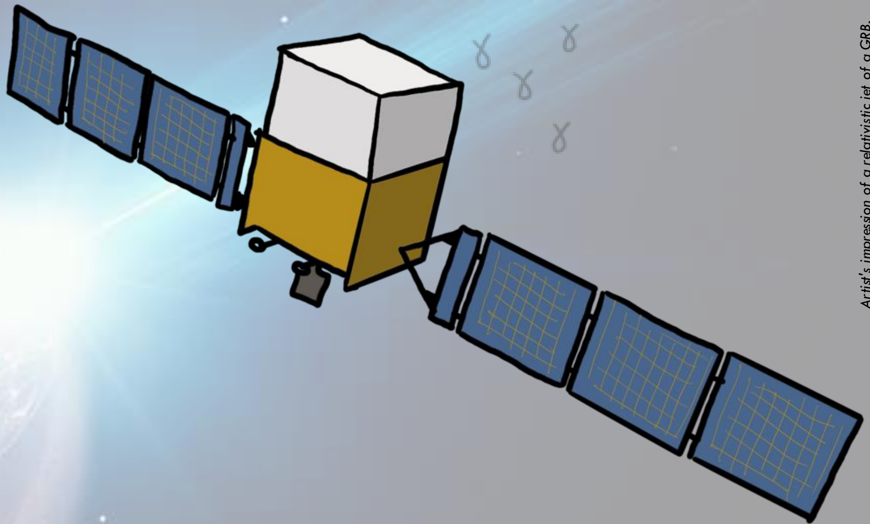
WIMPs, WISPs, and Gammas

Searches for Dark Matter and New Physics with Fermi Large Area Telescope



Artist's impression of a relativistic jet of a GRB.
Credit: DESY, Science Communication Lab

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Postdoctoral Fellow at the Oskar Klein Centre
milena.crnogorcevic@fysik.su.se

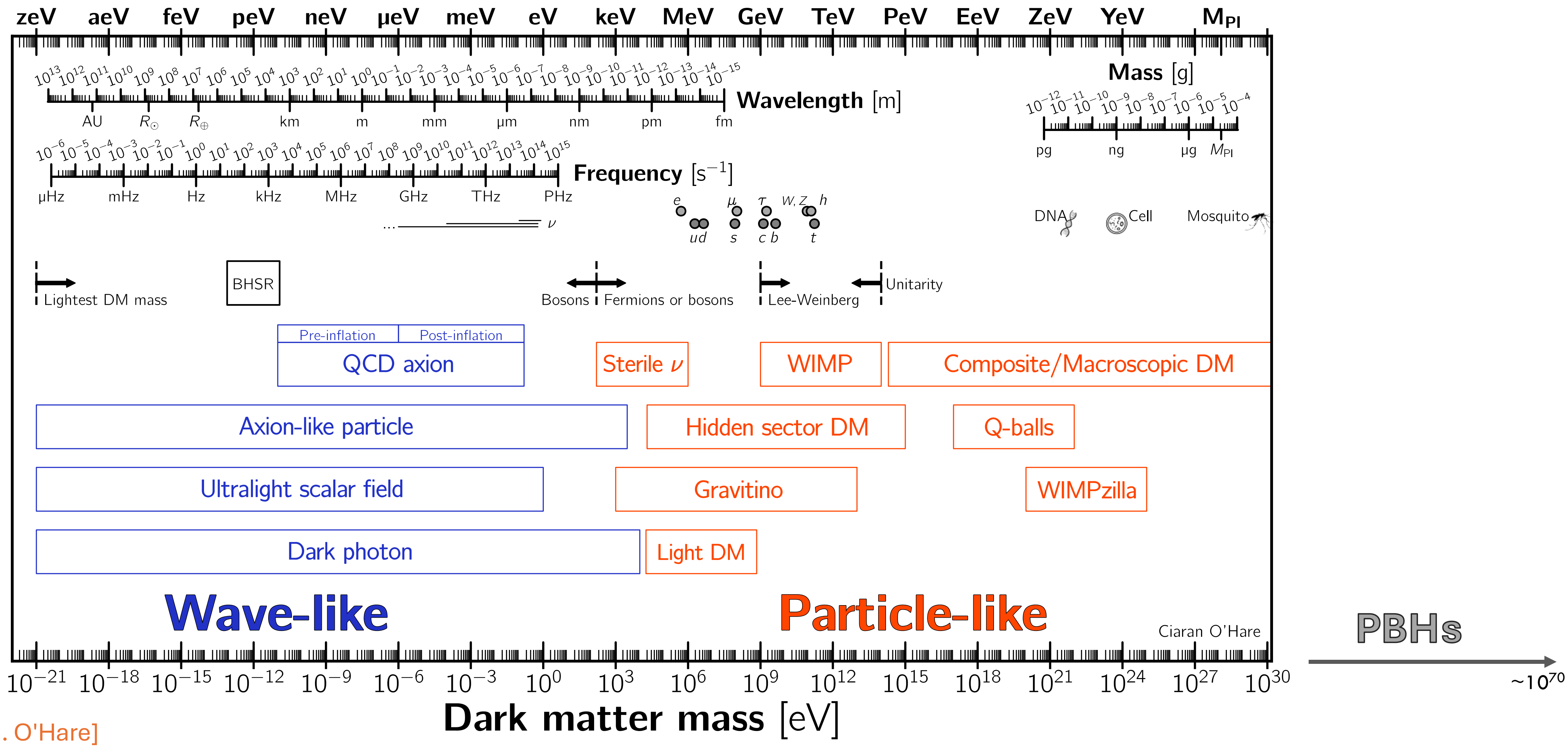
COSMIC WISPERS
CA21106

2^{nd} General Meeting of COST Action Cosmic WISPers

September 4, 2024

Stockholm University

Dark Matter Landscape: A Theorist's View

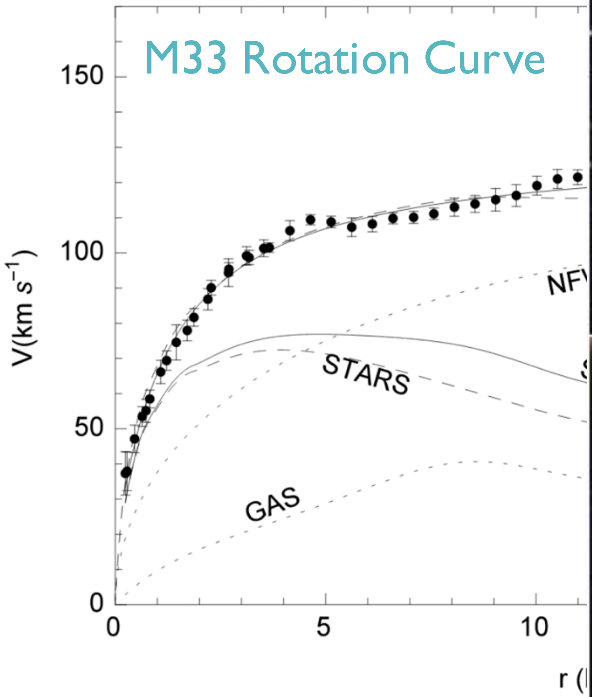


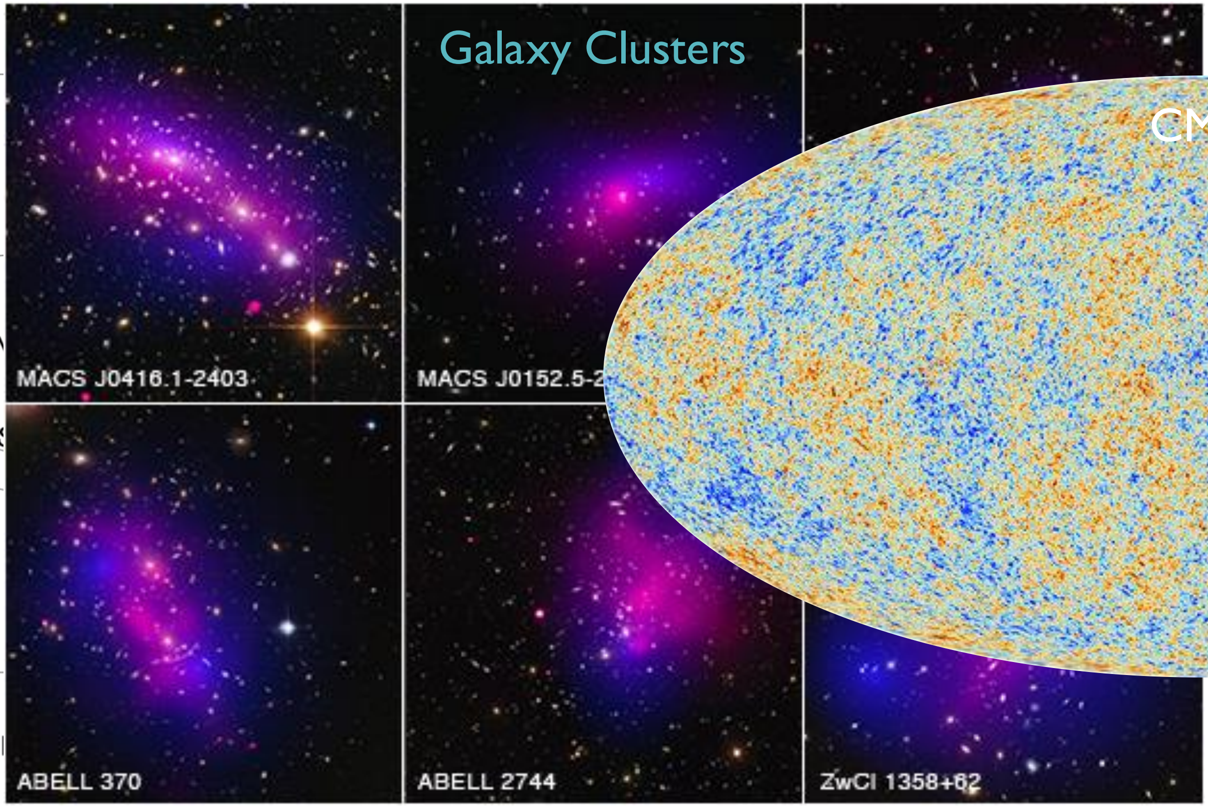
[Ciaran A. J. O'Hare]

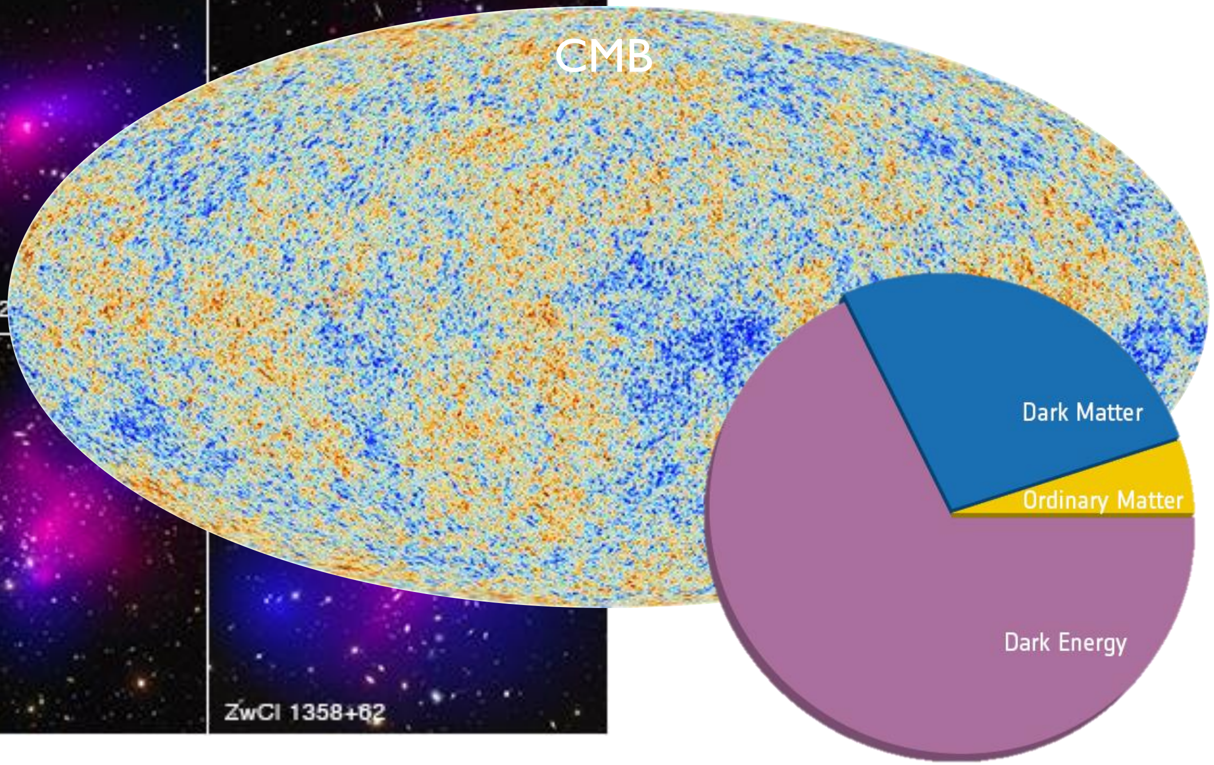
Dark Matter Landscape: An Observer's View

Overwhelming *indirect* evidence for the existence of dark matter

X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D.Harvey & NASA/CXC/Durham Univ/R.Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)







