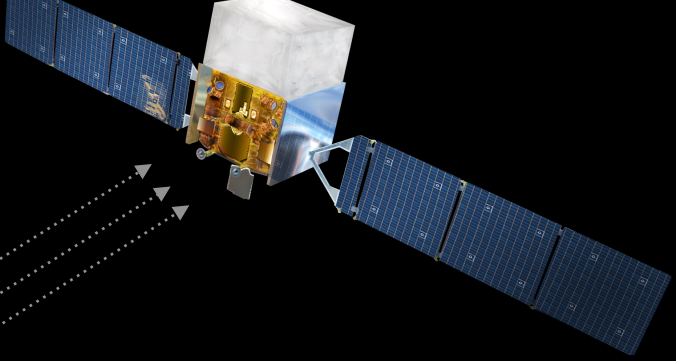
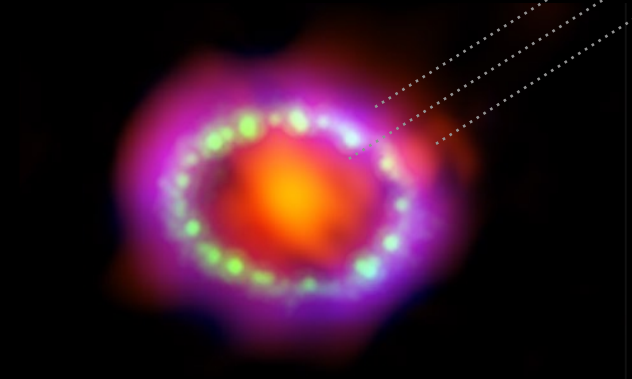
SED Director's Seminar
NASA Goddard Space Flight Center
February 17, 2023



Beyond the visible: New Messengers & New Physics

Searching for Axion-Like Particles from transient astrophysical events



SN1987A*

Milena Crnogorčević (she/her)
University of Maryland/NASA Goddard
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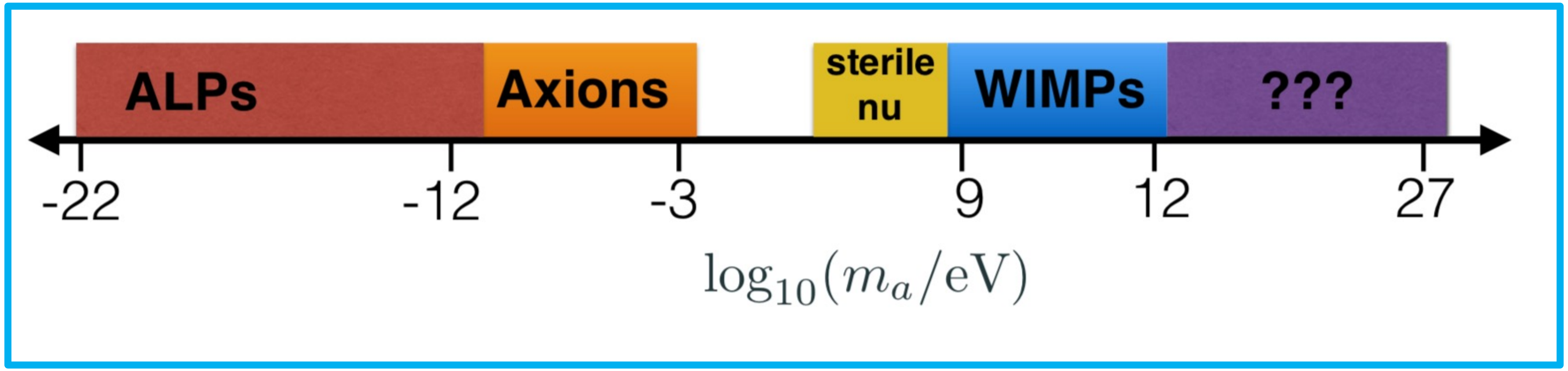
Credit: X-ray: NASA/CXC/SAO/PSU/K.Frank et al.; Optical: NASA/STScI; Millimeter: ESO/NAOJ/NRAO/ALMA

What are Axion-Like Particles (ALPs)?

- Extension of the axion, a proposed solution of the strong charge-parity problem in QCD

- <u>WISPs</u>: weakly-interacting sub-eV particles (mass $\lesssim 10^{-10}$ eV)



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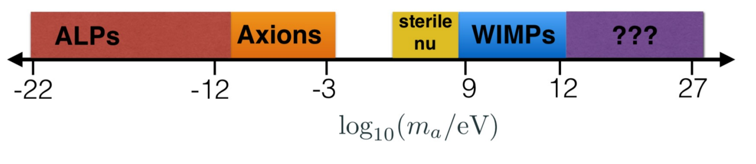
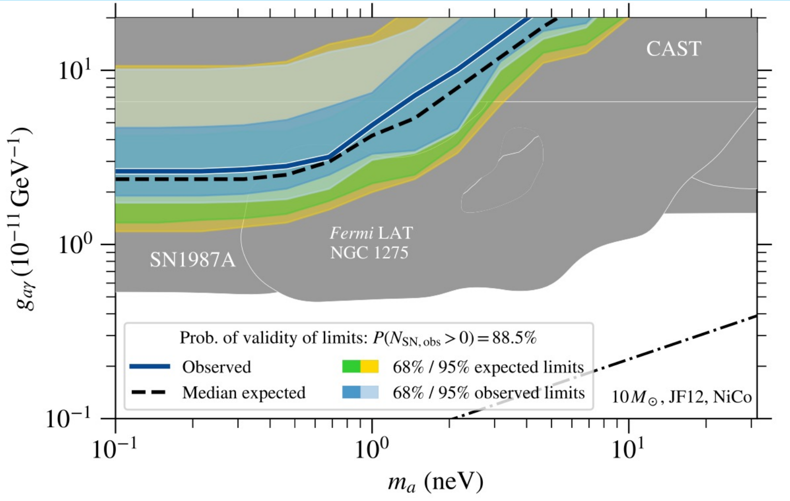
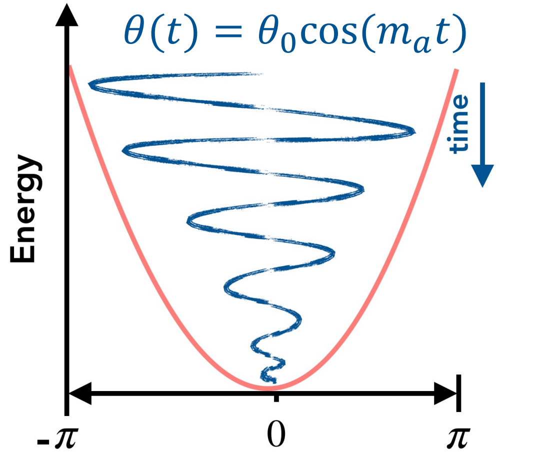


- <u>Cold</u> matter requirements:
  - ✓ feeble interactions with standard model particles
  - ✓ cosmological stability
- Direct and indirect searches → limits on coupling/mass parameter space
- **Non-thermal** production of ALPs via ***misalignment mechanism*** or inverse ***Primakoff process***

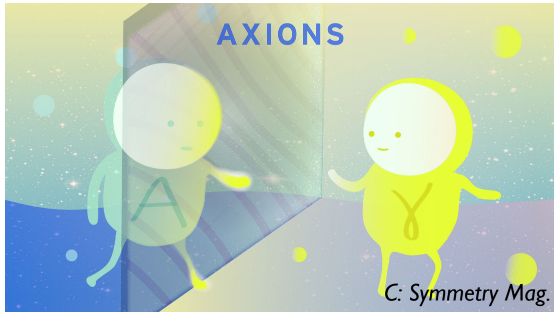


Exclusion plot for ALPs. [Meyer & Petrushevska 2020]



