The Dark Matters of the Universe

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Sydney-CPPC Seminar Series
February 6, 2025

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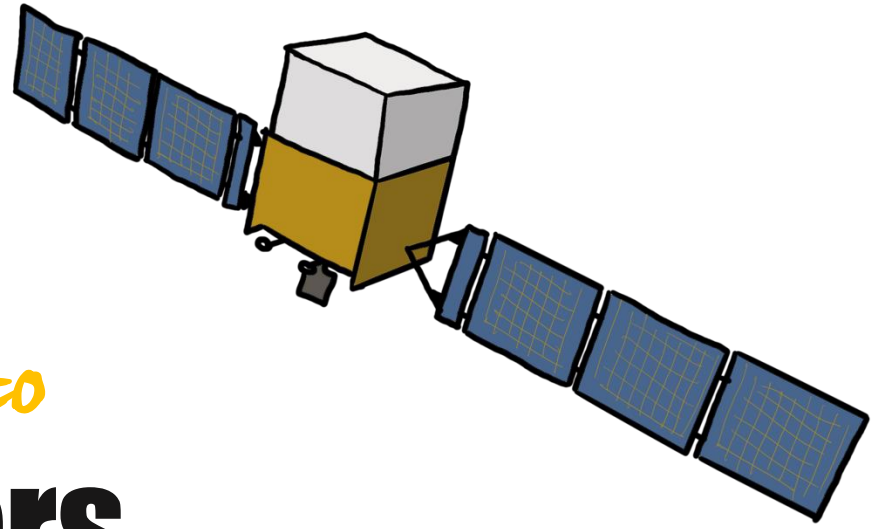

A γ-ray Window into

The Dark Matters of the Universe

Establishing Fermi-LAT's Legacy

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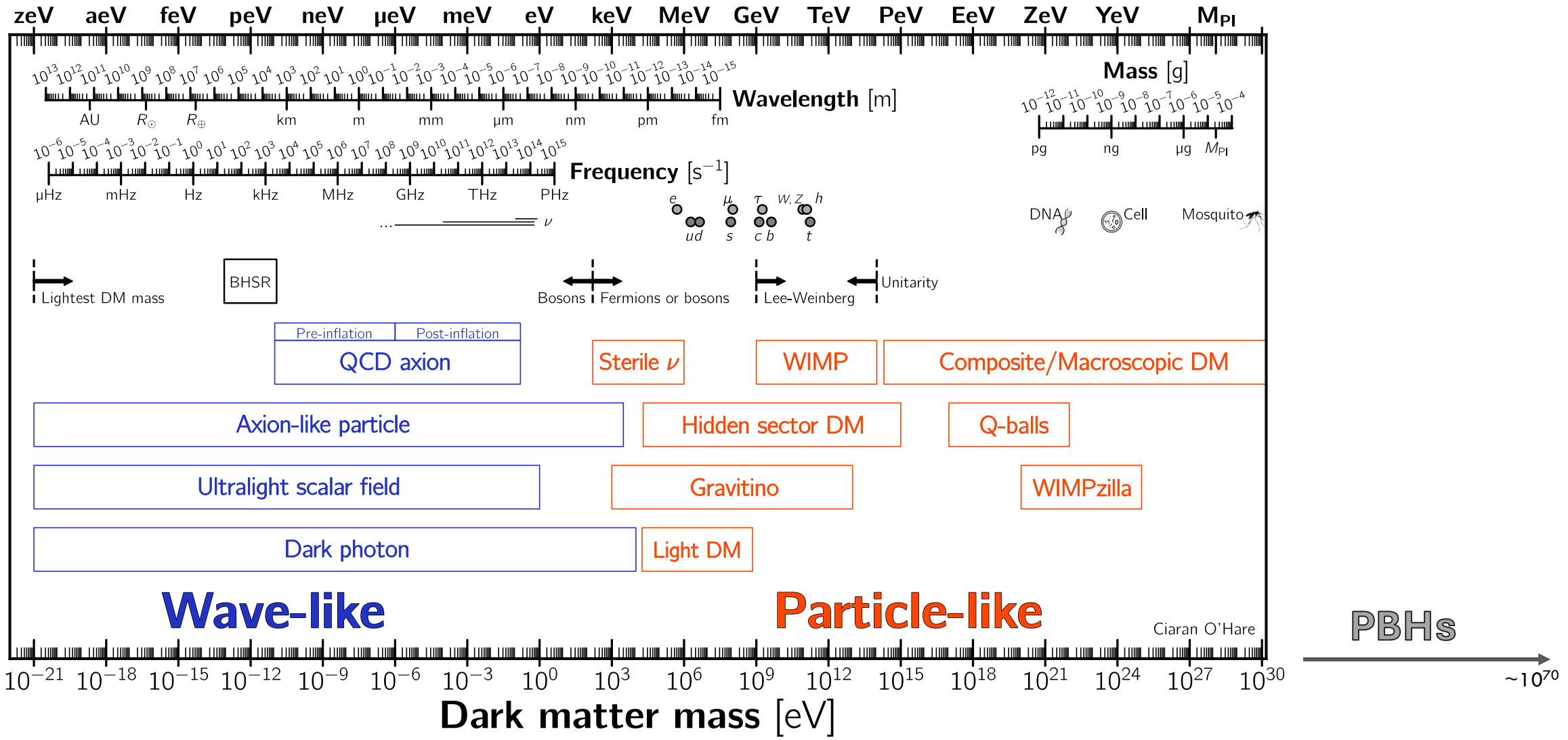
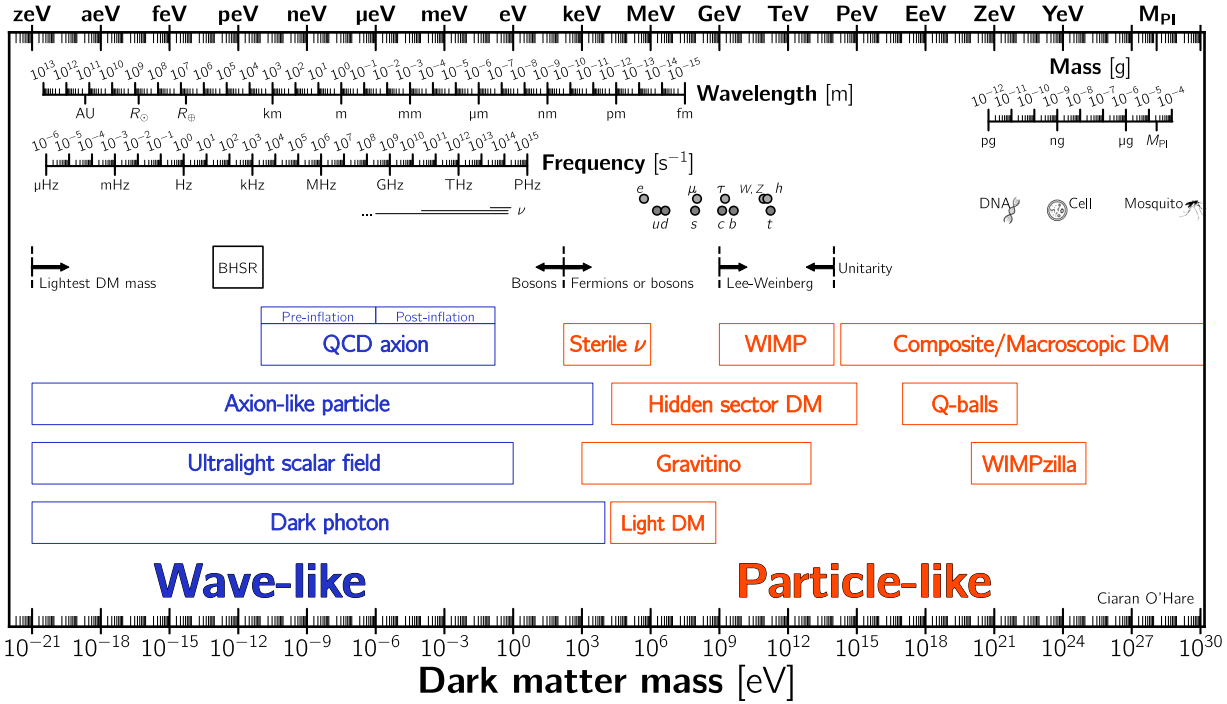
Dark Matter Landscape: A Theorist's View



[Ciaran A. J

Dark Matter Landscape: A Theorist's View



[Ciaran A. J. O'Hare]

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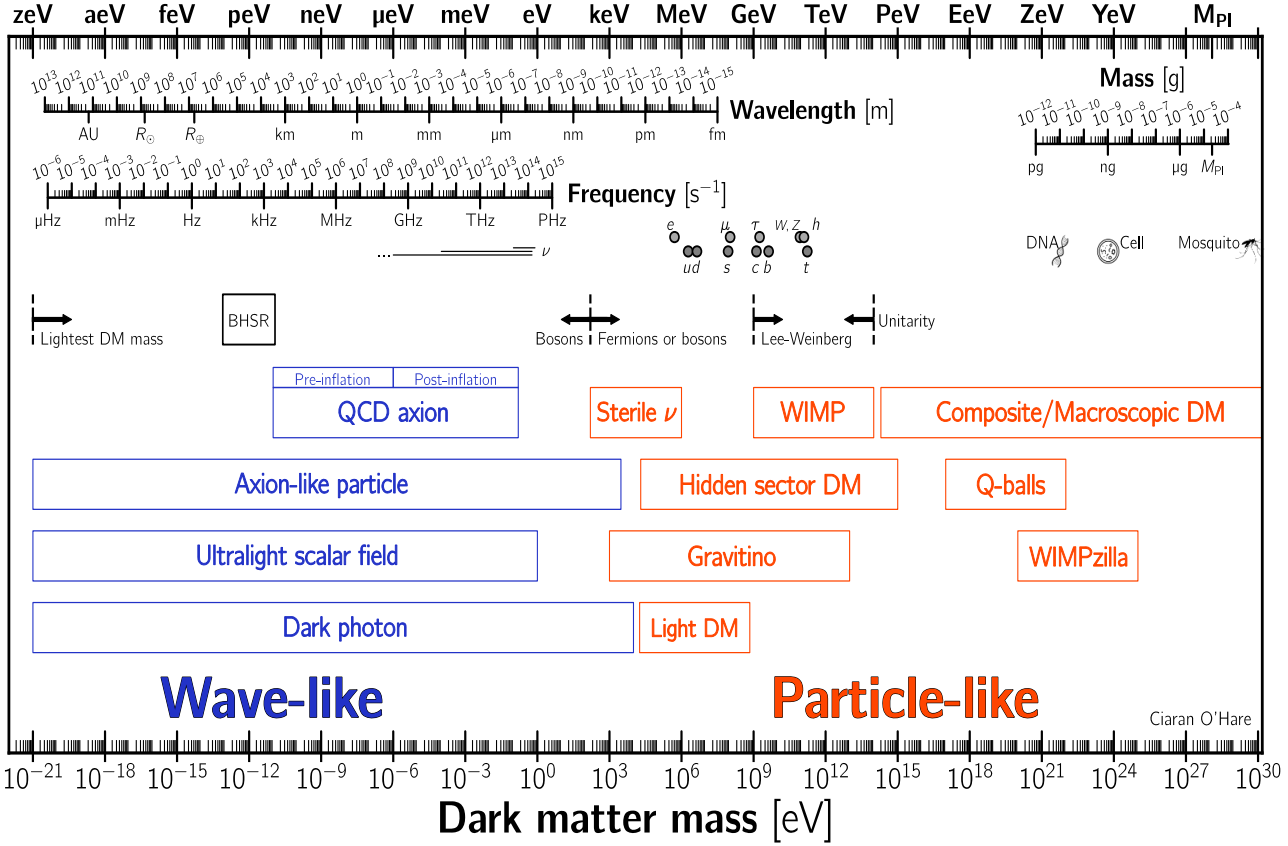


DM candidates with a range of properties

…we are biased in our search strategies:

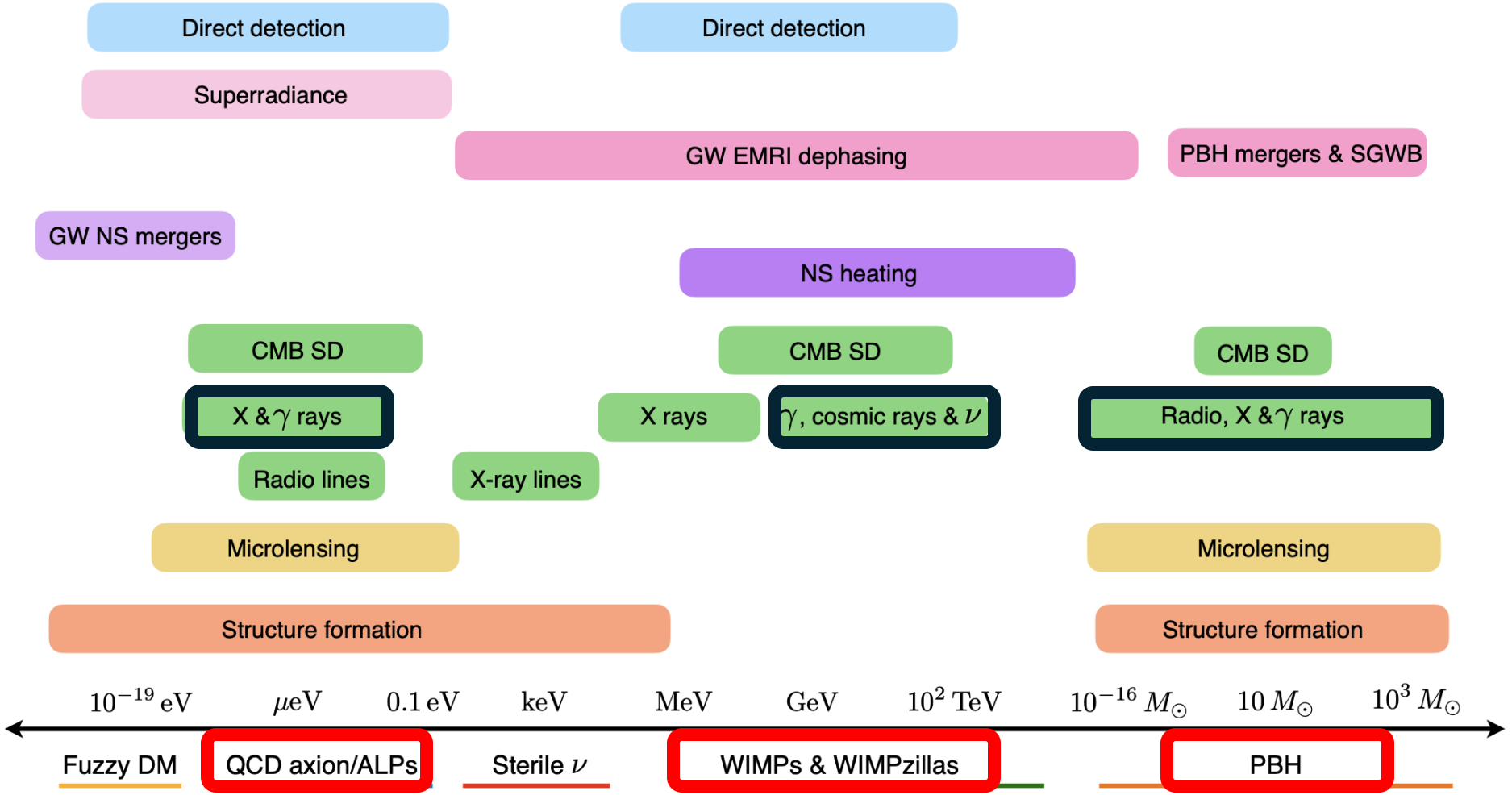
- Observable signatures
- Data availability
- Model dependency

PBHs

$\sim 10^{70}$

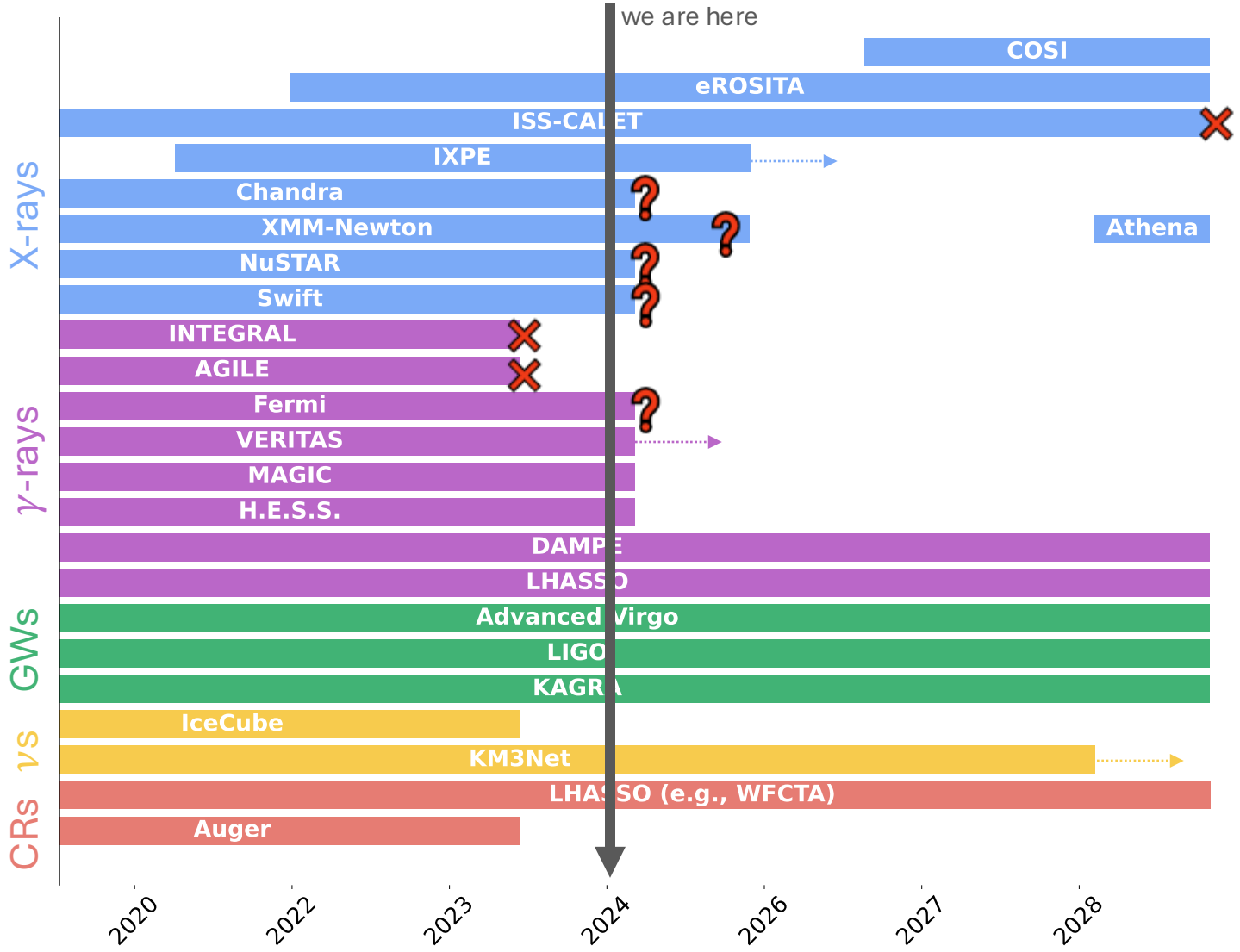
[Ciaran A. J. O'Hare]

