



# New Messengers & New Physics

## *A Survey of the High-energy Universe*

Dissertation Presentation at HEAD 21

Milena Crnogorčević (she/her)

Postdoctoral Fellow at the Oskar Klein Centre

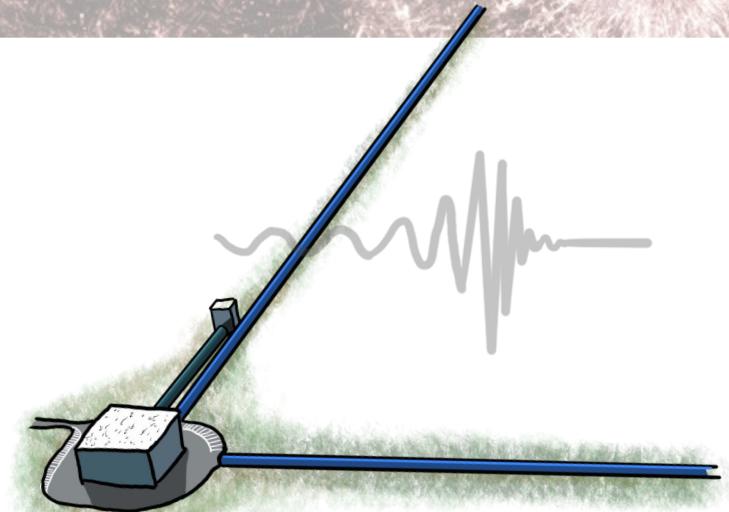
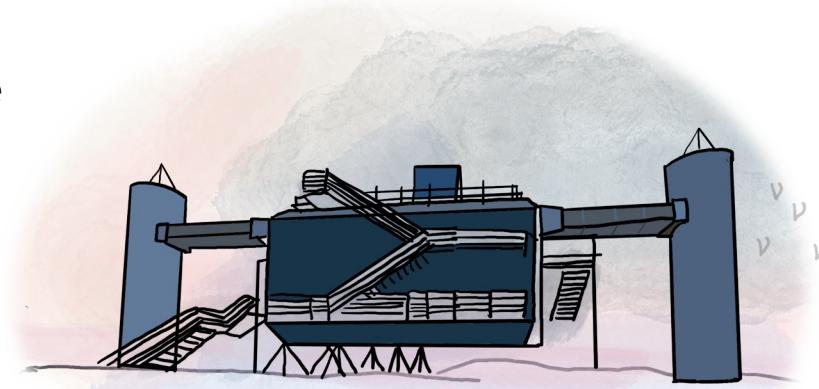
[milena.crnogorcevic@fysik.su.se](mailto:milena.crnogorcevic@fysik.su.se)

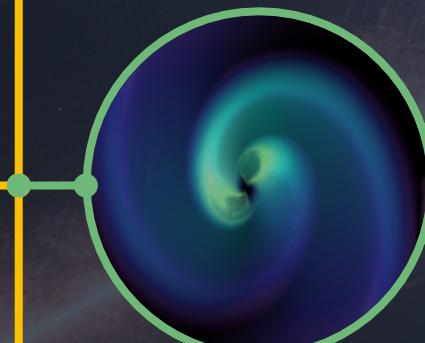
PhD Advisor: Dr. Regina Caputo

Work done with the support of:



DEPARTMENT OF  
ASTRONOMY

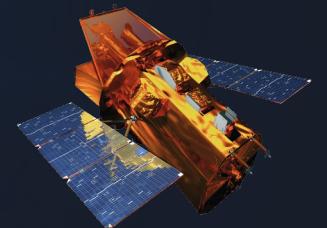




New Physics: ALPs x  $\gamma$



New Messengers I: GWs x  $\gamma$



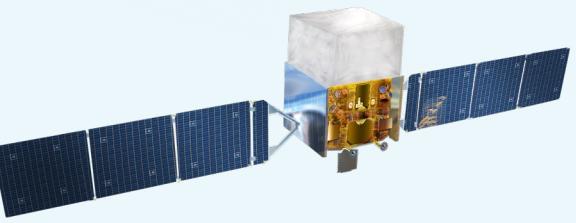
New Messengers II:  $\nu$  x  $\gamma$



## Dedication

To all the curious kids  
with a fire in their belly  
and a tremble in their voice

# OBSERVATORIES

Fermi	Swift	LIGO/Virgo/KAGRA	IceCube
			
<p><b>GBM: Gamma-ray Burst Monitor</b></p> <ul style="list-style-type: none"><li>• FoV: entire unocculted sky</li><li>• 8 keV to 40 MeV</li><li>• 2300+ bursts (~1 every day or two)</li></ul> <p><b>LAT: Large Area Telescope</b></p> <ul style="list-style-type: none"><li>• Pair-production telescope</li><li>• FoV: 2.4 sr (~20% of sky)</li><li>• 20 MeV to &gt;300 GeV</li></ul>	<p><b>BAT: Burst Alert Telescope</b></p> <ul style="list-style-type: none"><li>• One of three instruments onboard</li><li>• FoV: ~ 2 sr</li><li>• Localization ~few arcmin</li><li>• 15 keV to 150 keV</li></ul>	<ul style="list-style-type: none"><li>• <b>LIGO</b>: detectors in Hanford, WA, and Livingston, LA</li><li>• <b>Virgo</b>: Cascina, Italy</li><li>• <b>KAGRA</b>: Gifu Prefecture, Japan</li></ul> <ul style="list-style-type: none"><li>• Michelson interferometer gravitational wave detectors</li></ul>	<ul style="list-style-type: none"><li>• Neutrino detector located at the South Pole</li><li>• 5,000+ optical modules</li><li>• ~10 GeV to &gt;1 EeV</li><li>• All-sky (Northern vs. Southern hemisphere)</li></ul>

GBM: C. Meegan et al. 2009, LAT: Atwood et al. 2009

Barthelmy et al. 2005

The LVK Collaboration (Abbott et al. 2009)

The IceCube Collaboration (Aartsen et al. 2017)

## CHAPTERS III-IV

SEARCHING FOR AXION-LIKE PARTICLES WITH *FERMI*

## CHAPTER V

A JOINT *FERMI* & *SWIFT* ANALYSIS OF THE THIRD  
GRAVITATIONAL-WAVE OBSERVING RUN

## CHAPTER VI

CROSS-CORRELATING ICECUBE NEUTRINOS AND THE  
*FERMI* UNRESOLVED GAMMA-RAY SKY

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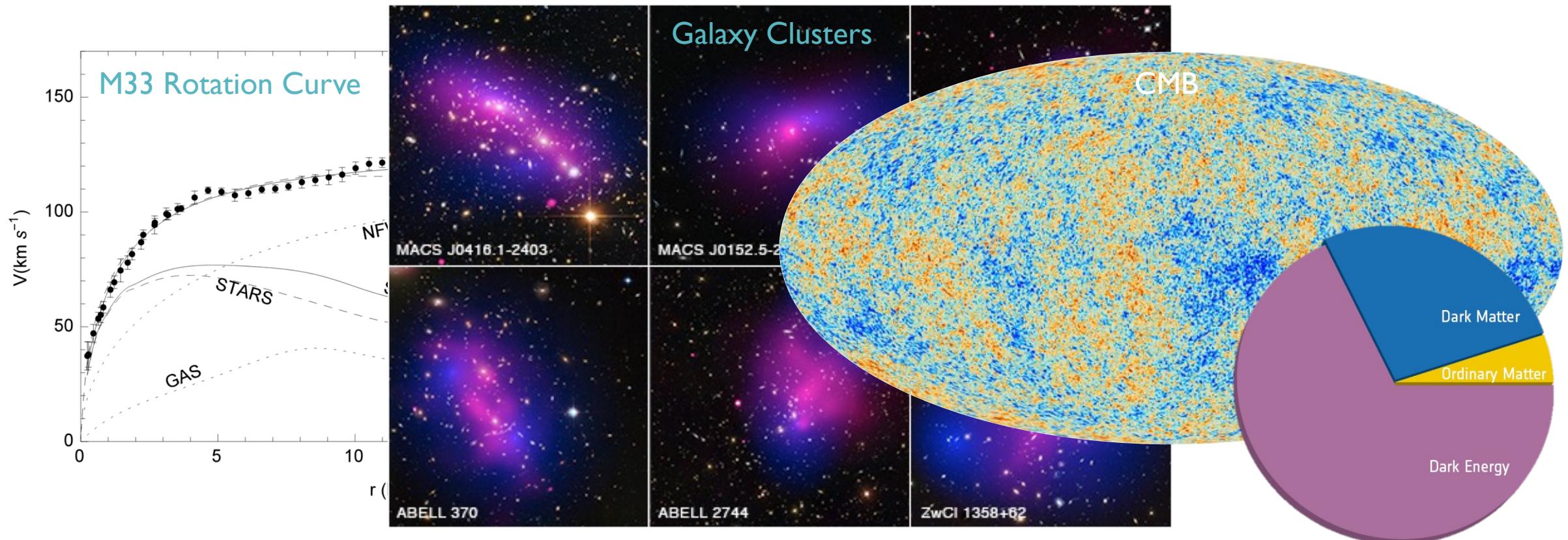
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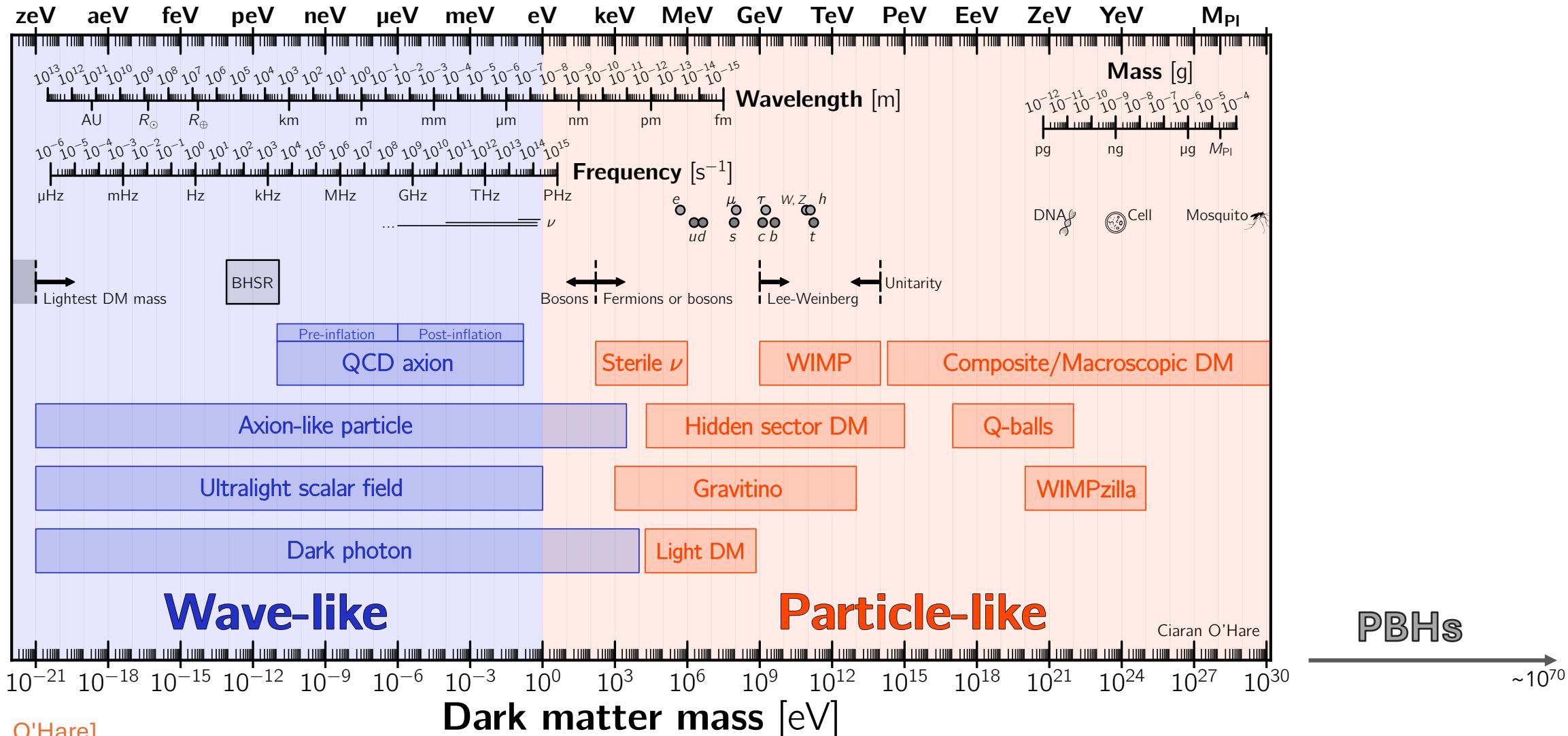
# Dark Matter Landscape: An Observer's View

Overwhelming 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)

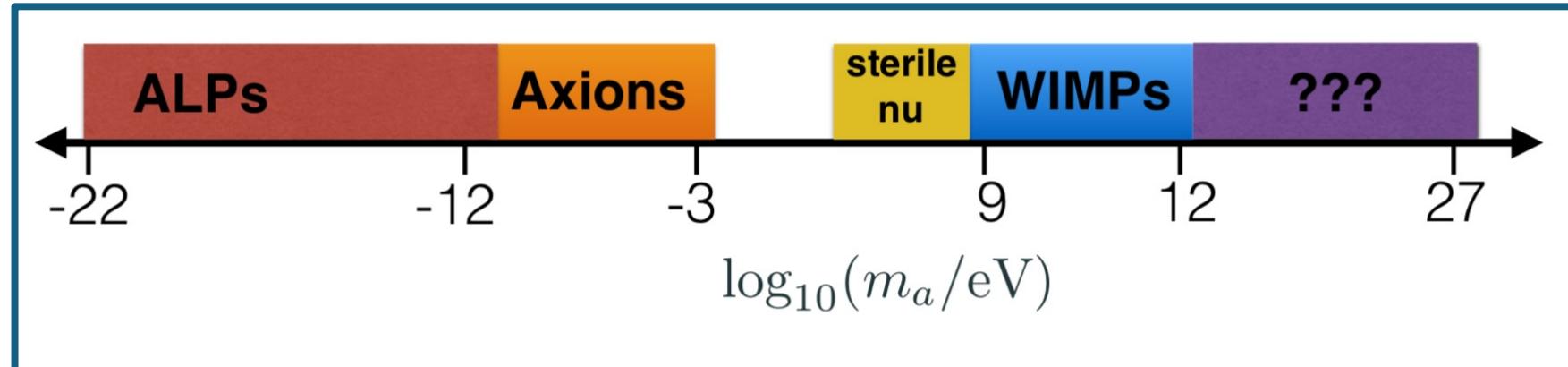


# Dark Matter Landscape: A Theorist's View



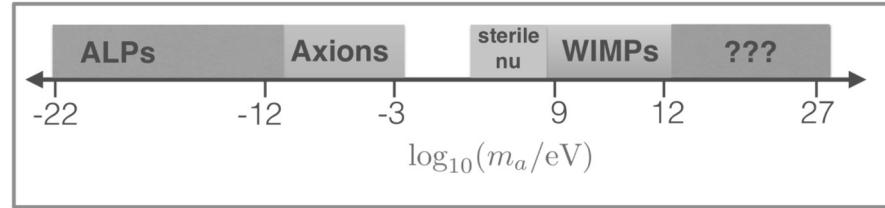
# What are Axion-Like Particles (ALPs)?