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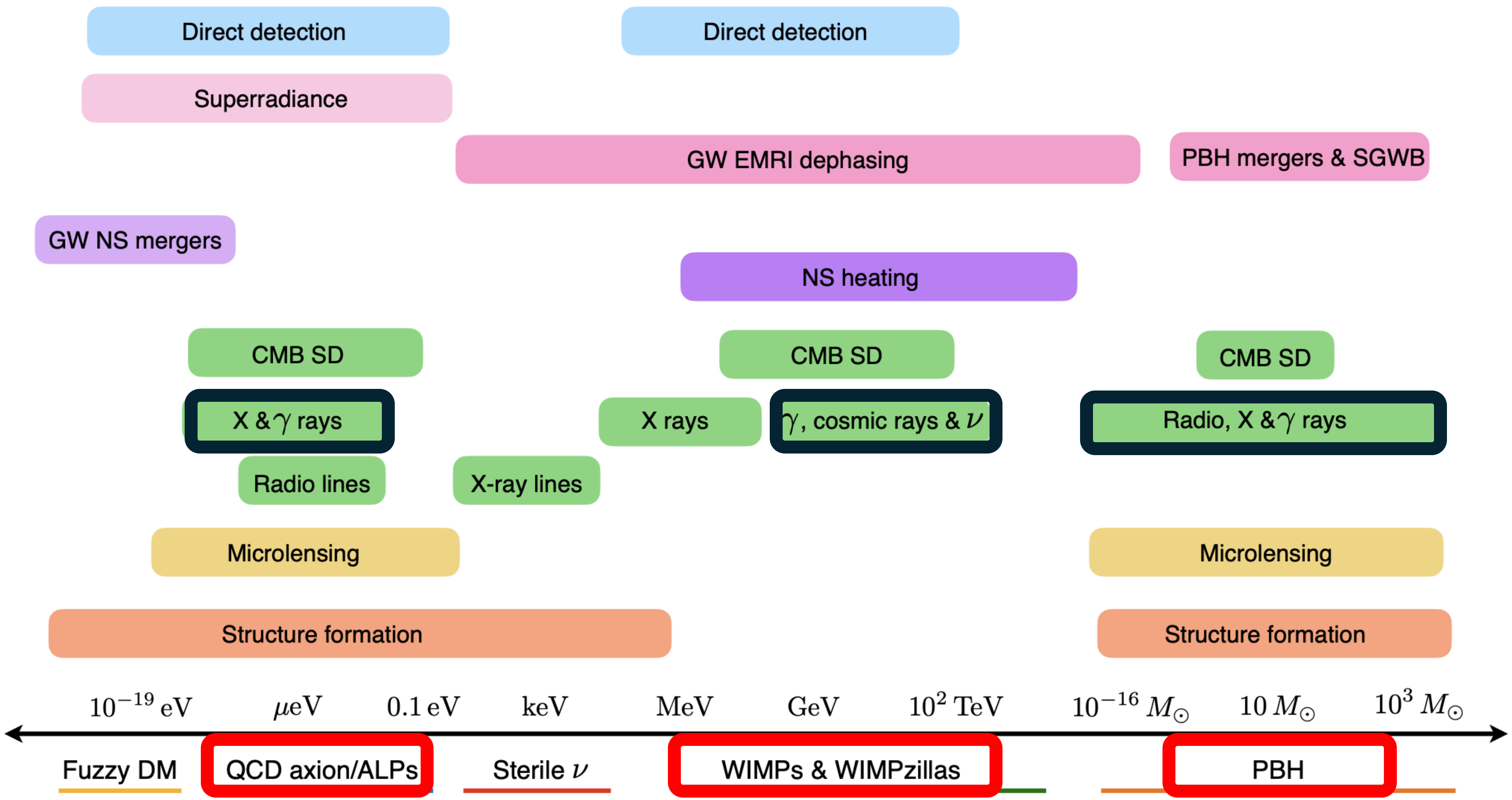
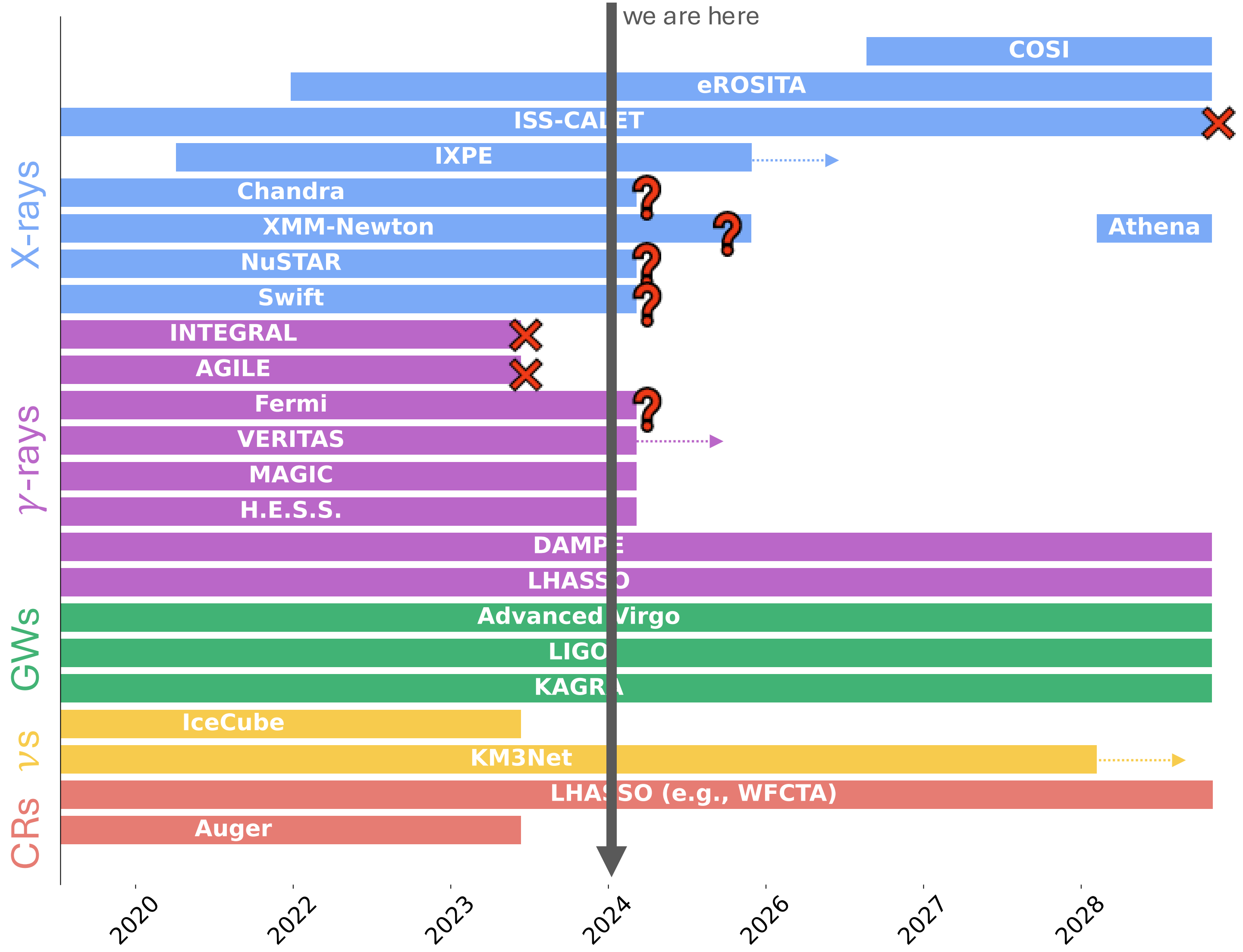


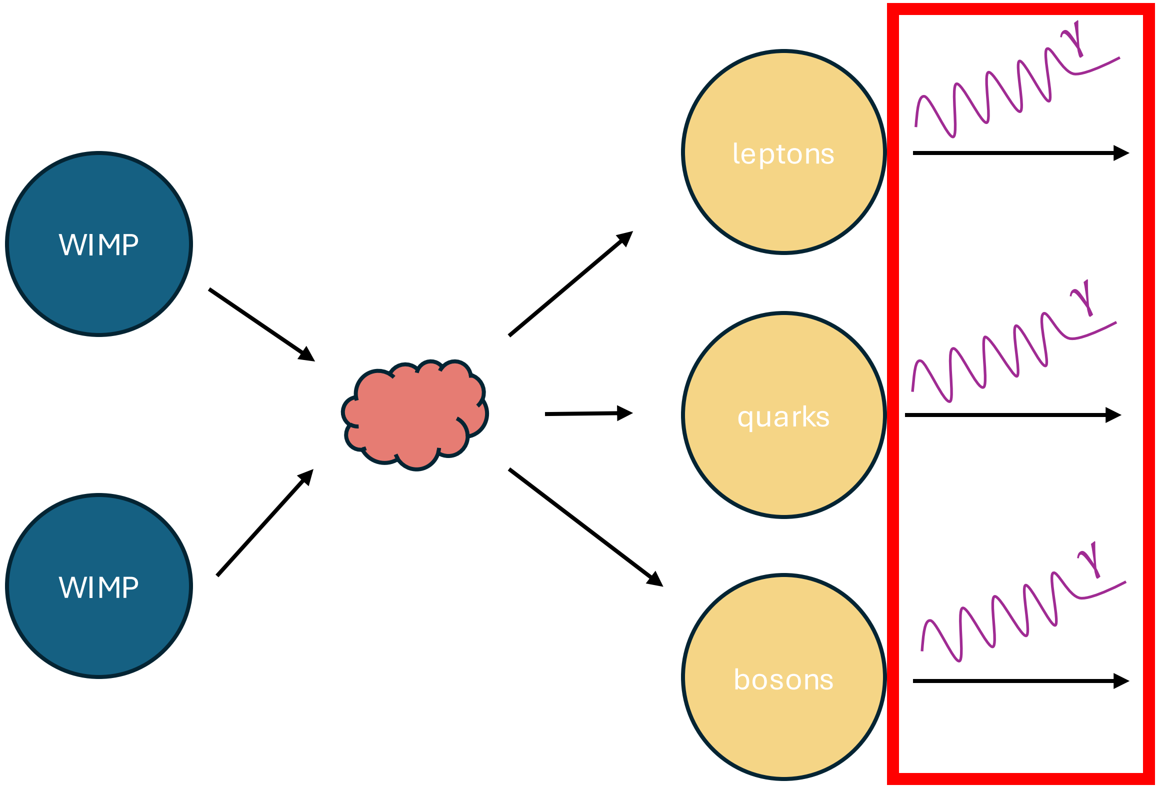
[EuCAPT WhitePaper, 2021]

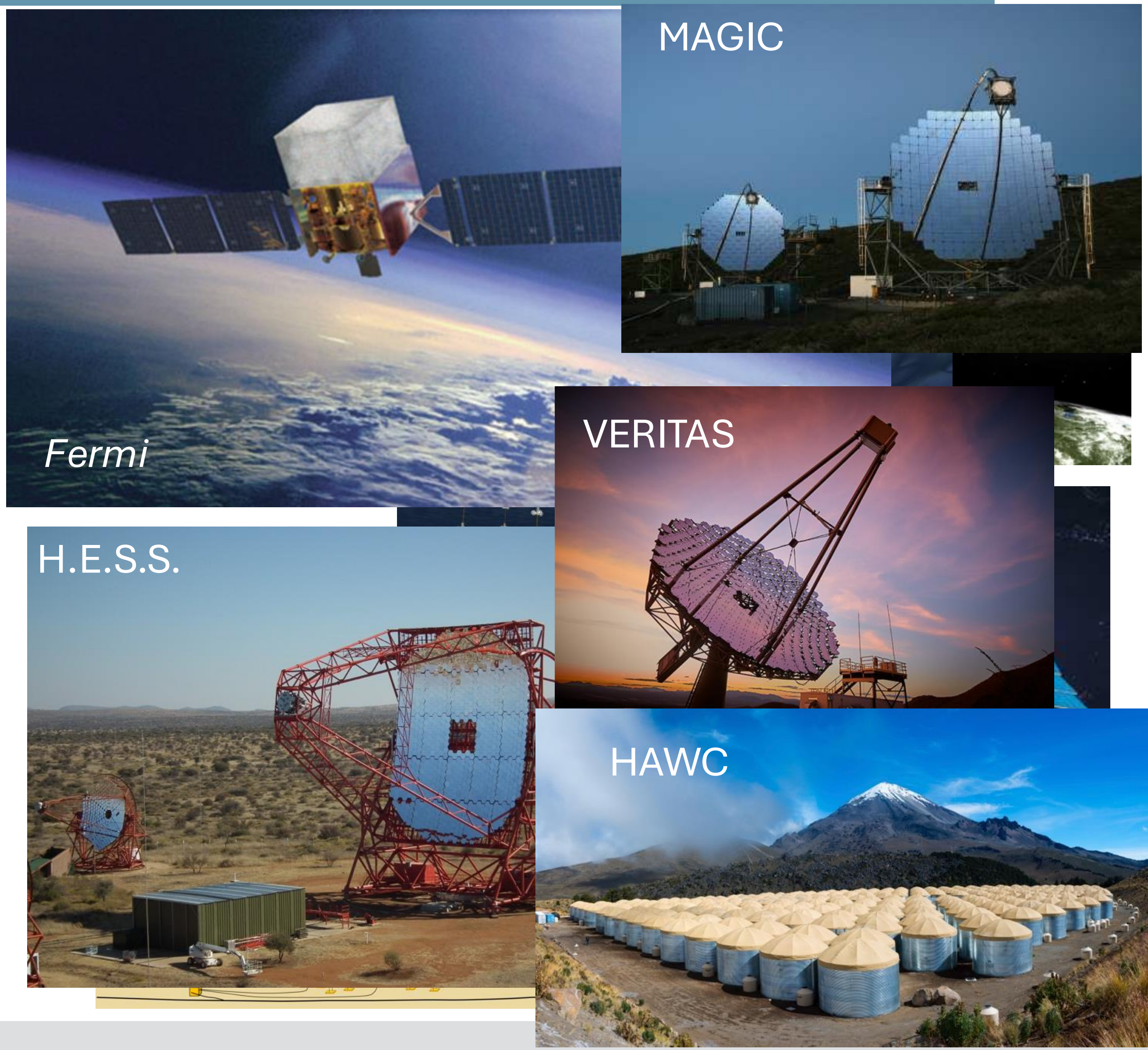
Dark Matter Landscape: An Instrumentationalist's View



WIMPs

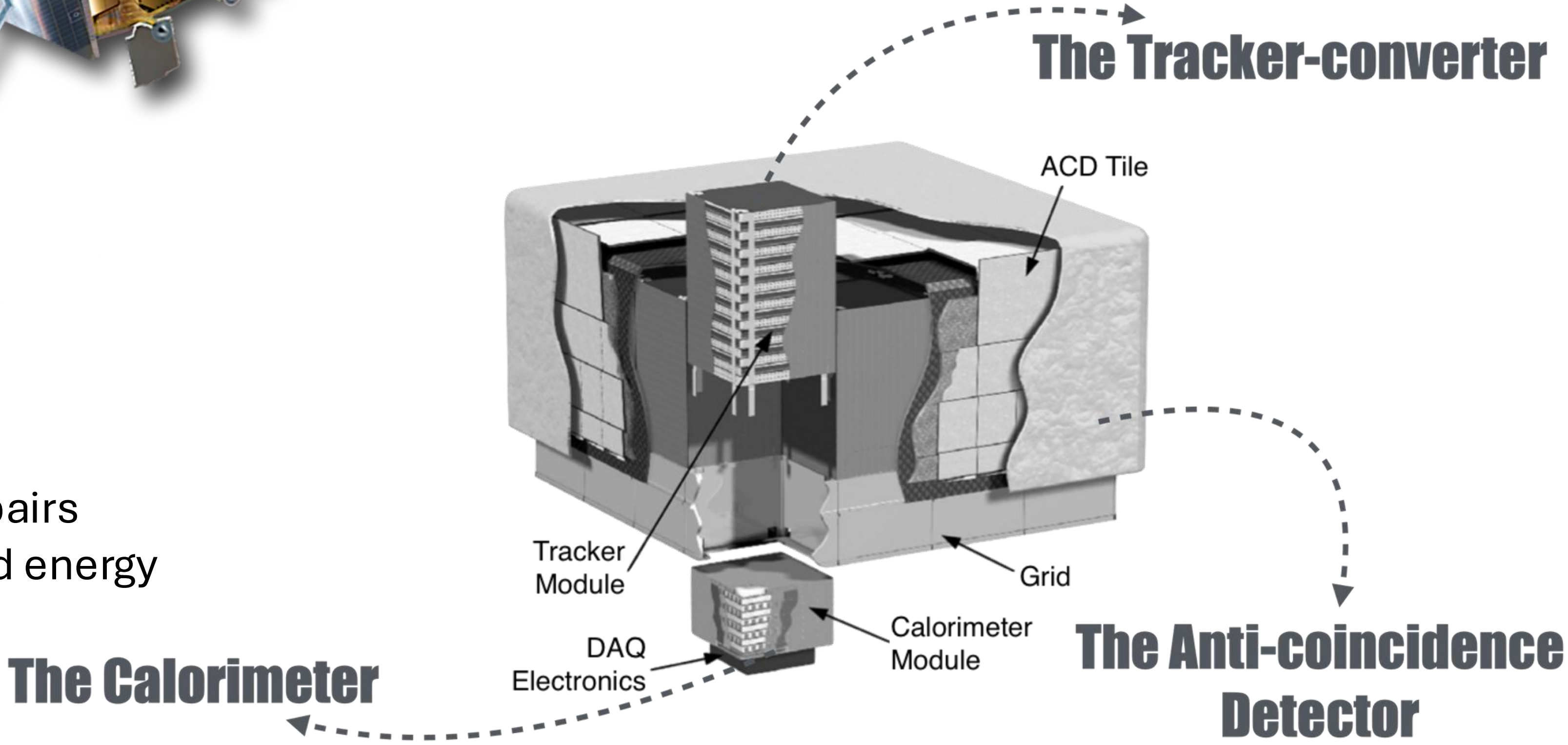
Dark Matter Landscape: An Observer's View