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

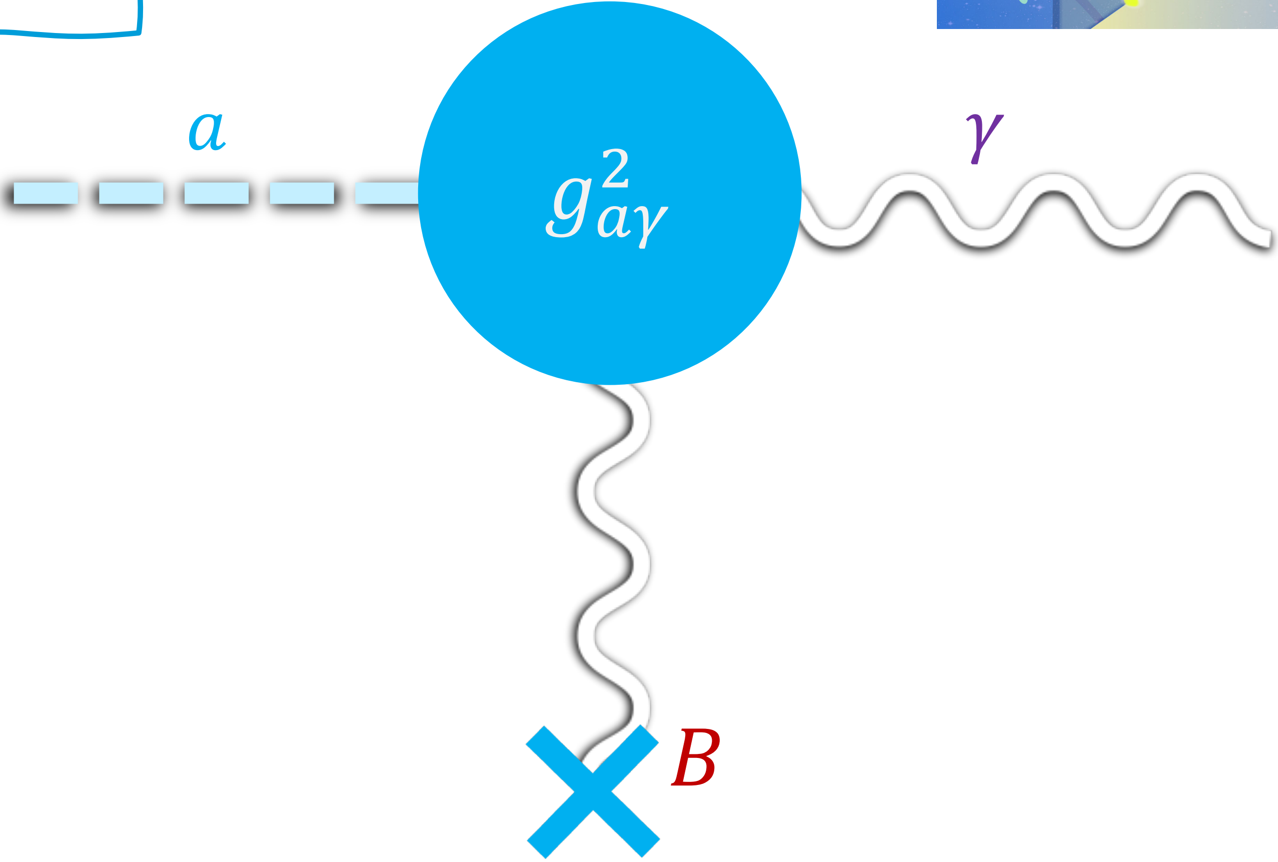
Observing ALPs with γ rays



- **Primakoff process:** converting ALPs into photons
  - In the presence of an external magnetic field, **B**, ALPs undergo a conversion into gamma-rays:

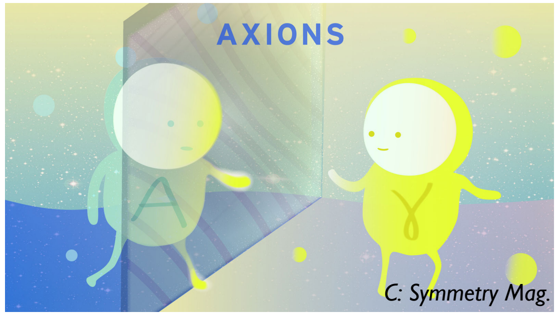
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

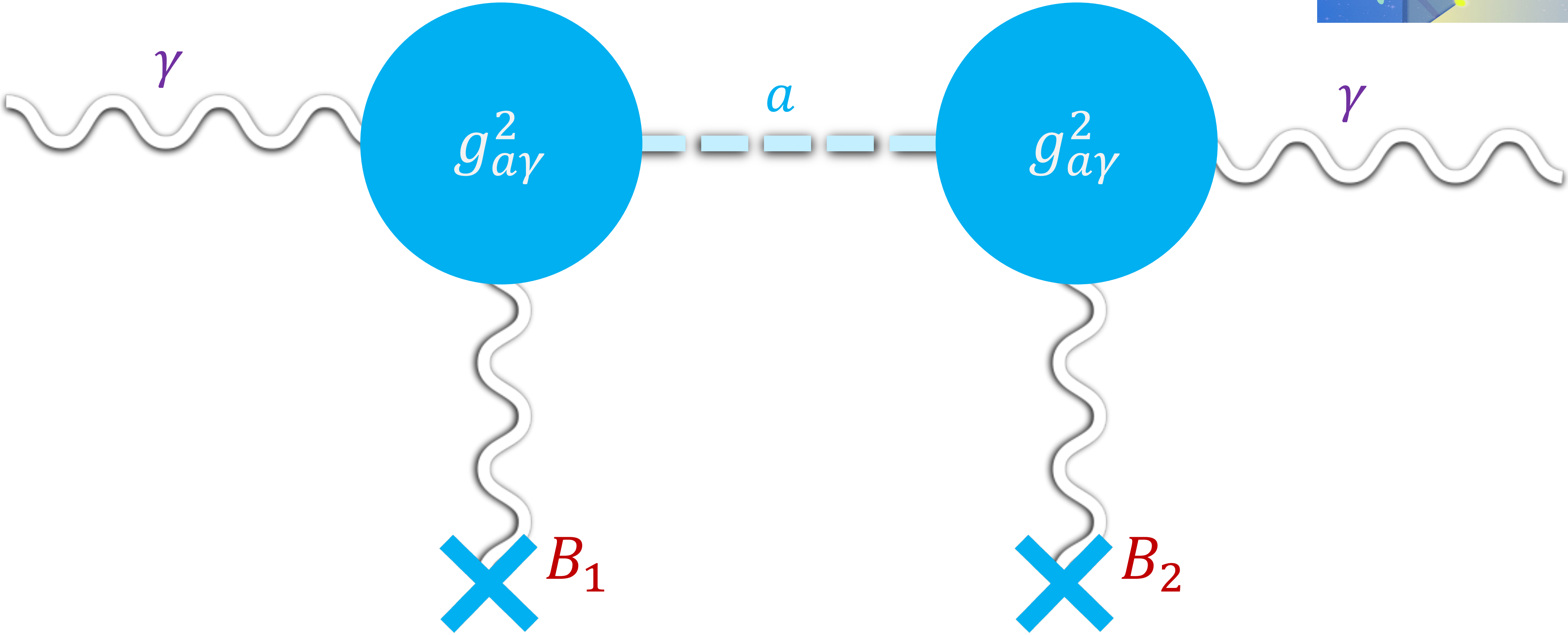
where $g_{a\gamma}$ is ALP-photon coupling rate, and a is the axion field strength.



