Multi-messenger lifetime constraints on heavy decaying dark matter

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CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

INSTITUT DE FÍSICA CORPUSCULAR

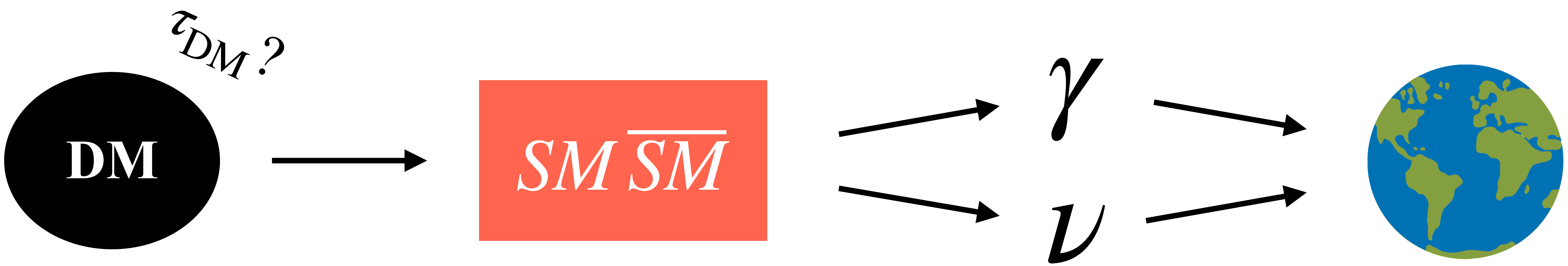
Essential Asymmetries of Nature

based on M. Chianese, D. Fiorillo, RH, G. Miele, S. Morisi and N. Saviano JCAP05(2021)074 arXiv: [2103.03254] and *JCAP*11(2021)035 arXiv:[2108.01678]

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: $(m_{\rm DM}\,,\,\tau_{\rm DM})$



Why heavy decaying dark matter?

Forecasted neutrino limits

Current gamma-ray limits

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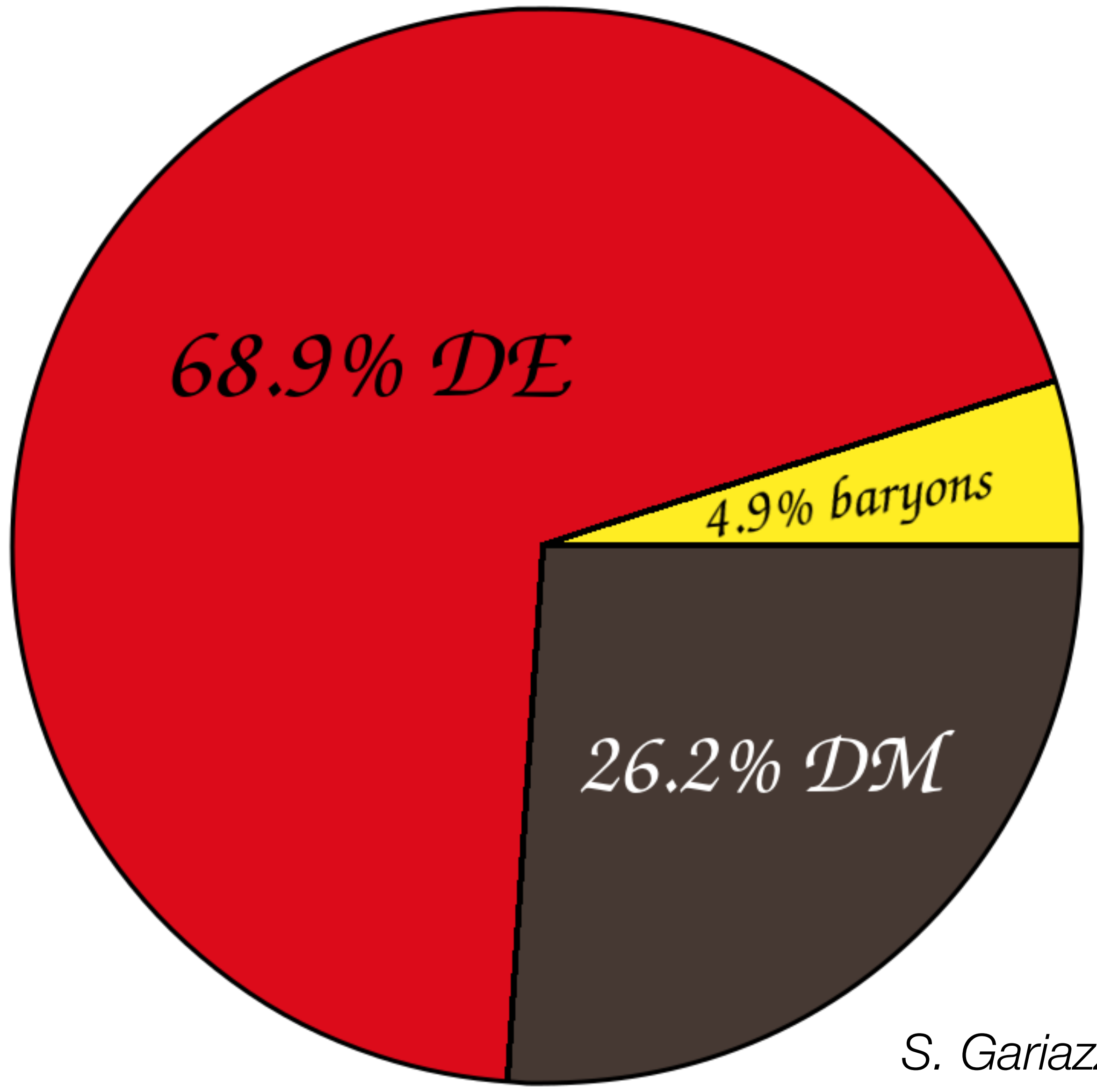
Forecasted neutrino limits

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)



S. Gariazzo (2018)

- 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:

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

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

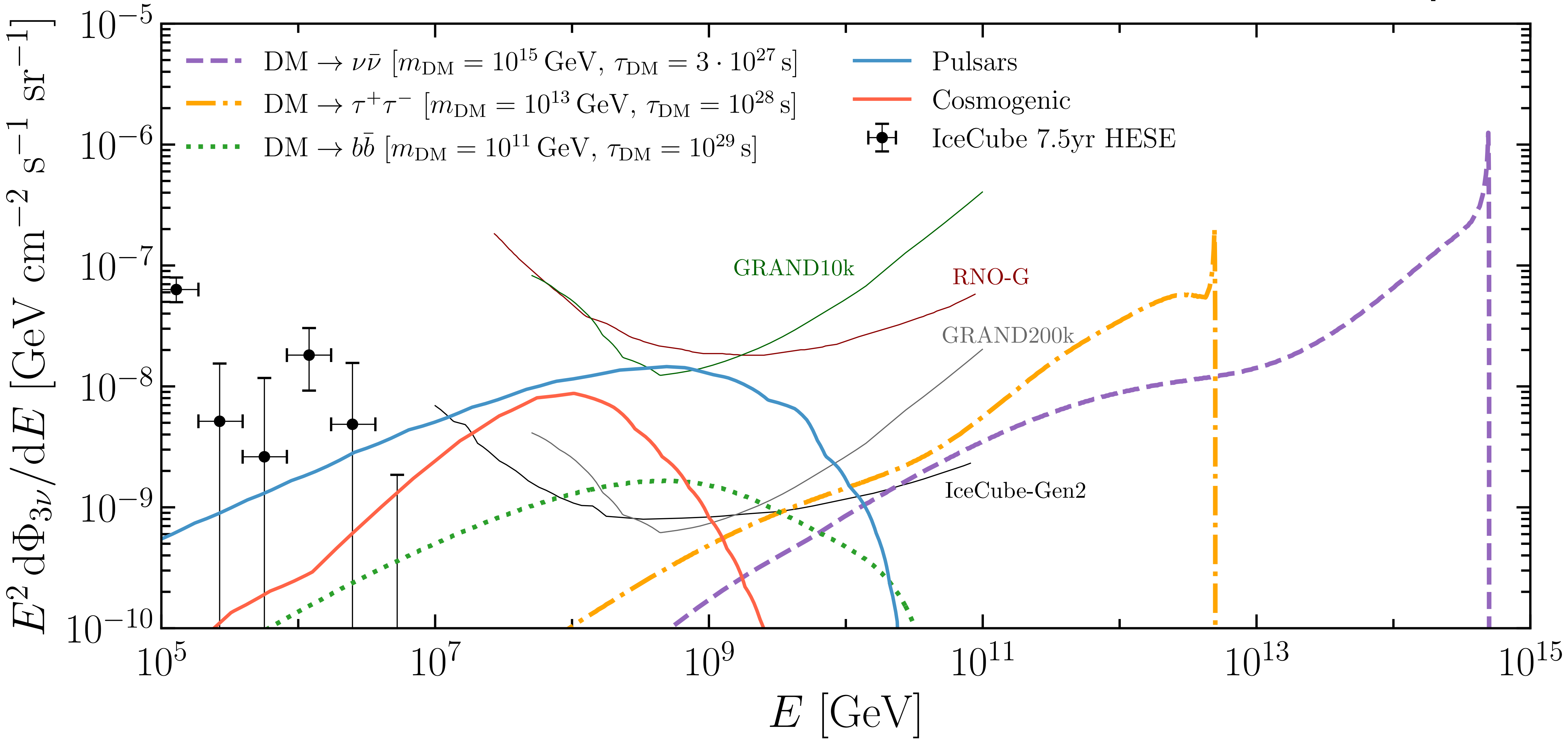
$$\phi_\nu^{\rm dec} \ggg \phi_\nu^{\rm ann}$$

Why heavy decaying dark matter?

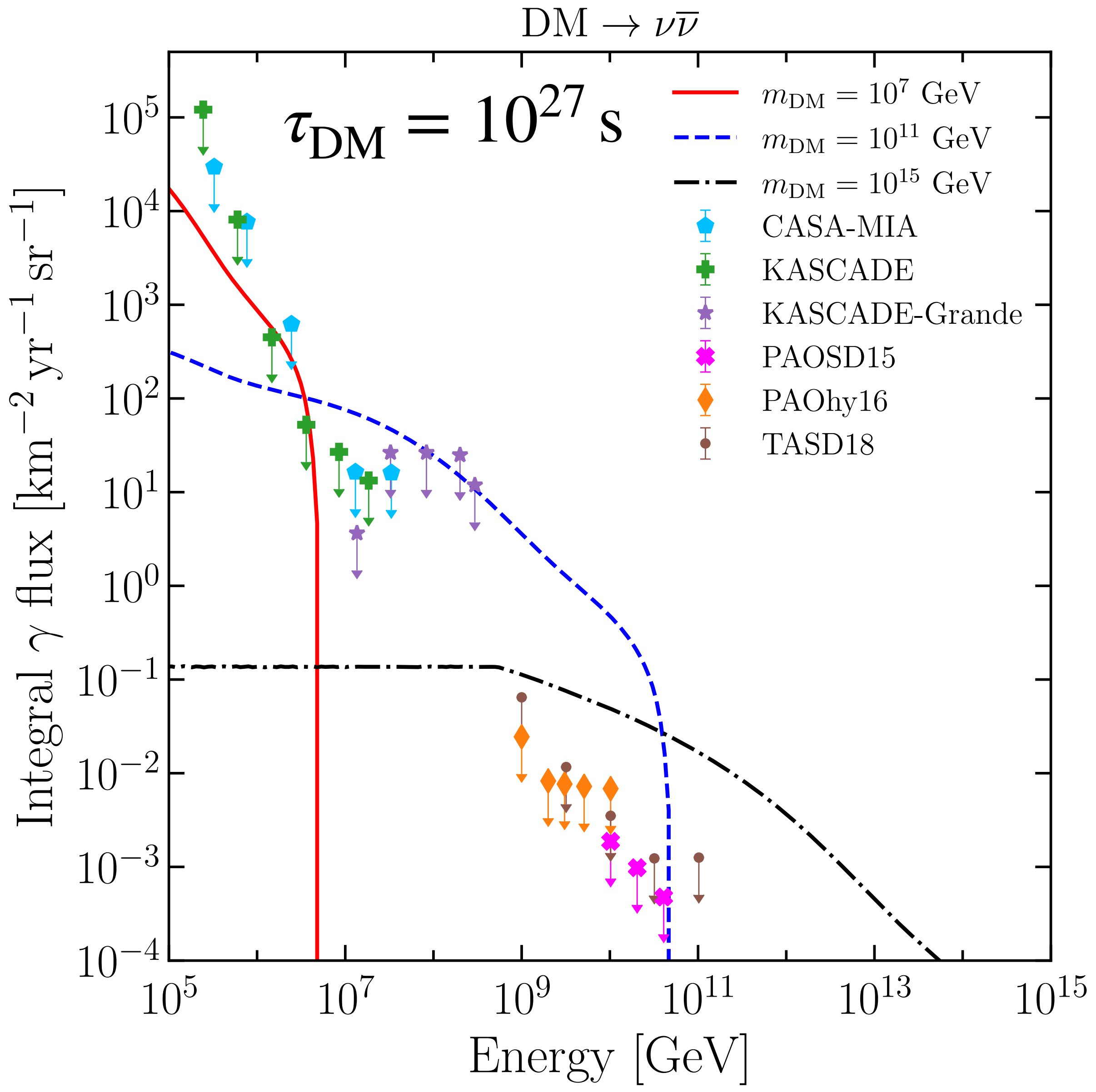
Heavy Dark Matter

ν

Produced fluxes on the reach of future radio neutrino telescopes



Expected gamma-ray fluxes on the range of UHE measurements



γ

Why heavy decaying dark matter?

