Neutrinos and Dark Matter

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Technische Universität München

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Boston
6 June 2014

Neutrinos and Dark Matter

Outline:

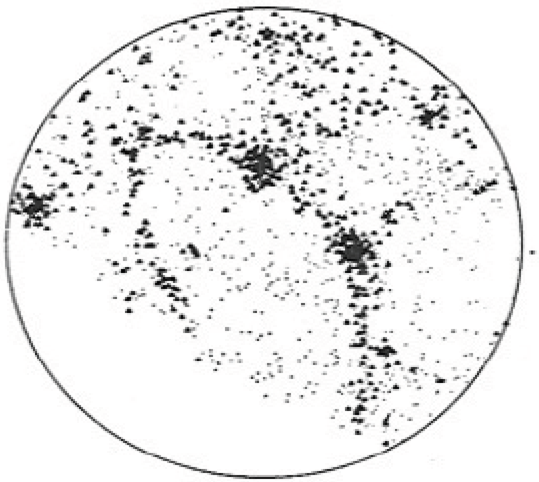
Neutrinos as dark matter

Neutrinos from dark matter

Neutrinos as dark matter

The dark matter plays a central role in the formation of the first structures in our Universe

White'86

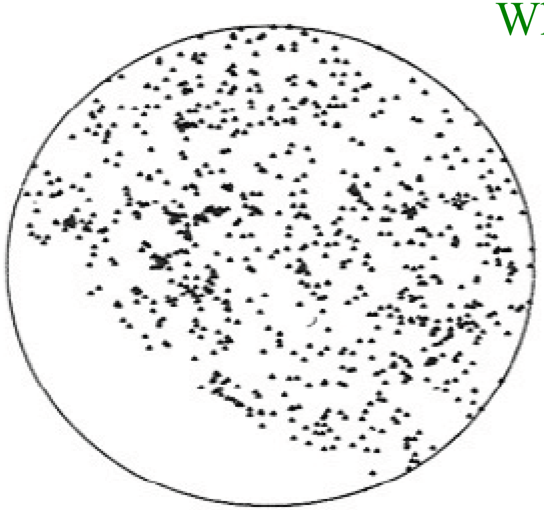


HDM

Hot Dark Matter

Relativistic

(neutrino dark matter)



CDM

Cold Dark Matter

Non-relativistic

Neutrinos as dark matter

The dark matter plays a central role in the formation of the first structures in our Universe

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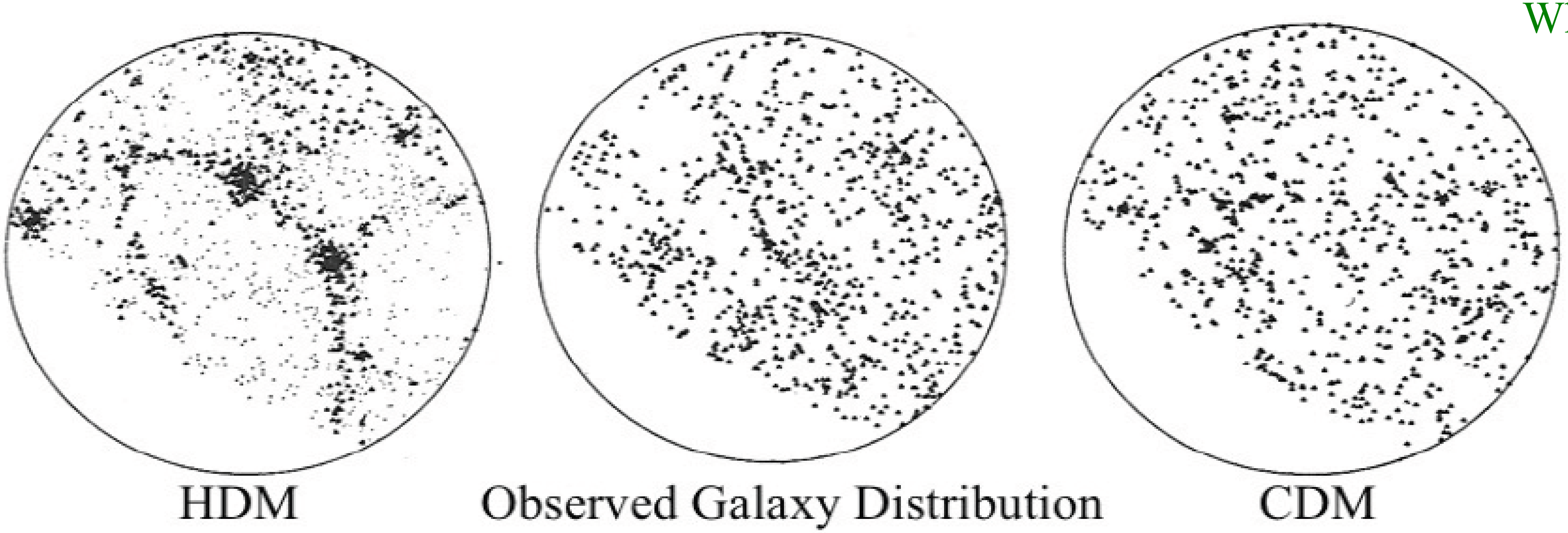

Hot Dark Matter
Relativistic
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Cold Dark Matter
Non-relativistic

Neutrinos as dark matter

THE ASTROPHYSICAL JOURNAL, **274**:L1–L5, 1983 November 1

CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

SIMON D. M. WHITE,[1,2] CARLOS S. FRENK,[1] AND MARC DAVIS[1,3]
University of California, Berkeley
Received 1983 June 17; accepted 1983 July 1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.

Subject headings: cosmology — galaxies: clustering — neutrinos

The existence of dark matter constitutes
an evidence for physics beyond the Standard Model

Sterile neutrinos as dark matter

Simplest scenario accounting for the dark matter of the Universe

- One new particle, ν_s
- No new symmetries
- Two new parameters: m_{DM}, θ_{as}.

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Five things to know about sterile neutrino dark matter

① Sterile neutrinos can be produced in the early Universe via mixing ν_a - ν_s.

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② Sterile neutrinos should not be overproduced ⇒ upper limit on the mixing angle as a function of the DM mass

③ The existence of a lepton asymmetry can resonantly enhance the dark matter production, via the MSW mechanism.

Sterile neutrinos as dark matter

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The observed DM density in dwarf galaxies implies a lower limit on the DM mass.

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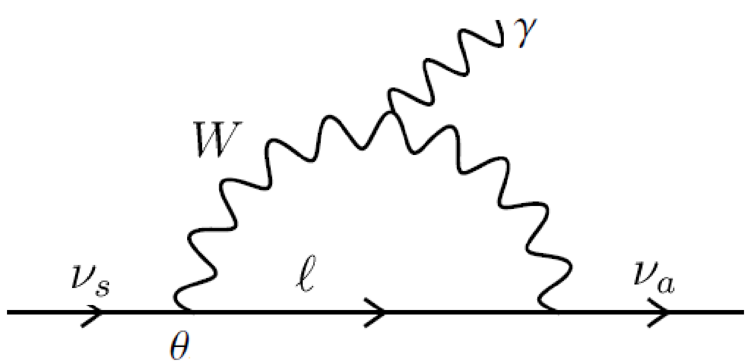
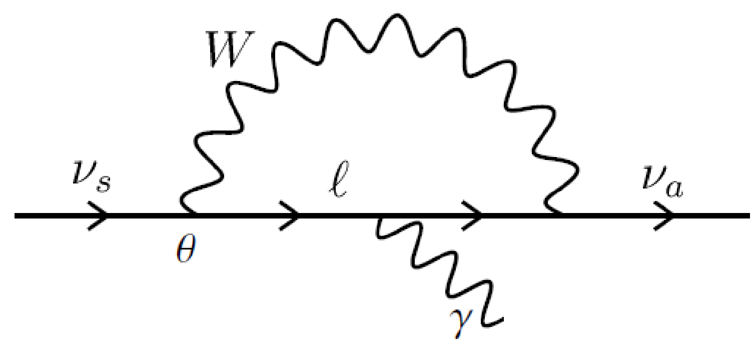
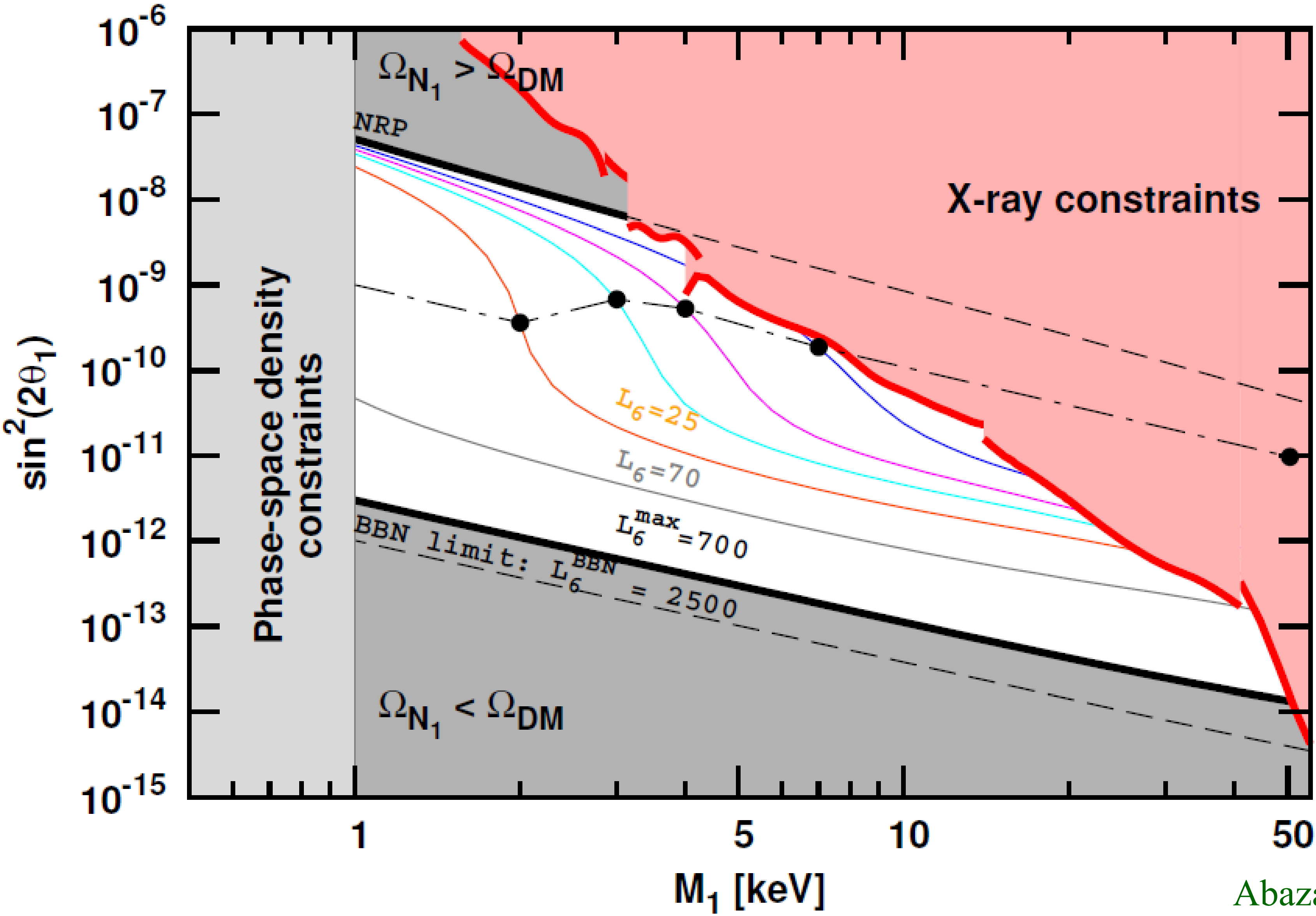
⑤ Sterile neutrinos are not absolutely stable