The *Fermi*-LAT

e^+e^- pair-conversion telescope

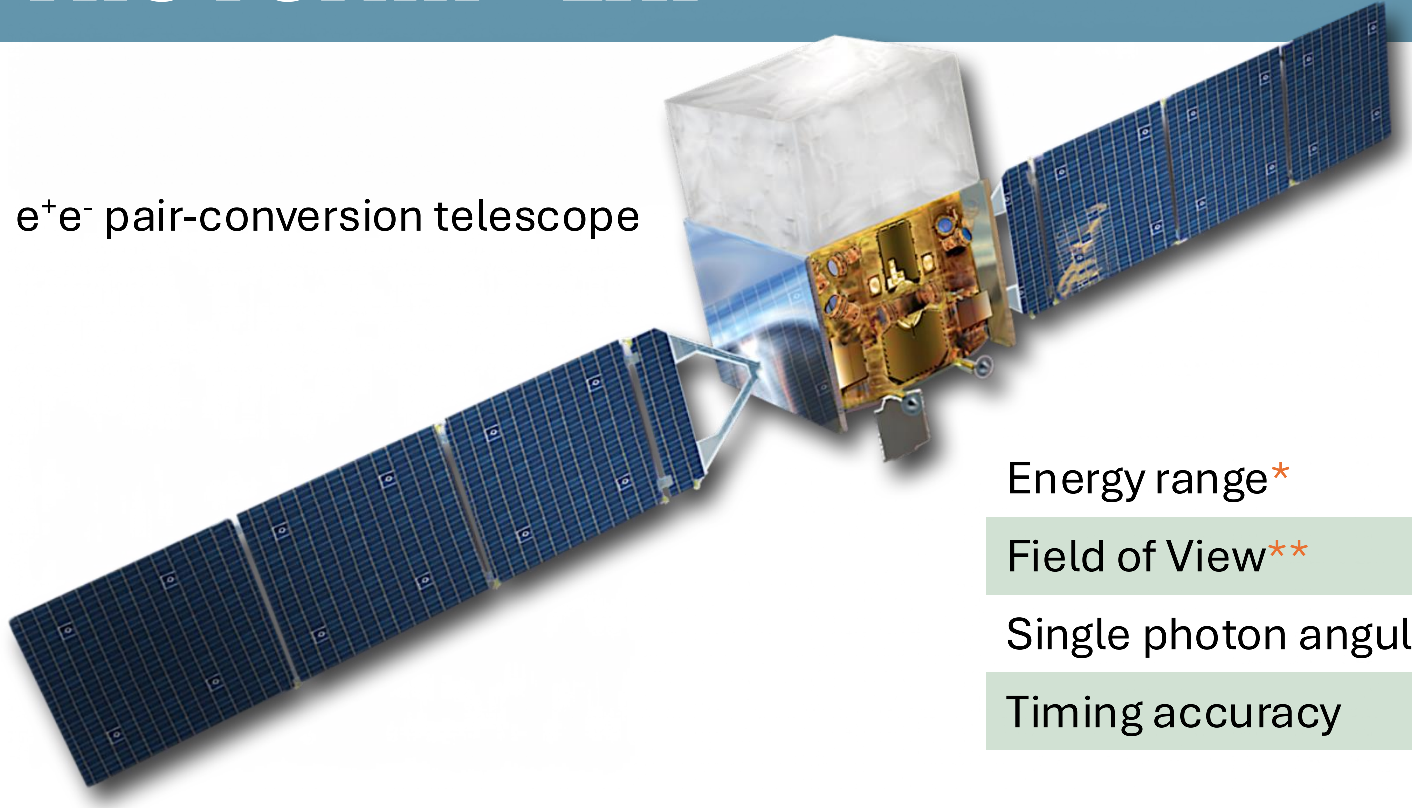


individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

...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

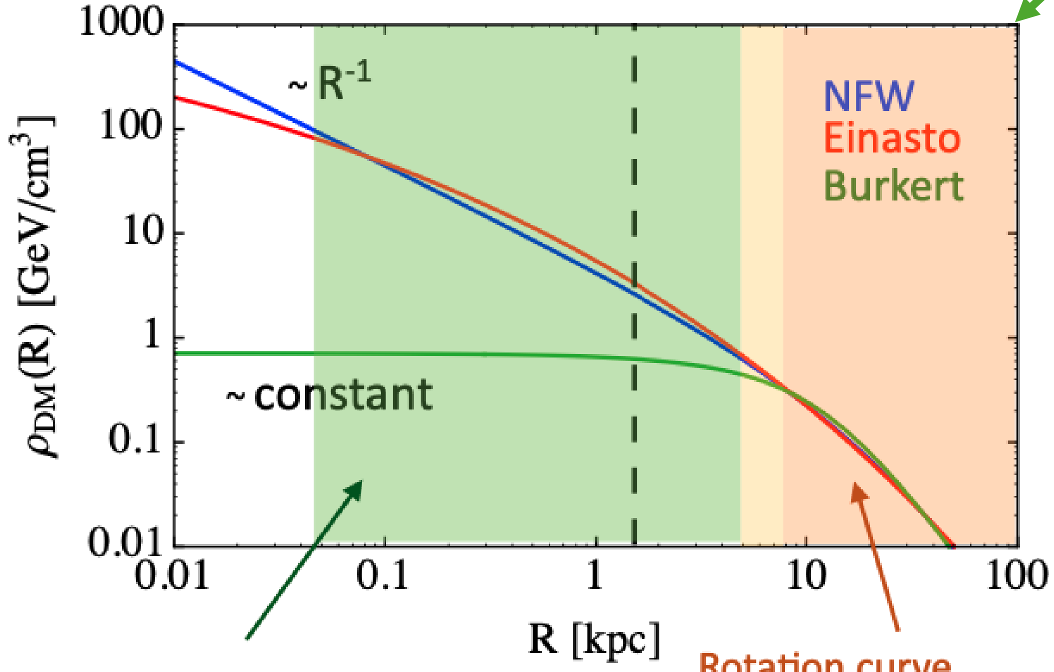
*ideally suited for WIMP searches
**whole sky every ~3 hours
***point-source localization <0.5 arcmin

...it also detects electrons.

Dark Matter Signal

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

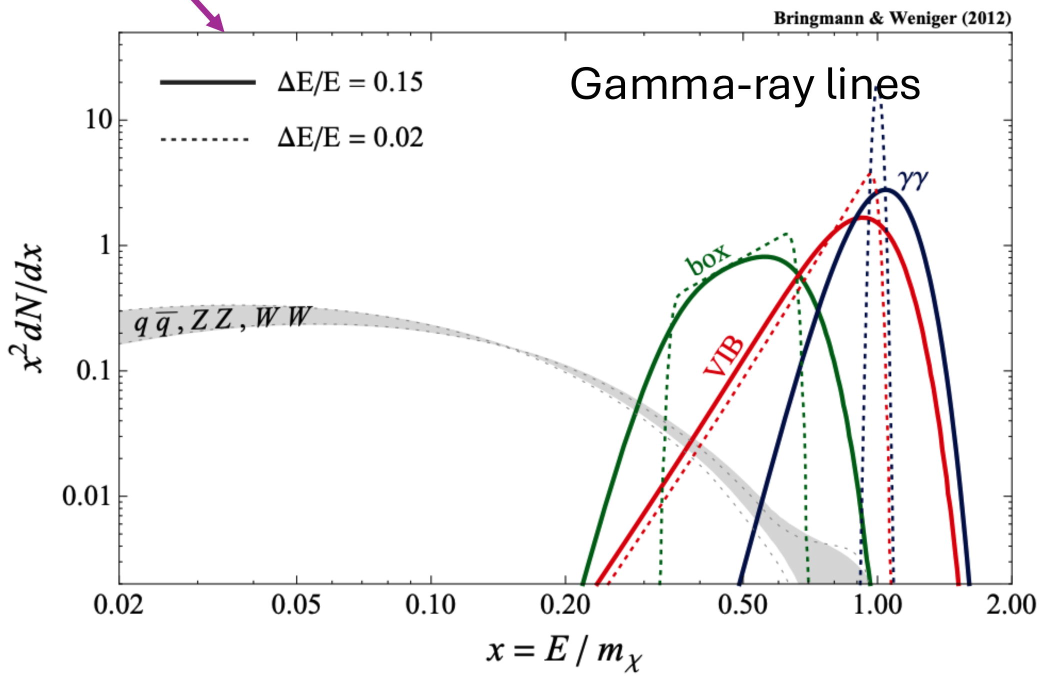
DM γ-ray flux = astrophysics J-factor x particle physics



Simulations w/ baryons
[Schaller+ '16, Calore+ '15]

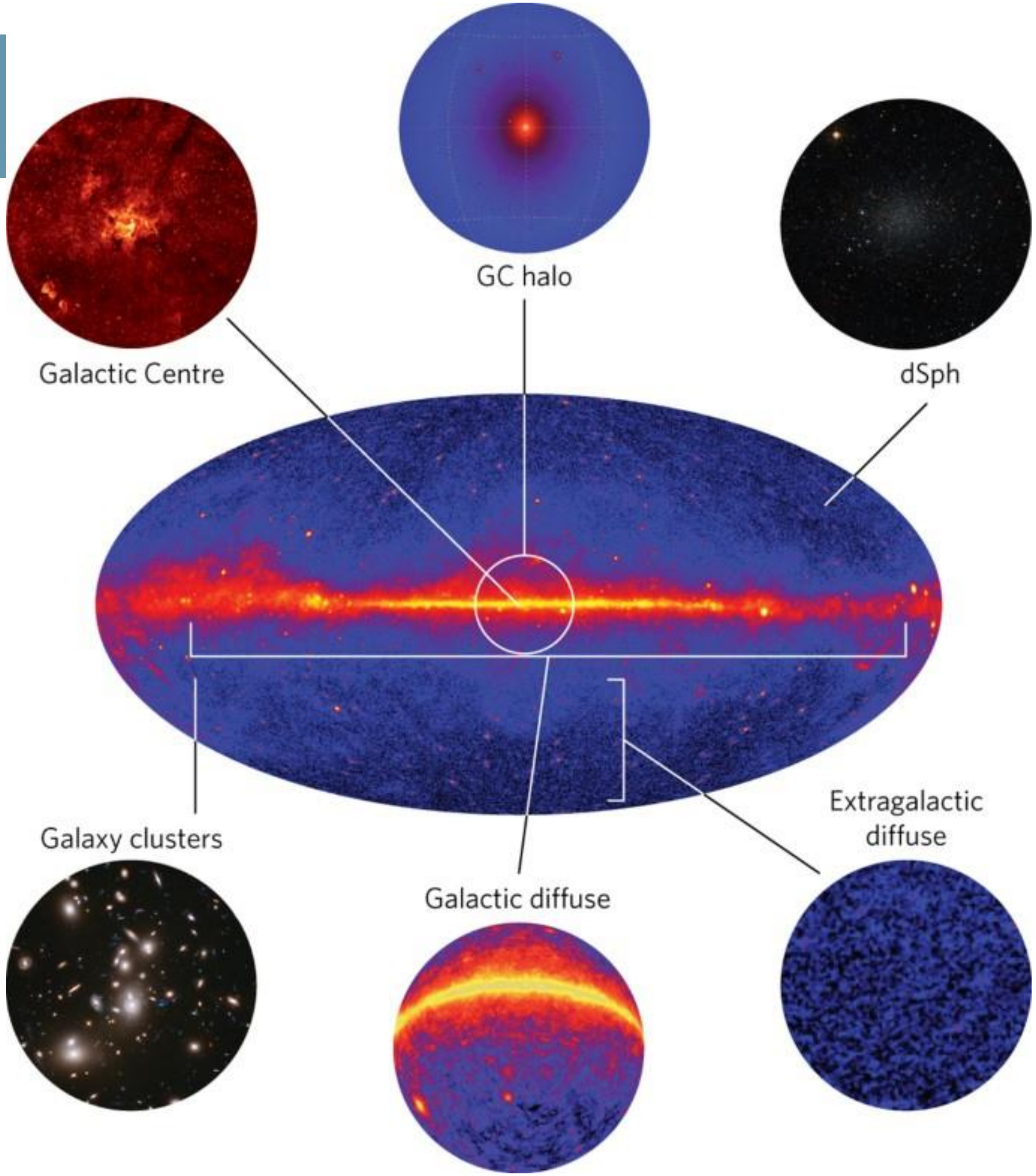
Rotation curve
[Iocco+ '15]

Adapted from F. Calore.



