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

NEW PHYSICS THROUGH A MULTIMESSENGER LENS

Searching for Axion-like Particles from Transient Astrophysical Events

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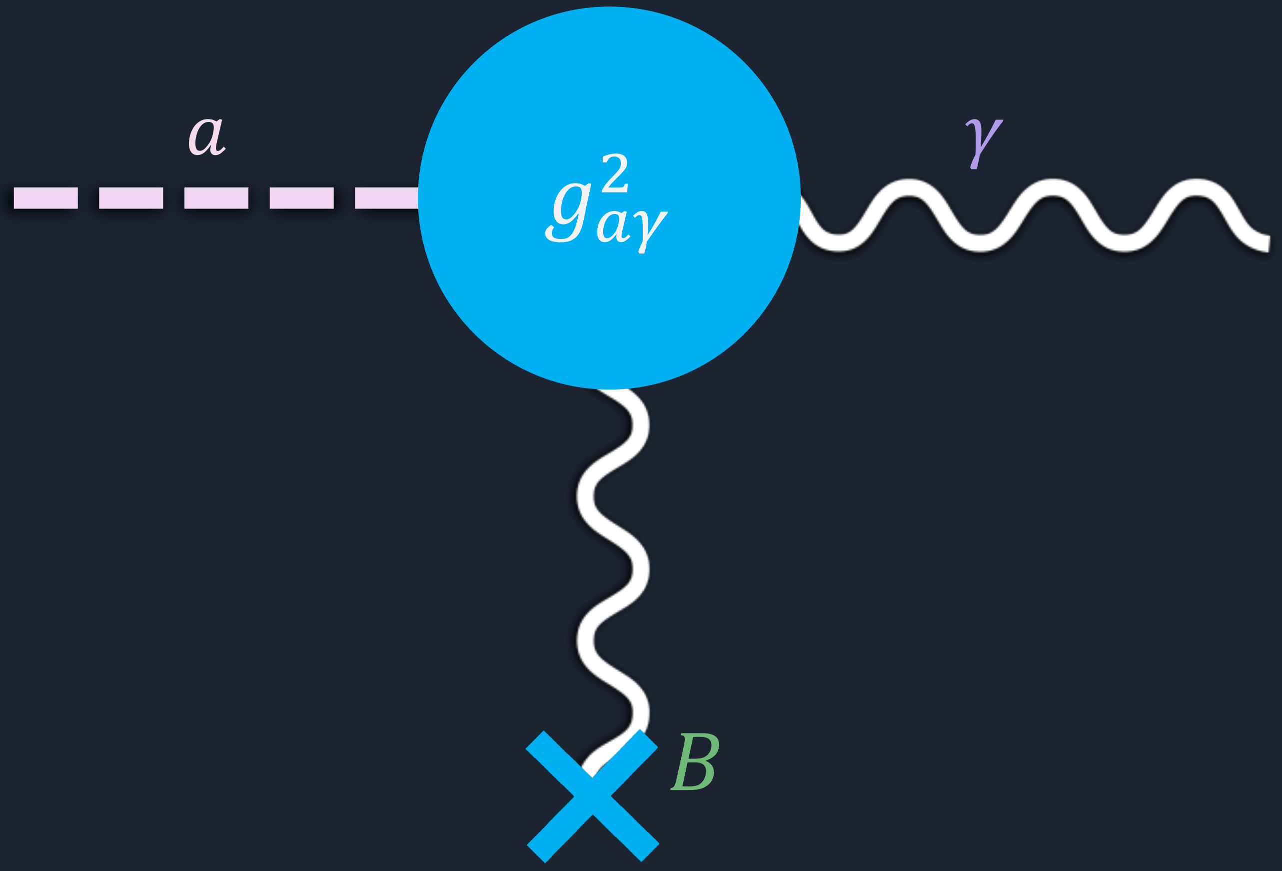
Postdoctoral Fellow @Stockholm University

OBSERVING ALPS WITH GAMMA RAYS

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

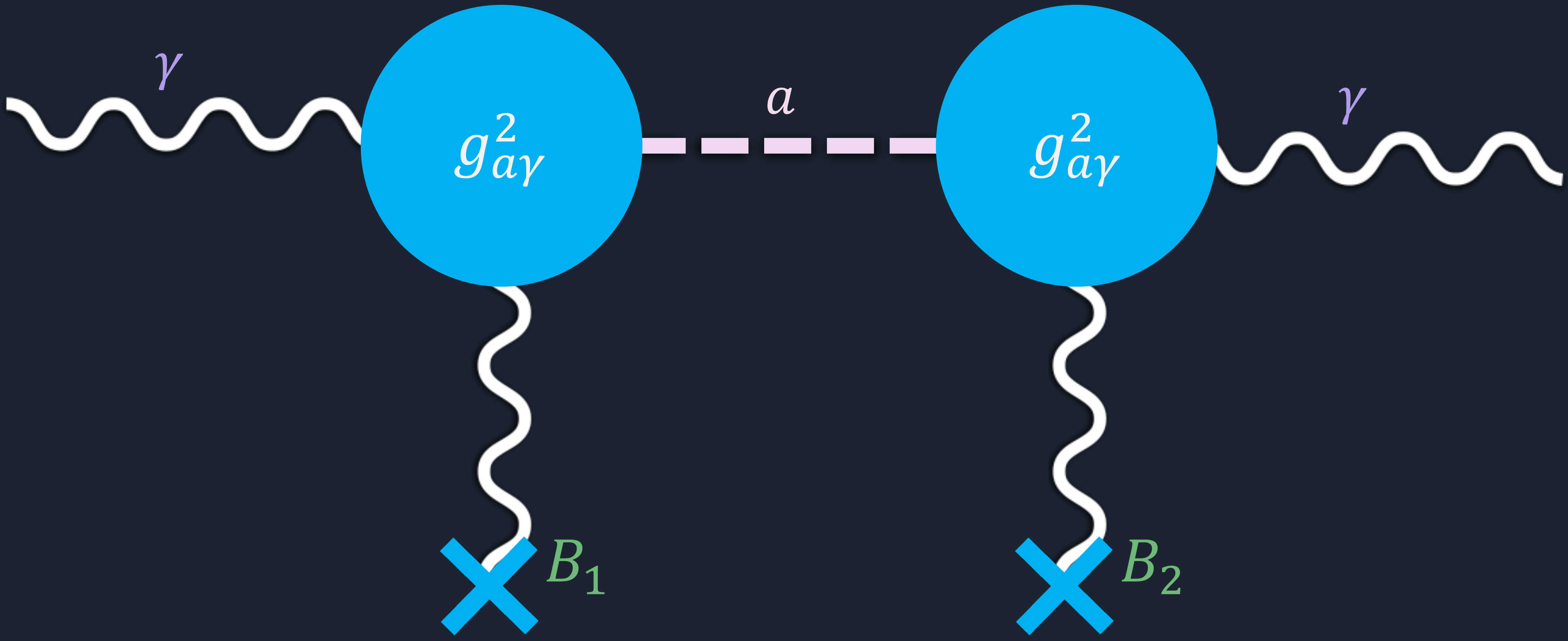
$$\mathcal{L}_{a\gamma} \supset g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

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

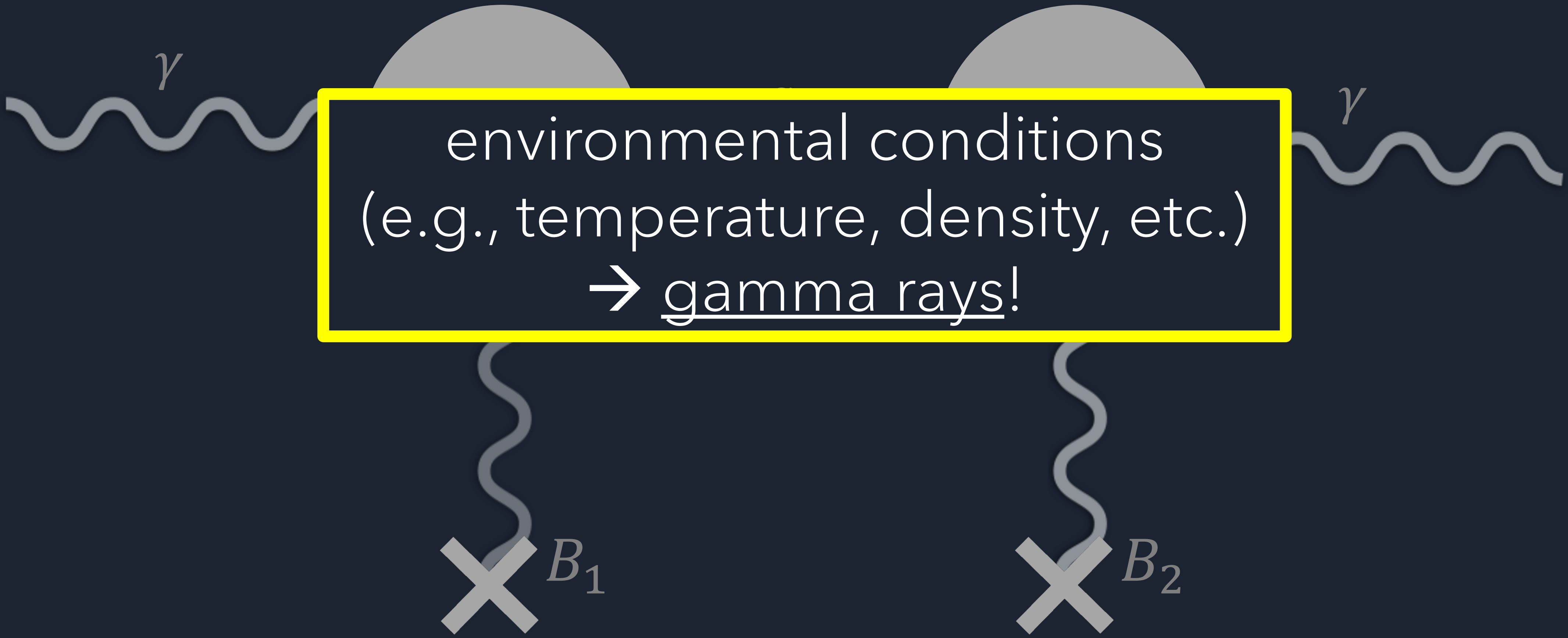


(production: Primakoff process)

(detection: inverse Primakoff process)

Primakoff process: converting ALPs into photons

OBSERVING ALPS WITH GAMMA RAYS



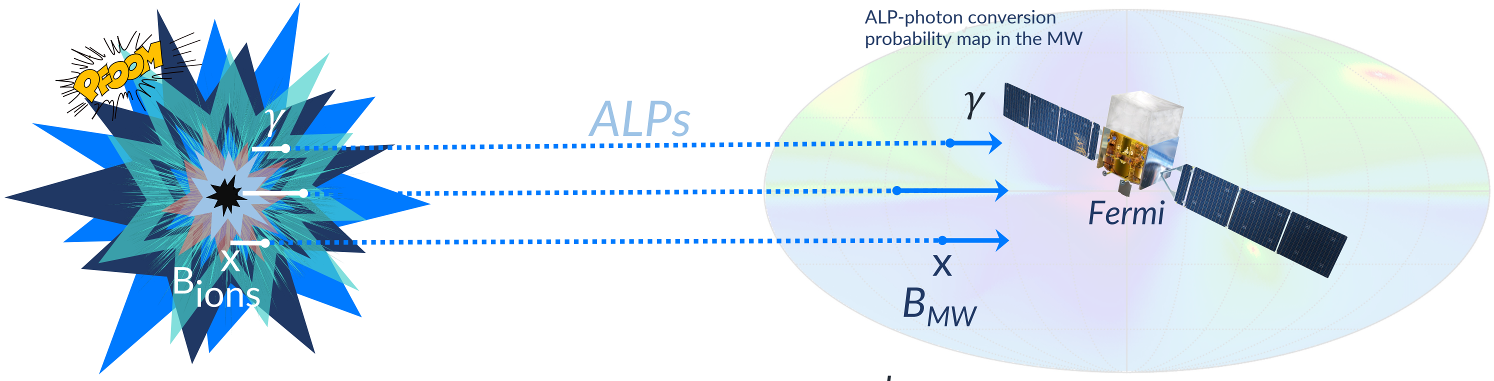
environmental conditions
(e.g., temperature, density, etc.)
→ <u>gamma rays</u>!

