Indirect Dark Matter searches with Neutrinos

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IFIC, CSIC-U. València

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XXIX INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS

DARK MATTER AT NEUTRINO 2020

Neutrinos as dark matter

Neutrinos as dark matter

Talk by
K. Abazajian

Neutrinos with
dark matter
detectors

Talk by
J. Monroe

Neutrinos as dark matter

DARK MATTER

Talk by
K. Abazajian

Neutrinos with dark matter detectors

Talk by
J. Monroe

TRINO
20

Talk by
C. Frugiuele

Dark sector with fixed-target experiments

DARK MATTER

Neutrinos as dark matter

Talk by
K. Abazajian

Neutrinos with dark matter detectors

Talk by
J. Monroe

This talk

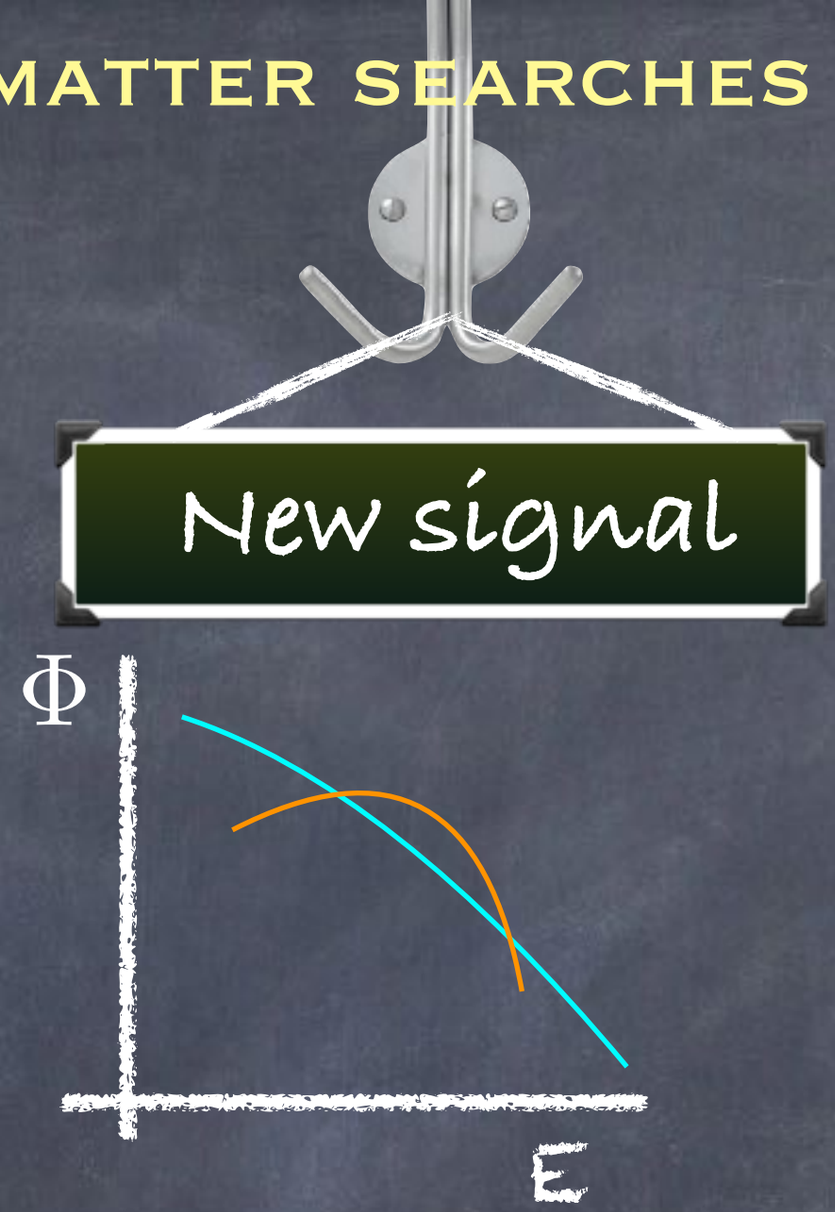
Indirect dark matter with neutrino (detectors)

Talk by
C. Frugiuele

Dark sector with fixed-target experiments

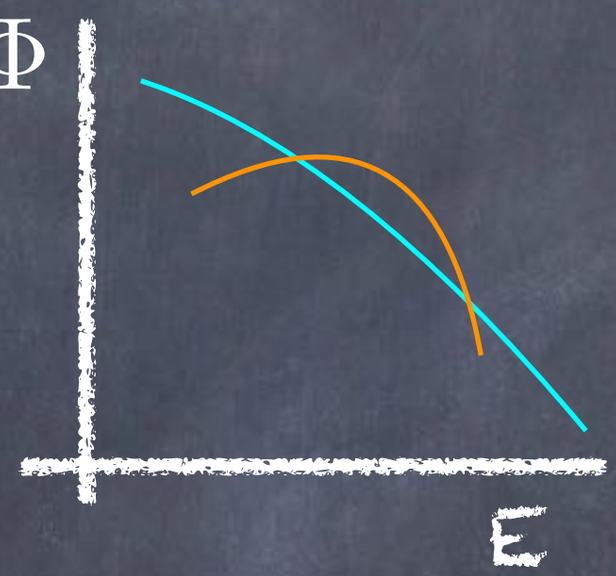
Indirect dark matter searches with neutrinos

Indirect dark matter searches with neutrinos



Indirect dark matter searches with neutrinos

New signal



Features on known spectra

Indirect dark matter searches with neutrinos

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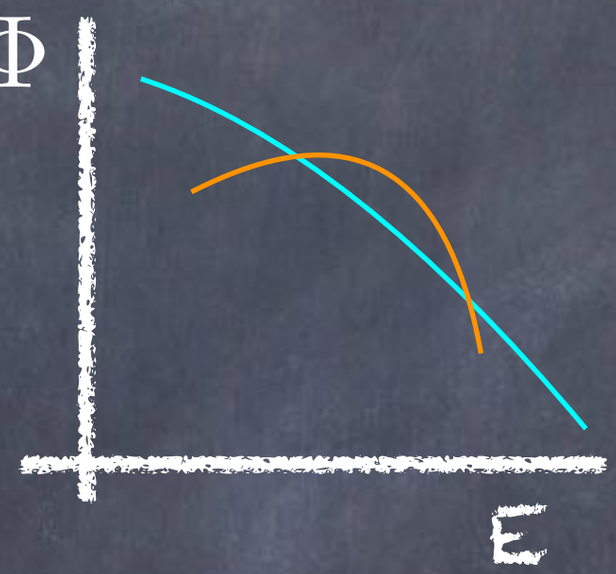

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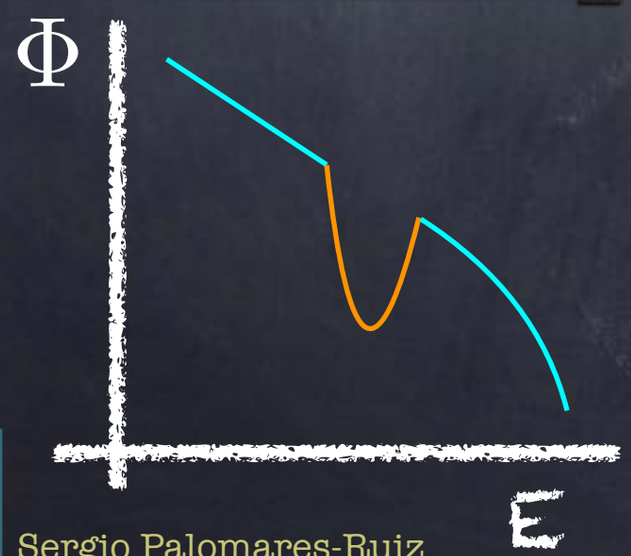
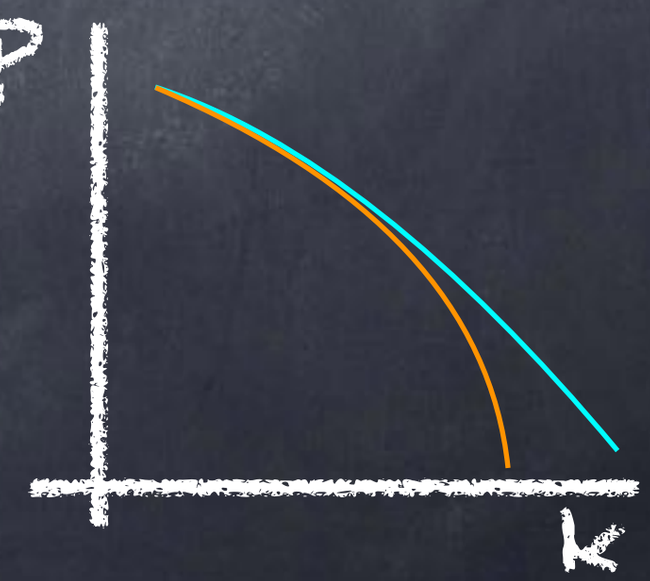
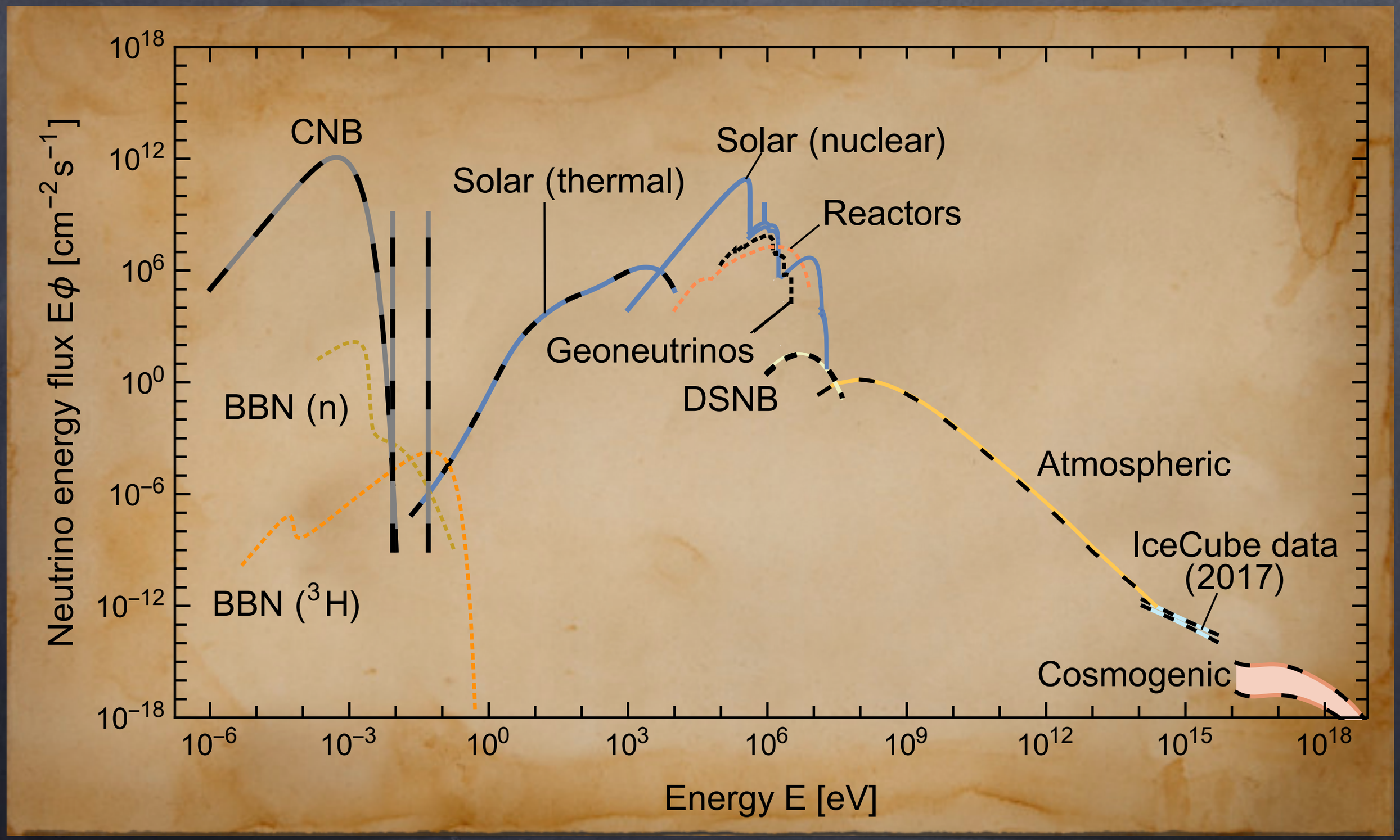


Cosmo/Astro effects

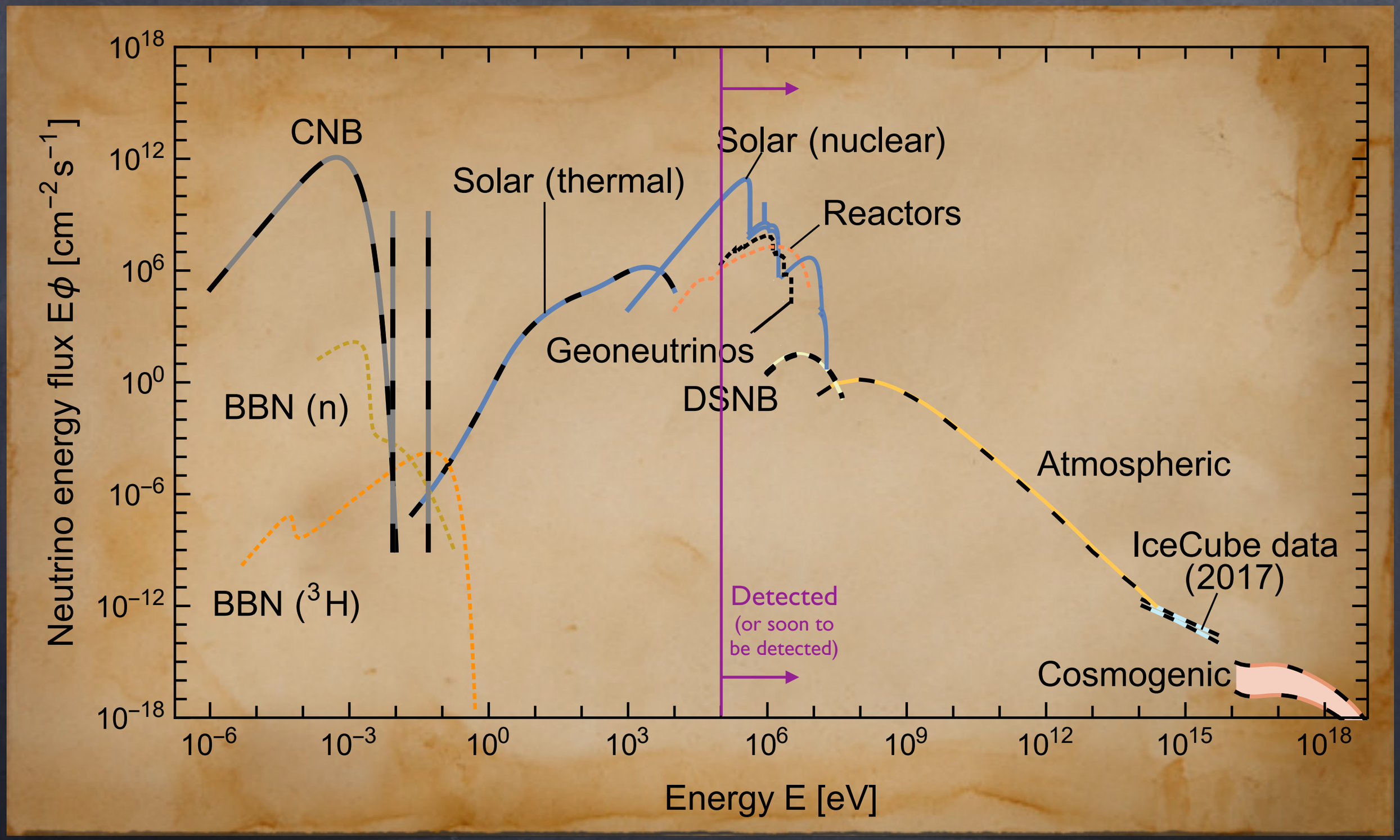


(Standard) Grand Unified Neutrino Spectrum



E. Vitagliano, I. Tamborra and G. Raffelt, arXiv:1910.11878

(Standard) Grand Unified Neutrino Spectrum



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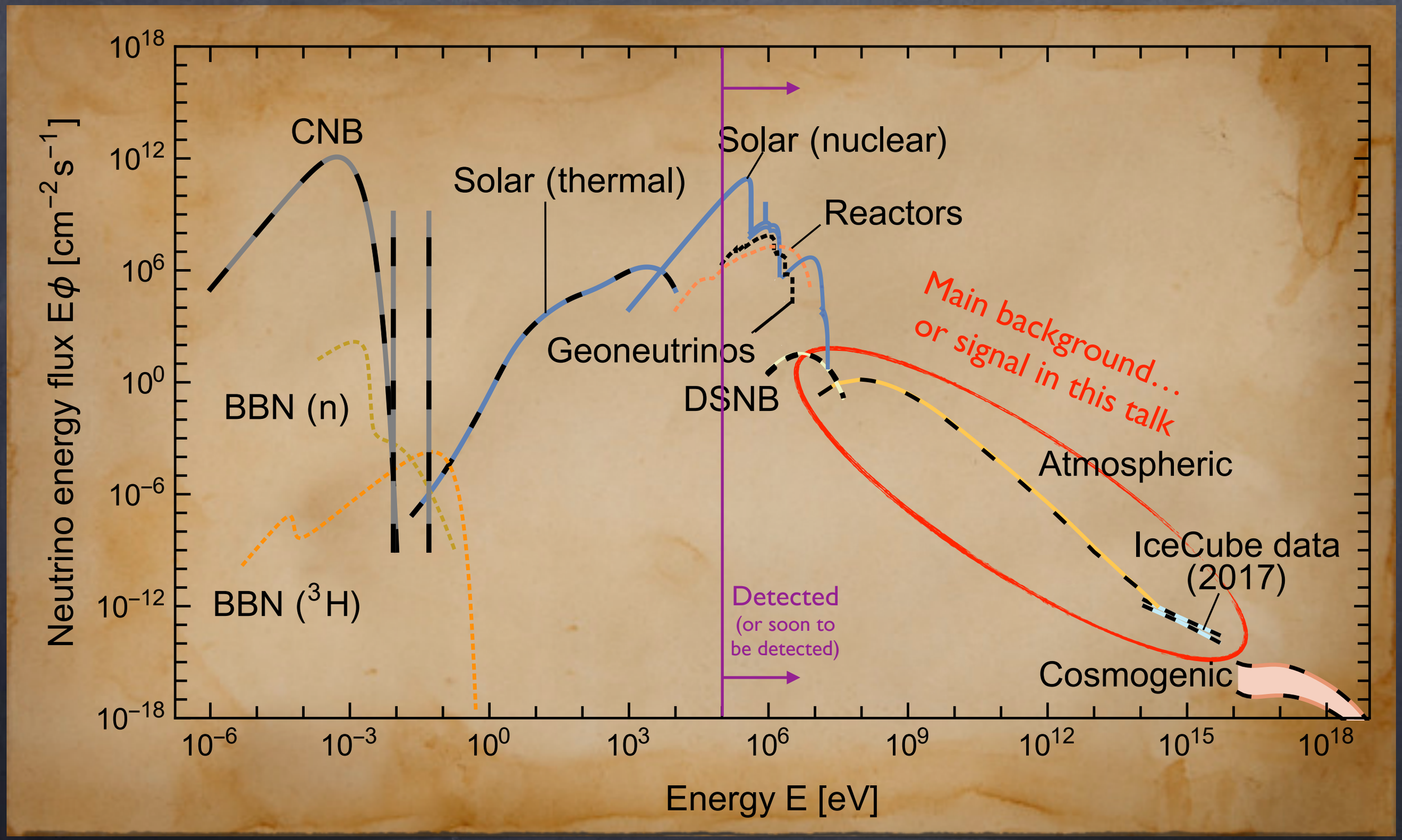

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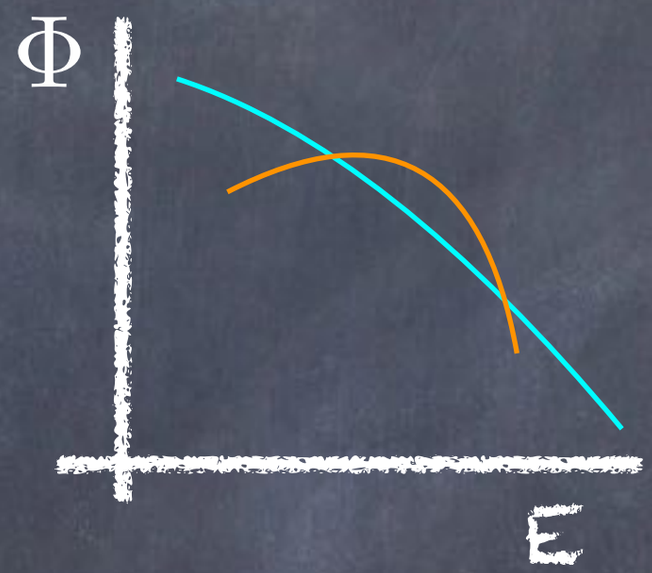
Annihilation of captured DM in the Sun/Earth