- Extension of the axion, a proposed solution of the strong charge-parity problem in QCD
- WISPs: weakly-interacting sub-eV particles (mass  $\lesssim 10^{-10}$  eV)

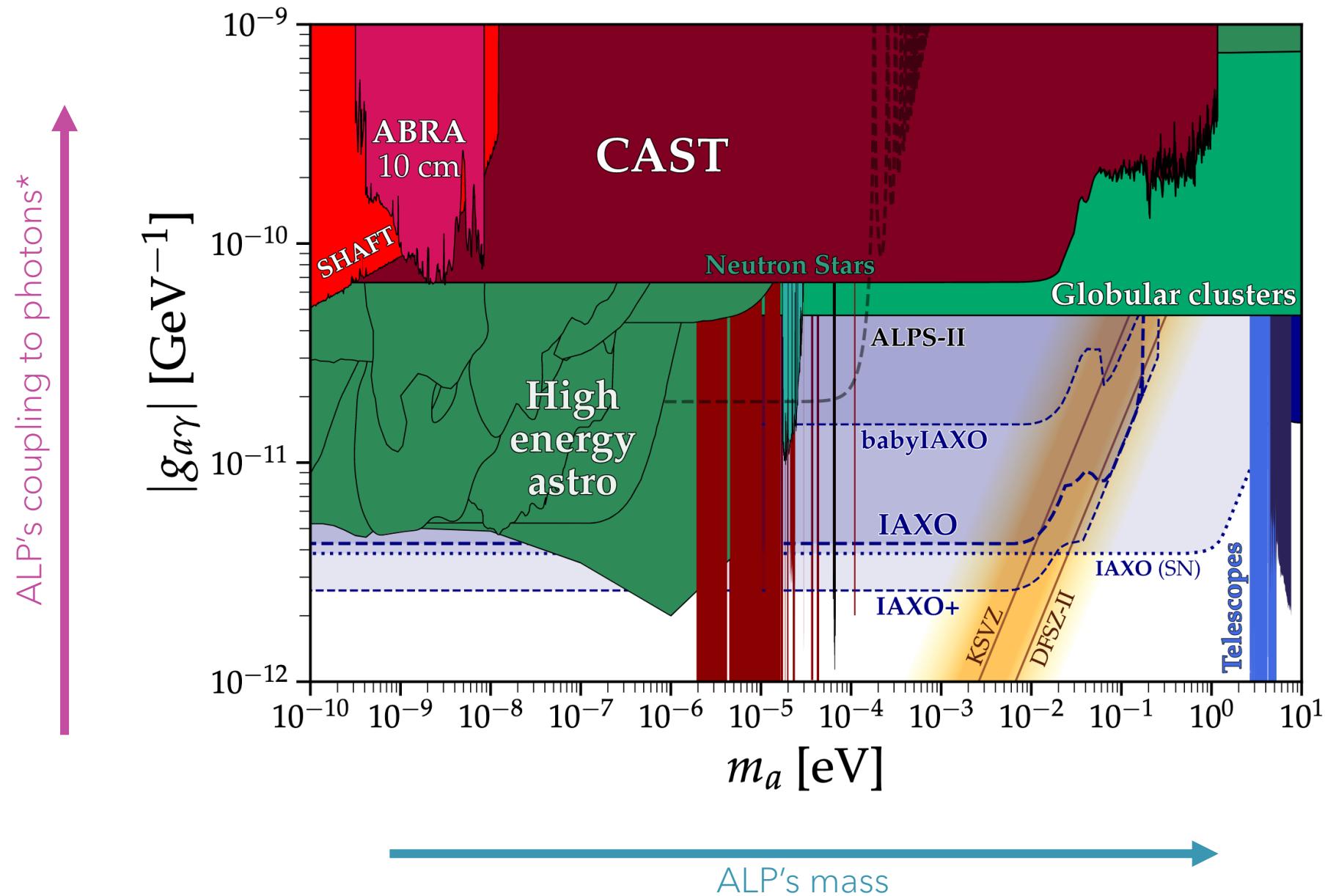


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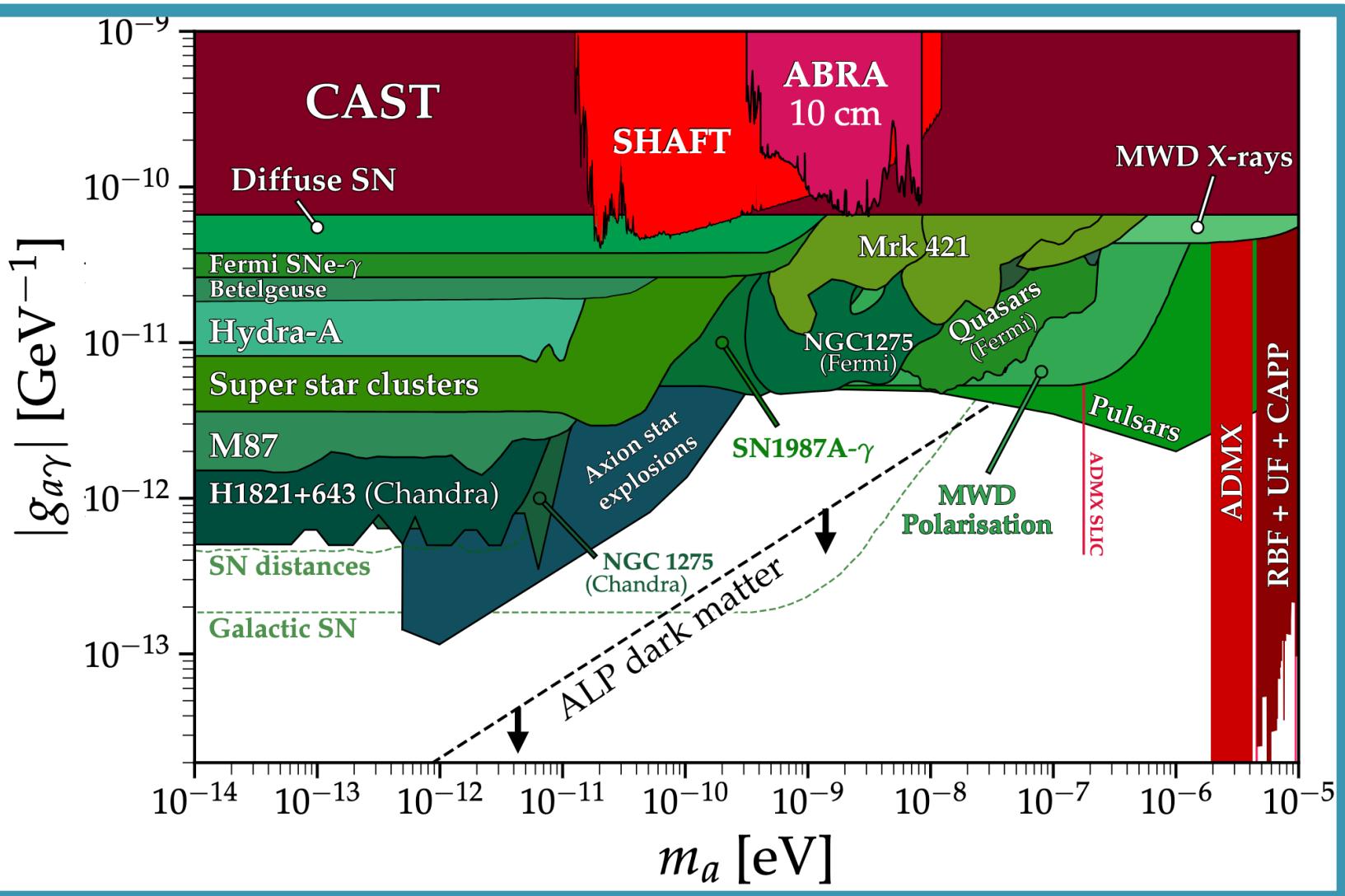
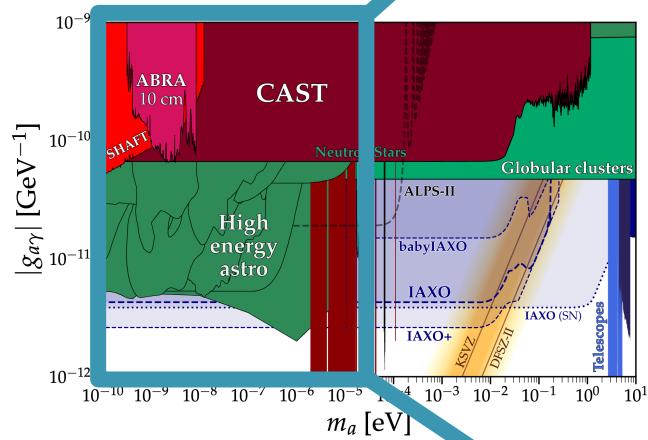


- ❖ Cold matter requirements:
  - ✓ feeble interactions with standard model particles
  - ✓ cosmological stability
  - ✓ Non-thermal production → cold
- ❖  $\rho_{a,0} \lesssim 1 \frac{\text{keV}}{\text{cm}^3} \frac{m_a(t_0)}{\text{eV}} \left( \frac{\theta(t_1)}{53 \text{TeV}} \right)^2 \rightarrow \text{Dark Matter!}$
- ❖ Direct and indirect searches → limits on coupling/mass parameter space



\*analogous to a WIMP cross-section

Plot produced using: <https://cajohare.github.io/AxionLimits/>

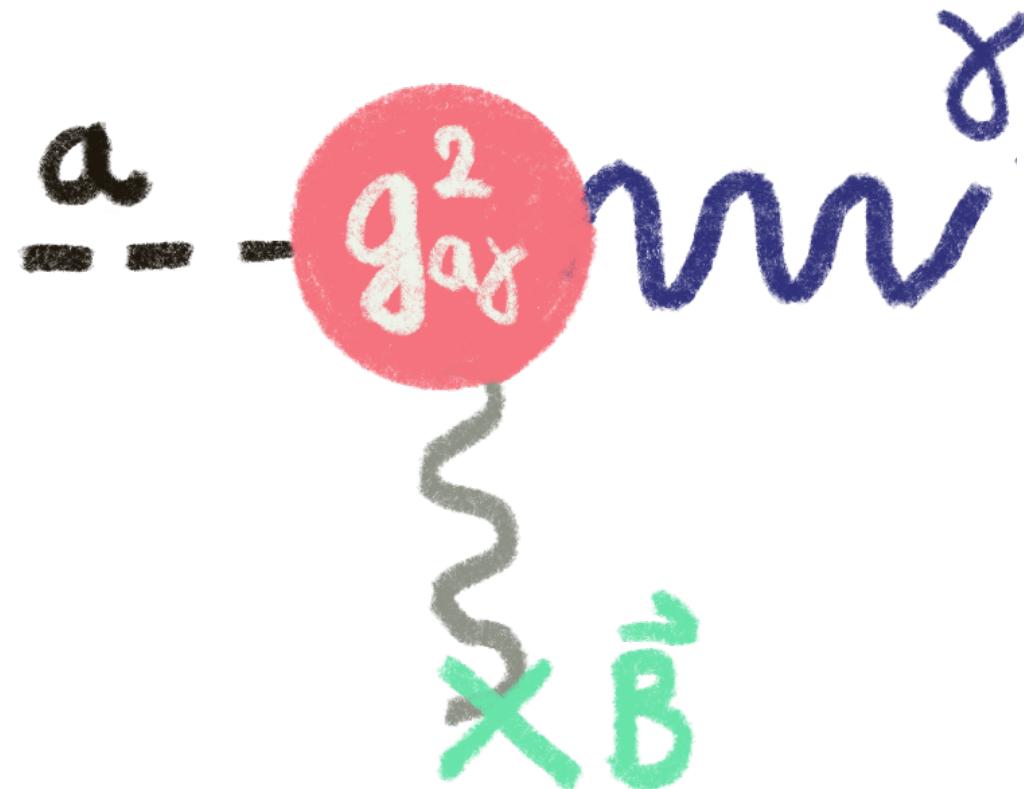
Plot produced using: <https://cajohare.github.io/AxionLimits/>

# Observing ALPs with Gamma Rays

In the presence of an external magnetic field,  $\mathbf{B}$ , ALPs undergo a conversion into photons:

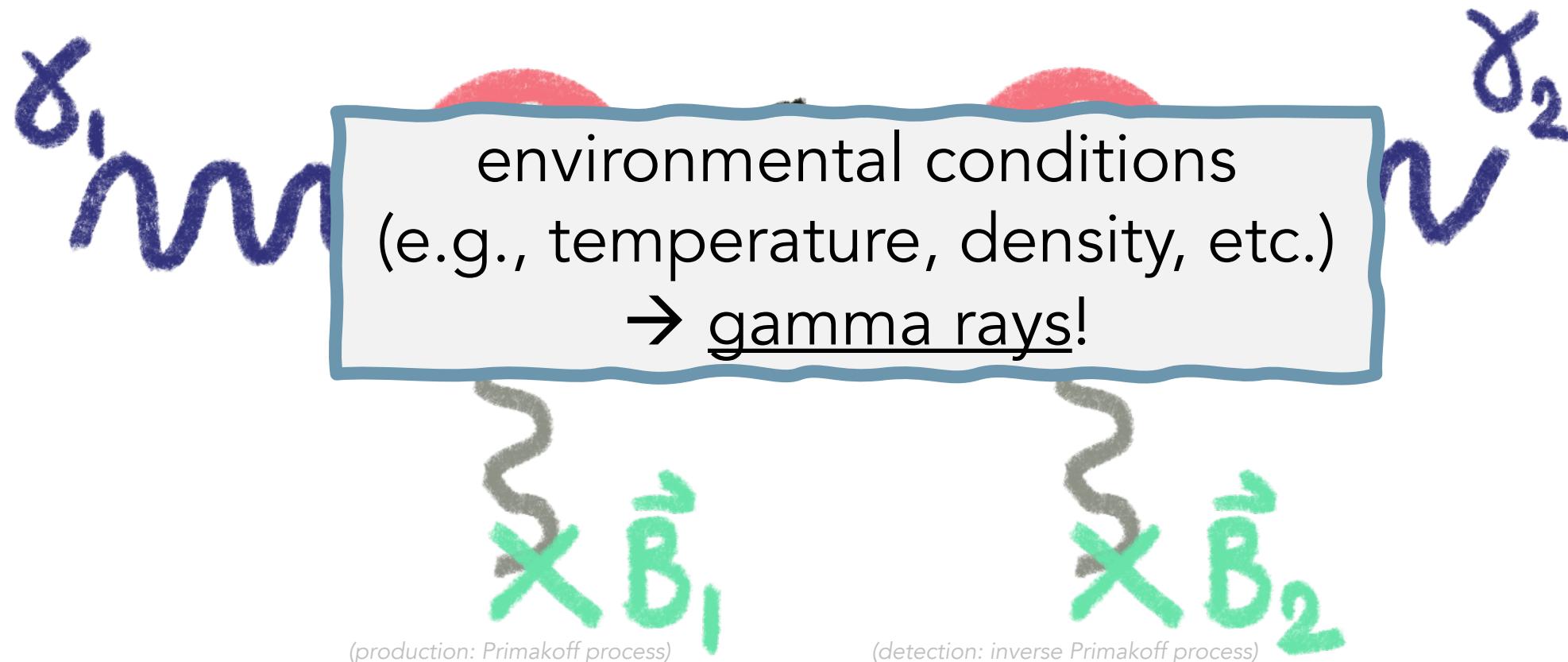
$$\mathcal{L}_{a\gamma} \supset g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$

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

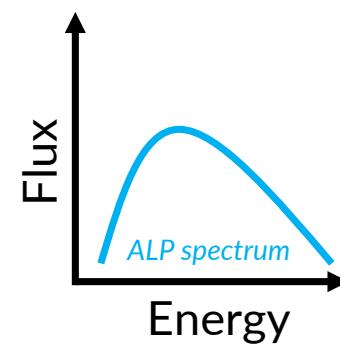
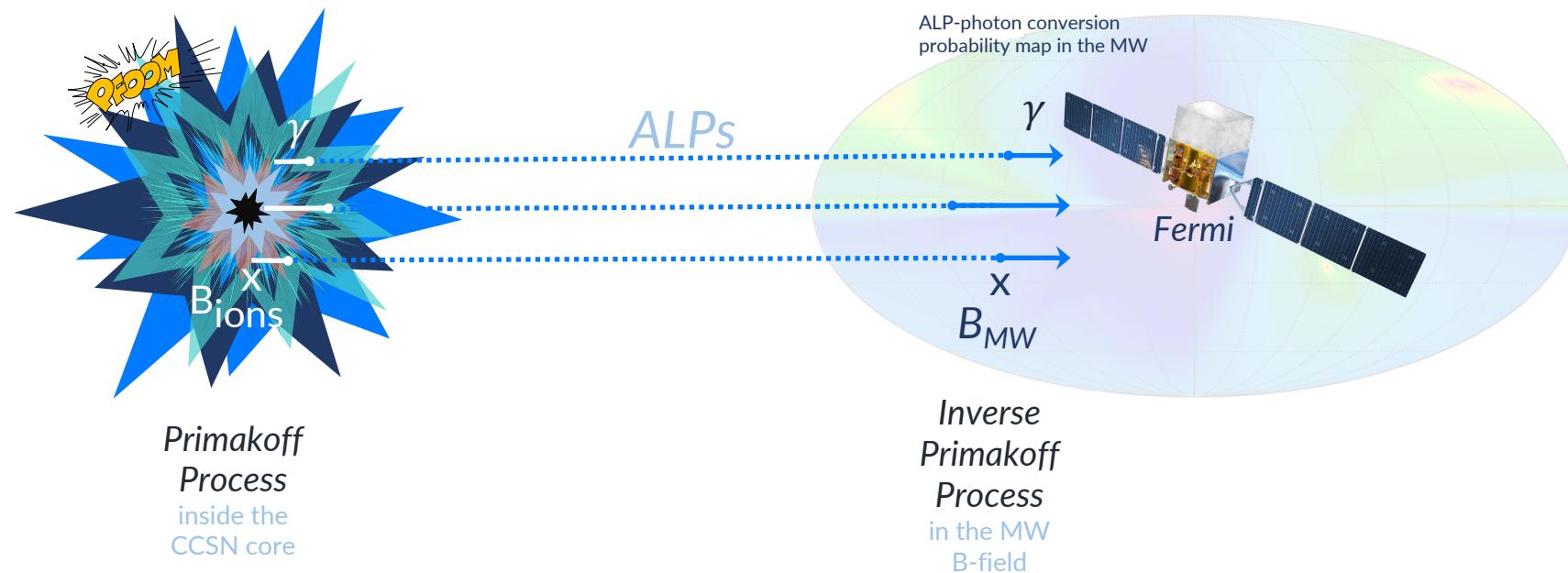


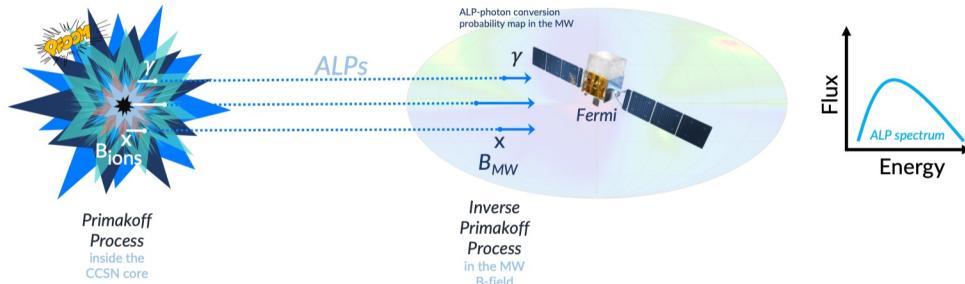
# ALP...