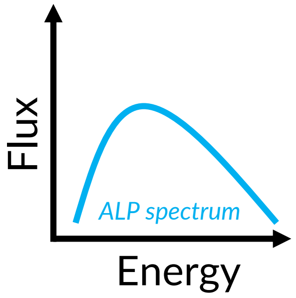
(production: Primakoff process)

(detection: inverse Primakoff process)

Primakoff process: converting ALPs into photons

Physical System set-up

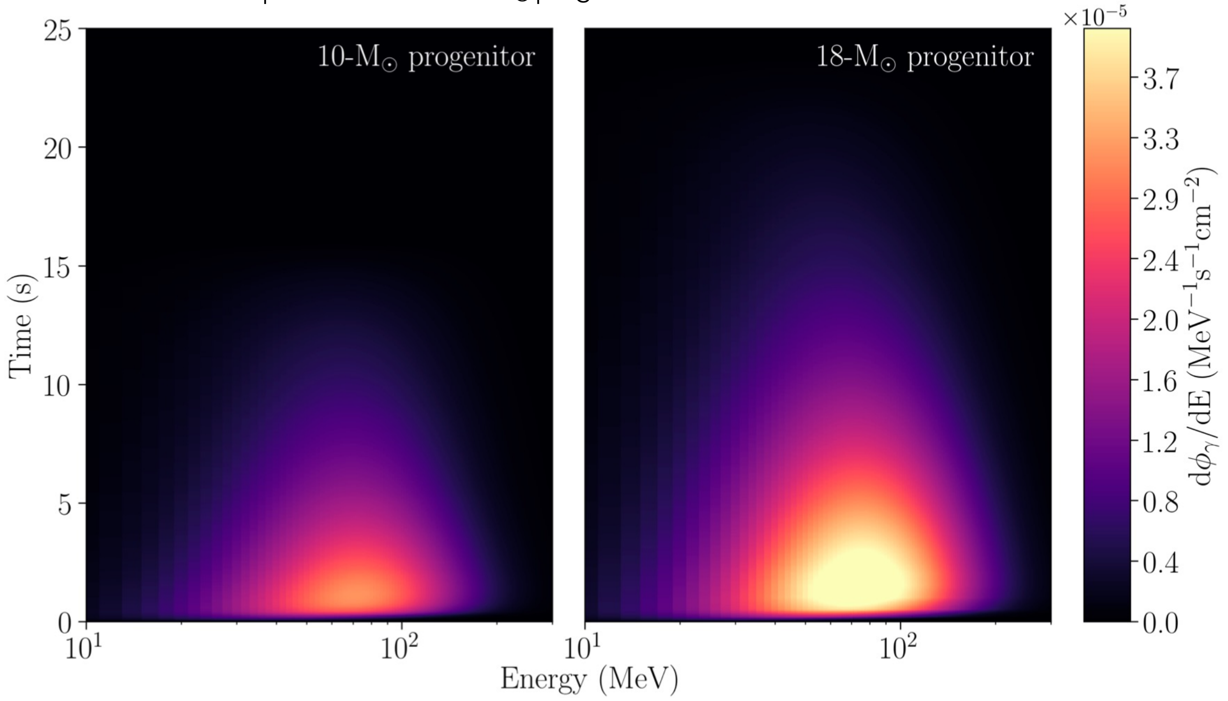




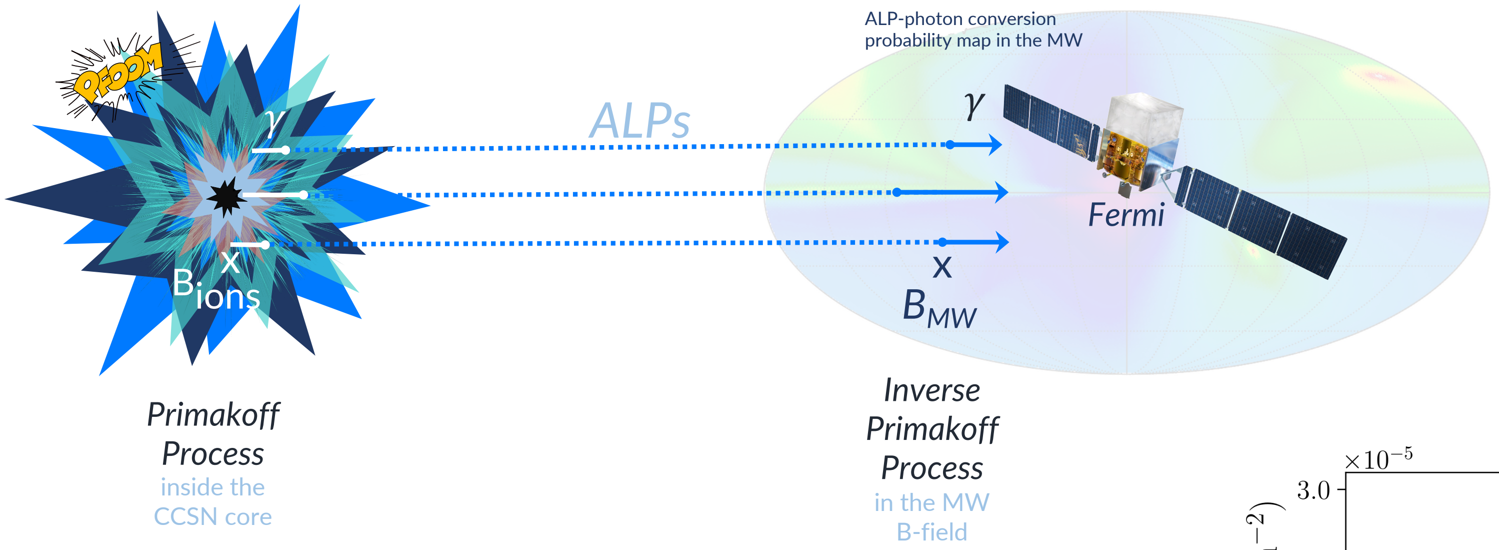
Primakoff Process inside the CCSN core

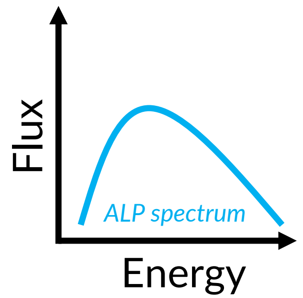
Inverse Primakoff Process in the MW B-field

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

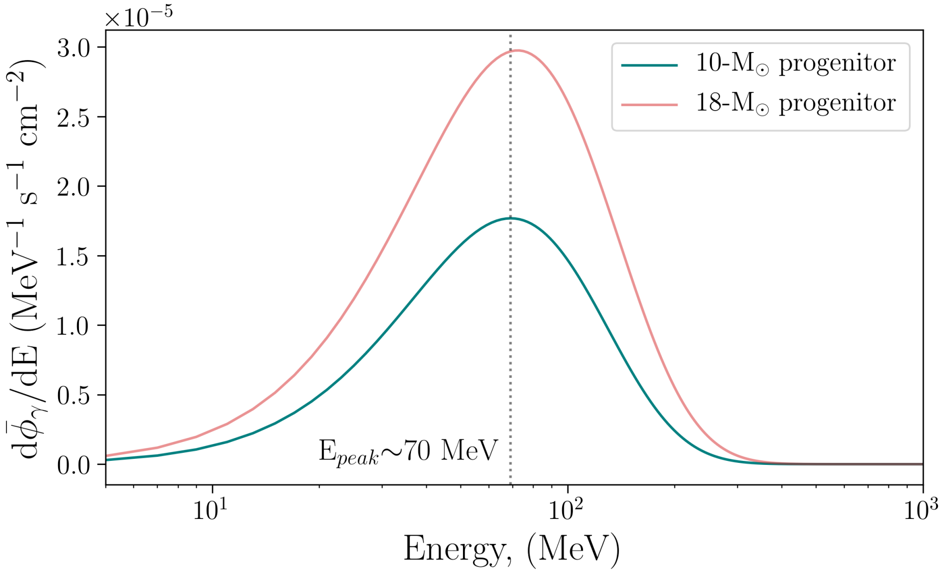


Physical System set-up



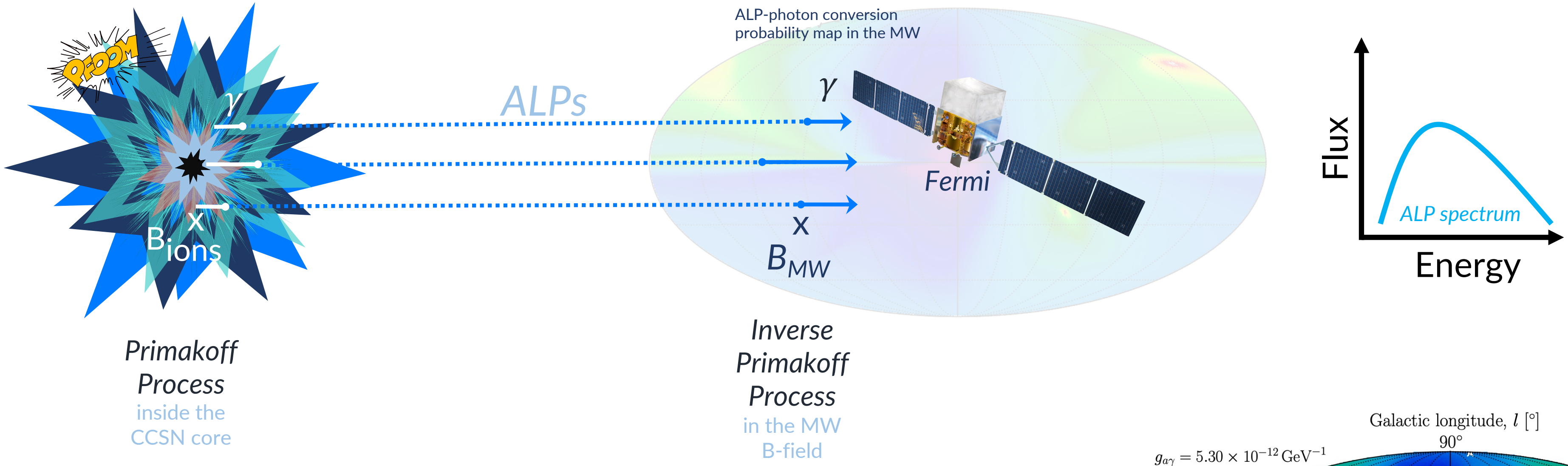


- **Motivation:** ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.