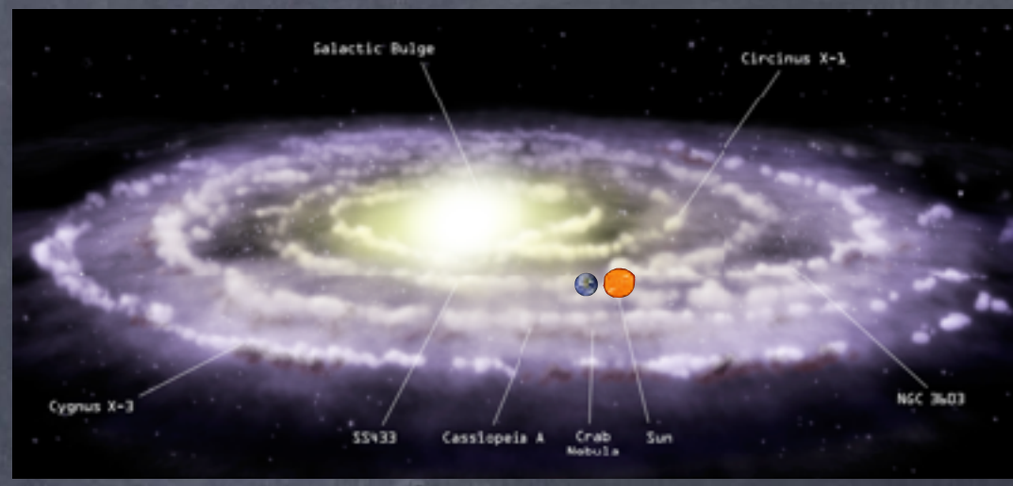
Sensitive to scattering cross section
Only for m > few GeV

New signal



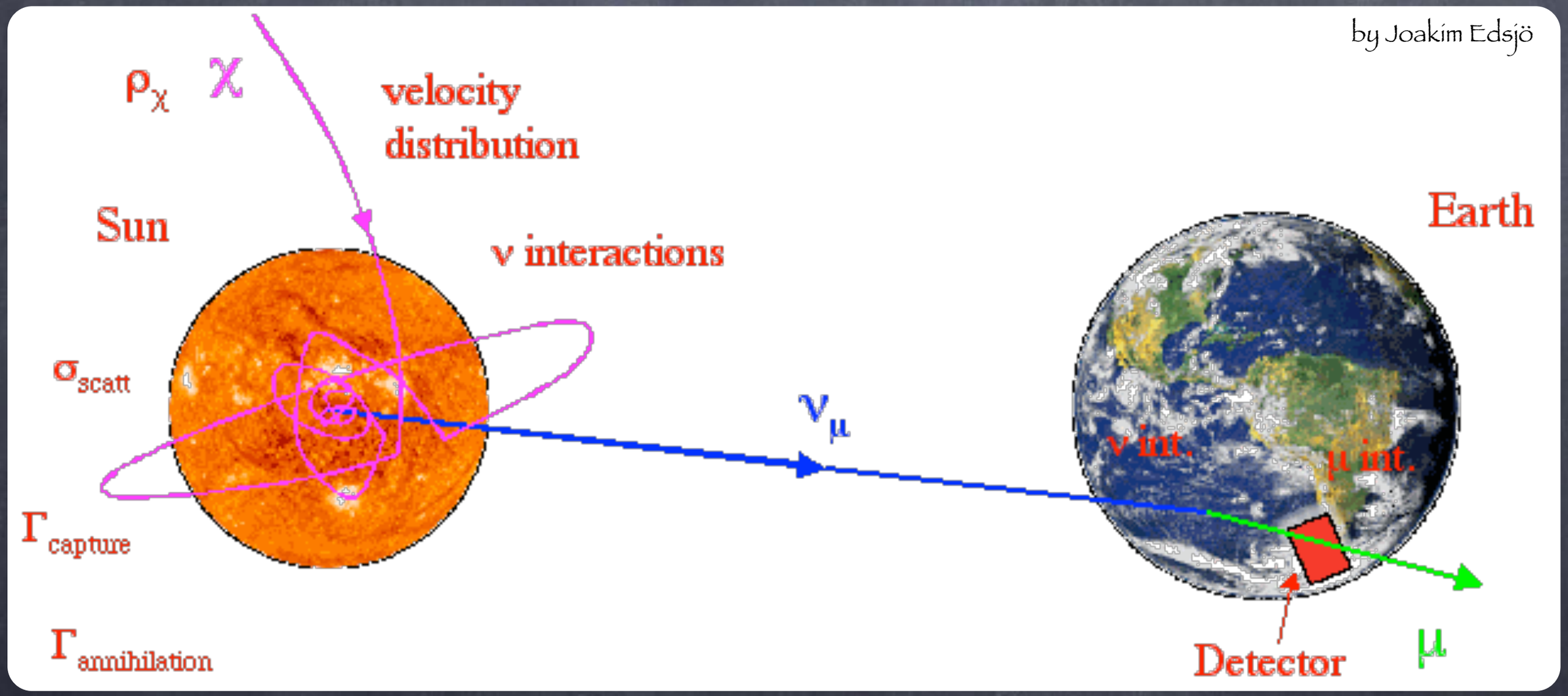
Annihilations/decays in halos

Sensitive to annihilation cross section (link to thermal production in the early Universe?) and lifetime



DM annihilations or decays

Dark Matter capture in the Sun/Earth



J. Silk, K. A. Olive and M. Srednicki, Phys. Rev. Lett. 55:257, 1985
T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986
M. Srednicki, K. A. Olive and J. Silk, Phys. B279:804, 1987
K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987

Dark Matter capture in the Sun/Earth

- DM particles elastically scatter with the nuclei of the Sun to a velocity smaller than the escape velocity, and they can get gravitationally bound and finally trapped inside

Additional scatterings give rise to an isothermal distribution

$$C_\odot \simeq 9\times10^{23}\,s^{-1}\left(\frac{\rho_o}{0.3\ \mathrm{GeV}/\mathrm{cm}^3}\right)\left(\frac{270\ \mathrm{km}/s}{\bar{v}_{local}}\right)^3\left(\frac{\sigma_{SD}}{10^{-3}\ \mathrm{pb}}\right)\left(\frac{50\ \mathrm{GeV}}{m_\chi}\right)^2$$

- Trapped DM particles can annihilate into SM particles
- After some time, annihilation and capture rates typically equilibrate

$$\Gamma(t_\odot) \simeq \frac{1}{2}C_\odot \tanh^2\left(\frac{t_\odot}{t_\odot}\right) \simeq \frac{1}{2}C_\odot$$

- Only neutrinos can escape

J. Silk, K. A. Olive and M. Srednicki, Phys. Rev. Lett. 55:257, 1985
T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986
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Evolution equation

A. Gould, Astrophys. J. 321:571, 1987; K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987; A. Gould, Astrophys. J. 321:560, 1987

$$\frac{dN}{dt} = C_\odot - A_\odot N^2 - E_\odot N$$

(relevant for m < few GeV)

Capture rate
(velocity distribution and scattering cross section)

Annihilation rate
(annihilation cross section)

Evaporation rate
(distribution in the Sun and scattering cross section)

$$N(t_\odot) = \frac{1}{\tau_\odot A_\odot} \frac{\tanh\left(\sqrt{1+(E_\odot\tau_\odot/2)}\,(t_\odot/\tau_\odot)\right)}{\sqrt{1+(E_\odot\tau_\odot/2)} + (E_\odot\tau_\odot/2)\tanh\left(\sqrt{1+(E_\odot\tau_\odot/2)}\,(t_\odot/\tau_\odot)\right)} \quad ; \quad \tau_\odot \equiv \frac{1}{\sqrt{C_\odot A_\odot}}$$

$$\Gamma(t_\odot) = \frac{1}{2} A_\odot N(t_\odot)^2$$

$$E_\odot \approx 0 \rightarrow \Gamma(t_\odot) \simeq \frac{1}{2} C_\odot \tanh^2(t_\odot/\tau_\odot)$$

→ Neutrino spectra in the Sun → Propagation through the Sun and to the Earth: absorption and oscillations

Poster #434: Q. Liu

Evolution equation

A. Gould, Astrophys. J. 321:571, 1987; K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987; A. Gould, Astrophys. J. 321:560, 1987

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Poster #434: Q. Liu

Limits from the Sun

SK: (3902.7 + 4206.7) days

K. Choi et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 114:141301, 2015

IceCube: 532 days

M. G. Aartsen et al. [IceCube Collaboration], Eur. Phys. J. C77:146, 2017

Baksan: 24.12 yrs

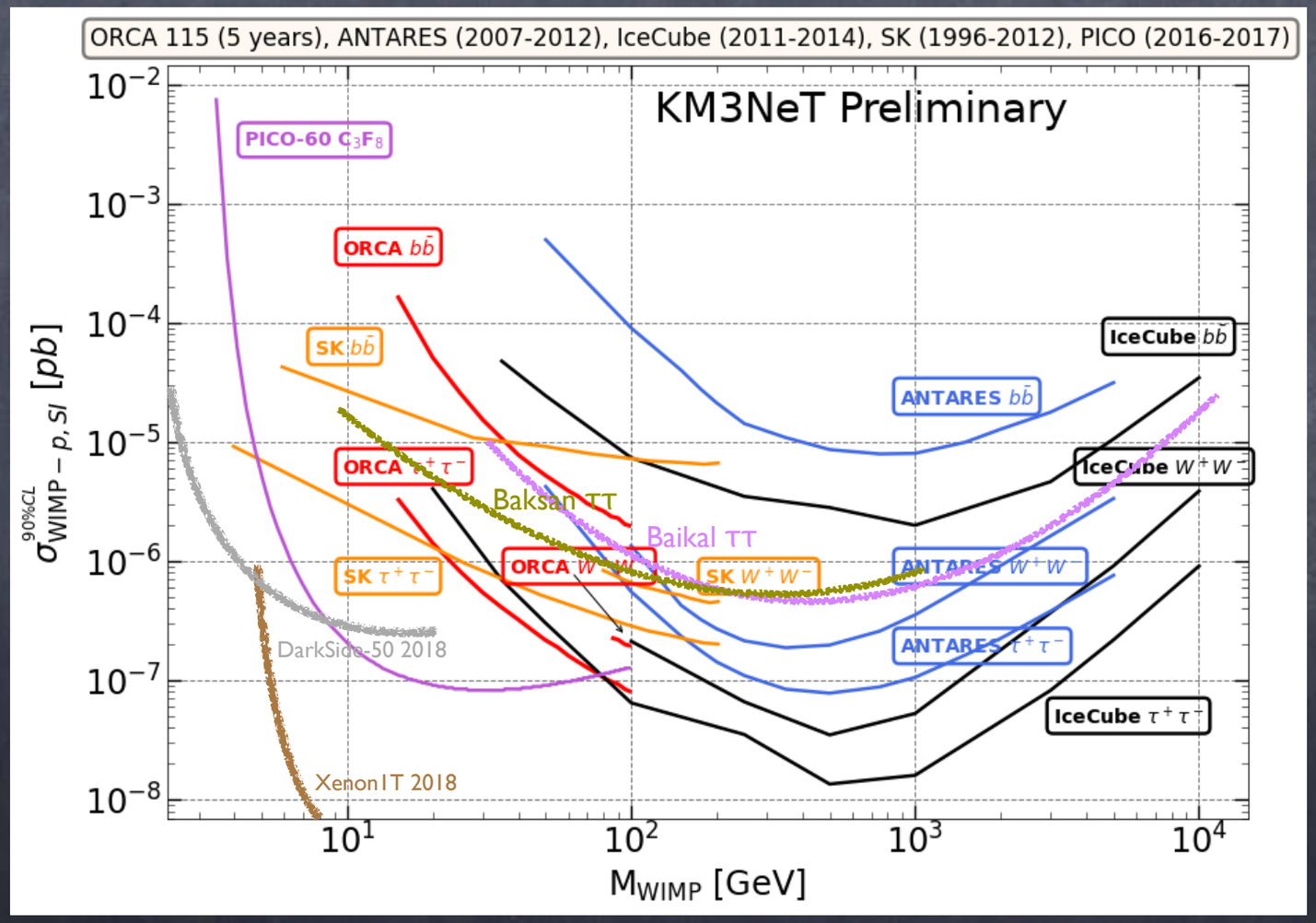
M. M. Boliev et al., JCAP 09:019, 2013

Baikal: 1038 days

A. D. Avrorin et al. [Baikal Collaboration], Astropart. Phys. 62:12, 2015

ANTARES: 5 yrs

S. Adrián-Martínez et al. [ANTARES Collaboration], Phys. Lett. B759:69, 2016



S. Navas, D. López-Coto and J. D. Zornoza [KM3NeT Collaboration], PoS(ICRC2019)536, 2020

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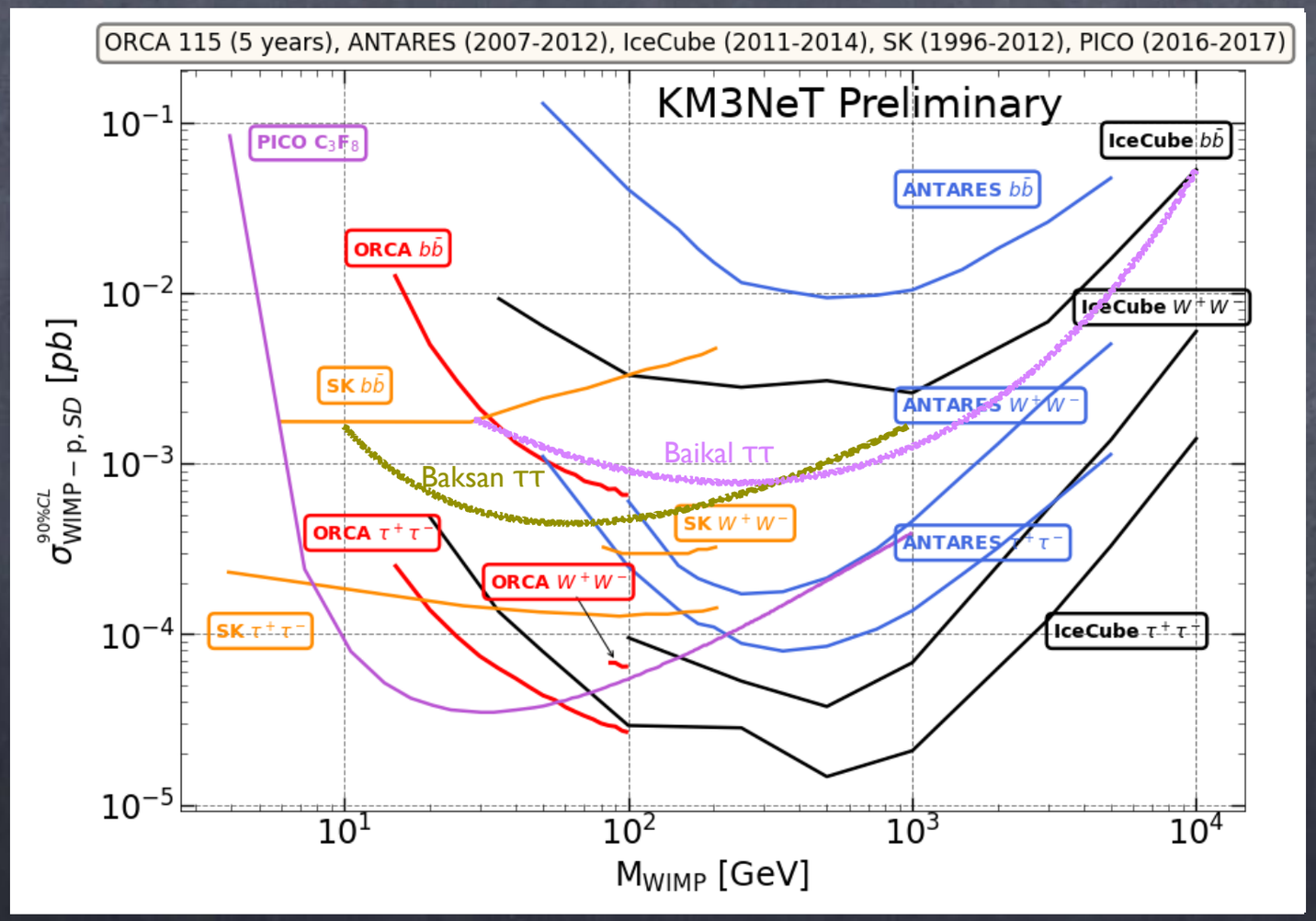

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ANTARES: 5 yrs

S. Adrián-Martínez et al. [ANTARES Collaboration], Phys. Lett. B759:69, 2016

Prospects for INO

S. Choubey, A. Ghosh and D. Tiwari, JCAP 05:006, 2018

Poster #288: D. Tiwari

Prospects for DUNE

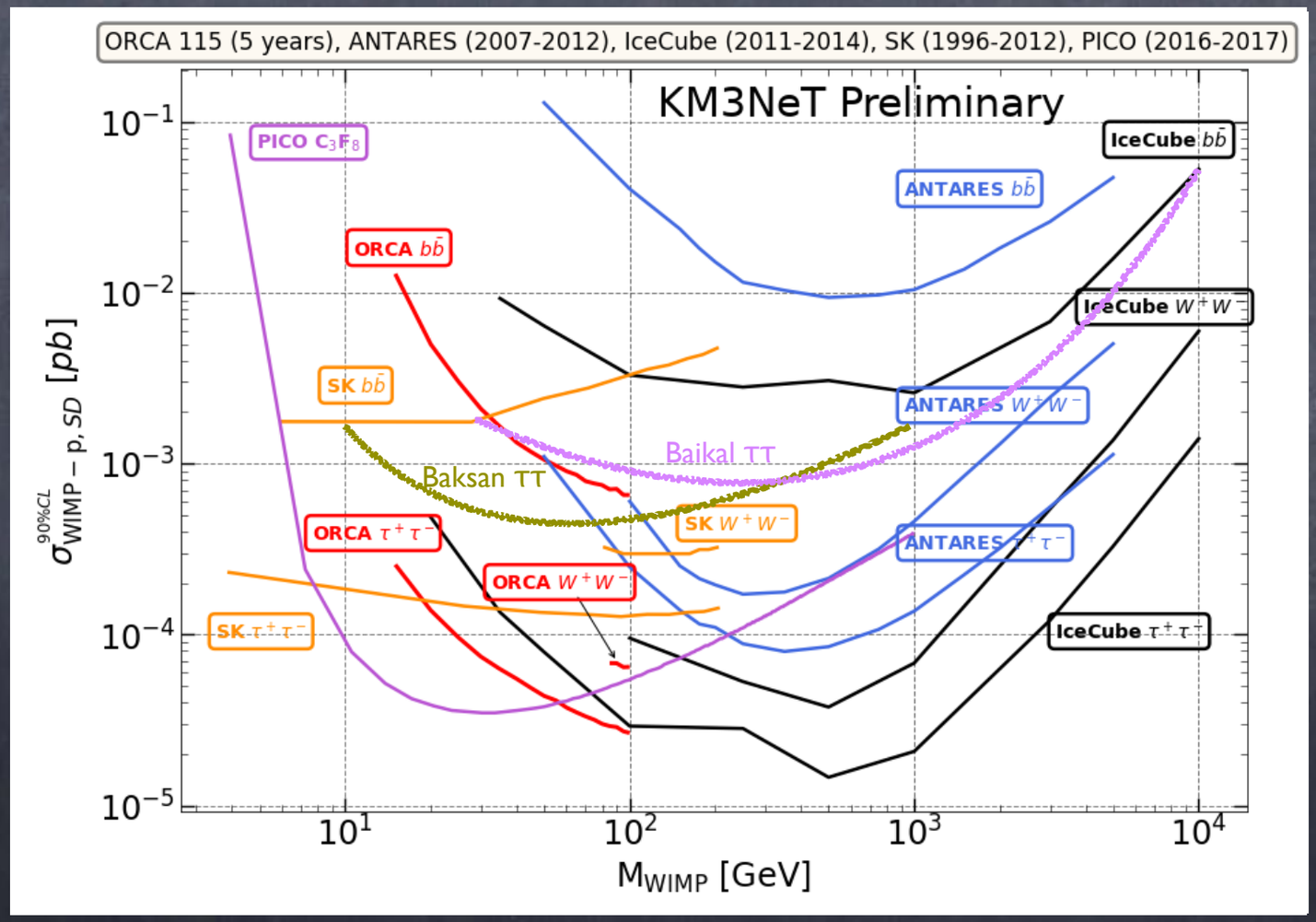
C. Rott et al., JCAP 07:006, 2019

Using KamLAND

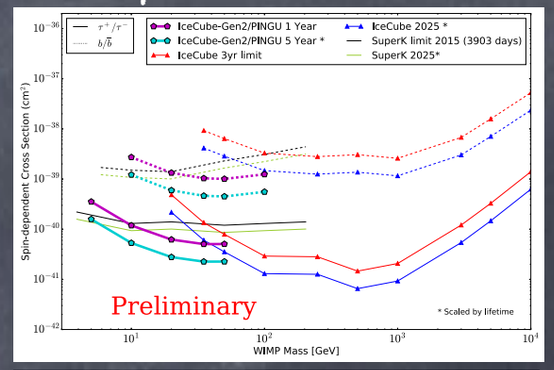
J. Kumar and P. Sandick, JCAP 06:035, 2015

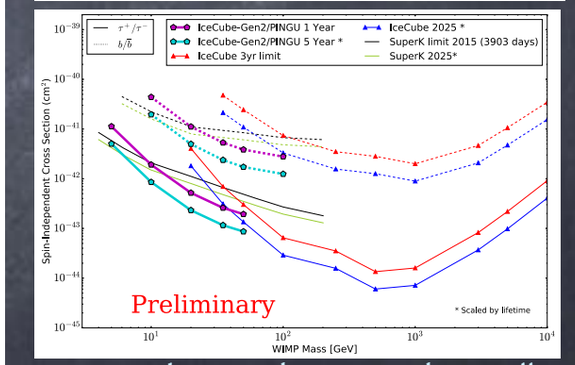
Using NOvA

Poster #358: M. Strait



Prospects for IceCube





S. In and K. Wiebe [Icecube Coll.], PoS(ICRC2017)912, 2018

From the Earth: IC 8 yrs

Poster #155: G. Renzi

S. Navas, D. López-Coto and J. D. Zornoza [KM3NeT Collaboration], PoS(ICRC2019)536, 2020

Usually only considered annihilations into heavy quarks, gauge bosons or tau leptons...

