Dark Matter Particle Searches and Prospects with High-Energy Gamma Rays

CTAO | LST COLLABORATION

MAGIC

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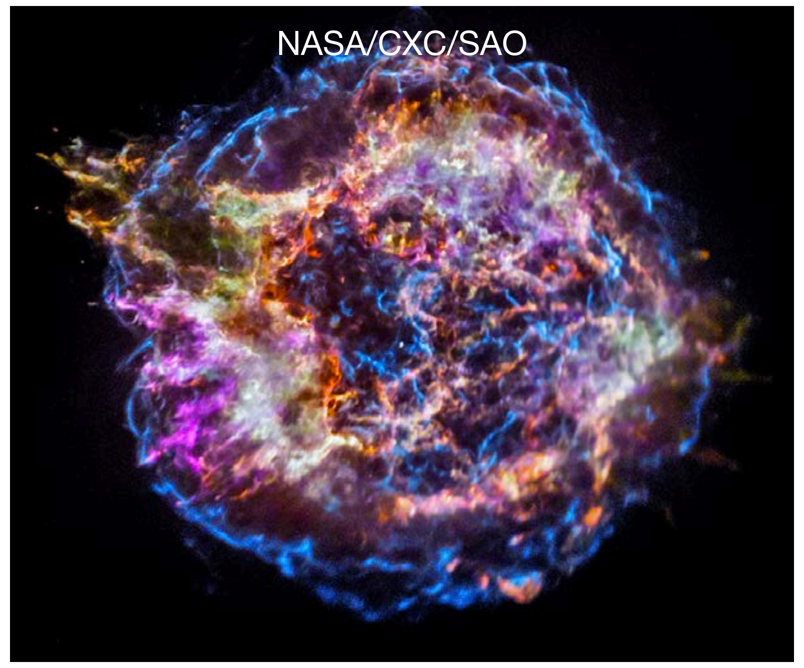
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

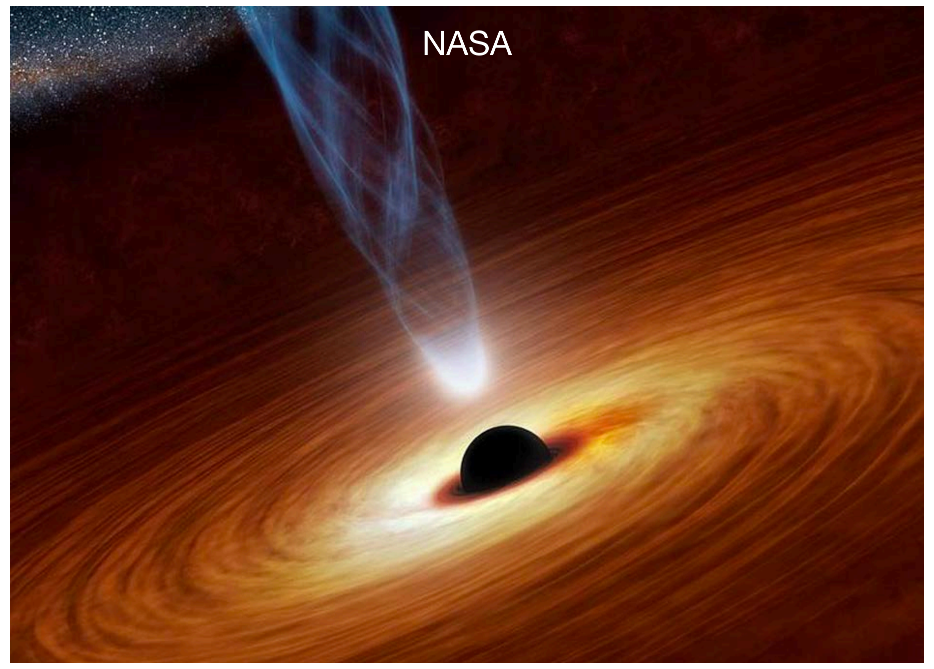
Introduction

High energy phenomena in the universe

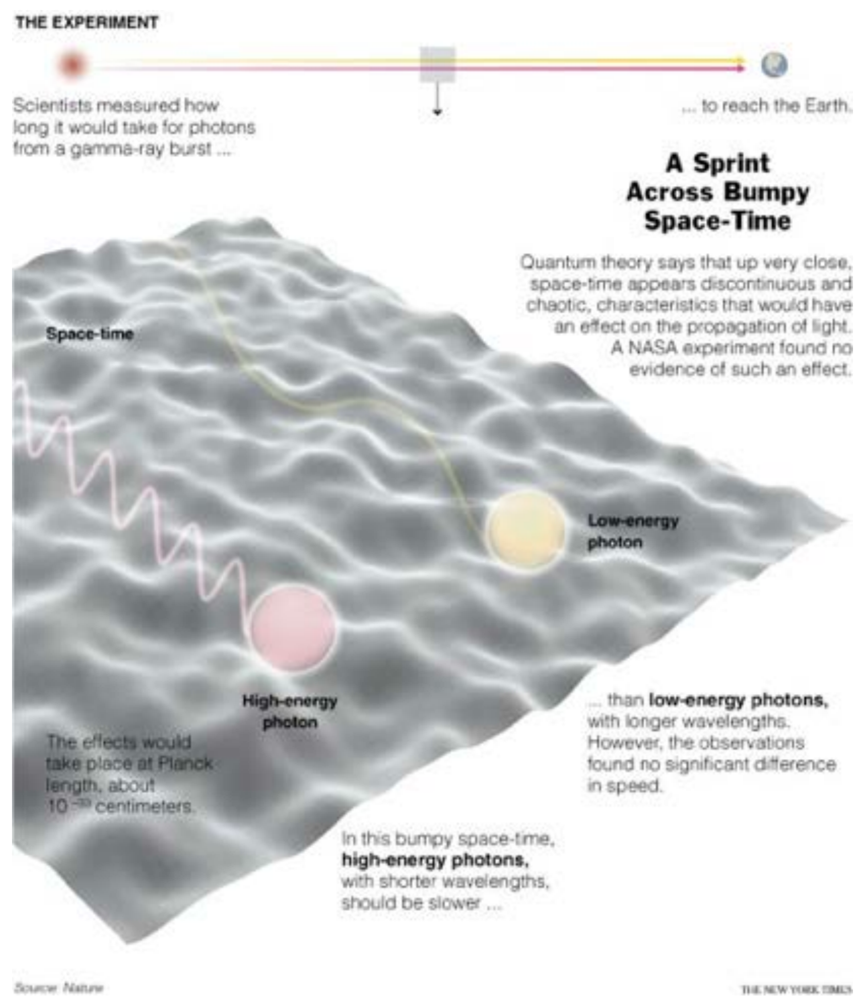
Origin of Cosmic Rays



Supernova Remnant

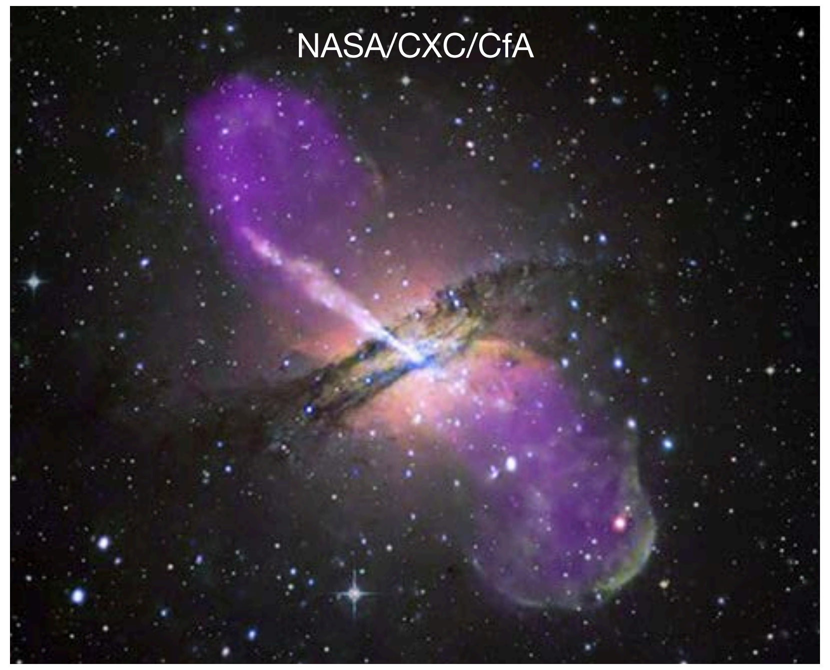


Supermassive Black Hole

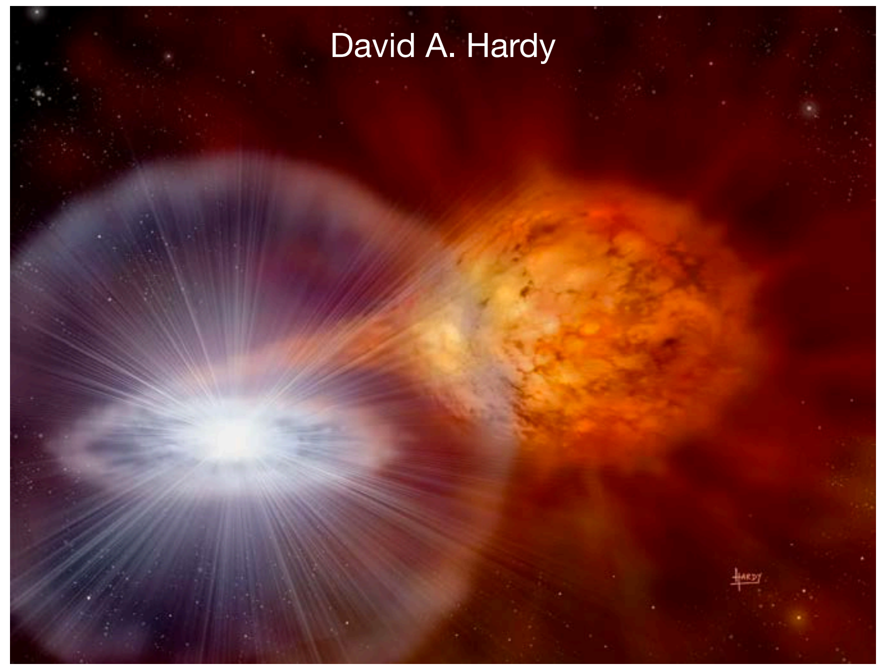


Bounds on Lorentz Invariance Violation

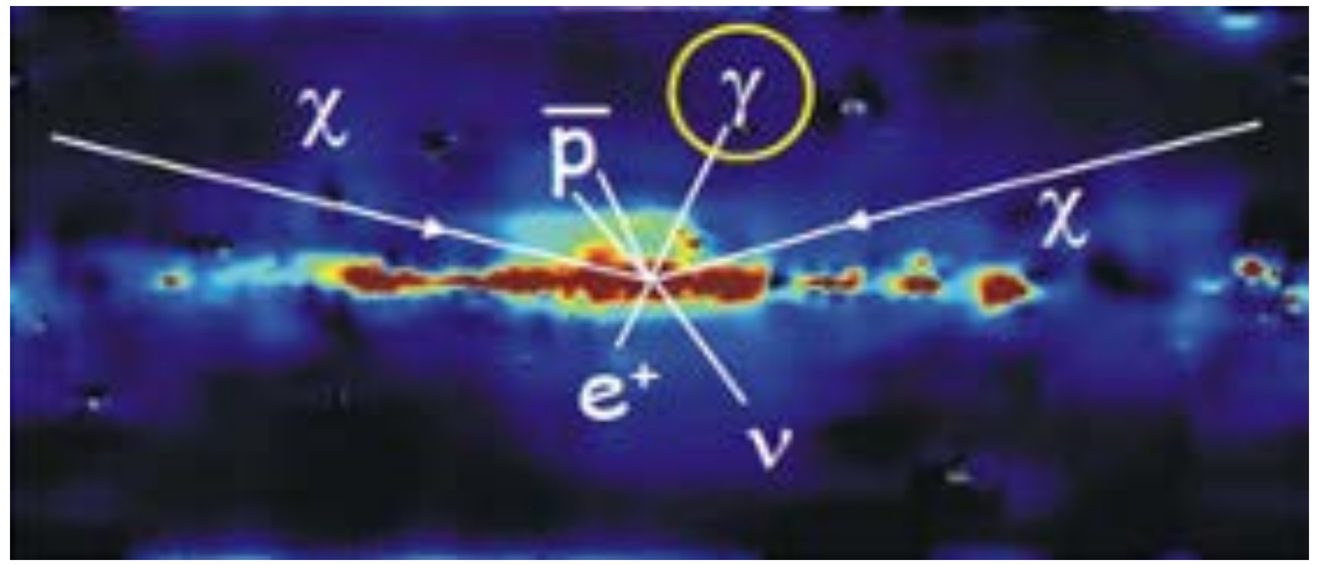
Gamma Ray Burst



Active Galactic Nuclei



Binary / Nova

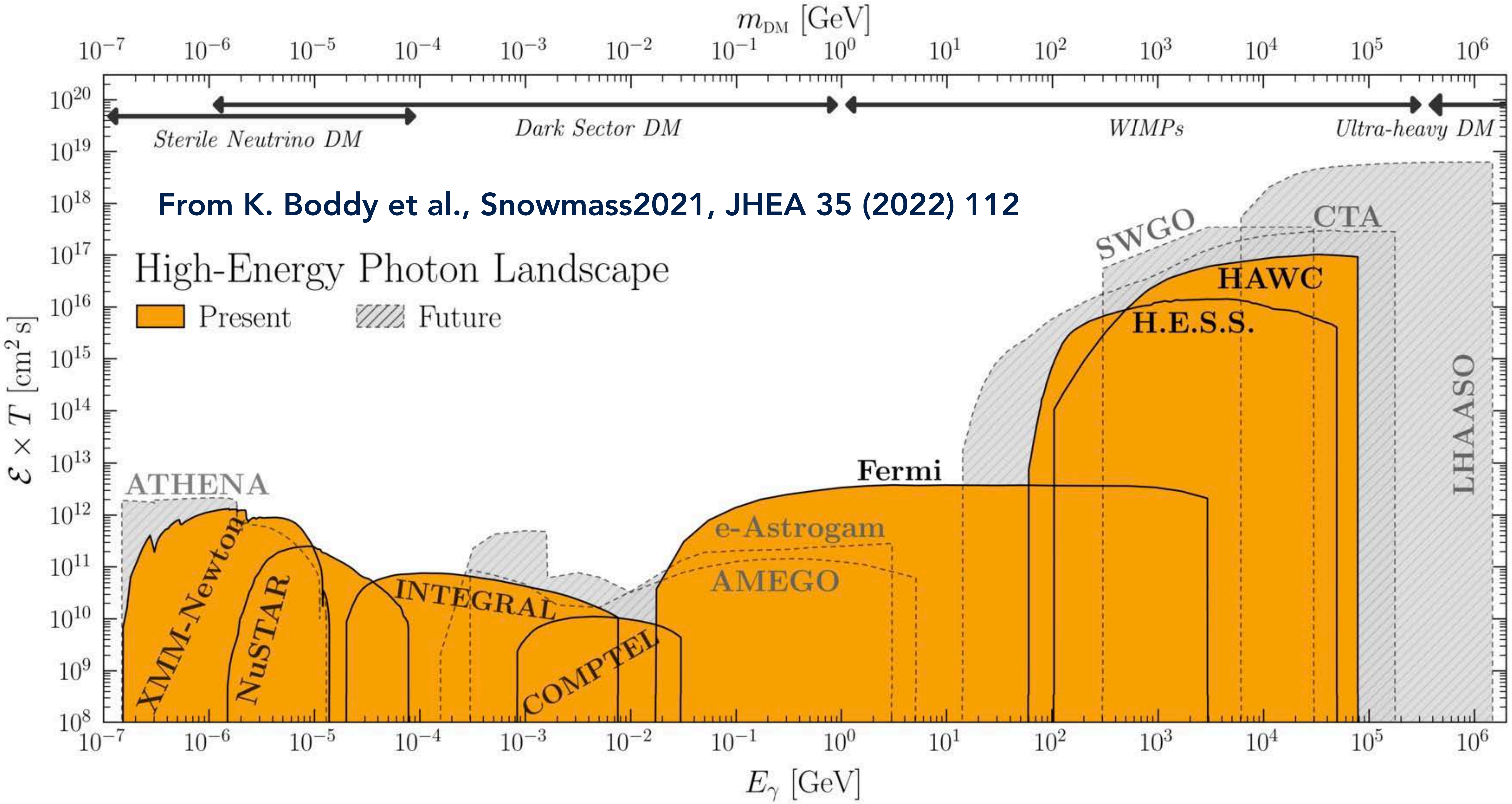


Dark Matter Search

There are plenty of interesting topics in High Energy Universe

We focus on the Dark Side of the Universe

Exposure of instruments for High-Energy Photons toward DM searches



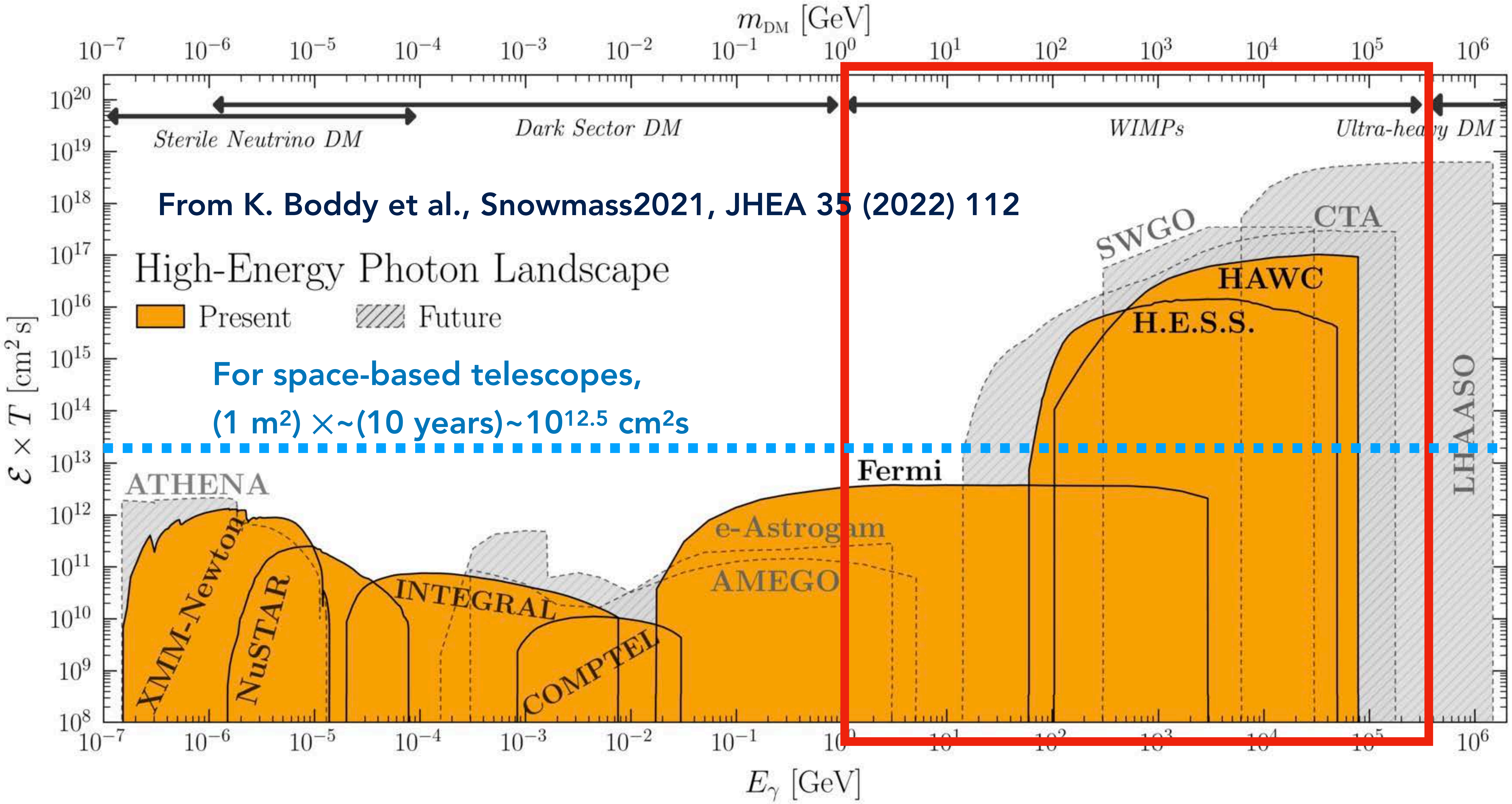
ε : Effective area
T : Observation time

Nb of detected photons :

$\propto \Phi \times \varepsilon \times T$

Disclaimer:
- one of the many ways to compare instruments
- for some DM searches, FoV or energy resolution can be critical as well

Exposure of instruments for High-Energy Photons toward DM searches



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Disclaimer:
- one of the many ways to compare instruments
- for some DM searches, FoV or energy resolution can be critical as well

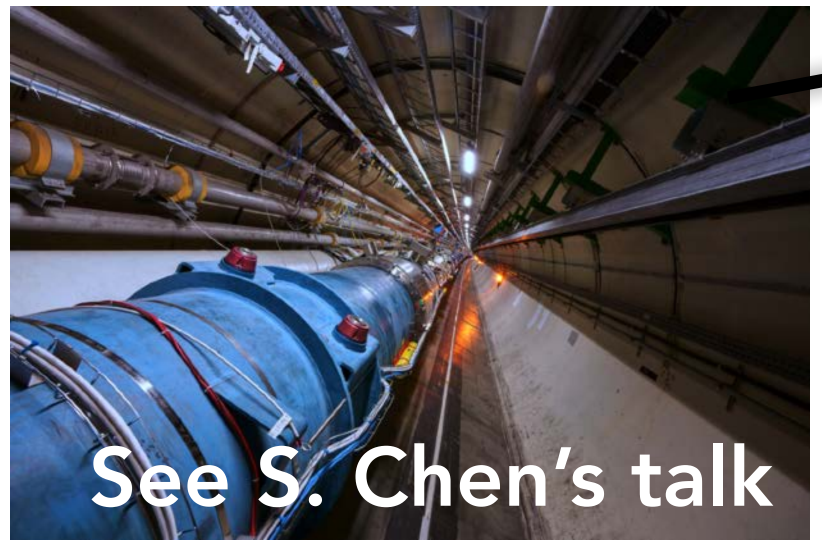
High Energies: dramatic improvement is expected within next decade

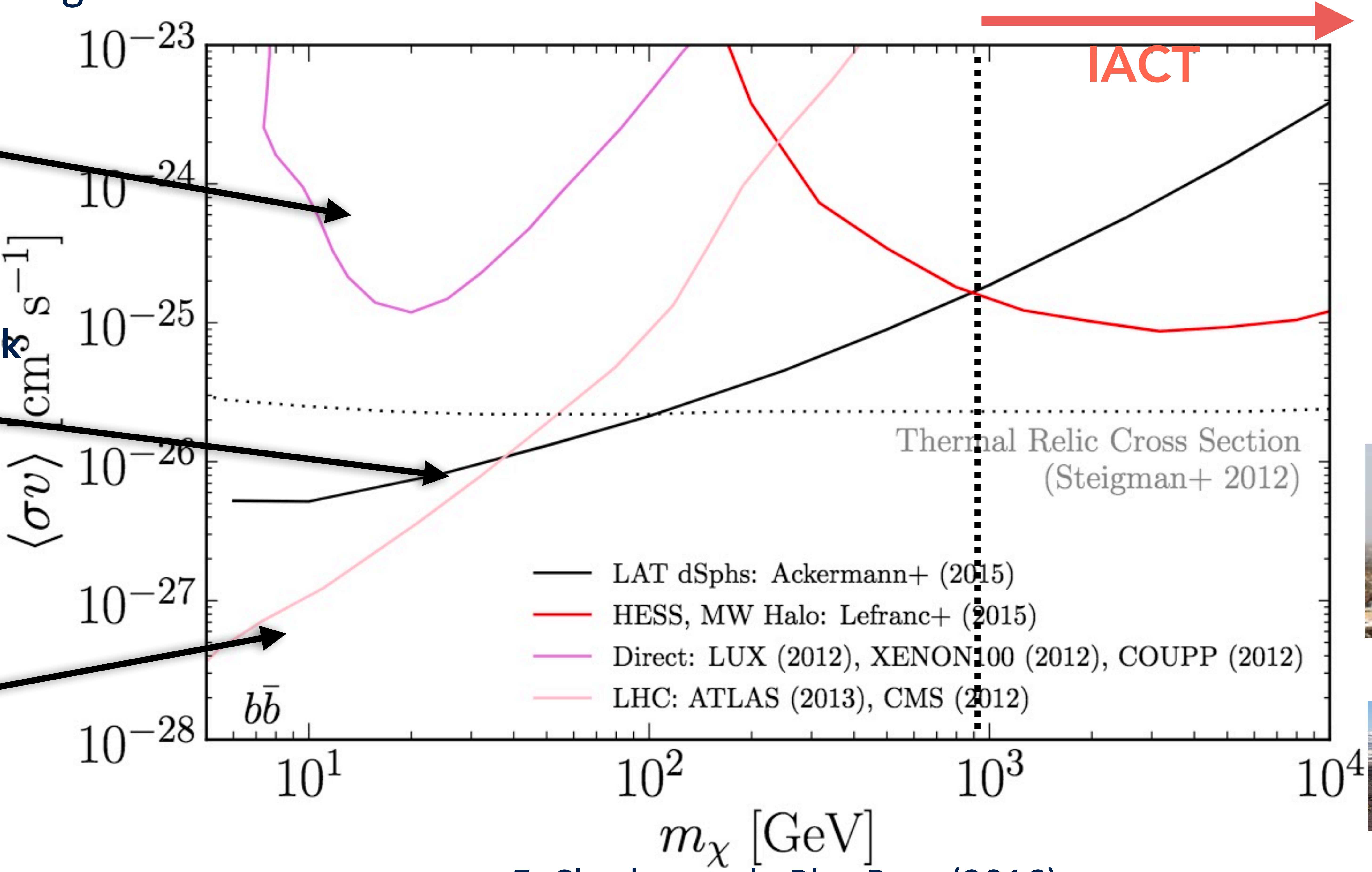
Complementarity of WIMP DM Searches

Various experiments covers huge DM parameter space -> Complementarity!!

