Astrophysical probes of DM on the diffuse sky: present and future prospects

Marco Chianese

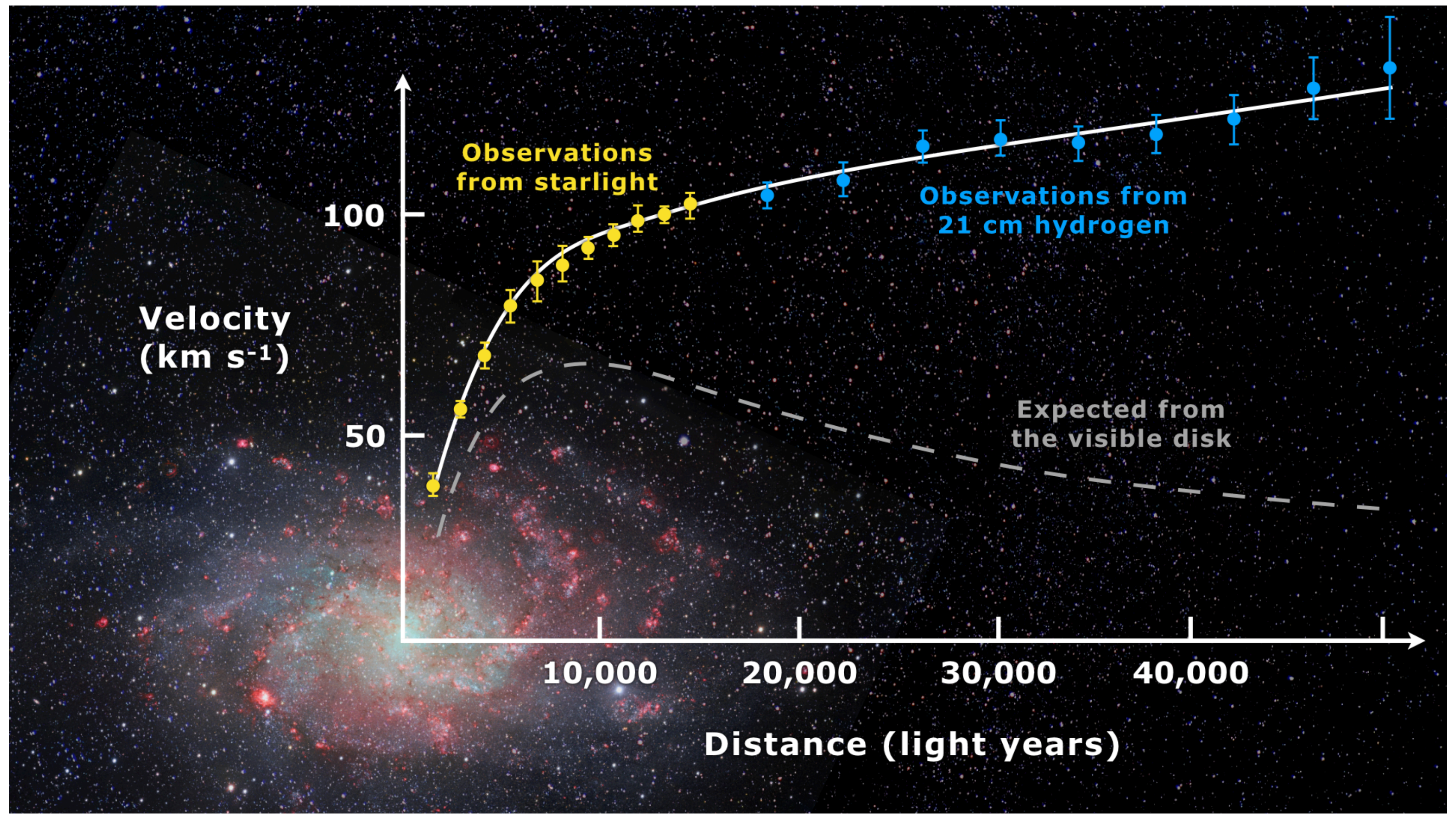
20 - 22 September 2022, second KM3NeT Town Hall Meeting, Catania

- MC, Fiorillo, Miele, Morisi, Pisanti, JCAP 11 (2019) 046 [arXiv:1907.11222]
- Dekker, MC, Ando, JCAP 09 (2020) 007 [arXiv:1910:12917]
- Basegmez Du Pree, Arina, Cheek, Dekker, MC, Ando, JCAP 05 (2021) 054 [arXiv:2103.01237]
- Skrzypek, MC, Argüelles, arXiv:2205.03416

Università degli Studi di Napoli Federico II
NAP Theory
INFN Napoli

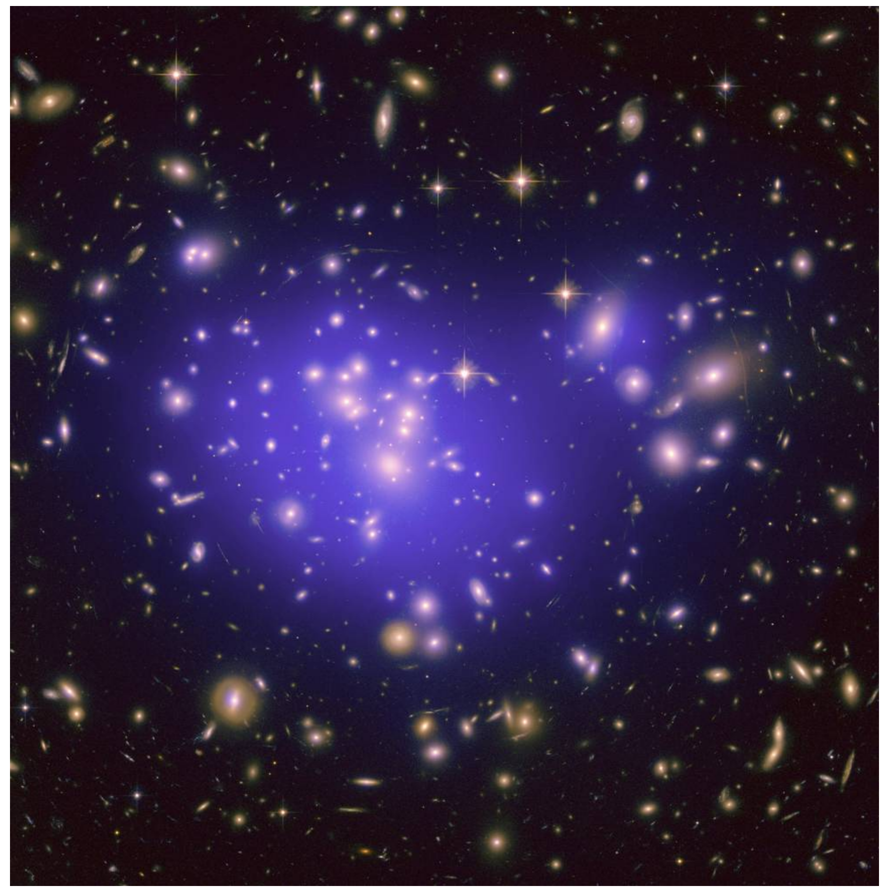
Evidences for dark matter

Galactic Rotation Curves



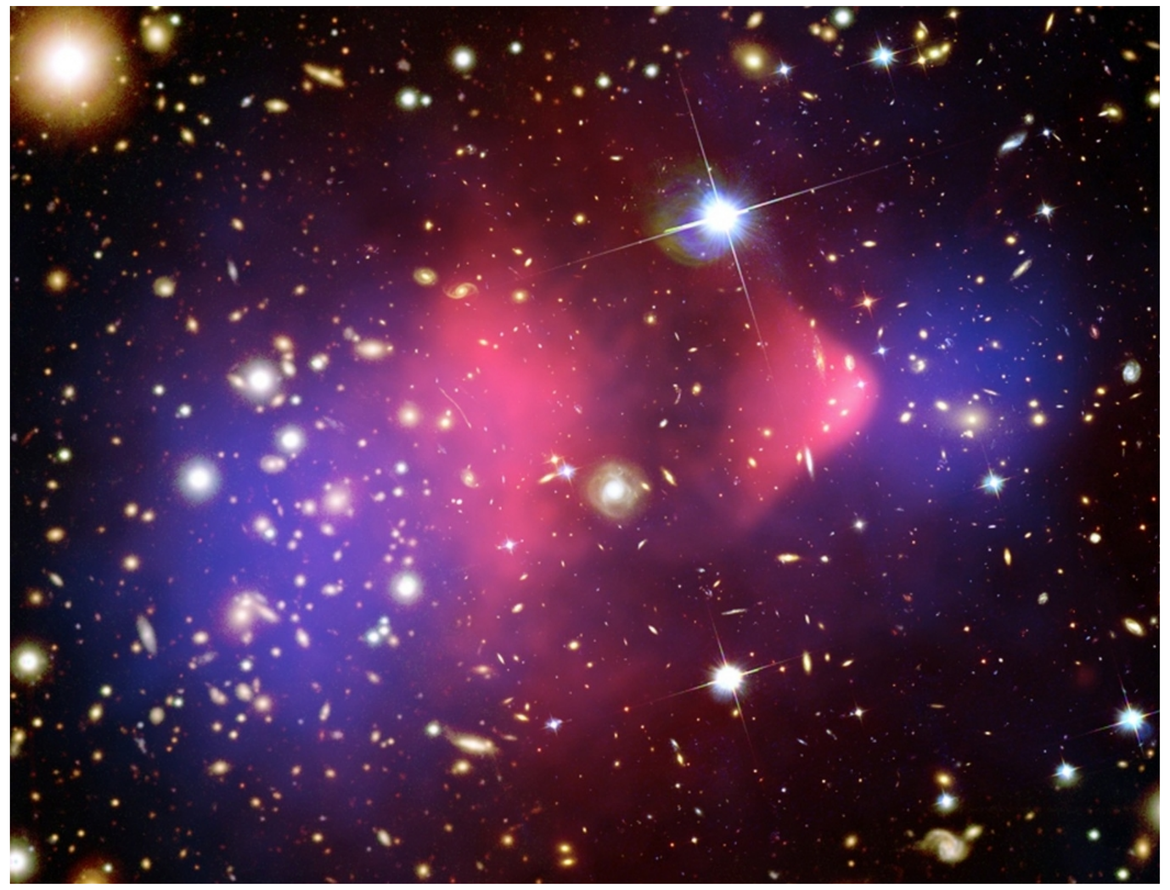
~10 kpc

Galaxy Clusters



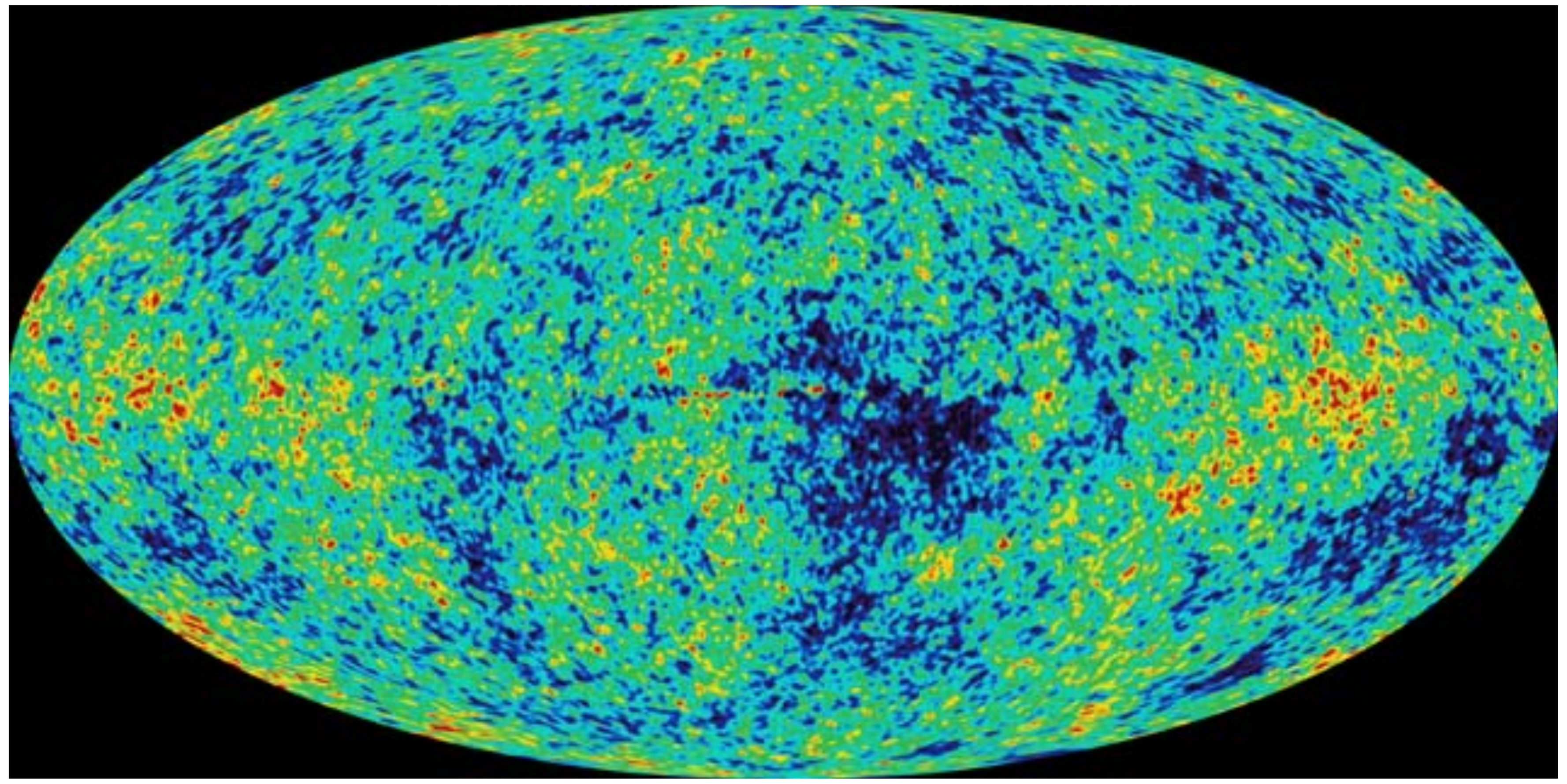
~100 kpc

Bullet Clusters

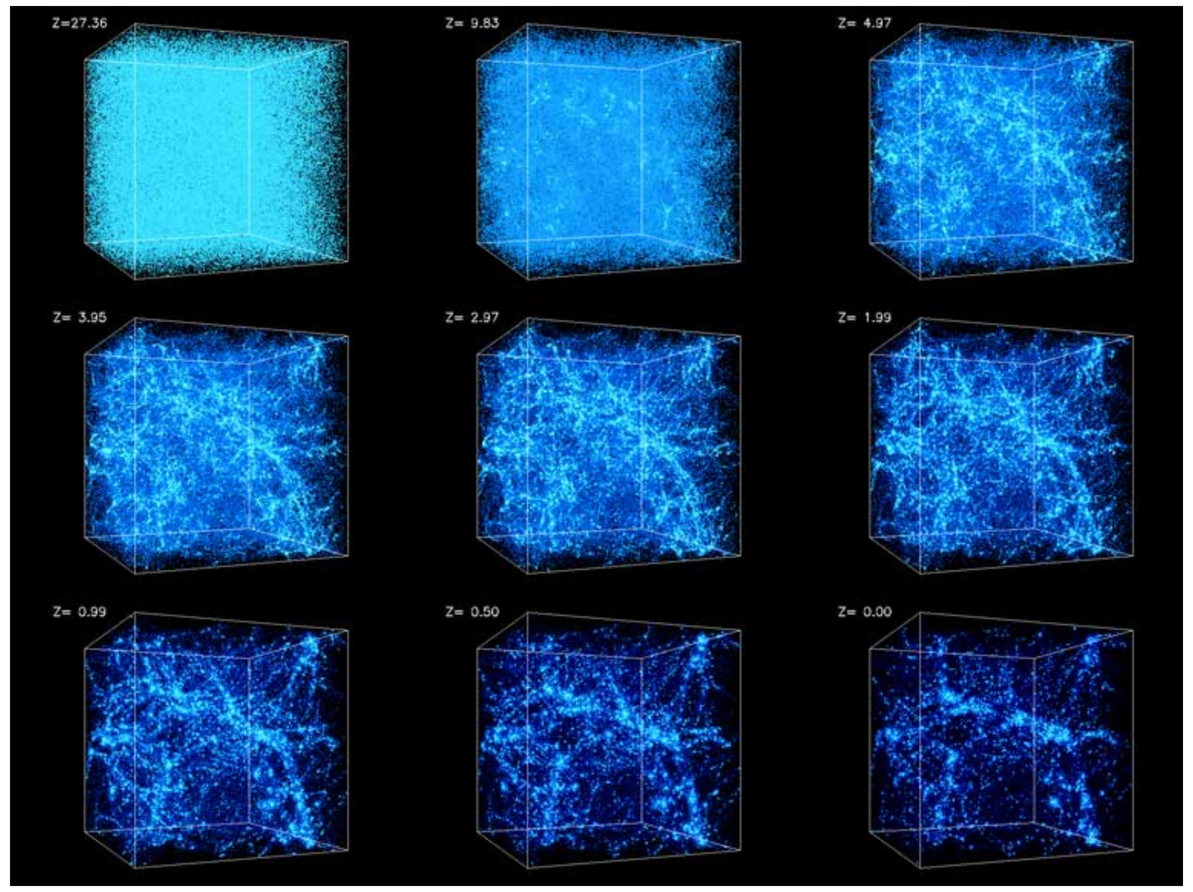


~1 Mpc

Cosmic Microwave Background (CMB)