[e.g. Raffelt & Stodoslky 1988]

Observing ALPs with γ rays





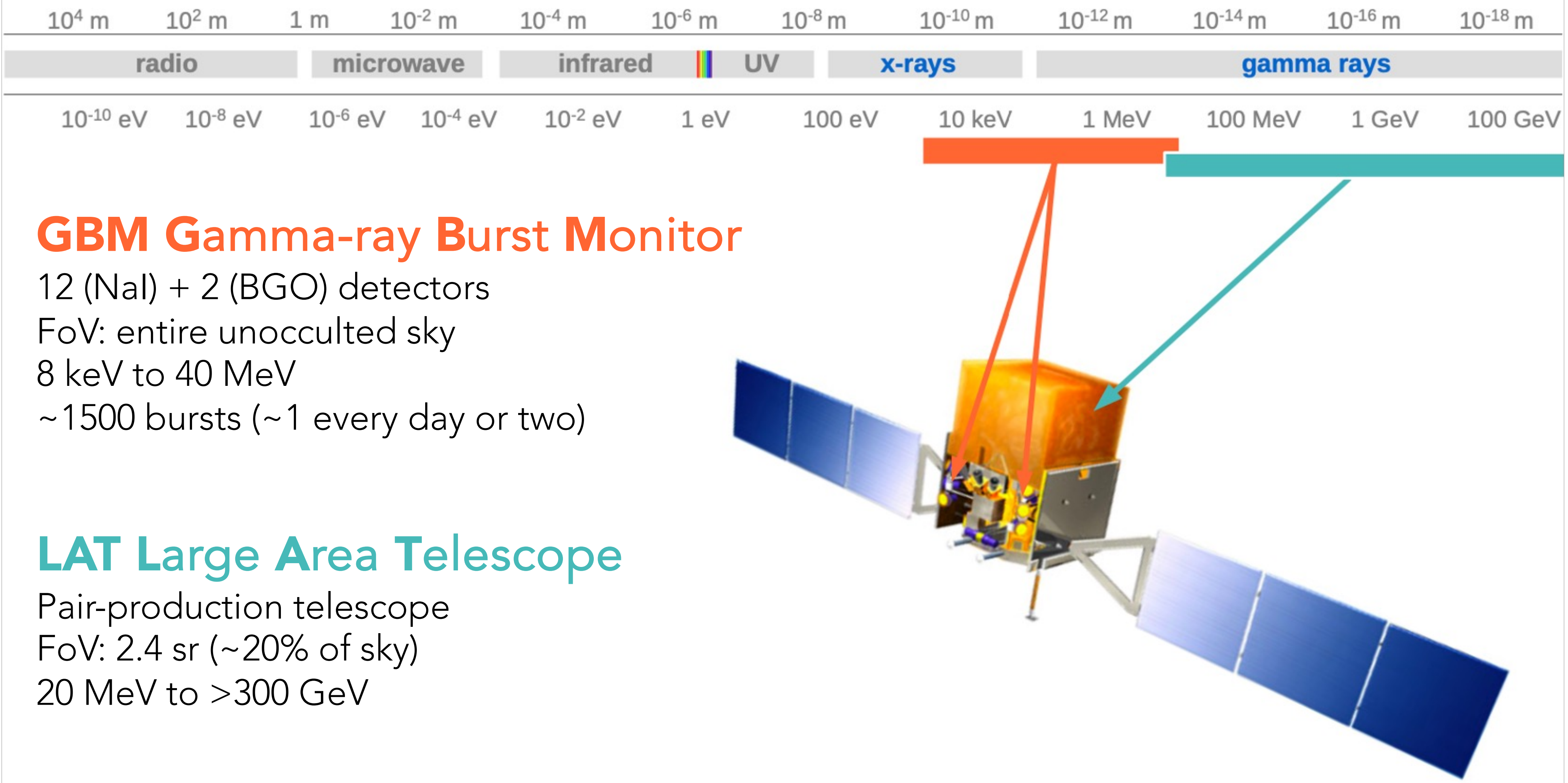
(production: Primakoff process)

(detection: inverse Primakoff process)

[e.g. Raffelt & Stodoslky 1988]

Take-away points about ALPs

- Viable *cold* dark-matter candidate (WISPs)
- They convert into photons in the presence of a magnetic field (Primakoff process)
- Gamma-ray observations can probe ALP parameter space



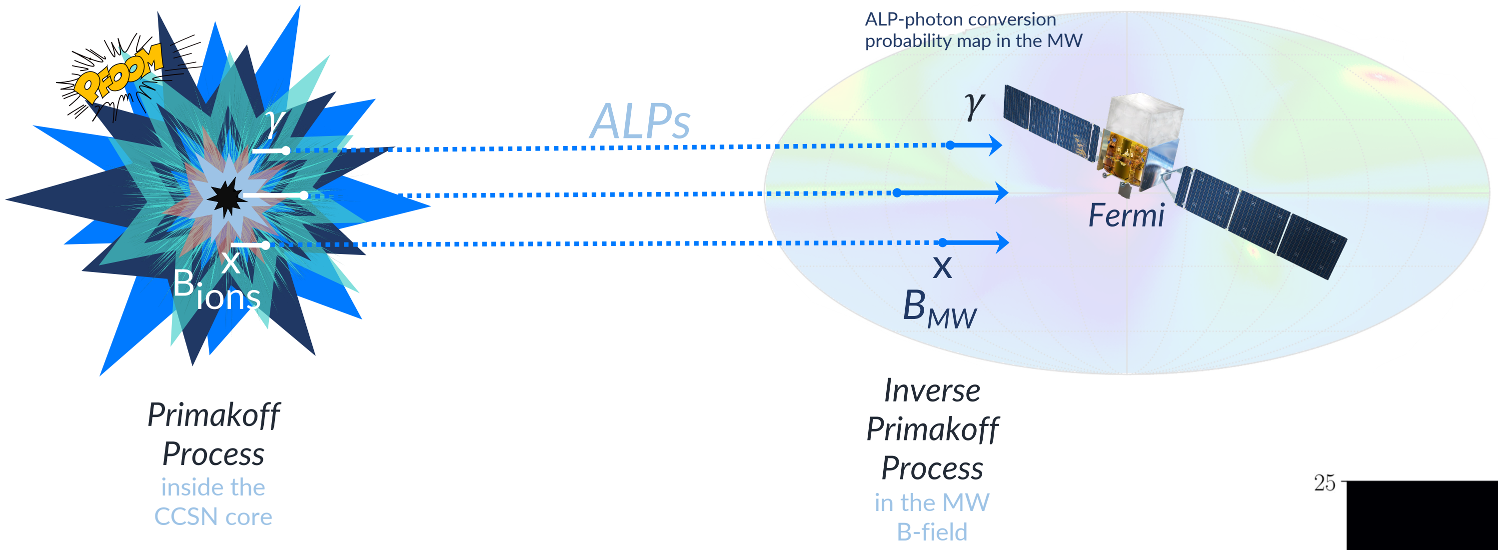
GBM Gamma-ray Burst Monitor

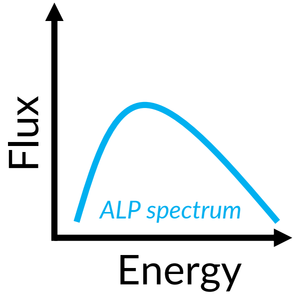
12 (NaI) + 2 (BGO) detectors
FoV: entire unocculted sky
8 keV to 40 MeV
~1500 bursts (~1 every day or two)

