Indirect dark matter search and Physics Beyond the Standard Model

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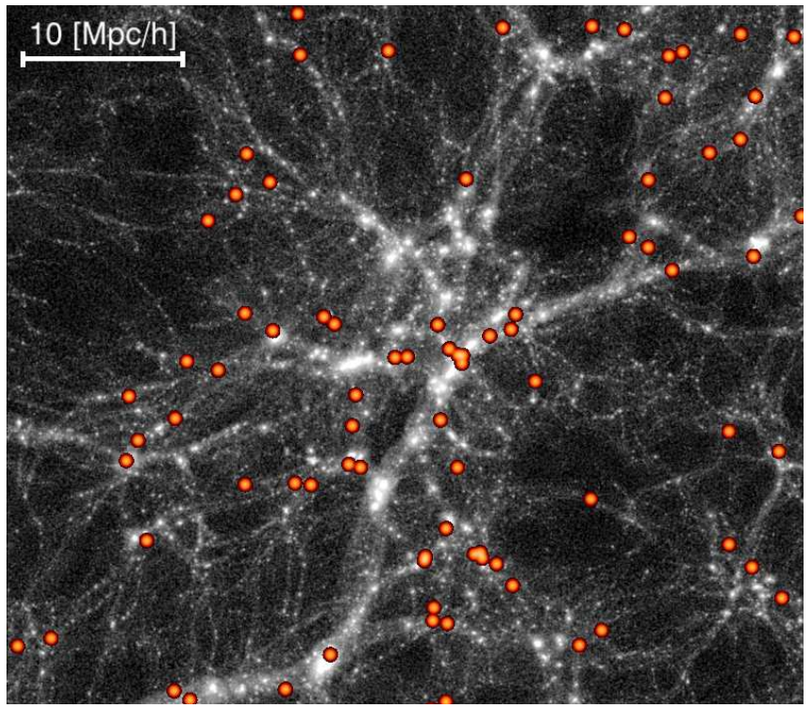
First Pan-African Astro-Particle and Collider Physics Workshop

Dark matter

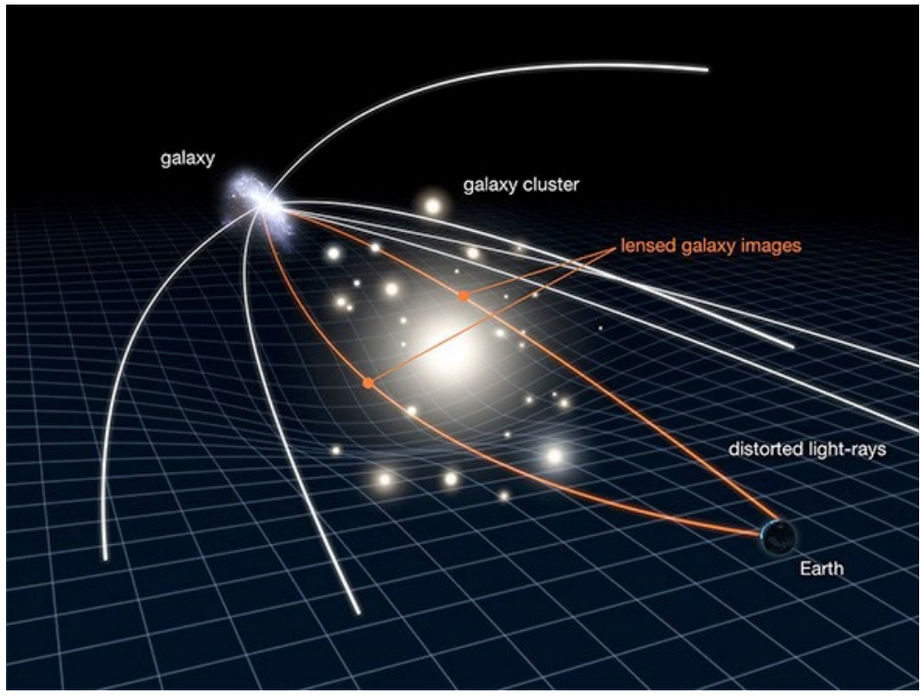
an essential building block of the Standard Model of Cosmology

large scale structures



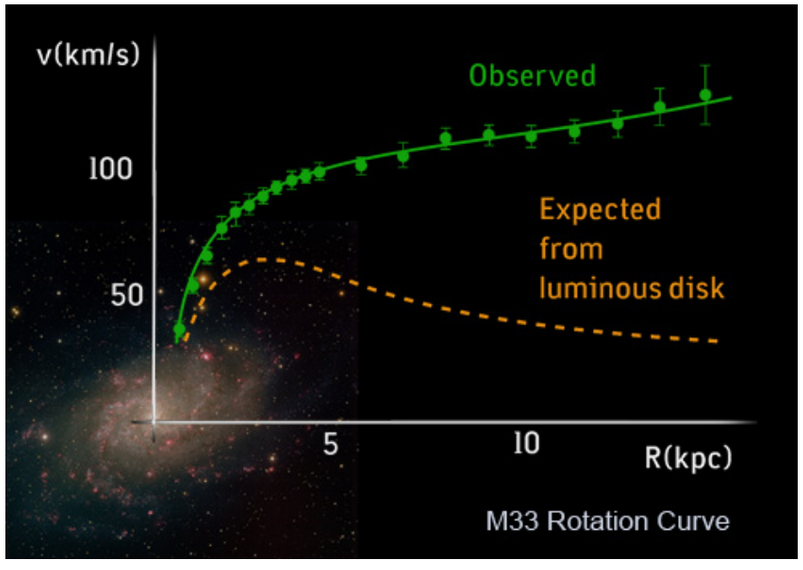
100s Mpc

clusters of galaxies



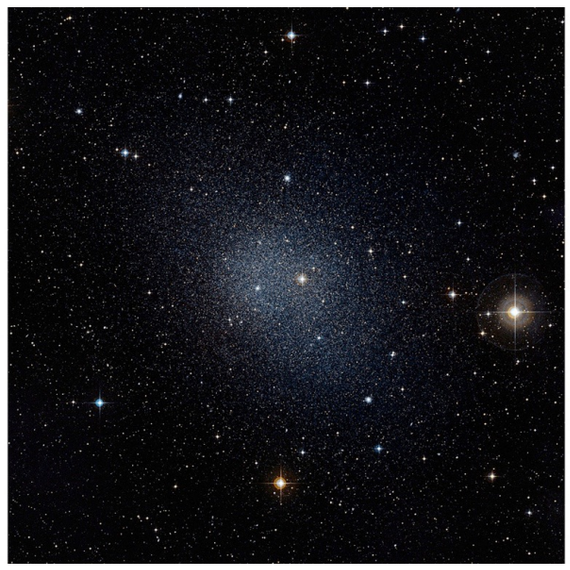
Mpc

Milky Way-size galaxies



100s kpc

dwarf galaxies



<~ kpc

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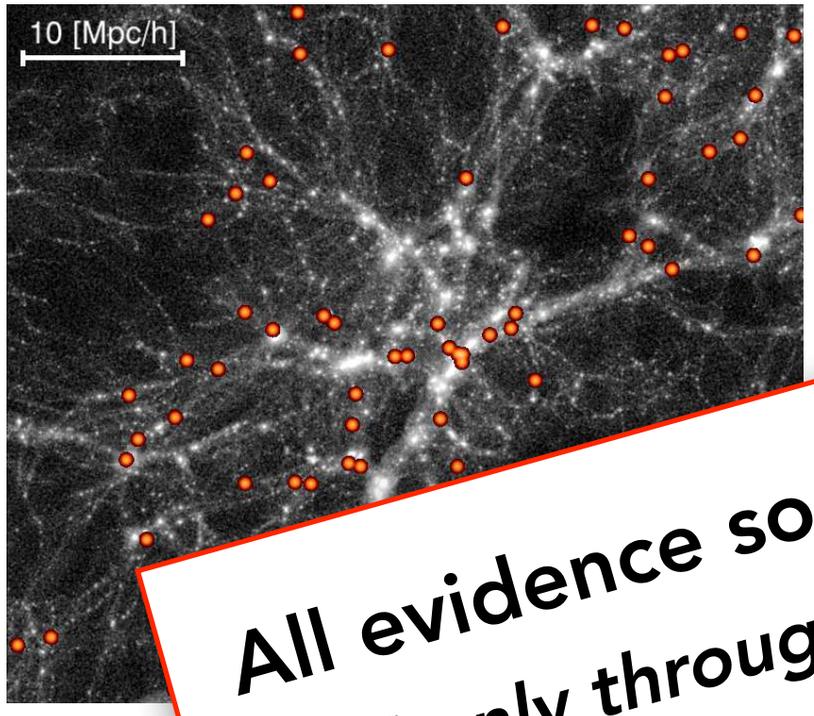

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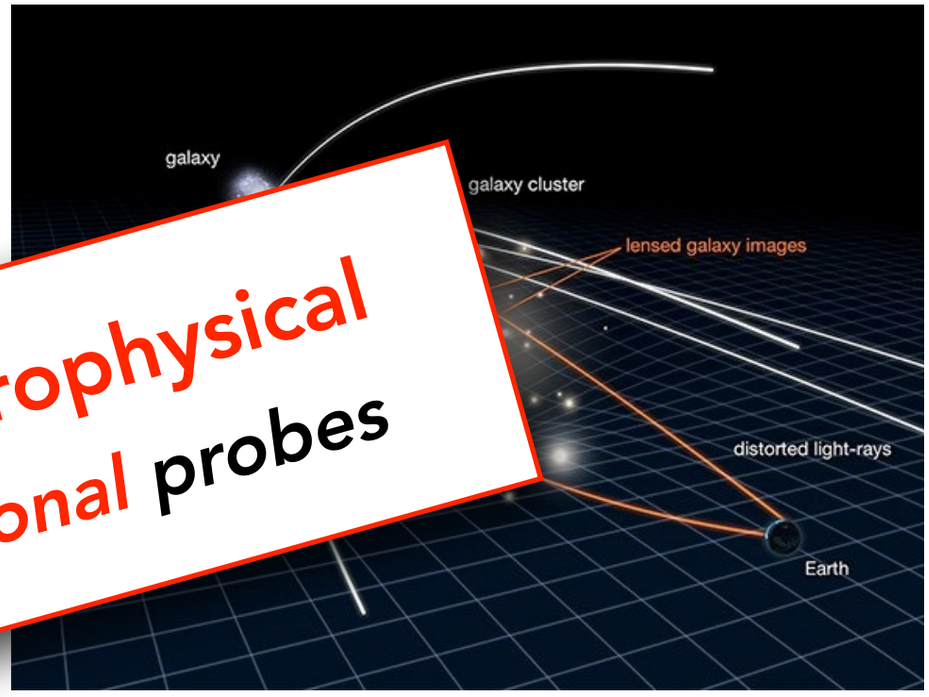
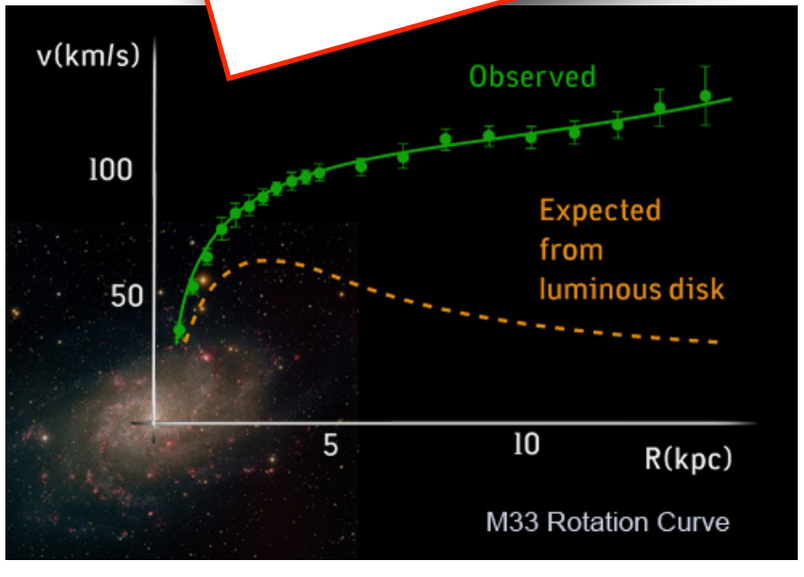


Mpc

All evidence so far is astrophysical
And only through gravitational probes

Milky



100s kpc

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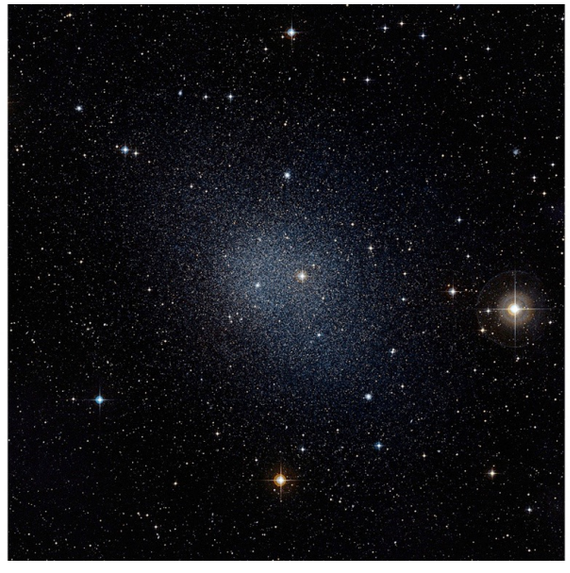
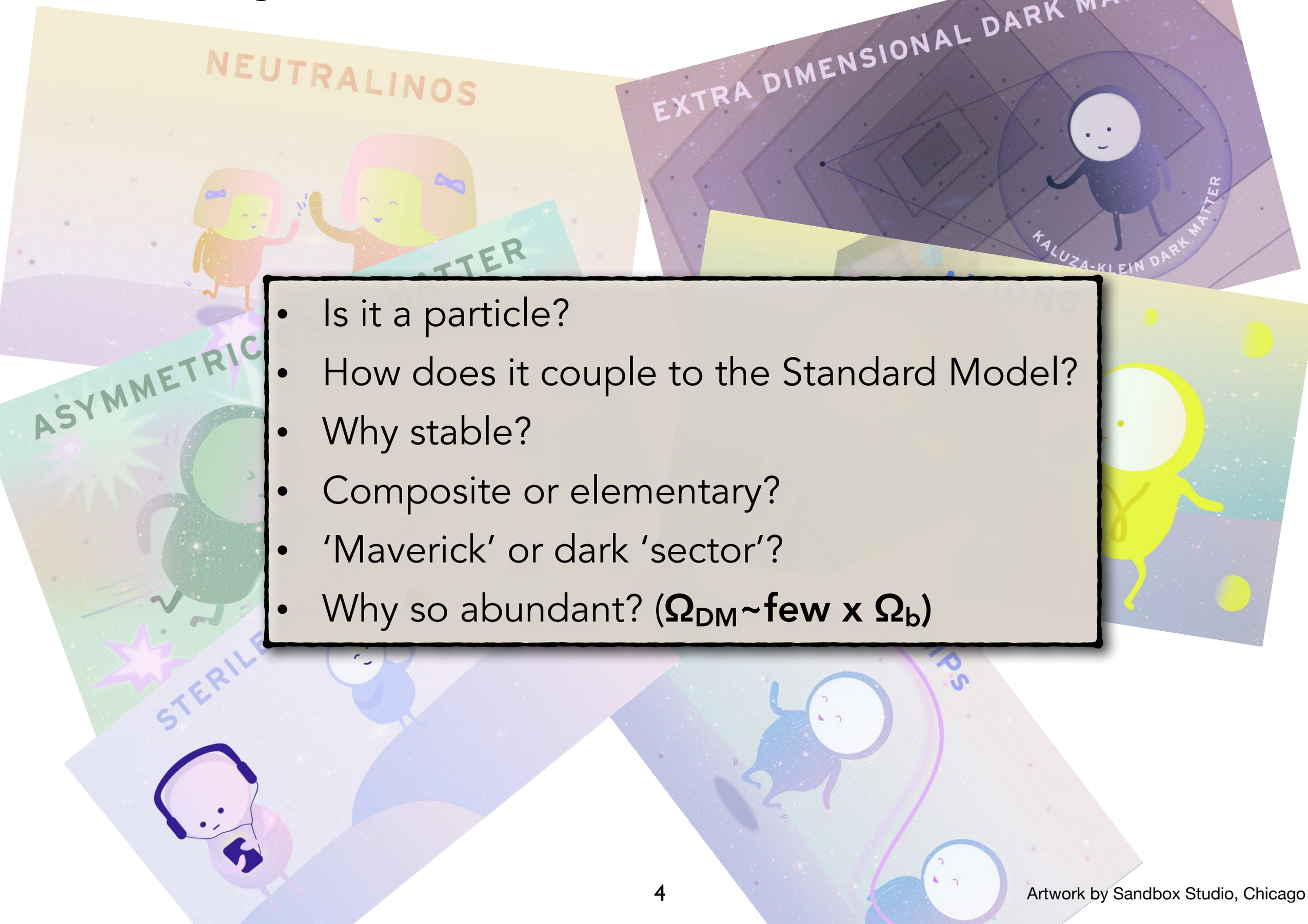


<~ kpc

The challenge



- Is it a particle?
- How does it couple to the Standard Model?
- Why stable?
- Composite or elementary?
- ‘Maverick’ or dark ‘sector’?
- Why so abundant? (Ω_{DM}~few x Ω_b)

Artwork by Sandbox Studio, Chicago

What are the options?

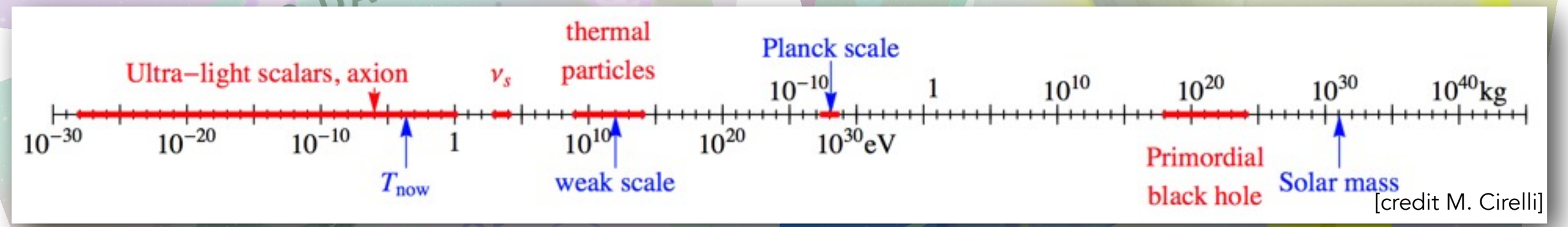
NEUTRALINOS

EXTRA DIMENSIONAL DARK MATTER

KALUZA-KLEIN DARK MATTER

DARK MATTER

AXIONS



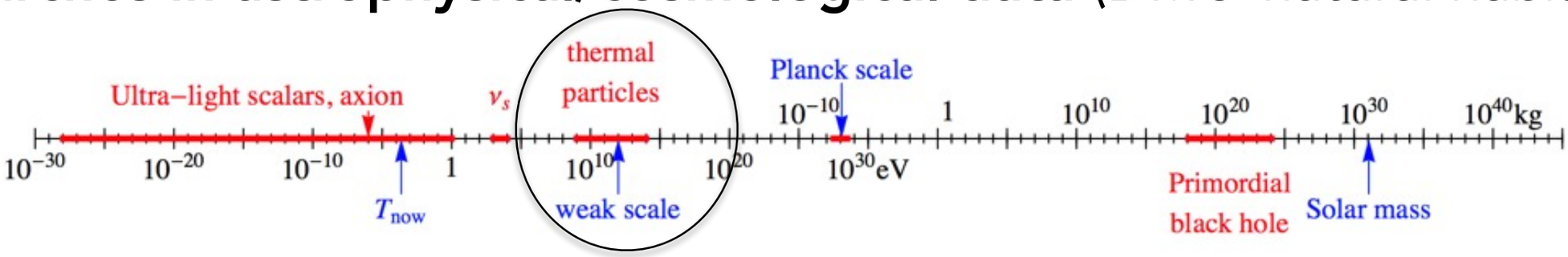
[credit M. Cirelli]

STERILE NEUTRINOS

SIMPS

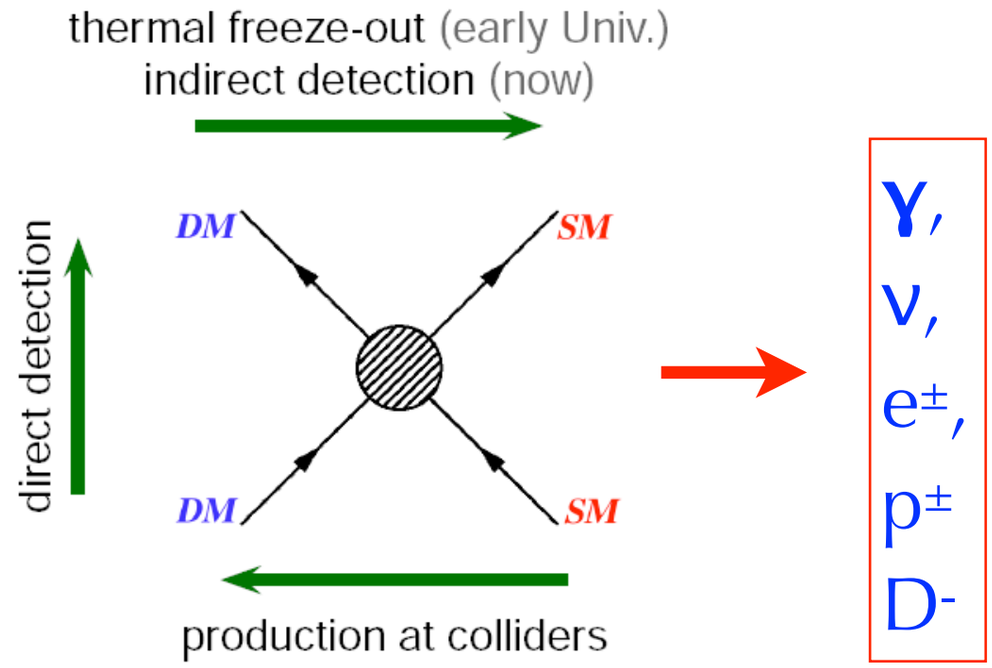
Artwork by Sandbox Studio, Chicago

Searches in astrophysical/cosmological data *(DM's 'natural habitat')*



1. Look for DMDM induced ***SM particle injection***

Special case: **'thermal' DM**



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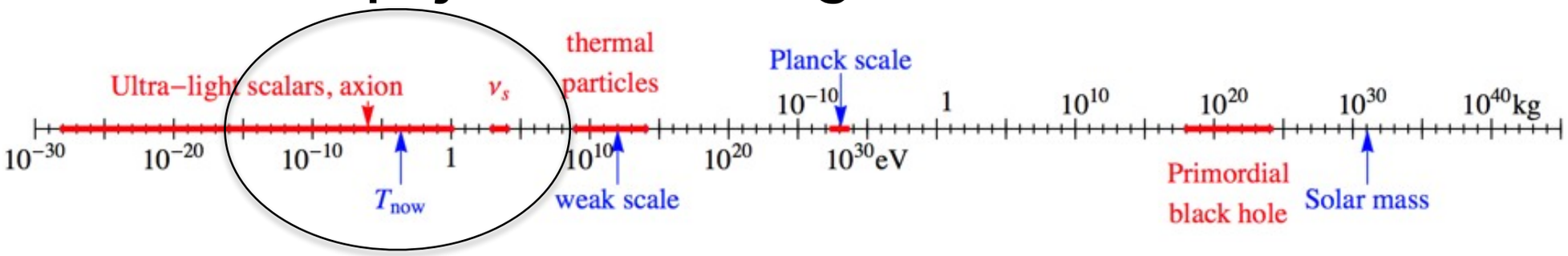

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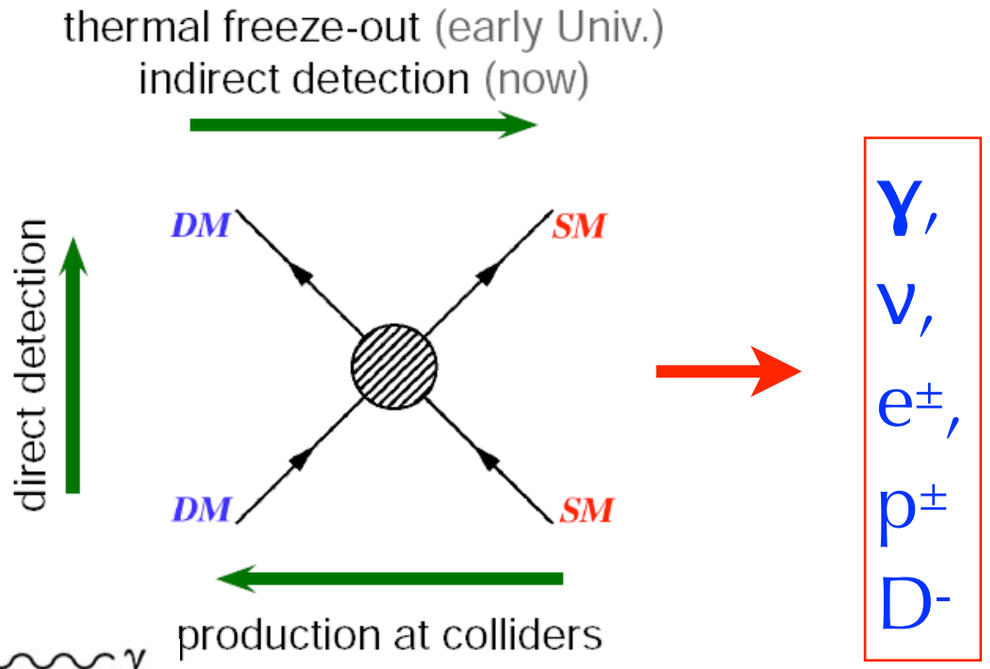
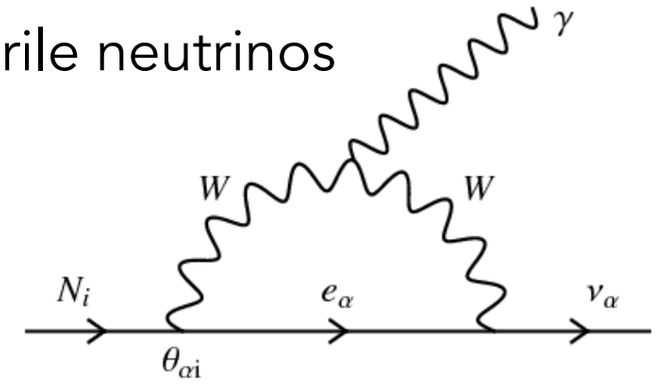
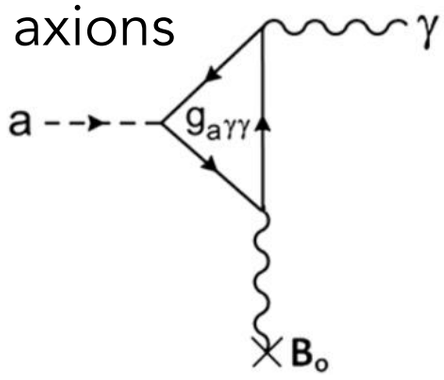