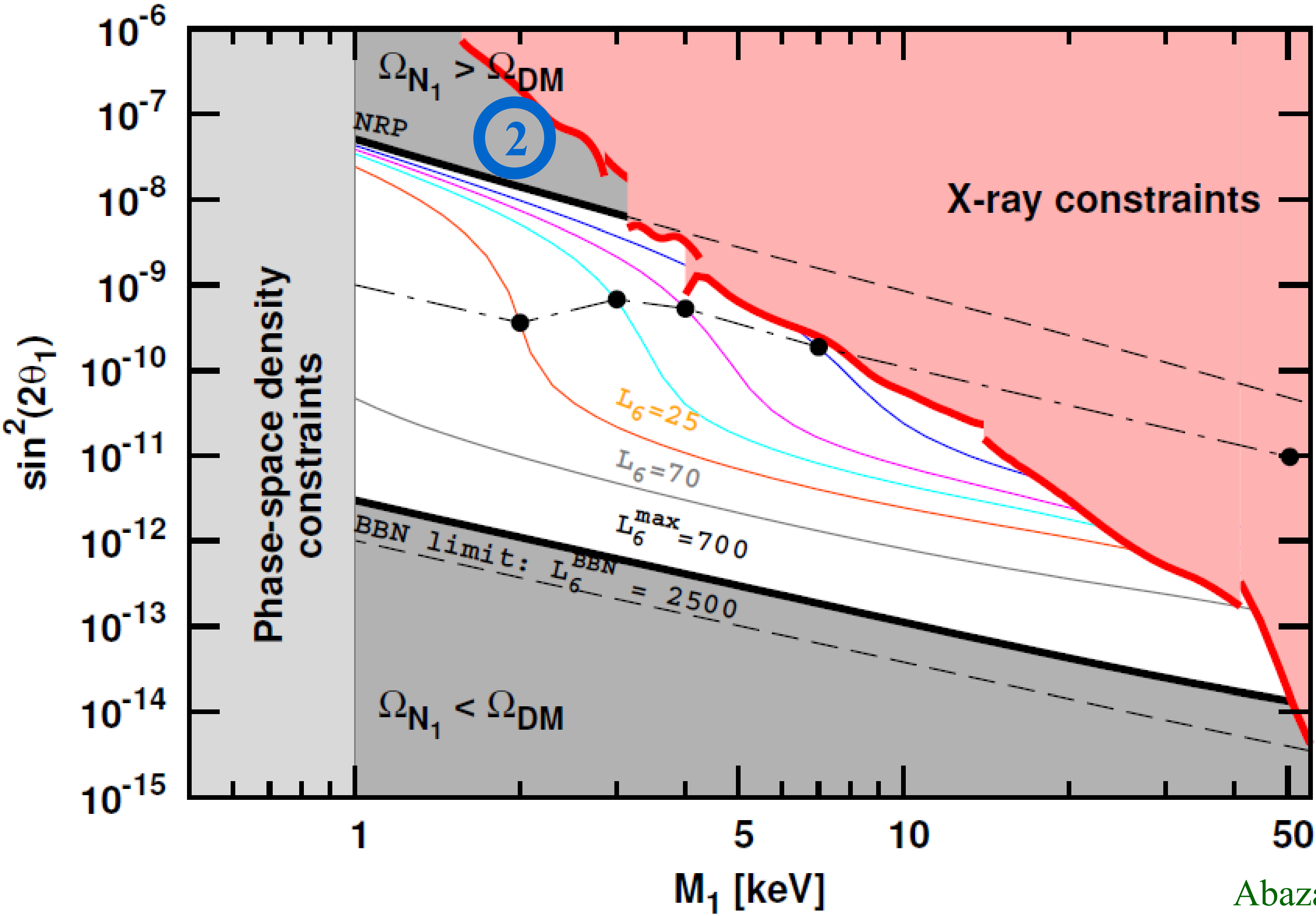


Sterile neutrinos as dark matter



Abazajian et al.
arXiv:1204.5379

Sterile neutrinos as dark matter



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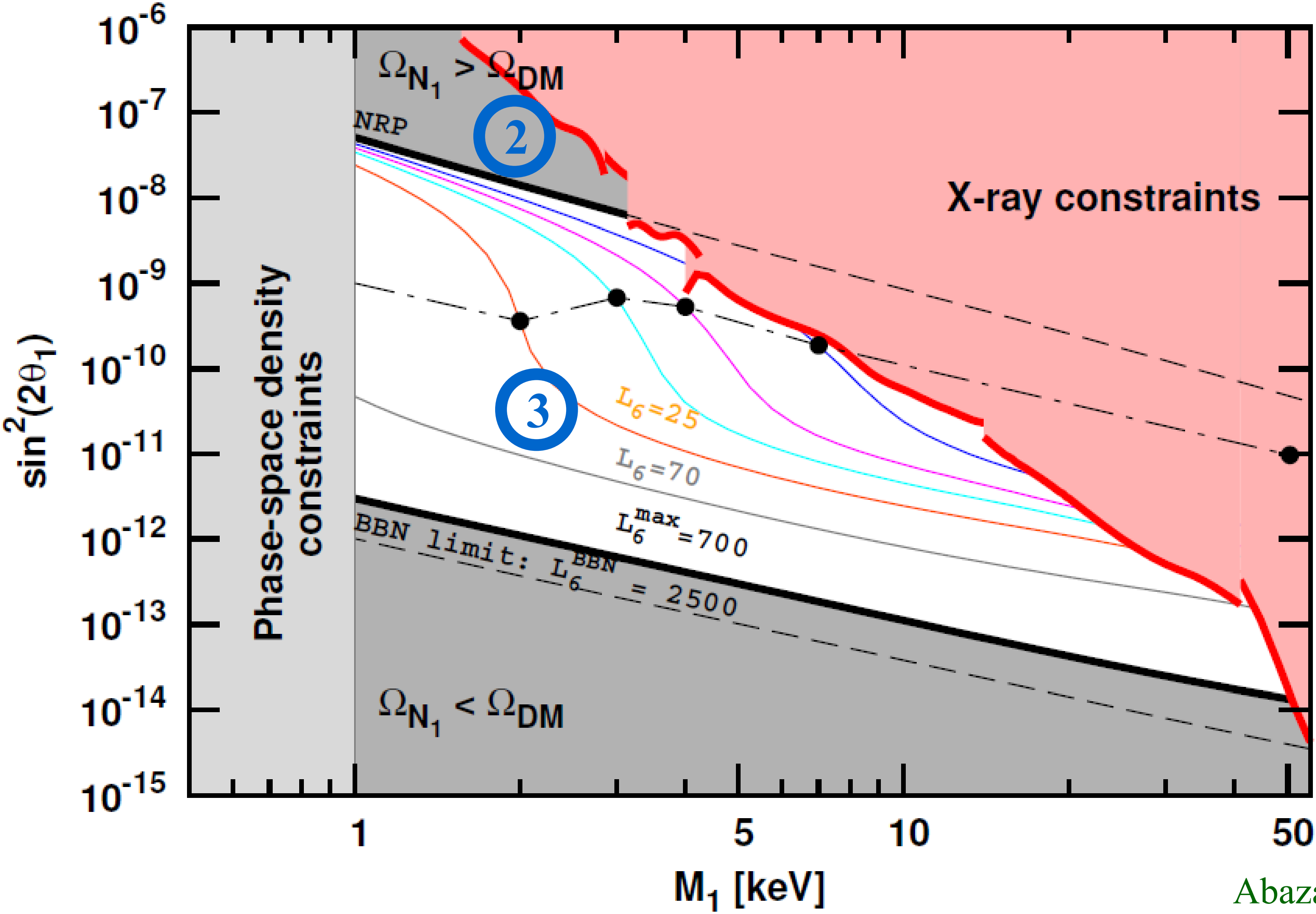

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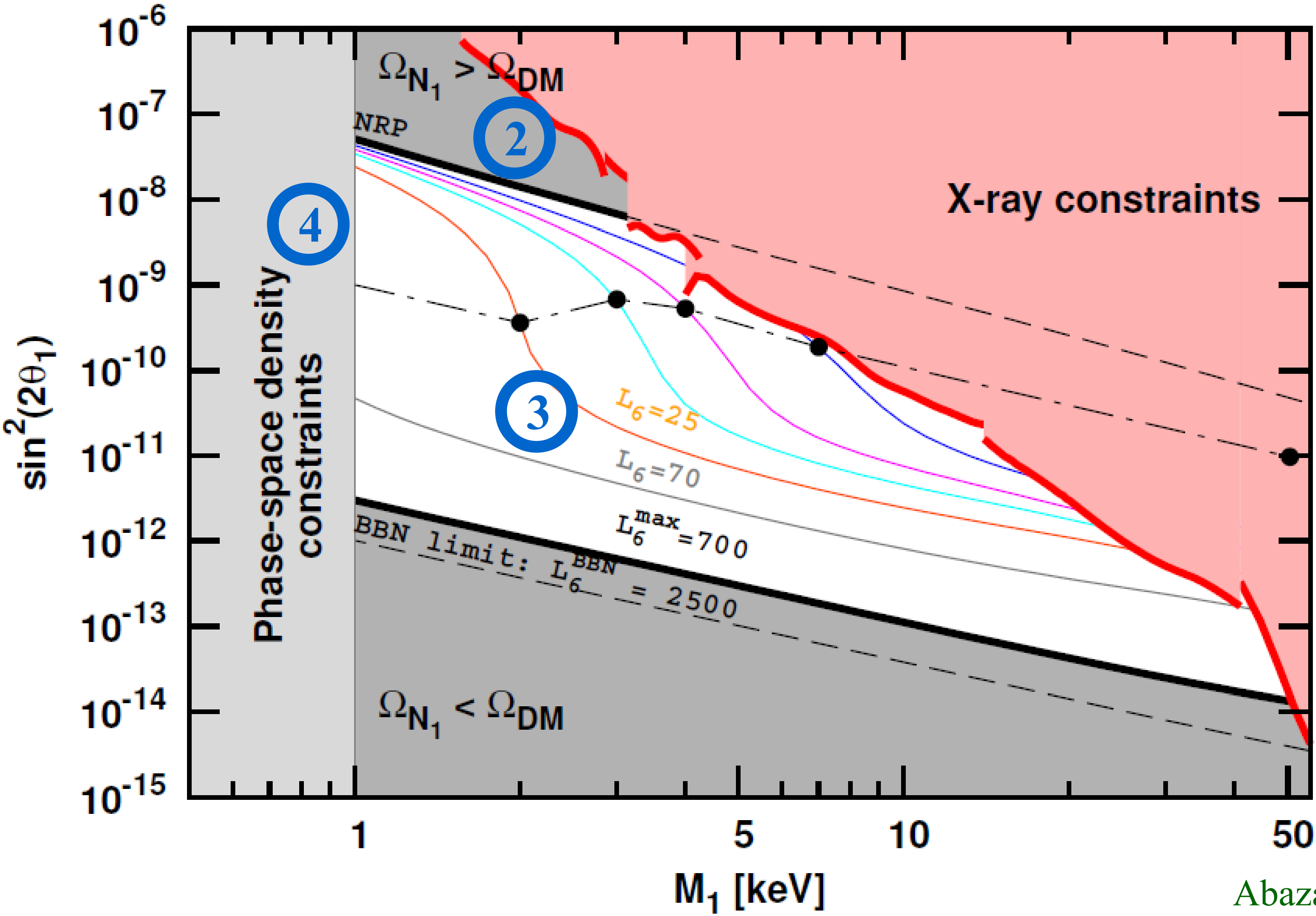

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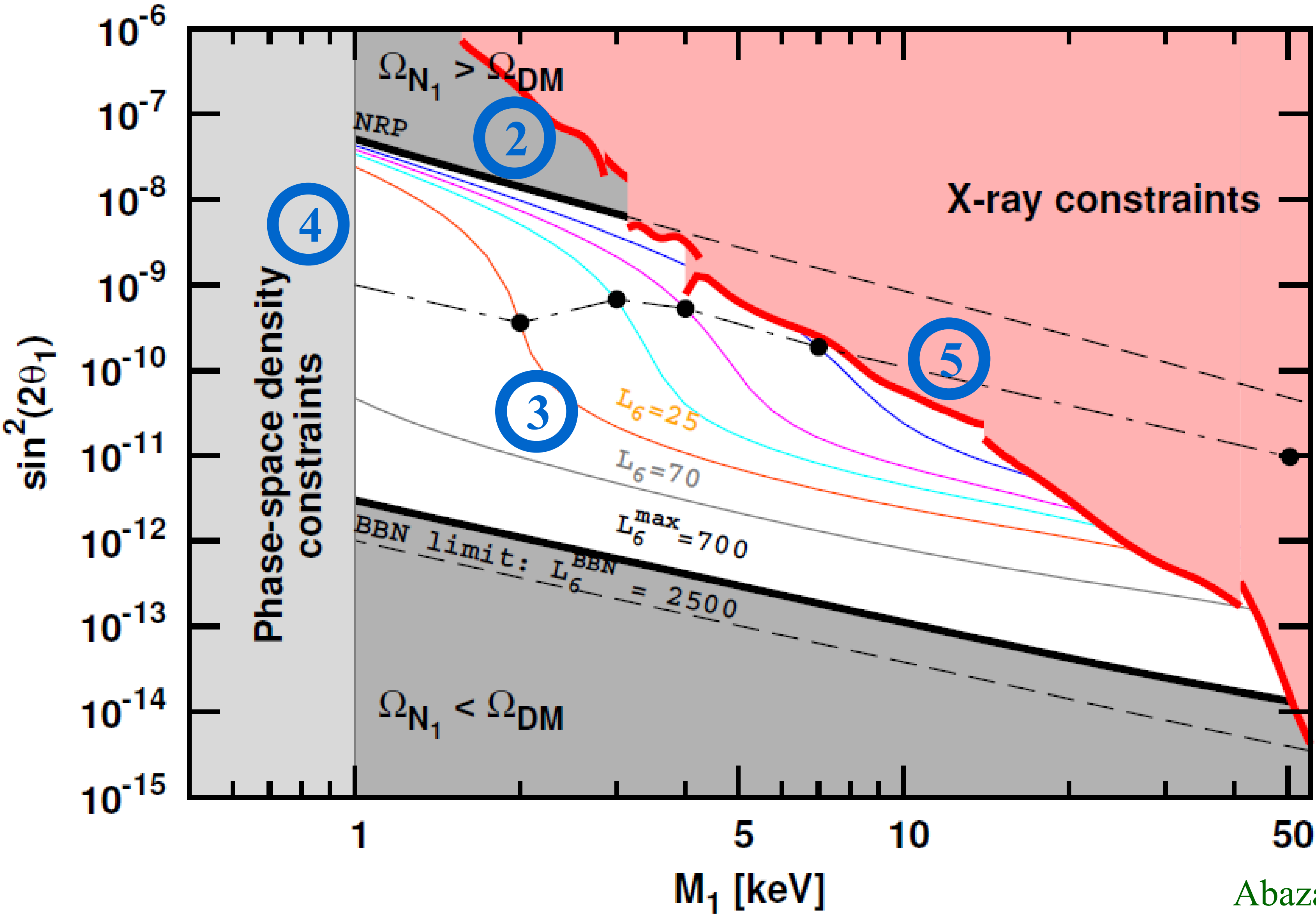

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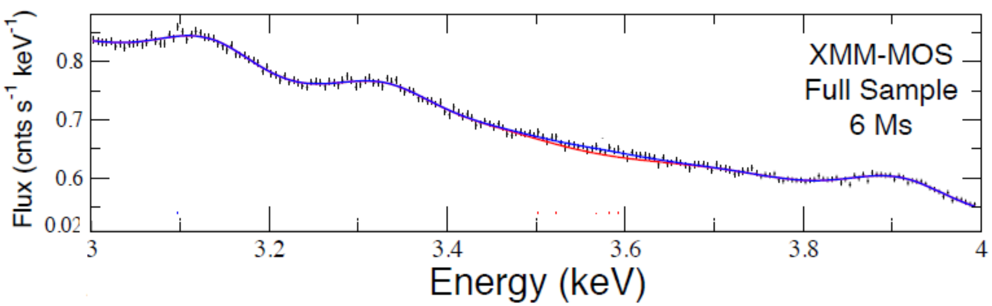
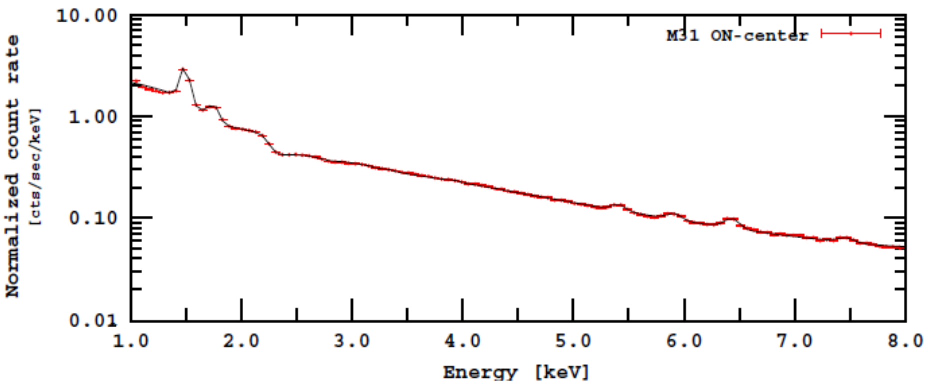
Sterile neutrinos as dark matter

Recent hints for an unidentified X-ray line signal

Bulbul et al, 1402.2301



Boyarsky al, 1402.4119



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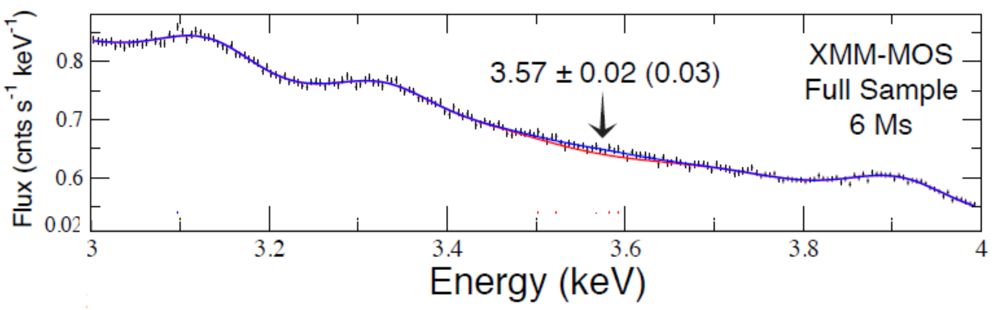

