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

NEW MESSENGERS & NEW PHYSICS

A Survey of the High-energy Universe

Dissertation Defense
April 24, 2023

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Prof. Chris Reynolds[1,3]

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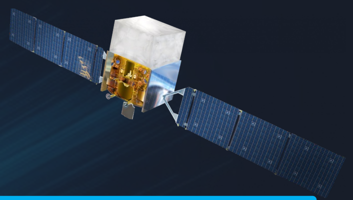
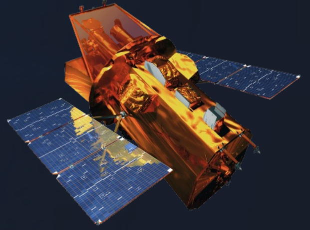
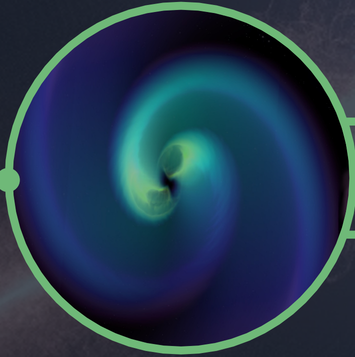
New Physics: ALPs x γ







New Messengers I: GWs x γ

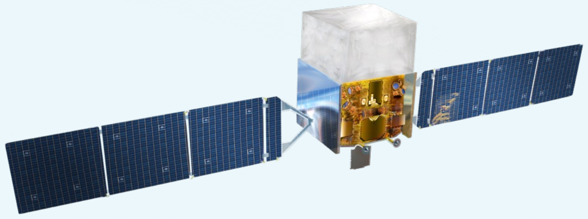
LIGO VIRGO KAGRA

New Messengers II: ν x γ

IceCube Neutrino Observatory

OBSERVATORIES

Fermi

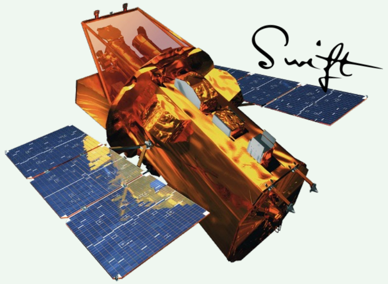


GBM: Gamma-ray Burst Monitor
- FoV: entire unocculted sky
- 8 keV to 40 MeV
- 2300+ bursts (~1 every day or two)

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

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

Swift



BAT: Burst Alert Telescope
- One of three instruments onboard
- FoV: ~ 2 sr
- Localization ~few arcmin
- 15 keV to 150 keV

Barthelmy et al. 2005

LIGO/*Virgo*/KAGRA

- LIGO: detectors in Hanford, WA, and Livingston, LA
- *Virgo*: Cascina, Italy
- KAGRA: Gifu Prefecture, Japan

- Michelson interferometer gravitational wave detectors

The LVK Collaboration (Abbott et al. 2009)

IceCube

- Neutrino detector located at the South Pole
- 5,000+ optical modules
- ~10 GeV to >1 EeV
- All-sky (Northern vs. Southern hemisphere)

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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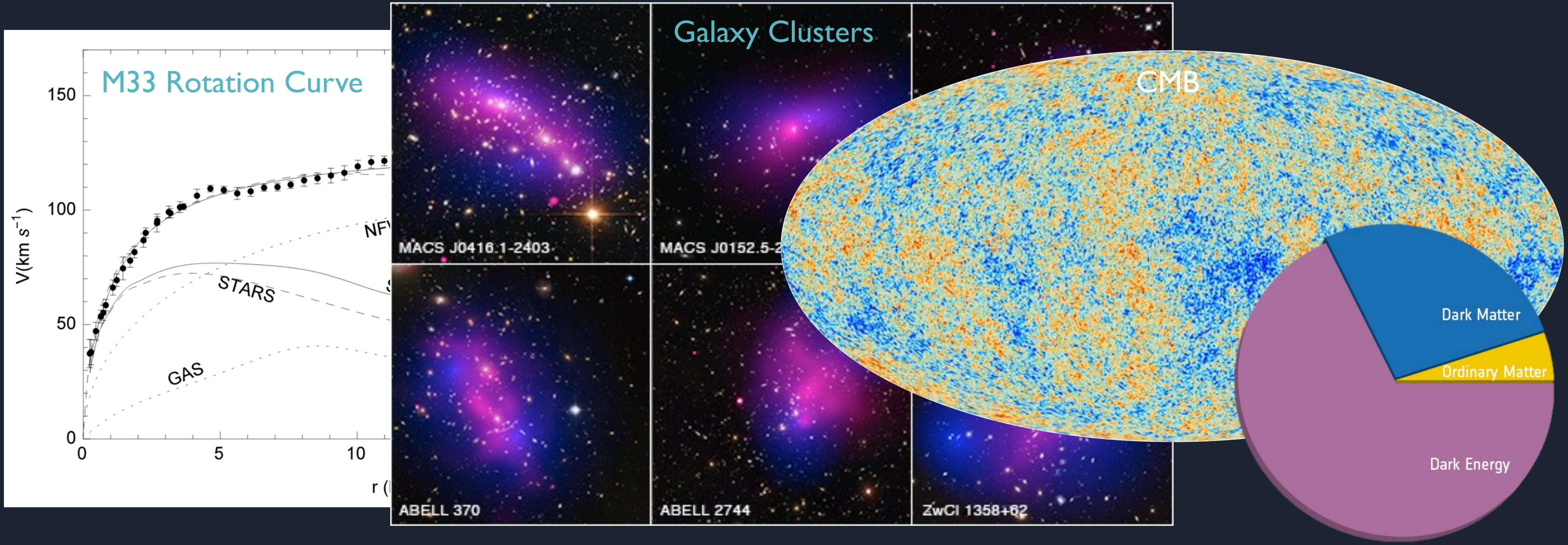
OVERWHELMING EVIDENCE FOR THE EXISTENCE OF DARK MATTER

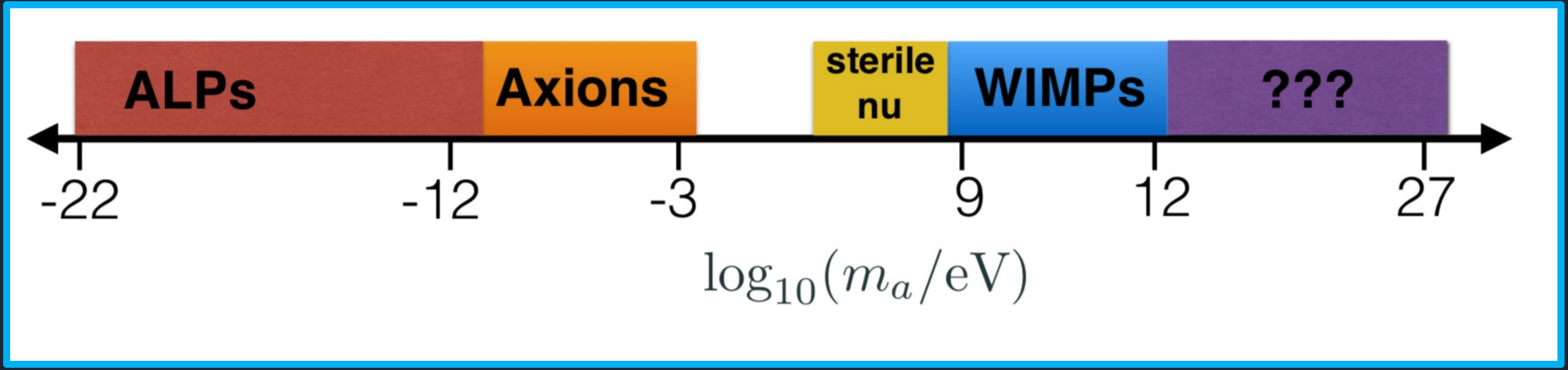
X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D.Harvey & NASA/CXC/Durham Univ/R.Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)



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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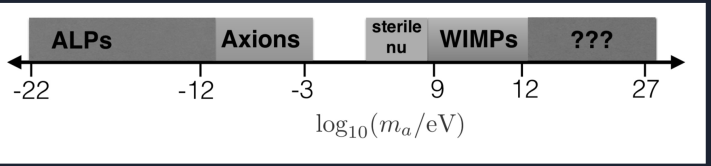
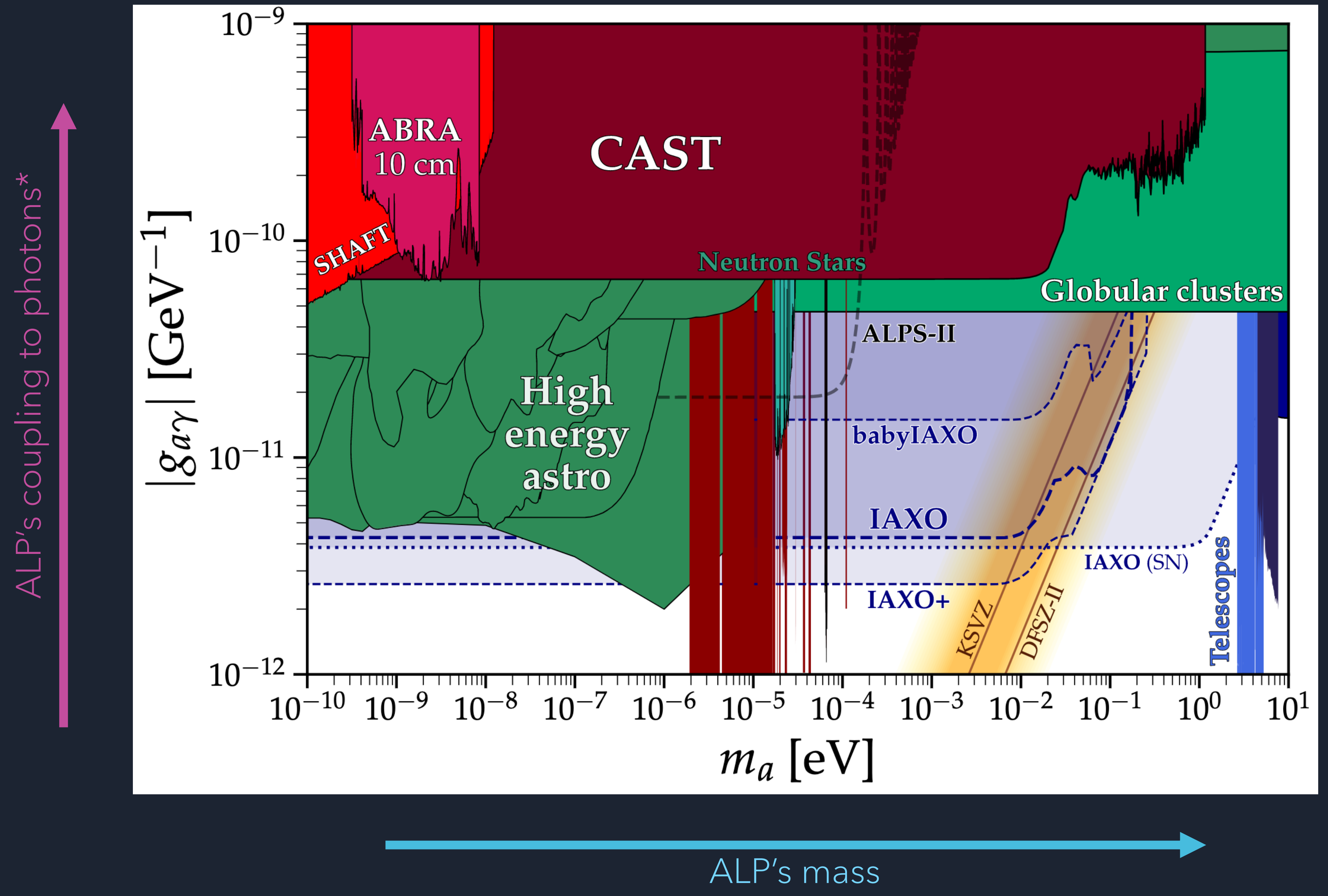


- Cold matter requirements:
  - ✓ feeble interactions with standard model particles
  - ✓ cosmological stability
  - ✓ Non-thermal production → cold

$$\rho_{a,0} \lesssim 1 \frac{keV}{cm^3} \frac{m_a(t_0)}{eV} \left(\frac{\theta(t_1)}{53\,TeV}\right)^2$$ → Dark Matter!

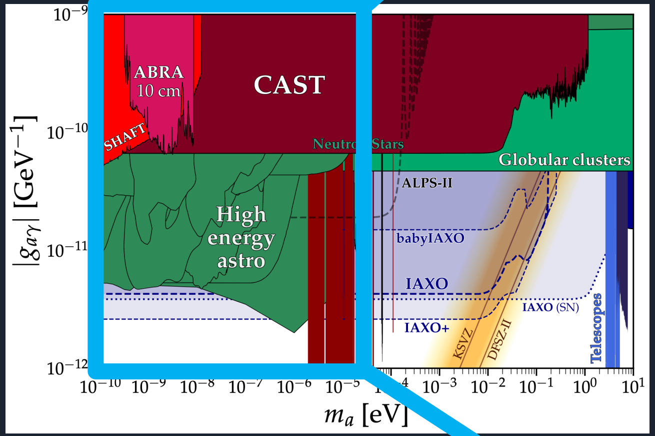
- Direct and indirect searches → limits on coupling/mass parameter space

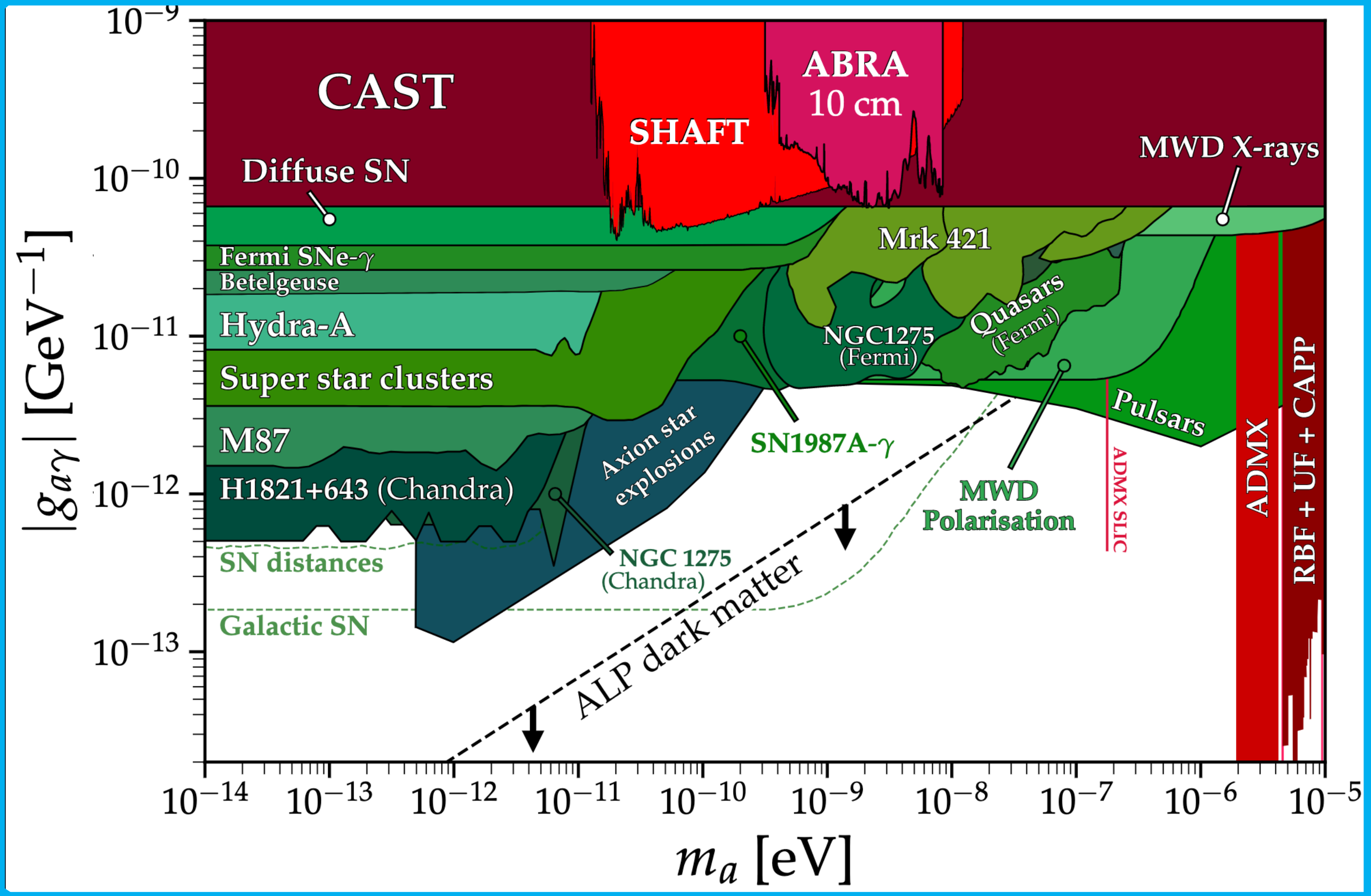
Chapters III & IV: Introduction and Motivation



