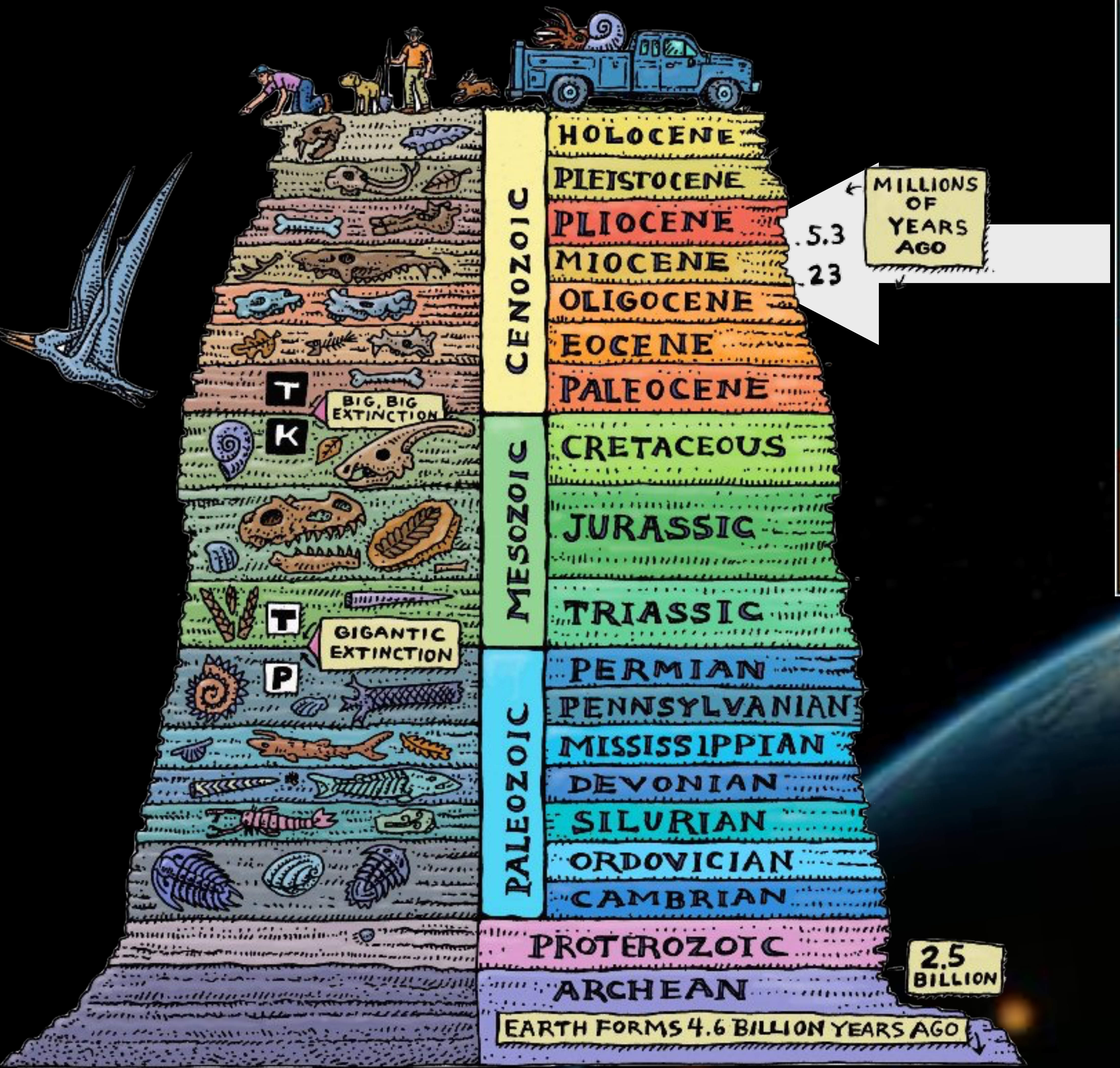
GRB 200415A

And the third class of gamma-ray bursts

A LONG
TIME AGO
IN A GALAXY
FAR, FAR AWAY...

11.4 Million years ago…

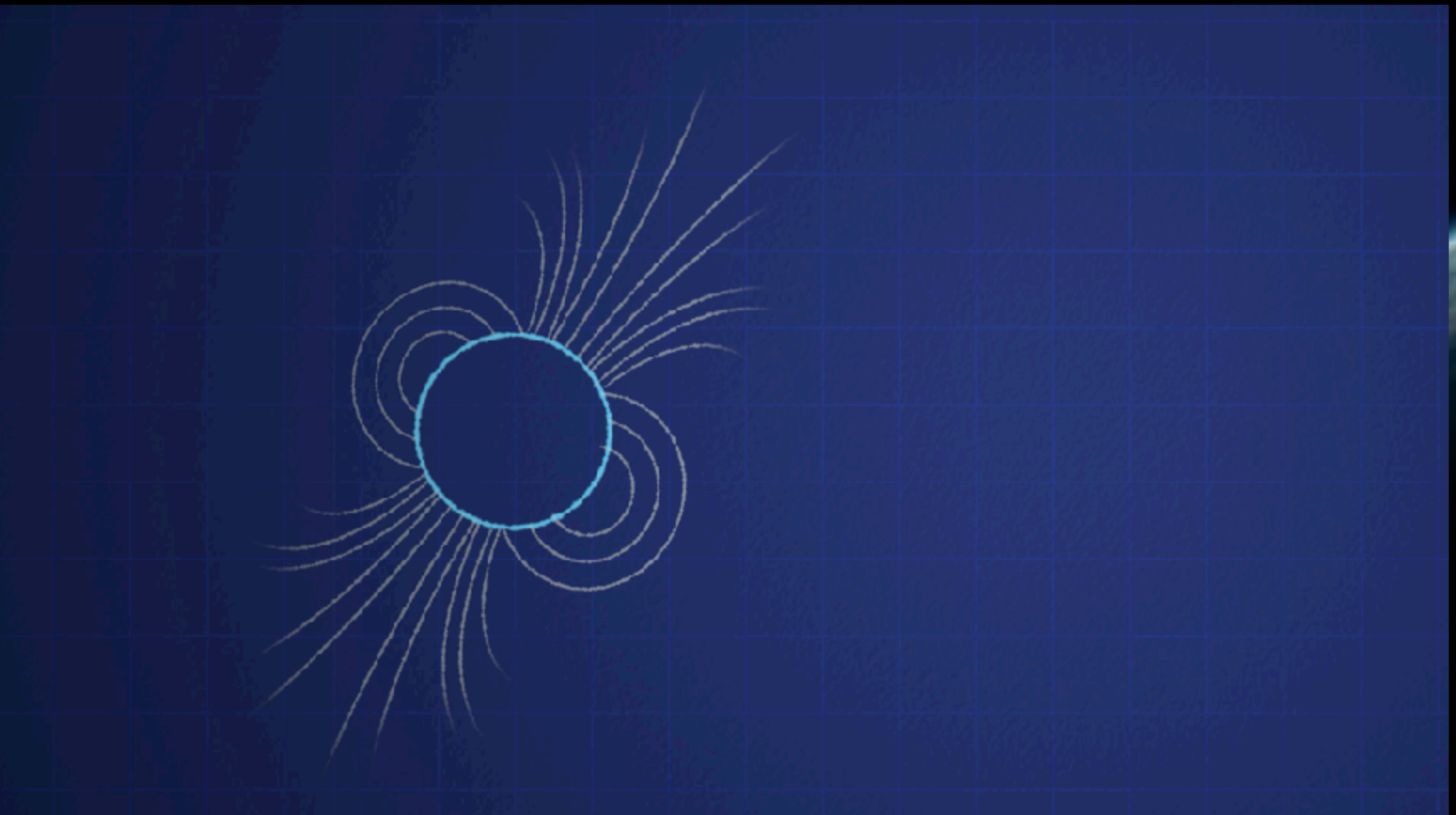
11.4 Million years ago…

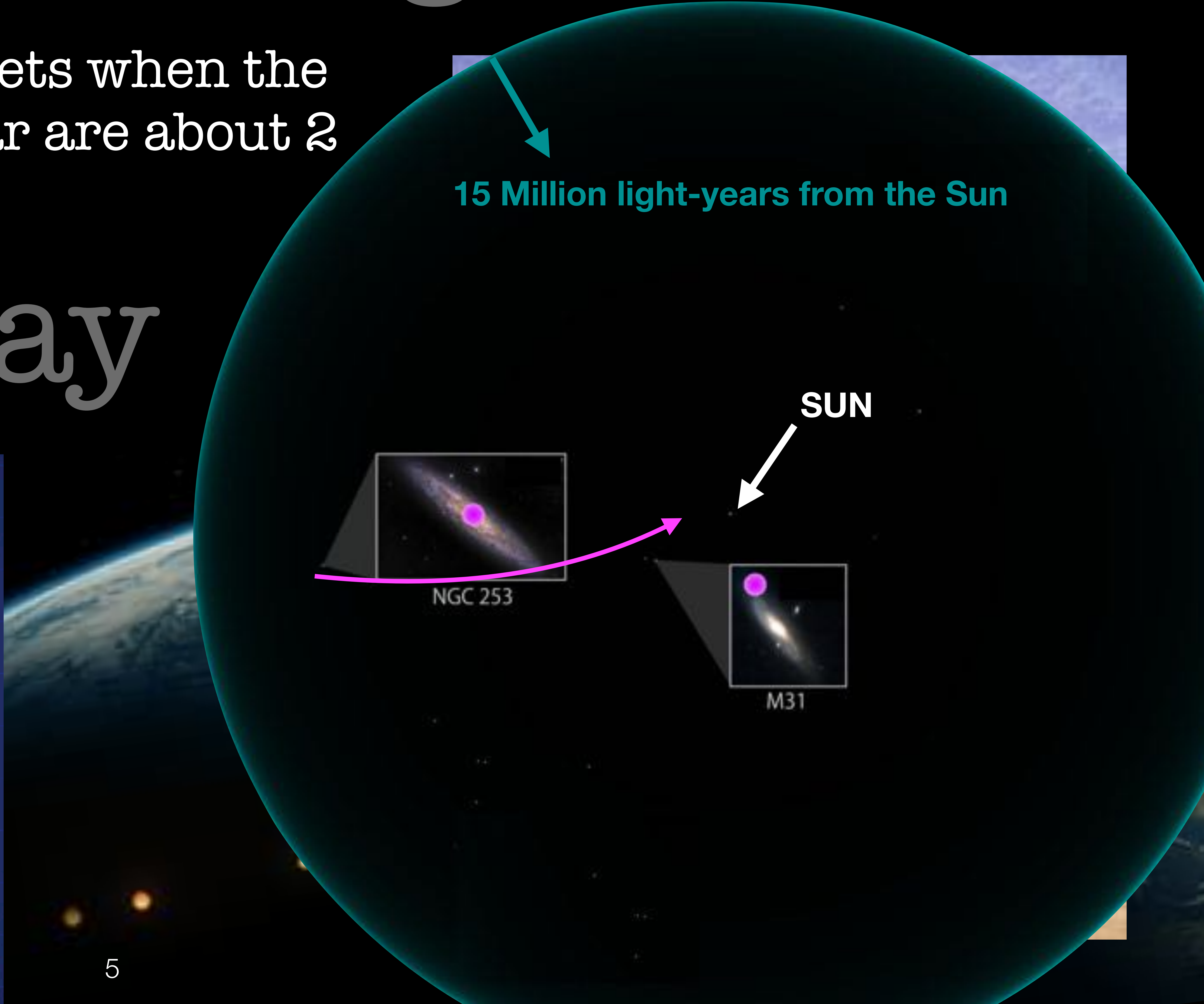


~2 Million years ago…

Homo habilis populates the planets when the photons emitted by the magnetar are about 2 million light years away…

~0.6 Mpc away





1783…

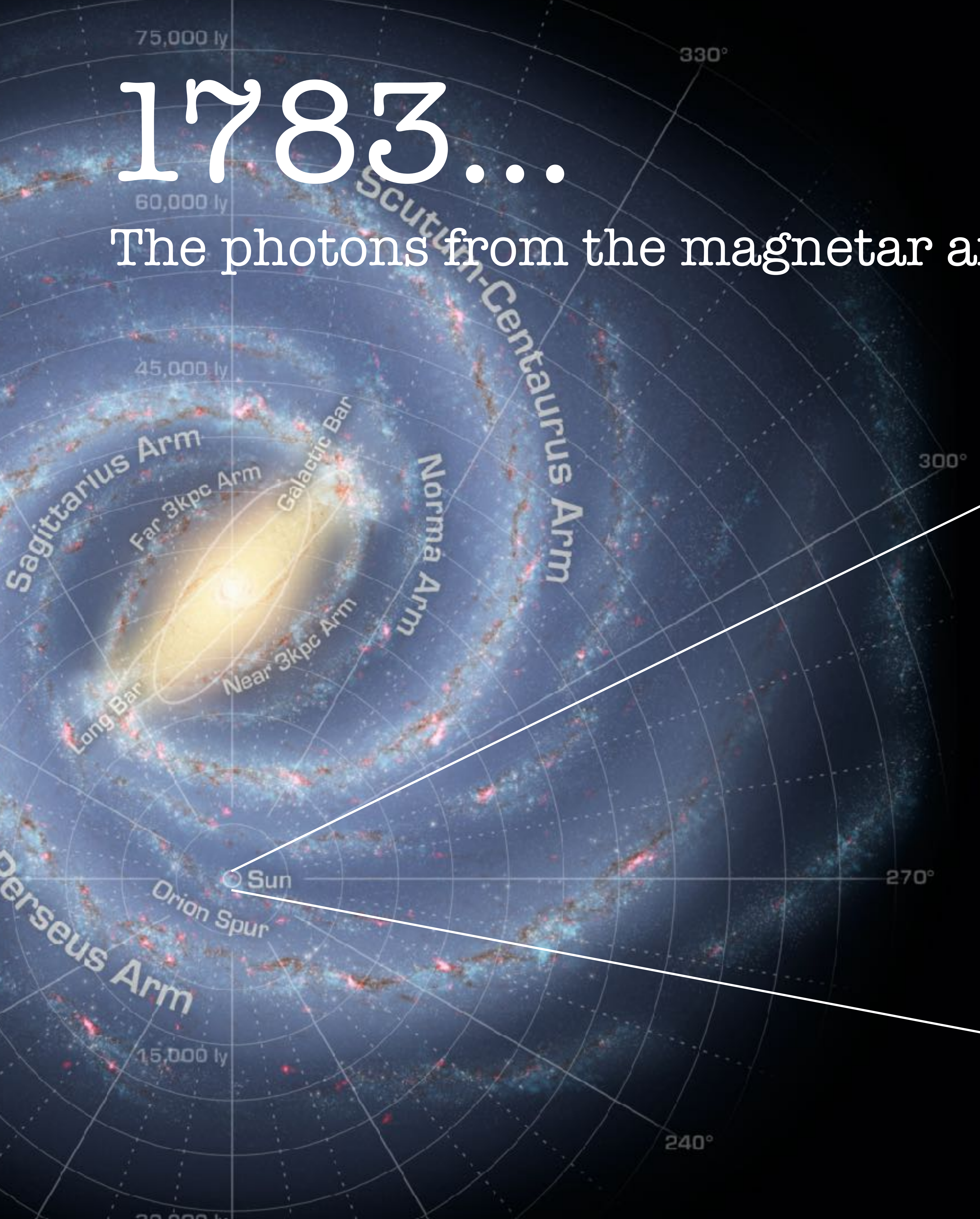
Caroline Hershel discovered Sculptor galaxy

Sculptor Galaxy

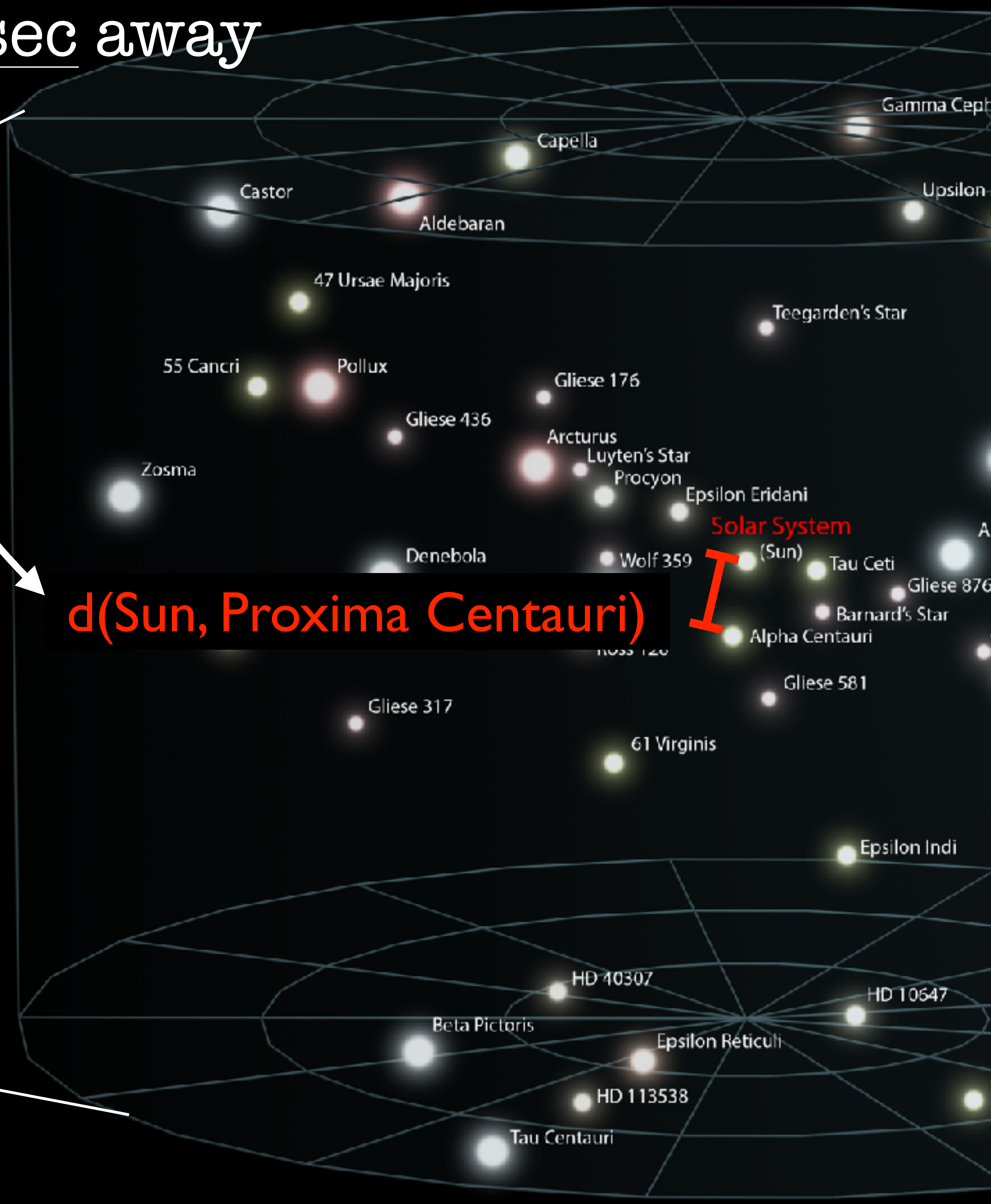
Sculptor Galaxy ...aka NGC 235

1783...

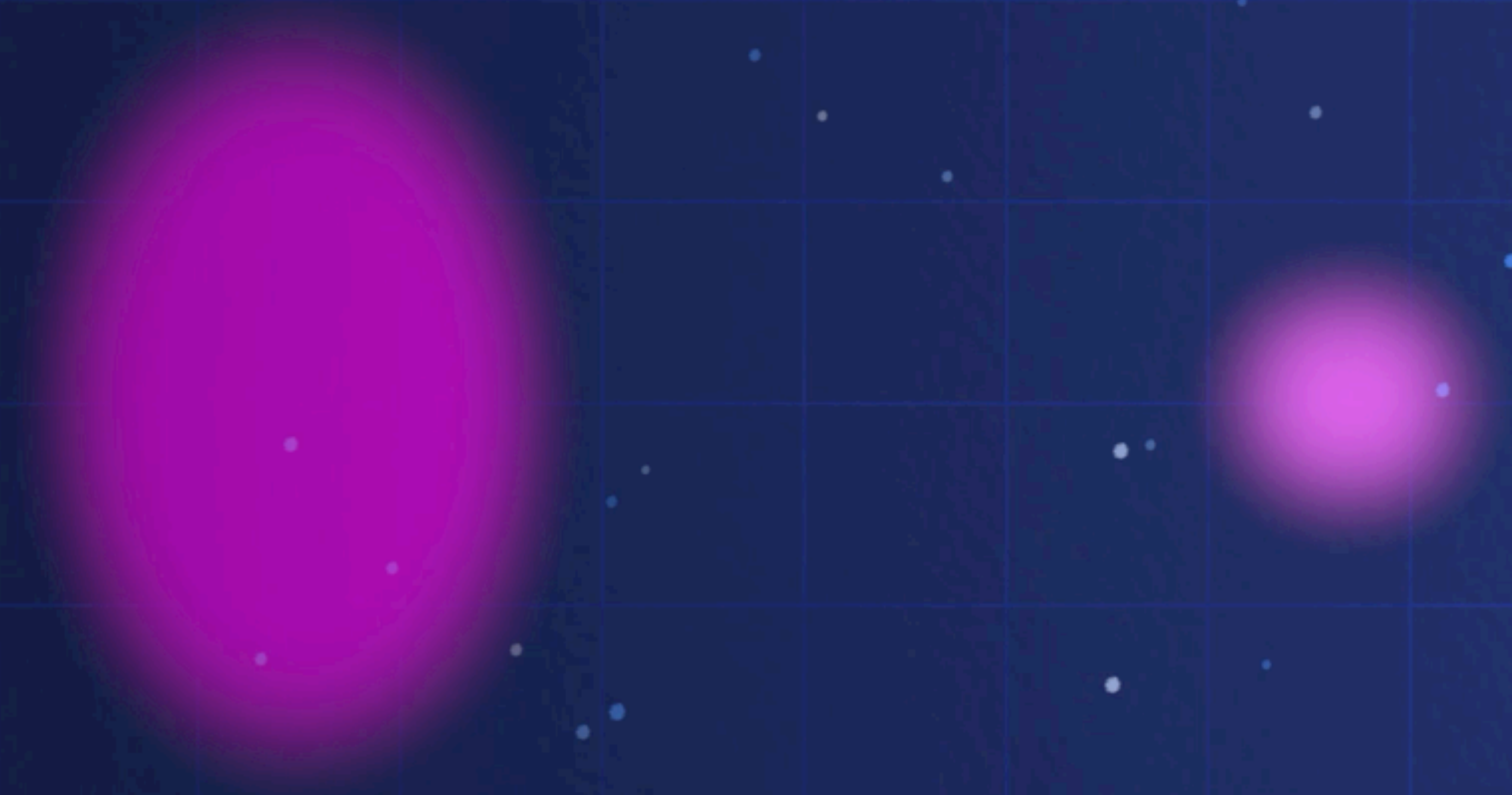
The photons from the magnetar are only 73 parsec away



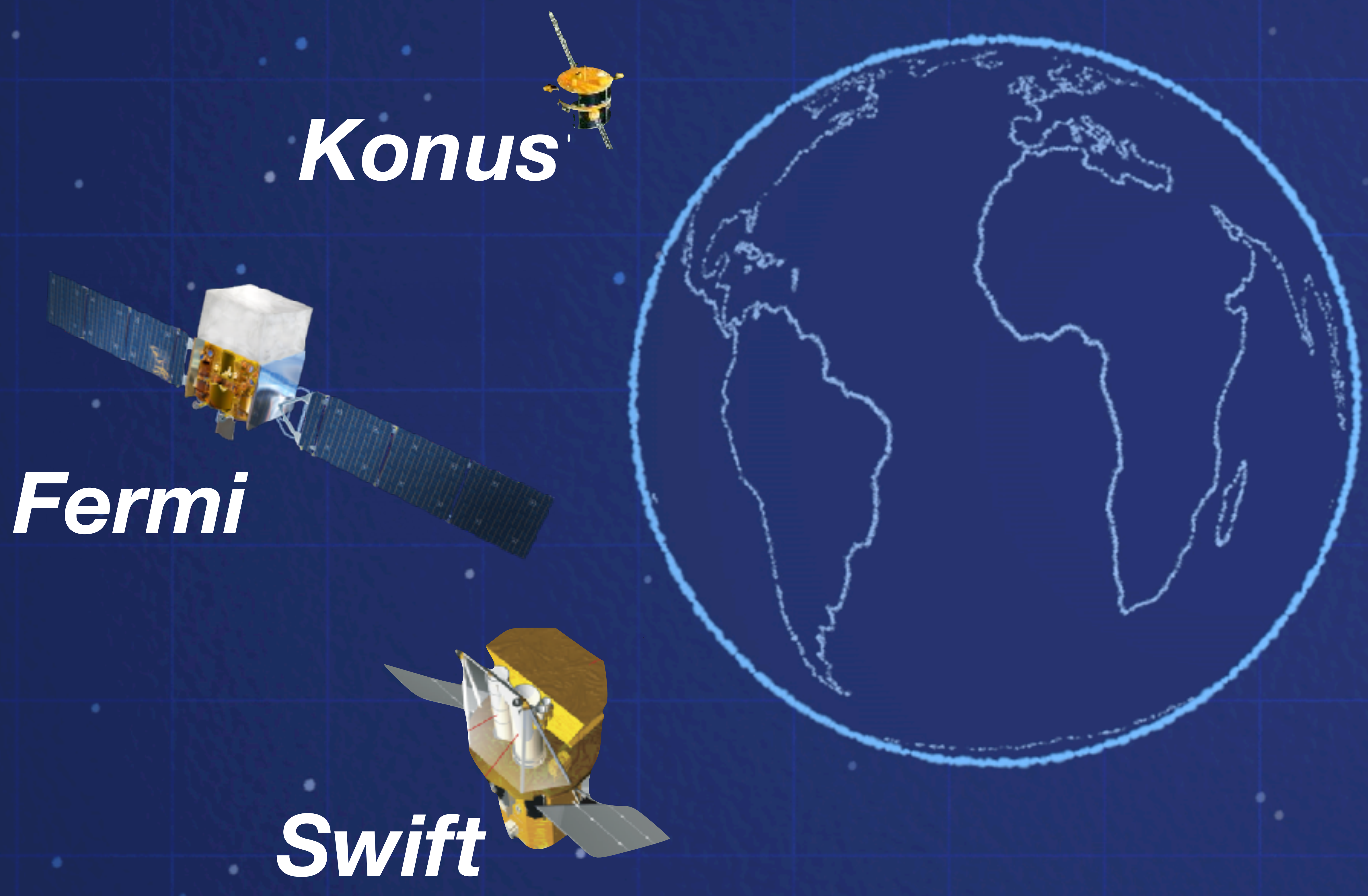
× 53



15 April 2020…



15 April 2020…



OUTLINE

1. Something about Magnetars
2. GRB 200415A GeV detection
3. Extragalactic magnetar giant flares population

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From SGRs to magnetars

Historically, magnetars first appeared in astronomy under the names **soft gamma repeaters**.