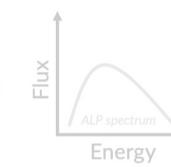
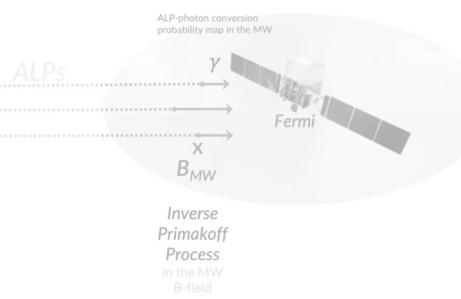
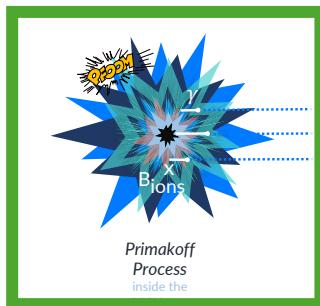
is a viable *cold* dark-matter candidate

converts into photons in the presence of a magnetic field

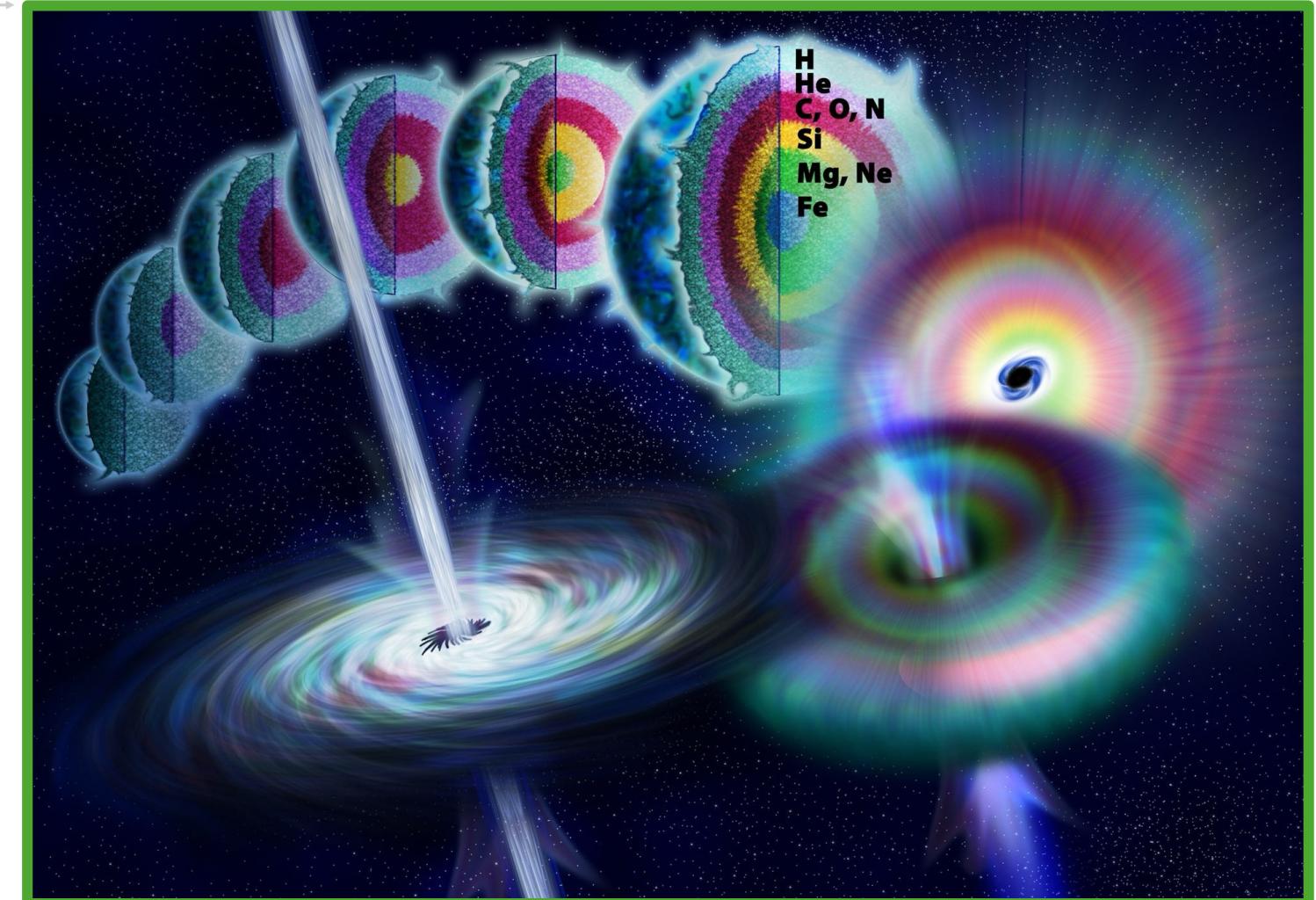
parameter space can be probed with gamma-ray  
observations

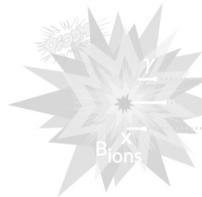




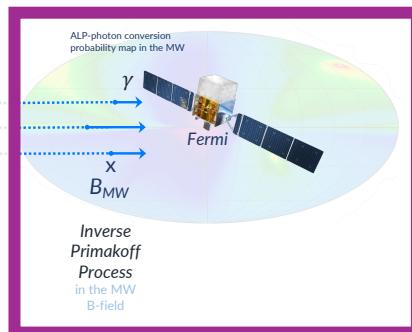


**CCSN --- Gamma-ray Burst relationship**

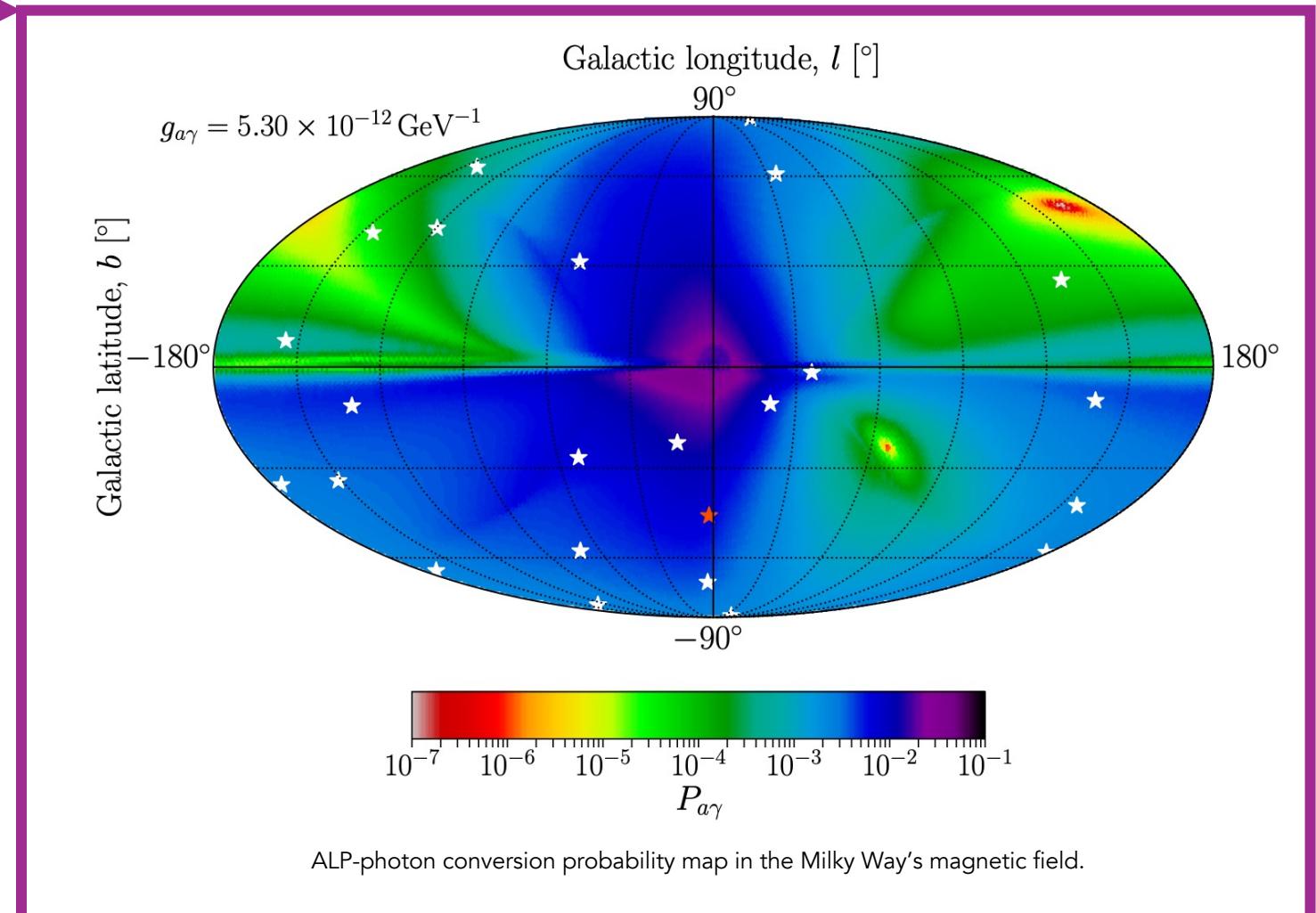


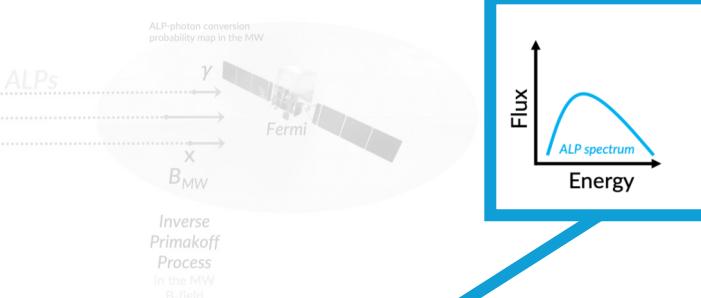
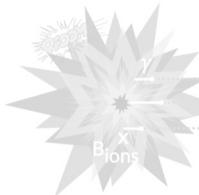


Primakoff  
Process  
Inside the  
CCSN core

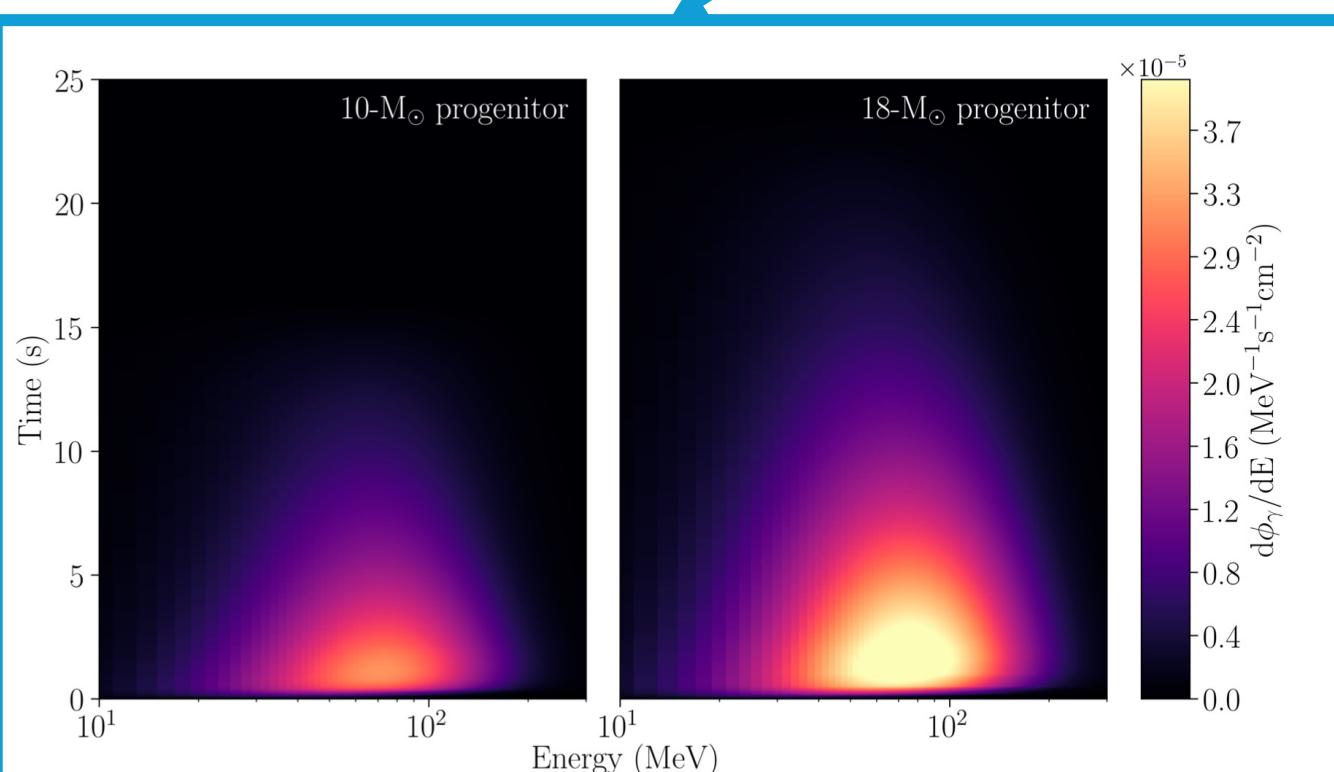


**Assumptions:** magnetic fields: only considering the MW magnetic field, neglecting IGMF

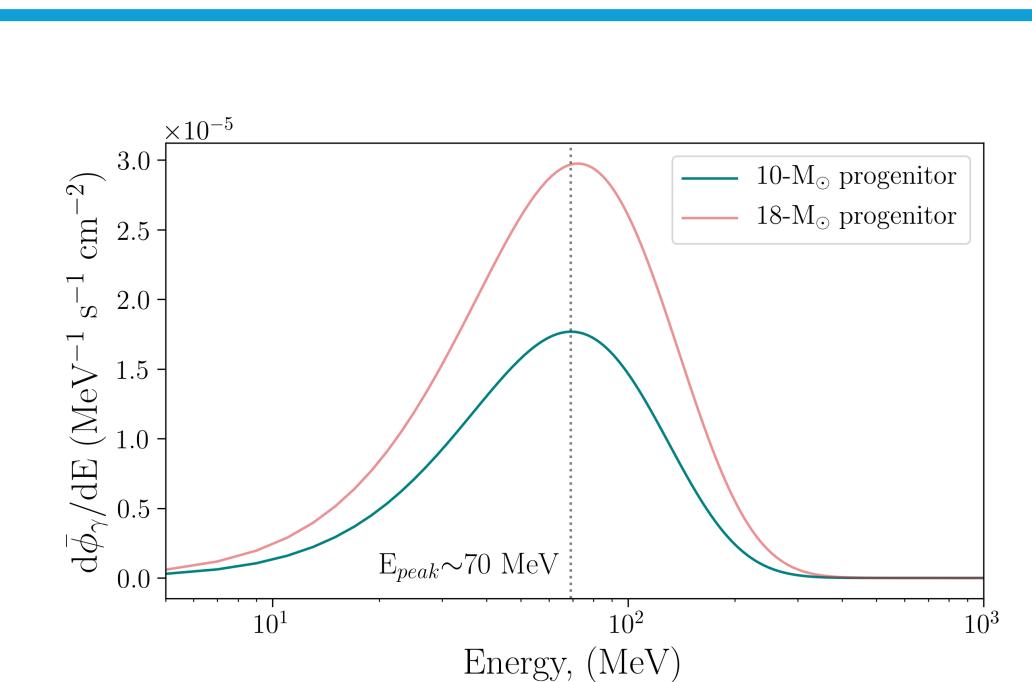




**Motivation:** ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.

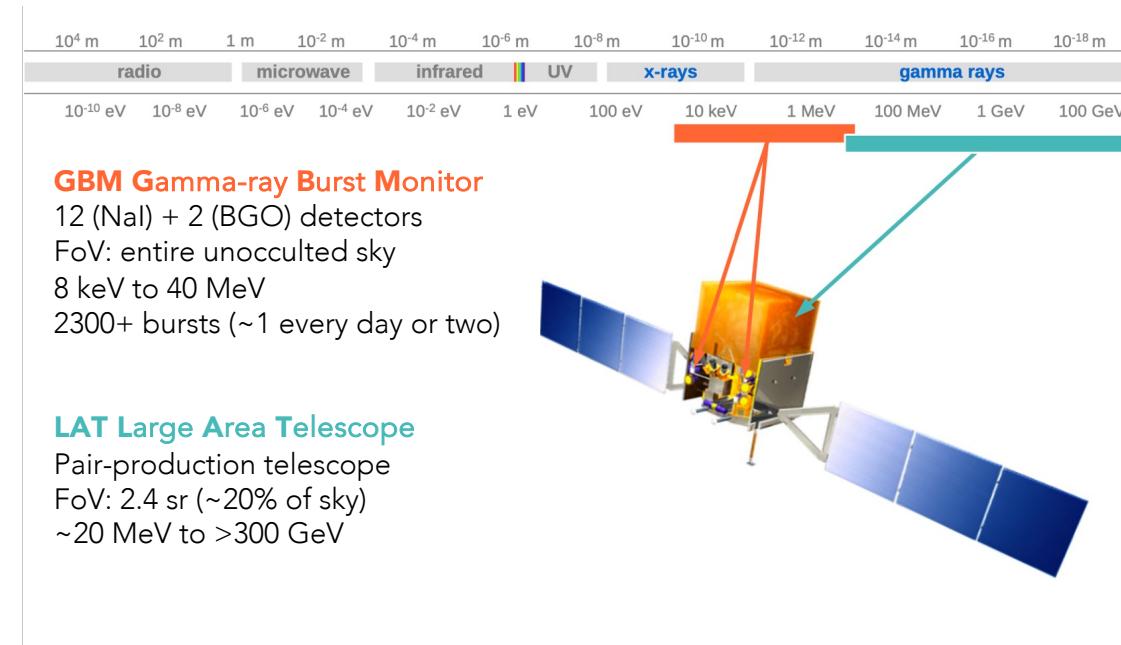
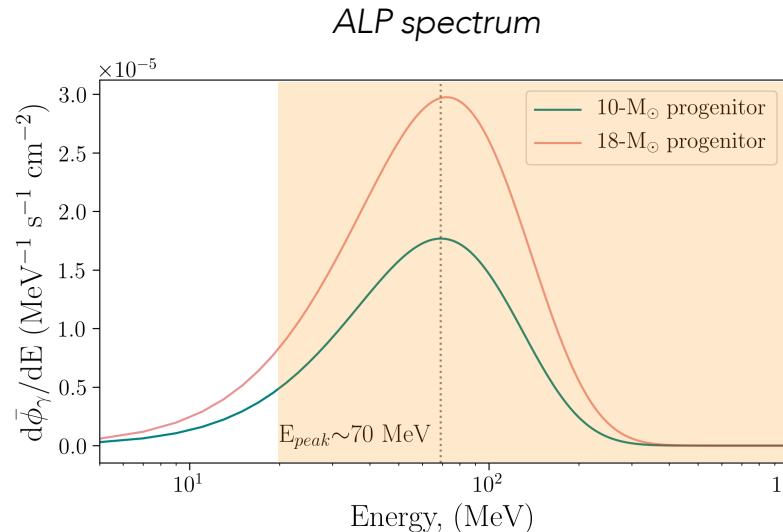


The observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a 10 and 18- $M_\odot$  progenitor.