*analogous to a WIMP cross-section

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





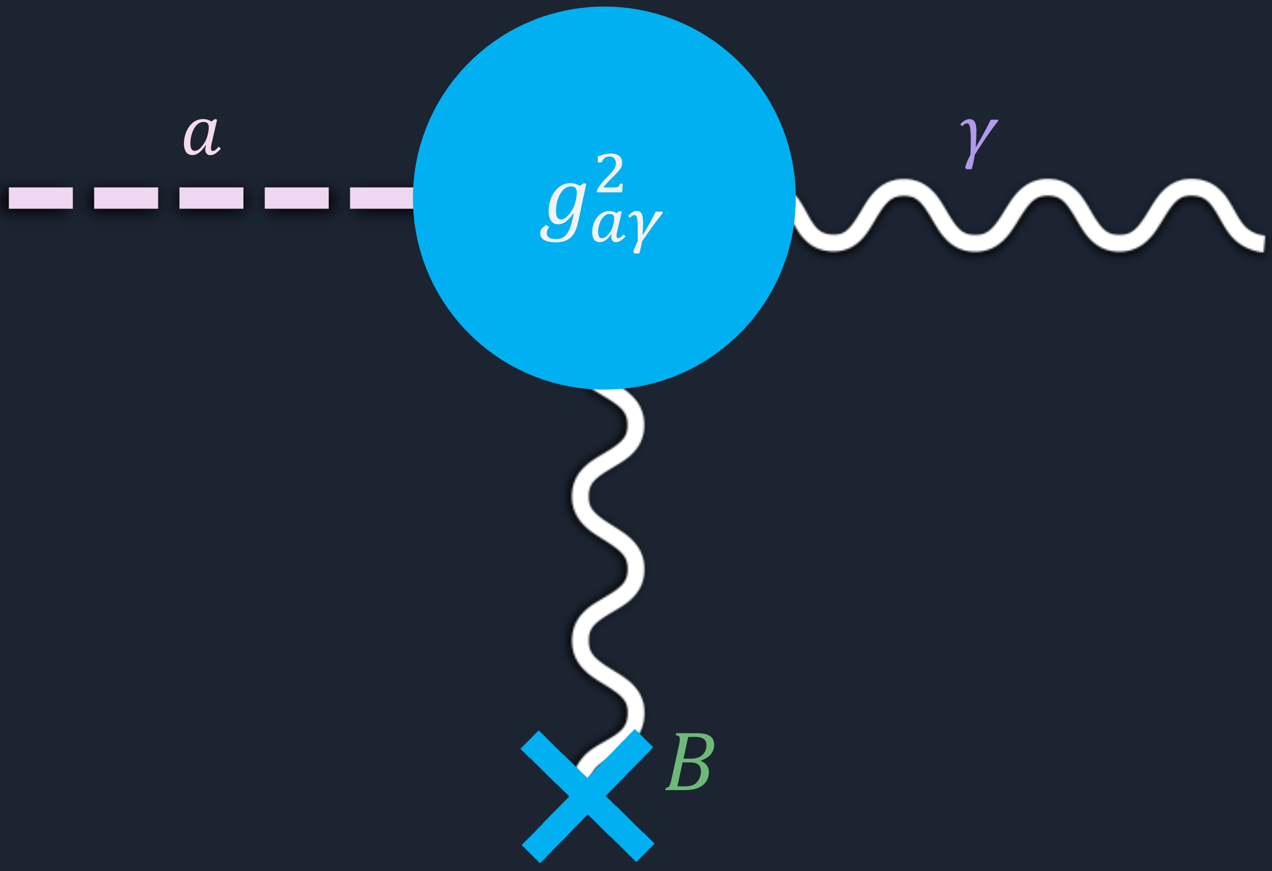
Plot produced using: https://cajohare.github.io/AxionLimits/

OBSERVING ALPS WITH GAMMA RAYS

- In the presence of an external magnetic field, B, ALPs undergo a conversion into photons:

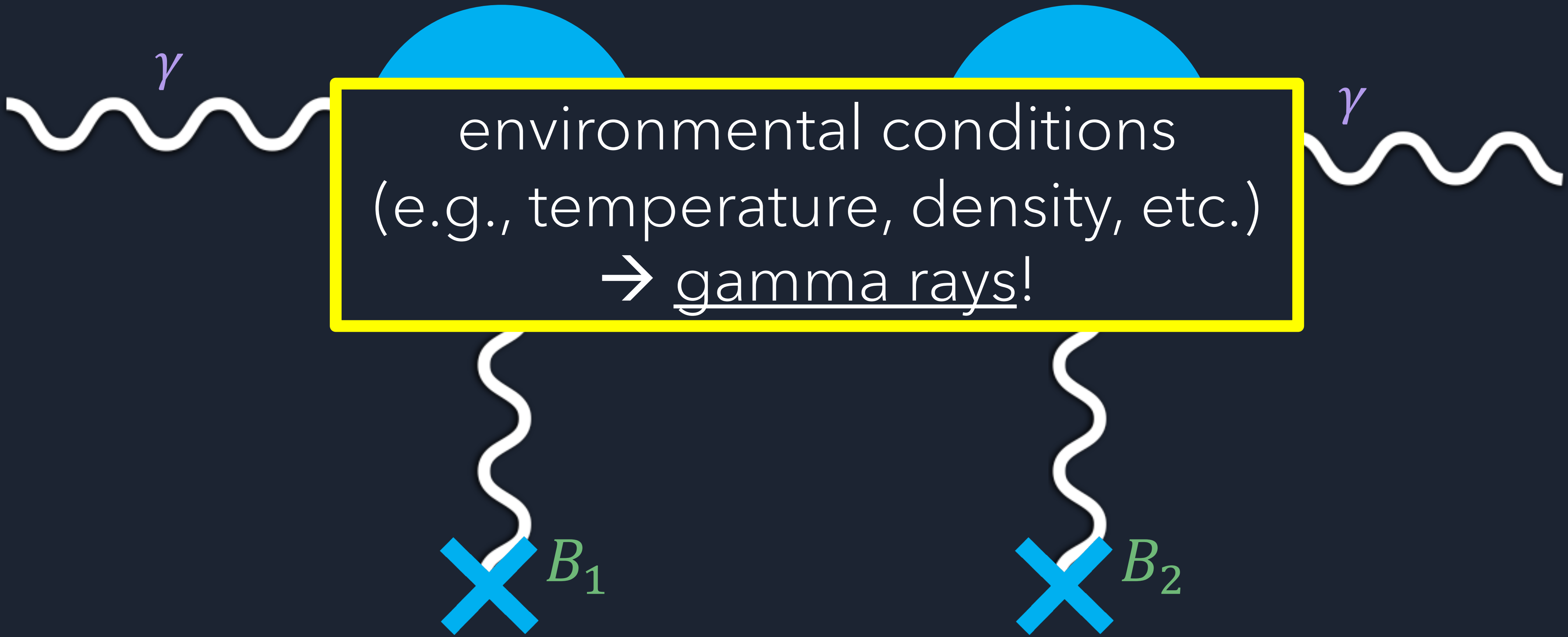
$$\mathcal{L}_{a\gamma} \supset g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

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



Primakoff process: converting ALPs into photons

OBSERVING ALPS WITH GAMMA RAYS



environmental conditions
(e.g., temperature, density, etc.)
→ gamma rays!

(production: Primakoff process)

(detection: inverse Primakoff process)

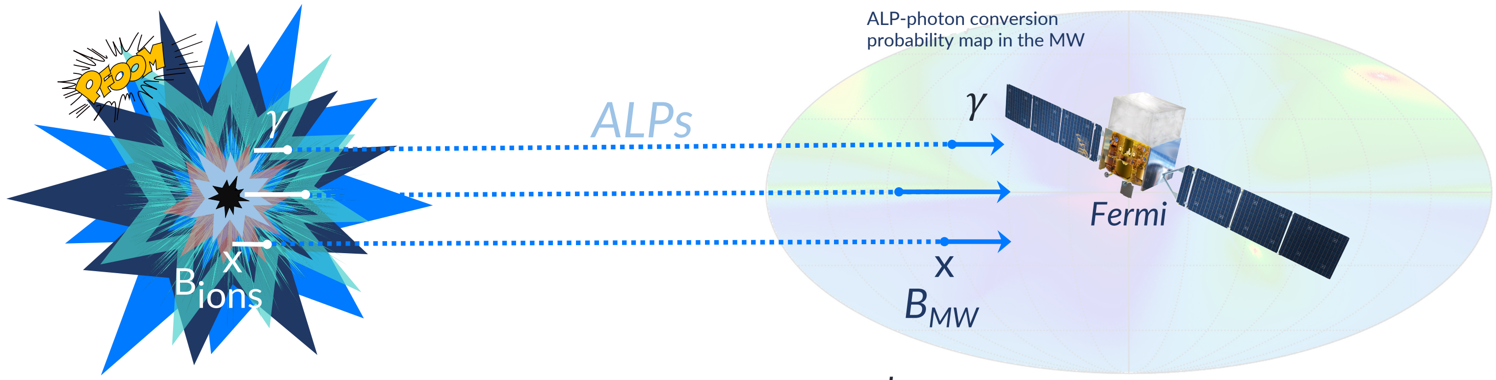
Primakoff process: converting ALPs into photons

ALP…

is a viable *cold* dark-matter candidate

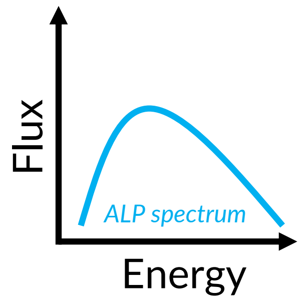
converts into photons in the presence of a magnetic field

parameter space can be probed with gamma-ray observations

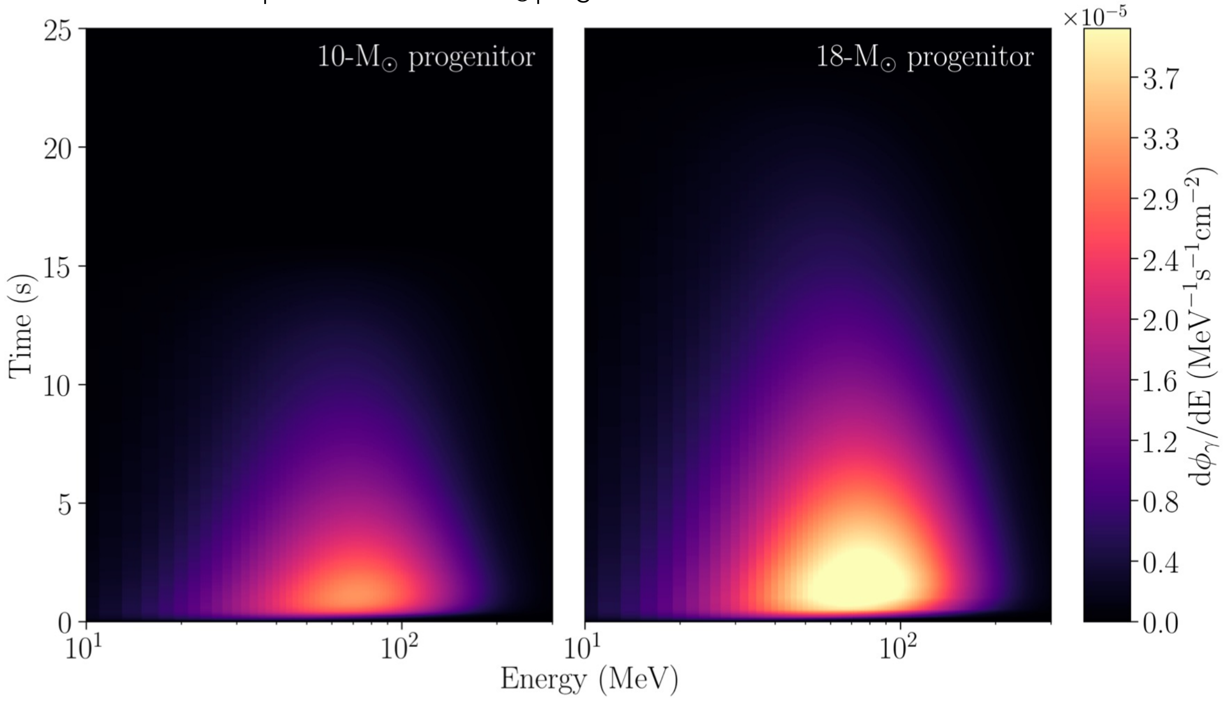


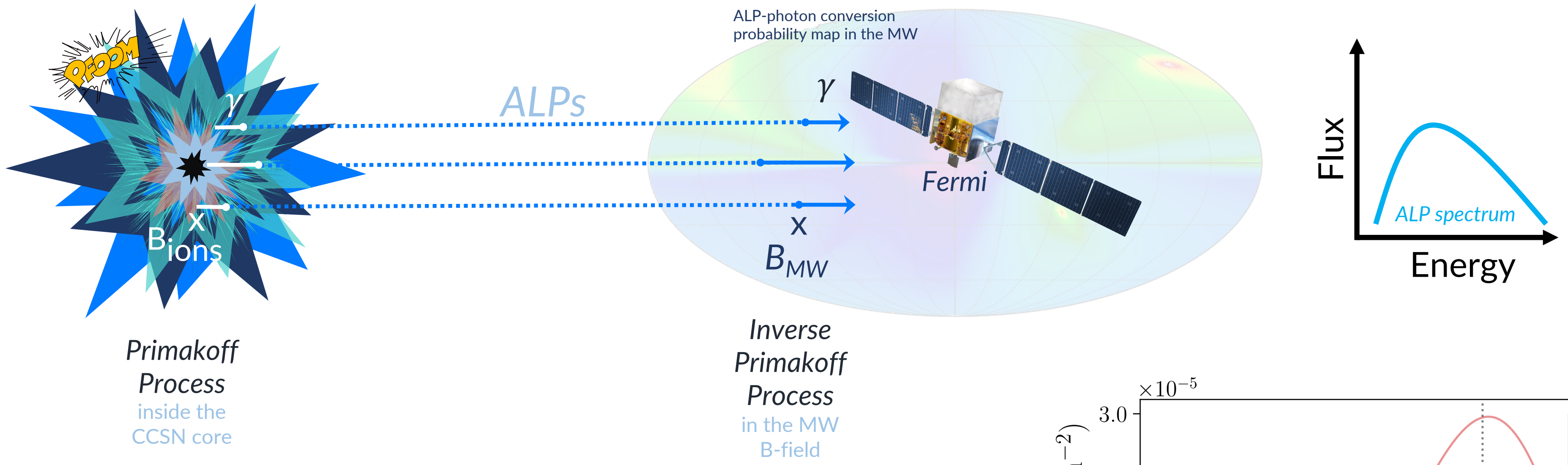
Primakoff Process inside the CCSN core

Inverse Primakoff Process in the MW B-field

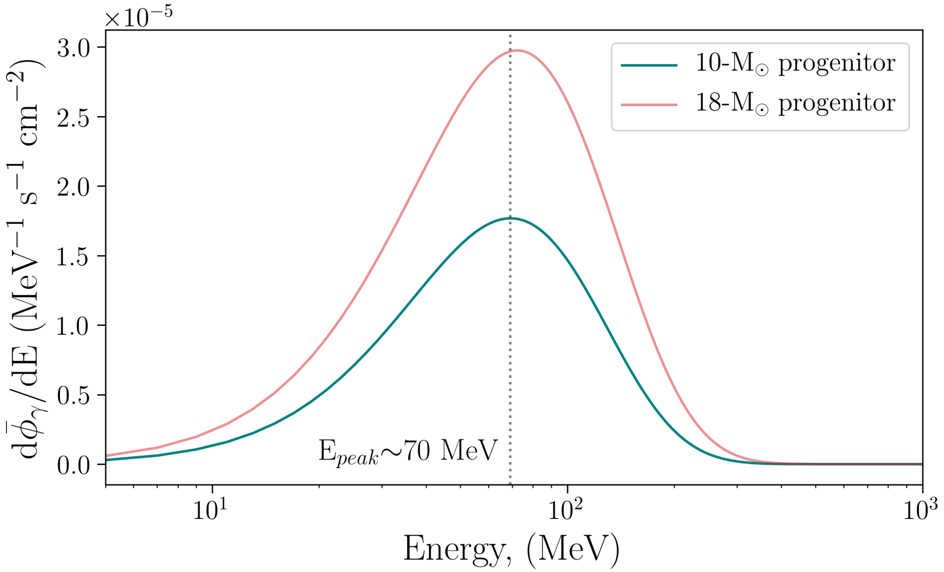


Observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a 10 and 18-M⊙ progenitor.



