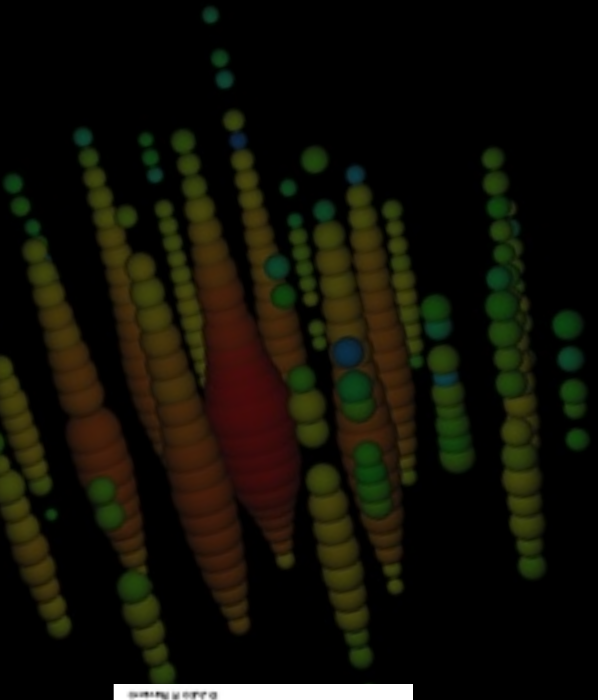
PROBING EXOTIC DM SCENARIOS WITH NEUTRINOS

Sergio Palomares Ruiz

IFIC, CSIC-U. Valencia

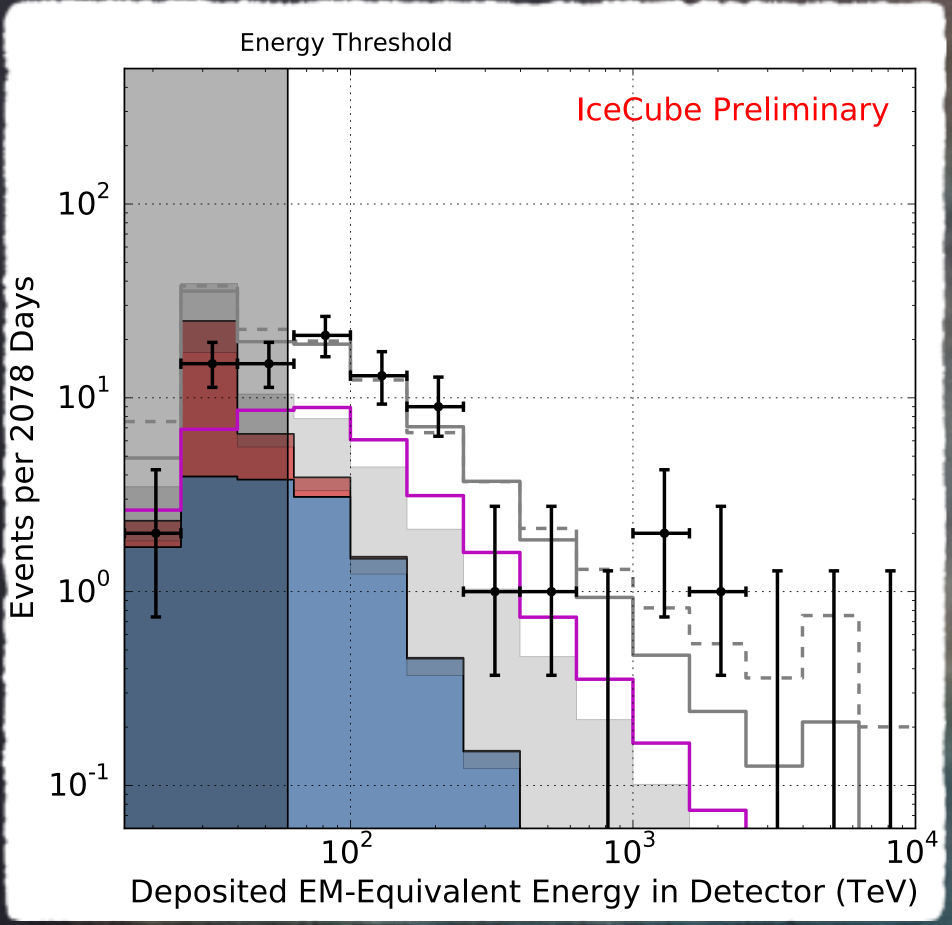


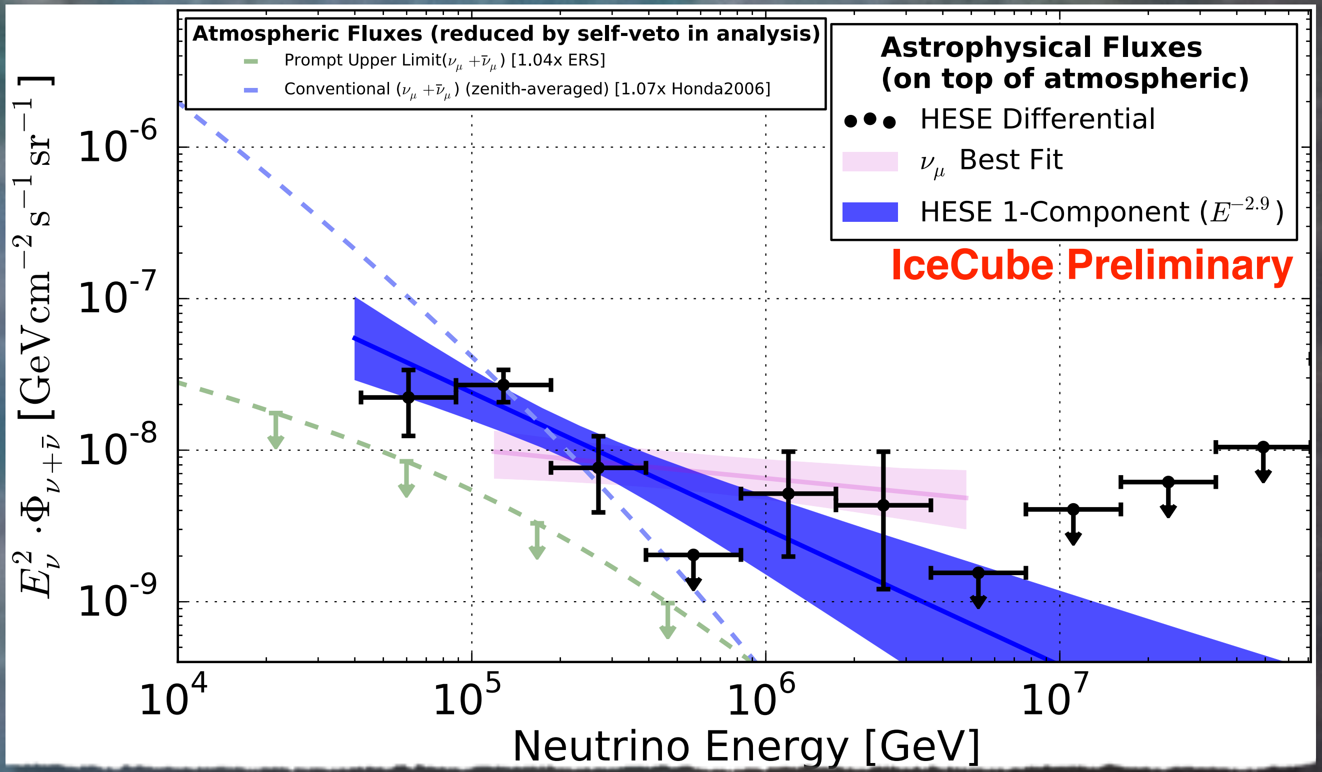
The small-scale structure of cold(?) dark matter

KITP, Santa Barbara

April 24, 2018

HIGH-ENERGY NEUTRINO FLUX





C. Kopper [IceCube Collaboration], PoS (ICRC2017) 981

standard searches

Astrophysical flux
(energy, direction and flavor)
Atmospheric prompt flux
Point sources
Multi messenger

new physics searches

as source

as signature

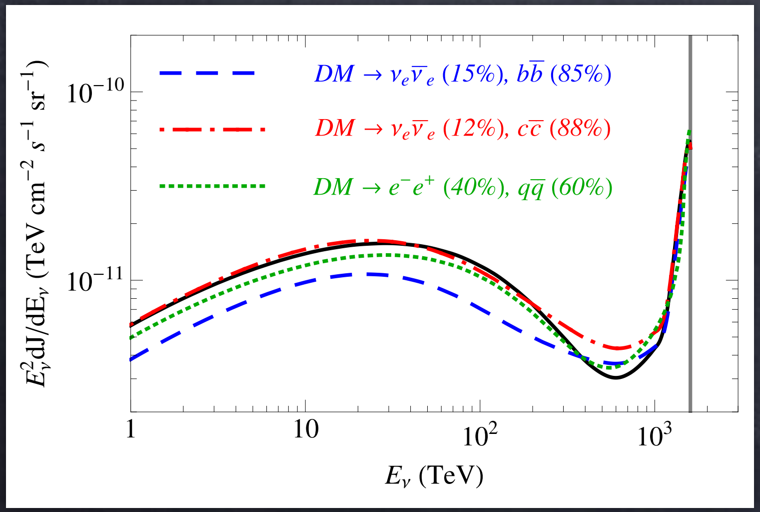
DARK MATTER DECAYS

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

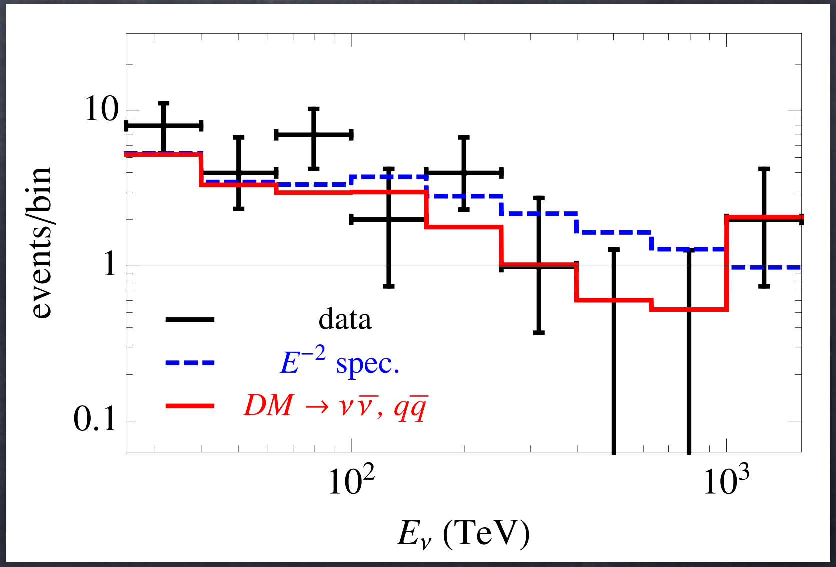
$$\text{Rate} \sim V\, N_N\, \sigma_N\, L_{MW} \frac{\rho_{DM}}{m_{DM}} \frac{1}{\tau_{DM}} \sim 10/\text{year} \rightarrow \left(\frac{\tau_{DM}}{10^{28}\,\text{s}}\right)\left(\frac{m_{DM}}{1\ \text{PeV}}\right) \sim 1$$

B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, Phys, Rev. D88:015004, 2013

Can ALL IceCube neutrinos be explained by heavy dark matter decays?



2-year HESE data



combination of soft and hard channels

A. Esmaili and P. D. Serpico, JCAP 1311:054, 2013

NEUTRINOS FROM DARK MATTER DECAYS

Two components

GALACTIC EXTRA-GALACTIC

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

$$\frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} = \frac{1}{4\pi m_{DM}\tau_{DM}}\frac{dN_{\nu_\alpha}}{dE_\nu}\int_0^\infty \rho\left[r(s,b,l)\right] ds$$

$$\frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu} = \frac{\Omega_{DM}\rho_c}{4\pi m_{DM}\tau_{DM}}\int_0^\infty dz\,\frac{1}{H(z)}\frac{dN_{\nu_\alpha}}{dE_\nu}\left[(1+z)E_\nu\right]$$

DM mass

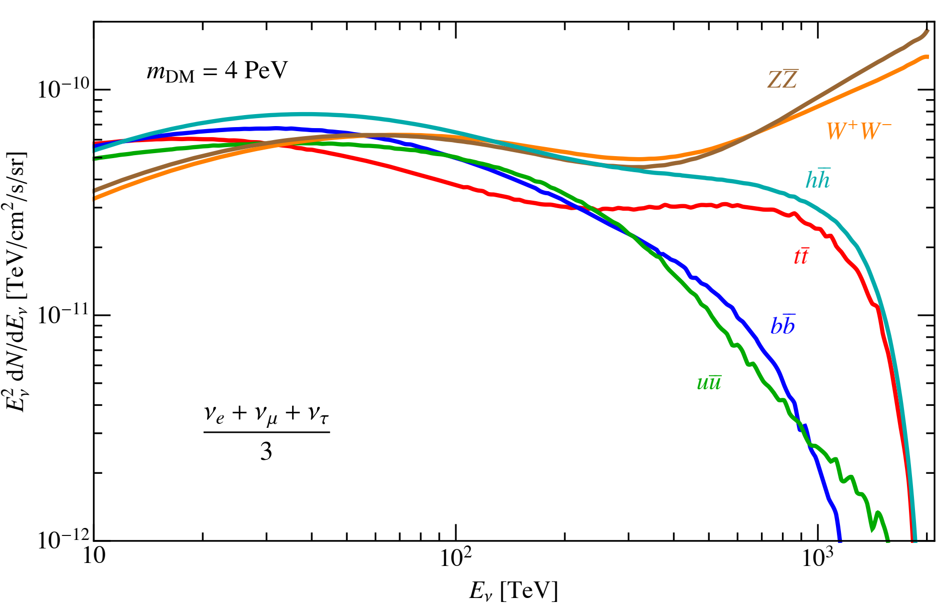
DM lifetime

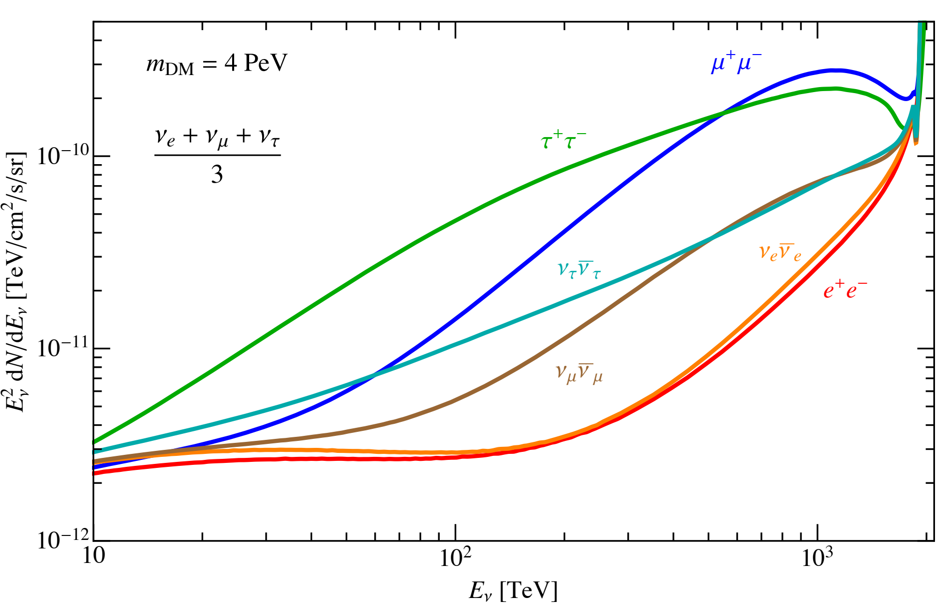
neutrino flux at production

DM galactic density

DM density of the Universe

Hubble function



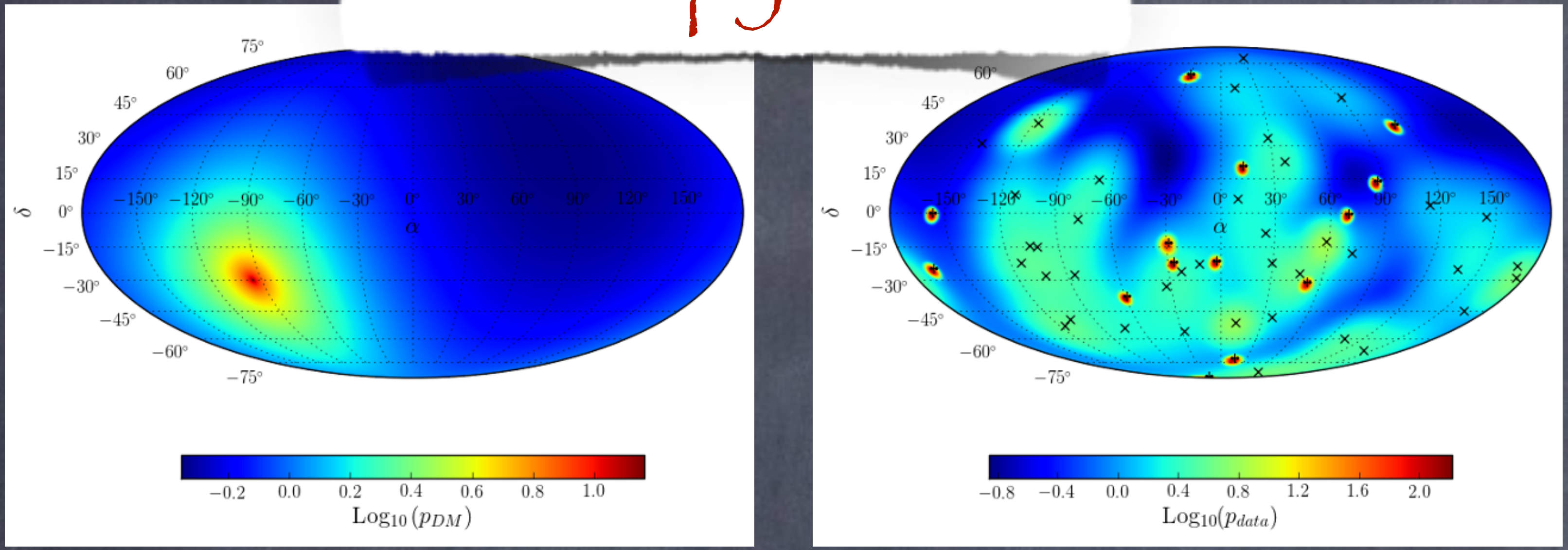


A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 1707:027, 2017

DARK MATTER DECAYS

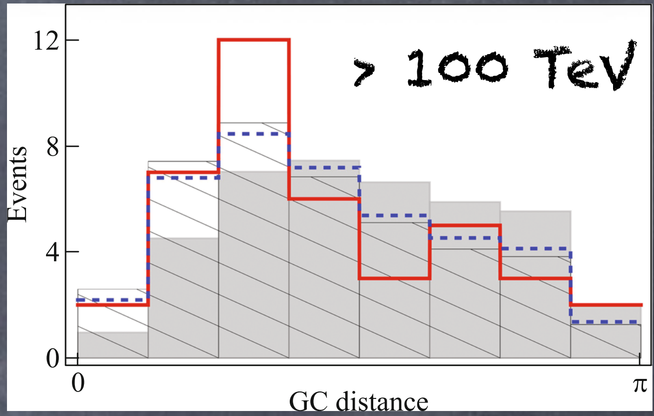
Are neutrinos from DM decays compatible with the angular distribution of the IceCube events?

is isotropy better?



