Probing heavy dark matter with IceCube HESE data

Sergio Palomares-Ruiz

IFIC, CSIC-U. València

CSIC

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

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VIRTUAL CONFERENCE
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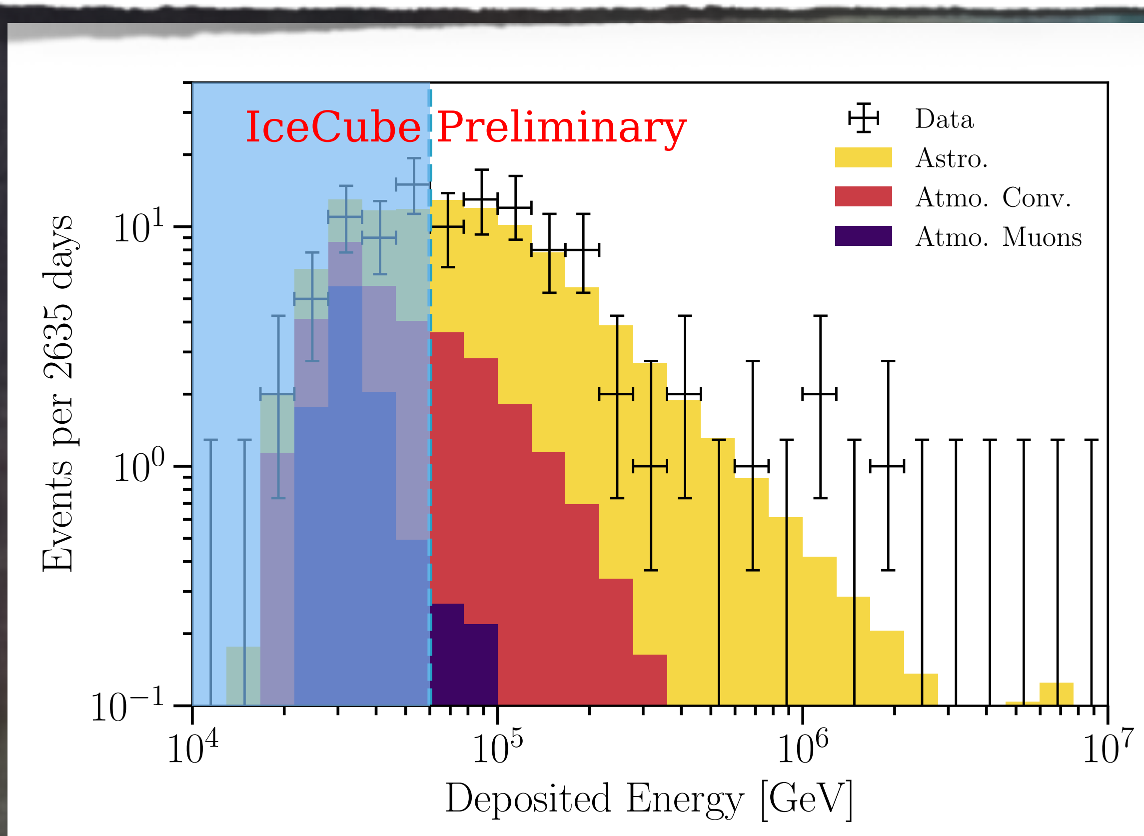
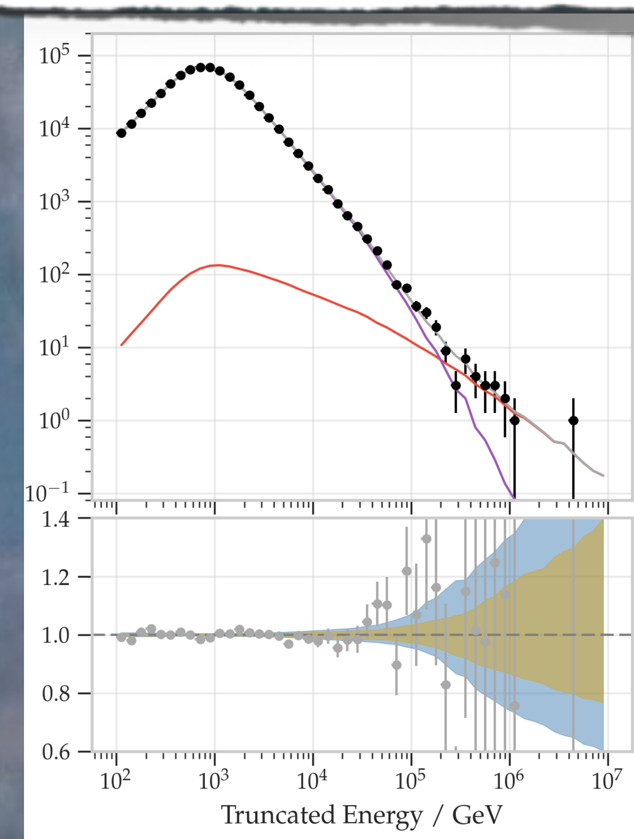
PRAGUE, CZECH REPUBLIC

July 29, 2020

High-energy neutrino flux

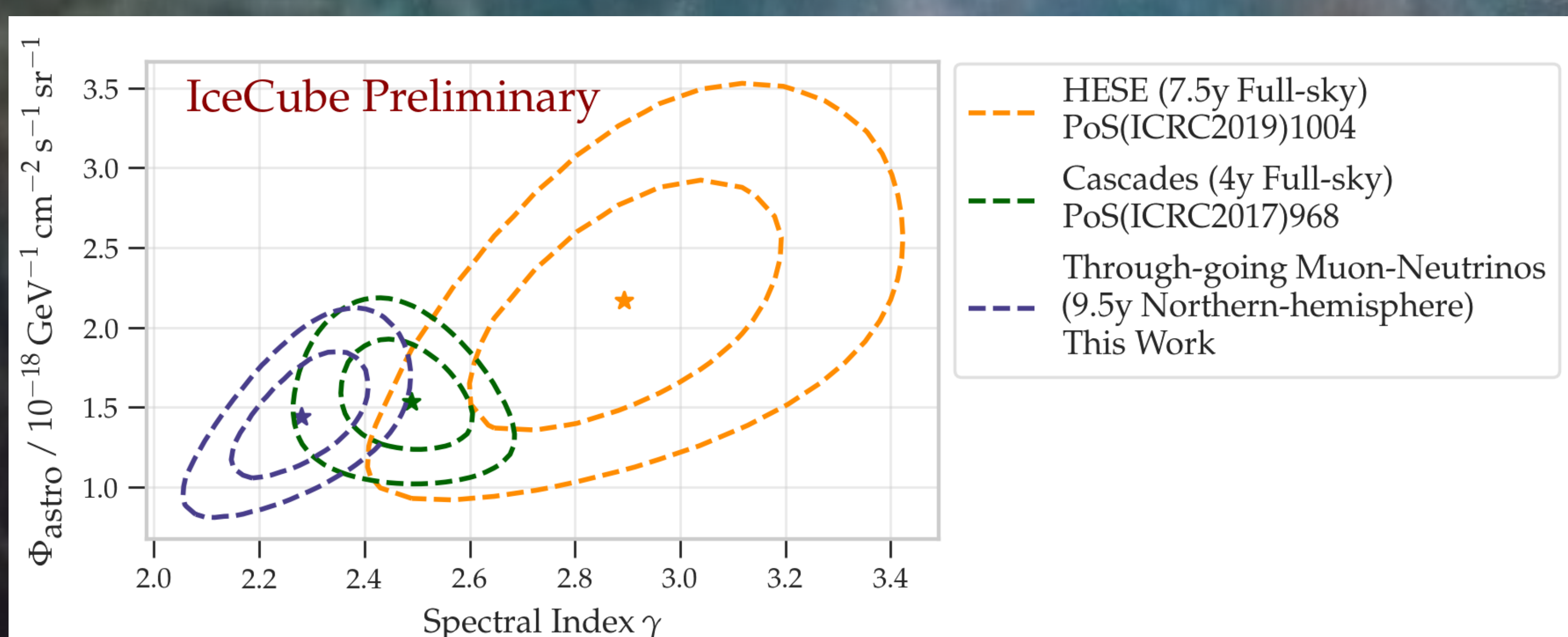
Two types of searches: contained events and through-going muons





A. Schneider [IceCube Collaboration], PoS (ICRC2019) 1004

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



D. N. Williams [IceCube Collaboration], PoS (ICRC2019) 016

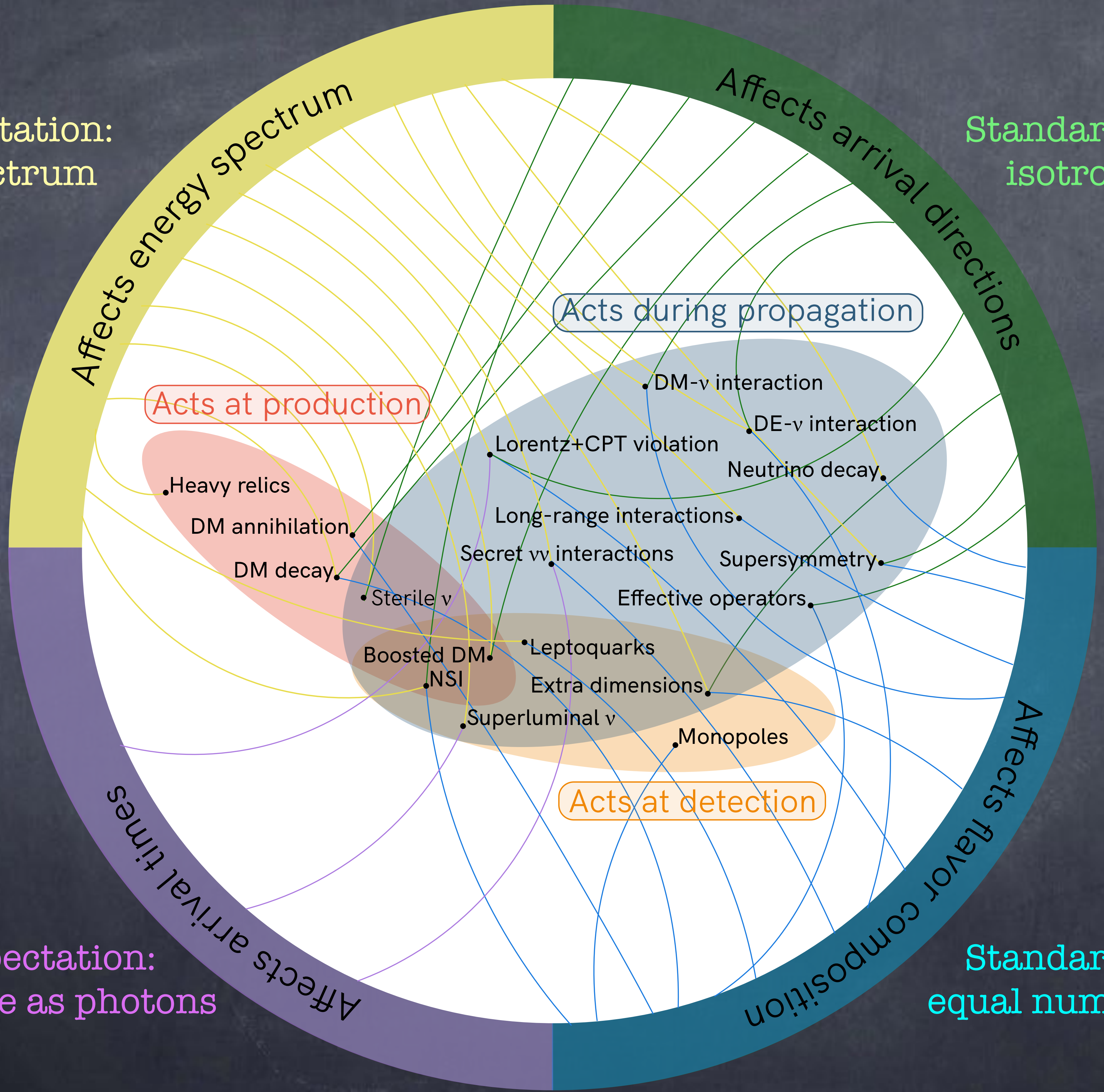
$$\frac{d\Phi}{dE_\nu} = \phi \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma}$$

Note: Not an exhaustive list of scenarios

New physics

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

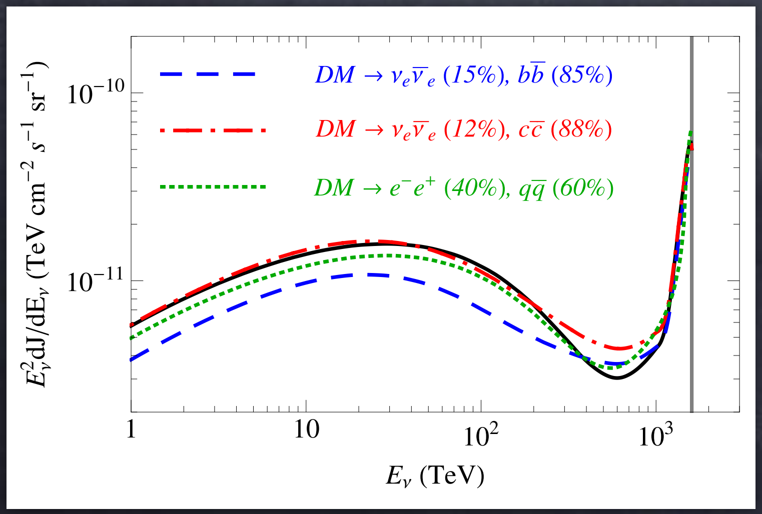
Dark matter decays

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

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

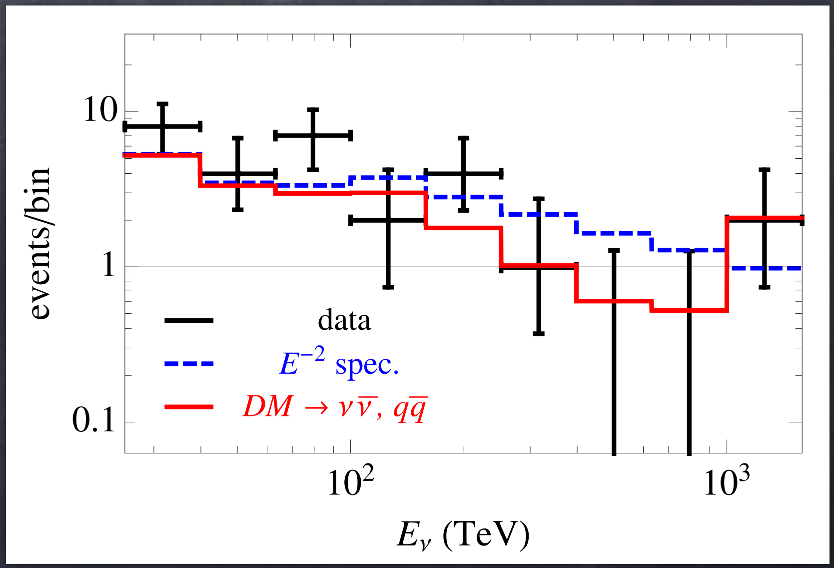
B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, Phys, Rev. D88:015004, 2013

