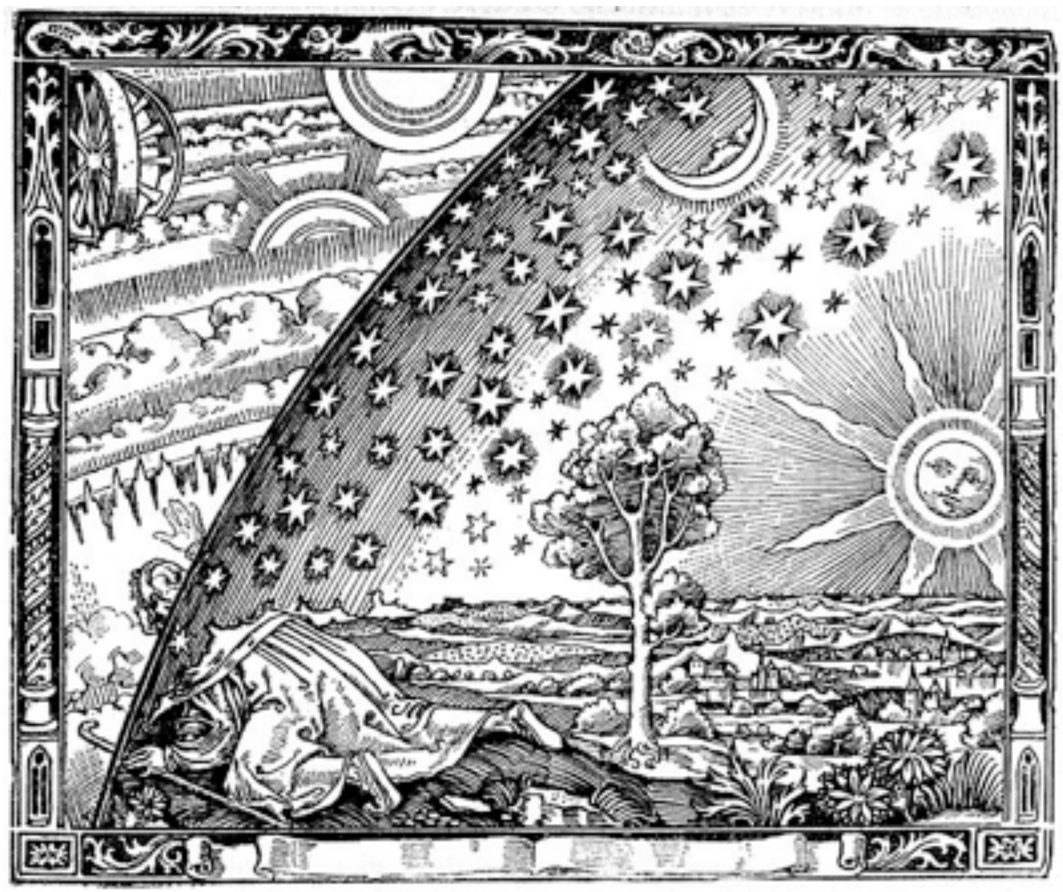
Research in Astrophysics & Cosmology at LAPTh

Camille Flammarion (Paris, 1888) "L'Atmosphere: Météorologie Populaire"



Un missionnaire du moyen âge raconte qu'il avait trouvé le point
où le ciel et la Terre se touchent...

Pasquale D. Serpico

Who we are

3 Enseignant-Chercheurs

Pascal Chardonnet

Pierre Salati

Richard Taillet

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Pascal Chardonnet

Pierre Salati

Richard Taillet

Guilhem Bernard

2 PhD students

Andrei Baranov

myself

Céline Boehm

Julien Lesgourgues

3 Chercheurs CNRS

What we are interested in

- Cosmic Rays, sources and propagation
(PS, RT, GB, PDS)

- **Indirect Dark Matter Searches, signals & backgrounds**
(PS,RT, PDS, CB)

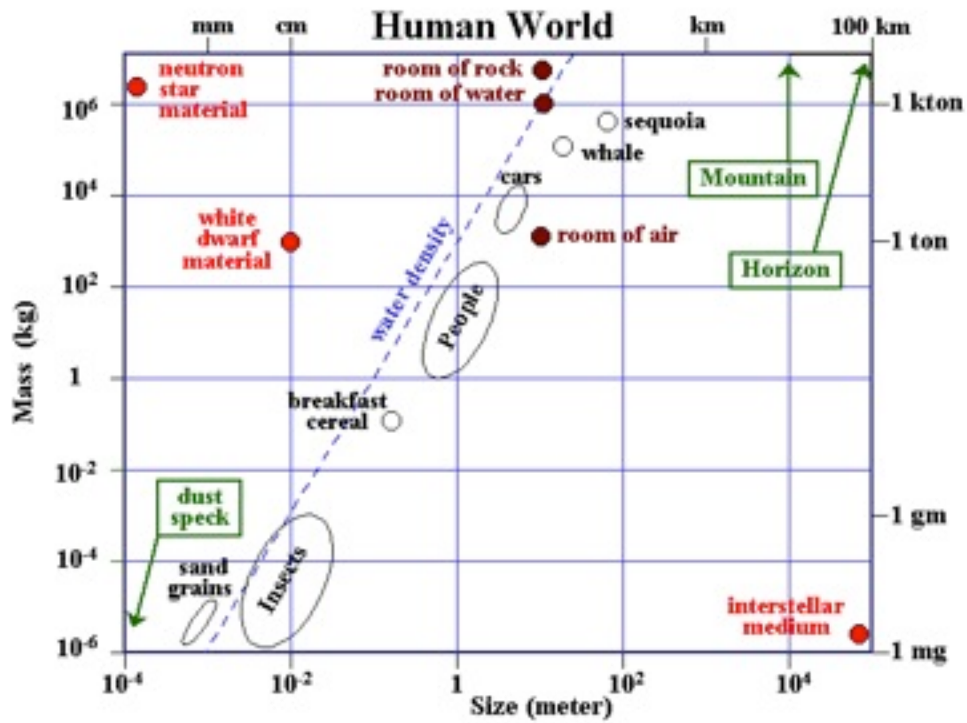
- GRB as a new mode of stellar collapse
(PC, AB)

