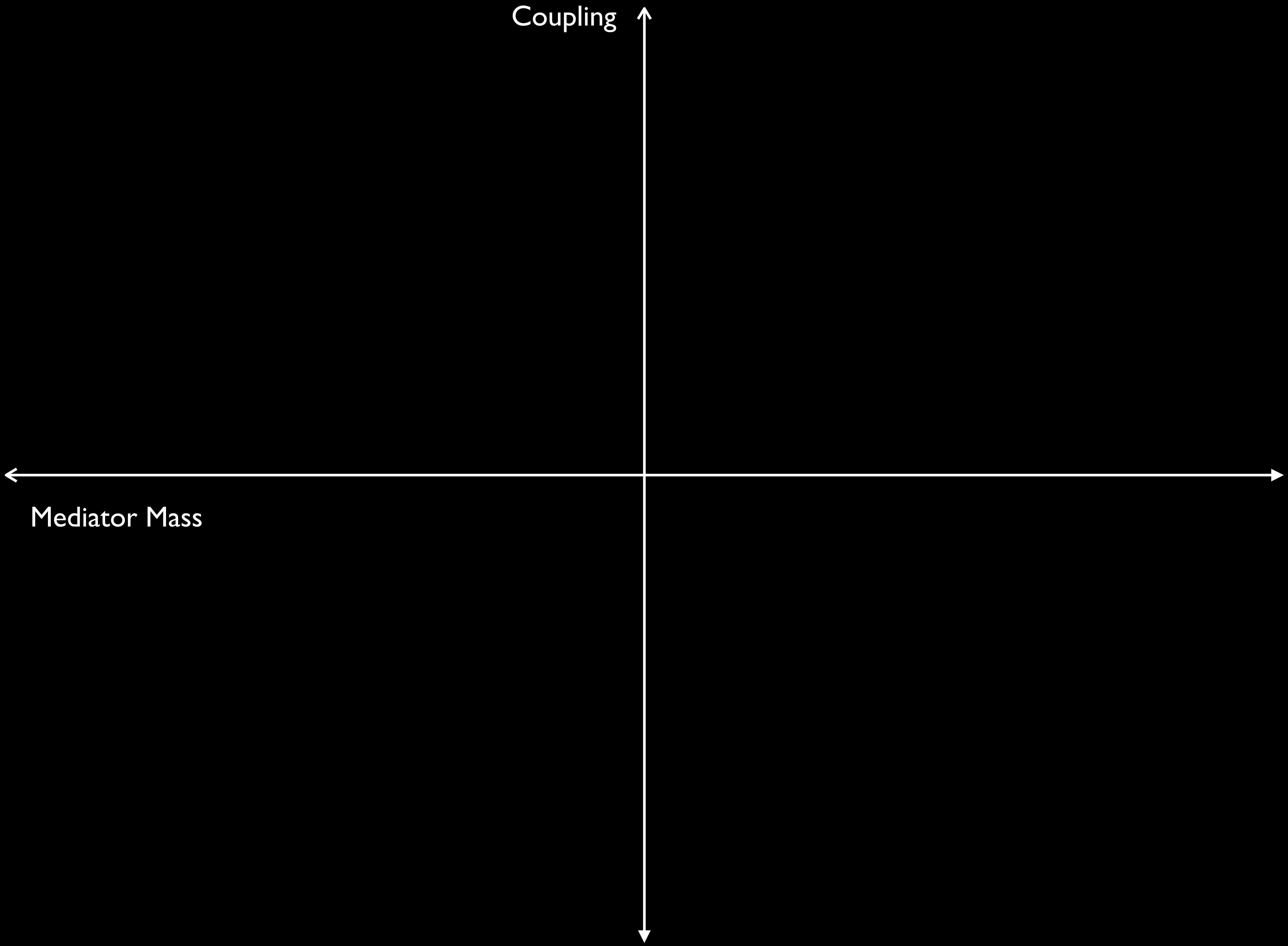
Simplified Models?