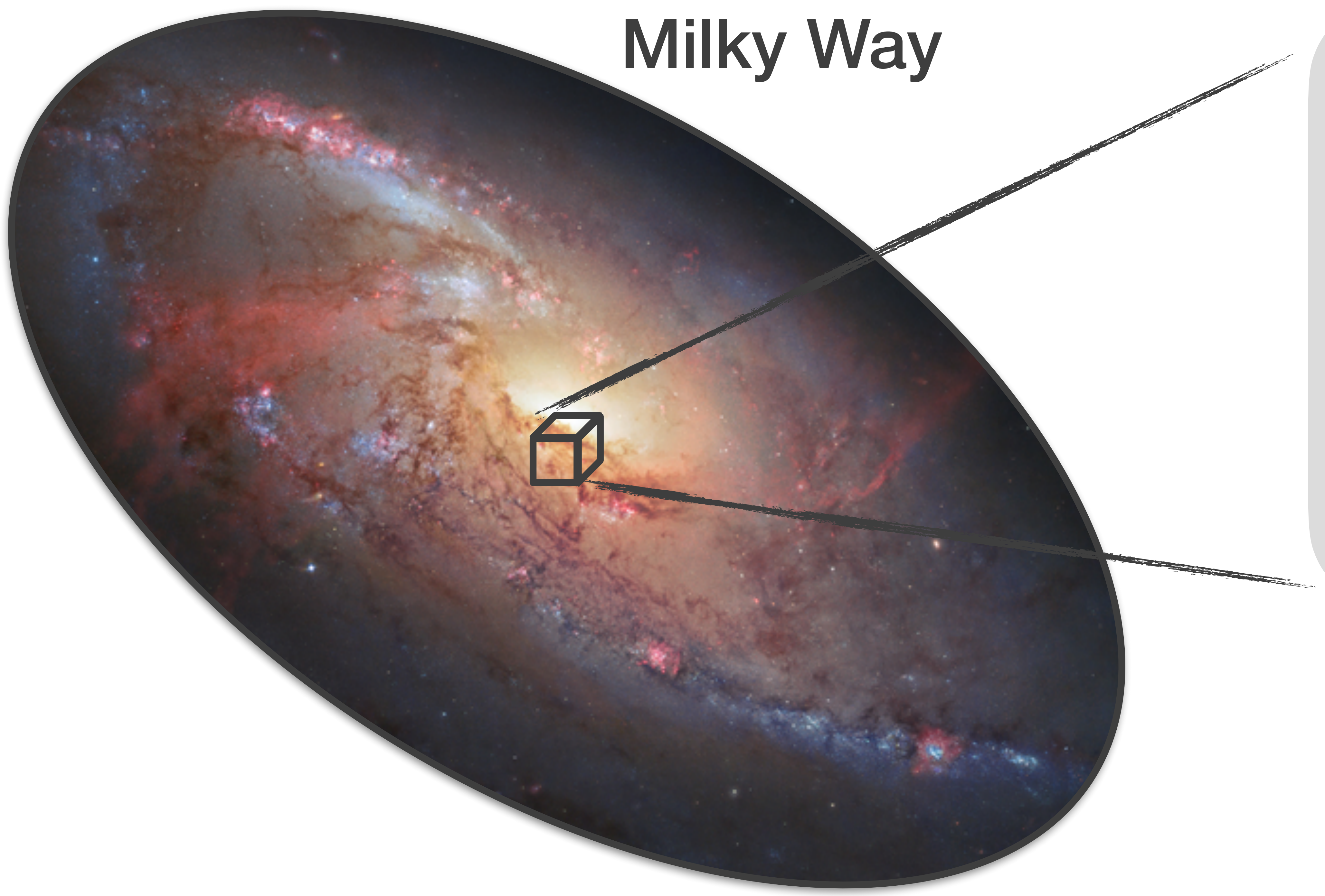


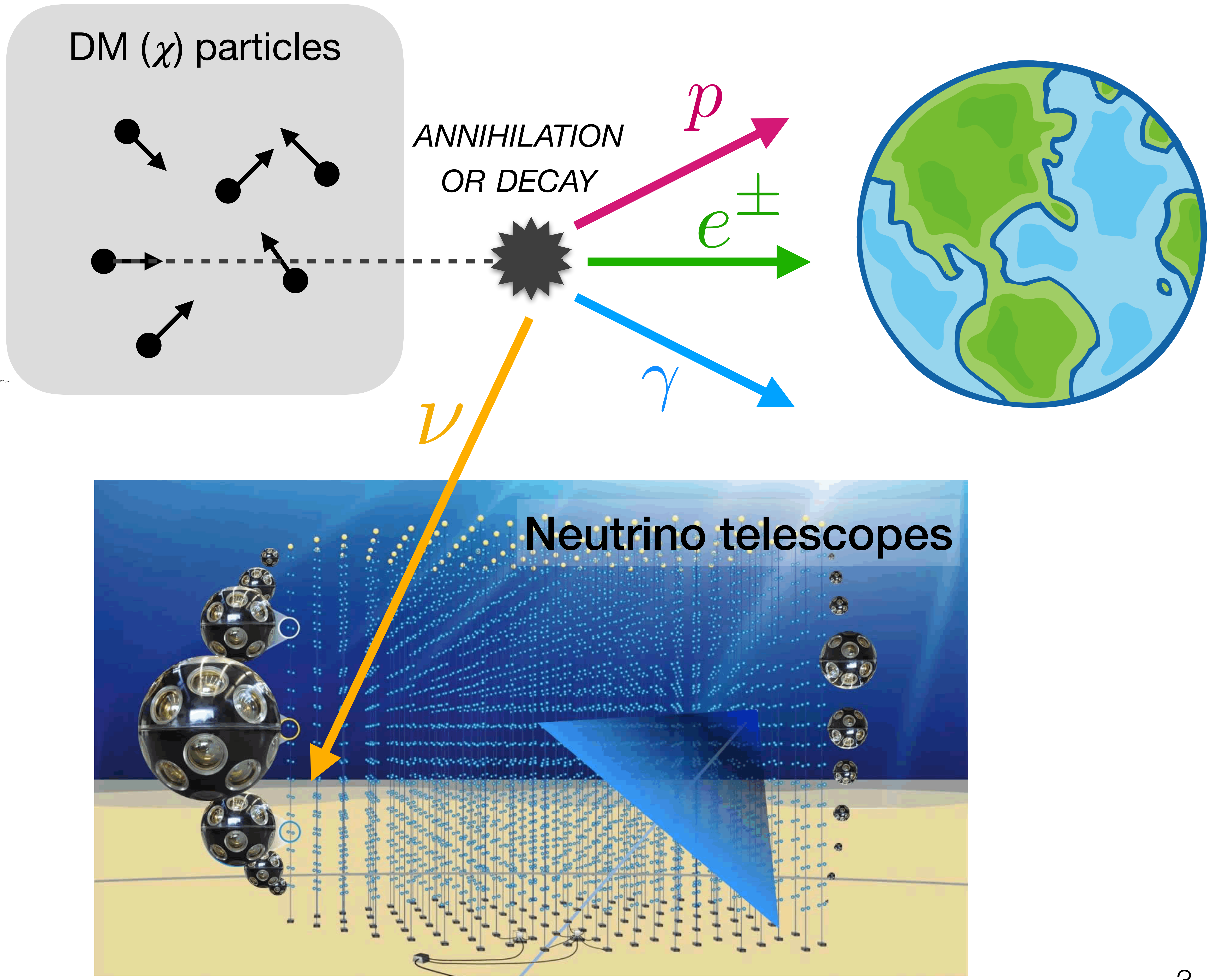
Structure Formation



cosmological scales

Indirect dark matter signals

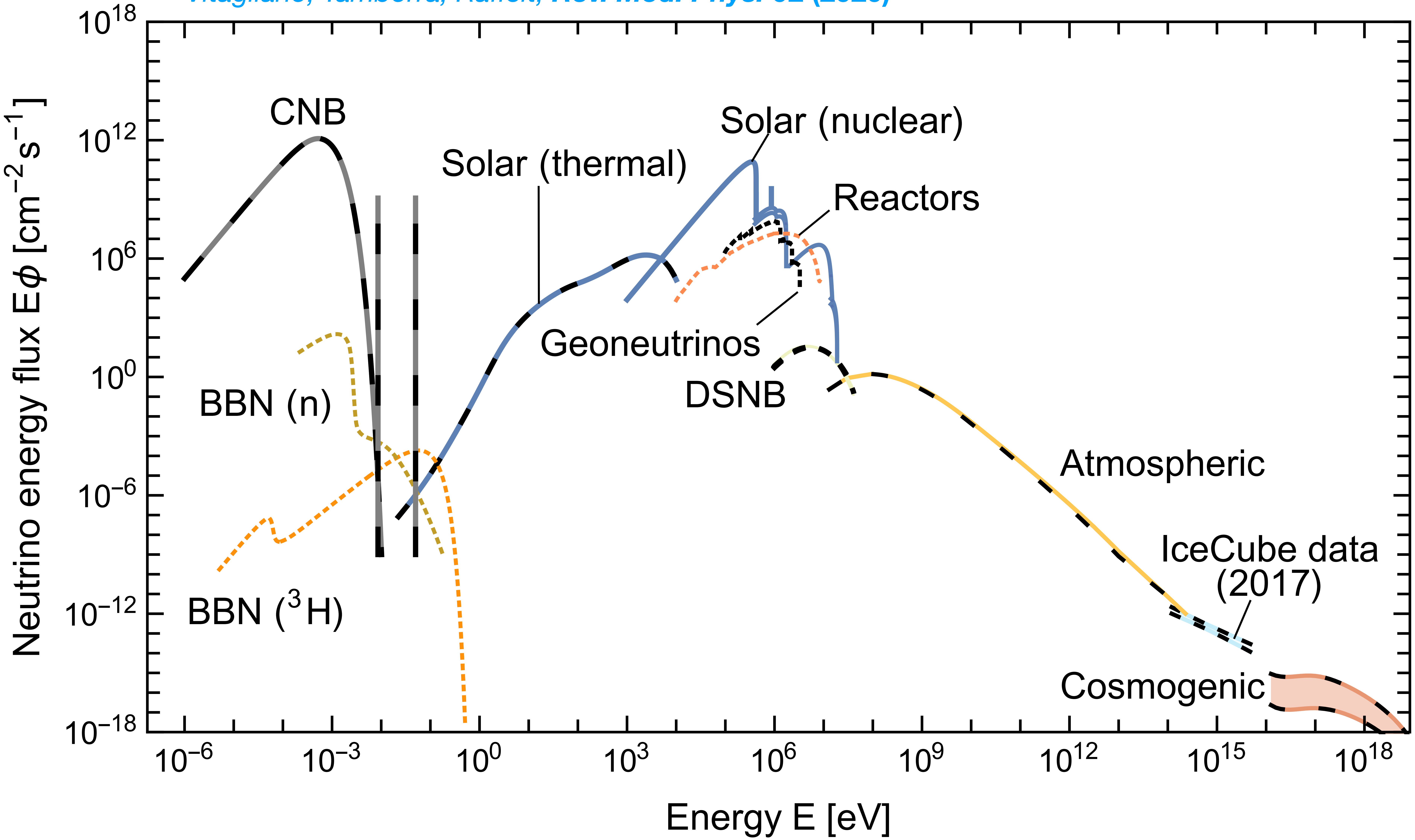




Multi-messenger indirect searches!

Grand Unified Neutrino Spectrum

Vitagliano, Tamborra, Raffelt, ***Rev. Mod. Phys.* 92 (2020)**



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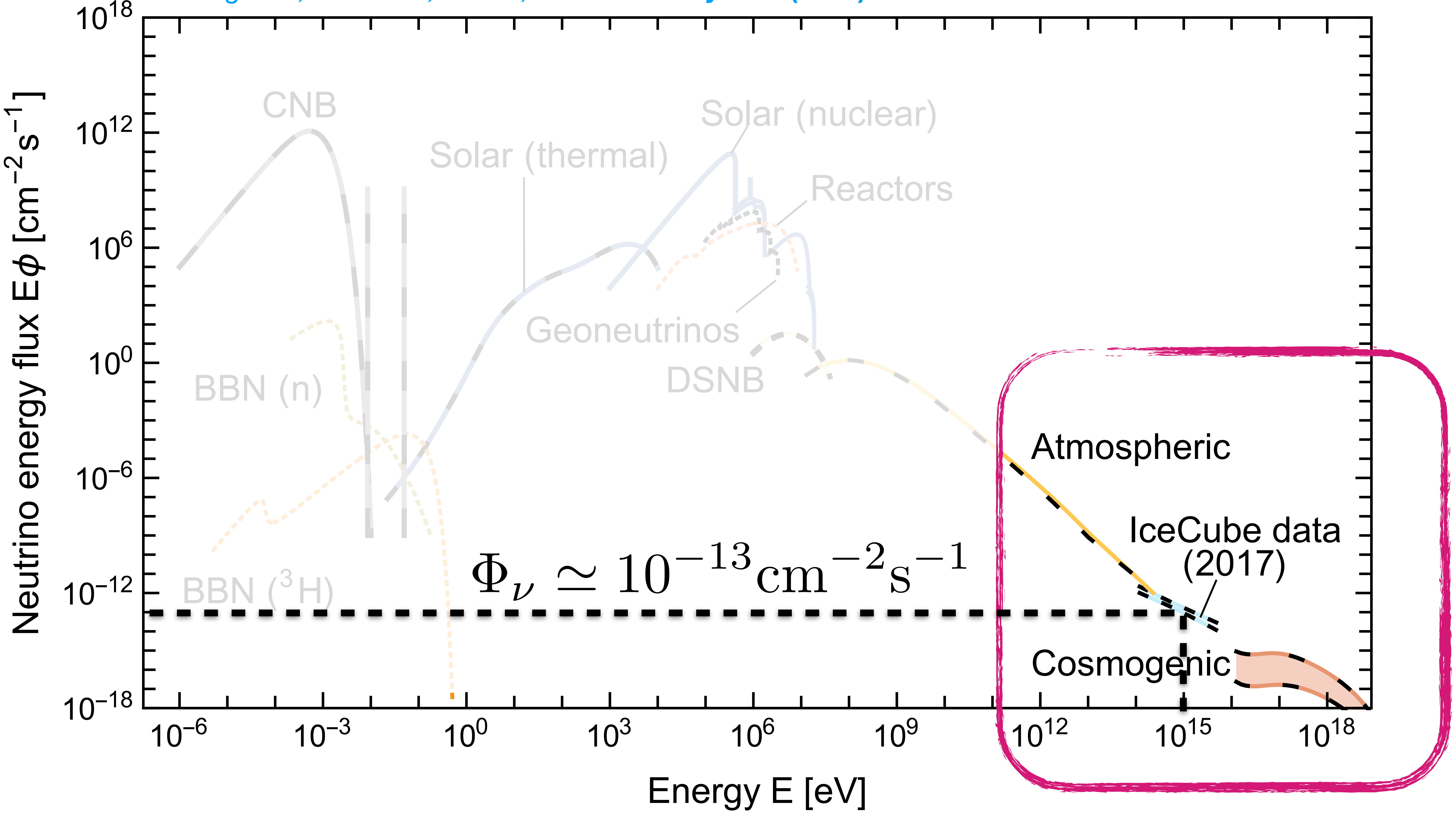

Order-of-magnitude estimate

ANNIHILATING DARK MATTER

$$\Phi_\nu^{\rm ann} \sim \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^2 \langle\sigma v\rangle L \lesssim 10^{-19}\ {\rm cm^{-2}s^{-1}} \left(\frac{10^7\ {\rm GeV}}{m_{\rm DM}}\right)^4 \left(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV/cm^3}}\right)^2 \left(\frac{10^{-3}\, c}{v}\right)$$

Constrained by unitarity (s-wave)

$$\langle\sigma v\rangle \lesssim 1.5\times 10^{-23}{\rm cm^3 s^{-1}} \left(\frac{10^{-3}\, c}{v}\right)\left(\frac{10^5\ {\rm GeV}}{m_{\rm DM}}\right)^2$$

DECAYING DARK MATTER

$$\Phi_\nu^{\rm dec} \sim \frac{\rho_{\rm DM}}{m_{\rm DM}}\frac{1}{\tau_{\rm DM}} L \sim 10^{-13}\ {\rm cm^{-2}s^{-1}} \left(\frac{10^7\ {\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^{28}\ {\rm s}}{\tau_{\rm DM}}\right)\left(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV/cm^3}}\right)$$

DM particle properties *Astrophysics: DM density*

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Upper bound

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IceCube observations!

DM particle properties

Astrophysics: DM density

Order-of-magnitude estimate

ANNIHILATING DARK MATTER → **Atmospheric neutrinos (below 10^5 GeV)**

$$\Phi_\nu^{\rm ann} \sim \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^2 \langle\sigma v\rangle L \lesssim 10^{-19}\ {\rm cm^{-2}s^{-1}} \left(\frac{10^7\ {\rm GeV}}{m_{\rm DM}}\right)^4 \left(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV/cm^3}}\right)^2 \left(\frac{10^{-3}\,c}{v}\right)$$

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DECAYING DARK MATTER → **Astrophysical neutrinos (above 10^5 GeV)**

$$\Phi_\nu^{\rm dec} \sim \frac{\rho_{\rm DM}}{m_{\rm DM}}\frac{1}{\tau_{\rm DM}} L \sim 10^{-13}\ {\rm cm^{-2}s^{-1}} \left(\frac{10^7\ {\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^{28}\ {\rm s}}{\tau_{\rm DM}}\right)\left(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV/cm^3}}\right)$$

IceCube observations!

DM particle properties

Astrophysics: DM density

Outline

Atmospheric neutrinos (below 100 TeV)

- Robust WIMP limits from upcoming KM3NeT telescope
- Implications on minimal dark matter models
- High complementarity with other experimental constraints

Basegmez Du Pree, Arina, Cheek, Dekker, MC, Ando,
JCAP 2105 [arXiv:2103.01237]

Astrophysical neutrinos (100 TeV — 10 PeV)

MC, Fiorillo, Miele, Morisi, Pisanti,
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- Inner tension among IceCube data and with gamma rays
- Dark matter interpretation of the 100 TeV neutrino excess
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Atmospheric neutrinos

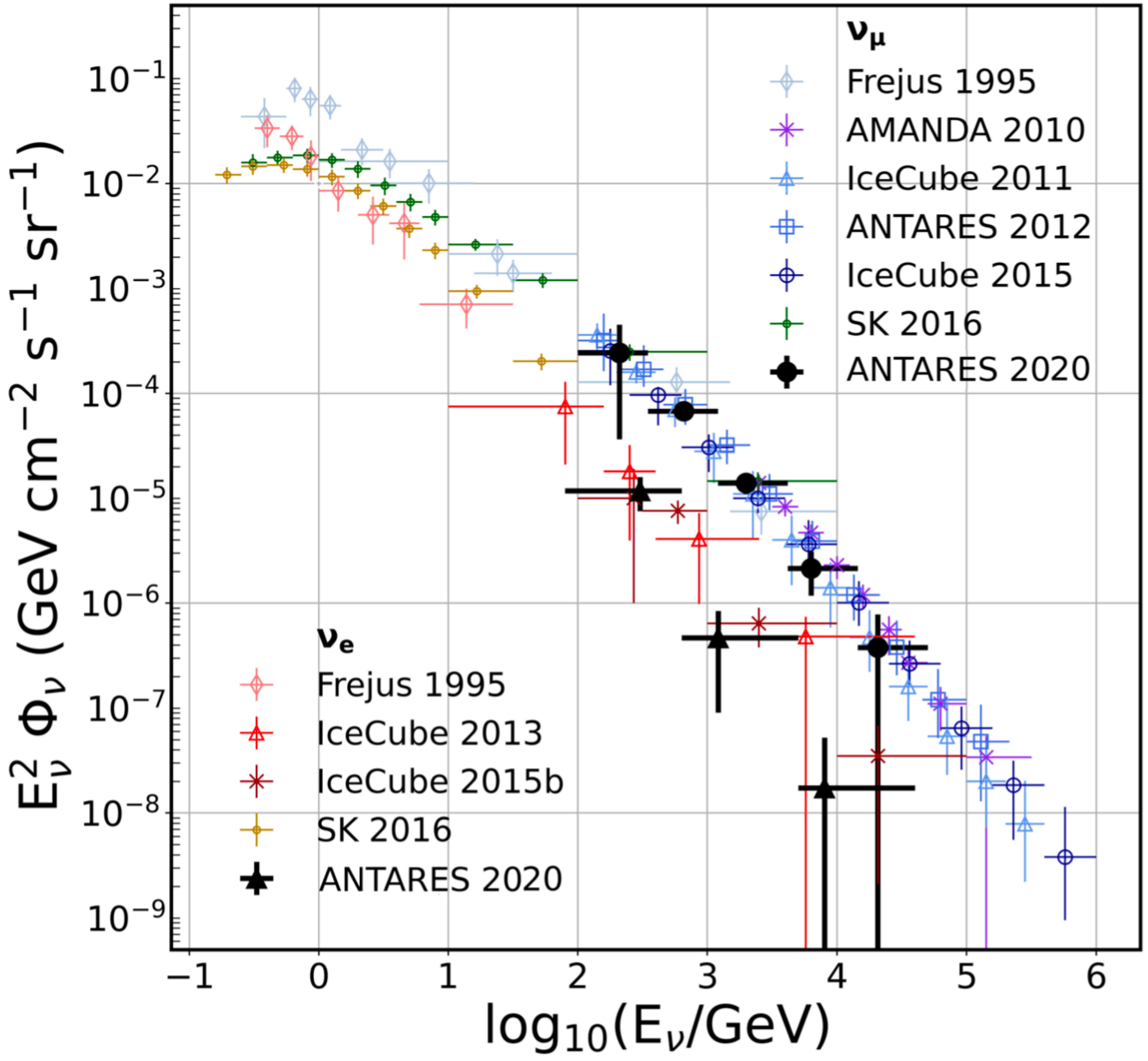
- Produced by cosmic-ray interactions in the Earth's atmosphere
- Decay products in hadronic cascades: pions and Kaons (*conventional neutrinos*), and charm mesons (*prompt neutrinos*)
- Background for dark matter searches