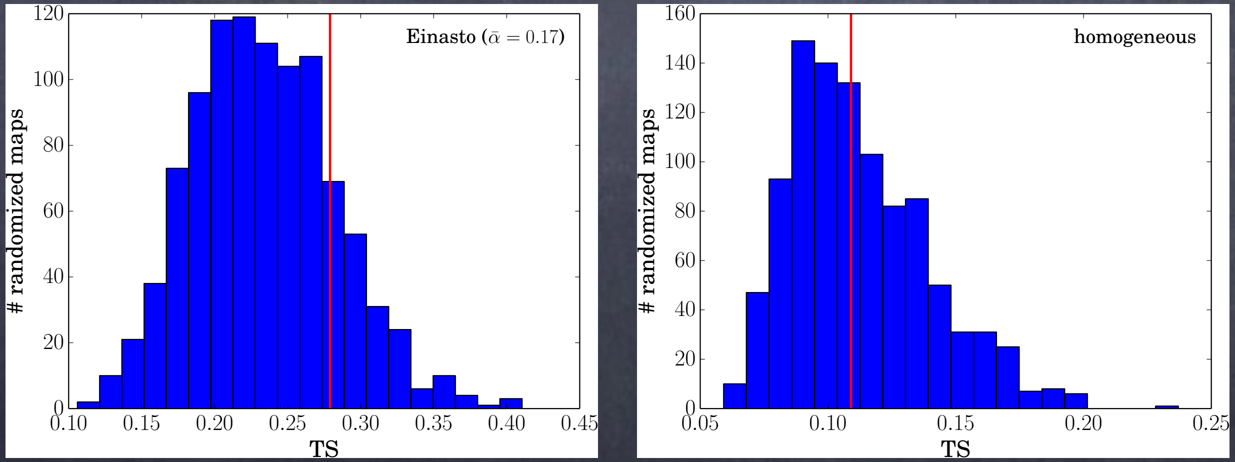
Y. Bai, R. Lu and J. Salvadó, JHEP 1601:161, 2016

is DM better?



S. V. Troitsky, JETP Letters 102:785, 2015

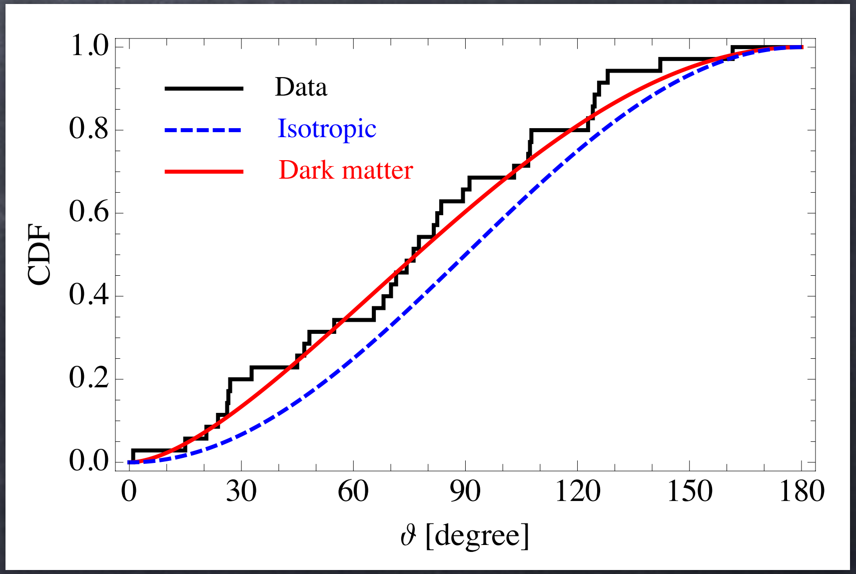
only galactic contribution



Scenario		KS
Astrophysics	Gal. plane	0.007–0.008
	Iso. dist.	0.20–0.55
DM decay	NFW	0.06–0.16
	Isoth.	0.08–0.22

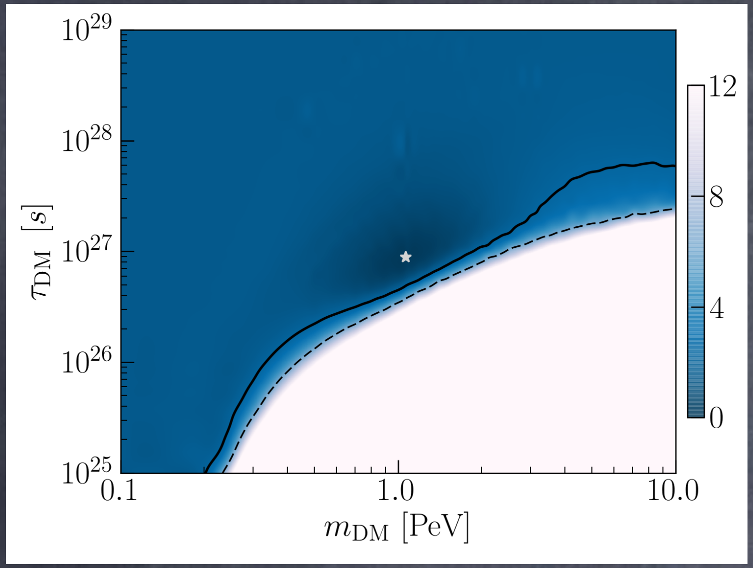
excess at 60-100 TeV

M. Chianese, G. Miele, S. Morisi and E. Vitagliano, Phys. Lett. B757:251, 2016

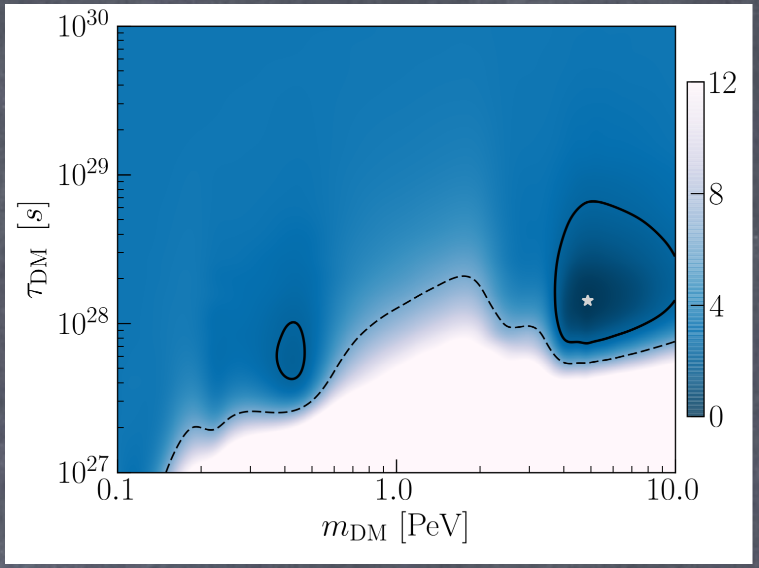


A. Esmaili, S. K. Kang and P. D. Serpico, JCAP 1412:054, 2014

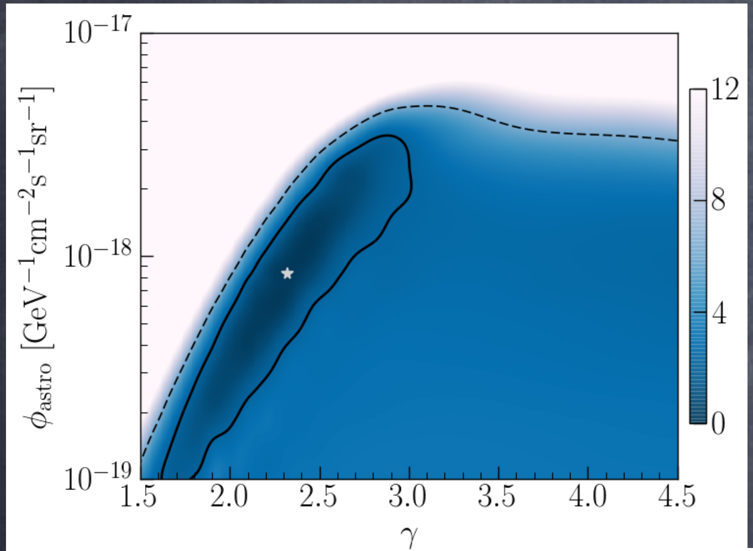
DM DECAYS + ASTRO: HESE ANALYSIS



short lifetimes ✗
(problem with
gamma-rays)

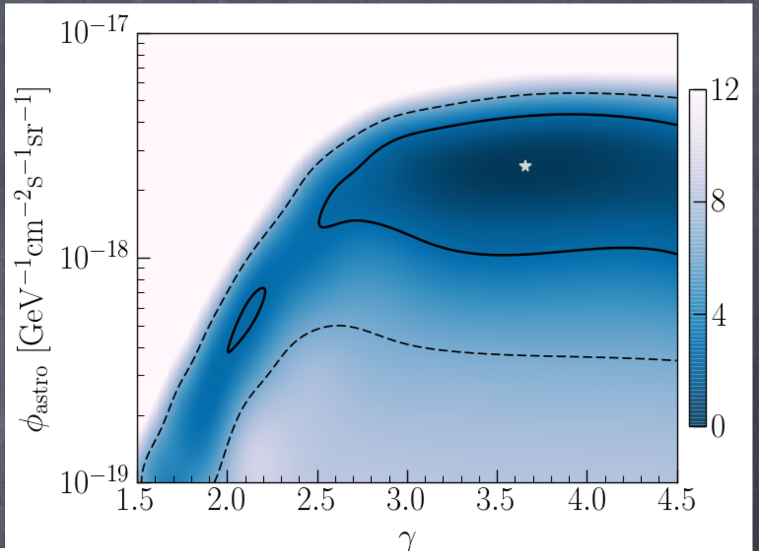


longer lifetimes ✓

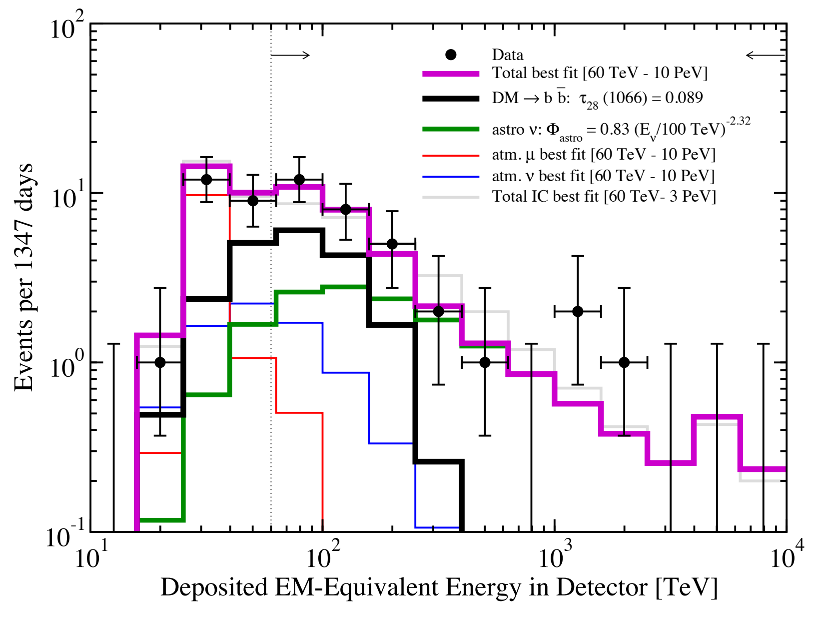


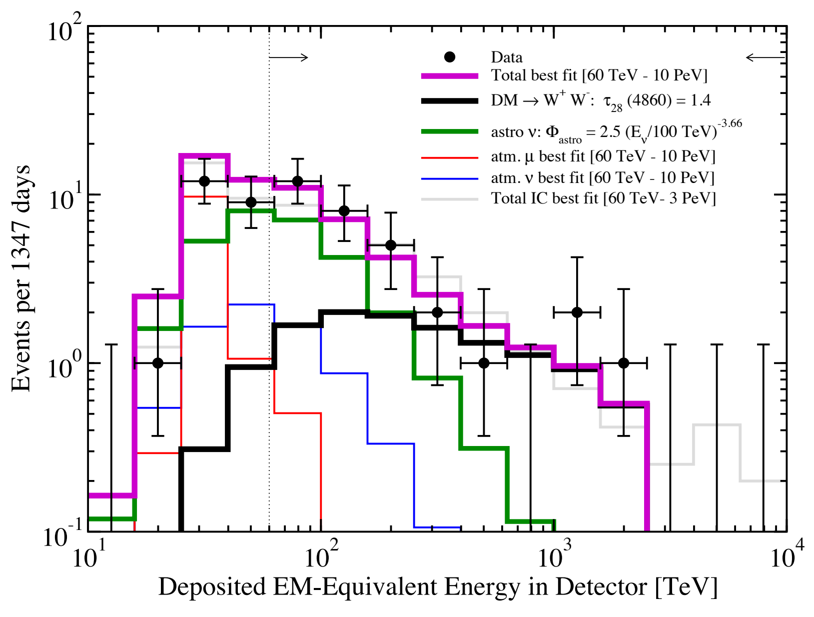
relatively hard
astro spectrum ✓

very soft astro
spectrum ✗



$DM \to b\bar{b}$

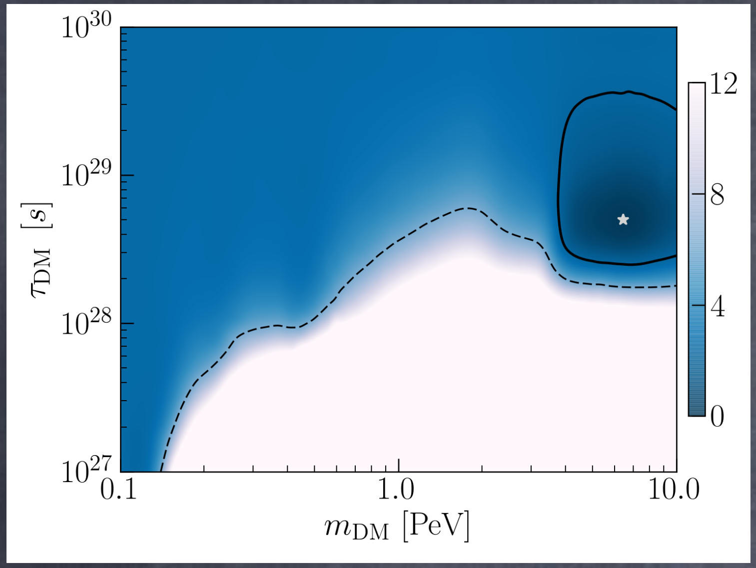




$DM \to W^+W^-$

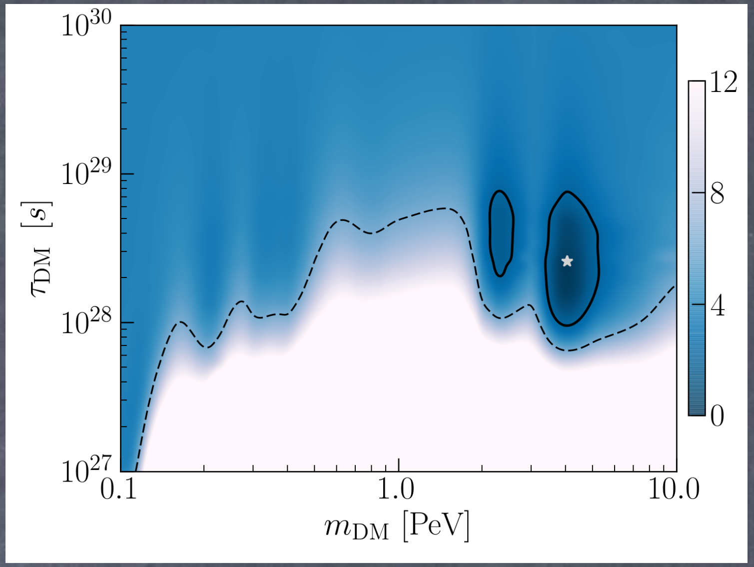
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 1707:027, 2017