2. Look for **decay** or '**conversions'** to SM

sterile neutrinos



axions



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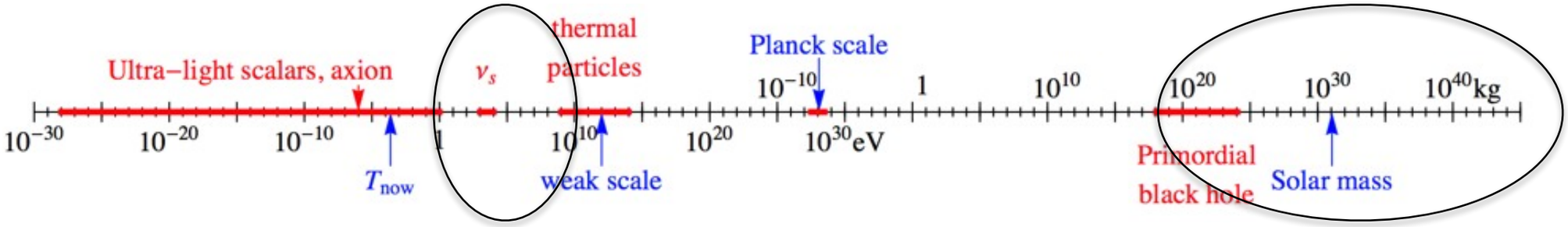

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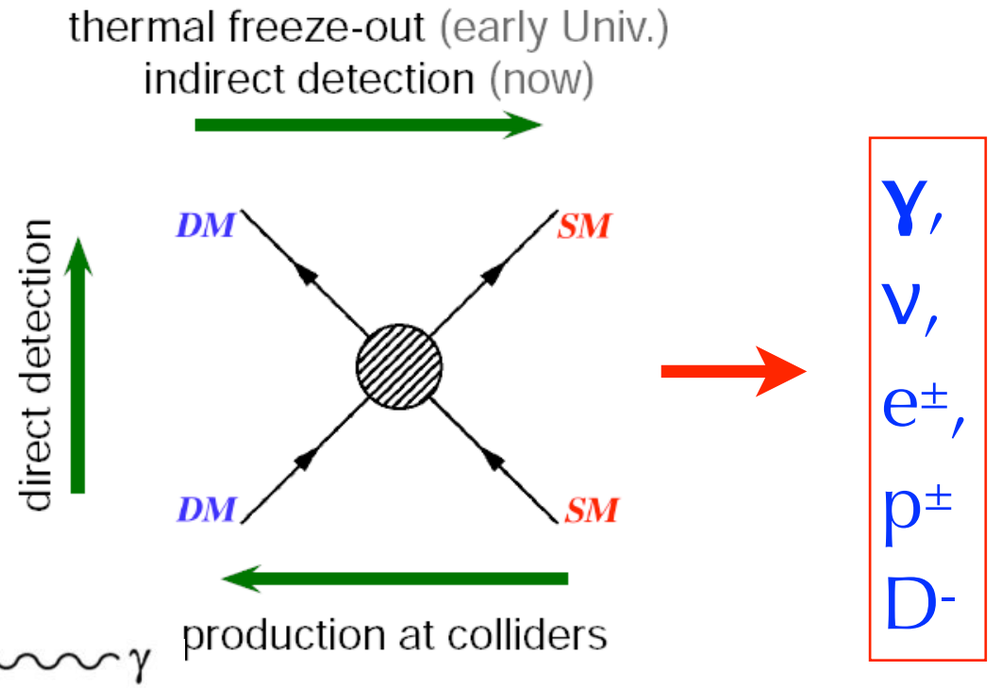

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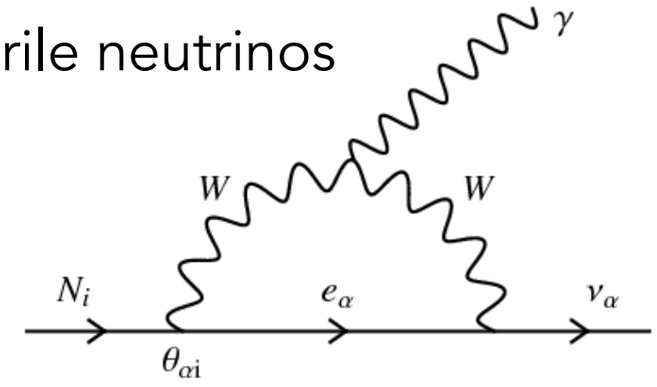

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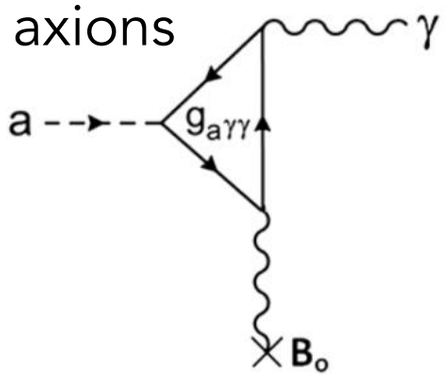
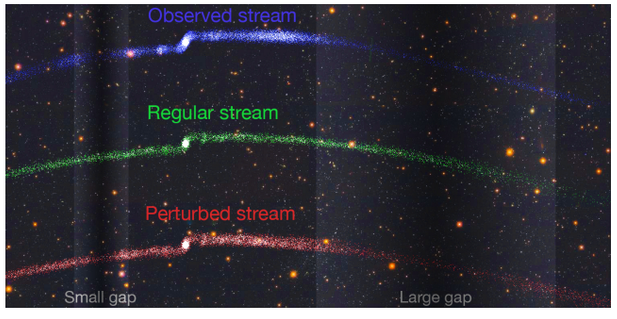


3. Look for **gravitational signatures**



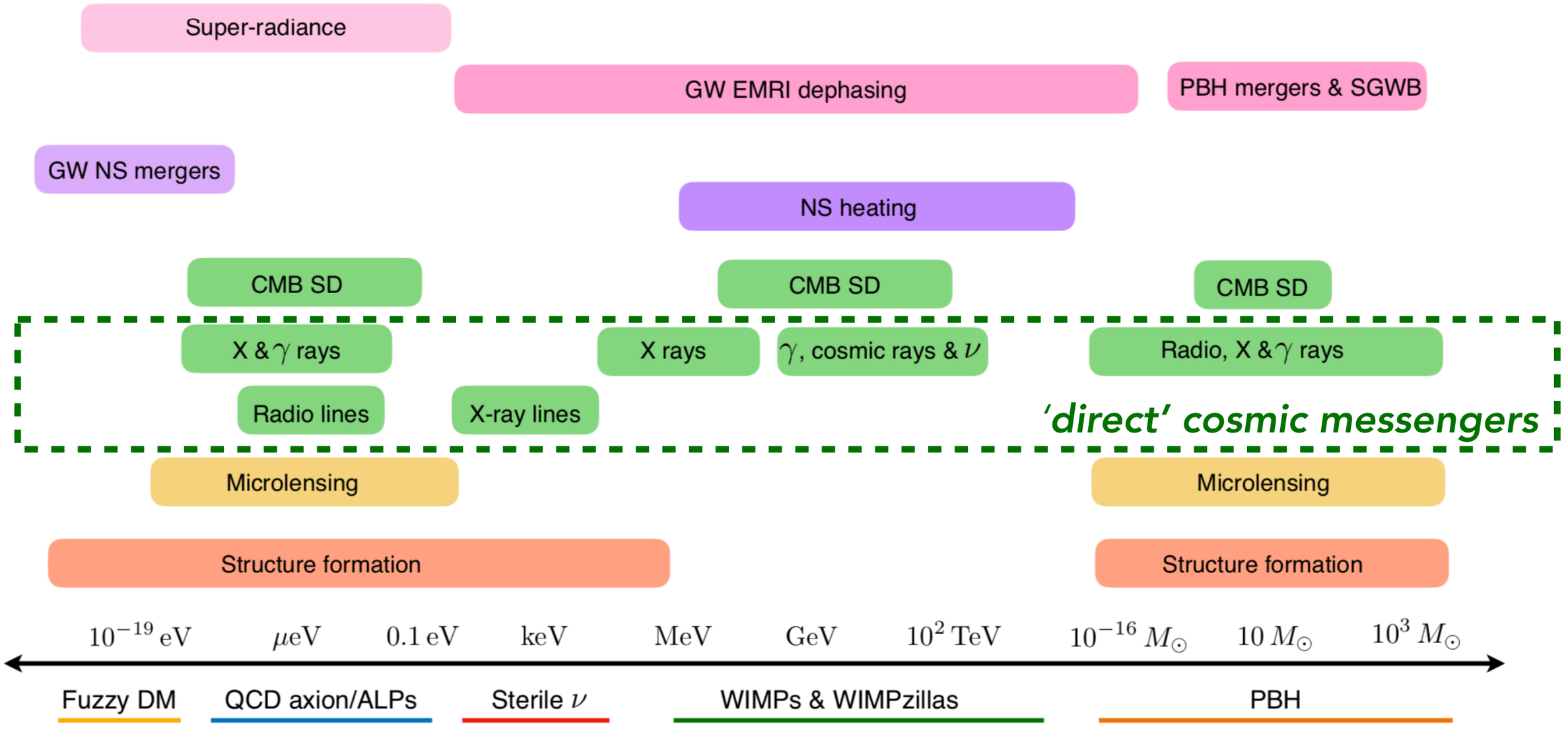
- gravitational lensing (PBHs);
- stellar tidal stream disruptions (warm DM),
- stellar wakes (Gaia)

+ gravitational waves !

PROs: worked so far…

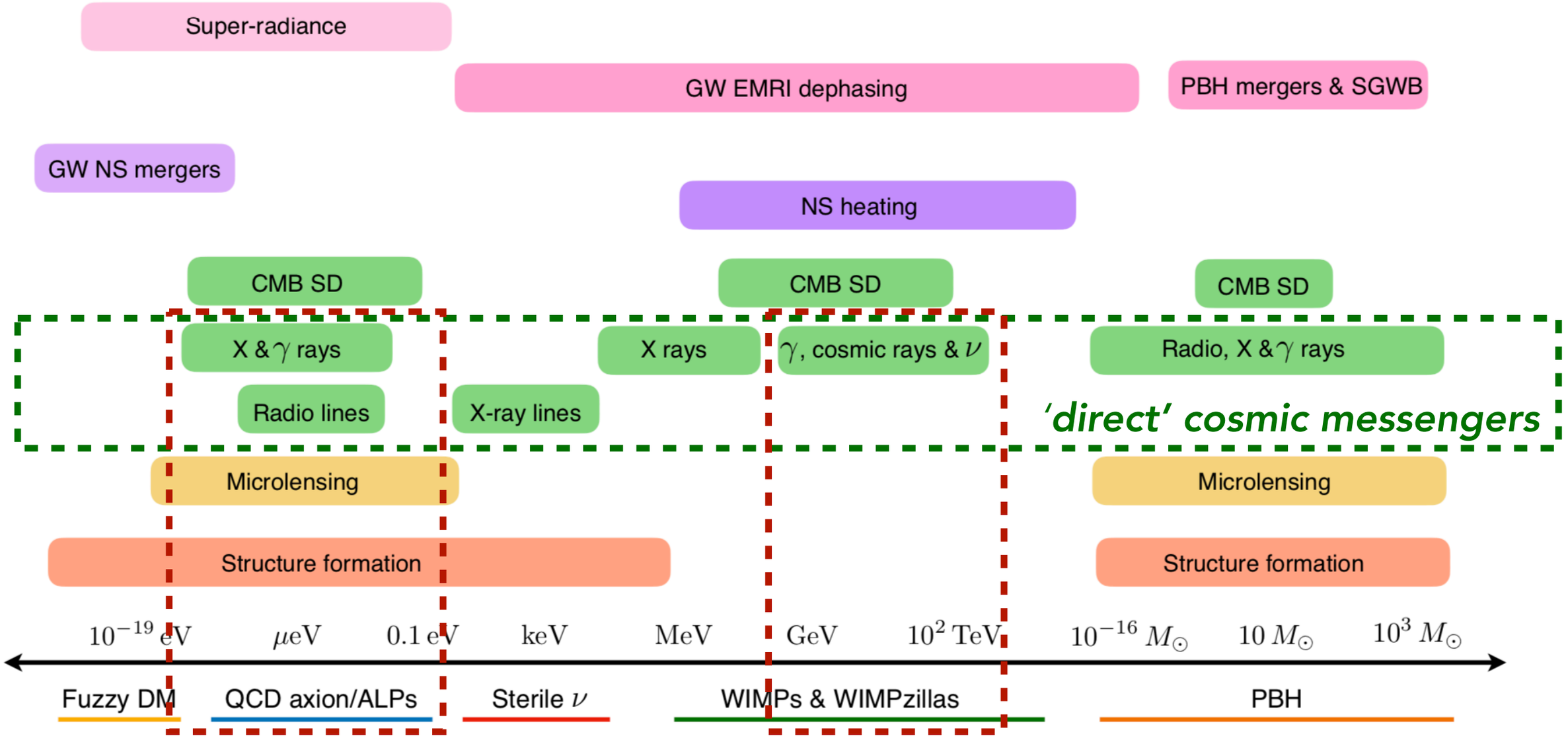
CONs: does not probe interactions with SM directly

In terms of detection strategies:



EuCAPT white paper,
arXiv: 2110.10074

In terms of detection strategies:



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Focusing on DM search via gamma-rays
(WIMPs, ALPs, PBHs…)

- Where to look/DM distribution
- What (gamma-ray) tools do we have
- What strategies to adopt (WIMPs vs ALPs)
- Future

See also **Prof. Francoise Combes's talk!**

Where to look?

- 'locally'

dSph Galaxies

30 kpc

Galactic Centre

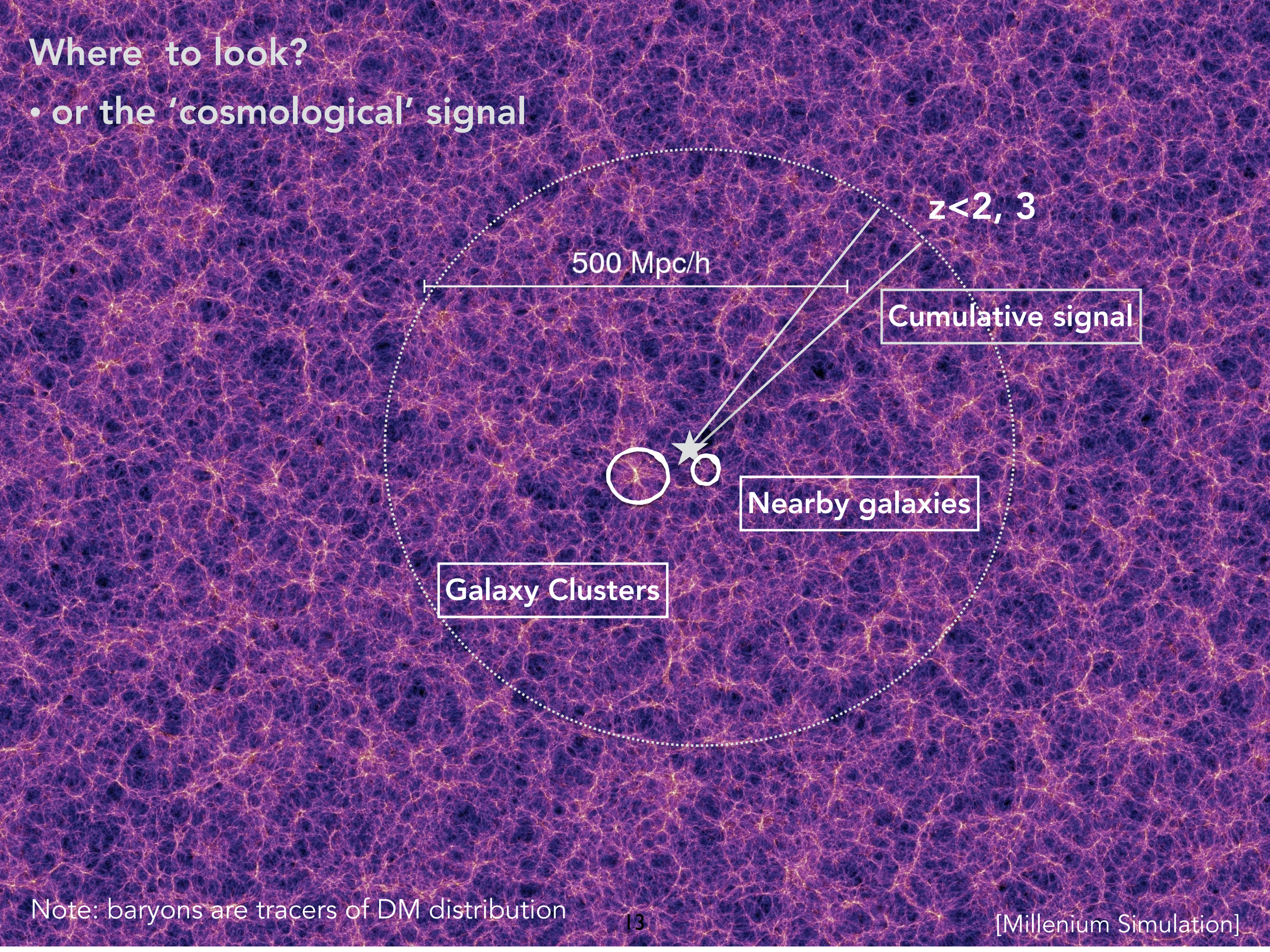
Dark sub halos

Note: baryons are tracers of DM distribution

[Aquarius Simulation]

Where to look?

- or the 'cosmological' signal



Note: baryons are tracers of DM distribution

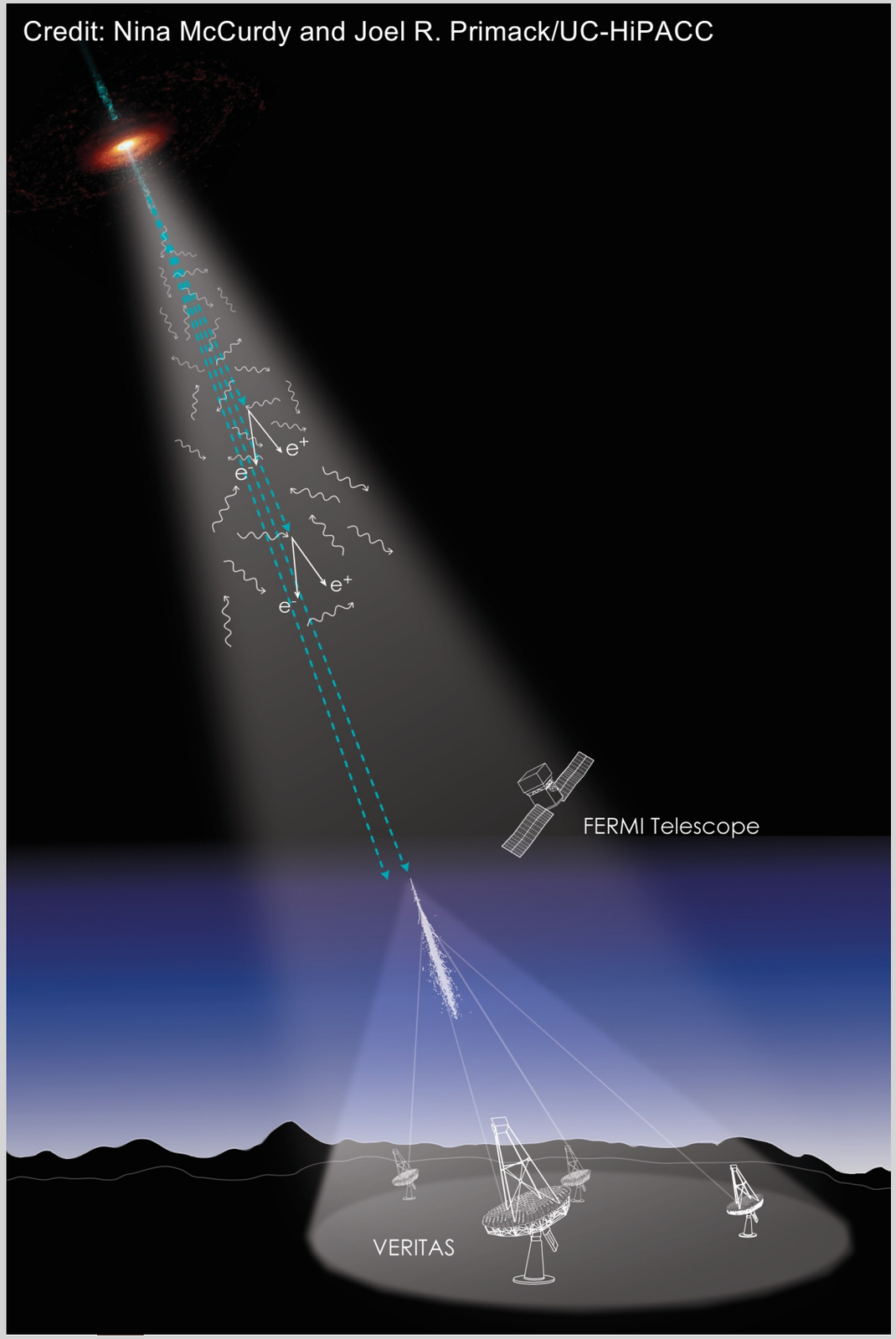
[Millenium Simulation]

What tools?

γ's 'blocked' by the atmosphere

→ ***satellites***

(EGRET (1991- 2001), AGILE (2007-), Fermi LAT (2008-))



What tools?

γ's 'blocked' by the atmosphere → ***satellites***

(EGRET (1991- 2001), AGILE (2007-), Fermi LAT (2008-))

or ground based

Imaging Atmospheric Cherenkov Telescopes

(…,H.E.S.S. (2002 -), MAGIC (2004 -), VERITAS (2007 -))

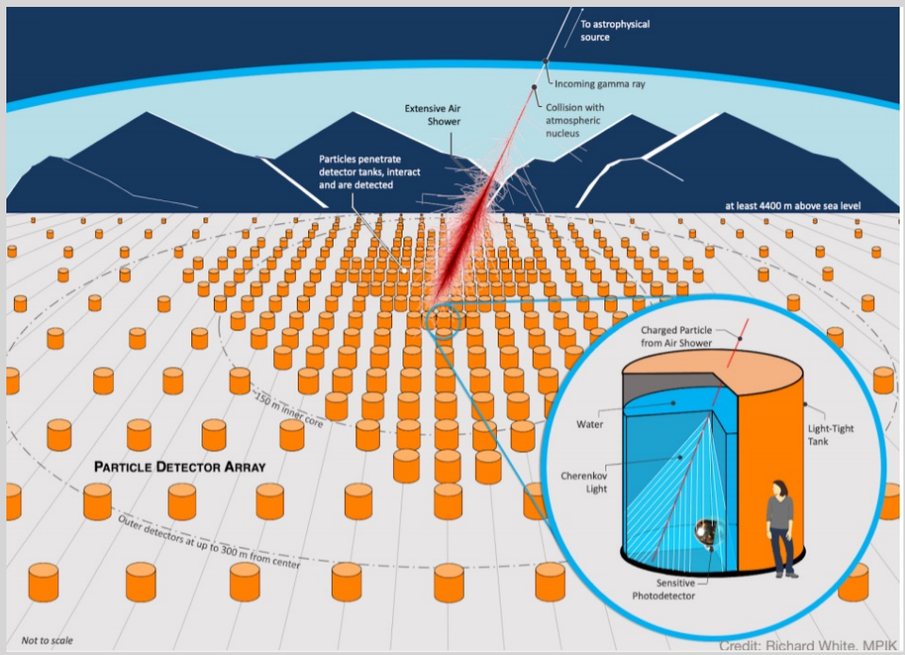
Water Cherenkov detectors

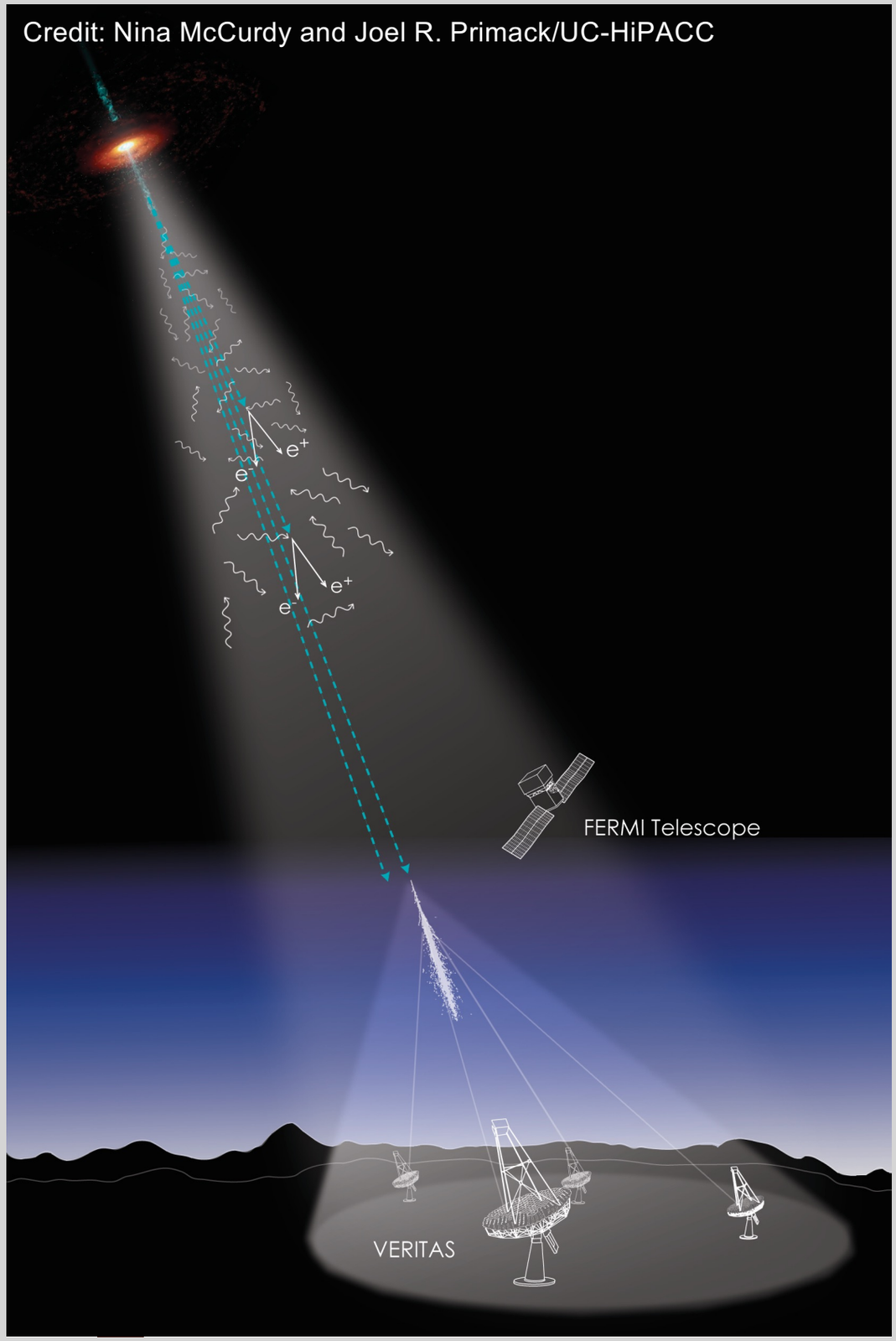
('observing Universe with a bucket of water')