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



combination of soft and hard channels

2-year HESE data



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

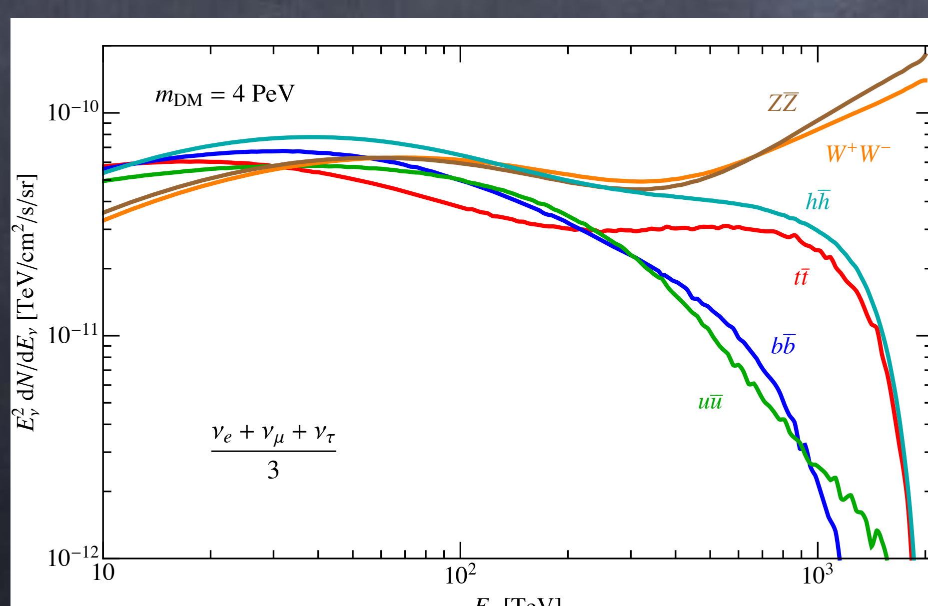
neutrino flux at production

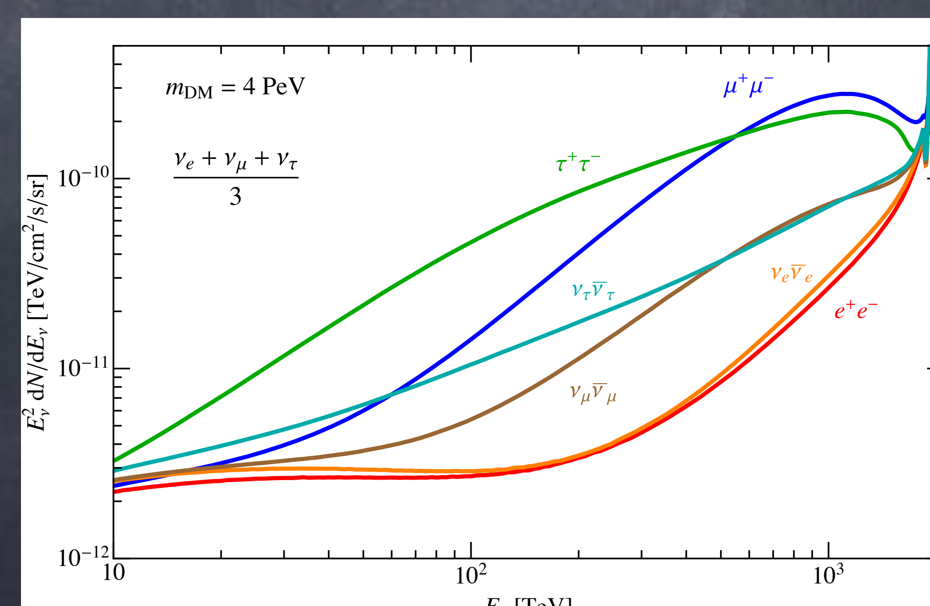
DM galactic density

DM density

Hubble function

energy redshift





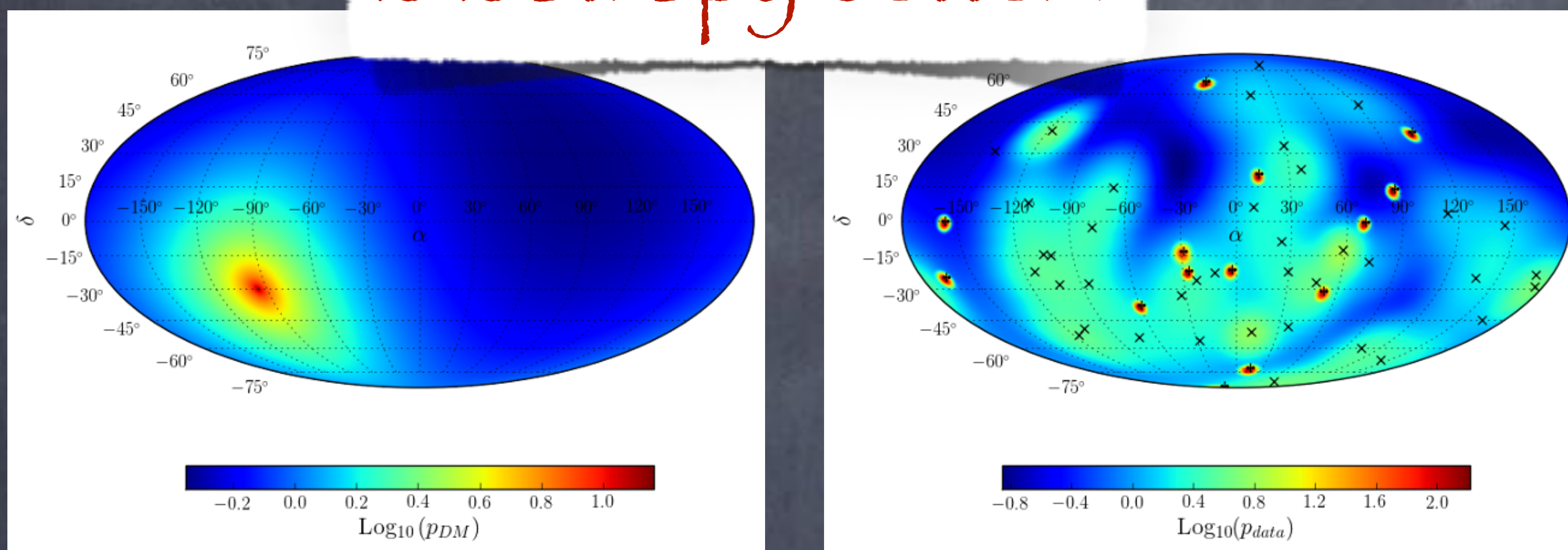
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 1707:027, 2017

Dark matter decays

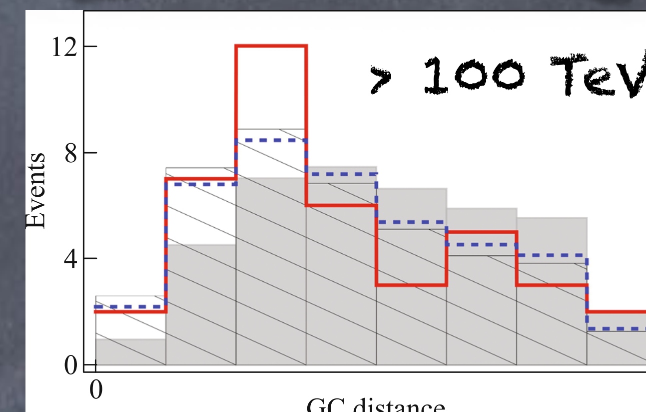
Are neutrinos from DM decays compatible with the angular distribution of the IceCube events?

is isotropy better?

is DM better?

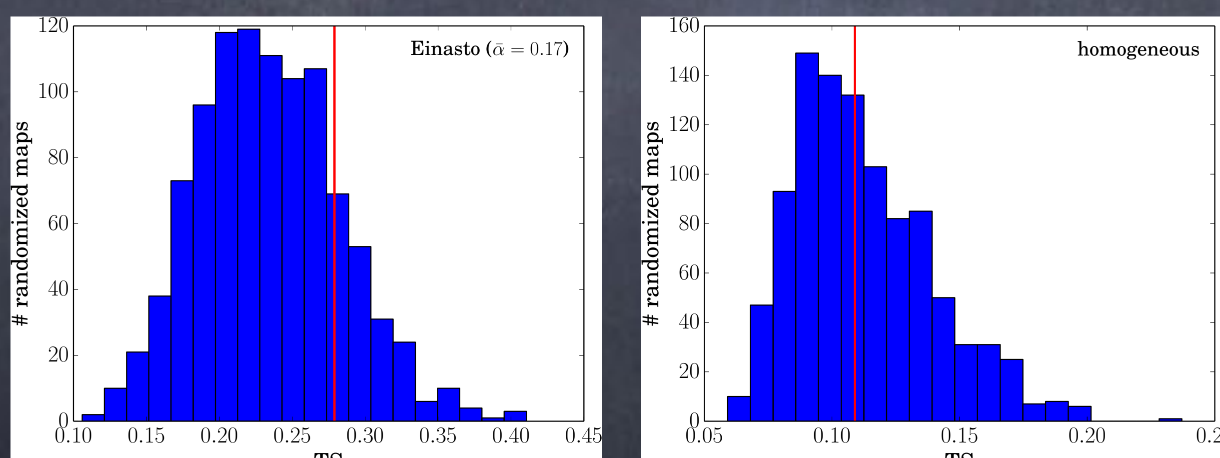


Y. Bai, R. Lu and J. Salvado, JHEP 1601:161, 2016



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

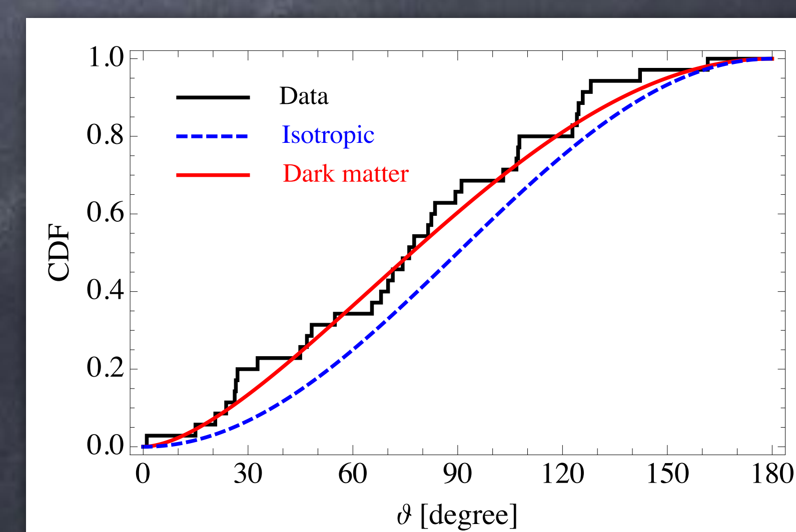
only galactic contribution



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



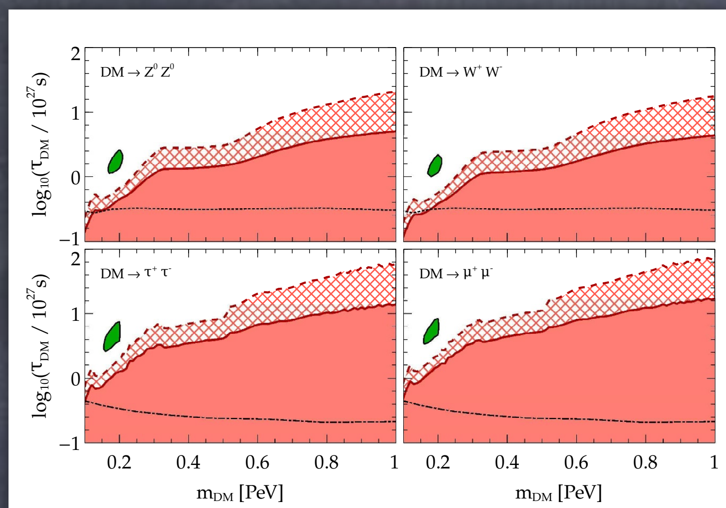
A. Esmaili, S. K. Kang and P. D. Serpico, JCAP 1412:054, 2014

Dark matter decays (+astro)

several energy spectrum analyses

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

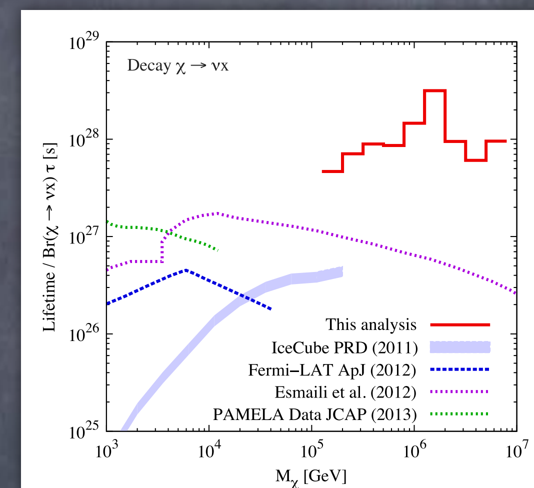
Low energies: DM+astro (index=2)



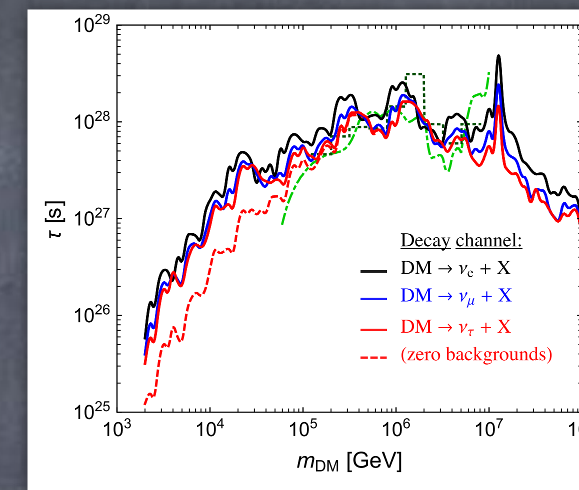
A. Bhattacharya, M. H. Reno and I. Sarcevic, JHEP 1406:110, 2014

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

limits on monochromatic decays

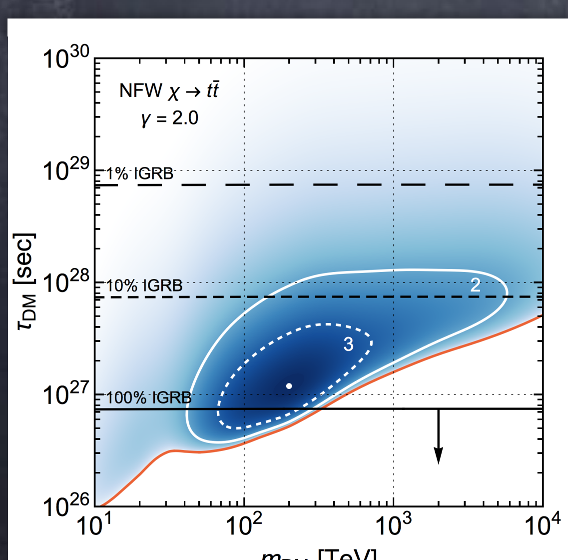


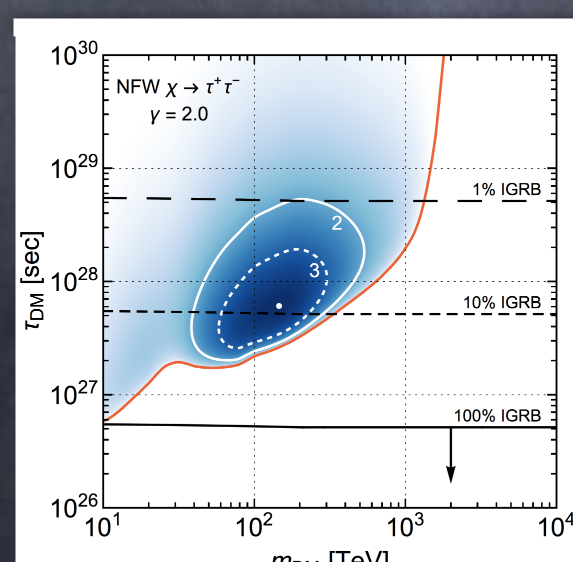
C. Rott, K. Kohri and S. C. Park, Phys. Rev. D92:023529, 2015



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

Low energies (MESE), fixing astro index





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

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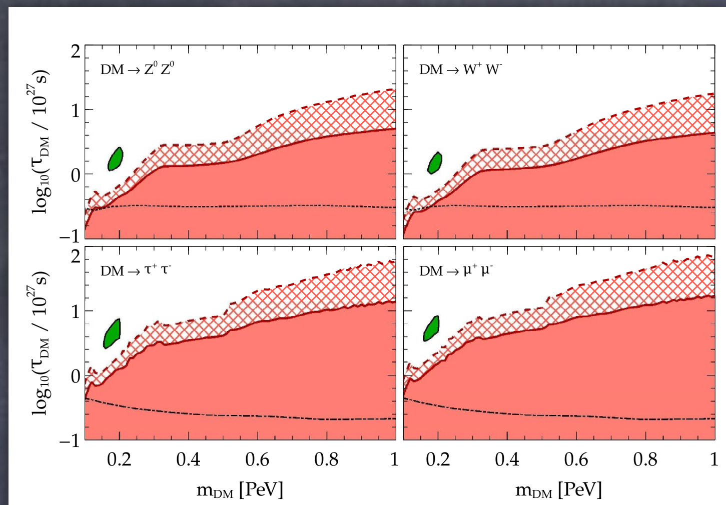

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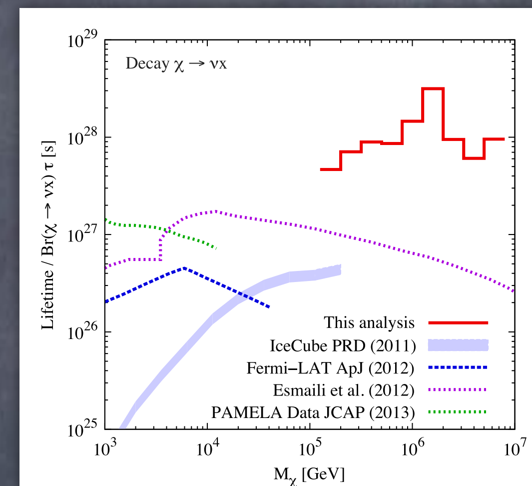

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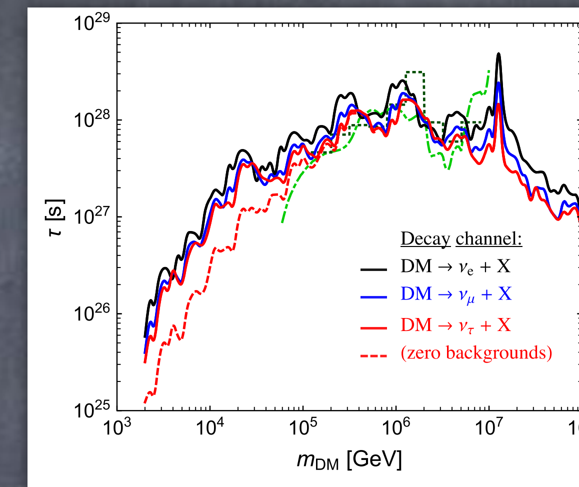
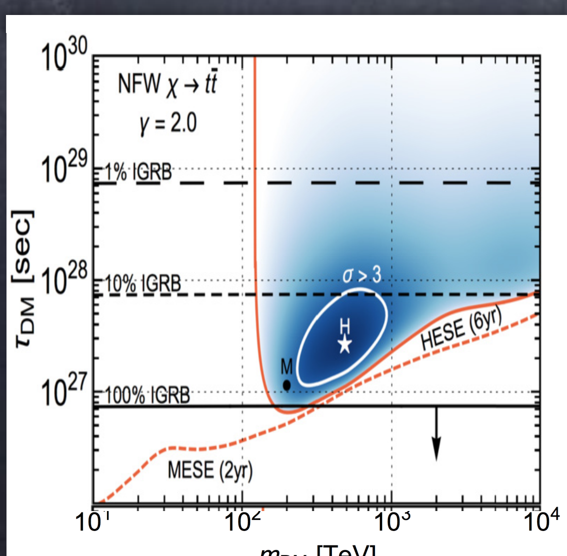
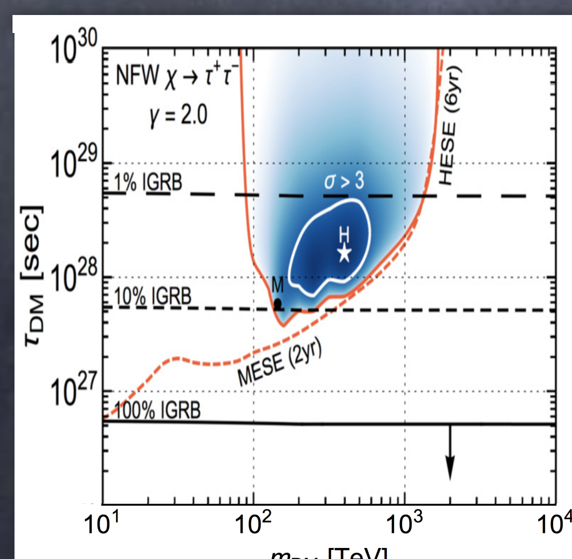