Dark Matter Landscape: An Observer's View



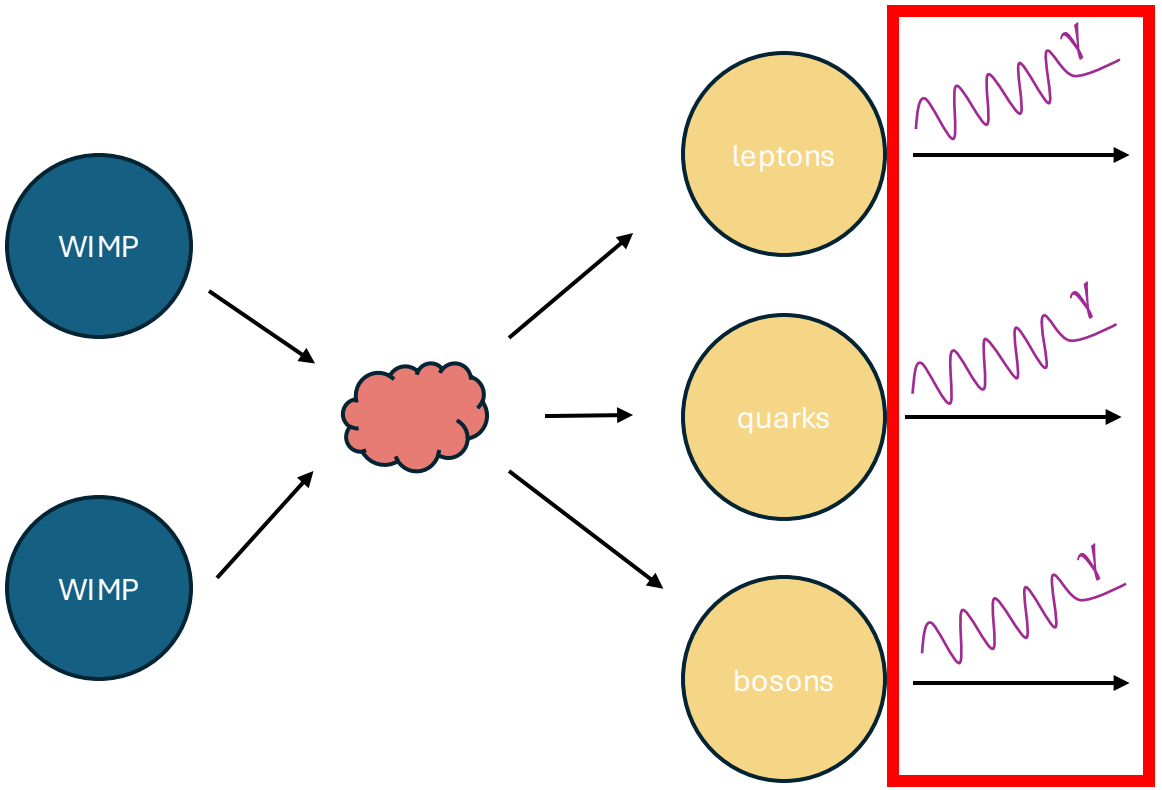
[EuCAPT WhitePaper, 2021]

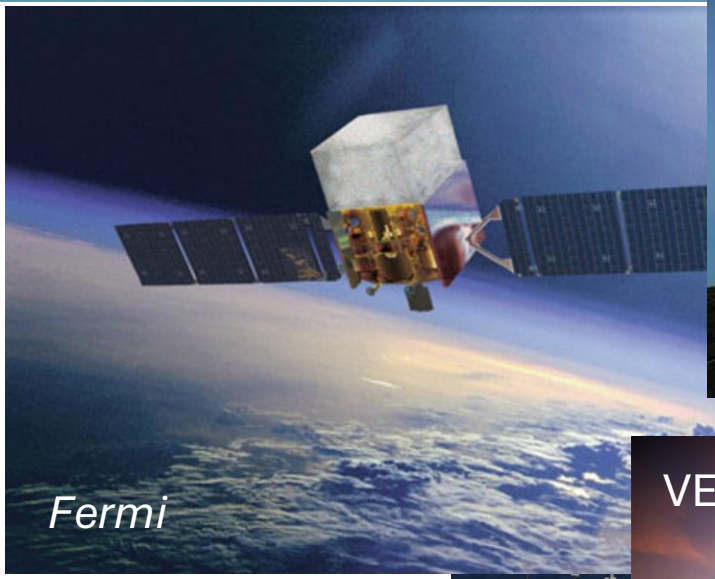
Dark Matter Landscape: An Instrumentationalist's View

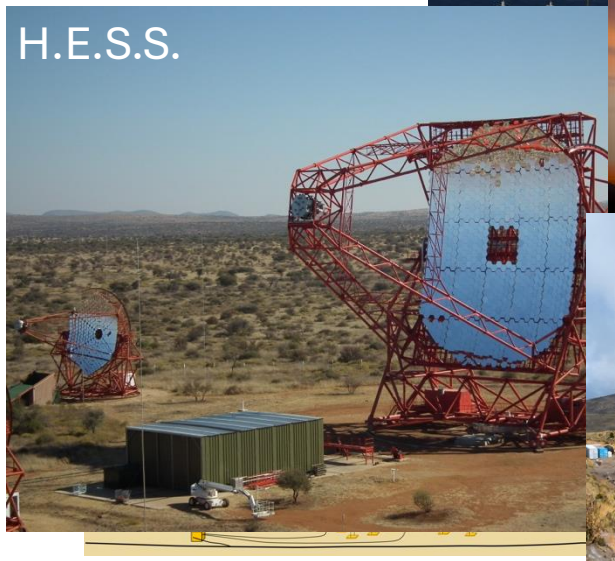


BEYOND&WIMPs

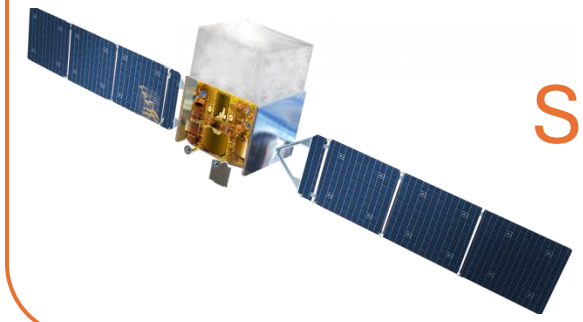
Dark Matter Landscape: An Observer's View







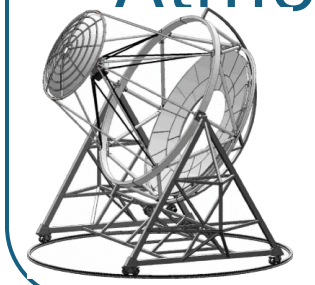
Dark Matter Landscape: An Instrumentationalist's View



Satellite

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

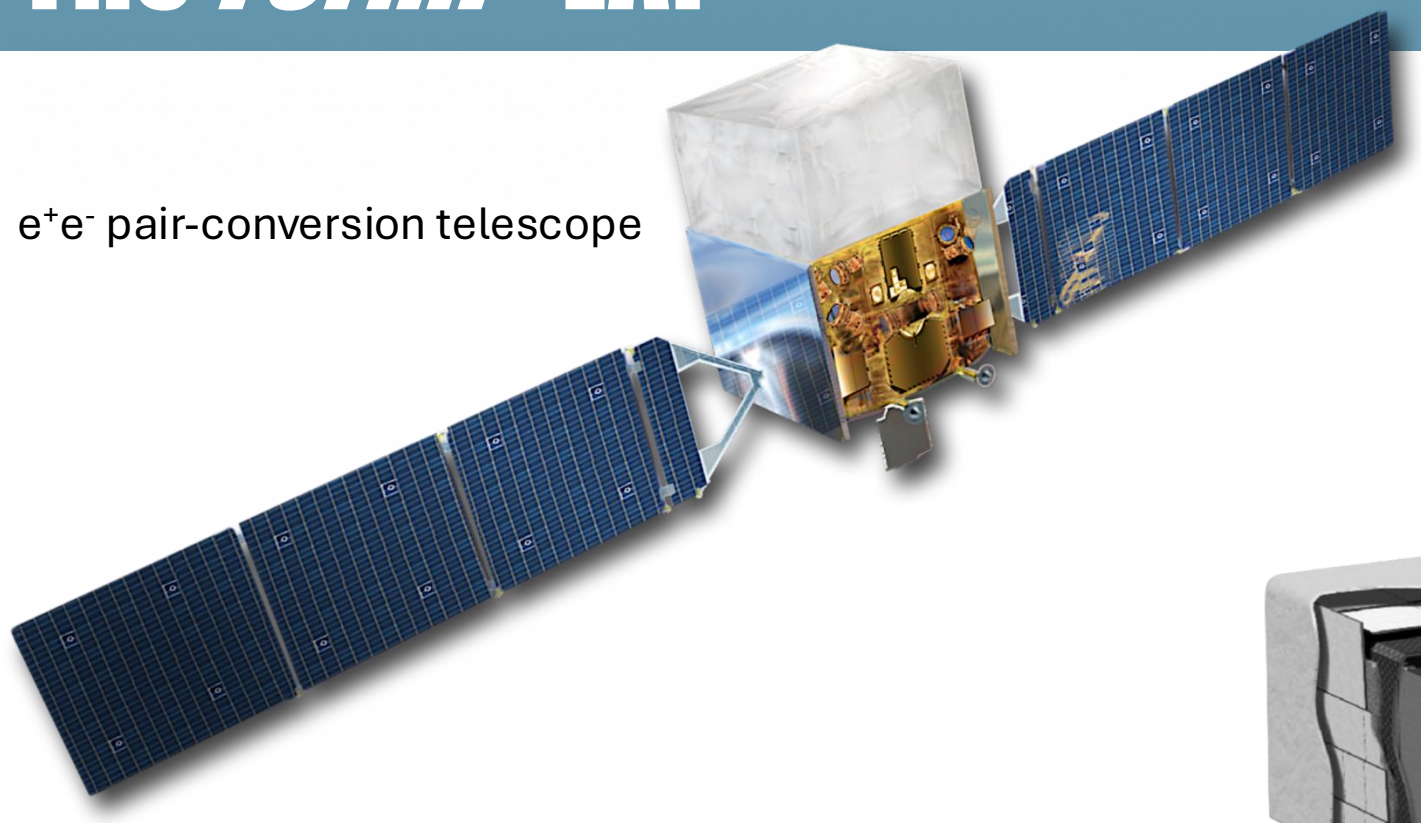
Atmospheric/water Cherenkov Telescopes

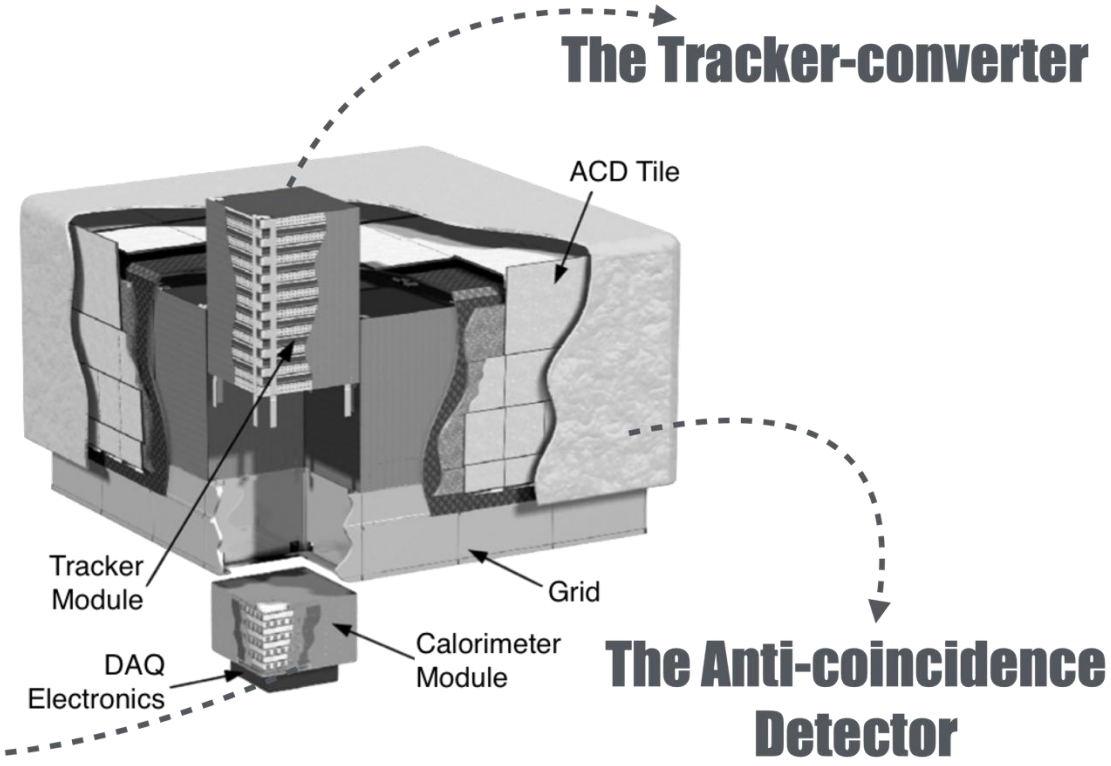


- VERITAS, MAGIC, HESS, HAWC
- Atmosphere/water = calorimeter, particle showers

The *Fermi*-LAT

e^+e^- pair-conversion telescope



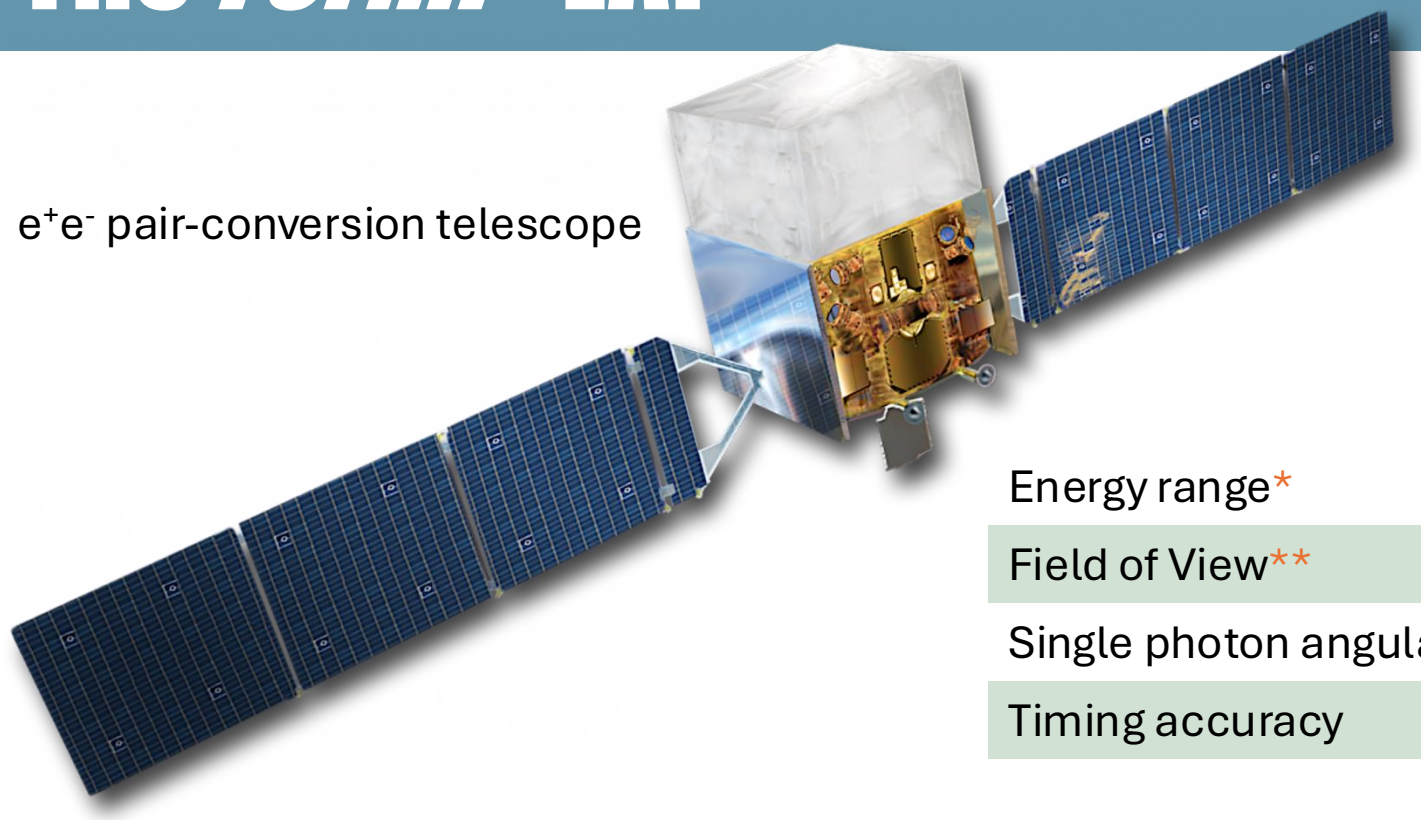


individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

...it also detects electrons.

The *Fermi*-LAT

e^+e^- pair-conversion telescope



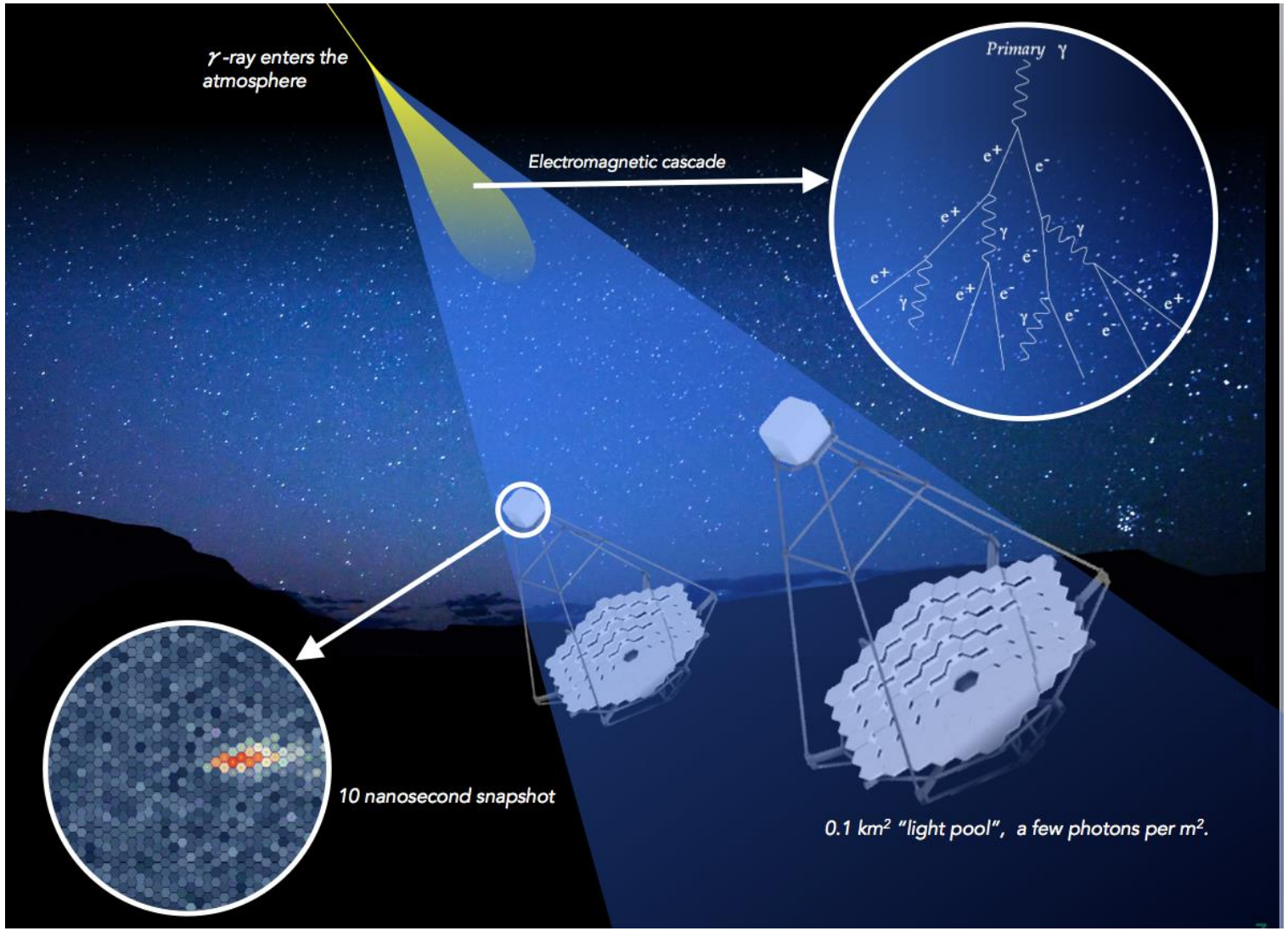
Energy range*	20 MeV to > 300 GeV
Field of View**	2.4 sr (~1/5 of the whole sky)
Single photon angular resolution***	< 1 deg at 1 GeV
Timing accuracy	1 microsecond

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

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

...it also detects electrons.