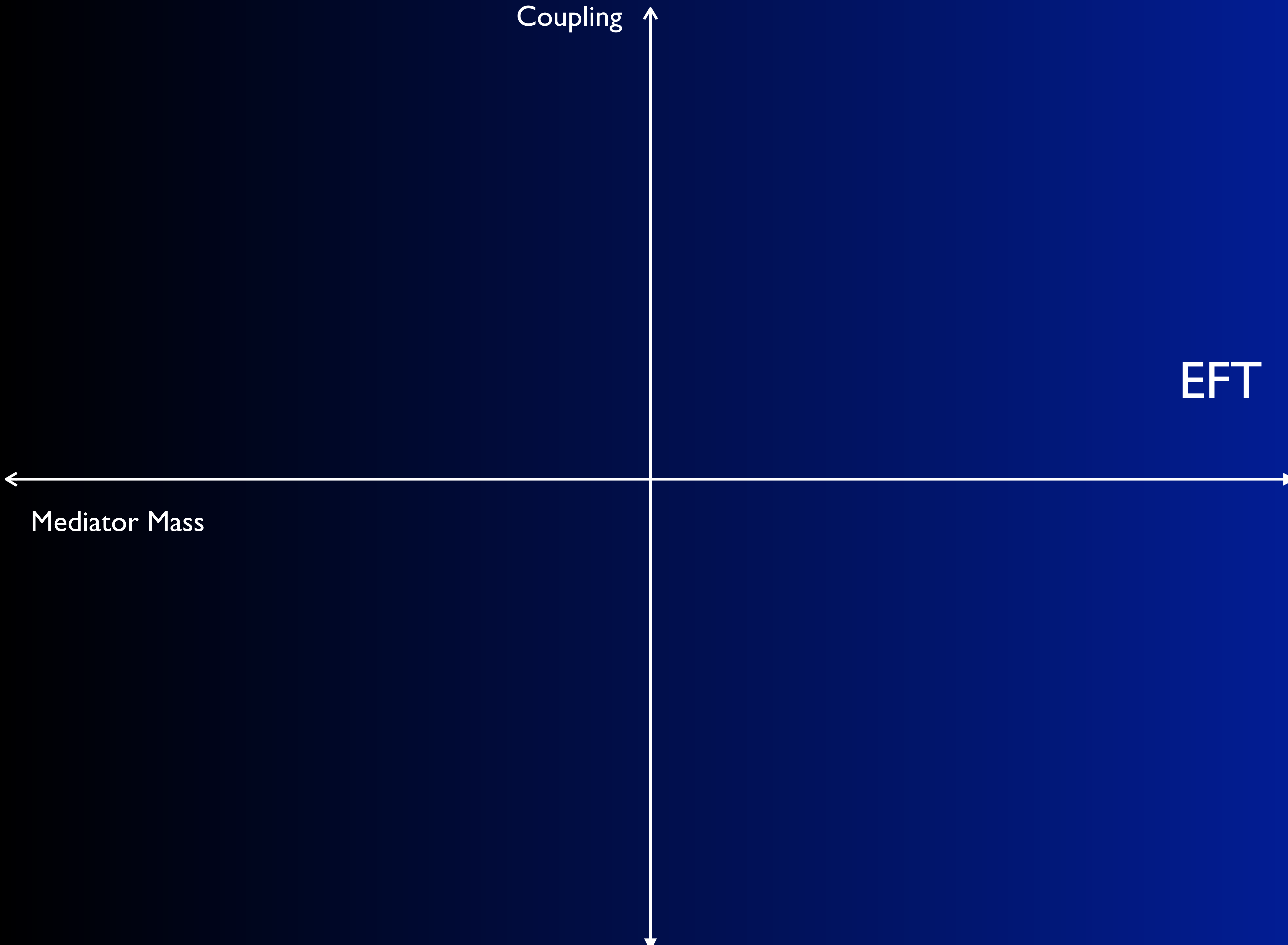


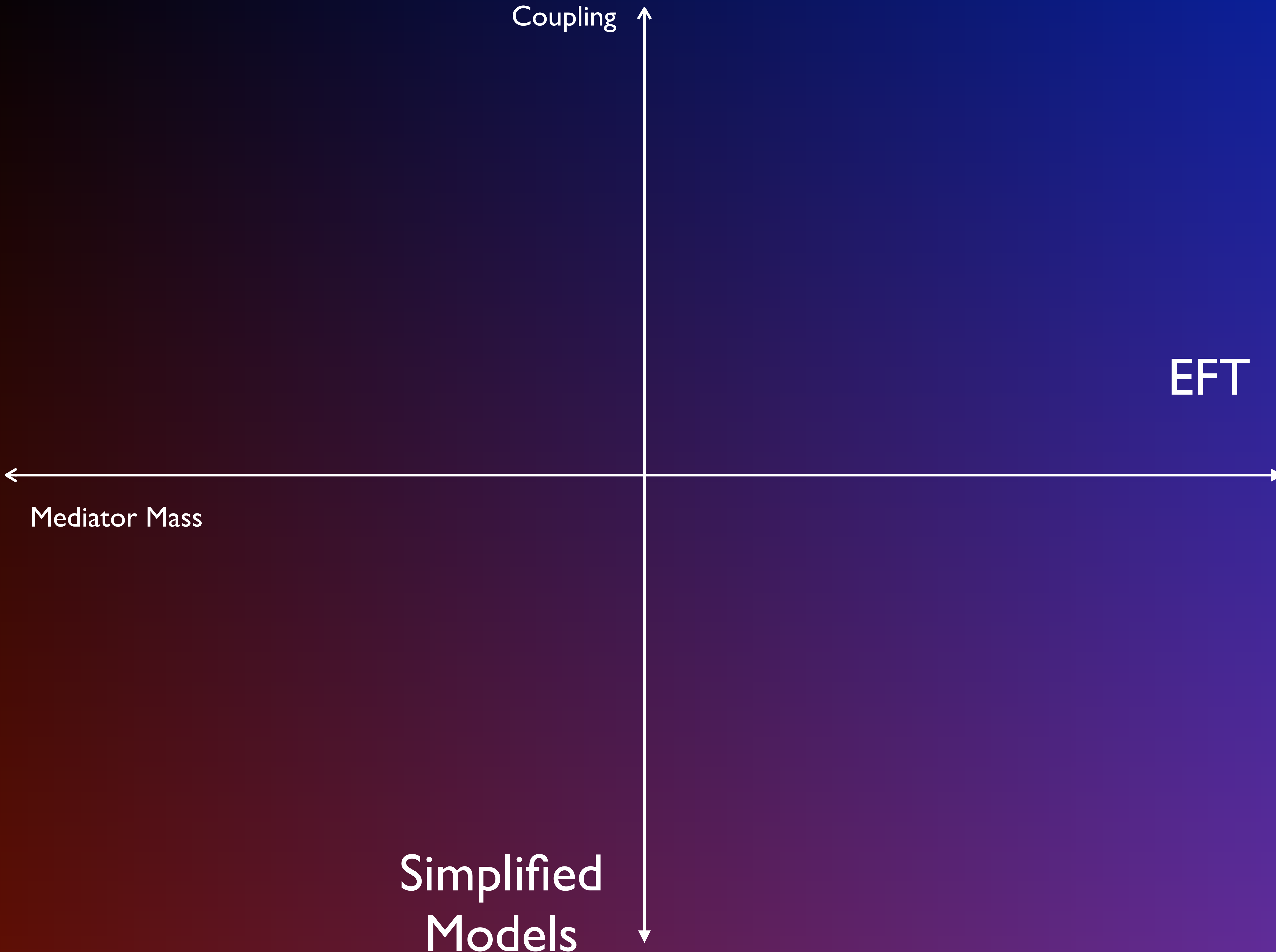
“t-channel” mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

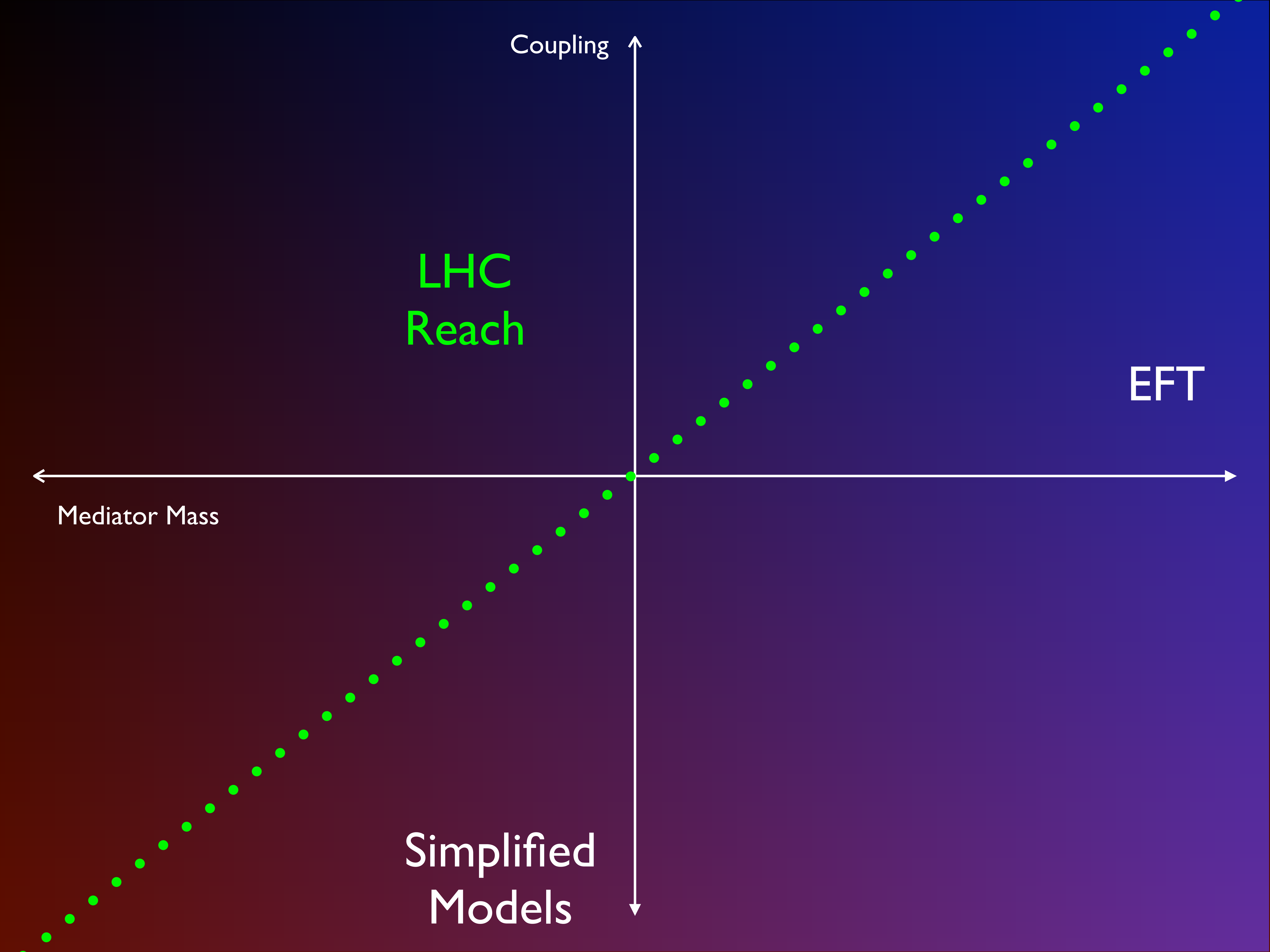
“s-channel” mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.

One strategy is to try to write down some theories with mediators explicitly included.