C. El Aisati, M. Gustafsson and T. Hambye, Phys. Rev. D92:123515, 2015

HESE 6-yr, fixing astro index





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

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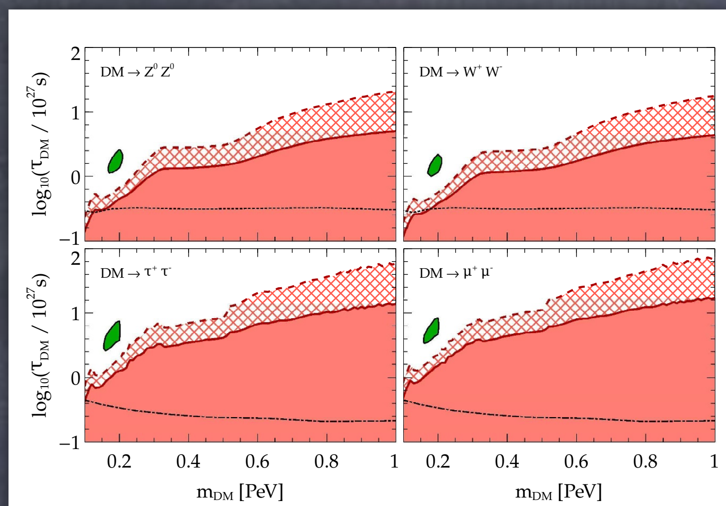

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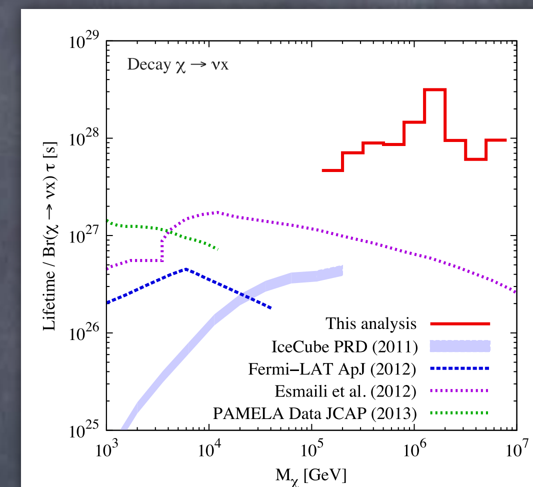

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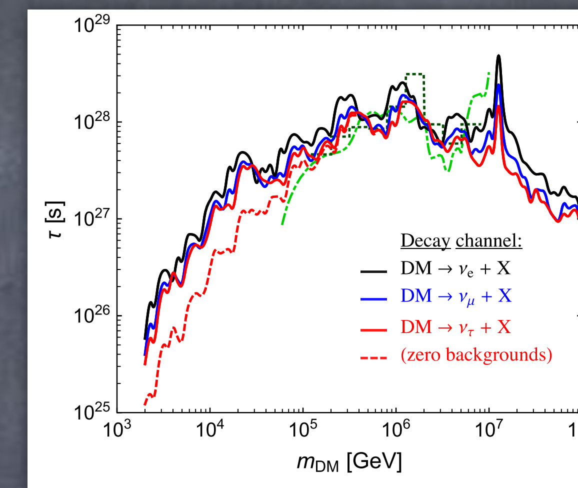

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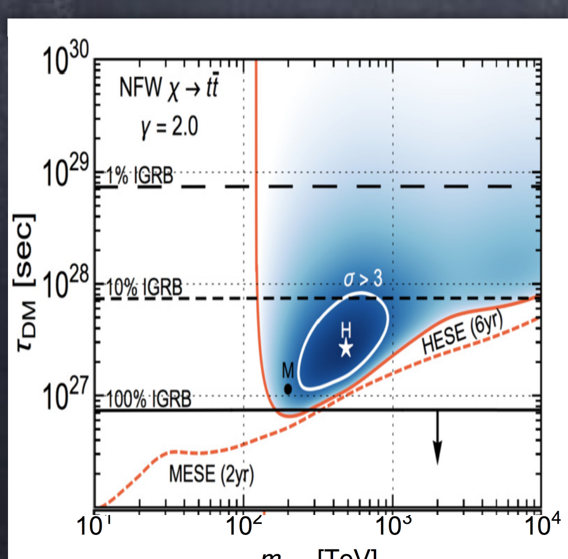
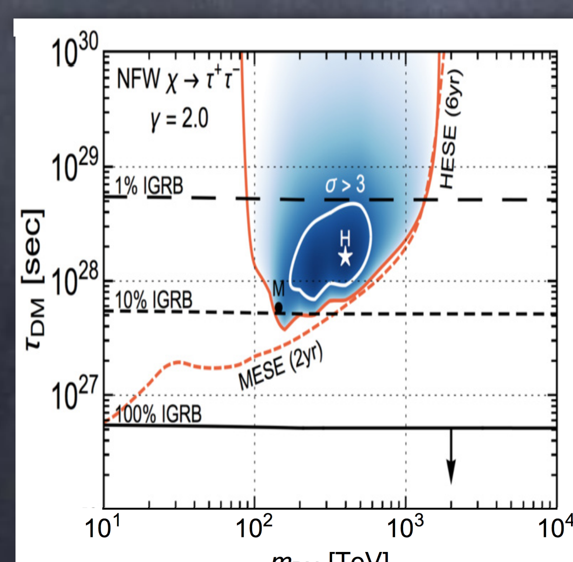
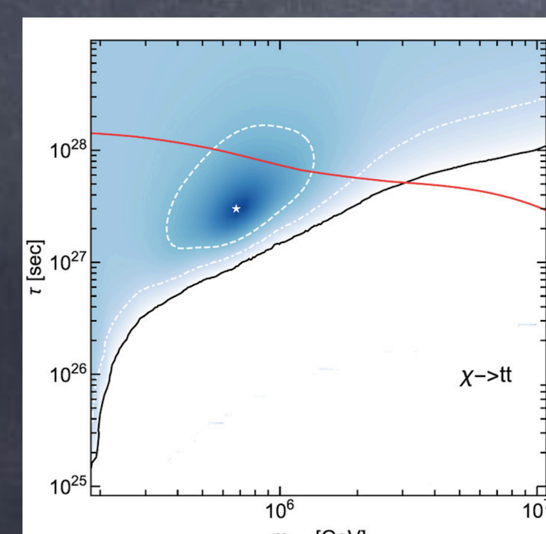
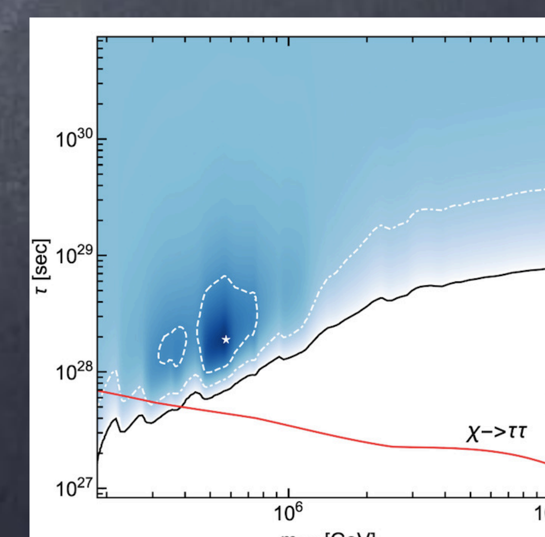




M. Chianese, G. Miele and S. Morisi, Phys. Lett. B773:591, 2017

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

Dark matter decays: gamma-ray bounds

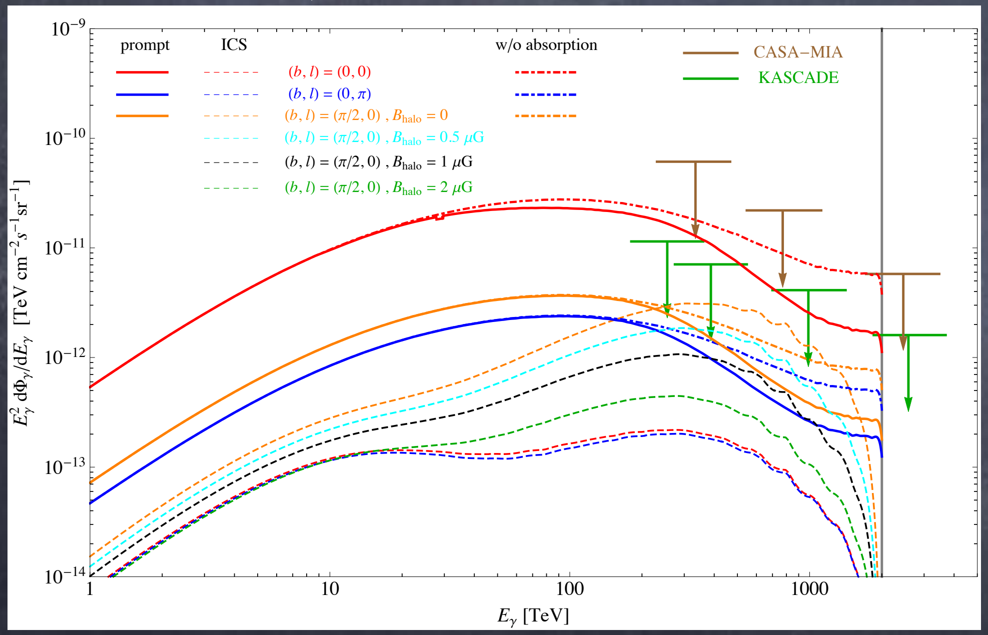
The neutrino spectrum from DM decays is accompanied by a gamma-ray spectrum

However, at energies E > 10-100 TeV, the Universe is opaque 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

It may seem to be OK....



A. Esmaili and P. D. Serpico, JCAP 1510:014, 2015

See also: M. Cirelli et al., Phys. Rev. D86:083506, 2012
K. Murase and J. F. Beacom, JCAP 1201:043, 2012
K. Murase et al., Phys. Rev. Lett. 115:071301, 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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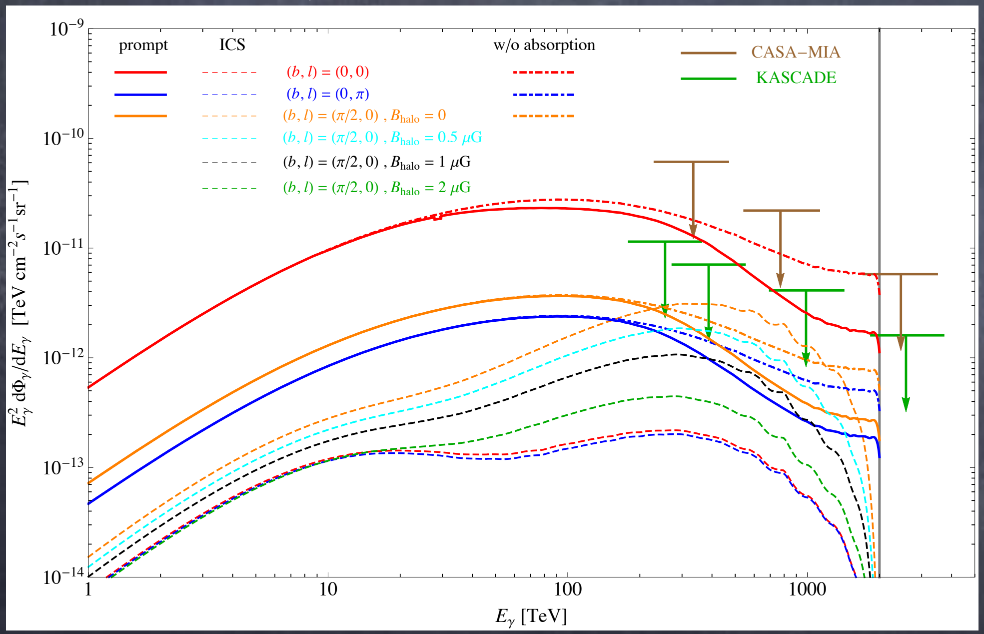
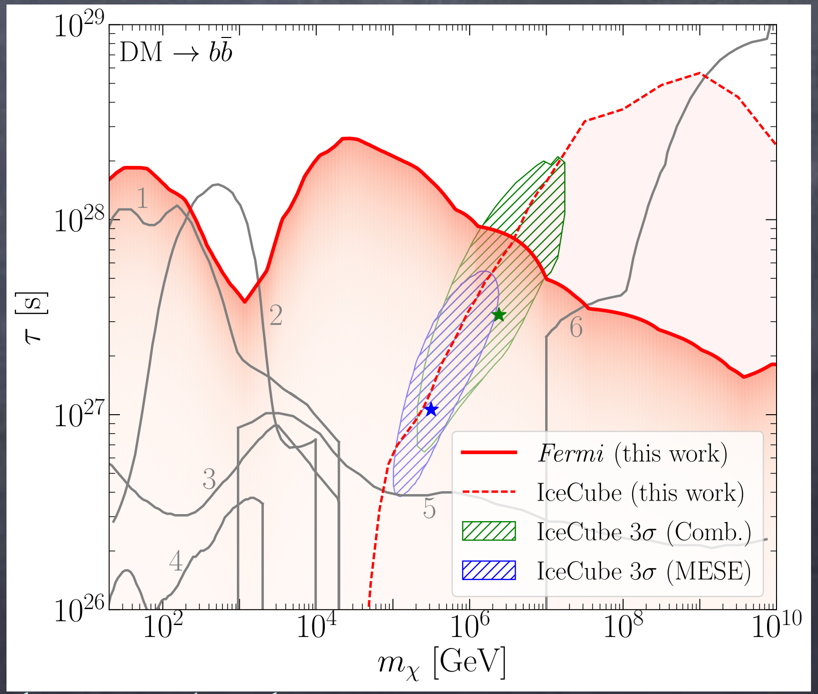


A. Esmaili and P. D. Serpico, JCAP 1510:014, 2015

...but tension for some channels....



