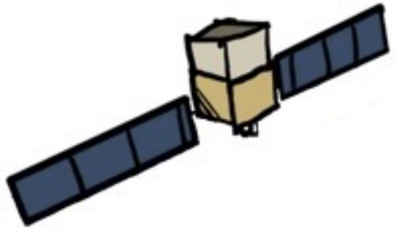


Astrophysical probes of dark matter

past, present, & future of gamma-ray observations

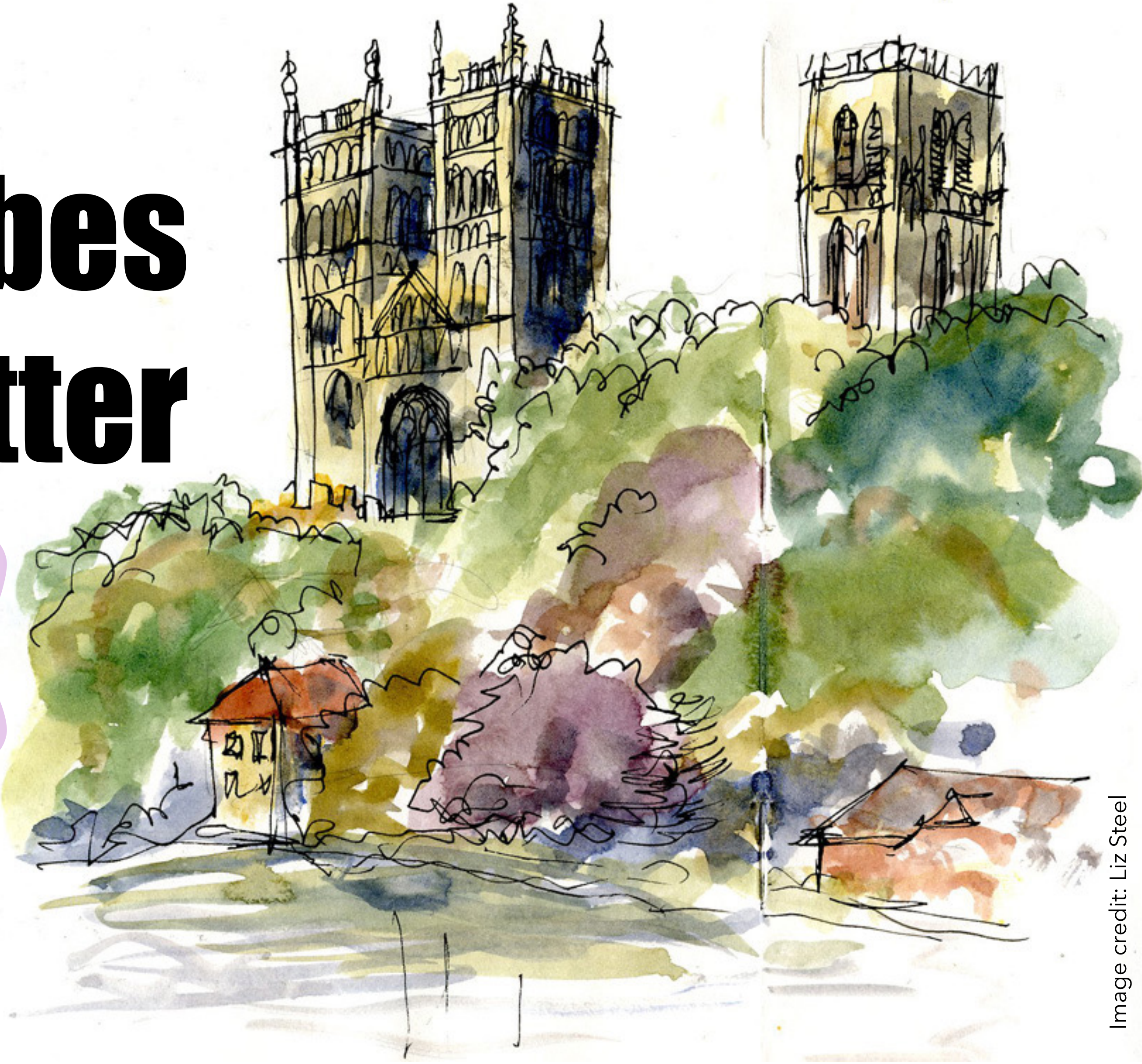
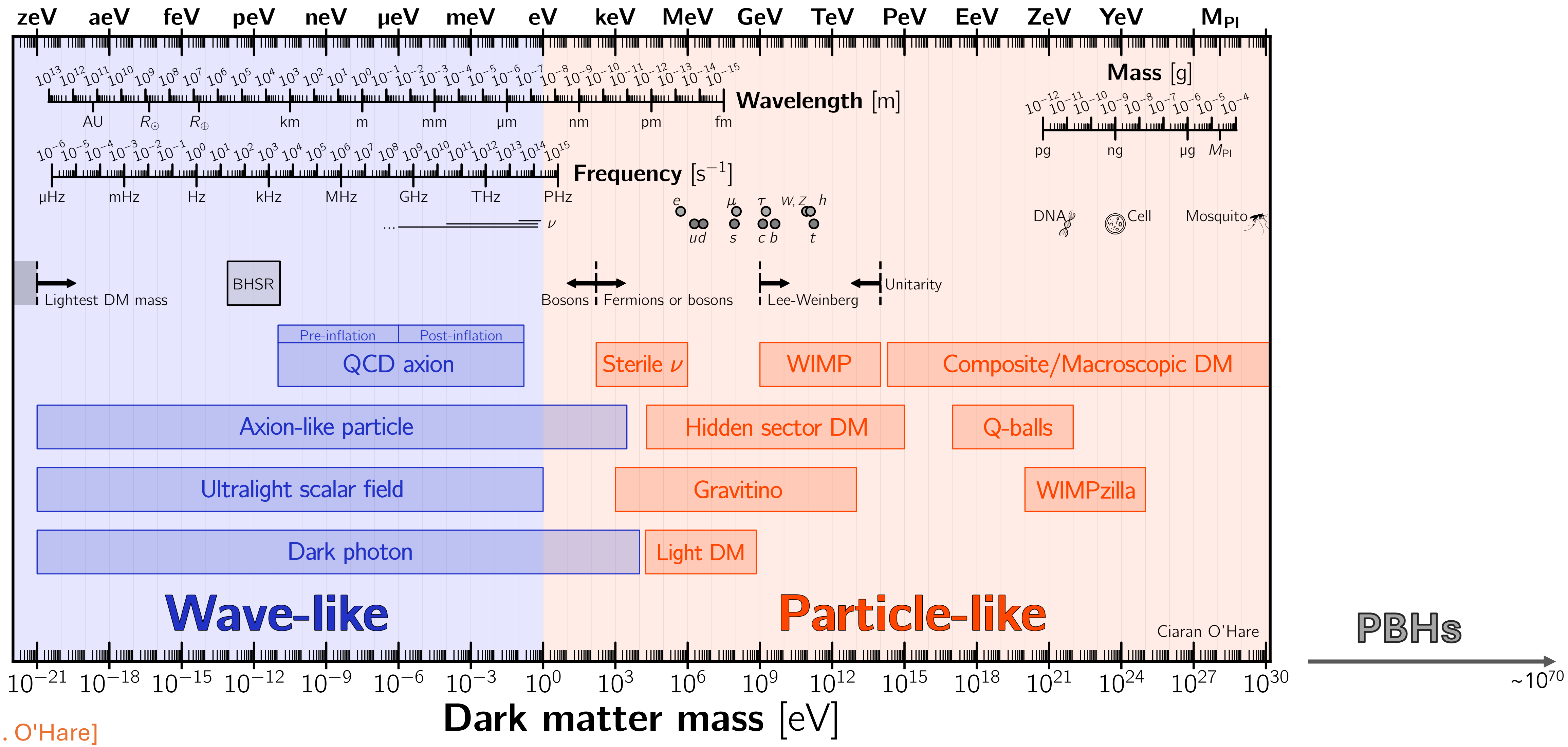


Image credit: Liz Steel

Milena Crnogorčević
Oskar Klein Centre/Stockholm University
milena.crnogorcevic@fysik.su.se

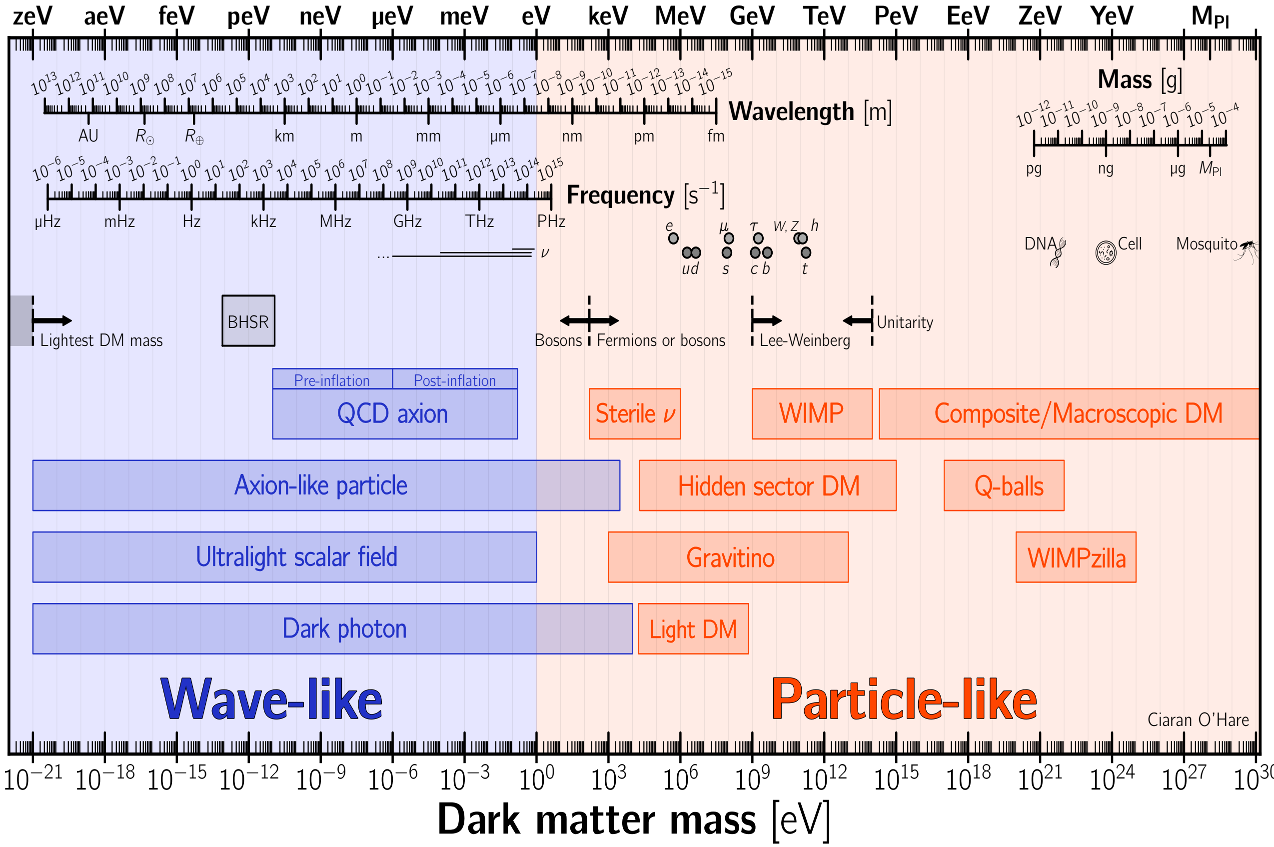
Beyond Weak Scale Workshop II @ Durham University

Dark Matter Landscape: A Theorist's View



[Ciaran A. J. O'Hare]

Dark Matter Landscape: A Theorist's View



DM candidates with a range of properties

…we are biased in our search strategies:

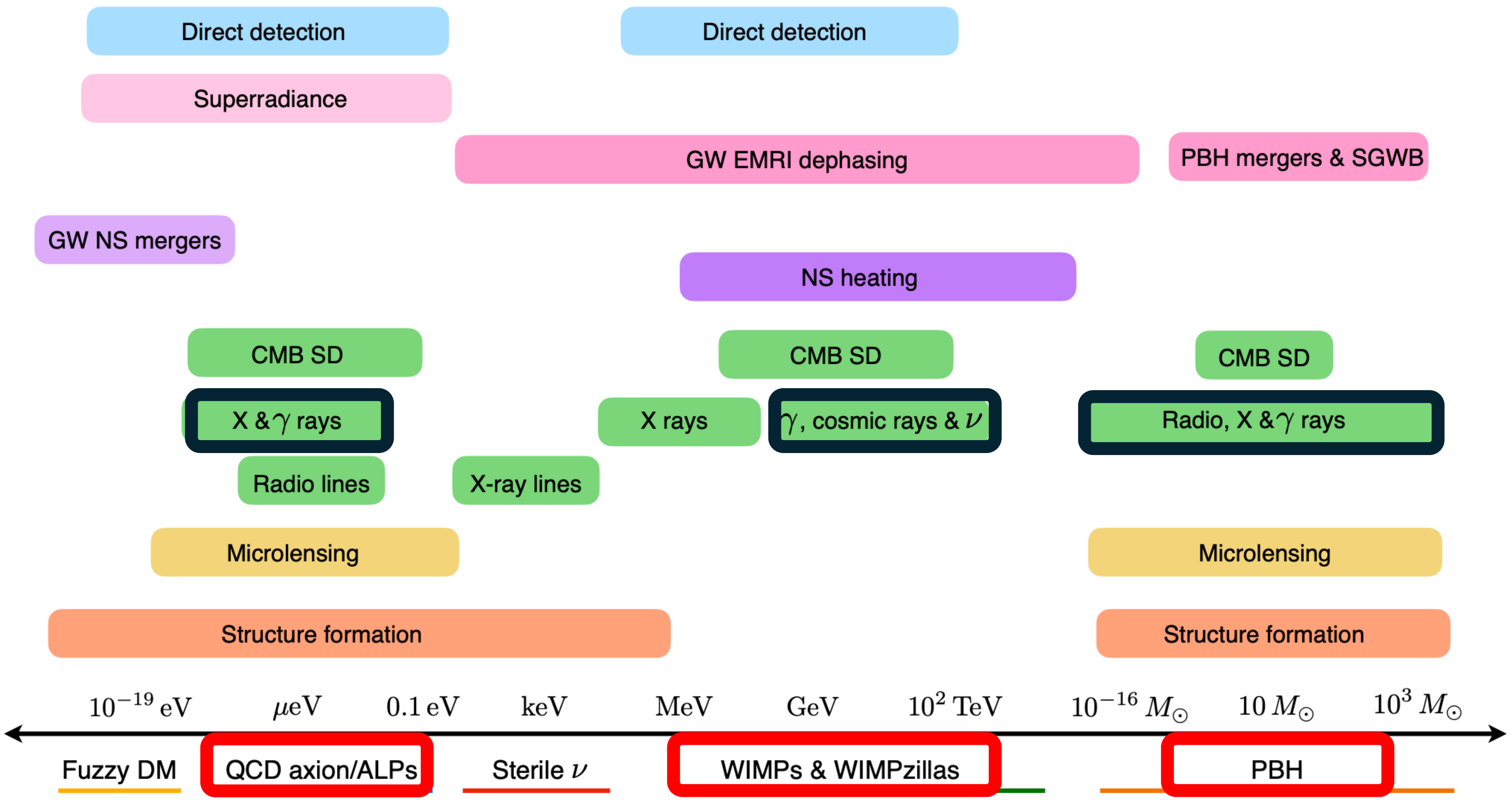
- Observable signatures
- Data availability
- Model dependency

PBHs

$\sim 10^{70}$

[Ciaran A. J. O'Hare]

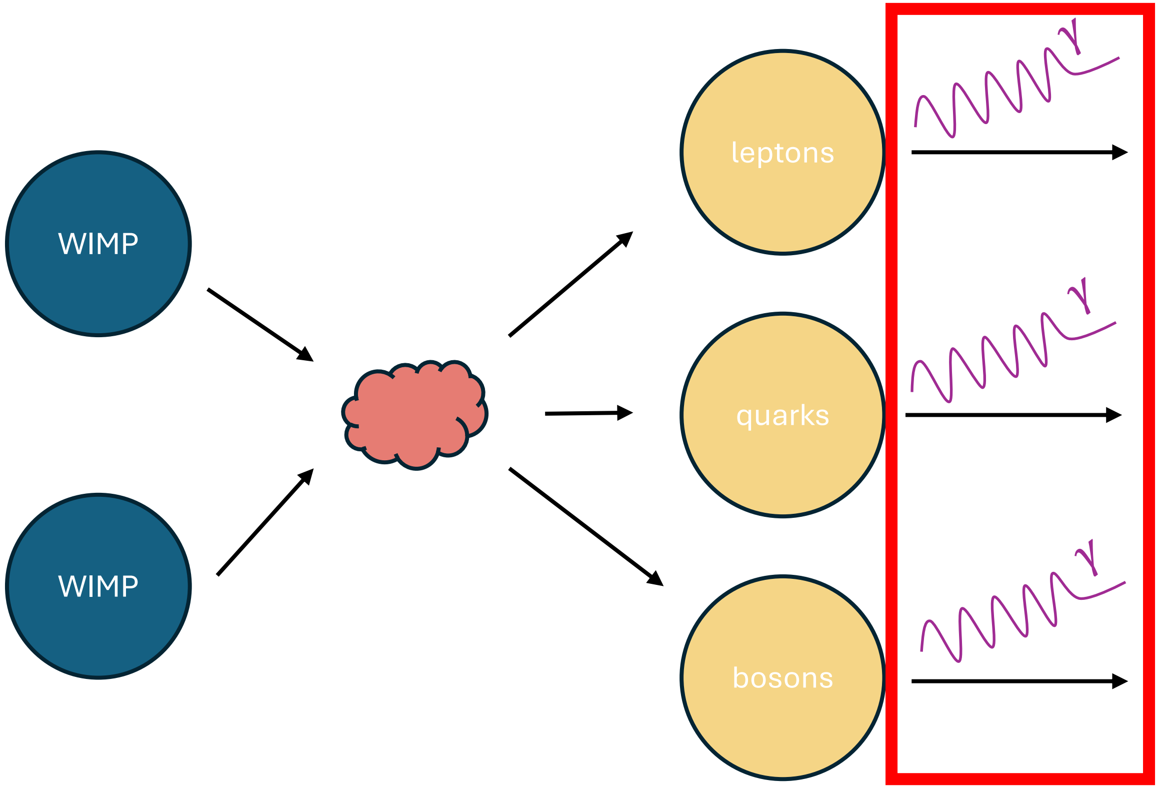
Dark Matter Landscape: An Observer's View