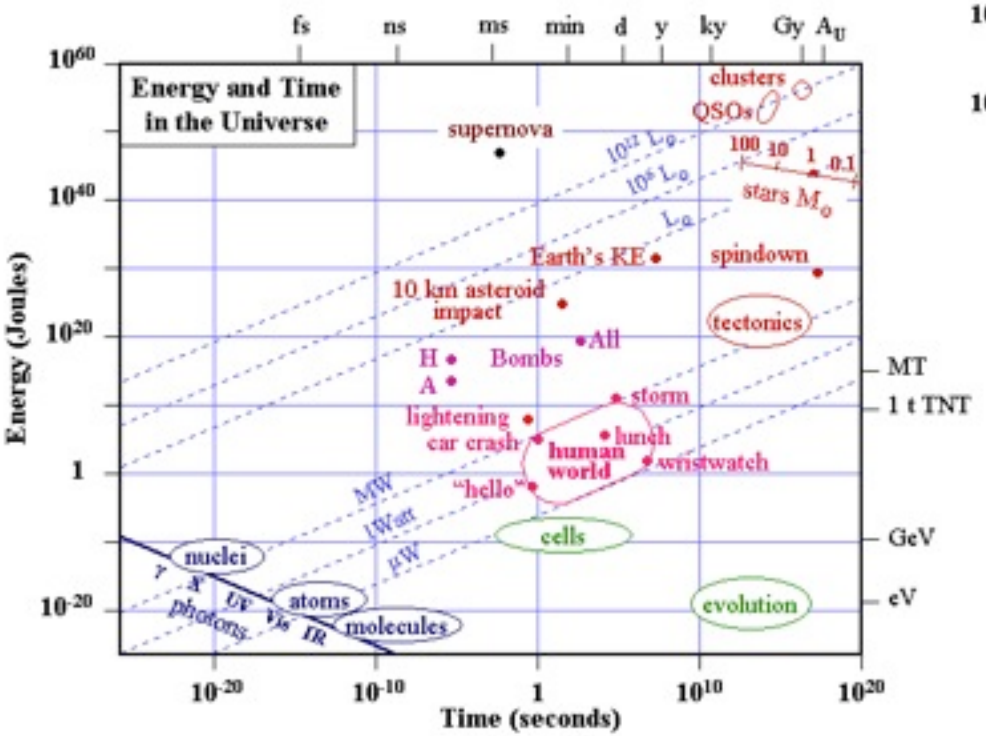
- Supernova Neutrinos, especially non-linear flavour evolution + phenomenology at giant detectors (PDS)

- **Cosmology**
(JL, CB, PDS, occasionally PS, RT)

Why we are interested in it?

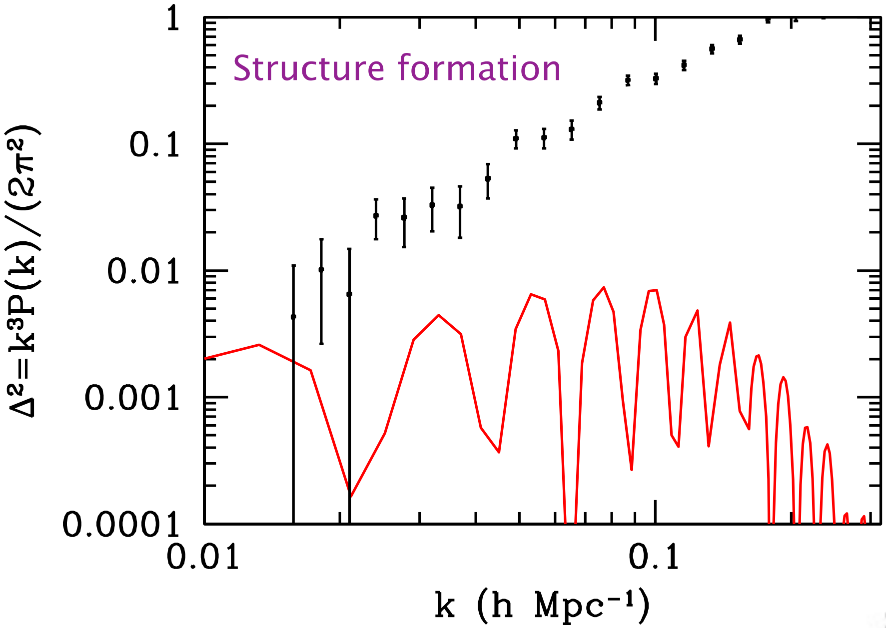
Astroparticles: using fundamental physics to understand astrophysical phenomena, one can test physics in environments whose features are too extreme (density, temperature, time or space scales...) to be reproduced in a lab (or because it's cheaper)



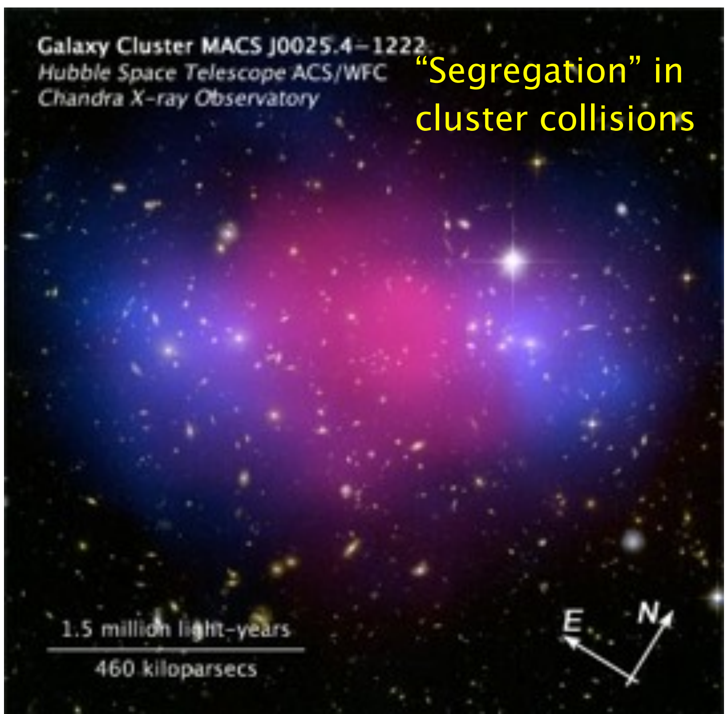


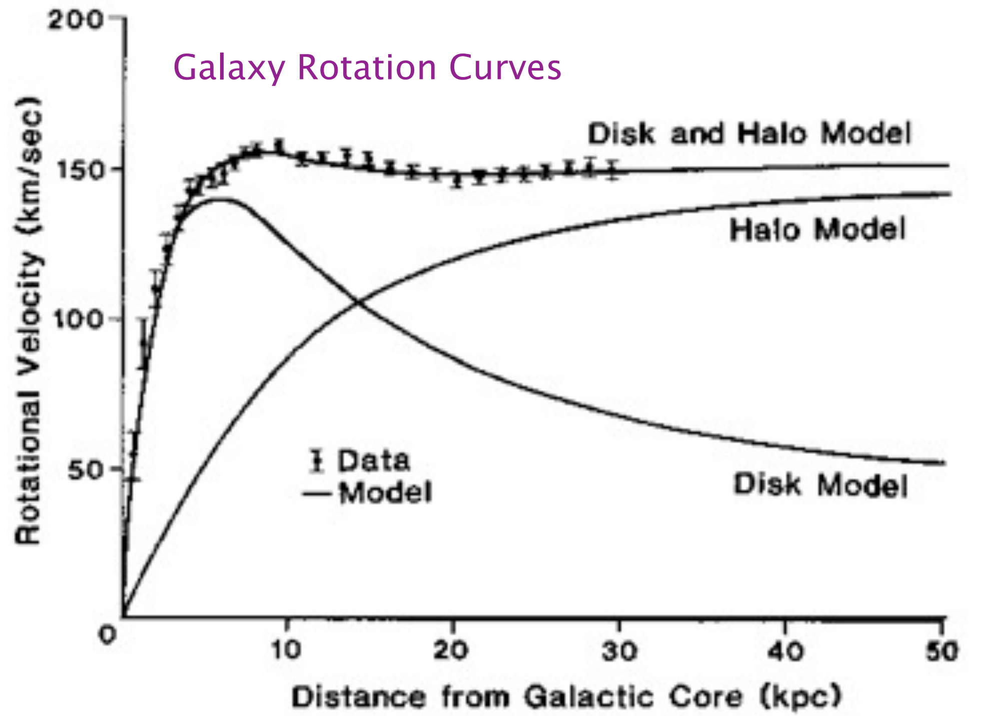
"Unusual" scales by many orders of magnitude... not crazy to think that some physical laws may break down and new phenomena could be discovered → connections with other research groups.