Forecast analysis with KM3NeT-ARCA telescope

- Good field of view to the Galactic Center of Milky Way
- High angular resolution for track-like muon neutrino events (less than ~1° at 90% CL)

*KM3NeT, **arXiv:1601.07459***

*ANTARES, **PLB 816 (2021)***

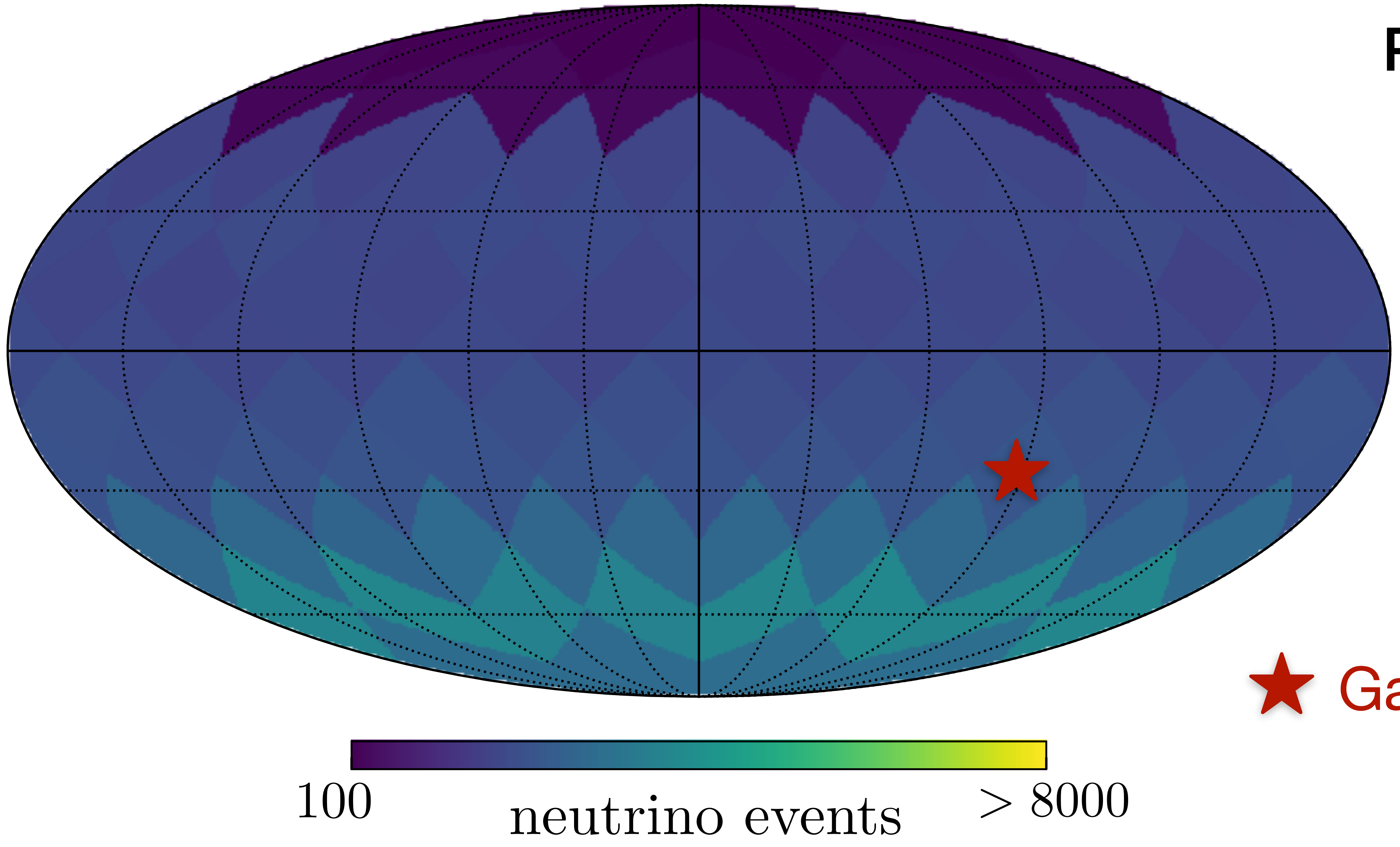


We adopt the model: Honda et al., **PRD 92 (2015)*

Analysis on muon neutrino angular distribution

Simulated sky-maps of track-like muon neutrinos with 10-year KM3NeT-ARCA exposure.

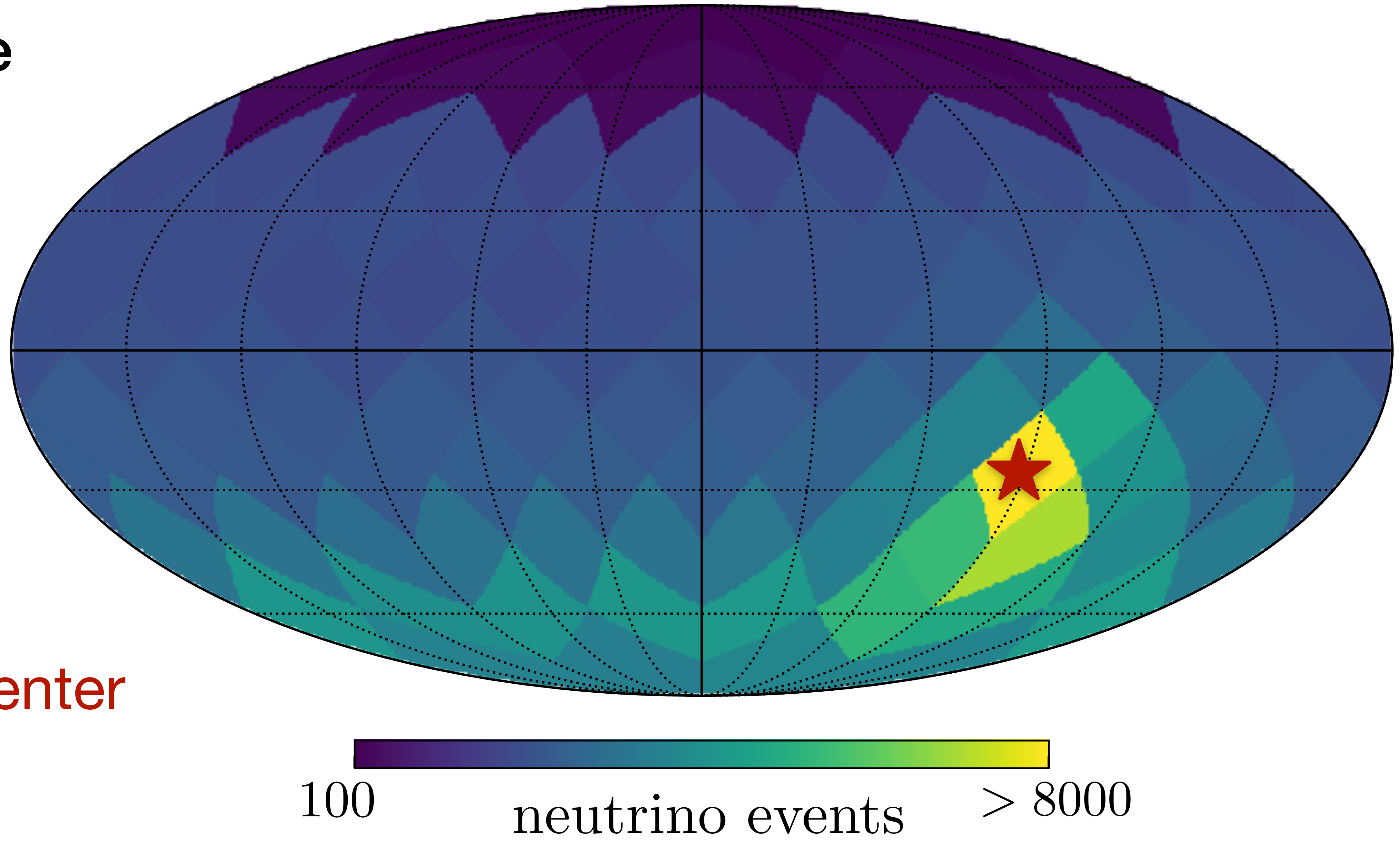
NULL HYPOTHESIS (ATM.)



Pixel size
10°x10°

★ Galactic Center

ALTERNATIVE HYPOTHESIS (ATM. + DM)



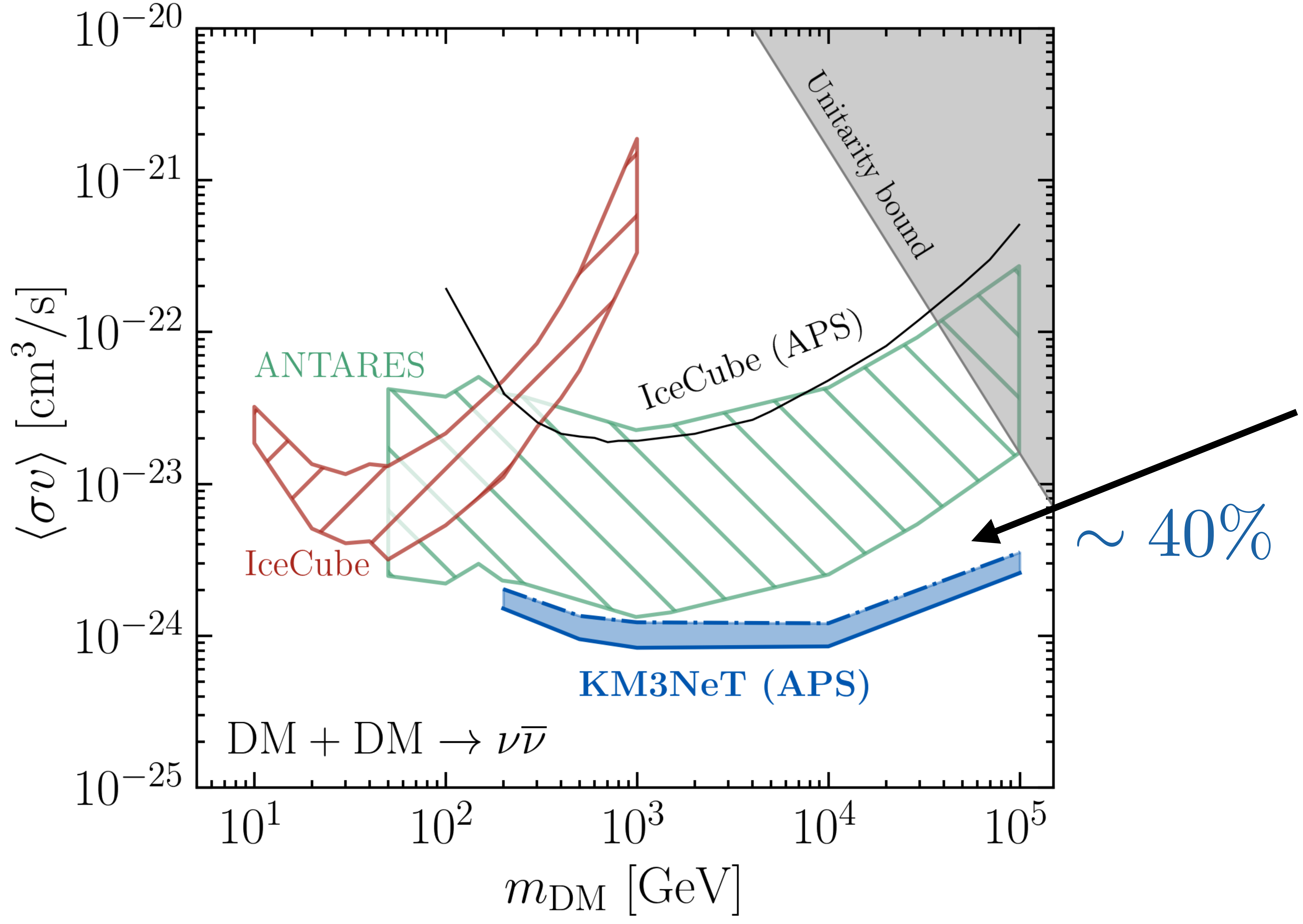
- We compare the two hypotheses by means of the **angular power spectrum method!**

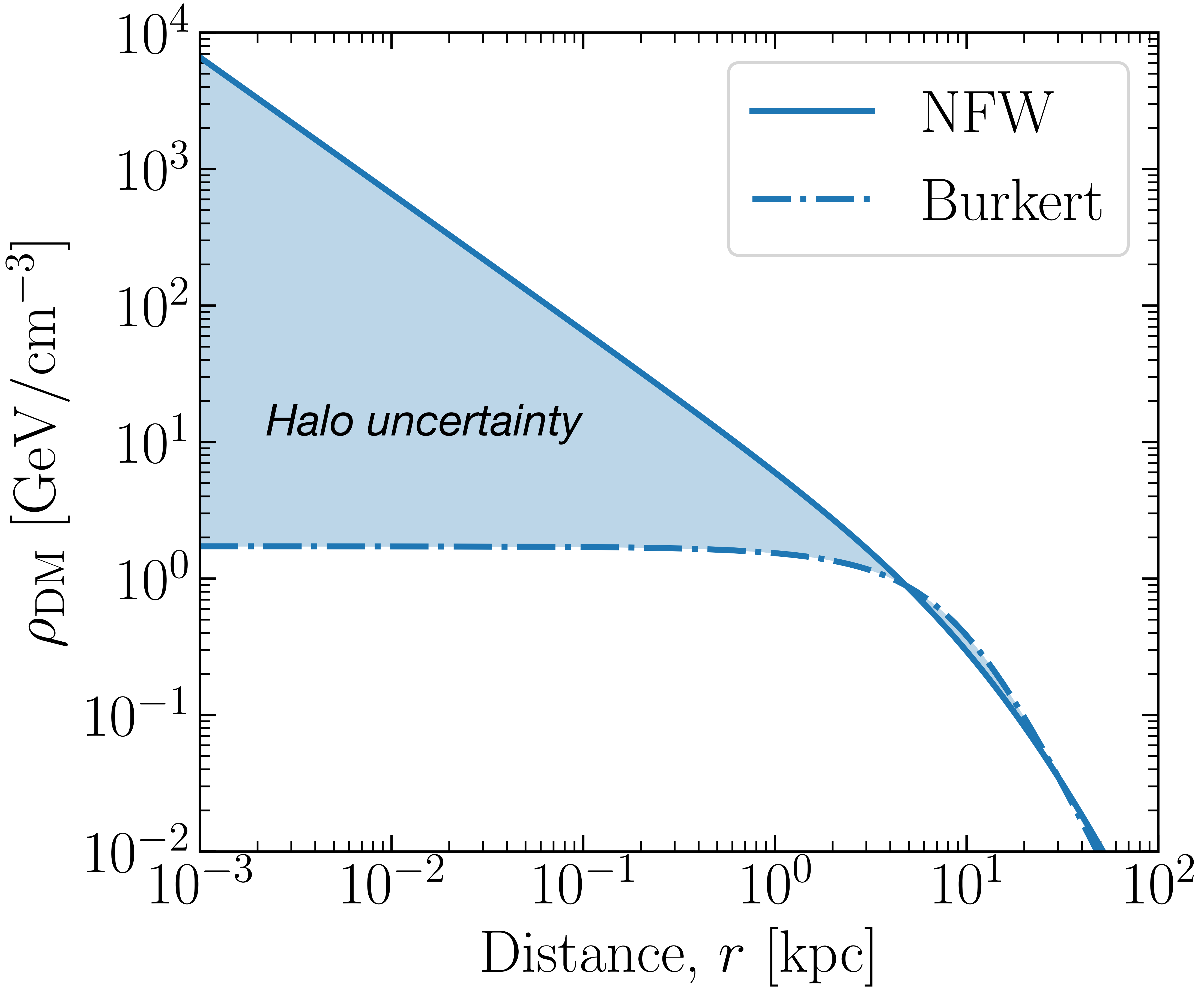
$$N(\theta, \phi) = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi)$$

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

Forecasted limits

Upper-limits at 90% CL (bands cover the Monte Carlo simulations) for 10-year KM3NeT-ARCA exposure

