Probing High-Energy Light Dark Matter with IceCube

based on Gang Guo, Yue-Lin Sming Tsai, MRW, arXiv:2004.03161

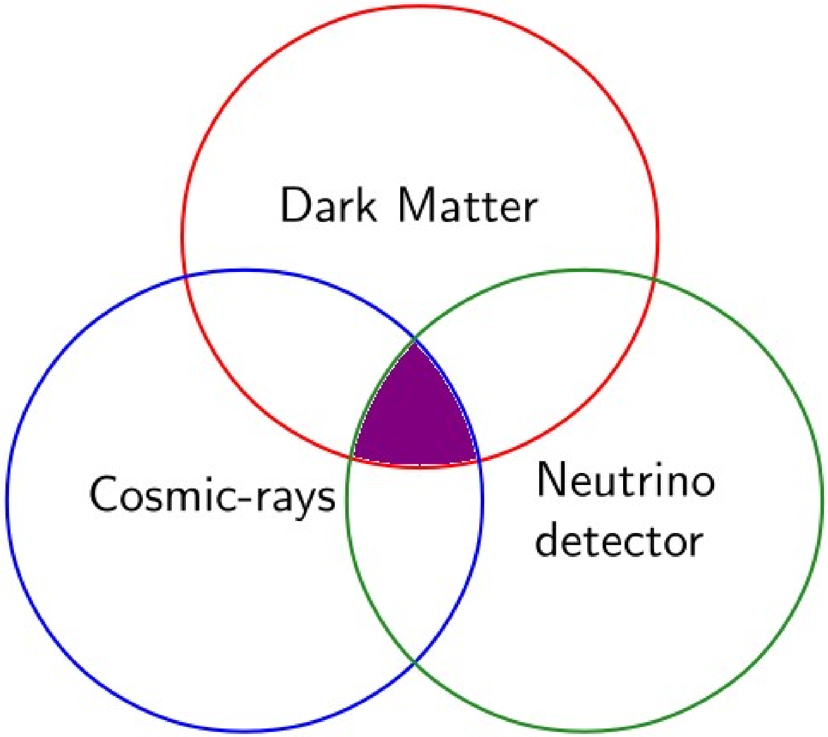
Meng-Ru Wu (Institute of Physics, Academia Sinica)

Brookhaven HET virtual seminar, May 20th, 2020

中央研究院物理研究所
INSTITUTE OF PHYSICS, ACADEMIA SINICA
NCTS
MOST 科技部
Ministry of Science and Technology

Outline

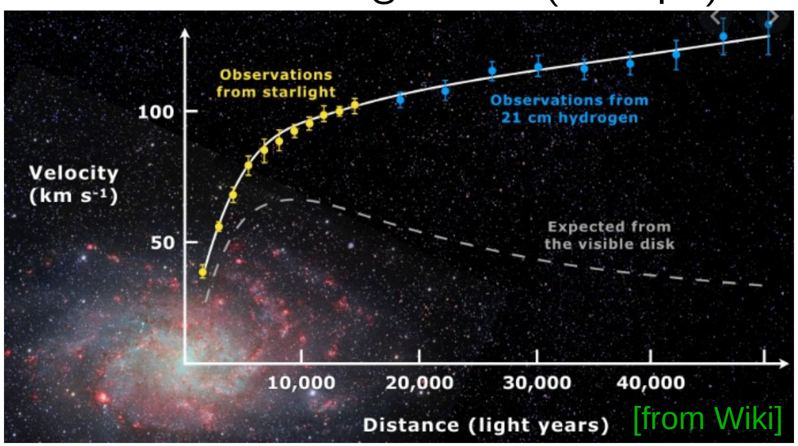
- Introduction
- Cosmic-ray up-scattered dark matter at $\sim$ PeV
  - galactic and extragalactic
- Events at IceCube and constraints on $\sigma_{\chi p}$
- Summary



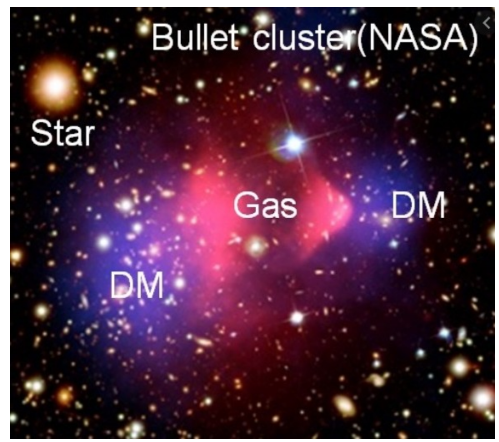
Dark Matter

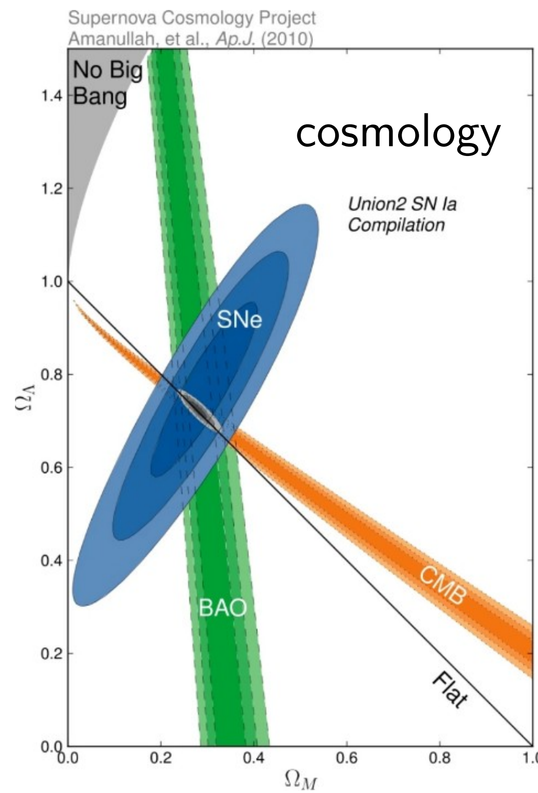
Various astrophysical and cosmological observations have shown that there may exist some non-relativistic particles contributing as additional gravity sources at different scales.

rotation curves in galaxies ($<$ Mpc)



galaxy clusters $>$ Mpc

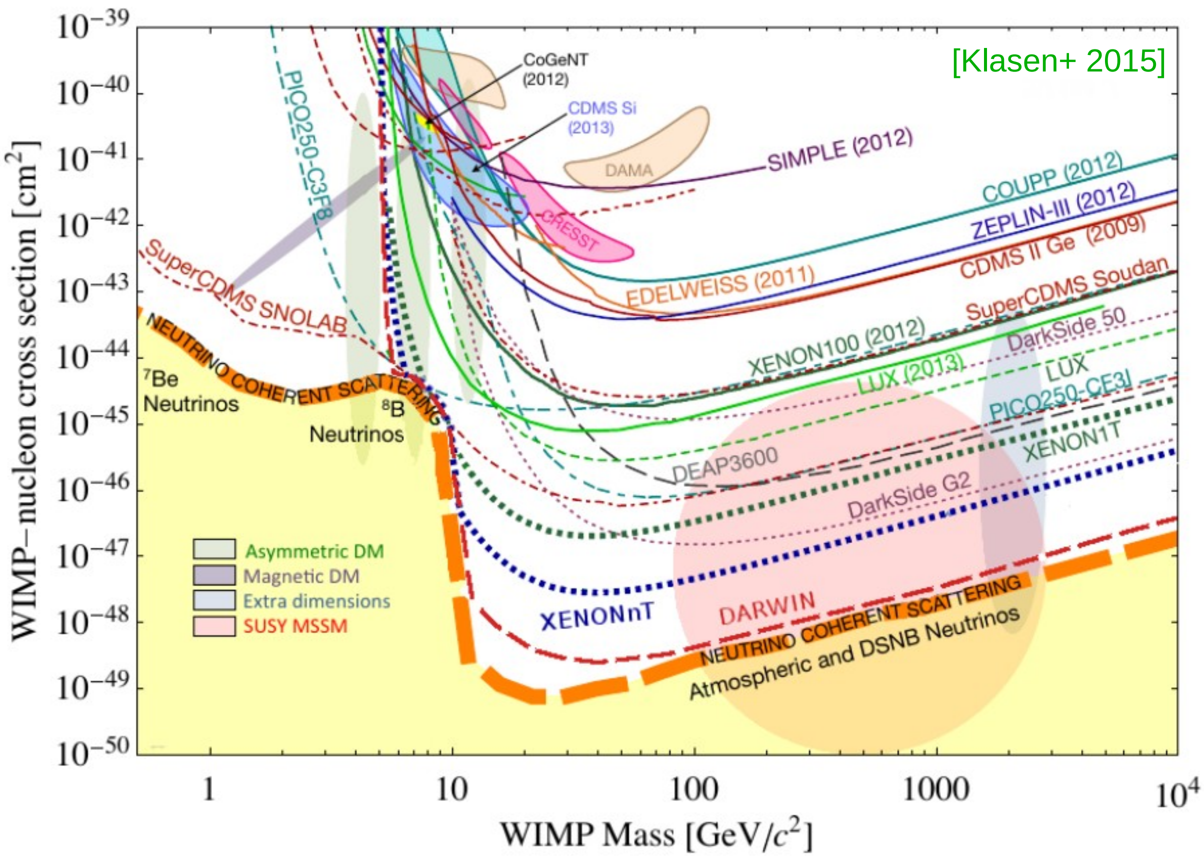




Do they interact with known particles in the Standard Model?