Example: DM detected on astronomical scales!



But gravity is "universal", does not permit particle identification: a discovery via other channels is needed to clarify the particle physics framework





One strategy: indirect DM detection

One looks for consequences of DM interactions elsewhere (not in the Lab!), such as decays, annihilations, energy transfer to baryons.

- ★ *It's a natural thing to do (DM is seen "elsewhere"!)*
- ★ *these features may imply an impact on cosmology or astrophysics.*
- ★ *It is an additional handle on properties one cannot probe otherwise in the Lab.*

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✓ **The presence of indirect signatures is by no means guaranteed (model-dependent)**

✓ **It needs not to be a GeV-TeV-scale signature, neither necessarily an annihilation one (notable example: ~ keV sterile neutrino X-ray decay line)**

✓ **There is no <u>astrophysical or cosmological</u> evidence whatsoever for the electroweak scale being the right one for explaining the DM problem.**

Most people bet on WIMPs (...but science≠democracy!)

Weakly Interacting Massive Particle "miracle" (?)

thermal relic with α_{ew} & $m_X \approx 0.01$– 1 TeV matches cosmological measurement, $\Omega_X \approx 0.25$

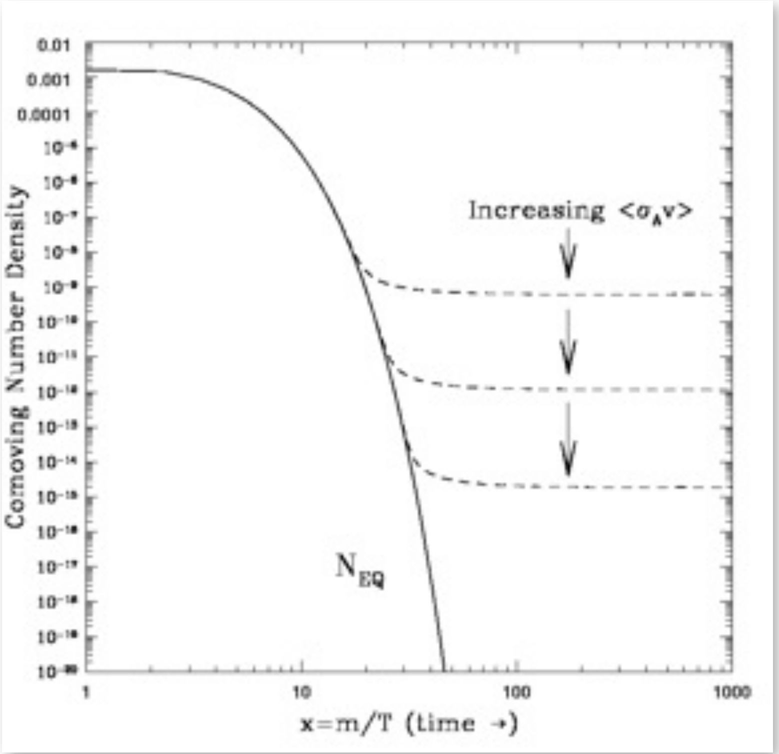
$$\Omega_{wimp} \sim 0.3/ <\sigma v>(pb)$$

EW scale BSM physics may be related to DM!

Stability↔Discrete Symmetry↔Pair produced@ Collider (SUSY R-parity, K-parity in ED, T-parity in Little Higgs)
Also would ease agreement with EW observables, Proton stability…

EW-scale candidates have a rich phenomenology

(more room for creativity/entertainment) more detection strategies via collider, direct, and indirect techniques



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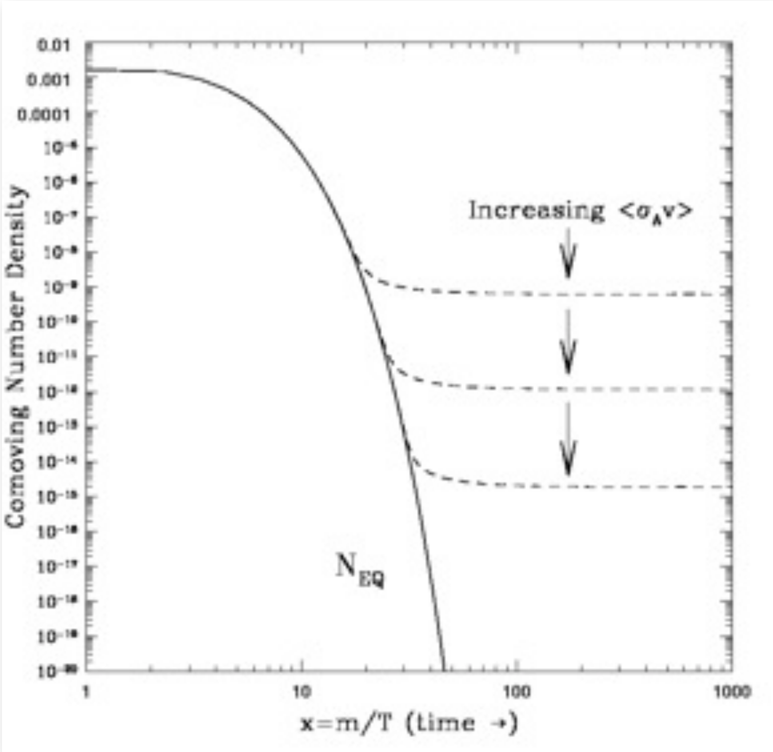

