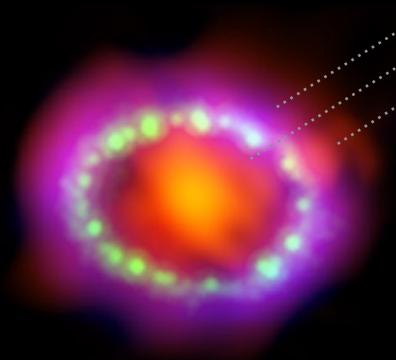


# Light at the end of the tunnel: Astrophysical searches for axion-like particles in gamma-ray energies



SN1987A\*

High-energy Particle Seminar  
Department of Physics, Columbia University  
December 6, 2022

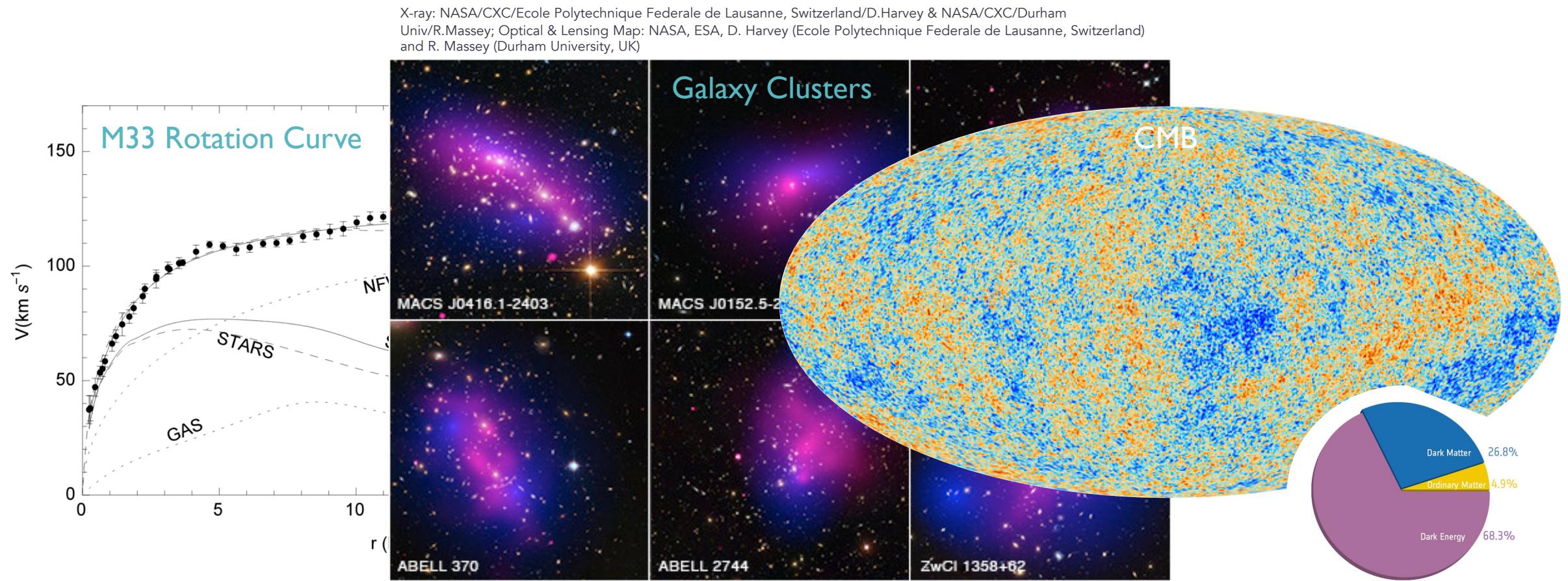
Milena Crnogorčević  
University of Maryland/NASA Goddard  
[mcrnogor@umd.edu](mailto:mcrnogor@umd.edu)

# 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

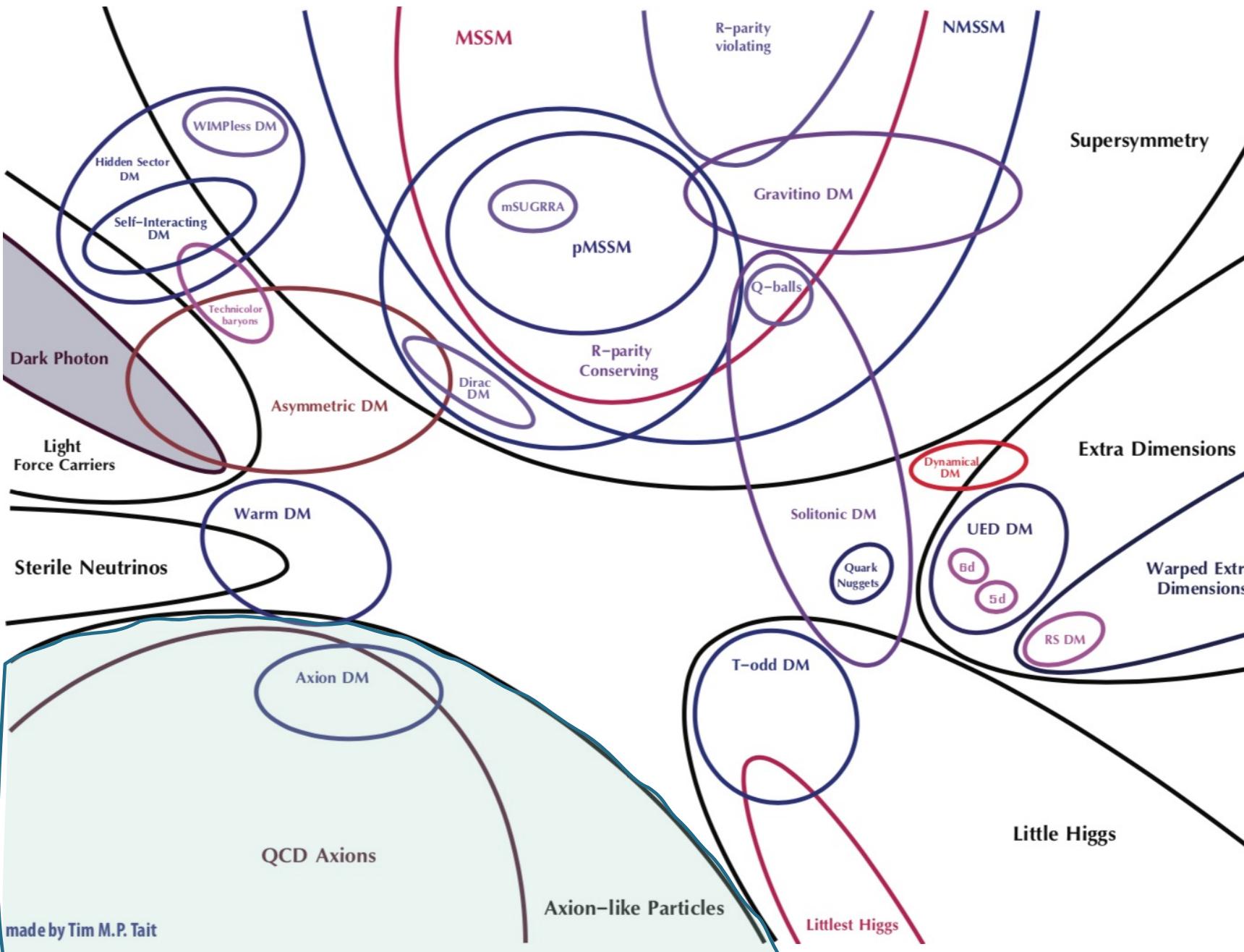
## INTRODUCTION AND MOTIVATION

# OVERWHELMING EVIDENCE FOR THE EXISTENCE OF DARK MATTER



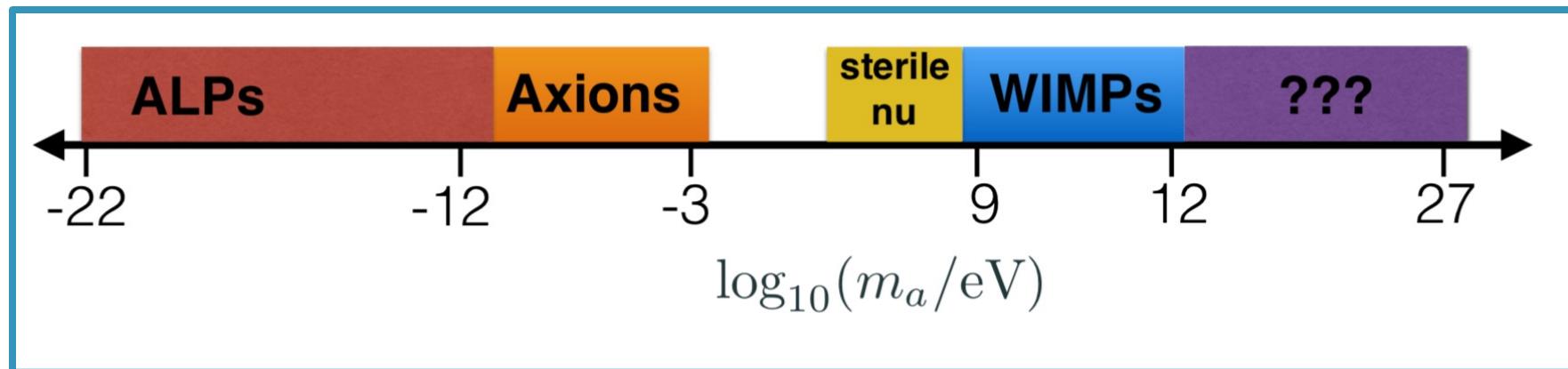
European Space Agency and Planck Collaboration

# THE PARTICLE NATURE OF DARK MATTER



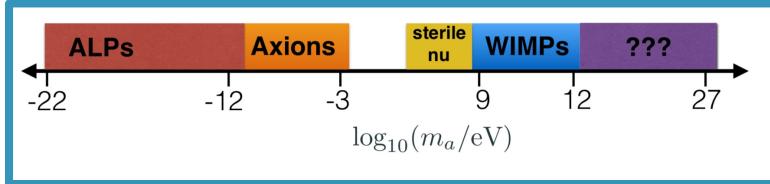
# WHAT ARE AXION-LIKE PARTICLES? (ALPs)