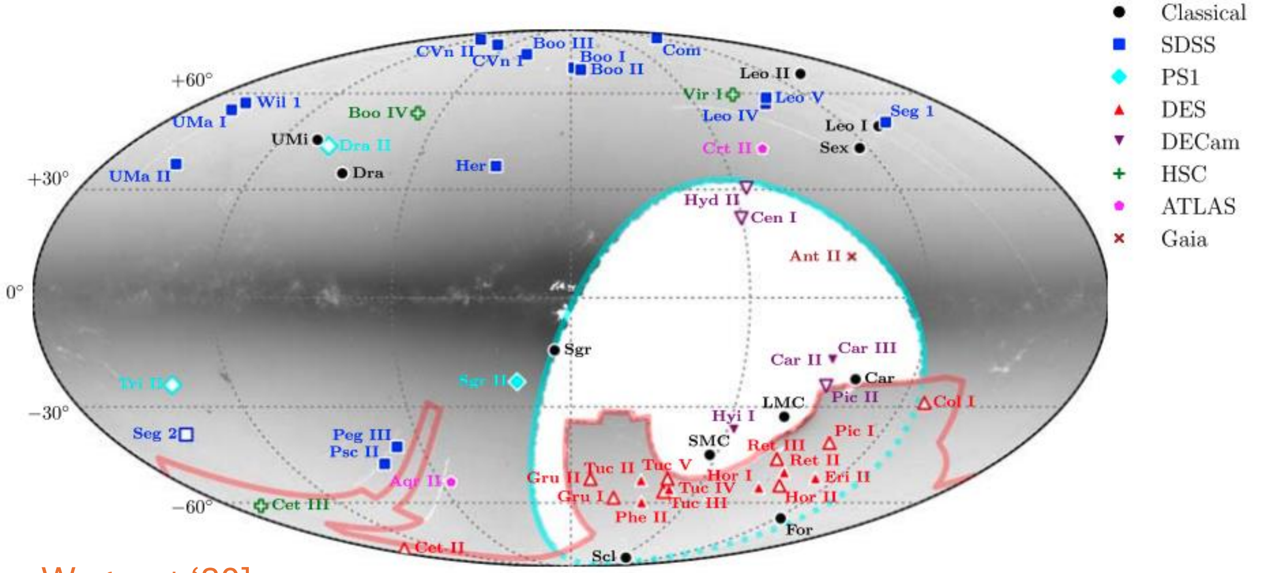
Adapted from Francesca Calore

DM targets



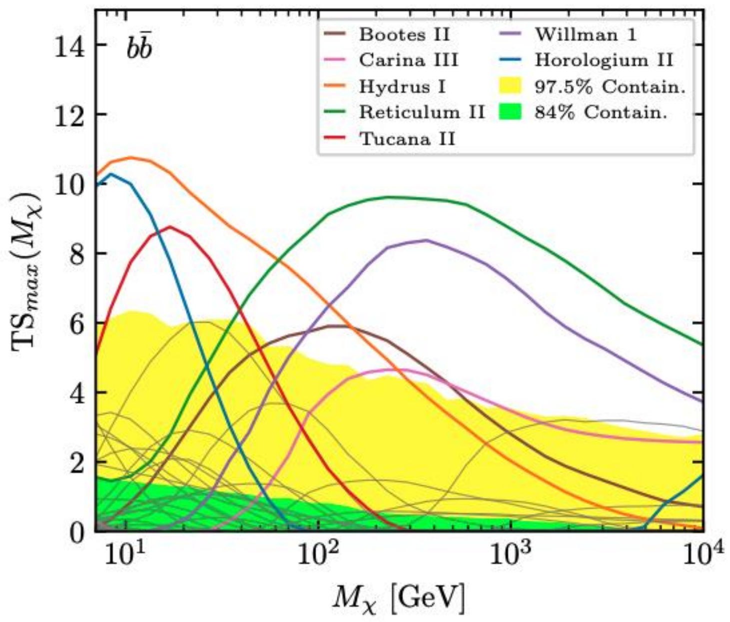
[Conrad & Reimer 2017]

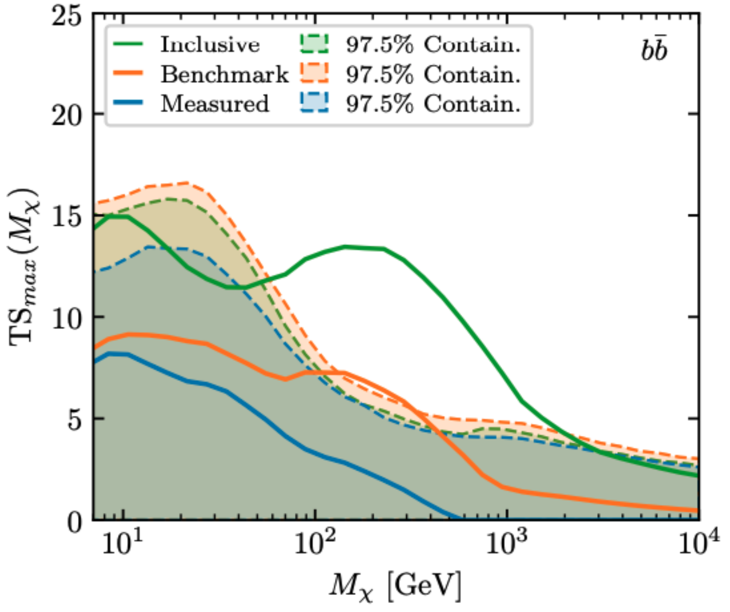
Dwarf Spheroidal Galaxies



[Drlica-Wagner+ '20]

[McDaniel+ LAT '24]



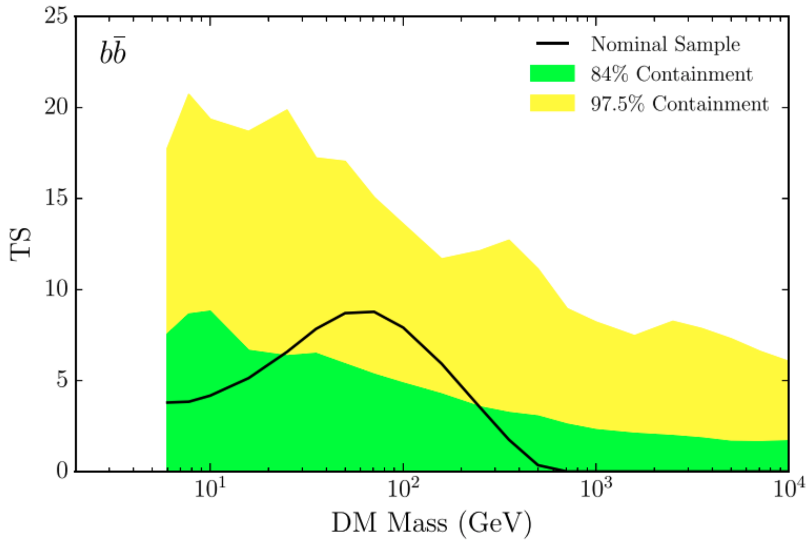


DM γ-ray flux = astrophysics J-factor x particle physics

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

Combined dSph Analyses - Comparison

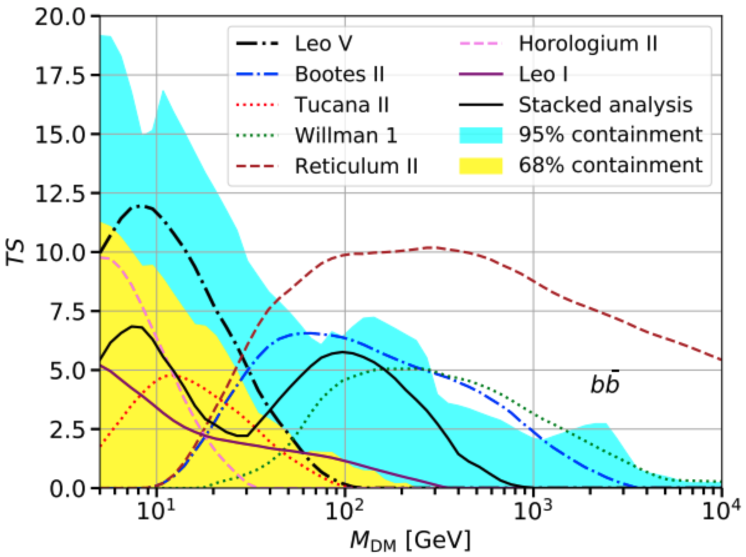
6 years



$< 2\,\sigma$

[Albert+ '17]

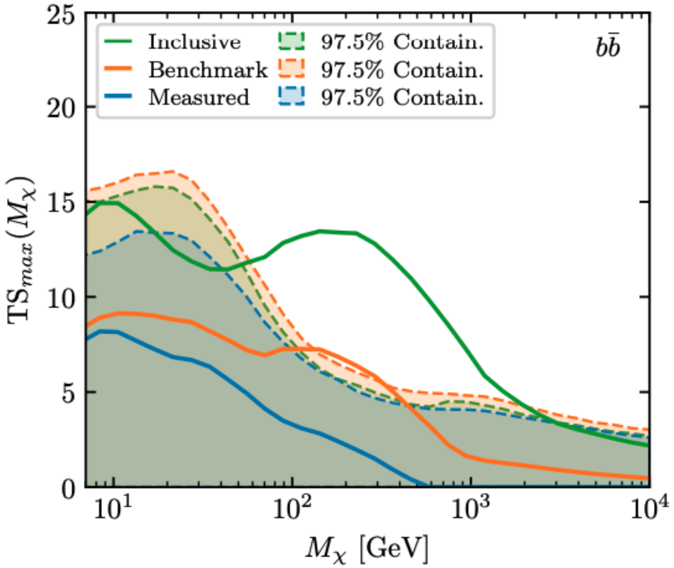
11 years



$\lesssim 2\,\sigma$

[DiMauro+ '21]

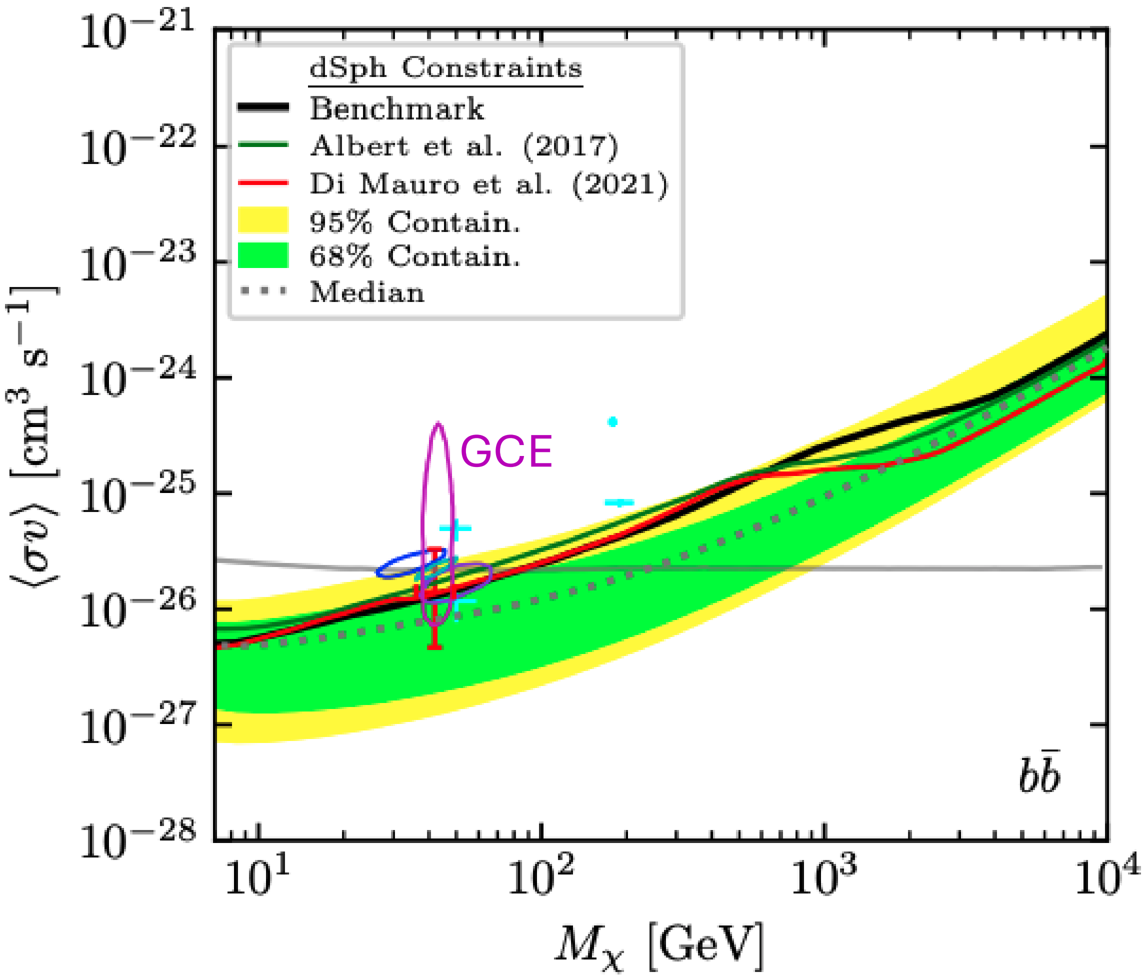
14 years



$\gtrsim 2\,\sigma$

[McDaniel+ '24]

Limits on the parameter space



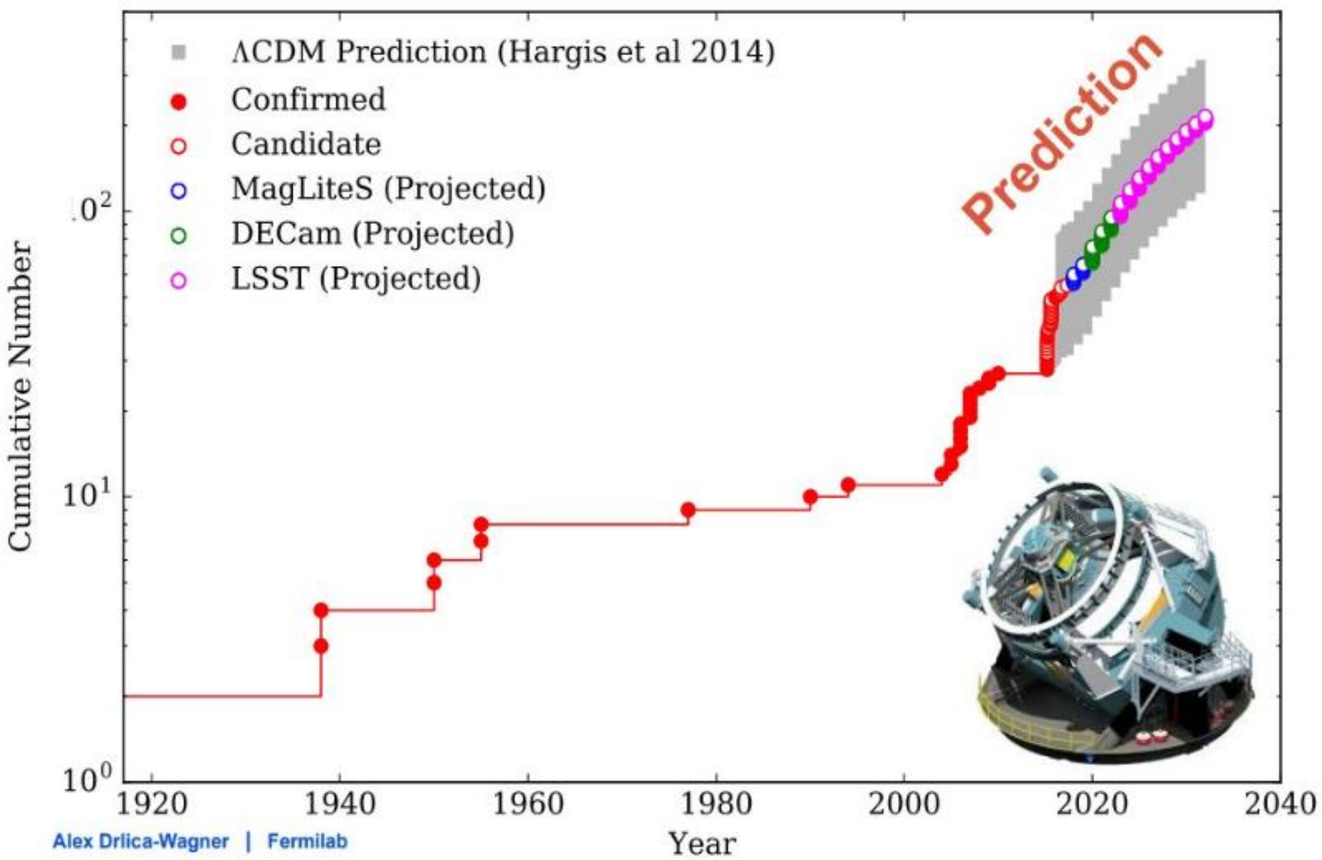
Trials factor reduces significance to 0.5 σ.