Cherenkov Telescopes



+LHAASO

+ LHAASO

Energy coverage

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

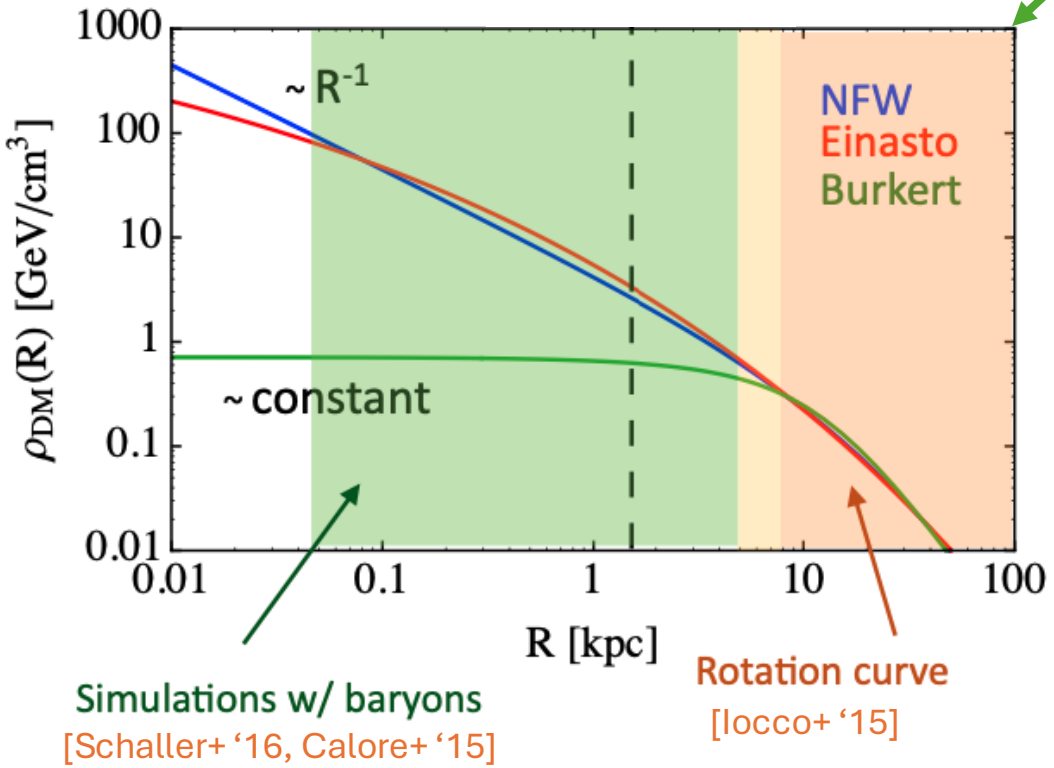
MeV GeV TeV

Adapted from Celina Armand TeVPA '22 talk.

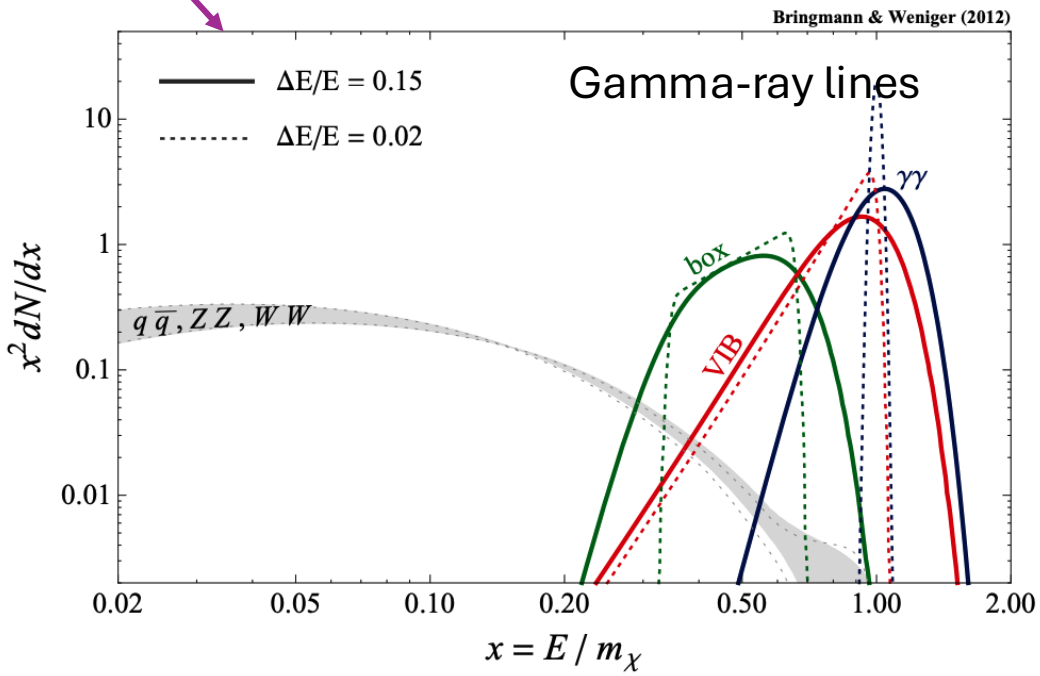
Dark Matter Signal

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

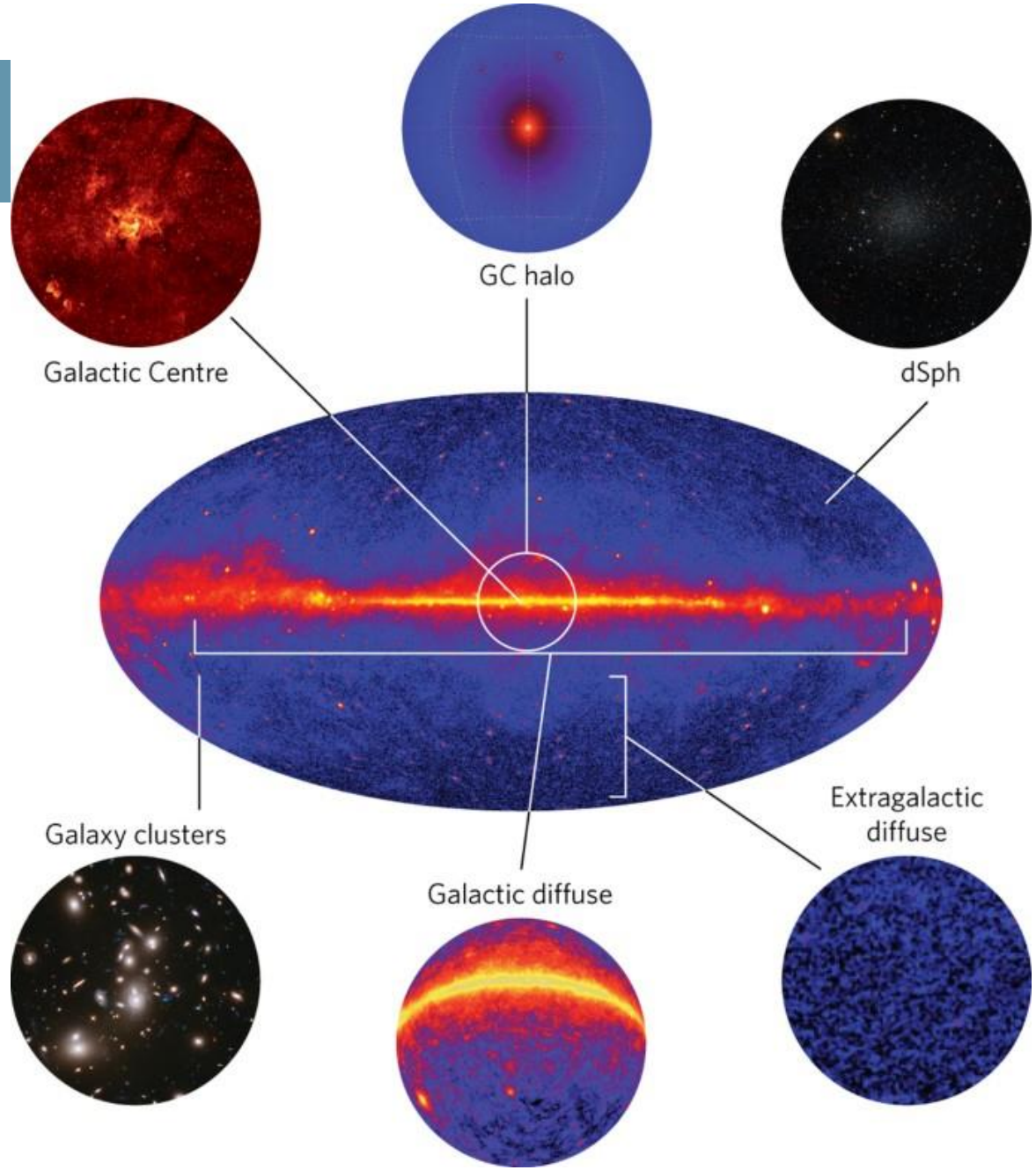
DM γ-ray flux = astrophysics J-factor x particle physics



Adapted from F. Calore.

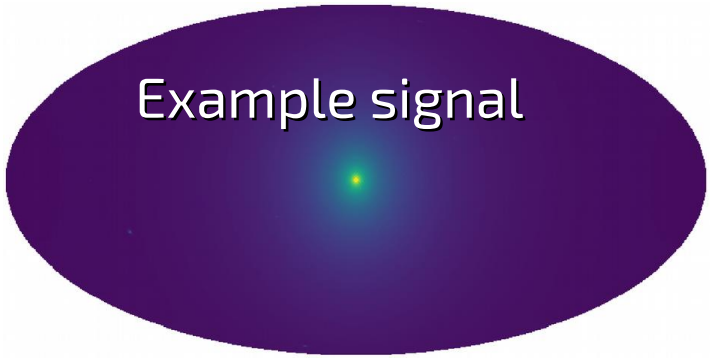


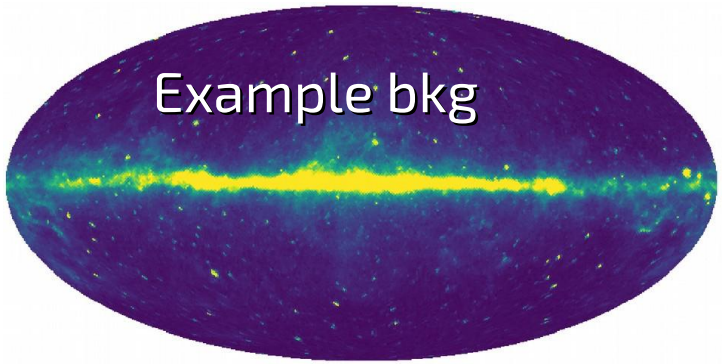
DM targets

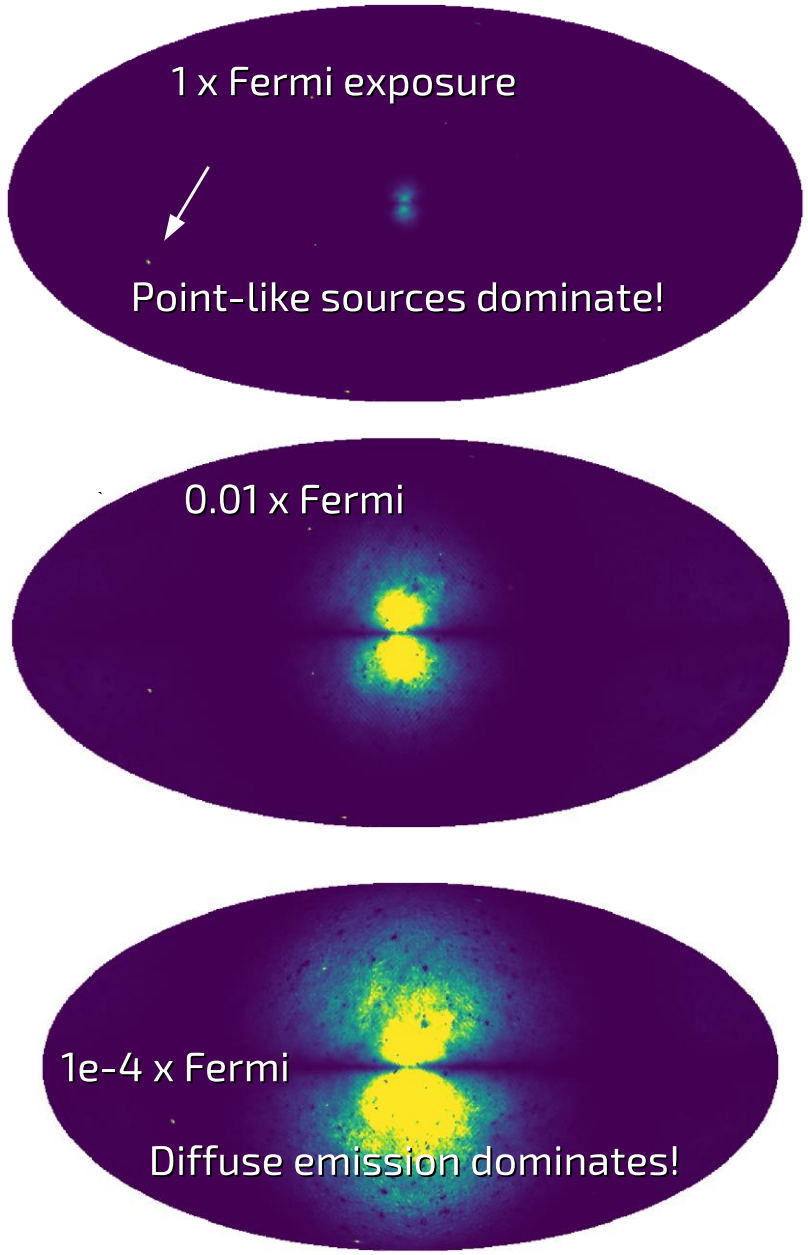


[Conrad & Reimer 2017]

Signal in *Fermi*-LAT



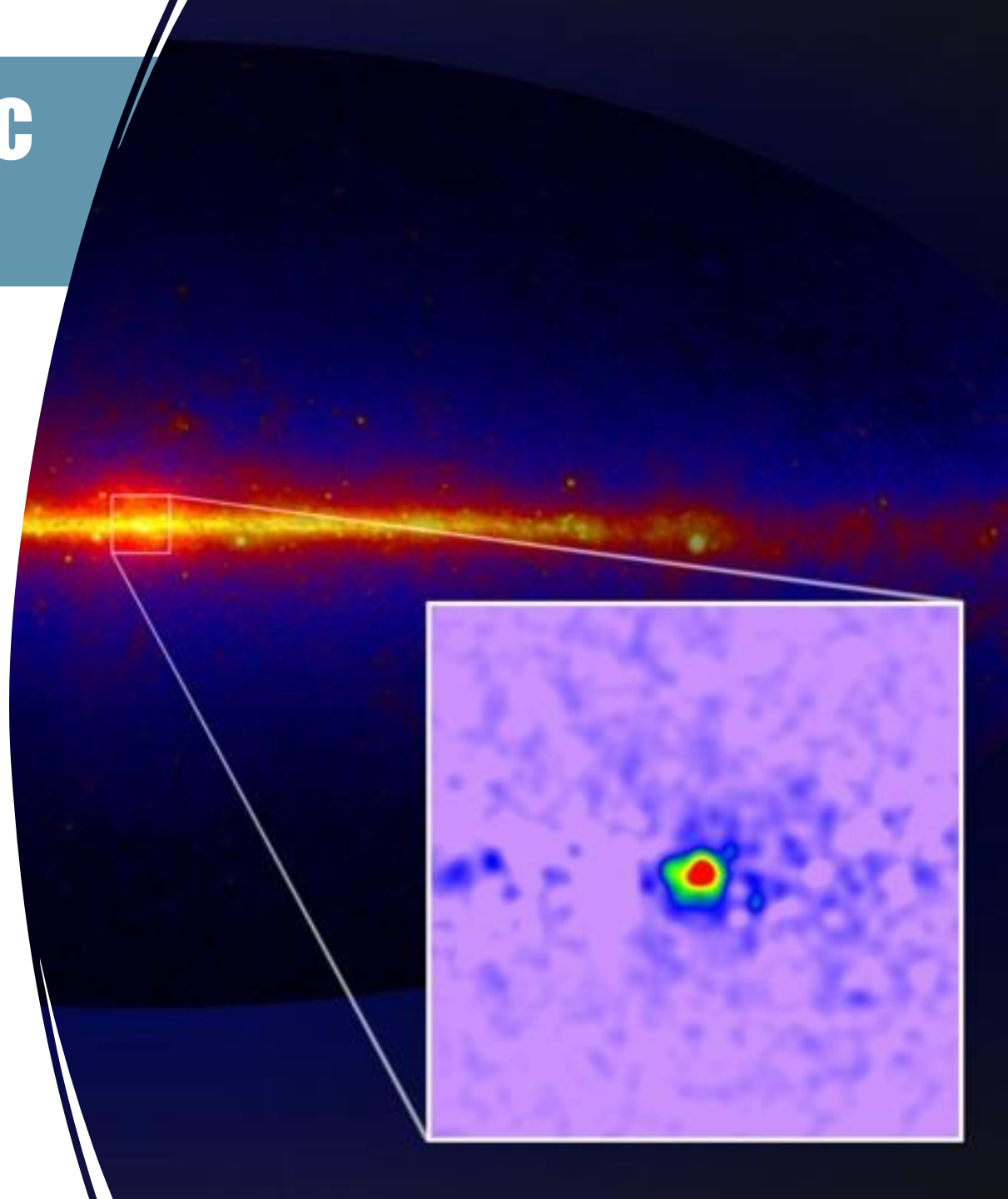




[Adapted from the *Fermi* Summer School]

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)



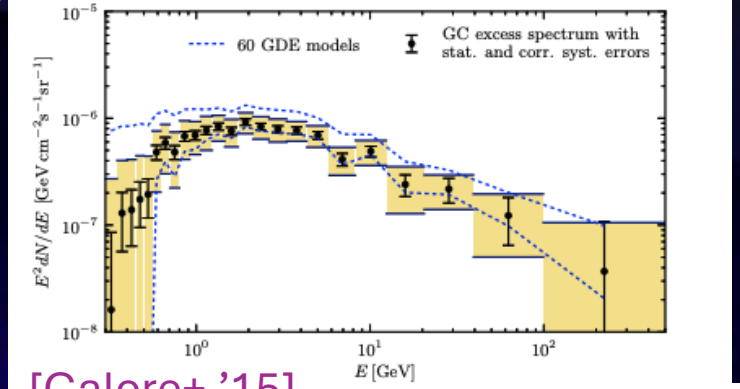
Hooper, Goodenough (2009, 2010) Hooper, Linden (2011)
Abazajian, Kaplinghat (2012) Gordon, Macias (2013) Daylan, et al. (2014)
Calore, Cholis, Weniger (2014) Murgia, et al. (2015) Ackermann et al. (2017)

Gamma rays from the Galactic Center

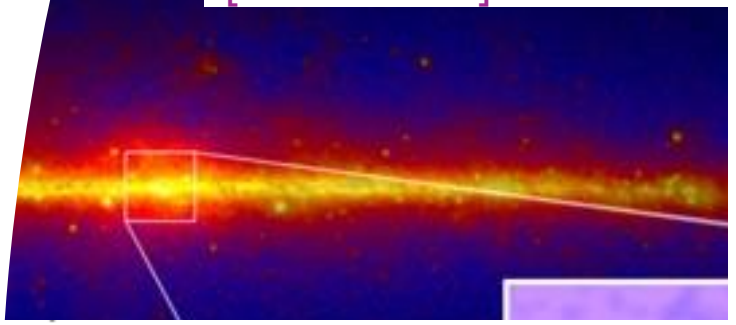
- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT
- Extended emission up to ~10 degrees (1.5 kpc)

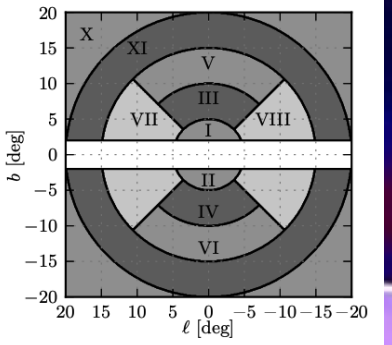
Maybe Dark Matter.