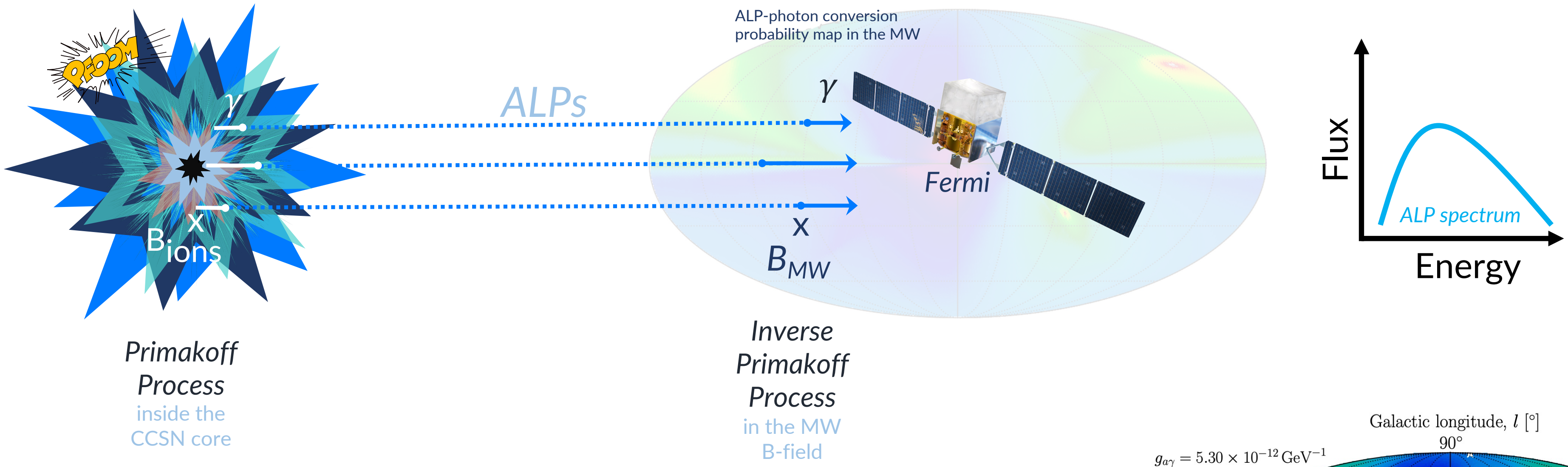


- **Motivation:** ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.

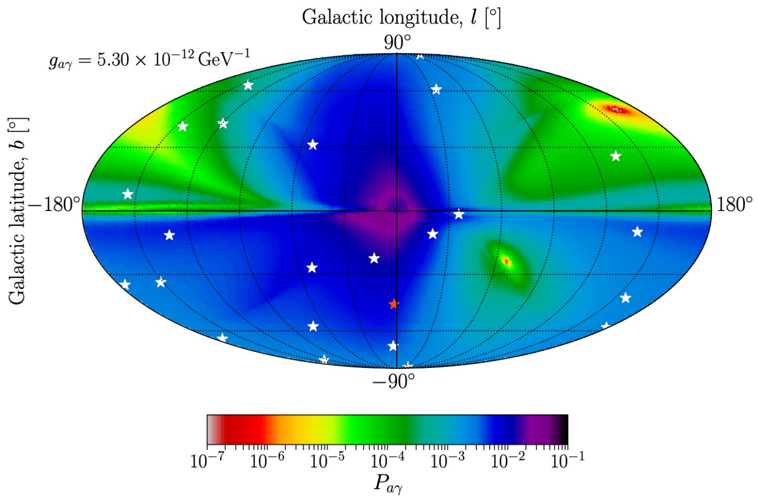


The observed ALP-induced gamma-ray spectrum for 10 and 18-M⊙ progenitors averaged over 10 seconds.

Chapters III & IV: Physical System set-up

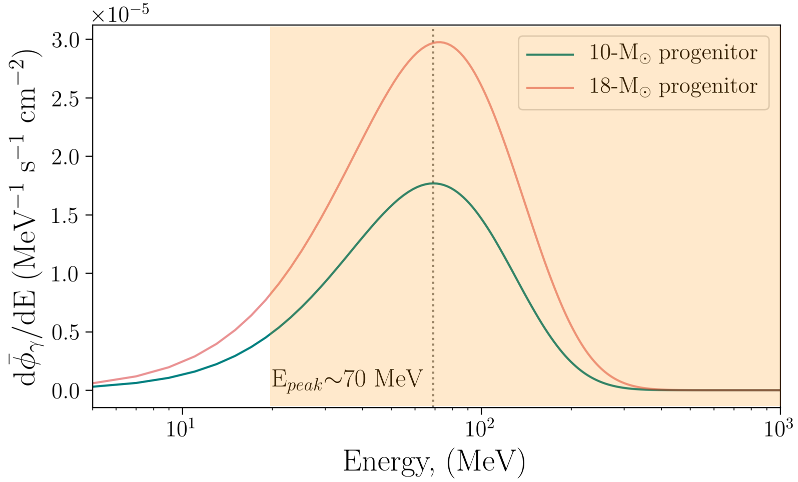


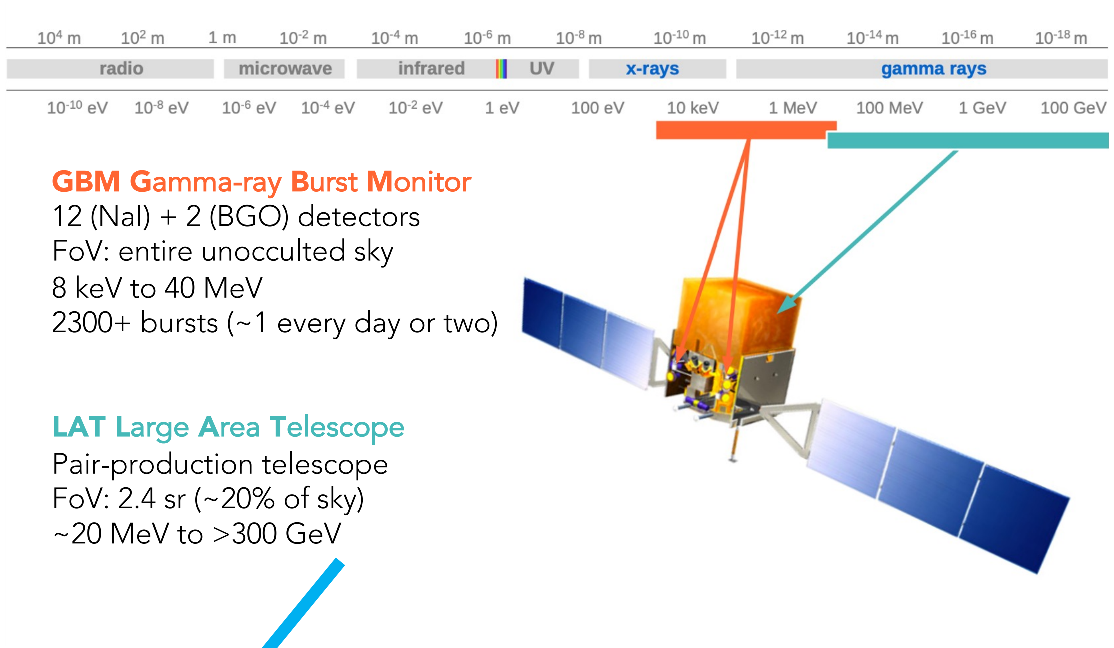
- **Motivation:** ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.
- **Assumptions:** magnetic fields: only considering the MW magnetic field, neglecting IGMF
- **CCSN – Gamma-ray Bursts relationship**



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

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

LAT LOW ENERGY (LLE) TECHNIQUE

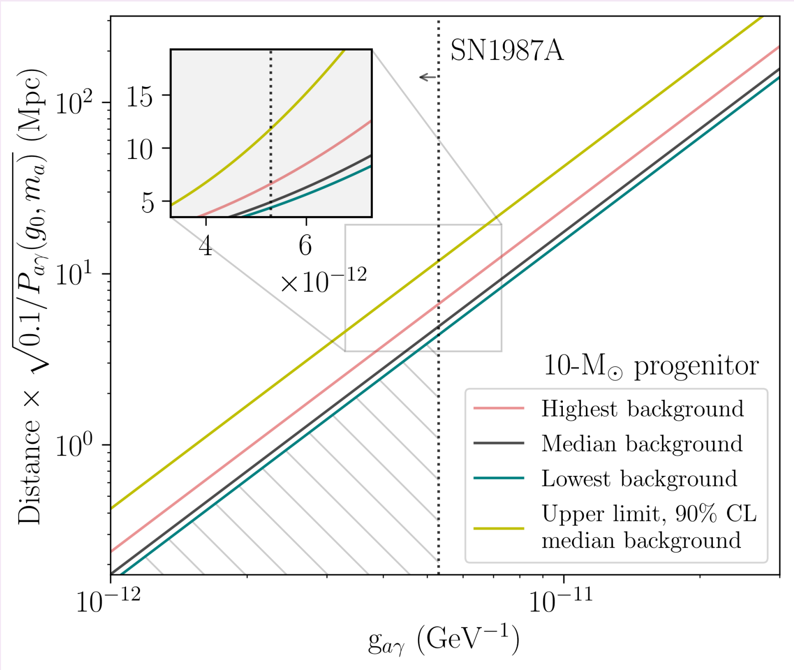
- Standard LAT analysis: >100 MeV vs. LLE analysis: > 20 MeV
- LLE: maximizing the effective area of the LAT instrument in the low-energy regime
- More signal, but also more background

Solar-flare LLE analysis: arXiv:1304.5559

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

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

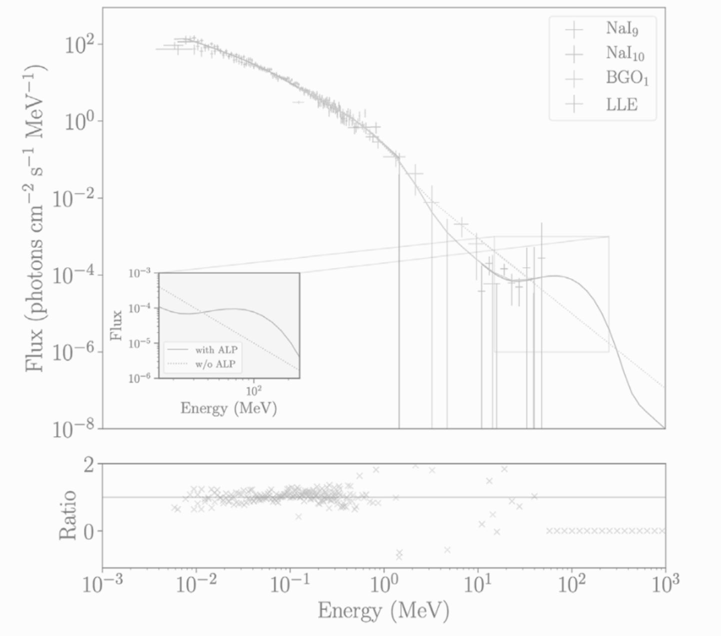
Fermi-LLE Sensitivity



- LLE can reach up to ~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)

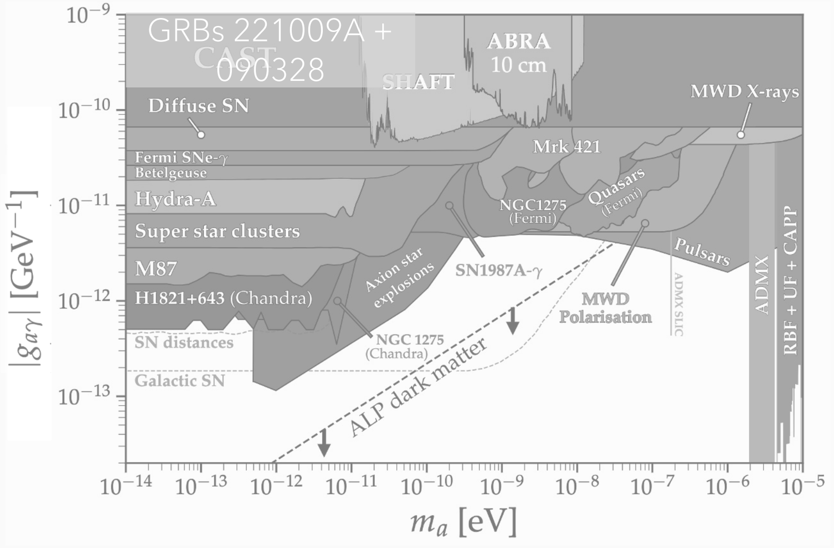
GRB searches



- 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)

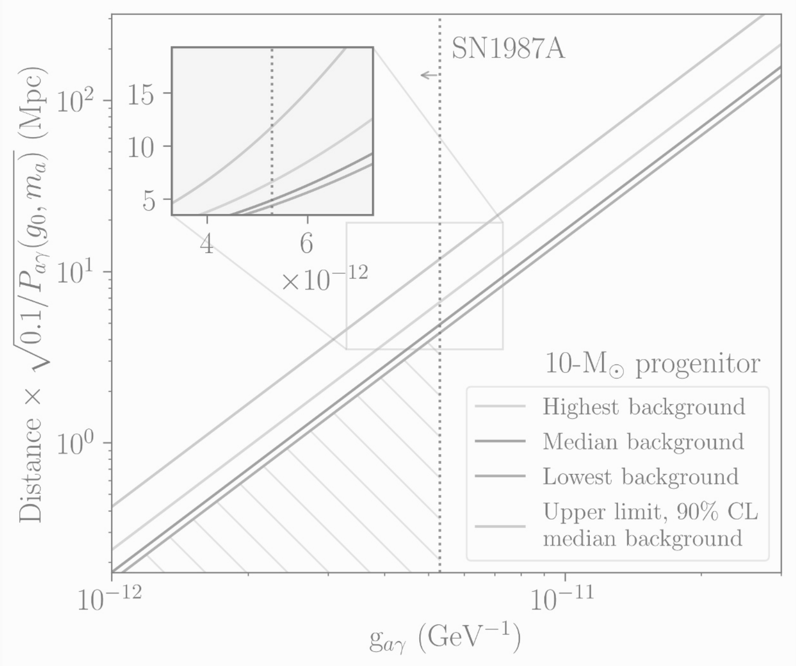
QUESTION 2: *HAVE WE ALREADY SEEN ANY ALP EMISSION IN LLE GRBS?*

