Neutrino-Dark matter connections with high-energy neutrinos

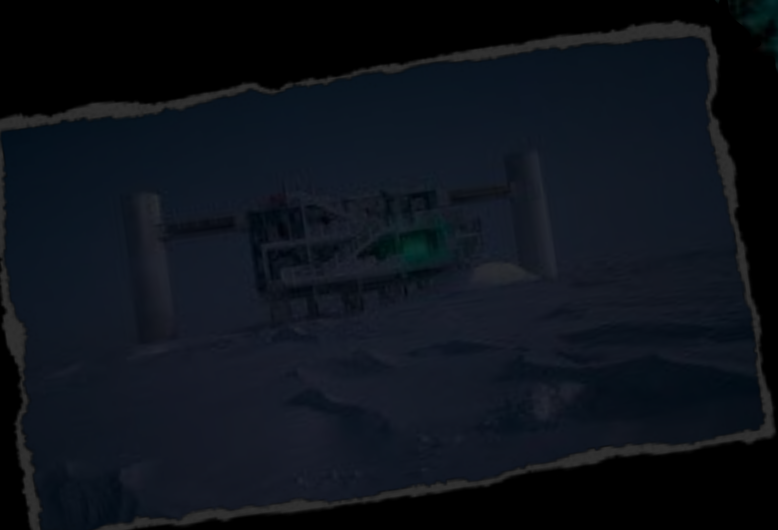
Sergio Palomares-Ruiz

IFIC, CSIC-U. València

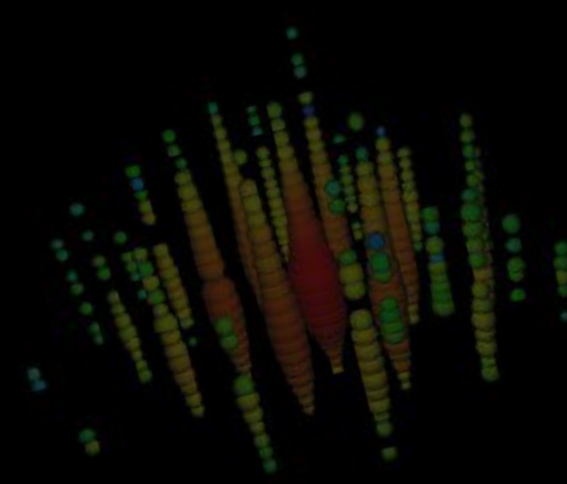
CSIC
Consejo Superior de Investigaciones Científicas

IFIC
Institut de Física Corpuscular

Vniversitat de València



May 19, 2021



University of Birmingham

Two doors to new physics: Neutrinos and dark matter

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Neutrino oscillations → Neutrinos are massive particles

Overwhelming (gravitational) evidence of dark matter existence: galactic curves, lensing, LSS, CMB,…

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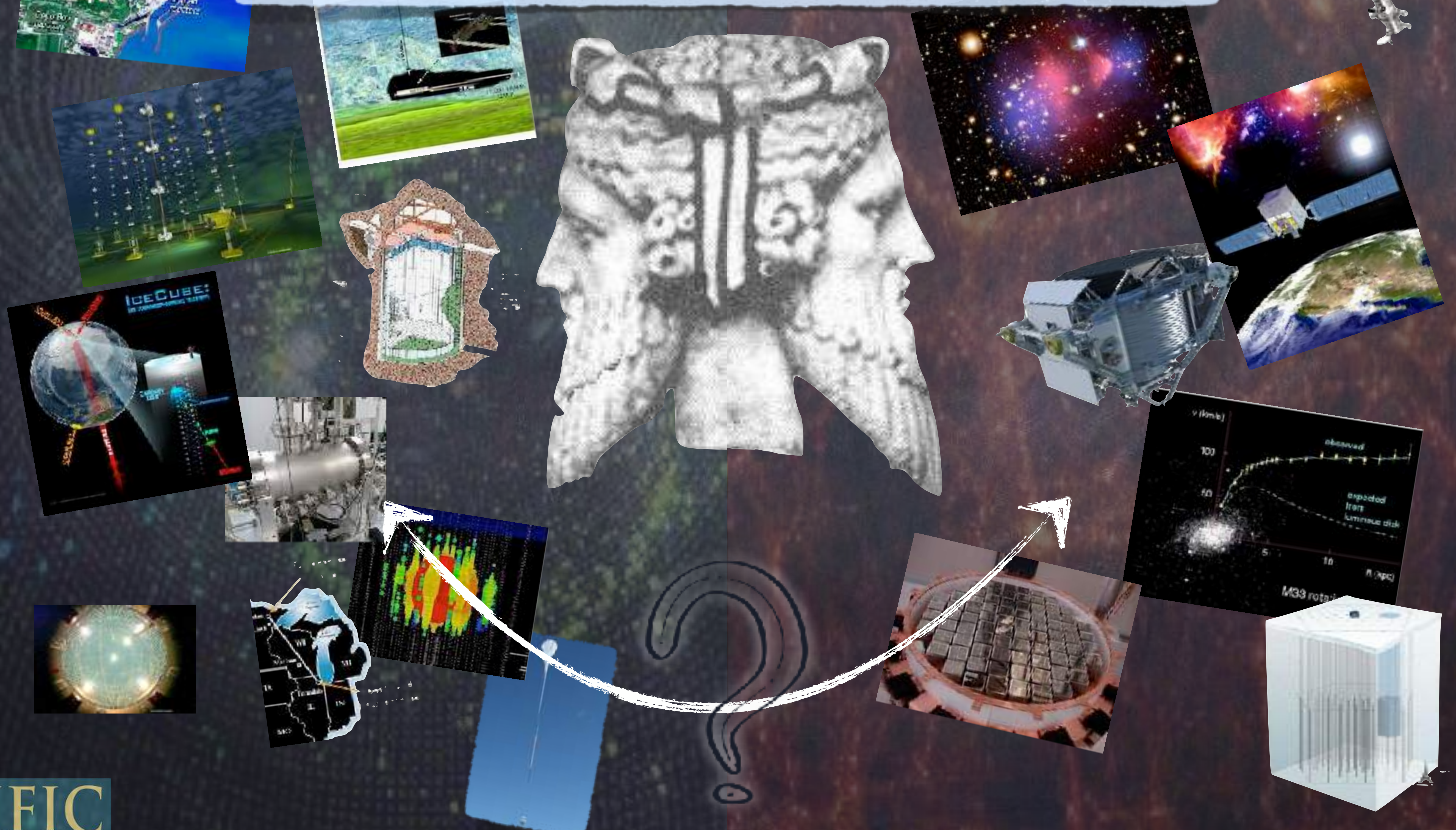


Neutrino-dark matter connections

Neutrinos

Dark matter

Neutrino-dark matter connections

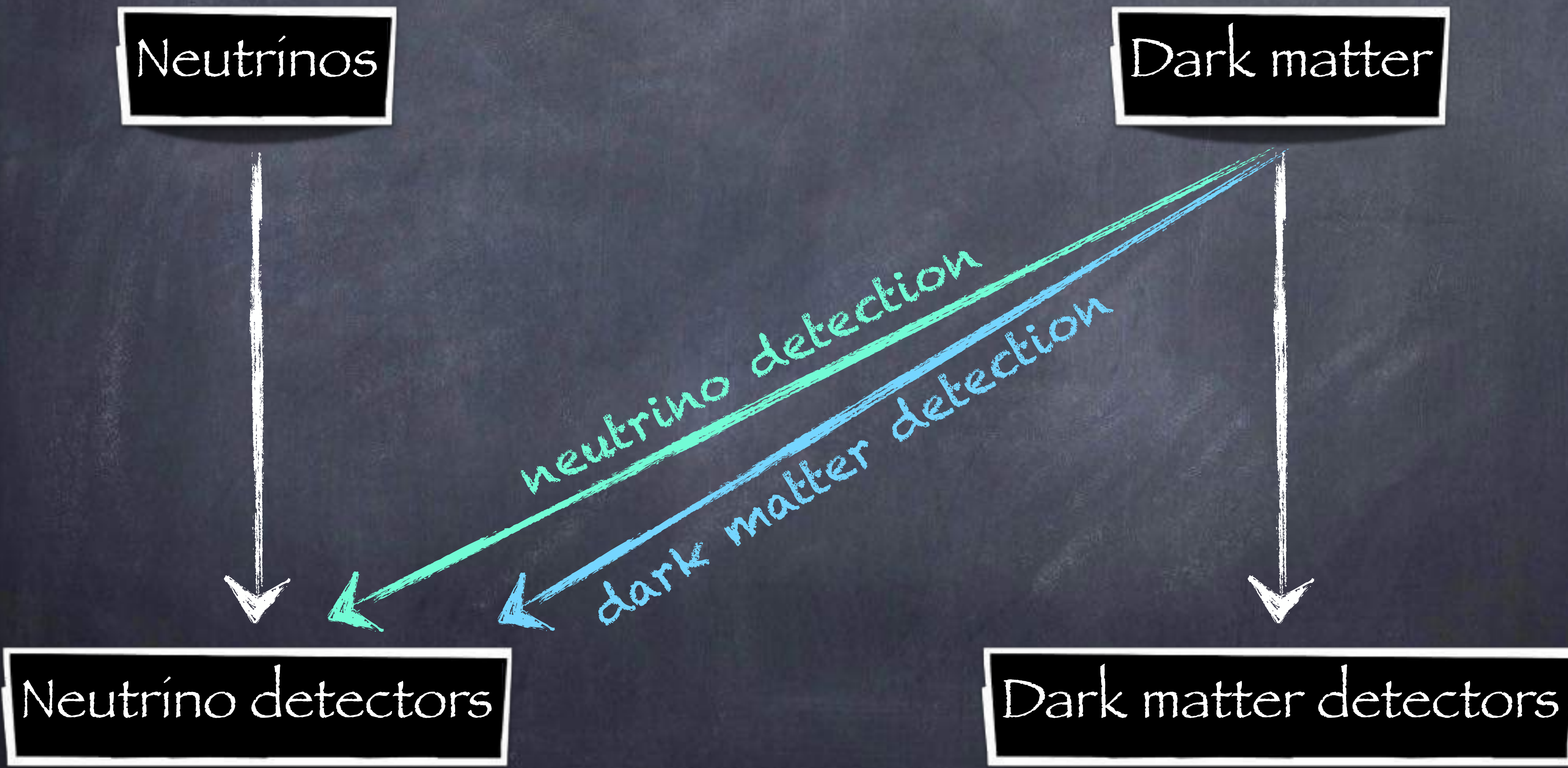
Neutrinos

Dark matter

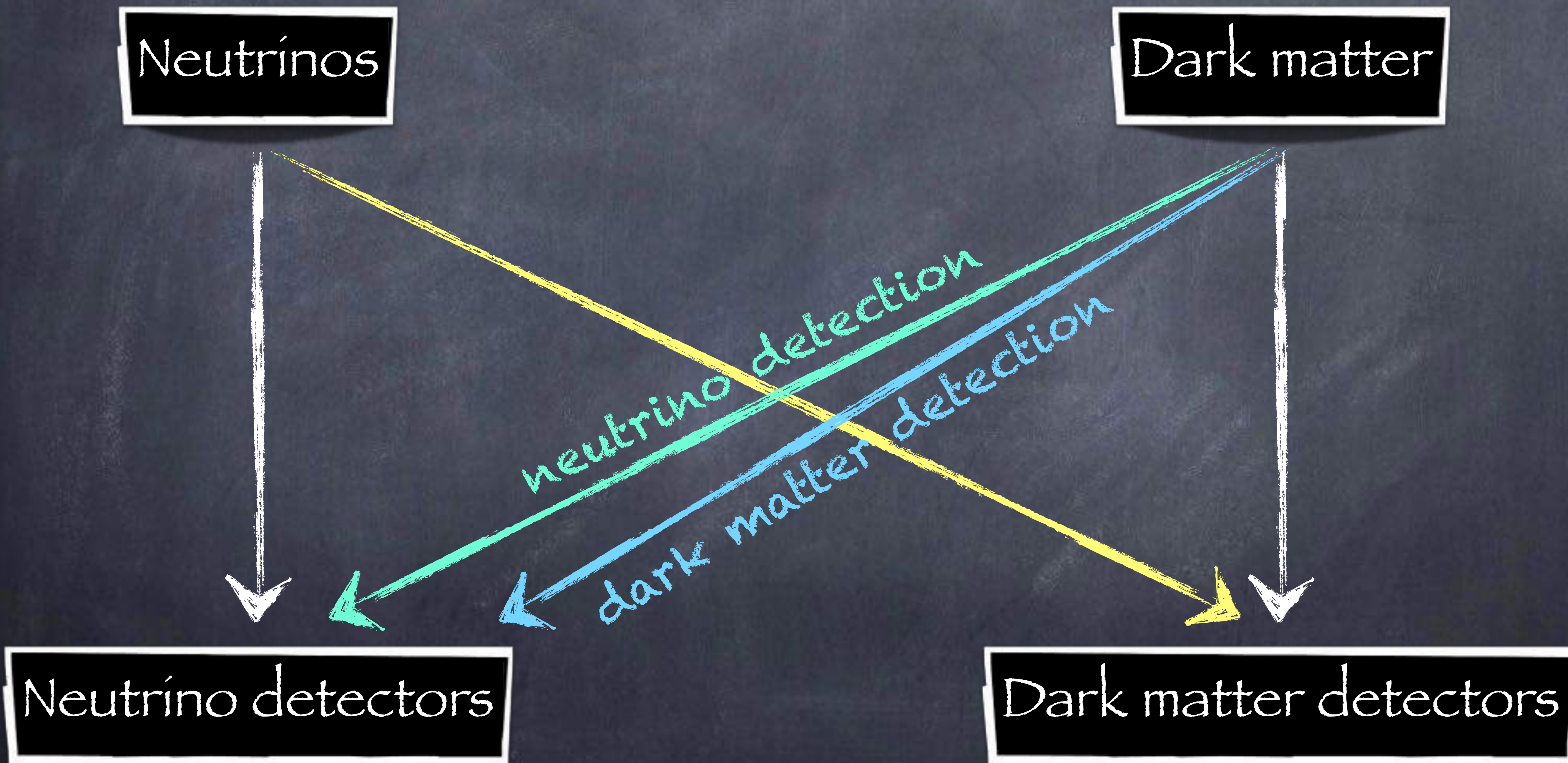
Neutrino detectors

Dark matter detectors

Neutrino-dark matter connections



Neutrino-dark matter connections



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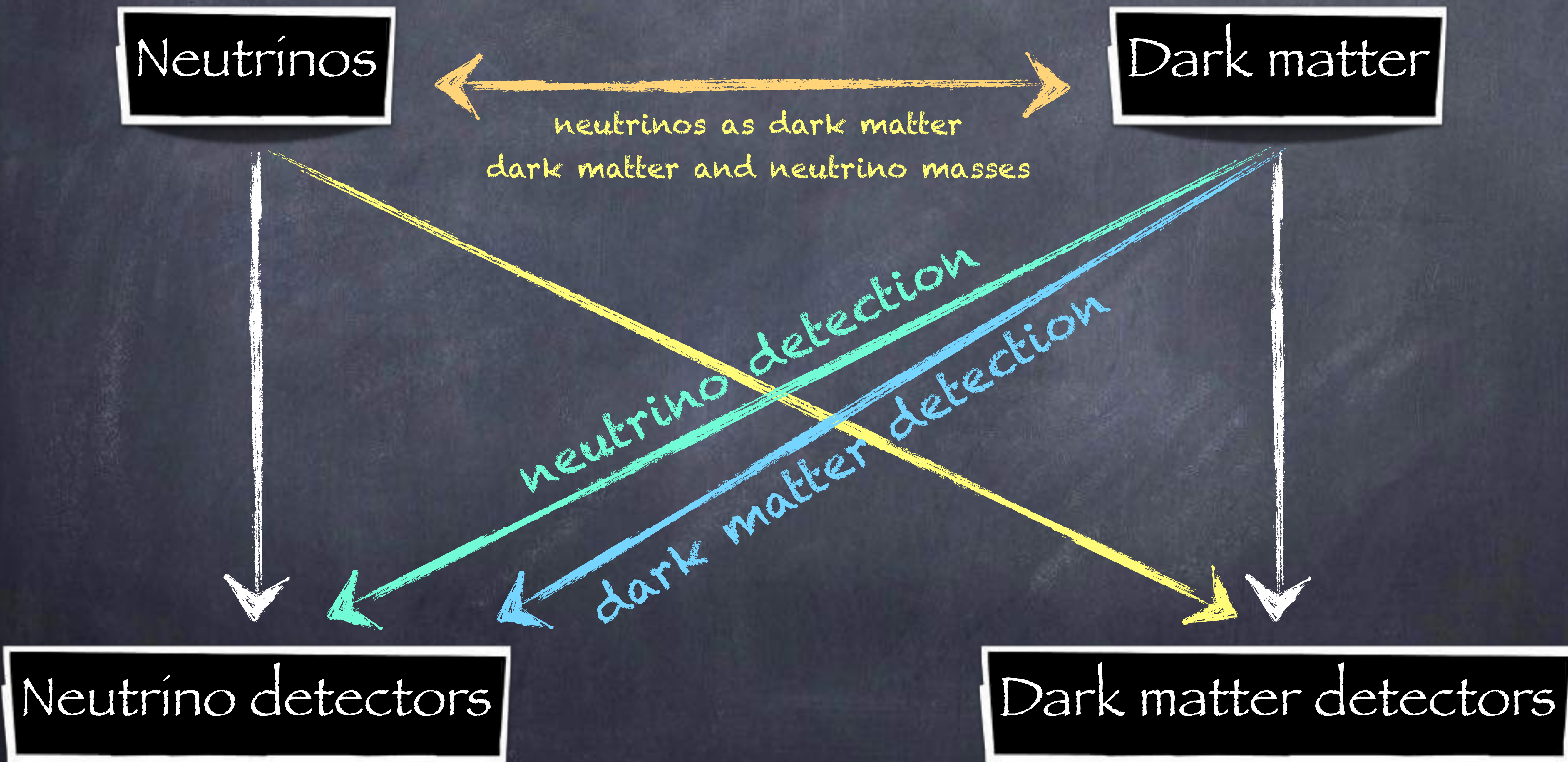

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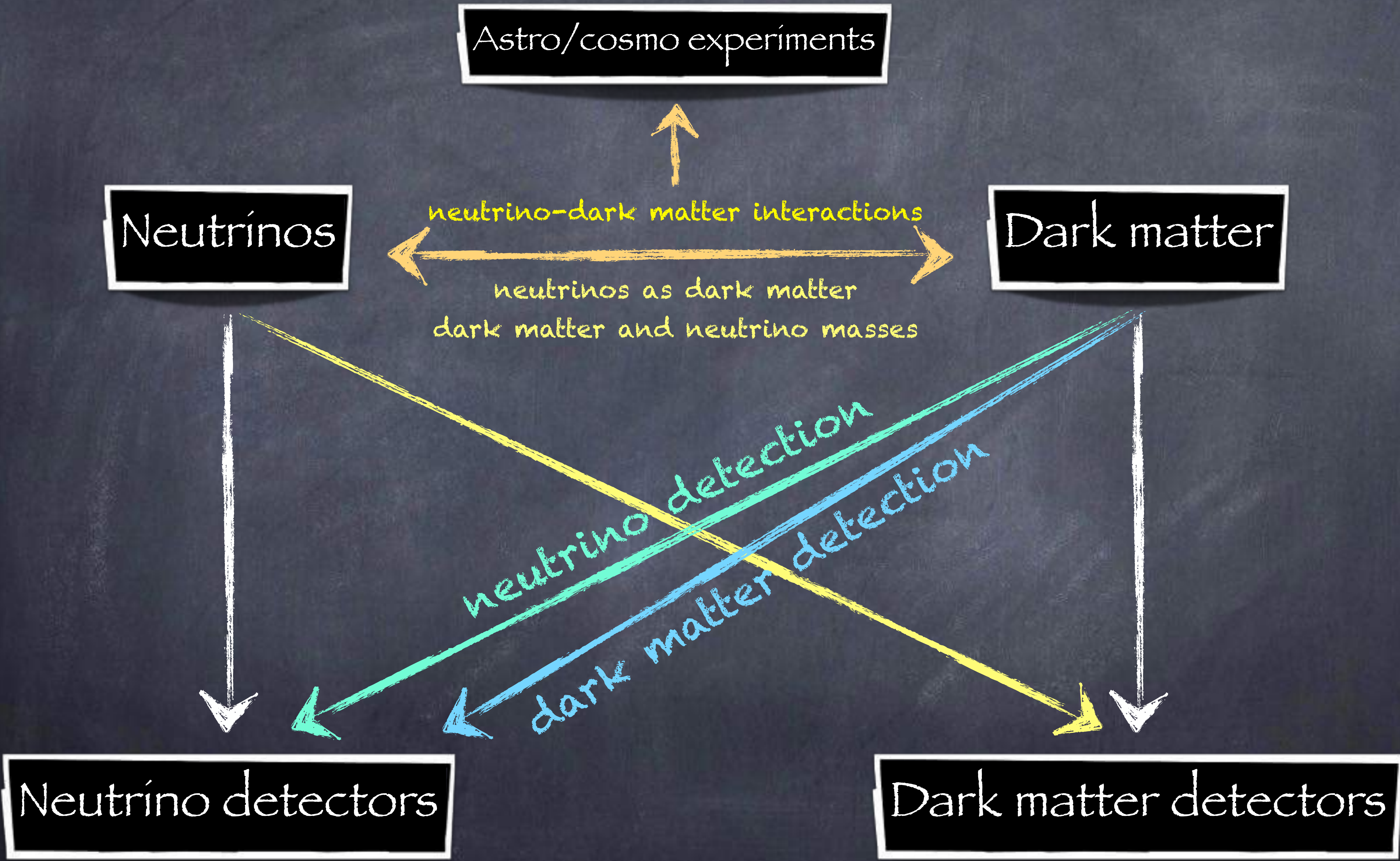
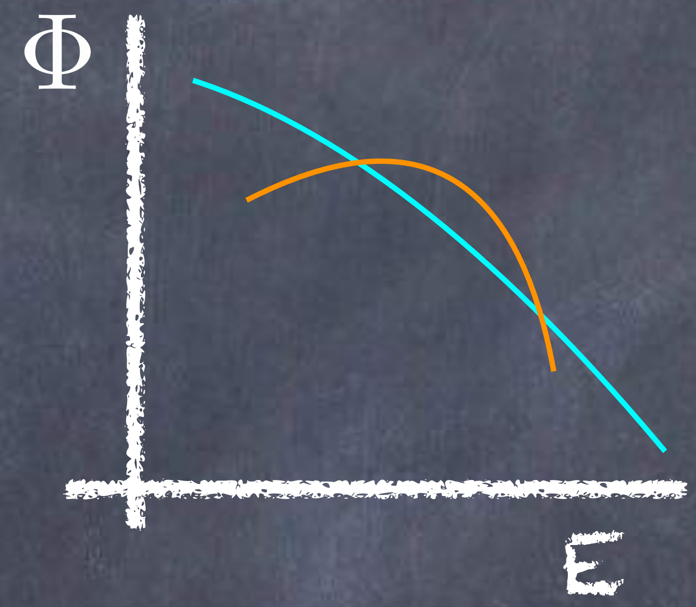


Neutrino-dark matter interactions

Neutrino-dark matter interactions

New signal



Neutrino-dark matter interactions

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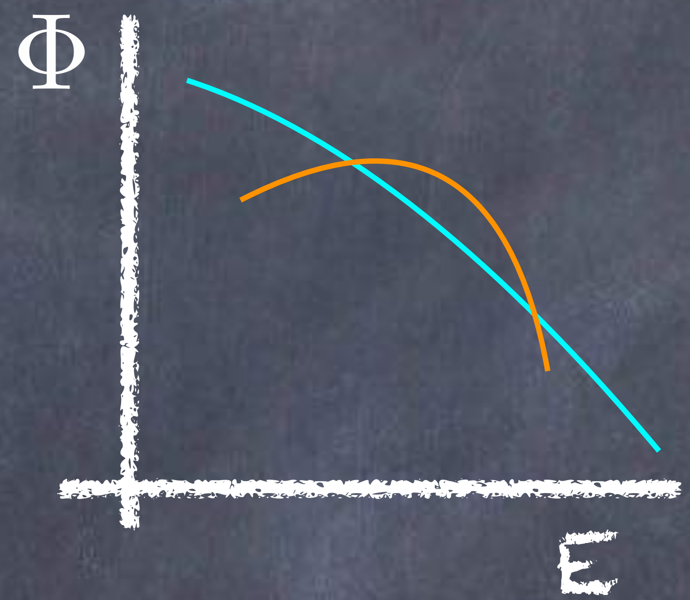
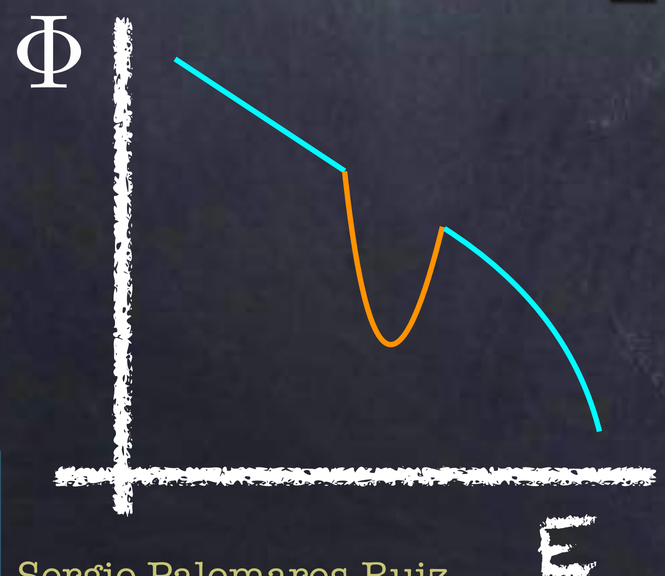


Features on known spectra



Neutrino-dark matter interactions

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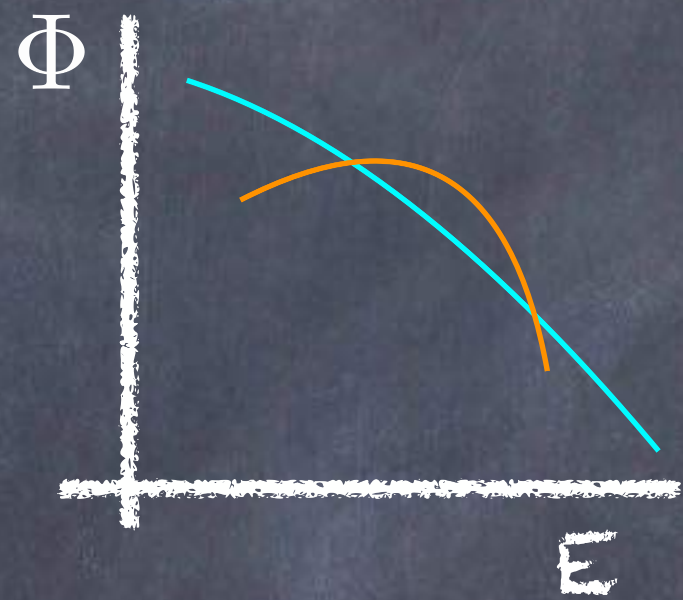

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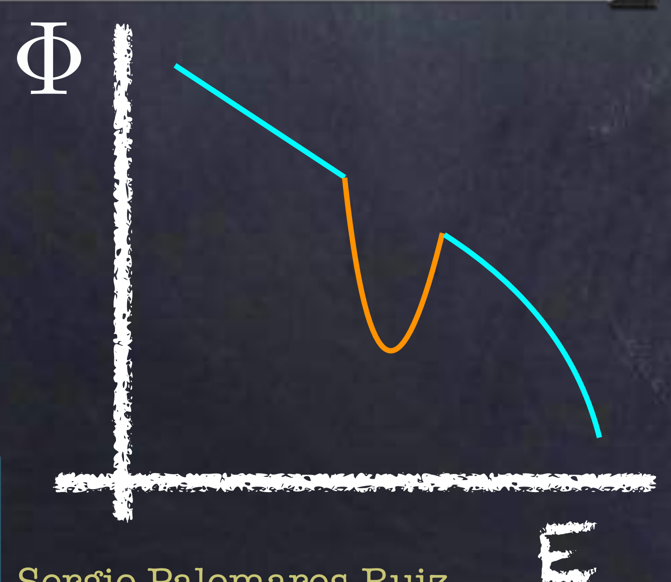
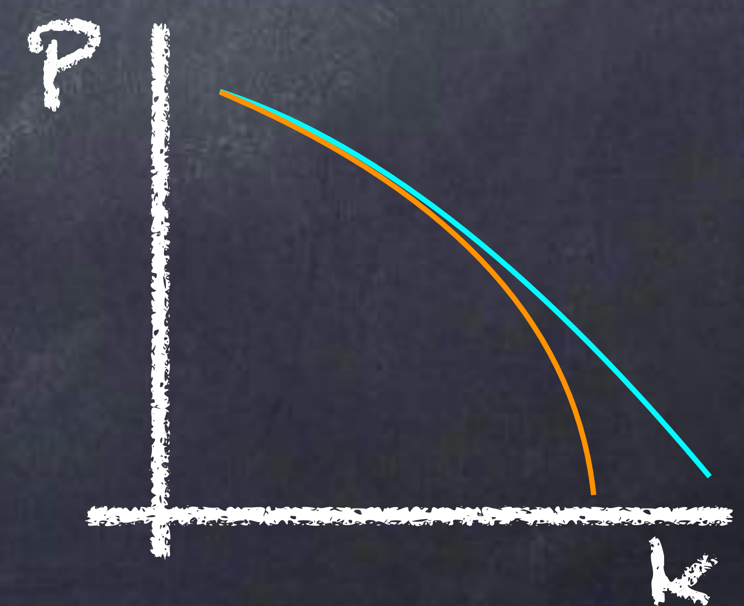