What about annihilations into light quarks, muons or even electrons?

- Electrons/positrons do not produce neutrinos...
- Muons lose energy electromagnetically very rapidly and decay at rest

$$\tau_{stop} \approx 3 \cdot 10^{-10} \left(\frac{E}{10\ \mathrm{GeV}} \right) s \ll \tau_{decay} \approx 2 \cdot 10^{-4} \left(\frac{E}{10\ \mathrm{GeV}} \right) s$$

- Light-quark hadrons, as pions, are stopped via nuclear interactions and decay at rest

$$\tau_{\mathrm{int}} \approx 10^{-11} s \ll \tau_{decay} \approx 10^{-6} \left(\frac{E}{10\ \mathrm{GeV}} \right) s$$

Usually only considered annihilations into heavy quarks, gauge bosons or tau leptons...

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What about the low-energy (tens of MeV) neutrinos from pion and muon decays at rest?

C. Rott, J. Siegal-Gaskins and J. F. Beacom, Phys. Rev. D88:055005, 2013

N. Bernal, J. Martín-Albo and SPR, JCAP 08:011, 2013

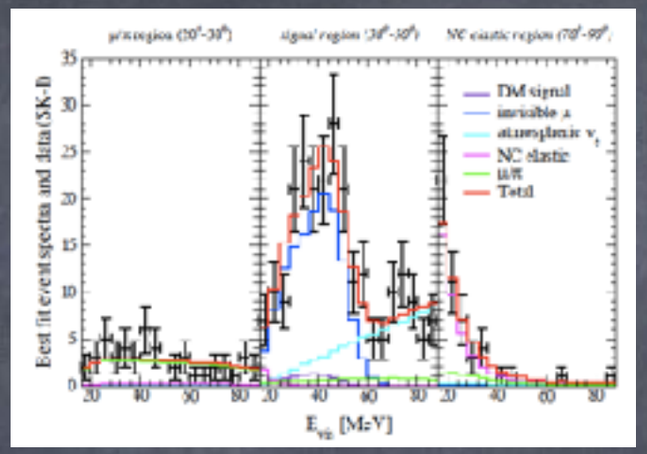
from kaon decays: C. Rott et al., JCAP 11:039, 2015; JCAP 01:016, 2017

- [illegible] pions, are stopped via nuclear interactions and decay at rest

$$\tau_{\rm int} \approx 10^{-11} s \ll \tau_{decay} \approx 10^{-6} \left(\frac{E}{10 \text{ GeV}} \right) s$$

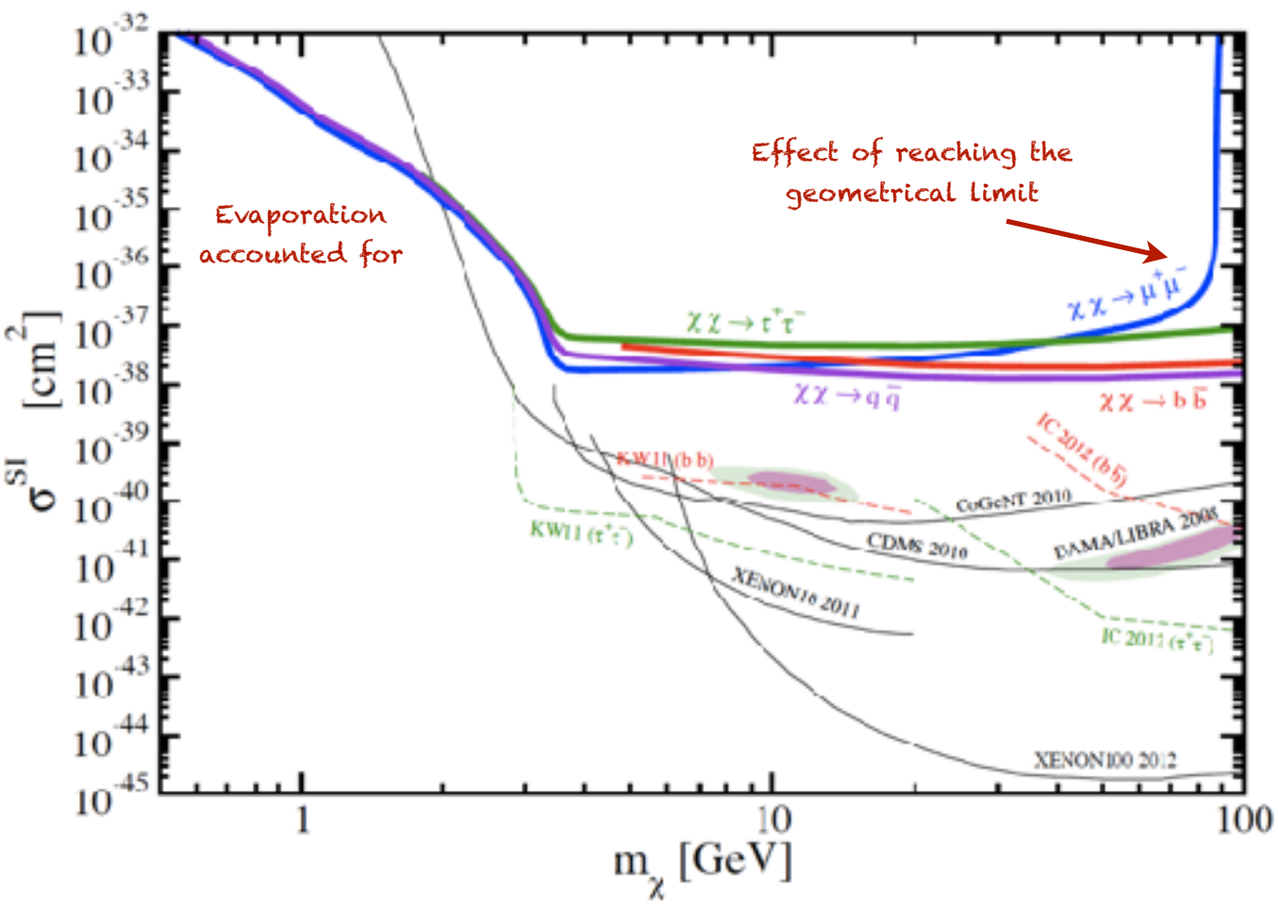
Low-energy neutrinos

Using SK data (DSNB analysis)

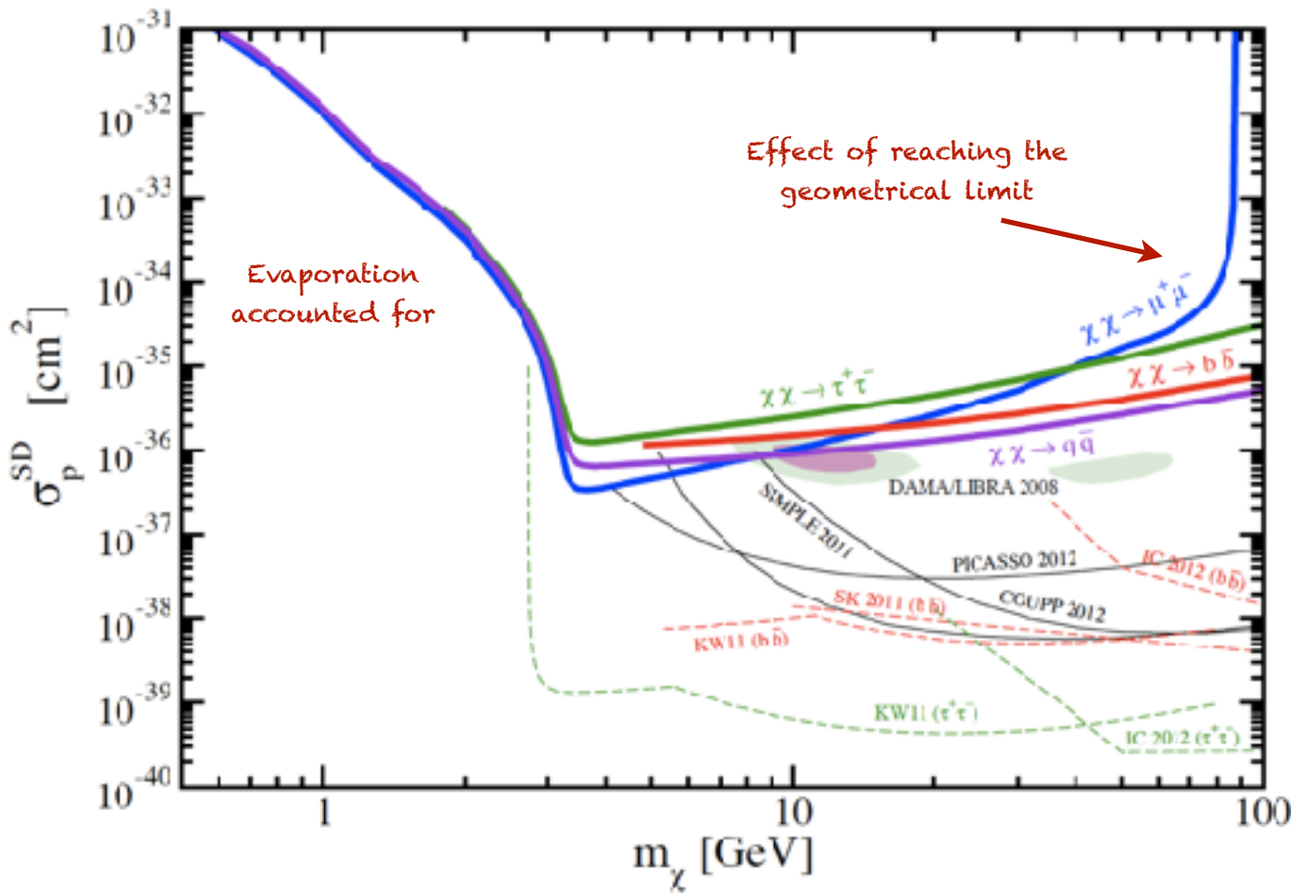


Unique limits (from DM in the Sun) on annihilations into light quarks or muons

spin-independent



spin-dependent



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Low-energy neutrinos

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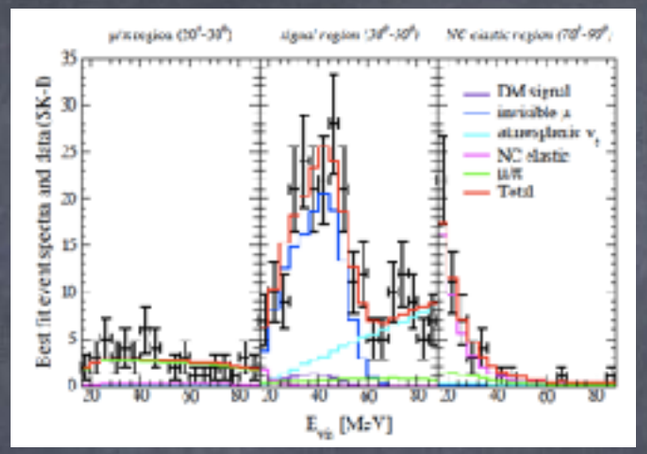

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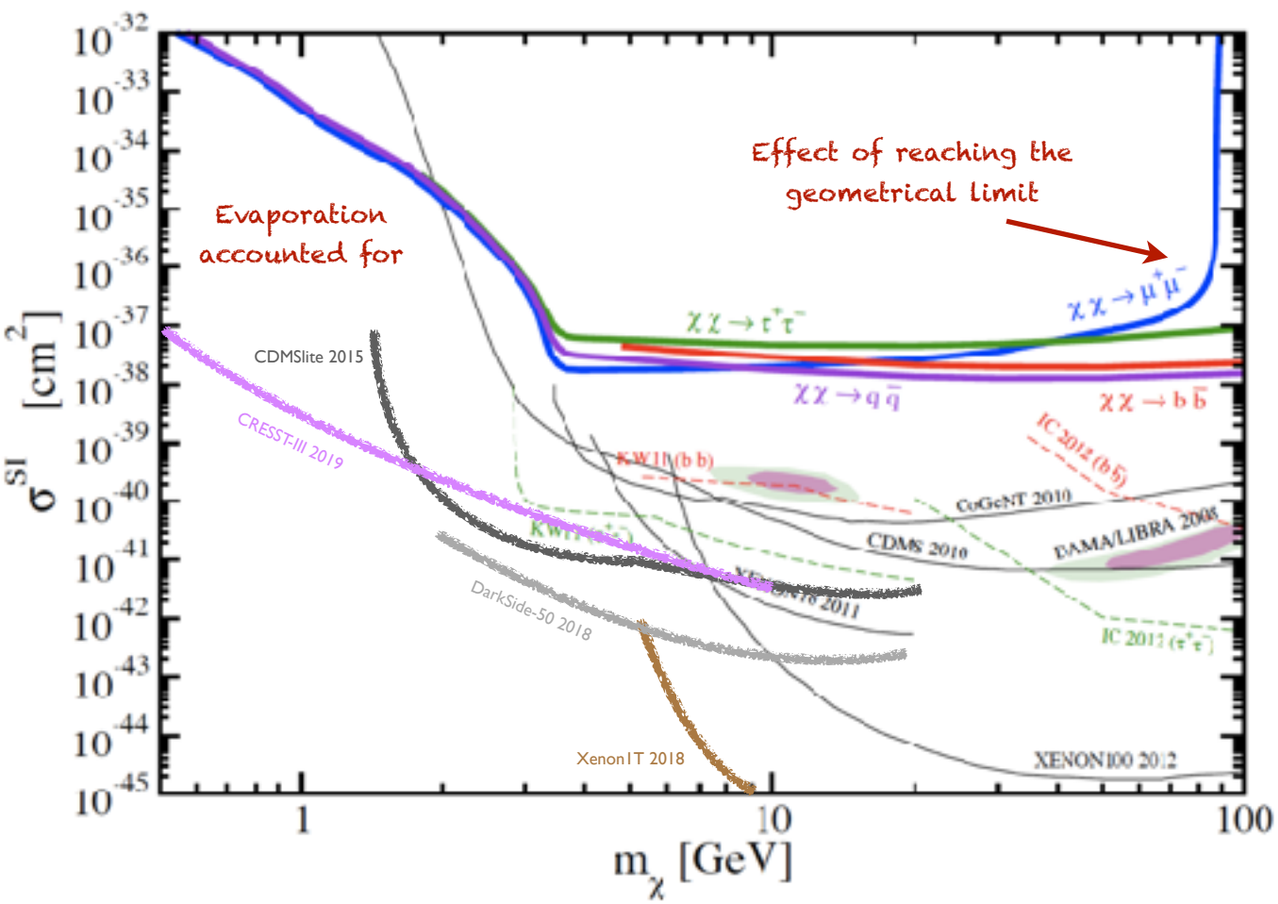

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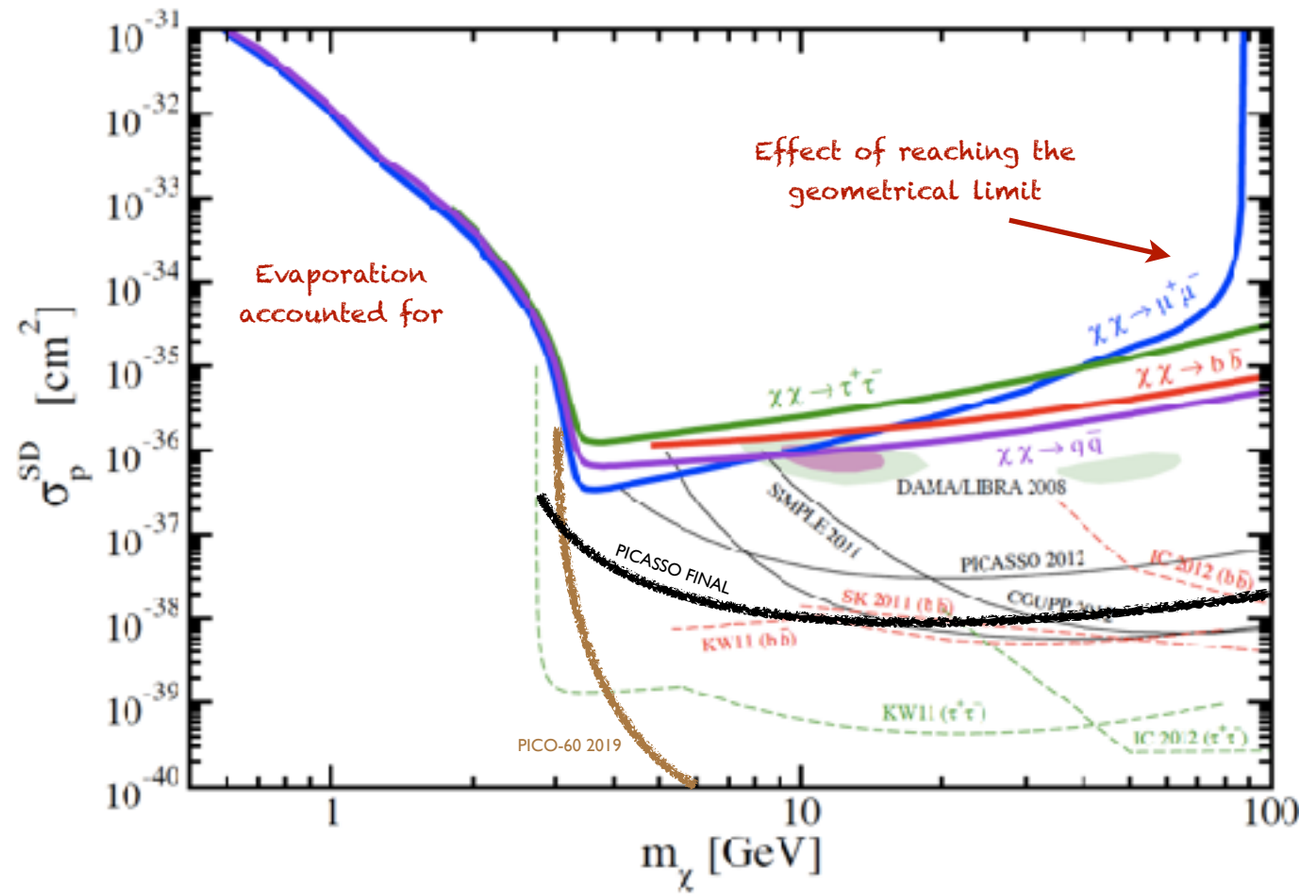