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

See also: M. Cirelli et al., Phys. Rev. D86:083506, 2012
K. Murase and J. F. Beacom, JCAP 1201:043, 2012
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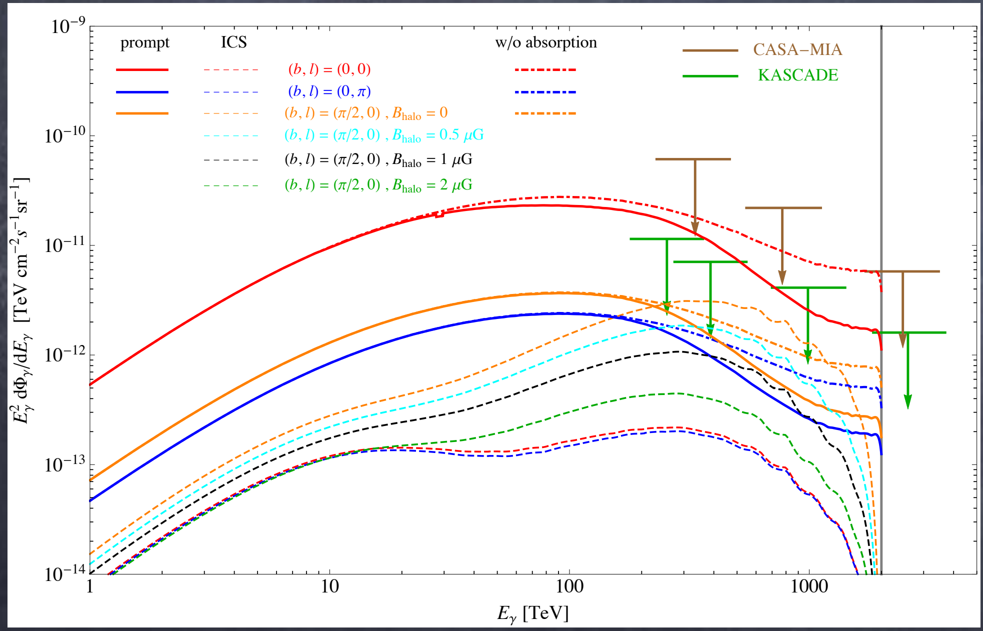

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See also: M. Cirelli et al., Phys. Rev. D86:083506, 2012
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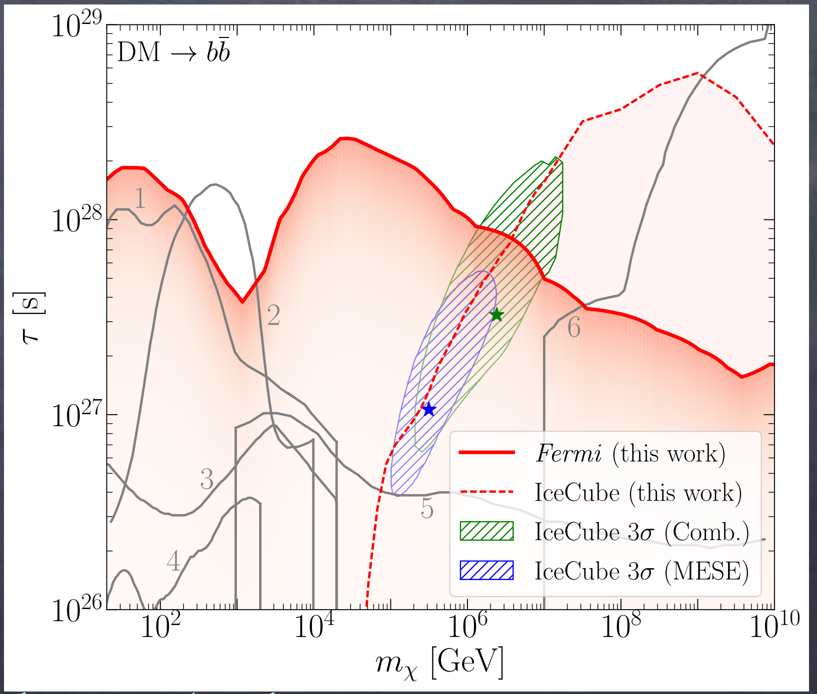
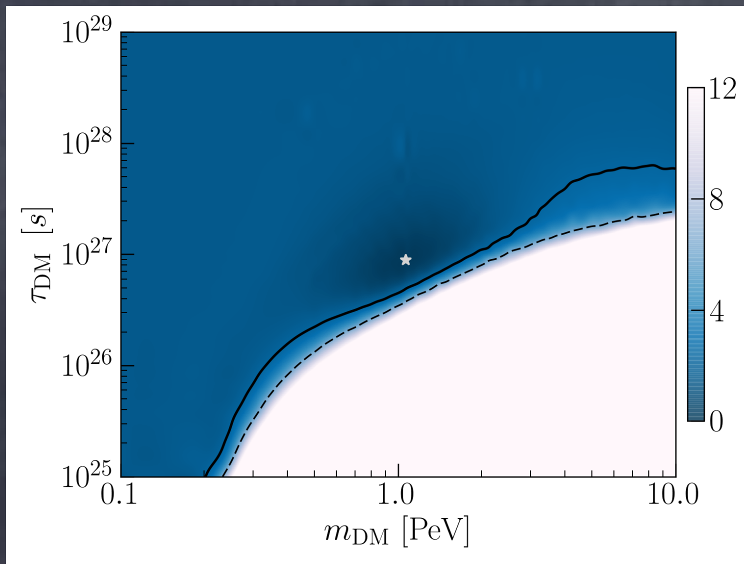


T. Cohen et al., Phys. Rev. Lett. 119:021102, 2017

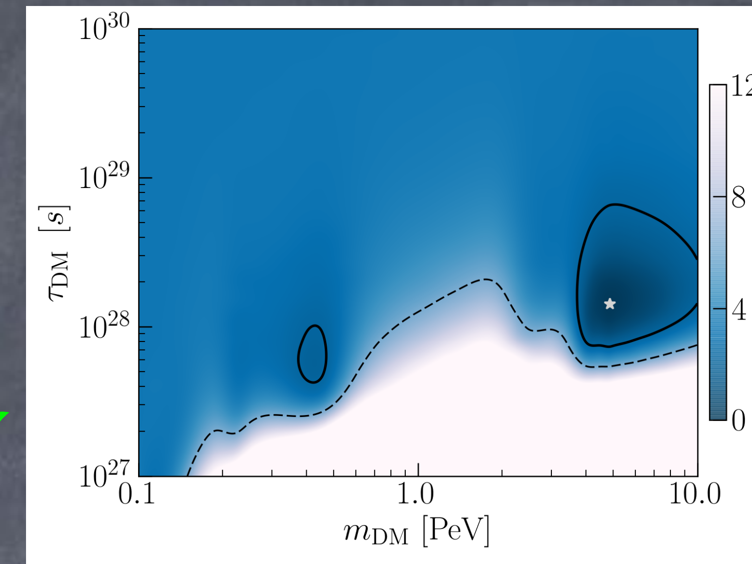
high-galactic latitude counterparts?

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

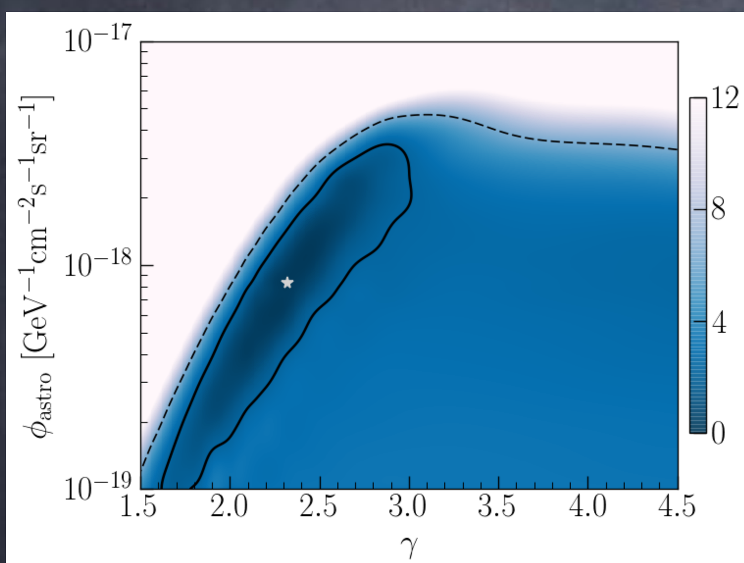
DM decays + Astro: 4-yr HESE analysis



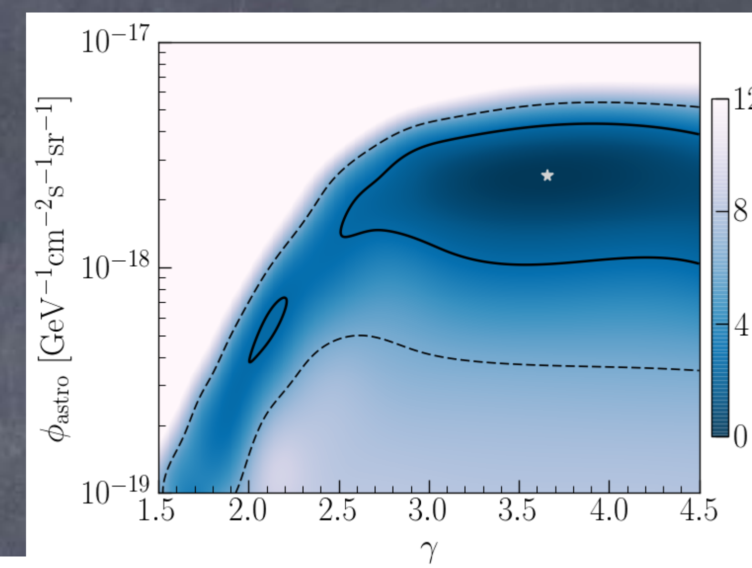
short lifetimes ✗
(problem with gamma-rays)