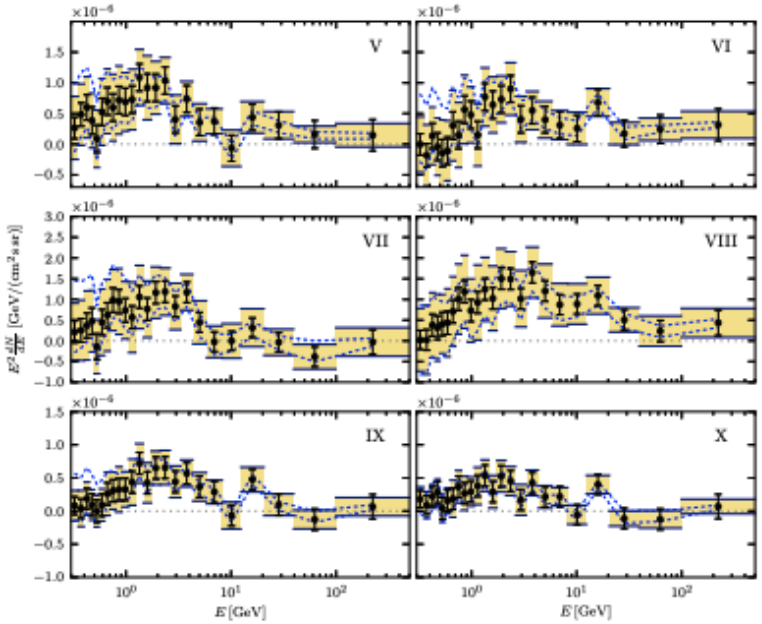
- Morphology approximately spherical, extending far out of the center
- Intensity well-fit by thermal particle dark matter
- Spectrum seemingly invariant with position and shape

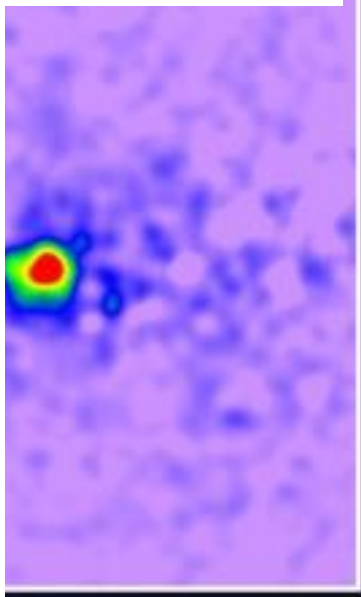


[Calore+ ’15]







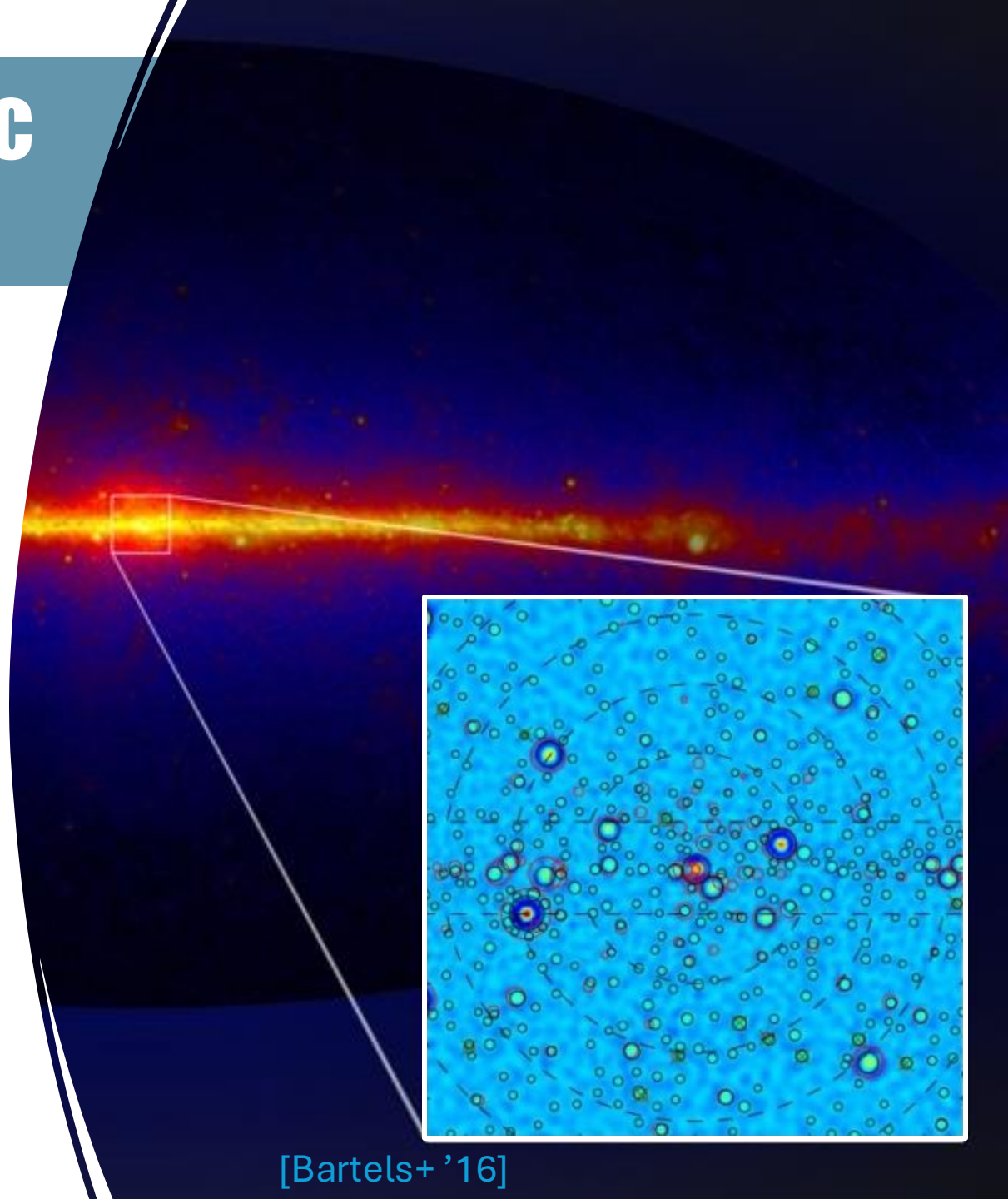


Gamma rays from the Galactic Center

- 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]

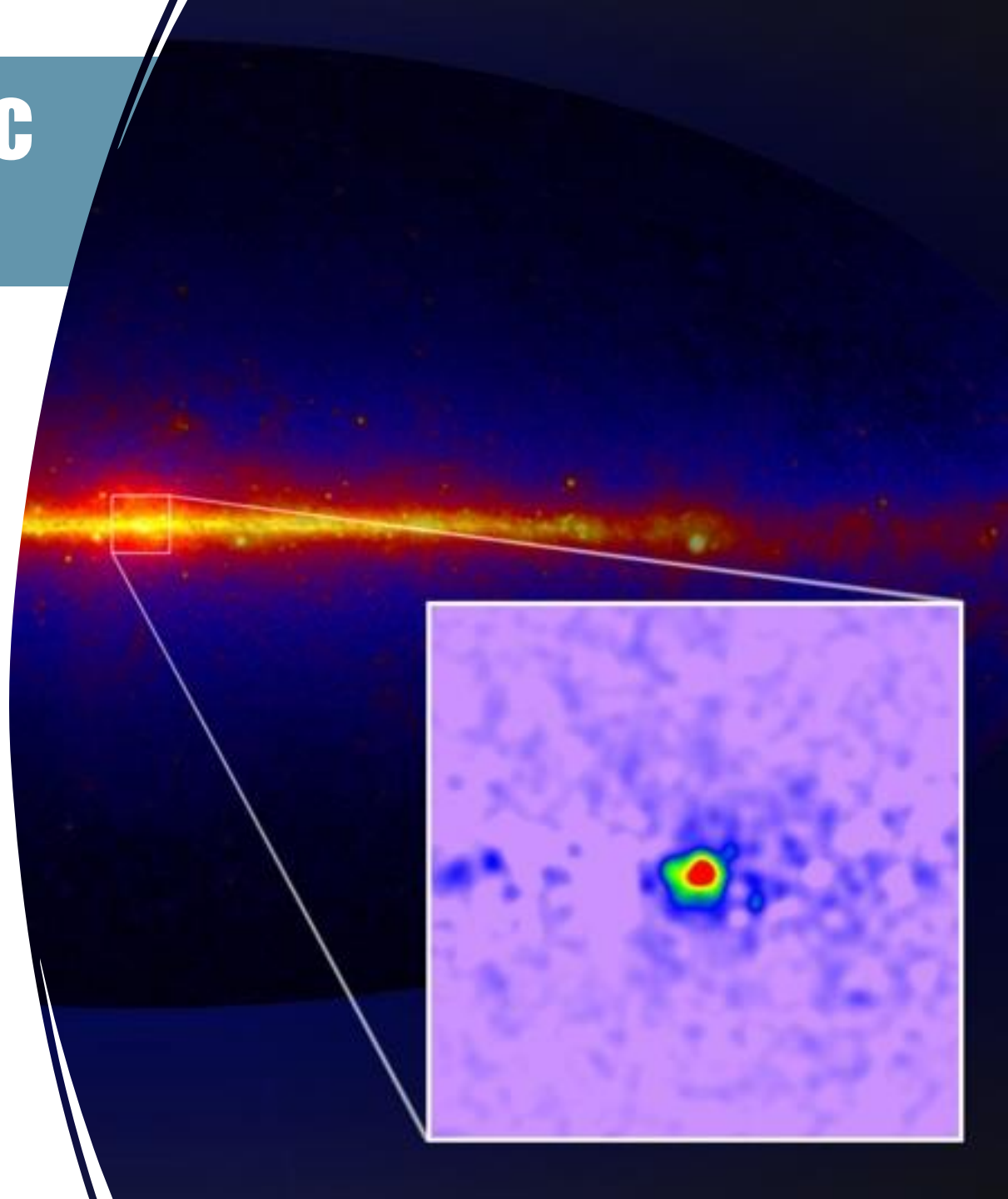
Gamma rays from the Galactic Center

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?*

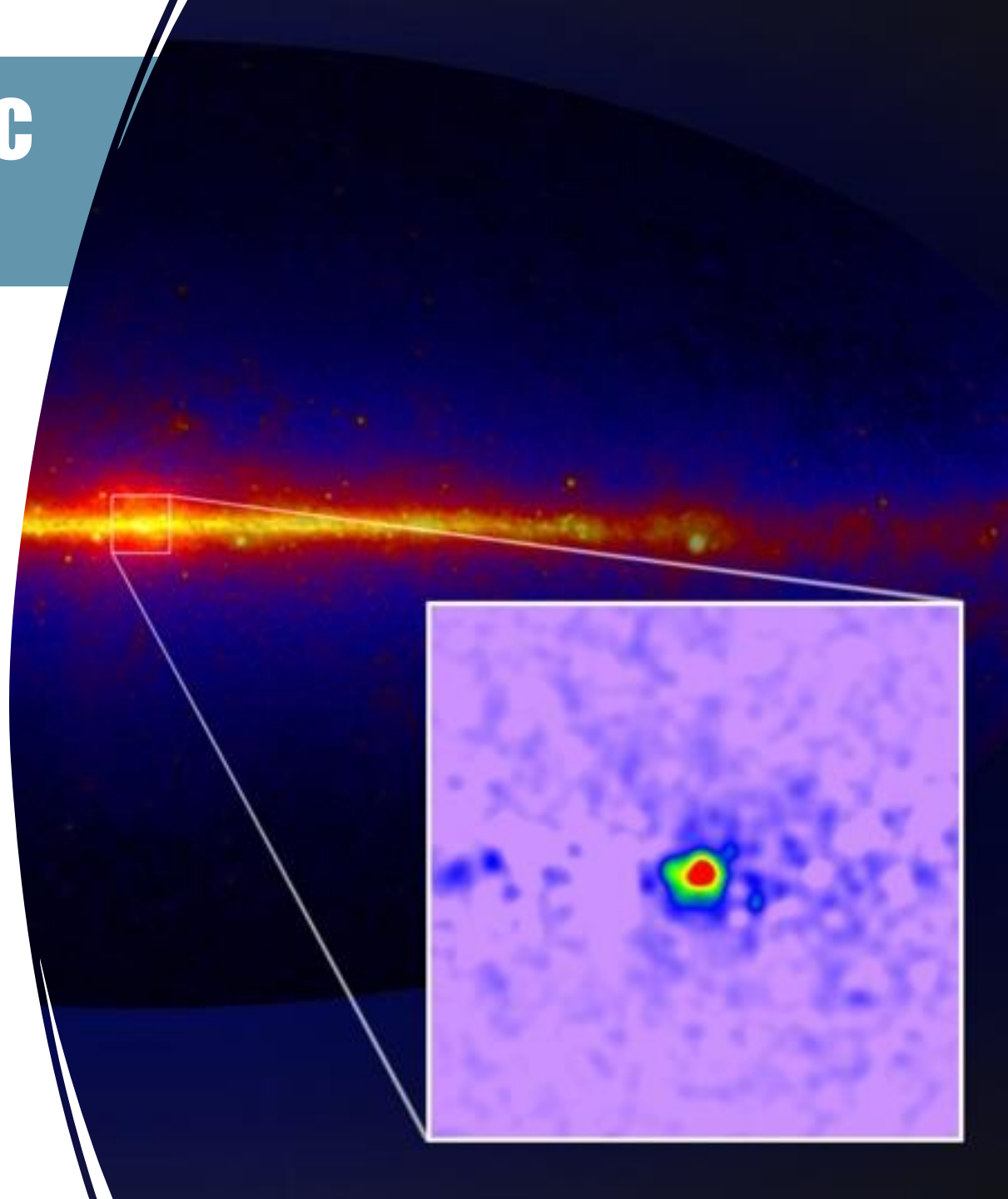


Gamma rays from the Galactic Center

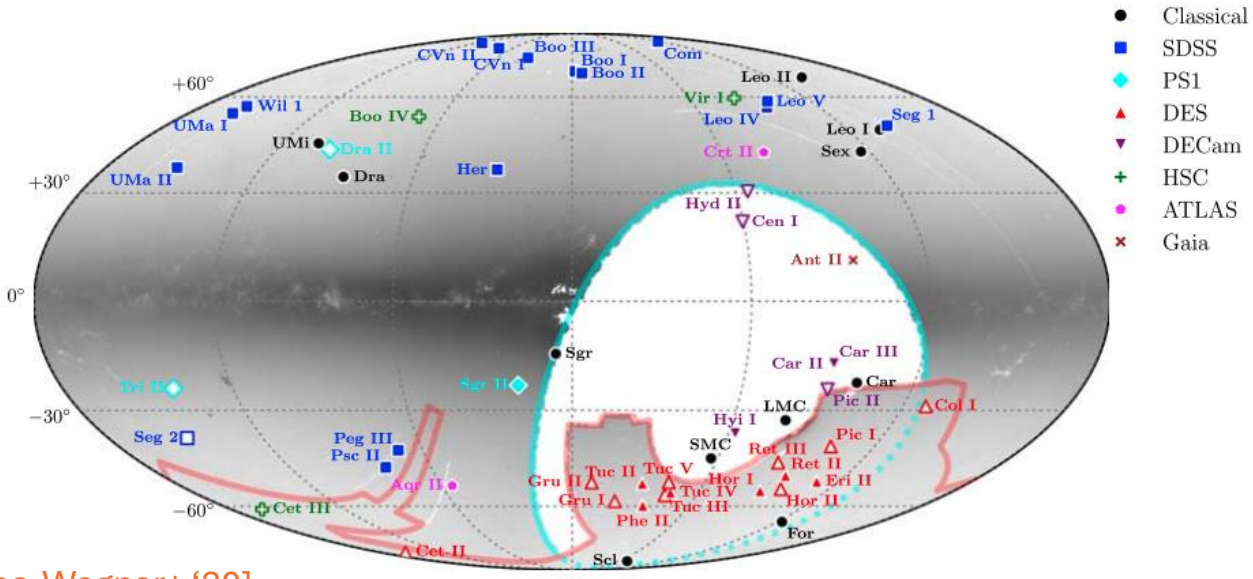
Where now?