(…, HAWC (2011 -))

Other techniques (scintilators) + combinations

(Tibet ASγ (1990-), LHASSO (2021 -))





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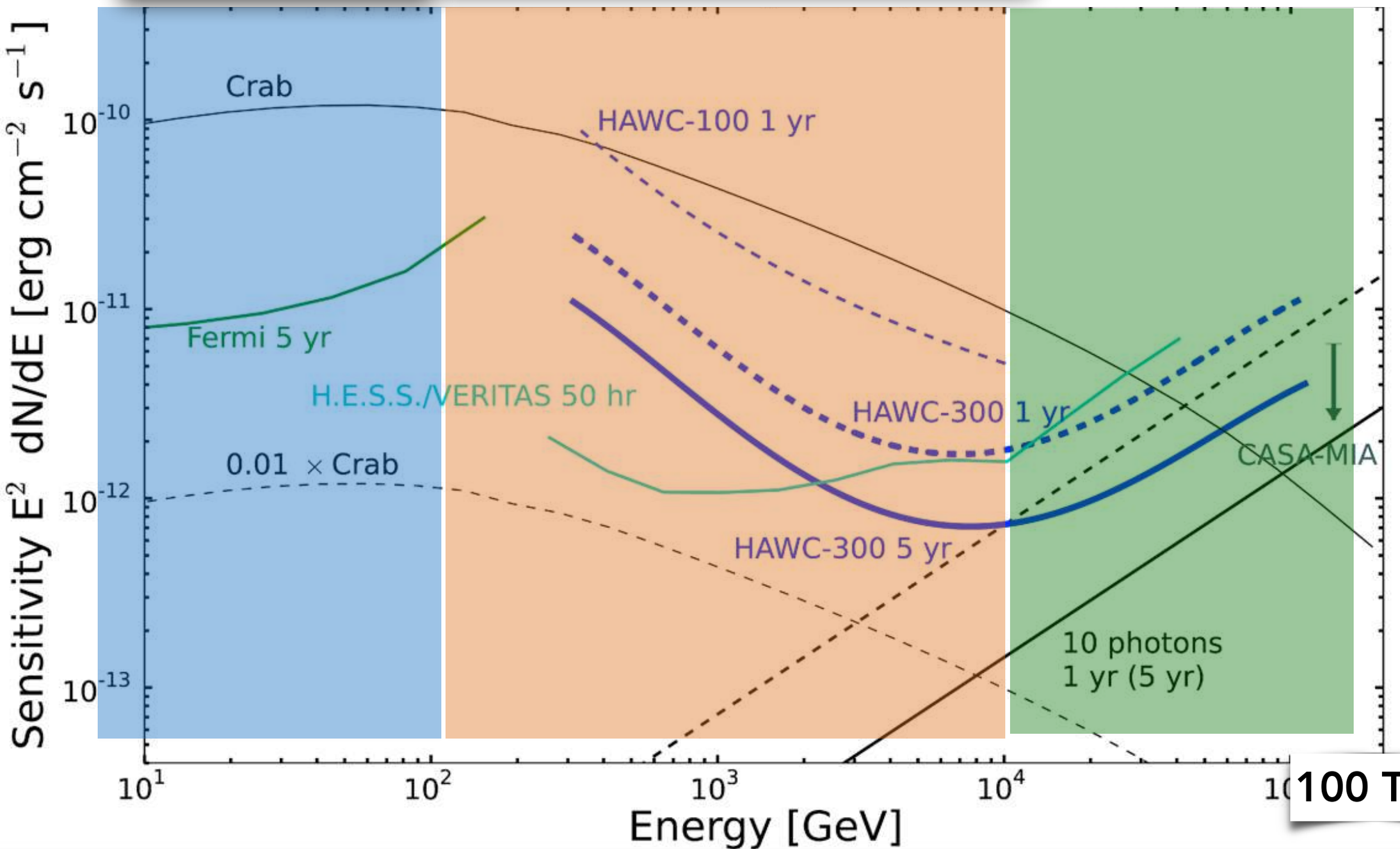
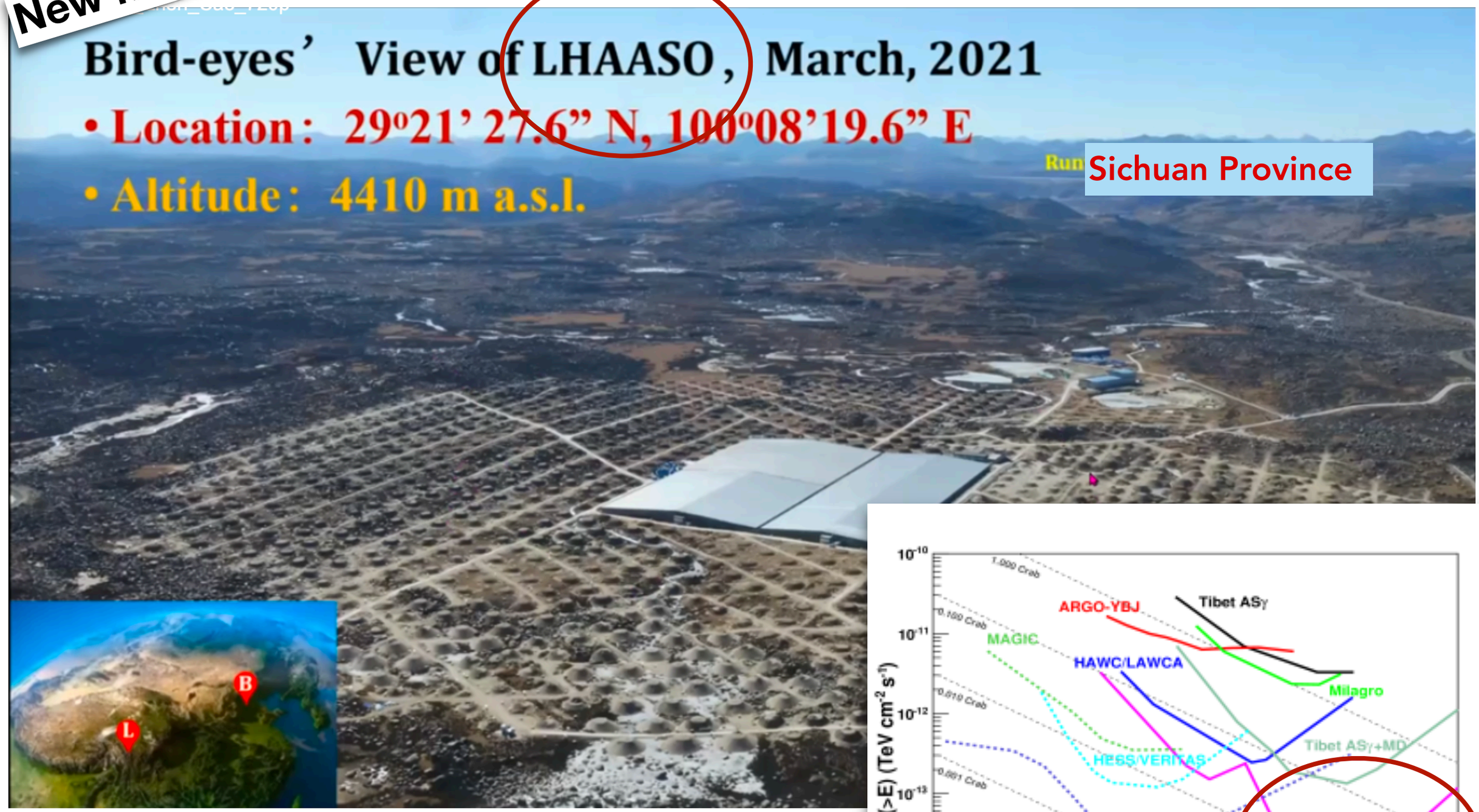
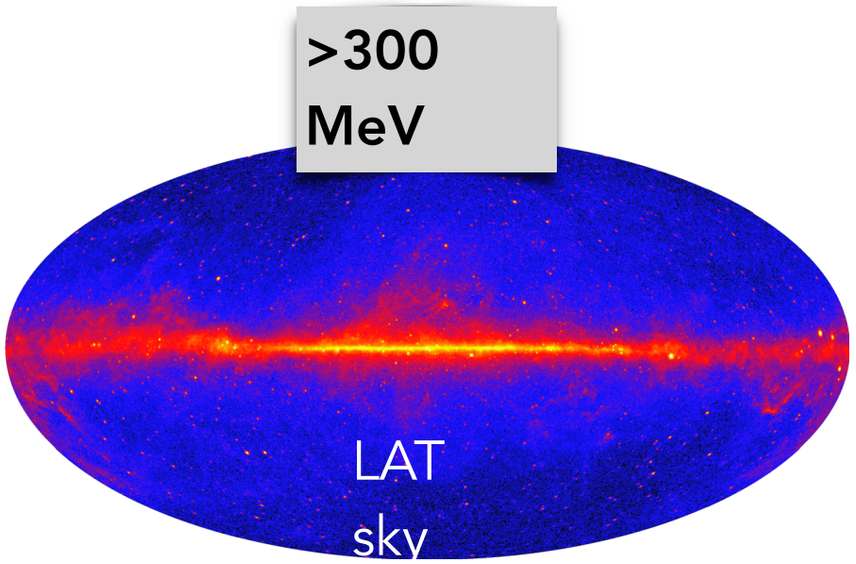


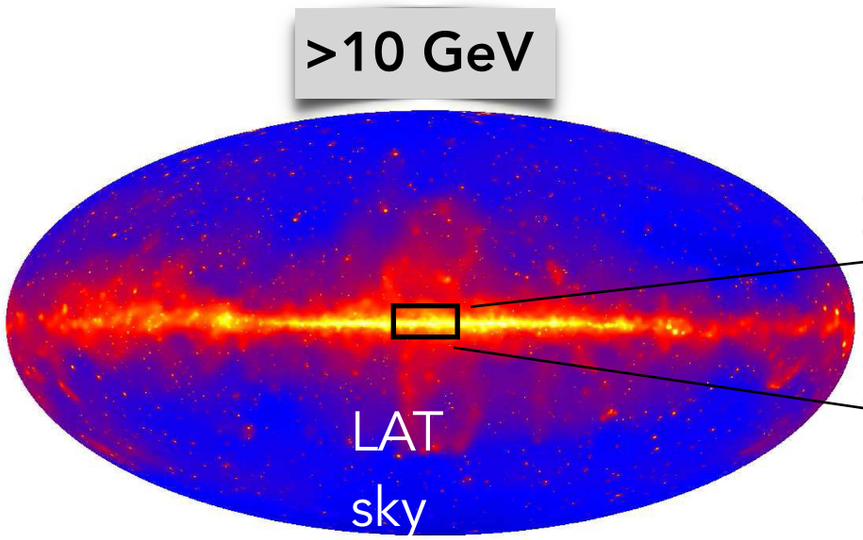
100 TeV

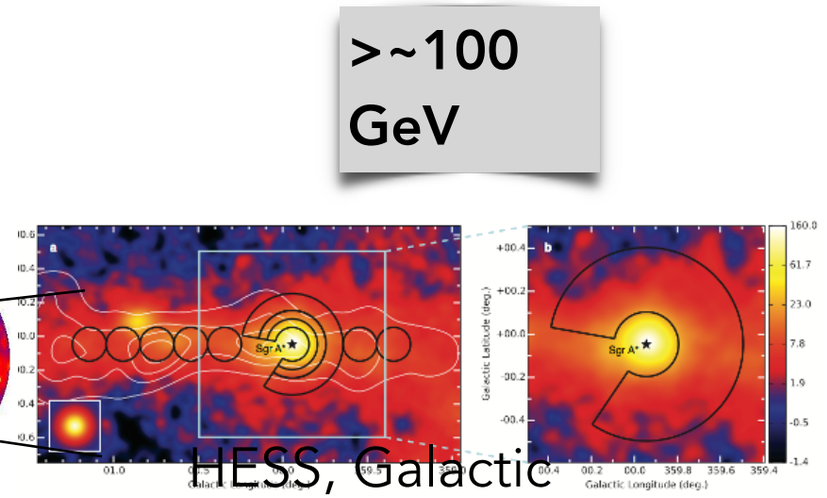
New kid on the block !



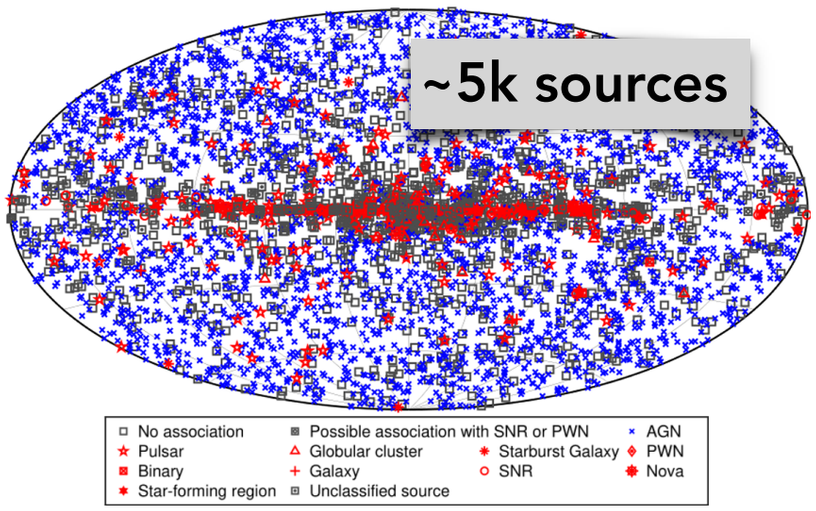
GeV vs TeV



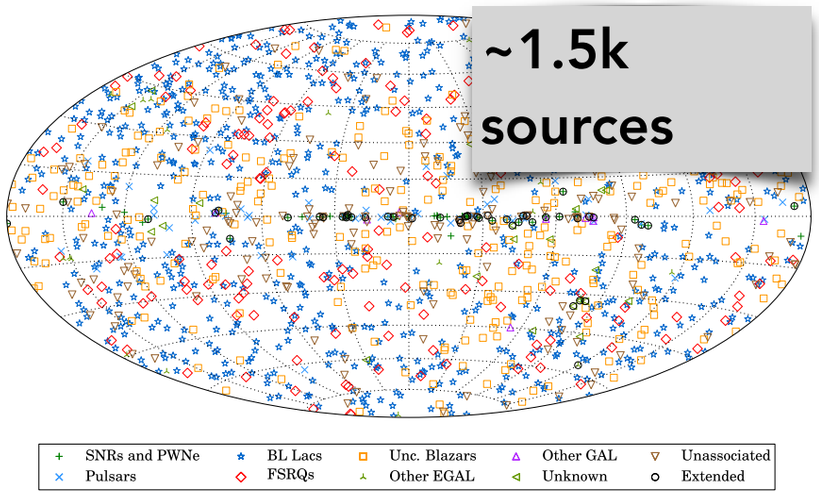




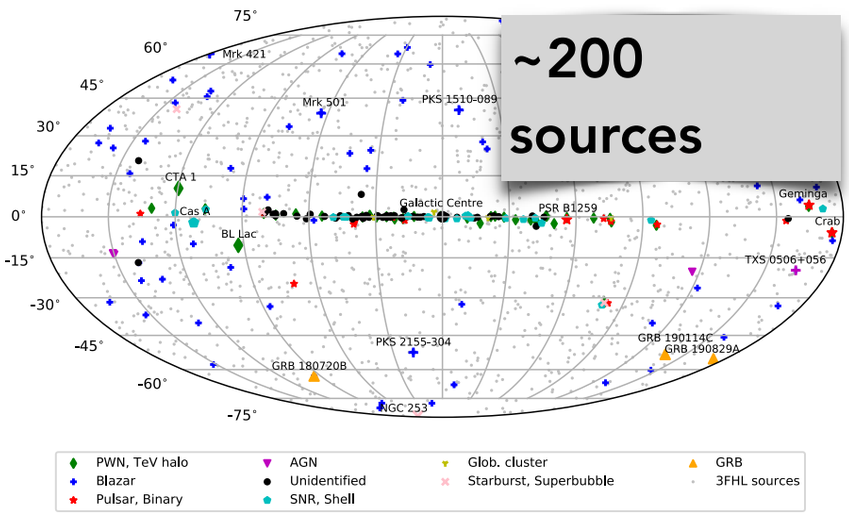
HESS, Galactic center Ridge



LAT source catalogue, >300 MeV (4FGL)



LAT source catalogue, **>10 GeV** (3FHL)

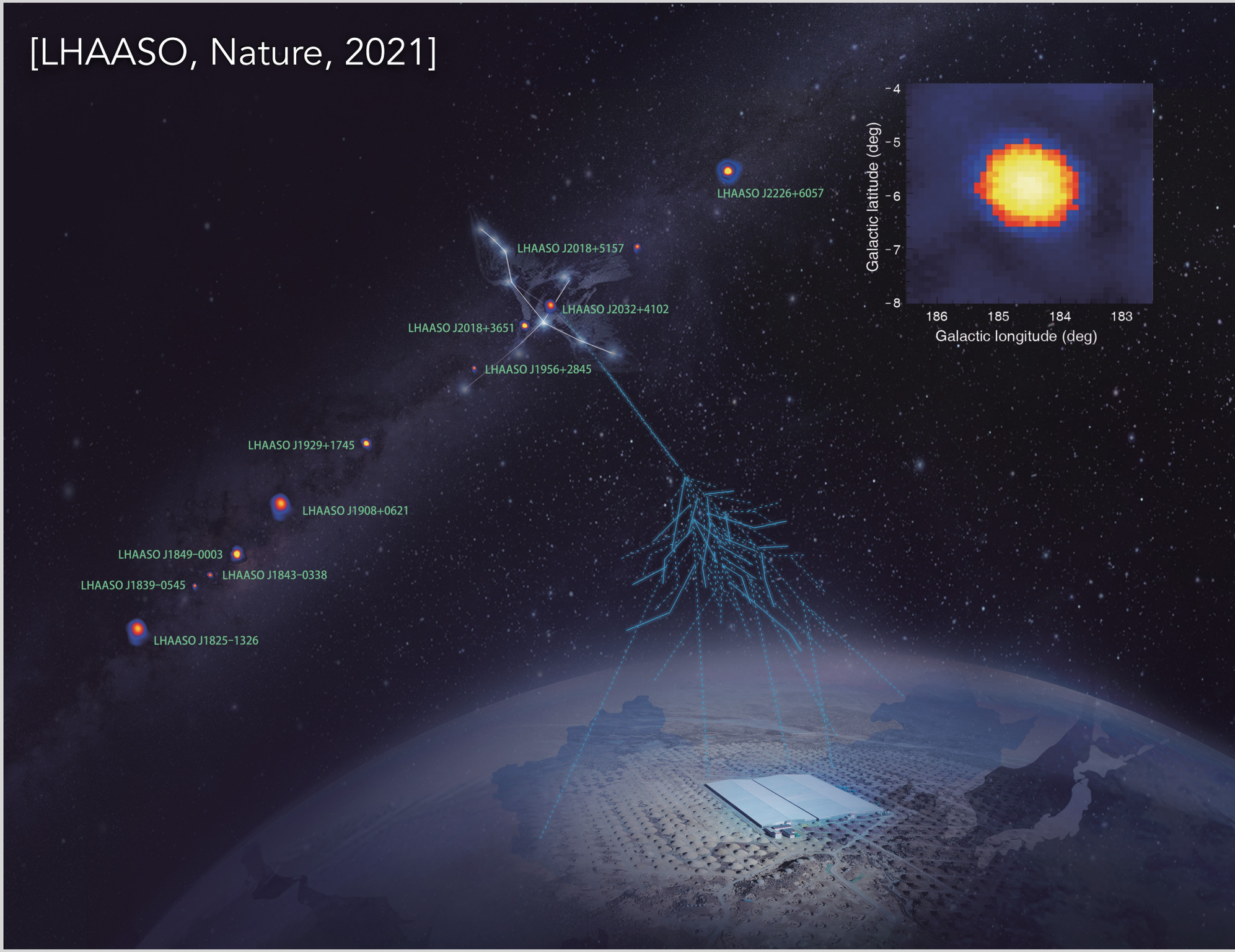


TeVCat, 2019

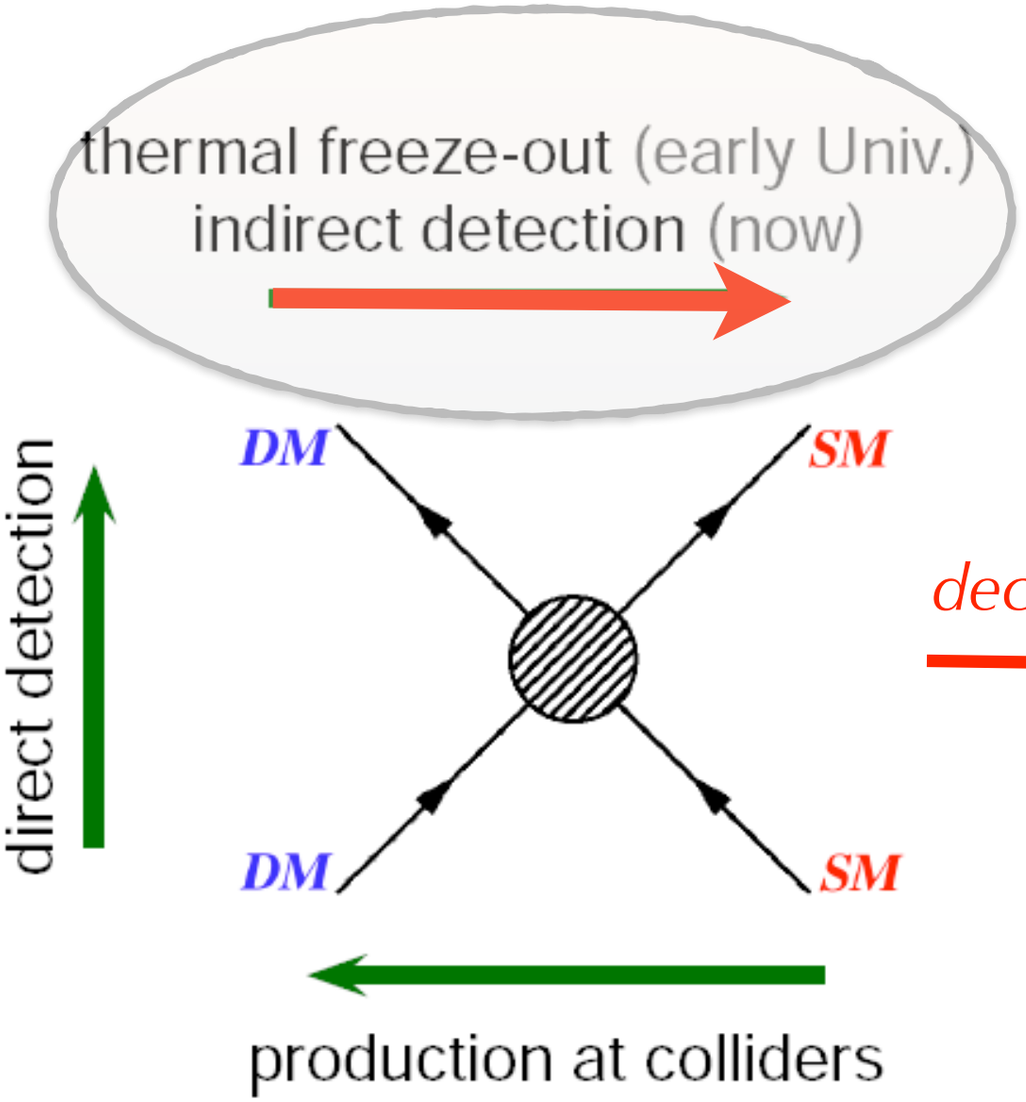
Galactic PeVatrons ?

LHAASO detected **12 sources at > 0.1 PeV**, based on more than **530 photons** (including photons up to **1.4 PeV**)!

In the proximity of known gamma ray emitters, ***PWNe, SNRs and star-forming regions (+Crab nebula)***



What strategy: '**Weakly interacting Massive Particles' (WIMPs)**



decay

γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}

@ $\mathcal{O}(M_Z)$

In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle_{thermal}$.

Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle_{thermal}$, *in places where its* **density is enhanced**!