Dark Matter

Searches for DM heavier than $\gtrsim$ few GeV –TeV thus far have yet found evidence of DM–nucleon (χN) interaction and will eventually reach the neutrino floor



→ (partly) "motivates" the consideration of other candidates with different masses and/or interactions

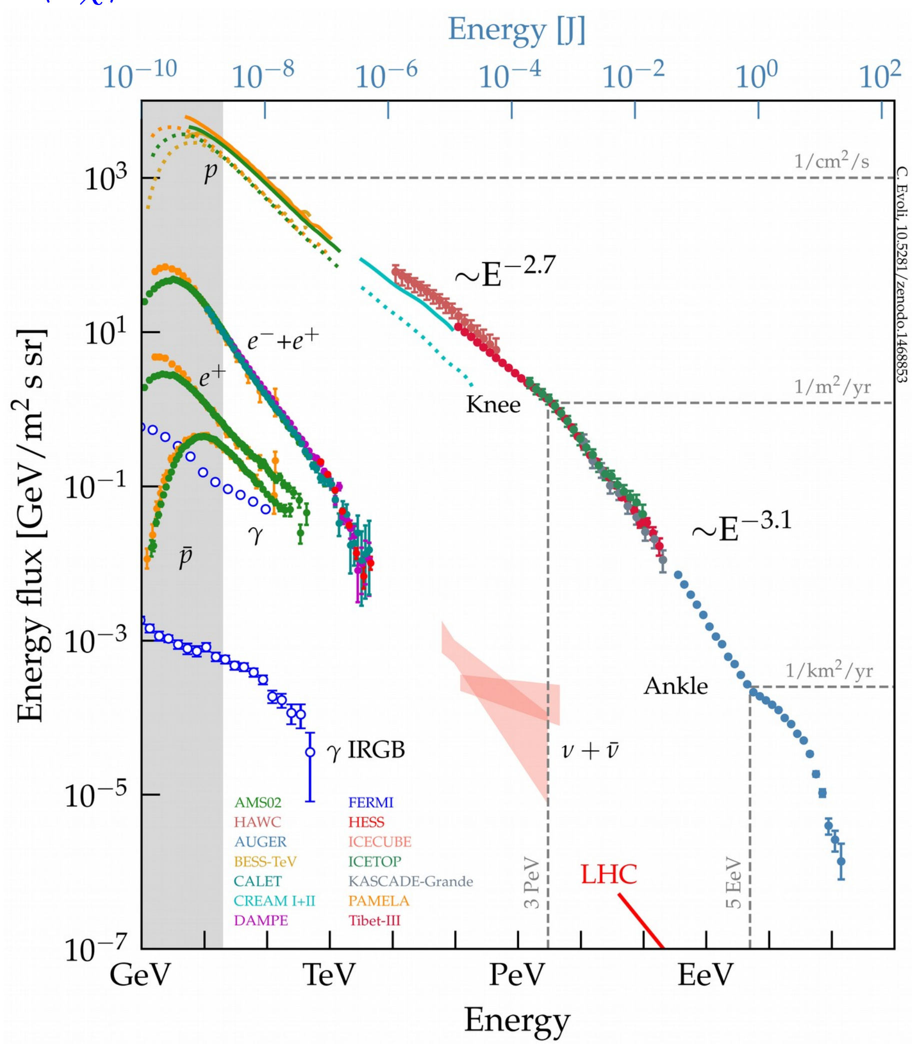
Dark Matter with high velocities/energies?

Experiments relying on nuclear recoils to probe the DM–nucleon cross-section quickly lose sensitivities for m_χ going below a few GeV, assuming local DM velocity distribution is $\sim$ virialized, i.e., $\langle v_\chi \rangle \sim 10^{-3}\, c$

Dark Matter with high velocities/energies?

Experiments relying on nuclear recoils to probe the DM–nucleon cross-section quickly lose sensitivities for m_χ going below a few GeV, assuming local DM velocity distribution is $\sim$ virialized, i.e., $\langle v_\chi \rangle \sim 10^{-3}\, c$

However, just like the existence of non-thermal components of SM particles, there can possibly be a "non-thermal" component of DM whose velocities far exceed $\langle v_\chi \rangle$



Dark Matter with high velocities/energies?

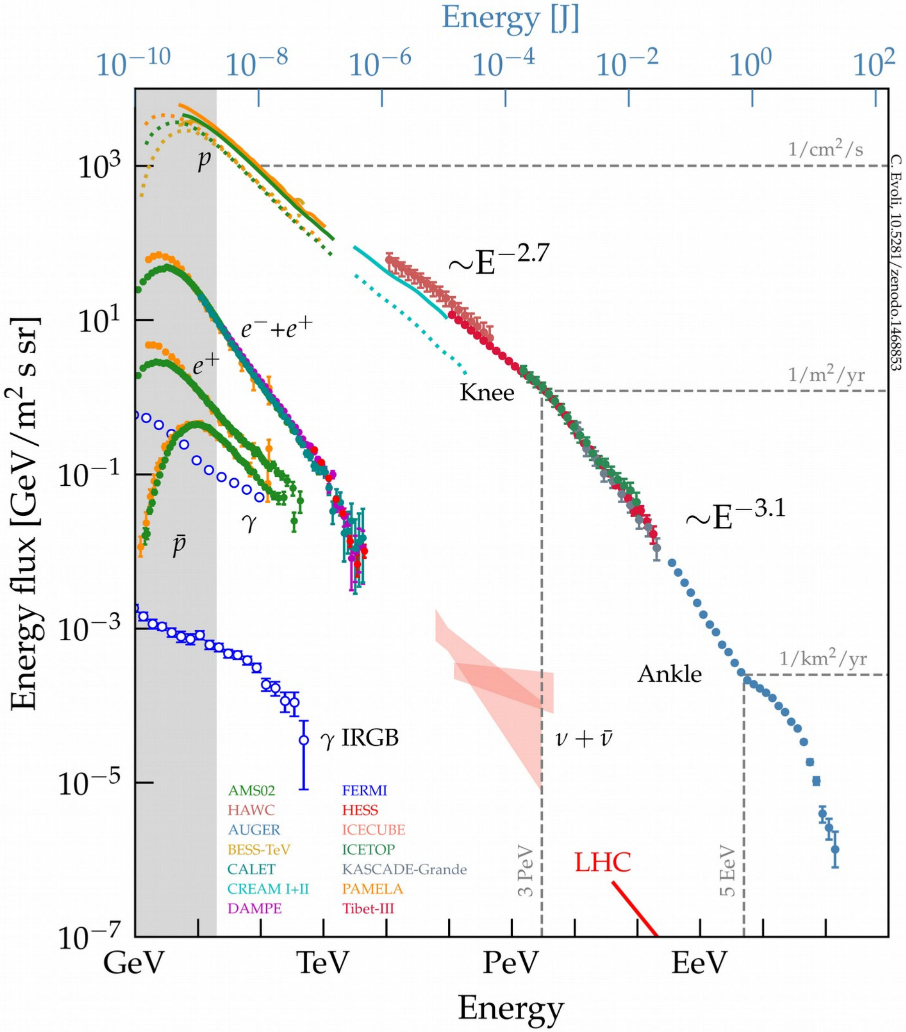
Experiments relying on nuclear recoils to probe the DM–nucleon cross-section quickly lose sensitivities for m_χ going below a few GeV, assuming local DM velocity distribution is $\sim$ virialized, i.e., $\langle v_\chi \rangle \sim 10^{-3}\, c$

However, just like the existence of non-thermal components of SM particles, there can possibly be a "non-thermal" component of DM whose velocities far exceed $\langle v_\chi \rangle$

– boosted (light) DM from the annhilation or decay of (heavy) DM
[Agashe+ 2014, Bhattacharya+ 2016,...]

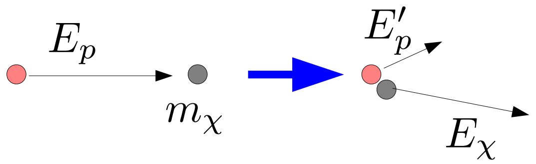
– upscattered DM by cosmic rays
[Bringmann+ 2018, Ema+ 2018, Cappiello+ 2019]

– many other theoretical possibilities...



Cosmic-ray up-scattered Dark Matter

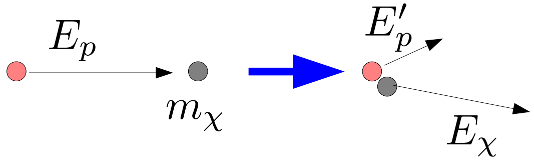
How many up-scattered DM?



For a simple 2-to-2 scattering, for $E_p \gg m_p \gg m_\chi$:

$$E_\chi^{\mathrm{max}} \simeq \frac{E_p}{1 + (m_p^2/(2m_\chi E_p))}$$

How many up-scattered DM?



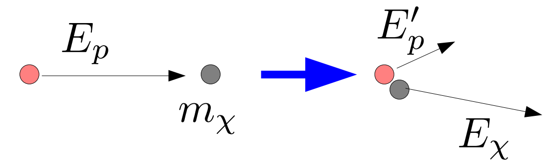
For a simple 2-to-2 scattering, for $E_p \gg m_p \gg m_\chi$:

$$E_\chi^{\max} \simeq \frac{E_p}{1 + (m_p^2/(2m_\chi E_p))}$$

Back-of-the-envelope estimation gives the up-scattered DM flux:

$$E^2\Phi_\chi \sim E^2\Phi_p \cdot (\rho_\chi/m_\chi) \cdot \sigma_{\chi p} \cdot L$$
$$\sim 10^{-8}\frac{\mathrm{GeV}}{\mathrm{cm}^2\ \mathrm{s}\ \mathrm{Sr}}\left(\frac{E}{\mathrm{PeV}}\right)^{-0.7}\left(\frac{\mathrm{MeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{\mathrm{GeV}\ \mathrm{cm}^{-3}}\right)\left(\frac{\sigma_{\chi p}}{10^{-30}\ \mathrm{cm}^2}\right)\left(\frac{L}{10\ \mathrm{kpc}}\right)$$

How many up-scattered DM?