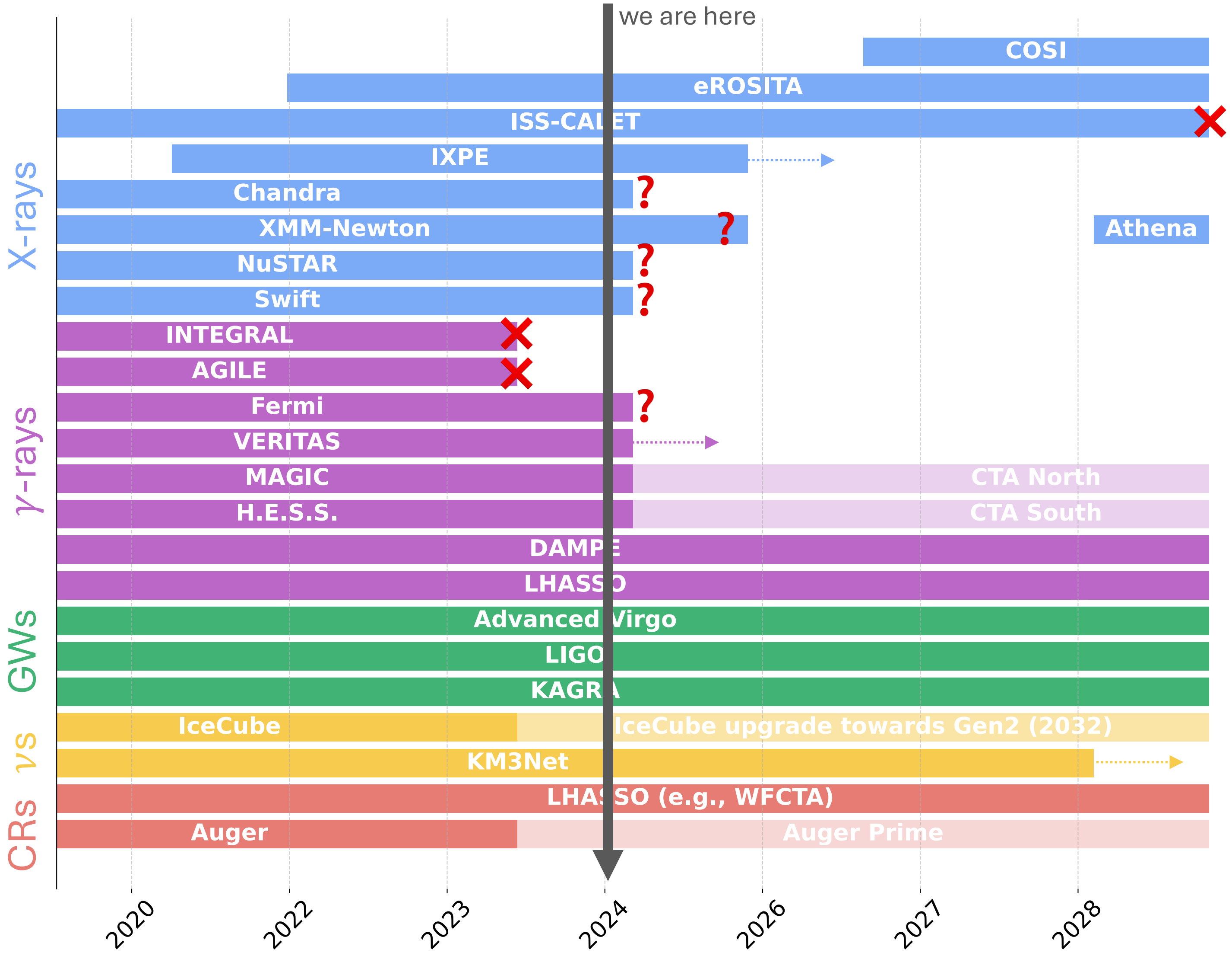
[EuCAPT WhitePaper, 2021]

BEYOND&WIMPs

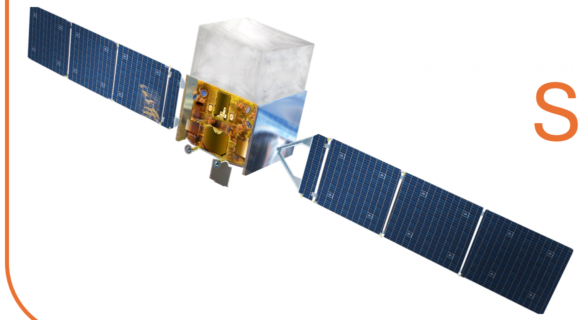
Dark Matter Landscape: An Observer's View



Dark Matter Landscape: An Instrumentationalist's View



Dark Matter Landscape: An Instrumentationalist's View



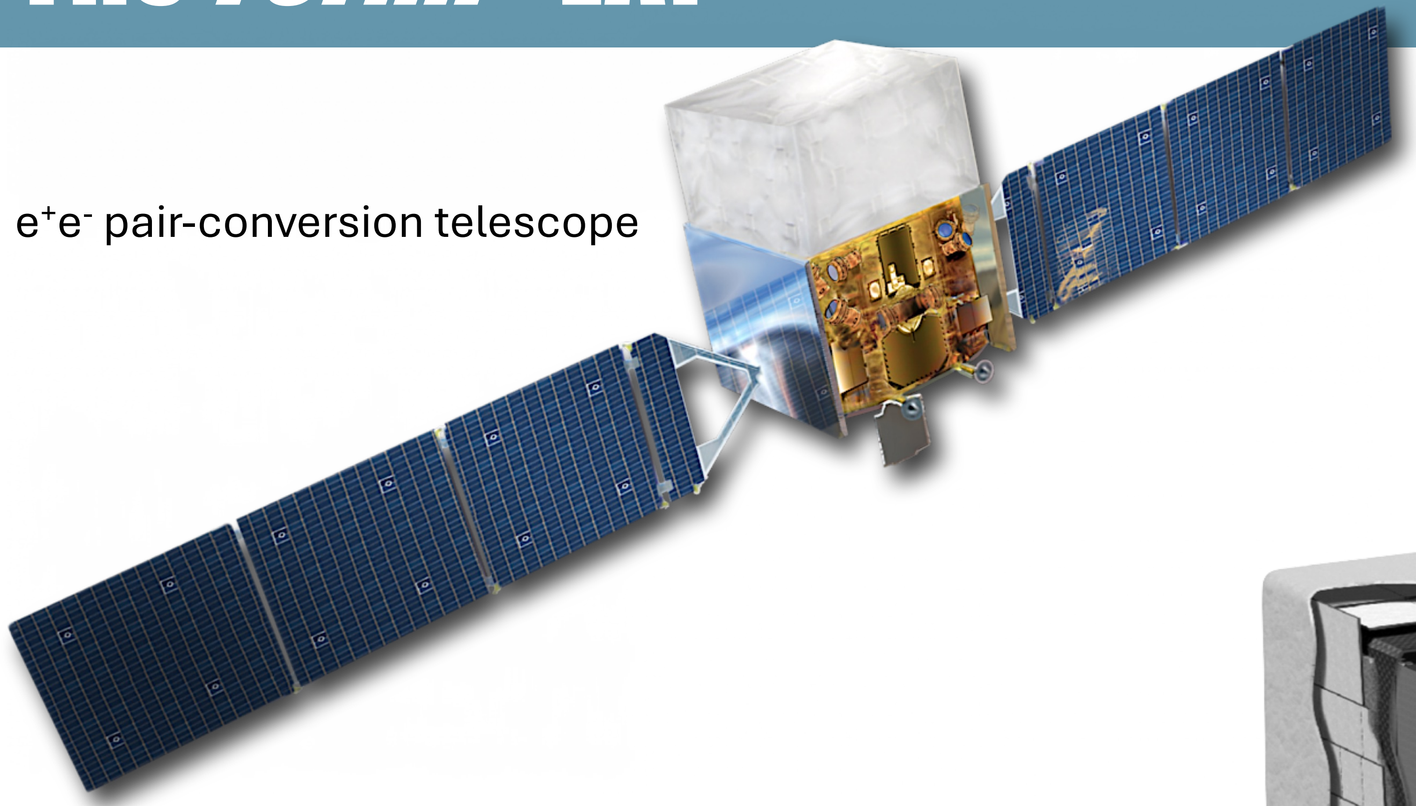
Satellite

- *Fermi* Large Area Telescope (LAT), AGILE (deorbited Feb 20, '24)
- Pair-conversion instruments

Atmospheric/water Cherenkov Telescopes

- VERITAS, MAGIC, HESS, HAWC
- Atmosphere/water = calorimeter, particle showers

The *Fermi*-LAT

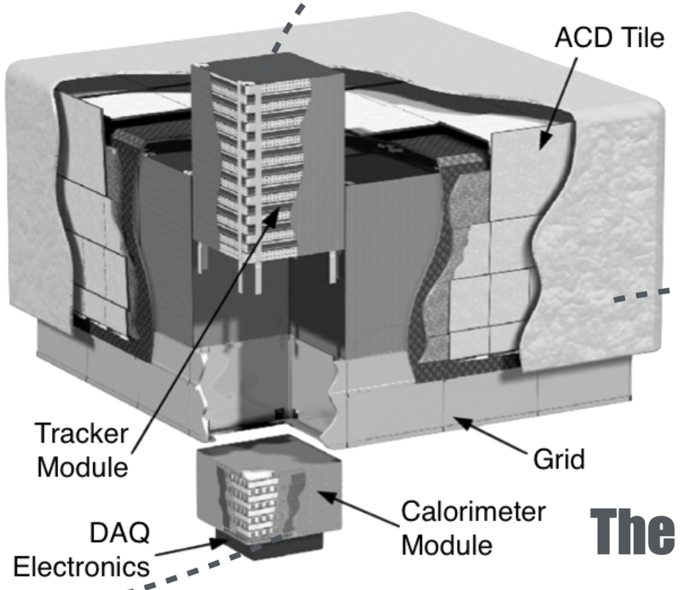


e⁺e⁻ pair-conversion telescope

individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

...it also detects electrons.

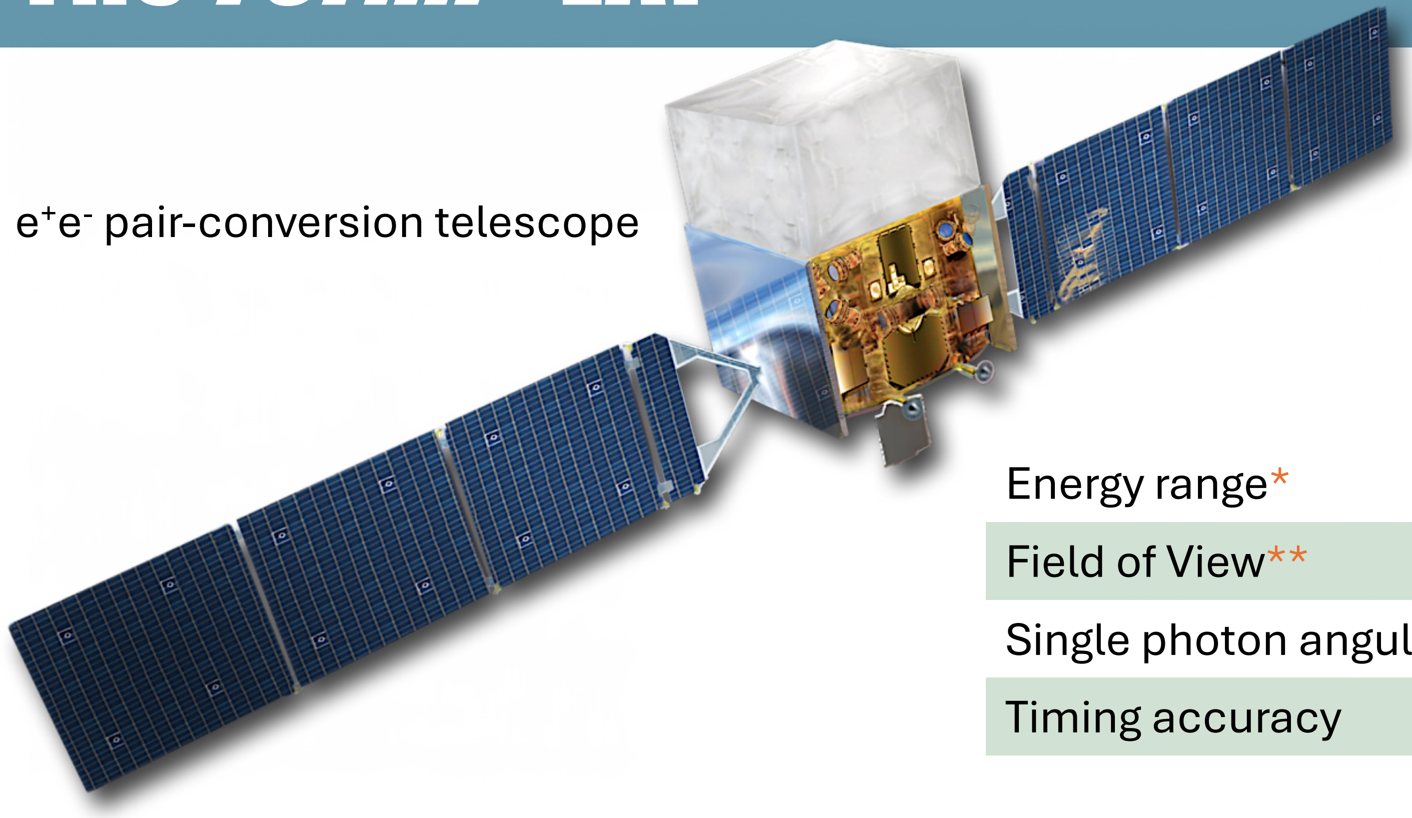
The Tracker-converter



The Anti-coincidence Detector

The Calorimeter

The *Fermi*-LAT



e^+e^- pair-conversion telescope

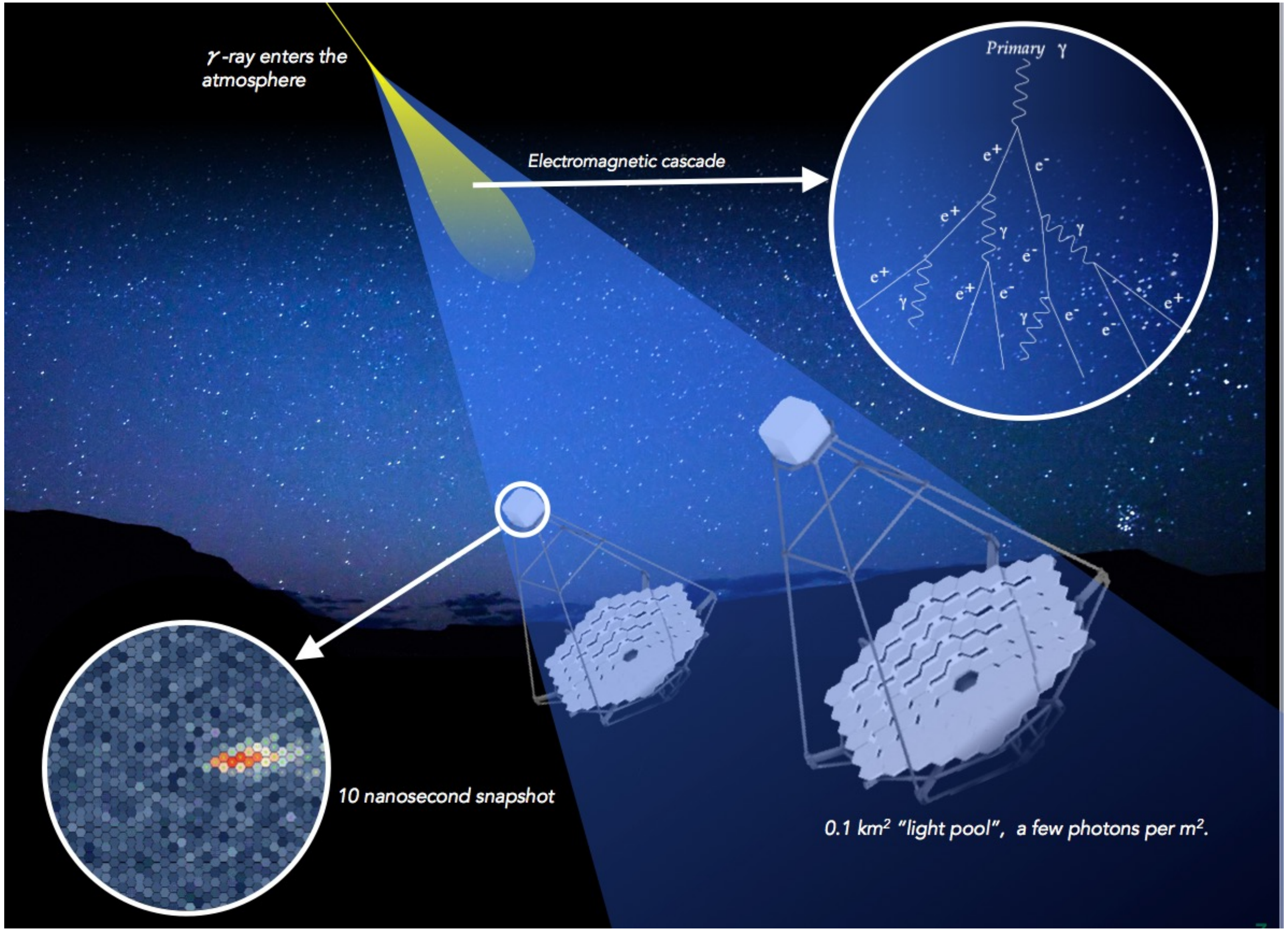
Energy range*	20 MeV to > 300 GeV
Field of View**	2.4 sr (~1/5 of the whole sky)
Single photon angular resolution***	< 1 deg at 1 GeV
Timing accuracy	1 microsecond

*ideally suited for WIMP searches
**whole sky every ~3 hours
***point-source localization <0.5 arcmin

individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

...it also detects electrons.