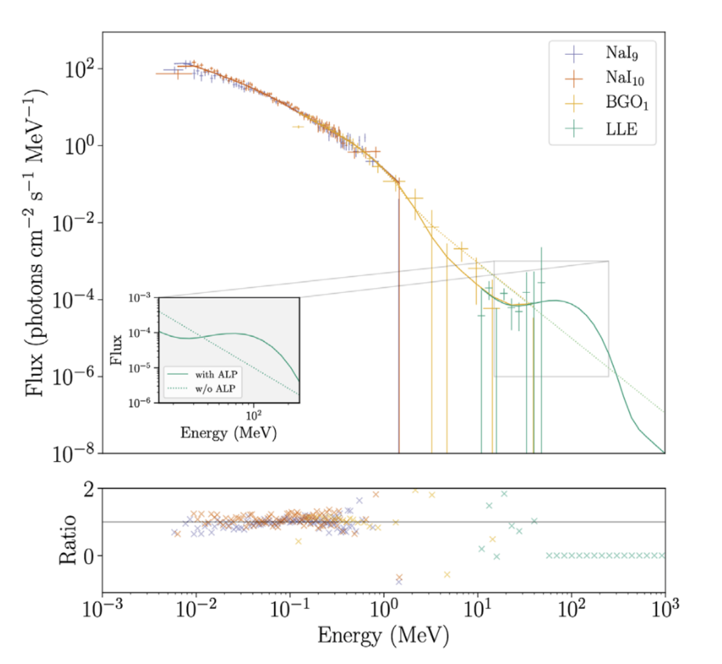
Reported in: Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

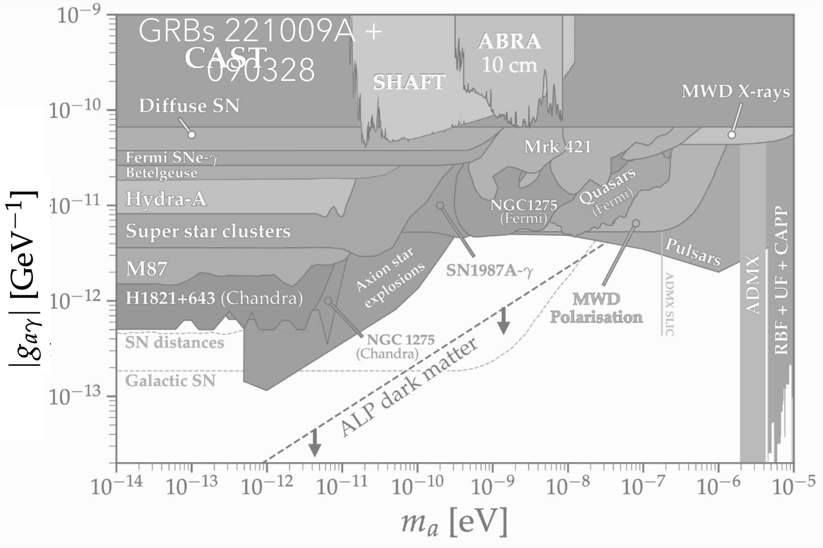
Fermi-LLE Sensitivity

GRB searches

GRB Precursors







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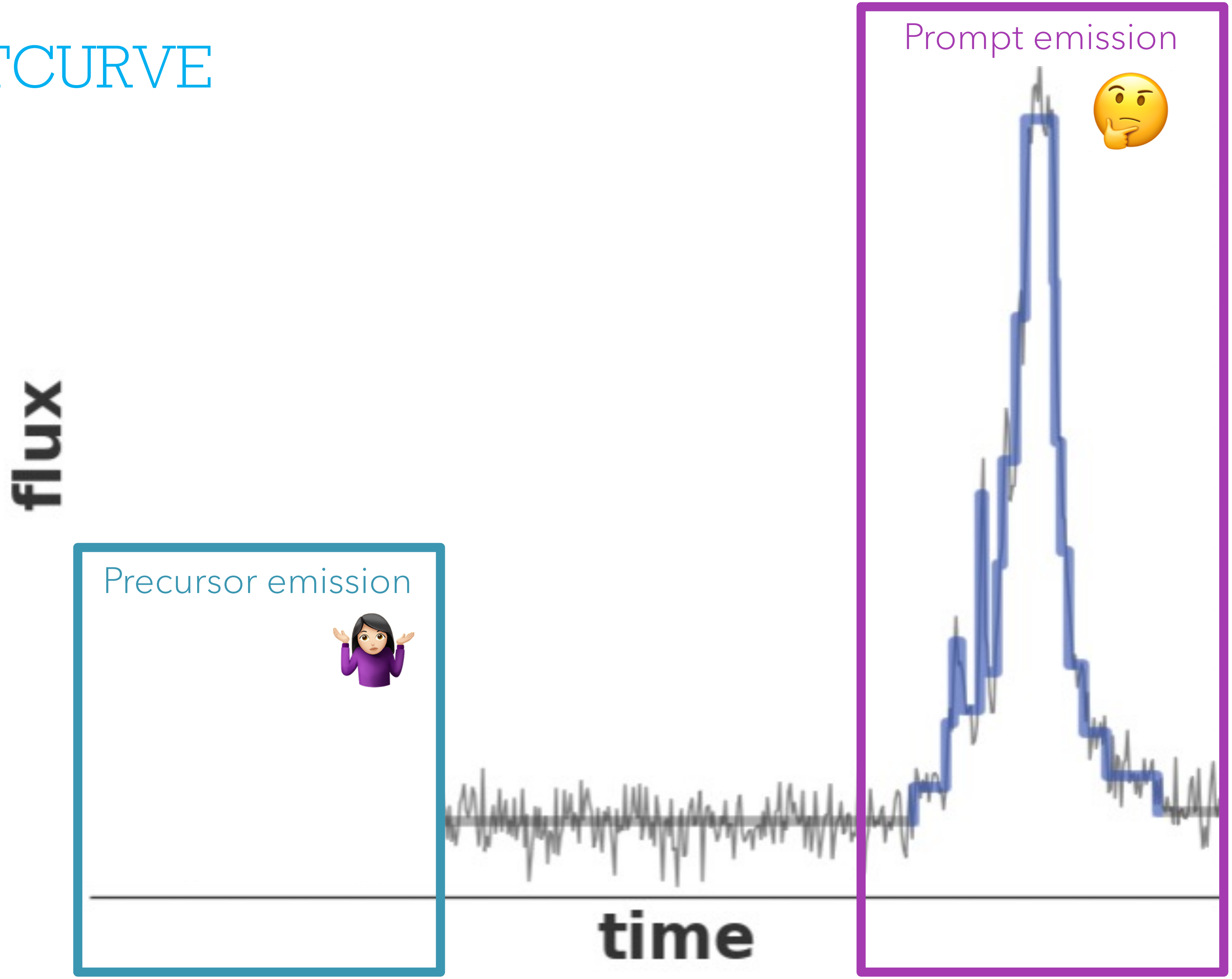
Crnogorčević et al. 2023 (under review)

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

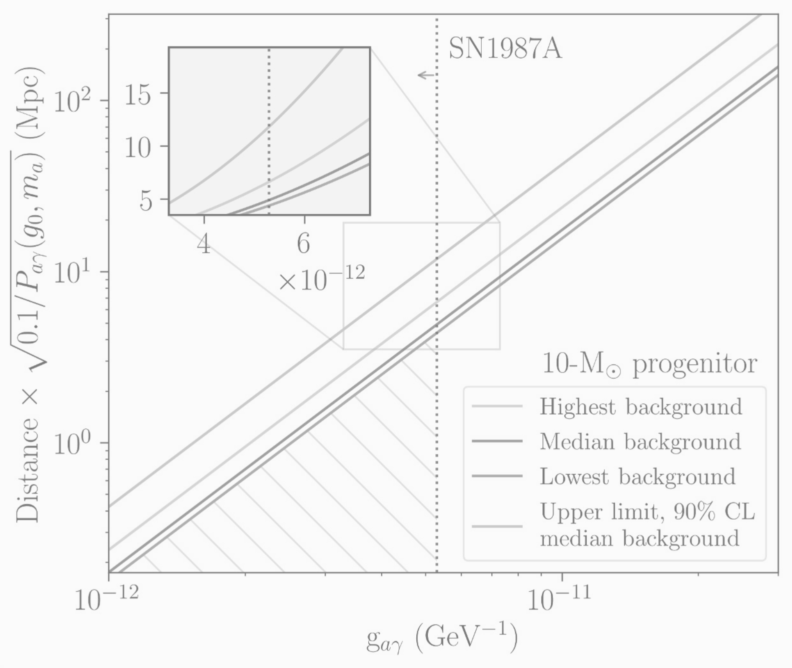
Fermi GI Program, Cycle 15; PI: Crnogorčević

Reported in: Crnogorčević et al. 2023 (under *Fermi*-LAT review)

GRB LIGHTCURVE



Fermi-LLE Sensitivity



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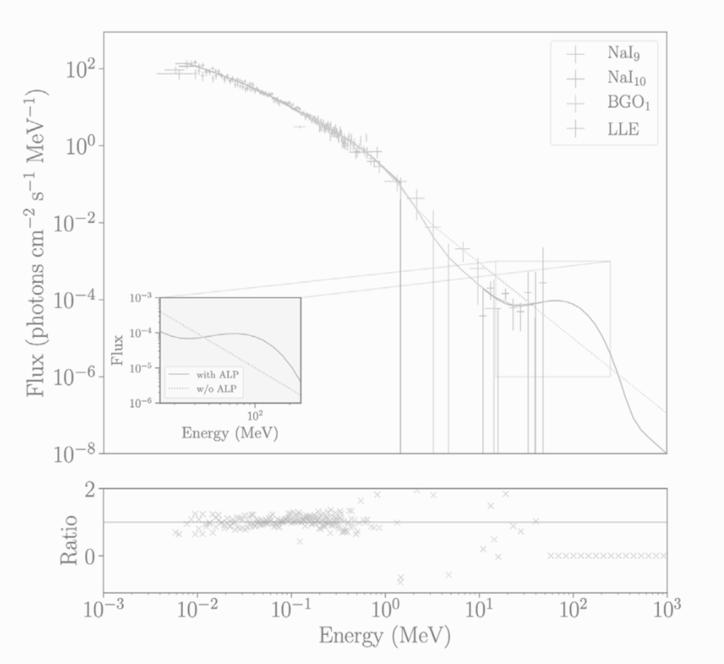
GRB searches



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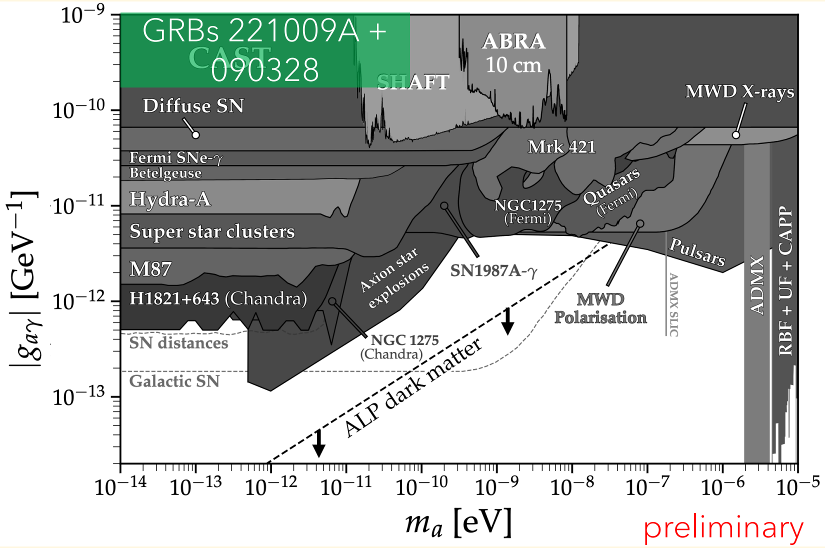

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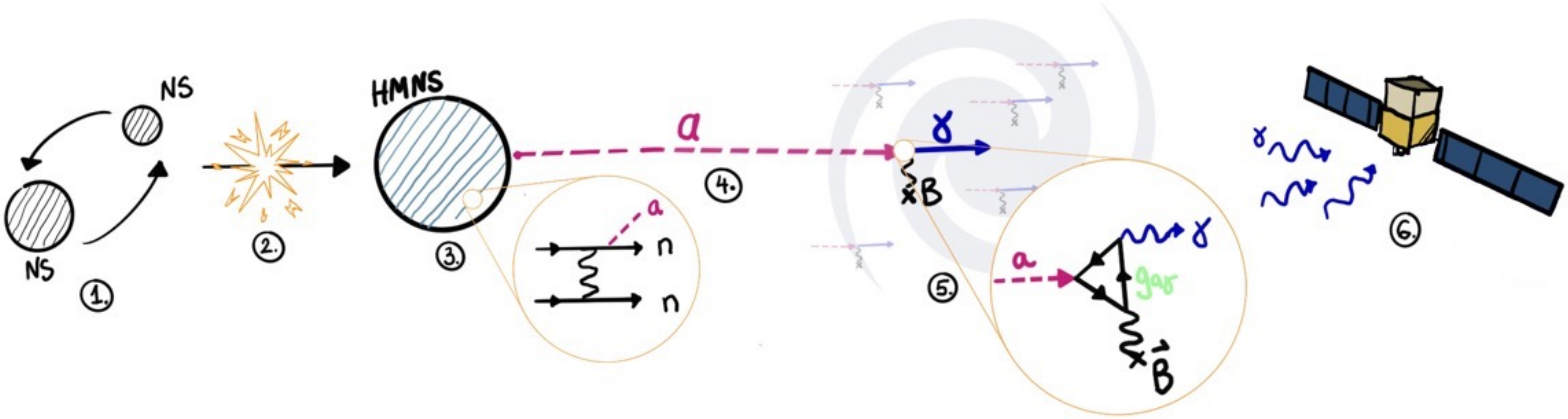

