New Physics through a Multimessenger Lens

An Exploration of the High-energy Universe

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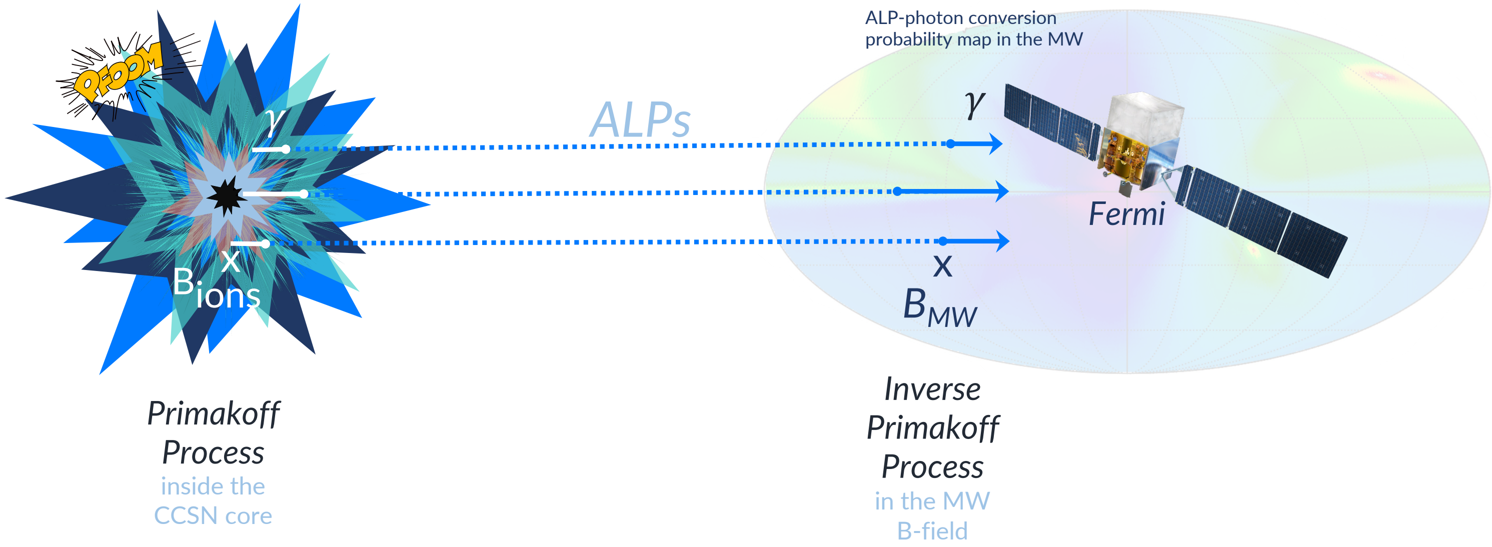
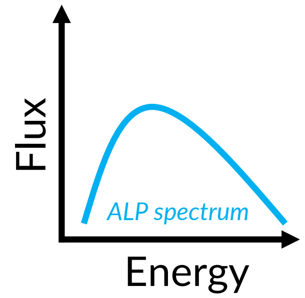
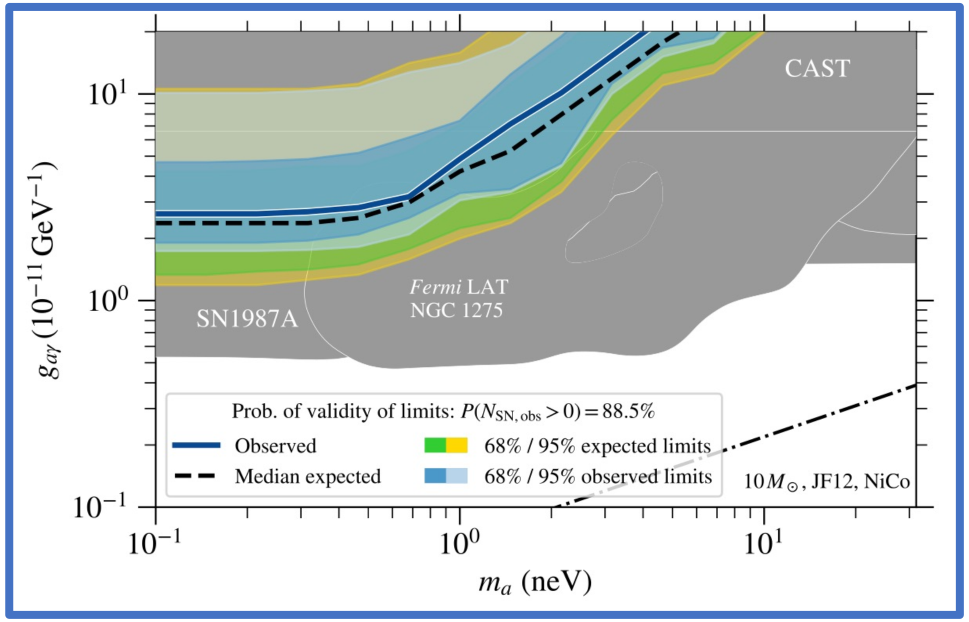
CCAPP Seminar
The Ohio State University
September 13, 2022

Image: Neutron Star Merger Seen in Gravity and Matter. Credit: Karan Jani/Georgia Tech



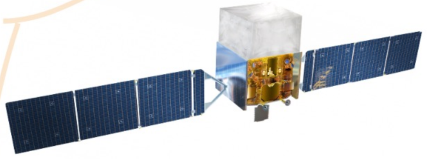


Axion-like particles with *Fermi* & future instruments



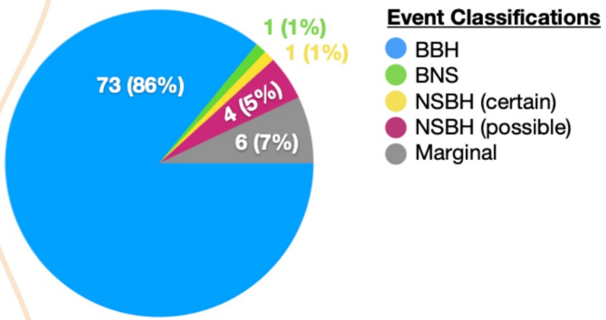
Exclusion plot for ALPs. [Meyer & Petrushevska 2020]

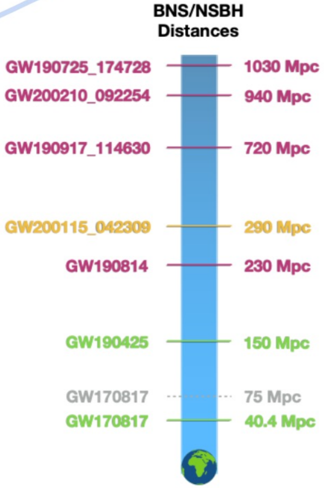
Gamma-ray counterparts to O3 gravitational-wave events with Fermi-GBM and Swift-BAT



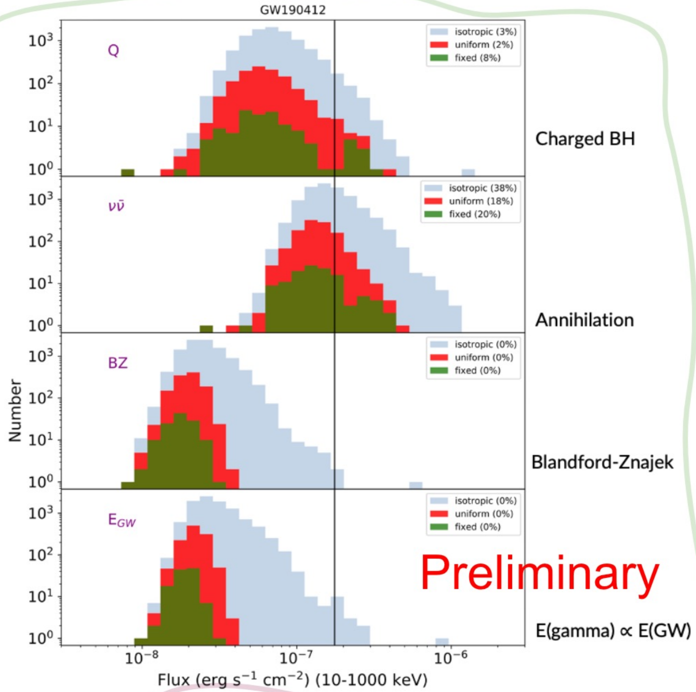
Why *Fermi* GBM?

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





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



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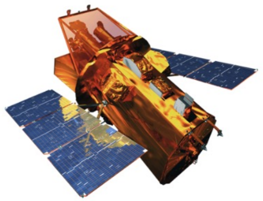
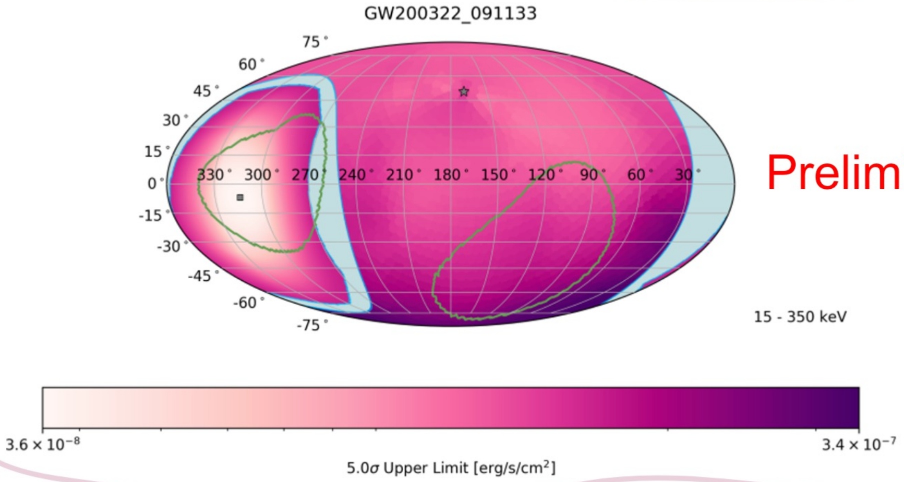
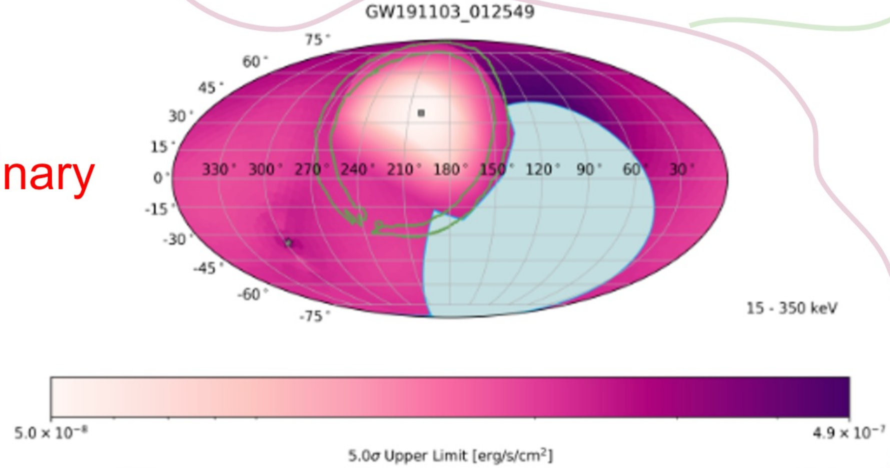


Why *Swift* BAT?

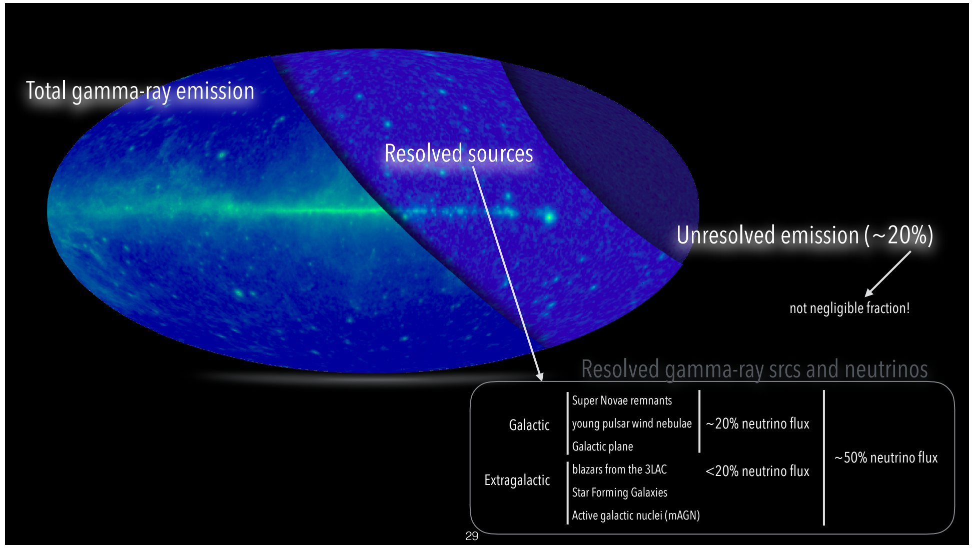
+ excellent localization sensitivity (~arcminute for detected GRBs)
+ energy coverage overlaps with the low-energy end of *Fermi* GBM



Preliminary



Cross-correlating astrophysical neutrinos & *Fermi* unresolved gamma-ray sky



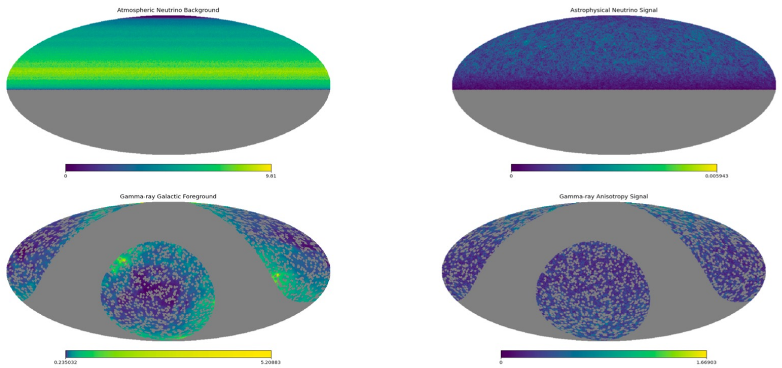


Fig. 7.— All-sky expected counts maps, in counts per 0.458$^{\circ 2}$ pixel (HEALPix nside=128) for simulated atmospheric neutrino (top left), astrophysical neutrino (top right), galactic gamma-ray foreground (bottom left) and gamma-ray signal (bottom right). The grey regions mark the masked pixels. See e.g. (Fang et al. 2020) for details on mask choice.

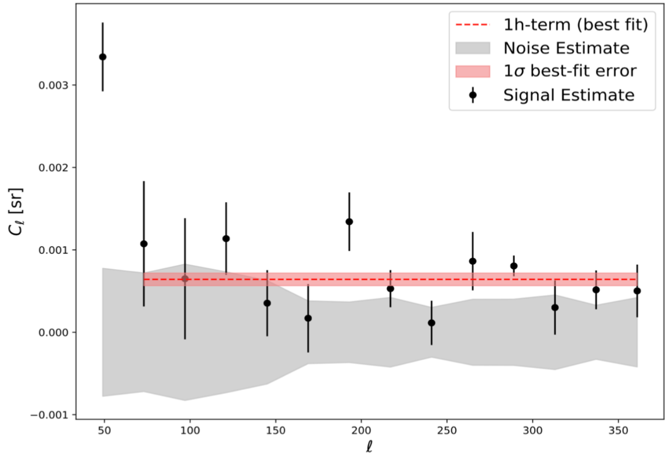


Fig. 8.— Comparison of expected signal and noise levels for cross-correlation of simulated 10-year neutrino data with gamma-ray data. The red dashed line and the red shaded band are the best fit and the relative 1σ error for a 1halo-term component, as described in the *halo model* formalism (Cooray & Sheth 2002).

GRAD MAP

Graduate Resources Advancing Diversity with Maryland Astronomy and Physics

umdgradmap.org

grad-map@umd.edu

mentoring MAP program

UMD ASTRO

ACE

Astronomy Community Engagement

UMD ASTRO

BANG! (Better Astronomy for a New Generation!)

Speaker: Professor Jim Gates (UMCP Physics)
Title: Equity Versus Excellence: A False Dichotomy in Science and Society

Speaker: Mangala Sharma (NSF)
Title: Astronomy and Science Diplomacy

Speaker: Gina Quan and Stephen Secules
Title: Using Student Perspectives to Understand Equity in STEM Education

Speaker: Maggie McAdam (UMD)
Title: Technology and Belonging on Campus: Perspectives from Underrepresented Students

Speaker: Alexis Williams, Ph.D. & Courtney Cook, M.S. (UMD/TLTC & Women's Studies)
Title: Pro-Disability Teaching: Removing the Deficit Model

Speaker: Kory Kreimeyer (FDA)
Title: Data Science at the FDA

Speaker: Dr. Rachel Ivie and Dr. Anne Marie Porter (AIP/SRC)
Title: "The Representation and Retention of Women in Physics and Astronomy"

Speaker: UMD Office of Diversity & Inclusion
Title: How to Have Crucial Diversity Conversations

Speaker: Patrick Banner and Adam Ehrenberg
Title: Mental Health Task Force

Speaker: Kelly Fast (NASA HQ)
Title: "Lemons are for Lemonade"

Speaker: Various + Special Guest Dr. Daus
Title: Thirty Meter Telescope Discussion III

Speaker: Laura Blecha (UMD)
Title: Why Science is Political

Speaker: Dr. Jeffrey Silverman (Samba TV, Data Scientist)
Title: From Astrophysics to Data Science

Speaker: Pradip Gatkine, Carolyn Kierans, Nathan Roth, Geoffrey Ryan, Eliza Kempton, Drake Deming
Title: "Postdoc Panel: Applying for Postdoc Positions in Astronomy"

Speaker: William Sedlacek, PhD (Prof Emeritus UMD)
Title: Limitations of the GRE and GPA in Selecting and Evaluating Graduate Students: What Alternatives are There?

Full schedule of past seminars: https://www.astro.umd.edu/events/past/bang/

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An Exploration of the High-energy Universe

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Image: Neutron Star Merger Seen in Gravity and Matter. Credit: Karan Jani/Georgia Tech

TODAY…

- an exploration of the physics beyond the Standard Model: axion-like particles & gamma-ray bursts with *Fermi*
- offline, subthreshold searches for gravitational-wave counterparts with *Swift* and *Fermi*, and
- cross-correlation studies between astrophysical neutrinos and the gamma-ray sky

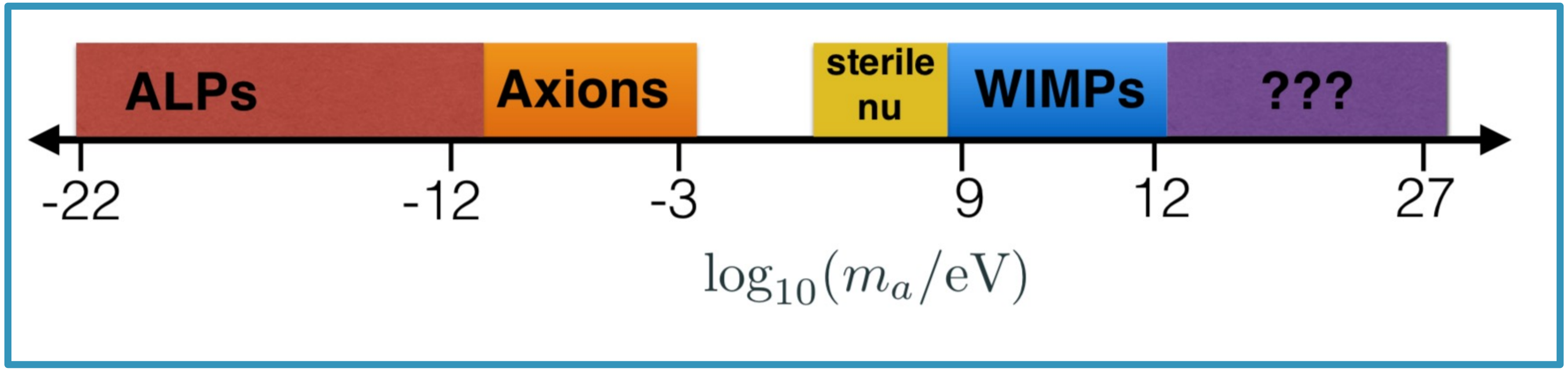
AN EXPLORATION OF THE PHYSICS BEYOND THE STANDARD MODEL: AXION-LIKE PARTICLES & GAMMA-RAY BURSTS WITH *FERMI*

- 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. Sneak Peak: *Fermi*-LAT GRB pre-cursor analysis

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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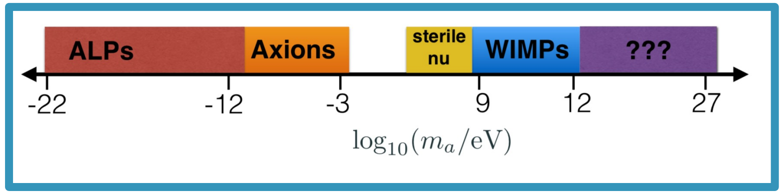
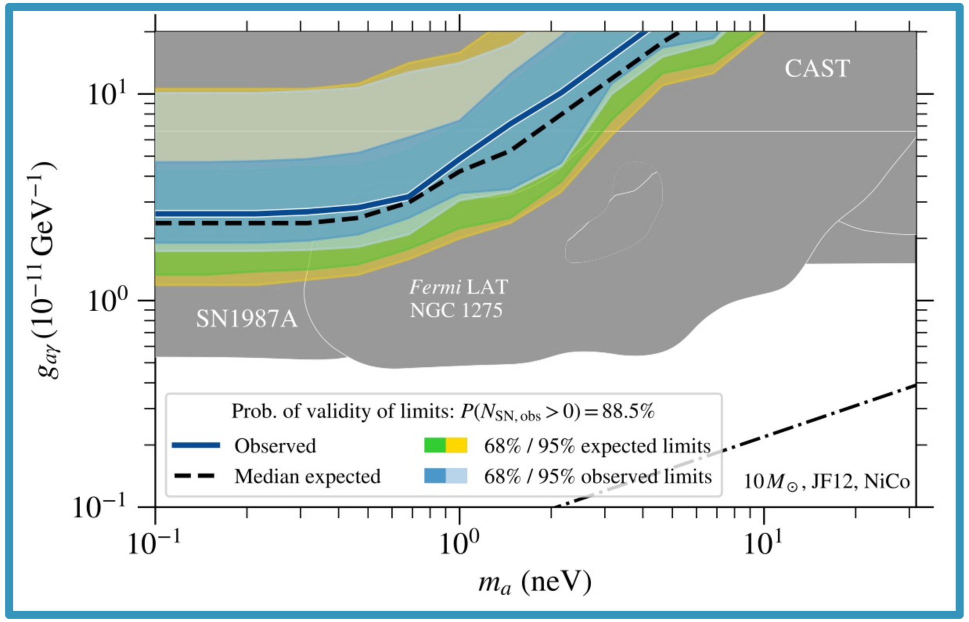


- <u>Cold</u> matter requirements:
  - ✓ feeble interactions with standard model particles
  - ✓ cosmological stability

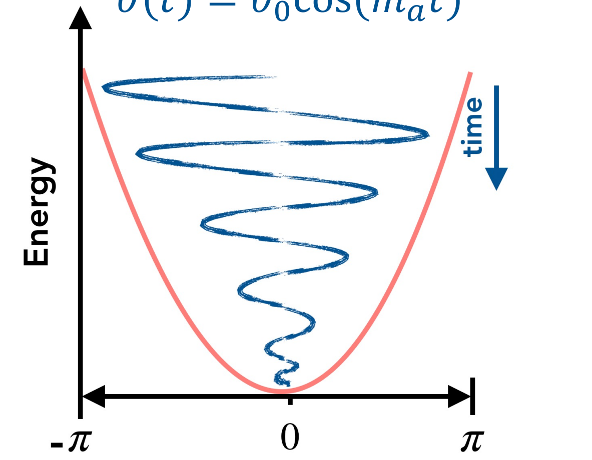
- Direct and indirect searches → limits on coupling/mass parameter space