longer lifetimes ✓

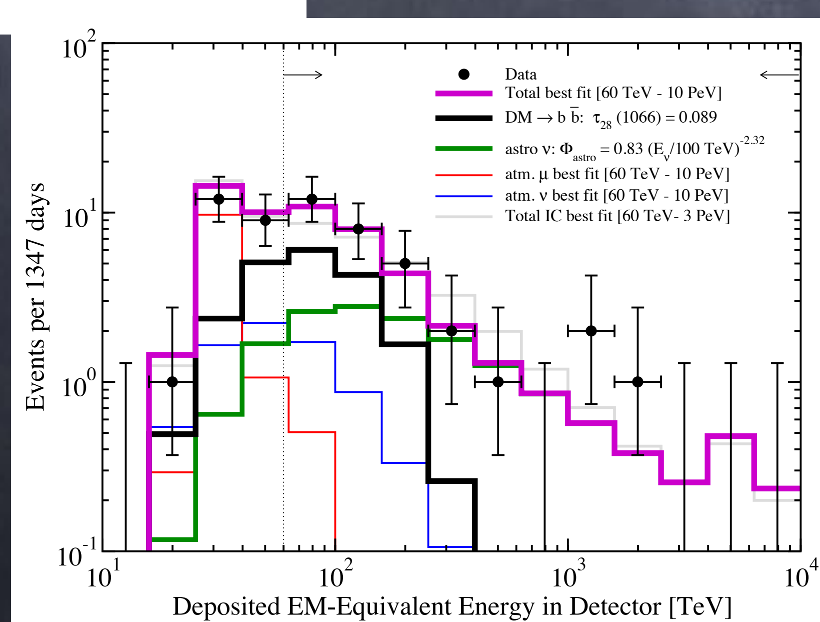


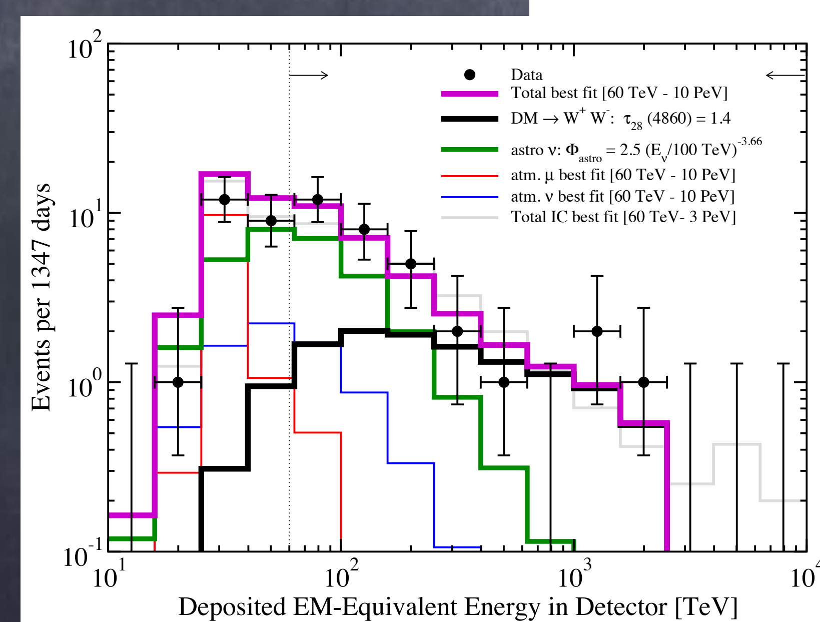
relatively hard astro spectrum ✓



very soft astro spectrum ✗

$DM \to b\bar{b}$

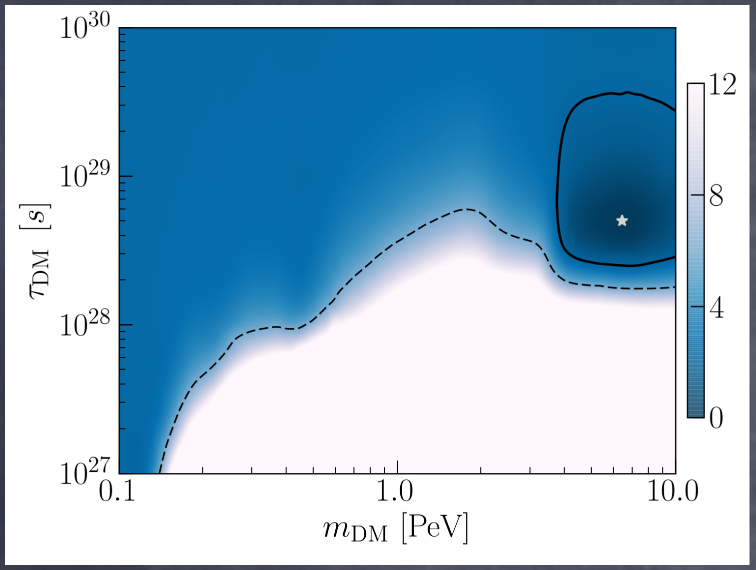




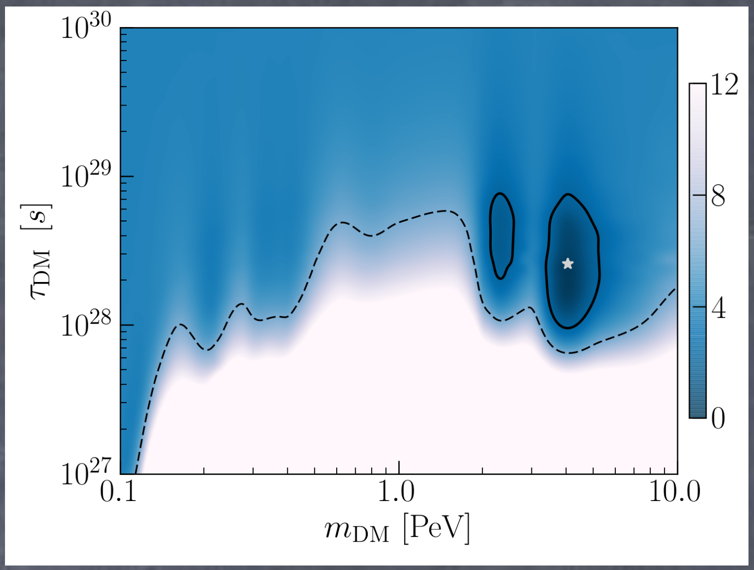
$DM \to W^+W^-$

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

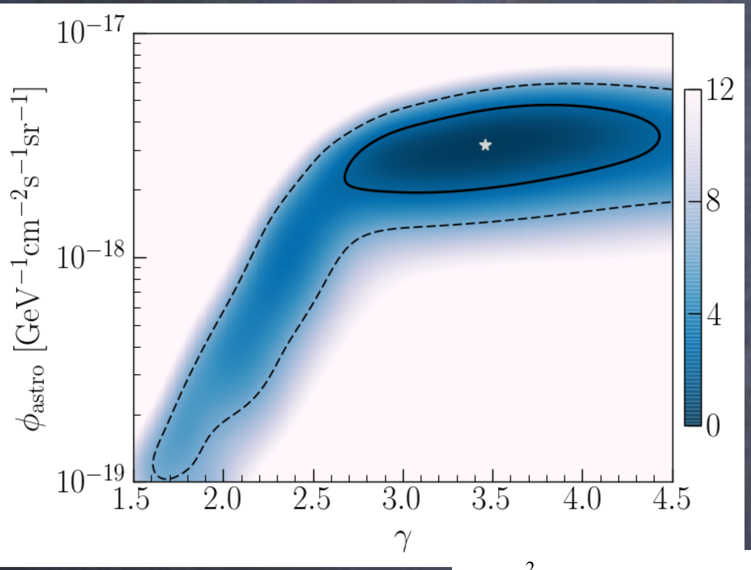
DM decays + Astro: 4-yr HESE analysis



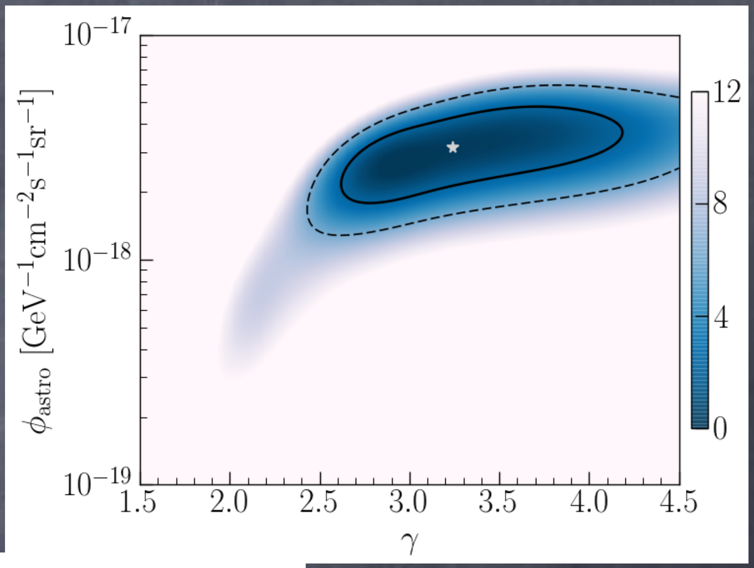
long lifetimes ✓



long lifetimes ✓

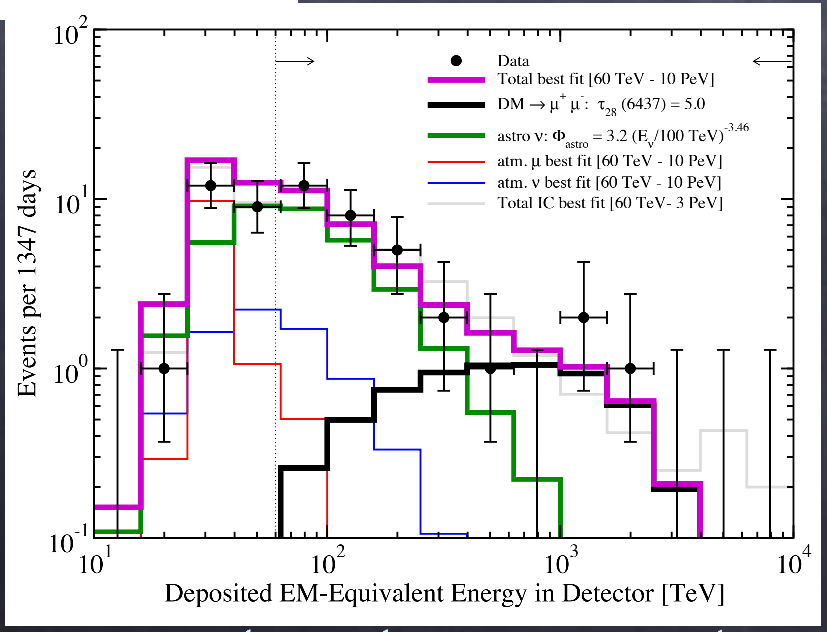


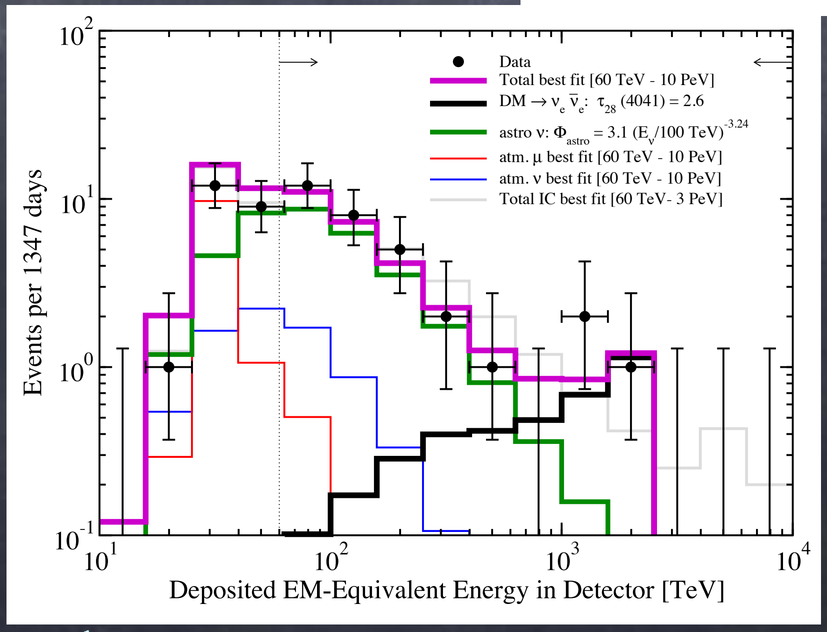
very soft astro spectrum ✗



very soft astro spectrum ✗

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



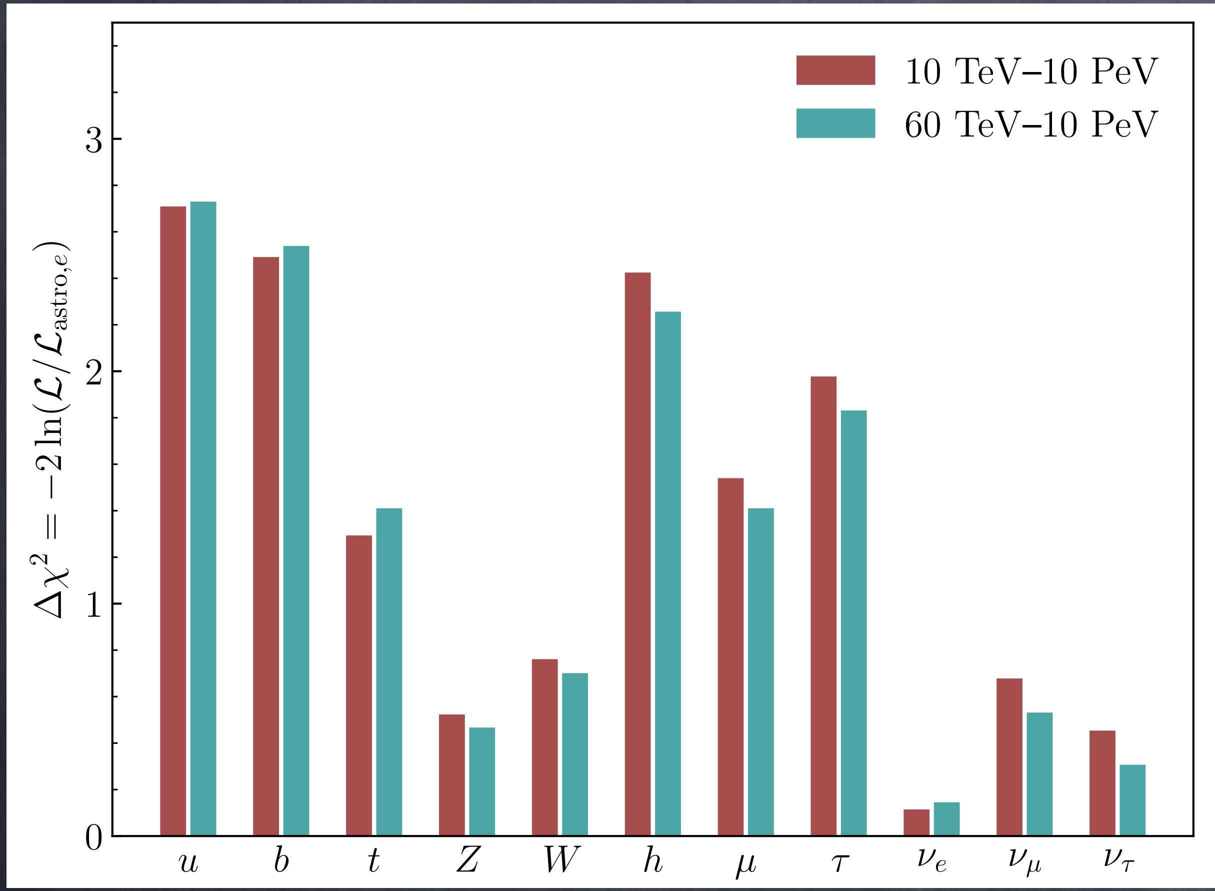


$DM \to \nu_e \bar{\nu}_e$

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^-



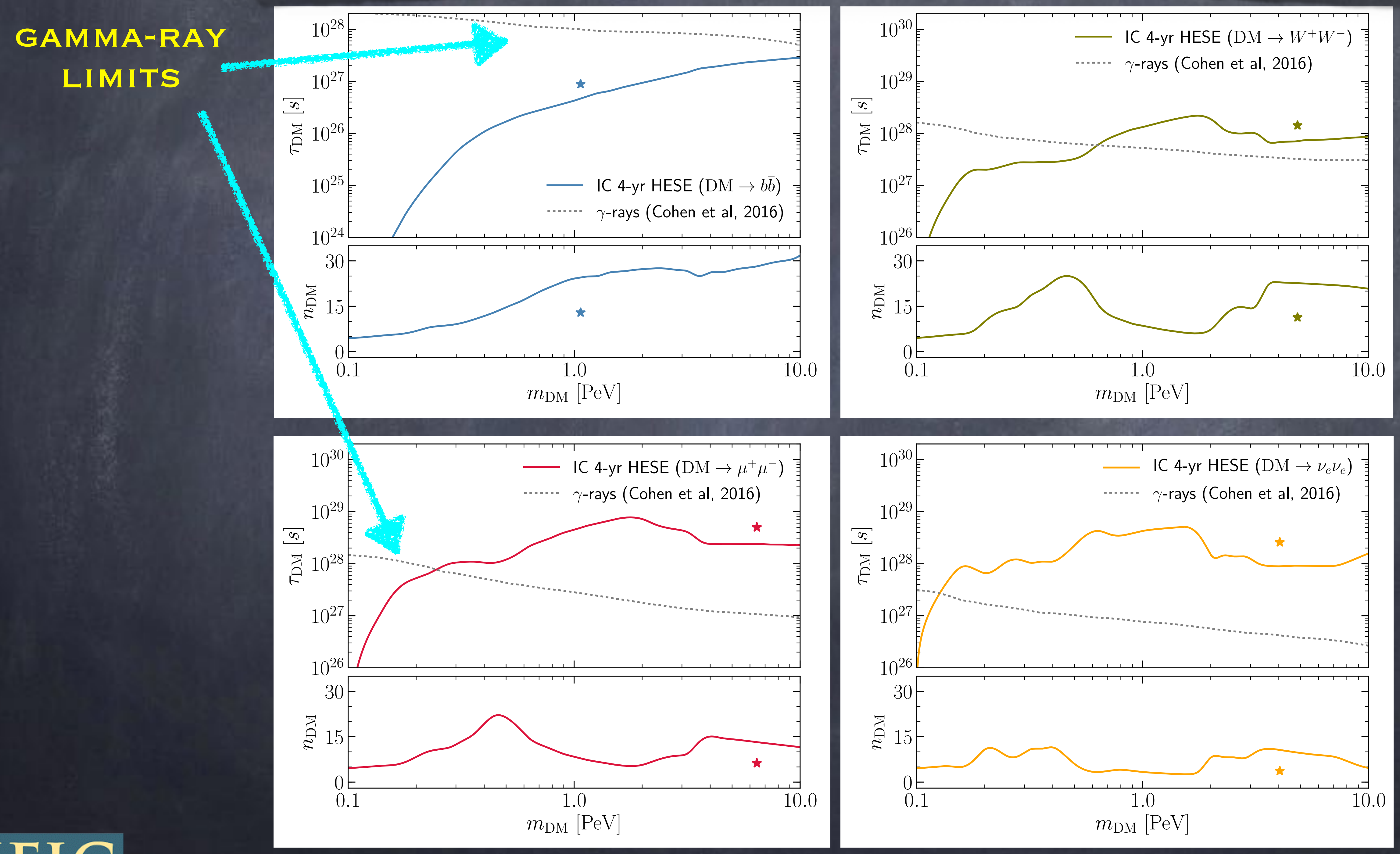
Decay channel	$N_{\rm DM}(\tau_{\rm DM}[10^{28}\,{\rm s}])$	$m_{\rm DM}$ [TeV]	$N_{\rm astro}(\phi_{\rm astro})$	γ
$u\,\bar{u}$	10.2 (0.021)	522	16.6 (1.2)	2.42
$b\,\bar{b}$	12.9 (0.089)	1066	13.8 (0.83)	2.32
$t\,\bar{t}$	16.1 (0.58)	11134	10.7 (1.9)	3.91
$W^+\,W^-$	11.3 (1.4)	4860	15.5 (2.5)	3.66
$Z\,Z$	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

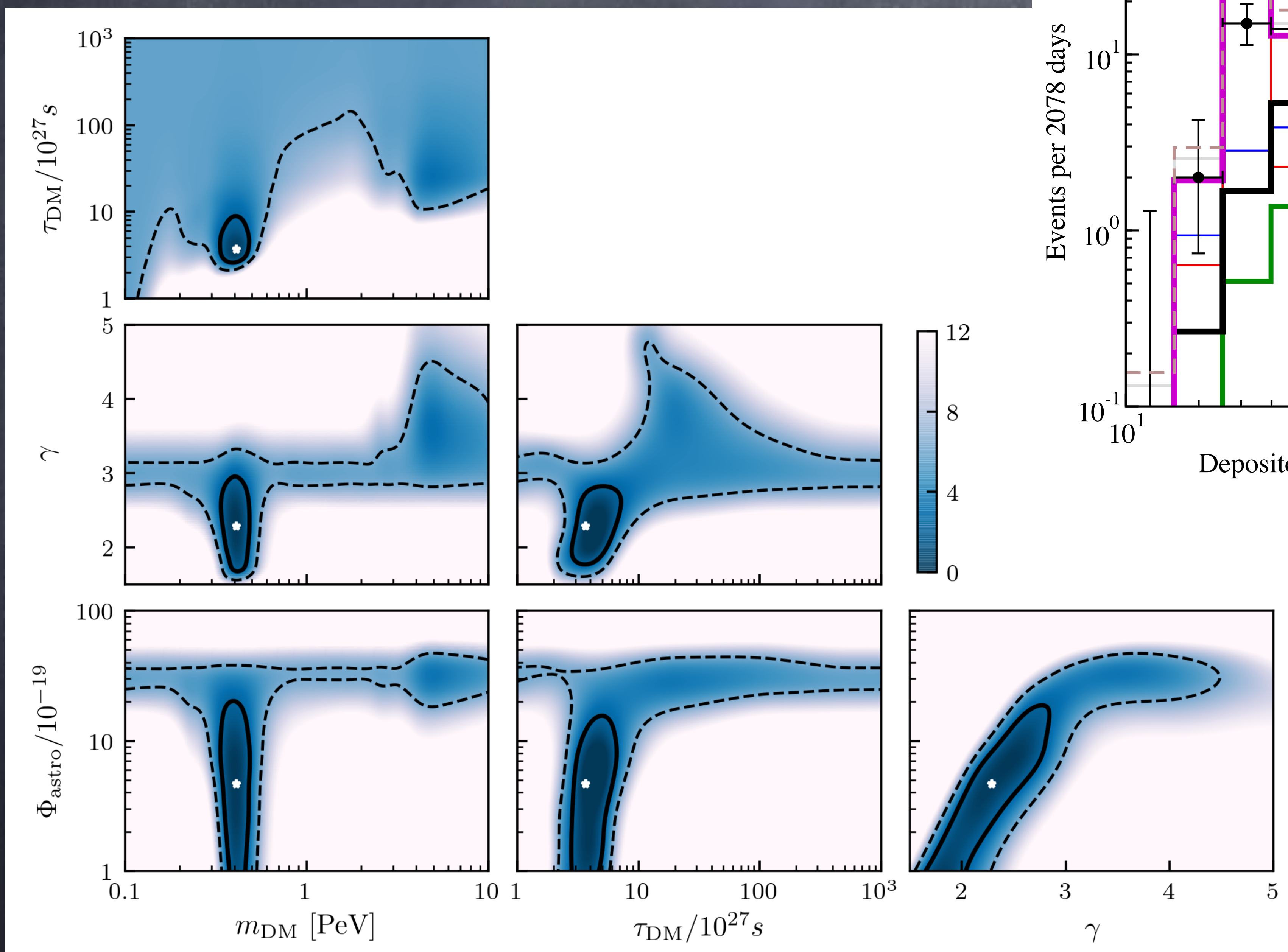
See also: A. Esmaili, A. Ibarra and O. L. G. Peres, JCAP 1211:034, 2012

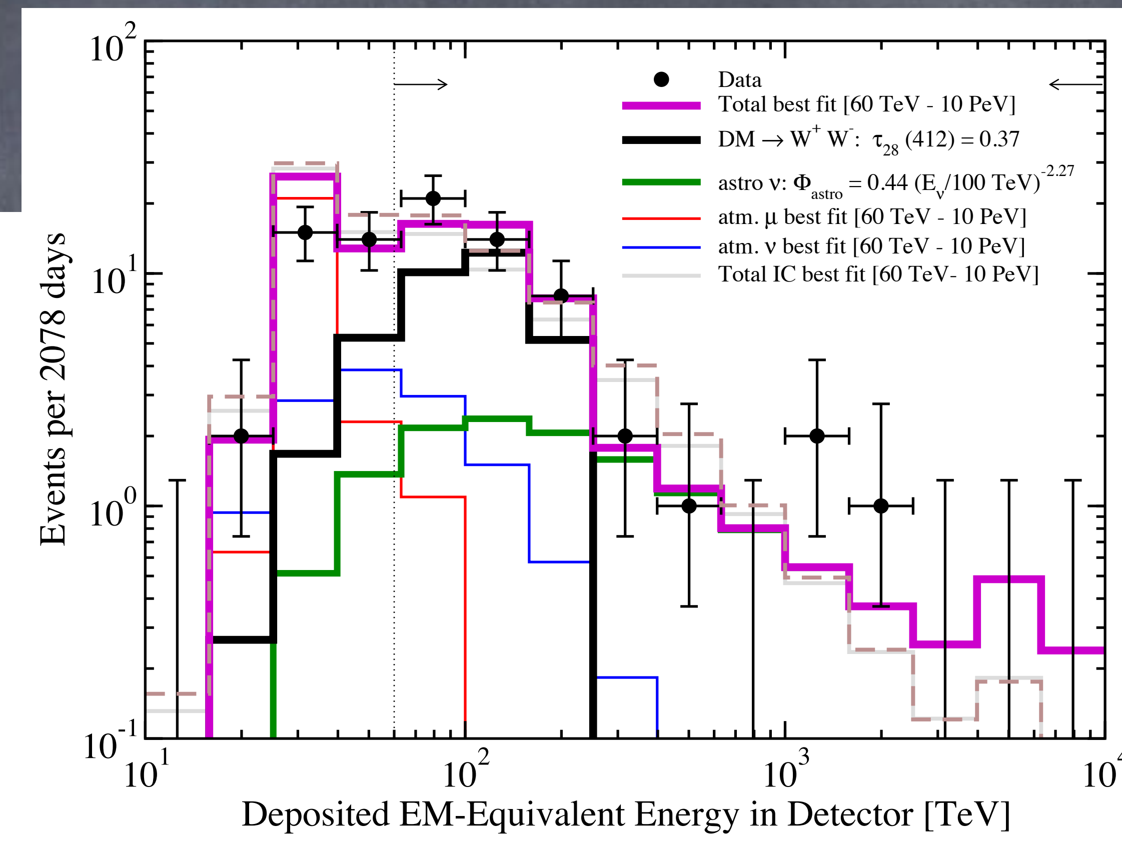
Neutrino limits are better than gamma-ray ones for relatively hard channels