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

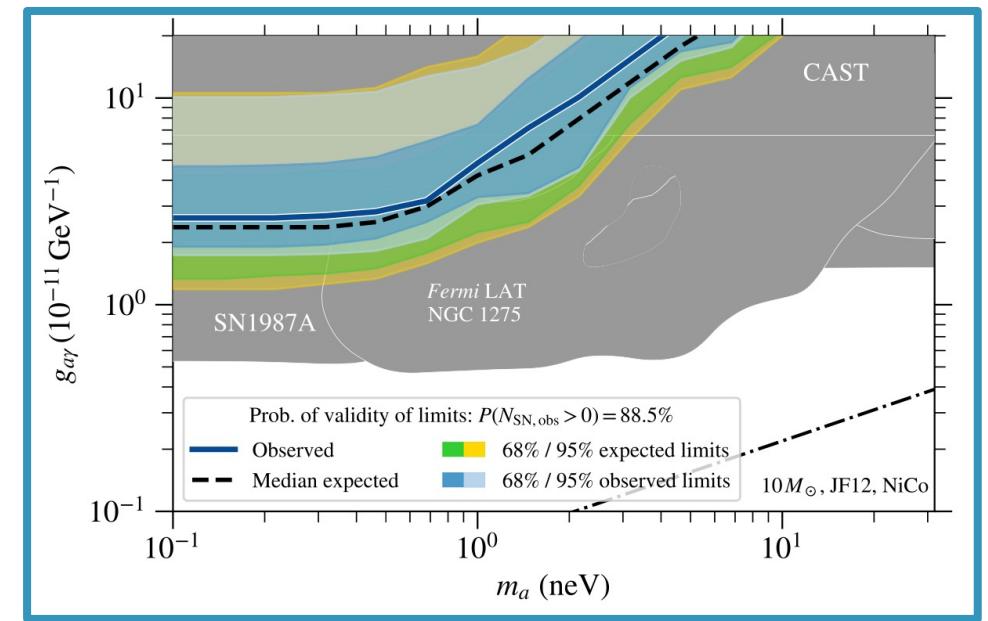


# WHAT ARE AXION-LIKE PARTICLES? (ALPs)

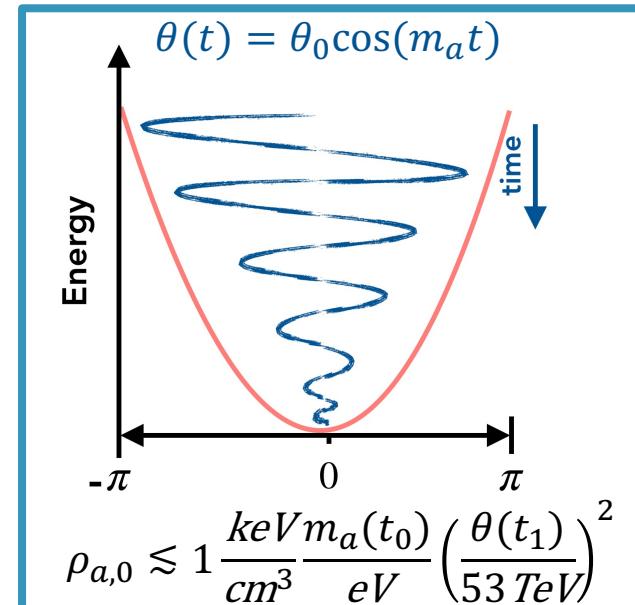
- Extension of the axion, a proposed solution of the strong charge-parity problem in QCD
- WISPs: weakly-interacting sub-eV particles (mass  $\lesssim 10^{-10}$  eV)



- Cold matter requirements:
  - ✓ feeble interactions with standard model particles
  - ✓ cosmological stability
- Direct and indirect searches  $\rightarrow$  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]



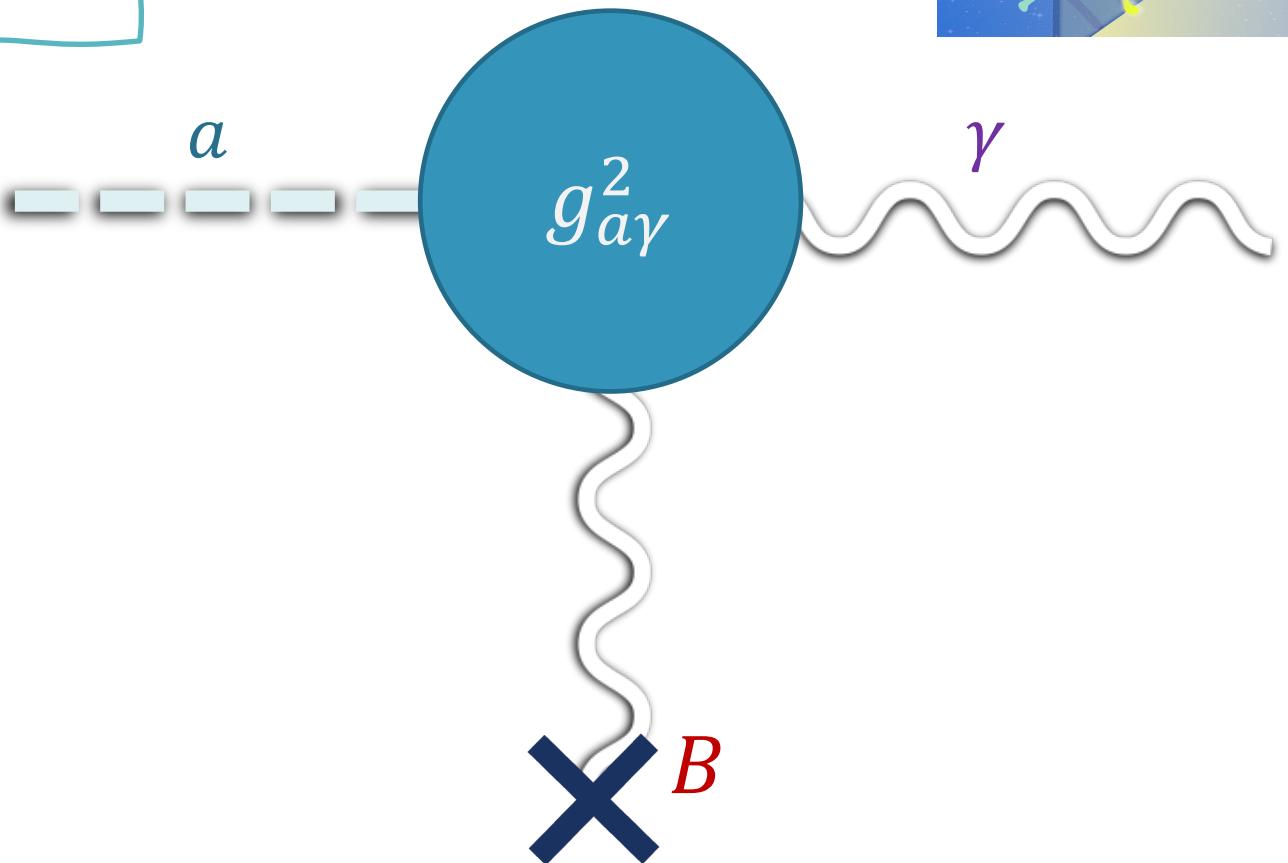
# OBSERVING ALPs WITH GAMMA-RAYS

- Primakoff process: converting ALPs into photons

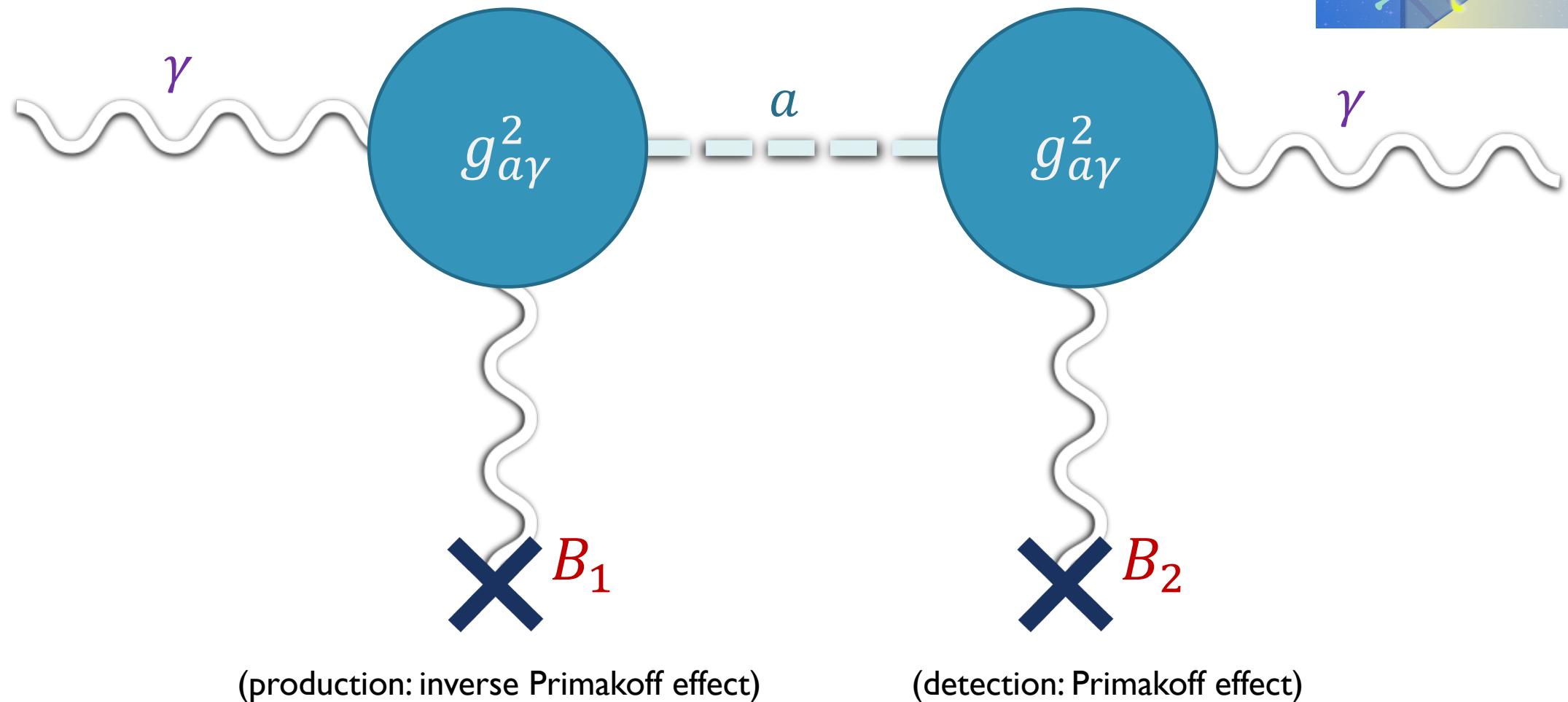
- ❖ In the presence of an external magnetic field,  $B$ , ALPs undergo a conversion into gamma-rays:

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

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



# OBSERVING ALPs WITH GAMMA-RAYS



8

# TAKE-AWAY POINTS ABOUT ALPs

- Viable *cold* dark-matter candidate, belonging to the family of WISPs (weakly-interacting sub- $\text{eV}$  particles)
- ALPs convert into photons in the presence of a magnetic field (inverse Primakoff process)
- Gamma-ray observations can probe ALP parameter space

