Indirect dark matter searches with neutrinos telescopes

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Laboratoire d'Astrophysique de Marseille

GDR Neutrinos

LPSC Grenoble

6-7th June 2016

Cold Dark Matter

Evidences

- *Cosmological scale :*

  CMB peaks

  structure formation

  (challenging for MOND whithout aditionnal fields)

  Galaxies form inside CDM halos

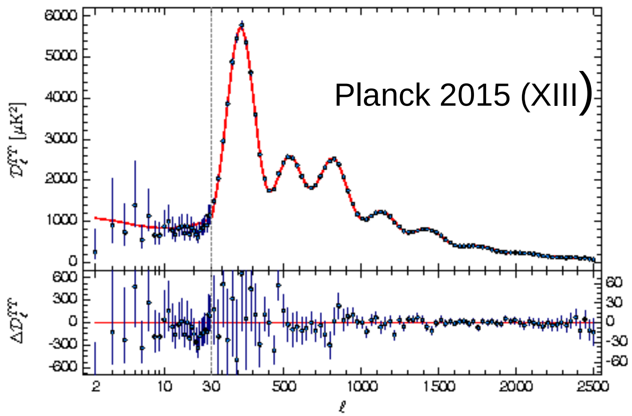
- *Galaxy cluster scale:*

  gravitational lensing

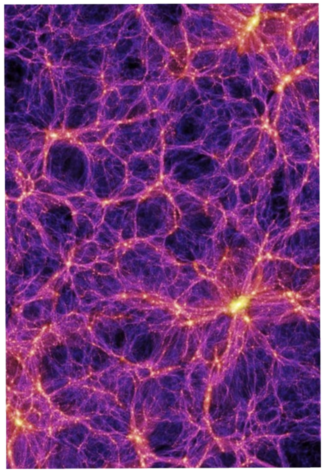
- *(sub)Galactic scales :*

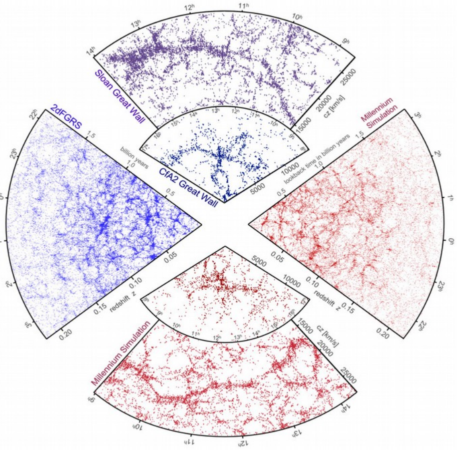
  Rotation curves of galaxies

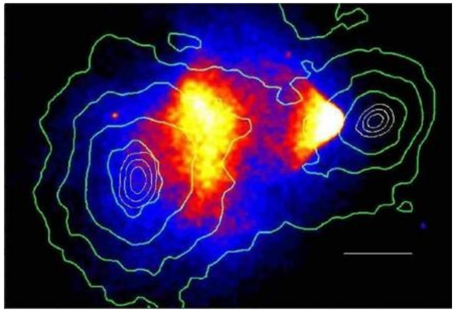
  Stellar dynamics in Dwarf spheroidal galaxies



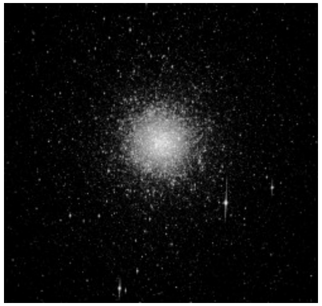
Millenium



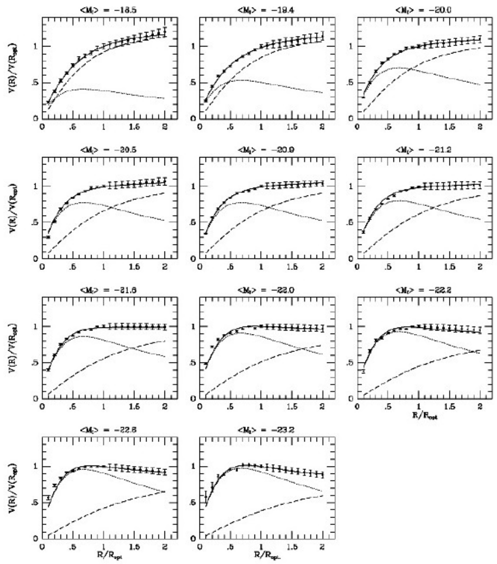




Clowe+ 06



Sagitarius Dsph



Salucci+ 2010

Theory + observations :
only gravitationnal evidences

Cold Dark Matter

How cold ?

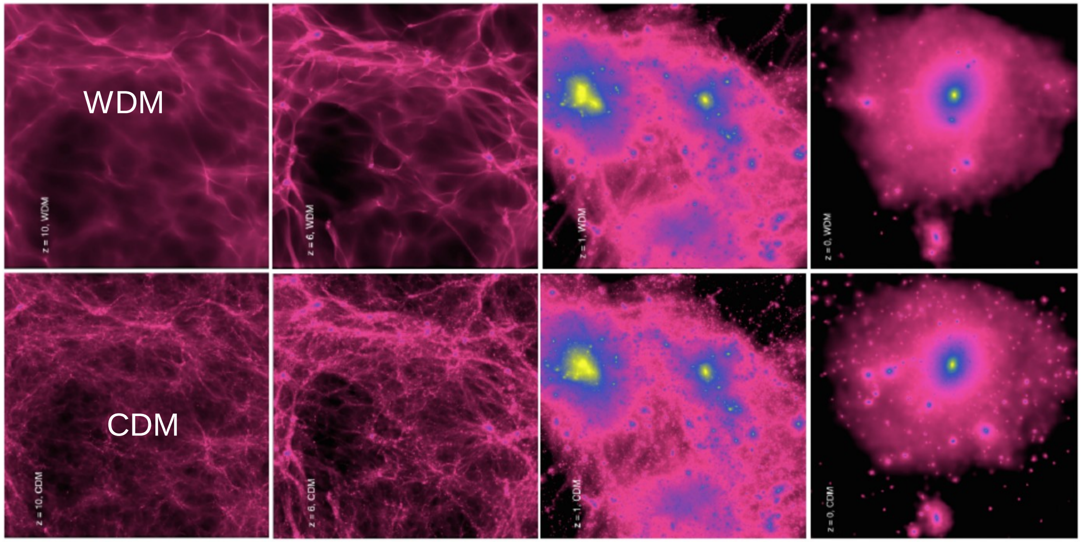
- Enough to form Dwarf galaxies.

  Tremaine & Gunn 79, Boyarsky+ 06: m > 1 keV

- consistency with Lyman-alpha forest.

  Boyarsky+ 08 => m > 5 keV (thermal)

- CDM and WDM allowed but WDM nearly cold



Bose+ 2016

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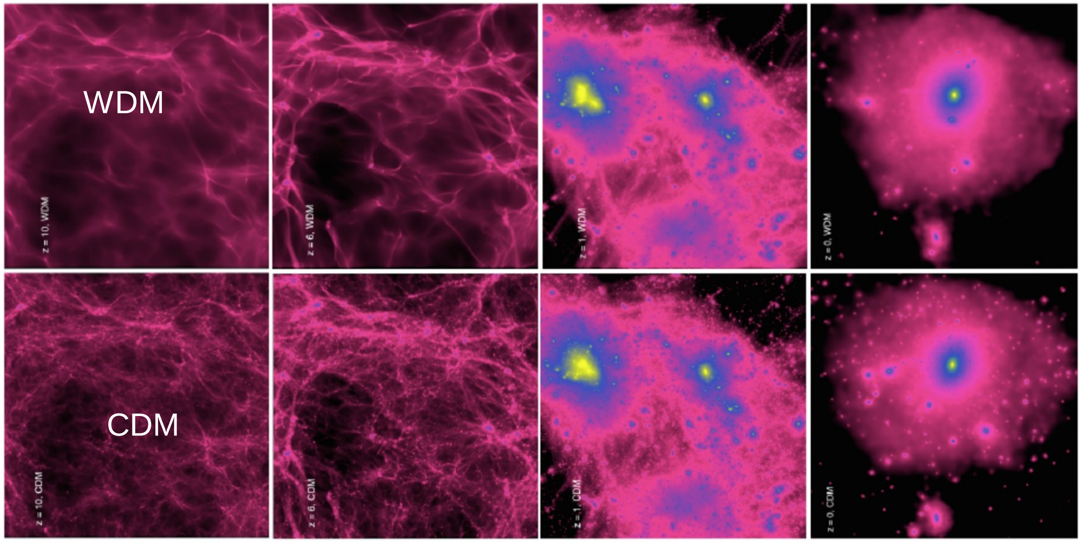

Bose+ 2016

Issues :

- *Small scales.*

  Too big to fail problem/missing satellites

Solutions ?

** Baryonic physics (in progress … see e.g Zolotov+2012, Savala + 1412.2748 but Pawlowski, Famaey+ APJ 2015, Pace 1605.05326*

** SIDM*

- *Core/cusp problem*

  Galaxies RC prefer DM cores

  DM only simulations prefer cusps (NFW profile)

  (but see Pineda+ 1602.07690)

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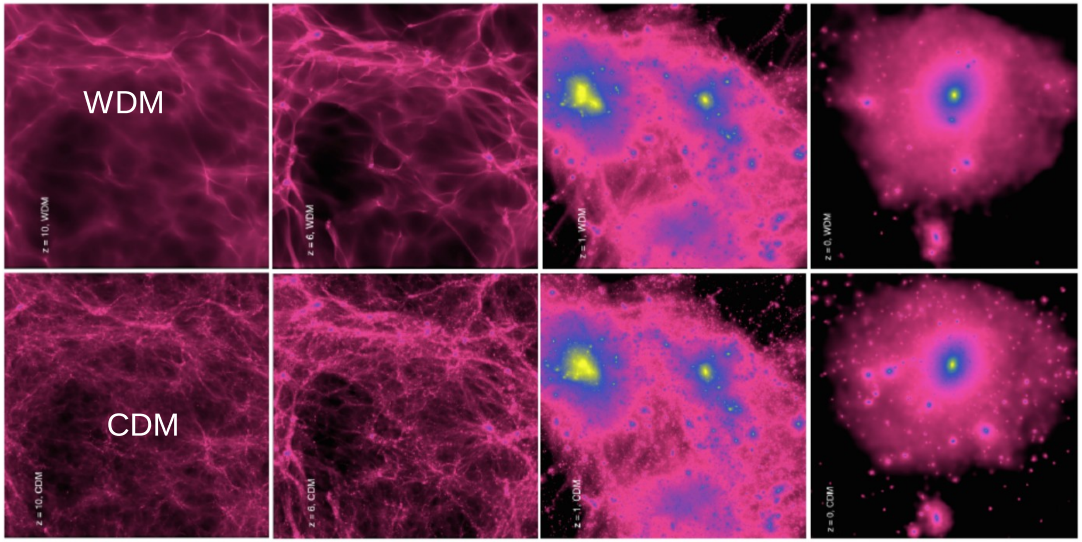

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  (but see Pineda+ 1602.07690)

- ***Detection !** **(only gravitationnal evidences so far)** **…** **Discovering the nature of DM, Identifying the particle ?***

Candidates

Standard model is not enough :