For a simple 2-to-2 scattering, for $E_p \gg m_p \gg m_\chi$:

$$E_\chi^{\max} \simeq \frac{E_p}{1 + (m_p^2/(2m_\chi E_p))}$$

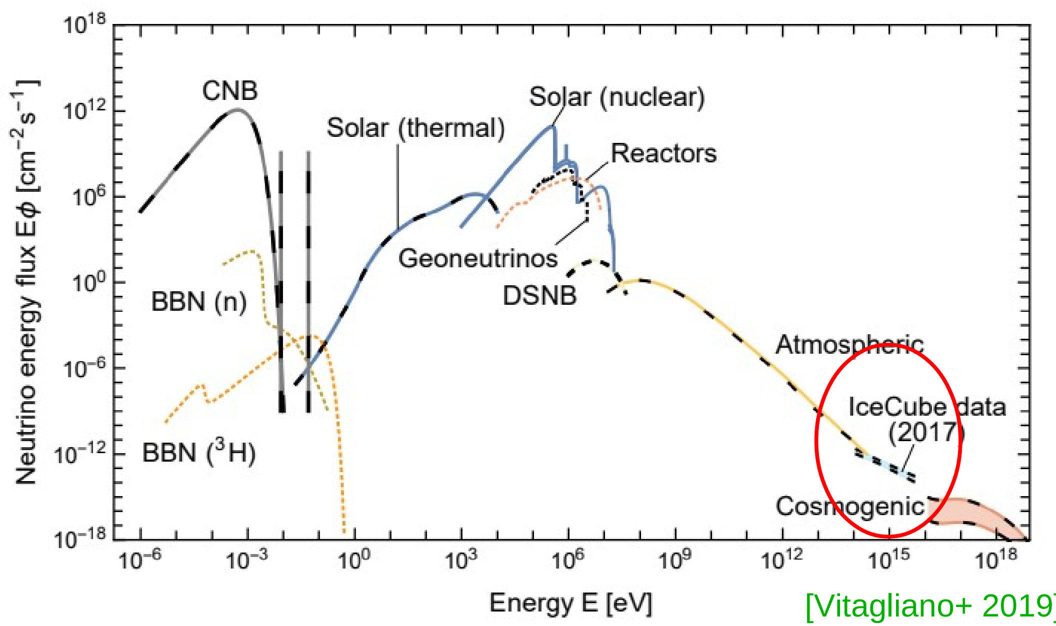
Back-of-the-envelope estimation gives the up-scattered DM flux:

$$\begin{aligned} E^2\Phi_\chi &\sim E^2\Phi_p \cdot (\rho_\chi/m_\chi) \cdot \sigma_{\chi p} \cdot L \\ &\sim 10^{-8}\frac{\mathrm{GeV}}{\mathrm{cm^2\ s\ Sr}}\left(\frac{E}{\mathrm{PeV}}\right)^{-0.7}\left(\frac{\mathrm{MeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{\mathrm{GeV\ cm^{-3}}}\right)\left(\frac{\sigma_{\chi p}}{10^{-30}\ \mathrm{cm^2}}\right)\left(\frac{L}{10\ \mathrm{kpc}}\right) \end{aligned}$$

$\rightarrow$ comparable to the neutrino flux per flavor at $\sim$ PeV

$\rightarrow$ possible to probe $\sigma_{\chi p} \gtrsim \sigma_{\nu p}$!

**Bringmann+ 2018 & Cappiello+2019 explored energy range of $\lesssim$ GeV, for which the DM flux is much smaller than the atomspheric neutrinos



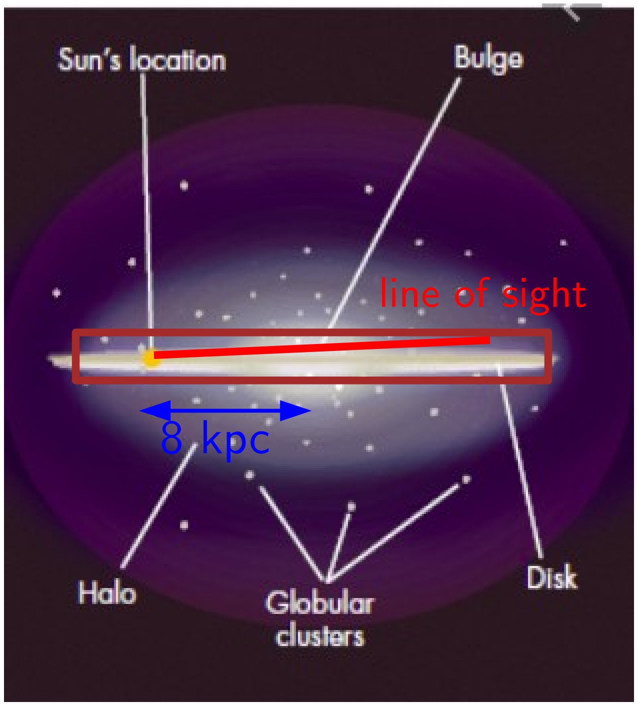
[Vitagliano+ 2019]

CR upscattered high-energy DM: Galactic case

The differential DM flux upscattered by cosmic rays in Milky Way:

$$\Phi_\chi^{\rm MW}(E_\chi,\Omega) \equiv \frac{d^2N_\chi}{dE_\chi d\Omega}(E_\chi,\Omega) = \int_{\rm l.o.s.} d\ell \int dE_p \underbrace{\frac{\rho_\chi(r)}{m_\chi}}_{\text{DM number density}} \underbrace{\Phi_p(E_p)}_{\text{cosmic rays spectrum}} D_{p\chi}(E_p,E_\chi)\sigma_{p\chi},$$

NFW profile



cosmic rays uniformly distributed within a disk with $R = 10$ kpc and $h = 1$ kpc

For isotropic CRs:

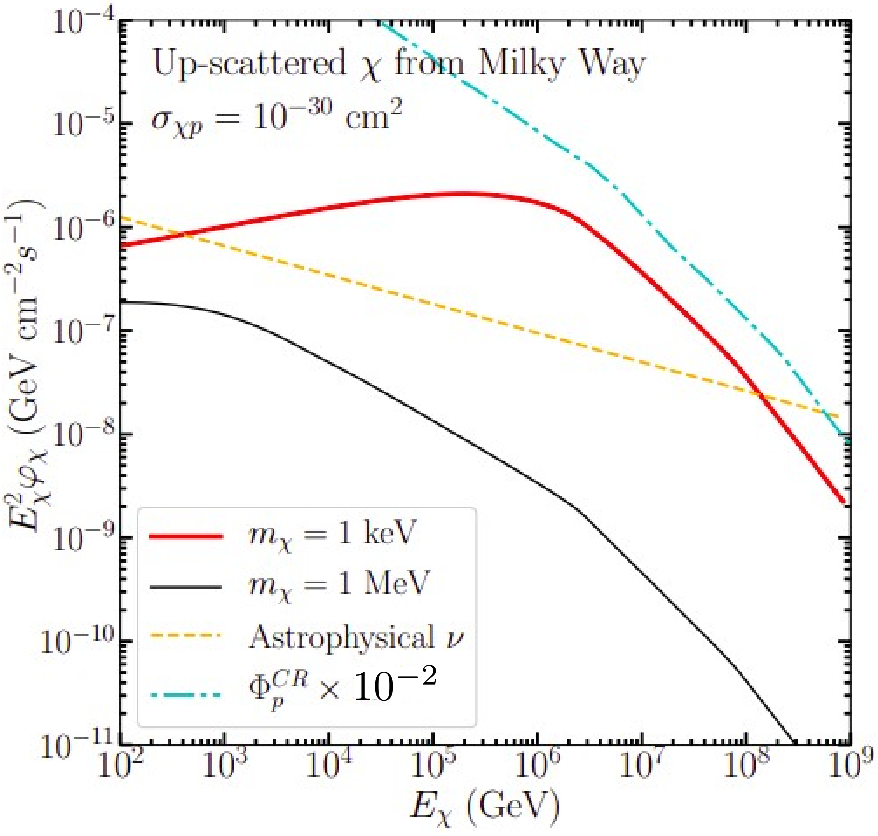
transfer function $D_{p\chi}(E_p,E_\chi) = \dfrac{\Theta[E_\chi^{\rm max}(E_p) - E_\chi]}{E_\chi^{\rm max}(E_p)}$

$$E_\chi^{\rm max} \simeq \frac{E_p}{1 + (m_p^2 + m_\chi^2)/(2m_\chi E_p)}$$

note that we have neglected the inelastic scattering which should take place when $s \gtrsim \mathcal{O}(1)$ GeV^2

CR upscattered high-energy DM: Galactic case

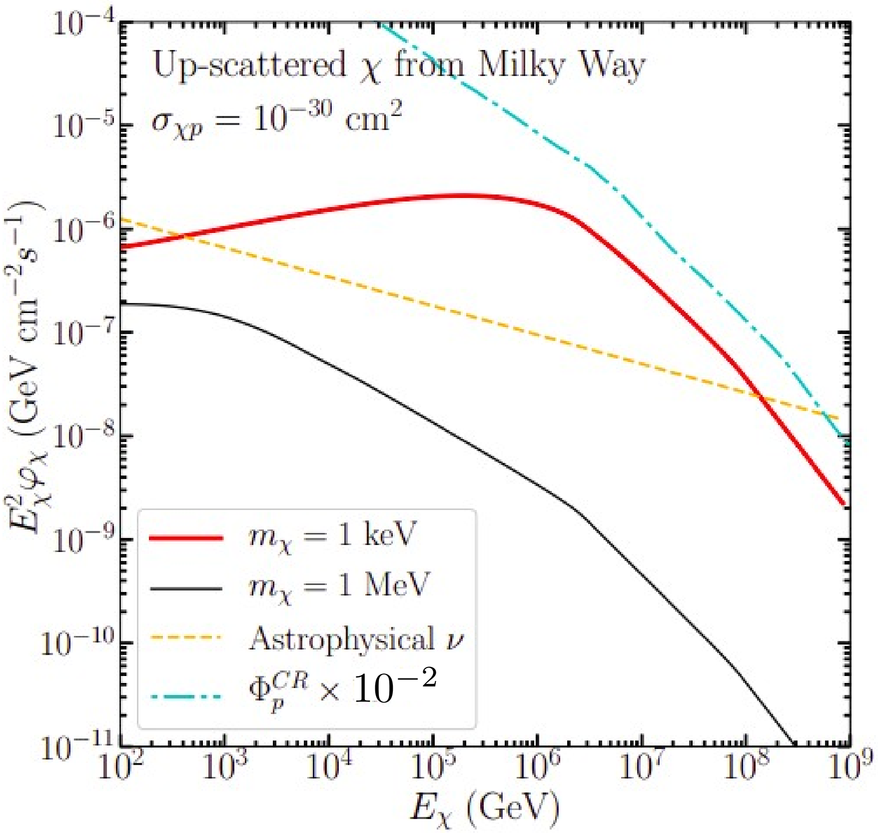
The DM energy spectrum:



spectral break at $E_\chi \simeq m_p^2/(2m_\chi)$

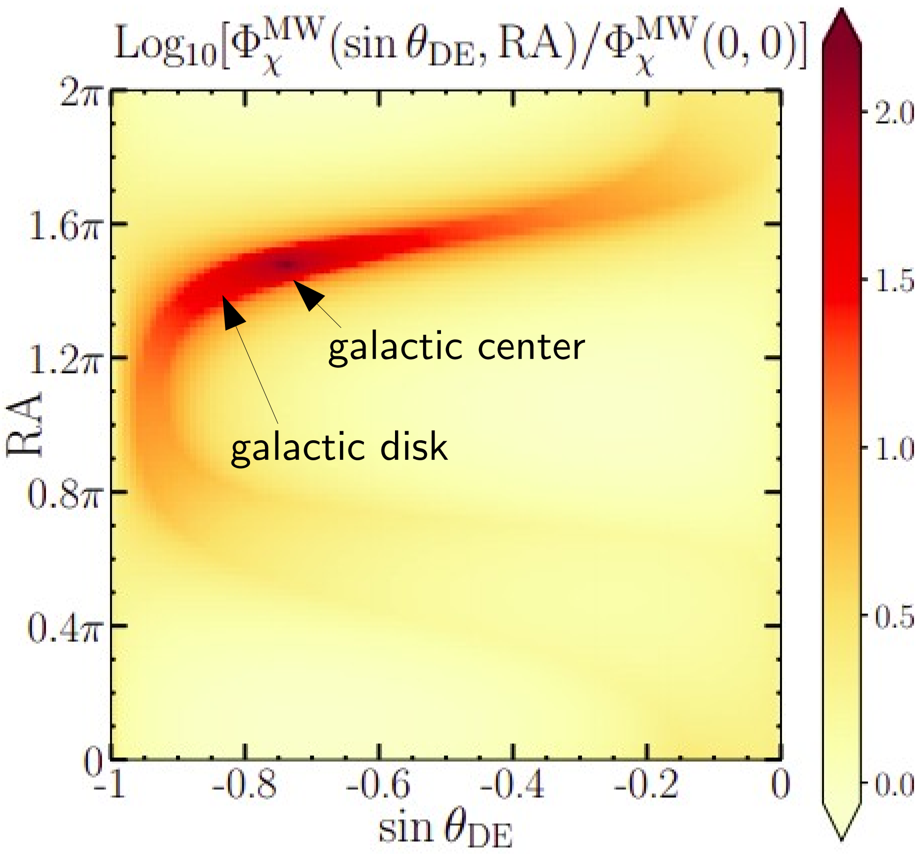
CR upscattered high-energy DM: Galactic case

The DM energy spectrum:



spectral break at $E_\chi \simeq m_p^2/(2m_\chi)$

The DM angular distribution:



strong angular dependence, peaked at the direction of galactic center

CR upscattered high-energy DM: Extragalactic cases

Intergalactic CRs can also upscatter relic DM (integrated over redshift z):

$$\Phi_\chi^{\rm EG}(E_\chi) = \int dE_p \int_0^\infty dz \sigma_{p\chi} n_\chi^0 (1+z)^4 F(E_p, z) D_{p\chi}(E_p, E_\chi(1+z)) \left|\frac{cdt}{dz}\right|$$

present-day relic DM number density: $n_\chi^0 \simeq 10^{-6}\ ({\rm GeV}/m_\chi)\ {\rm cm}^{-3}$

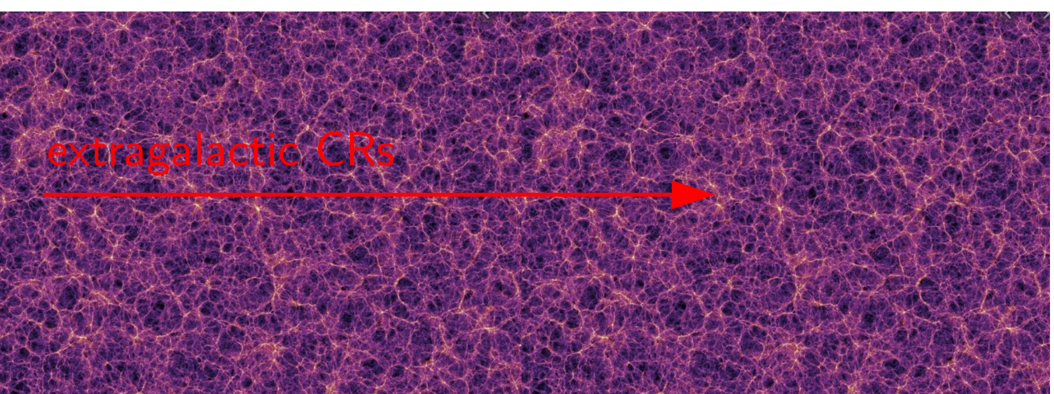
red-shift dependent CR flux:

$$F(E_p, z) = \frac{c}{4\pi}\int_z^\infty \underline{S(z')}\frac{1+z'}{1+z}\underline{F_{\rm inj}\left(\frac{1+z'}{1+z}E_p\right)}\left|\frac{dt}{dz'}\right| dz',$$

source evolution over the cosmic evolution

CR injection spectrum $\propto E_p^{-(2.4-2.6)}$ for $E_p > 1$ PeV

$\propto E_p^{-2}$ for $E_p \leq 1$ PeV



CR upscattered high-energy DM: Extragalactic cases

We have considered three cases:

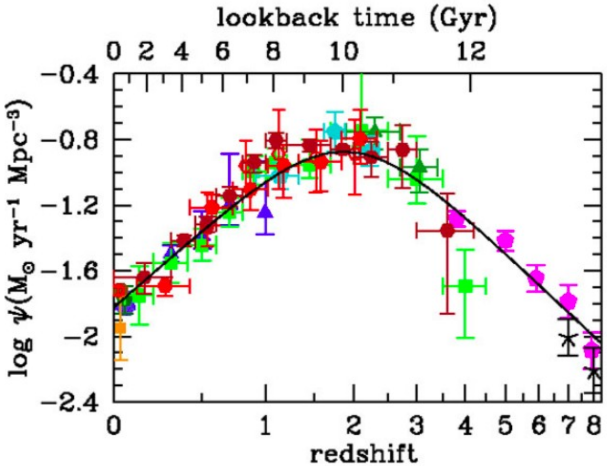
(i) EG1: no source evolution

(ii) EG2: $S(z') \propto$ the SFR

(iii) EG3: stronger (AGN-like) $S(z')$

[Alosio+ 2015, Batusta+ 2019]

SFR: star formation rate



[Madau & Dickinson 2014]

CR upscattered high-energy DM: Extragalactic cases

We have considered three cases:

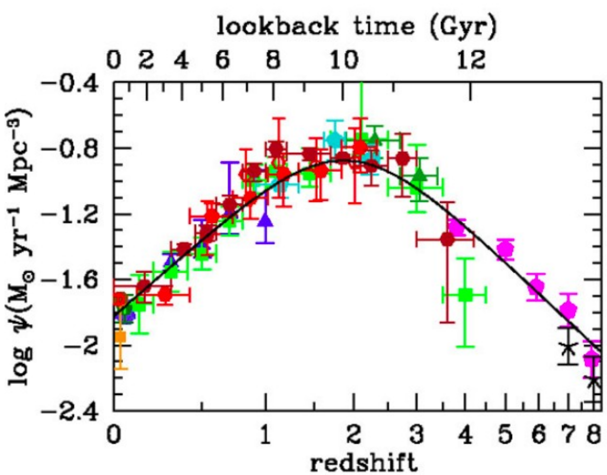
(i) EG1: no source evolution

(ii) EG2: $S(z') \propto$ the SFR

(iii) EG3: stronger (AGN-like) $S(z')$

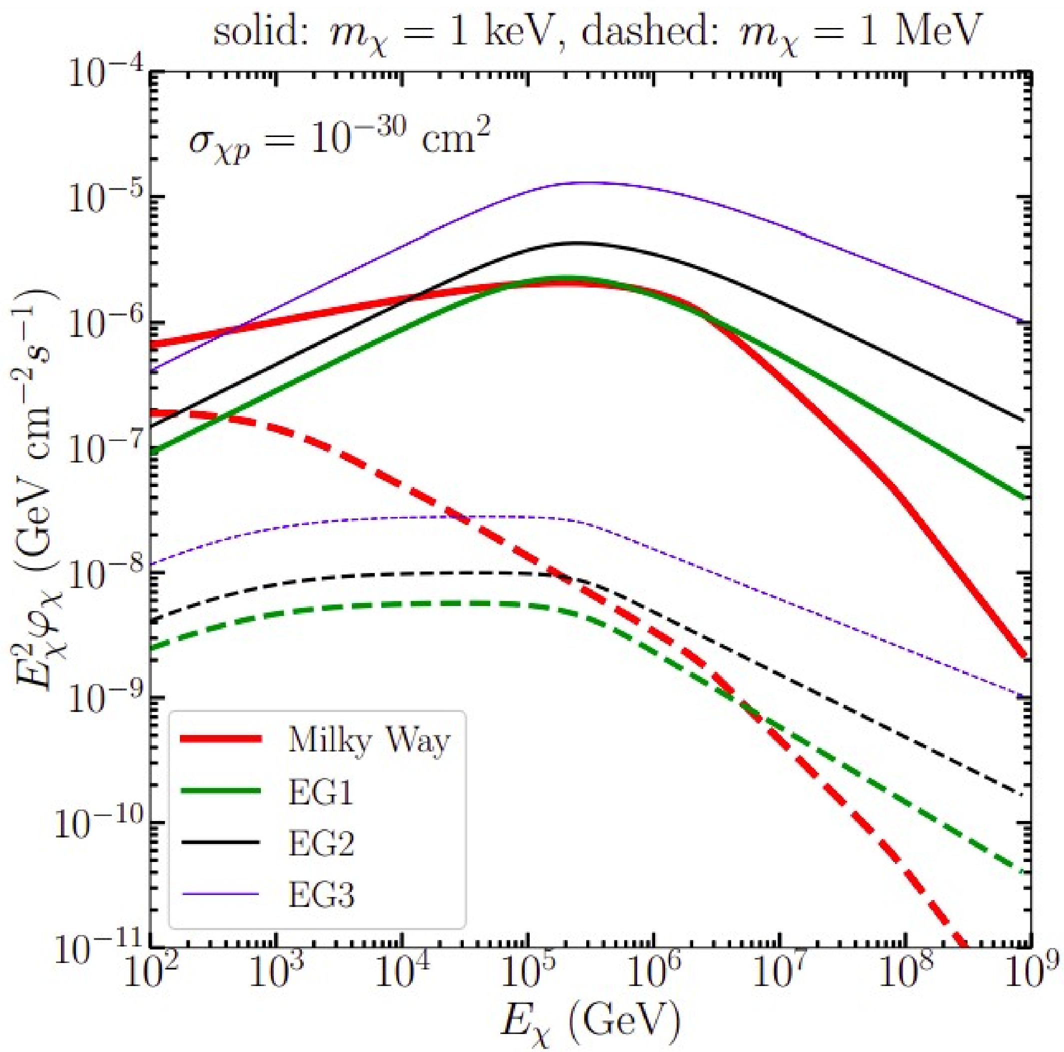
[Alosio+ 2015, Batusta+ 2019]

SFR: star formation rate



[Madau & Dickinson 2014]