Cherenkov Telescopes



Energy coverage

+ LHAASO

HAWC
300 water Cherenkov detectors
300 GeV to 100 TeV

VERITAS
4 imaging air Cherenkov telescopes (IACT)
85 GeV to 30 TeV

H.E.S.S.
5 imaging air Cherenkov telescopes (IACT)
30 GeV to 100 TeV

MAGIC
2 imaging air Cherenkov telescopes (IACT)
30 GeV to 100 TeV

Fermi-LAT
Space telescope
20 MeV to 1 TeV

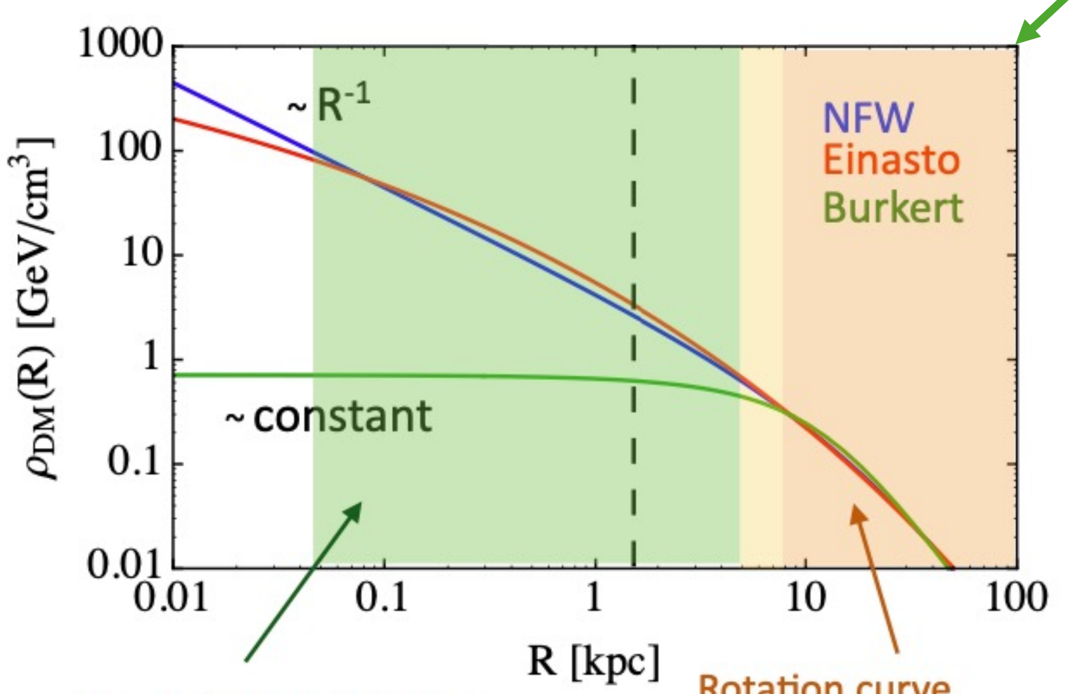
MeV GeV TeV

Adapted from Celina Armand TeVPA '22 talk.

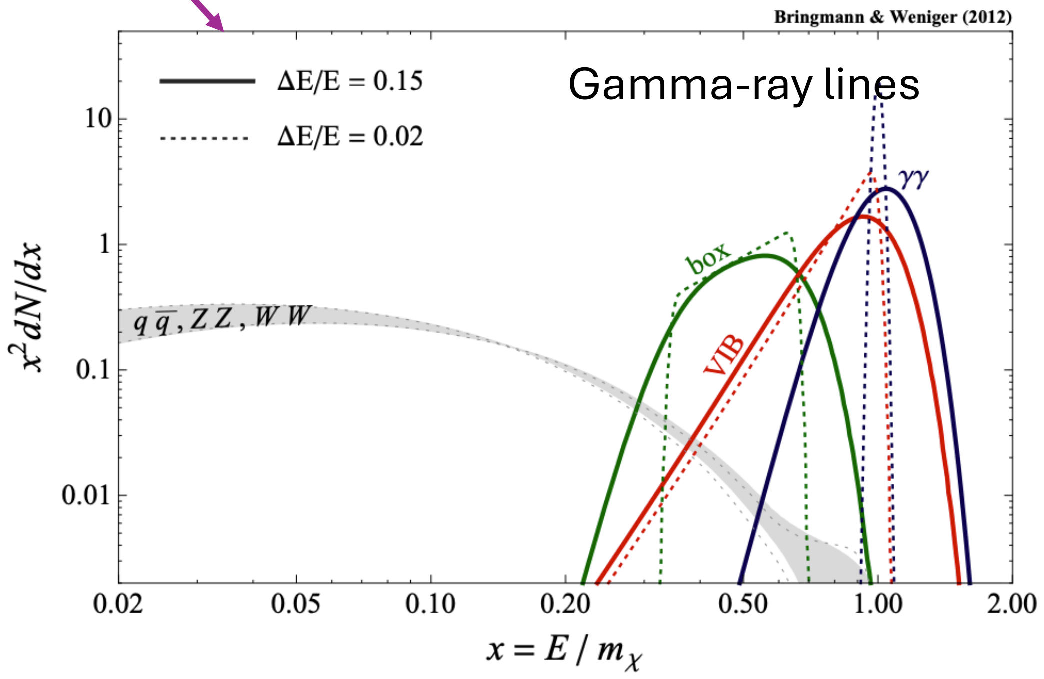
Dark Matter Signal

$$\frac{d\Phi}{dE} \propto \int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2 \times \frac{\langle\sigma v\rangle}{2M_{DM}^2}\sum B_i \frac{dN_\gamma}{dE}$$

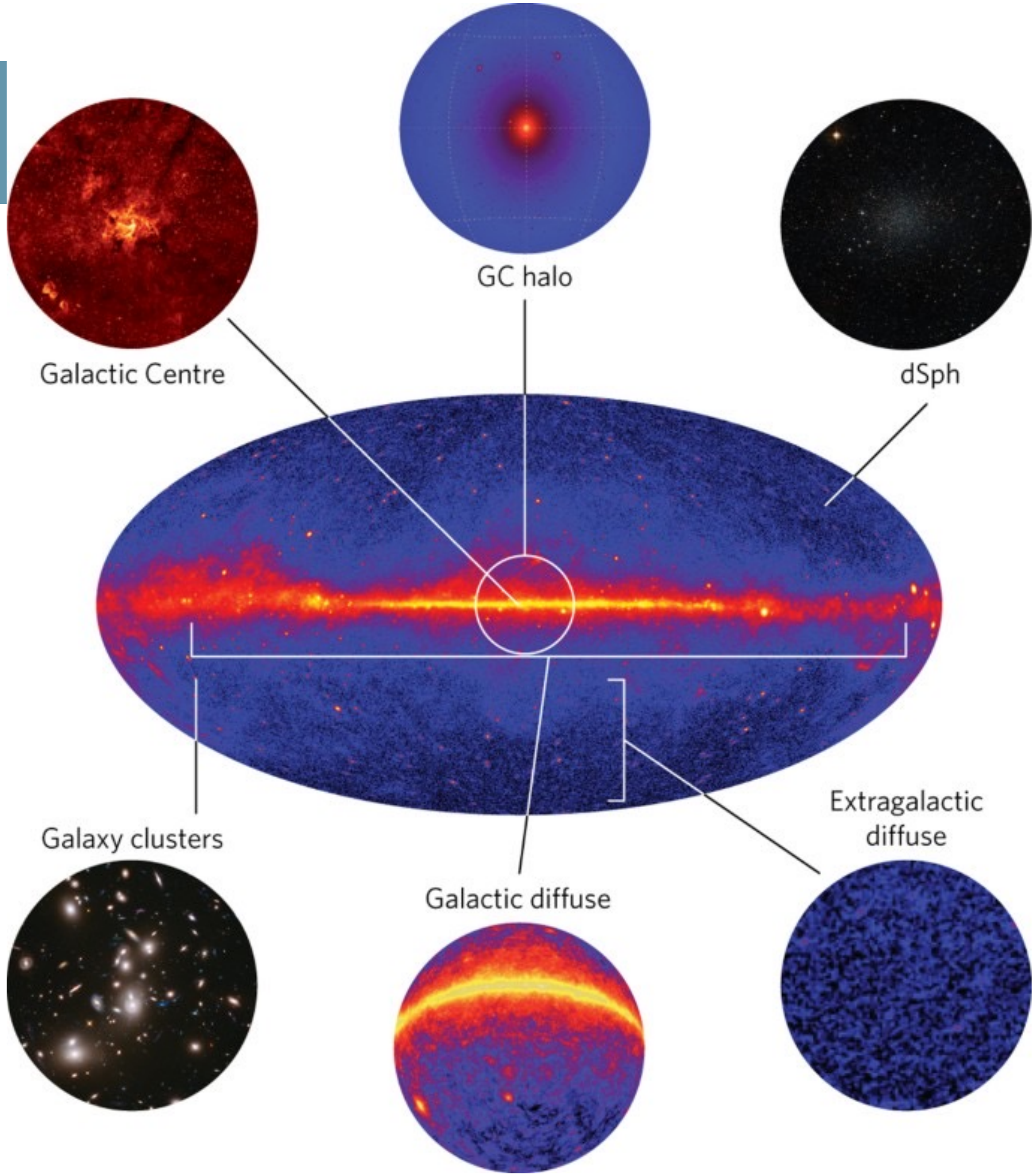
DM γ-ray flux = astrophysics J-factor x particle physics



Adapted from F. Calore.

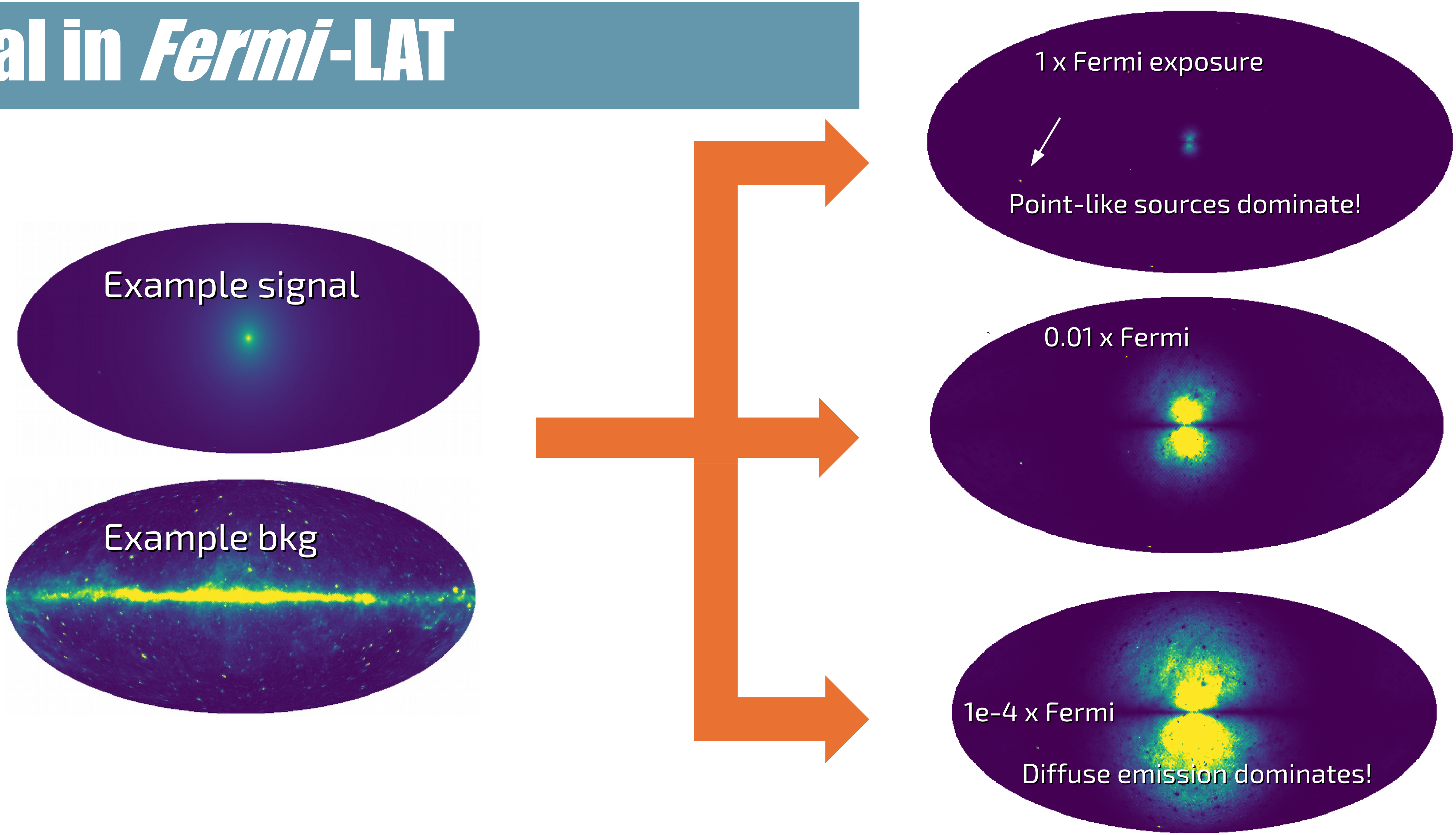


DM targets



[Conrad & Reimer 2017]

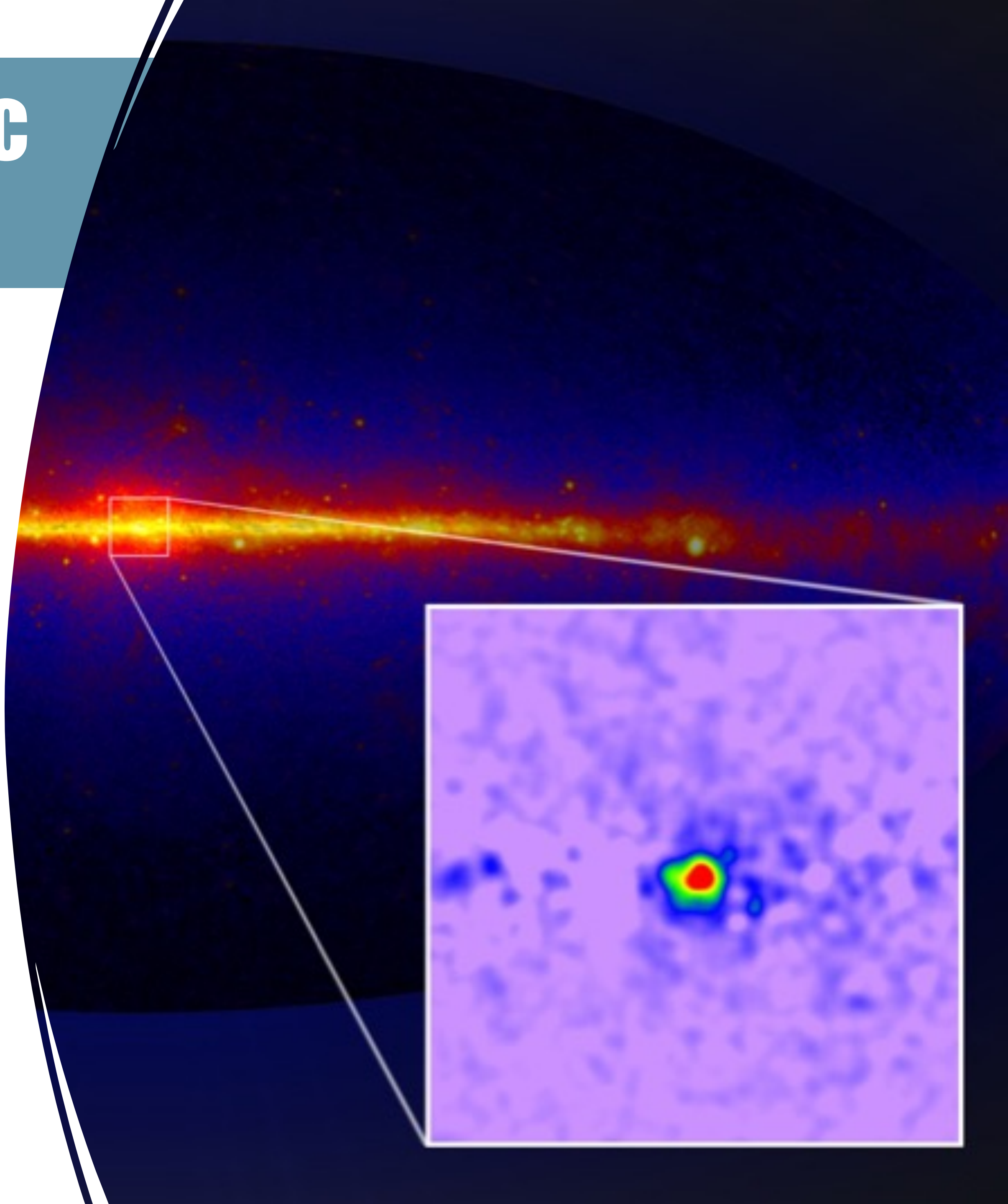
Signal in *Fermi*-LAT



[Adapted from the *Fermi* Summer School]

Gamma rays from the Galactic Center

- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT
- Extended emission up to ~10 degrees (1.5 kpc)



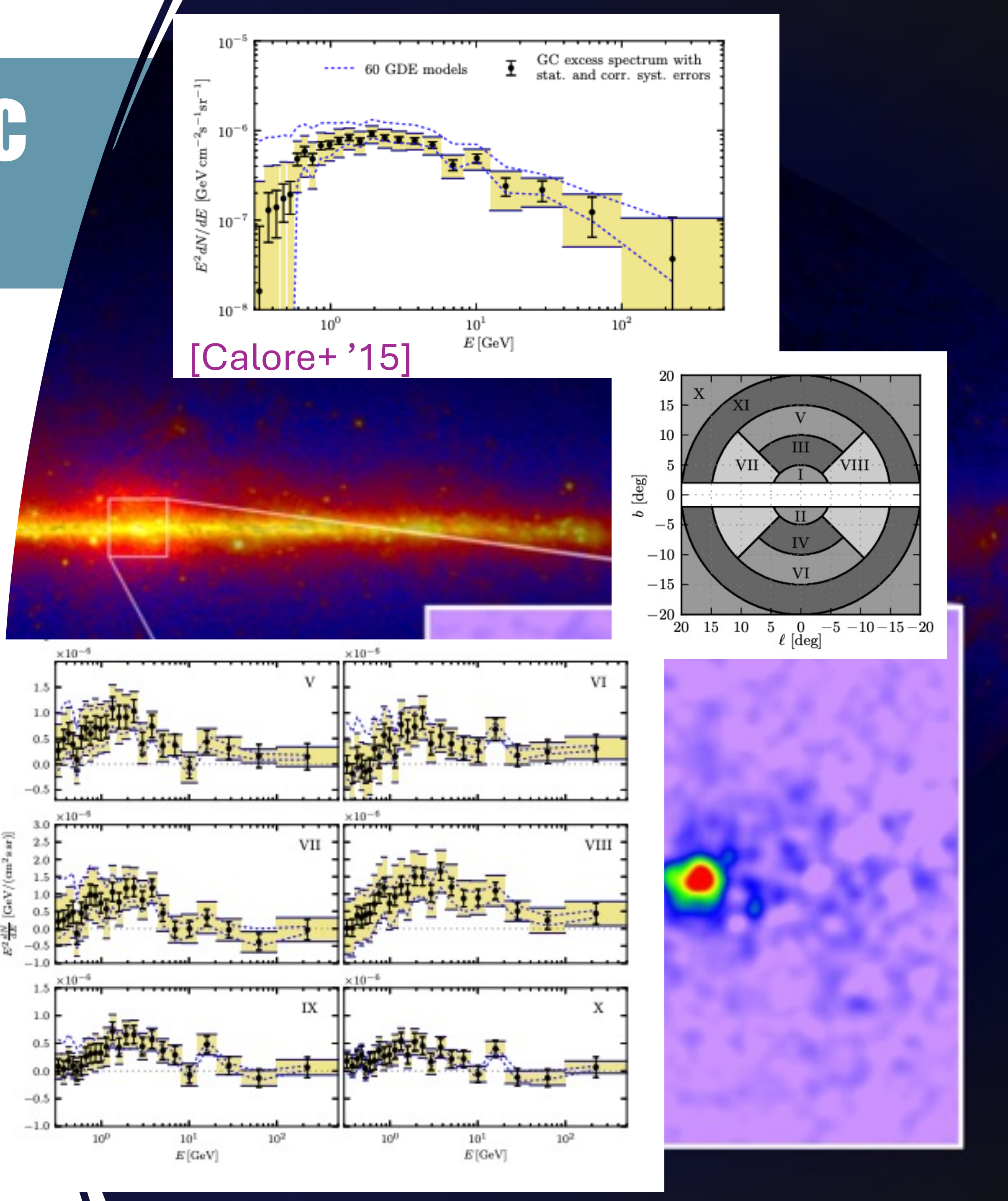
Hooper, Goodenough (2009, 2010) Hooper, Linden (2011)
Abazajian, Kaplinghat (2012) Gordon, Macias (2013) Daylan, et al. (2014)
Calore, Cholis, Weniger (2014) Murgia, et al. (2015) Ackermann et al. (2017)

Gamma rays from the Galactic Center

- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT
- Extended emission up to ~10 degrees (1.5 kpc)

Maybe Dark Matter.