Figure description: (1) Two neutron stars (NS) orbit each other until the (2) merger, followed by (3) the formation of a hypermassive neutron star (HMNS). There, ALPs are produced via the neutron-neutron bremsstrahlung process. Once produced, ALPs travel undisturbed (4), until they reach the magnetic 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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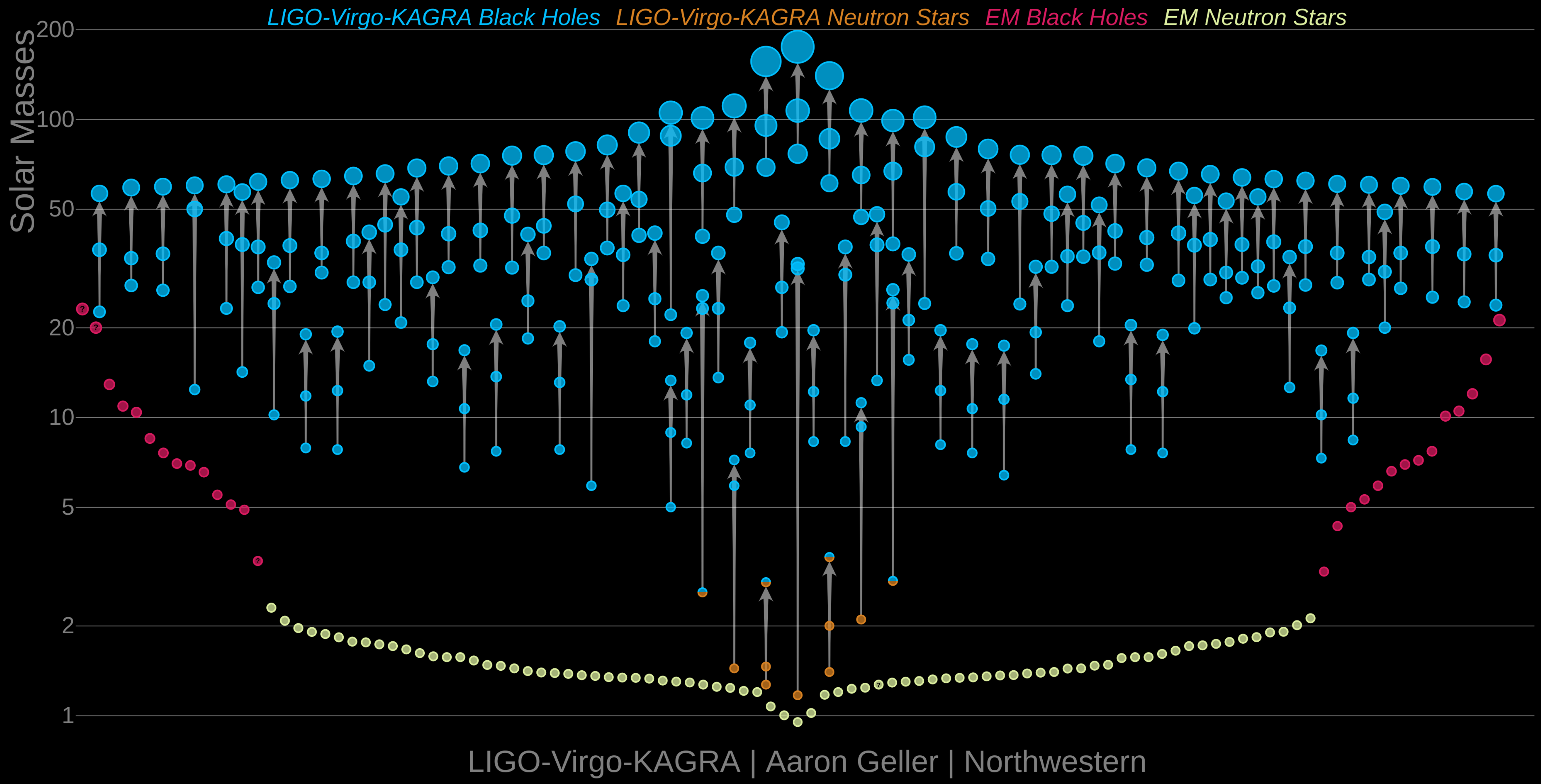
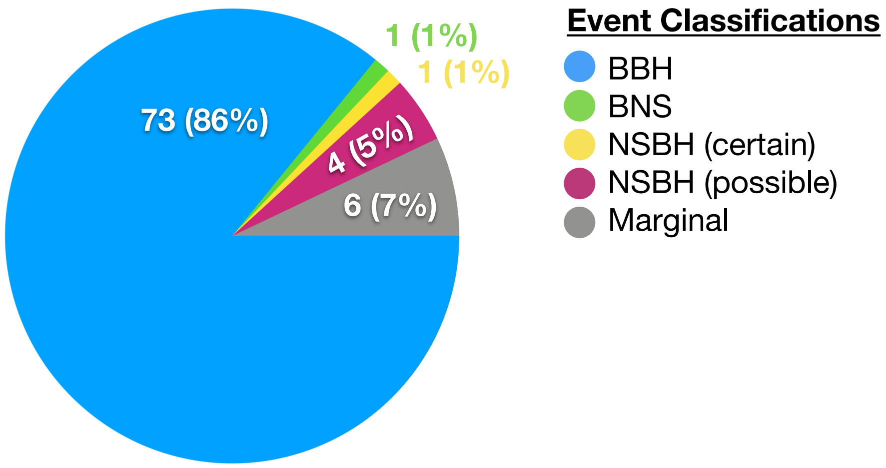
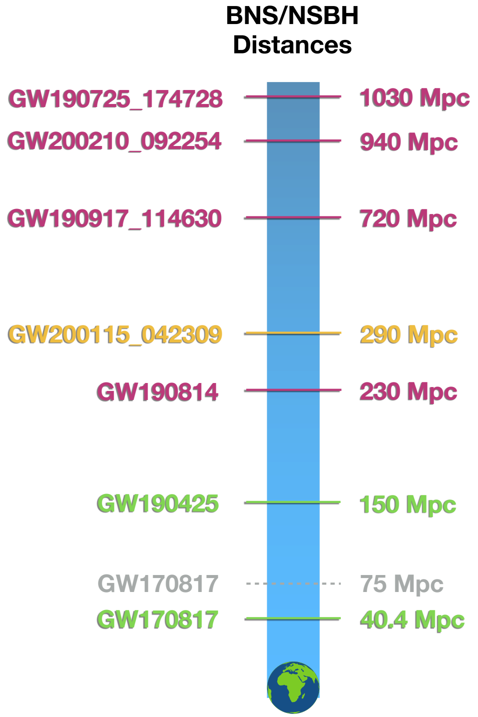
Masses in the Stellar Graveyard



O3: THE THIRD OBSERVING RUN

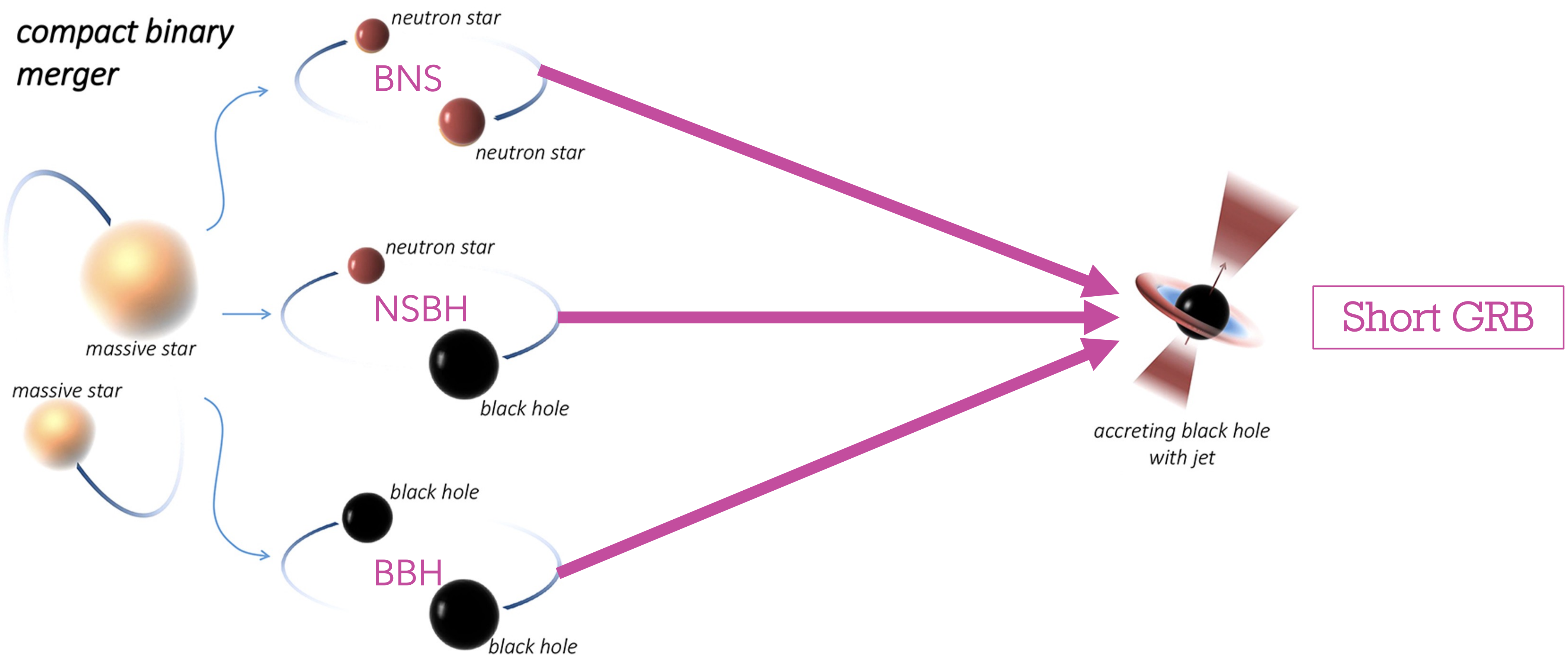
Third LIGO/Virgo observing run (O3): April 2019 -- March 2020 (commissioning break in October 2019)



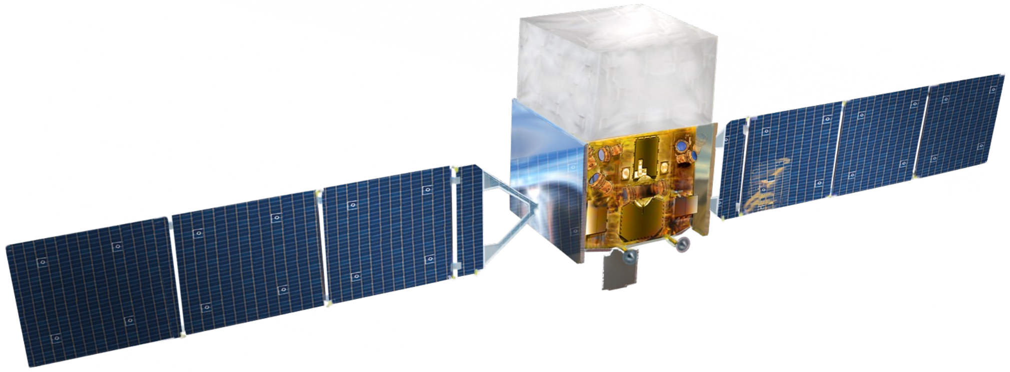


75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

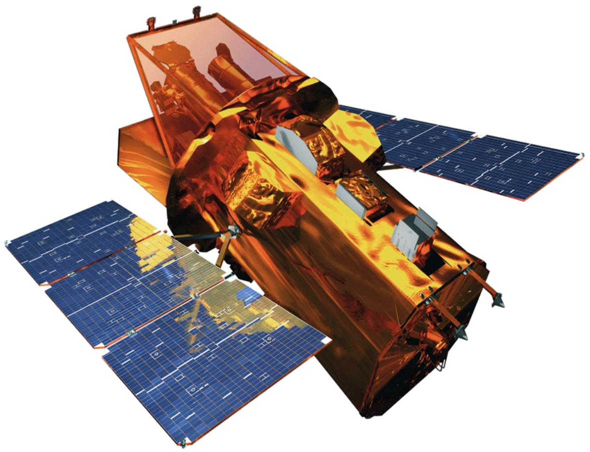
WHERE TO SEARCH FOR GWs: COMPACT BINARY MERGERS



Bartos & Kowalski, 2017



+



Why *Fermi* GBM?

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

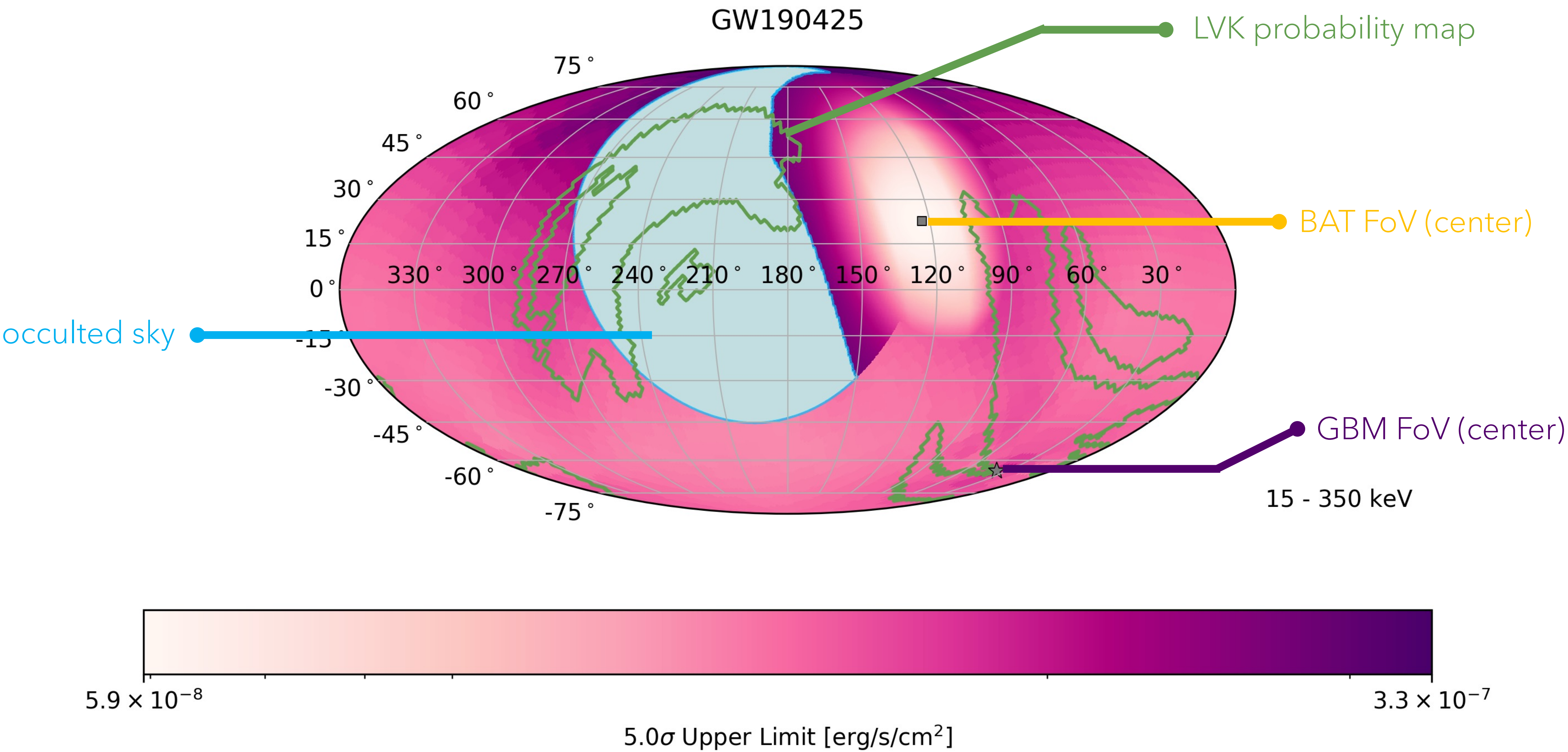
Why *Swift* BAT?