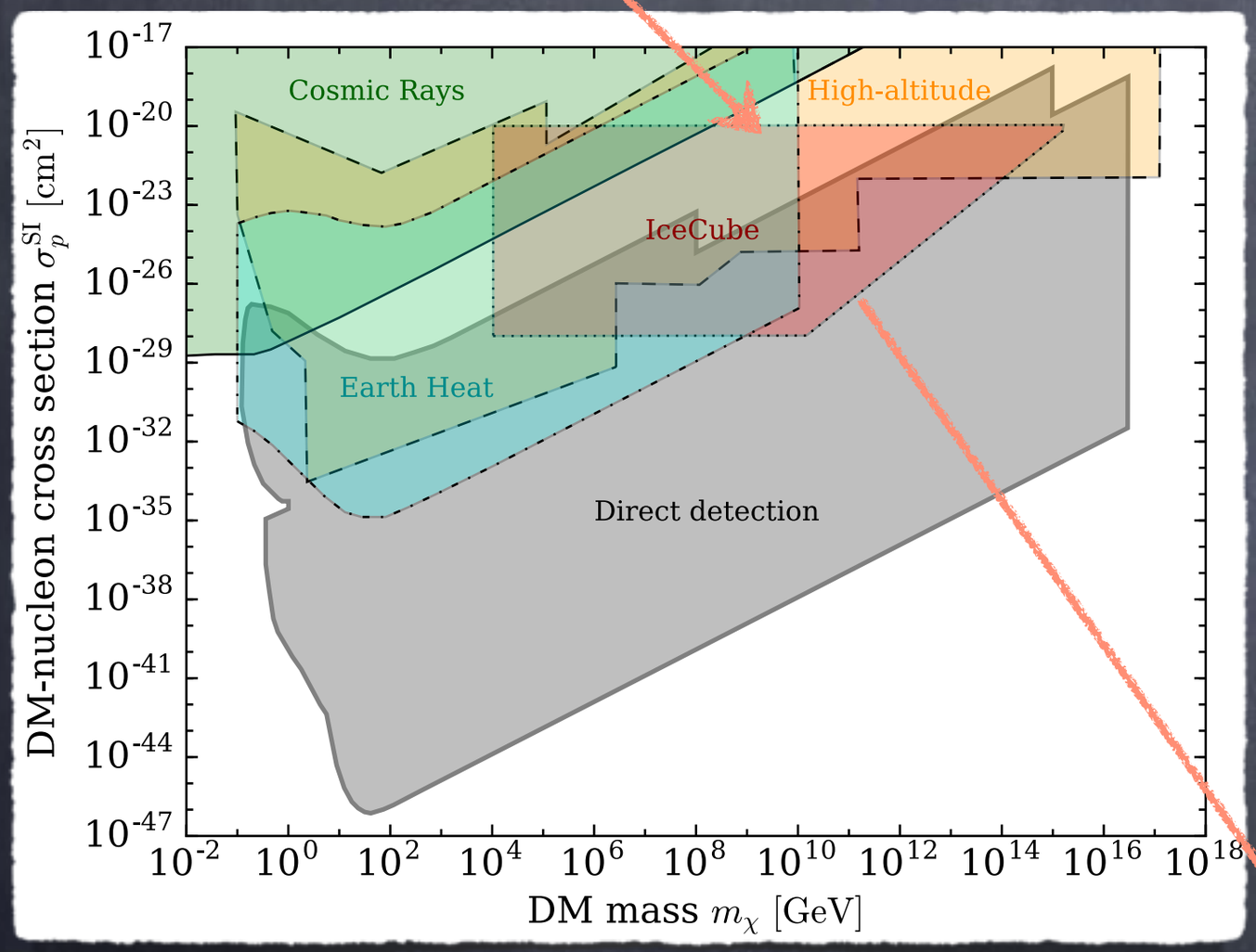
N. Bernal, J. Martín-Albo, SPR, JCAP 08:011, 2013

STRONGLY INTERACTING (HEAVY) DARK MATTER

I. F. M. Albuquerque, L. Hui and E. W. Kolb, Phys. Rev. D64:083504, 2001

104.3 days IC22

I. F. M. Albuquerque and C. Pérez de los Heros, Phys. Rev. D81:063510, 2010



B. J. Kavanagh, Phys. Rev. D97:123013, 2018

R. H. Cyburt et al., Phys. Rev. D65:123503, 2002
G. D. Mack, J. F. Beacom and G. Bertone, Phys. Rev. D76:043523, 2007
G. D. Mack and A. Manohar, J. Phys. G40:115202, 2013

Thick regime:
interaction probability very high

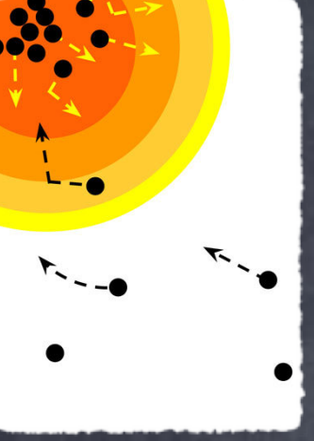
$$n\,\sigma\,R_\odot \gg 1$$

However... the typical momentum transfer (per collision) is ~ m_N/m_{DM}

Key quantity: $q \equiv \dfrac{m_{DM}}{m_N\, n\, \sigma\, R_\odot}$

$q > 1$: very frequent collisions, but result similar to the thin regime → capture rate scales with inverse of DM mass squared

$q < 1$: efficient energy transfer → capture rate scales with inverse of DM mass



Scattering off electrons

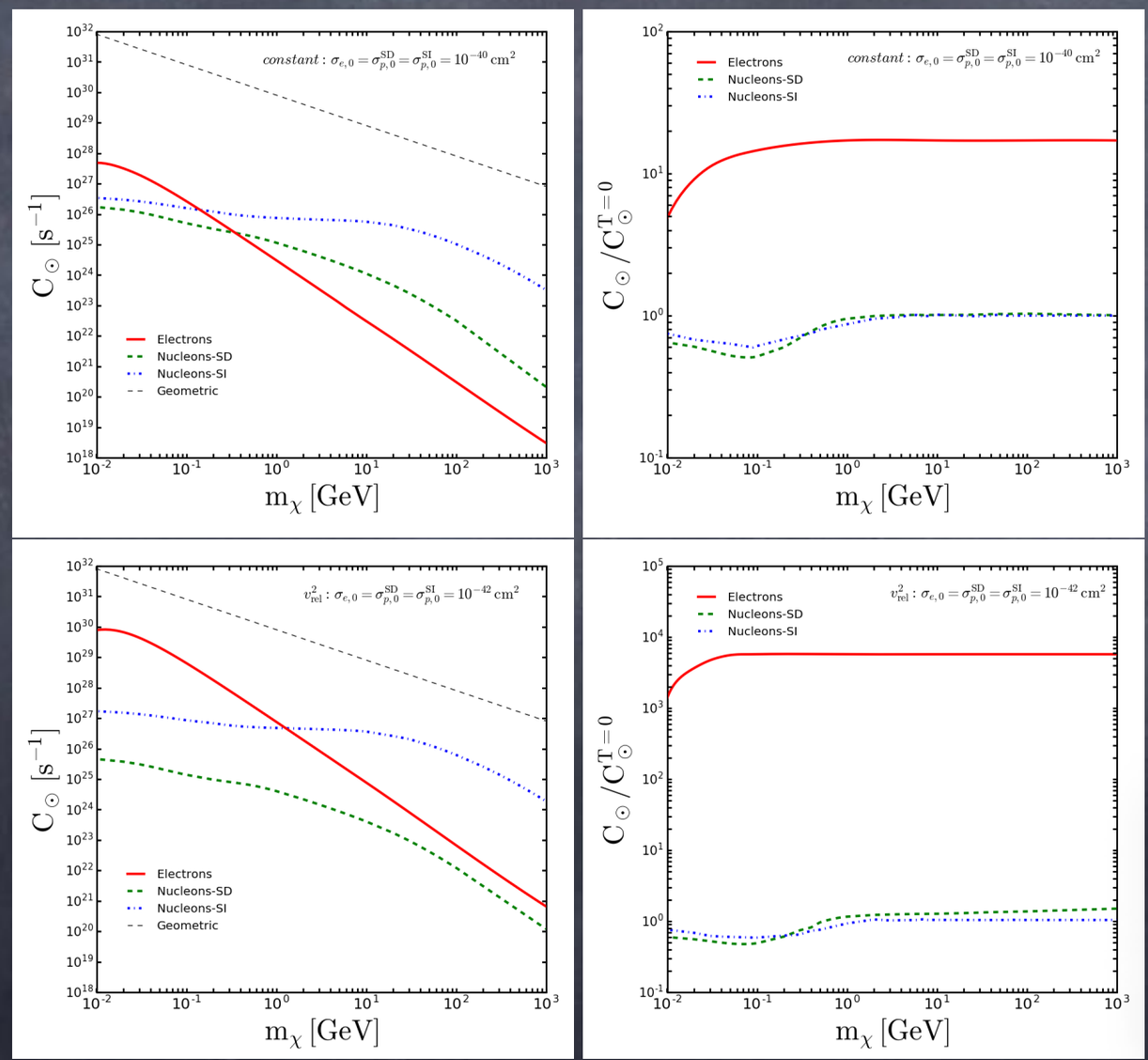
What about interactions with electrons?

J. Kopp et al, Phys. Rev. D80:083502, 2009

smaller mass of targets ⟶ thermal motion is crucial

constant scattering cross section

velocity-dependent scattering cross section



R. Garani and SPR, JCAP 05:007, 2017

huge impact of thermal motion!

In leptophilic scenarios, DM-nucleon could occur at loop level. Yet, in some cases DM-electron could be more important than DM-nucleon

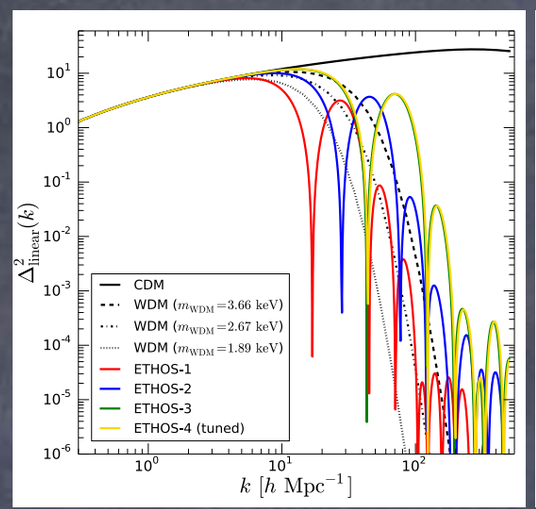
R. Garani and SPR, in preparation

Self-interacting Dark Matter

D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. 84:3760, 2000

Suppresses small-scale structure

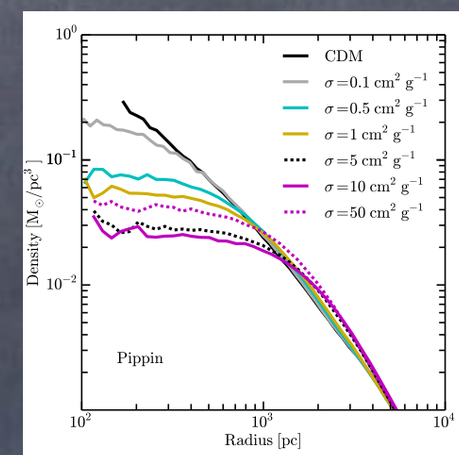
C. Boehm, P. Fayet and R. Schaeffer, Phys. Lett. B518:8, 2001



M. Vogelsberger et al., MNRAS 460:1399, 2016

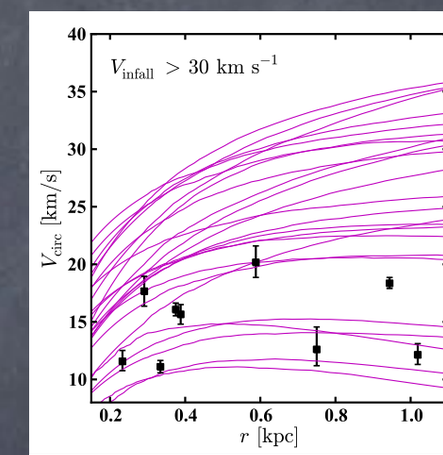
Alleviates cusp-core, too-big-to-fail problems

R. A. Flores and J. R. Primack, Astrophys. J. 427:L1, 1994
B. Moore, Nature 370:629, 1994



O. D. Elbert et al., MNRAS 453:29, 2015

M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat, MNRAS 415:L40, 2011; MNRAS 422:1203, 2012



M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat, MNRAS 422:1203, 2012

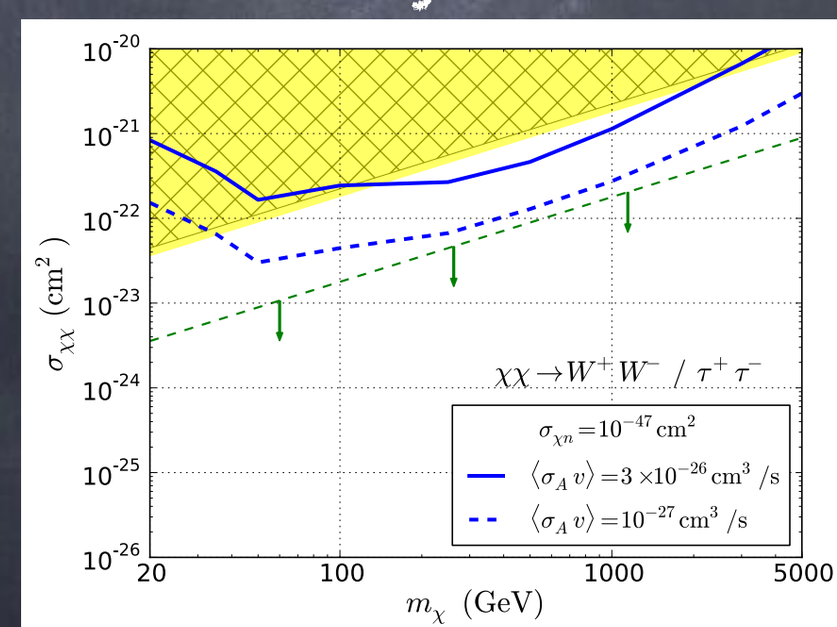
Capture in the Sun

A. R. Zentner, Phys. Rev. D80:063501, 2009

Self interactions enhance the capture rate

DM could reach equilibrium, even if it wouldn't without self-interactions

317 days IC79



I. F. M. Albuquerque, C. Pérez de los Heros and D. S. Robertson, JCAP 02:047, 2014

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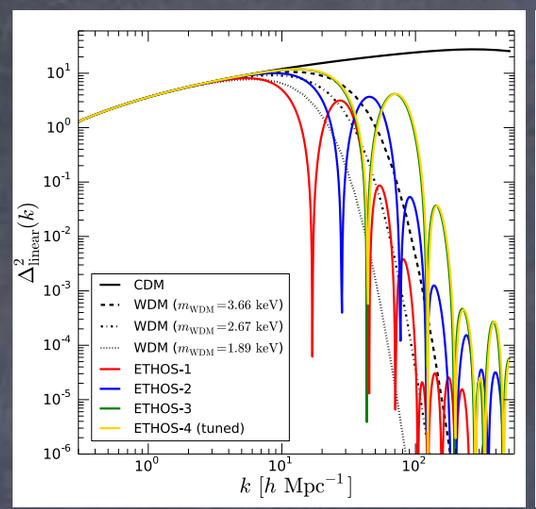

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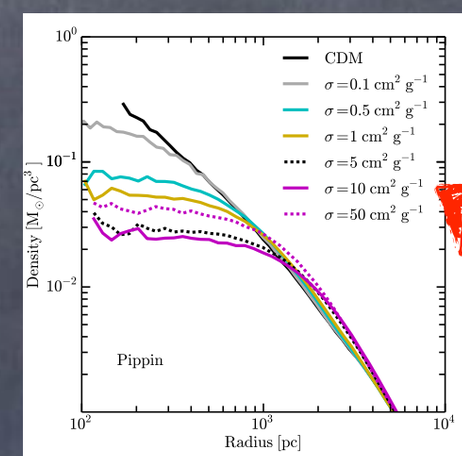
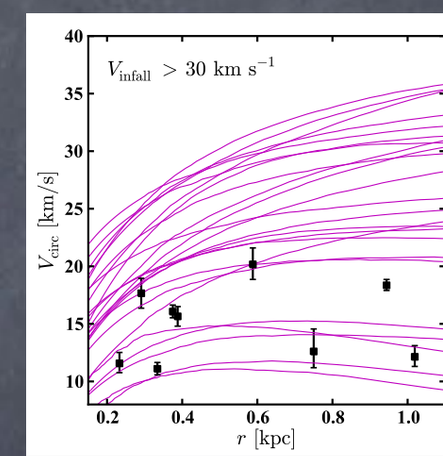
M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat, MNRAS 415:L40, 2011; MNRAS 422:1203, 2012





O. D. Elbert et al., MNRAS 453:29, 2015

M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat, MNRAS 422:1203, 2012

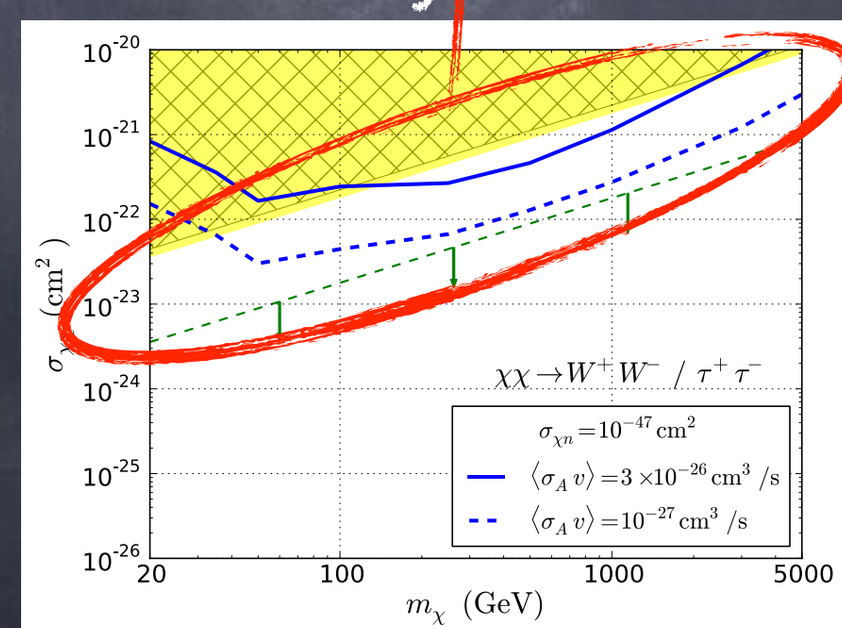
Capture in the Sun

A. R. Zentner, Phys. Rev. D80:063501, 2009

Self interactions enhance the capture rate

DM could reach equilibrium, even if it wouldn't without self-interactions

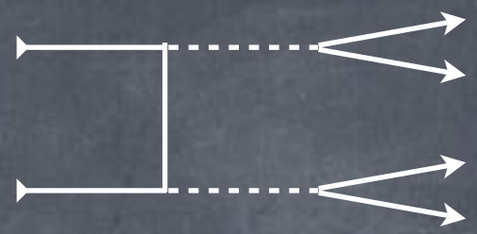
317 days IC79



I. F. M. Albuquerque, C. Pérez de los Heros and D. S. Robertson, JCAP 02:047, 2014

Secluded Dark Matter

Metastable mediator (dark photon, dark scalar...) coupled to DM, that subsequently could decay into SM particles



M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B662:53, 2008

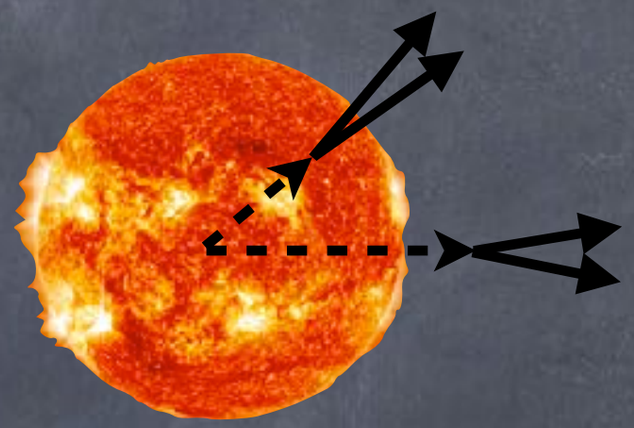
Neutrino signals:

Once captured, DM would decay into mediators, which would (partially) escape the Sun and decay into SM before reaching the Earth