Forecasted neutrino limits

Current gamma-ray limits

Ultra-high-energy neutrino flux

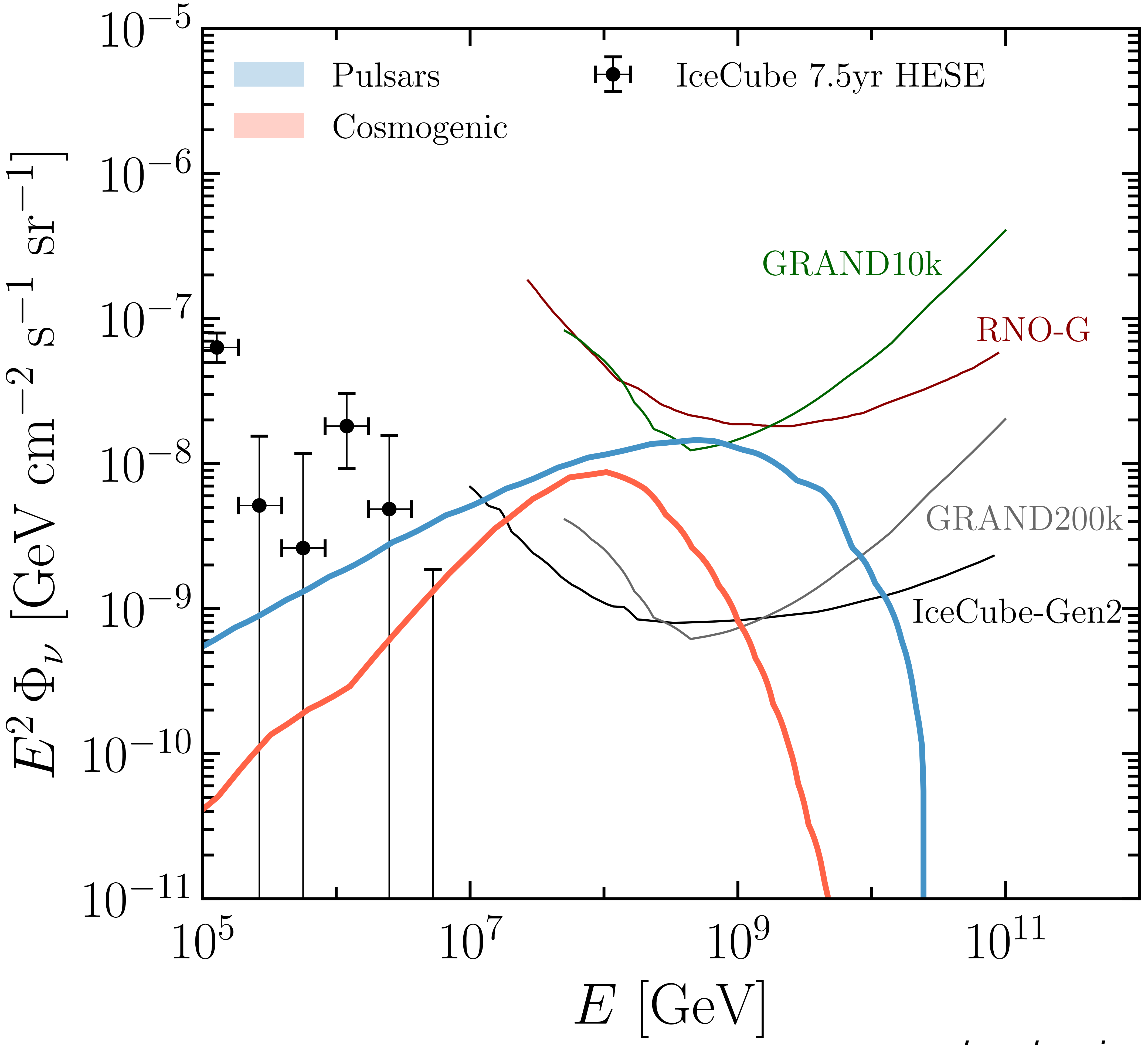
- High energy ν flux is unknown. Possible contributions:

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]

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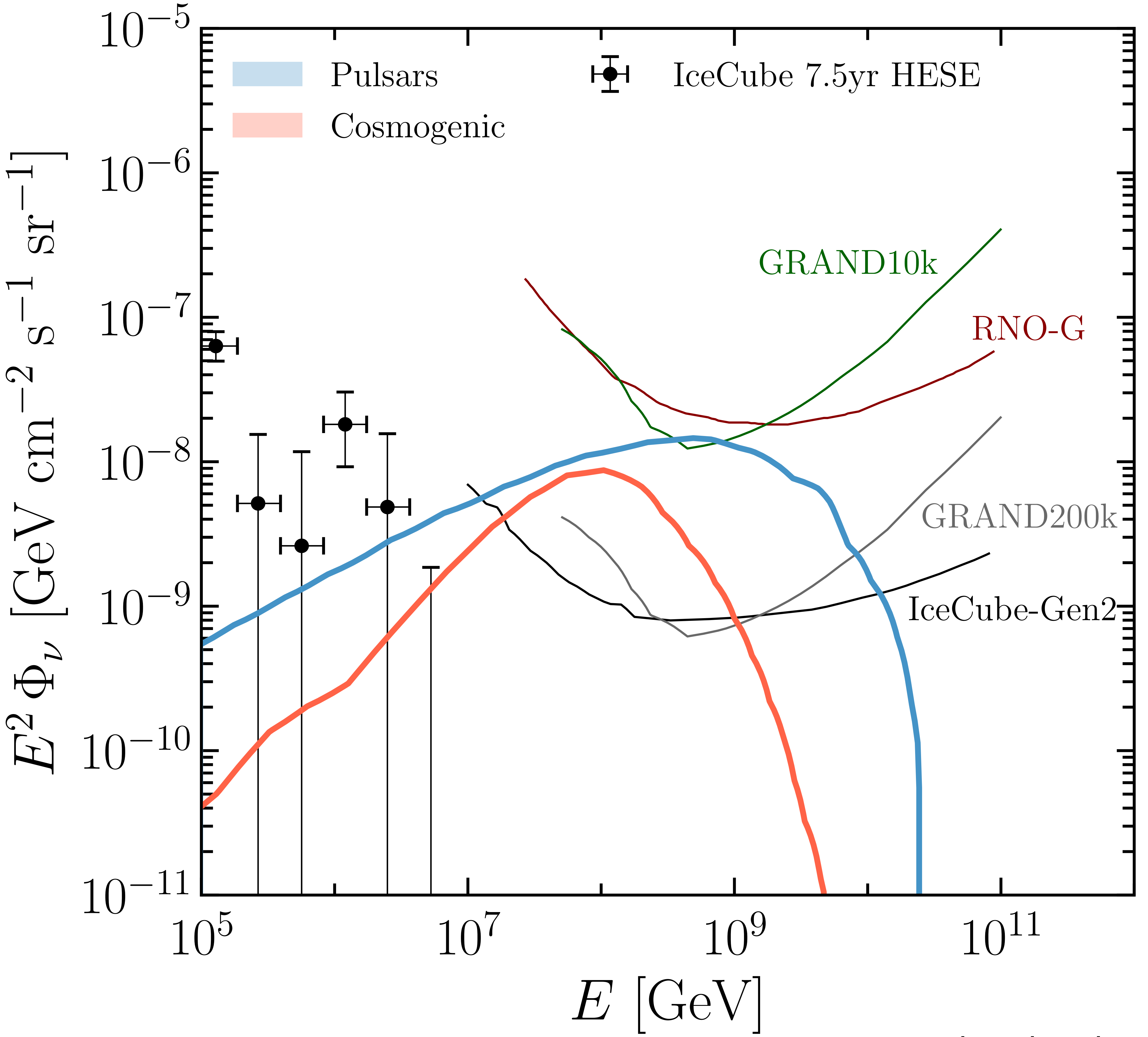


colored regions from J. Álvarez-Muniz et. al. [1810.09994]

- Decaying DM expected fluxes:

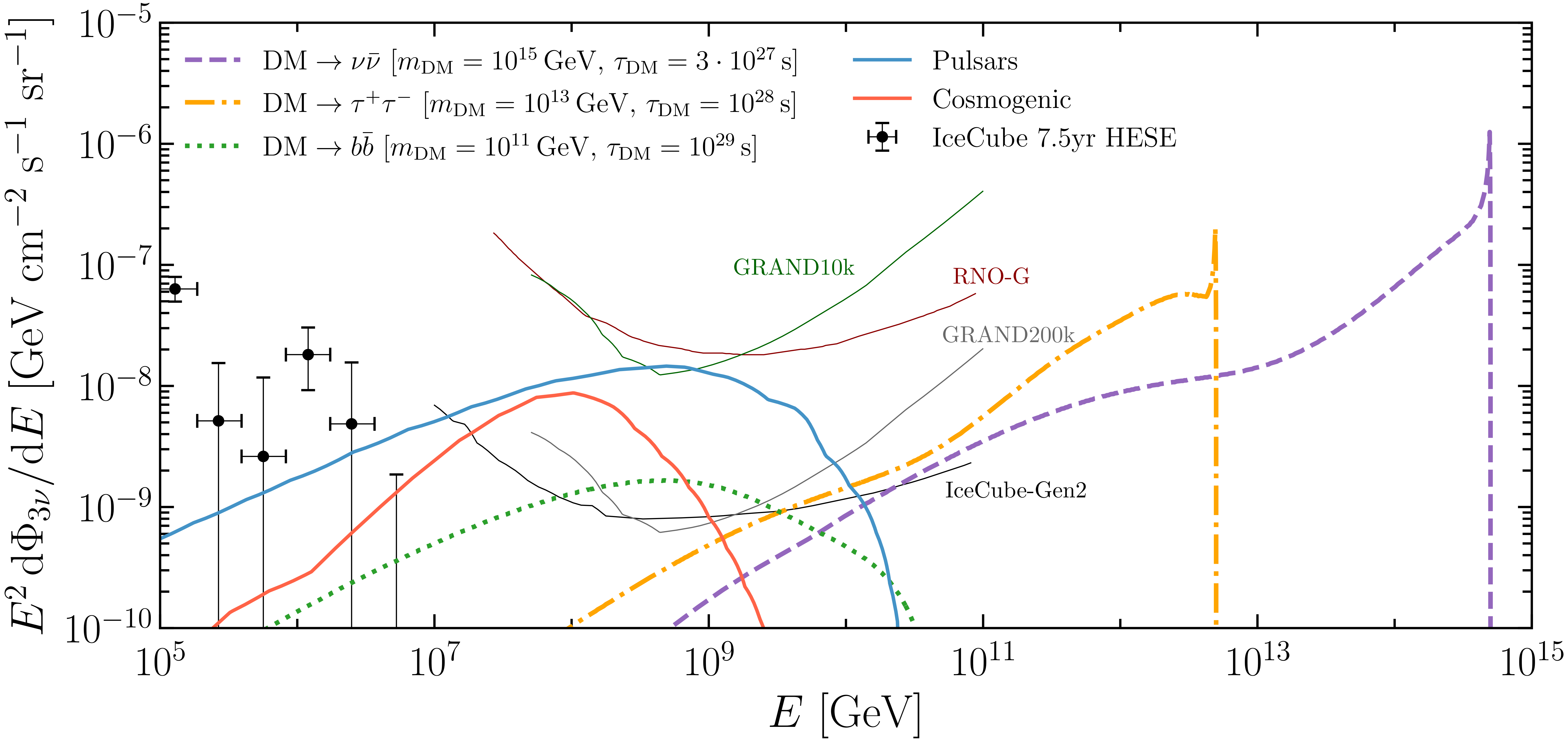
NFW profile

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

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

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

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

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

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

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

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

Forecasted limits on HDDM

$N_{\rm astro} = 0$
Cosmogenic
Pulsars

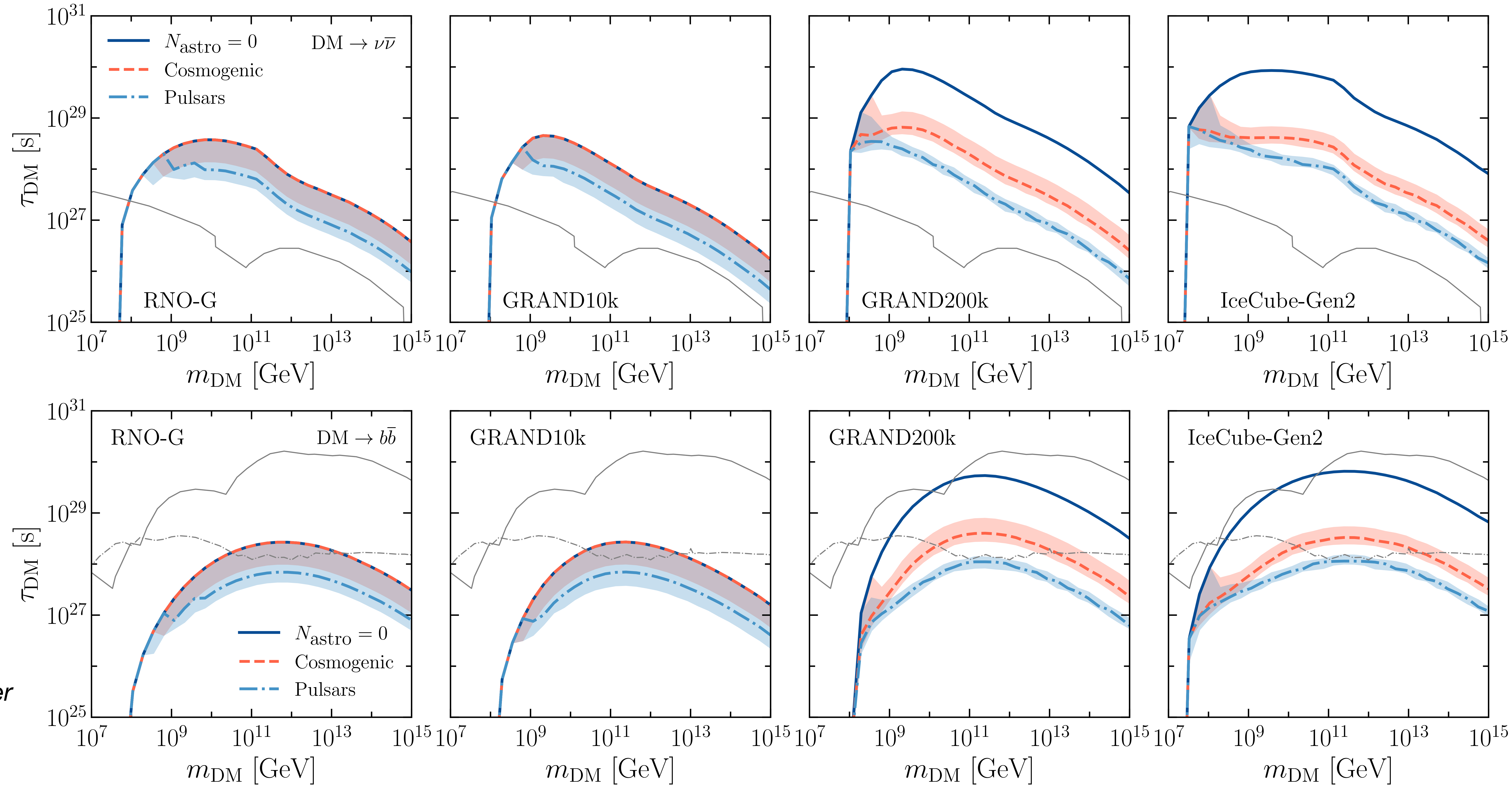
T_{obs} = 3 years

$\mathrm{DM} \to \nu\bar{\nu}$

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

$\mathrm{DM} \to b\bar{b}$

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



Forecasted limits on HDDM

$N_{\rm astro} = 0$
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$\mathrm{DM} \to \tau^+\tau^-$