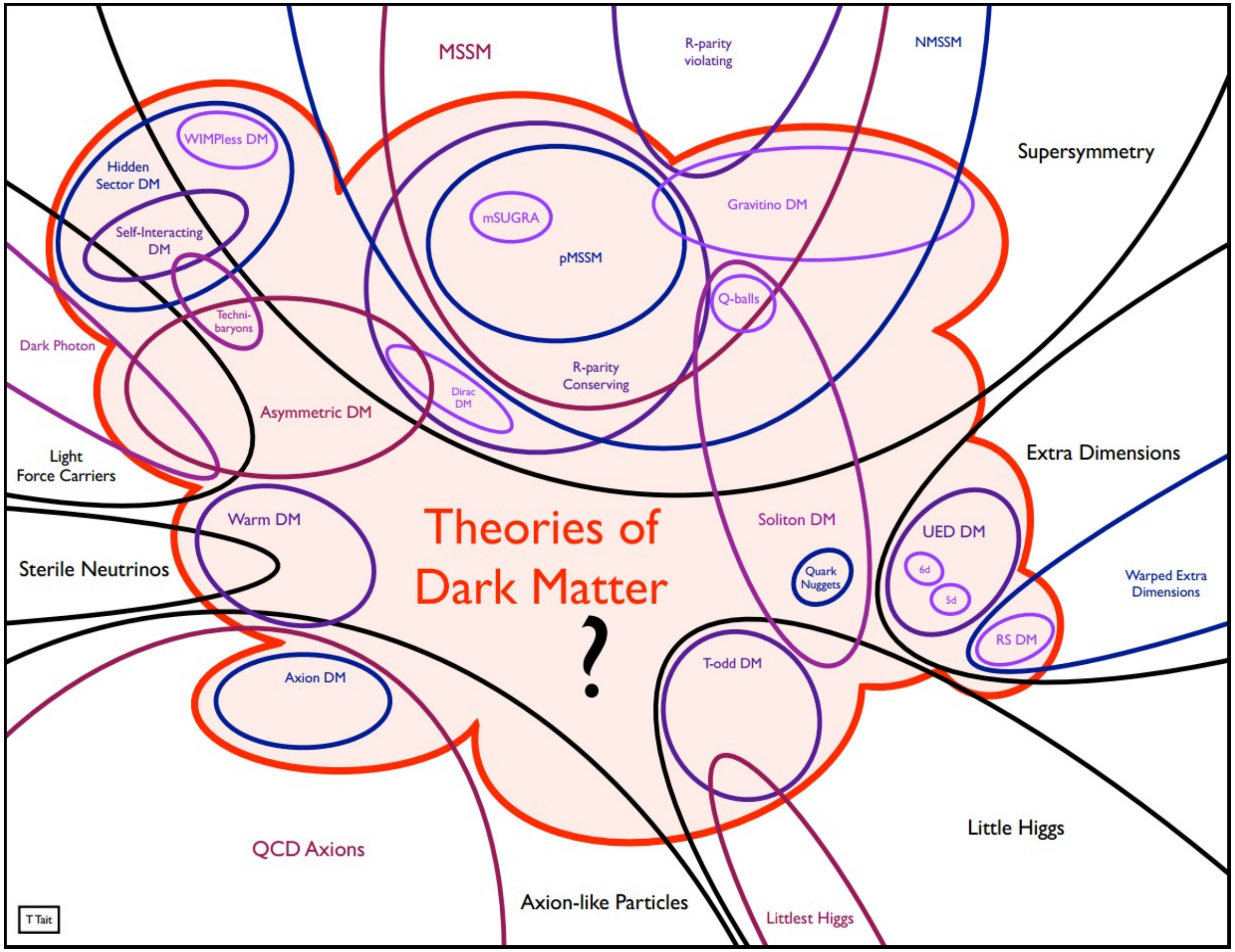
Issues:
- Hierarchy problem (EW scale vs GUT or Planck scale)
- Forces unification
- Neutrino masses (⇐ oscillations)
- matter-antimatter asymmetry of the universe

Some scenarios:
- SUSY (Supersymmetry)
- Xtra dimensions ⇐ *String Th, GUT ...*
- Extended scalar sector
- Extended gauge group
- Axions like particles

Standard model extensions provide new fields and particles,

→ *dark matter candidates*

Candidates



Courtesy Tim Tait

- *Sterile neutrinos*

  e.g Dodelson & Widrow 94, Shaposhnikov+06

- *ALPs-WISPs*

Hidden/Dark photons

Axions : *from QCD since 70th*
Peccei-Quinn, Wilczek, Weinberg, Zakharov, Dine, Sikivie …
μeV-meV mass range, ultra cold, non thermal

- ***WIMPs:***

Weakly Interacting Massive Particles

Wimp miracle :
annihilation
thermal freeze-out scenario : $\Omega_{WIMP} \sim \Omega_{DM}$
~ GeV - 100 TeV mass

Appealing for detection

- *SIDM ...*

Dark matter indirect detection with neutrino telescopes

TARGETS :

Dark matter can accumulate in cosmic storage rings
Decay of dark matter annihilation products generate neutrino fluxes

$$DM\ DM \xrightarrow{ann} W, Z, b, t, \mu, \tau ... \xrightarrow{decay} \nu, \gamma, e^+, \overline{p}...$$

Galactic center, Halo, Dsphs, Clusters, Sun, Earth, Nearby galaxies …

BACKGROUND

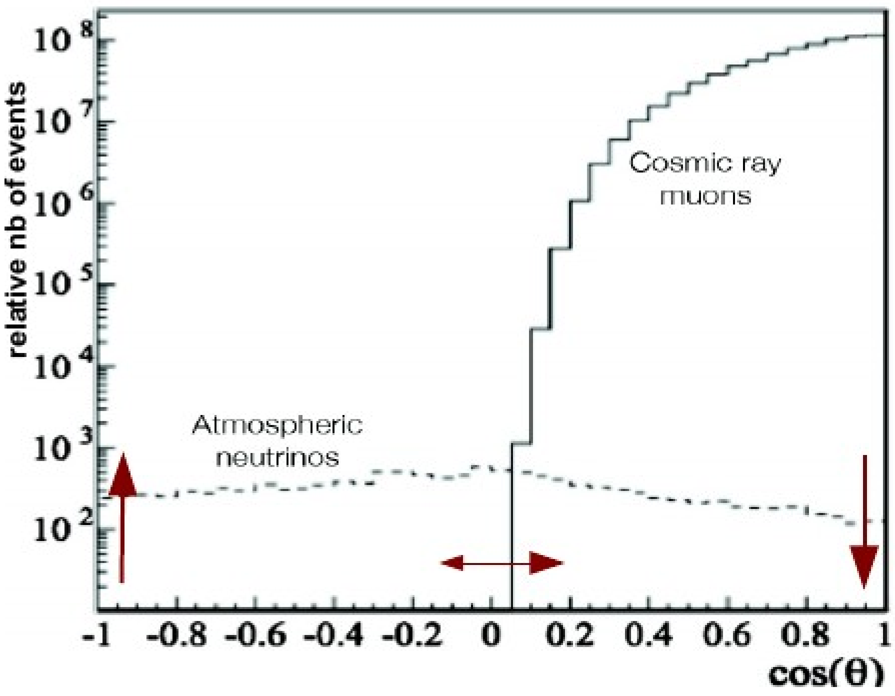
Atmospheric muons: select only upgoing
(or starting track in the detector)

Atmospheric neutrinos: irreductible

$$p(\text{cosmic}) + X(\text{atmospher}) \rightarrow \pi^+ + Y$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

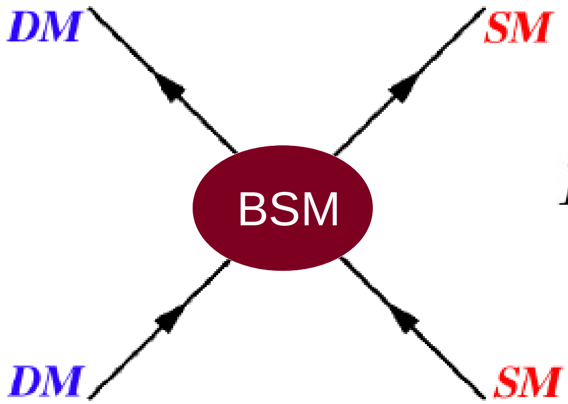
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$



Neutrino fluxes from dark matter annihilation/decay

GC, MW Halo, Dsphs, Clusters …

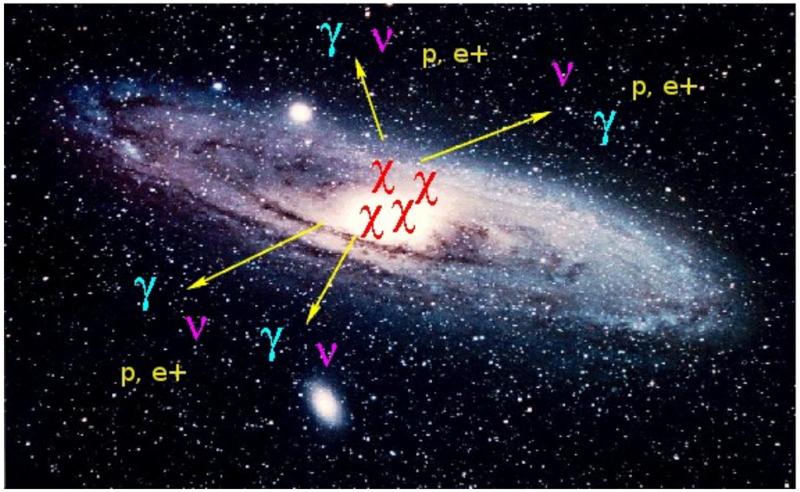
indirect detection (now)



$$\frac{d\phi_\nu^{ann.}}{dE} = \frac{\delta}{4\pi}\frac{\langle\sigma v\rangle}{m_{DM}^2}\frac{dN_\nu}{dE}\int_{res.} d\Omega \int_{l.o.s} \rho_{DM}^2(r)dl$$

Decay of dark matter annihilation products

$$DM\ DM \xrightarrow{ann} W, Z, b, t, \mu, \tau ... \xrightarrow{decay} \nu, \gamma, e^+, \overline{p} ...$$



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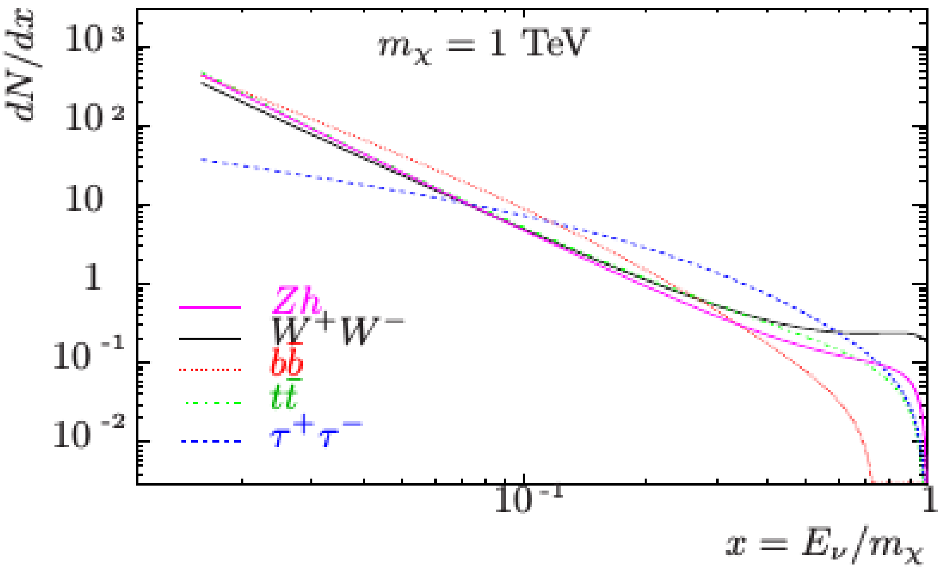
Particle physics

Annihilation cross section
Dark matter mass
Annihilation induced spectra

Any BSM extension (SUSY, Xtra dim ...) with WIMP candidate



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Observations (RC of spirals, lensing, Kinematics in Dsphs, Lensing in clusters …)

Jeans equation

MW Mass models

Semi-analytic models

Cosmological simulations

Astrophysics:

Dark matter distribution in the halo

See e.g
Famaey 1501.01788
Mac Millan 2011
Lavalle+ 08
Pieri+2011
Berezinsky+2015
CLUMPY package (Halo, GC, Clusters, Dsphs ...)J factors, neutrino and gamma fluxes)
Nezri+2012,Bonnivard+ 2016

Neutrino fluxes from dark matter annihilation/decay

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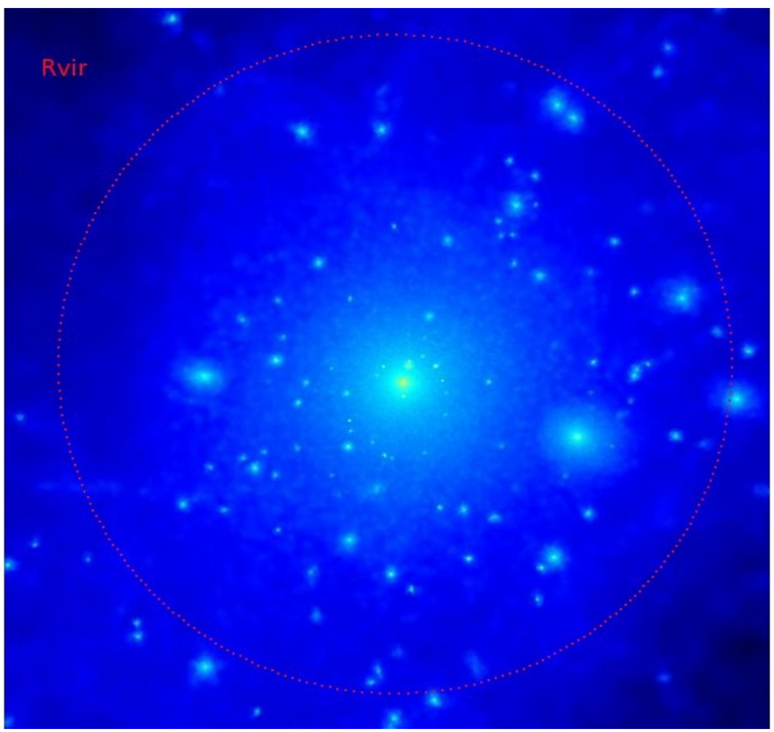

Horizon,Aquarius,Via Lactea,Ghalos
Fire, Eagles,Apostle ...

Astrophysics:

Dark matter distribution in the halo

Clumps
Mas spectrum
Concentration
Spatial distribution

$$\frac{dN_{cl}}{dM} \propto \left(\frac{M}{M_H}\right)^n \quad n \sim -1.8-2$$

Density profile
Cusp/core
Baryons ?
Compression ? Blumental+ 1986

$$M_i(r_i)r_i = [M_b(r_f) + M_{DM}(r_f)]r_f$$

Stellar formation/SN feedback ?
DM halo driven by the history of assembly of baryons. Flattening ?
Pedrosa+09 Pontzen+2012 Governato+2012 ...

Neutrino fluxes from dark matter annihilation/decay

GC, MW Halo, Dsphs, Clusters …

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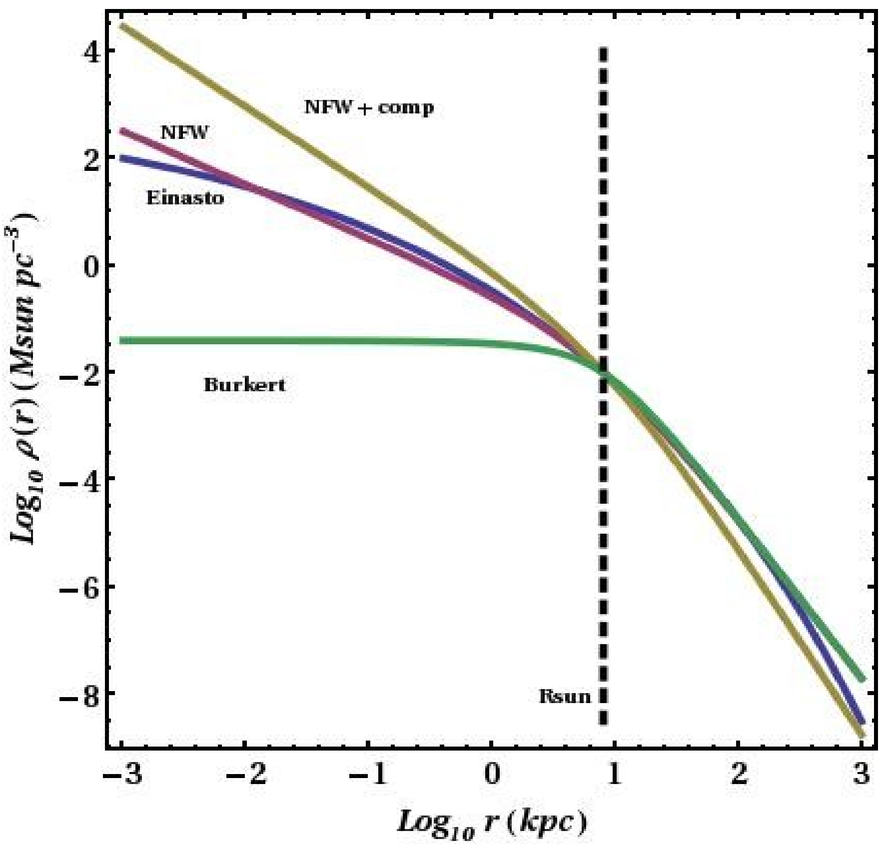

Einasto $\rho_{DM}(r) = \rho_{-2} e^{-\frac{2}{\alpha}[(r/r_{-2})^\alpha - 1]}$

Astrophysics:

Dark matter distribution in the halo

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$$\rho_{DM}(r) = \frac{\rho_s}{(r/r_s)^\gamma[1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

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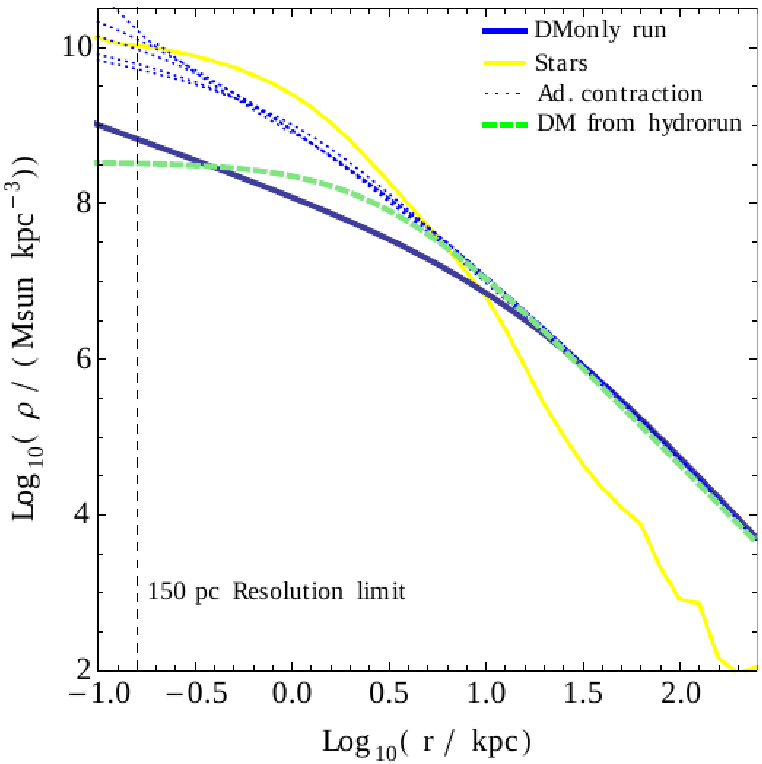

Mollitor,EN,Teyssier 1405.4318
Contraction + flattening

Similar features in
Calore+ 1509.02164
Schaller+ 1509.02166

Astrophysics:

Dark matter distribution in the halo

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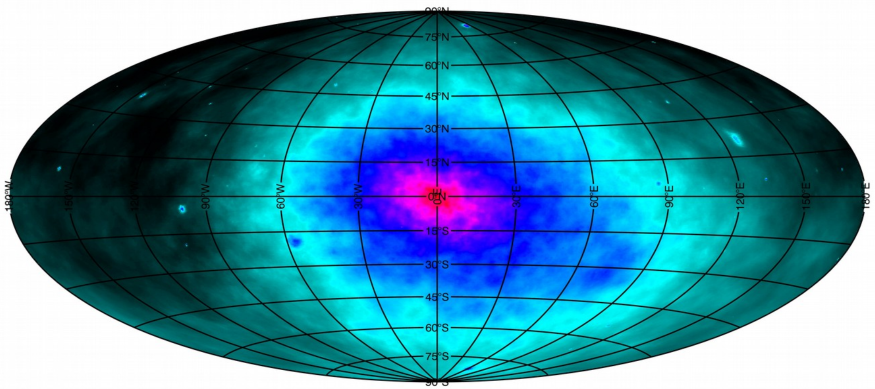
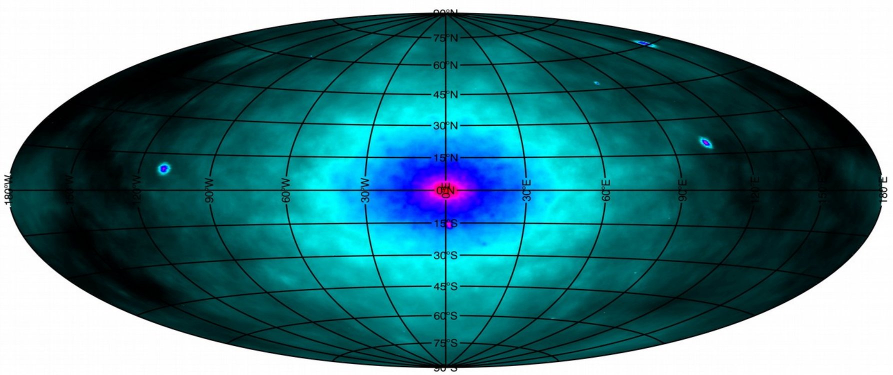
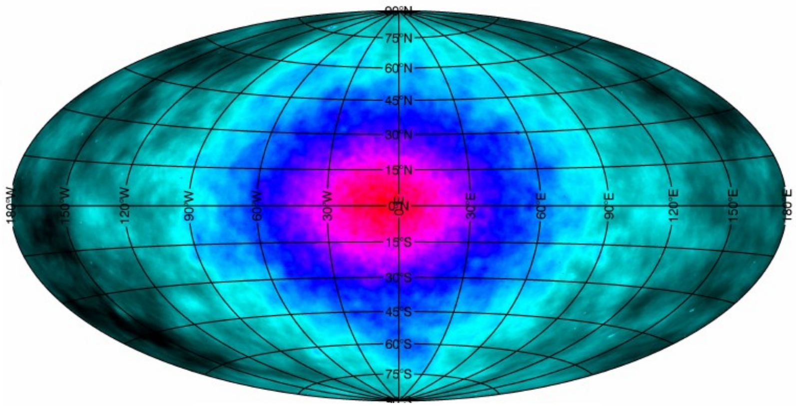
Astrophysics contribution (J factor)