P. Meade et al., JHEP 06:029, 2010

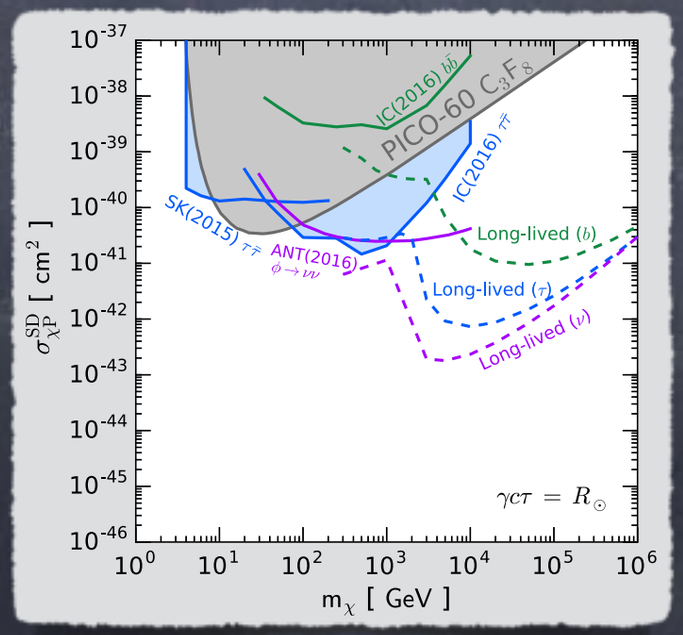
P. Schuster, N. Toro and I. Yavin, Rhys. Rev. D81:016002, 2010

N. F. Bell and K. Petraki, JCAP 04:003, 2011



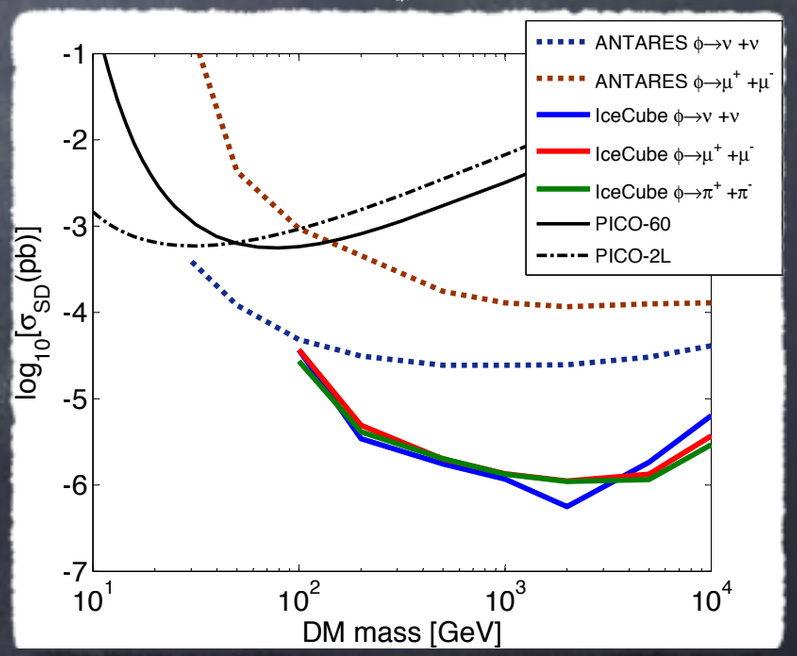
Higher energy neutrinos: mainly from pions/kaons if decays occur outside the Sun

Less absorption: more important for higher energy neutrinos and thus, for larger DM masses



R. K. Leane, K. C. Y. Ng, J. F. Beacom, Phys. Rev. D95:123016, 2017

136 days IC79



M. Ardid et al., JCAP 04:10, 2017

See also: D. S. Robertson and I. F. M. Albuquerque, JCAP 02:056, 2018

C. Tönnis [IceCube Collaboration], PoS(ICRC2019)548, 2019

More on Secluded Dark Matter

Self-interactions (dissipative DM): add a capture component and could result in a lower velocity dispersion (dark disc)

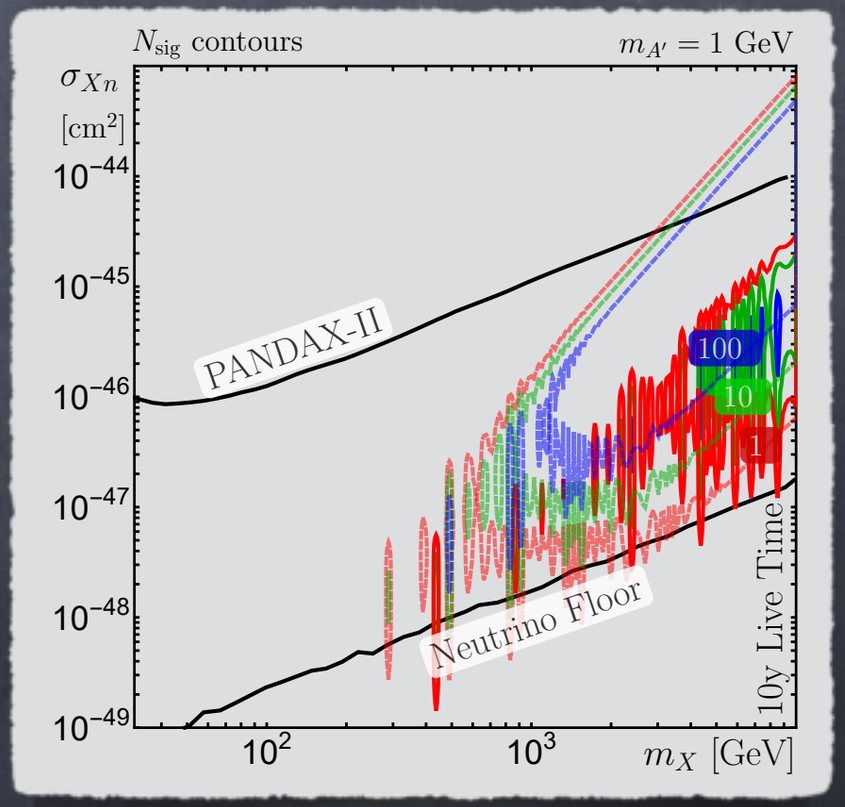
T. Bruch et al., Phys. Lett. B674:250, 2009
J. Fan, A. Katz and J. Shelton, JCAP 06:059, 2014

Long-range interactions: Sommerfeld enhanced annihilation cross section → particularly important for Earth signals

C. Delaunay, P. J. Fox and G. Perez, JHEP 05:099, 2009
J. Chen et al., JCAP 12:021, 2015
J. L. Feng, J. Smolinsky and P. Tanedo, Phys. Rev. D93:015014, 2016

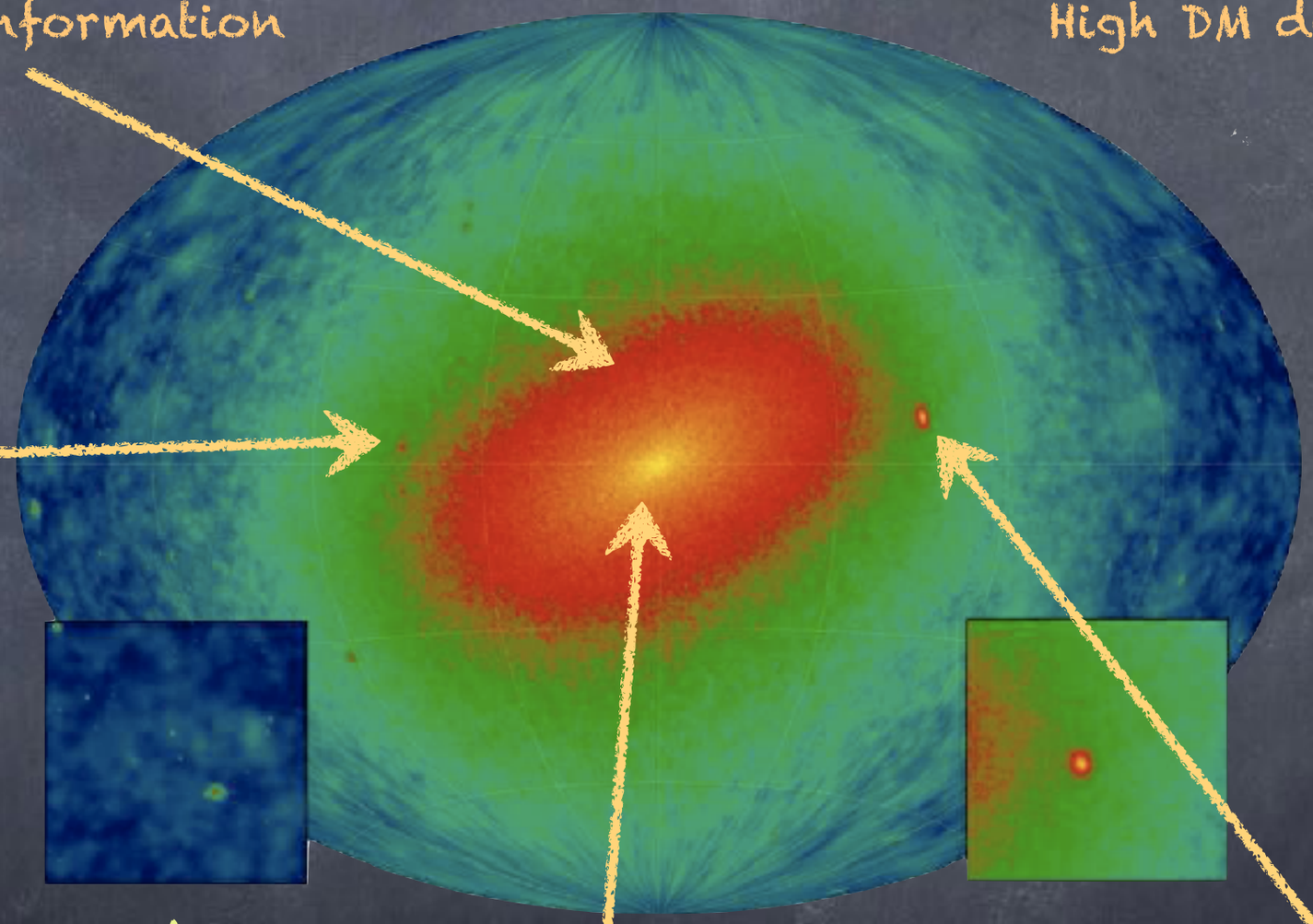
Di-muon signals from the Earth: collinear pair of muons

P. Meade et al., JHEP 06:029, 2010



J. L. Feng, J. Smolinsky and P. Tanedo, Phys. Rev. D93:015014, 2016

DM Annihilations/Decays in Halos: where to look?



Galactic halo
best statistics, angular information

Galaxy clusters
High DM densities

DM clumps
bright enough?

Extragalactic background
DM contribution from all z

Galactic center
brightest DM source

Dwarf galaxies
High DM densities

Figure from J. Diemand, M. Kuhlen and P. Madau, Astrophys. J. 657:262, 2007

DARK MATTER ANNIHILATIONS/DECAYS

Two components

Averaged oscillations

Galactic Extra-galactic

$$\frac{d\Phi_{\nu_\beta}}{dE_\nu} = \sum_\alpha P_{\beta\alpha}\left[\frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu}\right]$$

Decays

Particle physics Astrophysics

$$\frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} = \frac{1}{4\pi\, m_{DM}\tau_{DM}}\frac{dN_{\nu_\alpha}}{dE_\nu}\int_{los}\rho\, ds$$

$$\frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu} = \frac{\Omega_{DM}\rho_c}{4\pi\, m_{DM}\tau_{DM}}\int\frac{dz}{H(z)}\frac{dN_{\nu_\alpha}[(1+z)E_\nu]}{dE_\nu}$$

DM mass

DM lifetime

neutrino flux at production

DM galactic density

DM density

Hubble function

energy redshift

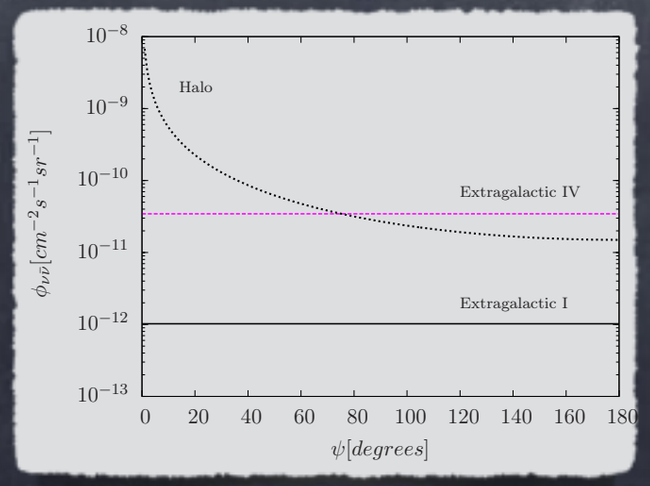
Annihilations

$$\frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2\, m_{DM}^2}\frac{dN_{\nu_\alpha}}{dE_\nu}\int_{los}\rho^2\, ds$$

$$\frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu} = \frac{(\Omega_{DM}\rho_c)^2}{4\pi}\frac{\langle\sigma v\rangle}{2\, m_{DM}^2}\int\frac{dz}{H(z)}\xi^2(z)\frac{dN_{\nu_\alpha}[(1+z)E_\nu]}{dE_\nu}$$

annihilation cross section

halo enhancement



Galactic contribution very likely to be larger

A. Moliné, A. Ibarra and SPR, JCAP 06:005, 2015

Annihilations in the Galaxy and others

SK: (5325.8 + 5629.1) days

K. Abe et al. [Super-Kamiokande Collaboration], arXiv:2005.05109

IceCube: 1007 days

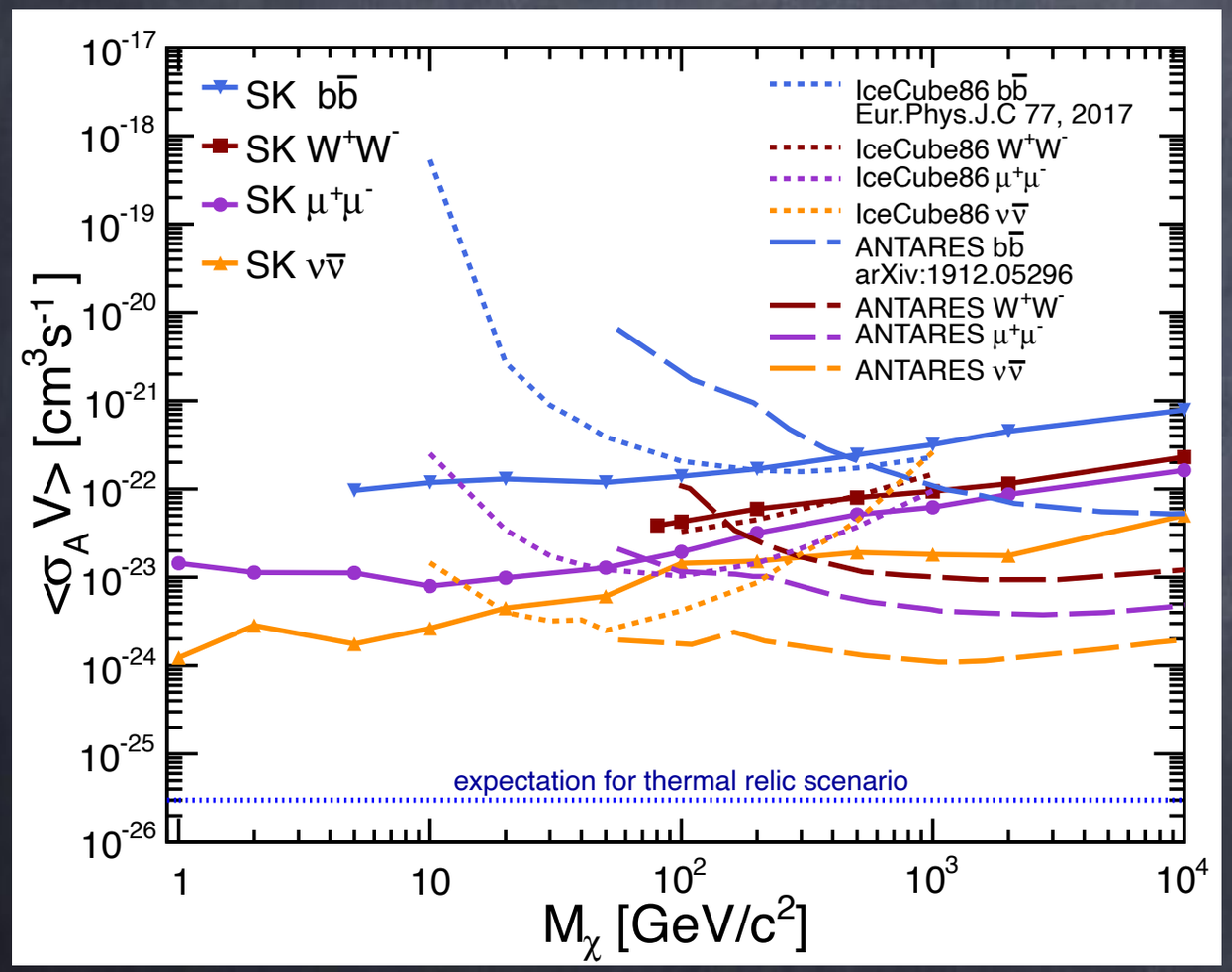
M. G. Aartsen et al. [IceCube Collaboration], Eur. Phys. J. C77:627, 2017

ANTARES: 3170 days

A. Albert et al. [ANTARES Collaboration], Phys. Lett. B805:135439, 2020

Poster #466: S. R. Gozzini

Combined IceCube/ANTARES analysis



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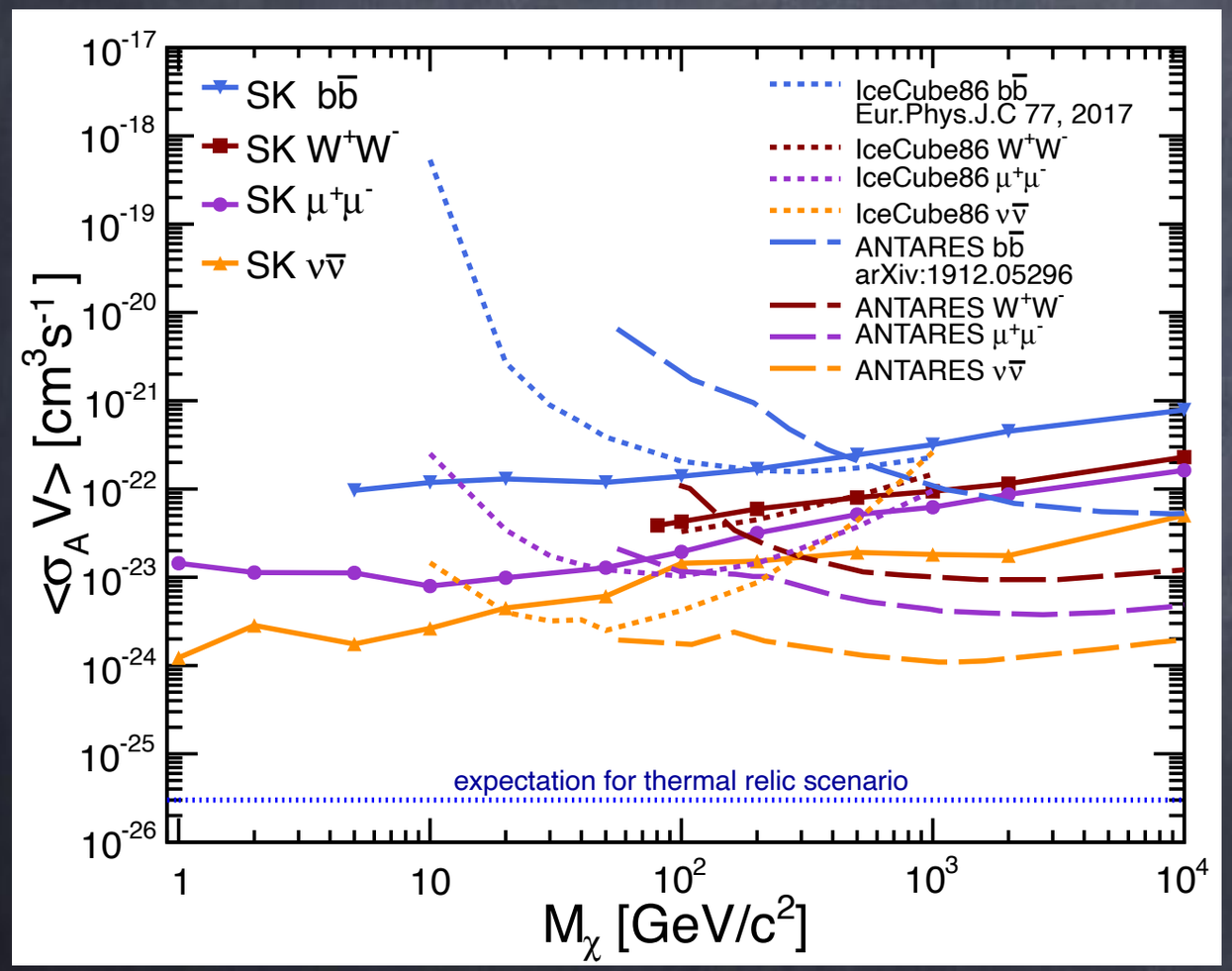
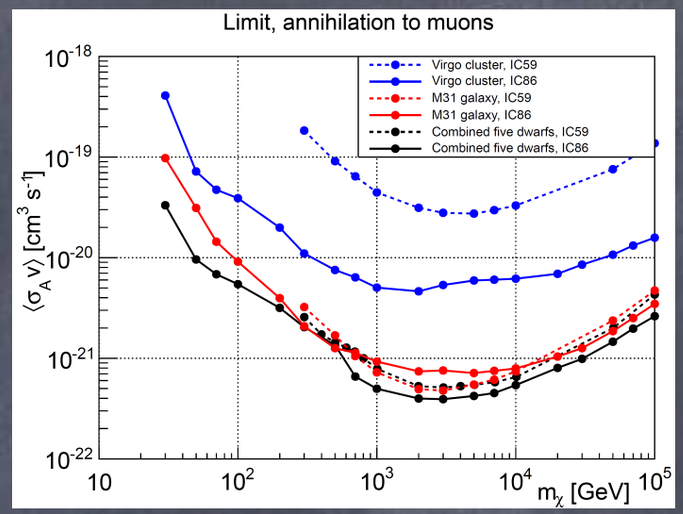