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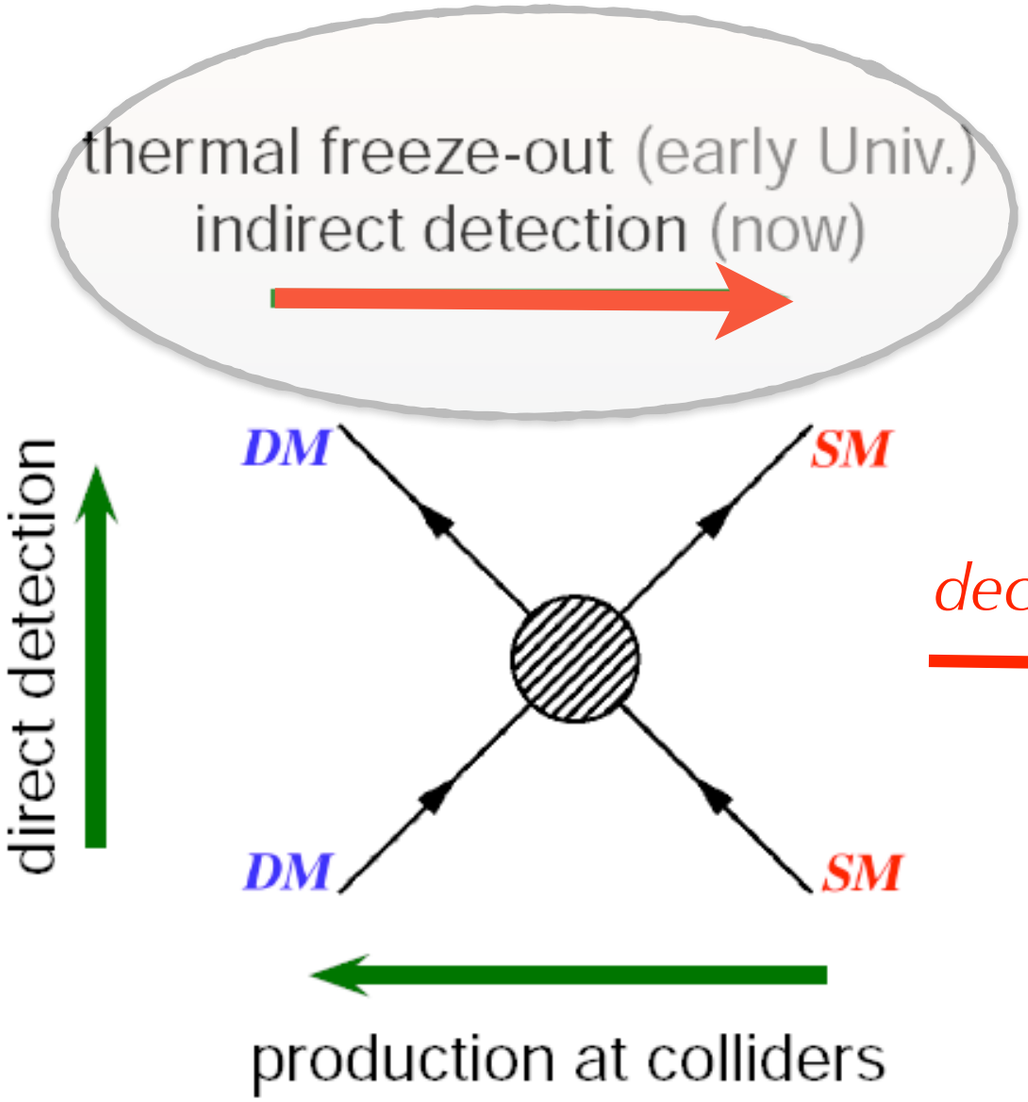

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Predictive:

TeV scale & $\langle \sigma v \rangle_{thermal}$

Gamma-ray DM signature

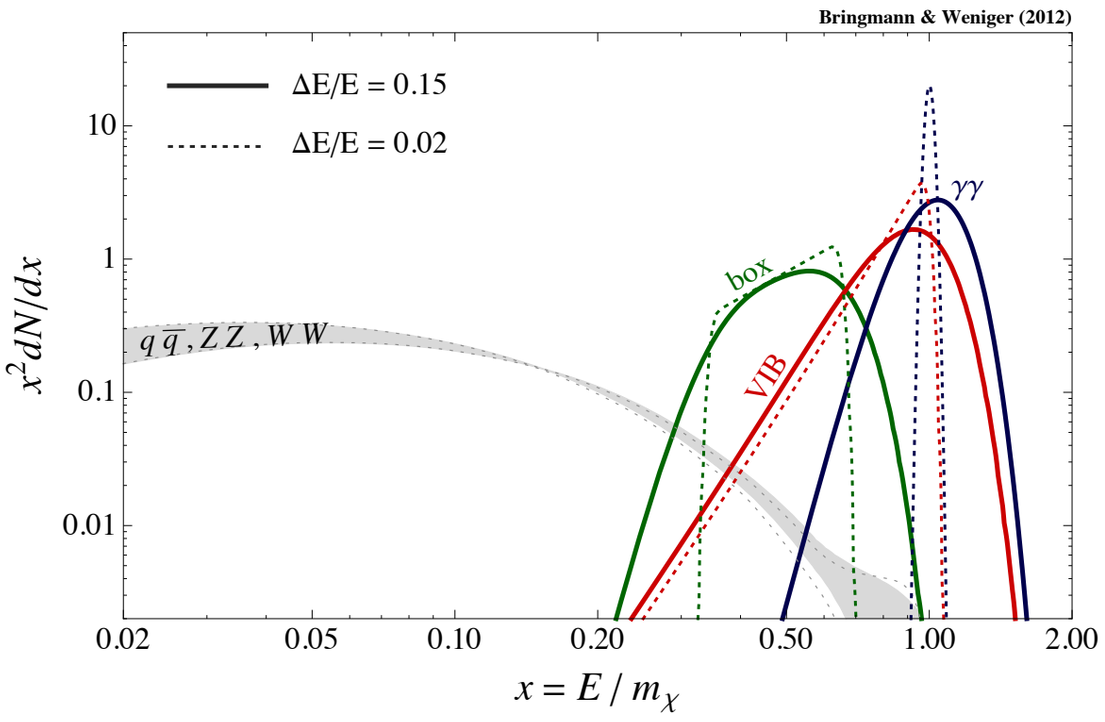
particle physics

cosmology

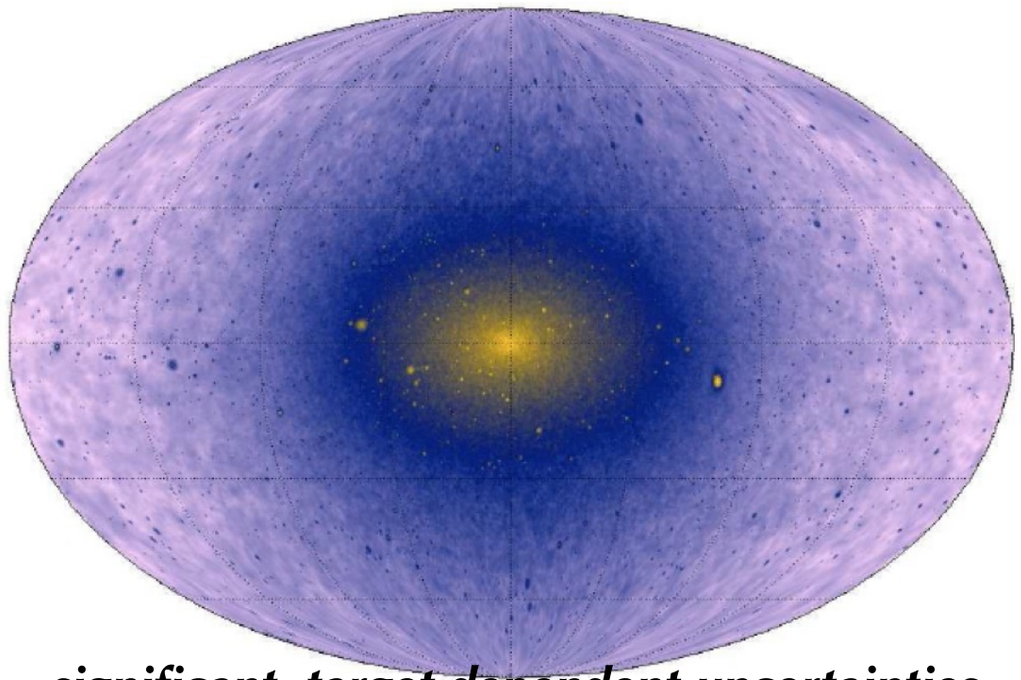
$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{(\sigma_{\mathrm{ann}} v)}{2\, m_\chi^2} \times \sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s, \Omega)$$

this is what we are after!

flux of SM particles per DM annihilation



integrated DM density squared along the line of sight

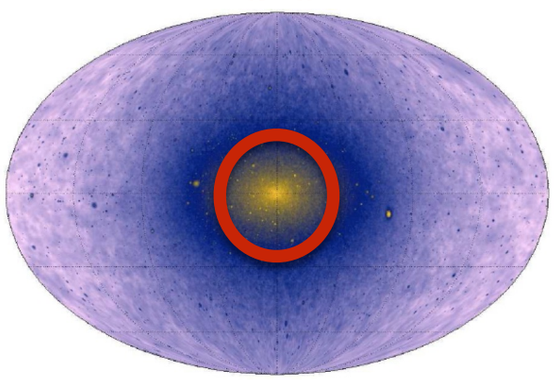


significant, target dependent uncertainties

Strategies for thermal dark matter

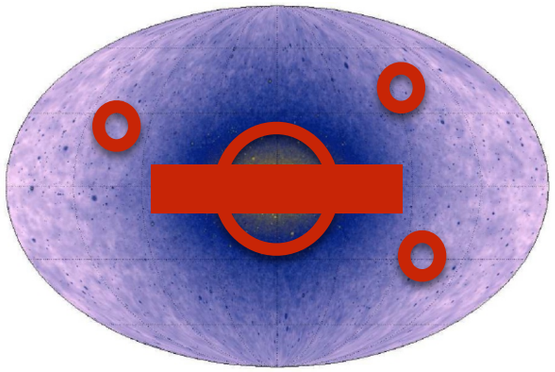
signal strength

GC



[Archaryya et al. JCAP 2020.]

GC halo

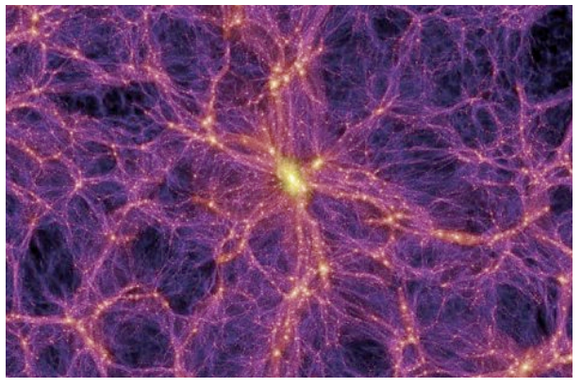


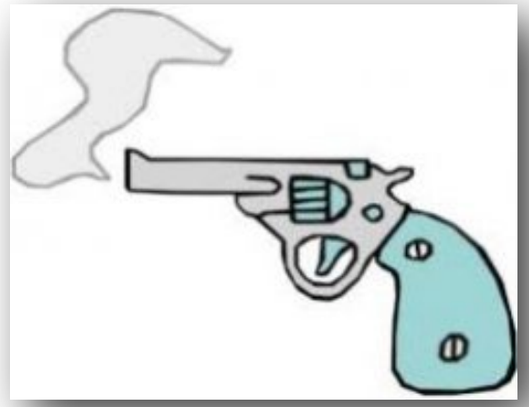
+ dark subhalos

[J. C-B. + Phys.Dark Univ. 32 (2021)]

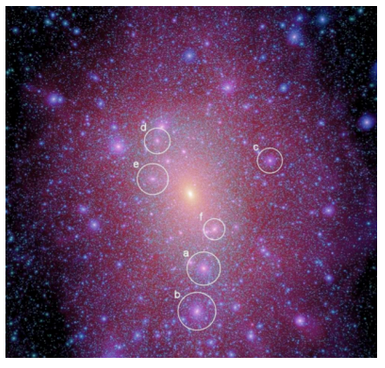
Extragalactic sources:

- **clusters of galaxies**
- **other galaxies (M31, M33, LMC, SMC)**





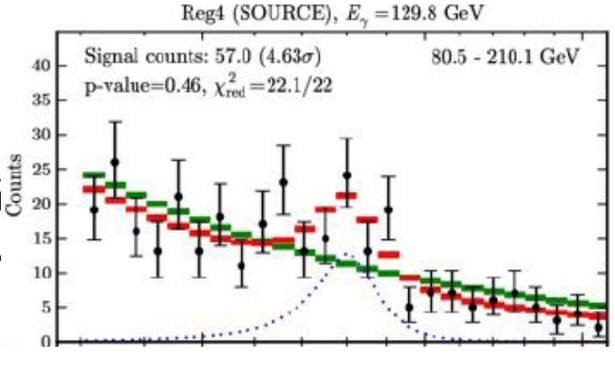
dwarf satellites



Cosmological signal/UEBG:

- **Spectral flux**
- **Auto-correlations**
- **Cross-correlations w G**
  catalogs and cosmic sh

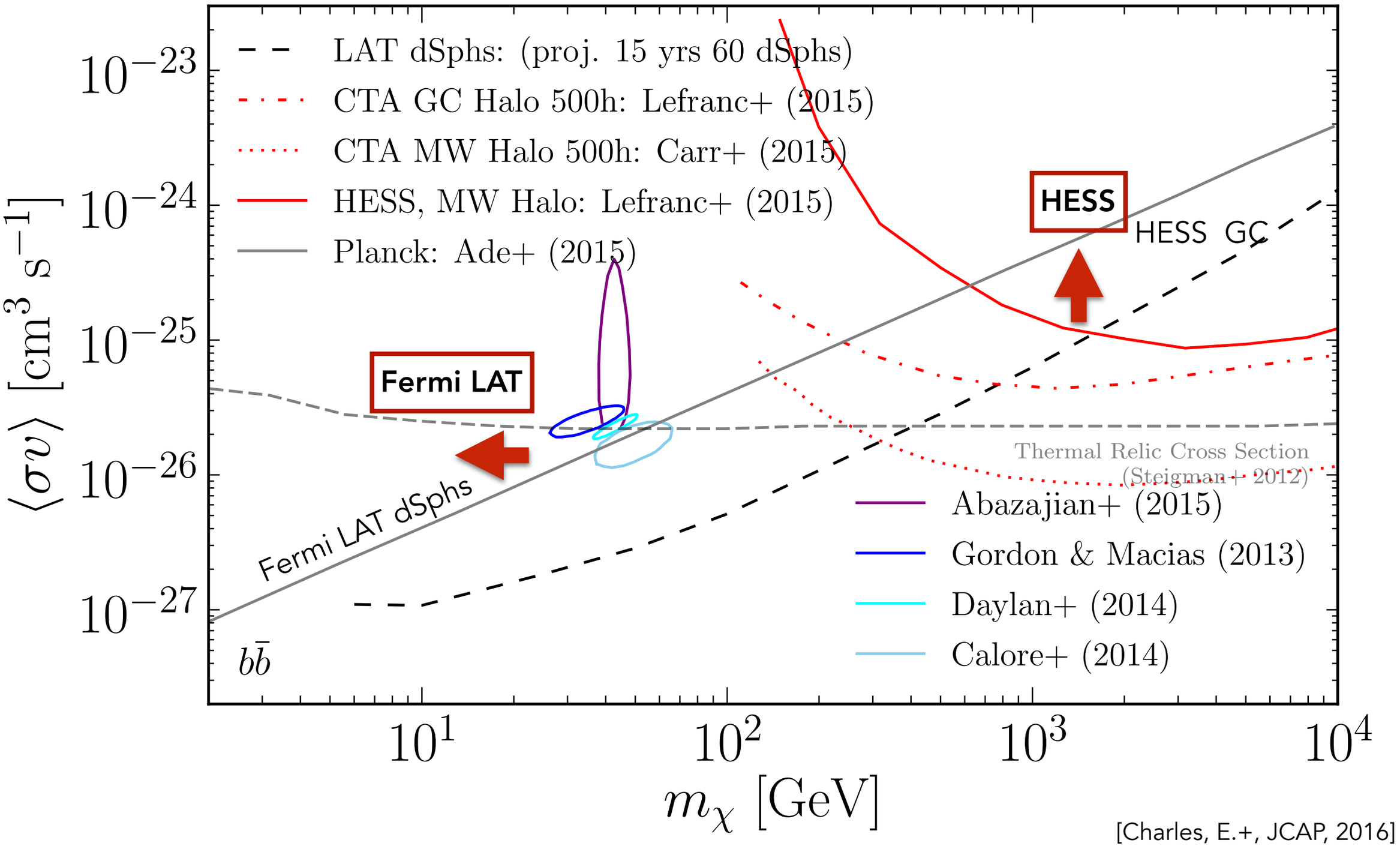
spectral line



[adapted from: H.-S. Zechlin]

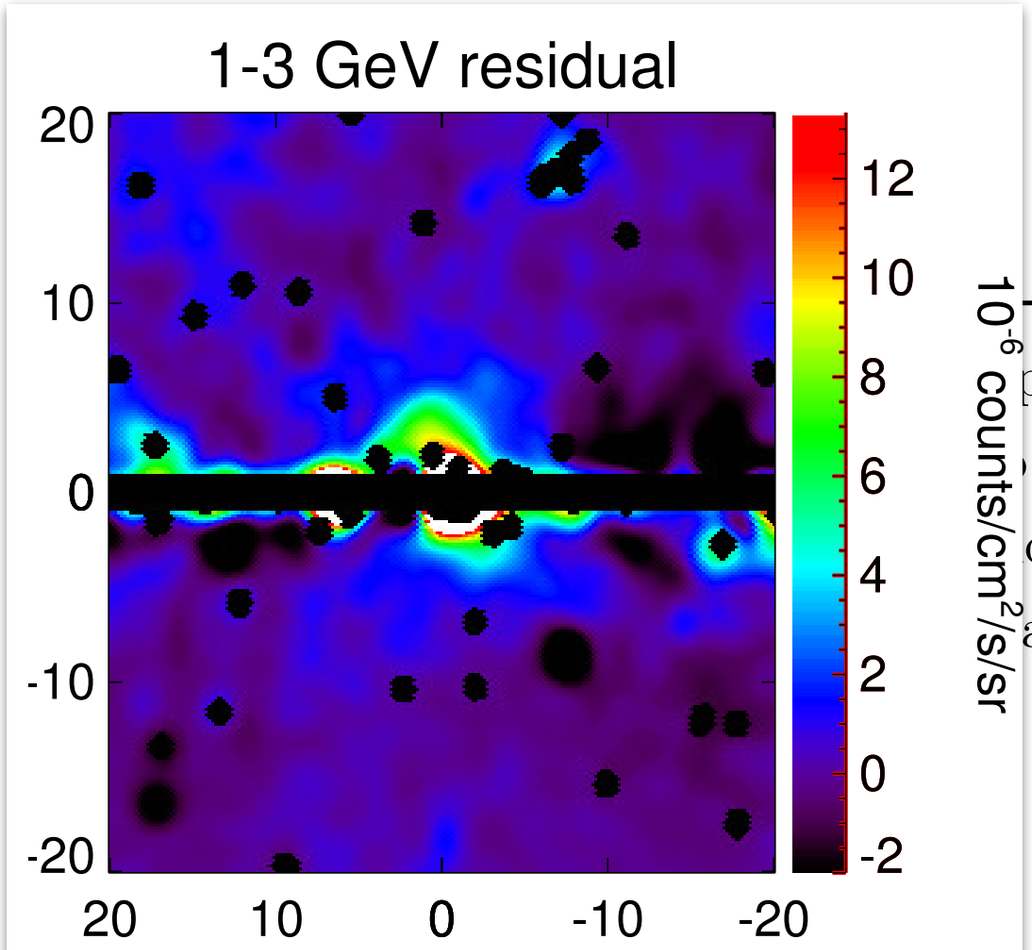
robustness

State-of-the-art



[Charles, E.+, JCAP, 2016]

State-of-the-art



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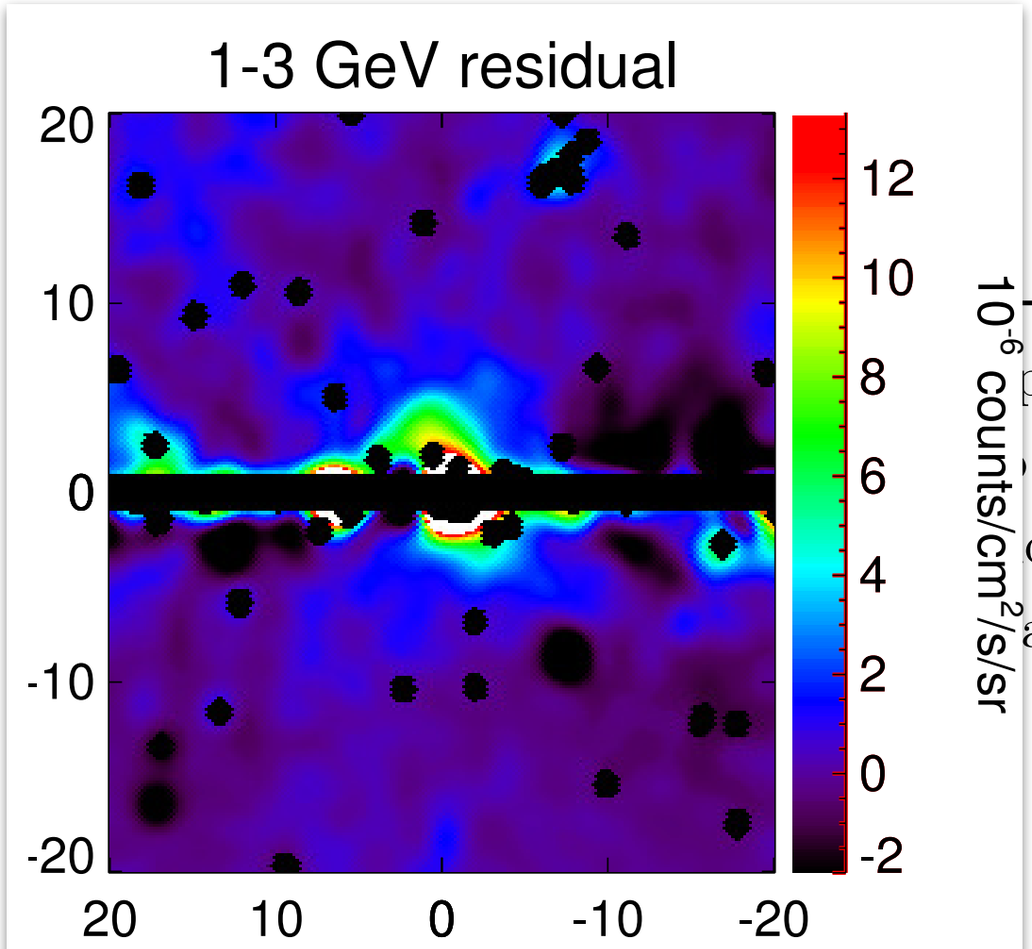


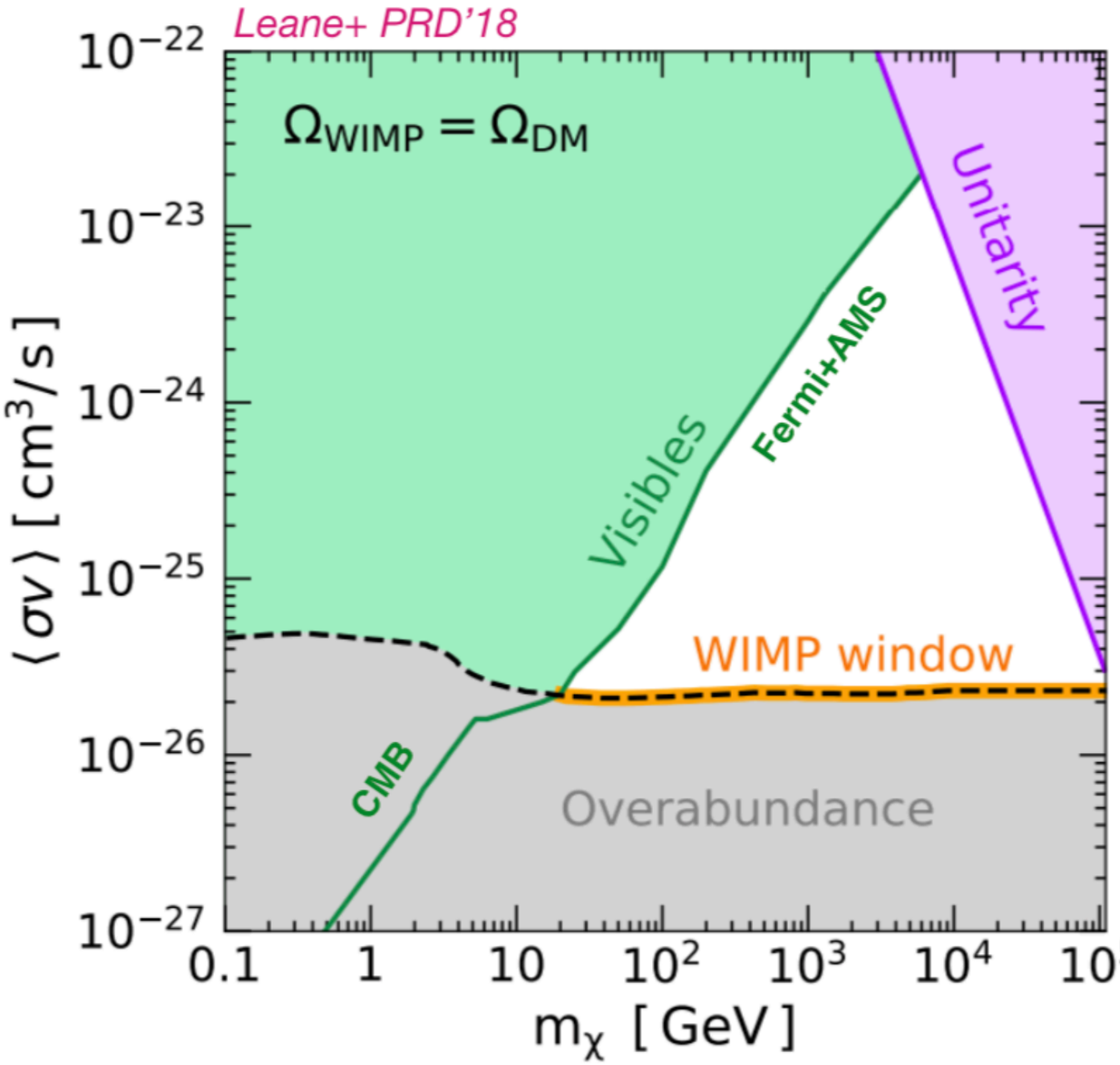
Right on the spot where WIMP DM is supposed to be!

Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)

Baltz et al (2007)

State-of-the-art

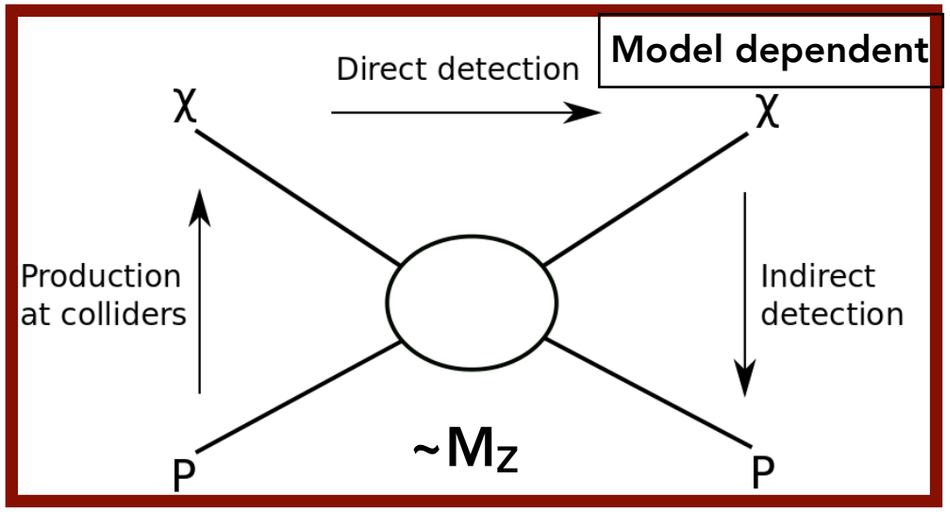
'cornering the WIMP'

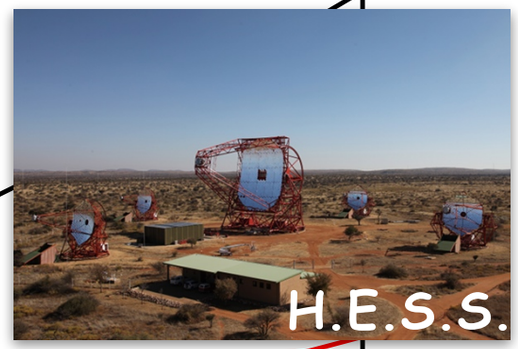


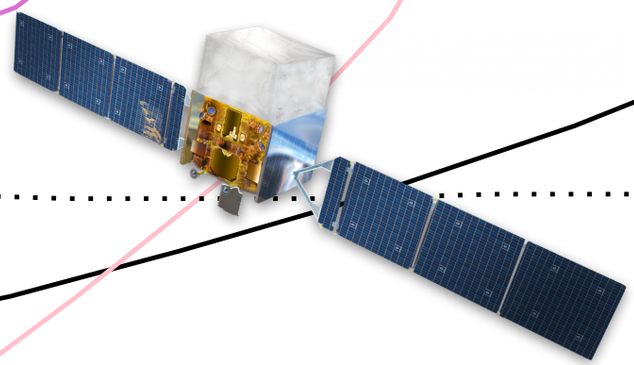
$\langle \sigma v \rangle$ *thermal*

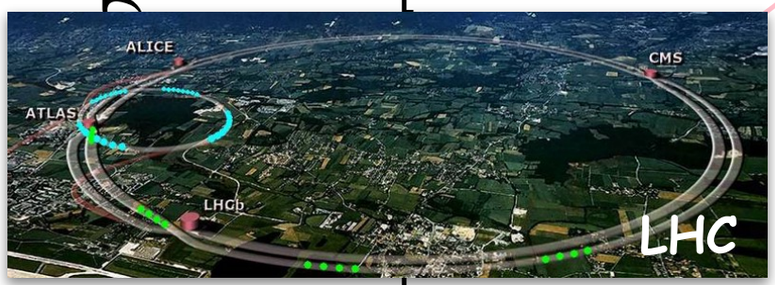
State-of-the-art

'cornering the WIMP'









EFT assumed

Thermal Relic Cross Section
(Steigman+ 2012)

LAT dSphs: Ackermann+ (2015)
HESS, MW Halo: Lefranc+ (2015)
Direct: LUX (2012), XENON100 (2012), COUPP (2012)
LHC: ATLAS (2013), CMS (2012)

$b\bar{b}$

10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-28}

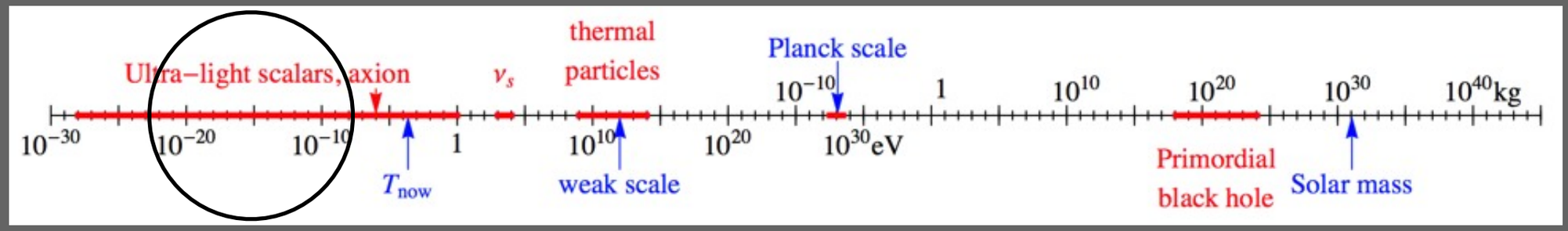
$\langle \sigma v \rangle$ [cm^3 s^{-1}]

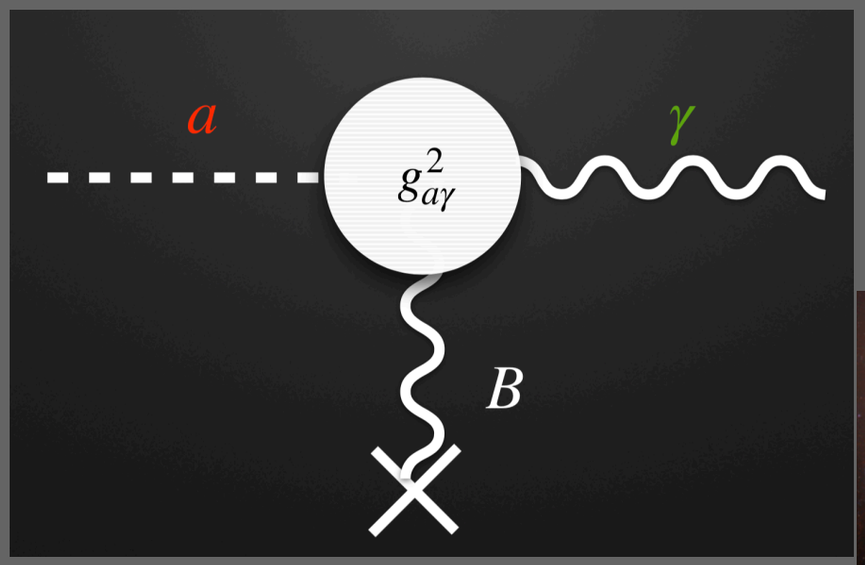
10^1 10^2 10^3 10^4

m_χ [GeV]

[Charles, E.+, JCAP, 2016]

How about **ALPs?**



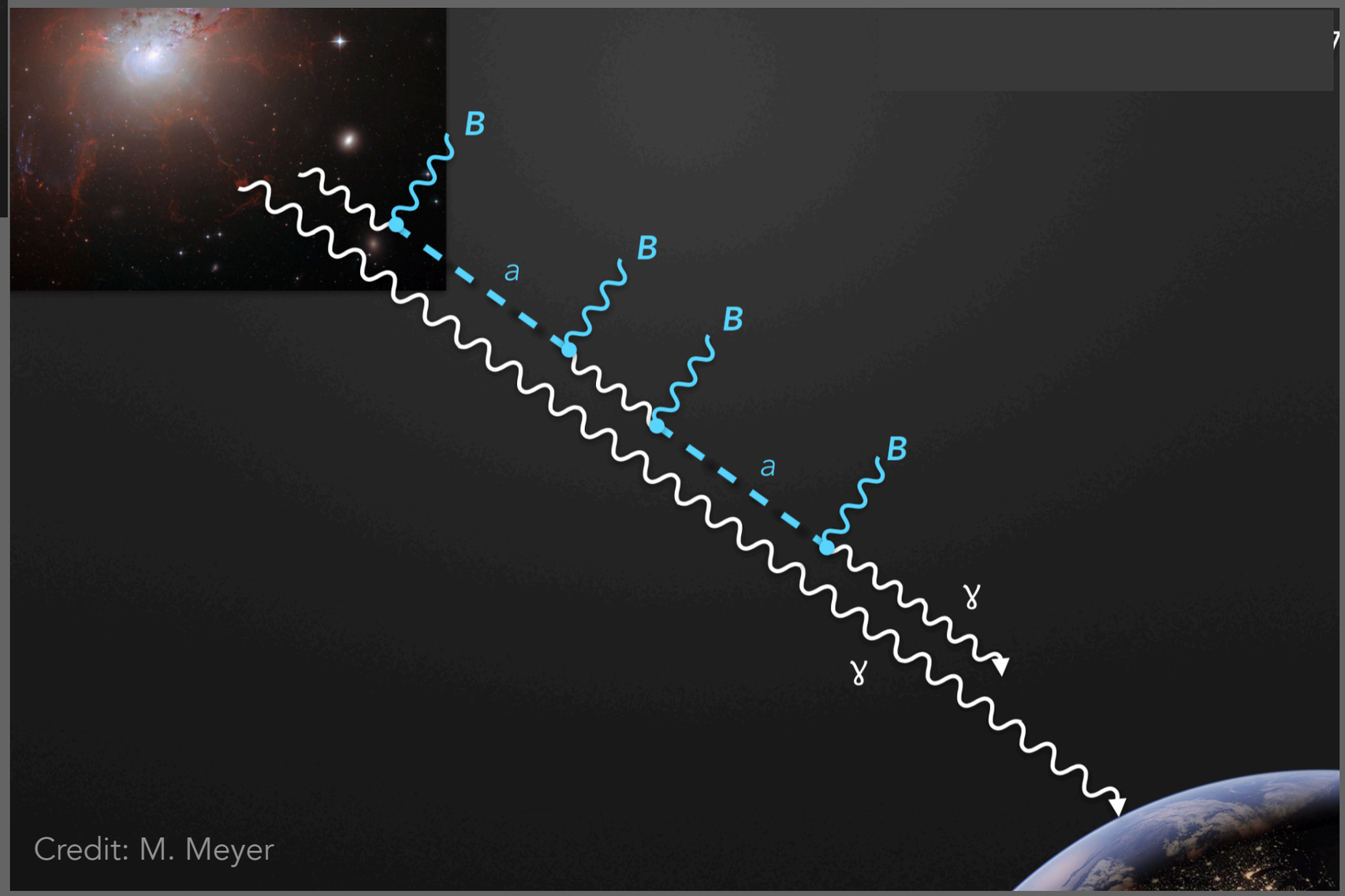


$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\, \mathbf{B} a$$

Where to look?

- strong magnetic fields
- large distances

→ e.g. **galaxy clusters**

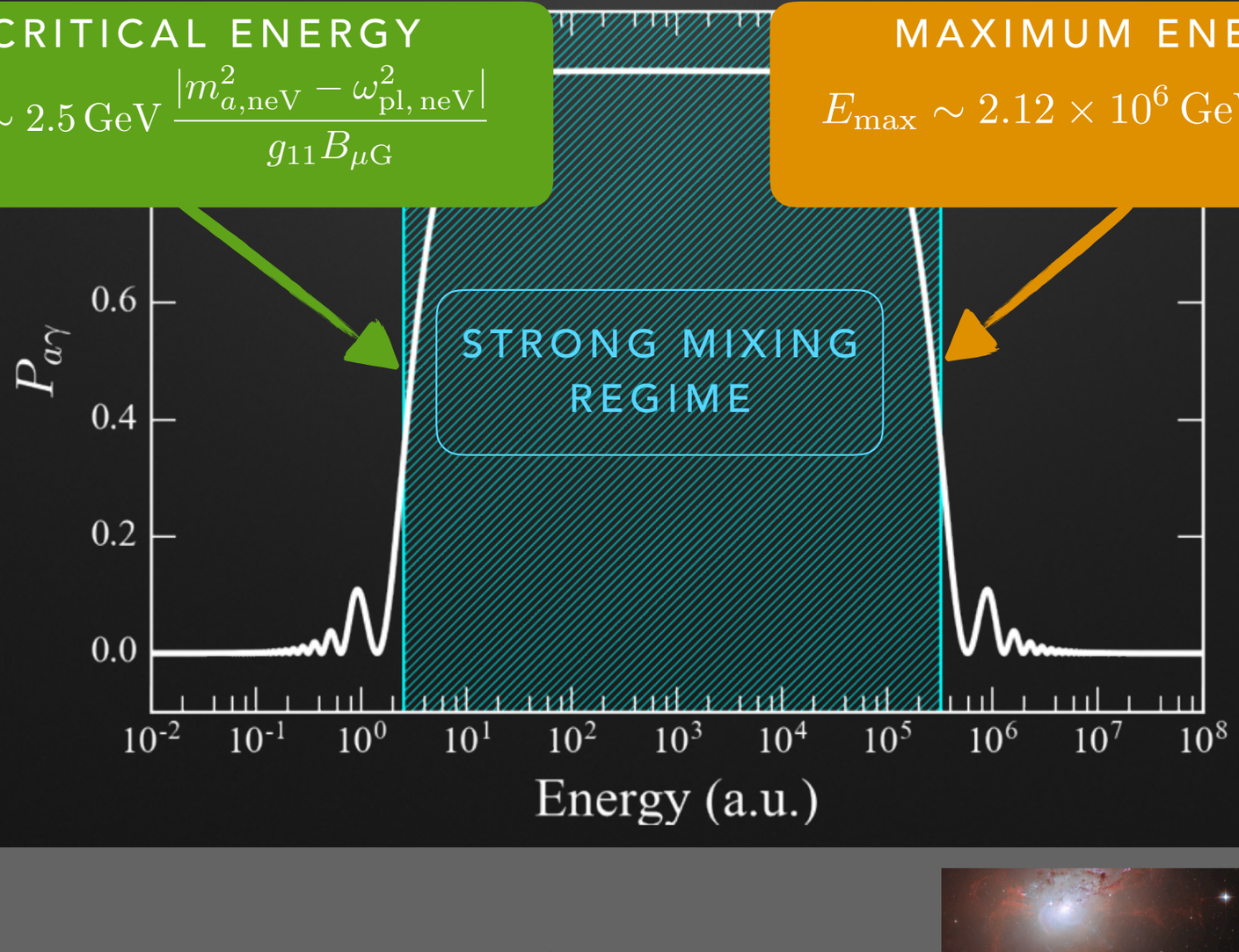


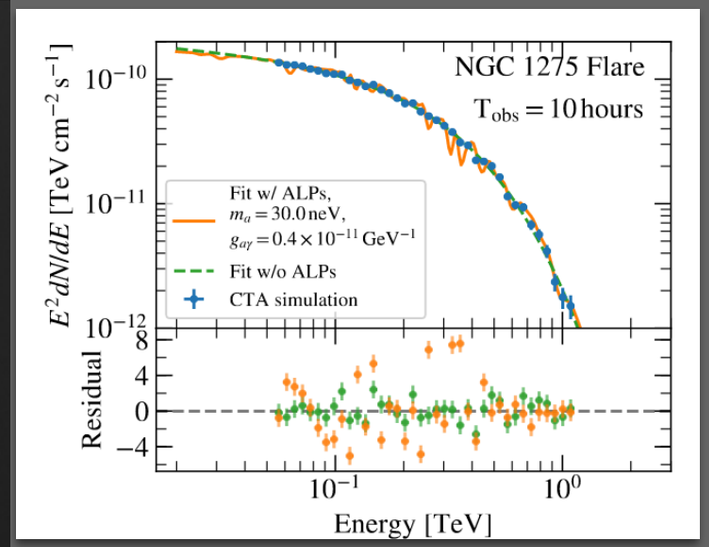
CRITICAL ENERGY

$$E_{\rm crit} \sim 2.5\,{\rm GeV}\,\frac{|m^2_{a,{\rm neV}} - \omega^2_{{\rm pl,\,neV}}|}{g_{11} B_{\mu{\rm G}}}$$

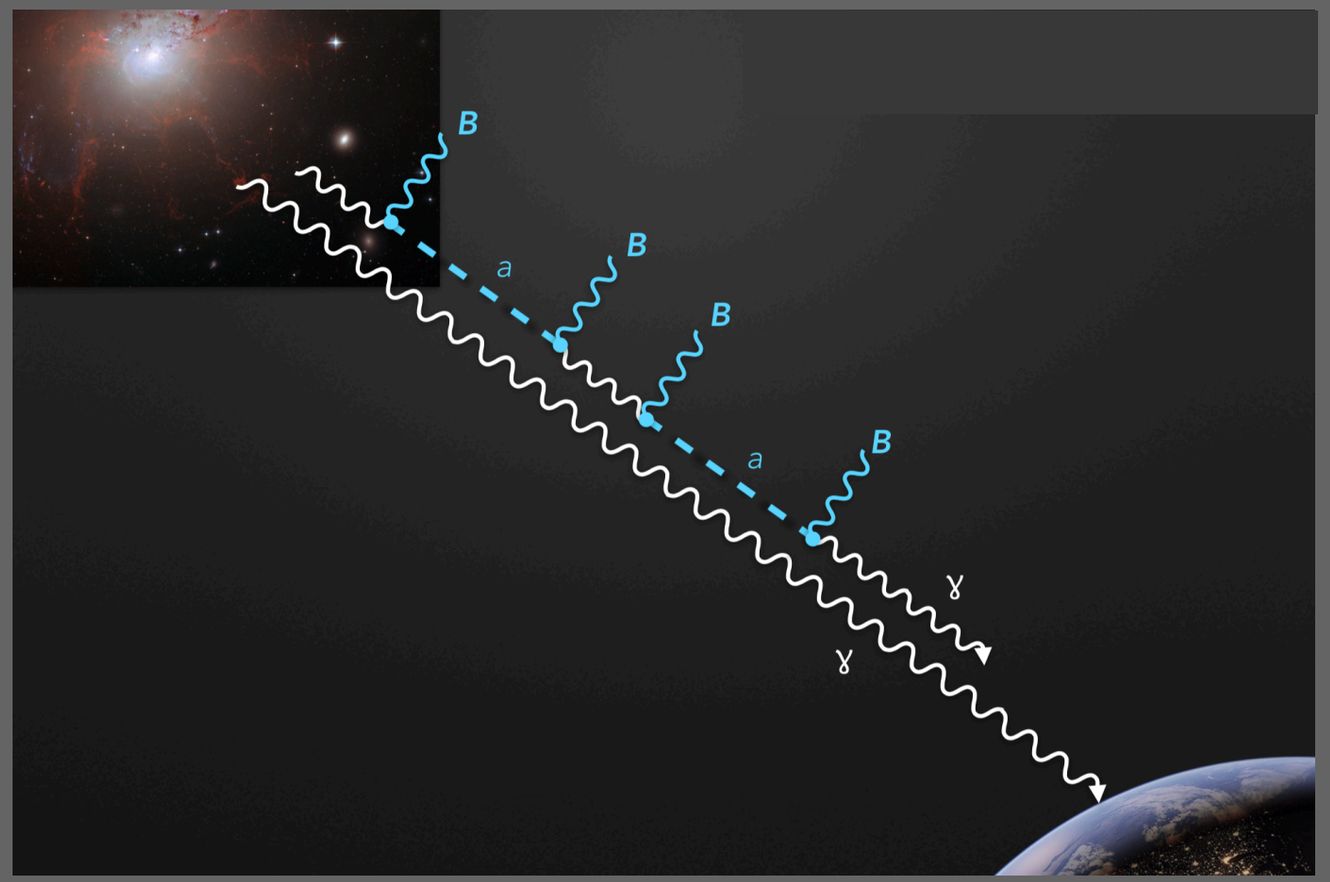
MAXIMUM ENERGY

$$E_{\rm max} \sim 2.12 \times 10^6\,{\rm GeV}\,g_{11} B^{-1}_{\mu{\rm G}}$$





Strategy 1: examine the γ spectra of astro sources and use it to constrain the probability of ALP-γ conversion

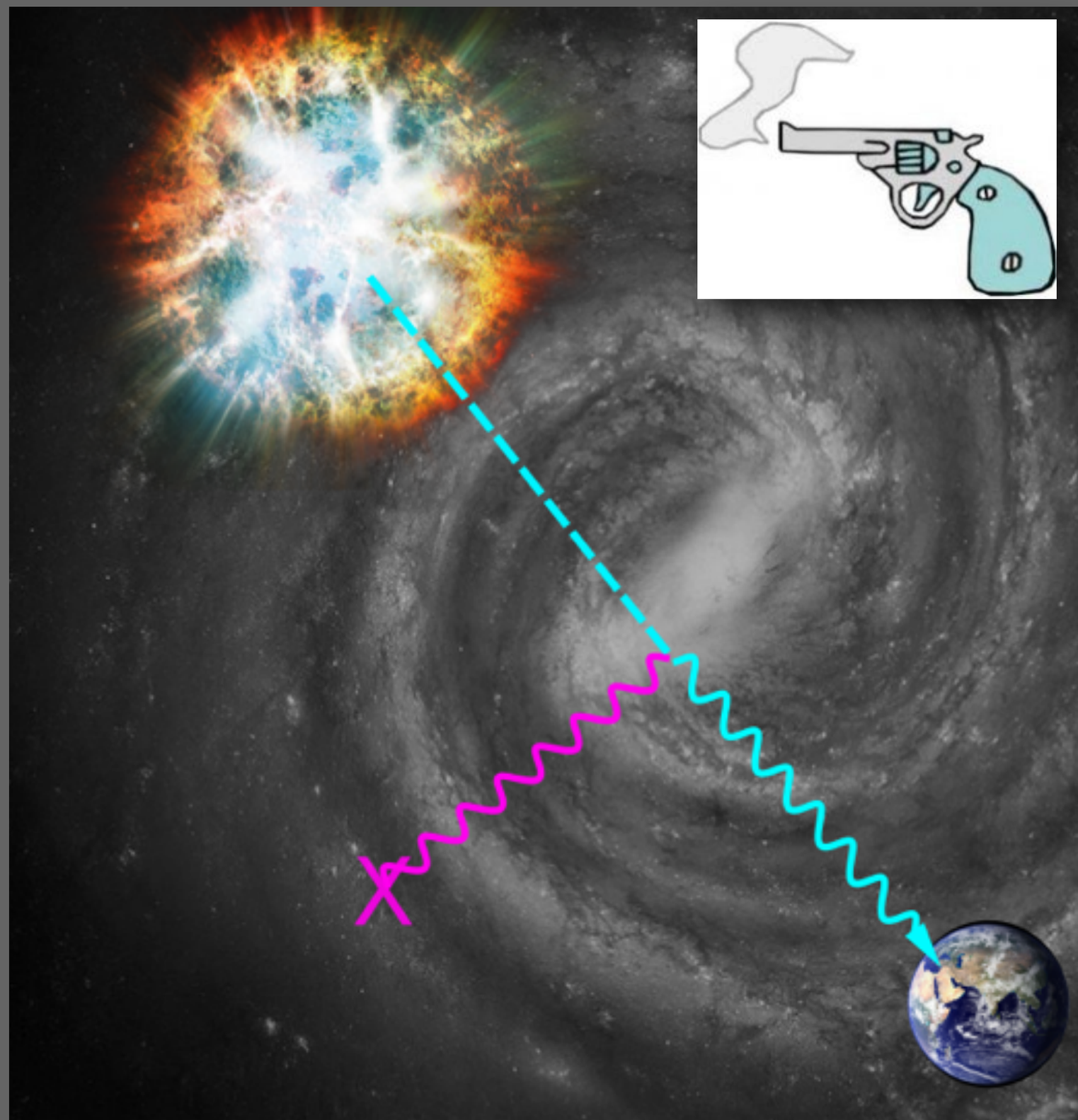


Credit: M. Meyer

How about **ALPs?**

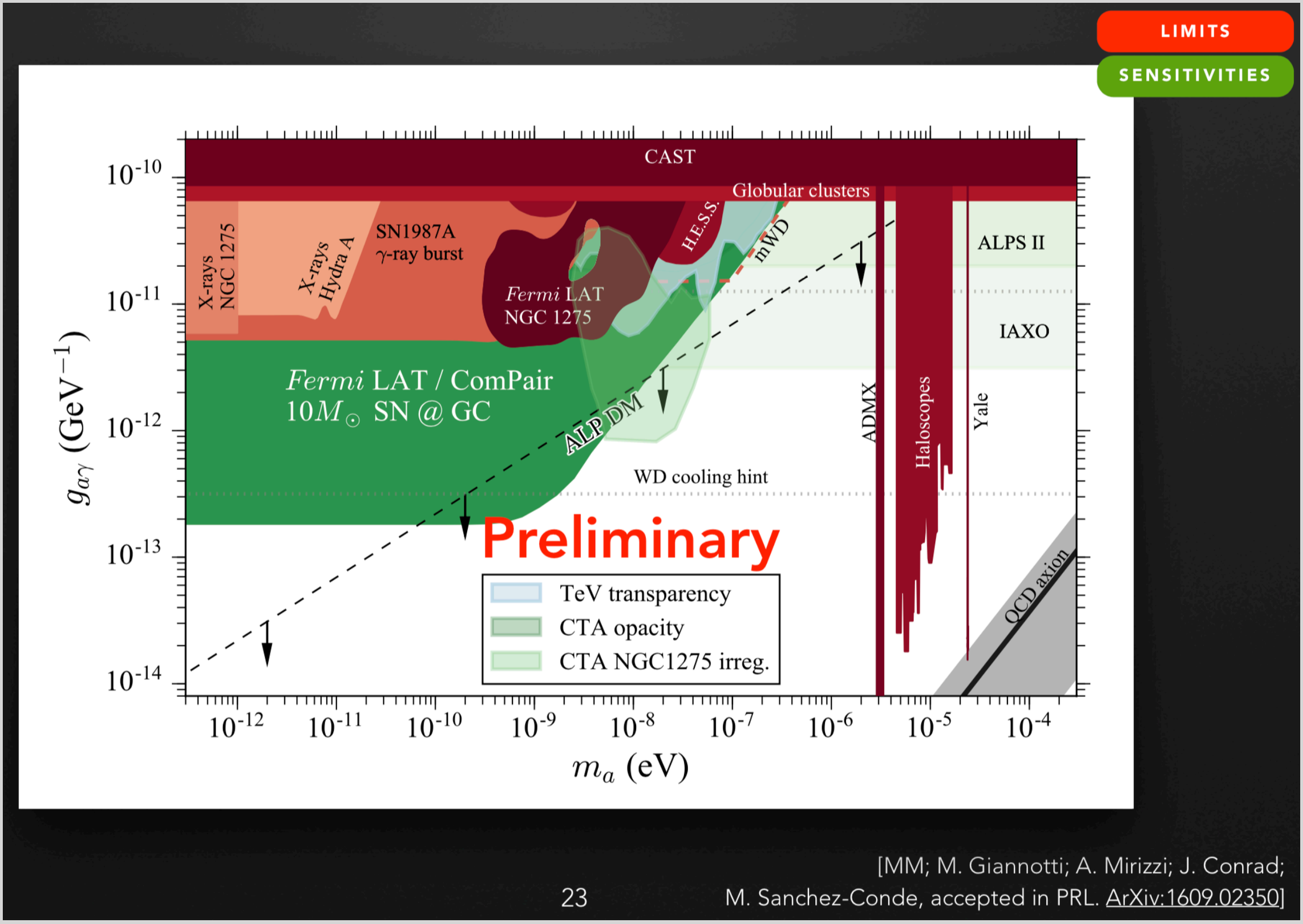
Strategy 2: ALPs would be produced in a core-collapse SN explosion via Primakoff process

Smoking gun! Gamma rays would arrive contemporary with neutrinos.