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

# LAT Low Energy Technique (LLE)

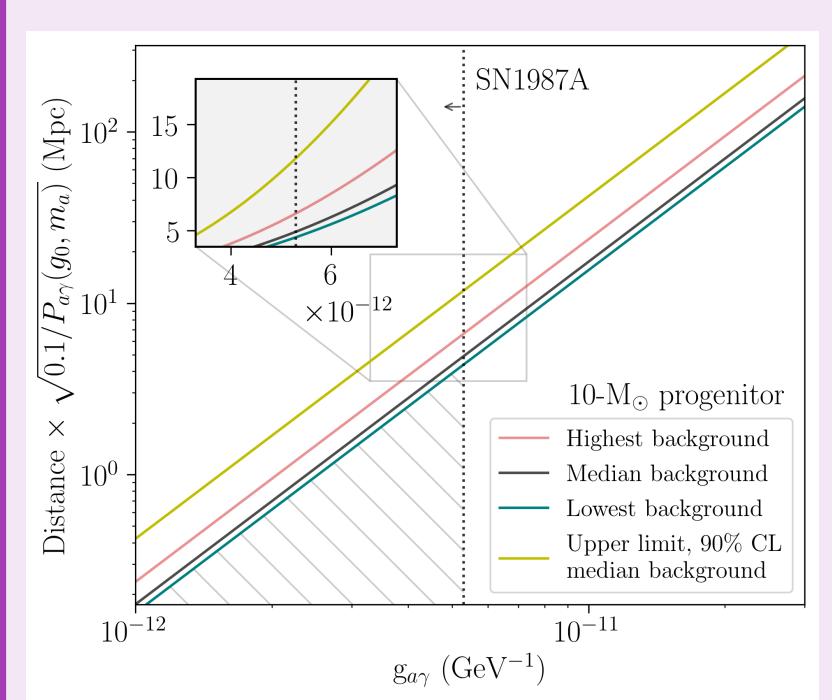


- Standard LAT analysis: >100 MeV **vs.** LLE
- LLE: maximizing the effective area of the LAT instrument in the low-energy regime
- More signal, but also more background

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

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

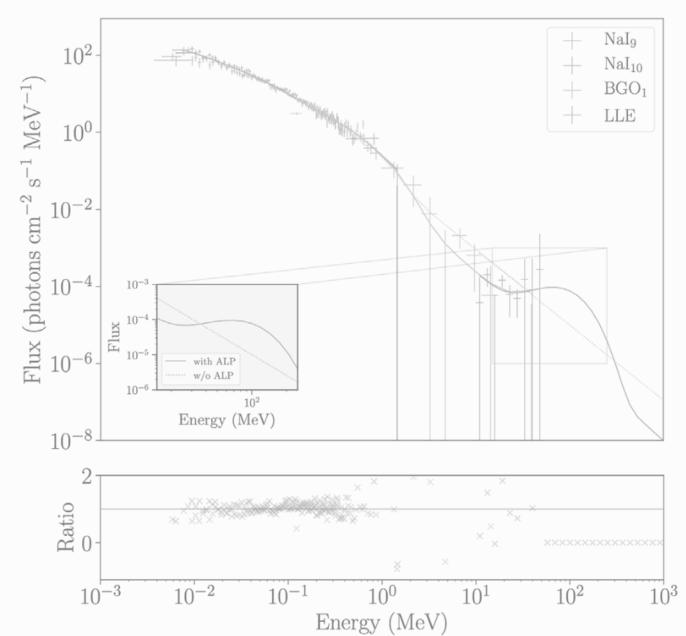
# Fermi-LLE Sensitivity



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

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

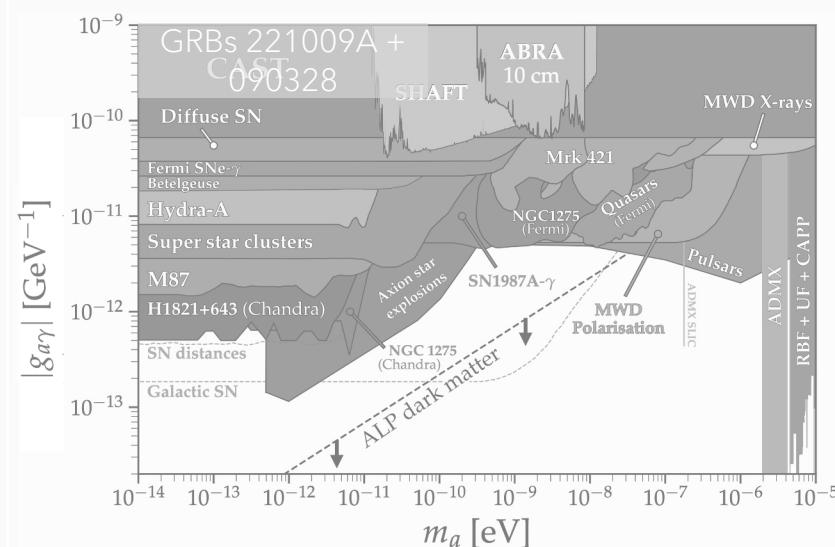
# GRB searches



- No excess signal found.
- 24 long GRBs that pass the selection criteria.
- GRB 101123A at  $\sim 2.4 \sigma$ . Trials factor  $\rightarrow p \sim 0.3$ .
- *Method: model comparison*

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

# GRB Precursors



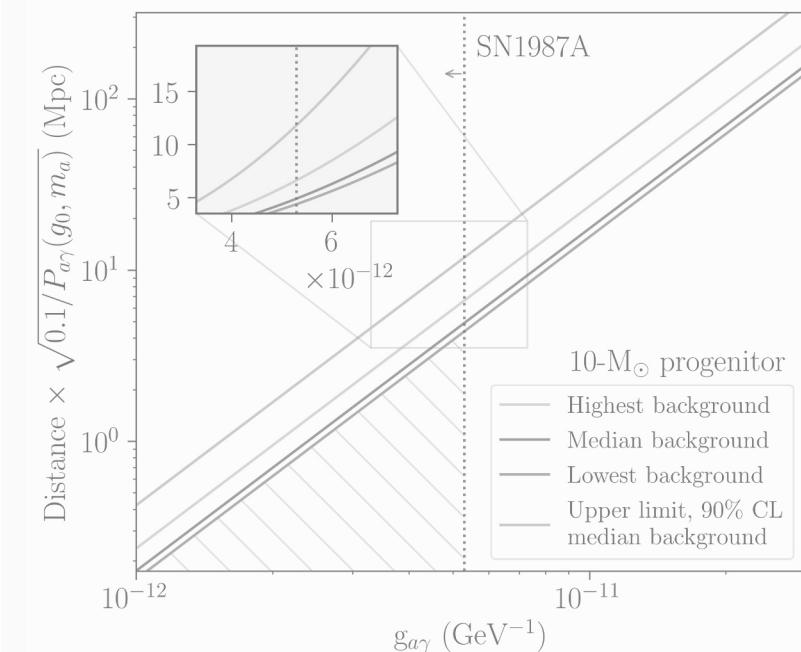
- No significant detections.
- From the ALP amplitude we calculate upper limits.
- *Method: model comparison*

Crnogorčević et al. 2024 (in prep.)

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

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

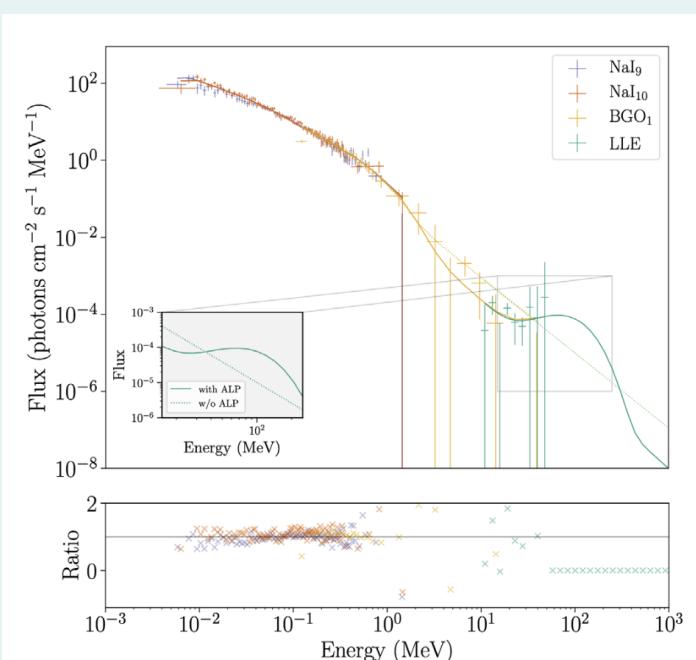
# *Fermi*-LLE Sensitivity



- LLE can reach up to ~10 Mpc (comparable to the standard LAT analysis)
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- Method: signal injection simulations*

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

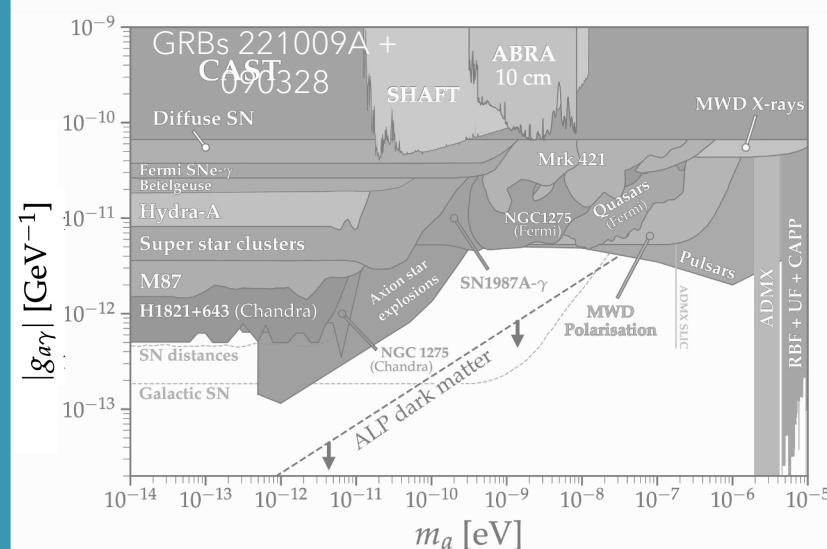
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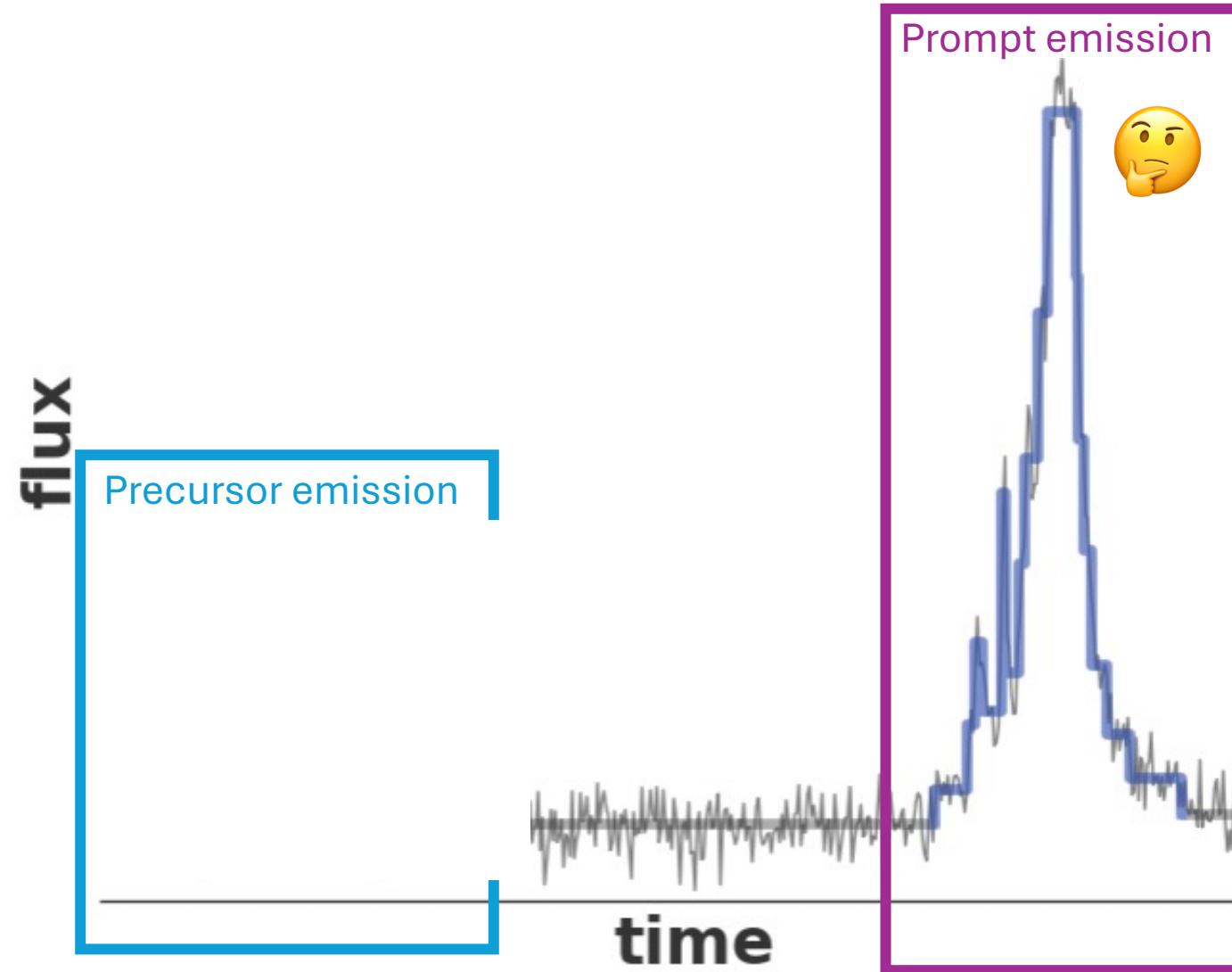
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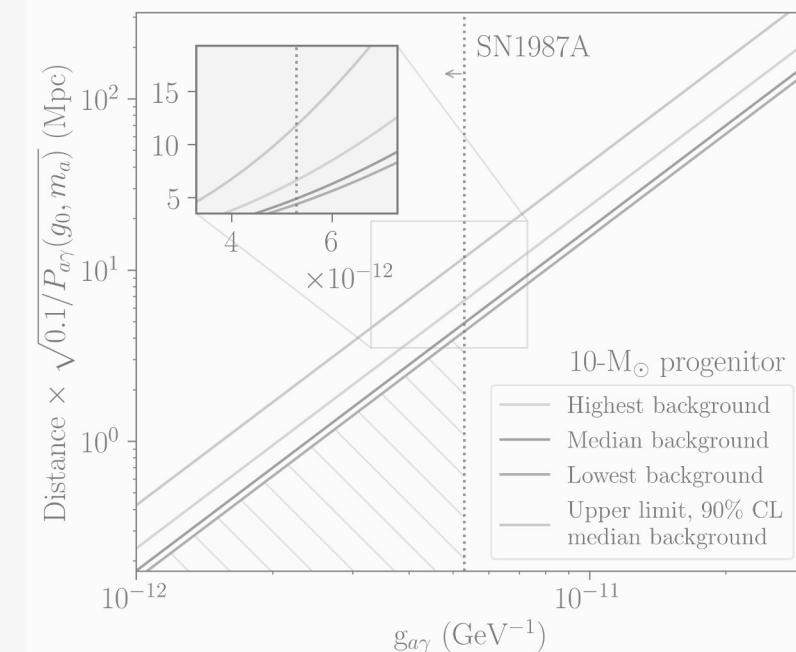
# QUESTION 3: *WHEN SHOULD WE SEARCH FOR ALPS FROM GRBS?*

*Fermi* GI Program, Cycle 15; PI: Crnogorčević  
Reported in: Crnogorčević et al. 2024 (in prep.)