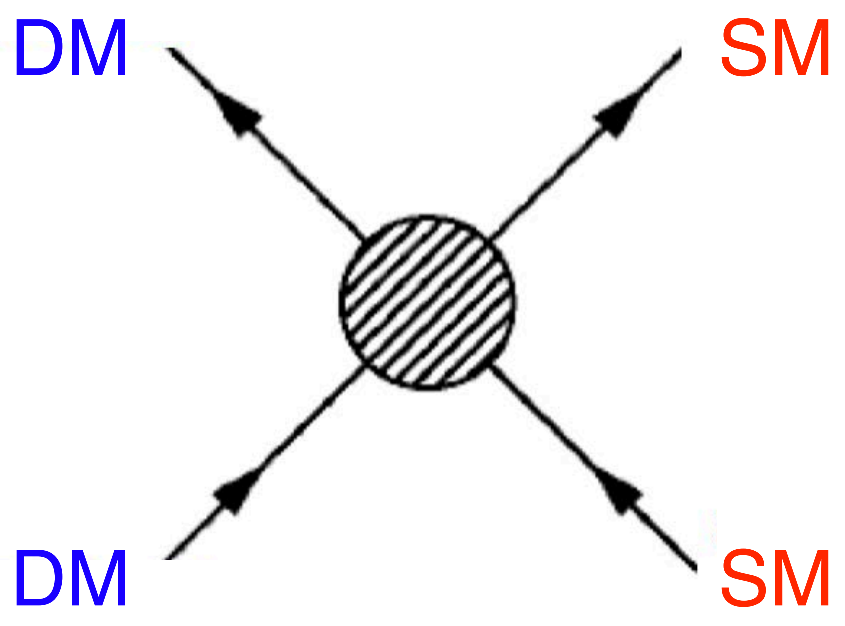
- **TeV-scale: well-covered by the indirect DM technique**
  - **With Imaging Atmospheric Cherenkov Telescopes (IACTs)**
- Large exposure gives us access to heavier masses

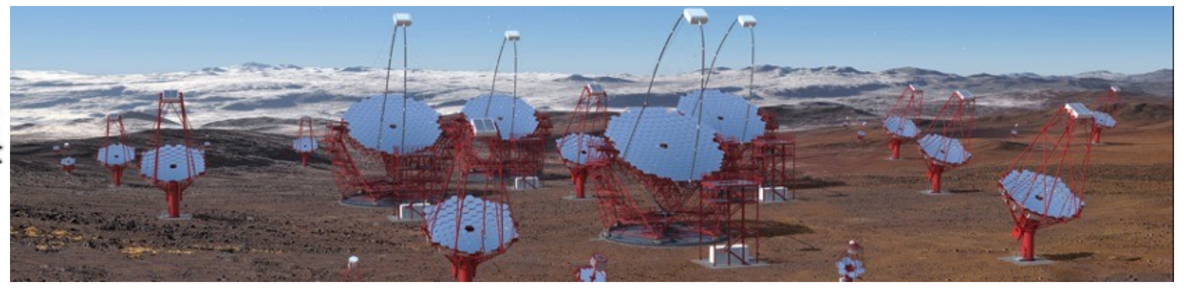
See M.Kobayashi's talk



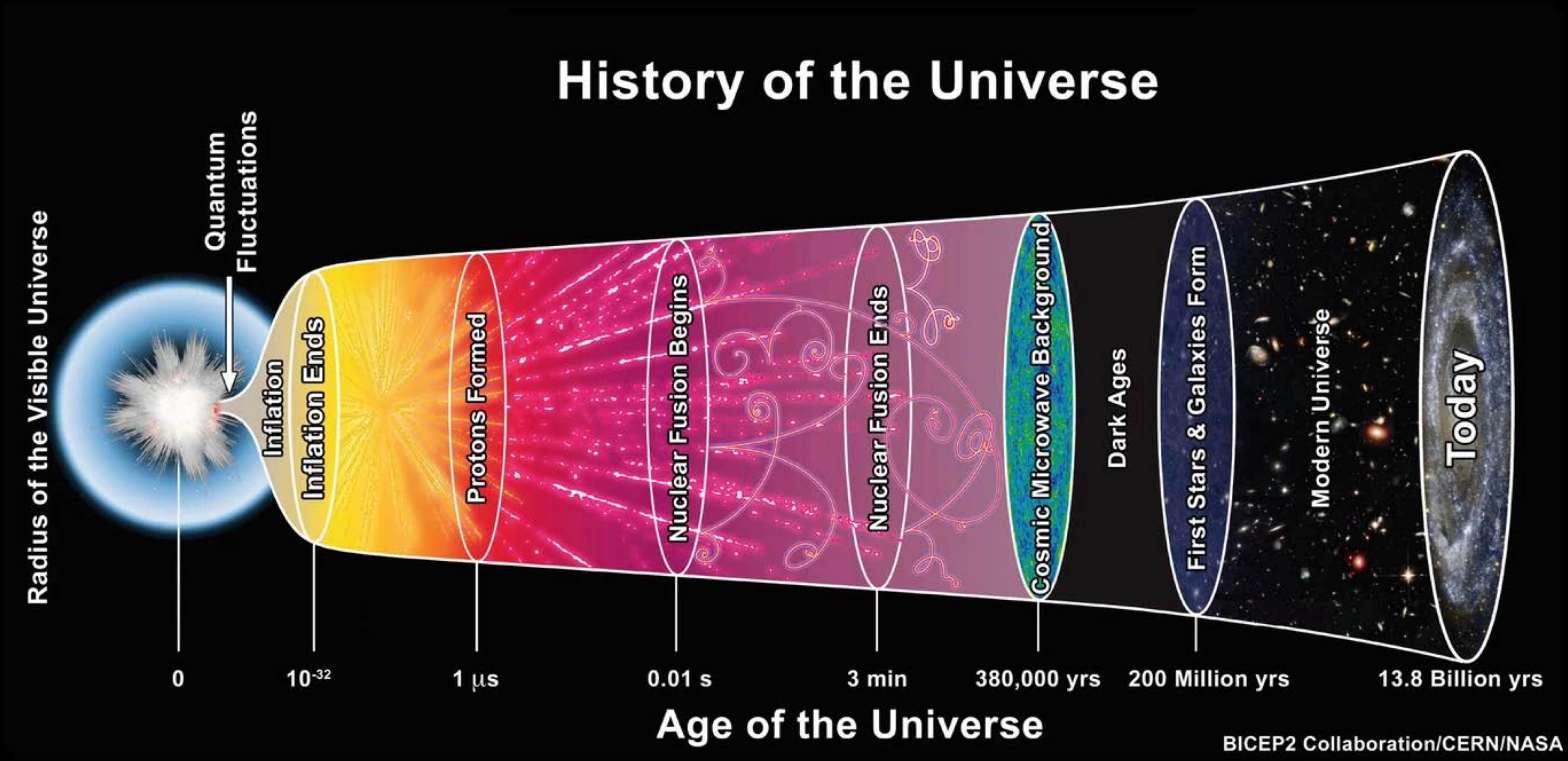


E. Charles et al., PhysRep, (2016)



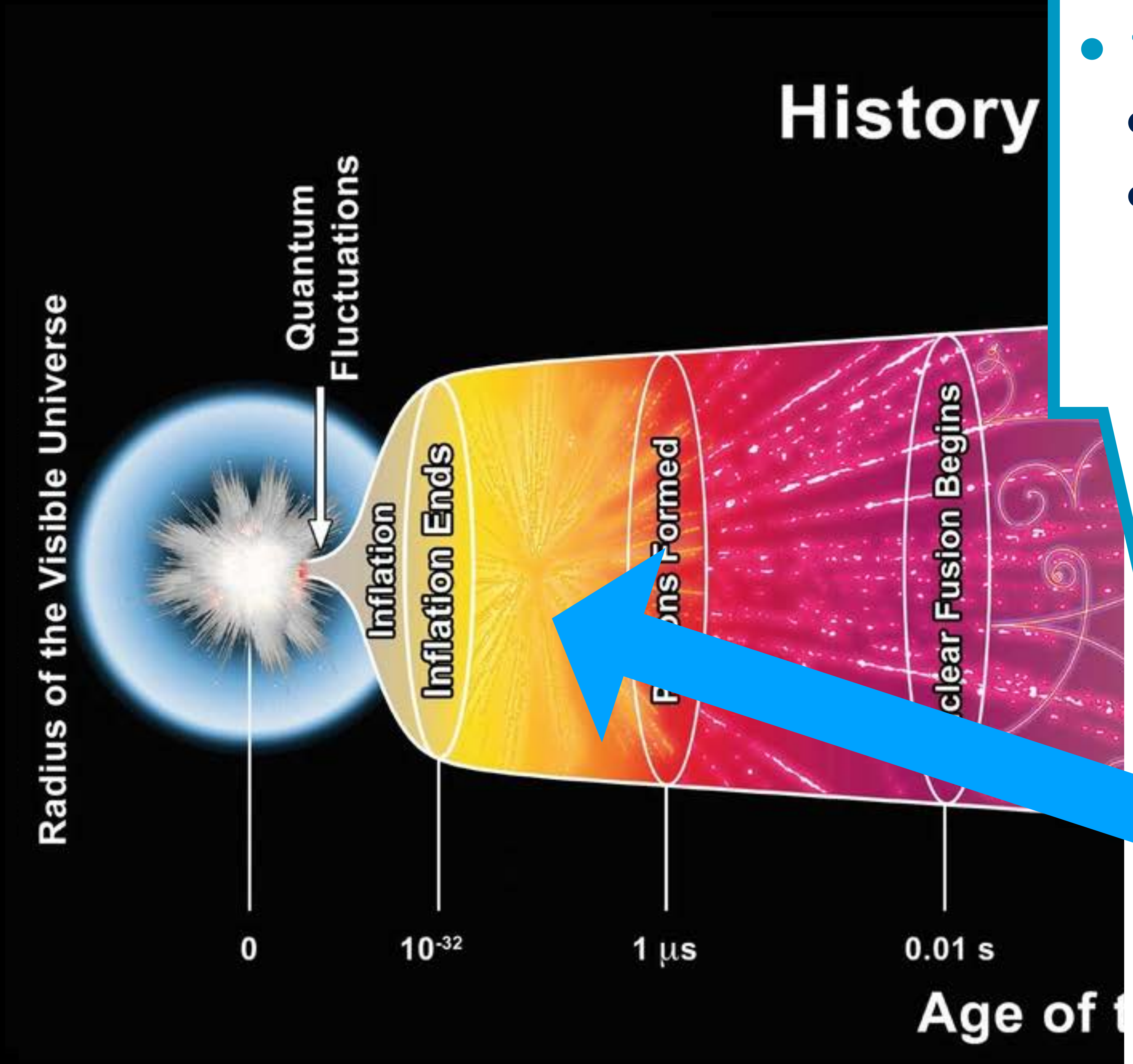


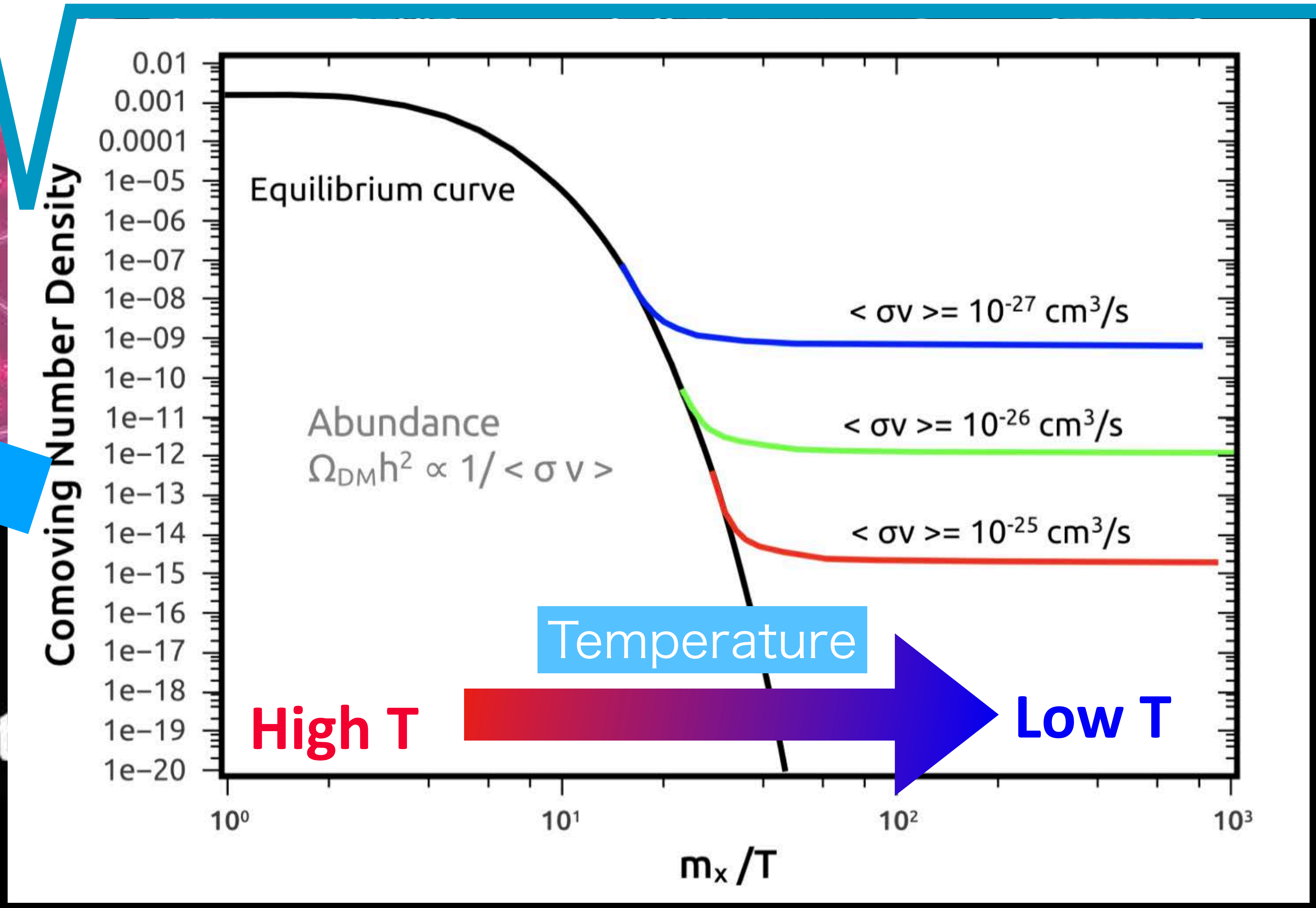
Why indirect method for WIMP DM?



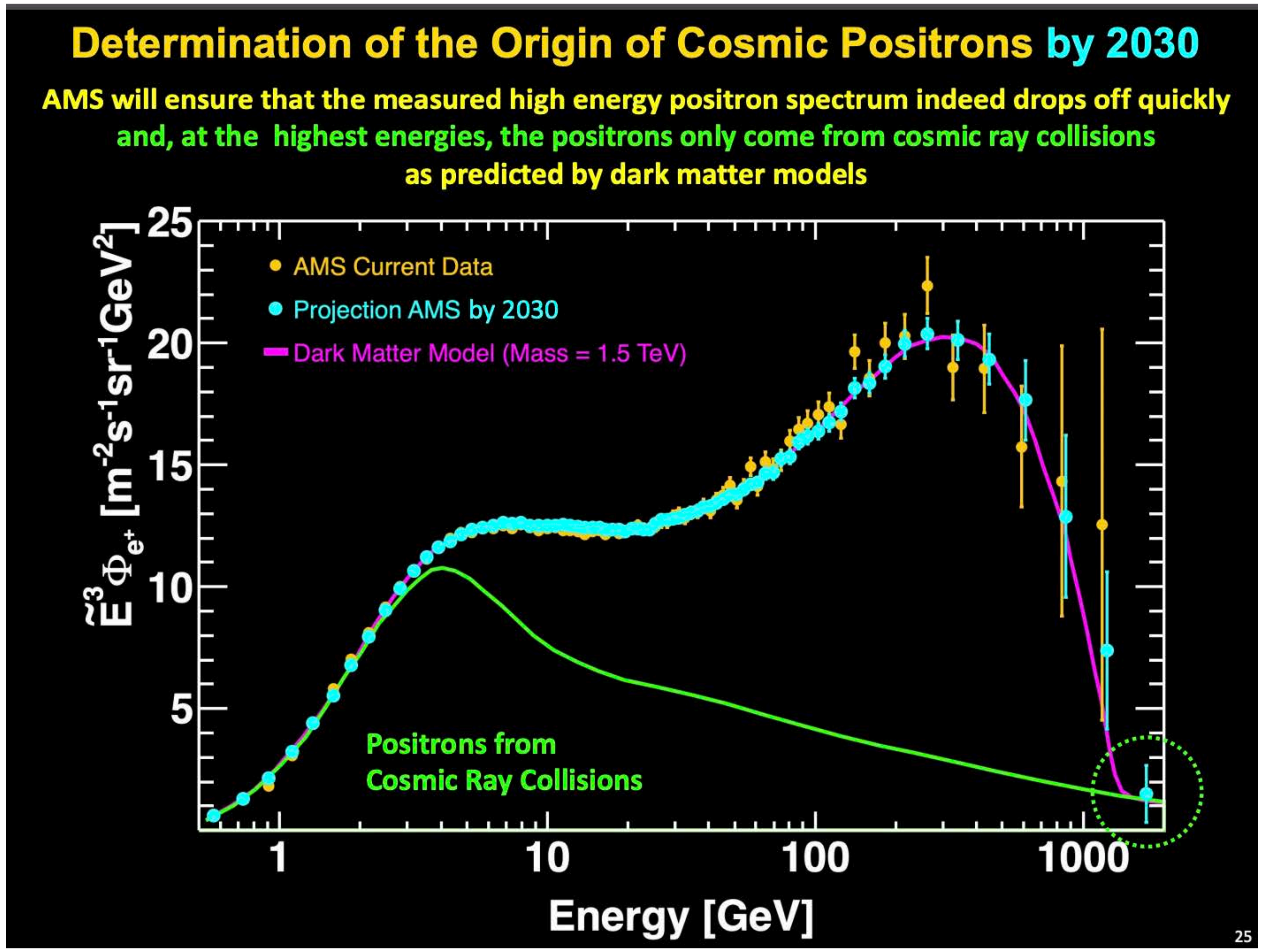
Why indirect method for WIMP DM?

- **Test of particle DM**
  - DM mass, a coupling constant… particle information
- **Test of DM production mechanism**
  - When produced? Thermally freeze-out or not
  - Measure annihilation cross-section
    - Benchmark: <σv> ~ $3 \times 10^{-26} cm^3 s^{-1}$
    - So-called **“thermal relic” cross-section**

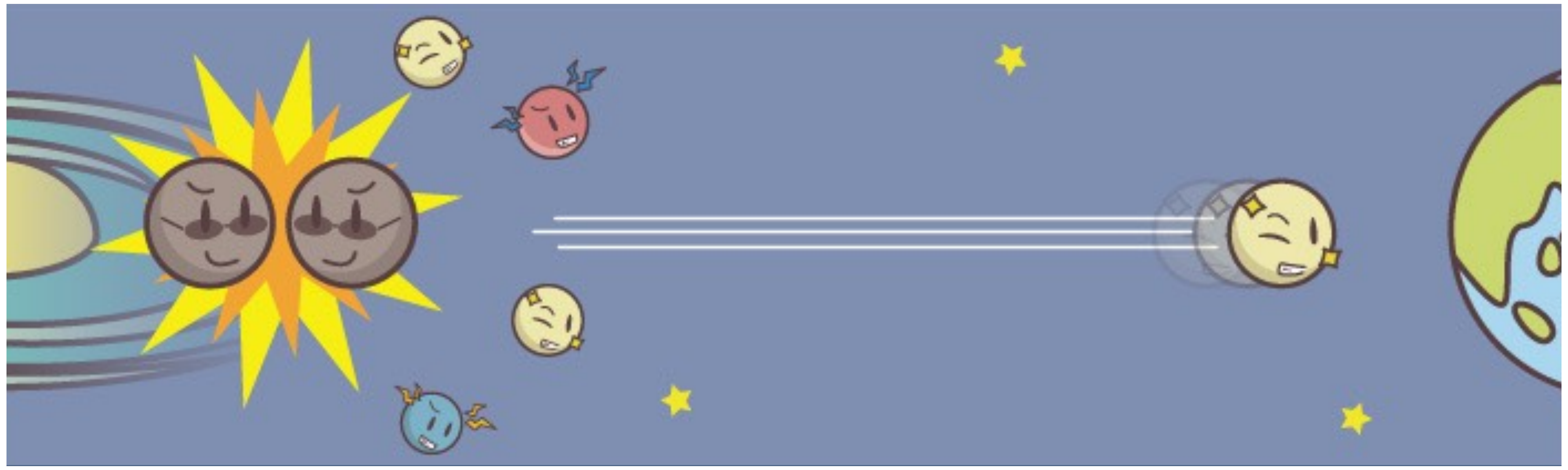




Why Gamma-Ray? - “Direction-Sensitive”

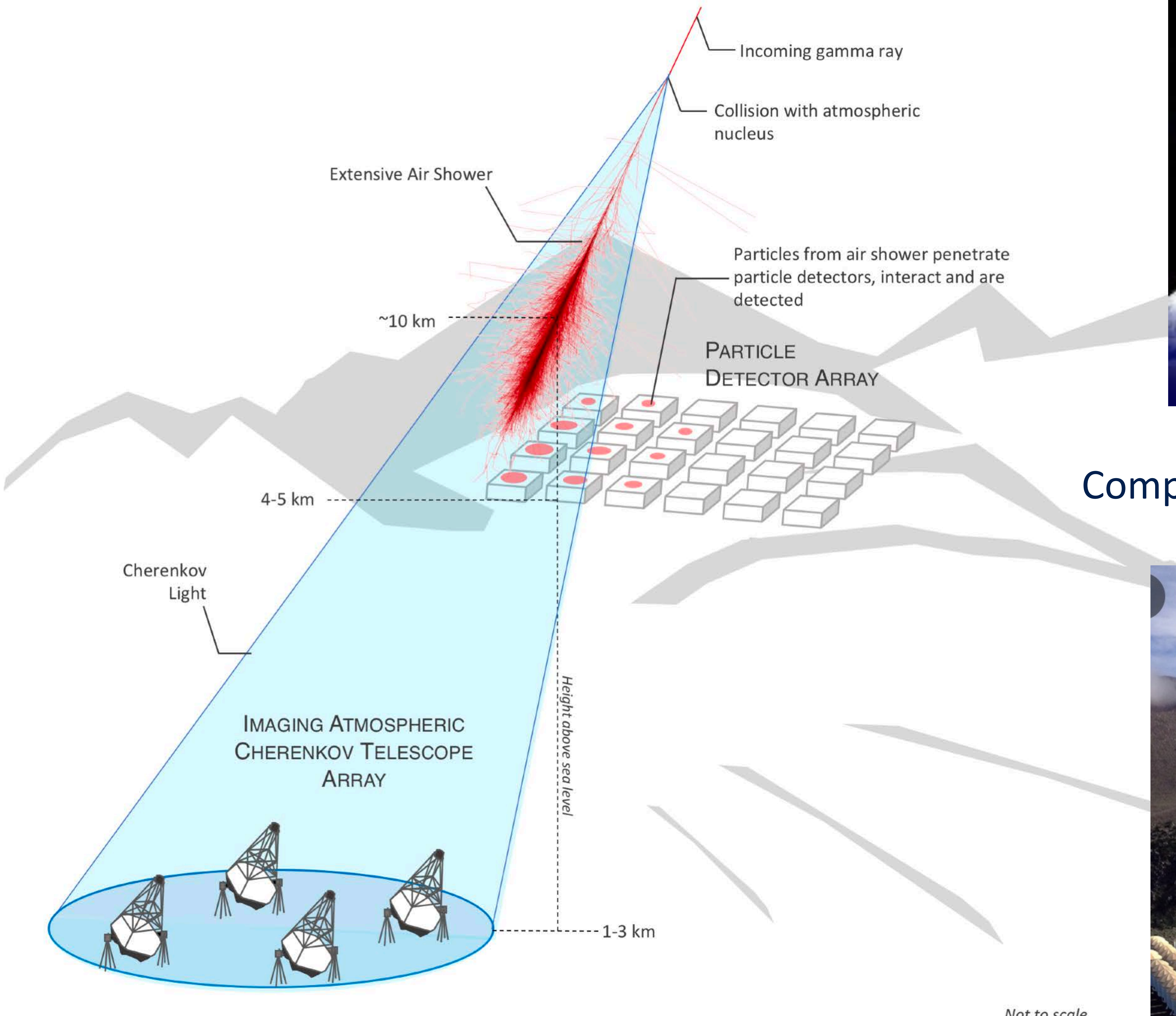


- Cosmic position spectra reported by AMS-02
  - 1.5 TeV Dark Matter Mass?
- However, possible other origins (e.g. pulsar)
- To be conclusive, have to associate arrival direction of signals with origins (i.e. a source)
  - “Direction-Sensitive” indirect dark matter searches



Easy to associate with the source, not affected by B-fields

Gamma-ray detectors

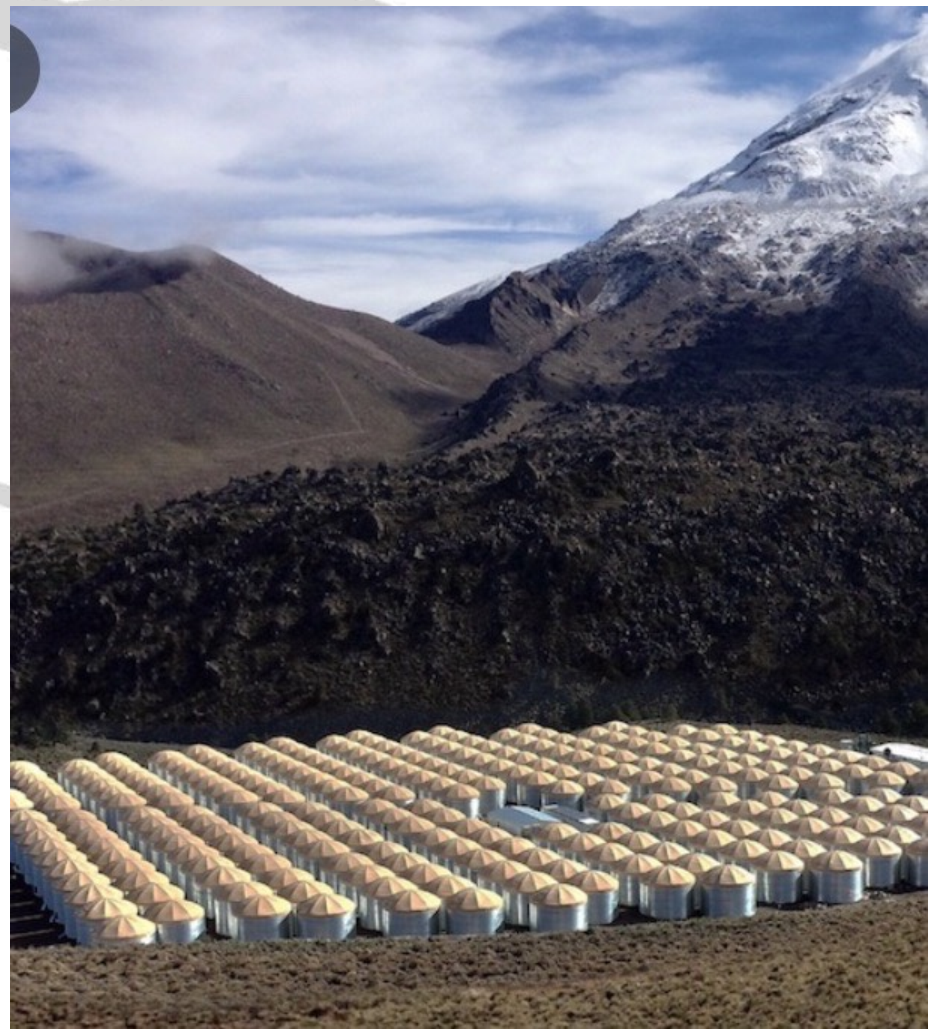


credit: Richard White, MPIK

MeV-GeV range
Satellite-borne detectors

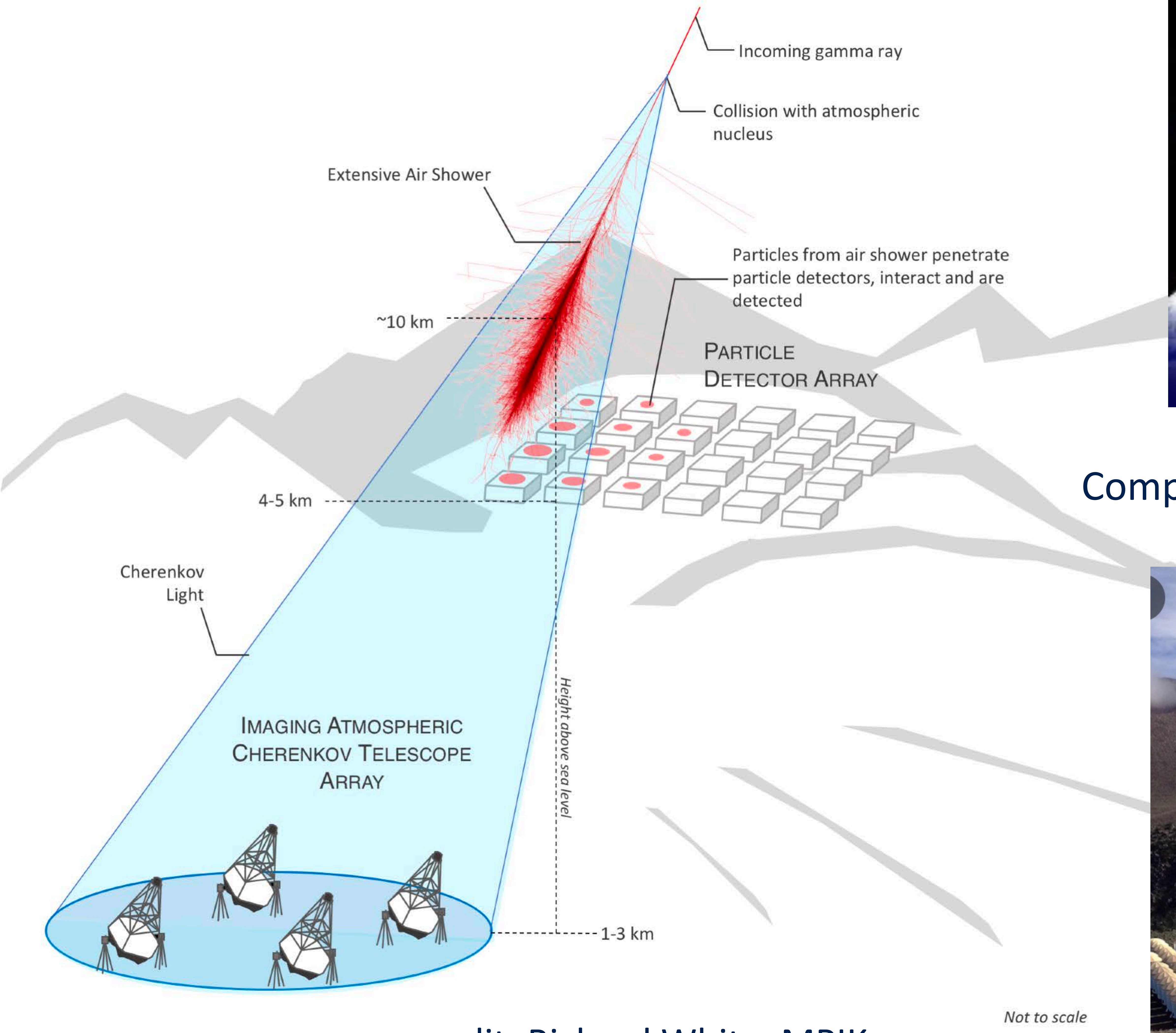
TeV range
Ground-based detectors (light)

TeV-PeV range
Compact Ground based detectors (particles)



>PeV range
Wide Ground-based detectors (particles)

Gamma-ray detectors



credit: Richard White, MPIK

MeV-GeV range
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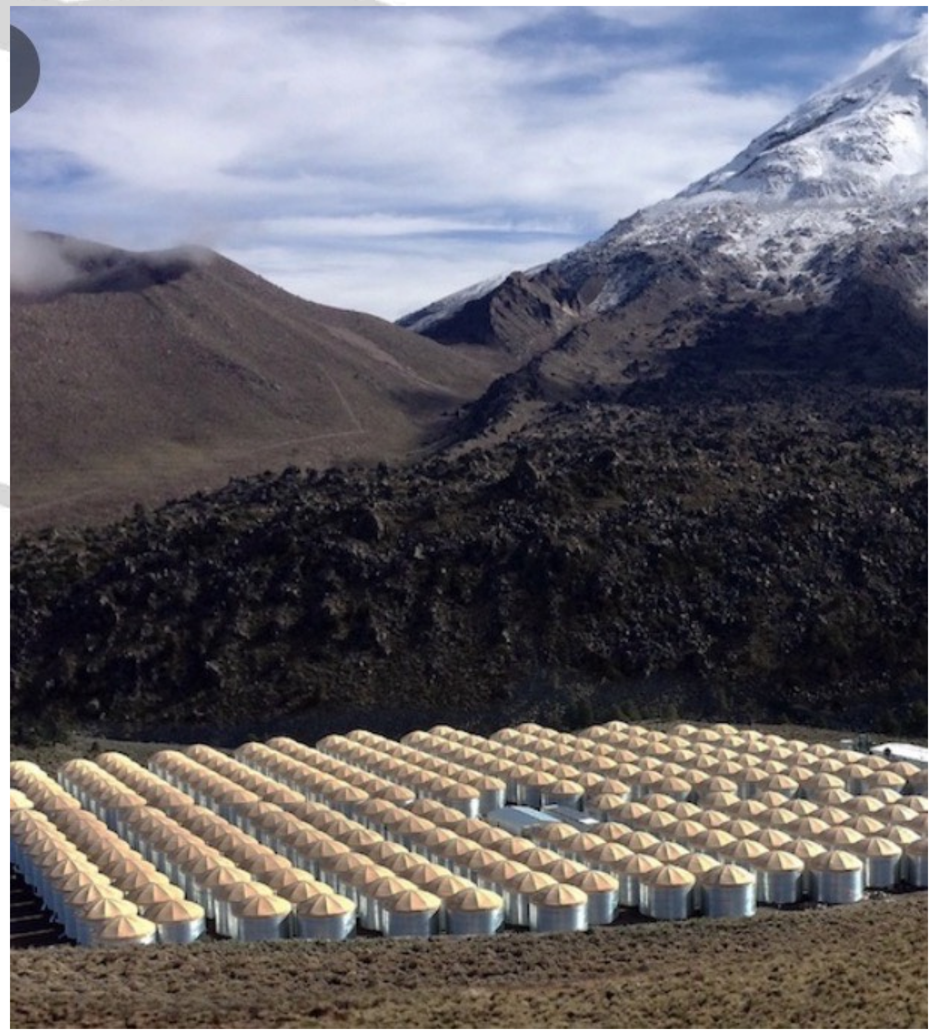


