

Multi-messenger lifetime constraints on heavy decaying dark matter



Granada, 30th March - 1st April 2022

31 March - 1 April 2022
Dark Ghosts Workshop

Rasmi Hajjar

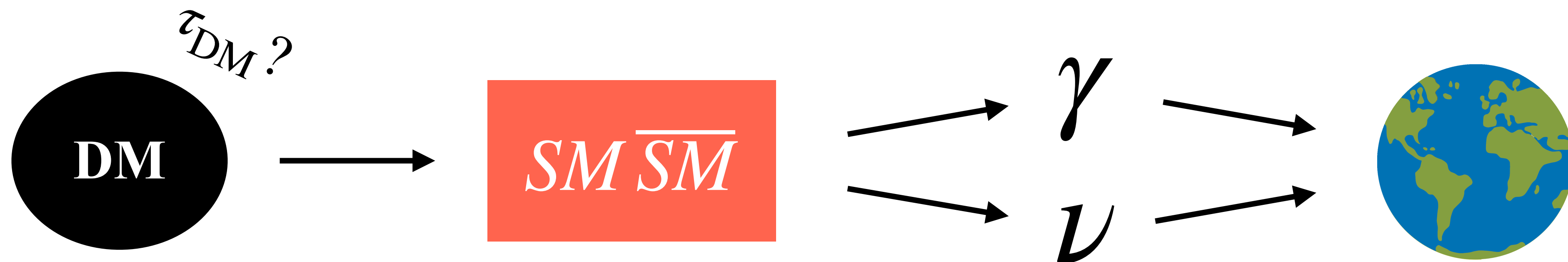
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Main goal of this work

- The main goal of this work is to obtain multichannel lifetime limits of Heavy Dark Matter (HDM) particles using UHE gamma-ray measurements and forecasted neutrino ones.
- We assume that the DM particles decay to a pair of SM particles and the minimal decaying DM scenario with only two parameters: $(m_{\text{DM}}, \tau_{\text{DM}})$



Why heavy decaying dark matter?

Forecasted
neutrino
limits

Current
gamma-ray
limits

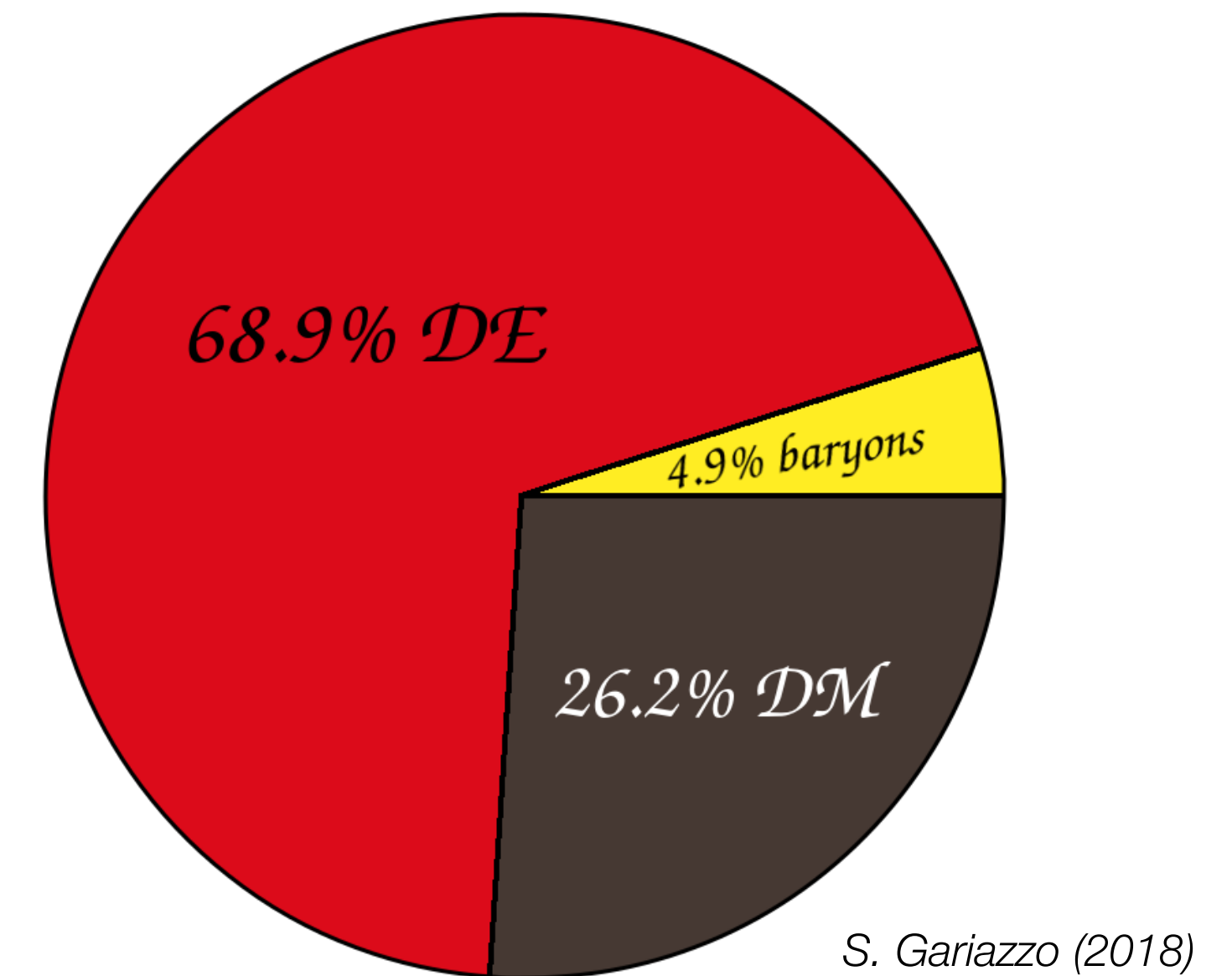
Why heavy decaying dark matter?

Forecasted
neutrino
limits

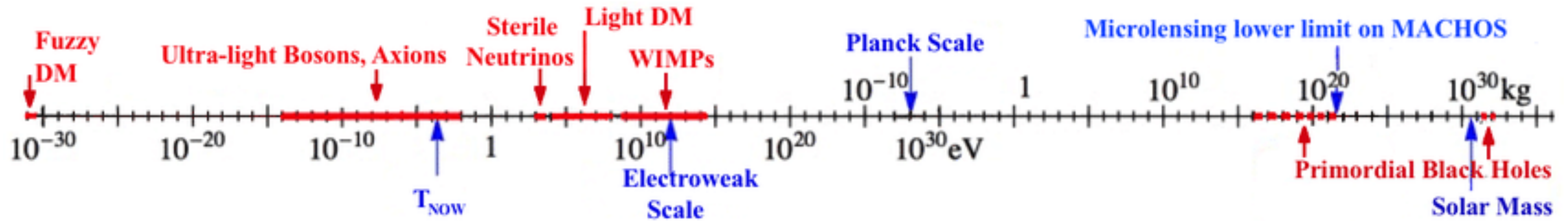
Current
gamma-ray
limits

Introduction

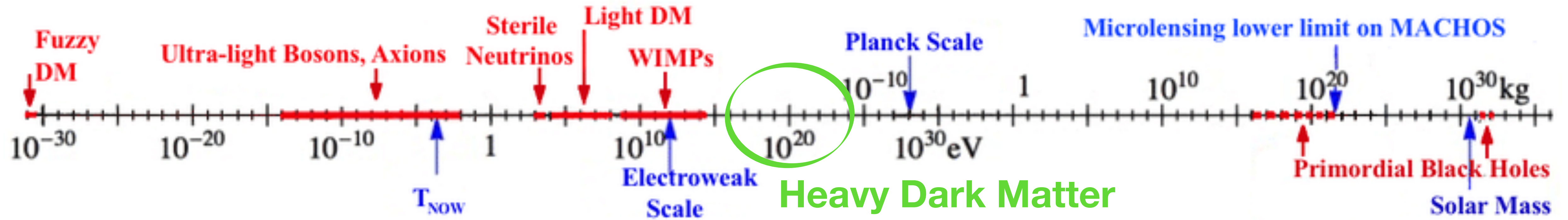
- DM is one of the pillars of the standard cosmological model.
- We have only seen DM interacting gravitationally, no other direct observations.
- Indirect DM detection via CRs, gamma-rays and neutrinos emitted by annihilation or decay of the DM particles (multi-messenger astronomy)
- We want to test DM using the ultra-high-energy neutrino and gamma-ray fluxes.



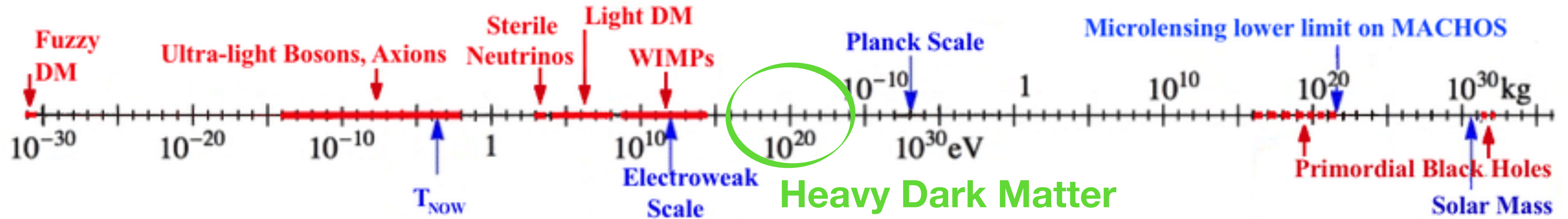
Why heavy decaying dark matter?



Why heavy decaying dark matter?



Why heavy decaying dark matter?



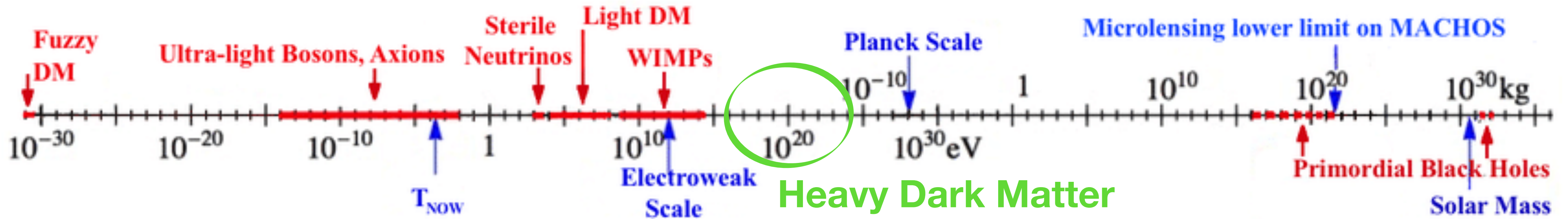
For typical values of the parameters:

$$\phi_{\nu}^{\text{dec}} \sim \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \frac{1}{\tau_{\text{DM}}} L \sim 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \left(\frac{\rho_{\text{DM}}}{0.4 \text{ GeV/cm}^3} \right) \left(\frac{10^9 \text{ GeV}}{m_{\text{DM}}} \right) \left(\frac{10^{29} \text{ s}}{\tau_{\text{DM}}} \right)$$