# TALK OUTLINE

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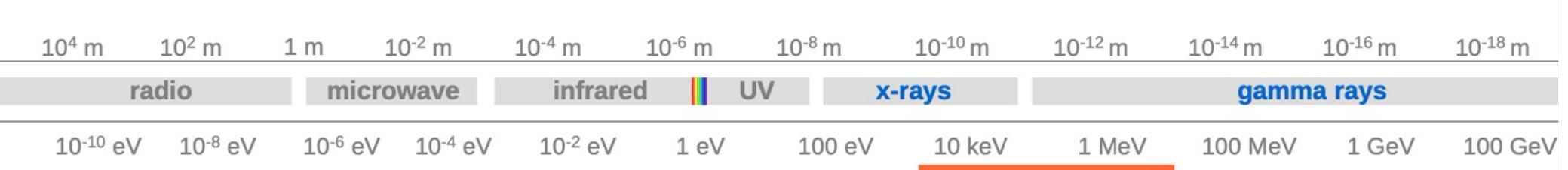
## TALK OUTLINE

- Axion-like particles: Introduction and motivation
- ✓ *Fermi-LAT* Low Energy Technique: Sensitivity study
- ✓ Sensitivity of the future MeV instruments
- ✓ Gamma-ray Bursts as ALP factories: what has *Fermi* seen so far?
- ⌚ *Fermi-LAT* GRB pre-cursor analysis
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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](#))



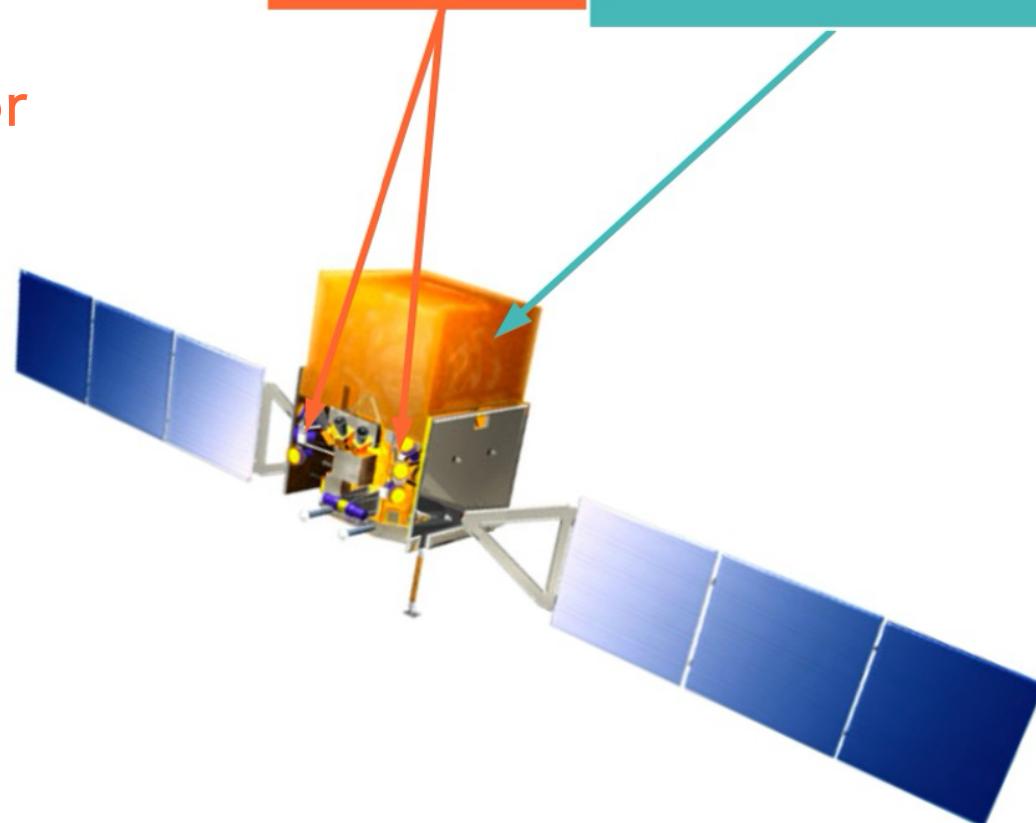
## GBM Gamma-ray Burst Monitor

12 (NaI) + 2 (BGO) detectors

FoV: entire unocculted sky

8 keV to 40 MeV

~1500 bursts (~1 every day or two)



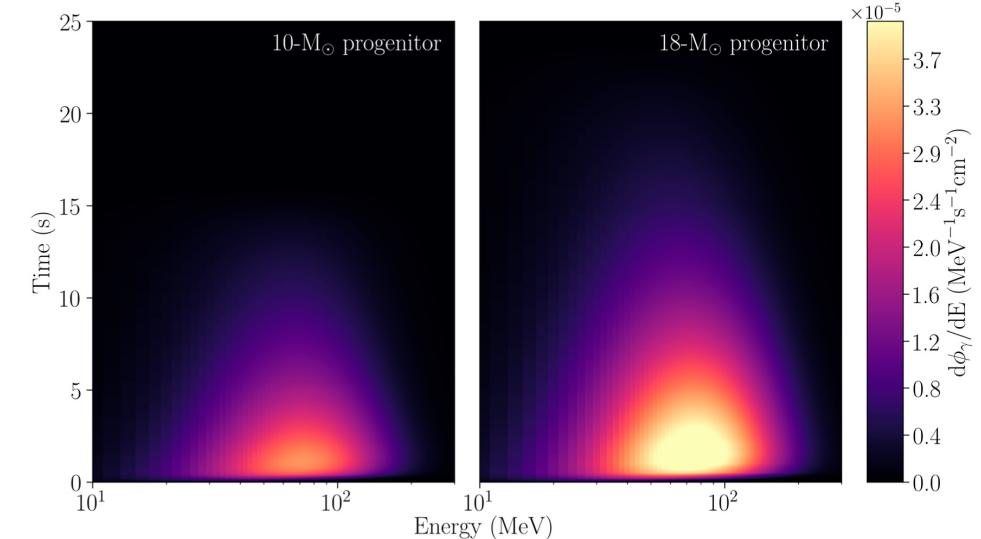
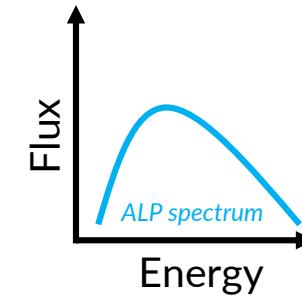
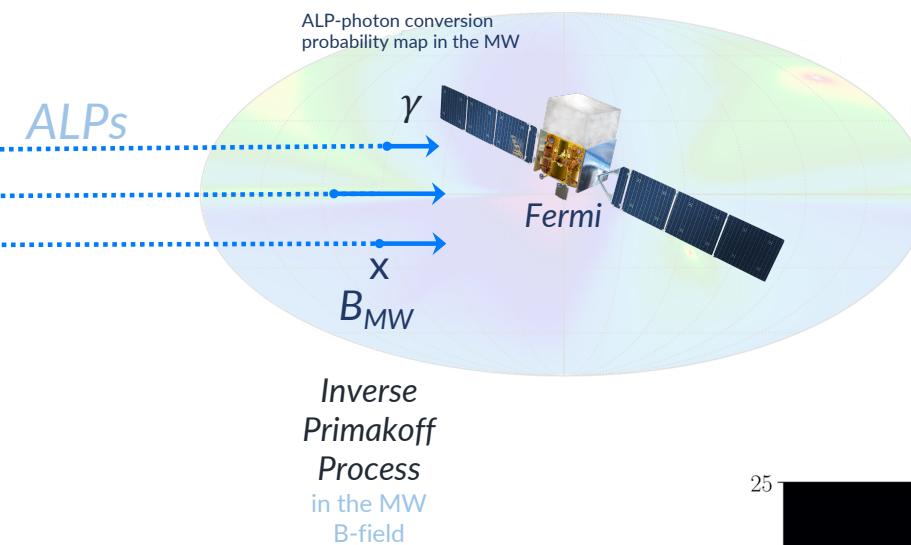
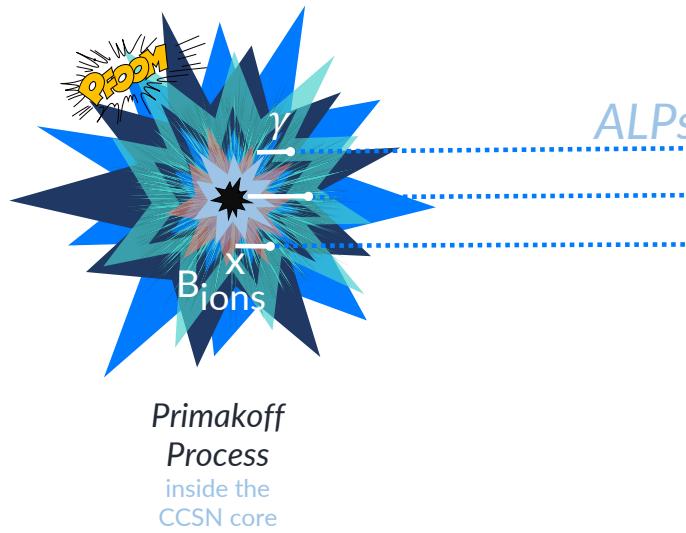
## LAT Large Area Telescope

Pair-production telescope

FoV: 2.4 sr (~20% of sky)