[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

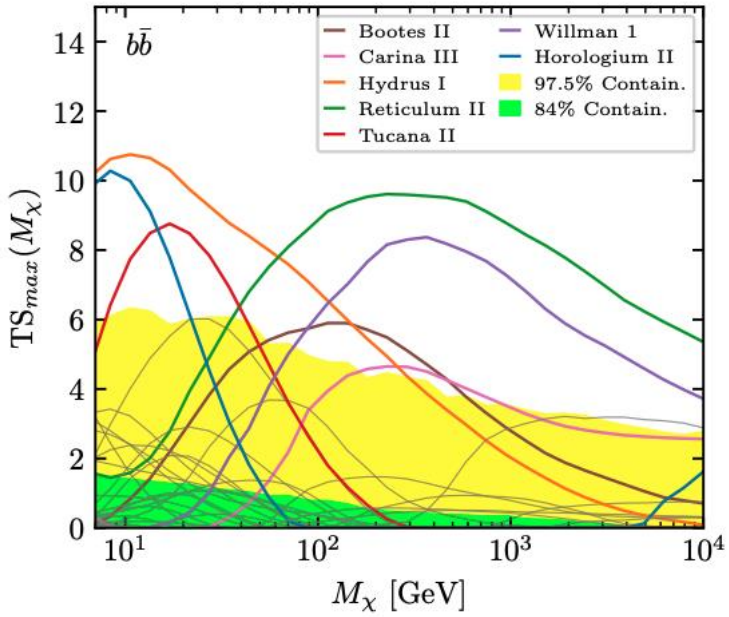


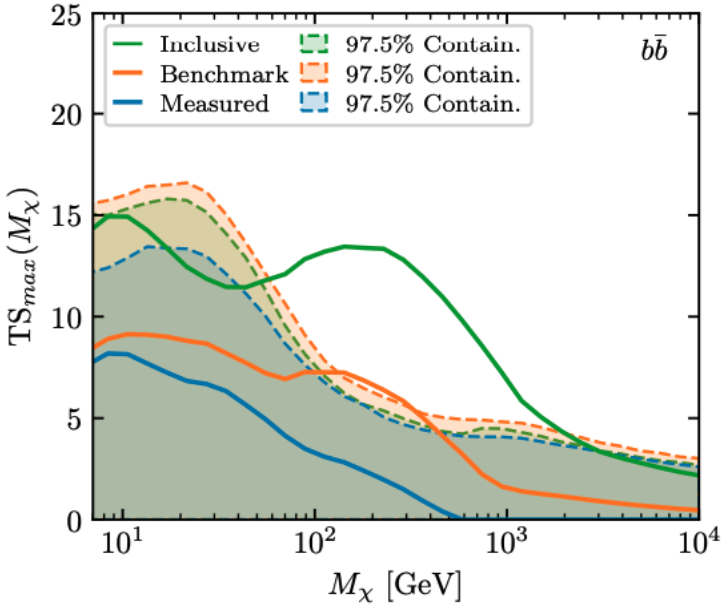
Dwarf Spheroidal Galaxies



[Drlica-Wagner+ ‘20]

[McDaniel+ LAT ‘24]



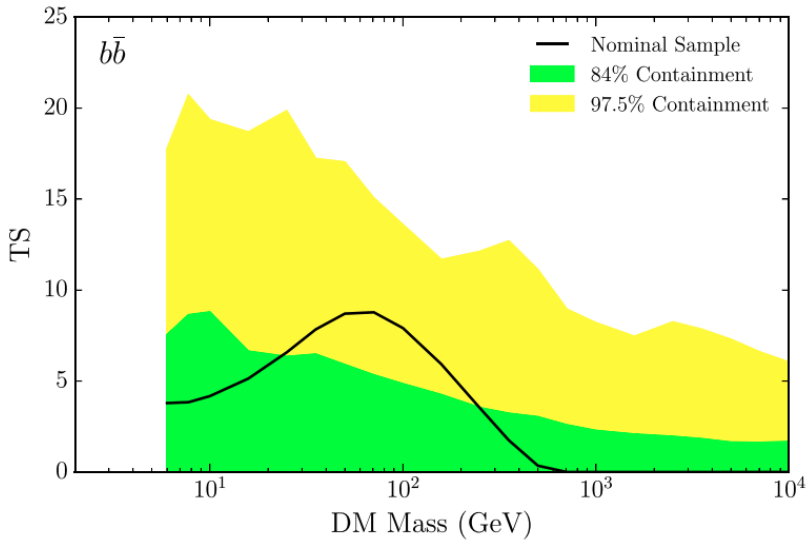


DM γ-ray flux = astrophysics J-factor x particle physics

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

Combined dSph Analyses - Comparison

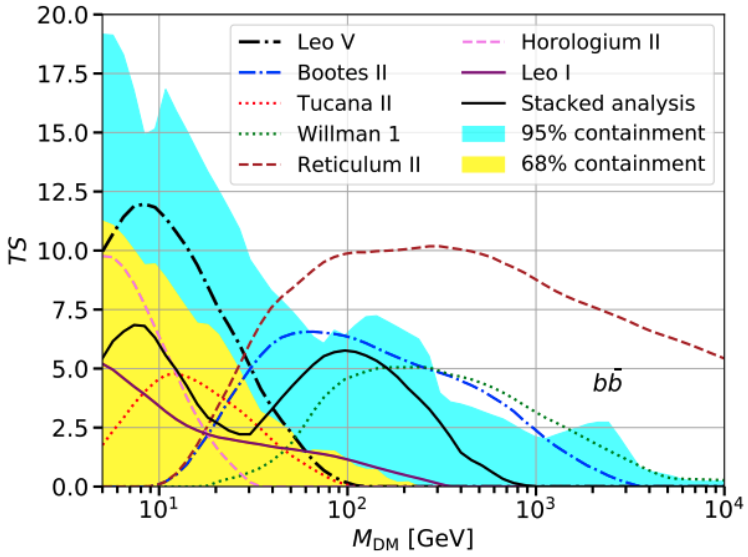
6 years



$< 2\,\sigma$

[Albert+ '17]

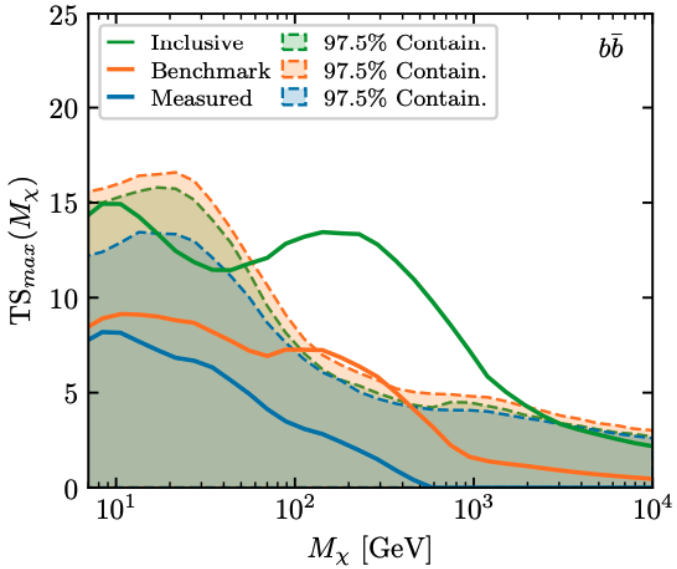
11 years



$\lesssim 2\,\sigma$

[DiMauro+ '21]

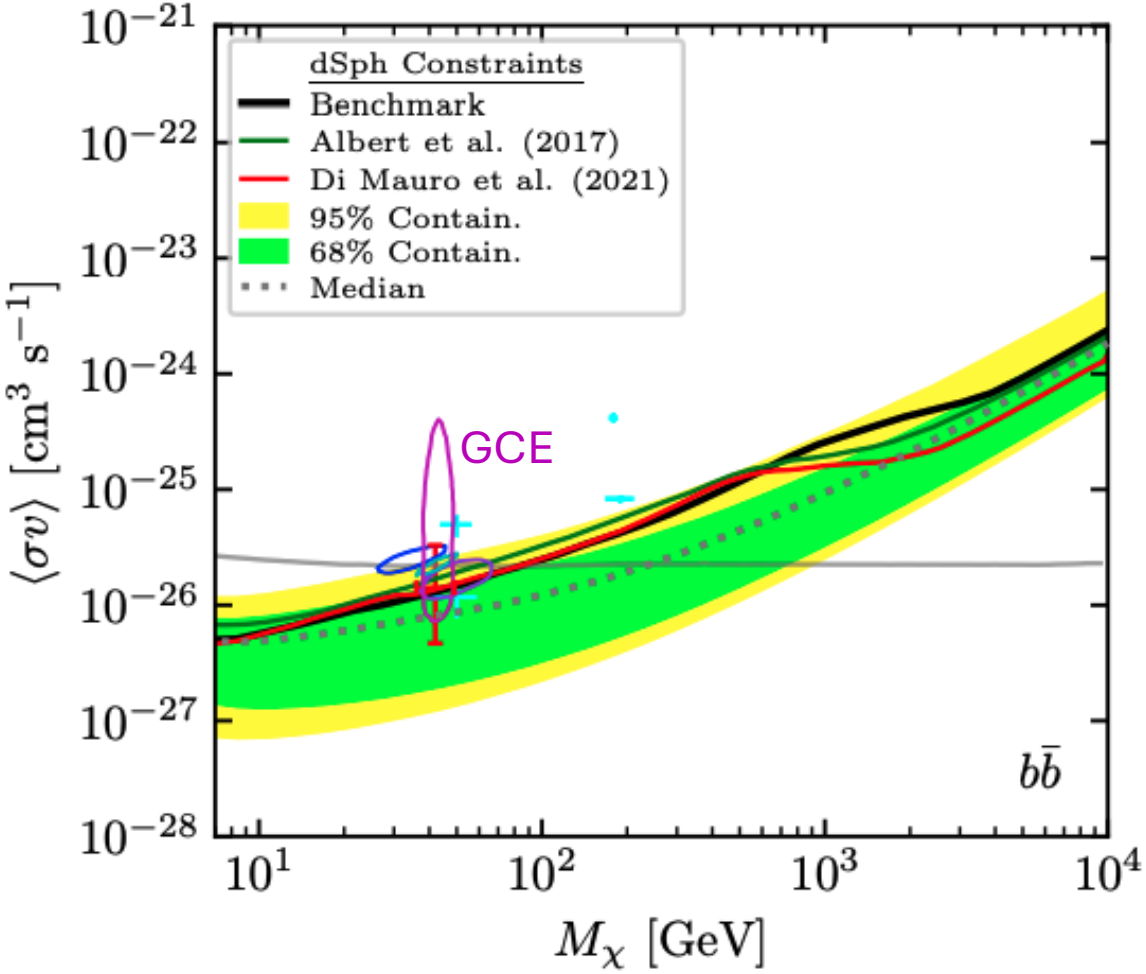
14 years



$\gtrsim 2\,\sigma$

[McDaniel+ '24]

Limits on the parameter space



[McDaniel+ '24]

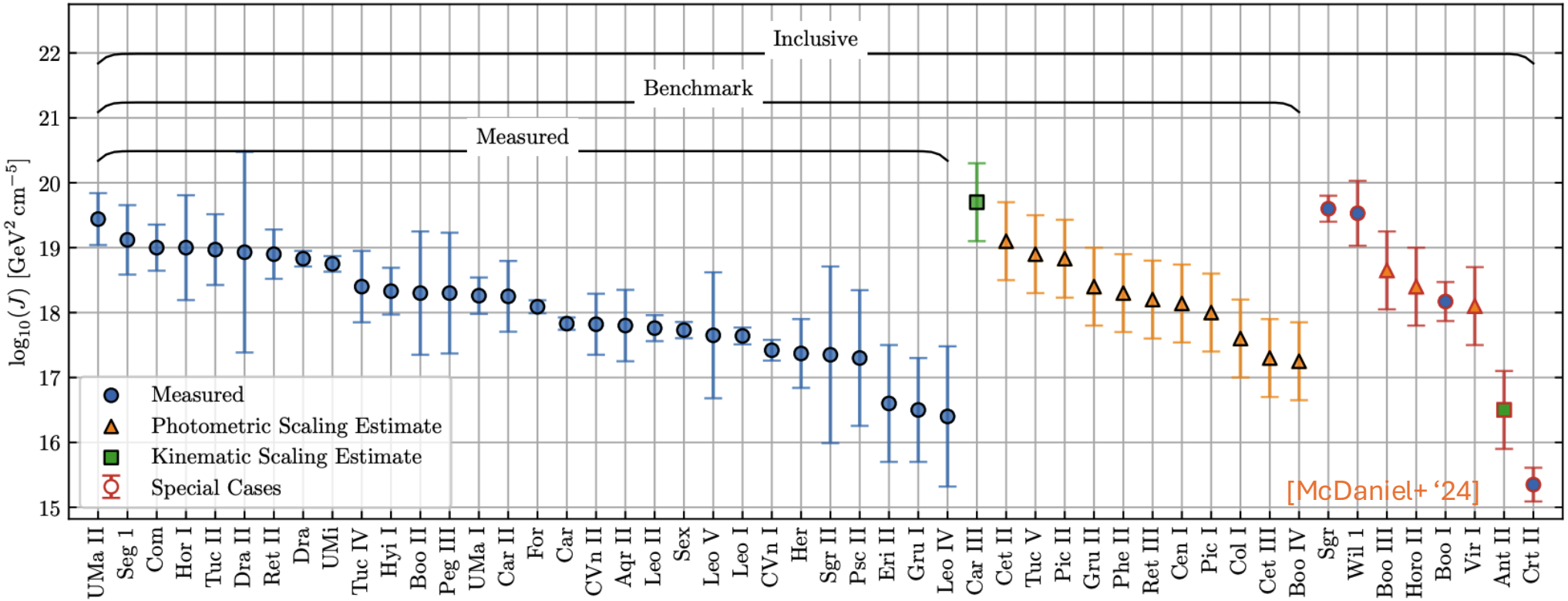
Trials factor reduces significance to 0.5 σ.

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

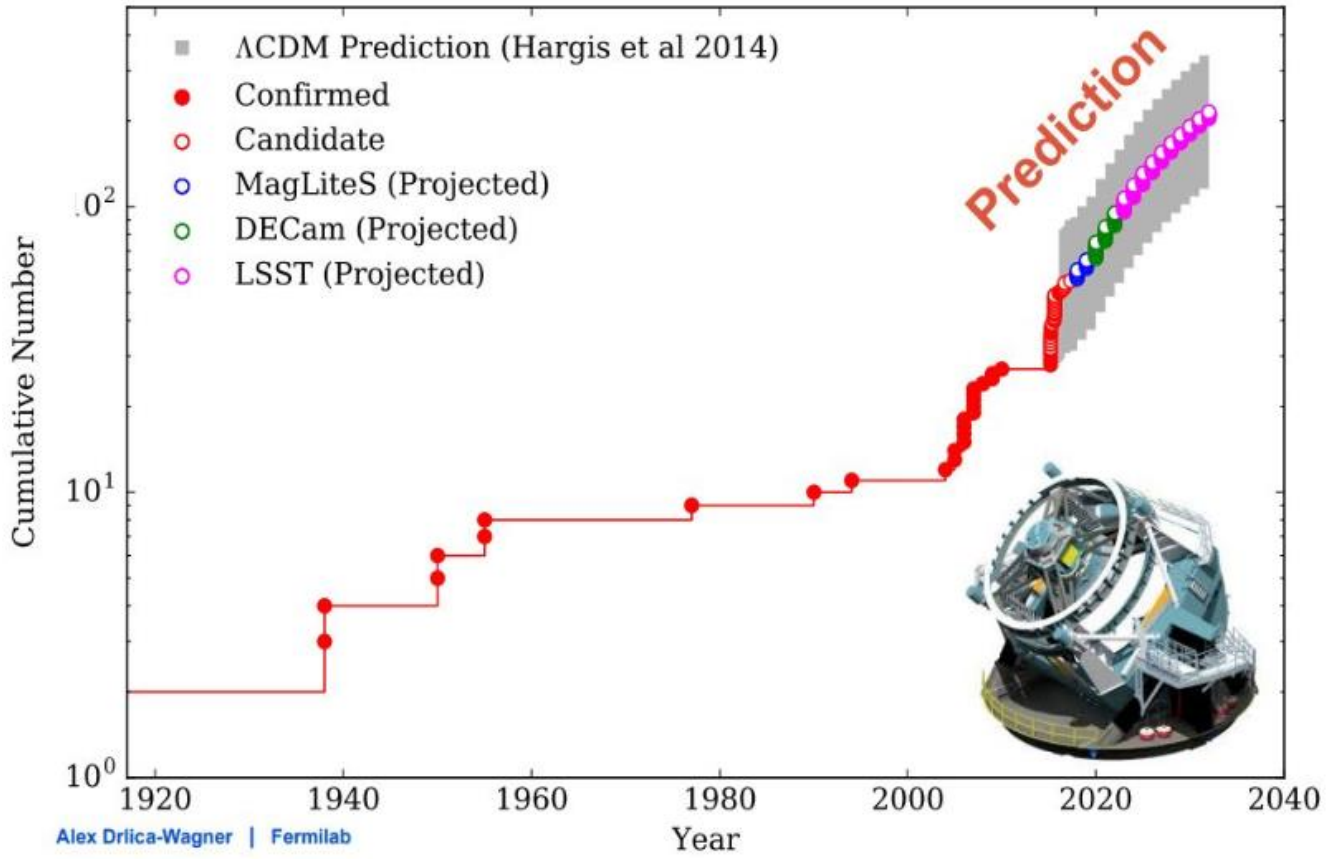


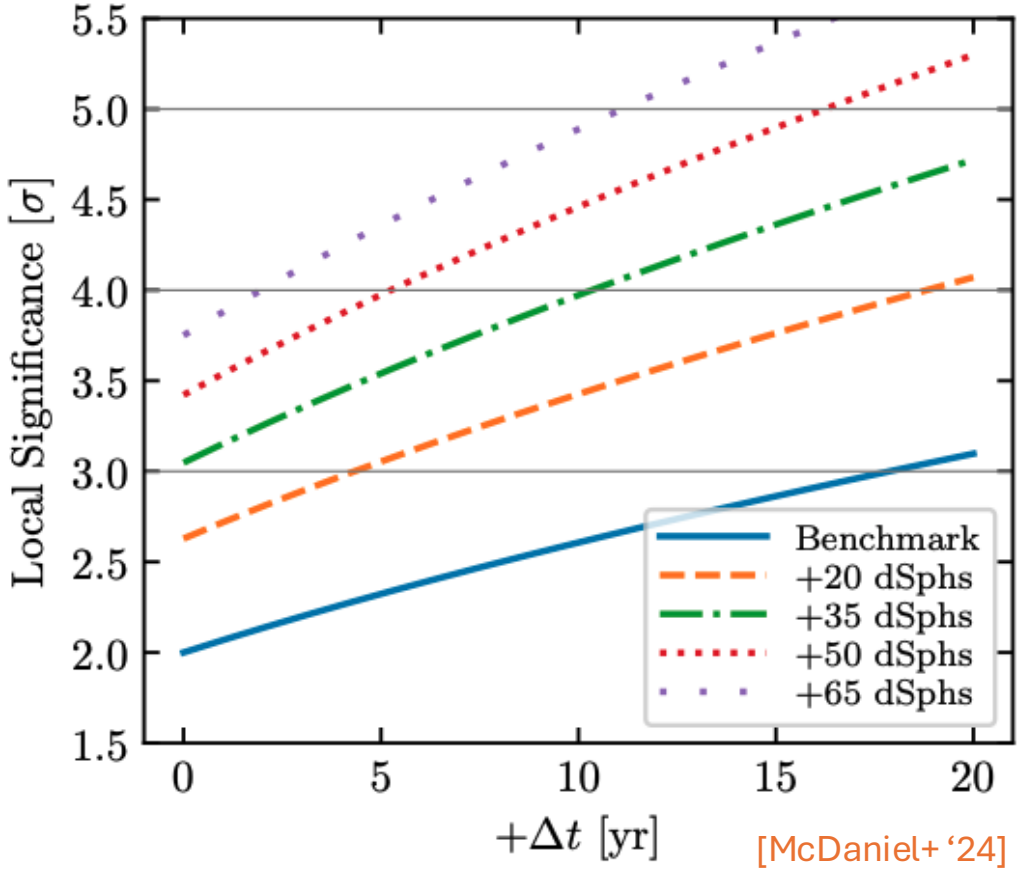
J-factor considerations:

- 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 a talk from Christoph Weniger.

Future of dSph DM searches





[McDaniel+ '24]

How many dwarf galaxies do we *really* need?