>PeV range
Wide Ground-based detectors (particles)

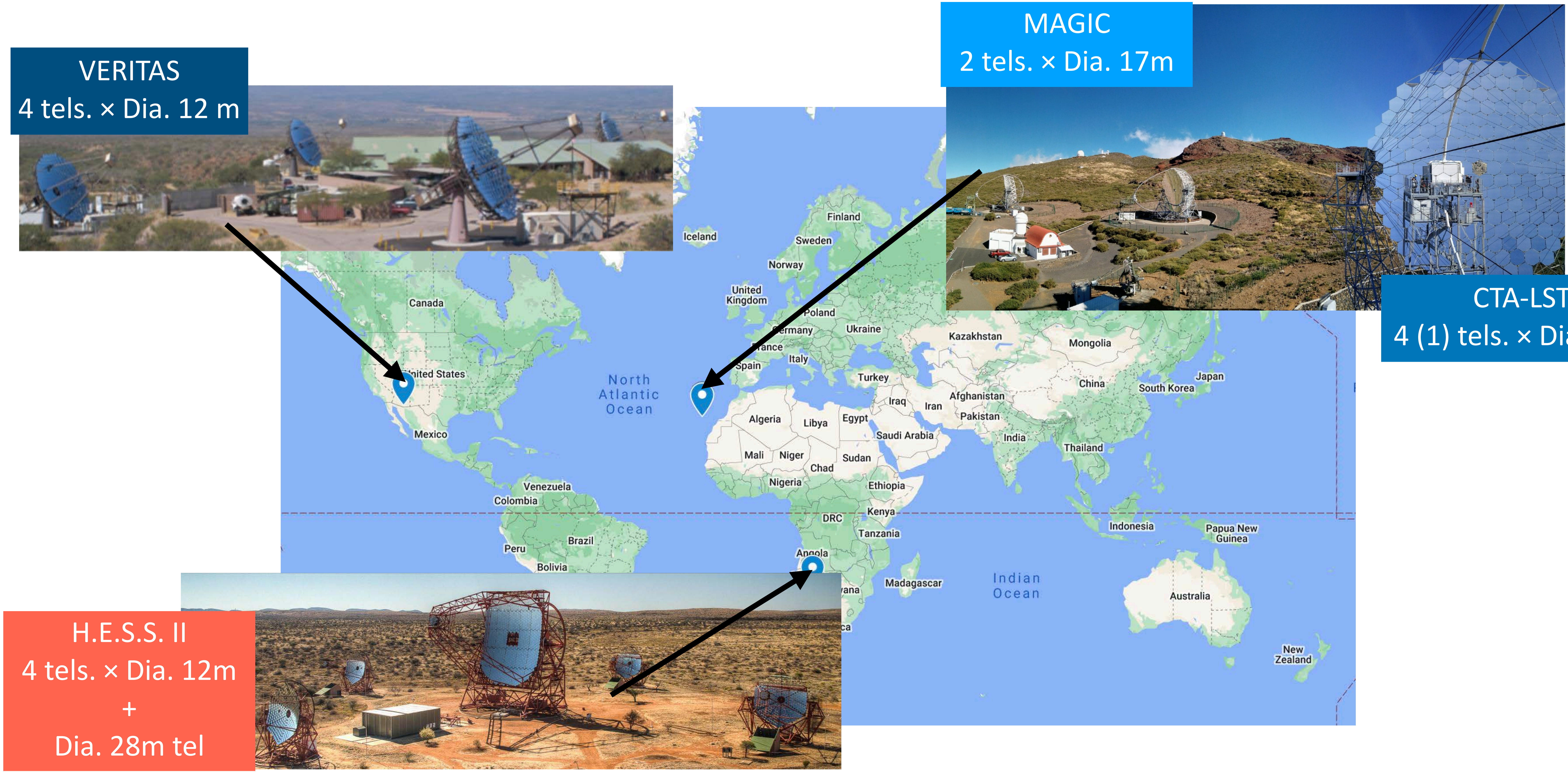
Imaging Atmospheric Cherenkov Telescopes (IACTs)

VERITAS
4 tels. × Dia. 12 m

MAGIC
2 tels. × Dia. 17m

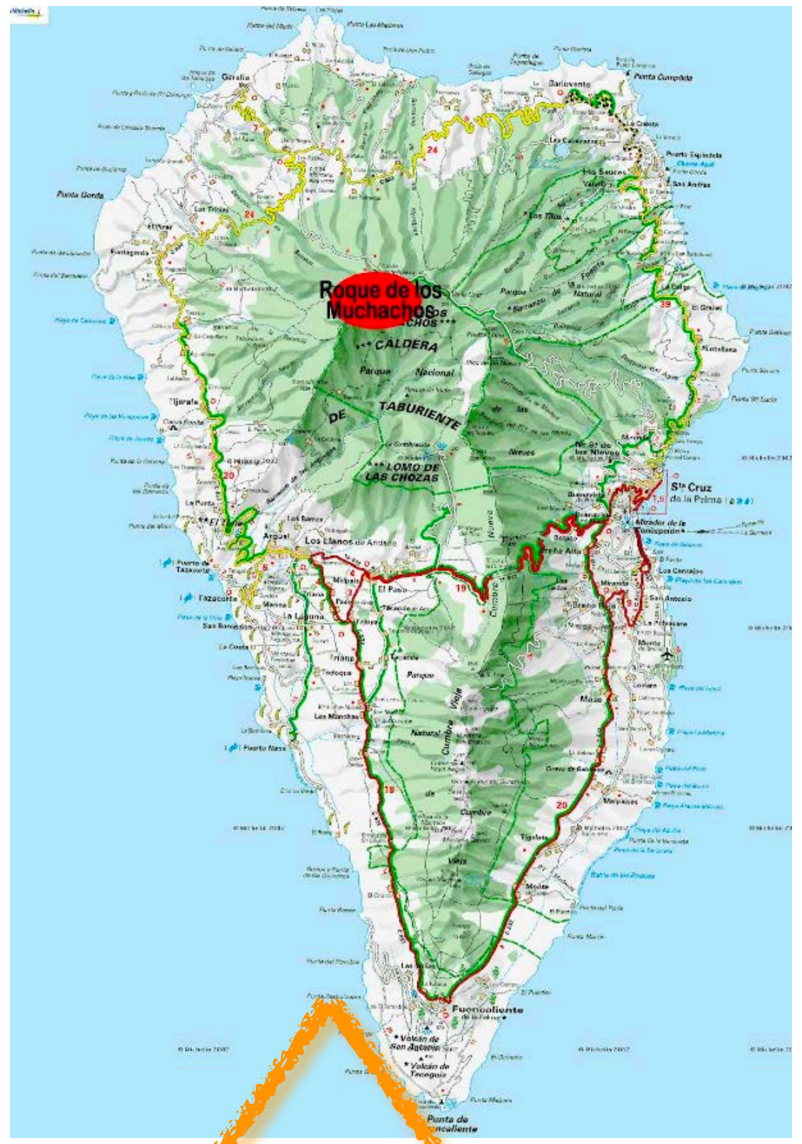
CTA-LST
4 (1) tels. × Dia. 23m

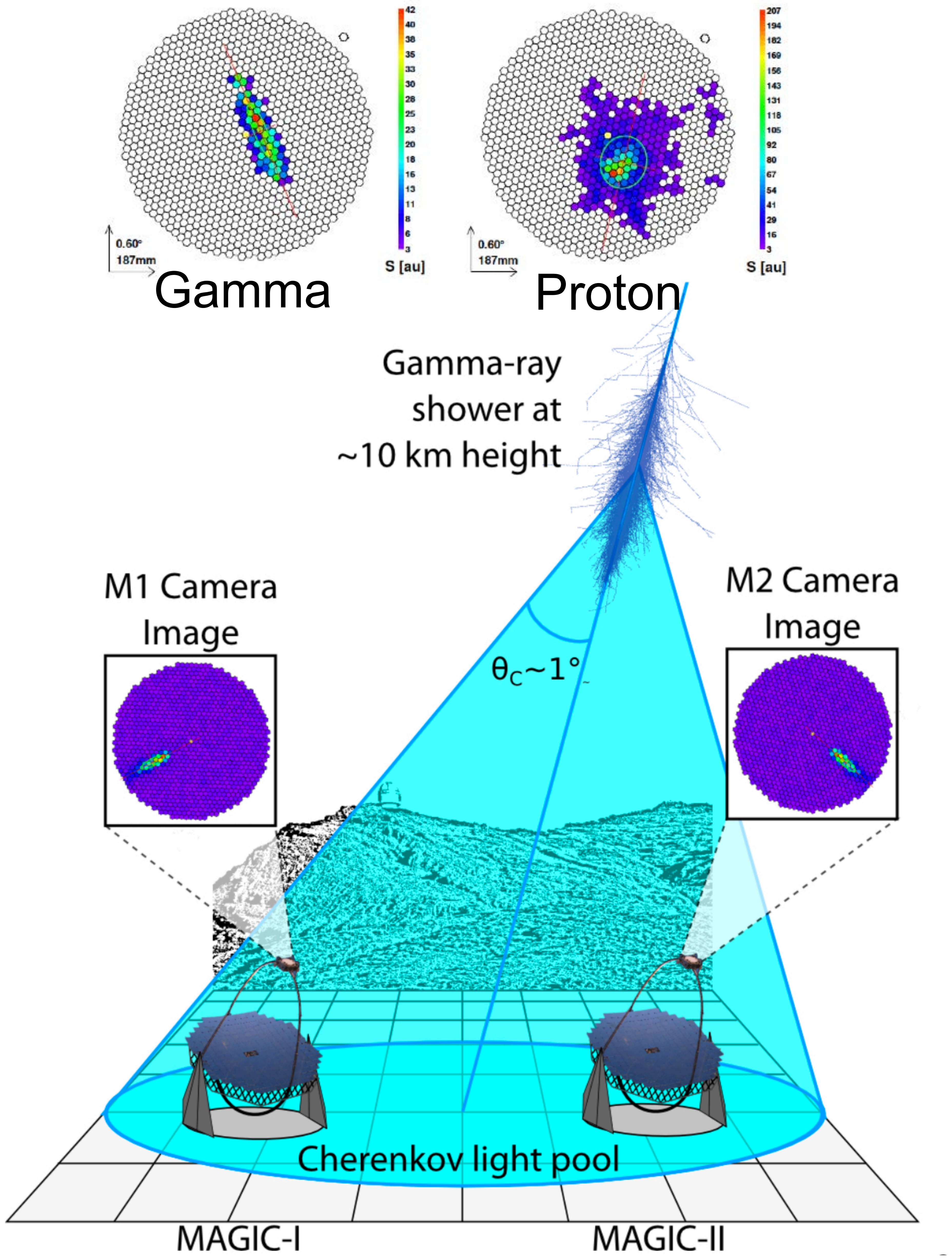
H.E.S.S. II
4 tels. × Dia. 12m
+
Dia. 28m tel



The MAGIC telescopes

- Observatorio del Roque de los Muchachos (ORM)
  - ~ 2200 m a.s.l., La Palma, Canary Islands, Spain
  - 2-telescope stereoscopic system
    - 17m diameter
- Energy : 50 GeV - 50 TeV (Low Zd ~20°)
- FoV : 3.5°
- Angular resolution : 0.06° @ 1 TeV
- Energy resolution : 15 % - 25 %

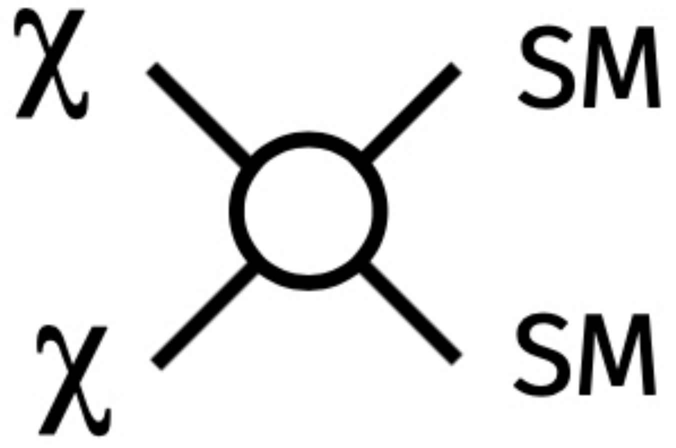




Expected gamma-ray flux from DM annihilation/decay

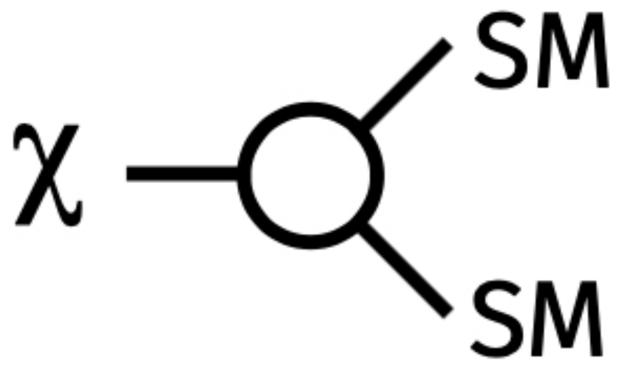
Annihilation

$$\frac{d\Phi^{ann.}}{dE_\gamma} = \frac{1}{4\pi}\frac{\sigma v}{2m_\chi^2} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho^2(s,\Omega)$$



Decay

$$\frac{d\Phi^{dec.}}{dE_\gamma} = \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho(s,\Omega)$$



Particle physics term

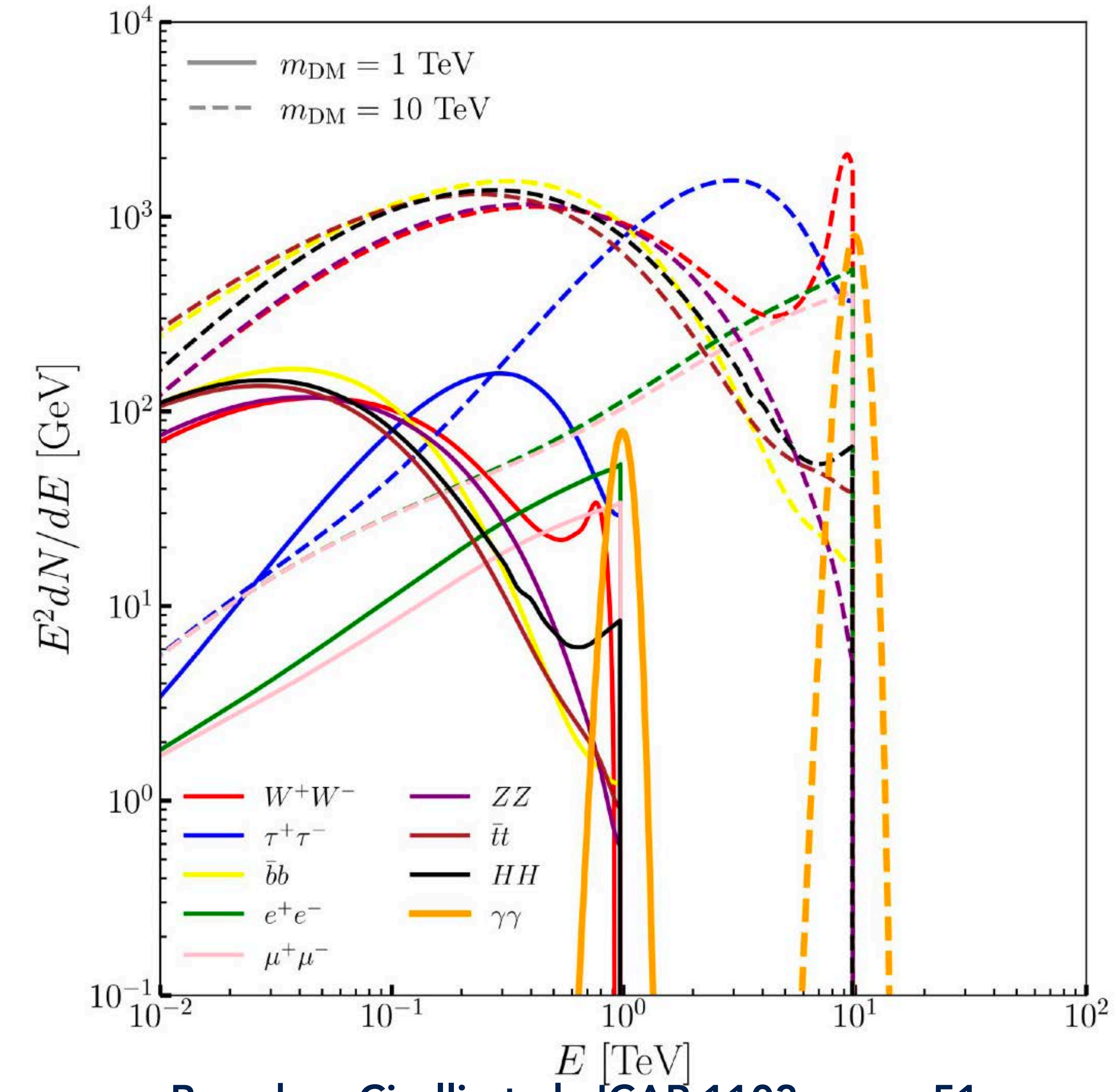
σv : annihilation cross-section, τ : lifetime
mχ : Mass of DM particle
BR_i : branching ratio of each channel
dN^i/dE : differential gamma-ray yield of each channel

Continuum spectra

- Sharp cut off at DM masses

Line-like emission

- clear peak, no contamination astrophysical component



Based on Cirelli et al. JCAP 1103, page 51

Expected gamma-ray flux from DM annihilation/decay

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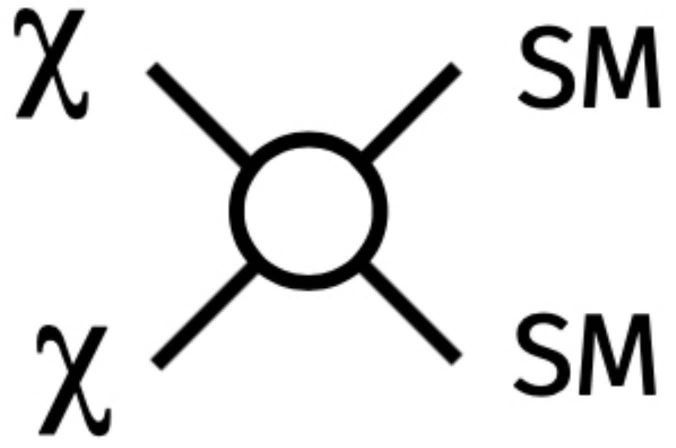

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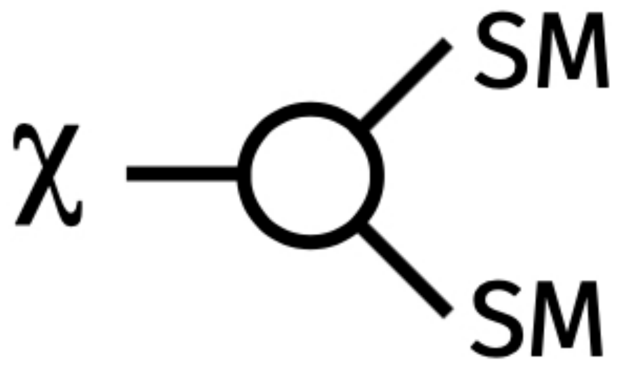
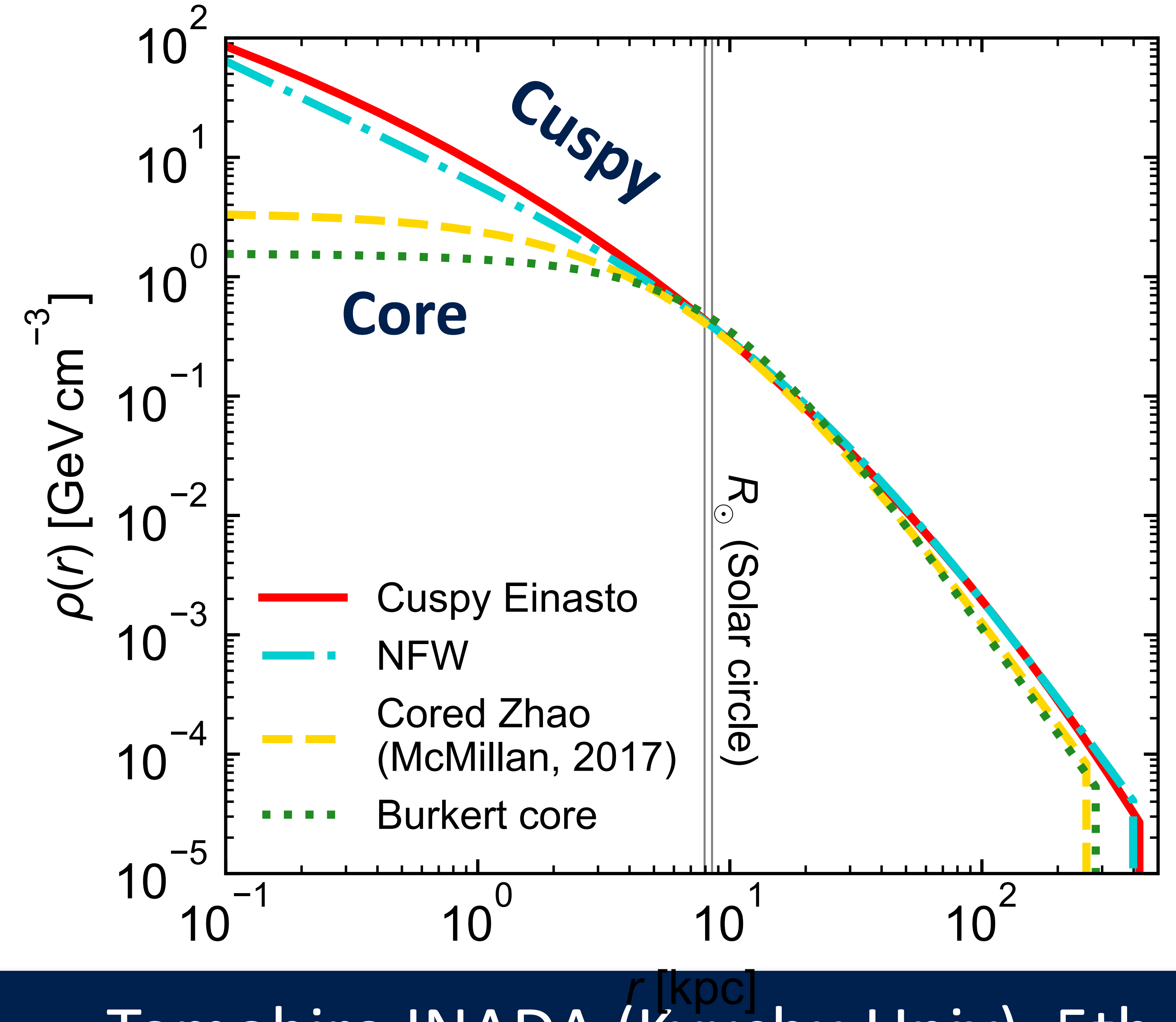




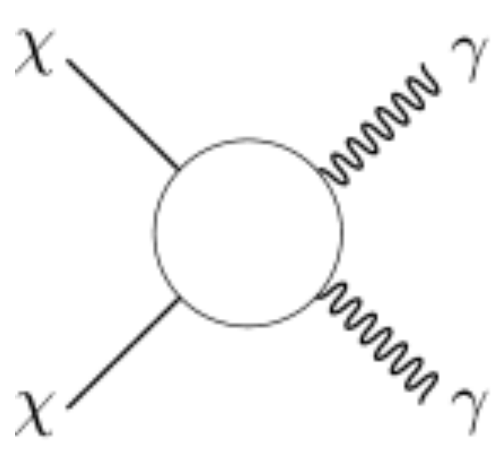
Astrophysics term

ρ : dark matter density (source-dependent)

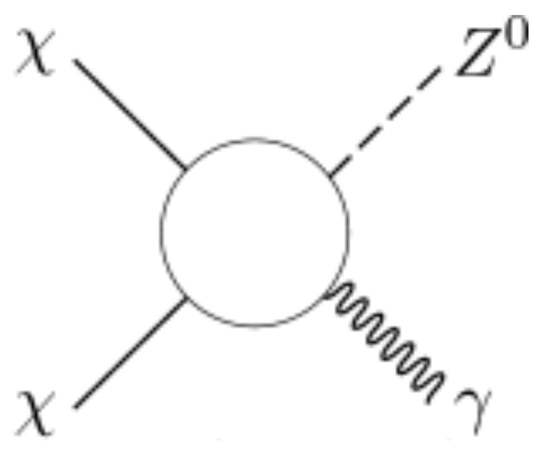
J-factor : Integrated DM density along the line of sight (in case of decay, called "D-factor")

Motivation for Gamma-ray Line signal searches

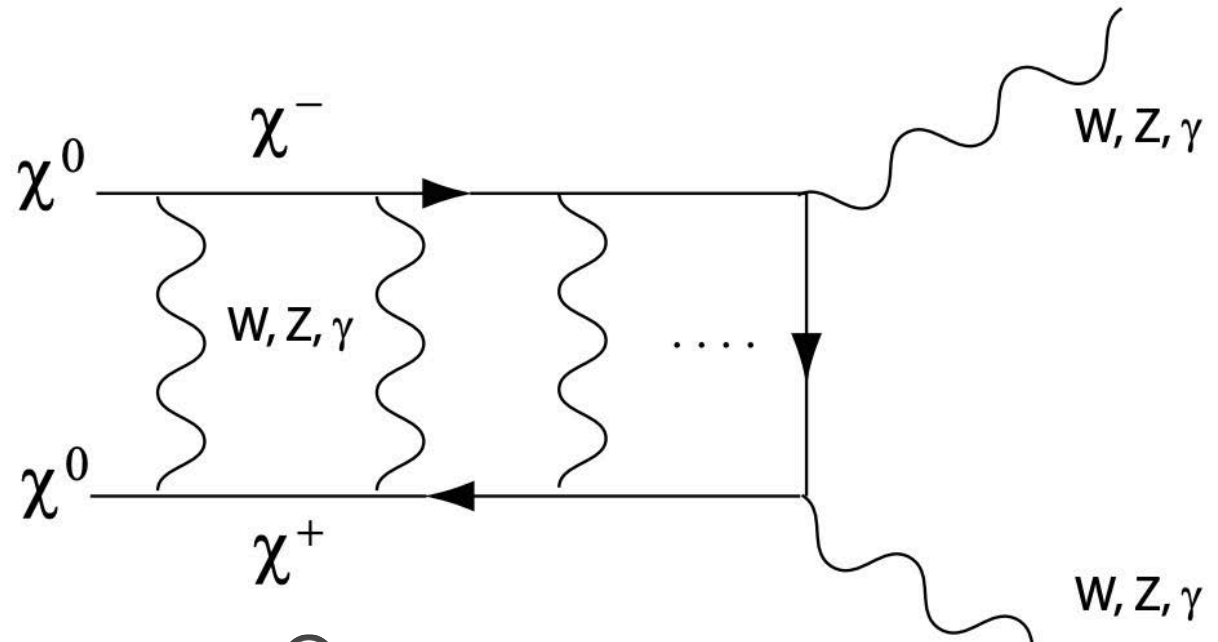
- **Clear peak at DM mass:** No astrophysical contamination
- Loop-suppressed by α^2 (i.e. the fine-structure constant)
- Some heavy DM (e.g. SUSY) models enhance their annihilation rate, called **Sommerfeld enhancement**