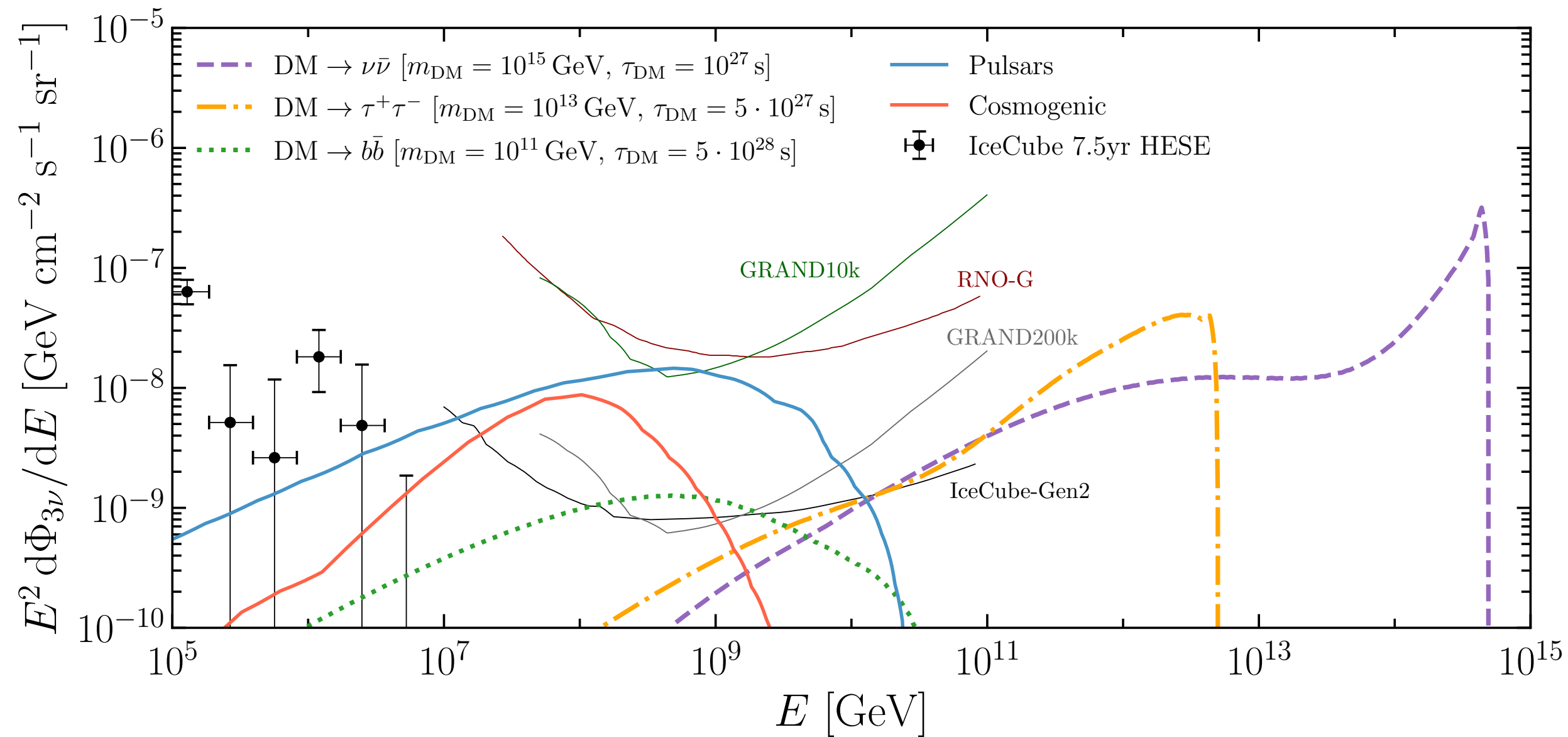
$$\phi_{\nu}^{\text{ann}} \lesssim 10^{-27} \text{ cm}^{-2} \text{ s}^{-1} \left(\frac{\rho_{\text{DM}}}{0.4 \text{ GeV/cm}^3} \right)^2 \left(\frac{10^9 \text{ GeV}}{m_{\text{DM}}} \right)^4 \left(\frac{10^{-3} c}{v_{\text{DM}}} \right)$$

$$\phi_{\nu}^{\text{dec}} \gg \gg \phi_{\nu}^{\text{ann}}$$

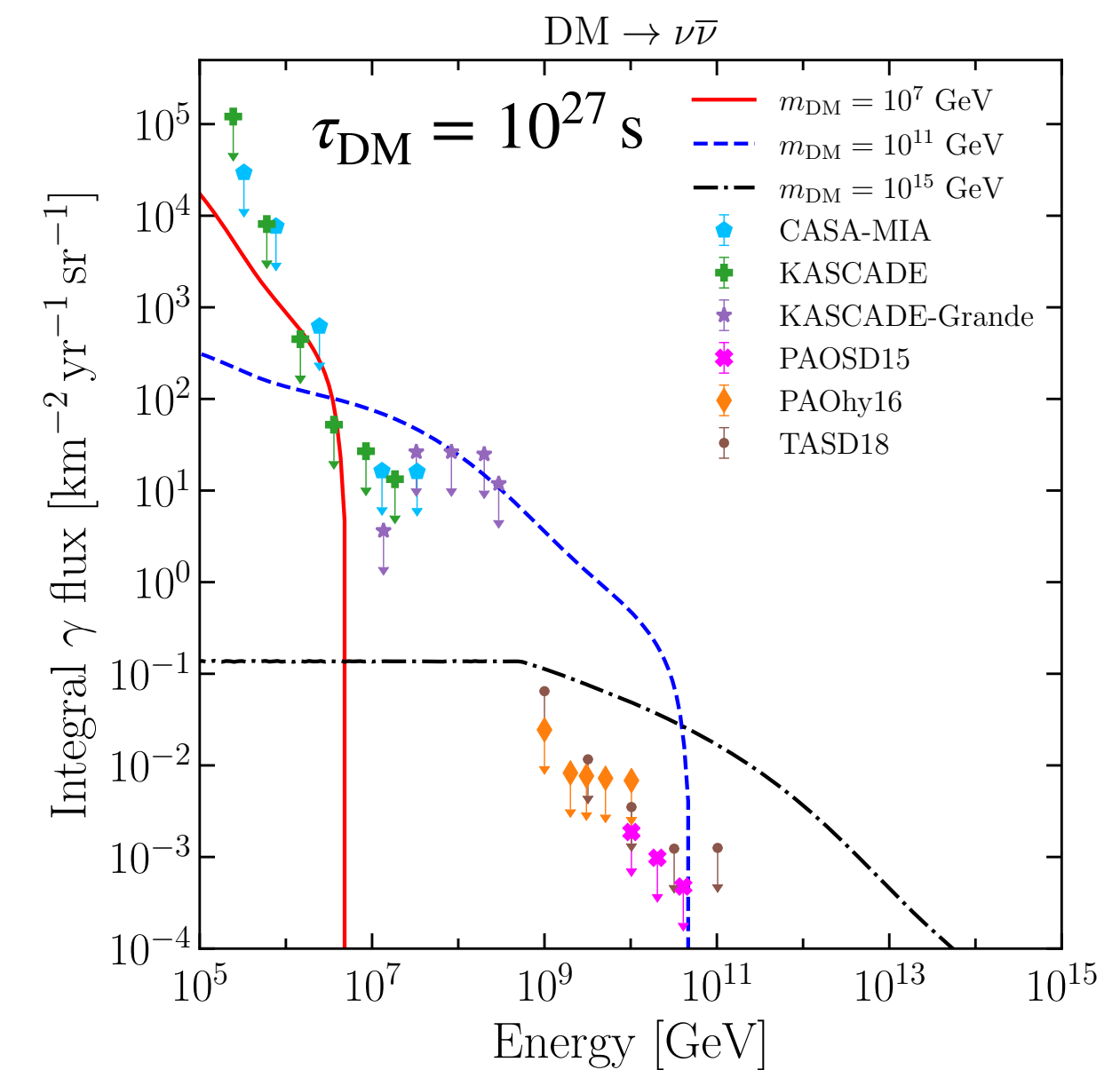
Why heavy decaying dark matter?



Produced fluxes on the reach of future radio neutrino telescopes



Expected gamma-ray fluxes on the range of UHE measurements



ν

γ

Why heavy decaying dark matter?

Forecasted
neutrino
limits

Current
gamma-ray
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Ultra-high-energy neutrino flux

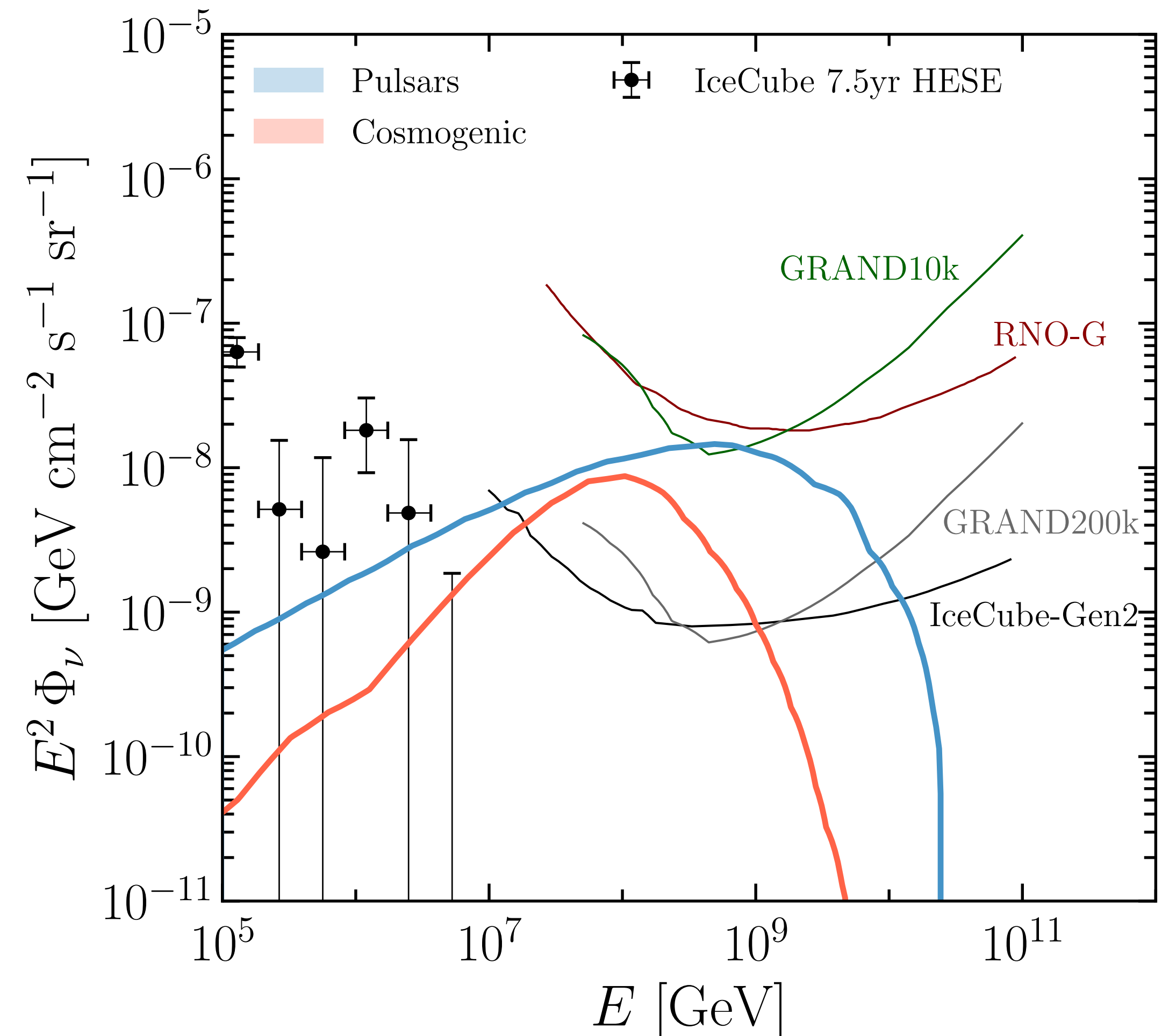
- High energy ν flux is unknown. Possible contributions:

Cosmogenic

guaranteed but uncertain magnitude, come from CRs interacting with CMB

Newborn Pulsars

higher expected astrophysical contribution in literature for neutrino radio telescopes



colored regions from
J. Álvarez-Muniz et. al. [1810.09994]

Ultra-high-energy neutrino flux

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Newborn Pulsars

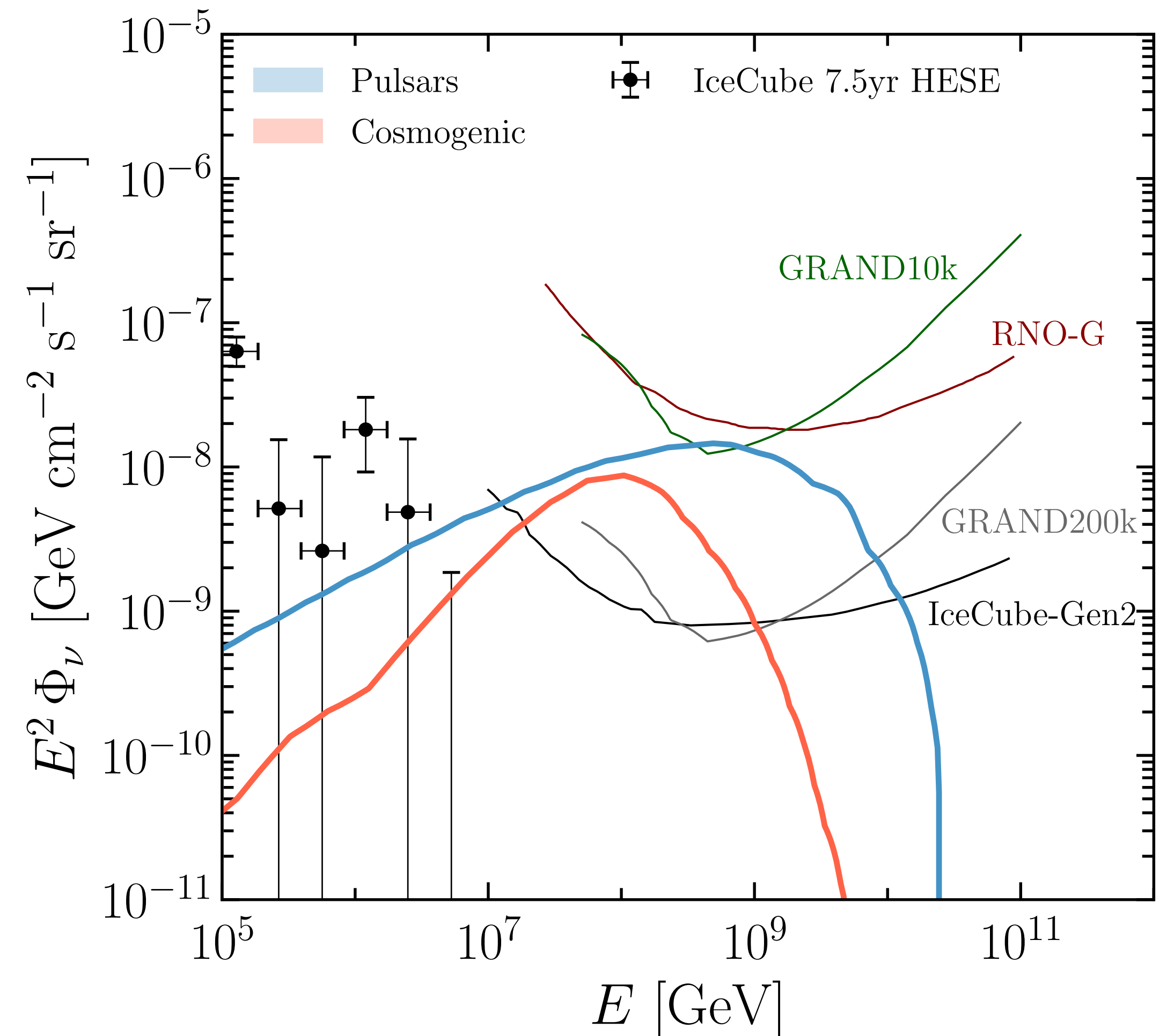
higher expected astrophysical contribution in literature for neutrino radio telescopes

- Decaying DM expected fluxes:

$$\frac{d\Phi_{\nu_\alpha + \bar{\nu}_\alpha}^{\text{gal.}}}{dE_\nu d\Omega} = \frac{1}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \frac{dN_\alpha}{dE_\nu} \int_0^\infty ds \rho_{\text{DM}}[r(s, \ell, b)]$$

NFW profile

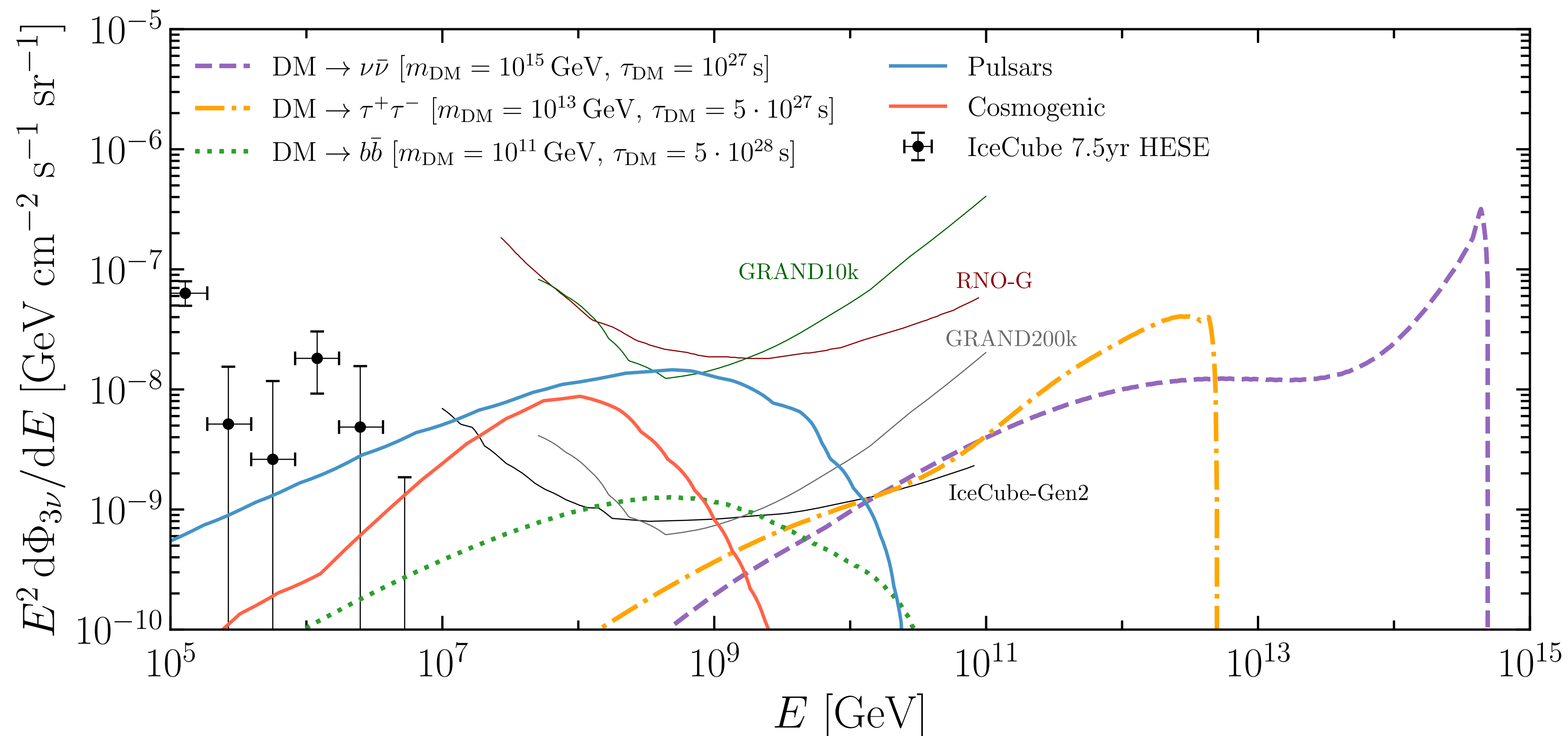
$$\frac{d\Phi_{\nu_\alpha + \bar{\nu}_\alpha}^{\text{ext.gal.}}}{dE_\nu d\Omega} = \frac{\Omega_{\text{DM}} \rho_c}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \int_0^\infty \frac{dz}{H(z)} \frac{dN_\alpha}{dE'_\nu} \Bigg|_{E'_\nu = E_\nu(1+z)}$$



colored regions from
J. Álvarez-Muniz et. al. [1810.09994]

Neutrino fluxes from DM

- HDMSpectra to generate DM fluxes: *C. W. Bauer et. al. [2007.15001]*
- Astrophysical neutrinos act as a background.
- Conservative choice: highest theoretical astro fluxes.



Methodology

- For each astrophysical scenario the probability to observe N_{obs} events is

$$p(N_{\text{obs}} | N_{\text{astro}}) = \frac{(N_{\text{astro}})^{N_{\text{obs}}} e^{-N_{\text{astro}}}}{N_{\text{obs}}!}$$

N_{obs} stochastic random variable
 N_{astro} expected astrophysical events

- Conservative choice: constrain signals N_{events} of DM $> N_{\text{events}}$ observed.
- Test statistic: (\mathcal{L} assumed Poisson)

$$\text{TS}(m_{\text{DM}}, \tau_{\text{DM}}) = \begin{cases} 0 & \text{for } n_{\text{DM}} < N_{\text{obs}} \\ -2 \ln \left(\frac{\mathcal{L}(N_{\text{obs}} | n_{\text{DM}})}{\mathcal{L}(N_{\text{obs}} | N_{\text{obs}})} \right) & \text{for } n_{\text{DM}} \geq N_{\text{obs}} \end{cases}$$

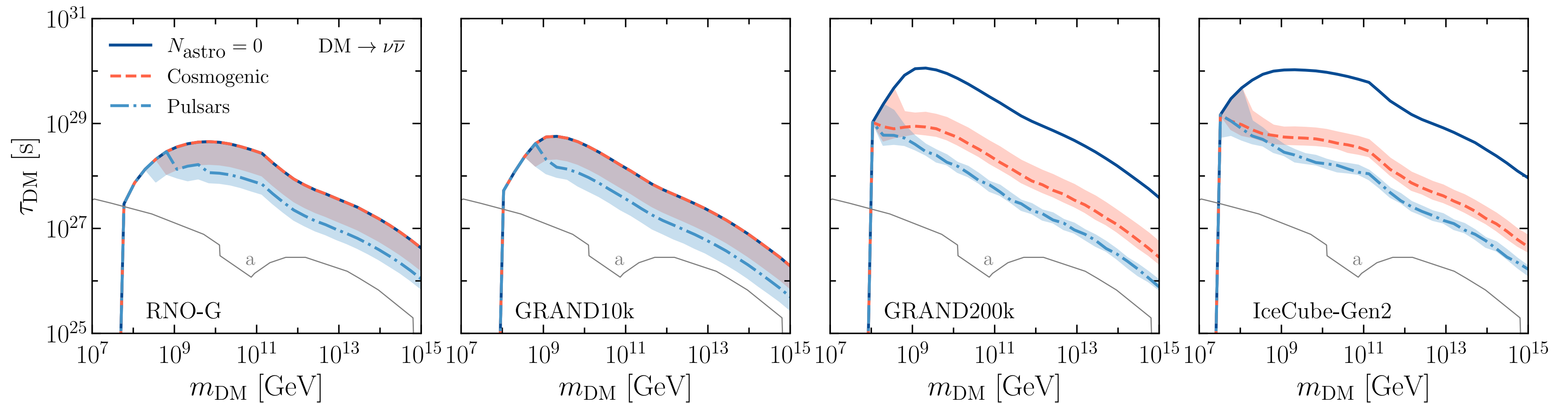
- For m_{DM} and N_{astro} we can determine the lifetime limits.