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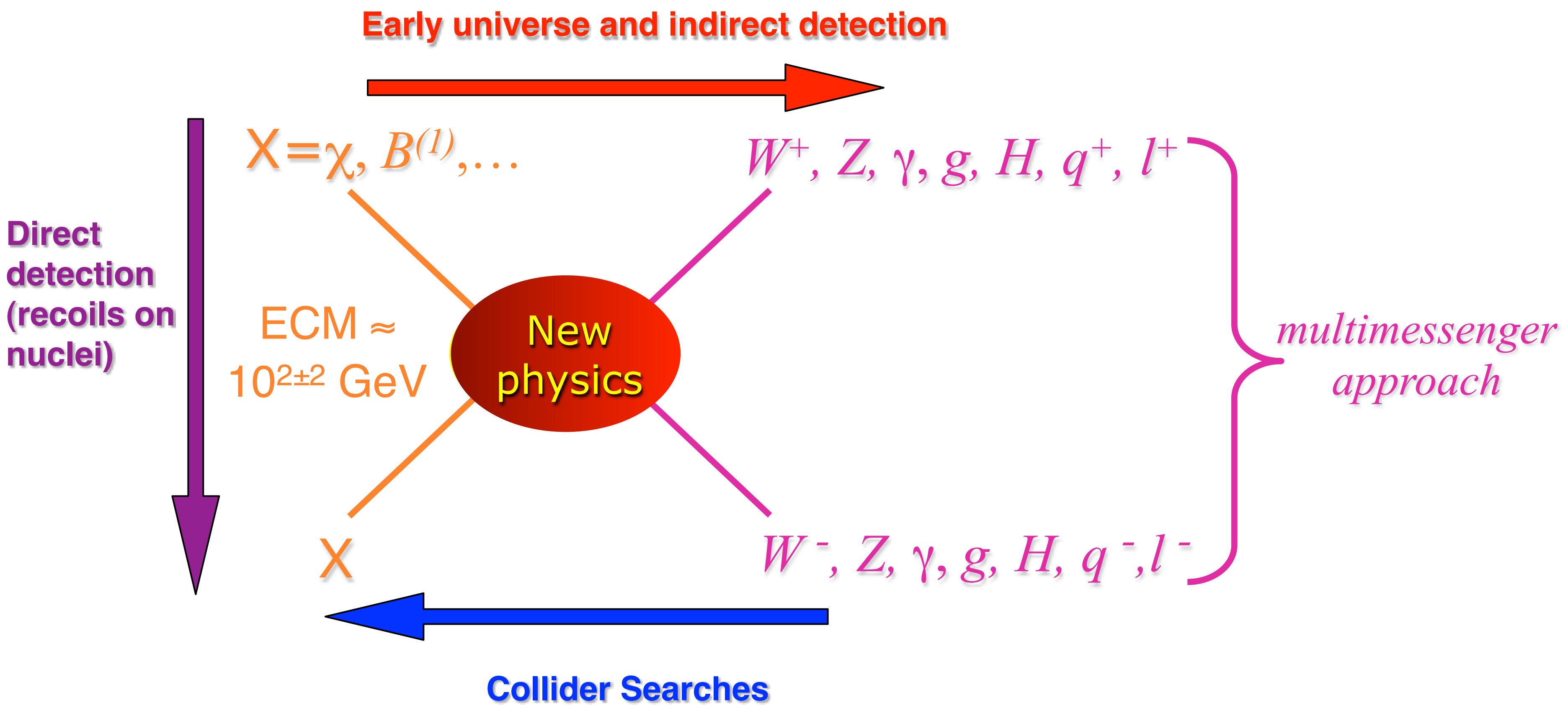
Warning: keep in mind other possibilities!
(Axions, SuperHeavy DM, SuperWIMPs, TIMPs, sterile neutrinos…)
They have peculiar signatures and require ad hoc searches

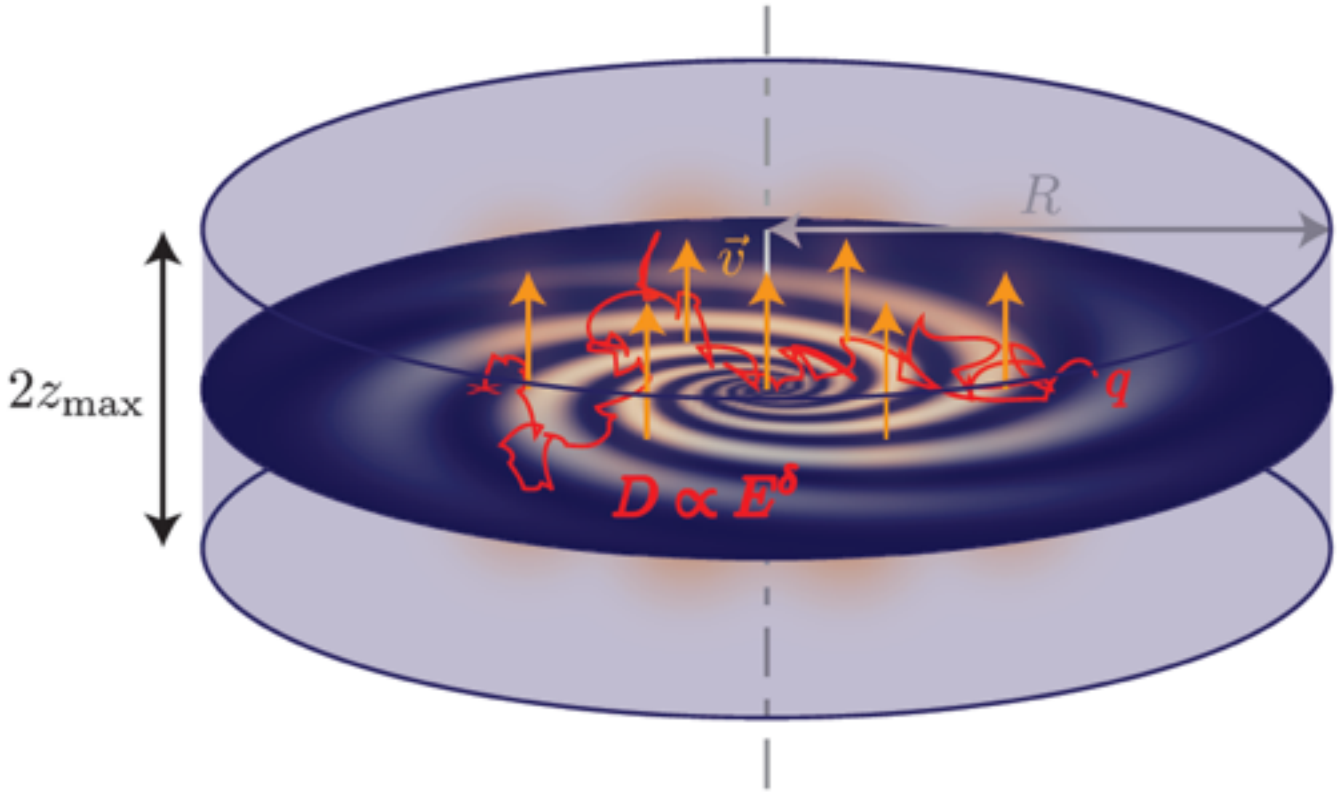
A benchmark diagram & the discovery program