K. Abe et al. [Super-Kamiokande Collaboration], arXiv:2005.05109

339.8 day IC59: Dwarfs, M31, Virgo



M. M. de With, Ph. D. thesis, 2018

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. D88:122001, 2013

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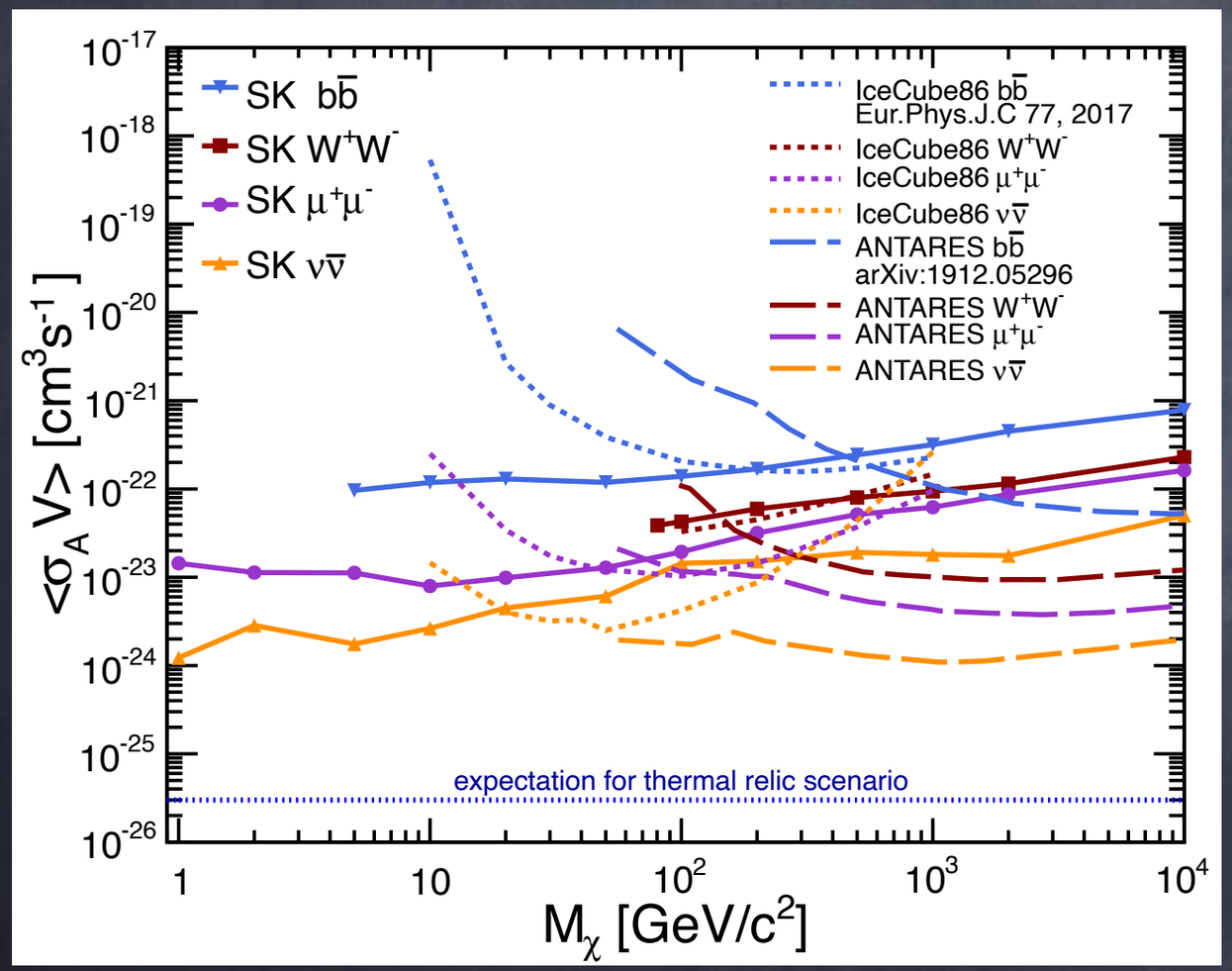

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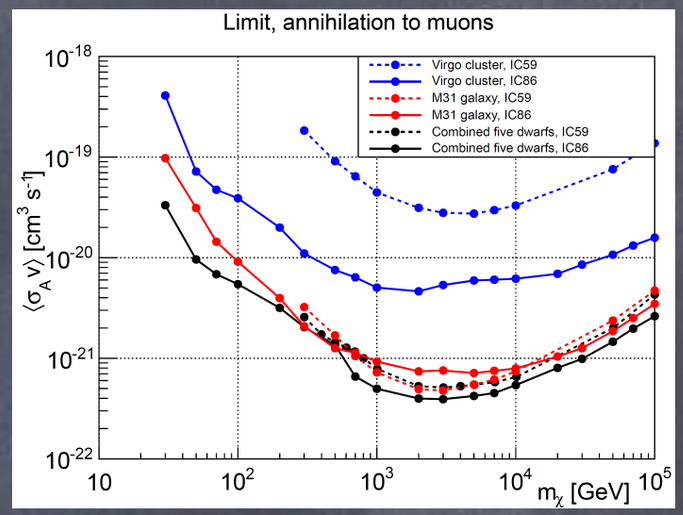
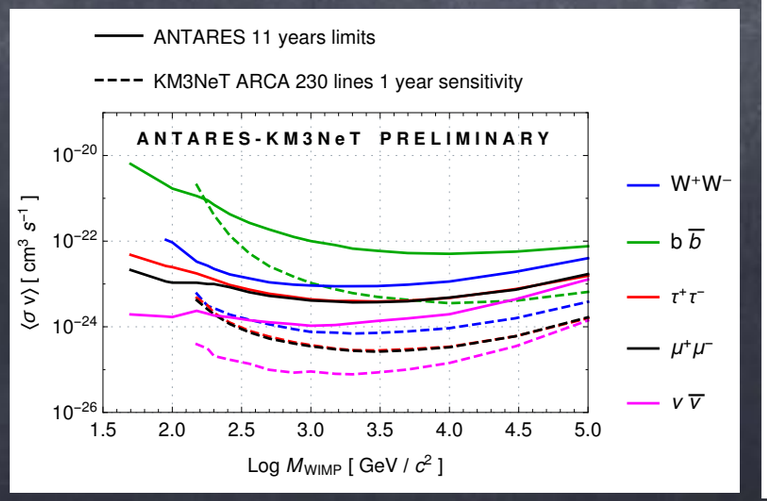


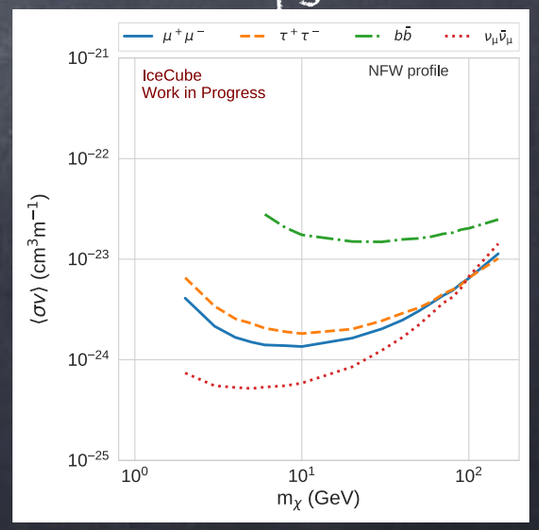
M. M. de With, Ph. D. thesis, 2018

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. D88:122001, 2013

Sensitivities for ARCA and IceCube upgrade



S. R. Gozzini and J. D. Zornoza [KM3NeT Collaboration], PoS(ICRC2019)552, 2020



S. Baur [IceCube Collaboration], PoS(ICRC2019)506, 2020

Decays in the Galaxy and others

For E < 10 TeV, there are (almost) no limits on the neutrino flux from DM decays... by the experimental collaborations

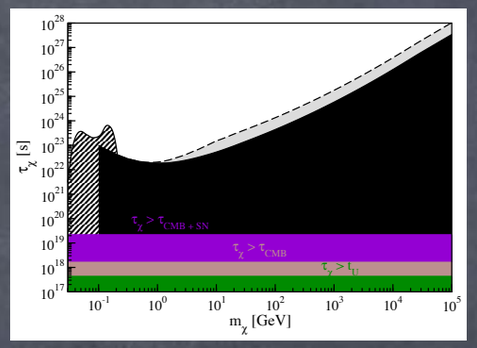
First bounds on the diffuse neutrino flux

V. Berezinsky, LNGS 91/02 preprint, 1991
J. Ellis et al., Nucl. Phys. B373:399, 1992
P. Gondolo, G. Gelmini and S. Sarkar, Nucl. Phys. B392:111, 1992

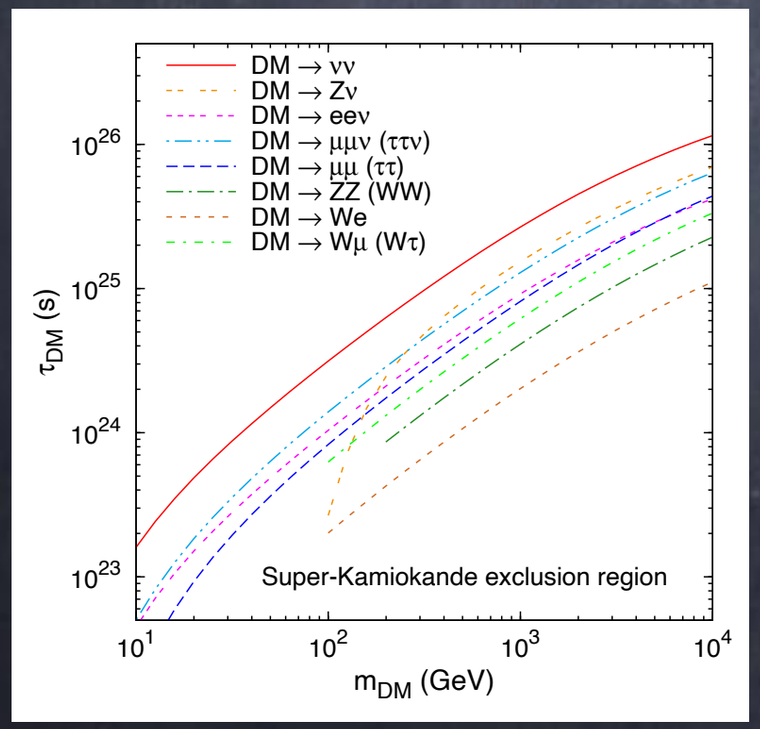
First bounds considering the galactic flux

P. Gondolo, Phys. Lett. B295:104, 1992

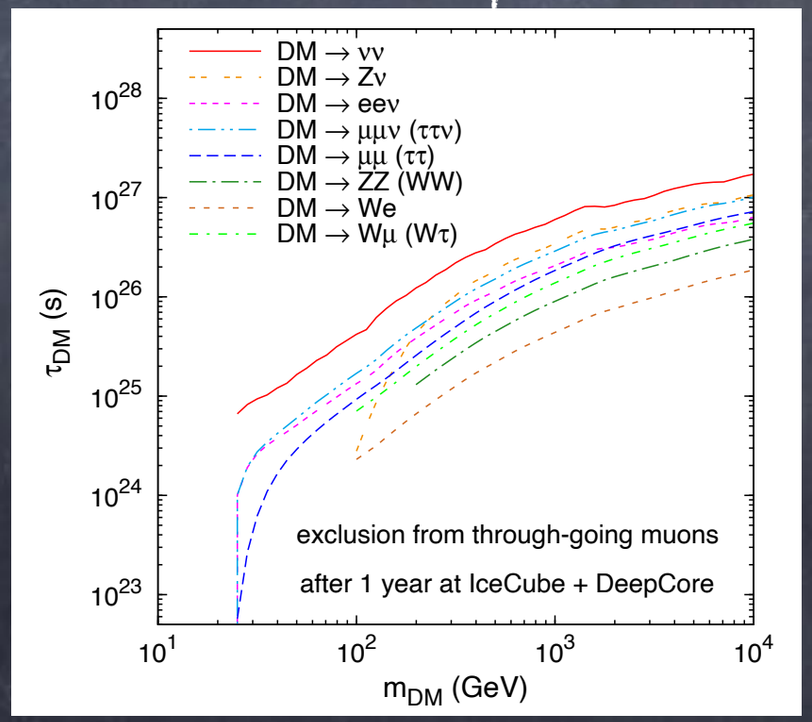
SPR, Phys. Lett. B665:50, 2008



Super-Kamiokande data

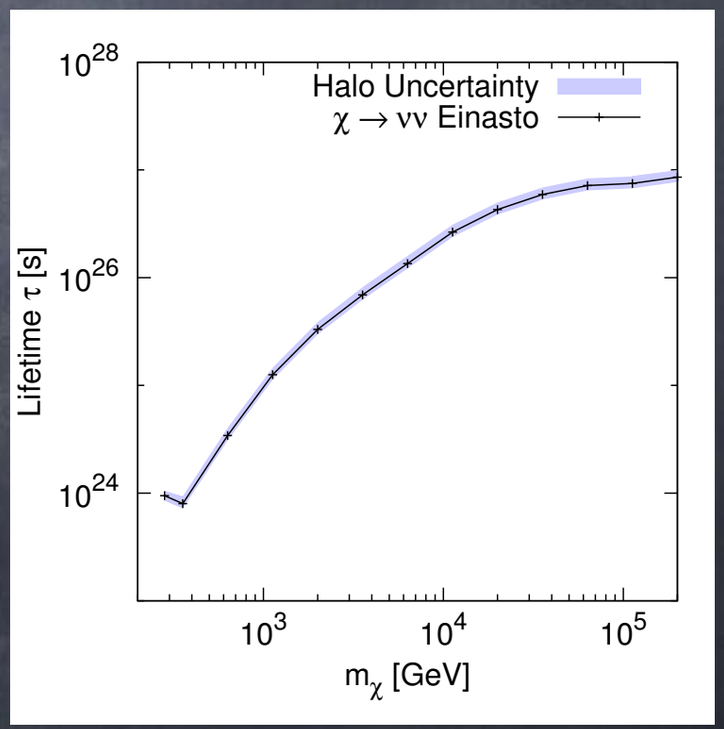


Prospects with 1 year IceCube+DeepCore



L. Covi et al., JCAP 04:017, 2010

276 days IC22



R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D84:022004, 2011

Heavy Dark Matter

Can the highest energy IceCube neutrinos be explained by heavy dark matter annihilations/decays?

B. Feldstein et al., Phys, Rev. D88:015004, 2013

A. Esmaili and P. D. Serpico, JCAP 11:054, 2013

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annihilations

$$\text{Rate} \sim V N_N \sigma_N L_{MW} \left(\frac{\rho_{DM}}{m_{DM}}\right)^2 \langle \sigma v \rangle \sim 10/\text{year} \rightarrow \langle \sigma v \rangle \sim 10^{-21} \text{cm}^3/\text{s} \left(\frac{m_{DM}}{\text{PeV}}\right)^2$$

Unitarity limit → non-thermal or composite DM or non-standard Universe evolution

K. Griest and M. Kamionkowski, Phys. Rev. Lett. 64:615, 1990,

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decays

$$\text{Rate} \sim V N_N \sigma_N L_{MW} \frac{\rho_{DM}}{m_{DM}} \frac{1}{\tau_{DM}} \sim 10/\text{year} \rightarrow \left(\frac{\tau_{DM}}{10^{28}\,\text{s}}\right)\left(\frac{m_{DM}}{1\,\text{PeV}}\right) \sim 1$$

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Many analyses have followed

Poster #190: M. Chianese

Poster #494: A. Dekker

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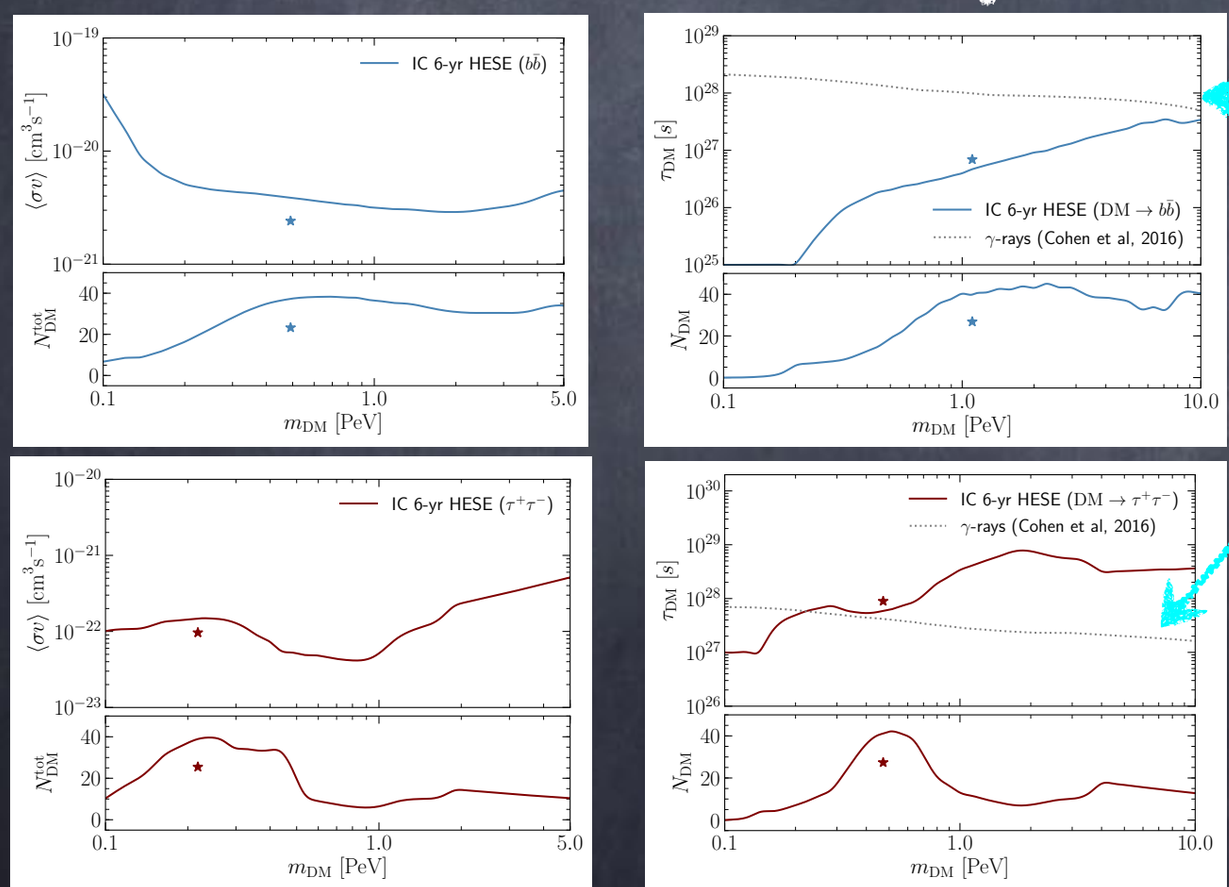
6-yr HESE: Astro + DM

