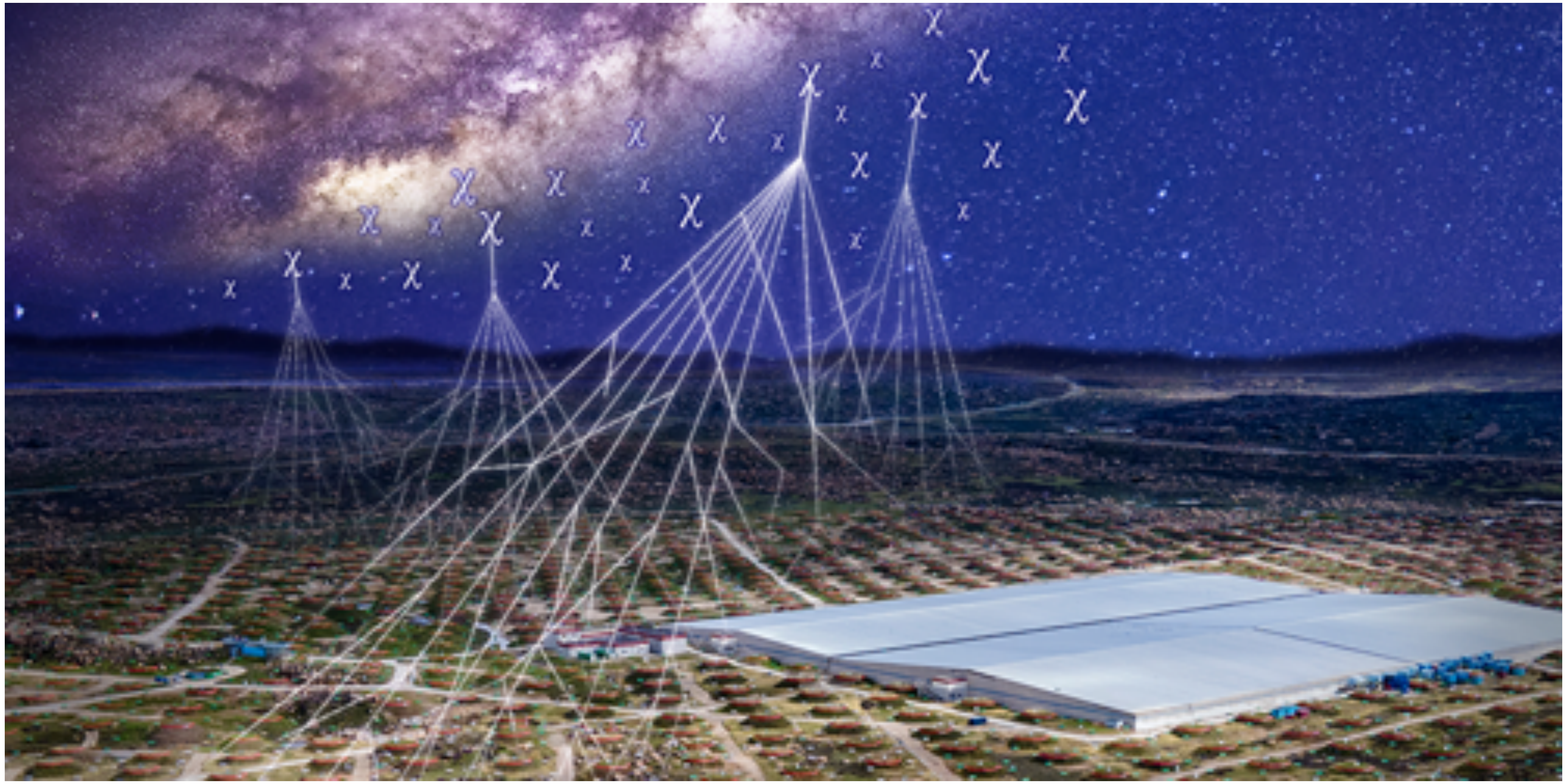
Constraints on decaying dark matter with LHAASO



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Constraints on Heavy Decaying Dark Matter from 570 Days of LHAASO Observations

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LHAASO Collaboration

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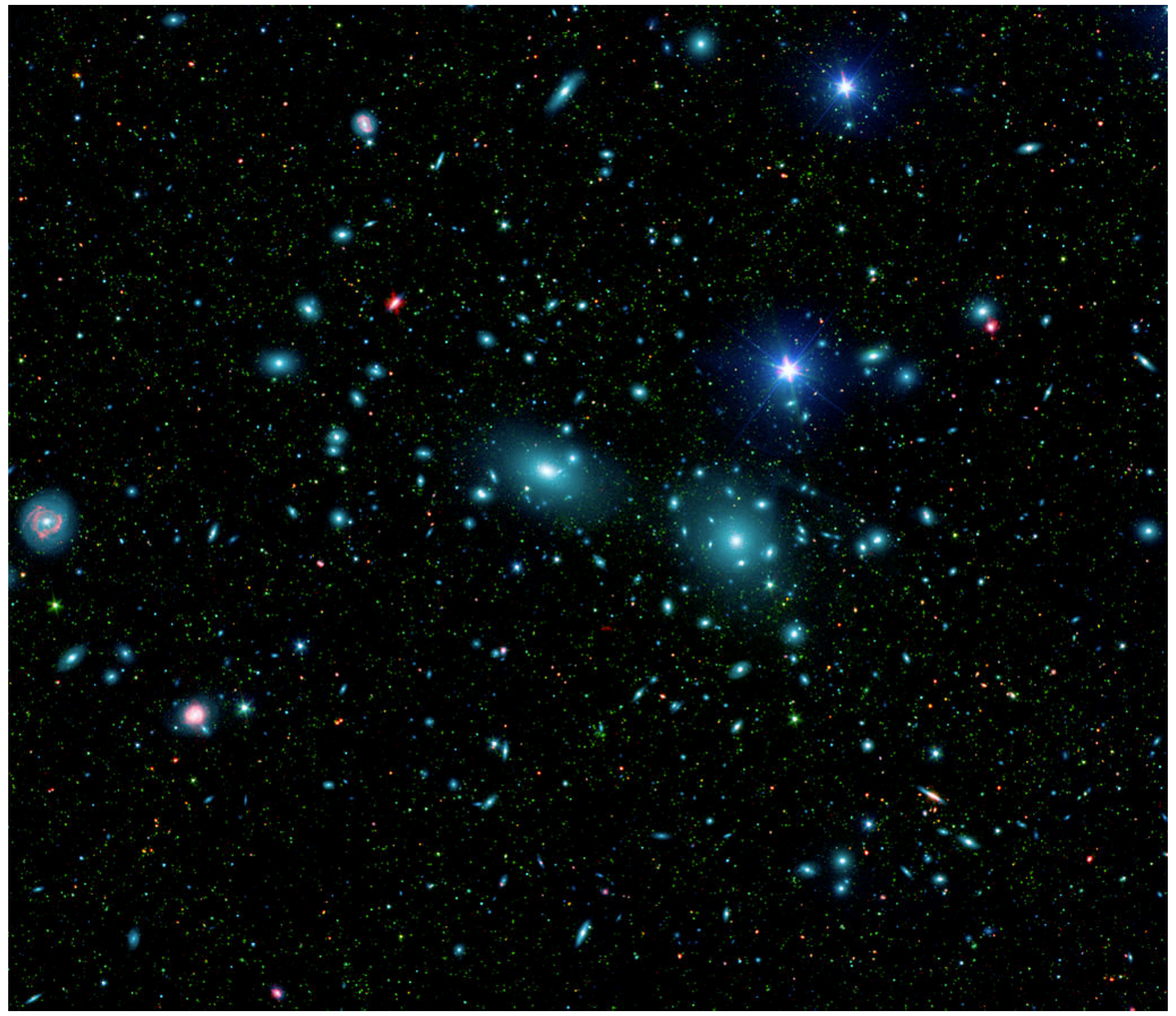
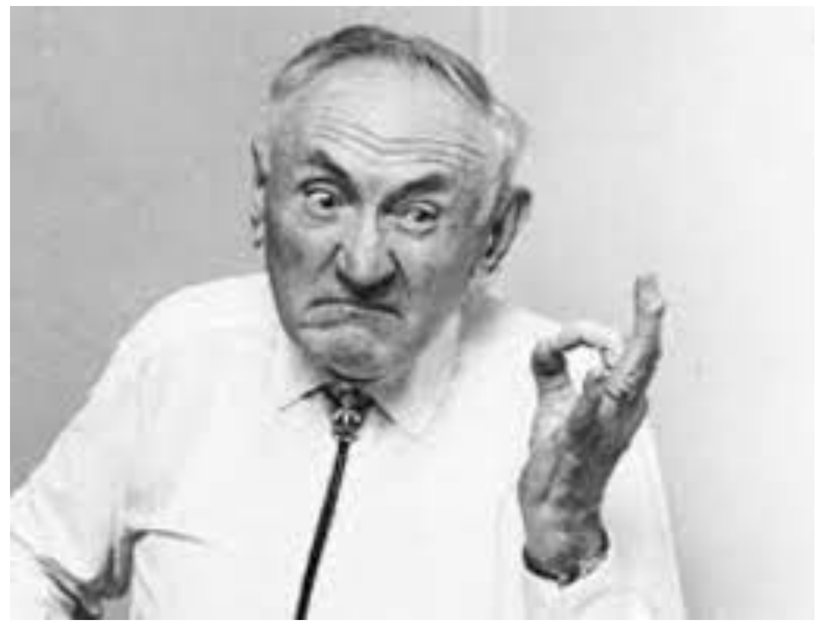
Evidence of Dark Matter

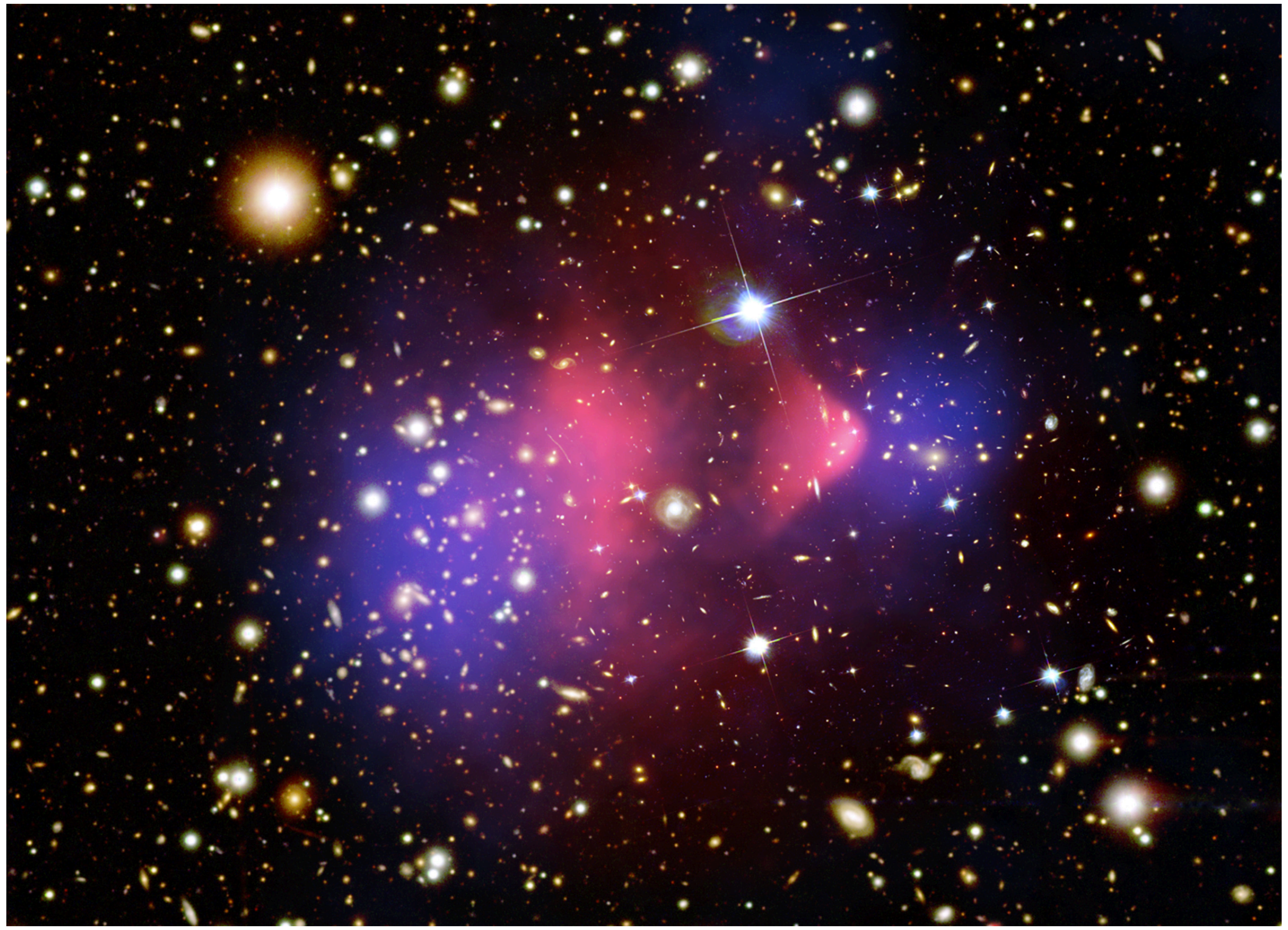
- Cluster Scales
  - Cluster velocity disperson
  - Bullet Cluster





~1930 Zwicky
Coma Cluster

Velocity ~ Gravitational mass >> Observable mass

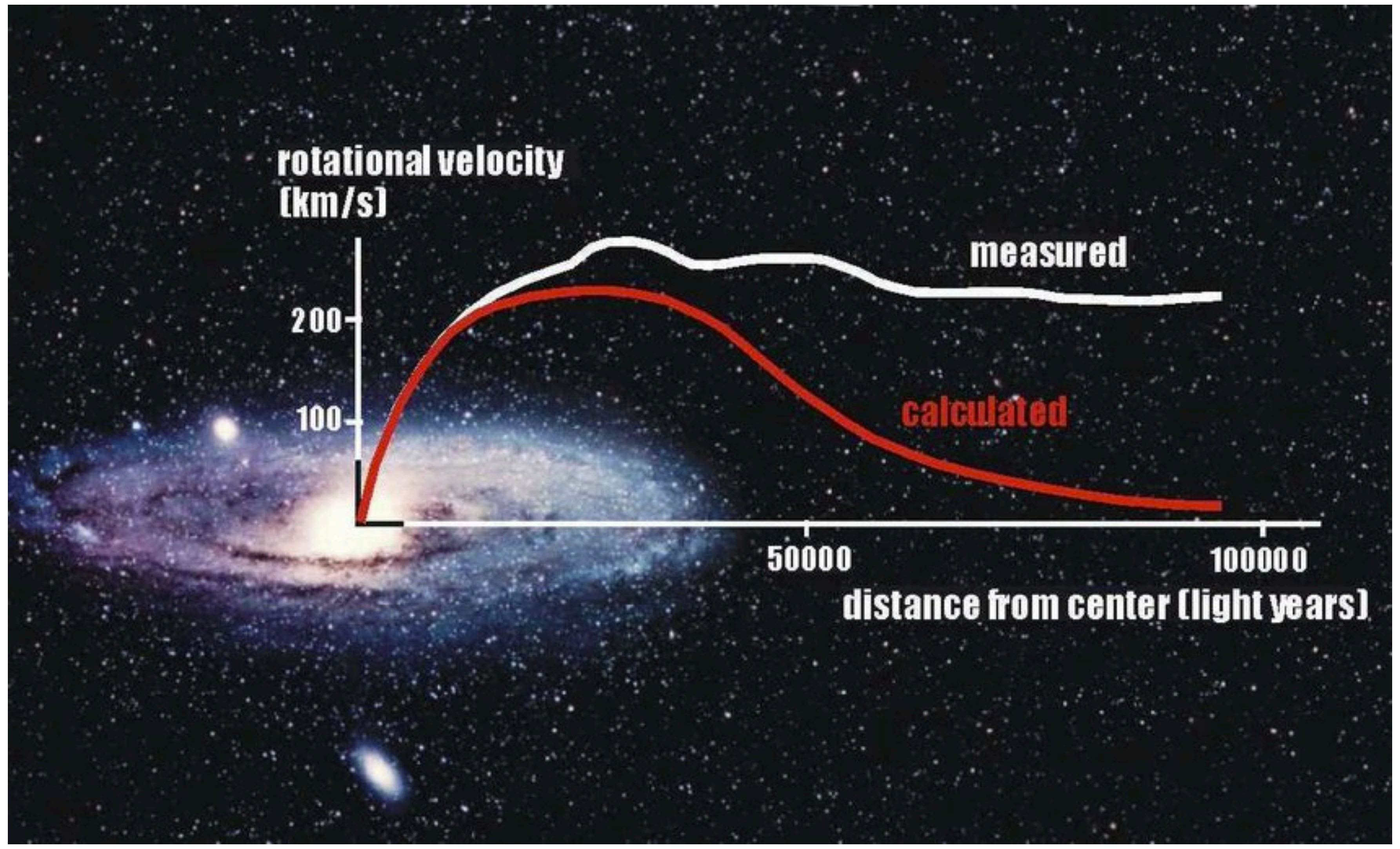


Gravitational mass from gravitational lensing(blue)
Baryonic mass form X-ray (red)

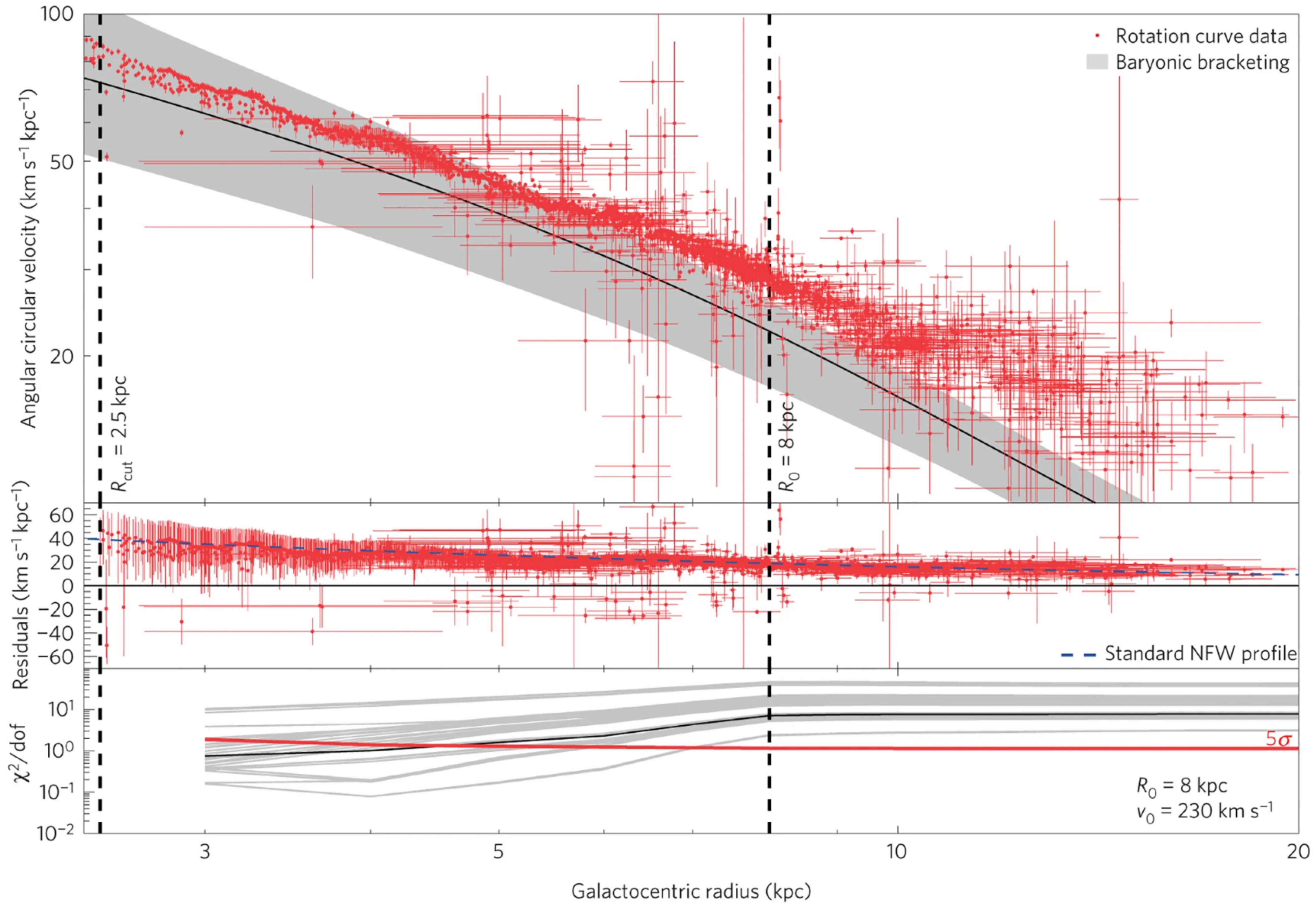
==> Missing mass -> “collisionless Dark Matter”

Evidence of Dark Matter

- Galaxy Scales
  - Galaxy Rotation Curve
  - Local stellar dynamics



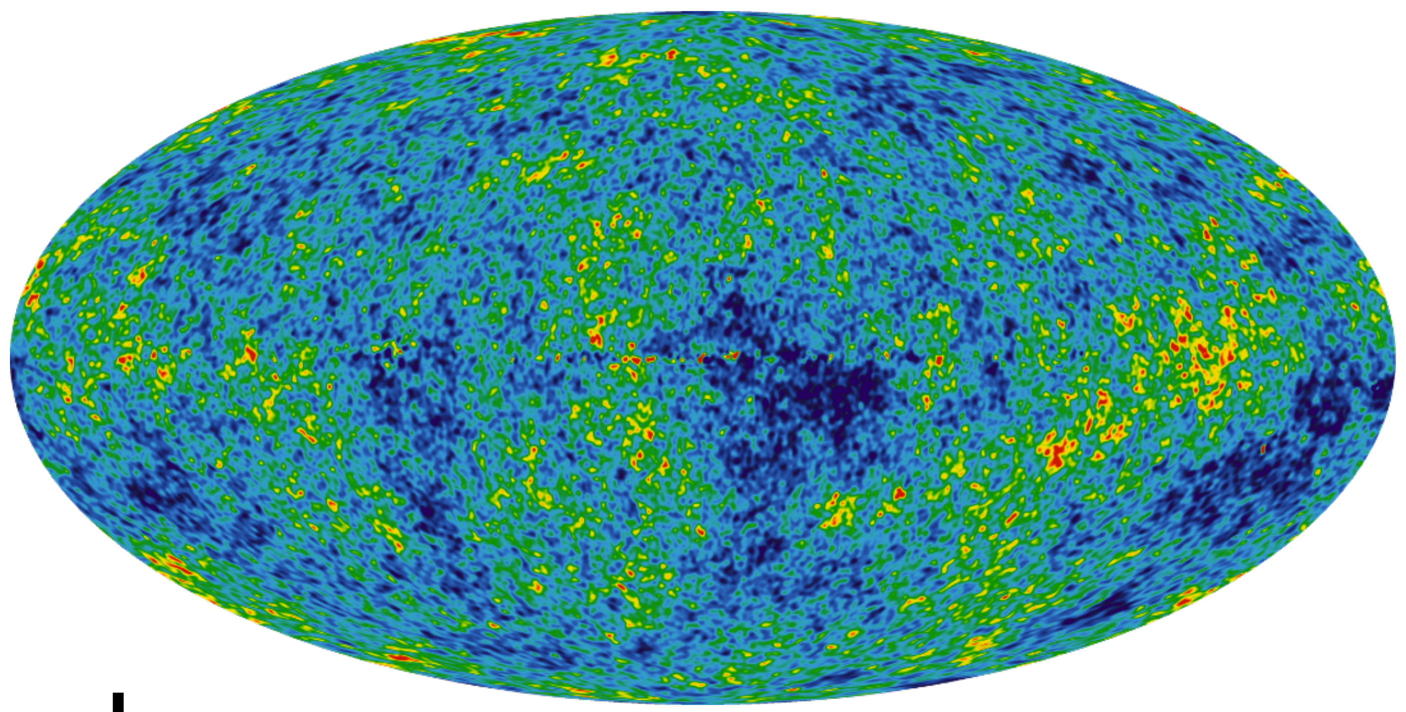
~1970 Rubin, Galaxy Rotation curves
Unobserved mass contributes to gravity

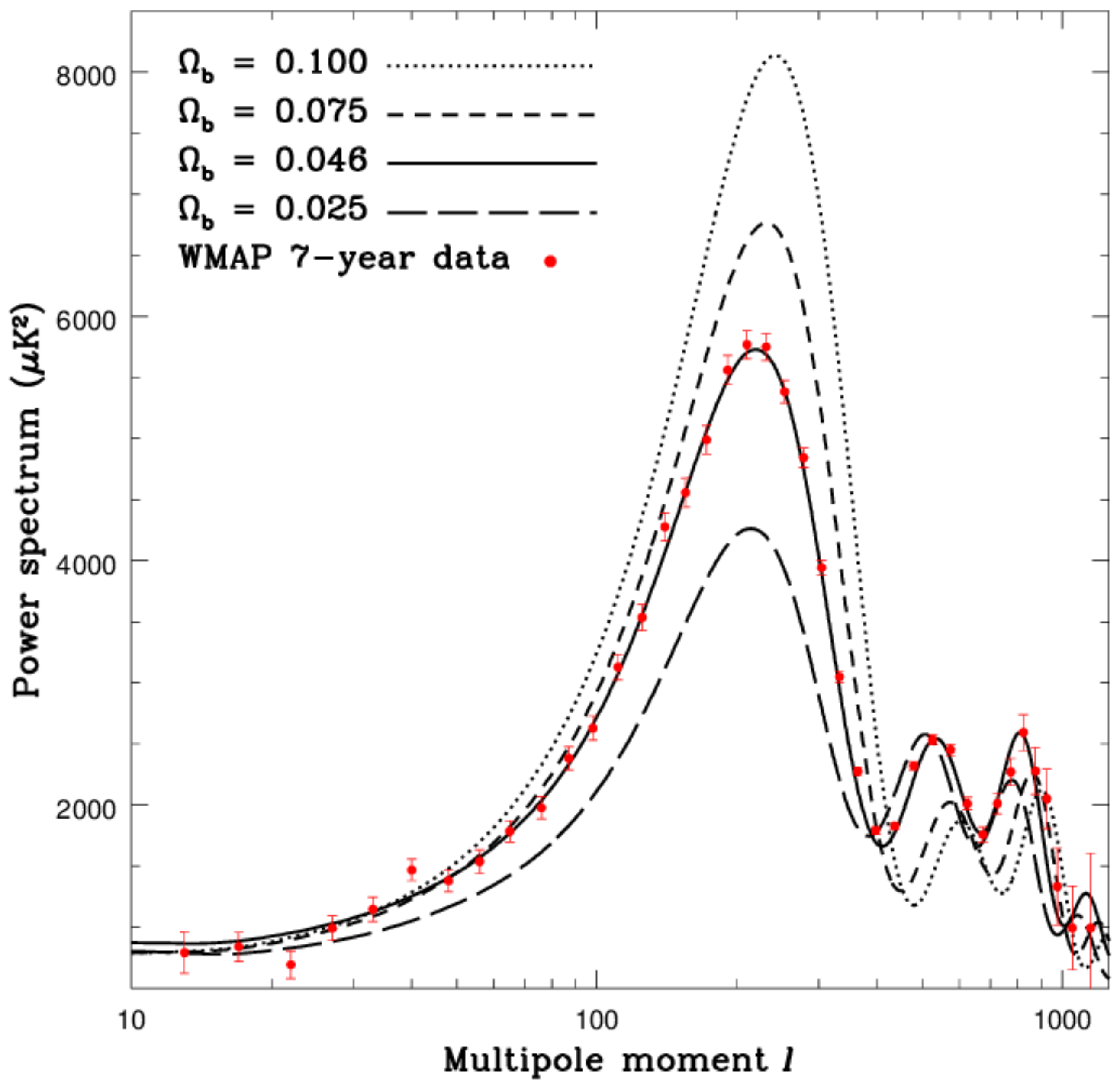


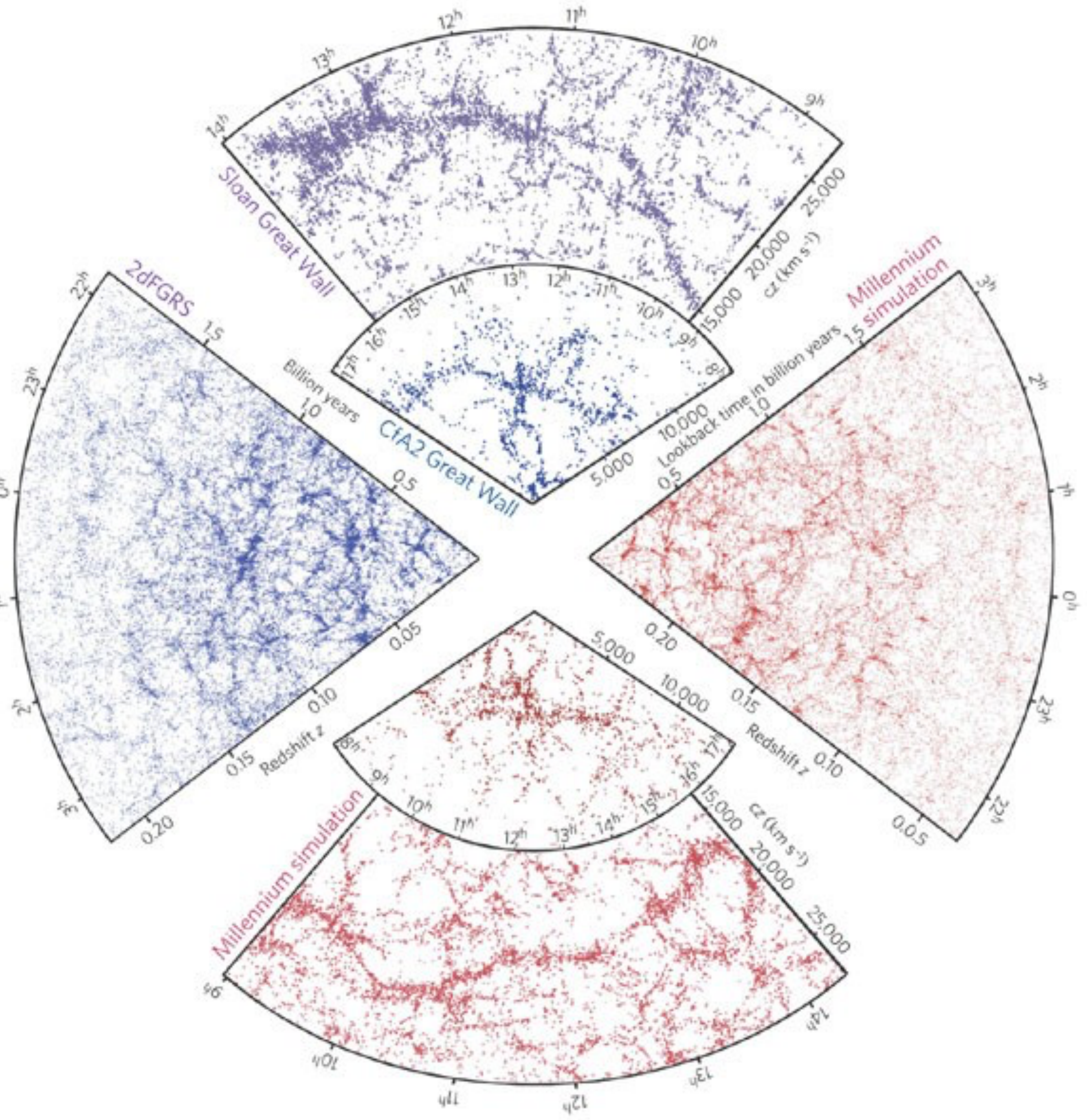
Local stellar dynamics required extra mass
=> $\rho_\chi \simeq 0.3\,\mathrm{GeV cm^{-3}}$
https://arxiv.org/abs/1502.03821