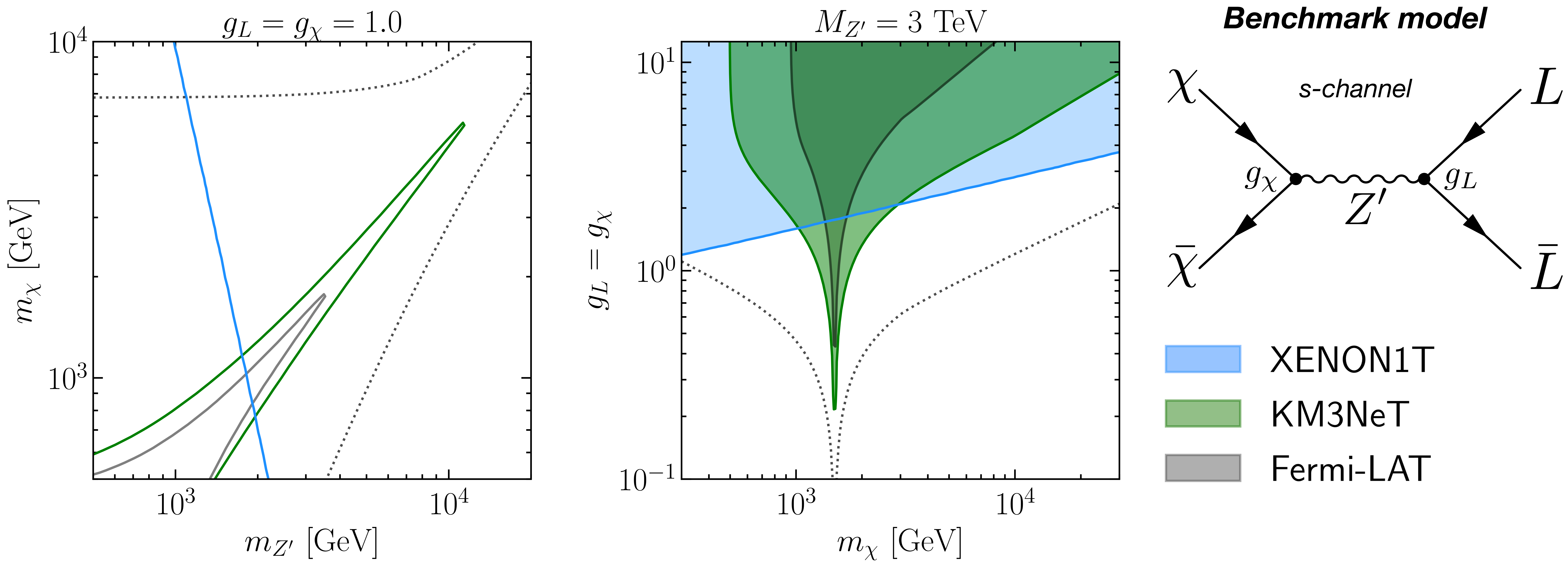




Orders-of-magnitude improvement for Burkert profile

Analysis very stable over different dark matter profiles for Galactic halo

Minimal dark matter models: Z' case

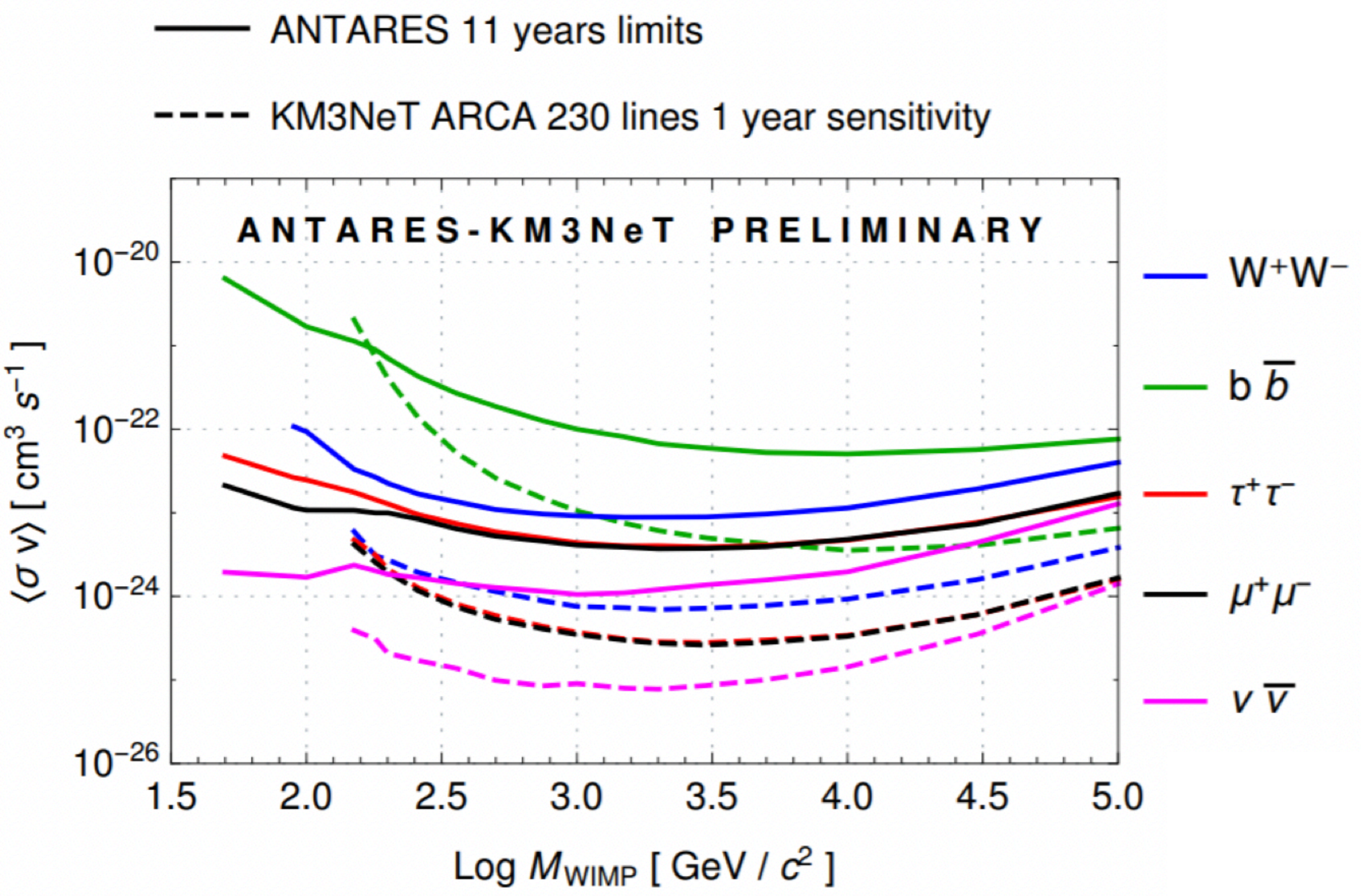


- **High complementarity** with direct searches (**XENON1T**) and indirect gamma-ray searches (**Fermi-LAT**).
- Very **competitive probes** of minimal dark matter models with neutrino telescopes.

Constraints from diffuse analysis

- Whole sky
- Energy + angular distribution
- More powerful: improvement of ~2 orders of magnitude
- But less robust: affected more by astrophysical uncertainties

KM3NeT, **36th ICRC, PoS 552 (2019)**



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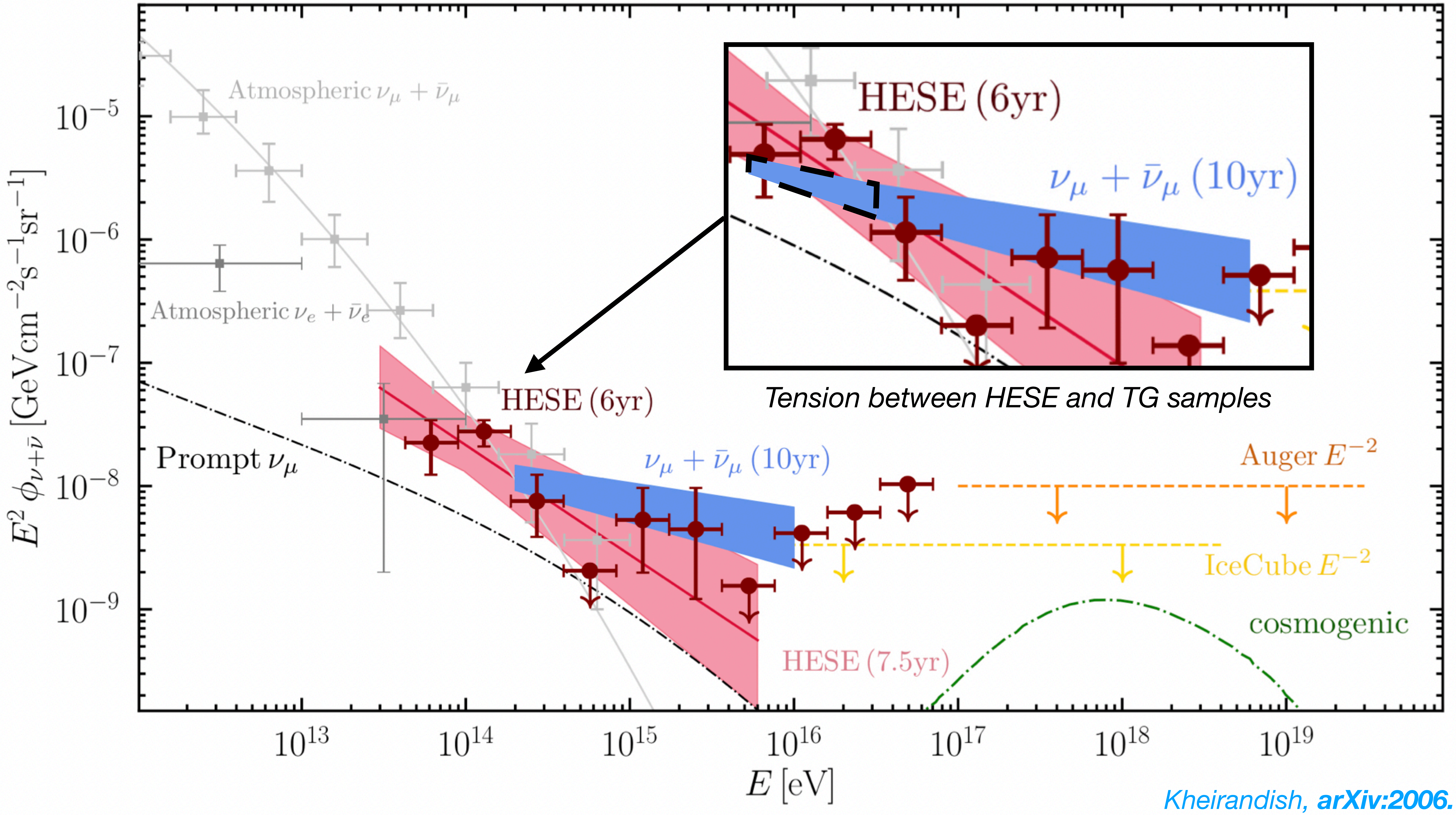
High-energy astrophysical neutrinos

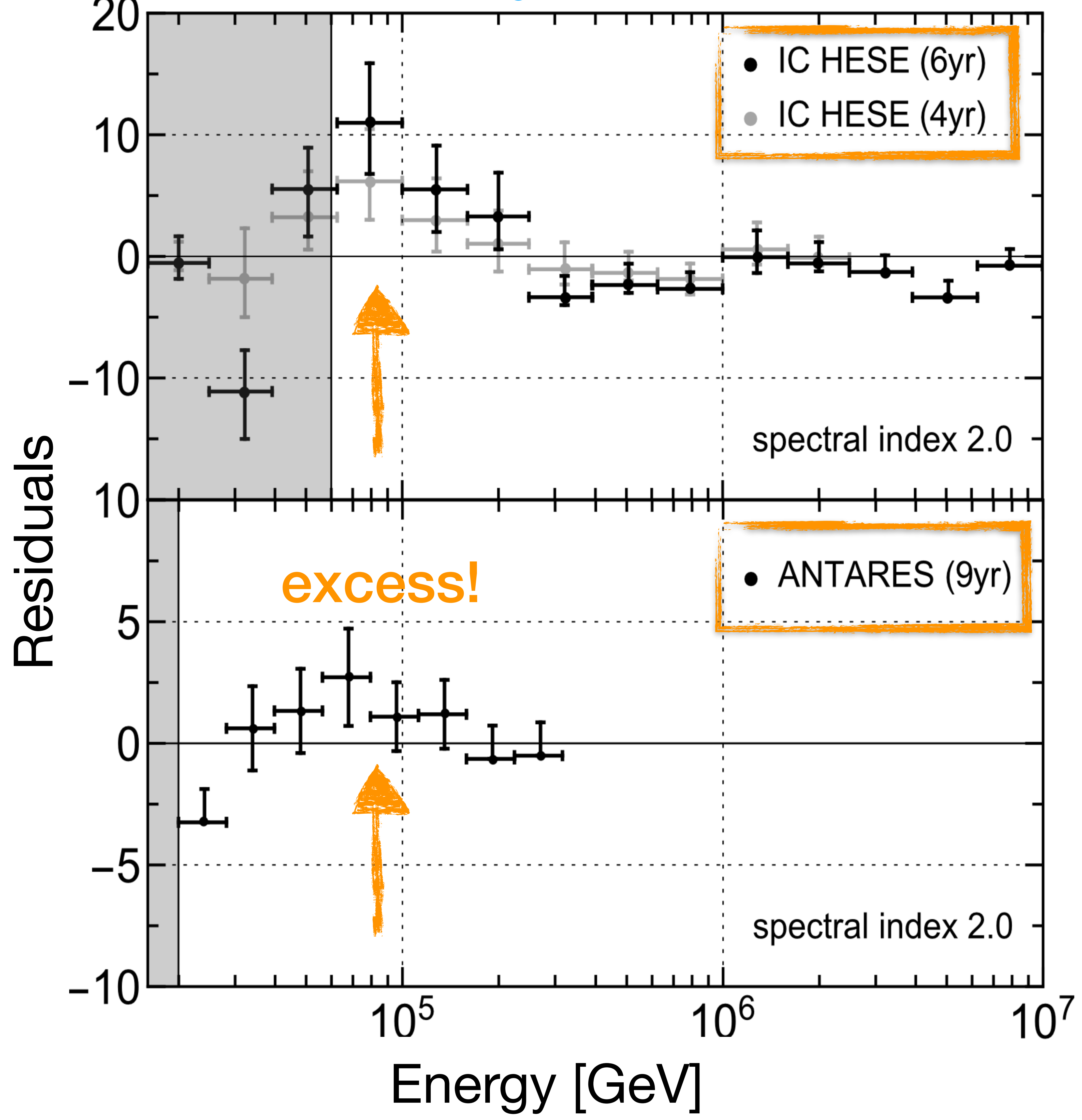


Tension between HESE and TG samples

Kheirandish, ***arXiv:2006.16087***

The low energy excess

MC, Mele, Miele, Migliozzi, Morisi, ***ApJ 851 (2017)***



Residuals with respect to an astrophysical power-law with spectral index 2.0

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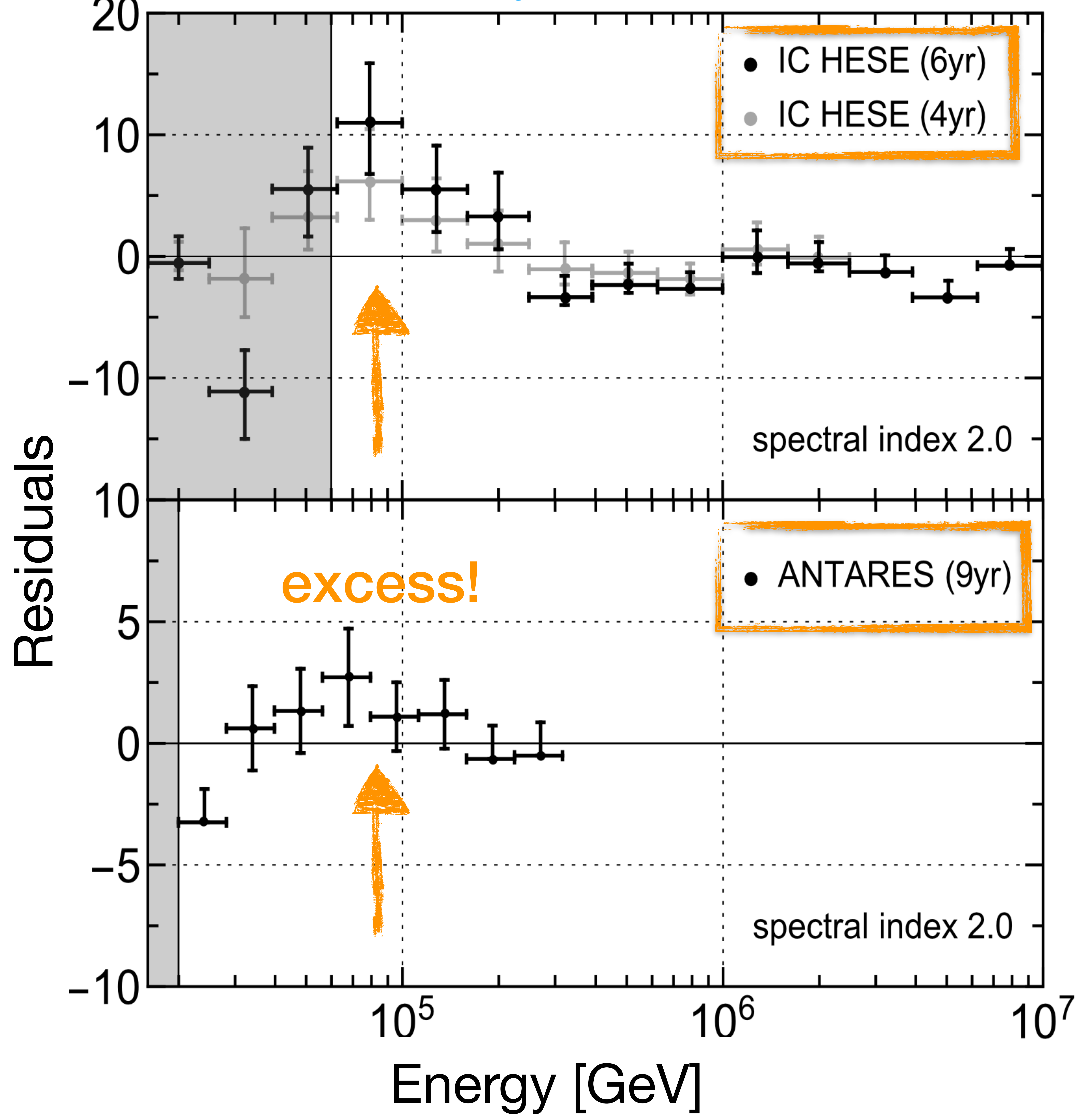
MC, Mele, Miele, Migliozzi, Morisi, ***ApJ 851 (2017)***