Cosmo/Astro effects



Sources of neutrinos

Natural sources

Farther away

Atmosphere

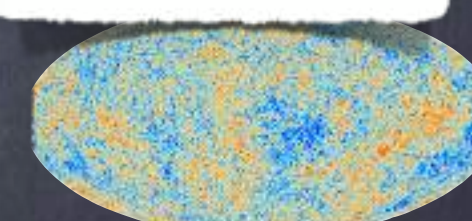
Earth

Sun

Supernova explosions

Astrophysical sources

Cosmic relics

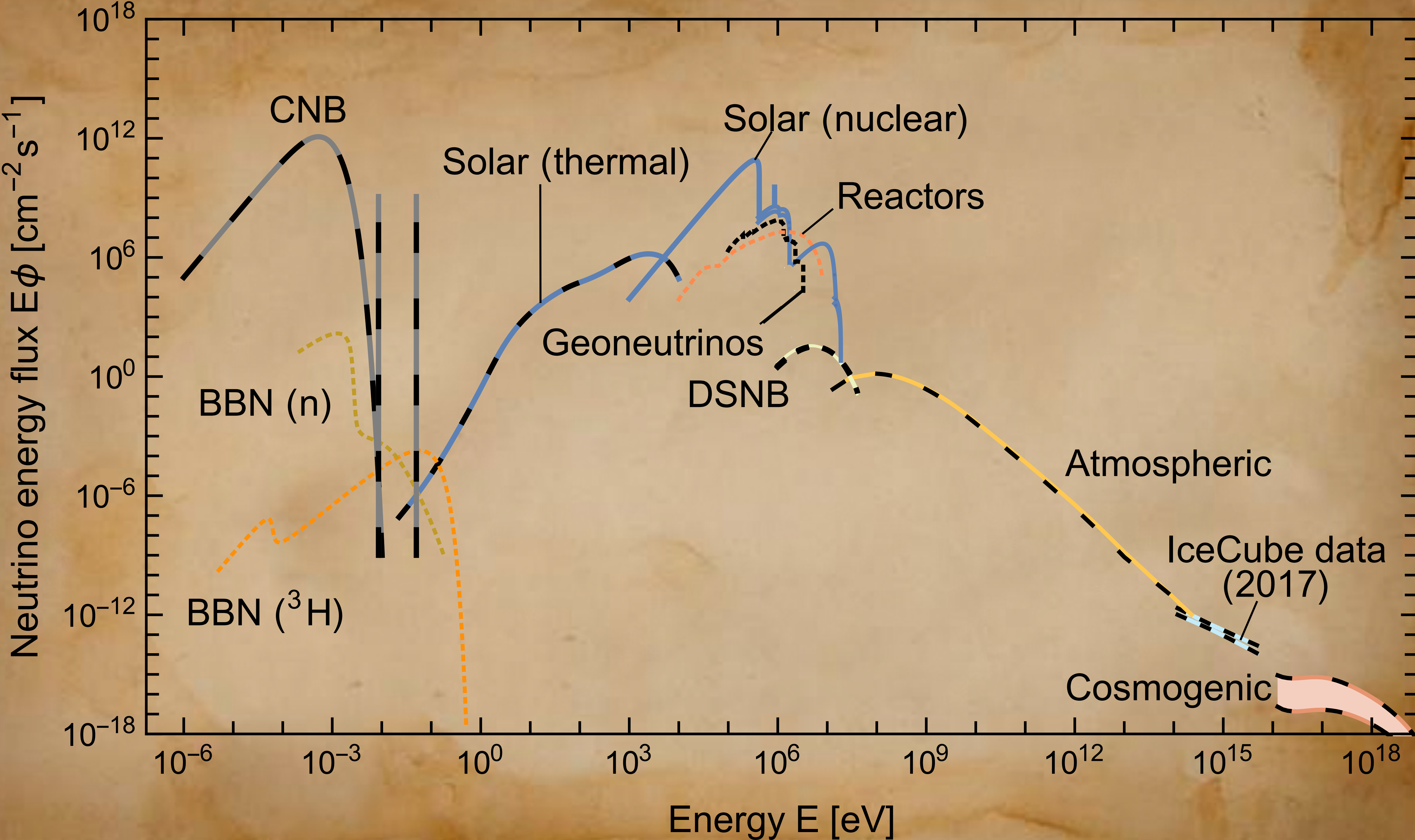


Man-made sources

Nuclear reactors

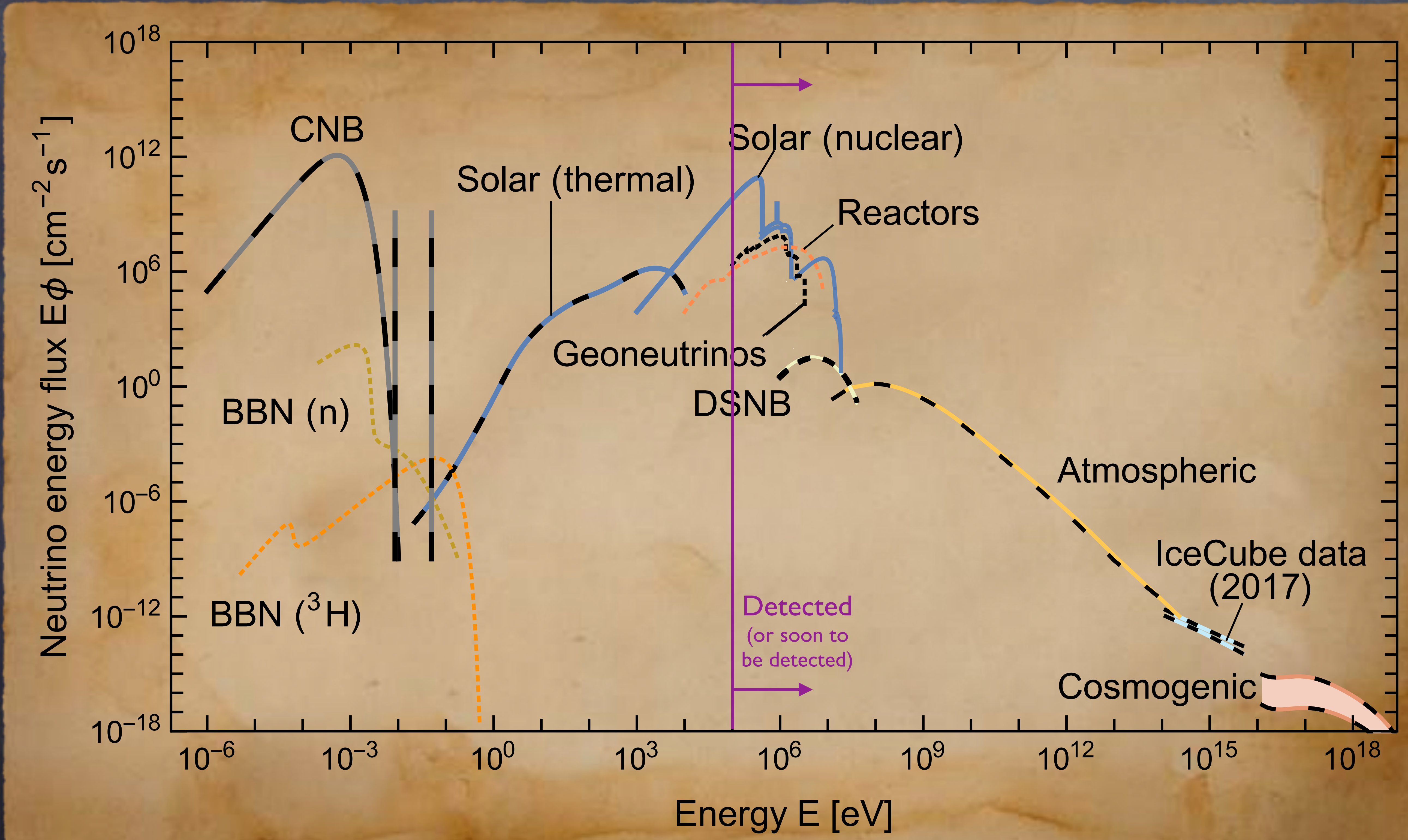
Particle accelerators

(Standard) Grand Unified Neutrino Spectrum



E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92:45006, 2020

(Standard) Grand Unified Neutrino Spectrum



E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92:45006, 2020

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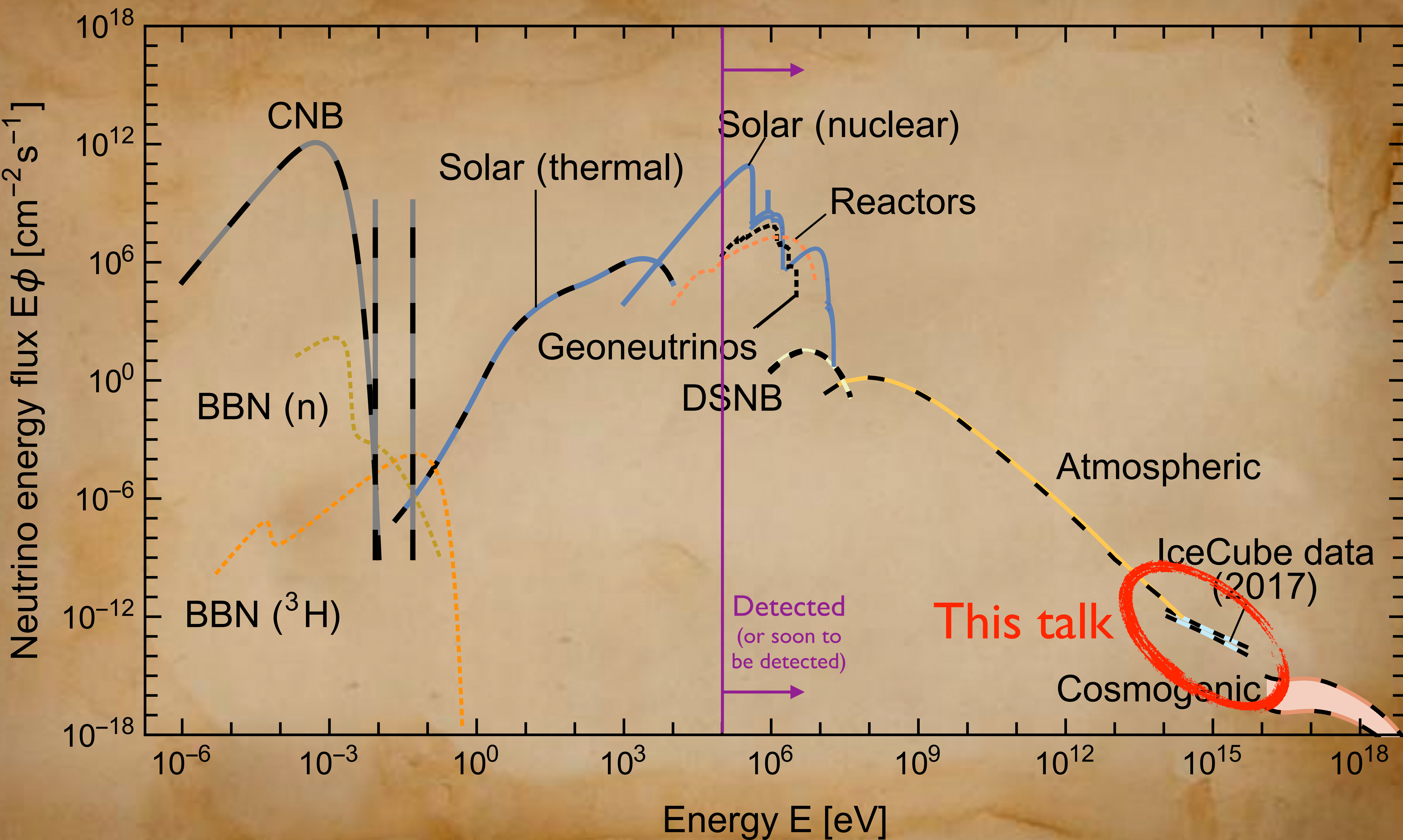

E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92:45006, 2020

Why do we care about high-energy neutrinos?

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Neutrinos point back to their cosmic sources
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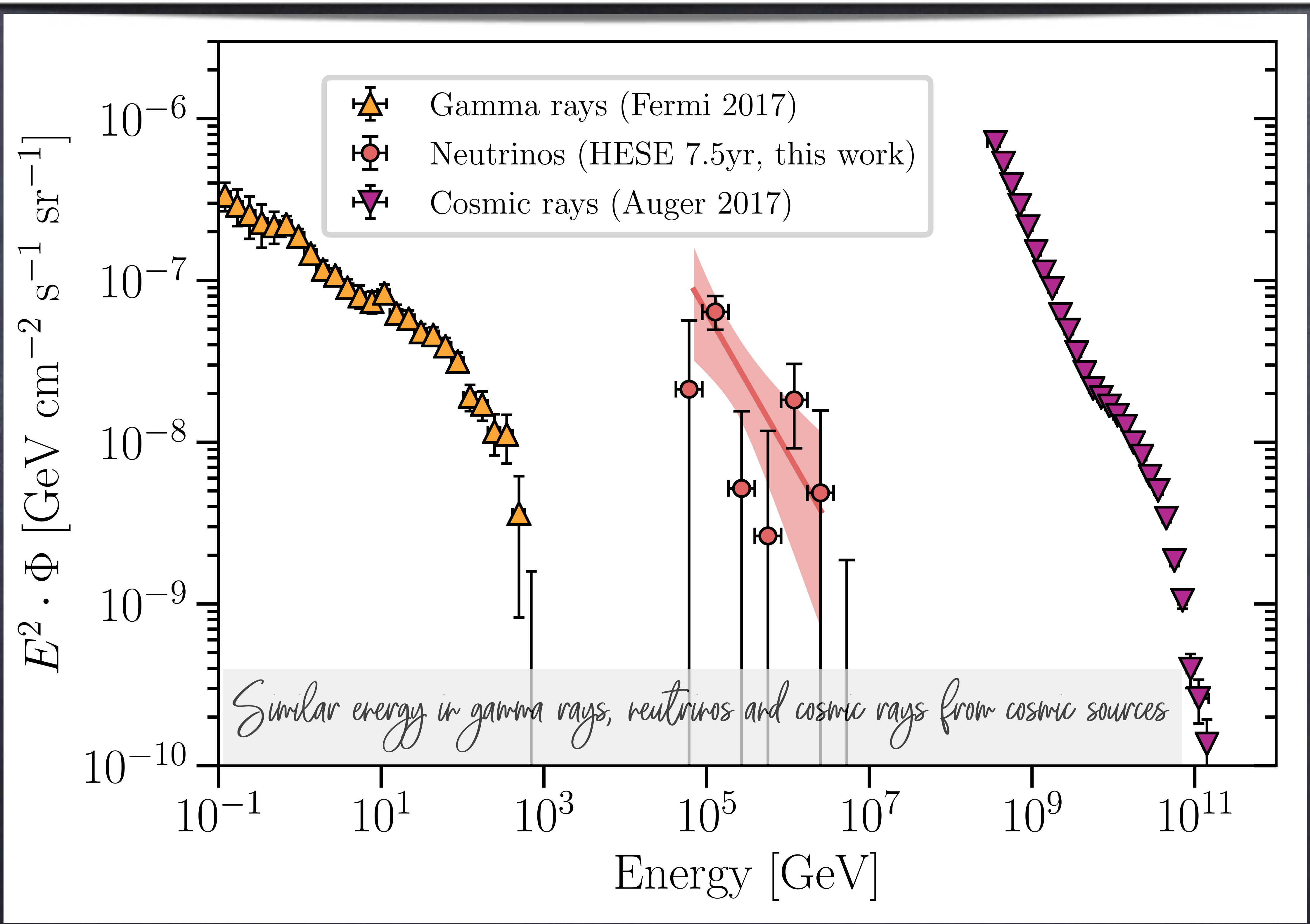
Neutrinos carry a quantum number that cosmic rays and photons do not have: flavor

The CR/Gamma-ray/Neutrino Connection

Neutrinos and photons are guaranteed byproducts of high-energy cosmic-rays



R. Abbasi et al. [IceCube Collaboration], arXiv:2011.03545

The CR/Gamma-ray/Neutrino Connection

Neutrinos and photons are guaranteed byproducts of high-energy cosmic-rays

Cosmic-ray interactions in the atmosphere

$p + X \rightarrow \pi^{\pm} / K^{\pm} + \pi^{0} + Y$ E < 100 TeV

atmospheric neutrinos

Cosmic-ray interactions at the source

pp or $p\gamma$ E > 100 TeV

astrophysical neutrinos

Cosmic-ray interactions off CMB photons

$p + \gamma_{CMB} \rightarrow \Delta \rightarrow n + \pi^{+}$

$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^{0}$

E > 100 PeV

cosmogenic neutrinos

Exotics

e.g., heavy dark matter

Neutrino Telescopes

IceCube

At the South Pole

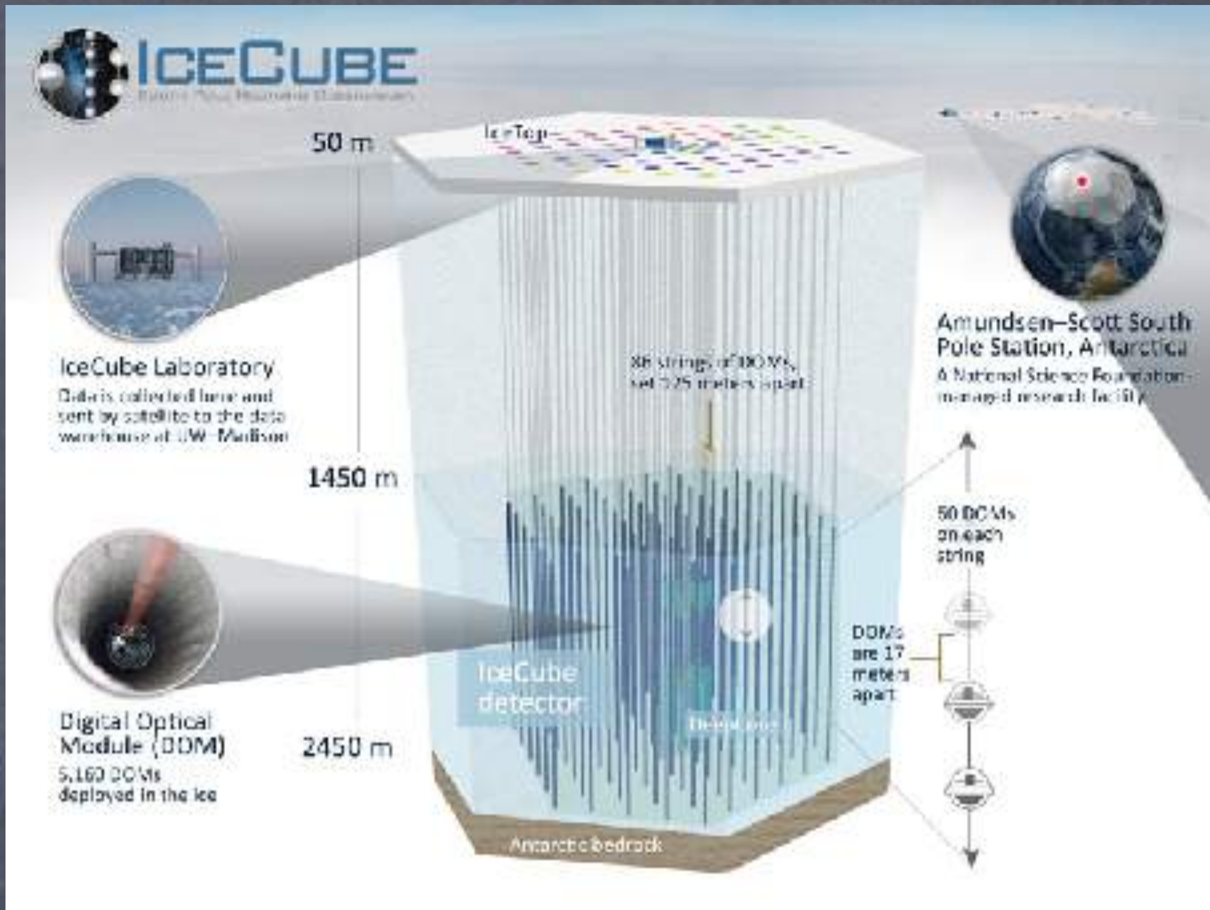
86 strings with 60 DOM/string 125 m apart

17 m vertical spacing between PMTs

8 DeepCore strings 75 m apart

81 IceTop stations: two tanks/station, two DOMs/tank

completed in 2011



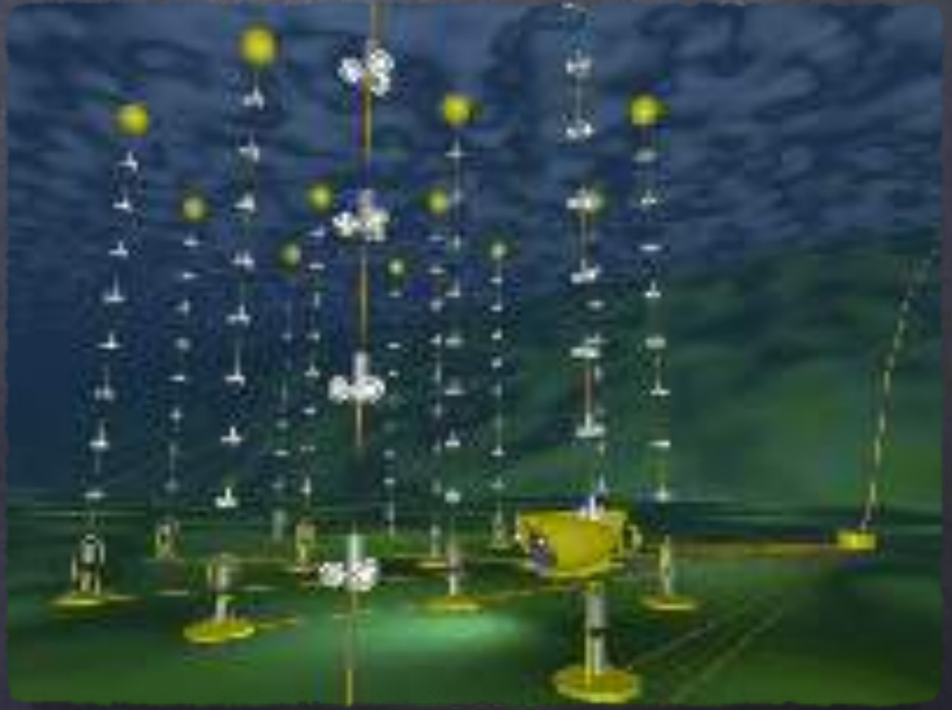
Antares

In the Mediterranean sea:
it sees the Galactic Center

about 1000 photomultiplier tubes in 12 vertical strings

area: about 0.1 km^2

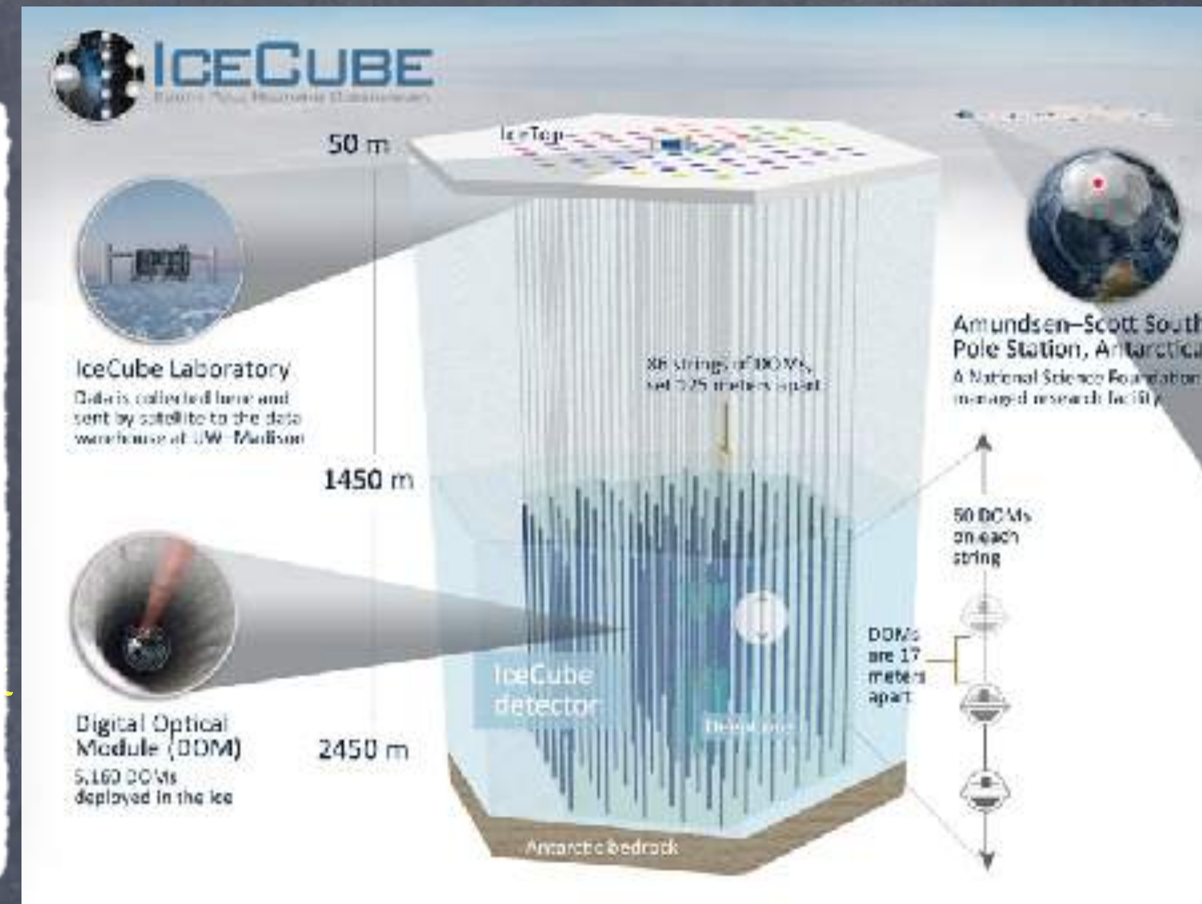
active height: about 350 m



Secondary particles detected via Čerencov radiation

Neutrino Telescopes

IceCube



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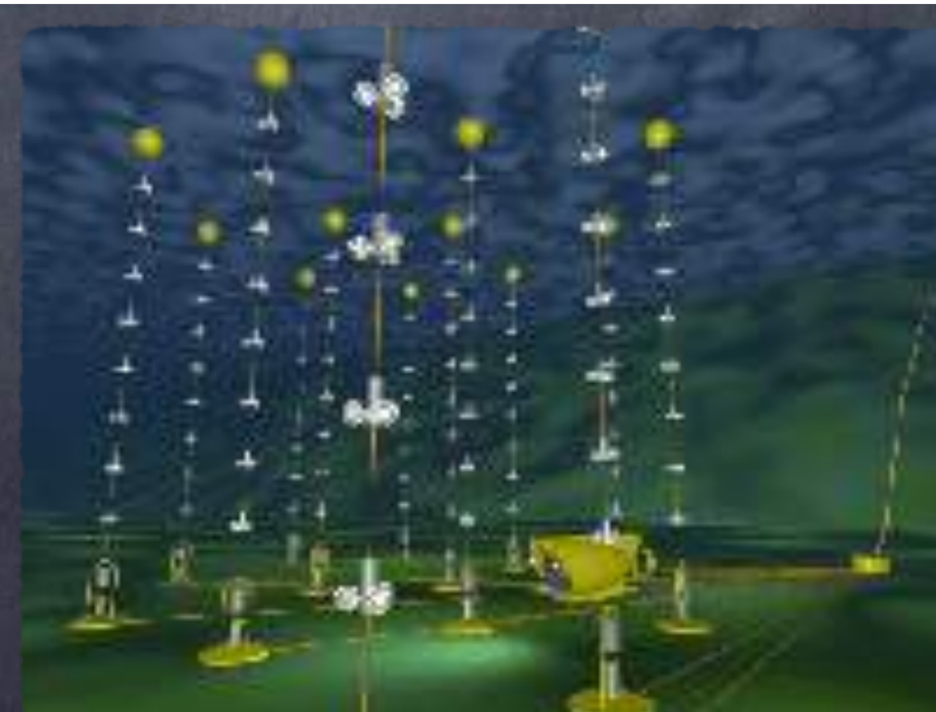
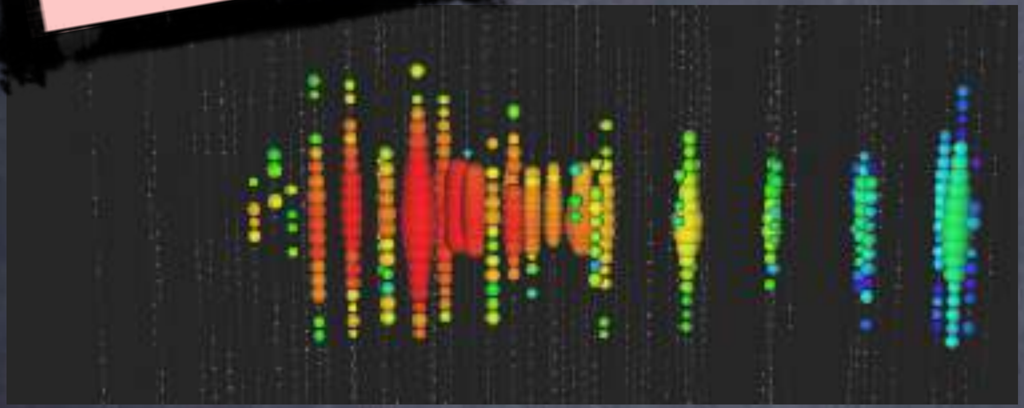


Secondary particles detected via Čerencov radiation

Type of events in IceCube

muon tracks

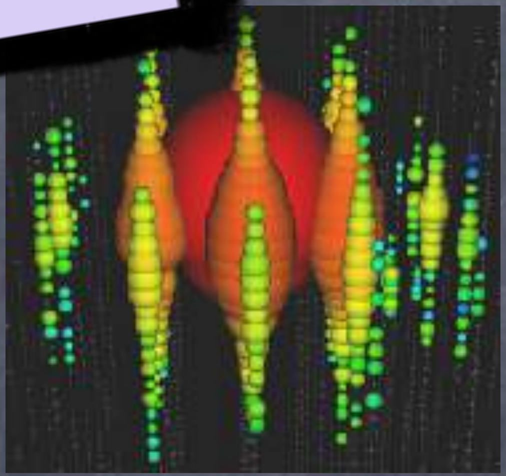


$$\nu_\mu + N \rightarrow \mu + X$$

$$\nu_\tau + N \rightarrow \tau + X \xrightarrow{18\%} \mu + \nu_\mu + \nu_\tau$$

~15% deposited energy resolution
(factor of ~2 in neutrino energy resolution)
~1° angular resolution

cascades



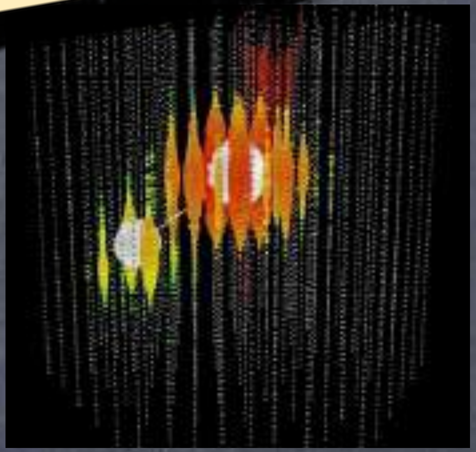
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

$$\nu_\tau + N \rightarrow \tau + X \xrightarrow{82\%} e + \nu_e + \nu_\tau, \quad \nu_\tau + X$$

~10% deposited energy resolution
~ 10° angular resolution

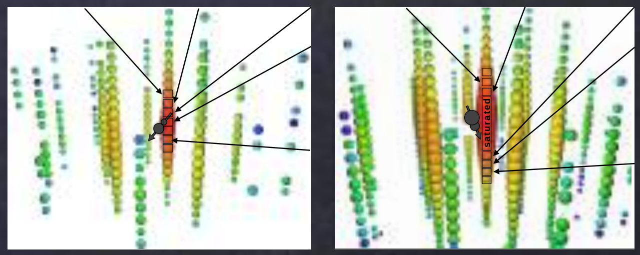
double cascades



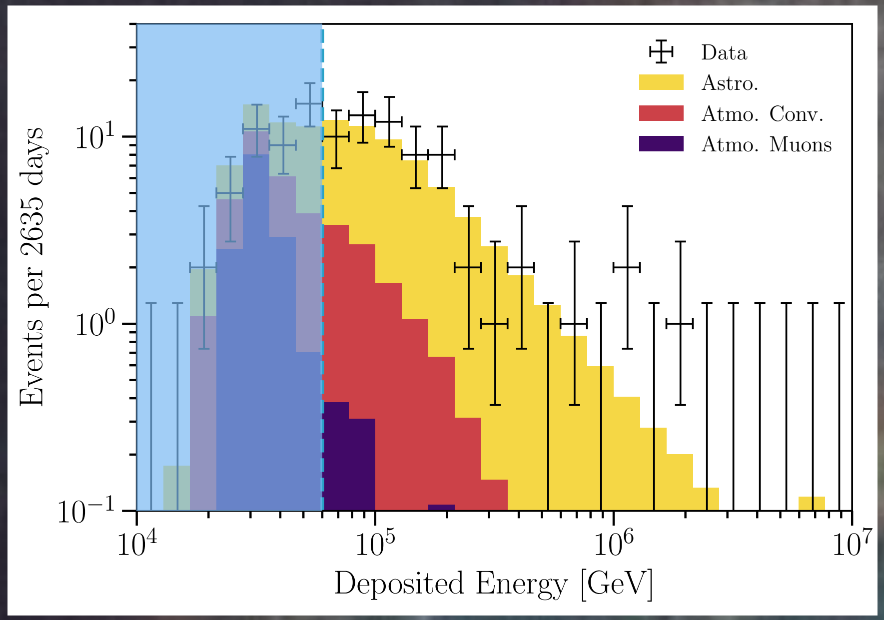
$$\nu_\tau + N \rightarrow \tau + X \xrightarrow{82\%} e + \nu_e + \nu_\tau, \quad \nu_\tau + X$$

Two candidates!