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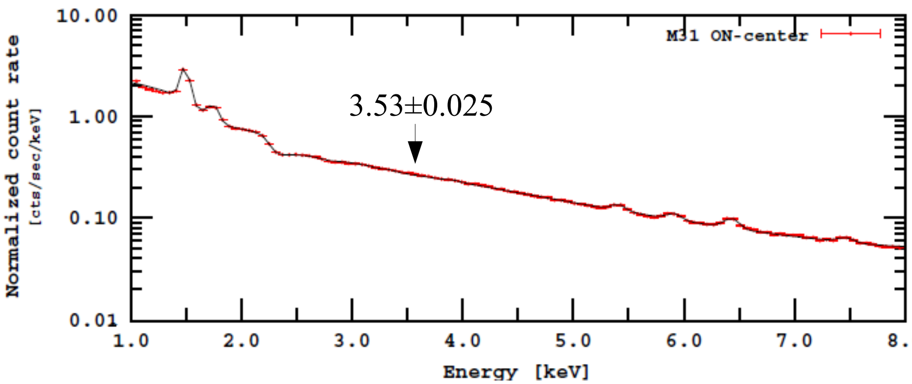

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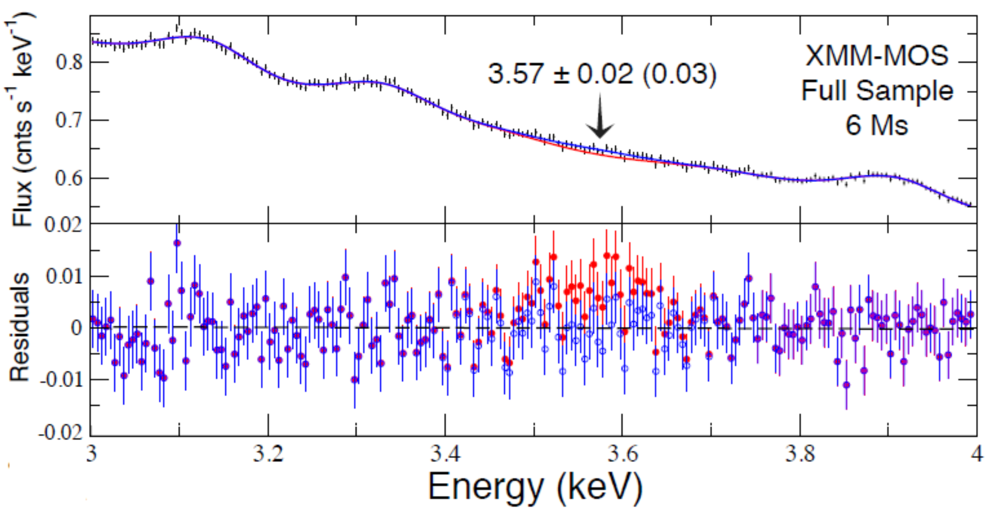

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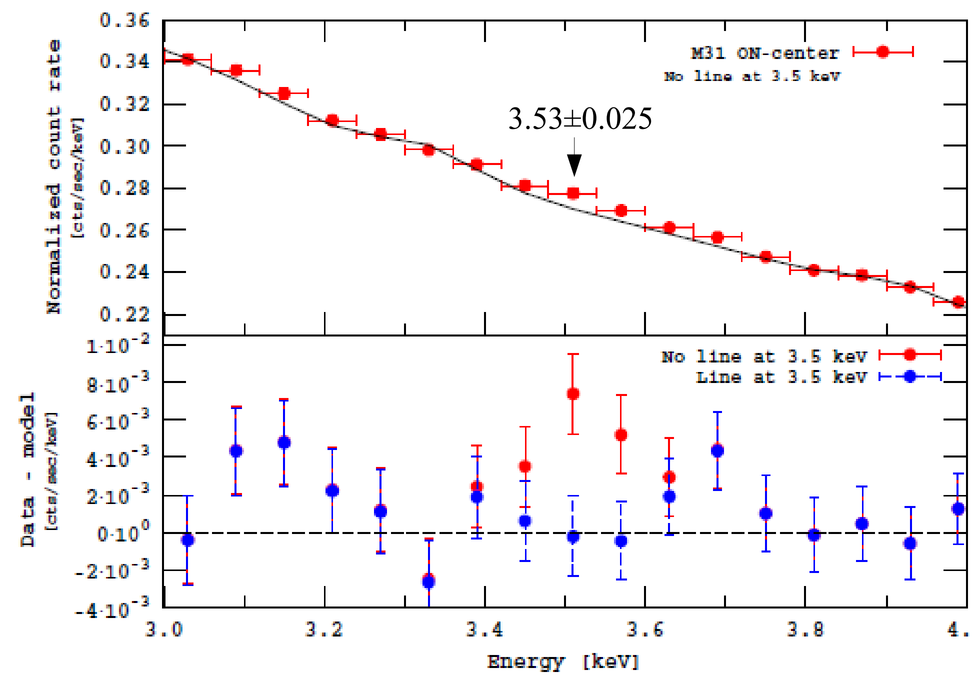

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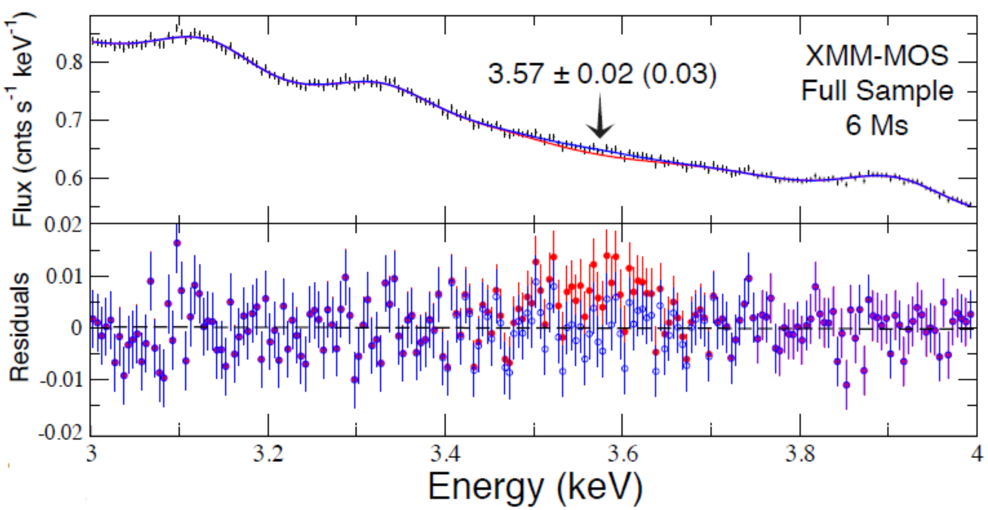

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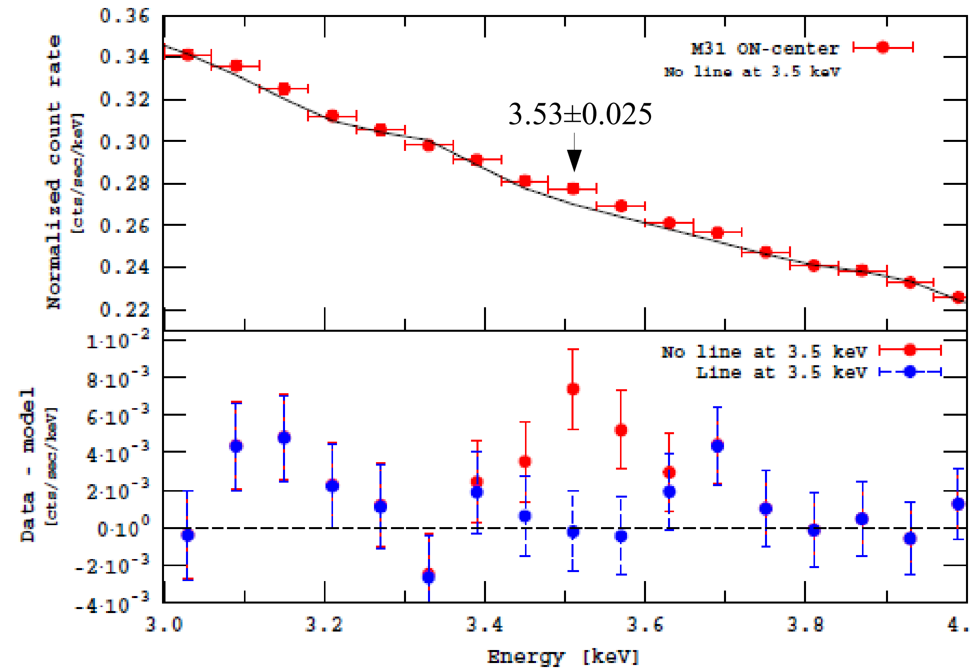

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- Observed in different datasets at different redshifts.
- Atomic origin not demonstrated: candidate atomic lines expected to be much fainter.

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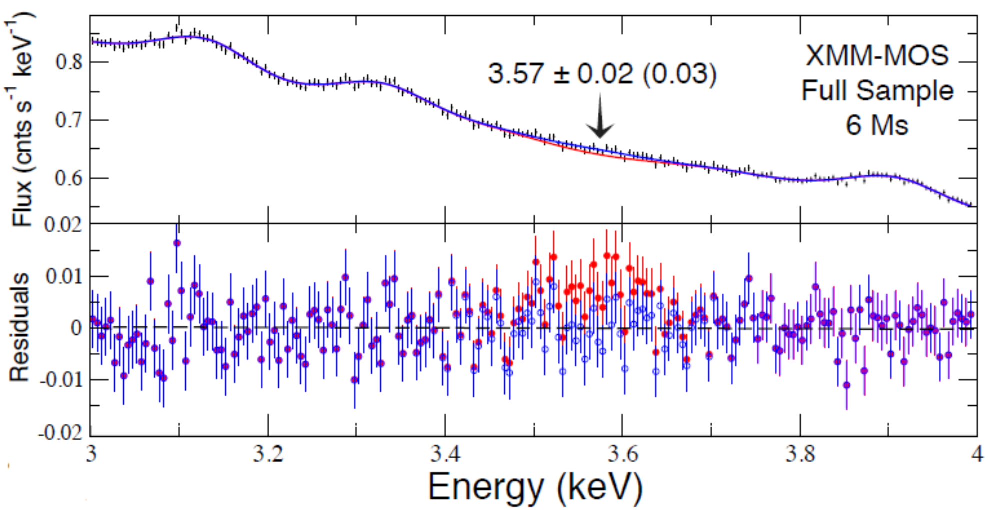

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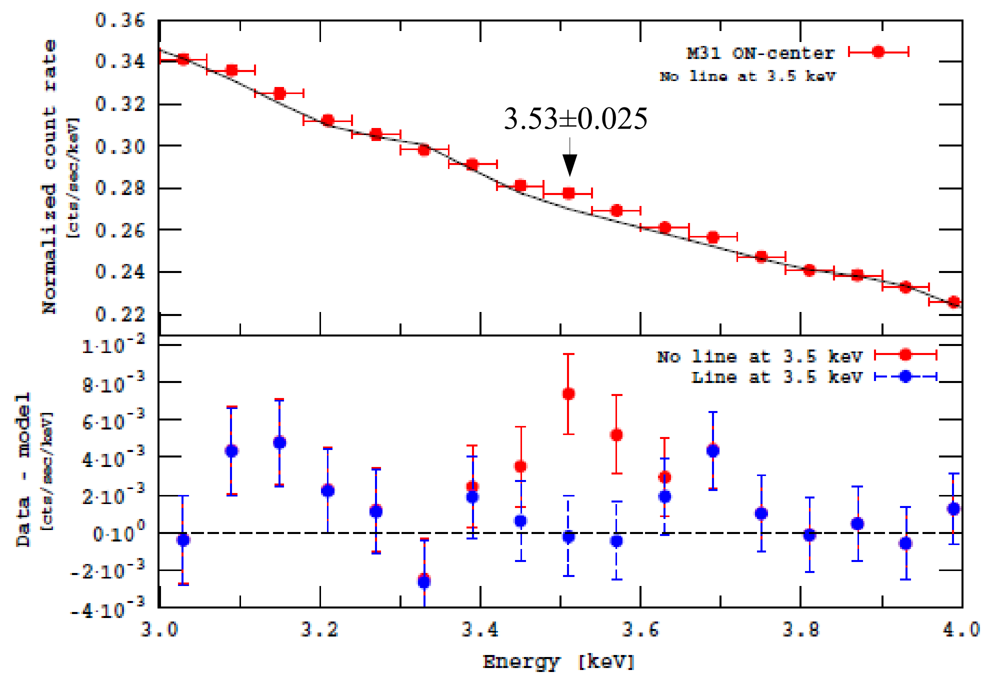

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- Originated by sterile neutrino decay?

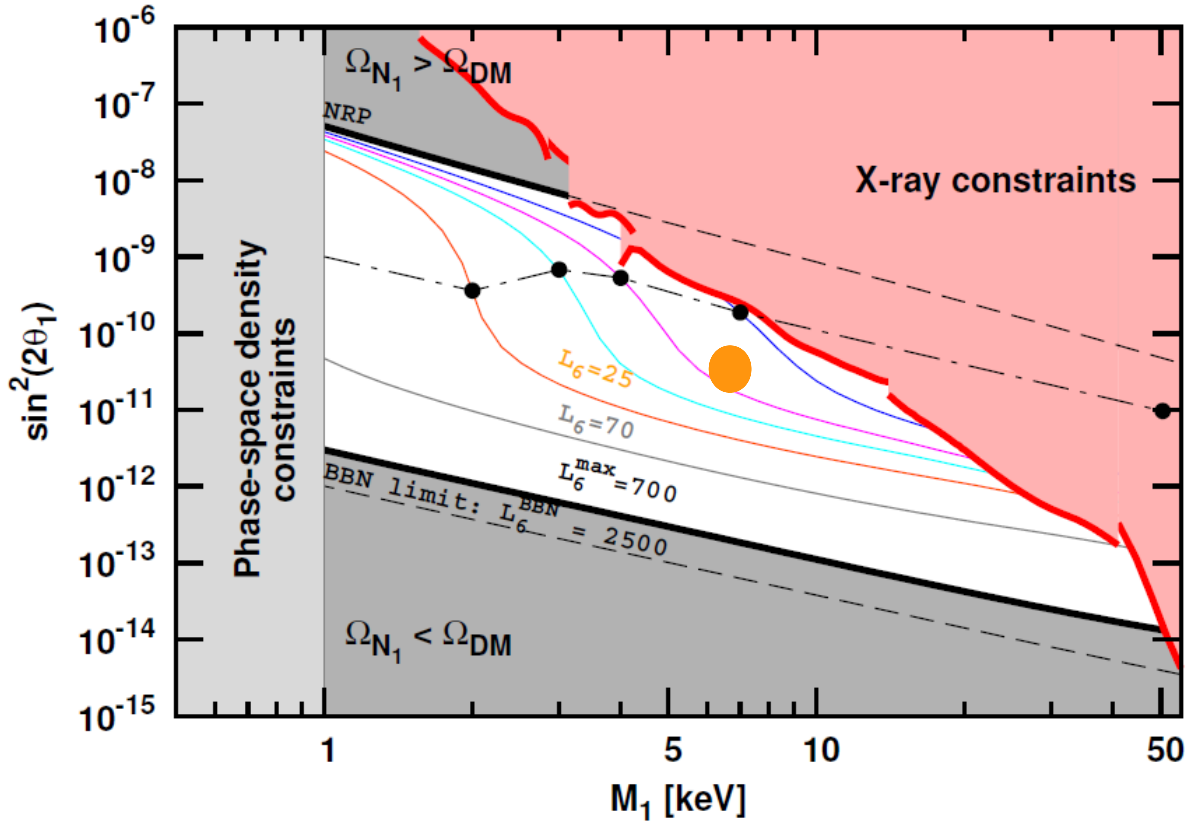
Sterile neutrinos as dark matter

Bulbul et al, 1402.2301

$$m_{\rm DM} = 7.1\,{\rm keV}$$
$$\sin^2 2\theta \approx 7\times 10^{-11}$$

Boyarsky al, 1402.4119

$$m_{\rm DM} = 7.06 \pm 0.05\,{\rm keV}$$
$$\sin^2 2\theta = (2.2 - 20)\times 10^{-11}$$



Requires $n_L/s \sim 10^{-5}$ (compared to $n_B/s \sim 10^{-10}$)

The future Astro-H mission will hopefully clarify the nature of this line.