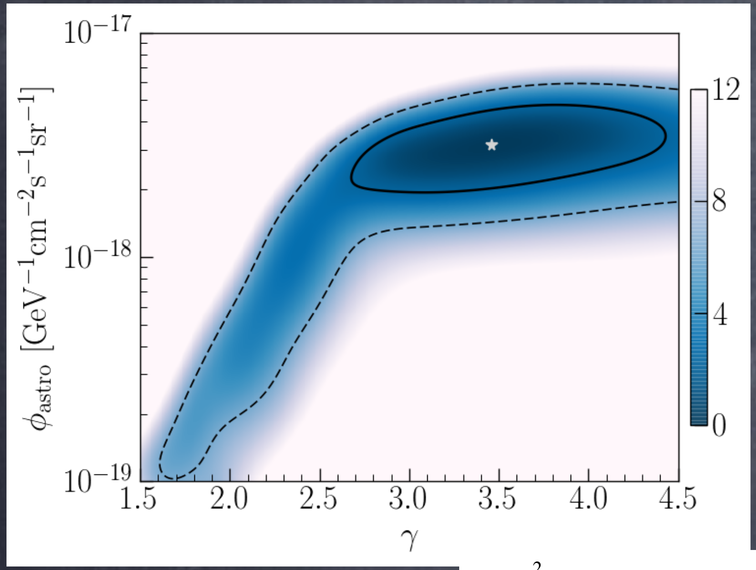
DM DECAYS + ASTRO: HESE ANALYSIS



long lifetimes ✓

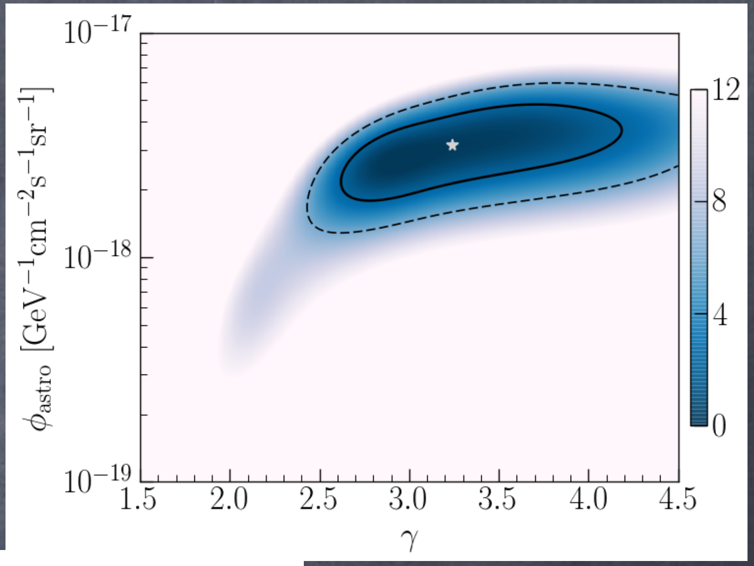
long lifetimes ✓



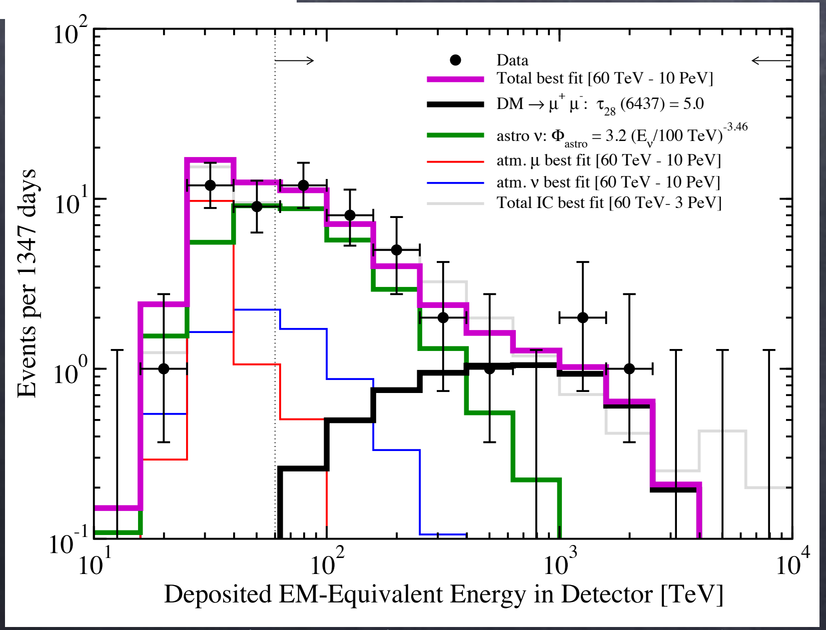


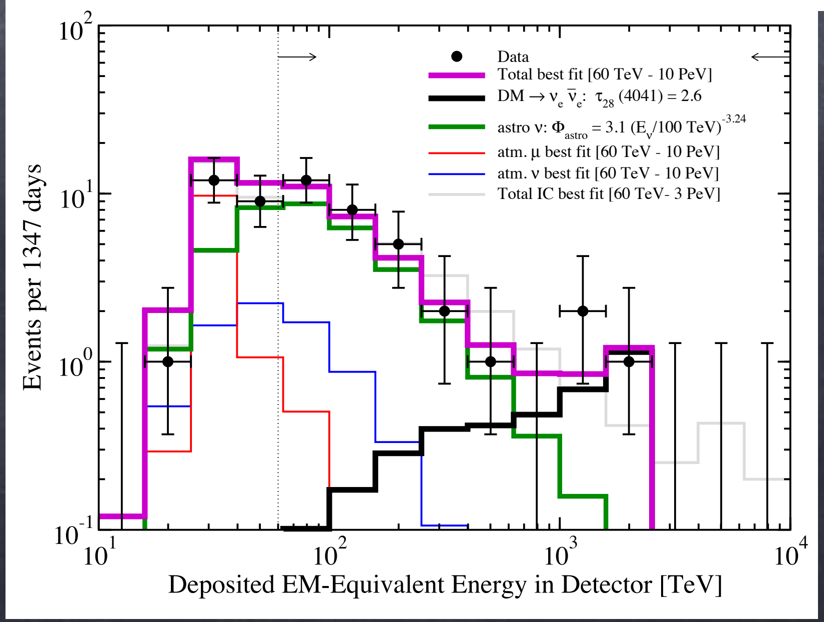
very soft astro spectrum ✗

very soft astro spectrum ✗



$DM \rightarrow \mu^+\mu^-$





$DM \rightarrow \nu_e \bar{\nu}_e$

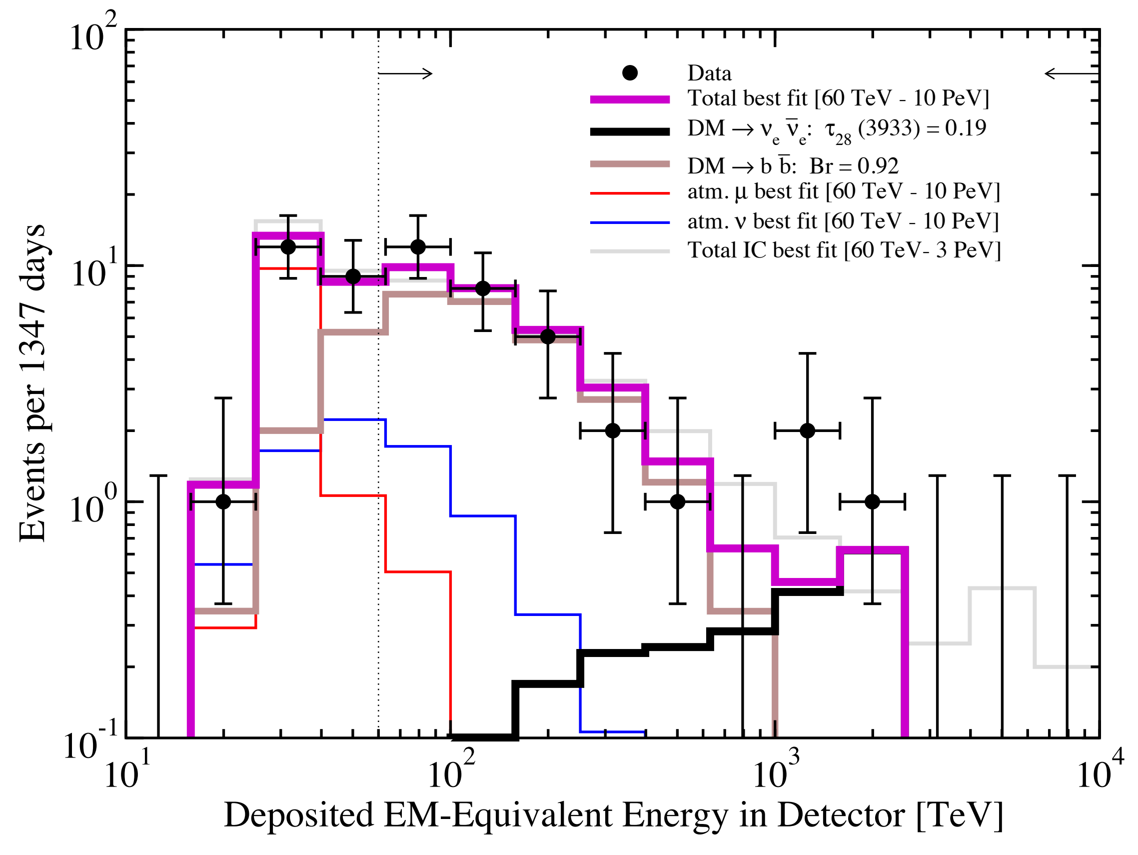
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 1707:027, 2017

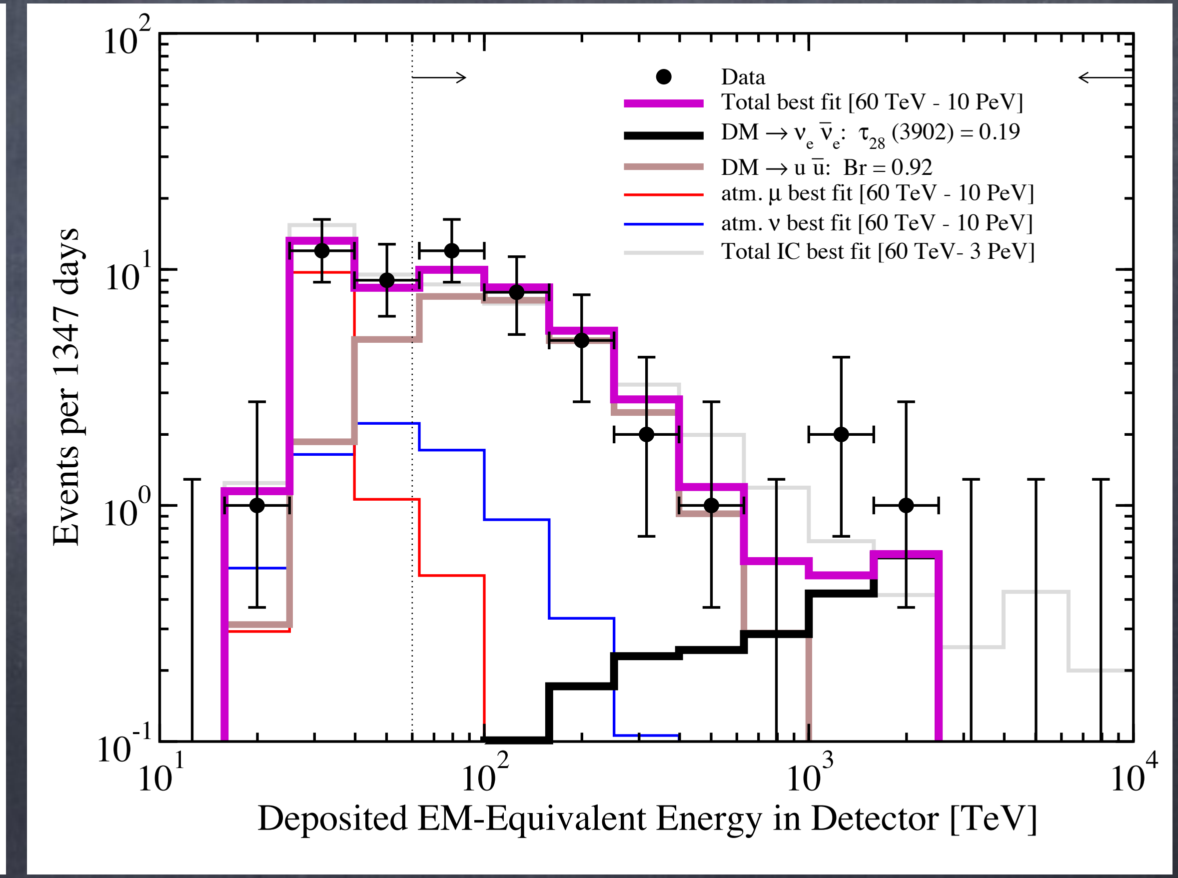
Only DM decays: HESE analysis

Only DM?
Two decay channels

but too much contribution from soft channels?

$$DM \rightarrow \left\{92\%\ b\bar{b};\ 8\%\ \nu_e\bar{\nu}_e\right\} \qquad DM \rightarrow \left\{92\%\ u\bar{u};\ 8\%\ \nu_e\bar{\nu}_e\right\}$$





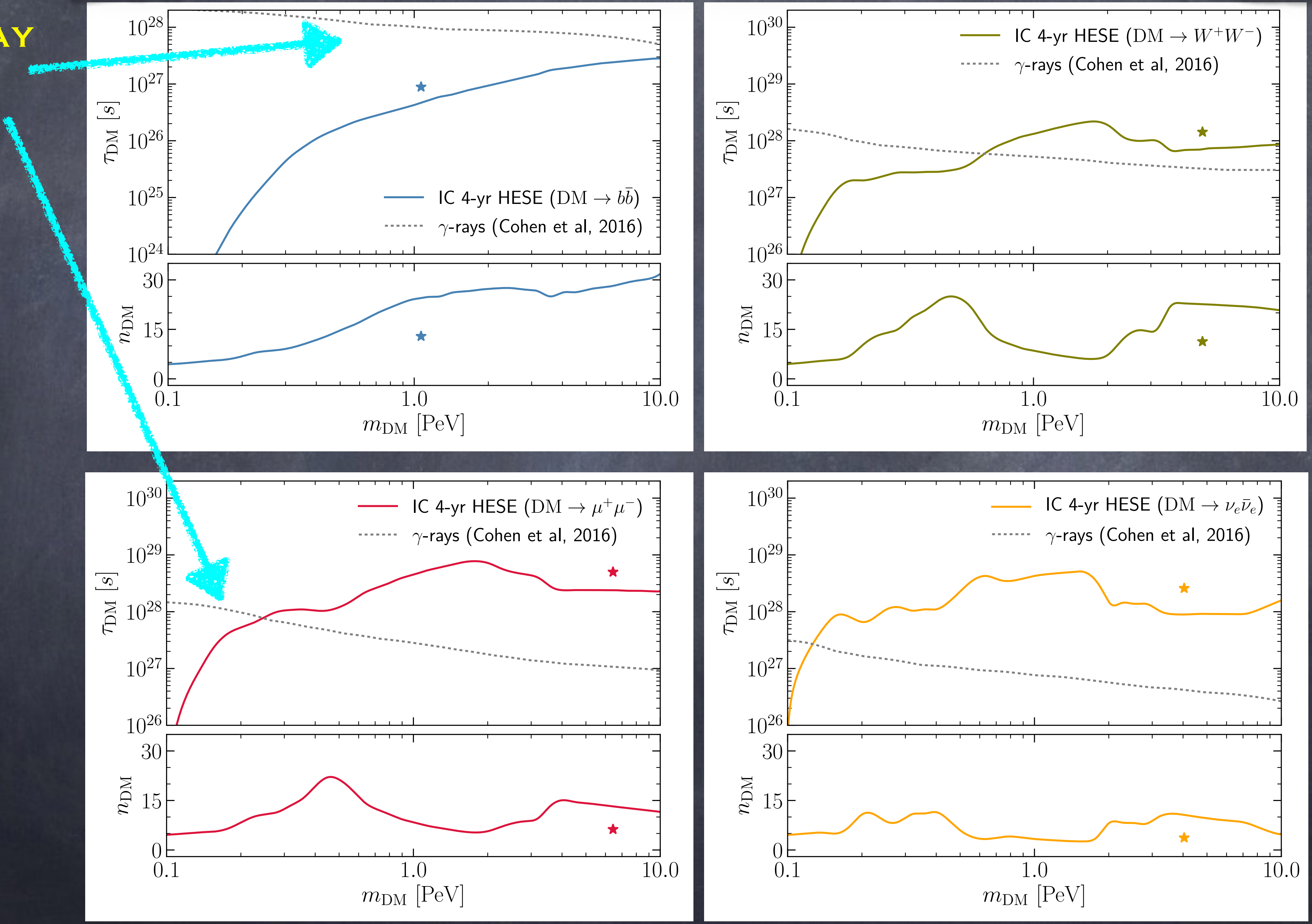
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 1707:027, 2017