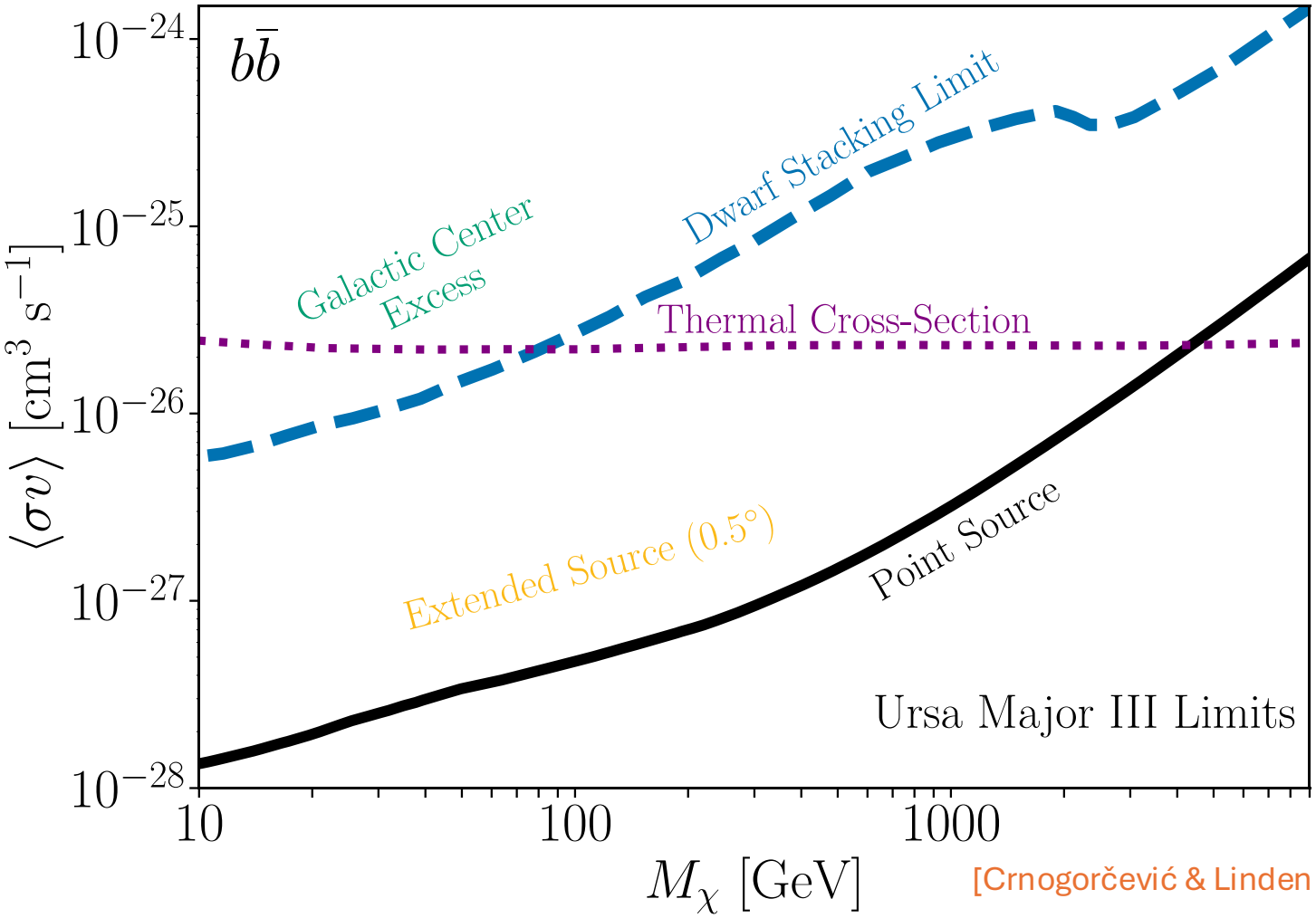
Maybe just one, but a good one?

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…*

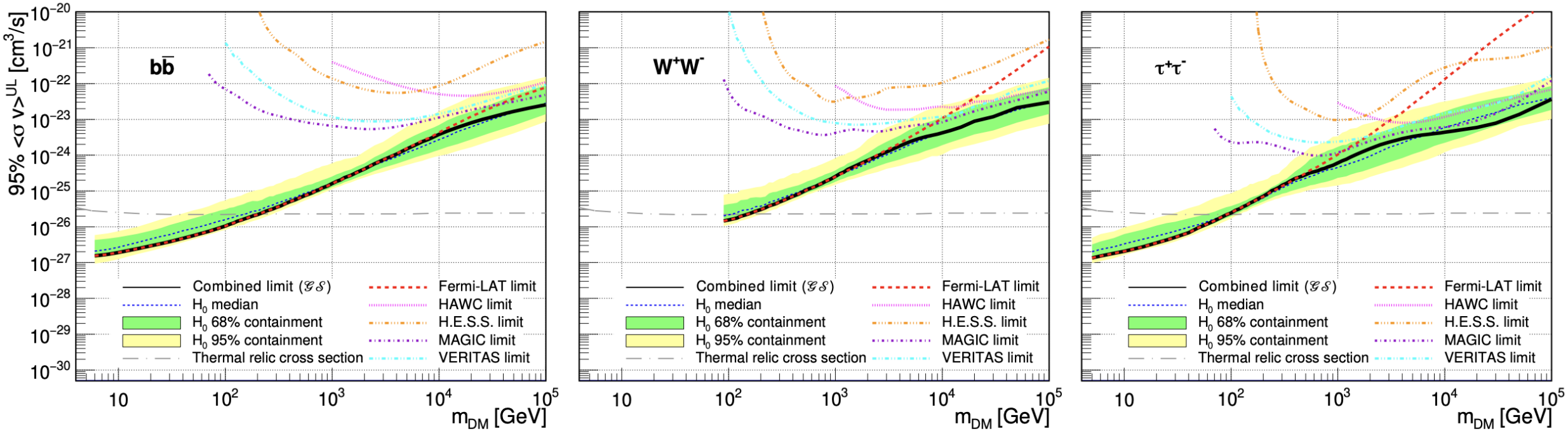


[Crnogorčević & Linden '23]

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

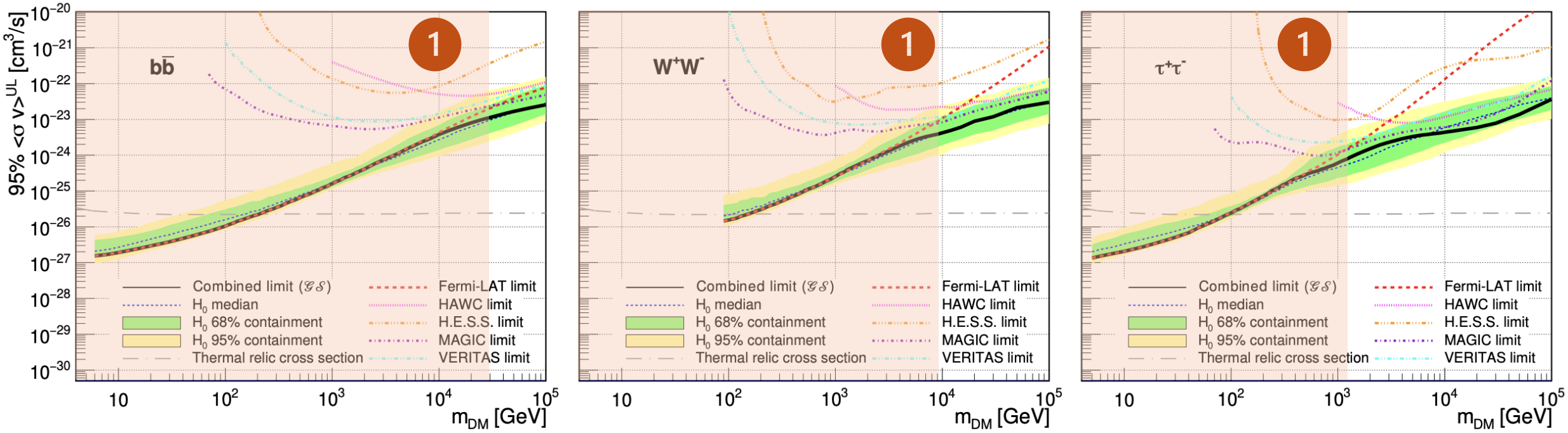
- Perform multi-instrument and multi-target analysis to obtain the most sensitive and robust results
- Focus: dSphs
- Limits driven by LAT sensitivity
- Legacy analysis of the current-generation gamma-ray instruments

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



Adapted from Celina Armand TeVPA '22 talk.

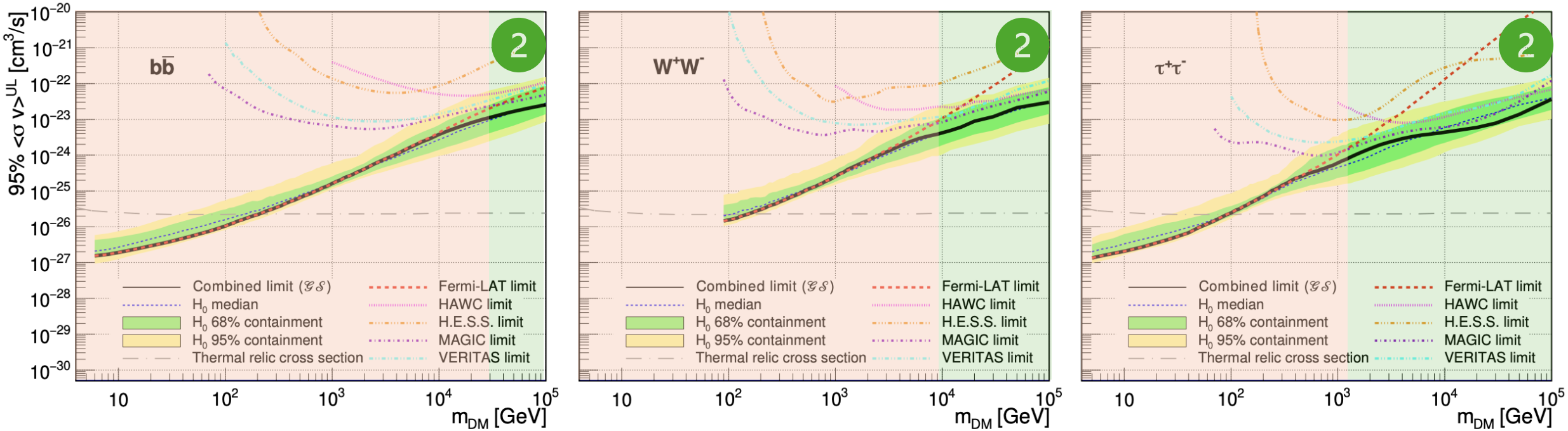
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



Dominated by *Fermi* LAT [1]

Adapted from Celina Armand TeVPA '22 talk.

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

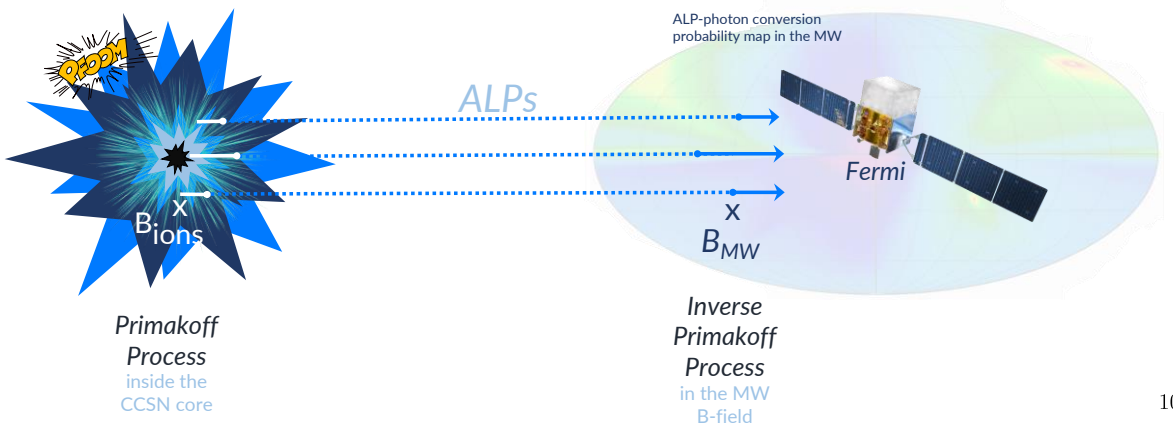


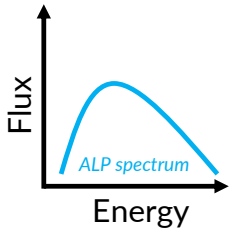
HAWC, HESS, MAGIC, VERITAS take over 2

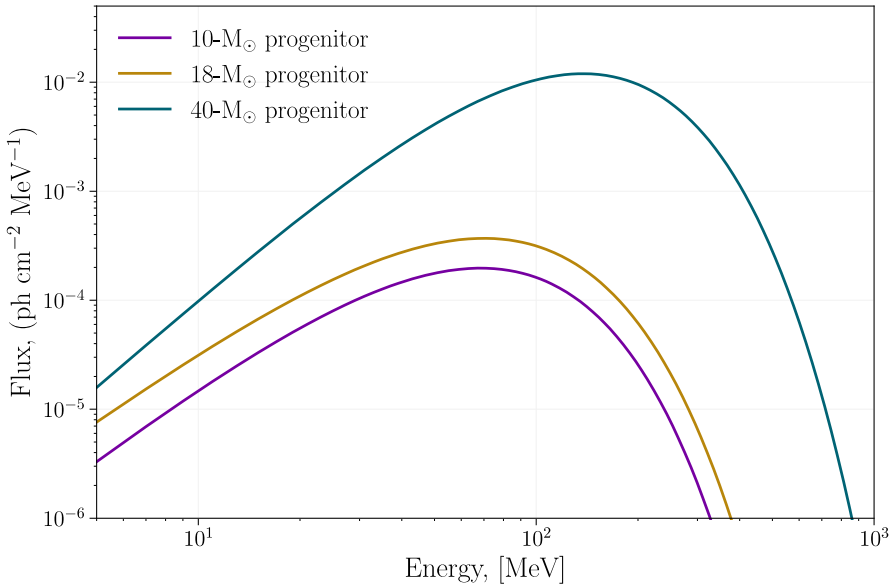
Dark Matter subhaloes, stellar streams, tidal disturbance/stripping of dwarfs, dark matter spikes, brown dwarfs, etc.

Adapted from Celina Armand TeVPA '22 talk.

Beyond WIMPs: Axion-like Particles







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 energyx

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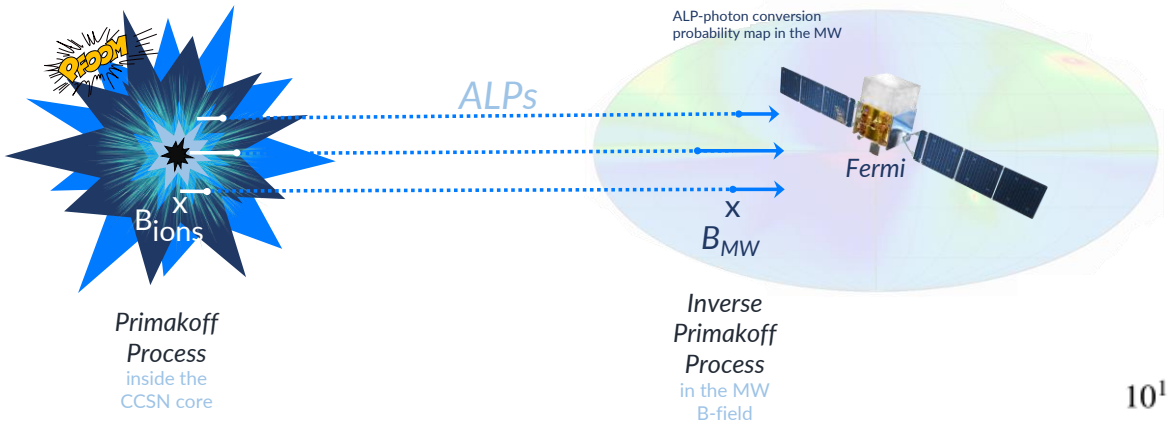

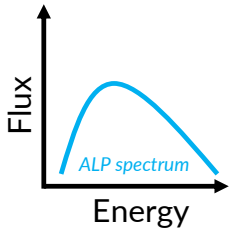

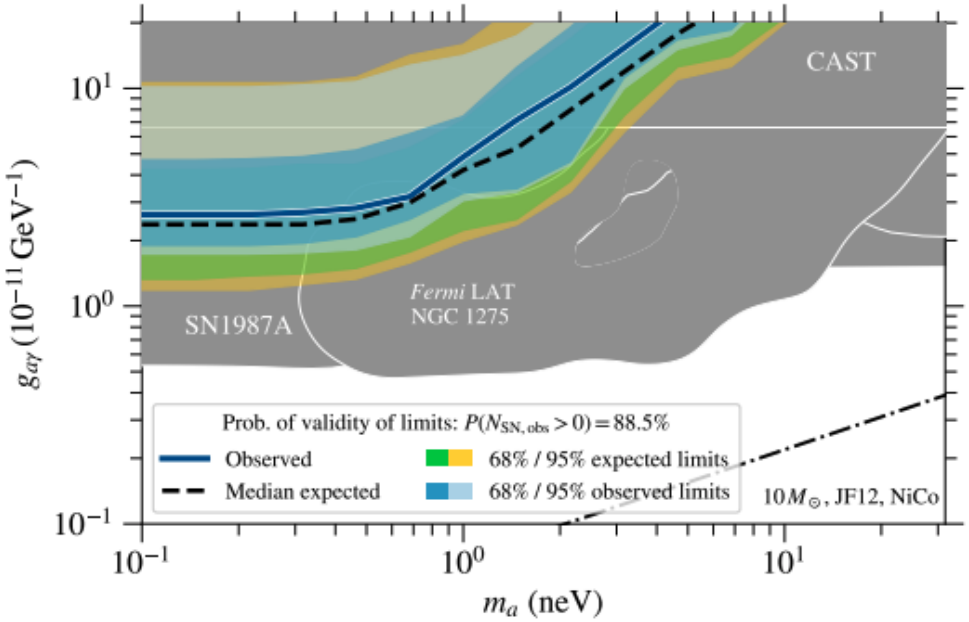

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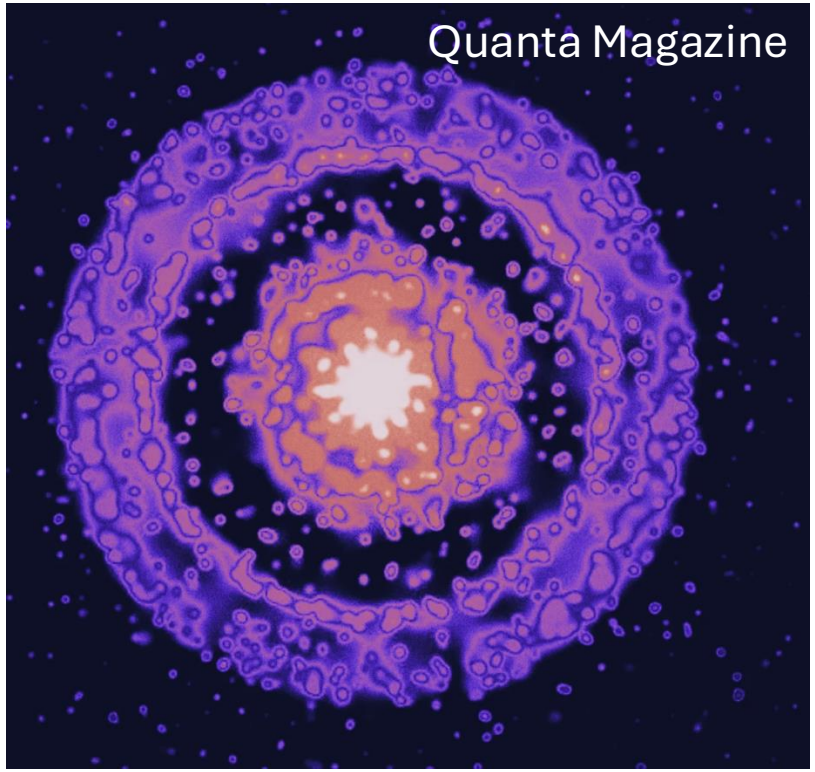
[see e.g.,Crnogorčević+ '21, Meyer & Petrushevska '20]

Honorable mention: GRB 221009A (BOAT)