- Morphology approximately spherical, extending far out of the center
- Intensity well-fit by thermal particle dark matter
- Spectrum seemingly invariant with position and shape



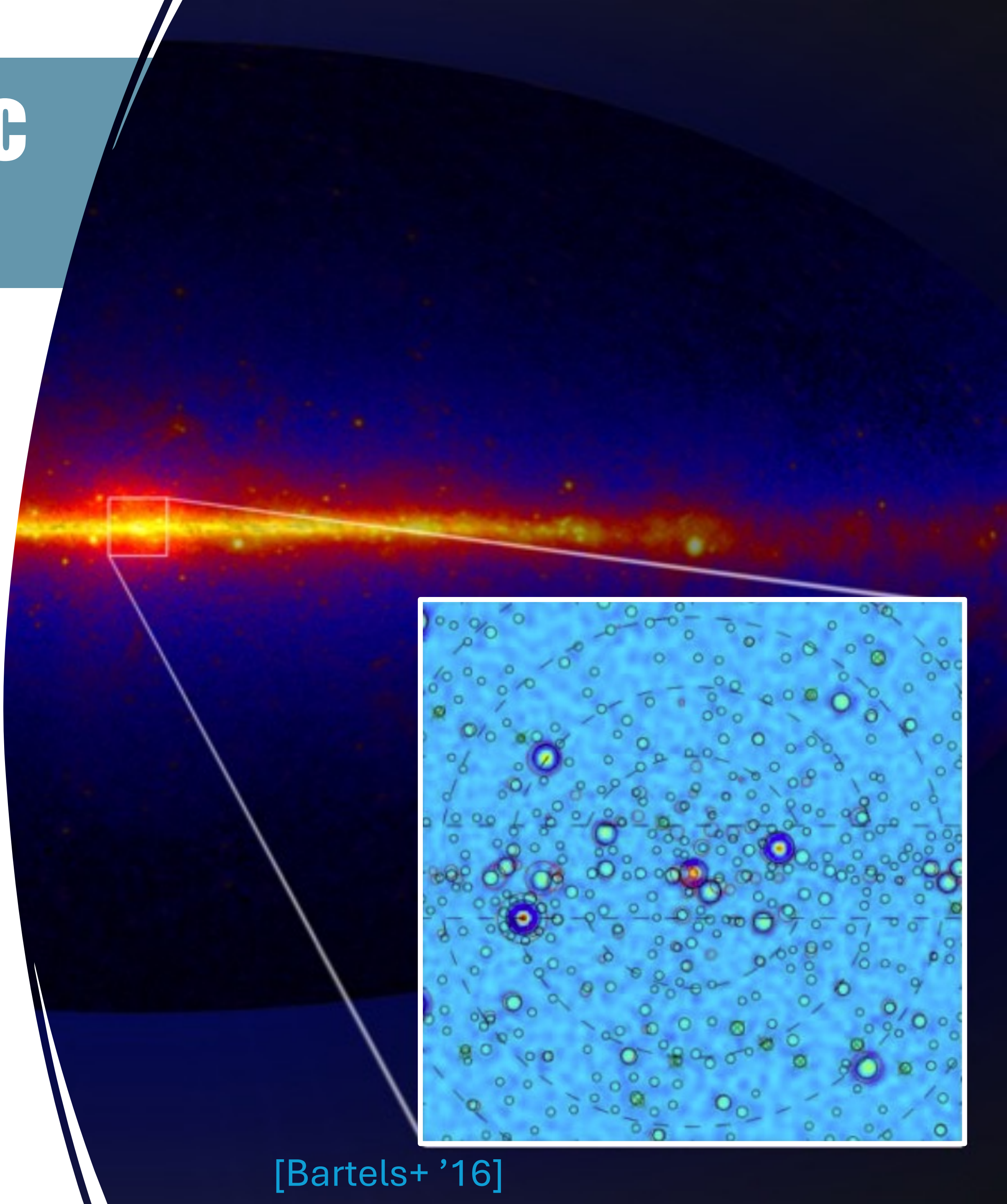
[Calore+ ’15]

Gamma rays from the Galactic Center

- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT
- Extended emission up to ~10 degrees (1.5 kpc)

Maybe not. Millisecond pulsars?

- Unresolved sources could collectively explain GCE
- **Dark matter is smooth.** Point sources are clumpy.
    - Non-poissanian template fitting.
    - Wavelet transforms.
- [Lee+ ‘15, ‘16, Bartels+ ’16, Buschmann+ ‘20]
- [Leane & Slatyer ’19, Zhong+ ‘19, Leane & Slatyer ’20a,b]



[Bartels+ ’16]

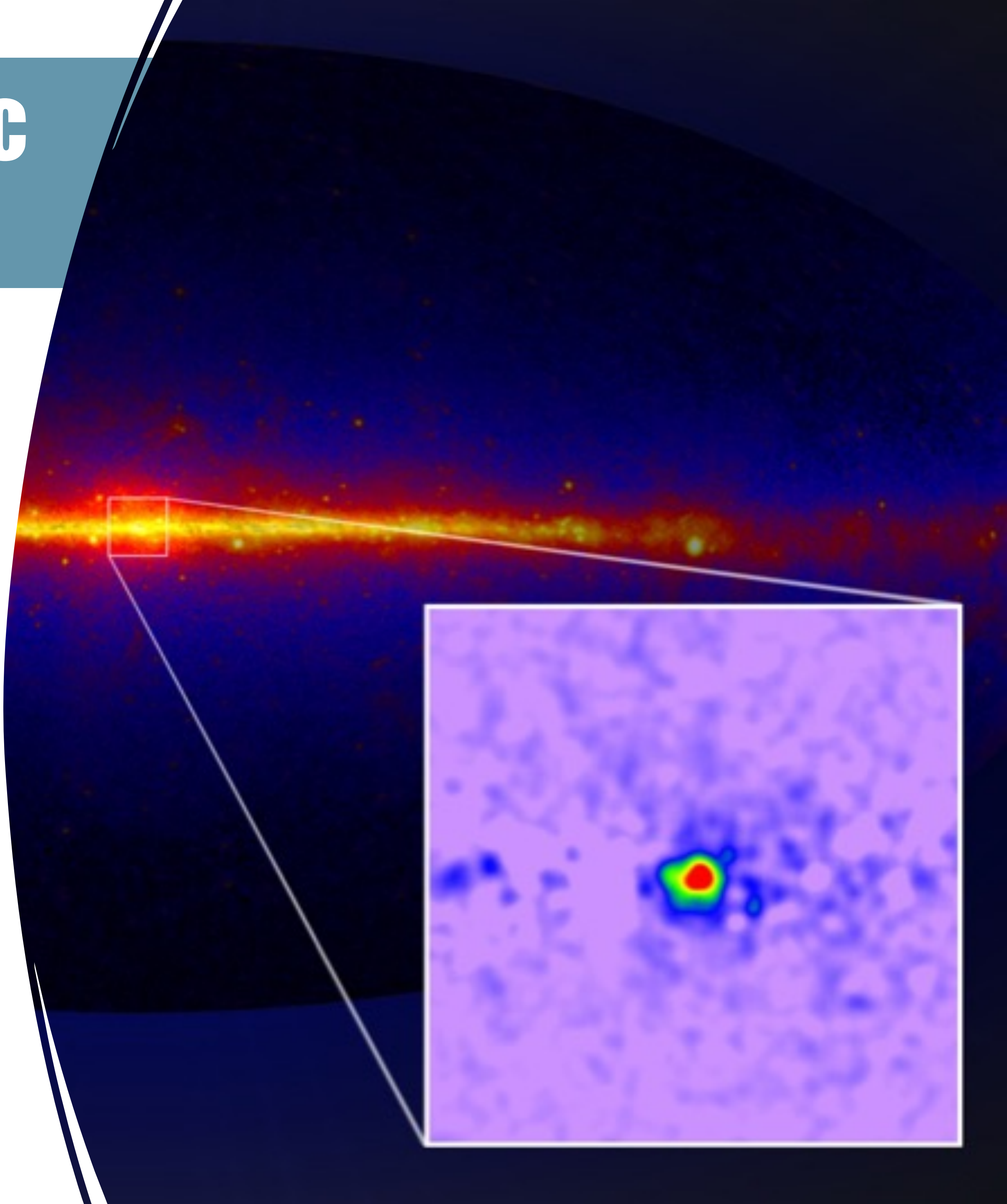
Gamma rays from the Galactic Center

Where now?

[2107.09070], [2110.06931], [2401.02481], [2402.05449], [2402.04733], [2002.12371], [1908.10874] [2211.09796]

Questions considered in the last few months:

- *Does the total profile look like MSP or DM?*
- *Does it look clumpy of smooth?*

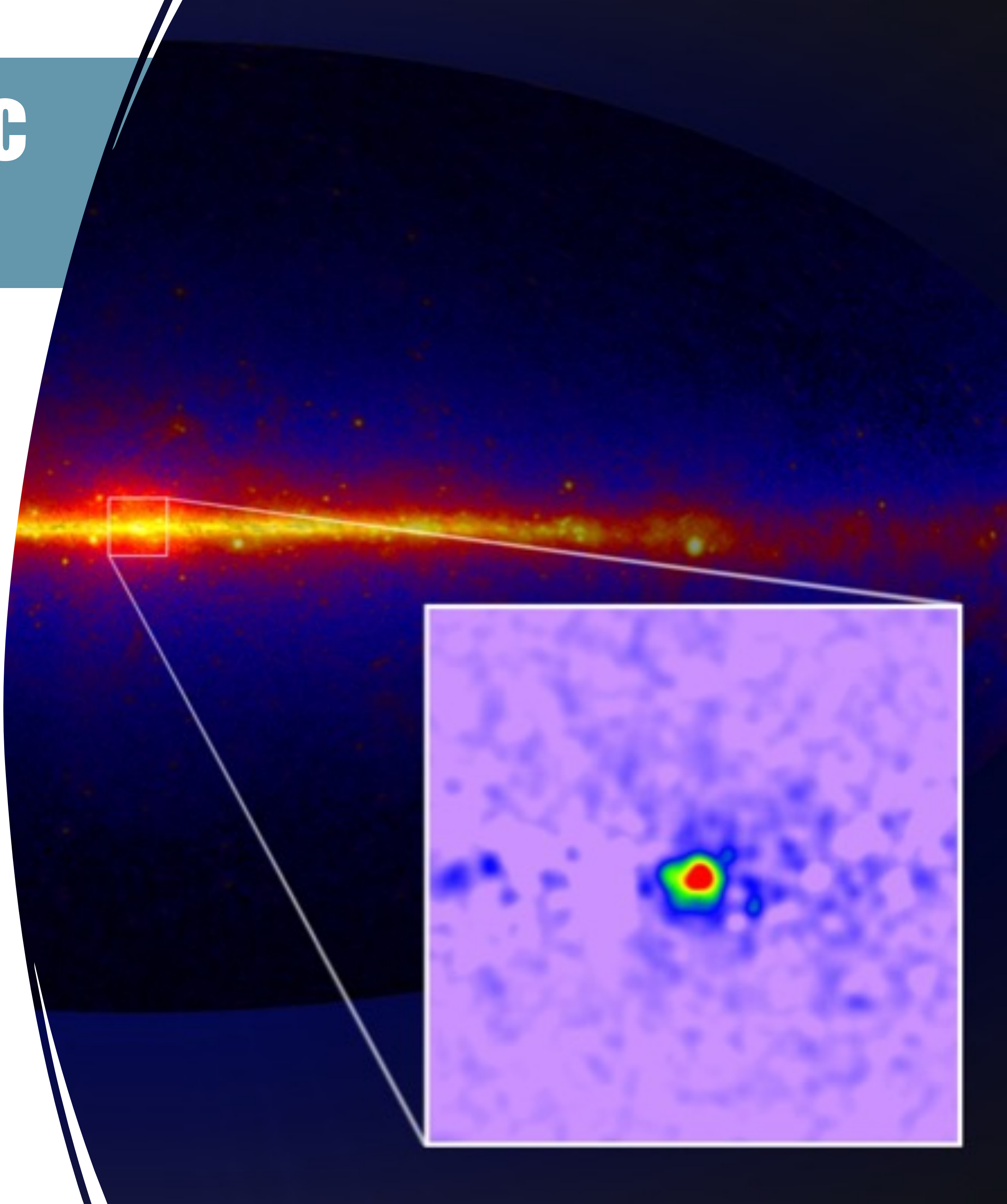


Gamma rays from the Galactic Center

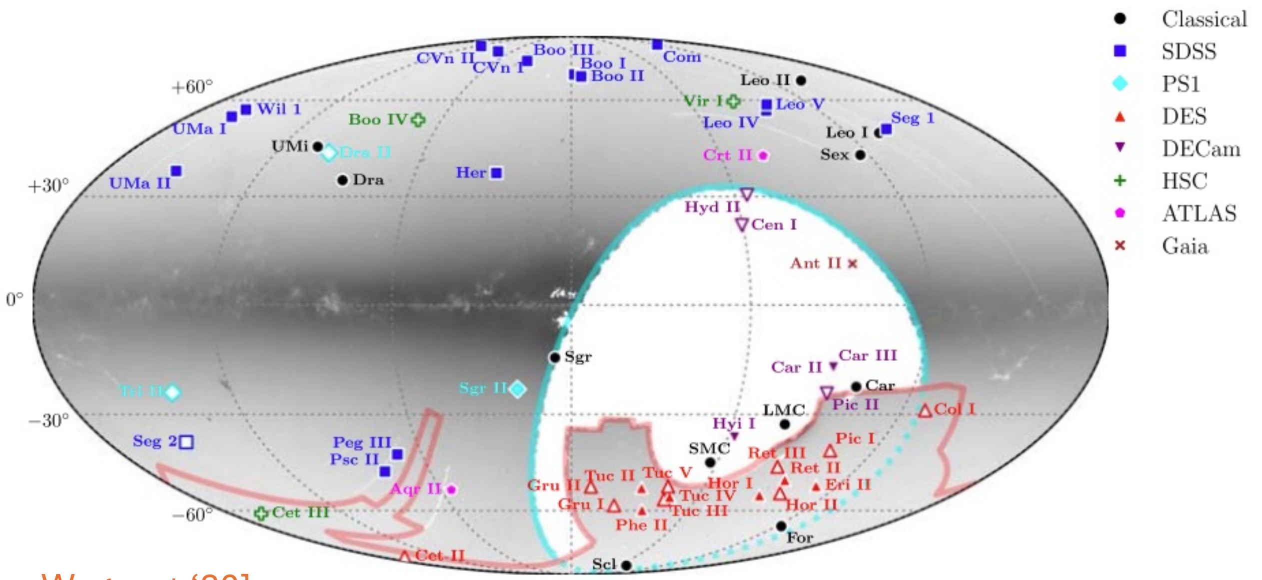
Where now?