DM DECAYS + ASTRO: HESE ANALYSIS

See also: A. Esmaili, A. Ibarra and O. L. G. Peres, JCAP 1211:034, 2012

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

GAMMA-RAY LIMITS



A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 1707:027, 2017

BOOSTED DARK MATTER

A. Bhattacharya, R. Gandhi and A. Gupta, JCAP 1503:027, 2015

DM composed of two particles:

a dominant contribution with a mass m_ϕ= few PeV

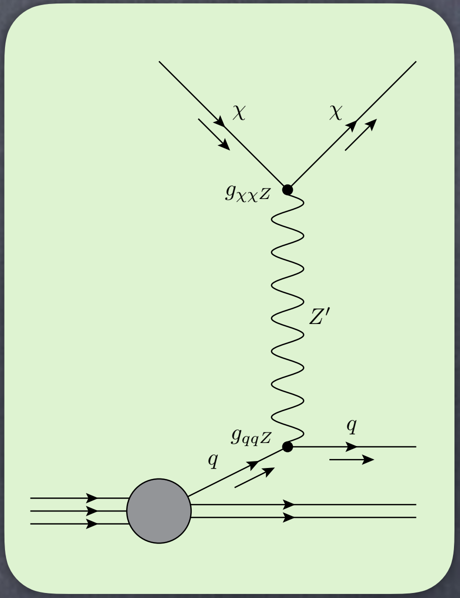
a lighter one χ ($m_\chi \ll m_\phi$) produced from decays of ϕ

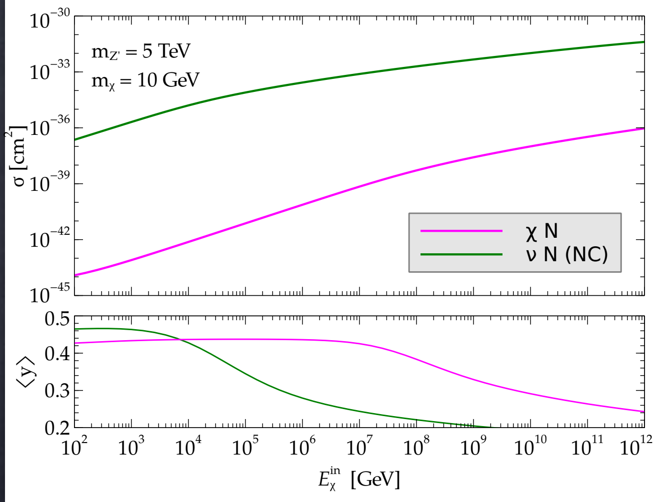
Signal:

scatterings of highly relativistic χ

with nucleons of the detector

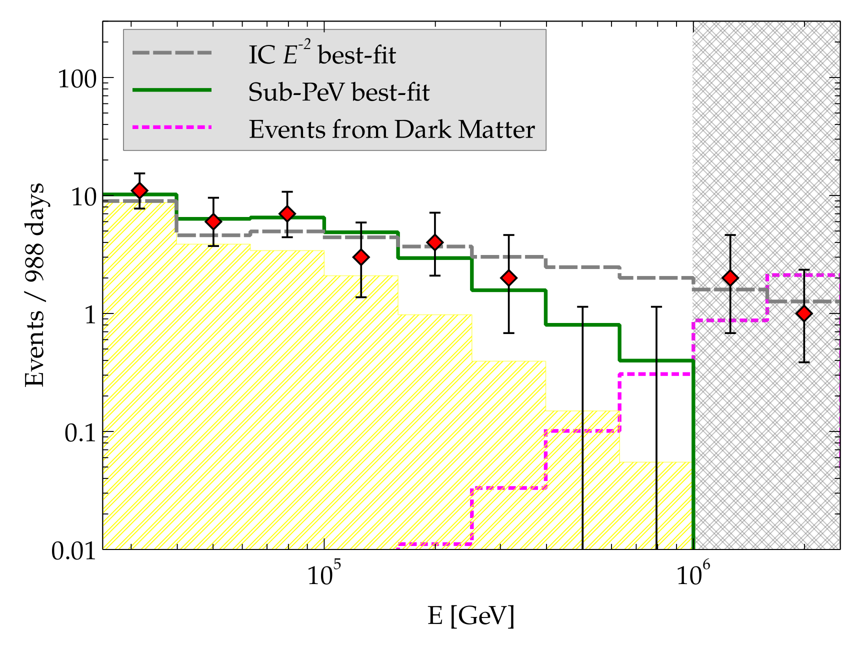
undistinguishable from NC neutrino interactions





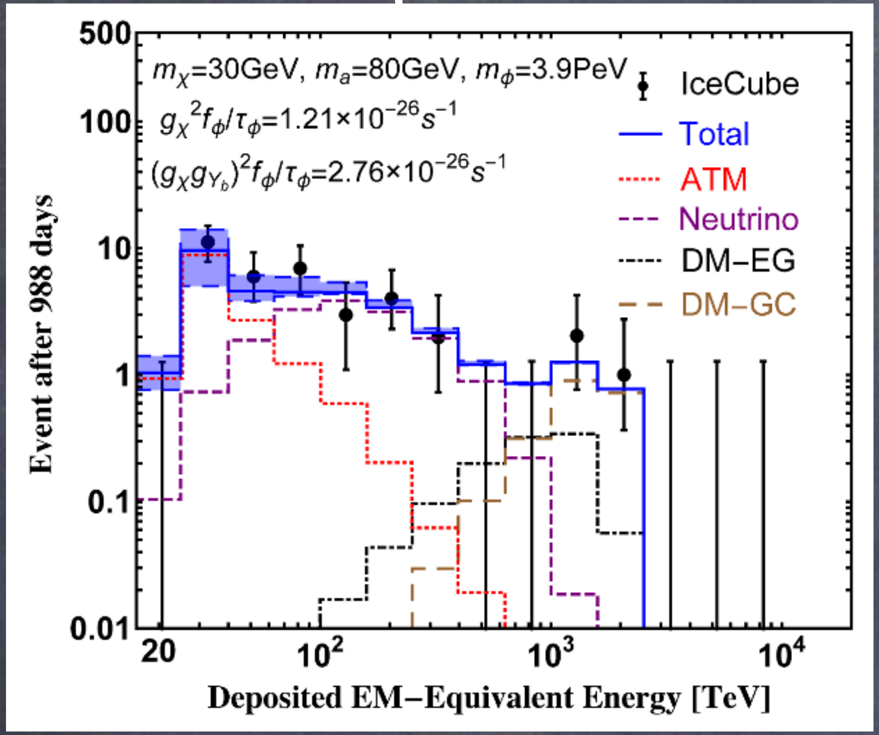
To explain PeV events

$$\frac{\tau}{G^2} \sim 2 \times 10^{24}\,\mathrm{s}$$



BOOSTED DARK MATTER

Adding bremsstrahlung of the (pseudo-scalar) mediator, produces also a low-energy neutrino flux

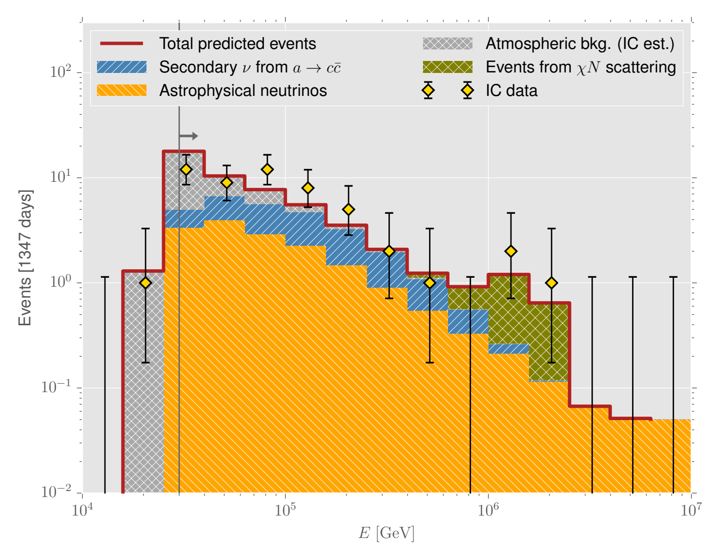


J. Kopp, J. Liu and X.-P. Wang, JHEP 1504:105, 2015

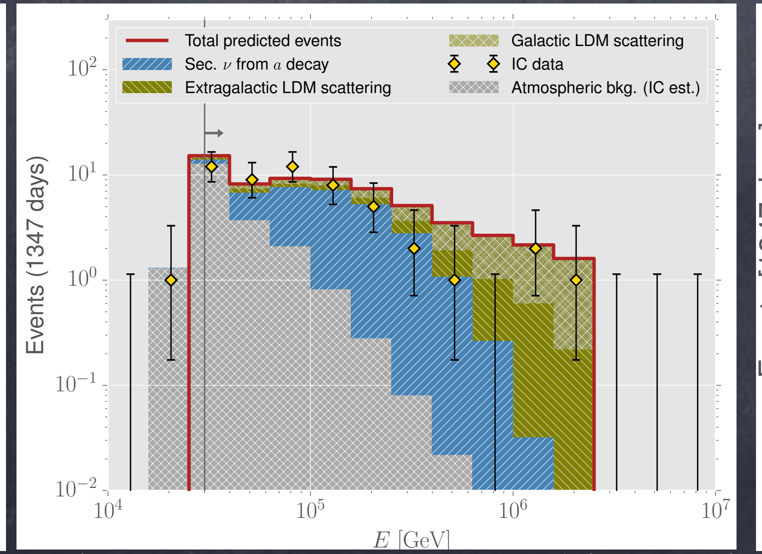
no need of astro neutrinos
DM could explain all events!

may even explain GC gamma-ray excess

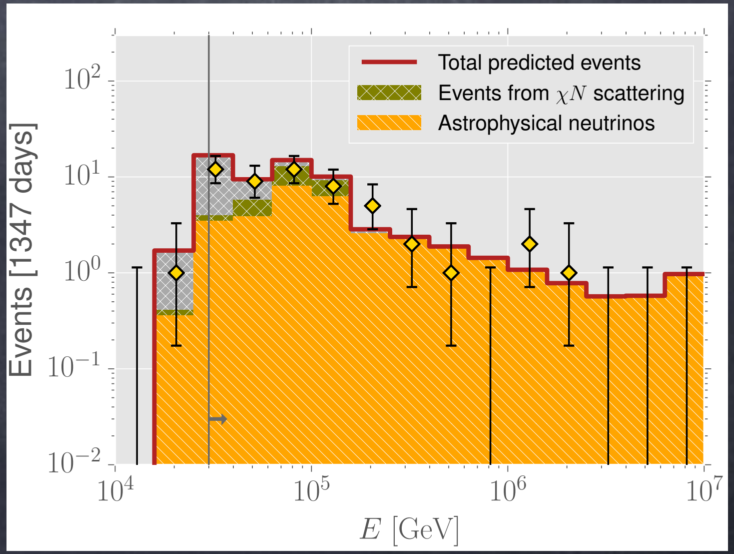
SCALAR MEDIATOR



LIGHT VECTOR MEDIATOR



PSEUDO-SCALAR MEDIATOR
LOWER DM MASS



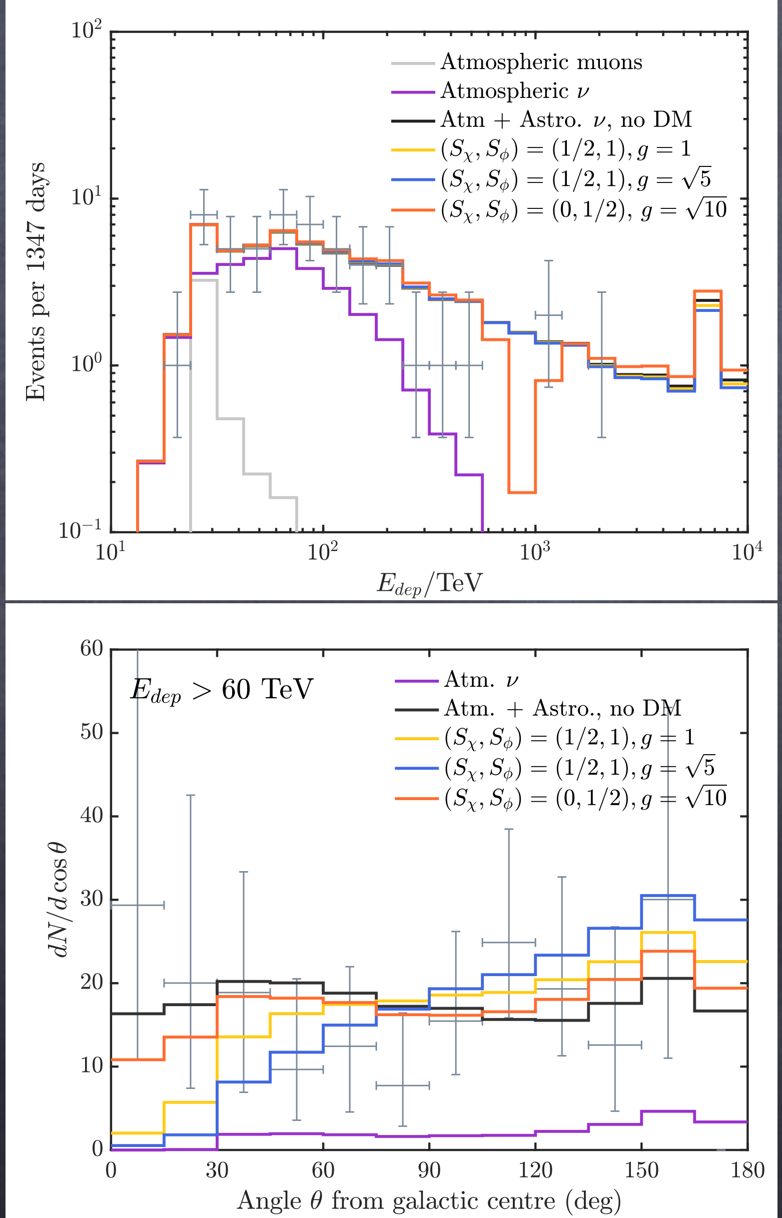
A. Bhattacharya, R. Gandhi, A. Gupta and S. Mukhopadhyay, JCAP 1705:002, 2017

Neutrino-DM interactions

As neutrinos pass through the Milky Way, they would be more attenuated in the direction of the GC