First published report in 1979: repeated bursts were seen by hard X-ray/soft gamma-ray instruments

Thompson & Duncan (1995, 1996):

SGR phenomena are nicely explained by spontaneous magnetic field decay serving as an energy source for the transient bursts and outbursts as well as for the persistent emission seen in these sources.

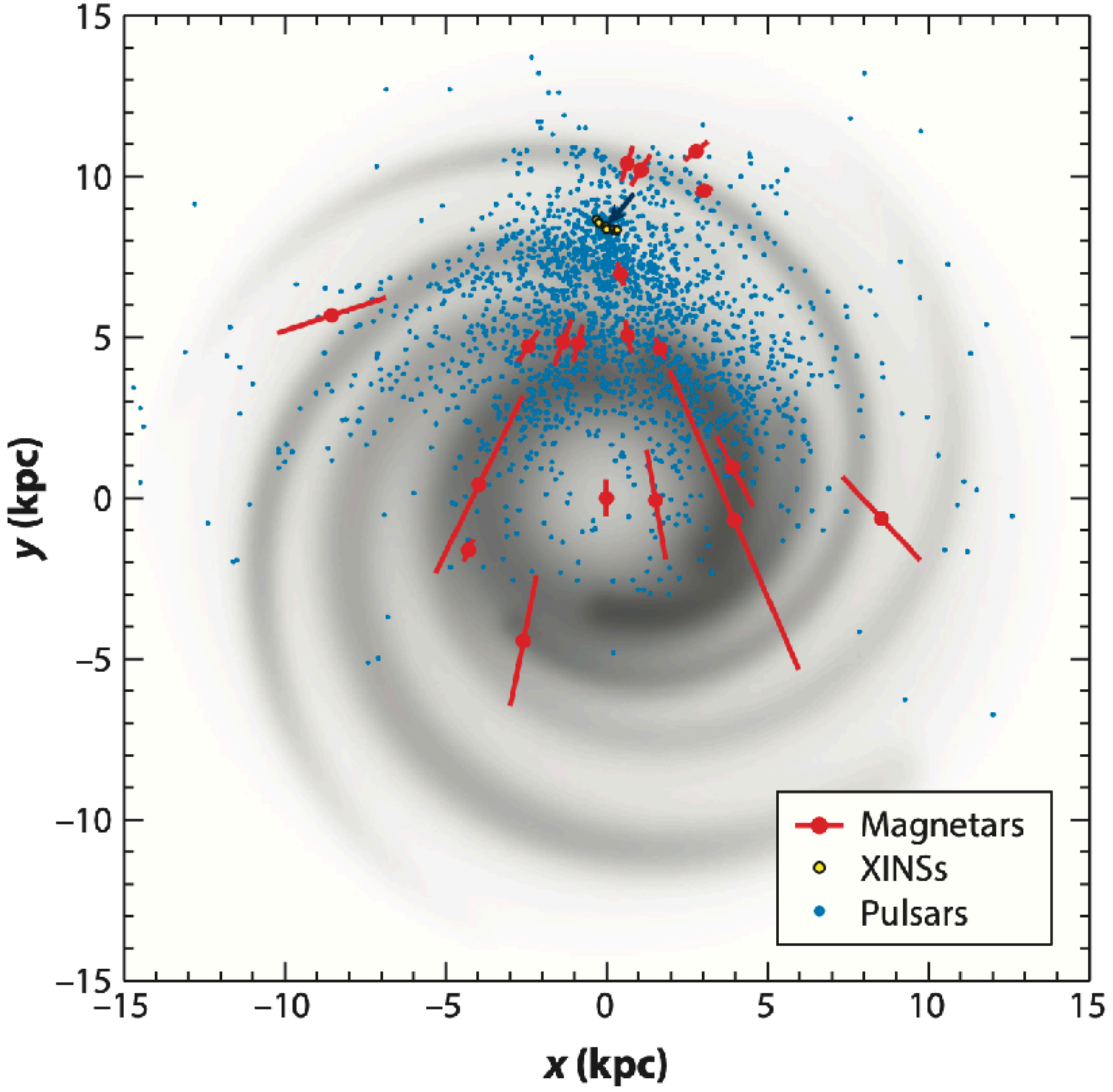
MAGNETARS

Predicted magnetic field:

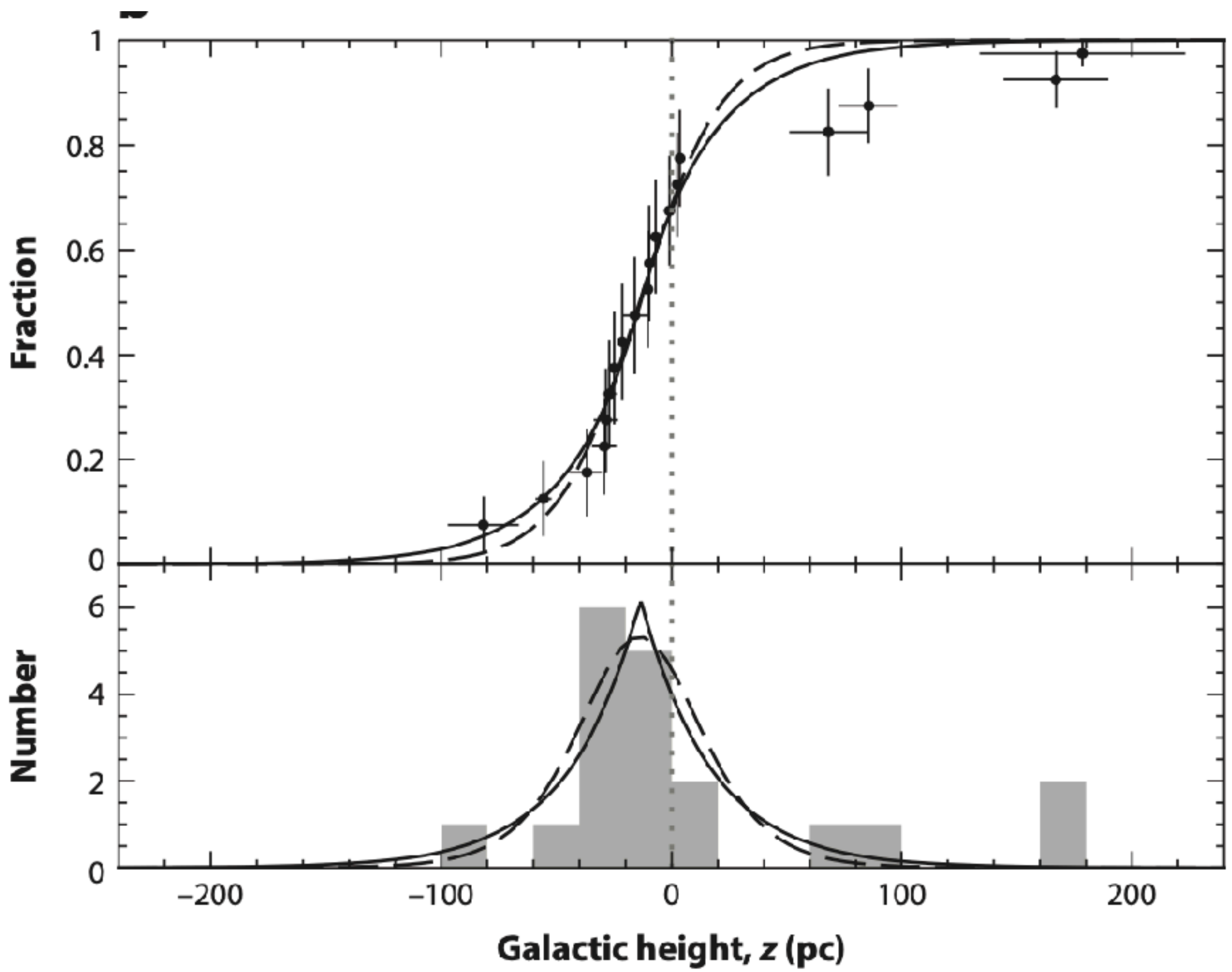
Magnetic field **B = 10^{14} - 10^{15} Gauss** (x100 pulsars)

Thompson & Duncan (1995, 1996)

Known Magnetar population



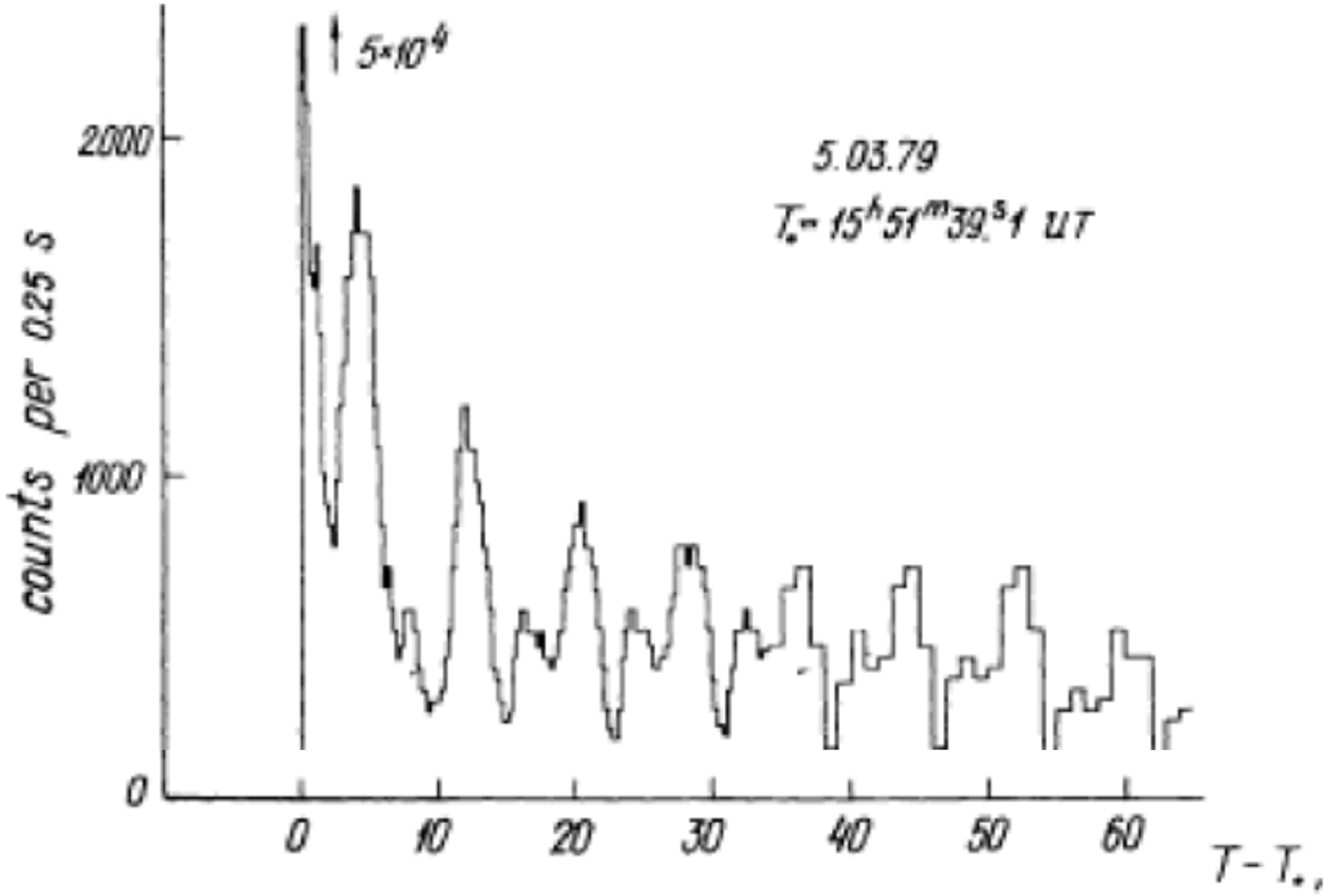
- ✳ 30 magnetars (10% of the young neutron-star population)
- ✳ Close to the Galactic plane: **very young** (v~200 km/s)
- ✳ High spin down timescale ~a few thousand years
- ✳ Periods range: 0.3-9 seconds



Magnetars outbursts

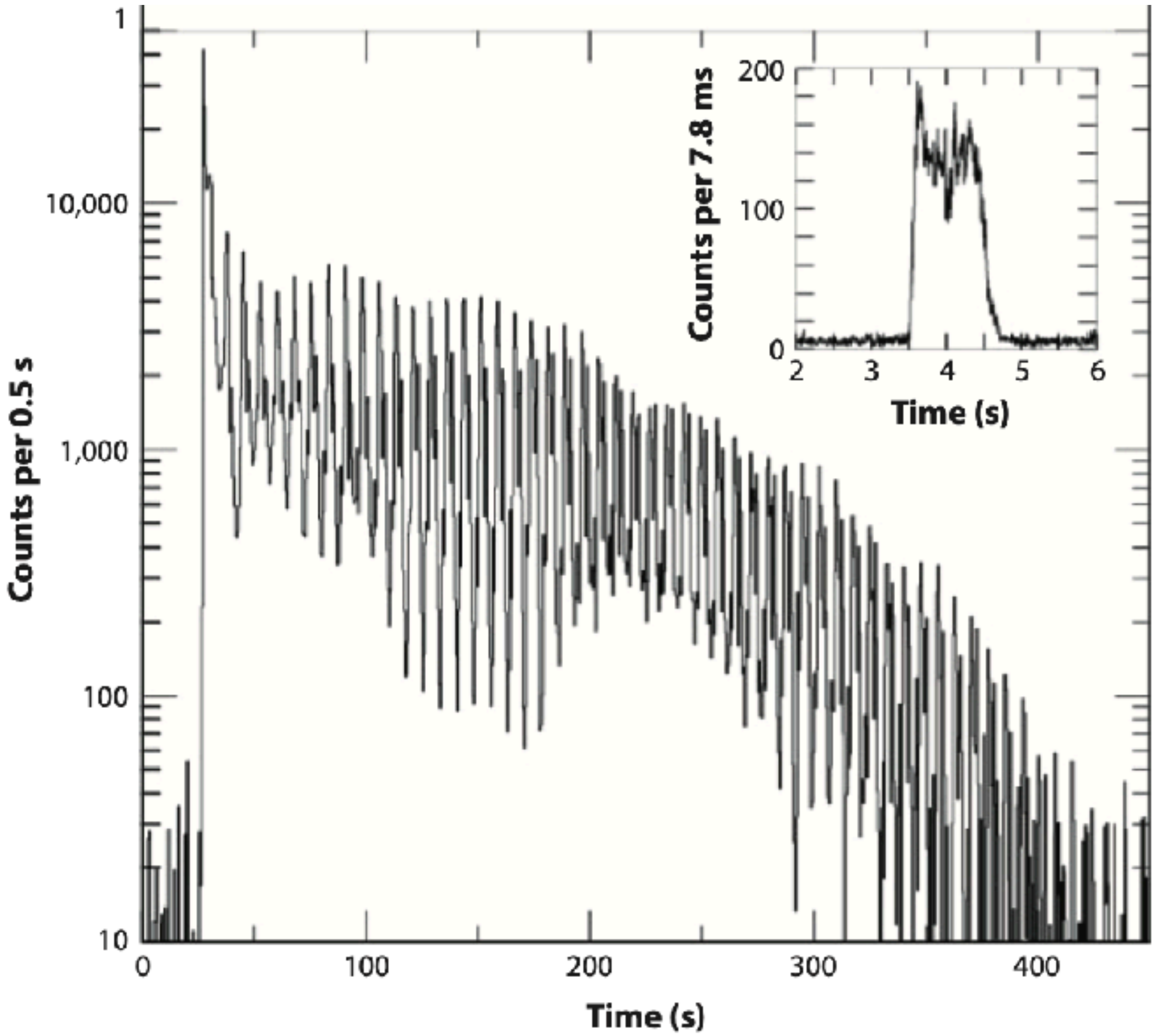
- ✳ Bursts — Energy released ~ 10^{37} - 10^{40} ergs
- ✳ Giant Flares — Energy released ~ **10^{44} - 10^{46} ergs**

March 5, 1979 enormous flare in Large Magellanic Cloud



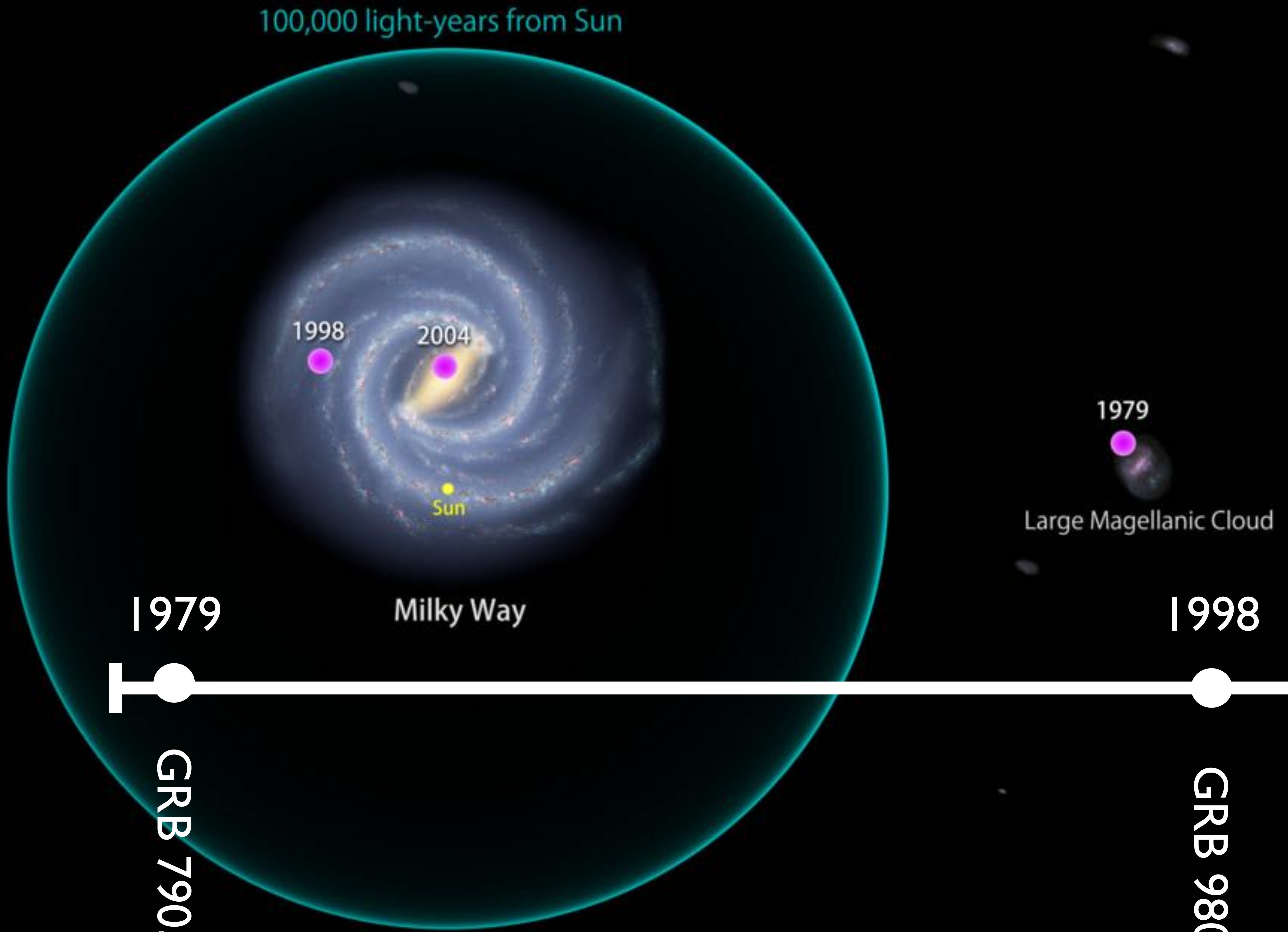
Venera 12 space probe. (E.P. Mazets et al., 1979, Nature

December 27, 2004 exceptionally bright flare from SGR 1806−20



Hurley, K et al, Published in Nature (2005)