Possible explanations

- Multi-component flux with a galactic contribution and/or starburst galaxies

  see e.g. Gaggero+ ***ApJL 815 (2015)****, Ambrosone+,* ***MNRAS 503 & 515***

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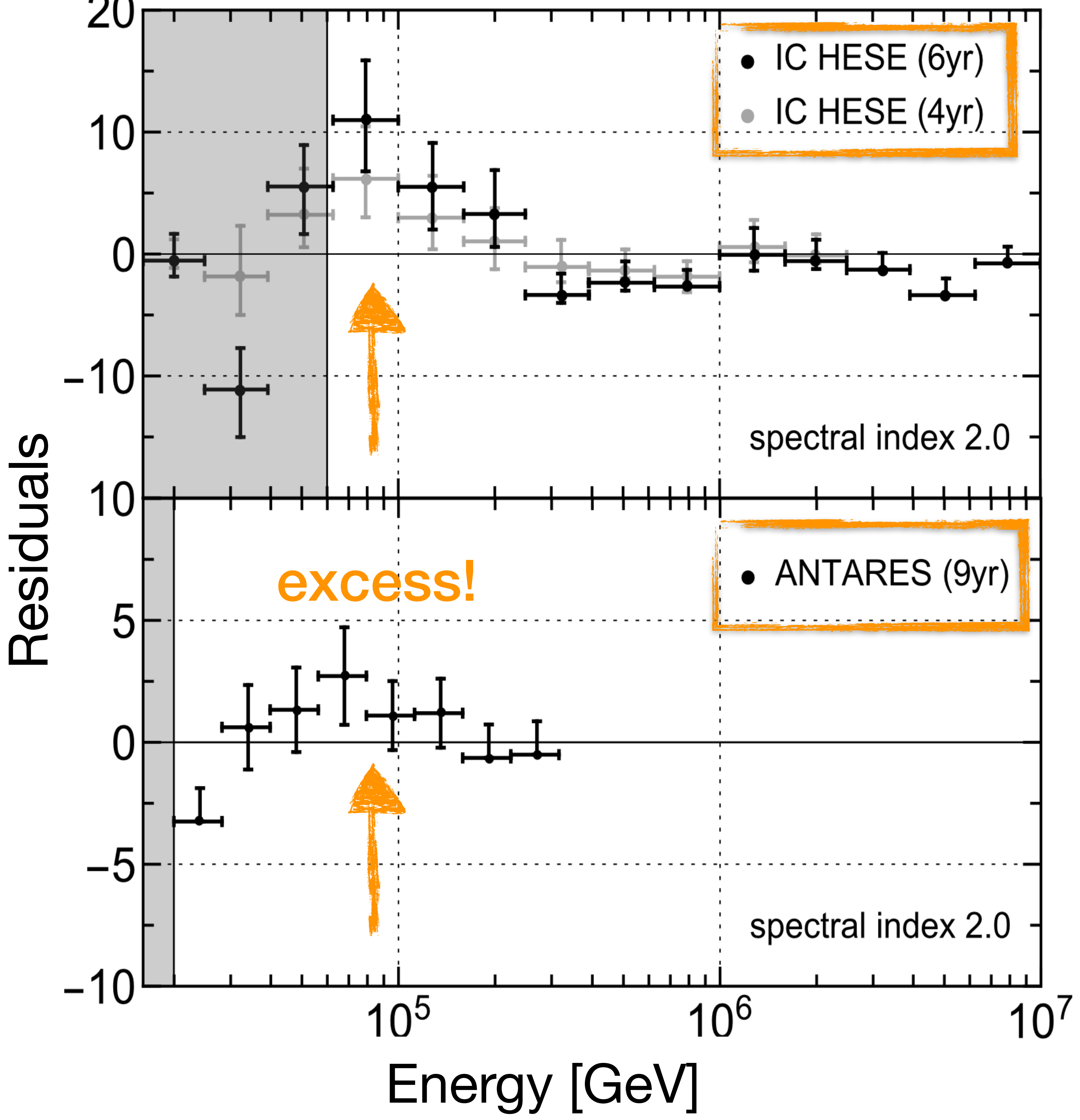

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  Kimura, Murase, Toma, ***ApJ 806***
  Murase, Guetta, Ahlers, ***PRL 116***
  Tamborra, Ando, ***PRD 93***
  Senno, Murase, Meszaros, ***PRD 93***
  Denton, Tamborra, ***ApJ 855***
  Denton, Tamborra, ***JCAP 1804***

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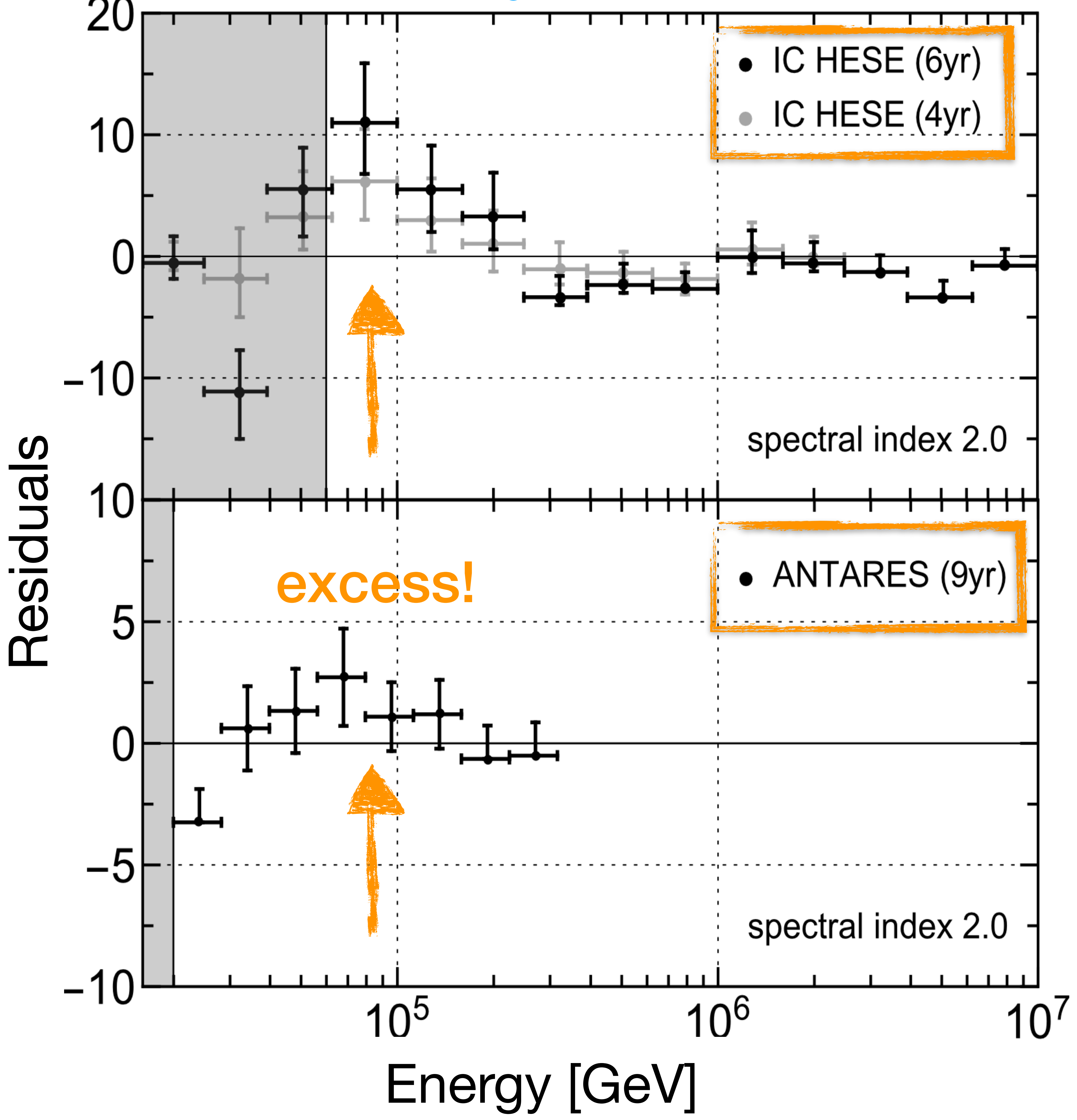

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- Active neutrino decays

  *Denton, Tamborra, **PRL 121 (2018)***
  *Abdullahi, Denton, **PRD 102 (2020)***

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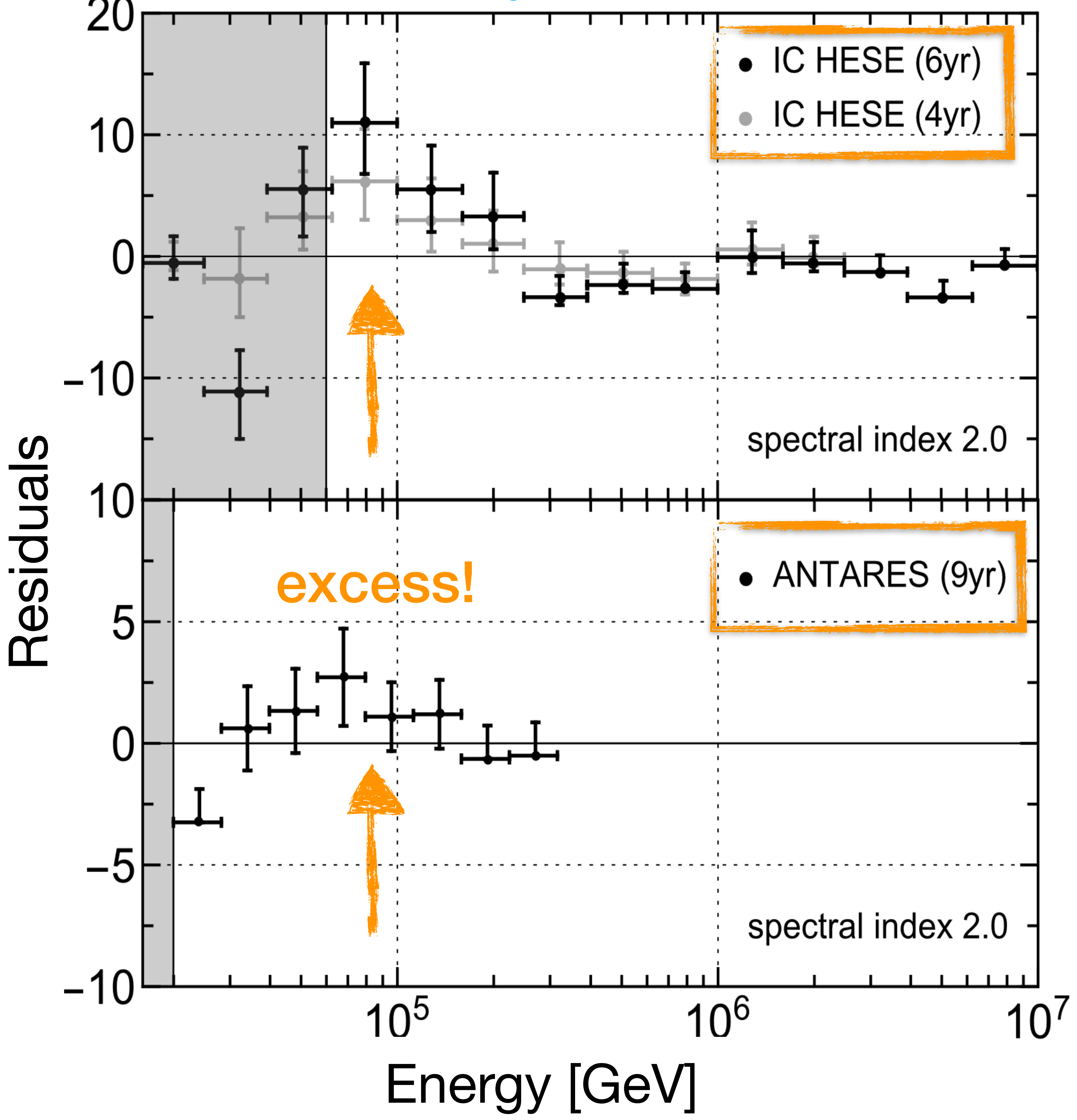

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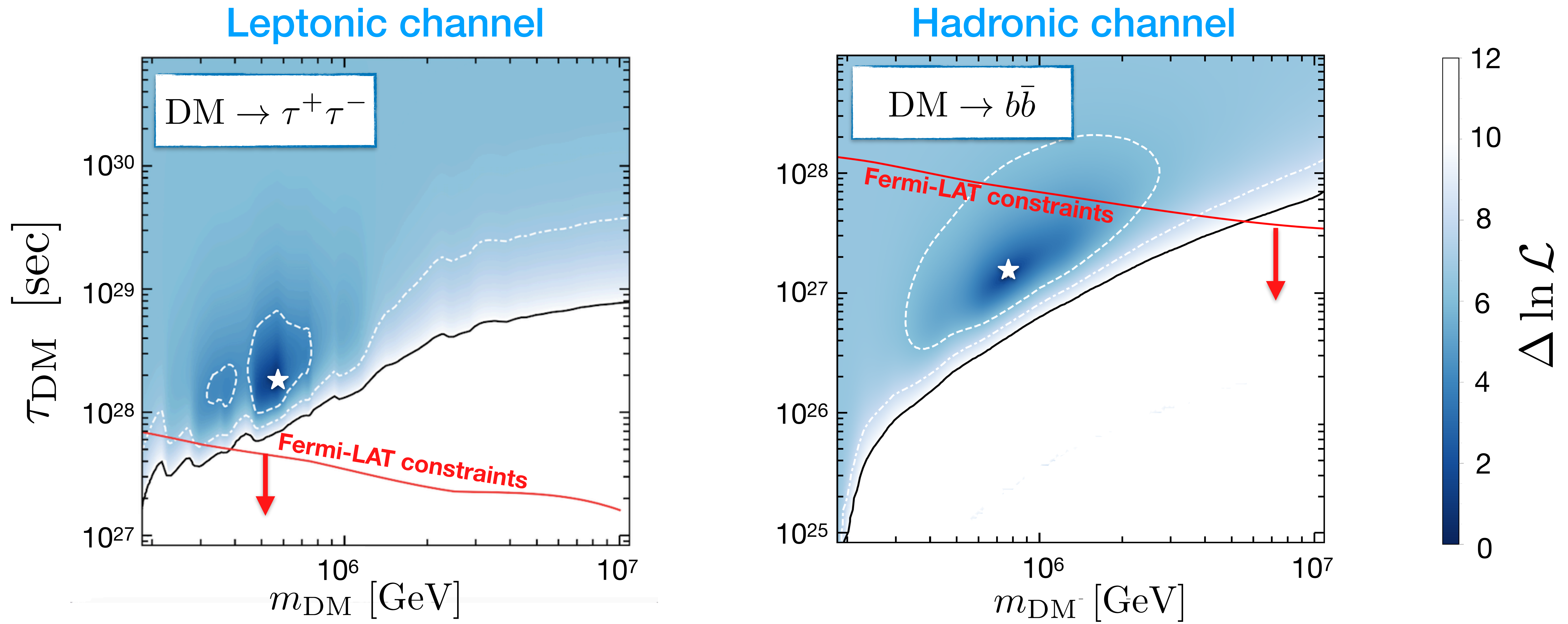
  Denton, Tamborra, ***PRL 121 (2018)***
  Abdullahi, Denton, ***PRD 102 (2020)***

- **Leptophilic decaying dark matter**

  MC, Miele, Morisi, Vitagliano, ***PLB 757 (2016)***
  MC, Miele, Morisi, ***JCAP 1701***
  MC, Miele, Morisi, ***PLB 773 (2017)***
  MC, Fiorillo, Miele, Morisi, Pisanti, ***JCAP 1911***

Highlighted results



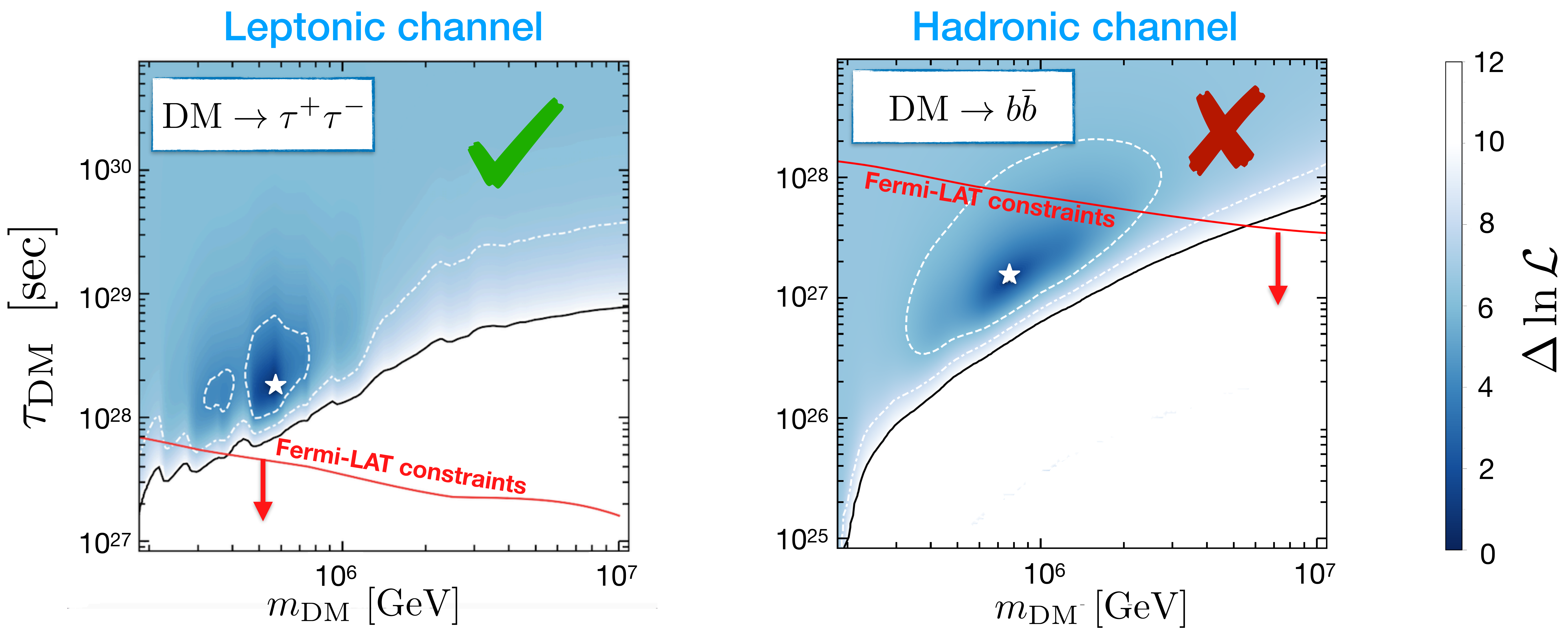
Two-component neutrino flux

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E\mathrm{d}\Omega} = \frac{\mathrm{d}\Phi_\nu^{\mathrm{DM}}}{\mathrm{d}E\mathrm{d}\Omega} + \frac{\mathrm{d}\Phi_\nu^{\mathrm{astro}}}{\mathrm{d}E\mathrm{d}\Omega}$$

power-law flux with parameters following a Gaussian prior compatible with IceCube TG muon neutrino data