Neutrinos from dark matter

Many pieces of evidence for particle dark matter. However, very little is known about the properties of the dark matter particle:

Spin: 0 or 1/2 or 1 or 3/2 (or possibly higher if composite)

Mass: 10^{-15} GeV $\longrightarrow$ 10^{15} GeV
(axions) (WIMPzillas)

Annihilation cross section into SM particles: 10^{-40} pb $\longrightarrow$ 10^{-5} pb
(gravitinos) (neutralinos)

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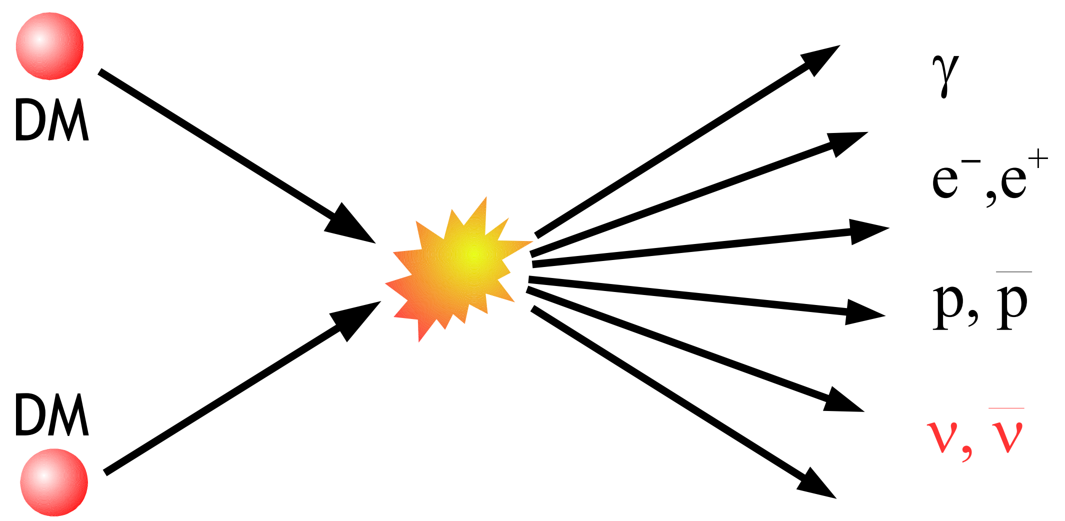
Constrained by neutrino telescopes

Limits on the annihilation cross-section

Neutrinos from dark matter annihilations in the Milky Way halo



Limits on the annihilation cross-section

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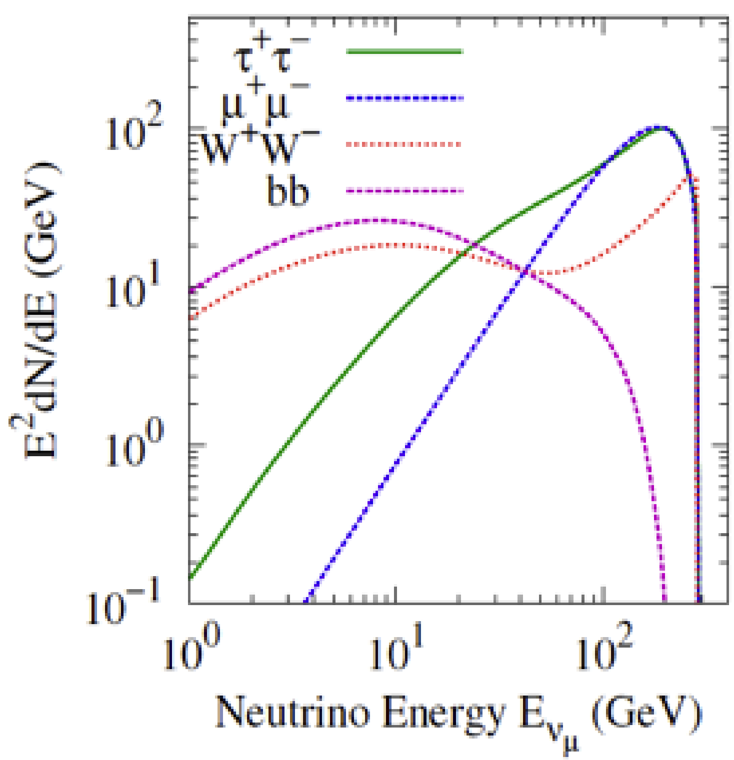
$$\frac{dJ_{\rm halo}}{dE_\nu} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\nu^f}{dE_\nu}B_f\right] \times \int_{\rm l.o.s.} \rho^2(\vec{l})\, d\vec{l}$$

Source term
(particle physics)

Line-of-sight integral
(astrophysics)



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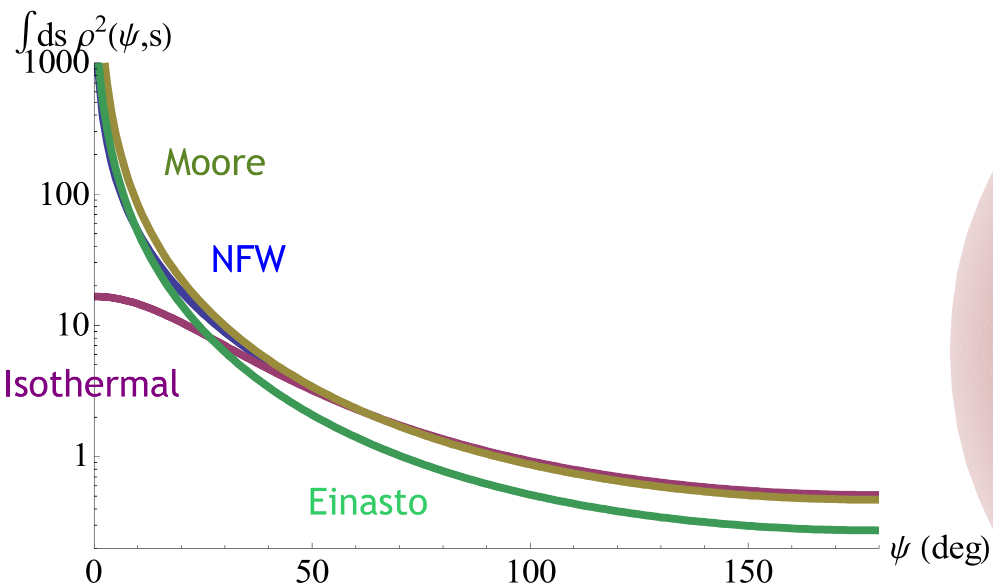

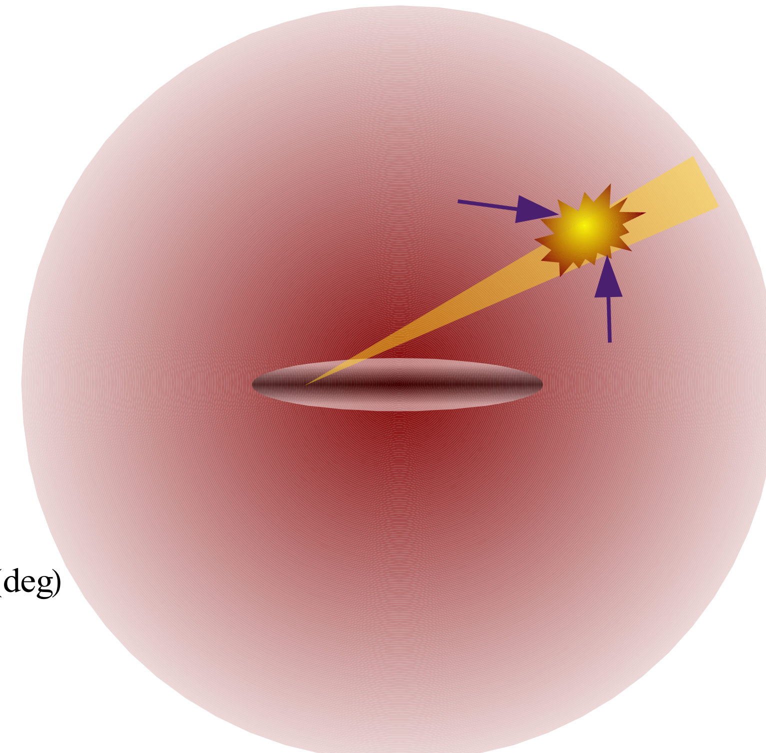

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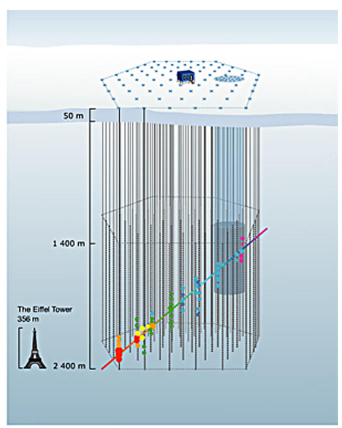
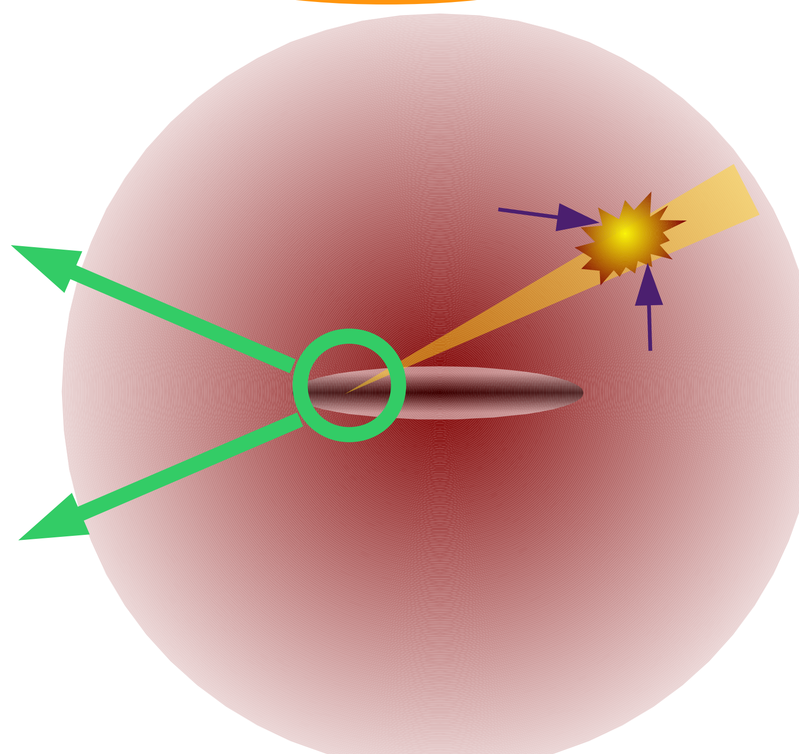
Source term
(particle physics)

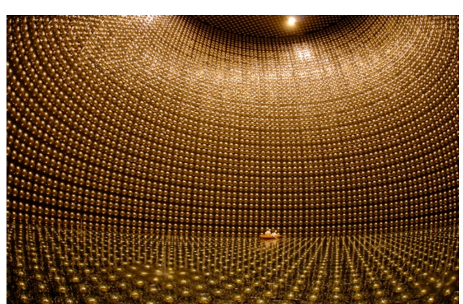
Line-of-sight integral
(astrophysics)

IceCube





SuperK



Limits on the annihilation cross-section

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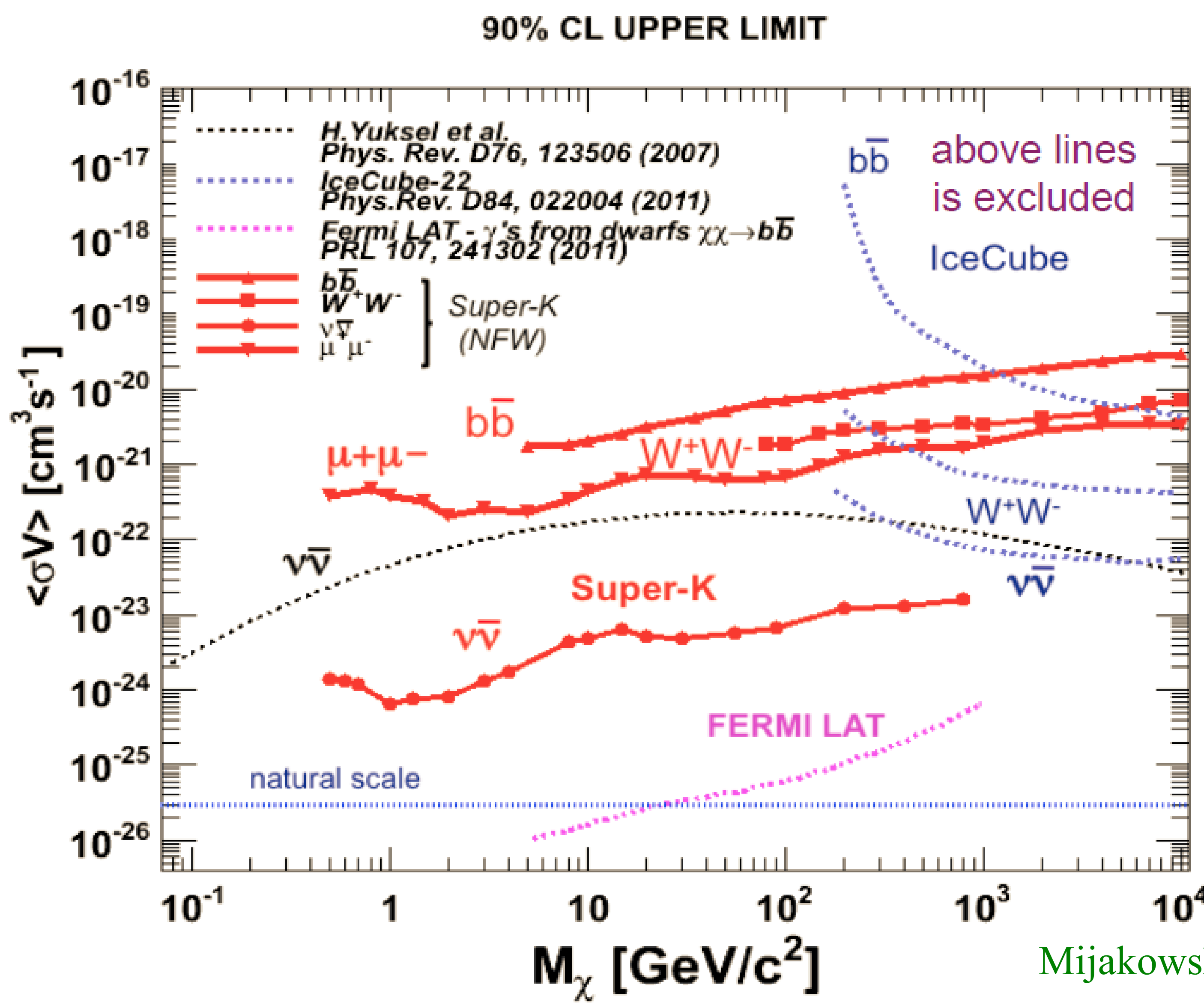