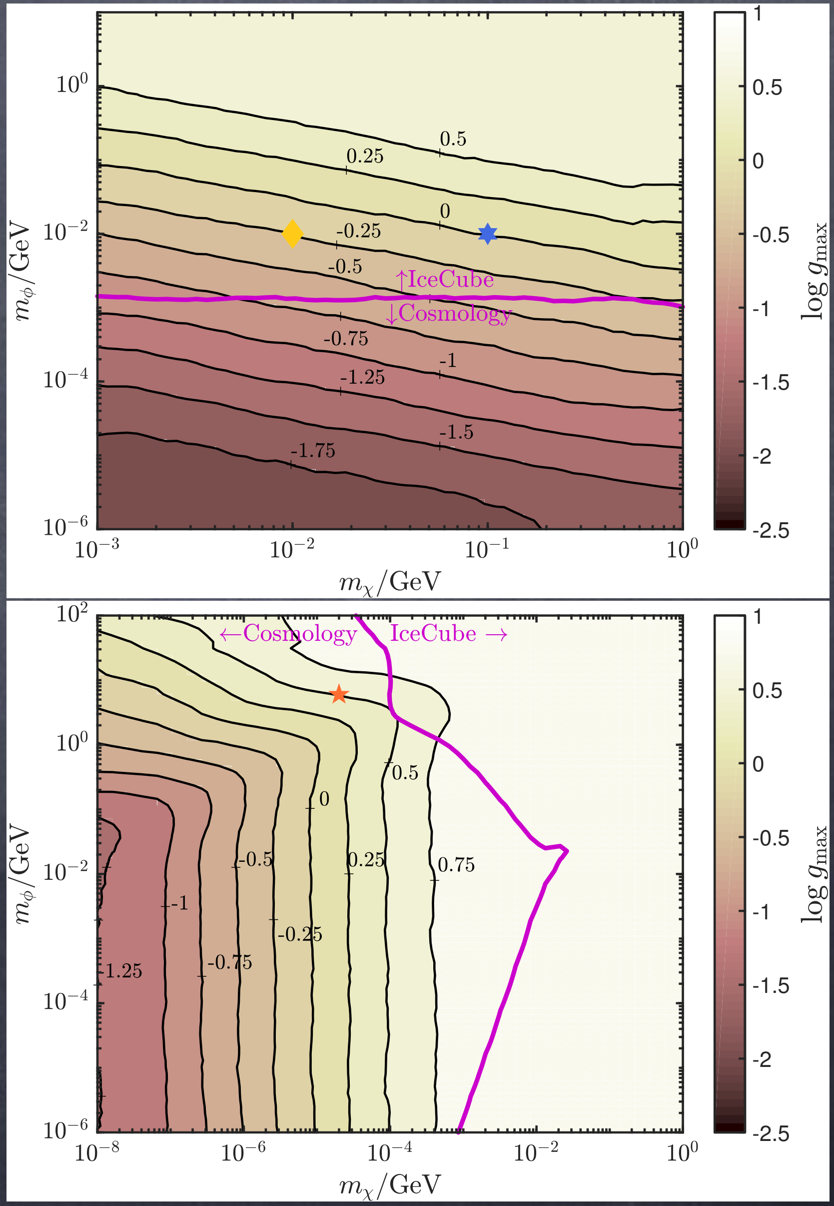
↓

energy-dependent anisotropy in the (otherwise isotropic) neutrino sky



FERMION DM/ VECTOR MEDIATOR

SCALAR DM/ FERMION MEDIATOR



suppression in the CG direction

C. A. Argüelles, A. Kheirandish, A. C. Vincent, Phys. Rev. Lett. 119:201801, 2017

NEUTRINO-DM INTERACTIONS

Contribution from all halos in the Universe

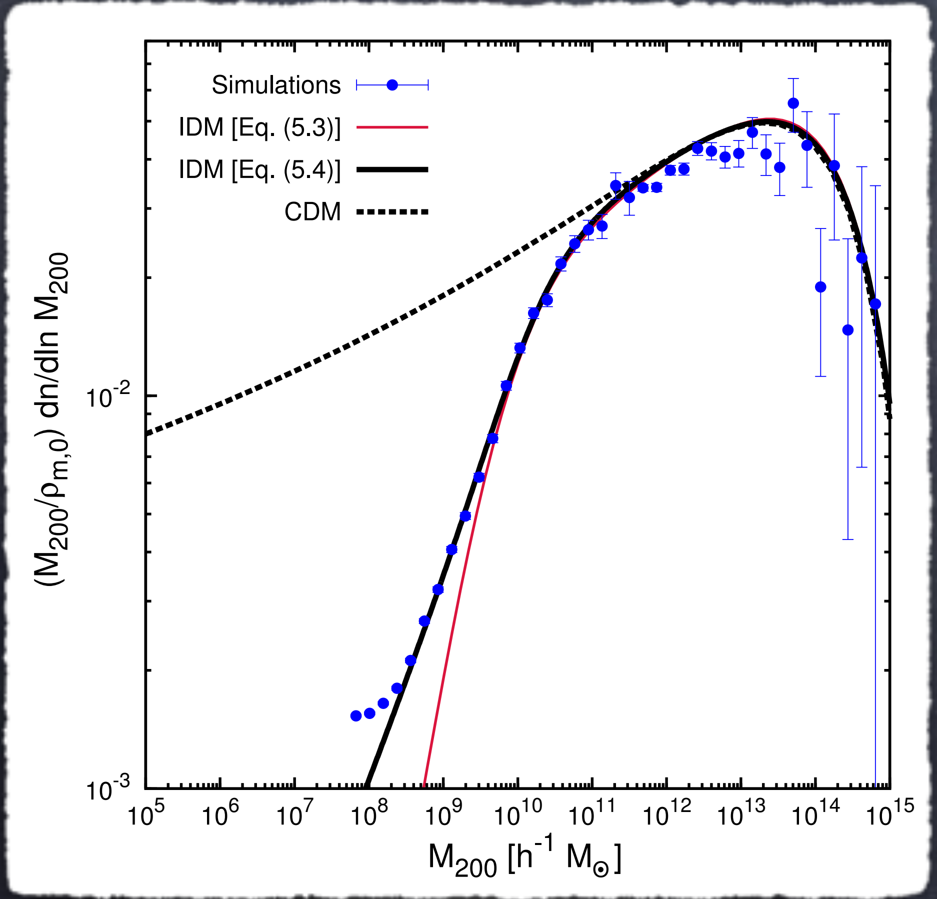
$$\frac{d\phi_\alpha}{dE_0} = \frac{\langle \sigma v \rangle}{2} \frac{\rho_0^2}{m_\chi^2} \int \frac{dz}{H(z)} \xi^2(z) \sum_{\beta, i} |U_{\alpha i}|^2 |U_{\beta i}|^2 \sum_k Br_k \frac{dN_{\beta k}(E_0(1+z))}{dE}$$

Enhancement

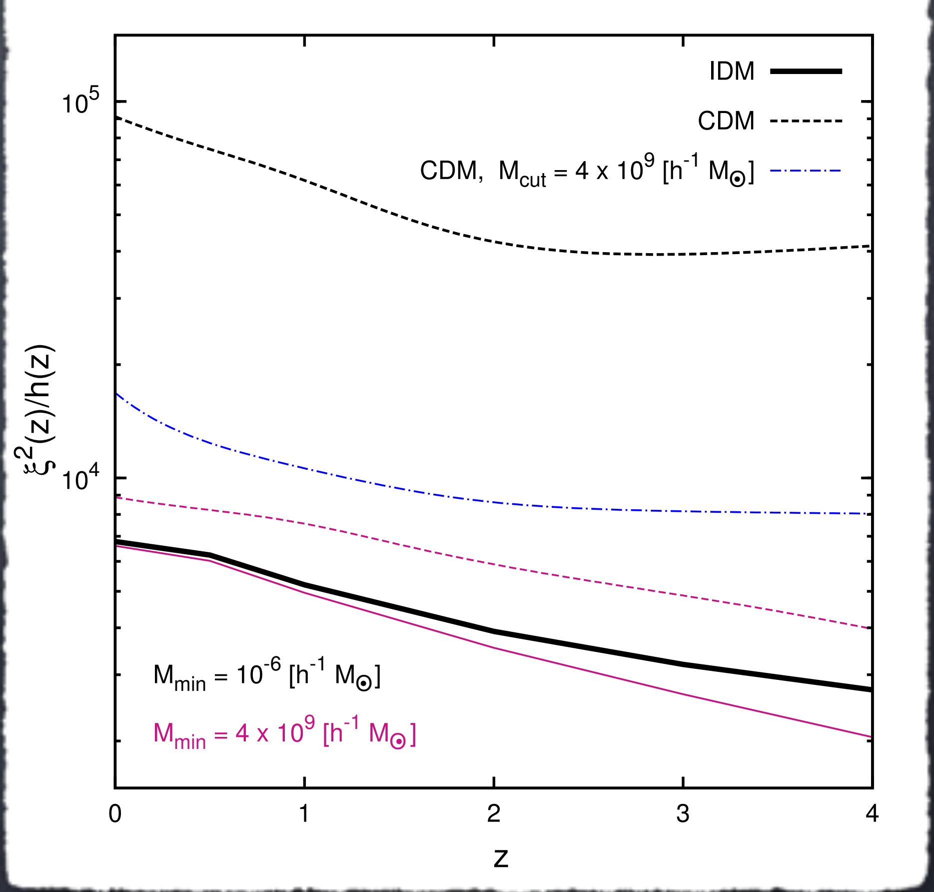
Oscillations

Flux from DM annihilations

$$\xi^2(z) = \frac{1}{\rho_0^2} \int dM \frac{dn(M,z)}{dM} \int \rho^2_{halo}(r; M, c(z))\, dV$$



Suppression at small scales

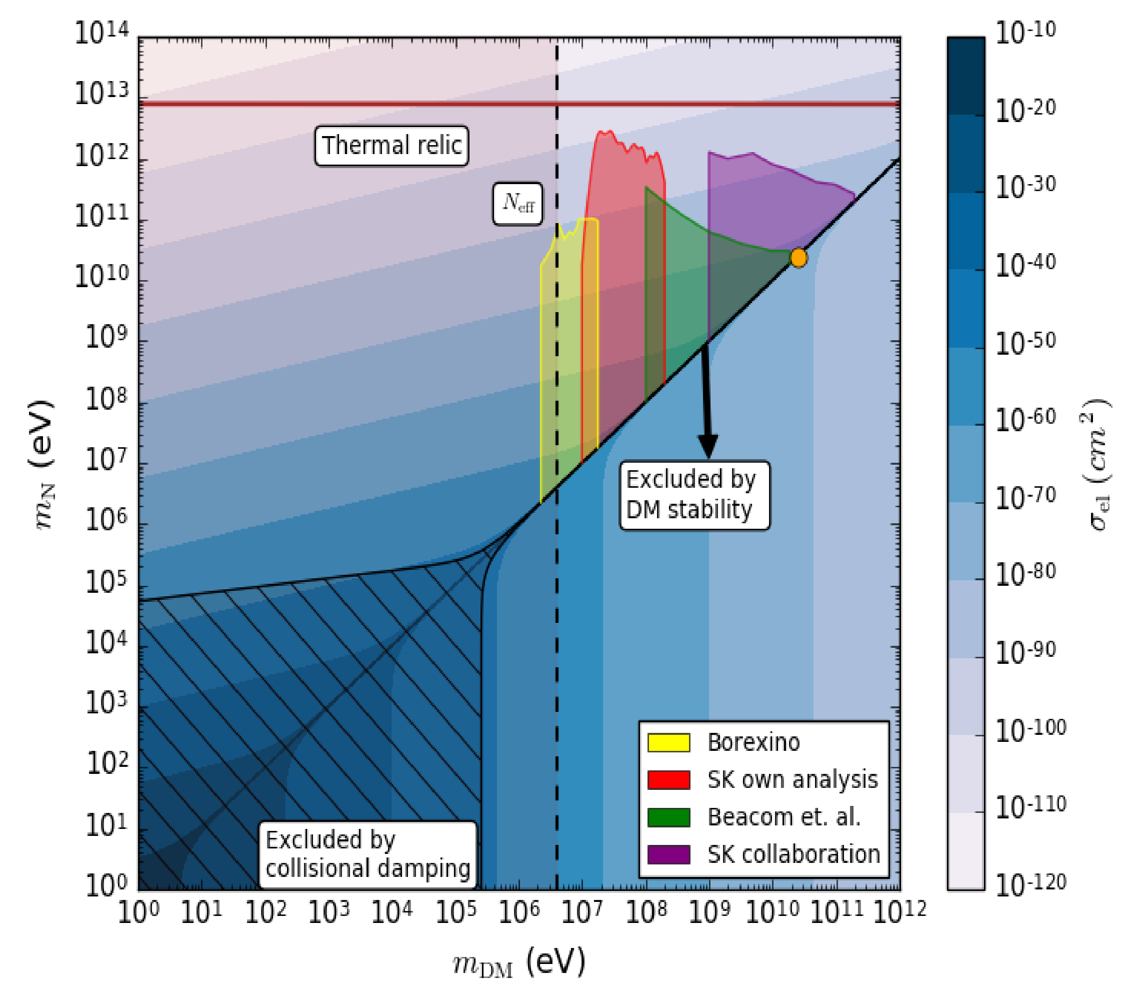


A. Moliné, J. A. Schewtschenko, SPR, C. Boehm and C. M Baugh, JCAP 1608: no. 09, 069, 2016

NEUTRINO-DM INTERACTIONS

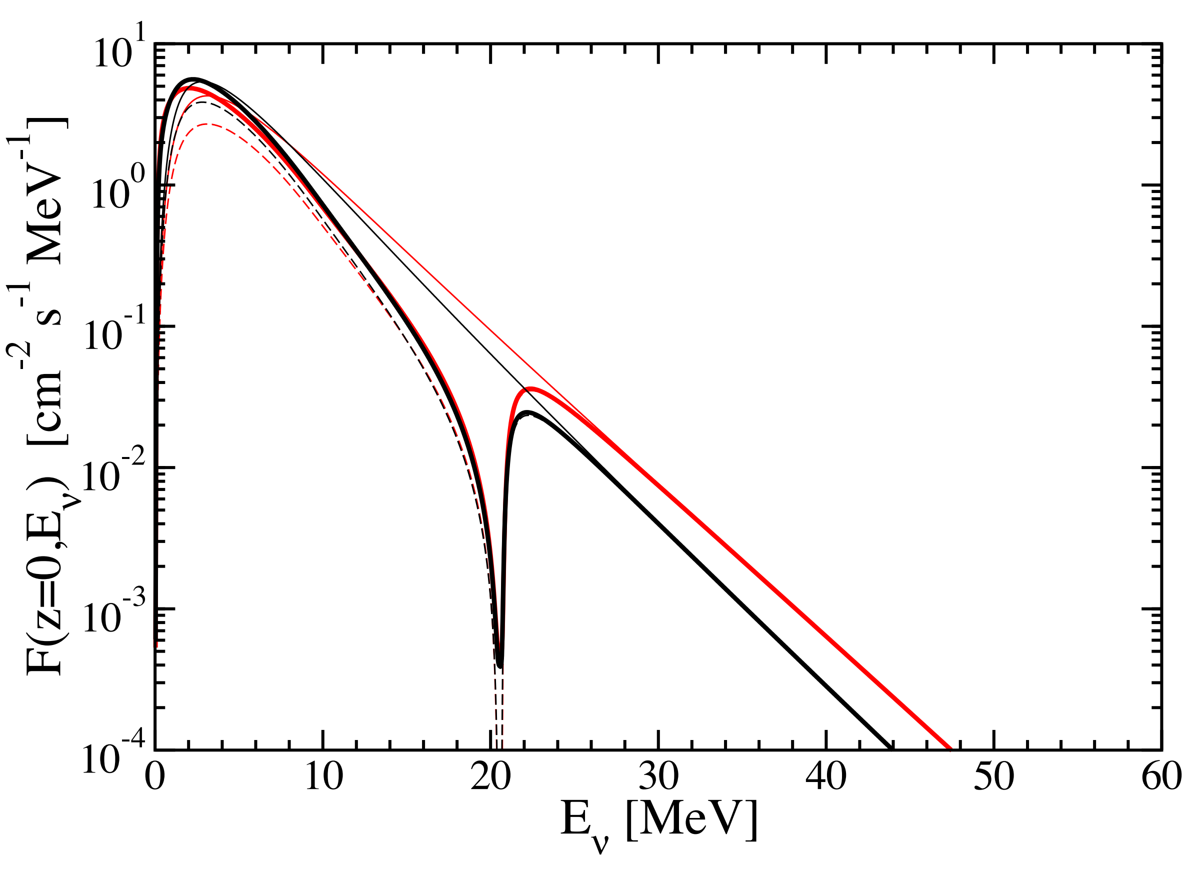
Study of all renormalizable operators coupling DM and neutrinos and use small-scale suppression and neutrino data

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



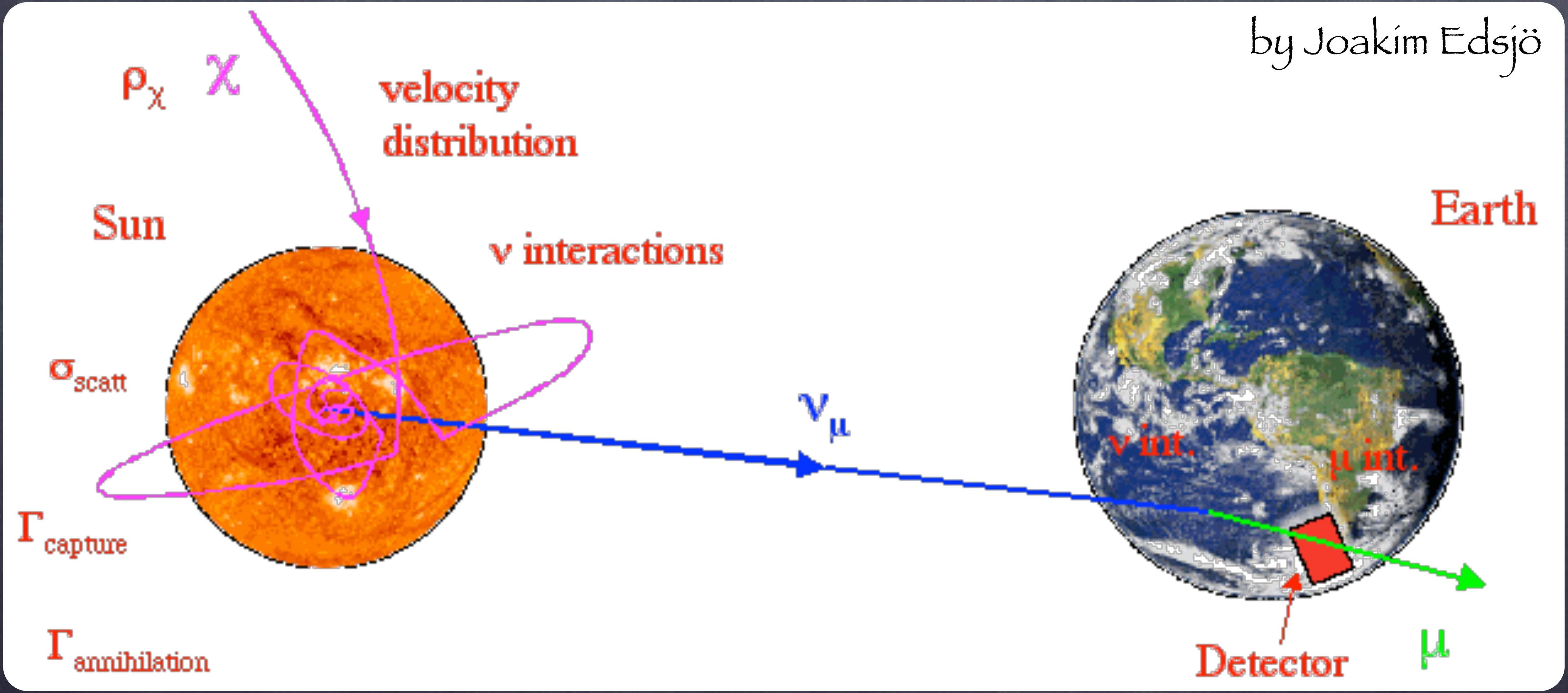
A. Olivares-Del Campo, C. Boehm, SPR and S. Pascoli, arXiv:1711.05283 (accepted in PRD)