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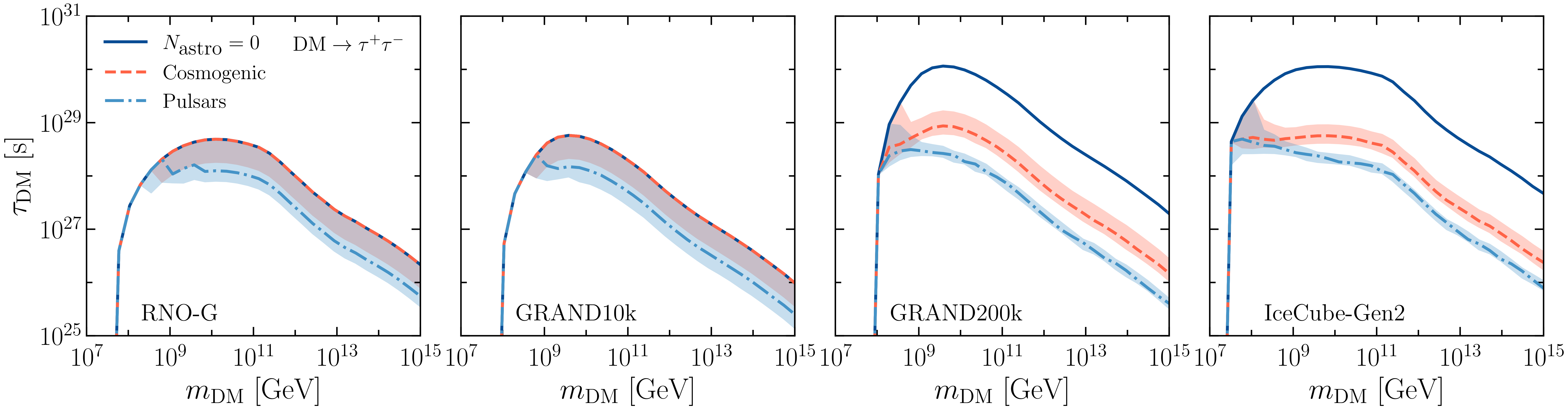


- New limits with upcoming neutrino radio telescopes.
  - Neutrino channel: higher constraints.
  - Tau channel: new constraints.
  - b channel: complementary constraints to gamma rays.

Why heavy decaying dark matter?

Forecasted neutrino limits

Current gamma-ray limits

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

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

  - Extragalactic prompt component
  - Inverse compton scattering component

Gamma-ray fluxes from DM

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

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

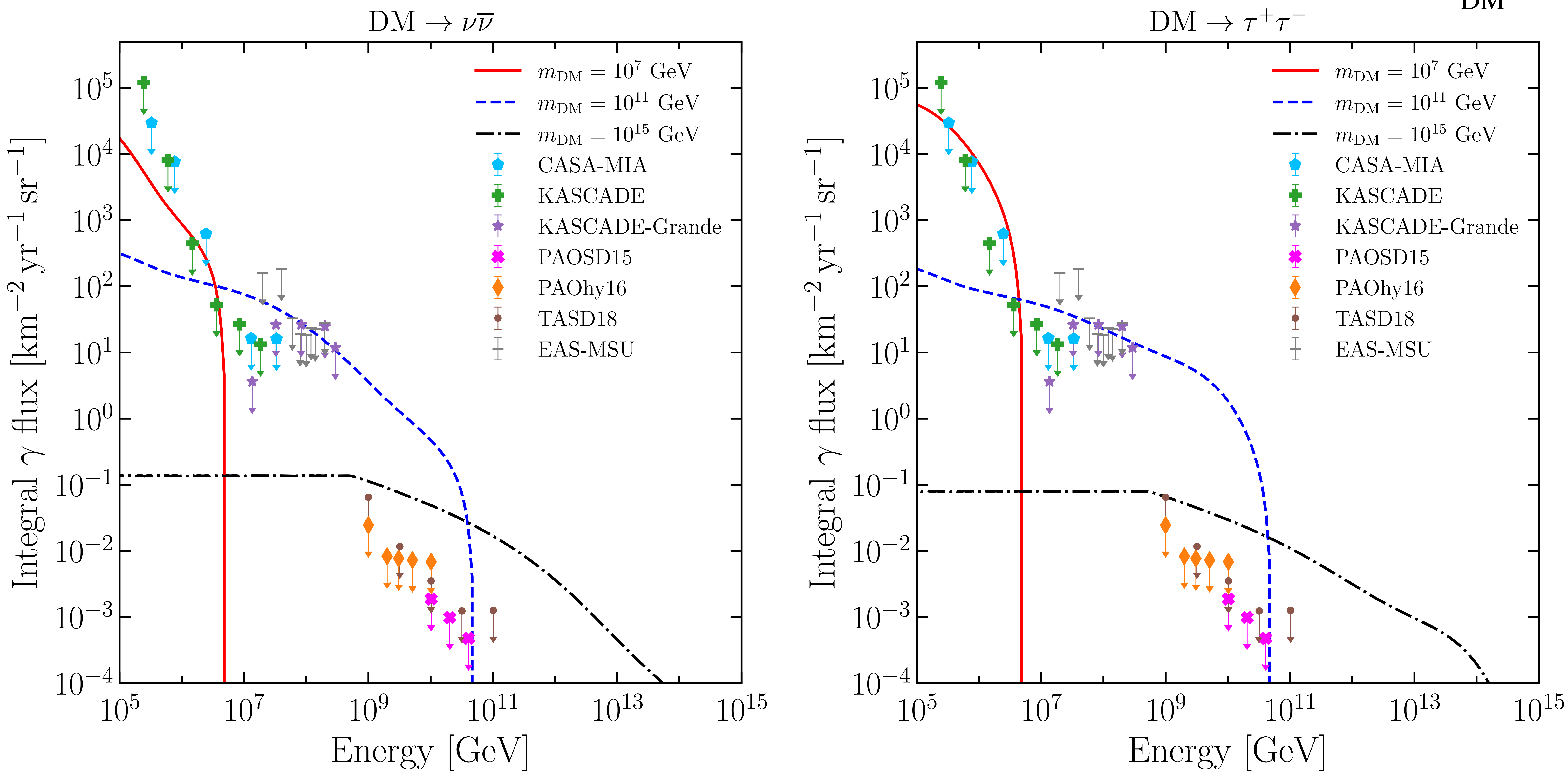
  - Extragalactic prompt component ✘
  - Inverse compton scattering component ✘

} SUBDOMINANT CONTRIBUTIONS

Gamma-ray UHE flux

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

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



Methodology

- For each experimental collaboration data we define

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

Methodology

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

95% CL LIMITS

Gamma-ray vs neutrino HDDM limits

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

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

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 $m_{DM} = 10^7 - 10^{15}$ GeV.
- Future neutrino telescopes will provide robustness to the results and possibly lead to stronger limits in particular channels