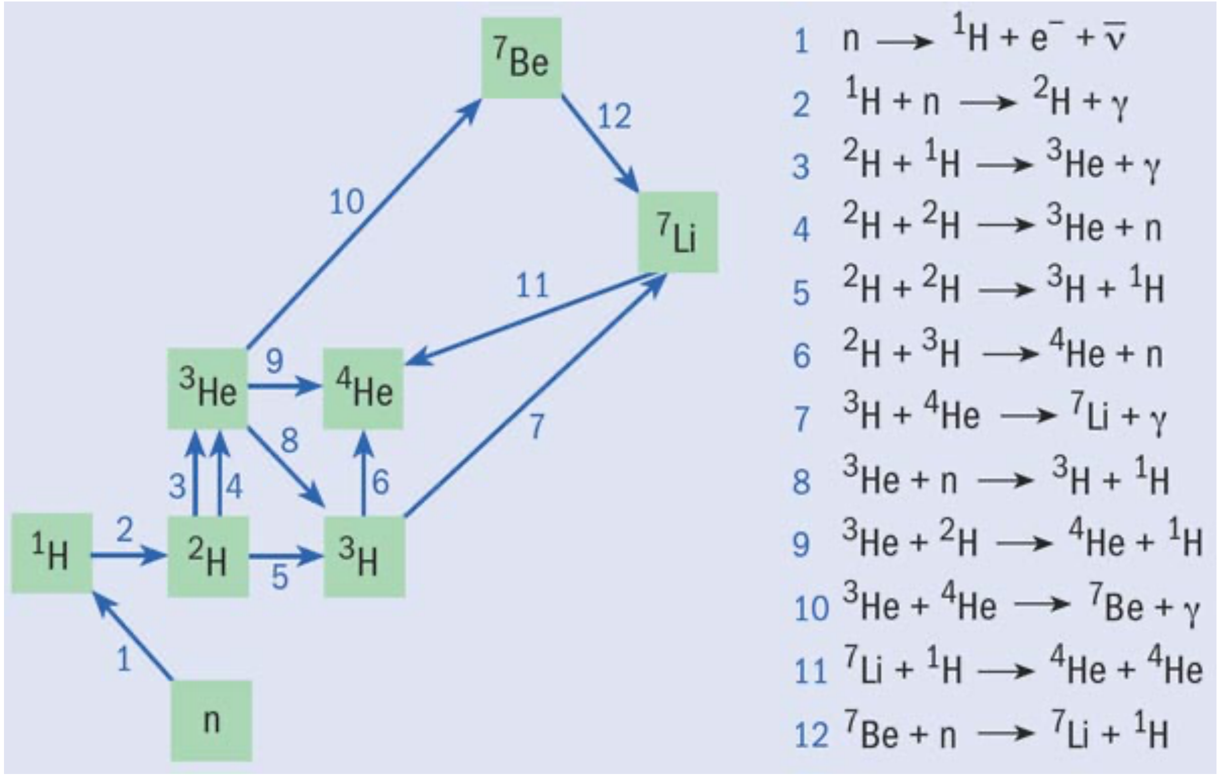
Evidence of Dark Matter

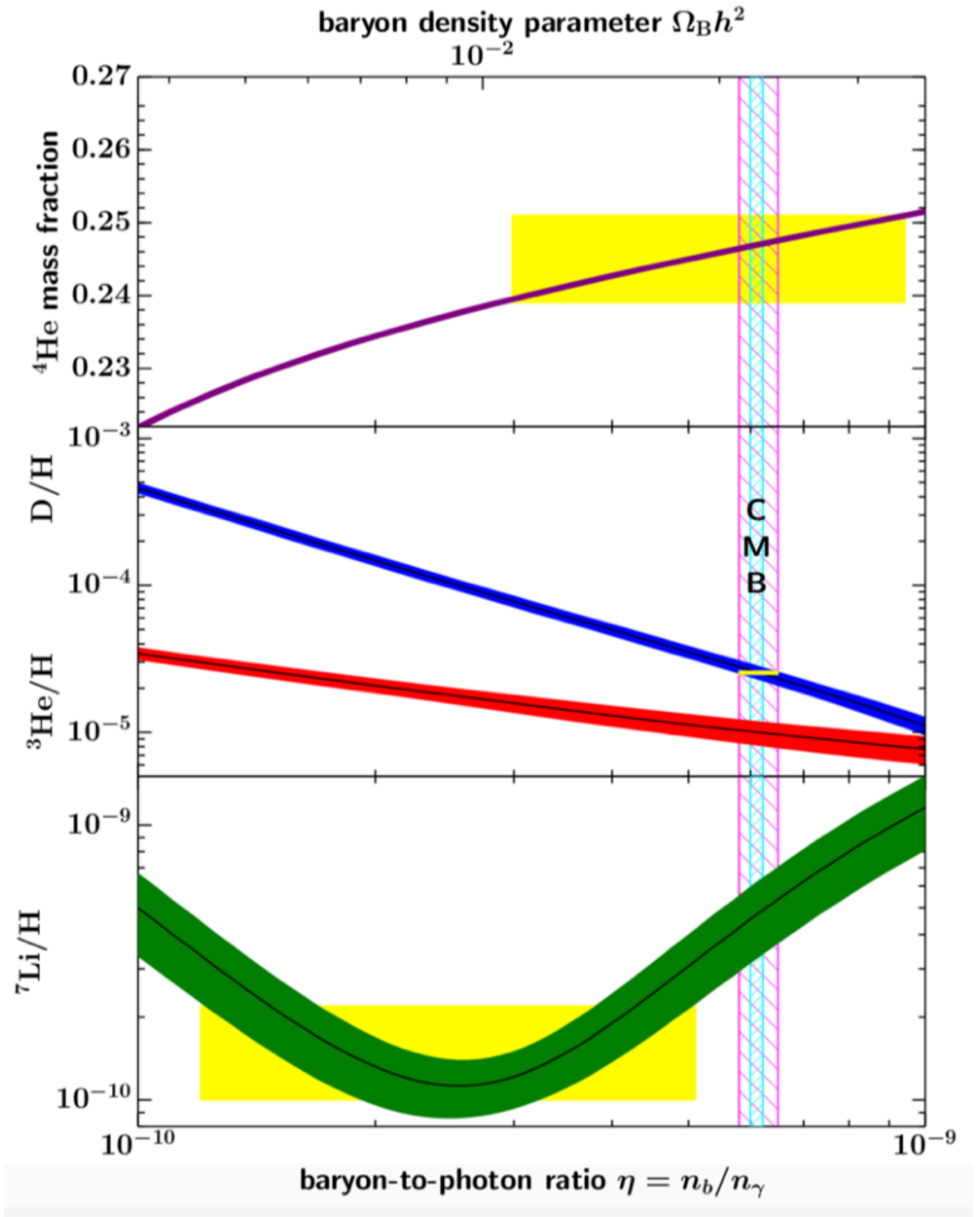
- Cosmological scales
  - Big Bang nucleosynthesis
  - Cosmic microwave background
  - large scale structure





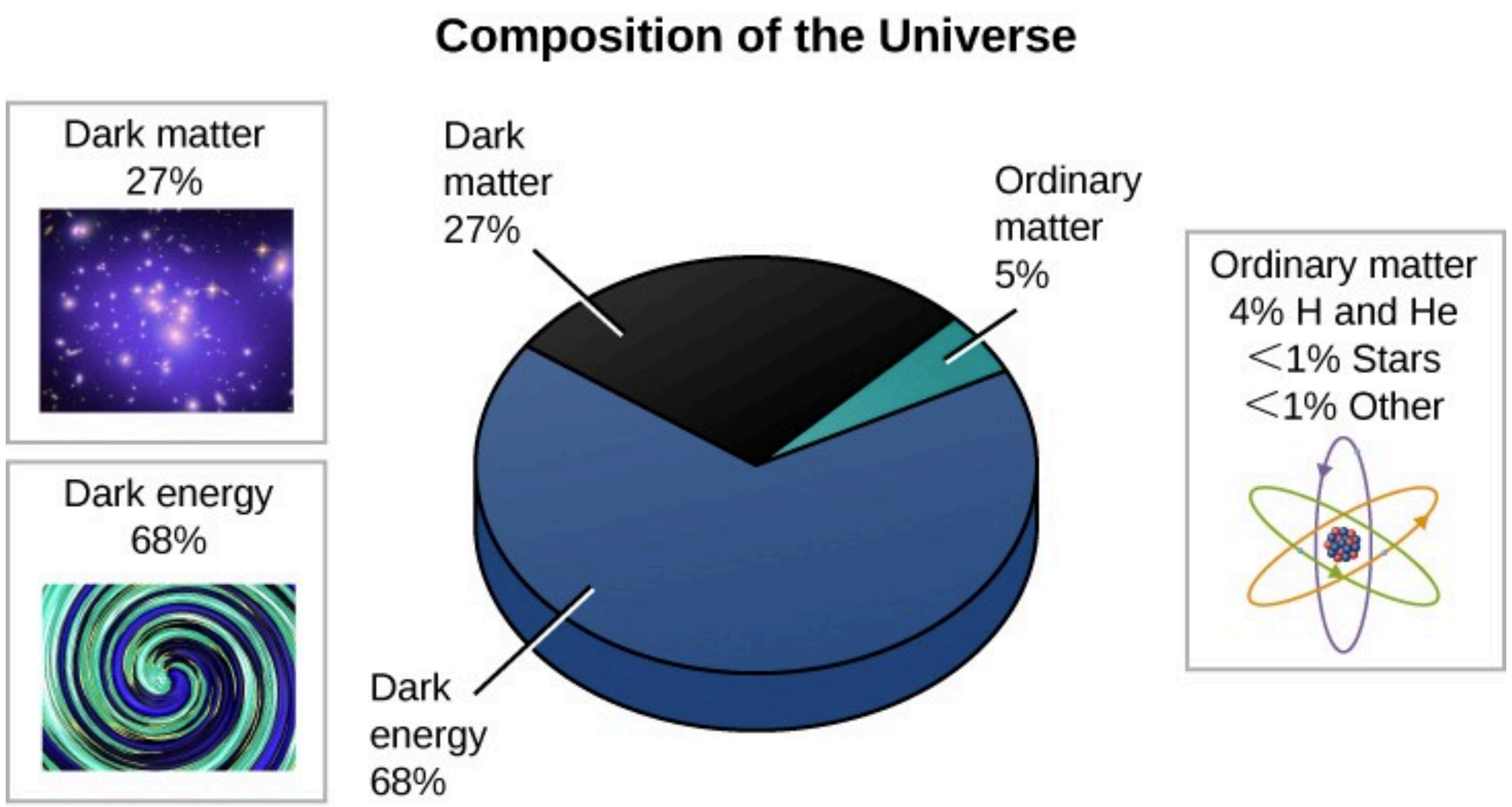






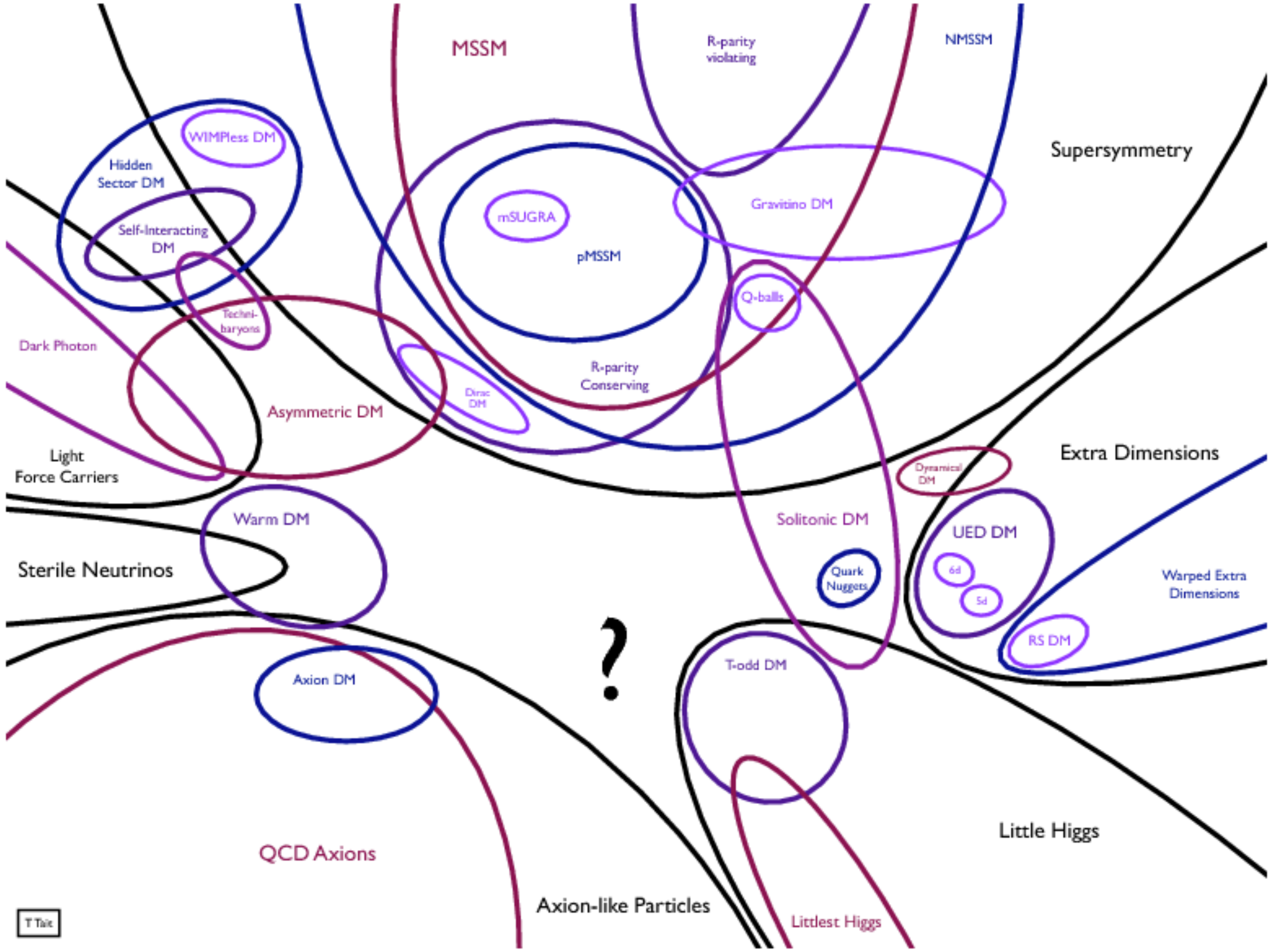
The ΛCDM model

- ~70% dark energy/cosmological constant
- ~30% Matter
  - ~25% Dark Matter
  - No particles in the Standard Model of particle physics can explain DM
  - New (Particle) Physics!
- Maybe gravity theory is wrong?
  - MOND, etc



Dark Matter Detection

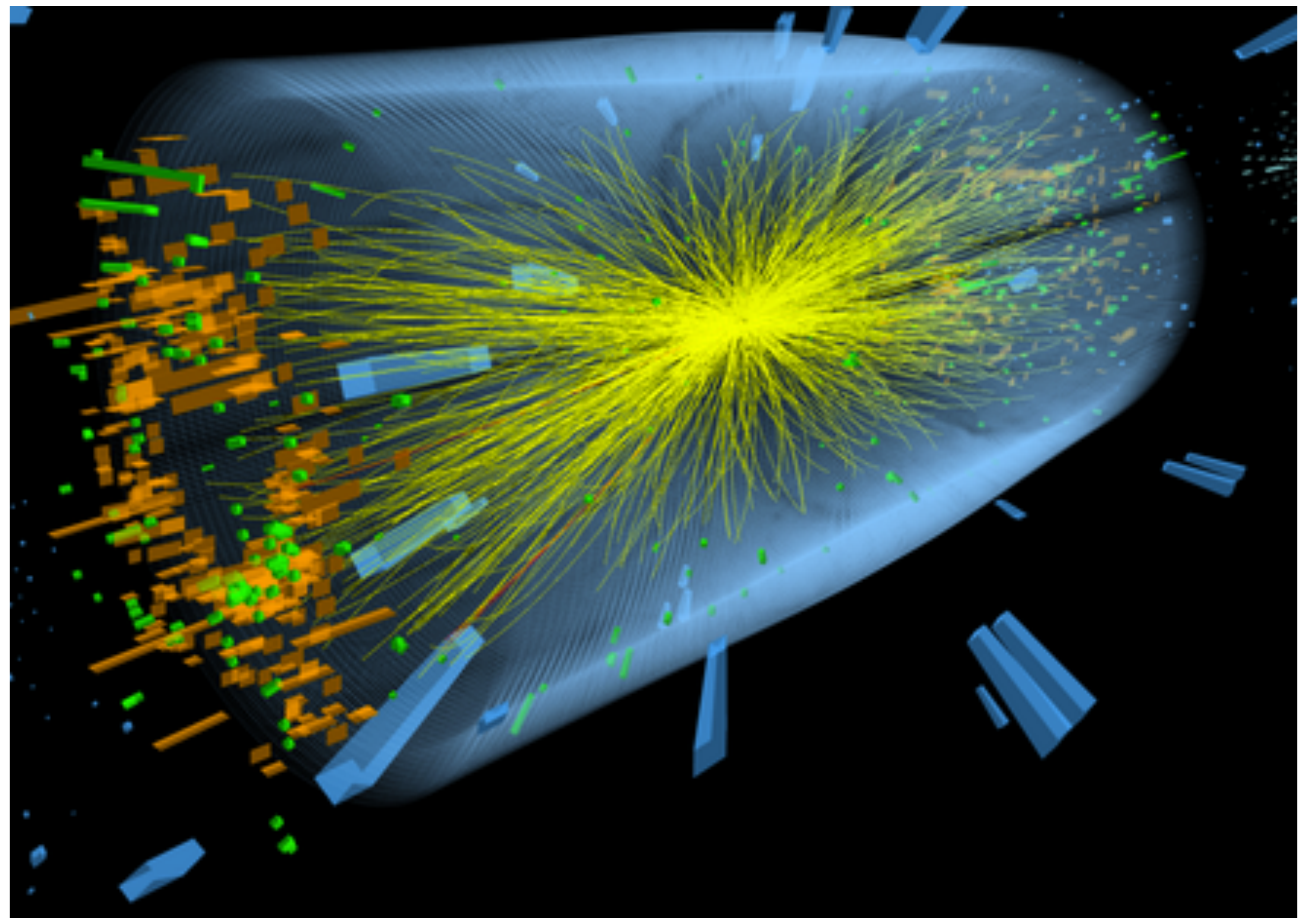
- ~70% dark energy/cosmological constant
- ~30% Matter
  - ~25% Dark Matter
  - No particles in the Standard Model of particle physics can explain DM
  - New (Particle) Physics!
- Maybe gravity theory is wrong?
  - MOND, etc



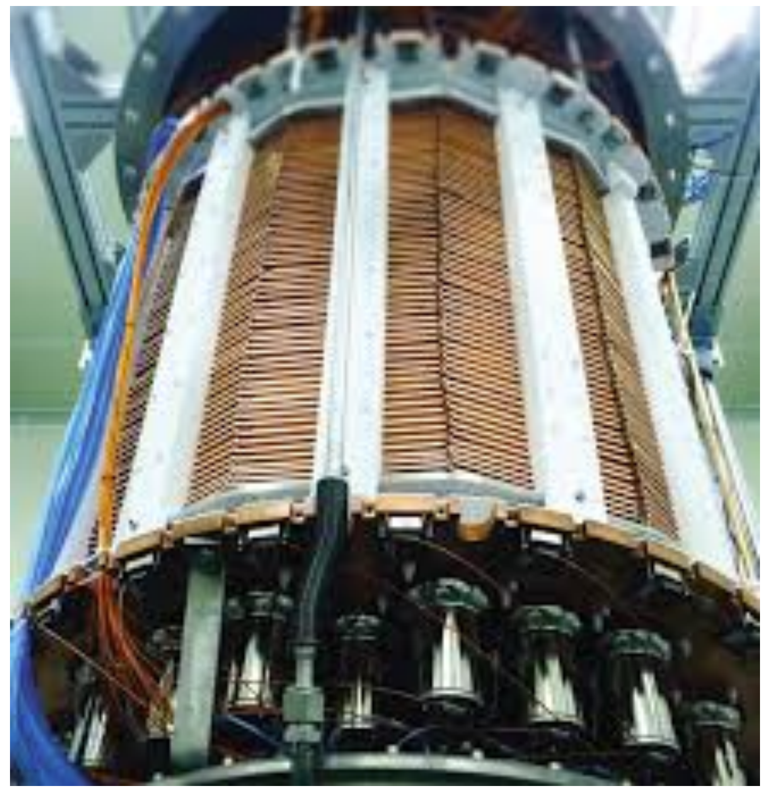
Too many candidates for particle dark matter!