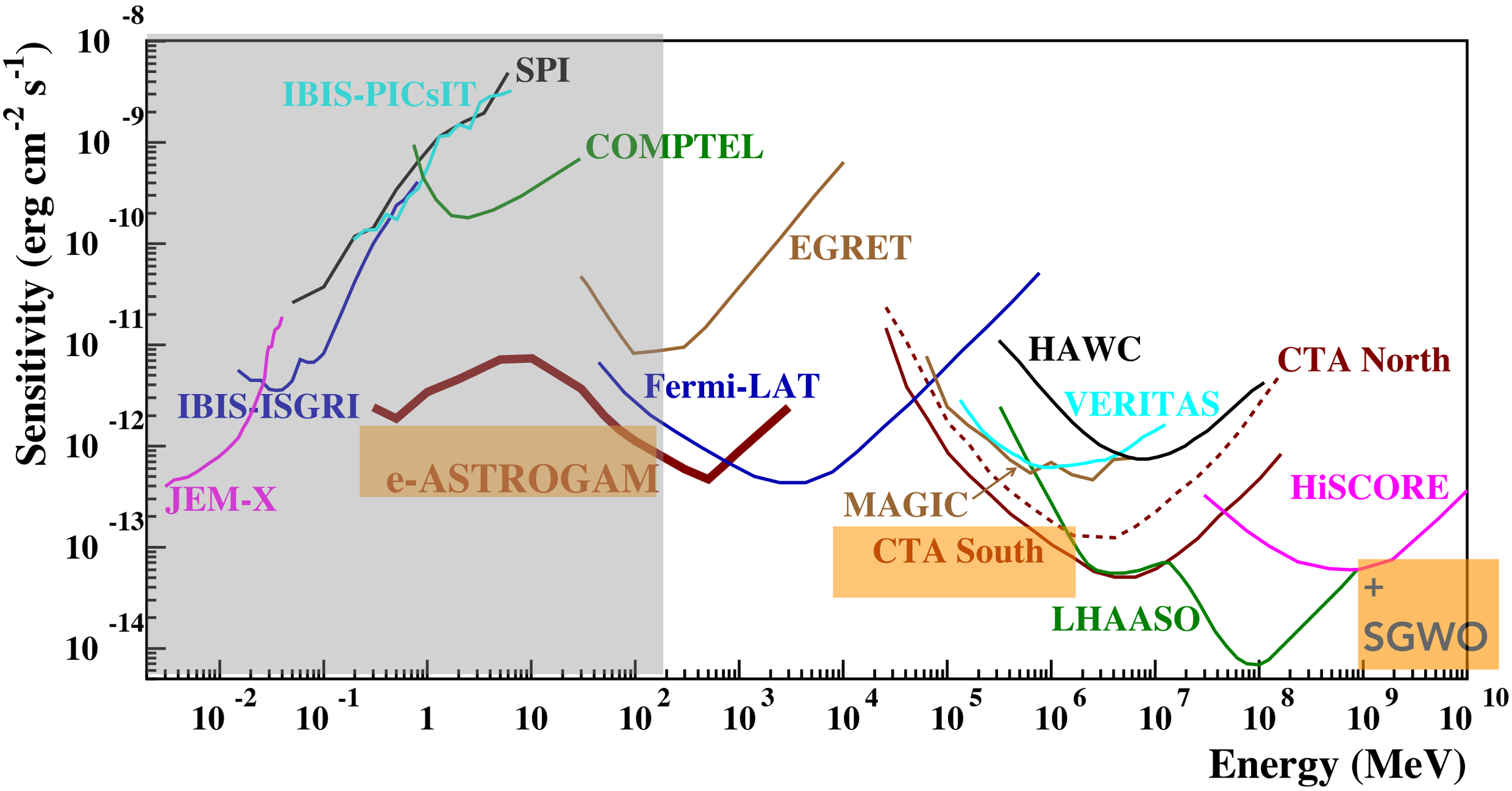
Credit: M. Meyer

State-of-the-art



[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde, accepted in PRL. ArXiv:1609.02350]

Future?



[e-Astrogam mission, 1611.02232]

CTA - Cherenkov Telescope Array

THE CTA CONSORTIUM

31 Countries
over 200 Institutes
over 1400 Members

CTA Headquarters: **Bologna**

Science Data Management Center: **DESY Zeuthen**

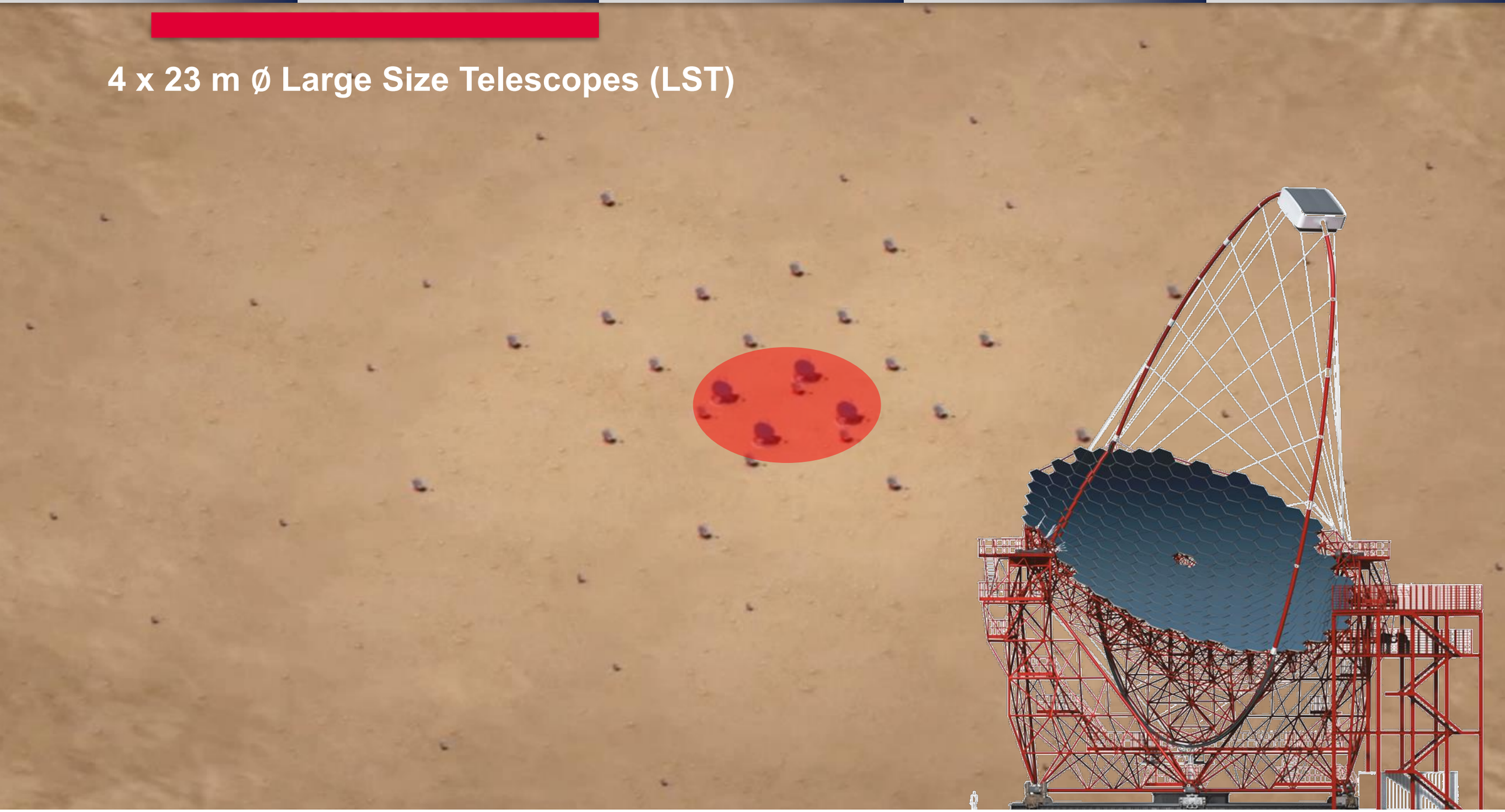
Credits: W. Hofmann and The CTA Consortium

10 GeV	100 GeV	1 TeV	10 TeV	100 TeV

Credits: W. Hofmann, 1st CTA Symposium, Bologna

10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

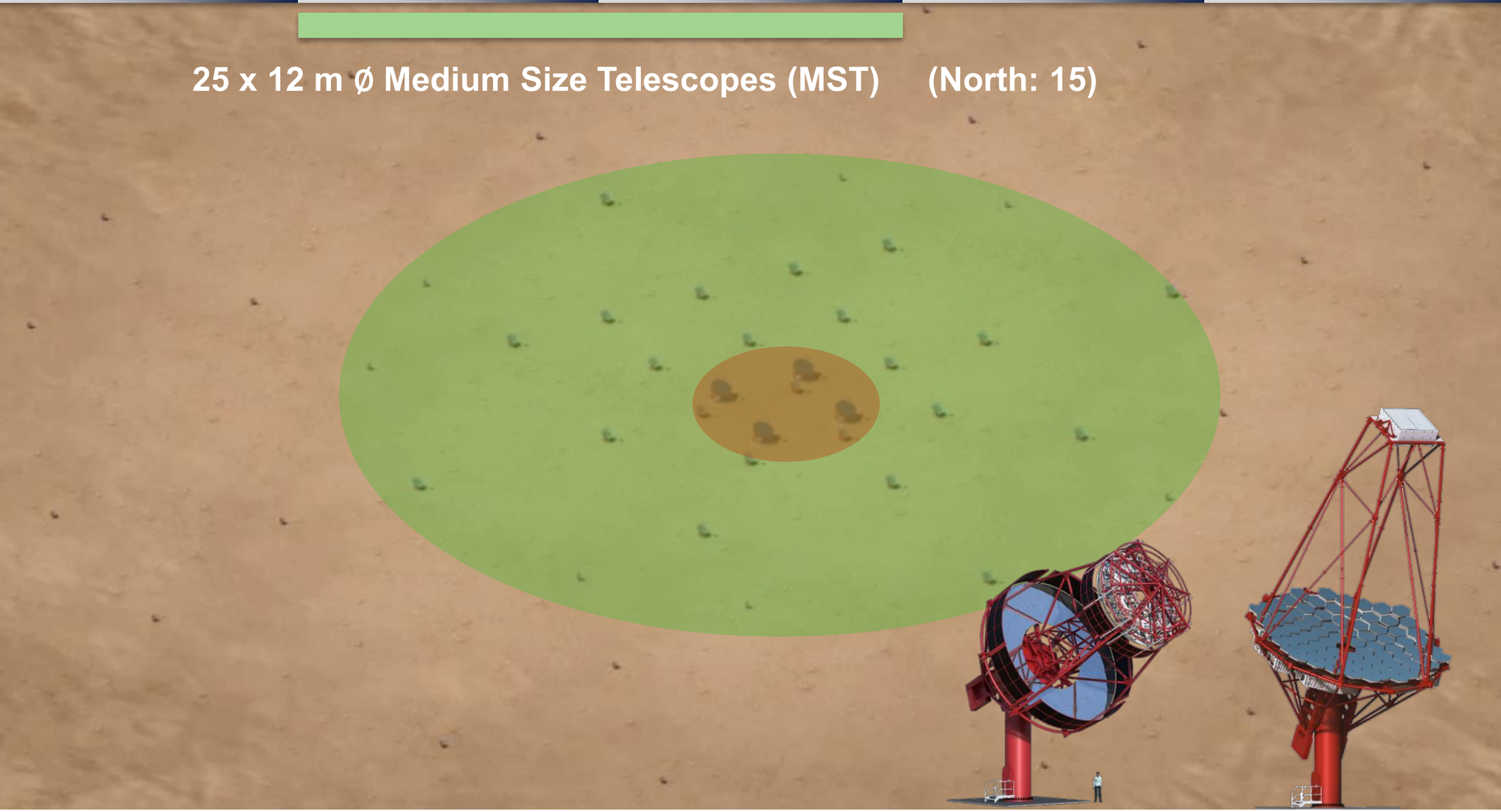
4 x 23 m Ø Large Size Telescopes (LST)



Credits: W. Hofmann and The CTA Consortium

10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

25 x 12 m ø Medium Size Telescopes (MST) (North: 15)

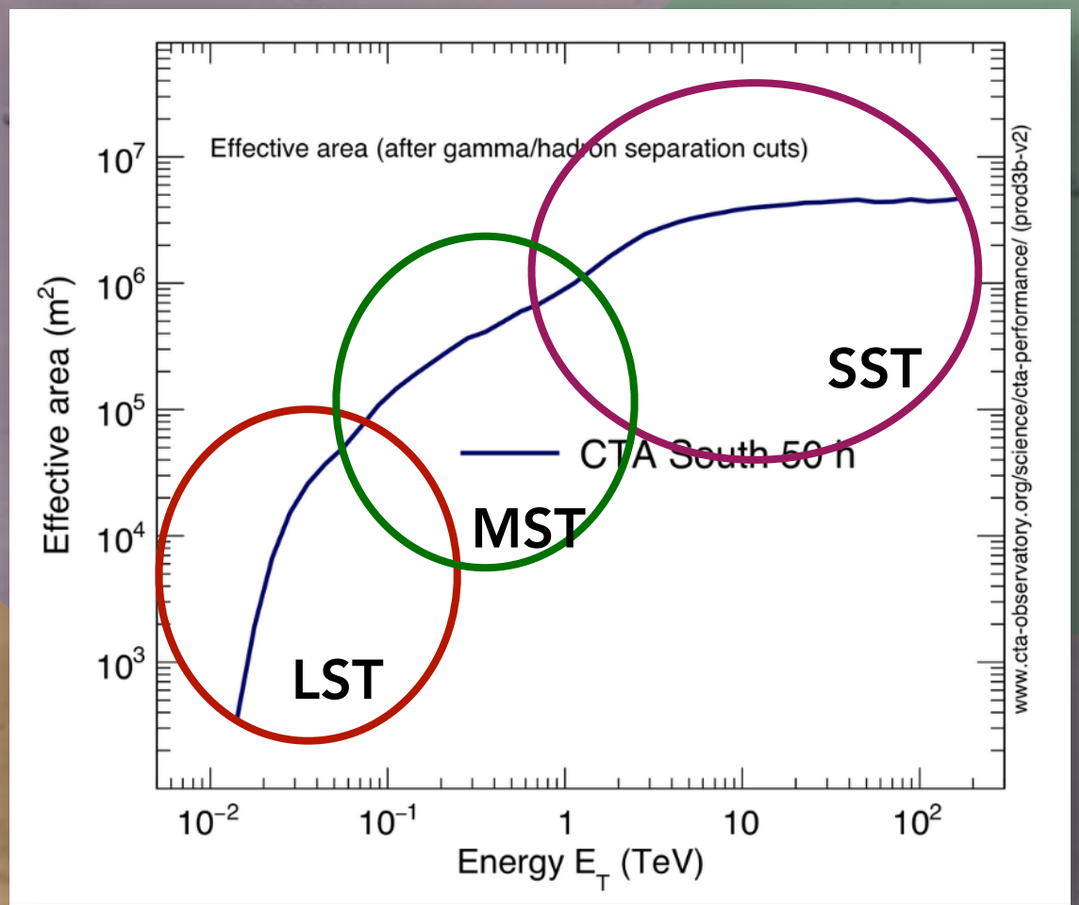


Credits: W. Hofmann and The CTA Consortium

10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

Angular resolution

70 x 4 m ø Small Size Telescopes (SST) (South)



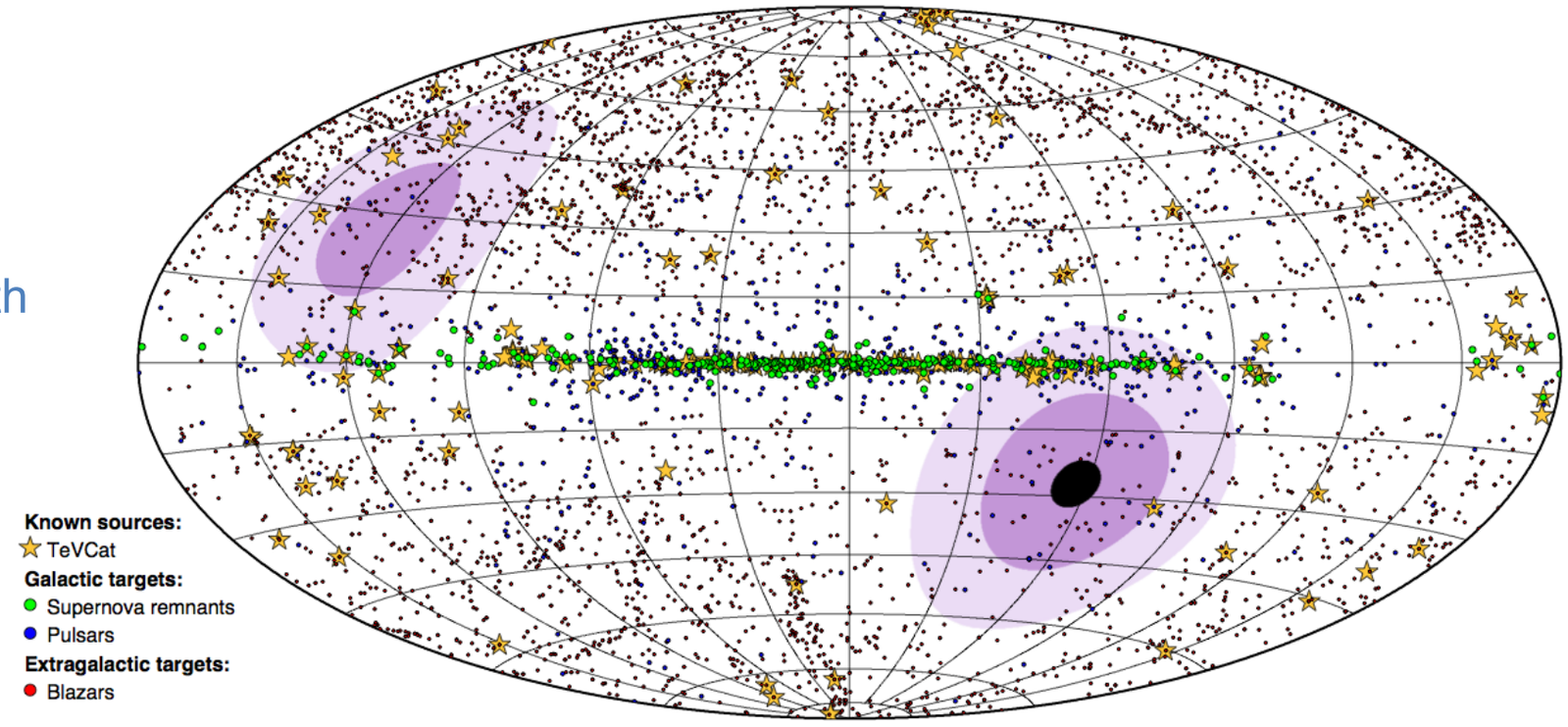
Effective area

Uniform telescope designs currently being evaluated

Credits: W. Hofmann and The CTA Consortium

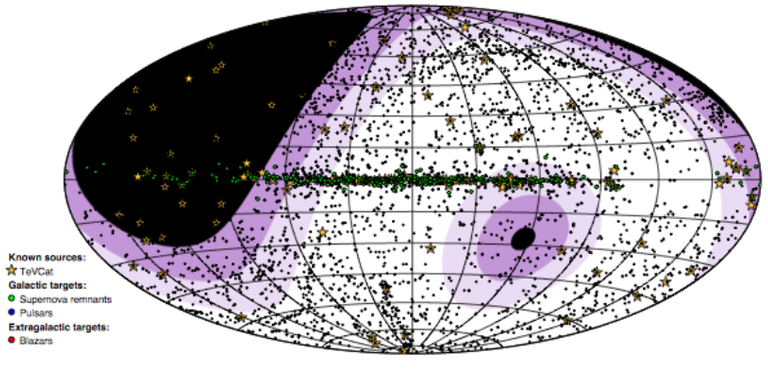
DESIGN DRIVER:
FULL-SKY COVERAGE

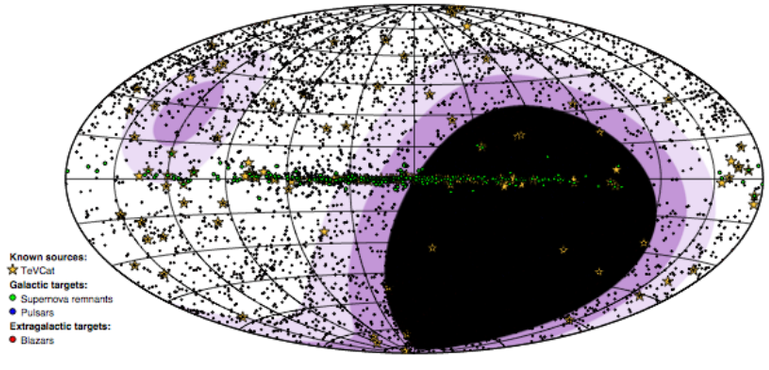
North+South



>60° zenith
45°-60°
30°-45°

South



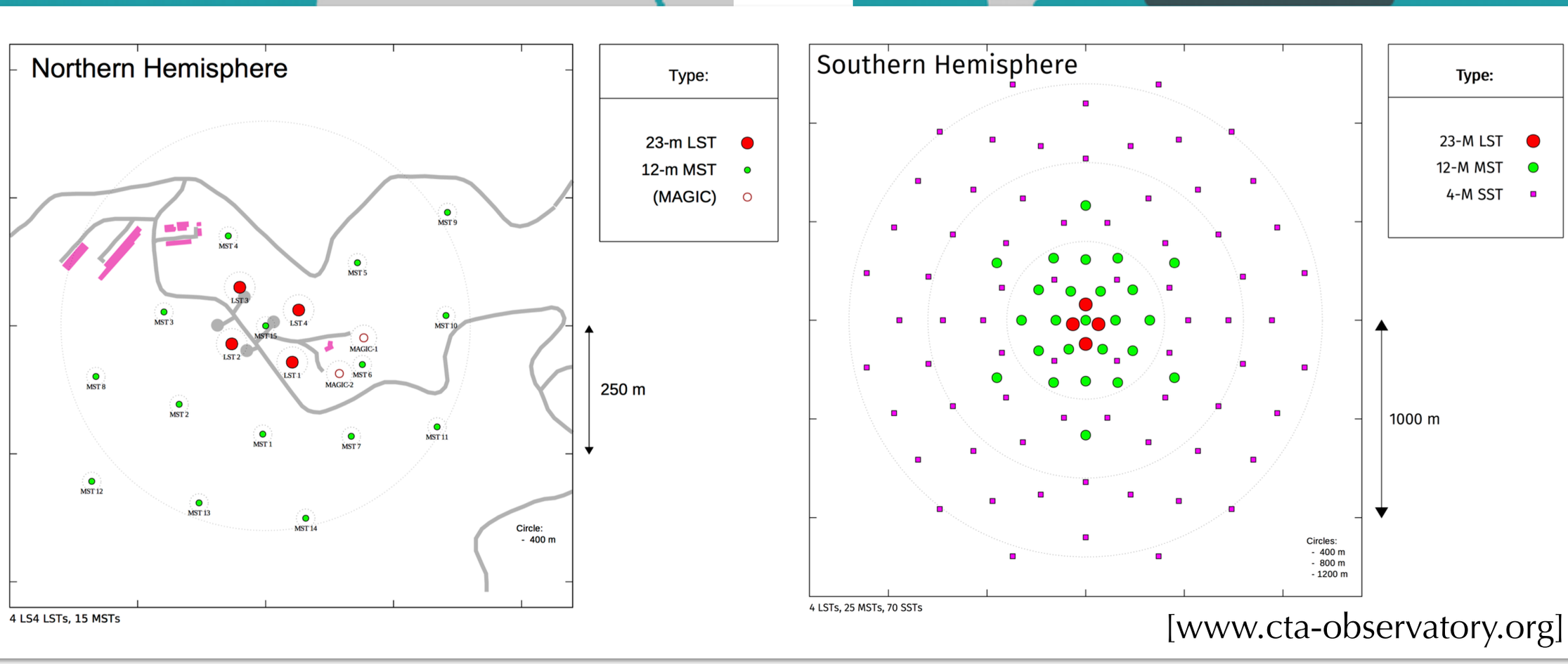


North

Credits: W. Hofmann and The CTA Consortium

CTA

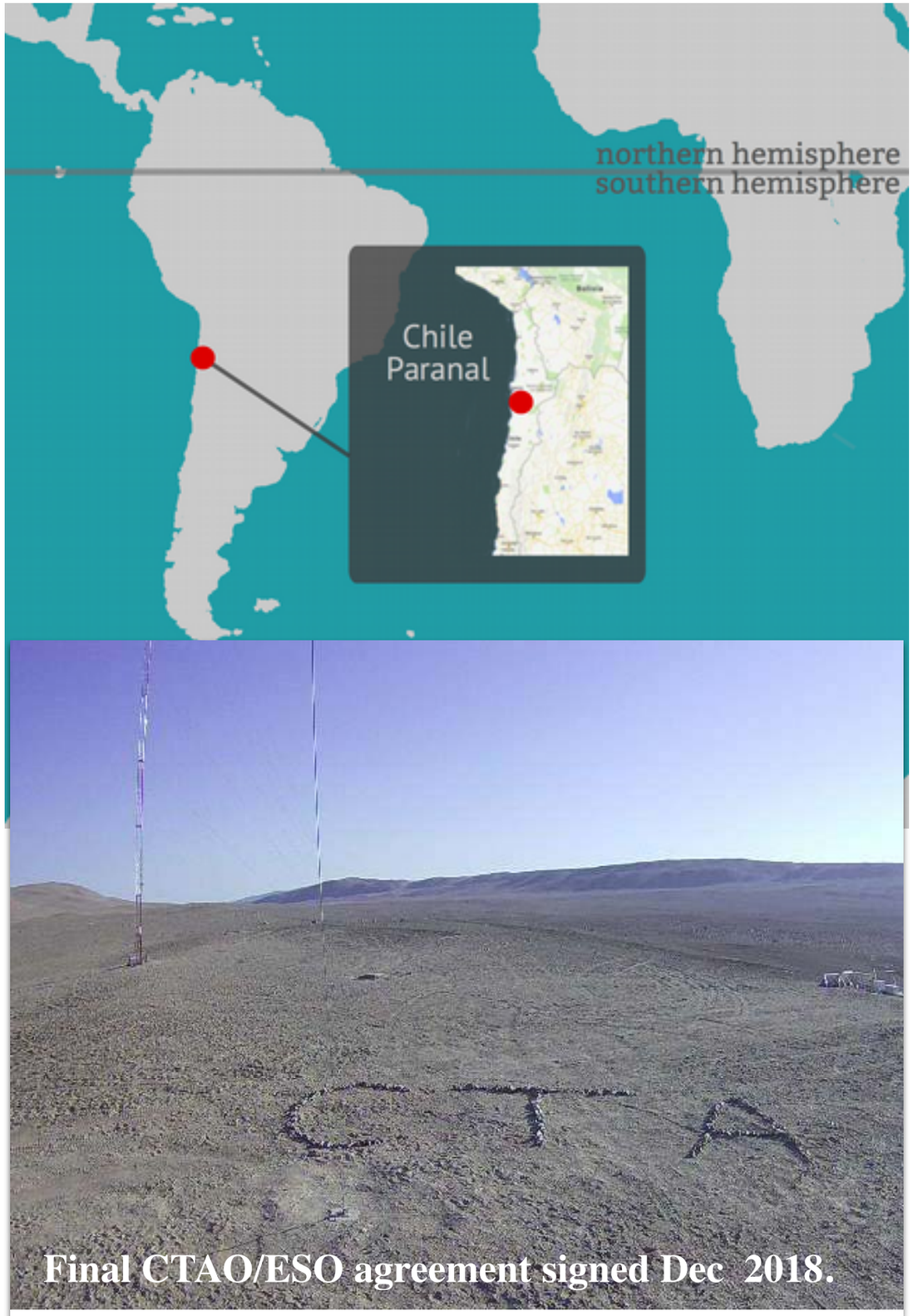
sites and example telescope layouts



[www.cta-observatory.org]