*see also Skrzypek, MC, Argüelles, **arXiv:2205.03416***

Highlighted results



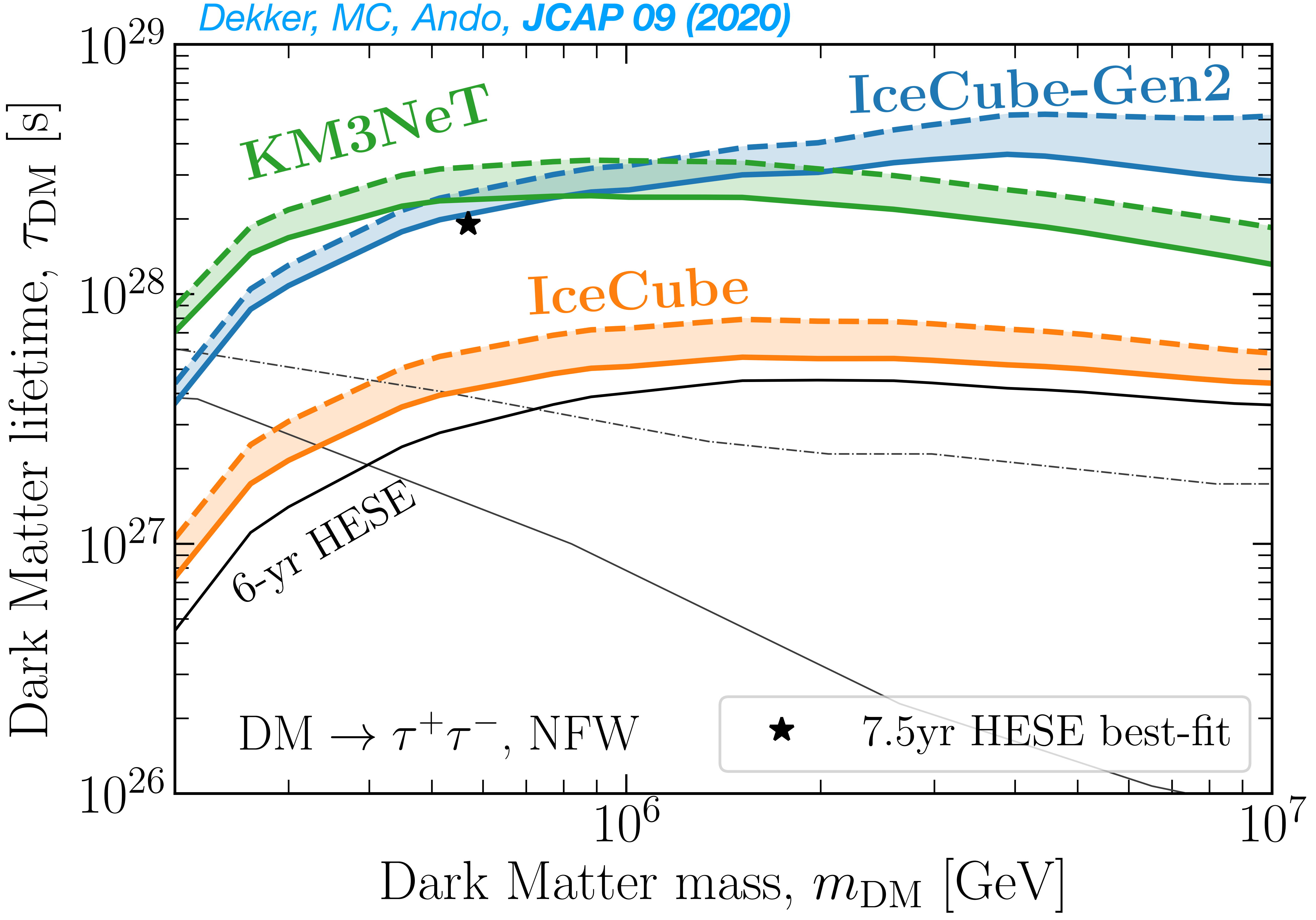
Main results

- Leptophilic decaying dark matter scenario is allowed
- Hadronic channels are already excluded by gamma-ray constraints (Fermi-LAT)

see also Skrzypek, MC, Argüelles, **arXiv:2205.03416**

Angular power spectrum analysis

Dekker, MC, Ando, **JCAP 09 (2020)**



- Exclusion at 95% CL after 10 years of observations
- Bands covering the median and the conservative 95% sensitivity from Monte Carlo simulations
- Gamma-ray constraints shown with grey lines: HAWC (solid) and global (dot-dashed)

HAWC: Abeysekara et al., **JCAP 1802**
Global: Cohen, Murase, Rodd, Safdi, Soreq, **PRL 119 (2017)**

Future neutrino telescopes will firmly probe the dark matter hypothesis!

Conclusions

- Neutrino telescopes are probing still-unexplored regions of the dark matter parameter space.

- **Atmospheric neutrinos** (below 100 TeV): unprecedented KM3NeT sensitivity to WIMP dark matter

  ★**High complementarity with direct and indirect (gamma-ray) searches**

- **Astrophysical neutrinos** (100 TeV — 10 PeV): tension among different neutrino data sets, and between multi-messenger data and astrophysical models

  ★**Leptophilic decaying dark matter still viable for IceCube**

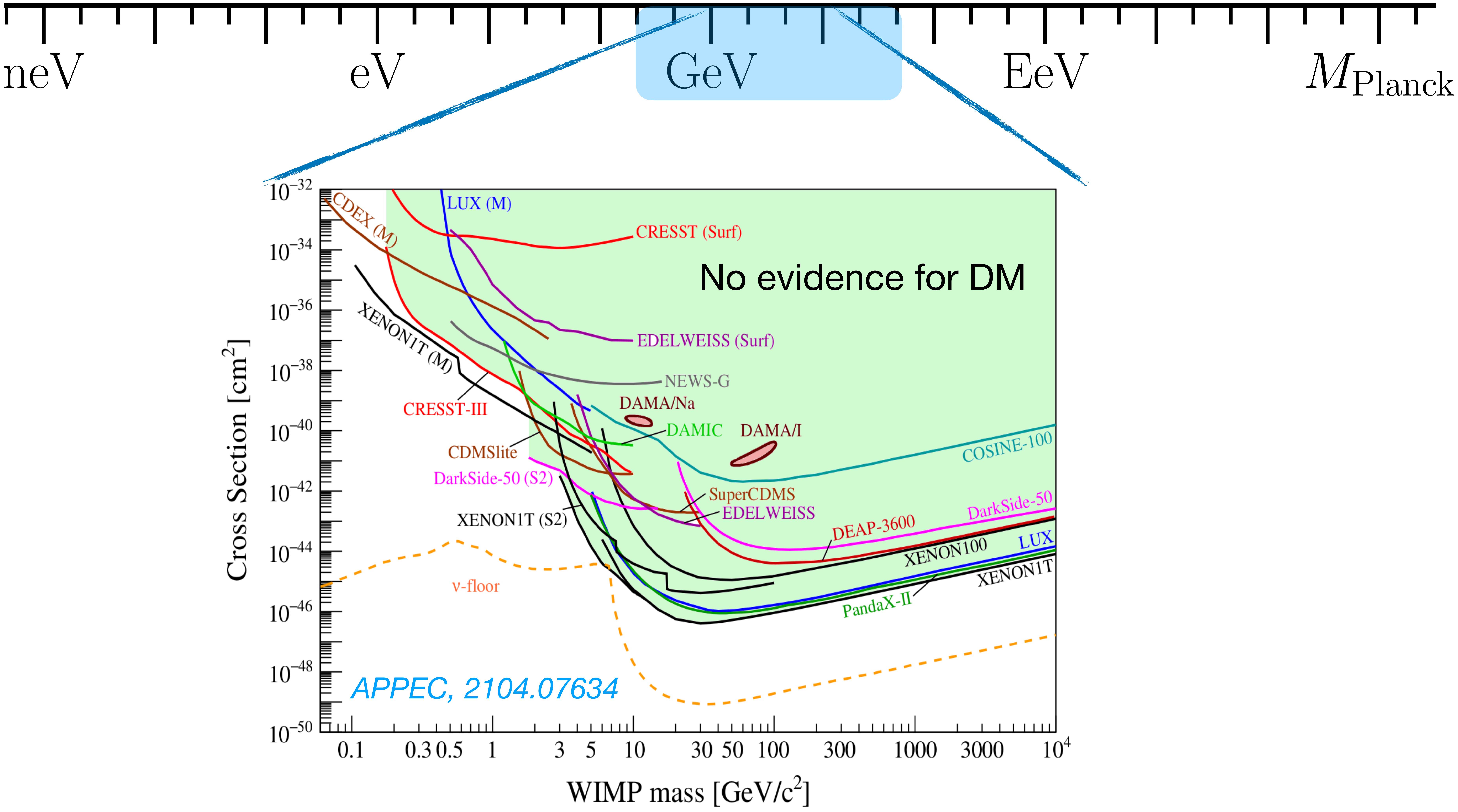
- The future is bright for astrophysical neutrinos: *KM3NeT, Baikal-GVD, P-ONE*….**stay tuned!**

Thanks for listening

BACKUP SLIDES

The vast dark matter landscape

Weakly Interactive Massive Particles (WIMPs)



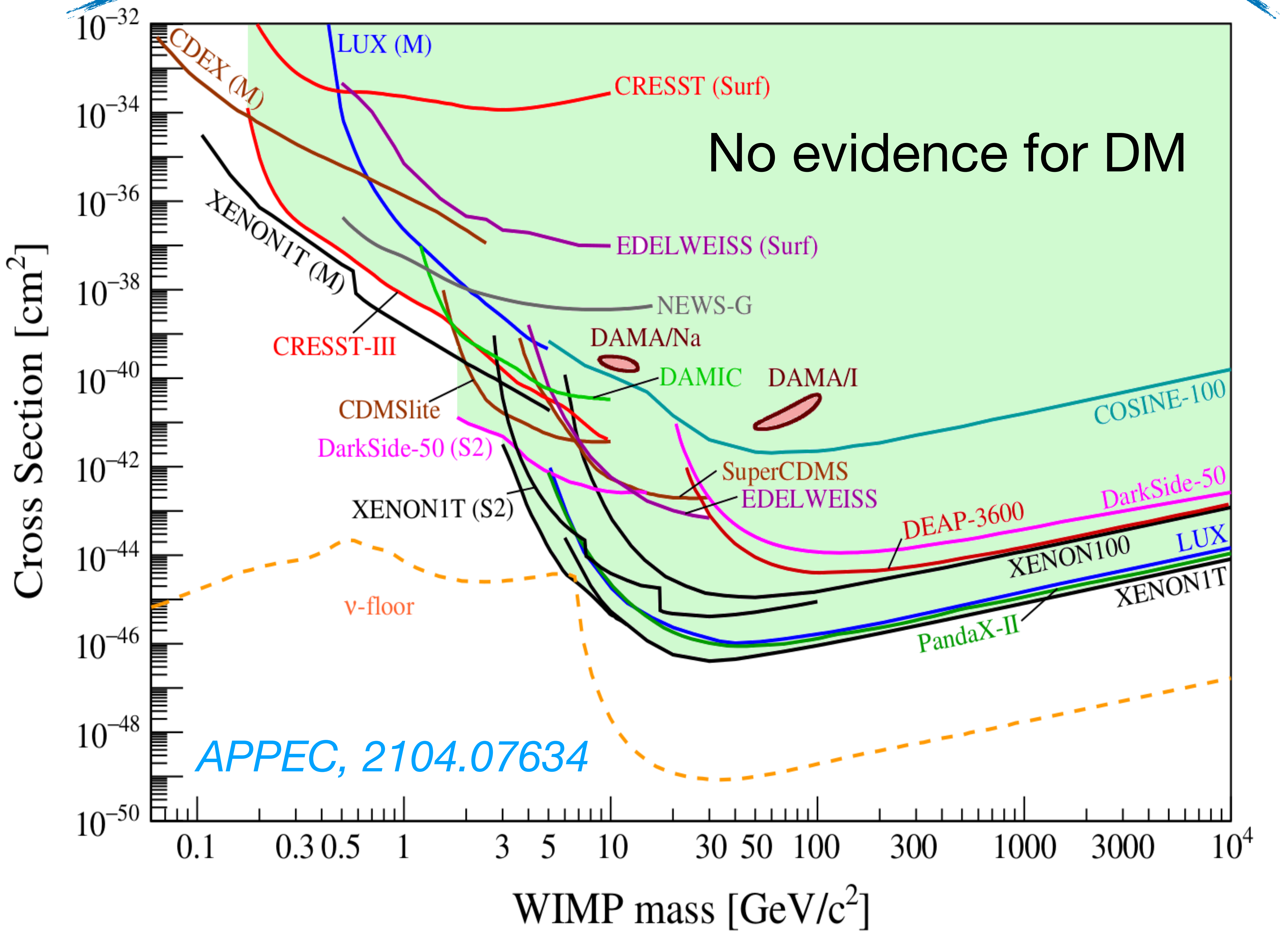
No detection at colliders and direct experiments!

see e.g.: Bertone, Hooper, Silk, ***Phys. Rept. 405 (2005)****; Bertone, Tait,* ***Nature 562 (2018)***

The vast dark matter landscape

Light Dark Matter **WIMPs** **Heavy Dark Matter**

- *keV sterile neutrinos*
- *QCD axions (μeV)*
- *Axion-Like Particles*
- ……



No detection at colliders and direct experiments!

- *WIMPzilla — FIMPzilla*
- *Planckian Interacting Massive Particles*
- *Heavy sterile neutrinos*
- ……

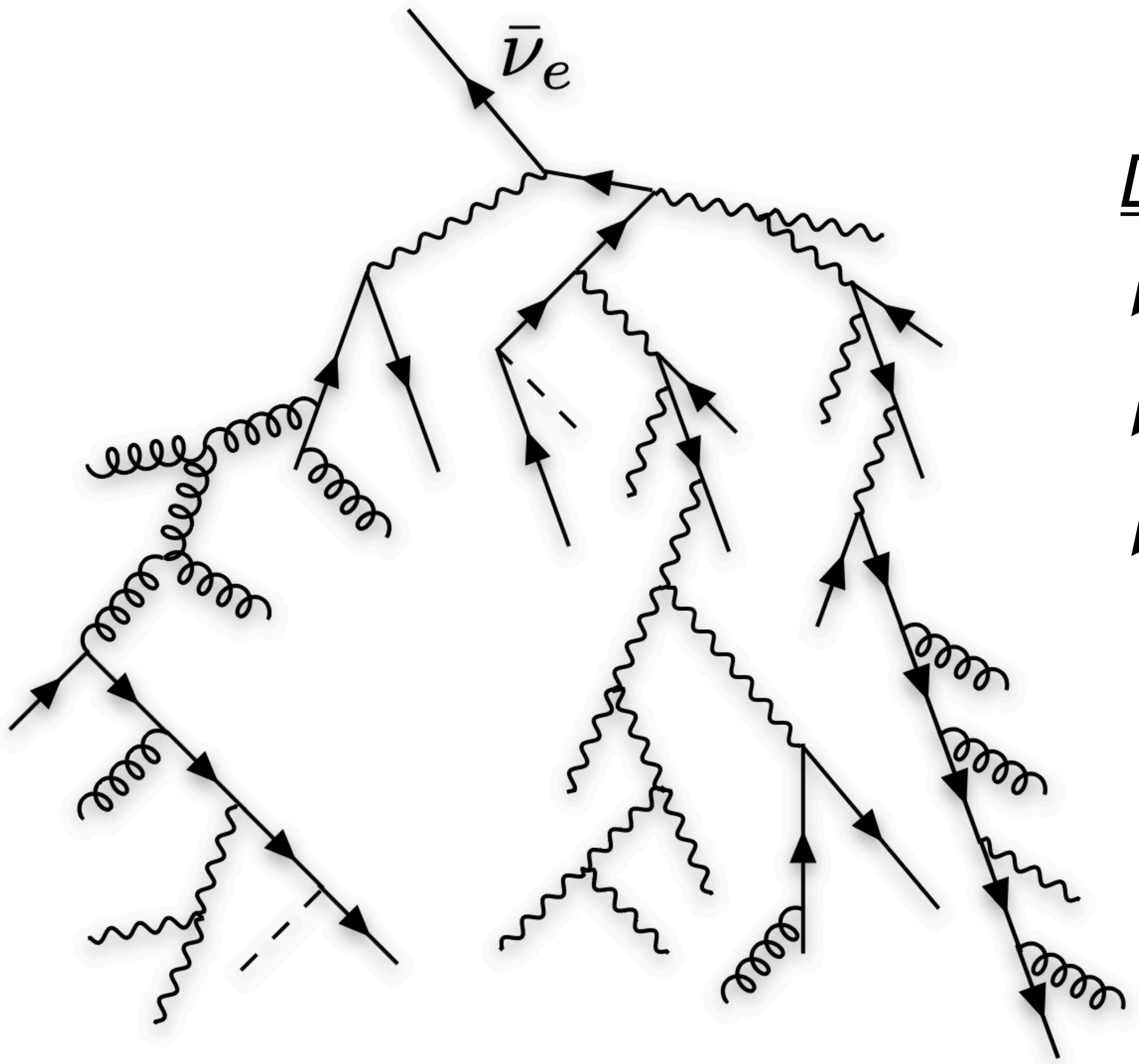
see e.g.: Bertone, Hooper, Silk, **Phys. Rept. 405 (2005)**; Bertone, Tait, **Nature 562 (2018)**

Dark matter particle spectra

DM particles can have different decay/annihilation final states:

- Leptophilc $\chi \to \ell\bar{\ell},\ \nu\bar{\nu}$
- Quarkphilic $\chi \to q\bar{q}$
- Electroweak (EW) bosons $\chi \to W^+W^-,\ ZZ,\ hh$

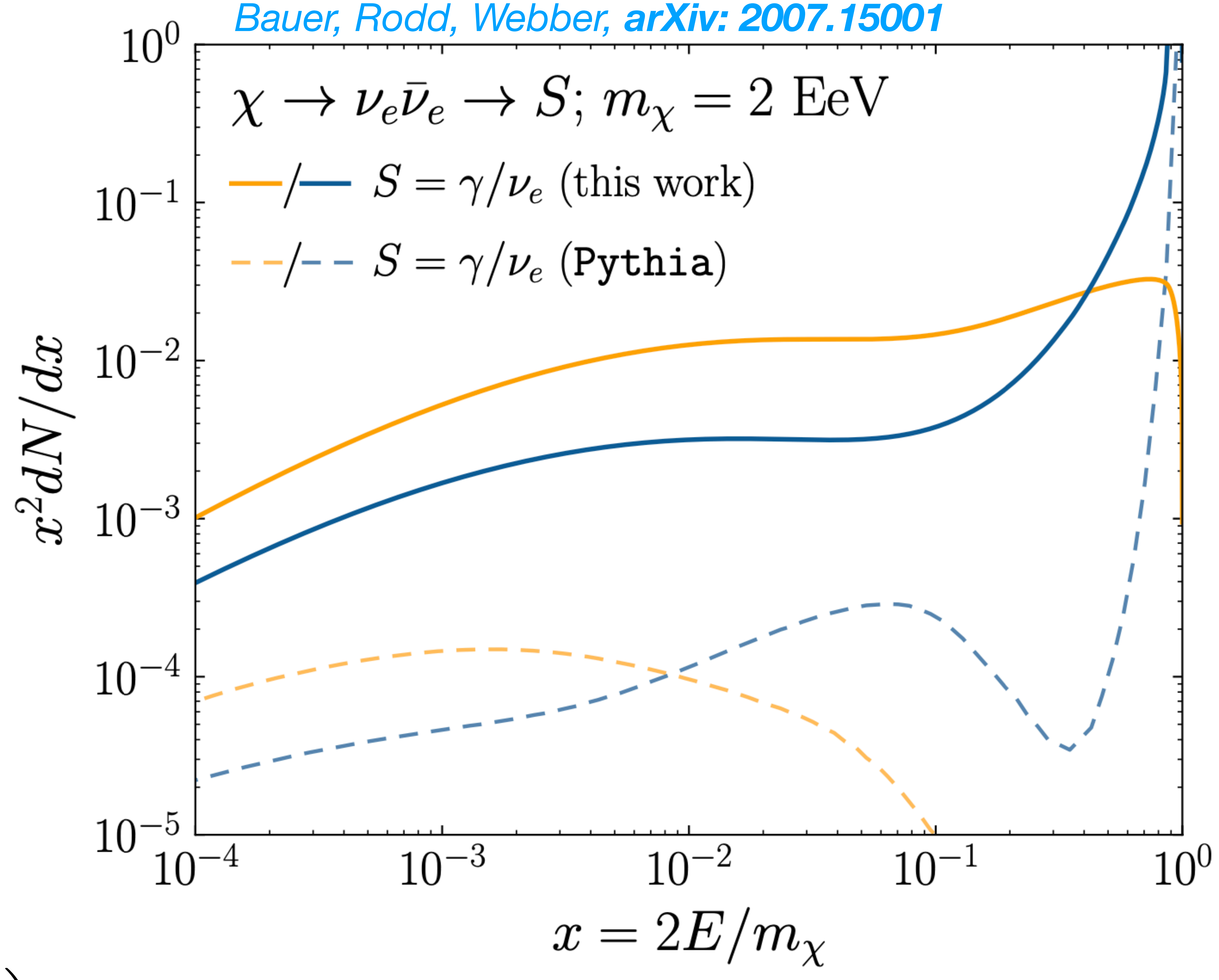
At high masses, EW corrections are relevant!