$\chi\chi \to \gamma\gamma$

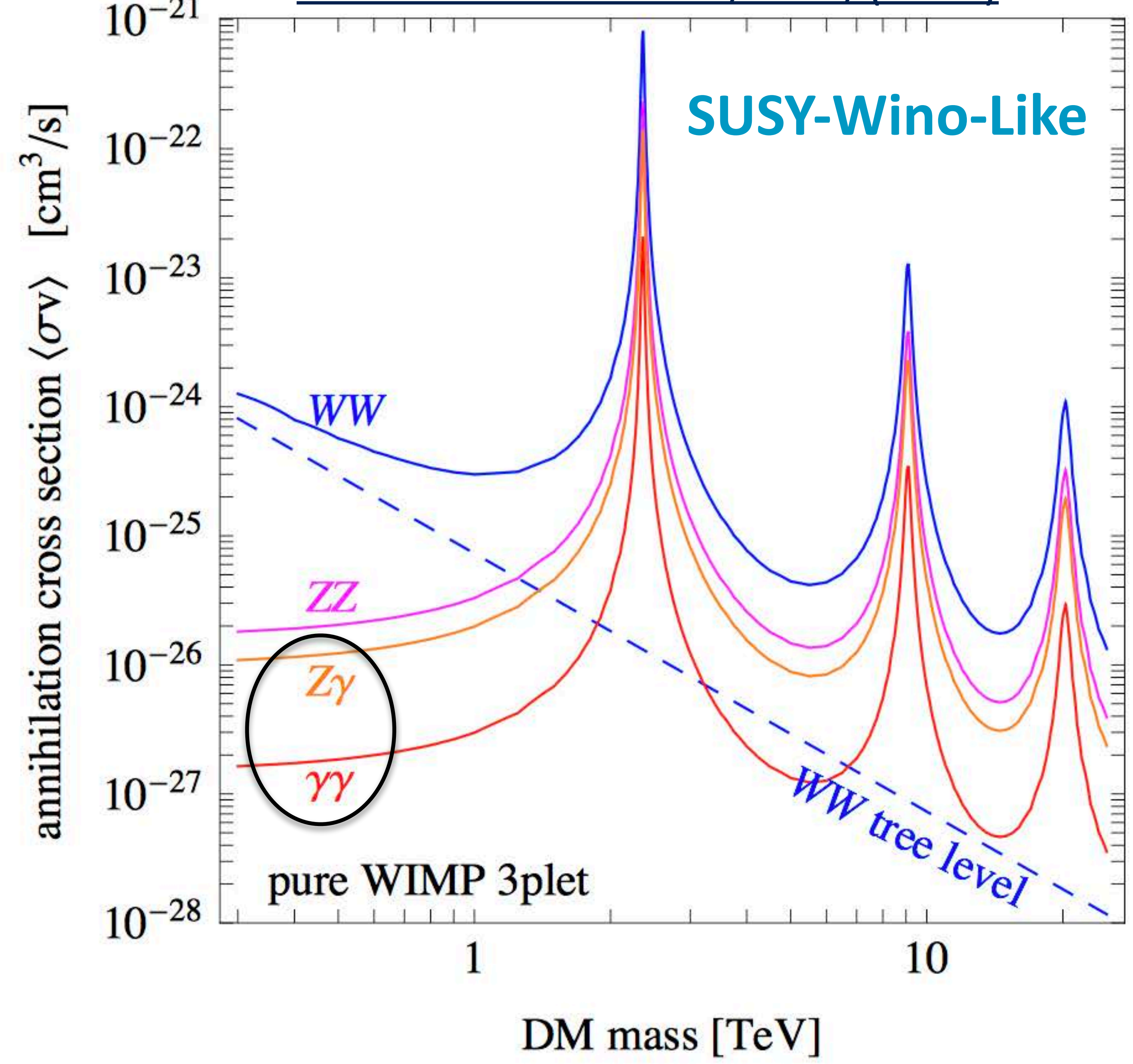


$\chi\chi \to Z\gamma$

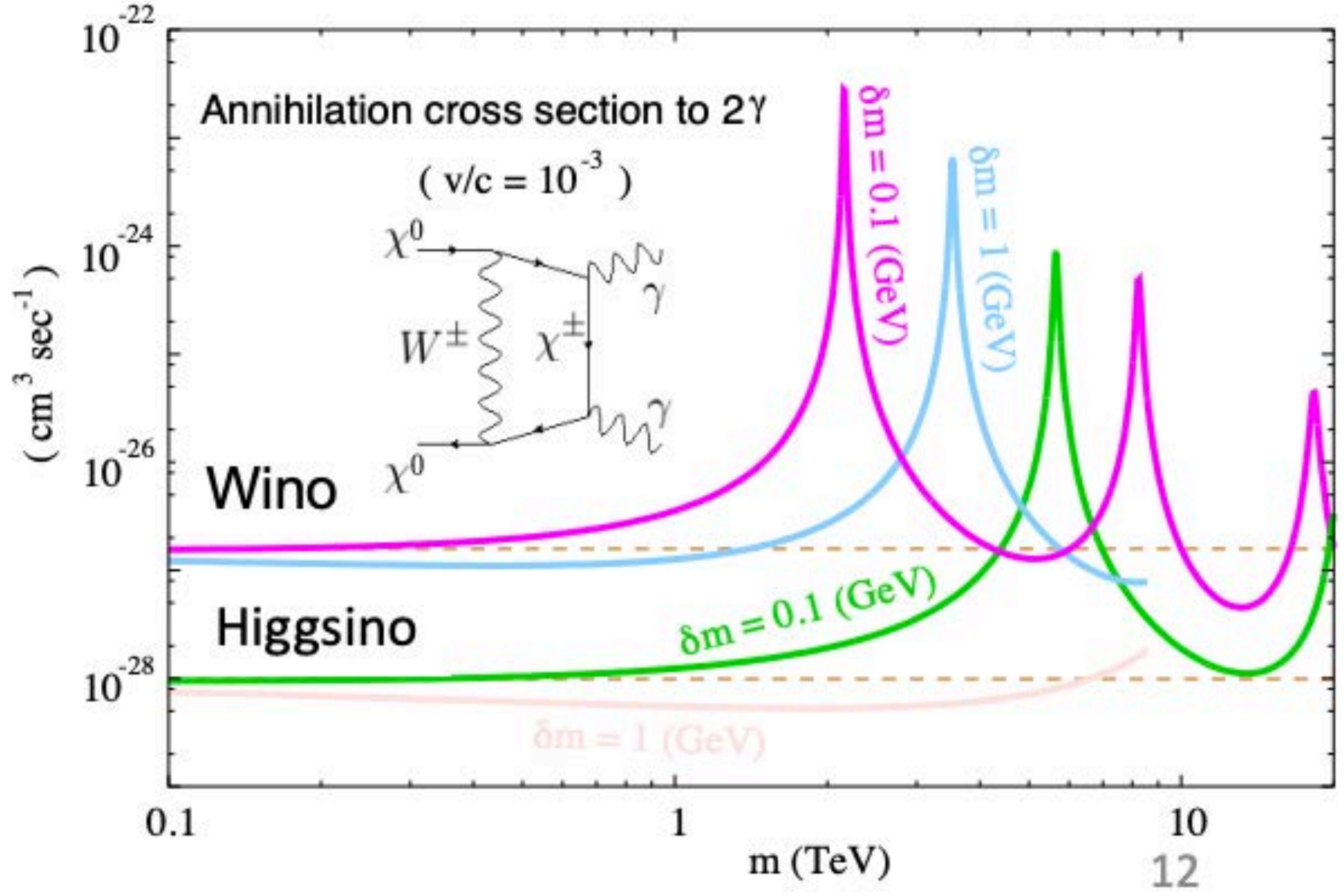


© L.Bergström

H.E.S.S. collaboration, JCAP, (2018)



J. Hisano, S. Matsumoto, and M. M. Nojiri (2004)



Observational targets

Dwarf Galaxies (dSph)

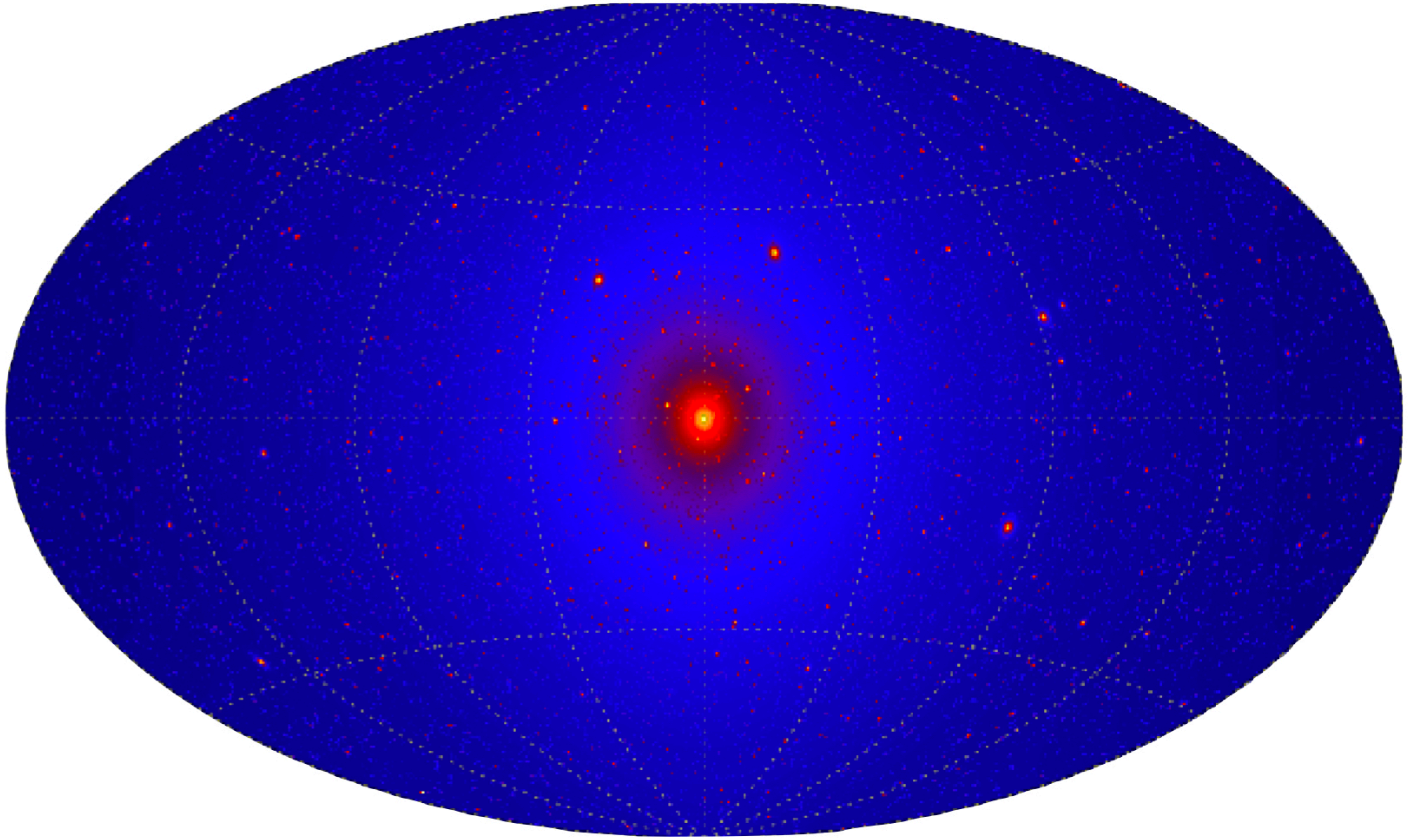
- DM dominated system
  - **less bkg**
  - low J-factor
  - **small extension**
  - Lower uncertainties in J-factor

Popular target for DM annihilation searches

$J_{ann} \sim \int DM\_density^2$

Galactic Center and Halo

- **The largest J-factor**
- Extended
- src confusion, diffuse bkg and **Cuspy/core differences in DM profiles**



Simulated all-sky map of gamma-rays from DM annihilation (Galactic coordinates) PRD 83, 023518 (2011)
N-Body simulation Via Lactea II

Galaxy Clusters

- Huge DM content
- Extended
- High Astrophysical contamination

Popular target for DM decay

$J_{dec} \sim \int DM\_density$

Current Dark Matter Searches with IACTs

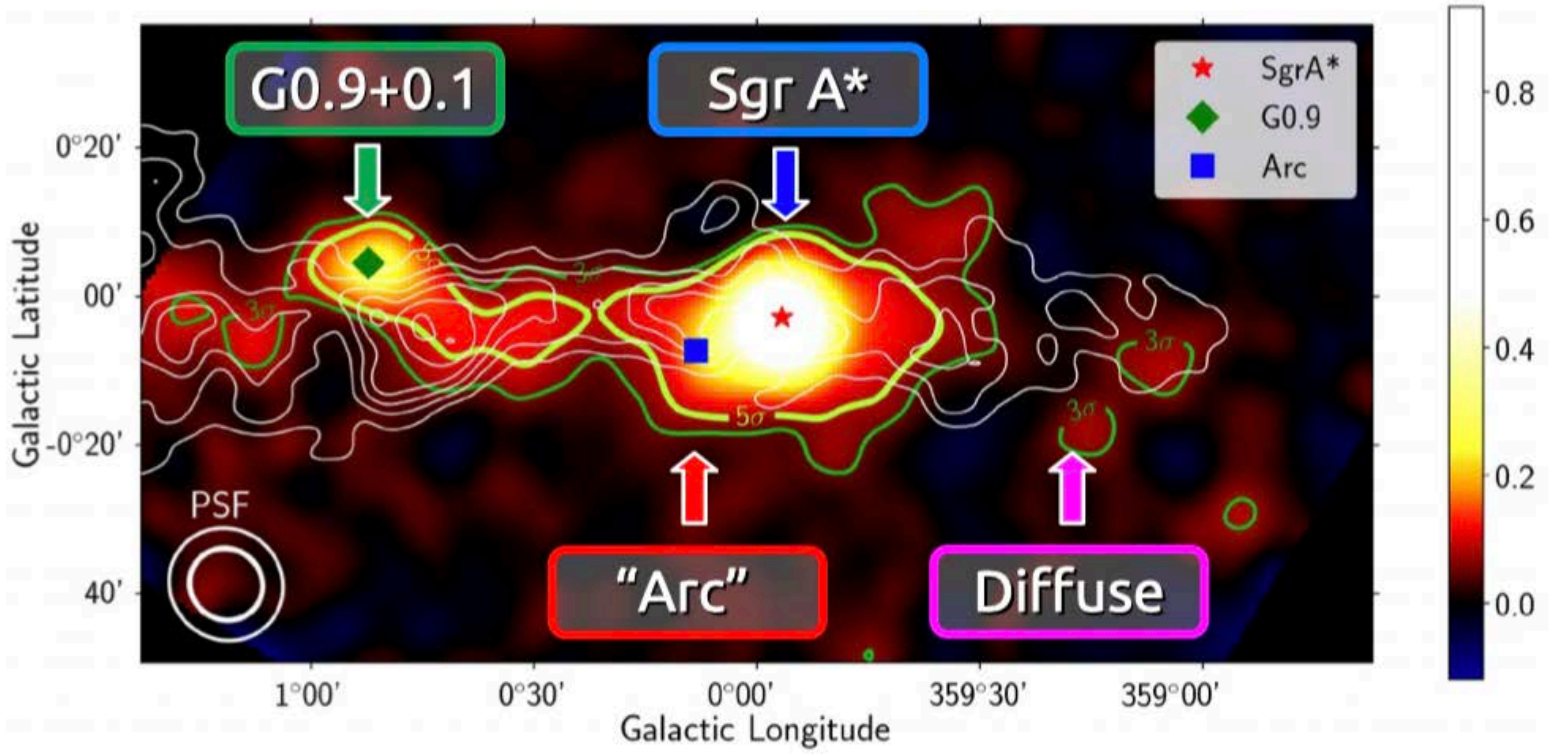
The Dark side of the Galactic Centre

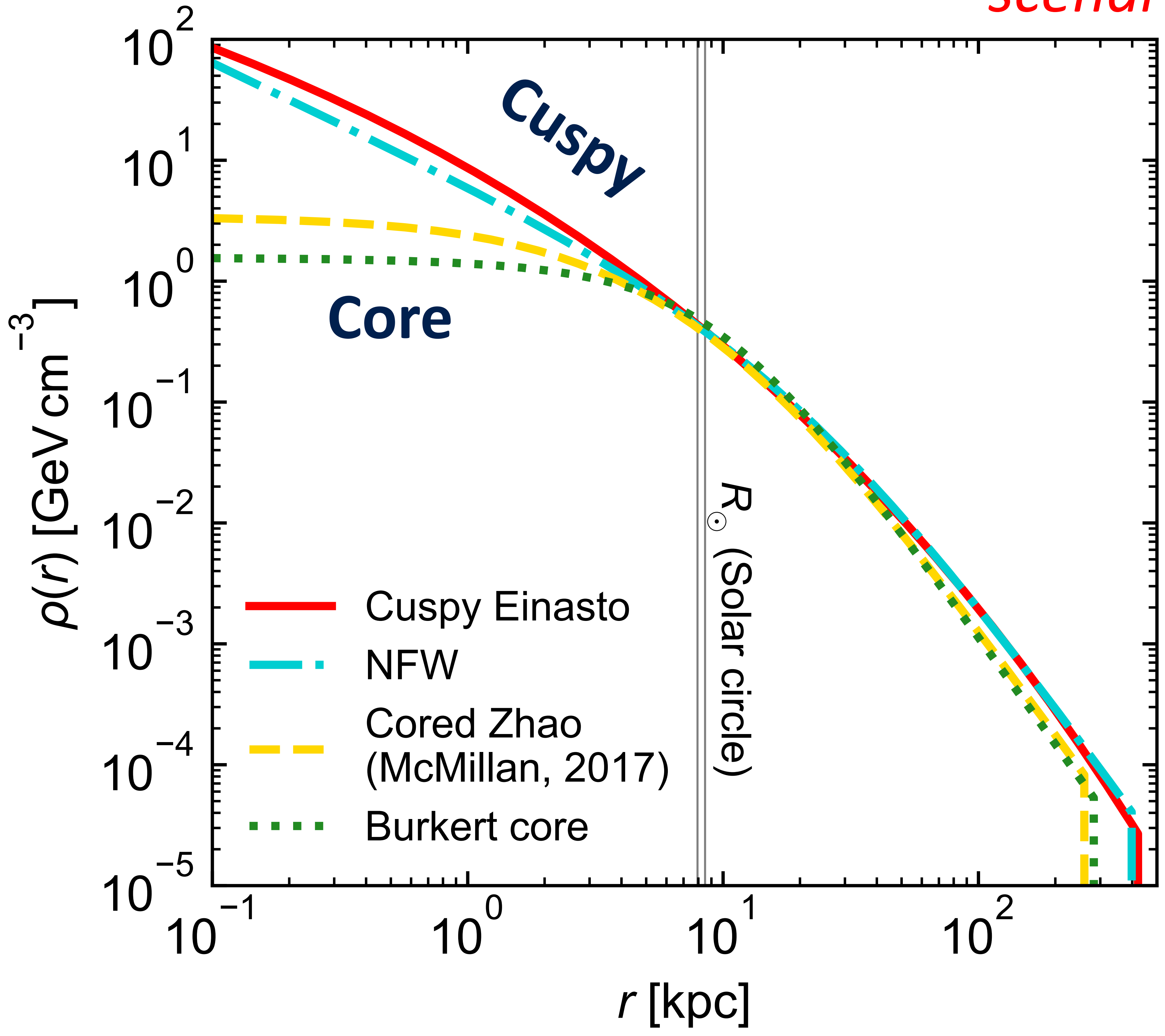
😀Pros: **The largest J-factor → the most promising!!**

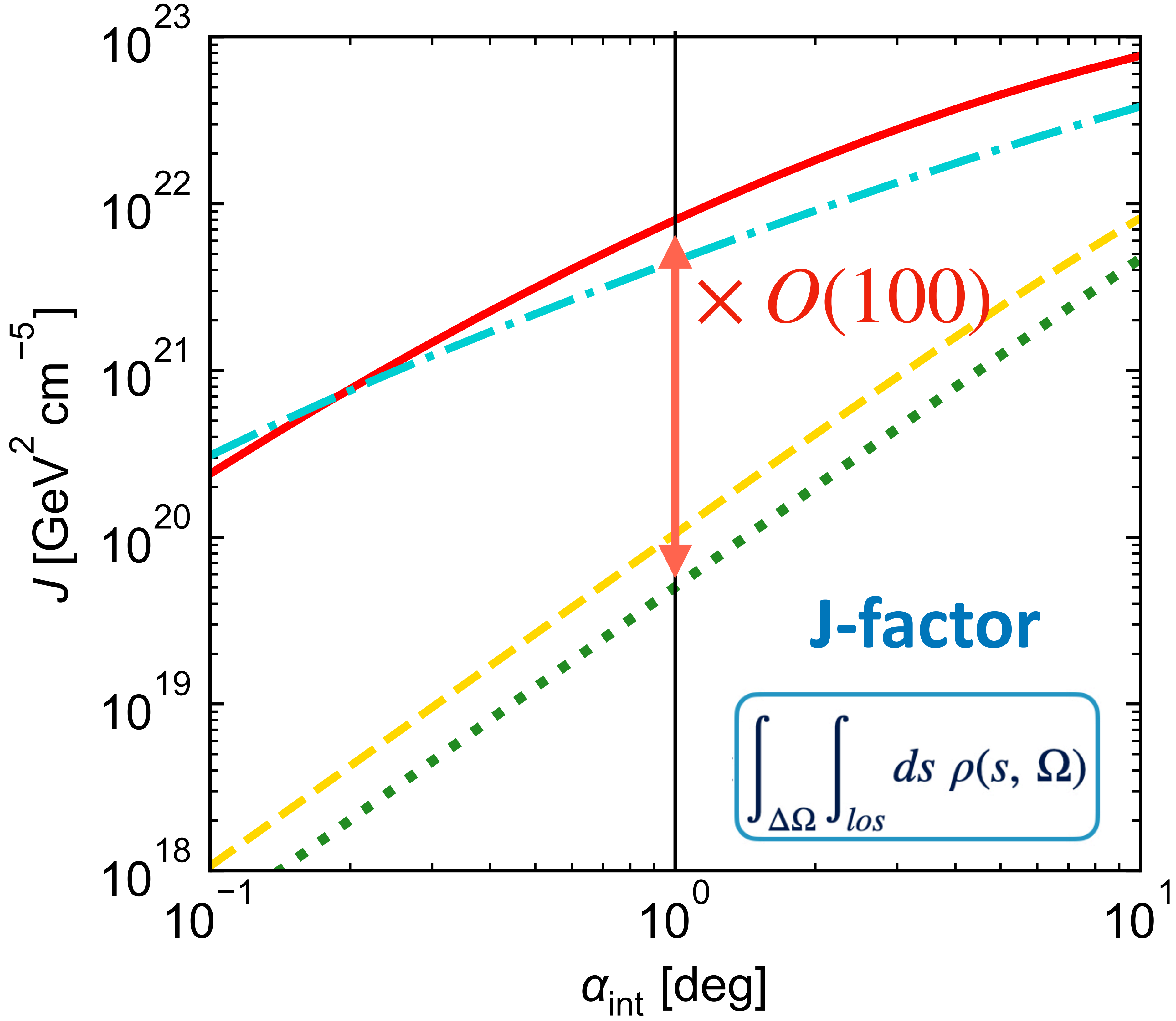
🤔Cons: Extended, src confusion, diffuse bkg

<u>**Cuspy/core differences in DM profiles**</u>

Need to think about both scenarios separately







Current status at DM searches at the GC

Dark Matter searches at the GC

- Full of excellent results from H.E.S.S. collaboration in GeV-TeV ranges due to good observational conditions for South
- Mainly focusing on **only Cuspy profiles**
  - **No results by northern telescopes for first ∼ 15 years**
- Northern telescopes need a strategy to be complementary

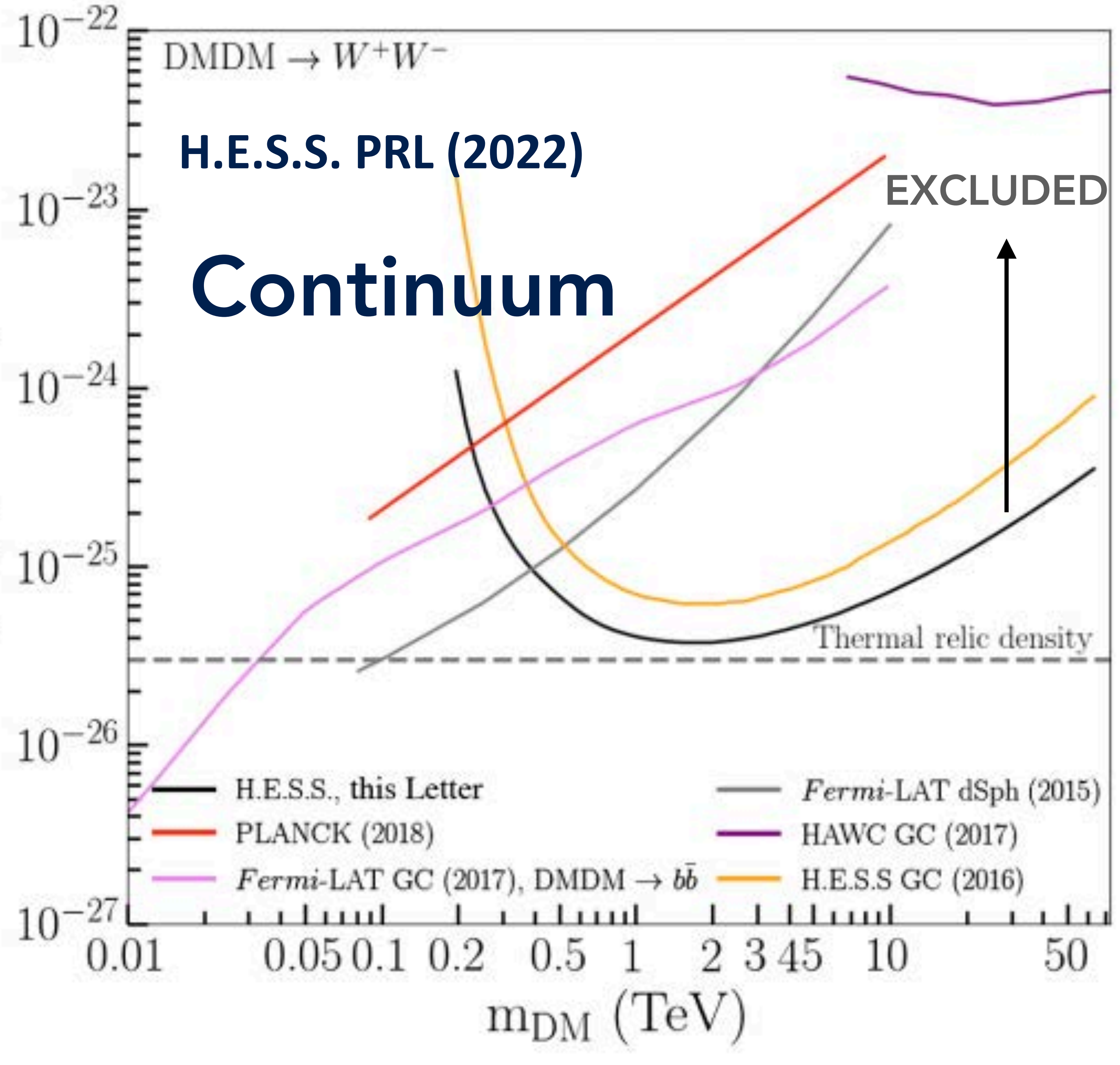
15 years

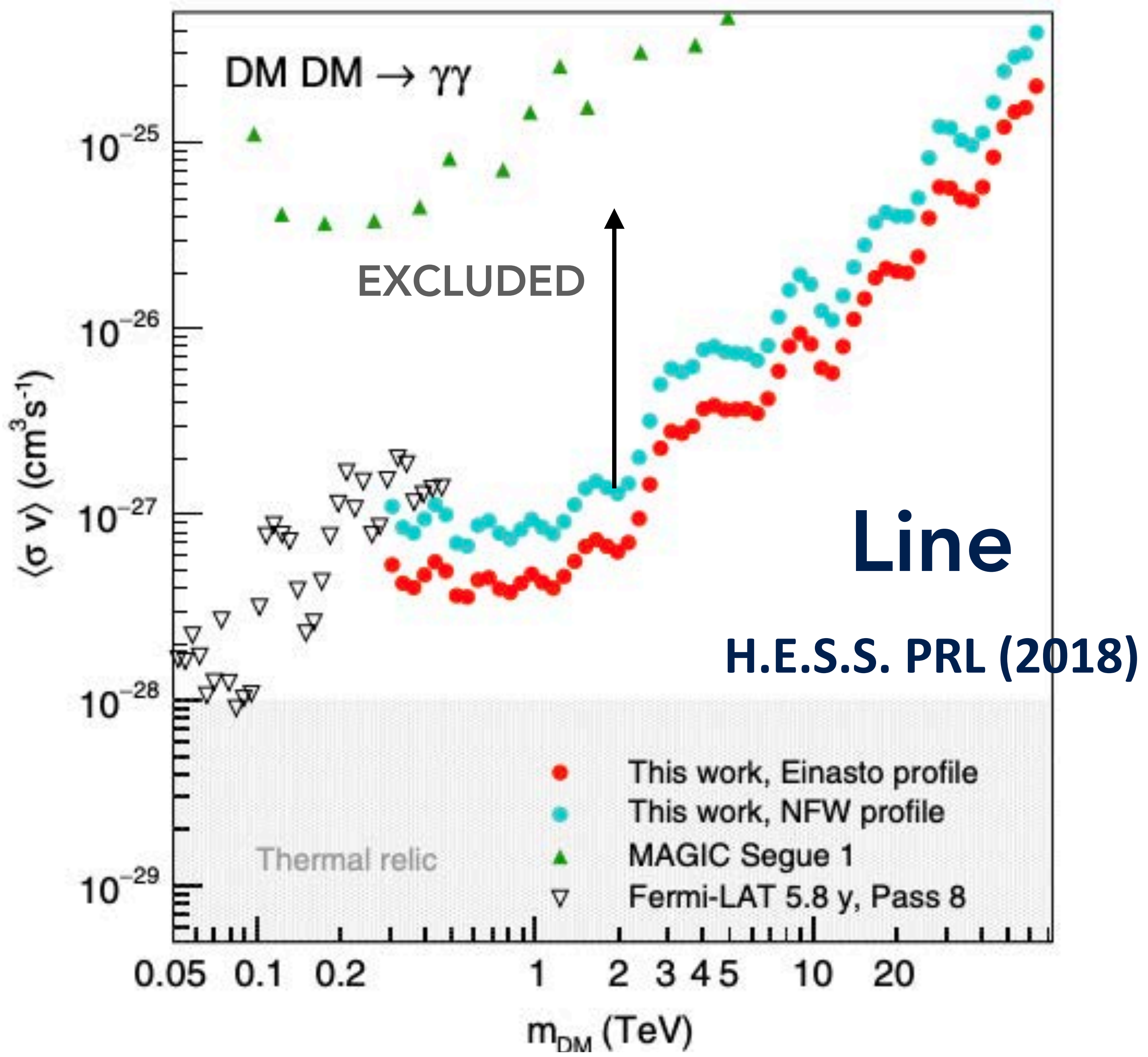
Target	Year	Time [h]	IACT	Limit	Ref.
The Milky Way central region & halo					
MW Centre	2004	(48.7)	H.E.S.S.	Ann.	Aharonian et al. (2006)
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2010	9.1		Ann.	Abramowski et al. (2015)
	2004 – 2014	254		Ann.	Abdallah et al. (2016)
	2014 – 2020	546	H.E.S.S.†	Ann.	Montanari et al. (2021)
Line searches					
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2013c)
	2014	15.2	H.E.S.S.†	Ann.	Abdalla et al. (2016)
	2004 – 2014	(254)	H.E.S.S.	Ann.	Abdalla et al. (2018b)
	2013 – 2019	204	MAGIC	Ann.	Inada et al. (2021)