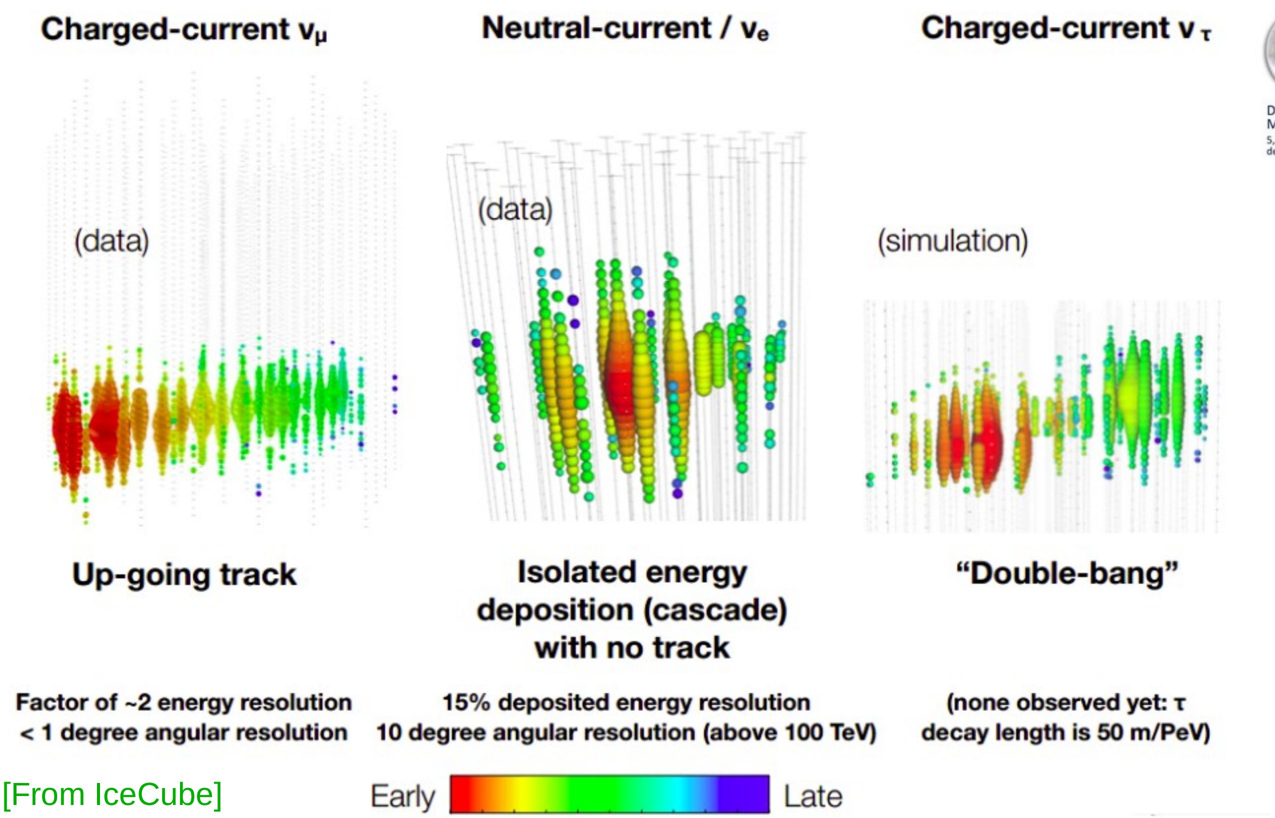
→ comparable flux as the galactic case!

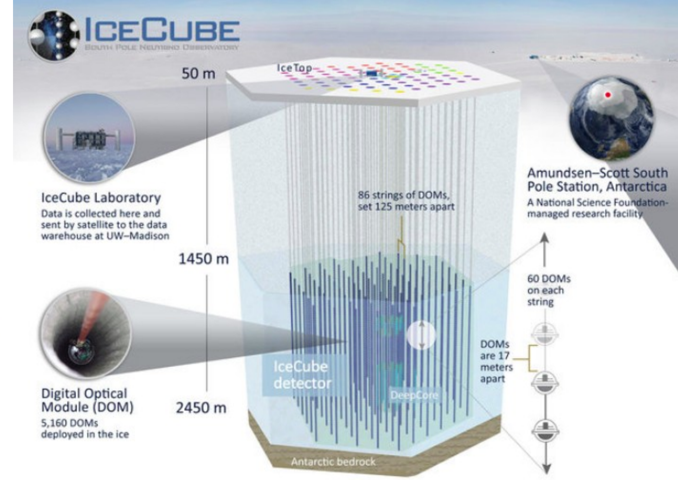


High-energy DM Events at IceCube and Constraints

IceCube – a high-energy neutrino telescope

Typical event types seen in IceCube:



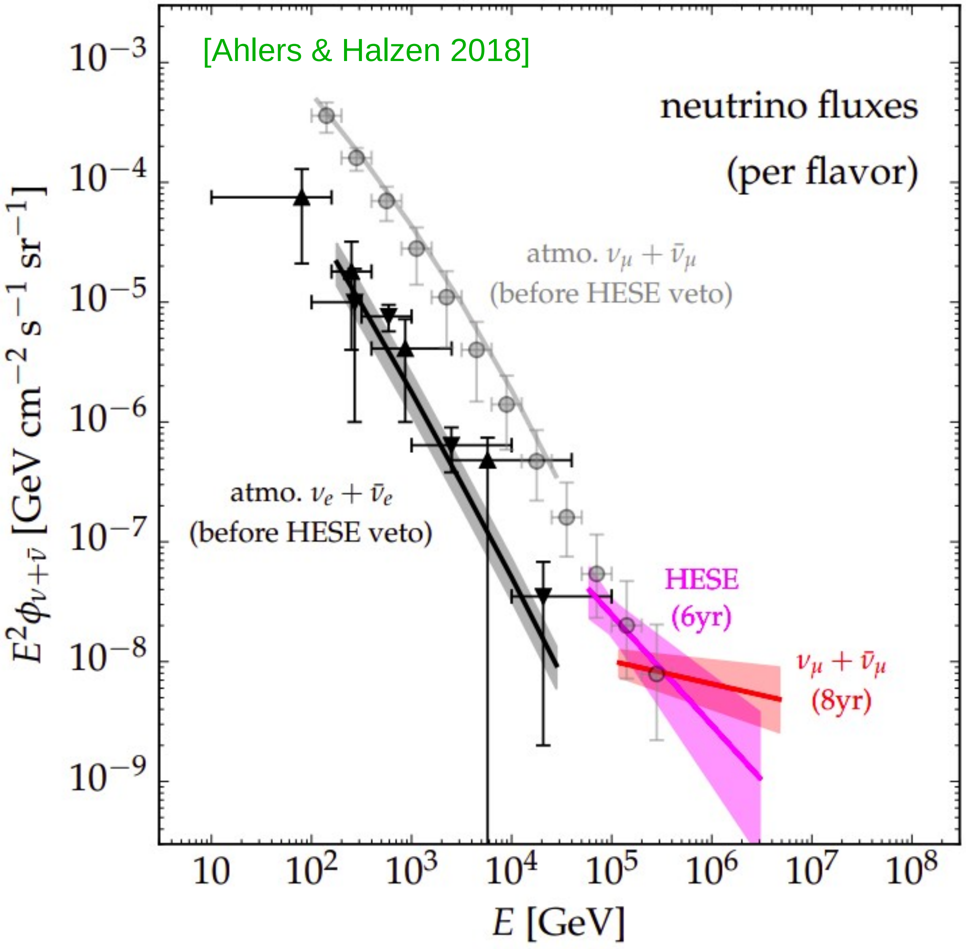


DM–nucleon scattering can possibly disguise as a NC event

$\rightarrow$ one can use IceCube to probe high-energy DM

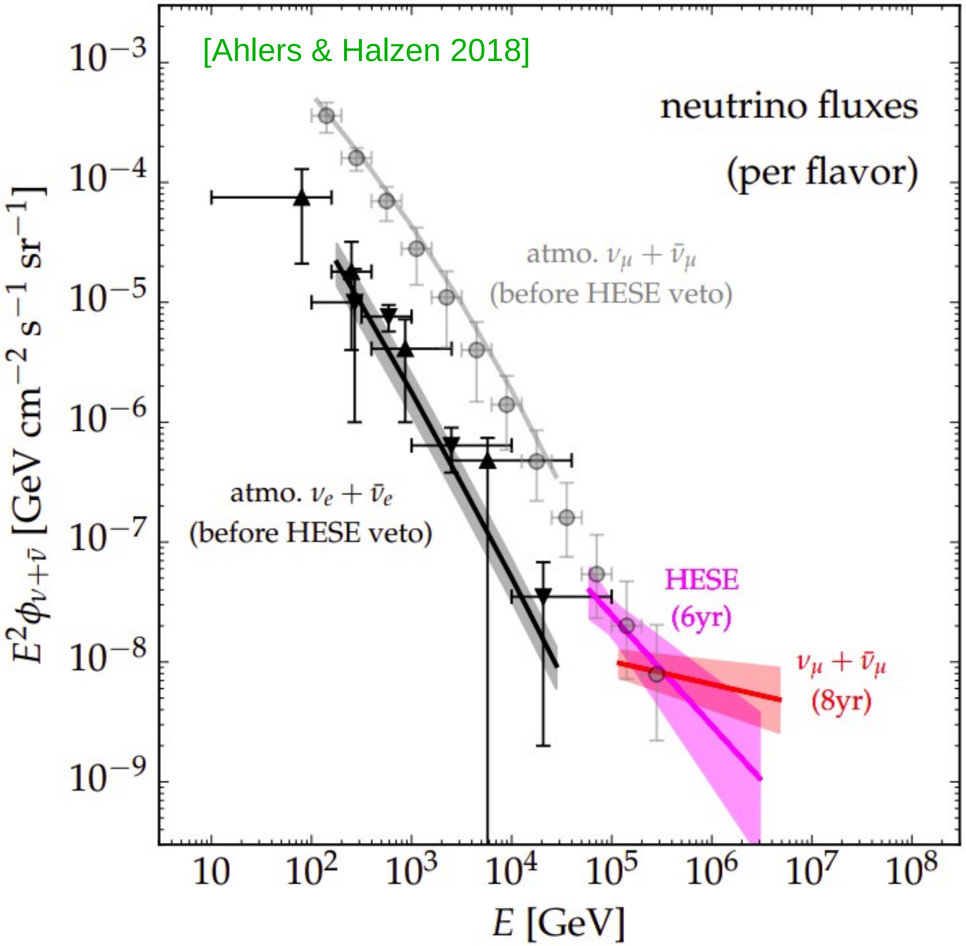
IceCube – a high-energy neutrino telescope