- ✓ demonstrate that astrophysical DM is made of particles (locally, via DD; remotely, via ID)
- ✓ Possibly, create DM candidates in the controlled environments of accelerators
- ✓ Find a consistency between properties of the two classes of particles. Ideally, we would like to calculate abundance and DD/ID signatures → link with cosmology/test of production

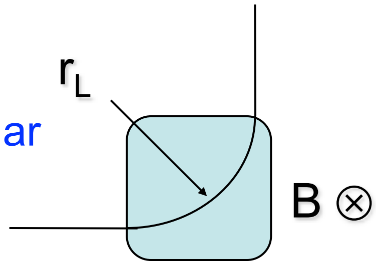
Energetic Charged Particles

Not only DM physics (sigma's, b.r.) and astrophysics (halo distribution) matter, but also plasma astrophysics (diffusion in the Galaxy)
Antimatter is preferred due to lower astro background



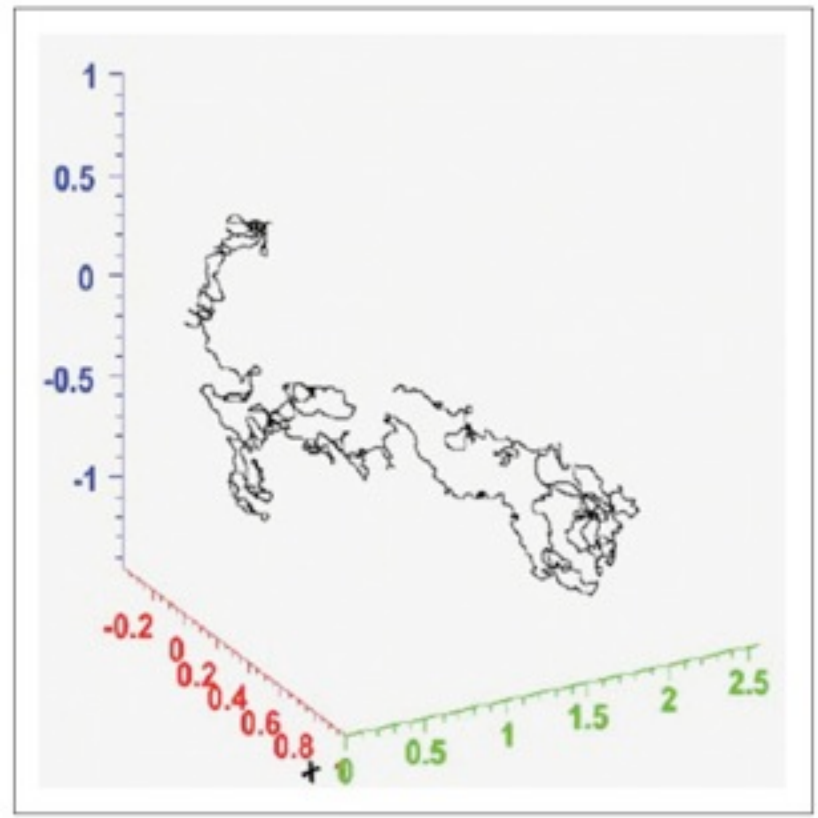
Cosmic Rays: a century long problem

Charged particles are deflected in the interstellar medium B-field



Main Problem

How to identify sources without **directionality**? (the basis of astronomy!) How to **disentangle source** properties **from** those of the **propagation** medium?



Note: Distance scales are in units of kpc.

FIGURE 2: A cosmic ray trajectory in a 1 μG turbulent magnetic field as might be found in our galaxy. This track is modelled by following a 10 PeV proton through Kolmogorov turbulence (equivalent to a conventional diffusion model). Super-diffusion models have occasional long straighter paths between major changes of direction.

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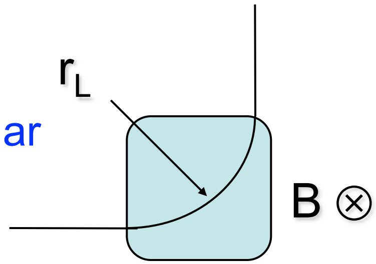

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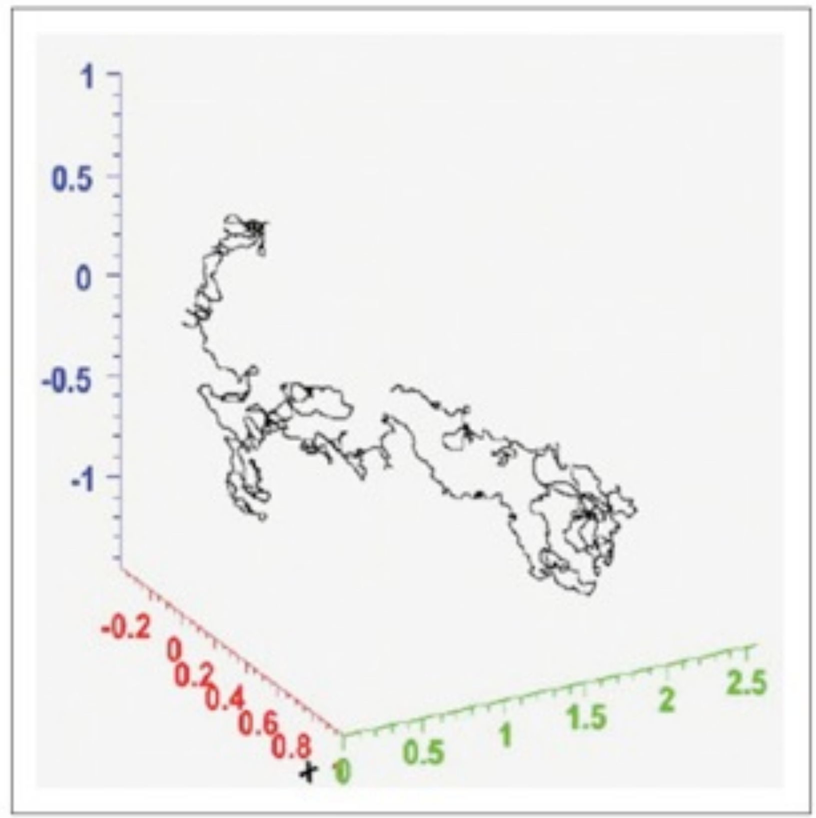
Different stategies possible: one can...

- compare observations with theoretical models for the production and propagation of CRs (AMS-02)
- try to identify sources thanks to photons (& ν's) emitted via CR interactions/energy losses in/around sources (HESS...CTA, Antares/Icecube)
- Go to sufficiently high energies... that CRs propagate almost in straight line (Energy domain of Auger?)