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

DM decays + Astro: 6-yr HESE analysis

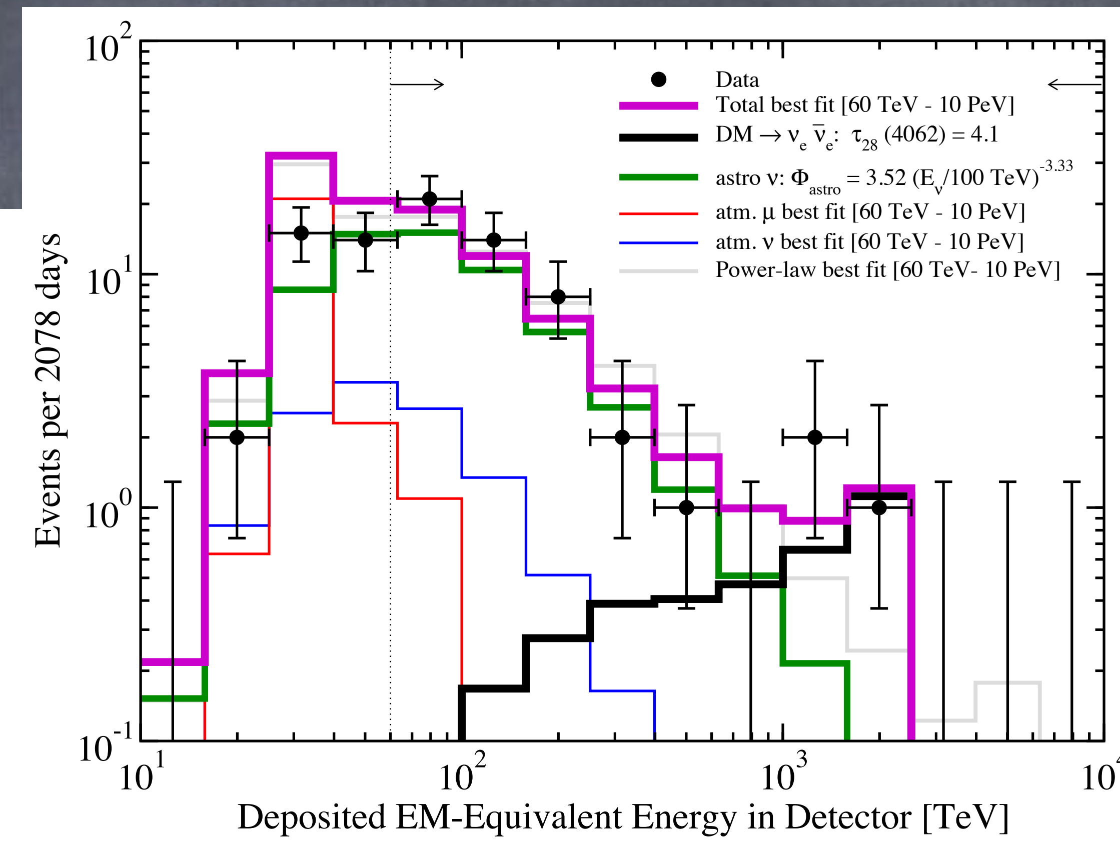


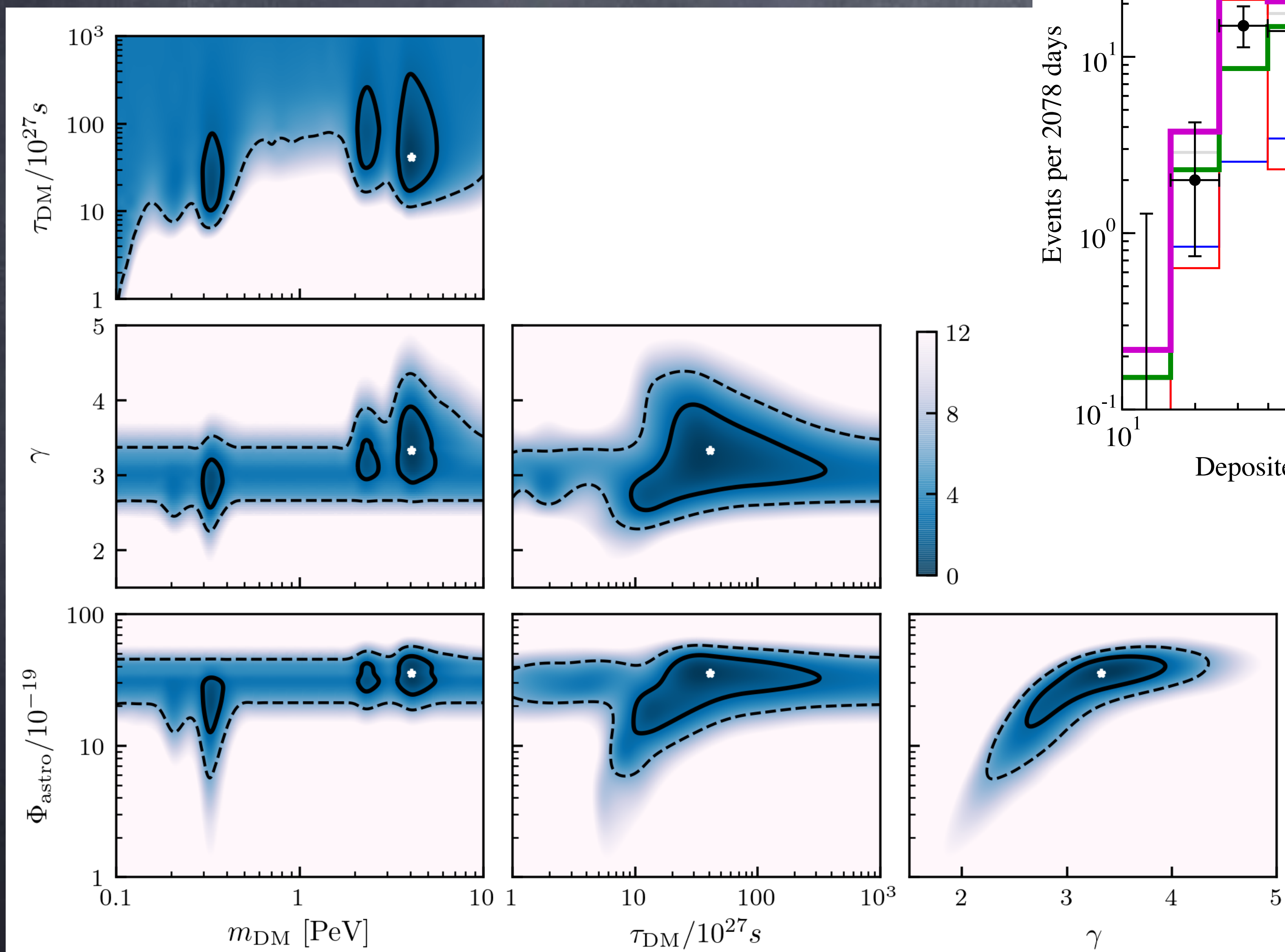


$DM \to W^+W^-$

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

DM decays + Astro: 6-yr HESE analysis



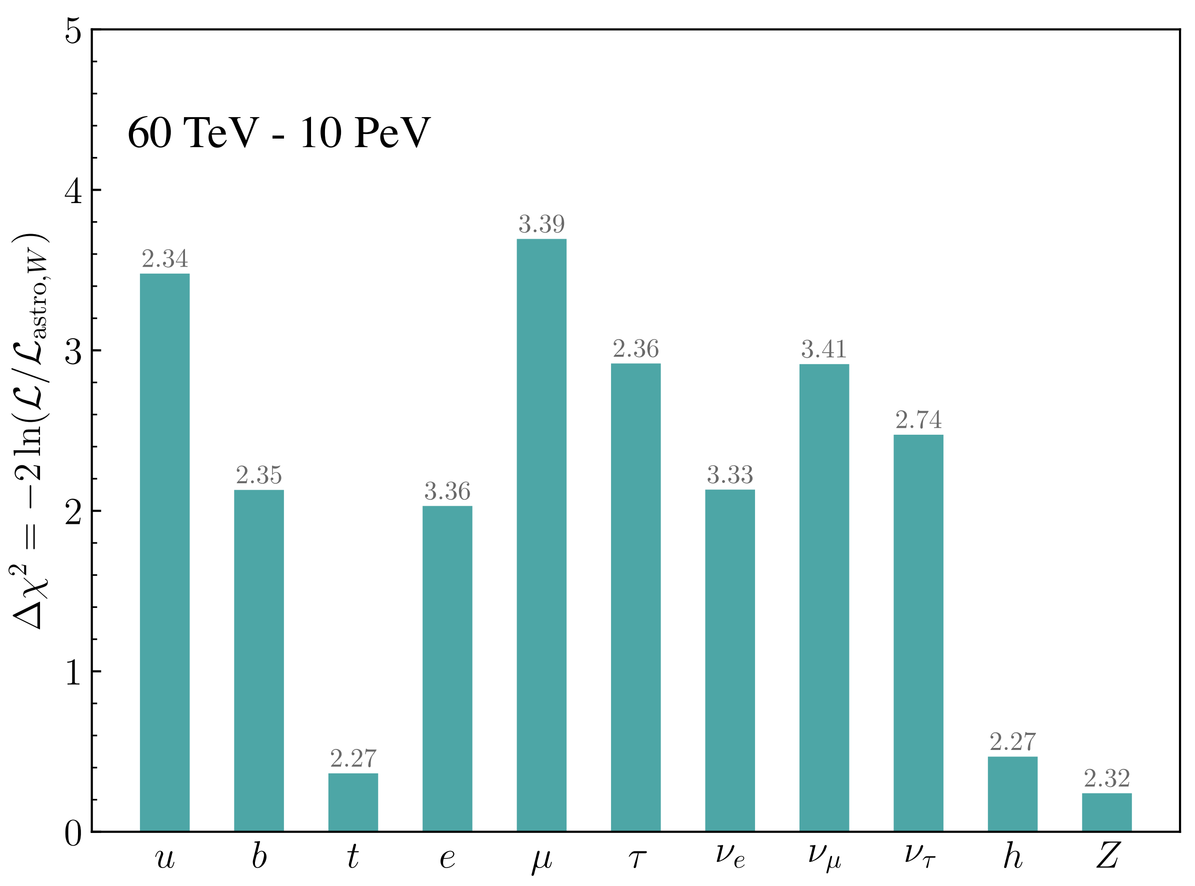


$DM \rightarrow \nu_e \bar{\nu}_e$

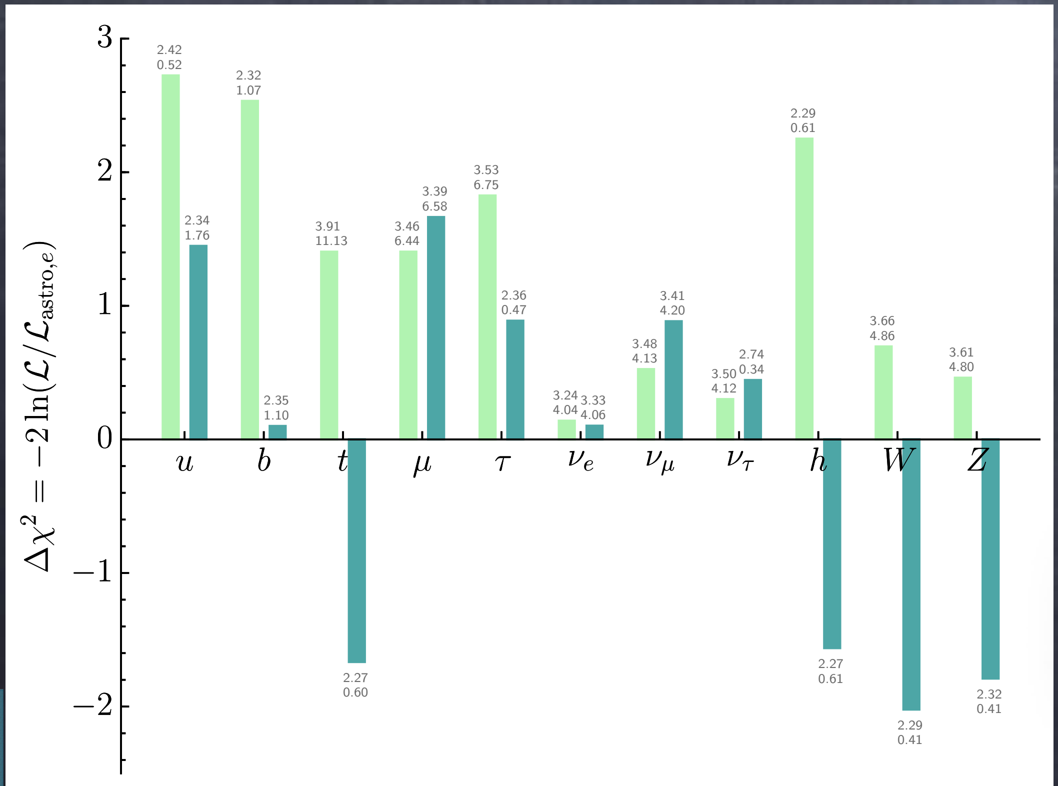
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

DM decays + Astro: 6-yr HESE analysis

Best fit: Astro (hard) + DM $\rightarrow W^+W^-$



Decay channel	$\tau_{\mathrm{DM}}[10^{28}$ s]	(N_{DM})	m_{DM} [TeV]	ϕ_{astro}	(N_{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



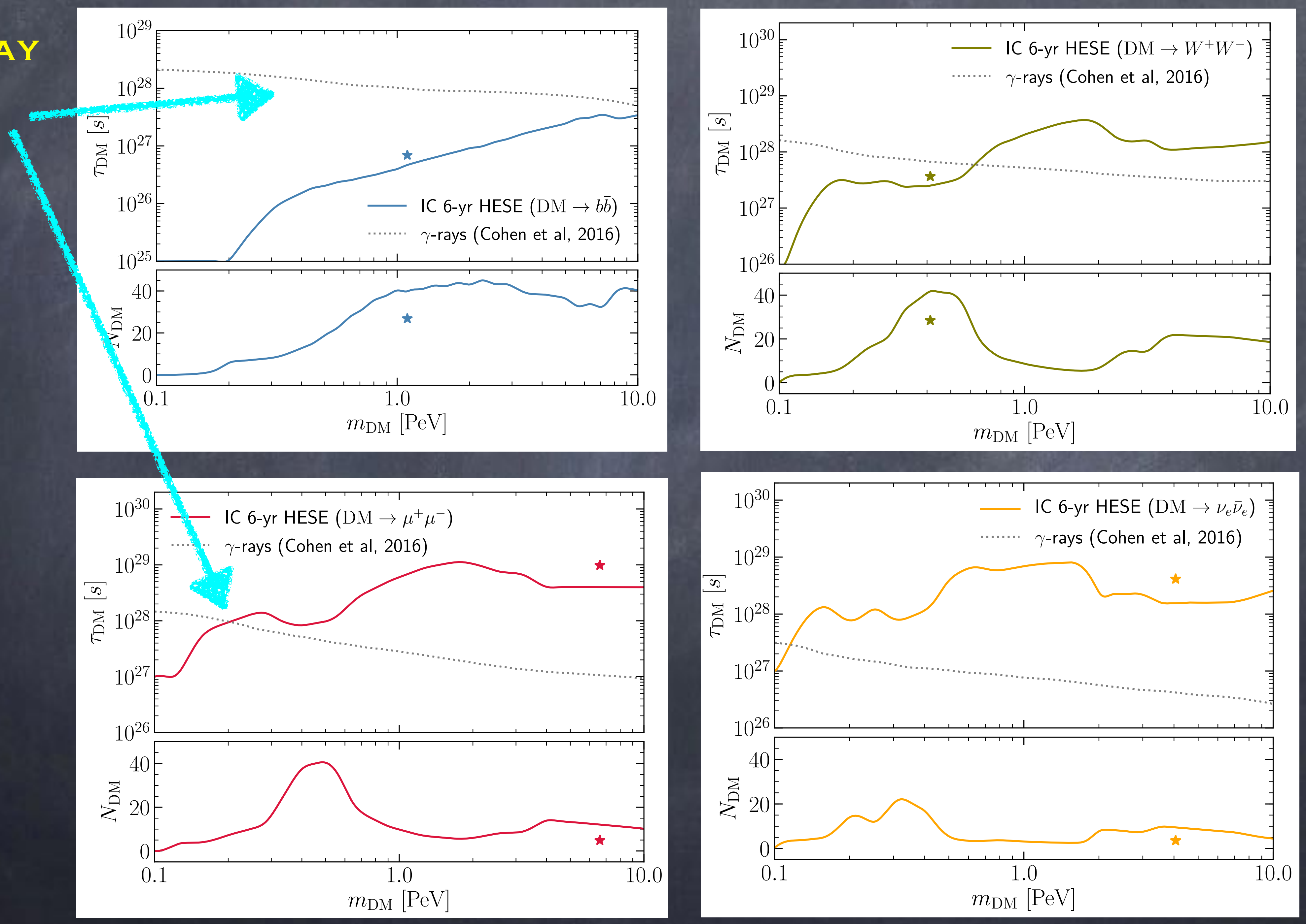
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, JCAP 05:051, 2019