# GRB lightcurve



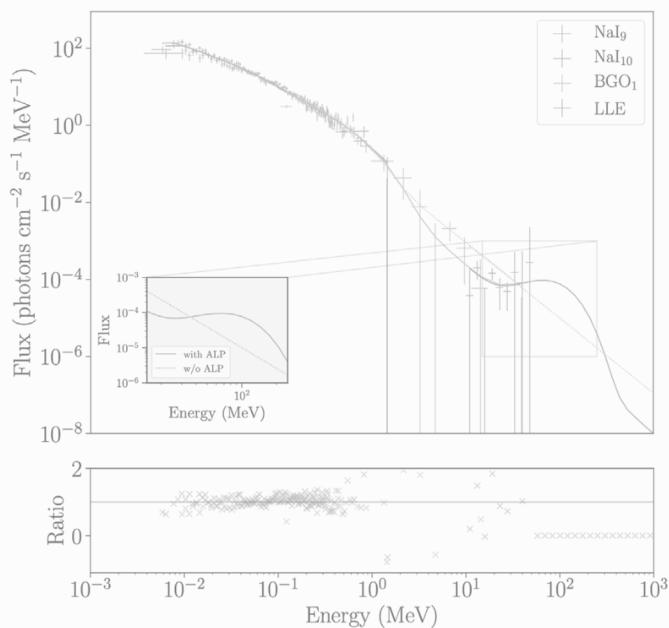
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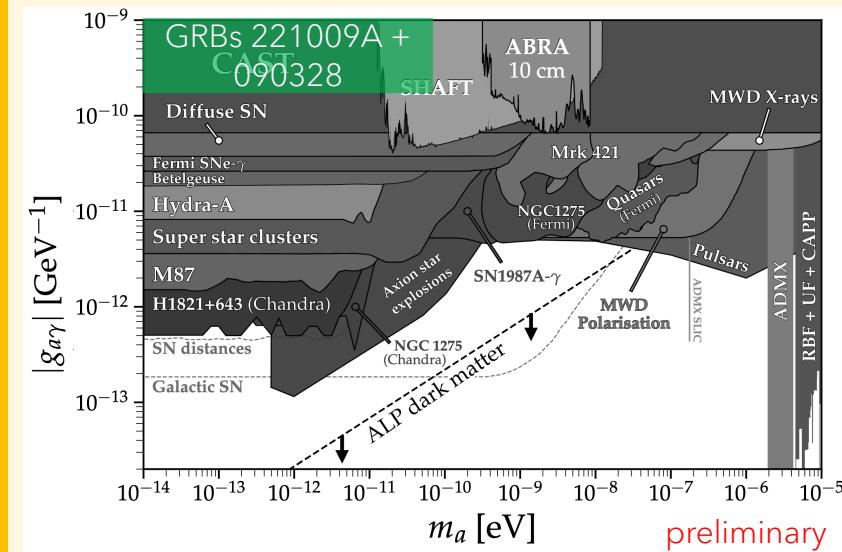
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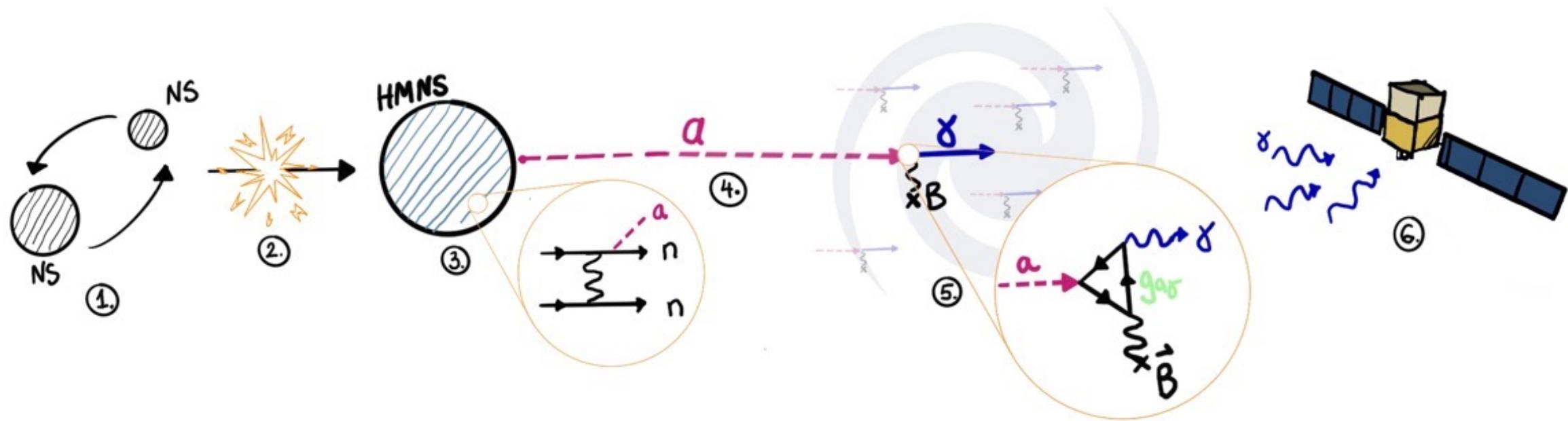


Figure description: (1) Two neutron stars (NS) orbit each other until the (2) merger, followed by (3) the formation of a hypermassive neutron star (HMNS). There, ALPs are produced via the neutron-neutron bremsstrahlung process. Once produced, ALPs travel undisturbed (4), until they reach the magnetic field of the Milky Way (5). In the Milky Way's magnetic field, ALPs convert into gamma-rays, which then can be detected by *Fermi* (6).

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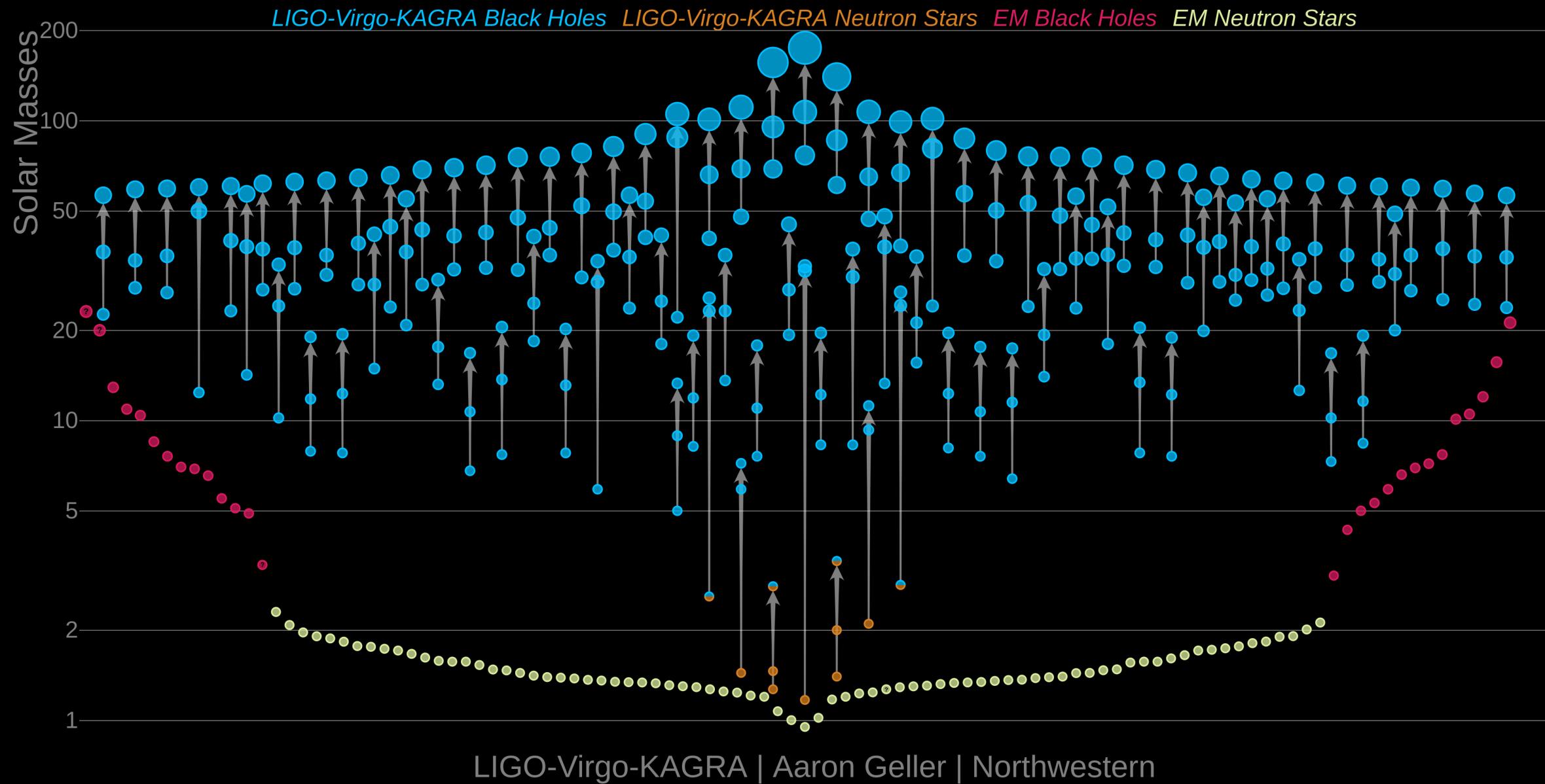
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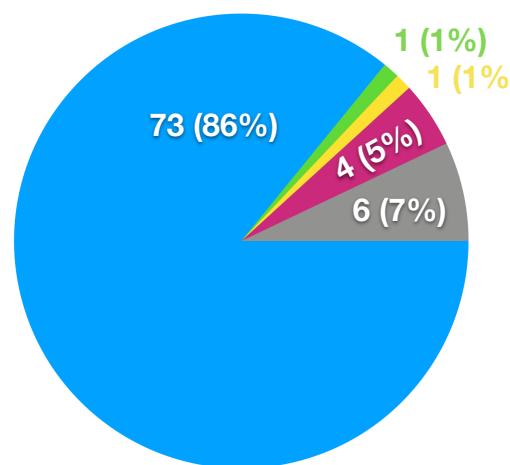
CROSS-CORRELATING ICECUBE NEUTRINOS AND THE  
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# Masses in the Stellar Graveyard



# 03: The Third Observing Run

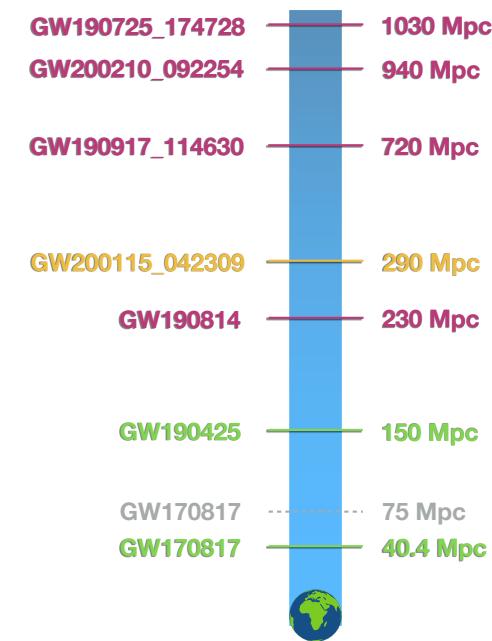
Third LIGO/Virgo observing run (O3): April 2019 -- March 2020 (commissioning break in October 2019)



## Event Classifications

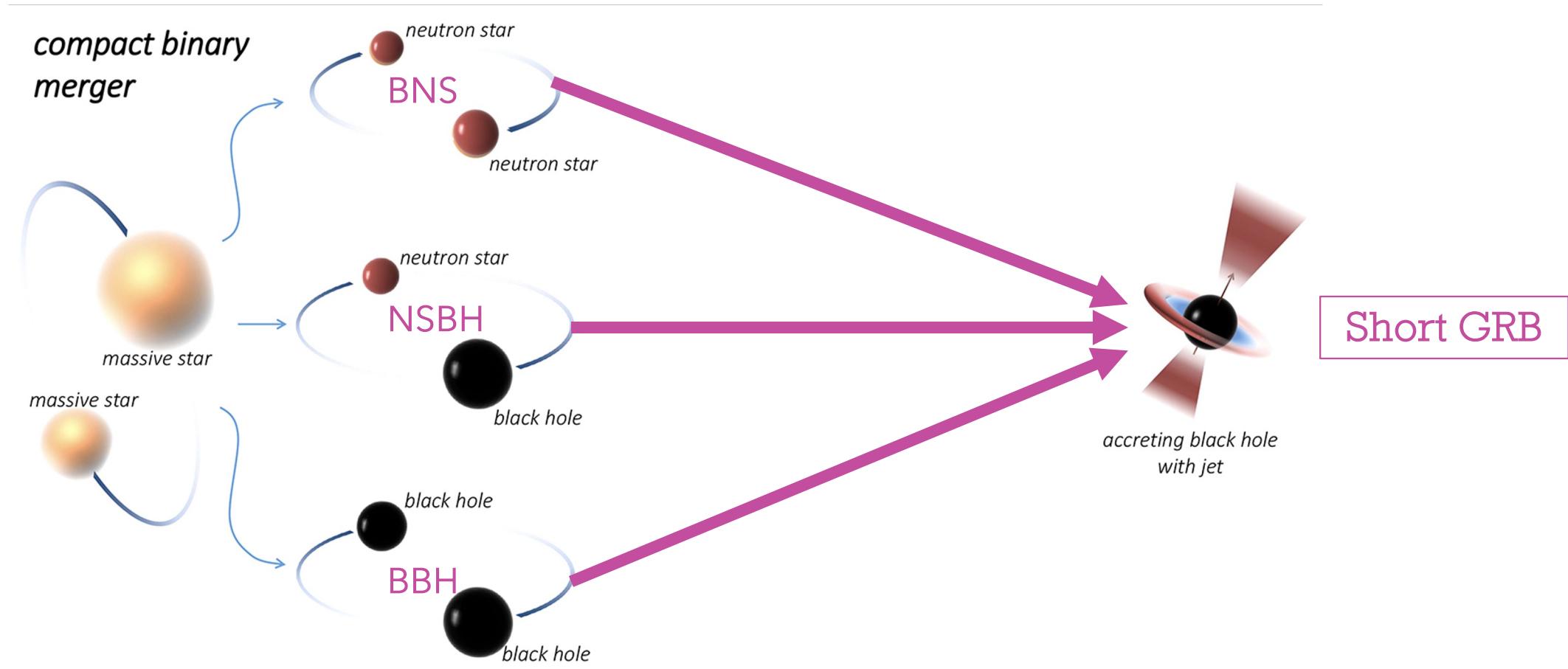
- BBH
- BNS
- NSBH (certain)
- NSBH (possible)
- Marginal

## BNS/NSBH Distances

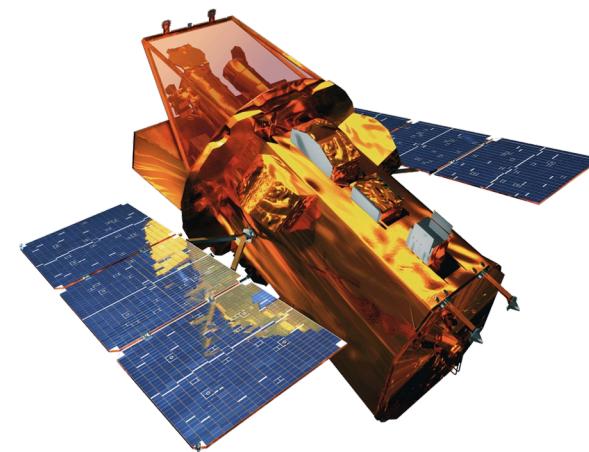
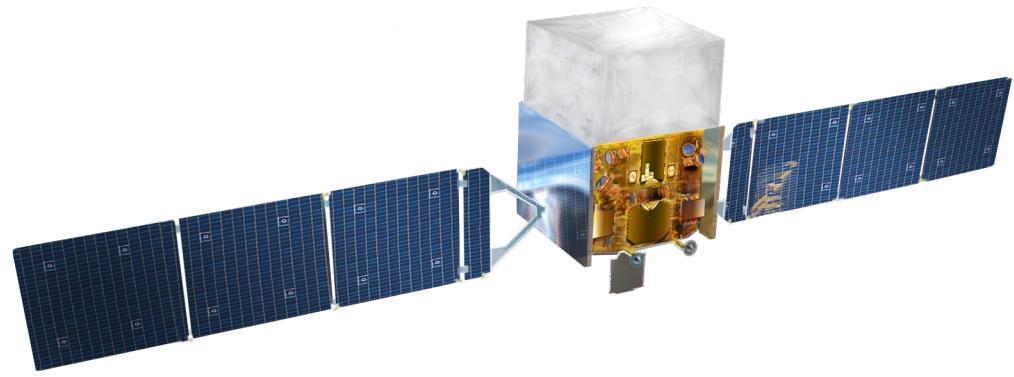


75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

# Where to search for GWs: Compact Binary mergers



Bartos &amp; Kowalski, 2017



## Why *Fermi* GBM?

- + ~full-sky field of view
- + energy coverage spanning the peak of GRB emission

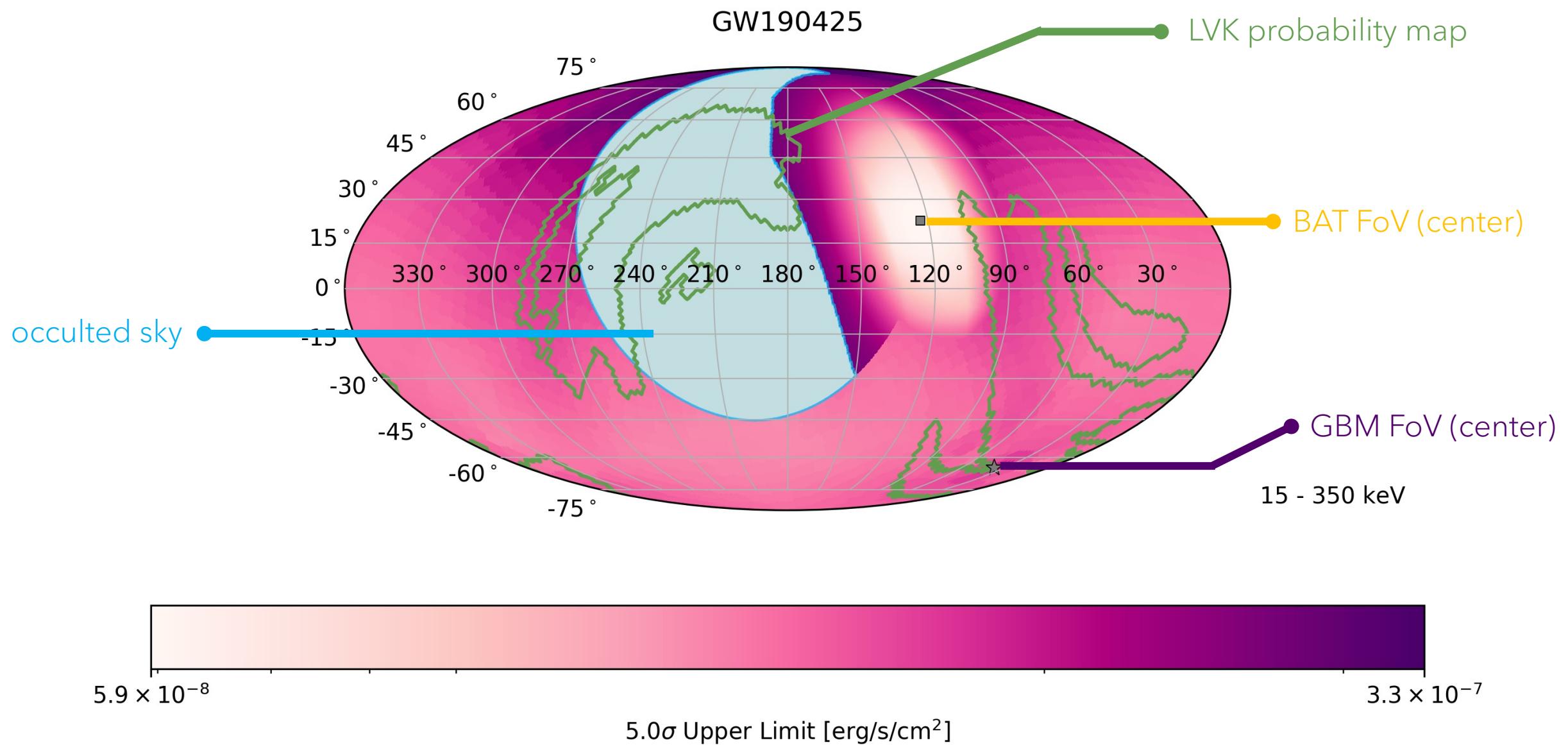
## Why *Swift* BAT?