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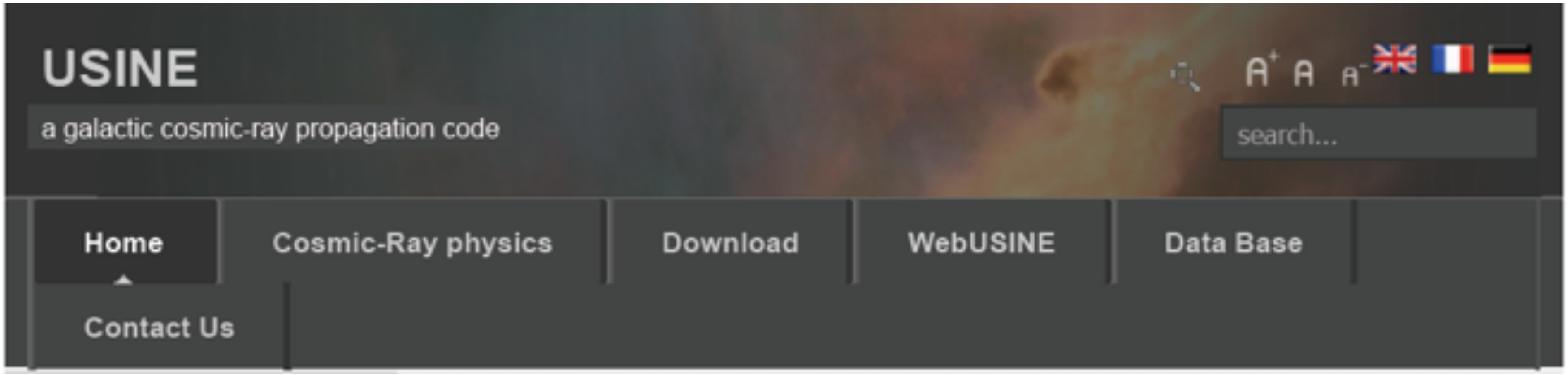
Activities in Cosmic Rays and Indirect DM detection

- Development and refinement of Numerical tools to interpret CR spectra.

  http://lpsc.in2p3.fr/usine/



- Compute uncertainties on the CR signals of DM and related astrophysical CR backgrounds.

- Improvement in the understanding of the physics of CR sources and CR propagation.

See e.g.

J. Lavalle and P. Salati, "Dark Matter Indirect Signatures," arXiv:1205.1004

PDS, "Astrophysical models for the origin of the positron 'excess'," arXiv:1108.4827

Some domains of expertise in cosmology

- **Big Bang Nucleosynthesis**
- **Phenomenology of cosmological models (e.g. CMB and LSS spectra computations)**
- **Data Analysis (... waiting for PLANCK)**
- **Particular expertise is in several aspects of neutrino cosmology, especially effects/consequences of neutrino mass**

See e.g. J. Lesgourgues and S. Pastor, "Massive neutrinos and cosmology," Phys. Rept. 429, 307 (2006)

Forthcoming:
A short introduction to neutrino cosmology

The Birth of cosmological ν's

T>> 1 MeV
Neutrinos in equilibrium

$$f_\nu(p,T) = f_{FD}(p,T) = \frac{1}{e^{p/T}+1} \qquad T_\nu = T_e = T_\gamma$$

Above ~MeV-scale temperatures, $e^{\pm}$ pairs can be created "Boltzmann unsuppressed". ν's are populated (& reach a thermal distribution) via reactions of the kind

$$\nu_a \nu_b \leftrightarrow \nu_a \nu_b$$
$$\nu_a \bar{\nu}_a \leftrightarrow \nu_b \bar{\nu}_b$$
$$\nu_a \bar{\nu}_a \leftrightarrow e^+ e^-$$
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$\nu_a \bar{\nu}_a \leftrightarrow e^+ e^-$

$\nu_a e^- \leftrightarrow \nu_a e^-$

They decouple from the plasma at T~O(1) MeV

Rate of weak processes

$$\Gamma_w \approx n\,\sigma\,c \approx g\,a^{-3}\,G_F^2 E^2 \approx g\,G_F^2 T^5$$

Hubble expansion rate

$$H \approx \sqrt{G_N \rho} \approx \sqrt{g\,G_N}\,T^2$$

$$\frac{\Gamma_w}{H} \approx \left(\frac{T}{\mathrm{MeV}}\right)^3$$

After this epoch (~O(1) s after Big Bang) ν's evolve only due to gravity

"Detection" of the CνB

- Pseudo-thermal distribution: T_ν = 1.95 K
- Number density ($\nu + \bar{\nu}$): 112 cm^{-3}/flavour
- Mean kinetic energy: << meV

lower than 2.7 K of CMB due to later
$e^+ e^- \to \gamma\,\gamma$
(heating of photons)

Direct searches hopeless?

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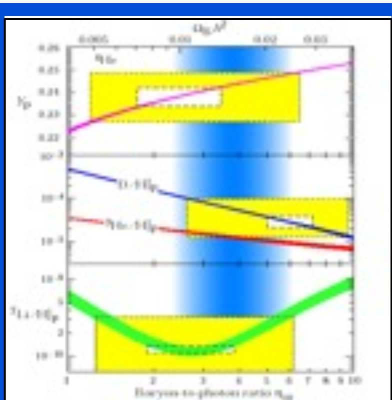
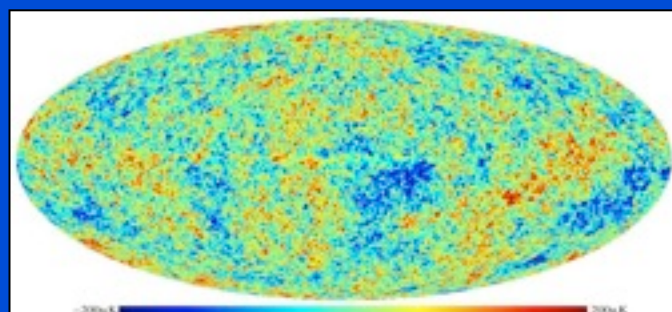
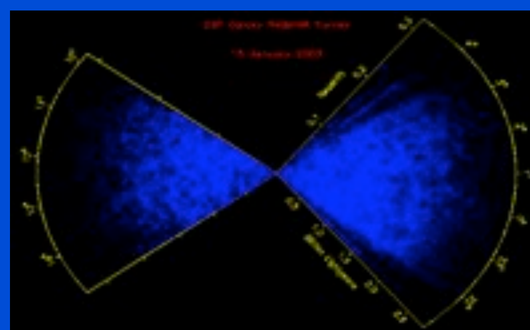
Indirect searches: Cosmological observables







BBN	CMB	LSS
T ~ MeV	T ~ eV	
ν_e vs. $\nu_{\mu,\tau}$ N_{eff}	Gravity only (no flavor discr.)	N_{eff} & m_{ν}

Neutrinos & BBN: How do ν's enter the game?