Coupling
Mediator Mass


Coupling
EFT
Mediator Mass


Coupling
EFT
Mediator Mass
Simplified
Models

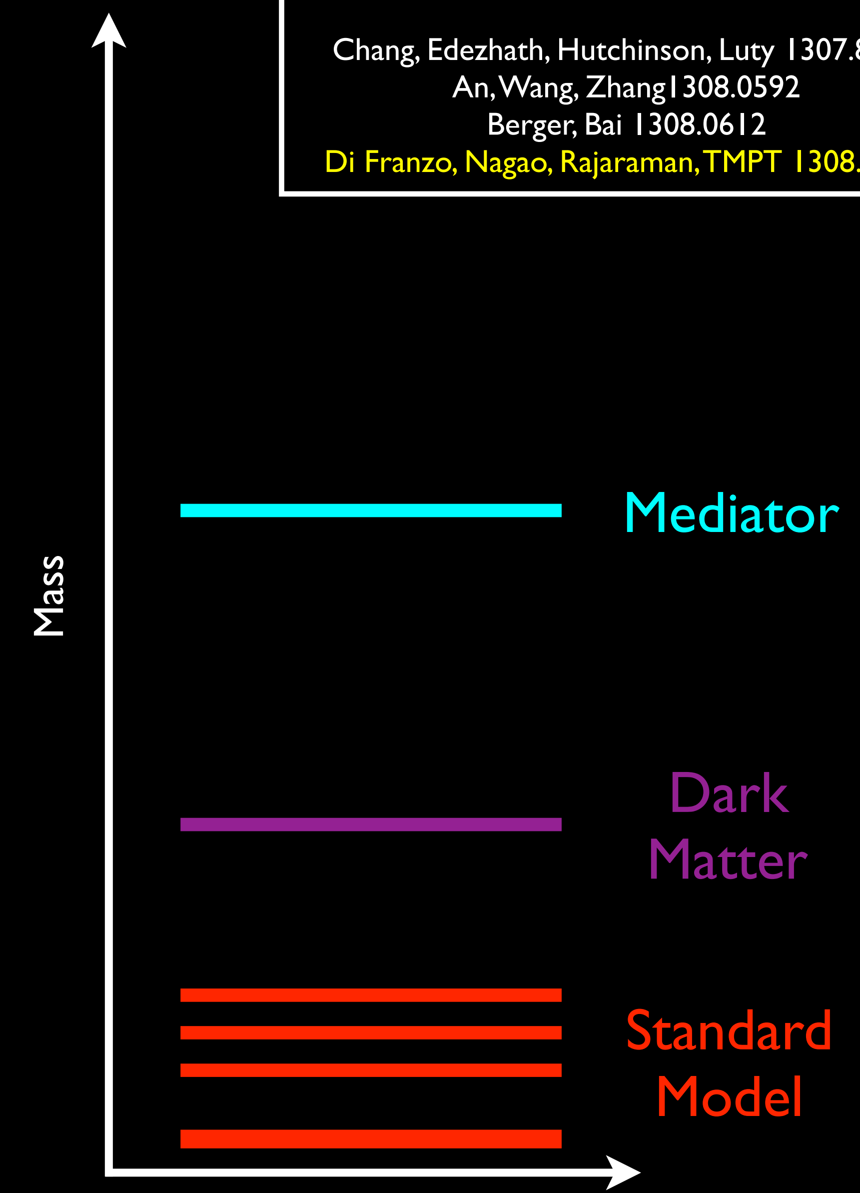

Coupling
LHC
Reach
EFT
Mediator Mass
Simplified
Models

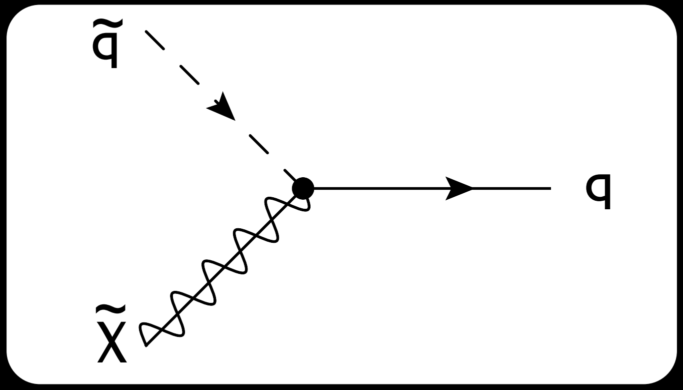
Simplified Model

- Moving toward a more complete theory, we can also consider a model containing the dark matter as well as the most important particle mediating its interaction with the Standard Model.
- For example, if we are interesting in dark matter interacting with quarks, we can sketch a theory containing a colored scalar particle which mediates the interaction.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, etc.
- There are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.

Lots of Recent Activity:

Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang 1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679



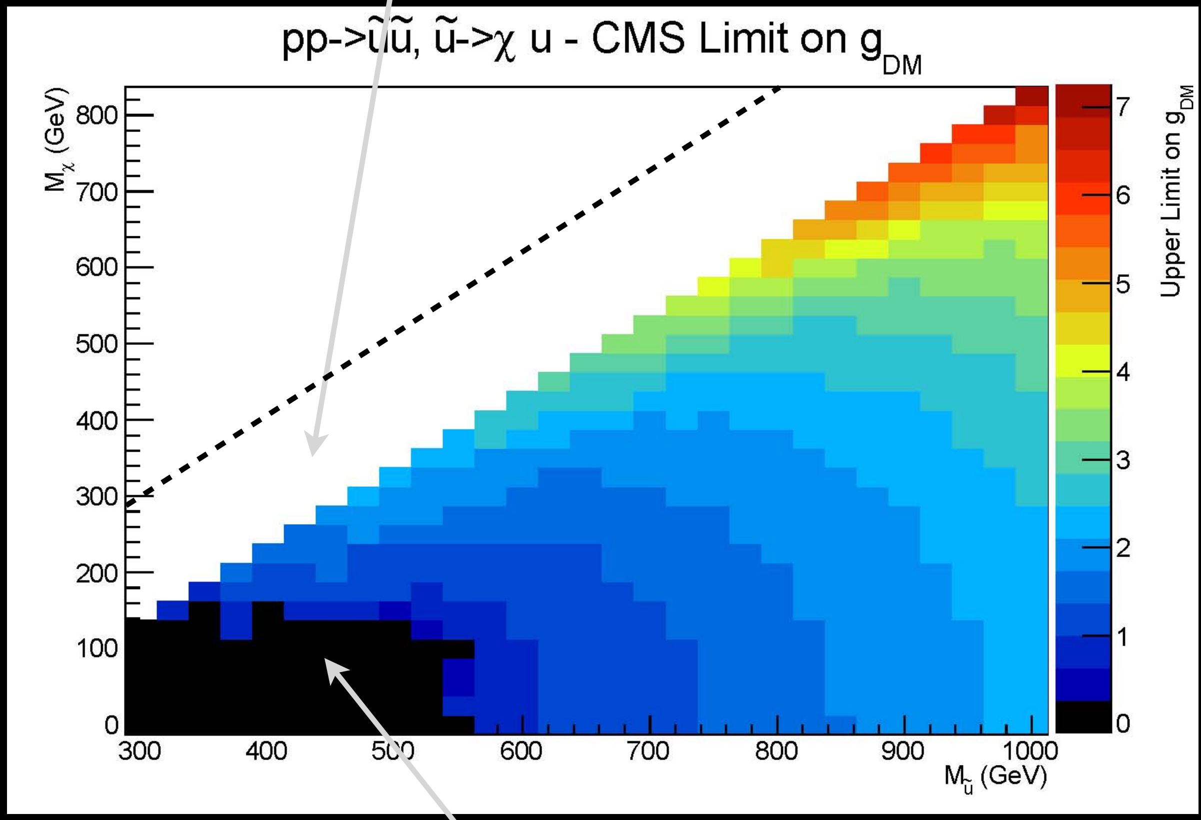


$\tilde{u}_R$ Model

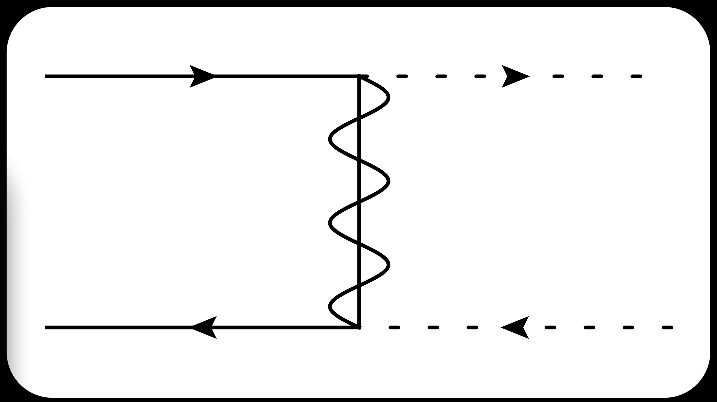
- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force (QCD; mostly from initial gluons) or through the interaction with quarks.
- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.

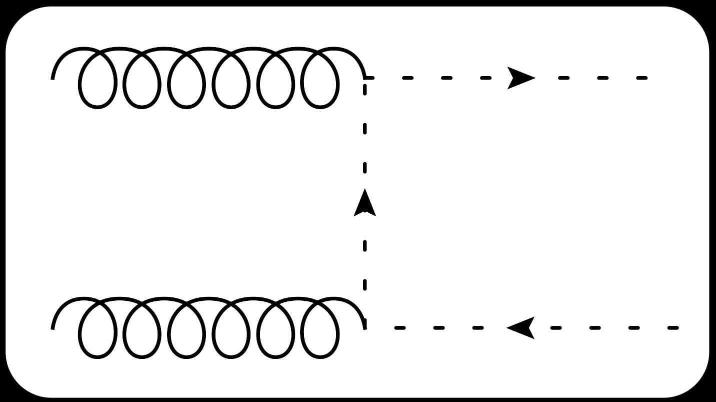
Weak bounds in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



QCD production saturates the CMS limits, resulting in no allowed value of g.