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



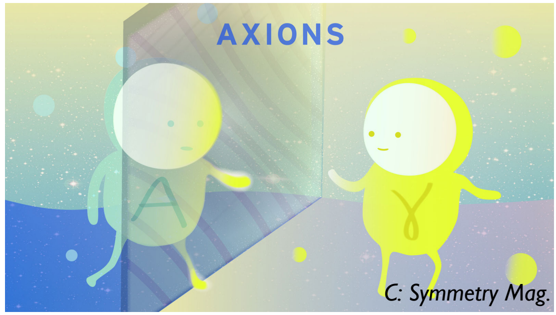
Exclusion plot for ALPs. [Meyer & Petrushevska 2020]

$$\theta(t) = \theta_0 \cos(m_a t)$$



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

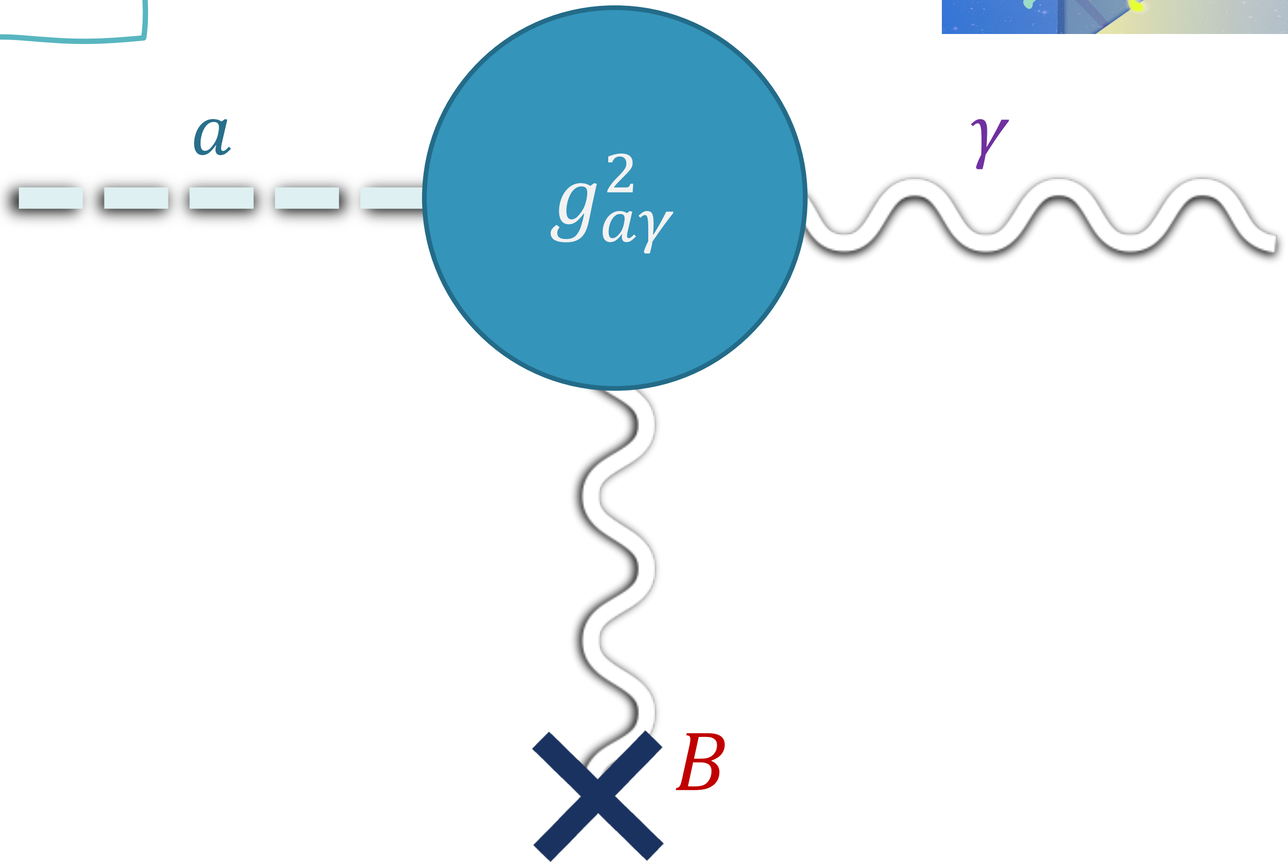
OBSERVING ALPs WITH GAMMA-RAYS



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

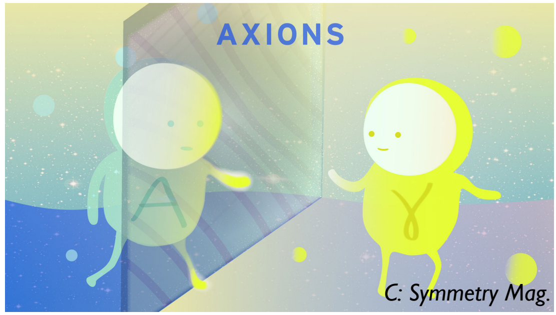
$$\mathcal{L}_{a\gamma} \supset -\frac{1}{4} g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

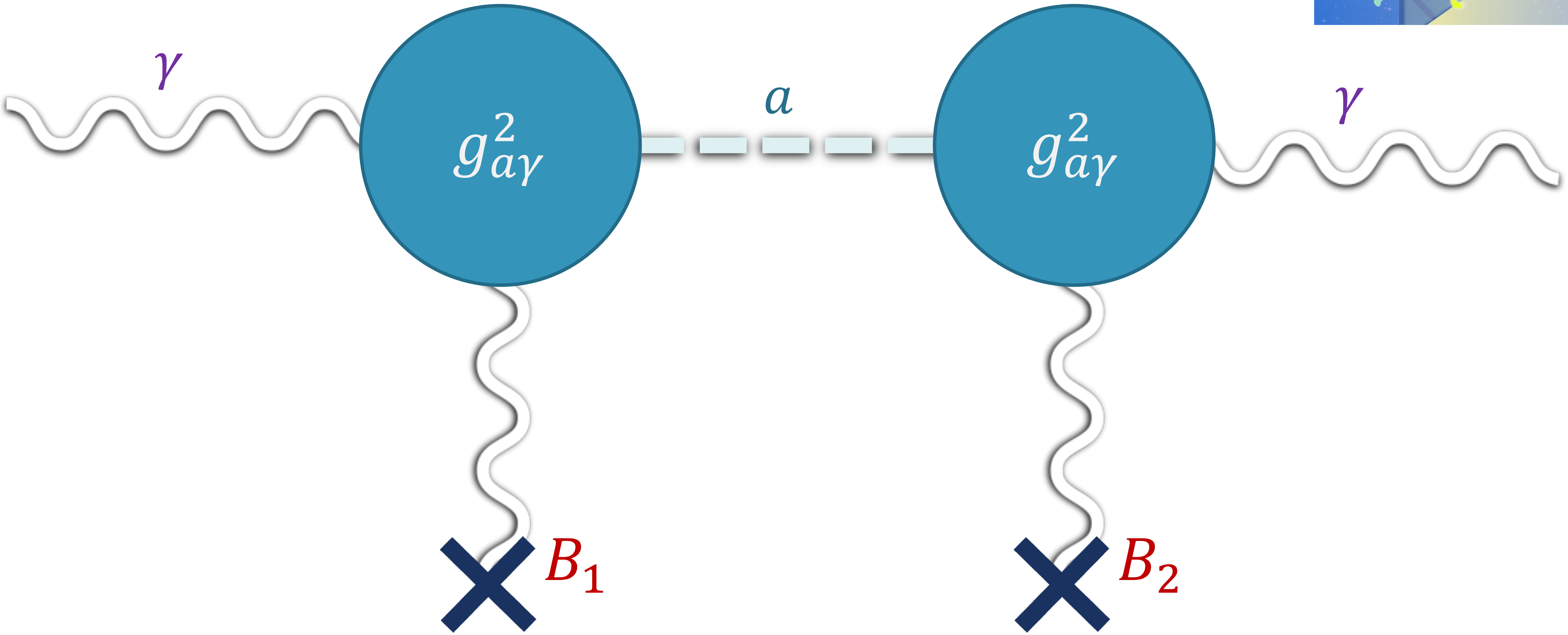
where $g_{a\gamma}$ is ALP-photon coupling rate, and a is the axion field strength.



[e.g. Raffelt & Stodoslky 1988]

OBSERVING ALPs WITH GAMMA-RAYS





(production: Primakoff effect)

(detection: inverse Primakoff effect)

[e.g. Raffelt & Stodoslky 1988]

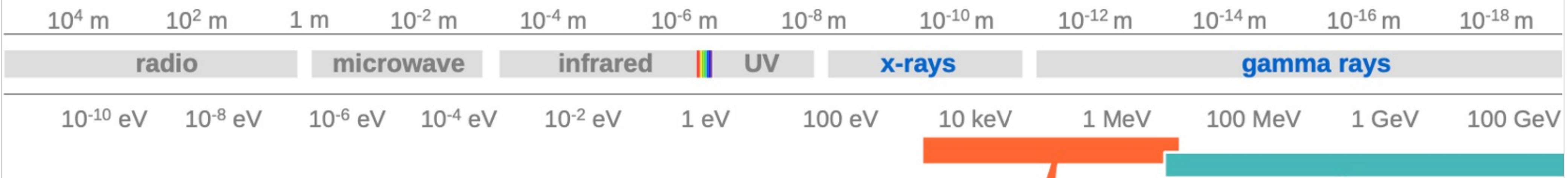
TAKE-AWAY POINTS ABOUT ALPs

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

HOW FAR CAN FERMI SEE?

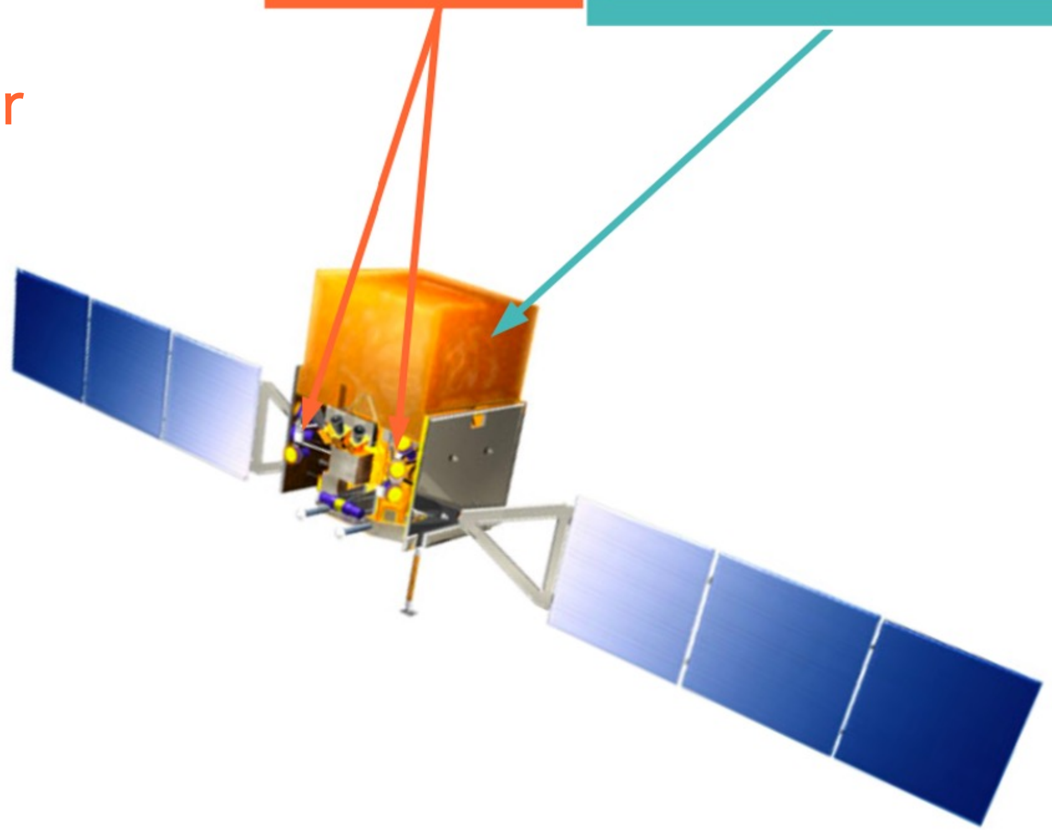
Axion-like Particles from Core-collapse Supernovae: Investigating *Fermi* Sensitivity with the LAT Low-energy Technique

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



GBM Gamma-ray Burst Monitor

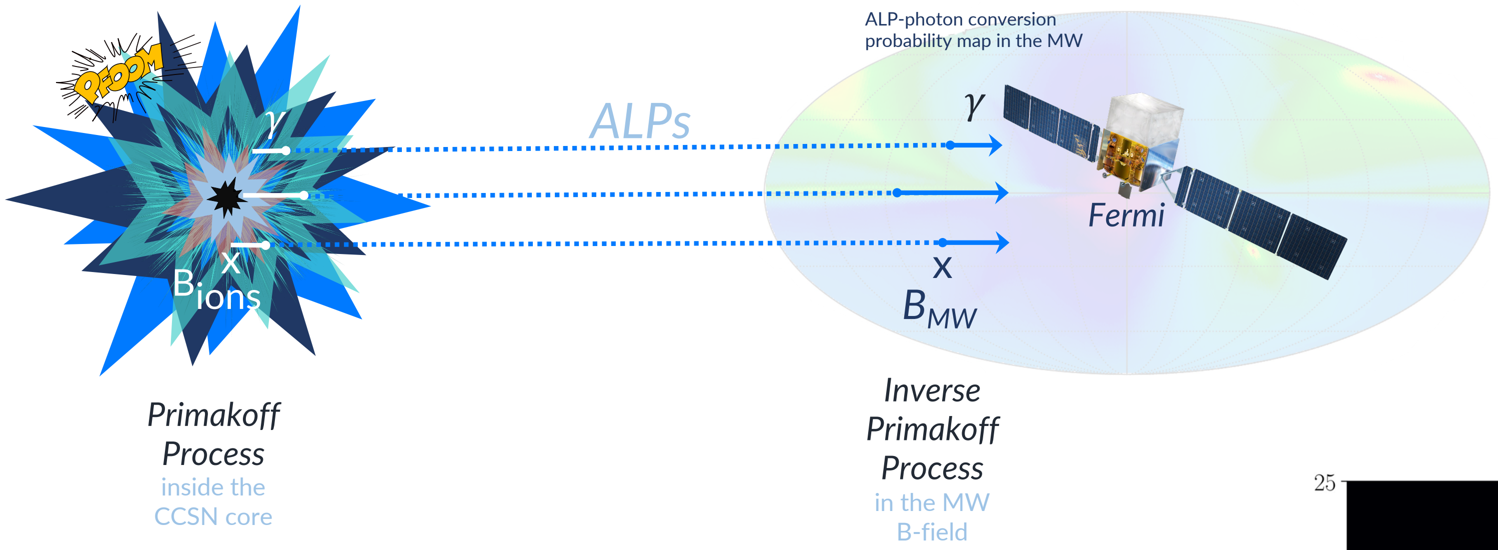
12 (NaI) + 2 (BGO) detectors
FoV: entire unocculted sky
8 keV to 40 MeV
~1500 bursts (~1 every day or two)

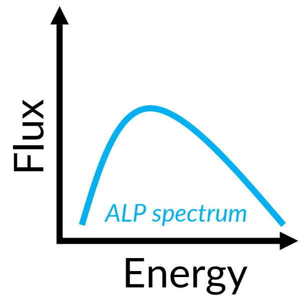


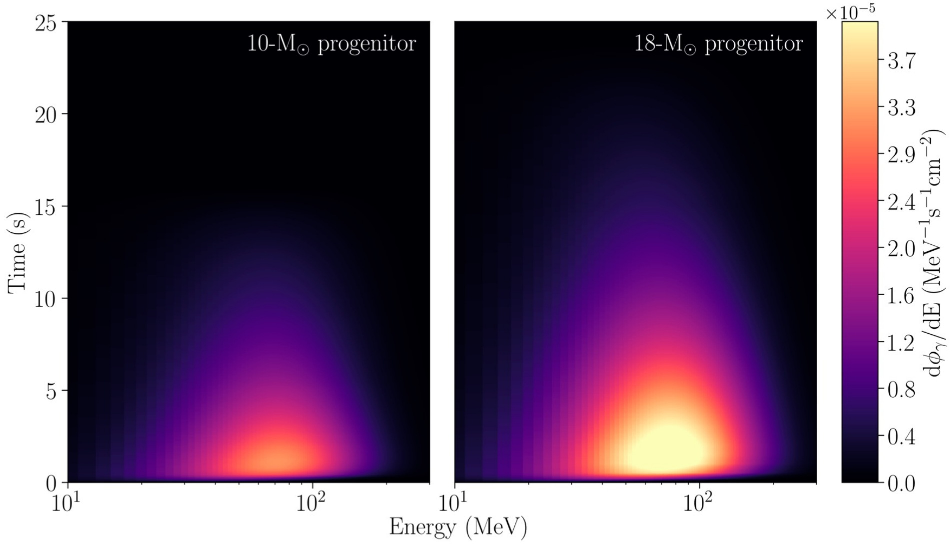
LAT Large Area Telescope

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

MOTIVATION AND ASSUMPTIONS

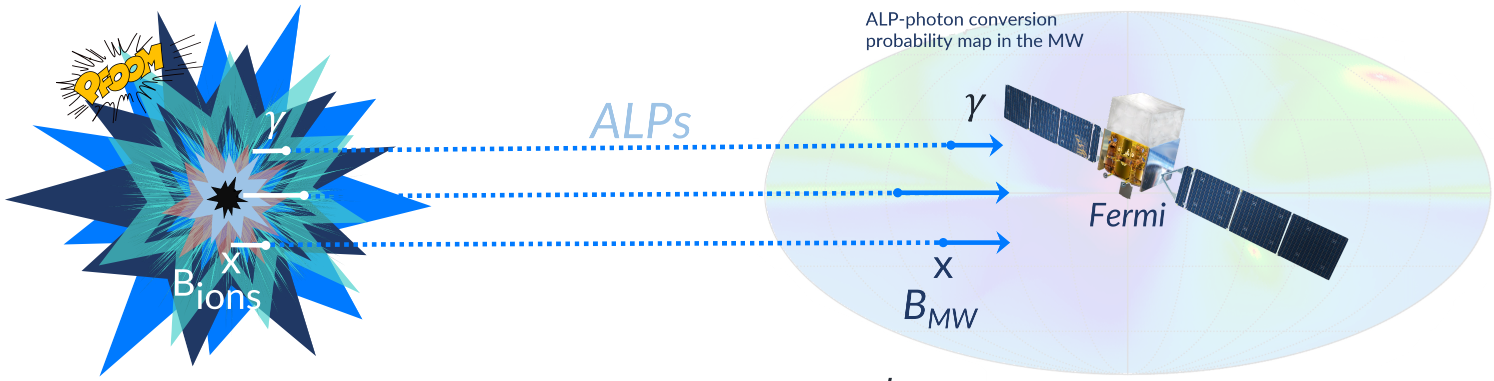






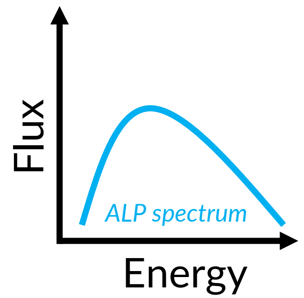
Observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a 10 and 18-M⊙ progenitor.

MOTIVATION AND ASSUMPTIONS

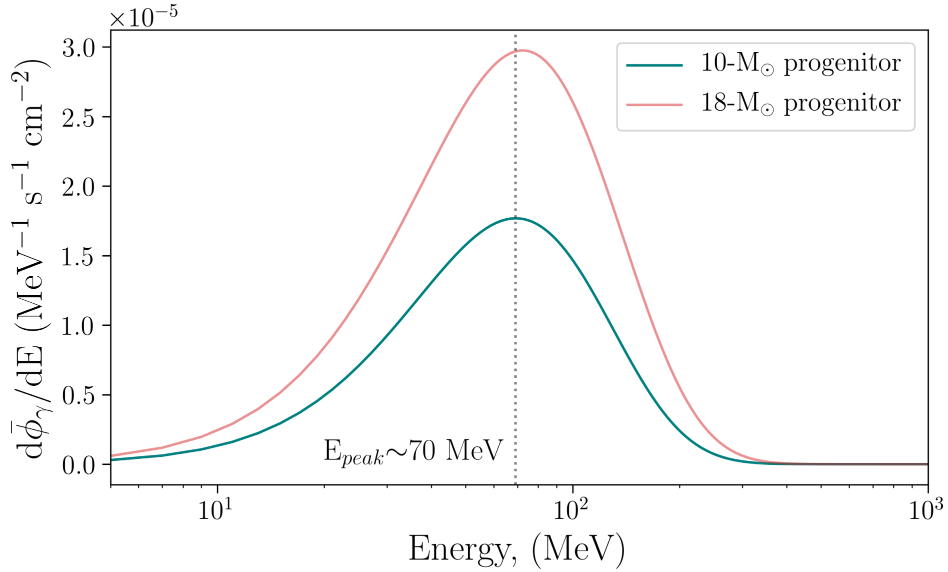


Primakoff Process
inside the CCSN core

Inverse Primakoff Process
in the MW B-field

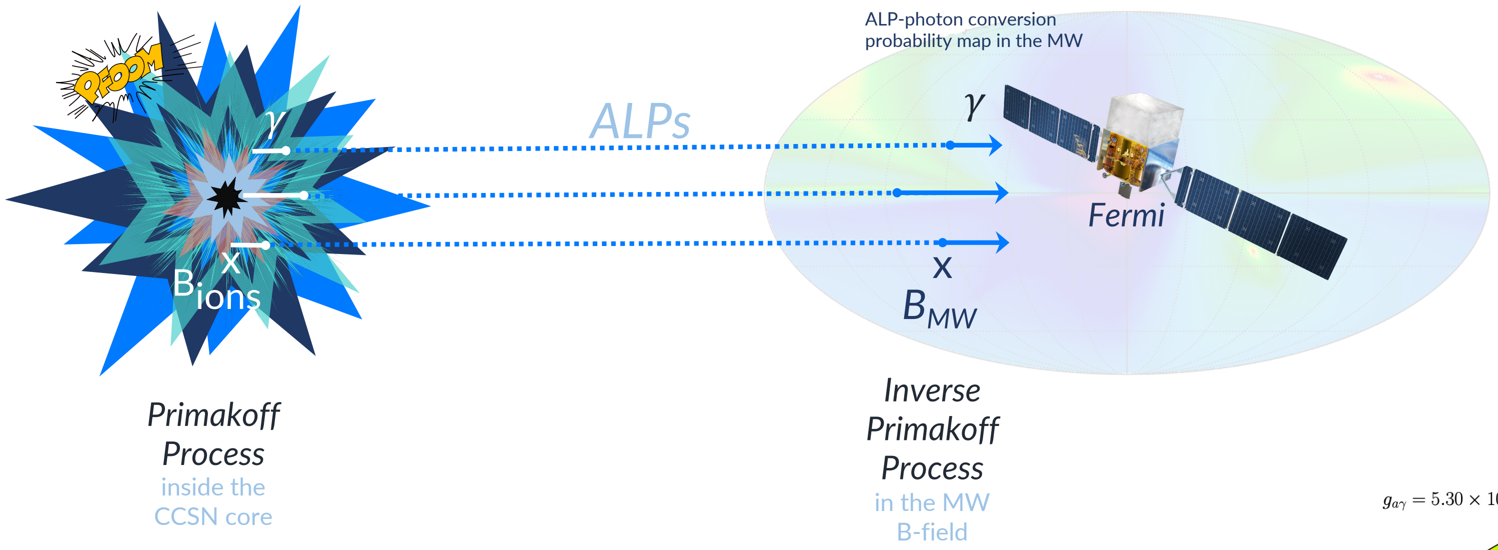


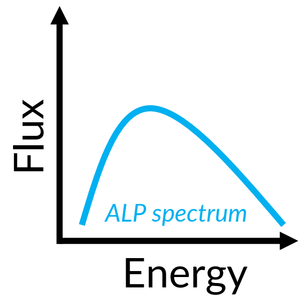
- **Motivation:** ALPs are theorized to have a unique spectral signature in the gamma-ray spectrum of a CCSN. No other known physical processes are predicted to produce such signature.