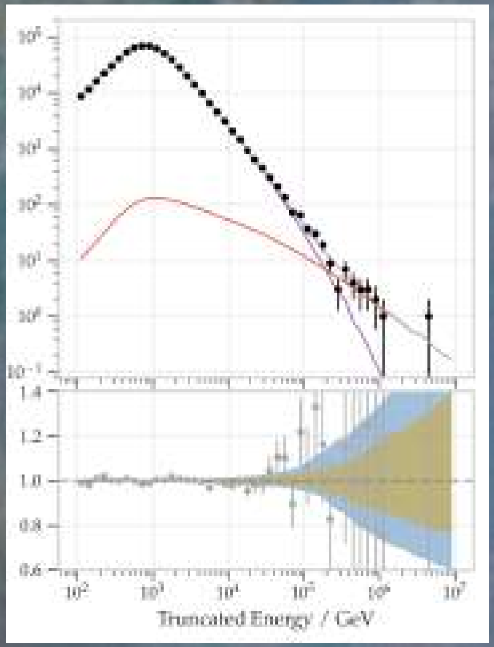
R. Abbasi et al. [IceCube Coll.], arXiv:2011.03561



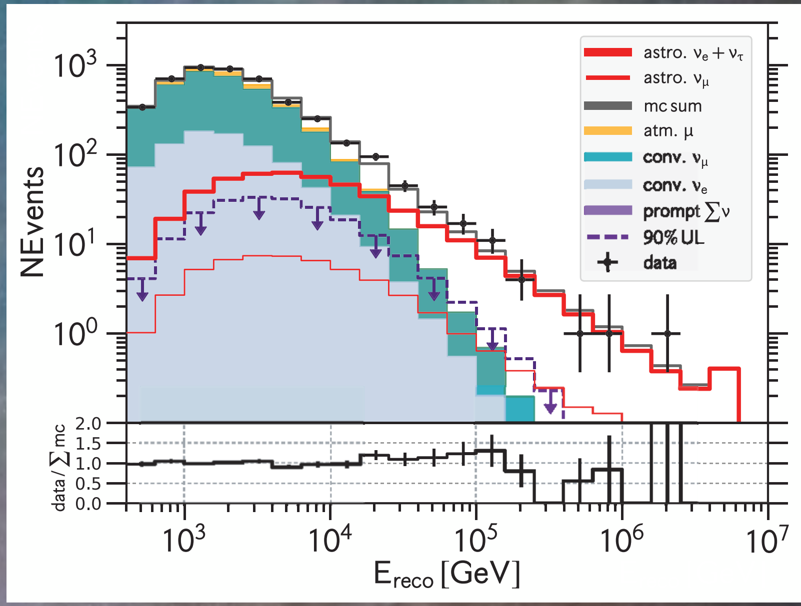
Two types of searches: contained events and through-going muons



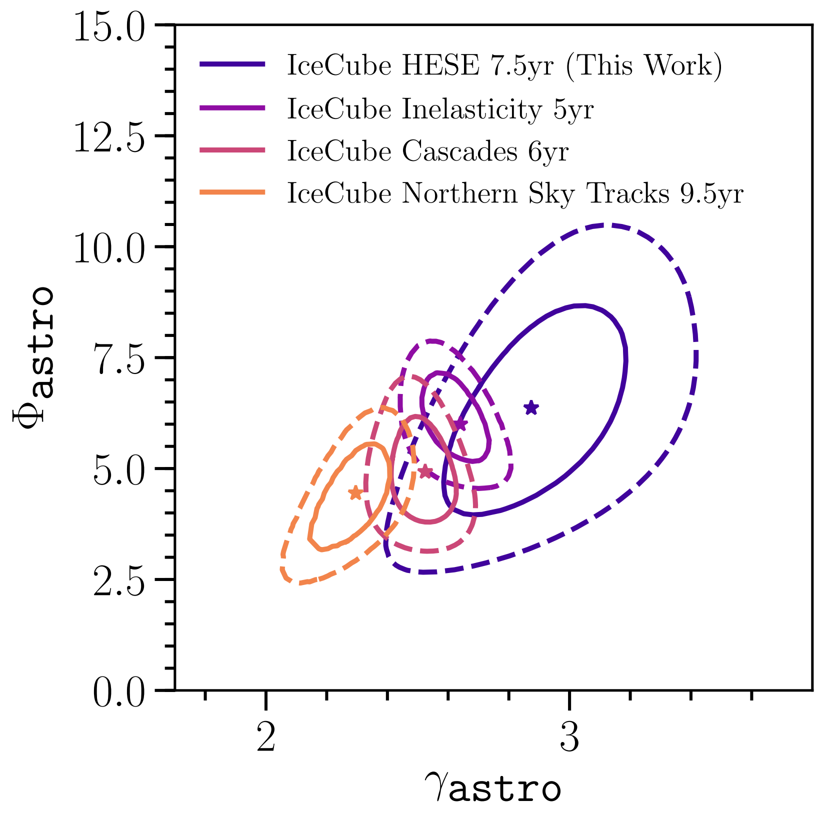
R. Abbasi et al. [IceCube Collaboration], arXiv:2011.03545



J. Stettner [IceCube Collaboration], PoS (ICRC2019) 1017



M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 125:121104, 2020



R. Abbasi et al. [IceCube Collaboration], arXiv:2011.03545

$$\frac{d\Phi}{dE_\nu} = \phi \left(\frac{E_\nu}{100\ \mathrm{TeV}} \right)^{-\gamma}$$

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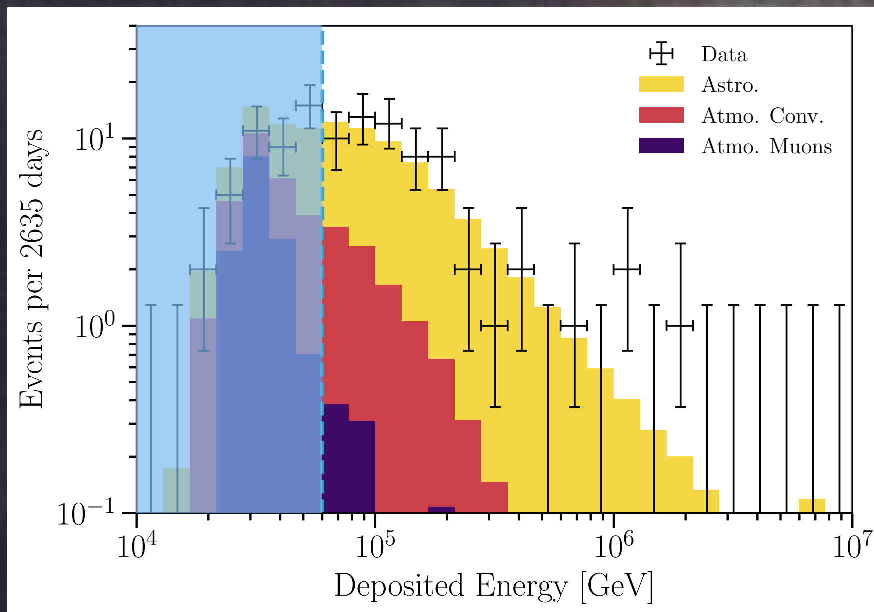
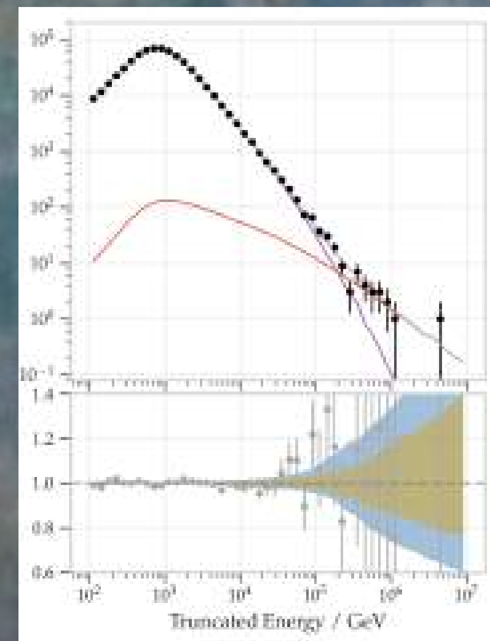
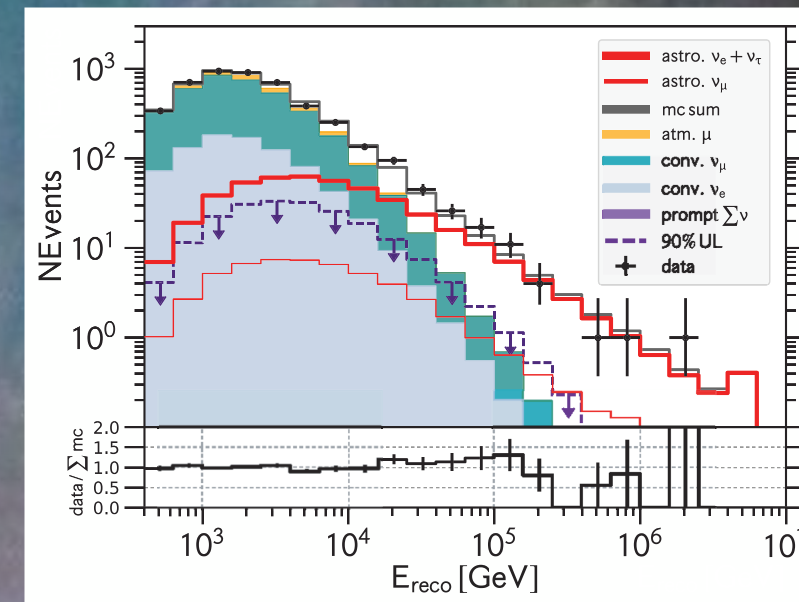


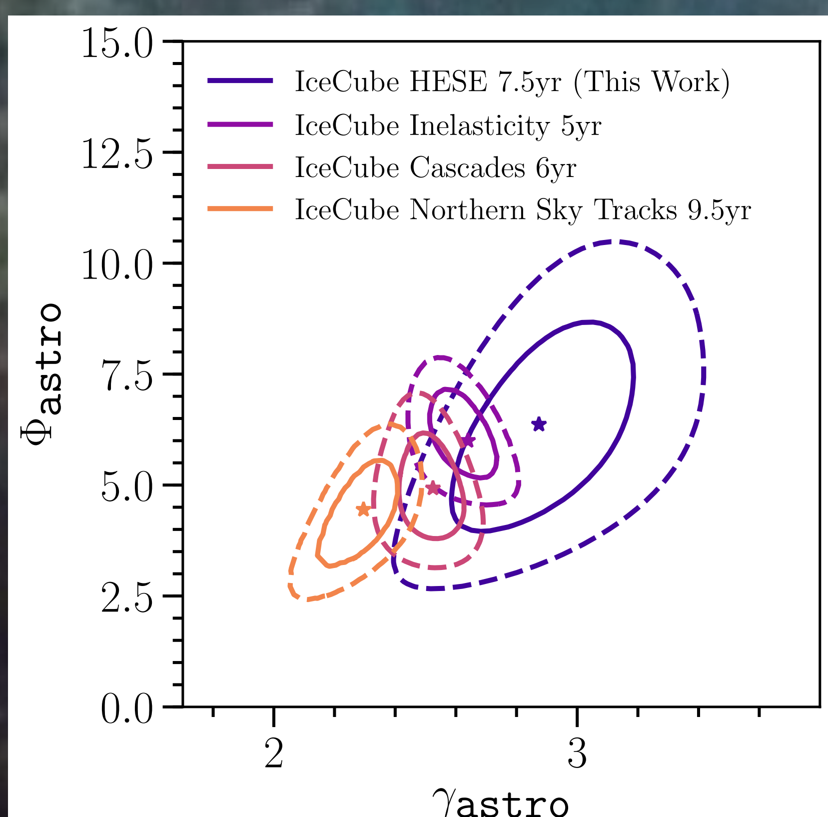
R. Abbasi et al. [IceCube Collaboration], arXiv:2011.03545



J. Stettner [IceCube Collaboration], PoS (ICRC2019) 1017



M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 125:121104, 2020

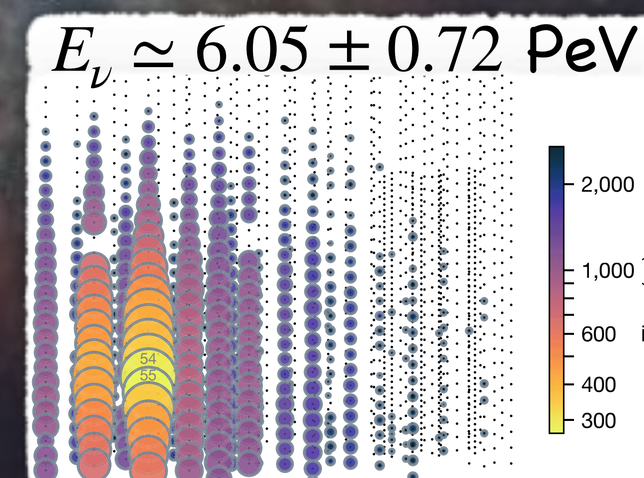


R. Abbasi et al. [IceCube Collaboration], arXiv:2011.03545

$$\frac{d\Phi}{dE_\nu} = \phi \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma}$$

but also partially contained events…

First Glashow resonance event!



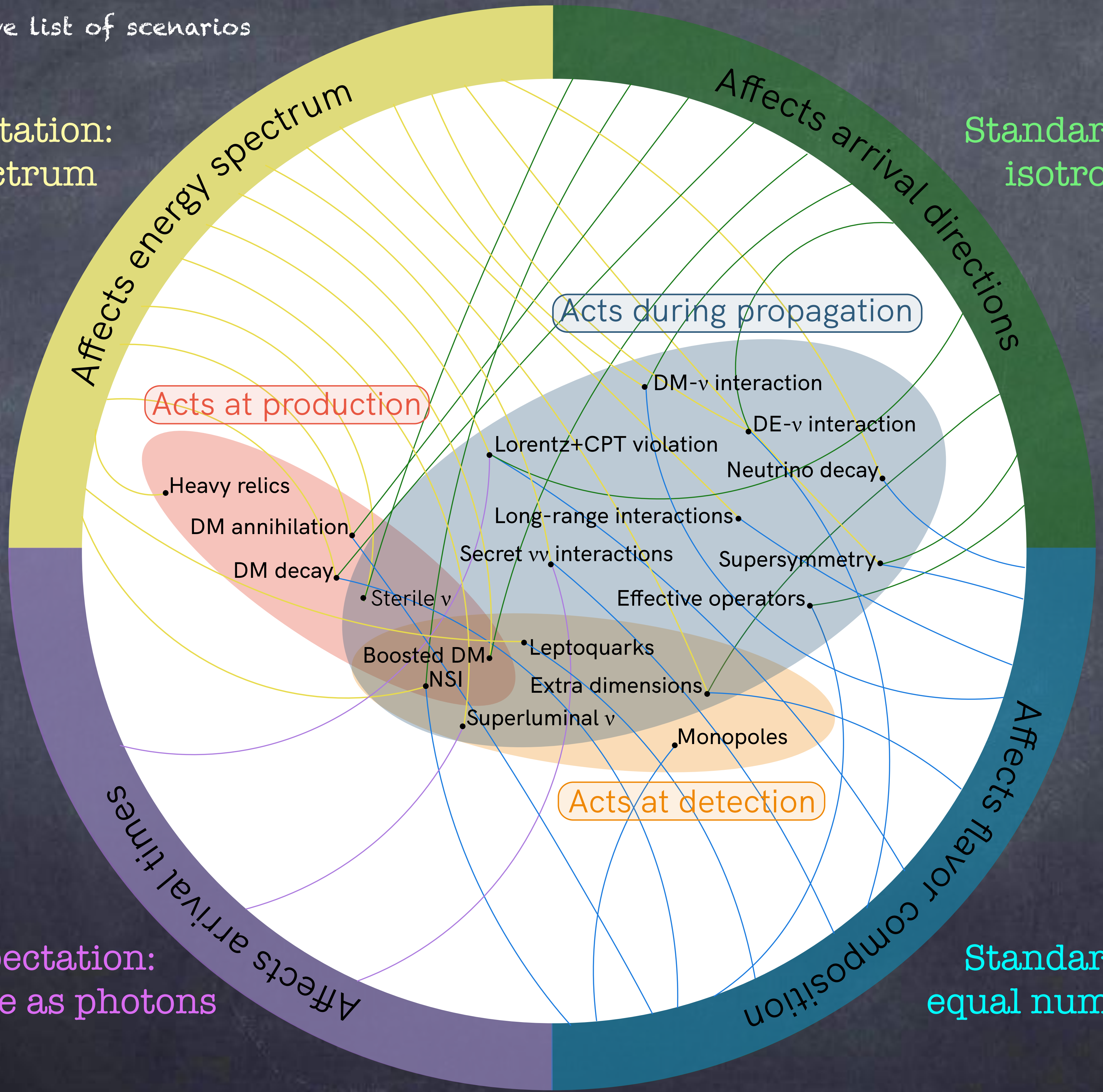
M. G. Aartsen et al. [IceCube Collaboration], Nature 591:220, 2021

Searching for new physics

Note: Not an exhaustive list of scenarios

Standard expectation: power-law spectrum

Standard expectation: isotropy (diffuse)



Standard expectation: same arrival time as photons

Standard expectation: equal number of all flavors

C. Argüelles, M. Bustamante, A. Kheirandish, SPR, J. Salvado and A. C. Vincent, PoS(ICRC2019)849, 2020

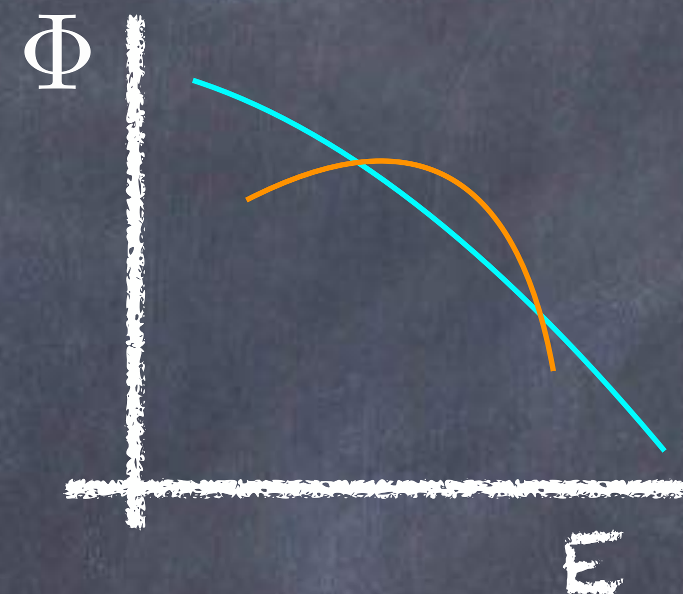
DM annihilations or decays

Annihilation of captured DM in the Sun/Earth

Sensitive to scattering cross section

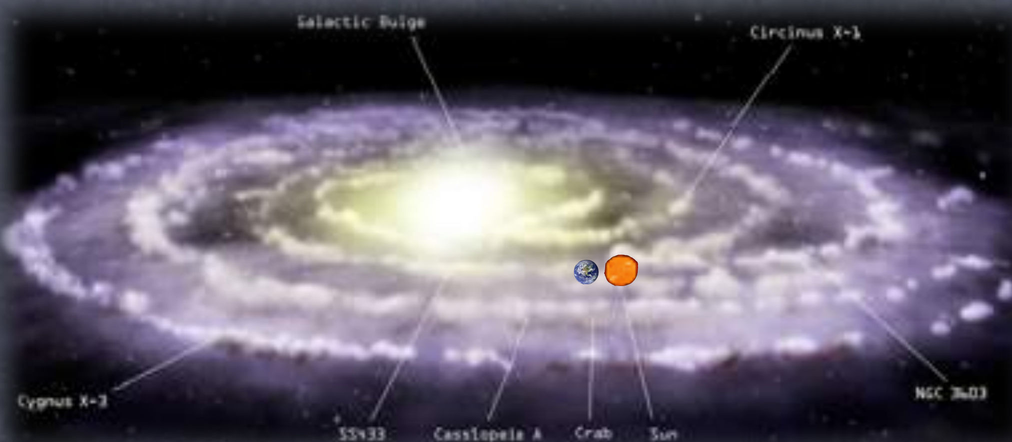
Only for m > few GeV

e.g., R. Garani and SPR, arXiv:2104.12757



Annihilations/decays in halos

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



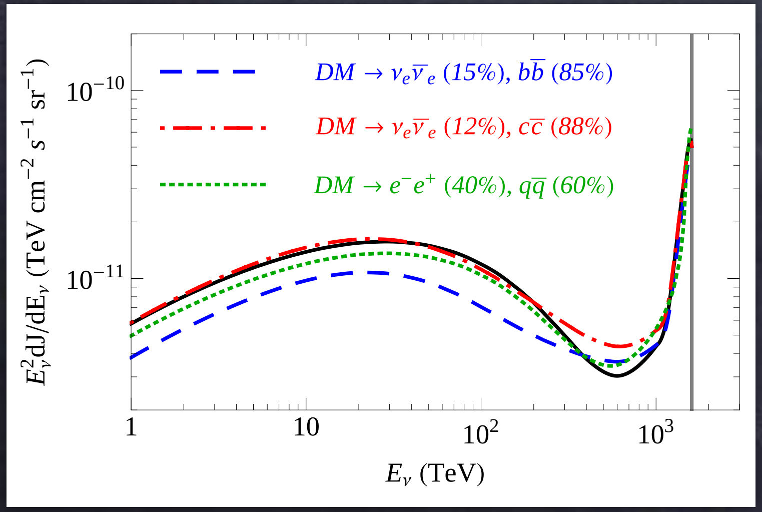
Dark matter decays

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

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

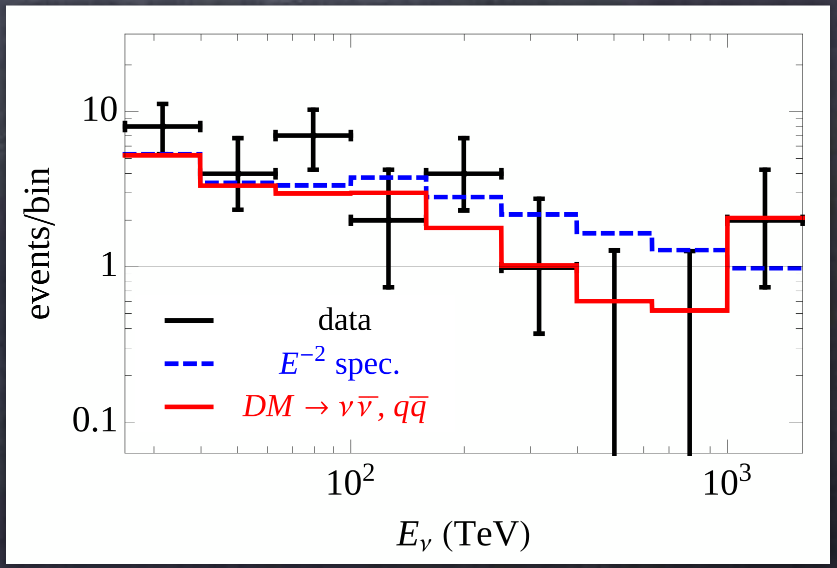
B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, Phys, Rev. D88:015004, 2013

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

Averaged oscillations

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

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

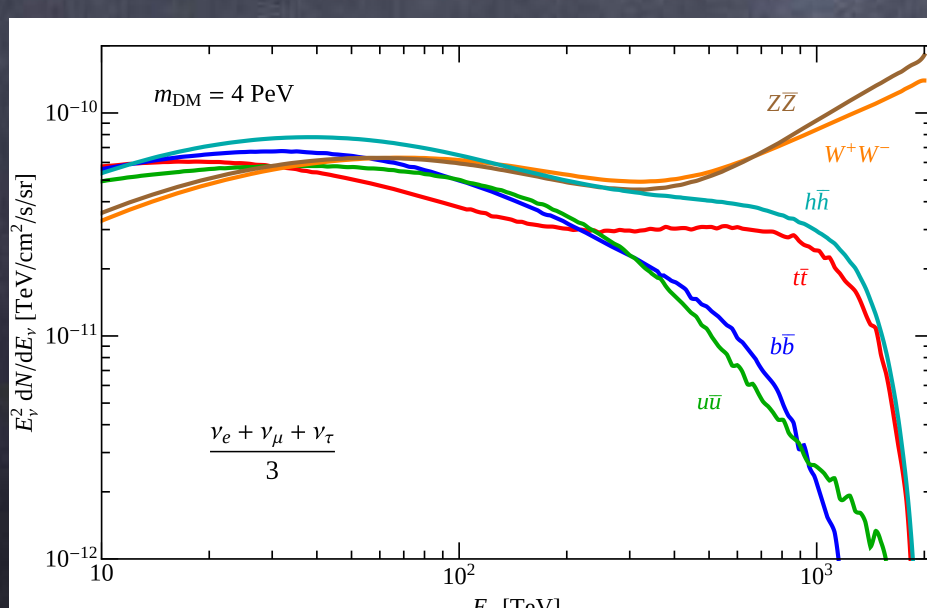
neutrino flux at production

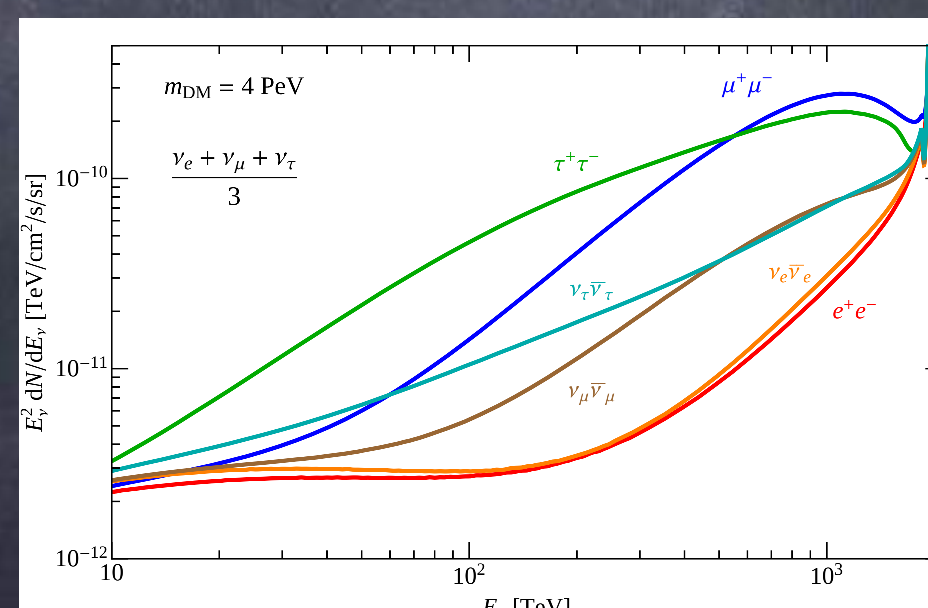
DM galactic density

DM density

Hubble function

energy redshift





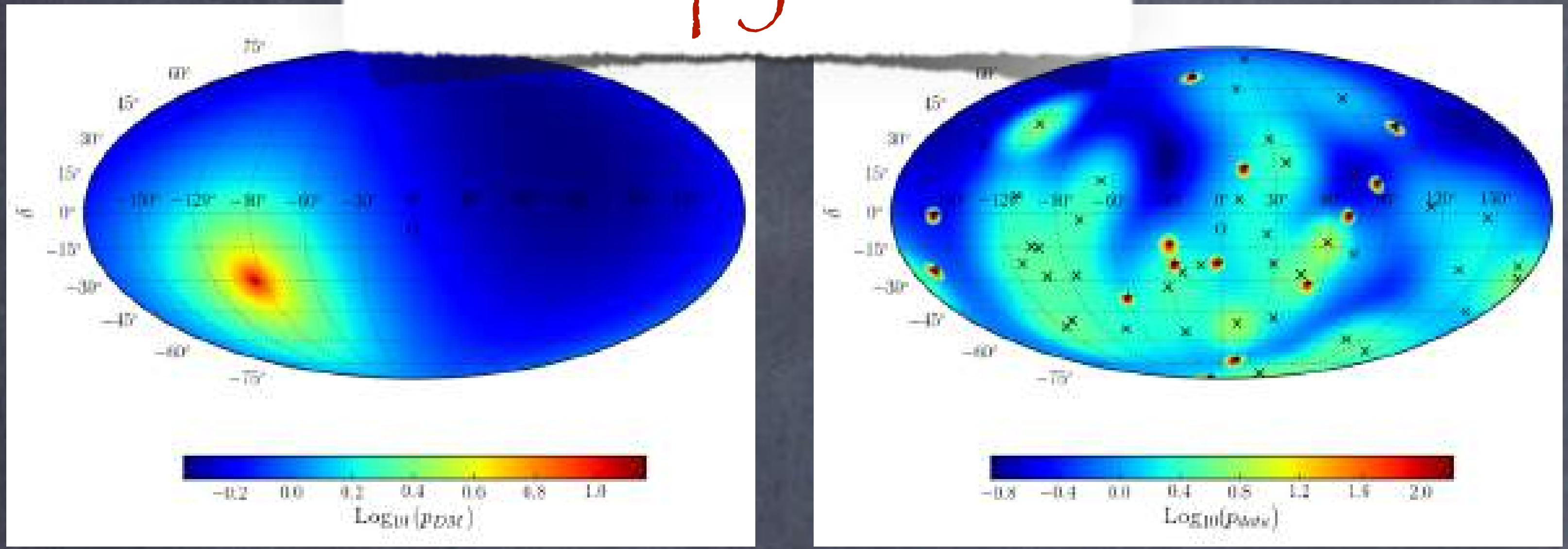
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 1707:027, 2017

Dark matter decays

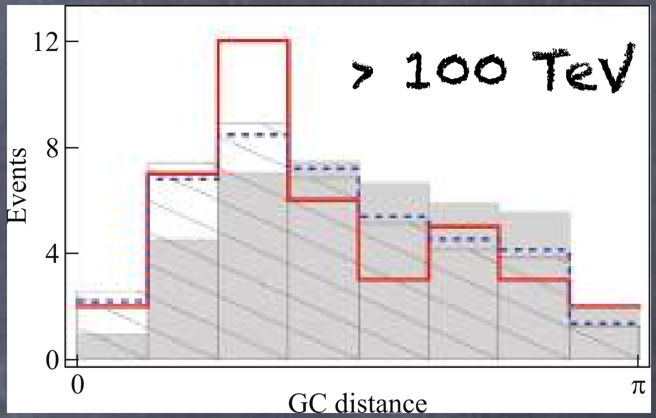
Are neutrinos from DM decays compatible with the angular distribution of the IceCube events?

is isotropy better?

is DM better?