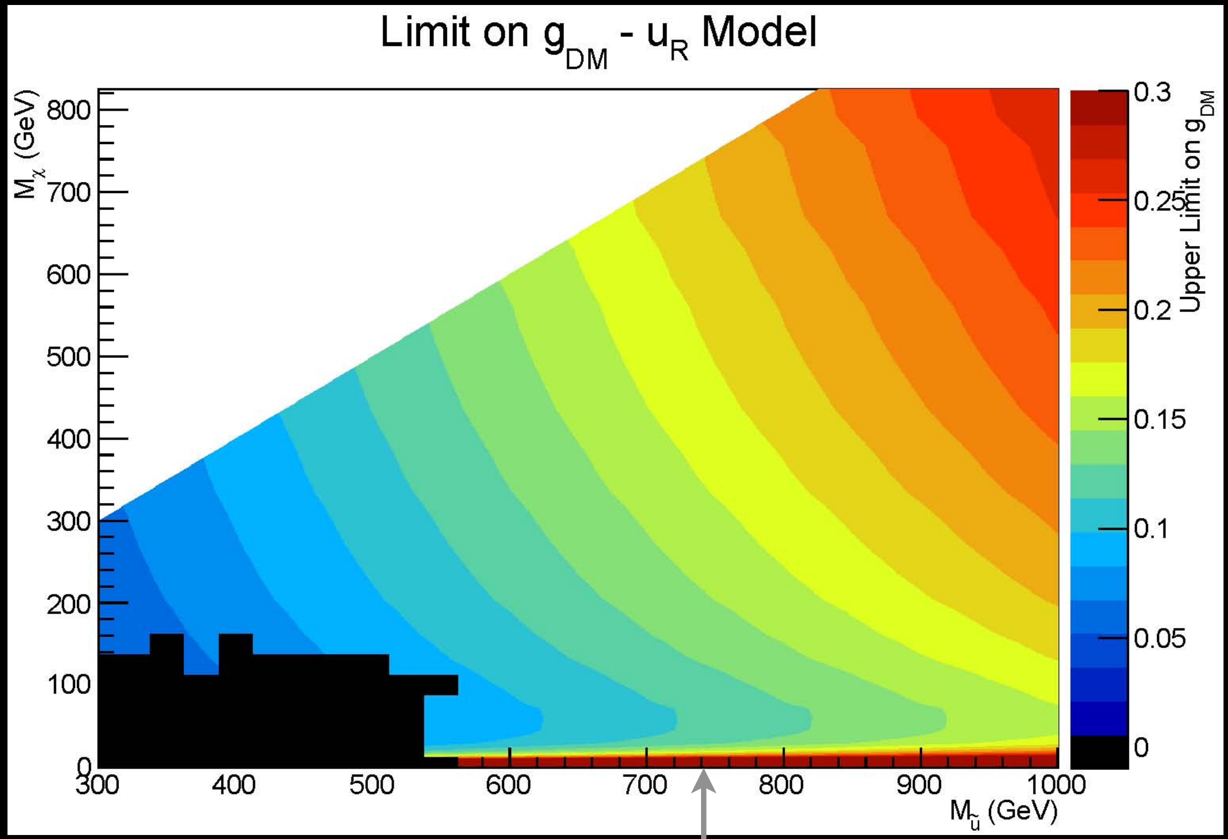




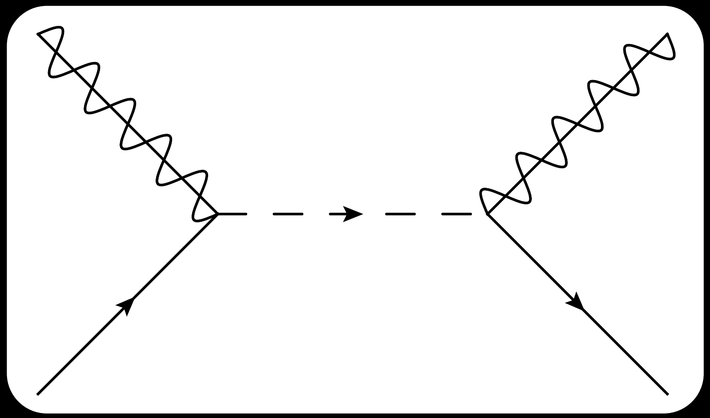
$\tilde{u}_R$ Model

- A Dirac WIMP also has spin-independent scattering with nucleons. For most of the parameter space, there are bounds from the Xenon-100 experiment. (And recently LUX has improved these limits by about a factor of two...).
- Elastic scattering does not rule out any parameter space, but it does impose stricter constraints on the allowed size of the coupling in the regions the LHC left as allowed.

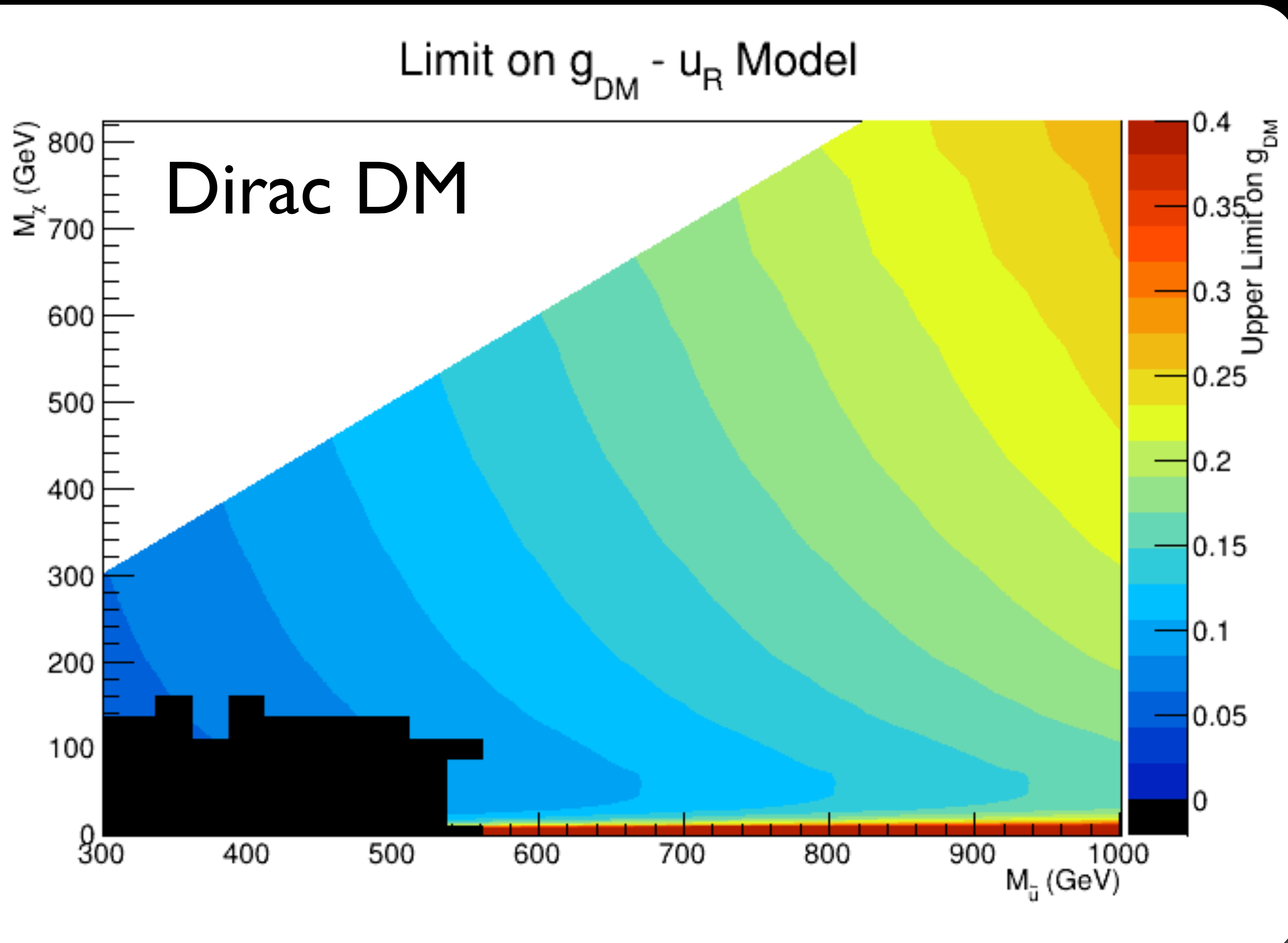
DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



Traditional direct detection searches peter out for masses below about 10 GeV.