Mijakowski '13

Limits on the annihilation cross-section

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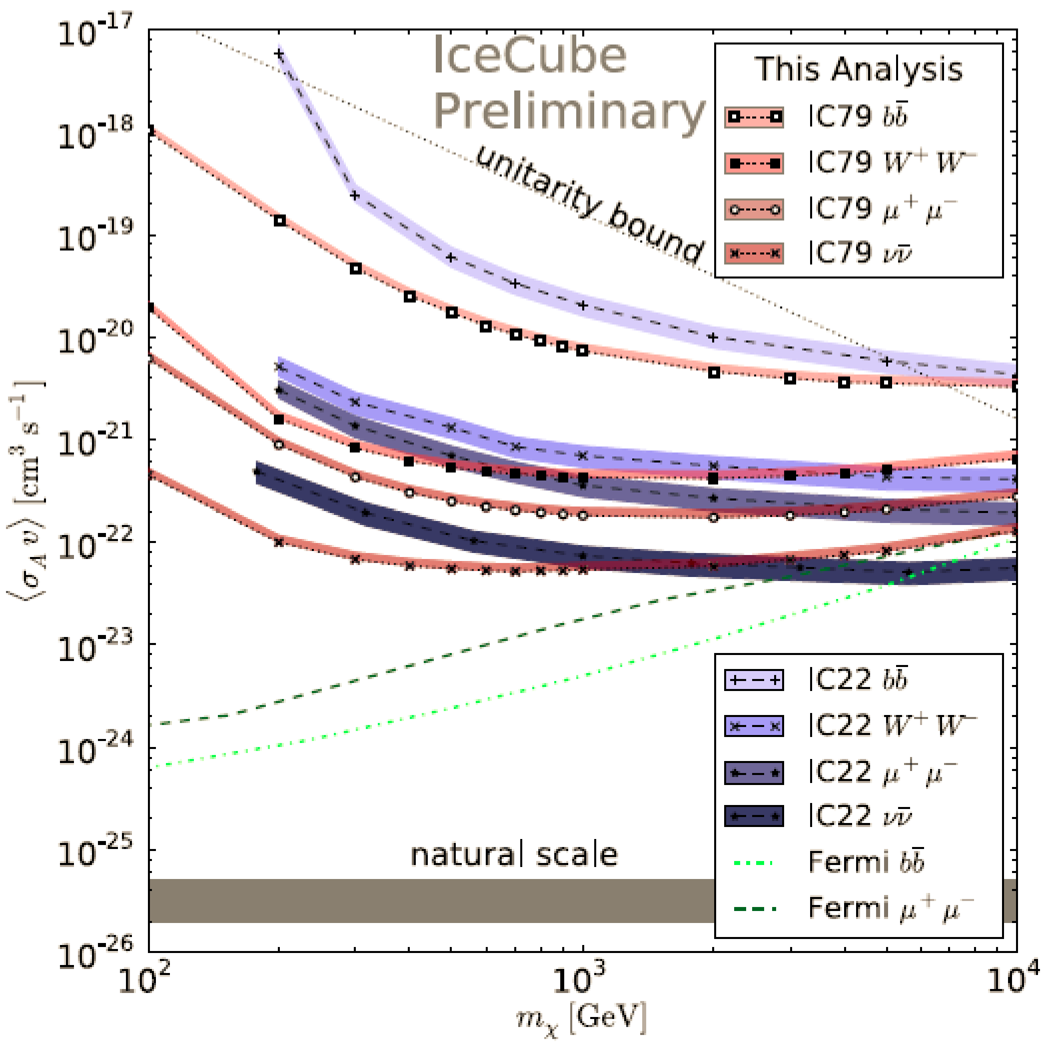
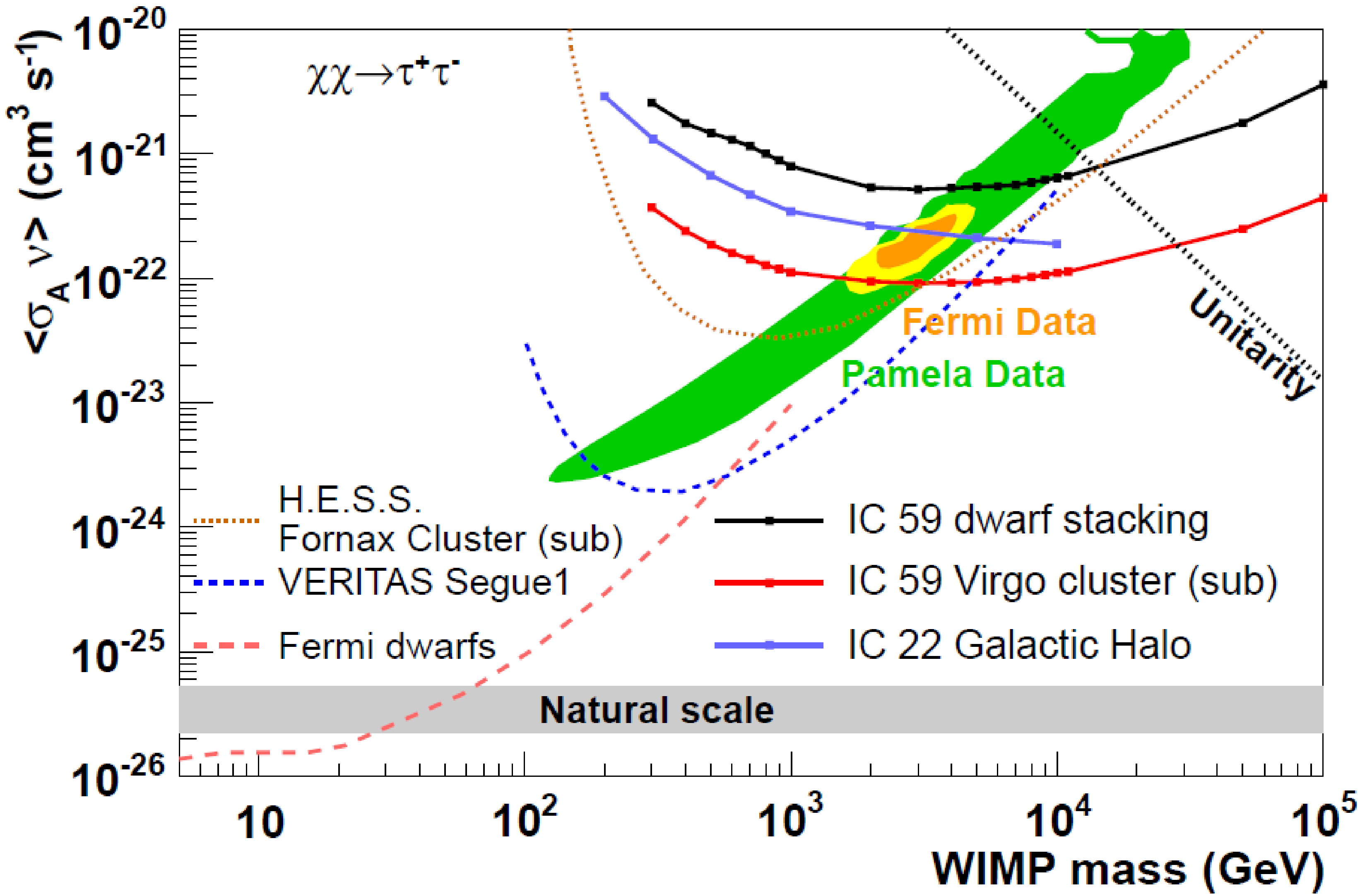


IceCube collaboration.
ICRC 2013

(For the preliminary limits from ANTARES, see talk by J.J. Hernández-Rey)

Limits on the annihilation cross-section

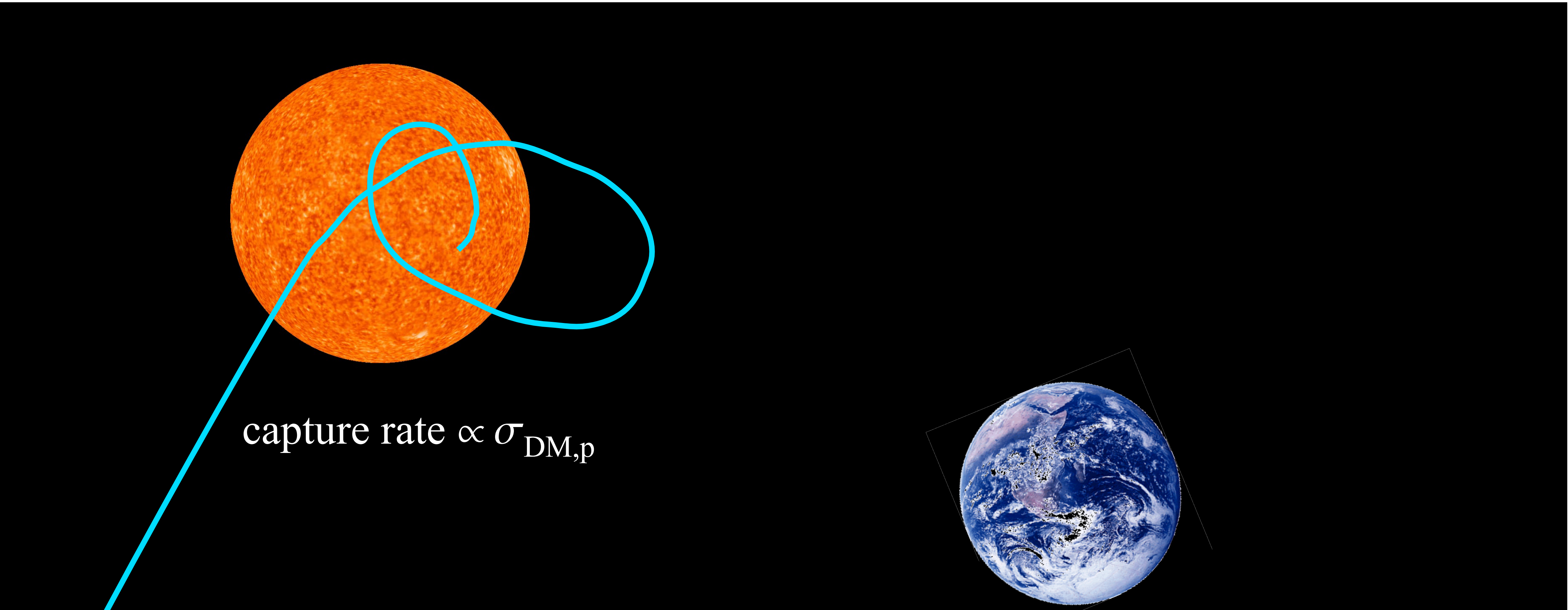
Neutrinos from dark matter annihilations in dwarf galaxies & galaxy clusters.



Aartsen et al., arXiv:1307.3473

Limits on the scattering cross-section

● If the dark matter particles have a "sizable" interaction cross section with ordinary matter, they can be captured inside the Sun (and inside the Earth).



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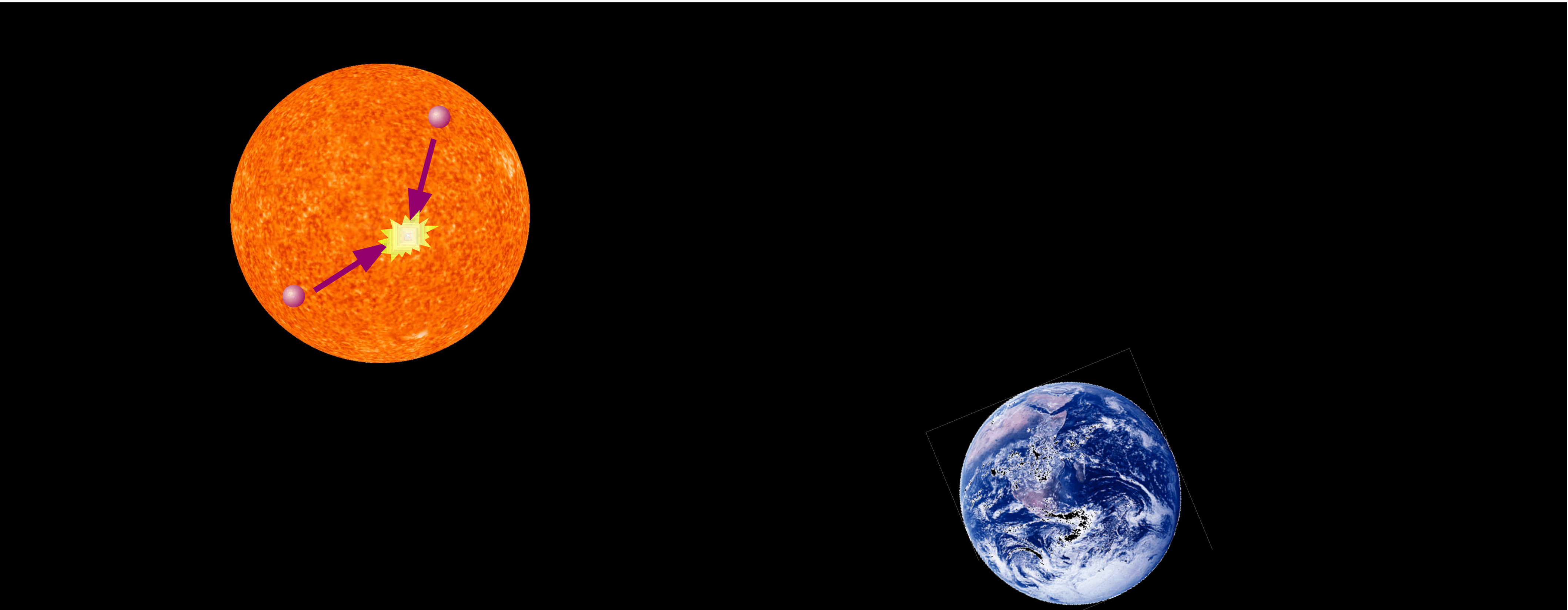

