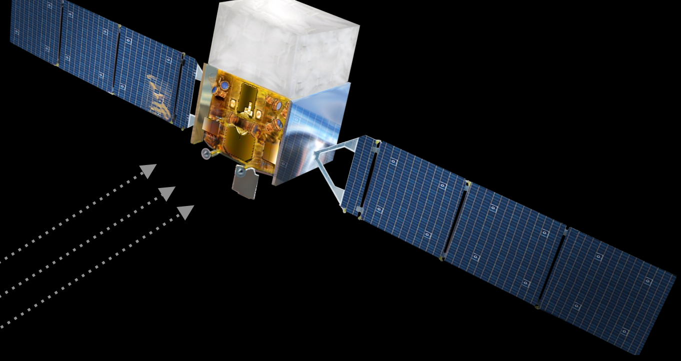
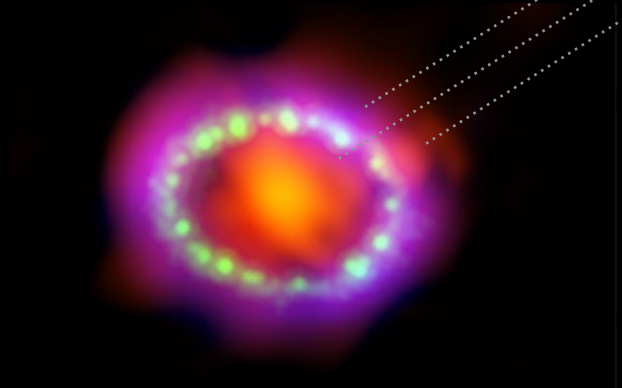
Center for Neutrino Physics Seminar Series
April 5, 2023



New Physics through a Multimessenger Lens

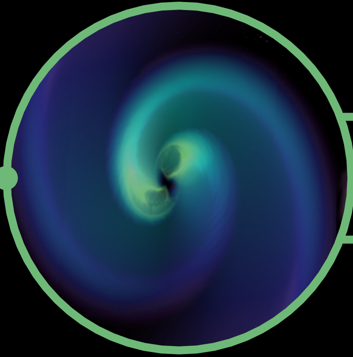
Searching for Axion-Like Particles from transient astrophysical events



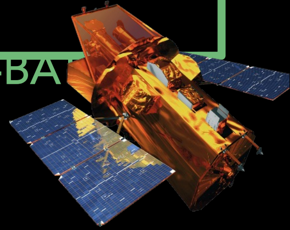
SN1987A*

Milena Crnogorčević (she/her)
University of Maryland/NASA Goddard
mcrnogor@umd.edu

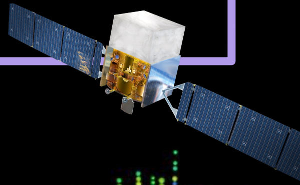
*Credit: X-ray: NASA/CXC/SAO/PSU/K.Frank et al.; Optical: NASA/STScI; Millimeter: ESO/NAOJ/NRAO/ALMA

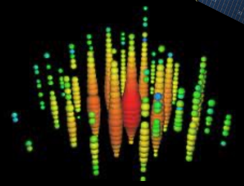


Searching for GRB Counterparts to Gravitational-wave
Events from O3 with Fermi-GBM and Swift-BA



Cross-correlation study between the *Fermi*-LAT UGRB
and the IceCube neutrino events





Happening now!

Milena Crnogorčević (she/her)
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mcrnogor.github.io

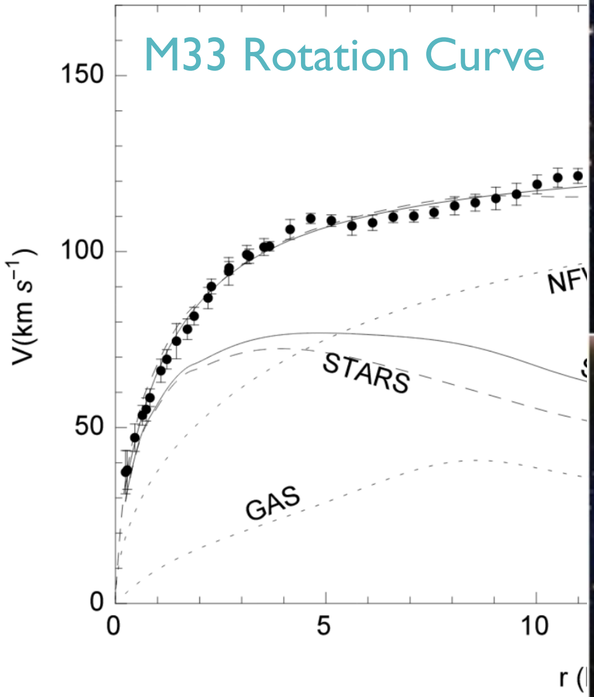
TALK OUTLINE

- Axion-like particles: Introduction and motivation

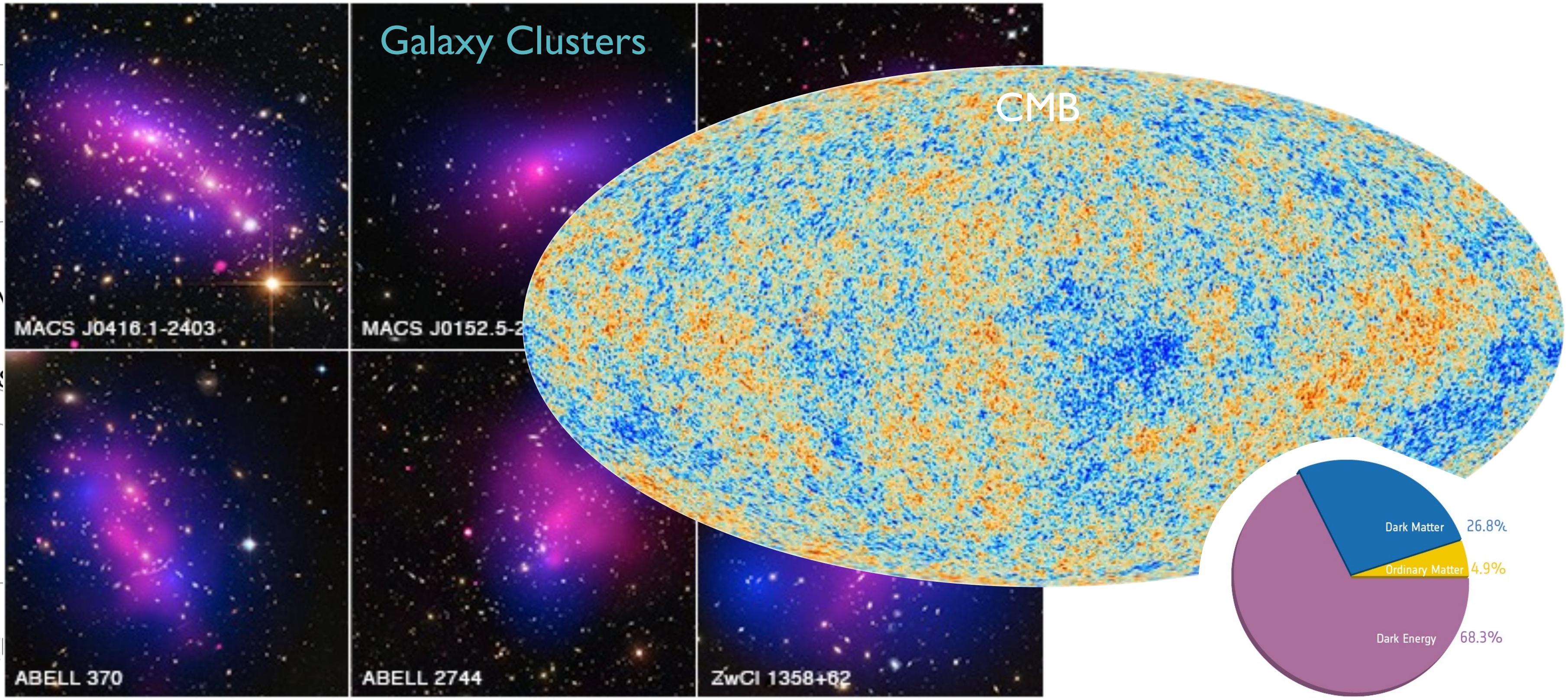
1. *Fermi*-LAT Low Energy Technique: Sensitivity study
2. Sensitivity of the future MeV instruments
3. Gamma-ray Bursts as ALP factories: what has *Fermi* seen so far?
4. Fermi-*LAT* GRB pre-cursor analysis
5. Prospects: neutron-star mergers?

- Conclusions

OVERWHELMING EVIDENCE FOR THE EXISTENCE OF DARK MATTER

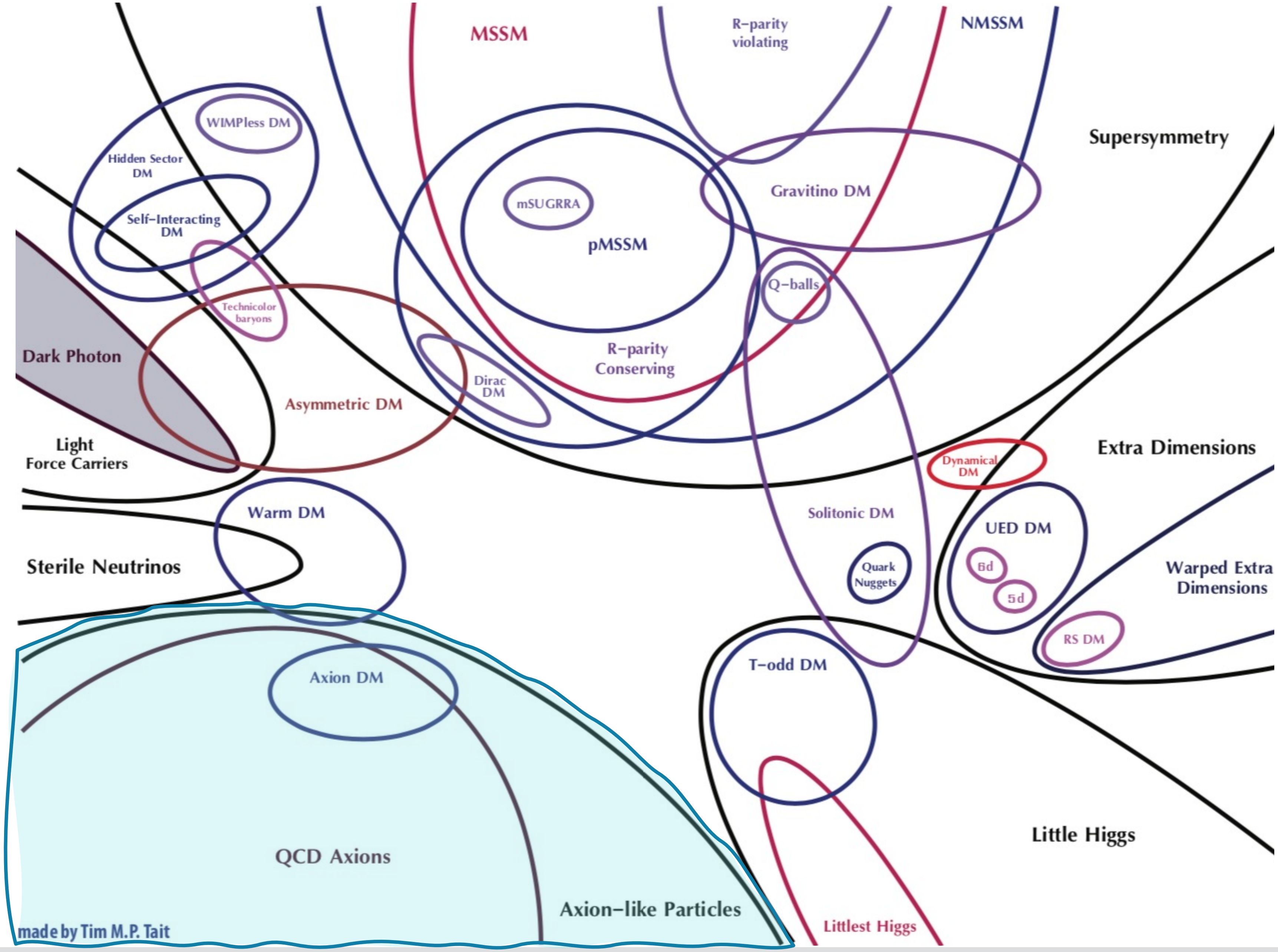


X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D.Harvey & NASA/CXC/Durham Univ/R.Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)