[2107.09070], [2110.06931], [2401.02481], [2402.05449], [2402.04733], [2002.12371], [1908.10874] [2211.09796]

- **Diffuse models are not representative of the data**
- Confirming pulsars: future detections of radio emission by MeerKat and SKA
- Confirming dark matter: check for signals elsewhere



Dwarf Spheroidal Galaxies

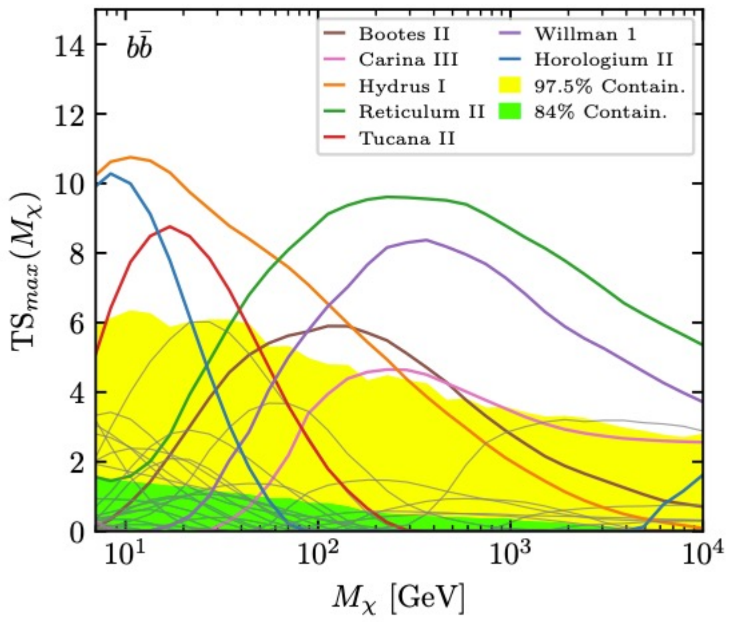


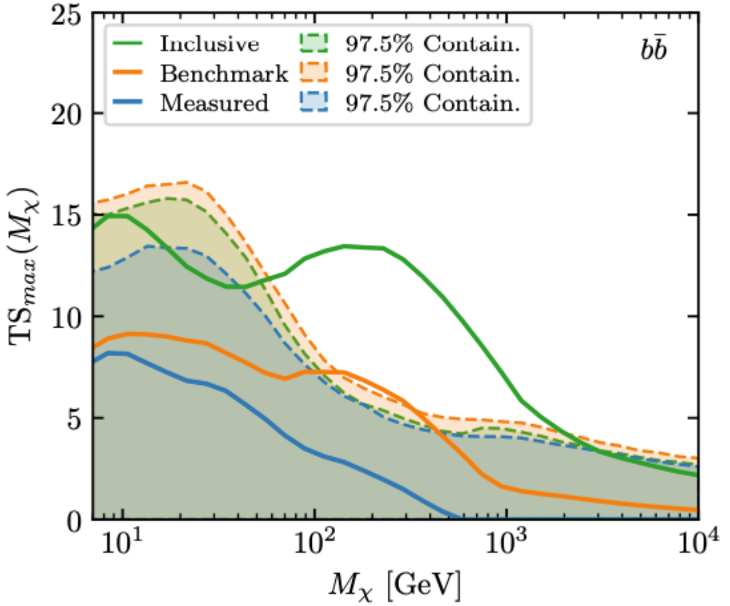
[Drlica-Wagner+ '20]

DM γ-ray flux = astrophysics J-factor x particle physics

$$\frac{d\Phi}{dE} \propto \int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2 \times \frac{\langle \sigma v \rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$

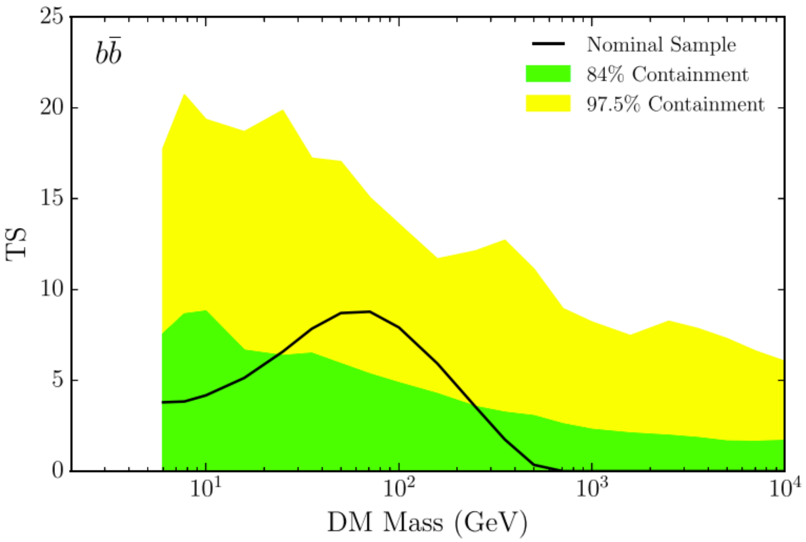
[McDaniel+ LAT '24]





Combined dSph Analyses - Comparison

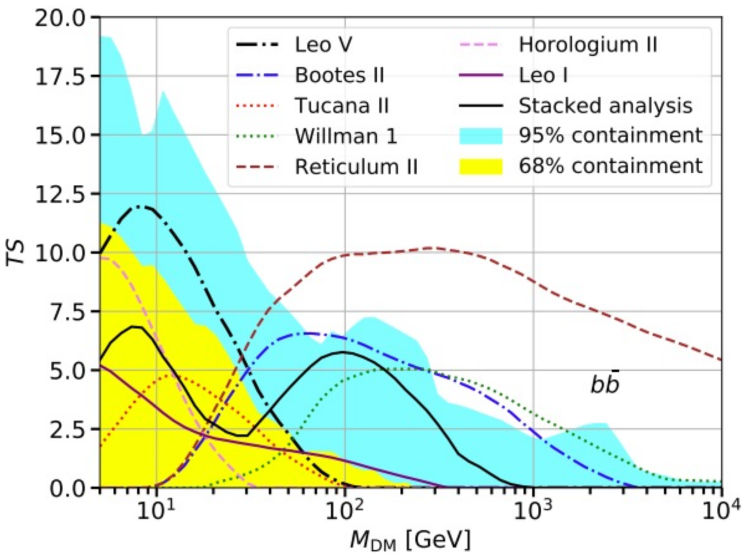
6 years



$< 2\,\sigma$

[Albert+ '17]

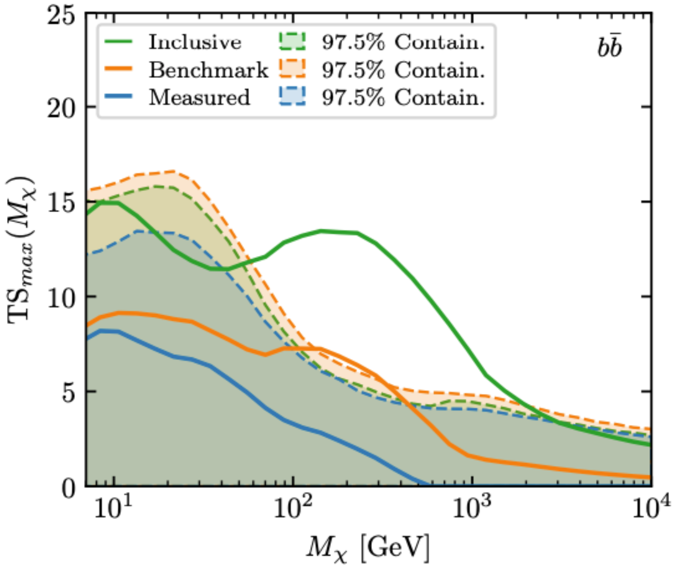
11 years



$\lesssim 2\,\sigma$

[DiMauro+ '21]

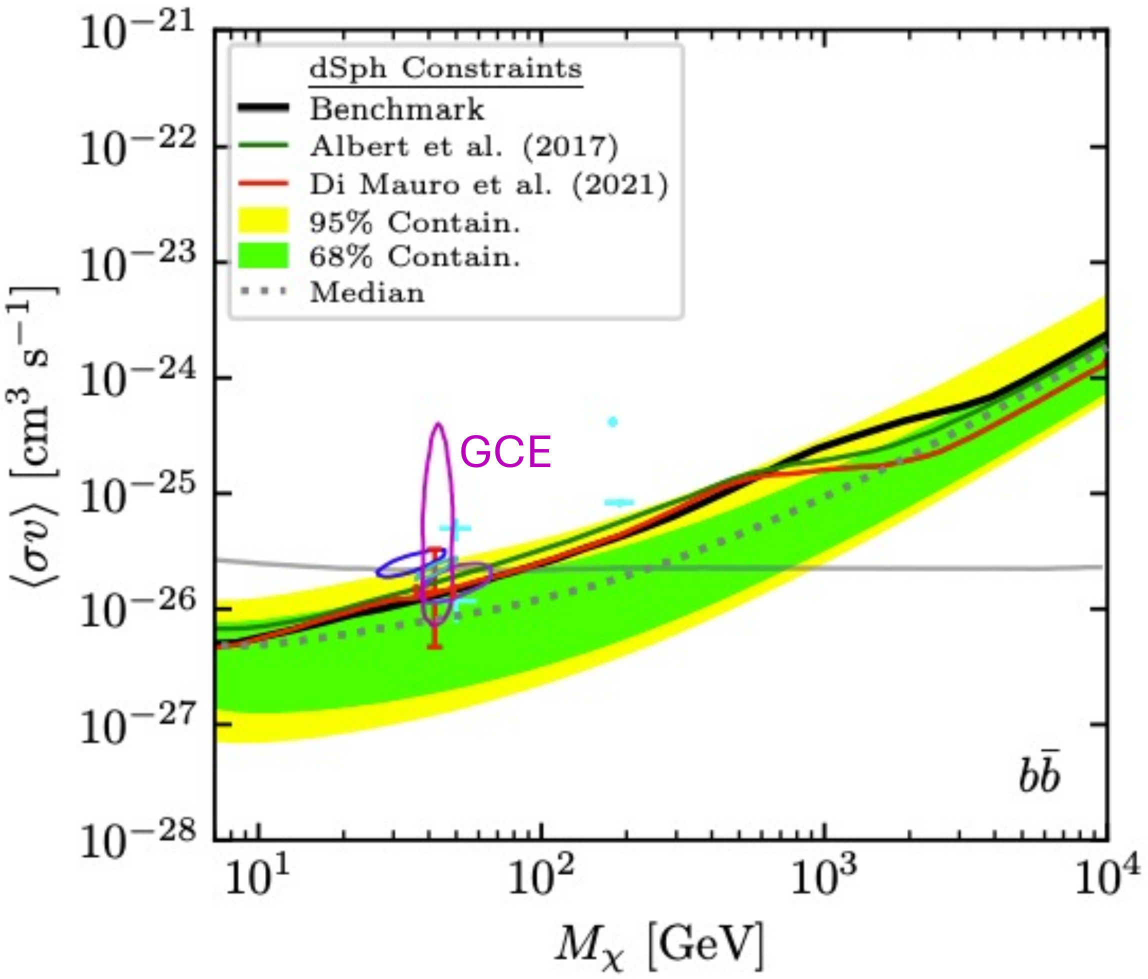
14 years



$\gtrsim 2\,\sigma$

[McDaniel+ '24]

Limits on the parameter space



[McDaniel+ '24]

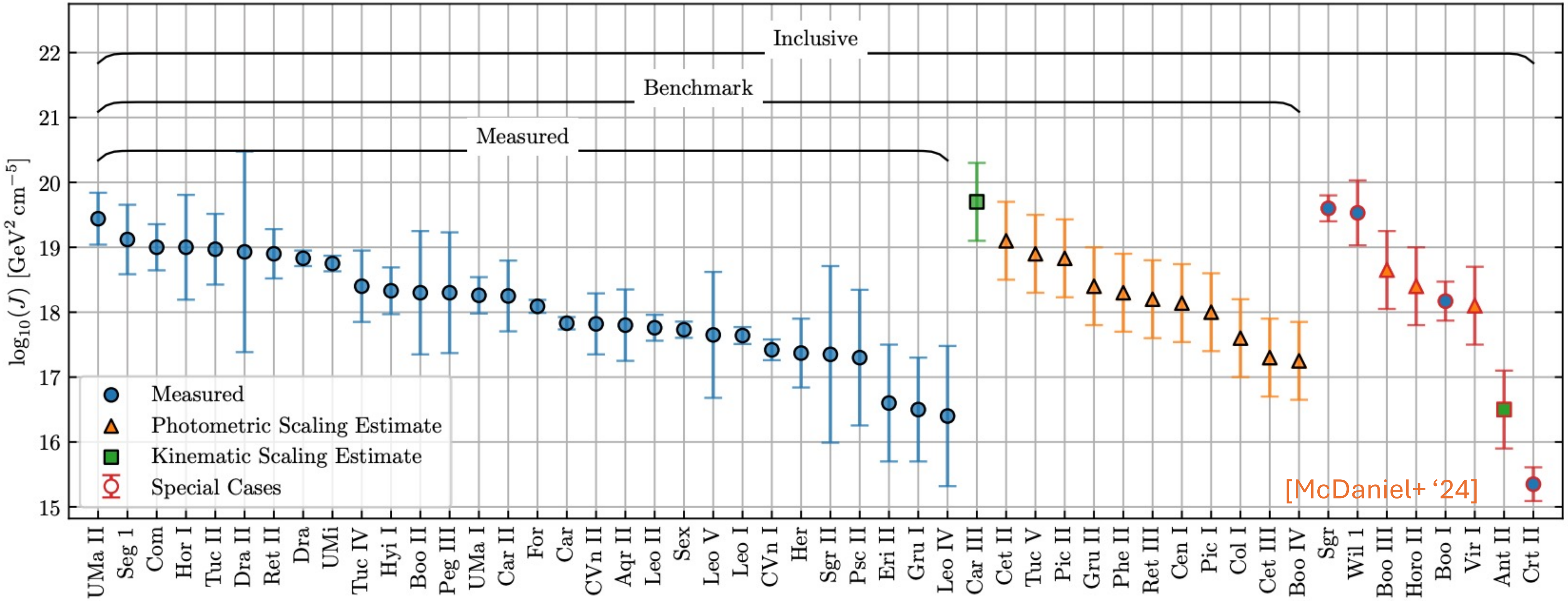
Trials factor reduces significance to 0.5 σ.

Observations:

- generally consistent with previous limits; *in tension with the GCE results*

- cannot rule out DM given the uncertainties in GC DM profile and diffuse model

J-values

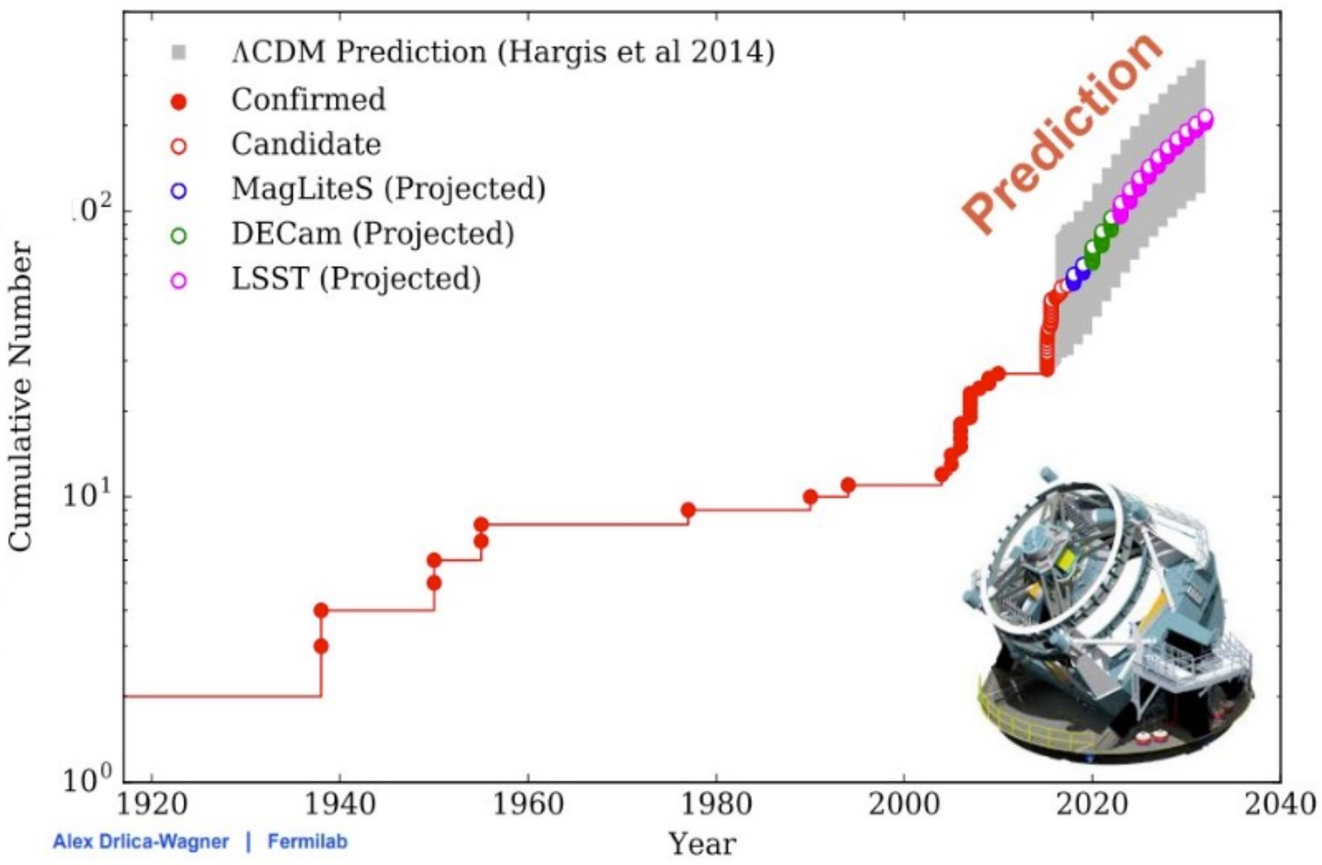


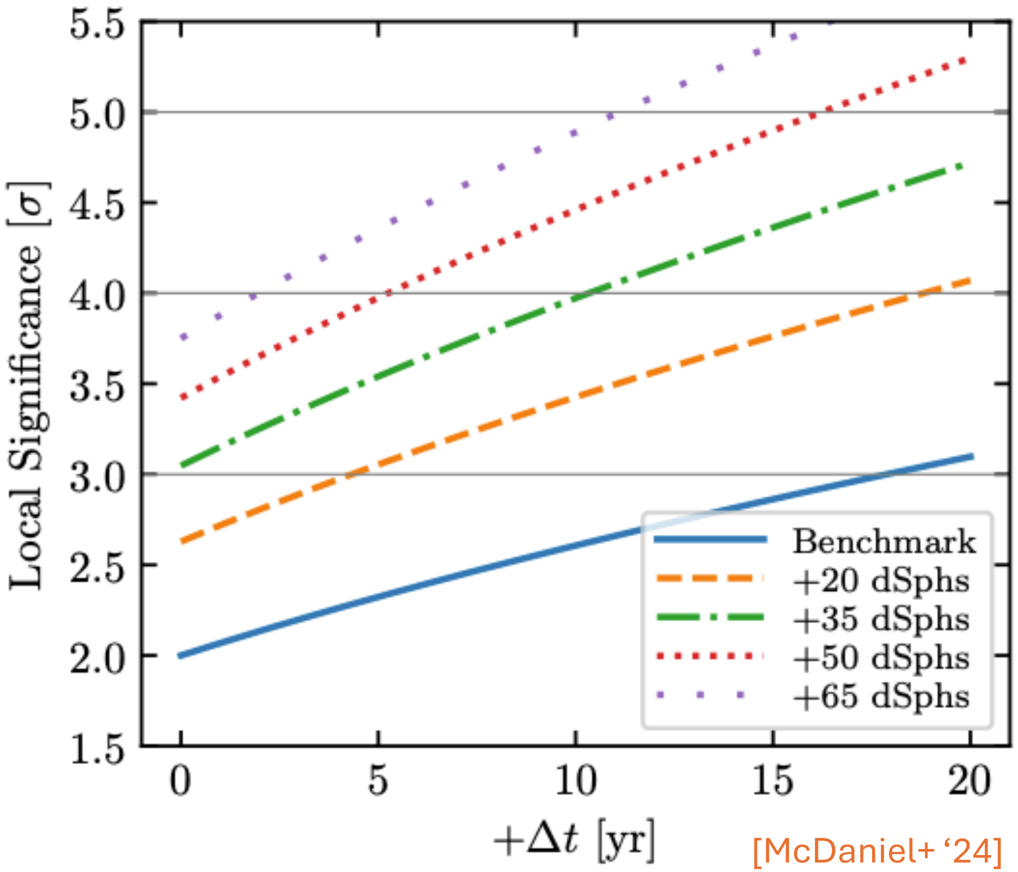
J-factor considerations:

- Calculations of J-factor values rely on several underlying assumptions (e.g., dark matter distribution models, parametric/non-parametric approaches, observational limitations) [e.g., Bonnivard+ '15, Geringer-Sameth+ '15]
- Triaxiality may affect the J-factor around 2x [e.g., Bonnivard+ '15, Hayashi+ '16]
- Non-parametric approach may reduce the J-factor by a factor of ~ 4 [Ullio & Valli '15]

Adapted from Christoph Weniger.