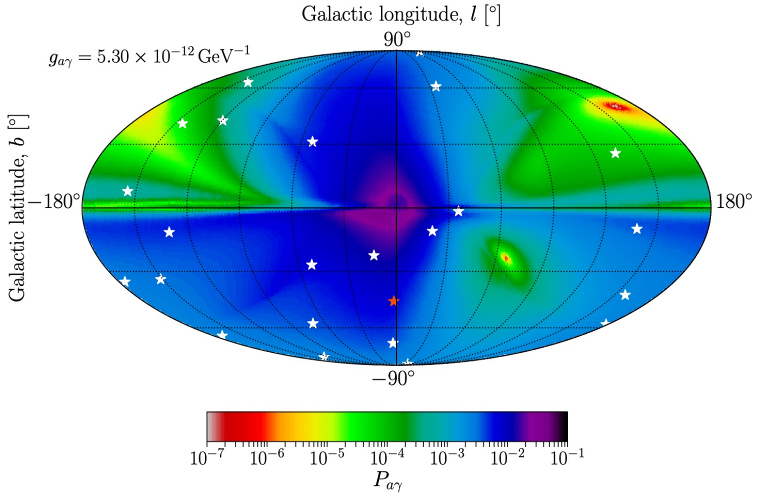


The observed ALP-induced gamma-ray spectrum for 10 and 18-$M_\odot$ progenitors averaged over 10 seconds.

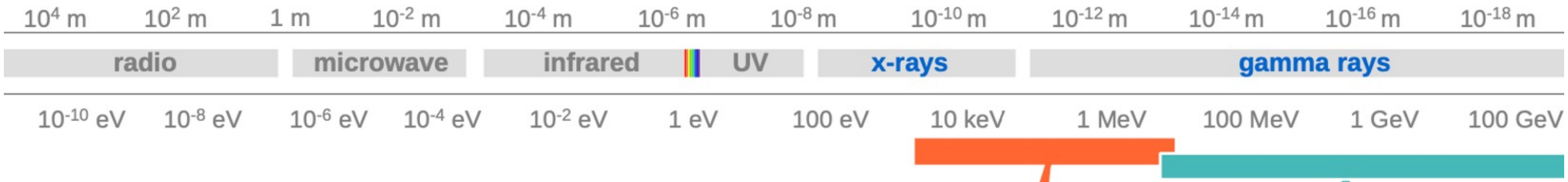
Physical System set-up



- **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**

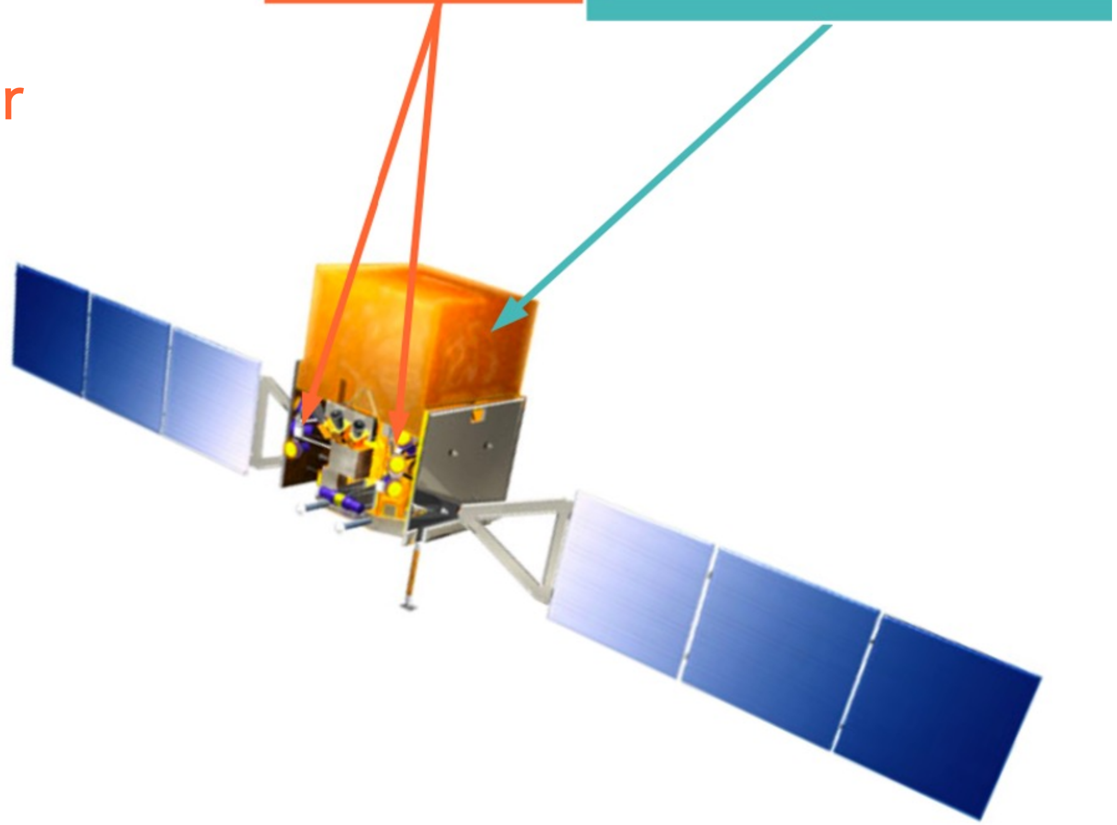


ALP-photon conversion probability map in the Milky Way's magnetic field.



GBM Gamma-ray Burst Monitor

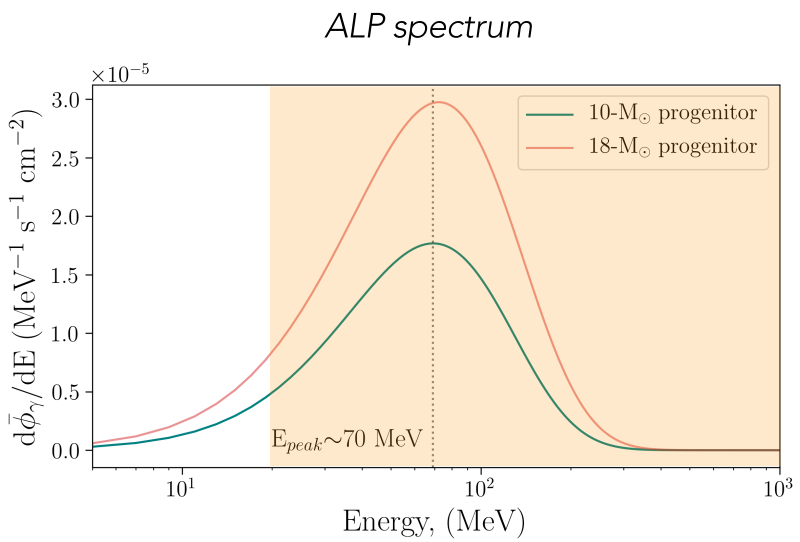
12 (NaI) + 2 (BGO) detectors
FoV: entire unocculted sky
8 keV to 40 MeV
~2500 bursts (~1 every day or two)

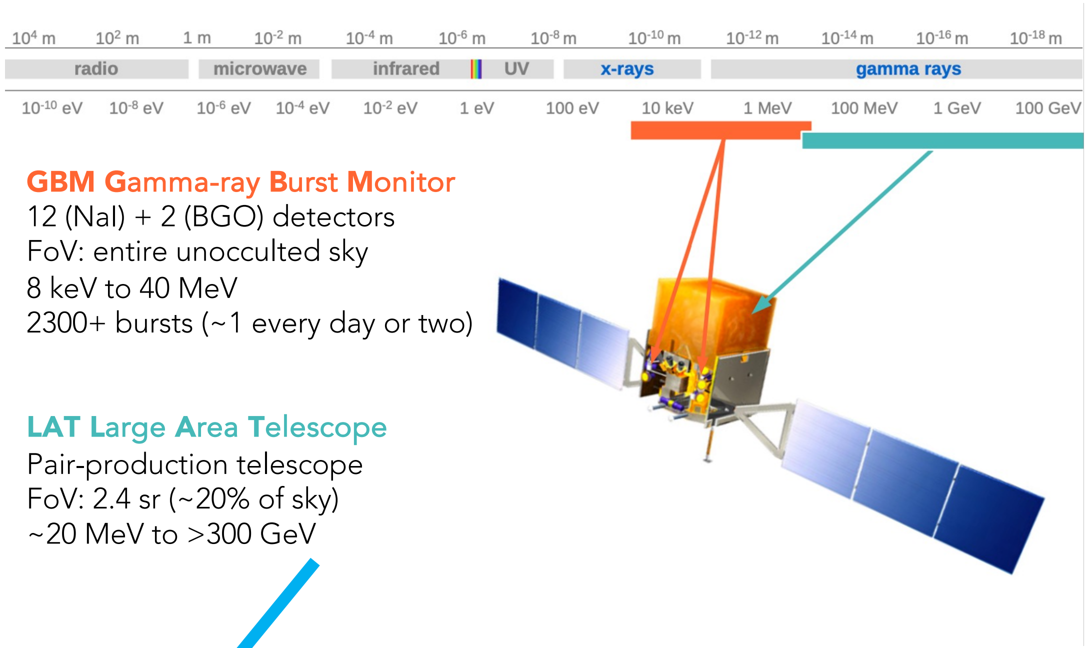


LAT Large Area Telescope

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

Searching for ALPs





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

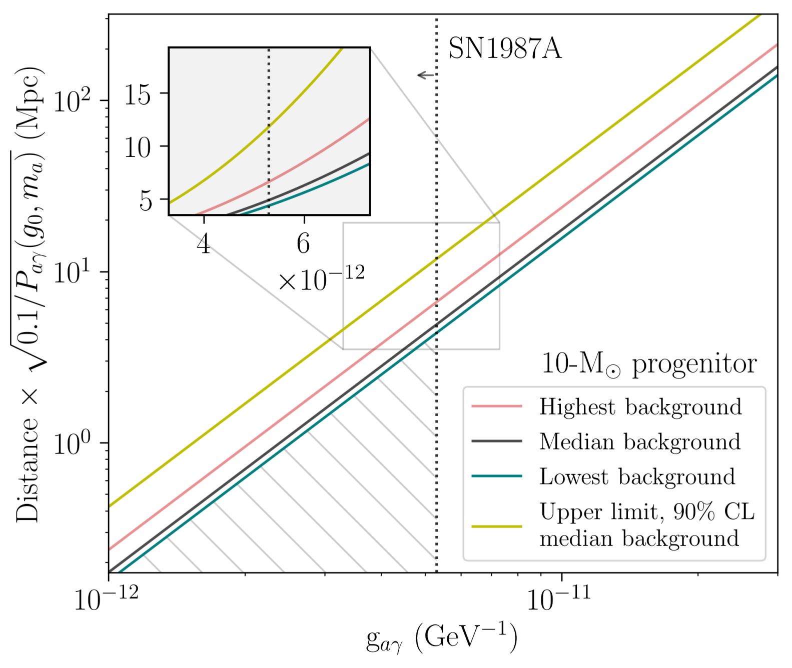
Solar-flare LLE analysis: arXiv:1304.5559

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

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

Fermi LLE sensitivity

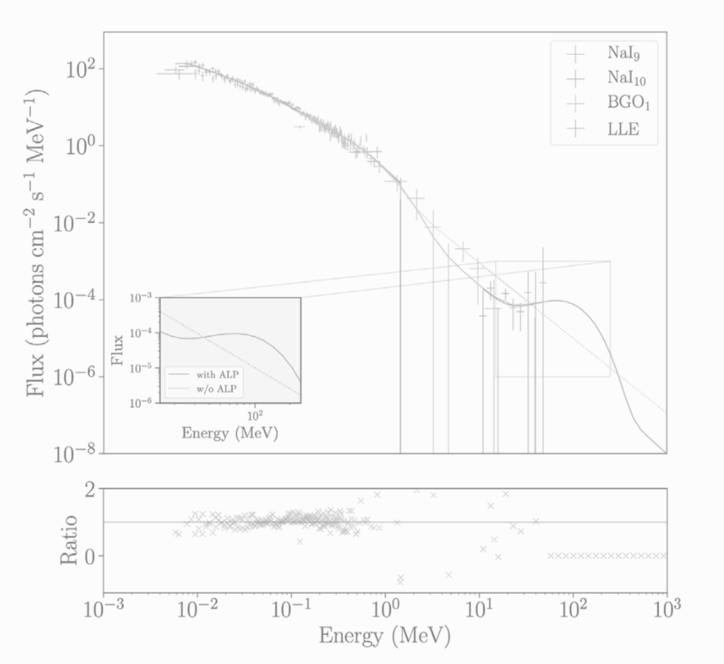
Fermi-LLE Sensitivity



- 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)