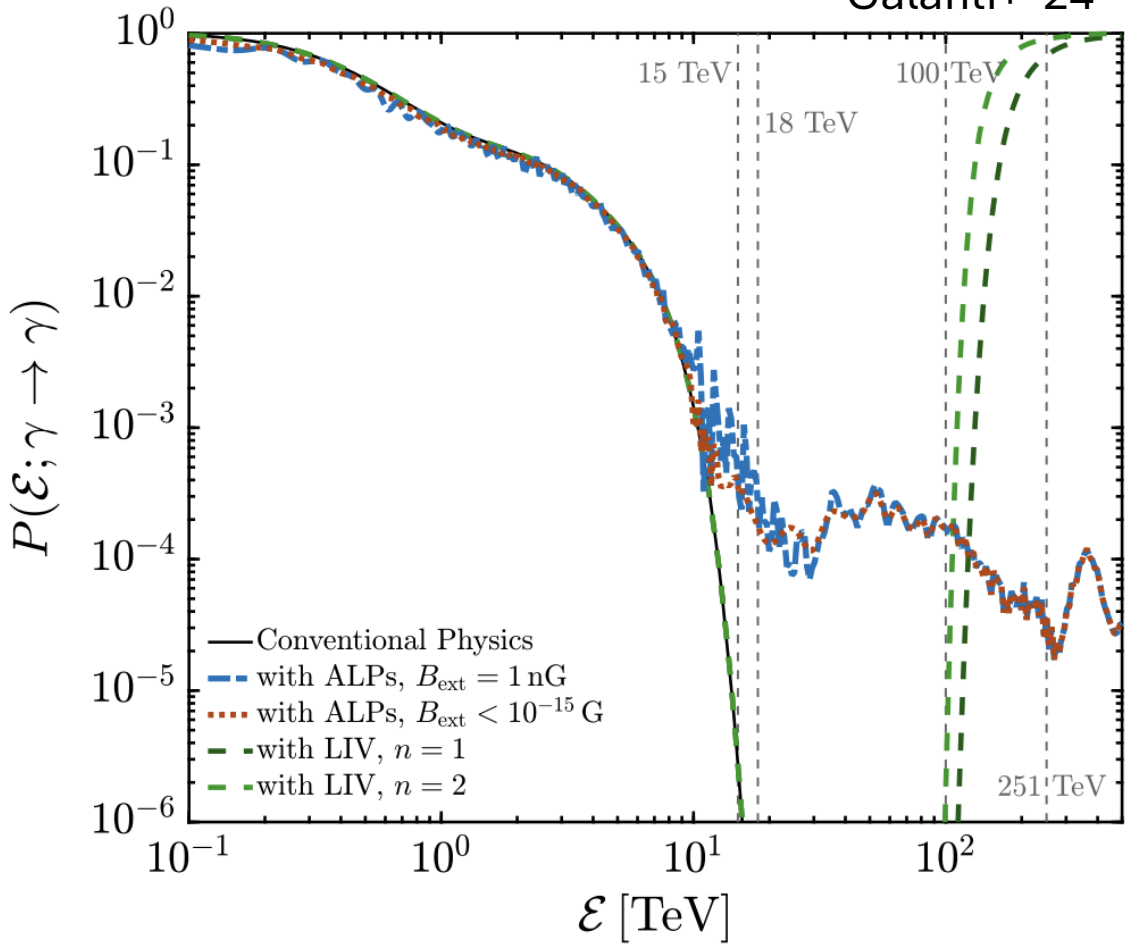


- **LHAASO observation of multi-TeV photons (18 and *maybe* 150+ TeV)**
- Redshift: 0.1505

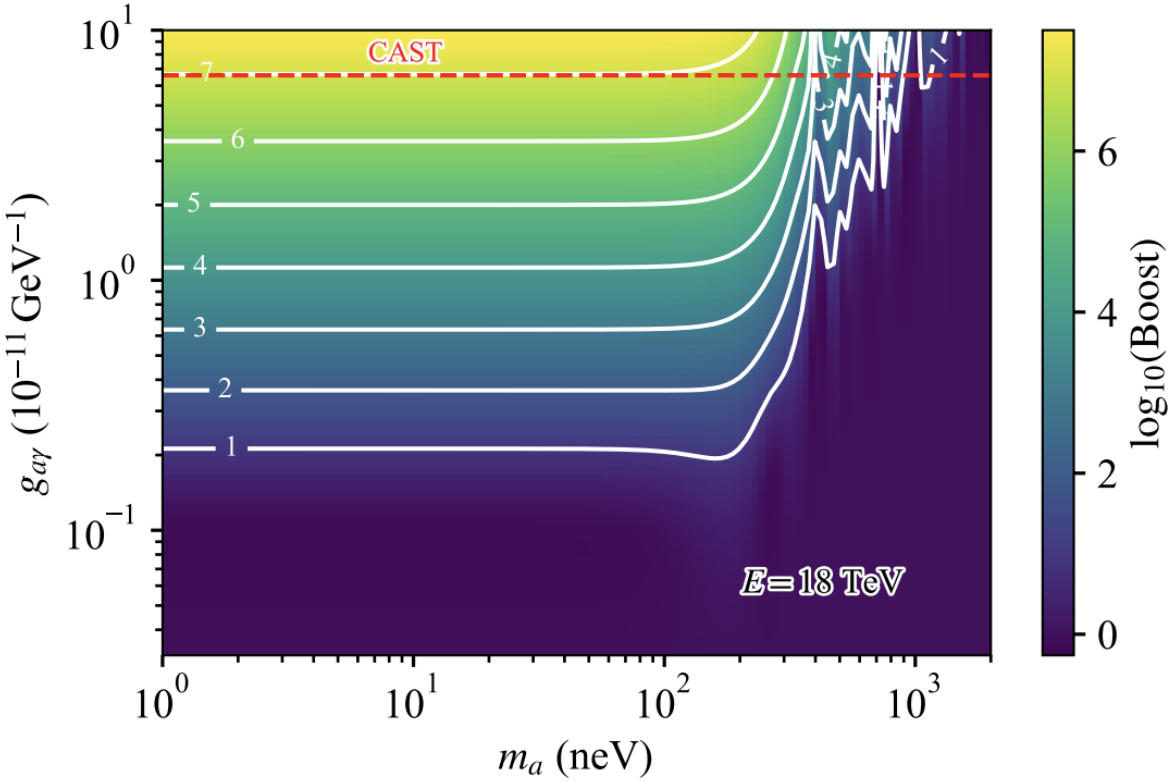
EBL attenuation should not allow for such energies to reach us

Honorable mention: GRB 221009A (BOAT)

Galanti+ ‘24



Meyer+ ‘24



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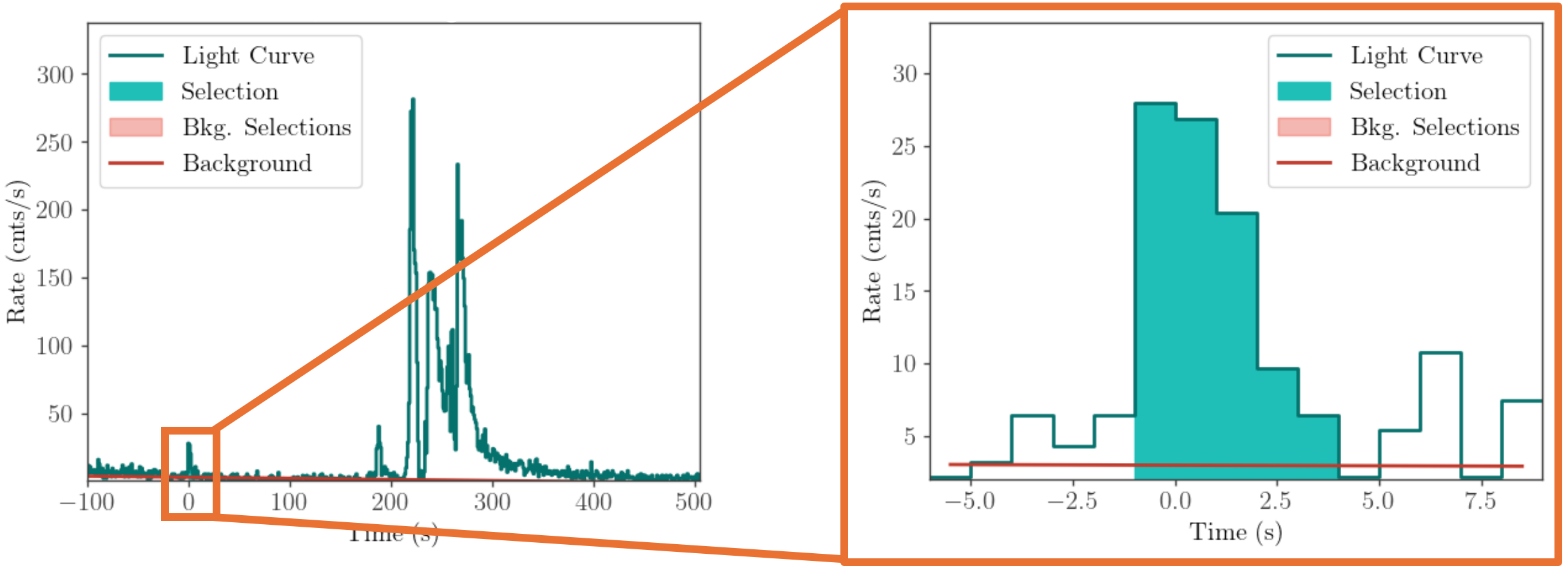

Crnogorčević+ in prep

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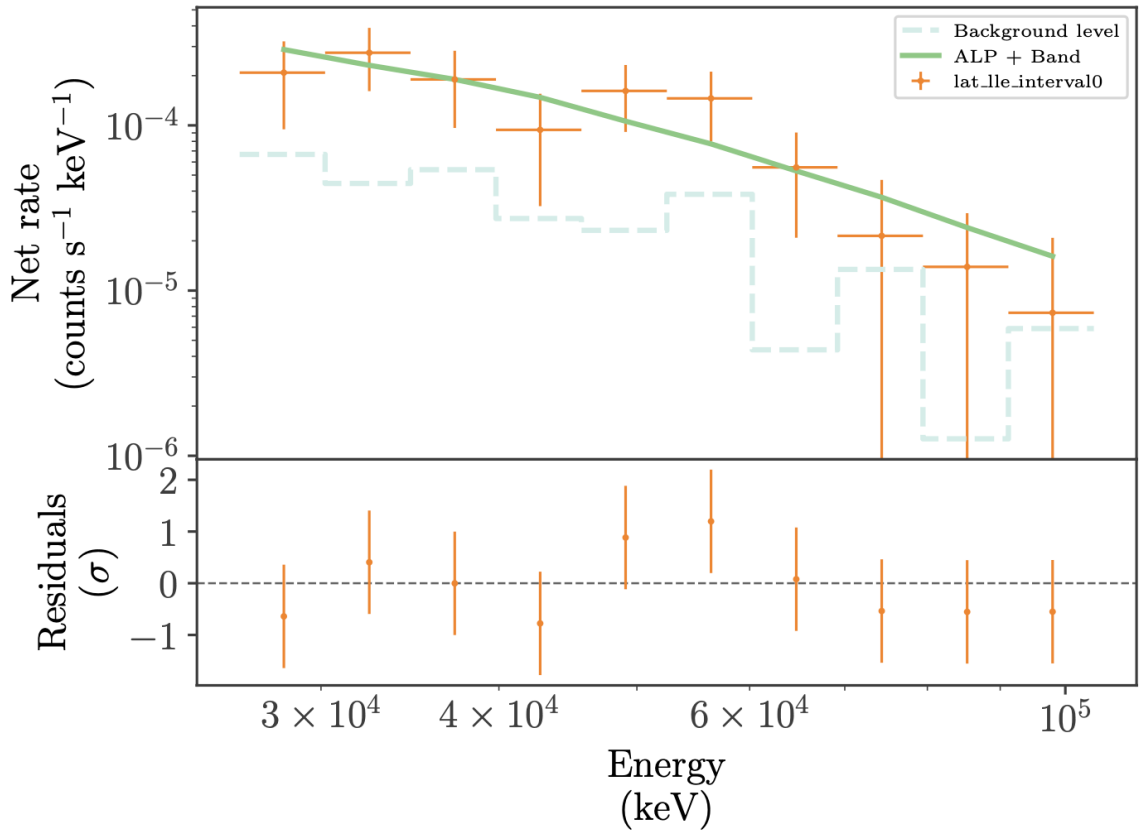
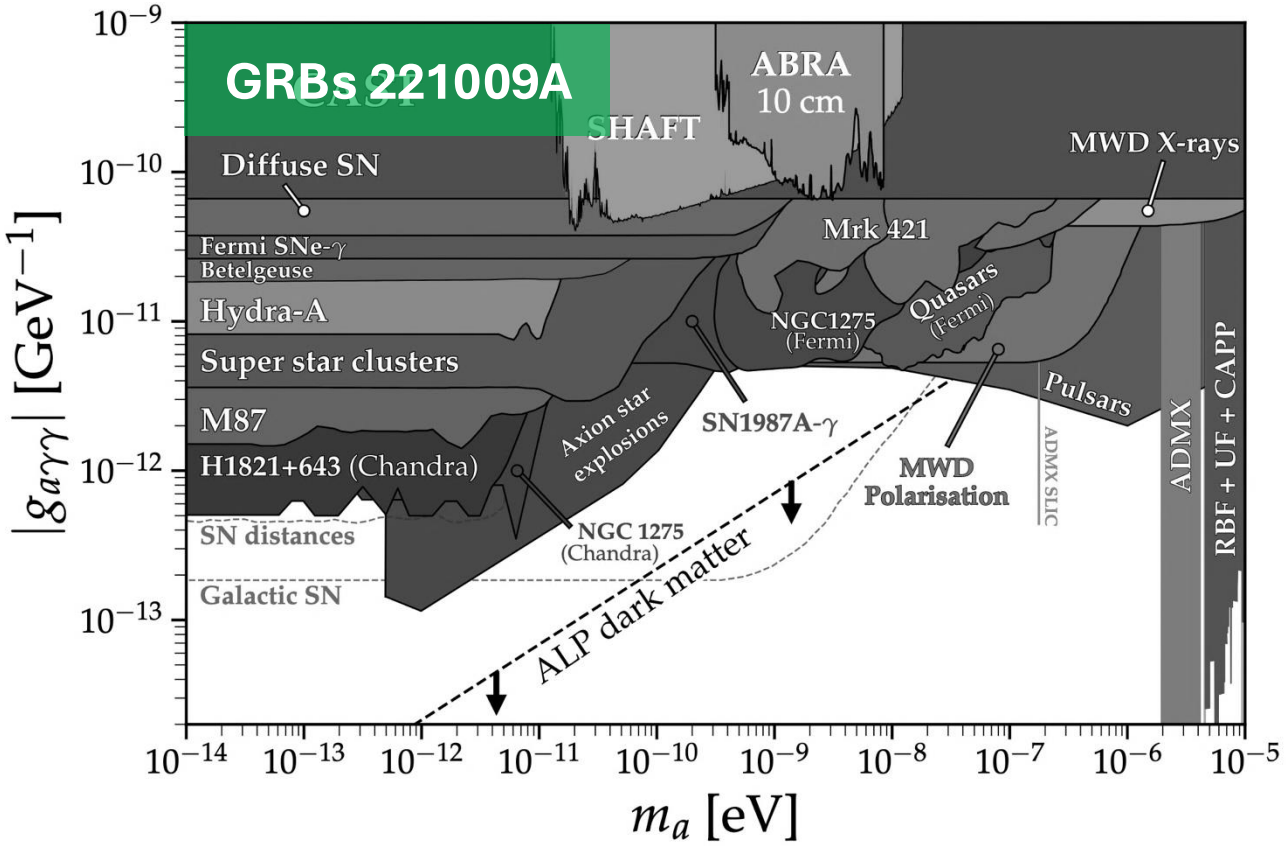
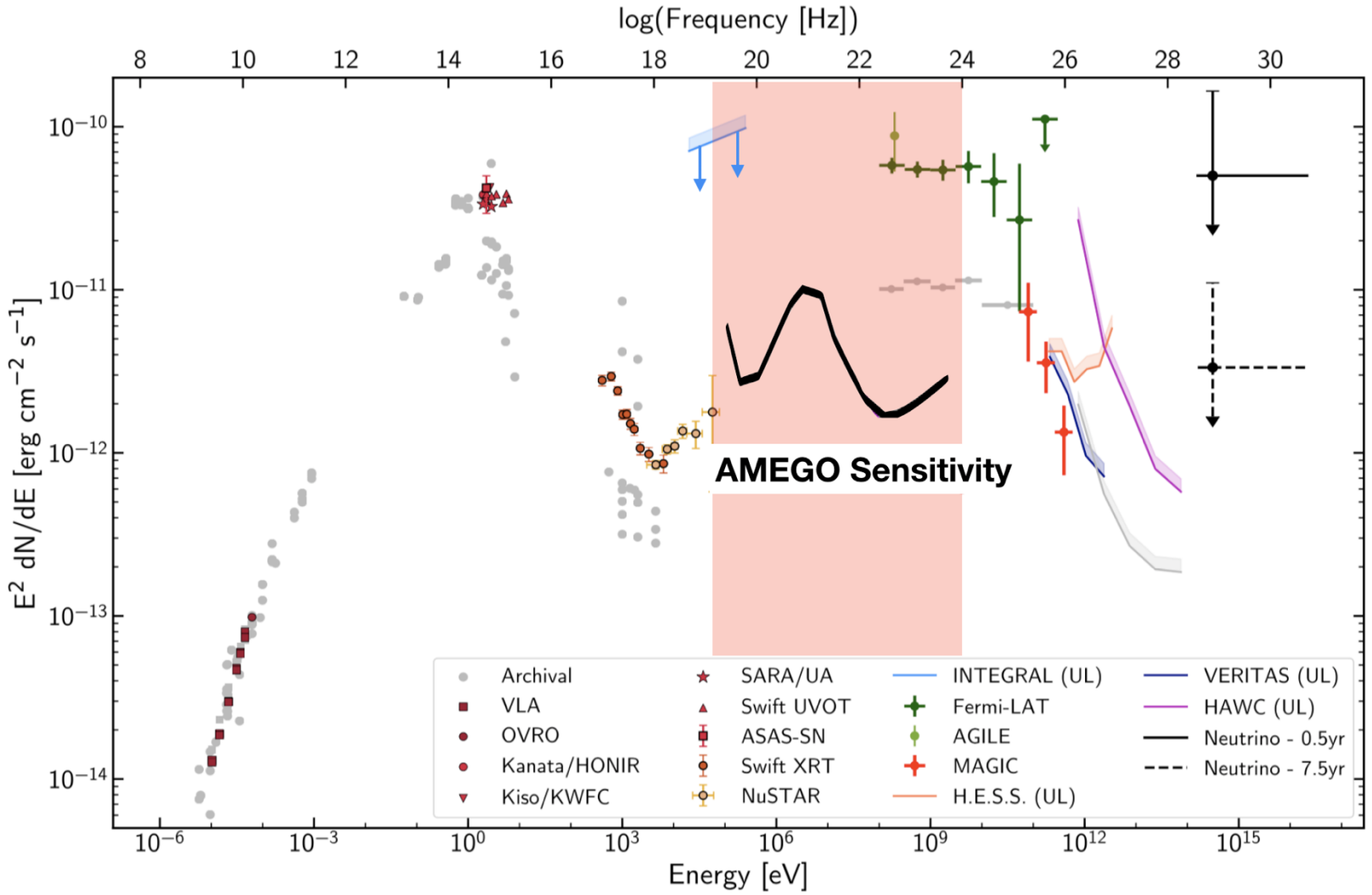




Crnogorčević+ in prep

The MeV Gap

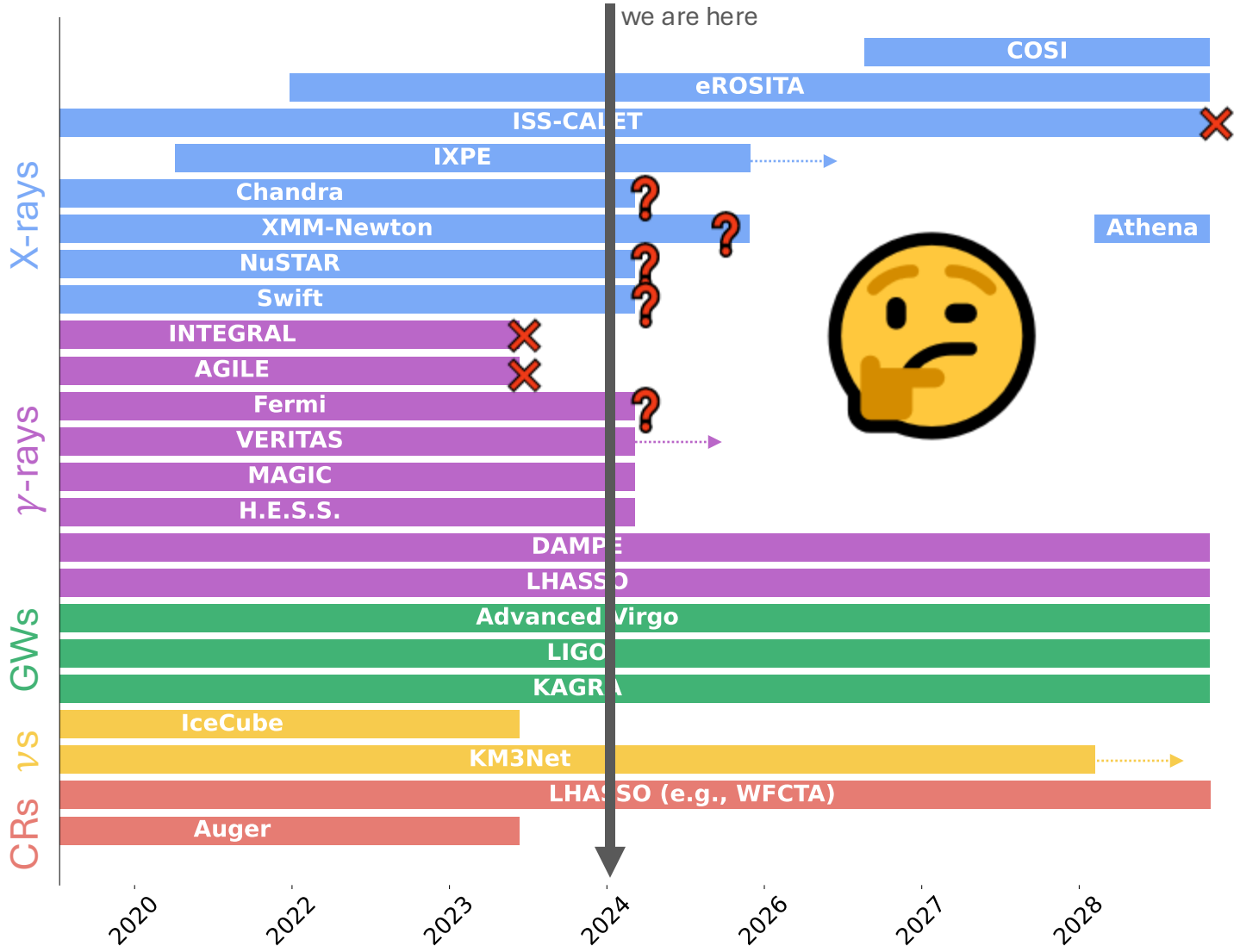

log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
AMEGO Sensitivity
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC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

Where next?