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

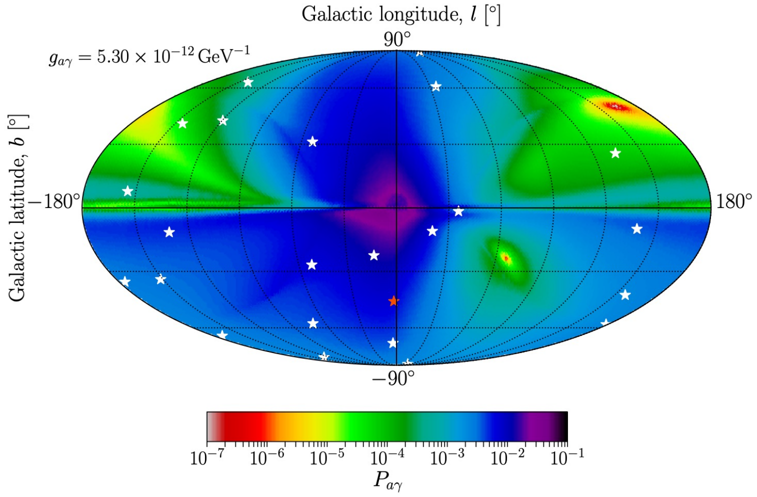
MOTIVATION AND ASSUMPTIONS



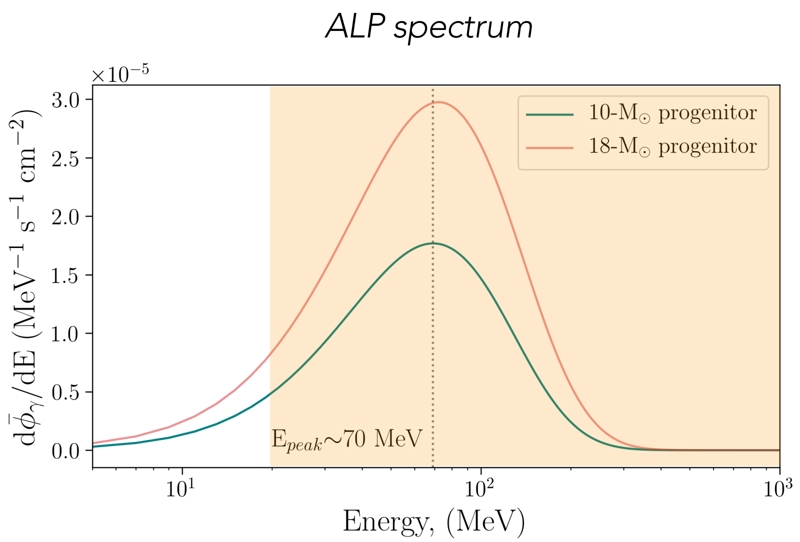


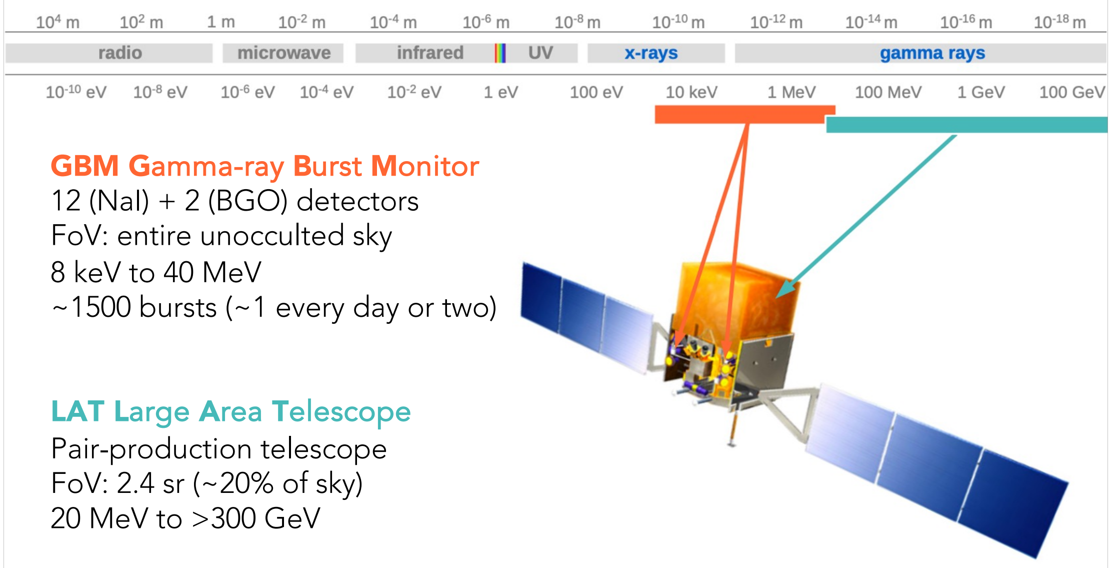
- **Motivation:** ALPs are theorized to have a unique spectral signature in the gamma-ray spectrum of a CCSN. No other known physical processes are predicted to produce such signature.
- **Assumptions:**

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.

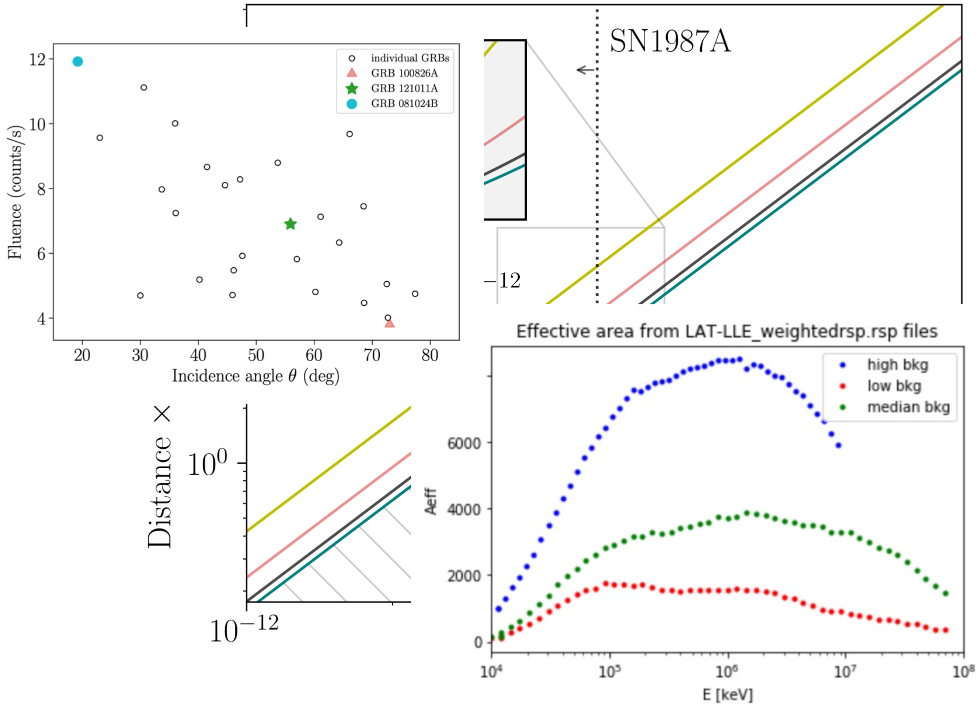
Find the min, max, and median background levels.

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.



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

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?*

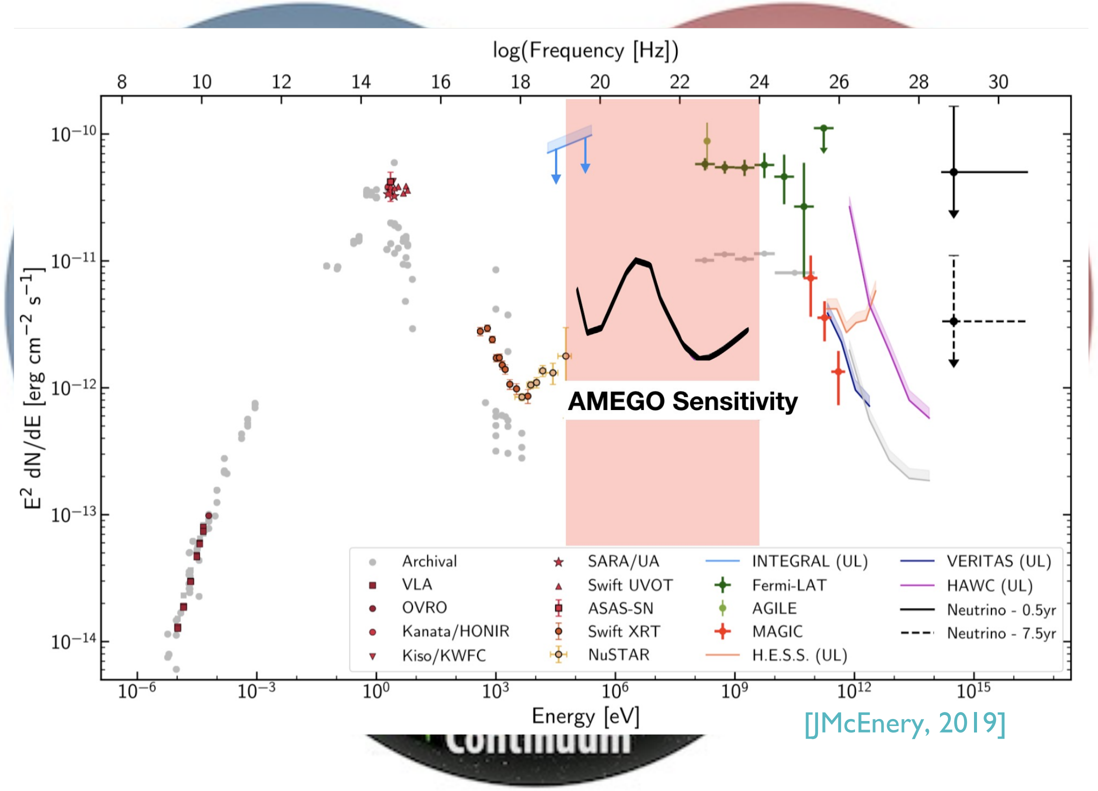
- **Tools:** a developed pipeline for calculating distance limits for the current and future gamma-ray instruments for the given ALP mass and coupling
- **Novel results:** using a transient data class as observed by *Fermi* to probe its sensitivity. Results are consistent with the analysis using the 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

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]

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levels comparable to LAT in the l

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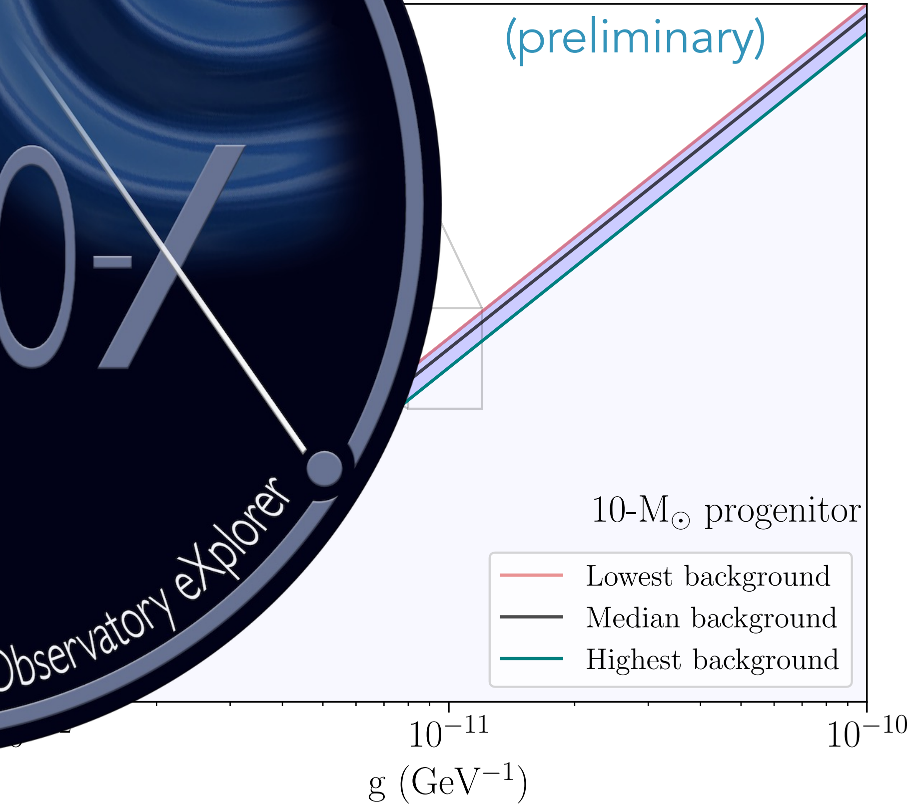
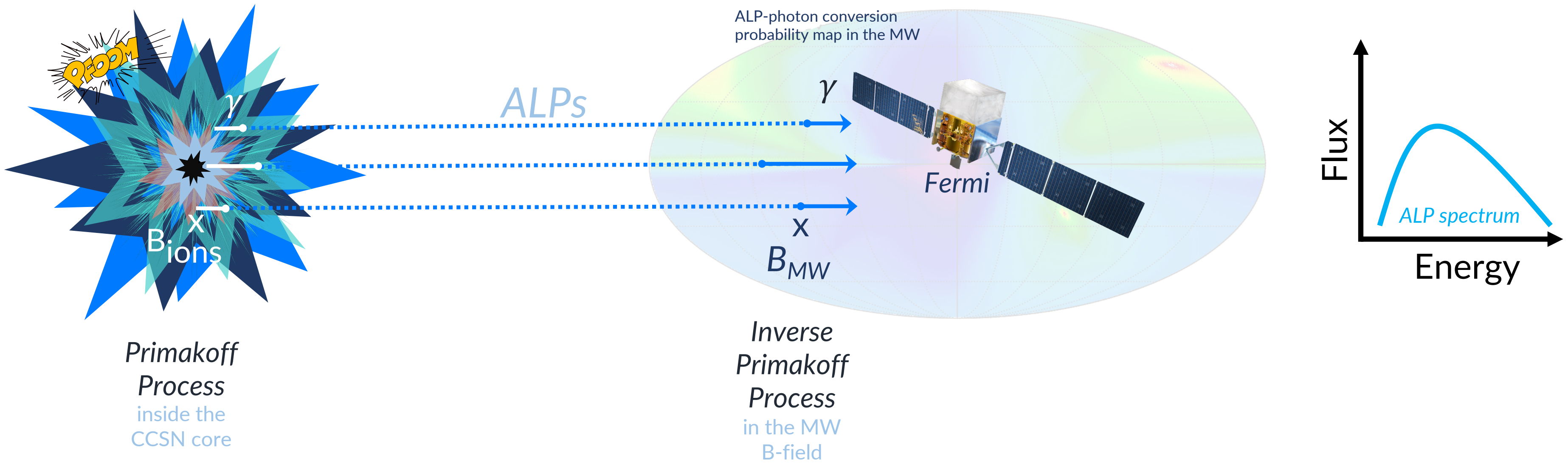


TALK OUTLINE

- 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
- Conclusions & future work

MOTIVATION AND ASSUMPTIONS



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)

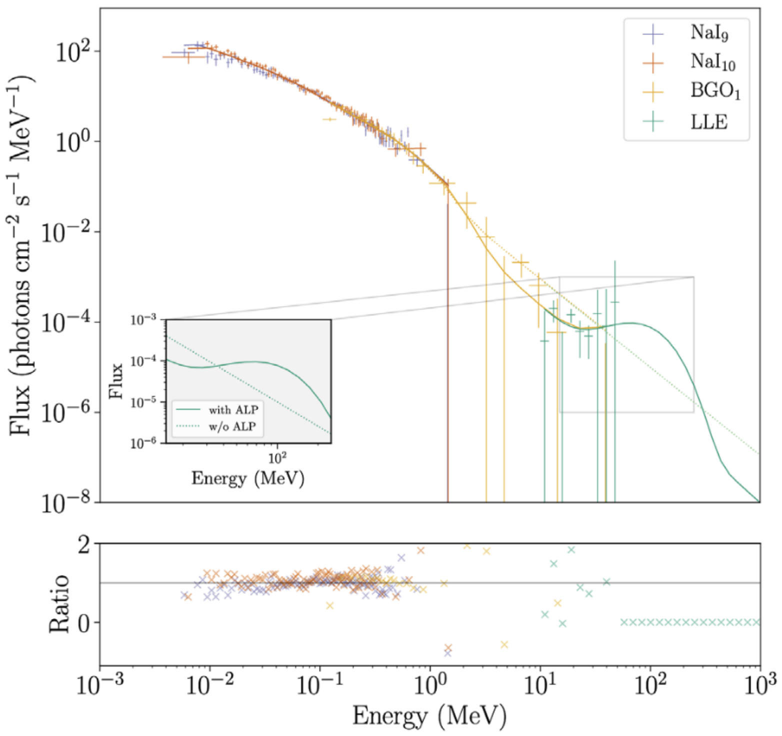
Initial sample: 186 LAT-detected GRBs

Applying the selection criteria

24 GRBs

GRB ANALYSIS RESULTS

			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.

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
- Conclusions & future work

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

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 (PI: Crnogorčević)

GOALS

Precursor emission in Fermi-detected GRBs: a comprehensive search for ALP signatures in different time windows

- Multiple theoretical models have been proposed to address the question of precursor emission in GRBs, none conclusive [e.g., Koshut et al. 1995, Lazzati et al. 2005, Burlon et al. 2008, Troja et al. 2010, Tsang et al. 2011, Coppin et al. 2020]
- We propose that the precursor emission **may be accounted for by ALPs**
- <u>Assumption: that the ALP breakout time corresponds to the pre-cursor time tag</u>

- Goals:

1. Determine whether an addition of an ALP model component improves the fit for the GRB precursor emission in the LLE data
2. Compute constraints on the ALP parameter space from a consideration of LAT/LLE emission at the time of the expected precursor

WHAT HAVE WE DONE SO FAR?

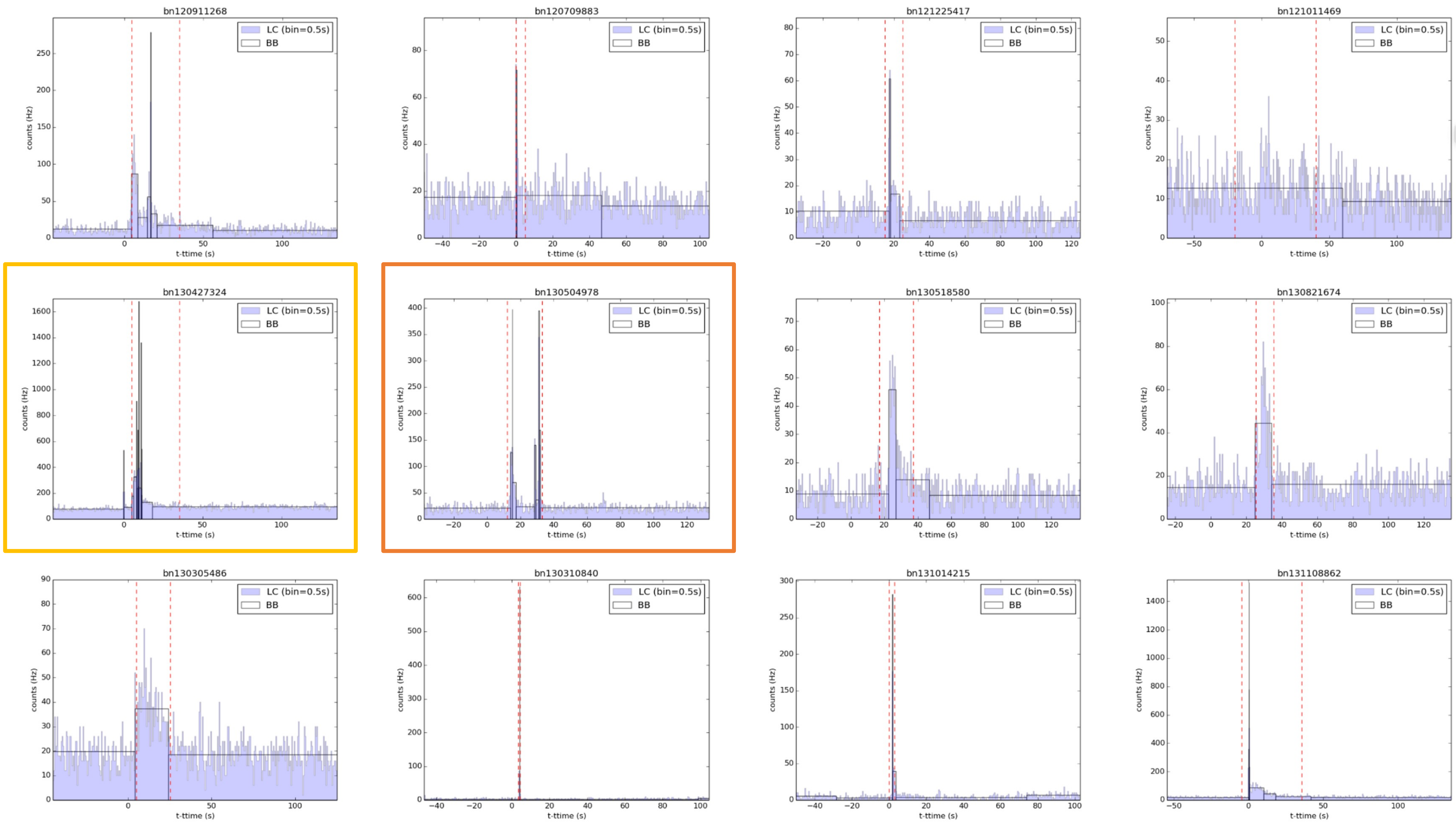
Bayesian Block Analysis on the LLE-detected GRBs

- Using the code developed by Vianello 2014
- 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_{FoV} to T_0 – 10 sec] [Zhang et al. 2019]
    - T_{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 +/- 400 s])

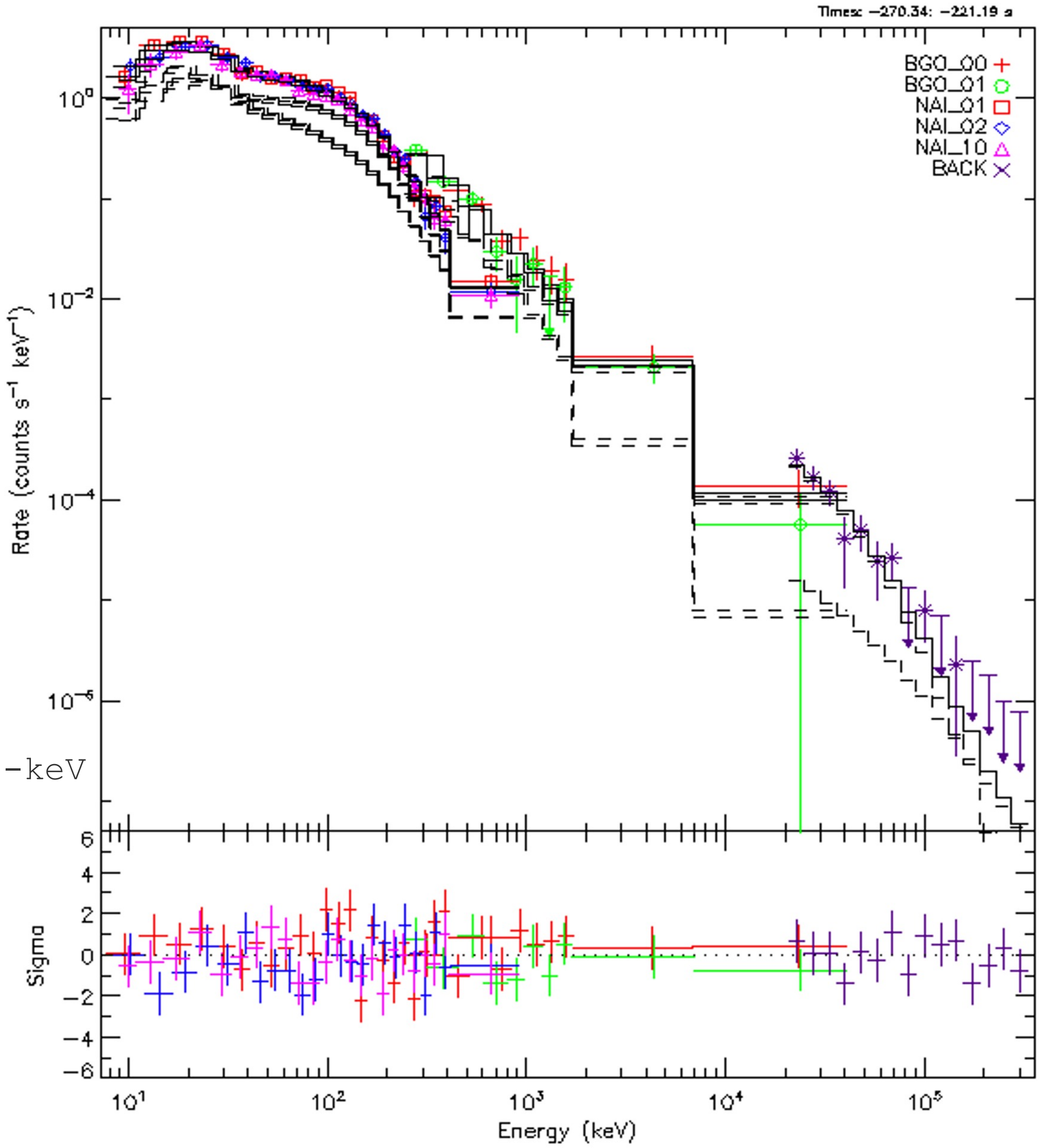


Preliminary

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-cm2-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 (we should not expect ALP emission)
- 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

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

Selection criteria:

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

→ 9 LAT bursts, 12 GBM bursts

SUMMARY OF ALP SEARCHES

- 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!