DM only ~ NFW *+EN+ 2009*



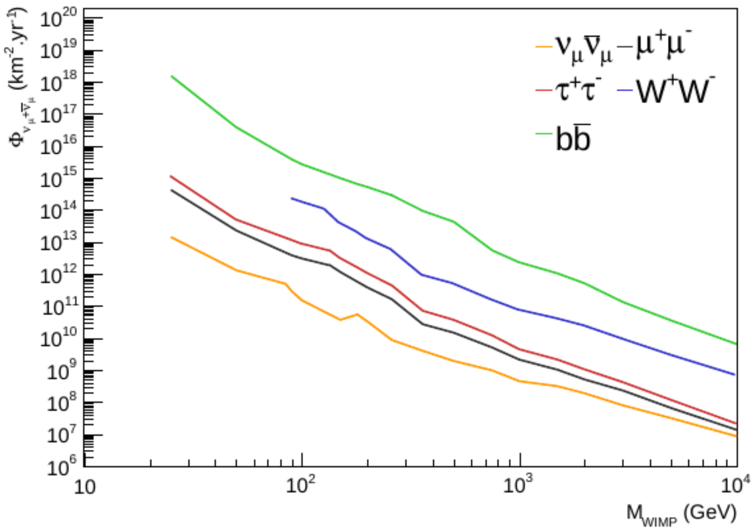
Hydro : contraction *EN+ 2012*

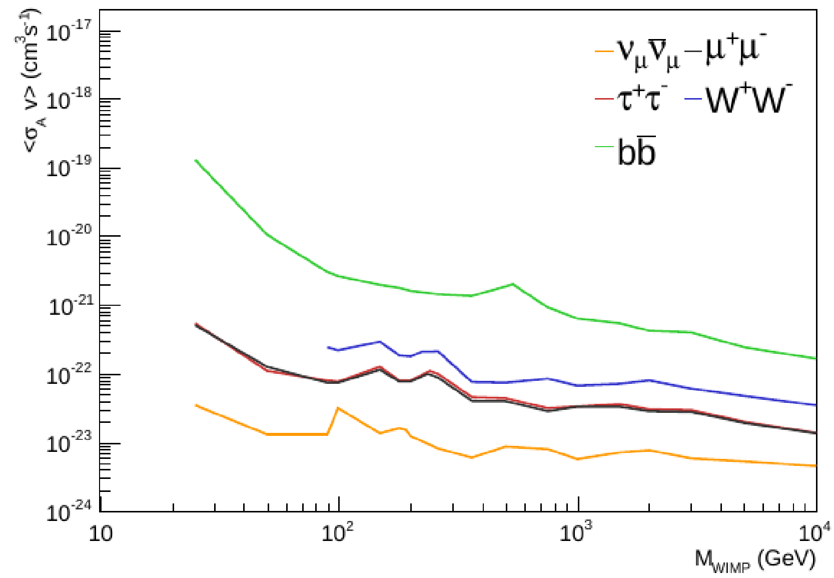


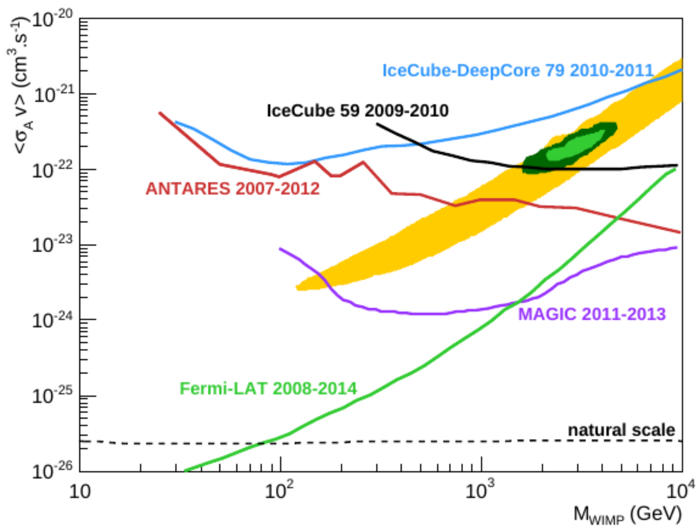
Hydro : core *EN,Lavalle in progress*

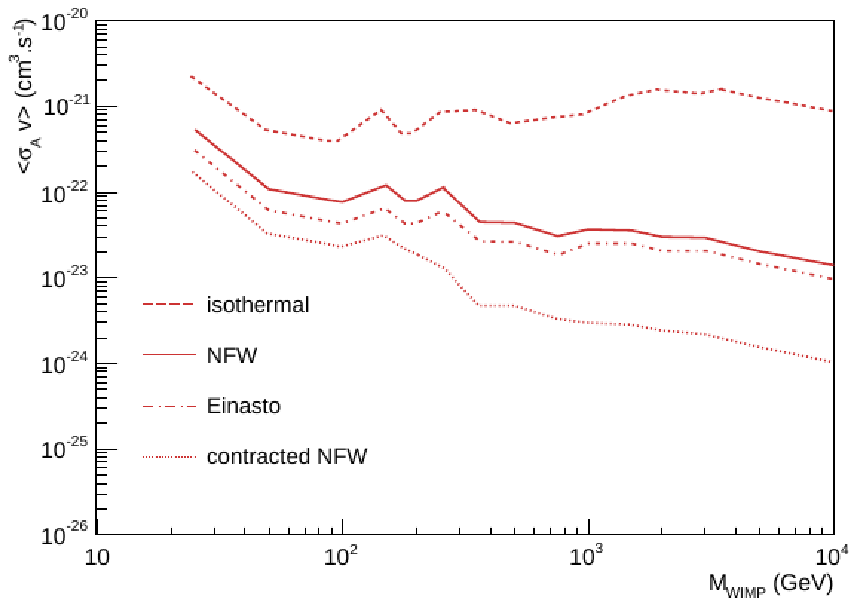
Galactic Center

ANTARES 1505.04866









Galactic Center

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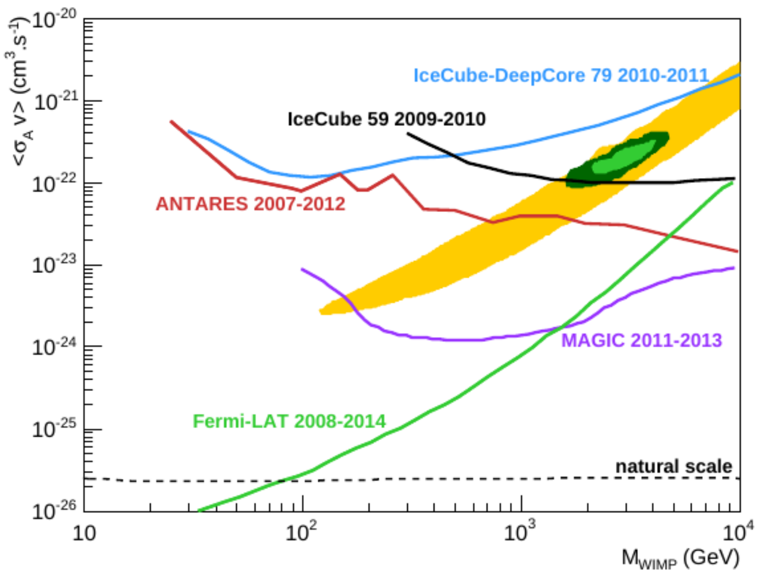

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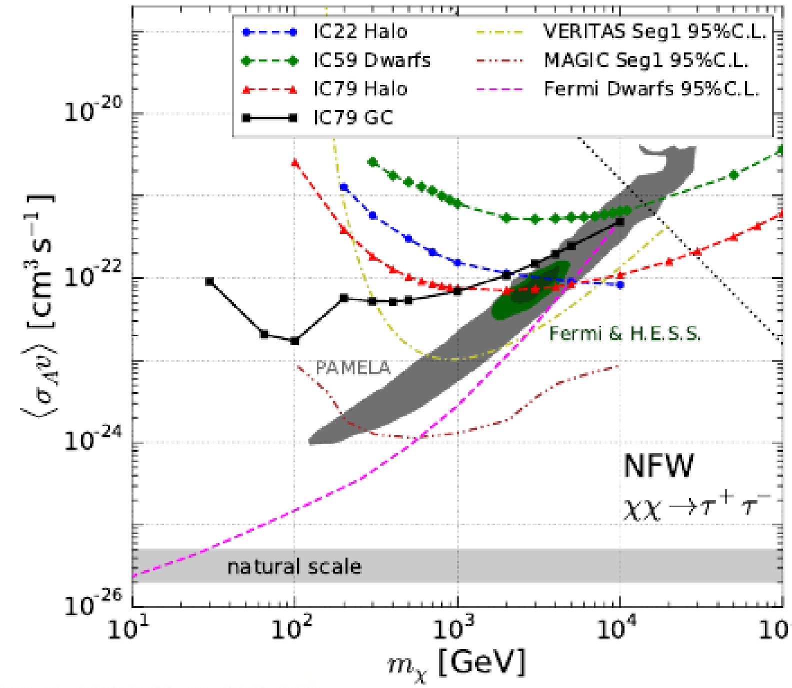
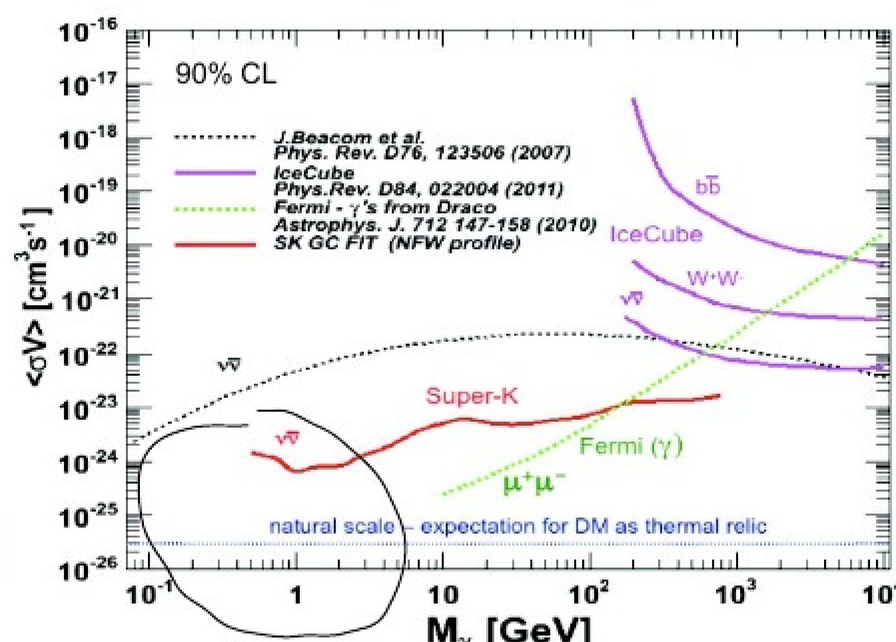