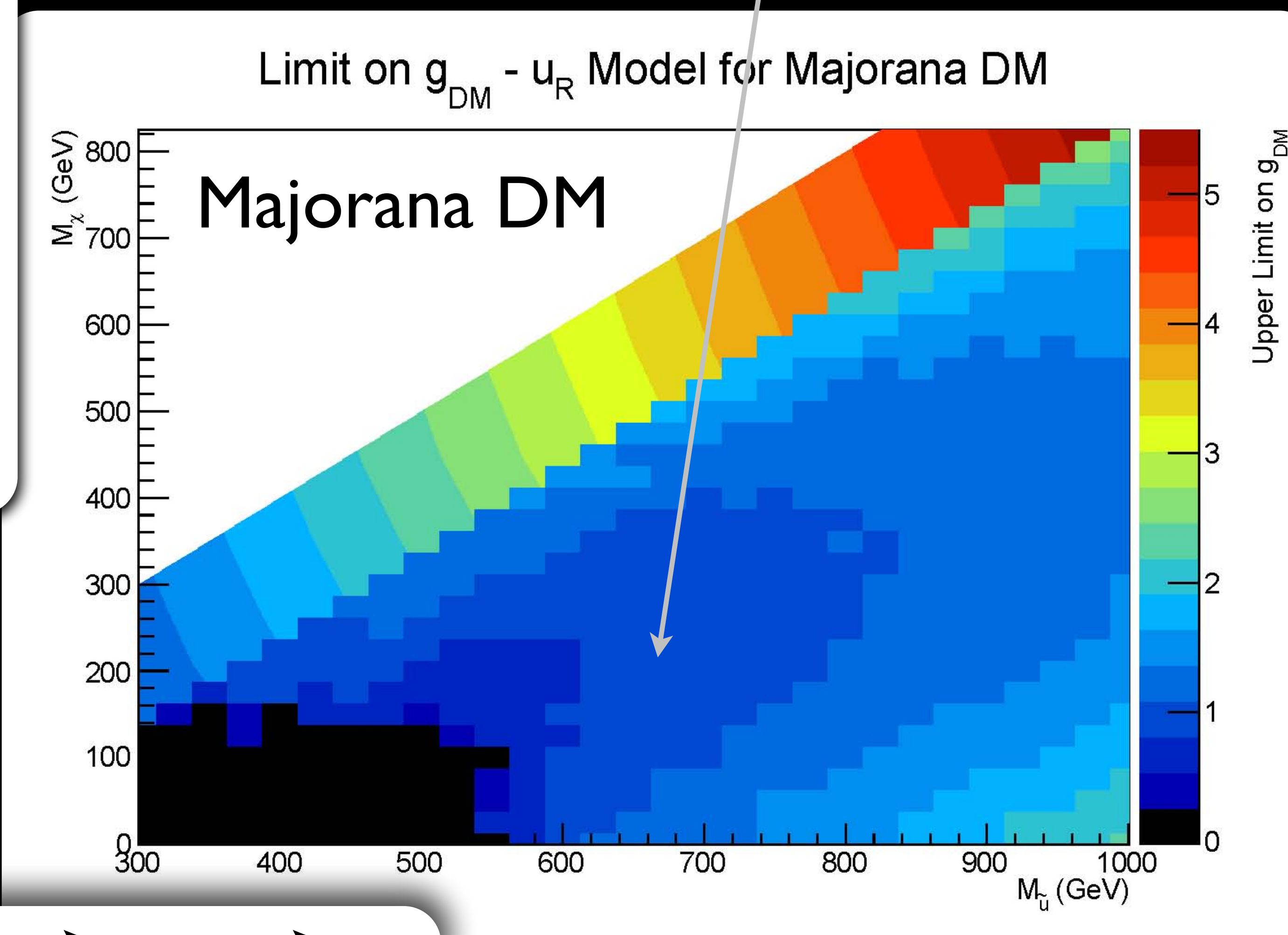


Majorana versus Dirac



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

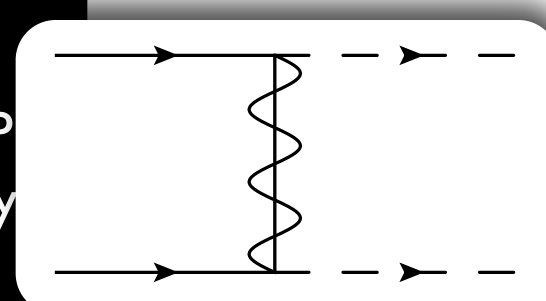
Collider bounds tend to dominate for Majorana DM.



There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

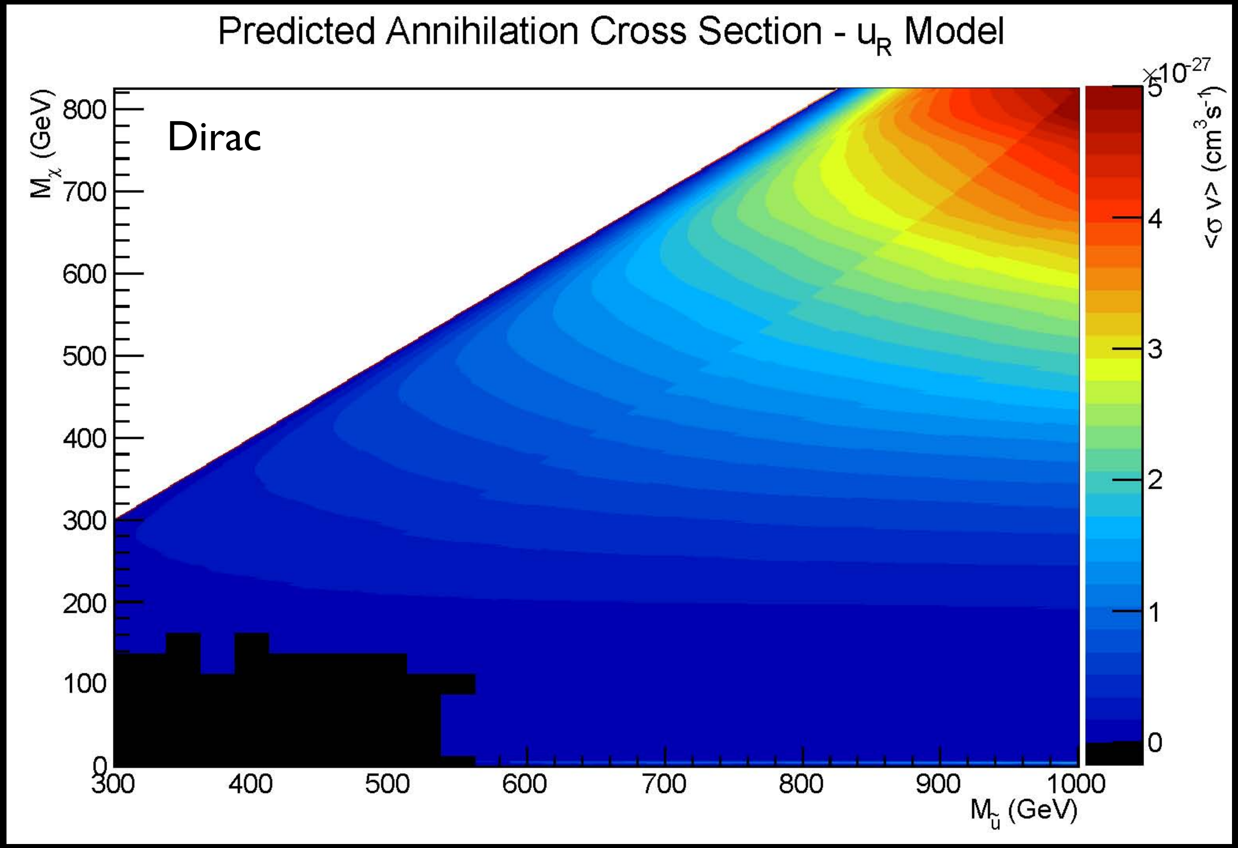
Majorana WIMPs have no tree-level spin-independent scattering in this model.