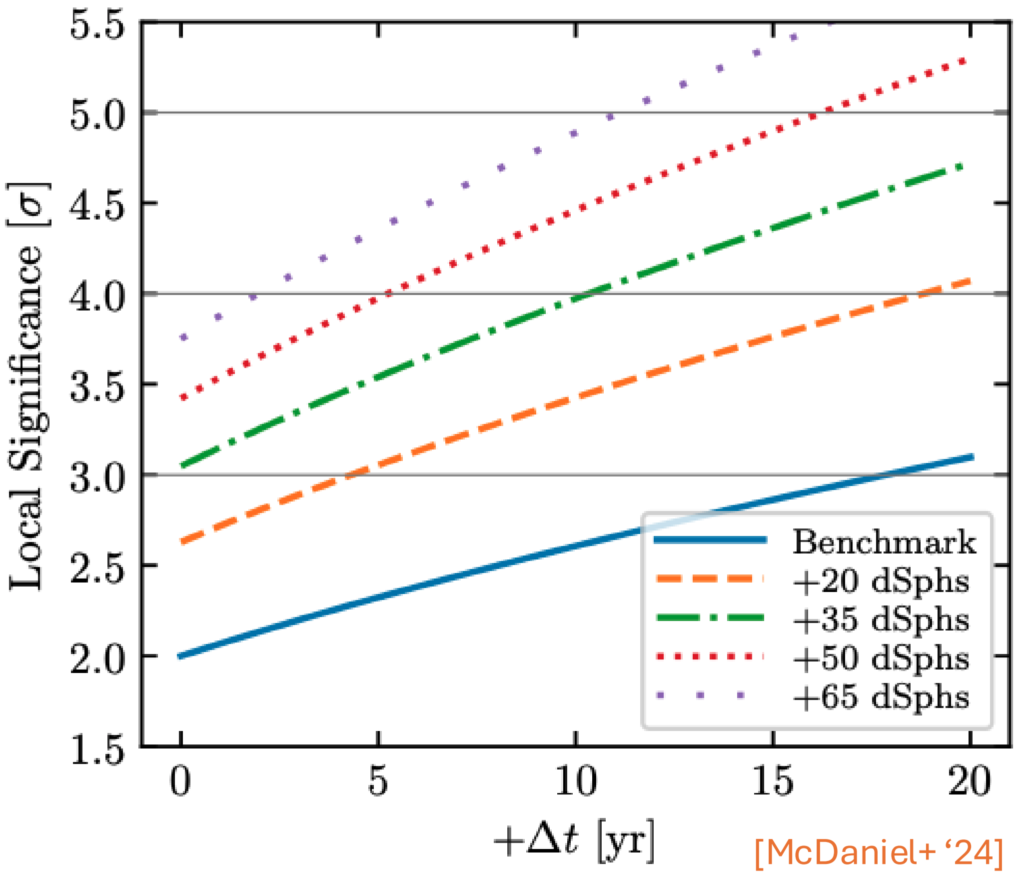
- generally consistent with previous limits; *in tension with the GCE results*

- Can we rule DM out? Not yet.

[McDaniel+ ‘24]

Future of dSph DM searches





[McDaniel+ '24]

How many dwarf galaxies do we *really* need?

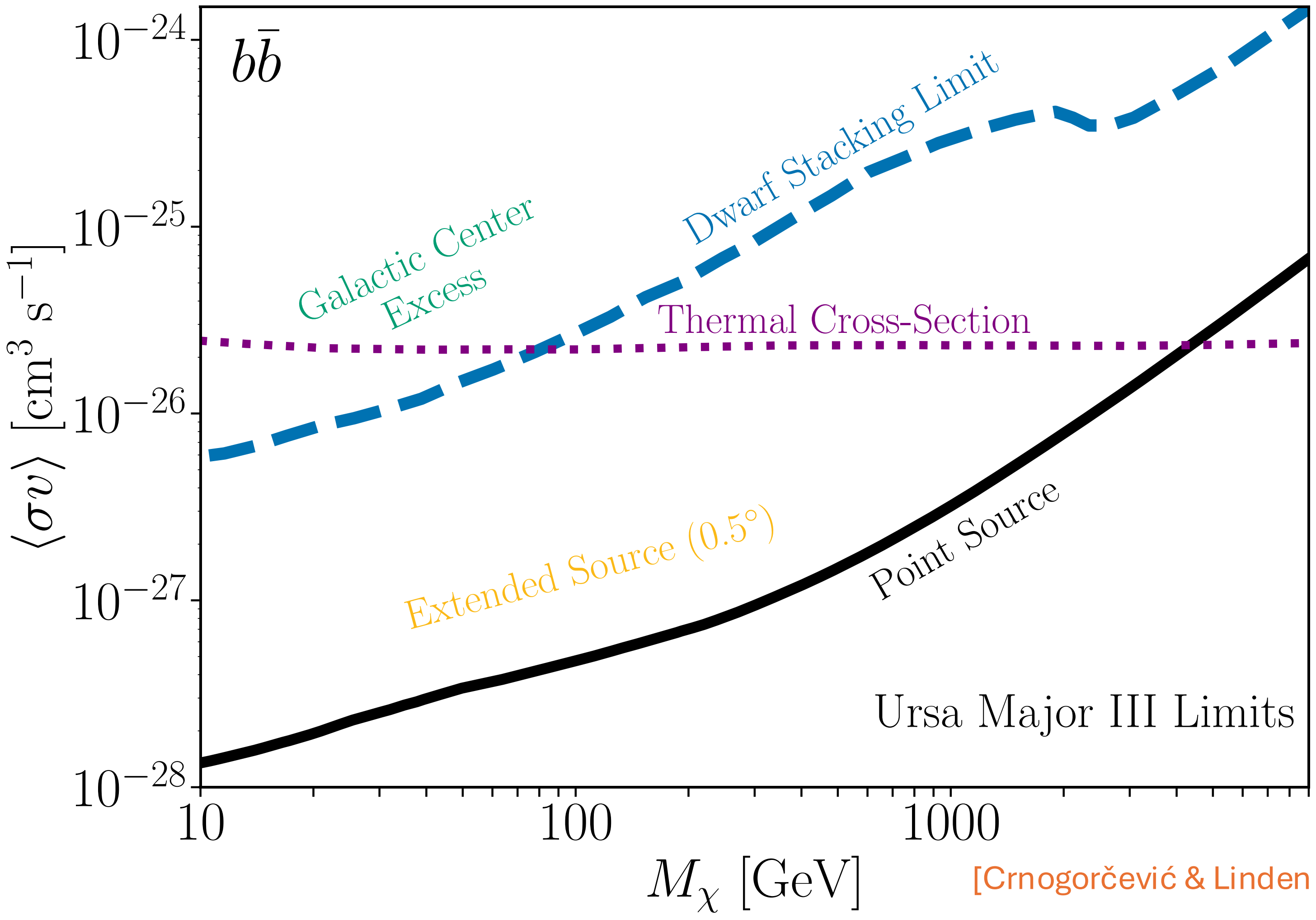
Maybe just one, but a good one?

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]

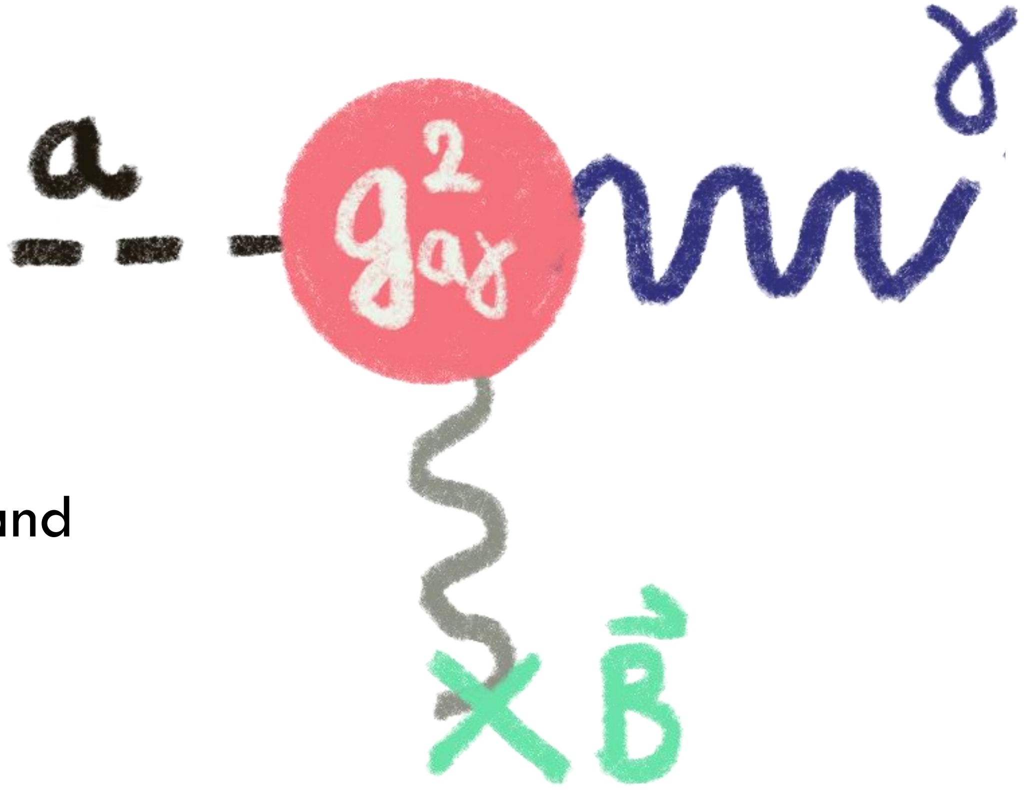
BEYOND WIMPs

Observing ALPs with Gamma Rays

In the presence of an external magnetic field, **B**, axion-like particles (ALPs) undergo a conversion into photons:

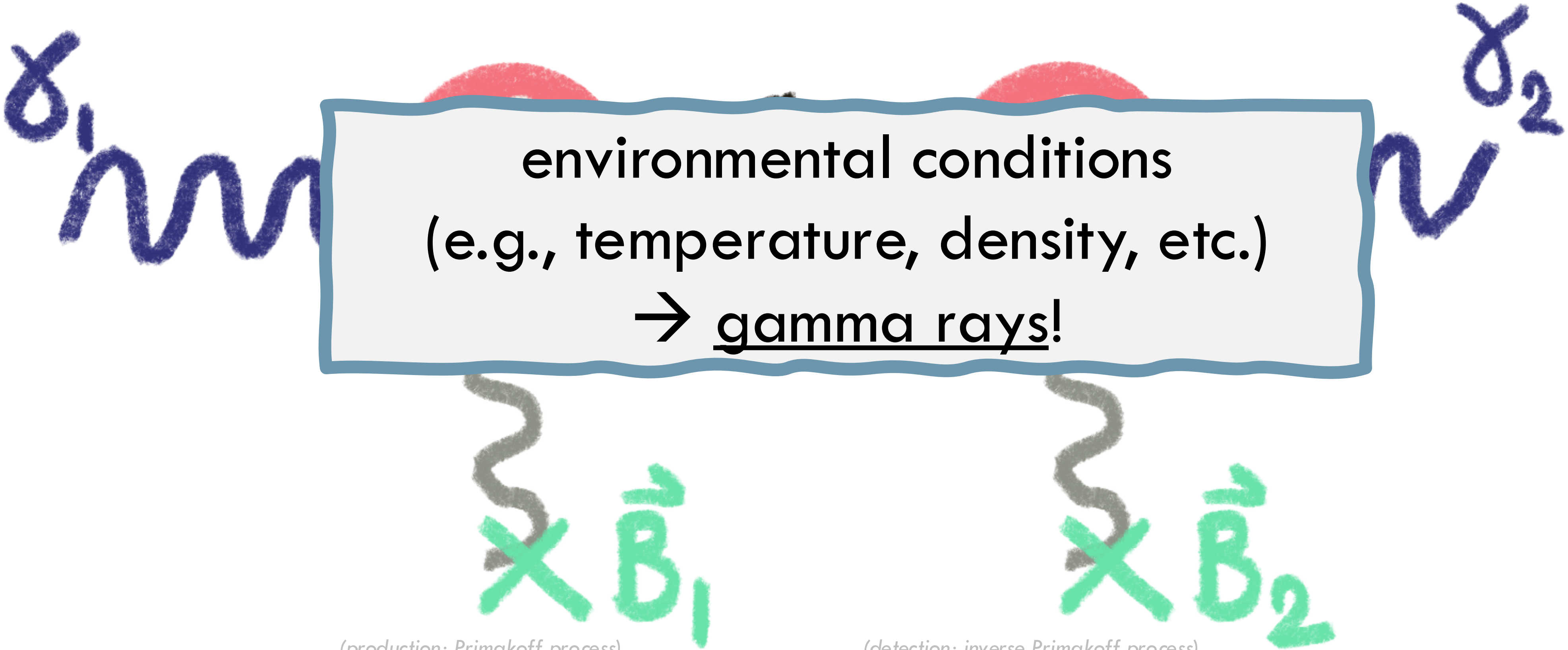
$$\mathcal{L}_{a\gamma} \supset g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

where $g_{a\gamma}$ is ALP-photon coupling rate, and a is the ALP field strength.