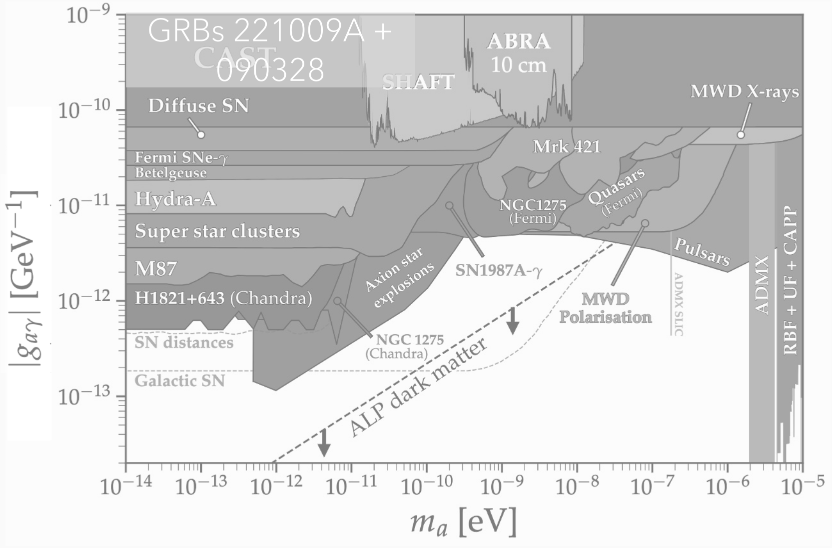
GRB searches



- 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



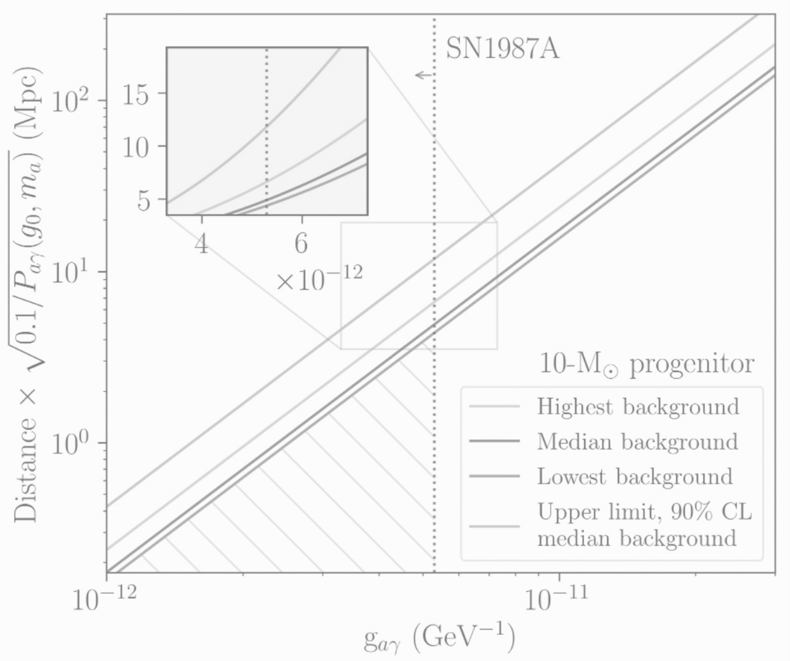
- No significant detections.
- From the ALP amplitude we calculate upper limits.
- *Method: model comparison*

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



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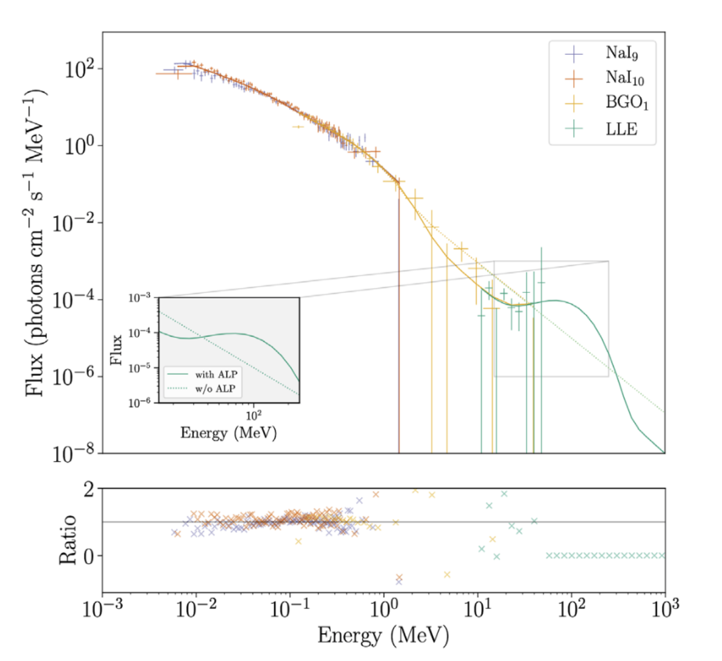
Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

GRB searches



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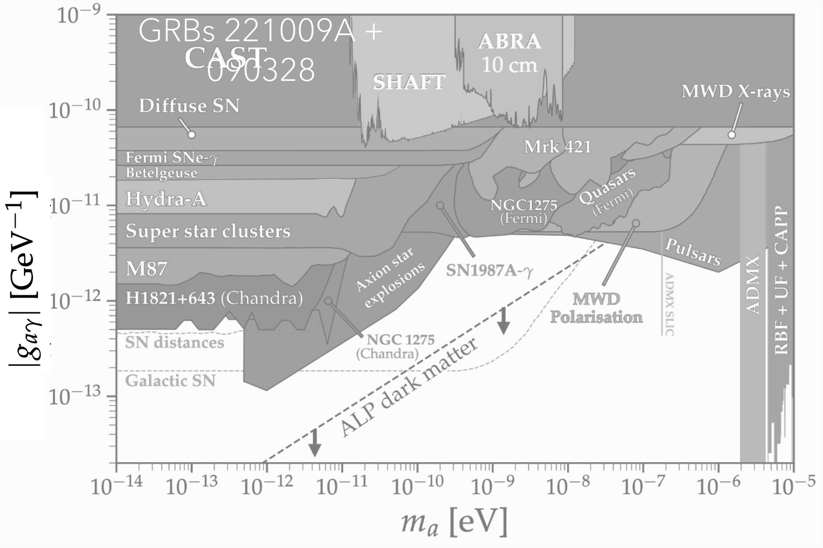
GRB Precursors



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

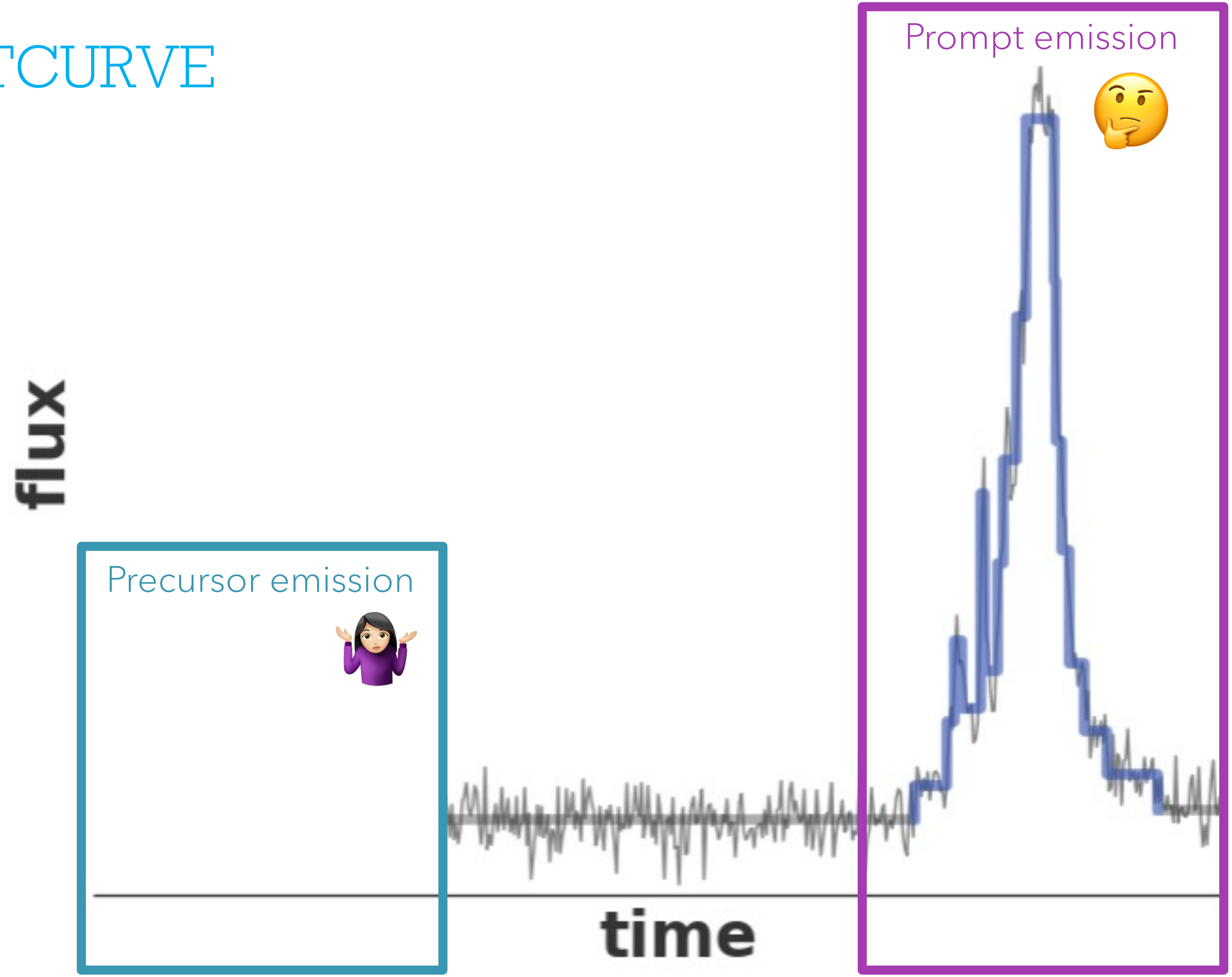
Crnogorčević et al. 2023 (under review)