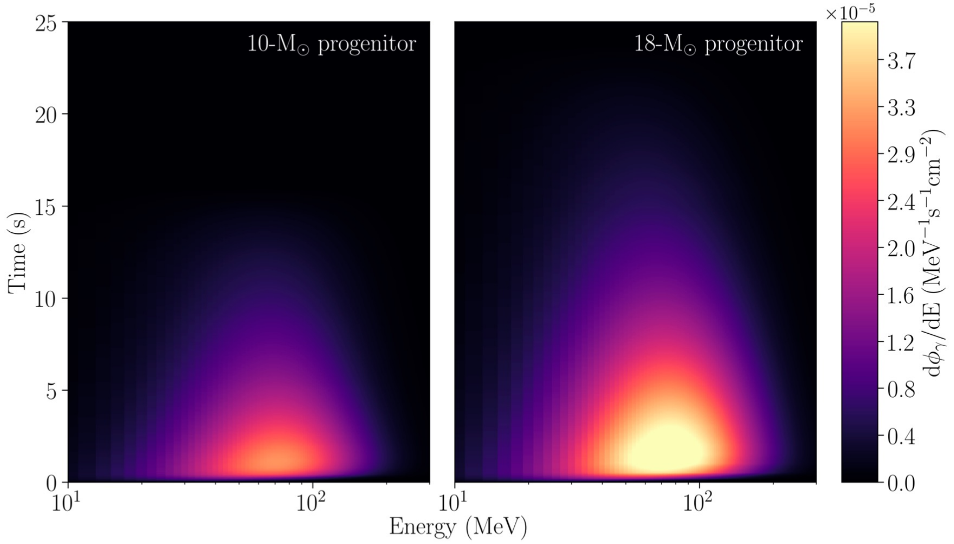
LAT Large Area Telescope

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

Motivation and assumptions

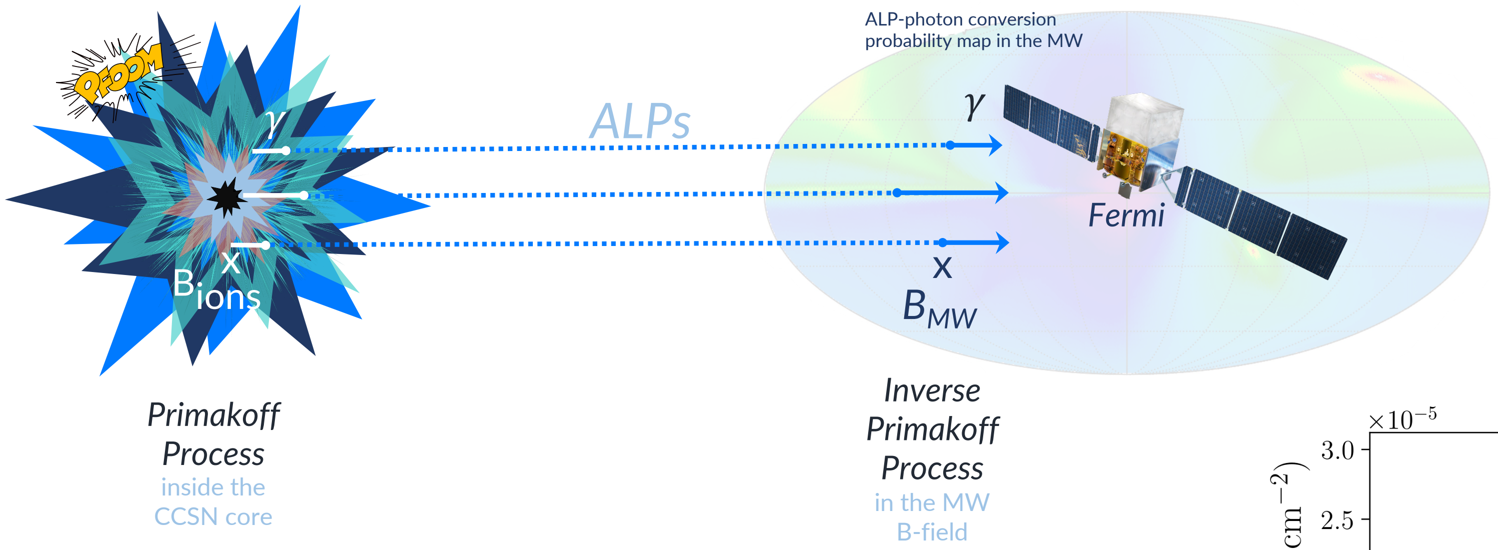


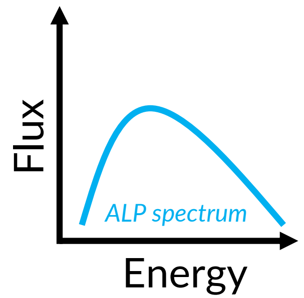




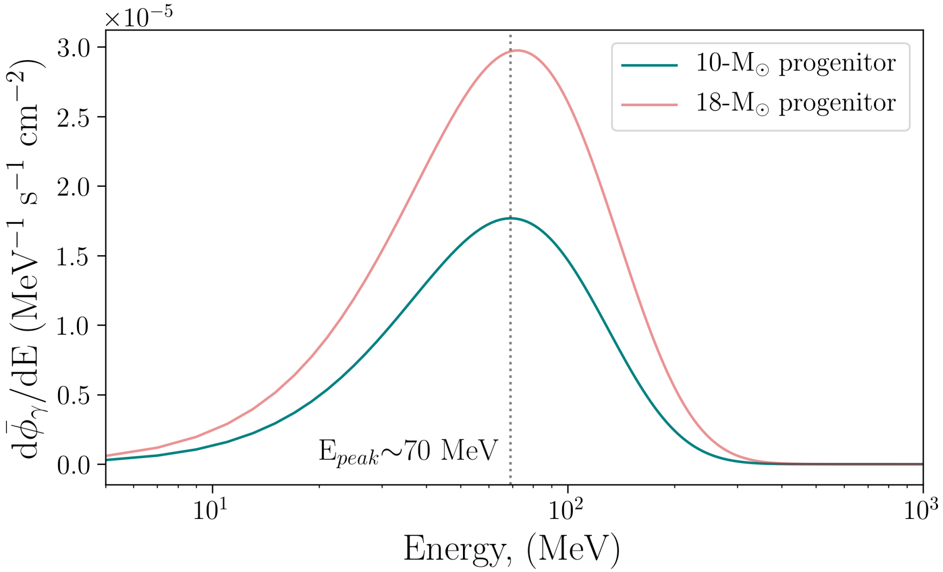
Observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a 10 and 18-M⊙ progenitor.

Motivation and assumptions



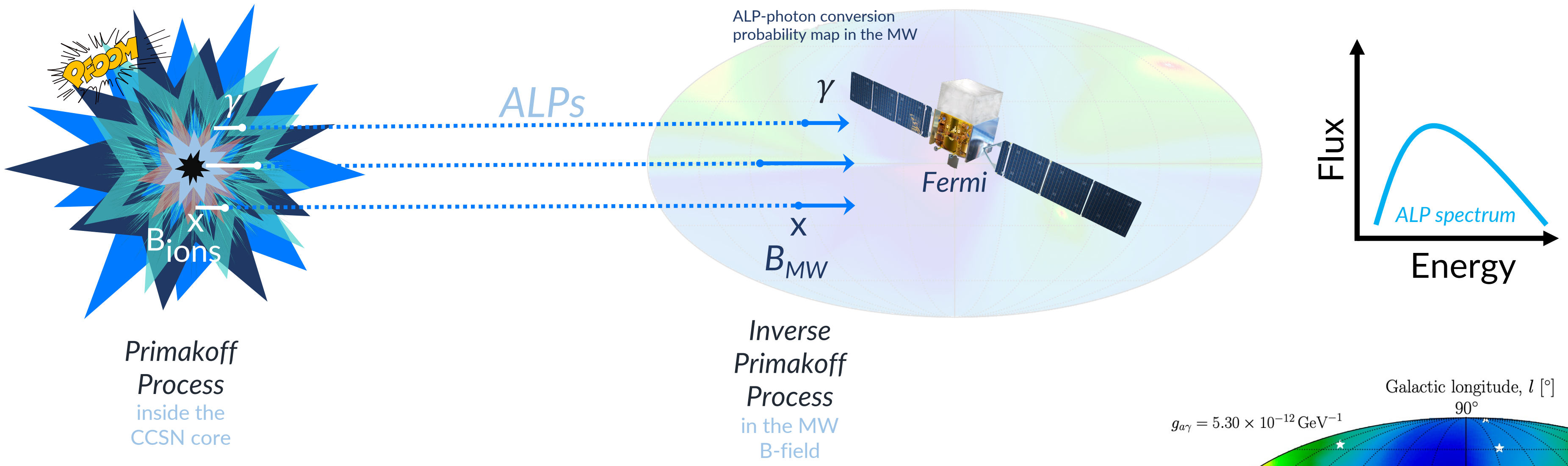


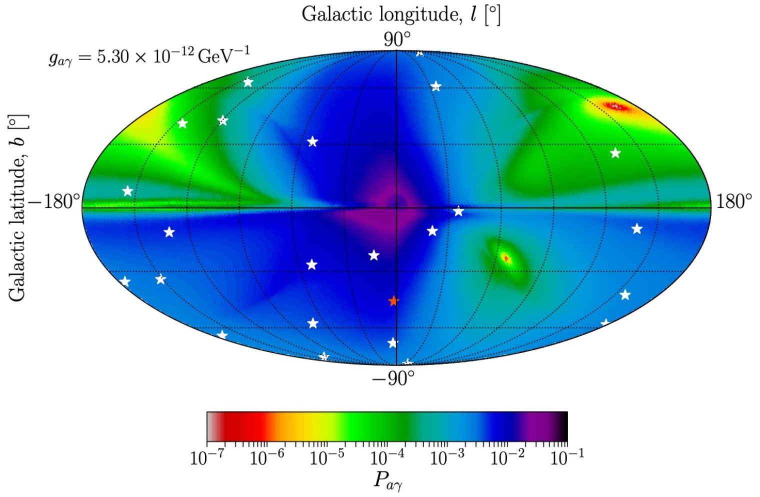
- **Motivation:** ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.