Resonant absorption
Dips in the DSNB



Y. Farzan and SPR, JCAP 1406:014, 2014

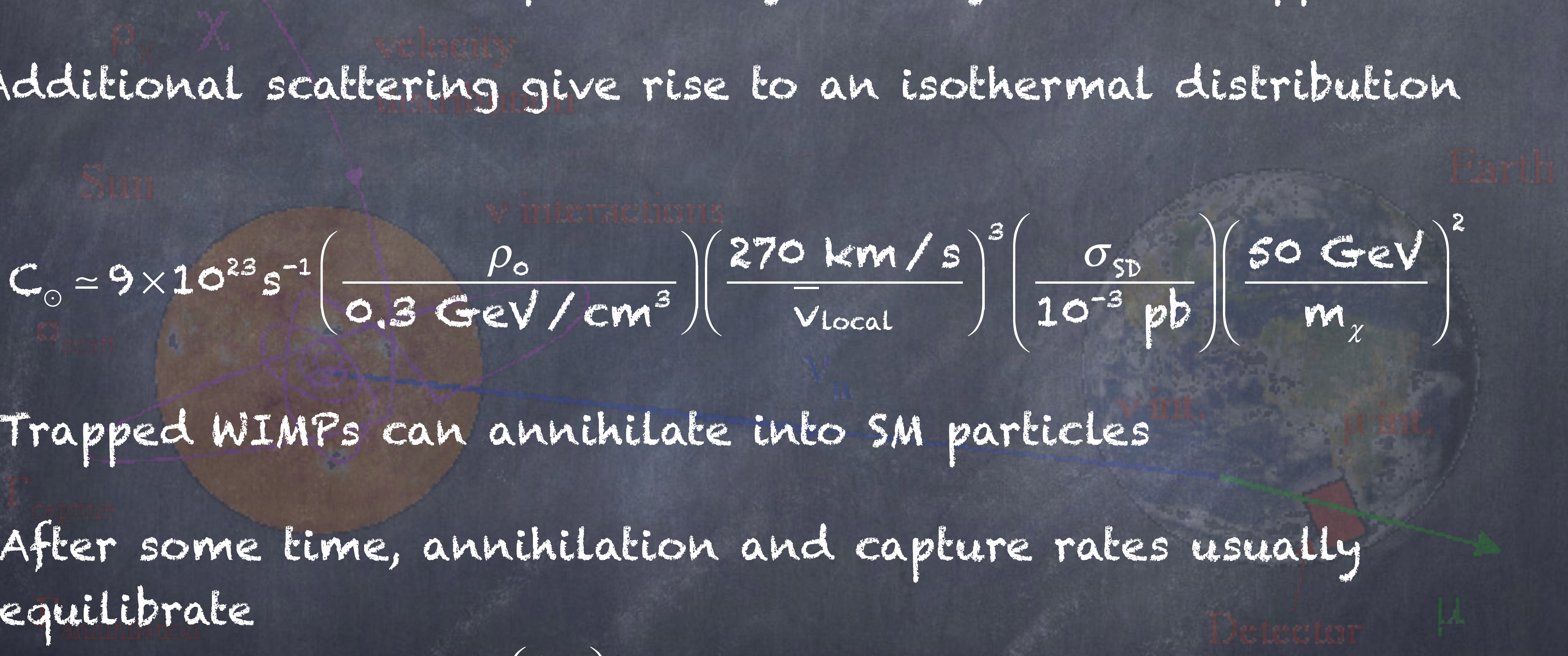
DARK MATTER: IN THE SUN



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: IN THE SUN

- WIMPs elastically scatter with the nuclei of the Sun to a velocity smaller than the escape velocity, so they remain trapped inside



Additional scattering give rise to an isothermal distribution

$$C_\odot \simeq 9\times10^{23}\,s^{-1}\left(\frac{\rho_0}{0.3\ \mathrm{GeV/cm^3}}\right)\left(\frac{270\ \mathrm{km/s}}{\bar{v}_{local}}\right)^3\left(\frac{\sigma_{SD}}{10^{-3}\ \mathrm{pb}}\right)\left(\frac{50\ \mathrm{GeV}}{m_\chi}\right)^2$$

- Trapped WIMPs can annihilate into SM particles

- After some time, annihilation and capture rates usually equilibrate

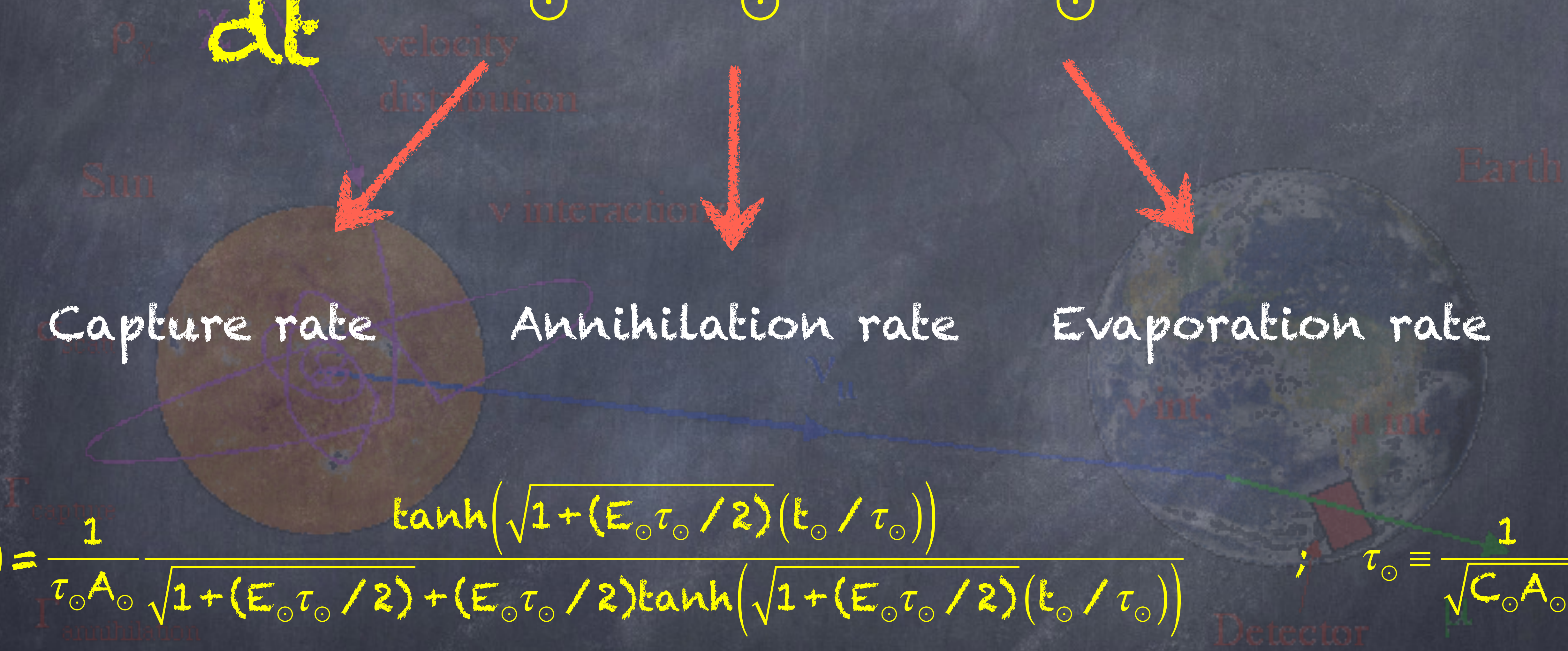
$$\Gamma(t_\odot) \simeq \frac{1}{2} C_\odot \tanh^2\left(\frac{t_\odot}{t_\odot}\right) \simeq \frac{1}{2} C_\odot$$

- 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
M. Srednicki, K. A. Olive and J. Silk, Phys. B279:804, 1987
K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987

EVOLUTION EQUATION

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



Capture rate

Annihilation rate

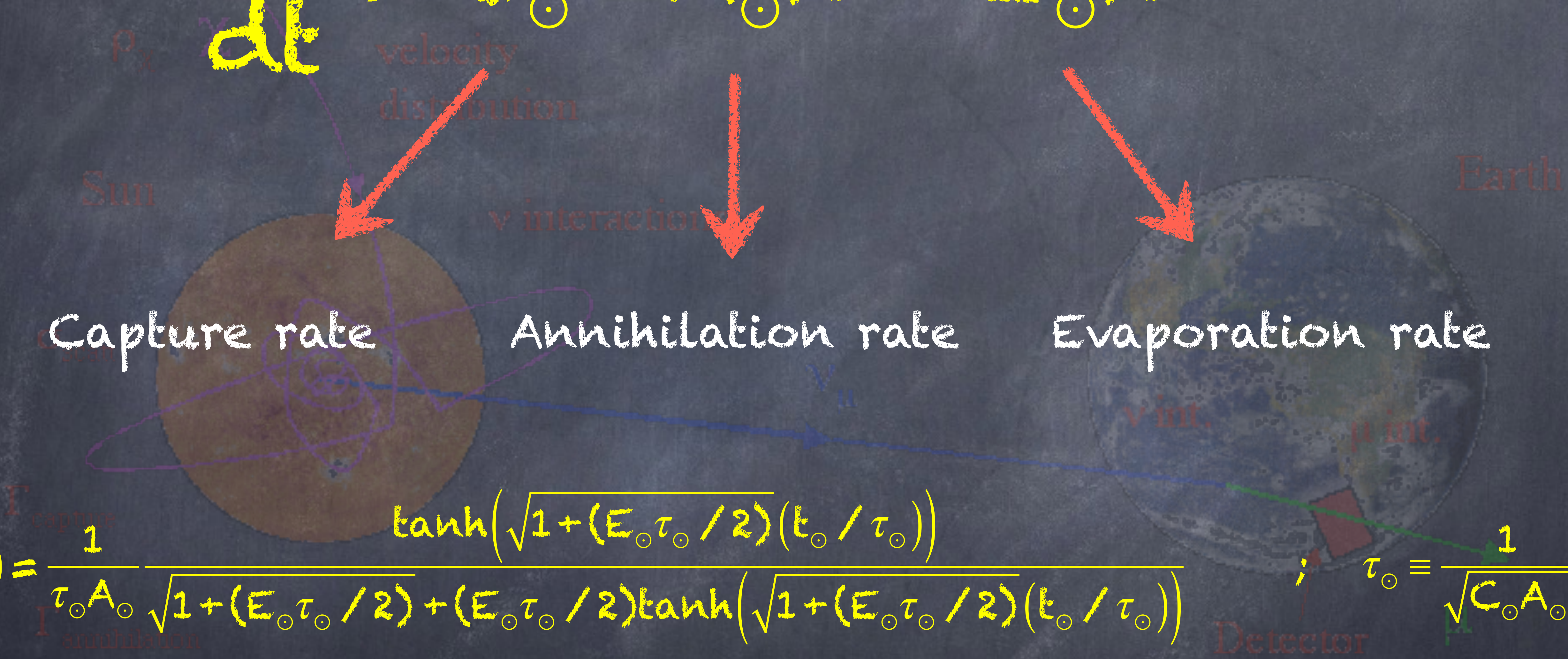
Evaporation rate

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

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

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

EVOLUTION EQUATION



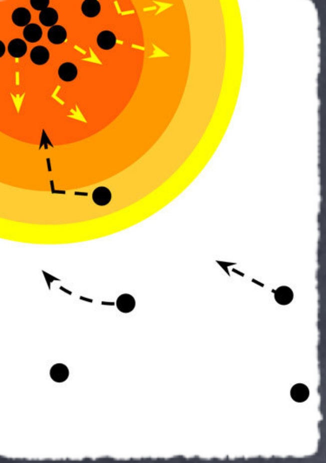
$$\frac{dN}{dt} = C_\odot - A_\odot N^2 - E_\odot N$$

Capture rate　　Annihilation rate　　Evaporation rate

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

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

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



SCATTERING ON ELECTRONS

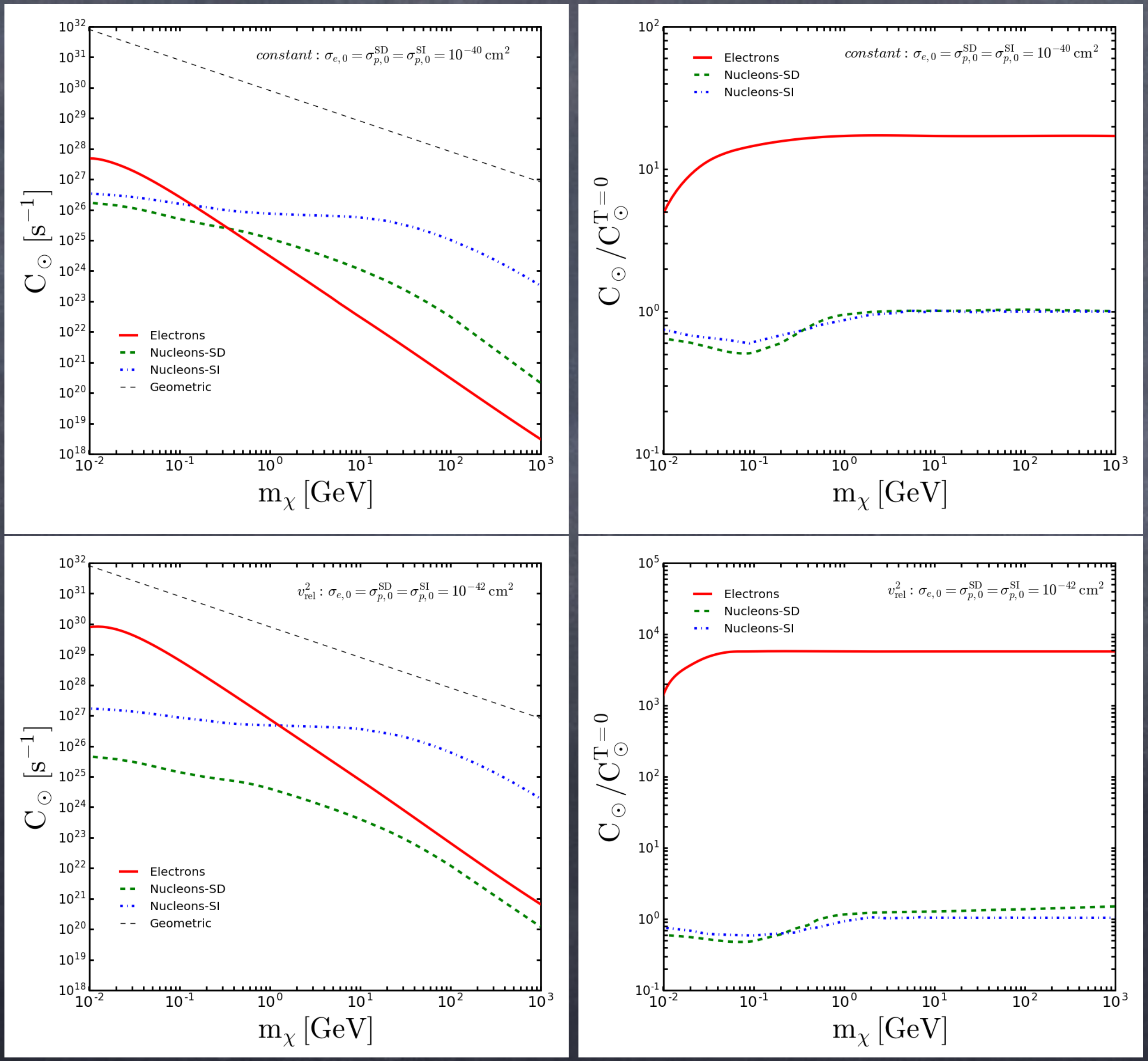
What about interactions with electrons?