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

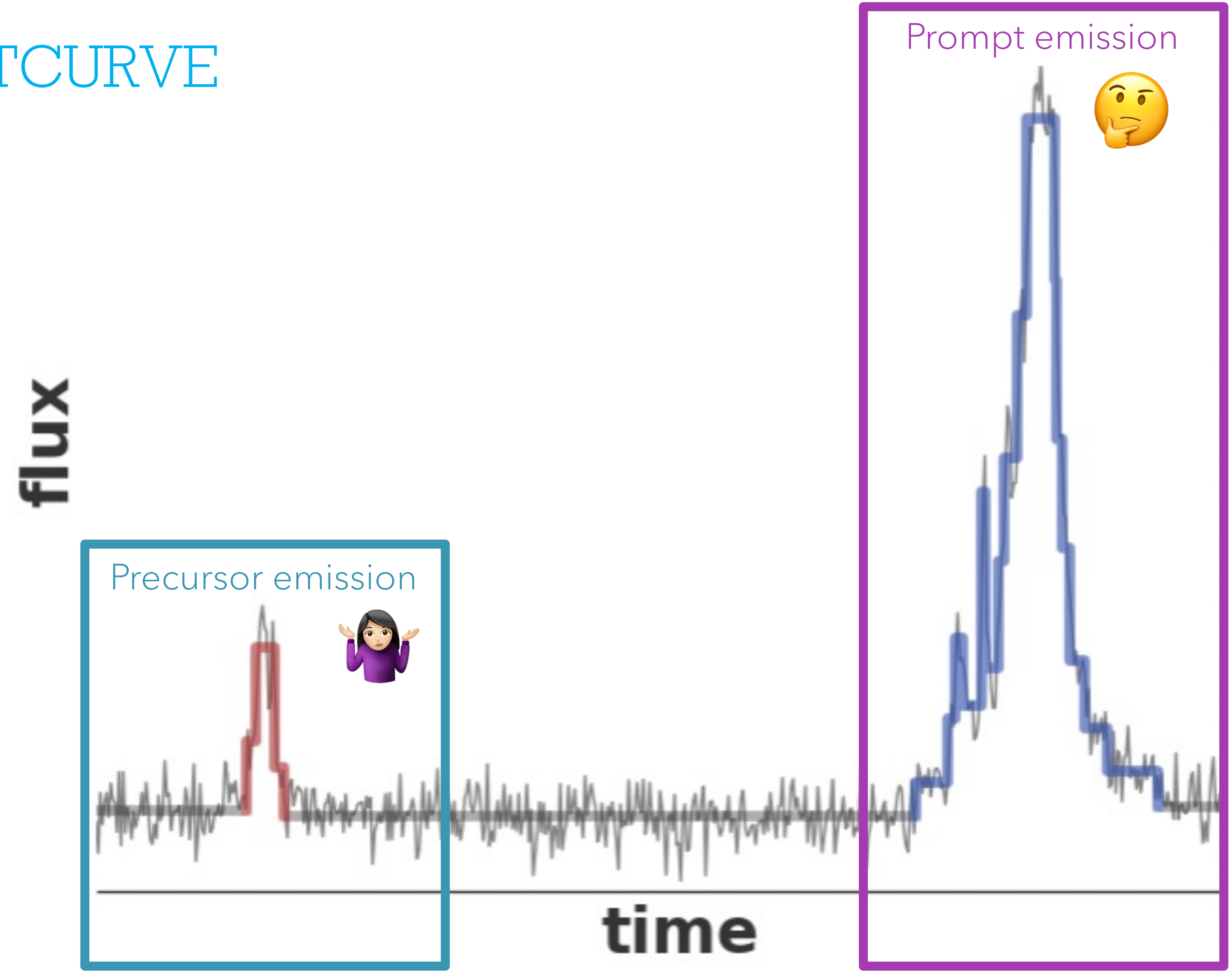
Fermi GI Program, Cycle 15; PI: Crnogorčević

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

GRB LIGHTCURVE



GRB LIGHTCURVE



Precursors may come from…

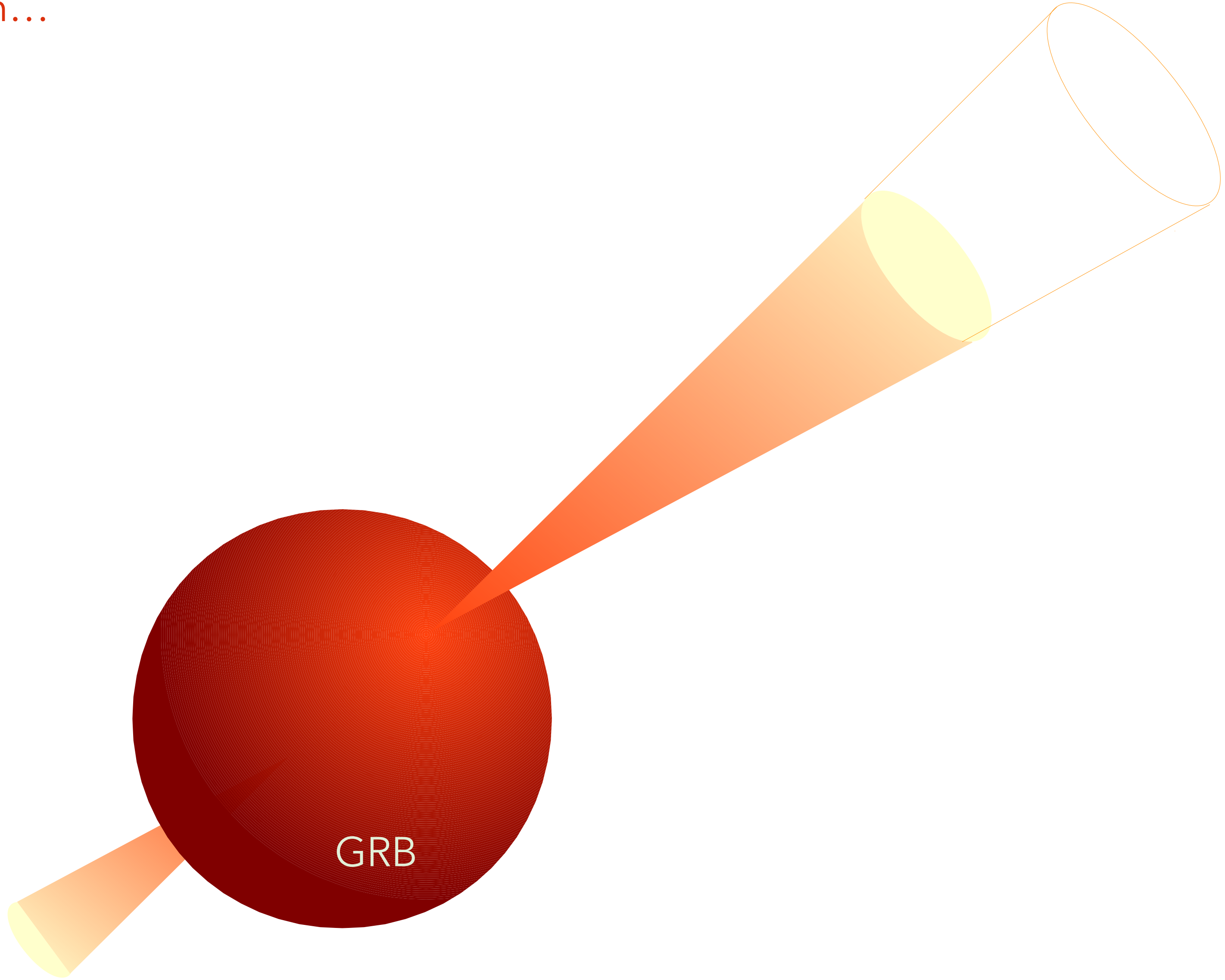
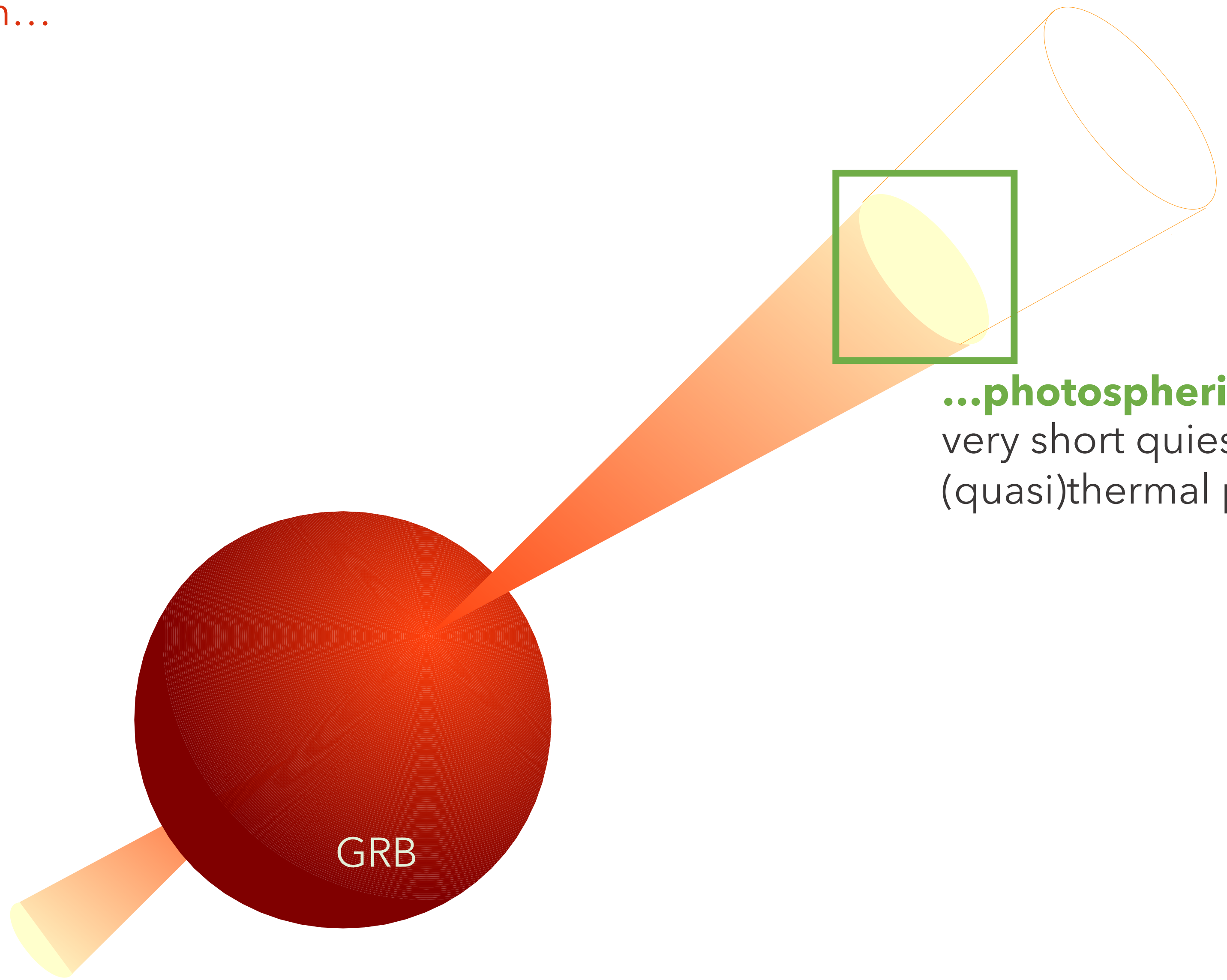