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

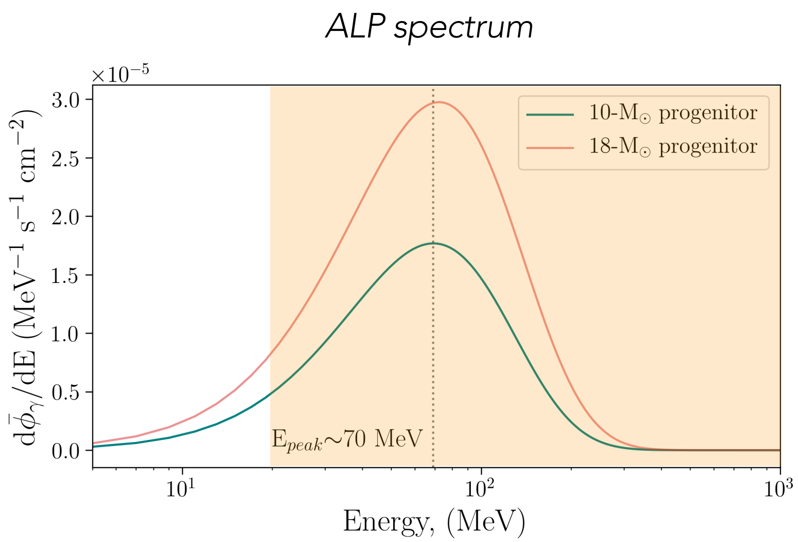
Motivation and assumptions

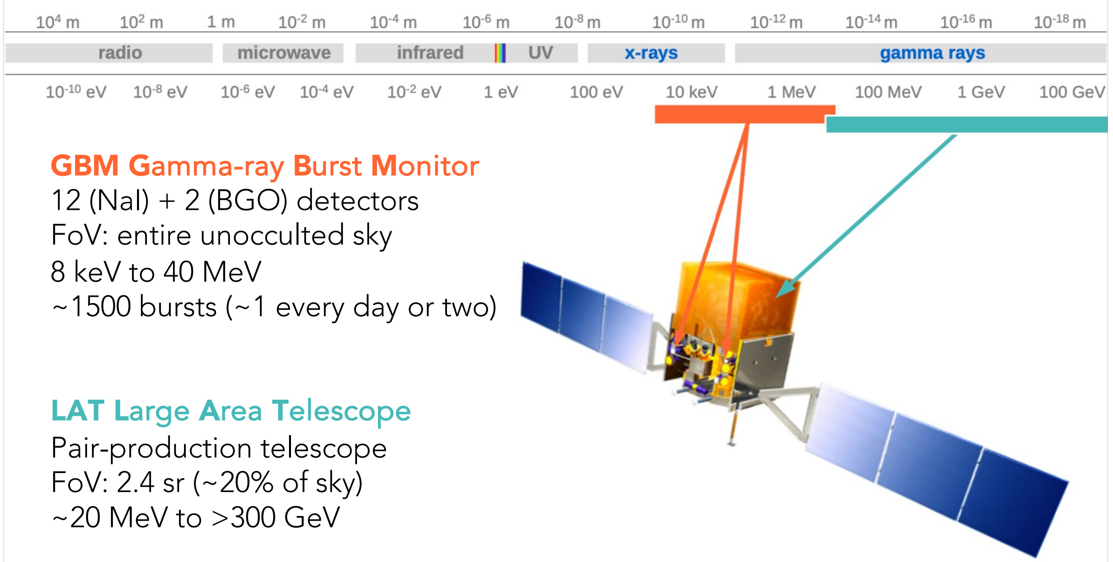




ALP-photon conversion probability map in the Milky Way's magnetic field.

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





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LAT Low Energy (LLE) technique

- Standard LAT analysis: >100 MeV (Meyer et al. 2020). LLE analysis: > 20 MeV
- Goal: maximizing the effective area of the LAT instrument in the low-energy regime
  - Relaxing requirements on the background rejection: more signal, but also more background!
  - Only works for pulse-like sources (i.e., transients)
  - Direction information necessary
  - Additional response functions needed (Monte Carlo simulations of a bright point source at the position of interest)
- Systematics: flux values on average lower than those from the standard LAT analysis (see arXiv:1304.5559)

Sensitivity testing: analysis & results

Model backgrounds from the considered LLE-detected GRB sample.

↓

Find the min, max, and median background levels.

↓

Produce ALP signal normalized by a value from the normalization grid for 10-and 18-solar-mass progenitors.

↓

Produce 2000 realizations of the backround+ALP spectrum and their corresponding (GRB) response functions (XSPEC fakeit function.)

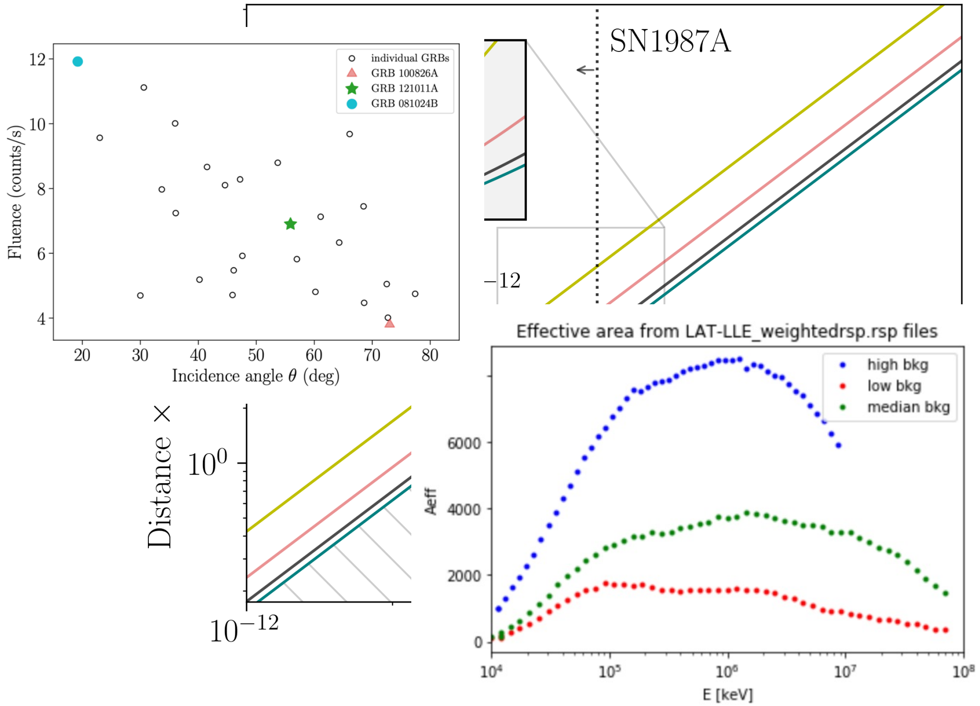
↓

Fit the ALP and the "background-only" model. Apply Wilks' Theorem and LLR test to fins for which normalization ALP model is preferred.

↓

Find the coupling-distance parameter space for that normalization.