A Population of Magnetar Giant Flares

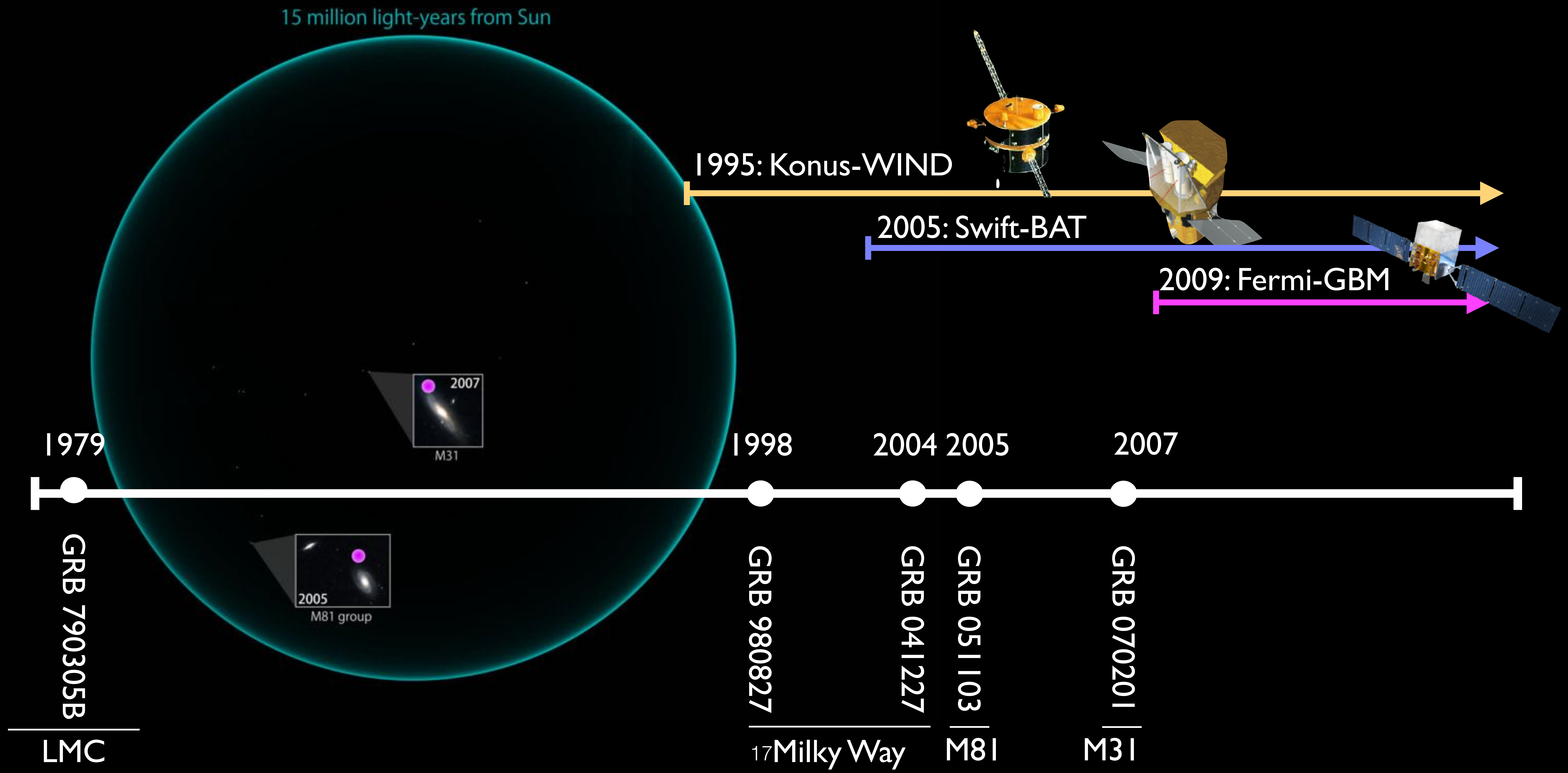


1979 — GRB 790305B — LMC

1998 — GRB 980827 — Milky Way

2004 — GRB 041227 — Milky Way

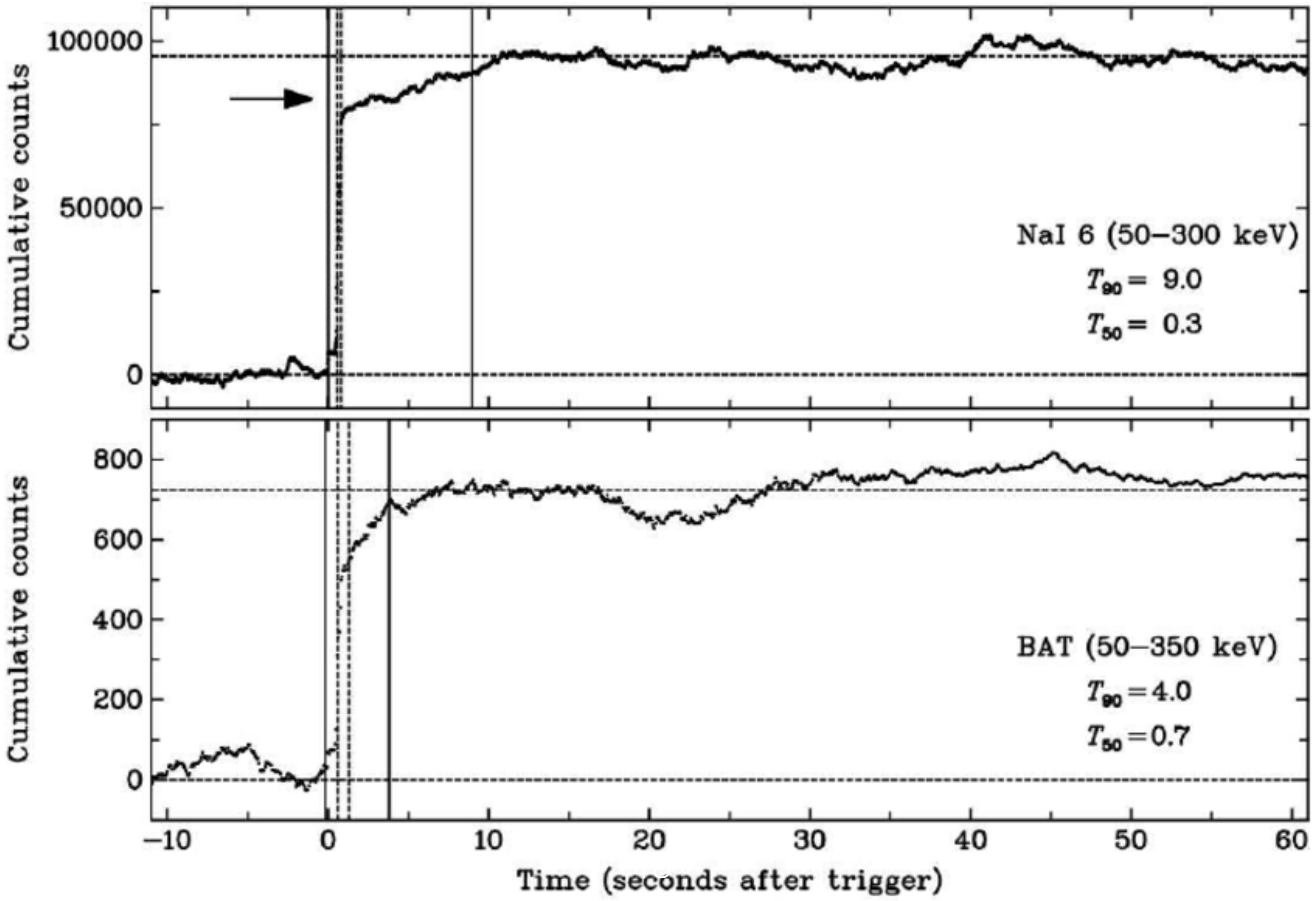
A Population of MGFs



Gamma-ray bursts

Short T90 = 2 s **Long**

T90 = The time taken to accumulate 90% of the burst fluence starting at the 5% fluence level.

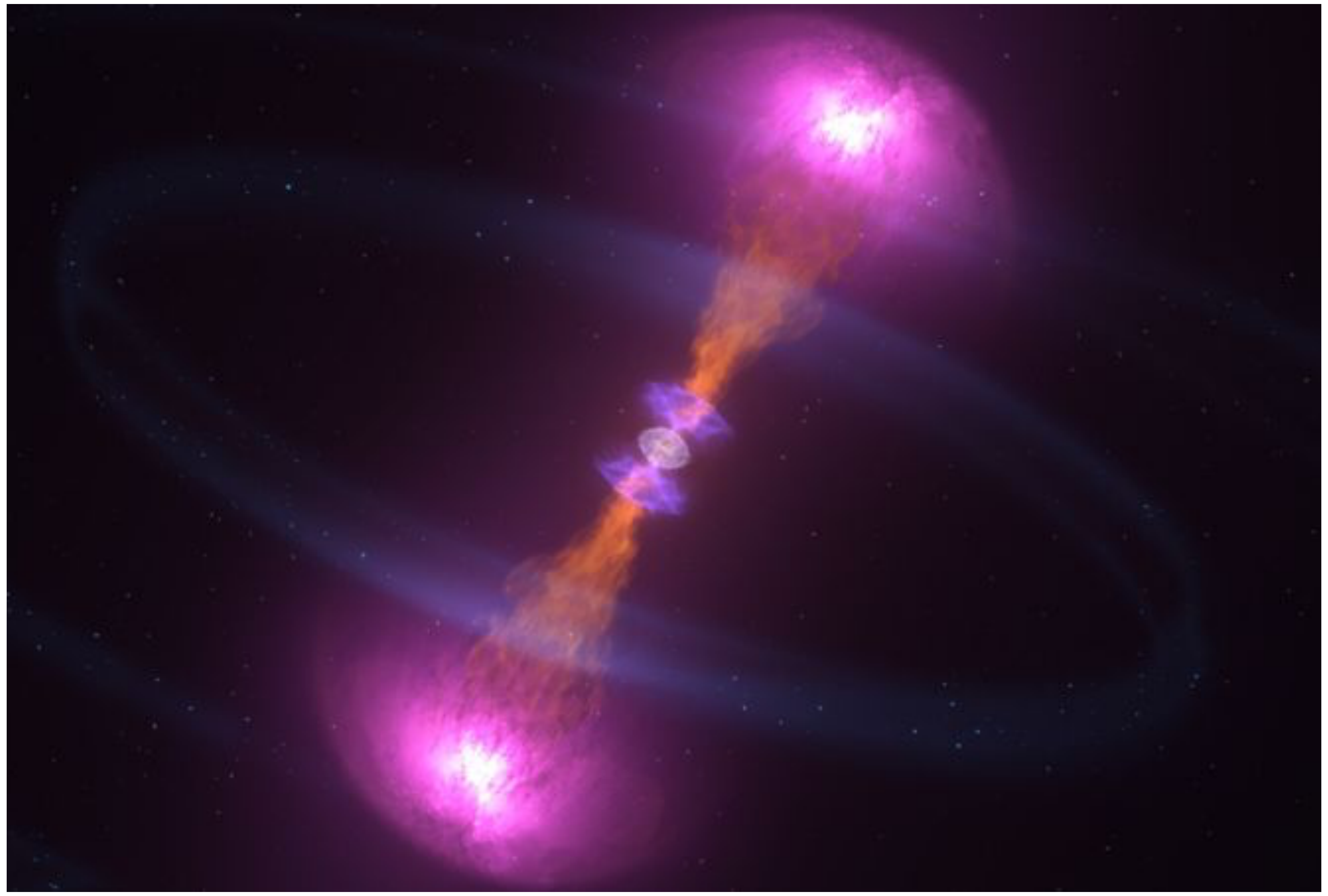


Gamma-ray bursts

Short T90 = 2 s Long

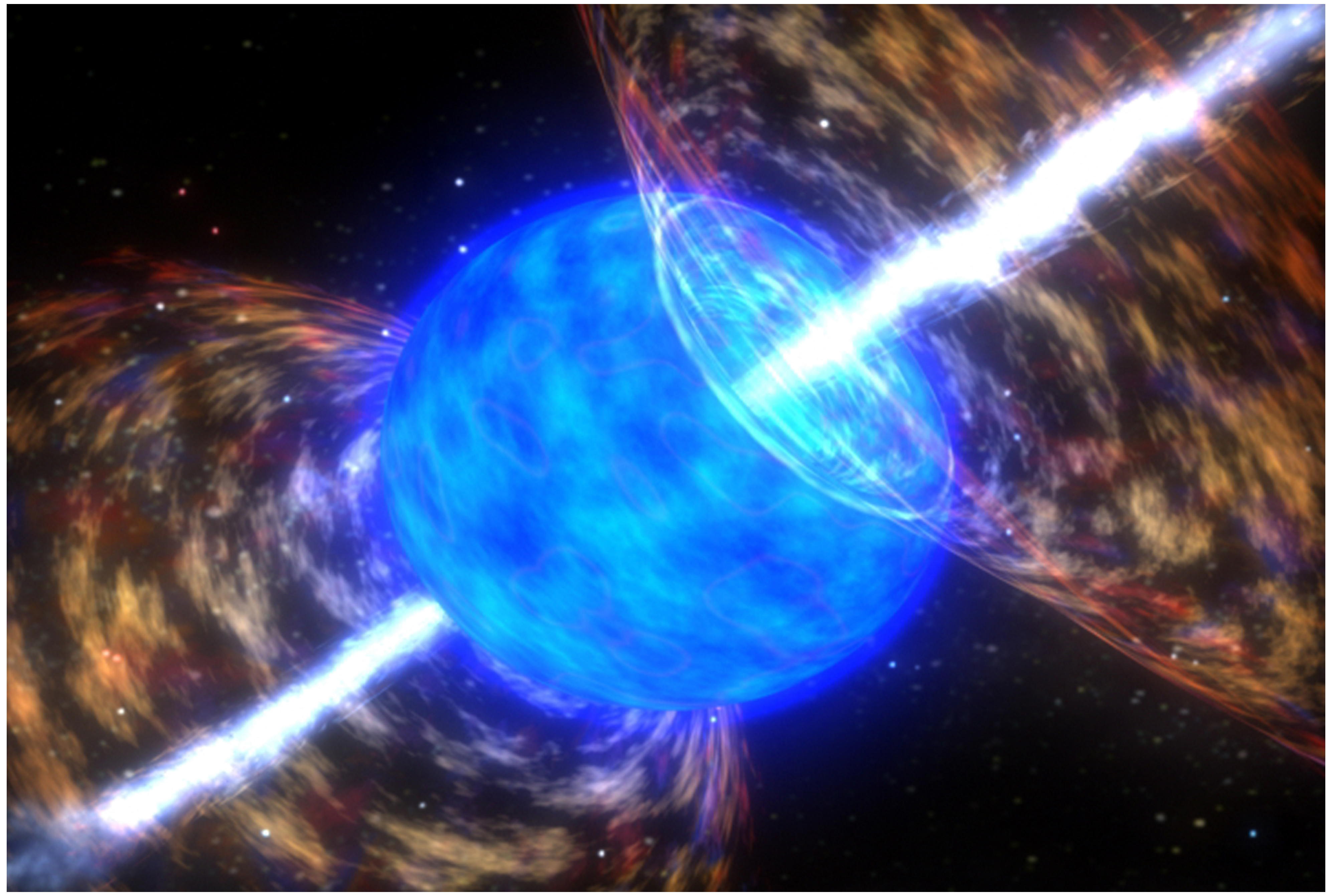
T90 = The time taken to accumulate 90% of the burst fluence starting at the 5% fluence level.

Credit: NASA Goddard / CI Lab



2017: Short GRBs come from neutron star mergers, proven by LIGO, Virgo, Fermi, and INTEGRAL.

Credit: NASA/SkyWorks Digital



1998: Long GRBs come from a rare type of core-collapse supernova (Collapsars), proven by BeppoSAX and follow-up observations.

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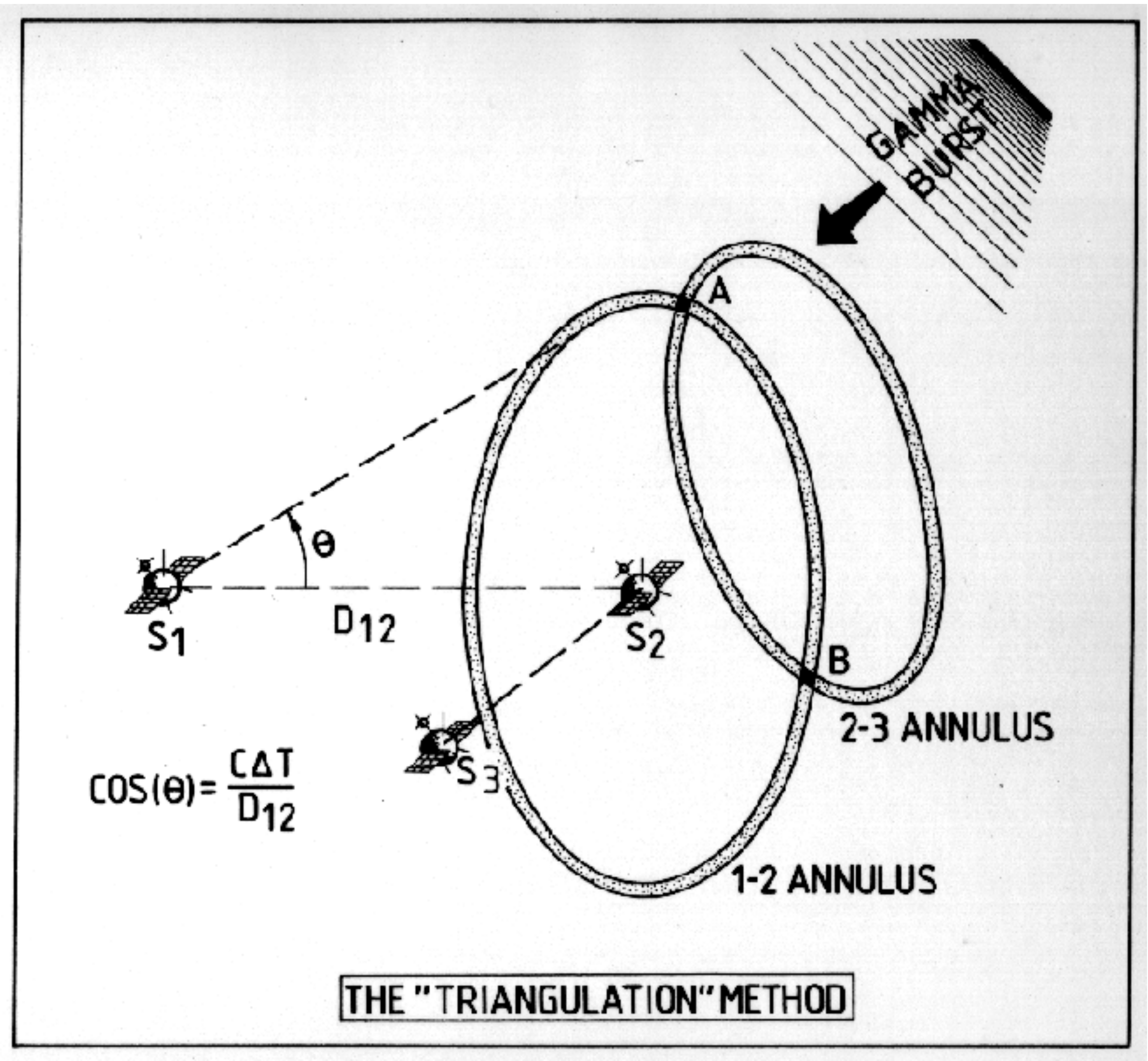
Inter Planetary Network

The **InterPlanetary Network** (IPN) is a group of spacecraft equipped with gamma-ray burst (GRB) detectors

Since 1990: Third IPN (IPN3)

Today, the main spacecraft contributing:

✳ Konus-WIND,
✳ 2001 Mars Odyssey,
✳ INTEGRAL
✳ Swift
✳ Fermi
✳ BepiColombo.

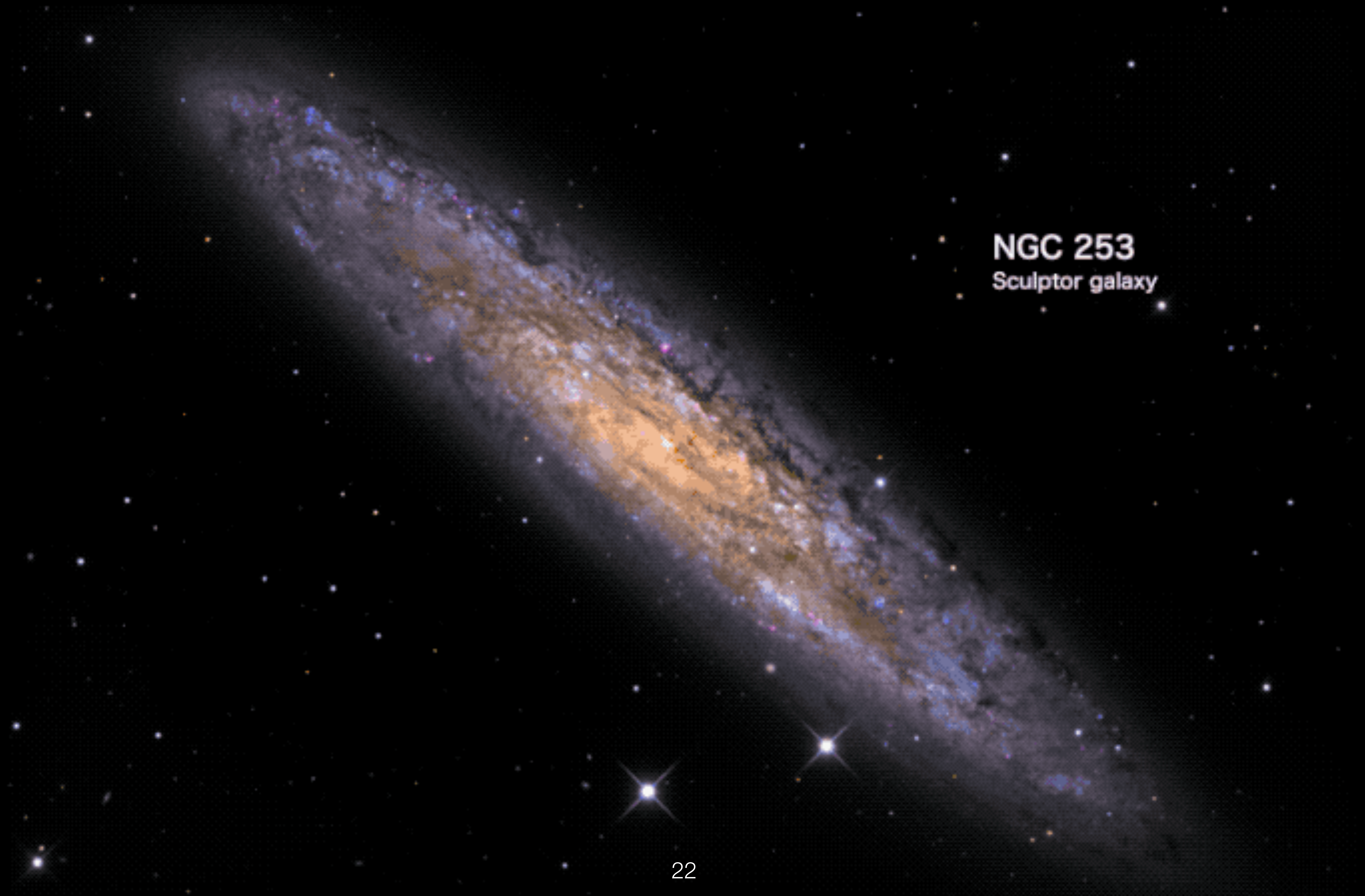


By timing the arrival of a burst at several spacecraft, its precise location can be found.

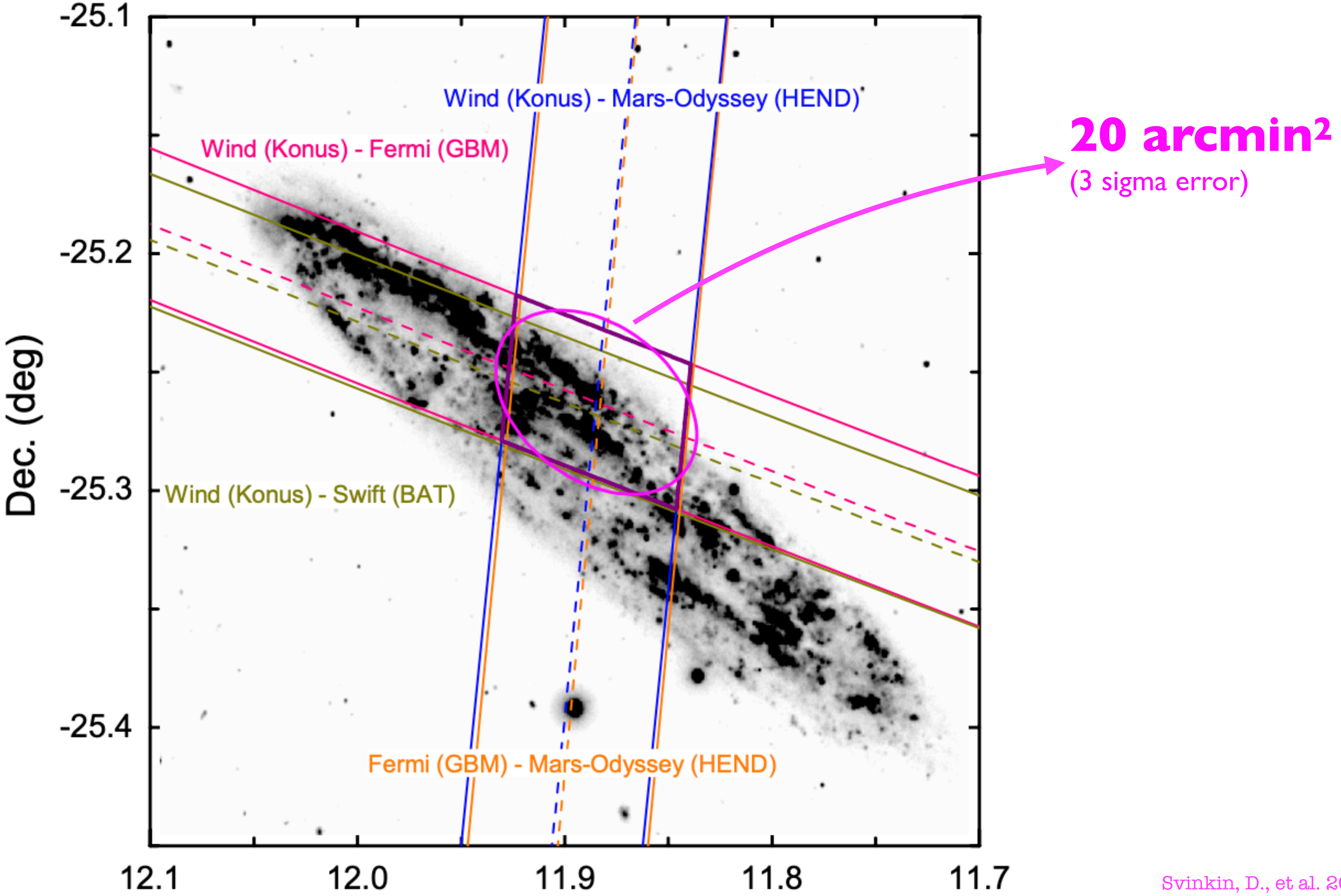
Each pair of spacecraft, like S1 and S2, gives an annulus of possible arrival directions whose center is defined by the vector joining the two spacecraft, and whose radius theta depends on the difference in the arrival times divided by the distance between the two spacecraft.