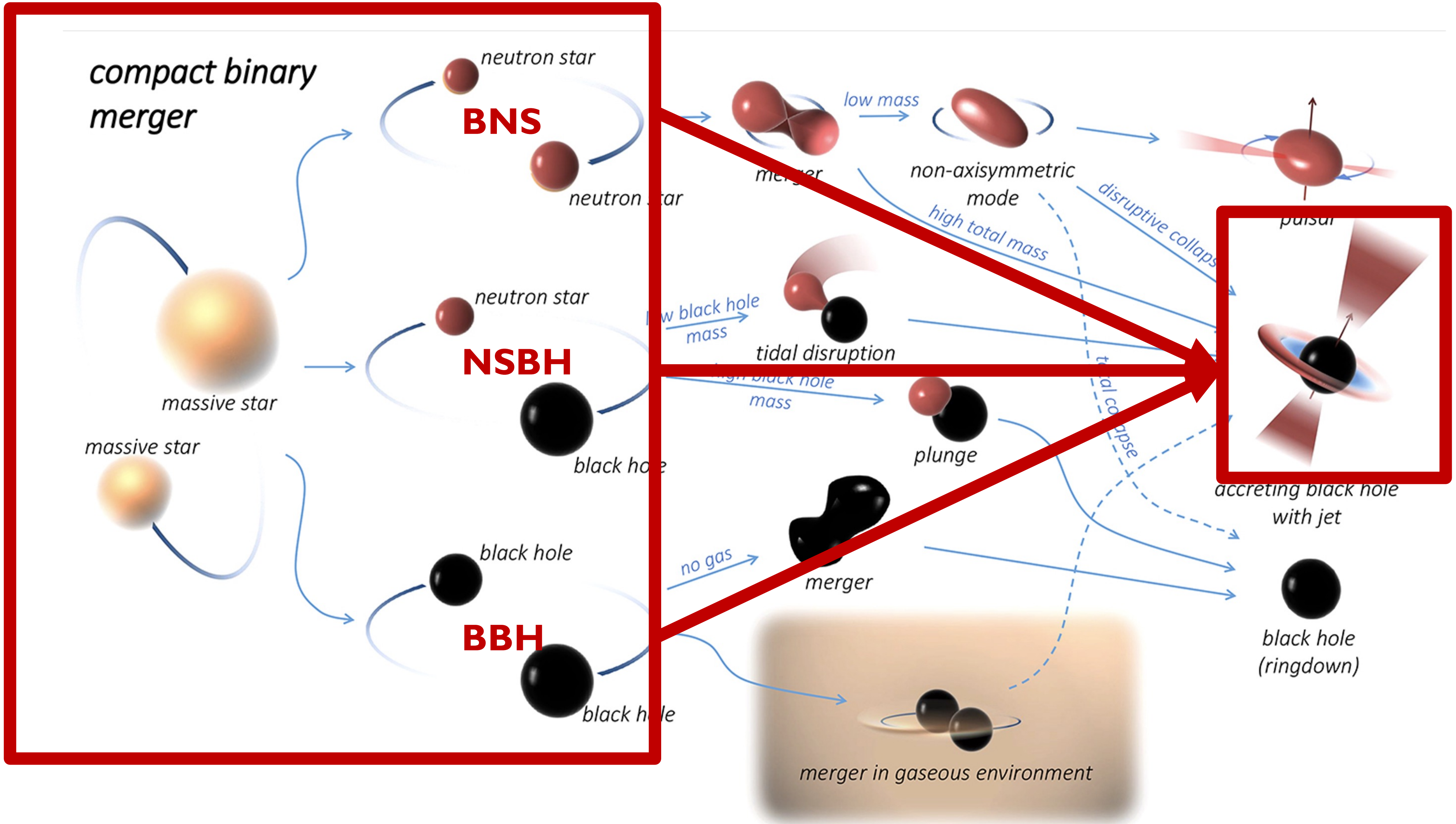
TODAY…

- an exploration of the physics beyond the Standard Model: axion-like particles & gamma-ray bursts with *Fermi*
- offline, subthreshold searches for gravitational-wave counterparts with *Swift* and *Fermi*, and
- cross-correlation studies between astrophysical neutrinos and the gamma-ray sky

OFFLINE, SUBTHRESHOLD SEARCHES FOR GRAVITATIONAL-WAVE COUNTERPARTS WITH *SWIFT* AND *FERMI*

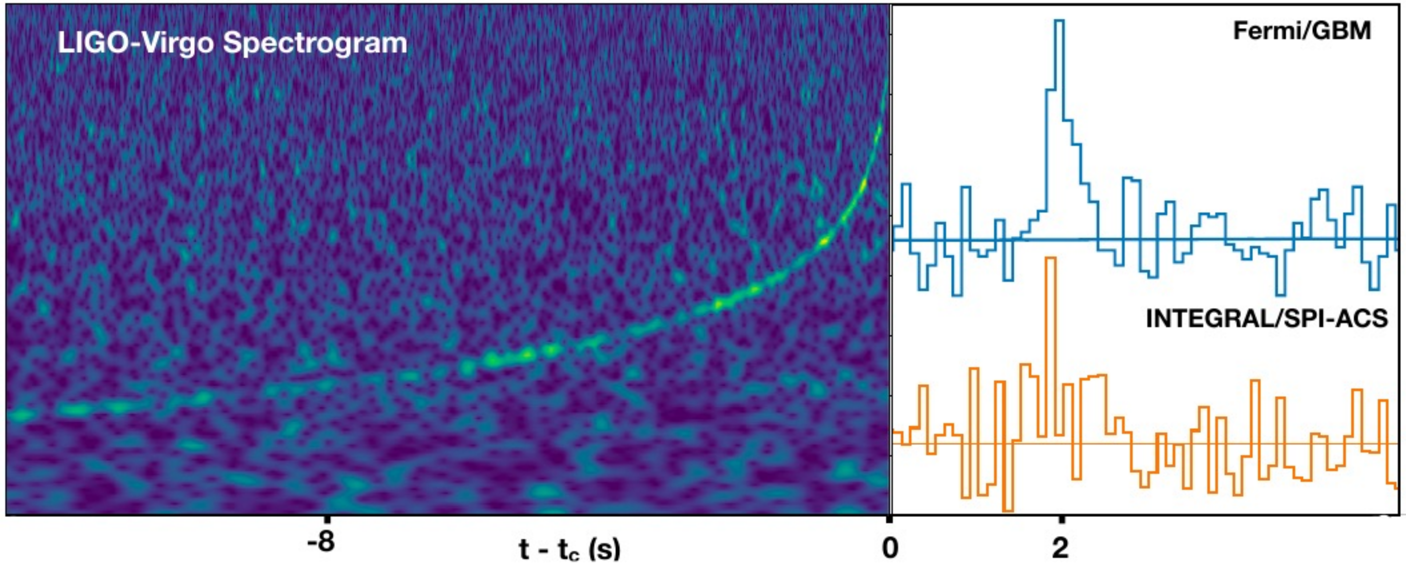
- Introduction and motivation: GW170817 & GRB 170817A
  1. *Swift* BAT Analysis
  2. *Fermi* GBM Analysis
  3. Combining the results
  4. Binary-black-hole systems: what can we learn?
  5. On the horizon…

WHERE TO SEARCH FOR GWs: COMPACT BINARY MERGERS

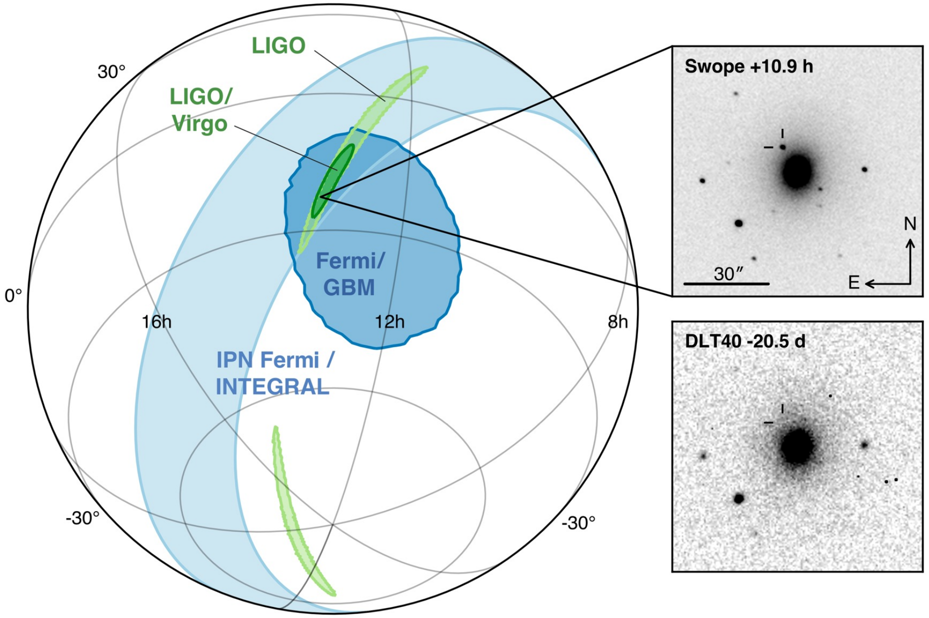


Bartos & Kowalski, 2017

GW 170817 & GRB 170817A

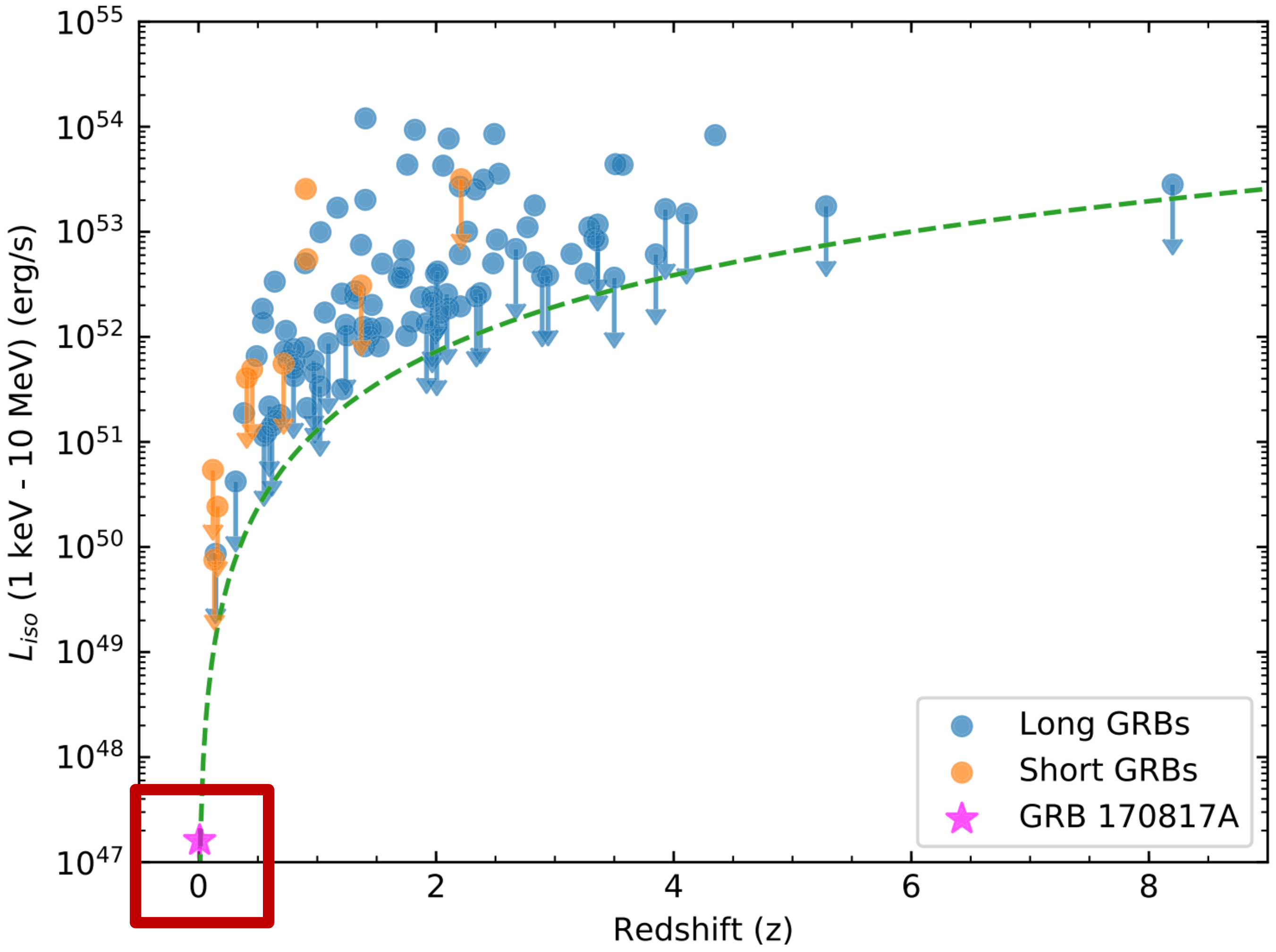


GW170817
[Abbott et al., 2017c]
GRB 170817A
[Goldstein et al., 2017,
Abbott et al., 2017b]



SSS17a
EM170817…
AT 2017gfo
[Abbott et al., 2017d]

GW 170817 & GRB 170817A



B. P. Abbott *et al* 2017 *ApJL* **848** L13

Intrinsically dim and but nearby (40 Mpc)

Off-axis viewing angle

GW170817 & GRB 170817A: THE STORY IT TOLD

Astrophysics & nuclear physics:

- Origin of heavy nuclei
- BNS physical system dynamics and the physics of kilanovae
- Jets and post-merger remnants
- Neutron-star equation of state
- Cosmology: speed of gravity, Hubble constant

Multimessenger Astronomy:

- Follow-up operations
- Setting up for the following observing run (O3)
- Renewed interest in multimessenger astronomy

GW170817 & GRB 170817A: WHAT'S LEFT TO UNDERSTAND?

Astrophysics & nuclear physics:

- Origin of heavy nuclei: **are BNS merger rates enough to account for the element abundance?**
- BNS physical system dynamics and the physics of kilanovae: **high-energy particle accelerators?**
- Jets and post-merger remnants: **jet physics?**
- Neutron-star equation of state: **?**
- Cosmology: speed of gravity, Hubble constant: **more independent measurements**

Multimessenger Astronomy:

- Follow-up operations
- Setting up for the next observing runs (O4, O5)
- Renewed interest in multimessenger astronomy

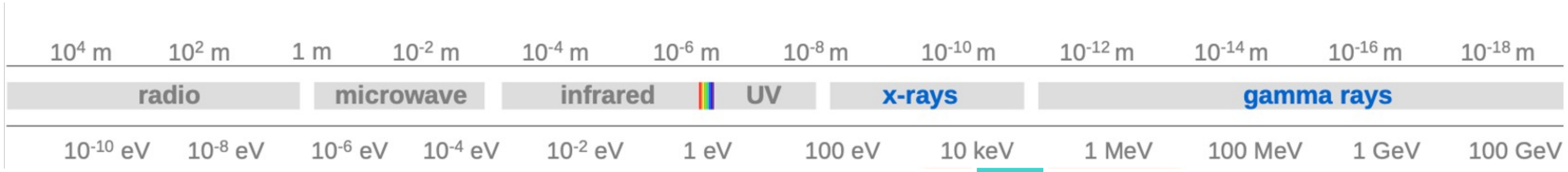
MOTIVATION FOR OUR PROJECT: more measurements!

- Since the coincident detection of gravitational waves from a binary neutron-star merger, (GW170817), and the corresponding short gamma-ray burst (GRB170817A), ***detecting an analogous event has been a critical research topic in the multimessenger community***
- The Third Gravitational Wave Transient Catalog (GWTC-3) provided an **8-fold increase** in the number of *likely-astrophysical* GW events

GOALS

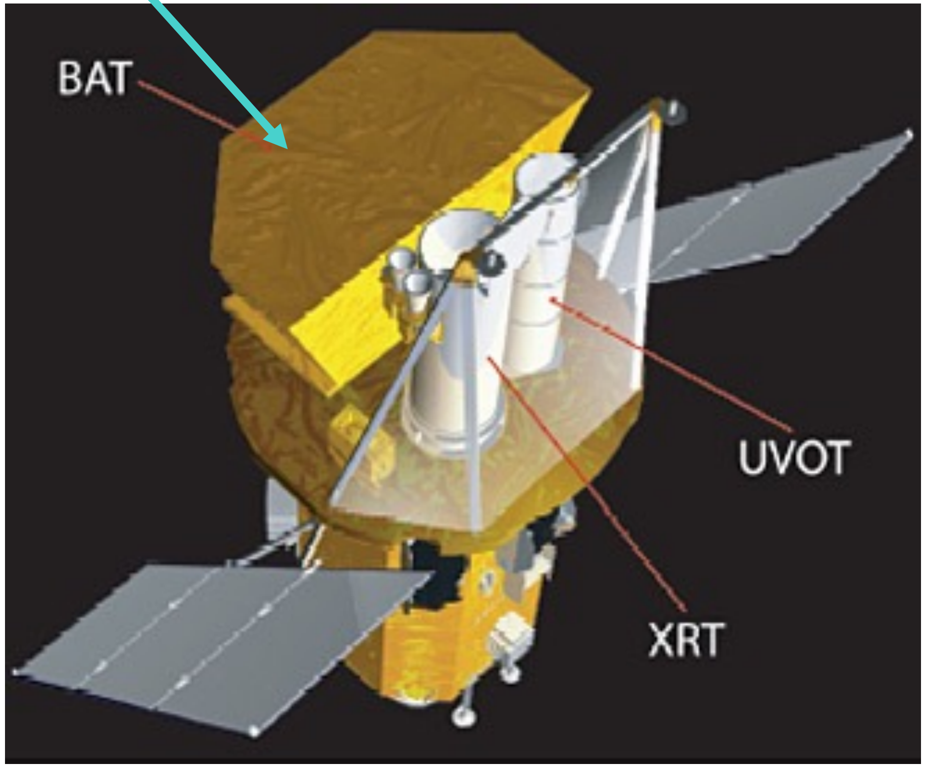
1. **Identify potential electromagnetic (EM) counterparts to GW triggers in GWTC-3 using data from the *Fermi* Gamma-ray Burst Monitor (GBM) and the *Swift* Burst Alert Telescope (BAT)**
2. **Constrain theoretical models for γ-ray emission from GW events**

SWIFT BURST ALERT TELESCOPE (BAT)

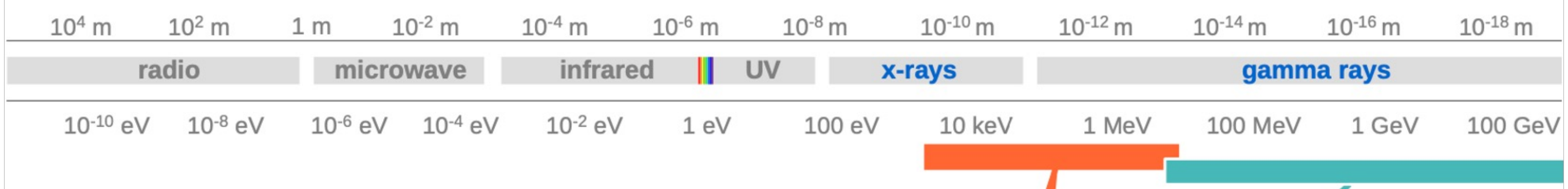


BAT Burst Alert Telescope

- One of three instruments onboard
- FoV: ~ 2 sr
- Localization ~few arcmin
- 15 keV to 150 keV
- On-board triggers + ground processing



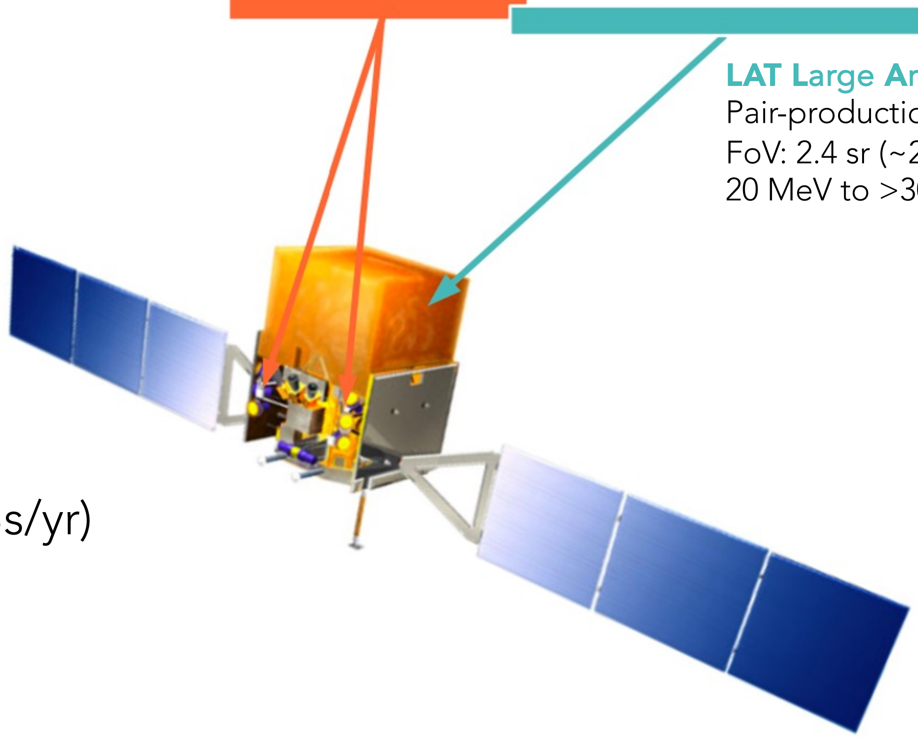
FERMI GAMMA-RAY BURST MONITOR (GBM)

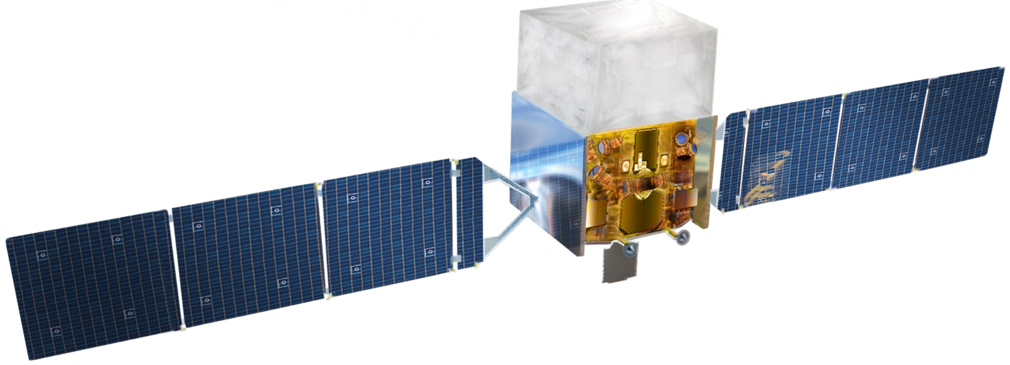


LAT Large Area Telescope
Pair-production telescope
FoV: 2.4 sr (~20% of sky)
20 MeV to >300 GeV

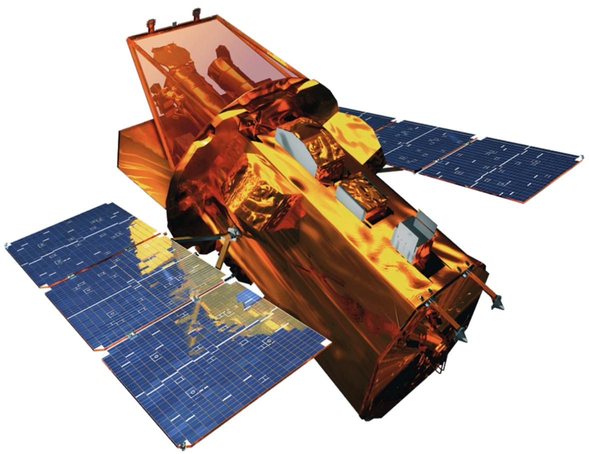
GBM Gamma-ray Burst Monitor

- 12 (NaI) + 2 (BGO) detectors
- FoV: entire unocculted sky (~8 sr)
- Covers the entire sky every ~90 min
- Localization ~few degrees
- 8 keV to 40 MeV
- ~240 GRBs/year (~40 sGRBs/yr, ~200 lGRBs/yr)





+



Why *Fermi* GBM?

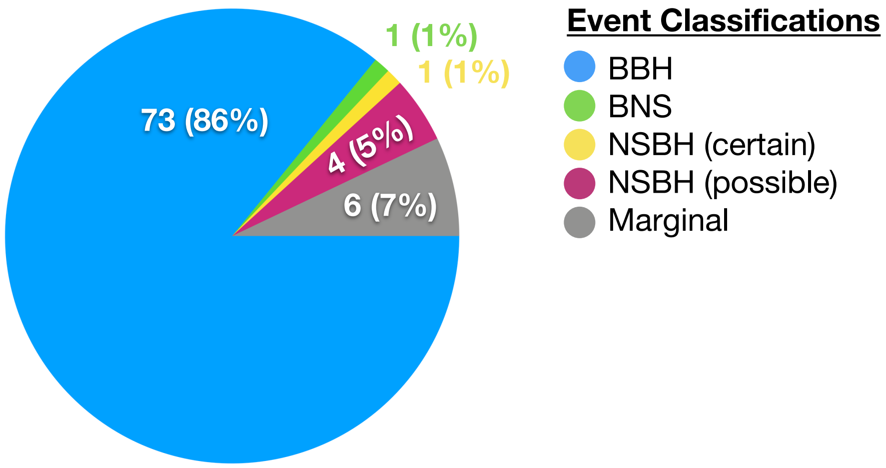
+ ~full-sky field of view
+ energy coverage spanning the peak of GRB emission

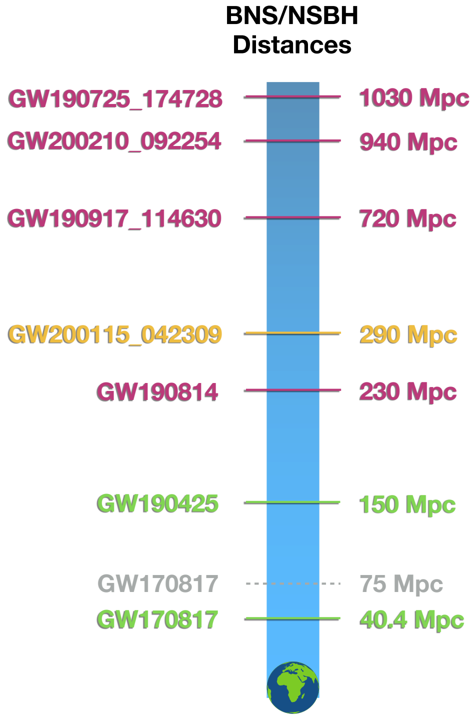
Why *Swift* BAT?