Hubble Expansion Law

Gravity only, mostly integral quantity, extra relativistic species

$$H=\frac{\dot{a}}{a}=\left(\frac{8\pi G_N}{3}\right)^{1/2}(\rho_\gamma+\rho_e+\rho_b+\rho_\nu+\rho_X)^{1/2}$$

$$\rho_\nu+\rho_X \rightarrow \frac{7}{8}\,\frac{4^{1/3}}{11^{1/3}}\,N_{eff}\,\rho_\gamma$$

$N_{eff}=3$
(SM only & instantaneous decoupling)

For a review, see e.g. F. Iocco et al.
"Primordial Nucleosynthesis: from Precision Cosmology to fundamental physics"
Phys. Rept. 472, 1 (2009) [arXiv:0809.0631]

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Weak Rates: p↔n equilibrium

Very sensitive to weak interactions (only e-flavour matters), energy spectrum.

$$\nu_e + n \leftrightarrow e^- + p$$

$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

$$\bar{\nu}_e + e^- + p \leftrightarrow n$$

Final n/p (& hence ^{4}He, where most neutrons are ultimately locked) depends on "when" $\Gamma_w=H$

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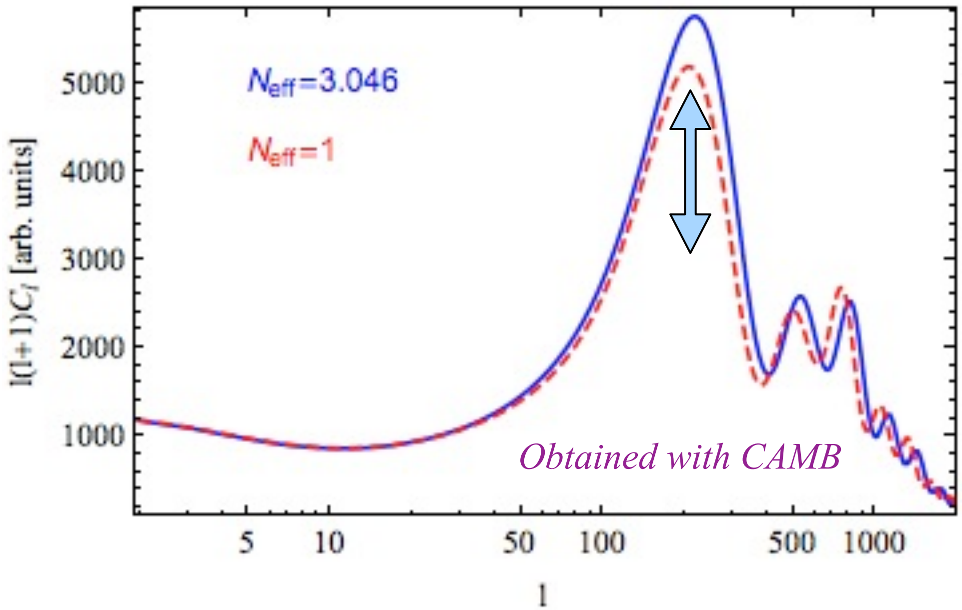
Neutrinos & CMB

For eV scale neutrinos, both m_ν and N_{eff} *mostly* affect the time of matter-radiation equality. All the rest fixed:

- Raising N_{eff} means more radiation, hence delayed equality.
- Lowering m_ν means that part of the total that we call now (dark) matter was behaving as ~radiation at CMB formation, hence delayed equality.

correlation expected!

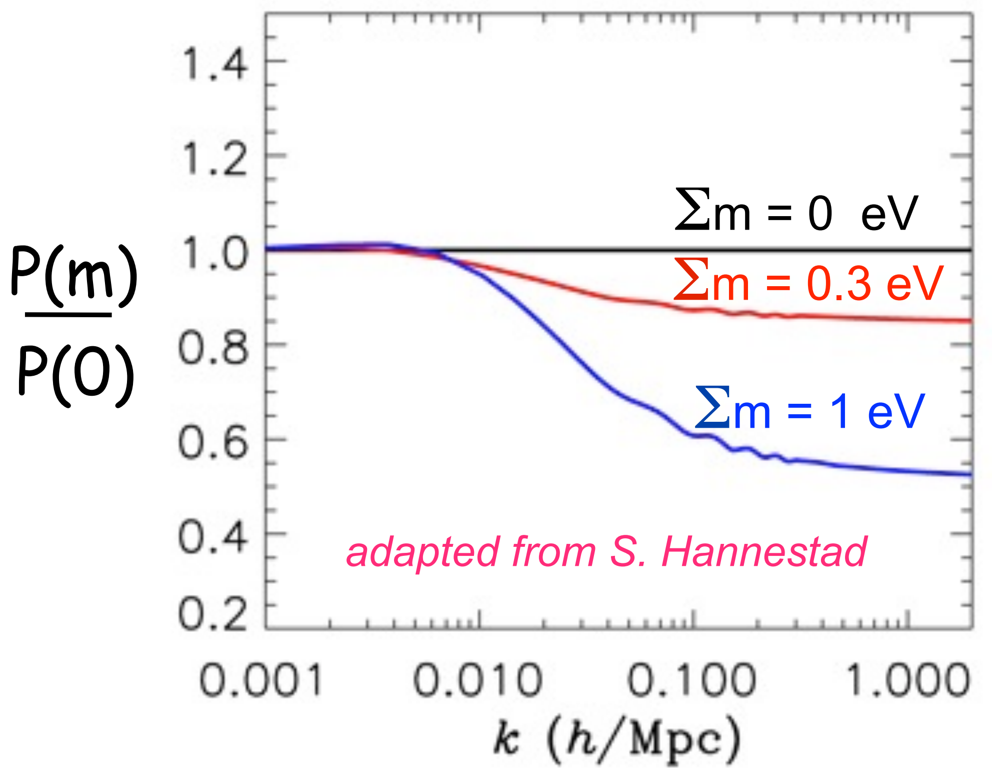


$$1 + z_{eq} = \frac{\Omega_m}{\Omega_r} \simeq \frac{\Omega_m}{\Omega_\gamma} \frac{1}{1+0.23\, N_{eff}}$$

Suppression of power-spectrum due to m_ν

Unitl non-relativistic, ν's do not contribute to gravitational clustering below the free-streaming scale, but they do contribute to the homogeneous expansion. This "unbalance" introduces a peculiar spectral suppression. In linear theory one finds

$$\frac{\Delta P}{P} \approx -8\, \frac{\Omega_\nu}{\Omega_m} \approx -0.8\, \frac{\Sigma m_i}{1\text{ eV}}\, \frac{0.1}{\Omega_m h^2} \qquad @\ k > k_{NR} \approx 0.015\, (\Sigma m_{eV} \times \Omega_m h^2)^{1/2}\ \text{Mpc}^{-1}$$