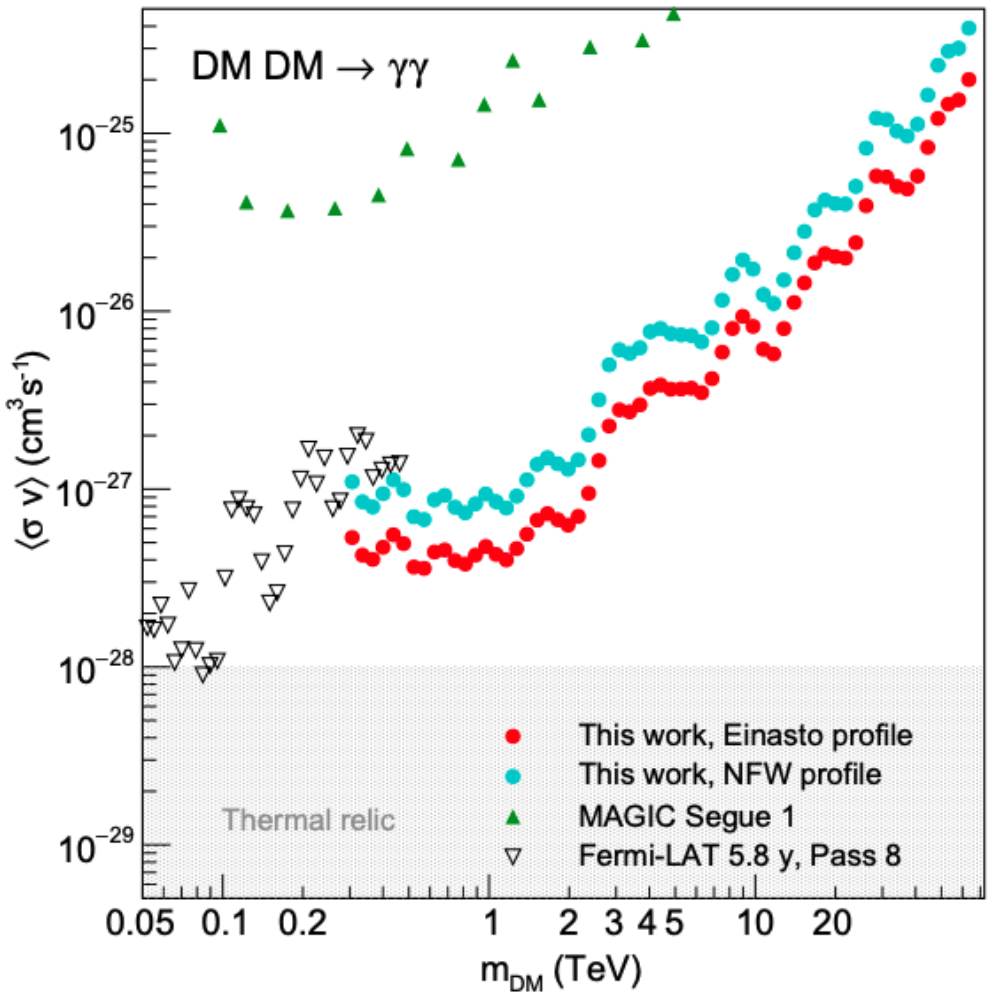
“Expecting to uncover dark matter in the next two decades is akin to waiting for a sunny [British summer]. Hopeful, yet perennially disappointed.”

ChatGPT, 2024

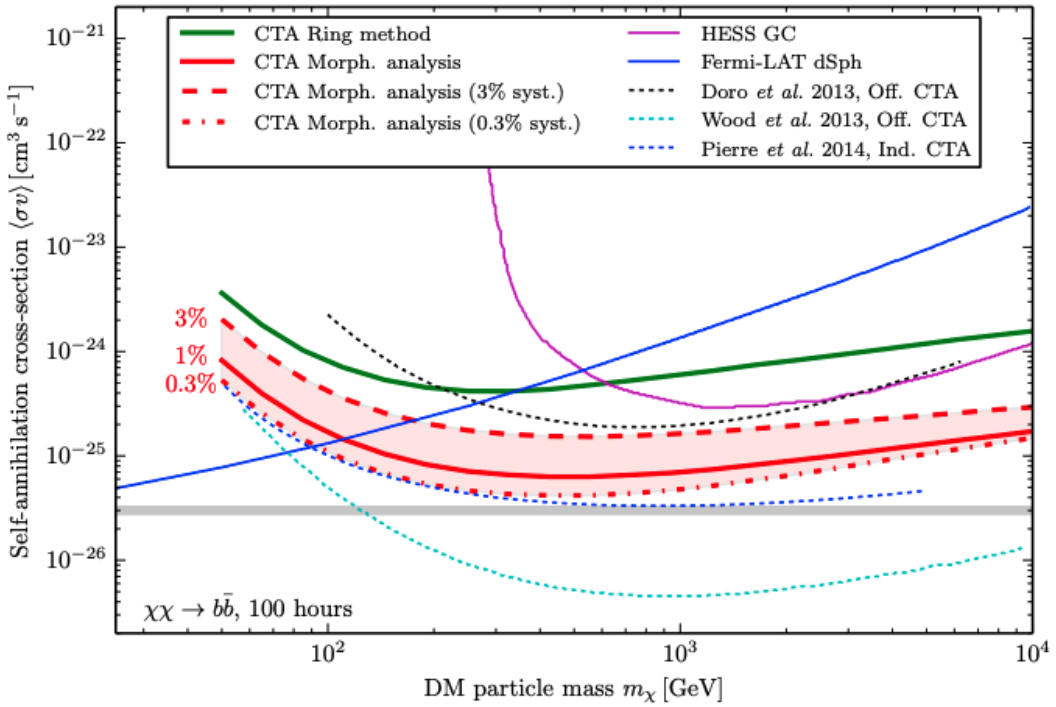
Dark Matter Landscape: An Instrumentationalist's View



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



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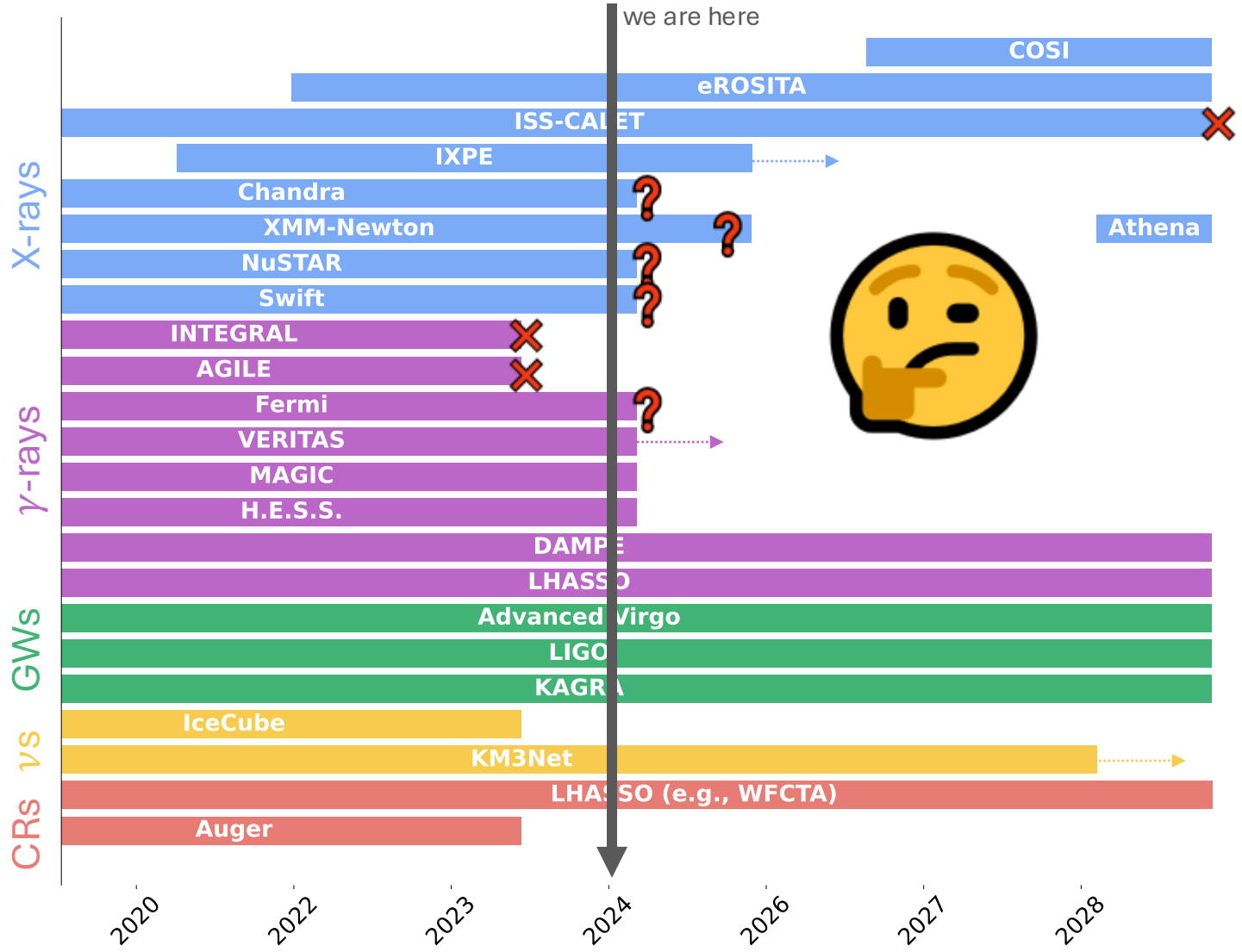


Future Innovations in Gamma rays

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.**

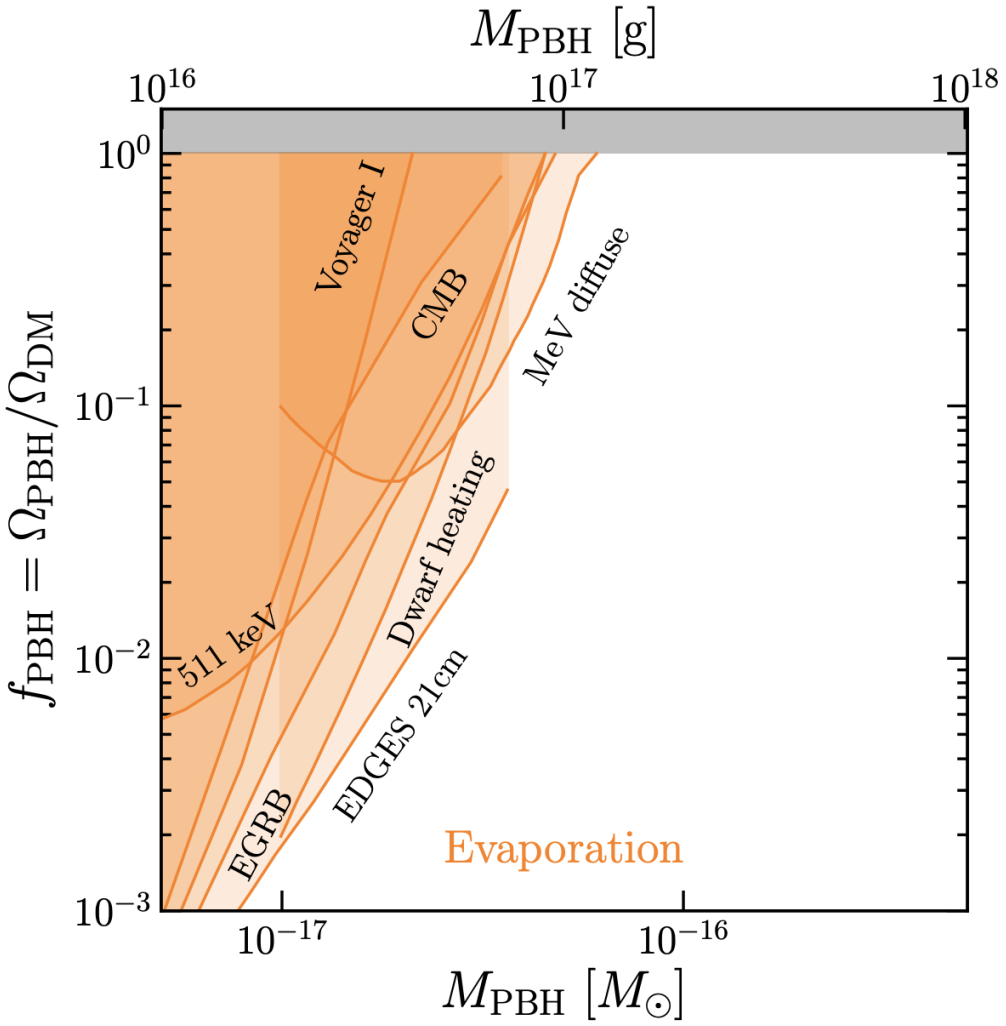
FIG SAG Terms of Reference

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
- Future experiment development is crucial
- Our next space gamma-ray experiment is uncertain---***join FIG SAG to make a strong case to funding agencies***

PBH high-energy emission



- PBH can emit **charged cosmic rays** and **photons** via Hawking radiation => Almost-black (grey) body emission

$$T_{\rm PBH} \sim \frac{10^{13}\,\mathrm{g}}{M_{\rm PBH}}\,\mathrm{GeV}$$

- Sufficient emission from $M_{PBH} > 10^{14}$ g to set limits on their evaporation products today

Page & Hawking ApJ'76; Carr & MacGibbon Phys. Rep.'98

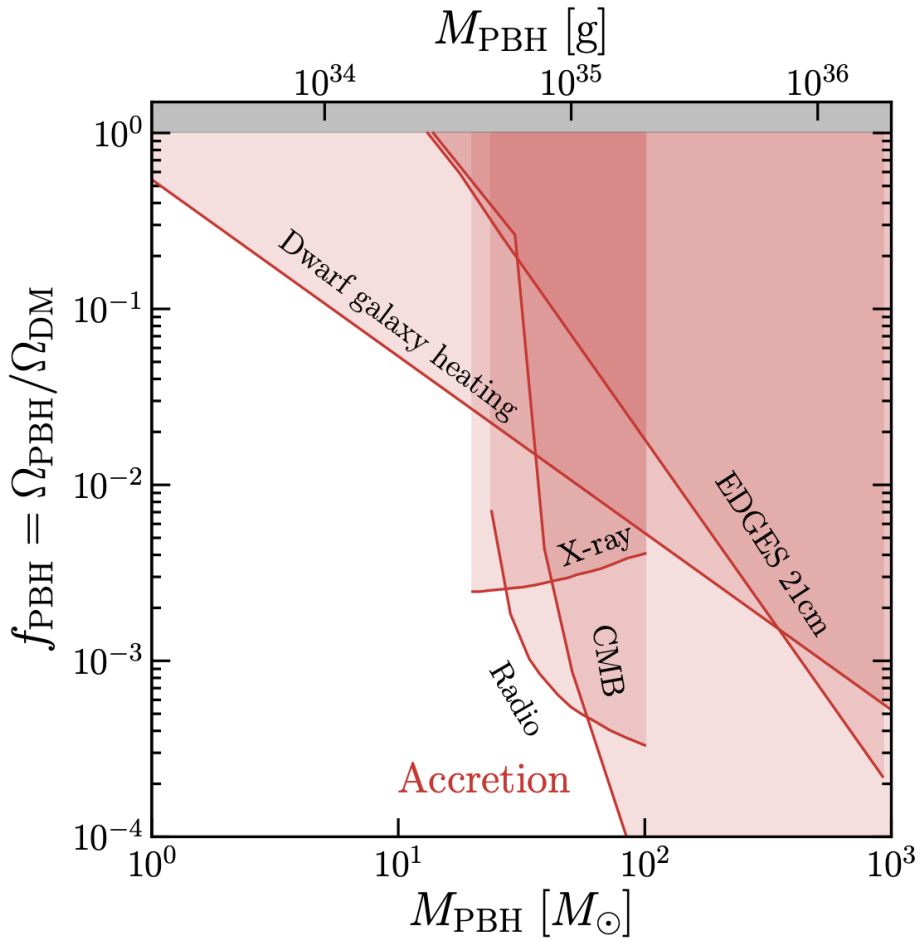
- **Current** constraints:

  ✓ Photon contribution to the extragalactic gamma-ray and X-ray backgrounds *Carr+ PRD'10; Ballesteros+ PLB'20; Iguaz+ PRD'21*

  ✓ Positron and electron production constrained by Voyager I and SPI/INTEGRAL data *Boudaud&Cirelli PRL'18; DeRocco & Graham PRL'19; Laha PRL'19*

Future e-ASTROGAM and ASTRO-H will allow a more precise measurement of the isotropic gamma-ray and X-ray backgrounds => Improved constraints in the **10^{16}–10^{18} g mass window**

PBH high-energy emission



- **10-100 solar mass** PBH can accrete interstellar gas and produce observable **X-ray** and **radio emission** today

  Gaggero, FC+ PRL'17; Inoue & Kusenko JCAP'17; Lu+ ApJL'21

- Same mechanism can also modify the recombination history of the Universe => constraints set by anisotropies and spectrum of the **CMB**

  Carr MNRAS 1981; Ricotti+ ApJ'08; Poulin, FC+ PRD'17

- Significant **theoretical uncertainties**: e.g. accretion rate and the ionizing effects of the radiation; impact of more realistic/complex mass functions

  Manshanden+ JCAP'19

Future radio facilities (**SKA**, **ngVLA**) have the potential to either set very strong constraints on PBH abundance or to detect a population of PBHs at the GC

Weltman+ PASA'20