Different codes in the market:

- *Pythia*
- *PPPC*
- *HDMSpectra*

Bauer, Rodd, Webber, **arXiv: 2007.15001**

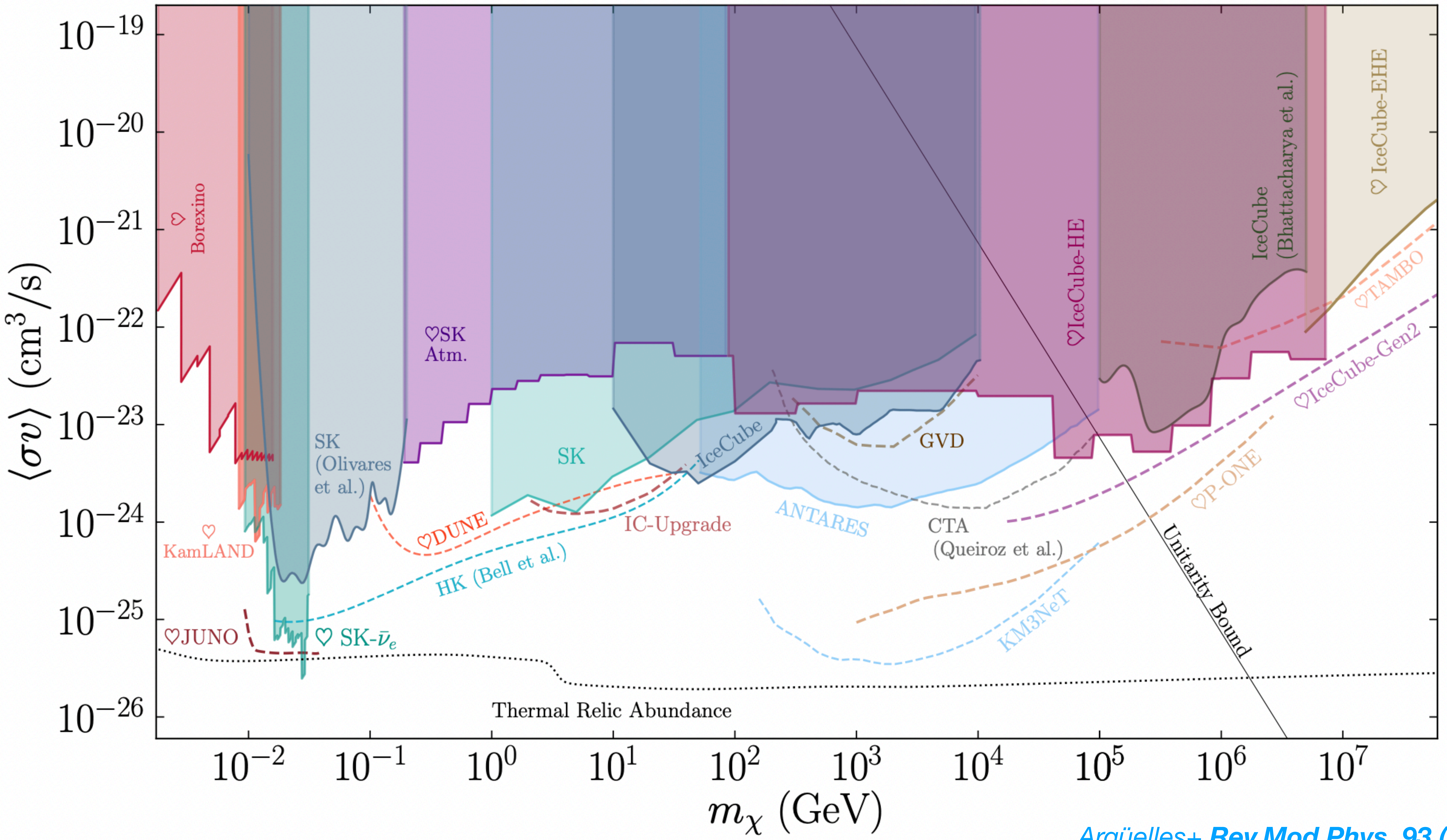


$$\Delta\sigma/\sigma \sim \alpha_{\rm EW} \ln^2\left(\frac{m_{\rm DM}^2}{M_Z^2}\right)$$

$$\simeq 75\% \ \text{ for } \ m_{\rm DM} = 10^3 \text{ GeV}$$

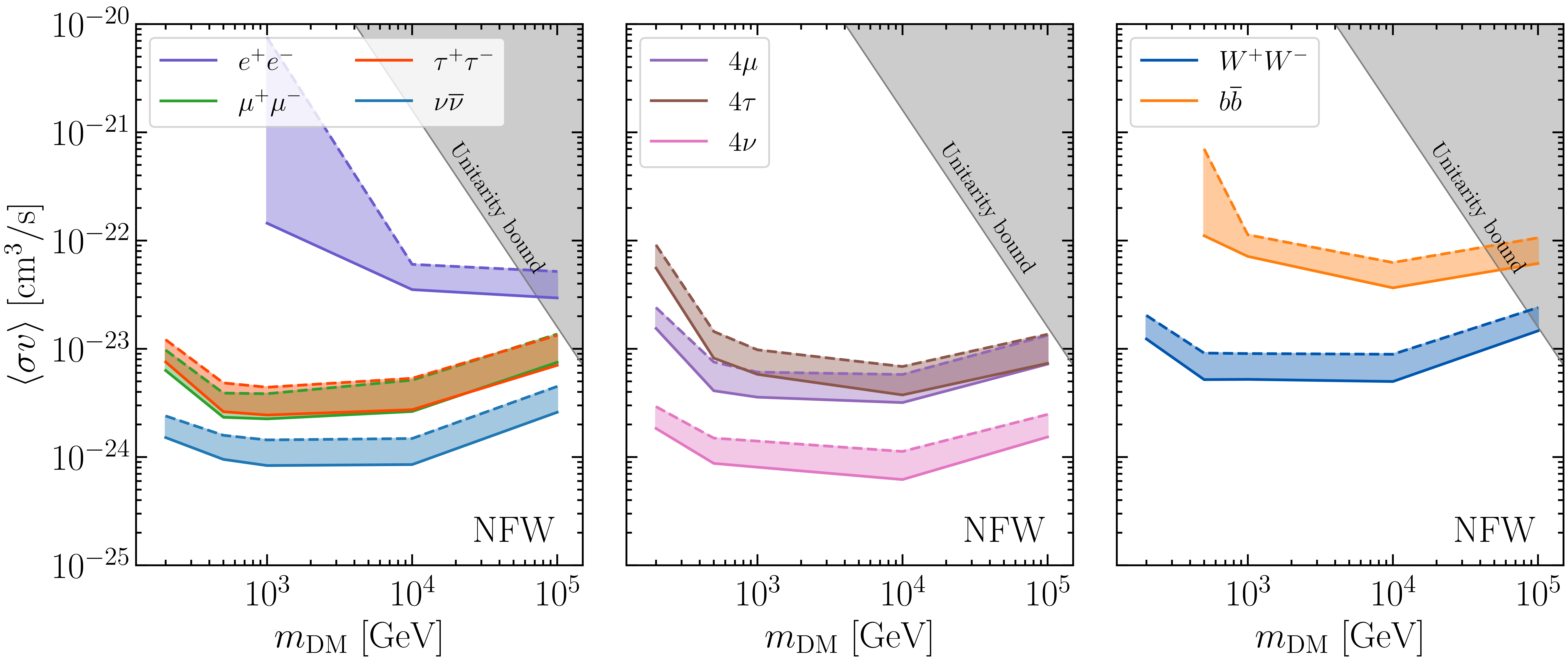
see also: Ciafaloni et al., **JCAP 1103**

Comparison with other experiments



Argüelles+ ***Rev.Mod.Phys. 93 (2021)***

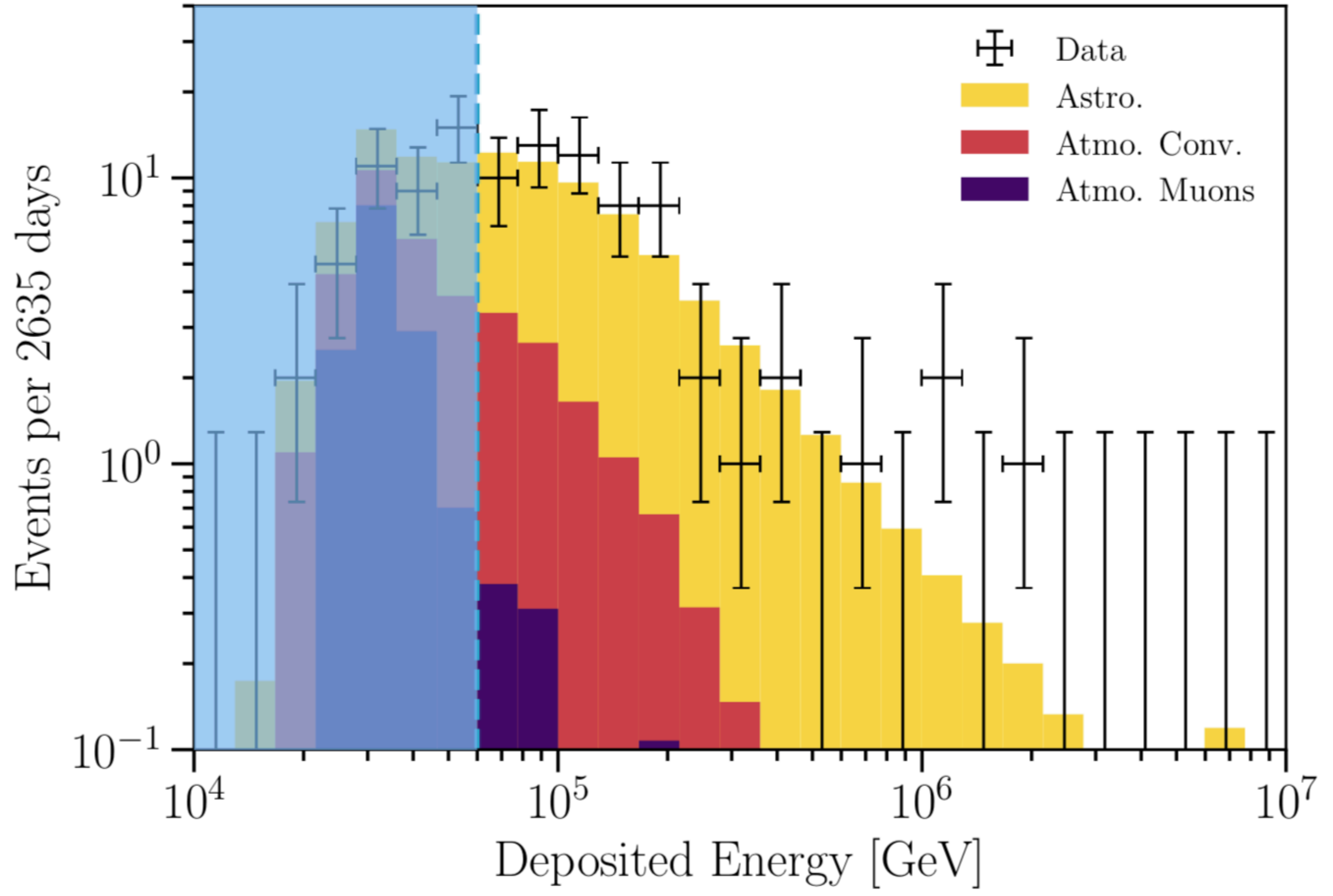
Forecasted limits



Upper-limits at 90% CL (bands cover the Monte Carlo simulations) for 10-year KM3NeT-ARCA exposure

High-energy astrophysical neutrinos

IceCube Collaboration, ***arXiv:2011.03545***



7.5-year High-Energy Starting Events (HESE)

- Observed by IceCube telescope since 2011
- More than 100 neutrino events above 30 TeV
- Bkg-only hypothesis excluded at more than 7σ
- Diffuse flux

However, their origin is still unknown…

Astrophysical production

Hadronic interactions

dust, gas, …

$$p + p \to \pi^+ \pi^- \pi^0 \ldots$$

Cosmic-rays from SNe, AGN jets, …

expected for reservoirs, where CRs are confined in magnetized environments for a long time

Photo-hadronic interactions

CMB, EBL, …

$$p + \gamma \to \Delta \to \begin{cases} \pi^+ & 1/3 \text{ of cases} \\ \pi^0 & 2/3 \text{ of cases} \end{cases}$$

Cosmic-rays from SNe, AGN jets, …

expected for accelerators, for which CRs escape to the intergalactic space

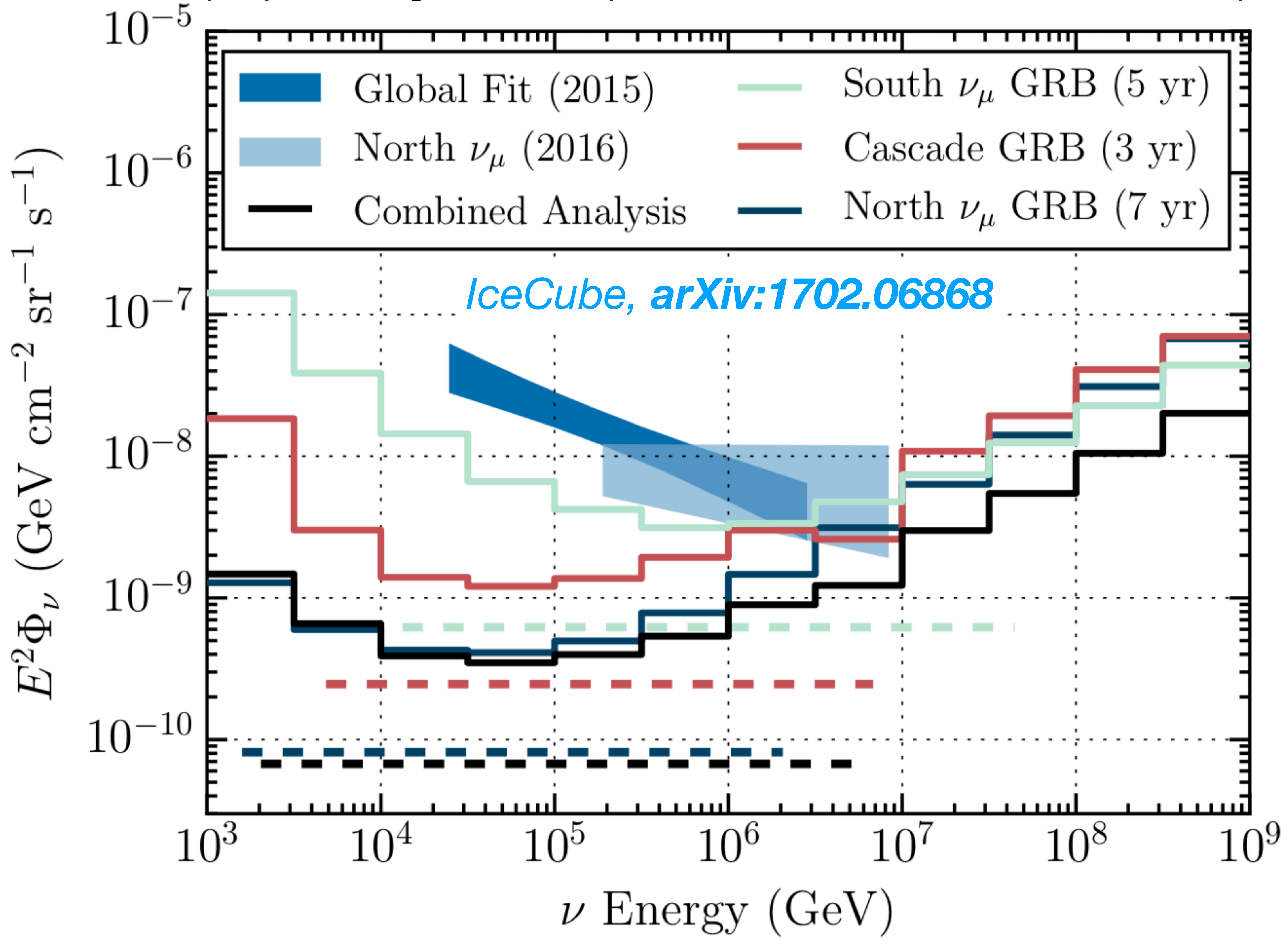
- Neutrinos and gamma-rays from pion decays: $\pi^\pm \to e^\pm \nu_e \nu_\mu \bar{\nu}_\mu \, , \quad \pi^0 \to \gamma\gamma$
- Power-law behaviors due to CRs seed: $\phi_\nu(E_\nu) \sim E_\nu^{-\alpha}$
- Proposed sources: *gamma-ray bursts* (**GRBs**), *active galactic nuclei* (**AGNs**), *starburst galaxies* (**SBGs**), …

Time-dependent and stacking analysis

Absence of angular and temporal correlations between neutrinos and known gamma-ray sources (*expect for few remarkable cases: TXS0506+056, NGC1068, AT2019dsg, …*).