J. Kopp, V. Niro, T. Schwetz and J. Zupan, Phys. Rev. D80:083502, 2009

smaller mass of targets ⟶ thermal motion is crucial

constant scattering cross section

velocity-dependent scattering cross section



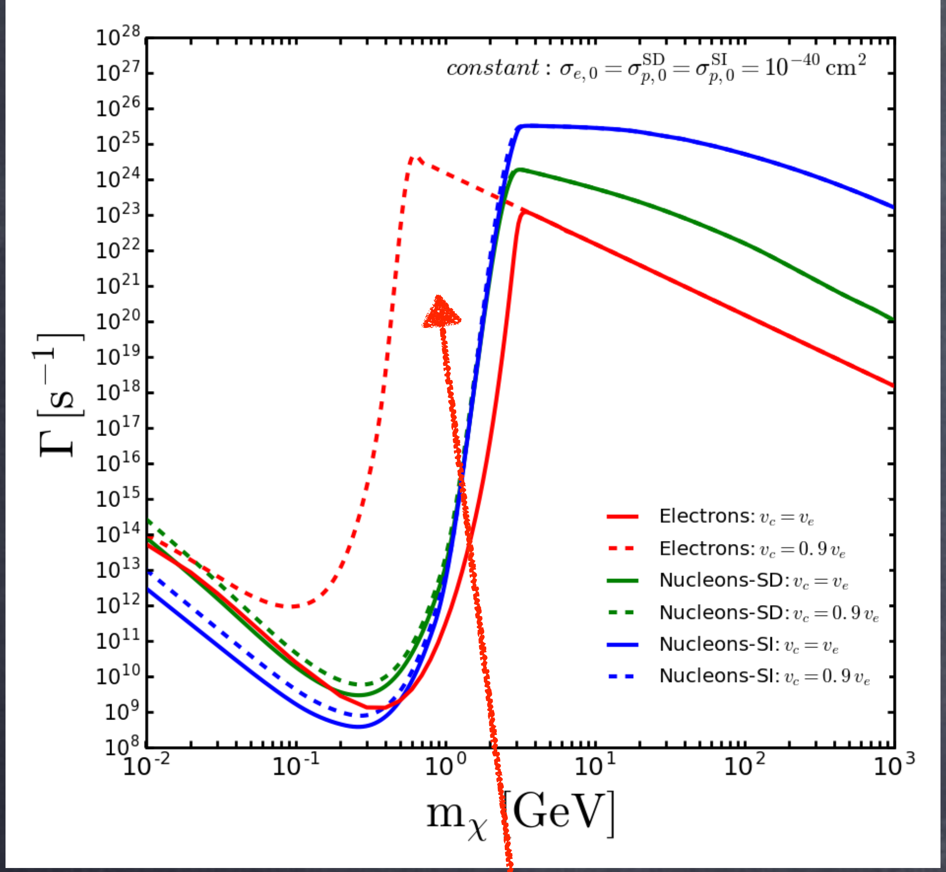
huge impact!

R. Garani and SPR, JCAP 1705:007, 2017

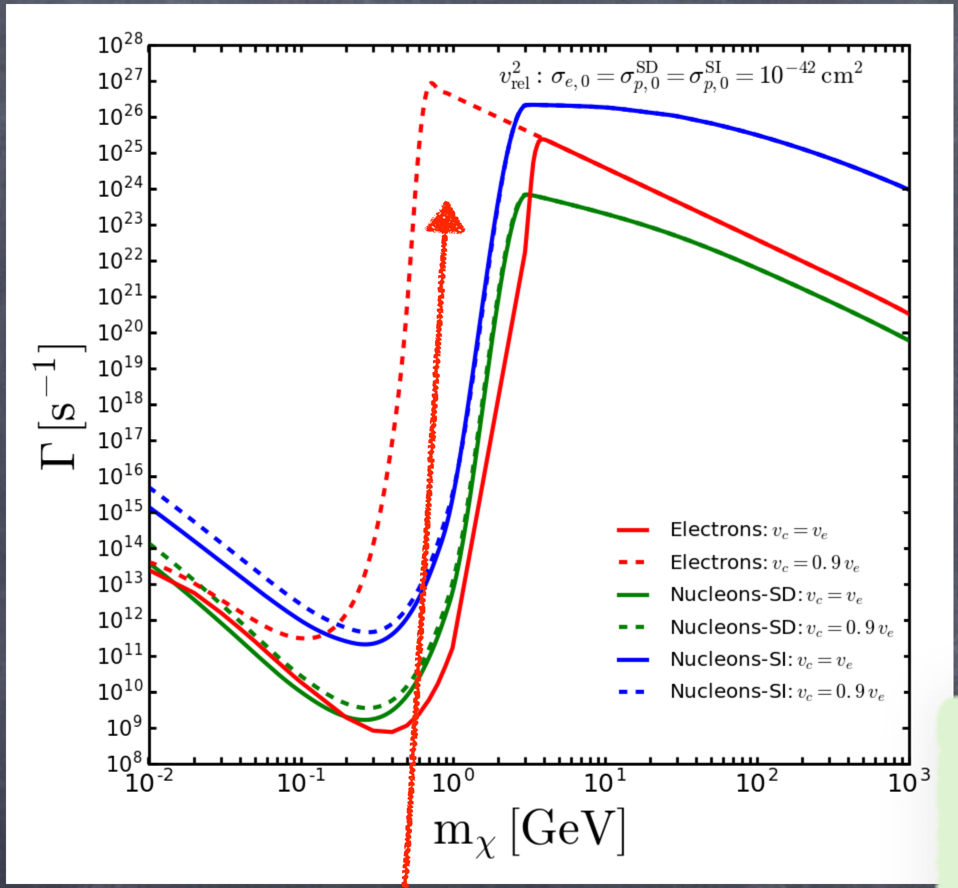
Scattering on electrons

Neutrino rates

constant



velocity-dependent



R. Garani and SPR, JCAP 1705:007, 2017

DM distribution affects the evaporation mass

In some cases DM-electron could be more important than DM-nucleon

R. Garani and SPR, in preparation

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

Why not annihilations into light quarks, muons or

- 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...

Why not annihilations into li

- Electrons (

What about the low-energy neutrinos from pion and muon decay at rest?

N. Bernal, J. Martín-Albo and SPR, JCAP 1308:011, 2013

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

- s, as pions, are stopped via nuclear i ctions and decay at rest

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

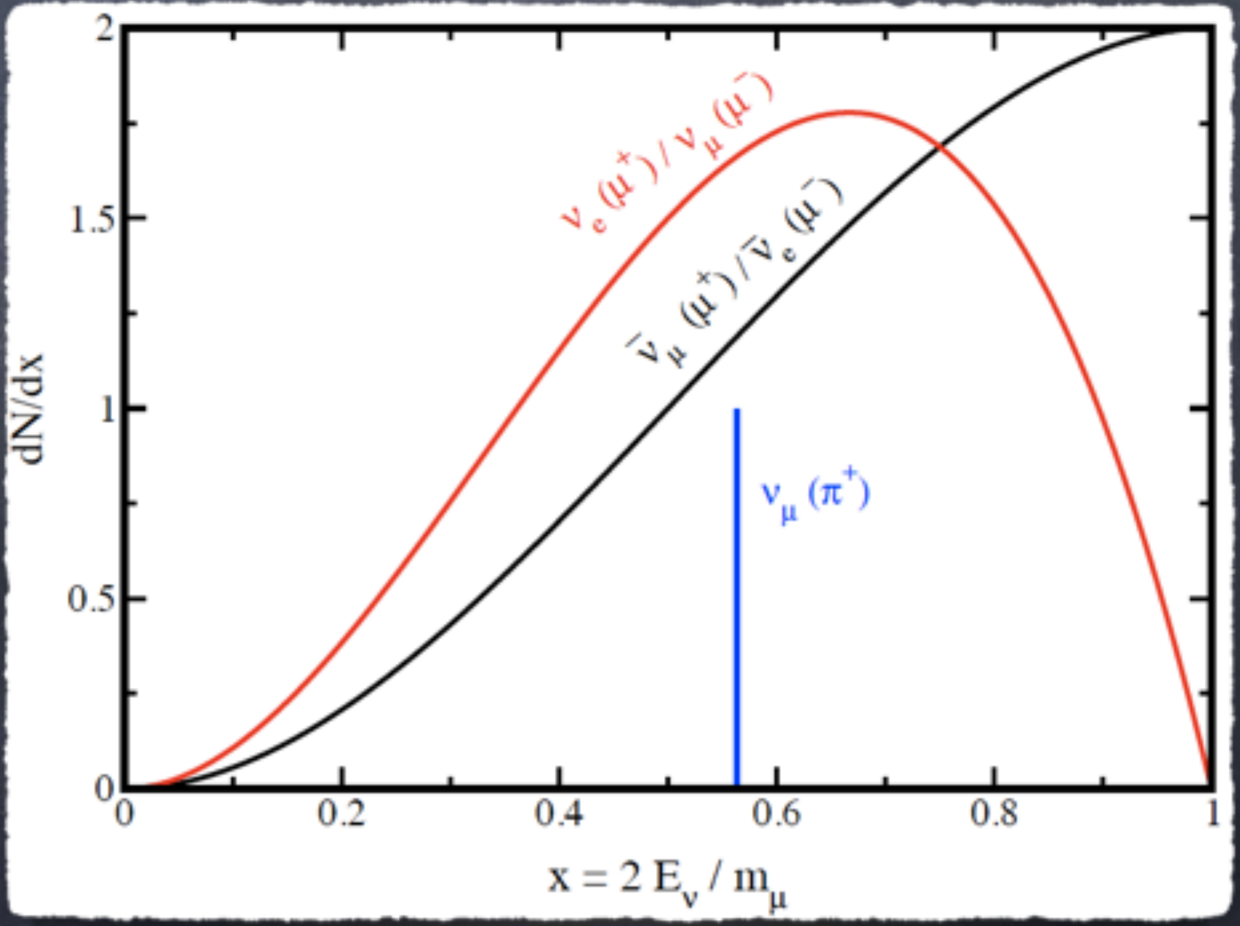
- Electrons/positrons, in their propagation in the Sun, could produce pions, which then can decay at rest
- Muons lose energy electromagnetically and decay at rest
- Pions get stopped

π^+ decay at rest

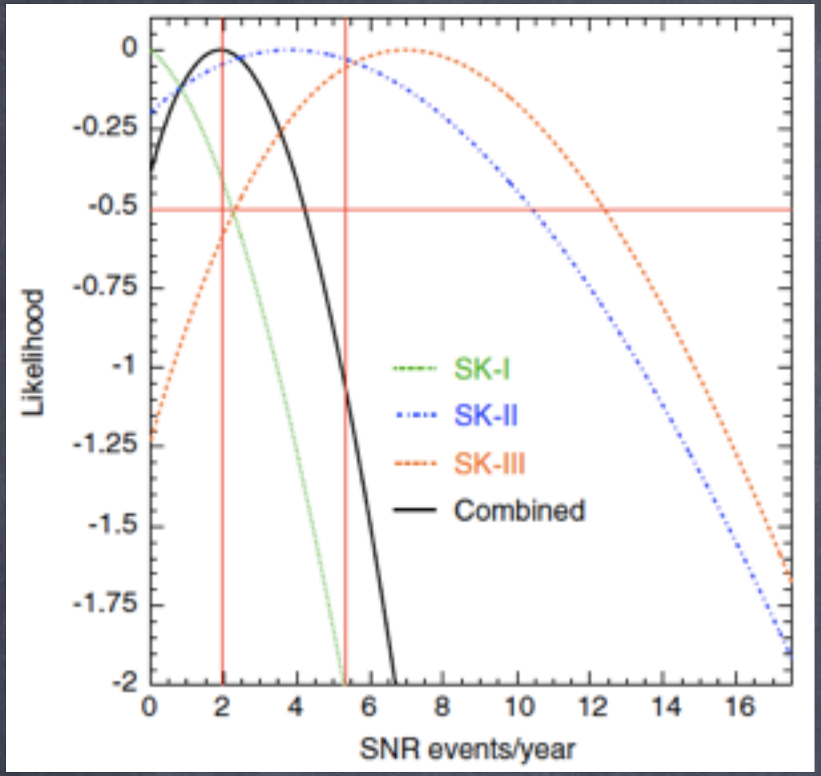
π^- are captured by nuclei and practically all get absorbed

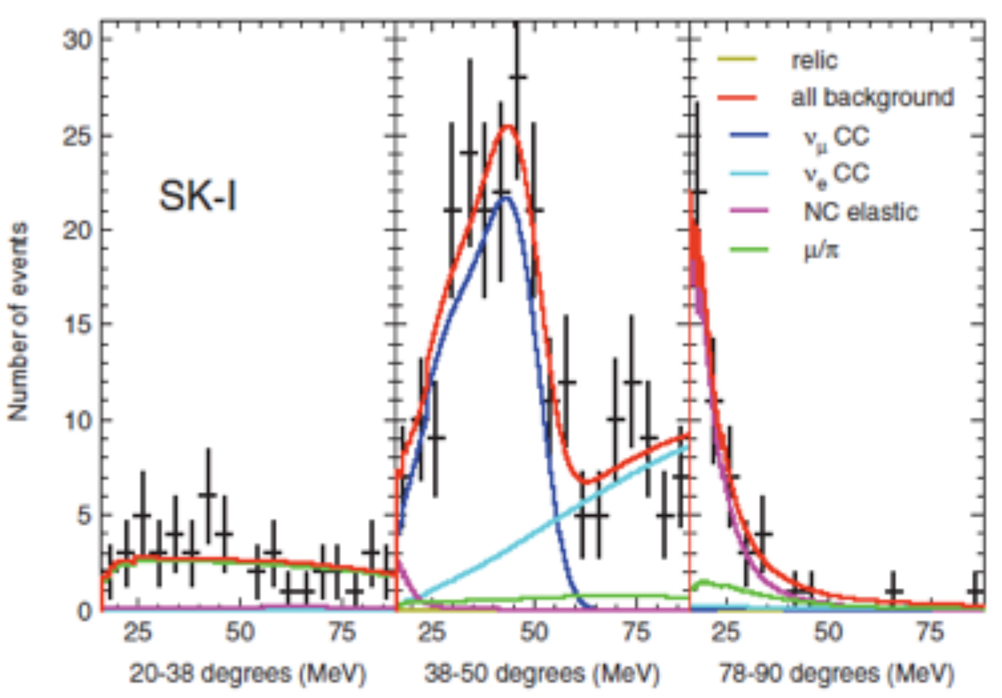
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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



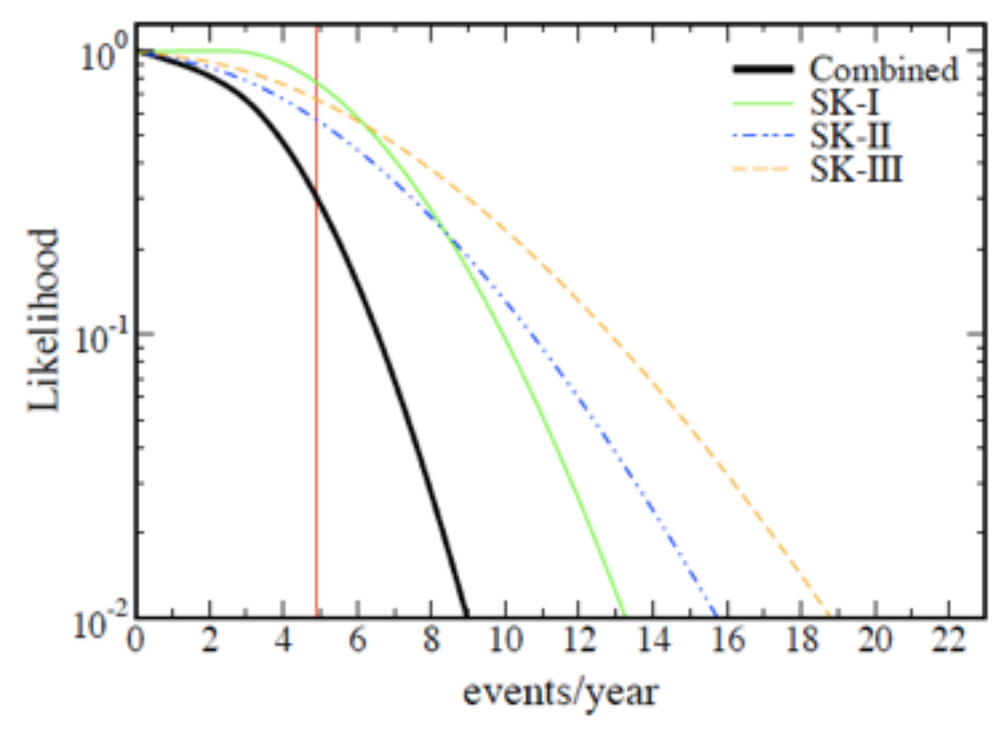
Diffuse Supernova Neutrino Background search