Diagram adapted from Sylvia Zhu's dissertation

Precursors may come from…



…photospheric emission
very short quiescent periods
(quasi)thermal precursor

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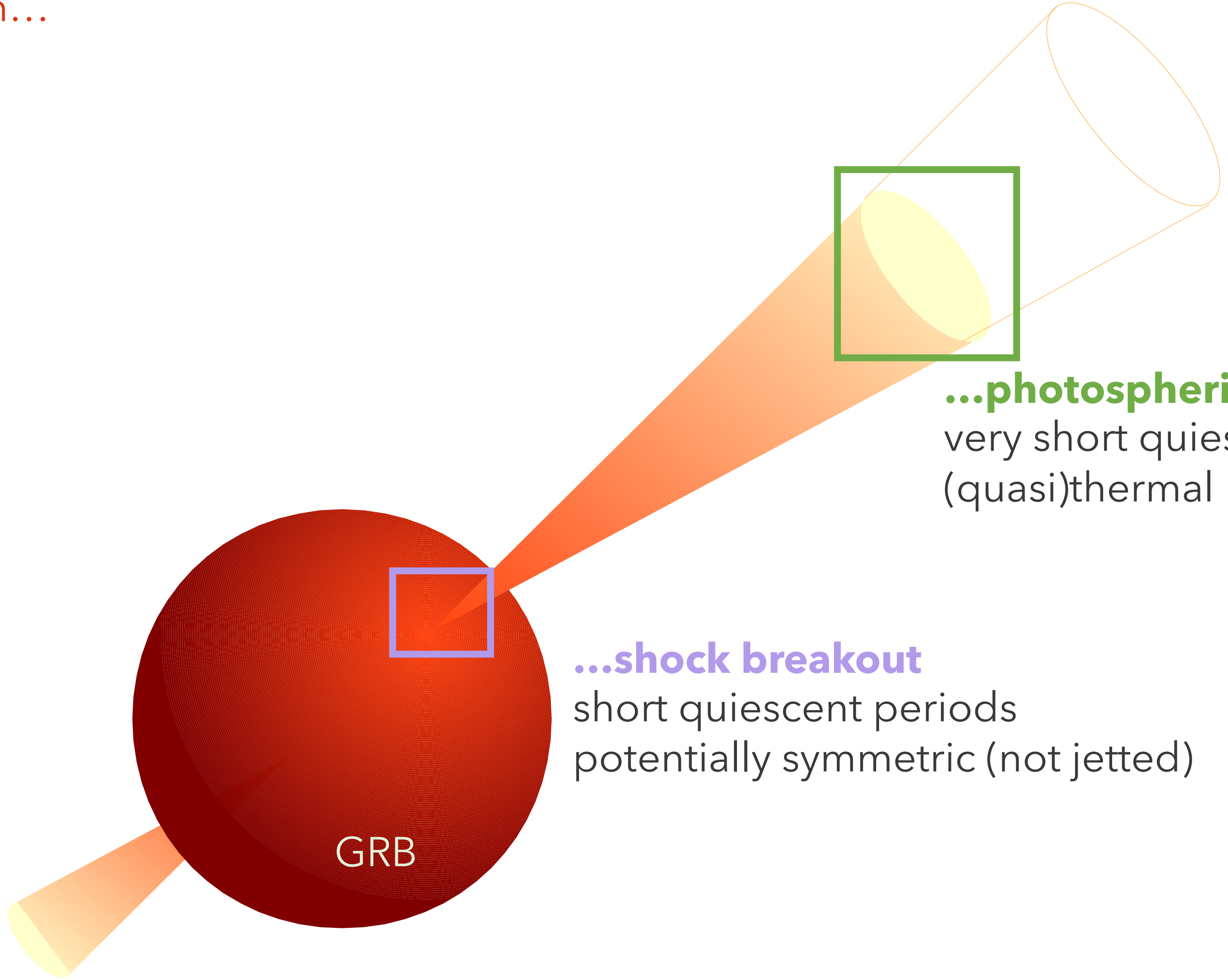
Precursors may come from…



…photospheric emission
very short quiescent periods
(quasi)thermal precursor

…shock breakout
short quiescent periods
potentially symmetric (not jetted)

Diagram adapted from Sylvia Zhu's dissertation

Precursors may come from…

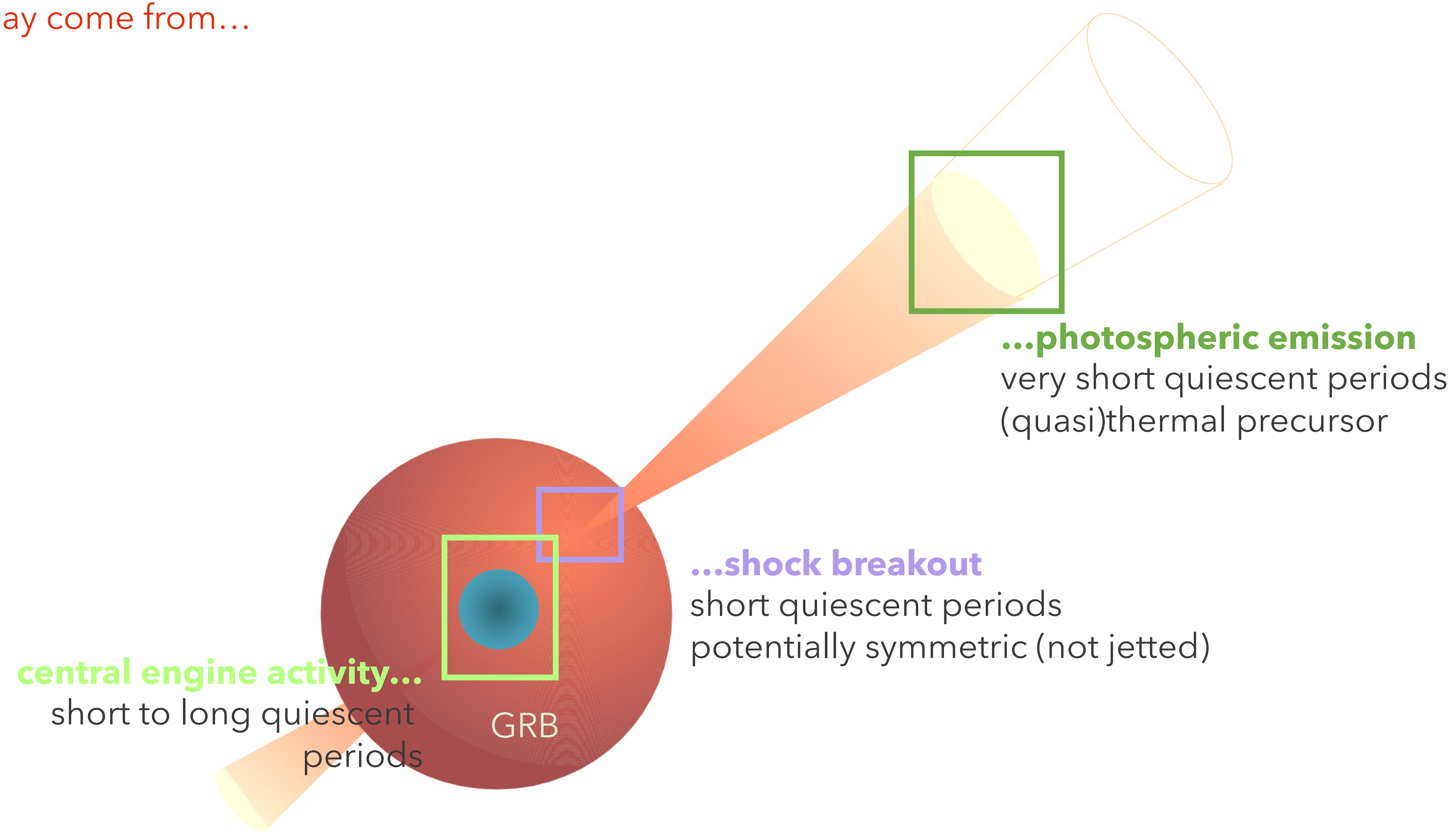
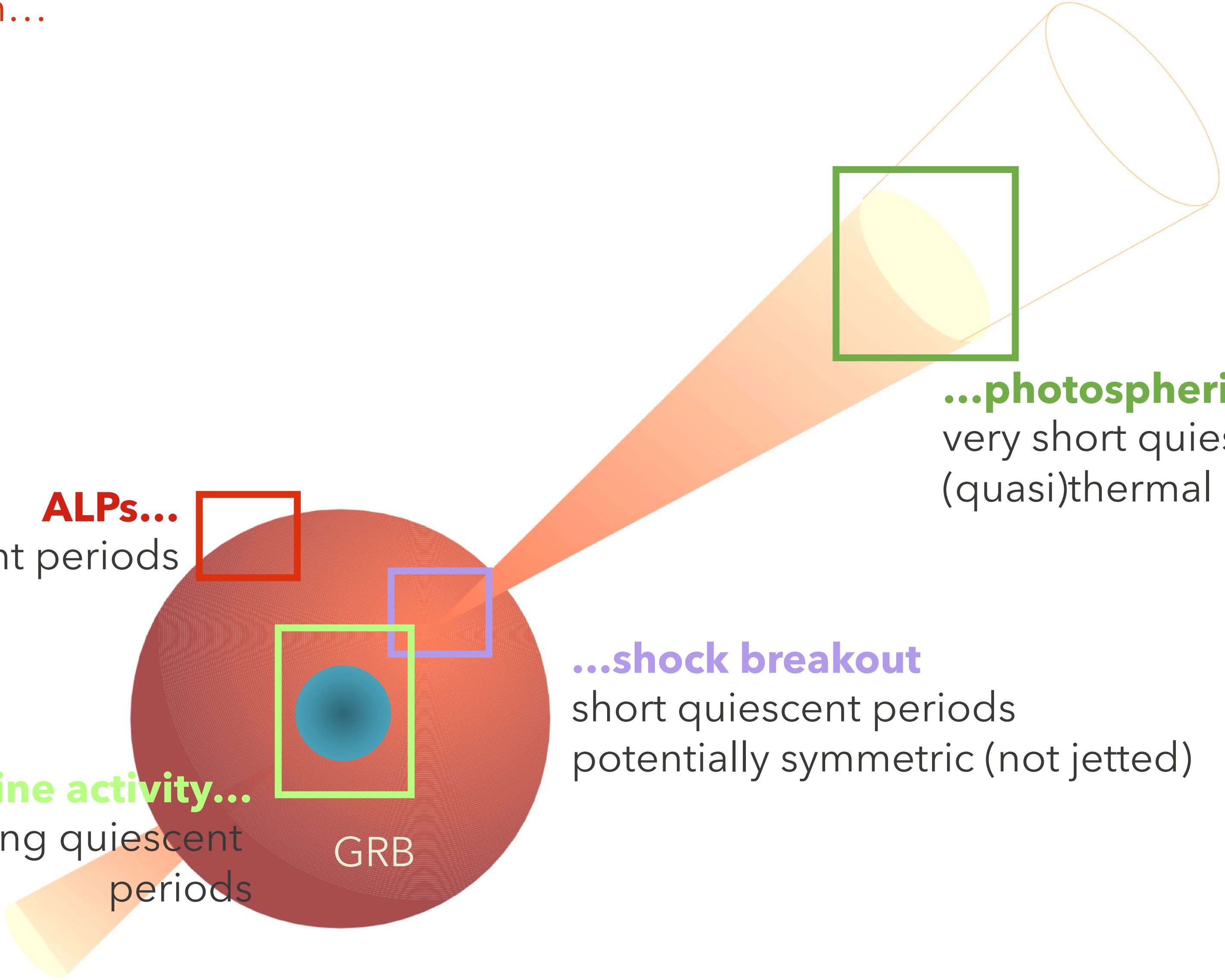