Comparison to 4-yr HESE

DM decays + Astro: 6-yr HESE analysis

Very similar limits to 4-yr HESE

Gamma-ray limits



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

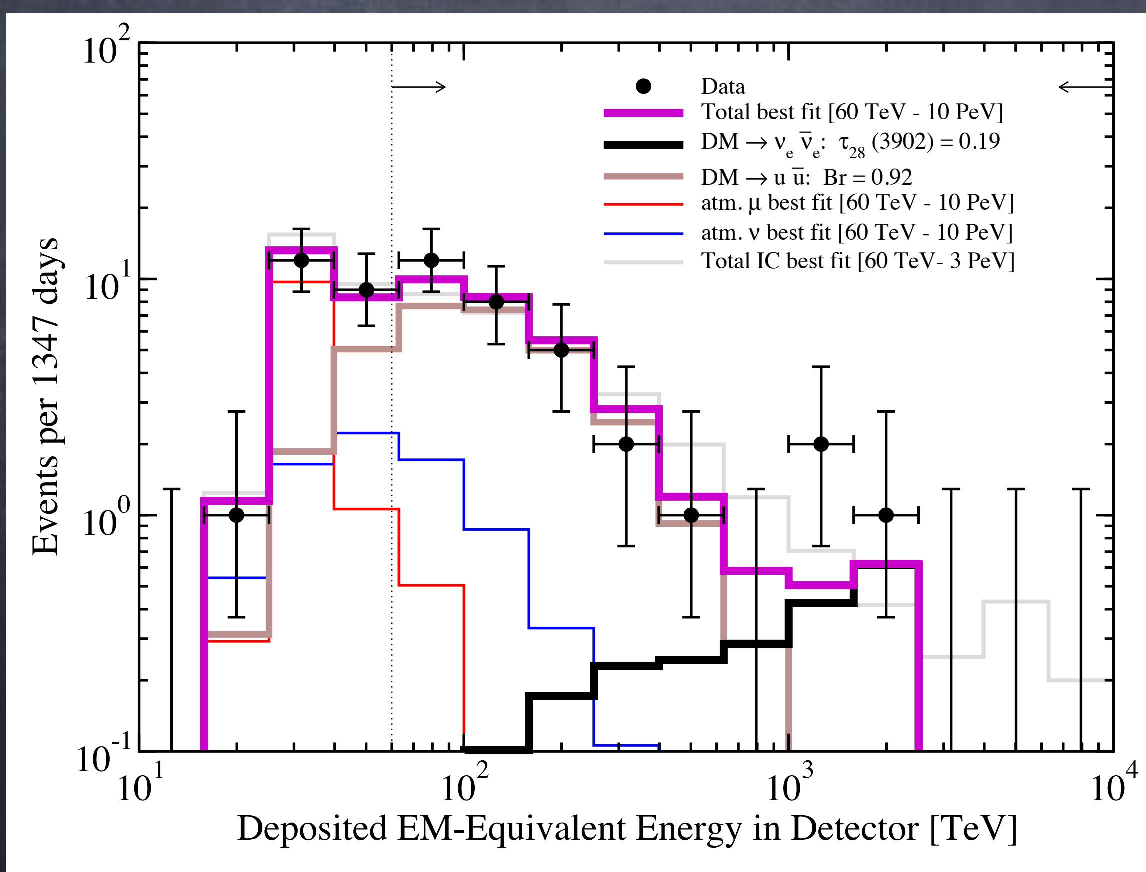
Only DM decays: HESE analysis

Only DM?
Two decay channels

but too much contribution from soft channels?

4-yr

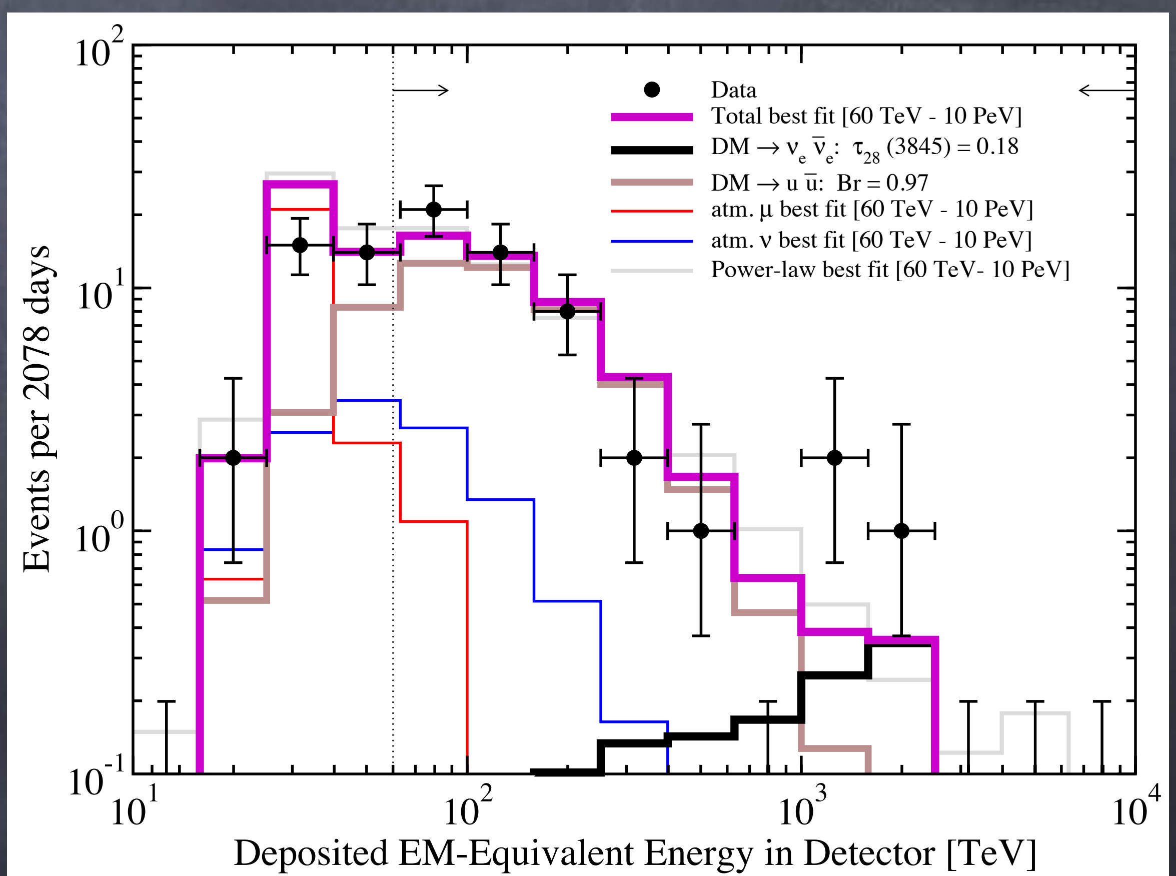
$DM \rightarrow \{92\%\ u\bar{u};\ 8\%\ \nu_e\bar{\nu}_e\}$



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

6-yr

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



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

Neutrinos from dark matter annihilations

Two components

Galactic — Extra-galactic

Averaged oscillations

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

Particle physics — Astrophysics

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

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

- $\frac{1}{4\pi}\langle\sigma v\rangle$: annihilation cross section
- m_{DM}: DM mass
- $\frac{dN_{\nu_\alpha}}{dE_\nu}$: neutrino flux at production
- $\int_{los}\rho^2\,ds$: DM galactic density
- $(\Omega_{DM}\rho_c)^2$: 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

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

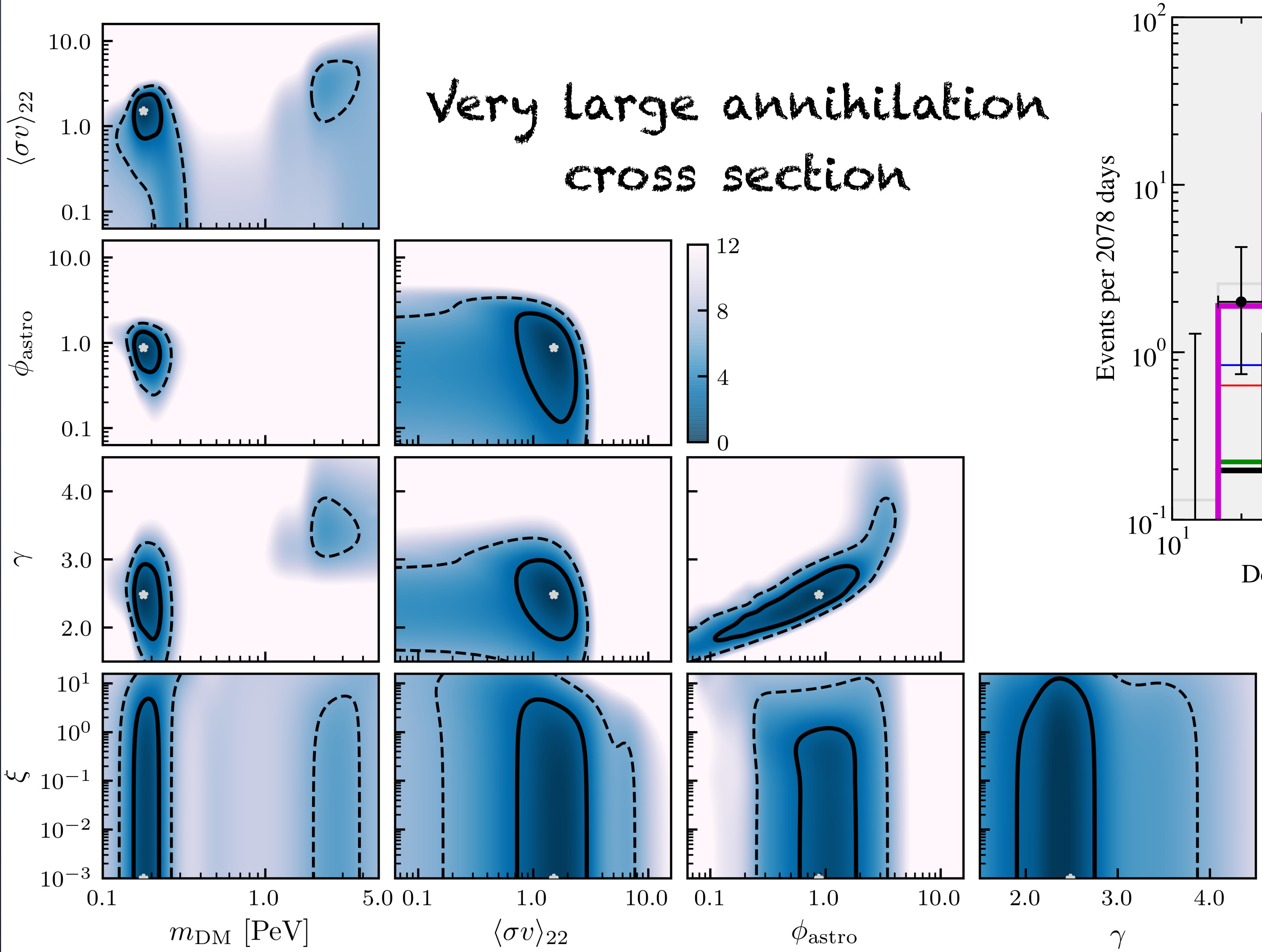
- annihilation cross section
- DM mass
- neutrino flux at production
- DM galactic density
- DM density
- Hubble function
- halo enhancement
- energy redshift

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

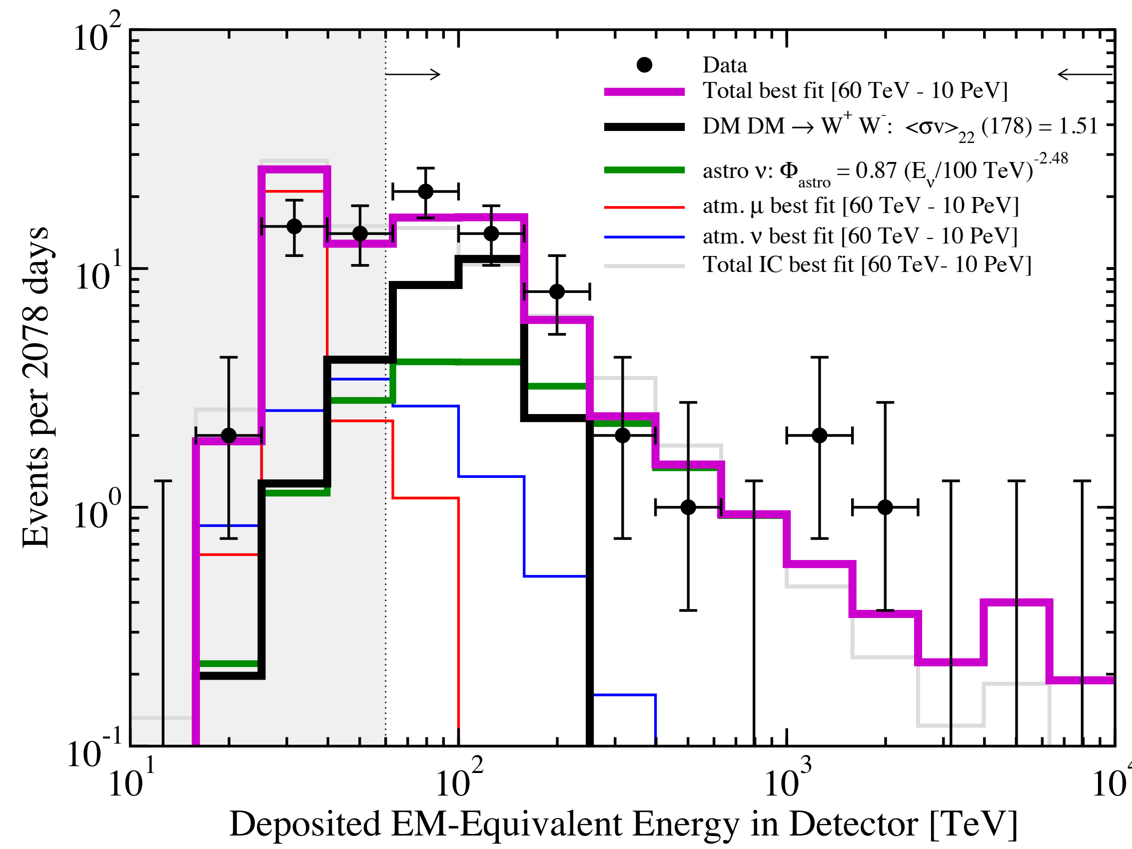
Very large annihilation cross section (above the unitarity limit)