http://www.ssl.berkeley.edu/ipn3/index.html

Localization of GRB 2000415A

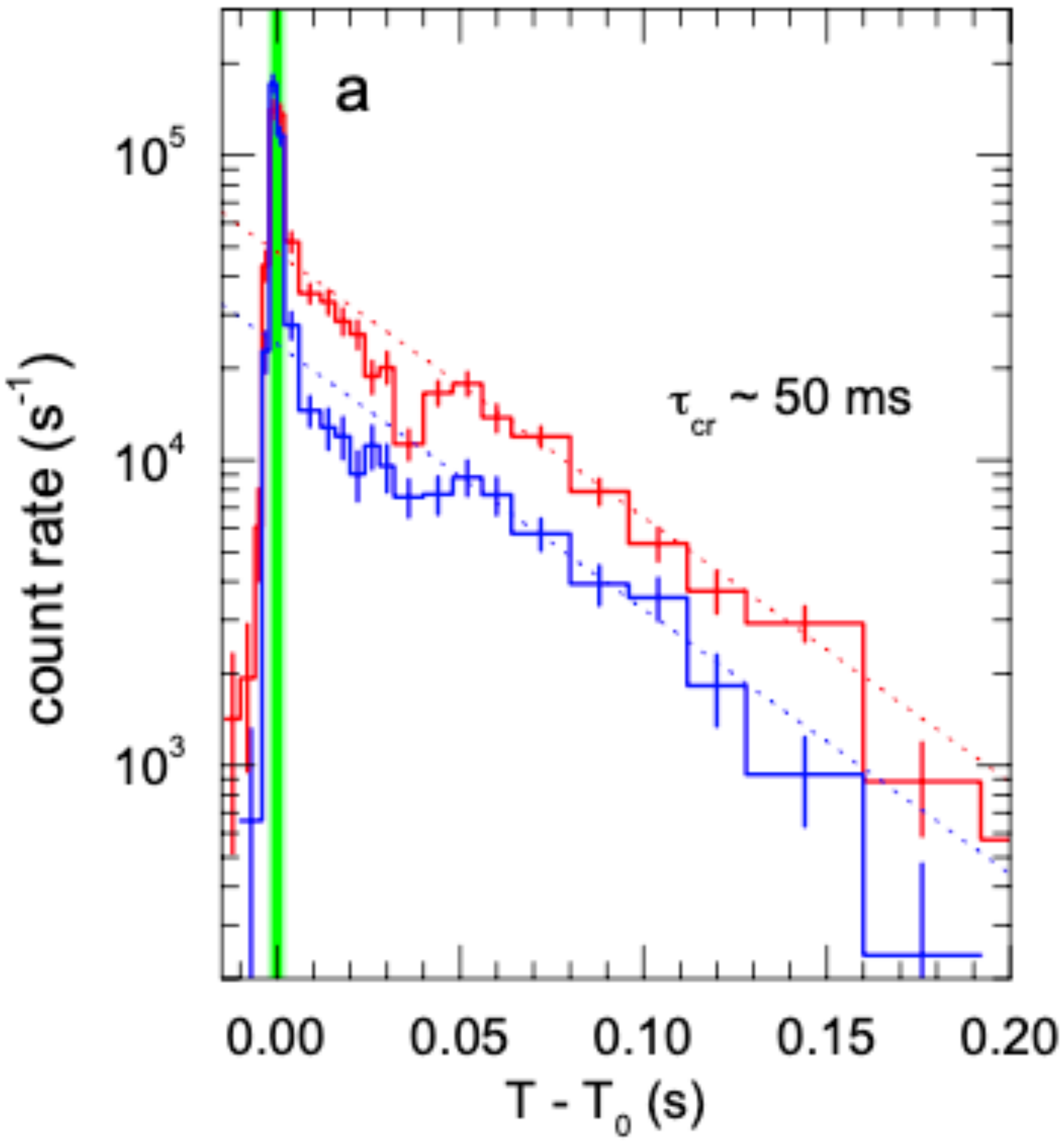


IPN localization of GRB 2000415A



Svinkin, D., et al. 2021, Published in Nature

GRB 2000415A spectral evolution

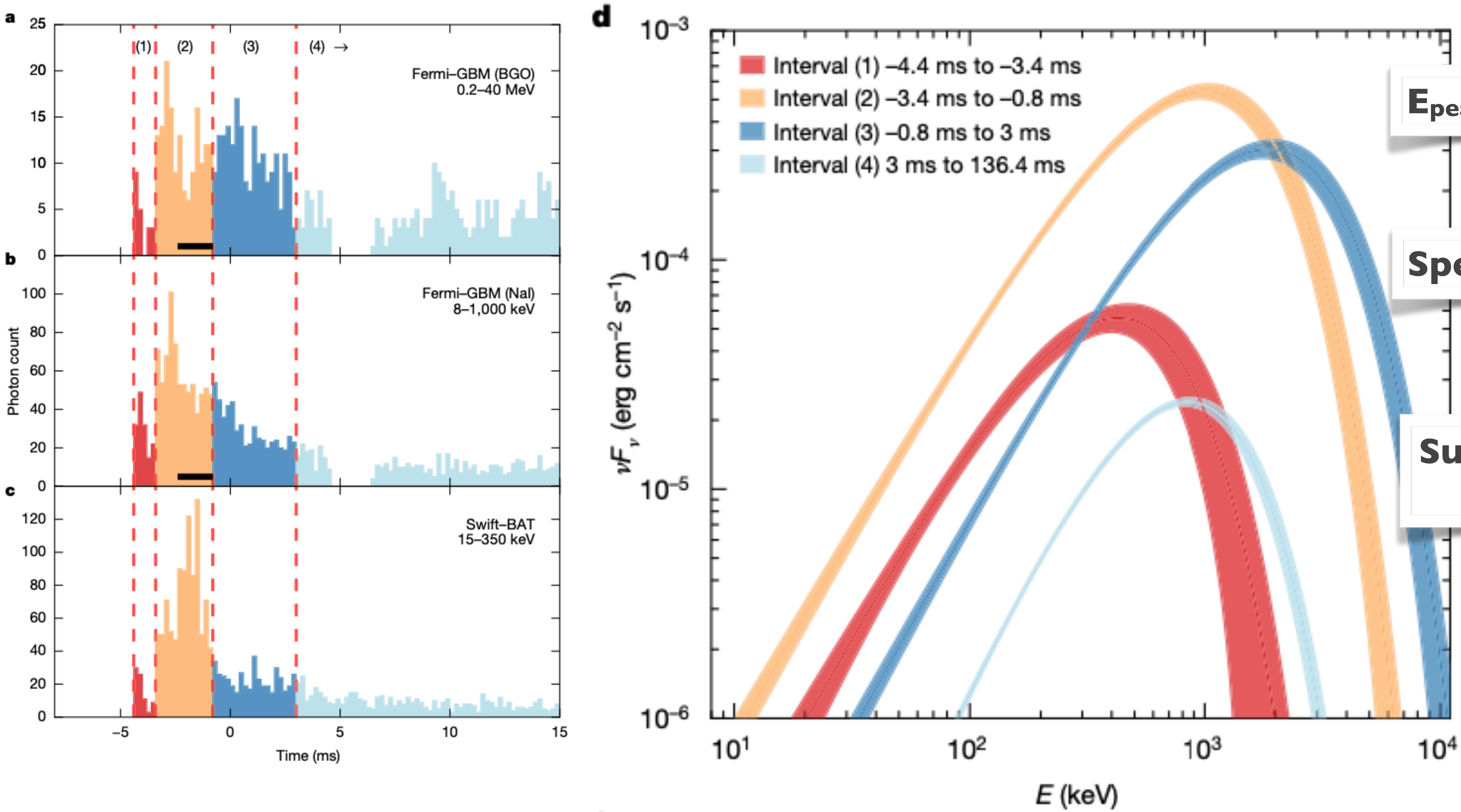


GRB 051103 - M81
GRB 200415A - Sculptor (NGC 253)

- start with a sharp rise of an exceptionally bright, narrow (4 ms) initial pulse (green)
- followed by an exponential decay
- At inferred distances, the energy released ~ Galactic MGF (SGR 1806-20), but higher peak luminosity and > x5 more luminous
- No astrophysical signal with these temporal, spectral properties and energetics have ever been reported
- **the most significant candidates for extragalactic magnetar giant flares**

Svinkin, D., et al. 2021, Published in Nature

Fermi–GBM detection



E_{peak} ~ 1.5 MeV

Typical value for SGRB is ~ 0.6 MeV

Spectral index ~ 0

Typical value for SGRB is ~ -0.4

Sub-ms spectral evolution

O.j. Roberts, et al. 2021, Published in Nature

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What did trigger the Fermi-LAT

Receiving the circular about the gamma-ray burst, automatically triggers the search in LAT data:

- ✳ Region of interest: (12x12)deg around Fermi-GMB localization
- ✳ 10-500 2 after the trigger (time inside the LAT FoV)

Time since T_0 (s)	Energy (MeV)	R.A. (°)	Dec (°)	Prob.	Dist.$_{NGC253}$ (°)	σ_{68} (°)
19.18	**480**	**11.8**	**−25.0**	**0.990**	**0.3**	**1.0**
130.21	110	359.2	−26.4	0.13	11.4	6.7
135.92	410	19.9	−25.7	0.13	7.3	2.3
157.96	131	5.9	−28.9	0.26	6.4	2.9
180.22	**1300**	**11.7**	**−25.7**	**0.988**	**0.5**	**0.9**
221.92	310	7.1	−26.8	0.50	4.5	1.5
262.17	350	16.3	−25.9	0.31	4.1	1.3
276.87	530	12.8	−27.2	0.73	2.1	1.0
284.05	**1700**	**11.0**	**−25.0**	**0.999**	**0.9**	**0.4**
357.32	350	17.5	−30.9	0.14	7.5	2.6
471.16	140	10.1	−21.5	0.75	4.2	2.8

LAT Collab (MN). 2021, Published in Nature Astronomy

What did trigger the LAT

Study the localization of the γ-ray signal observed by the LAT: likelihood analysis and Test Statistics

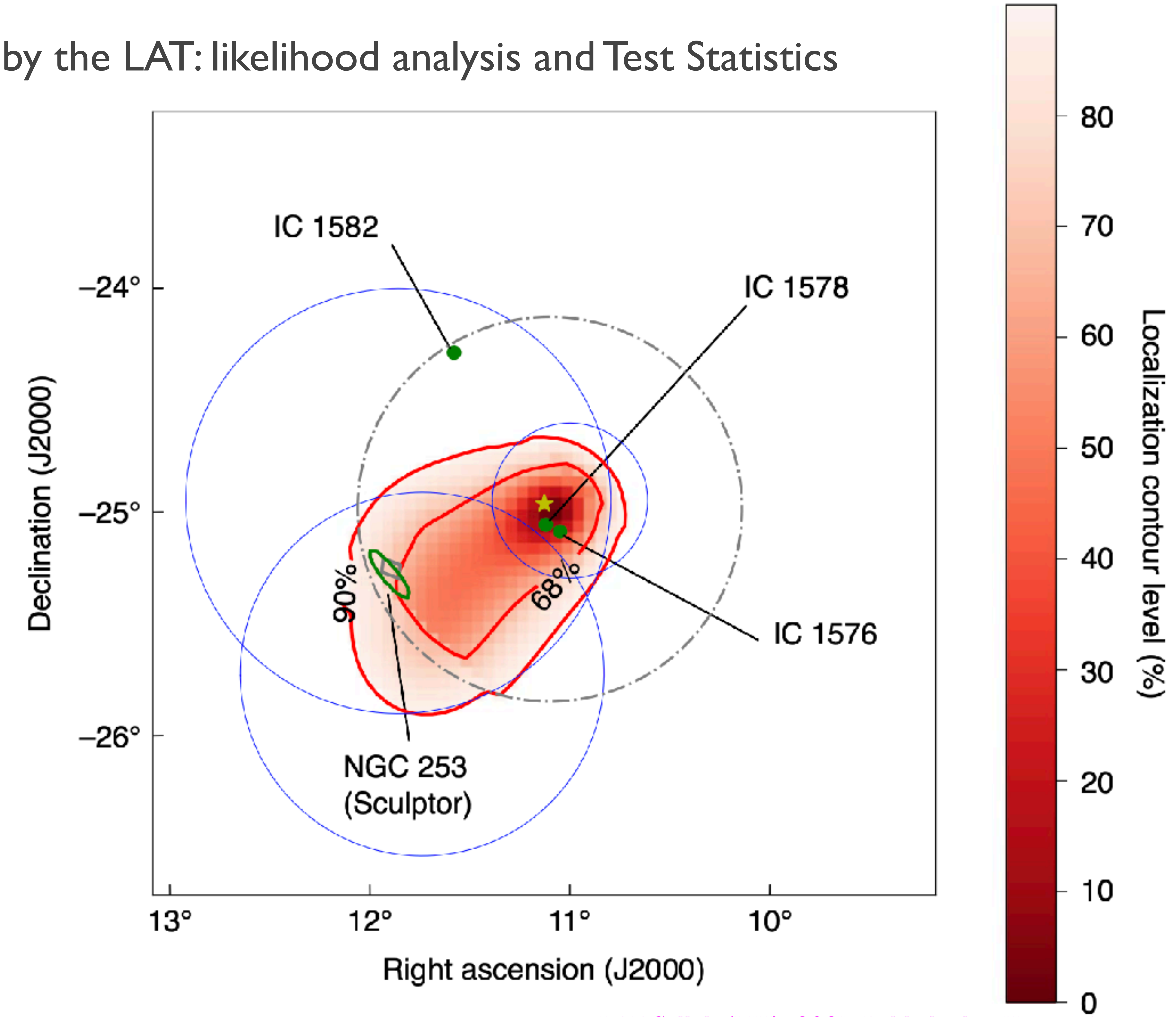
- ✴ **H0**: LAT photons coming from background
- ✴ **H1**: LAT photons coming from a source (at different positions, power-law spectrum)

$$TS = 2(log(L(H1)) - log(L(H0)))$$

TSmax=29:
RA = 11.13°, dec. = −24.97° (J2000)

Detection significance:

$$TS_{distrib} = \frac{1}{2}\chi^2_2 \rightarrow 5.0\sigma$$



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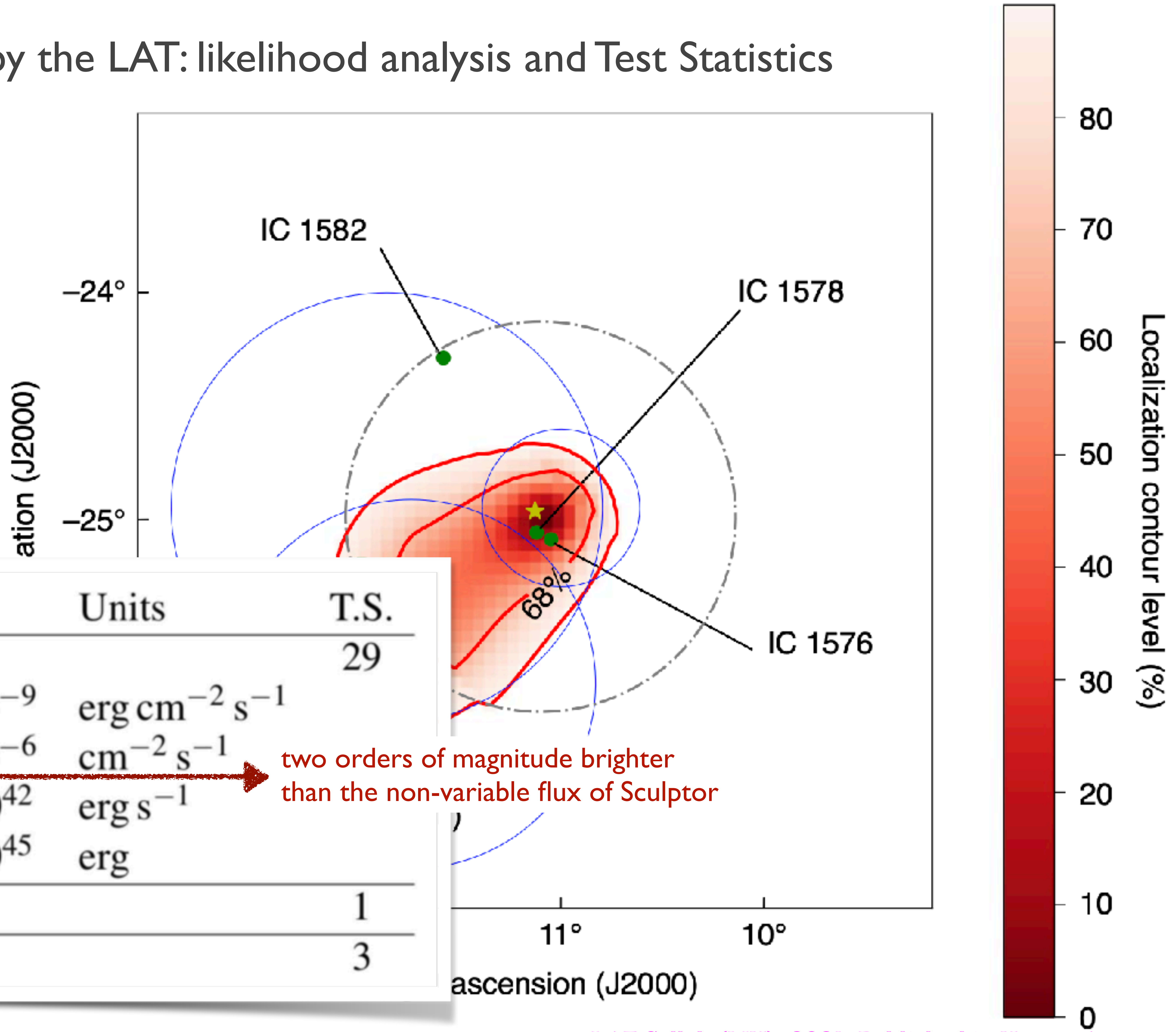


Source	Parameter	Value	Units	T.S.
LAT source	Index (Γ)	-1.7 ± 0.3		29
	Energy Flux	$(4.8 \pm 2.7) \times 10^{-9}$	$\mathrm{erg\,cm^{-2}\,s^{-1}}$	
	Flux	$(4.1 \pm 2.2) \times 10^{-6}$	$\mathrm{cm^{-2}\,s^{-1}}$	
	L_{iso}	$(7.4 \pm 4.2) \times 10^{42}$	$\mathrm{erg\,s^{-1}}$	
	E_{iso}	$(3.6 \pm 2.1) \times 10^{45}$	erg	
GalacticTemplate	Const	1 (fixed)		1
IsotropicTemplate	Const	1.0±0.8		3

Typical LAT detected SGRB

two orders of magnitude brighter than the non-variable flux of Sculptor

LAT Collab (MN). 2021, Published in Nature Astronomy

What did trigger the LAT

How likely is the detected source to be associated to NGC 253?

4 sources in the 99% circular region from TS_{max}:
- ✳ IC1576
- ✳ IC1578
- ✳ IC1582
- ✳ NGC253

Likelihood Ratio (LR) method:

$$r_{\alpha,\beta} = \frac{d}{r_{68}}$$

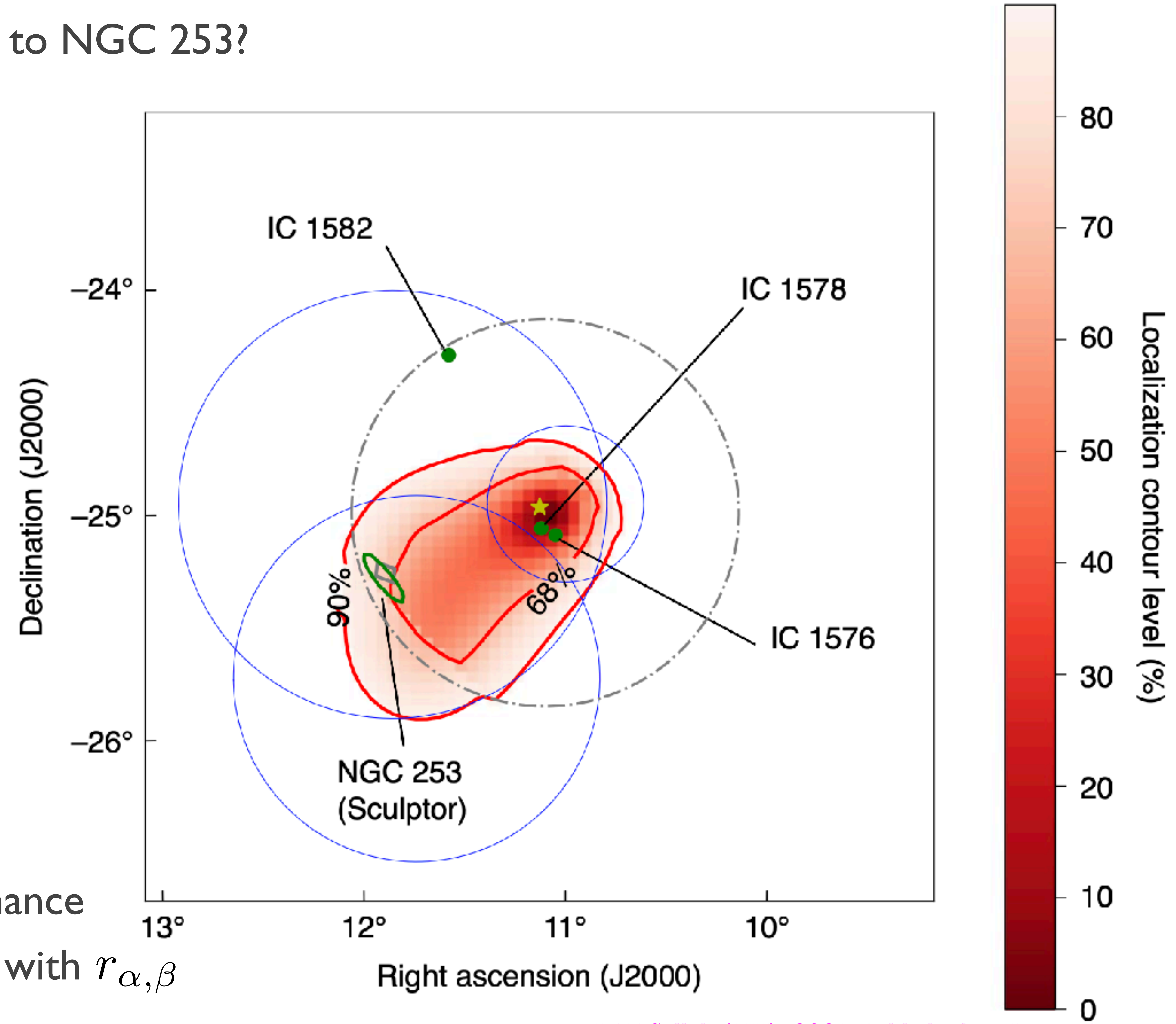
d: ang. dist. between the γ-ray localization α and the counterpart candidate β

r_{68}: γ-ray location uncertainty (at the 68% confidence level)

The probability that β lies at a distance $r_{\alpha,\beta}$ from α is distributed as a Rayleigh distribution:

$$r_{\alpha,\beta} e^{-r^2_{\alpha,\beta}/2}$$

The probability that β is a background source by chance close to the position α follows a linear distribution with $r_{\alpha,\beta}$



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✳ IC1576
✳ IC1578
✳ IC1582
✳ NGC253

Likelihood Ratio (LR) method:

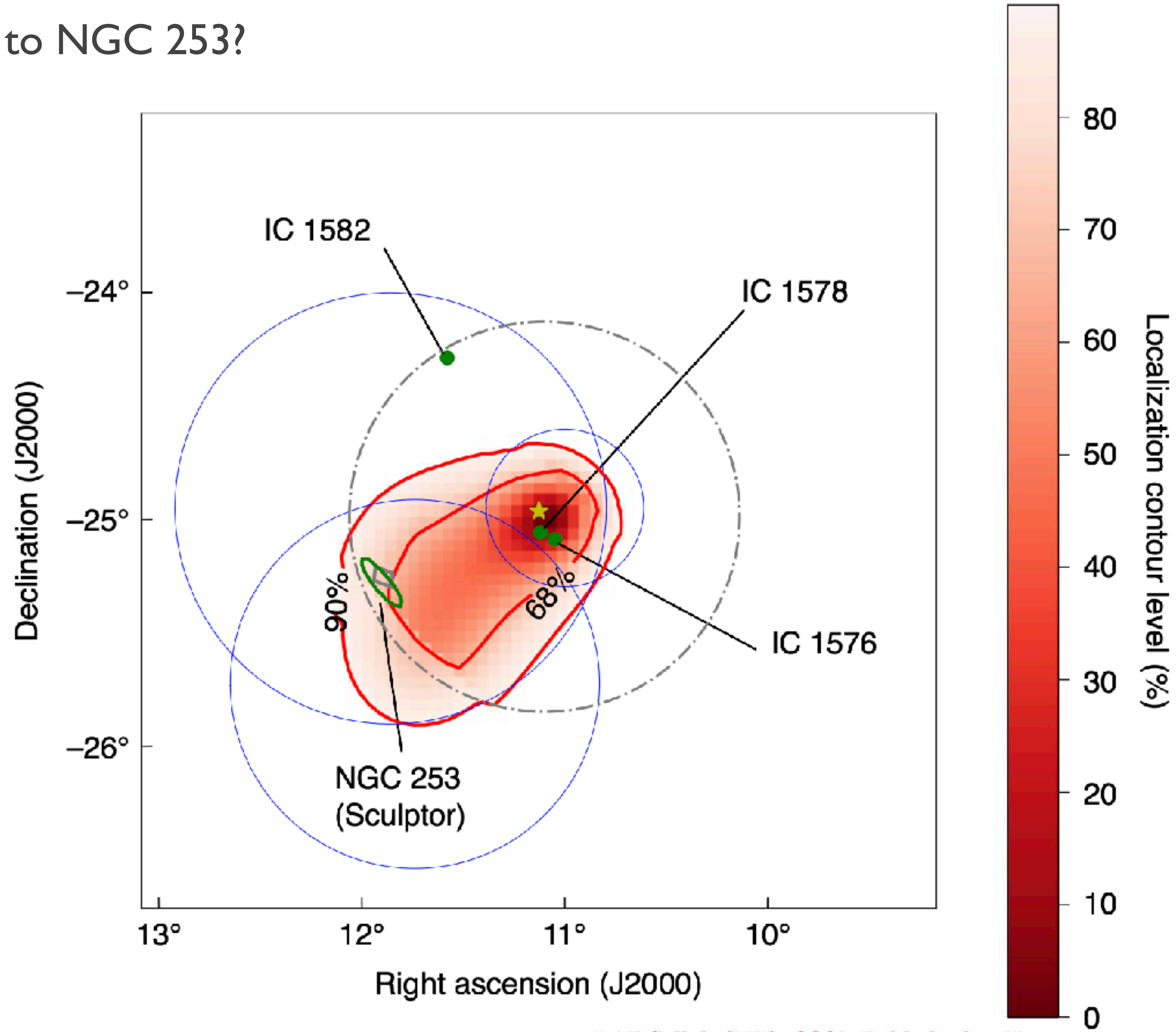
$$LR = \frac{e^{-r^2_{\alpha,\beta}/2}}{N(\leq m_\beta)A}$$

LR = 2.1 (IC 1576),

LR = 2.9 (IC 1578)

LR = 0.3 (IC 1582)

LR = 60 (NGC 253)



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What did trigger the LAT

How likely is the detected source to be associated to NGC 253?