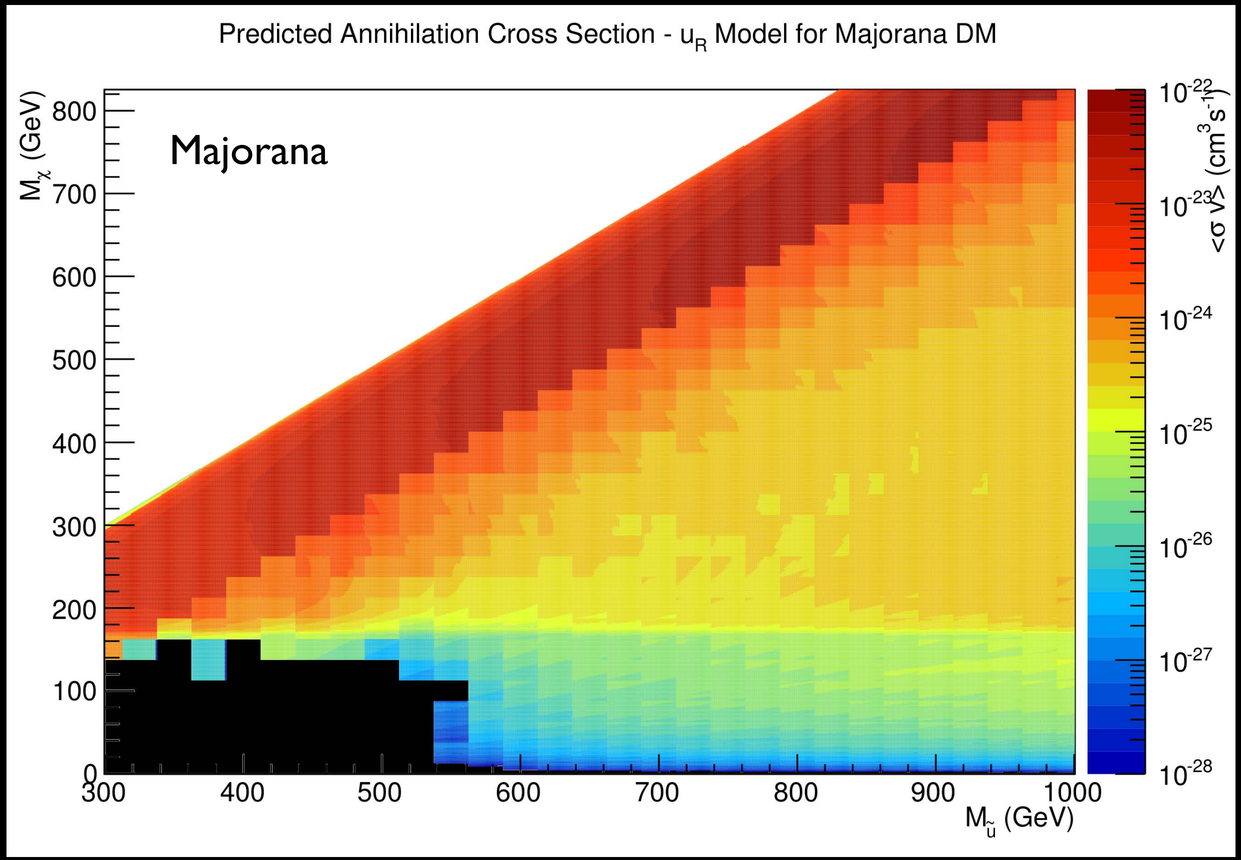
At colliders, t-channel exchange of a Majorana WIMP can produce two mediators, leading to a PDF-friendly qq initial state.



$\tilde{u}_R$ Model: Forecasts

- Similarly, we can forecast for the annihilation cross section.
- The Fermi LAT does not put very interesting constraints at the moment, but it is very close to doing so, and limits from dwarf satellite galaxies are likely to be relevant in the near future for Majorana Dark Matter.
- We can also ask where in parameter space this simple module would lead to a thermal relic with the correct relic density.





DiFranzo, Nagao, Rajaraman, TMPT
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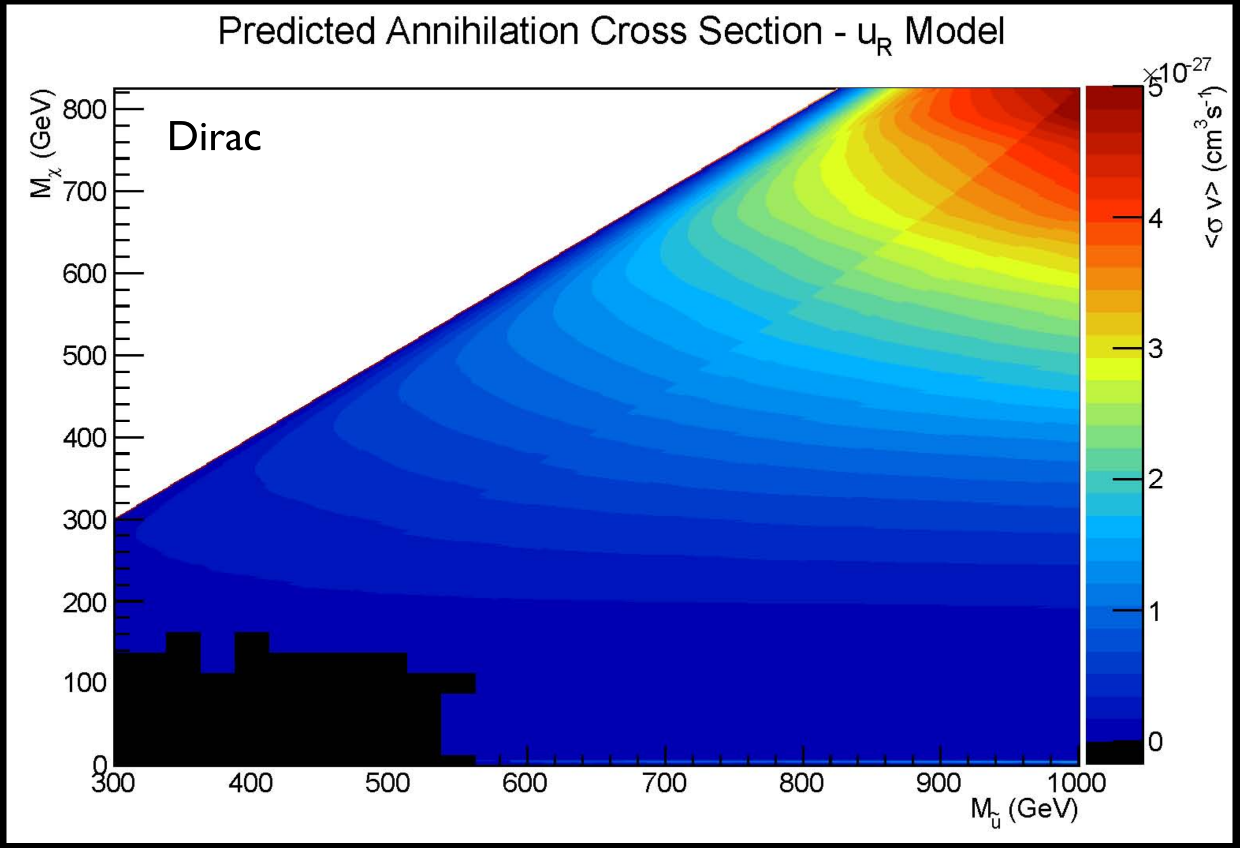
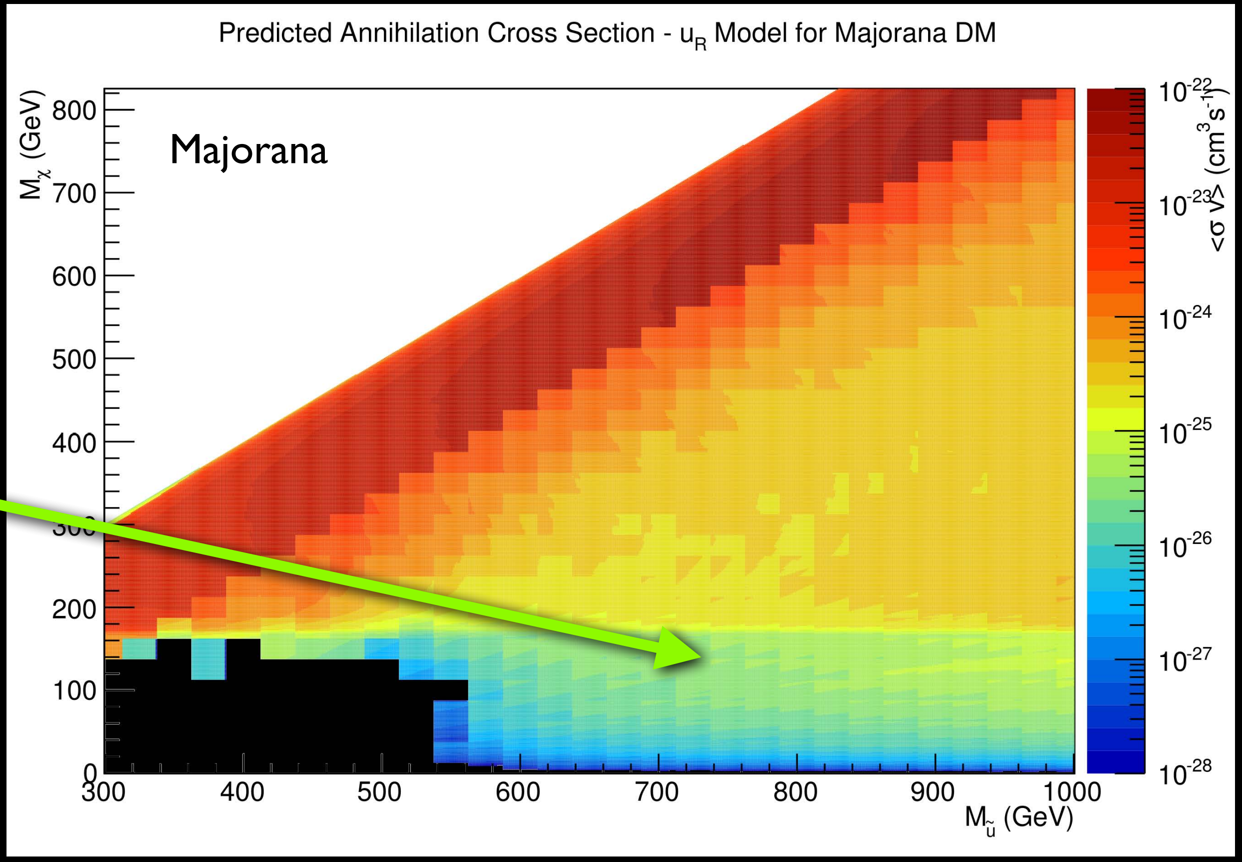
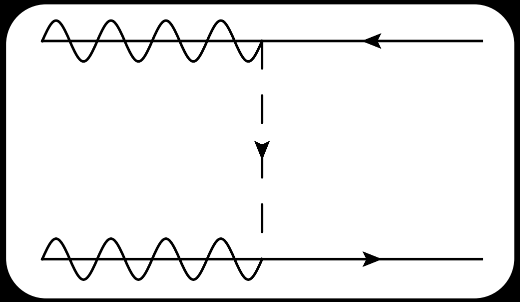
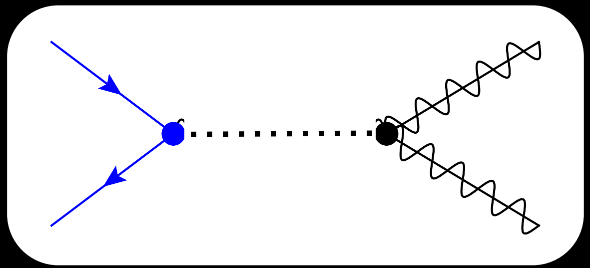