This is the key effect used to derive bounds on massive neutrinos from LSS

Cosmological constraints on Σm_i – LSS & others

At present, when combining LSS, CMB & other cosmological data, one obtains typical 95% CL bounds $\Sigma m_\nu < 0.4\text{-}0.5$ eV

e.g.: Hannestad et al. arXiv:1004.0695

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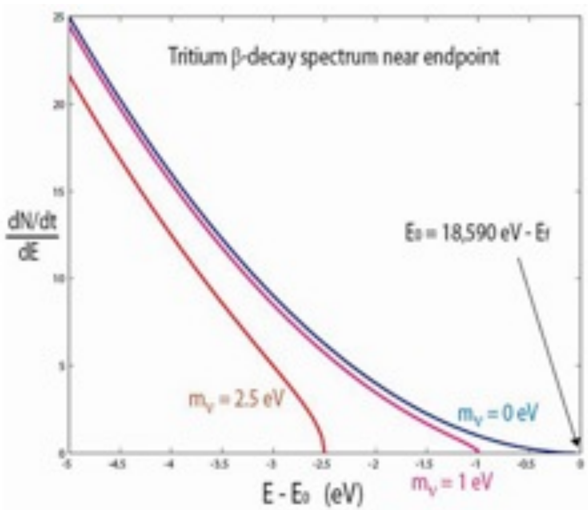
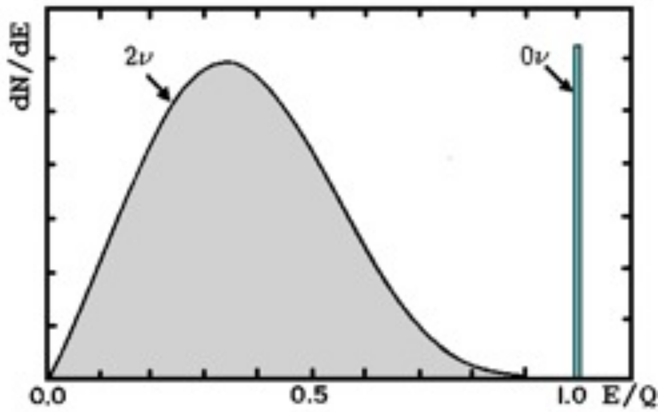


It is worth noting the complementarity with other techiques for direct mass measurements



Cosmology	$\sim \sum_i m_i$	$< 0.2\text{-}1.0$ eV
Tritium β-decay	$\left(\sum_i \lvert U_{ei}\rvert^2 m_i^2\right)^{1/2}$	< 2.3 eV
0νββ (majorana)	$\left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	$< 0.3\text{-}1.2$ eV

Depends on cosmological model

Most model-independ, weakest (now)

Requires L-violation

Forecast on future reach on N_{eff}...

It is very difficult to make accurate predictions, especially about the future (Niels Bohr)

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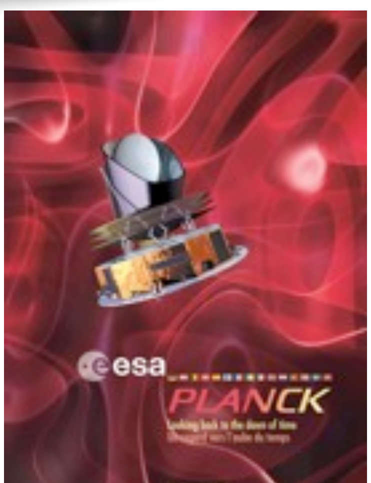
PLANCK CMB mission

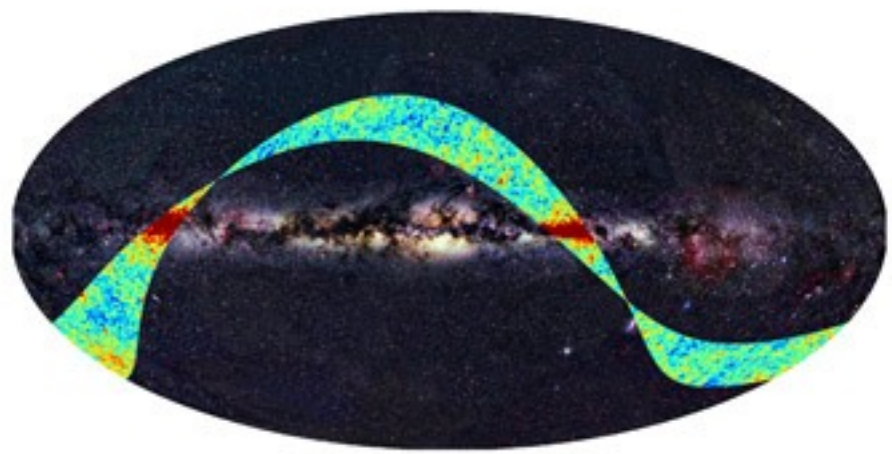
Sensitivity ΔN_{eff}~0.05-0.1

Realistically (including degeneracies) ΔN_{eff}~0.2

Lopez et al. PRL 82 3952 '99
Bowen et al., MNRAS 334 '02
Bashinsky & Seljak, PRD 69 '04
Hamann et al JCAP 07 (2010) 022

In 2013 we should know if there is any other major (>10%) component of light degrees of freedom (like axions, gravitinos, ν_R) in the "cosmic soup"





...and Σm_ν

	Planck	P+BAO	P+HPS	P+HST	P+HST+BAO	P+HST+HPS
ω_{dm}	0.22	0.24	0.20	0.21	0.21	0.19
N_{eff}	0.21	0.21	0.22	0.21	0.21	0.22
$\sum m_\nu$	0.68	0.81	0.44	0.67	0.73	0.44
w	2.14	1.16	0.72	0.74	0.76	0.55
n_S	0.46	0.48	0.49	0.46	0.48	0.48

Hamann et al JCAP 07 (2010) 022

Very likely, extra states would leave their imprints also due to their mass, if heavier that ~0.4 eV...
In addition with future surveys, this number is going to improve even more!

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ω_{dm}	0.22	0.24	0.20	0.21	0.21	0.19
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Mission/Method	Σm_i (eV)	$\sigma(\Sigma m_i)$ (eV)	Ref.
PLANCK + Weak Lensing surveys	0.07	0.04	Hannestad et al. '06
Inflation Probe with Lensing	0.00-0.05	0.035	Lesgourgues et al. '06
Galaxy Cluster surveys+other	0.00-0.05	~ 0.034	Wang '05
CMBpol, Lensing, Cosmic Shear	~ 0.05	~ 0.013	Song & Knox '04
CMB, SKA	~ 0.05	~ 0.015	Abdalla & Rawlings '07

Summary

- At LAPTh, there is a healthy program of research in theoretical astroparticle physics/cosmology, with a young and varied group of people.

- Main topics of interest are phenomenological, directly linked with the interpretation of the recent wealth of data accessible in this field (WMAP, PAMELA, Fermi, X-rays, etc.)

- Work is both in theoretical models and in contributing to open access software for a larger community (USINE, CLASS, PARTHENOPE, contributions to MicrOMEGAs...)

- Frequent interactions with particle physicists (especially in the realm of dark matter search strategies)

- Good connections with experimental/observational groups (AMS-02, HESS, PLANCK...) occasionally leading to joint projects (e.g. within ANR projects) and/or explicit participation to design of future instruments (e.g. EUCLID).