CTA

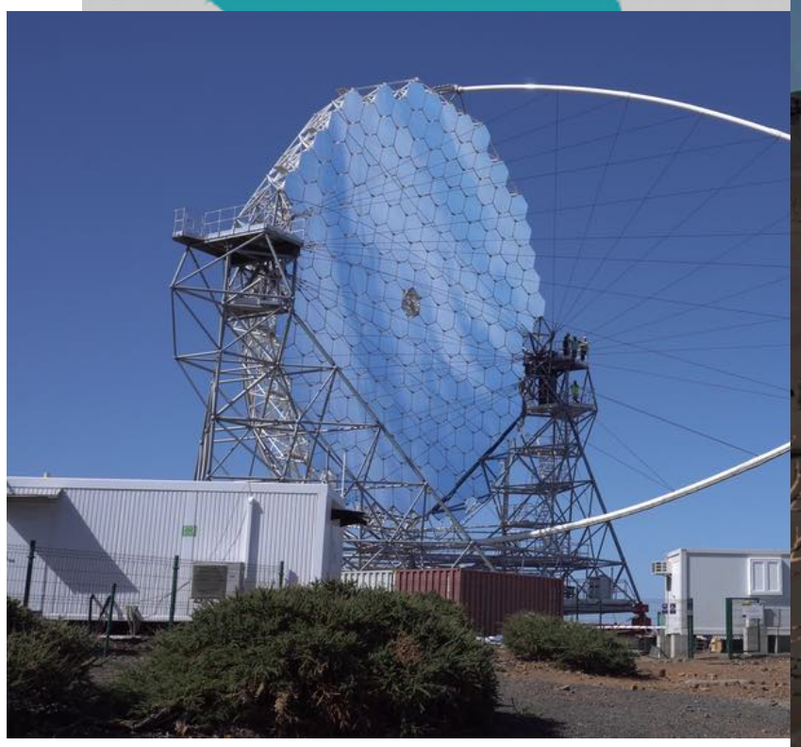
sites and example telescope layouts



CTA-S location (Paranal)

CTA

sites and example telesco



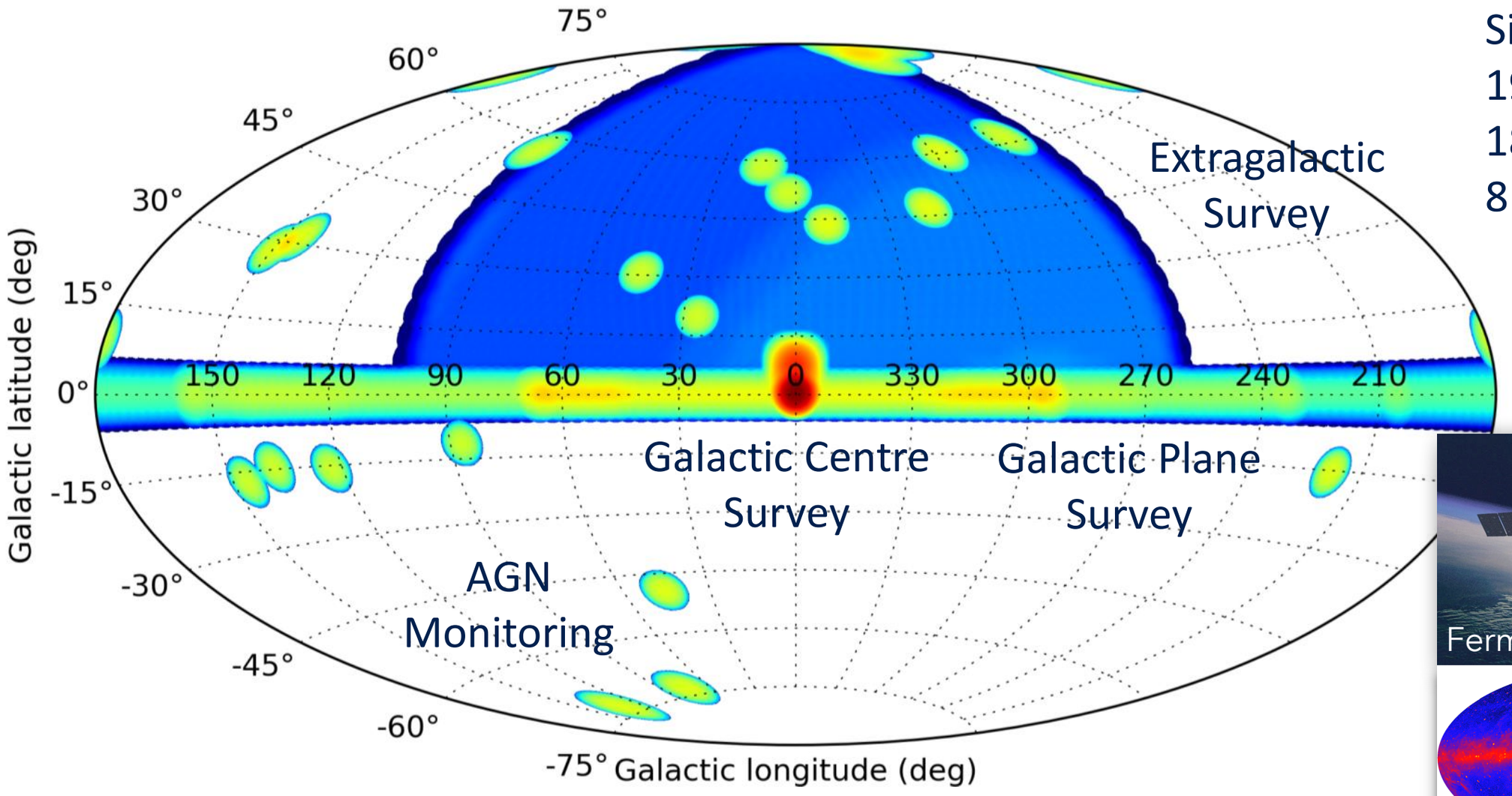
CTA-S location (Paranal)

CTA as a whole-sky observatory

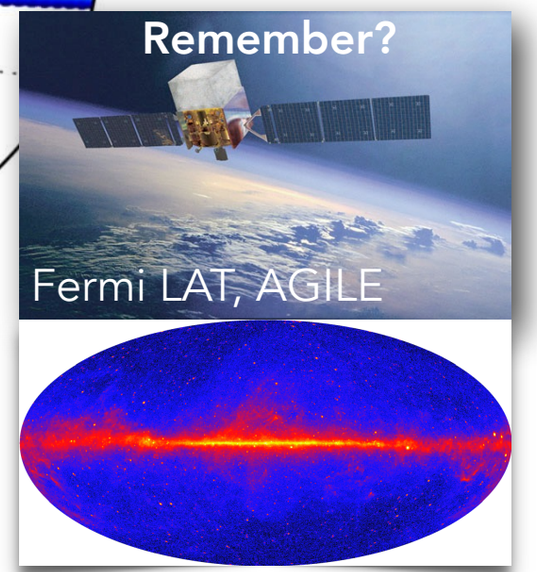
Novel observational strategy: **sky surveys**

(thanks to a large number of CTA telescopes)

- **Unbiased view** of the sky
- Bridging the differences with **satellite data**

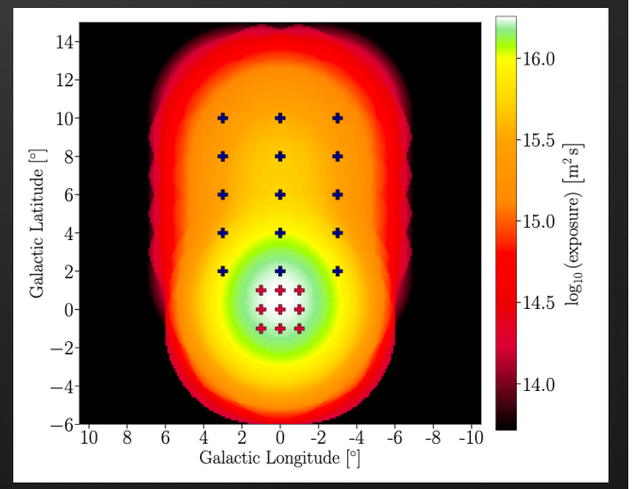


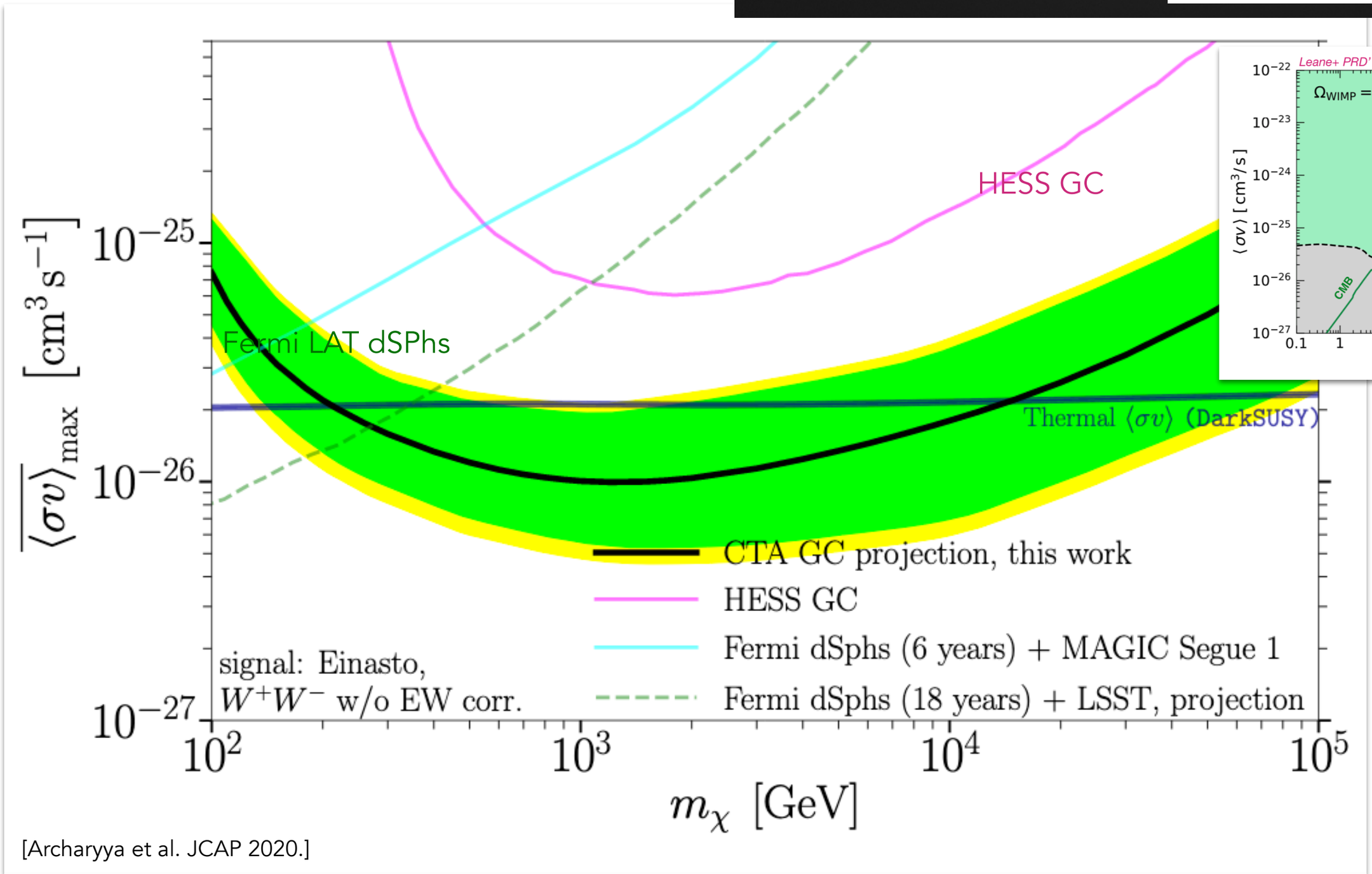
Simulated:
1980 h South
1815 h North
8132 pointings

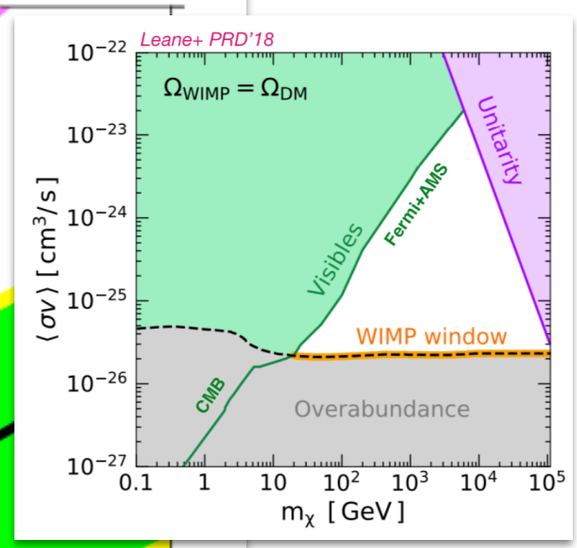


CTA
WIMPs@ GC

- **Galactic center survey**: 525 hours over first 10 years
- **Extended survey**: additional 300 hours





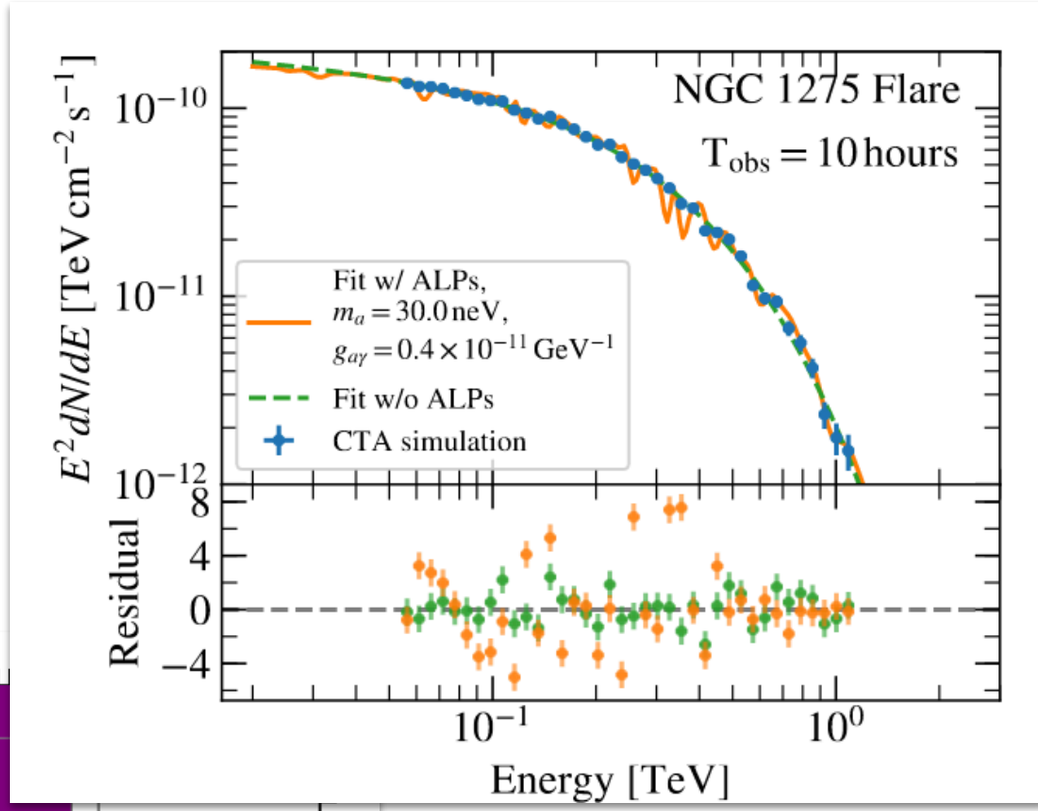


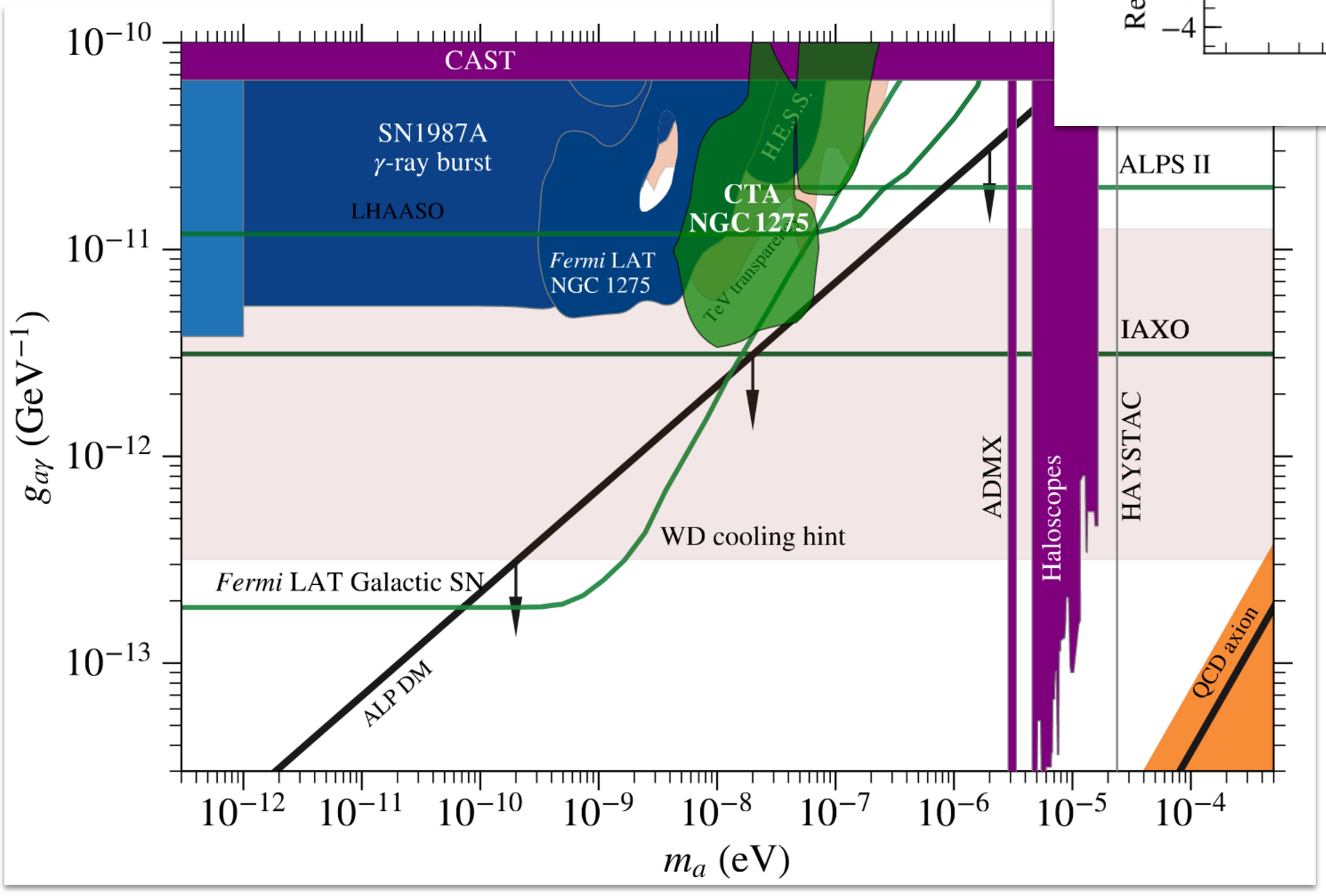
[Archaryya et al. JCAP 2020.]

CTA

ALPs@ NGC1275

NGC 1275 is the central galaxy of the Perseus cluster, at a distance of ~ 75 Mpc (z = 0.01756). The cool-core Perseus cluster harbors a strong magnetic field, as large as 25 μG in the cluster center.





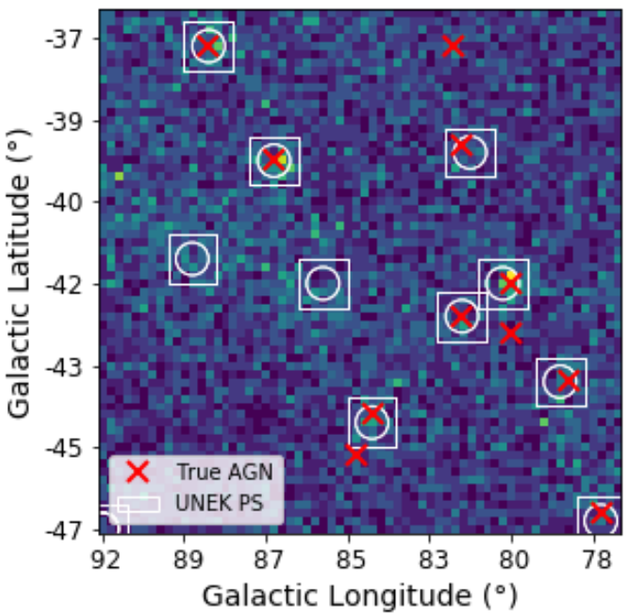
[Archaryya et al. JCAP 2021.]

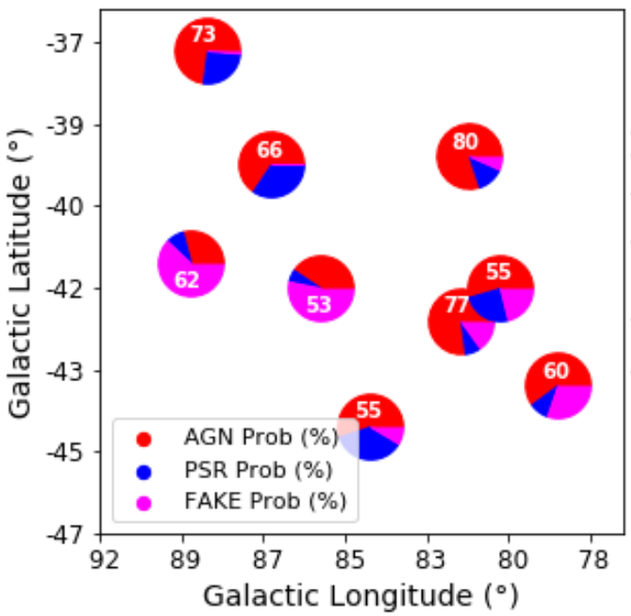
Future? New analysis techniques

Machine learning & point source detection and classification

Gamma rays, AutoSourceID (www.autosourceid.org, A&A, 2103.11068)

Results for High Latitude: $|b| > 20°$

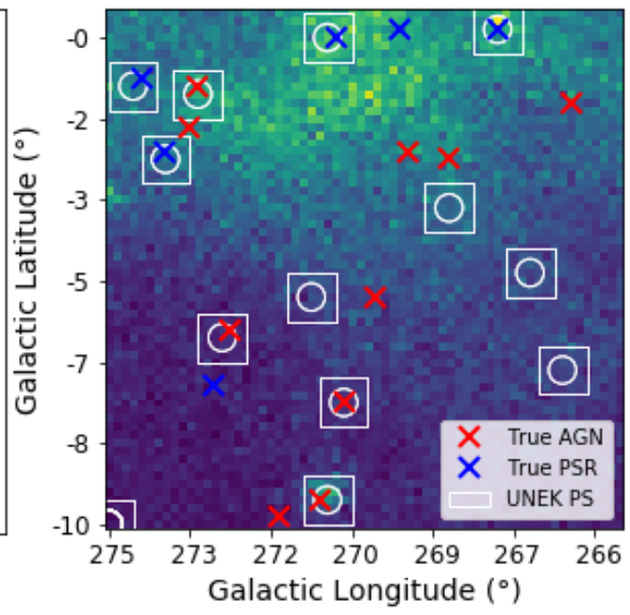


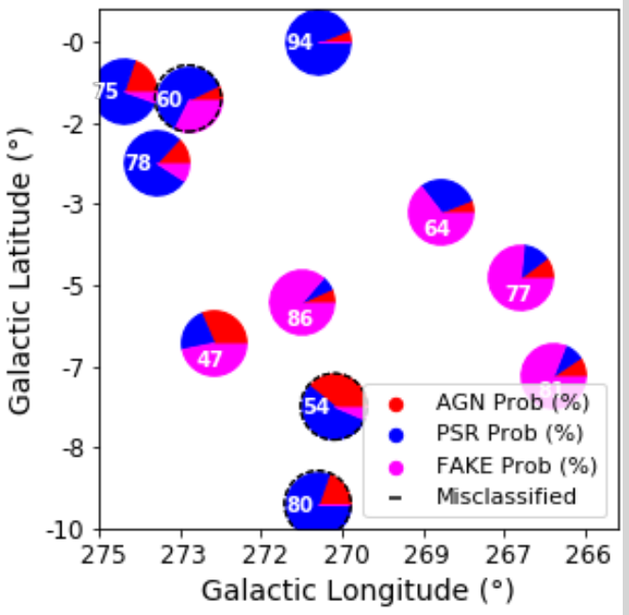


Low background emission. Higher accuracy in localization.