Future of dSph DM searches





[McDaniel+ '24]

How many dwarf galaxies do we *really* need?

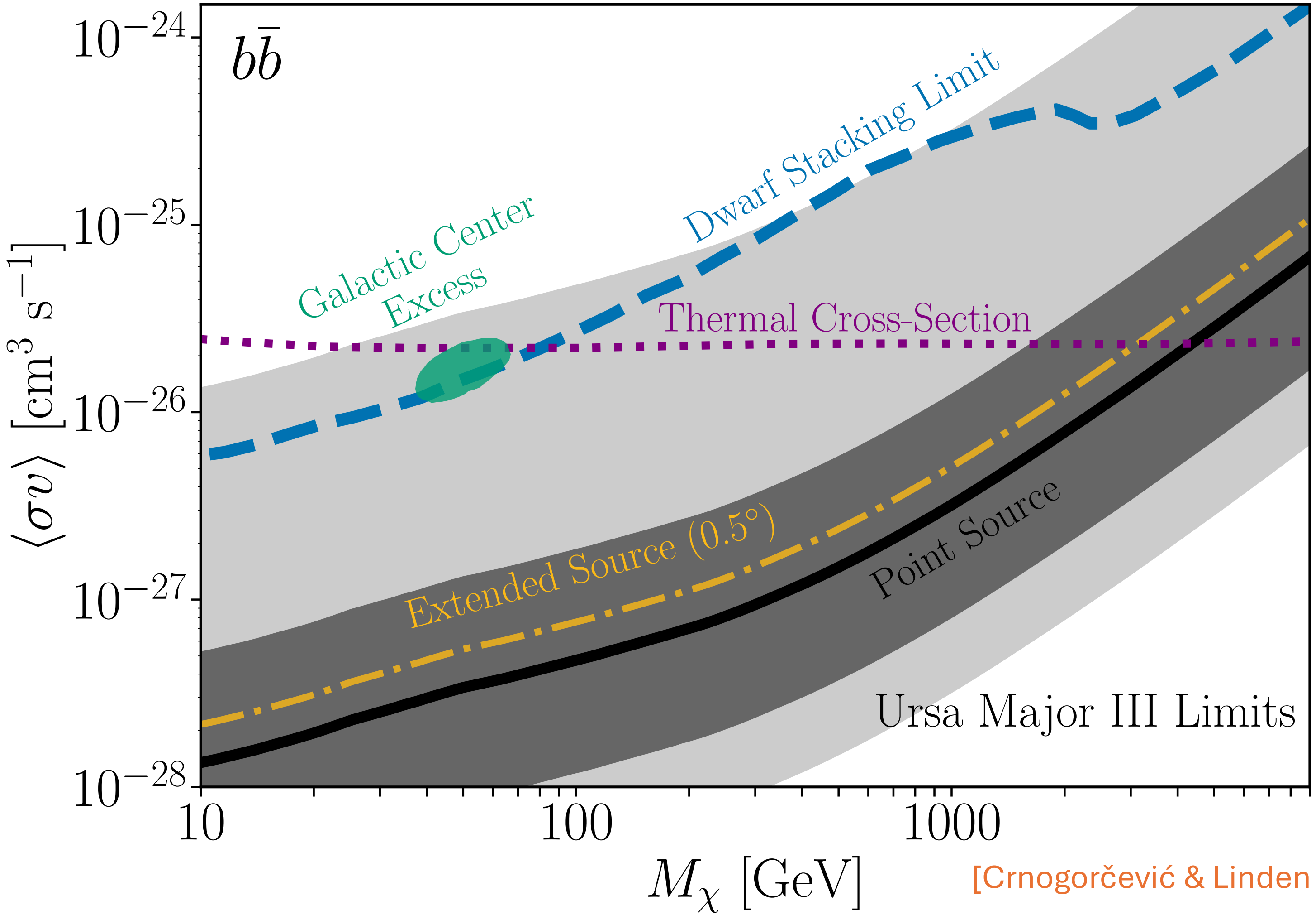
one, but a good one

Ursa Major III

[Discovery: Smith+ 2023]

[J-factor: Errani+ 2023]

- Unstable unless large DM content
- Nearby (~10 kpc)
- Strong constraints on DM annihilation
- *Confirming the dark matter density…*



[Crnogorčević & Linden '23]

Dark Matter subhaloes

[Zhu+ '16]

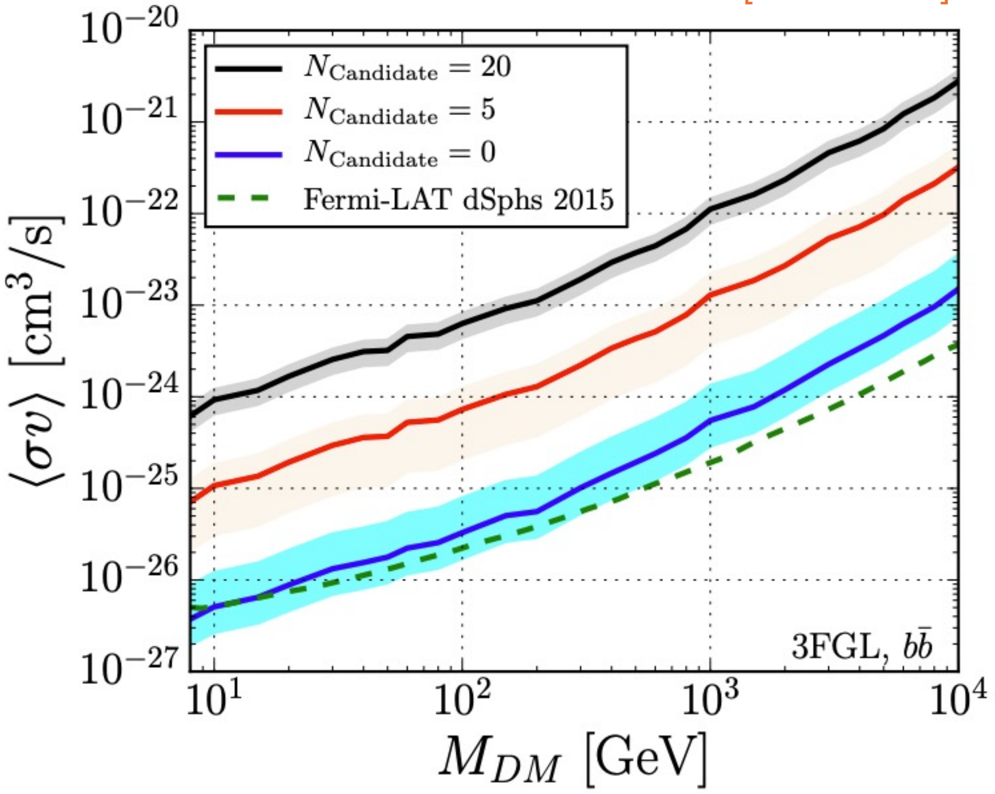
- Large-scale structure simulations predict the distribution and masses of halos
- Gamma rays: unassociated sources in *Fermi*-LAT?

Have we seen any gamma rays from subhalos already?

Dark Matter subhaloes

- No significant detection in LAT.
  - Other works: strong gravitational lensing [Vegetti+ ‘12] or applying the Machine Learning methods for identifying candidates [Mirabal+ ‘16, Salvetti+ ‘17] or Bayesian Neural Networks [Butter+ ’24]
- Improvements:
  - Identification of point sources by optical surveys (GAIA, Rubin, etc.)
  - CTA’s sensitivity to subhalos detection on par with the dSphs
  - Increased resolution of hydrodynamic simulations

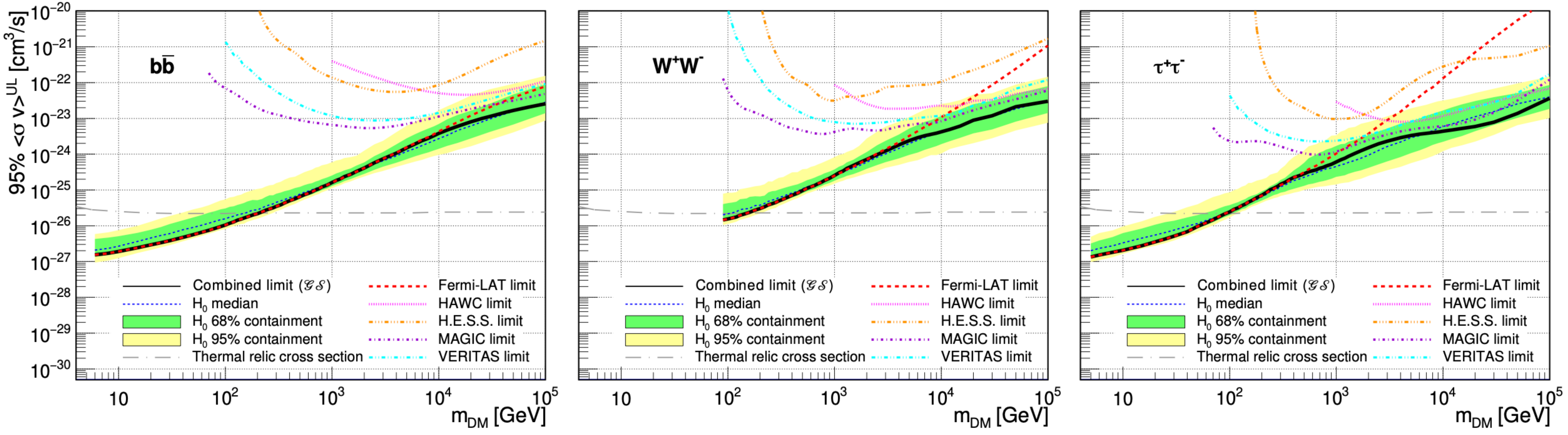
[Calore+ ’17]



GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)

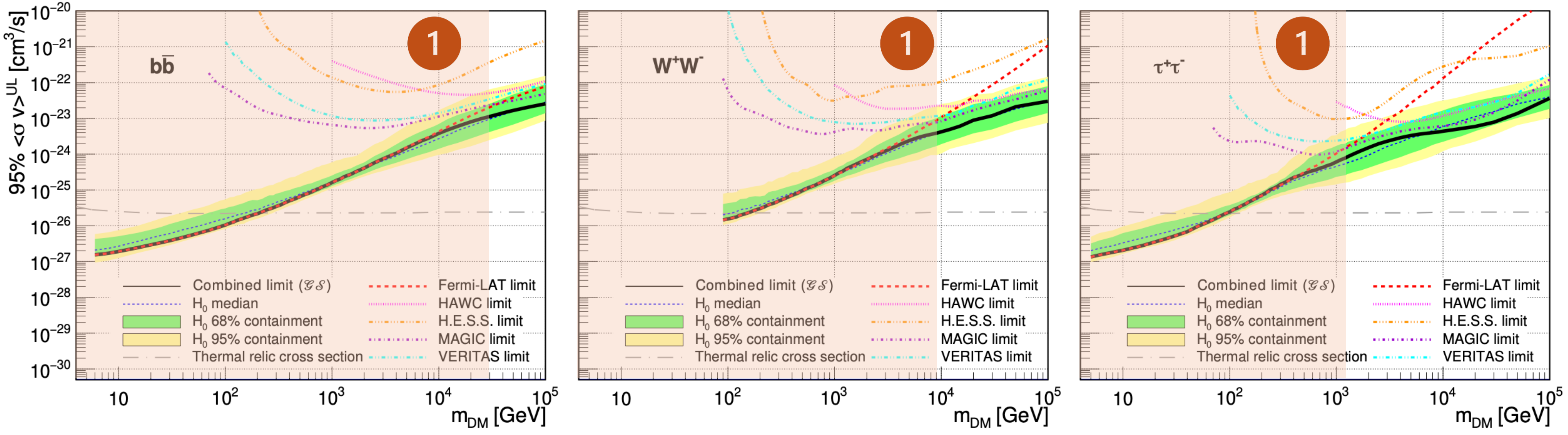
- Perform multi-instrument and multi-target analysis to obtain the most sensitive and robust results
- Focus: dSphs
- Limits driven by LAT sensitivity
- Legacy analysis of the current-generation gamma-ray instruments

GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



Adapted from Celina Armand TeVPA '22 talk.

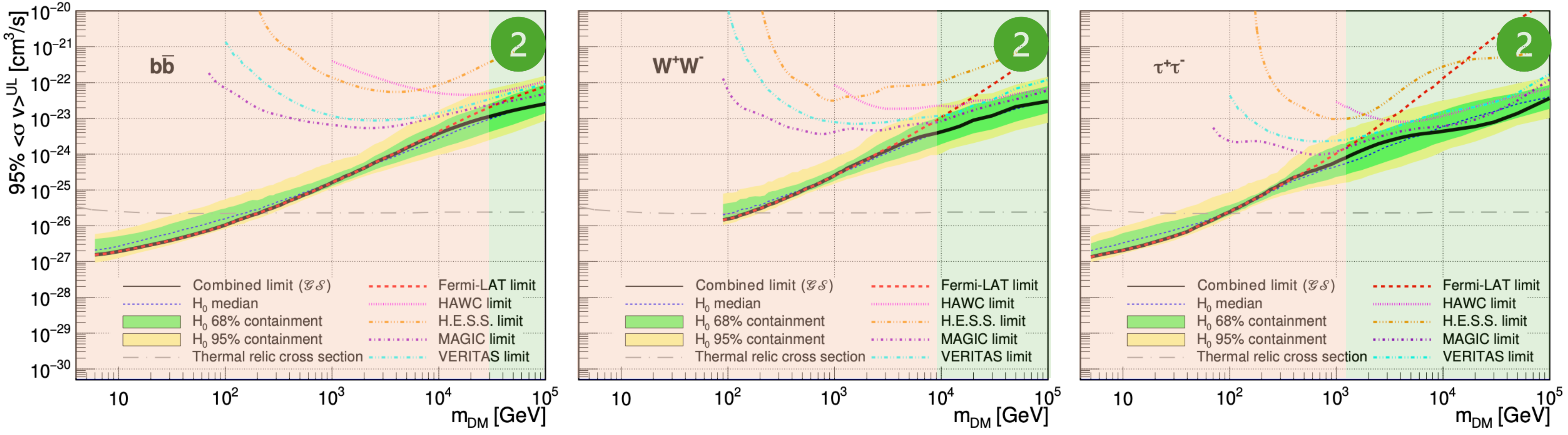
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



Dominated by *Fermi* LAT 1

Adapted from Celina Armand TeVPA '22 talk.

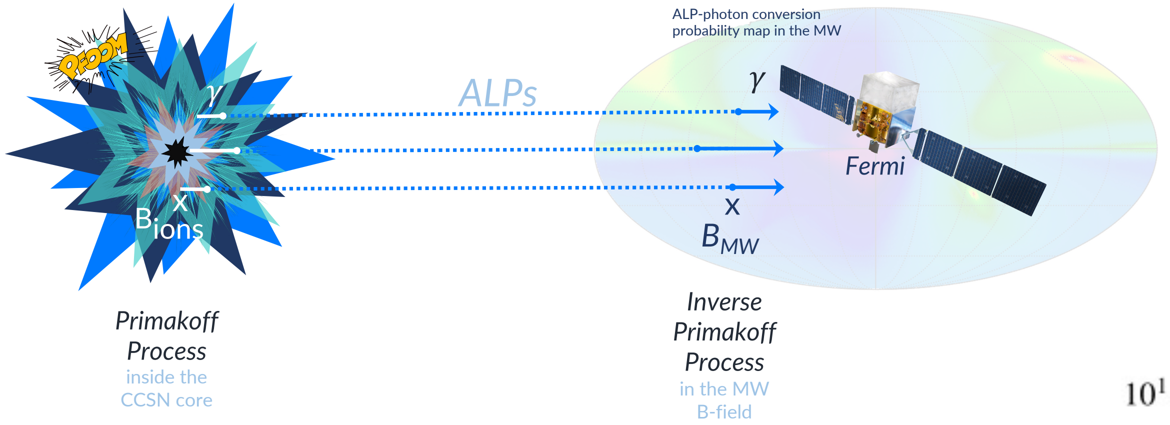
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)

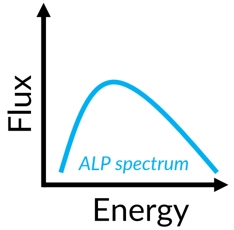


Adapted from Celina Armand TeVPA '22 talk.

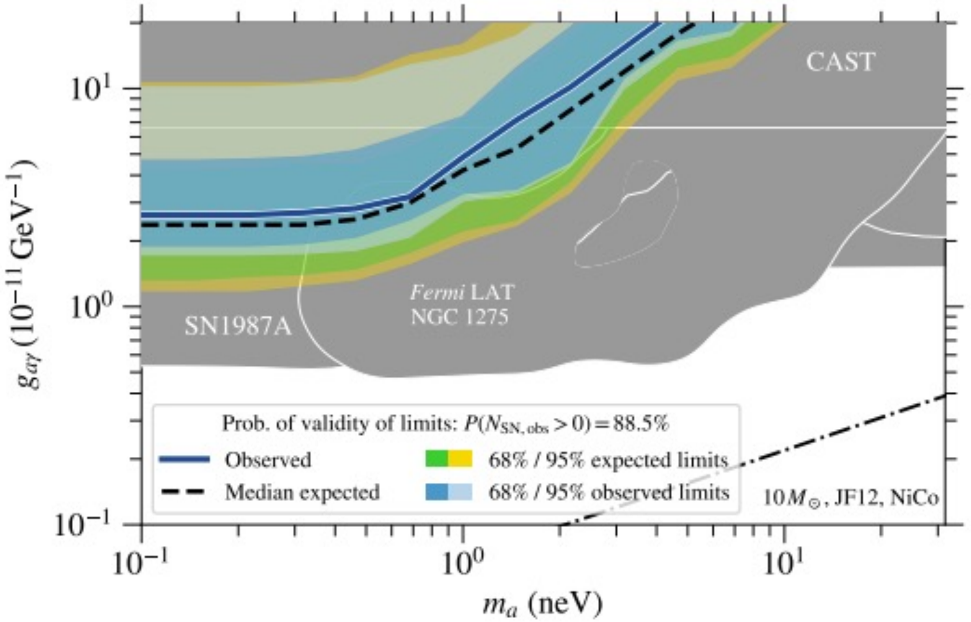
HAWC, HESS, MAGIC, VERITAS take over 2

Beyond WIMPs: Axion-like Particles





[see e.g.,Crnogorčević+ ‘21, Meyer & Petrushevska ‘20]

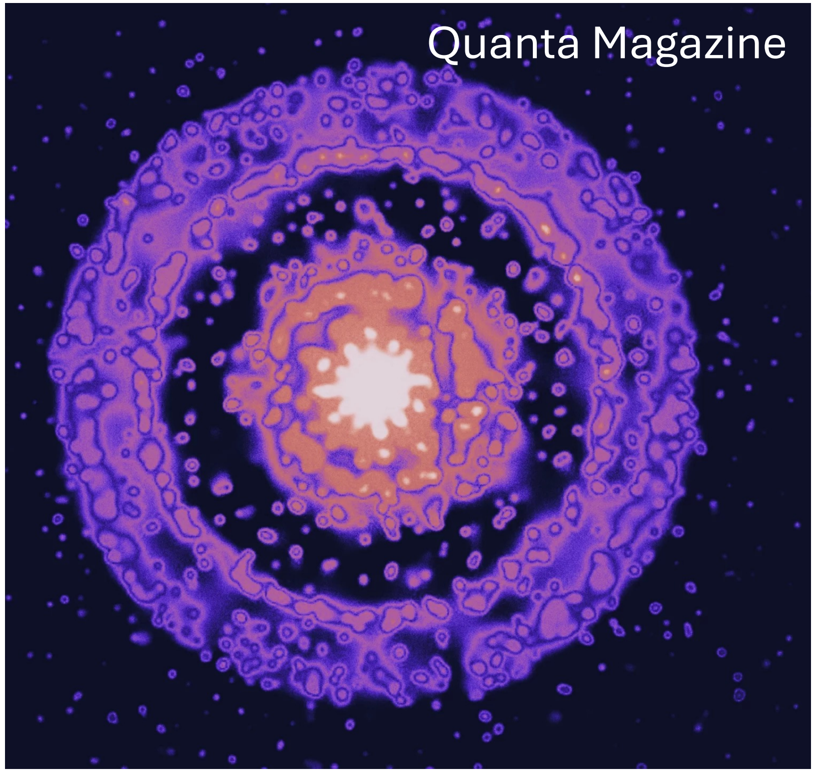


Motivation: ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.