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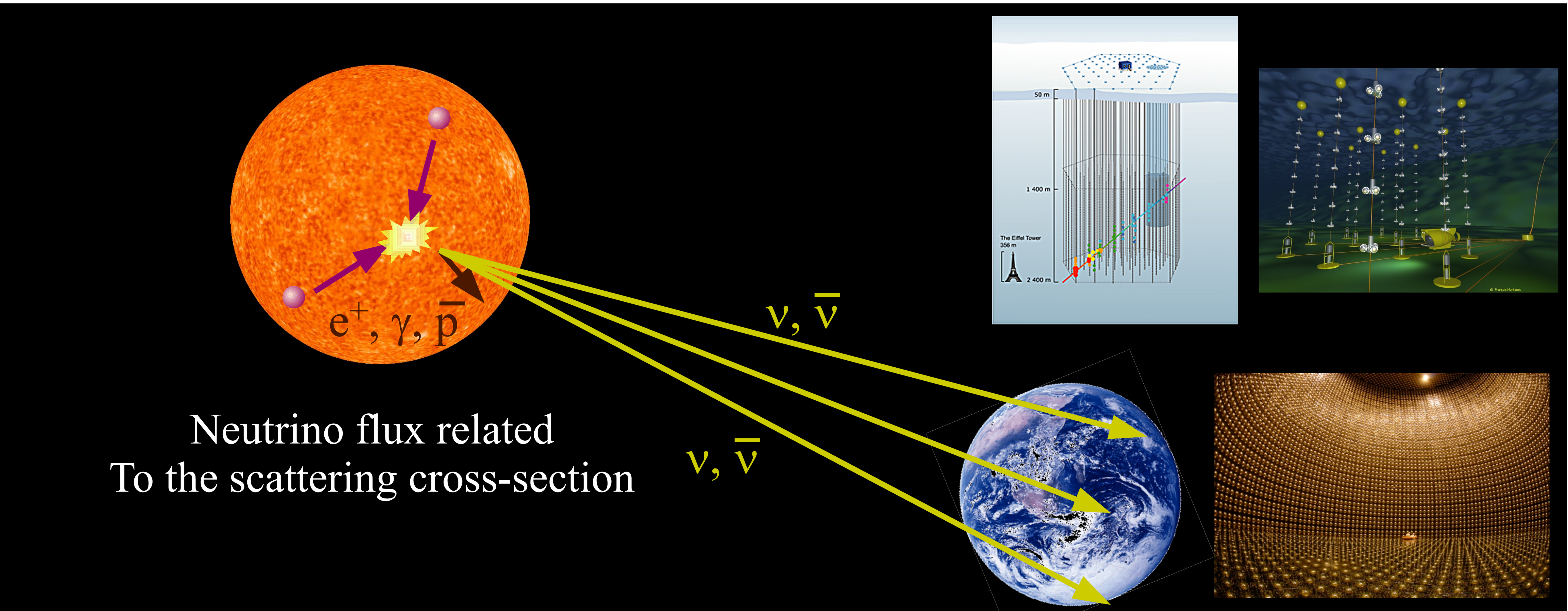
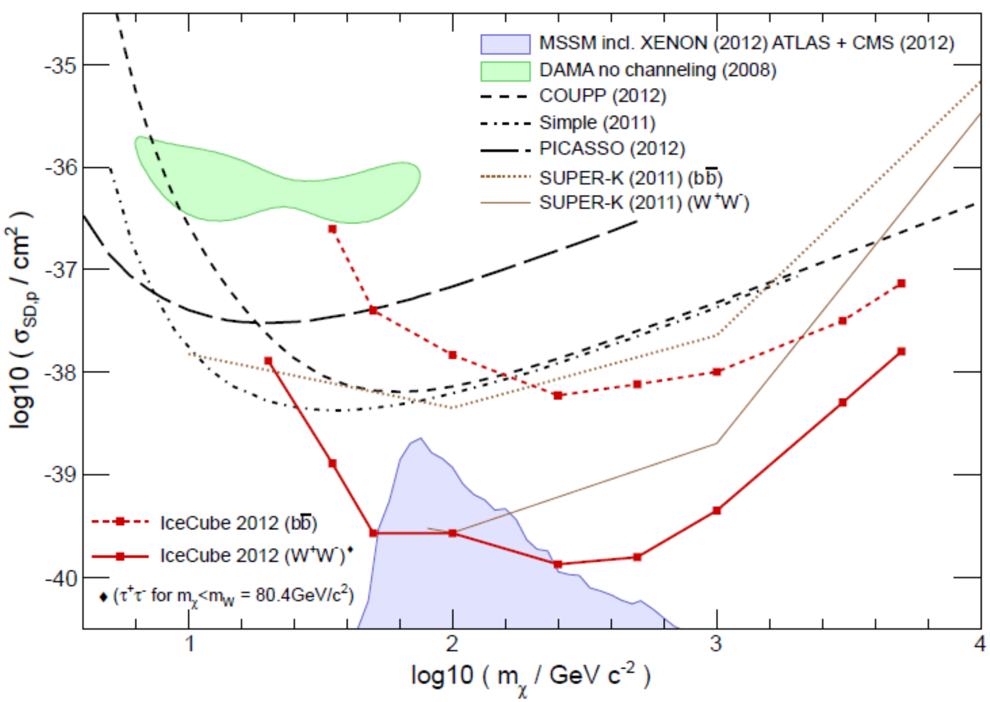
- DM particles captured inside the Sun can annihilate.

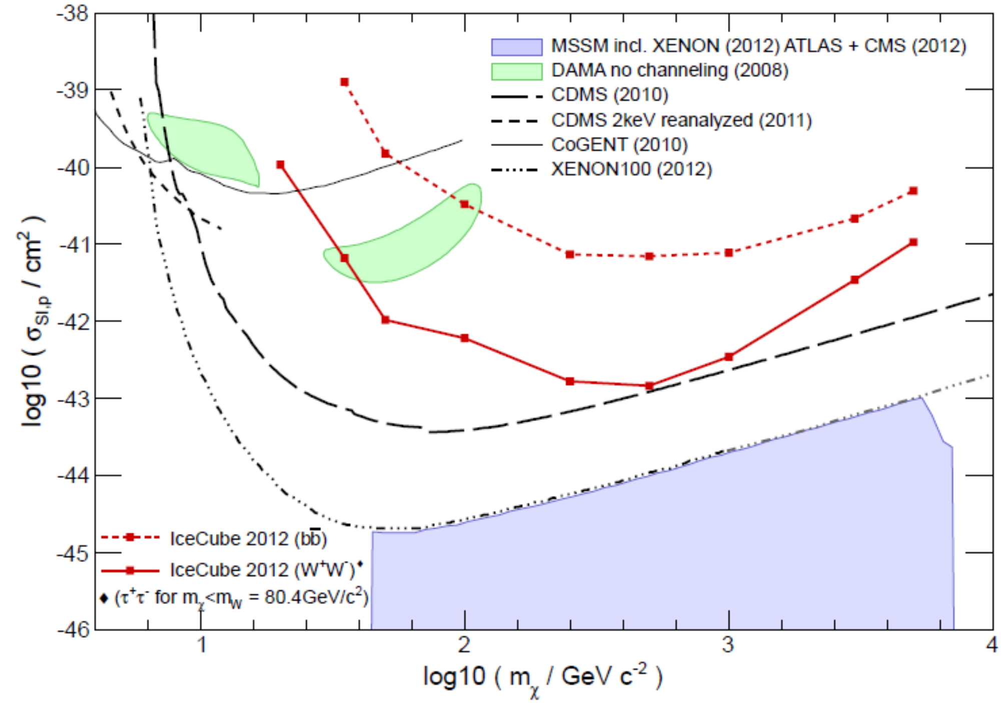
- The annihilation produces a neutrino flux which might be detected in neutrino observatories. All other annihilation products (gammas, positrons, antiprotons...) are absorbed before escaping the Sun.



Limits on the scattering cross-section

Limits on the spin-dependent and spin-independent scattering cross section of dark matter particles with protons.



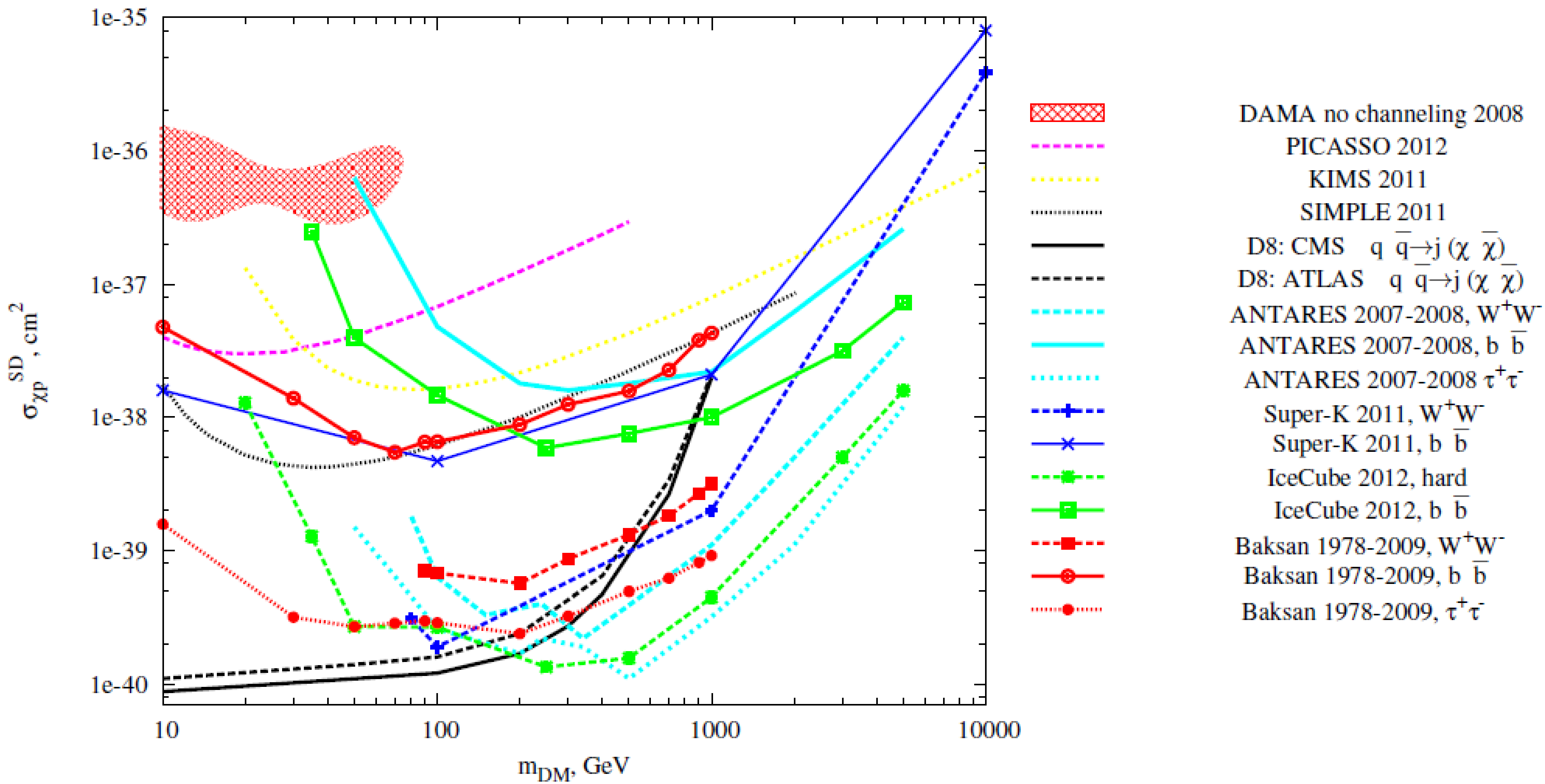


IceCube Collaboration
arXiv:1212.4097

(Super-Kamiokande limits from arXiv:1108.3384)

Limits on the scattering cross-section

Competitive limits from ANTARES and Baksan



Boliev et al.
arXiv:1301.1138

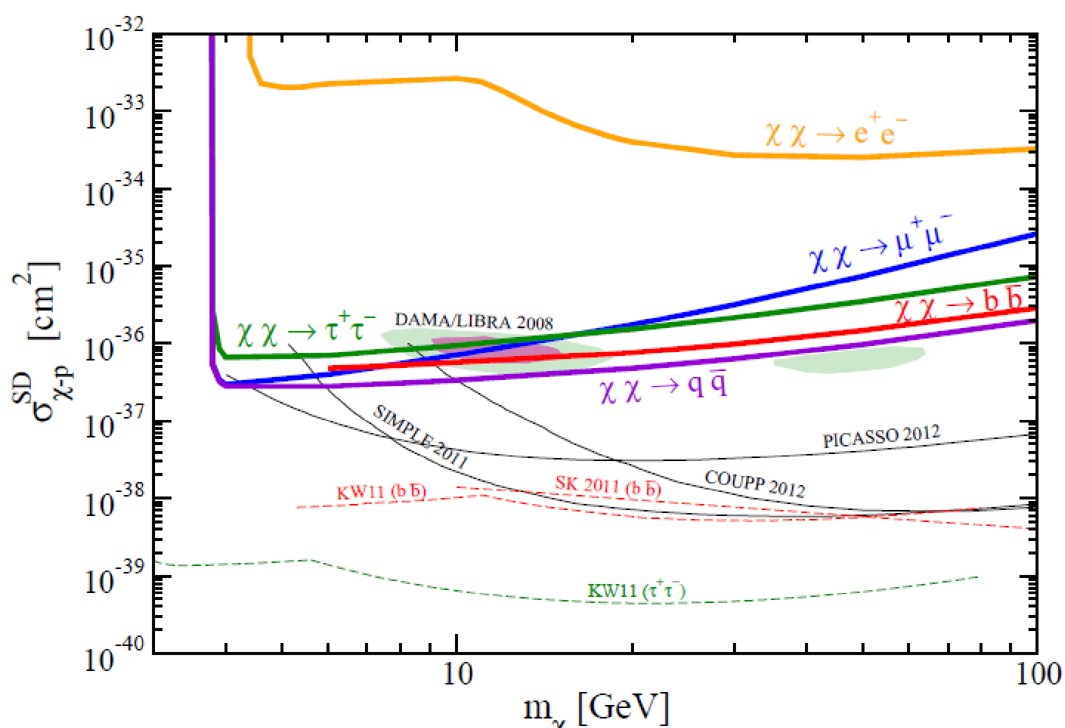
(ANTARES limits from arXiv:1212.2416)

Limits on the scattering cross-section

Limits on annihilations channels into light fermions.

The annihilation DM DM $\to q\,\bar{q}$, with q a light quark, does not produce high energy neutrinos. The light quark produces pions which are quickly stopped in the solar interior before decaying. This annihilation channel produces only MeV neutrinos.