European Space Agency and Planck Collaboration

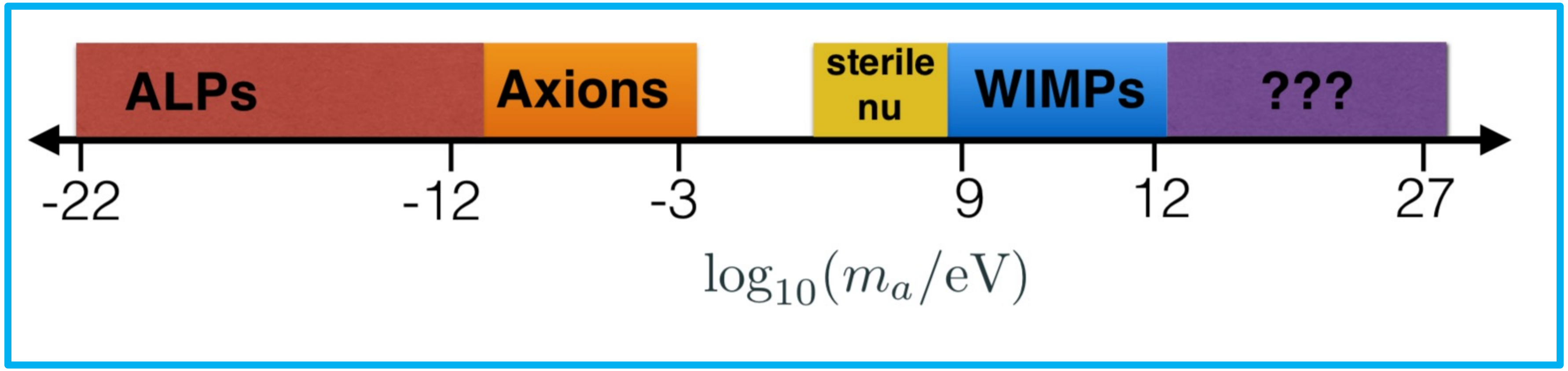
THE PARTICLE NATURE OF DARK MATTER



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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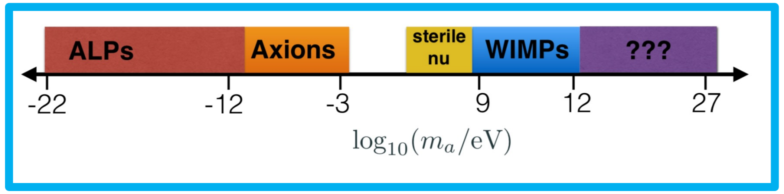
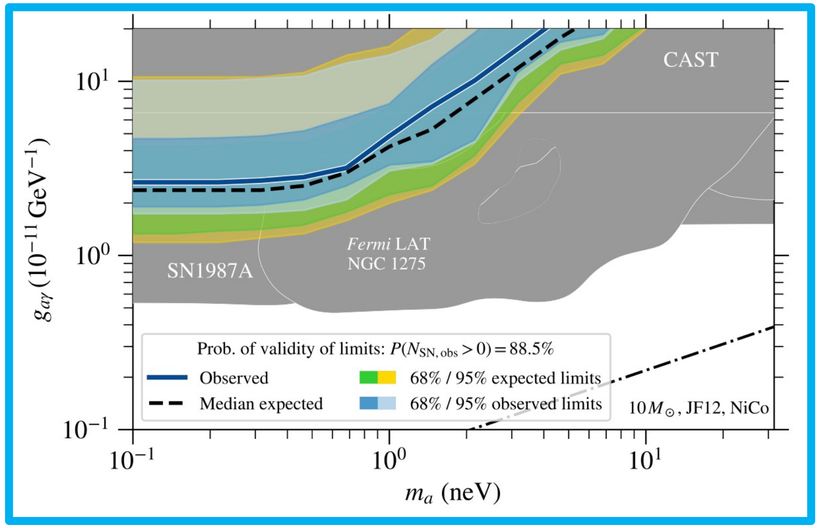


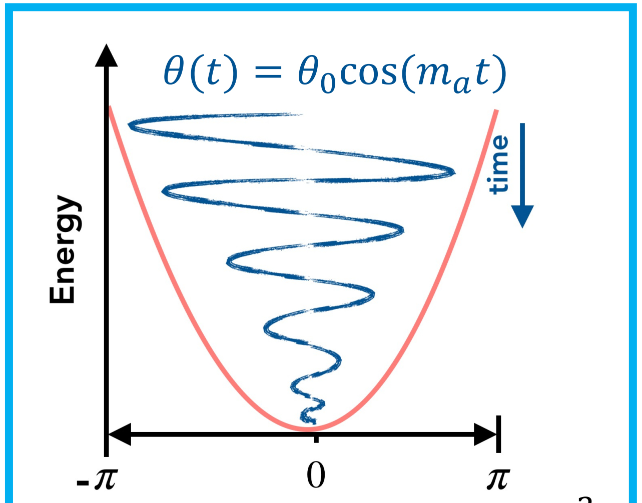
- Cold matter requirements:
  - ✓ feeble interactions with standard model particles
  - ✓ cosmological stability

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

- **Non-thermal** production of ALPs via ***misalignment mechanism*** or inverse ***Primakoff process***

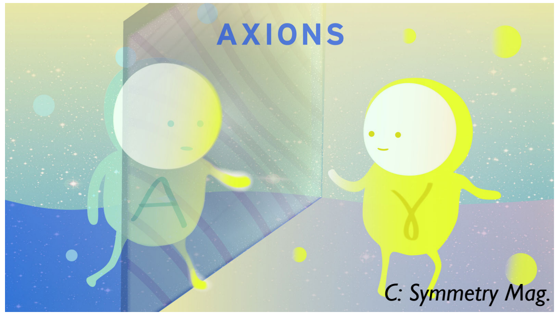


Exclusion plot for ALPs. [Meyer & Petrushevska 2020]



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

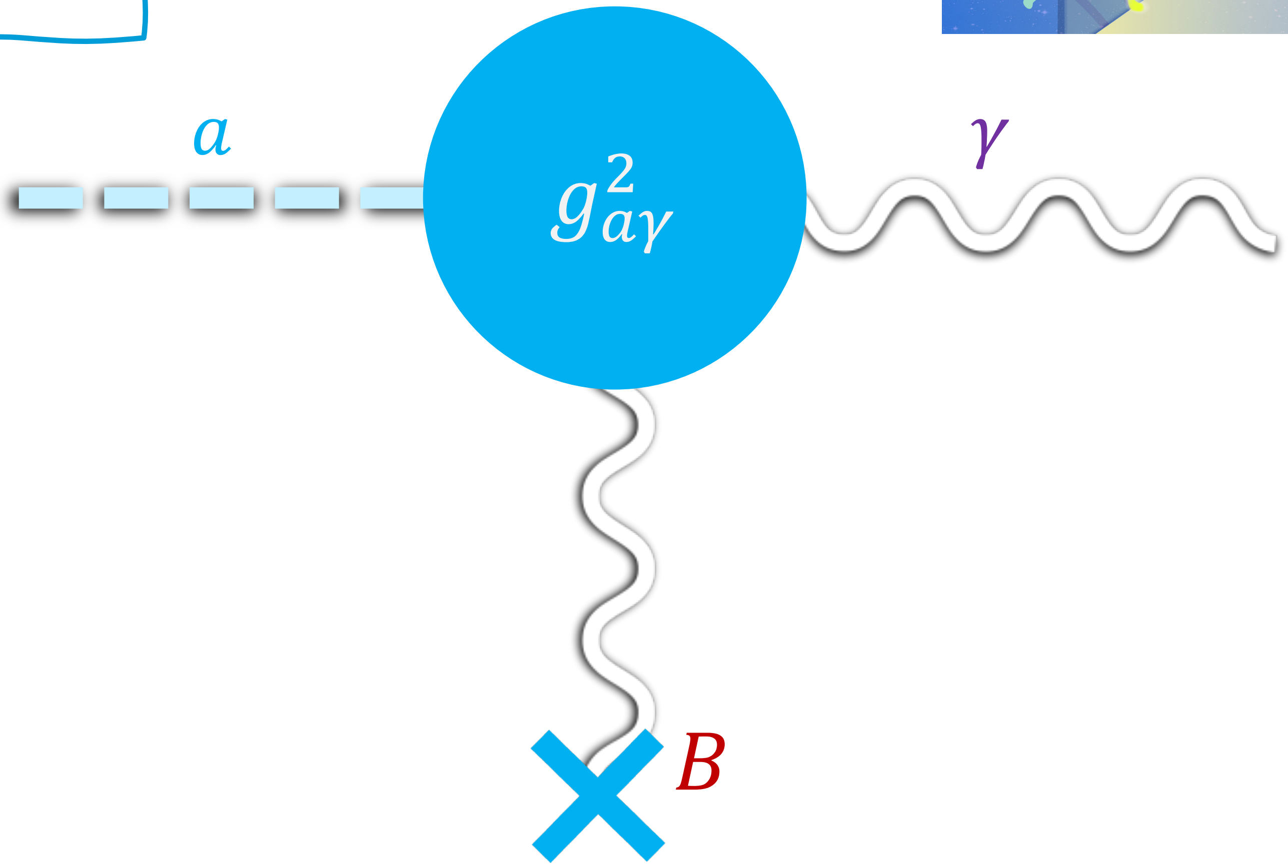
Observing ALPs with γ rays



- $\boxed{\textbf{Primakoff process:}\text{ converting ALPs into}}$ photons
  - In the presence of an external magnetic field, **B**, ALPs undergo a conversion into gamma-rays:

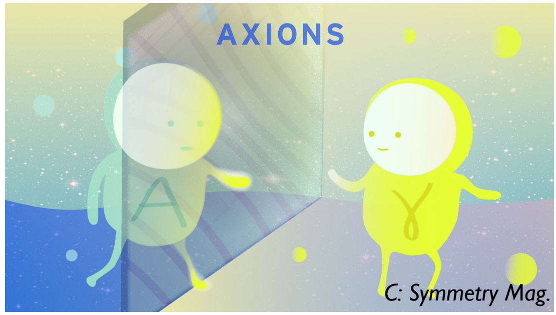
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} \, \mathbf{E} \cdot \mathbf{B} \, a$$

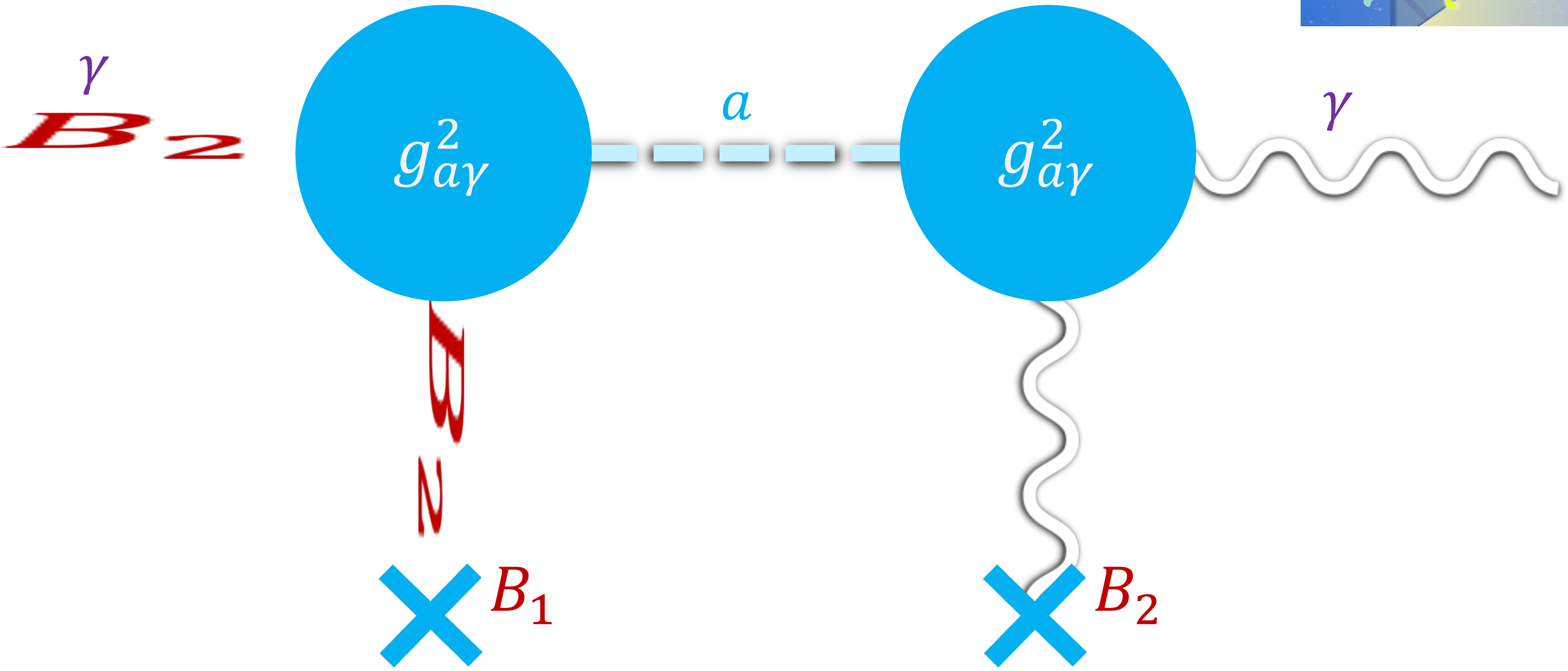
where $g_{a\gamma}$ is ALP-photon coupling rate, and a is the axion field strength.