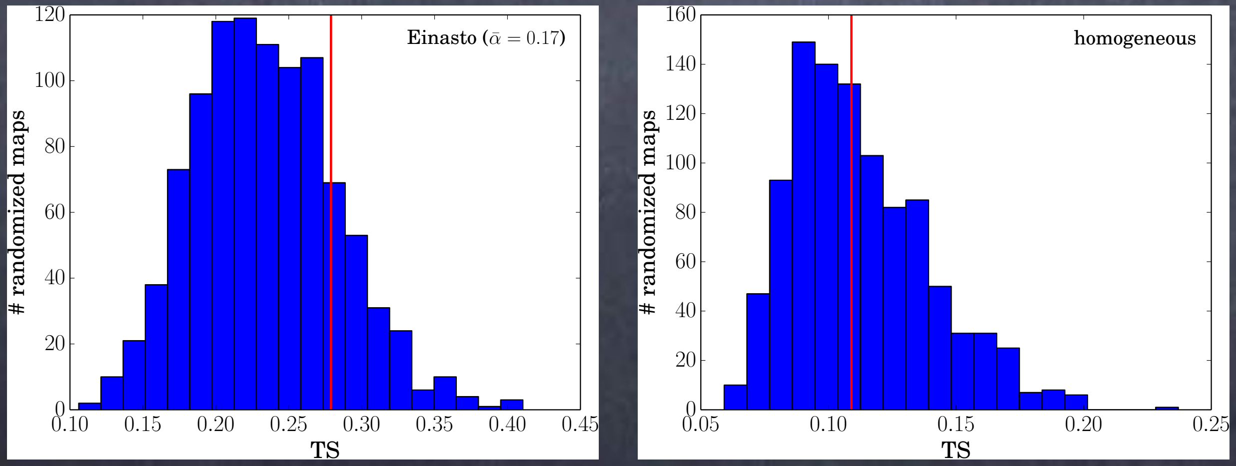


Y. Bai, R. Lu and J. Salvado, JHEP 1601:161, 2016



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

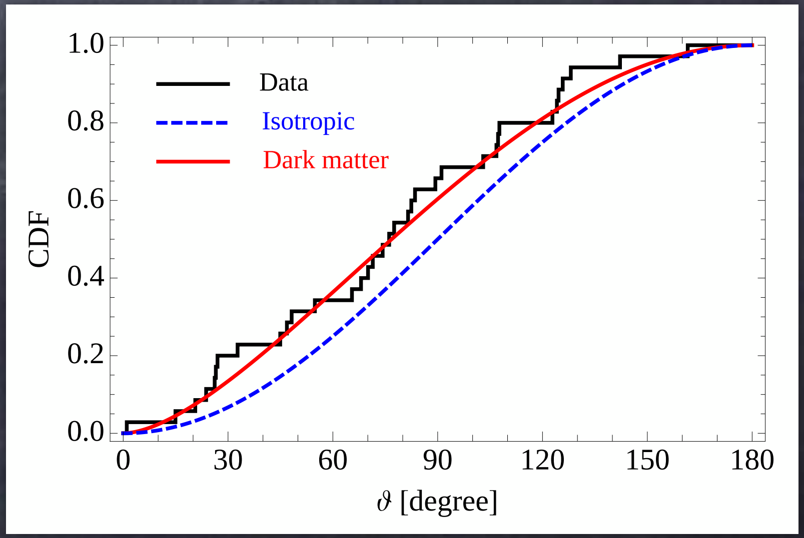
only galactic contribution



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



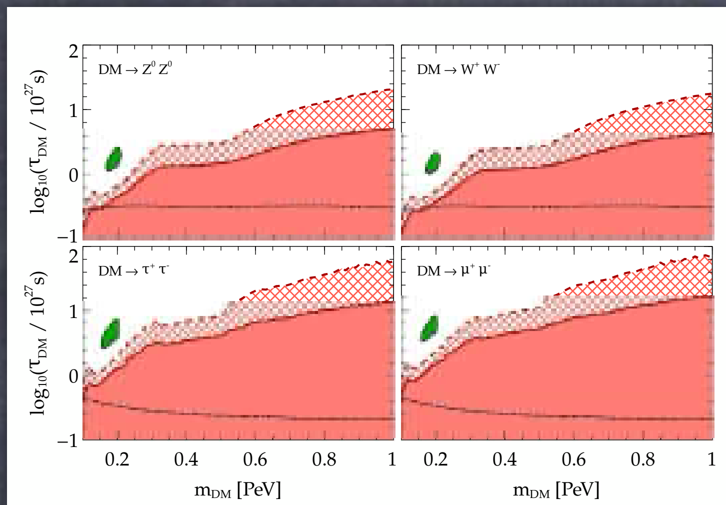
A. Esmaili, S. K. Kang and P. D. Serpico, JCAP 1412:054, 2014

Dark matter decays (+astro)

several energy spectrum analyses

$$\frac{d\Phi_\nu}{dE_\nu} = \phi_{astro}\left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-\gamma}$$

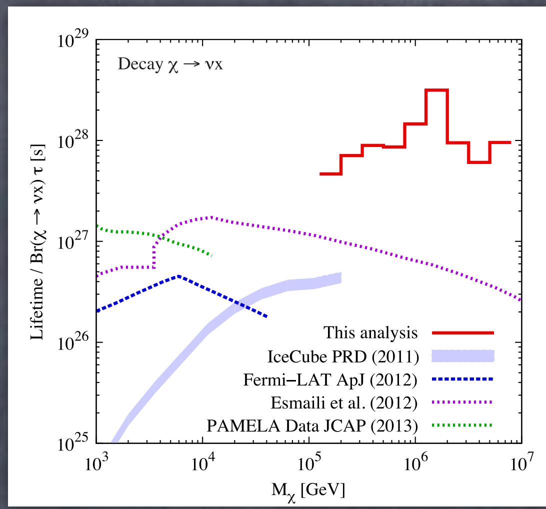
Low energies: DM+astro (index=2)



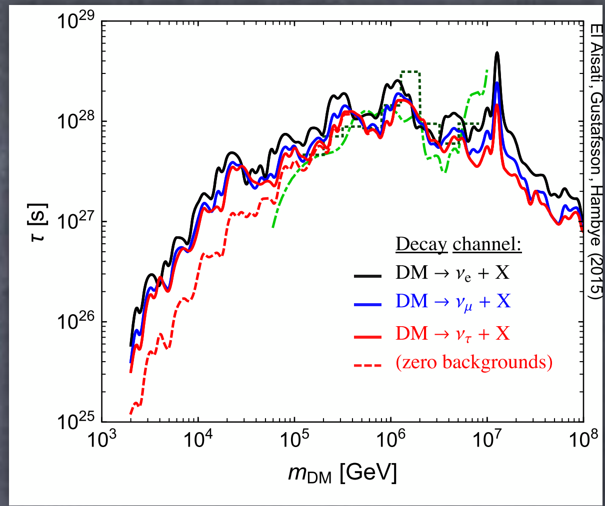
A. Bhattacharya, M. H. Reno and I. Sarcevic, JHEP 1406:110, 2014

See also: C. S. Fong et al., JHEP 1502:189, 2015

limits on monochromatic decays

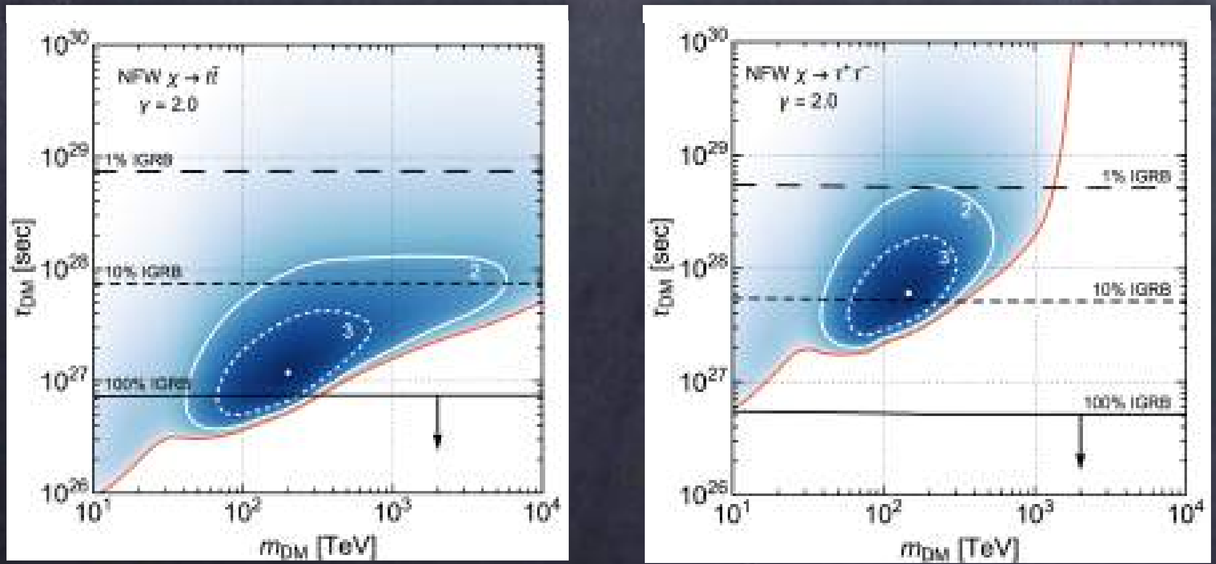


C. Rott, K. Kohri and S. C. Park, Phys. Rev. D92:023529, 2015



C. El Aisati, M. Gustafsson and T. Hambye, Phys. Rev. D92:123515, 2015

Low energies (MESE), fixing astro index



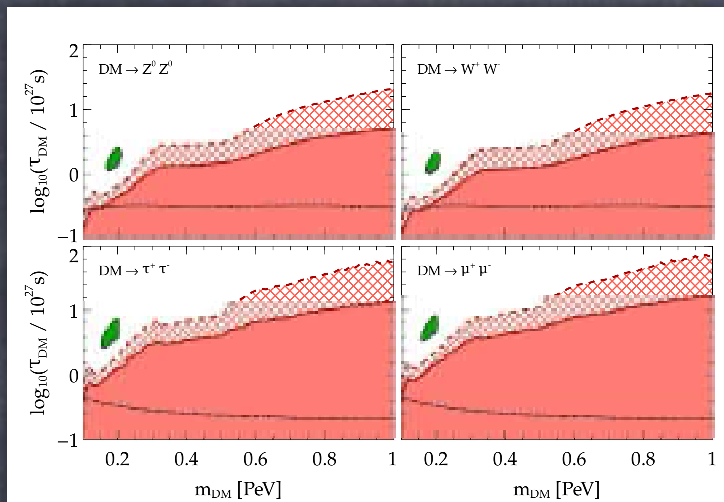
M. Chianese, G. Miele and S. Morisi, JCAP 1701:007, 2017

Dark matter decays (+astro)

several energy spectrum analyses

$$\frac{d\Phi_\nu}{dE_\nu} = \phi_{astro}\left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma}$$

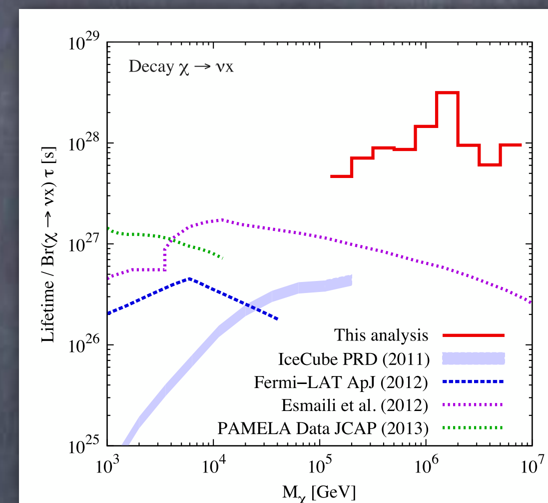
Low energies: DM+astro (index=2)



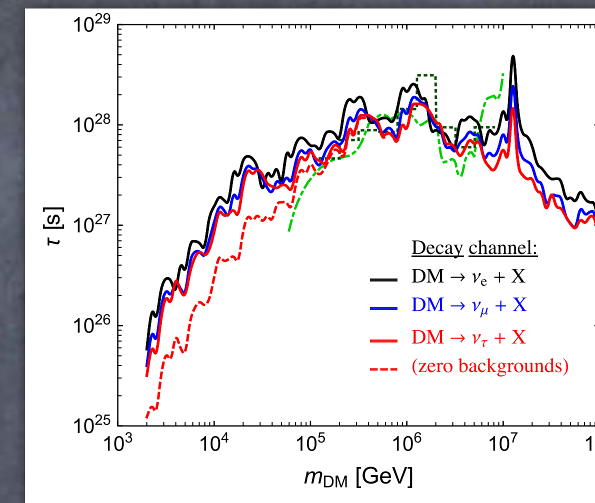
A. Bhattacharya, M. H. Reno and I. Sarcevic, JHEP 1406:110, 2014

See also: C. S. Fong et al., JHEP 1502:189, 2015

limits on monochromatic decays

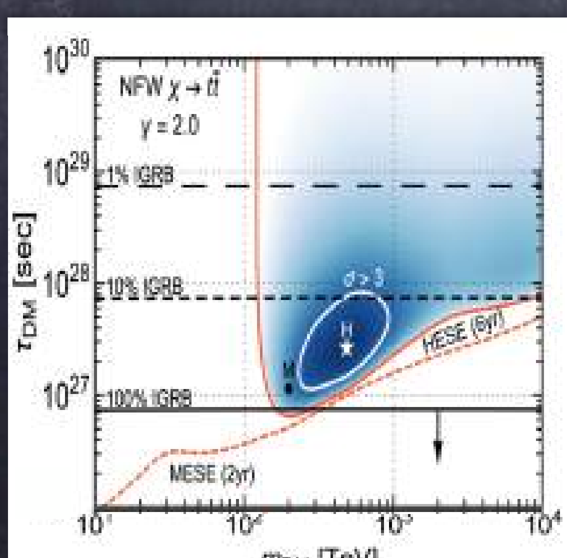


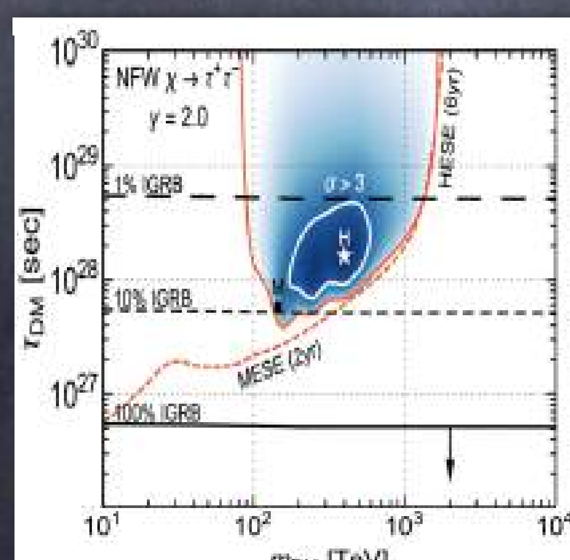
C. Rott, K. Kohri and S. C. Park, Phys. Rev. D92:023529, 2015



C. El Aisati, M. Gustafsson and T. Hambye, Phys. Rev. D92:123515, 2015

HESE 6-yr, fixing astro index





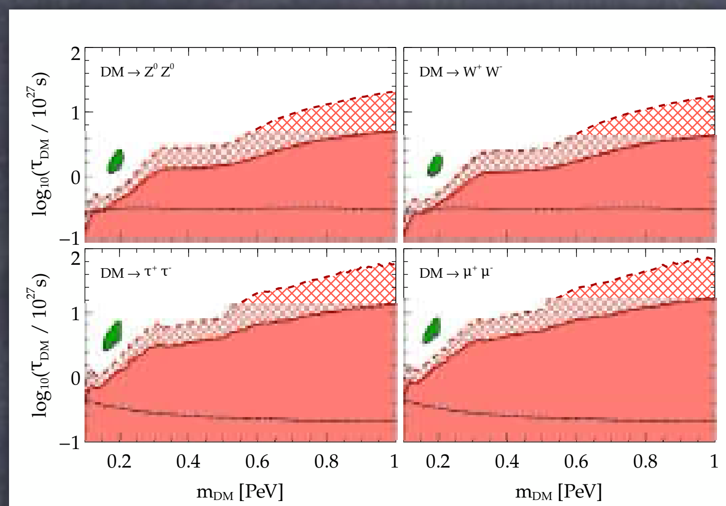
M. Chianese, G. Miele and S. Morisi, Phys. Lett. B773:591, 2017

Dark matter decays (+astro)

several energy spectrum analyses

$$\frac{d\Phi_\nu}{dE_\nu} = \phi_{astro}\left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma}$$

Low energies: DM+astro (index=2)



A. Bhattacharya, M. H. Reno and I. Sarcevic, JHEP 1406:110, 2014

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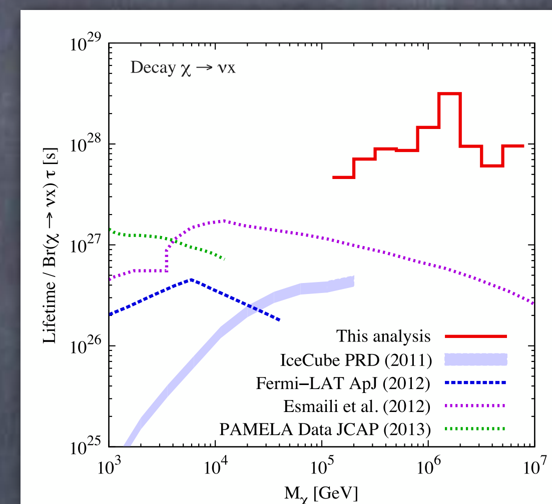
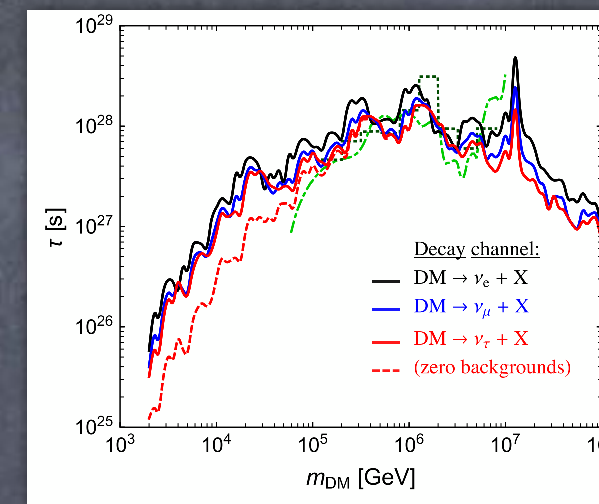
limits on monochromatic decays

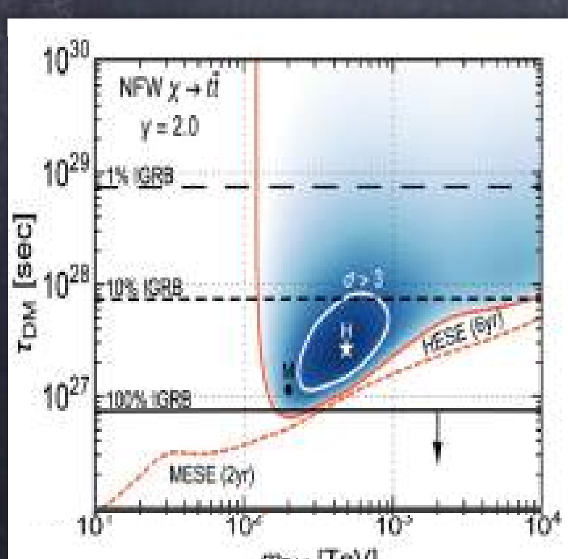


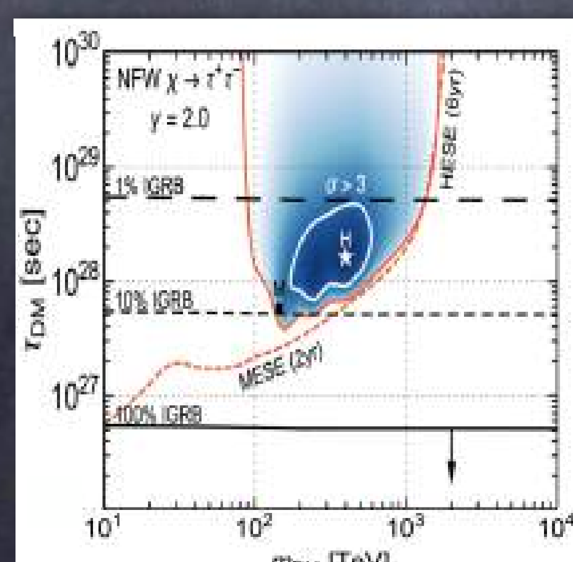
C. Rott, K. Kohri and S. C. Park, Phys. Rev. D92:023529, 2015



C. El Aisati, M. Gustafsson and T. Hambye, Phys. Rev. D92:123515, 2015

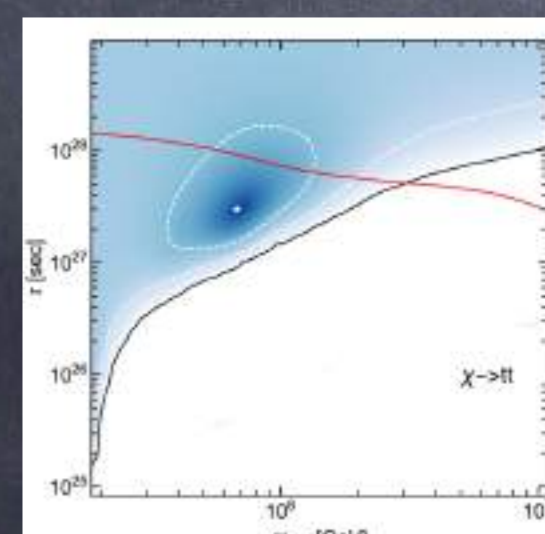
HESE 6-yr, fixing astro index

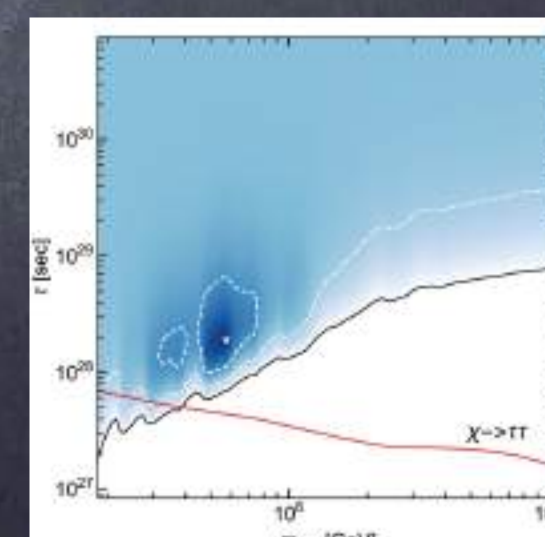




M. Chianese, G. Miele and S. Morisi, Phys. Lett. B773:591, 2017

HESE 7.5-yr, adding TG priors

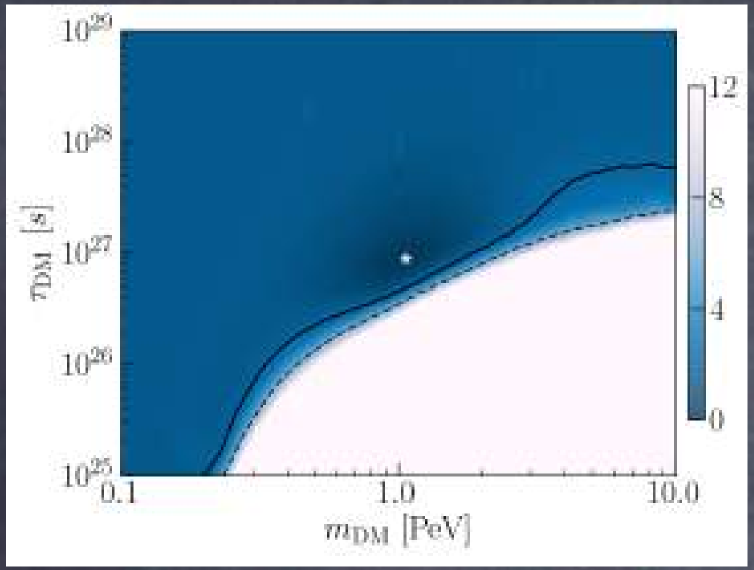




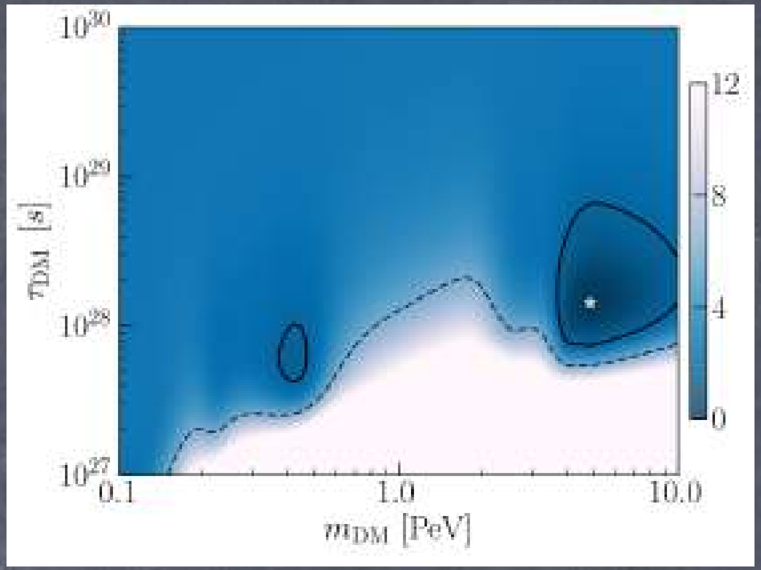
M. Chianese et al., JCAP 11:046, 2019

See also: Y. Sui and P. B. Dev, JCAP 07:020, 2018

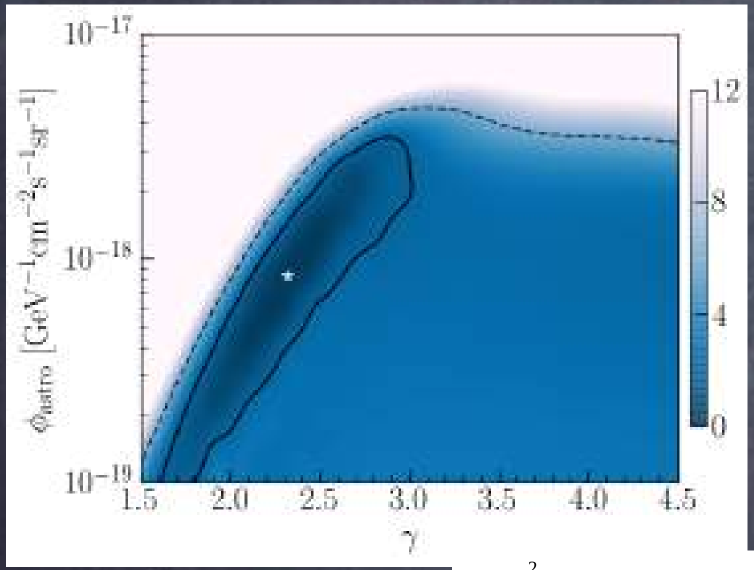
DM decays + Astro: 4-yr HESE analysis



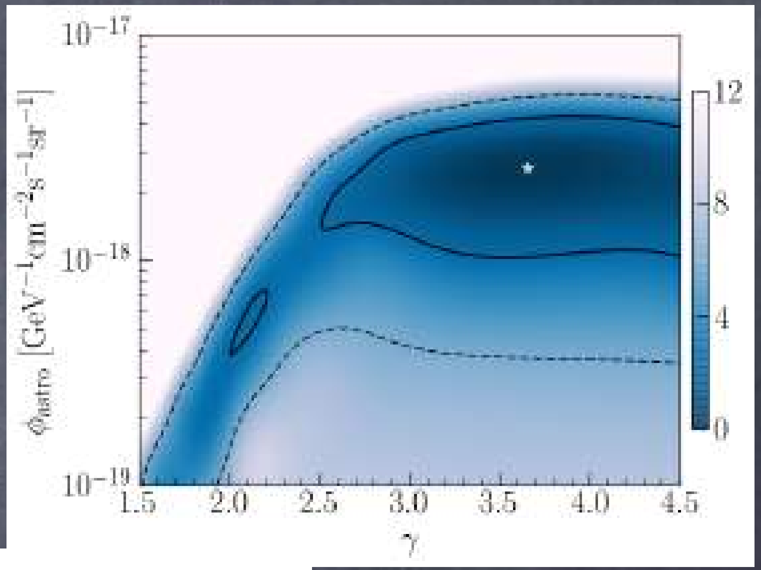
short lifetimes ✗
(problem with gamma-rays)