+ 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?*

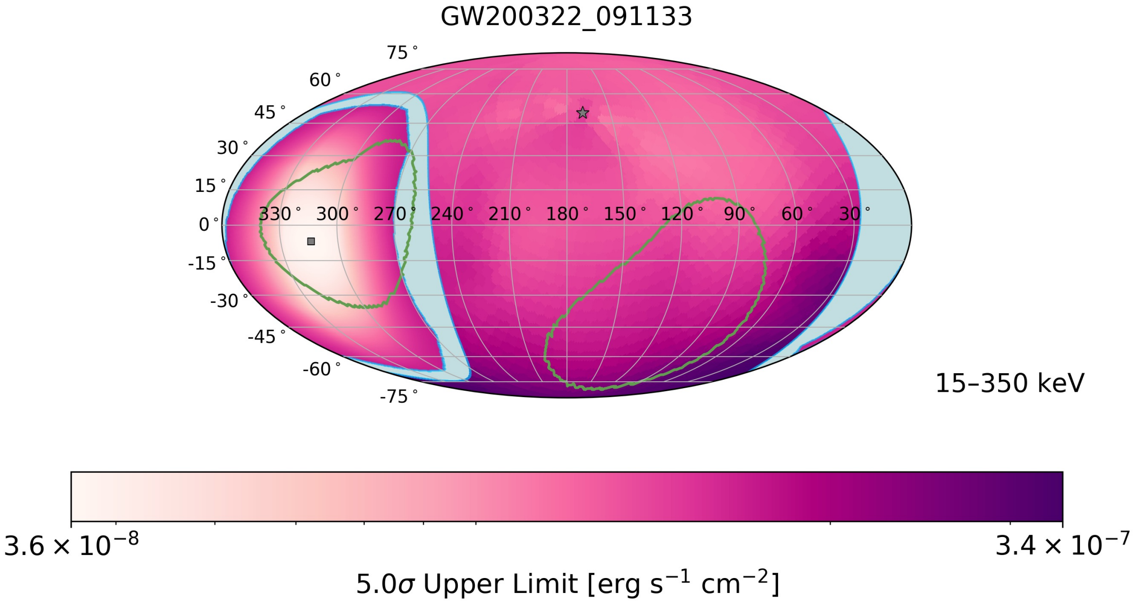
Fletcher et al. on behalf of GBM, Crnogorčević et al. on behalf of BAT, and LVK, 2023 (under review)

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

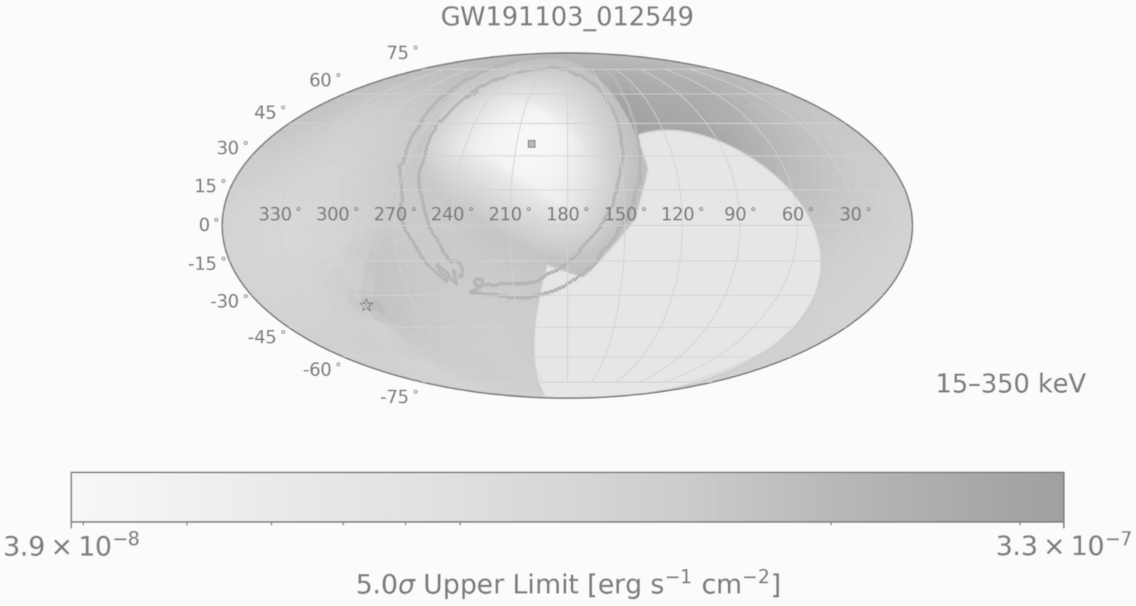

GW190425
LVK probability map
BAT FoV (center)
GBM FoV (center)
occulted sky
15 - 350 keV
75 °
60 °
45 °
30 °
15 °
0 °
-15 °
-30 °
-45 °
-60 °
-75 °
330 ° 300 ° 270 ° 240 ° 210 ° 180 ° 150 ° 120 ° 90 ° 60 ° 30 °
5.9×10^{-8}
3.3×10^{-7}
5.0σ Upper Limit [erg/s/cm^2]

Combining the upper limits

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



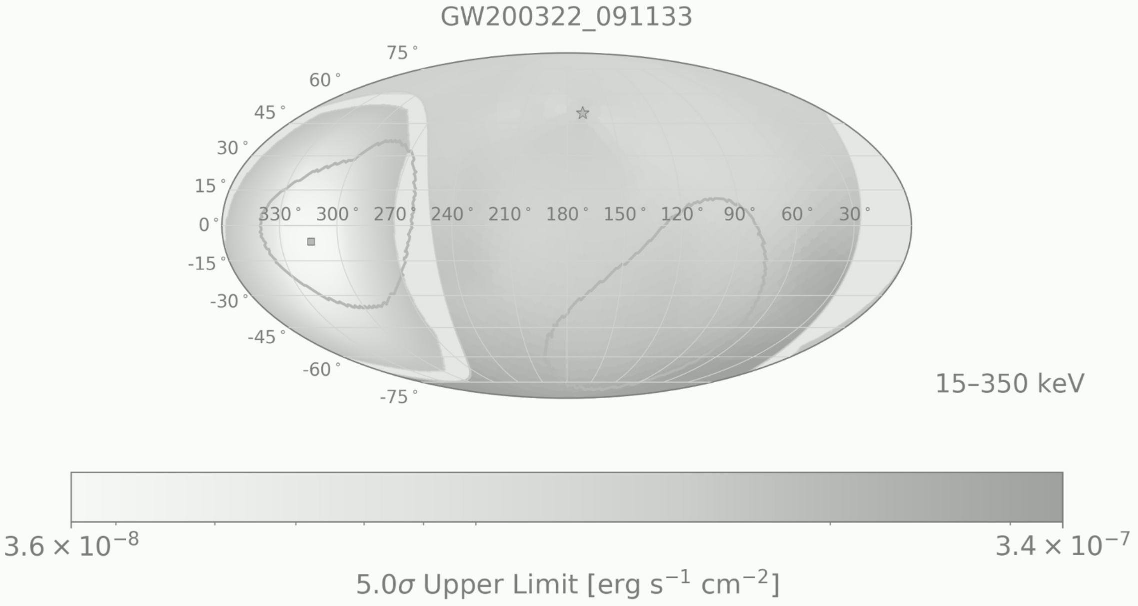
BAT ensures more sensitivity when the GW trigger is inside its FoV