Super K

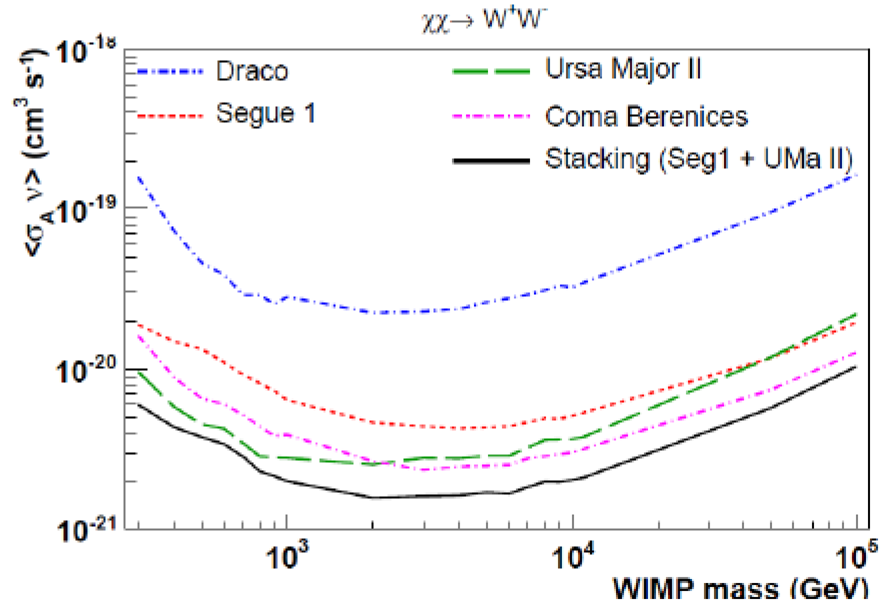


Dsphs/Clusters

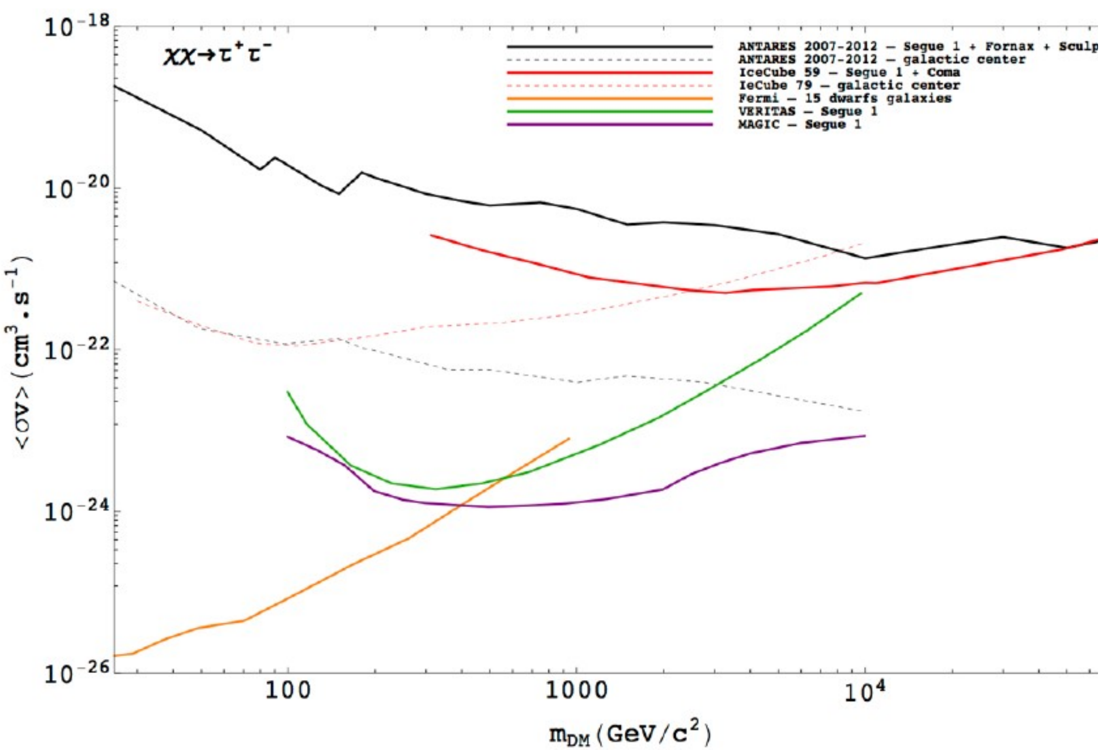
- *Dwarf spherodal galaxies (Dsphs) Kinematics of star + Jeans Equation, simulations*

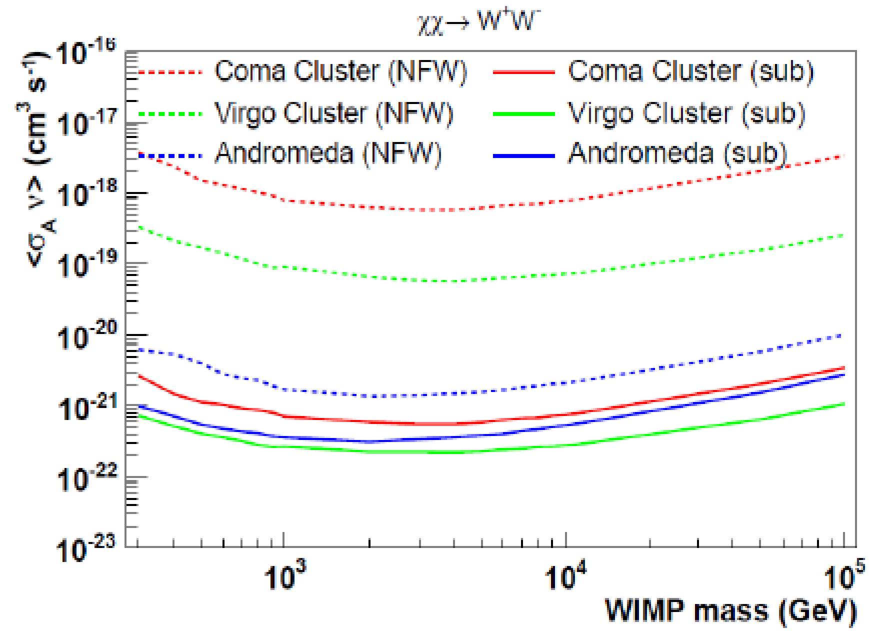
- *Clusters: Xray catalogues, lensing, simulations*

IceCube Phys. Rev. D88 (2013) 122001

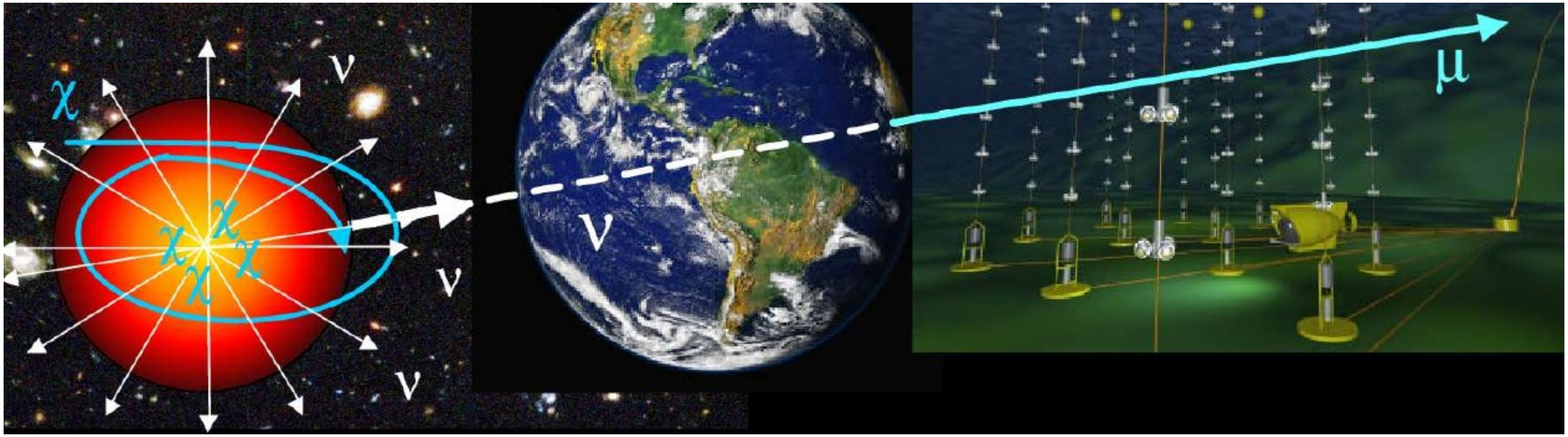


ANTARES Dsphs





SUN



$$\frac{dN}{dt} = C - C_A N^2 - C_E N$$

Gould 87
Jungmann+ 96

$$\Gamma_A = \frac{1}{2} C_A N_\chi^2 = \frac{C}{2} \tanh^2 \sqrt{C C_A} t$$

$$\sqrt{C C_A} t \; > \; 1, \; \Gamma_A \; \sim \; \frac{C}{2} \; = \; cste$$

Equilibrium

$$\sqrt{C C_A} t << 1, \Gamma_A \approx \tfrac{1}{2} C^2 C_A t^2$$

Capture rate in the Sun

$$\frac{dC_i}{dV} = \frac{\rho_H}{M_\chi} \int_0^\infty du \frac{f_\eta(u)}{u} \Omega_i(Q)$$

Particle physics

BSM model
Dark matter mass
Cross section
Quark contents of the nucleon (Lattice QCD, Exp)

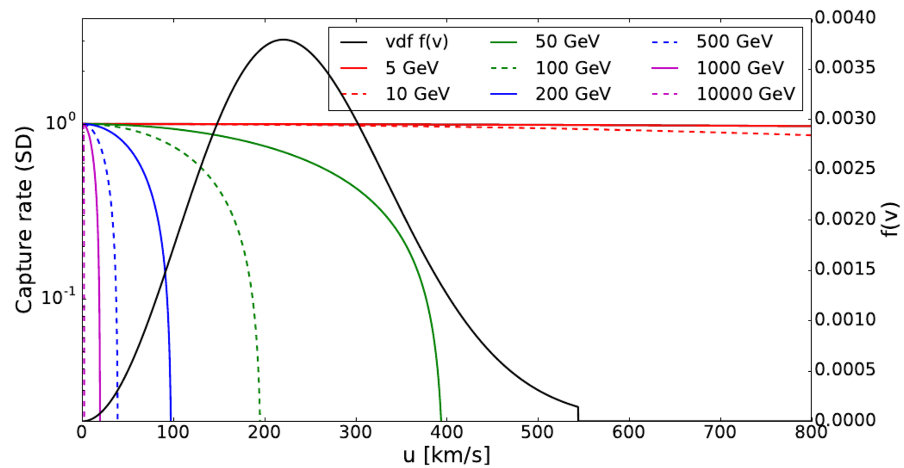
Astrophysics

Local dark matter density (Read 2014, Famaey 2015)

Velocity distribution

Escape velocity (Piffl+ 2014 from RAVE and simus

Dark disk ? Disruption of satellites in the disk
Density enhancement, corotating population



Gould 87
Jungmann+ 96

See also e.g
Read+ 09
Brush+ 09
Ling 10

Choi+ 1312.0273

Capture rate in the Sun

$$\frac{dC_i}{dV} = \frac{\rho_H}{M_\chi} \int_0^\infty du \frac{f_\eta(u)}{u} \Omega_i(Q)$$

Astrophysics:

Usual assumptions :
Standard Halo Model (SHM)

Maxwellian velocity distribution
(self-grav isothermal sphere)

$$f_{\vec{v}}(\vec{v}) = \frac{1}{v_0^3 \pi^{3/2}} \exp\left(-\frac{|\vec{v}|^2}{v_0^2}\right)$$

$$v_c = 220 \text{ km/s}, \quad v_0 = v_c$$

$$\rho_\odot = 0.3 \text{ GeV/cm}^3 \qquad v_{esc} = 544 \text{ km/s}$$

Capture rate in the Sun

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Astrophysics:

Maxwellian

$$f_{\vec{v}}(\vec{v}) = \frac{1}{v_0^3 \pi^{3/2}} \exp\left(-\frac{|\vec{v}|^2}{v_0^2}\right)$$

Generalised Maxwellian (+exp cut off)