IceCube has measured astrophysical neutrinos at ~ 100 TeV – few PeV

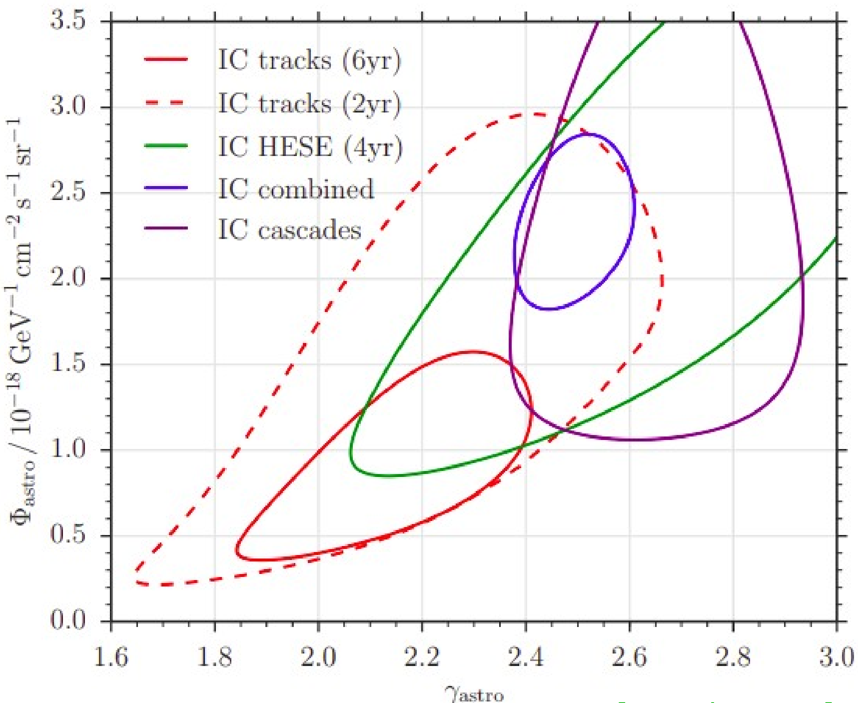


IceCube – a high-energy neutrino telescope

IceCube has measured astrophysical neutrinos at ~ 100 TeV – few PeV



slight tension in the spectral index fitted by track events v.s. that from cascades



[IceCube 2016]

$\rightarrow$ excited some work to "help" E.g., boosted DM, neutrino decay,...

Computing the DM events in IceCube

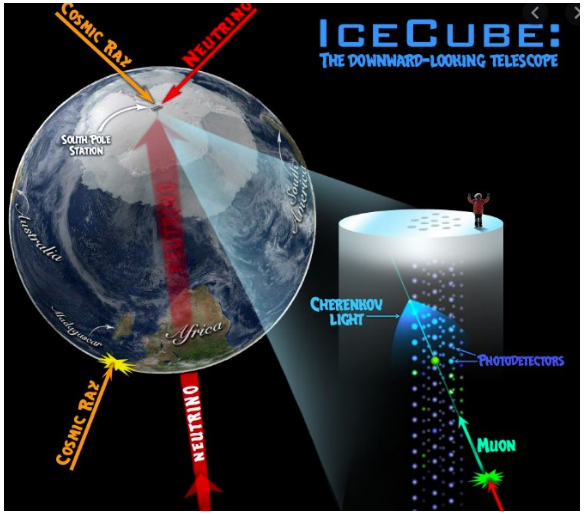
We rescale the "effective area" of ν_e NC cascade events released by IceCube to compute the DM events

$$N_{\rm event}(E_d,\Omega_d) = \int dt dE_s d\Omega_s A_{\rm eff}(E_s,\Omega_s,E_d,\Omega_d)\Phi_s(E_s,\Omega_s)$$

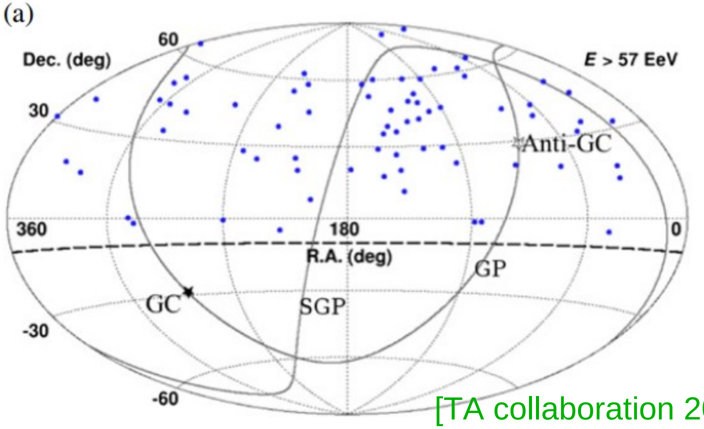
s: source, d: detector

$$A^{ijkm}_{{\rm eff},\chi} = A^{ijk}_{{\rm eff},\nu_e,{\rm NC,cascade}} \frac{\langle e^{-\tau_\chi}\sigma_{\chi p}\rangle^{ikm}}{\langle e^{-\tau_{\nu_e}}\sigma^{\rm NC}_{\nu_e p}\rangle^{ikm}}$$

$$(E_s \leftrightarrow i; E_d \leftrightarrow j; \theta_s = \theta_d \leftrightarrow k; \phi_s = \phi_d \leftrightarrow m)$$



(a)



[TA collaboration 2014]

Computing the DM events in IceCube

We rescale the "effective area" of ν_e NC cascade events released by IceCube to compute the DM events

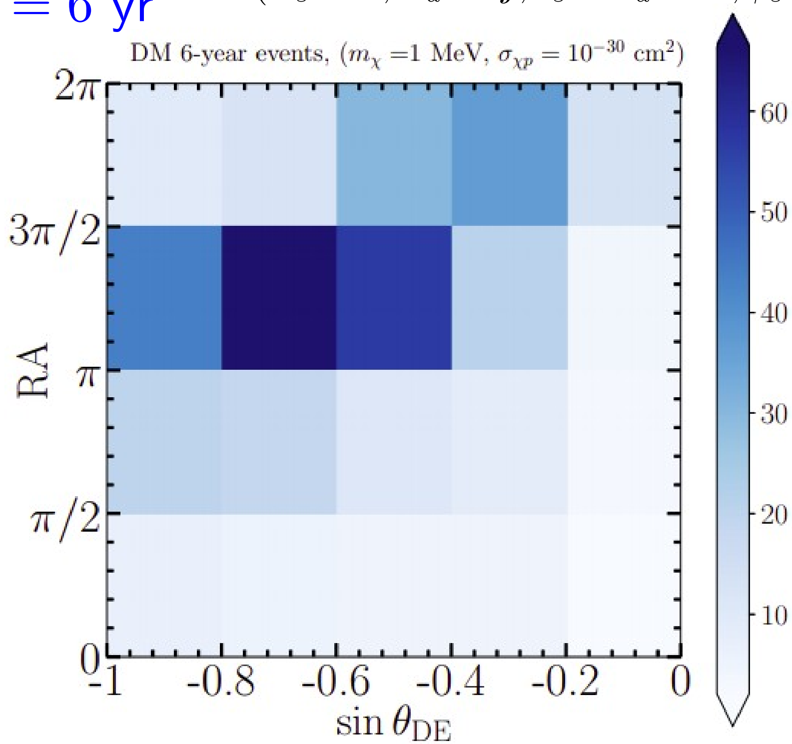
$$N_{\text{event}}(E_d,\Omega_d) = \int dt dE_s d\Omega_s A_{\text{eff}}(E_s,\Omega_s,E_d,\Omega_d)\Phi_s(E_s,\Omega_s)$$

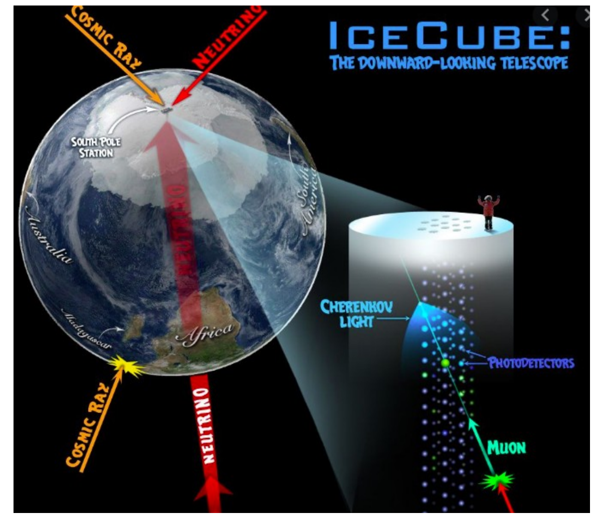
s: source, d: detector

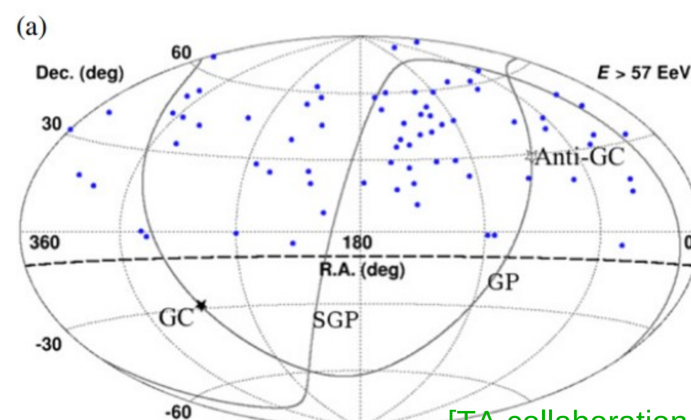
$$A^{ijkm}_{\text{eff},\chi} = A^{ijk}_{\text{eff},\nu_e,\text{NC},\text{cascade}} \frac{\langle e^{-\tau_\chi}\sigma_{\chi p}\rangle^{ikm}}{\langle e^{-\tau_{\nu_e}}\sigma^{\text{NC}}_{\nu_e p}\rangle^{ikm}}$$

$$(E_s \leftrightarrow i; E_d \leftrightarrow j; \theta_s = \theta_d \leftrightarrow k; \phi_s = \phi_d \leftrightarrow m)$$

For $T = 6$ yr







[TA collaboration 2014]