Forecasted limits on HDDDM

- $N_{\text{astro}} = 0$
- - - Cosmogenic
- · - Pulsars

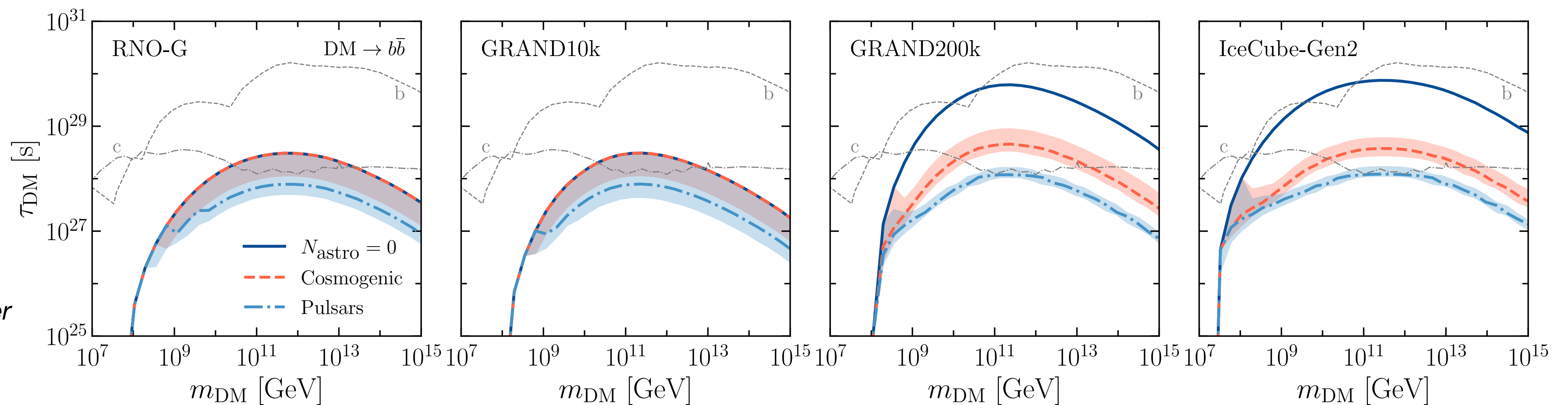
$$\text{DM} \rightarrow \nu\bar{\nu}$$

a) IceCube + PAO + ANITA
A. Esmaili et. al. [1205.5281]



$$\text{DM} \rightarrow b\bar{b}$$

b) galactic Multi-Messenger K. Ishiwata et. al. [1907.11671]
c) extragalactic Multi-Messenger K. Ishiwata et. al. [1907.11671]

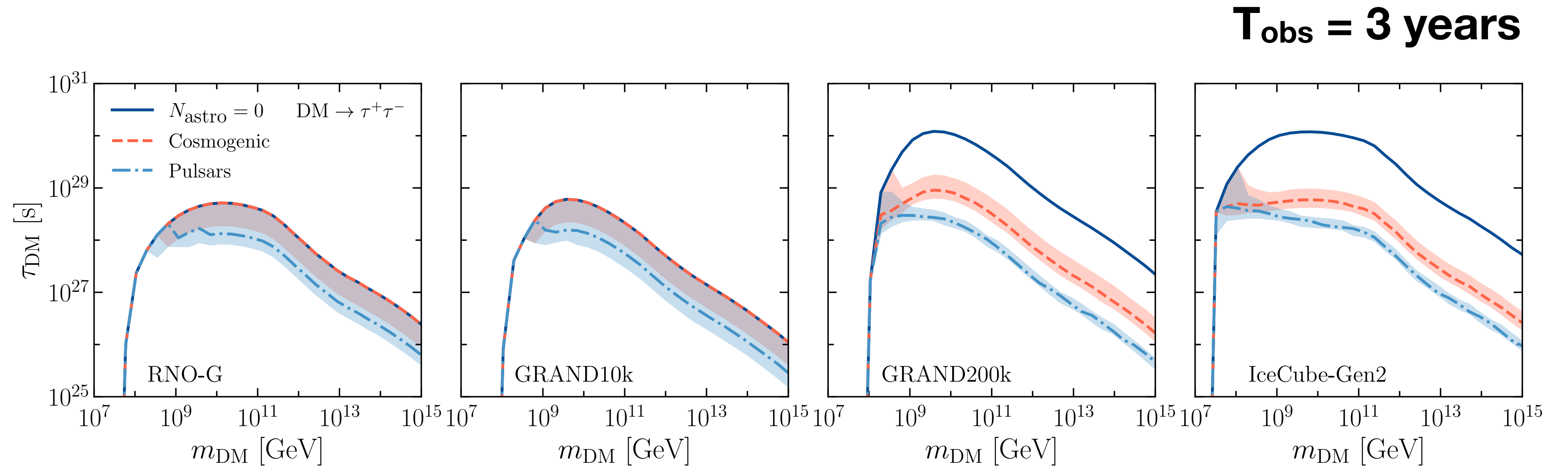


$T_{\text{obs}} = 3 \text{ years}$

Forecasted limits on HDDDM

- $N_{\text{astro}} = 0$
- - - Cosmogenic
- · - Pulsars

DM $\rightarrow \tau^+ \tau^-$



- New limits with upcoming neutrino radio telescopes.
 - Neutrino channel: higher constraints.
 - Tau channel: new constraints.
 - b channel: complementary constraints to gamma rays.

Why heavy decaying dark matter?

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Gamma-ray fluxes from DM

- Decaying DM expected **gamma-ray** fluxes:
 - Galactic prompt component
 - Extragalactic prompt component
 - Inverse compton scattering component

Gamma-ray fluxes from DM

- Decaying DM expected **gamma-ray** fluxes:
- Galactic prompt component

$$\frac{d\Phi_\gamma}{dE_\gamma d\Omega}(E_\gamma, b, l) = \frac{1}{4\pi m_{\text{DM}}\tau_{\text{DM}}} \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \int_0^\infty \rho_{\text{DM}}[r(s, b, l)] e^{-\tau_{\gamma\gamma}(E_\gamma, s, b, l)} ds$$

- Extragalactic prompt component
- Inverse compton scattering component

Gamma-ray fluxes from DM

- Decaying DM expected **gamma-ray** fluxes:
- Galactic prompt component

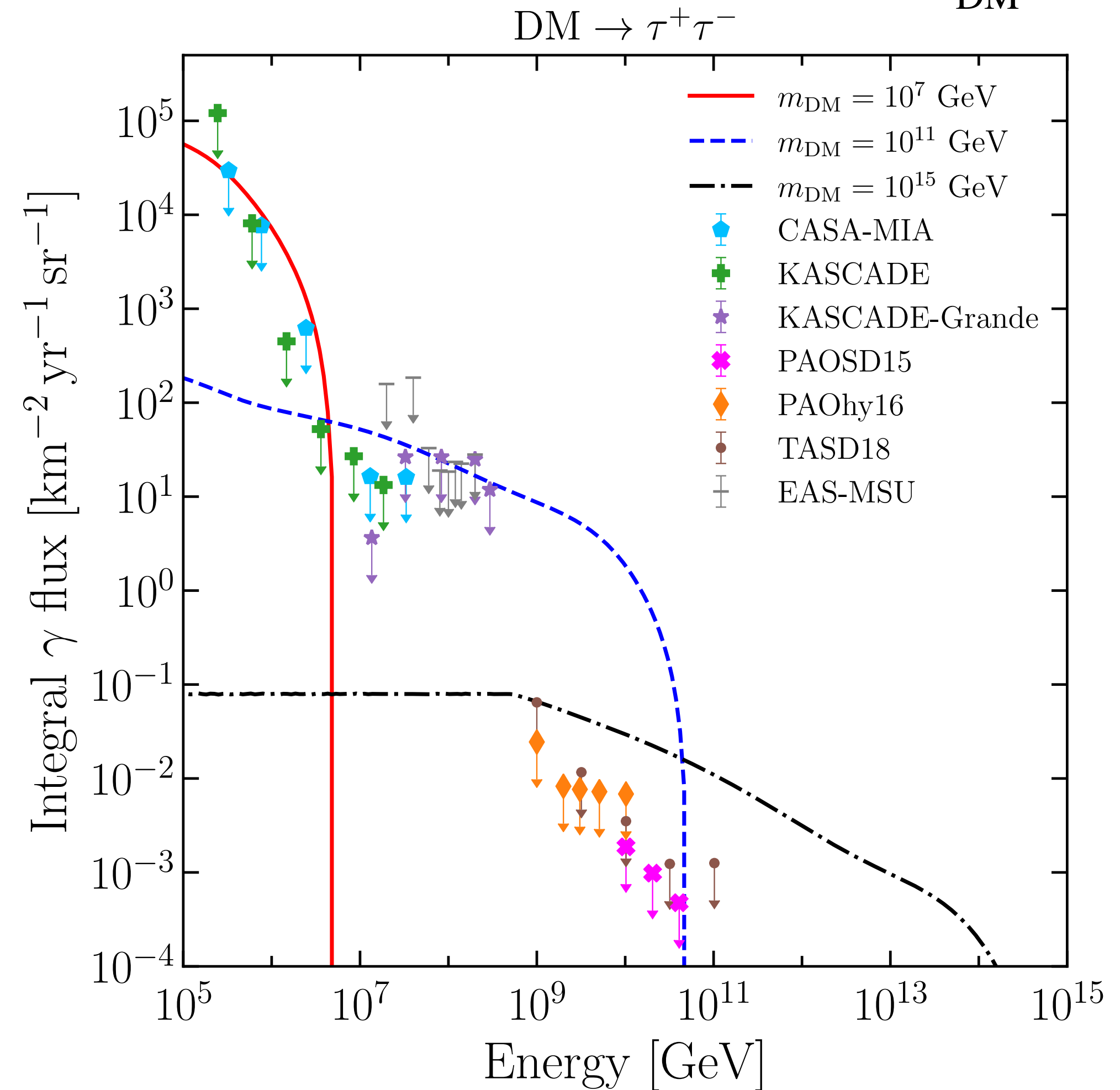
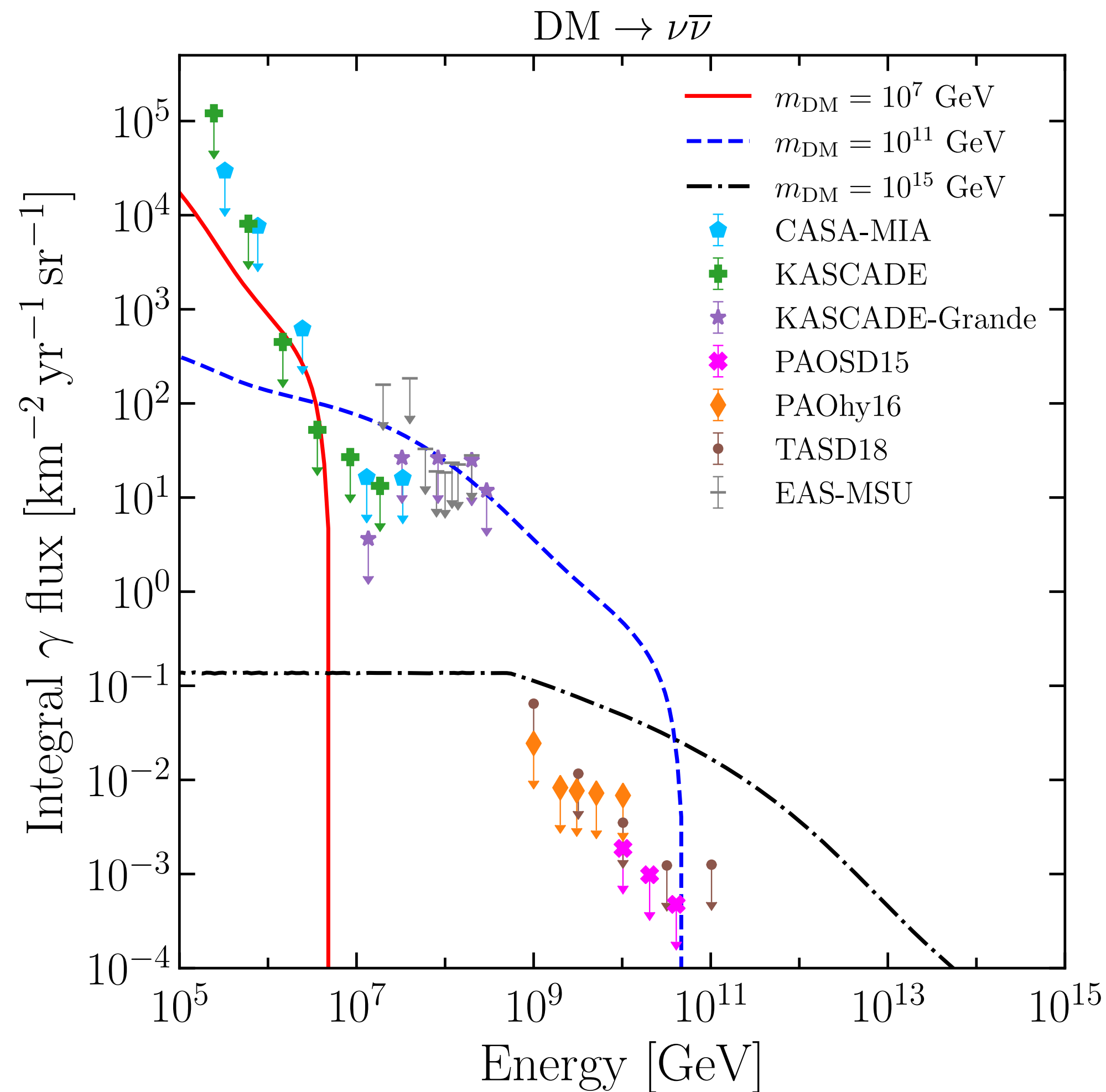
$$\frac{d\Phi_\gamma}{dE_\gamma d\Omega}(E_\gamma, b, l) = \frac{1}{4\pi m_{\text{DM}}\tau_{\text{DM}}} \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \int_0^\infty \rho_{\text{DM}}[r(s, b, l)] e^{-\tau_{\gamma\gamma}(E_\gamma, s, b, l)} ds$$