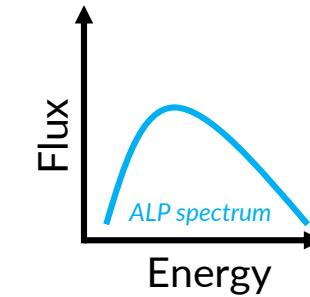
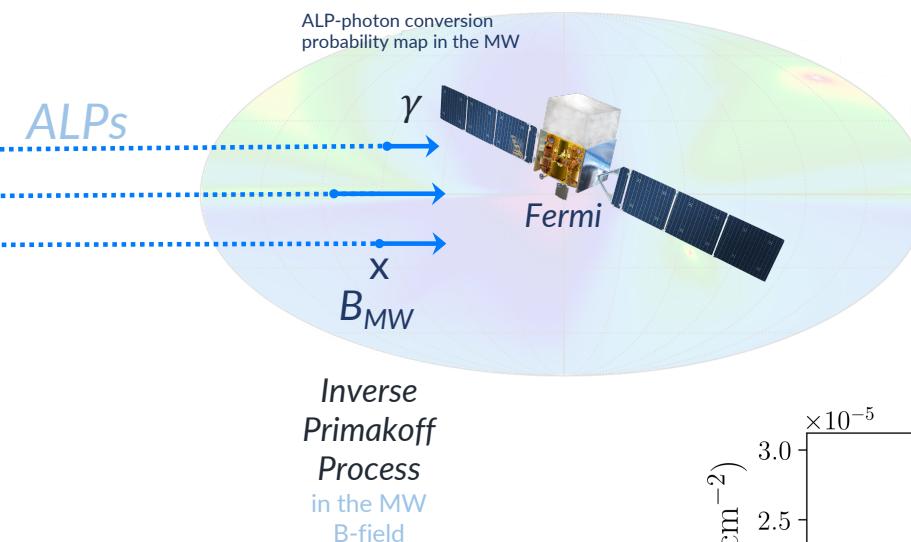
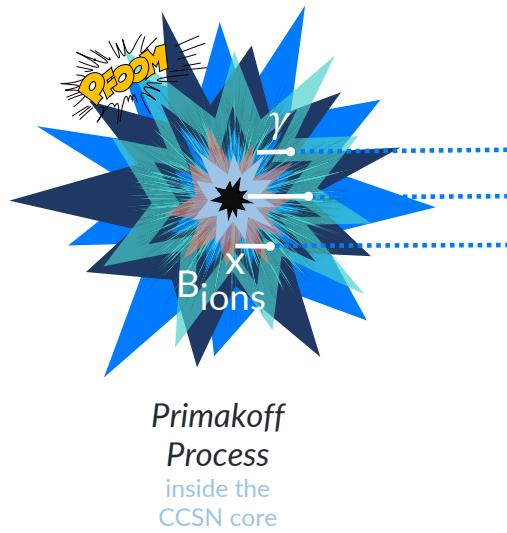
20 MeV to >300 GeV

# MOTIVATION AND ASSUMPTIONS

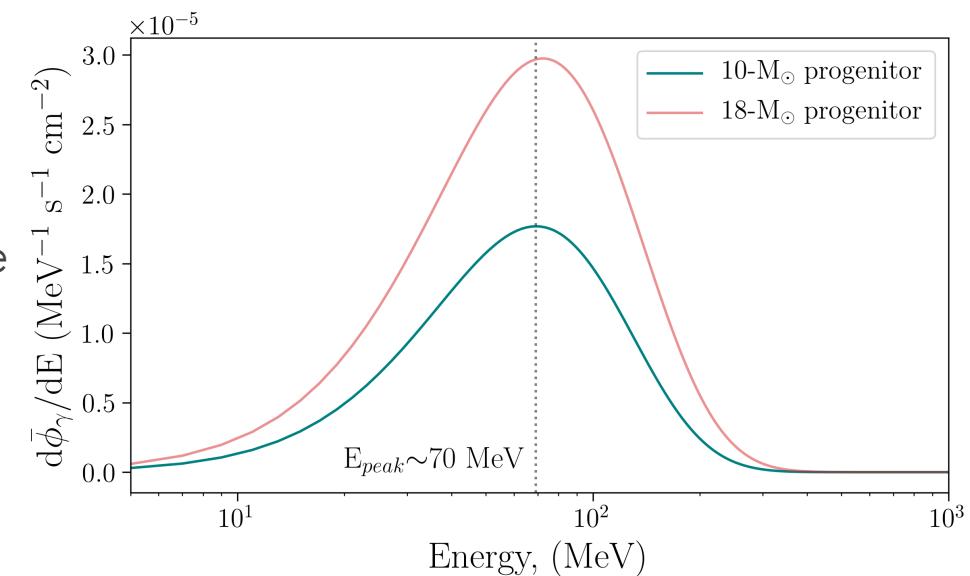


Observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a  $10$  and  $18\text{-M}_\odot$  progenitor.

# MOTIVATION AND ASSUMPTIONS

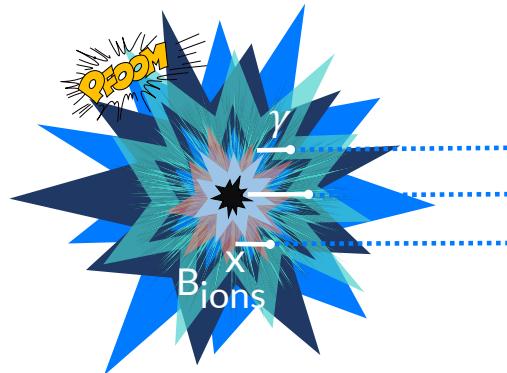


- **Motivation:** ALPs are theorized to have a unique spectral signature in the spectrum of a CCSN. No other known physical processes are predicted to produce such signature.

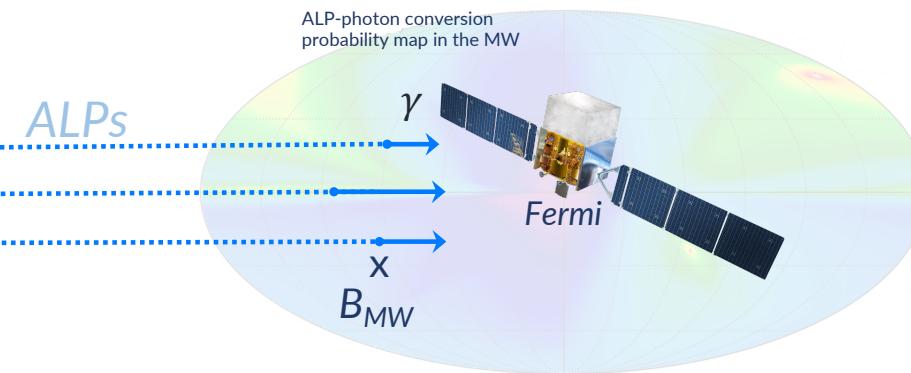


The observed ALP-induced gamma-ray spectrum for 10 and  $18-M_\odot$  progenitors averaged over 10 seconds.

# MOTIVATION AND ASSUMPTIONS



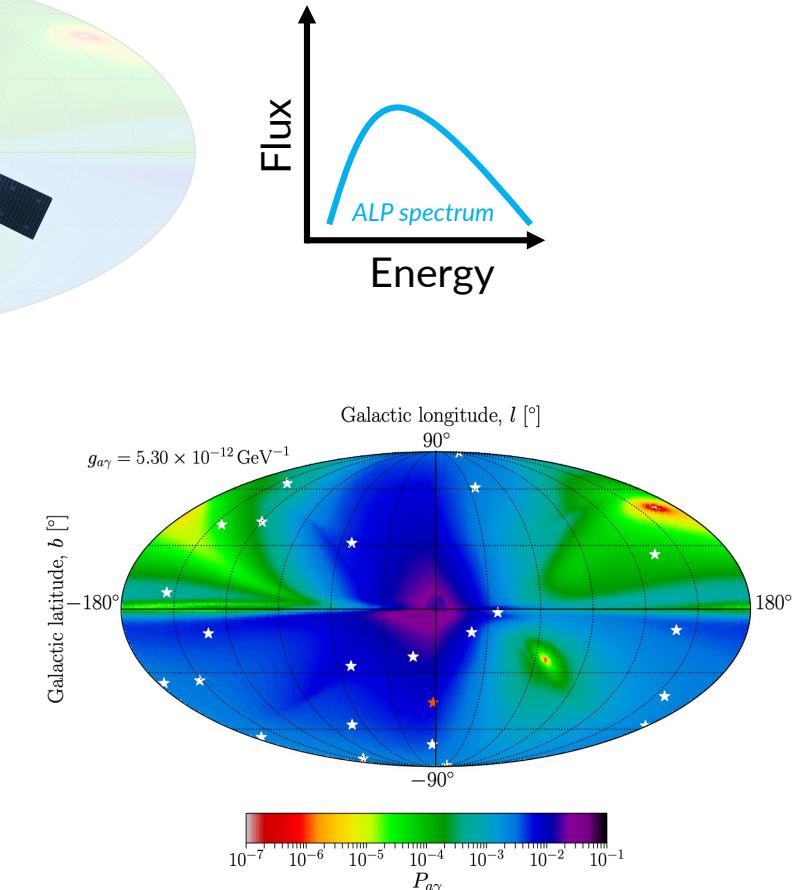
Primakoff  
Process  
inside the  
CCSN core



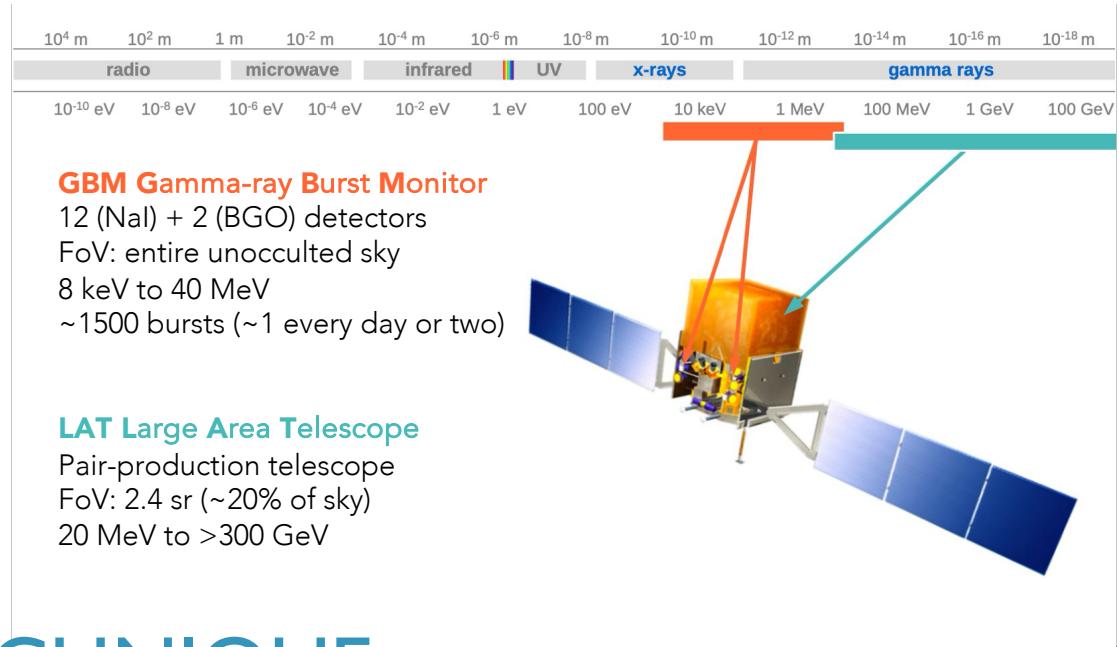
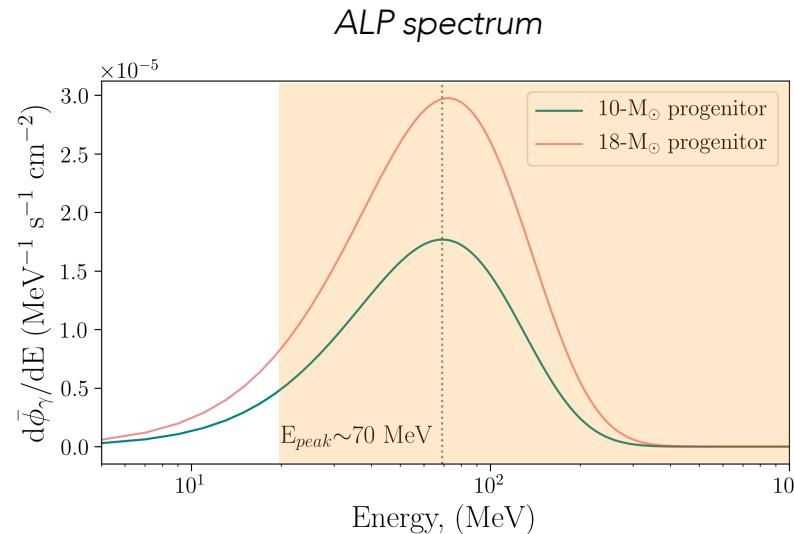
‣ **Motivation:** ALPs are theorized to have a unique spectral signature in the spectrum of a CCSN. No other known physical processes are predicted to produce such signature.