Diagram adapted from Sylvia Zhu's dissertation

Precursors may come from…



ALPs…
short to long quiescent periods

…photospheric emission
very short quiescent periods
(quasi)thermal precursor

…shock breakout
short quiescent periods
potentially symmetric (not jetted)

central engine activity…
short to long quiescent periods

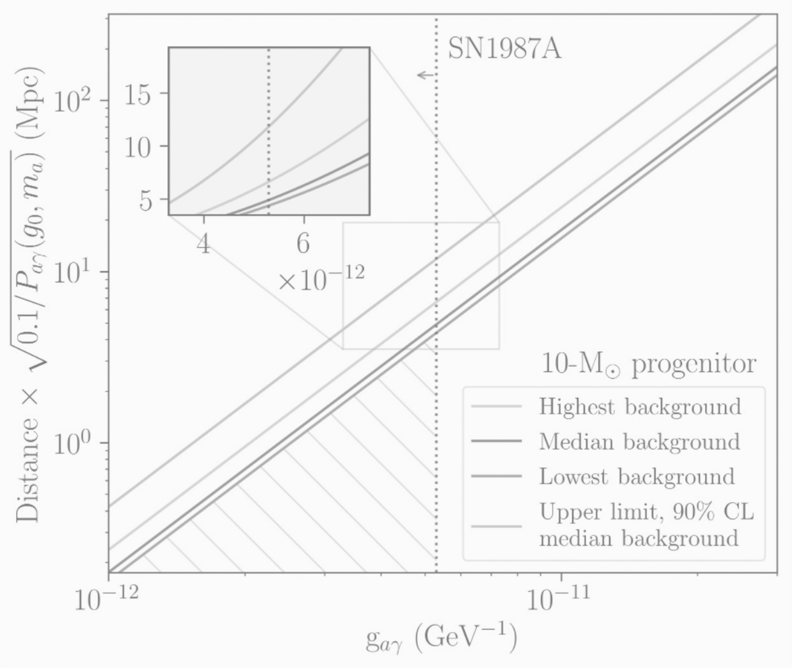
Diagram adapted from Sylvia Zhu's dissertation

QUESTION 4: *DO WE SEE ANYTHING IN PRECURSORS?*

Fermi GI Program, Cycle 15; PI: Crnogorčević

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

Fermi-LLE Sensitivity



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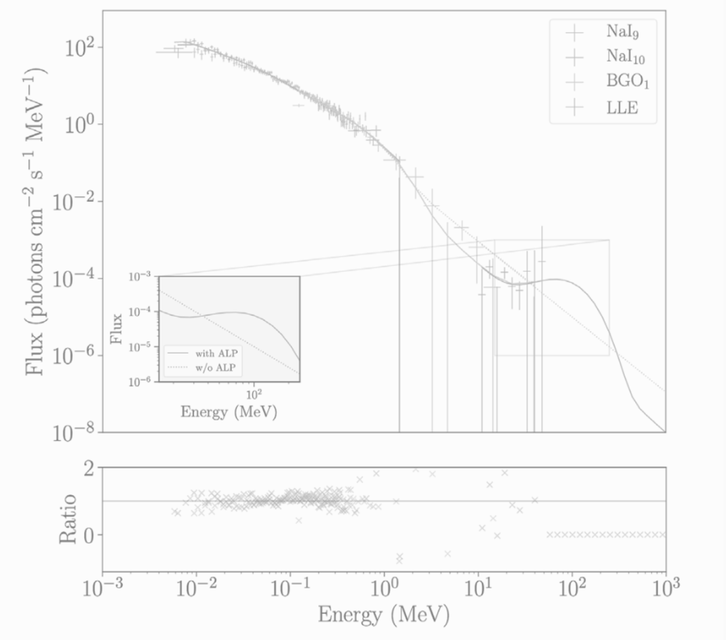
Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

GRB searches



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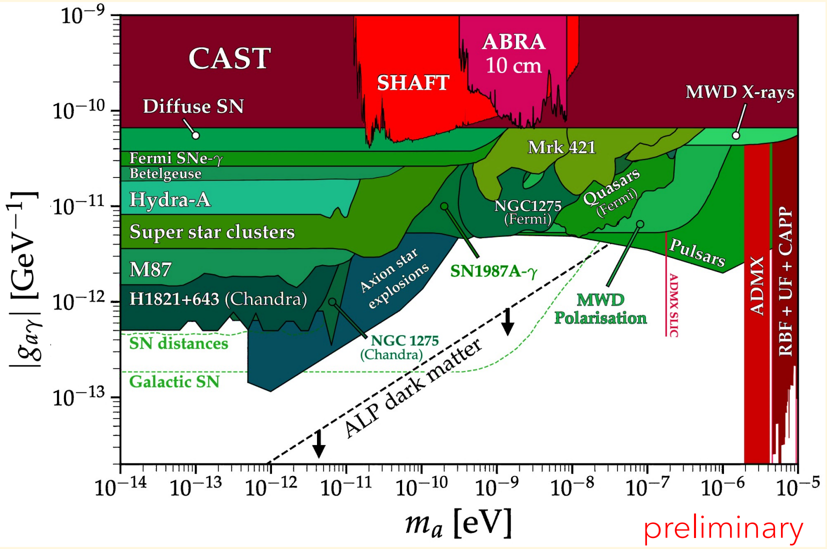
- *Method: model comparison*

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

GRB Precursors

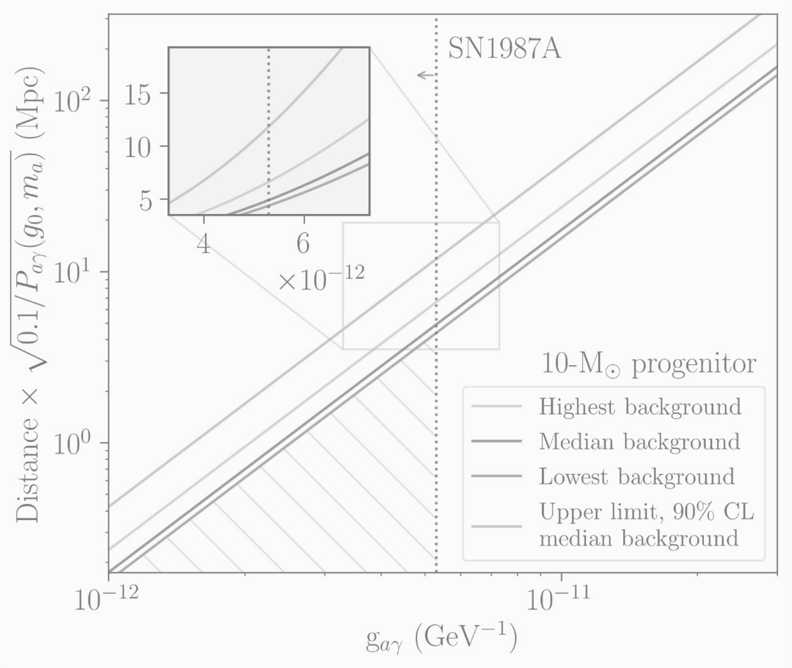


- No significant detections.
- From the ALP amplitude we calculate upper limits.
- *Method: model comparison*

Crnogorčević et al. 2023 (under review)

GRB precursors & ALPs

Fermi-LLE Sensitivity



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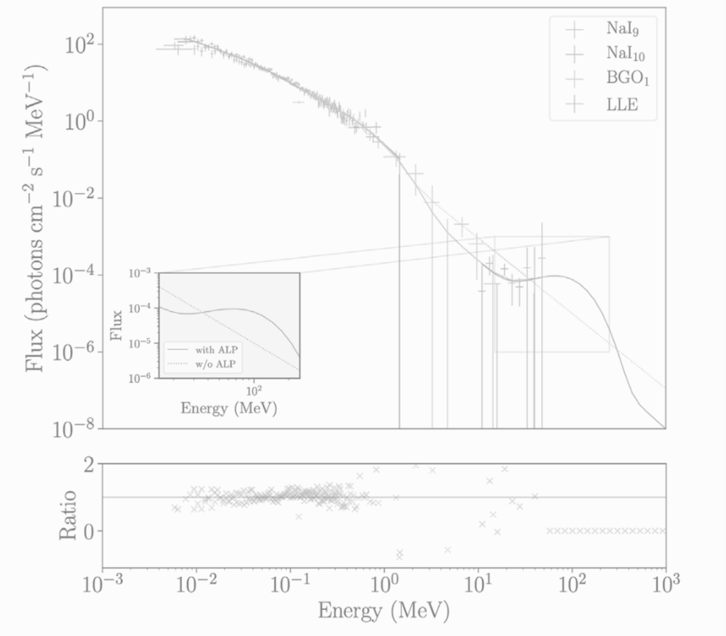
GRB searches



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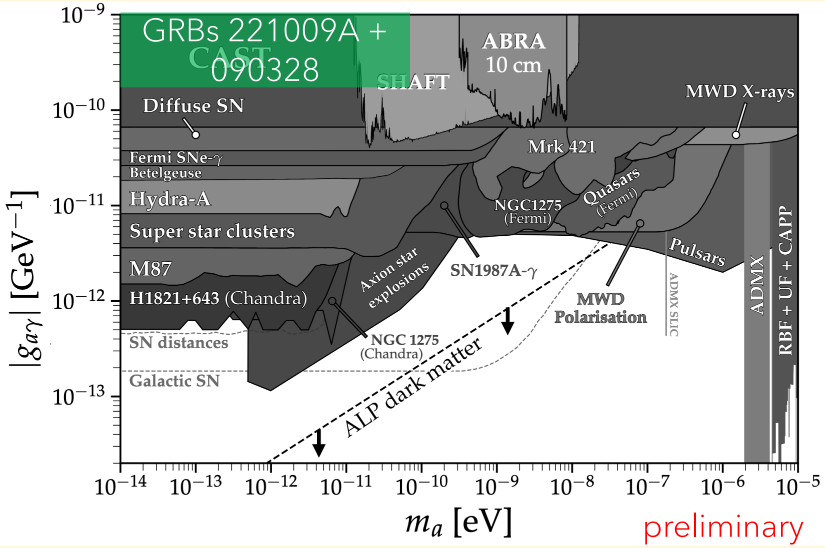
GRB Precursors



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Crnogorčević et al. 2023 (under review)

QUESTION 5: *WHAT ABOUT BINARY NEUTRON-STAR MERGERS?*

(sneak peak): What's next?