[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

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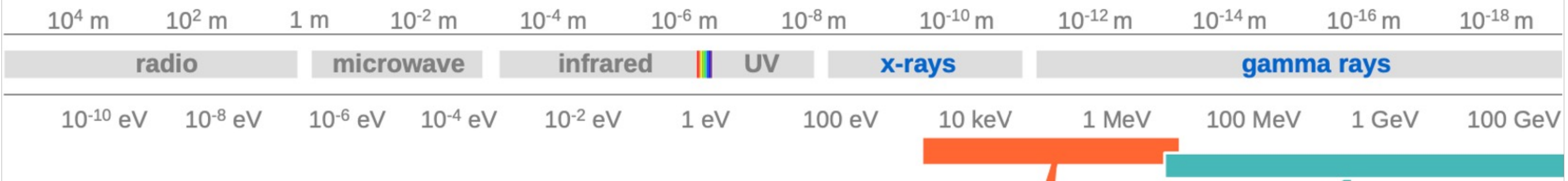
HOW FAR CAN FERMI SEE?

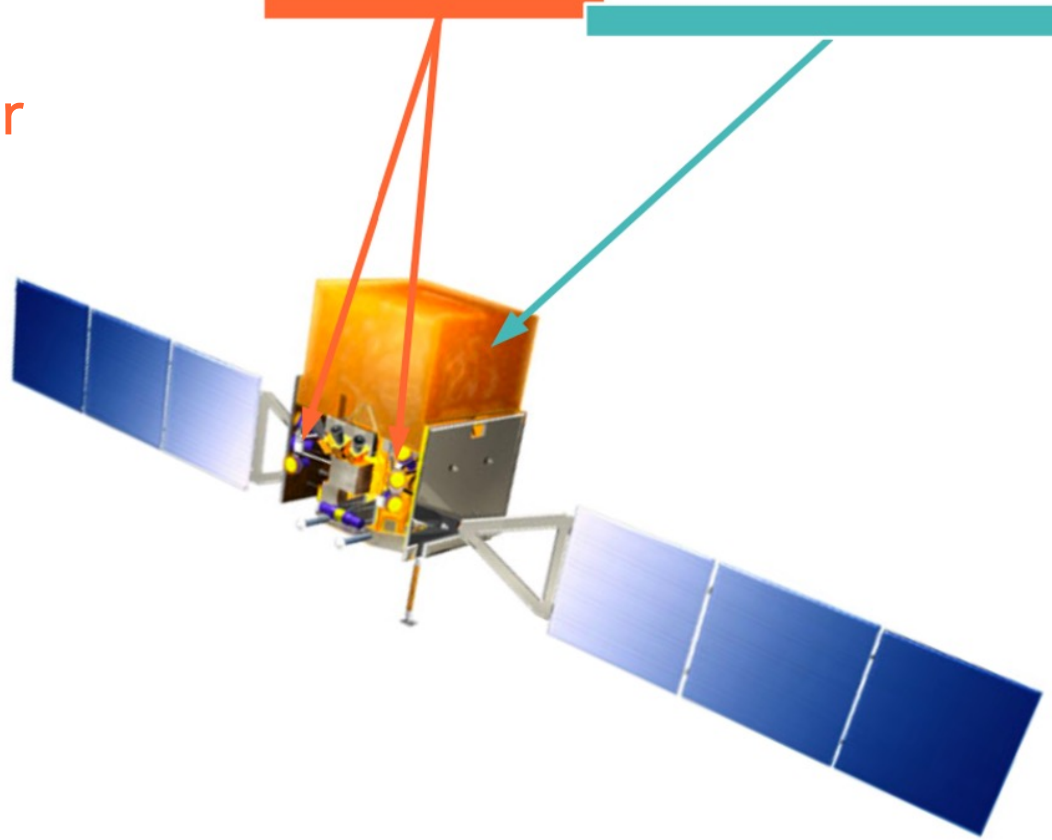
Axion-like Particles from Core-collapse Supernovae: Investigating *Fermi* Sensitivity with the LAT Low-energy Technique

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



GBM Gamma-ray Burst Monitor

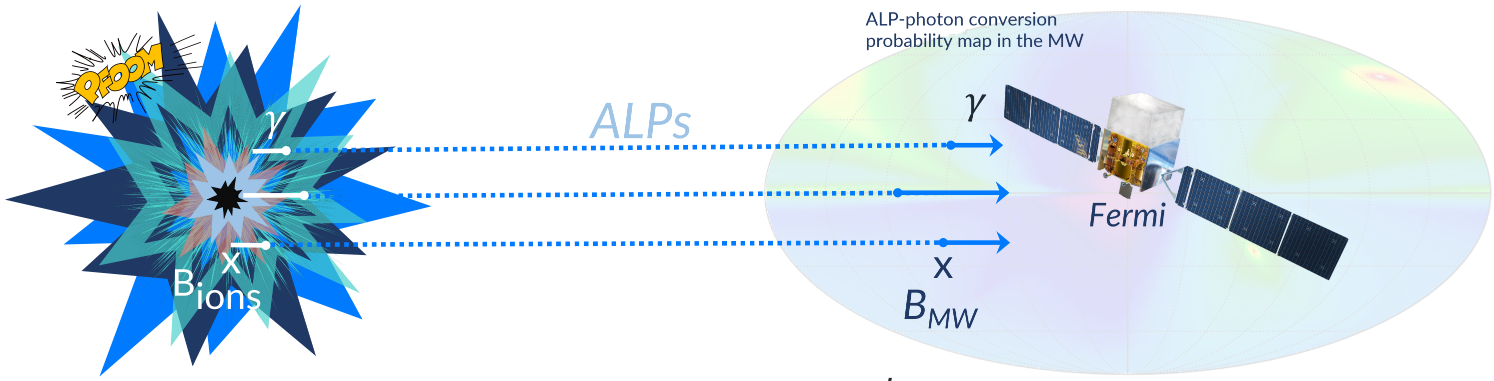
12 (NaI) + 2 (BGO) detectors
FoV: entire unocculted sky
8 keV to 40 MeV
~1500 bursts (~1 every day or two)



LAT Large Area Telescope

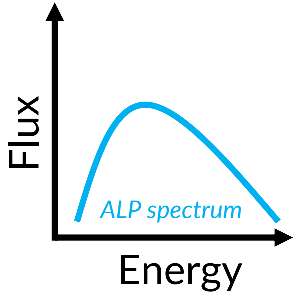
Pair-production telescope
FoV: 2.4 sr (~20% of sky)
20 MeV to >300 GeV

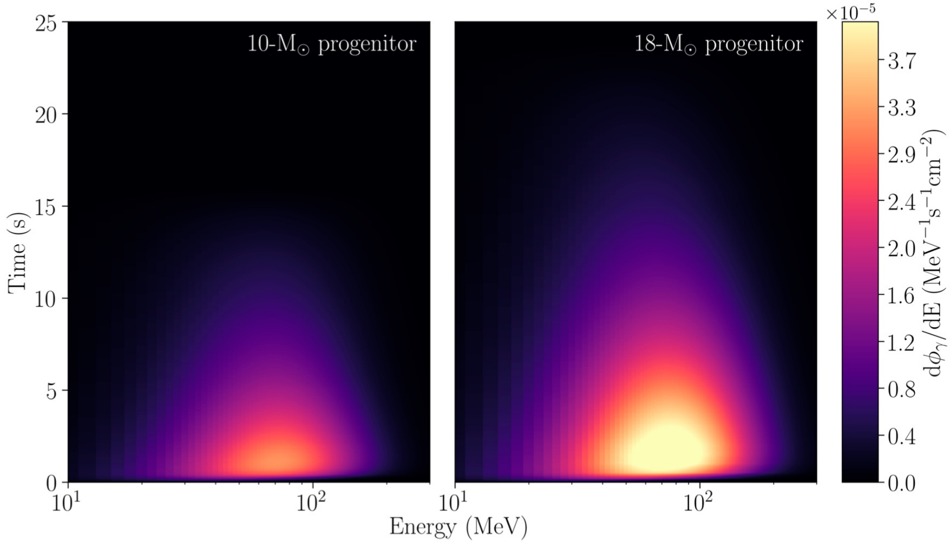
Motivation and assumptions



Primakoff Process
inside the CCSN core

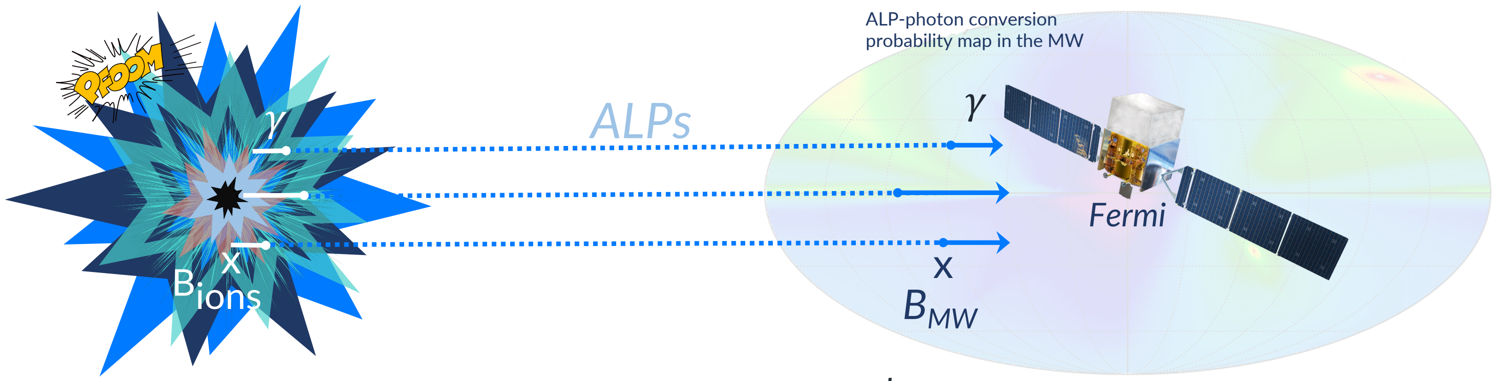
Inverse Primakoff Process
in the MW B-field





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 and assumptions



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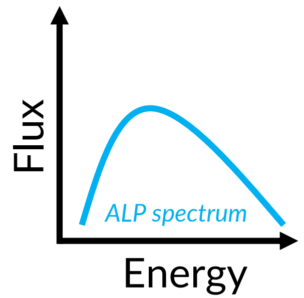
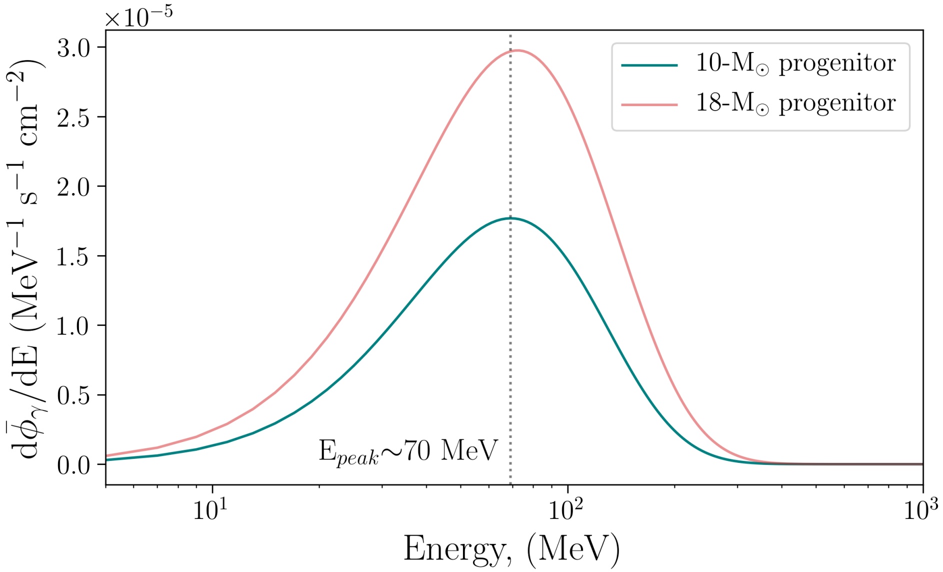
Inverse Primakoff Process in the MW B-field

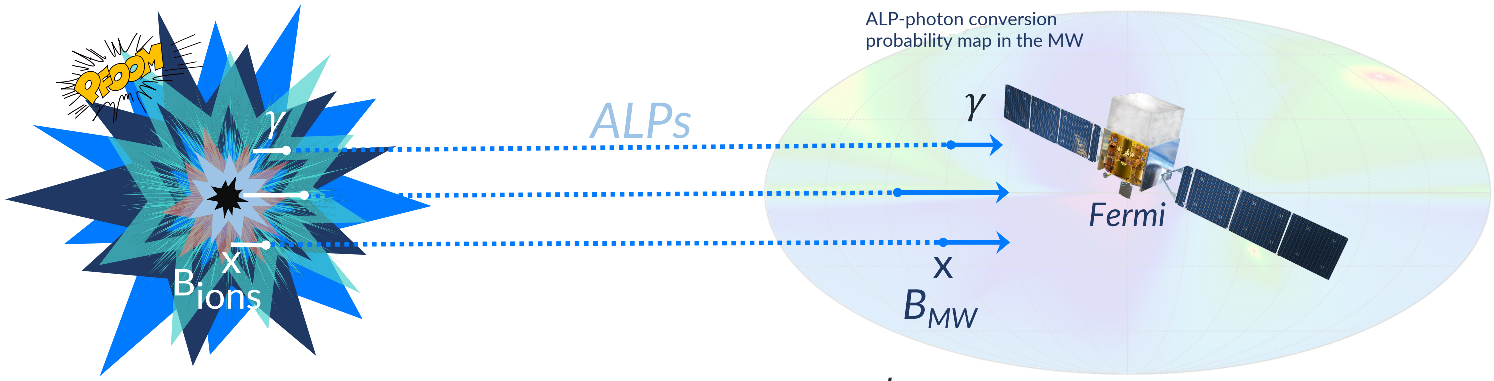


- **Motivation:** ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.