- Extragalactic prompt component **X**
 - Inverse compton scattering component **X**
- } SUBDOMINANT CONTRIBUTIONS

Gamma-ray UHE flux

- HDMSpectra DM fluxes *Bauer+20 JHEP 06 (2021) 121*

$$\tau_{\text{DM}} = 10^{27} \text{ s}$$



Methodology

- For each experimental collaboration data we define

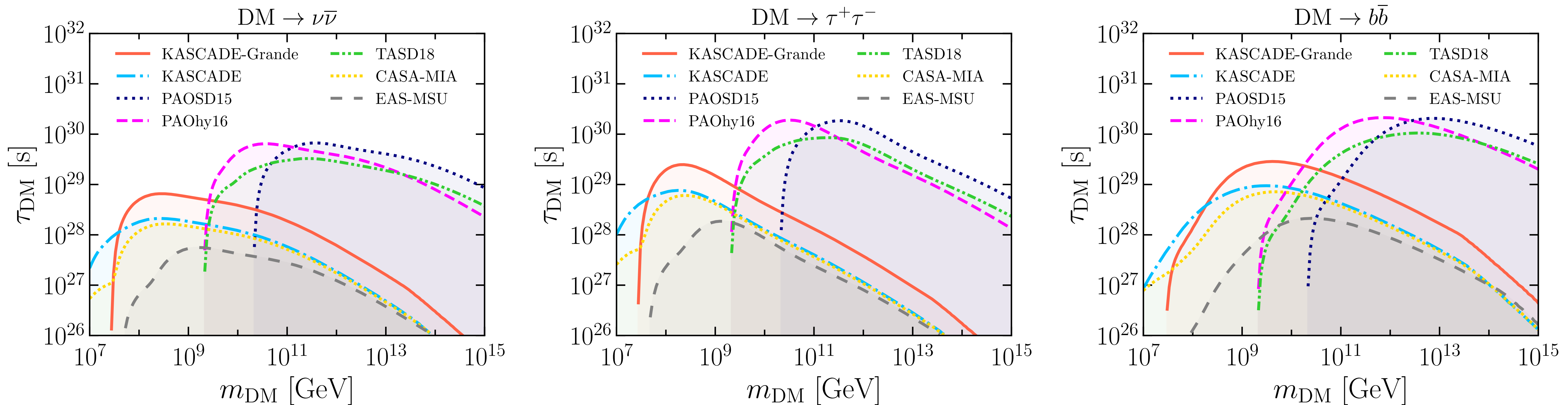
$$\text{TS}(m_{\text{DM}}, \tau_{\text{DM}}) = \sum_{i=1}^N \left[\frac{\Phi_{\gamma, i}(m_{\text{DM}}, \tau_{\text{DM}}) - \Phi_{\gamma, i}^{\text{data}}}{\sigma_i} \right]^2$$

Methodology

- For each experimental collaboration data we define

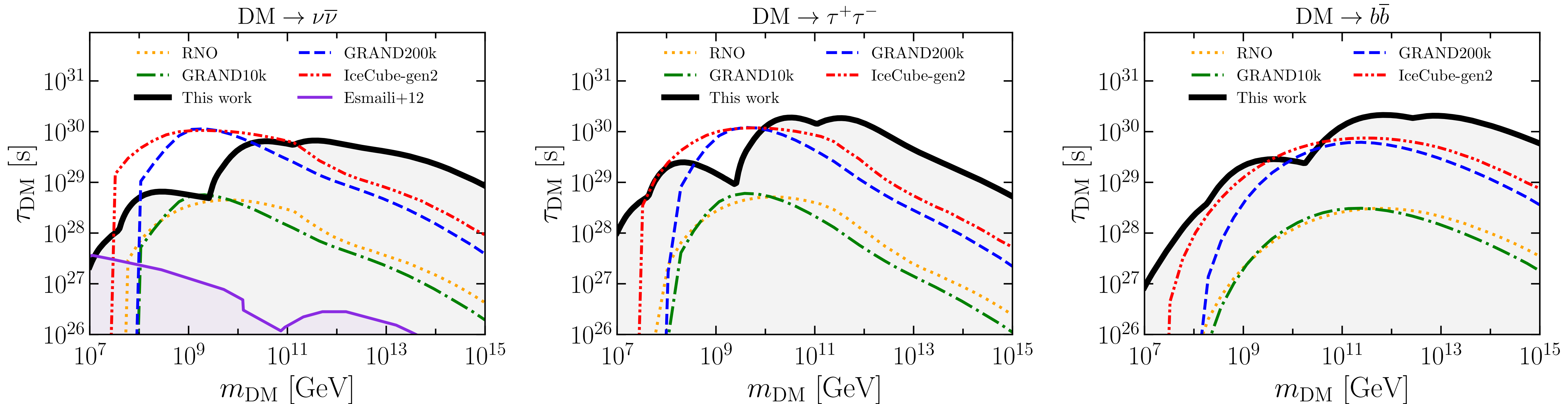
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95% CL LIMITS



Gamma-ray vs neutrino HDDDM limits

- Comparison of the limits obtained in this work with existing neutrino constraints and future forecasted ones

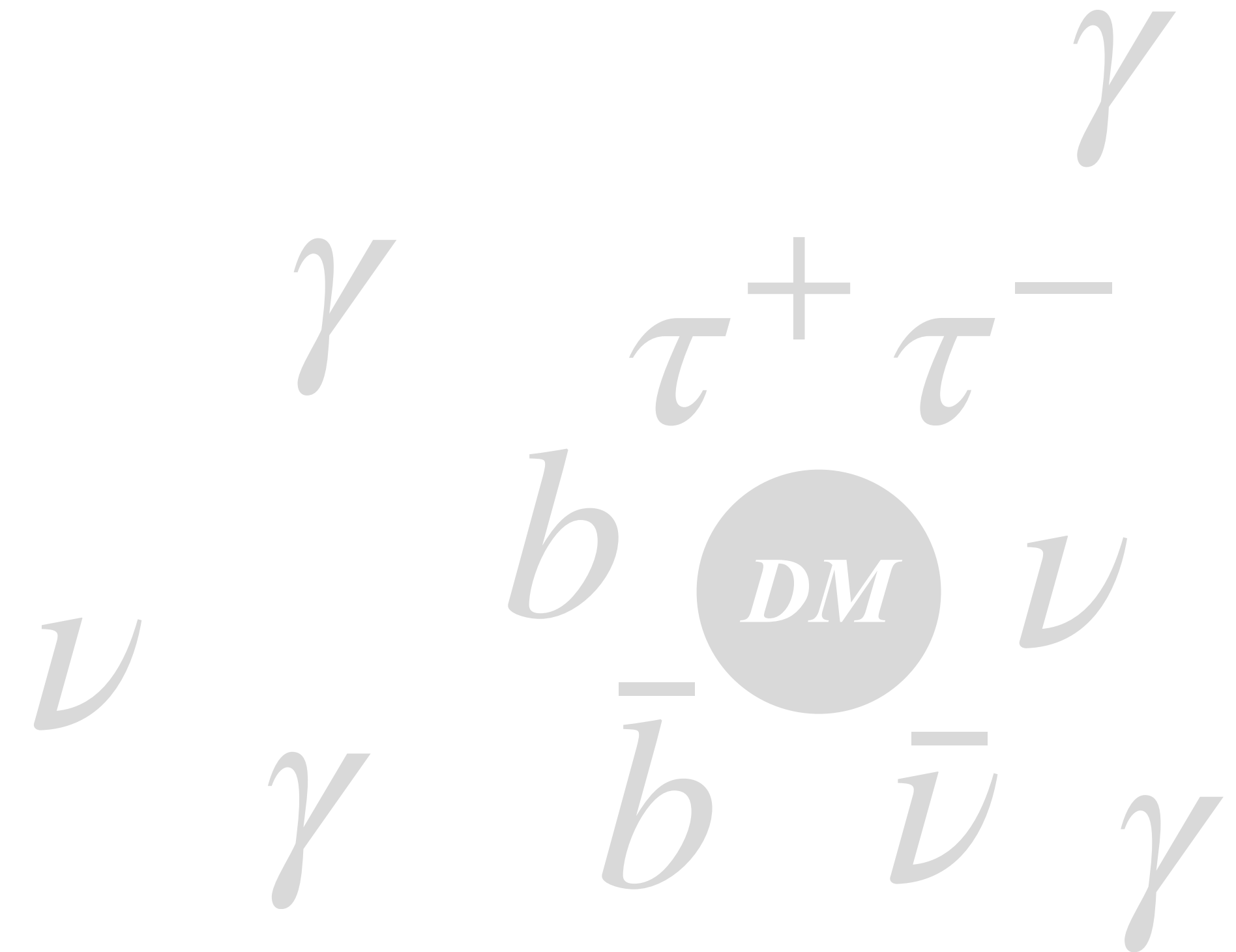


Esmaili+12:
JCAP 11 (2012) 034

Neutrino radio telescopes:
Chianese, Fiorillo, **RH**, Miele, Morisi, Saviano JCAP 05 (2021) 074