- + excellent localization sensitivity (~arcminute for detected GRBs)
- + energy coverage overlaps with the low-energy end of *Fermi* GBM

QUESTION: *DID WE SEE ANY GAMMA-RAY  
EMISSION IN SPATIAL AND TEMPORAL  
CORRESPONDENCE TO THE LVK O3 EVENTS?*

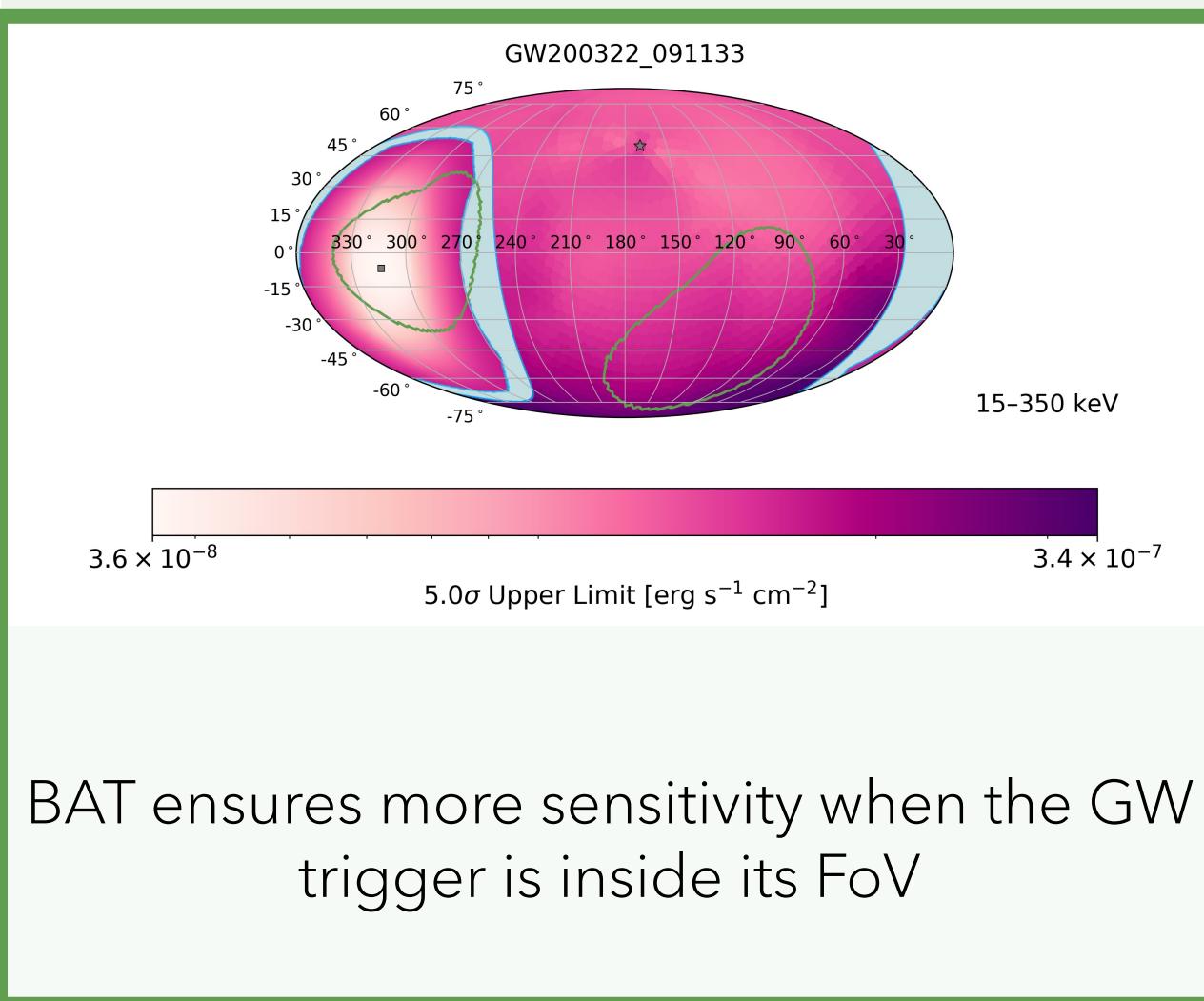
Fletcher et al. on behalf of GBM, Crnogorčević et al. on behalf of BAT, and LVK, 2023 (arXiv: 2308.13666)  
ApJ. 964 (2024) 2, 149

We report *no* significant coincidence discoveries in O3; neither with *Fermi*-GBM, nor *Swift*-BAT

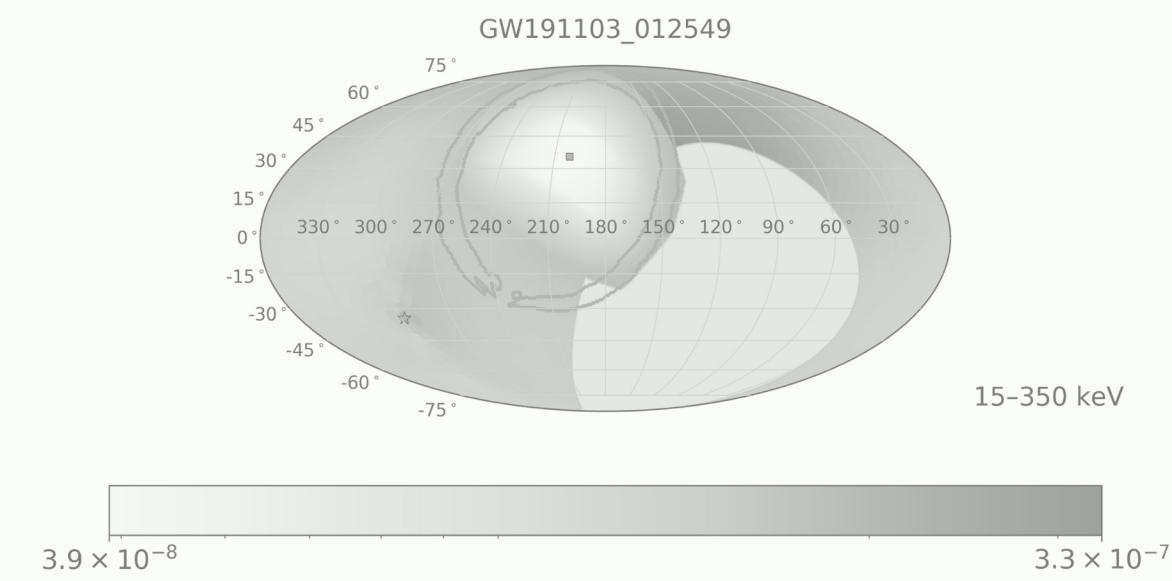


# Combining the upper limits

Choosing the most constraining limit for each point in the sky (independent measures from GBM & BAT)



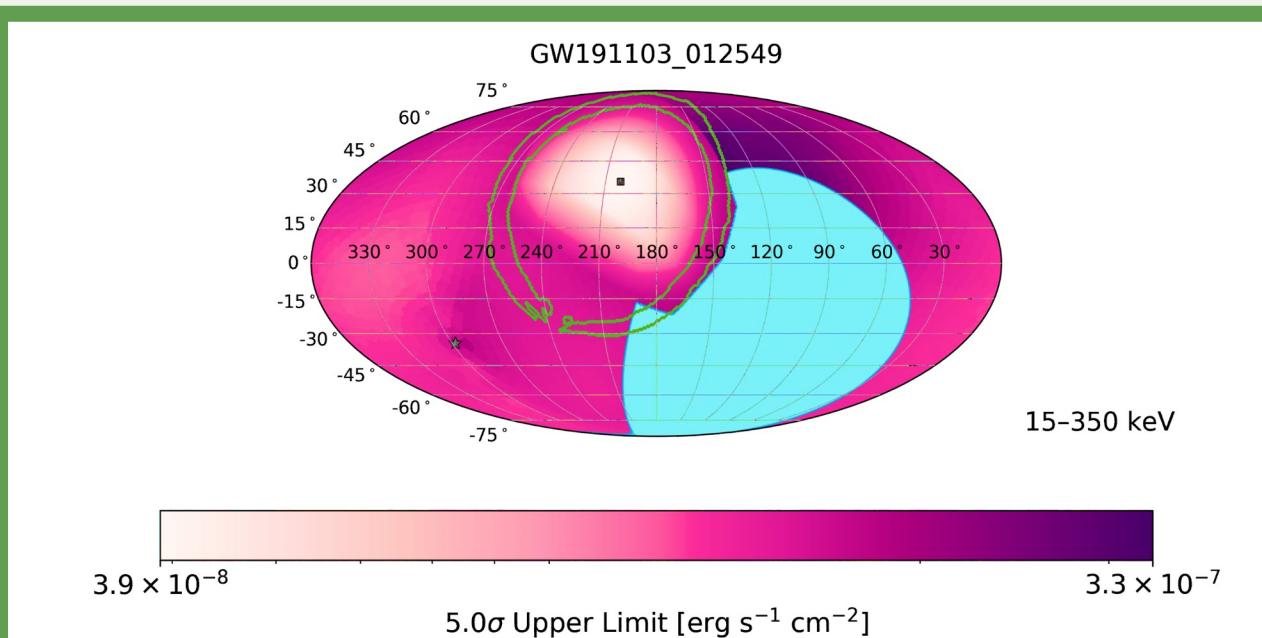
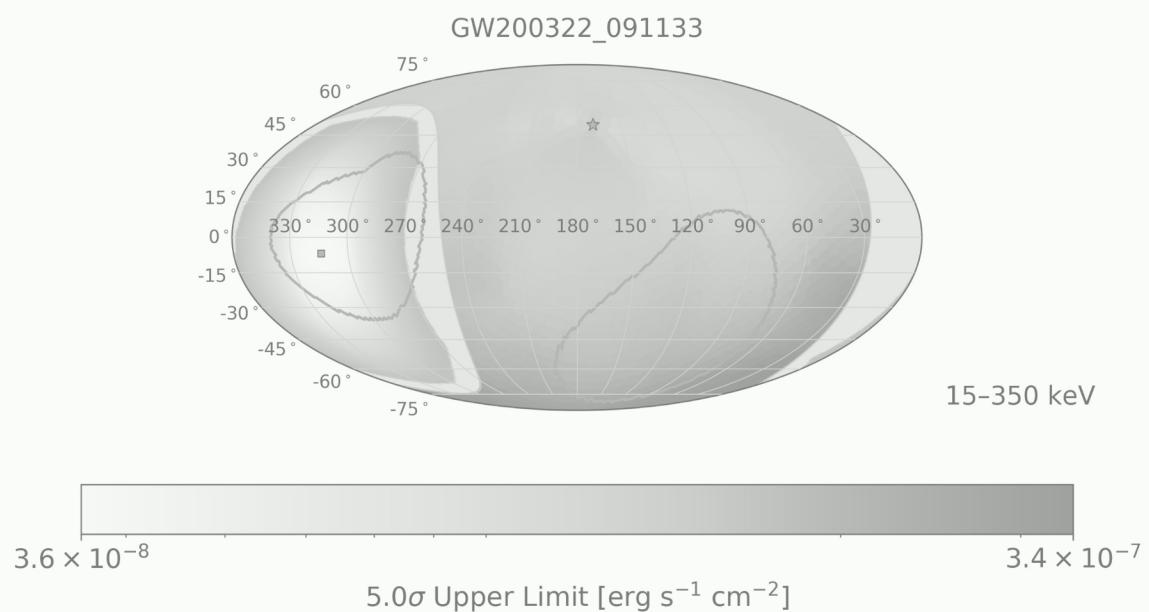
BAT ensures more sensitivity when the GW trigger is inside its FoV



GBM's ensures a more likely coverage of the GW trigger with its large FoV

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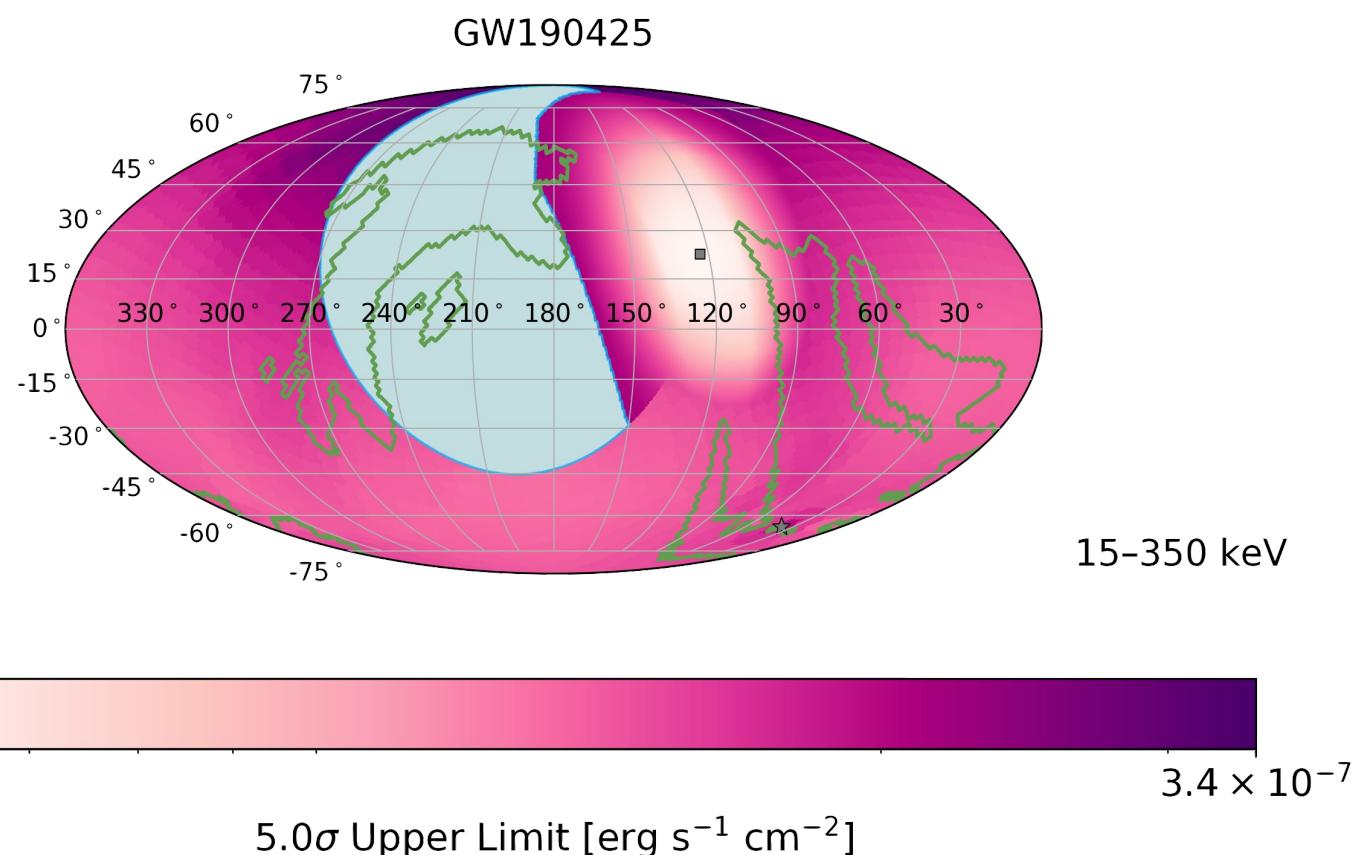