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

Motivation and assumptions



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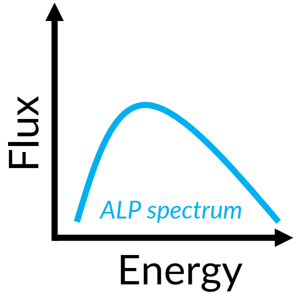
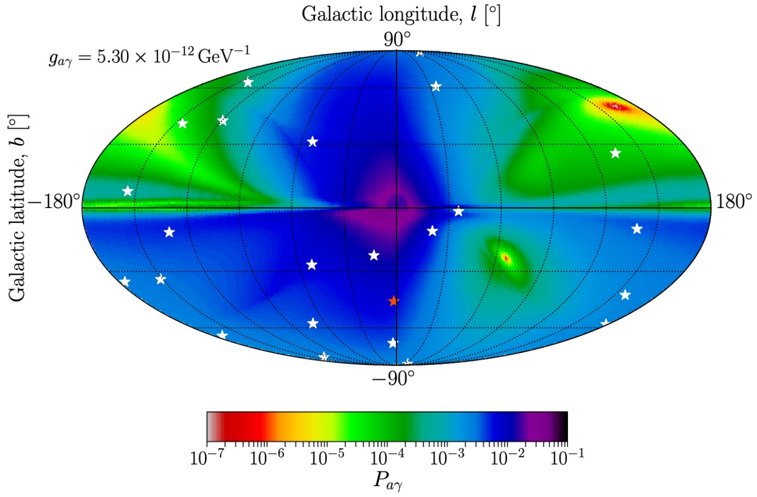
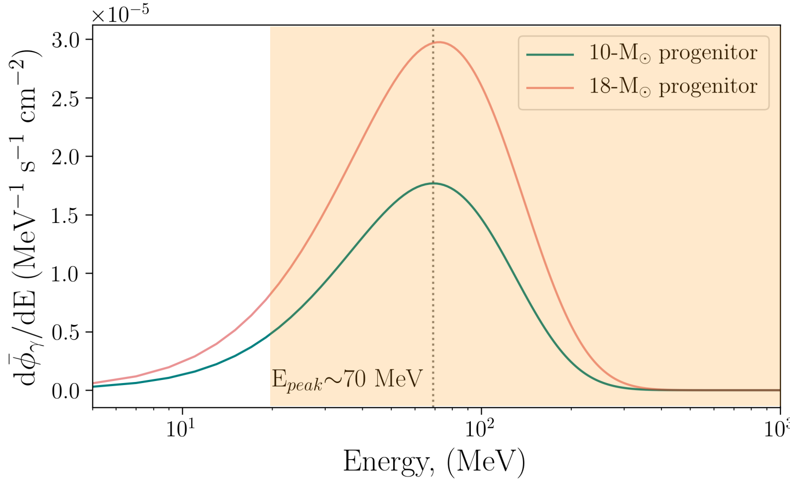


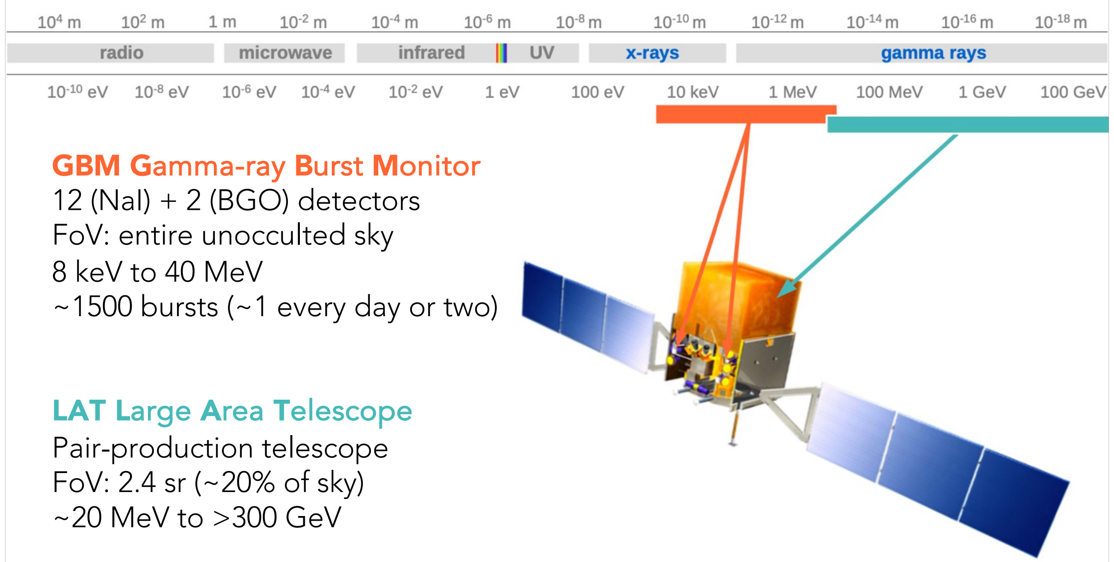


ALP-photon conversion probability map in the Milky Way's magnetic field.

- **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

ALP spectrum





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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

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.

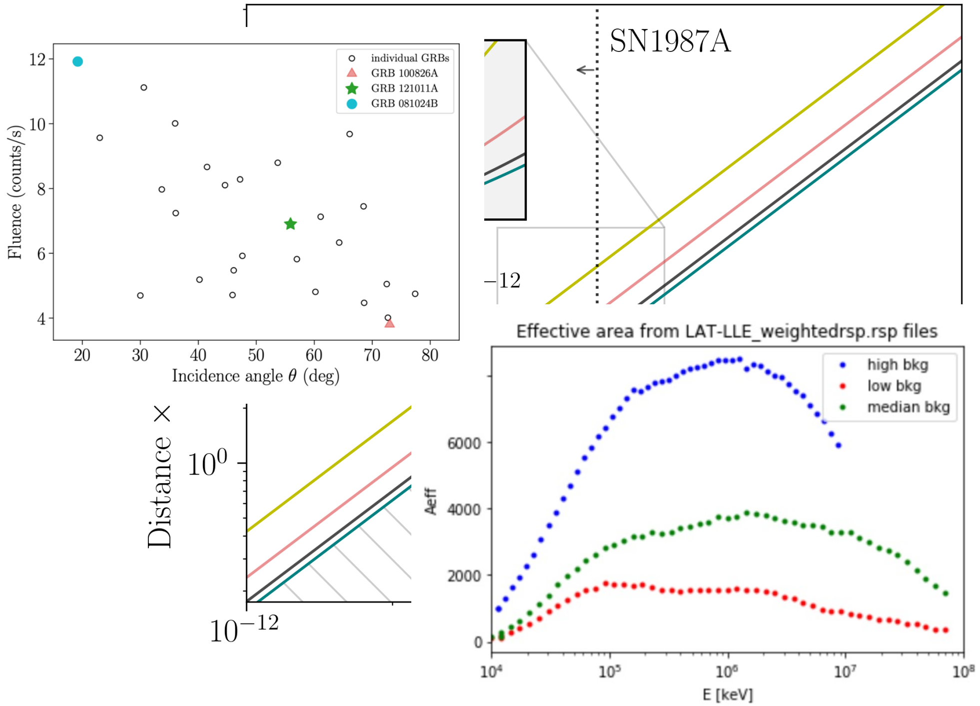
Produce ALP signal normalized by a value from the normalization grid for 10-and 18-solar-mass progenitors.

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.

$$N \propto 1/d^2$$



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)

RESULTS I. *HOW FAR CAN FERMI SEE?*

- **Tools:** a developed pipeline for calculating distance limits for the current and future gamma-ray instruments for the given ALP mass and coupling
- **Novel results:** using a transient data class as observed by *Fermi* to probe its sensitivity. Results are consistent with the analysis using the standard LAT data [Meyer et al. 2016].
- **Good scientific case for the future instruments:** they need more sensitivity in the MeV region in order to be able to increase the statistics of sources considered

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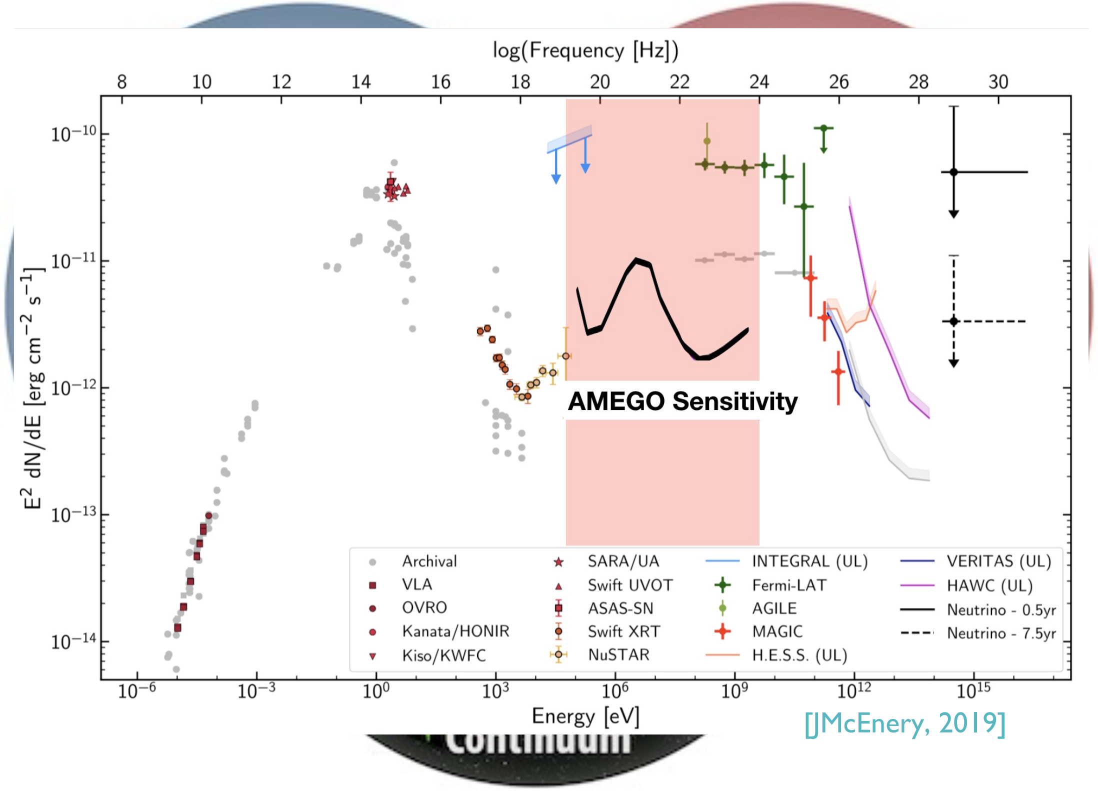
ADDITIONAL CONSIDERATION

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)

Quick factsheet about AMEGO:

- Probe-class mission concept
- High-sensitivity (200 keV – 10 GeV)
- Wide FoV, good spectral resolution, polarization
- Multimessenger astronomy (NS mergers, SNe, AGN)
- Order-of-magnitude improvement compared to previous MeV missions



[JMcEnery, 2019]