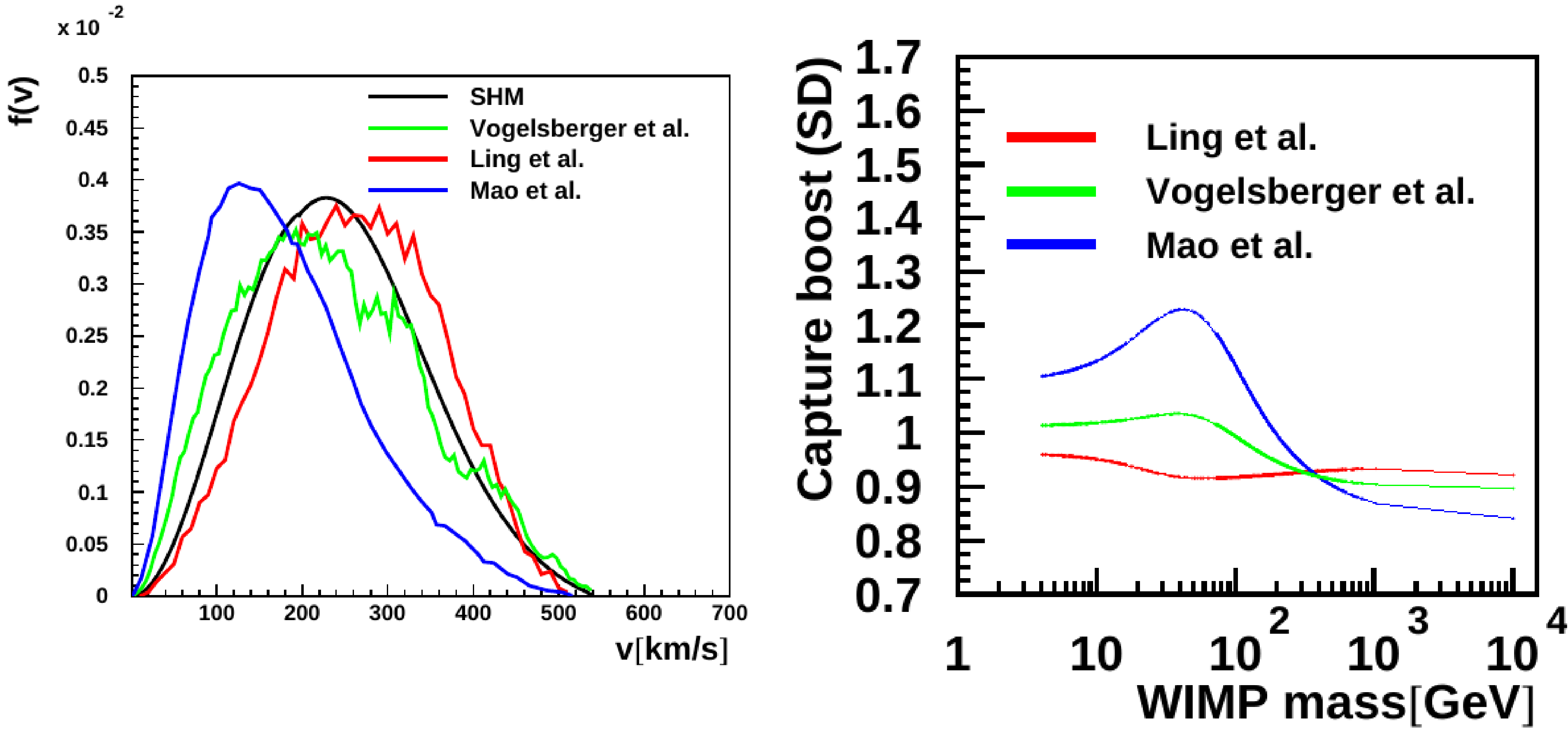
Tsallis

$$\mathrm{f}(\vec{v}) = \frac{1}{N(v_0, q)} \left(1 - (1-q)\frac{\vec{v}^2}{v_0^2}\right)^{q/(1-q)}$$

Mao+ 2013

$$f(v, v_0, v_{\rm esc}, p) = \frac{1}{N} v^2 \exp^{-\frac{v}{v_0}} (v_{\rm esc}^2 - v^2)^p$$

Capture rate in the Sun



Choi+ 1312.0273

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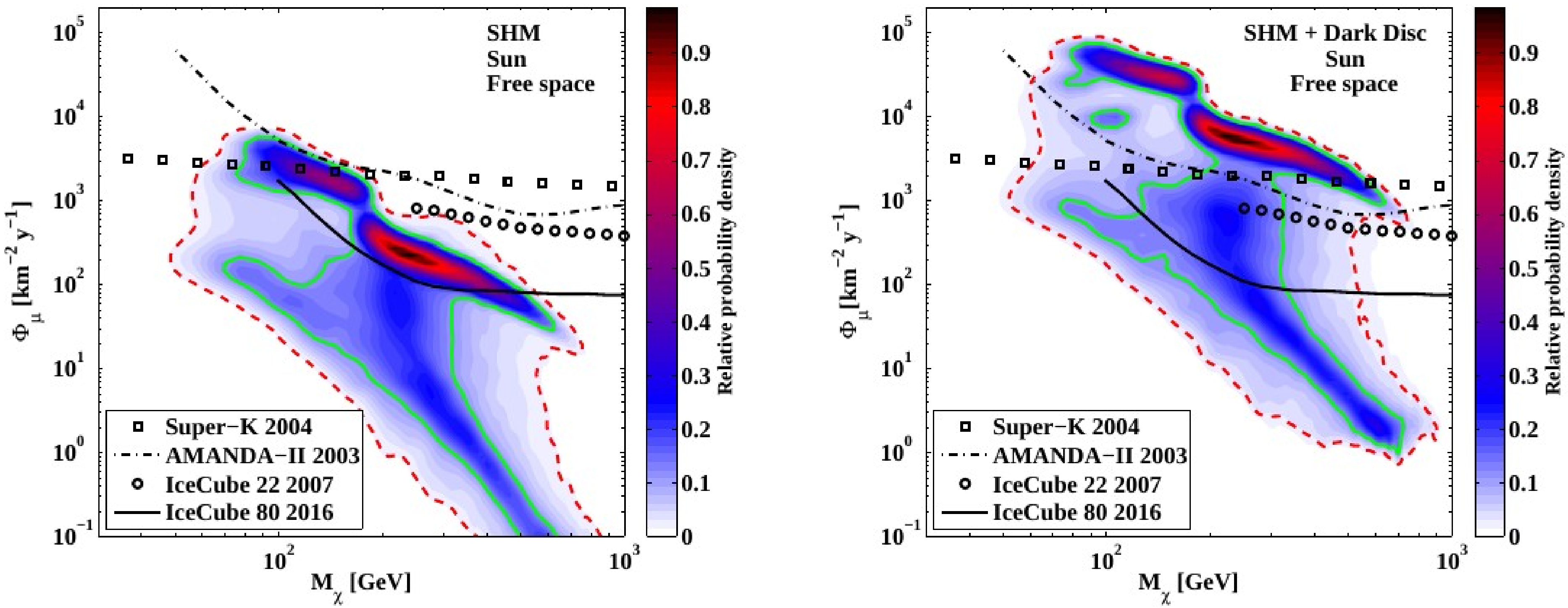


Dark disk:

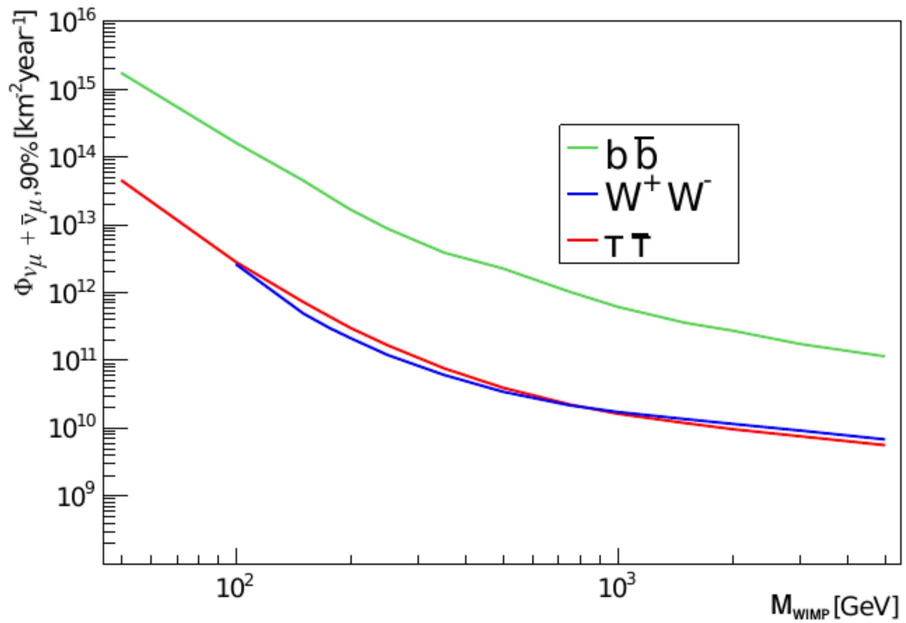
Read+ 09
Brush+ 09

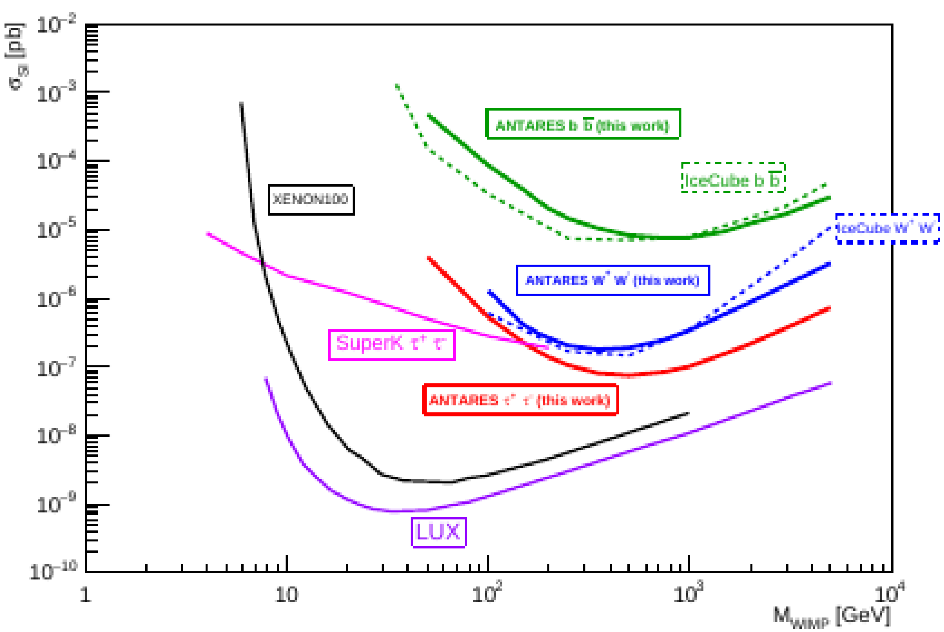
Ling 10

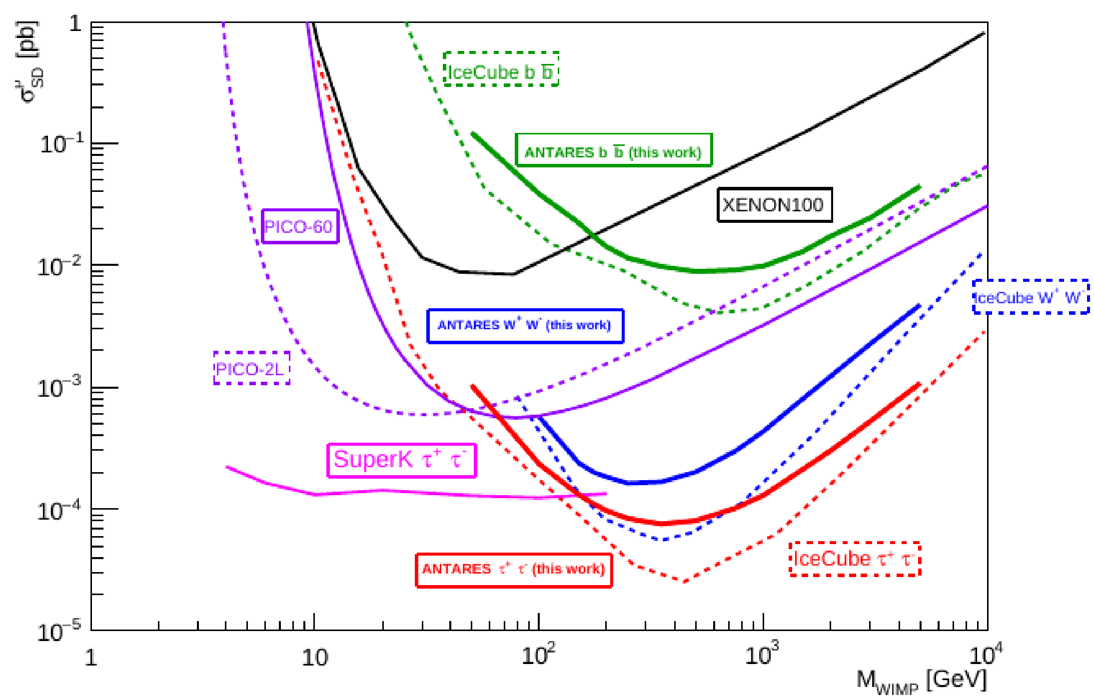
But Schaller+1605.02770
No significant dark disk in recent hydro simulations (Eagles,Apostle)