Observing ALPs with Gamma Rays

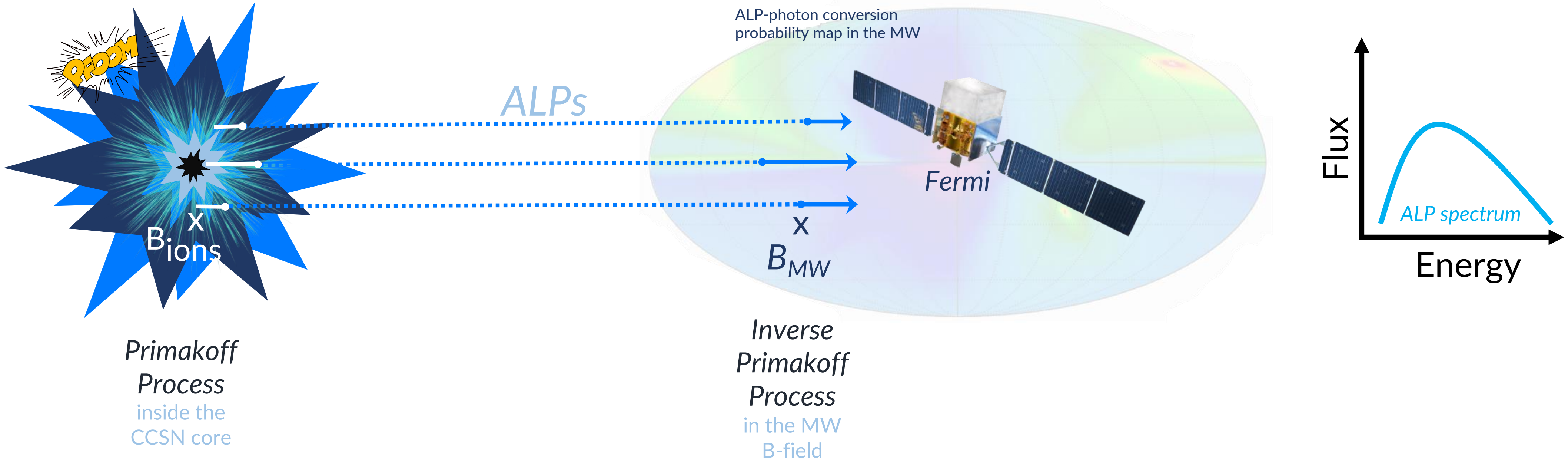
Primakoff process: converting ALPs into photons



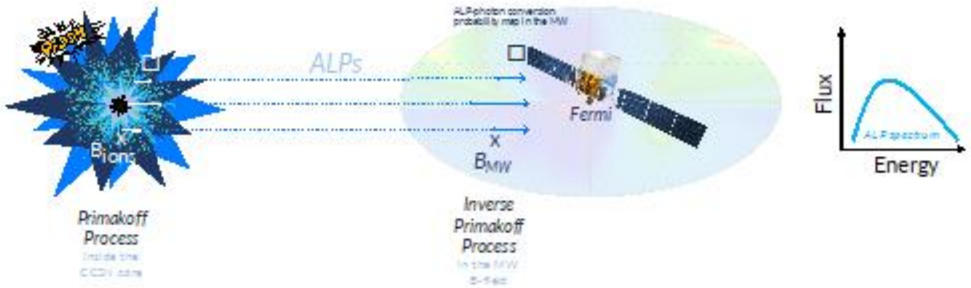
environmental conditions
(e.g., temperature, density, etc.)
→ <u>gamma rays</u>!

(production: Primakoff process)

(detection: inverse Primakoff process)



ALP-photon conversion
probability map in the MW
ALPs
Fermi
x
B_{ions}
x
B_{MW}
Primakoff
Process
inside the
CCSN core
Inverse
Primakoff
Process
in the MW
B-field
Flux
Energy
ALP spectrum


ALPs
ALP-photon conversion probability map in the MW
Fermi
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Primakoff Process
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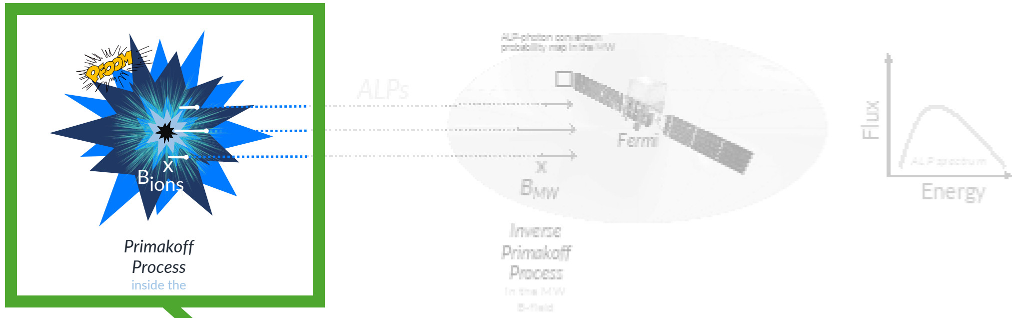
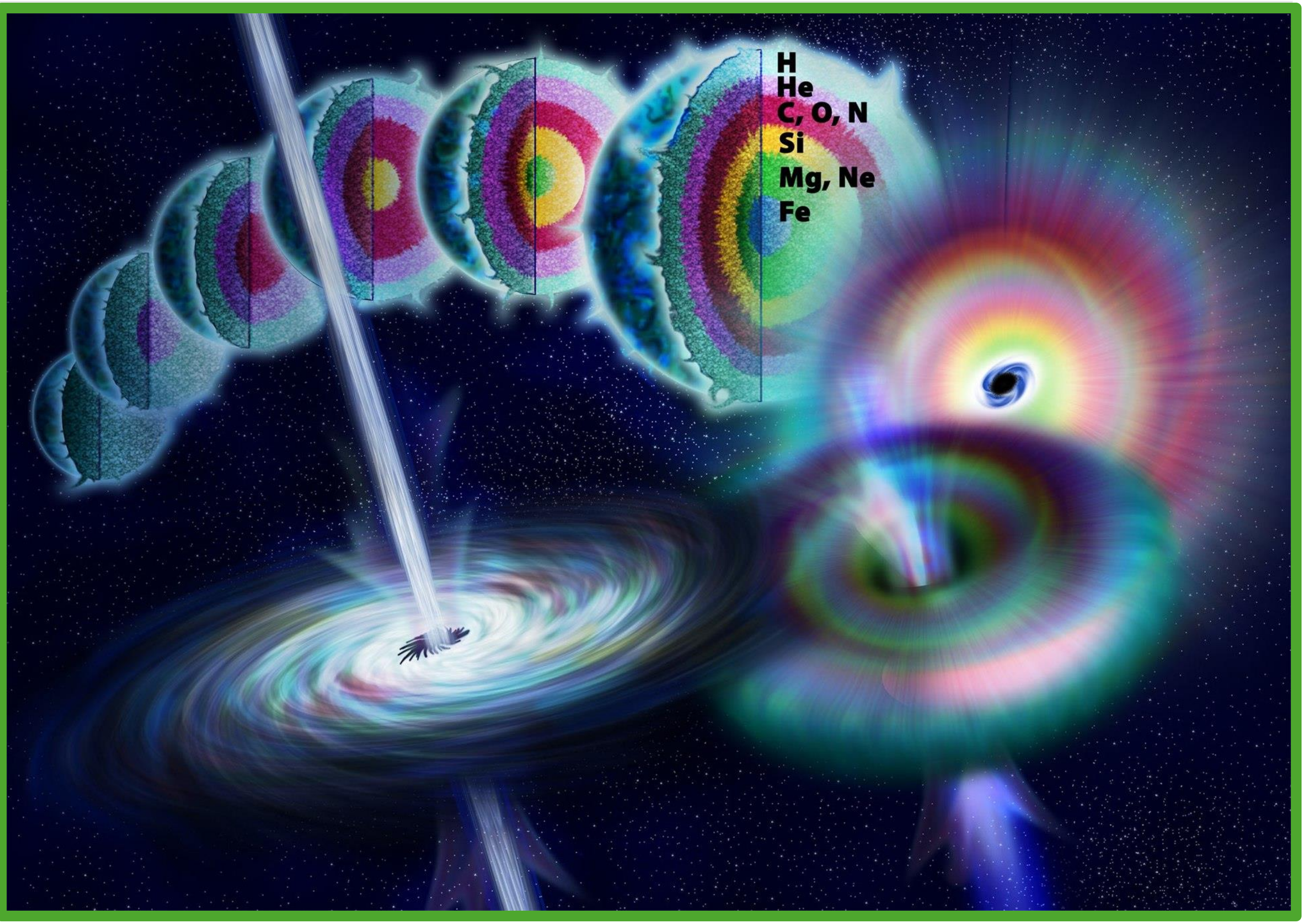
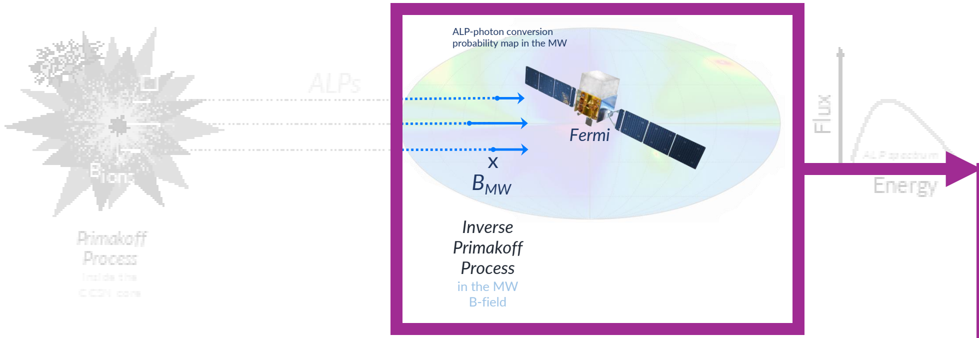
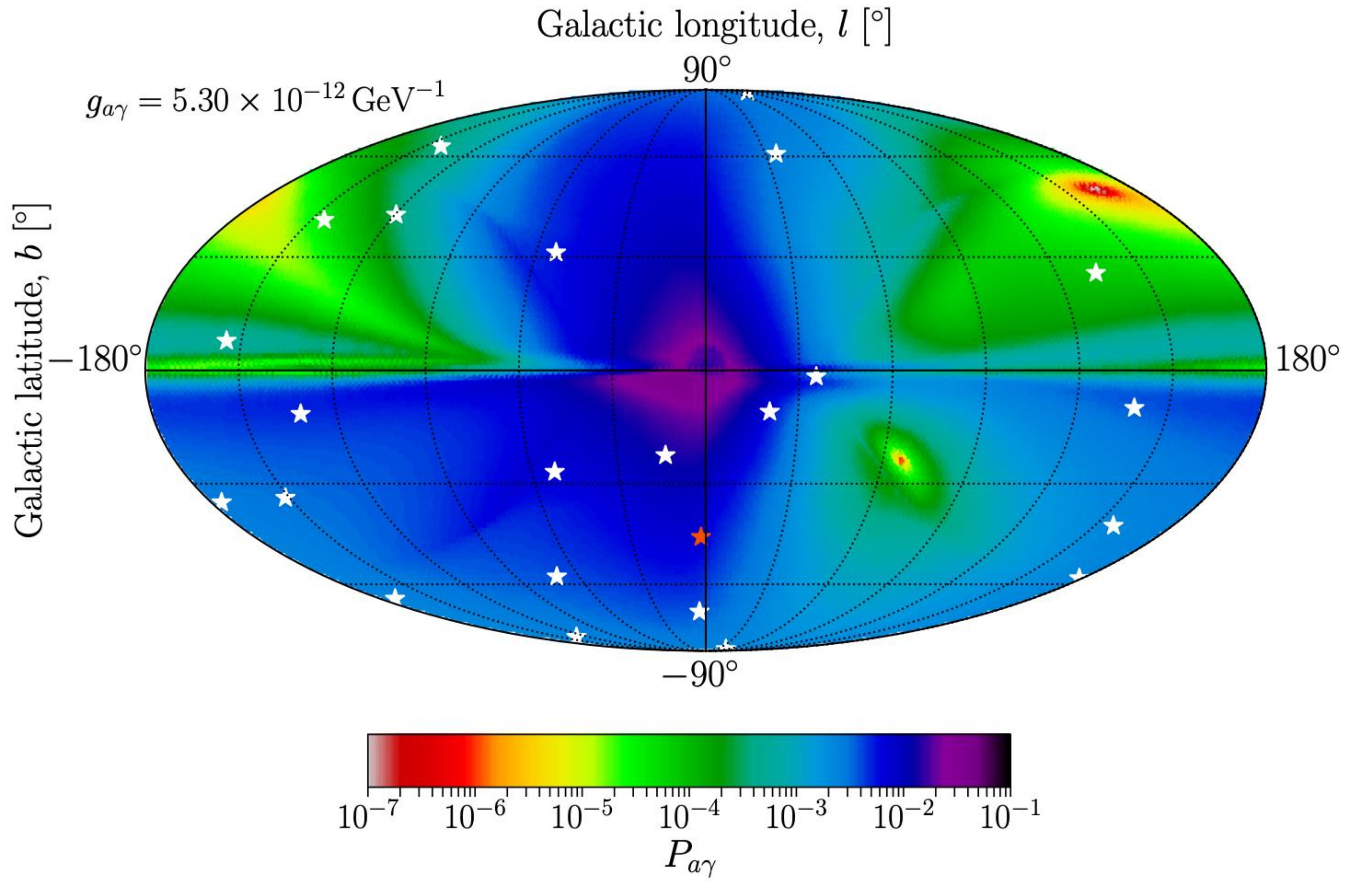


CCSN --- Long Gamma-ray Burst relationship



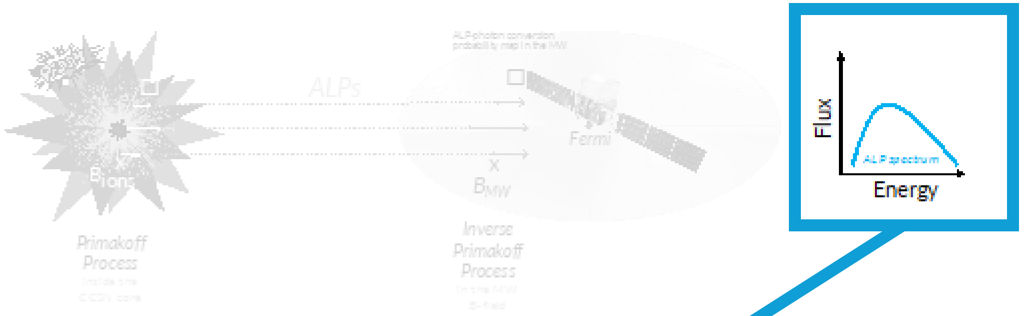


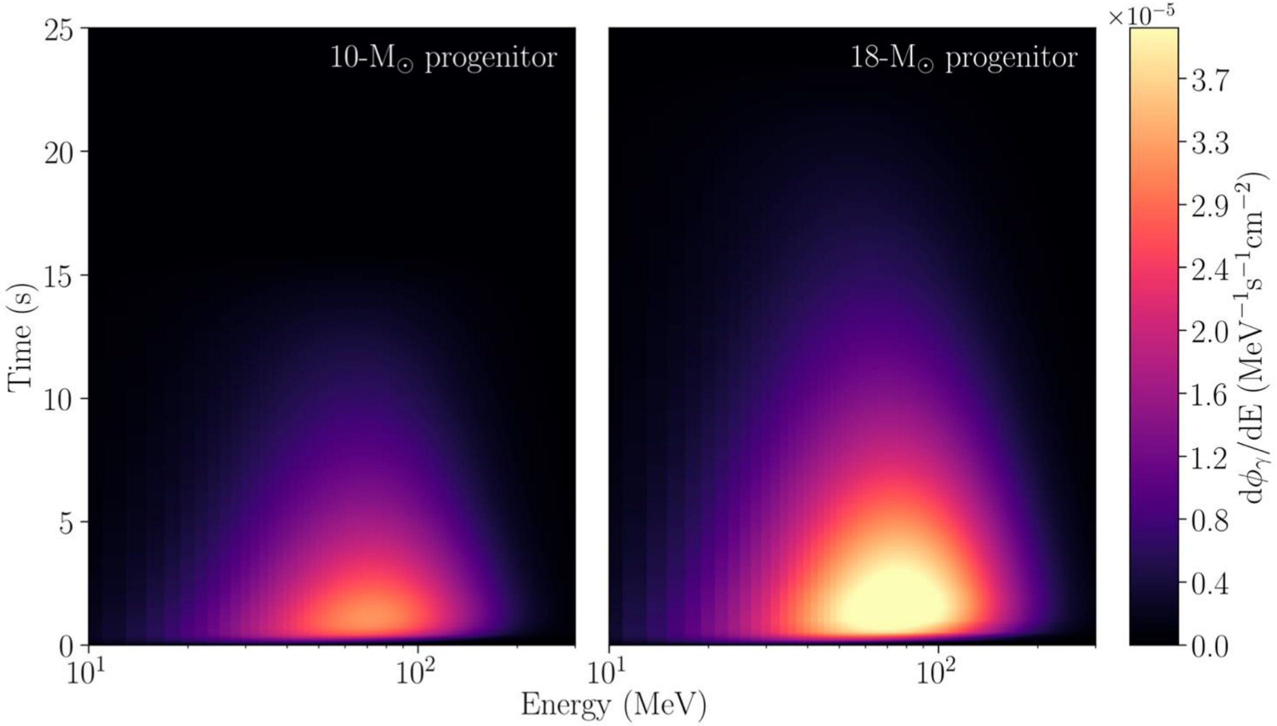
Assumptions: magnetic fields: only considering the MW magnetic field, neglecting IGMF