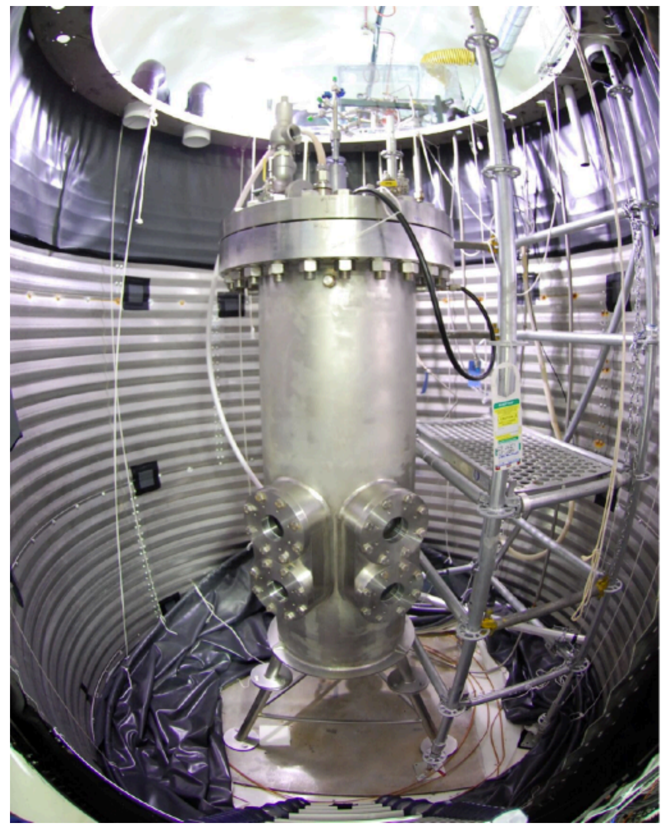
Dark Matter Detection

- Collider search

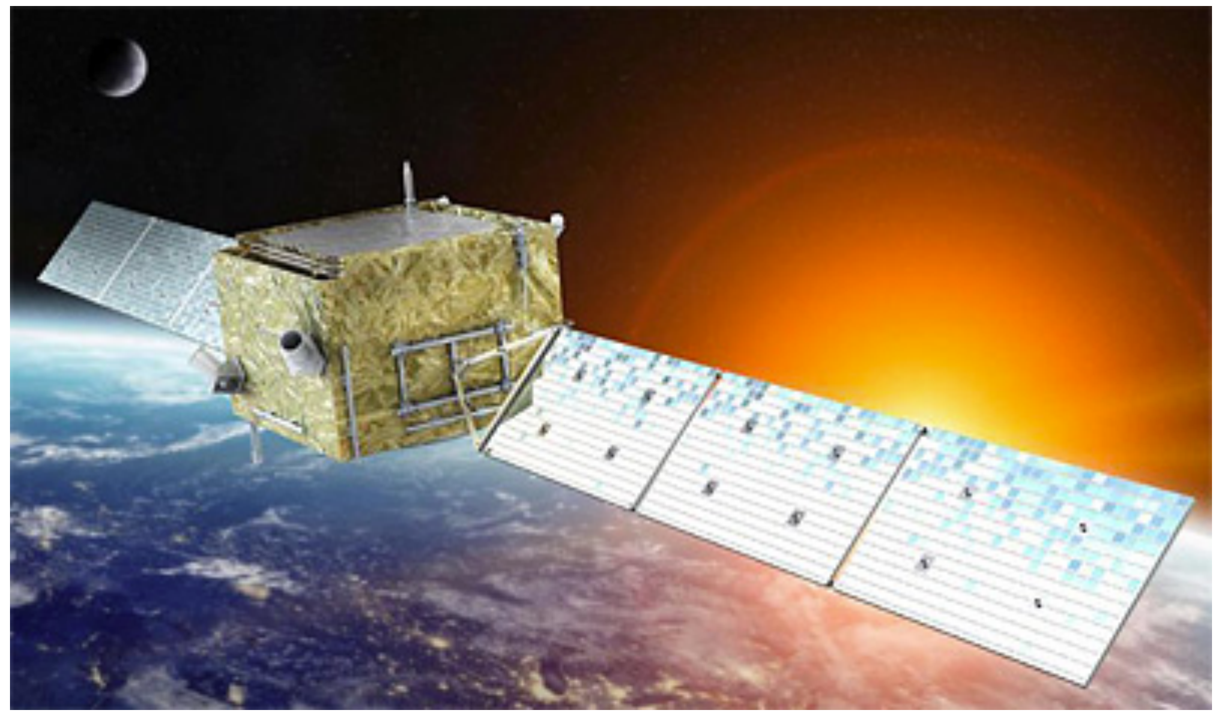


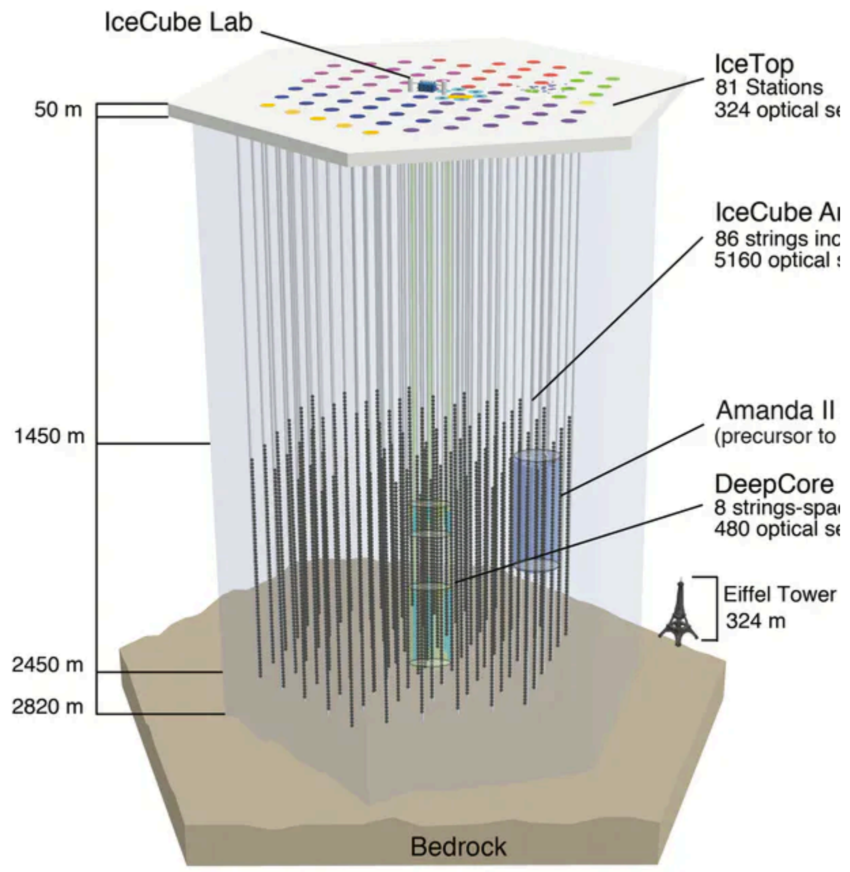
- Direct Detection



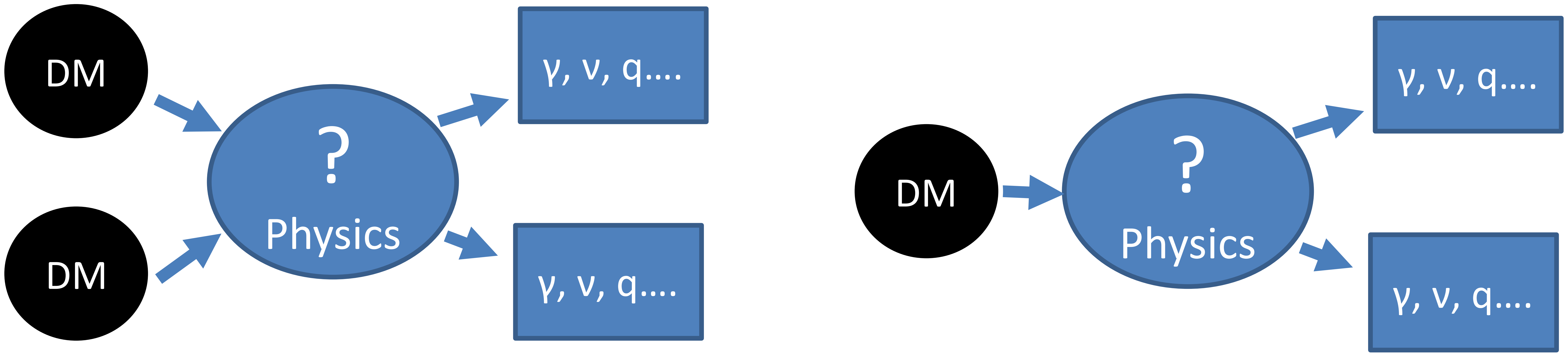


- Astrophysical search/ Indirect detection



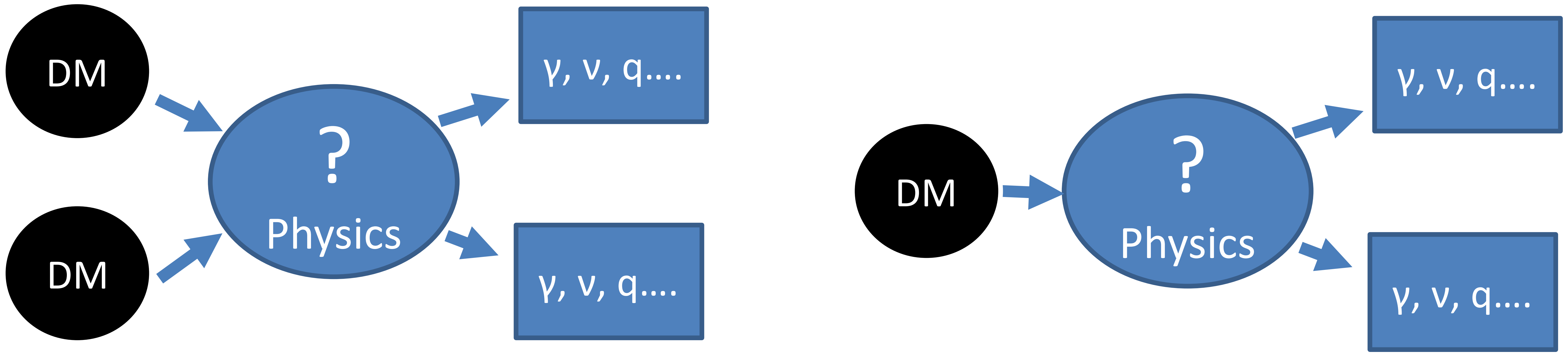


Indirect Detection

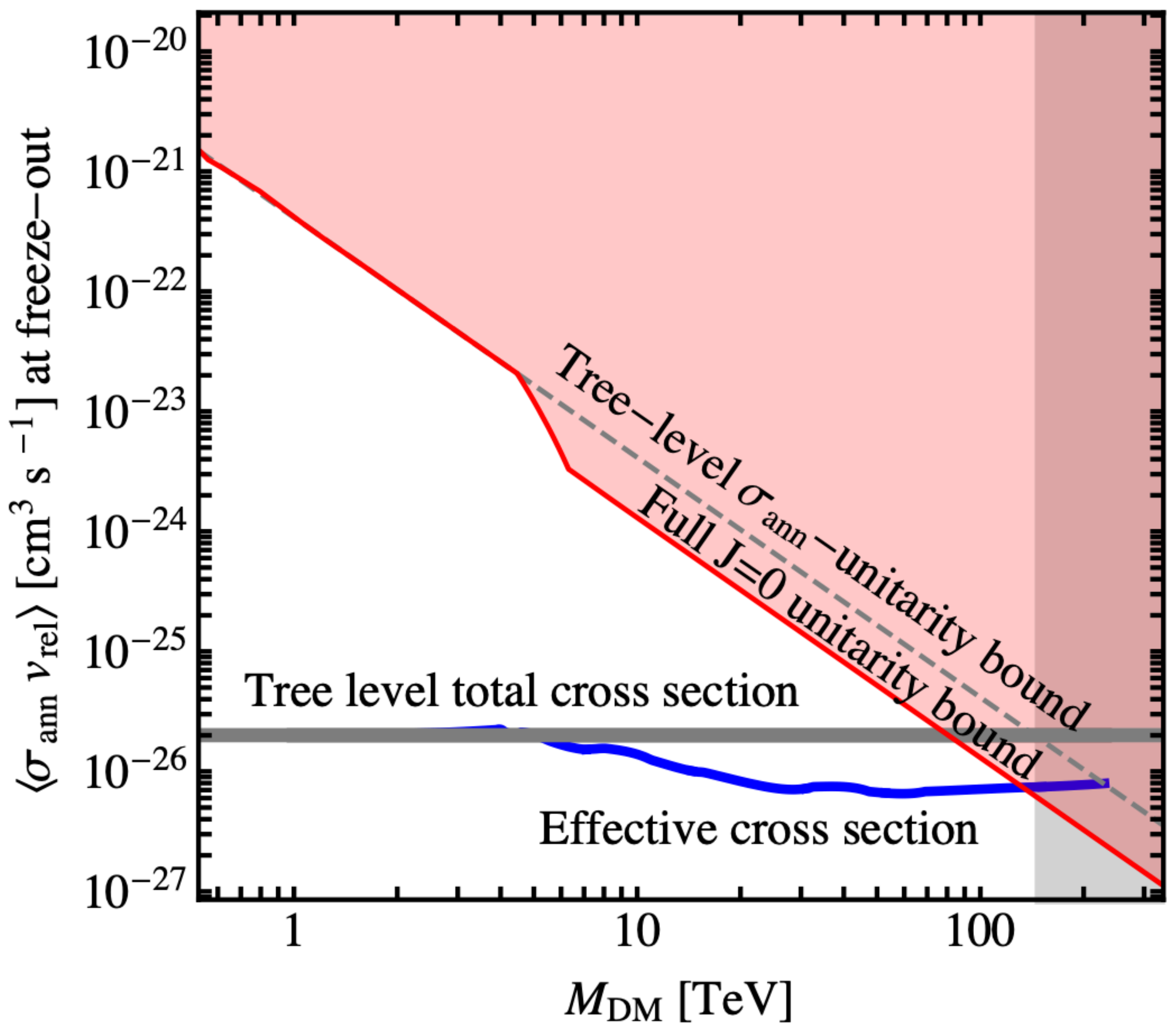


- Dark Matter could annihilate or decay into standard model particles
- Final products include
  - gamma rays
  - neutrinos
  - electrons/positrons, etc

Decay Vs Annihilation

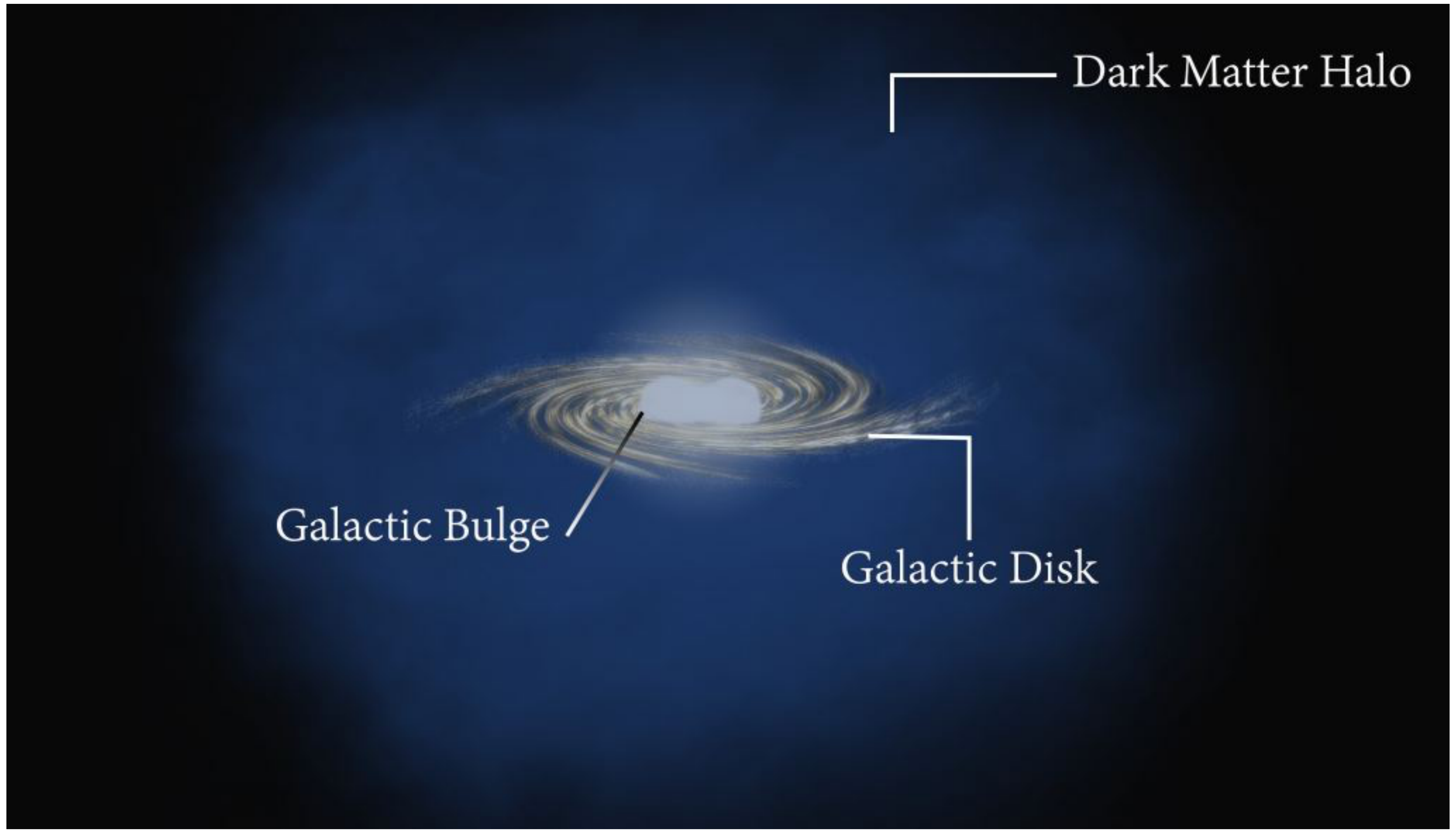


- Generally, annihilation for dark matter above 100 TeV is theoretically disfavoured.

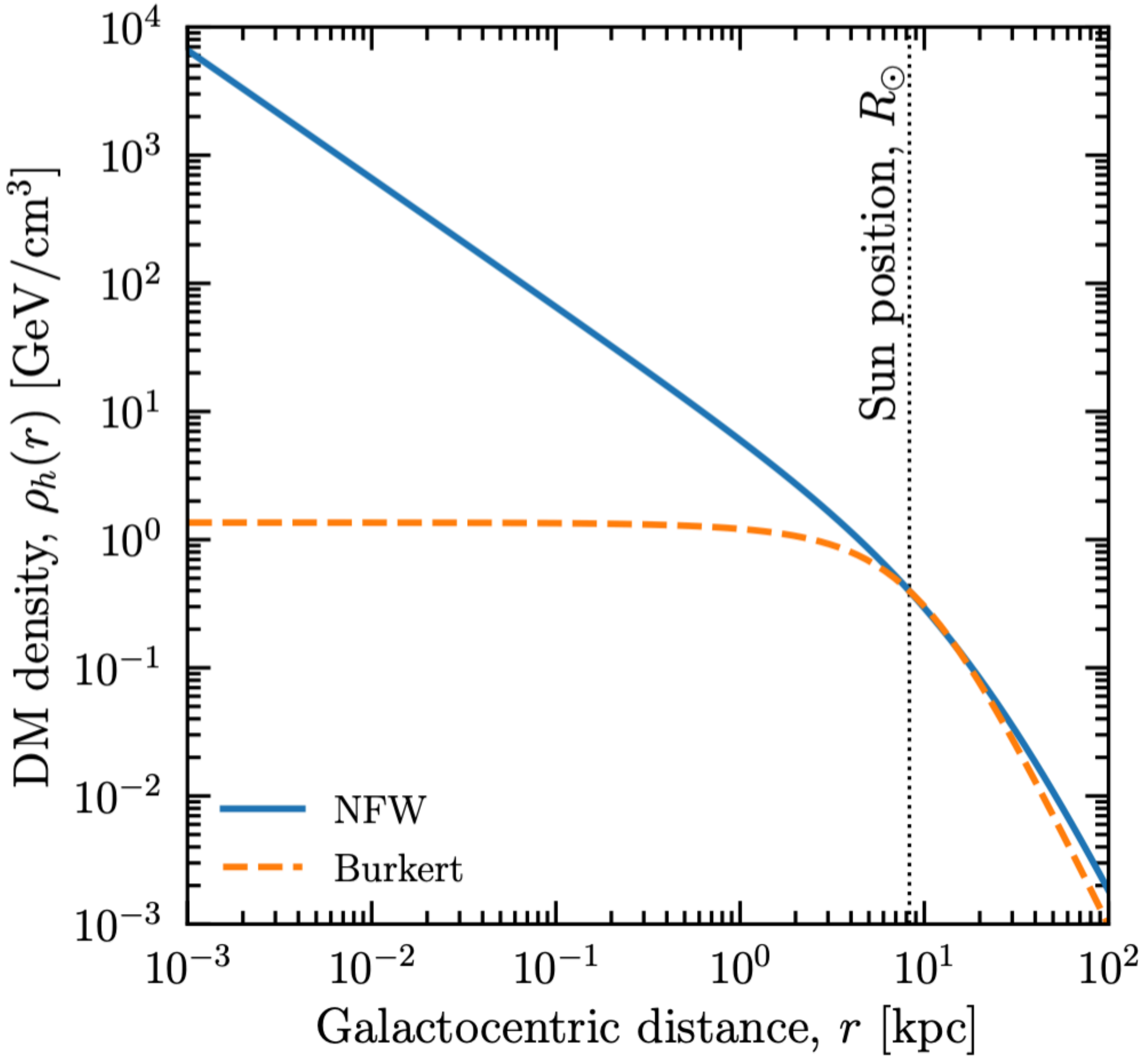


https://arxiv.org/pdf/1904.11503.pdf

Dark Matter decay detection



- The Milky Way lives inside a dark matter halo
  - Spherically symmetric density distribution
  - E.g., NFW profile $$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$



However, the density closer to the Center is quite uncertain

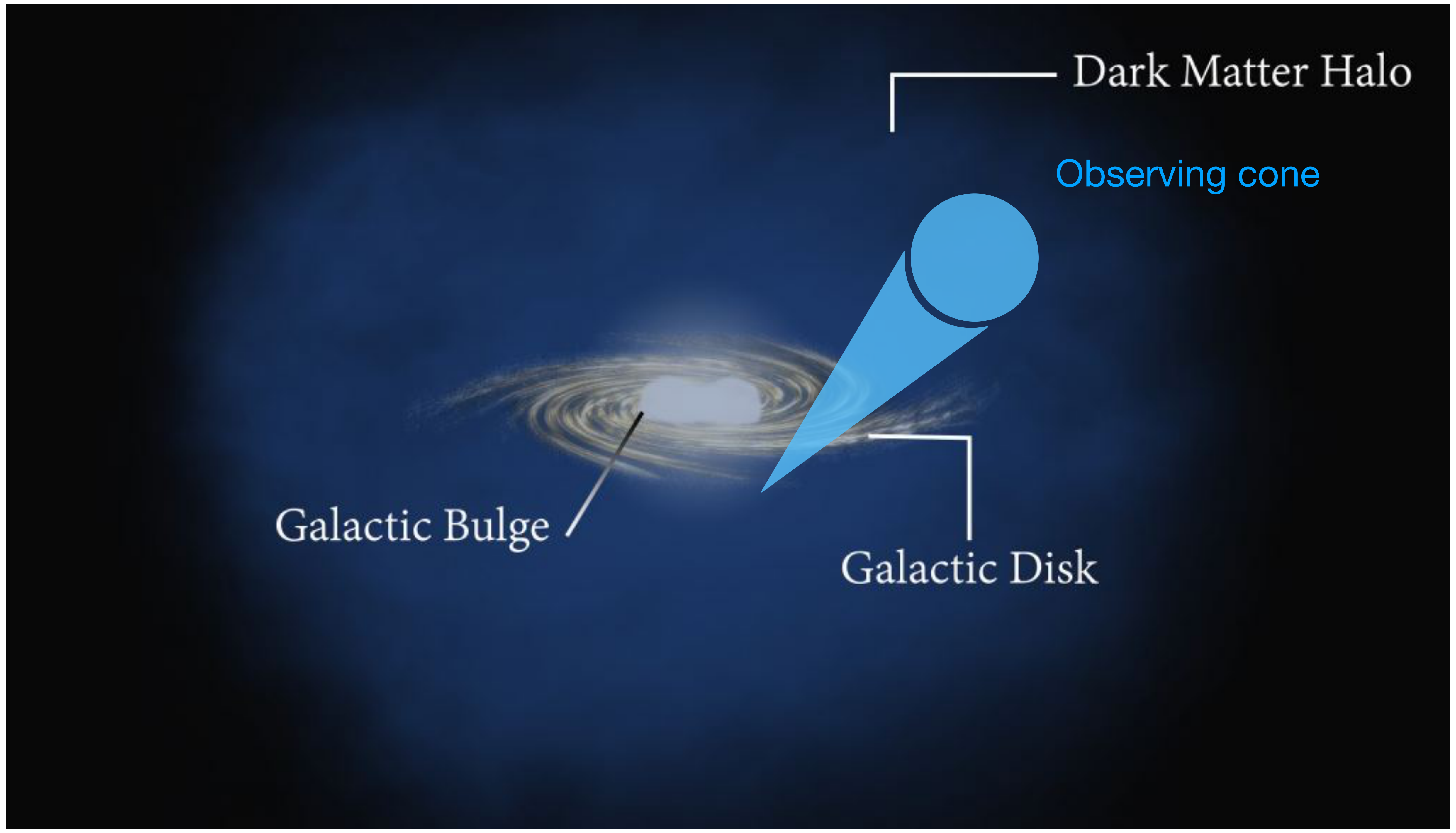
Galactic Dark Matter decay

- The decays of dark matter in the Milky Way
- produce detectable high-energy signal

Particle Physics

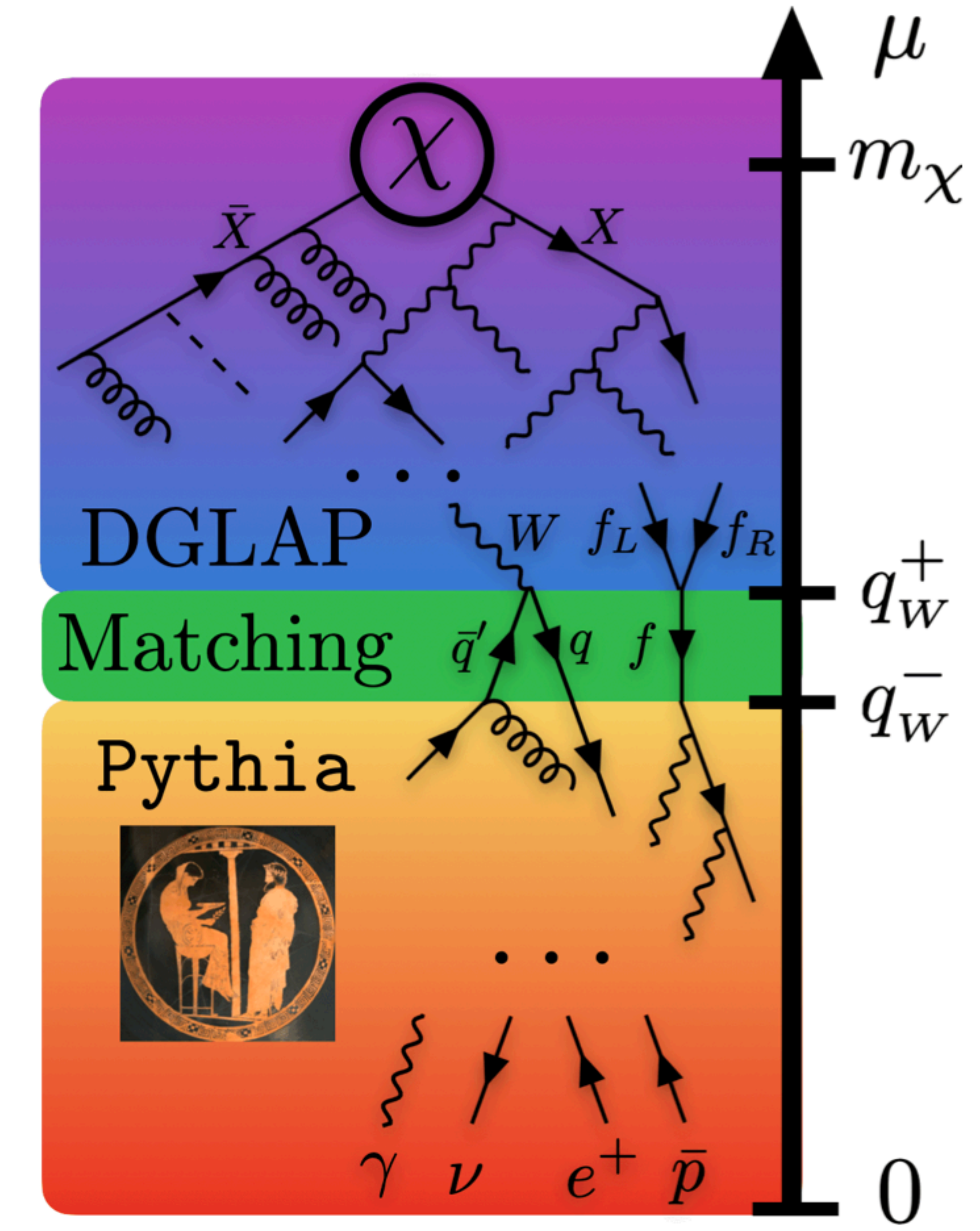
Astrophysics
D-factor

$$\frac{dF}{dE} = \frac{1}{4\pi}\frac{\Gamma}{m_\chi}\frac{dN}{dE}\int d\Omega \int d\ell \rho_\chi[r(\ell)]$$

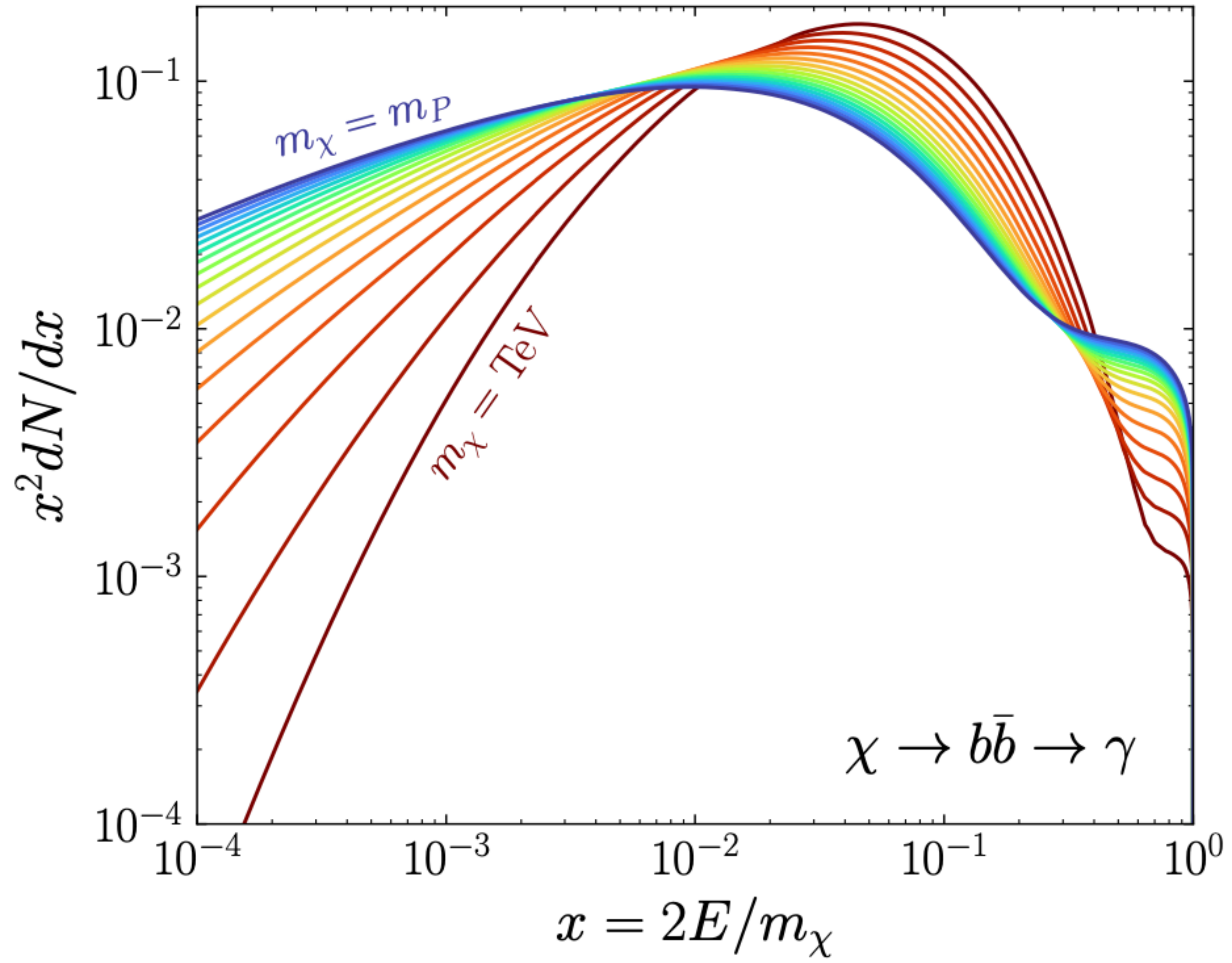


- Flux proportional to
  - Γ (dark matter decay rate = $1/\tau_{DM}$)
  - dN/dE: gamma-ray flux per decay, e.g., $\chi \to \tau^+\tau^-$
  - The D factor: line of sight integral of dark matter density

Dark Matter decay spectrum dN/dE



- For LHAASO, we are interested in heavy dark matter
- m_χ between TeV to PeV



- HDMspectra
  - Baur, Rodd, Webber 2007.15001

Prompt component

$$\frac{\mathrm{d}I_\gamma^{\mathrm{prompt}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi\, m_{\mathrm{DM}} \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} D(E_\gamma, b, \ell)$$

D-factor

$$D(E_\gamma, b, \ell) = \int_0^\infty \mathrm{d}s\, \rho_h\left[r(s, b, \ell)\right] e^{-\tau_{\gamma\gamma}(E_\gamma, s, b, \ell)}$$