SUN

ANTARES 1603.02228

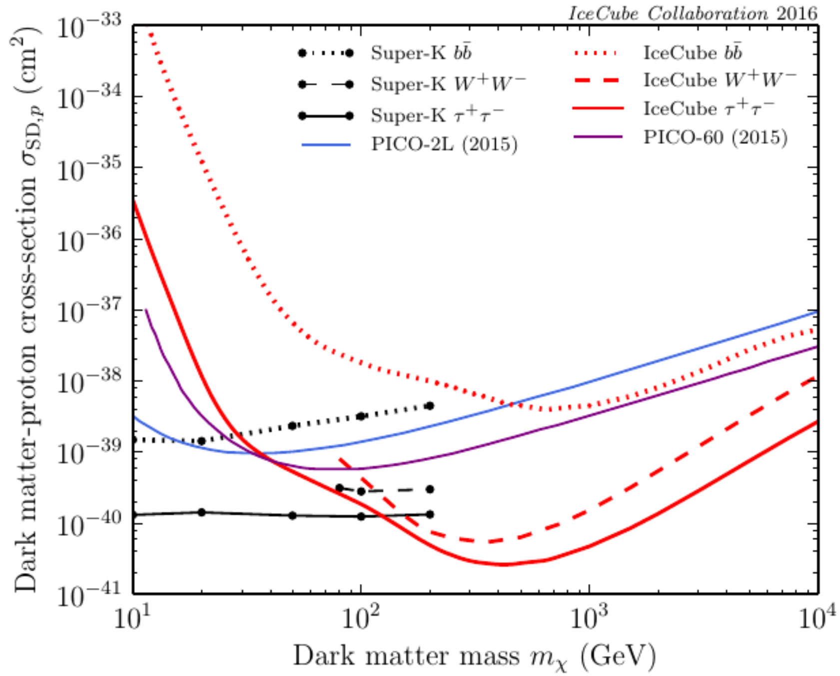


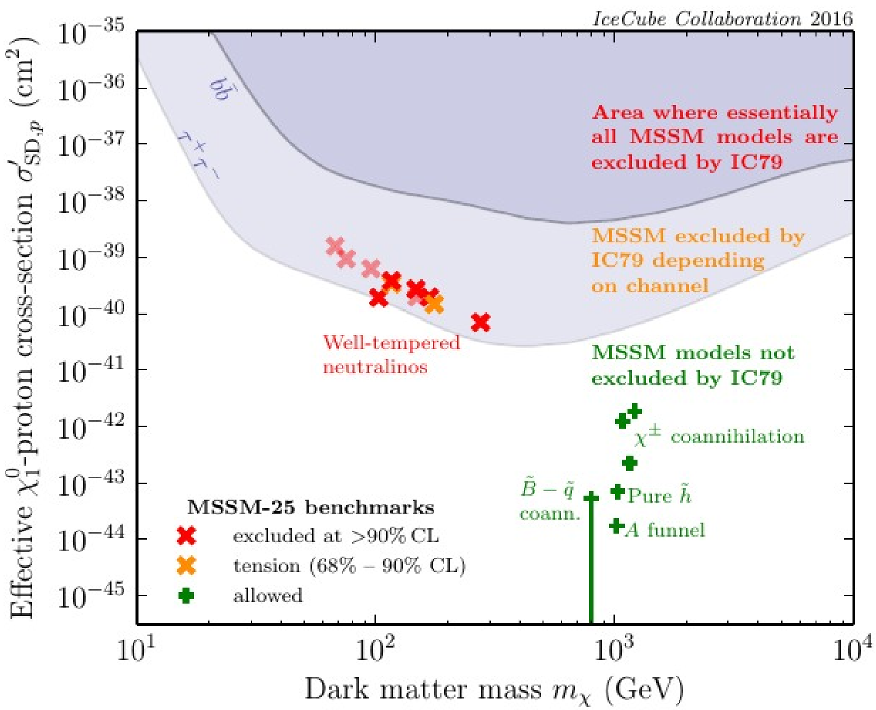


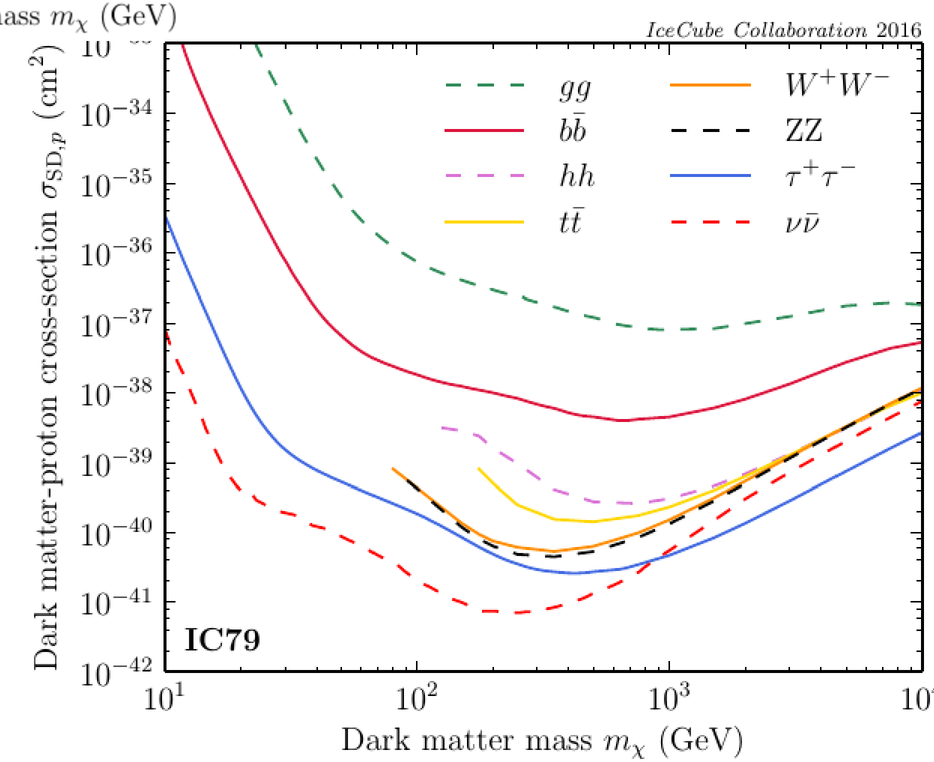


SUN

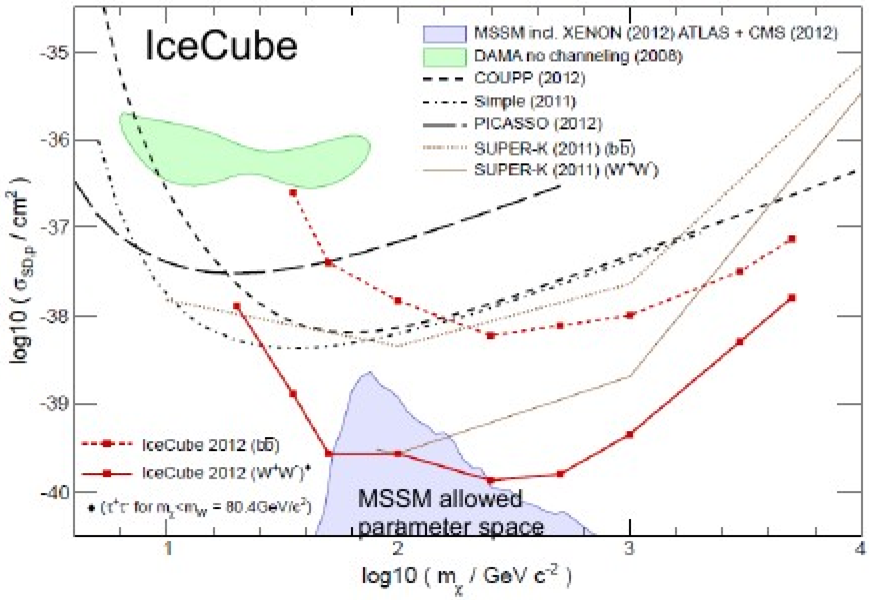
ICECUBE 1601.00653

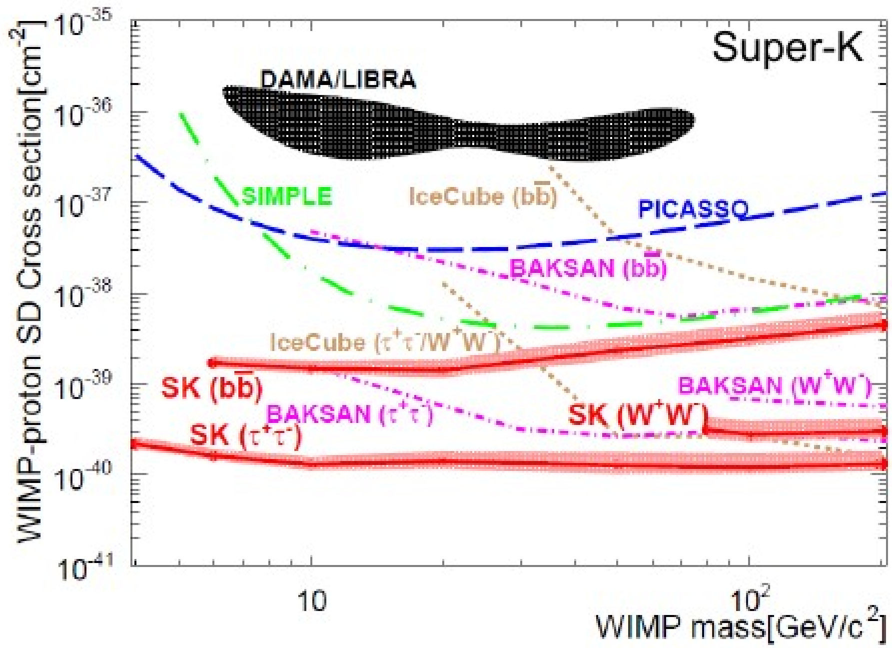


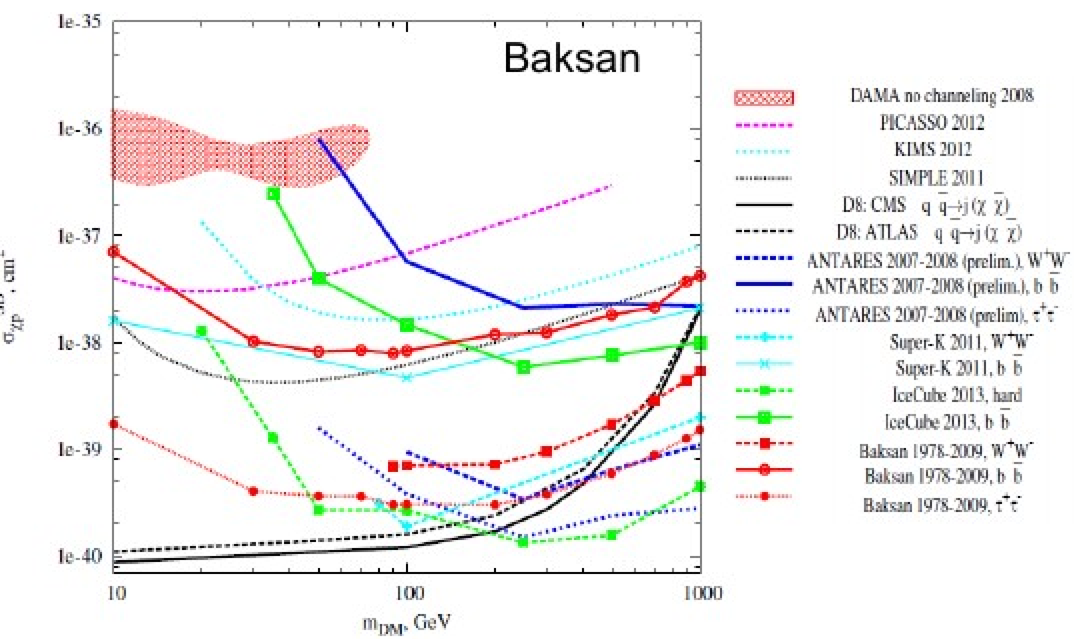


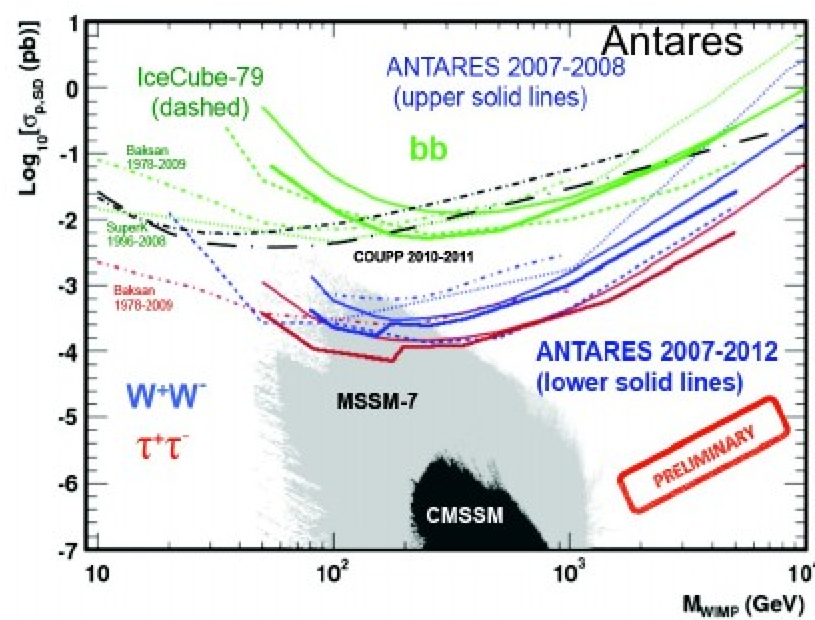


SUN


IceCube
MSSM incl. XENON (2012) ATLAS + CMS (2012)
DAMA no channeling (2008)
COUPP (2012)
Simple (2011)
PICASSO (2012)
SUPER-K (2011) (bb̄)
SUPER-K (2011) (W+W-)
IceCube 2012 (bb̄)
IceCube 2012 (W+W-)*
MSSM allowed
parameter space
log10 (mχ / GeV c-2)
log10 (σSD,p / cm2)


Super-K
DAMA/LIBRA
SIMPLE
IceCube (bb̄)
PICASSO
BAKSAN (bb̄)
IceCube (τ+τ-/W+W-)
SK (bb̄)
BAKSAN (W+W-)
BAKSAN (τ+τ-)
SK (W+W-)
SK (τ+τ-)
WIMP-proton SD Cross section[cm-2]
WIMP mass[GeV/c2]


Baksan
DAMA no channeling 2008
PICASSO 2012
KIMS 2012
SIMPLE 2011
D8: CMS
D8: ATLAS
ANTARES 2007-2008 (prelim.), W+W-
ANTARES 2007-2008 (prelim.), b b̄
ANTARES 2007-2008 (prelim), τ+τ-
Super-K 2011, W+W-
Super-K 2011, b b̄
IceCube 2013, hard
IceCube 2013, b b̄
Baksan 1978-2009, W+W-
Baksan 1978-2009, b b̄
Baksan 1978-2009, τ+τ-
mDM, GeV


Antares
IceCube-79
(dashed)
ANTARES 2007-2008
(upper solid lines)
bb
COUPP 2010-2011
ANTARES 2007-2012
(lower solid lines)
W+W-
τ+τ-
MSSM-7
CMSSM
PRELIMINARY
Log10[σp,SD (pb)]
MWIMP (GeV)

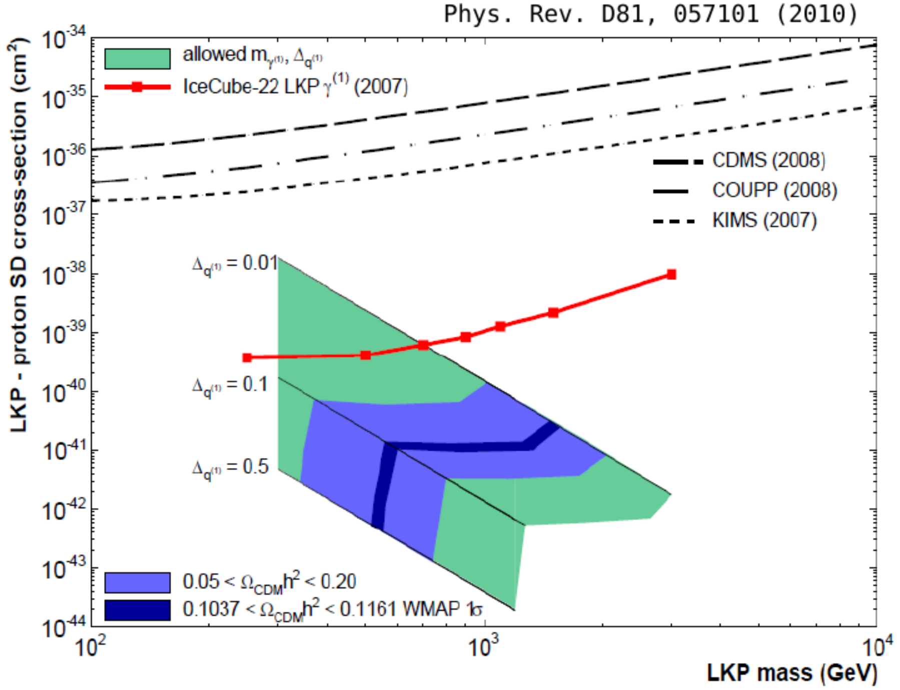
SUN

ICECUBE
Xtra dim LKP dark matter