Thank you for your attention

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Backup slides

Neutrino fluxes from DM

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

$b\bar{b}$

$\tau^+\tau^-$

$\nu\bar{\nu}$

NFW profile

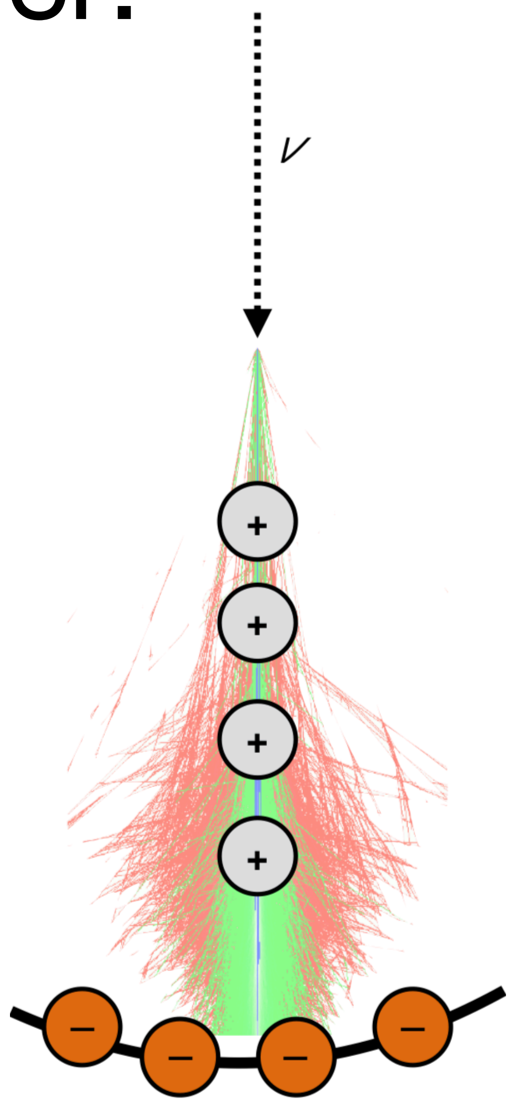
$$\frac{{\rm d}\Phi^{\rm gal.}_{\nu_\alpha+\bar{\nu}_\alpha}}{{\rm d}E_\nu {\rm d}\Omega} = \frac{1}{4\pi m_{\rm DM}\tau_{\rm DM}}\frac{{\rm d}N_\alpha}{{\rm d}E_\nu}\int_0^\infty {\rm d}s\,\rho_{\rm DM}[r(s,\ell,b)]$$

$$\frac{{\rm d}\Phi^{\rm ext.gal.}_{\nu_\alpha+\bar{\nu}_\alpha}}{{\rm d}E_\nu {\rm d}\Omega} = \frac{\Omega_{\rm DM}\rho_c}{4\pi m_{\rm DM}\tau_{\rm DM}}\int_0^\infty \frac{{\rm d}z}{H(z)}\frac{{\rm d}N_\alpha}{{\rm d}E'_\nu}\bigg|_{E'_\nu=E_\nu(1+z)}$$

$$\frac{{\rm d}\Phi^{\rm DM}_{3\nu}}{{\rm d}E_\nu} = \sum_\alpha \int {\rm d}\Omega \left[\frac{{\rm d}\Phi^{\rm gal.}_{\nu_\alpha+\bar{\nu}_\alpha}}{{\rm d}E_\nu {\rm d}\Omega} + \frac{{\rm d}\Phi^{\rm ext.gal.}_{\nu_\alpha+\bar{\nu}_\alpha}}{{\rm d}E_\nu {\rm d}\Omega}\right]$$

Future radio ν telescopes

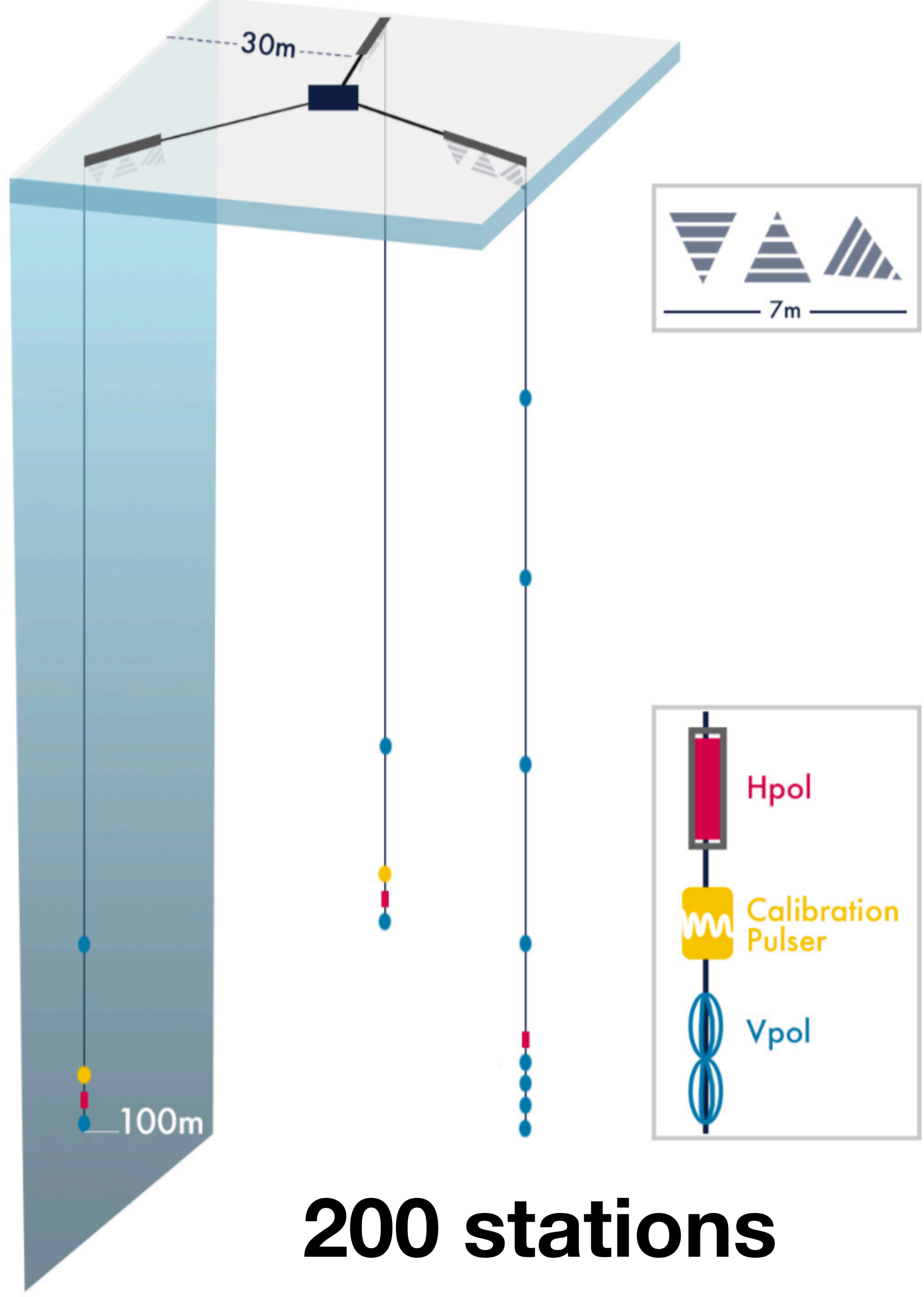
Radio emission from hadronic/EM shower:



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

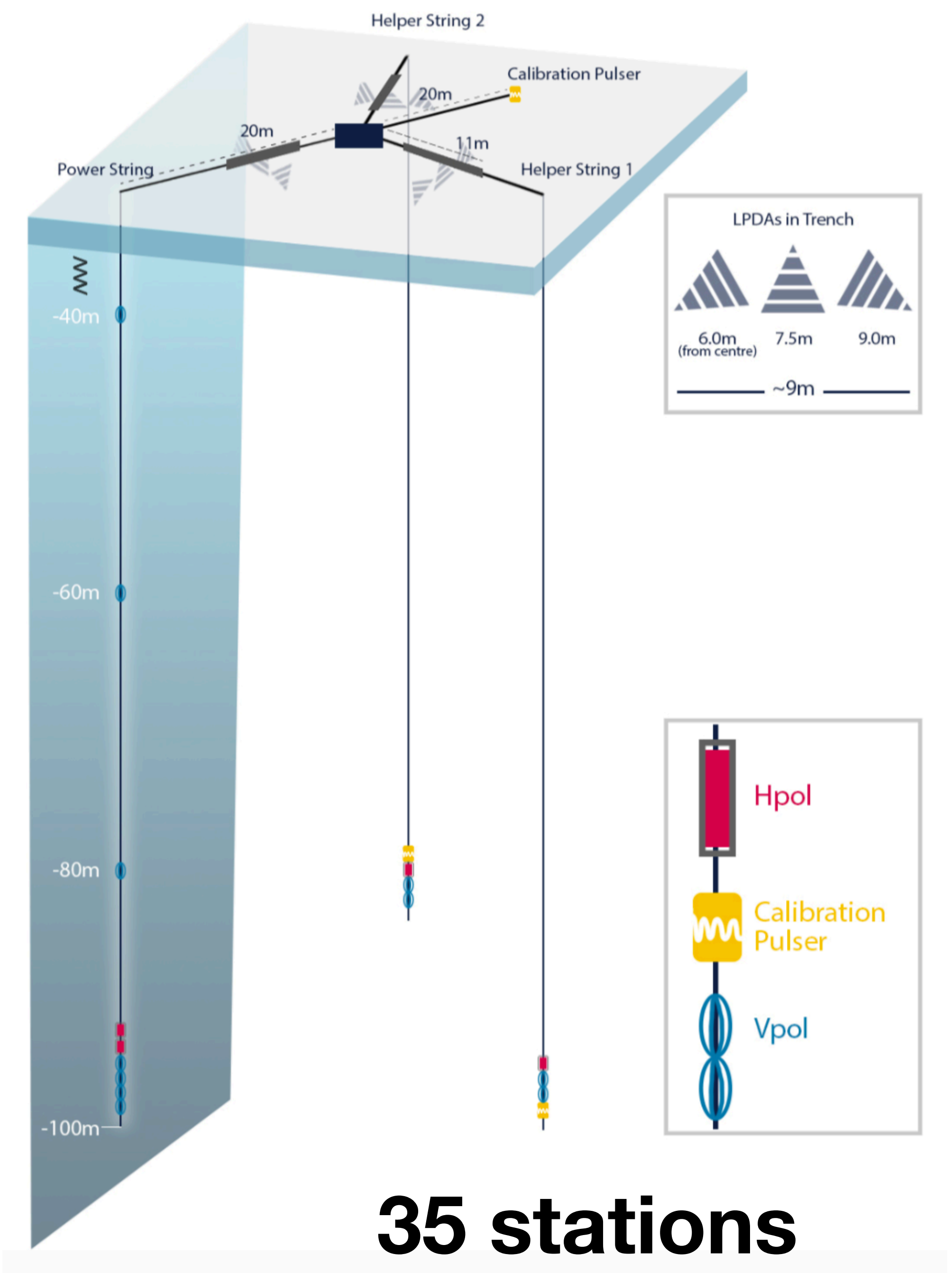
IceCube gen-2 radio

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



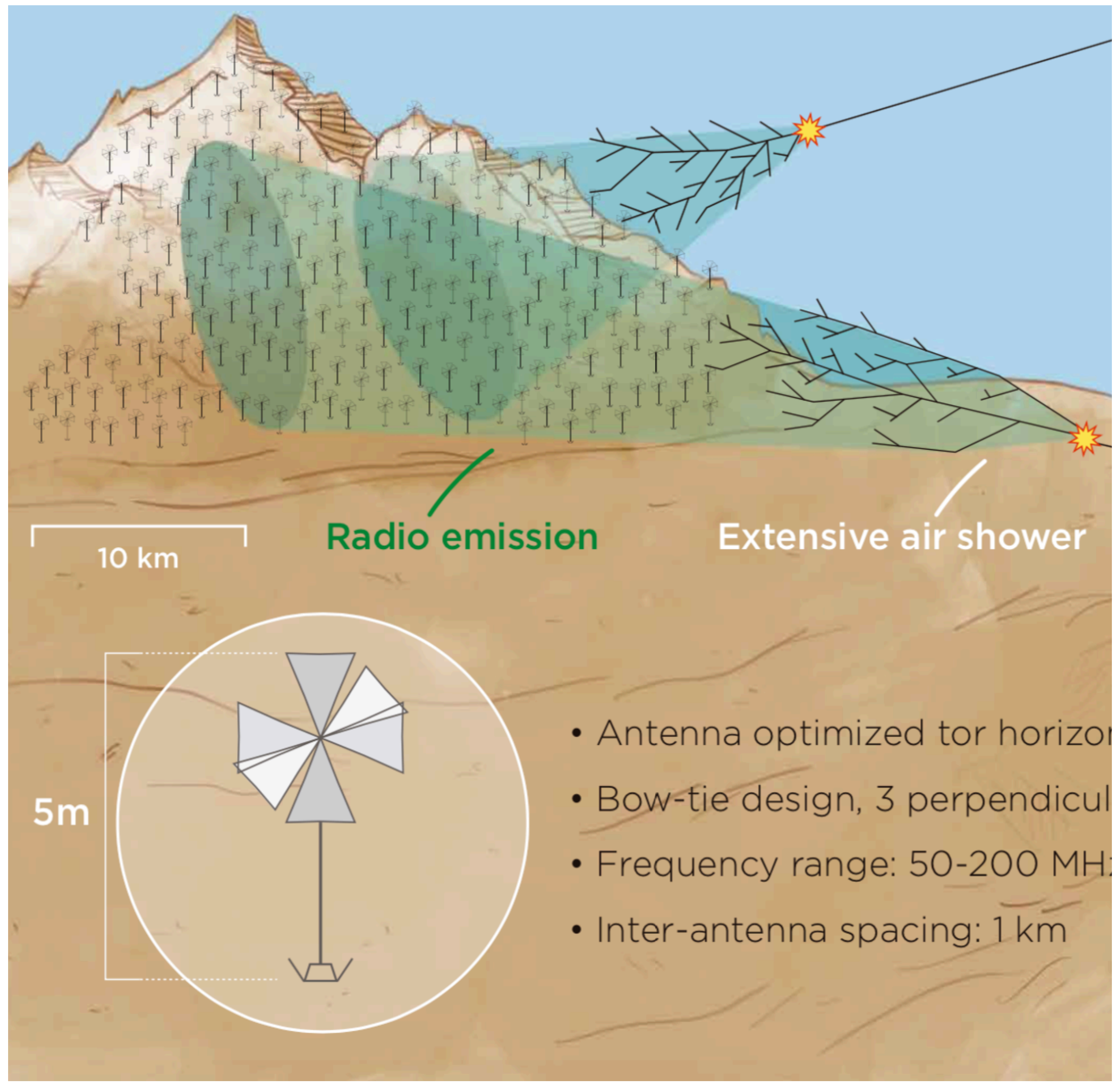
RNO-G

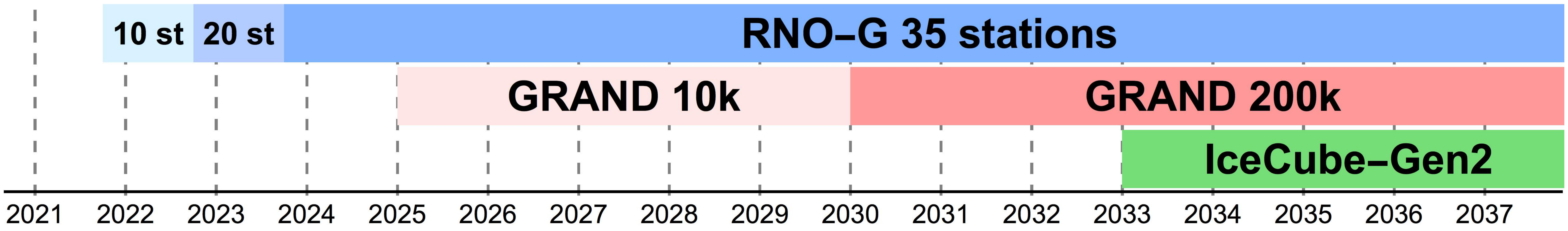
J.A. Aguilar et. al. [2010.12279]