Photon attenuation
*(CMB and SL+IR from **GALPROPv54**)*

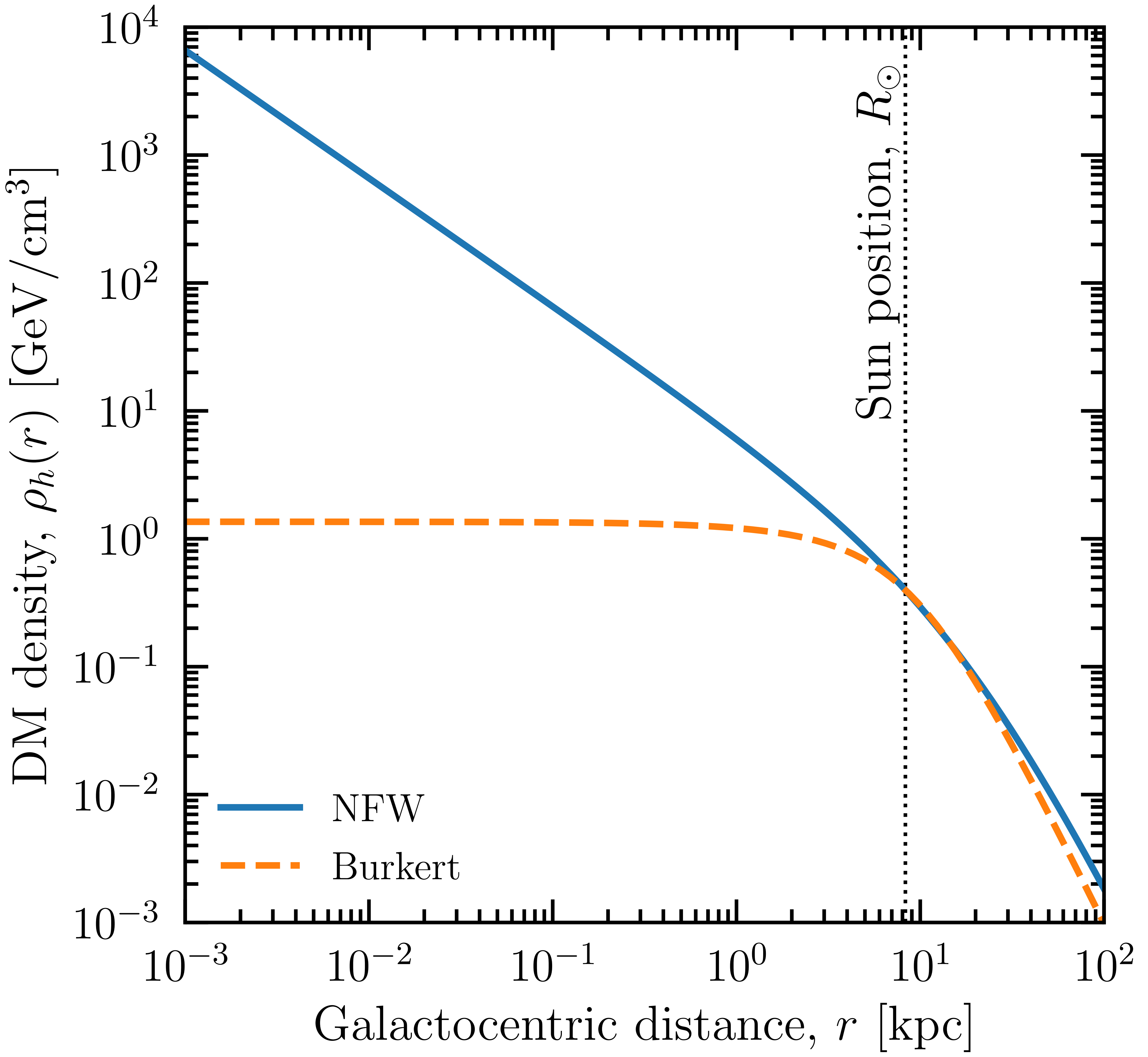
Different halo profiles

- Navarro-Frenk-White (NFW)
- Burkert

In our ROI, only small dependence on it

$$\int D\, \mathrm{d}\Omega \simeq 6.26\,(5.85) \times 10^{21}\ \mathrm{GeV/cm^2}$$

at 10^5 GeV for NFW (Burkert) profile



Inverse-Compton component

We solve the *stationary* diffusion-loss equation for e$^{+/-}$ injected by Galactic DM decays.

$$\frac{\mathrm{d}I_\gamma^{\mathrm{IC}}}{\mathrm{d}E_\gamma} = \frac{1}{2\pi E_\gamma m_{\mathrm{DM}} \tau_{\mathrm{DM}}} \int_0^\infty \mathrm{d}s\, \rho_h(r)\, e^{-\tau_{\gamma\gamma}(E_\gamma,\vec{x})} \int_{E_\gamma}^{\frac{m_{\mathrm{DM}}}{2}} \mathrm{d}E_e \frac{P_{\mathrm{IC}}(E_\gamma, E_e, \vec{x})}{b(E_e,\vec{x})} \int_{E_e}^{\frac{m_{\mathrm{DM}}}{2}} \mathrm{d}E'_e \frac{\mathrm{d}N_e}{\mathrm{d}E'_e}$$

Attenuation

IC radiated power

DM halo profile

Energy losses in the Galaxy

Electron energy spectrum per DM decay

Details

- The effect of spatial diffusion is subdominant *wrt* the energy losses
- Energy losses: IC and synchrotron processes $b(E_e,\vec{x}) = -\frac{\mathrm{d}E_e}{\mathrm{d}t} = b_{\mathrm{IC}} + b_{\mathrm{syn}}$
- We take the conventional galactic magnetic field

$$B(\vec{x}) B_0 \exp\left[-\frac{r - R_\odot}{r_B} - \frac{|z|}{z_B}\right]$$

$$B_0 = 4.78\ \mu\mathrm{G},\ r_B = 10\ \mathrm{kpc},\ z_B = 2\ \mathrm{kpc}$$

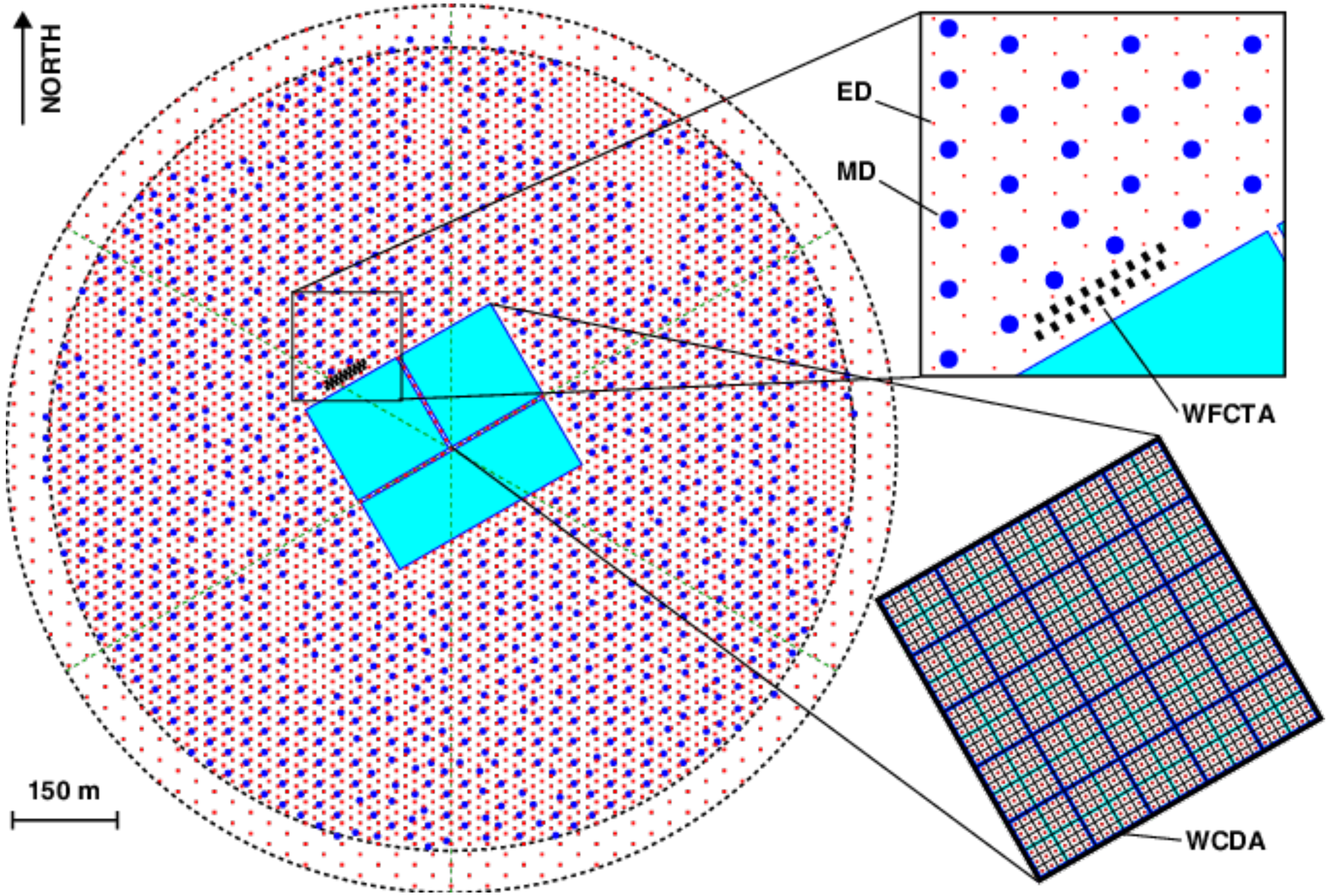
Strong, Moskalenko, Reimer, ***ApJ 541 (2000)***

References

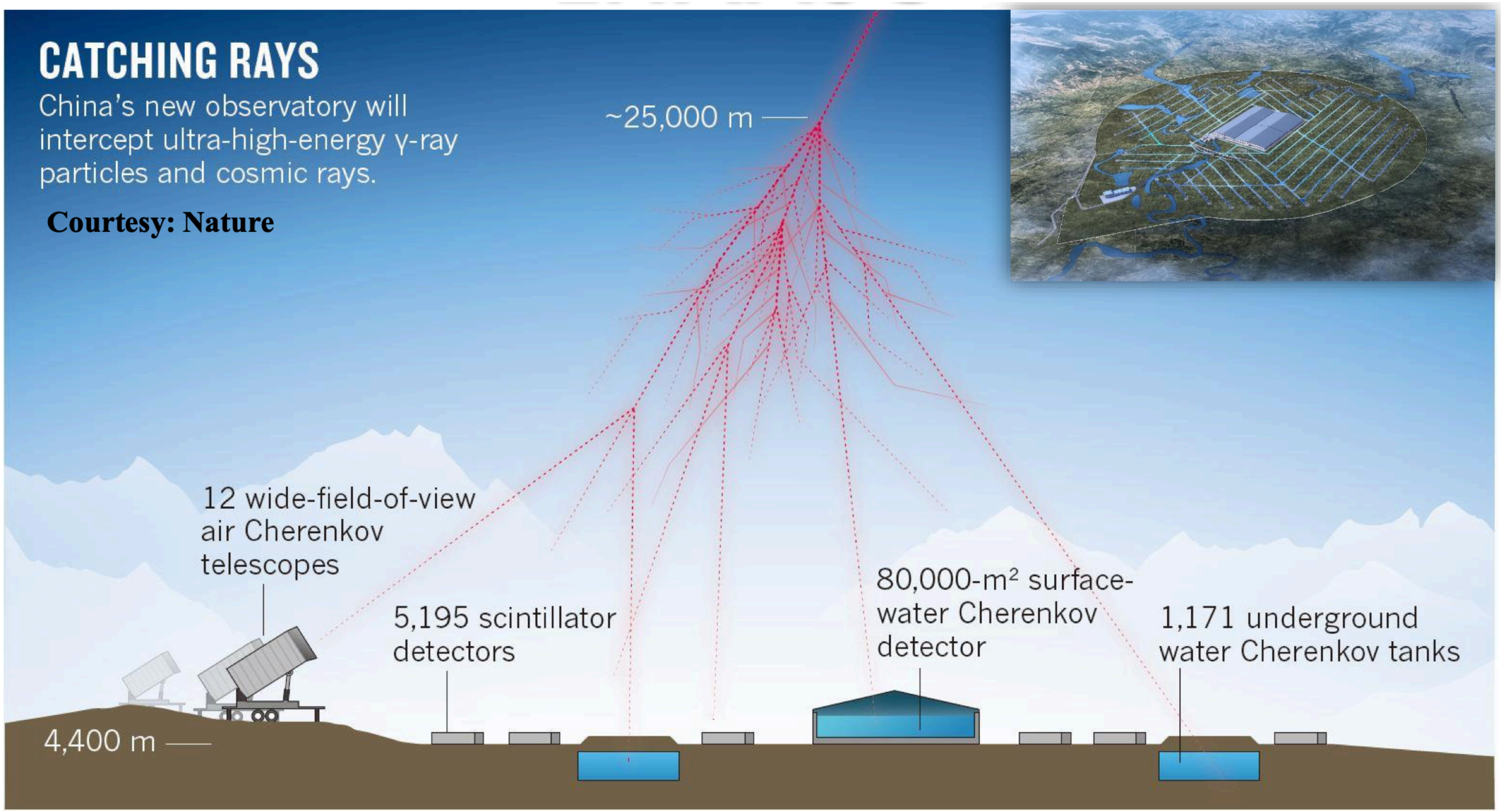
Cirelli et al., ***JCAP 03 (2011);***
Buch et al., ***JCAP 09 (2015);***
Esmaili, Serpico, ***JCAP 10 (2015);***
Chianese et al., ***JCAP 11 (2019)***

LHAASO observation

- Detectors
- kilometer square array (KM2A)
  - ED: electromagnetic detector
  - MD: muon detector
- Water Cherenkov detector array (WCDA)
- Wide field of view Cherenkov telescope array (WFCTA)
-



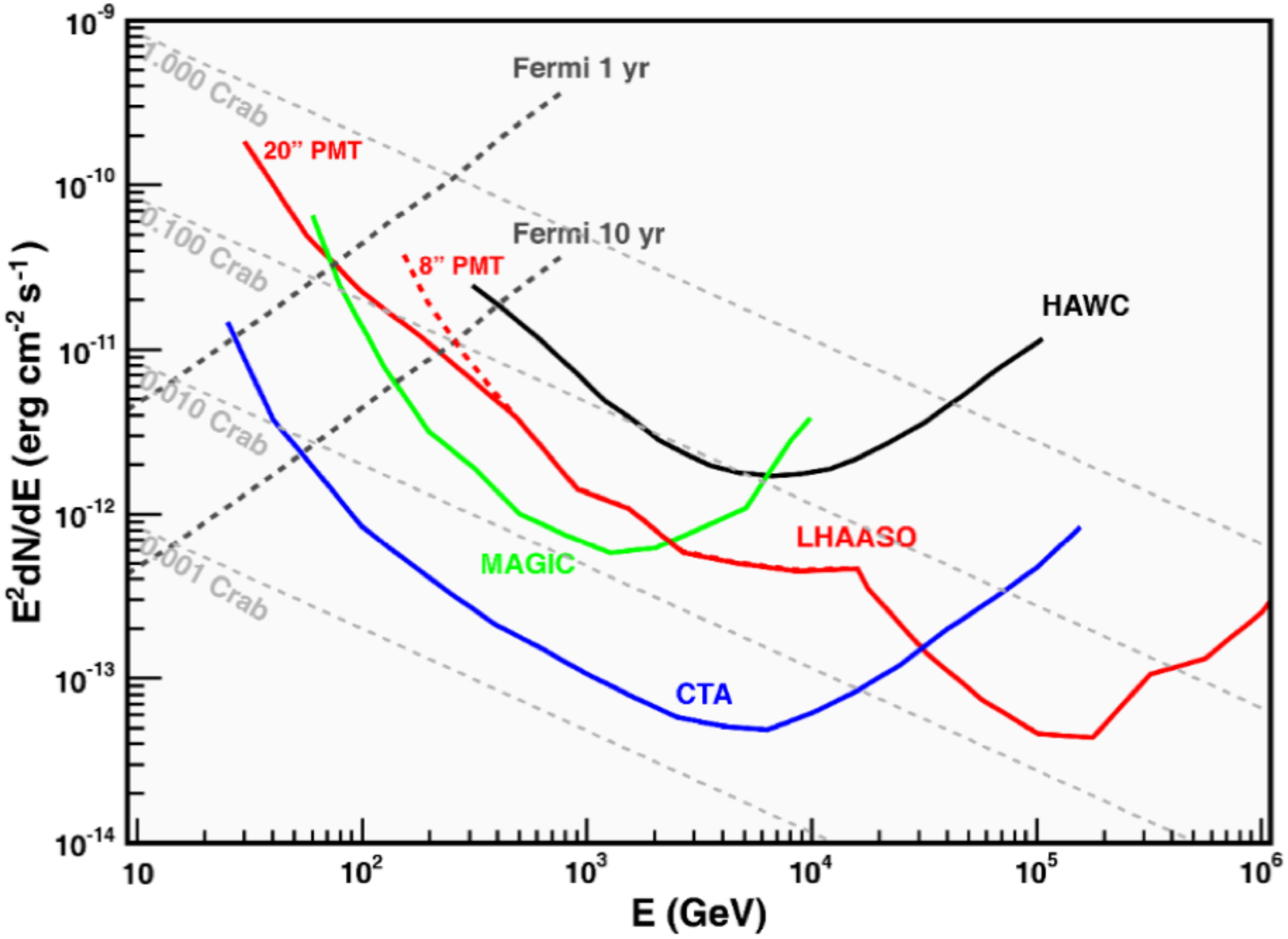
LHAASO observation



Prof. Zhang Yi
https://indico-tdli.sjtu.edu.cn/event/43/contributions/400/attachments/179/300/20191129LHAASOmultimsg.pdf

LHAASO observatory

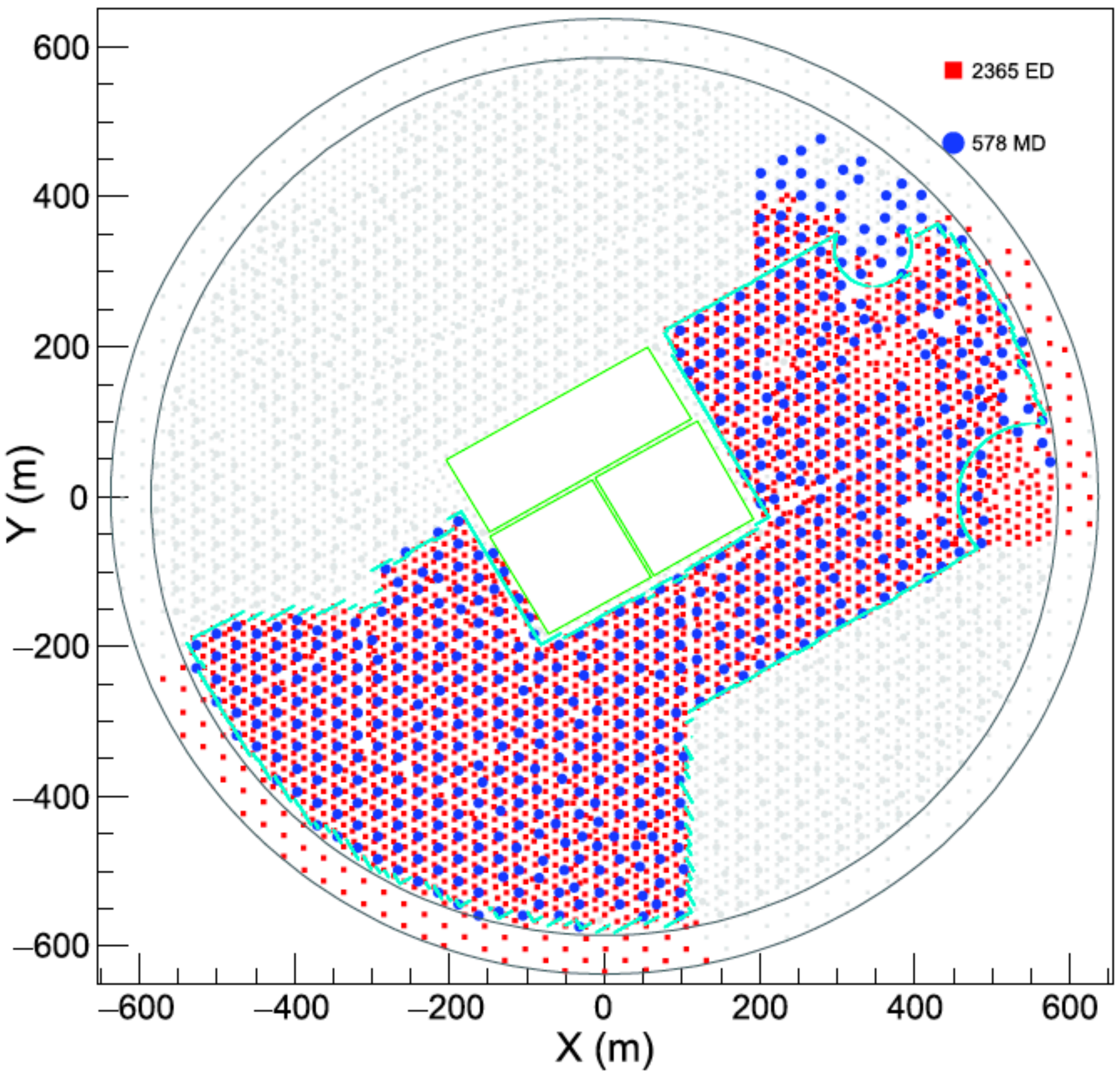
- All weather, large FOV survey observator
  - ~ 2sr, 60% sky per day
- VS CTA
  - night only.
  - Small FOV



- WCDA ~ 4 times size of HAWC
- KM2A: unparalleled sensitivity above 100TeV
-

This work: (1/2 + 3/4) KM2A only

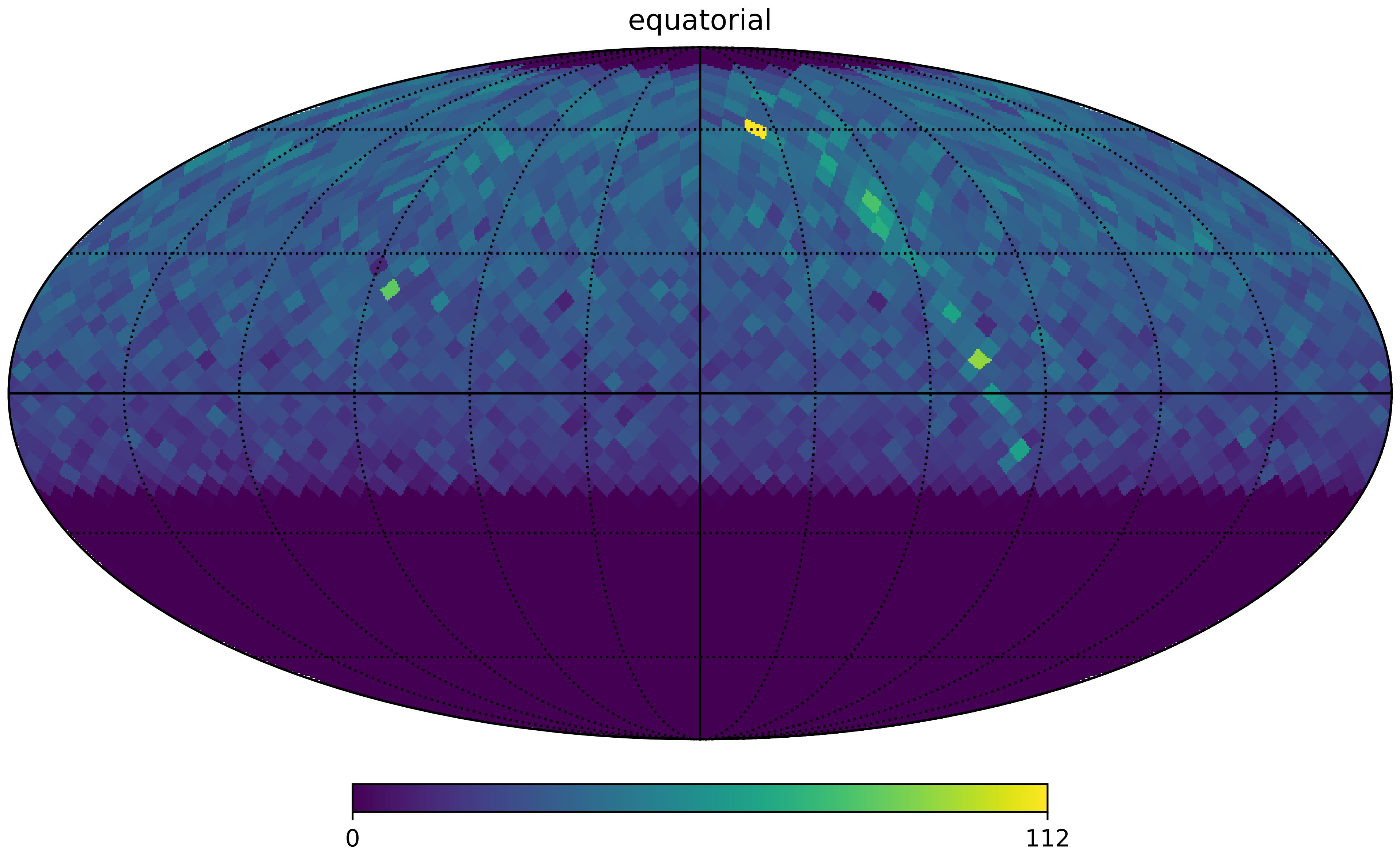
- 1/2 KM2A: 340 days
- 3/4 KM2A: 230 days
- Full array completed last year