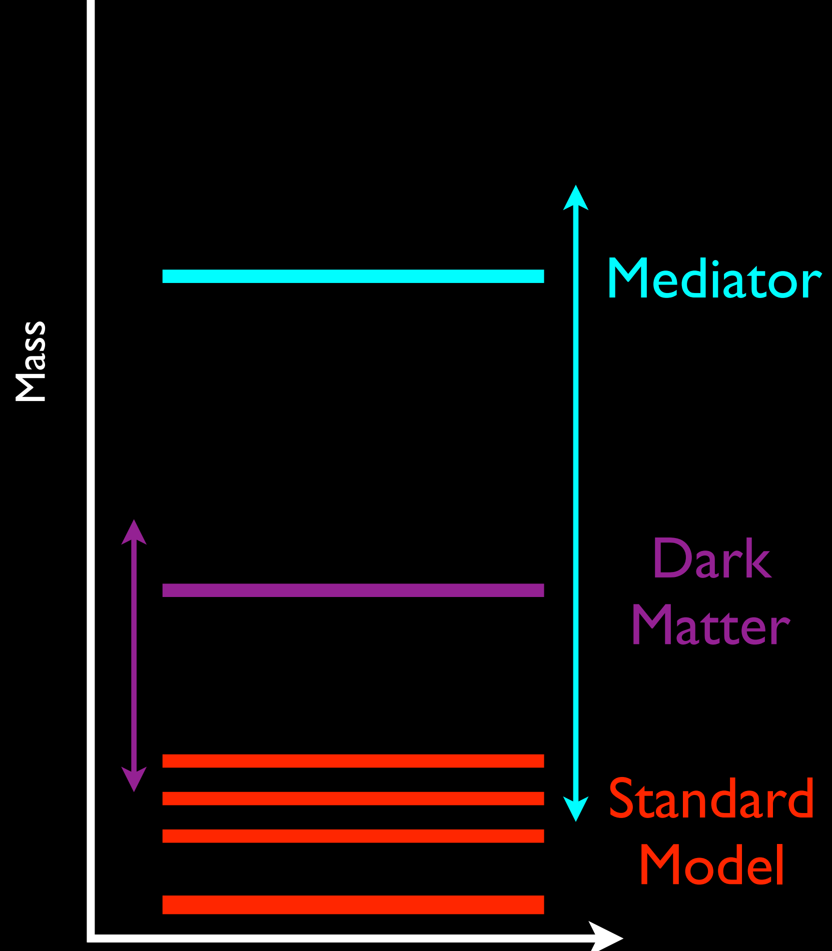




S-Channel : Scalar

- A singlet scalar could be real or complex.
- Scalar couplings are chirality flipping. The scalar mediator consistent with MFV couples proportionally to Yukawa couplings.
- In the SM, the only relevant parameters are the masses, and the degree of mixing with the SM Higgs through electroweak breaking.
- If the SM is extended to a two (or more) Higgs doublet model, the coupling to up-quarks, down-quarks, and/or leptons become decorrelated.
  - Inside each sector, they still go like Yukawa couplings.