The MeV neutrinos could be detected at Super-Kamiokande



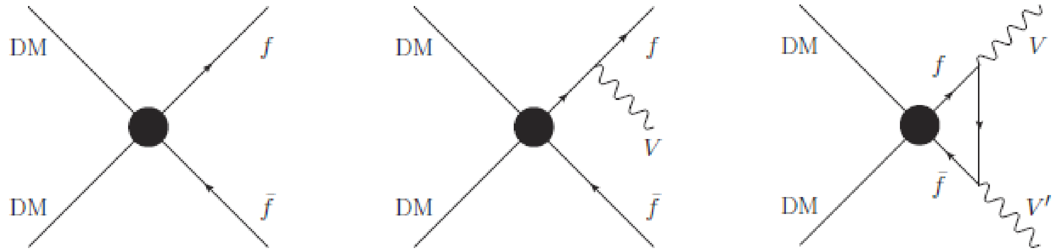
Bernal, Martín-Albo, Palomares-Ruiz, arXiv:1208.0834

See also Rott, Siegal-Gaskins, Beacom, arXiv:1208.0827

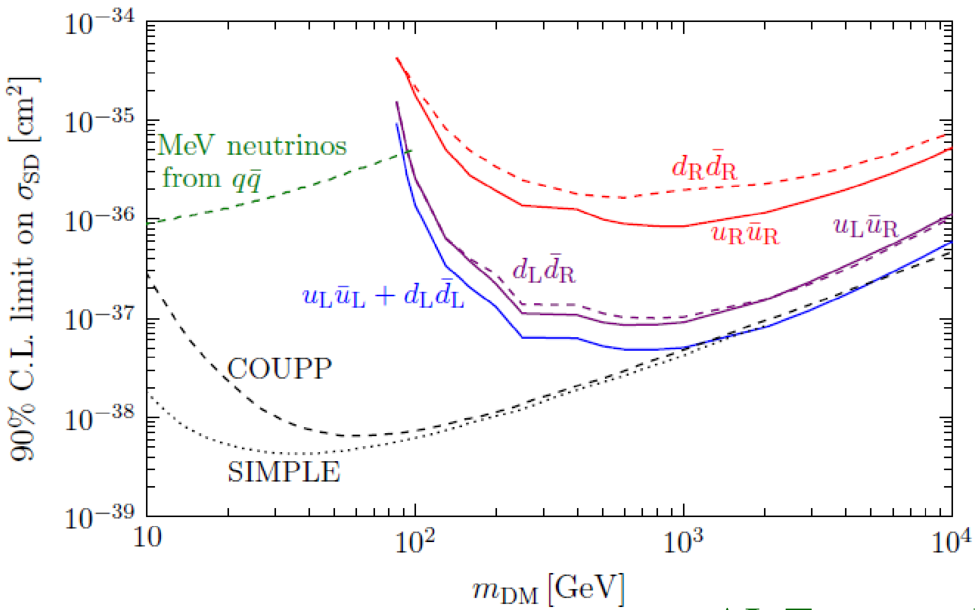
Limits on the scattering cross-section

Limits on annihilations channels into light fermions.

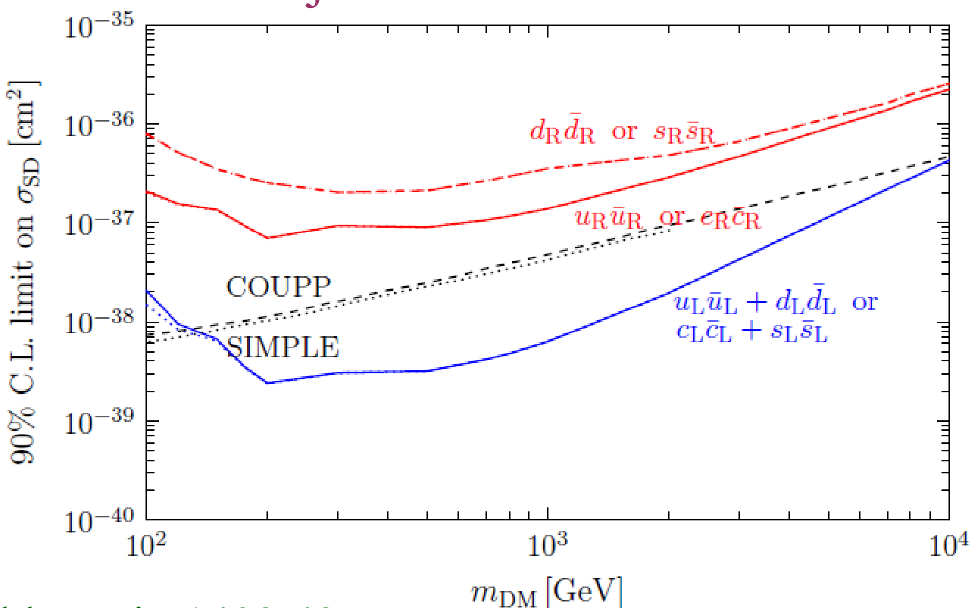
The higher order annihilations DM DM → q $\bar{q}$ Z or DM DM → Z Z do produce high energy neutrinos via the decay of the Z boson



Dirac dark matter

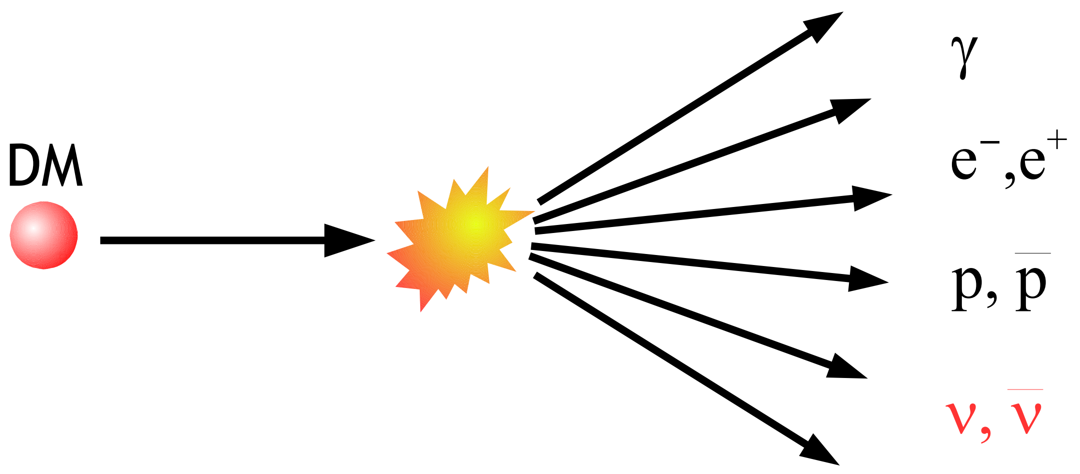


Majorana/scalar dark matter



AI, Totzauer, Wild, arXiv:1402.4375

Limits on the dark matter lifetime



Limits on the dark matter lifetime

Neutrinos from dark matter decay in the galactic halo

$$\frac{dJ_{\rm halo}}{dE_\nu} = \frac{1}{4\pi}\left[\frac{1}{\tau_{\rm DM}\, m_{\rm DM}}\sum_f \frac{dN_\nu^f}{dE_\nu} B_f\right] \times \int_{\rm l.o.s.} \rho(\vec{l})\, d\vec{l}$$

Source term (particle physics)

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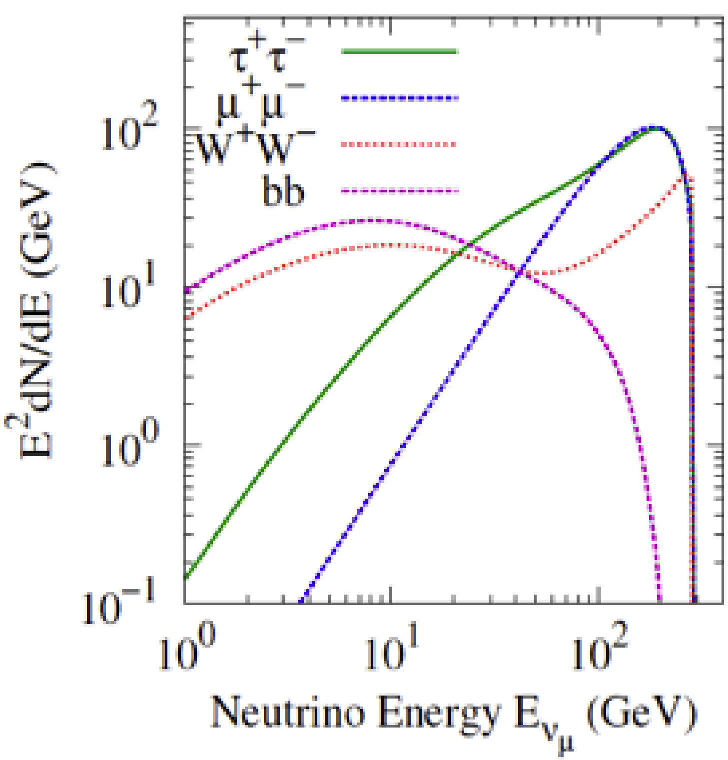

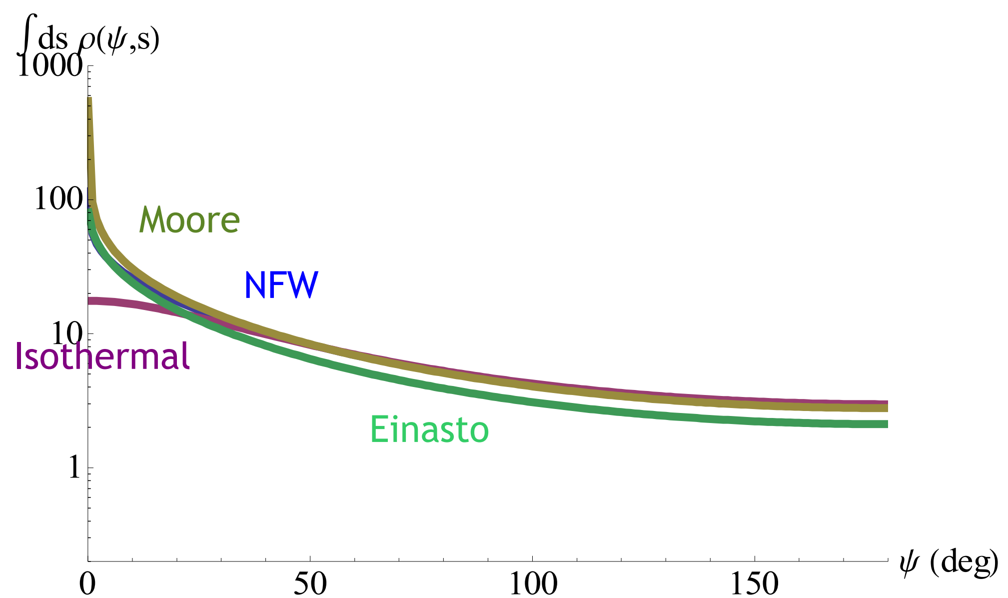

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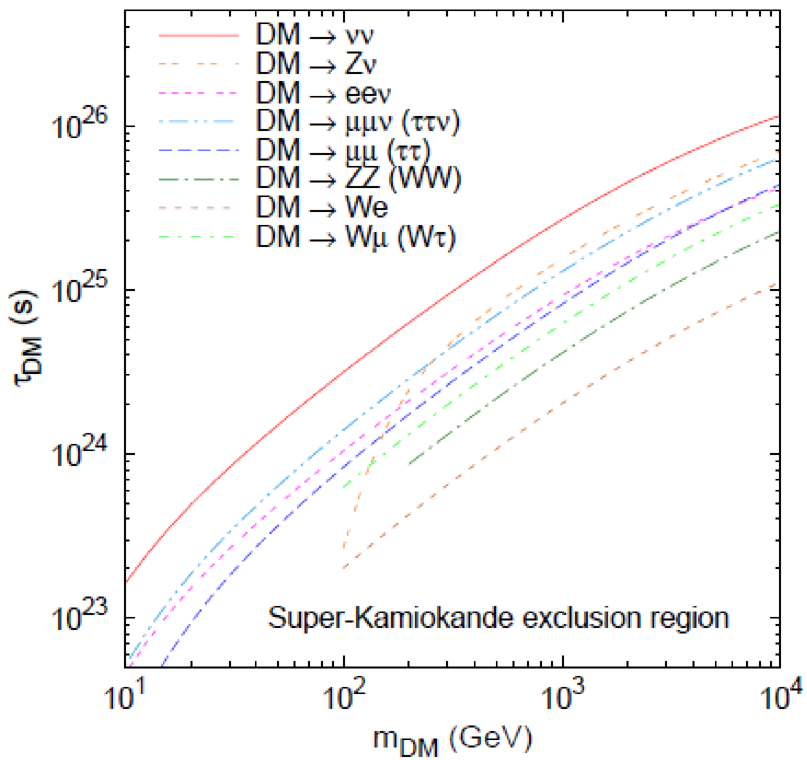
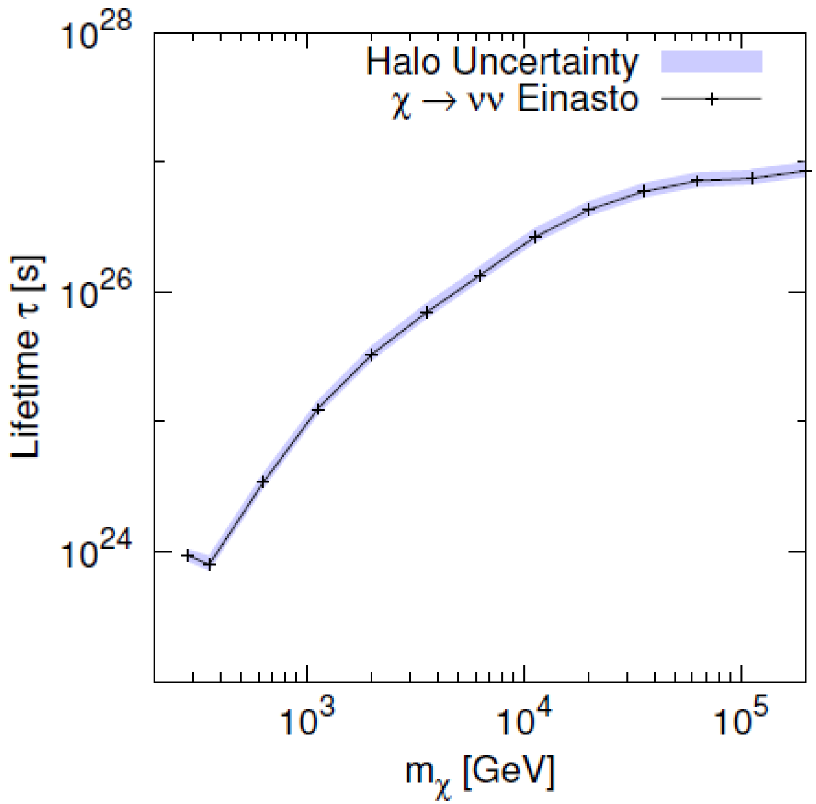


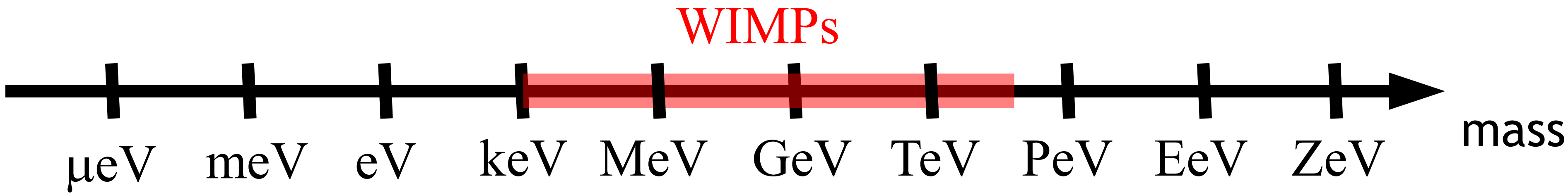
Covi, Grefe, AI, Tran
arXiv:0912.3521



IceCube collaboration
ArXiv:1101.3349

Limits on the dark matter lifetime

Opening up the dark matter mass window...