+ excellent localization sensitivity (~arcminute for detected GRBs)
+ energy coverage overlaps with the low-energy end of *Fermi* GBM

O3: THE THIRD OBSERVING RUN

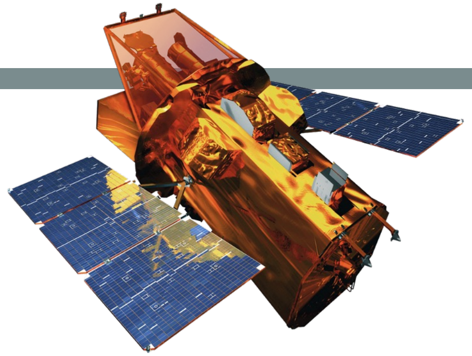
Third LIGO/Virgo observing run (O3): April 2019 -- March 2020 (commissioning break in October 2019)



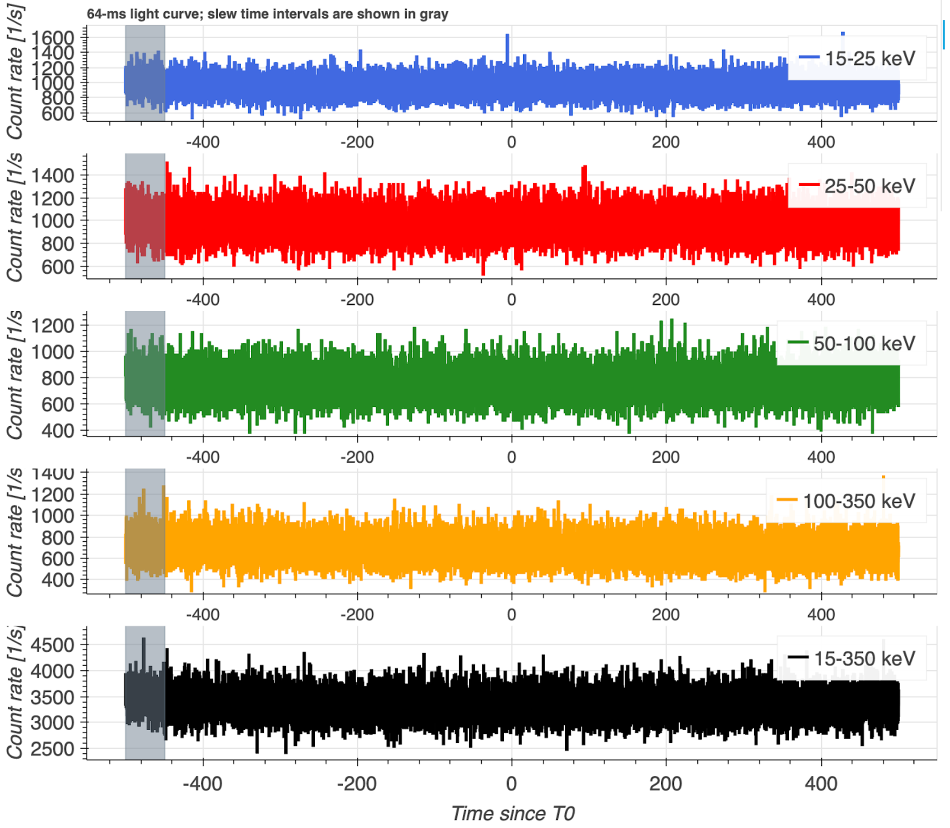


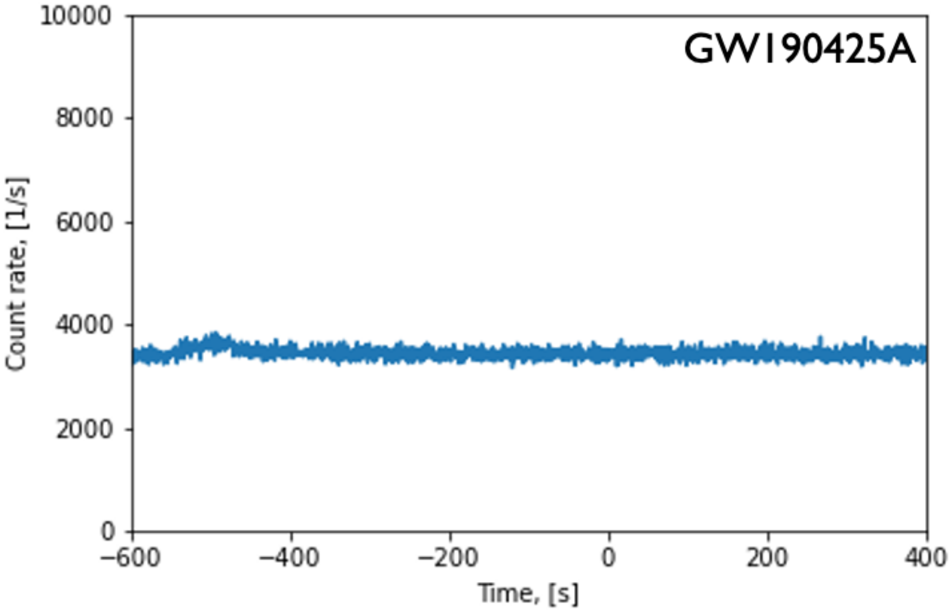
75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

FOLLOW-UP METHODS WITH SWIFT BAT



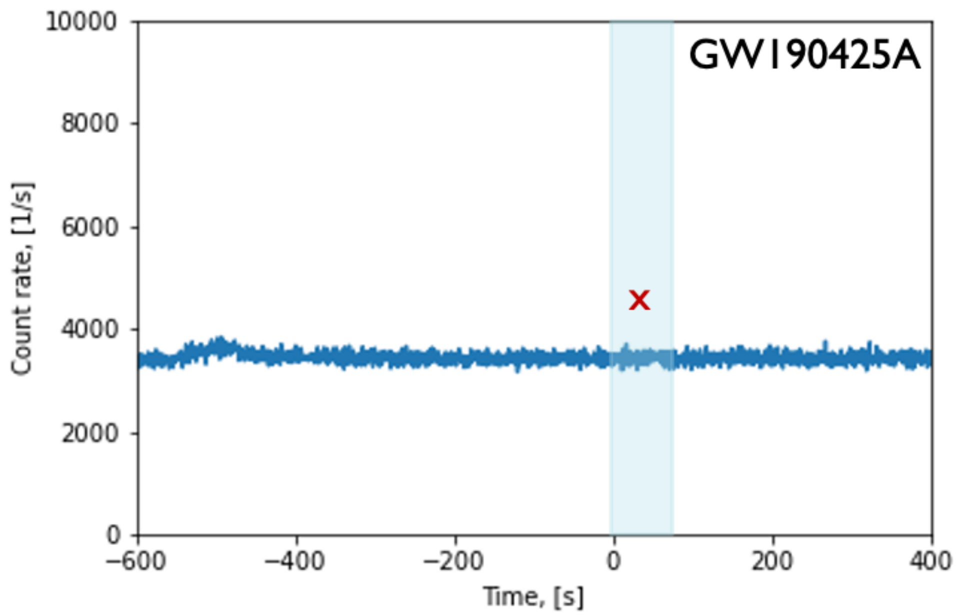
1. Extract BAT raw light curves in 64-ms time bins → rebin to 1 second





FOLLOW-UP METHODS WITH SWIFT BAT

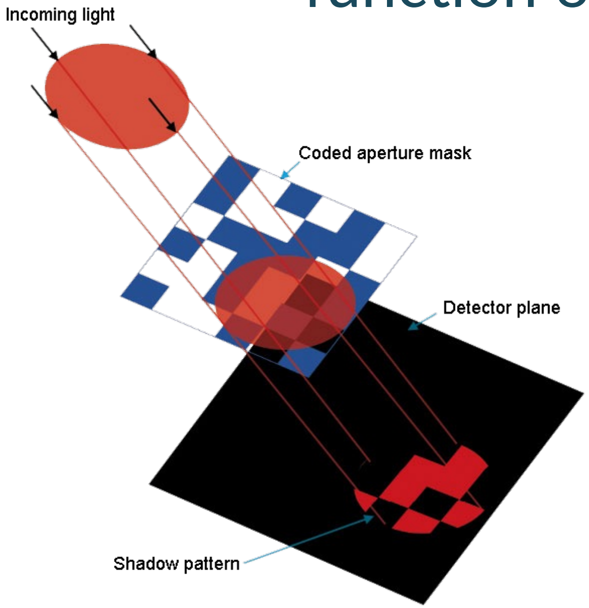
2. Calculate average counts and standard deviation using the data from -1 to +30 seconds around the trigger time



5-sigma detection?

FOLLOW-UP METHODS WITH SWIFT BAT

3. Use `NITRATES` to produce response functions for rate data, as a function of the incidence angle onto the BAT detector plane

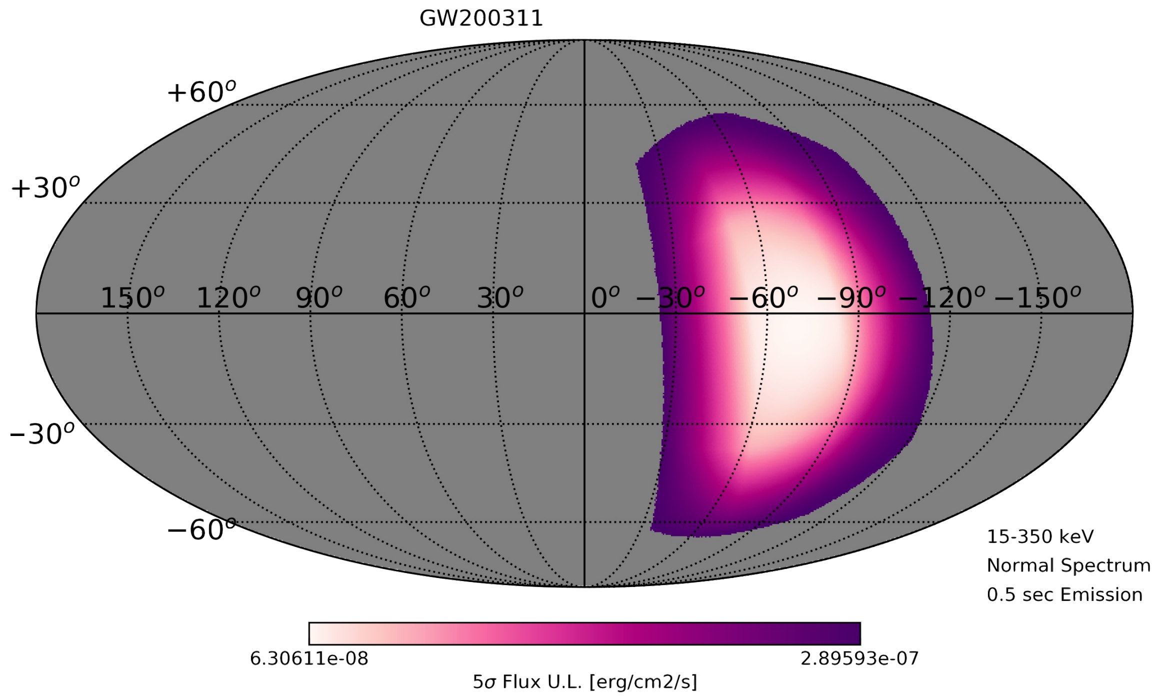


De Lunay & Tohuvavohu arXiv:2111.01769

FOLLOW-UP METHODS WITH SWIFT BAT

4. Calculate the expected counts using the phenomenological Band function as the expected GRB model

FOLLOW-UP METHODS WITH SWIFT BAT

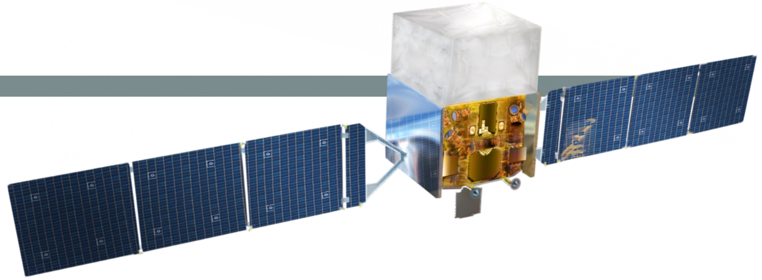


5. Find the corresponding upper-limit flux

→ Example of the upper-limit map: GW200311

Preliminary

FOLLOW-UP METHODS WITH FERMI GBM



Using *Fermi* GBM triggers and **two** sub-threshold searches:

- Targeted: scans -1 to 30 sec around a trigger time
- Untargeted: a blind search of the GBM data

→ Determine if there is any excess γ-ray excess emission coincident with GWTC-3 events

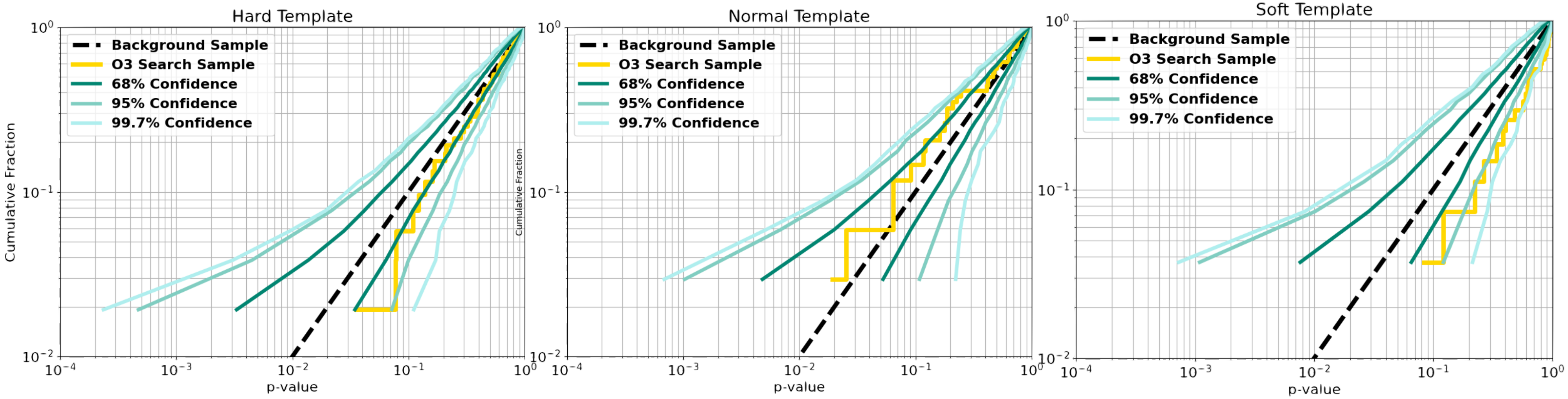
TARGETED SEARCH METHOD FOR COINCIDENT EVENTS

→ comparing the events found with the GBM targeted search around the GW event times with three spectral templates

Ranking statistic (R)

→ R is mapped to a p-value and compared to the cumulative fraction → **no statistically significant counterparts**

$$R = \frac{p_{\mathrm{astro}} \times p_{\mathrm{vis}} \times p_{\mathrm{assoc}}}{|\Delta t - D| \times FAR_{\mathrm{GBM}}}$$

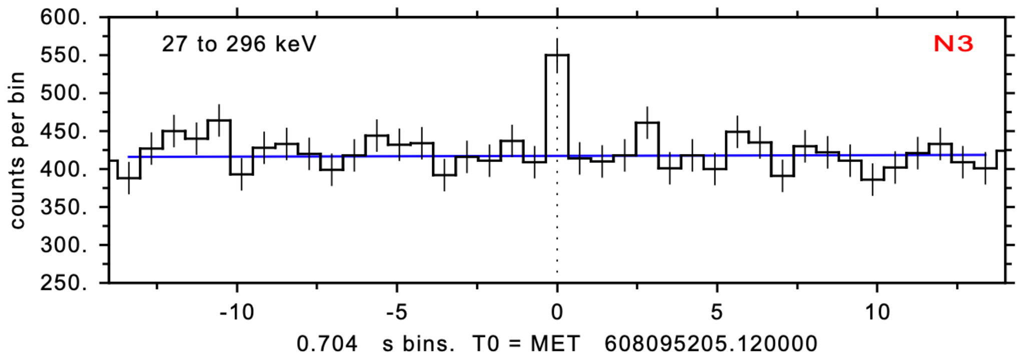


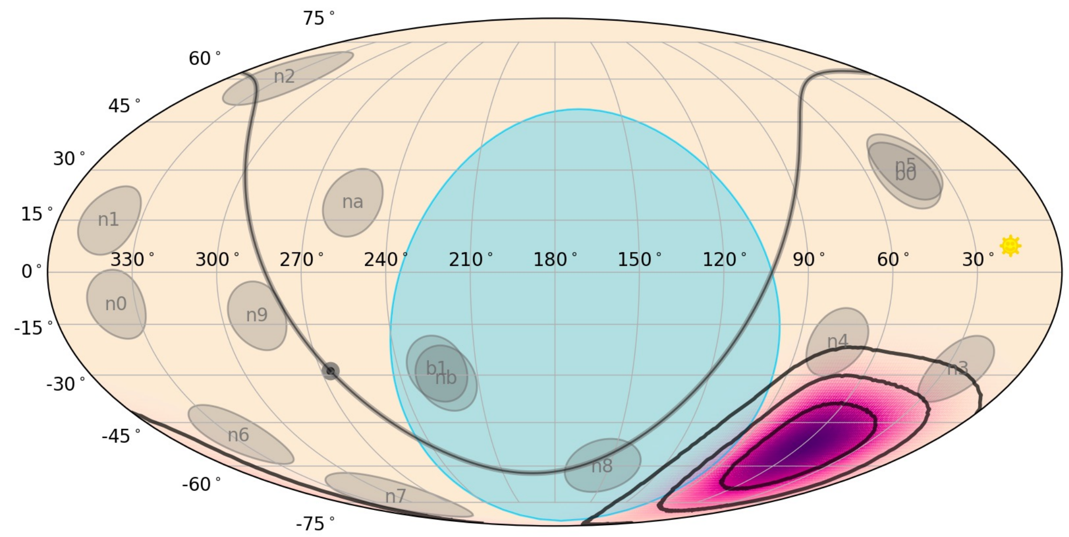
Equation: the probability the GW event is astronomical (p_{astro}), visible to GBM (p_{vis}), and that GW and GBM event are spatially associated (p_{assoc}), the GW-GBM time offset (Δt), GBM event duration (D), and the GBM False Alarm Rate (FAR_{GBM})

Preliminary

UNTARGETED SEARCH METHOD FOR COINCIDENT EVENTS

- Searches CTTE data continuously for GRB-like transients below the on-board trigger threshold with 4-5 hr latency



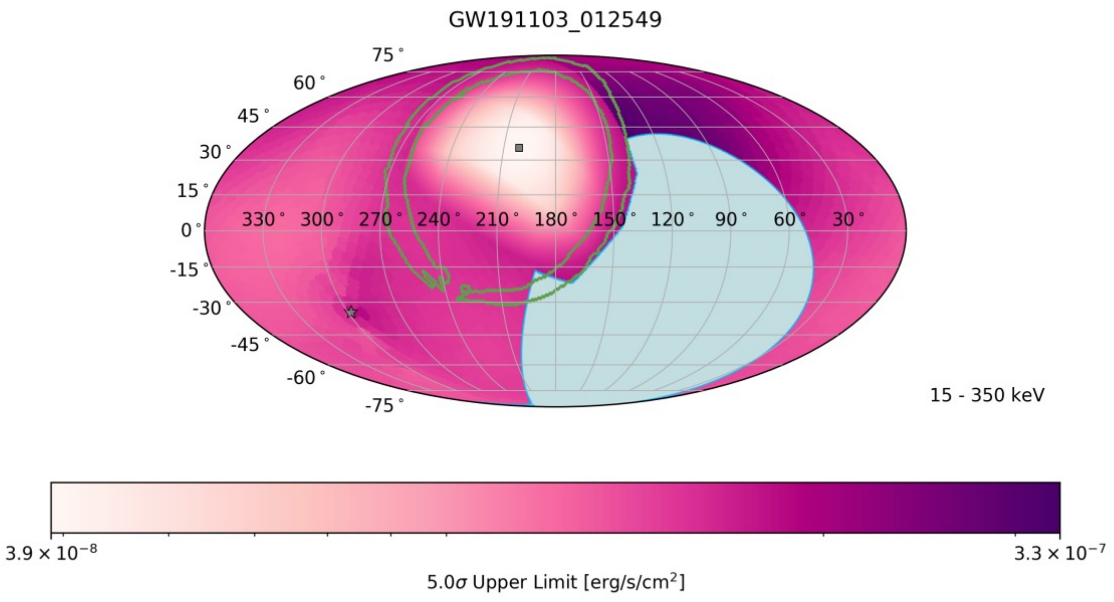


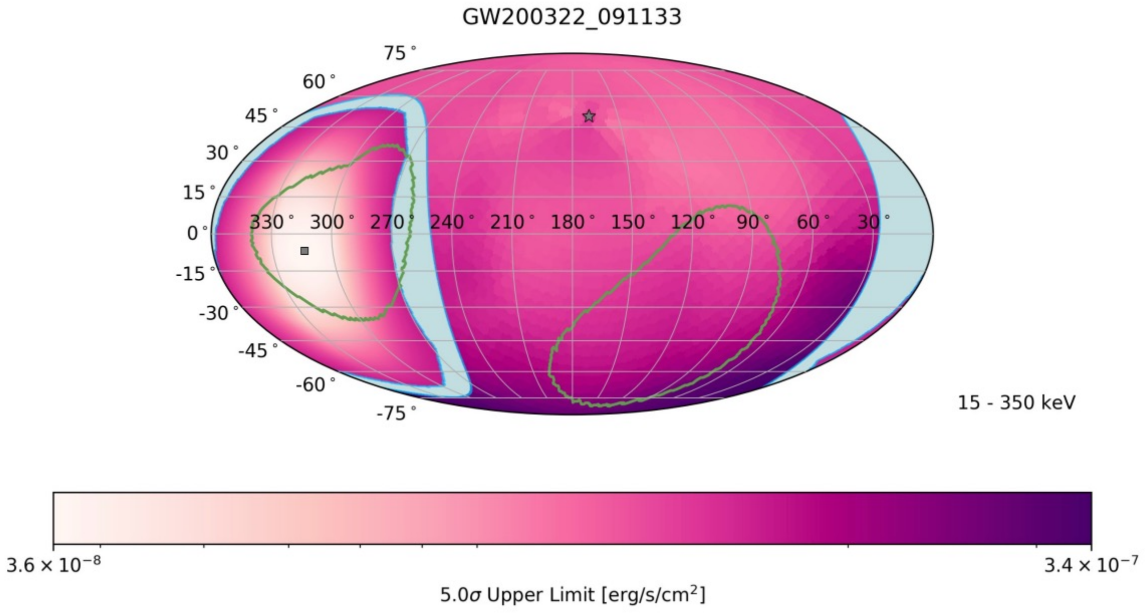
- No statistically significant discoveries.

We report *no* significant discoveries; neither with *Fermi* GBM, nor *Swift* BAT.