longer lifetimes ✓

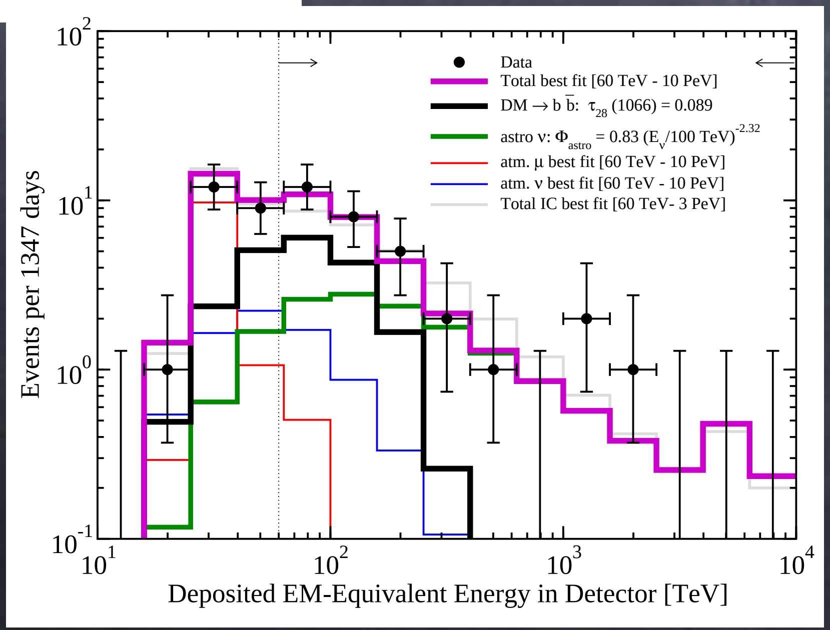


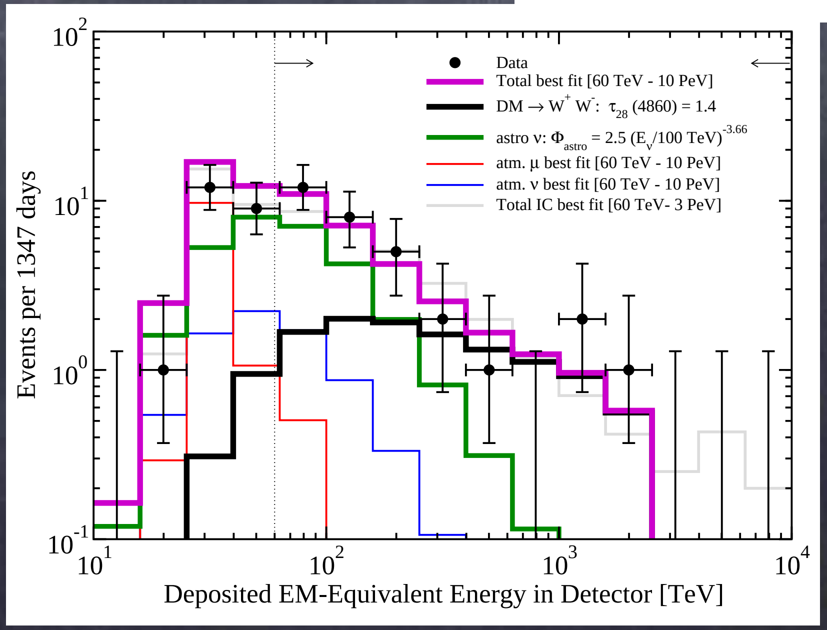
relatively hard astro spectrum ✓



very soft astro spectrum ✗

$DM \to b\bar{b}$

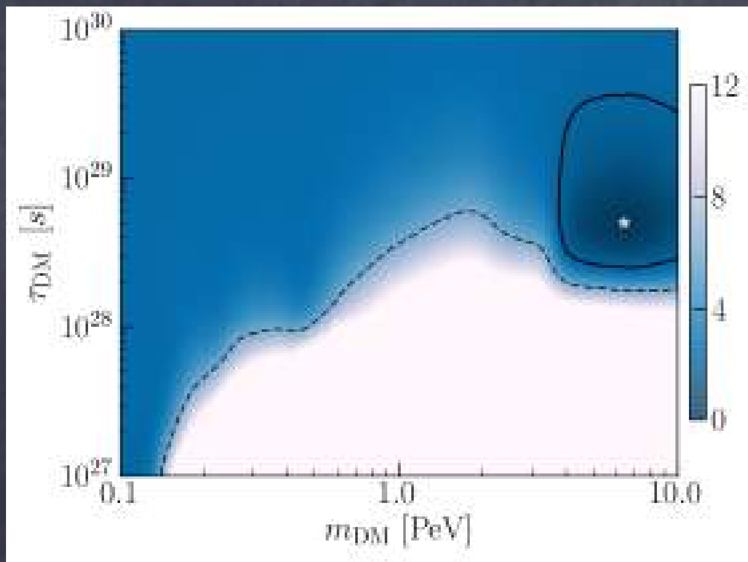




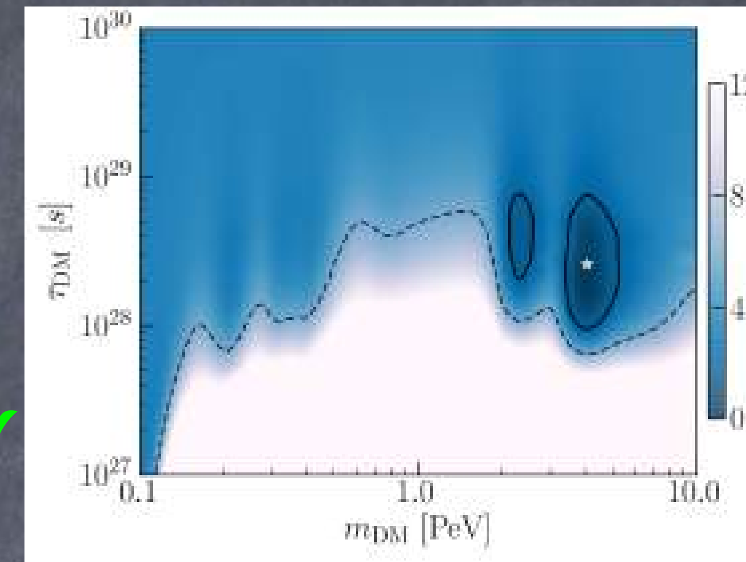
$DM \to W^+W^-$

A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 07:027, 2017

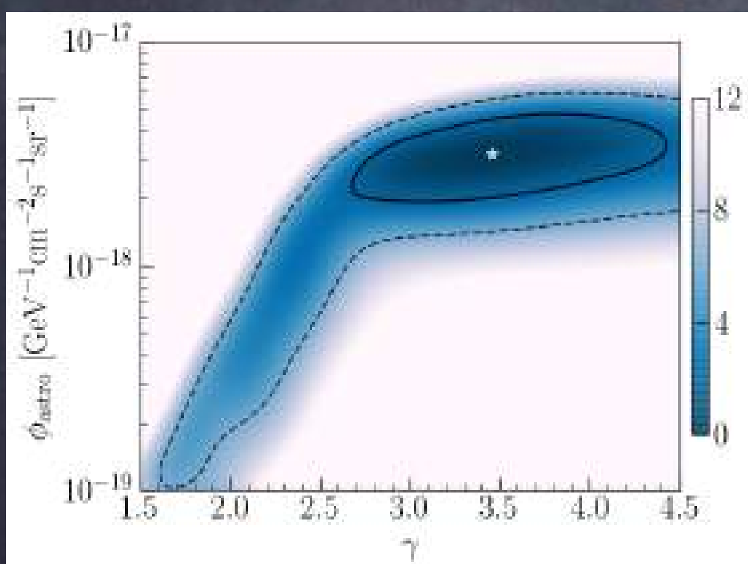
DM decays + Astro: 4-yr HESE analysis



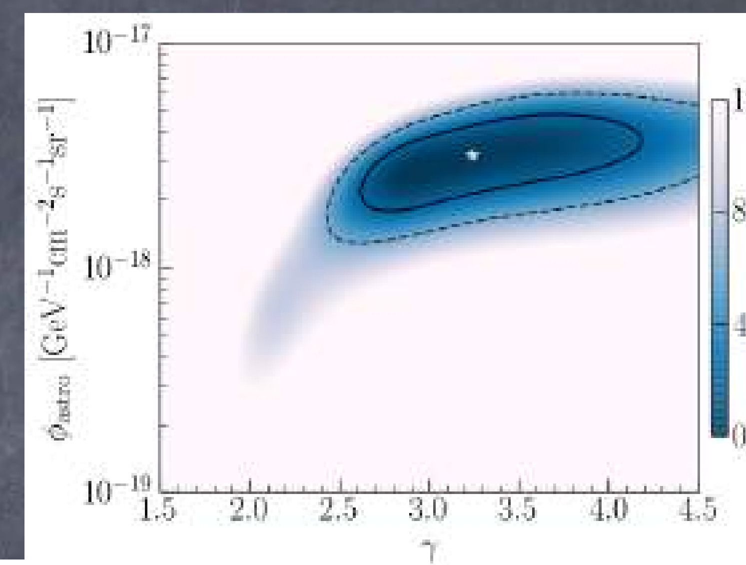
long lifetimes ✓



long lifetimes ✓

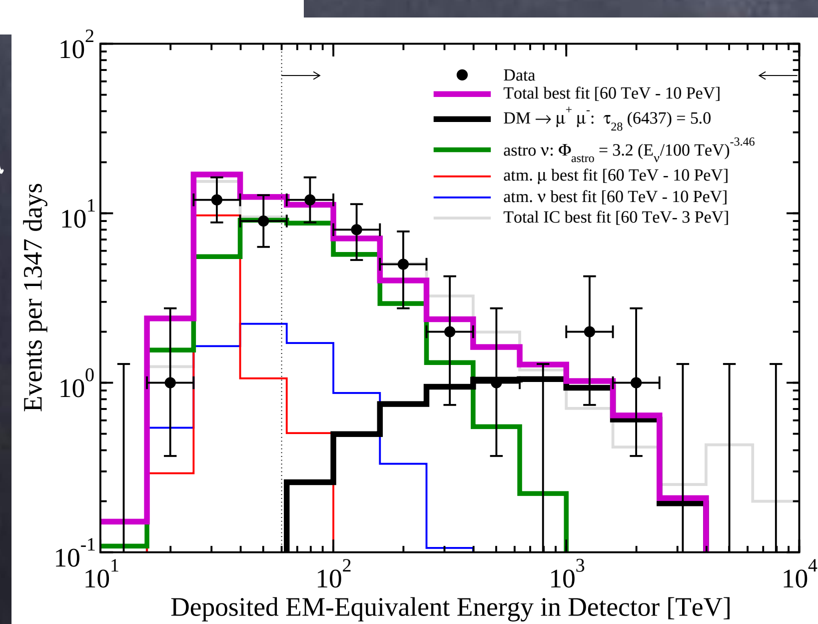


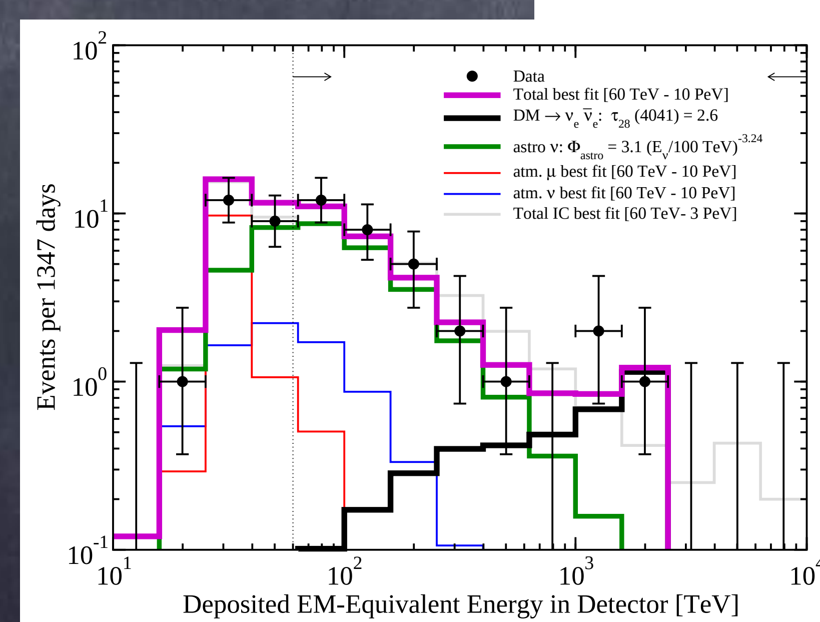
very soft astro spectrum ✗



very soft astro spectrum ✗

$DM \to \mu^+\mu^-$



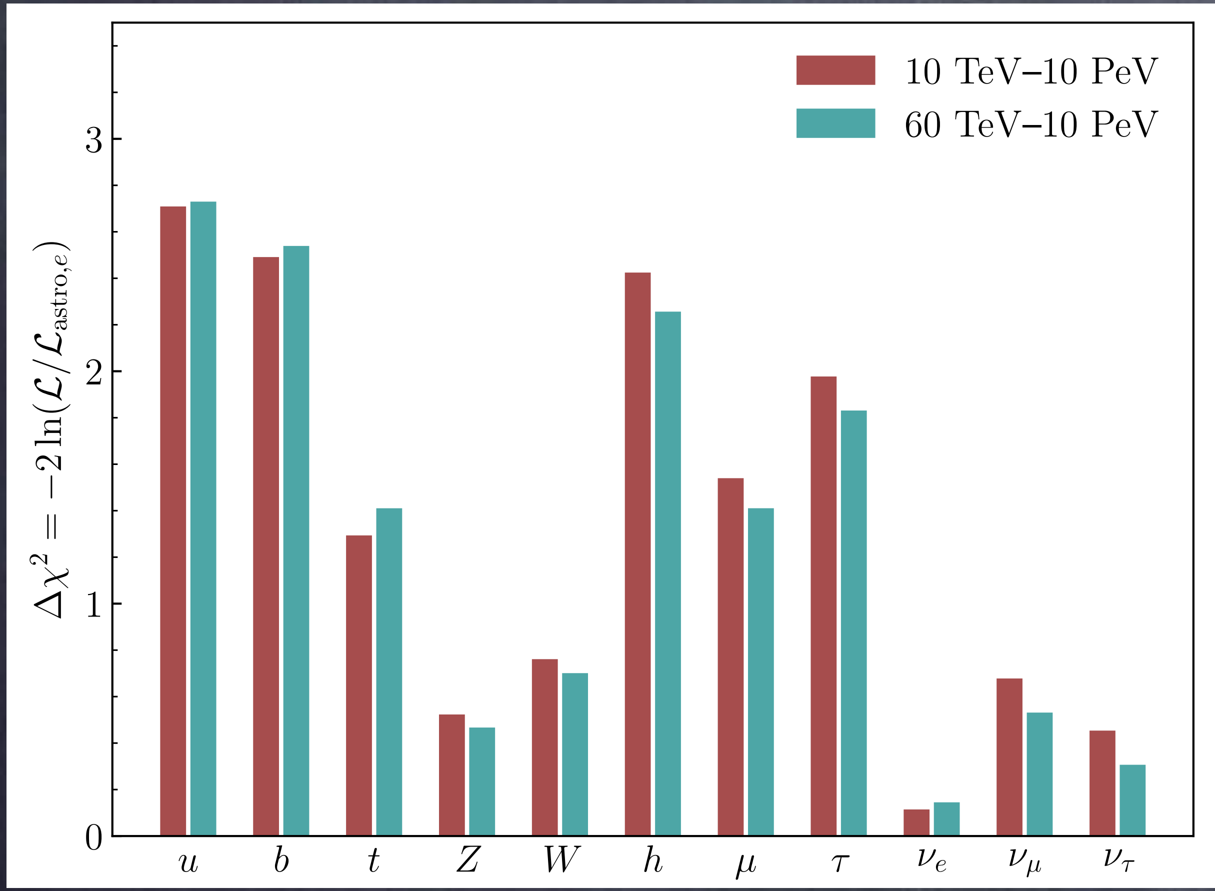


$DM \to \nu_e\bar{\nu}_e$

A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 07:027, 2017

DM decays + Astro: 4-yr HESE analysis

Best fit: Astro (soft) + DM → e^+e^-



Decay channel	$N_{\rm DM}(\tau_{\rm DM}[10^{28}\,{\rm s}])$	$m_{\rm DM}$ [TeV]	$N_{\rm astro}(\phi_{\rm astro})$	γ
$u\,\bar{u}$	10.2 (0.021)	522	16.6 (1.2)	2.42
$b\,\bar{b}$	12.9 (0.089)	1066	13.8 (0.83)	2.32
$t\,\bar{t}$	16.1 (0.58)	11134	10.7 (1.9)	3.91
$W^+\,W^-$	11.3 (1.4)	4860	15.5 (2.5)	3.66
$Z\,Z$	10.5 (1.6)	4800	16.3 (2.6)	3.61
$h\,h$	13.6 (0.17)	606	13.2 (0.76)	2.29
$e^+\,e^-$	5.0 (1.2)	4116	21.9 (3.2)	3.33
$\mu^+\,\mu^-$	6.3 (5.0)	6437	20.7 (3.2)	3.46
$\tau^+\,\tau^-$	7.6 (4.4)	6749	19.3 (3.0)	3.53
$\nu_e\,\bar{\nu}_e$	3.7 (2.6)	4041	22.7 (3.2)	3.24
$\nu_\mu\,\bar{\nu}_\mu$	6.4 (2.4)	4133	20.6 (3.2)	3.48
$\nu_\tau\,\bar{\nu}_\tau$	6.7 (2.3)	4117	20.1 (3.1)	3.50

A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 07:027, 2017

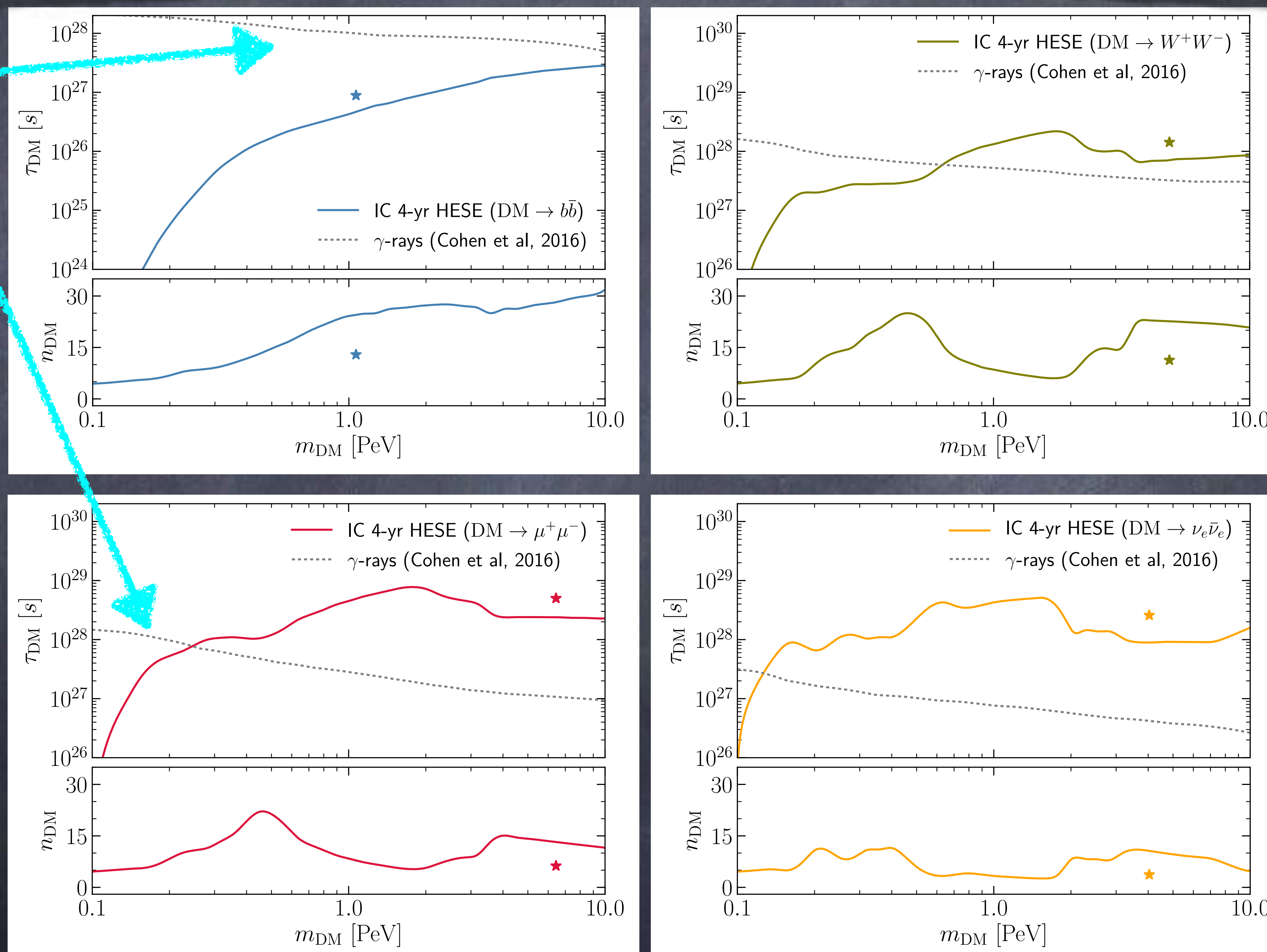
DM decays + Astro: 4-yr HESE analysis

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

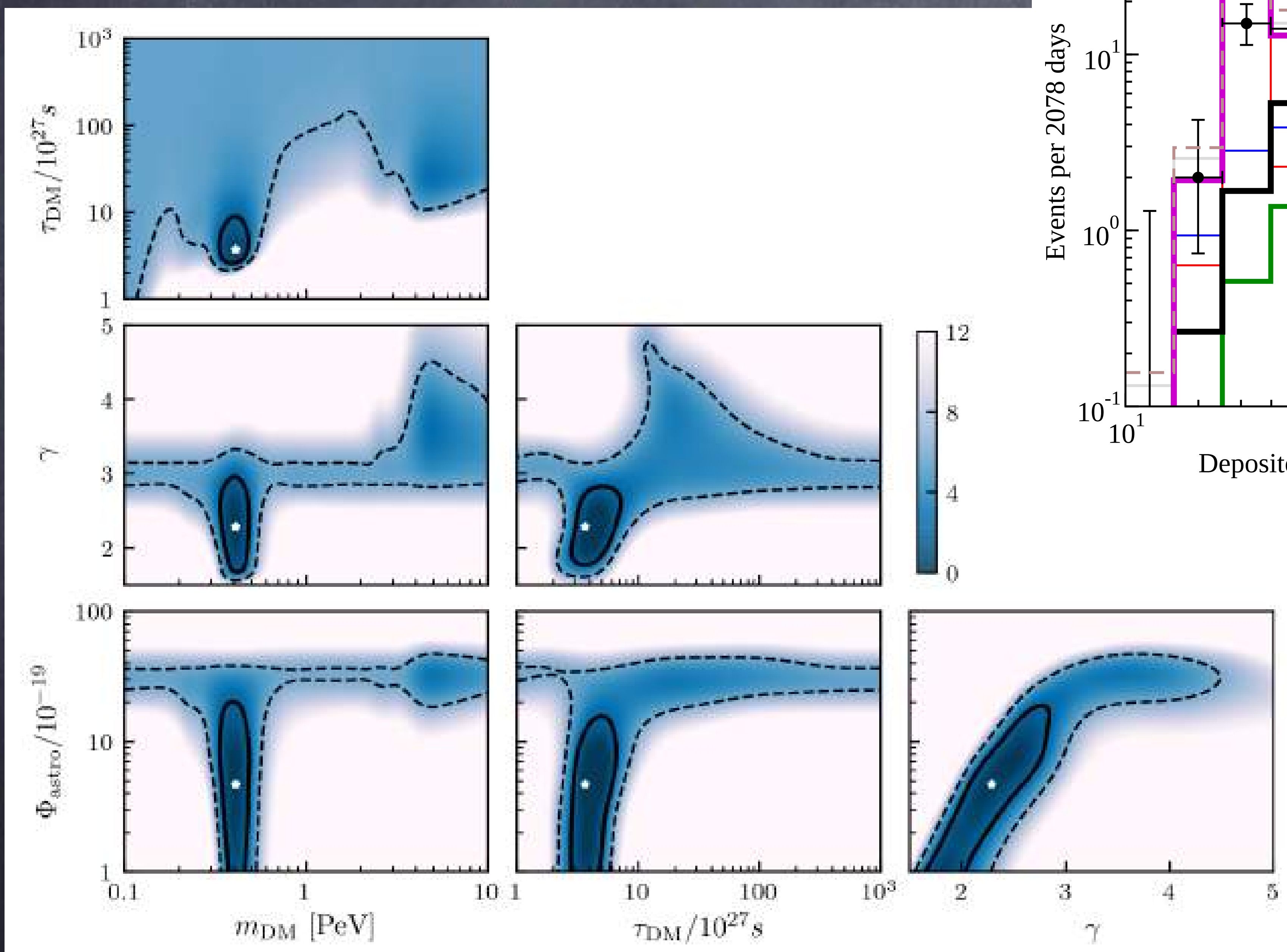
GAMMA-RAY LIMITS

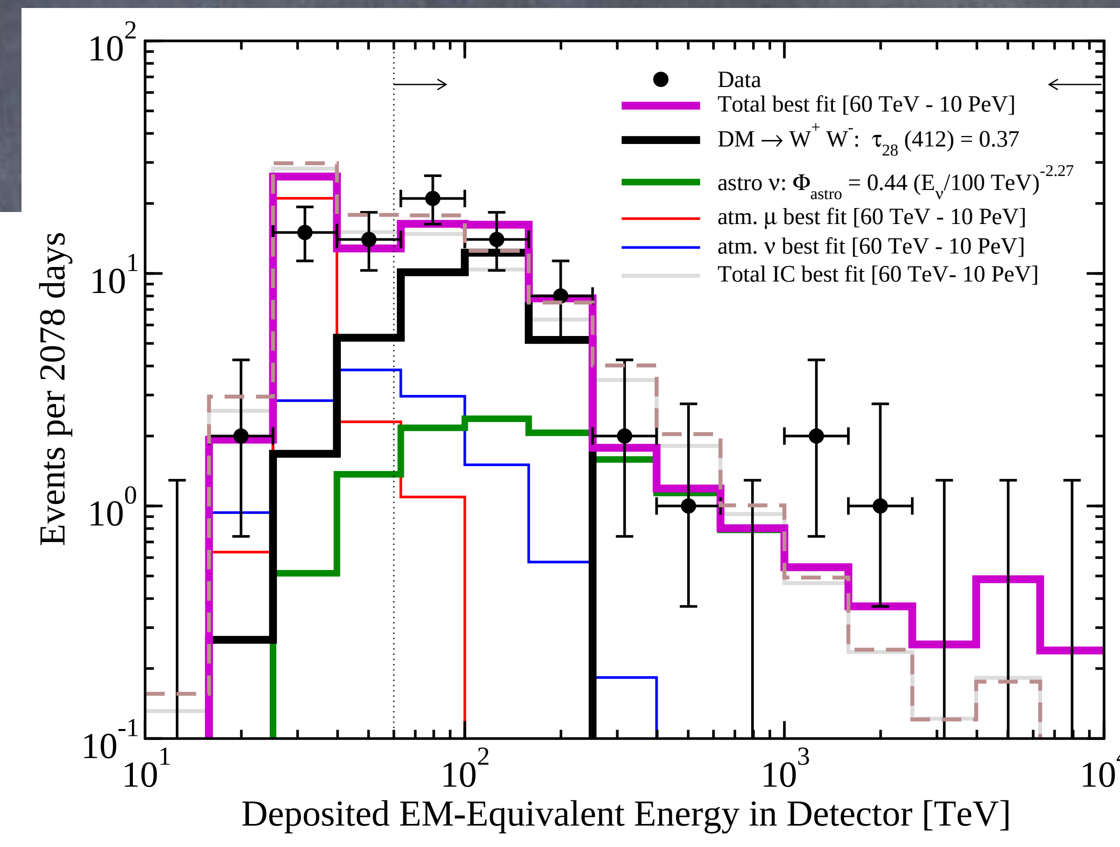
T. Cohen et al., Phys. Rev. Lett. 119:021102, 2017



A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 07:027, 2017

DM decays + Astro: 6-yr HESE analysis

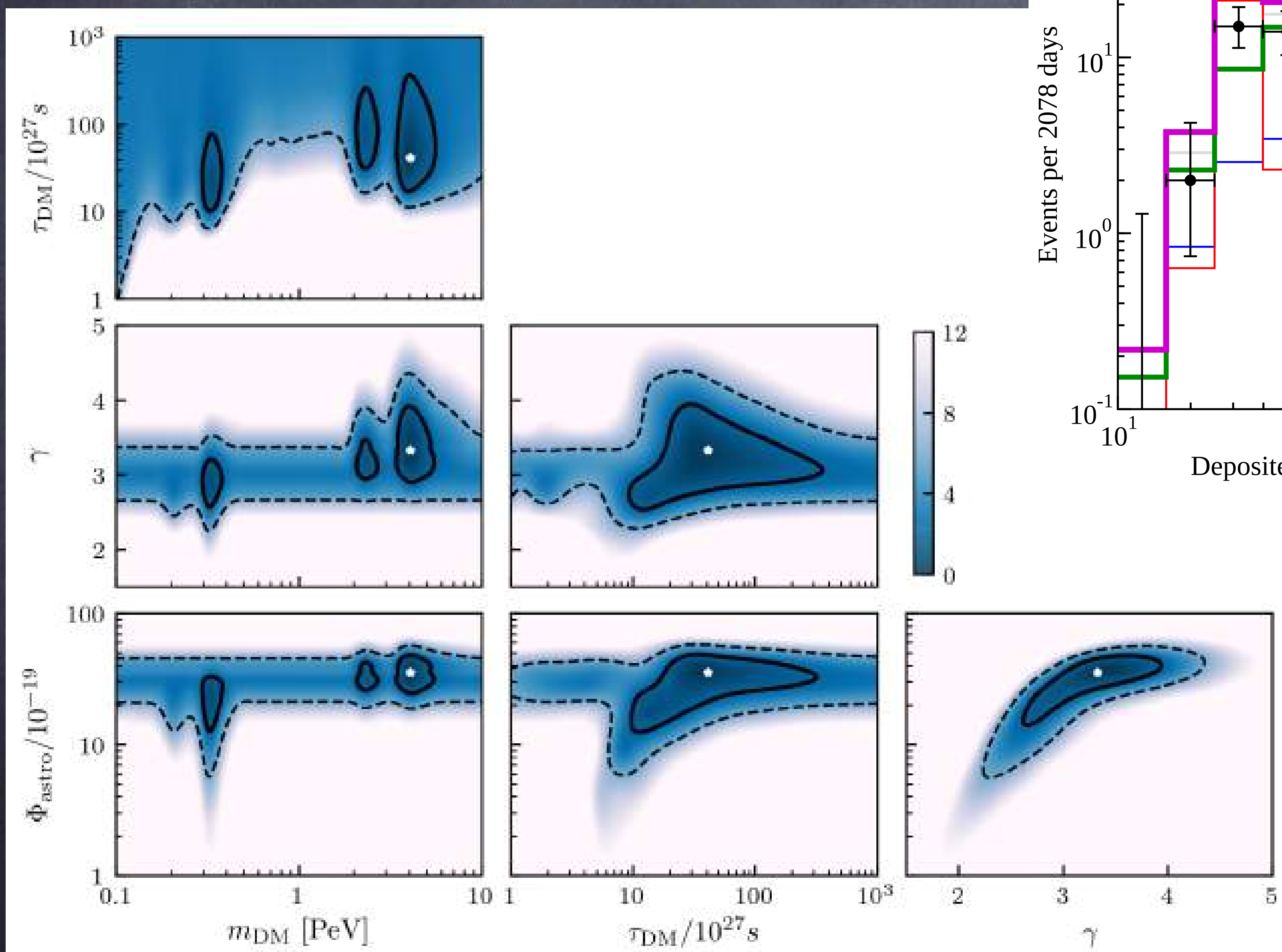


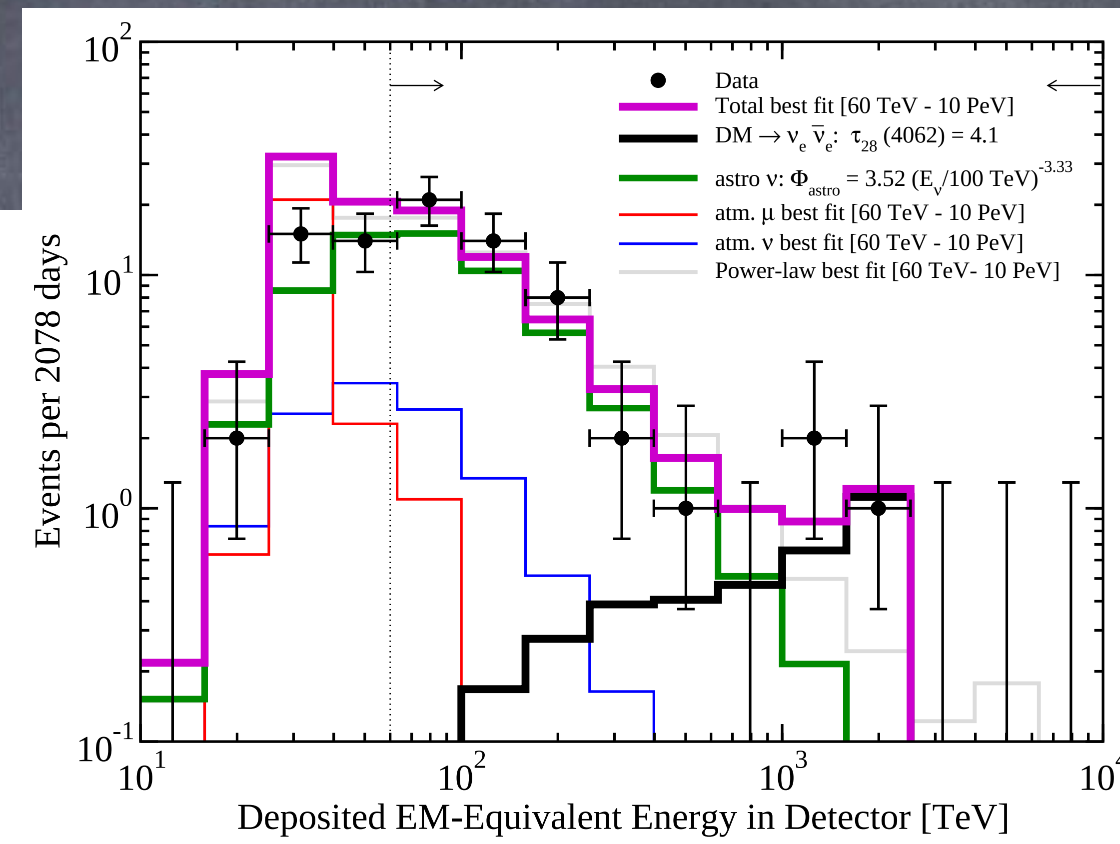


$DM \to W^+W^-$

A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

DM decays + Astro: 6-yr HESE analysis





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

A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

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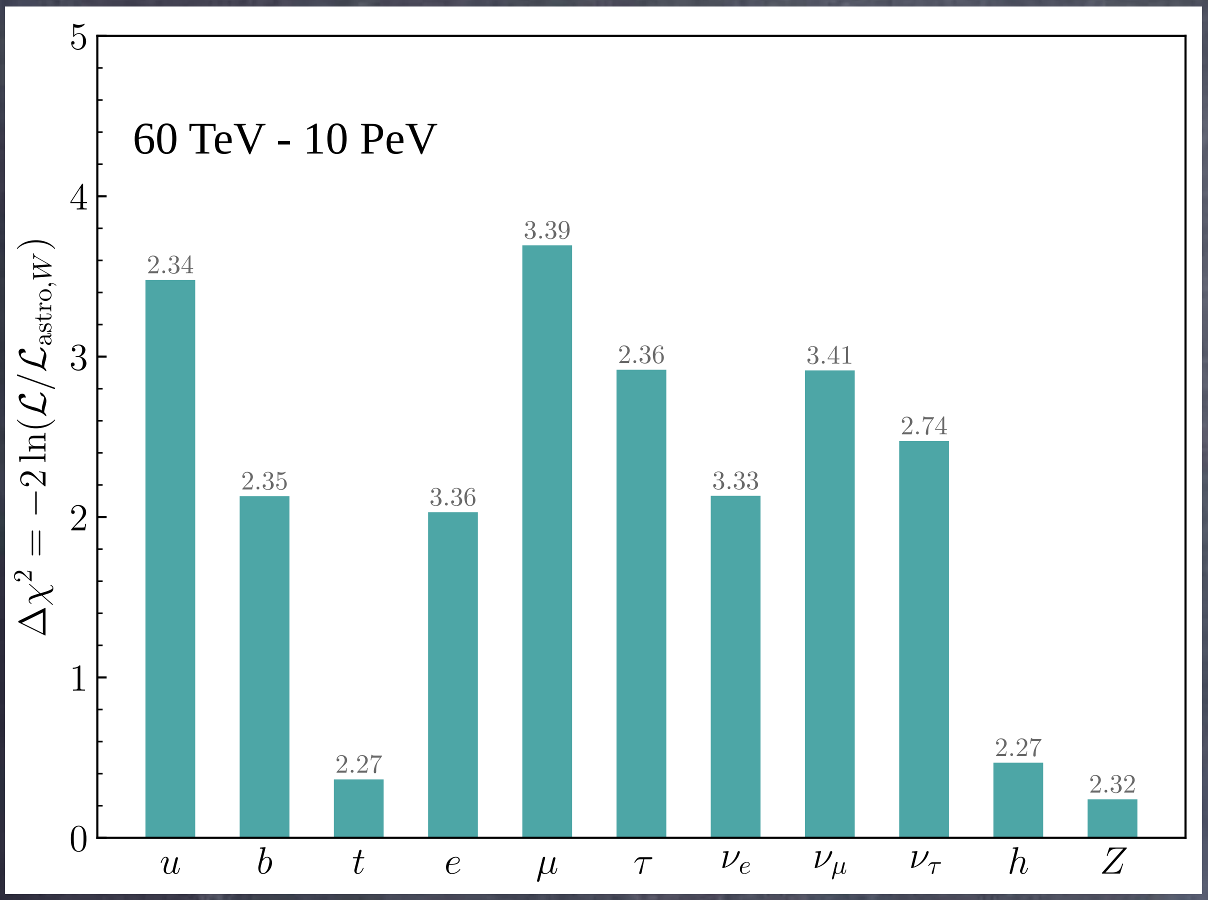
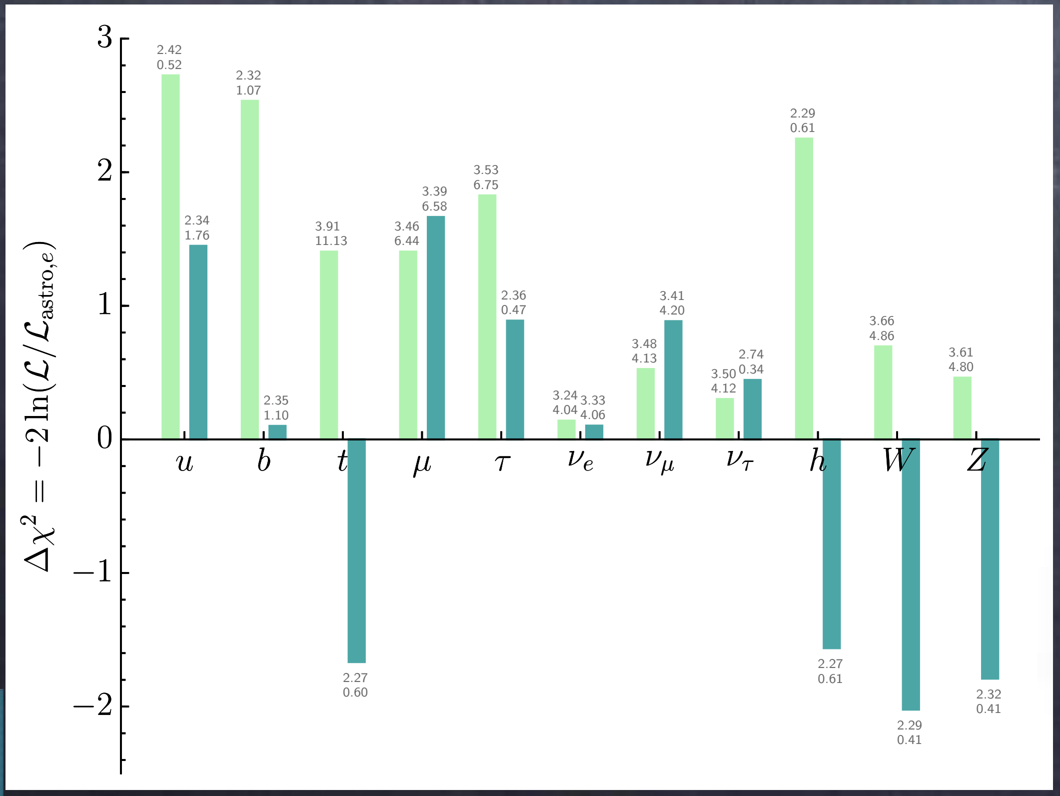
Best fit: Astro (hard) + DM → W^+W^-