LHAASO data

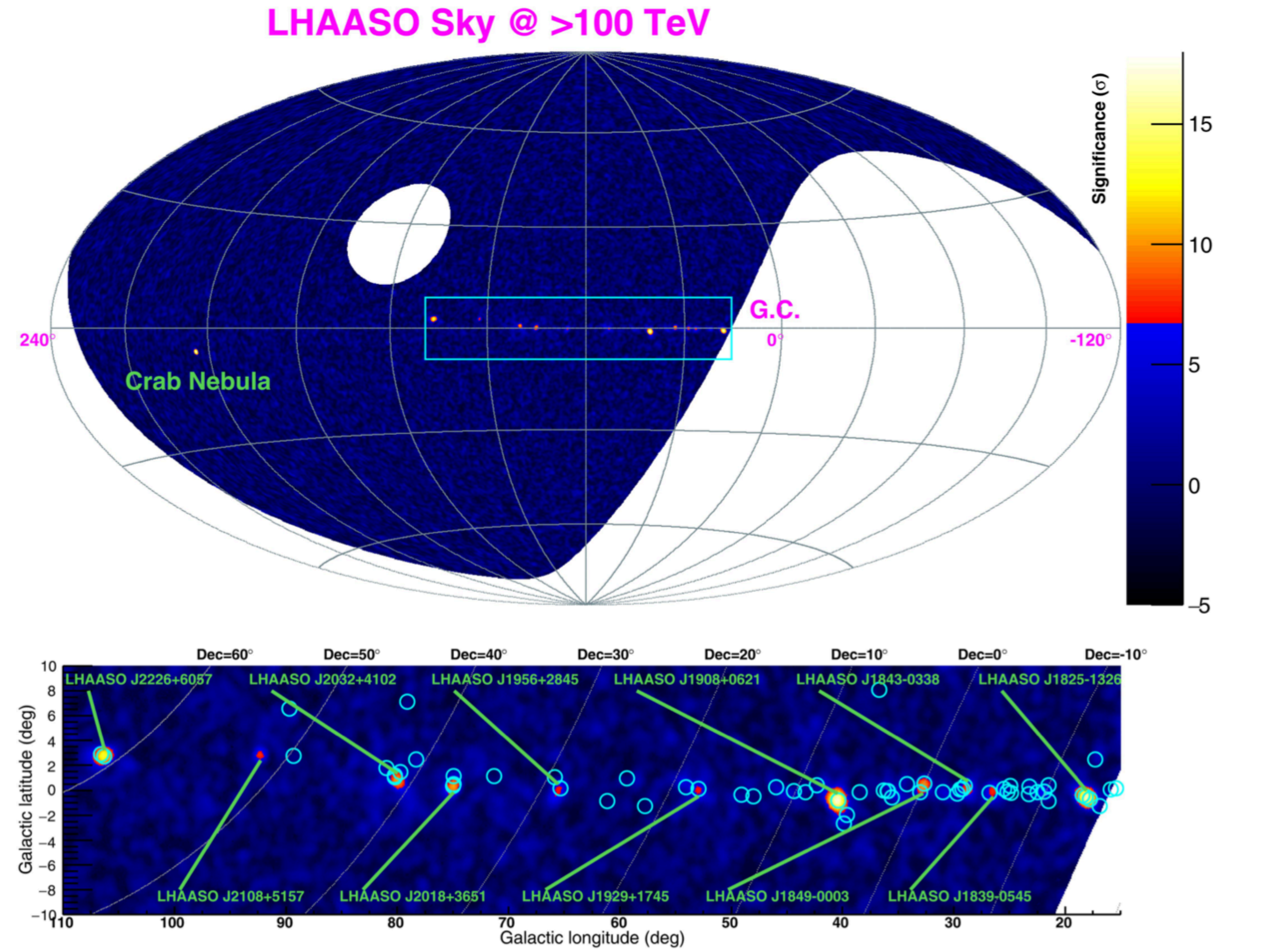
- LHAASO sky map

Equatorial coordinate



Galactic Coordinate

Article

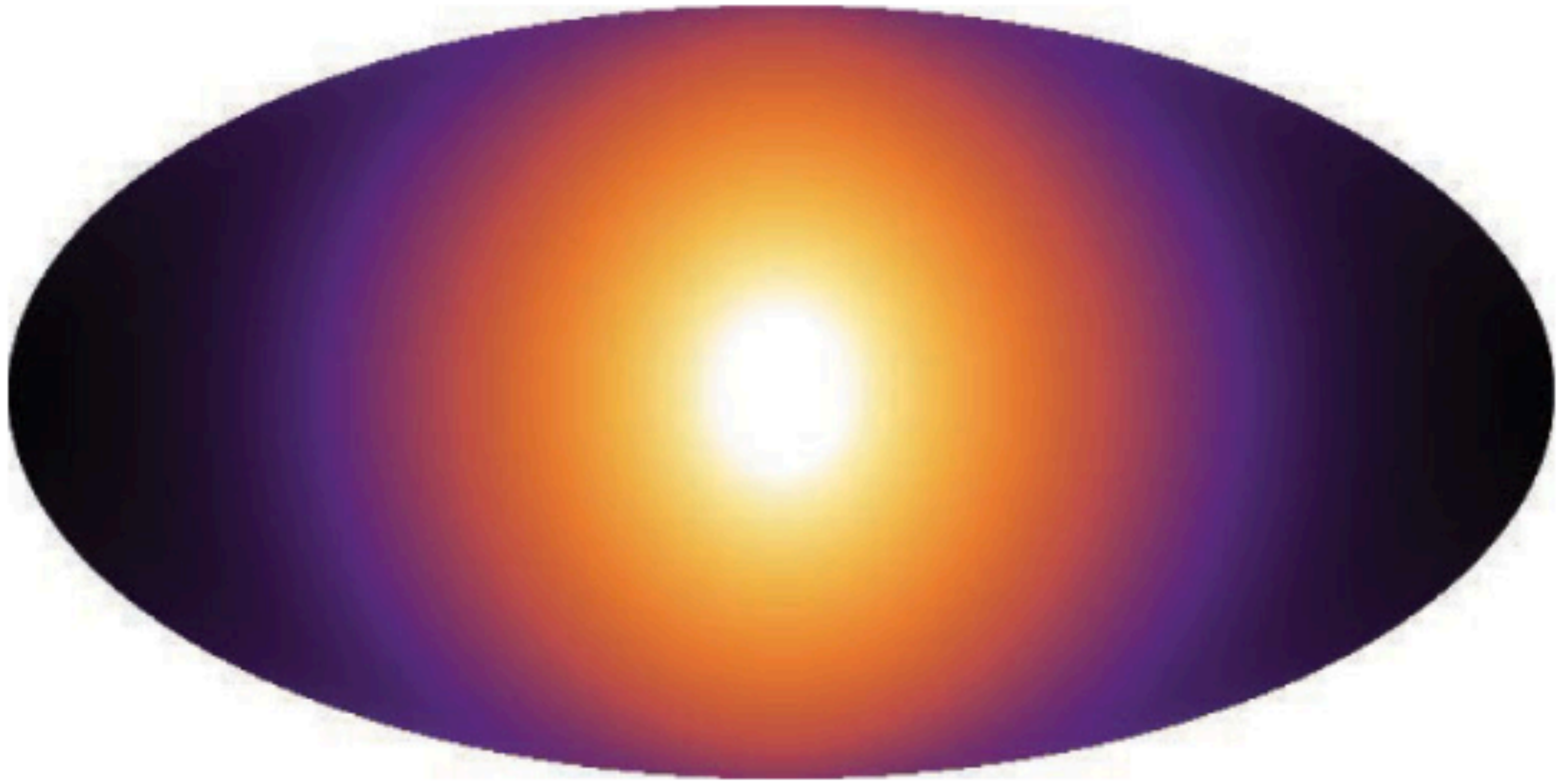


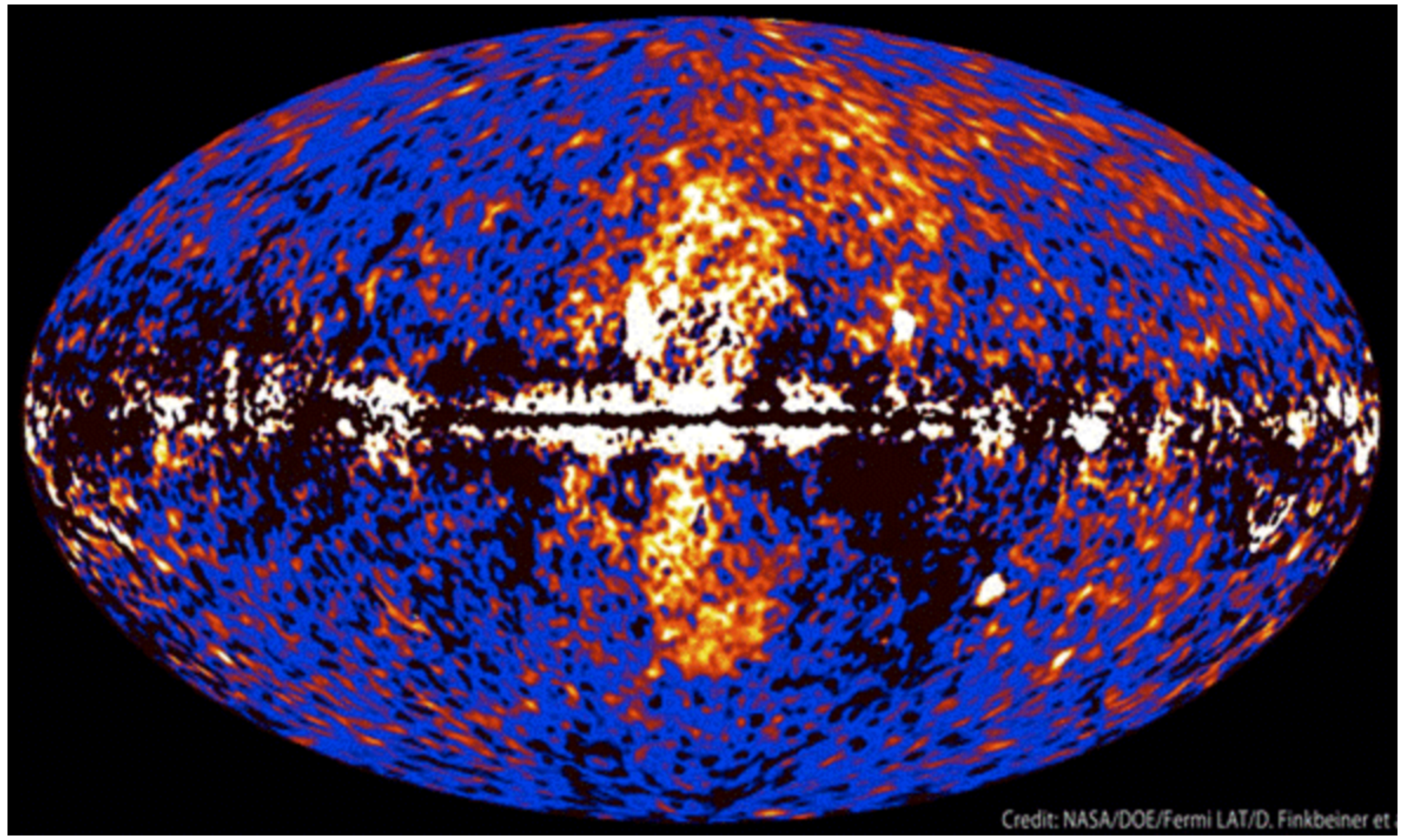
Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

Cao et al
Nature 2021

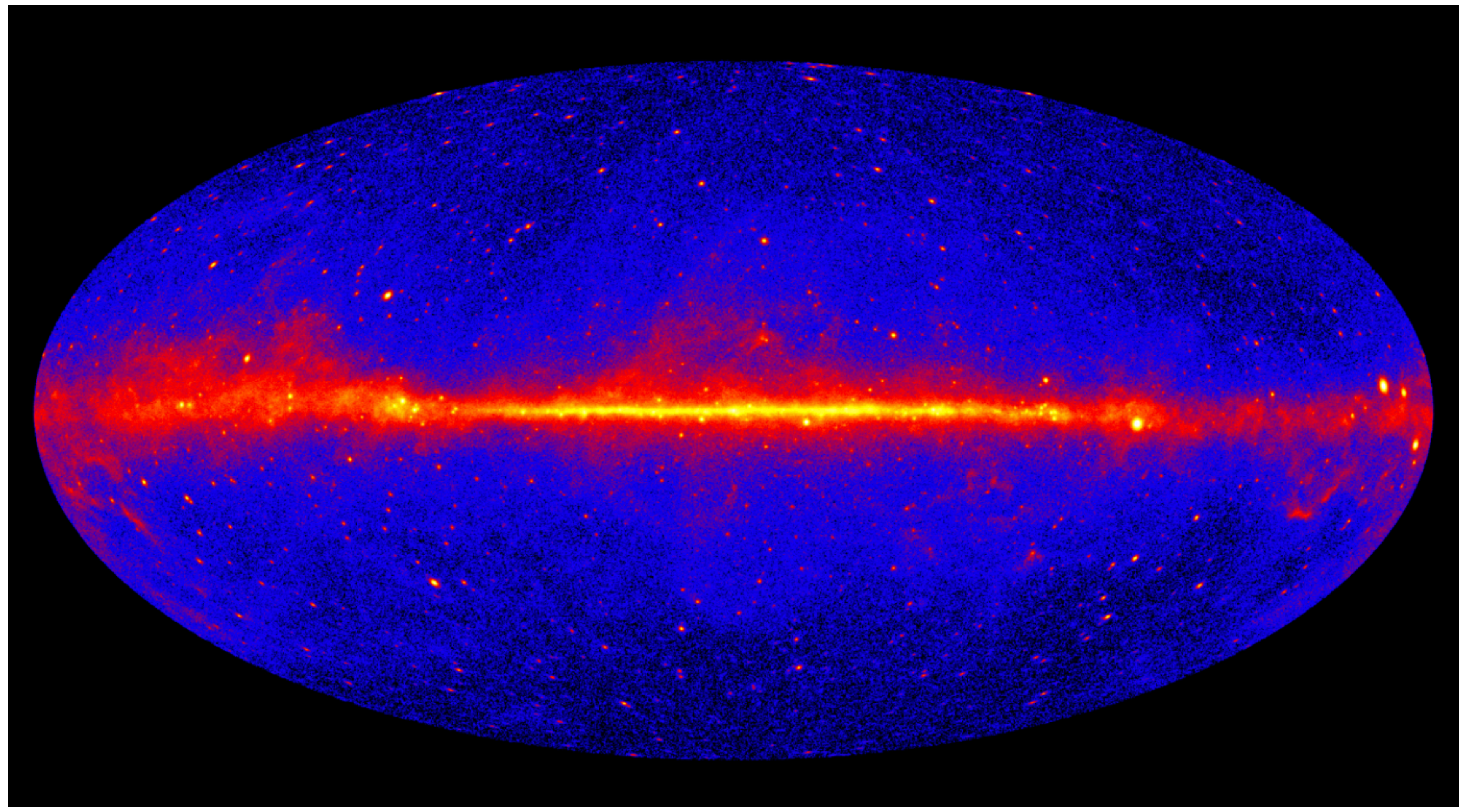
Dark Matter signal map

- Galactic coordinate dark matter signal map



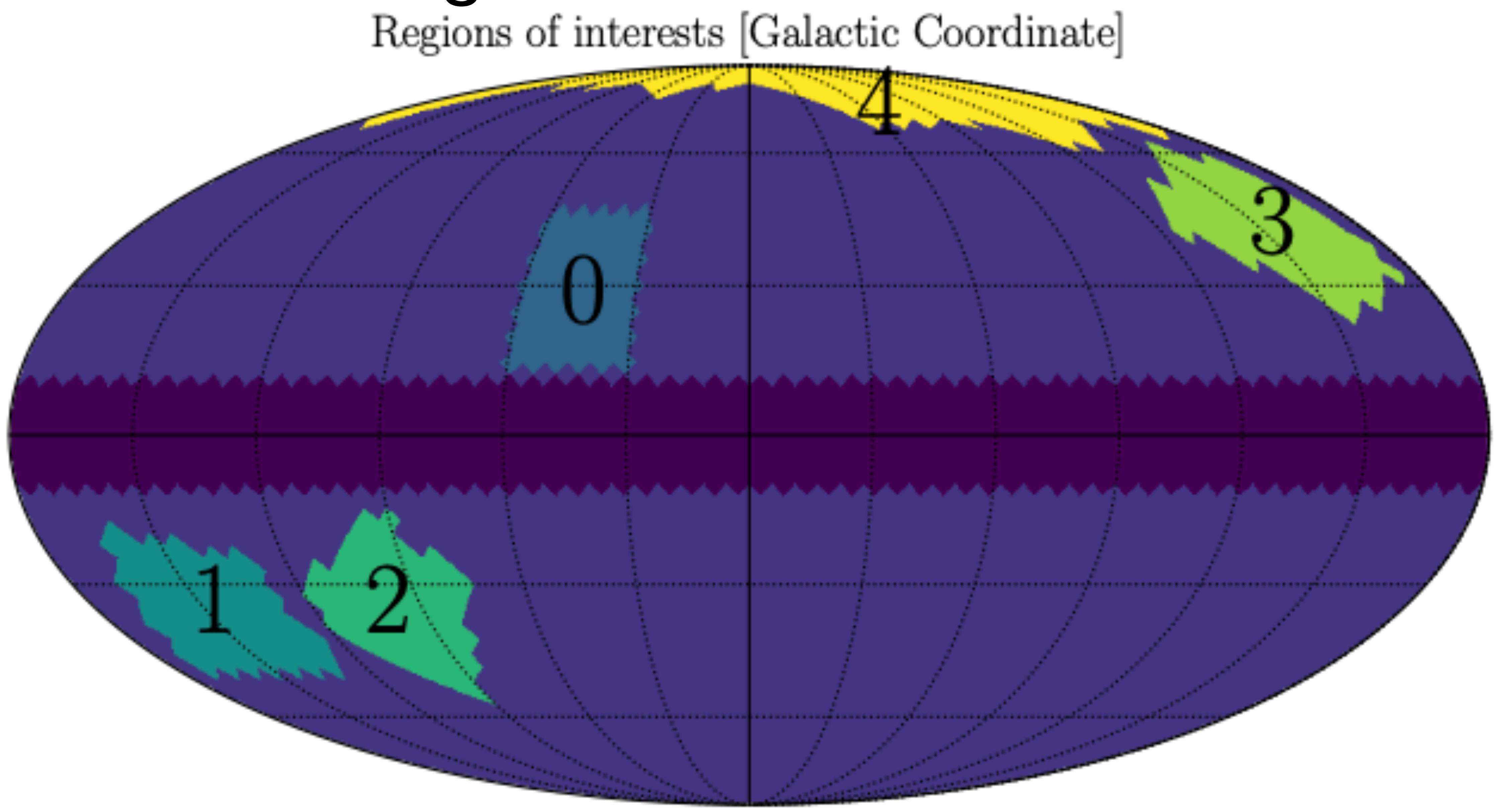


- Potential backgrounds from
  - galactic plane
  - Fermi bubble

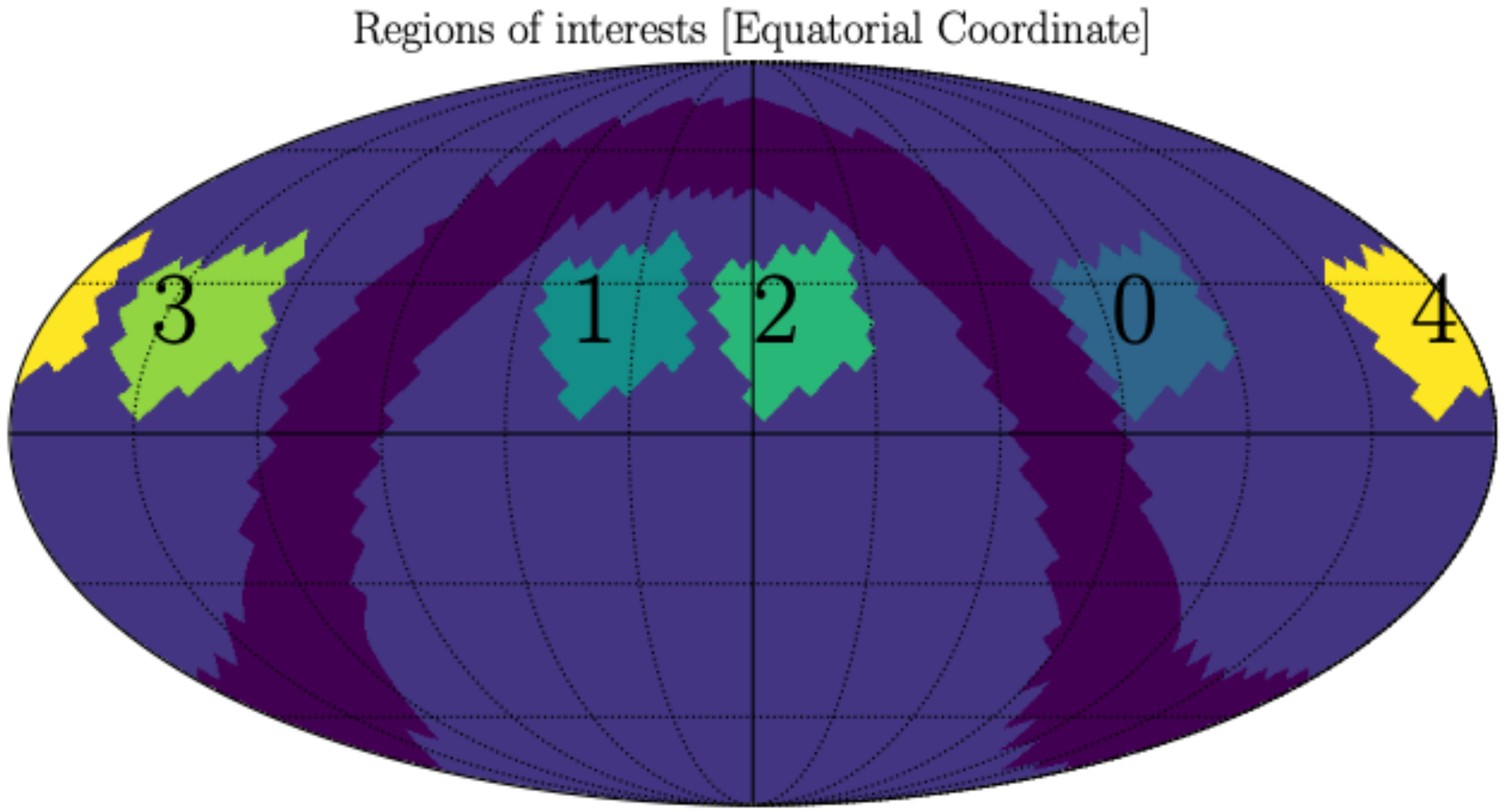


Dark Matter signal map

- 5 regions of interests
  - exclude Fermi bubble and the plane
- 0: closest to galactic center (signal)
- 1-4: away from galactic center
  - control regions

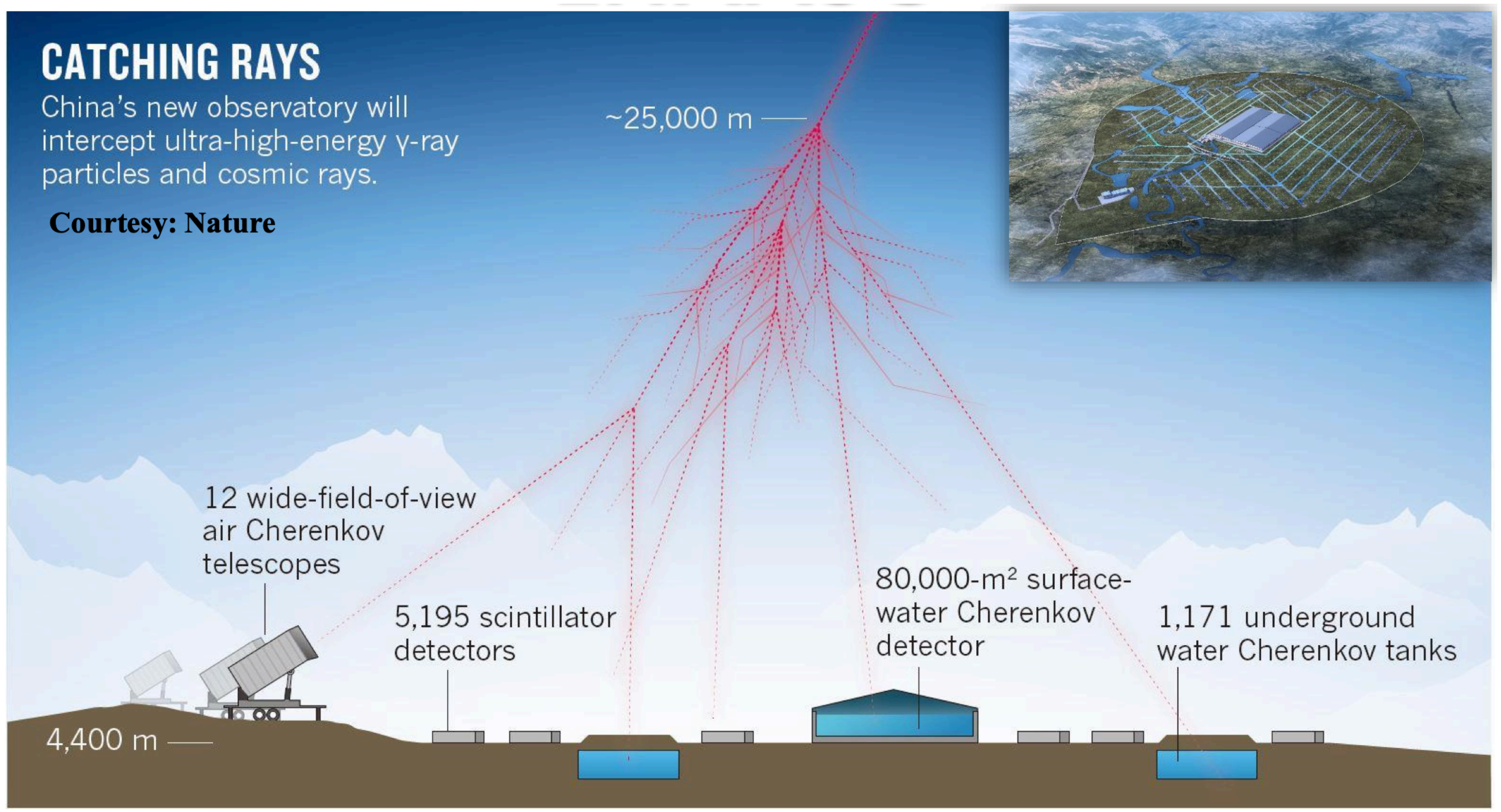


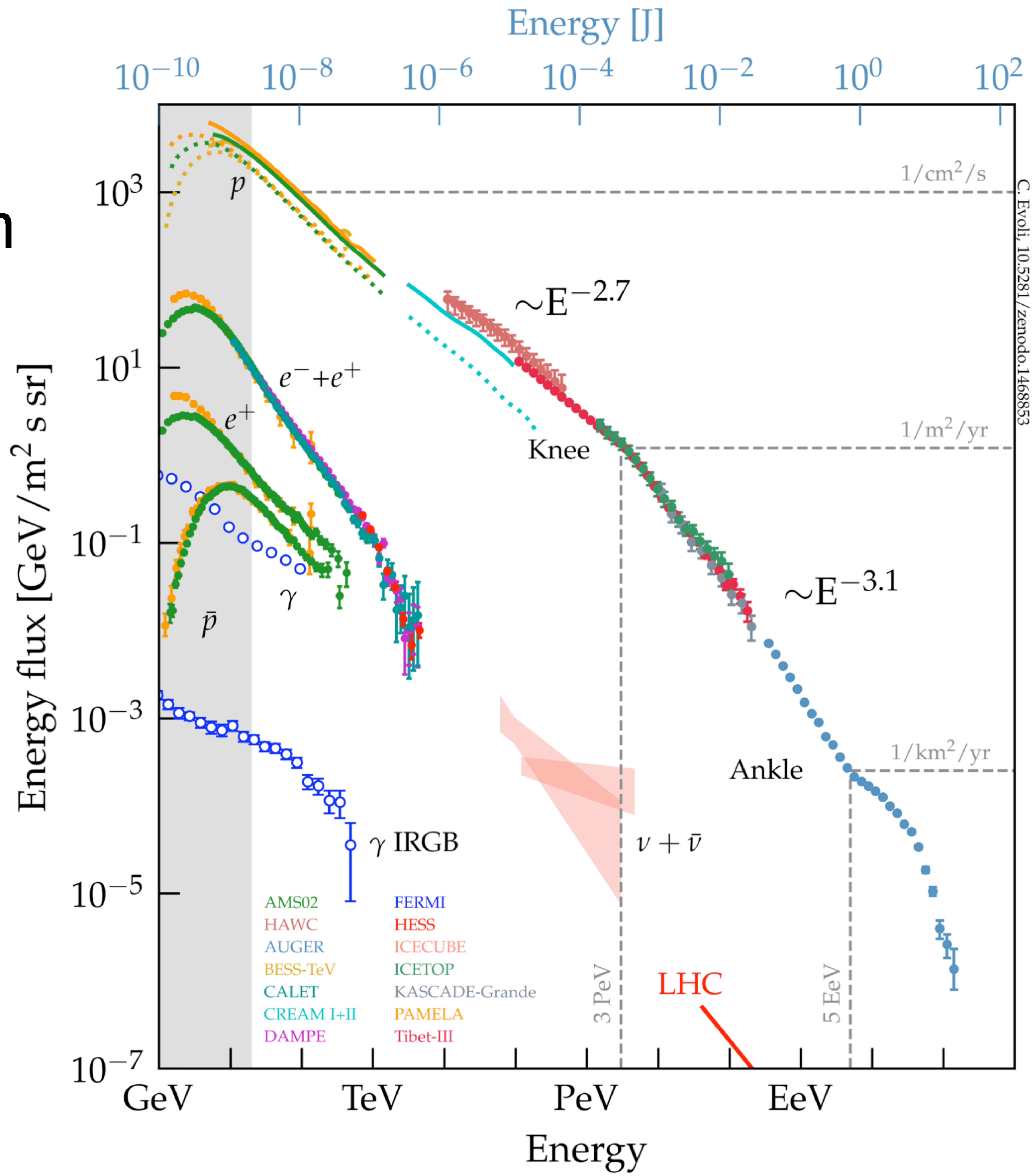
- Control regions:
  - same declination
  - same detector performance
  - for accurate background estimate
- Difference DM signal expectation



data reduction

- Most of the air showers are hadronic showers from protons etc
- Dominant background to remove