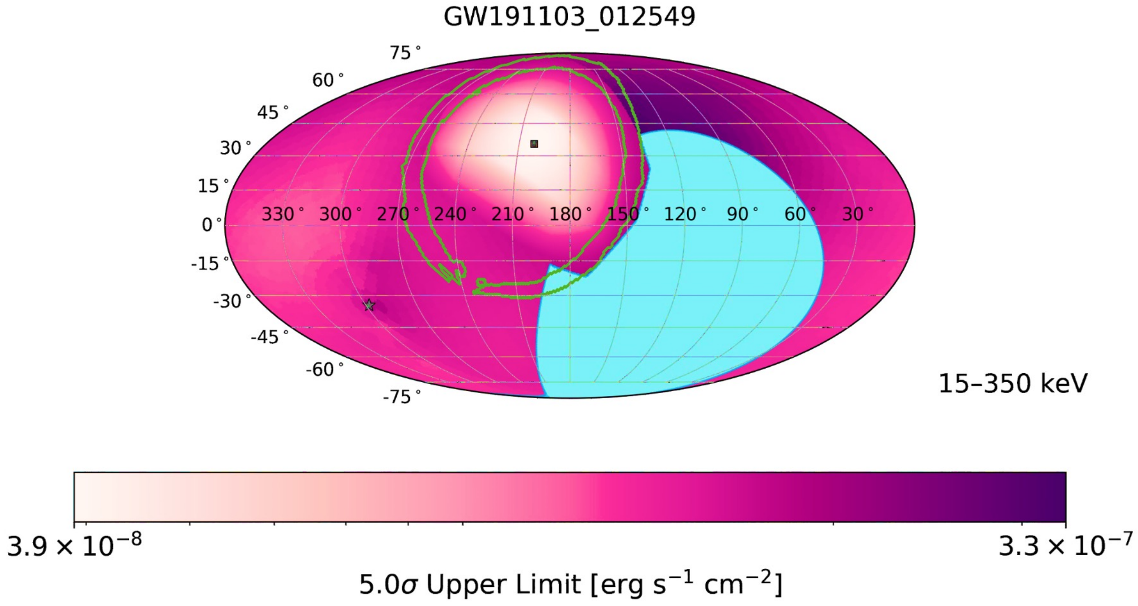


GBM's ensures a more likely coverage of the GW trigger with its large FoV

Combining the upper limits

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



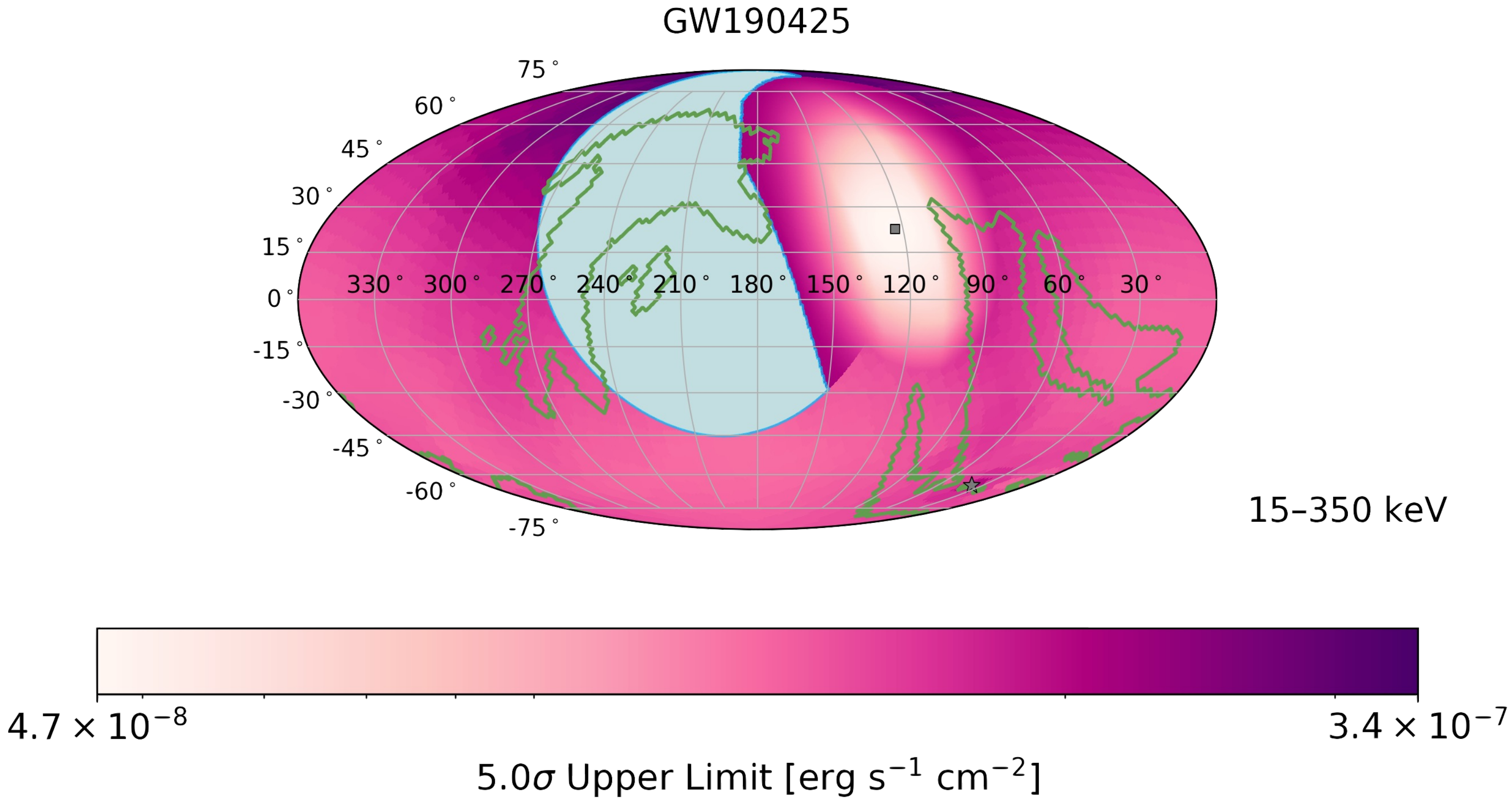


BAT ensures more sensitivity when the GW trigger is inside its FoV

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

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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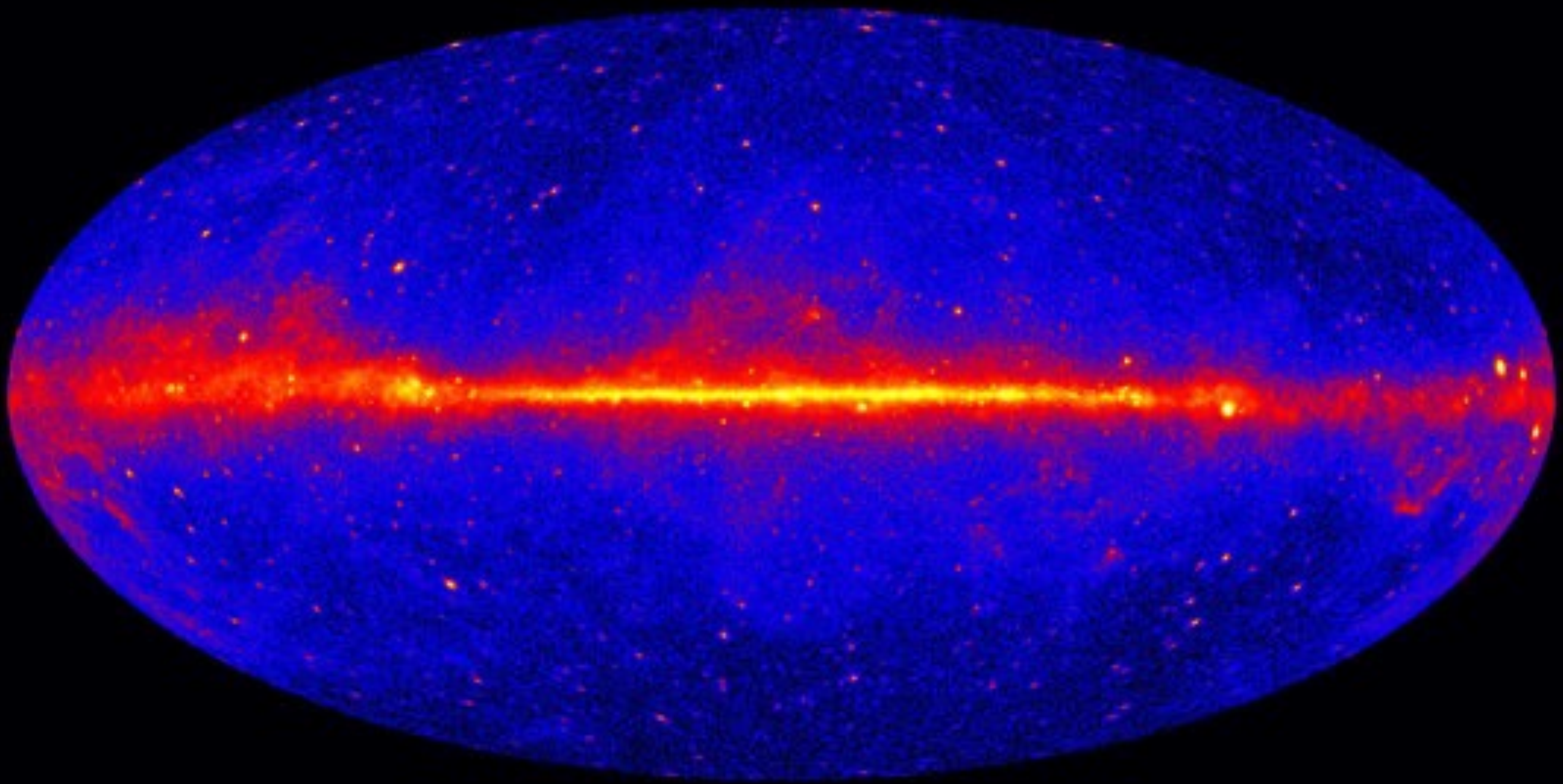
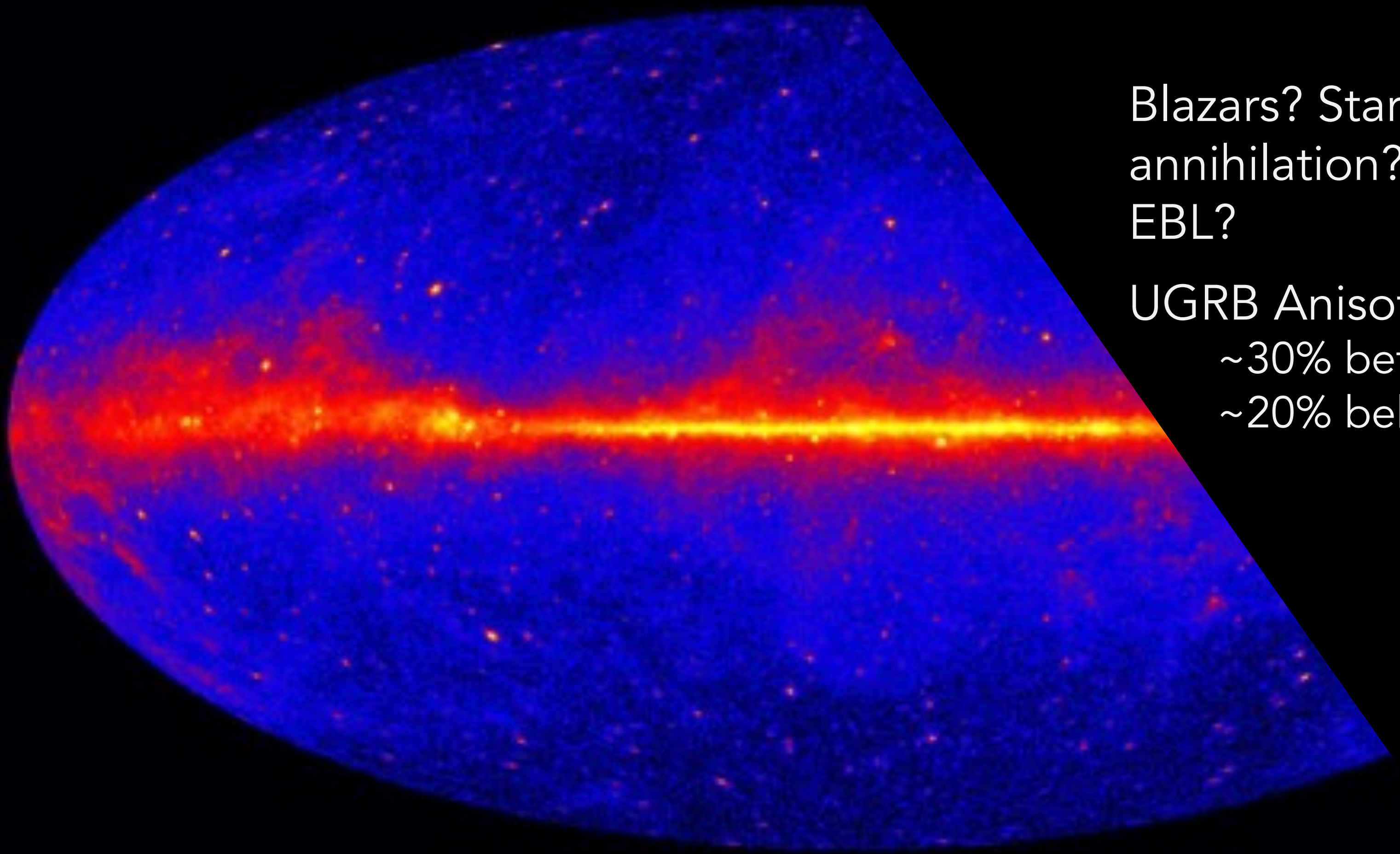
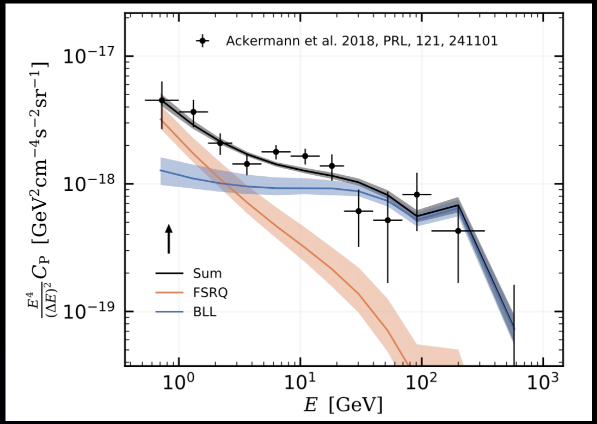


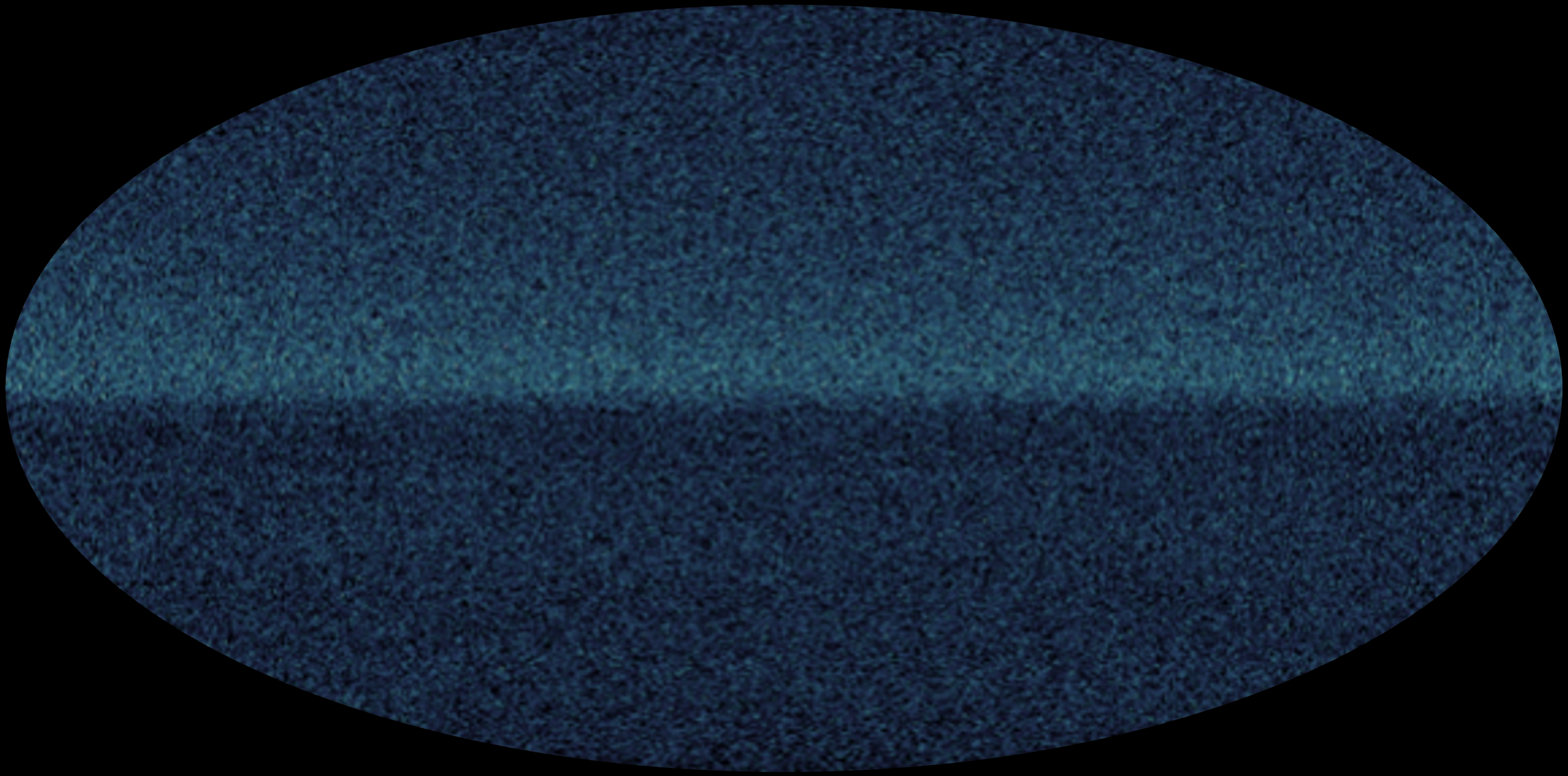
The Unresolved Gamma-ray Background (UGRB) ~20%

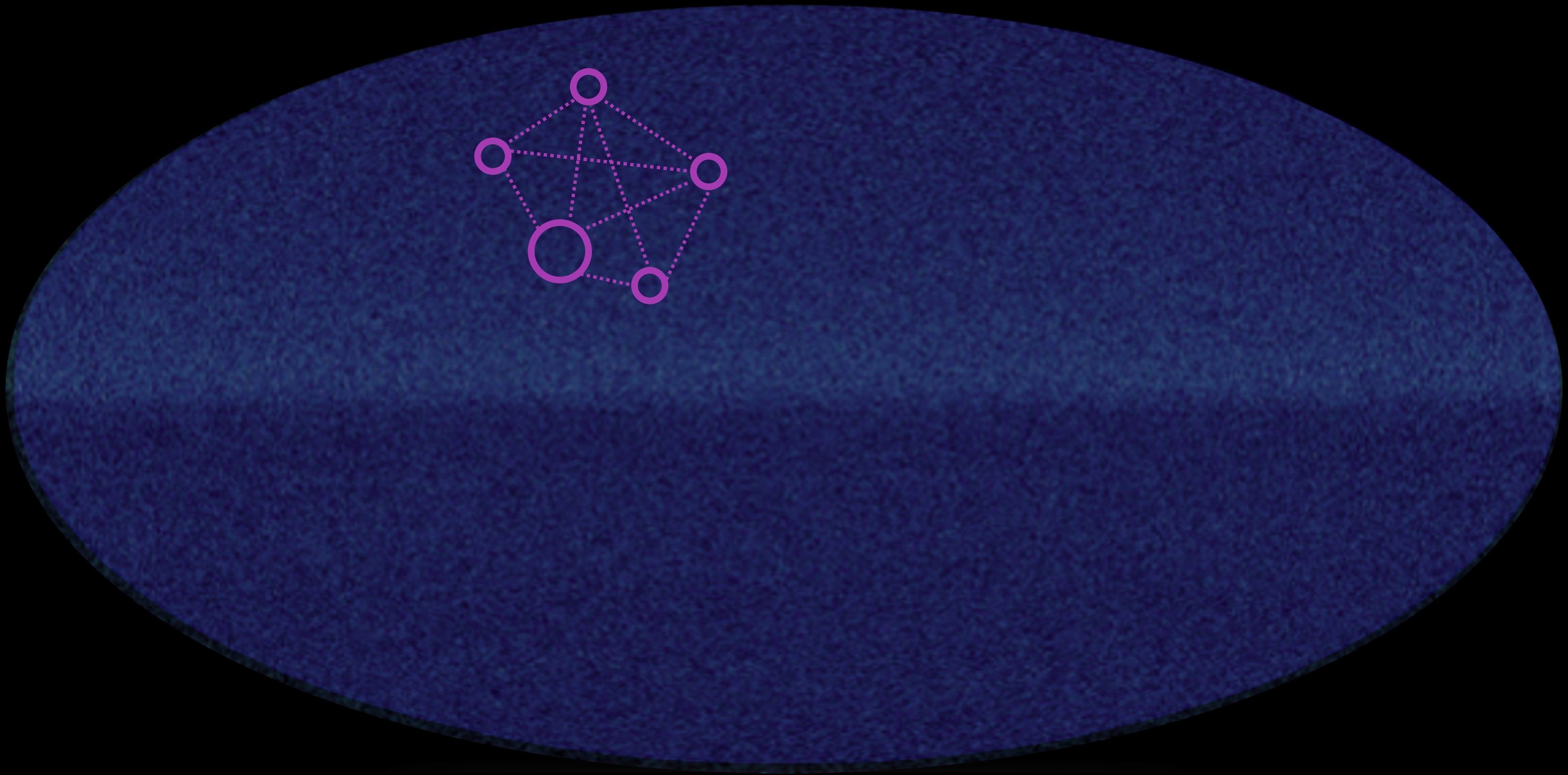


Blazars? Star-forming galaxies? DM annihilation? Photon interactions with EBL?

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





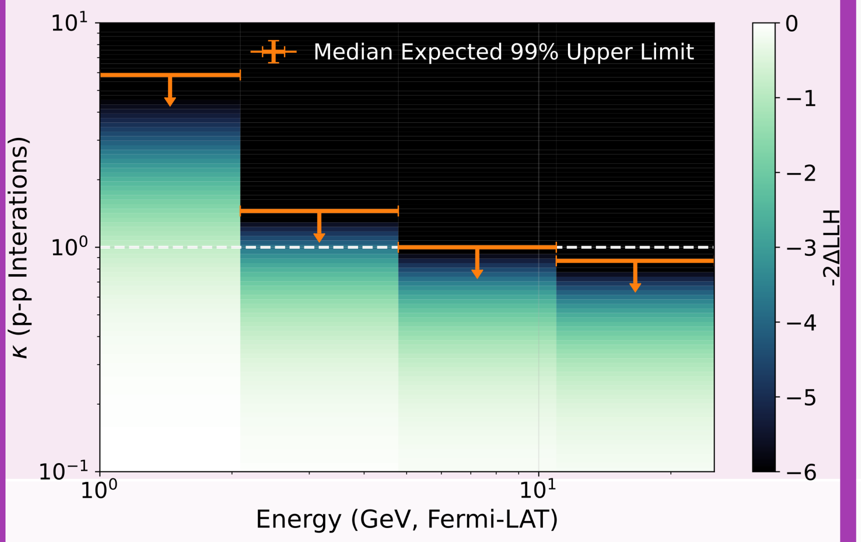


No cross-correlation signal identified

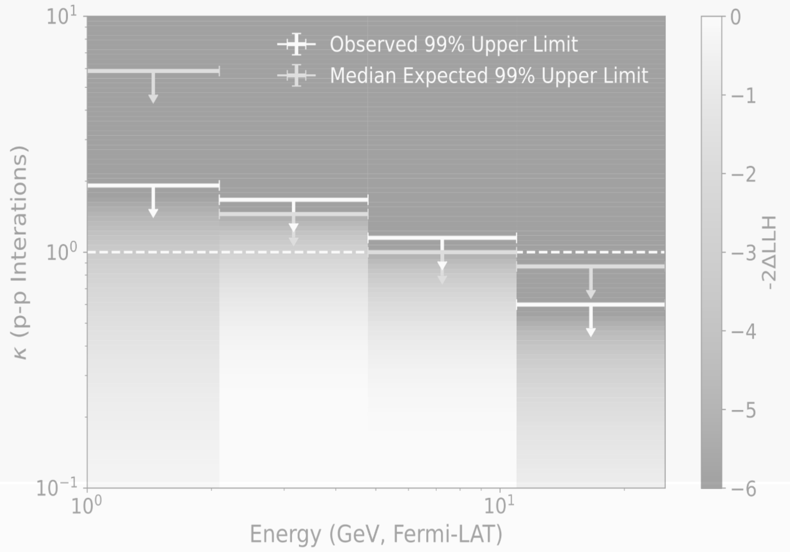
QUESTION 1: *WHAT FRACTION OF THE TOTAL NEUTRINO FLUX IS PRODUCED IN BLAZARS?*

Negro, Crnogorčević, et al. 2023 (submitted, arXiv:2304.10934)