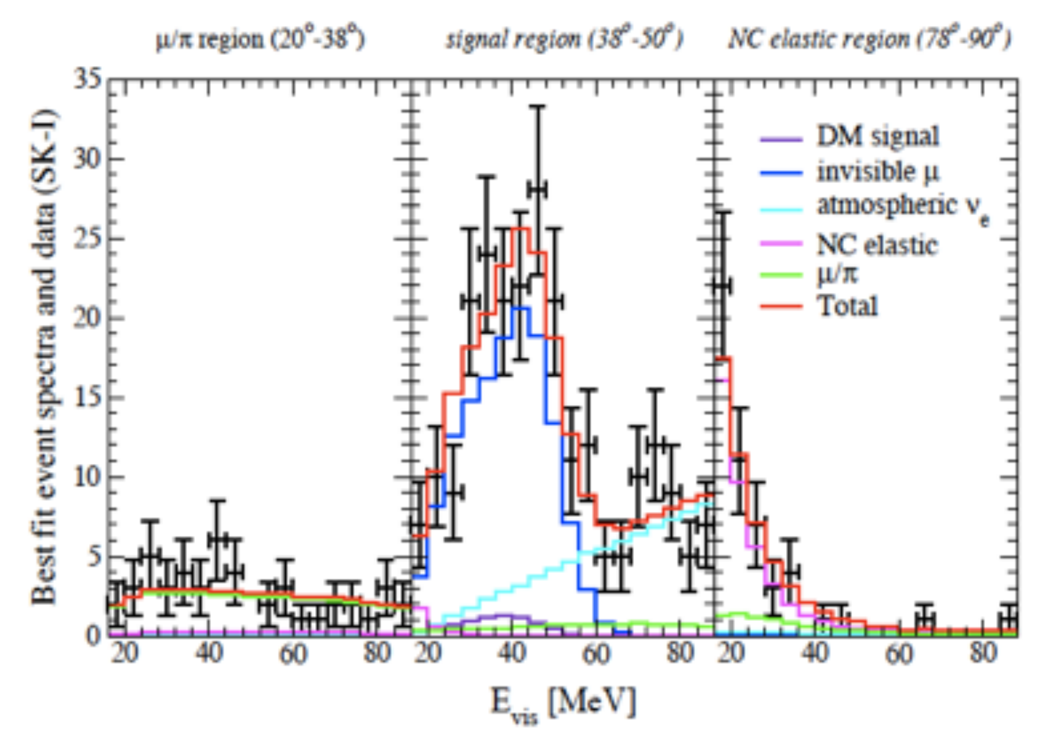




K. Bays et al. [Super-Kamiokande Collaboration], Phys. Rev. D85:052007, 2012

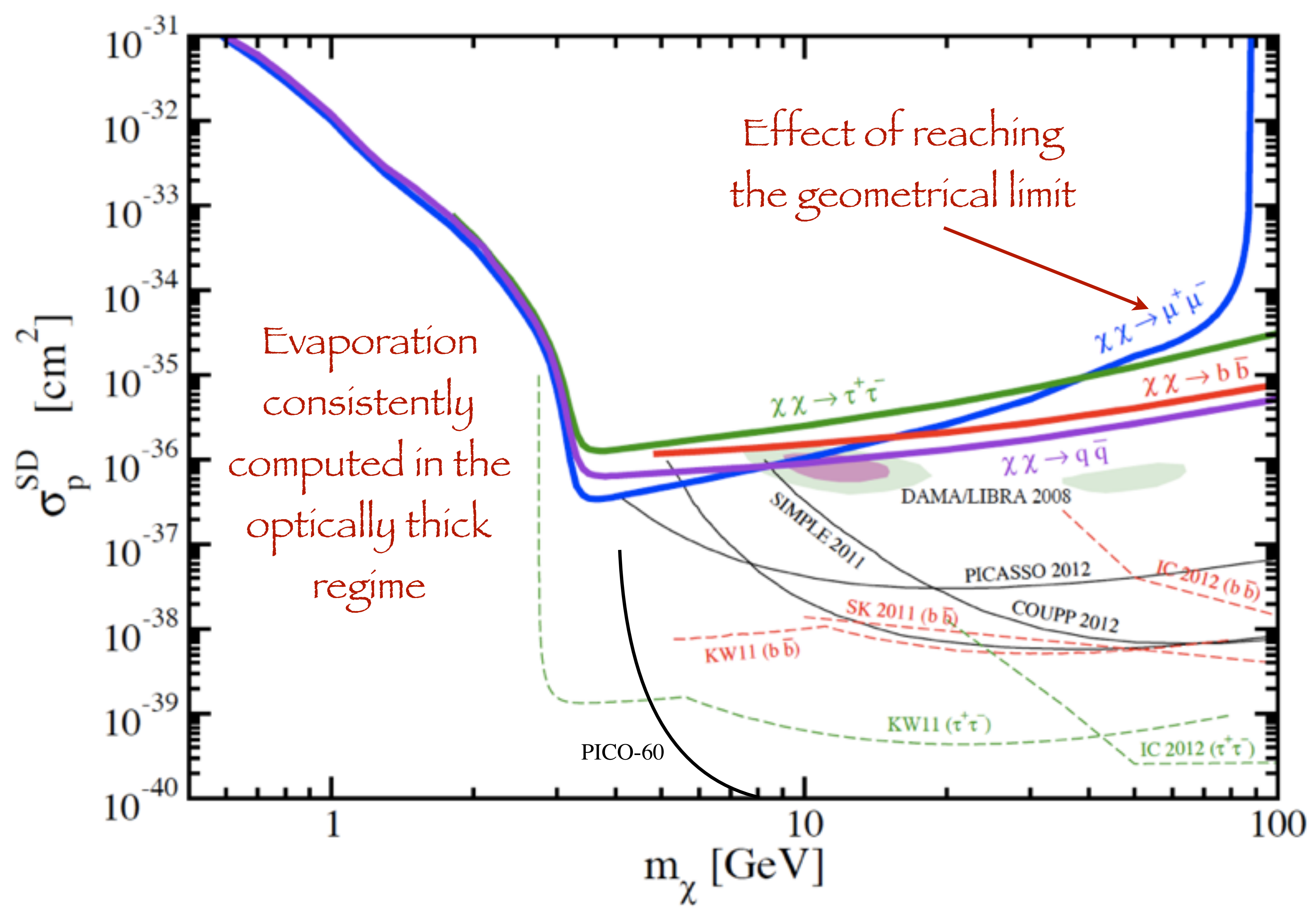
WIMPs annihilations in the Sun





N. Bernal, J. Martín-Albo and SPR, JCAP 1308:011, 2013

SD SCATTERING CROSS SECTION

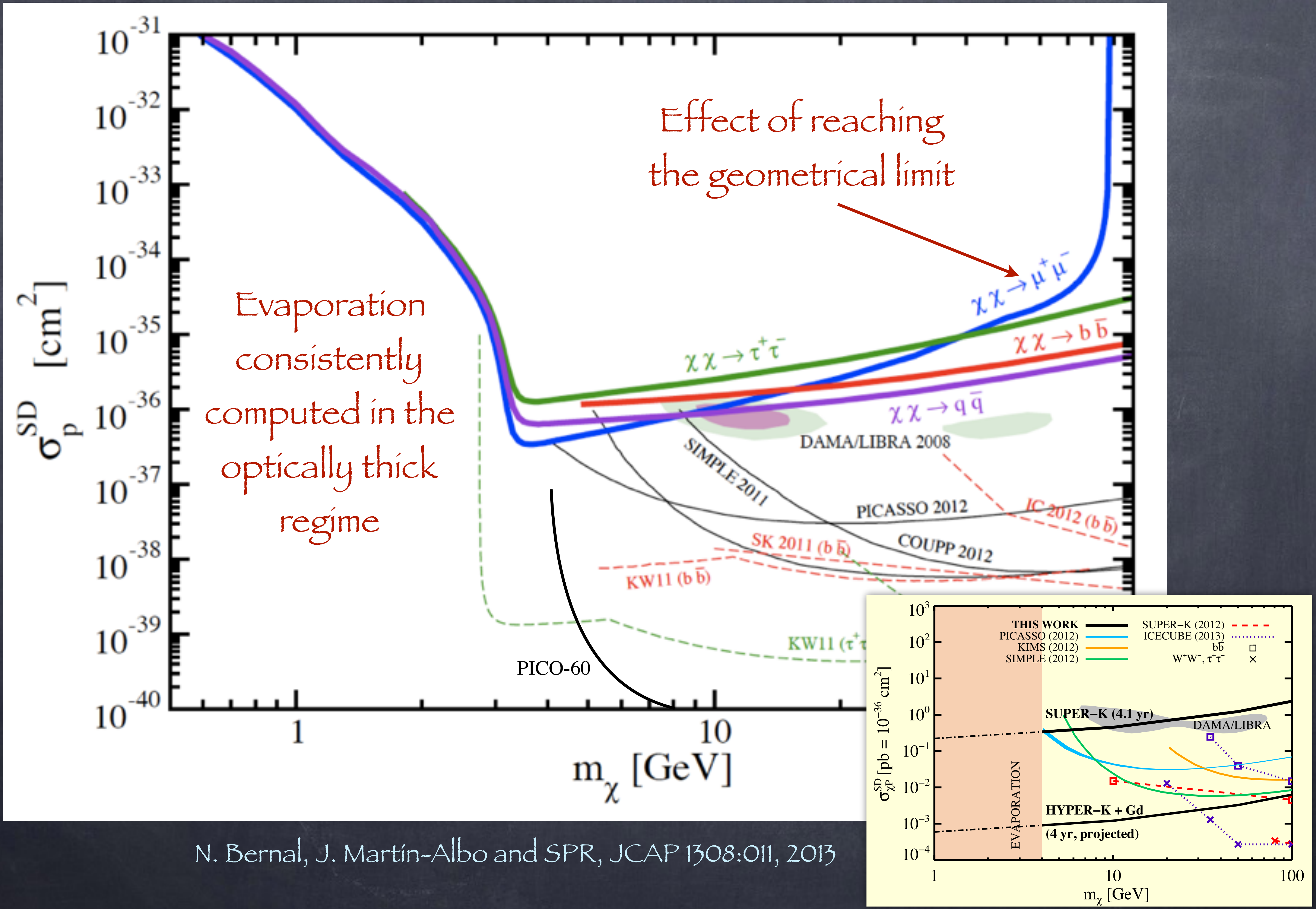


Effect of reaching the geometrical limit

Evaporation consistently computed in the optically thick regime

N. Bernal, J. Martín-Albo and SPR, JCAP 1308:011, 2013

SD SCATTERING CROSS SECTION



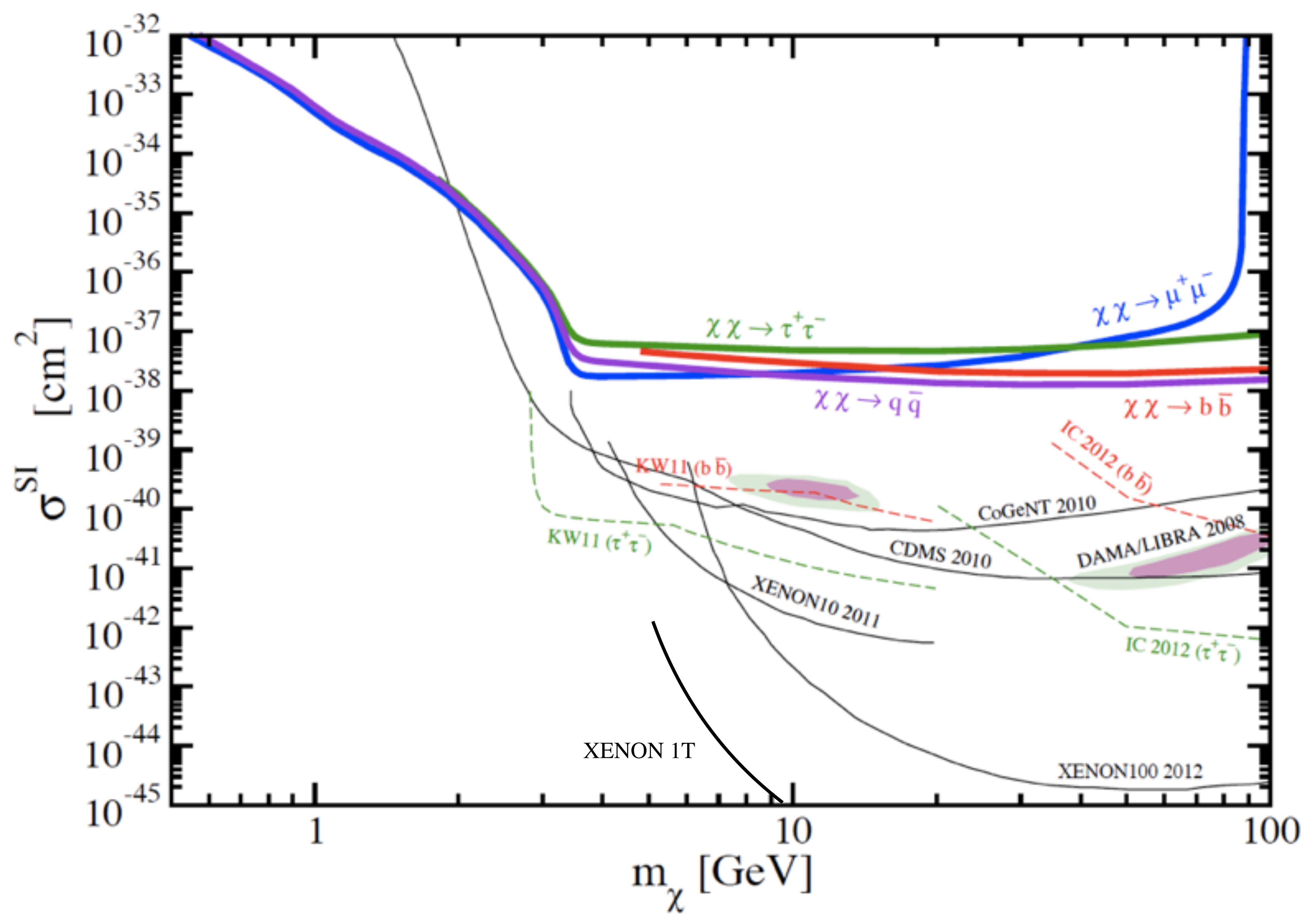
Effect of reaching the geometrical limit

Evaporation consistently computed in the optically thick regime

N. Bernal, J. Martín-Albo and SPR, JCAP 1308:011, 2013

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

SI SCATTERING CROSS SECTION



N. Bernal, J. Martín-Albo and SPR, JCAP 1308:011, 2013

SECLUDED DARK MATTER

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

Secluded from SM particles by a long-lived mediator

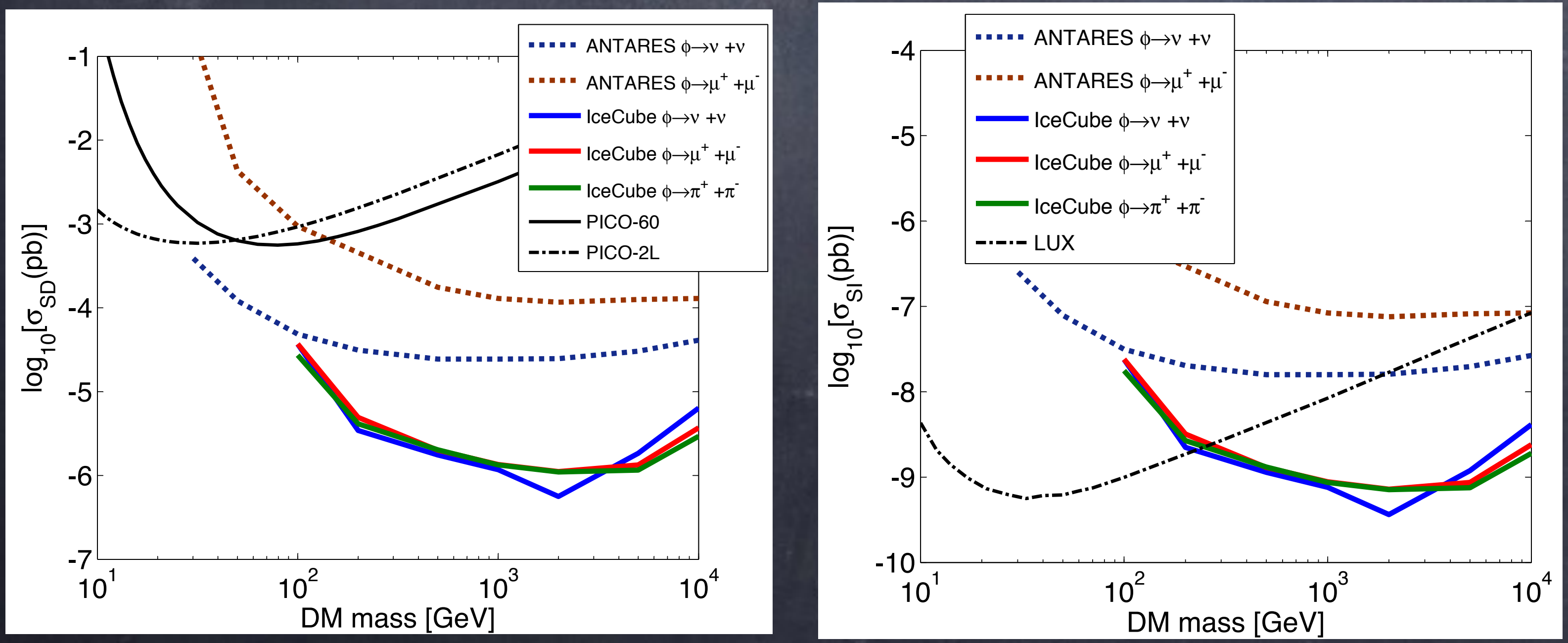
E.g., vector portal (or Higgs portal)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\chi}(\partial + ig A')\chi + m_\chi \bar{\chi}\chi - \frac{1}{4}F'^{\mu\nu}F^{\mu\nu} + \varepsilon F'^{\mu\nu}B^{\mu\nu} + \mathcal{L}_{dark}$$

signals in neutrino telescopes: from annihilation in the Sun

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

P. Meade, S. Nussinov, M. Papucci and T. Volansky, JHEP 1006:029, 2010



M. Ardid, I. Felis, A. Herrero and J. A. Martínez-Mora, JCAP 1704:010, 2017

In the simplest scenario, DM annihilates into 2 dark mediators, which after escaping the Sun, decay into SM particles

↓

2 coincident muons