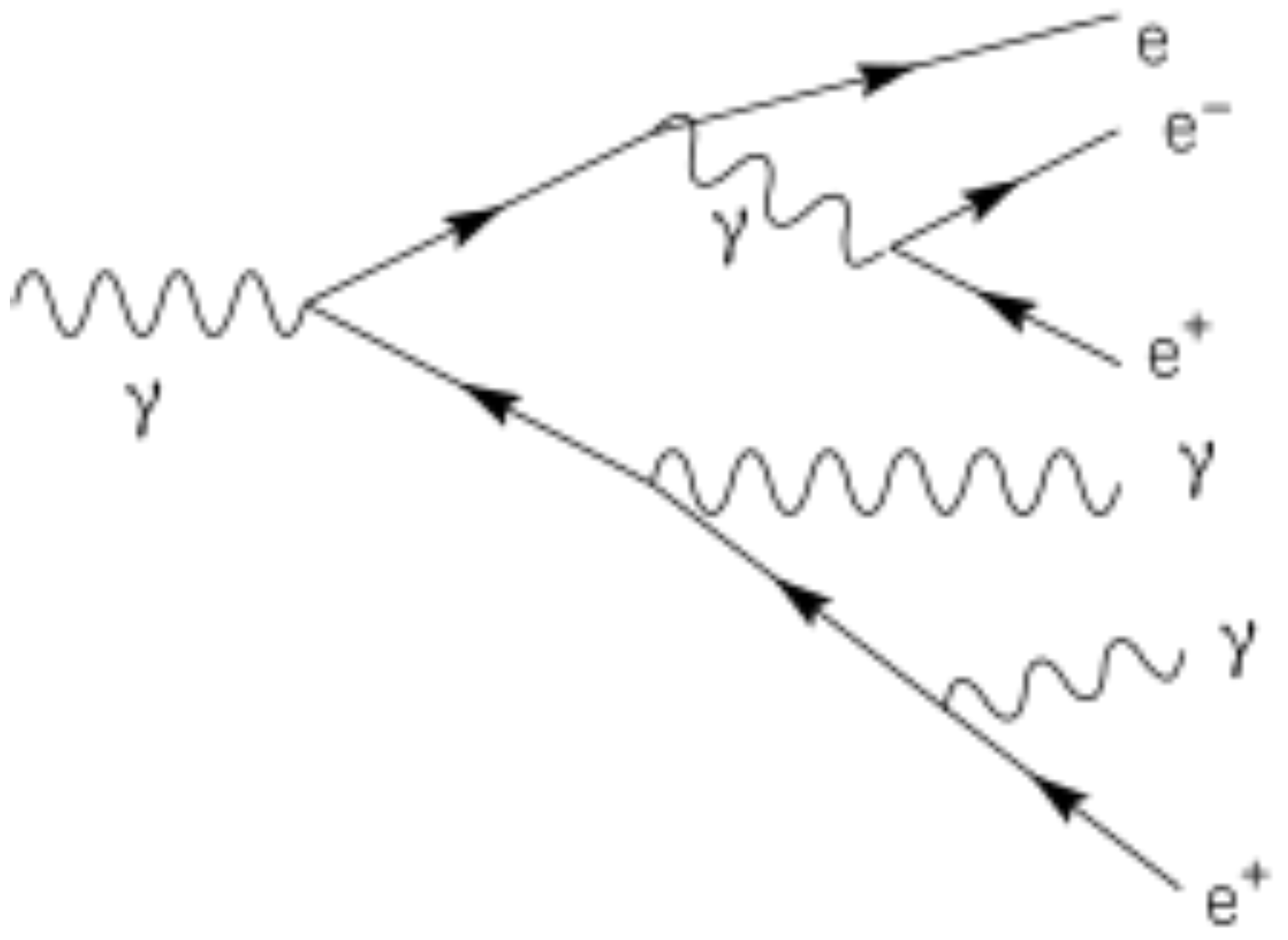


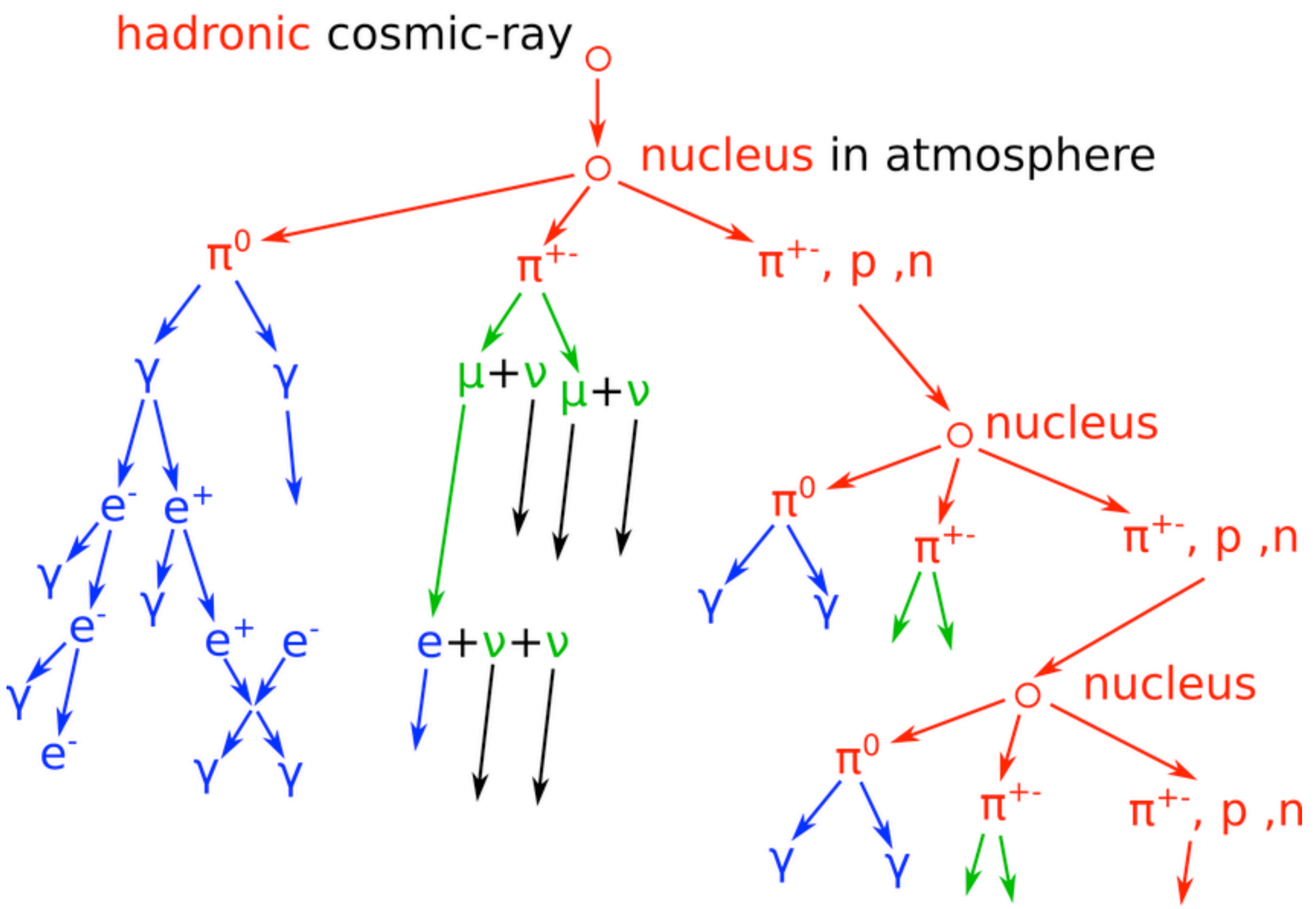


data reduction

- gamma rays: EM shower (muon poor)
- protons/nuclei: hadronic showers (muon rich)
- The ED and MD are efficient gamma/hadron seperators

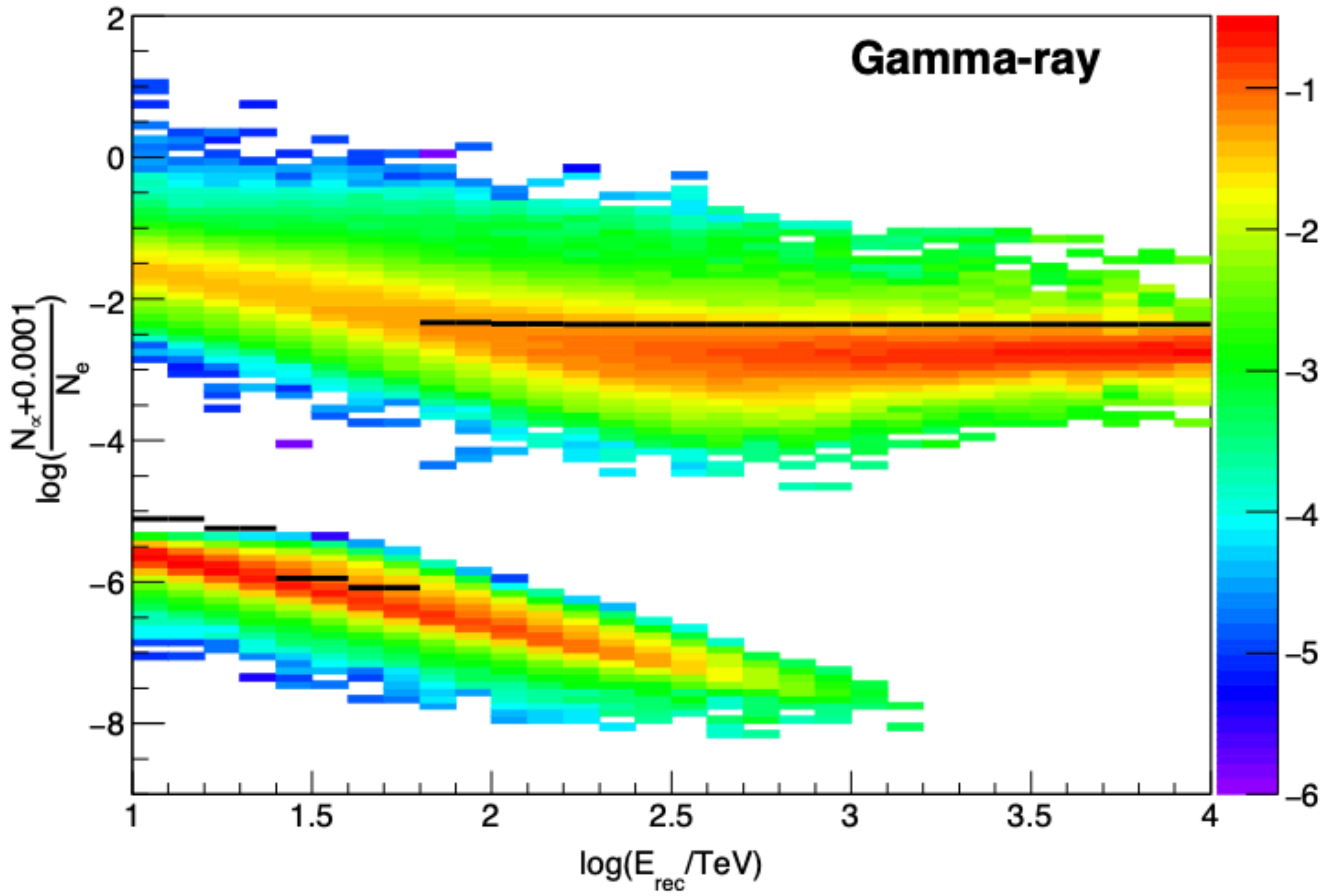
$$R = \log \frac{N_\mu + 0.0001}{N_e}$$

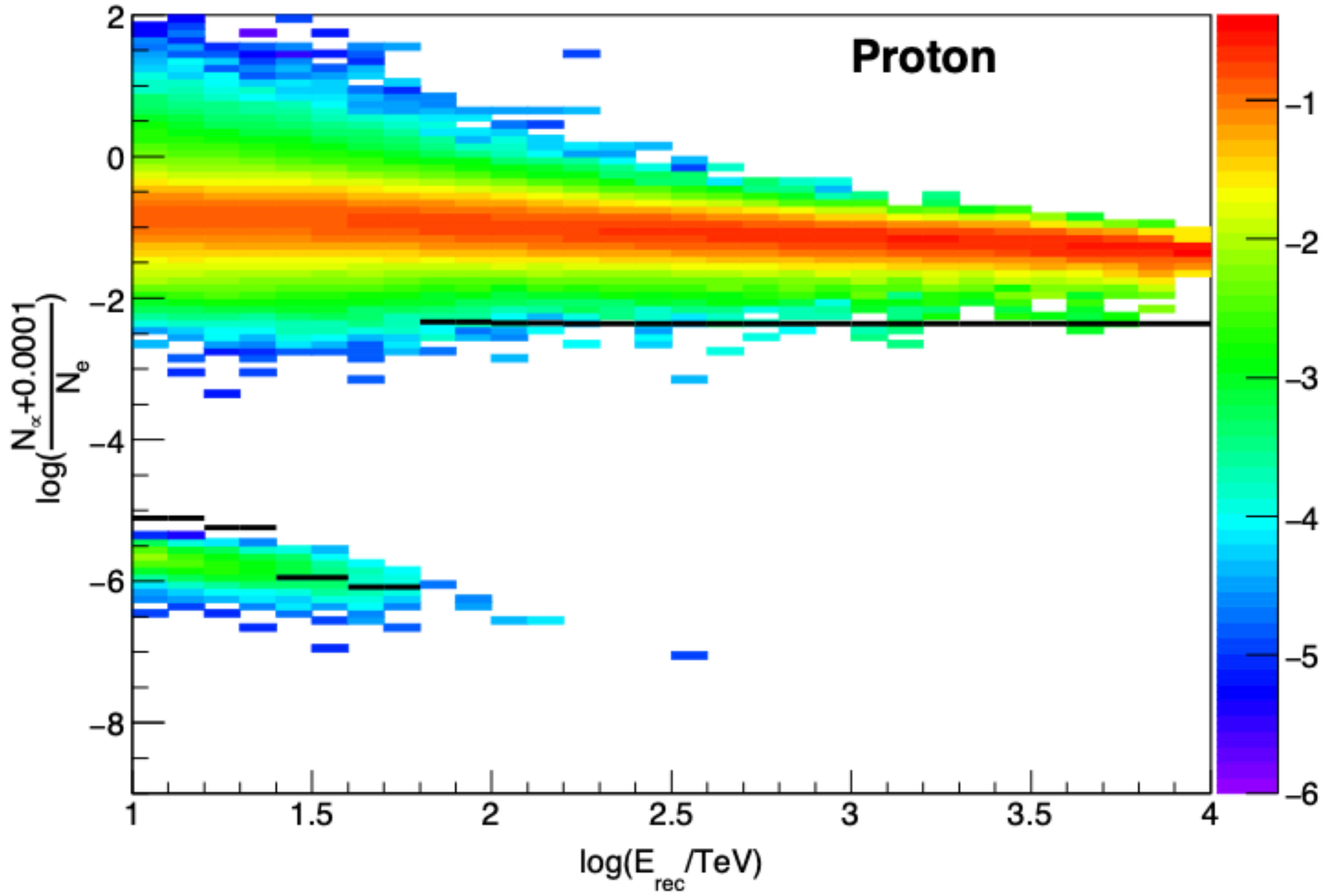


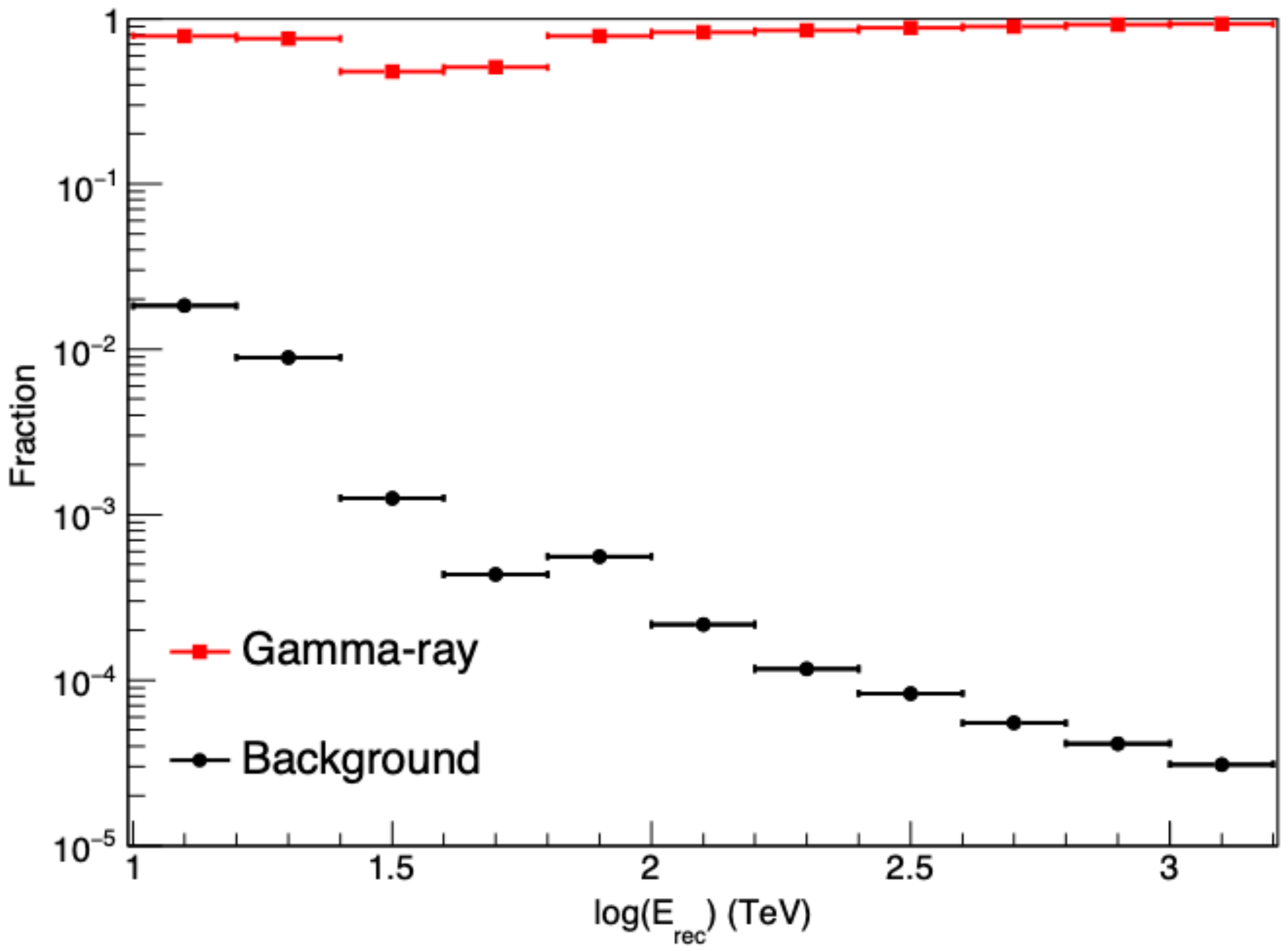


gamma/hadron seperation

- LHAASO performance study paper
- https://arxiv.org/pdf/2010.06205.pdf
- After the gamma-hadron cut
  - some proton survive
  - some gamma would be cut



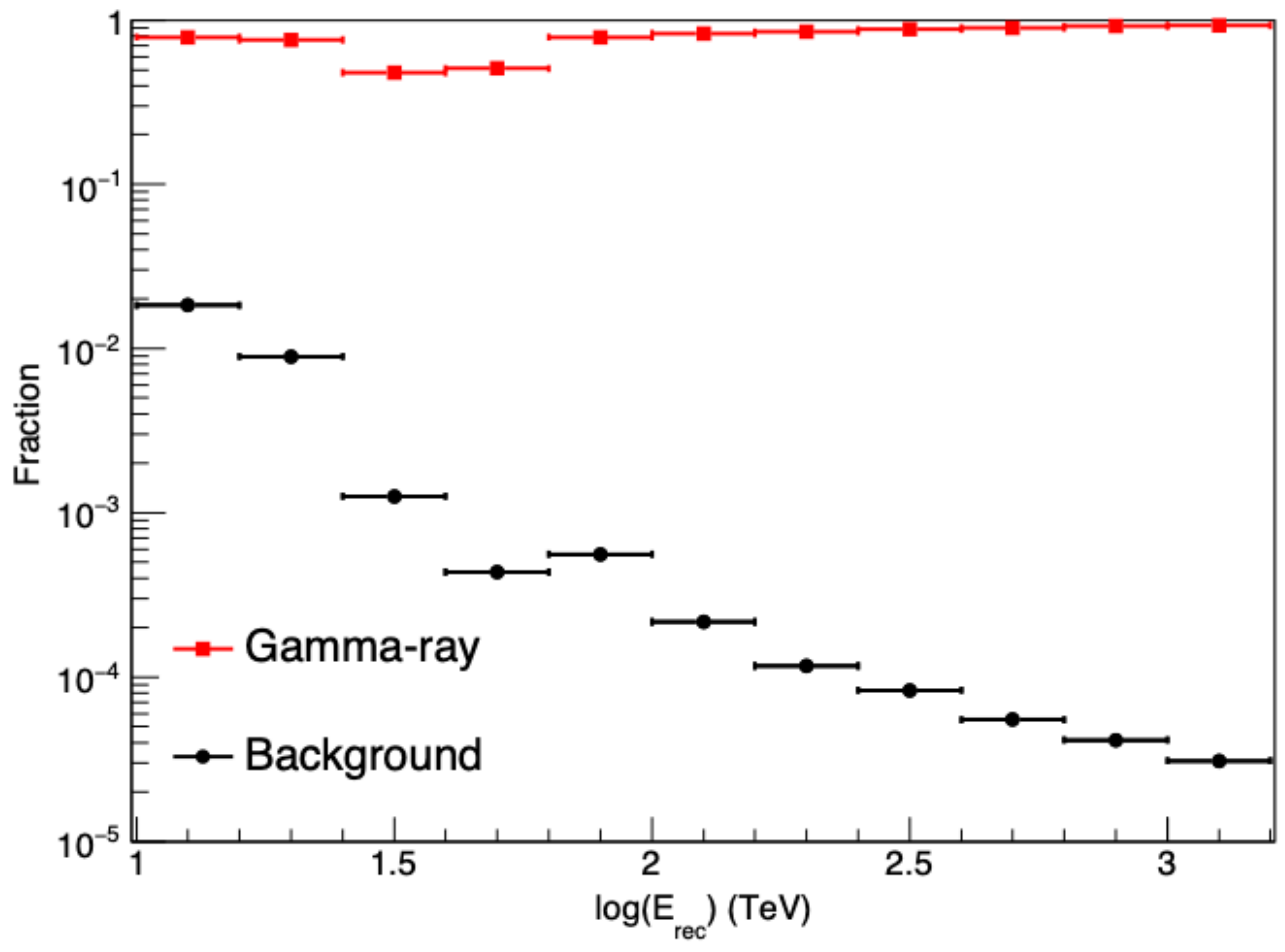




https://arxiv.org/pdf/2010.06205.pdf

gamma/hadron seperation

- For our work.
- We give away some gamma ray detection efficiency (ϵ_γ ~ 0.3) to further reduce the proton background



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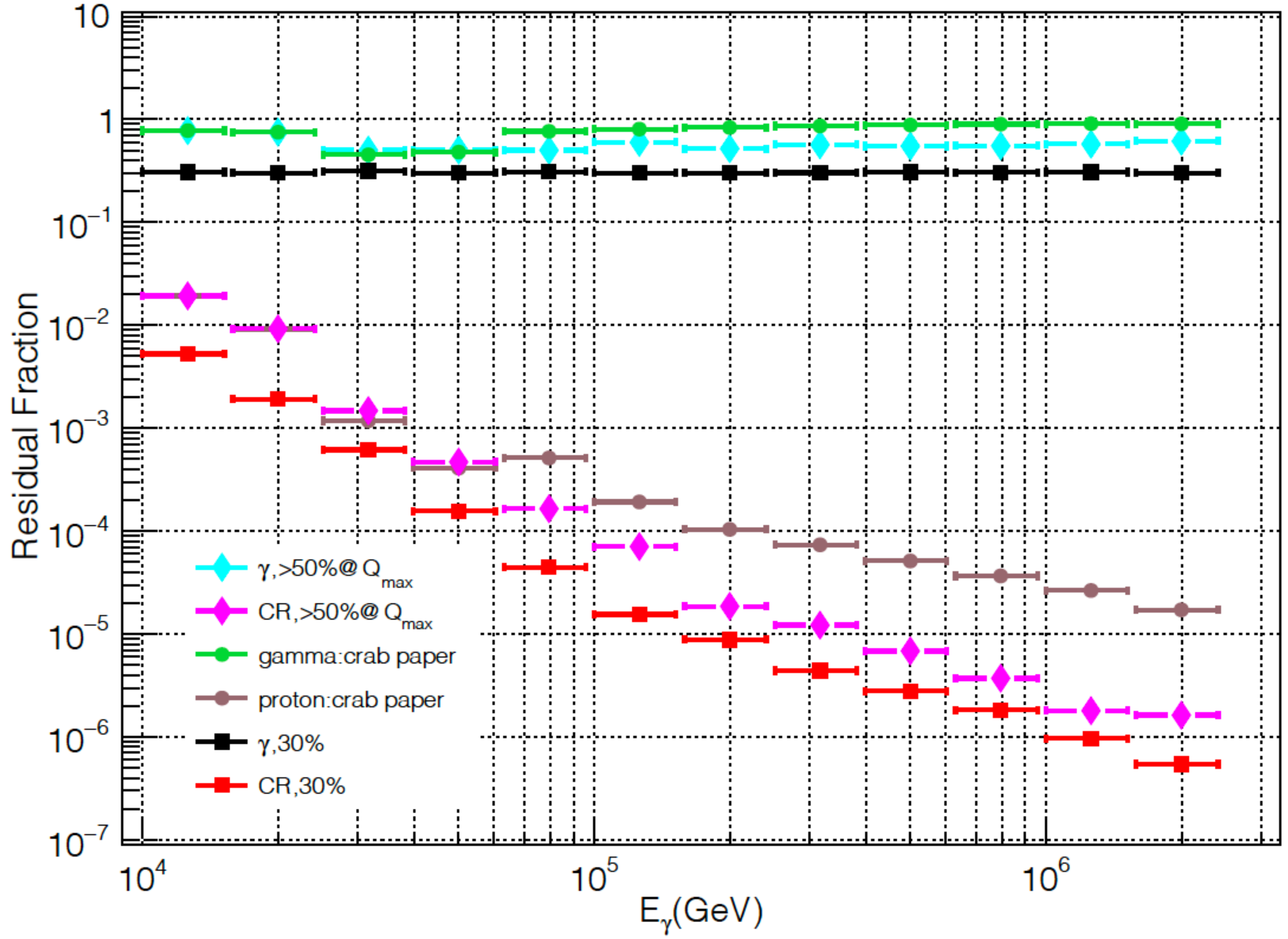

gamma/hadron seperation

- For our work.

- We give away some gamma ray detection efficiency (ϵ_γ ~ 0.3) to further reduce the proton background

- Events left after gamma/hadron separation

TABLE I. Residual events after γ/hadron separation in the search (ROI_0) and control ($ROI_1 - ROI_4$) regions with an observations of 340 days with 1/2-KM2A and 230 days with 3/4-KM2A.

Energy bin $[\log_{10}(E/\mathrm{GeV})]$	N_{ROI_0}	N_{ROI_1}	N_{ROI_2}	N_{ROI_3}	N_{ROI_4}
5.0–5.2	1209	1210	1112	1160	1157
5.2–5.4	150	147	148	150	153
5.4–5.6	51	58	51	41	43
5.6–5.8	15	13	14	6	9
5.8–6.0	7	7	2	1	7
6.0–6.2	1	0	3	1	2

Dark Matter signal search

- Hypothesis
- Total observed event for each ROI (k)
- = dark matter + background (b)

$$n_k^i(\tau_{\mathrm{DM}}, b) = (b^i + s_k^i(\tau_{\mathrm{DM}}))\mathcal{E}_k^i \Delta\Omega,$$

$$s_k^i(\tau_{\mathrm{DM}}) = \frac{1}{\Delta\Omega}\int d\Omega dE_\gamma \left(\frac{dI_\gamma^{\mathrm{prompt}}}{dE_\gamma} + \frac{dI_\gamma^{\mathrm{IC}}}{dE_\gamma}\right)$$

- $\mathcal{E}_k^i$: detector exposure, by tracking the ROI across the sky, compared with MC

TABLE I. Residual events after γ/hadron separation in the search (ROI_0) and control ($\mathrm{ROI}_1 - \mathrm{ROI}_4$) regions with an observations of 340 days with 1/2-KM2A and 230 days with 3/4-KM2A.