- **CCSNe in ZTF, TESS, ASAS-SN, etc.**

Other venues: ALPs in galactic sources, EBL absorption, oscillations below critical energy

Honorable mention: GRB 221009A (BOAT)

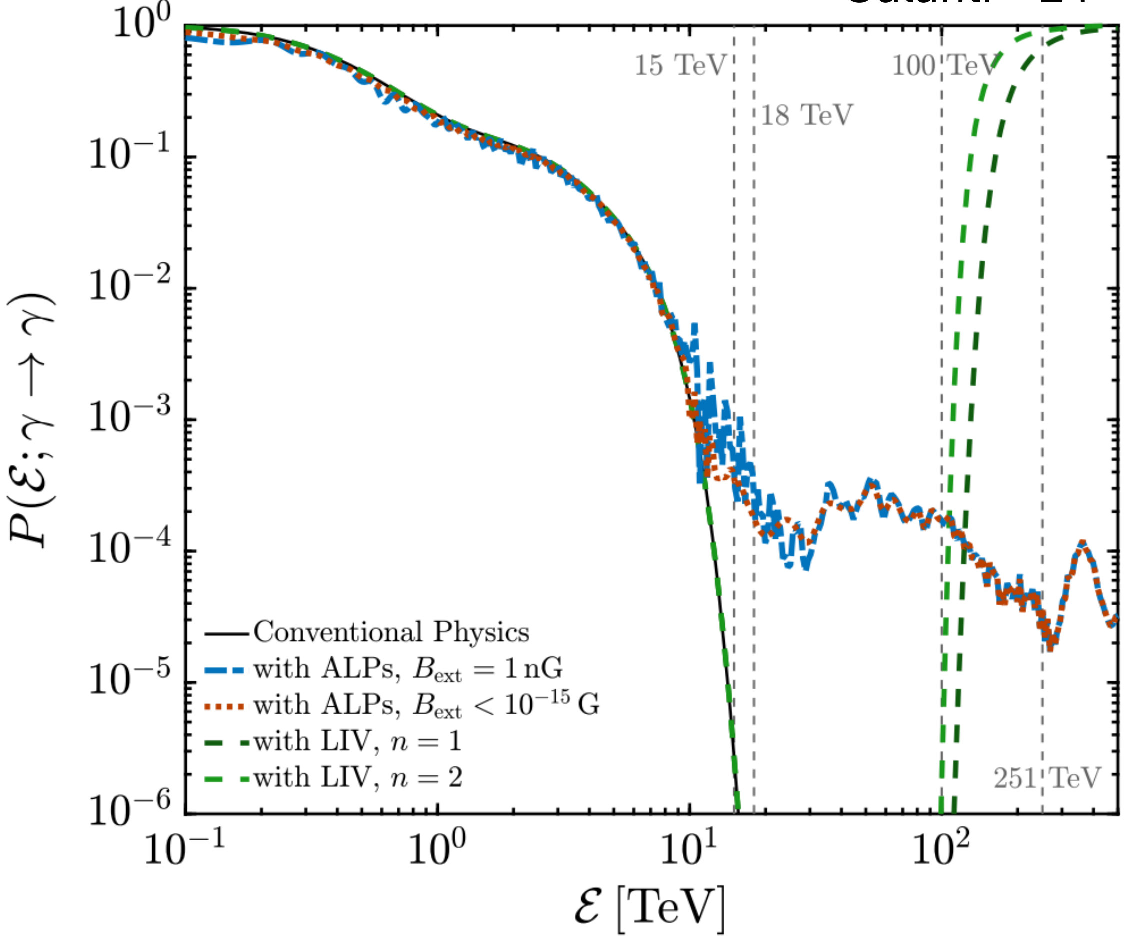


- LHAASO observation of multi-TeV photons (18 and *maybe* 150+ TeV)
- Redshift: 0.1505

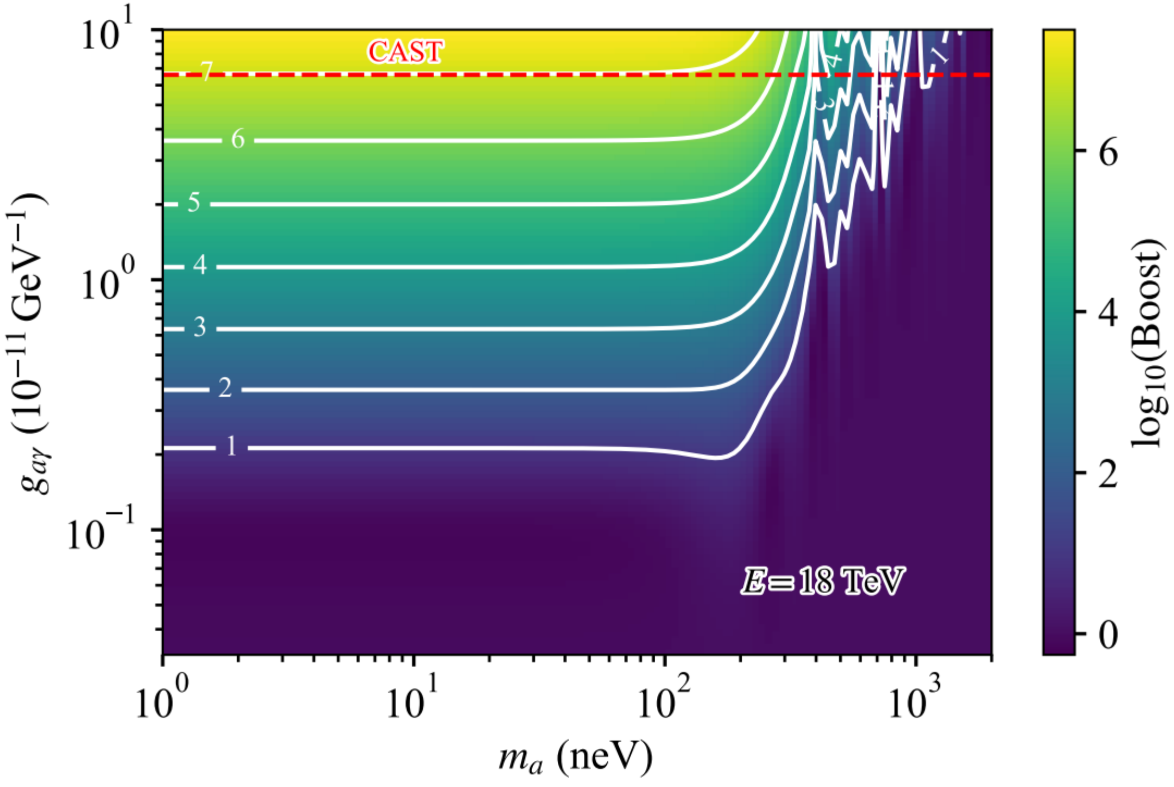
EBL attenuation should not allow for such energies to reach us

Honorable mention: GRB 221009A (BOAT)

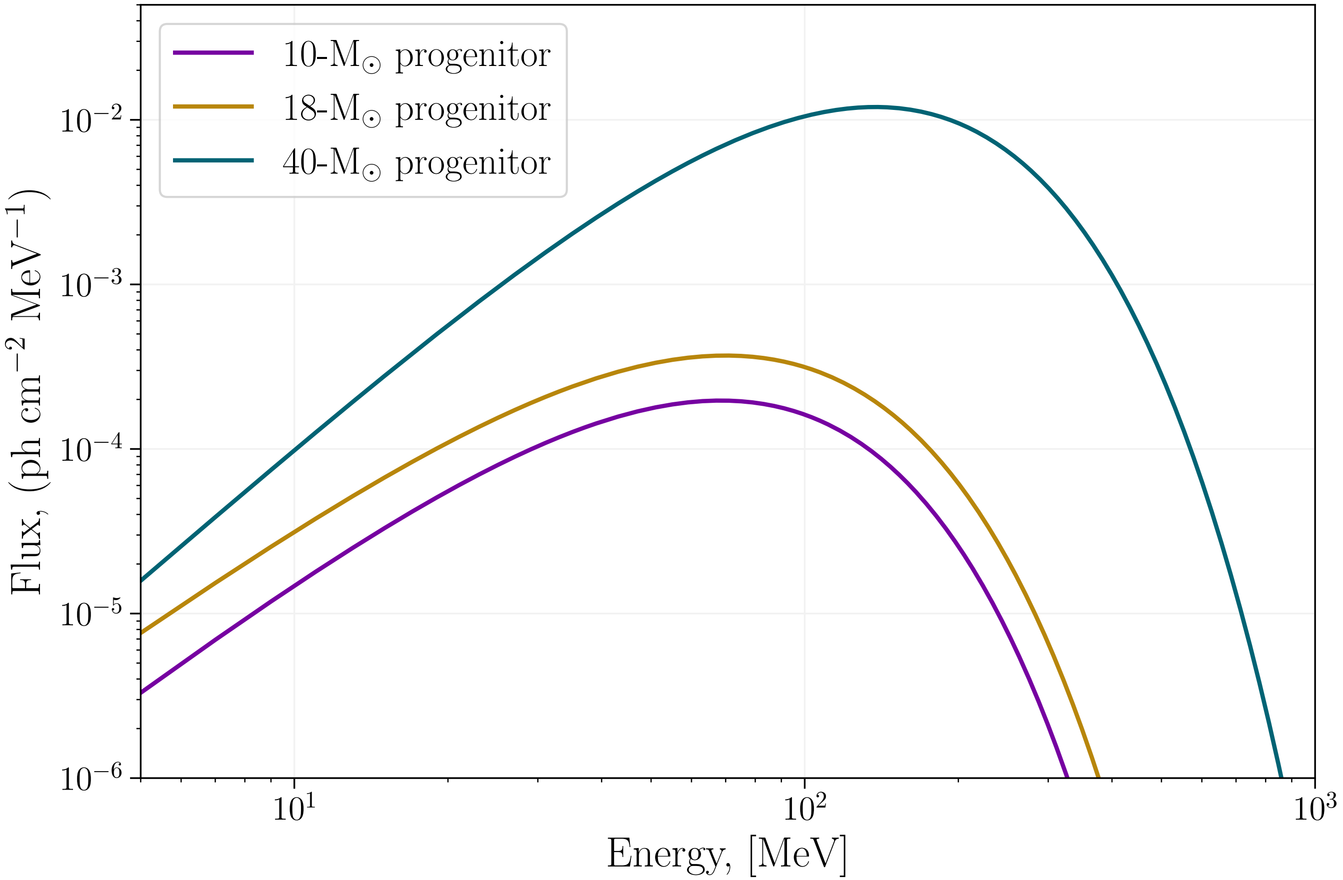
Galanti+ '24



Meyer+ '24

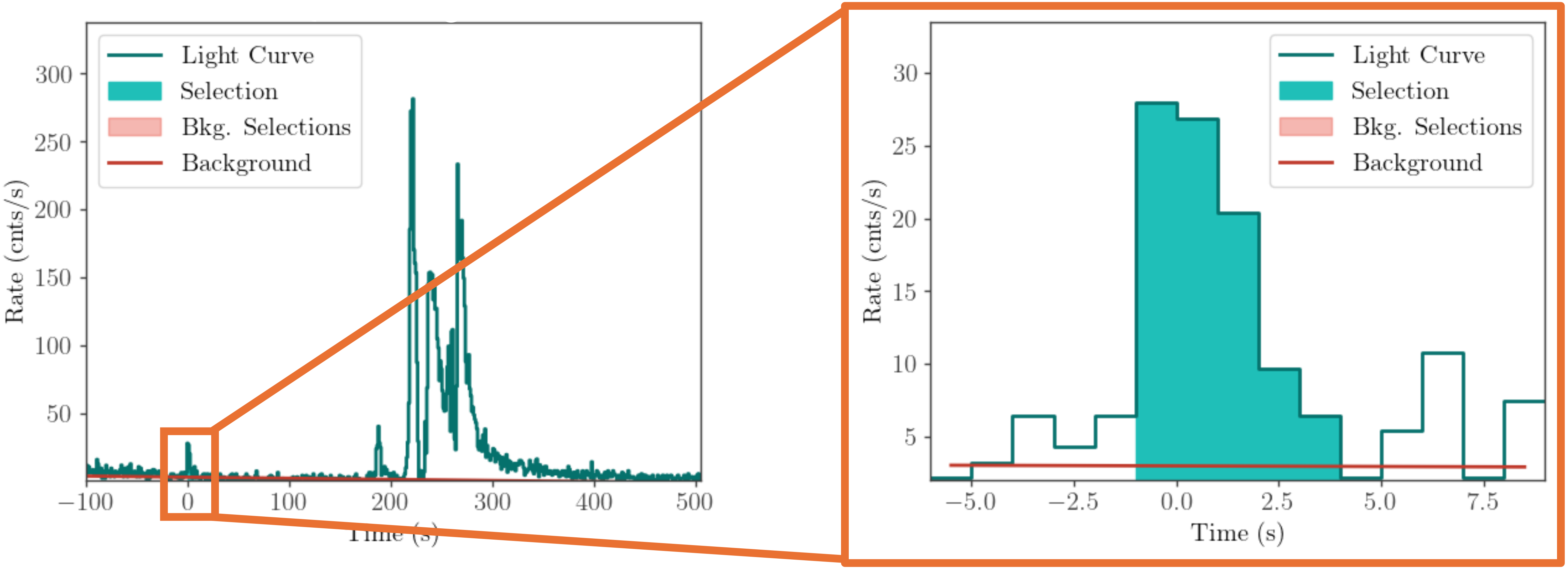


Honorable mention: GRB 221009A (BOAT)