GRAND

J. Álvarez-Muniz et. al. [1810.09994]



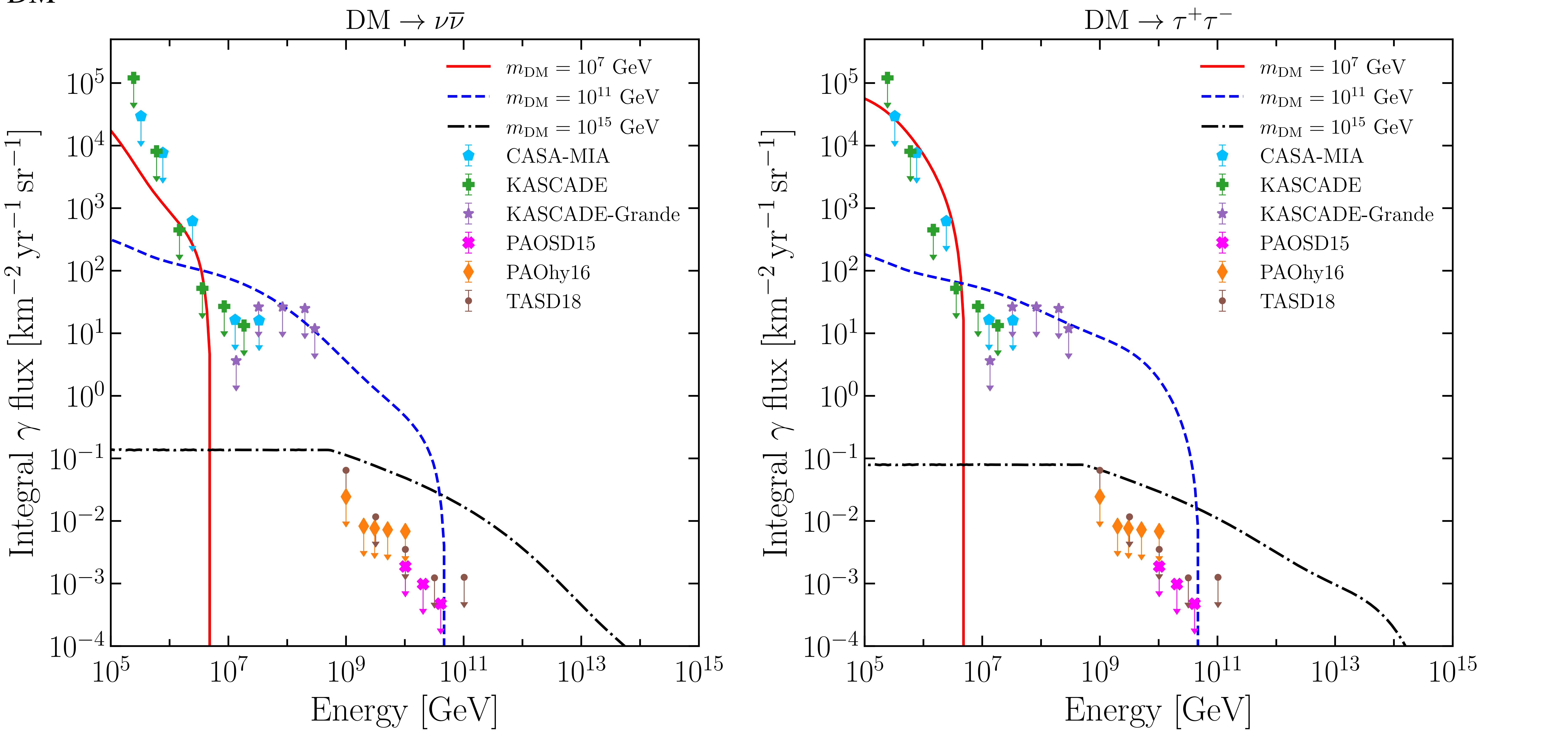


Gamma-ray UHE flux

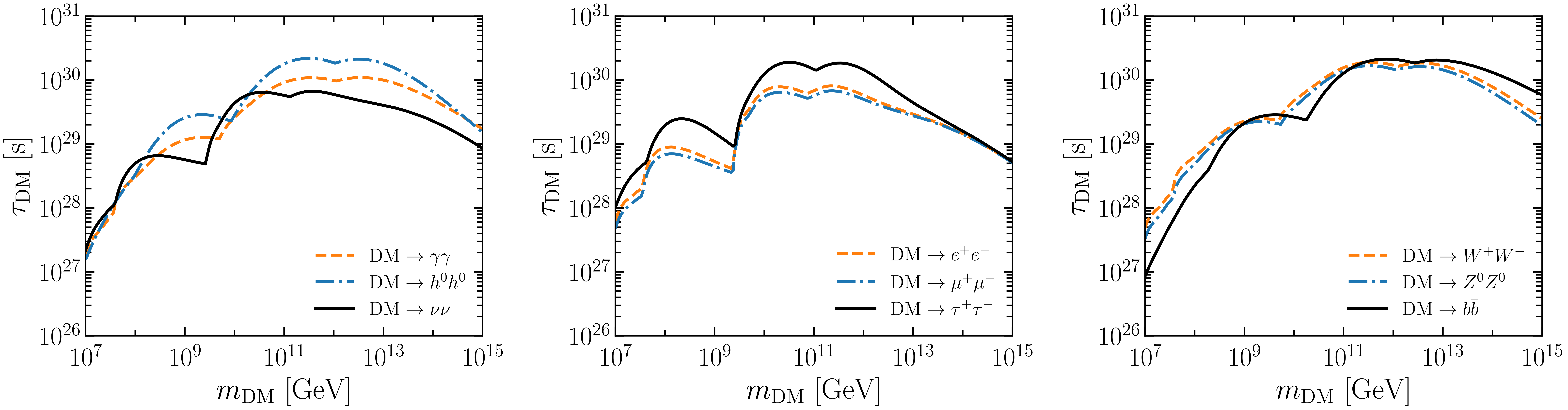
- HDMSpectra DM fluxes *Bauer+20 JHEP 06 (2021) 121*
- Work with angle-averaged integral fluxes:

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

$\tau_{\mathrm{DM}} = 10^{27}\,\mathrm{s}$



New limits on HDDM



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

W^+W^-, Z^0Z^0, $\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-, $\gamma\gamma$, h^0h^0 — **first limits placed for this mass range**

$b\bar{b}$, $\nu\bar{\nu}$ — **comparison with existing limits**

New limits on HDDM

- 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 HDDM

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