COMBINING THE UPPER LIMITS

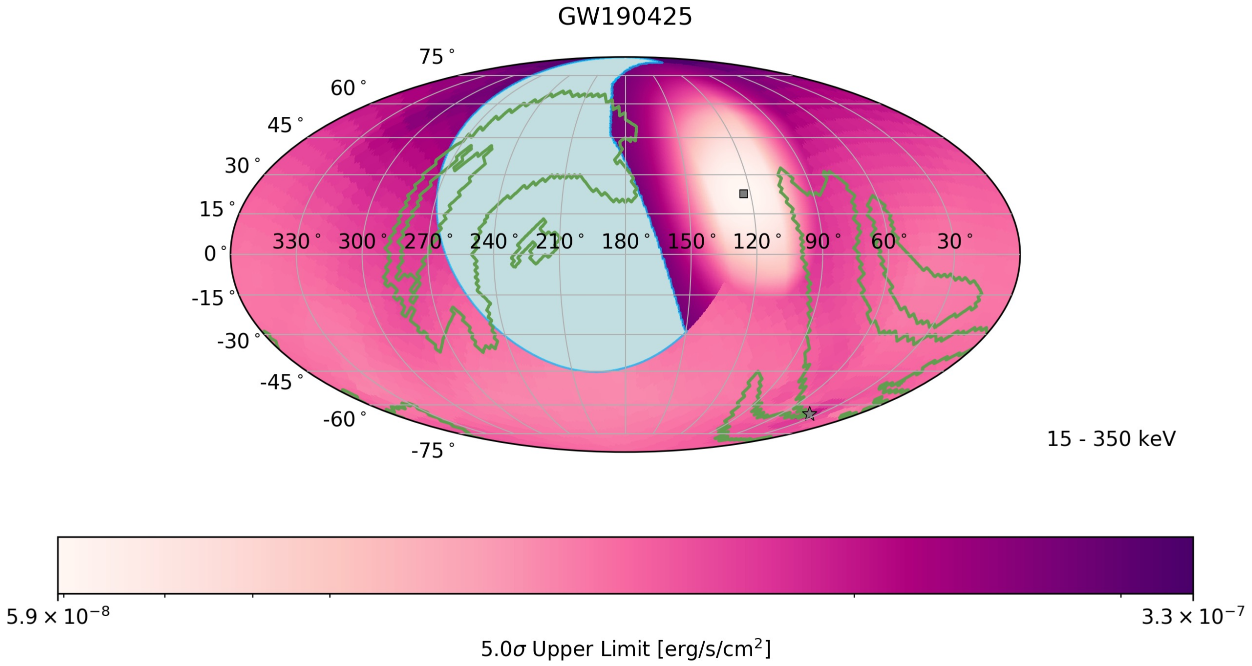
- Choosing the most constraining limit for each point in the sky (independent measures)





Preliminary

HONORABLE MENTION: BNS GW190425



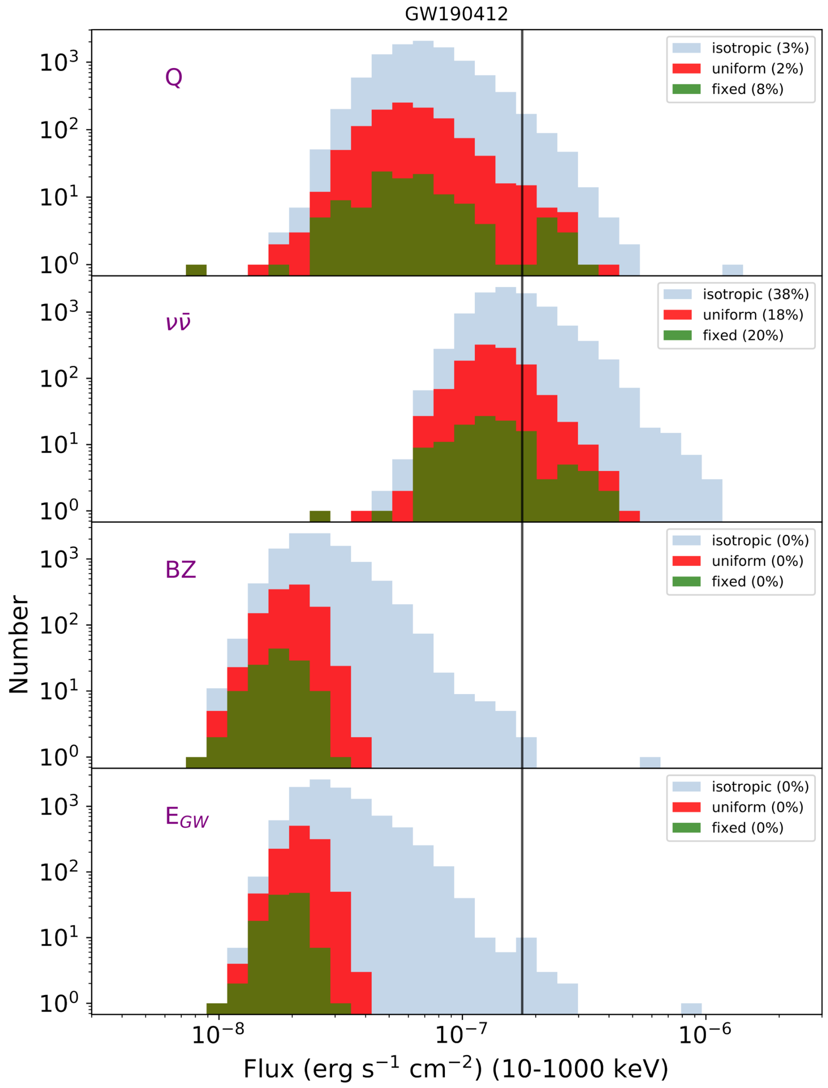
- BNS 190425 is 4 times further away than BNS 170817
- GBM/BAT only see ~60% of the GW localization region
- Inclination angle poorly constrained

Preliminary

EM RADIATION FROM BINARY-BLACK-HOLE MERGERS?

- Assuming association between BBH GW150914 & GW150914-GBM, we can use the BBH parameters to derive a distribution of γ-ray fluxes to compare with the GBM 3-σ flux upper limits (10 – 1000 keV)

- Four different models shown; vertical line represents the 3-σ flux upper limit, with the fraction of cases above that limit shown the legend



Preliminary

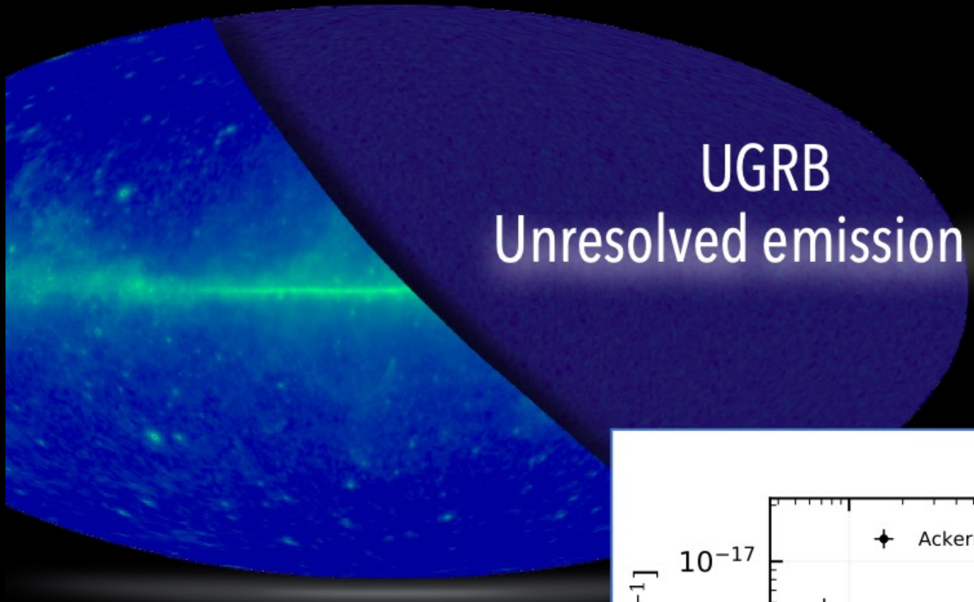
SUMMARY OF E&M COUNTERPART SEARCHES

- Using *Fermi* GBM triggers and sub-threshold searches, and *Swift* BAT's data to search for coincident **γ**-ray emission with the GWTC-3 events, **we found no statistically significant EM counterparts**
- We calculated the **flux upper limits** for both GBM and BAT and **present joint upper-limit skymaps**
- Comparing the upper limits expectations from various BBH merger theoretical models we find that **we can likely rule out the neutrino model** for producing EM emission
- Stay tuned for Fletcher, Crnogorčević *et al.* 2022, (currently under the LVK review)
- Getting ready for O4!

TODAY…

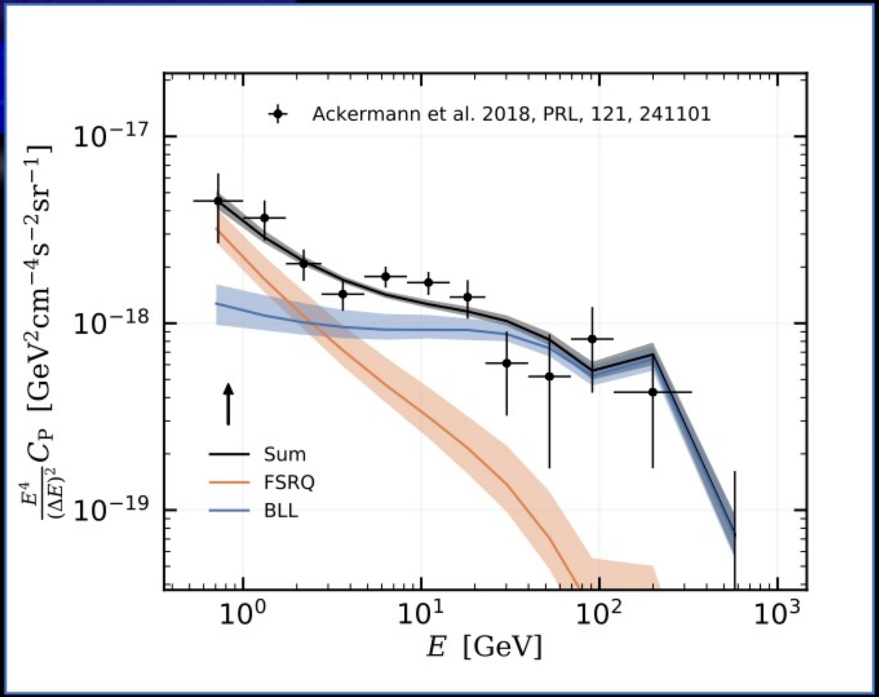
- an exploration of the physics beyond the Standard Model: axion-like particles & gamma-ray bursts with *Fermi*
- offline, subthreshold searches for gravitational-wave counterparts with *Swift* and *Fermi*, and
- cross-correlation studies between astrophysical neutrinos and the gamma-ray sky

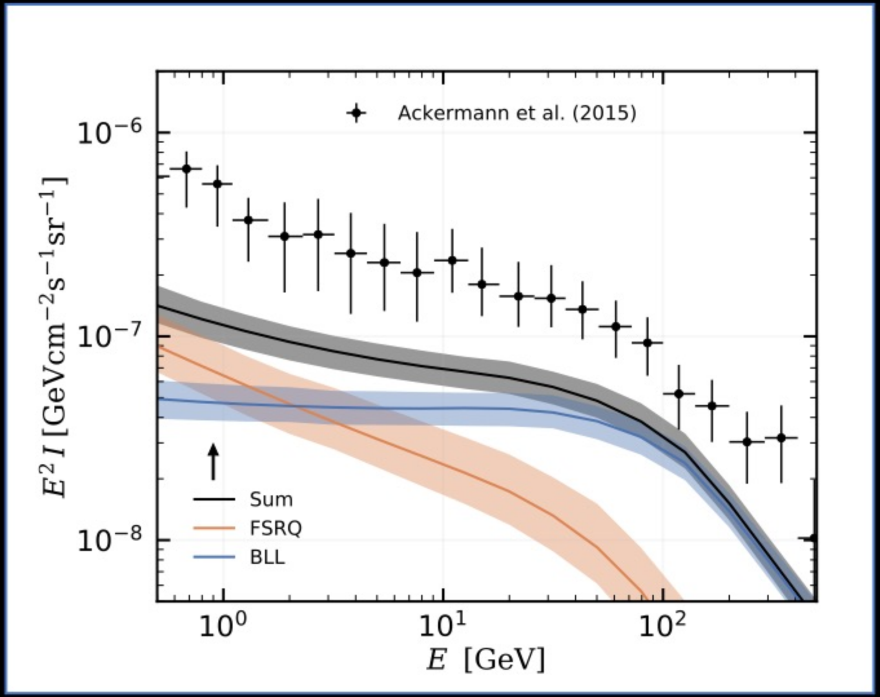
Unresolved Gamma-ray Background



FSRQ + BLL = 100% UGRB anisotropy

Those blazars provide a significant contribution to the UGRB
- about 30% between 10 and 100 GeV
- about 20% below 1 GeV





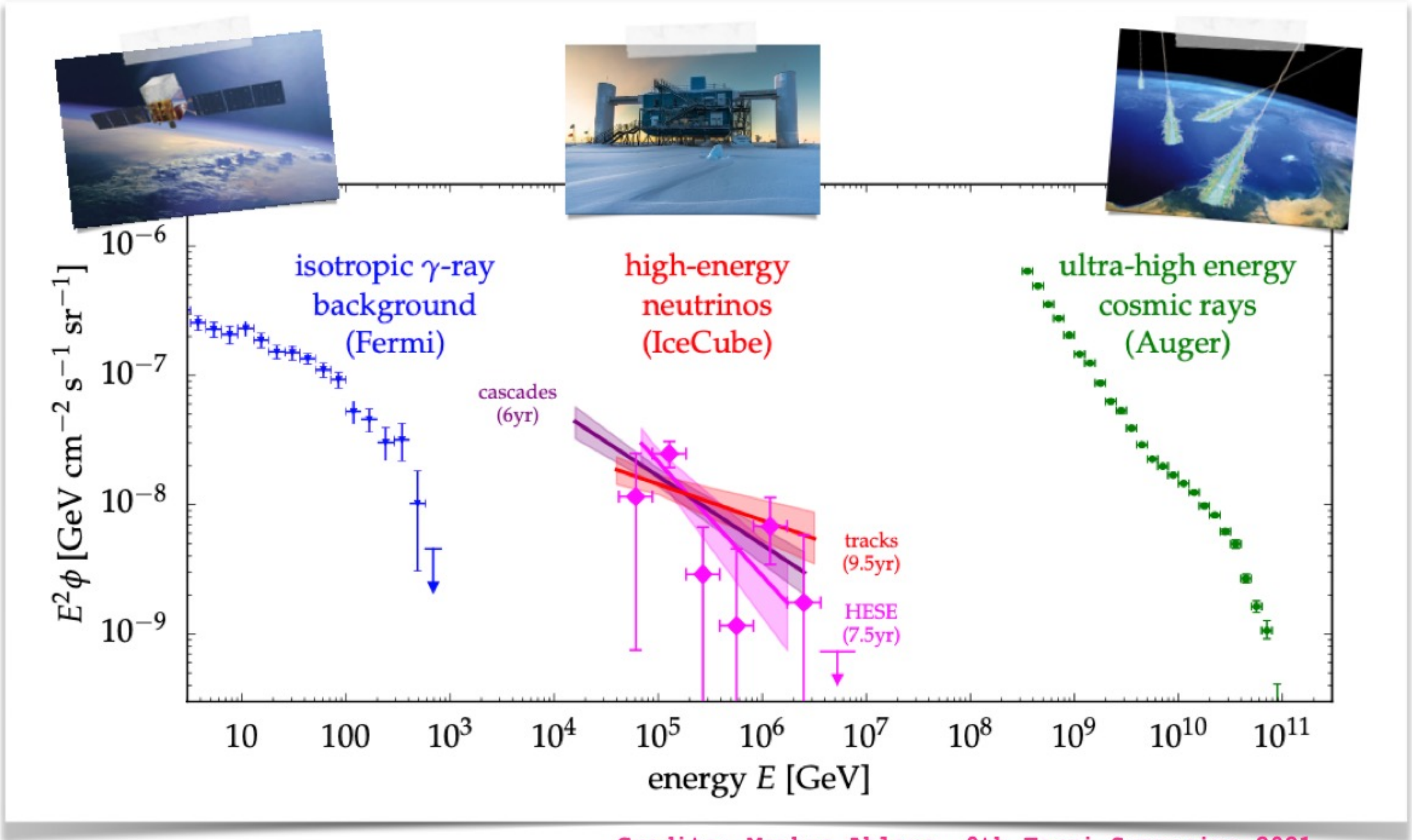
Korsmeyer, Pinetti, Negro, Regis, Fornengo, ApJ 2022

Slides adapted from Dr. Michela Negro

Diffuse TeV-PeV Neutrino

In 2013, IceCube discovered neutrinos of extragalactic origin. IceCube, Science 342 (2013)

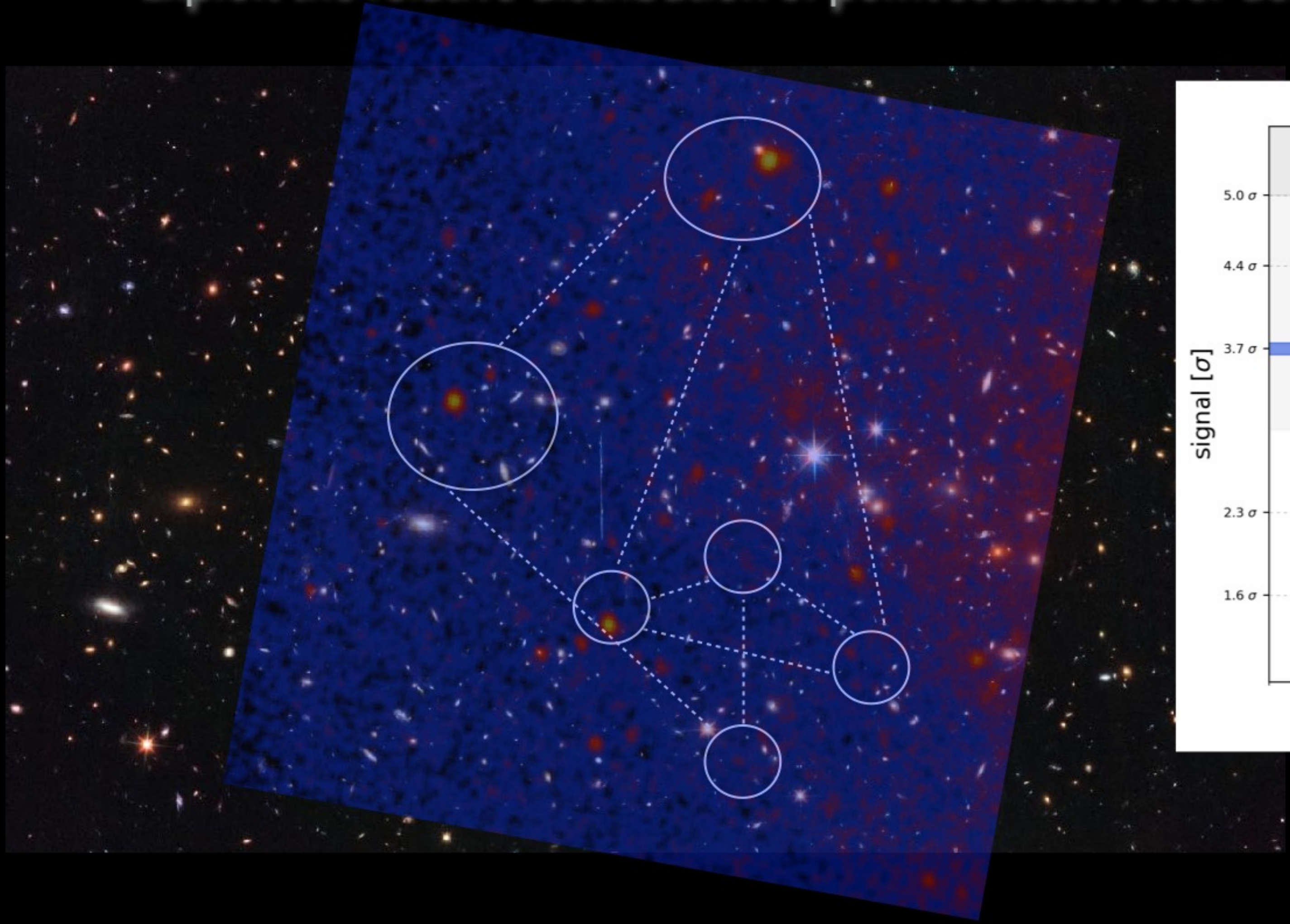
A measurement of the intensity of such a neutrino stream is known as a neutrino flux.

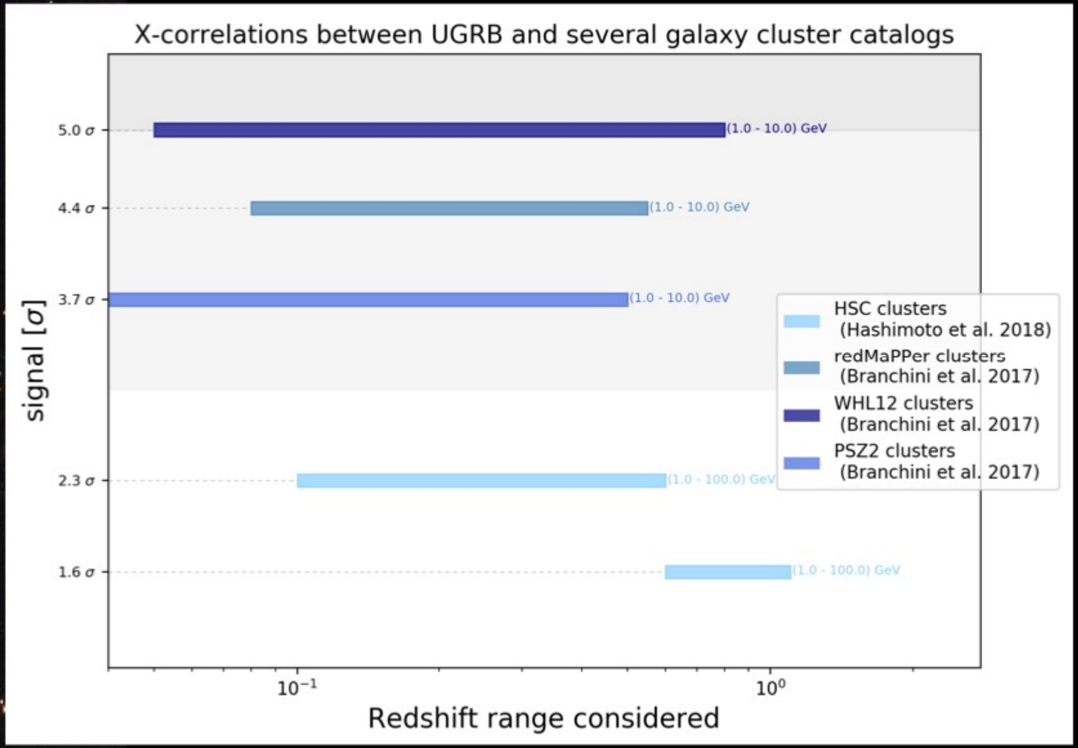


Credits: Markus Ahlers, 9th Fermi Symposium 2021

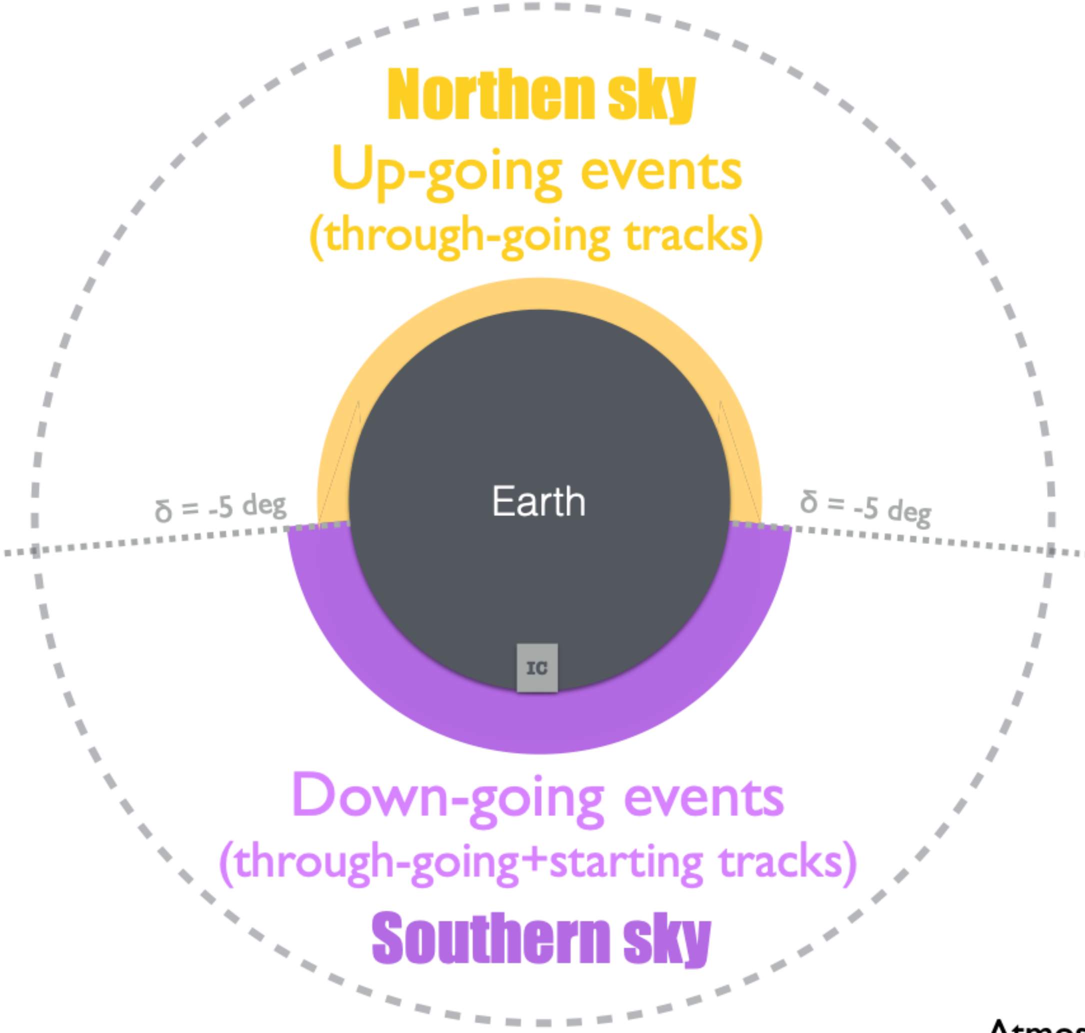
2 point cross-correlation function

Exploit the relative distribution of point sources / over-densities in the sky maps