ADDITIONAL CONSIDERATIO

ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY

Additional considerations: All-sky Me sensitivity analysis; motivation outlined the [Snowmass 2021 Letter] gorčević)

- For a 10-solar mass progenit

levels comparable to LAT in the l

Distance lim

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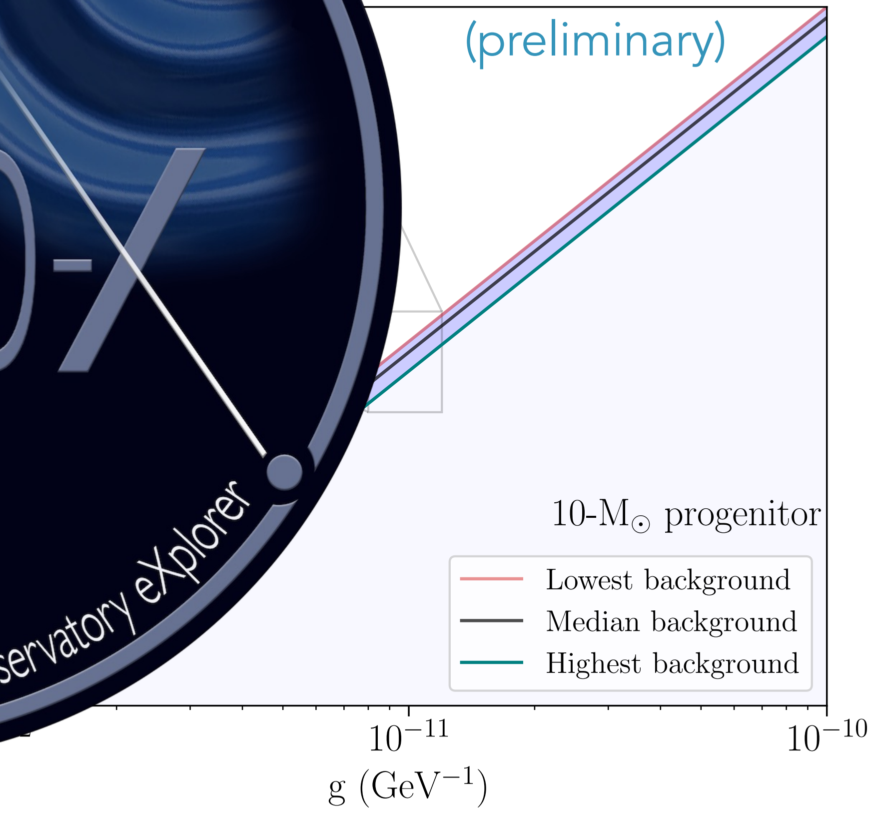

All-sky Medium Energy Gamma-ray Observatory eXplorer

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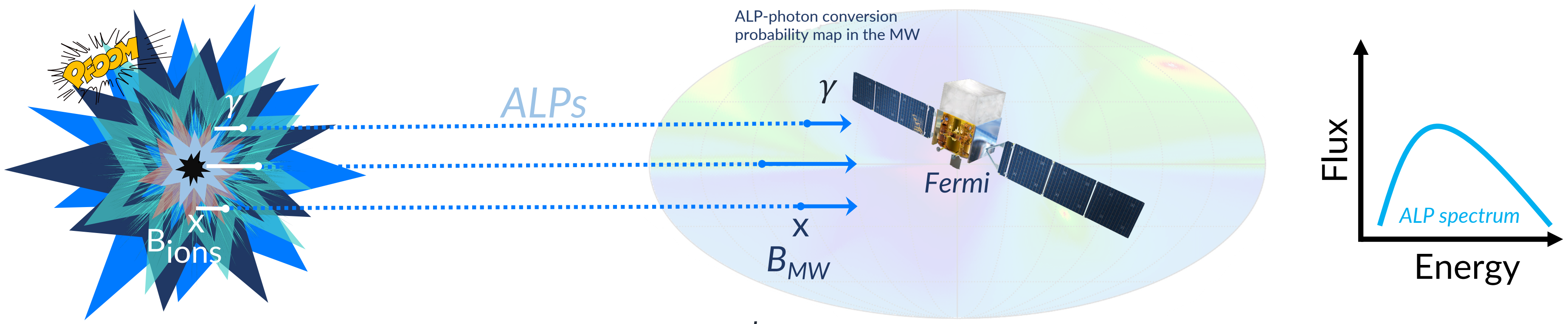


Primakoff Process
inside the CCSN core

Inverse Primakoff Process
in the MW B-field

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)

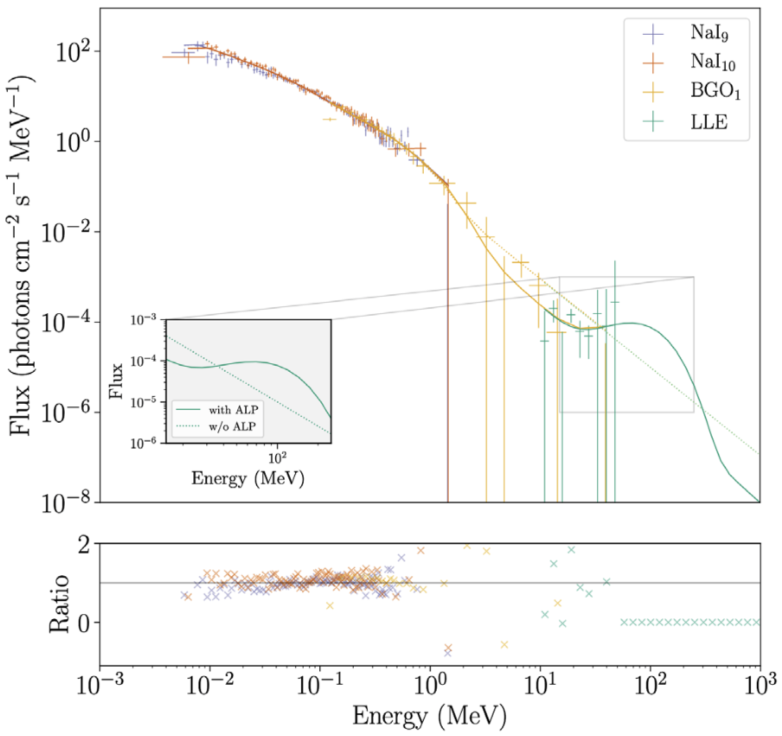
Initial sample: 186 LAT-detected GRBs

Applying the selection criteria

24 GRBs

GRB analysis

			grbm parameters			
GRB	T_{95} (s)	Best model(no ALP)	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

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- Conclusions

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)

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**

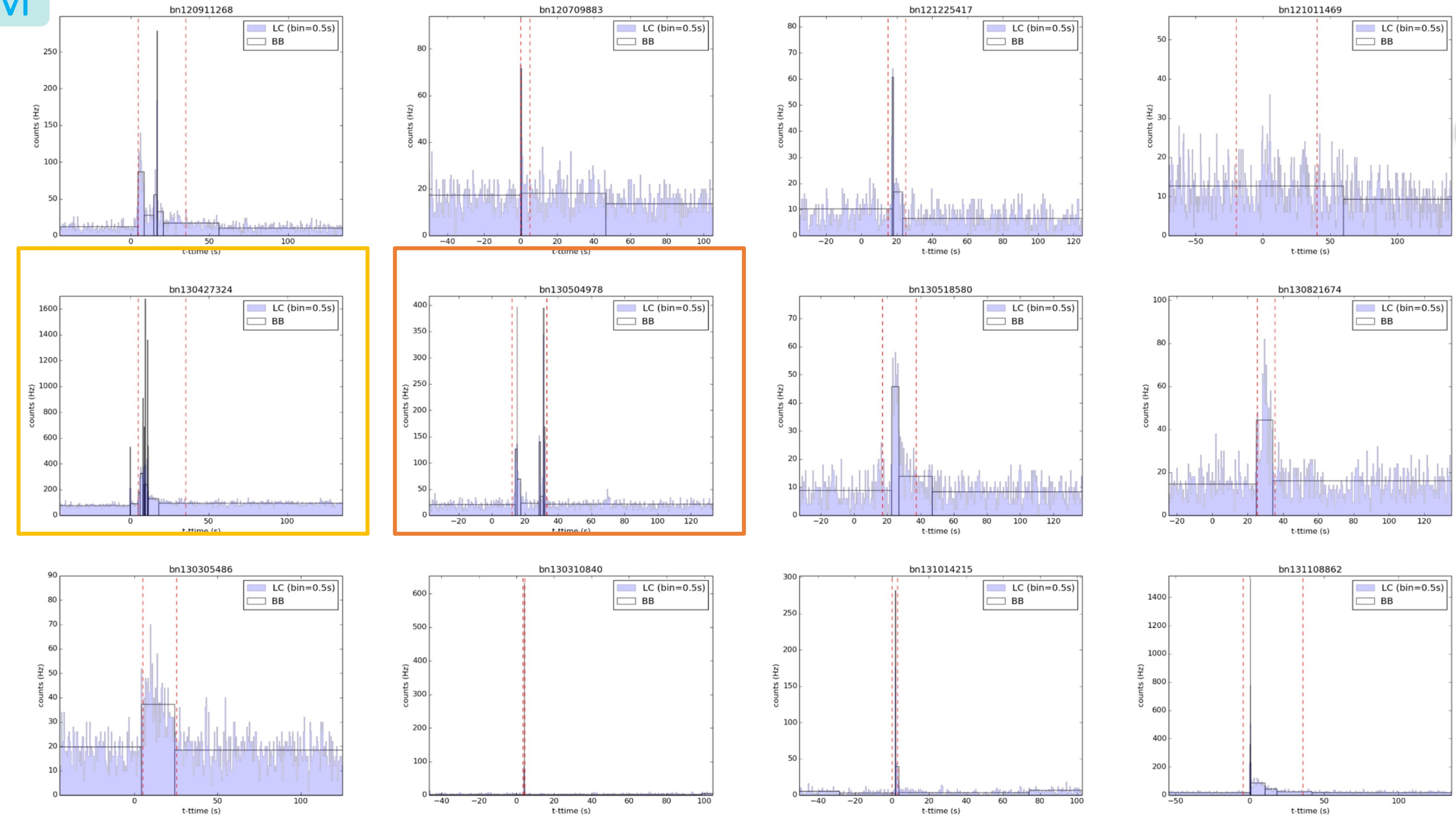
→ Method introduced in [Crnogorčević et al. 2021] using a sample of LAT-detected GRBs. No significant (5 σ) detections reported

→ A study of GBM/LAT bursts with precursor emission: a systematic search for ALP excess in targeted time windows *before* presumed gamma-ray jet emission

Example trial runs

(Note that all the following plots are in the [T_0 +/- 1000 s])