Decay channel	$\tau_{\rm DM}[10^{28}$ s]	$(N_{\rm DM})$	$m_{\rm DM}$ [TeV]	$\phi_{\rm astro}$	$(N_{\rm astro})$	γ
$u\bar{u}$	0.11	*(28.4)*	1761	0.52	*(13.0)*	2.34
$b\bar{b}$	0.07	*(26.9)*	1103	0.58	*(14.3)*	2.35
$t\bar{t}$	0.11	*(28.7)*	598	0.45	*(12.5)*	2.27
$\boldsymbol{W^+W^-}$	**0.37**	***(28.5)***	**412**	**0.47**	***(12.6)***	**2.29**
ZZ	0.43	*(27.8)*	407	0.52	*(13.3)*	2.32
hh	0.12	*(28.8)*	611	0.45	*(12.6)*	2.27
e^+e^-	2.20	*(4.0)*	4160	3.53	*(37.3)*	3.36
$\mu^+\mu^-$	9.77	*(4.9)*	6583	3.51	*(36.5)*	3.39
$\tau^+\tau^-$	0.89	*(27.4)*	472	0.59	*(14.3)*	2.36
$\nu_e\bar{\nu}_e$	4.12	*(3.6)*	4062	3.52	*(37.7)*	3.33
$\nu_\mu\bar{\nu}_\mu$	4.63	*(5.0)*	4196	3.52	*(36.4)*	3.41
$\nu_\tau\bar{\nu}_\tau$	0.96	*(16.6)*	341	1.58	*(24.9)*	2.74



A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

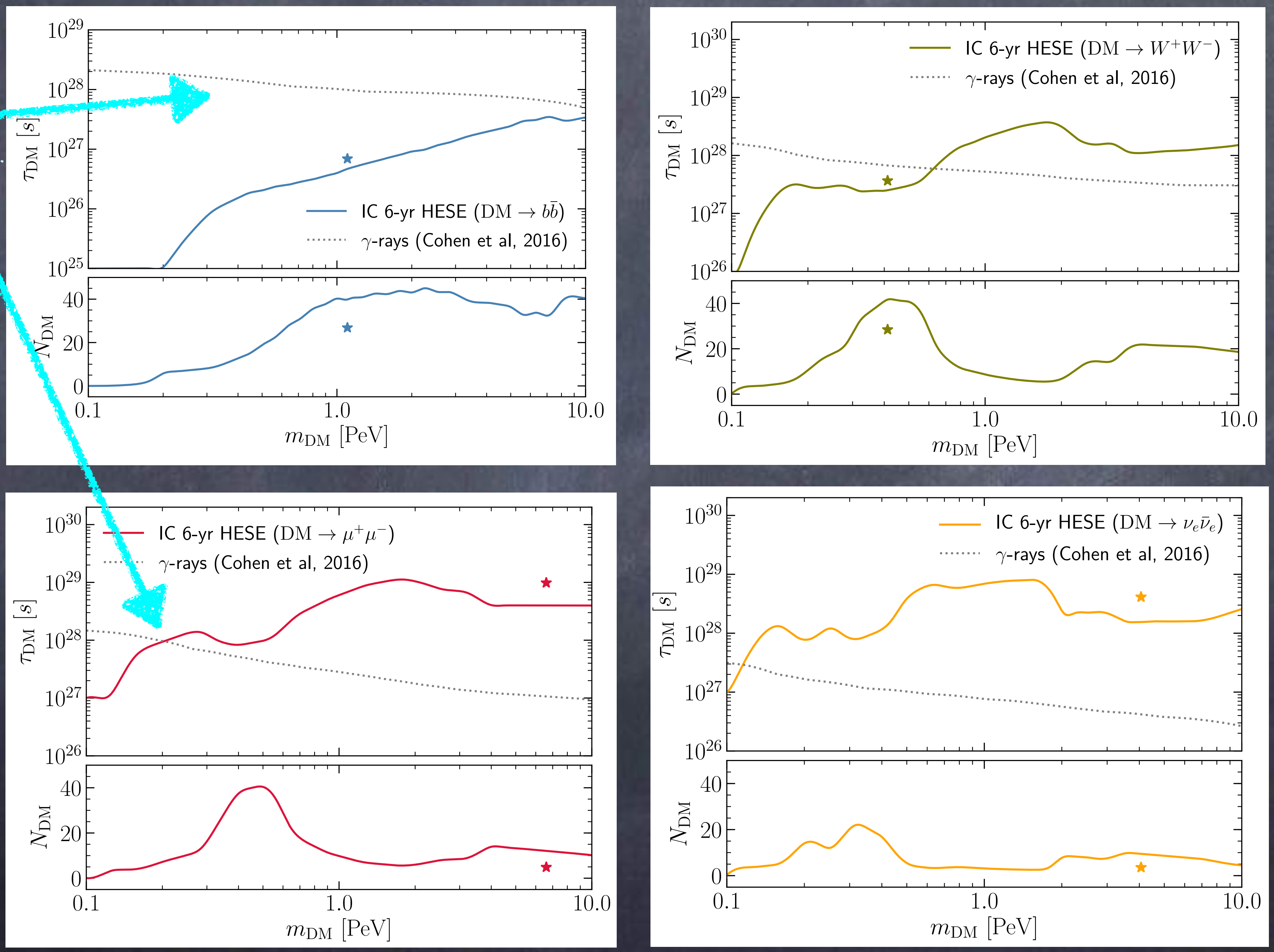
Comparison to 4-yr HESE

DM decays + Astro: 6-yr HESE analysis

Very similar limits to 4-yr HESE

GAMMA-RAY LIMITS

T. Cohen et al., Phys. Rev. Lett. 119:021102, 2017



A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

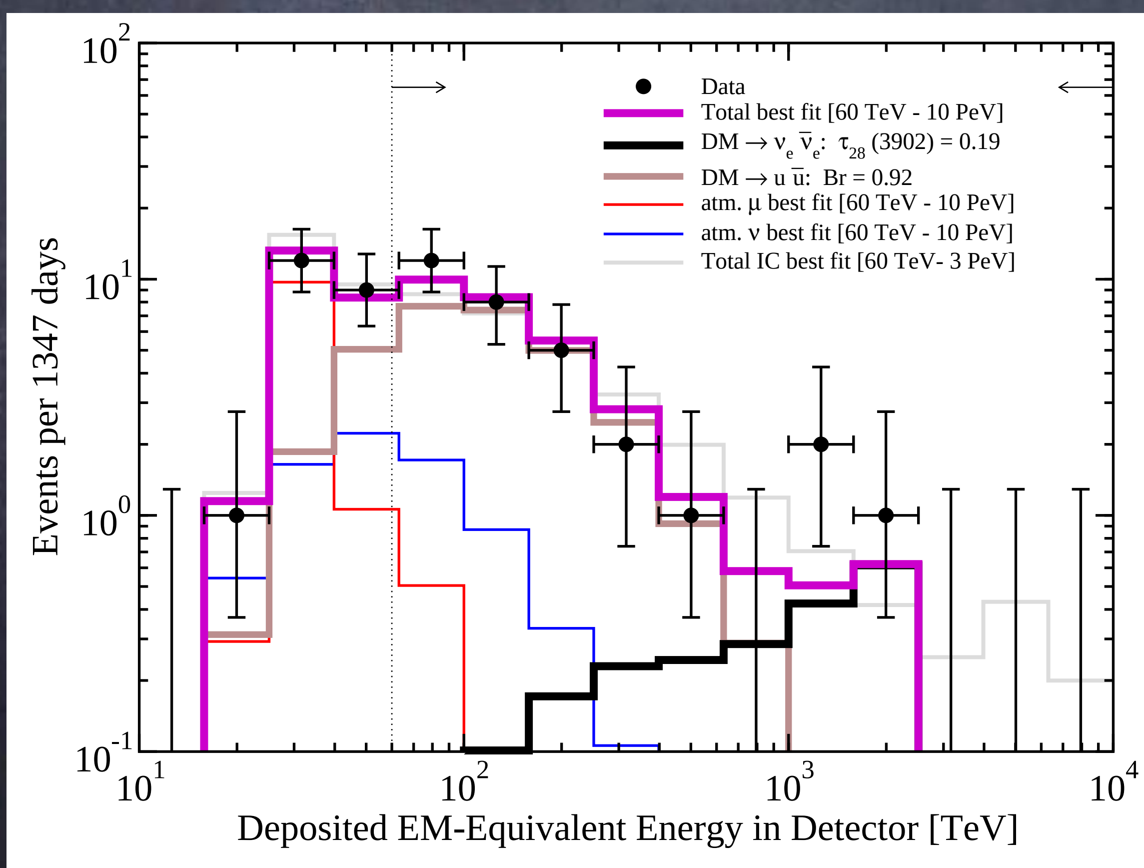
Only DM decays: HESE analysis

Only DM?
Two decay channels

but too much contribution from soft channels?

4-yr

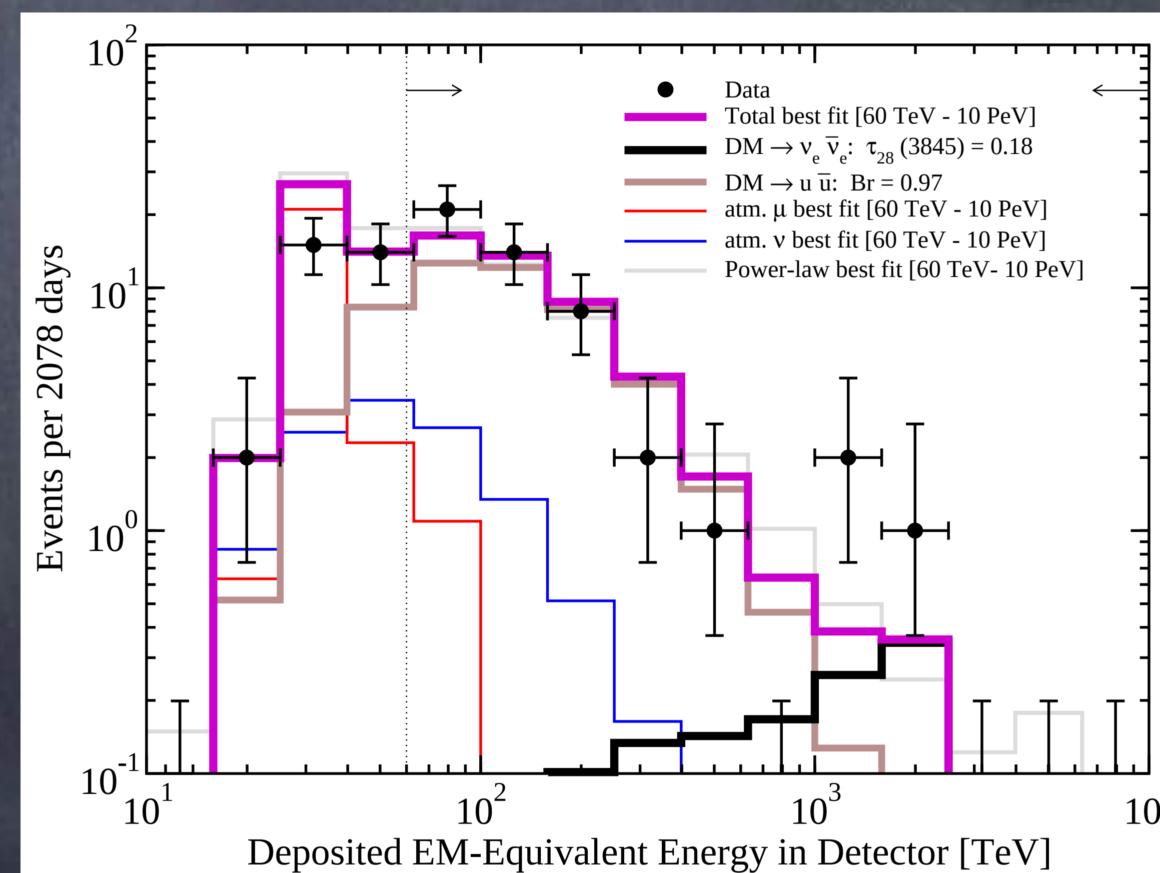
$DM \to \{92\%\ u\bar{u};\ 8\%\ \nu_e\bar{\nu}_e\}$



A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 07:027, 2017

6-yr

$DM \to \{97\%\ u\bar{u};\ 3\%\ \nu_e\bar{\nu}_e\}$



A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

Neutrinos from dark matter annihilations

Two components

Galactic | Extra-galactic

Averaged oscillations

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

Particle physics | Astrophysics

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

- $\langle\sigma v\rangle$: annihilation cross section
- m_{DM}: DM mass
- dN_{ν_α}/dE_ν: neutrino flux at production
- $\int_{los}\rho^2\,ds$: DM galactic density

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

- $(\Omega_{DM}\rho_c)^2$: DM density
- $H(z)$: Hubble function
- $\xi^2(z)$: halo enhancement
- $(1+z)E_\nu$: energy redshift

Neutrinos from dark matter annihilations

Two components

Galactic — Extra-galactic

Averaged oscillations

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

Particle physics — Astrophysics

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

annihilation cross section; DM mass; neutrino flux at production; DM galactic density; DM density; Hubble function; halo enhancement; energy redshift

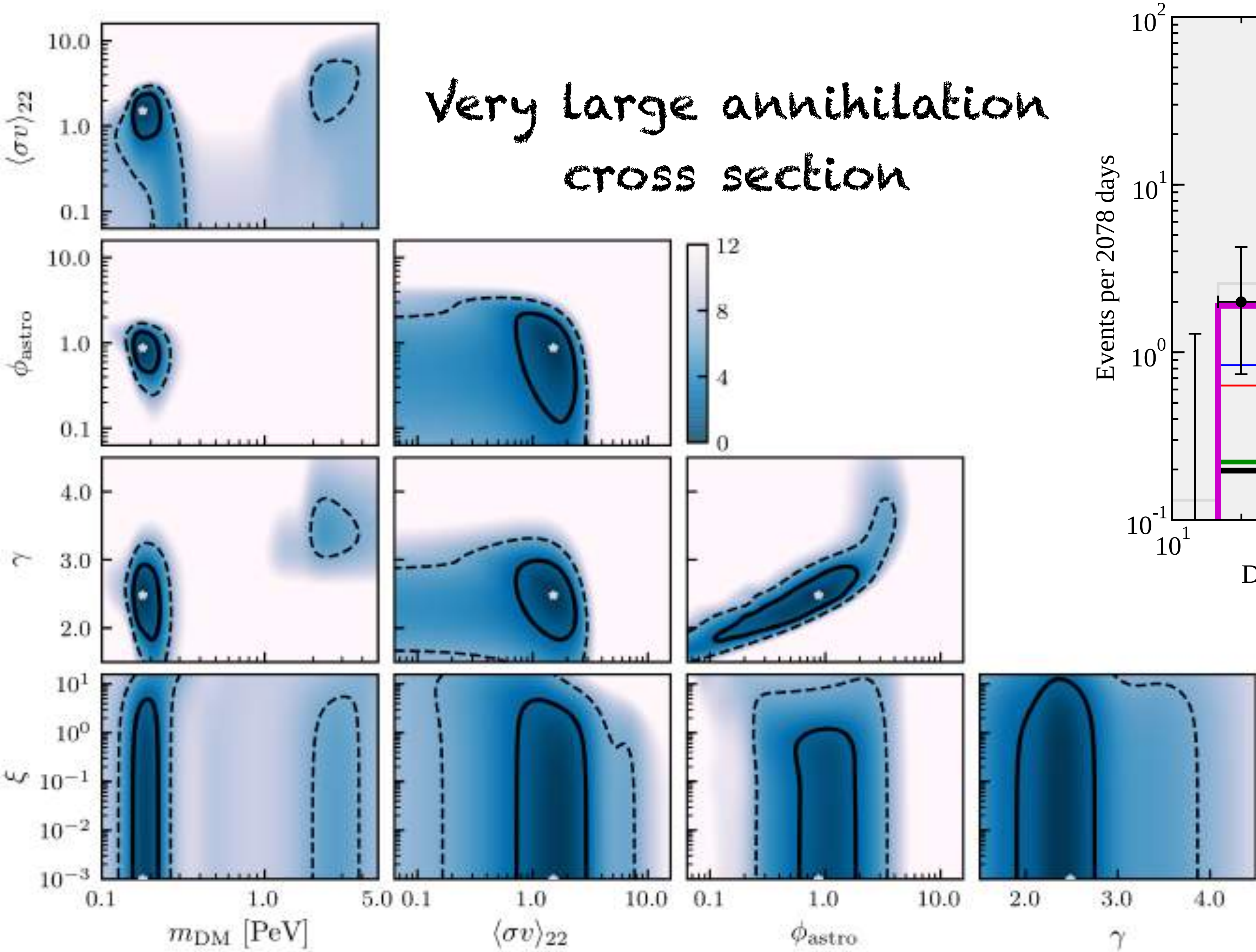
$$\text{Rate} \sim V\, N_N\, \sigma_N\, L_{MW}\frac{\rho_{DM}^2}{2m_{DM}^2}\langle\sigma v\rangle \sim 10/\text{year} \rightarrow \left(\frac{\langle\sigma v\rangle}{10^{-22}\,cm^3/s}\right)\left(\frac{1\,PeV}{m_{DM}}\right)^2 \sim 1$$

Very large annihilation cross section (above the unitarity limit) → non-thermal or composite DM or non-standard Universe evolution

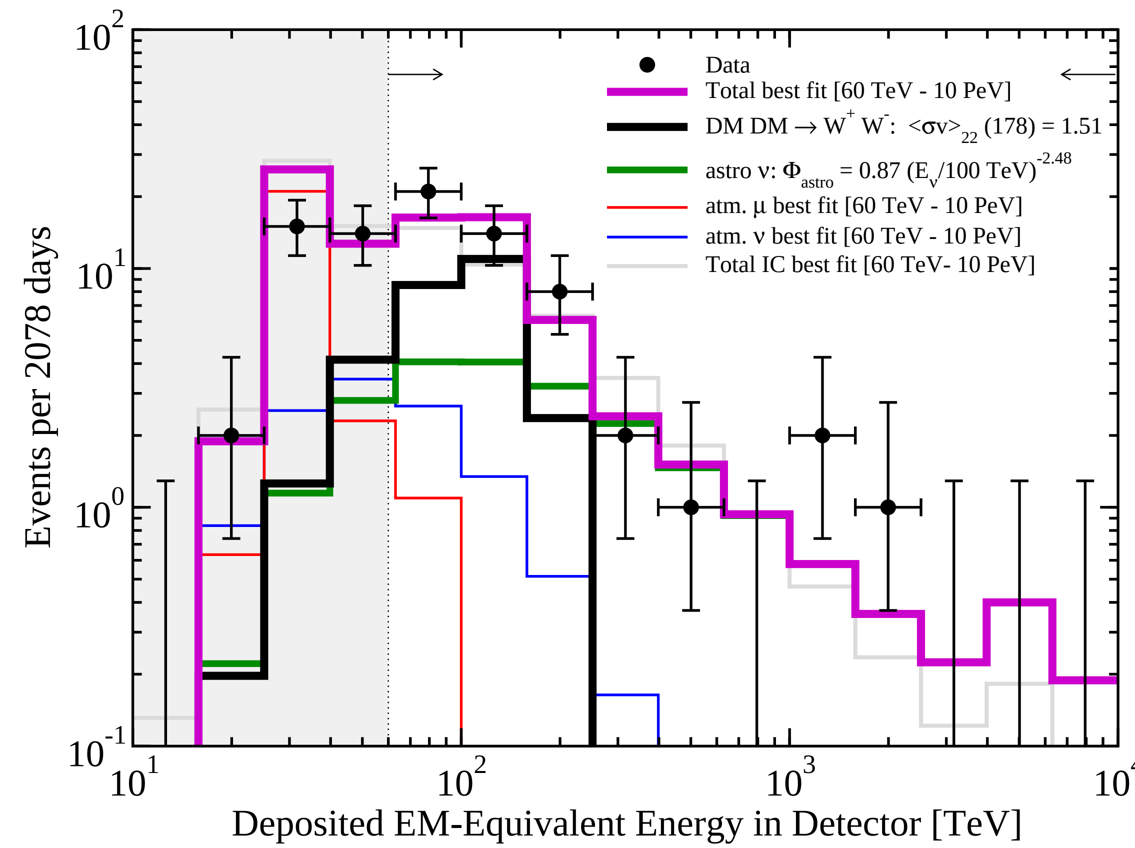
K. Griest and M. Kamionkowski, Phys. Rev. Lett. 64:615, 1990,

DM annihilations + Astro: 6-yr HESE analysis

$$\mathrm{DM\,DM} \rightarrow W^+W^-$$



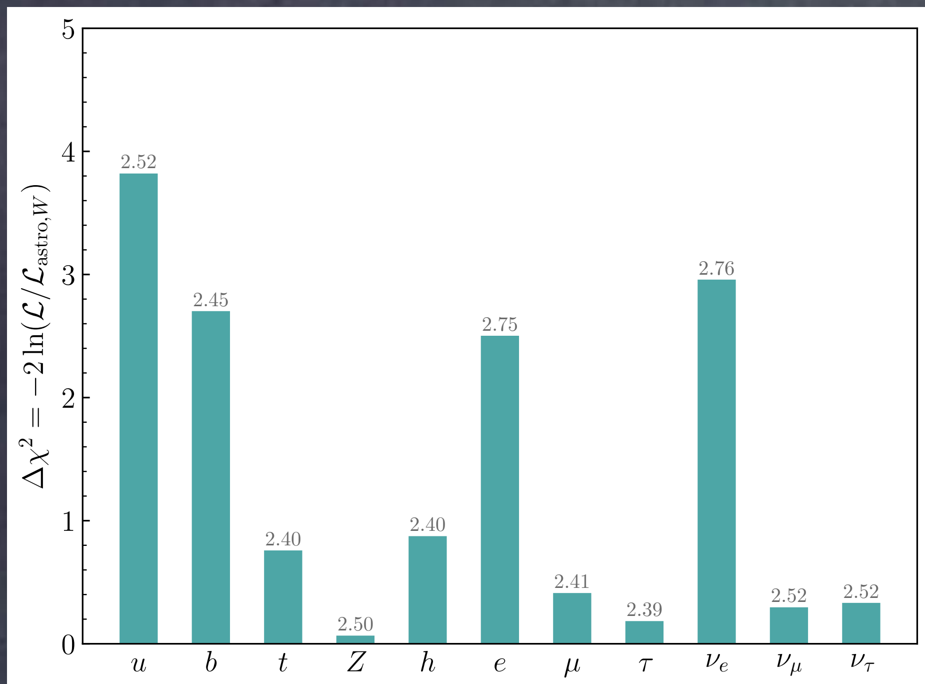
Very large annihilation cross section



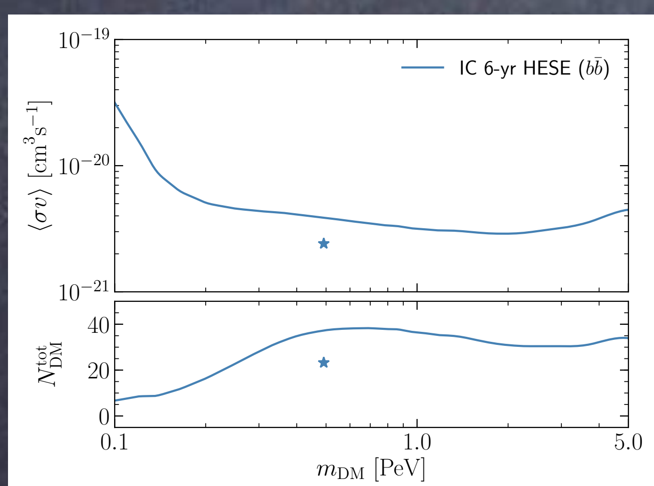
No significant ExGal contribution

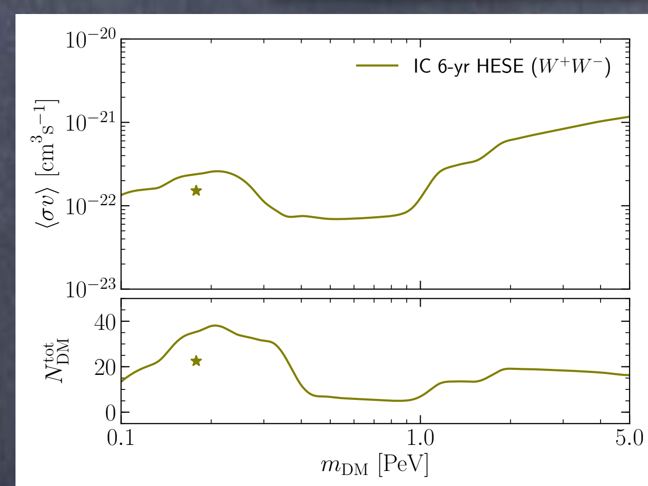
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

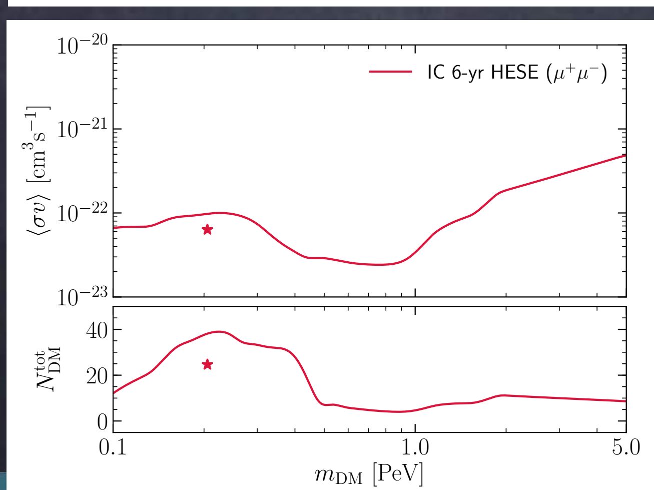
DM annihilations + Astro: 6-yr HESE analysis

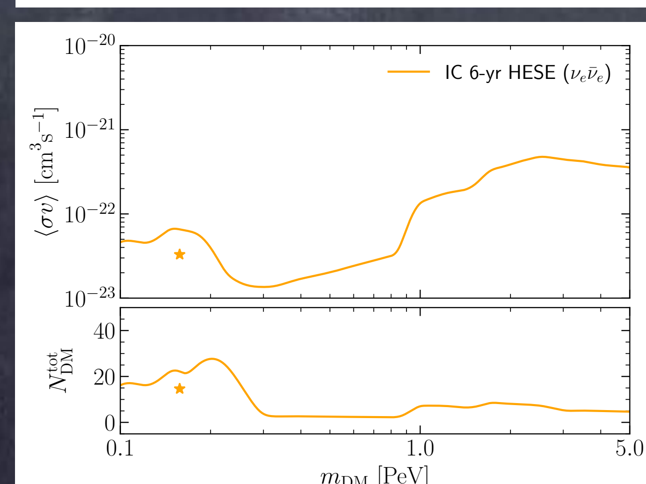


Ann. channel	$\langle\sigma v\rangle_{22}$	$m_{\rm DM}$ [TeV]	ξ	$\phi_{\rm astro}$	γ	$N^{\rm ann}_{\rm DM,G}$	$N^{\rm ann}_{\rm DM,EG}$	$N_{\rm astro}$
$u\bar{u}$	52.24	260	0.001	1.02	2.52	*20.6*	*0.0*	*20.2*
$b\bar{b}$	24.10	491	0.001	0.81	2.45	*23.2*	*0.0*	*17.3*
$t\bar{t}$	8.20	270	0.001	0.69	2.40	*24.8*	*0.0*	*15.8*
$\boldsymbol{W^+W^-}$	**1.51**	**178**	**0.001**	**0.87**	**2.48**	***22.5***	***0.0***	***18.1***
ZZ	1.27	177	0.001	0.91	2.50	*22.2*	*0.0*	*18.4*
hh	7.46	278	0.001	0.69	2.40	*24.9*	*0.0*	*15.8*
e^+e^-	1.03	159	0.635	1.65	2.75	*13.5*	*1.3*	*25.8*
$\mu^+\mu^-$	0.63	205	0.001	0.71	2.41	*24.6*	*0.0*	*15.9*
$\tau^+\tau^-$	0.96	218	0.001	0.66	2.39	*25.5*	*0.0*	*15.4*
$\nu_e\bar{\nu}_e$	0.33	158	3.388	1.67	2.76	*10.8*	*3.8*	*26.0*
$\nu_\mu\bar{\nu}_\mu$	0.70	159	1.791	0.96	2.52	*19.0*	*3.1*	*18.9*
$\nu_\tau\bar{\nu}_\tau$	0.70	159	1.945	0.96	2.52	*18.8*	*3.4*	*18.9*



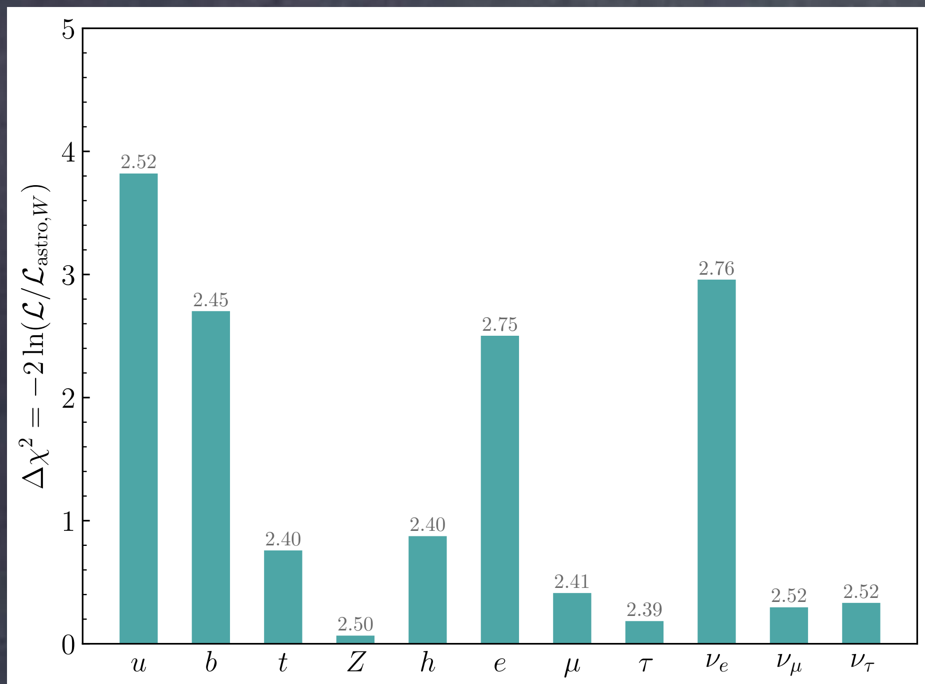




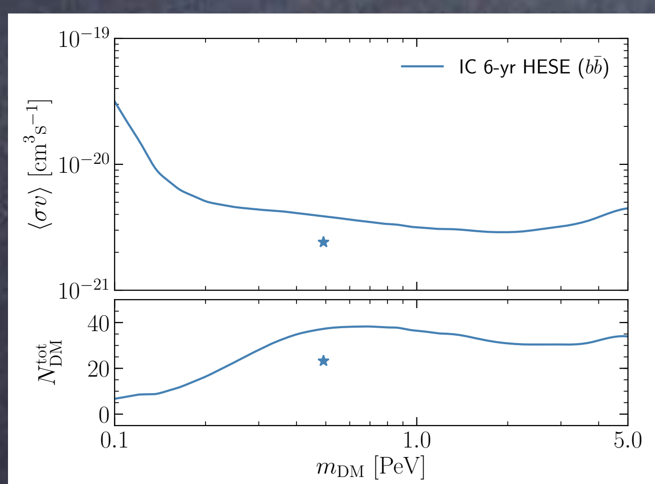


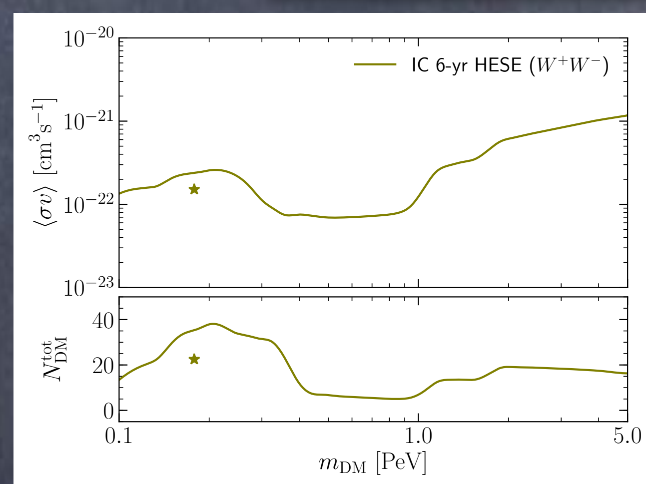
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