$N \propto 1/d$



Background level	Conversion probability, $P_\gamma(g_0)$	Distance limit (Mpc) 10 $M_\odot$	18 $M_\odot$
Low	0.1	4.4	6.5
Median	0.1	4.9	7.1
High	0.1	6.6	9.7
Low	0.05	3.1	4.6
Median	0.05	3.5	5.0
High	0.05	4.7	6.9
Low	0.01	1.4	2.1
Median	0.01	1.5	2.3
High	0.01	2.1	3.1
Low	0.001	0.4	0.7
Median	0.001	0.5	0.7
High	0.001	0.7	1.0

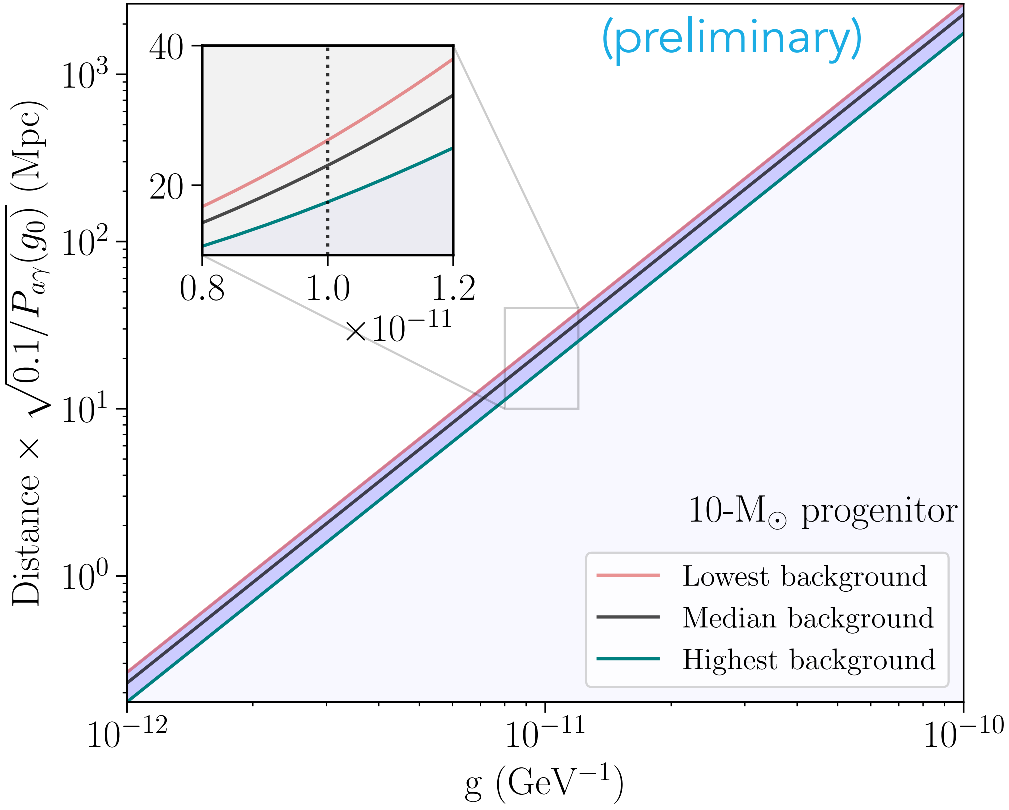
Crnogorčević et al. 2021 (PRD, arXiv:2109.05790)

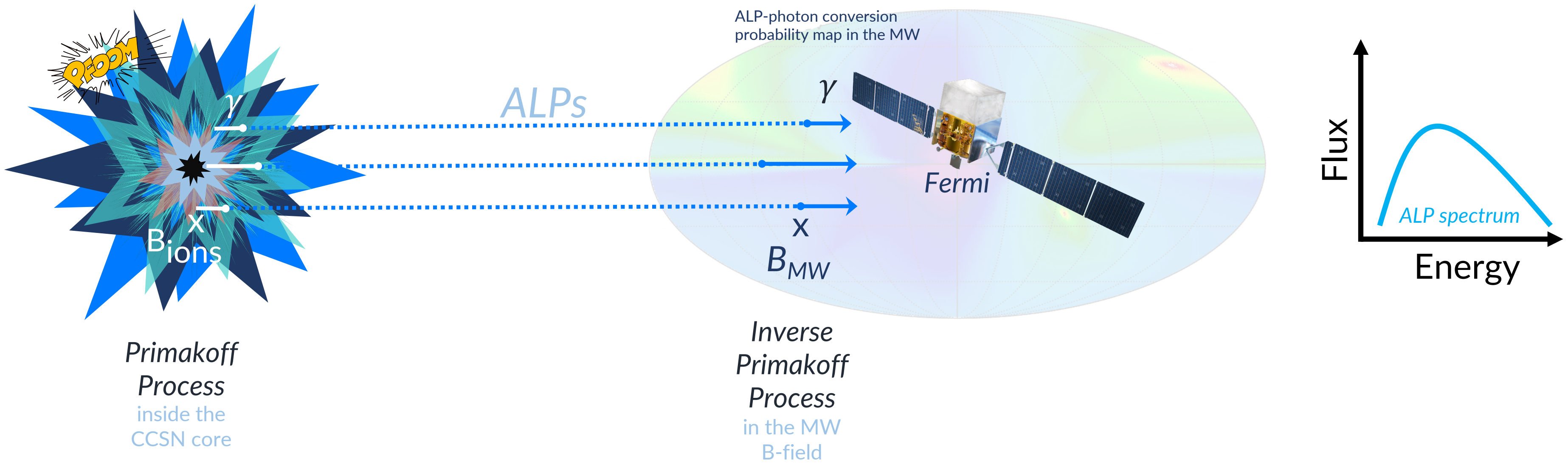
ADDITIONAL CONSIDERATION

Additional considerations: All-sky Medium Energy Gamma-ray Observatory (AMEGO) sensitivity analysis; motivation outlined the Snowmass 2021 Letter of Interest (Prescod-Weinstein et al. 2021, incl. Crnogorčević)

- For a 10-solar mass progenitor, and background levels comparable to LAT in the low-energy regime:

Distance limit improved by a factor of 5!





CCSNe → long Gamma-ray Bursts (GRBs)

GRB analysis

Property	Selection Criterion
Distance	unassociated (no redshift)
Detection significance	$\geq 5\sigma$ in LAT-LLE ($\gtrsim 30$ MeV)
Observed time interval	$\geq$ duration of the burst
Burst duration	long GRBs ($T_{95} \gtrsim 2$ seconds)