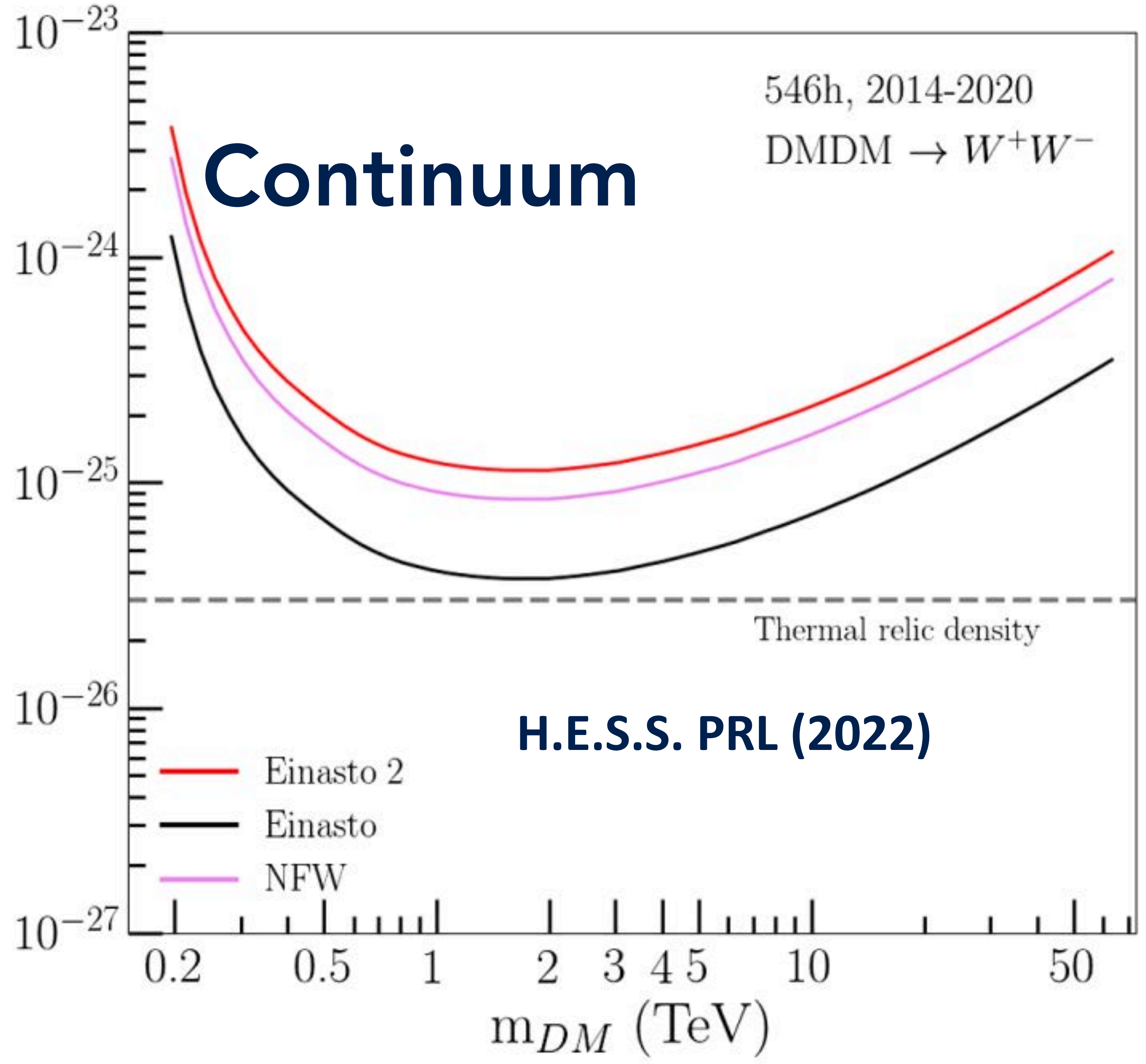
Continuum spectra search

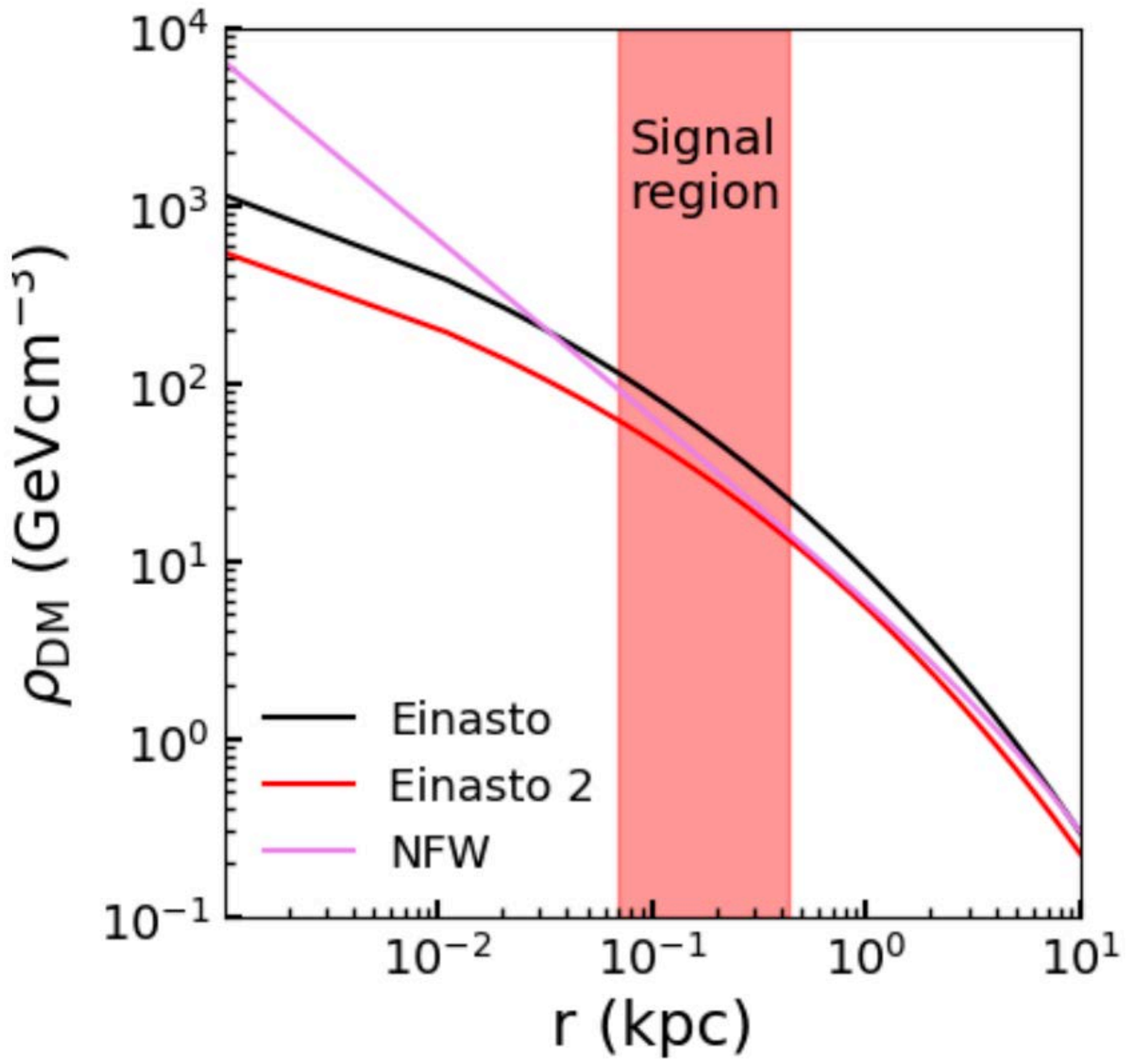
Line search

arxiv:2111.01198







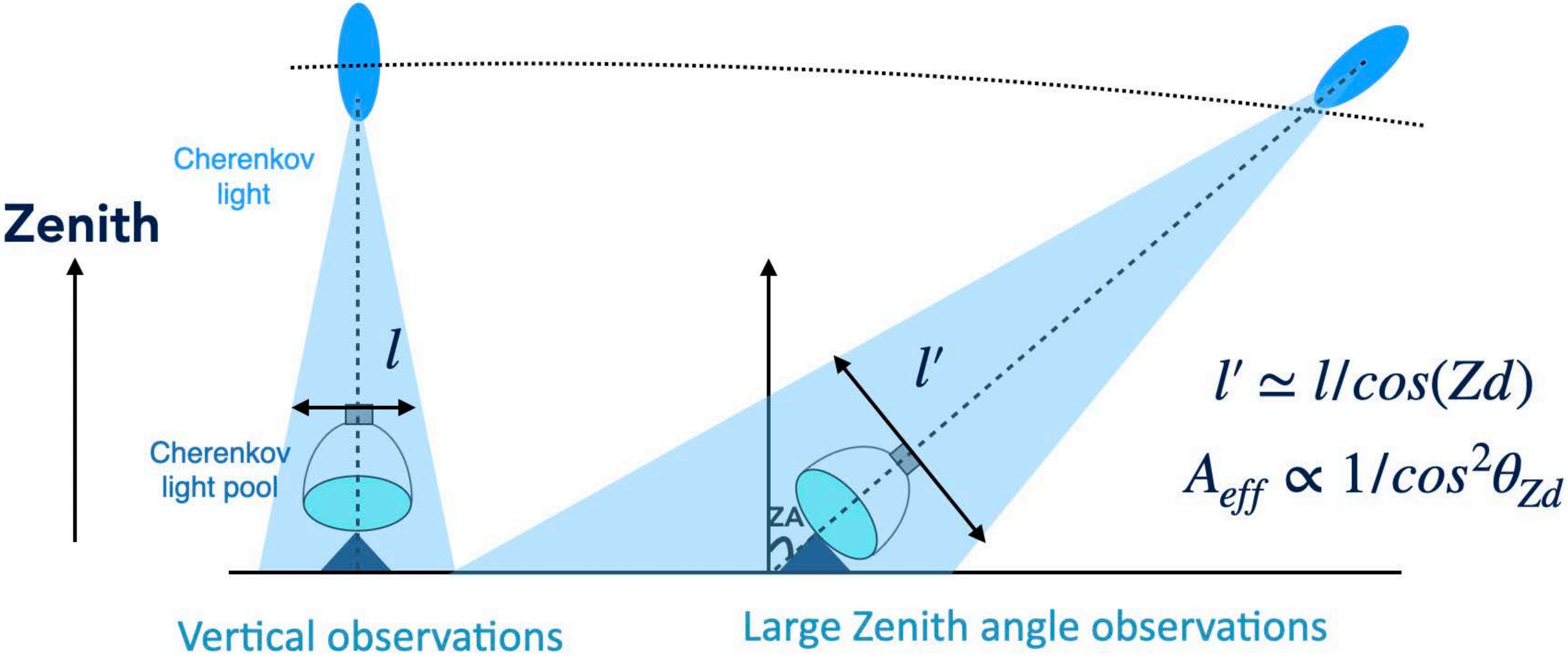


The GC observation

Key experimental fact:

- IACT performance depends on **zenith angles**
  - because of difference in a shower distance

- Nominal IACT setup: vertical observation

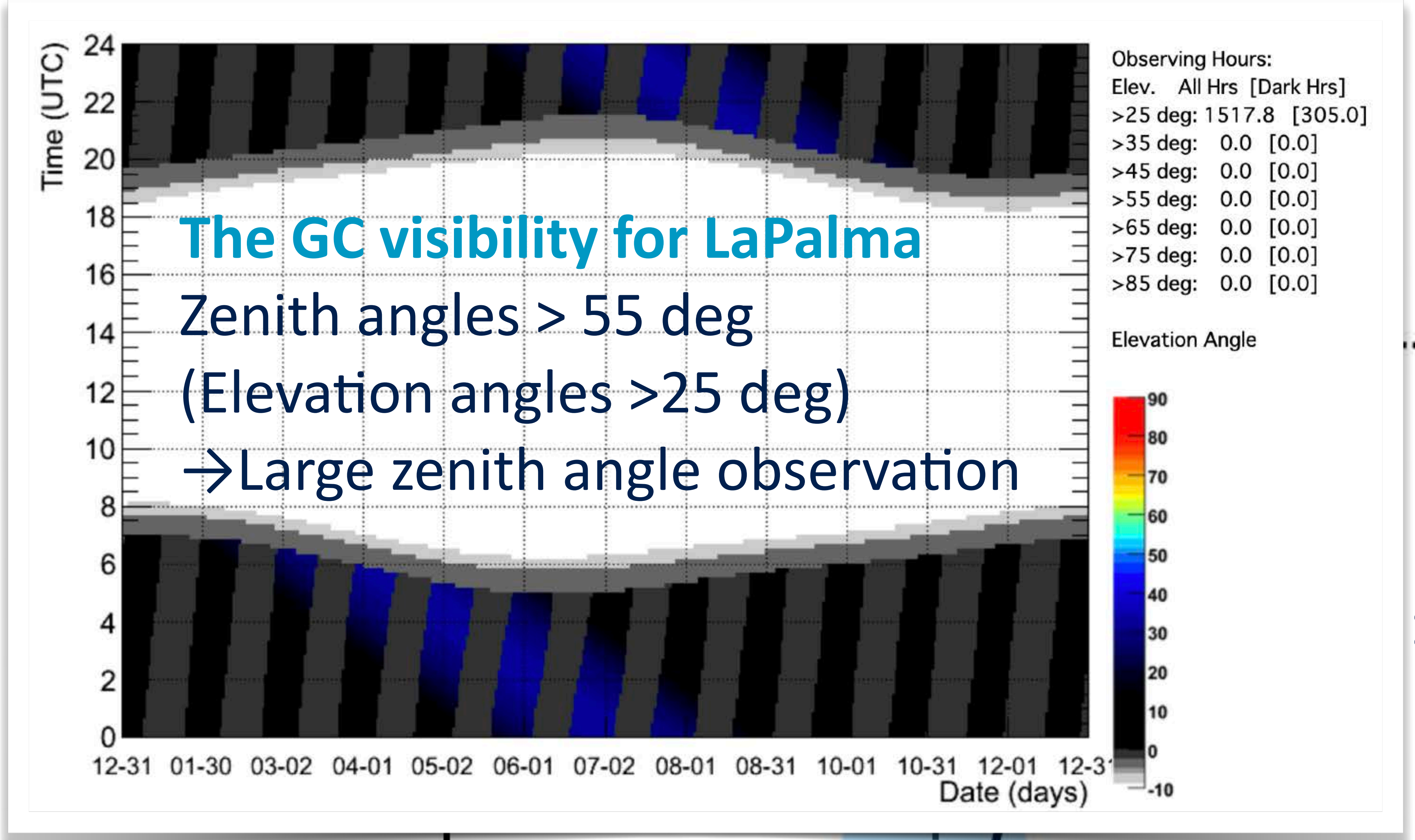


The GC observation with Northern IACTs

Key experimental fact:

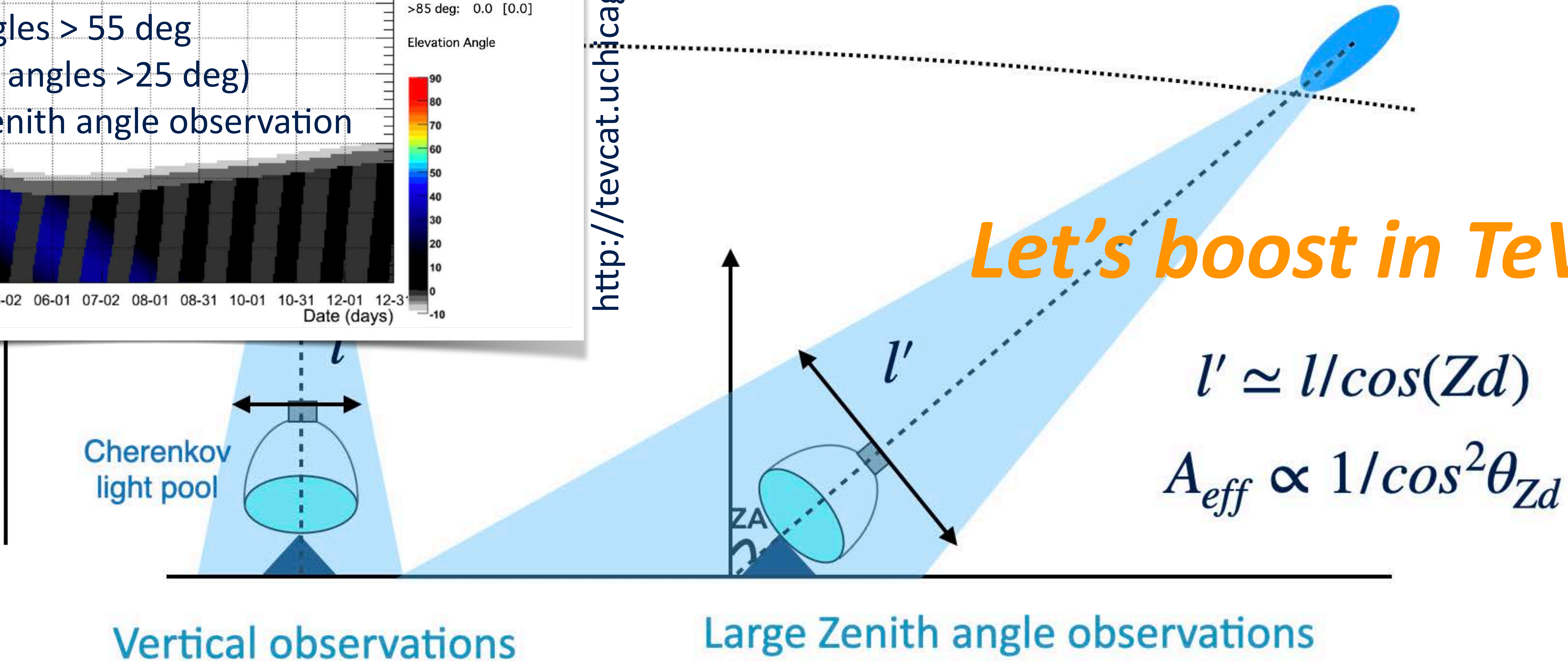
- IACT performance depends on zenith angles
  - because of difference in a shower distance

- ~~Nominal IACT setup: vertical observation~~
- **Large zenith angle observation**
  - Energy threshold: worse
  - Energy resolution: worse
  - Effective collection area: **better**
    - Good for **higher energetic** events



http://tevcat.uchicago.edu

Let's boost in TeV range!

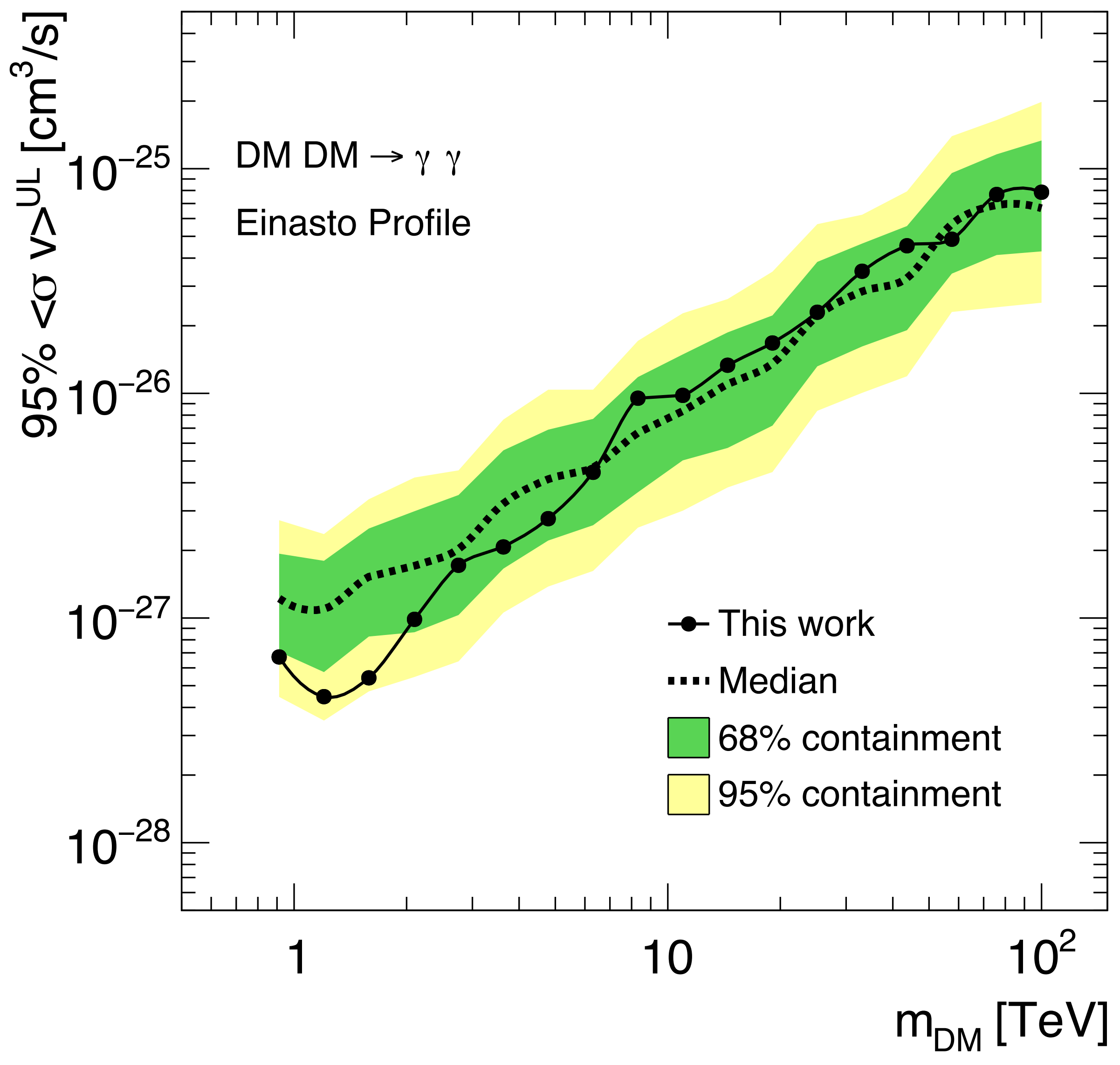


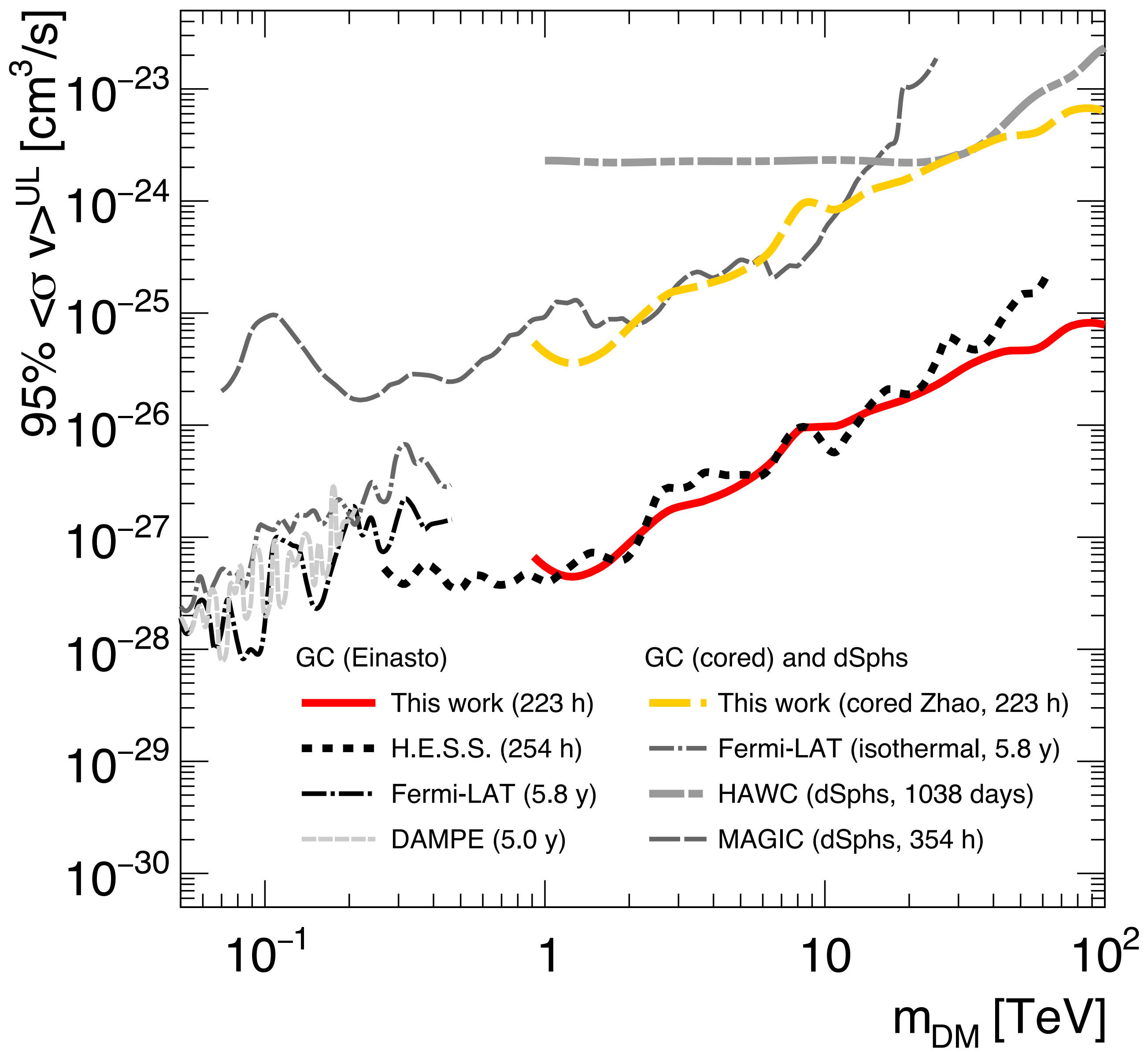
$$l' \simeq l/cos(Zd)$$

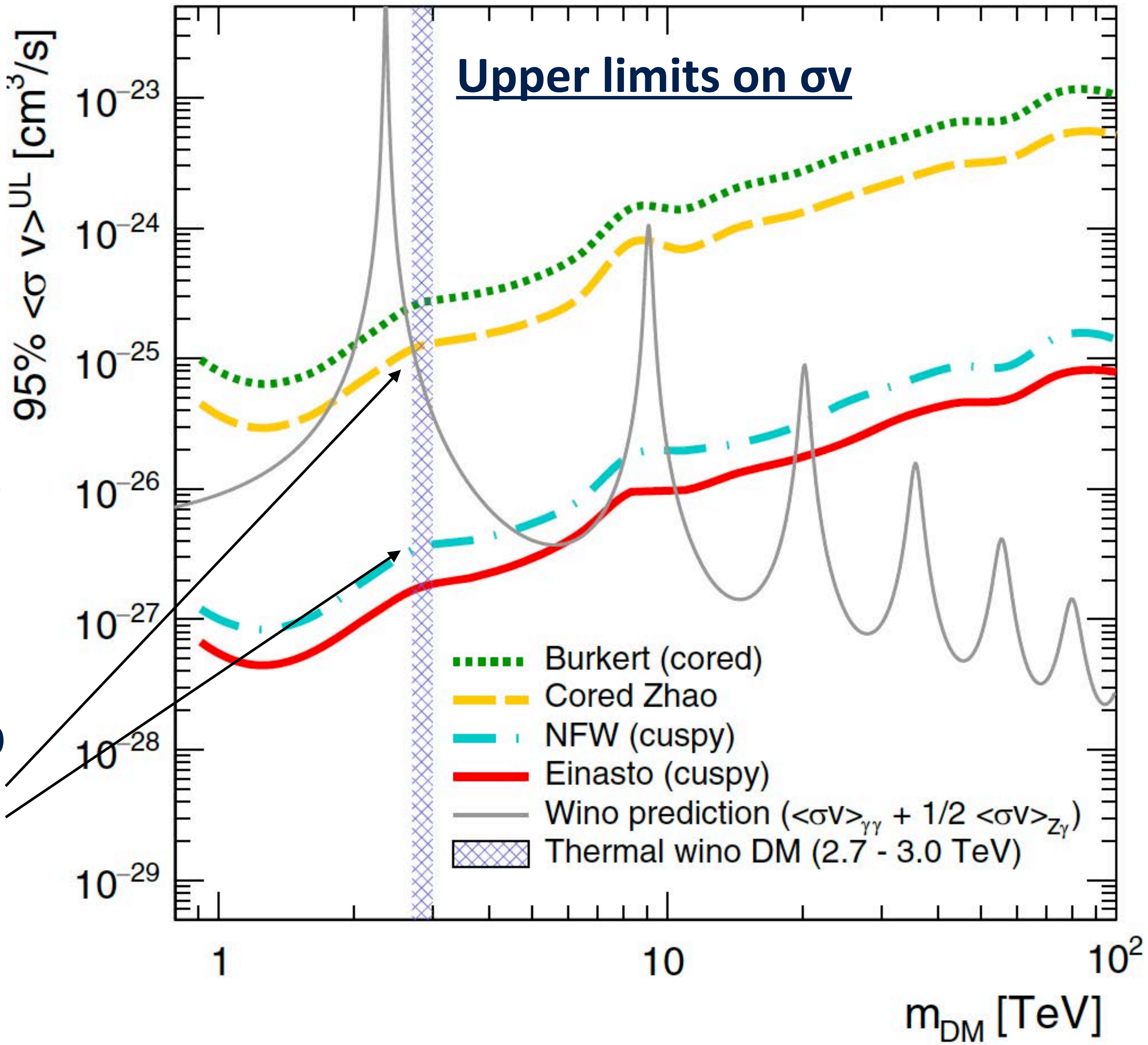
$$A_{eff} \propto 1/cos^2\theta_{Zd}$$

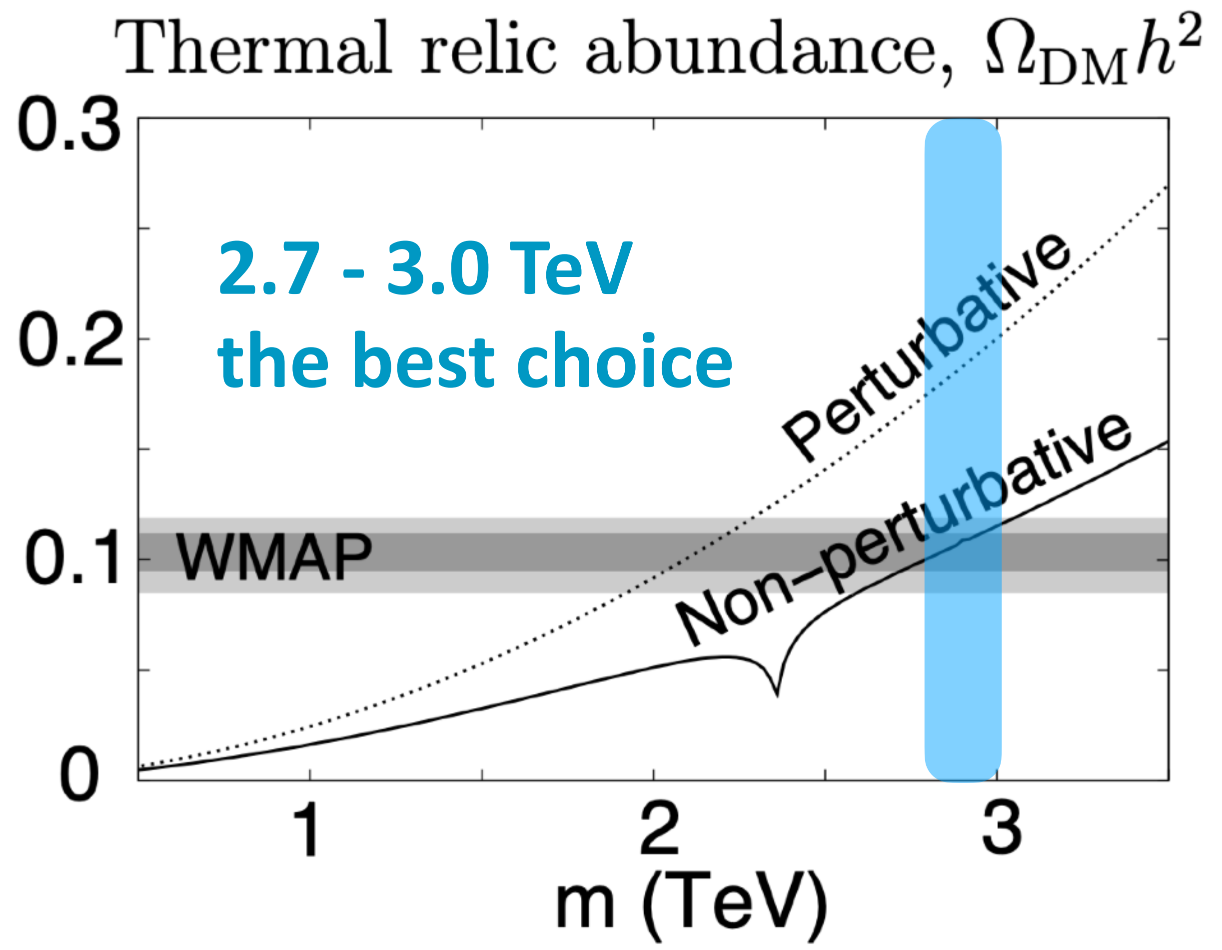
Testing SUSY-Wino with various DM profiles