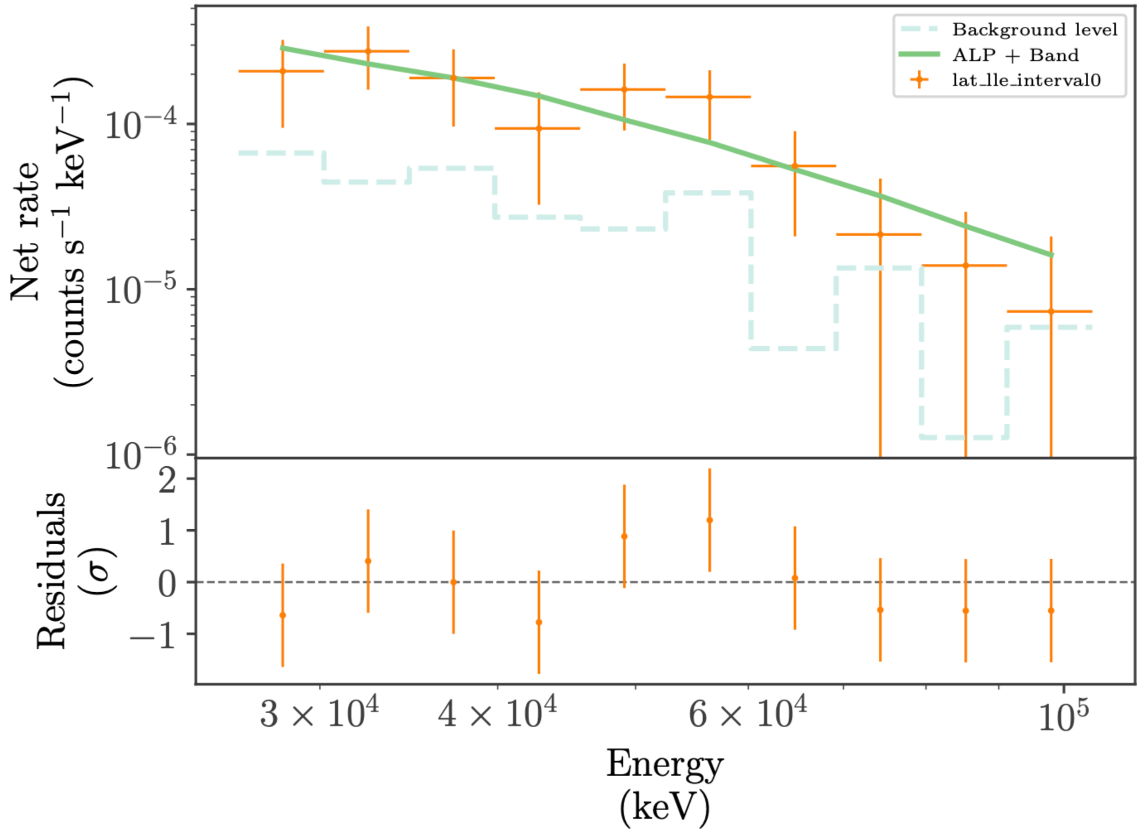
Light ALP emission from a CCSN

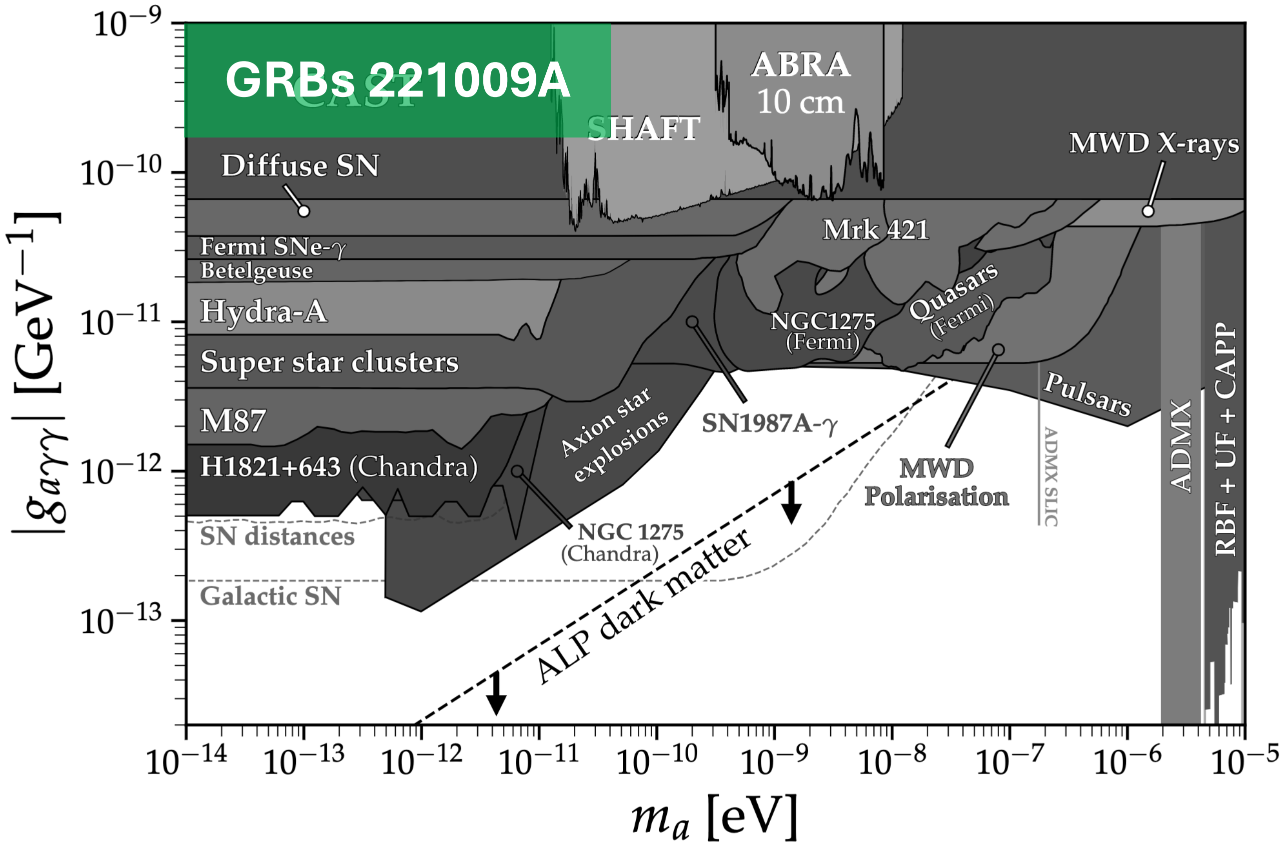
Honorable mention: GRB 221009A (BOAT)



Crnogorčević+ in prep

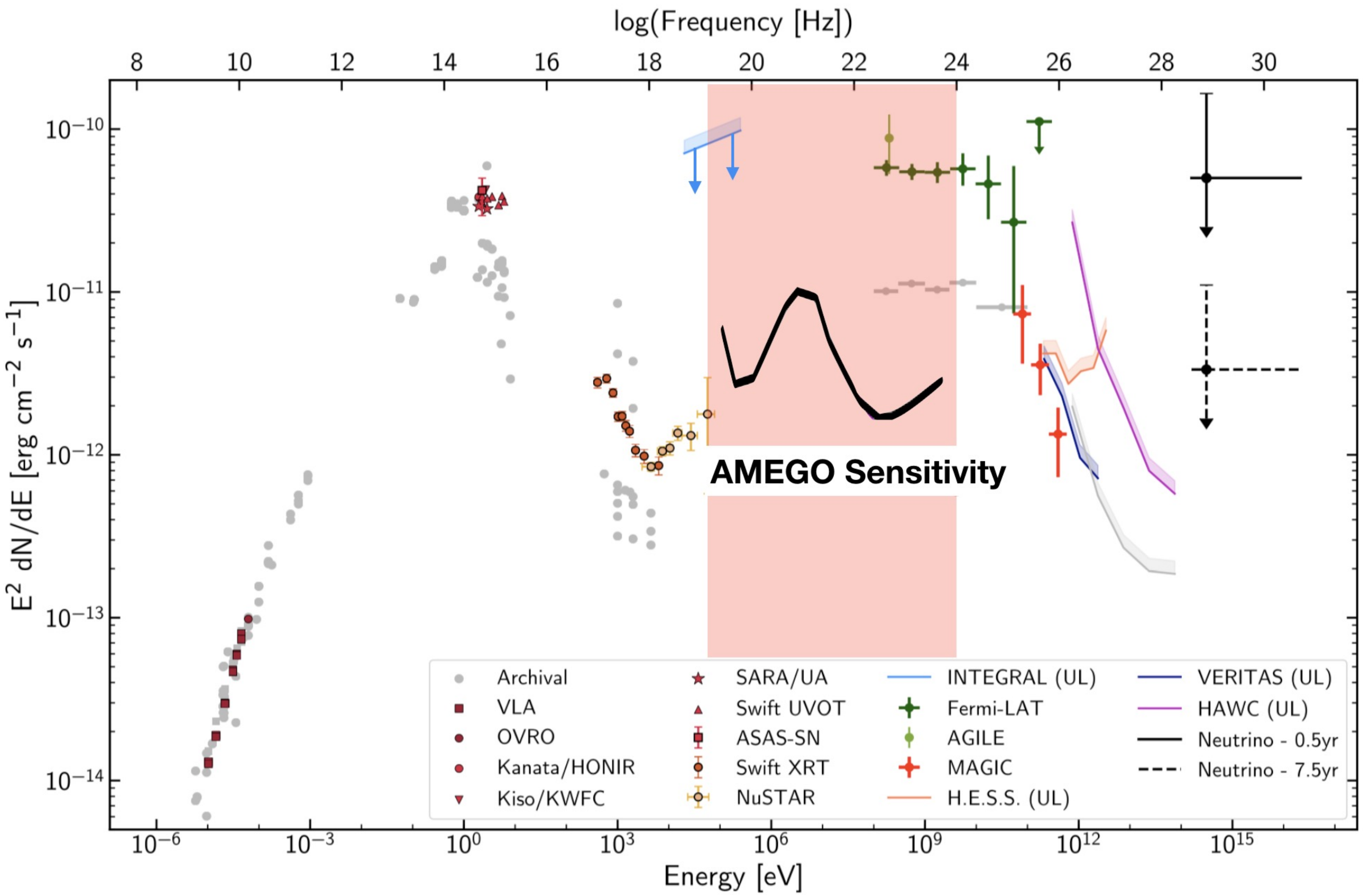
Honorable mention: GRB 221009A (BOAT)





Crnogorčević+ in prep

The MeV Gap



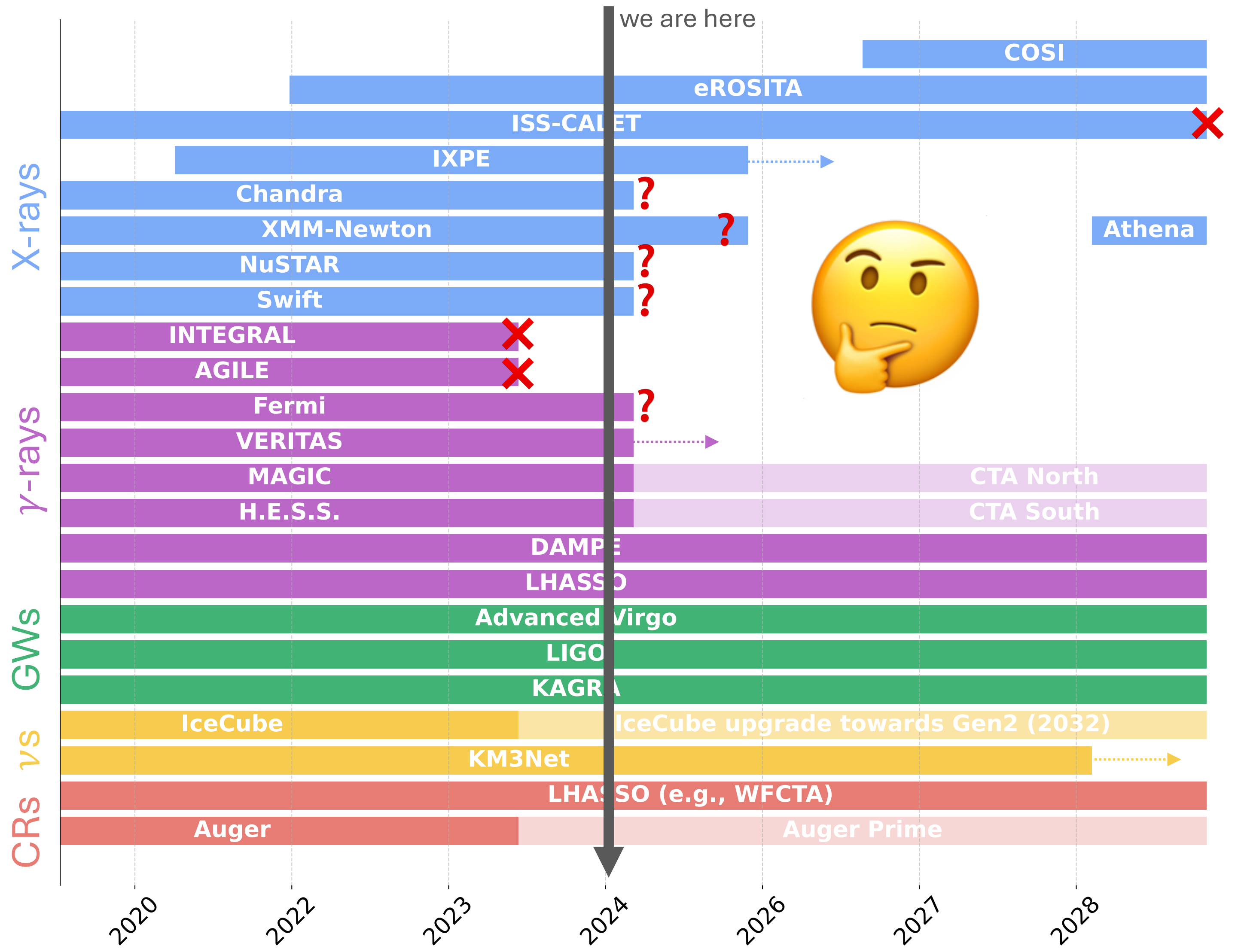
log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
AMEGO Sensitivity
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]

The future

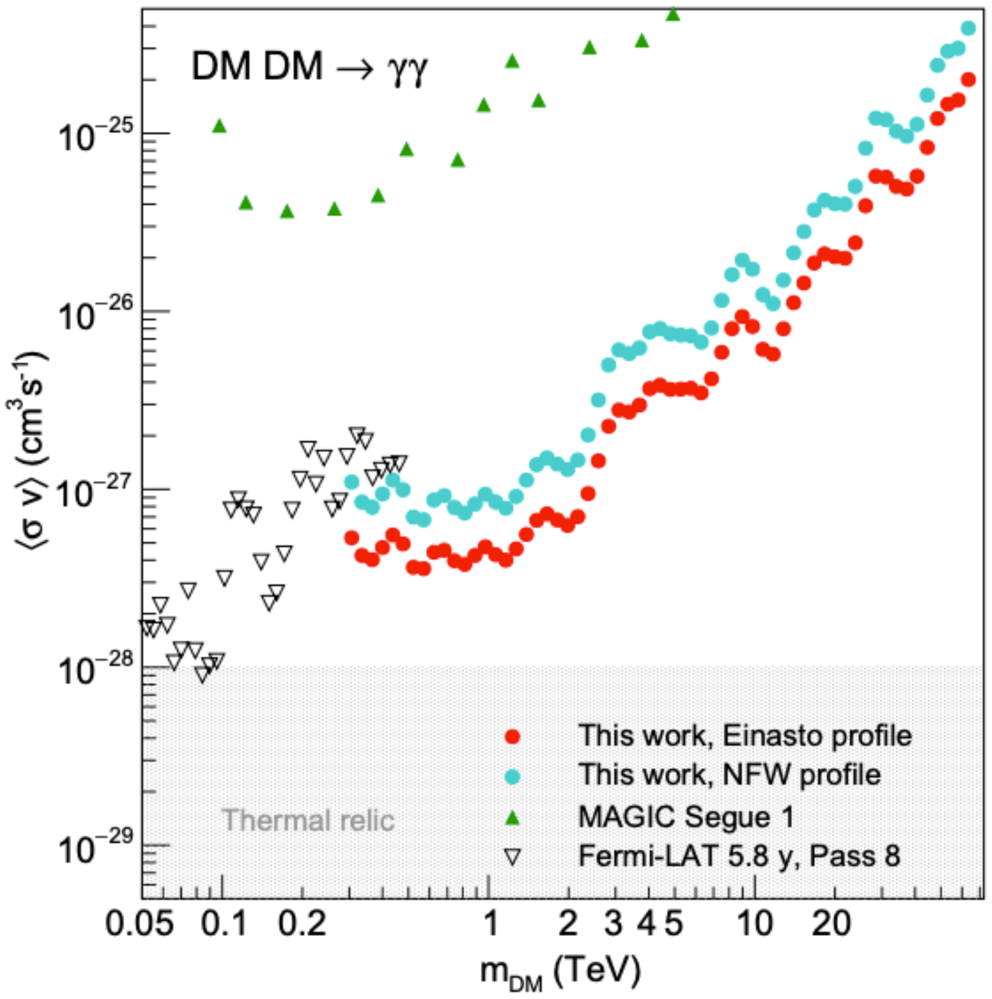
“Expecting to uncover dark matter in the next two decades is akin to waiting for a sunny Durham spring. Hopeful, yet perennially disappointed.”

ChatGPT, 2024

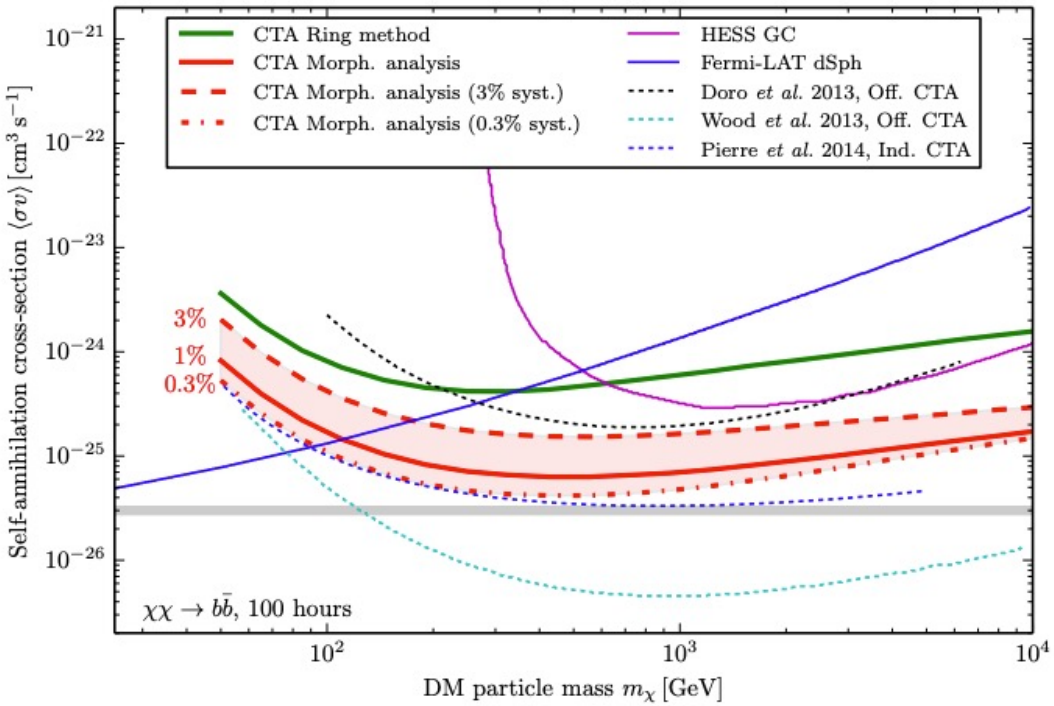
Dark Matter Landscape: An Instrumentationalist's View



GeV to TeV photons



- HESS: constraining results E > 1 TeV, challenging the TeV thermal DM
- HAWC is constraining limits from dSphs (> 1 TeV) and GC (> 100 TeV)
- CTA may improve HESS limits by 10x



Future Innovations in Gamma rays

Science Analysis Group

… to explore gamma-ray science priorities, necessary capabilities, new technologies, and theory/modeling needs drawing on the 2020 Decadal **to inspire work toward 2040.**

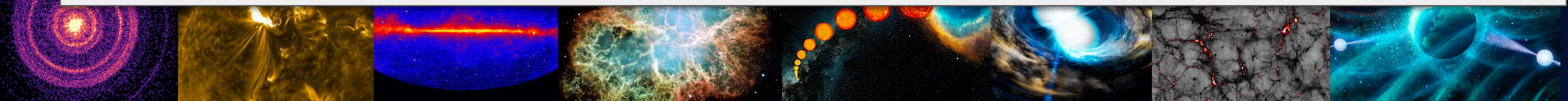


FIG-SAG

FIG SAG Terms of Reference

1. Gamma-ray Science Priorities: Identify opportunities uniquely afforded by gamma-ray observations.
2. Gamma-ray Mission Capabilities: Which science objectives are only done or best done by space-based gamma-ray missions, considering the current missions in extended operation and funded missions in development.
3. Technology Investment: What new technologies/methodologies exist and what is needed to achieve the science priorities.
4. Theory and Analysis Needs: What advances do we need to make in theory and analysis to achieve the science priorities.
5. Synergies with Other Programs: How do these goals tie to the broader astrophysics and physics community. What are the timelines to align with current priorities in multi-messenger astronomy.

Conclusions

- Gamma-ray observations provide unique tests for different dark matter models
- Indirect detection provides stringent constraints competitive with direct-measurement experiments
- Future experiment development is crucial in understanding the classical astrophysical backgrounds, allowing us to search for new physics signals
- Our next space gamma-ray experiment is uncertain---join FIG SAG to make a strong case to funding agencies