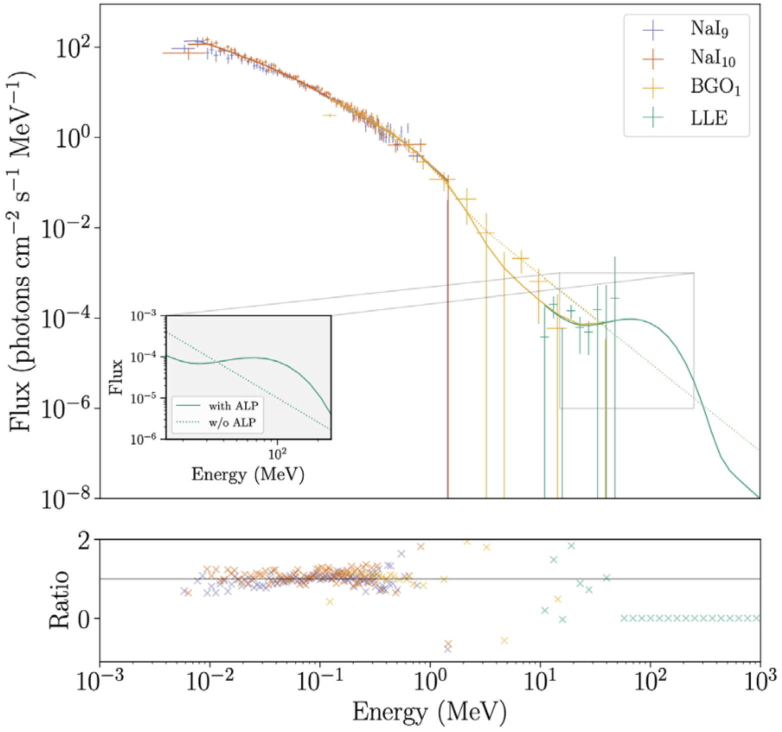
Initial sample: 186 LAT-detected GRBs

Applying the selection criteria

24 GRBs

GRB analysis

GRB	T_{95} (s)	Best model(no ALP)	grbm parameters α_1	α_2	E_c (keV)	LLR
080825C	22.2	grbm	$-0.65^{+0.05}_{-0.05}$	$-2.41^{+0.04}_{-0.04}$	143^{+13}_{-12}	0.2
090217	34.1	grbm	$-1.11^{+0.04}_{-0.04}$	$-2.43^{+0.03}_{-0.04}$	16^{+13}_{-8}	0.1
100225A	12.7	grbm	$-0.50^{+0.25}_{-0.21}$	$-2.28^{+0.07}_{-0.09}$	223^{+112}_{-68}	0.0
100826A	93.7	grbm+bb	$-1.02^{+0.04}_{-0.04}$	$-2.30^{+0.03}_{-0.04}$	484^{+72}_{-63}	0.0
101123A	145.4	grbm+cutoffpl	$-1.00^{+0.07}_{-0.08}$	$-1.94^{+0.15}_{-0.12}$	187^{+74}_{-62}	5.8
110721A	21.8	grbm+bb	$-1.24^{+0.02}_{-0.01}$	$-2.29^{+0.03}_{-0.03}$	1000^{+28}_{-39}	0.0
120328B	33.5	grbm+cutoffpl	$-0.67^{+0.06}_{-0.05}$	$-2.26^{+0.05}_{-0.05}$	101^{+12}_{-13}	0.0
120911B	69.0	grbm	$-2.50^{+0.92}_{-1.04}$	$-1.05^{+0.63}_{-0.38}$	11^{+10}_{-2}	0.0
121011A	66.8	grbm	$-1.08^{+0.10}_{-0.21}$	$-2.18^{+0.11}_{-0.16}$	997^{+84}_{-26}	0.0
121225B	68.0	grbm	$-2.38^{+1.02}_{-0.40}$	$-2.45^{+0.06}_{-0.07}$	11^{+89}_{-3}	0.0
130305A	26.9	grbm	$-0.76^{+0.03}_{-0.03}$	$-2.63^{+0.06}_{-0.06}$	665^{+61}_{-55}	0.0
131014A	4.2	grbm	$-0.55^{+0.33}_{-0.98}$	$-2.65^{+0.17}_{-0.19}$	255^{+36}_{-11}	0.63
131216A	19.3	grbm+cutoffpl	$-0.46^{+0.28}_{-0.24}$	$-2.67^{+1.94}_{-0.94}$	178^{+77}_{-92}	0.0
140102A	4.1	grbm+bb	$-1.10^{+0.12}_{-0.09}$	$-2.41^{+0.16}_{-0.11}$	206^{+65}_{-92}	2.3
140110A	9.2	grbm	$-2.49^{+1.64}_{-1.59}$	$-2.19^{+0.20}_{-0.22}$	11^{+23}_{-3}	0.0
141207A	22.3	grbm+bb	$-1.21^{+0.09}_{-0.06}$	$-2.33^{+0.11}_{-0.13}$	999^{+18}_{-70}	0.0
141222A	2.8	grbm+pow	$-1.57^{+0.03}_{-0.02}$	$-2.83^{+0.46}_{-1.74}$	9971^{+390}_{-832}	0.0
150210A	31.3	grbm+pow	$-0.52^{+0.04}_{-0.05}$	$-2.91^{+0.11}_{-0.38}$	1000^{+517}_{-234}	0.0
150416A	33.8	grbm	$-1.18^{+0.04}_{-0.04}$	$-2.36^{+0.13}_{-0.21}$	999^{+187}_{-269}	0.0
150820A	5.1	grbm	$-0.99^{+0.56}_{-1.30}$	$-2.01^{+0.82}_{-0.27}$	303^{+61}_{-39}	0.0
151006A	95.0	grbm	$-1.35^{+0.06}_{-0.03}$	$-2.24^{+0.07}_{-0.08}$	998^{+33}_{-84}	0.0
160709A	5.4	grbm+cutoffpl	$-1.44^{+0.18}_{-0.12}$	$-2.18^{+0.15}_{-0.18}$	9940^{+373}_{-511}	1.0
160917A	19.2	grbm+bb	$-0.78^{+3.45}_{-1.40}$	$-2.39^{+0.20}_{-0.10}$	994^{+634}_{-216}	0.9
170115B	44.8	grbm	$-0.80^{+0.02}_{-0.04}$	$-3.00^{+0.10}_{-0.07}$	1000^{+226}_{-106}	2.8



global p-value of ~0.3, indicating that this observation is not statistically significant.

"Uh-oh."

-Milena's Dissertation Committee

WHEN TO SEARCH FOR ALPs?

- **The ALP signal should be coincident with the neutrino emission from a supernova**

→ For extragalactic SN, no neutrino signal is expected current generation of neutrino detectors [Kistler et al. 2011]; in the Milky Way ~2-3 SNe/century [Türler et al. 2006)

- **We can use optical light curves of extragalactic SNe to determine explosion times**

→ Method introduced in [Cowen et al. 2010] and applied in the context of ALP searches in [Meyer et al. 2020], resulting in most stringent upper limits on the light ALP parameter space

- **We can look for an ALP signal at the time of GRB emission, assuming that the GRB is ALP-induced**

→ Method introduced in [Crnogorčević et al. 2021] using a sample of LAT-detected GRBs. No significant (5 σ) detections reported

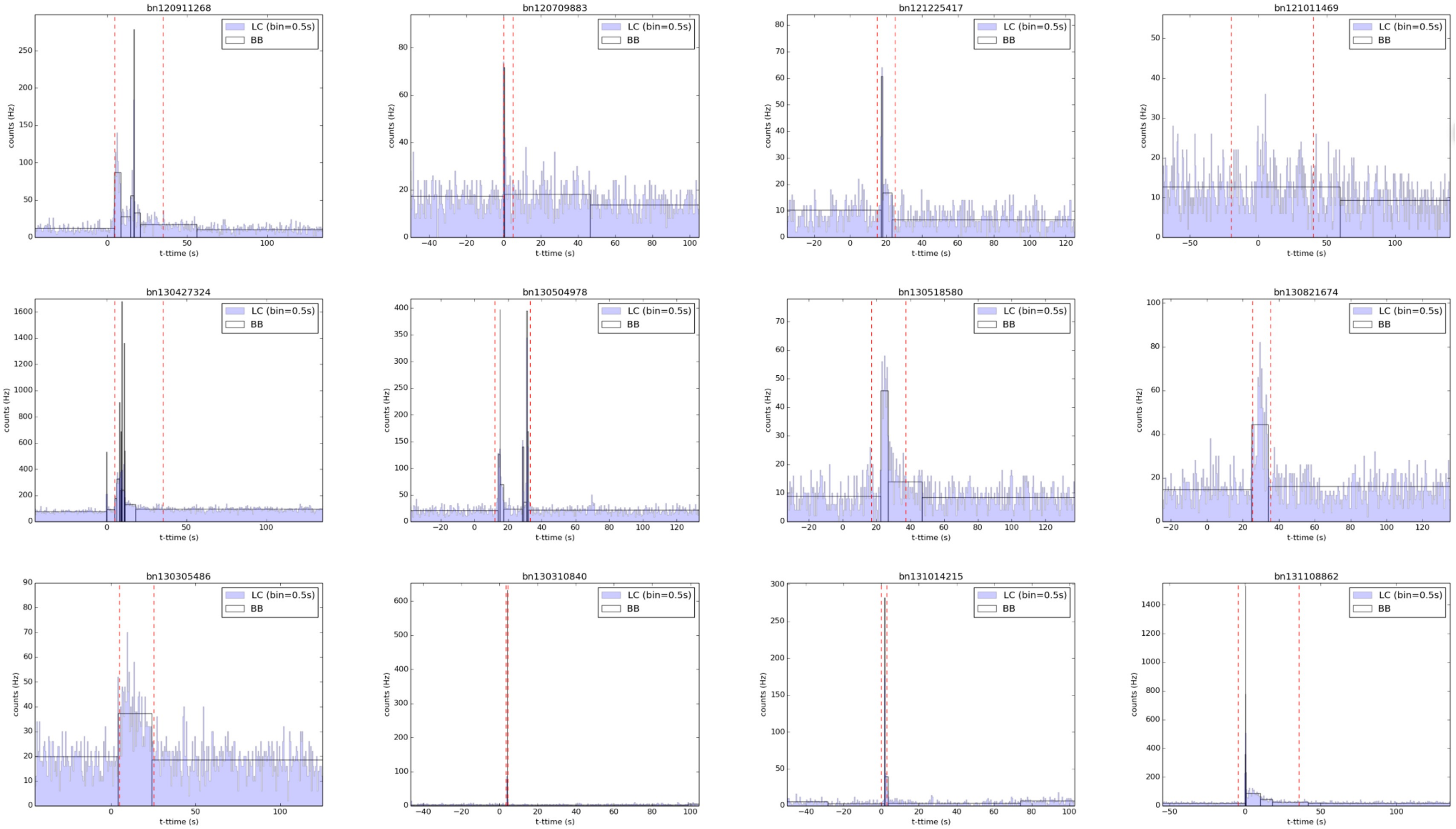
$\boxed{\text{→ A study of GBM/LAT bursts with precursor emission: a systematic search for ALP excess in targeted time windows } \textit{before} \text{ presumed gamma-ray jet emission}}$