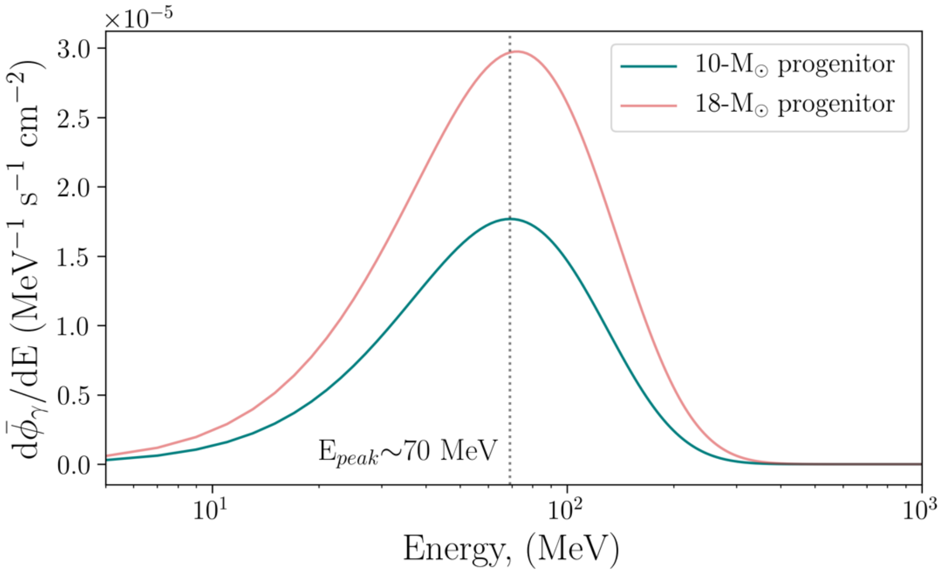
ALP-photon conversion probability map in the Milky Way's magnetic field.

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.





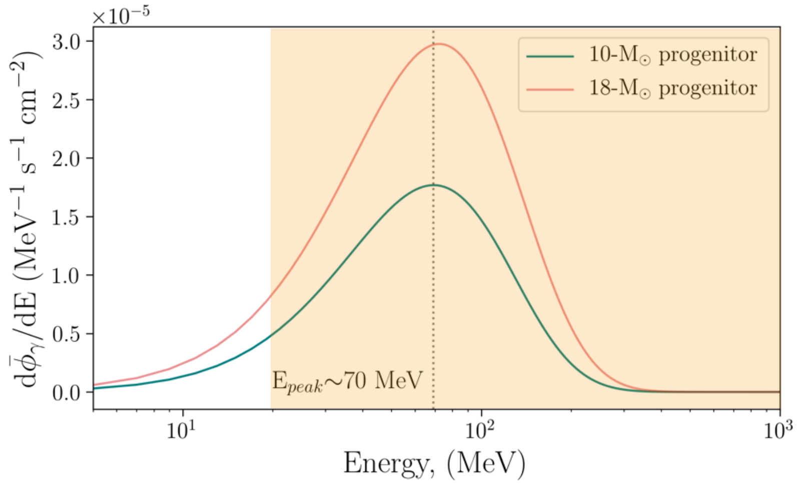
The observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a 10 and 18-$M_\odot$ progenitor.

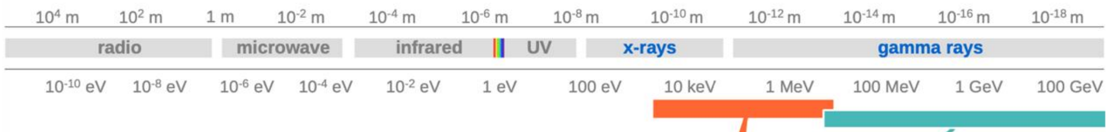


The observed ALP-induced gamma-ray spectrum for 10 and 18-$M_\odot$ progenitors averaged over 10 seconds.

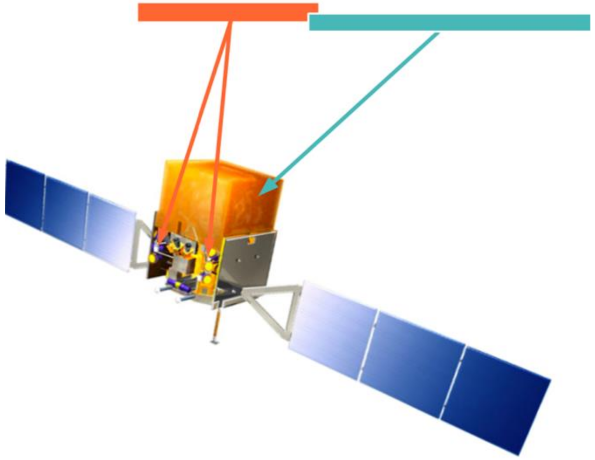
LAT Low Energy Technique (LLE)

ALP spectrum





GBM Gamma-ray Burst Monitor
12 (NaI) + 2 (BGO) detectors
FoV: entire unocculted sky
8 keV to 40 MeV
2300+ bursts (~1 every day or two)



LAT Large Area Telescope
Pair-production telescope
FoV: 2.4 sr (~20% of sky)
~20 MeV to >300 GeV

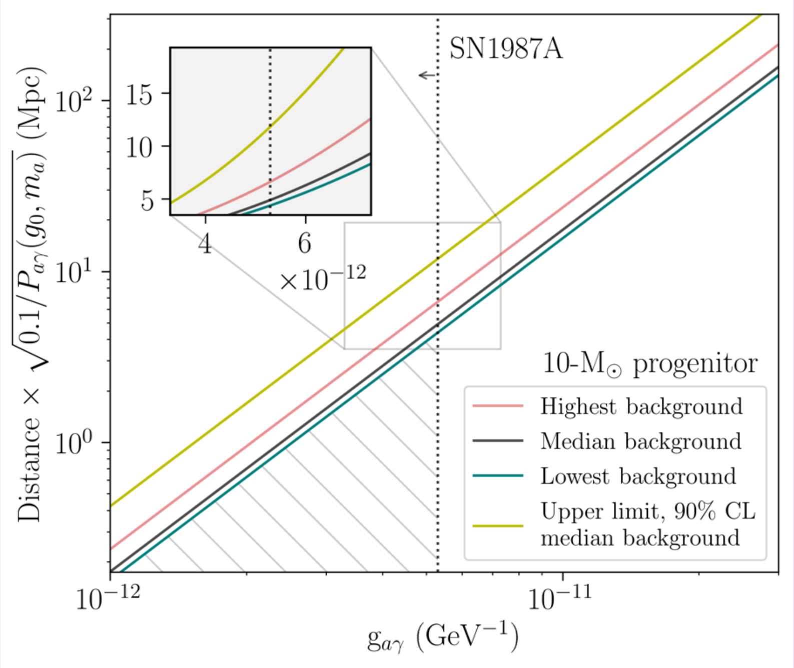
- Standard LAT analysis: >100 MeV vs. LLE
- LLE: maximizing the effective area of the LAT instrument in the low-energy regime
- More signal, but also more background

QUESTION 1: *HOW SENSITIVE IS LLE TO DETECTING AN ALP BURST?*

Reported in: Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

How sensitive is LLE to detecting ALPs?

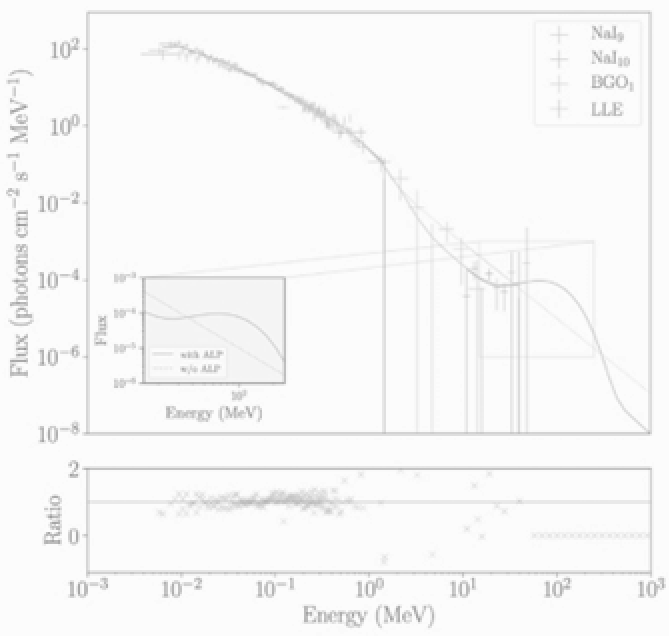
Fermi-LLE Sensitivity



- LLE can reach up to ~10 Mpc (comparable to the standard LAT analysis)
- Results strongly driven by the dominating background & decreased A_{eff} at high incidences
- *Method: signal injection simulations*

Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

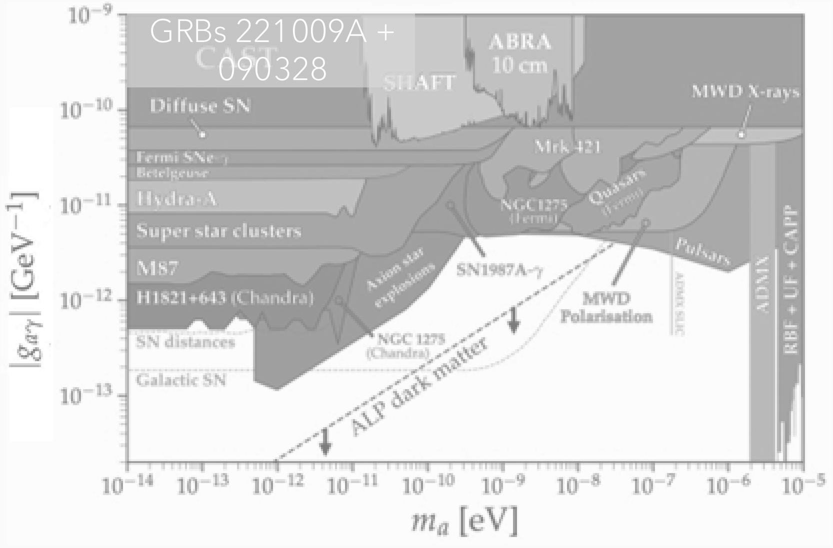
GRB searches



- No excess signal found.
- 24 long GRBs that pass the selection criteria.
- GRB 101123A at ~2.4 σ. Trials factor → p~0.3.
- *Method: model comparison*

Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

GRB Precursors



- No significant detections.
- From the ALP amplitude we calculate upper limits.
- *Method: model comparison*

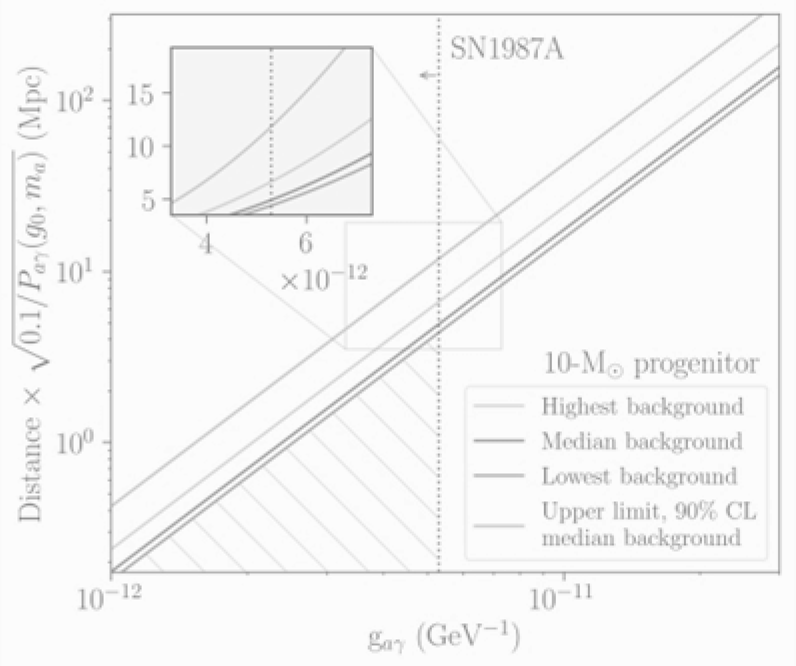
Crnogorčević et al. 2023 (under review)

QUESTION 2: *HAVE WE ALREADY SEEN ANY ALP EMISSION IN LLE GRBS?*

Reported in: Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

Have we already seen some emission from the GRBs?