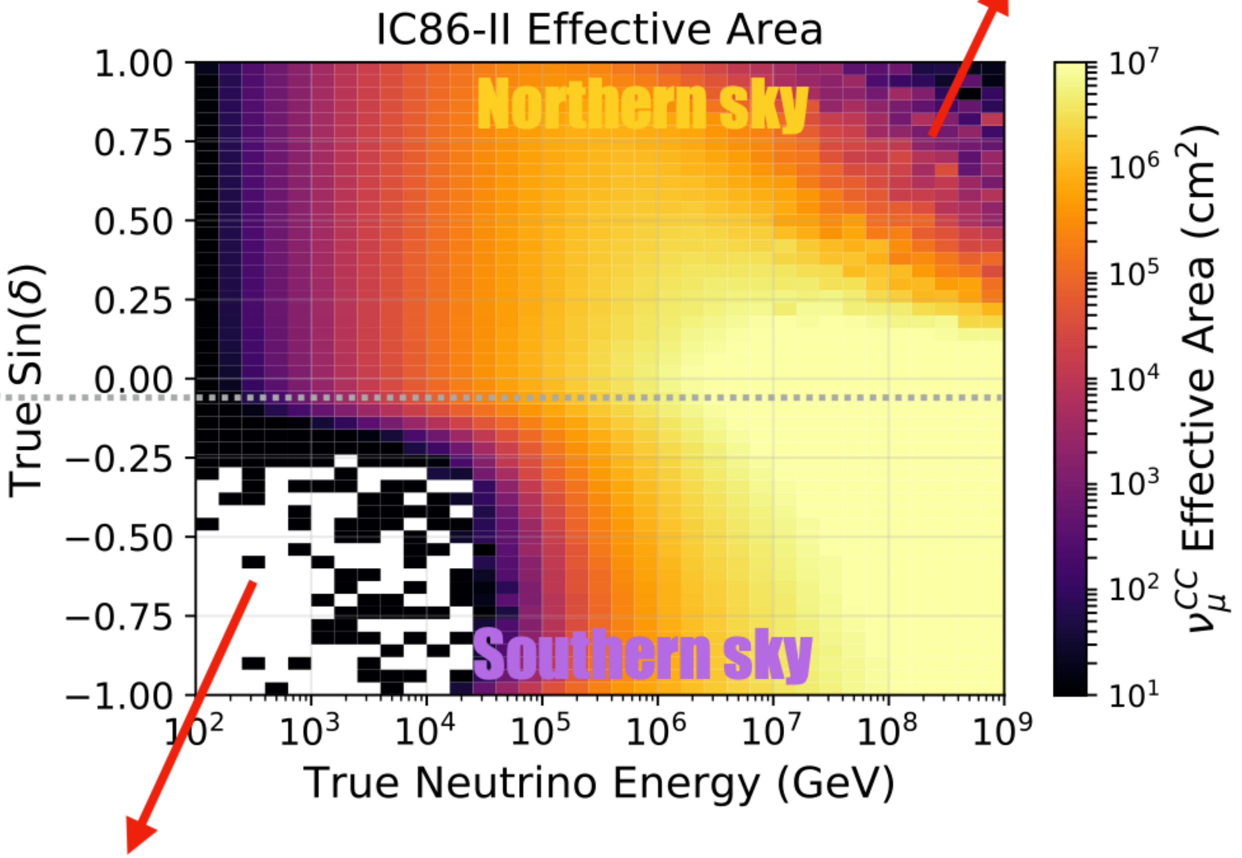




IceCube Effective Area

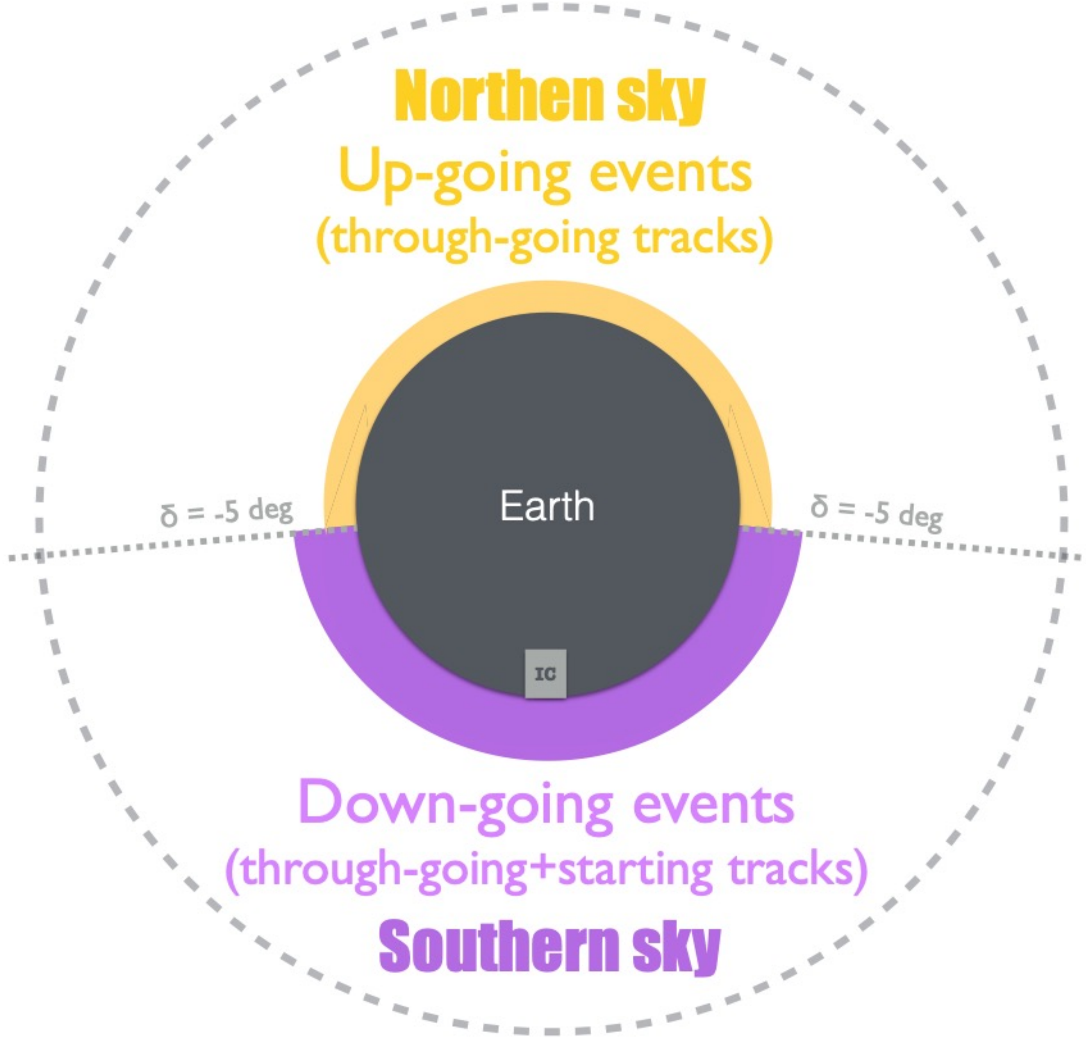


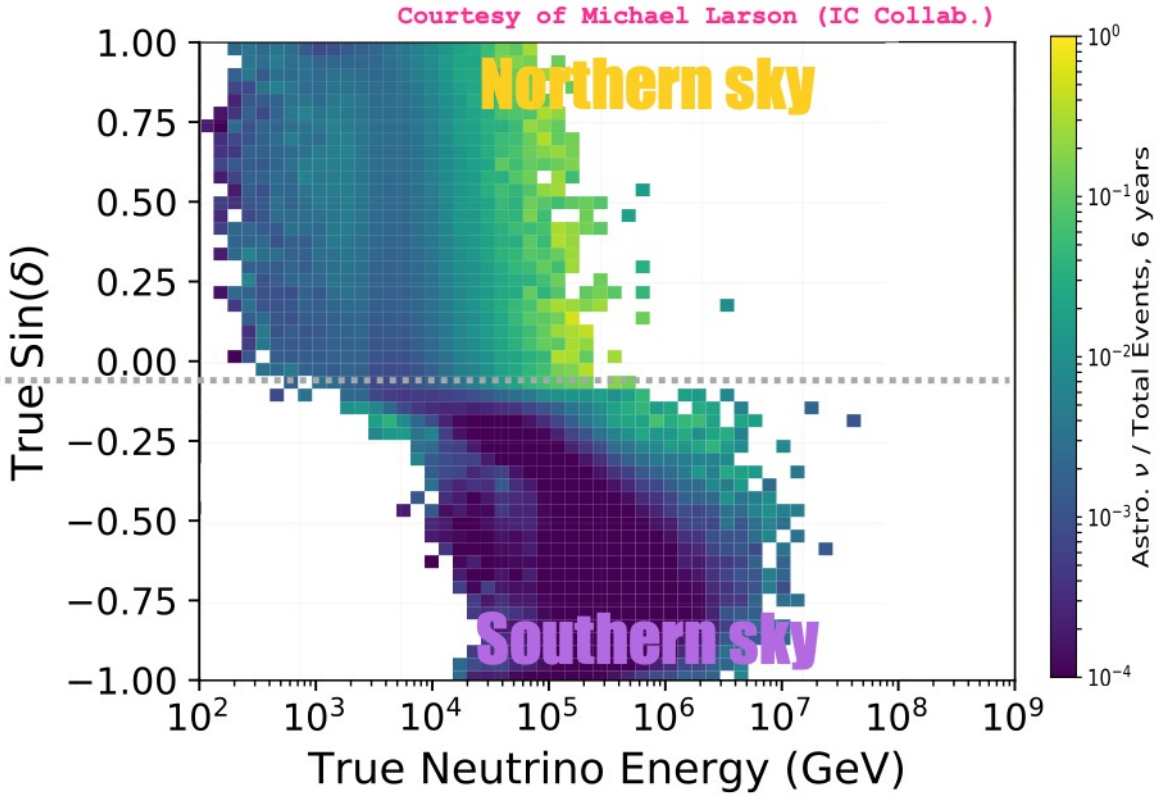
Earth not transparent to neutrino at these energies



Atmospheric muons >> atmospheric neutrinos >> astrophysical neutrinos

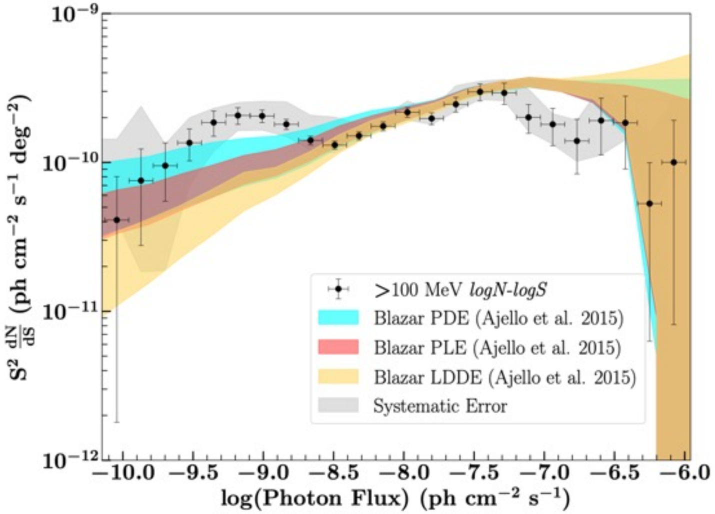
IceCube Sensitivity





Simulations - Positive test

We simulate a population of blazars reflecting the observed source count distribution in the 4FGL



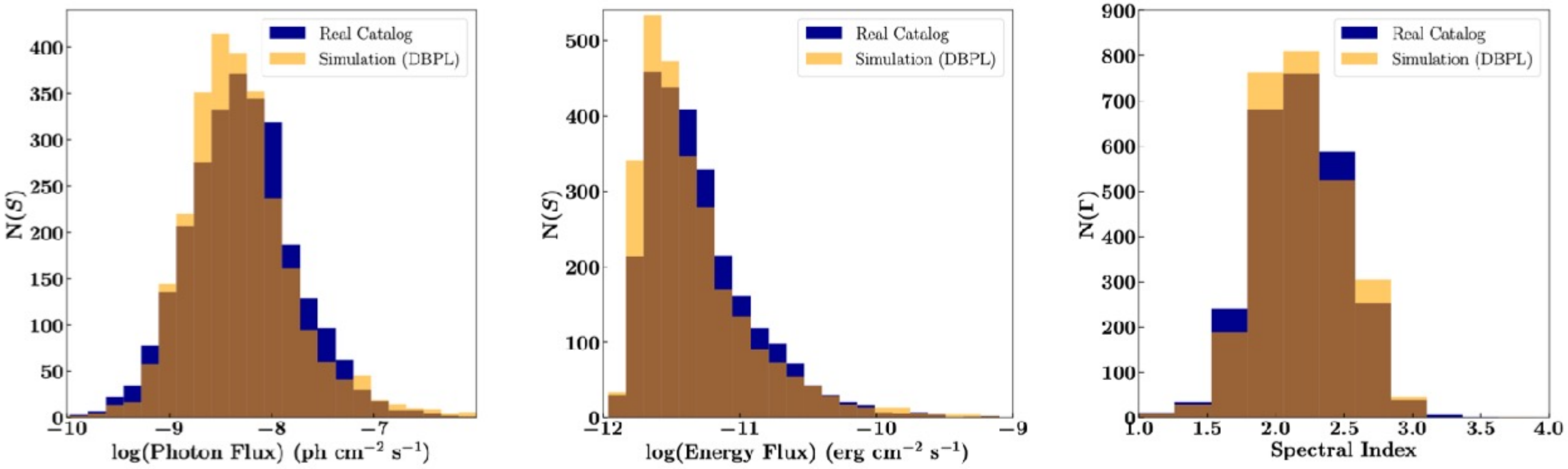
The model used is the Pure Density Evolution (PDE)

The simulation extends to unresolved regimes (80k sources)

By running the source search on the simulated gamma-ray sky, the recovered catalog of detected sources well matches the statistics of the 4FGL

Simulated intrinsic blazars spectra:

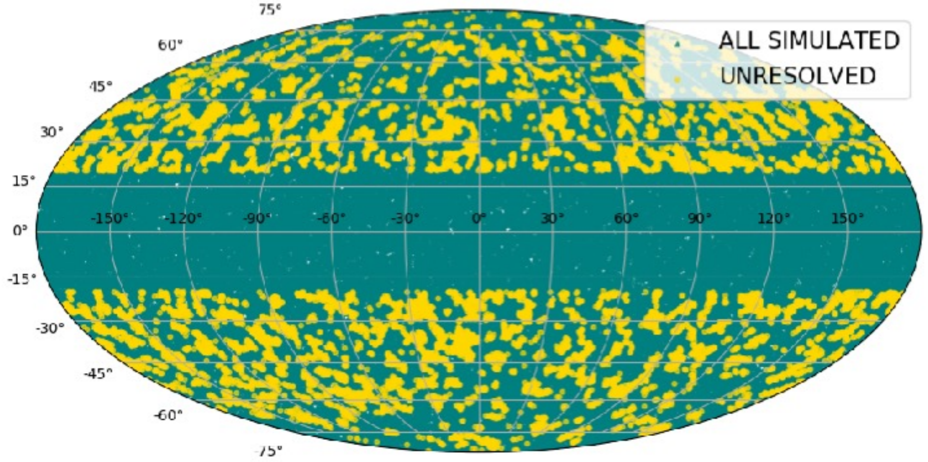
$$\frac{dN}{dE} = K\left[\left(\frac{E}{E_b}\right)^{\delta_1} + \left(\frac{E}{E_b}\right)^{\delta_2}\right]^{-1}$$



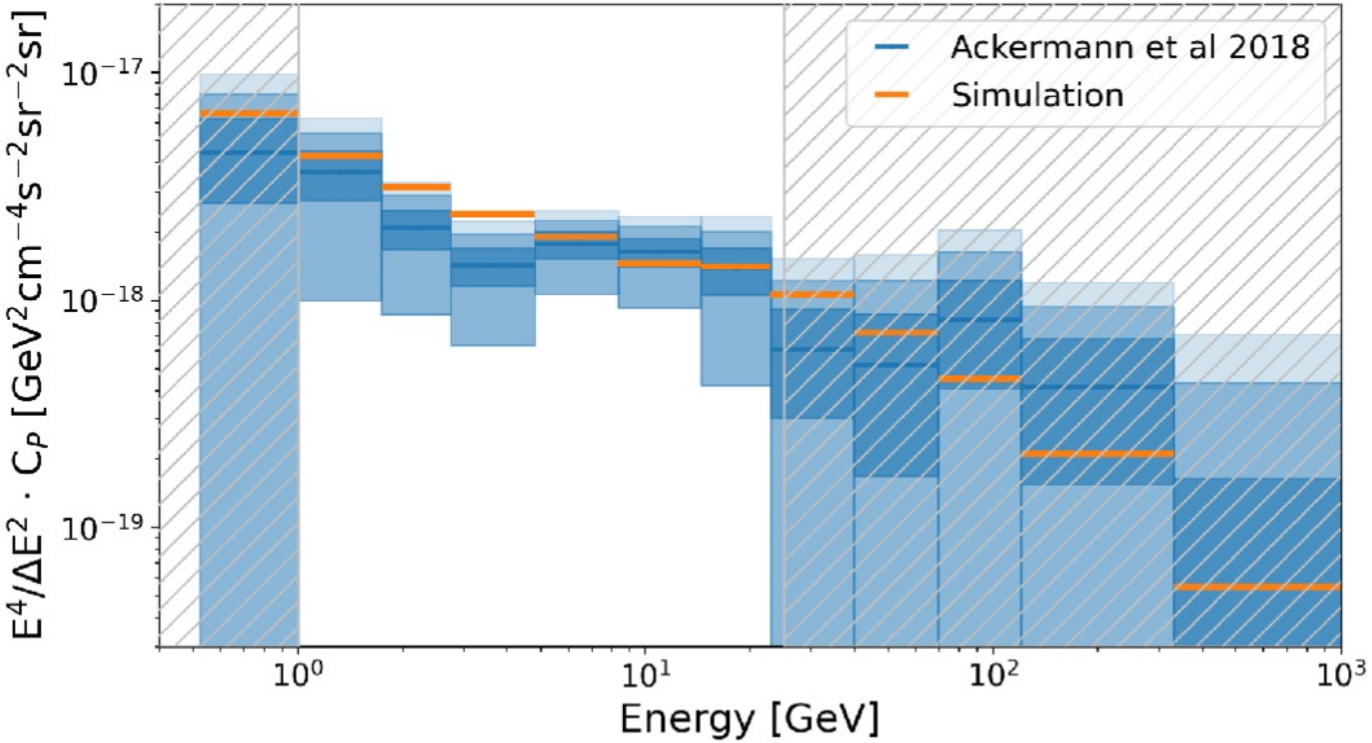
From the simulations of L. Marcotulli, M. Di Mauro, M. Ajello 2020
https://arxiv.org/pdf/2006.04703.pdf

Simulations

Also the statistics of the unresolved sources well reproduce the data



$$C_P(\Delta E) = \frac{1}{4\pi f_{sky}} \sum_{\mathrm{src}} [\Phi(\Delta E)]^2$$

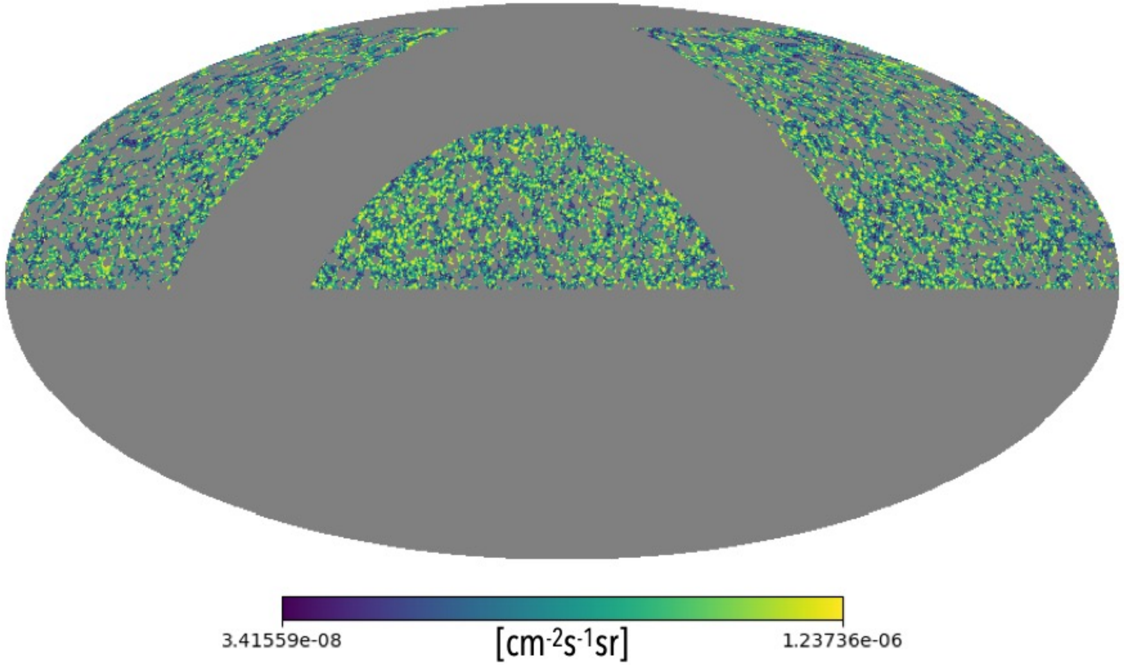


Simulations - Fermi maps

We generate simulated Fermi maps in 4 energy bins:

- Pass 8 DR3, SOURCEVETO, PSF1+2+3
- logaritmic energy bins between 1-25 GeV:
  - 1-2 GeV
  - 2-4 GeV
  - 4-10 GeV
  - 10-25 GeV

Example of UGRB simulated map (5-10 GeV)



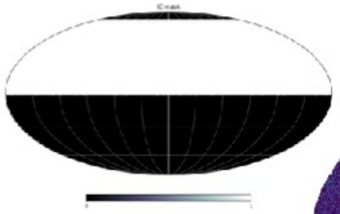
Pretty standard procedure:

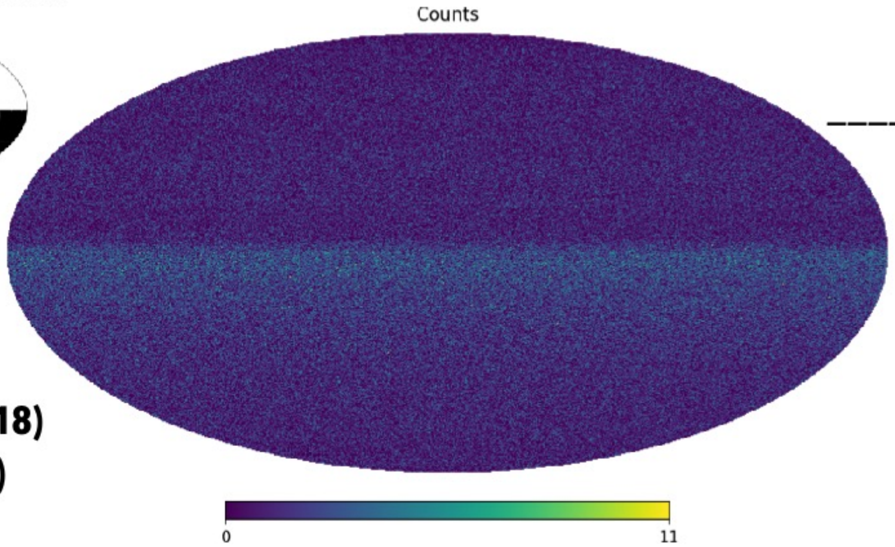
- Integrated source flux in the energy bin
- Convolution for the Fermi PSF(E, theta)
- Added Poisson noise to match the measured UGRB flux

Simulations - IceCube maps

We generate N (=trials) number of IC events realizations following these steps:

- Extrapolate the intrinsic blazars spectra to IC energies (> 100 GeV)
- Rescale the spectrum by a factor $\mathbf{f_{\%}}$ (to vary the amount of neutrino signal per gamma-ray)
- From the spectrum, generate a list of events as observed by IC, accounting for:
  - Declination dependence of the effective area
  - energy dispersion
  - smearing (or PSF)
- Add **randomized**** background events to match **real IC statistics***
- Compute the fluctuation map, averaging by declination bands -------> $\delta_{\text{pix}} = \dfrac{N_{\text{pix}} - \langle N \rangle_{\text{pix}}}{\langle N \rangle_{\text{pix}}}$
- Mask





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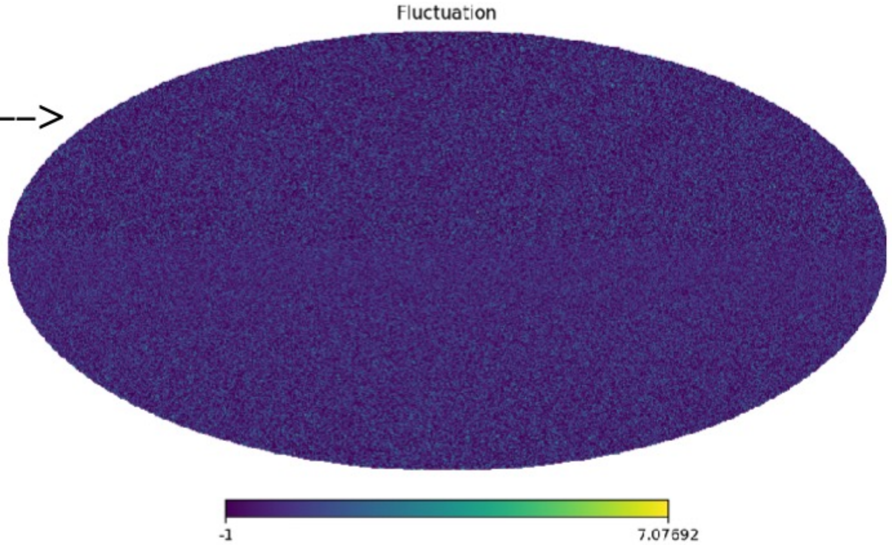


***6 years (2012-2018)**
****RA = rnd(0, 360)**

What does our scaling mean?