## ‣ Assumptions:

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



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



## 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

# SENSITIVITY TESTING: ANALYSIS & RESULTS

Model backgrounds from the considered LLE-detected GRB sample.

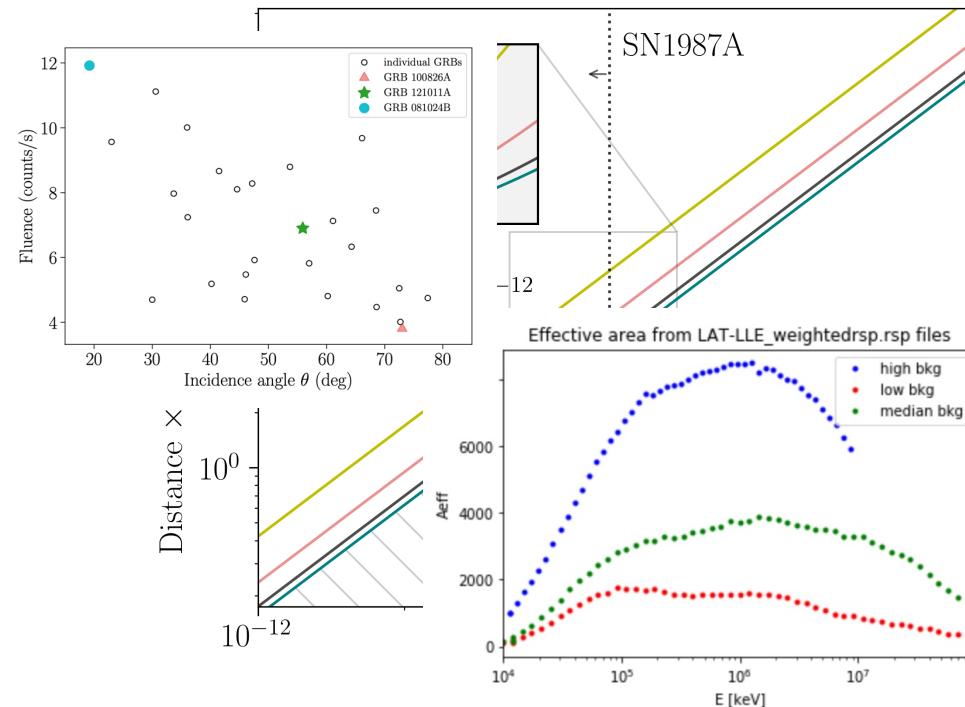
Find the min, max, and median background levels.

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

Produce 2000 realizations of the background+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 find for which normalization ALP model is preferred.

Find the coupling-distance parameter space for that normalization.



Background level	Conversion probability, $P_\gamma(g_0)$	Distance limit (Mpc) 10 M <sub>⊙</sub>	Distance limit (Mpc) 18 M <sub>⊙</sub>
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

$$N_{\text{ALP}} \propto \frac{g_{a\gamma}^4}{d^2}$$

Crnogorčević et al. 2021 (PRD, [arXiv:2109.05790](https://arxiv.org/abs/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

# TALK OUTLINE

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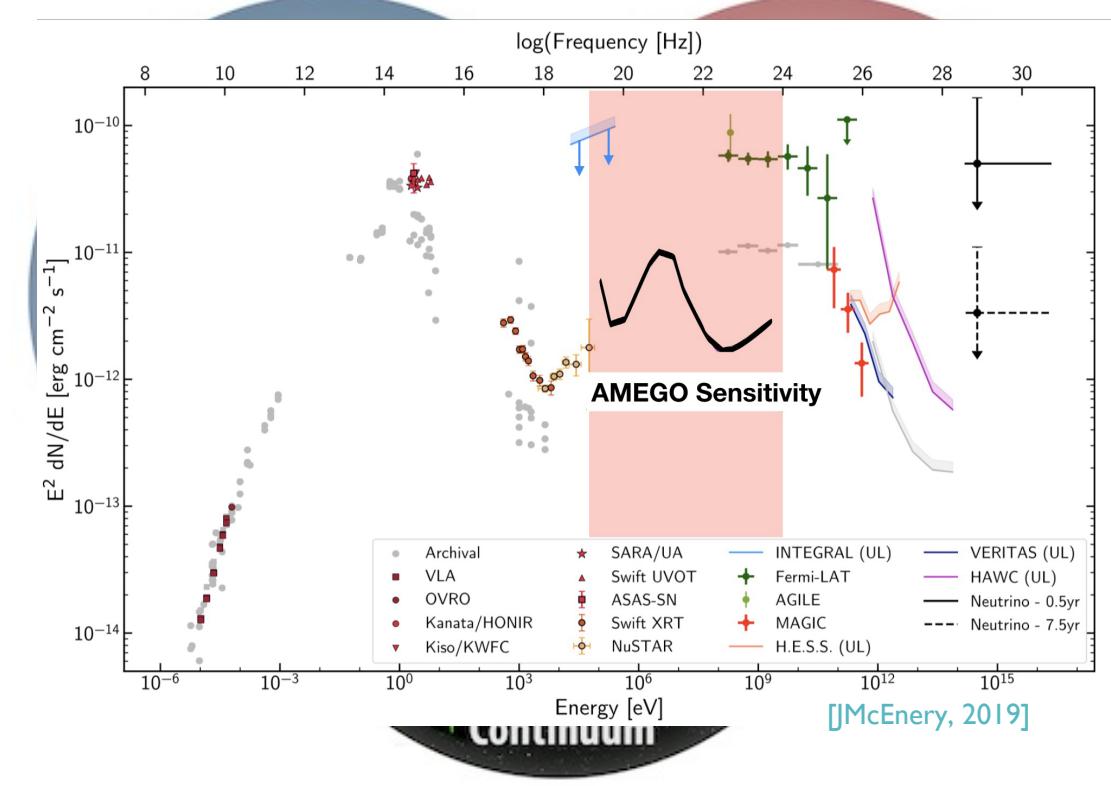
## ADDITIONAL CONSIDERATION



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



## ADDITIONAL CONSIDERATIONS

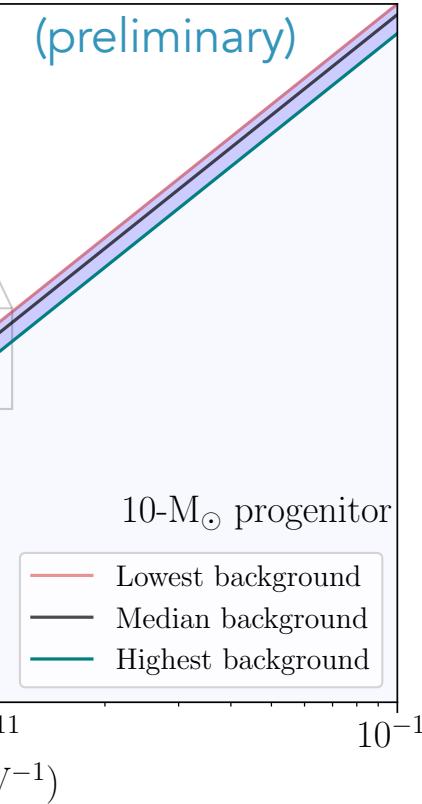
Additional considerations: All-sky Medium Energy Gamma-ray Observatory (MEGO-X) outlined the [Snowmass 2021 Letter](#)

- For a 10-solar mass progenitor, sensitivity levels comparable to LAT in the low energy range

Distance limit improved by a factor of

MEGO-X  
ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY

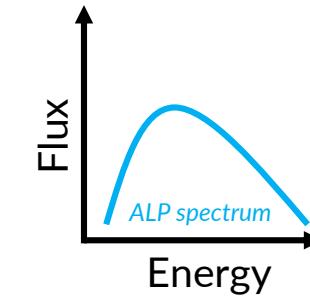
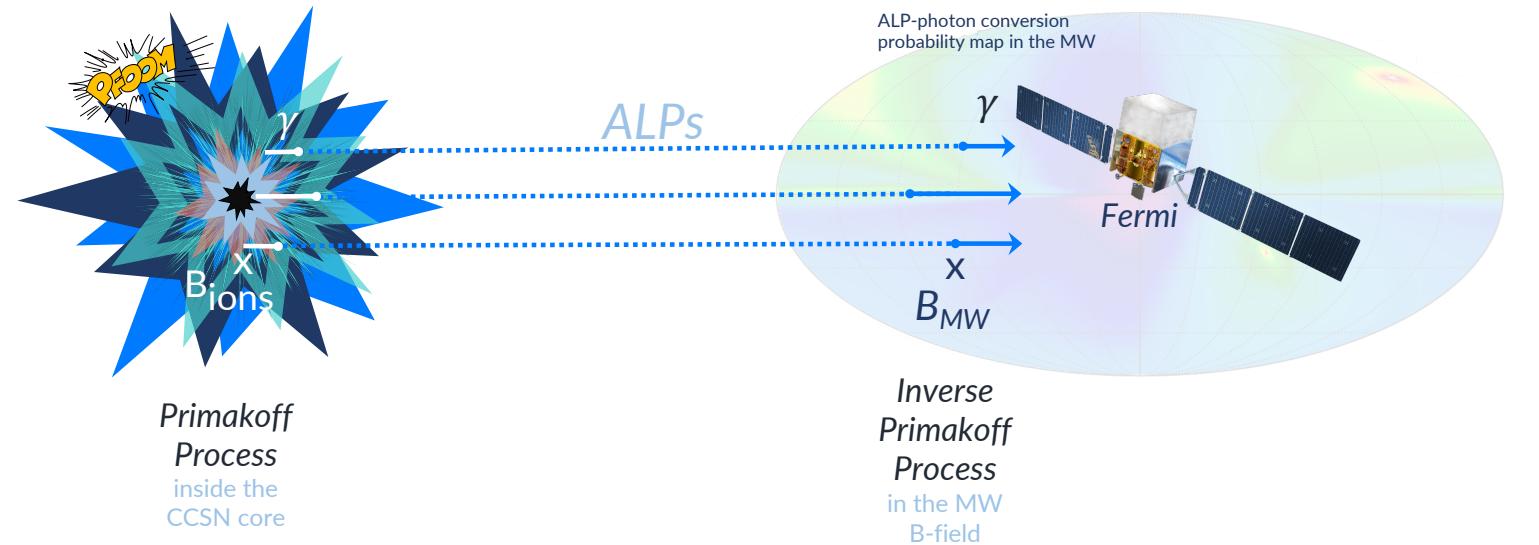
(sensitivity analysis; motivation  
(Crnogorčević)