Conclusions

- Radio neutrino telescopes will have potential to detect a contribution coming from DM.
- Neutrino and gamma-ray measurements are a powerful tool to test the lifetime of heavy dark matter particles.
- Forecast analysis in order to set conservative bounds on the lifetime of HDM particles with $m_{\text{DM}} = 10^7 - 10^{15}$ GeV.
- Future neutrino telescopes will provide robustness to the results and possibly lead to stronger limits in particular channels



**Thank you for
your attention**

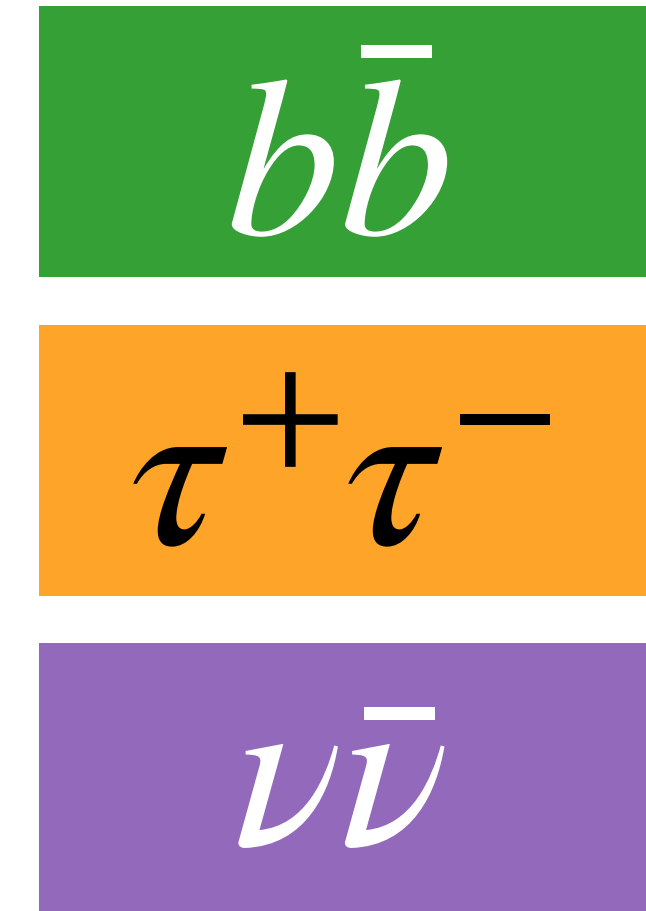




Back-up slides

Neutrino fluxes from DM

- Indirect DM detection via neutrinos
- Minimal Decaying Dark Matter model: $(m_{\text{DM}}, \tau_{\text{DM}})$
- Assume DM decay into a pair of SM particles: $(\text{DM} \rightarrow f\bar{f})$
- Decaying DM expected fluxes:

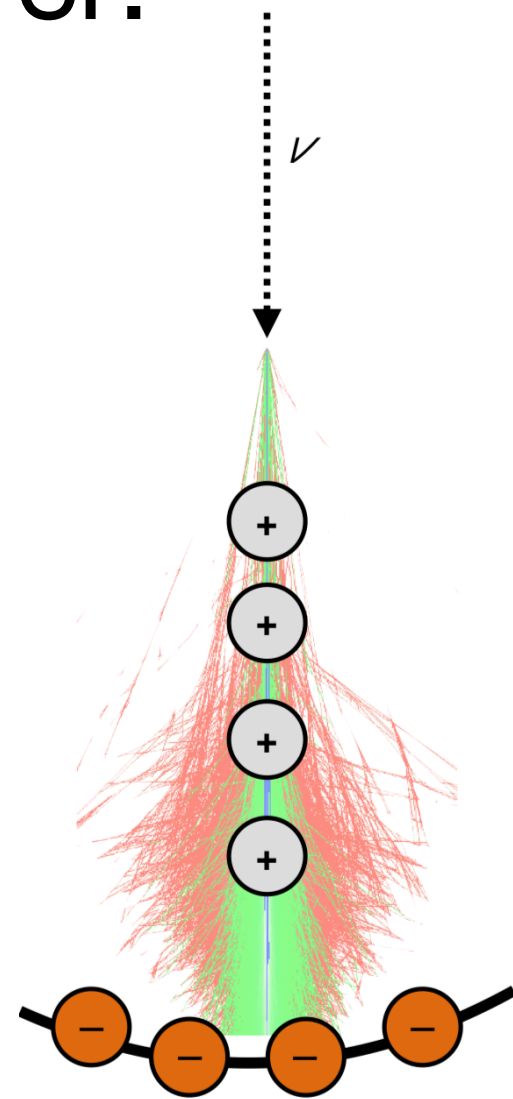


$$\left. \begin{aligned}
 \frac{d\Phi_{\nu_\alpha + \bar{\nu}_\alpha}^{\text{gal.}}}{dE_\nu d\Omega} &= \frac{1}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \frac{dN_\alpha}{dE_\nu} \int_0^\infty ds \rho_{\text{DM}}[r(s, \ell, b)] \\
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 \end{aligned} \right\} \begin{aligned}
 &\text{NFW profile} \\
 \frac{d\Phi_{3\nu}^{\text{DM}}}{dE_\nu} &= \sum_\alpha \int d\Omega \left[\frac{d\Phi_{\nu_\alpha + \bar{\nu}_\alpha}^{\text{gal.}}}{dE_\nu d\Omega} + \frac{d\Phi_{\nu_\alpha + \bar{\nu}_\alpha}^{\text{ext.gal.}}}{dE_\nu d\Omega} \right]
 \end{aligned}$$

Future radio ✓ telescopes

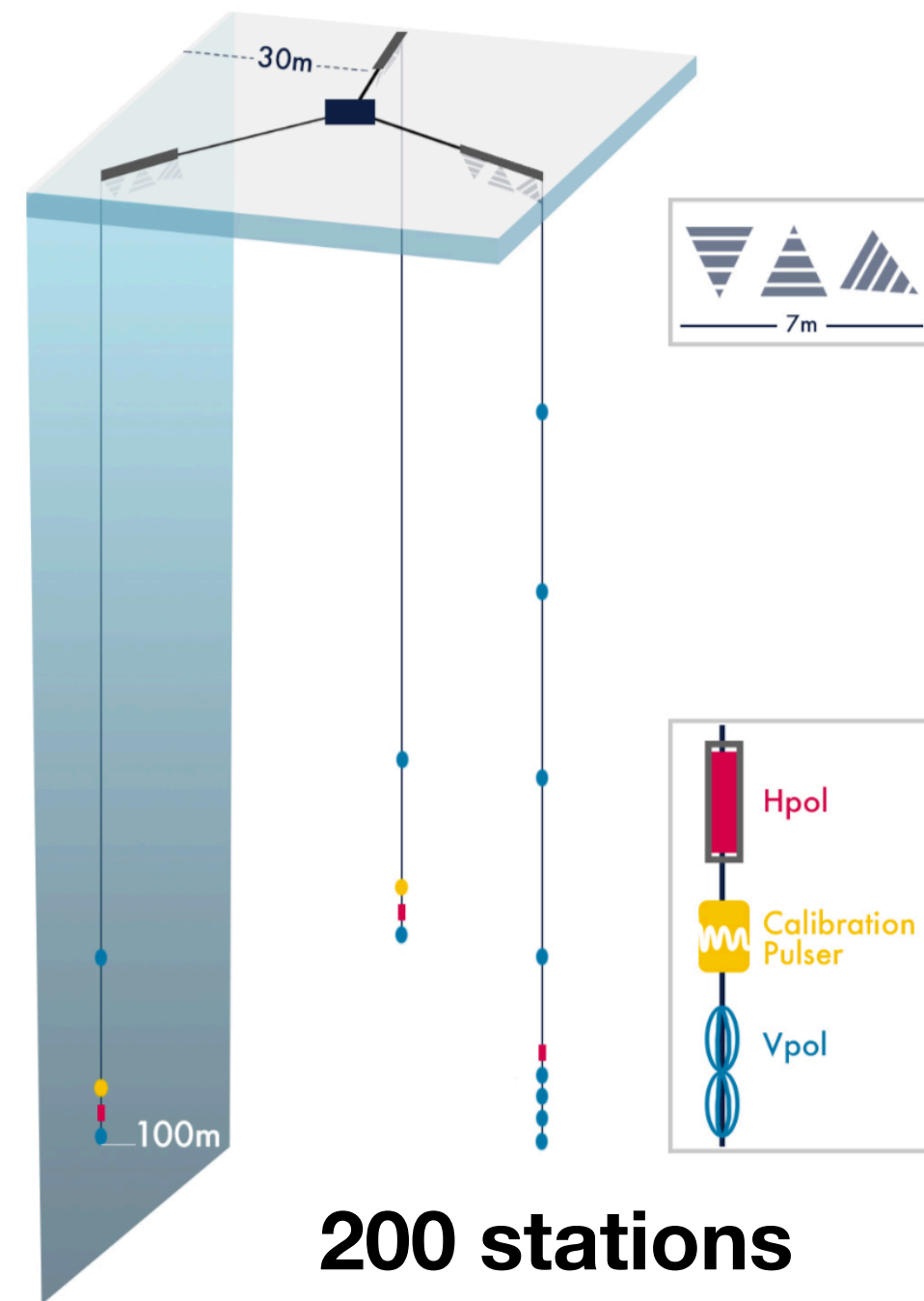
Radio emission from hadronic/EM shower:

Anna Nelles contribution to XVIII International Workshop on Neutrino Telescopes (2019)