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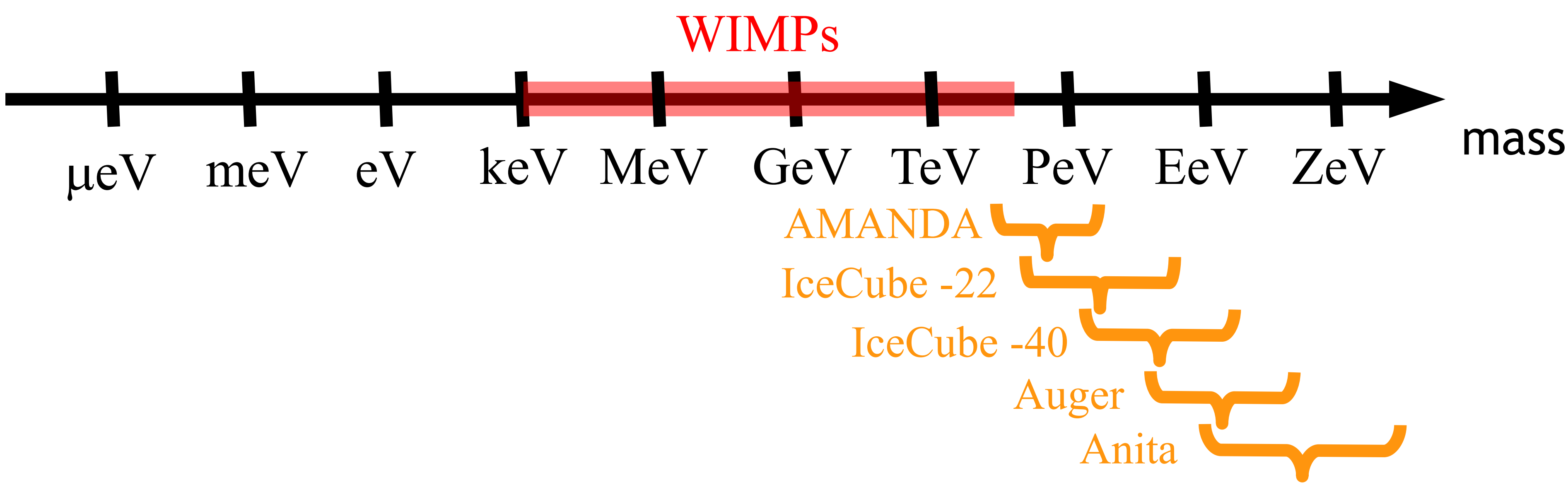

	$E_\nu^{min} - E_\nu^{max}$ (TeV)	N_{bg}	N_{sig}	N_{limit}	
AMANDA	$16 - 2.5 \times 10^3$	6	7	5.4	arXiv:0705.1315
IceCube-22	$340 - 2 \times 10^5$	0.6	3	6.1	arXiv:1202.4564
IceCube-40	$2 \times 10^3 - 6.3 \times 10^6$	0.1	0	2.3	arXiv:1103.4250
Auger	$10^5 - 10^8$	0	0	2.3	arXiv:1202.1493
ANITA	$10^6 - 3.2 \times 10^{11}$	0.97	1	3.3	arXiv:1011.5004

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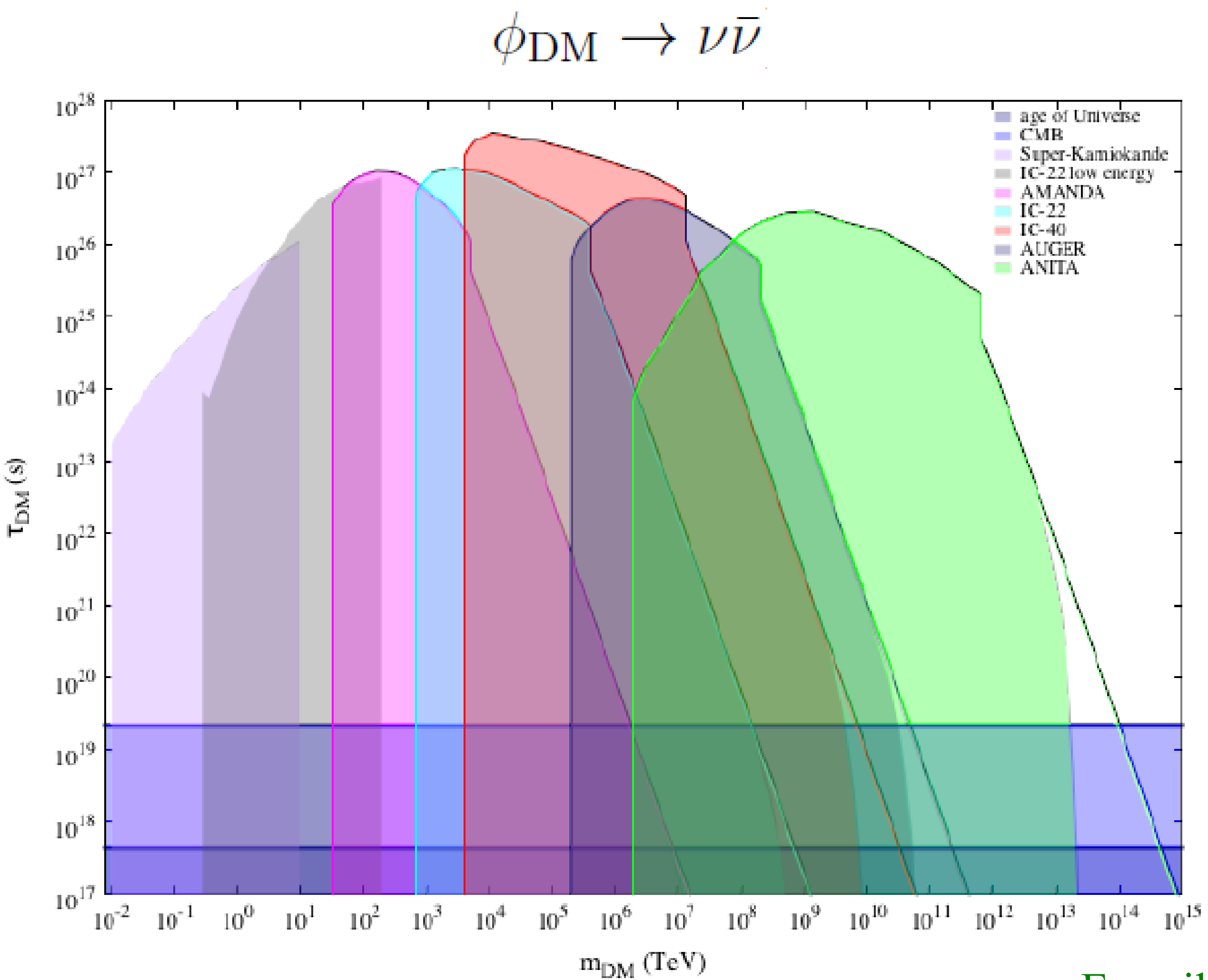
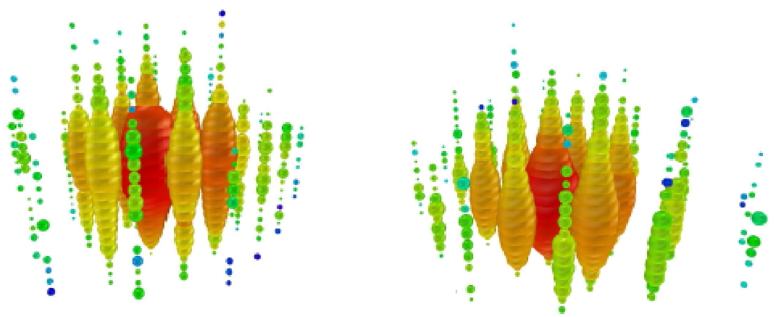


Esmaili, AI, Peres
arXiv:1205.5281

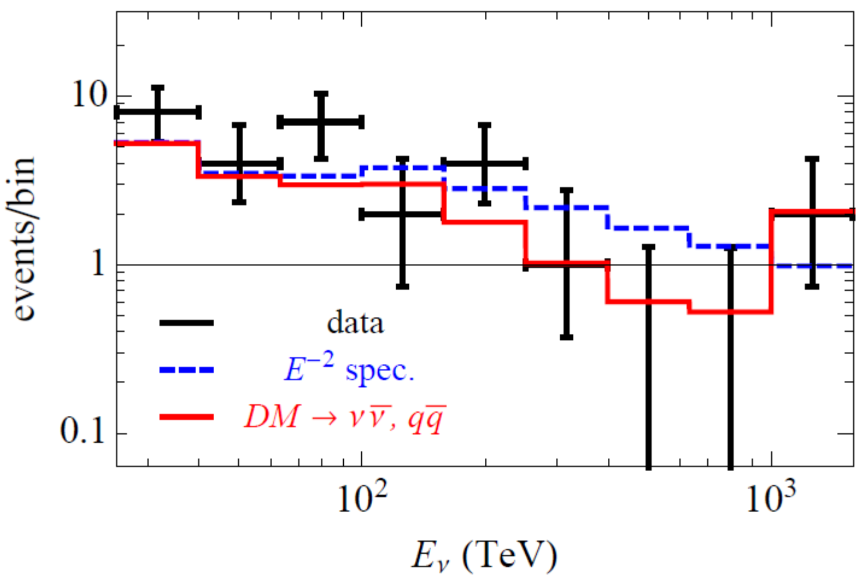
Limits on the dark matter lifetime

Decaying dark matter as the origin of the IceCube PeV neutrinos?



IceCube Collaboration, arXiv:1304.5356

$m_{DM} = 3.2\,\text{PeV} \quad \tau_{DM} = 2 \times 10^{27}\,\text{s}$



Esmaili, Serpico, arXiv:1308.1105
Feldstein et al, arXiv:1303.7320

Limits on the dark matter lifetime

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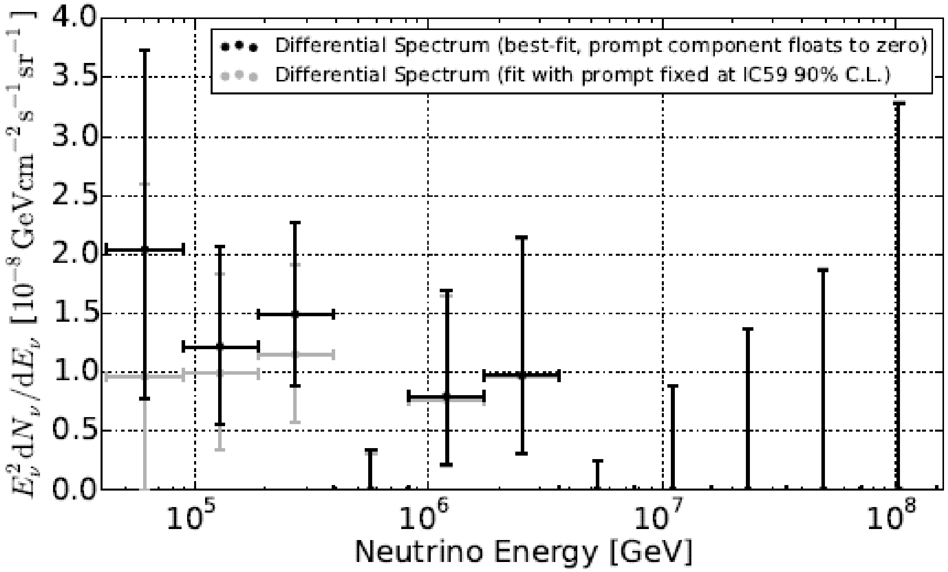

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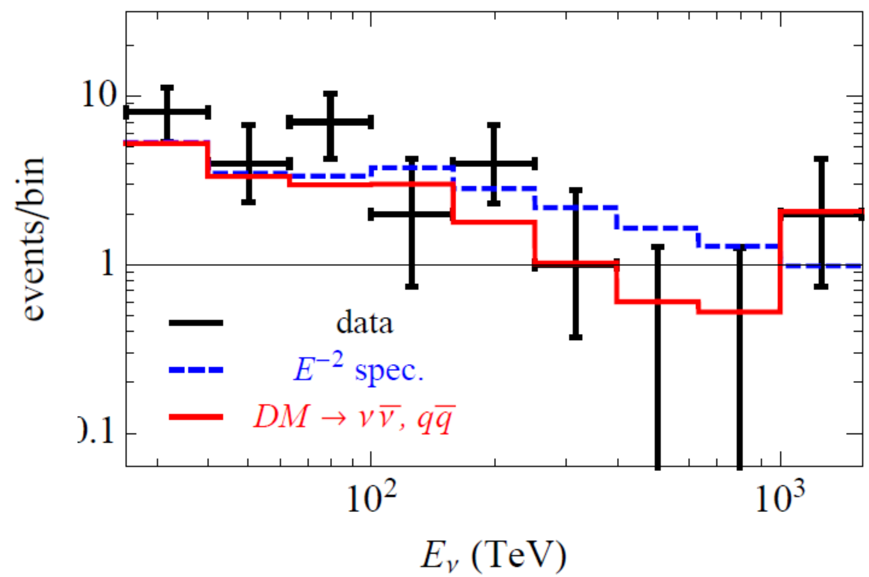

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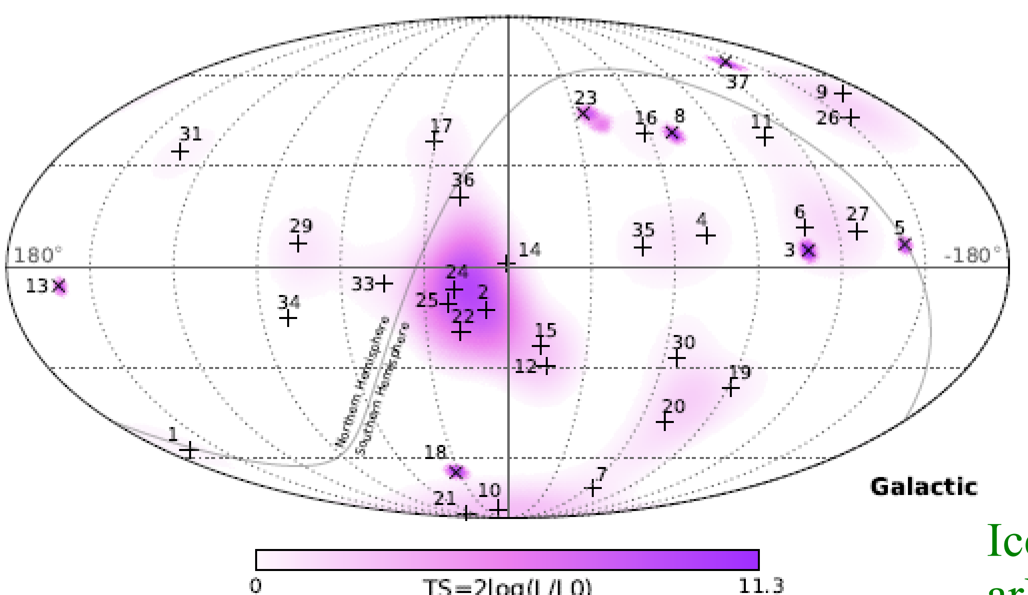

IceCube Collaboration, arXiv:1405.5303

Conclusions

- The three known active neutrinos contribute to the energy-density of the Universe (approx. 0.3%), but cannot account for all the dark matter.
- A simple extension of the SM accounting for the DM consists in introducing one sterile neutrino with mass ~ 1 – 50 keV. Strong limits on the model from X-ray observations (and possible signals?).
- The annihilation and decay of dark matter particles generically produce neutrinos. ↪ Limits on DM properties from neutrino telescopes.
- The limits are complementary to those from other experiments, although usually weaker. Except:

  - Annihilation cross section of WIMPs with mass few TeV – 100 TeV.
  - Spin-dependent scattering cross section WIMP-proton.
  - Lifetime of DM particles with mass few TeV – 10^{16} GeV.