LIGHT AT THE END OF THE TUNNEL

Search for Axion-like Particle Dark Matter in Precursor Emission of Long Gamma-ray Bursts

Crnogorčević et al. 2023 (*in prep.*)

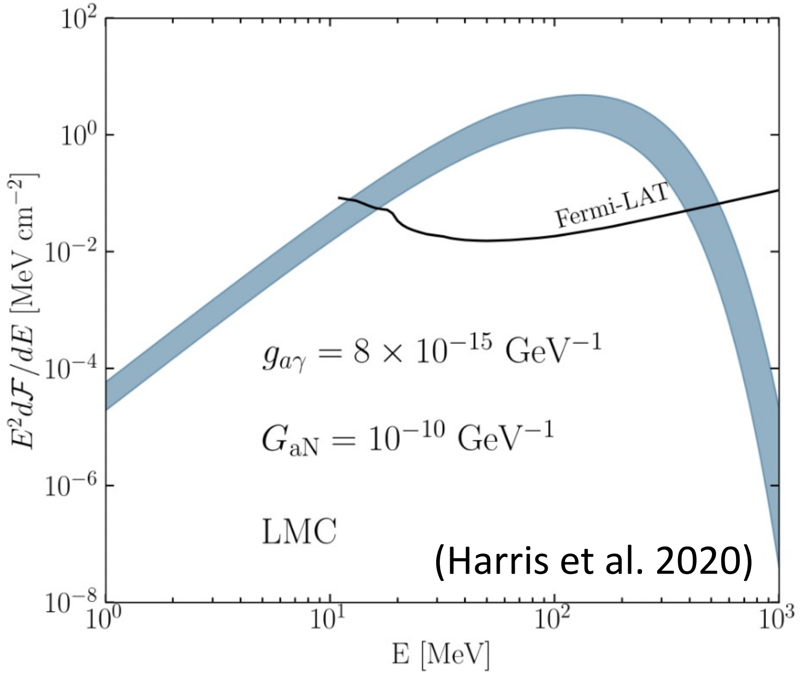
Fermi GI Cycle 15 (PI: Crnogorčević)



preliminary

What about binary neutron-star mergers?

PATH 1: INDIRECT DETECTION
GAMMA-RAY FLUX FROM BNS



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

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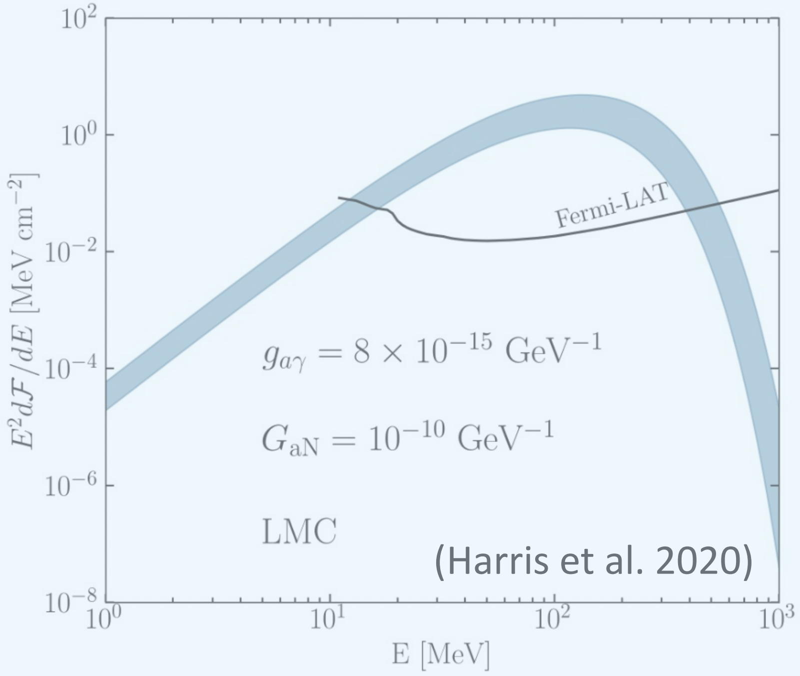

- Depends on NS temperature profile
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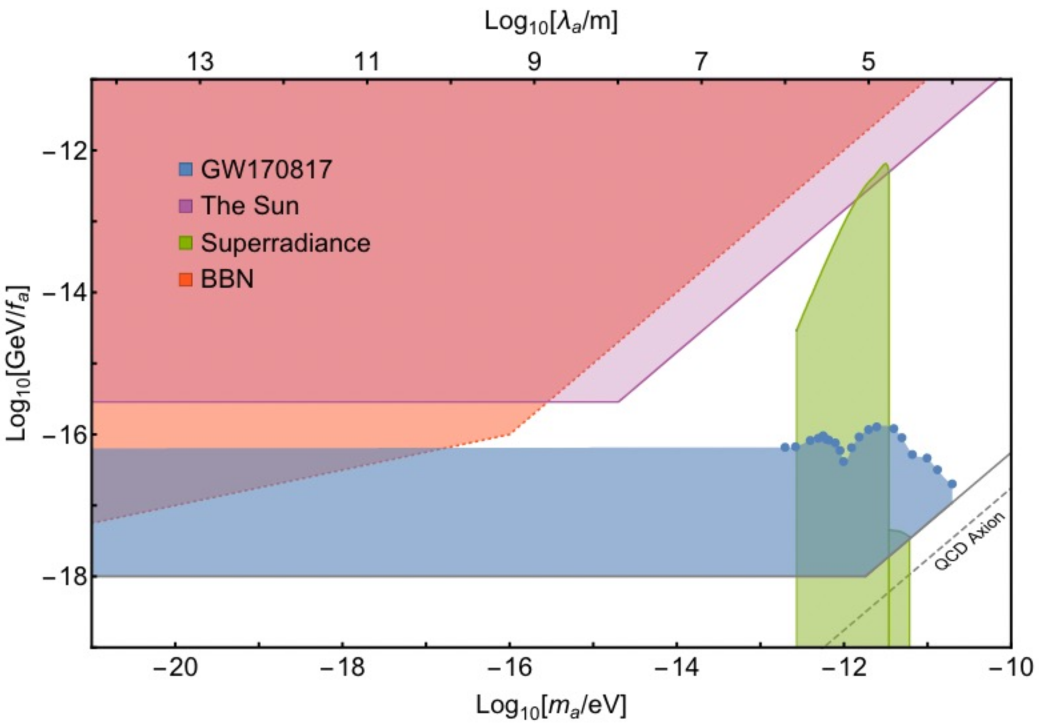
PATH 2: DIRECT DETECTION:GRAVITATIONAL WAVEFORM TEMPLATES



(Zhung et al. 2022)

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
  - Results driven by the dominating background in the LLE data & decreased effective area at high incidence angles
- Good science case for future MeV instruments
- We conduct ALP fitting to the unassociated, long, LLE-detected GRBs
- Result: No statistically significant detection in our sample
  - highly unlikely that the GRB trigger time is the same as the ALP emission time (most of the selected GRBs are well-fit by the common GRB models)
- Current work: upper-limit analysis at the time of precursor with LAT standard data & LLE
- Prospects: neutron-star mergers as excellent probes into new systems!
- Thesis defense: April 24, 2023, 2 PM @ PSC 1136 at UMD