GBM

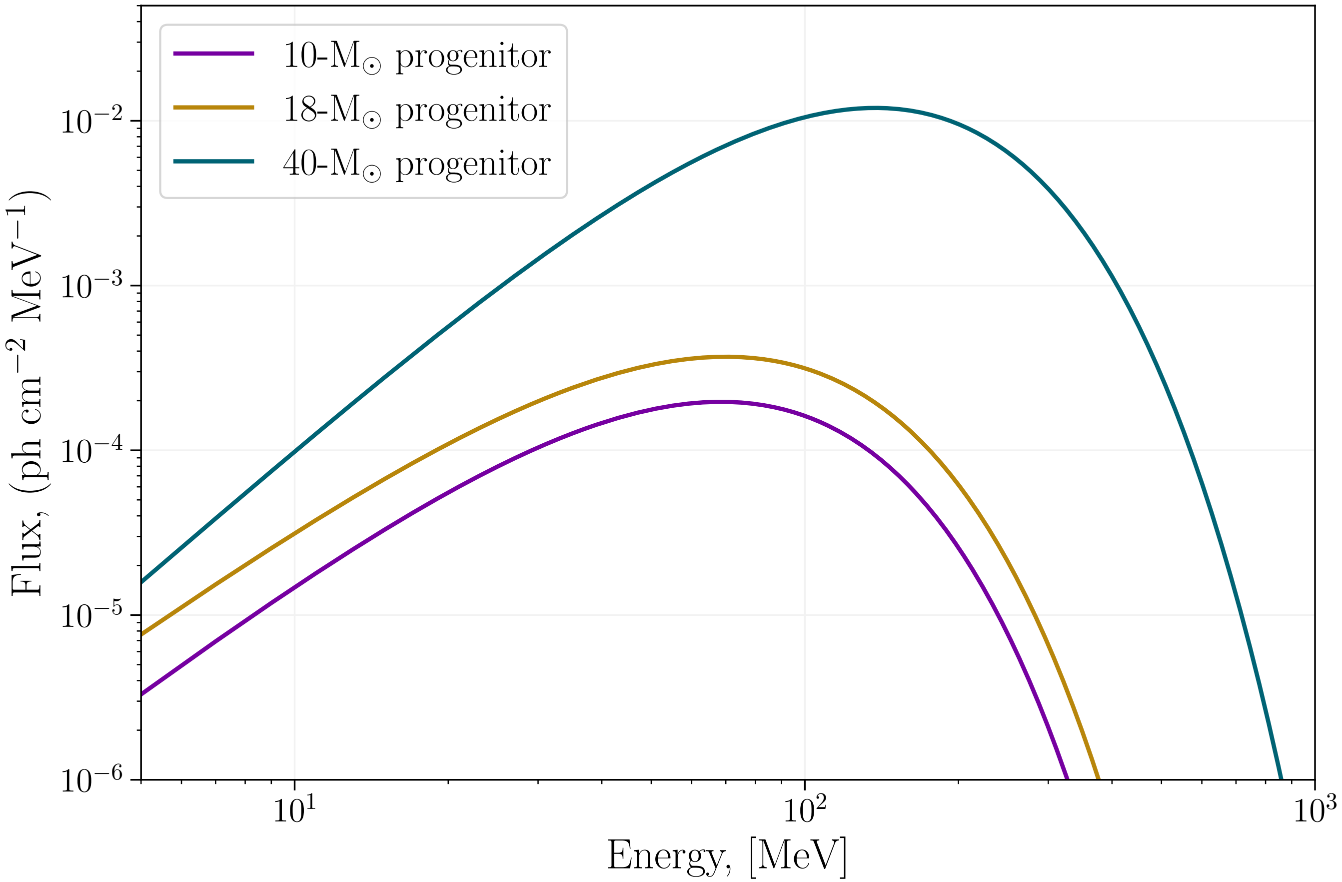


preliminary

	# of GRBs with a precursor
GBM	56 (up to 2018)
LAT (standard)	13 (up to 2023)
LLE	7 (up to 2023)

ALP model for a 40-solar mass progenitor

	# of GRBs with precursor
GBM	132 (?)
LAT (standard)	13
LLE	7



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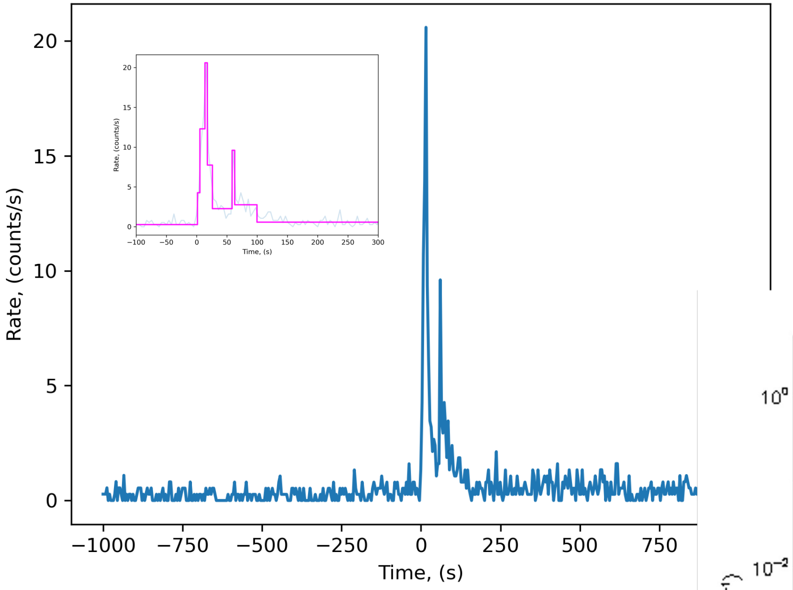

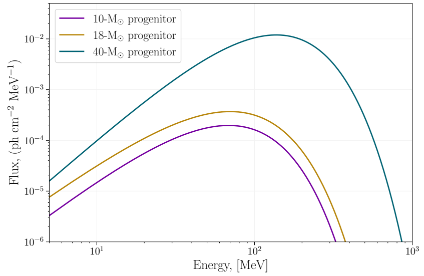

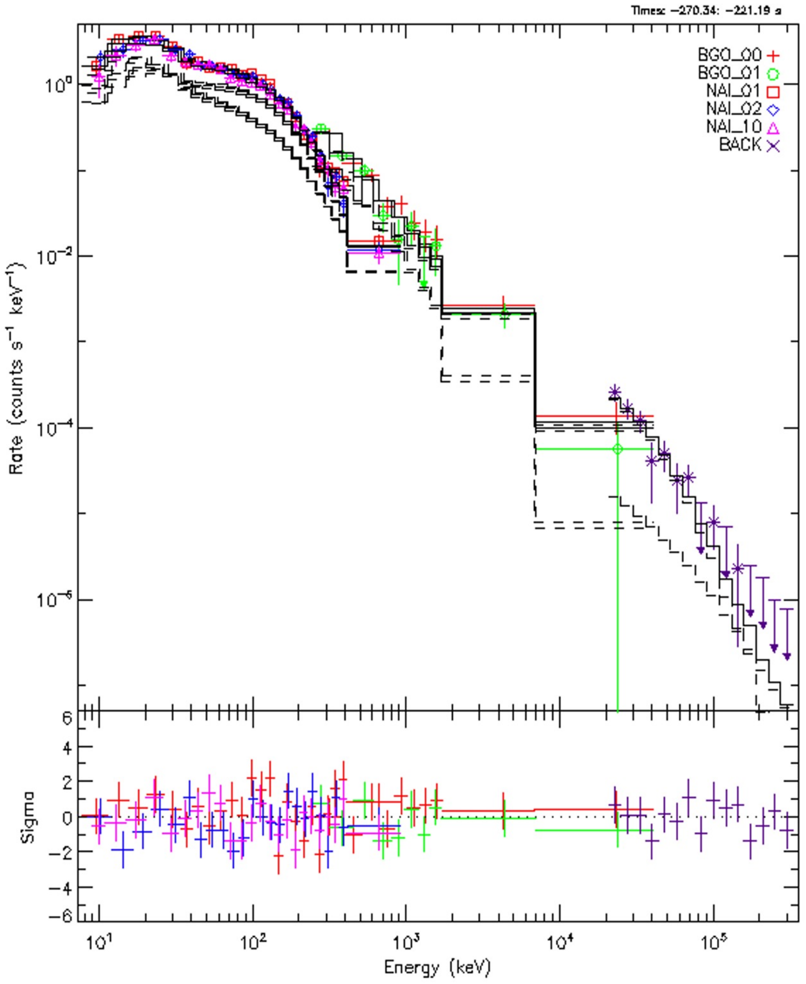

preliminary

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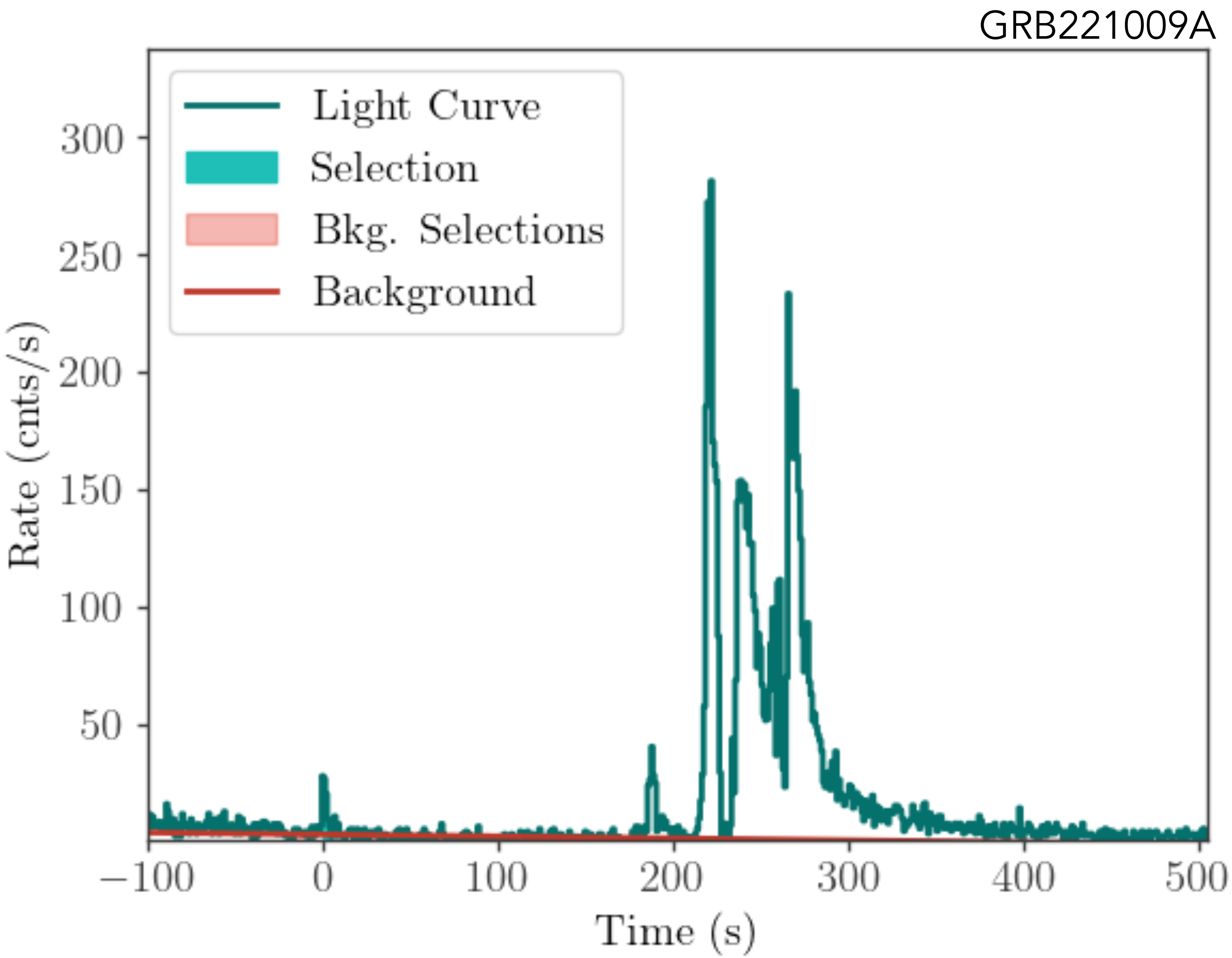