annihilations **decays**



Neutrino limits are better than gamma-ray ones for relatively hard channels

A. Bhattacharya et al., JCAP 05:051, 2019

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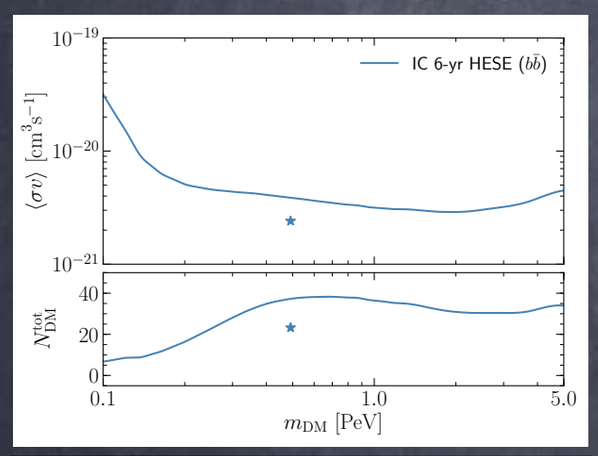
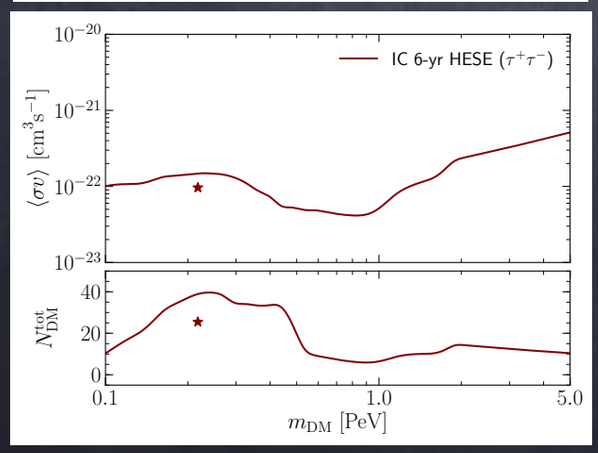
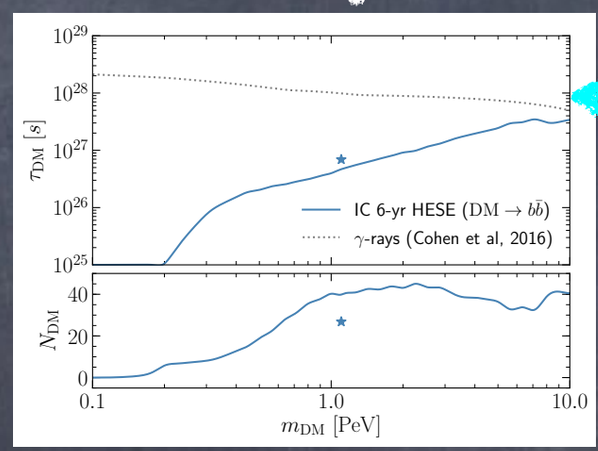
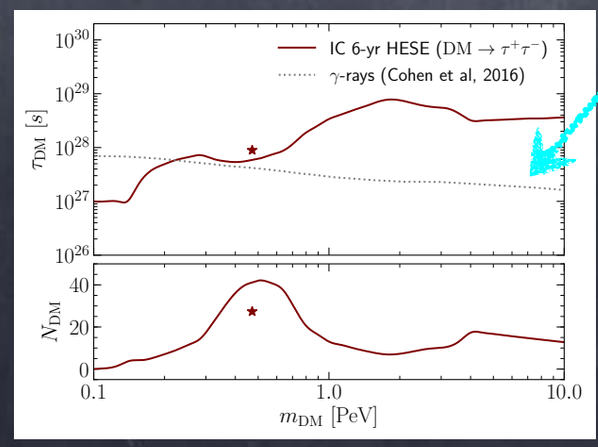




decays





A. Bhattacharya et al., JCAP 05:051, 2019

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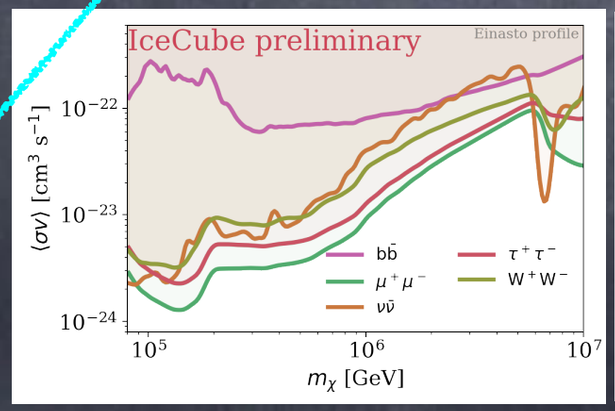
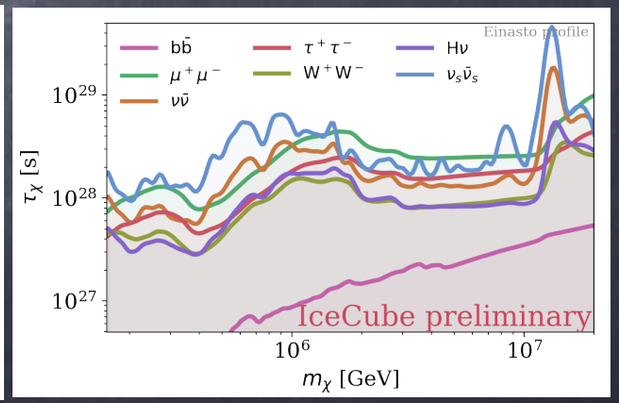
7.5-yr HESE





C. A. Argüelles and H. Dujmovic [IceCube Collaboration], PoS(ICRC2019)839, 2020

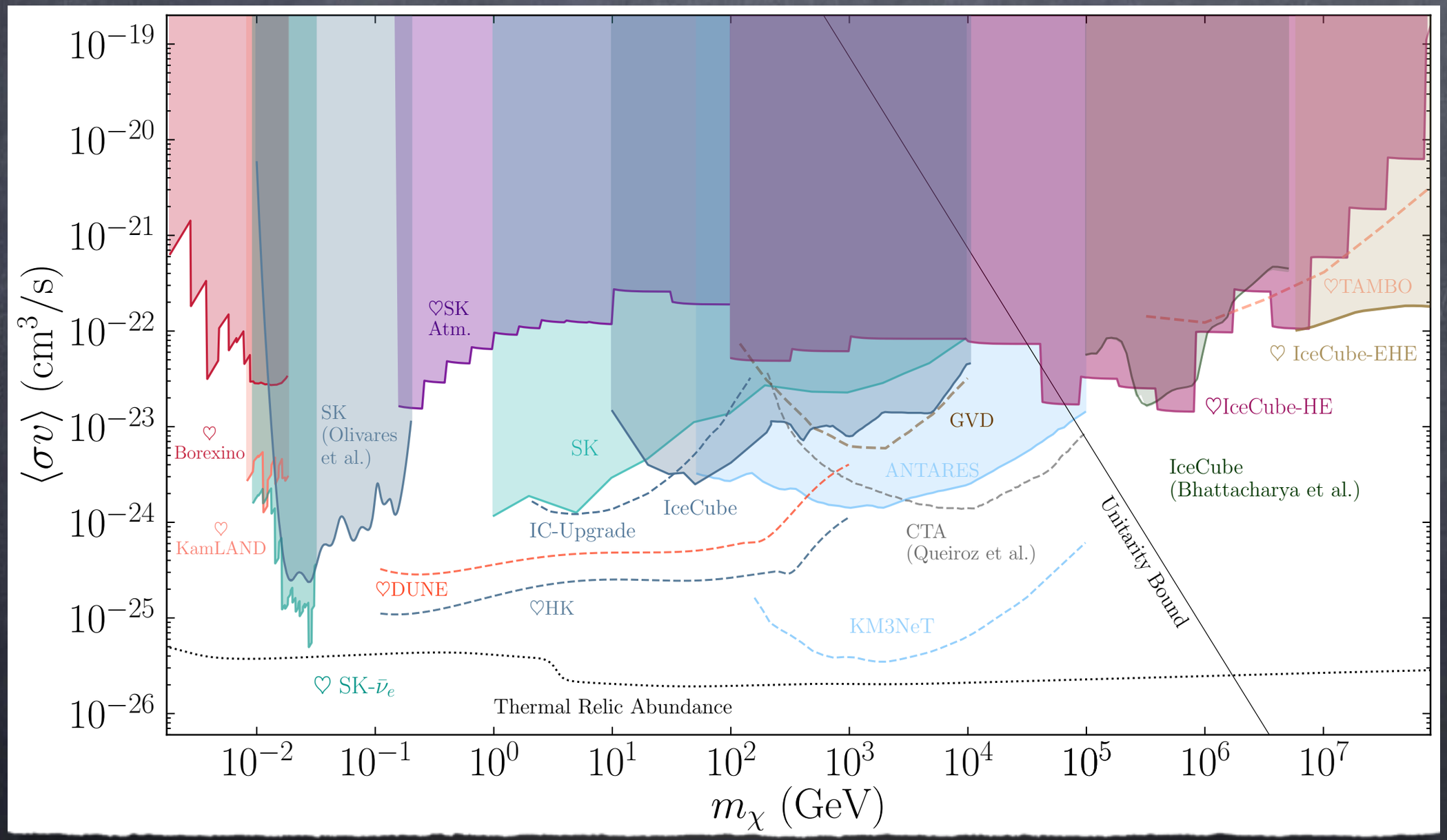
See also: M. G. Aartsen et al. [IceCube Collaboration], Eur. Phys. J. C78:831, 2018

Annihilations/Decays into monochromatic neutrinos

Given that neutrinos are the least detectable particles in the SM, considering DM annihilations/decays into a pair of neutrinos is the most conservative scenario

J. F. Beacom, N. F. Bell and G. D. Mack, Phys. Rev. Lett. 99:231301, 2007
H. Yüksel et al., Phys. Rev. D.76:123506, 2007

SPR and S. Pascoli, Phys. Rev. D77:025025, 2008
SPR, Phys. Lett. B665:50, 2008



C. A. Argüelles et al., arXiv:1912.09486

Prospects for INO
A. Khatun, R. Laha and S. K. Agarwalla, JHEP 06:057, 2017
D. Tiwari, Ph. D. thesis, 2018

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H. Yüksel et al., Phys. Rev. D.76:123506, 2007
SPR and S. Pascoli, Phys. Rev. D77:025025, 2008
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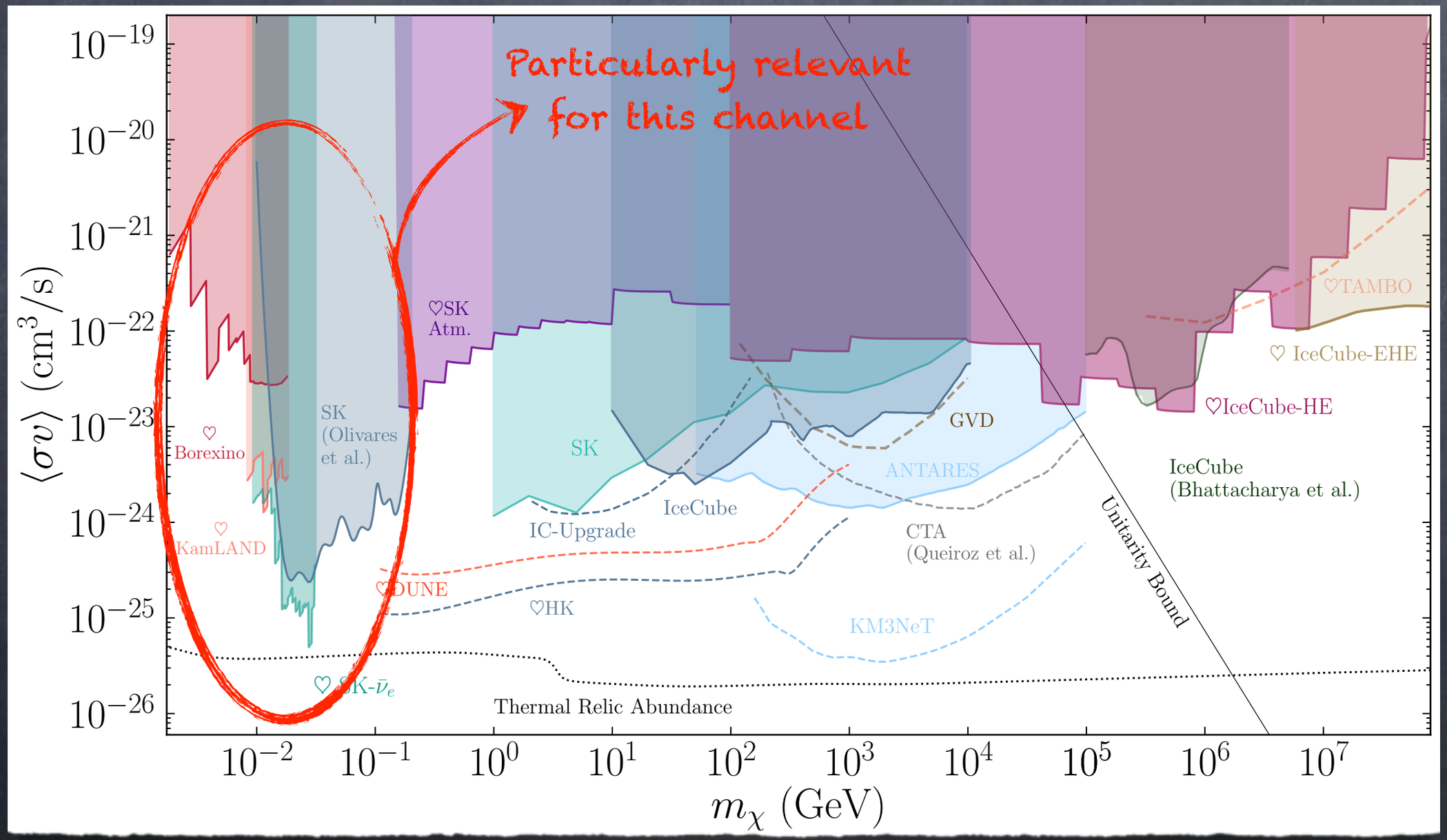

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A. Khatun, R. Laha and S. K. Agarwalla, JHEP 06:057, 2017
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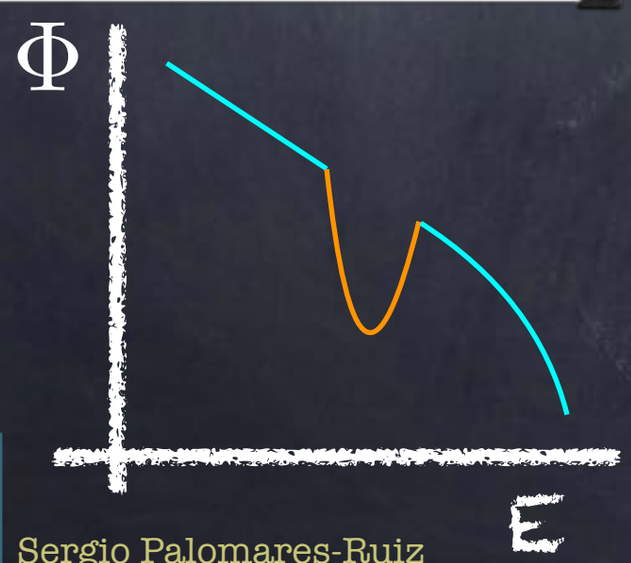
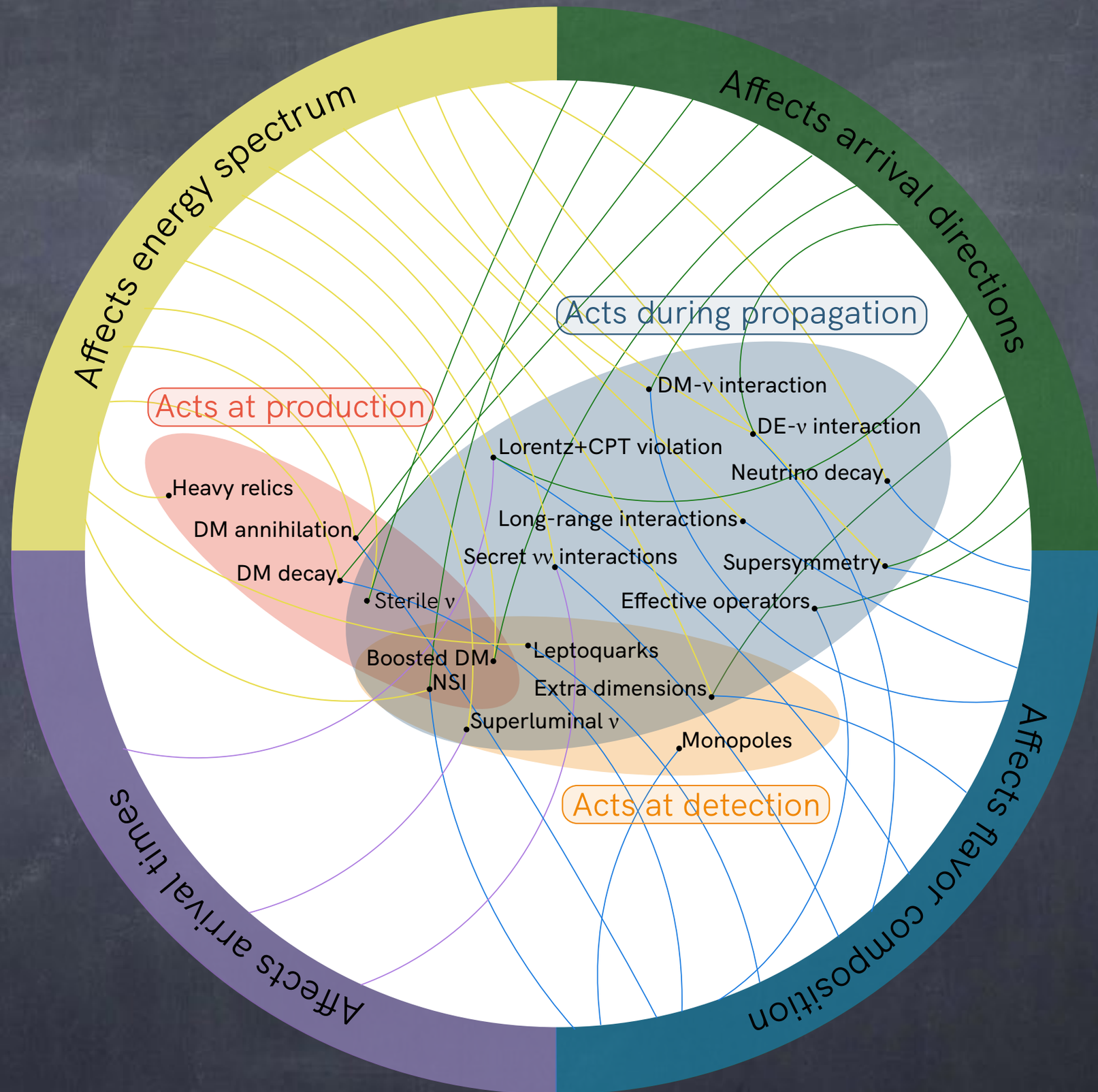
Features on known spectra





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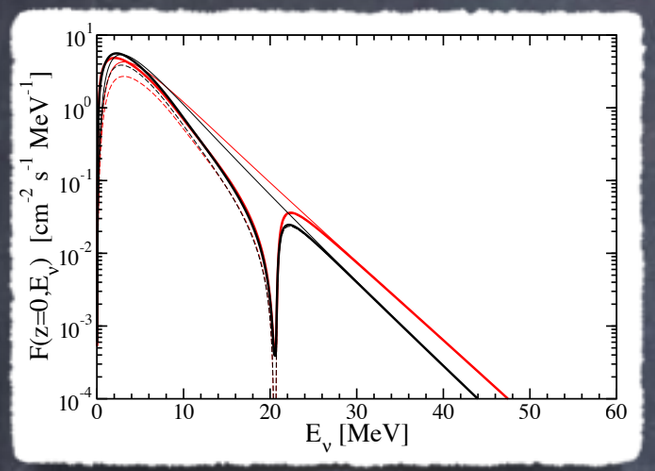
Neutrino-Dark Matter Interactions

Absorptive effects

Dips on the SN neutrino spectra

Y. Farzan and SPR, JCAP 06:014, 2014

T. Franarin, M. Fairbairn and J. H. Davis, arXiv:1806.05015



Full absorption of SN neutrinos

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Energy-dependent anisotropy of high-energy neutrinos