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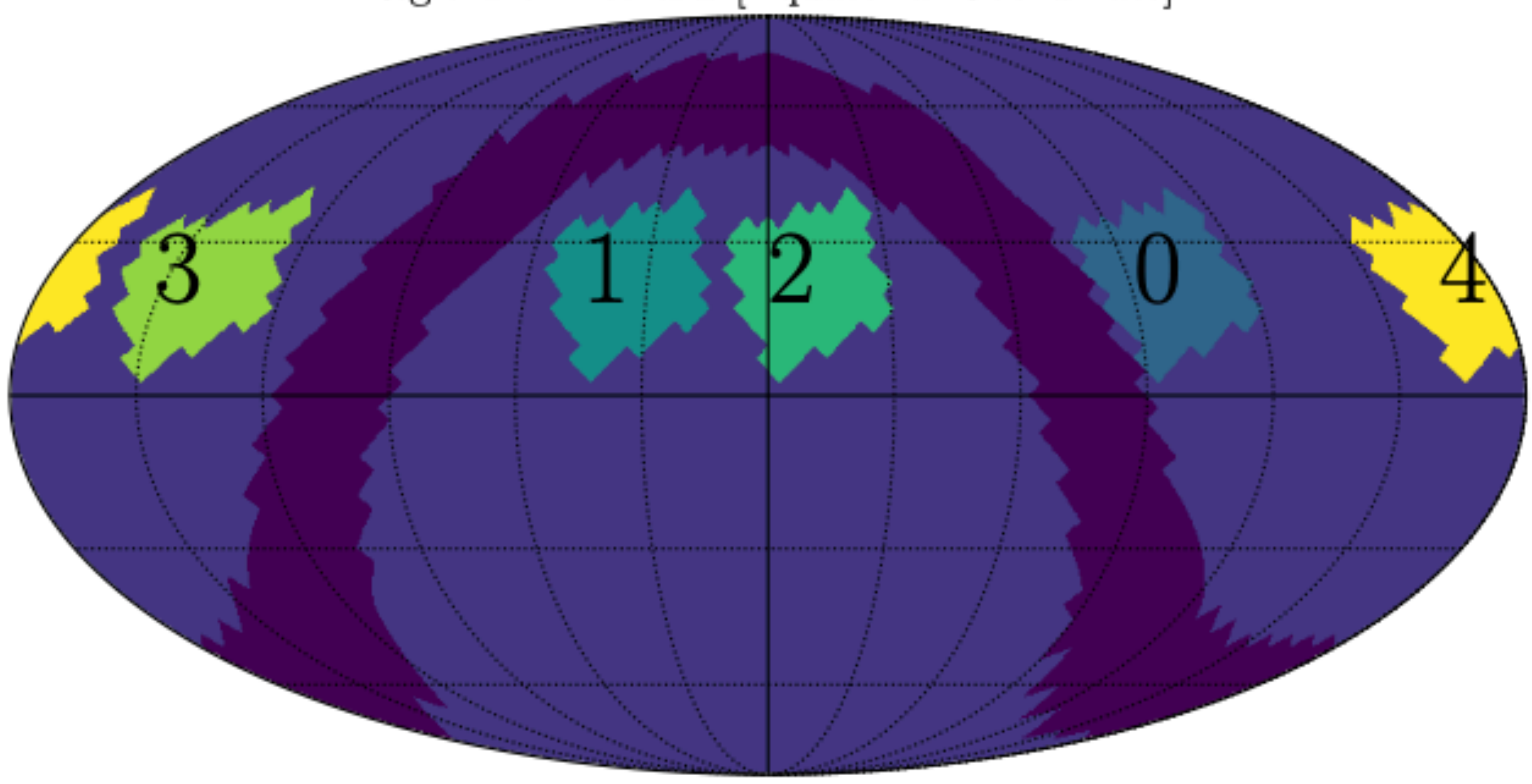
5.6–5.8	15	13	14	6	9
5.8–6.0	7	7	2	1	7
6.0–6.2	1	0	3	1	2

Dark Matter signal search

- Important features of this analysis

$$n_k^i(\tau_{\rm DM}, b) = (b^i + s_k^i(\tau_{\rm DM}))\mathcal{E}_k^i \Delta\Omega,$$



- The background model b^i, is independent of ROI
- Signal s_k^i , is different for each ROI, due to difference in D-factor
- We assume that we don't know b^i
  - allow it to be a free parameter (6 degrees of freedom)

$\log_{10}(E_\gamma/\mathrm{GeV})$	D-factor $[10^{22}\ \mathrm{GeV/cm^2}]$					$N_{\rm DM}(\mathrm{ROI}_0)$
	ROI_0	ROI_1	ROI_2	ROI_3	ROI_4	$\mathrm{DM} \to b\bar{b},\ \tau_{\rm DM} = 6.3 \times 10^{28}\,\mathrm{s}$
5.0 – 5.2	2.68	1.18	1.55	1.20	1.60	83.6
5.2 – 5.4	2.59	1.13	1.49	1.15	1.54	41.9
5.4 – 5.6	2.22	0.96	1.26	0.97	1.31	20.8
5.6 – 5.8	1.66	0.73	0.95	0.74	0.98	6.6
5.8 – 6.0	1.24	0.57	0.73	0.58	0.76	1.7
6.0 – 6.2	1.02	0.49	0.62	0.50	0.64	0.4

Likelihood analysis

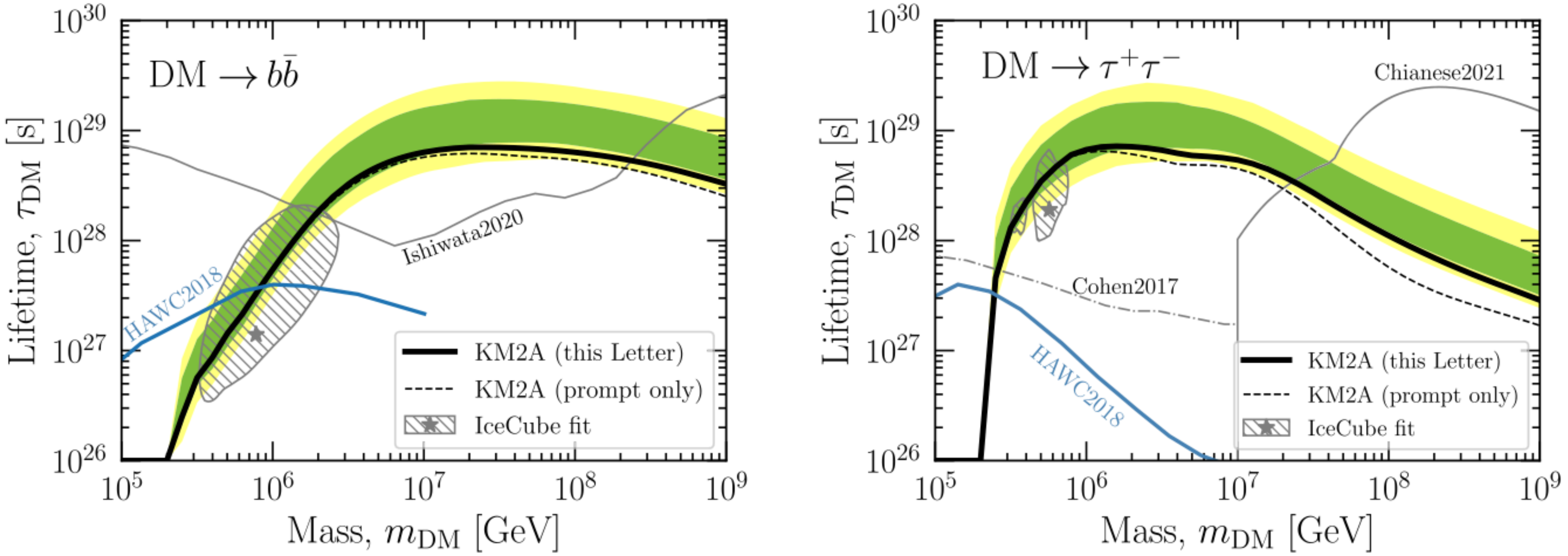
- For each ROI
- $$\ln L_k(\tau_{DM}, b) = \sum_i N_k^i \ln n_k^i - n_k^i$$
- Combined likelihood
- $$\ln L = \sum_{k=0}^{4} \ln L_k$$
- If positive detection
  - likelihood maximised at some decay lifetime (τ_{DM}) for some decay channel
  - Background model is always fitted to maximise the likelihood
    - treated as a nuisance parameter

Results

- We do not see significant level of detection
- (most significant fit is 1.4σ at 8PeV dark matter mass, for tau channel)
- Find the lower limit of decay lifetime
- $-2 \ln \frac{L(\tau_{95})}{\max(L)} = 2.71$

Results

- Lifetime limit plot vs DM mass
- Our results: black solid line
- green (68%) and yellow (95%) band obtained from monte carlo simulation for expected limit



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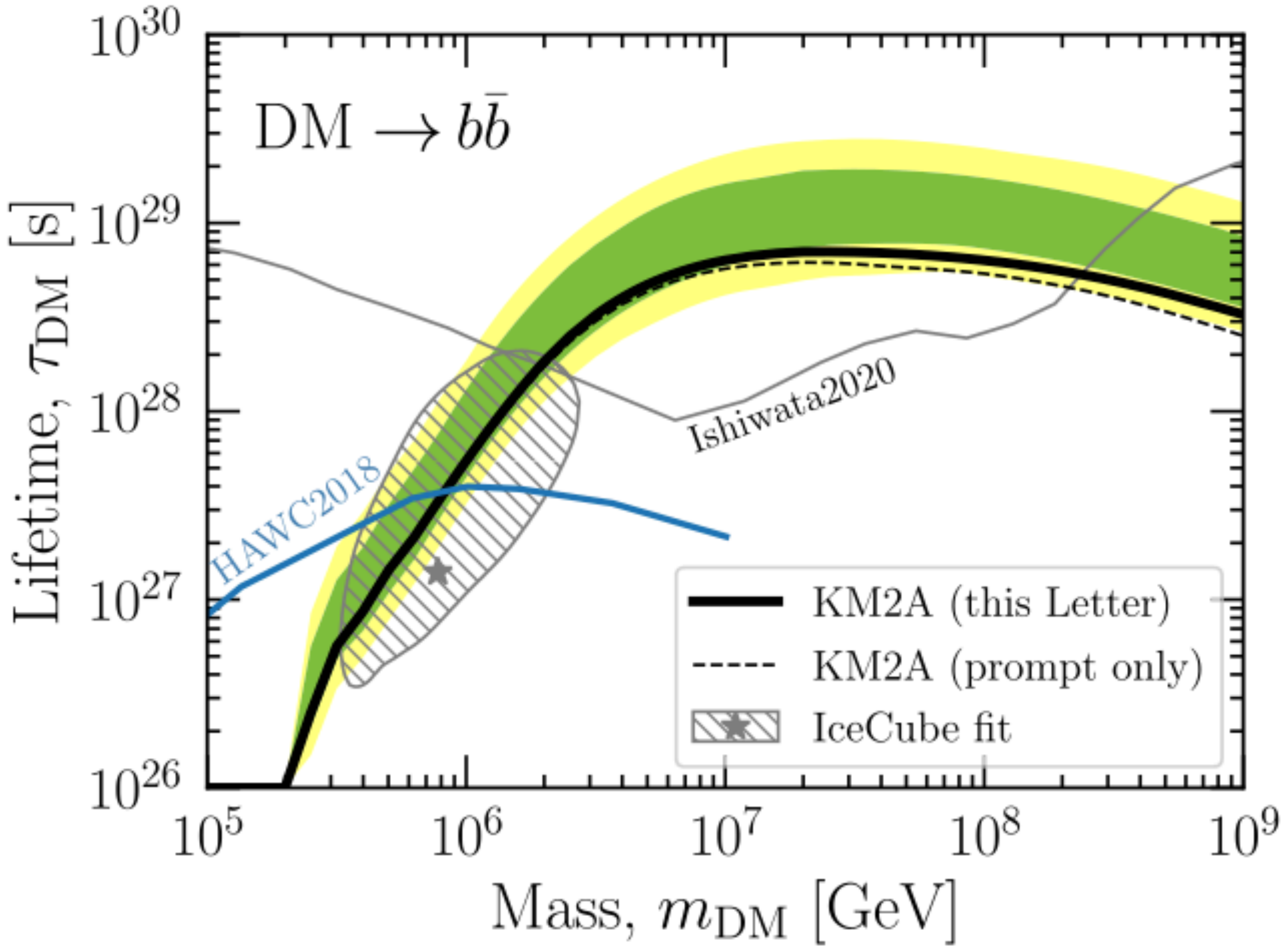
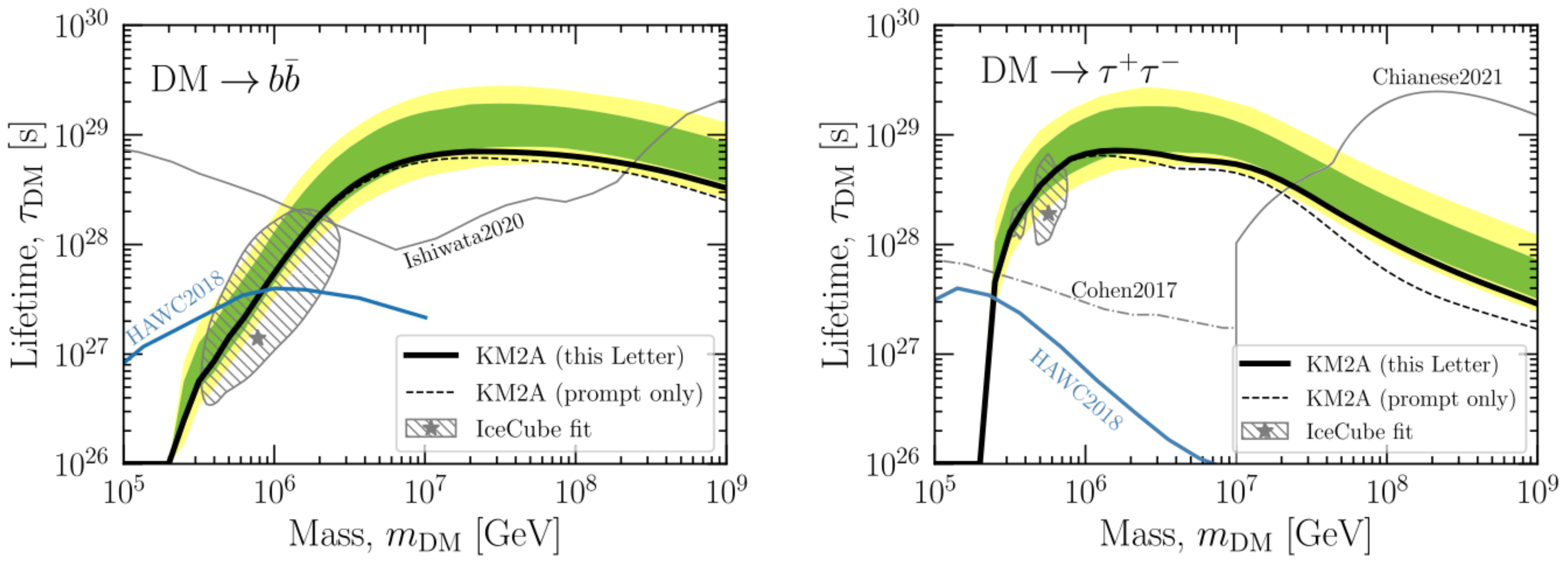


- MC assumes the common background model for all 5 ROIs
  - agreement verifies the background model hypothesis

- Actually limit is touching the 95% band.
  - -> 1.4 sigma ‘excess’

Results

- Strongest DM lifetime constraint at PeV to 10 PeV
- Stronger than HAWC
  - expected. will further improve at low energy with WCDA
- Ishiwata



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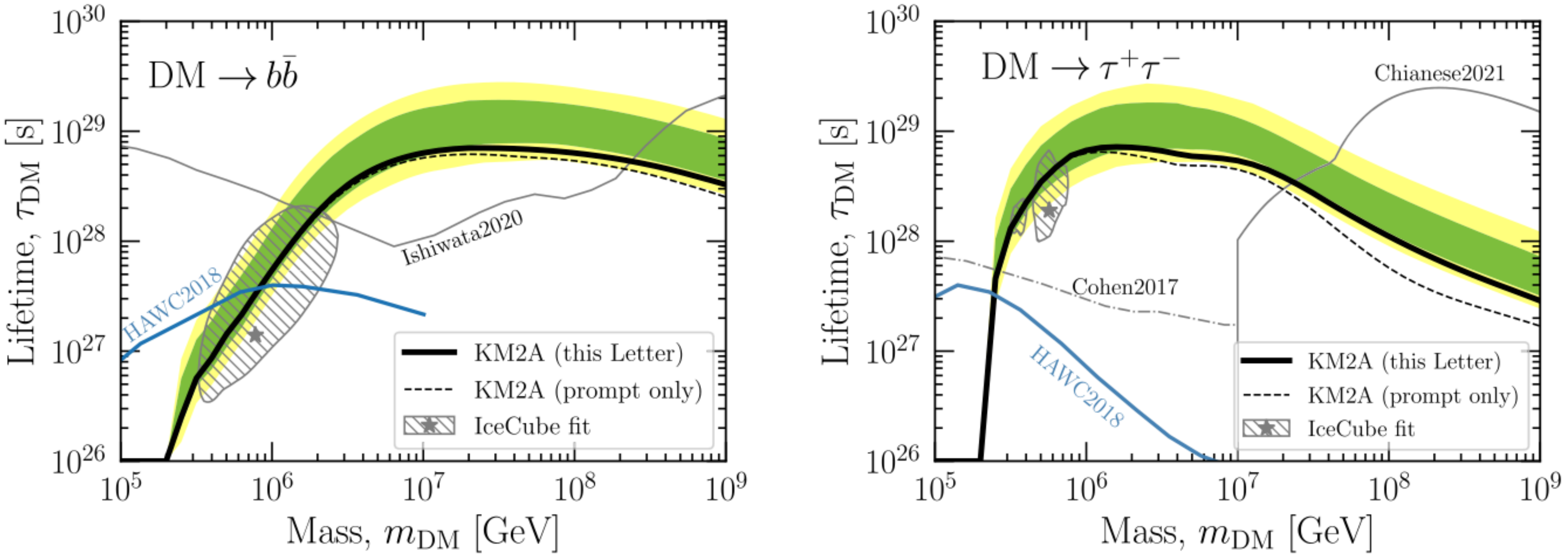
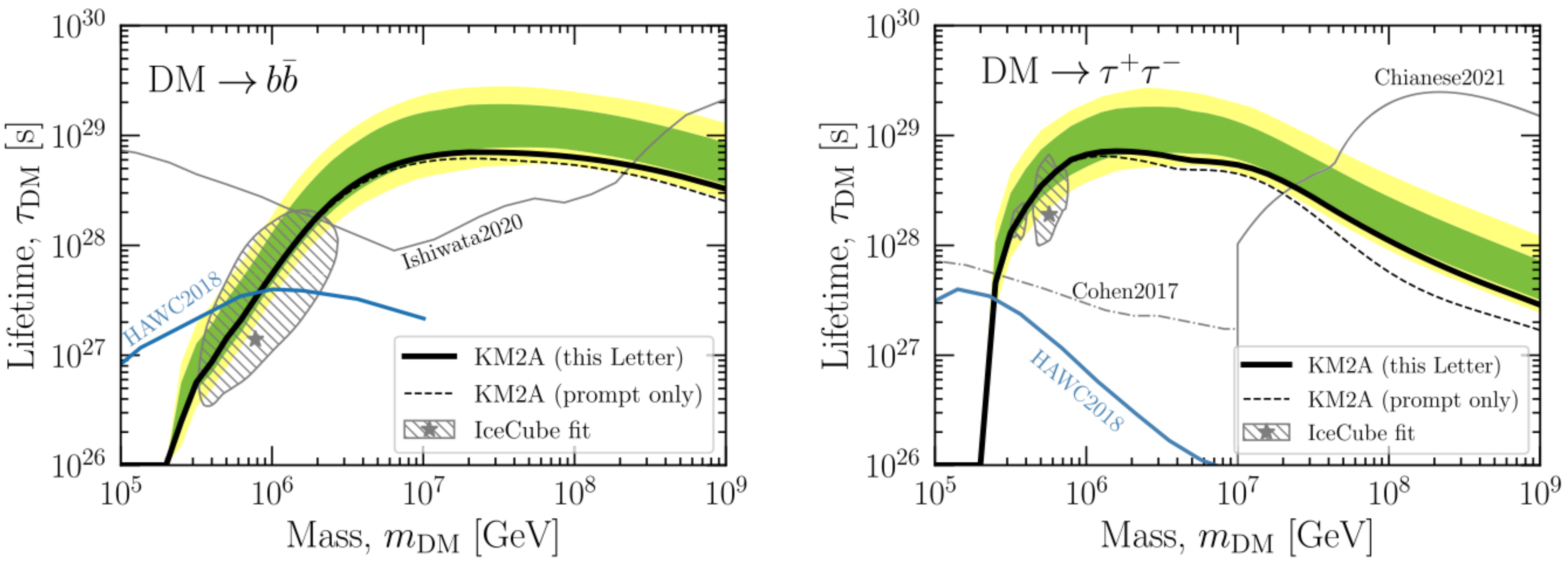


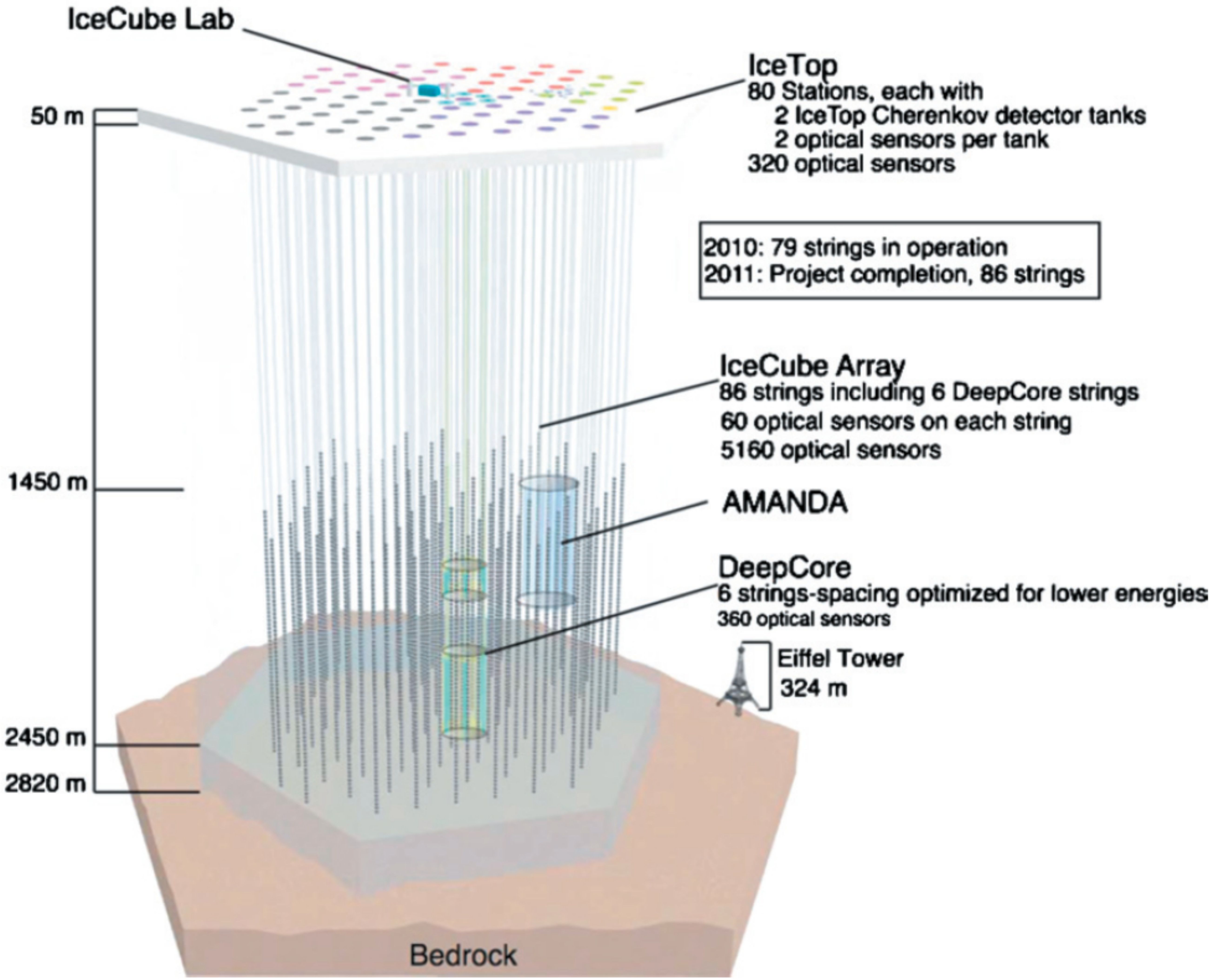
Results

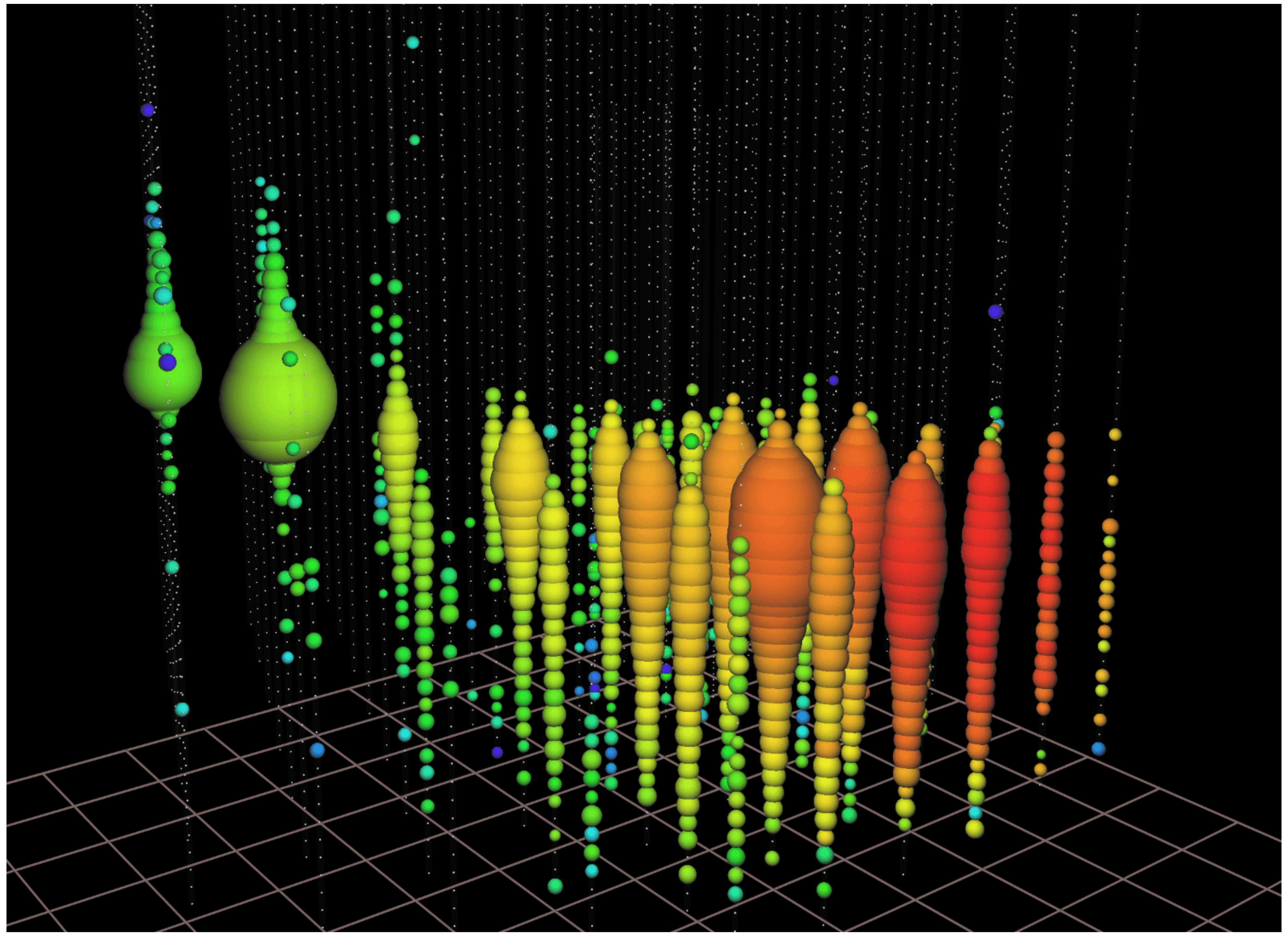
- Ishiwata2020: Fermi, CASA-MIA, etc
- Cohen2017: Fermi
- Chianese2021: CASA-MIA, KASCADE, PAO, etc