BAT ensures more sensitivity when the GW trigger is inside its FoV

GBM's ensures a more likely coverage of the GW trigger with its large FoV

# Honorable mention: BNS GW190425

Choosing the most constraining limit for each point in the sky (independent measures from GBM & BAT)



- BNS 190425 is 4 times further away than BNS 170817
- GBM/BAT only see ~60% of the GW localization region
- Inclination angle poorly constrained

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CROSS-CORRELATING ICECUBE NEUTRINOS AND THE  
*FERMI* UNRESOLVED GAMMA-RAY SKY

## CHAPTERS III-IV

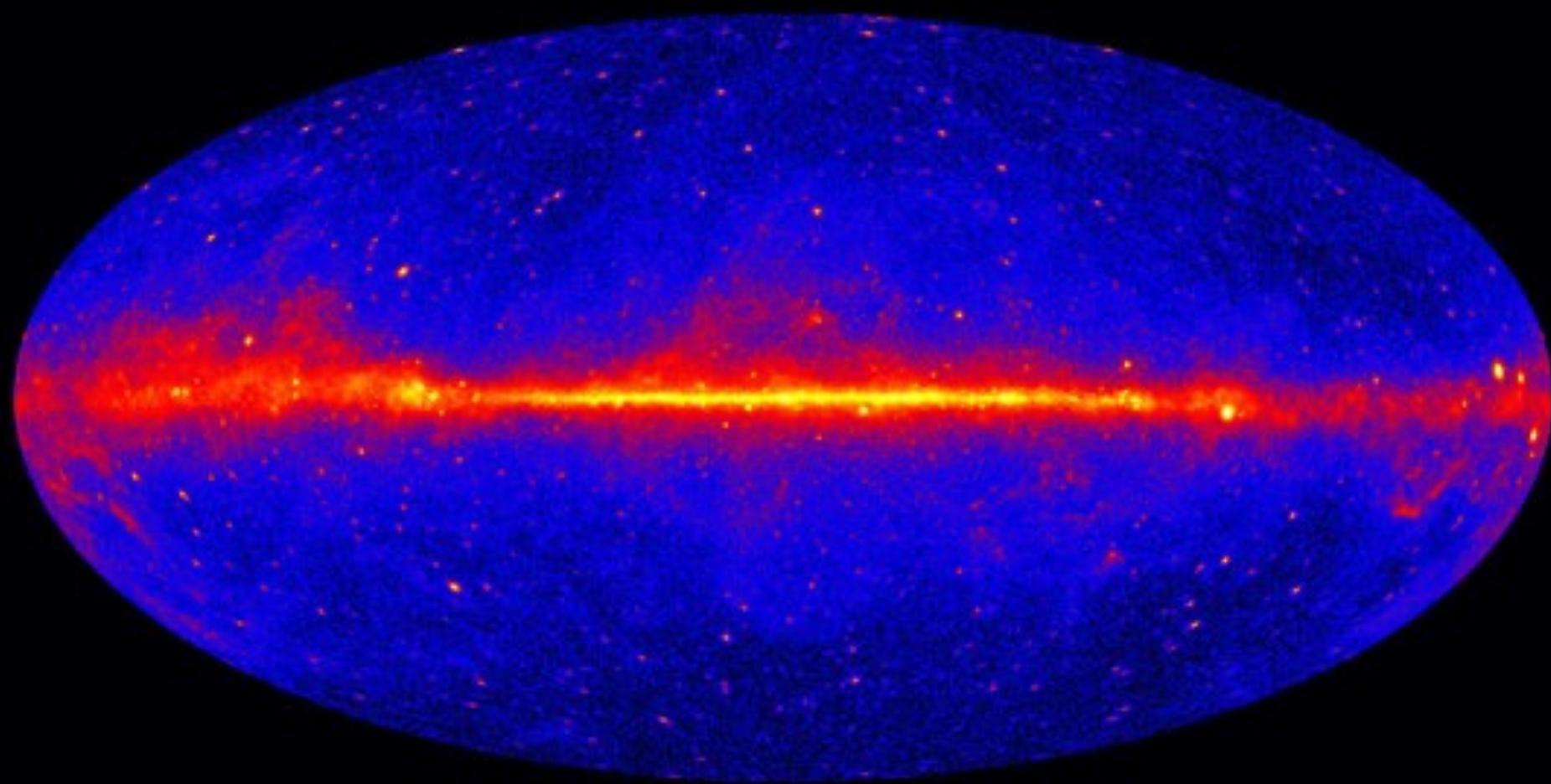
SEARCHING FOR AXION-LIKE PARTICLES WITH *FERMI*

## CHAPTER V

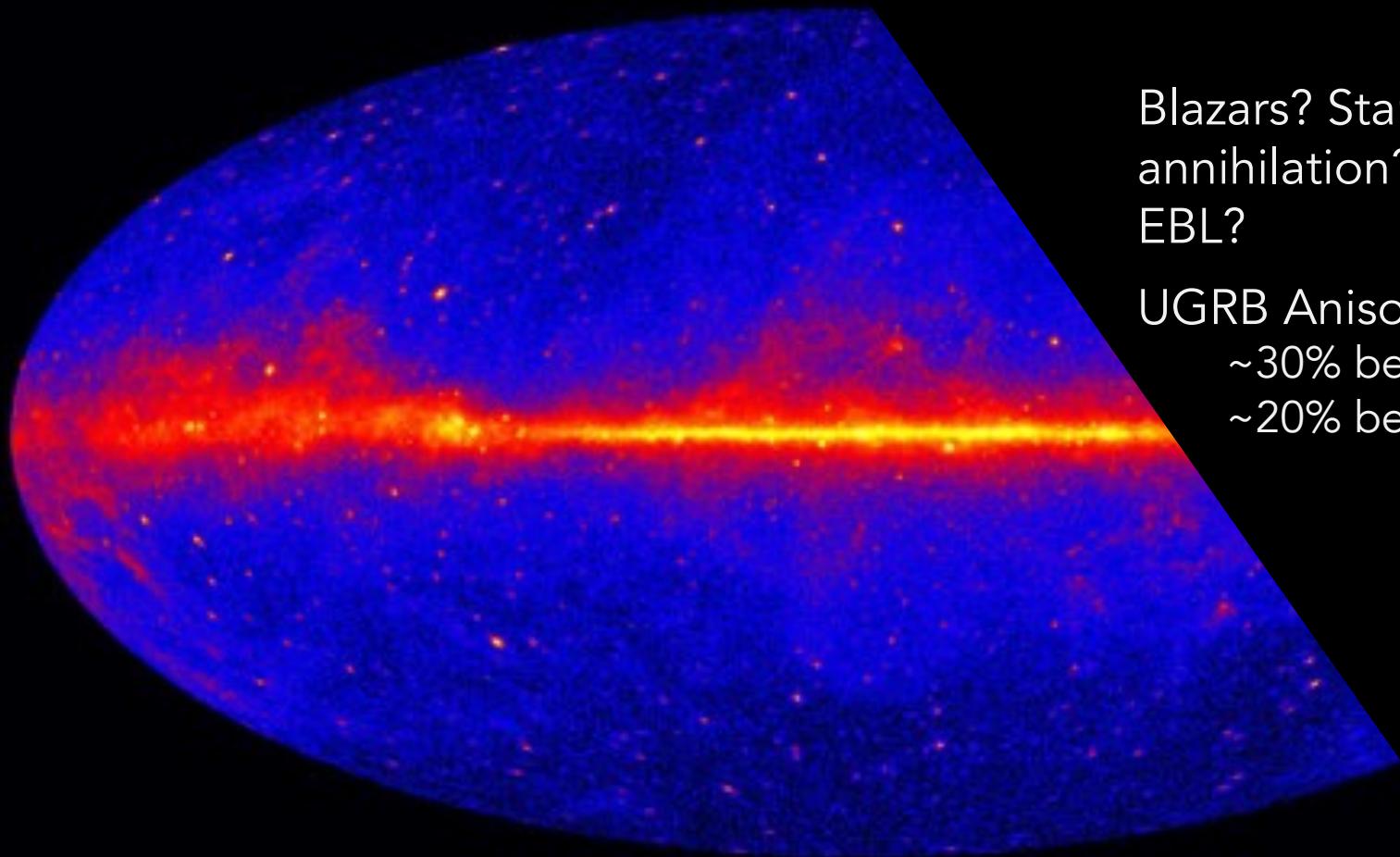
A JOINT *FERMI* & *SWIFT* ANALYSIS OF THE THIRD  
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## CHAPTER VI

CROSS-CORRELATING ICECUBE NEUTRINOS AND THE  
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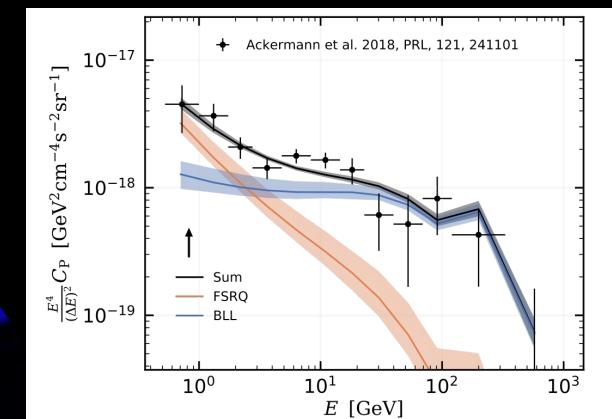


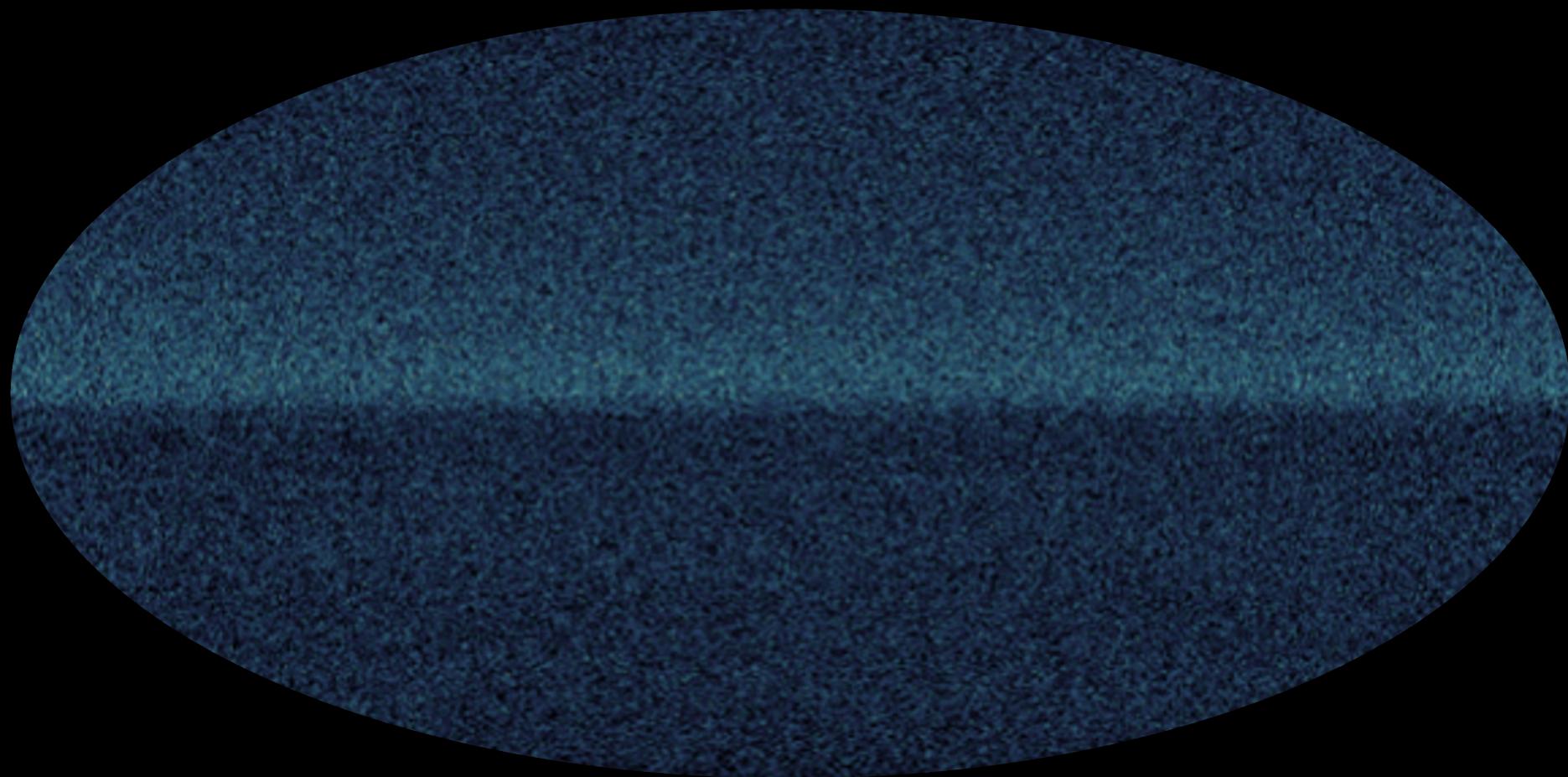
The Unresolved Gamma-ray Background (UGRB) ~20%

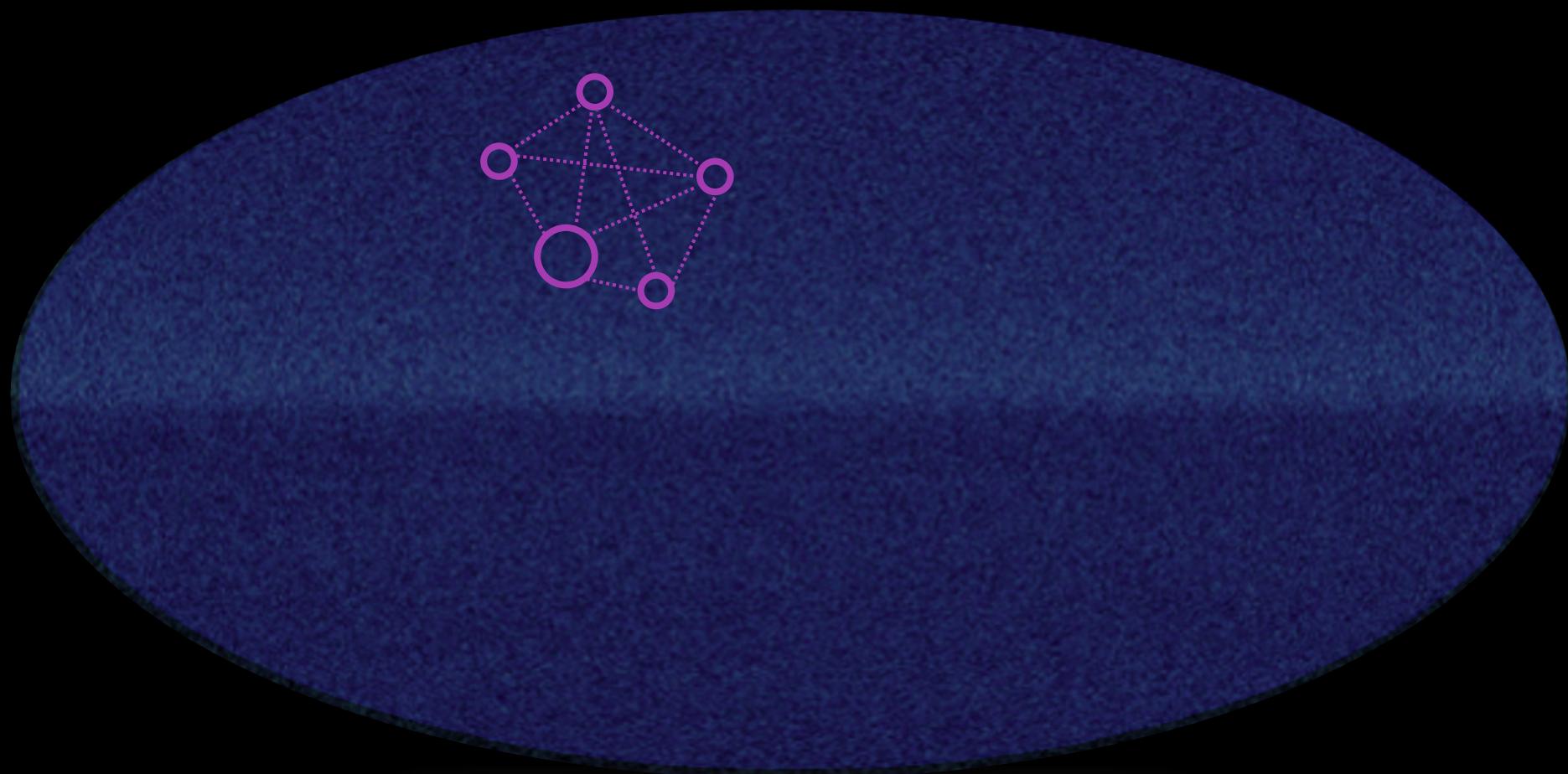


Blazars? Star-forming galaxies? DM annihilation? Photon interactions with EBL?