4 sources in the 99% circular region from TS_{max}:

- IC1576
- IC1578
- IC1582
- NGC253

Likelihood Ratio (LR) method:

Analysis	p-value	FAR (yr^{-1})
Spatial Association with the Sculptor galaxy		
LR (Rayleigh)	2.9×10^{-3}	4.7×10^{-3}
LR_{ext} (Rayleigh)	1.7×10^{-3}	2.9×10^{-3}
LR (TS Map)	3.6×10^{-4}	6.0×10^{-4}
LR_{ext} (TS Map)	3.2×10^{-4}	5.4×10^{-4}

False Alarm Rate
Assuming that the emission is from a SGRB, FAR = *P*-values X SGRB rate observed by the LAT.

1/(3000 yr) — 1/(54000 yr)

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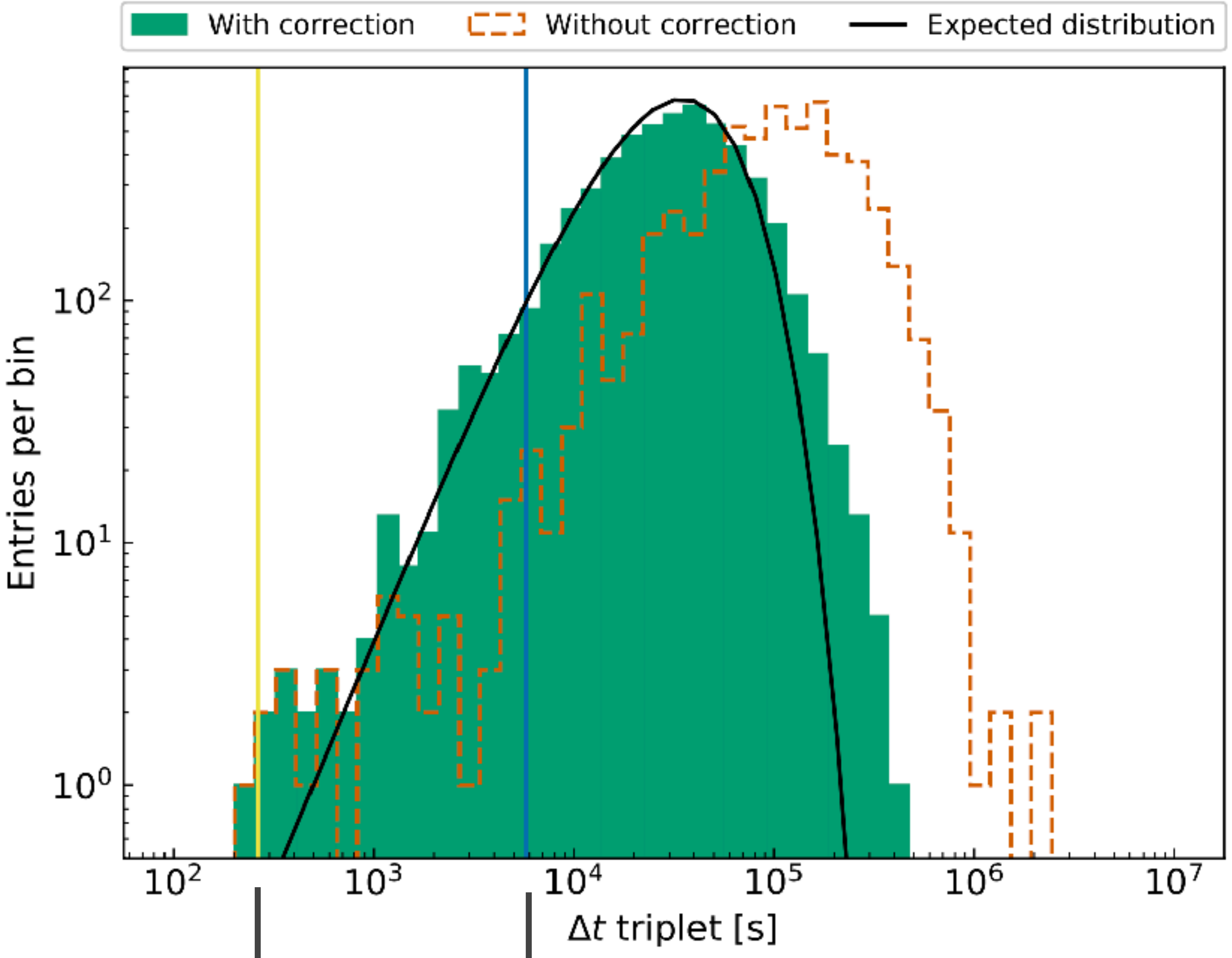
What did trigger the LAT

How often did we observed a triplet of photons above 100 MeV in a 500 second time window in the past 12 years?



Δt = 264.87 s

Period of the Fermi orbit (5,790 s)

Analysis	p-value	FAR (yr^{-1})
Temporal Association with GRB 200415A		
Triplet Analysis	8.3×10^{-7} (Li & Ma)	1.6×10^{-7}

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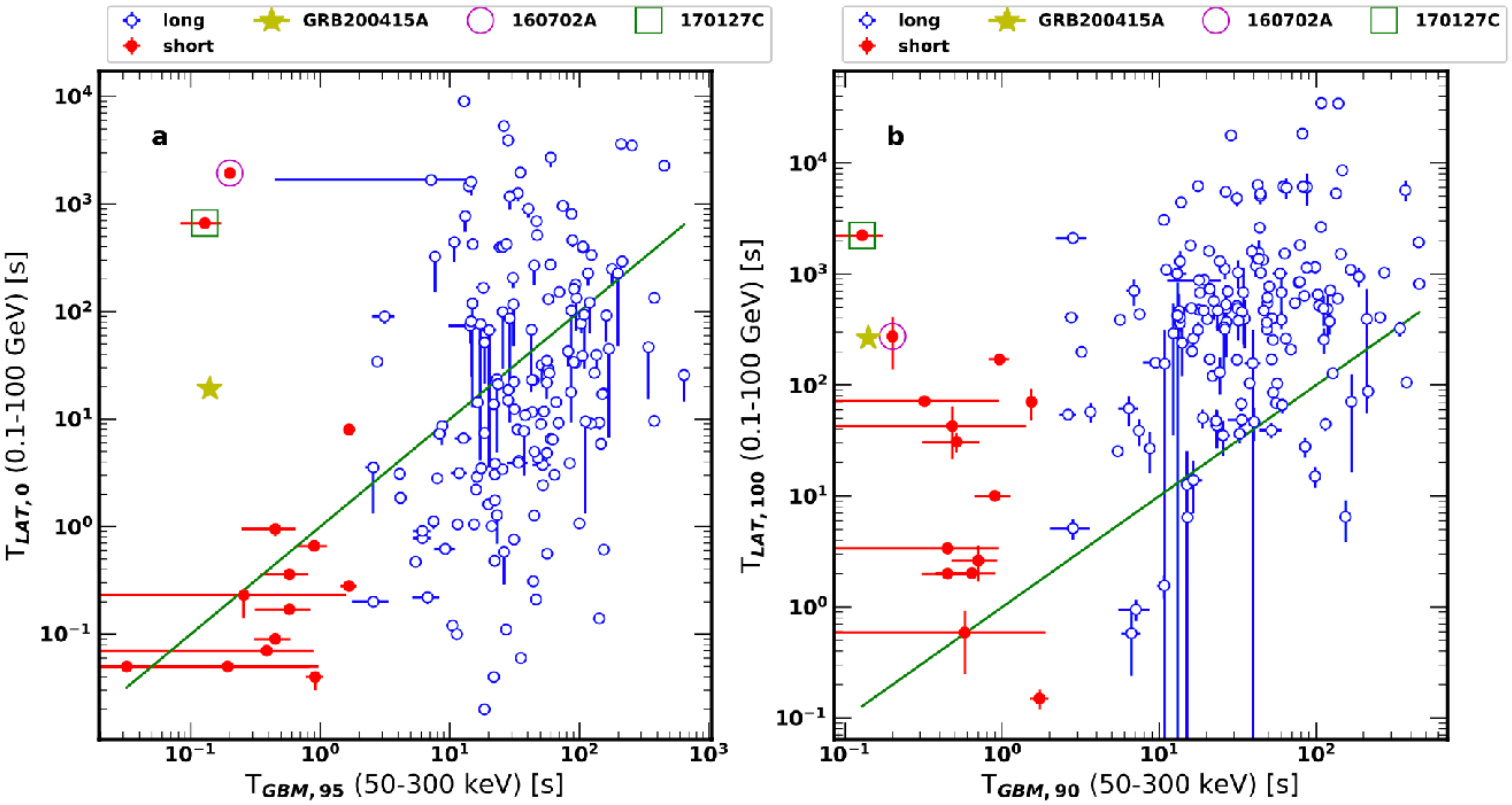
GeV signal delay

Only two other GRB (both short) detected by the LAT happened with such a big delay from the GBM trigger



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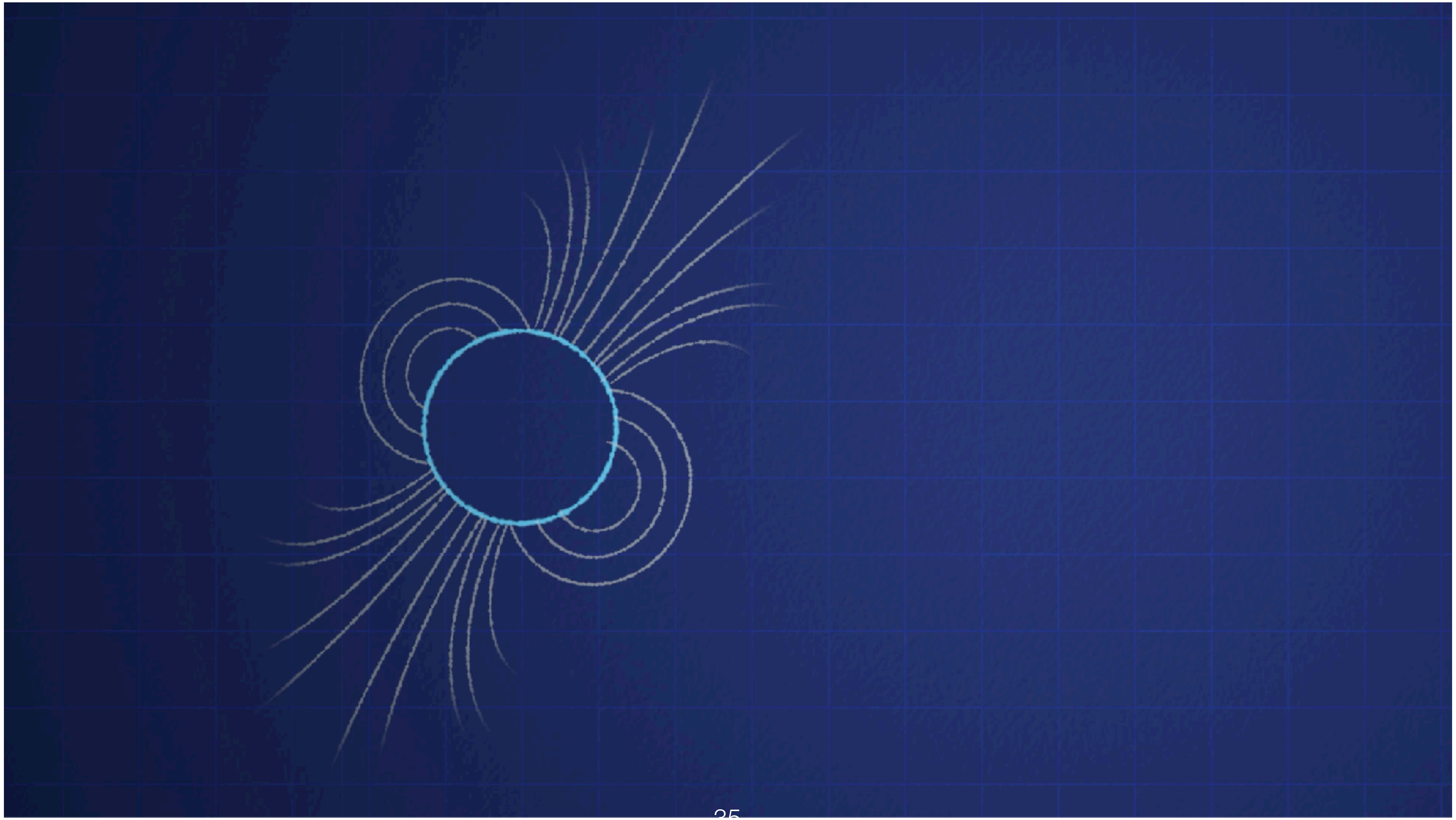
GeV signal delay

The delay suggests that the prompt MeV emission and the GeV emission are not generated in the same region.



Proposed scenario

The delay suggests that the prompt MeV emission and the GeV emission are not generated in the same region.

Proposed scenario:
GeV emission is associated with the collision between an ultra-relativistic outflow from the MGF and an external shell of swept-up material.

- ✳ Huge energy release: ~10^{47}erg: creates a very hot plasma (trapped radiation and e+e- pairs).
- ✳ The plasma accelerates under radiation pressure: "transparent" at R>10^8cm.
- ✳ Radiation escapes: spectrum spike (peaked at MeV)
- ✳ Cloud of particles: outward flow bulk
  Lorentz factor $\Gamma_{ej} \approx 100$;
  kinetic energy of ~3×10^{46} erg.


LAT Collab (MN). 2021, Published in Nature Astronomy

Proposed scenario

The delay suggests that the prompt MeV emission and the GeV emission are not generated in the same region.

Proposed scenario:

✳ During magnetar quiescent state a continual wind sweeps up interstellar gas : creates a shell at a distance $R_{bs} \approx 8 \times 10^{15}$ cm

✳ MGF outflows collides with the bow-shock shell

✳ propagates inside the bow-shock: electrons are accelerated to relativistic energies and

✳ emit synchrotron radiation up to GeV energies in shock-generated magnetic fields:

peak emission duration $R\text{bs}=2\Gamma^2_{sh}c$ ~ 400s

bulk Lorentz factor of the forward shock Γ^2_{sh} =20

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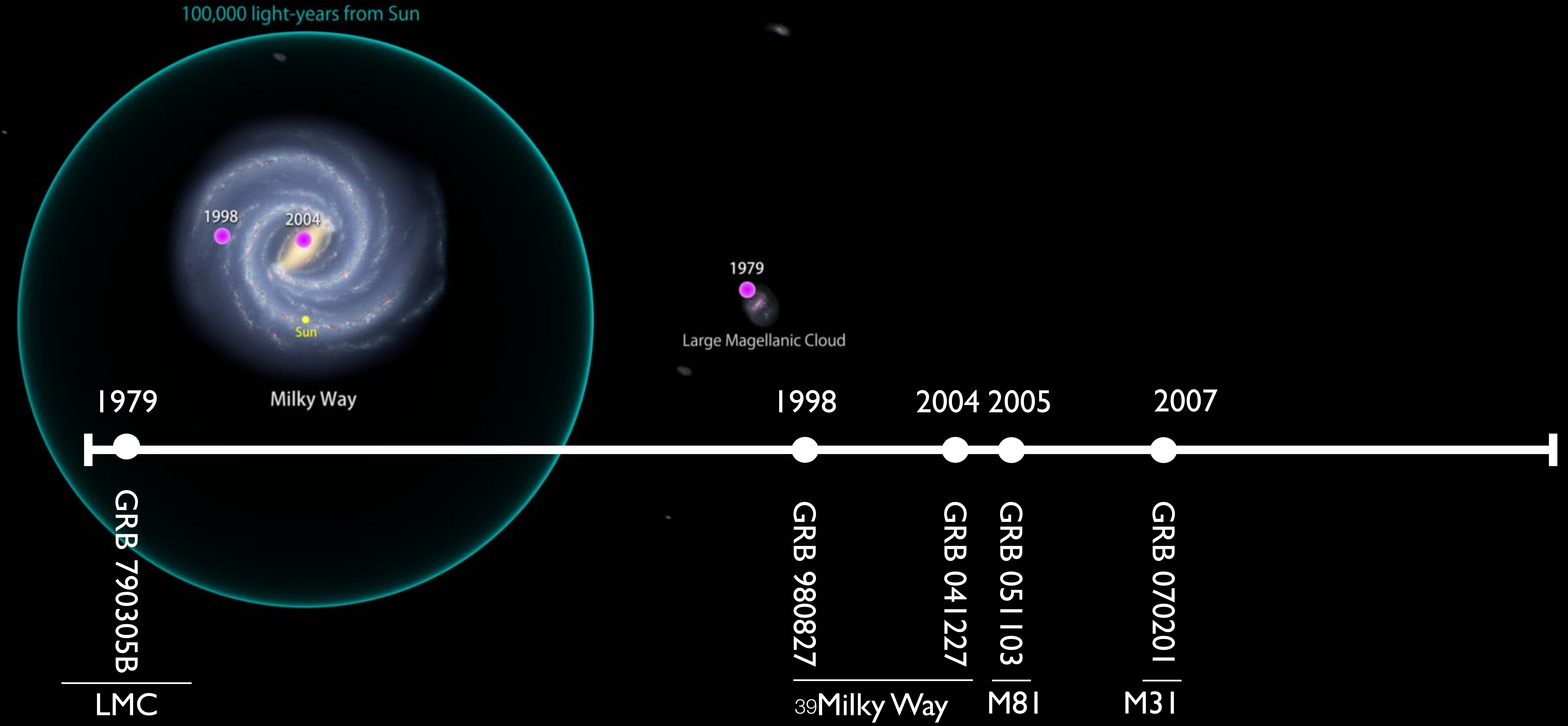
A Population of MGFs



Extragalactic MGFs and GRB

Known nearby MGF sample: GRB 790305B
GRB 980827
GRB 041227

HIGH INTRINSIC RATE!

Extragalactic counterparts observed as GRBs

Only two extragalactic MGF candidates in literature: GRB 051103, GRB 070201 → SGRB

Set upper bound:
SGRB to have MGF origin < 8%*

Set lower bound:
SGRB to have MGF origin > 1%*

*These studies and tehir conclu- sions generally assumed that the brightest MGFs could be detectable to tens of Mpc.

E. Burns et al. (MN). 2021, Published in Ap. J. Letters

Extragalactic MGFs and GRB

How to understand that MGFs are progenitors some SGRB?

PROBLEM:

Loss of the smoking gun signature

We carried out a study based on spatial information:

SGRBs with MGF origin have to be consistent with local* known galaxies

* within 50 Mpc

E. Burns et al. (MN). 2021, Published in Ap. J. Letters

Galaxies sample

Info for each galaxy:

- ✳ Position —> **(RA, DEC, d)**
- ✳ Angular extent (if > any resolution = ellipse)
- ✳ Star formation rate (SFR)
- ✳ 0.5-200 Mpc

z=0 Multiwavelength Galaxy Synthesis: **z0MGS = GALEX** (UV) + **WISE** (IR)

+ supplement <10 Mpc with the Local Volume Galaxy (LVG) Catalog
+ SFR, ang. ext. from Census of the Local Universe (CLU) Catalog

>100,000 galaxies

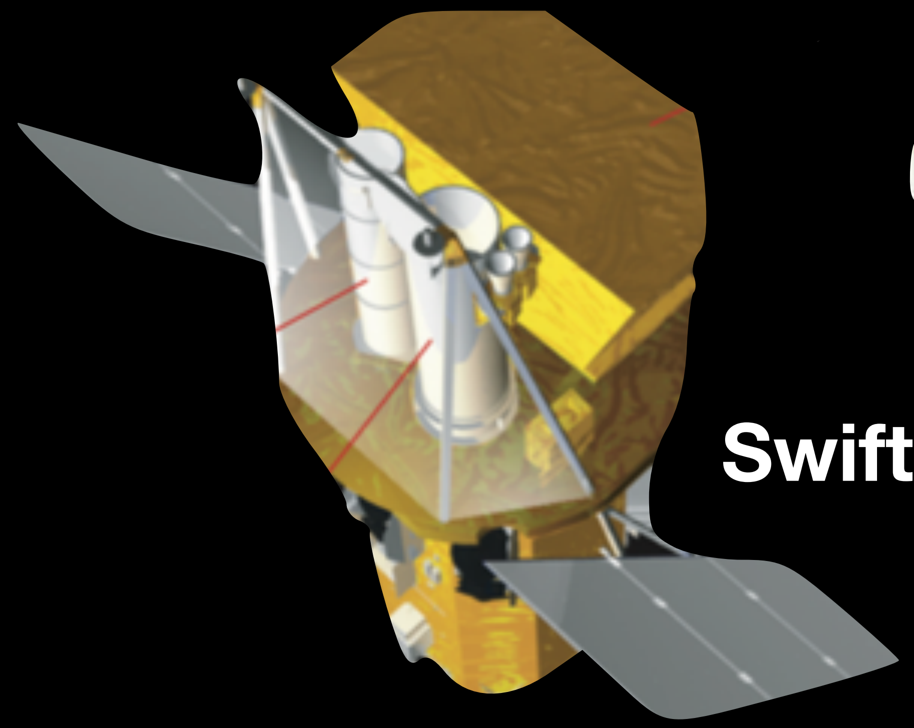
E. Burns et al. (MN), 2021, Published in Ap. J. Letters

GRB sample

GRB selection and info:

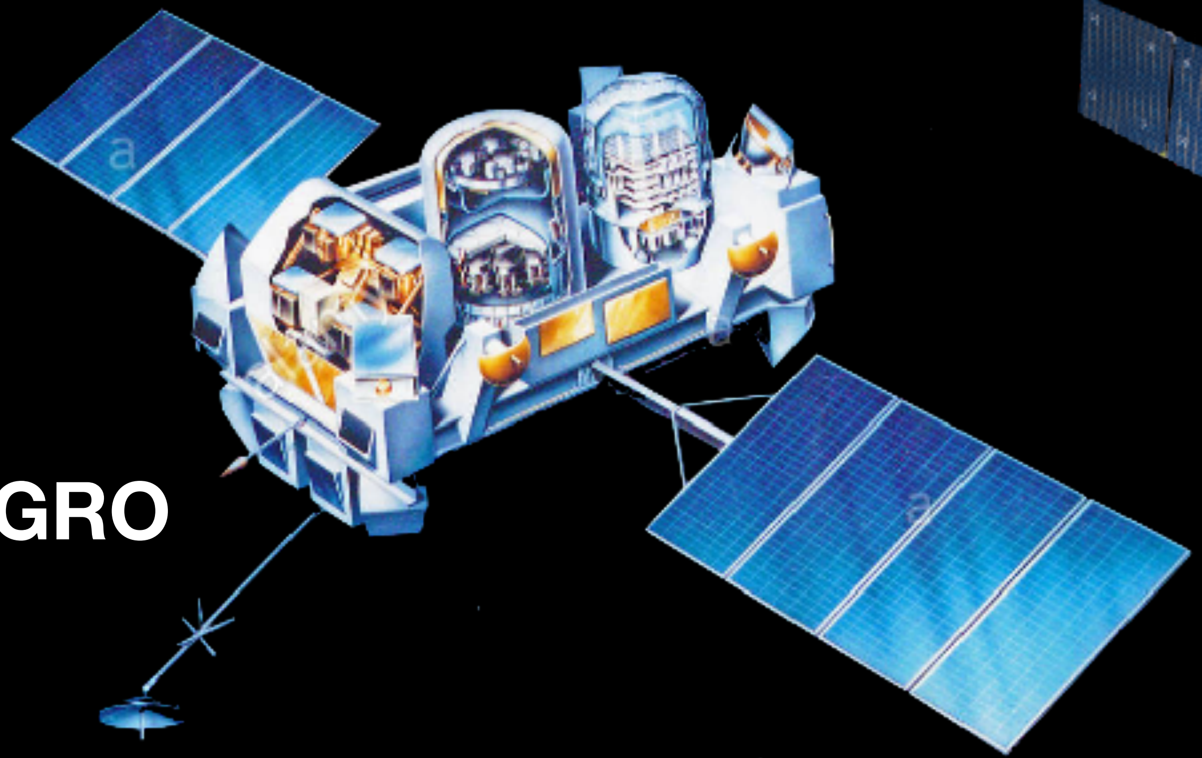
- ✳ SHORT! (T90 < 2 s)
- ✳ Bolomertic fluence at Earth(1 keV - 10 MeV) —> **S**
- ✳ Well localized (from all available info, IPN*)

* this work required additional 100 IPN locations: provided in the paper



CGRO-BATSE + Konus-WIND + Swift-BAT + Fermi-GBM
+ additional info from the IPN

250 SGRB

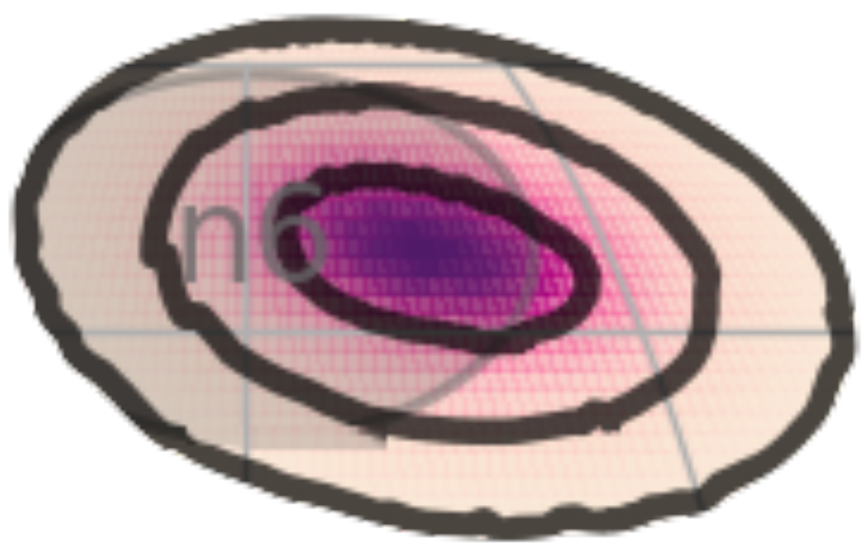


E. Burns et al. (MN). 2021, Published in Ap. J. Letters

The search

GRB probability distribution function at the i[th] sky position:

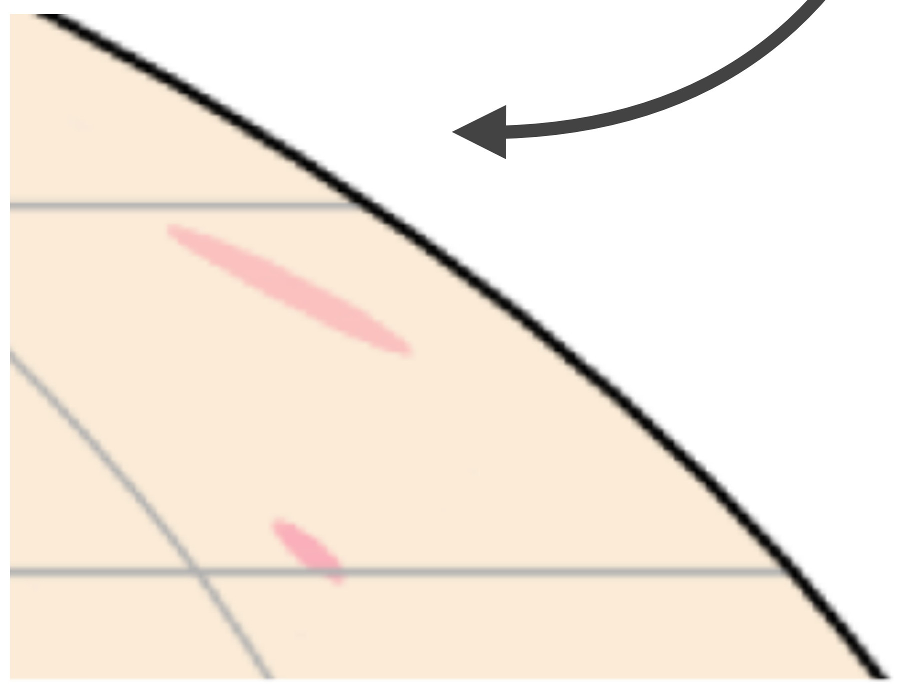
$$P_i^{GRB}$$



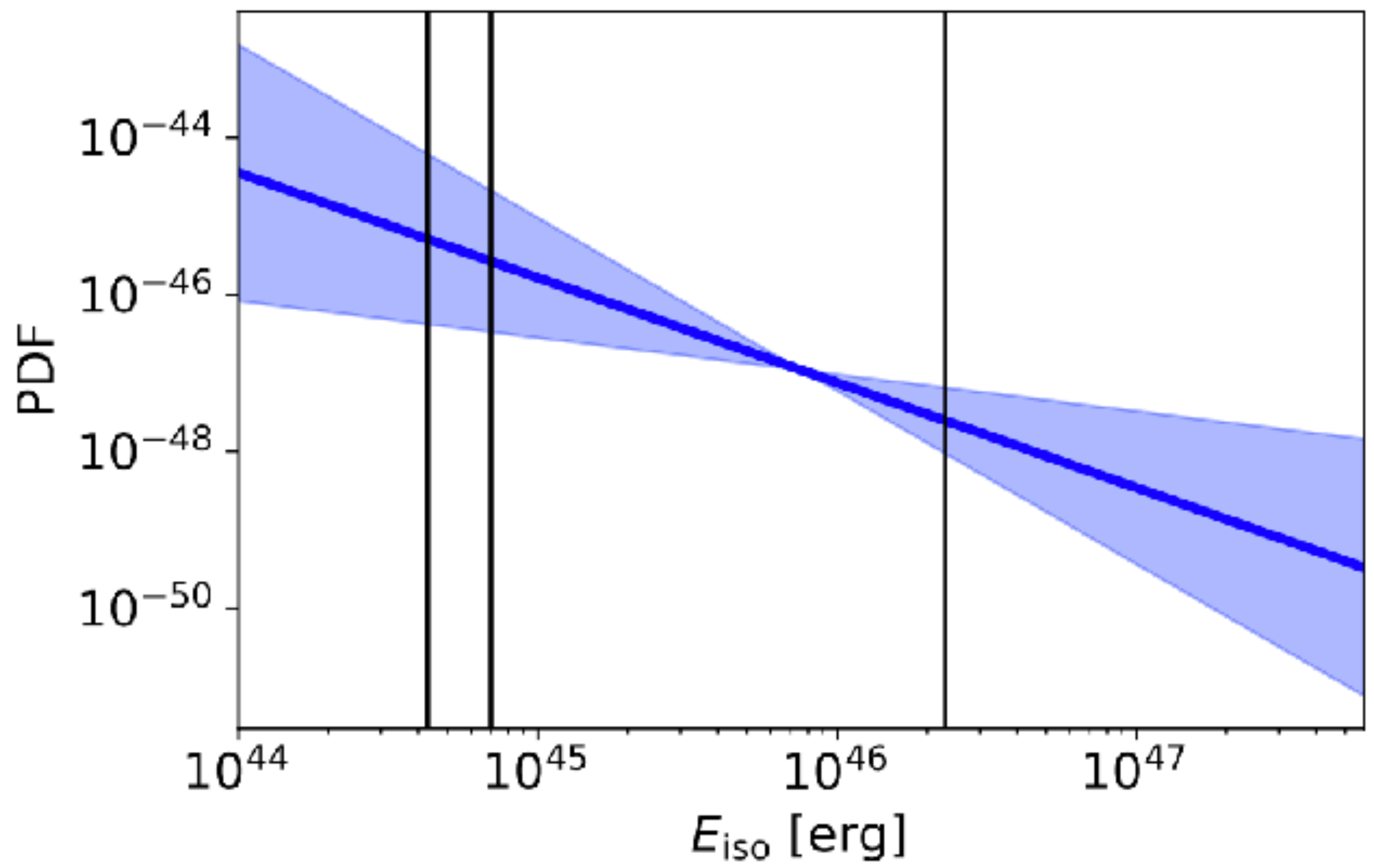
probability that a given position is to produce a MGF with a particular fluence at Earth

$$P_i^{MGF}$$

$$P_i^{MGF} = SFR_i \cdot PDF(E_{\text{iso}})$$



$$E_{\text{iso}} = \frac{4\pi d^2}{S}$$



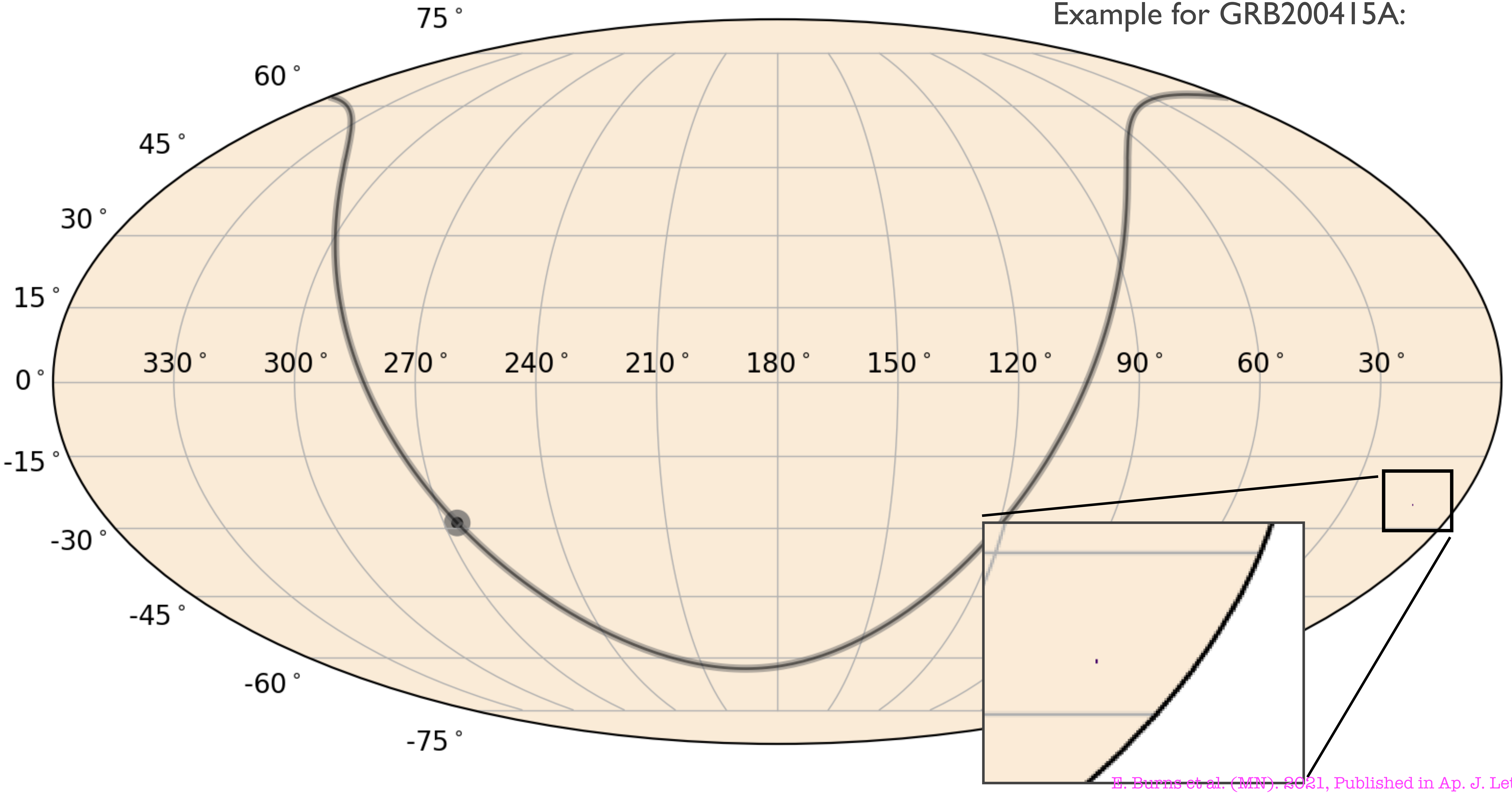
Likelihood that a given GRB has an MGF origin:

$$\Omega = \frac{4\pi \sum_i P_i^{GRB} P_i^{MGF}}{A_i}$$

E. Burns et al. (MN). 2021, Published in Ap. J. Letters

P_{GRB}

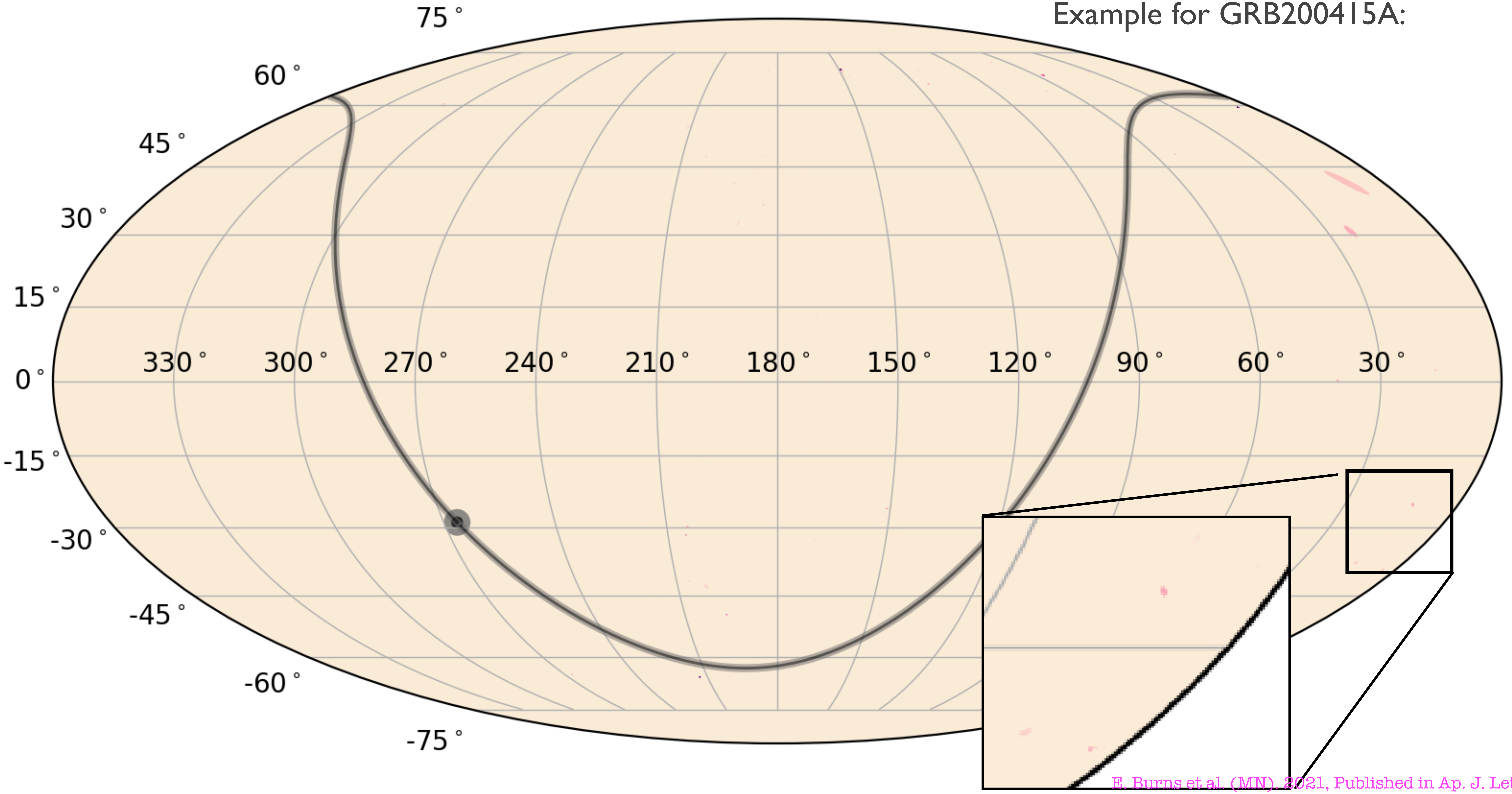
For each SGRB construct a P_{GRB}
Example for GRB200415A:



E. Burns et al. (MN). 2021, Published in Ap. J. Letters

P_{MGF}

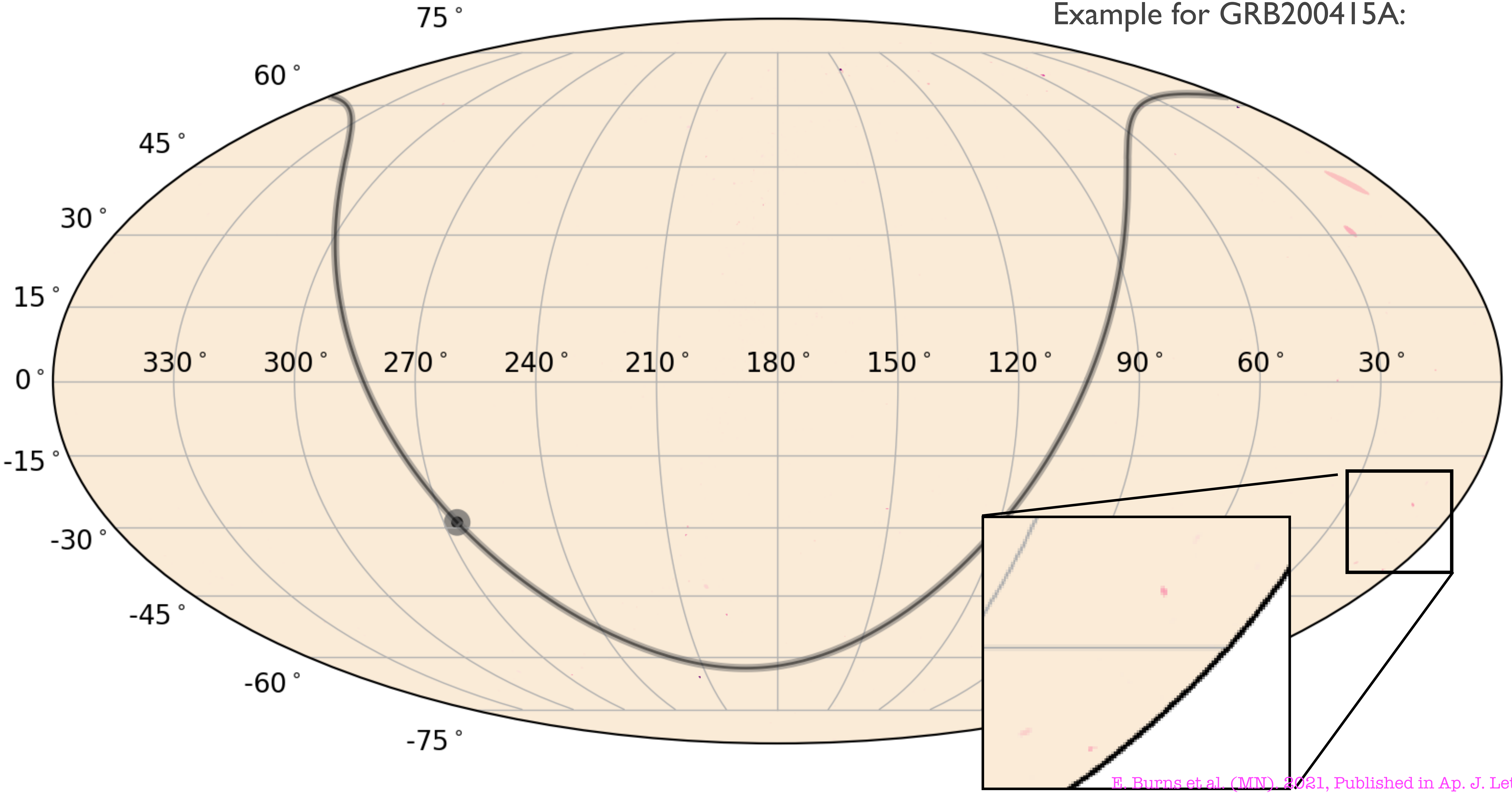
For each SGRB construct a P_{MGF}
Example for GRB200415A:



E. Burns et al. (MN), 2021, Published in Ap. J. Letters

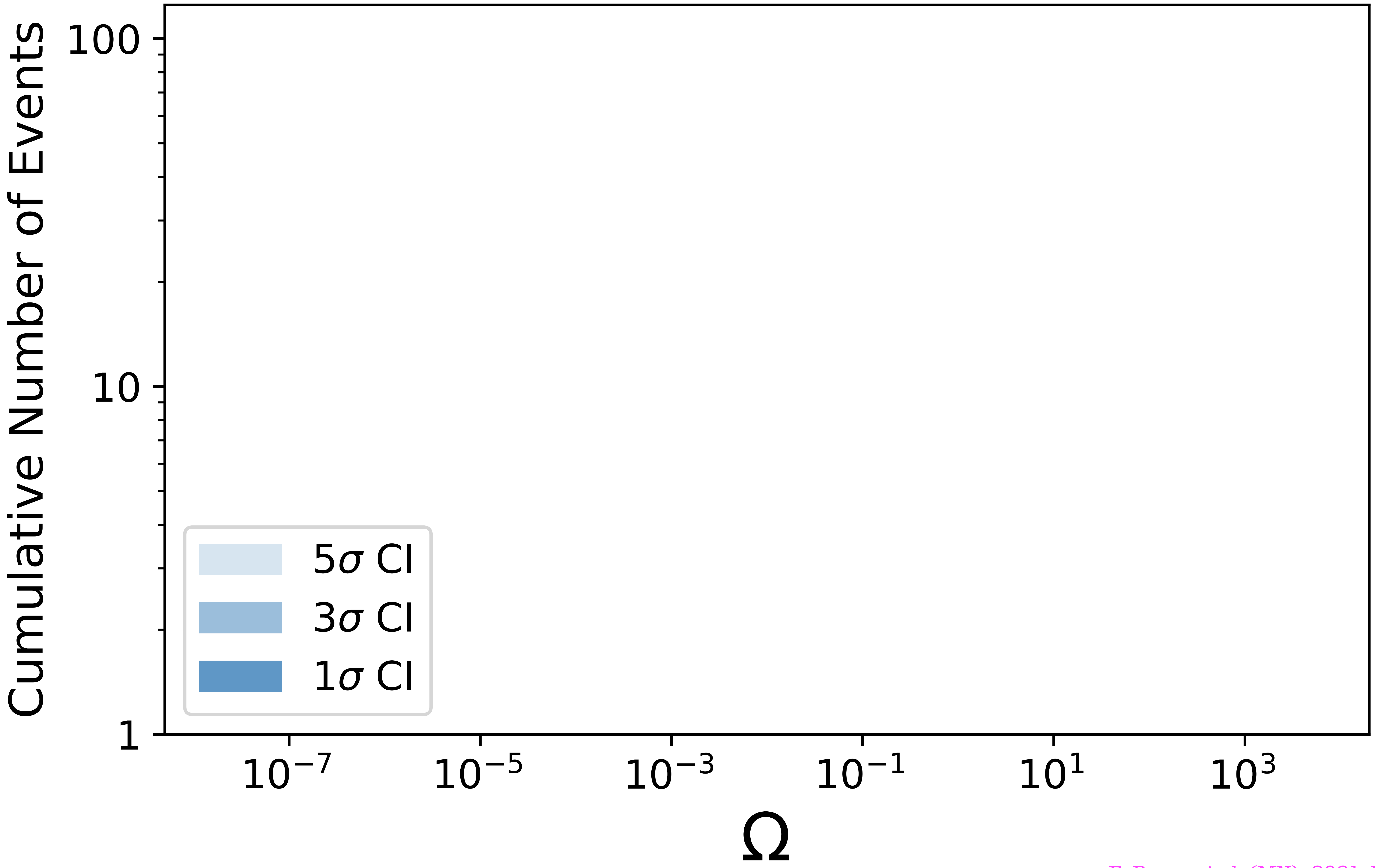
P_{MGF} x P_{GRB}

For each SGRB construct a P_{MGF}
Example for GRB200415A:



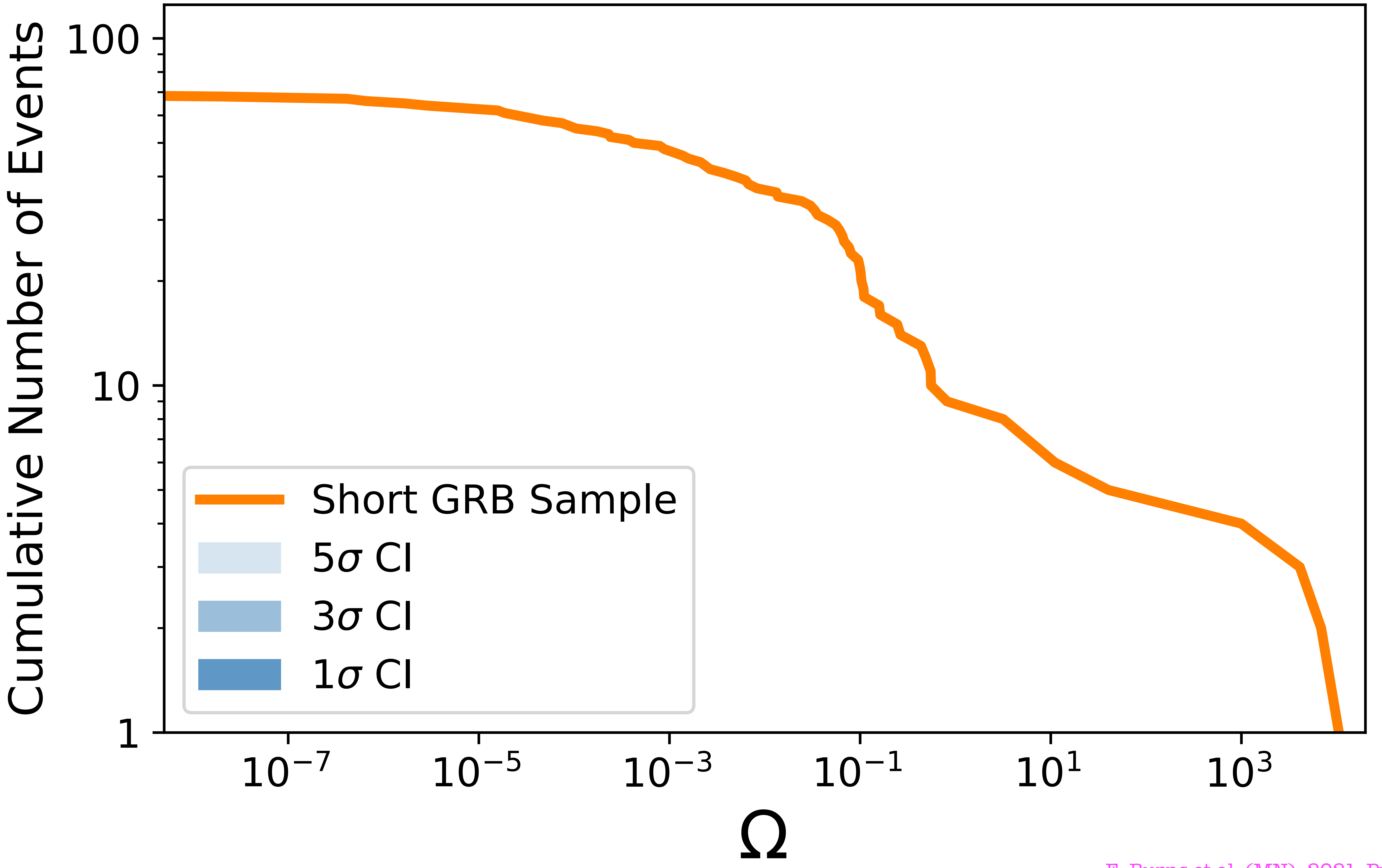
E. Burns et al. (MN), 2021, Published in Ap. J. Letters

Discovery of local extragalactic population of GRBs



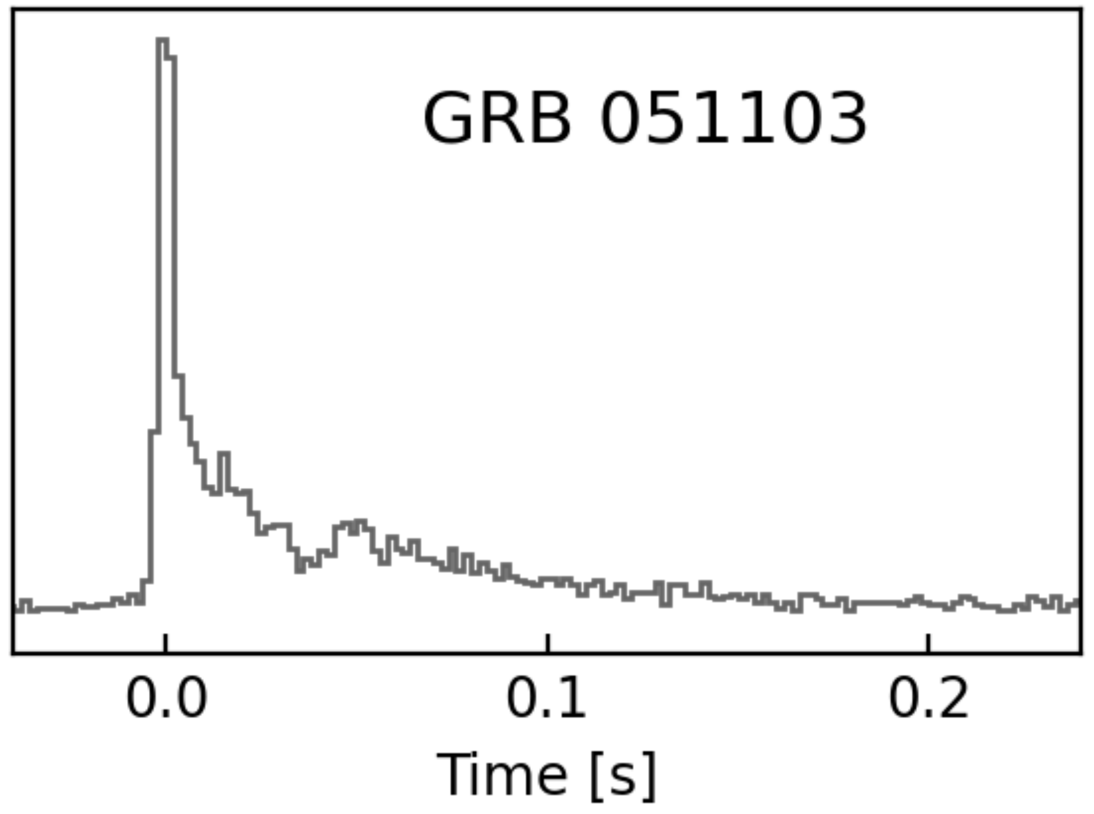
E. Burns et al. (MN). 2021, Published in Ap. J. Letters

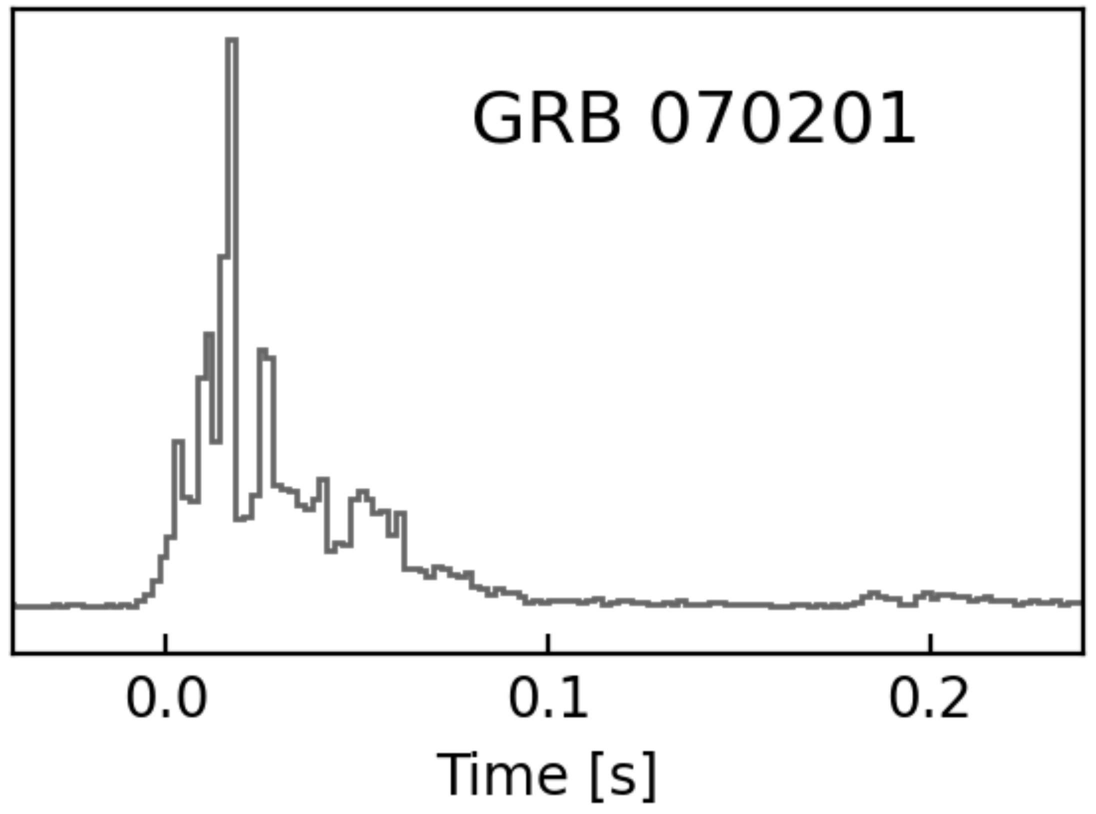
Discovery of local extragalactic population of GRBs

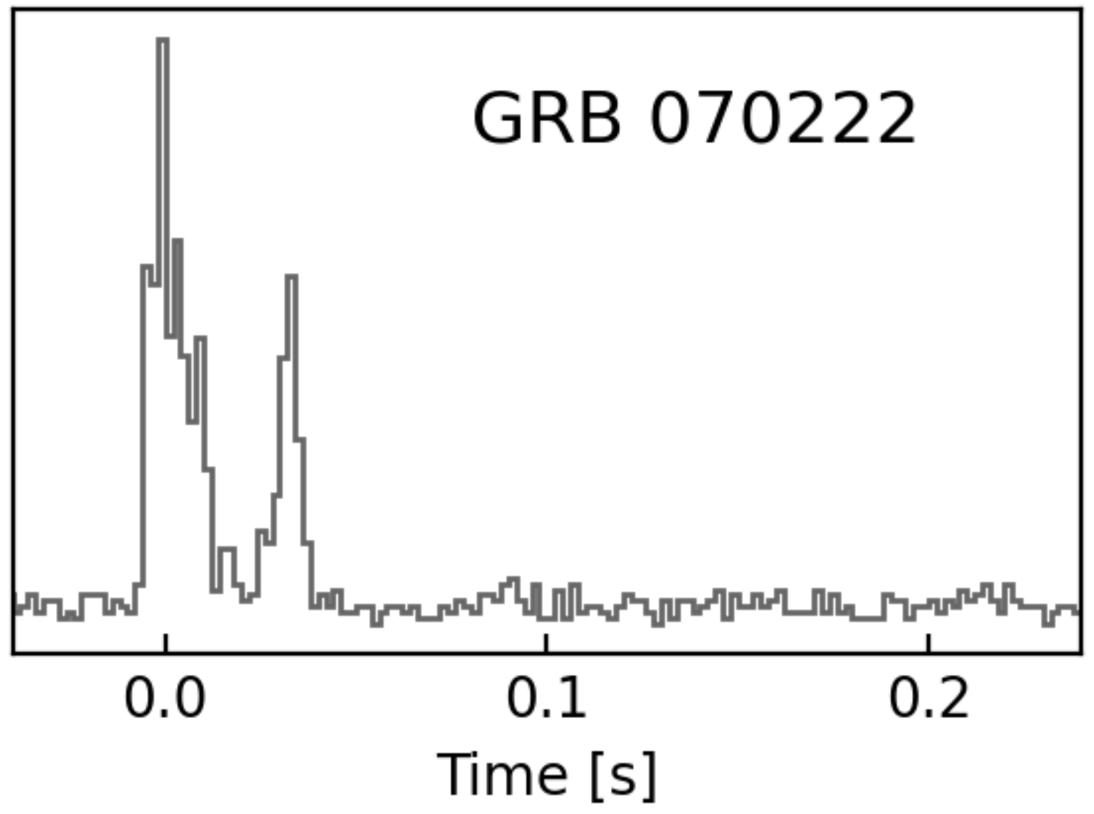


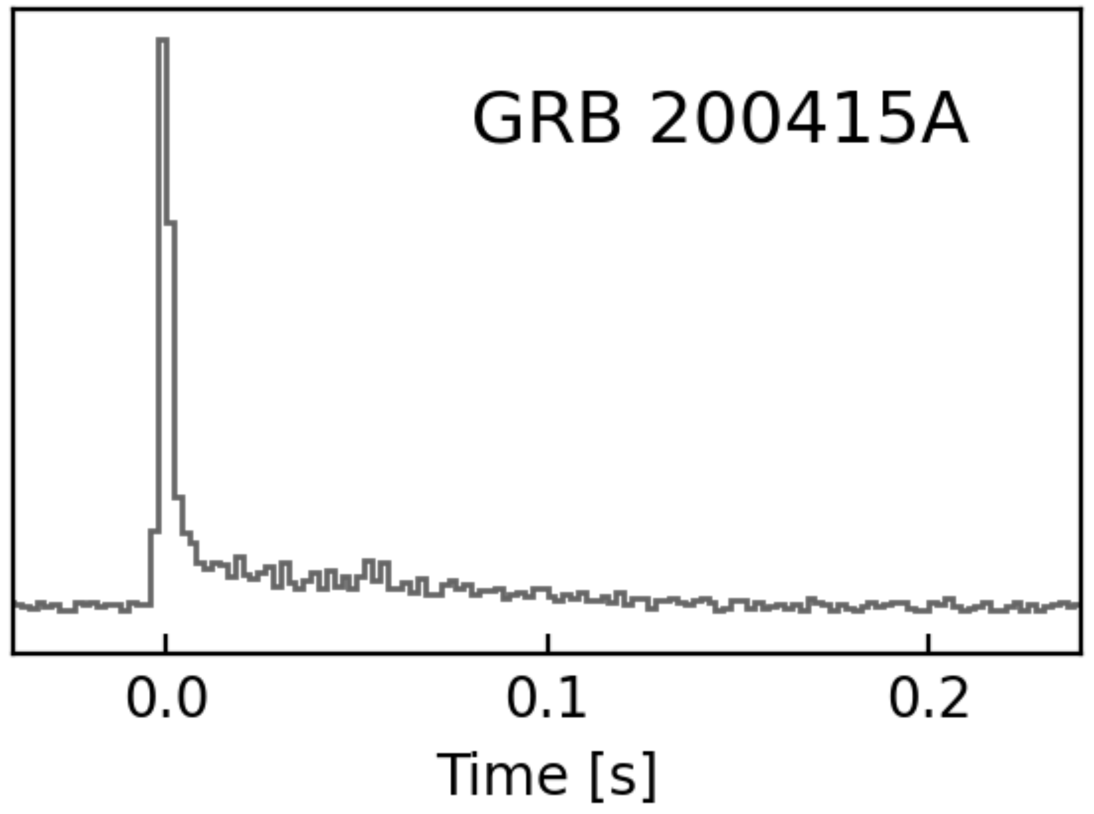
E. Burns et al. (MN). 2021, Published in Ap. J. Letters

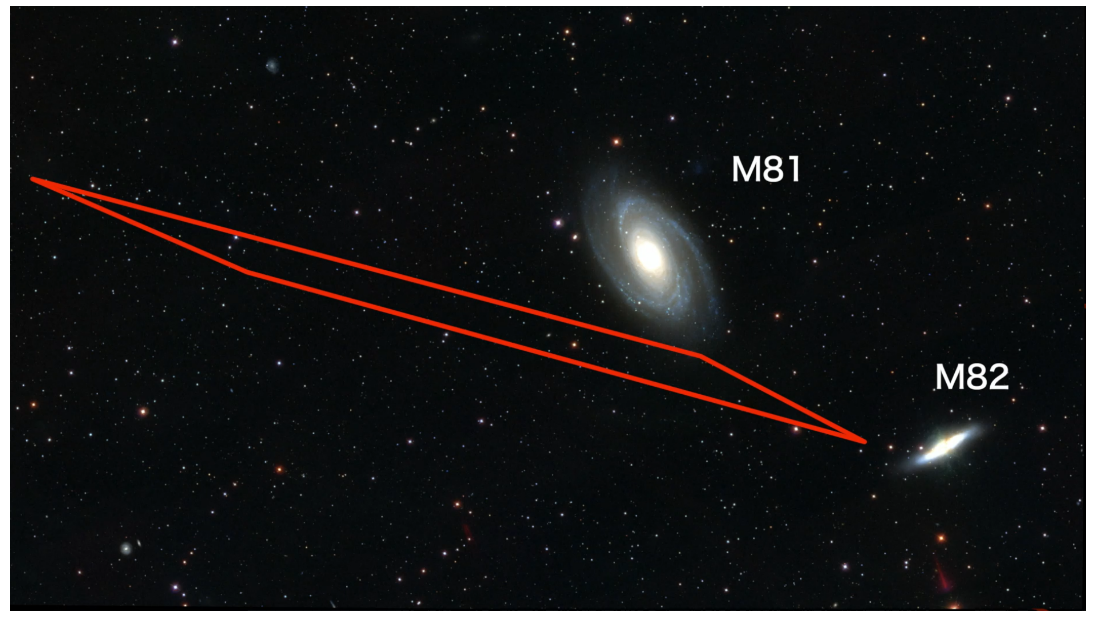
Four local GRBs, hosts, odds of chance alinement











1 in 70,000

1 in 10,000

1 in 130,000

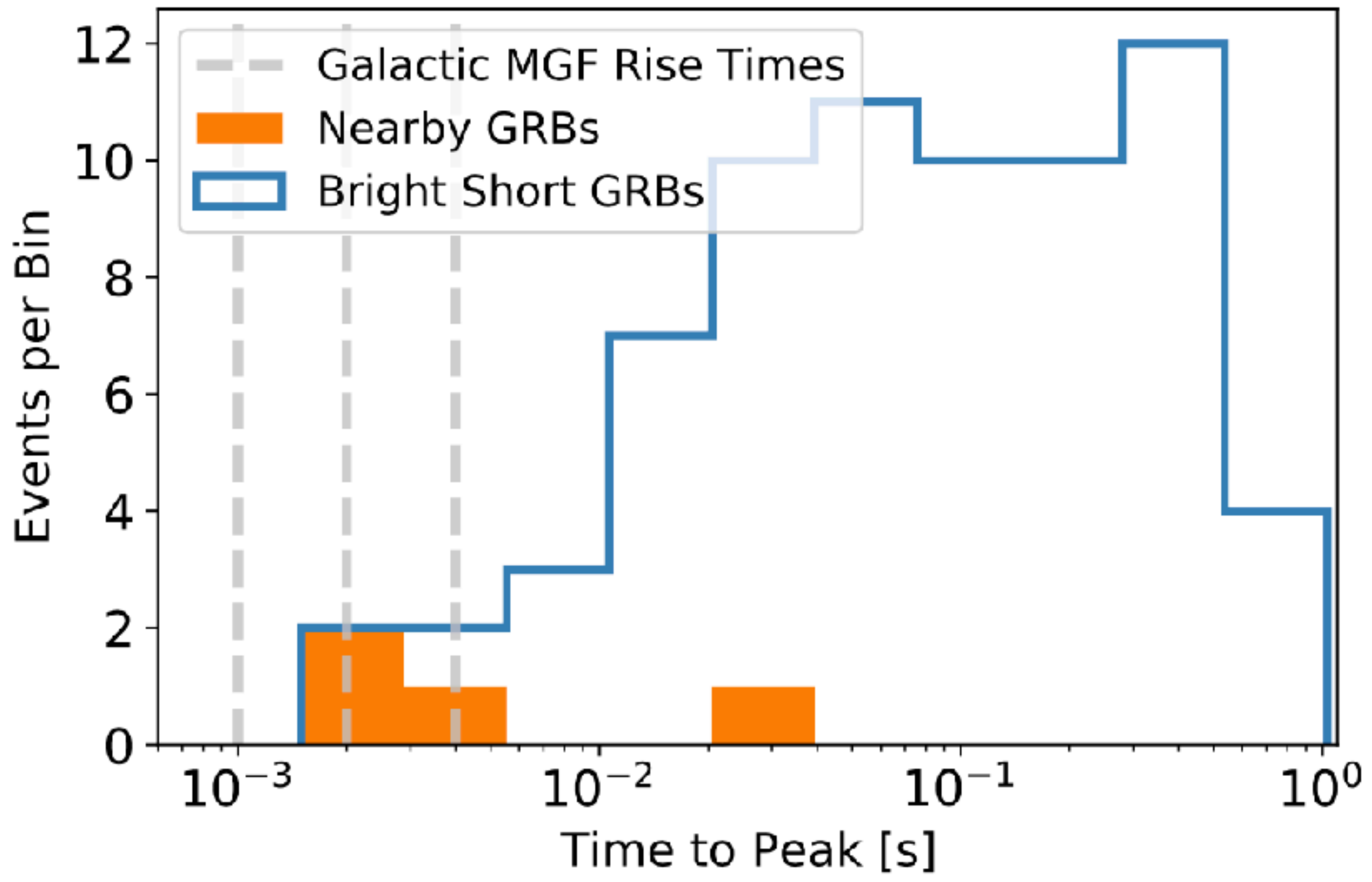
1 in 230,000

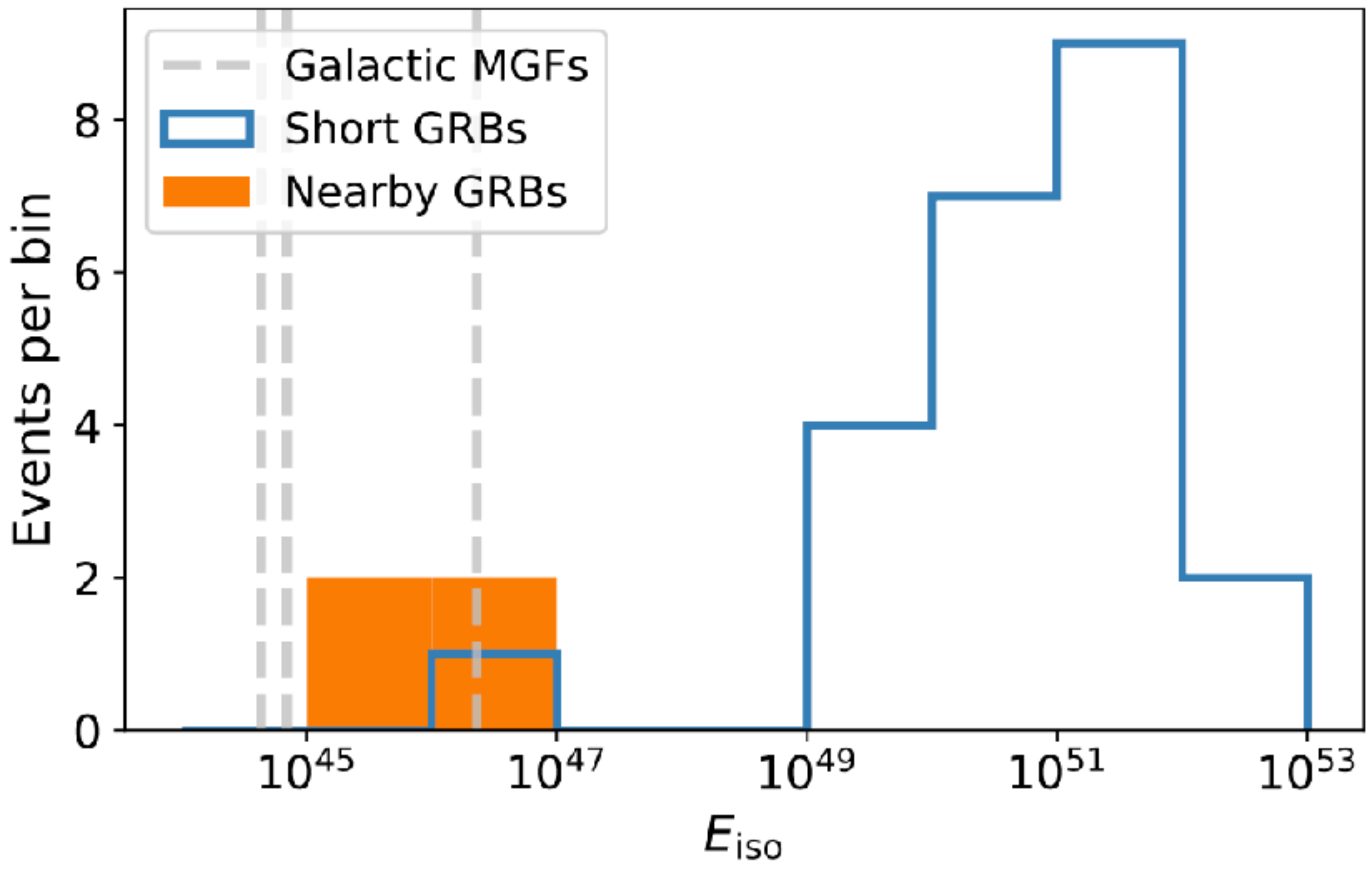
E. Burns et al. (MN). 2021, Published in Ap. J. Letters