Fermi-LLE Sensitivity



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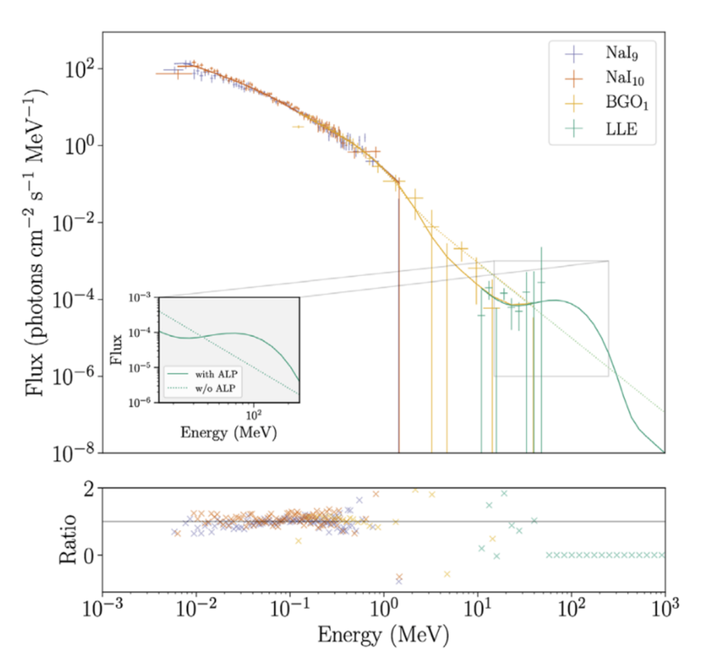

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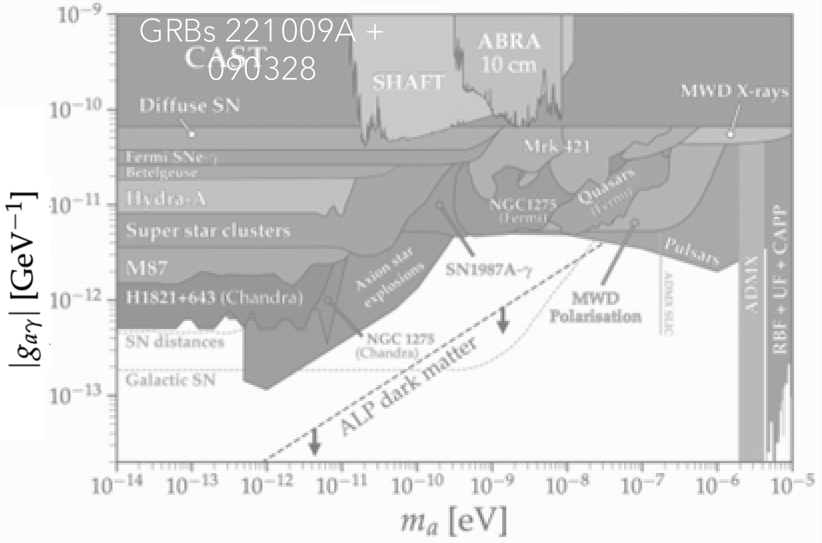


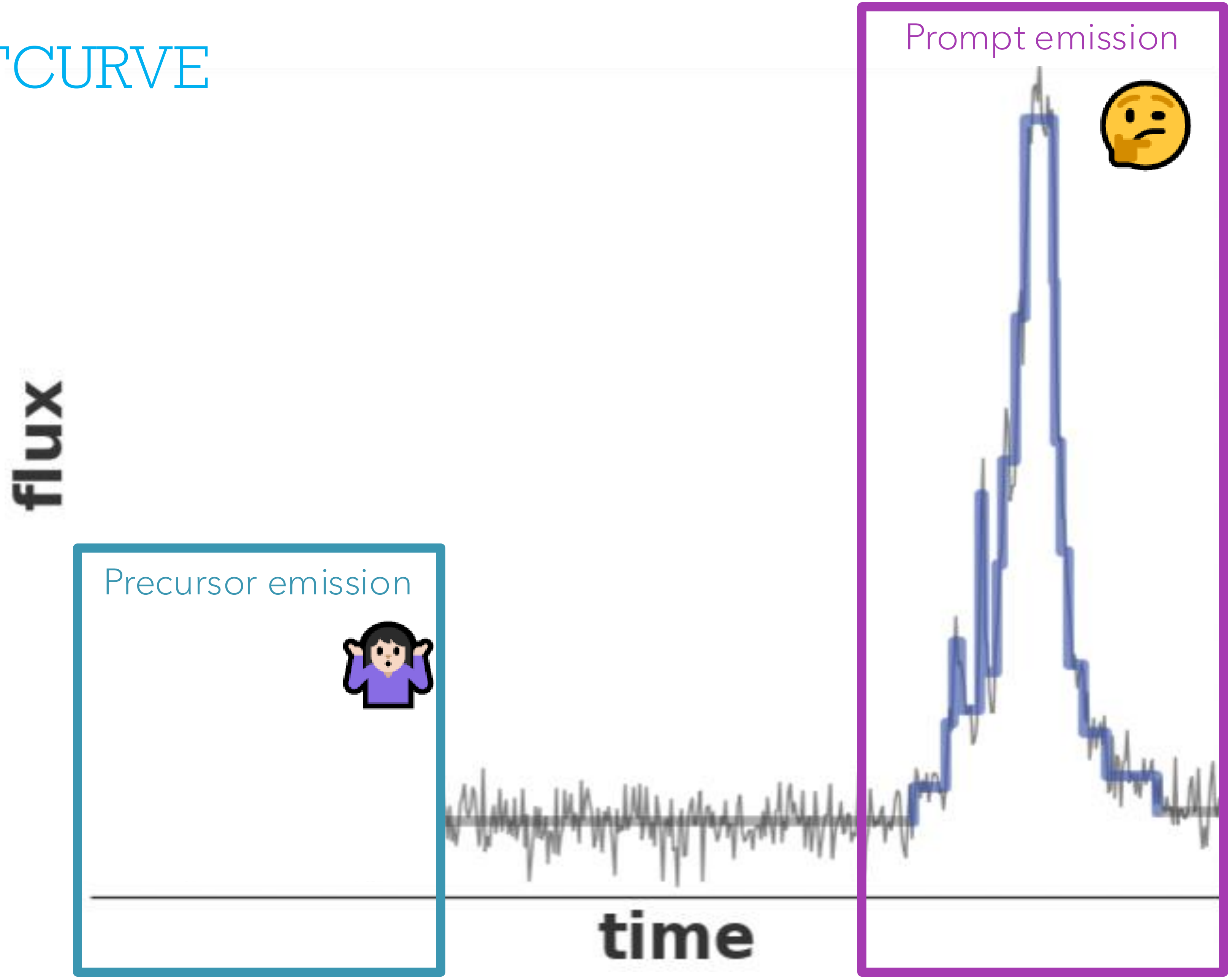
- No significant detections.
- From the ALP amplitude we calculate upper limits.
- *Method: model comparison*

Crnogorčević et al. 2023 (under review)

QUESTION 3: *WHEN SHOULD WE SEARCH FOR ALPS FROM GRBS?*

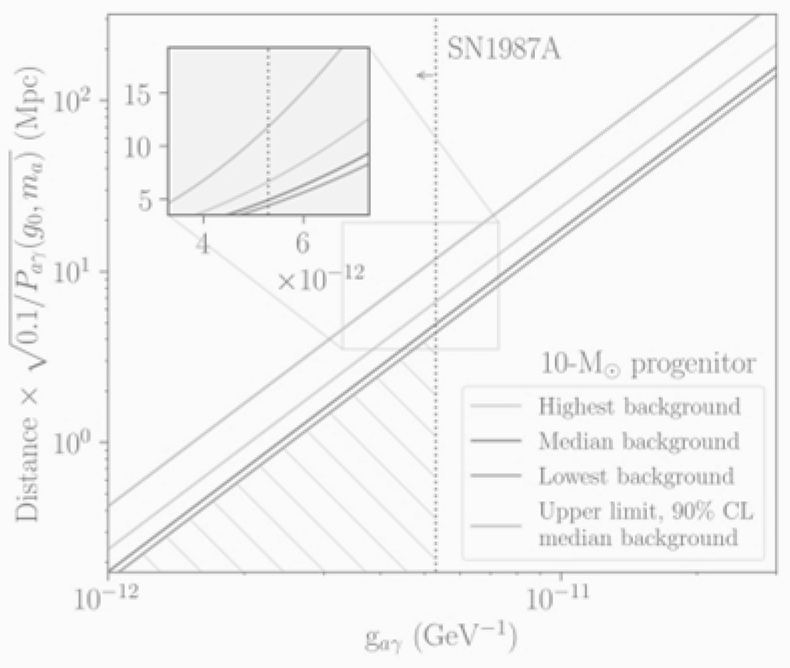
Fermi GI Program, Cycle 15; PI: Crnogorčević

GRB LIGHTCURVE



What about precursor emission?

Fermi-LLE Sensitivity



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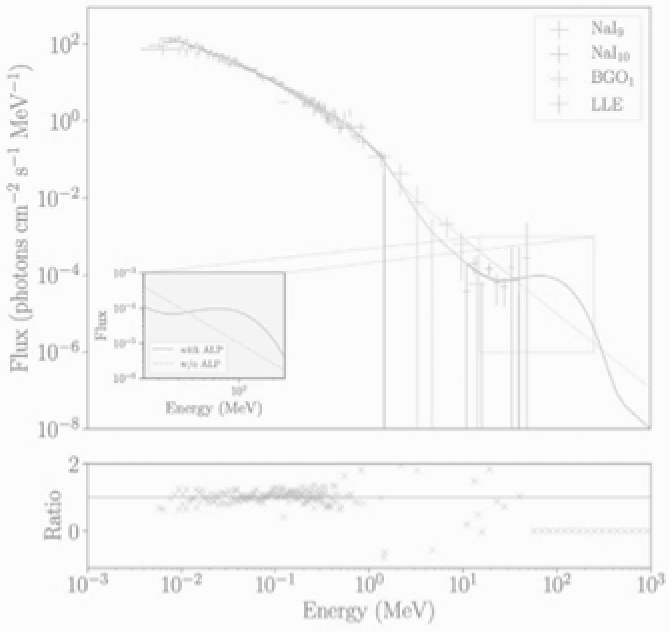

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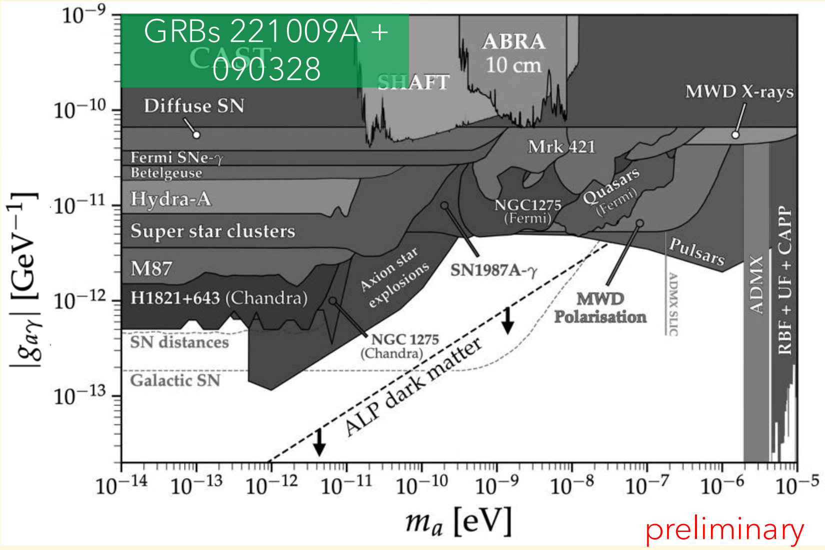

- No significant detections.
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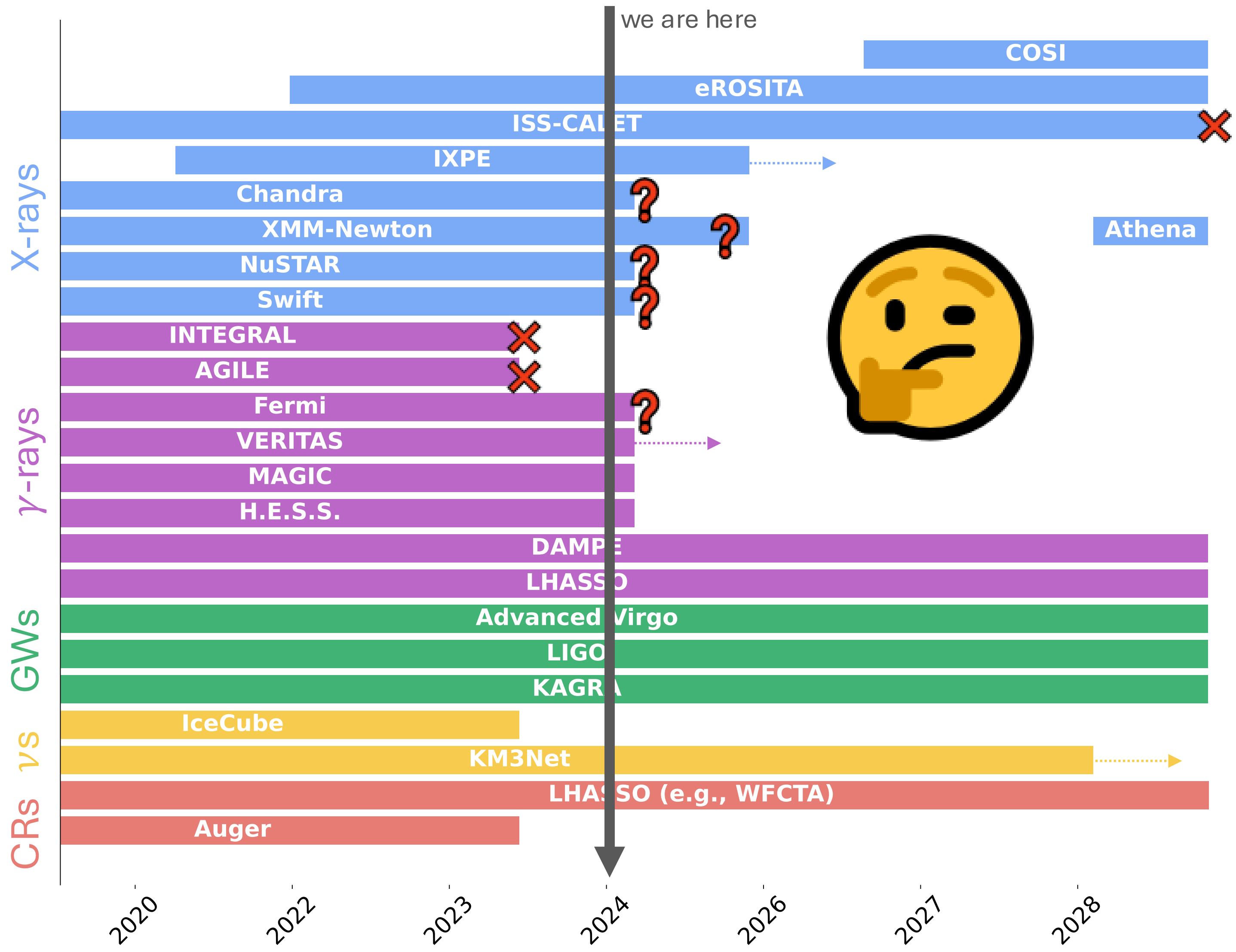
Crnogorčević et al. 2023 (under review)

Where next?

Dark Matter Landscape: An Instrumentationalist's View



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

Conclusions

- Gamma-ray observations provide unique tests for different dark matter and new physics 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:*** https://pcos.gsfc.nasa.gov/sags/figsag.php