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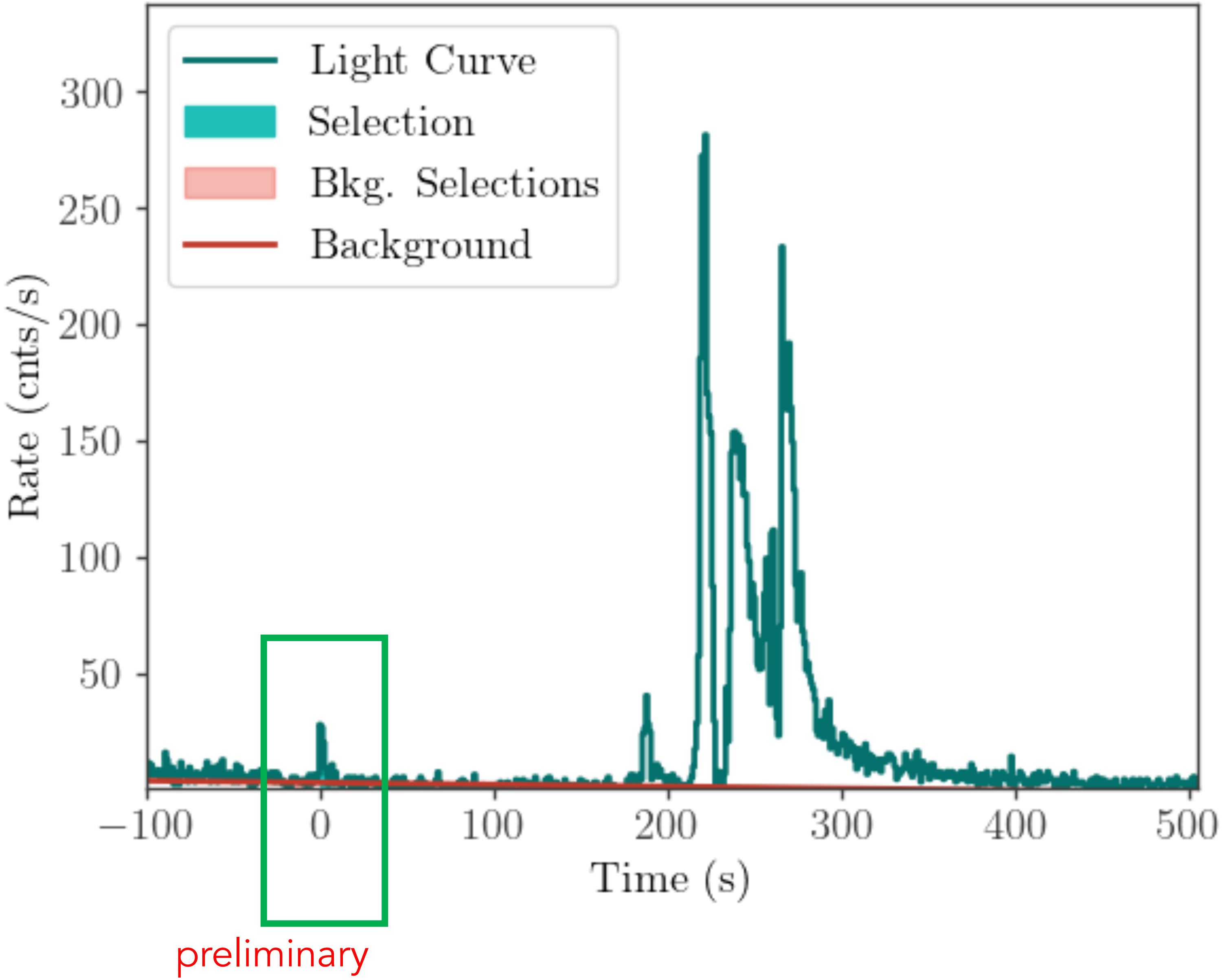
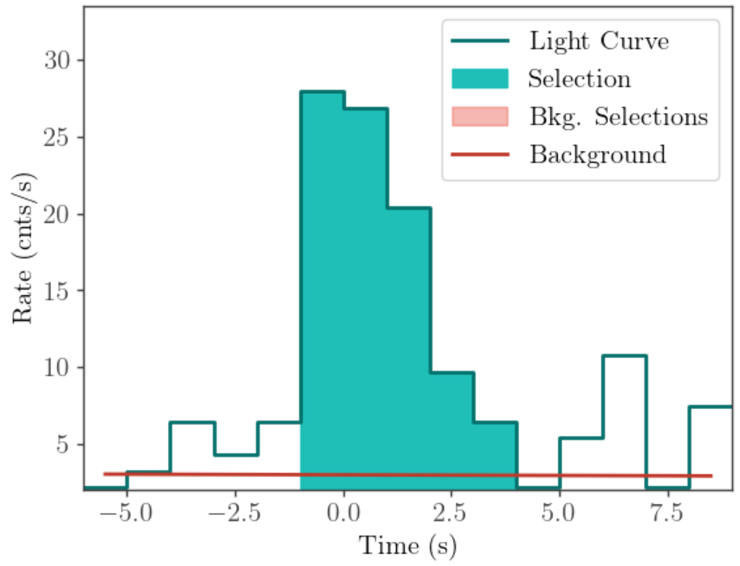
GRB221009A





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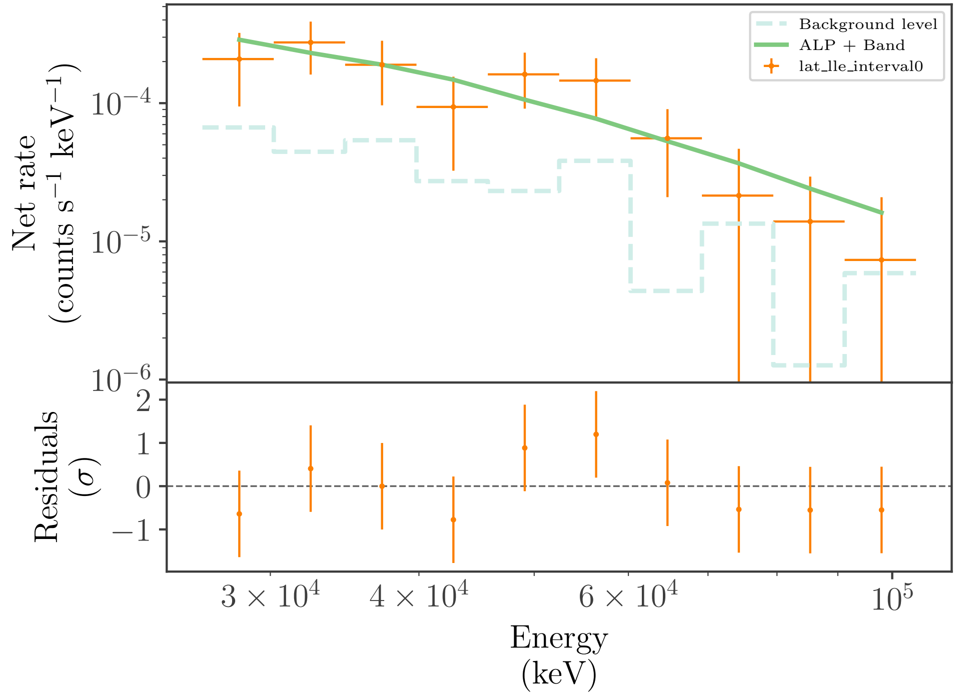

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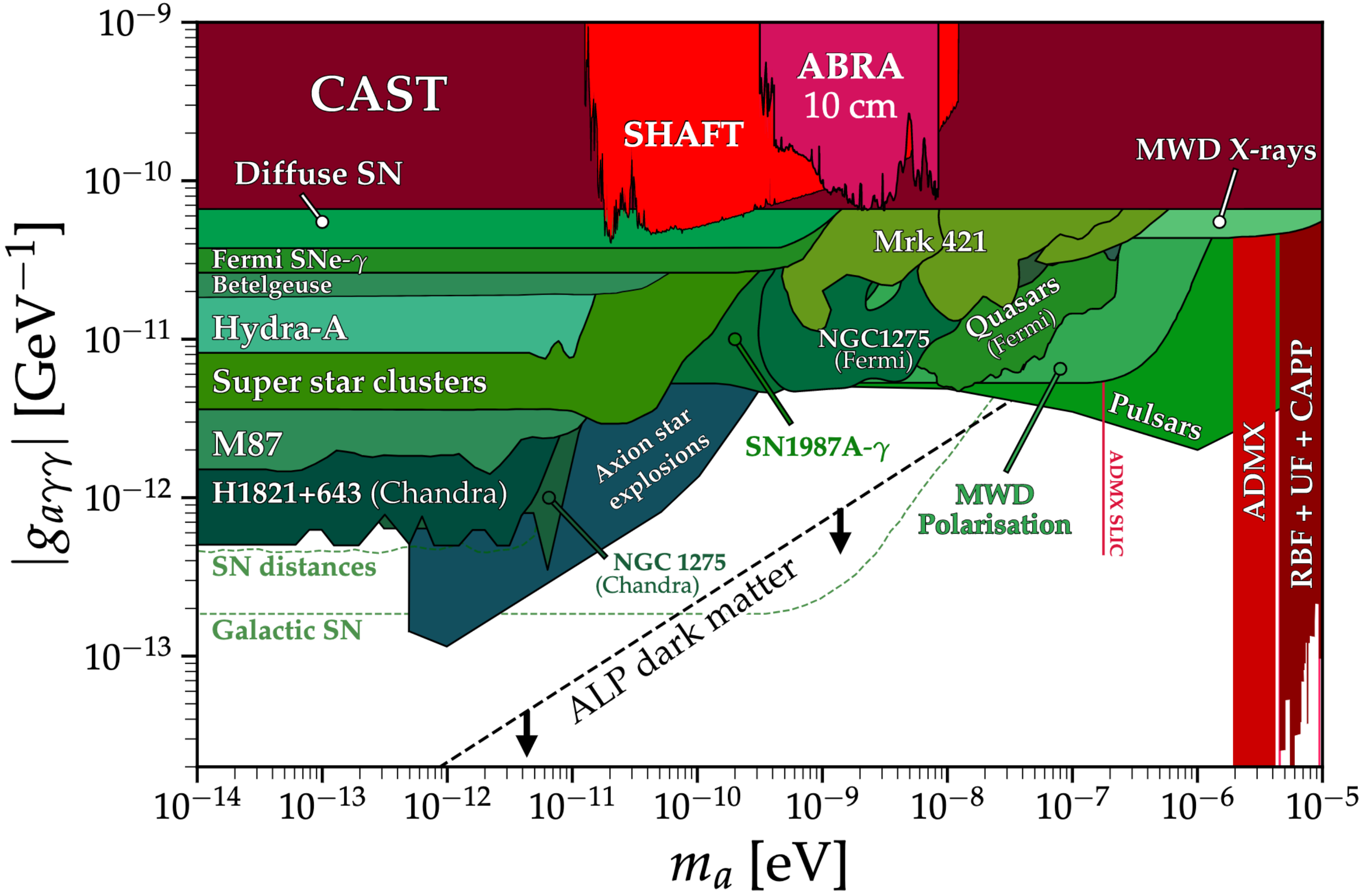

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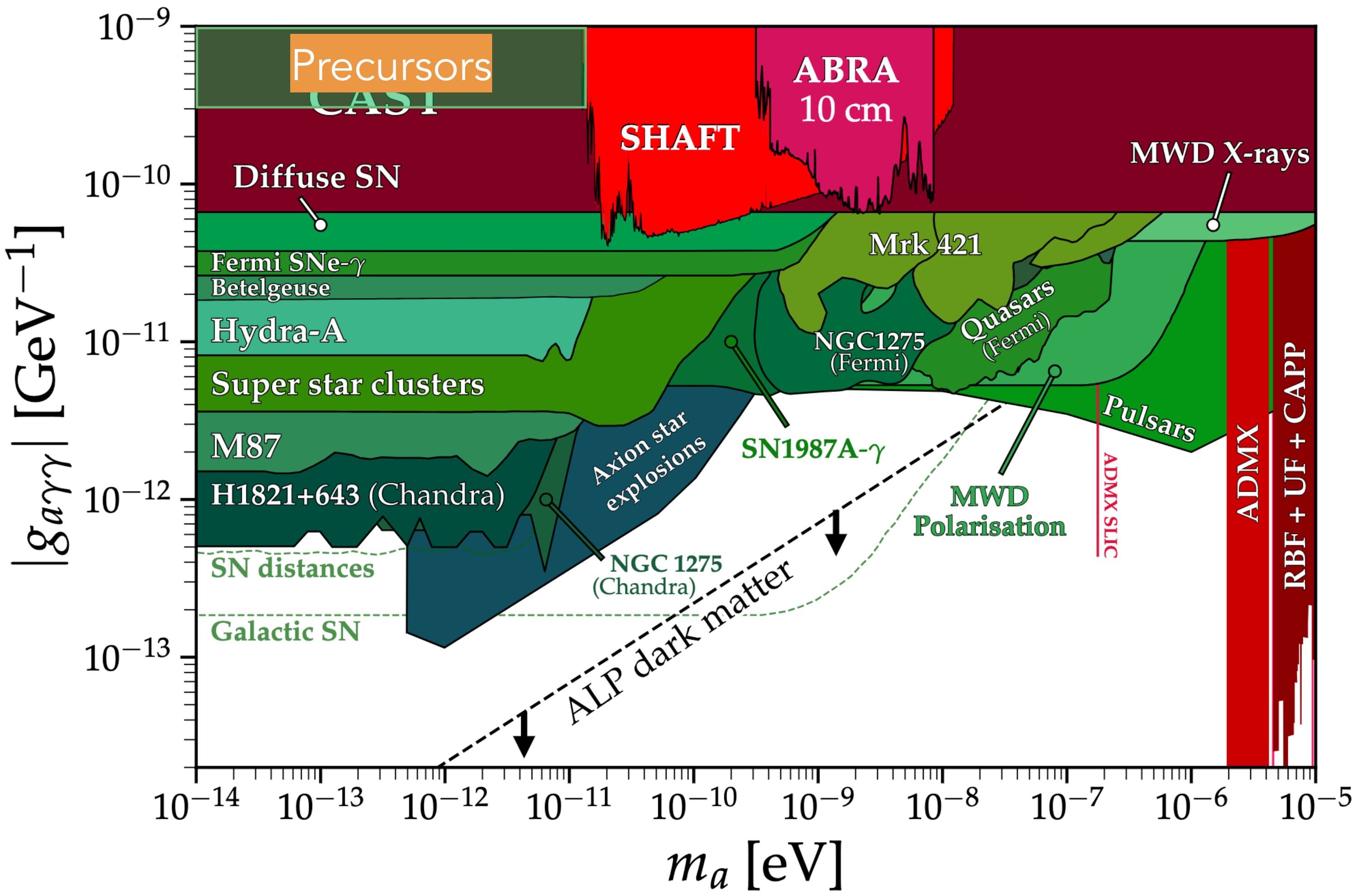


preliminary

TALK OUTLINE

- Axion-like particles: Introduction and motivation

1. *Fermi*-LAT Low Energy Technique: Sensitivity study
2. Sensitivity of the future MeV instruments
3. Gamma-ray Bursts as ALP factories: what has *Fermi* seen so far?
4. Fermi-*LAT* GRB pre-cursor analysis
5. **Prospects: neutron-star mergers?**