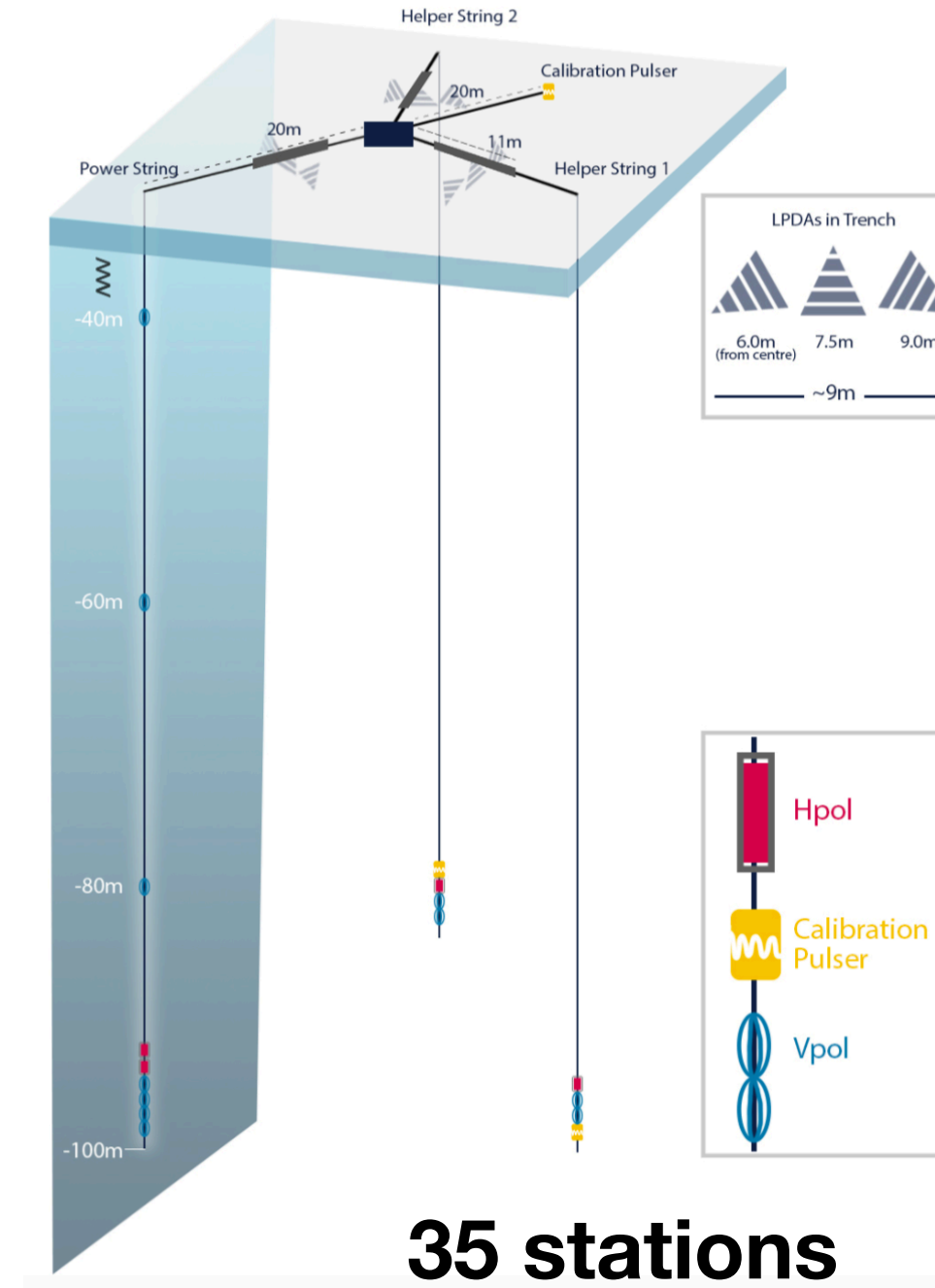
IceCube gen-2 radio

M.G. Aartsen et. al. [2008.04323]



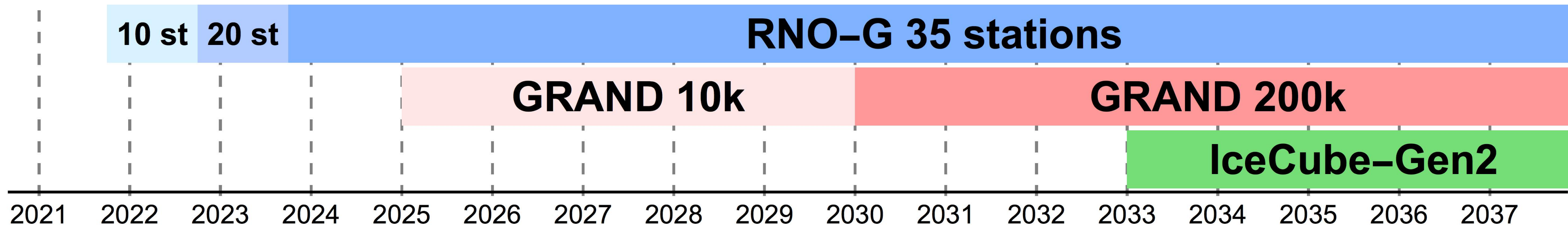
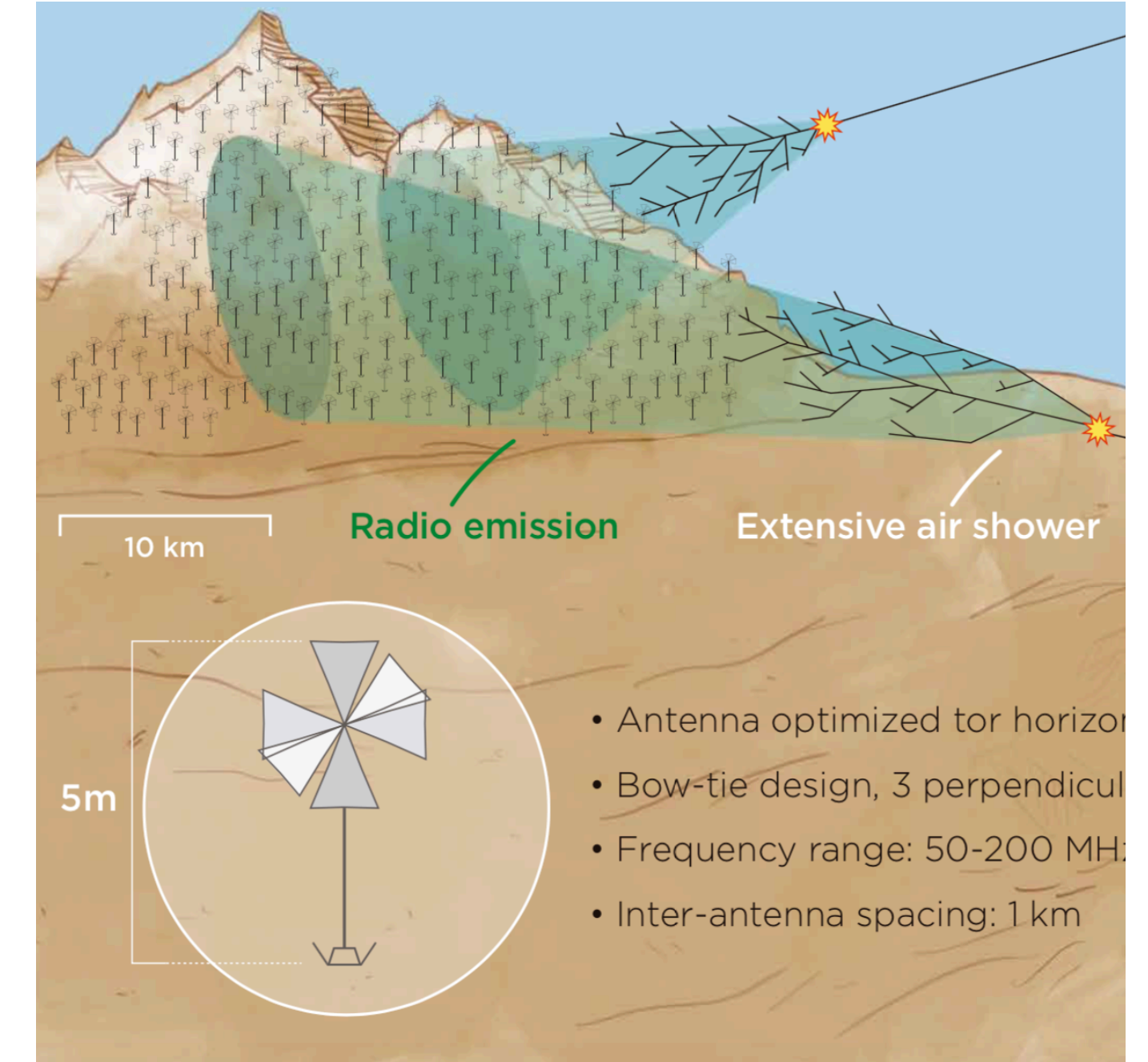
RNO-G

J.A. Aguilar et. al. [2010.12279]



GRAND

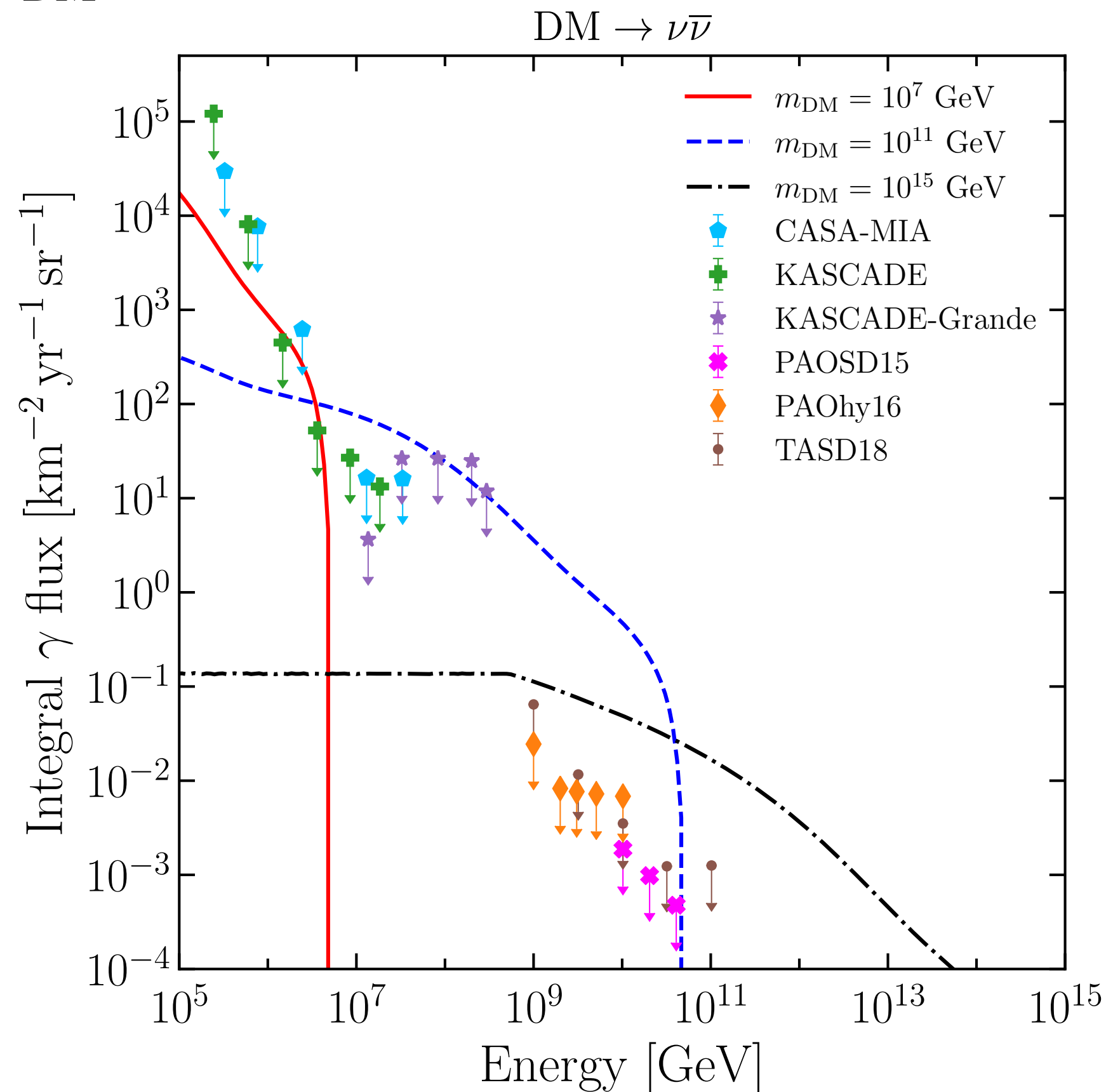
J. Álvarez-Muniz et. al. [1810.09994]