UGRB Anisotropy: 100% FSRQ + BLL  
~30% between 10 and 100 GeV  
~20% below 1 GeV





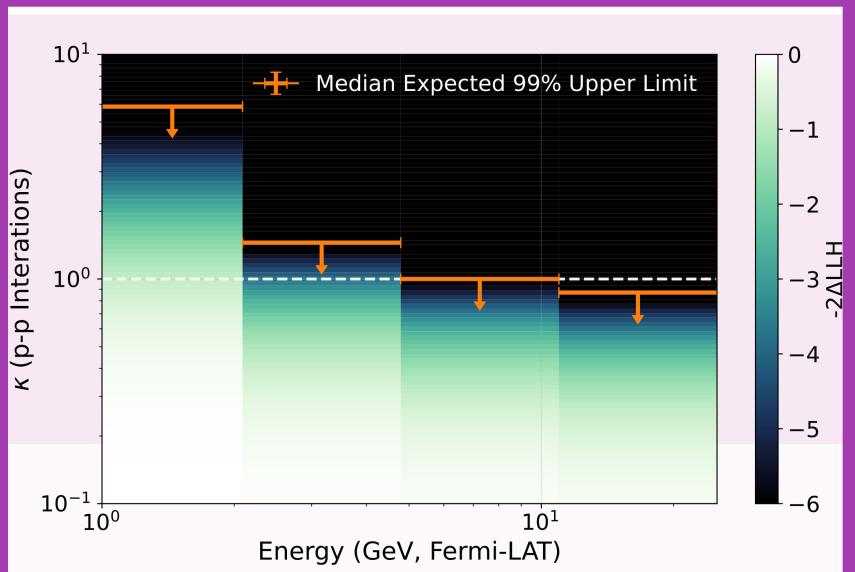


No cross-correlation signal identified

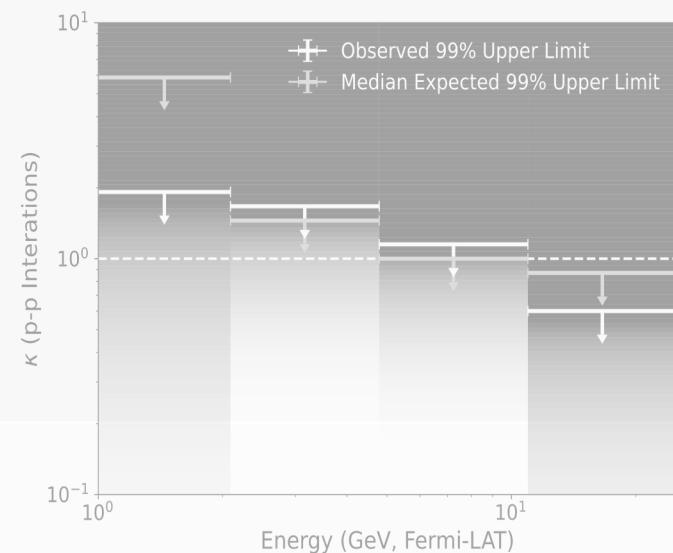
QUESTION 1: *WHAT FRACTION OF THE TOTAL NEUTRINO FLUX IS PRODUCED IN BLAZARS?*

Negro, Crnogorčević, et al. 2023 ([arXiv:2304.10934](https://arxiv.org/abs/2304.10934))  
ApJ. 951 (2023) 1, 83

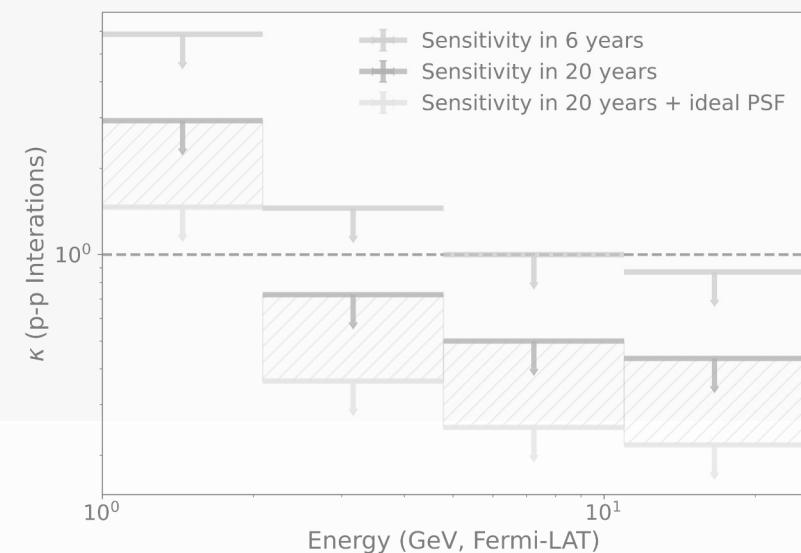
# Simulations



# Observations



# Predictions



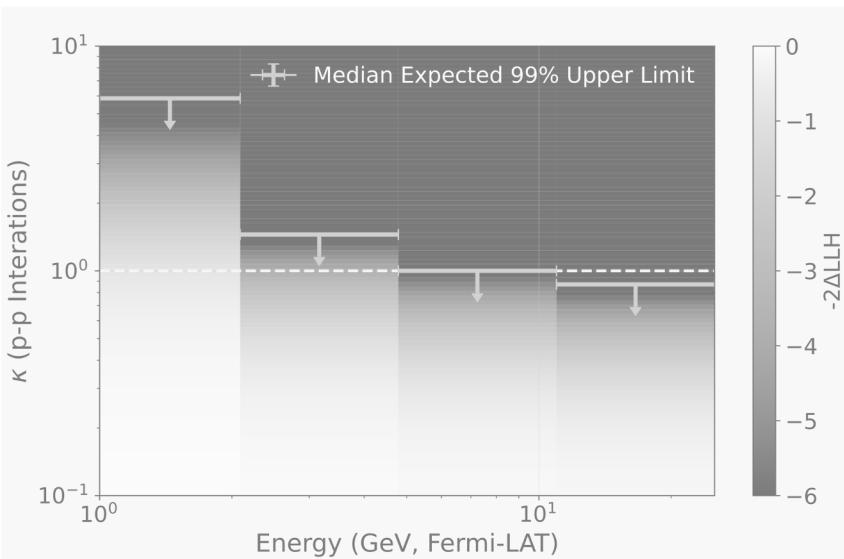
- Gamma rays produced in p–p interactions (Feng & Murase 2021):

$$E_\nu^2 \frac{dN_\nu}{dE_{nu}} \approx \frac{1}{2} \left( E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \right), \text{ at } E_\nu \approx \frac{E_\gamma}{2}$$

- Injecting the neutrino signal:

$$E_\nu^2 \frac{dN_\nu}{dE_{nu}} \approx \frac{\kappa}{2} \left( E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \right), \text{ at } E_\nu \approx \frac{E_\gamma}{2}$$

# Simulations



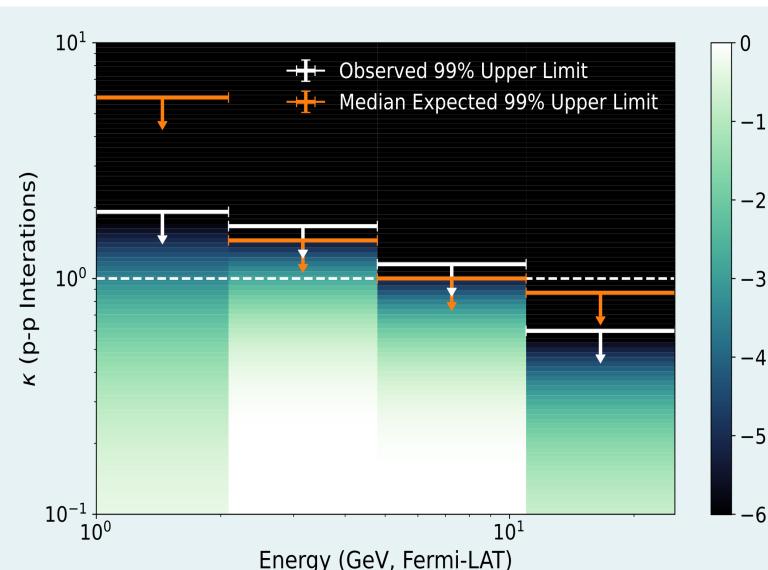
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- Injecting the neutrino signal:

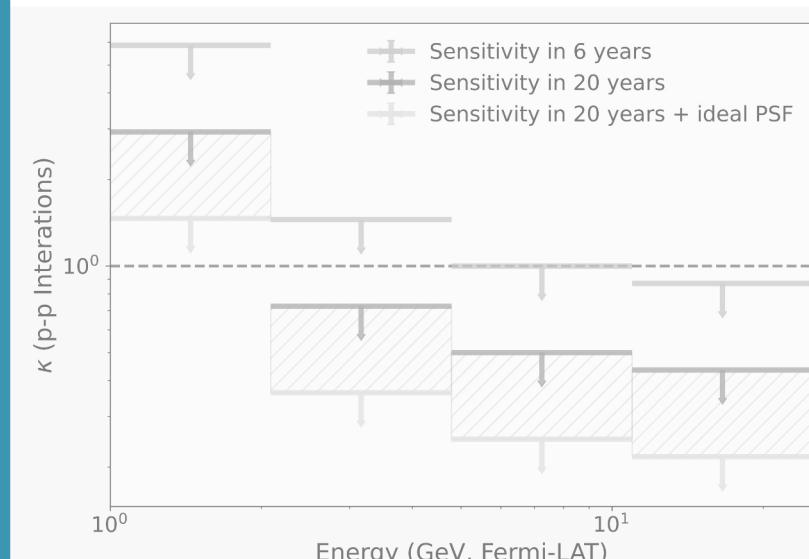
$$E_\nu^2 \frac{dN_\nu}{dE_{nu}} \approx \frac{\kappa}{2} \left( E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \right), \text{ at } E_\nu \approx \frac{E_\gamma}{2}$$

# Observations

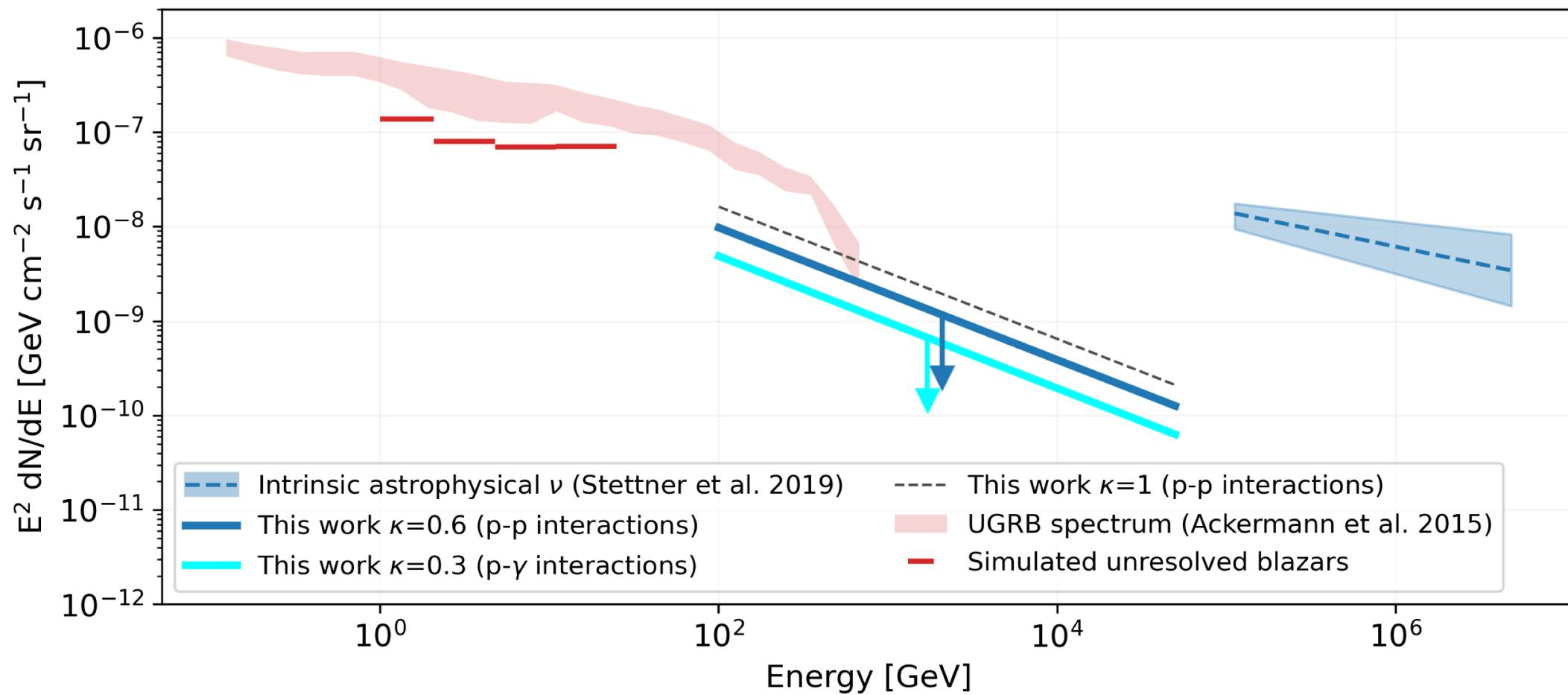


- IceCube 6-year map and Fermi-LAT 12 years of data
- Constraining limits in the last energy bin:  $\kappa < 0.6$

# Predictions



# Upper Limits on the $\nu_{\text{astro}}$ flux

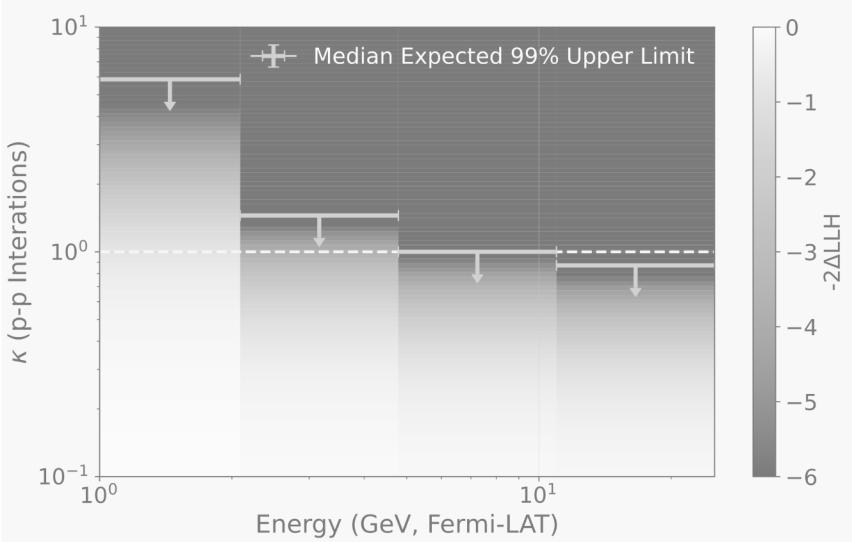


→ Unresolved blazars contribute ~1% at 100 TeV and ~10% at 1 TeV

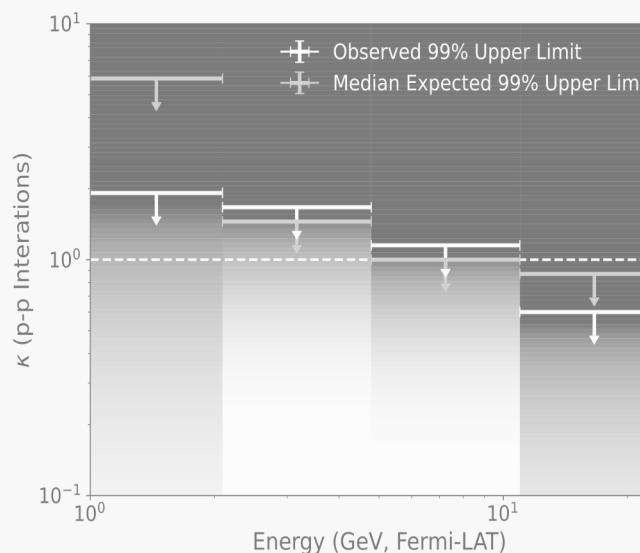
## QUESTION 3: *WHAT DO WE PREDICT?*

Negro, Crnogorčević, et al. 2023 ([arXiv:2304.10934](https://arxiv.org/abs/2304.10934))  
ApJ. 951 (2023) 1, 83

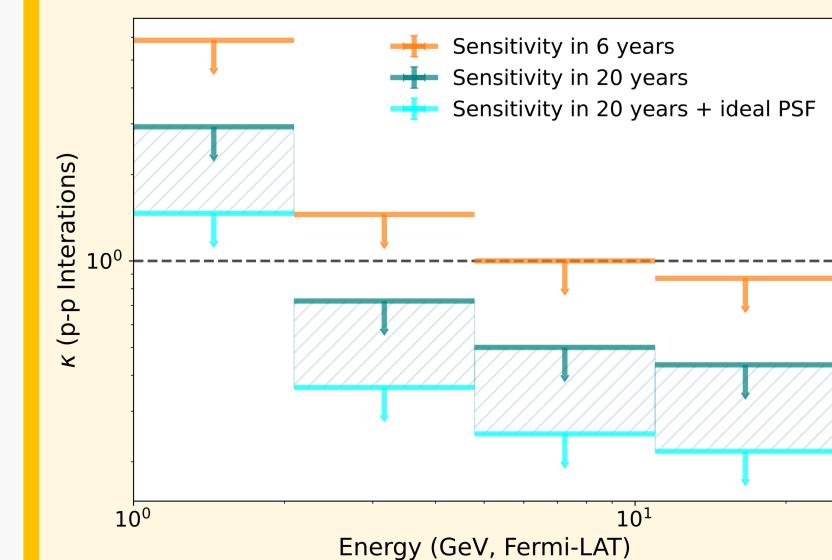
## Simulations



## Observations



## Predictions



- Keeping the *Fermi*-LAT UGRB emission the same
- Changing the IceCube statistics (alone, and with PSF)

## CHAPTERS III-IV

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Crnogorčević et al. 2021 (PRD), Crnogorčević et al. 2024 (in prep.)

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Fletcher et al. on behalf of GBM, Crnogorčević et al. on behalf of BAT, and LVK, 2023 (ApJ)

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Negro, Crnogorčević, et al. 2023 (ApJ)

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- UMD Astronomy's business office
- Terrapin Masters Swimming
- Friends & family
- And more!



# Thank you.