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# MOTIVATION AND ASSUMPTIONS



**CCSNe  $\rightarrow$  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)

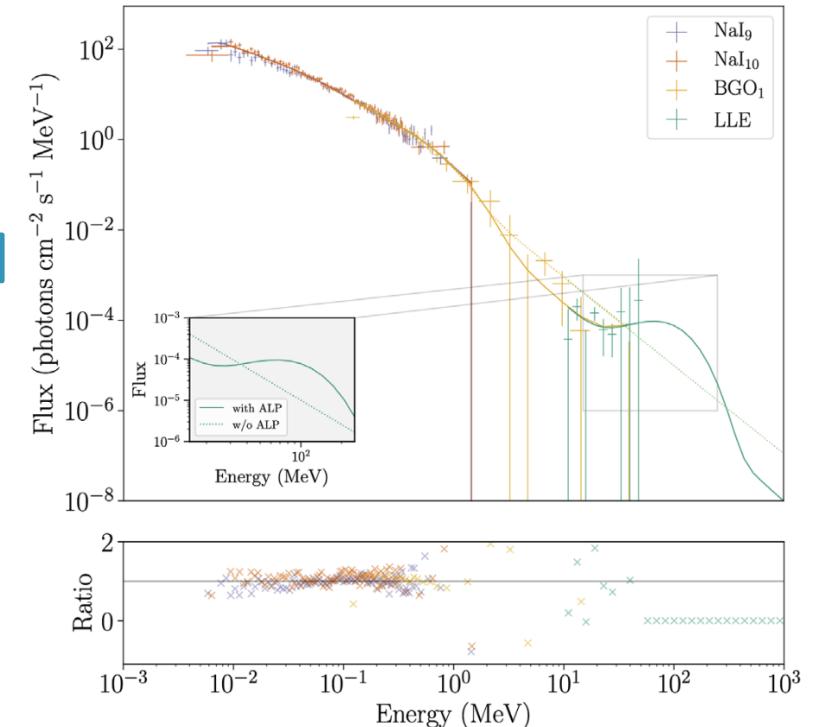
Initial sample: 186 LAT-detected GRBs

Applying the selection criteria

24 GRBs

# GRB ANALYSIS RESULTS

GRB	T <sub>95</sub> (s)	Best model(no ALP)	grbm parameters			
			$\alpha_1$	$\alpha_2$	E <sub>c</sub> (keV)	LLR
080825C	22.2	grbm	-0.65 <sup>+0.05</sup> <sub>-0.05</sub>	-2.41 <sup>+0.04</sup> <sub>-0.04</sub>	143 <sup>+13</sup> <sub>-12</sub>	0.2
090217	34.1	grbm	-1.11 <sup>+0.04</sup> <sub>-0.04</sub>	-2.43 <sup>+0.03</sup> <sub>-0.04</sub>	16 <sup>+13</sup> <sub>-8</sub>	0.1
100225A	12.7	grbm	-0.50 <sup>+0.25</sup> <sub>-0.21</sub>	-2.28 <sup>+0.07</sup> <sub>-0.09</sub>	223 <sup>+112</sup> <sub>-68</sub>	0.0
100826A	93.7	grbm+bb	-1.02 <sup>+0.04</sup> <sub>-0.04</sub>	-2.30 <sup>+0.03</sup> <sub>-0.04</sub>	484 <sup>+72</sup> <sub>-63</sub>	0.0
101123A	145.4	grbm+cutoffpl	-1.00 <sup>+0.07</sup> <sub>-0.08</sub>	-1.94 <sup>+0.15</sup> <sub>-0.12</sub>	187 <sup>+74</sup> <sub>-62</sub>	5.8
110721A	21.8	grbm+bb	-1.24 <sup>+0.02</sup> <sub>-0.01</sub>	-2.29 <sup>+0.03</sup> <sub>-0.03</sub>	1000 <sup>+28</sup> <sub>-39</sub>	0.0
120328B	33.5	grbm+cutoffpl	-0.67 <sup>+0.06</sup> <sub>-0.05</sub>	-2.26 <sup>+0.05</sup> <sub>-0.05</sub>	101 <sup>+12</sup> <sub>-13</sub>	0.0
120911B	69.0	grbm	-2.50 <sup>+0.92</sup> <sub>-1.04</sub>	-1.05 <sup>+0.63</sup> <sub>-0.38</sub>	11 <sup>+10</sup> <sub>-2</sub>	0.0
121011A	66.8	grbm	-1.08 <sup>+0.10</sup> <sub>-0.21</sub>	-2.18 <sup>+0.11</sup> <sub>-0.16</sub>	997 <sup>+84</sup> <sub>-26</sub>	0.0
121225B	68.0	grbm	-2.38 <sup>+1.02</sup> <sub>-0.40</sub>	-2.45 <sup>+0.06</sup> <sub>-0.07</sub>	11 <sup>+89</sup> <sub>-3</sub>	0.0
130305A	26.9	grbm	-0.76 <sup>+0.03</sup> <sub>-0.03</sub>	-2.63 <sup>+0.06</sup> <sub>-0.06</sub>	665 <sup>+61</sup> <sub>-55</sub>	0.0
131014A	4.2	grbm	-0.55 <sup>+0.33</sup> <sub>-0.98</sub>	-2.65 <sup>+0.17</sup> <sub>-0.19</sub>	255 <sup>+36</sup> <sub>-11</sub>	0.63
131216A	19.3	grbm+cutoffpl	-0.46 <sup>+0.28</sup> <sub>-0.24</sub>	-2.67 <sup>+1.94</sup> <sub>-0.94</sub>	178 <sup>+77</sup> <sub>-92</sub>	0.0
140102A	4.1	grbm+bb	-1.10 <sup>+0.12</sup> <sub>-0.09</sub>	-2.41 <sup>+0.16</sup> <sub>-0.11</sub>	206 <sup>+65</sup> <sub>-92</sub>	2.3
140110A	9.2	grbm	-2.49 <sup>+1.64</sup> <sub>-1.59</sub>	-2.19 <sup>+0.20</sup> <sub>-0.22</sub>	11 <sup>+23</sup> <sub>-3</sub>	0.0
141207A	22.3	grbm+bb	-1.21 <sup>+0.09</sup> <sub>-0.06</sub>	-2.33 <sup>+0.11</sup> <sub>-0.13</sub>	999 <sup>+18</sup> <sub>-70</sub>	0.0
141222A	2.8	grbm+pow	-1.57 <sup>+0.03</sup> <sub>-0.02</sub>	-2.83 <sup>+0.46</sup> <sub>-1.74</sub>	9971 <sup>+390</sup> <sub>-832</sub>	0.0
150210A	31.3	grbm+pow	-0.52 <sup>+0.04</sup> <sub>-0.05</sub>	-2.91 <sup>+0.11</sup> <sub>-0.38</sub>	1000 <sup>+517</sup> <sub>-234</sub>	0.0
150416A	33.8	grbm	-1.18 <sup>+0.04</sup> <sub>-0.04</sub>	-2.36 <sup>+0.13</sup> <sub>-0.21</sub>	999 <sup>+187</sup> <sub>-269</sub>	0.0
150820A	5.1	grbm	-0.99 <sup>+0.56</sup> <sub>-1.30</sub>	-2.01 <sup>+0.82</sup> <sub>-0.27</sub>	303 <sup>+61</sup> <sub>-39</sub>	0.0
151006A	95.0	grbm	-1.35 <sup>+0.06</sup> <sub>-0.03</sub>	-2.24 <sup>+0.07</sup> <sub>-0.08</sub>	998 <sup>+33</sup> <sub>-84</sub>	0.0
160709A	5.4	grbm+cutoffpl	-1.44 <sup>+0.18</sup> <sub>-0.12</sub>	-2.18 <sup>+0.15</sup> <sub>-0.18</sub>	9940 <sup>+373</sup> <sub>-511</sub>	1.0
160917A	19.2	grbm+bb	-0.78 <sup>+3.45</sup> <sub>-1.40</sub>	-2.39 <sup>+0.20</sup> <sub>-0.10</sub>	994 <sup>+634</sup> <sub>-216</sub>	0.9
170115B	44.8	grbm	-0.80 <sup>+0.02</sup> <sub>-0.04</sub>	-3.00 <sup>+0.10</sup> <sub>-0.07</sub>	1000 <sup>+226</sup> <sub>-106</sub>	2.8



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

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## 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 ( $5\sigma$ ) 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

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# *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. (*in prep.*)

*Fermi* GI Cycle 15 (Pl: Crnogorčević)