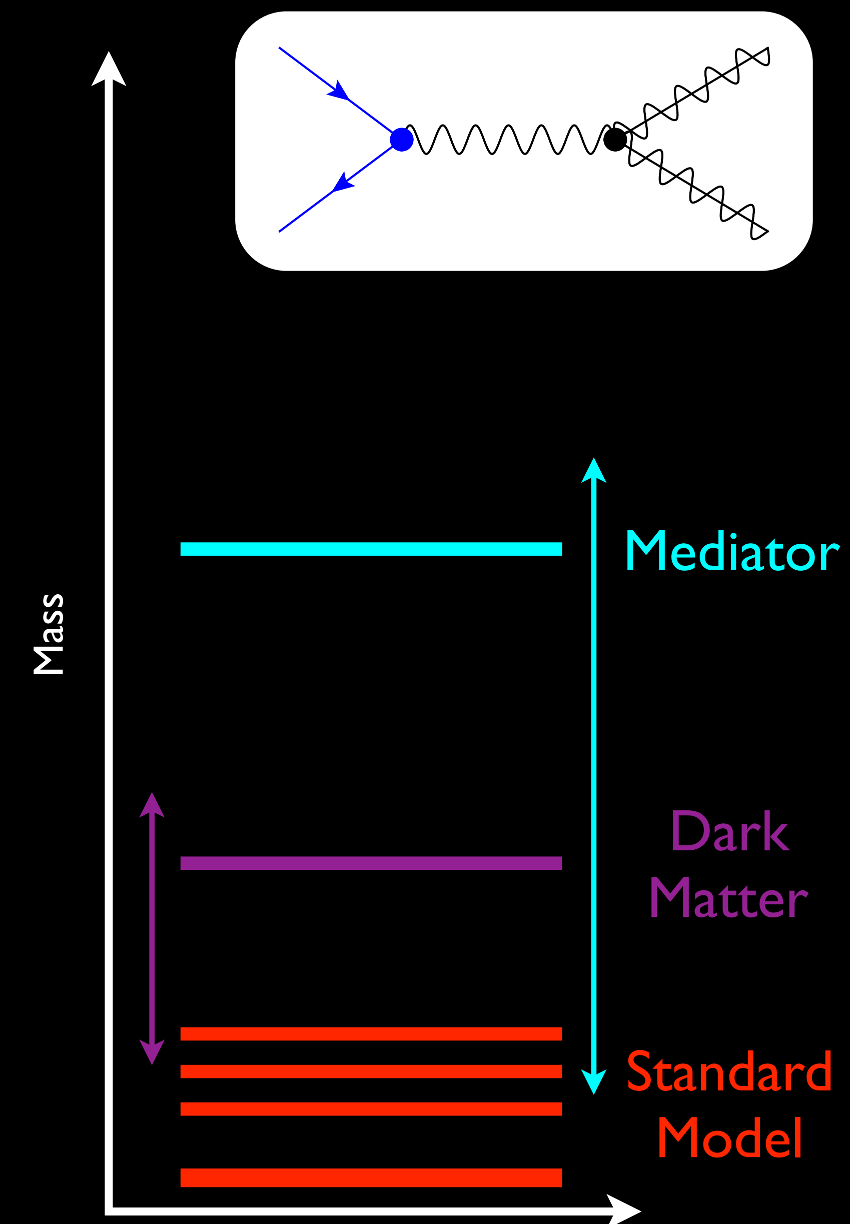




Parameters: $\{M_{\rm DM}, g_{\rm DM}, M_S, \theta_H\}$ or maybe $\{M_{\rm DM}, g_{\rm DM}, M_S, g_u, g_d, g_\ell\}$

S-Channel :Vector

- Vector models have more parameters consistent with MFV.
- uR, dR, qL, eR, lL all have family-universal but distinct charges, as does H.
    - We would like to be able to write down the SM Yukawa interactions.
    - Quarks need not have universal couplings.
- There could be kinetic mixing with $U(1)_Y$.
- There is a dark Higgs sector. It may not be very important for LHC phenomenology.
- Gauge anomalies must cancel, which also may not be very important for LHC phenomenology.



Parameters: $\{M_{\rm DM}, g, M_{Z'}, z_q, z_u, z_d, z_\ell, z_e, z_H, \eta\}$ + ...

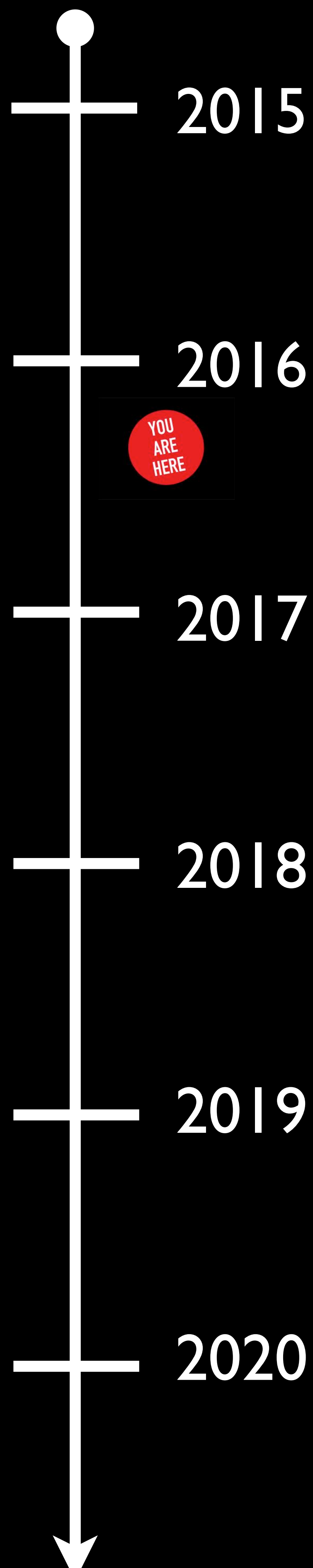
The Dark Matter Questionnaire

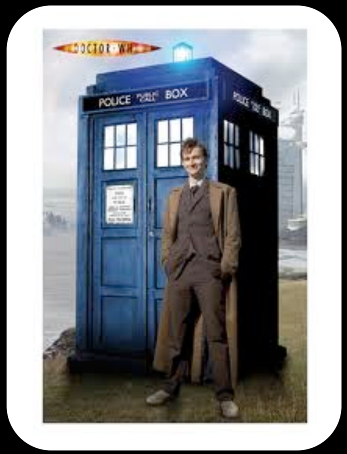
- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?
- ☐ Thermal Relic?
  - ☐ Yes ☐ No

A Possible Timeline





- [ ] Mass
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2015

2016

YOU ARE HERE

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

2017

2018

2019

2020

- [ ] ? Mass: < 200 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2015

2016

2017

2018

2019

2020

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2015

2016

YOU ARE HERE

2017

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2020

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Super-CDMS sees a similar signal.

Two LHC experiments see a significant excess of leptons plus missing energy.

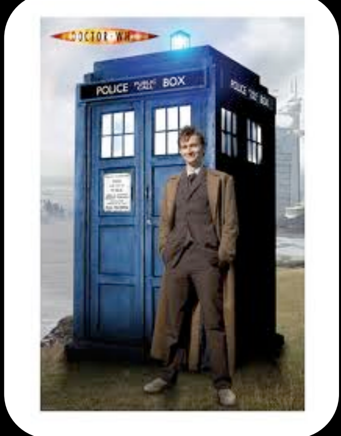
Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [?] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [?] Leptons?
- [ ] Thermal Relic?

A Possible Timeline



2015

2016

YOU ARE HERE

2017

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Super CDMS sees
nal.

Two LHC experiments see a significant excess of leptons plus missing energy.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

No jets + MET

Neutrinos are seen coming from the Sun by IceCube.

- [x] Mass: 150 +/- 15 GeV
- [x] Spin: > 0
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] ✗ Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [x] Leptons
- [ ] Thermal Relic?

A Possible Timeline

2015

2016

YOU ARE HERE

2017

2018

2019

2020

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Super-CDMS sees a similar signal.

A positive signal of axion conversion is observed at an upgraded ADMX.

Two LHC ... signific... plu...

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

☑ Mass: 150 +/- 15 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☒ Stable?
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak Interaction?	☑ Photon Interaction
☐ Higgs?	☐ Higgs?
☑ Quarks / Gluons	☐ Quarks / Gluons?
☑ Leptons	☐ Leptons?
☐ Thermal Relic?	☒ Thermal Relic?

A Possible Timeline

2015

2016

YOU ARE HERE

2017

2018

2019

2020

????

☑ Mass: 150 +/- 0.1 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☒ Stable?
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak Interaction?	☑ Photon Interaction
☐ Higgs?	☐ Higgs?
☑ Quarks / Gluons	☐ Quarks / Gluons?
☑ Leptons	☐ Leptons?
☑ Thermal Relic	☒ Thermal Relic?

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ons

Neutrinos are seen coming from the Sun by IceCube.

A positive signal of axion conversion is observed at an upgraded ADMX.

Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.

A Possible Timeline

2015

2016

YOU ARE HERE

2017

2018

2019

2020

????

LUX sees a h
scattering ev
with a DM m

Super-C
a simil

- [x] Mass: 150 +/- 0.1 GeV
- [x] Spin: > 0
- [ ] Stable?

Couplings:

- [x] Gravity
- ☒ Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [x] Leptons
- [x] Thermal Relic

- [x] Mass: 20 μeV
- [x] Spin: 0
- ☒ Stable?

Couplings:

- [x] Gravity
- [x] Weak Interaction
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?
- ☒ Thermal Relic?

A multi-pronged search strategy identifies a mixture of dark matter composed of classic WIMPs and axions.

ermi observes a faint gamma
ay line at 150 GeV from the
galactic center.

Neutrinos are seen coming
from the
Sun by IceCube.

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Recap

- In lecture 2, we saw more examples of theories of dark matter.
  - The UED WIMP serves to illustrate the case in which dark matter is a boson, either a vector (5d) or a scalar (6d).
  - Little Higgs theories with T-parity also have a vector WIMP, but one which prefers to couple to massive particles.
  - Both show big differences compared to a SUSY Majorana WIMP!
- Super-WIMPs are harder to search for, and may be a hint of a nonstandard thermal history.
- Designer dark matter tries to fit the dark matter to the observations, rather than the other way around.
  - Eventually, we can hope to assemble a designer theory of dark matter into a more fundamental theory with connections to deep questions.