The neutrino flux is the gamma flux extrapolated upward in energy and converted to neutrinos assuming proton-proton interaction

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx \frac{1}{2} \left(E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \right) \Bigg|_{E_\nu \approx E_\gamma / 2}$$

Feng and Murase 2021

The scaling factor **f%** scales observed neutrino flux relative to the flux expected assuming all gamma rays are produced via p-p interactions

cross-correlation measurement

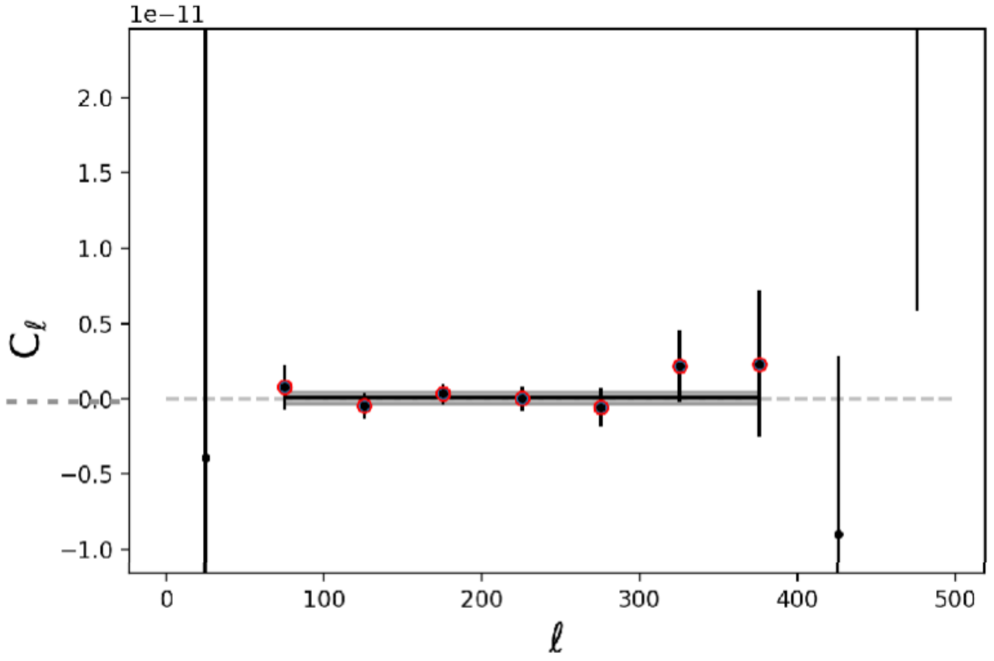
The 1halo term (C_P) is obtained by fitting the binned CAPS between a fiducial multipole range l=(50-380), by minimizing the χ^2:

$$C_\ell = \frac{C_\ell^{PolSpice}}{W_{LAT}^{beam} W_{IC}^{beam} W_{pix}^2}$$

$$\chi^2 = \Delta^T V^{-1} \Delta$$

$$\Delta = \begin{pmatrix} C_{\Delta\ell_1} - C_P \\ C_{\Delta\ell_2} - C_P \\ \cdots \\ C_{\Delta\ell_n} - C_P \end{pmatrix}$$

C_P



V being the binned covariance matrix corrected by the Wbeam and Wpix

$$V_{\ell\ell'} = V_{\ell\ell'}^{\text{raw}} / (W_\ell^2 W_{\ell'}^2)$$

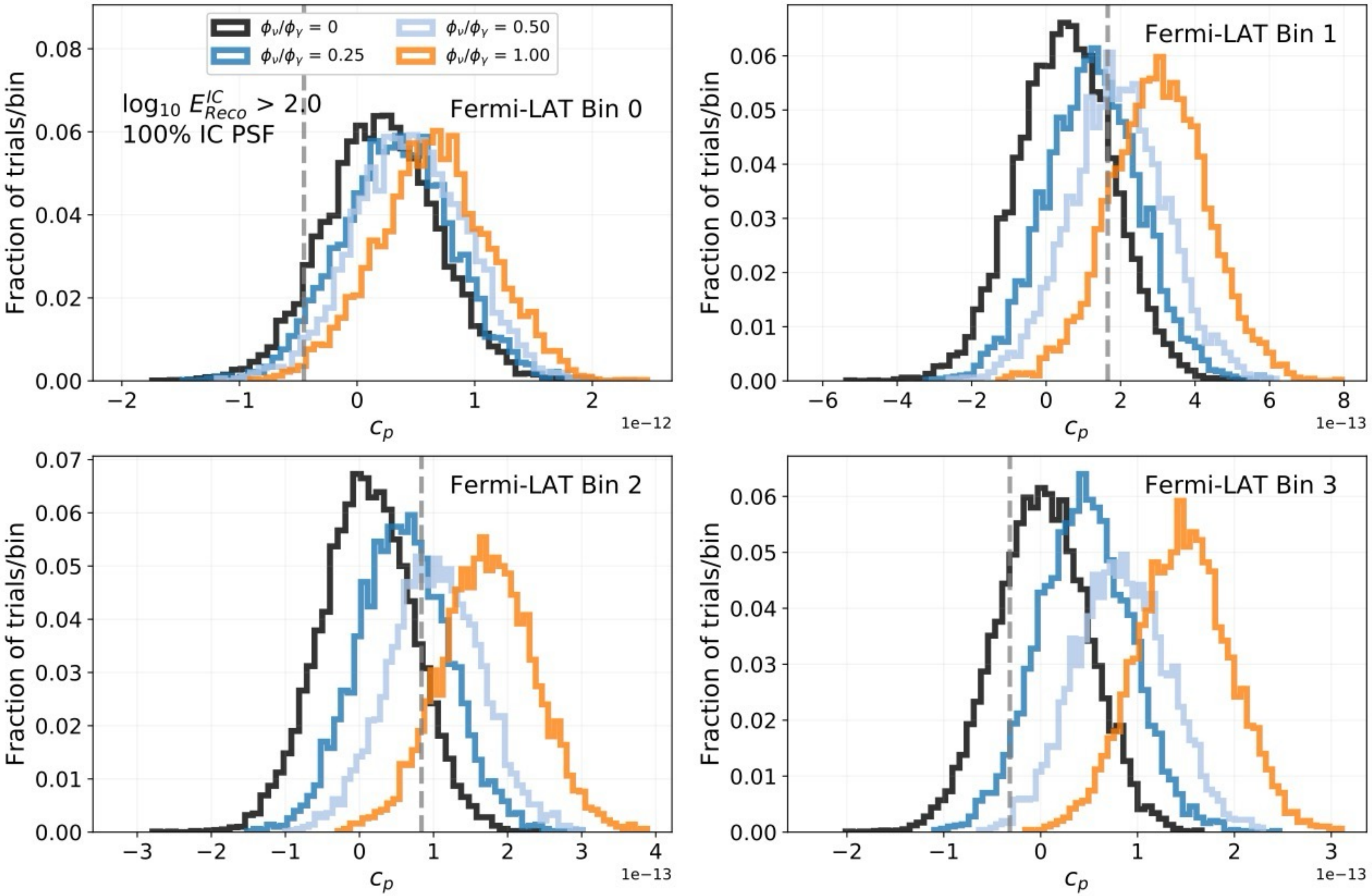
Simulations - Results

Build the Cp distribution for

- H_0: IC background
- H_1: IC signal ($f_{\%}$) + background ($1-f_{\%}$)

$f_{\%}$ varies

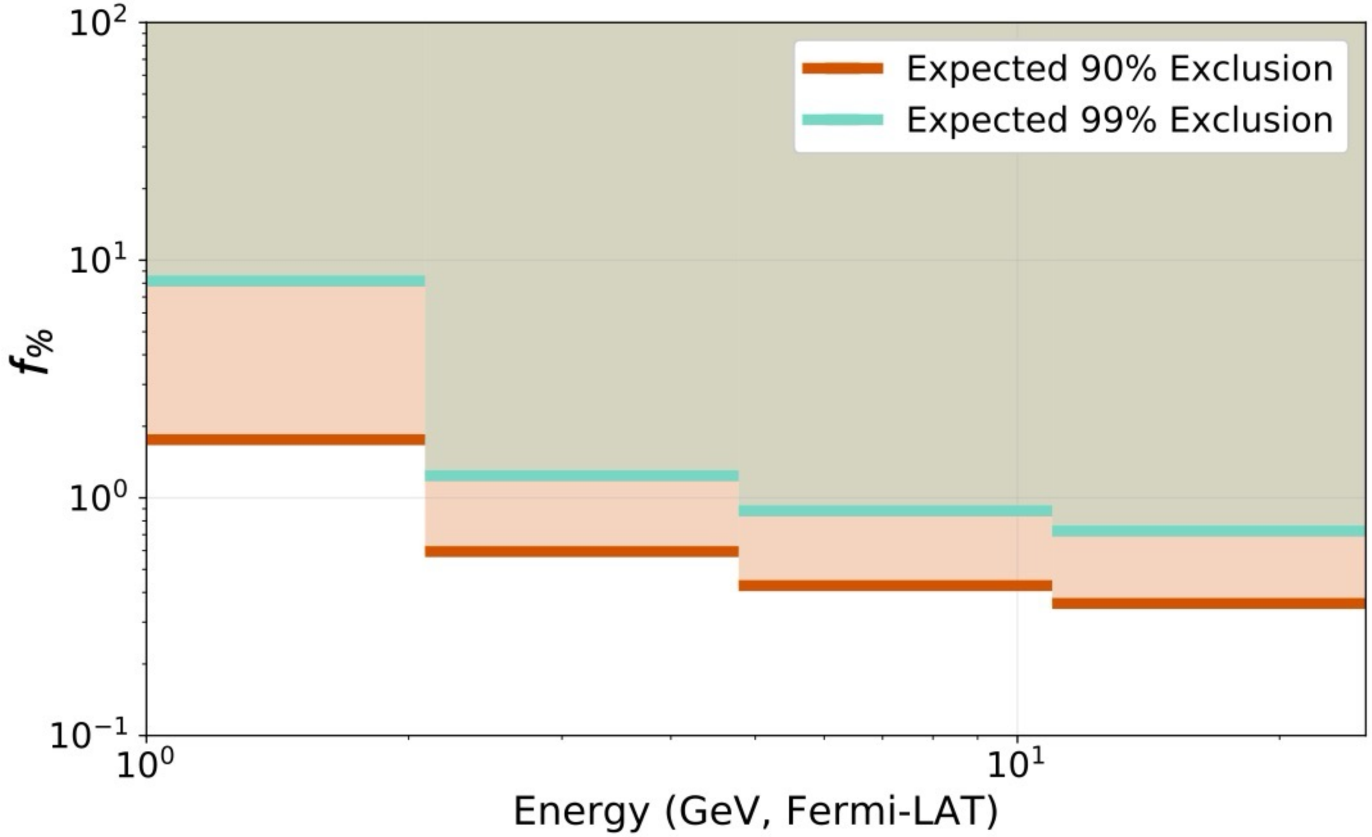
- 0 (= H_0)
- scan between 0.05 – 10.0



Preliminary

Simulations - Results

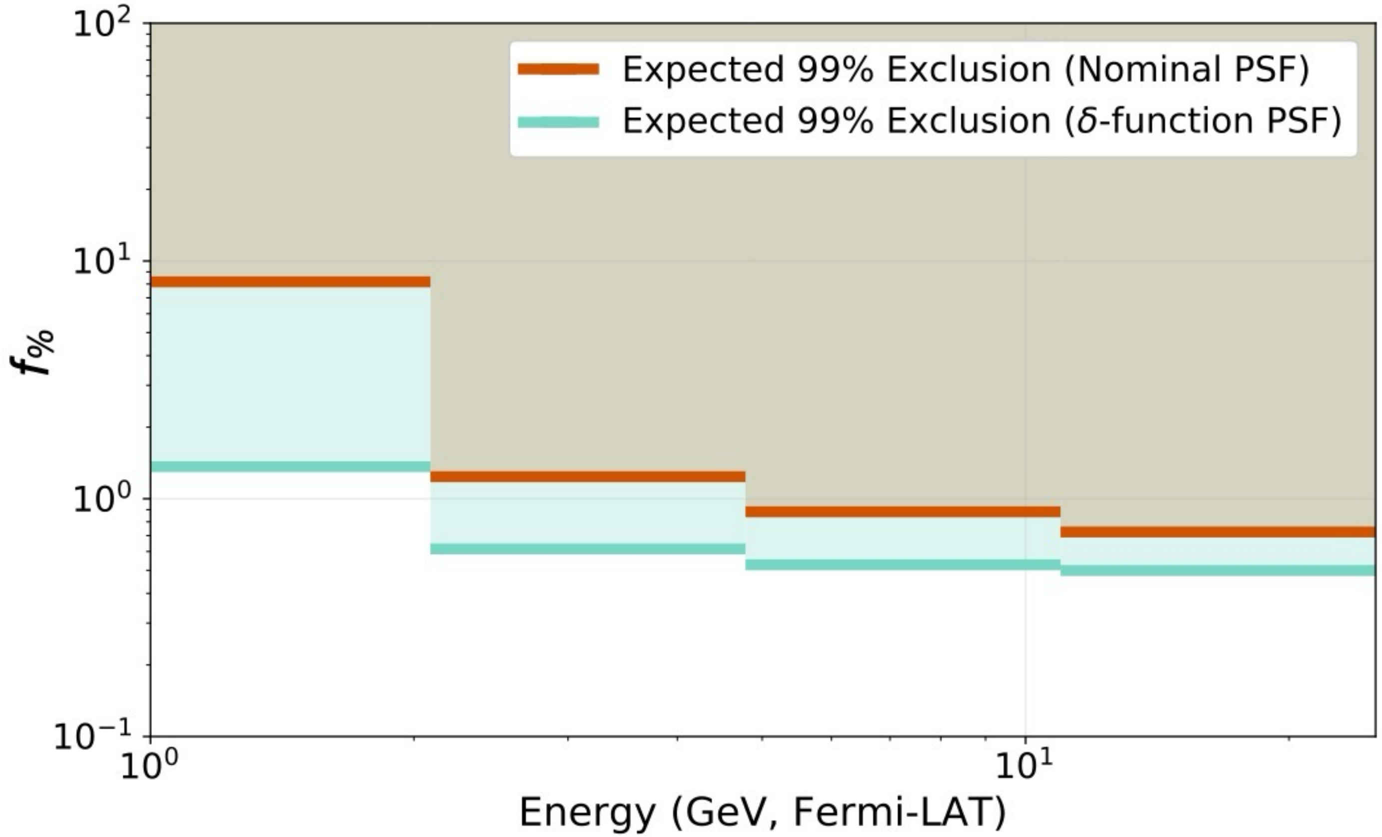
Expected 90% and 99% bounds on the $f_{\%}$ considering the average Cp background value



Preliminary

Simulations - Results

The major effect is the IC smearing:



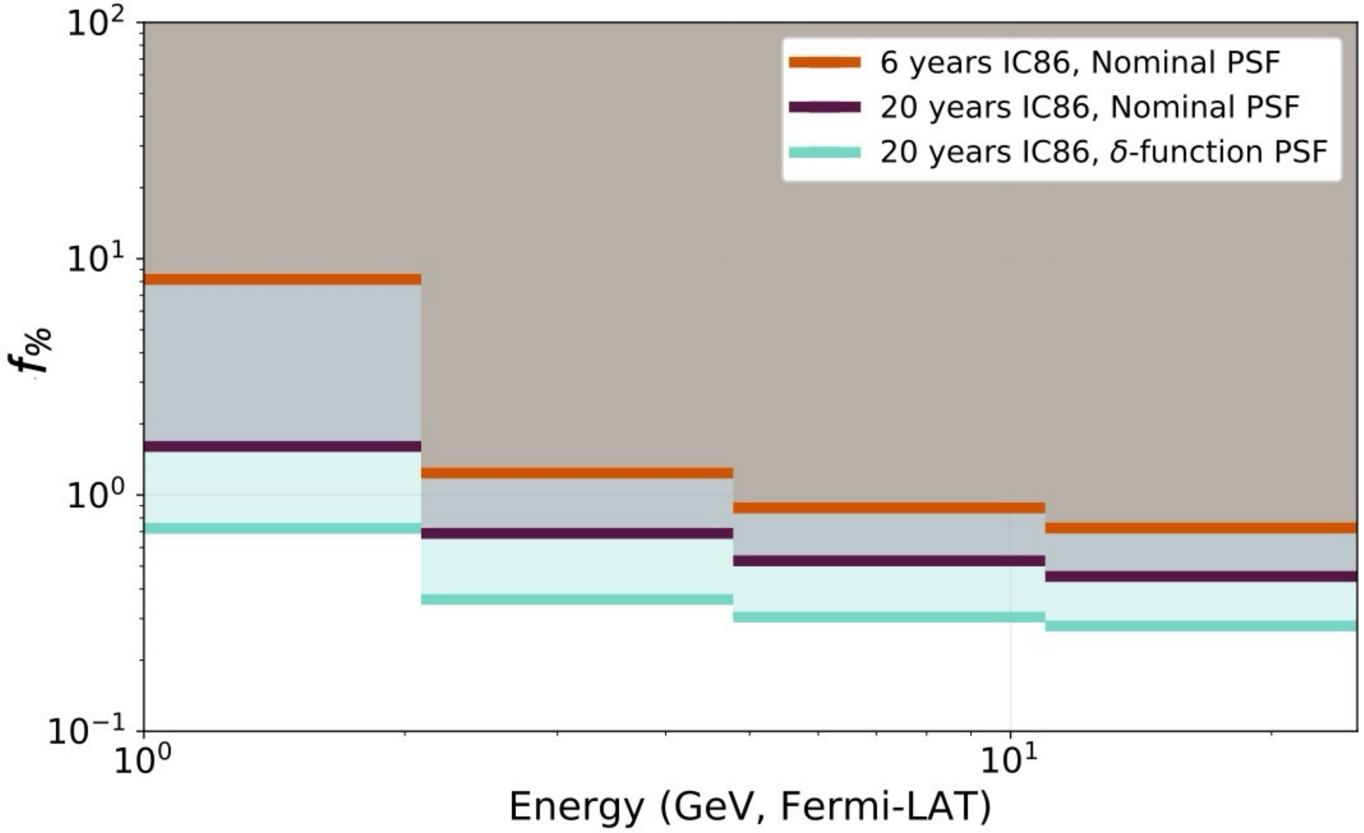
Preliminary

Future prospects

Another relevant effect is the statistics

Bounds for 20 years of IC observation

- Current PSF smearing
- 0% smearing (ideal case)



IC Gen2 will improve the reconstruction (PSF ~20% better)

Preliminary

New Physics through a Multimessenger Lens
An Exploration of the High-energy Universe

- an exploration of the physics beyond the Standard Model: axion-like particles & gamma-ray bursts with *Fermi*,
- offline, subthreshold searches for gravitational-wave counterparts with *Swift* and *Fermi*, and
- cross-correlation studies between astrophysical neutrinos and the gamma-ray sky

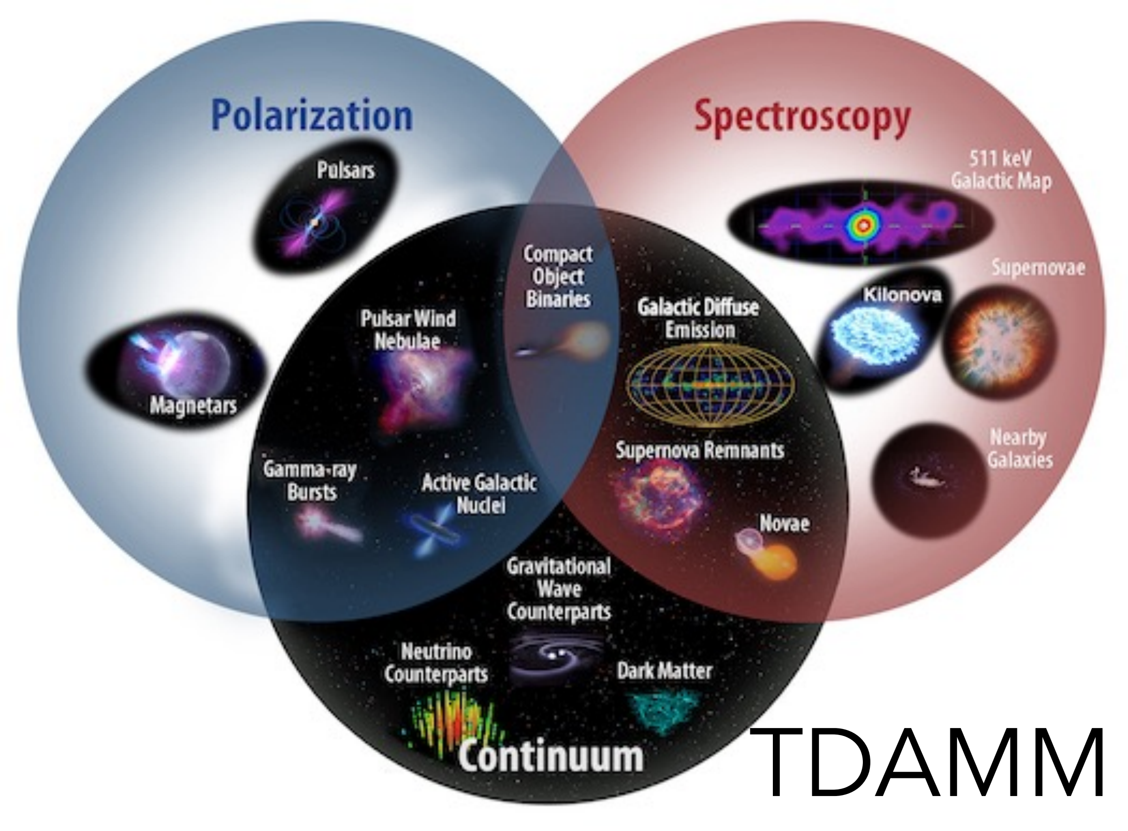
More…

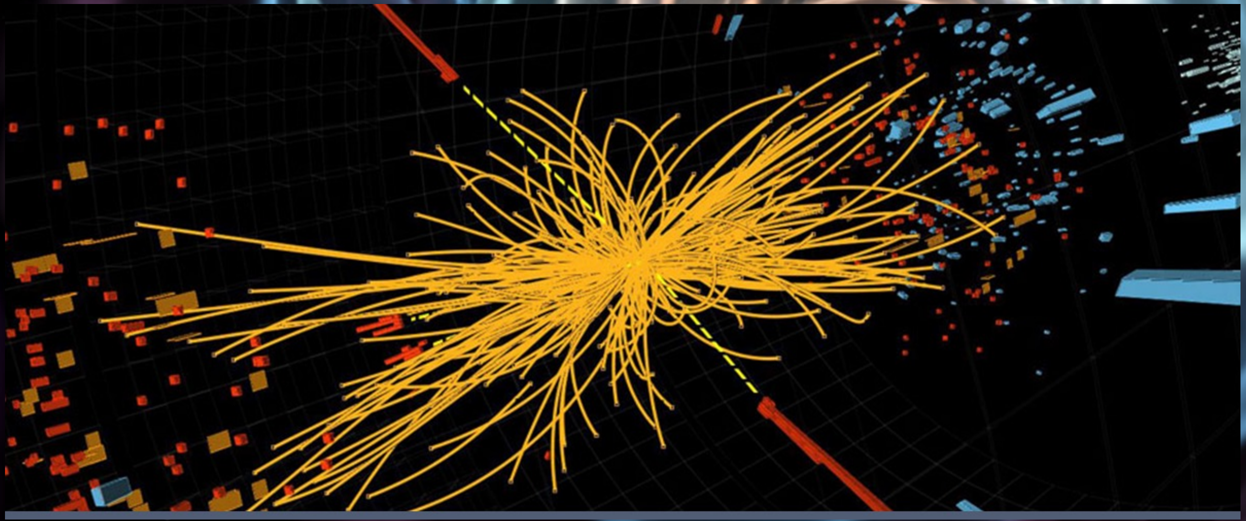
- Gravitational waves, neutrinos, and ALPs
  - Imprints on the gravitational wave templates: new physics
  - Time tagging of NS mergers & excess emission searches
  - Galactic supernovae and ALPs
- Gravitational waves and new physics:
  - BBH merger mechanisms: constraints on the physical parameters of black holes
  - BBH & electromagnetic production mechanisms
- Neutrinos x Gamma rays
  - Testing p-gamma neutrino production hypothesis

Image: Neutron Star Merger Seen in Gravity and Matter. Credit: Karan Jani/Georgia Tech

New Physics through a Multimessenger Lens

An Exploration of the High-energy Universe





TDAMM X BSM

Image: Neutron Star Merger Seen in Gravity and Matter. Credit: Karan Jani/Georgia Tech

TODAY…

- an exploration of the physics beyond the Standard Model: axion-like particles & gamma-ray bursts with *Fermi*
- offline, subthreshold searches for gravitational-wave counterparts with *Swift* and *Fermi*, and
- cross-correlation studies between astrophysical neutrinos and the gamma-ray sky