## WHAT HAVE WE DONE SO FAR?

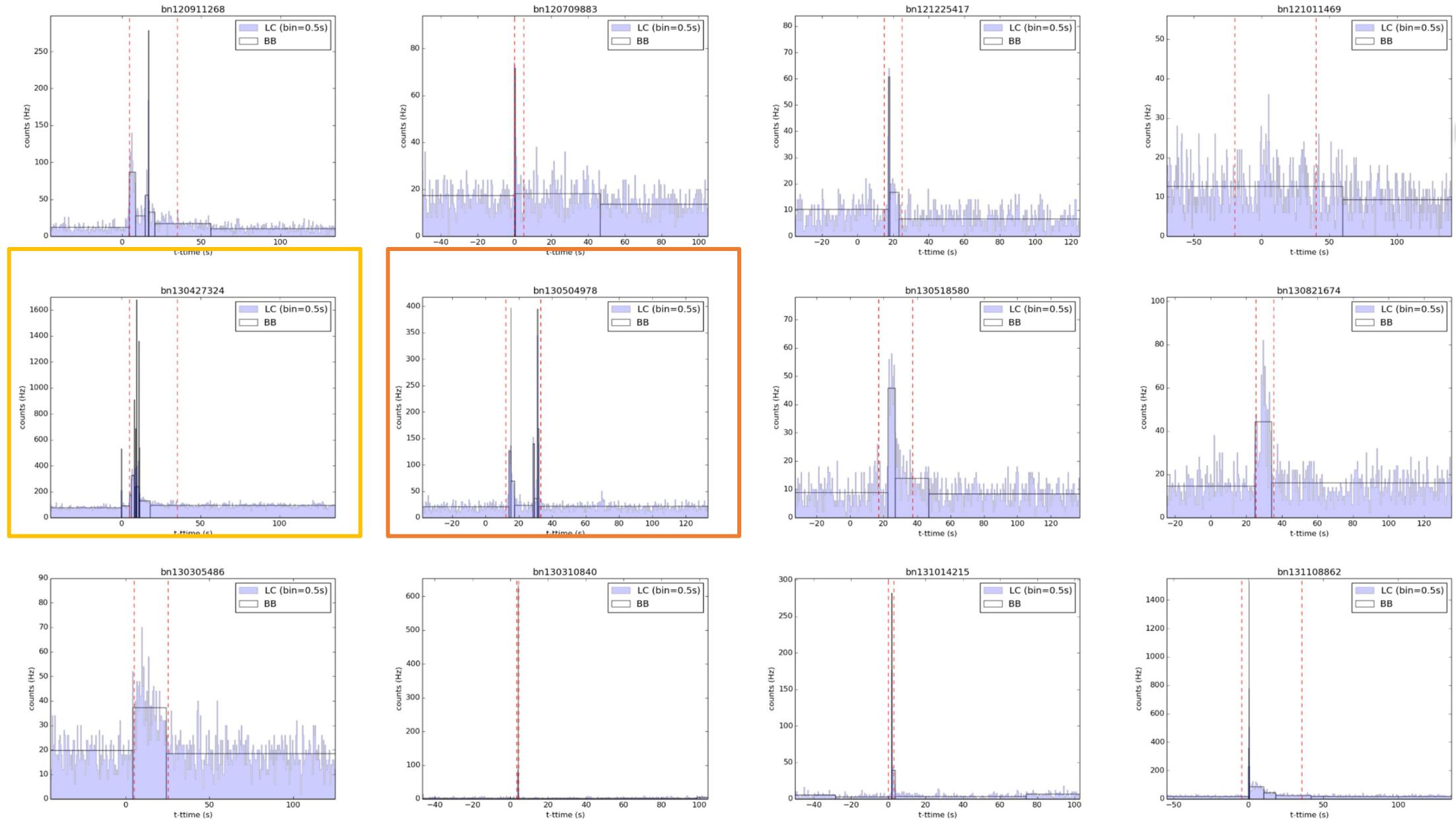
### Bayesian Block Analysis on the LLE-detected GRBs

- Using the code developed by Giacomo Vianello
- Allows for a selection of time bins for a time-resolved spectra
  - Default output: T90 interval (i.e. time in which 90% of the GRB fluence is emitted)
  - Time range:  $[T_{\text{FoV}} \text{ to } T_0 - 10 \text{ sec}]$  [Zhang et al. 2019]
    - $T_{\text{FoV}}$ : time the source enters LAT's FoV
    - $T_0$ : trigger time
- Considered so far: LLE-detected GRBs (56)

→ Goal: search for excess signal!

## Example trial runs

(Note that all the following plots are in the  $[T_0 \pm 400 \text{ s}]$ )



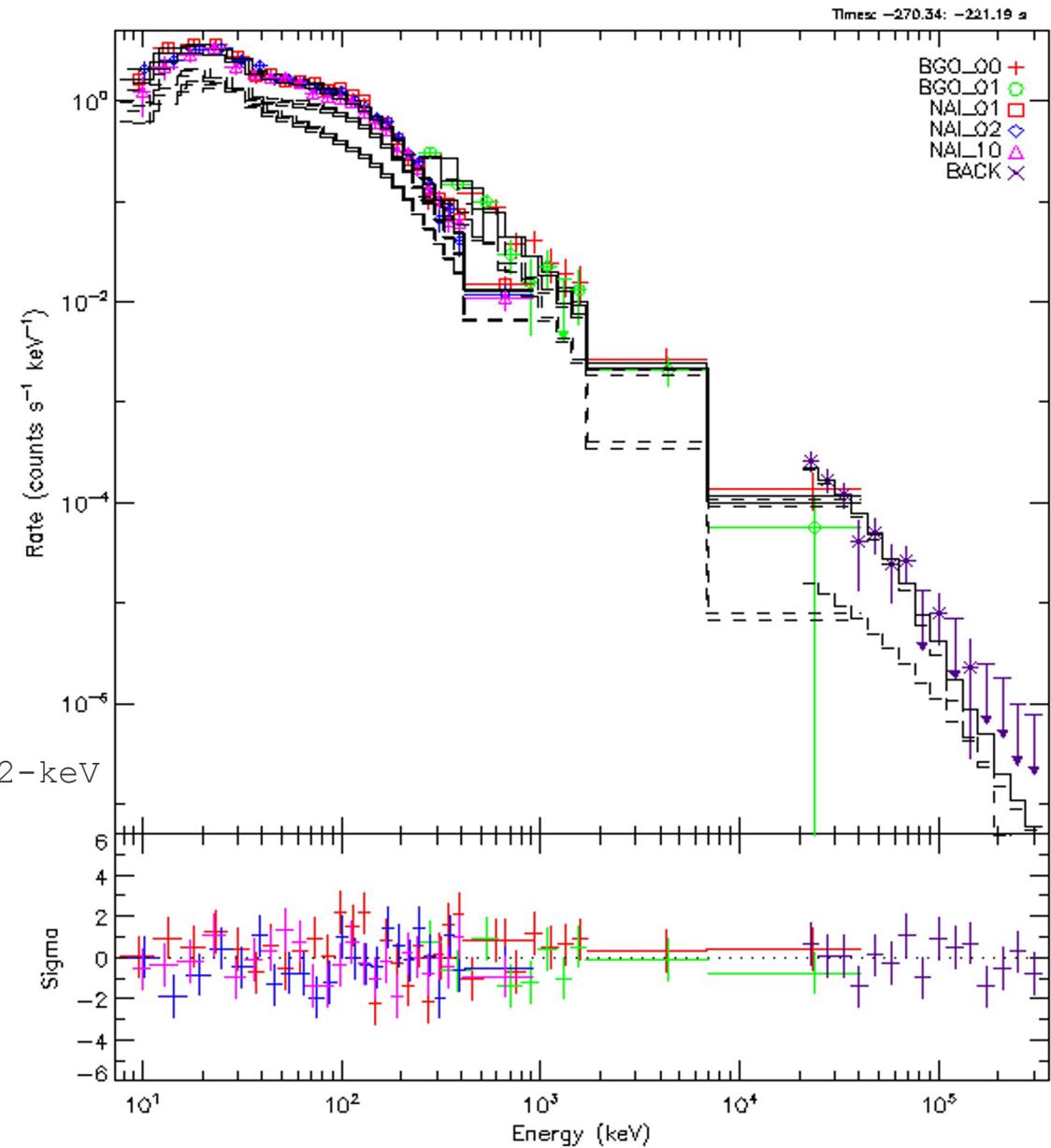
preliminary

# GRB 120624

- precursor emission in GBM & LLE
- precursor fit ( $T_0 - 270$  to  $T_0 - 220$  seconds)
- **Best fit: Band function**

## TERM: Band's GRB, Epeak

Amplitude	VARY	0.007494 +/-	0.000535 p/s-cm <sup>2</sup> -keV
Epeak	VARY	387.9 +/-	51.2 keV
alpha	VARY	-0.5282 +/-	0.216
beta	VARY	-2.597 +/-	0.320



preliminary

# *Searching for excess signal in precursor emission?*

Spectral analysis complete for GRBs up to 2018 (a total of 56 GRBs)

Summary:

- No significant detections
  - out of 56 GRBs with a precursor, 41 have precursors in GBM  
(should we expect ALP emission for them?)
- What is a significant detection for a subthreshold emission?
  - This question requires a bit of thought: the only statement we can make here is that the ALP spectral model fits the precursor emission better than the traditional GRB models; however, this does not imply a detection. Additional crosschecks would be required (some mentioned in the previous meeting: e.g. stacking)

# Upper-limit analysis

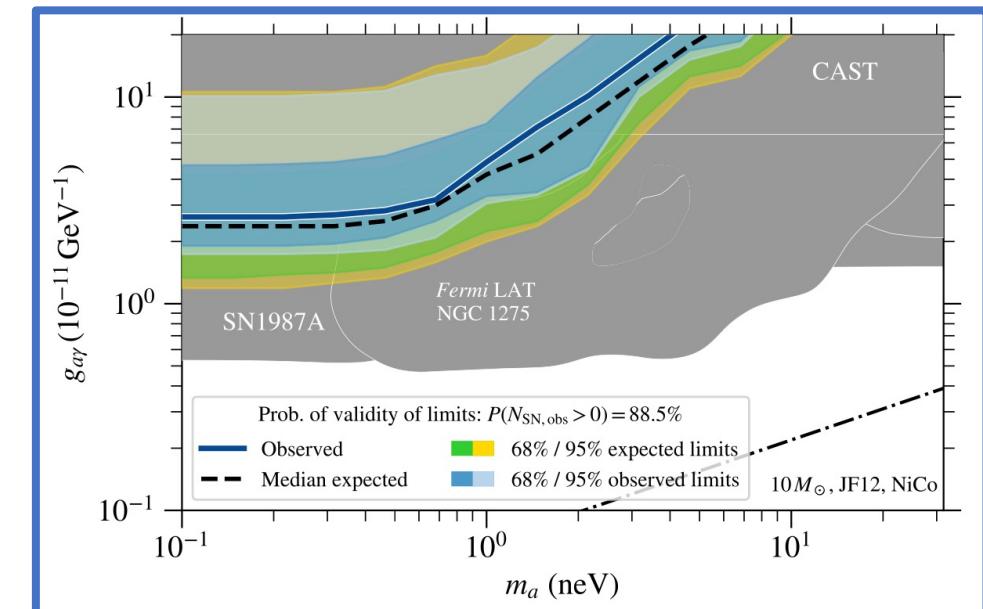
This analysis is partly analogous to Meyer & Petrushevska 2020, as well as Crnogorcevic et al. 2021, code here is developed based on those two work

Goal 2: consider LAT/GBM and use the standard LAT data analysis

Selection criteria:

- Long GRBs ( $T90 > 2$  seconds)
- Redshift  $< 0.6$  (for a competitive coupling,  $g < 2 \times 10^{-10} \text{ GeV}^{-1}$ )
- In LAT's FoV at least 10 seconds prior to the trigger time