GRBs: ~ 1%

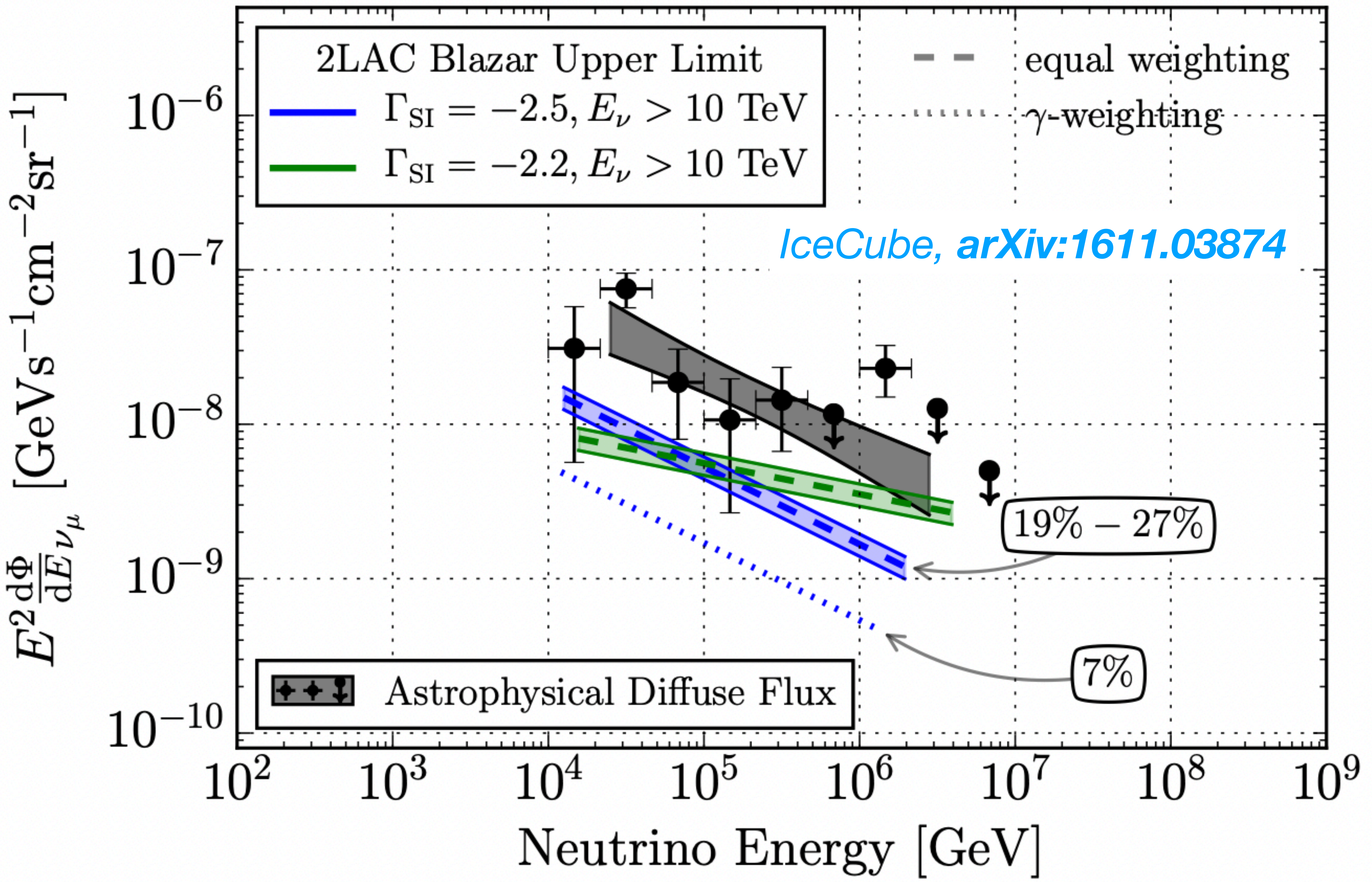
(depending on the spectral index and time-window)



see also: IceCube, ***PRL 122 (2019)***

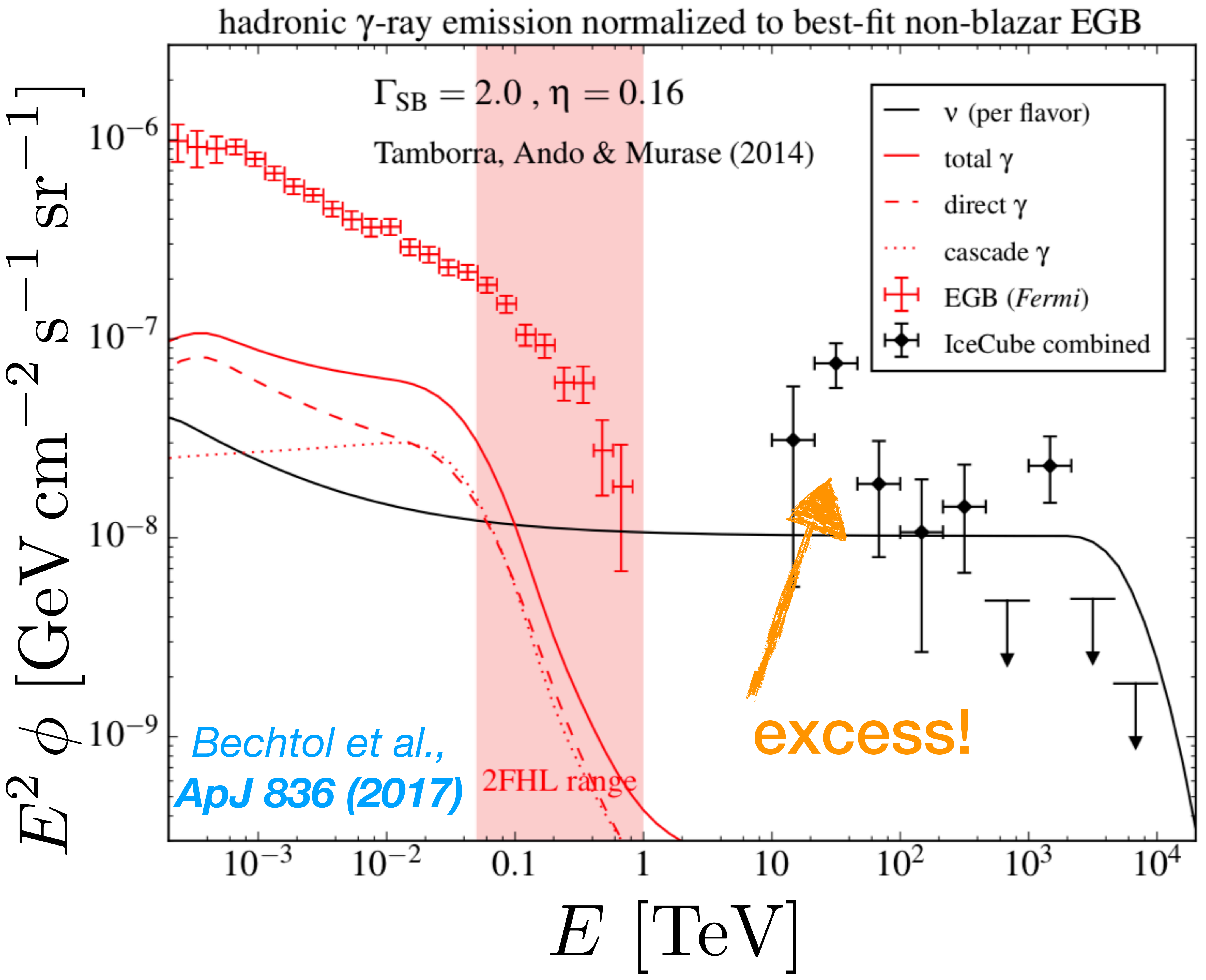
AGNs: ~ 19% — 27%

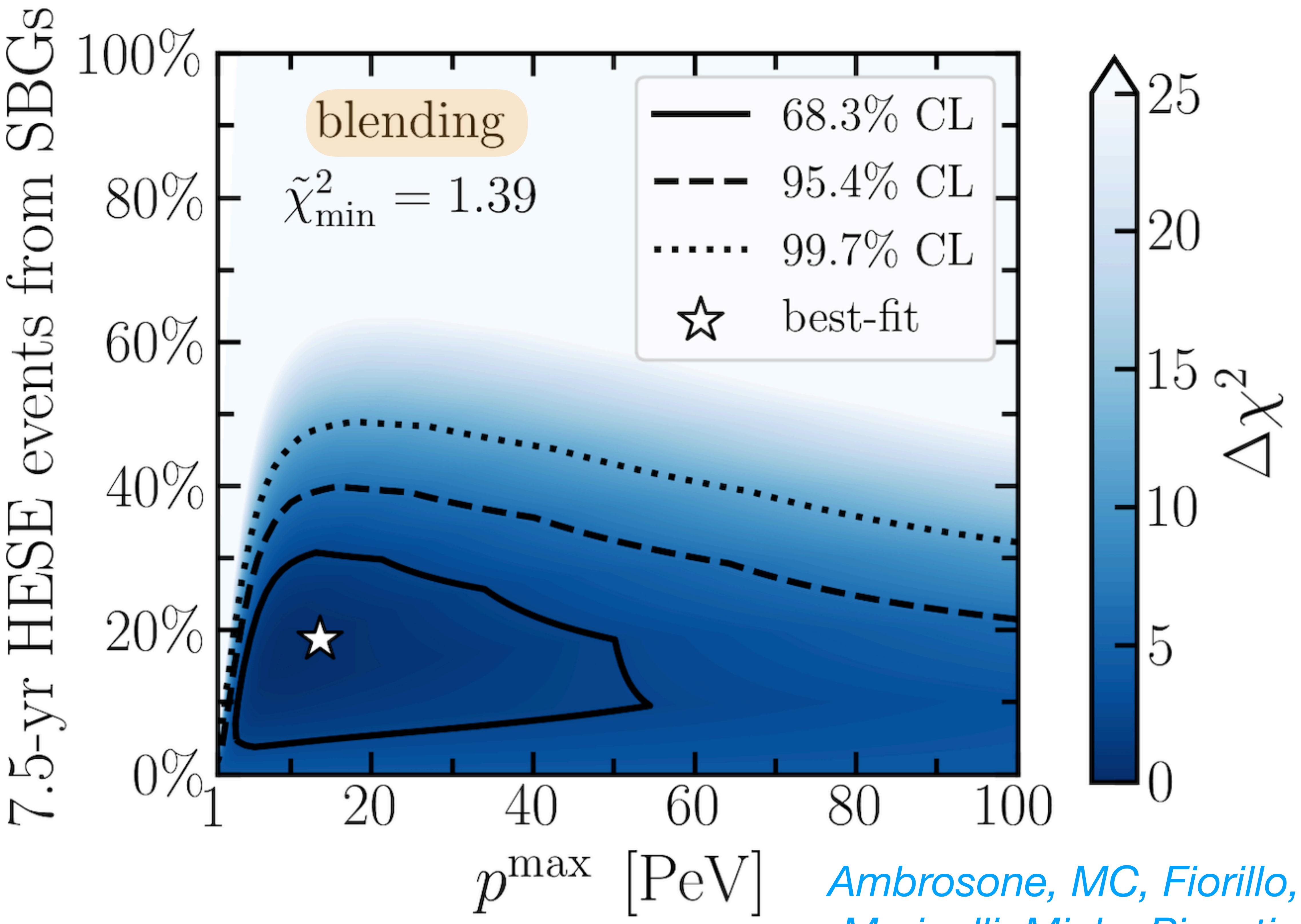
(depending on the spectral index)



see also: IceCube, ***ApJ 935 (2017)***

Tension between neutrinos and gamma rays



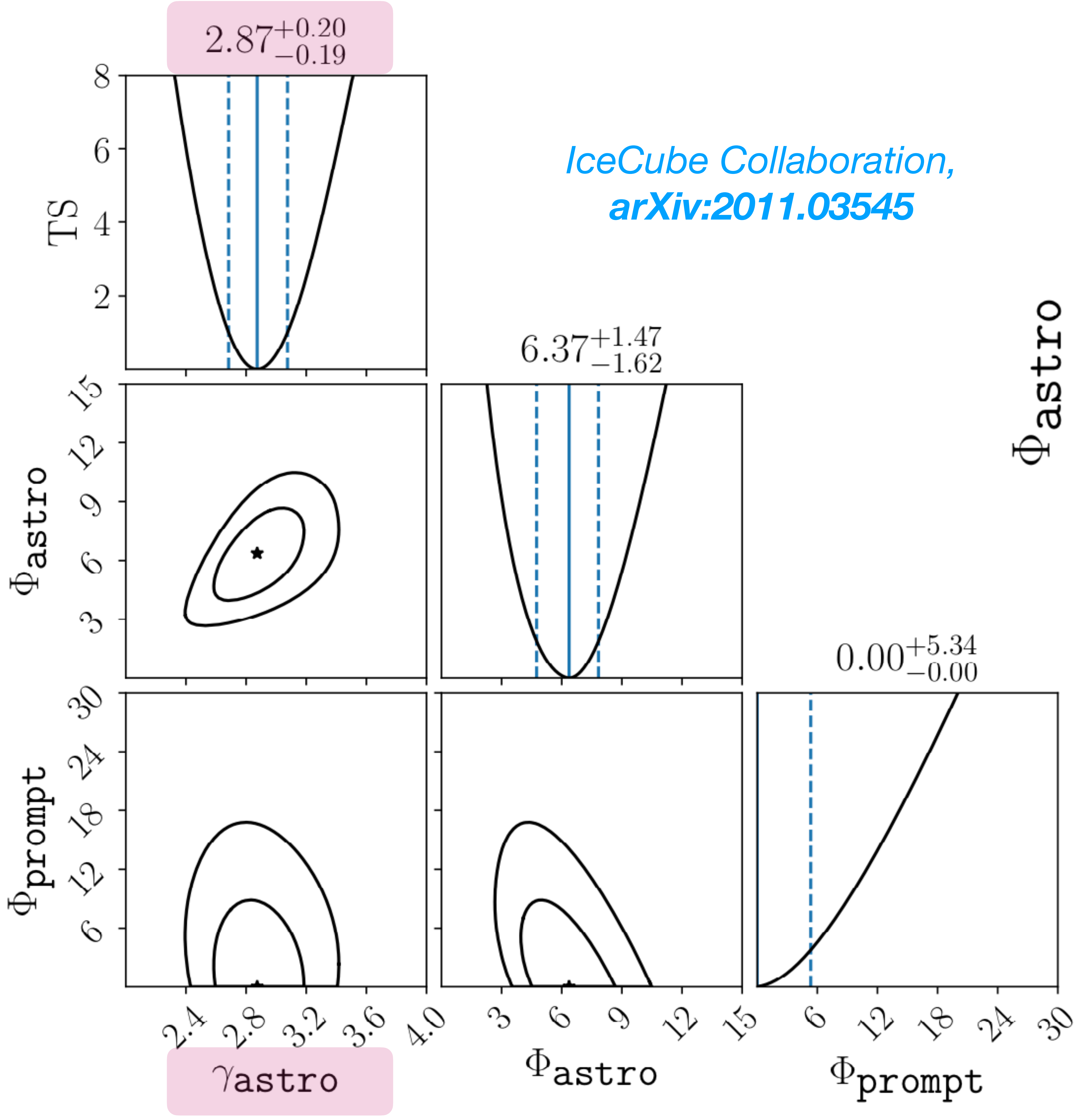


Ambrosone, MC, Fiorillo, Marinelli, Miele, Pisanti, ***MNRAS 503 (2021)***

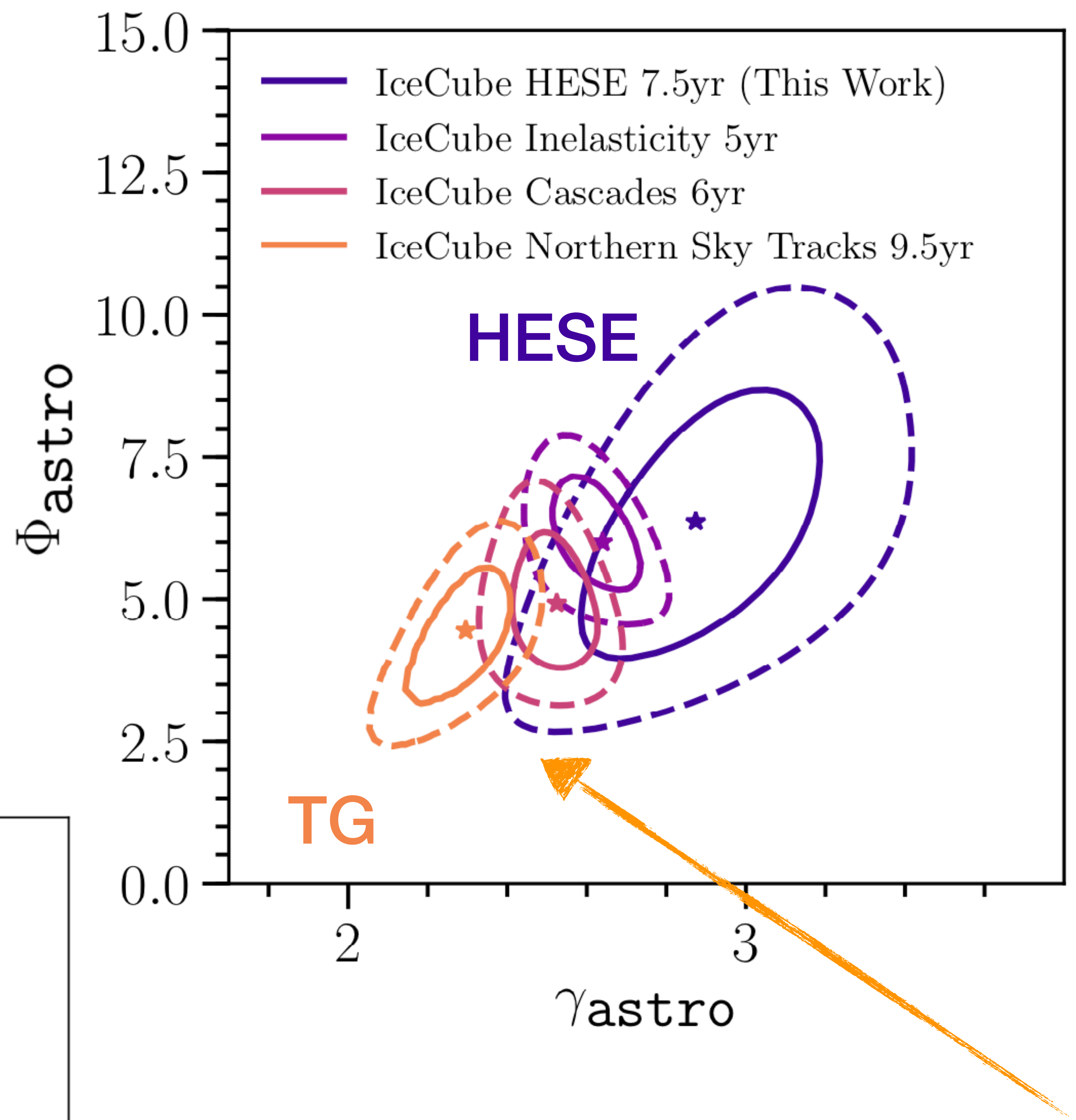
Explaining the **very large neutrino flux at 100 TeV** with *p-p* sources would over-produce Fermi-LAT gamma rays

One of the last population model (spectral index blending) allows **SBGs** to account for **up to 40% of the HESE events** at 95.4% CL

Tension among different IceCube data samples



IceCube Collaboration, ***arXiv:2011.03545***



Expected spectral indexes

- *Fermi mechanism:*

$$\gamma_{astro} = 2.0$$

- *p-p sources:*

$$\gamma_{astro} \leq 2.2$$

- *Blazar TXS 0506+056:*

$$\gamma_{astro} = 2.1 \pm 0.2$$

Tension between HESE (full sky) and Through-Going (Northern hemisphere)