Universal flat extra dimensions, all standard fields propagate in extra-dim :
boson dark matter LKP= $B^{(1)}$ 1st Kaluza-Klein state of the B field

90% CL LKP-p Xsection limit vs LKP mass

Phys. Rev. D81, 057101 (2010)

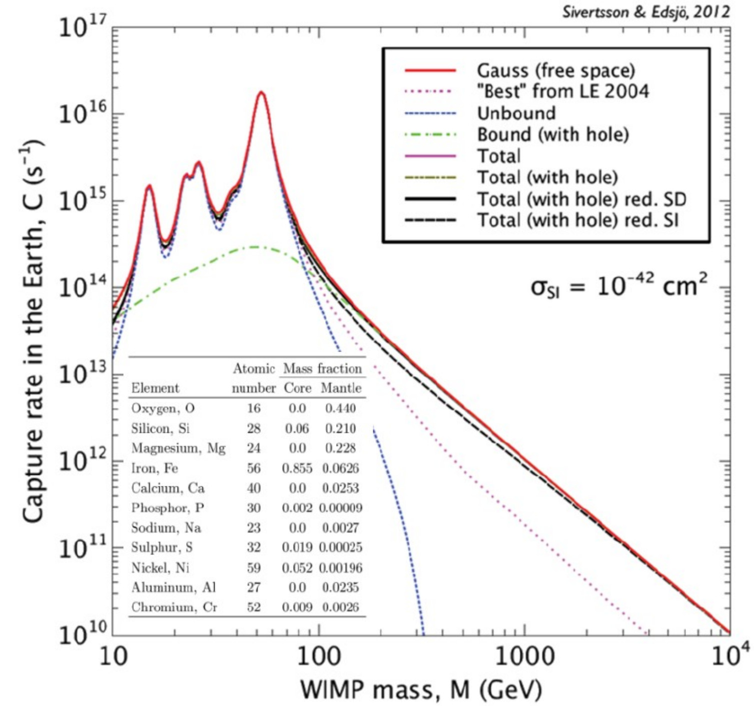


EARTH

Capture rate dominated by resonnance with heavy elements

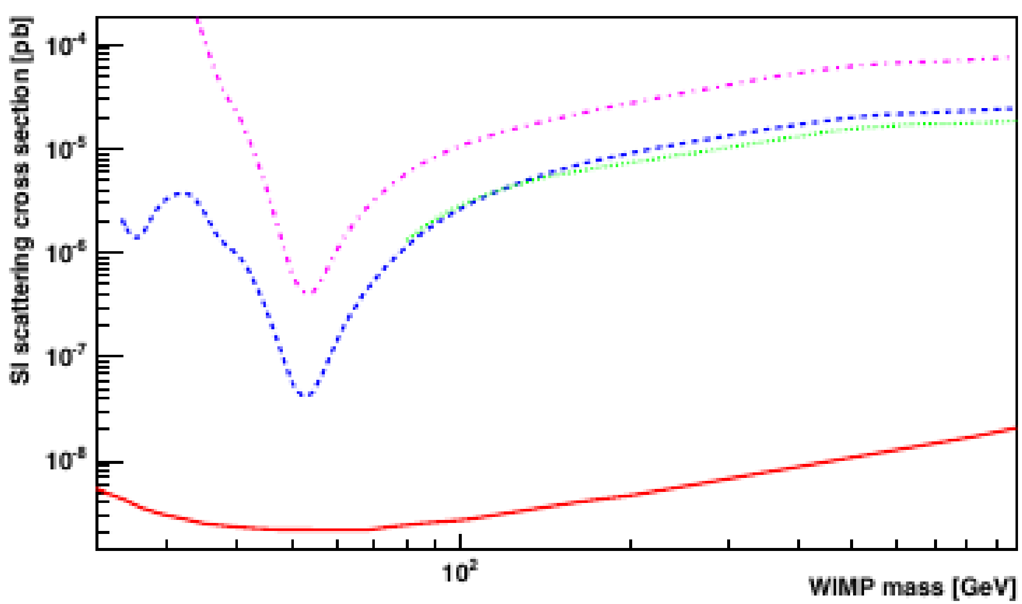
Dark matter not at equilibrium

Exclusion not competitive with direct detection



Element	Atomic number	Mass fraction Core	Mantle
Oxygen, O	16	0.0	0.440
Silicon, Si	28	0.06	0.210
Magnesium, Mg	24	0.0	0.228
Iron, Fe	56	0.855	0.0626
Calcium, Ca	40	0.0	0.0253
Phosphor, P	30	0.002	0.00009
Sodium, Na	23	0.0	0.0027
Sulphur, S	32	0.019	0.00025
Nickel, Ni	59	0.052	0.00196
Aluminum, Al	27	0.0	0.0235
Chromium, Cr	52	0.009	0.0026

ANTARES



Conclusion

Conclusion:

- *Astrophysics assumptions matter*
- *Astro sources (GC, Halo, Dsphs,Clusters) complementarity with gamma limits Complementarity between all dark matter searches*
- *SUN a golden target for neutrino telescopes to probe the WIMP dark matter scenario and local dark matter*
- *EARTH low capture rate, limits excluded by direct detection or need specific model*

Perspectives :

- *New data/analyses, KM3Net*
- *Considering all kinds of dark matter detection experiment : next decade is time to (un)validate WIMP hypothesis and TeV BSM*
- *GAIA, CTA,Xenon 1T, KM3Net ...*

Thanks