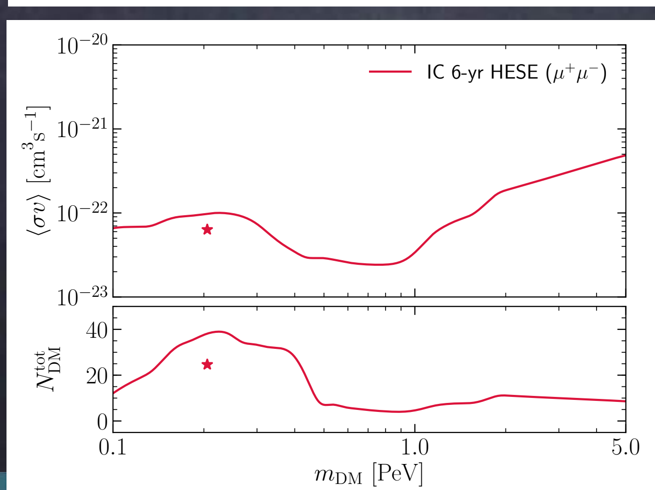
DM annihilations + Astro: 6-yr HESE analysis

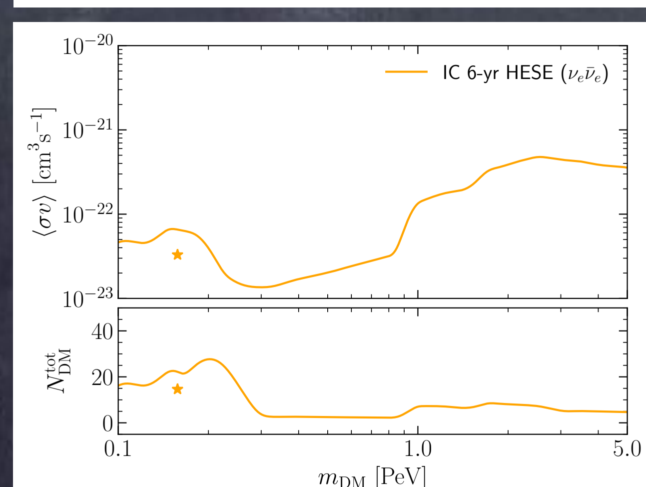


Ann. channel	$\langle\sigma v\rangle_{22}$	m_{DM} [TeV]	ξ	ϕ_{astro}	γ	$N^{\mathrm{ann}}_{\mathrm{DM,G}}$	$N^{\mathrm{ann}}_{\mathrm{DM,EG}}$	N_{astro}
$u\bar{u}$	52.24	260	0.001	1.02	2.52	*20.6*	*0.0*	*20.2*
$b\bar{b}$	24.10	491	0.001	0.81	2.45	*23.2*	*0.0*	*17.3*
$t\bar{t}$	8.20	270	0.001	0.69	2.40	*24.8*	*0.0*	*15.8*
$\boldsymbol{W^+W^-}$	**1.51**	**178**	**0.001**	**0.87**	**2.48**	***22.5***	***0.0***	***18.1***
ZZ	1.27	177	0.001	0.91	2.50	*22.2*	*0.0*	*18.4*
hh	7.46	278	0.001	0.69	2.40	*24.9*	*0.0*	*15.8*
e^+e^-	1.03	159	0.635	1.65	2.75	*13.5*	*1.3*	*25.8*
$\mu^+\mu^-$	0.63	205	0.001	0.71	2.41	*24.6*	*0.0*	*15.9*
$\tau^+\tau^-$	0.96	218	0.001	0.66	2.39	*25.5*	*0.0*	*15.4*
$\nu_e\bar{\nu}_e$	0.33	158	3.388	1.67	2.76	*10.8*	*3.8*	*26.0*
$\nu_\mu\bar{\nu}_\mu$	0.70	159	1.791	0.96	2.52	*19.0*	*3.1*	*18.9*
$\nu_\tau\bar{\nu}_\tau$	0.70	159	1.945	0.96	2.52	*18.8*	*3.4*	*18.9*

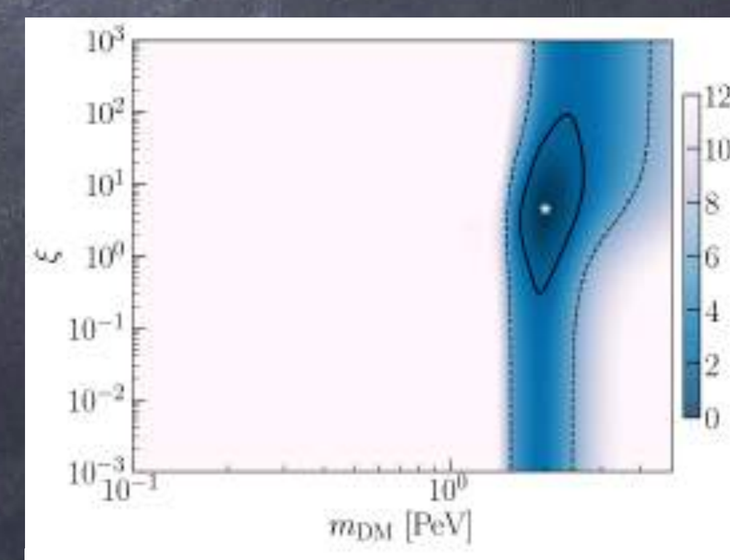








If only DM → ExGal needed, larger mass, hard-soft channels

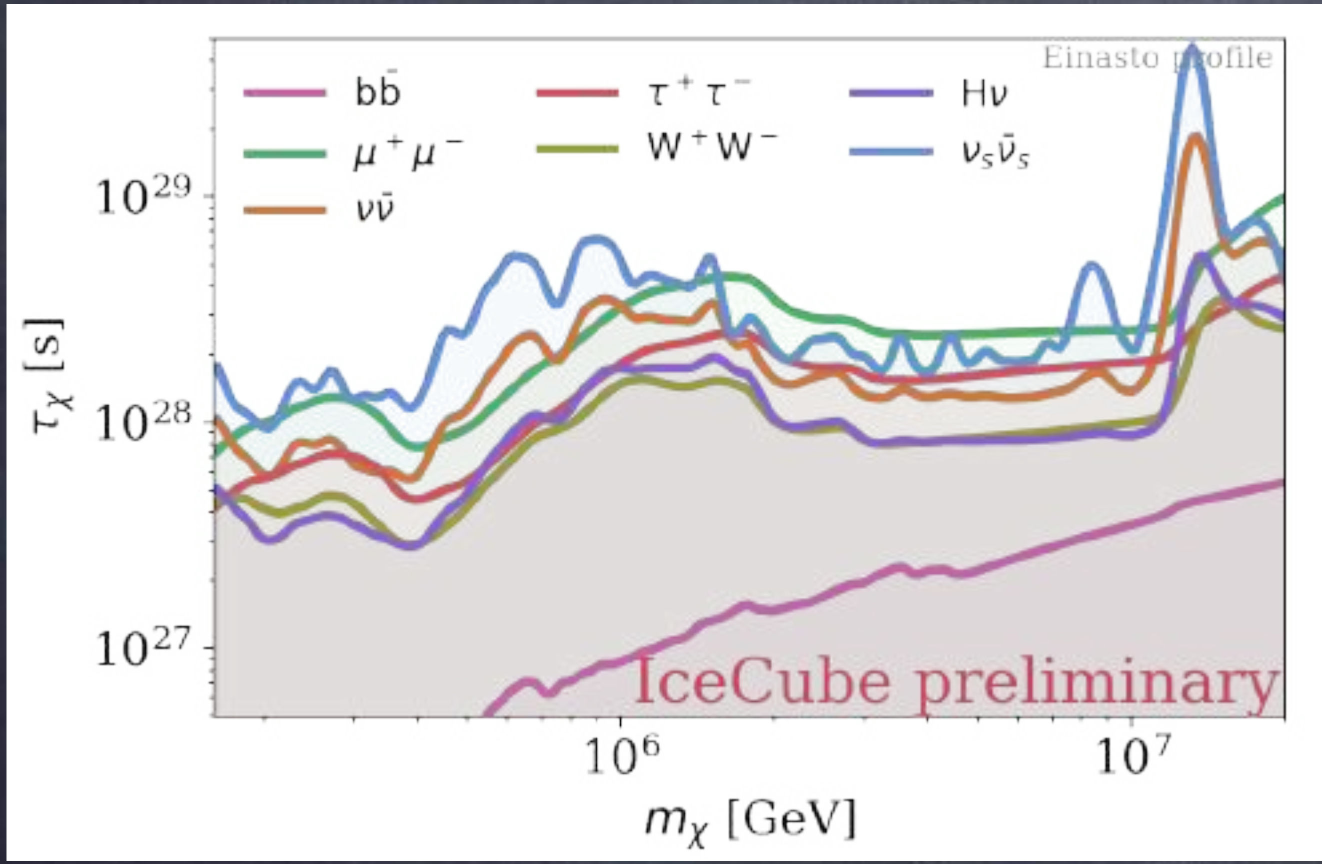


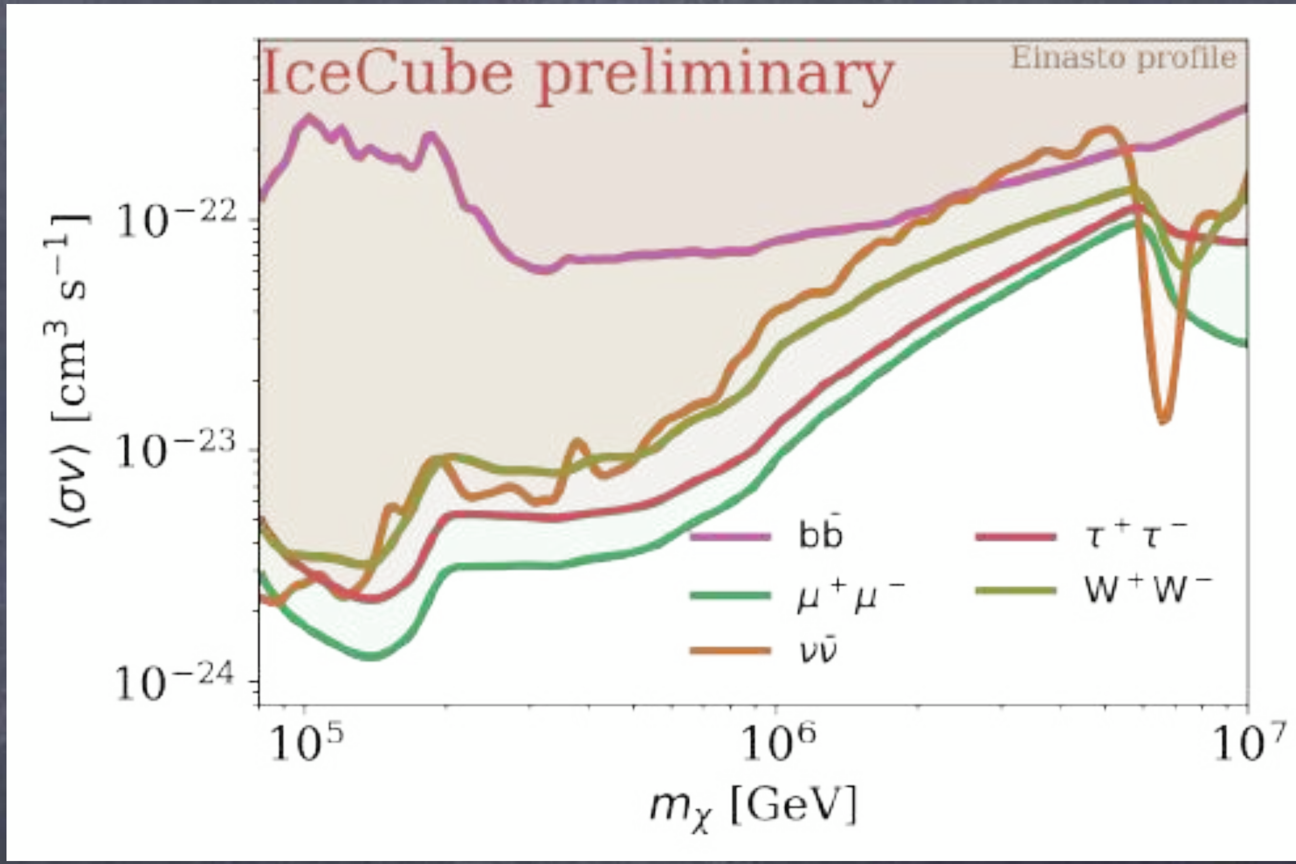
(a) DM DM → $\{u\bar{u}, e^+e^-\}$.

A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

DM bounds using the latest HESE data

7.5-yr HESE
(modified selection cuts, preliminary results)





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

Similar limits to 6-yr HESE

Dark matter decays: gamma-ray bounds

The neutrino spectrum from DM decays is accompanied by a gamma-ray spectrum

However, at energies E > 1 TeV, the Universe is not transparent to gamma-rays due to the interaction with the background radiation field (IR or CMB):

gamma-rays produce $e^{\pm}$ pairs, which produce further gamma-rays via inverse Compton onto CMB photons, until the energies fall below ~100 GeV

different absorption for extragalactic and galactic signals

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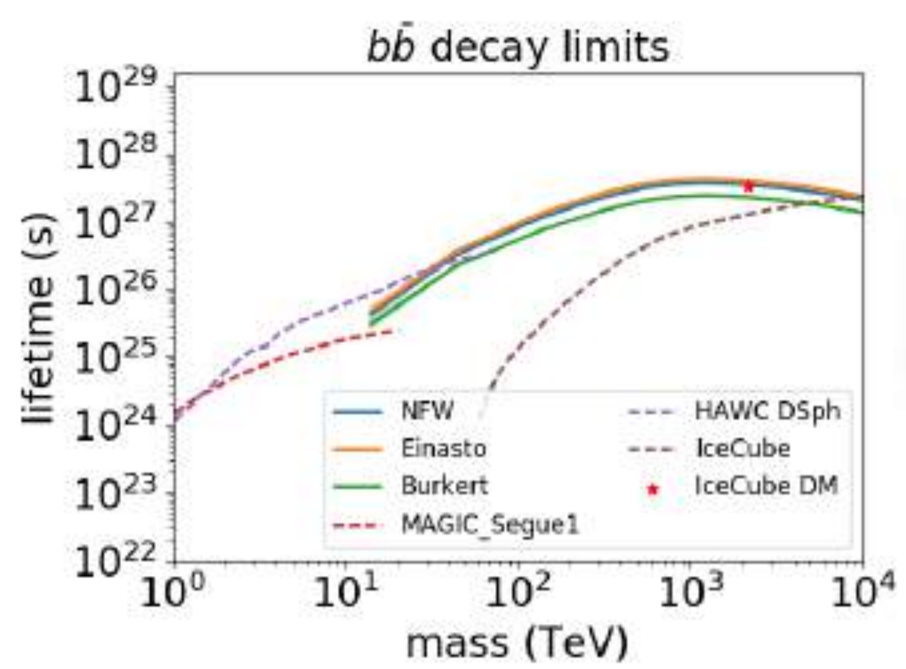
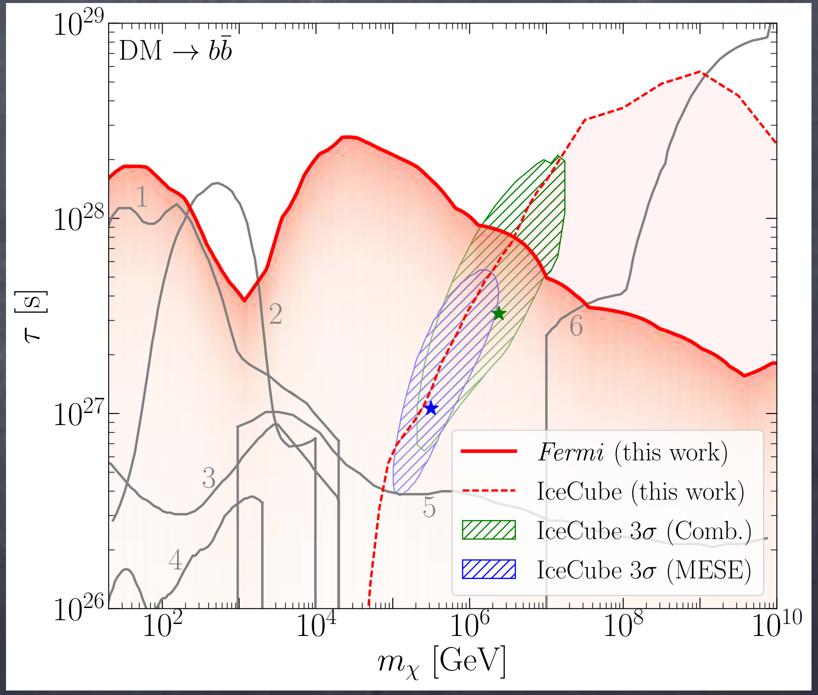
Galactic multi-TeV limits



A. U. Abeysekara et al. [HAWC Coll.], JCAP 02:049, 2018

Tension for hadronic channels

sub-TeV limits



T. Cohen et al., Phys. Rev. Lett. 119:021102, 2017

See also: K. Murase et al., Phys. Rev. Lett. 115:071301, 2015
A. Esmaili and P. D. Serpico, JCAP 1510:014, 2015
C. Blanco, J. P. Harding and D. Hooper, JCAP 04:060, 2018
K. Ishiwata et al., JCAP 01:003, 2020

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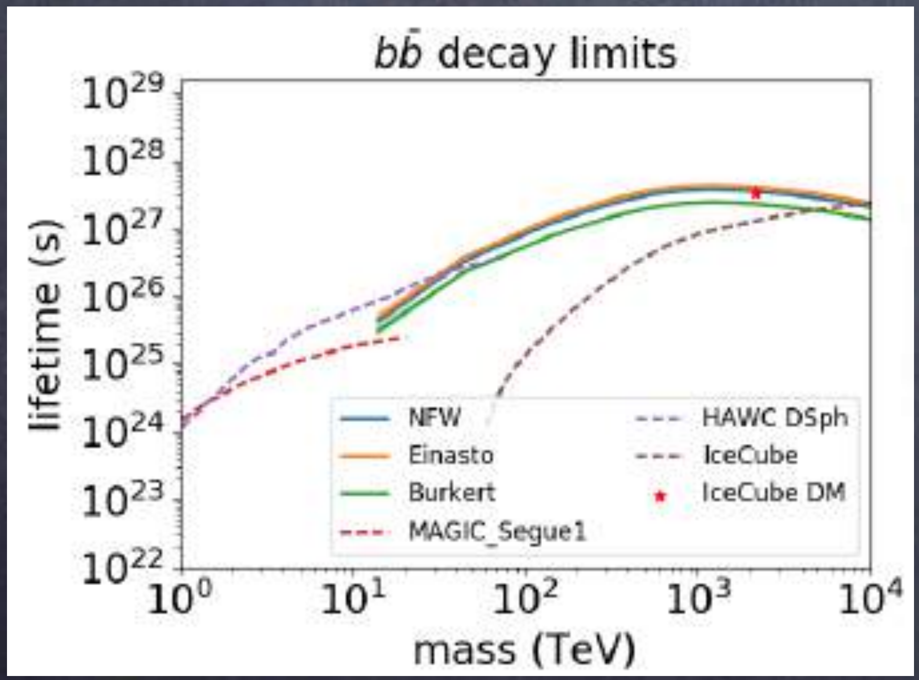

A. U. Abeysekara et al. [HAWC Coll.], JCAP 02:049, 2018

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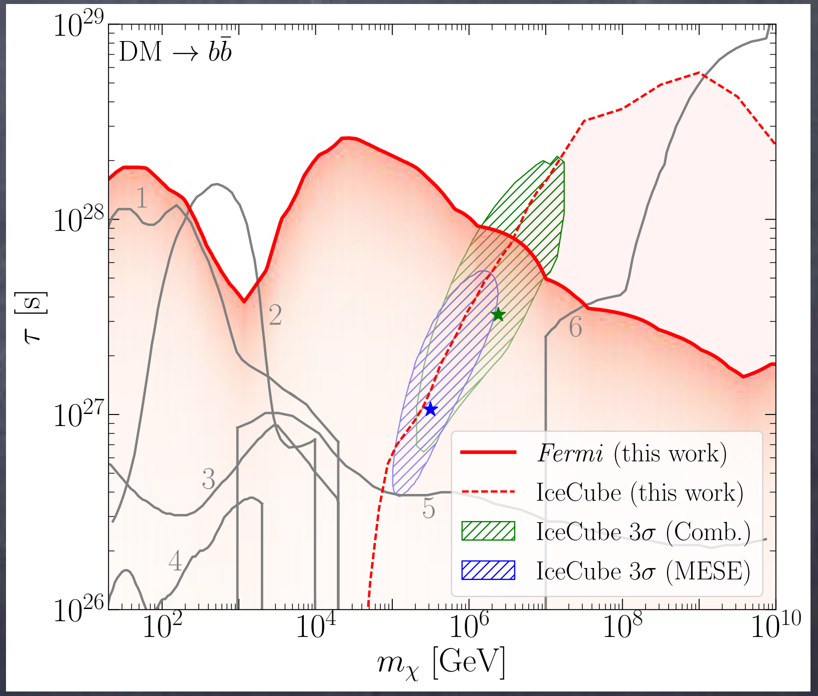

T. Cohen et al., Phys. Rev. Lett. 119:021102, 2017

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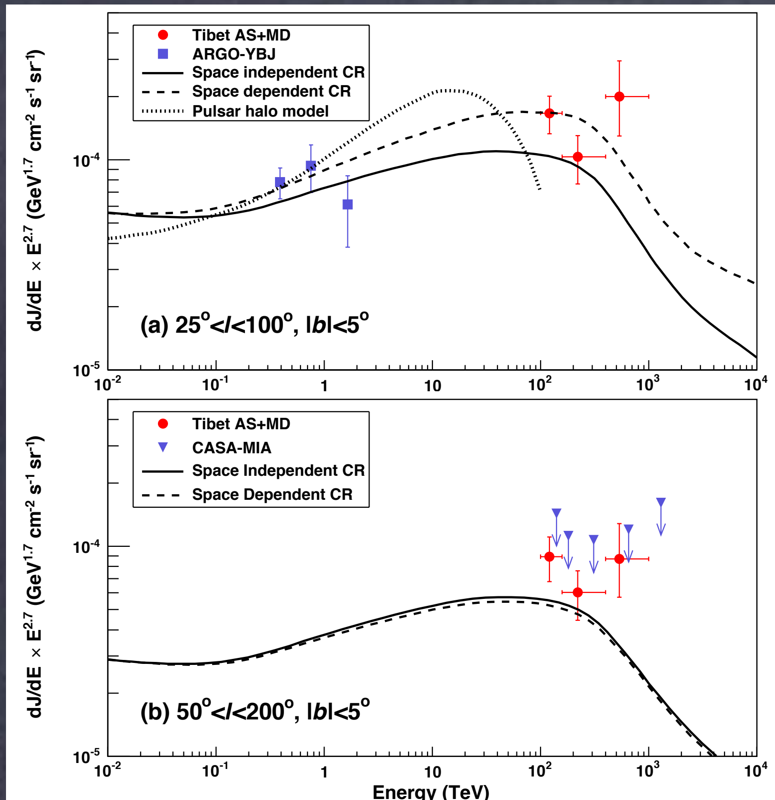
C. Blanco, J. P. Harding and D. Hooper, JCAP 04:060, 2018
K. Ishiwata et al., JCAP 01:003, 2020

high-galactic latitude counterparts?

A. Neronov, M. Kachelriess and D. V. Semikoz, Phys. Rev. D98:023004, 2018

Sub-PeV Galactic gamma rays

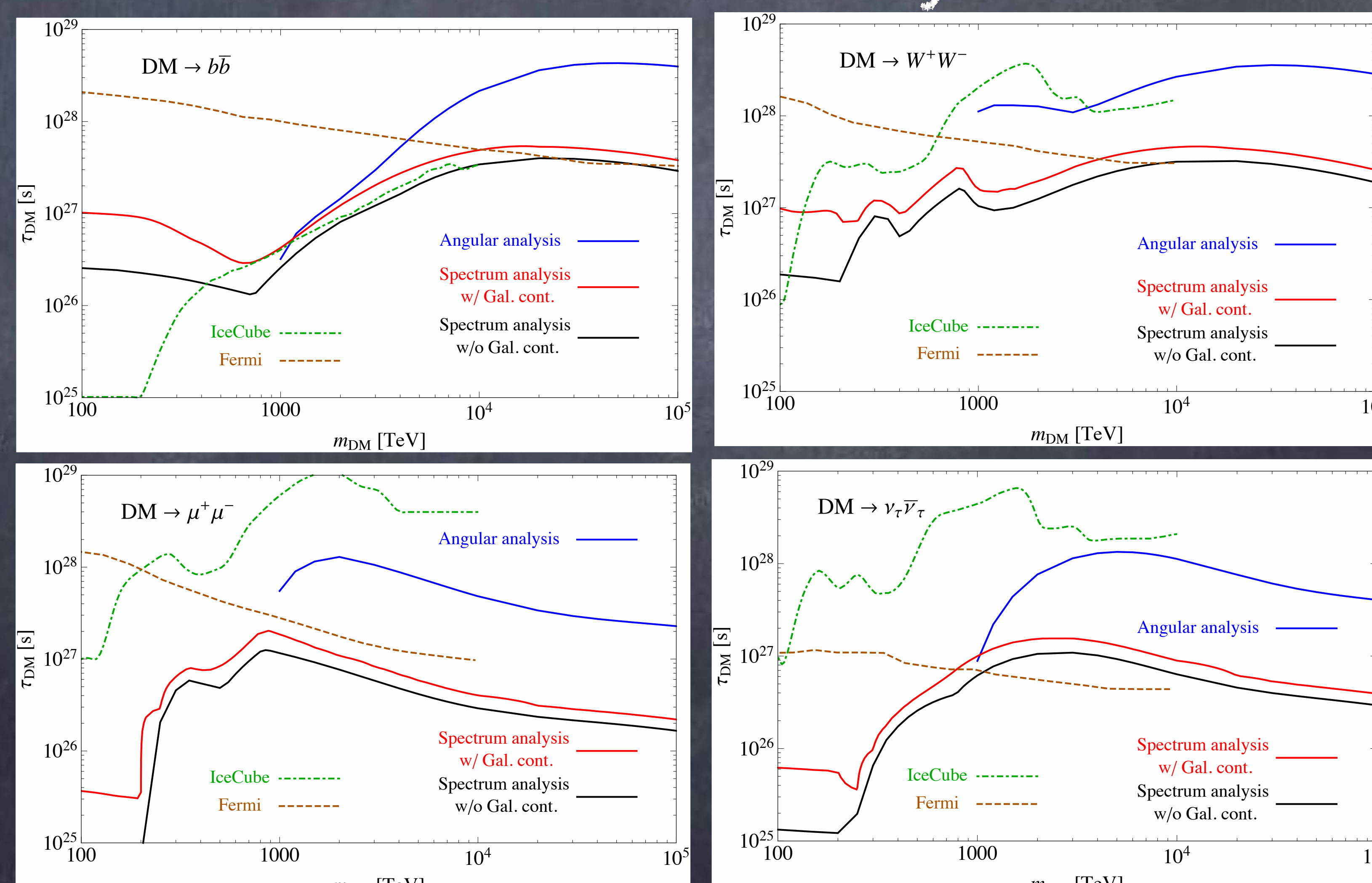


First detection of sub-PeV diffuse gamma rays from the galactic disk

Spectral and angular information

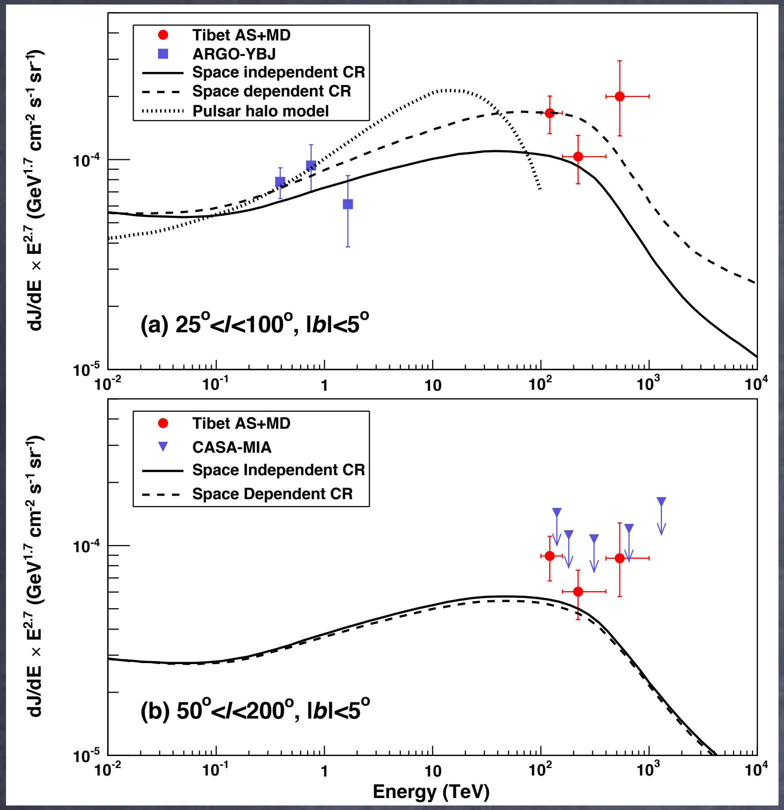
M. Amenomori et al. [Tibet ASγ Coll.], Phys. Rev. Lett. 126:141101, 2021