DM annihilations + Astro: 6-yr HESE analysis

$DM\,DM \to W^+W^-$



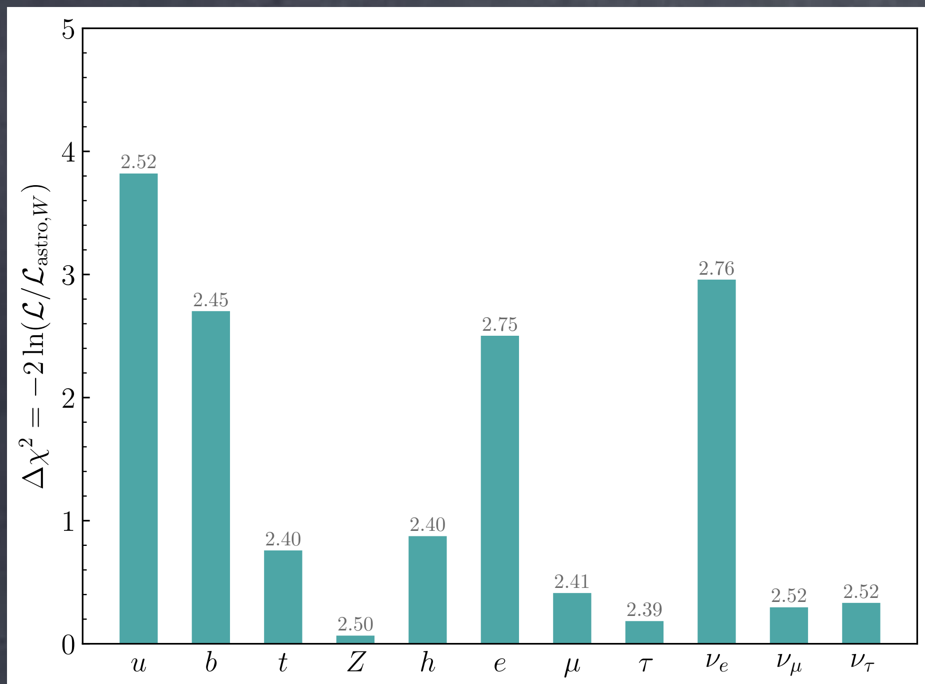
Very large annihilation cross section



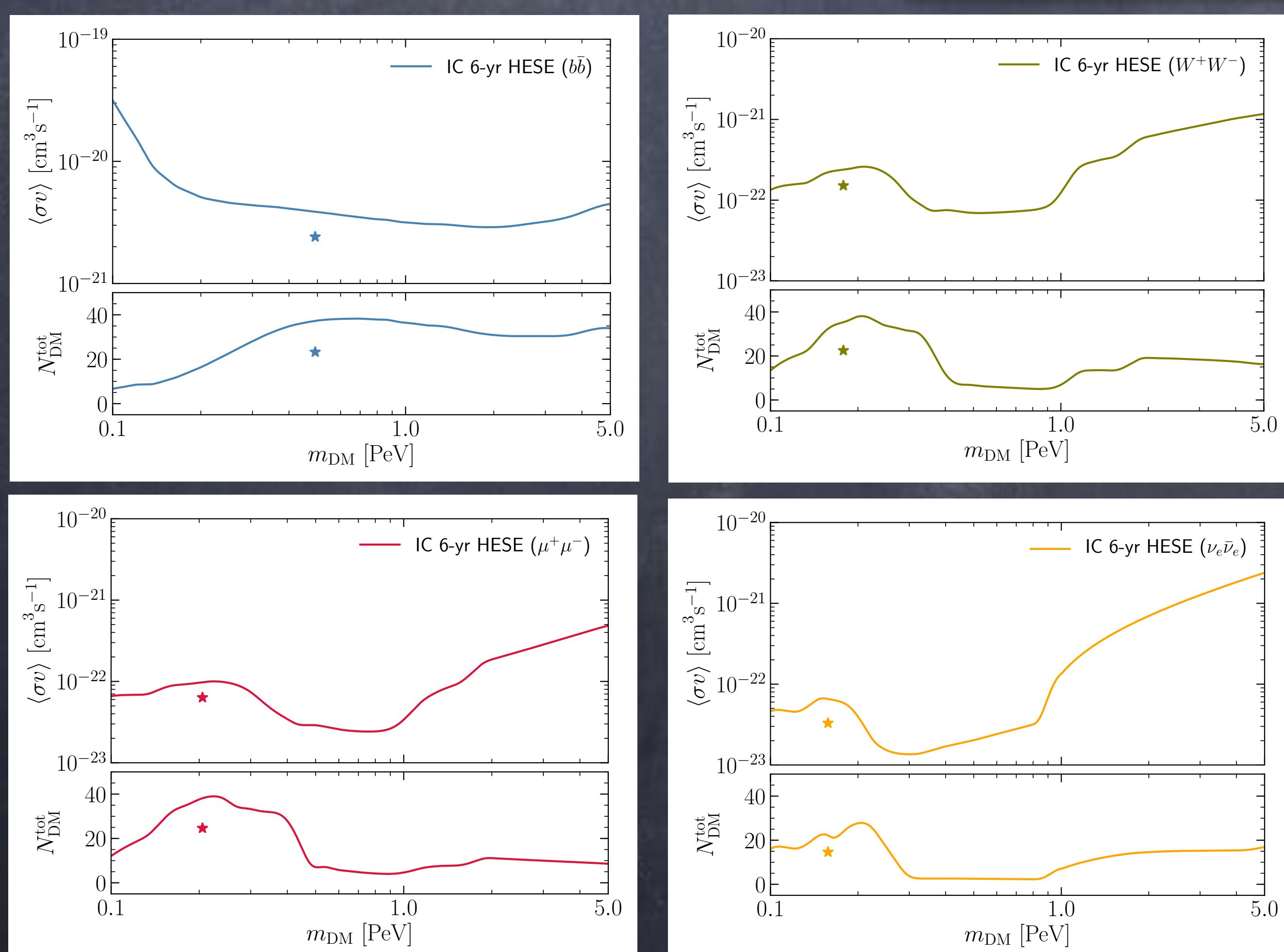
No significant ExGal contribution

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

DM annihilations + Astro: 6-yr HESE analysis

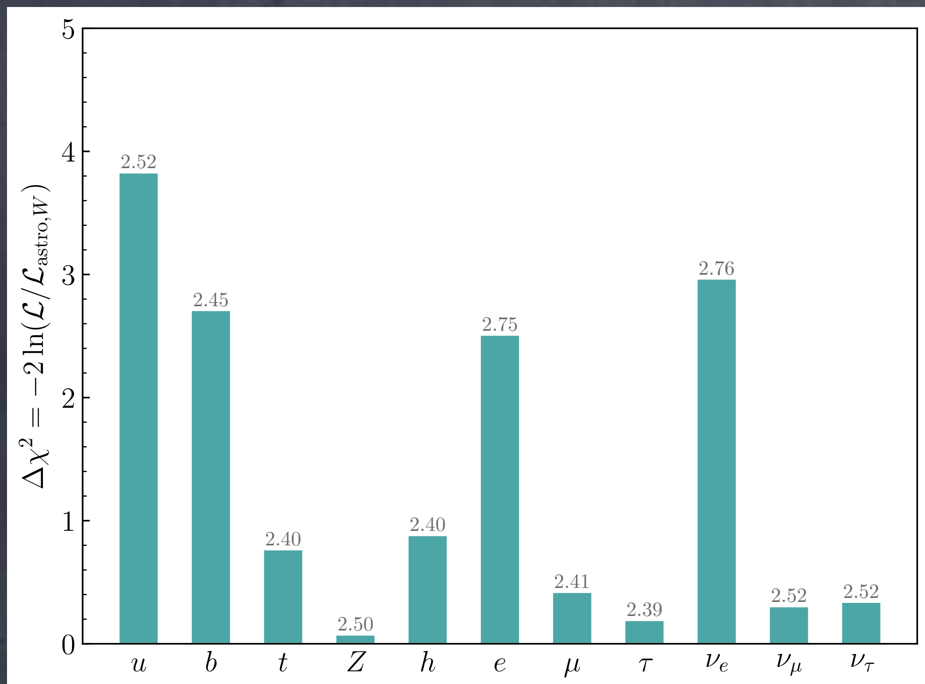


Ann. channel	$\langle\sigma v\rangle_{22}$	$m_{\rm DM}$ [TeV]	ξ	$\phi_{\rm astro}$	γ	$N^{\rm ann}_{\rm DM,G}$	$N^{\rm ann}_{\rm DM,EG}$	$N_{\rm astro}$
$u\bar{u}$	52.24	260	0.001	1.02	2.52	*20.6*	*0.0*	*20.2*
$b\bar{b}$	24.10	491	0.001	0.81	2.45	*23.2*	*0.0*	*17.3*
$t\bar{t}$	8.20	270	0.001	0.69	2.40	*24.8*	*0.0*	*15.8*
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



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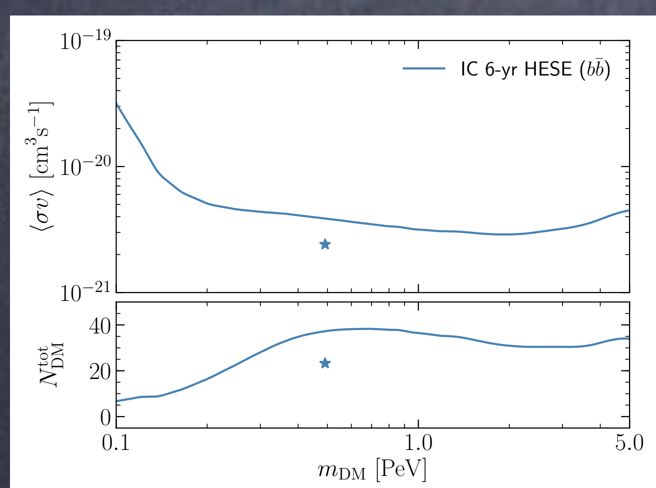
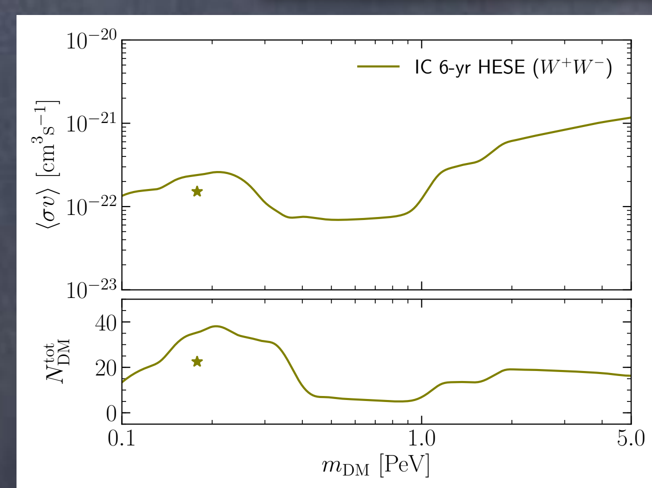
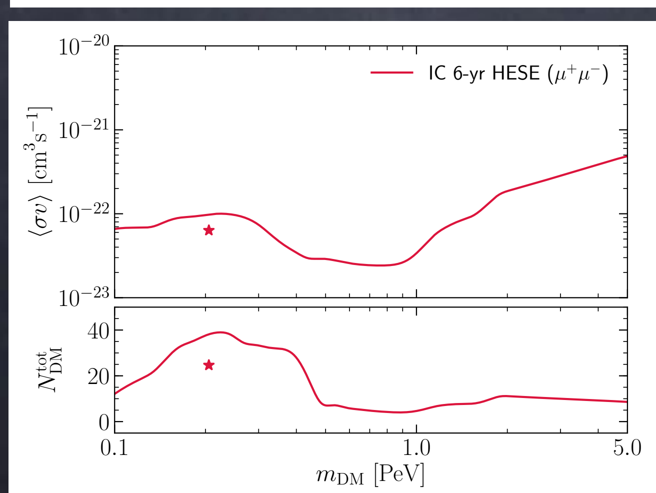
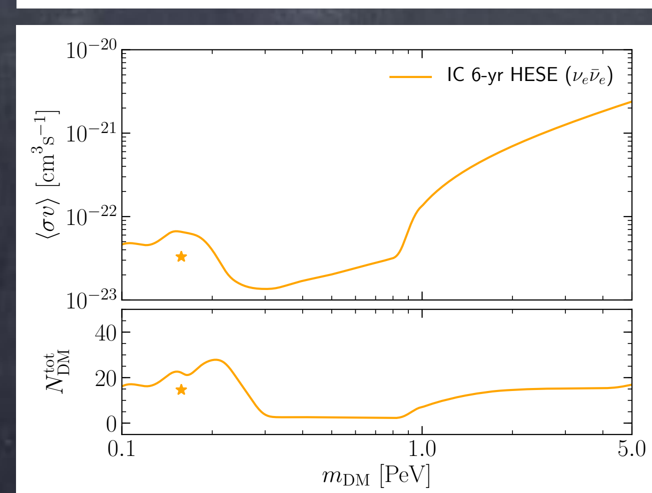
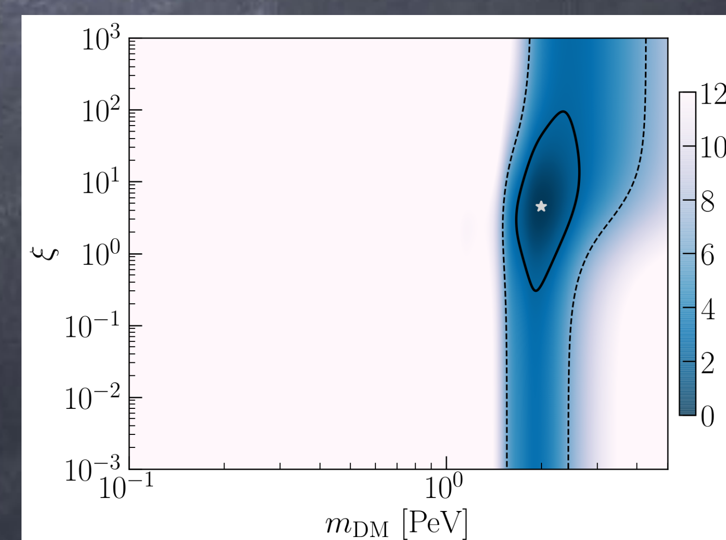








If only DM → ExGal needed, larger mass, hard-soft channels

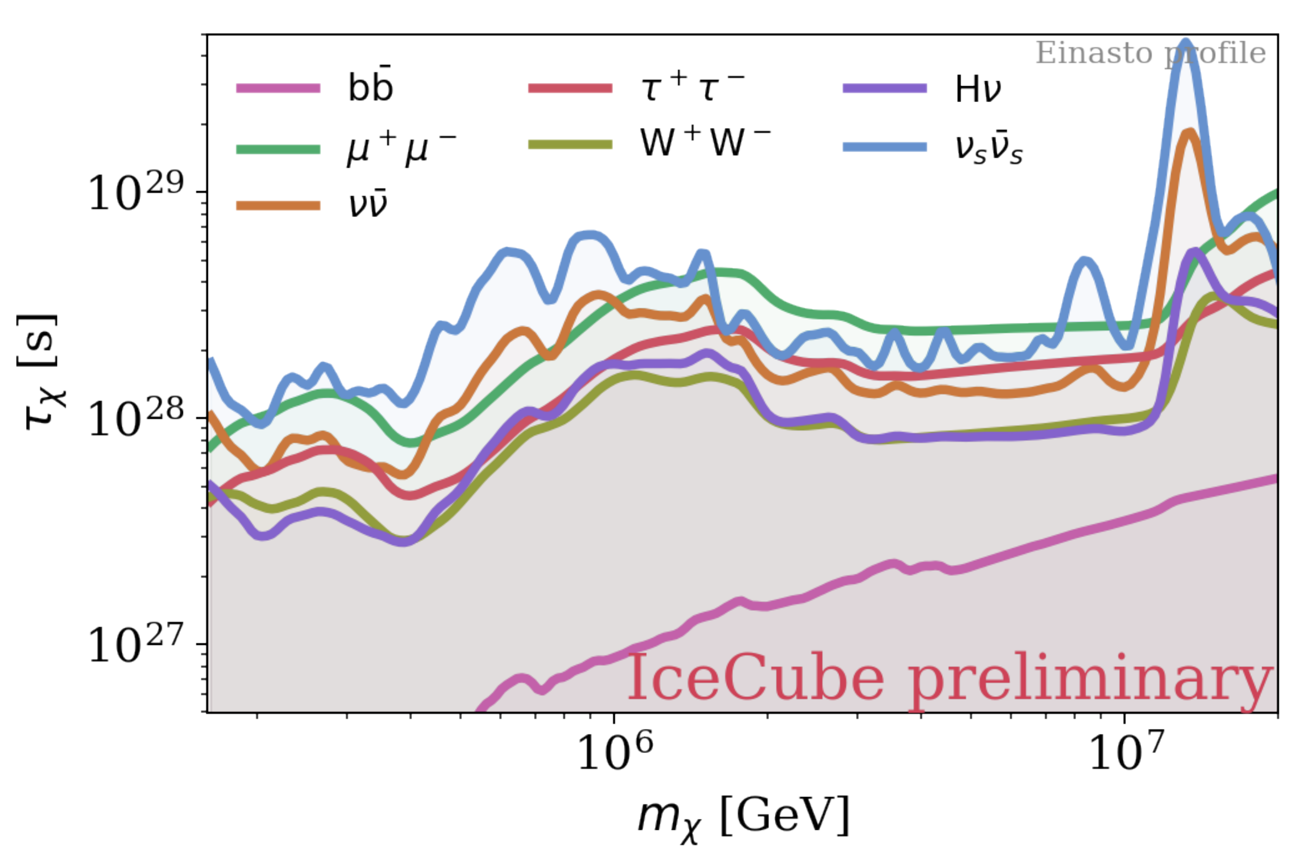


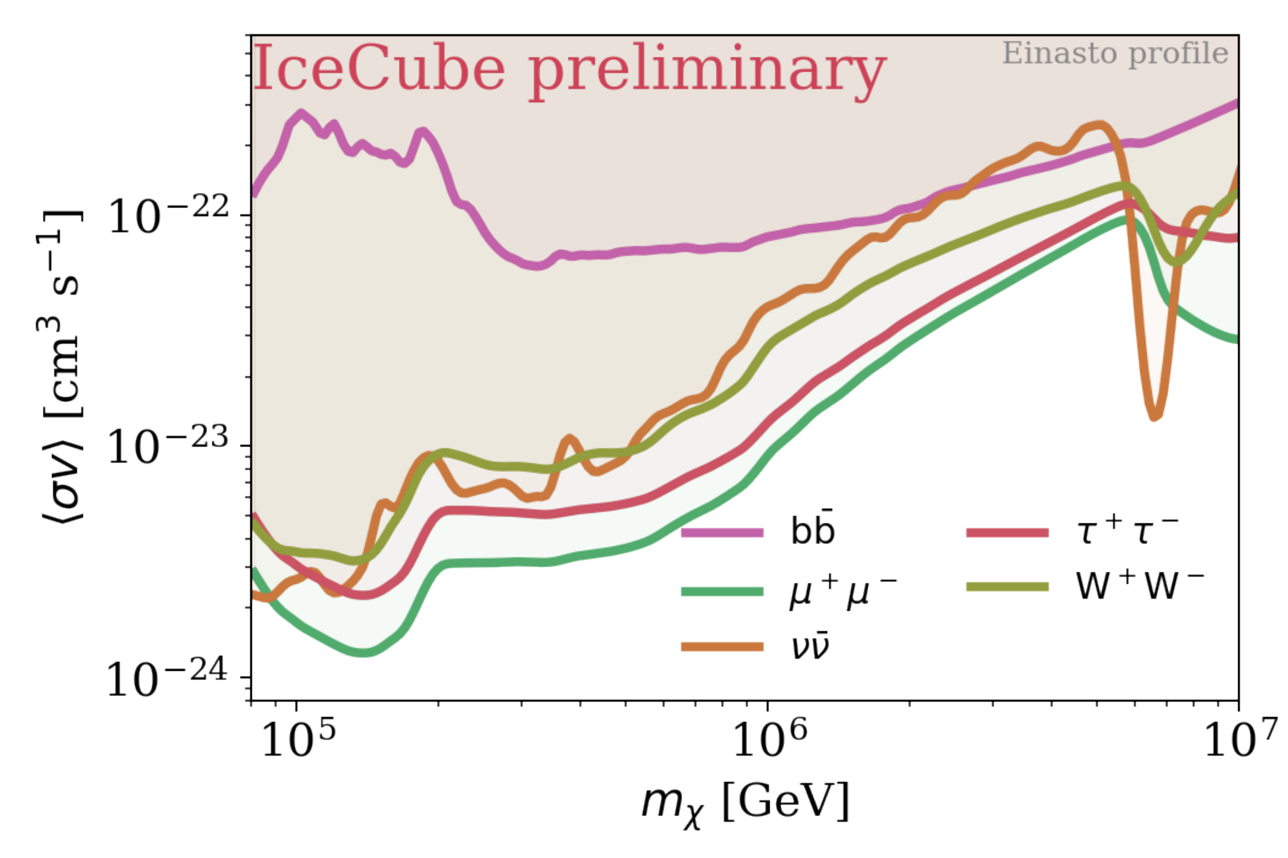
(a) DM DM → $\{u\bar{u}, e^+e^-\}$.

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, non-public yet)





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

Similar limits to 6-yr HESE

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

+

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)