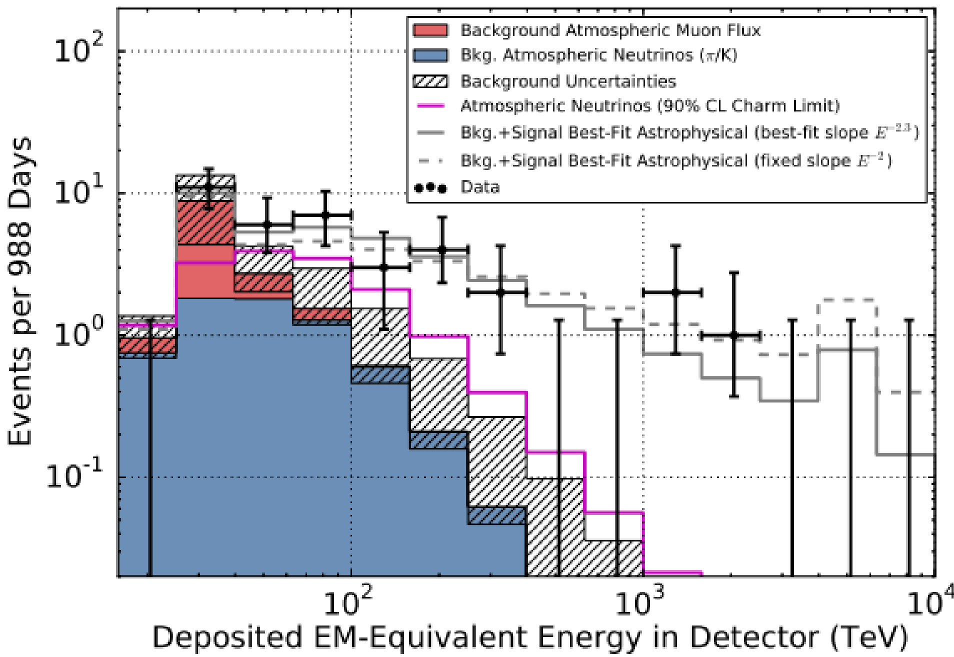
Backgrounds to high-energy DM searches in IceCube

Two main background sources to high-energy DM:

(i) Atomspheric muons and neutrinos from CR interactions

$\rightarrow$ we take from the available angular-dependent IceCube 3-year data, scaled to 6 years

[IceCube 2014]



(ii) Astrophysical high-energy neutrinos

a) assume Φ_ν constrained by through-going muon track events

$$\Phi_{\nu+\bar{\nu}}(E_\nu) = N_{\nu,0} \left(\frac{E_\nu}{100\ \mathrm{TeV}} \right)^{-\gamma_{\nu,0}} \times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

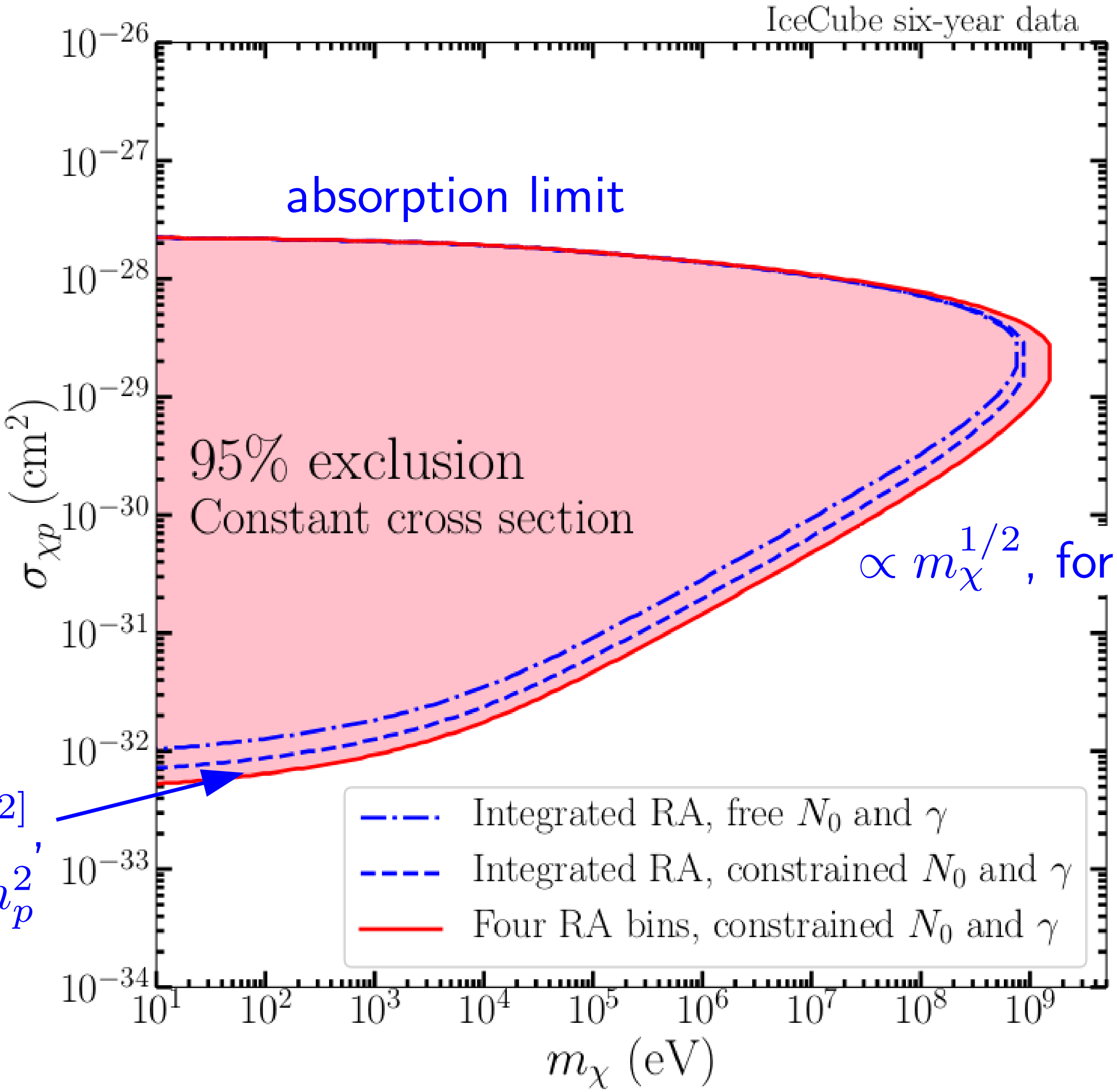
$$N_{\nu,0} = 1.44^{+0.25}_{-0.24} \quad \text{and} \quad \gamma_{\nu,0} = 2.28^{+0.08}_{-0.09}$$ [IceCube 2019]

b) do not assume any prior on $N_{\nu,0}$ and $\gamma_{\nu,0}$

Constraints on DM–N cross section: Galactic case

$N_{\rm event} \propto m_\chi^{-1} \sigma^2 \exp(-\sigma n L) \rightarrow$ exclusion ranges between two $\sigma_{\chi p}$ for a given m_χ

Scenarios	$E_{\rm d}$	$\sin\theta_{\rm DE}$	RA
Milky Way	1	5	1
	1	5	4
EG-1,2,3	1	5	1



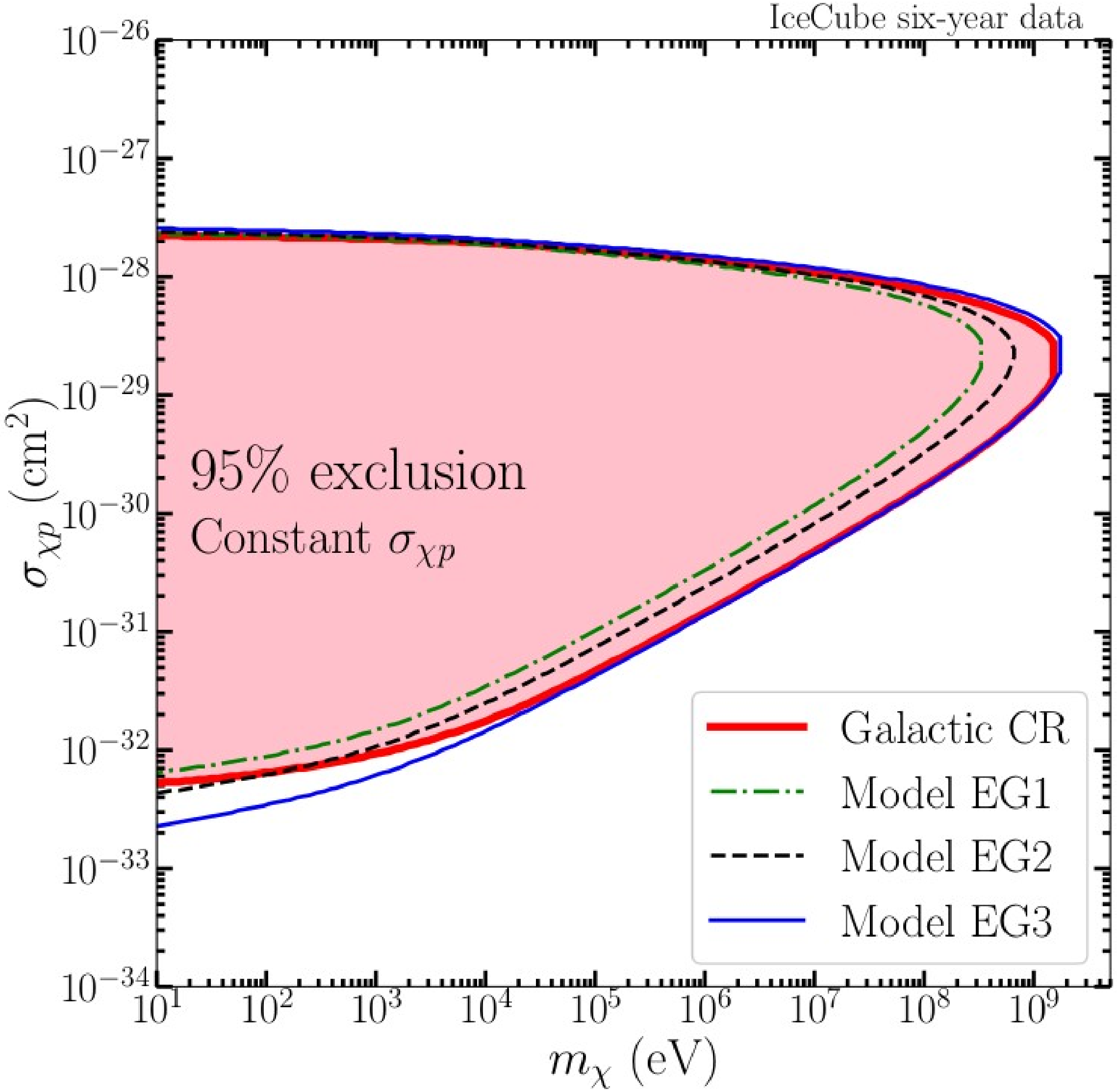
$\propto m_\chi^{1/2}$, for $m_\chi E_\chi \gtrsim m_p^2$