MAGIC Collaboration+N. Hiroshima, K. Kohri, Phys. Rev. Lett. (2023)





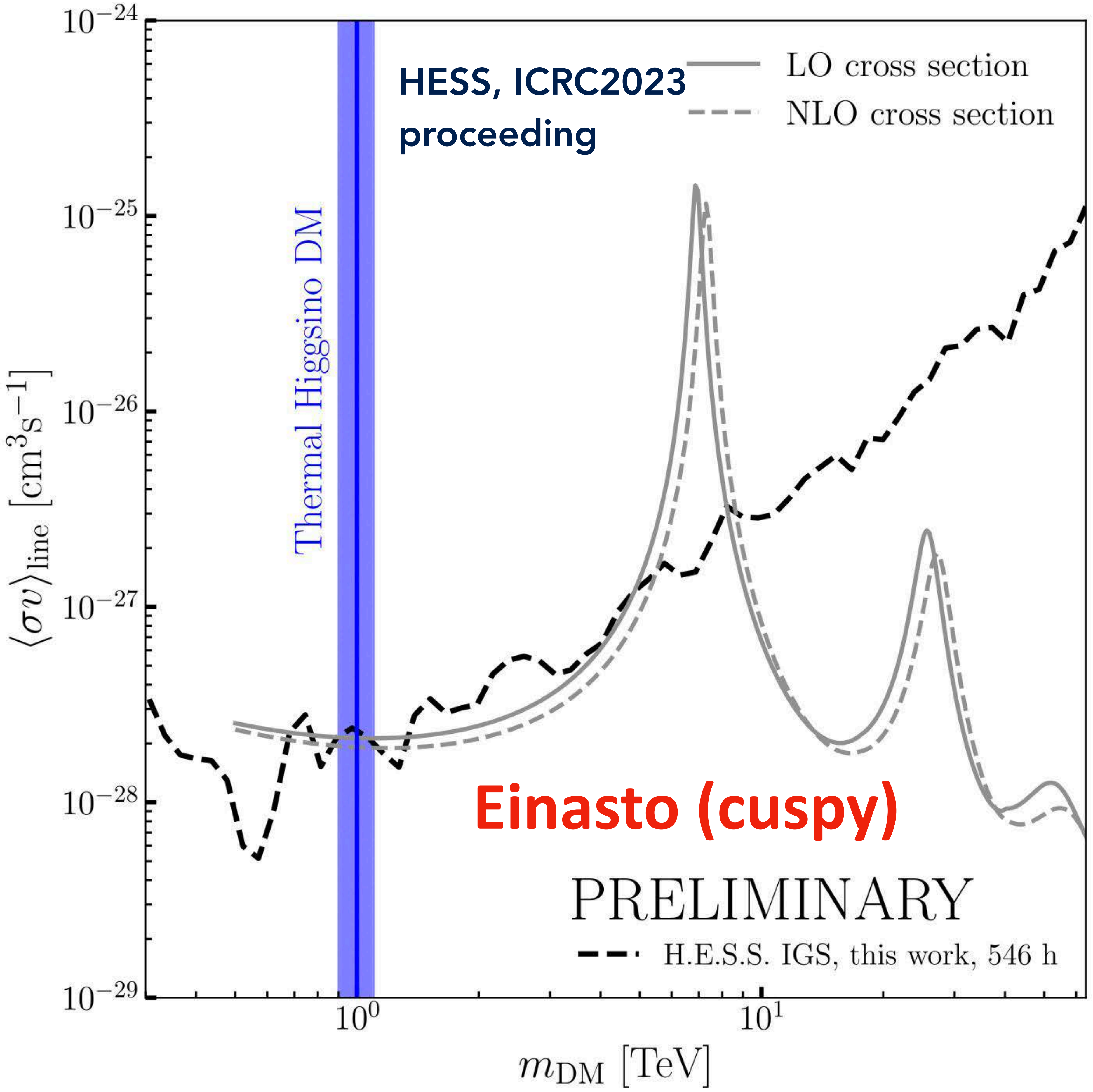




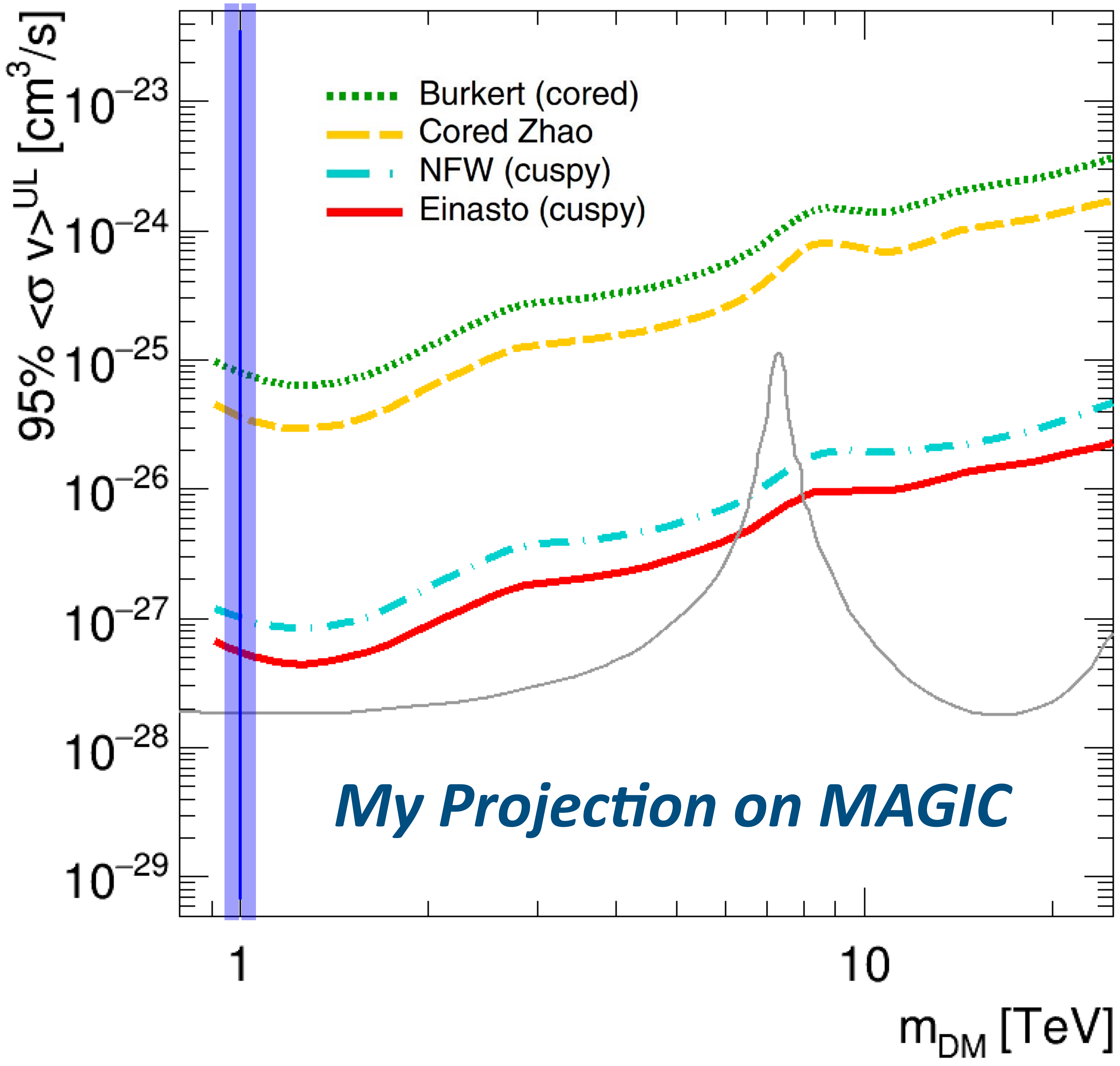
J.Hisano et al., Phys. Lett.B 646 (2007)

The first time to constrain **SUSY-wino DM** with **both cuspy** and **cored** profiles!

Challenge on Higgsino DM with the current IACT generation



Cross-section is baed on M. Beneke et al., JHEP 03 (2020), 030 [arXiv:1912.02034 [hep-ph]].



We are approaching *Higgsino DM* at *1.1 TeV*,
assuming the most optimistic a DM profile though

Dwarf Galaxies (dSph)

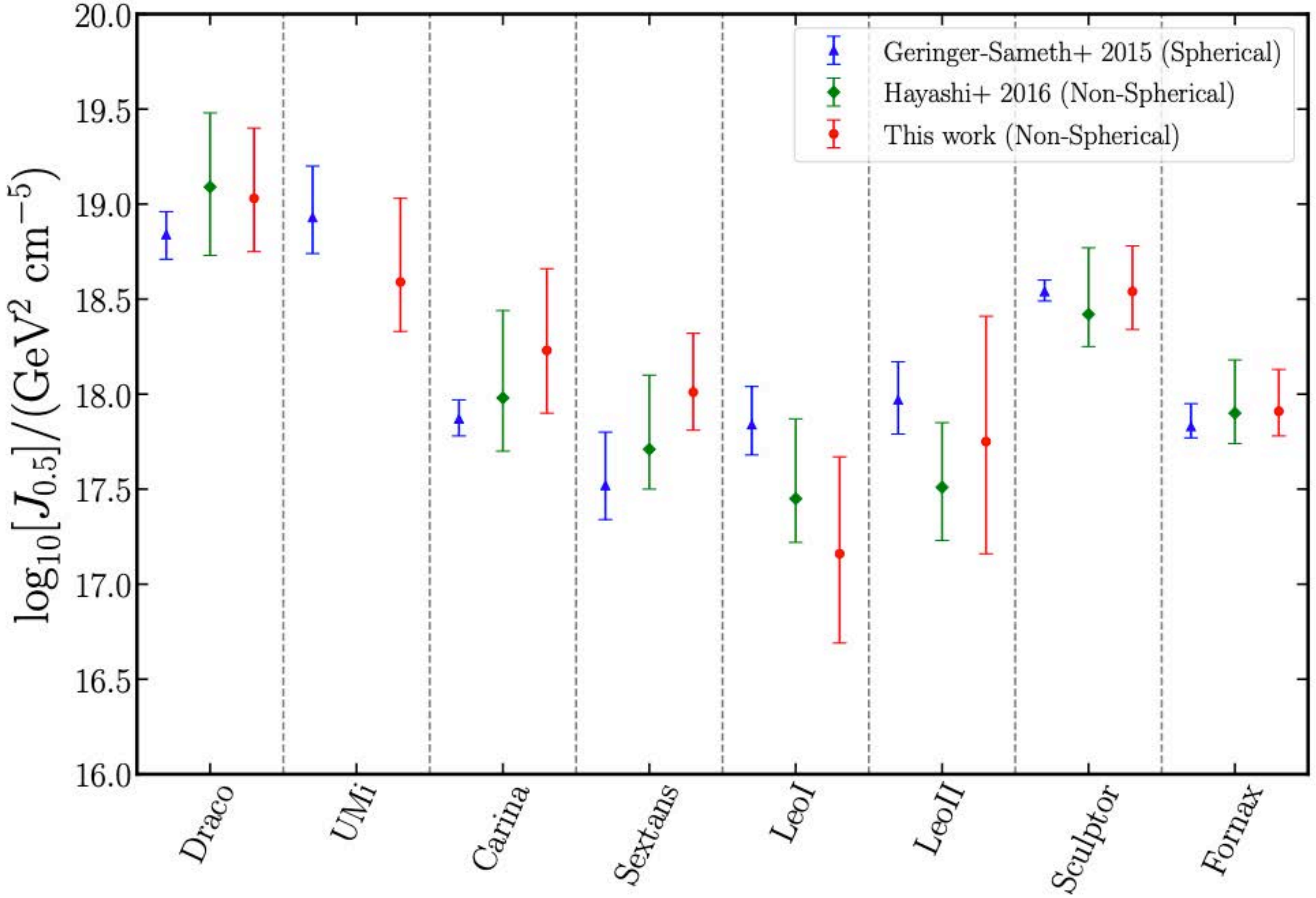
J-factor

$$\frac{d\Phi^{ann.}}{dE_\gamma} = \frac{1}{4\pi}\frac{\sigma v}{2m_\chi^2} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\, \rho^2(s,\Omega)$$

"Clean" target for DM searches

- Known satellites of the Milky Way
- high mass-to-light ration
  - Up to O(1000) M/L ratios
- very few astrophysical emission expected
- One of most robust astrophysical probe into nature of DM
  - although large uncertainties (up to ×10) of J-factor but less than the difference in the GC profile

K. Hayashi et al (2020) ApJ 904 45



See K.Hayashi' talk

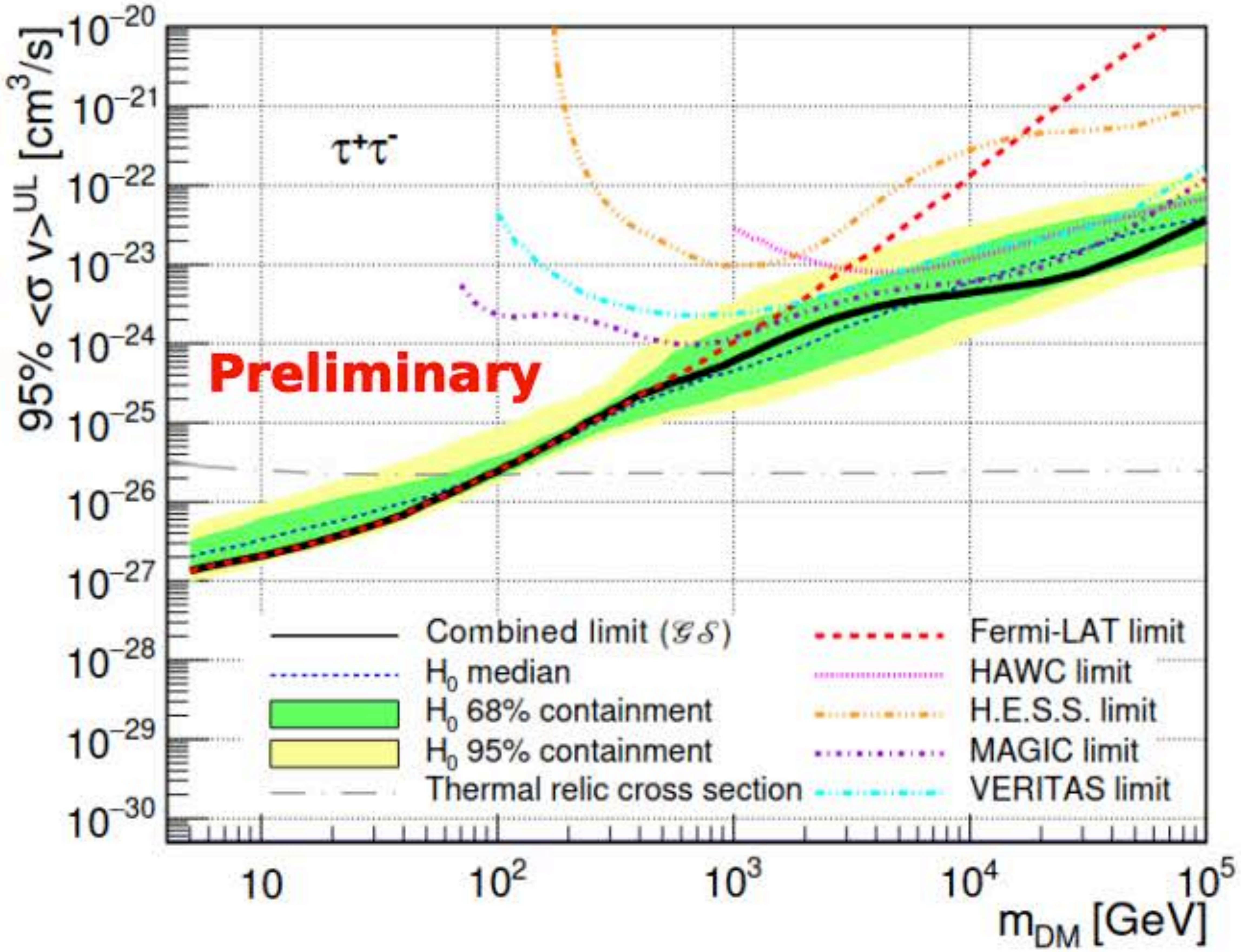
Combination of dSph results: five experiments

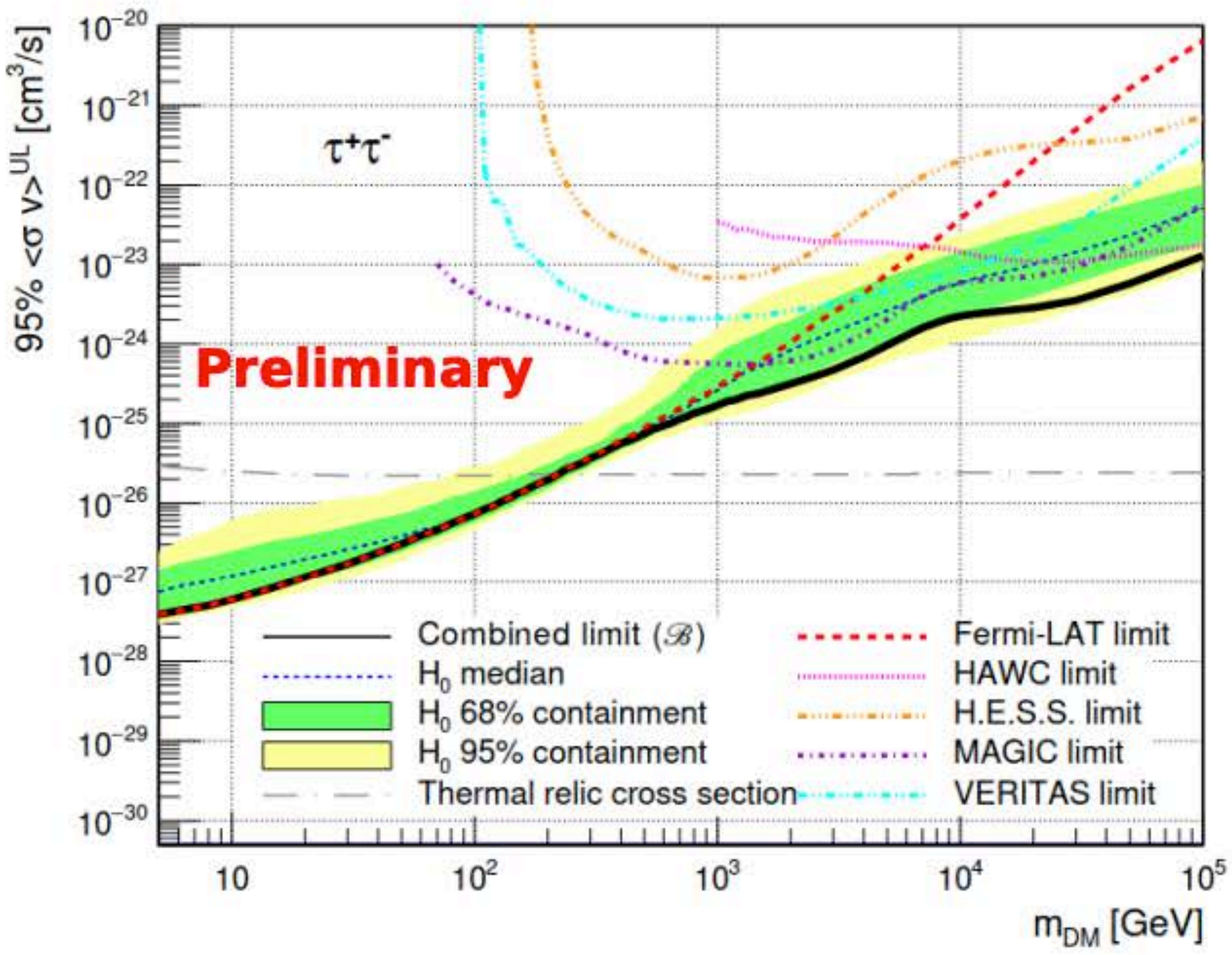
Source name	Experiments	Distance (kpc)	$\log_{10} J$ $\log_{10}(\mathrm{GeV}^2\mathrm{cm}^{-5}\mathrm{sr})$
Bootes I	*Fermi*-LAT, HAWC, VERITAS	66	$18.24^{+0.40}_{-0.37}$
Canes Venatici I	*Fermi*-LAT	218	$17.44^{+0.37}_{-0.28}$
Canes Venatici II	*Fermi*-LAT, HAWC	160	$17.65^{+0.45}_{-0.43}$
Carina	*Fermi*-LAT, H.E.S.S.	105	$17.92^{+0.19}_{-0.11}$
Coma Berenices	*Fermi*-LAT, HAWC, H.E.S.S., MAGIC	44	$19.02^{+0.37}_{-0.41}$
Draco	*Fermi*-LAT, HAWC, MAGIC, VERITAS	76	$19.05^{+0.22}_{-0.21}$
Fornax	*Fermi*-LAT, H.E.S.S.	147	$17.84^{+0.11}_{-0.06}$
Hercules	*Fermi*-LAT, HAWC	132	$16.86^{+0.74}_{-0.68}$
Leo I	*Fermi*-LAT, HAWC	254	$17.84^{+0.20}_{-0.16}$
Leo II	*Fermi*-LAT, HAWC	233	$17.97^{+0.20}_{-0.18}$
Leo IV	*Fermi*-LAT, HAWC	154	$16.32^{+1.06}_{-1.70}$
Leo T	*Fermi*-LAT	417	$17.11^{+0.44}_{-0.39}$
Leo V	*Fermi*-LAT	178	$16.37^{+0.94}_{-0.87}$
Sculptor	*Fermi*-LAT, H.E.S.S.	86	$18.57^{+0.07}_{-0.05}$
Segue I	*Fermi*-LAT, HAWC, MAGIC, VERITAS	23	$19.36^{+0.32}_{-0.35}$
Segue II	*Fermi*-LAT	35	$16.21^{+1.06}_{-0.98}$
Sextans	*Fermi*-LAT, HAWC	86	$17.92^{+0.35}_{-0.29}$
Ursa Major I	*Fermi*-LAT, HAWC	97	$17.87^{+0.56}_{-0.33}$
Ursa Major II	*Fermi*-LAT, HAWC, MAGIC	32	$19.42^{+0.44}_{-0.42}$
Ursa Minor	*Fermi*-LAT, VERITAS	76	$18.95^{+0.26}_{-0.18}$

arXiv:2108.13646v1

- combination of 20 dSph observations
  - 20 from Fermi-LAT: 10 yrs
  - 9 from IACTs: 500+ hrs
  - 12 from HAWC: 1000+ days
- 5 exp. covers 5 GeV to 100 TeV of DM masses

Comparison of the limits with 2 sets of J-factors

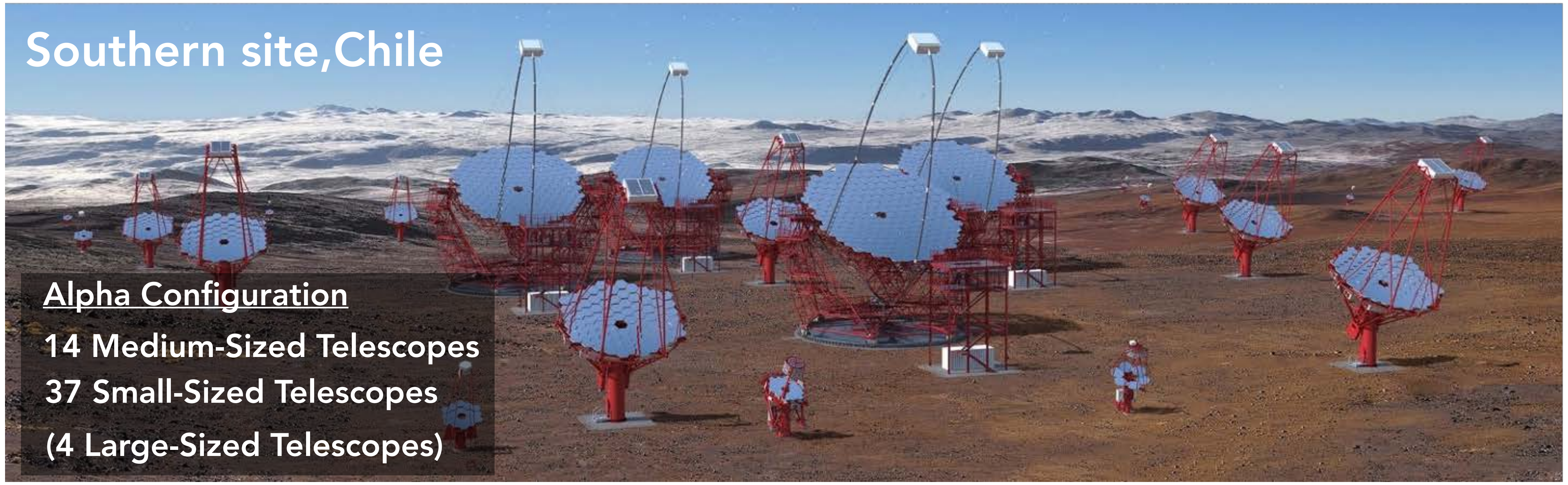


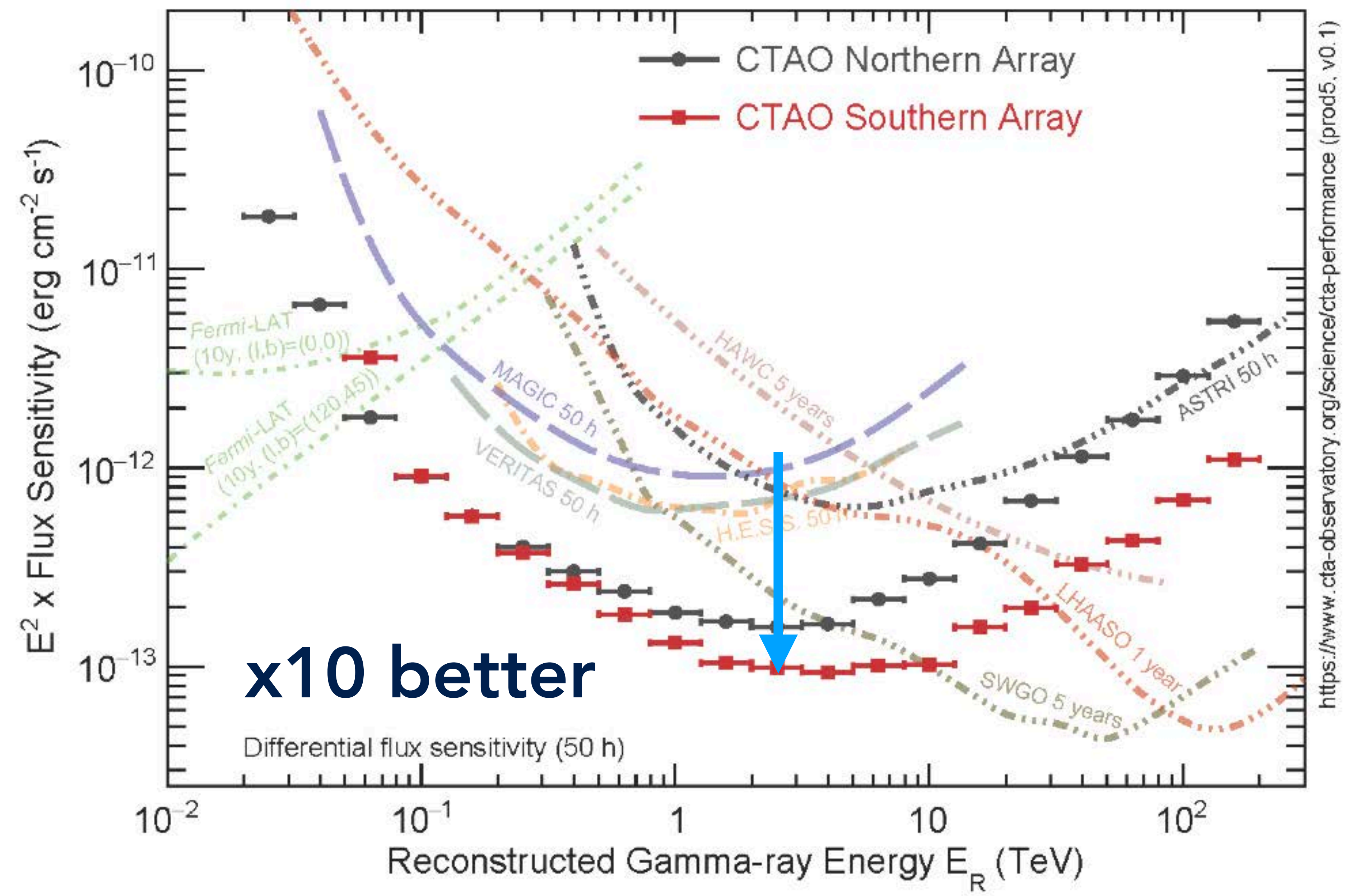


- Limits **2-6× more constraining** with the J-factors of Bonnivard et al.
- Below 10 TeV - DM limits largely dominated by Fermi-LAT
- above 10 TeV - IACTs and HAWC take over