- Conclusions

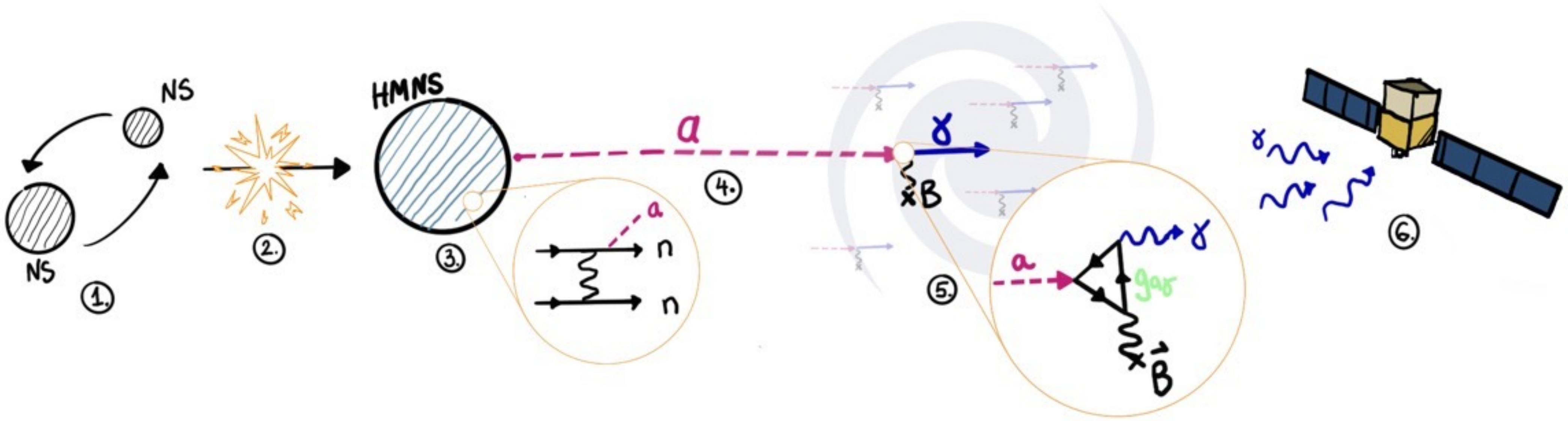
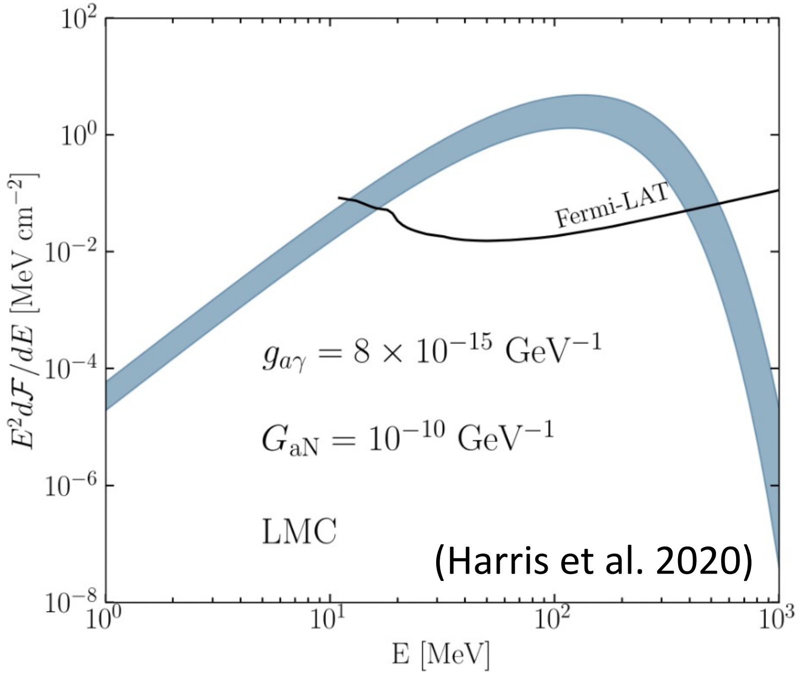


Figure description: (1) Two neutron stars (NS) orbit each other until the (2) merger, followed by (3) the formation of a hypermassive neutron star (HMNS). There, ALPs are produced via the neutron-neutron bremsstrahlung process. Once produced, ALPs travel undisturbed (4), until they reach the magnetic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

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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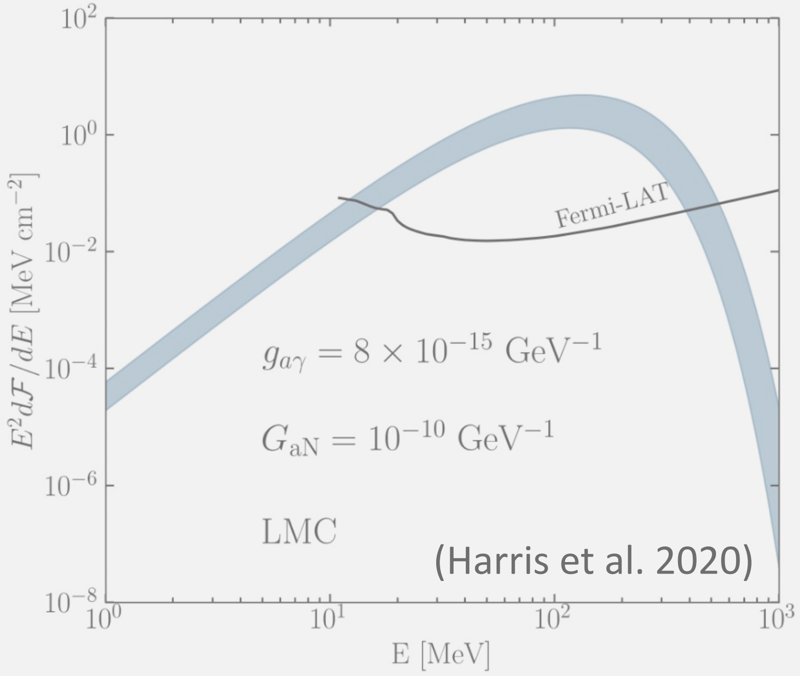
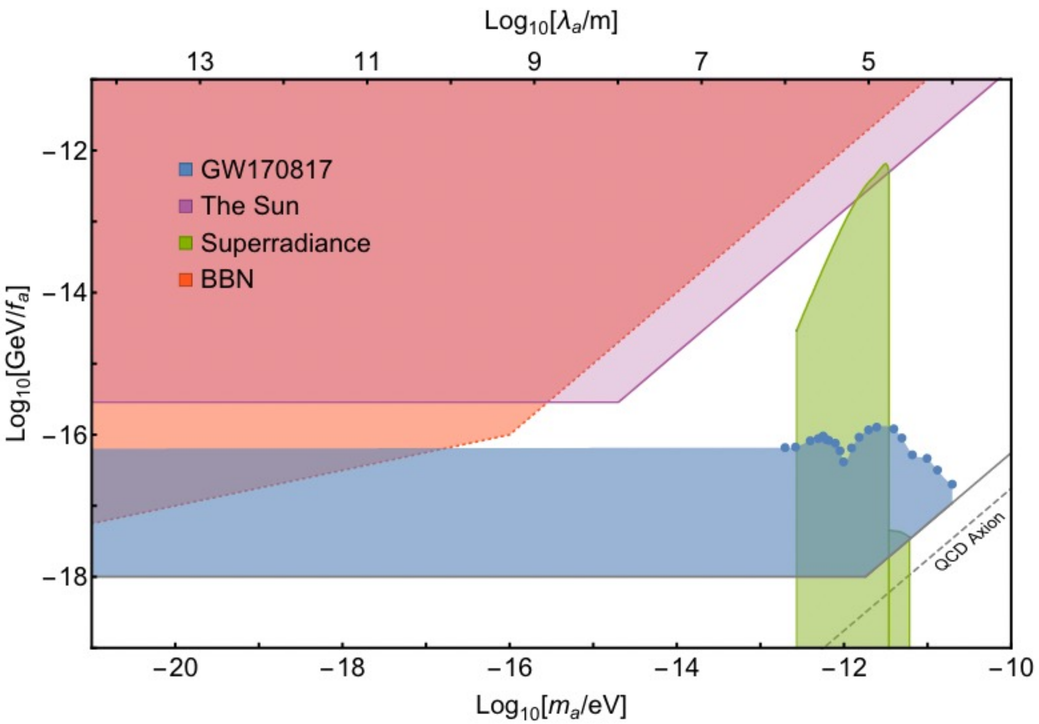


(Harris et al. 2020)

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

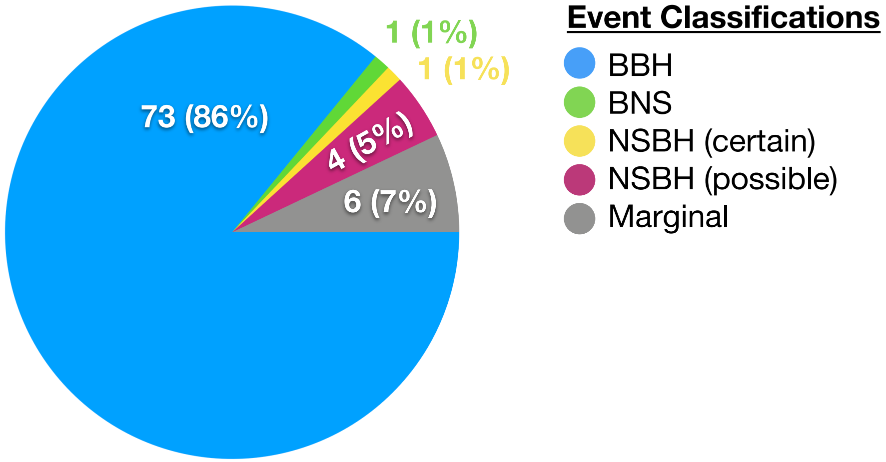
PATH 2: DIRECT DETECTION:GRAVITATIONAL WAVEFORM TEMPLATES

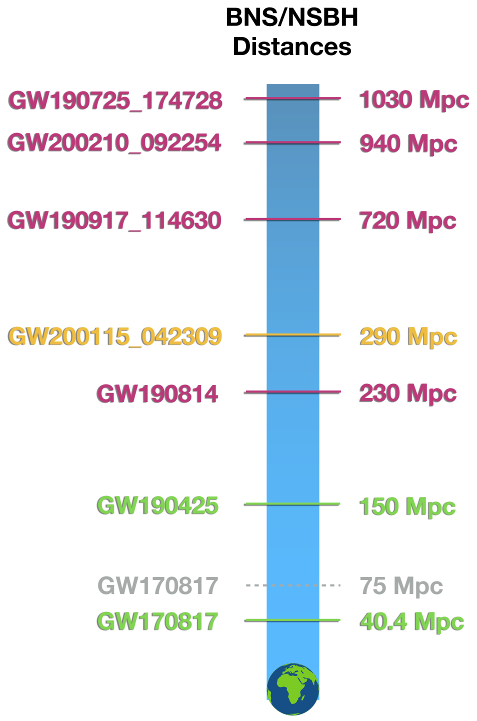


(Zhung et al. 2022)

The Case for Multimessenger Astronomy

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



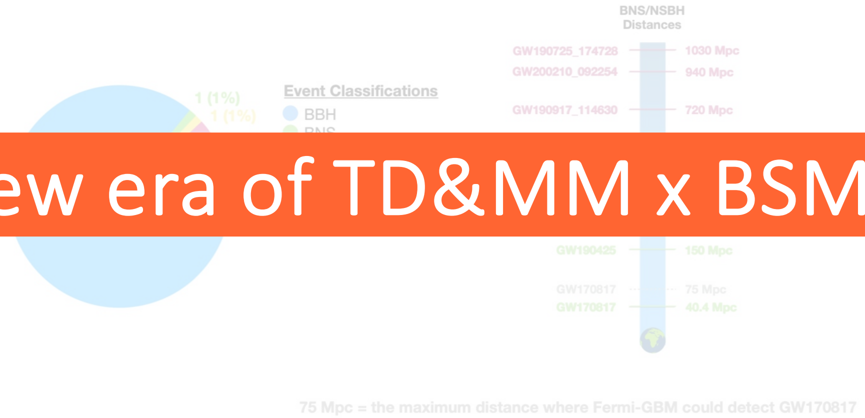


75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

The Case for Multimessenger Astronomy: O4

Fourth LIGO/Virgo/KAGRA observing run (O4): starting in May 2023!

- Unprecedented localization & sensitivity
- Annual number of detections (prediction):



New era of TD&MM x BSM!

		BNS	NSBH	BBH
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O3	HLVK	1^{+12}_{-1}	0^{+19}_{-0}	18^{+22}_{-12}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}

(LVK Collaboration)

- Use the extraordinary multimessenger infrastructure and network for ALP searches!

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!