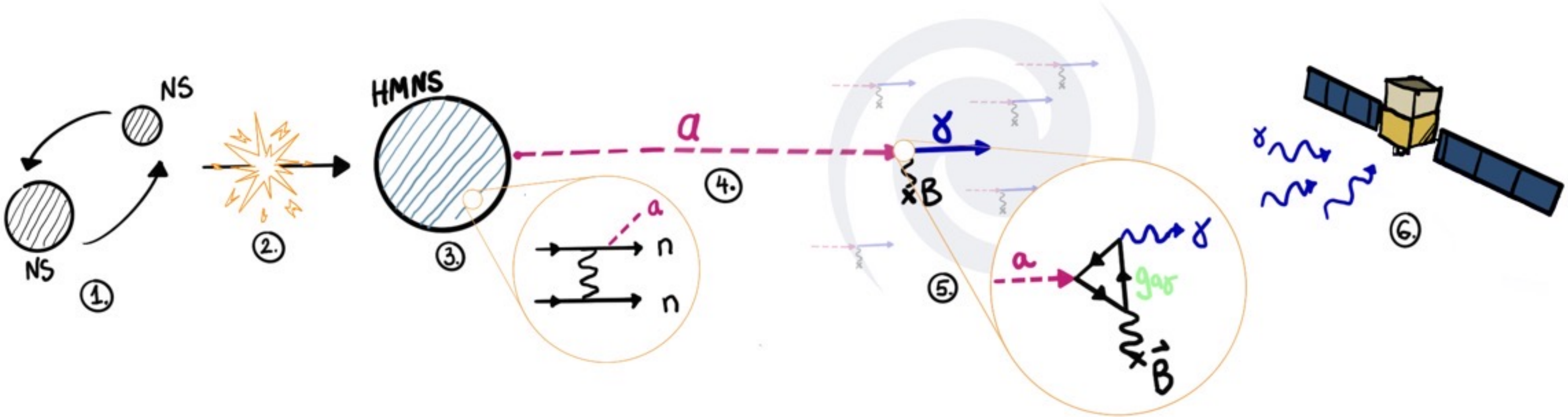
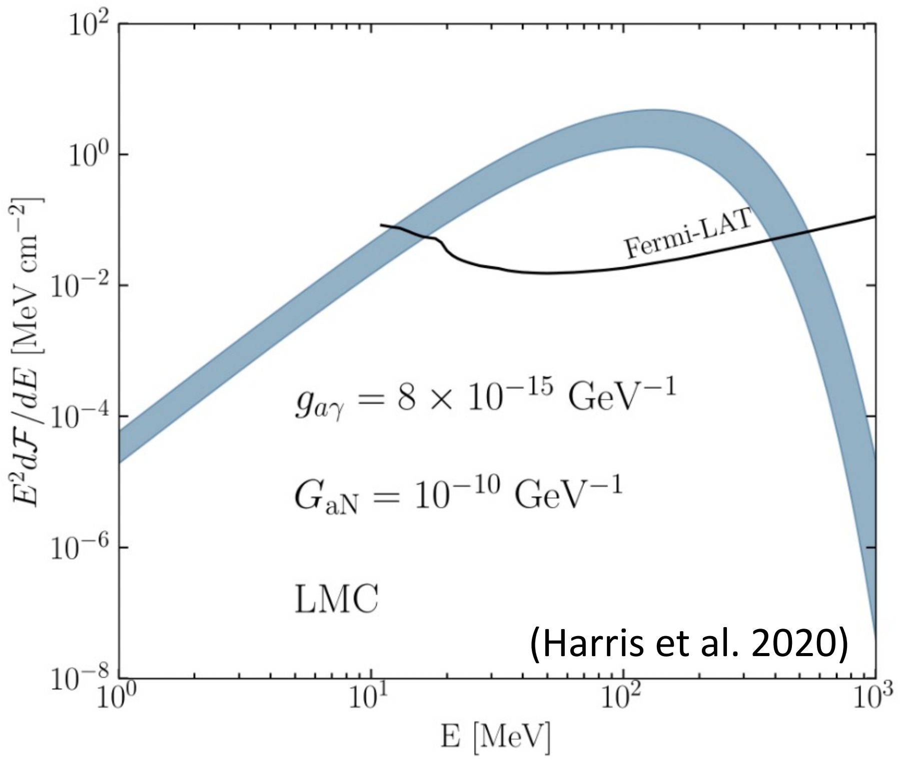


Figure description: (1) Two neutron stars (NS) orbit each other until the (2) merger, followed by (3) the formation of a hypermassive neutron star (HMNS). There, ALPs are produced via the neutron-neutron bremsstrahlung process. Once produced, ALPs travel undisturbed (4), until they reach the magnetic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

(sneak peak): What's next?

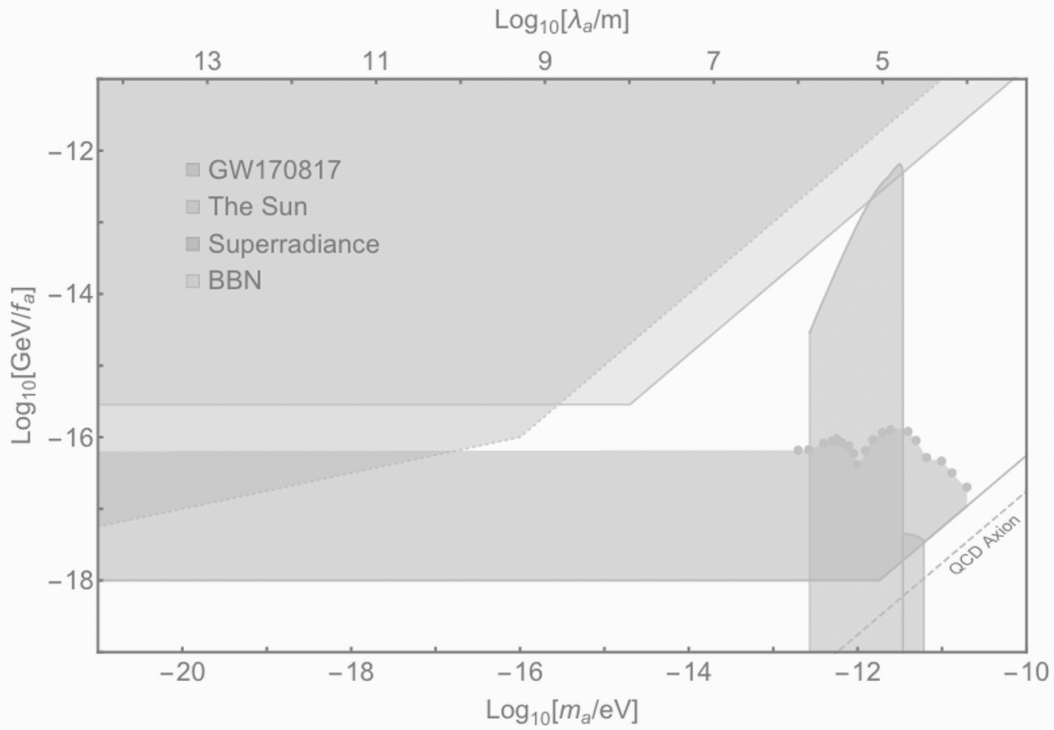
Indirect detection (γs)



(Harris et al. 2020)

- Depends on NS temperature profile
- Duration of the "supermassive" NS phase
- MW magnetic fields

Direct detection (GW)

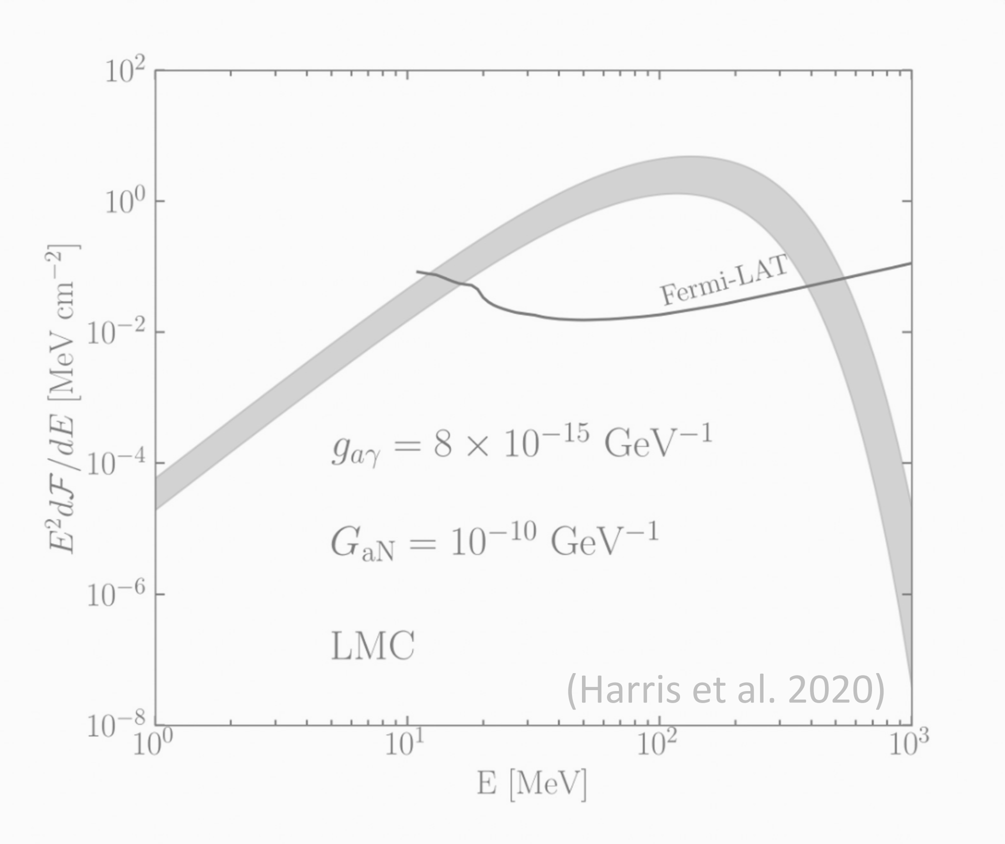


(Zhung et al. 2022)

- O4 (8-fold improvement in sensitivity)

(sneak peak): What's next?

Indirect detection (γs)



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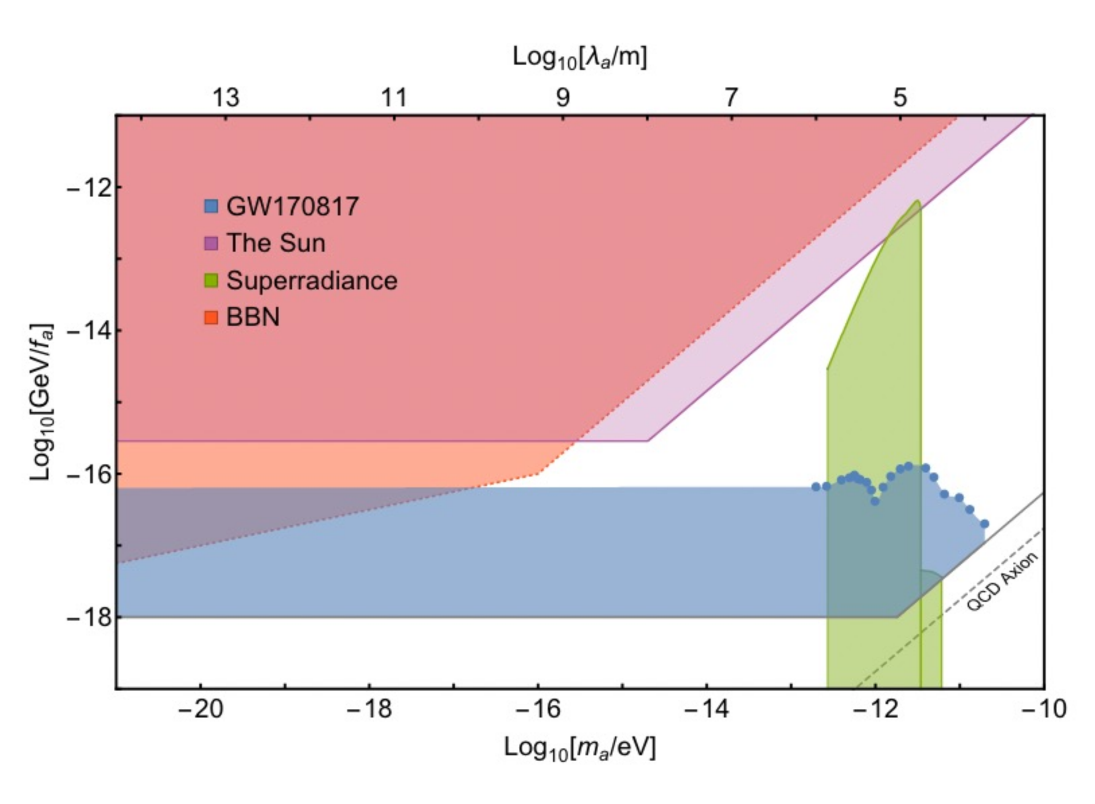

(Zhung et al. 2022)

- O4 (8-fold improvement in sensitivity)

Summary

- We test LAT sensitivity to detecting ALPs, including the LLE data cut and extending into energies relevant to the ALP spectral signature (a few tens of MeV)
- Result: LLE can reach up to ~10 Mpc for detecting ALPs
- We conduct ALP fitting to the unassociated, long, LLE-detected GRBs
- Result: No statistically significant detection in our sample
- We conduct ALP fitting to the unassociated, long, LLE-detected GRBs
- Result: No statistically significant detection in our sample
- Prospects: neutron-star mergers as excellent probes into new systems!

TeVPA 2023

Thank you!

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mcrnogor.github.io