Upcoming future prospects

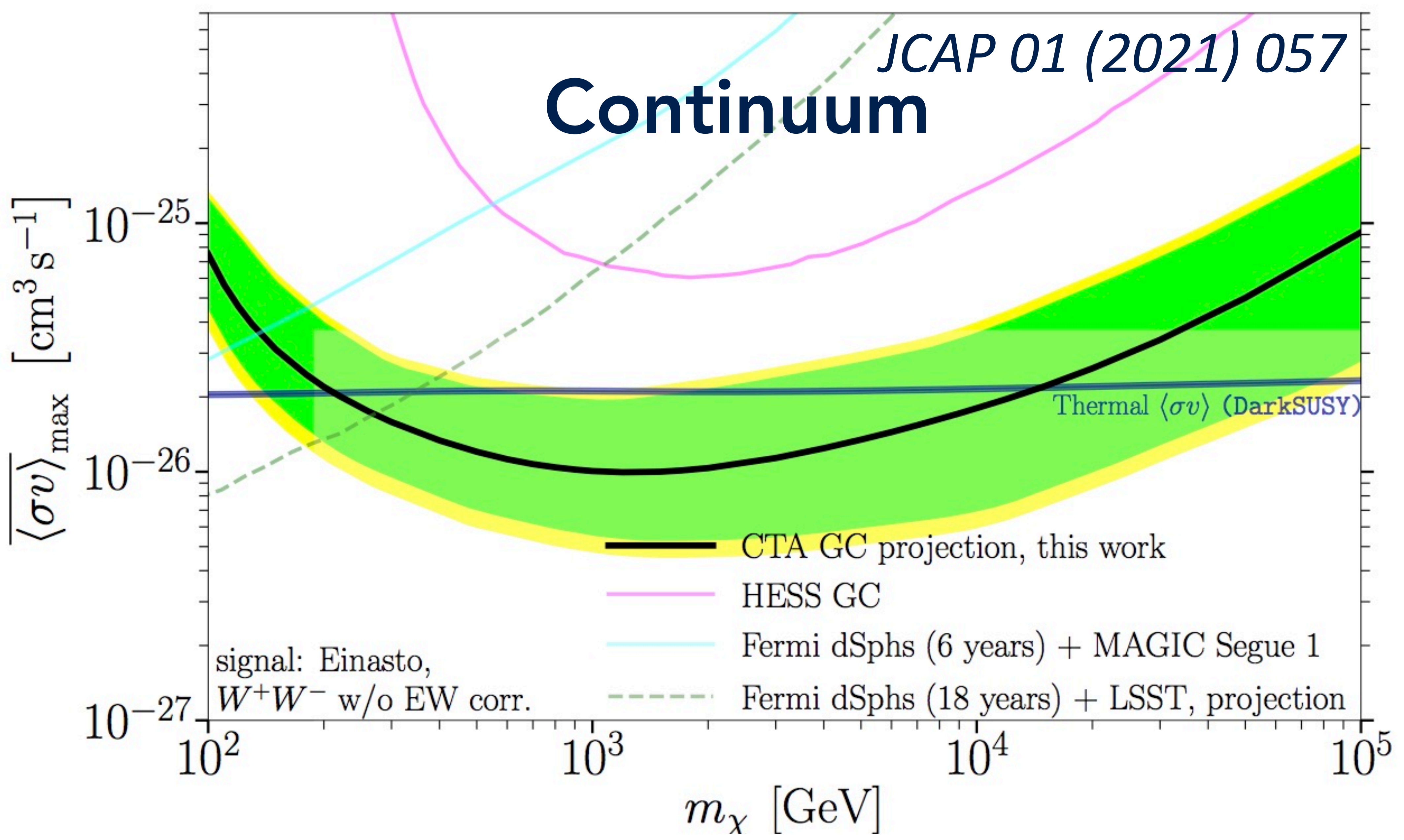
Cherenkov Telescope Array Observatory

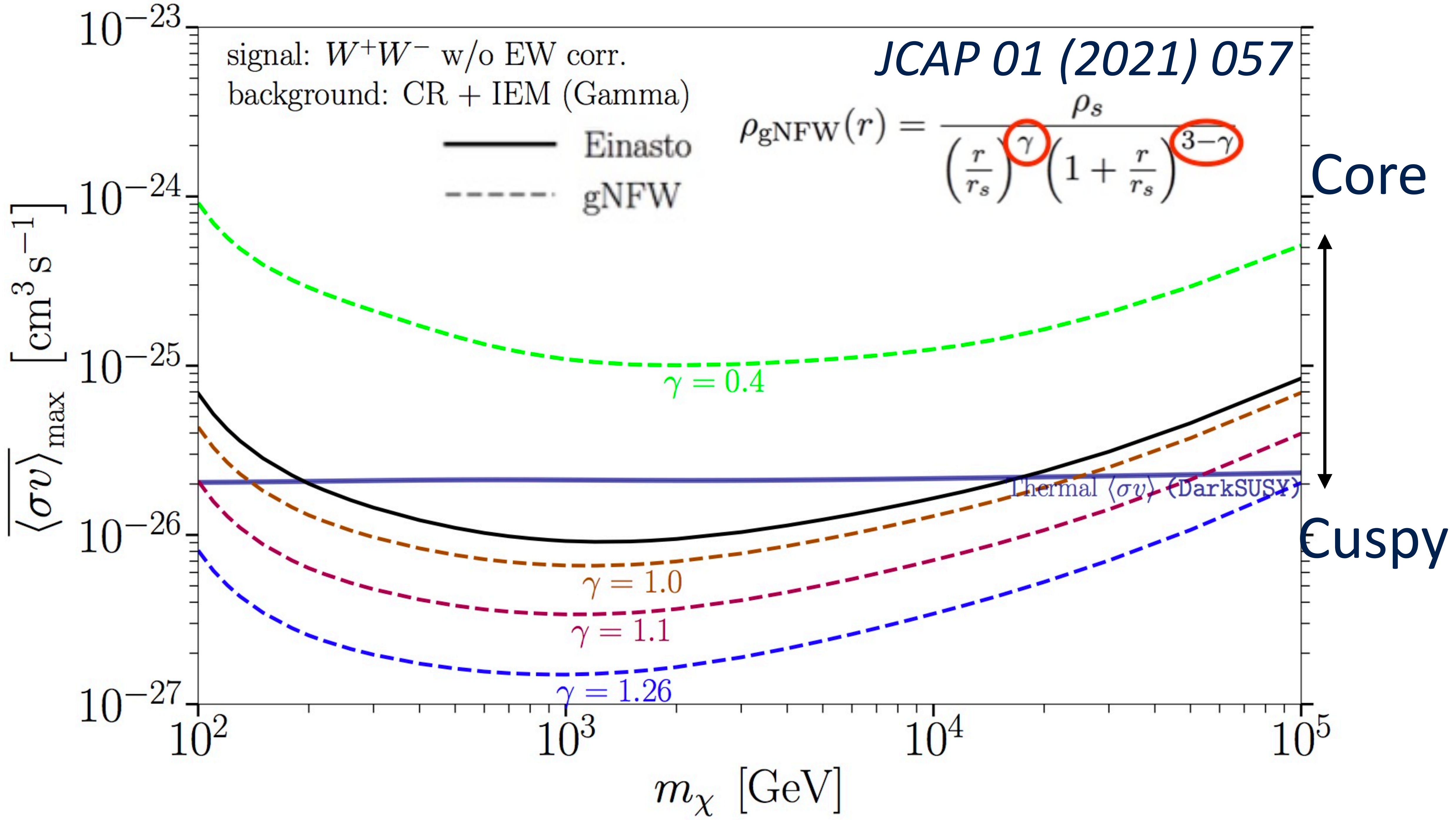


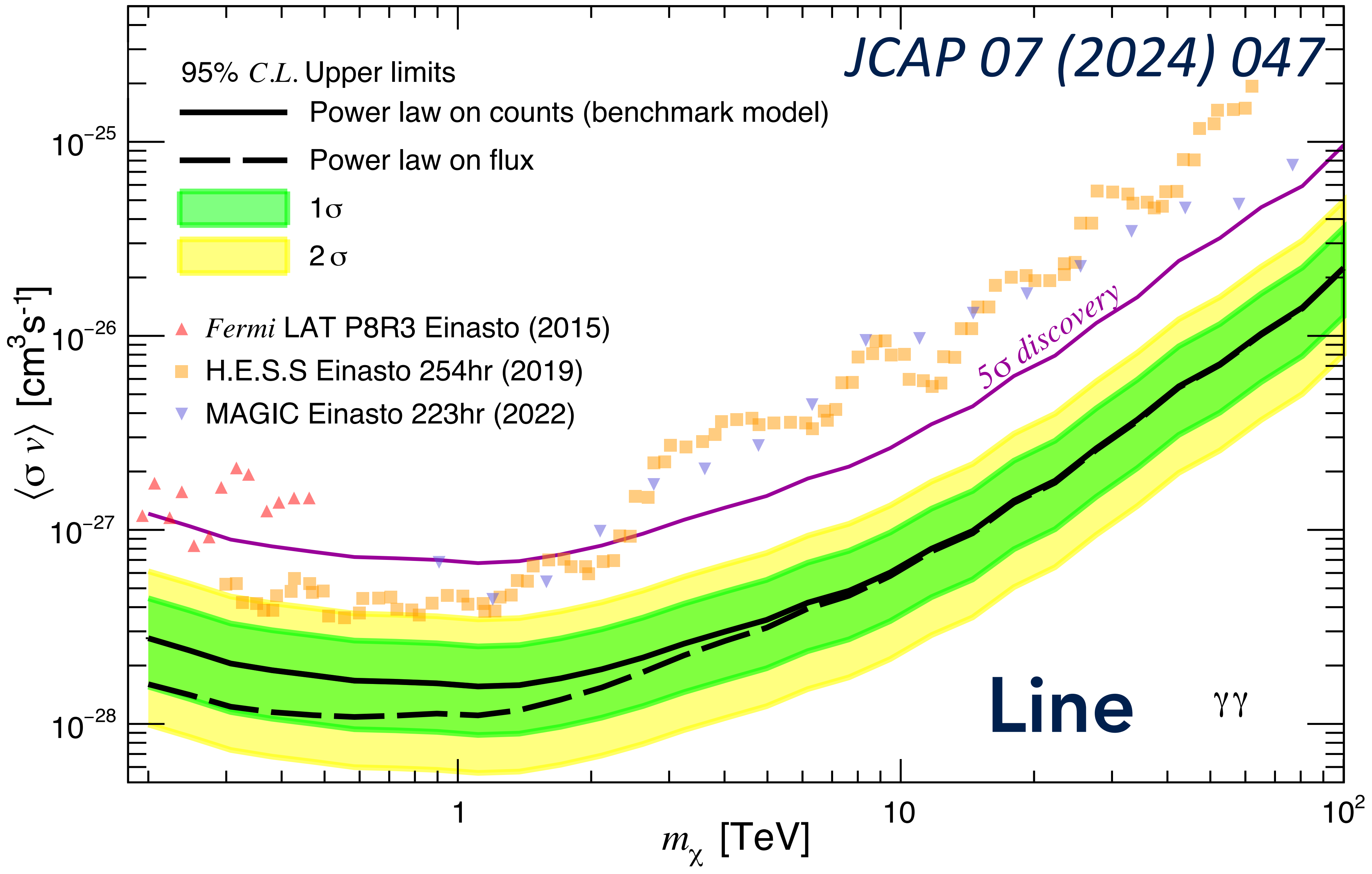


Next generation ground-based gamma-ray telescope: Two arrays of Cherenkov telescopes in **Chile/ La Palma**

- Over 100 telescopes, About 1500 scientists and engineers, About 200 institutes







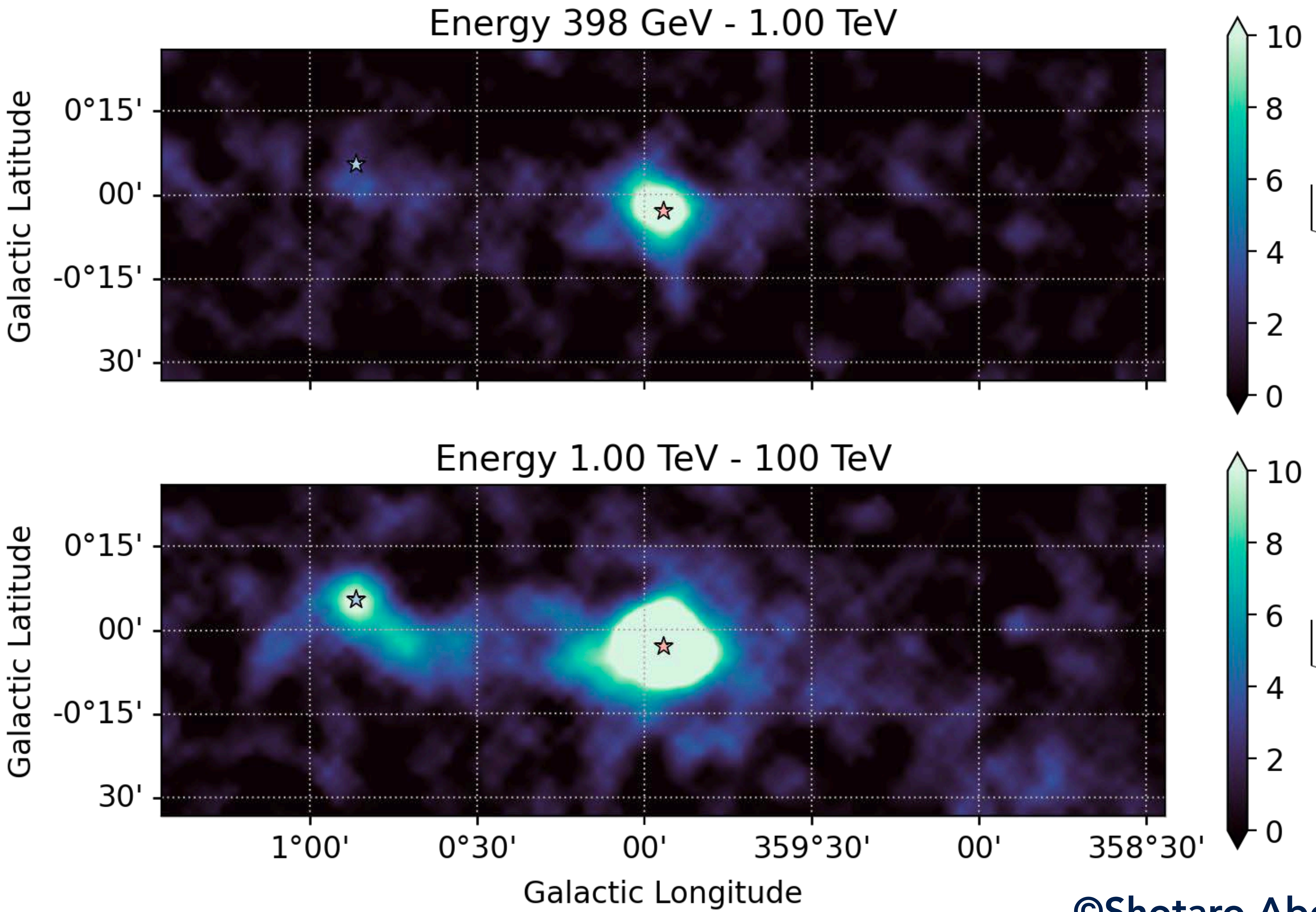
CTAO Alpha Configuration: Sensitivity to DM signal at the GC

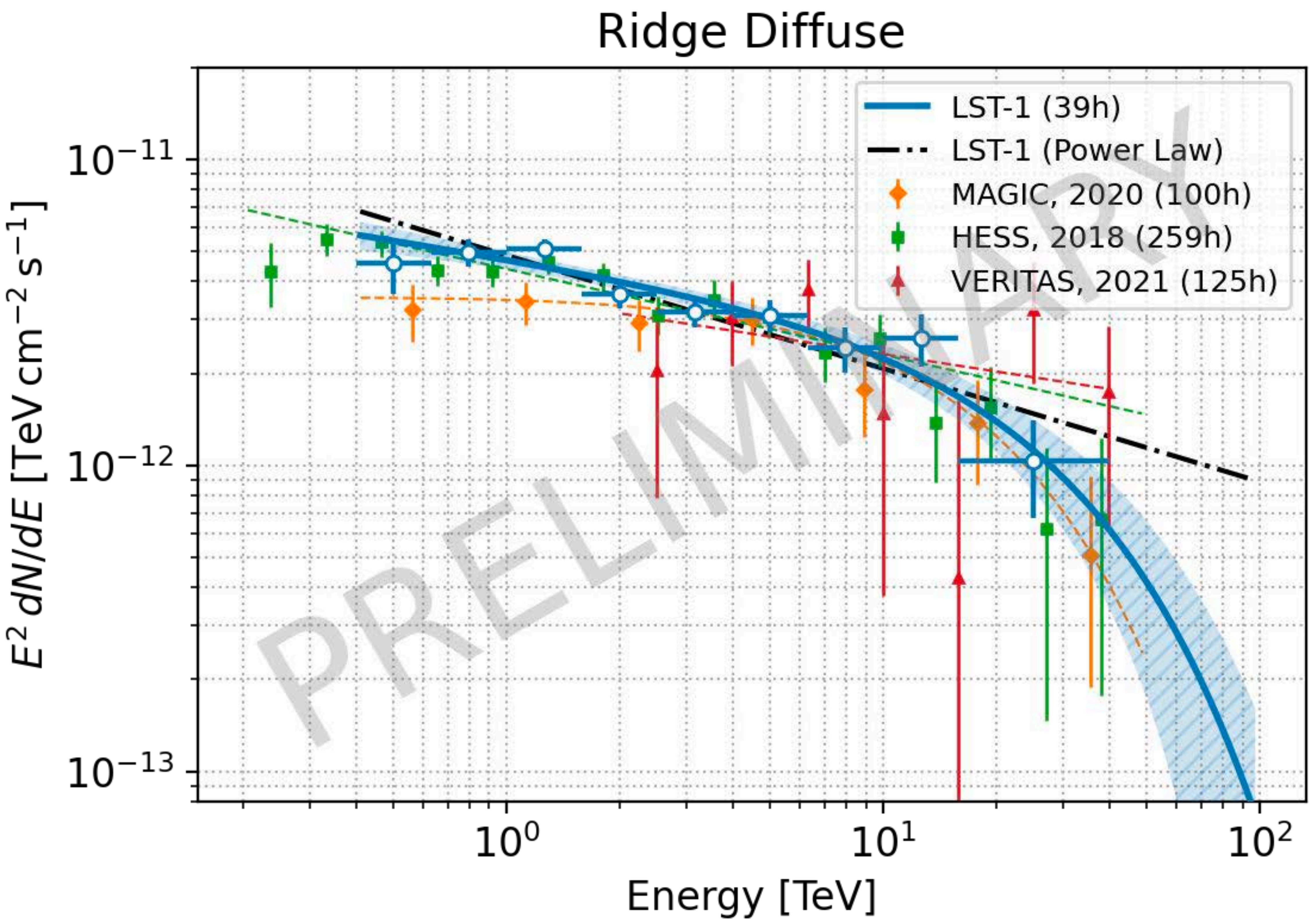
Galactic centre observations with CTAO can test the thermal relic cross section of **500 GeV - 10 TeV WIMPs**

Early science with LST-1 at the GC observation

The galactic centre of LST-1's view is observed for 39hrs with the Large Zenith Angle Technique

Pros: Getting several times larger collection area
Cons: Higher Threshold Energy (> 300GeV)





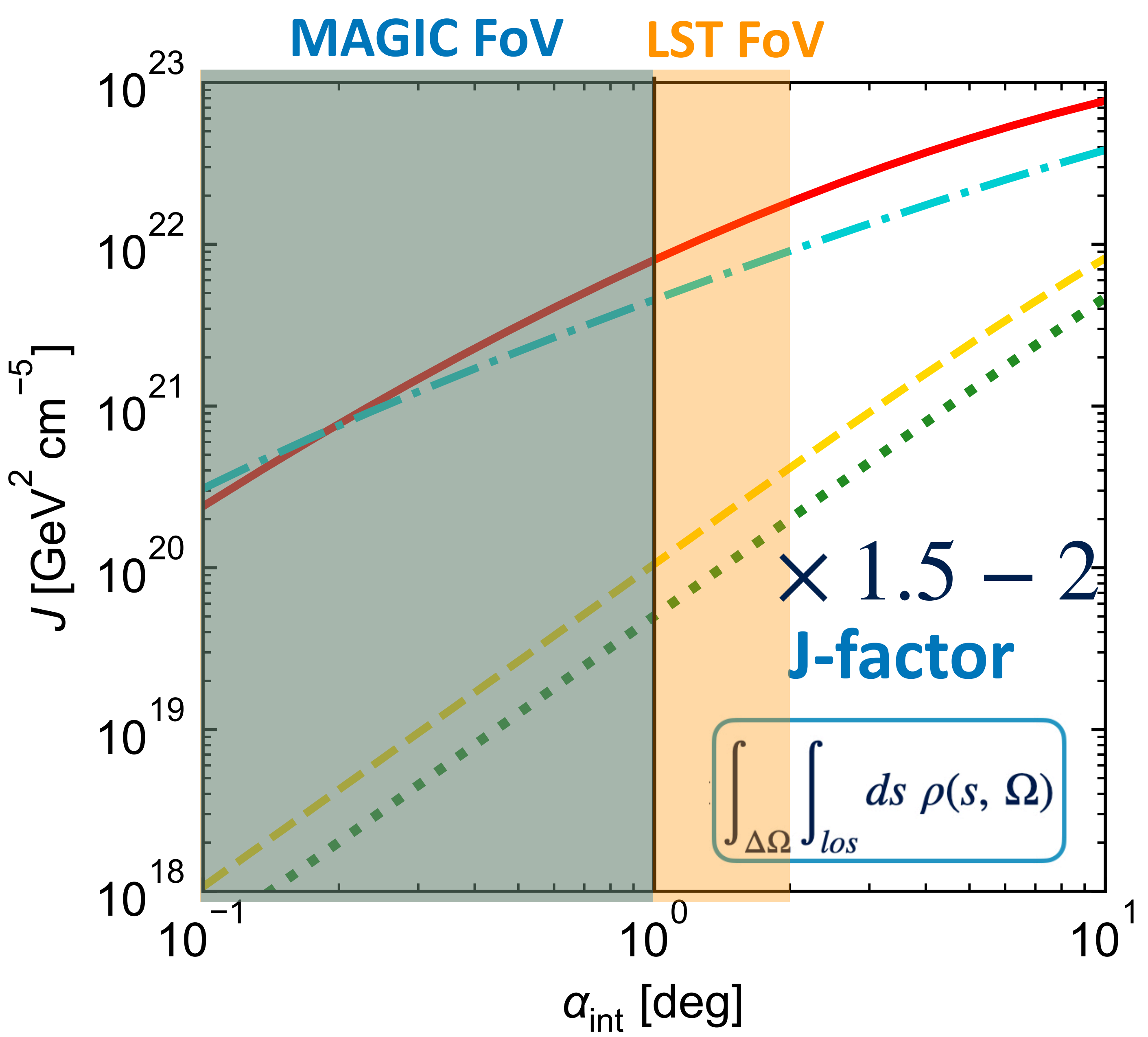
Some trials to derive spectra from individuals

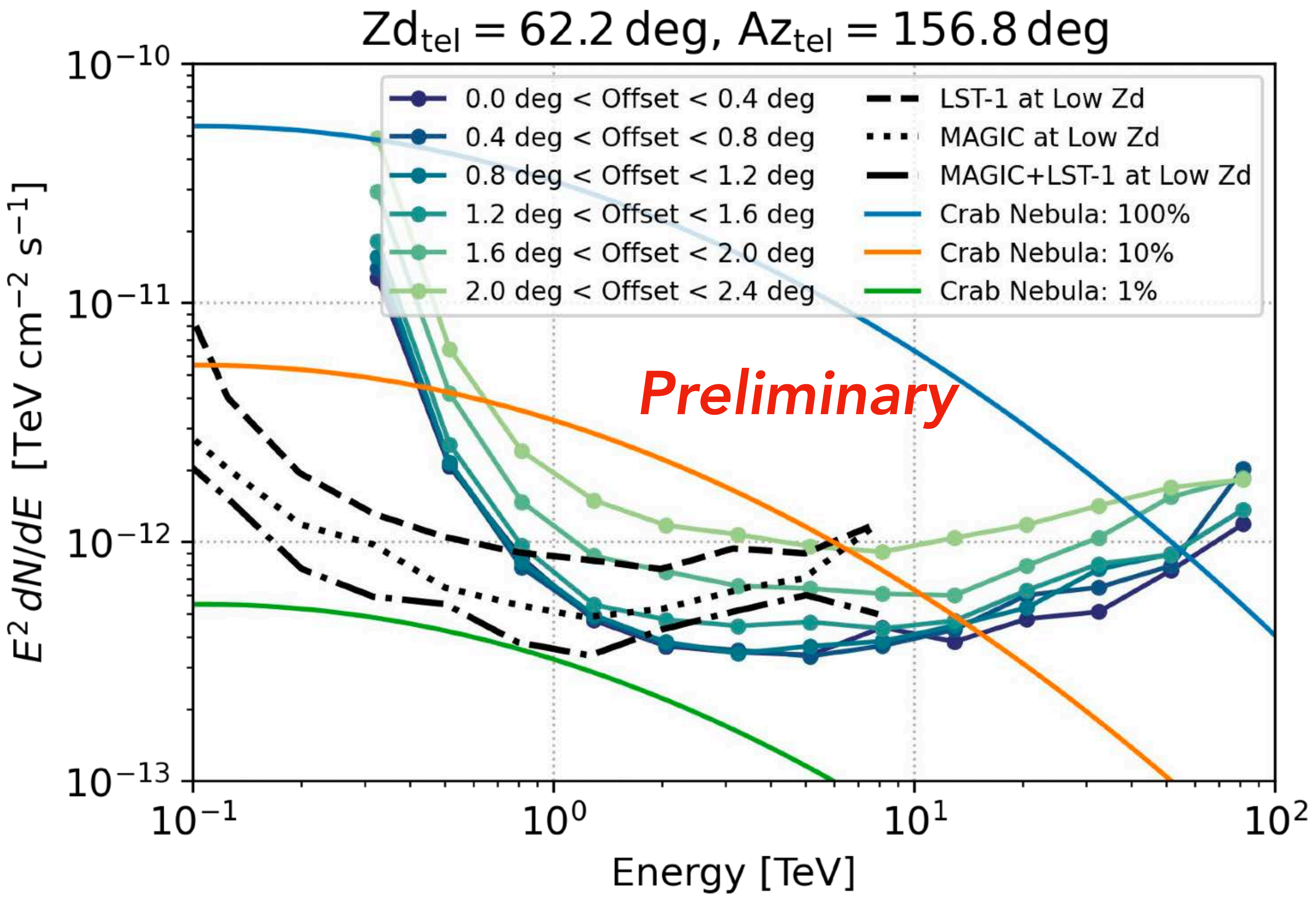
Toward Dark Matter Searches with LSTs

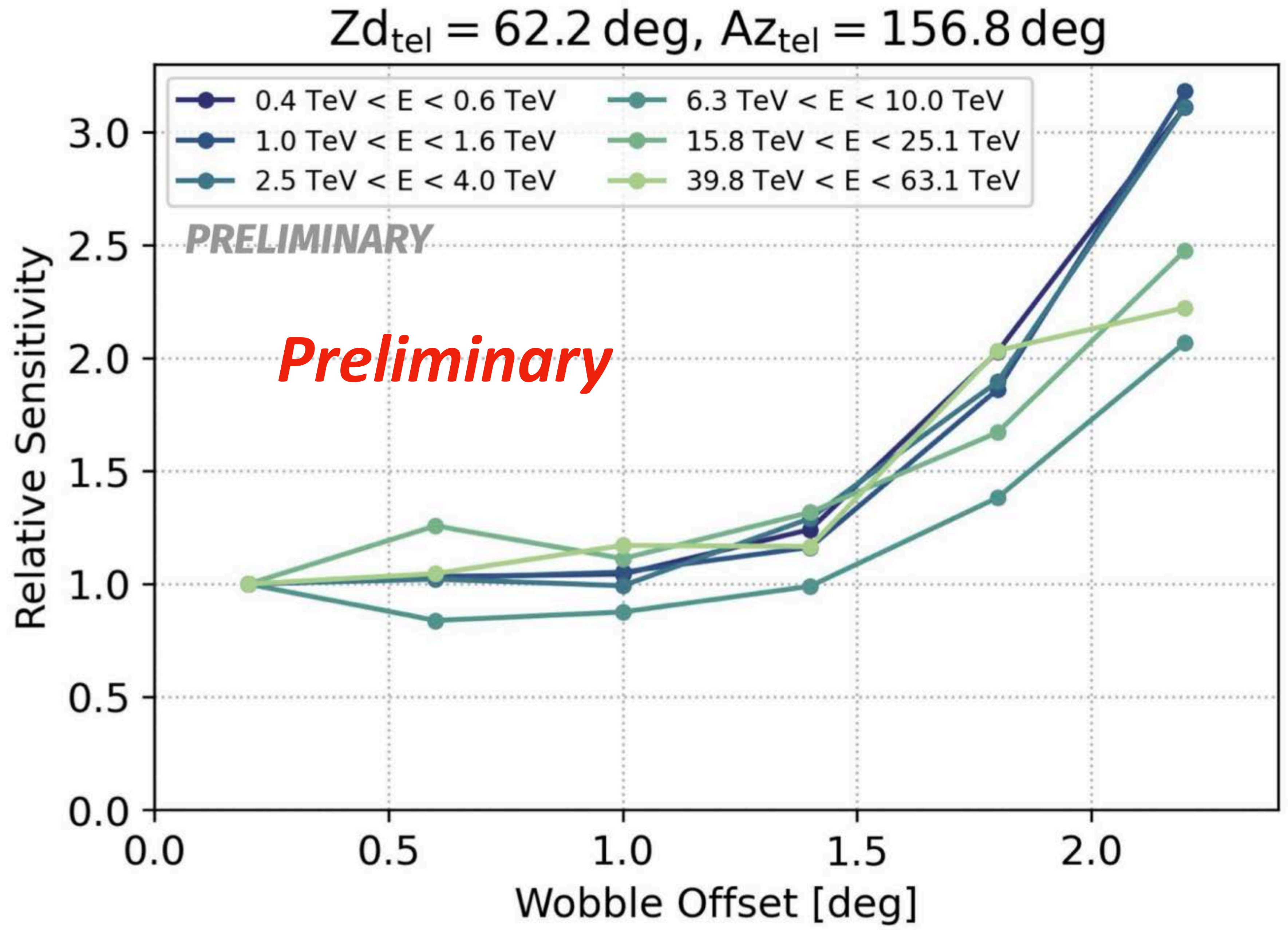
Large FoVs with flat acceptance is beneficial for ***J-factor***

Lower threshold *will allows us for* ***continuum spectra*** *study*

Galactic Center observations	HESS	MAGIC	VERITAS	LST-1
Zenith Angle	Low Zd	**Large Zd**	**Large Zd**	**Large Zd**
Field of View	**5.0 deg**	3.5 deg	3.5 deg	**4.5 deg**