Limits on DM decays



A. Esmaili and P. D. Serpico, arXiv:2105.01826

SUB-PEV GALACTIC GAMMA RAYS



First detection of sub-PeV diffuse gamma rays from the galactic disk

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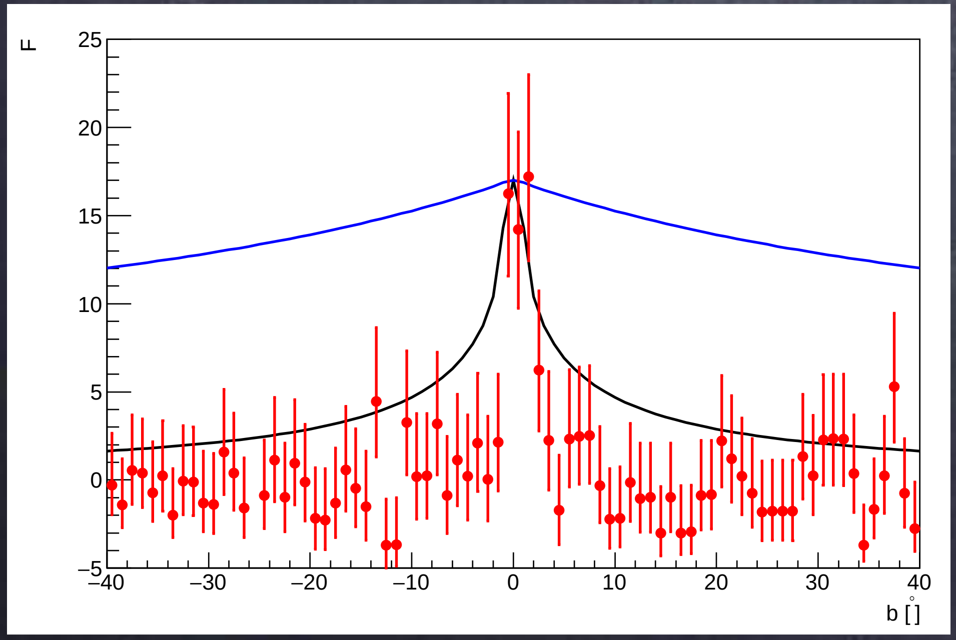
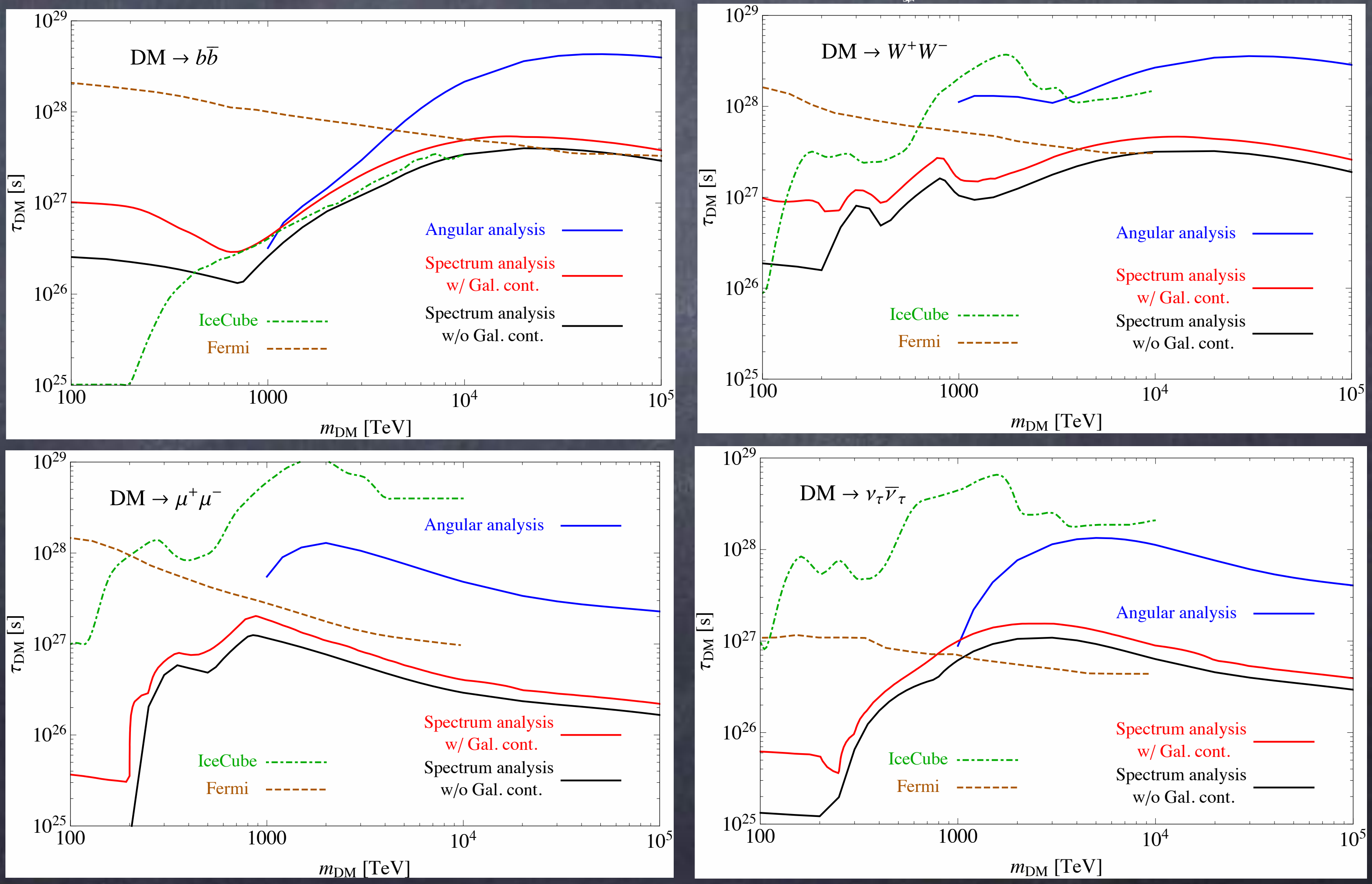
M. Amenomori et al. [Tibet ASγ Coll.], Phys. Rev. Lett. 126:141101, 2021

DM decays: at odds with the angular distribution



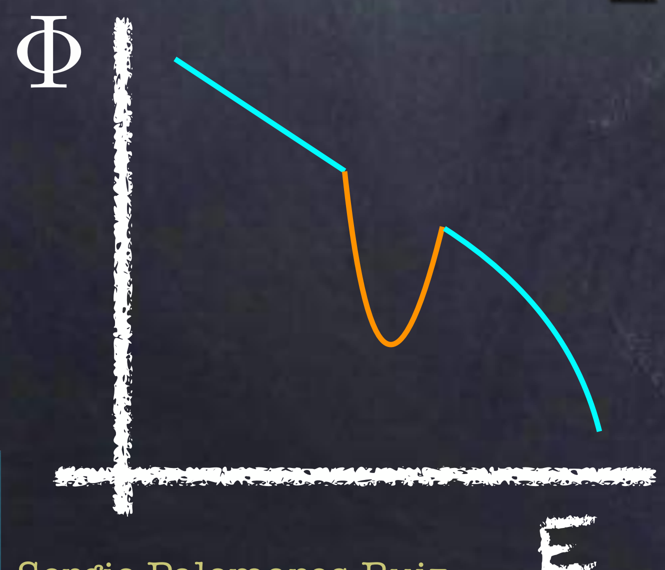
T. A. Dzhatdoev, arXiv:2104.02838

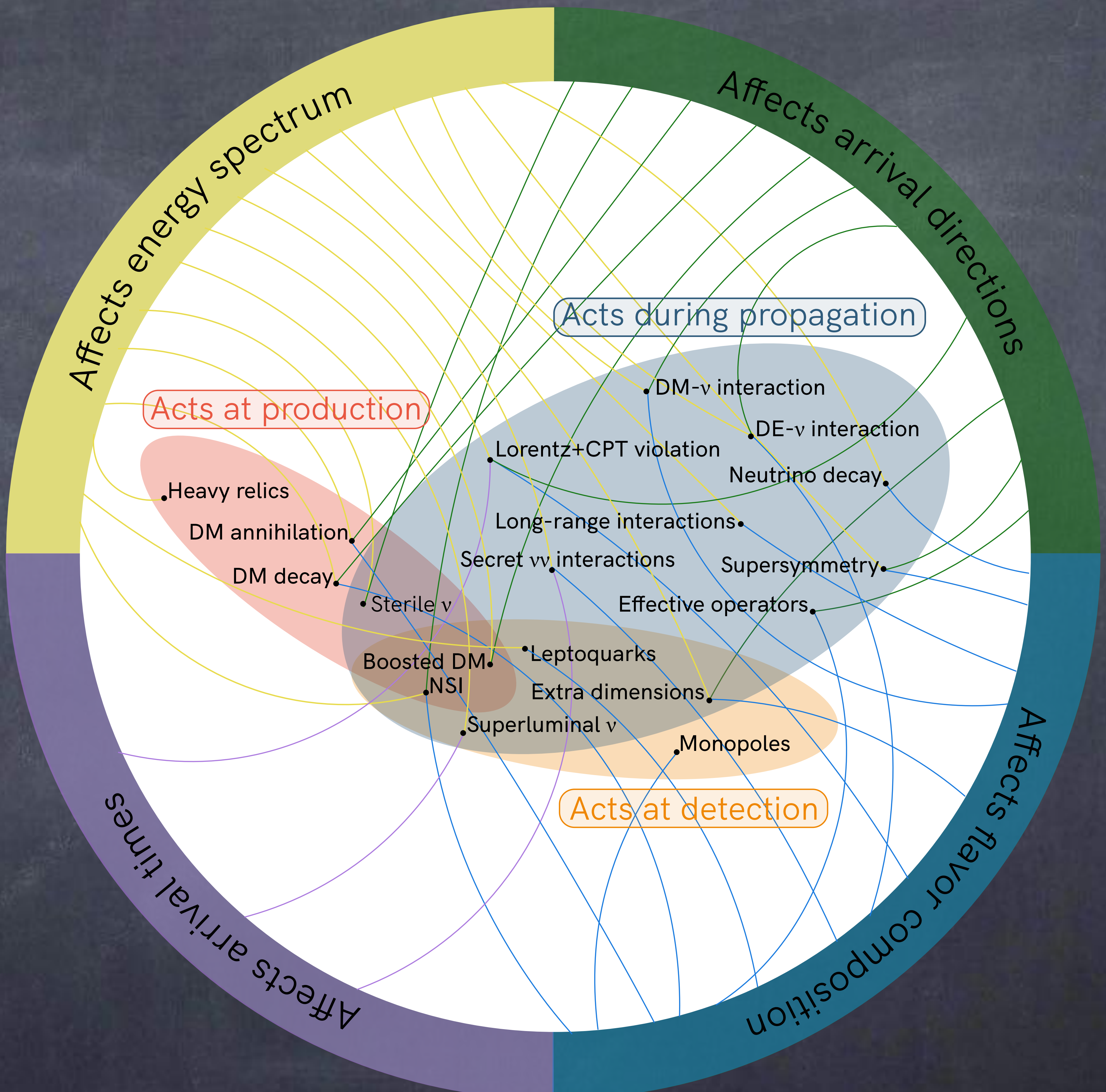
Limits on DM decays



A. Esmaili and P. D. Serpico, arXiv:2105.01826

Features on known spectra





C. Argüelles, M. Bustamante, A. Kheirandish, SPR,
J. Salvado and A. C. Vincent, PoS(ICRC2019)849, 2020

Neutrino-Dark Matter Interactions

Absorptive effects

produce absorption of the neutrino spectrum:
it could be energy, direction, flavor dependent...

$$\frac{d\phi_\nu(E_\nu,x)}{dx} \approx -n(x)\,\sigma(E_\nu)\,\phi_\nu(E_\nu,x)$$

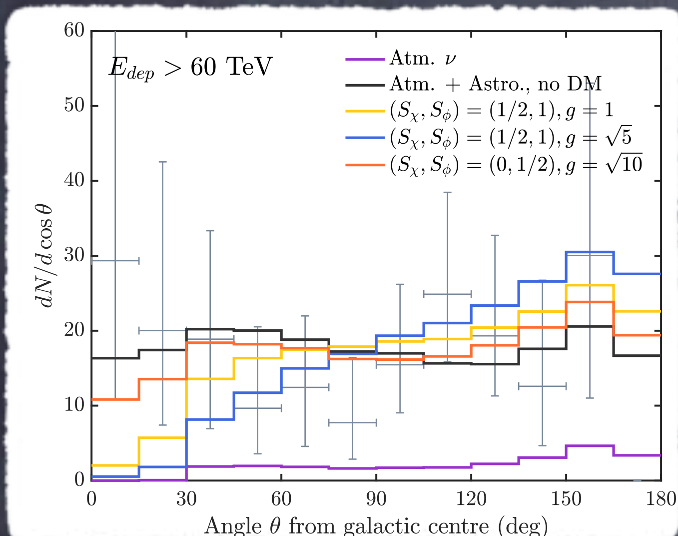
- $n(x)$: galactic or extra-galactic dark matter density
- $\sigma(E_\nu)$: neutrino interactions with dark matter
- $\phi_\nu(E_\nu,x)$: astrophysical neutrino flux

need of astrophysical distances for a significant cumulative effect

Neutrino-Dark Matter Interactions

Absorptive effects

Energy-dependent anisotropy of high-energy neutrinos



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

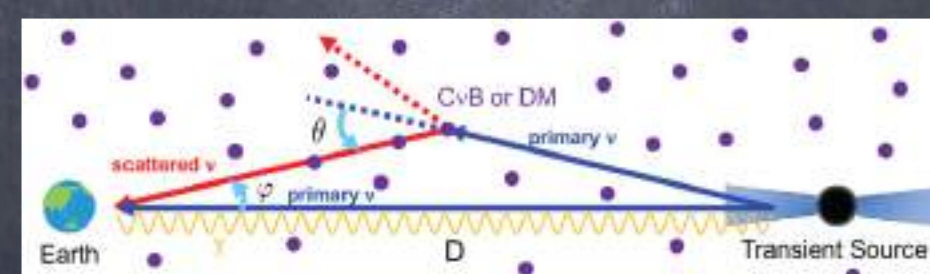
Distortion of high-energy neutrinos

J. Barranco et al., JCAP 10:007, 2011

M. M. Reynoso and O. A. Sampayo, Astropart. Phys. 82:10, 2016

S. Karmakar, S. Pandey and S. Rakshit, arXiv:1810.04192

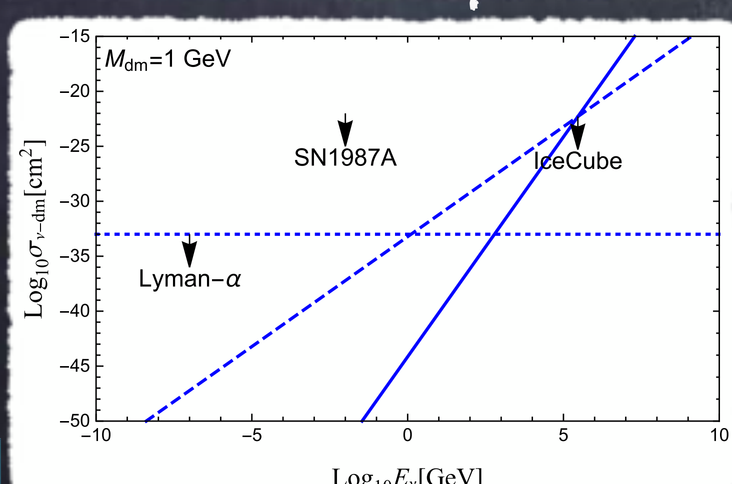
Time delays of high-energy neutrinos



S. Koren, JCAP 09:013, 2019

K. Murase and I. M. Shoemaker, Phys. Rev. Lett. 123:24, 2019

Full absorption of high-energy neutrinos from point sources



K. J. Kelly and P. A. N. Machado, JCAP 10:048, 2018

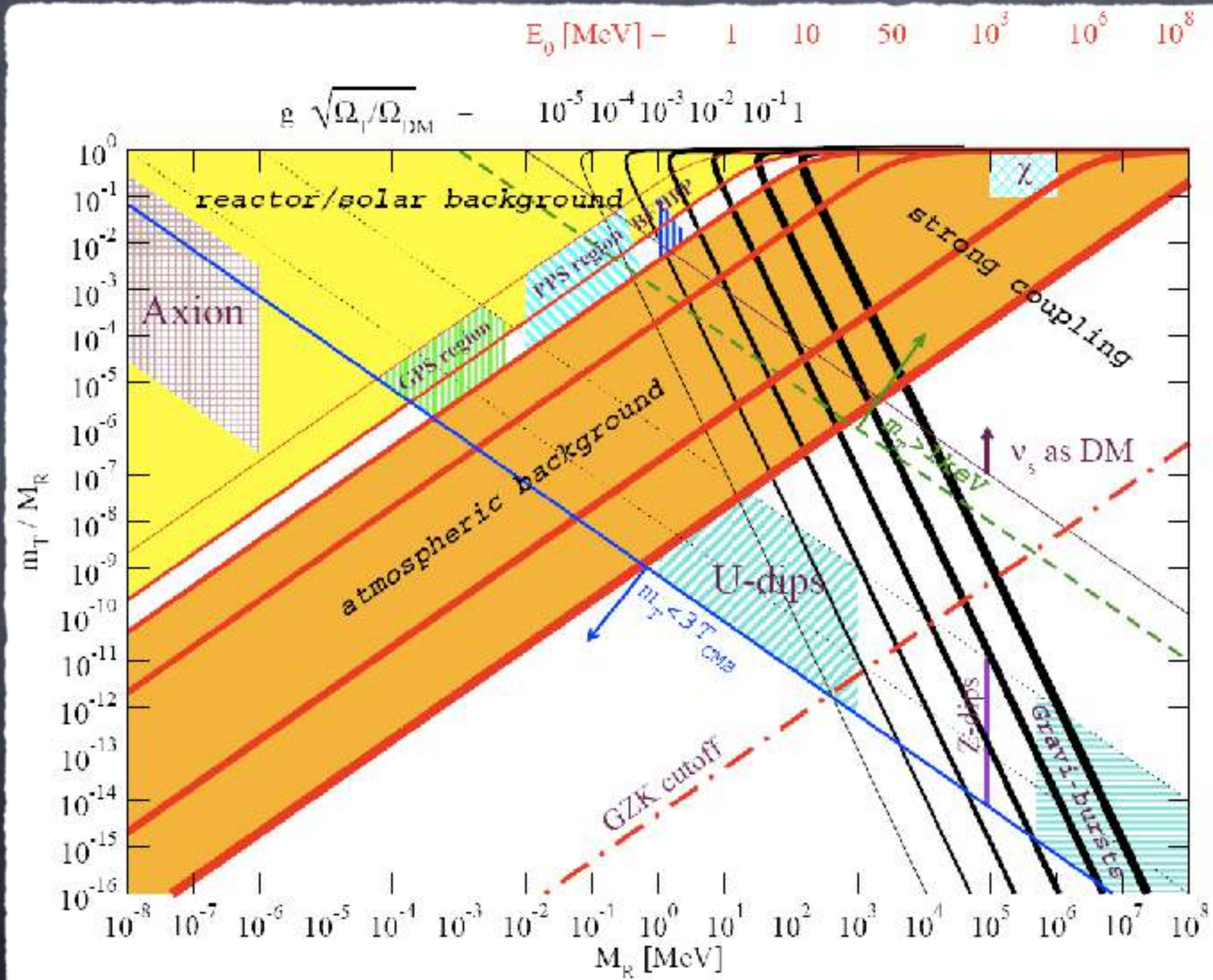
J. B. G. Alvey and M. Fairbairn, JCAP 07:041, 2019

K. Choi, J. Kim and C. Rott, Phys. Rev. D99:8, 2019

Redshift-Integrated Resonances (zIRs)

Dips in cosmic neutrino spectra

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



SPR and T. J. Weiler, 2006 (unpublished)

Neutrino-Dark Matter Interactions

Coherent effects

induce an effective mass or potential

$$\frac{d\phi_\nu(E_\nu,x)}{dx} = -i\left(U\,H_{vac}\,U^\dagger + V_m\right)\phi_\nu(E_\nu,x)$$

$$P_{2\nu}\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta^m \sin^2\left(\frac{\Delta^m L}{4E}\right)$$

$$\Delta^m = \sqrt{\left(\Delta m^2 \cos 2\theta \mp 2EV\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\sin^2 2\theta^m = \sin^2 2\theta \left(\frac{\Delta m^2}{\Delta^m}\right)^2$$

Neutrino-Dark Matter Interactions

Coherent effects

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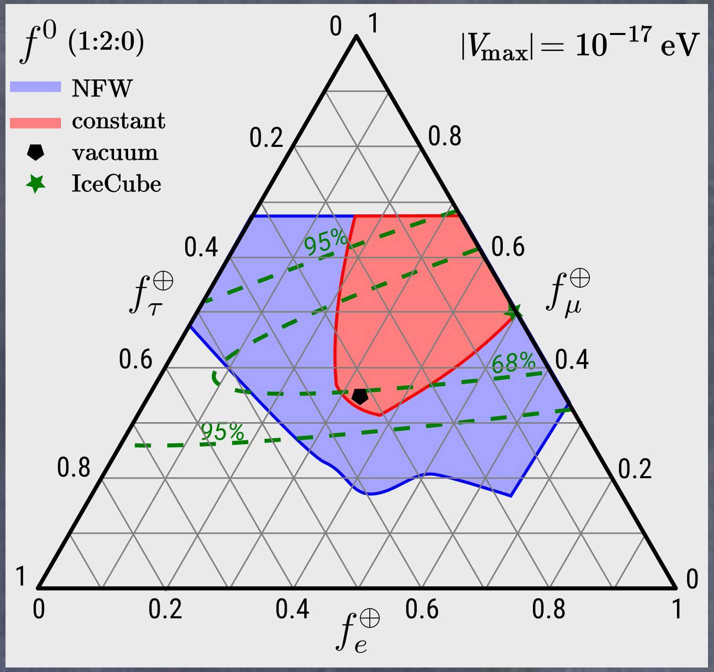
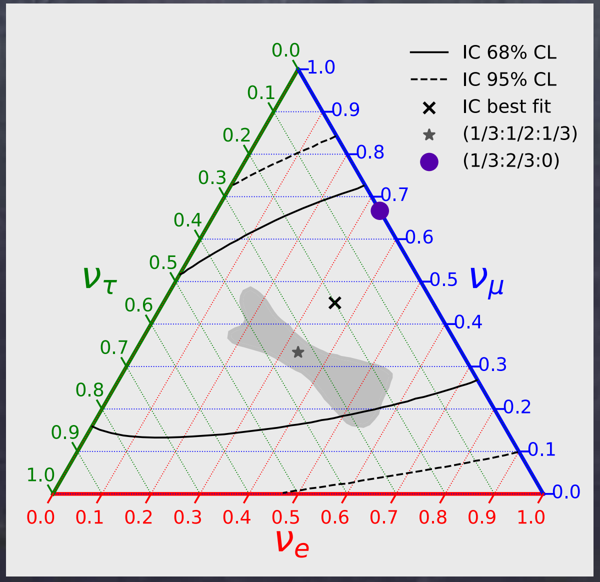


Resonance in active-sterile neutrino mixing: modifies observed spectrum

O. G. Miranda, C. A. Moura and A. Parada, Phys. Lett. B744:55, 2015

Alter flavor ratios

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



Preserve flavor ratios of high-energy neutrinos

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

Introduce energy dependence on flavor ratios

S. Karmakar, S. Pandey and S. Rakshit, arXiv:2010.07336

Dark matter scattering in IceCube

Boosted DM

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

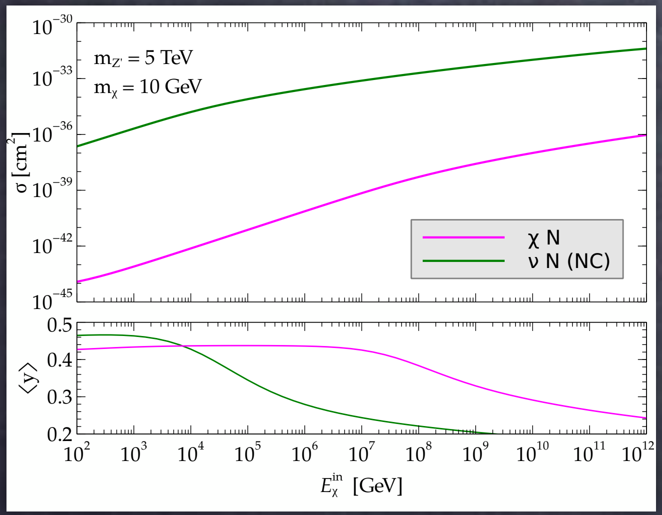
DM composed of two particles:

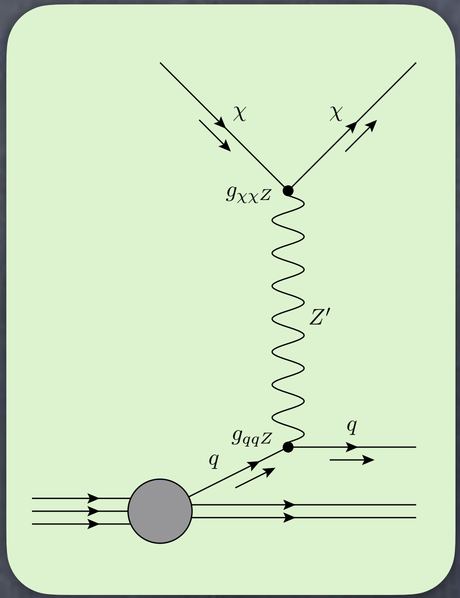
a dominant contribution with a mass m_ϕ= few PeV

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

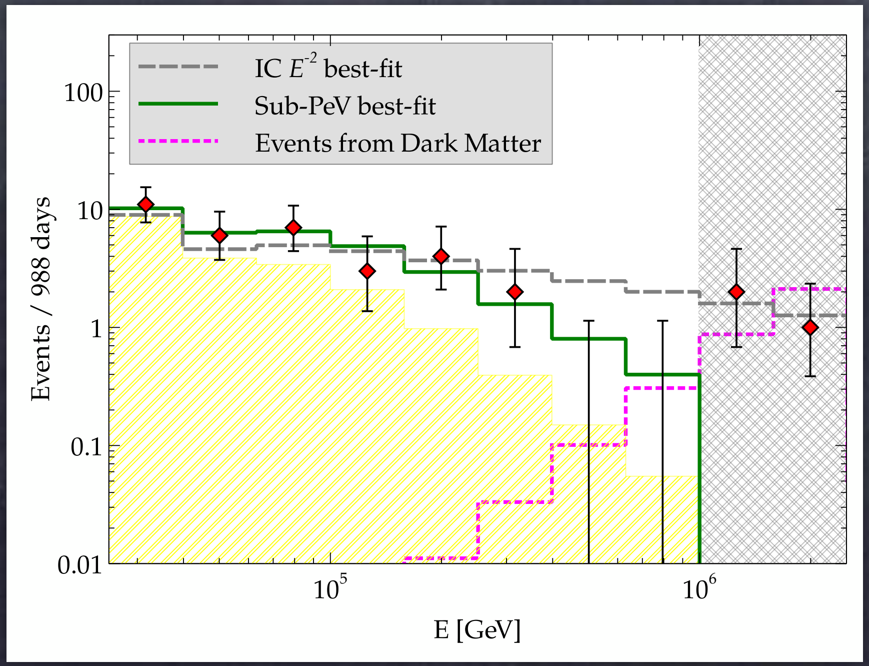
undistinguishable from NC neutrino interactions





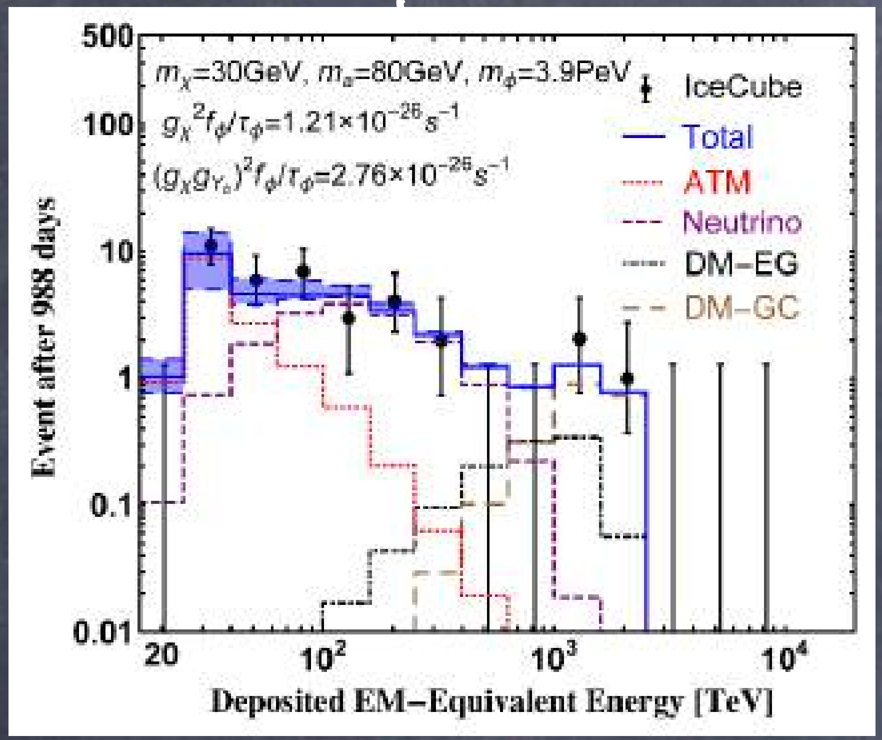
To explain PeV events

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



Dark matter scattering in IceCube

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



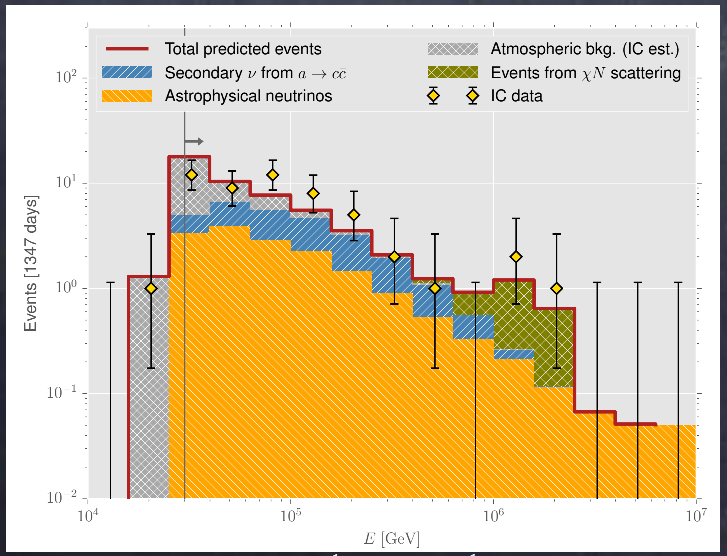
J. Kopp, J. Liu and X.-P. Wang, JHEP 1504:105, 2015

no need of astro neutrinos
DM could explain all events!

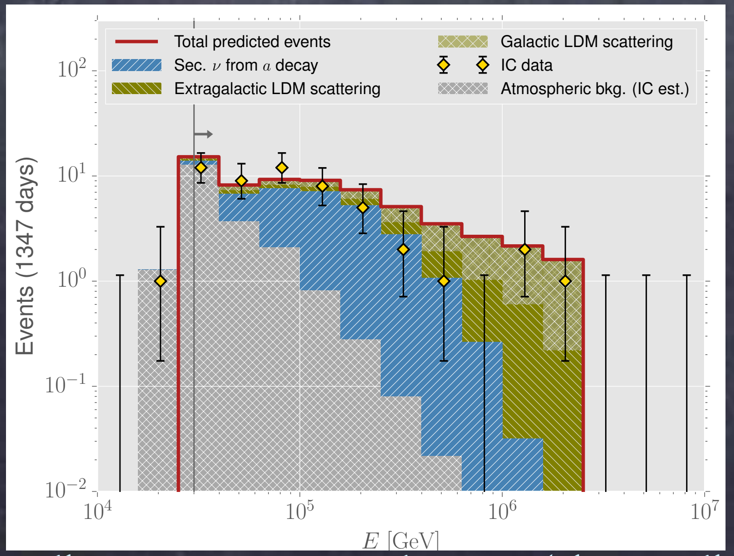
may even explain GC gamma-ray excess...

... but the scenario is less motivated after the first double cascade and GR events

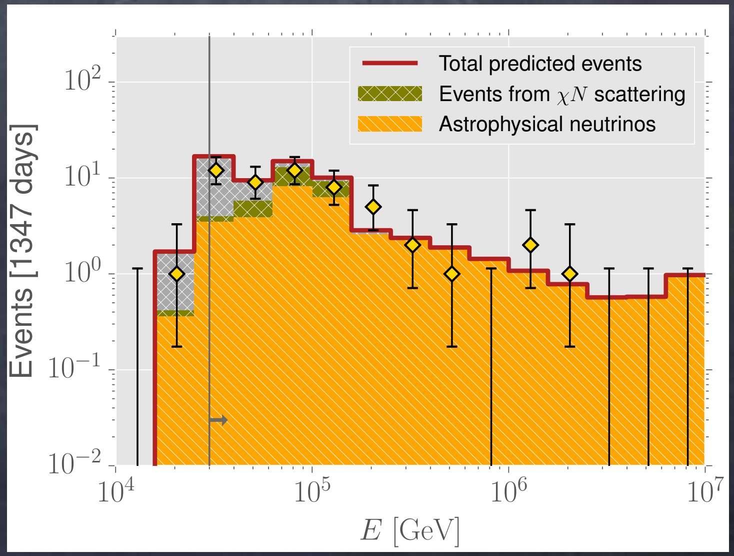
Scalar mediator



Light vector mediator



Pseudo-scalar mediator lower DM mass



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

Conclusions

In addition to be produced by standard mechanisms, high-energy neutrinos could be produced by DM decays/annihilations

IC data is compatible with a contribution from DM decays (annihilations?)

DM decays could explain the ~100 TeV HESE data (although some tension with gamma-ray data)

+

hard astrophysical spectrum could explain higher energy events (in agreement with through-going muon data)

Neutrino data set the strongest limits on the DM lifetime for hard channels (m > 100 TeV)

Many (potential) neutrino-dark matter connections can be tested with high-energy neutrinos

Thanks for your attention!

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