Gamma-ray UHE flux

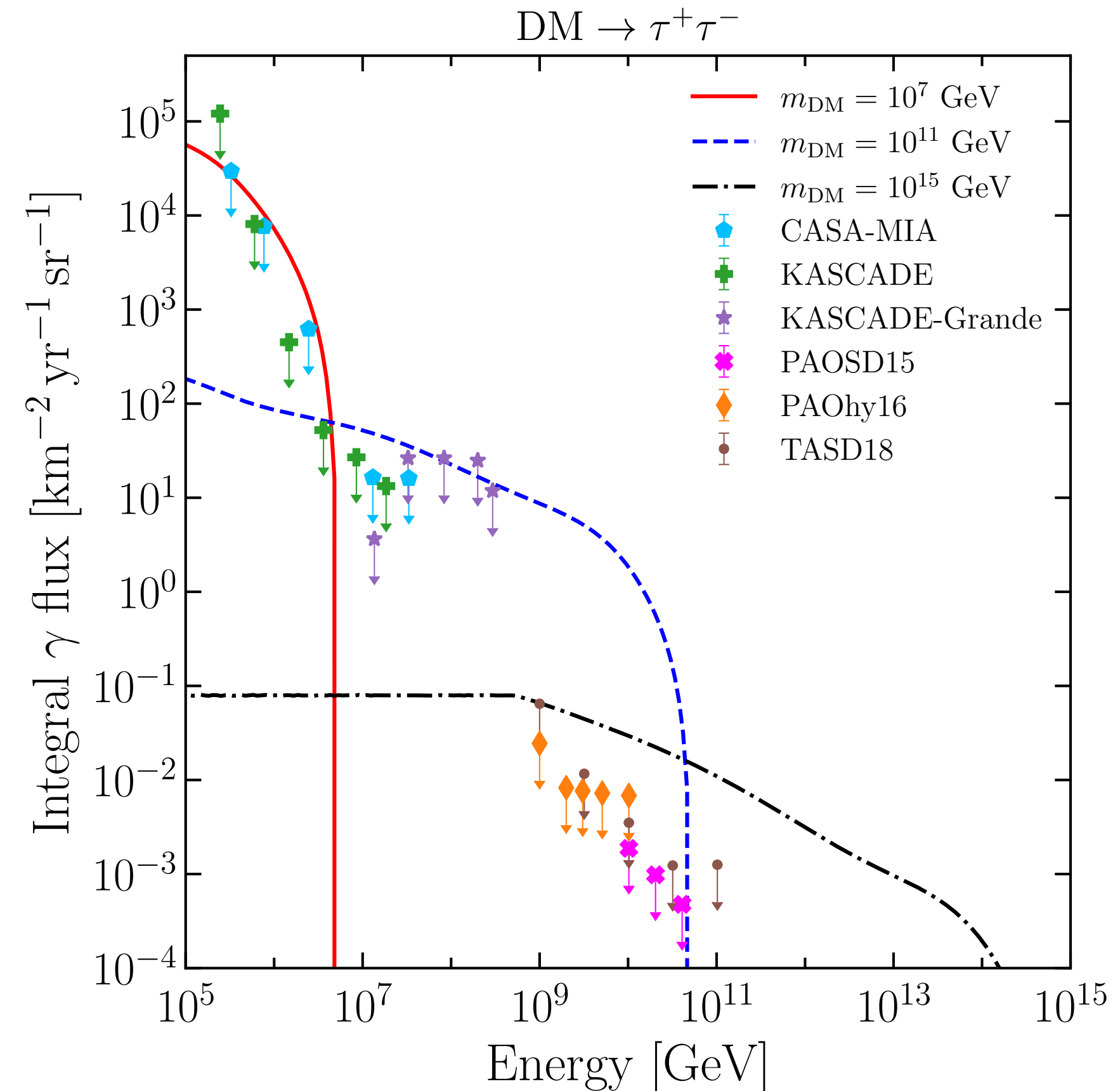
- HDMSpectra DM fluxes *Bauer+20 JHEP 06 (2021) 121*

$$\tau_{\text{DM}} = 10^{27} \text{ s}$$

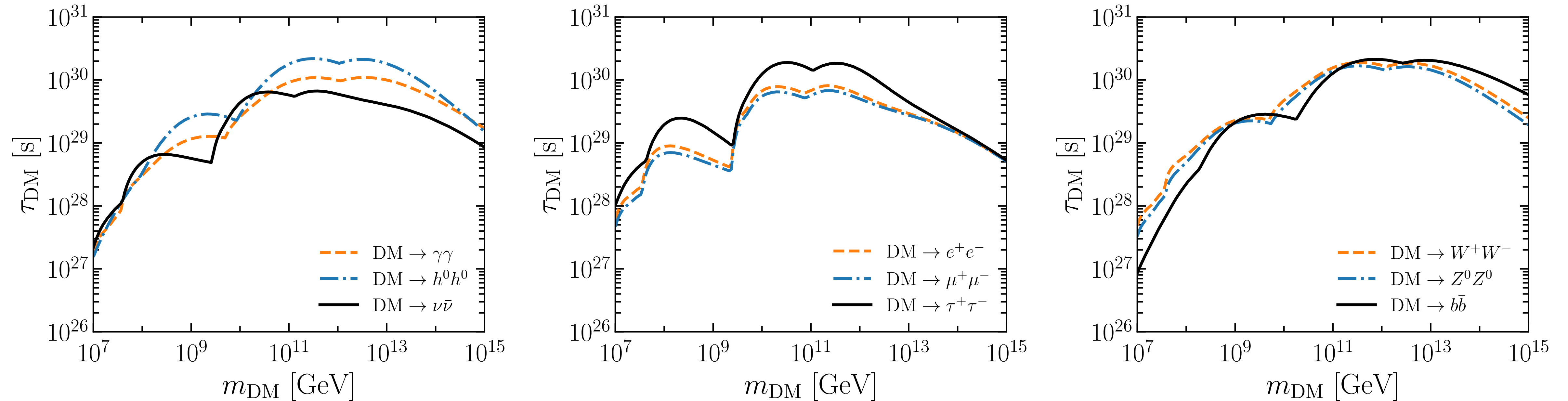


- Work with angle-averaged integral fluxes:

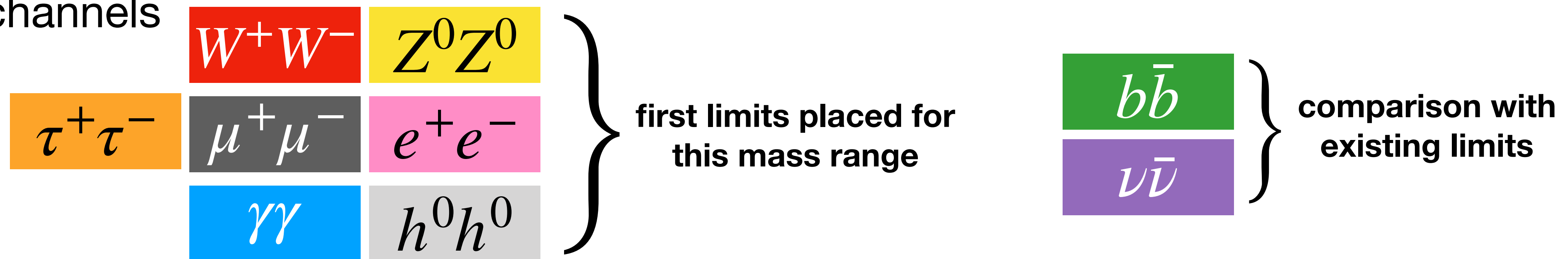
$$\Phi_{\gamma}(E_{\gamma}) = \frac{1}{4\pi} \int_{E_{\gamma}}^{\infty} dE'_{\gamma} \int_{4\pi} d\Omega \frac{d\Phi_{\gamma}}{dE'_{\gamma} d\Omega}$$



New limits on HDDDM

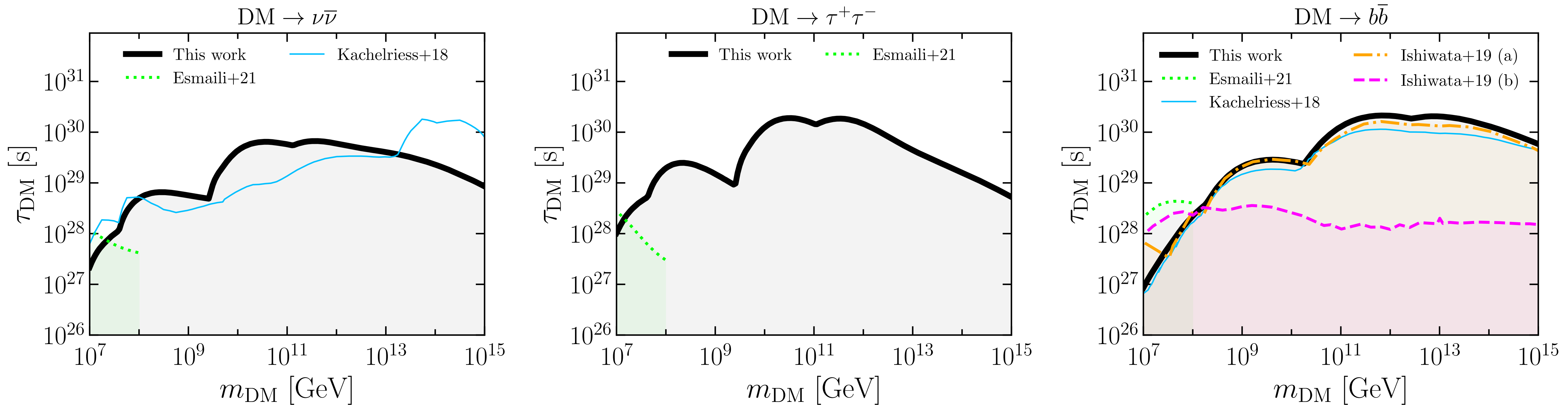


- We provide the current limits placed by the UHE gamma-ray measurements for 9 channels



New limits on HDDDM

- Comparison of the limits obtained in this work with existing gamma-ray constraints



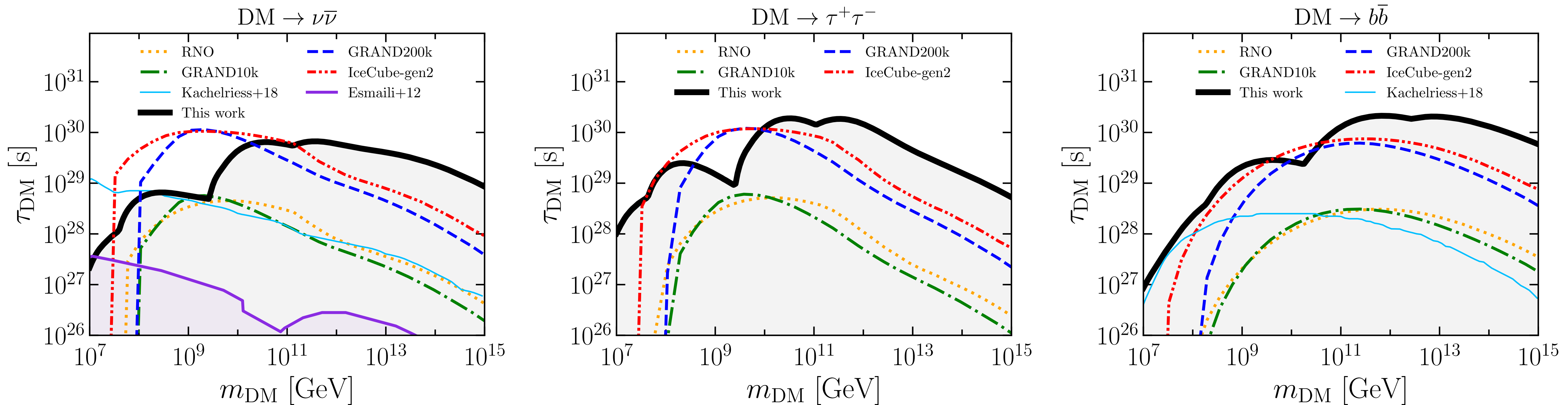
Kachelriess+18:
Phys.Rev.D 98 (2018) 8, 083016

Esmaili+21:
Phys.Rev.D 104 (2021) 2, L021301

Ishiwata+19:
JCAP 01 (2020) 003
 (a) galactic
 (b) extragalactic

New limits on HDDDM

- Comparison of the limits obtained in this work with existing neutrino constraints



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