Implication for IceCube Signal interpretation

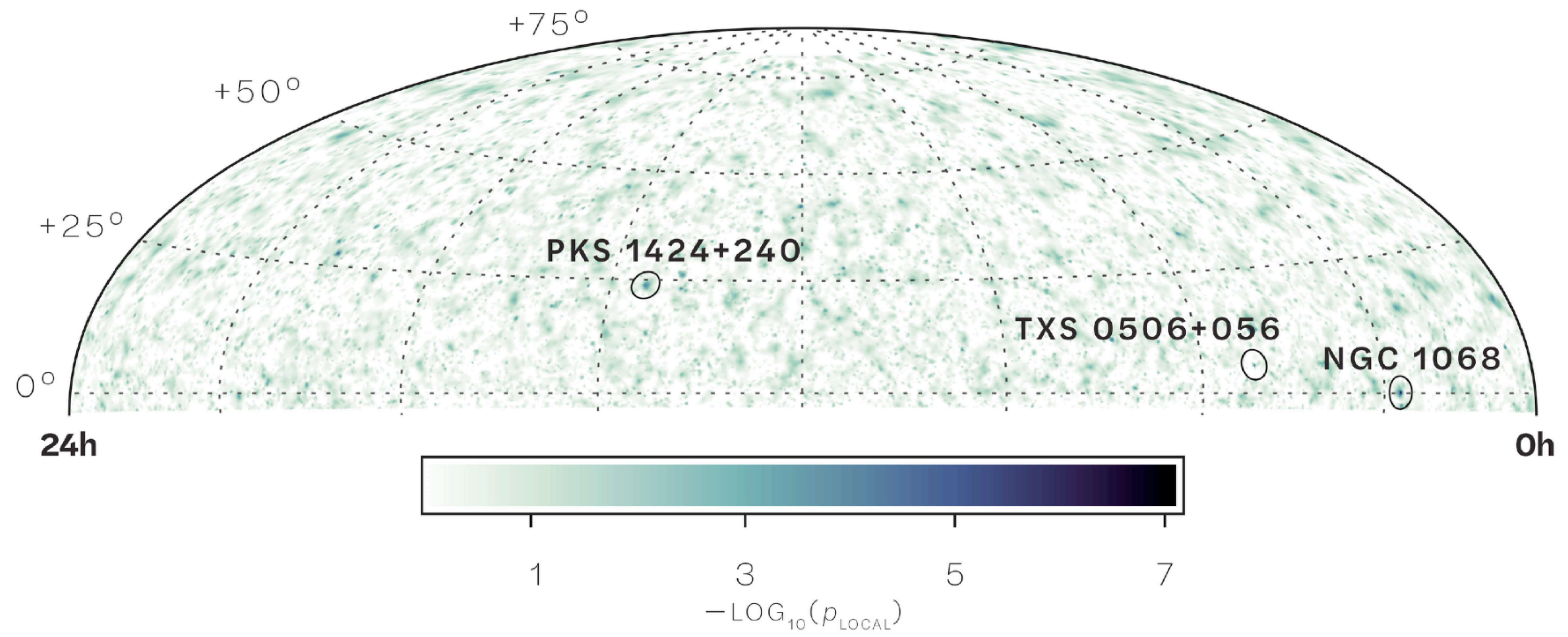
- IceCube neutrino detection

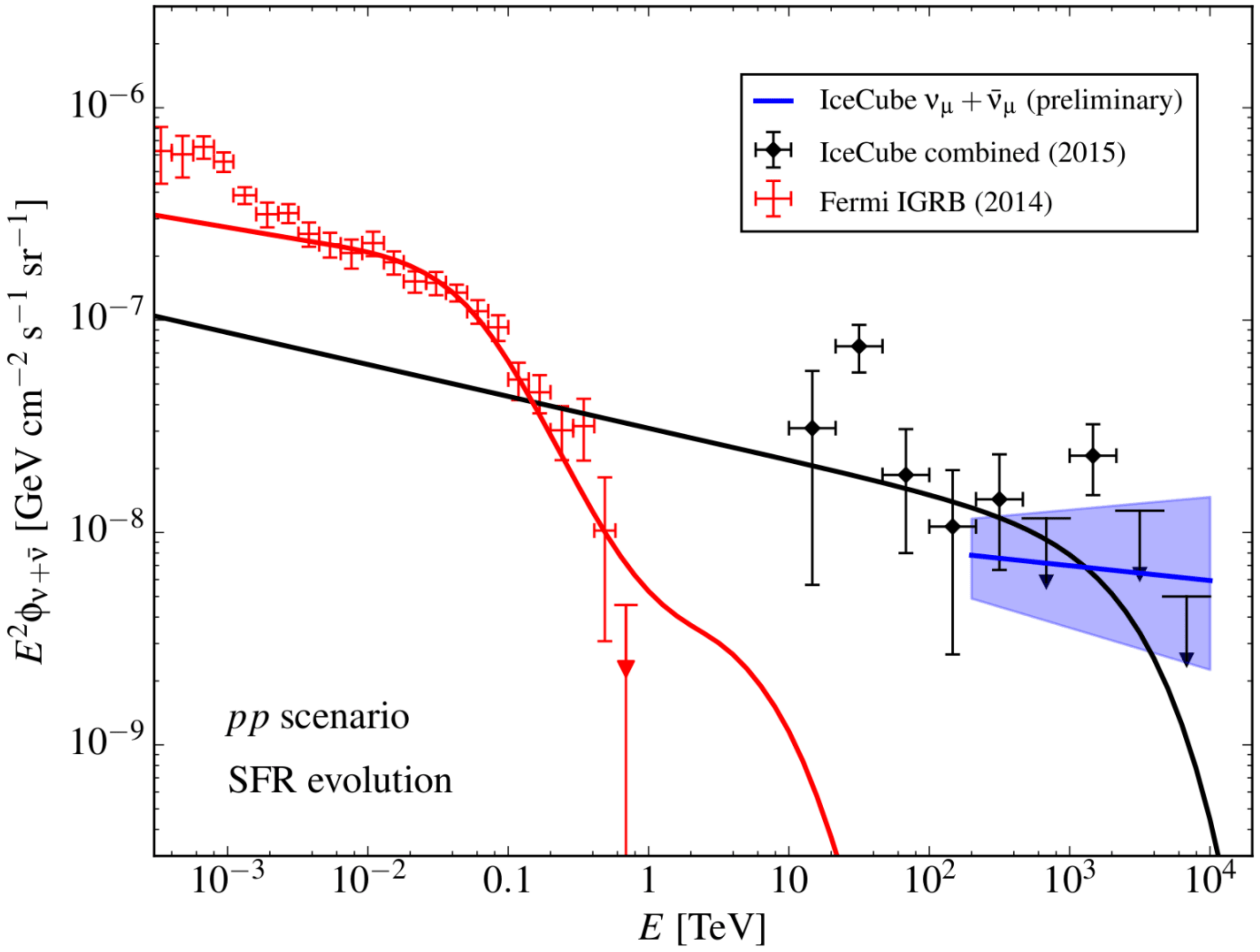




Implication for IceCube Signal interpretation

- IceCube neutrino detection
- Diffuse flux of astrophysical neutrinos
- Recent source identification

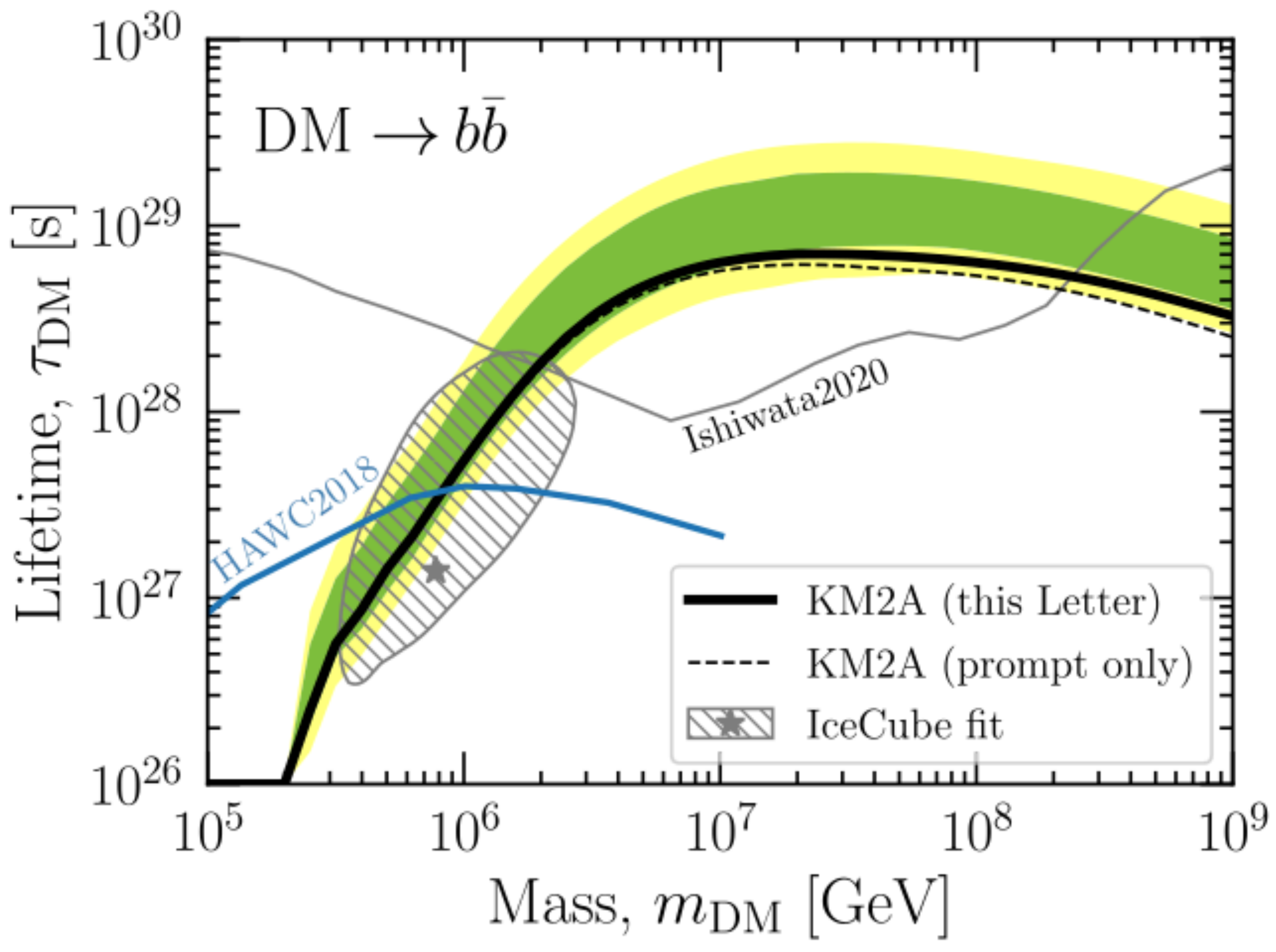


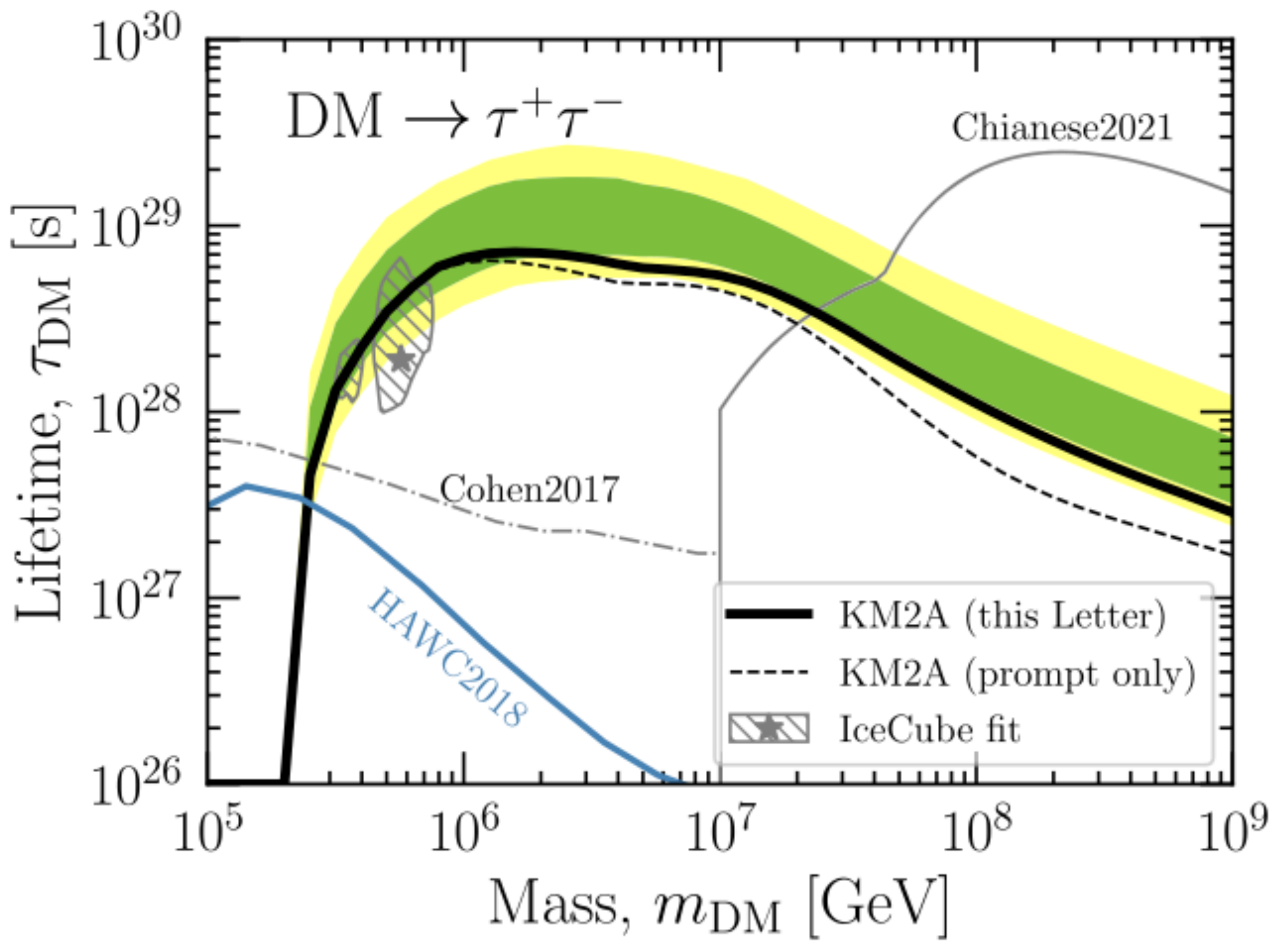


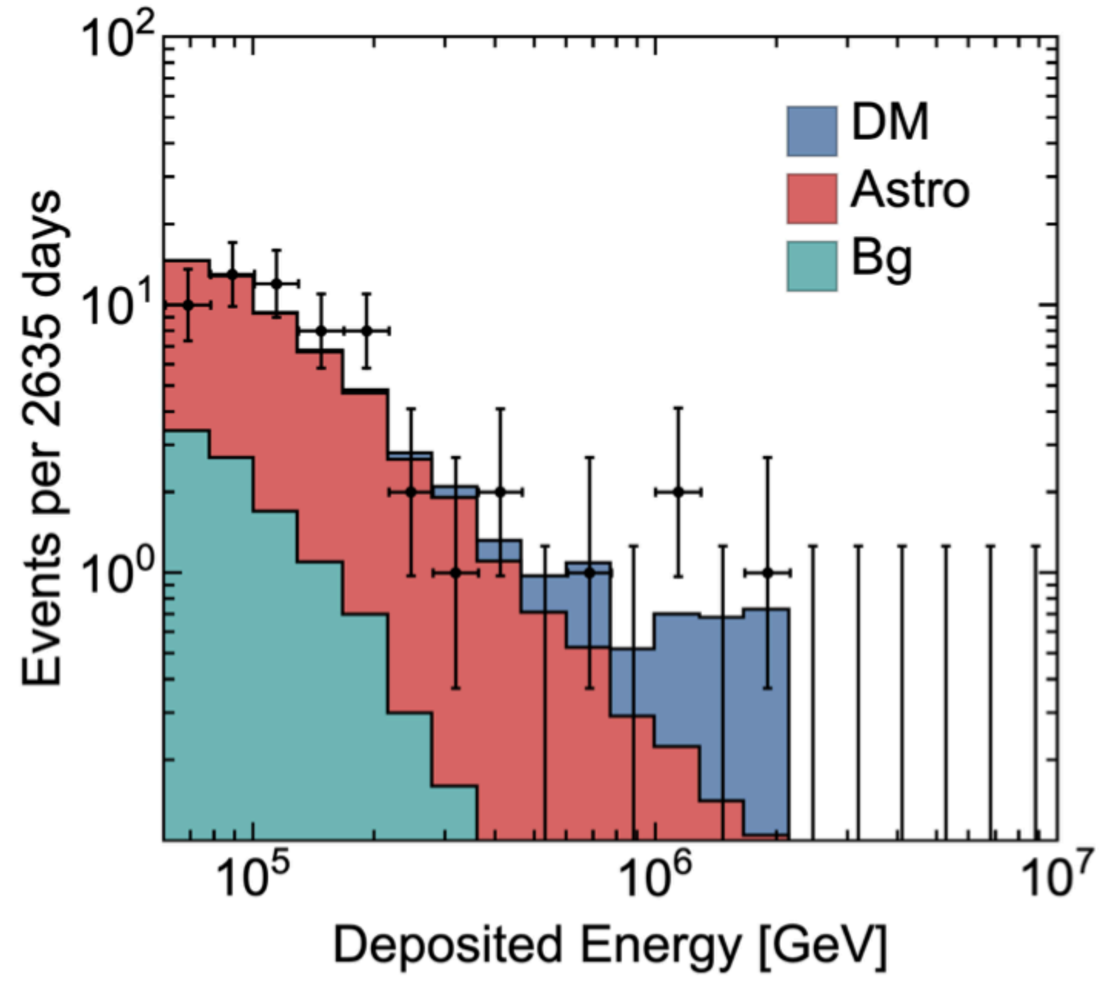
- Still, the full diffuse spectrum has not been fully explained

Implication for IceCube Signal interpretation

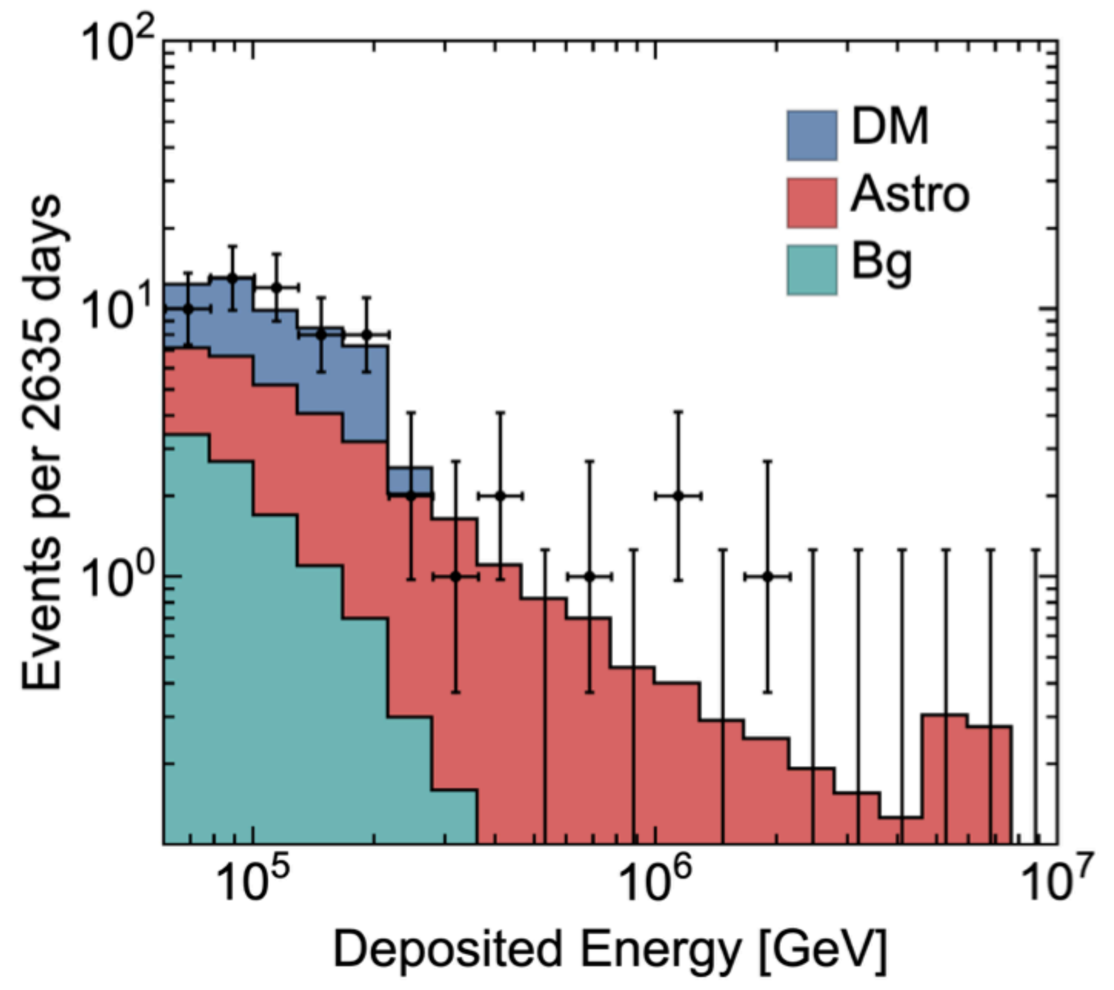
- DM has been proposed as an explanation for IceCube events







(a) Channel ν_e, no prior distribution.



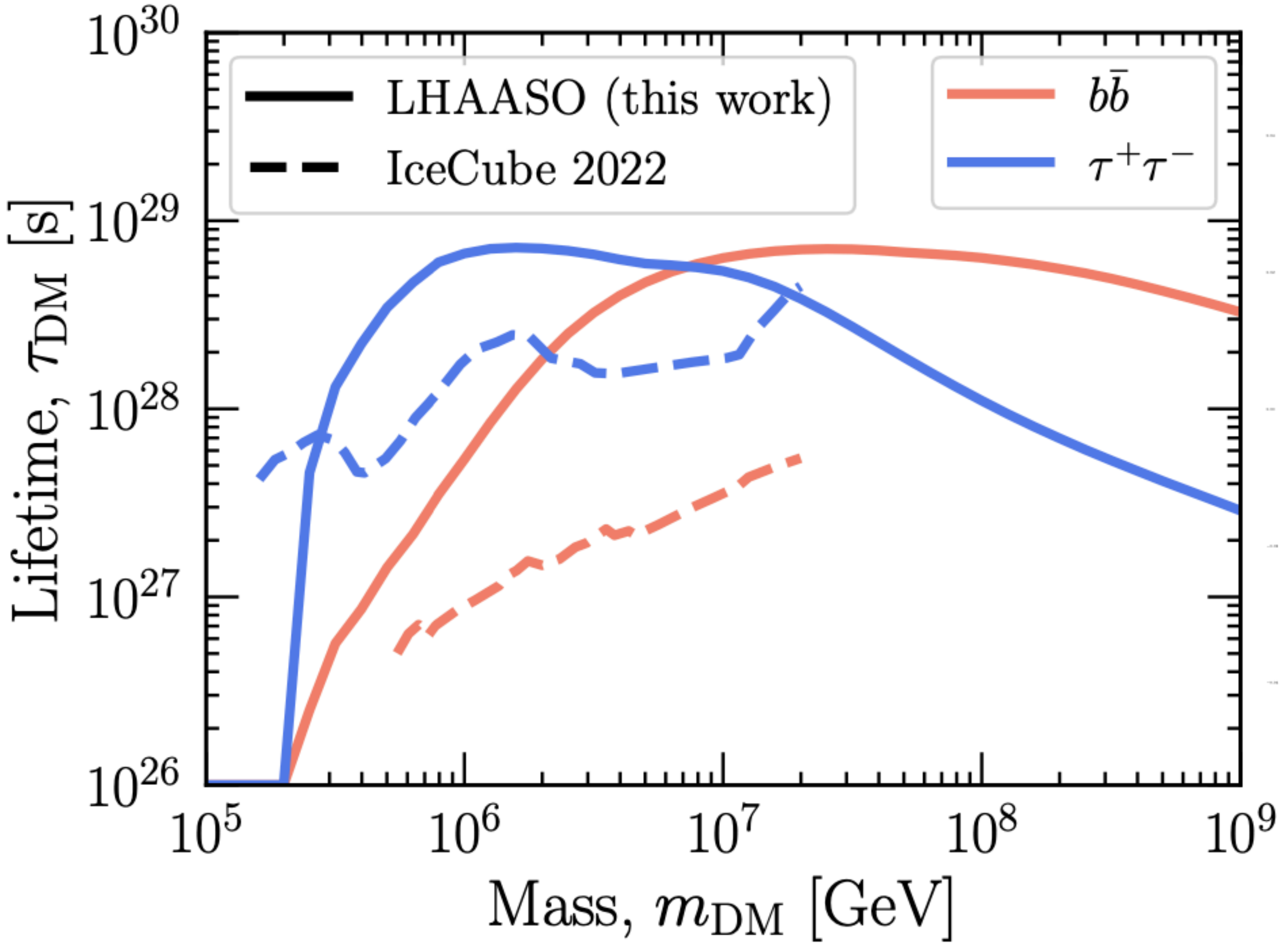
(c) Channel W, no prior distribution.

- LHAASO strongly constrain some IceCube DM interpretation

https://iopscience.iop.org/article/10.1088/1475-7516/2019/11/046/pdf

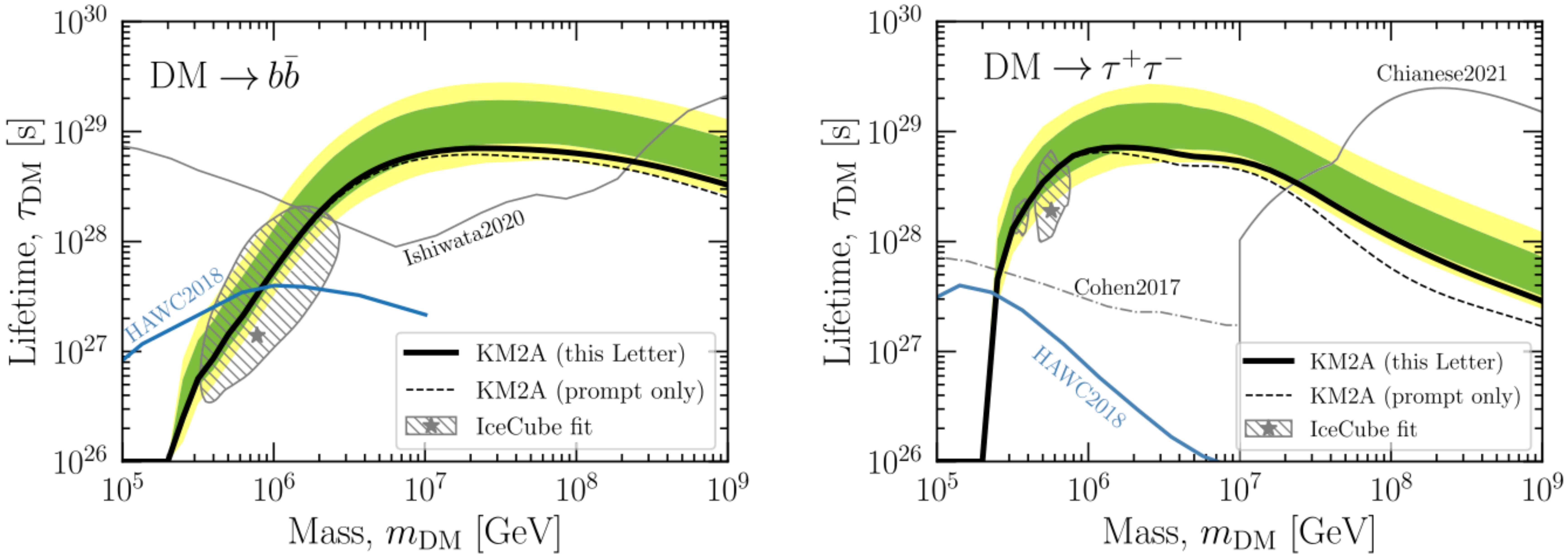
KM2A vs IceCube

- KM2A the best DM detector at 1PeV



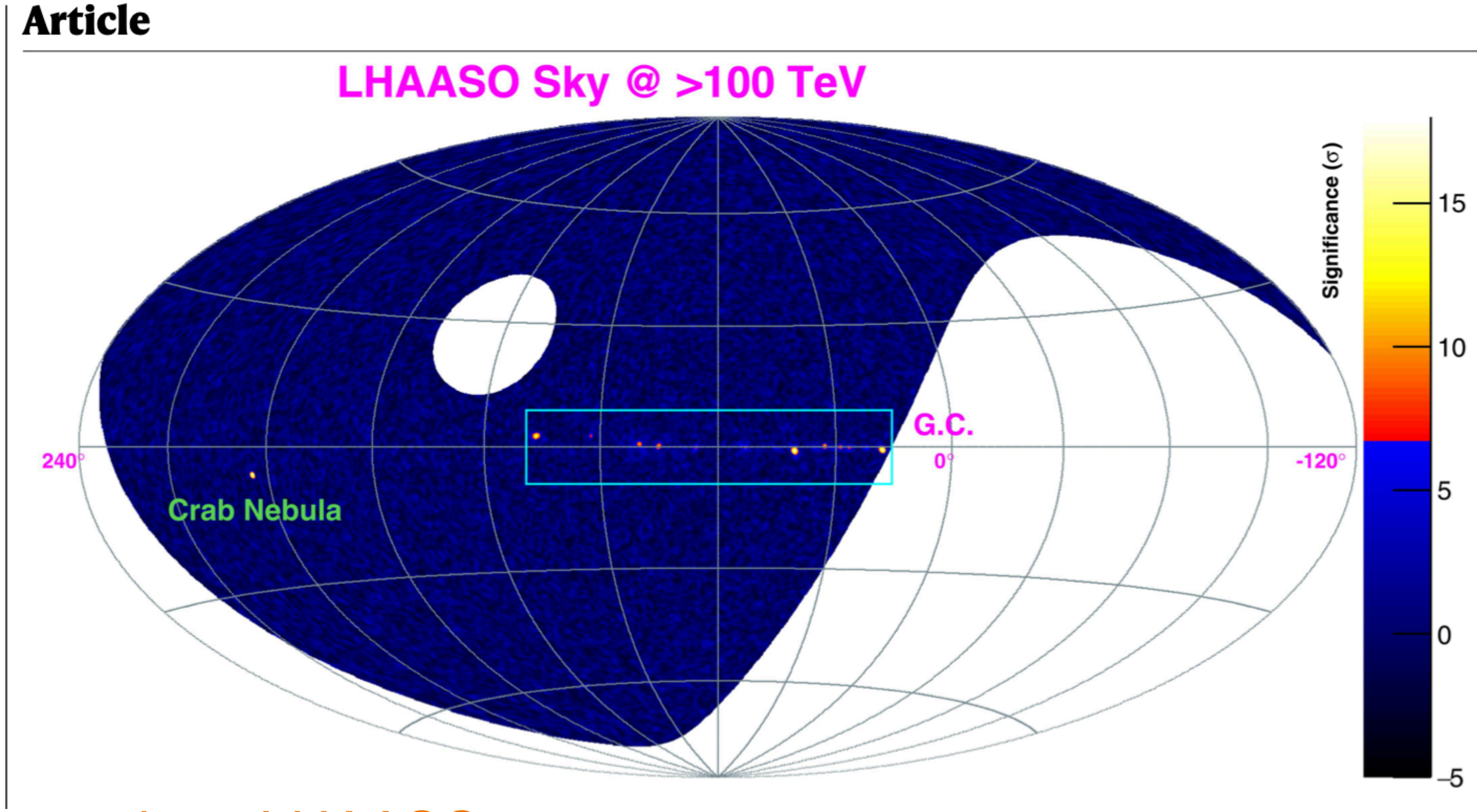
Summary

- We have obtained the strongest DM lifetime constraint at around 1PeV
- Analysis is robust
  - small dark matter profile uncertainty
  - few assumptions on background



Future

- Full array data
  - More data. Better gamma/hadron separation with WCDA?
- Including WCDA
  - extend to lower energy
- Fullsky data
  - include galactic plane?
  - require astrophysical modelling



- Each time with a groundbreaking detector such as LHAASO,
  - new hope for new detections (dark matter?)

Thanks!