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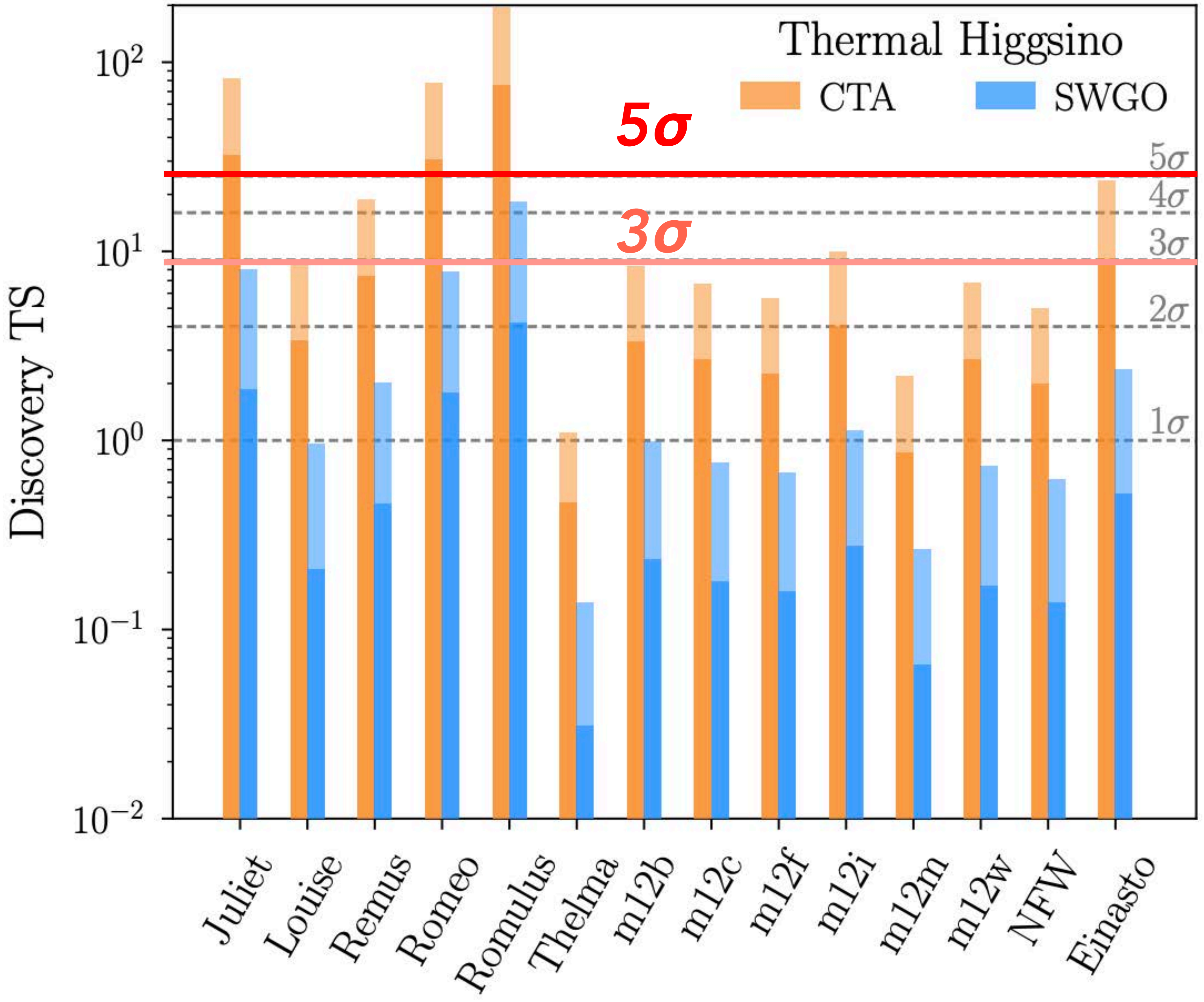
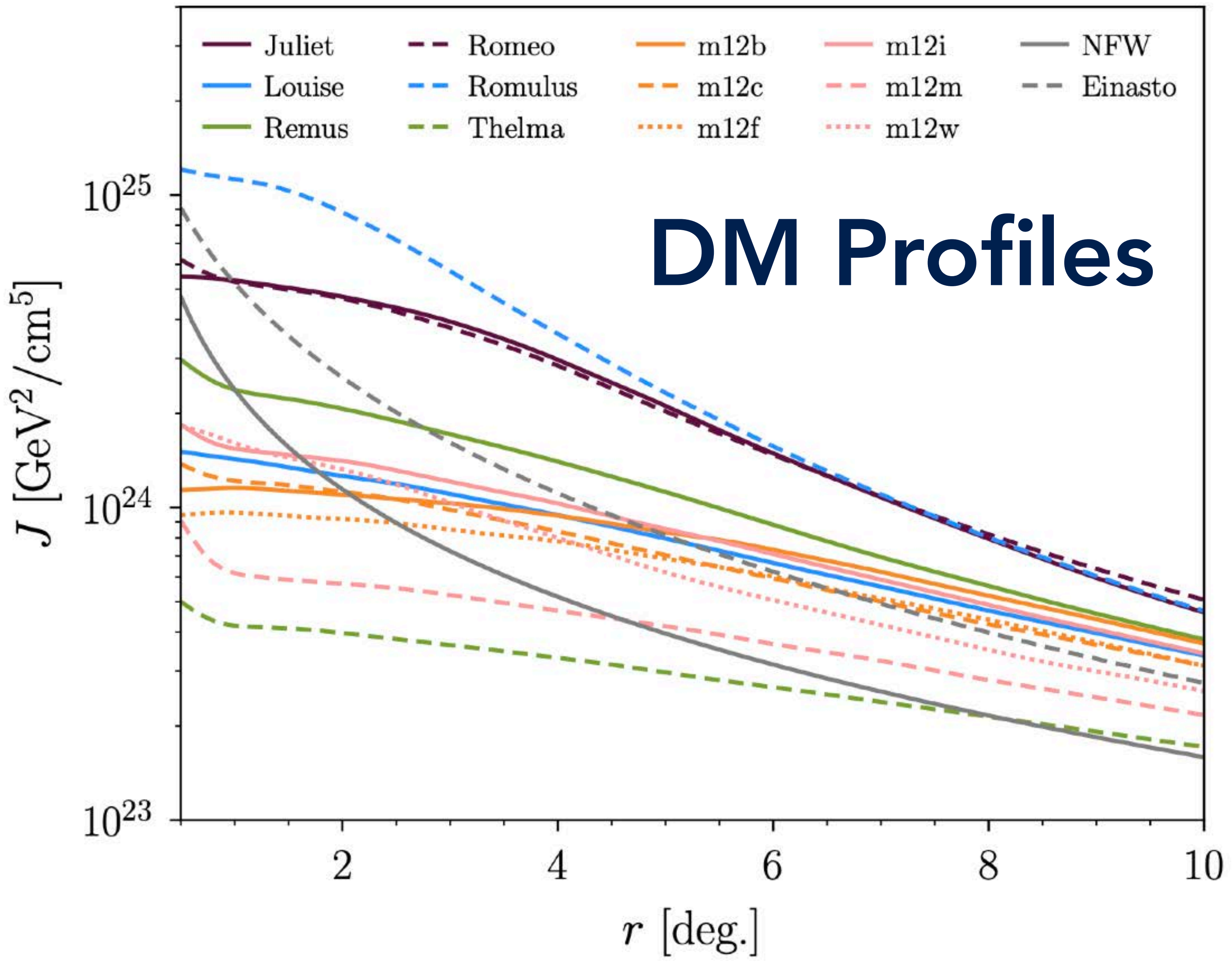
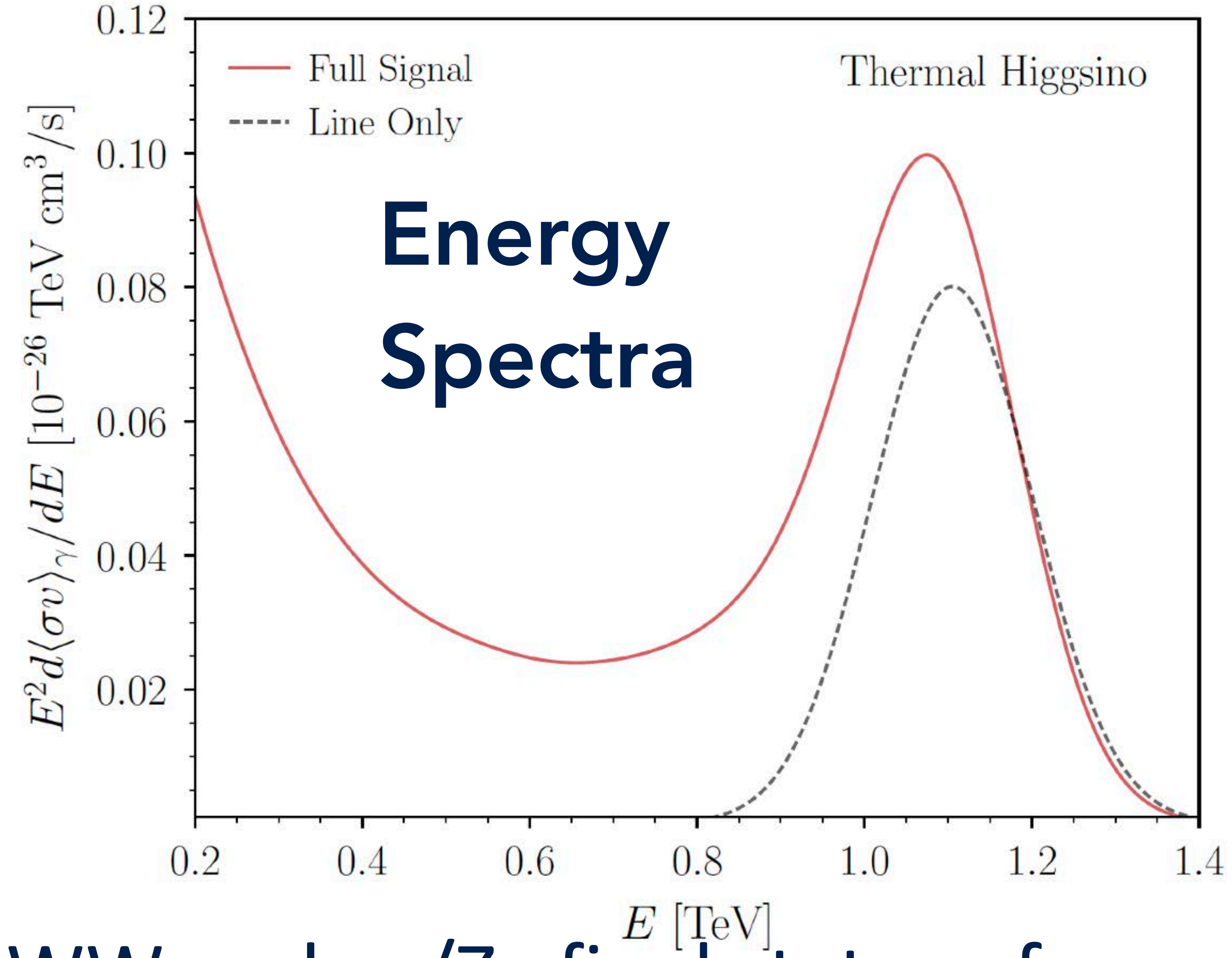
Higgsino detectability for the next decade

Phys.Rev.D 110 (2024) 4, 043003

500 hours of CTAO-S observation

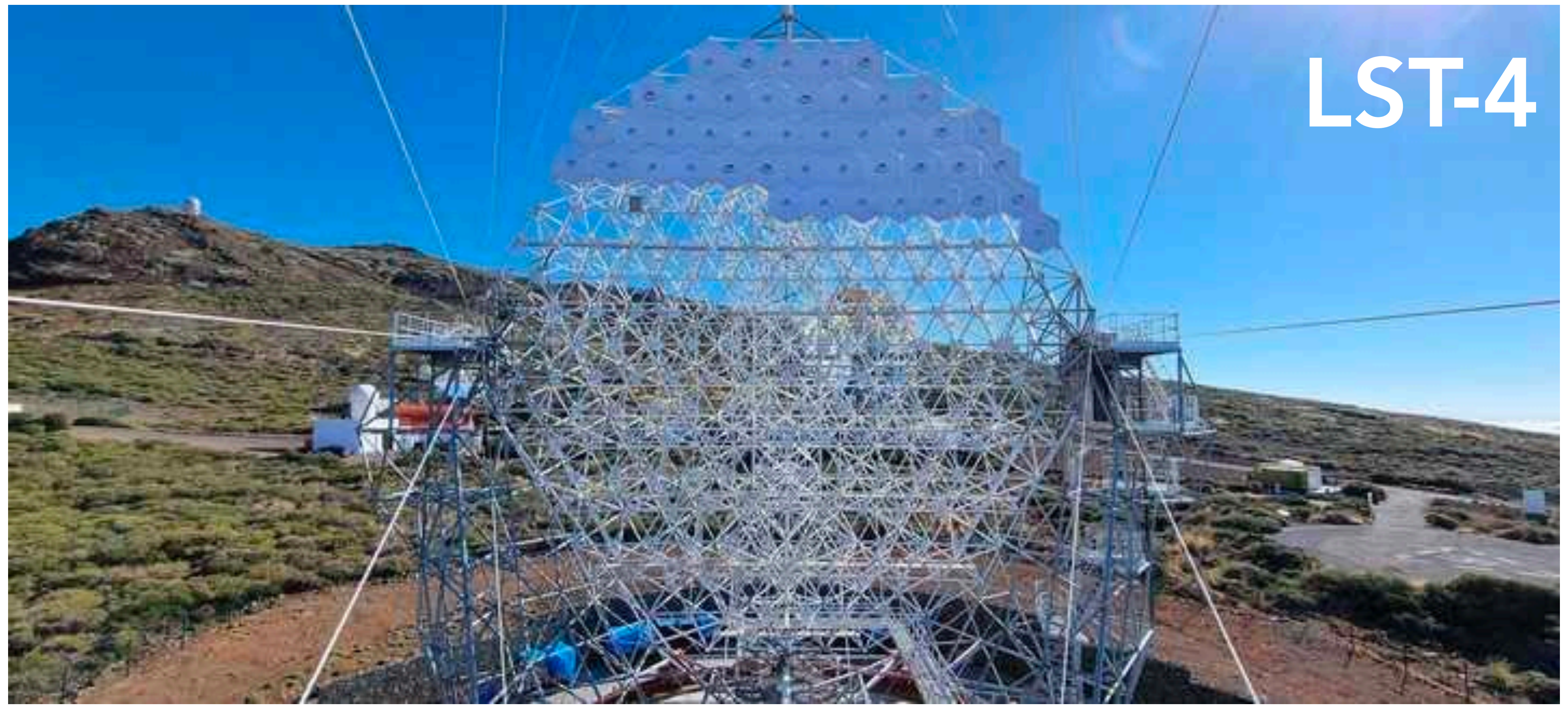


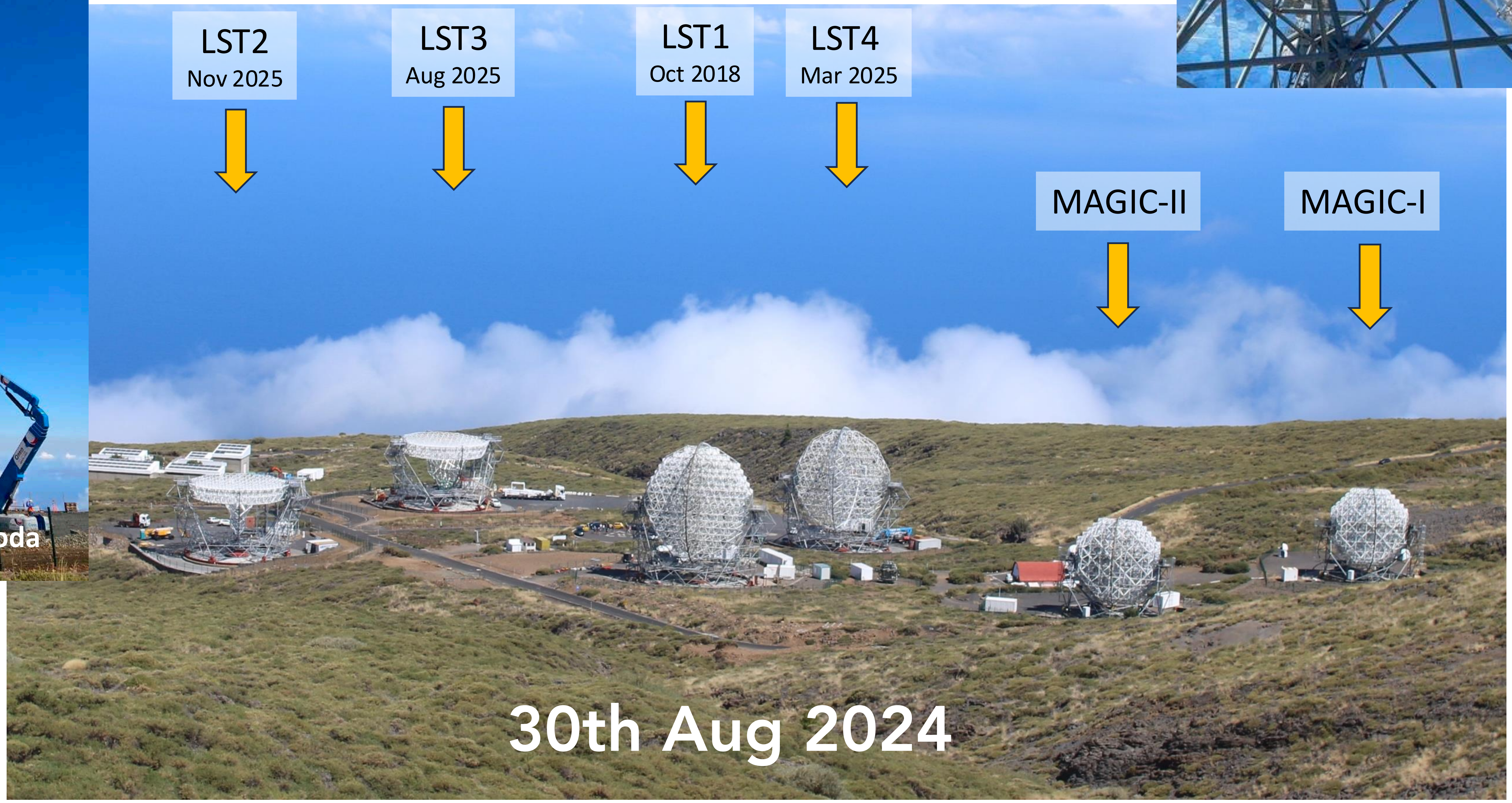




- Targeting photons for the WW and γγ/Zγ final states of **thermal Higgsino annihilation** at the mass of 1.1 TeV
- **500 h of observations with CTAO-S,** we would be able to see something more than 3σ, even more than 5σ, though assuming an optimistic profile model
- CTAO-S full operation will be 2030s.
- **4 LSTs of CTAO-N will start operation in 2026**
  - Would have a good chance for some cases such as Einasto etc within the next decade
  - A dedicated paper, discussing potential detectability, is in prep. Stay tuned.

CTAO-LSTs construction is in progress!





Three LSTs simuluteneously in construction!

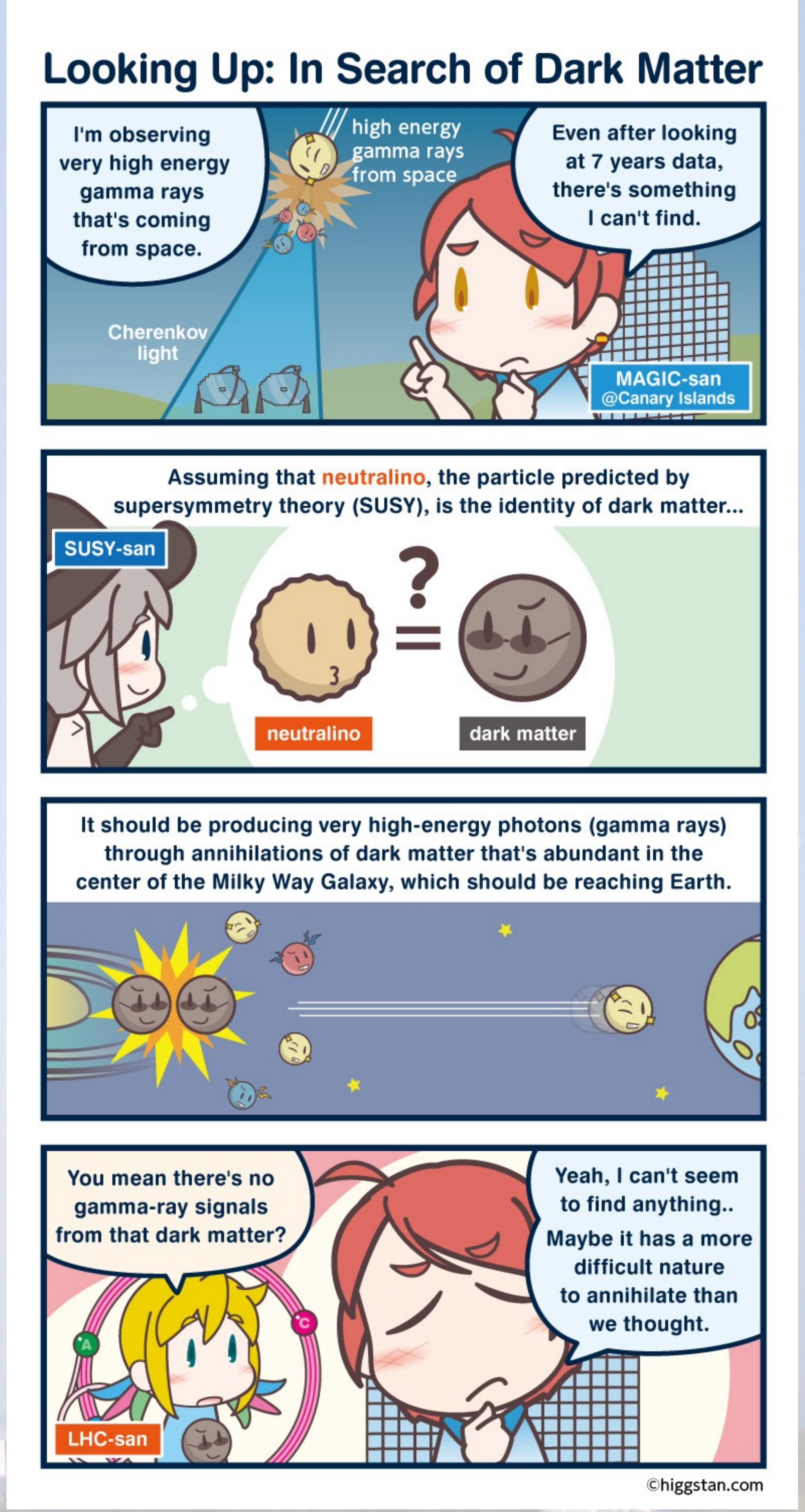
LST2-4 construction

Summary

- Indirect DM searches with gamma rays is complementary with other WIMP searches
  - In particular, good tool to access **heavy DM models**

- **Ground-based Gamma-ray telescopes (IACTs)** have a good sensitivity in TeV energy range
  - constrain WIMPs with variety of targets
    - **the Galactic Centre**: one of the most promising
    - MAGIC introduced the **large zenith angle observation**
      - Boosted the sensitivity at TeV energies
      - ***Proof-of-concept***: MAGIC Collaboration (2023) Phys. Rev. Lett.
        - Constraint on **SUSY-Wino** with **different DM density profiles**

- Next generation: **Cherenkov Telescope Array Observatory**
  - The first **Large-Sized Telescope** in **La Palma** is in operation
    - 4 LSTs array will be ready in 2026
  - **The Galactic Centre** analysis with **CTAO-LST** is ongoing
  - **Next decade**: challenge on Higgsino DM

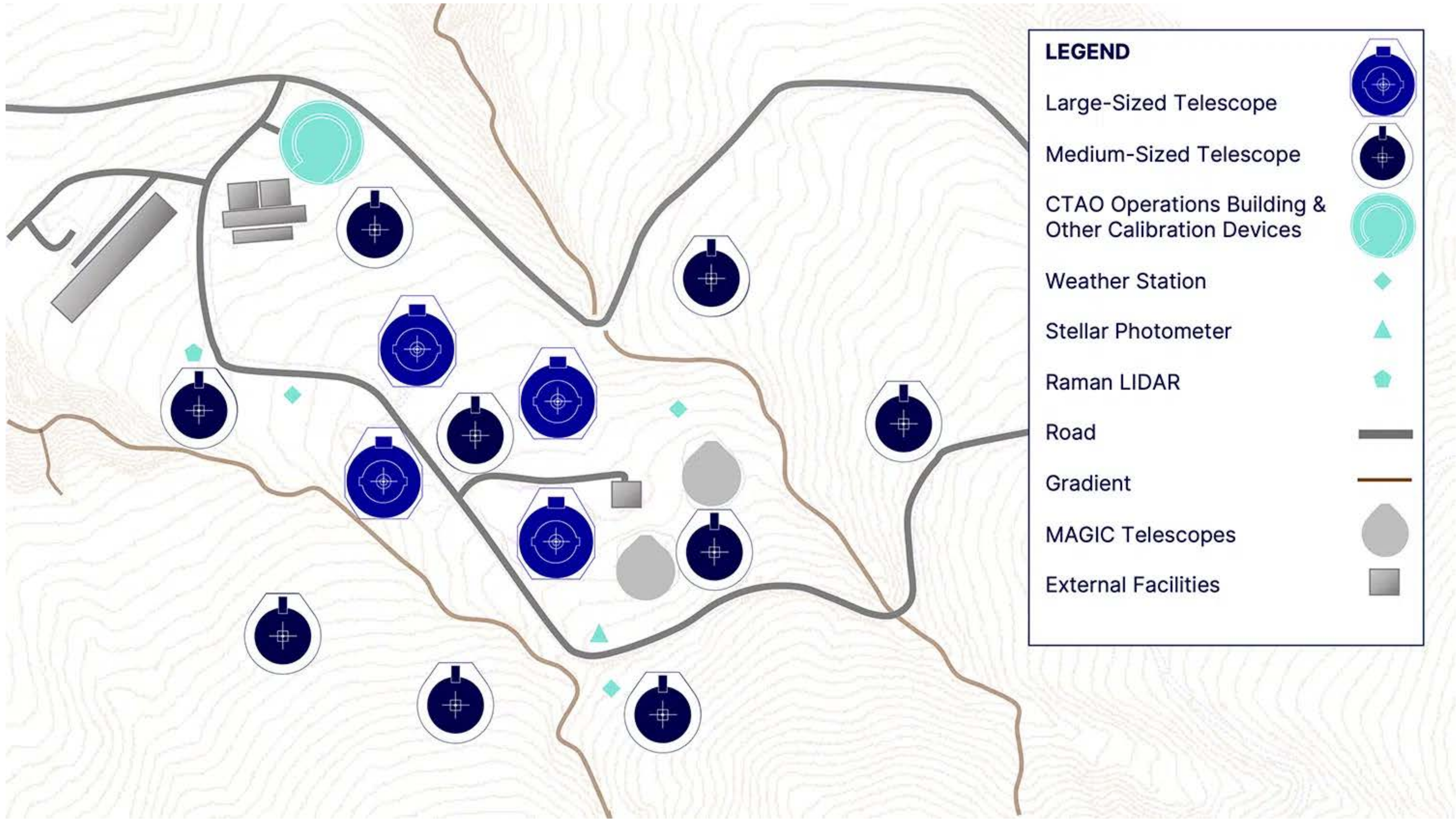


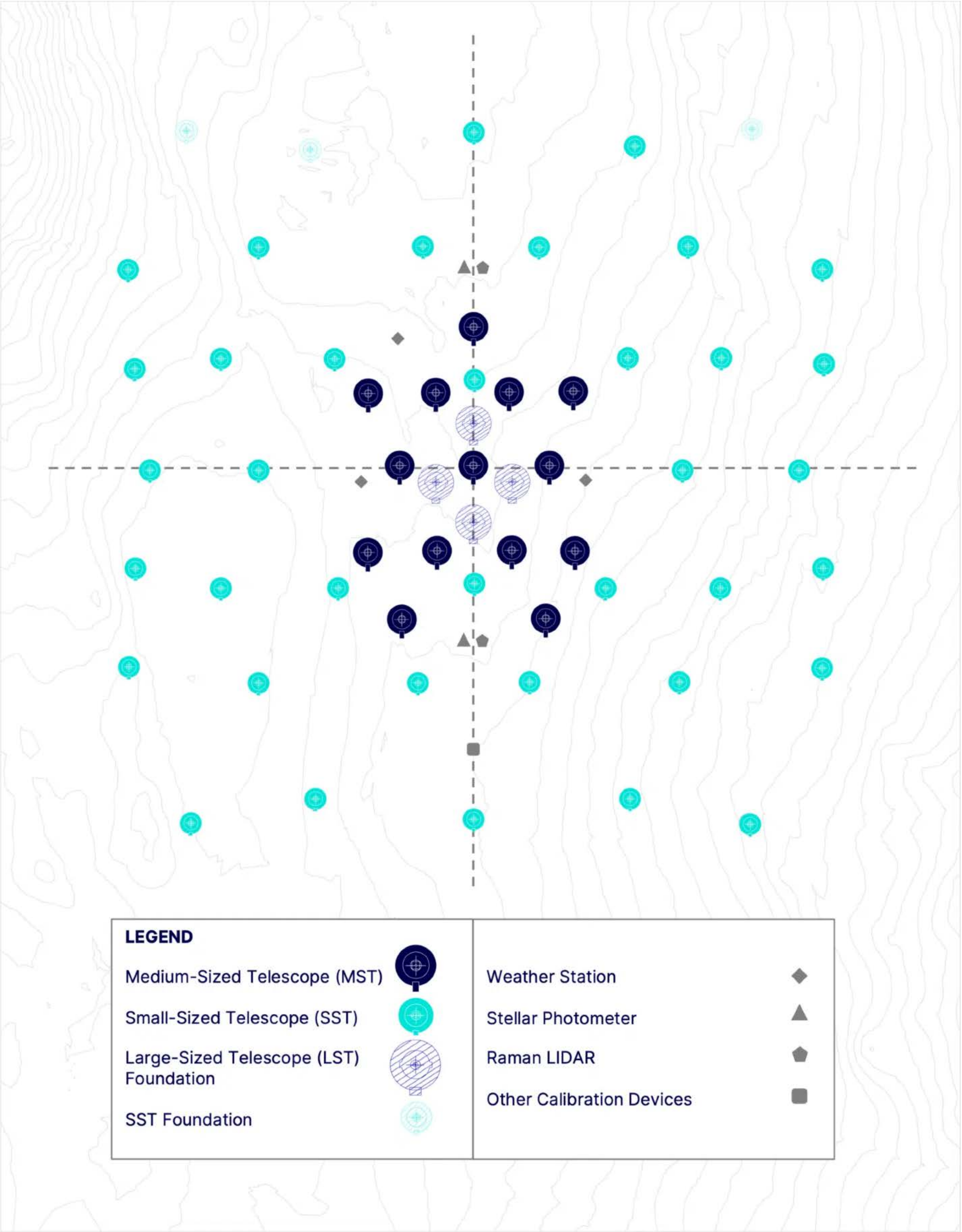
Higgstan

Back Up

LST-1 is taking data

CTAO Alpha Configuration





LST Coordinators (North)