→ 9 LAT bursts, GBM 12



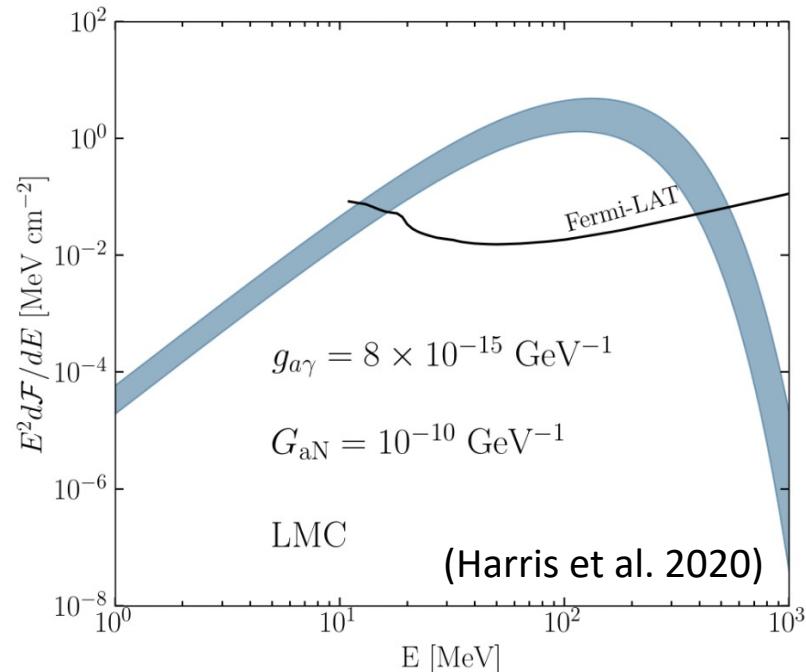
Exclusion plot for ALPs. [Meyer & Petrushevska 2020]

# 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

# What about binary neutron-star mergers?

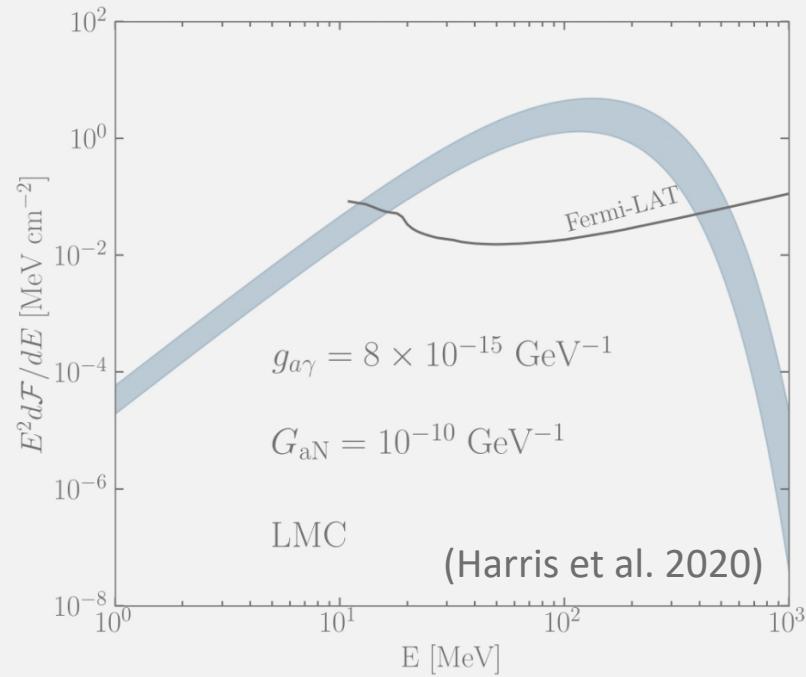
## PATH 1: INDIRECT DETECTION GAMMA-RAY FLUX FROM BNS



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

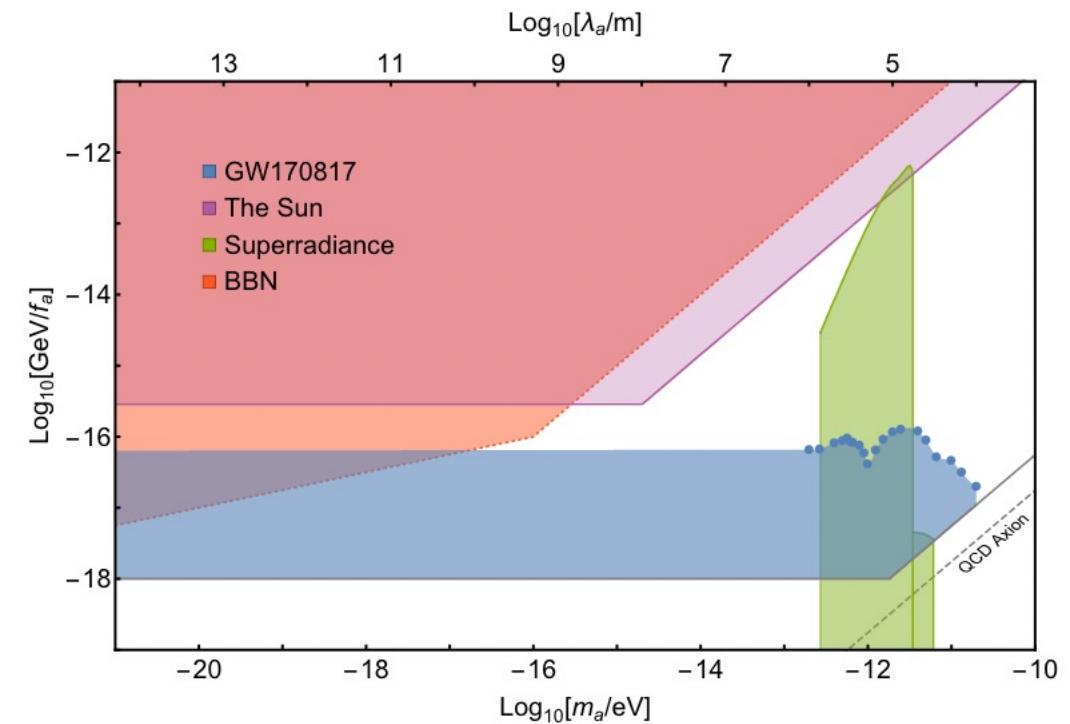
# What about binary neutron-star mergers?

## PATH 1: INDIRECT DETECTION GAMMA-RAY FLUX FROM BNS



- Depends on NS temperature profile
- Duration of the “supermassive” NS phase
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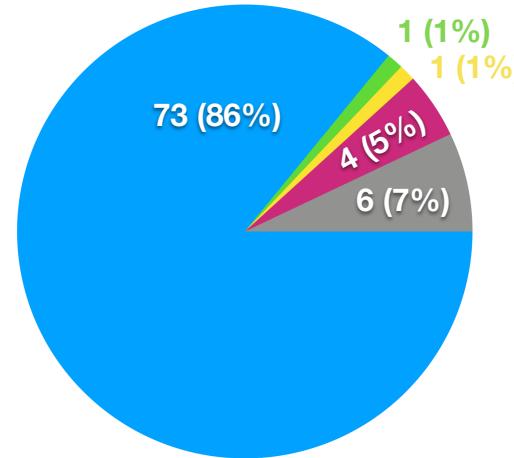
## PATH 2: DIRECT DETECTION:GRAVITATIONAL WAVEFORM TEMPLATES



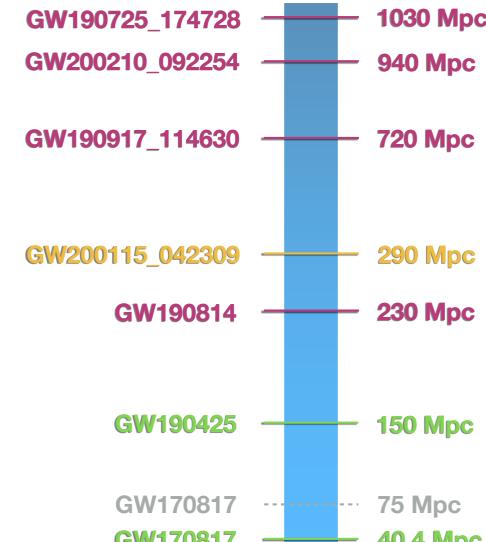
(Zhung et al. 2022)

# The Case for Multimessenger Astronomy

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



## BNS/NSBH Distances

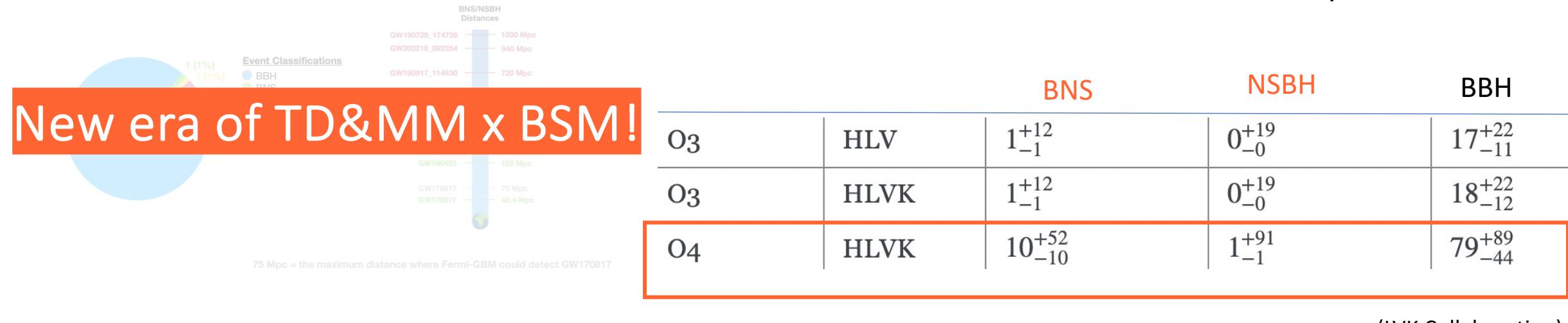


75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

# The Case for Multimessenger Astronomy: O4

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

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



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

# SUMMARY

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- We consider light ALPs, hypothetically produced in CCSNe, and converted into gamma-rays in the MW magnetic field
- We test LAT sensitivity, 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**
  - driven by the dominating background in the LLE data & decreased effective area at high incidence angles
- Good science case for future MeV instruments (AMEGO-X, etc.)
- 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)
  - Pre-cursor emission in LLE. **Preliminary results: no detection!**
  - Current work: upper-limit analysis at the time of precursor with LAT standard data.
  - Prospects: neutron-star mergers as excellent probes into new systems!