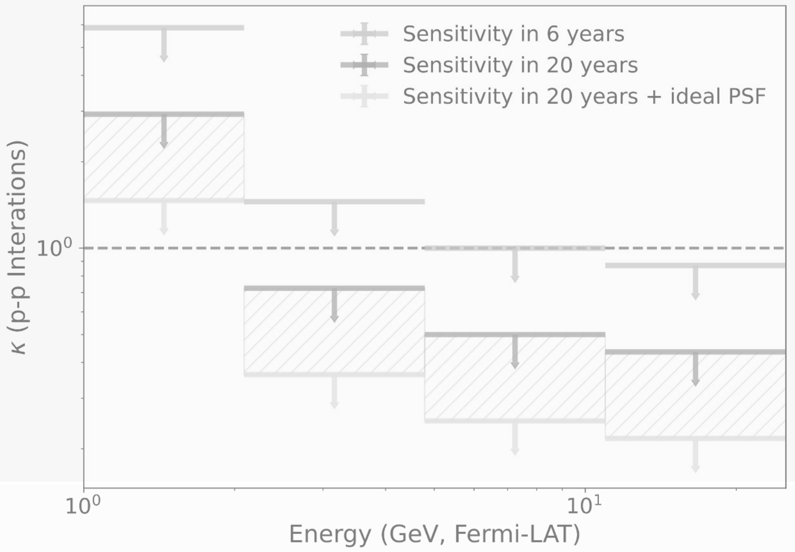
Simulations



Observations



Predictions



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

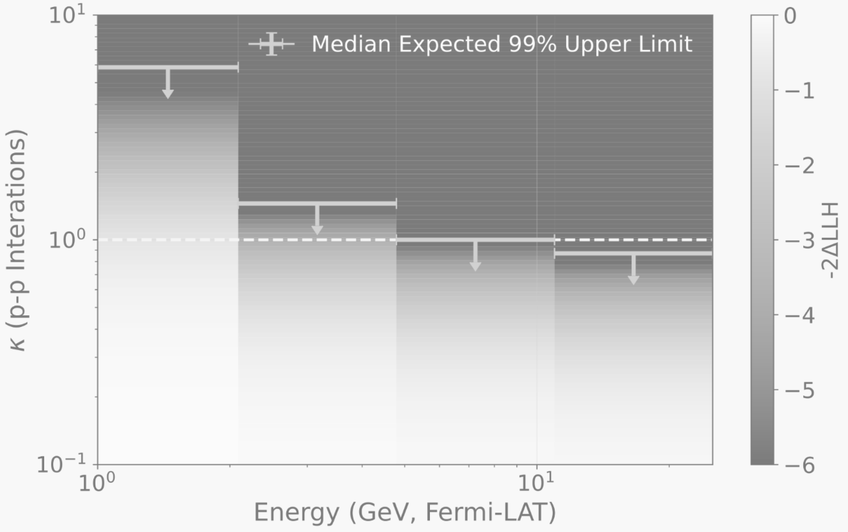
$$E_\nu^2 \frac{dN_\nu}{dE_{nu}} \approx \frac{1}{2}\left(E_\gamma^2 \frac{dN_\gamma}{dE_\gamma}\right), \text{ at } E_\nu \approx \frac{E_\gamma}{2}$$

- Injecting the neutrino signal:

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

Negro, Crnogorčević, et al. 2023 (ApJ, submitted)

Simulations



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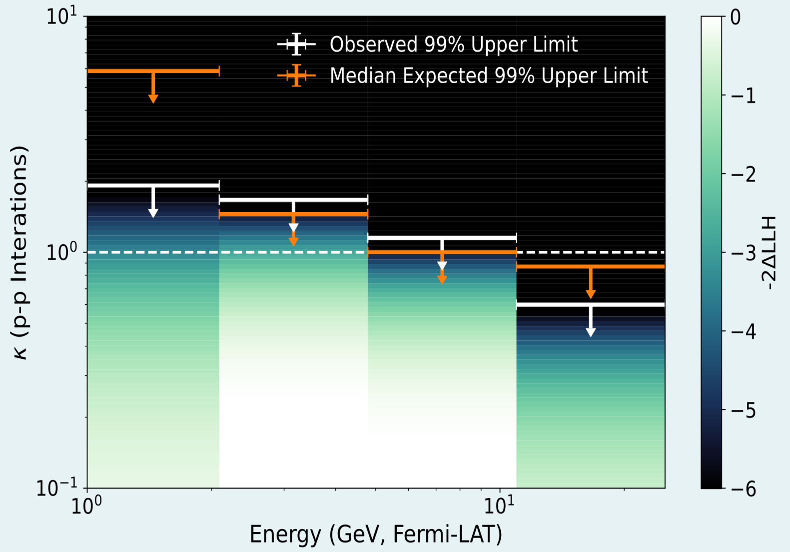
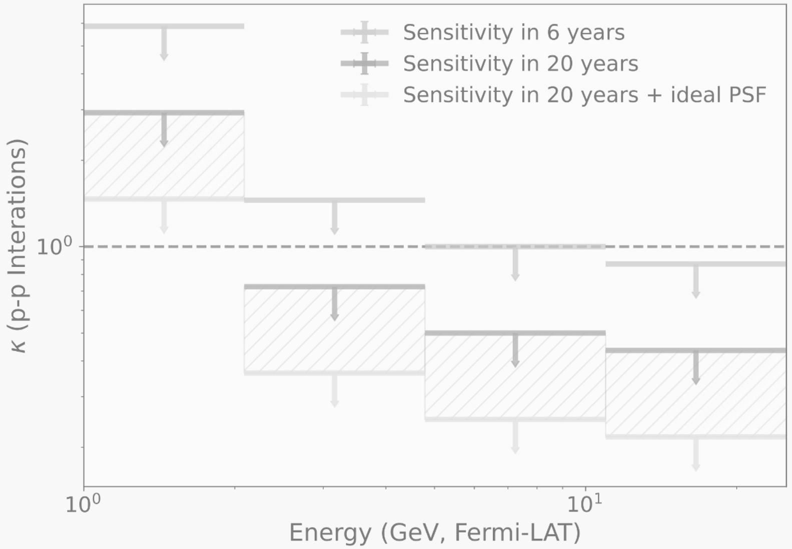
Observations

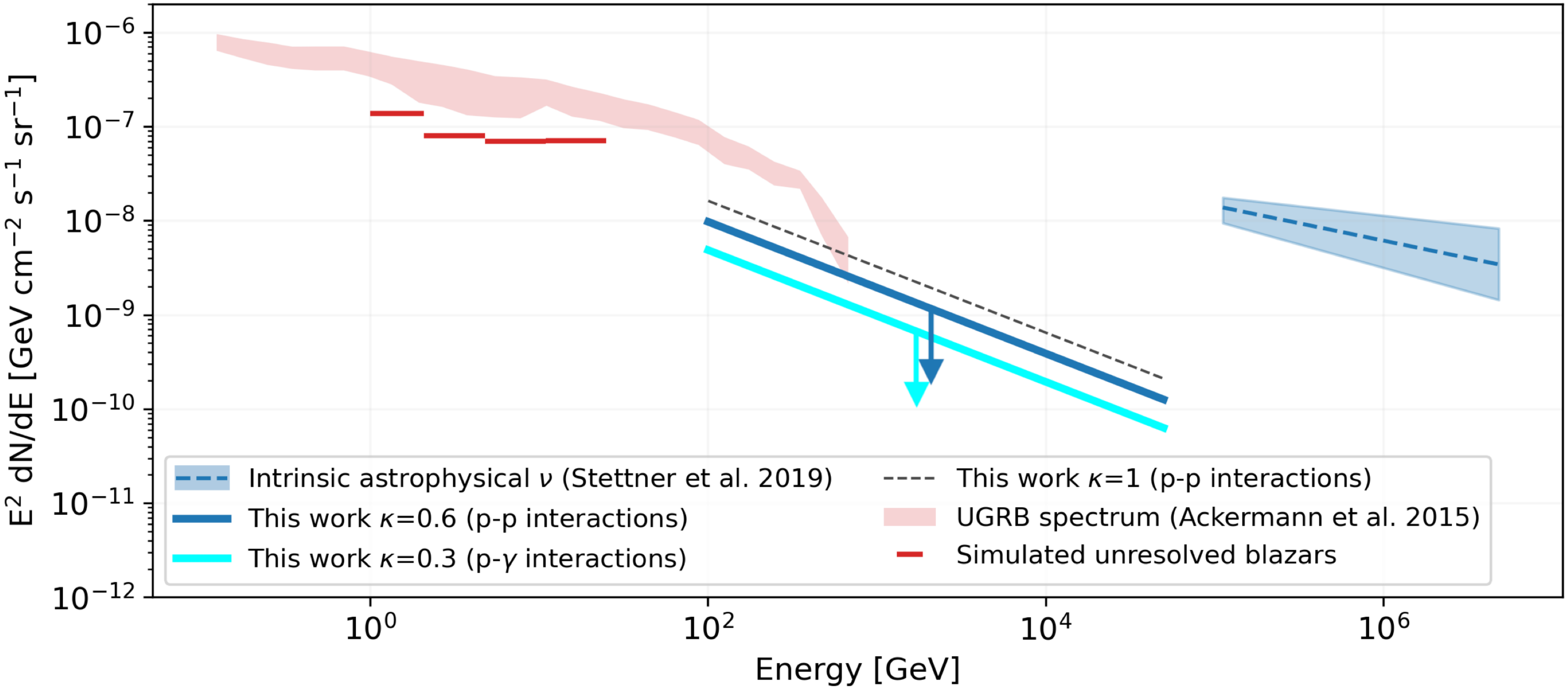


- IceCube 6-year map and *Fermi*-LAT 12 years of data
- Constraining limits in the last energy bin: $\kappa < 0.6$

Predictions



UPPER LIMITS ON THE ν_{ASTRO} FLUX

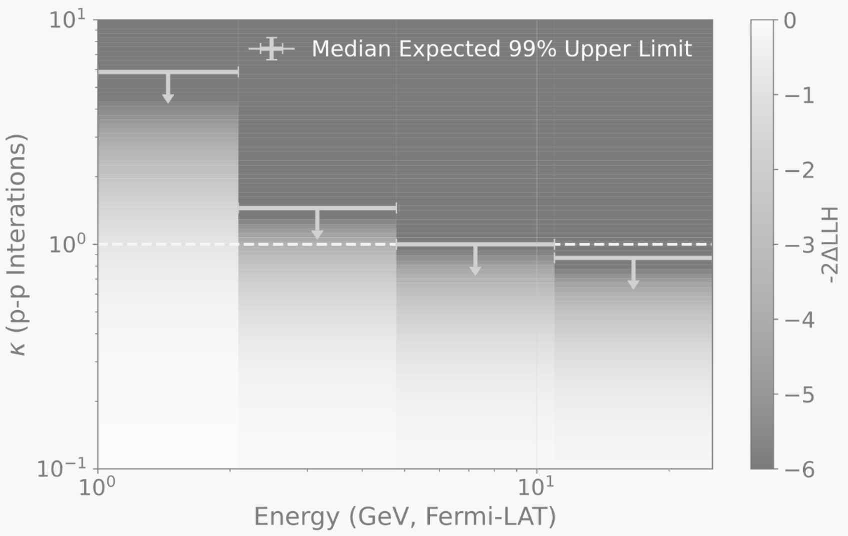


→ Unresolved blazars contribute ~1% at 100 TeV and ~10% at 1 TeV

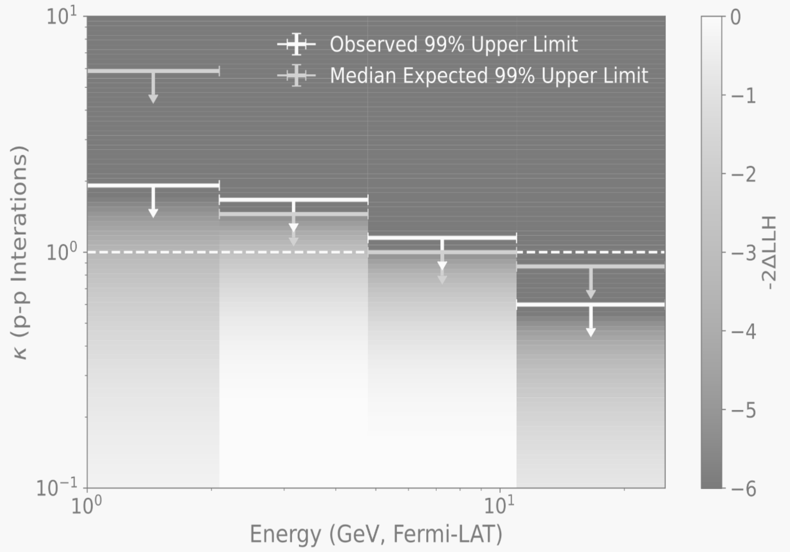
QUESTION 3: *WHAT DO WE PREDICT?*

Negro, Crnogorčević, et al. 2003 (submitted/accepted? ApJ)

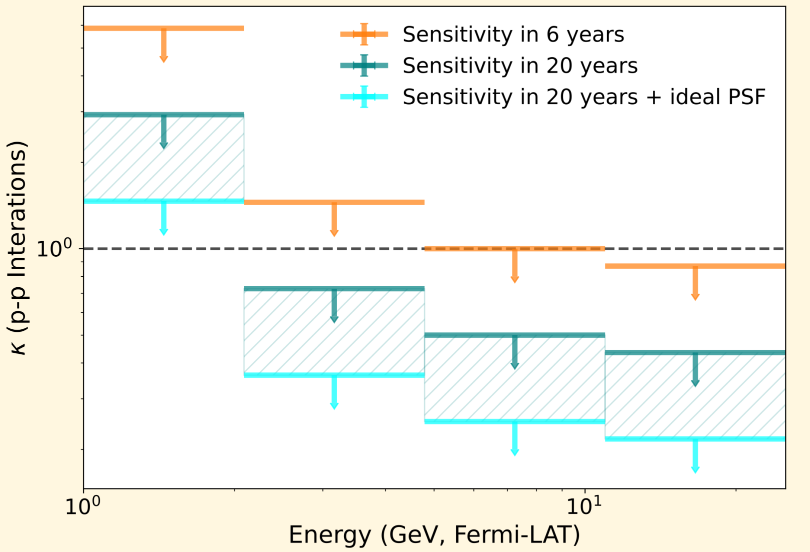
Simulations



Observations



Predictions



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

CHAPTERS III-IV

SEARCHING FOR AXION-LIKE PARTICLES WITH *FERMI*

Crnogorčević et al. 2021 (PRD), Crnogorčević et al. 2023 (under review)

CHAPTER V

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

Fletcher et al. on behalf of GBM, Crnogorčević et al. on behalf of BAT, and LVK, 2023 (ApJ, final stages of Collaborations' review)

CHAPTER VI

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

Negro, Crnogorčević, et al. 2023 (submitted, arXiv:2304.10934)

ACKNOWLEDGEMENTS

- My advisor, Dr. Regina Caputo
- My thesis and dissertation committee: Prof. Massimo Ricotti, Prof. Cole Miller, Prof. Peter Shawhan, Dr. Christopher Karwin, and Prof. Chris Reynolds
- My co-advisor, Prof. Manuel Meyer, *Fermi*-LAT Collaboration, GBM Team, and many collaborators across the globe
- Mentors, fellow graduate students, GRAD-MAP, BANG!, ACE, EDI, et al.
- Astronomy's business office
- Terrapin Masters Swimming
- Friends & family


Thank you.
Milena owns my ENTIRE heart!
UMAC