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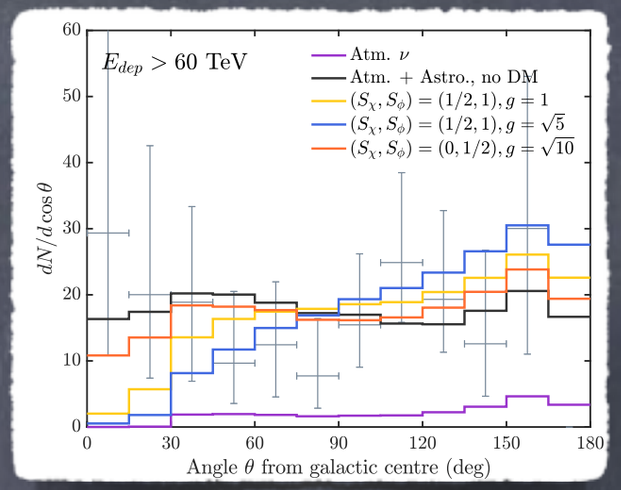

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Time delays of high-energy neutrinos

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Full absorption of high-energy neutrinos from point sources

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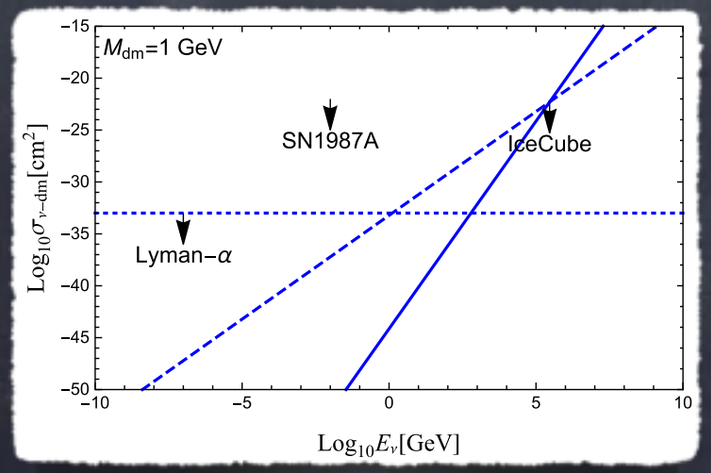
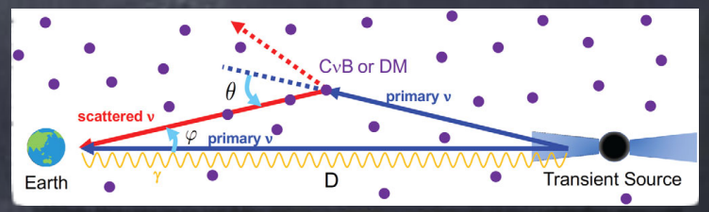
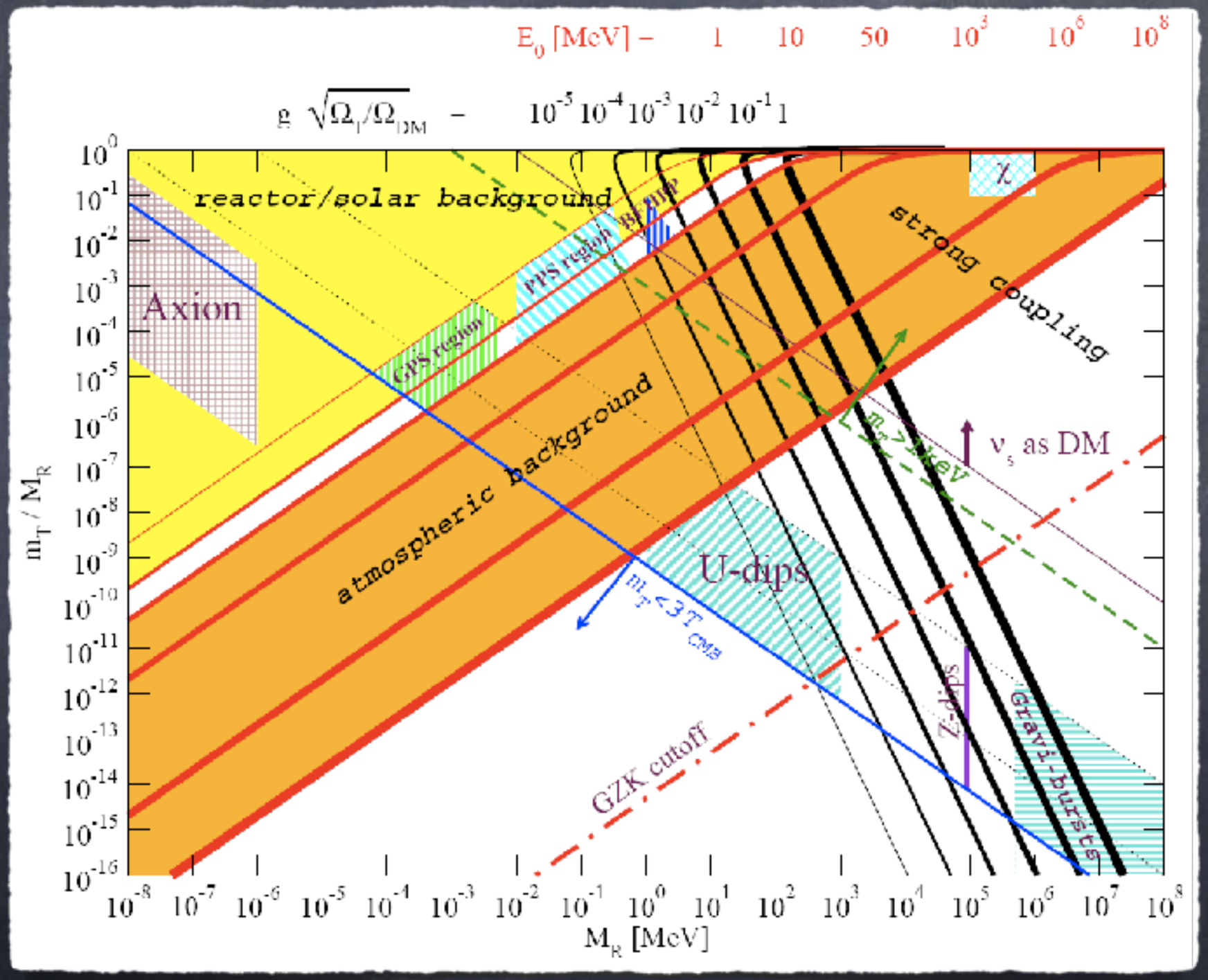




Redshift-Integrated Resonances (zIRs)

Dips in cosmic neutrino spectra

$$E_R \simeq \frac{M_R^2}{2 m_T}$$



SPR and T. J. Weiler, in preparation… since 2006

Neutrino-Dark Matter Interactions

Coherent effects

induce an effective mass or potential

Poster #568: J. Kim

on high-energy neutrinos

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P. F. de Salas, R. A. Lineros and M. Tórtola, Phys. Rev. D94:123001, 2016

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F. Capozzi, I. M. Shoemaker and L. Vecchi, JCAP 07:021, 2017
I. Lopes, Astrophys. J. 869:112, 2018

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If neutrinos couple to ultra-light dark matter, these interactions can...

alter flavor ratios of high-energy neutrinos

Y. Farzan and SPR, Phys. Rev. D99:051702(R), 2019

suppress sterile neutrino production in the early Universe

F. Bezrukov, A. Chudaykin and D. Gorbunov, JCAP 06:051, 2017
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induce time variations or distortions of masses and mixings

A .Berlin, Phys. Rev. Lett. 117:231801, 2016
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Neutrino-Dark Matter Interactions

collisional and mixed damping

C. Boehm, P. Fayet and R. Schaeffer, Phys. Lett. B518:8, 2001
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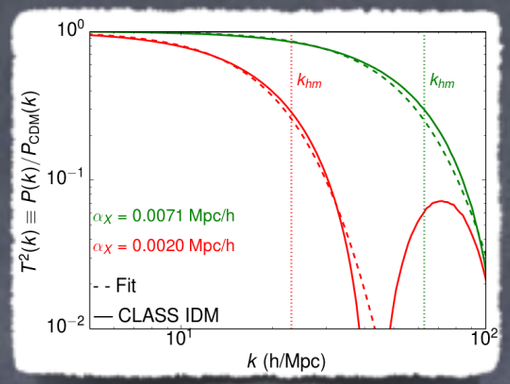

CMB anisotropies

G. Mangano et al., Phys. Rev., D74:043517, 2006
P. Serra et al., Phys.Rev.D 81:043507, 2010
R. J. Wilkinson, C. Boehm and J. Lesgourgues, JCAP 05:011, 2014
M. Escudero et al., JCAP 09:034, 2015
J. A. D. Diacoumis and Y. Y. Y. Wong, JCAP 01:001, 2019
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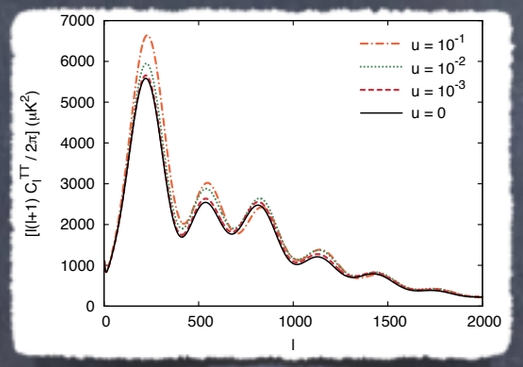
CMB spectral distortions

Y. Ali-Haïmoud, J. Chluba and M. Kamionkowski , Phys. Rev. Lett. 115:071304, 2015
J. A. D. Diacoumis and Y. Y. Y. Wong, JCAP 09:011, 2017



Cosmo/Astro effects

MW satellites

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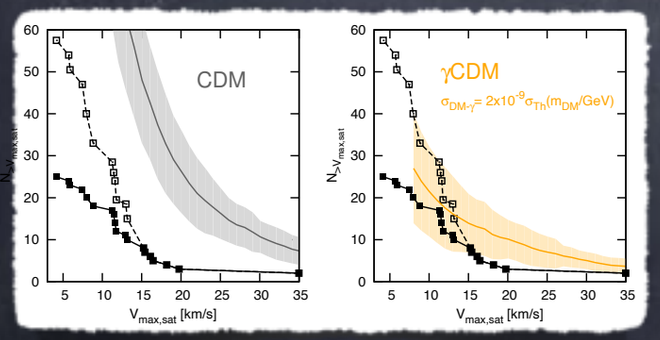
M. Escudero et al., JCAP 06:007, 2018



Galaxy surveys

P. Serra et al., Phys.Rev.D 81:043507, 2010
M. Escudero et al., JCAP 09:034, 2015

Lyman-alpha

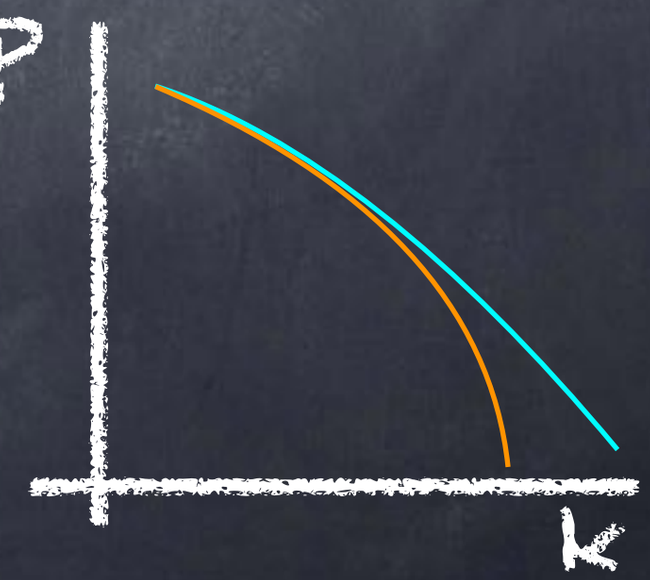
R. J. Wilkinson, C. Boehm and J. Lesgourgues, JCAP 05:011, 2014

$$\sigma_{el} < 10^{-33} \left(\frac{m_{DM}}{GeV}\right) cm^2$$

Diffuse neutrino flux from DM annihilations

A. Moliné et al., JCAP 08:069, 2016

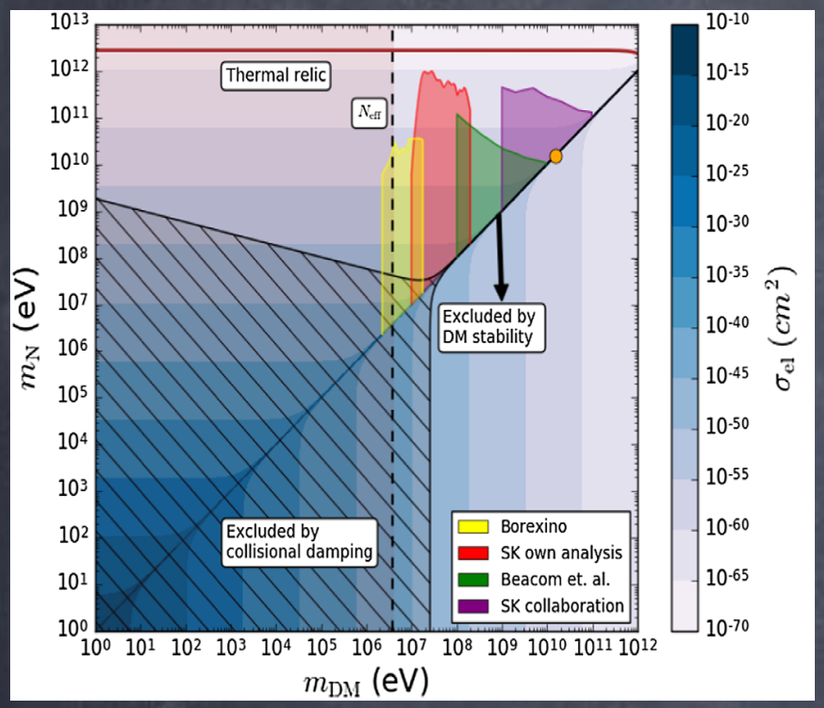
$$\sigma_{el} < 10^{-45} \left(\frac{m_{DM}}{GeV}\right) \left(\frac{T_\nu}{T_0}\right)^2 cm^2$$



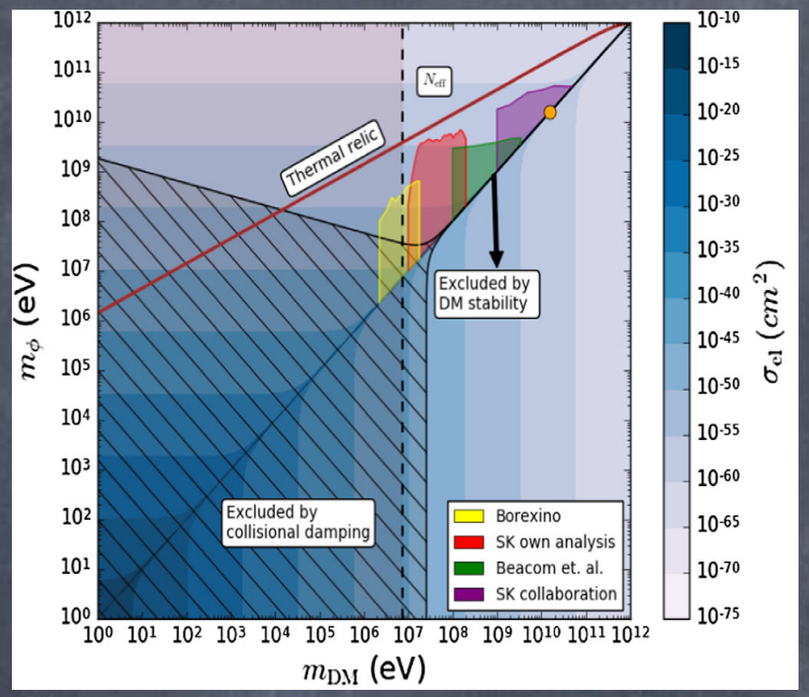
Combining results: interactions/annihilations

Considering all (12) possible dimension-4 operators describing neutrino-dark matter interactions

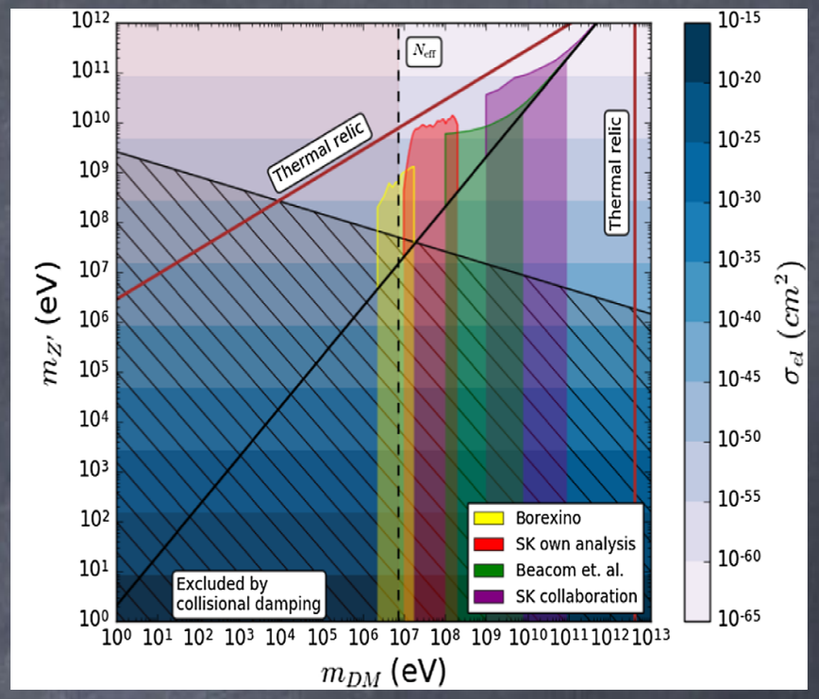
scalar DM – Majorana mediator



Dirac DM – scalar mediator



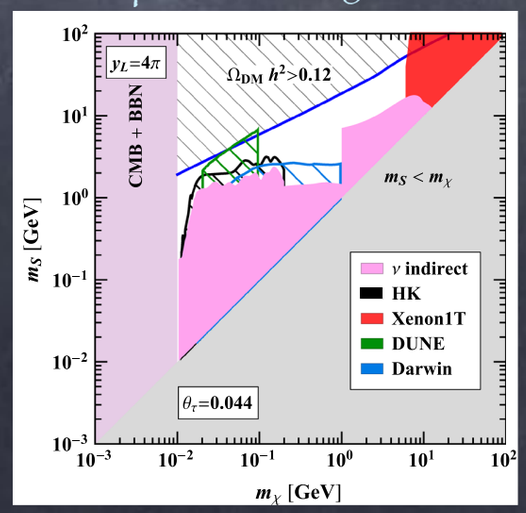
Dirac DM – vector mediator

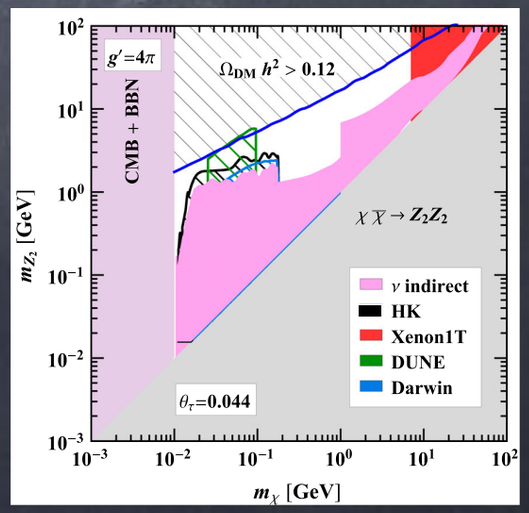


A. Olivares-Del Campo et al., Phys. Rev., D97:075039, 2018

Gauge-invariant scenarios: neutrino-portals

M. Blennow et al., Eur. Phys. J. C79:555, 2019





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M. Lindner, A. Merle and V. Niro, Phys. Rev., D82:123529, 2010

V. González Macías and J. Wudka, JHEP 07:161, 2015

Poster #195: A. Plascencia

Poster #281: S. Chakdar

Poster #584: J. Jones-Pérez

Poster #625: Y. Du

Conclusions

Different dark matter signatures for indirect searches (not all covered in this talk)...
some unique for neutrinos

Poster #467: S. R. Gozzini

Complementary to direct searches, to indirect searches with other messengers and to astro/cosmo observables

Set the strongest limits on spin-dependent scattering cross sections for $m > 100$ GeV

Set the strongest limits on the dark matter lifetime for $m > 100$ TeV (hard channels)

Huge range of energies covered by existing and future detectors: nice complementarity between North/South detectors

Thanks for your attention!

Thanks for your attention!