Better classification.

Results for Low Latitude: $|b| < 20°$





Regions closer to galactic plane. Background emission dominates.

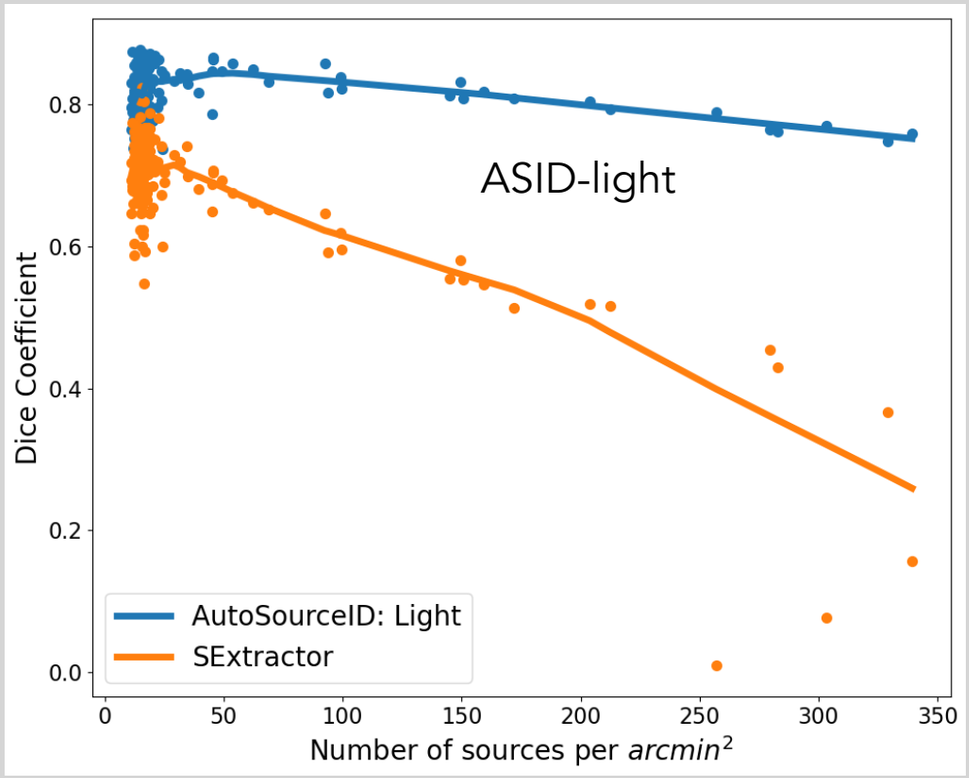
Algorithm performance deteriorates.

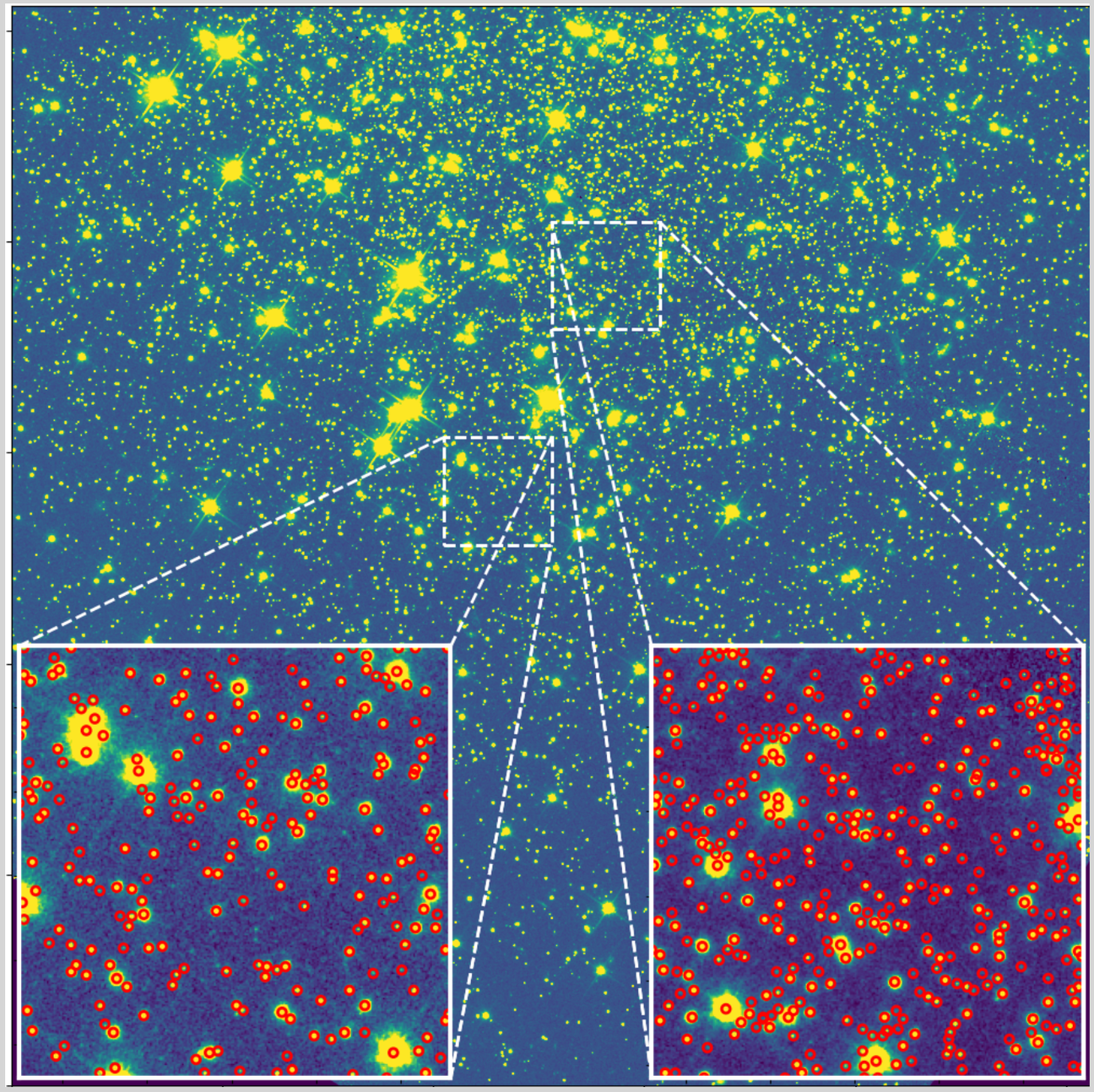
[*credit: Saptashwa Bhattacharyya, TeVPA 2021*]

Future? New analysis techniques

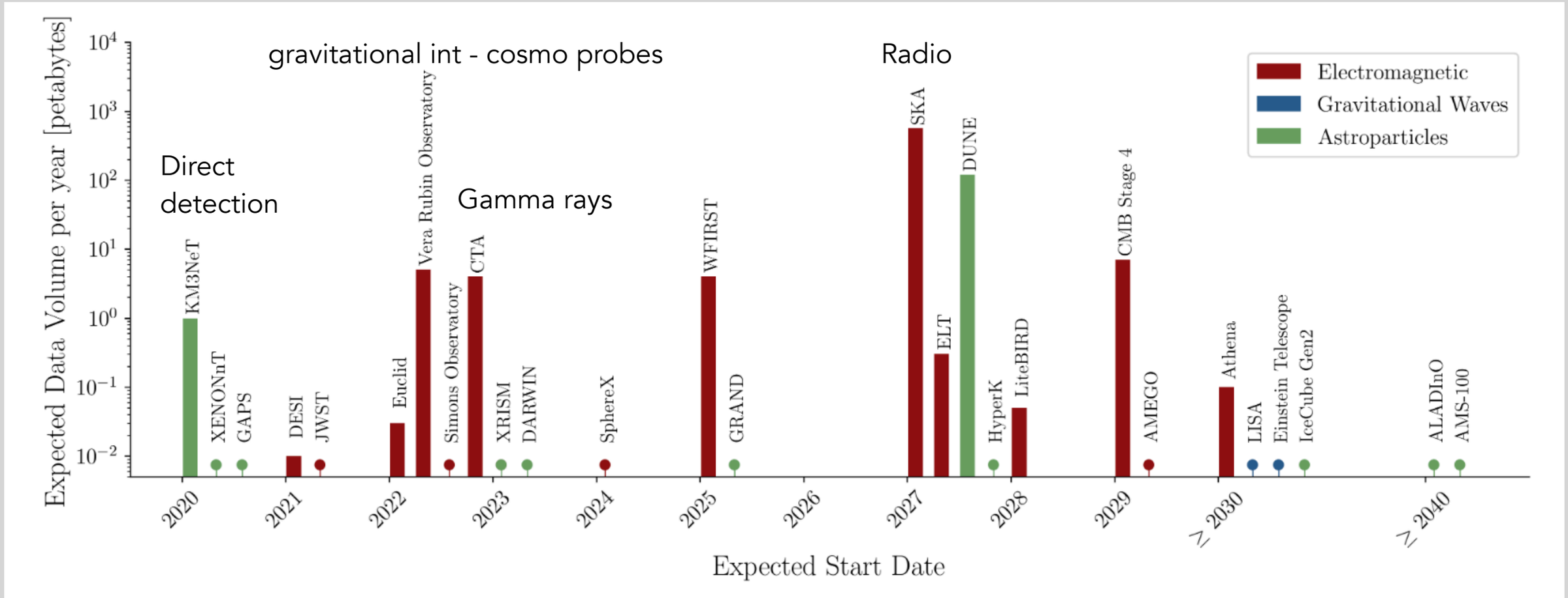
Machine learning & point source detection and classification

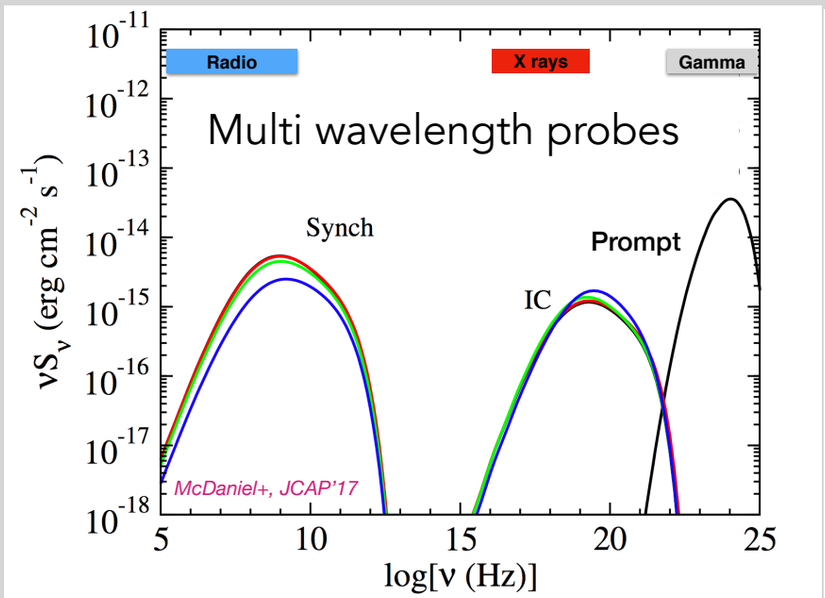
Optical, AutoSourceID - Light (A&A, 2202.00489) **multi-wavelength?**



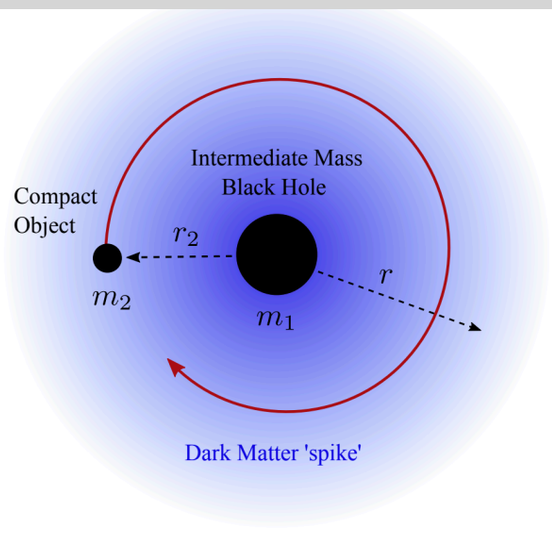


Future? Beyond gamma rays



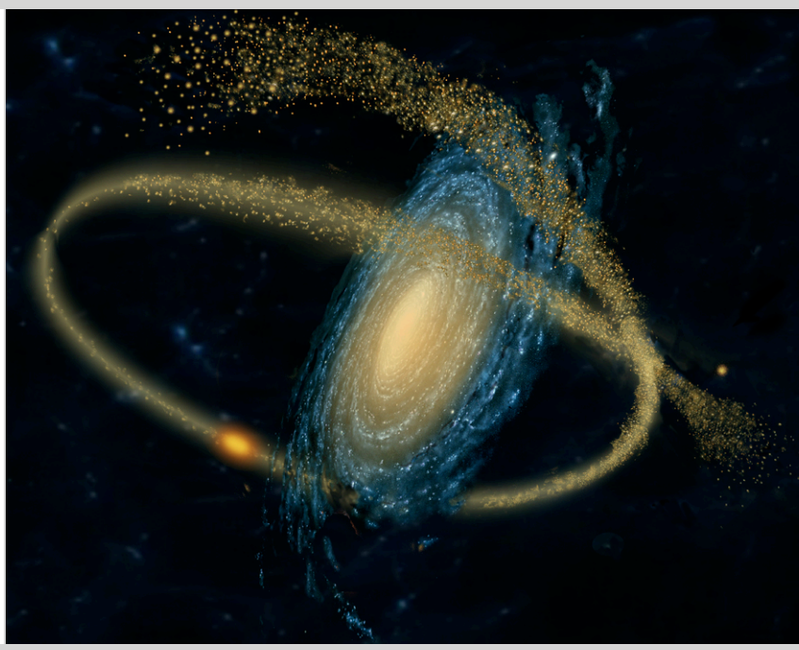


Example: Annihilation into b-quarks; m_{DM} = 100 GeV



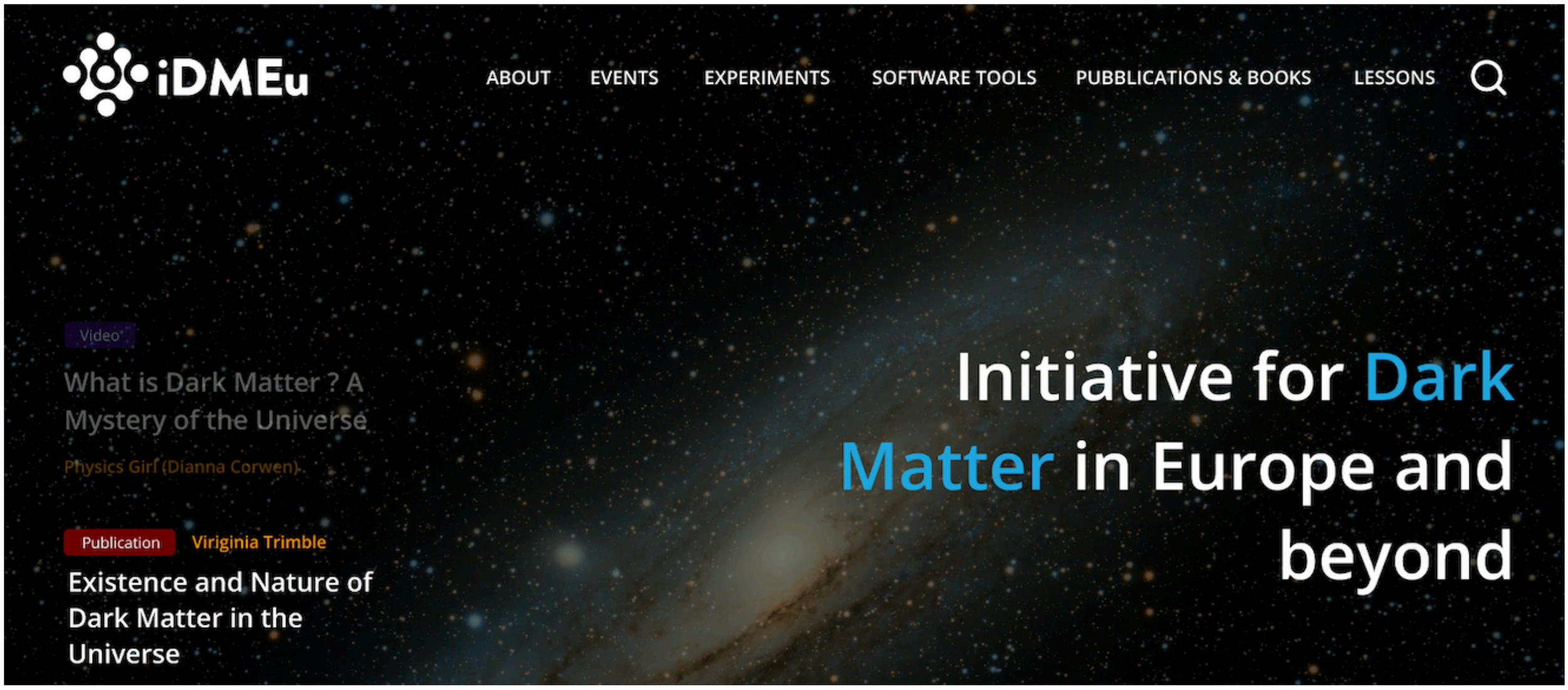
Cold DM "dress" around (P)BHs => de-phasing of GW-form

Gondolo&Silk PRD'99; Zhao&Silk PRD'05; Kavanagh+ PRD'18; Coogan+ arXiv:2108.04154



Curious to find out more?

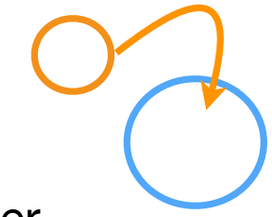
http://www.idmeu.org — ***a go-to place for all things dark matter***



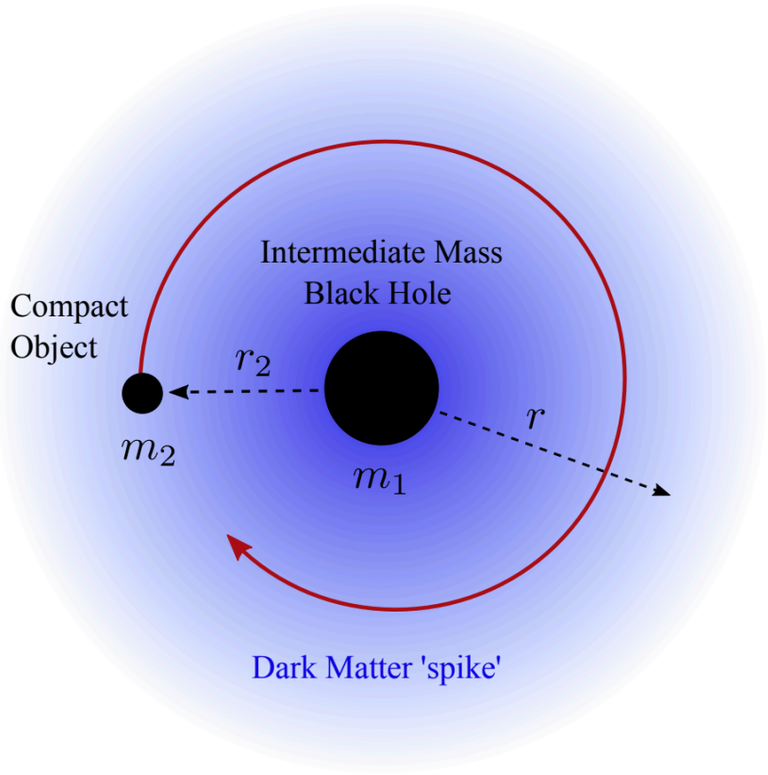
A hub for News/Events/Experiments/Models/Tools….

Extra Slides

GW from environmental effects



GW signals generated by local DM (or baryon) environments modifying the GW signal from a merger of two compact objects in a distinctive way



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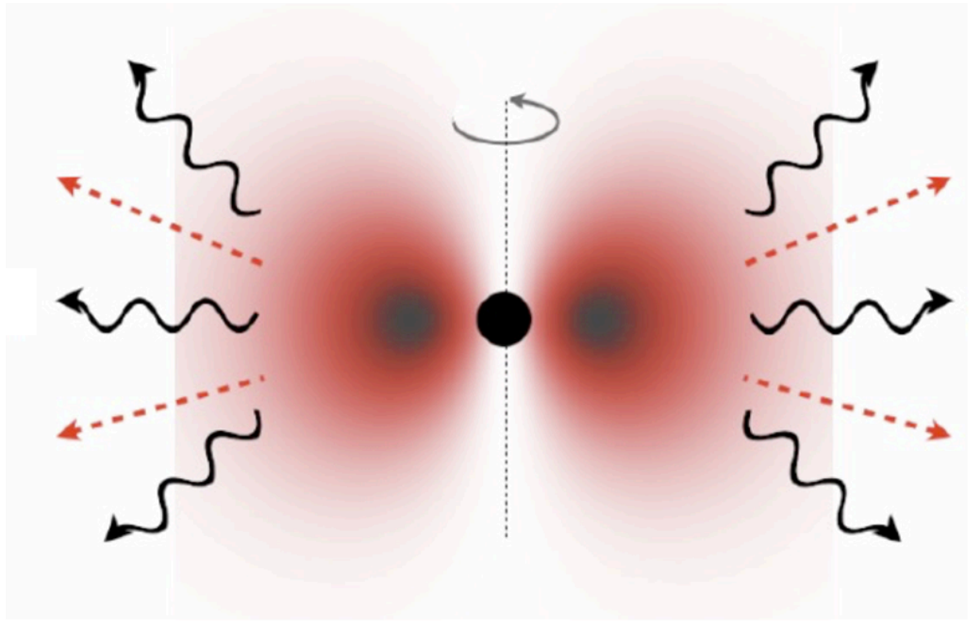


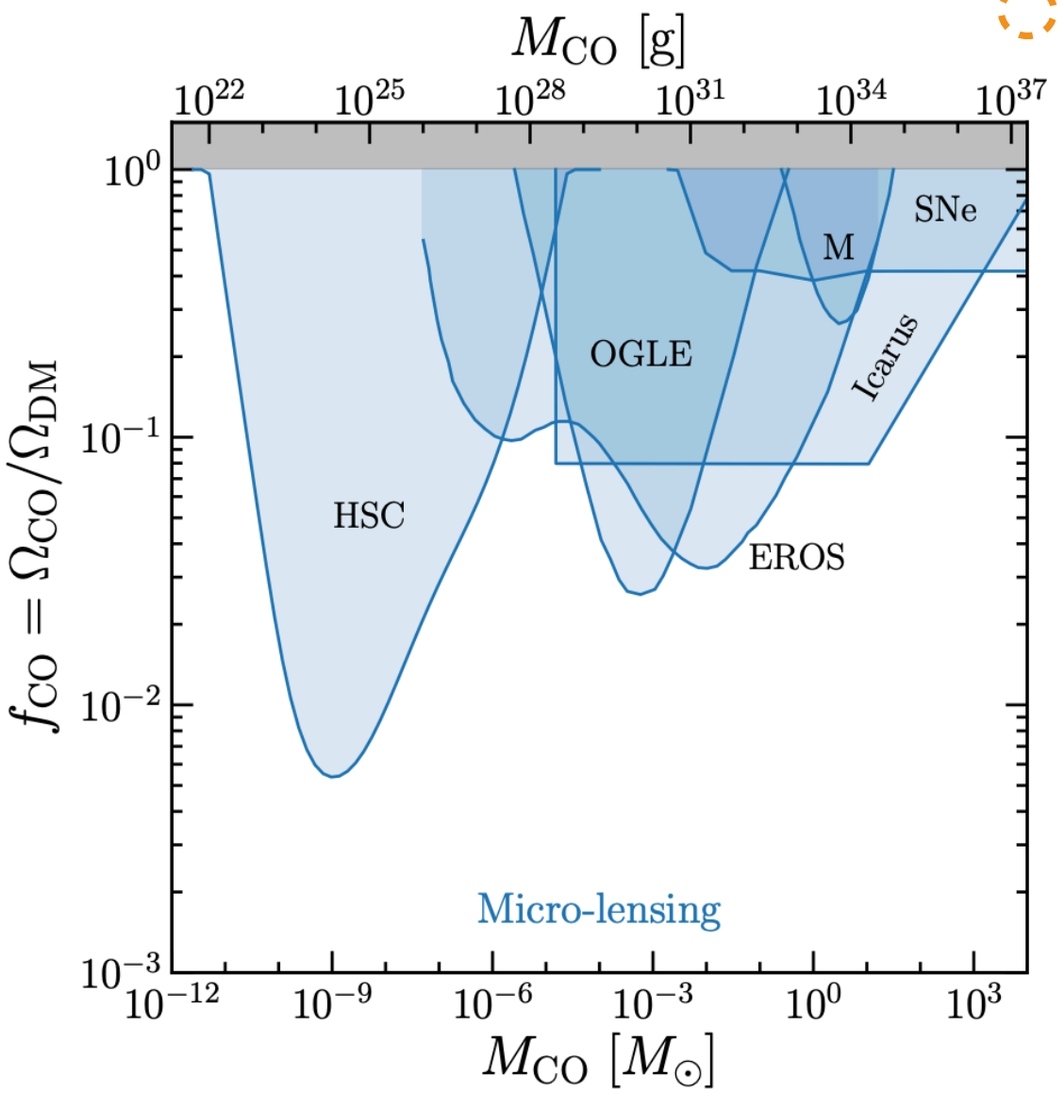
Light boson fields around BHs => Super-radiance

Brito+ Lect. Notes Phys.'15

Gravitational lensing

- Sensitive to DM substructures from **asteroid to solar masses**
- Used to constrain **PBHs, axion miniclusters, ultra-compact mini-halos**, or even **boson stars**

Green & Kavanagh J. Phys. G'19



Gravitational lensing

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Green & Kavanagh J. Phys. G'19

➡ GRB femtolensing or GRB lensing parallax measurements *Katz+ JCAP'18; Jung & Kim PRR'20*

➡ Precise micro-lensing surveys with Roman Space Telescope, Euclid and the Vera C. Rubin Observatory *Sugiyama+ MNRAS'20*

➡ Important to model wave optics effects and source finite size *Katz+ JCAP'18*

➡ Microlensing of X-ray pulsars with small source sizes *Bay & Orlofsky PRD'19*