$\propto m_\chi^{[2-(\gamma_p+1)/2]}$, for $m_\chi E_\chi \lesssim m_p^2$

Constraints on DM–N cross section: Extragalactic cases

Considering extragalactic component yields similar results

Scenarios	$E_{\rm d}$	$\sin\theta_{\rm DE}$	RA
Milky Way	1	5	1
	1	5	4
EG-1,2,3	1	5	1



Constraints on DM–N cross section: energy dependency

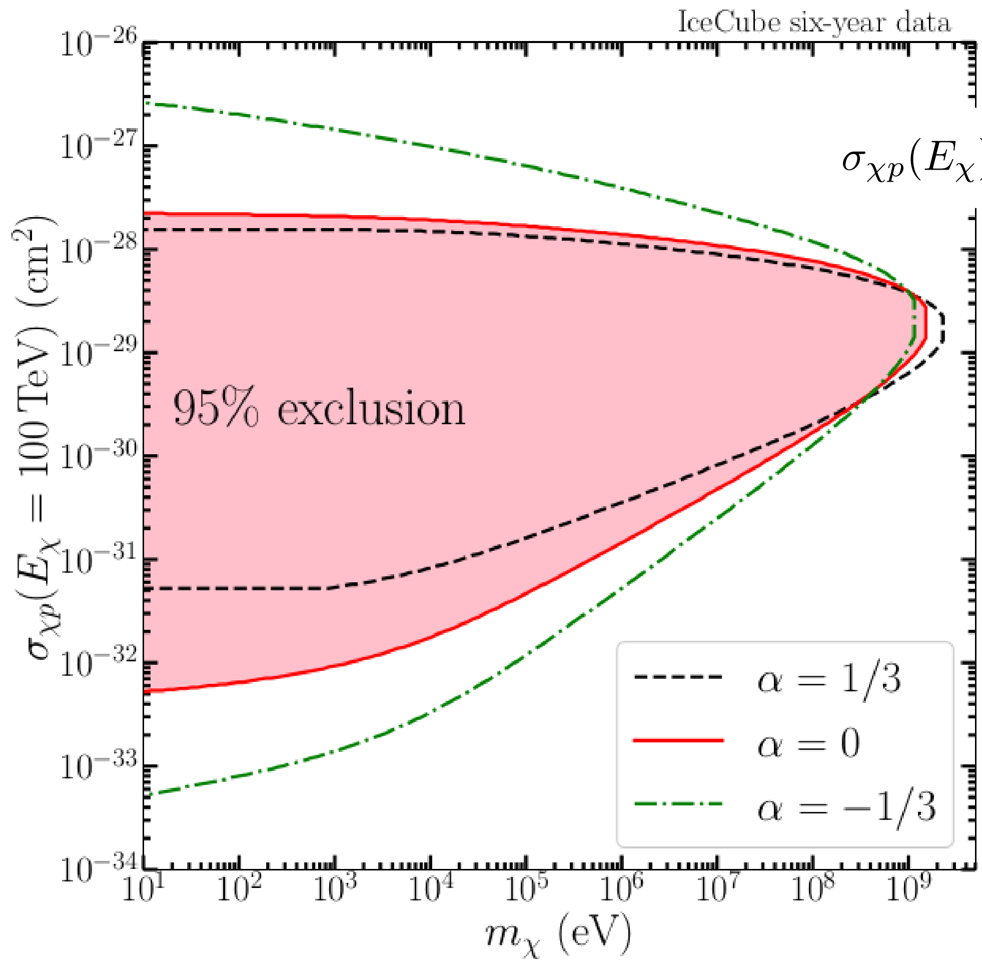
For a CR colliding with a DM at rest, $s \simeq E_p m_\chi$ is a factor of m_χ/m_p lower than $s' \simeq E_\chi m_p$ for a DM colliding with a proton at rest, when $E_p \sim E_\chi$

$\rightarrow$ energy-dependence of $\sigma_{\chi p}$ can affect the derived bounds

Constraints on DM–N cross section: energy dependency

For a CR colliding with a DM at rest, $s \simeq E_p m_\chi$ is a factor of m_χ/m_p lower than $s' \simeq E_\chi m_p$ for a DM colliding with a proton at rest, when $E_p \sim E_\chi$

$\rightarrow$ energy-dependence of $\sigma_{\chi p}$ can affect the derived bounds



$$\sigma_{\chi p}(E_\chi) = \sigma_{\chi p,0} \times \left(\frac{E_\chi}{100\ \mathrm{TeV}}\right)^\alpha$$

For $\sigma_{\nu p}$, $\alpha \sim 1/3$ for $s \gtrsim M_Z^2$

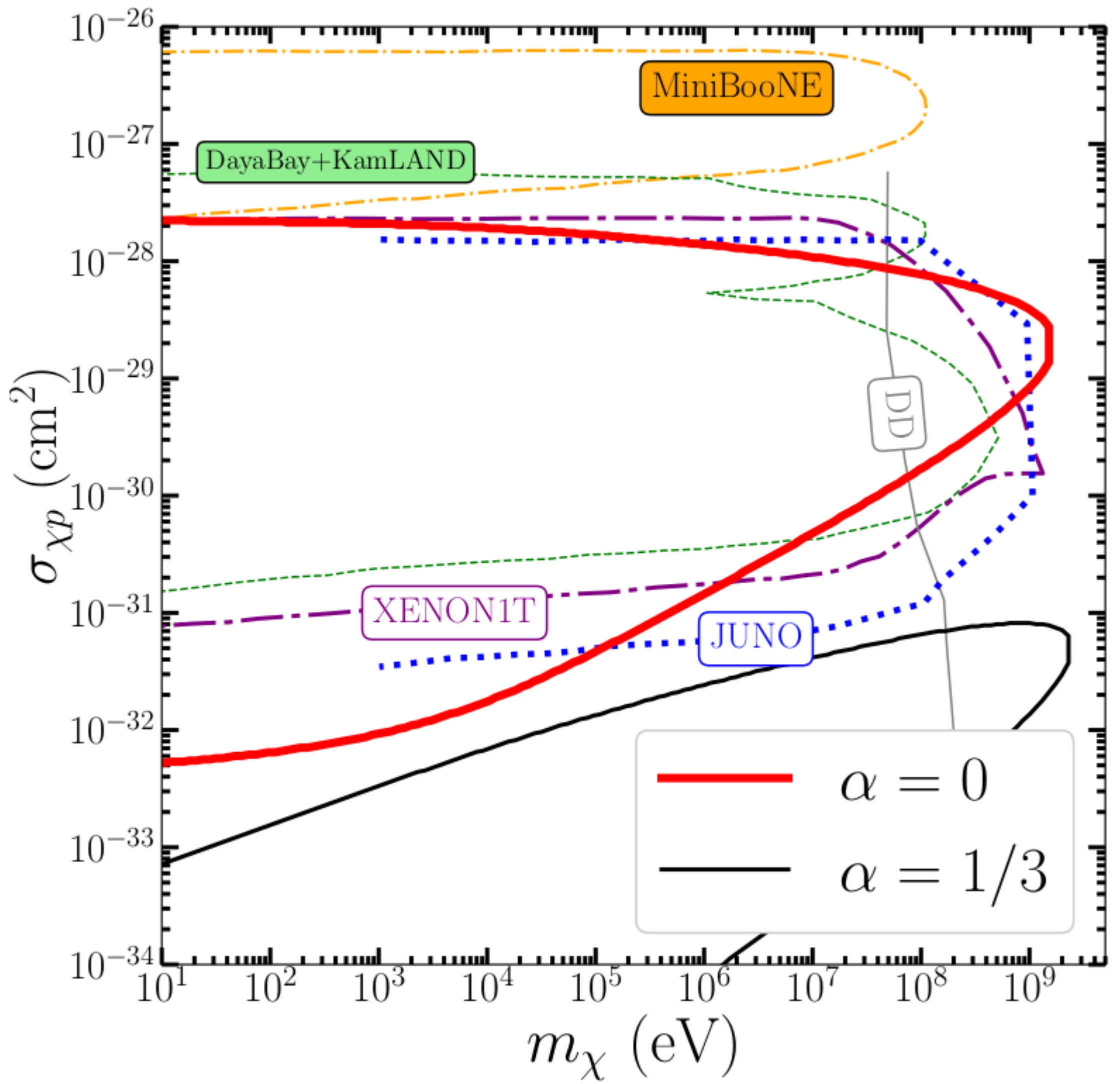
$\alpha \sim 1$ for $\mathrm{GeV}^2 \lesssim s \lesssim M_Z^2$

$\alpha \sim 2$ for $s \lesssim \mathrm{GeV}^2$

Extrapolating to low energy?

MiniBooNE & Xenon1T: Bringmann+2018
DYB+KamLAND & JUNO: Cappiello+2019

If $\sigma_{\chi p}$ is energy independent, our derived bound here can be somewhat better than bounds derived by considering CR-upscattered DM with $E_\chi \lesssim$ GeV



If we naively extrapolate $\sigma_{\chi p}$ all the way down to $v_\chi \simeq 10^{-3}\ c$ with $\alpha = 1/3$, the bounds can be shifted to much lower values

Summary

- Both the galactic and extragalactic $\sim$ PeV cosmic-rays can upscatter sub-GeV DM to produce a flux comparable to high-energy astrophysical neutrinos detected by IceCube for $\sigma_{\chi p} \sim 10^{-30}$ cm^2 at the rest-frame of the DM.
- These high-energy DM can then interact with targets in IceCube to produce events masquerading as the NC $\nu - p$ scatterings.
- Considering the IceCube six-year HESE sample, we then derive first constraints on $\sigma_{\chi p}$ down to $\sigma_{\chi p} \sim 10^{-32}$ cm^2 for $E_\chi \sim$ PeV at the rest-frame of a nucleon, complementary to other searches.
- The exact limit would depend on the energy-dependence of the cross-section, because the center-of-mass energy are different at the acceleration site from at the detection site. A consistent modeling is needed to combine (or compare) this bound at high-energy to others obtained at lower energy scale.