Key parameters comparison

Two main characteristics distinguish SGRB candidate to have a MGF origin from the rest SGRBs:

- ✴ Very short rise time (a few milli-seconds: far way shorter than cosmological GRBs)
- ✴ Intrinsic energetic (orders of magnitude fainter than cosmological GRBs)





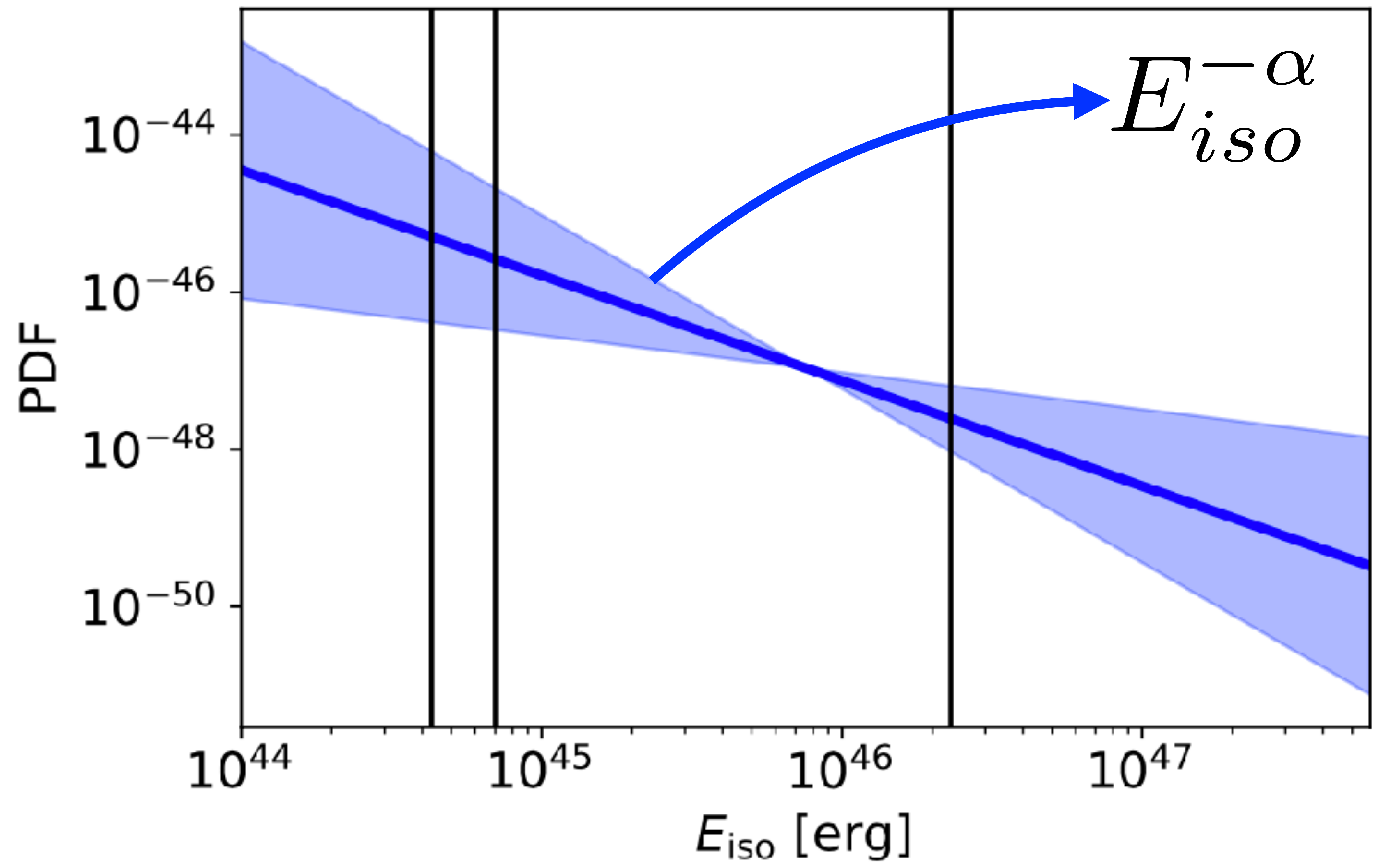
E. Burns et al. (MN). 2021, Published in Ap. J. Letters

MGFs Intrinsic Energetic

Simulate a large number of extragalactic MGFs:

- ✳ E_{iso} from PDFs over a range of α values
- ✳ Each assigned to specific host galaxy (weighted by its SFR and distance)

Detected events: those where the sampled E_{iso} and distance produce a flux greater than our detection threshold.



Anderson-Darling k-sample test to compare the detected simulated populations to the real one (4 eMGFs)

$$\alpha = 1.7 \pm 0.4$$

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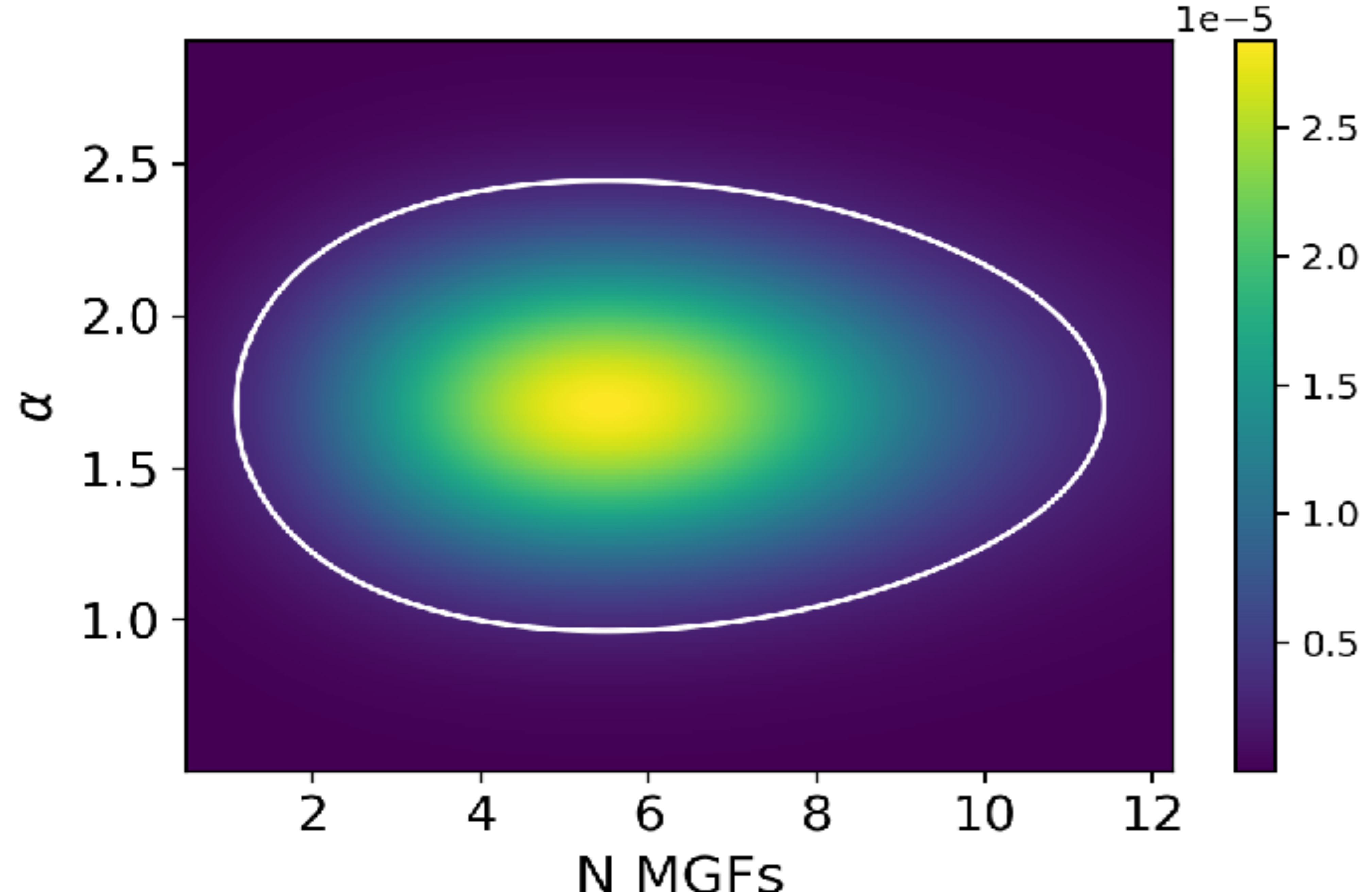
MGFs Intrinsic Rate

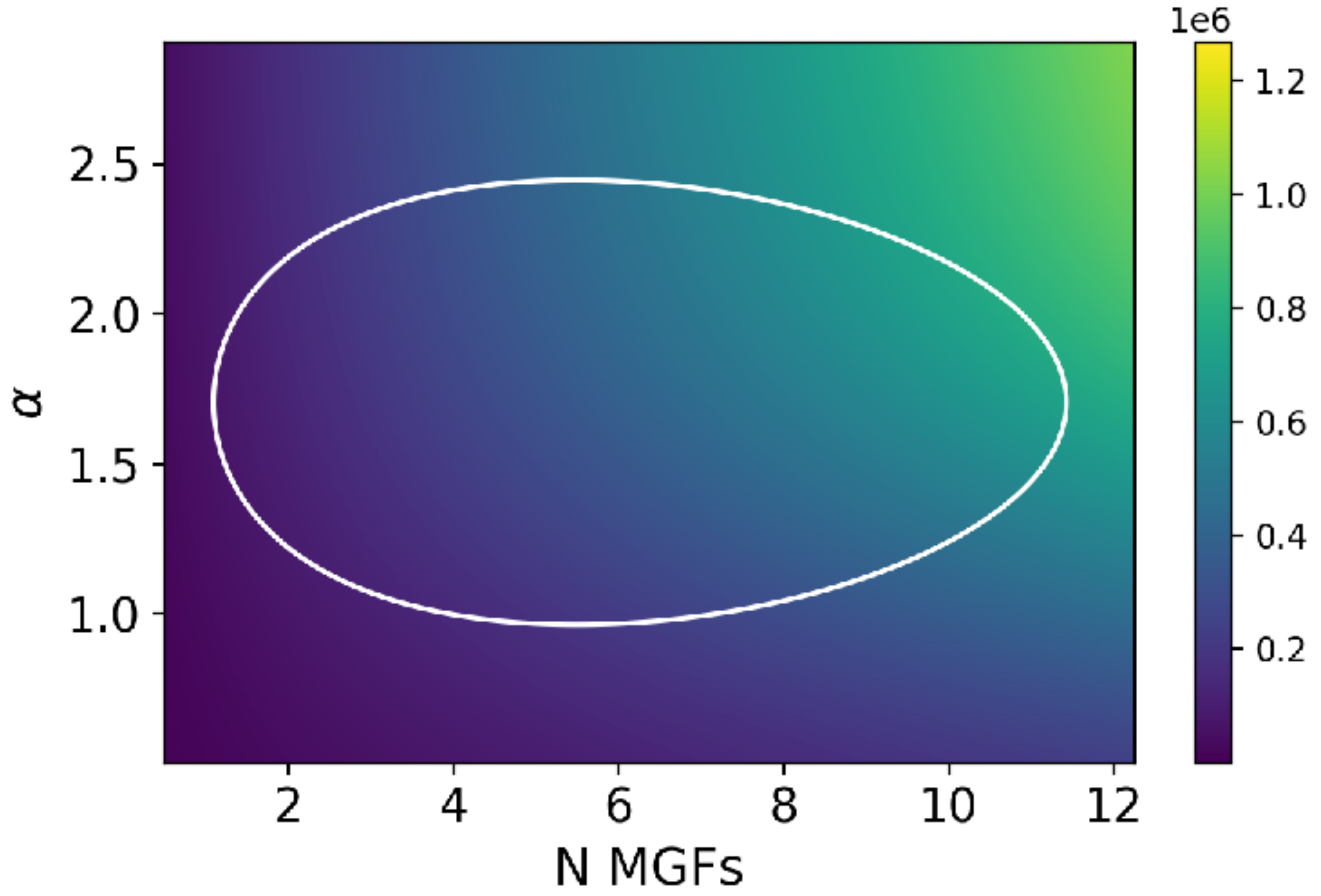
Convolution of

- ✳ 2D PDF for alpha VS number of detected MGFs (6*)
- ✳ Intrinsic rate expected for a given alpha and number of detected MGFs

$$R_{MGF} = 3.8^{+4.0}_{-3.1} \times 10^5 \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$



x



* the first detected MGF used a different IPN calibration, so we discarded it

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MGF Intrinsic Rate

Event	Local Rates ($Gpc^{-3}\ yr^{-1}$)	Identified events
Magnetar Giant Flares	380,000	7
Neutron Star Mergers (short GRBs)	320[a]	~ 2000
Collapsars (long GRBs)	~100[b]	~10,000
Type Ia Supernovae	30,100[d]	~15,000[e]
Core-Collapse Supernovae	~70,000[d]	~ 8000[e]

a – LSC 2020 arXiv:2010.14527
b – D. Siegel, et al. 2019 Nature 569, 241
c - S. Prajs, et al. 2017 MNRAS 464, 3
d – W. Li, et al. 2011 MNRAS 412, 3
e - https://sne.space/

Why have we not identified MGFs more and to greater* distances?

*they were thought to be detectable to tens of Mpc

E. Burns et al. (MN). 2021, Published in Ap. J. Letters

Summary of MGF sample today

As appeared from GRBs 200415A, 051103 and 070222:

SPECTRALLY HARD and HIGHER PEAK ENERGY!

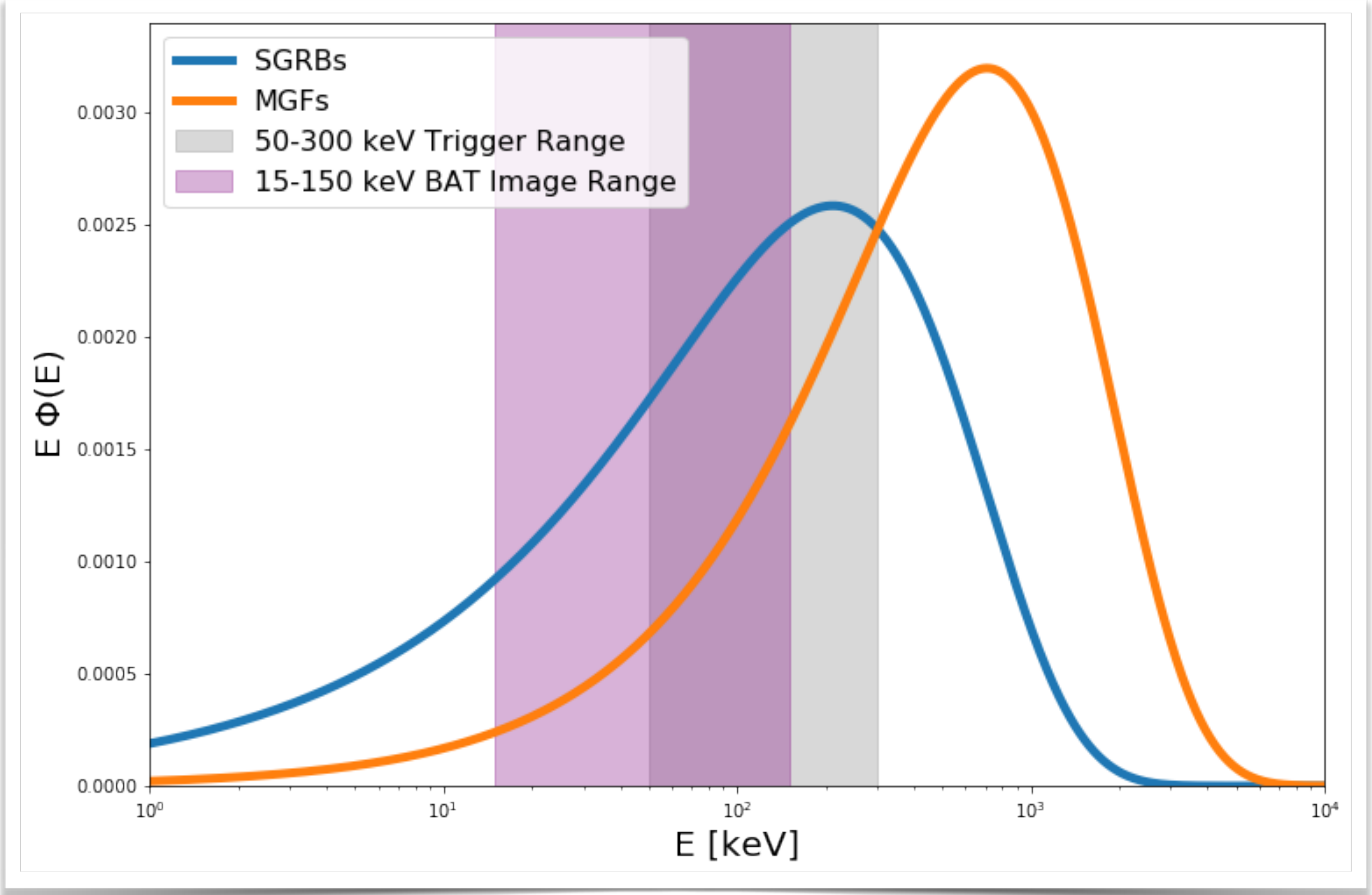
GRB detector are triggered by photon counts:
Detectable MGF number is reduced by ~ x5
(x >100 in volume)

Comptonized Spectrum:

$$\frac{dN}{dE} = \left(\frac{E}{100\ keV}\right)^{\alpha} e^{-(\alpha+2)\frac{E}{E_{peak}}}$$

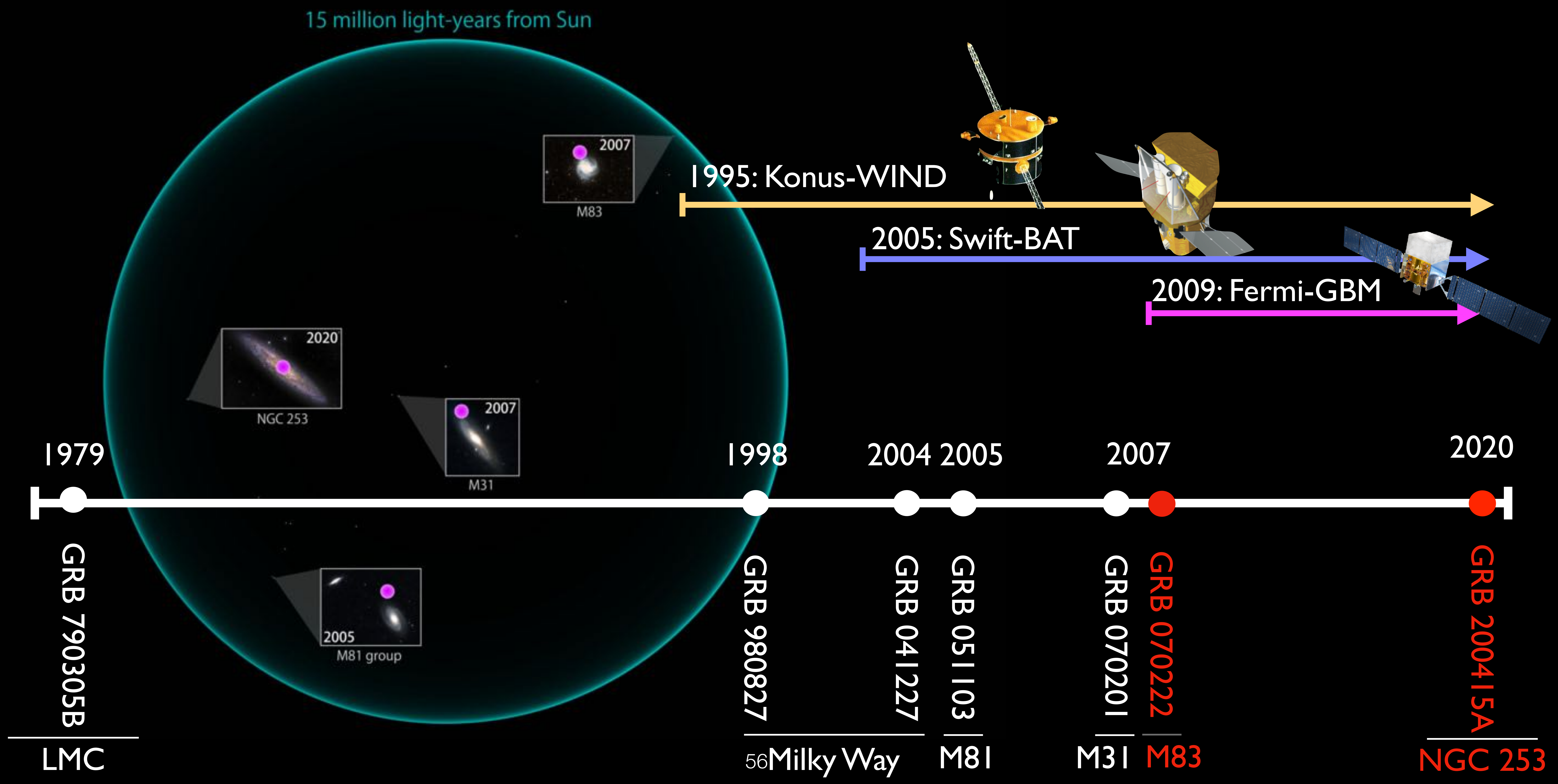
$\alpha^{SGRB} \approx -0.4$ $\alpha^{MGF} \approx 0$

$E_{peak}^{SGRB} \approx 0.6MeV$ $E_{peak}^{MGF} \approx 1.5MeV$



E. Burns et al. (MN). 2021, Published in Ap. J. Letters

A Population of MGFs



Summary

- ✳ 4 short GRBs occurred within ~5 Mpc which are the closest events by an order of magnitude in distance
- ✳ They are inconsistent with a collapsar or neutron star merger origin (lack of SN or GW counterparts)
- ✳ Their prompt emission is inconsistent with the properties of cosmological GRBs
- ✳ They originate from star-forming galaxies, including those with metallicity that prevents collapsars from occurring
- ✳ 4 out of 250 SGRBs have MGFs origin: ~2% of detected short GRBs
- ✳ Intrinsic energetics distribution of MGFs: a power-law with index $\alpha = 1.7 \pm 0.4$
- ✳ The volumetric rates are $R_{MGF} \sim 380000\ Gpc^{-3}yr^{-1}$.
- ✳ The rates and host galaxies of these events favor CCSN as the dominant formation channel for magnetars, requiring at least 0.5% of CCSN to produce magnetars.
- ✳ Our results suggest that some magnetars produce multiple MGFs: this would be the first known source of repeating GRBs.
- ✳ GRB 070222 suggests MGFs can have multiple pulses.
- ✳ MGFs may not be detectable to tens of Mpc with existing instruments due to their spectral hardness.
- ✳ The LAT detection is the first GeV detected emission form a MGFs
- ✳ LAT detected delay suggests the prompt MeV emission and GeV emission are generated in different regions opening new windows for possible explanations.

GRB 200415A

And the third class of gamma-ray bursts

THANK YOU!

References

1. Something about Magnetars

Magnetars — Victoria M. Kaspi, Andrei Beloborodov
Ann.Rev.Astron.Astrophys. 55 (2017) 261-301 • DOI: 10.1146/annurev-astro-081915-023329

2. GRB 200415A GeV detection

Rapid spectral variability of a giant flare from a magnetar in NGC 253 — O.J. Roberts et al. (GBM team)
Nature 589 (2021) 7841, 207-210 • DOI: 10.1038/s41586-020-03077-8

Bright twin γ-ray flares in two nearby galaxies as giant magnetar flares — D. Svinkin et al. (IPN team)
Nature 589 (2021) 7841, 207-210 • DOI: 10.1038/s41586-020-03077-8

High-energy emission from a magnetar giant flare in the Sculptor galaxy — M. Ajello et al. +MN (LAT team)
Nature Astronomy (2021) • DOI: 10.1038/s41550-020-01287-8

3. Extragalactic magnetar giant flares population

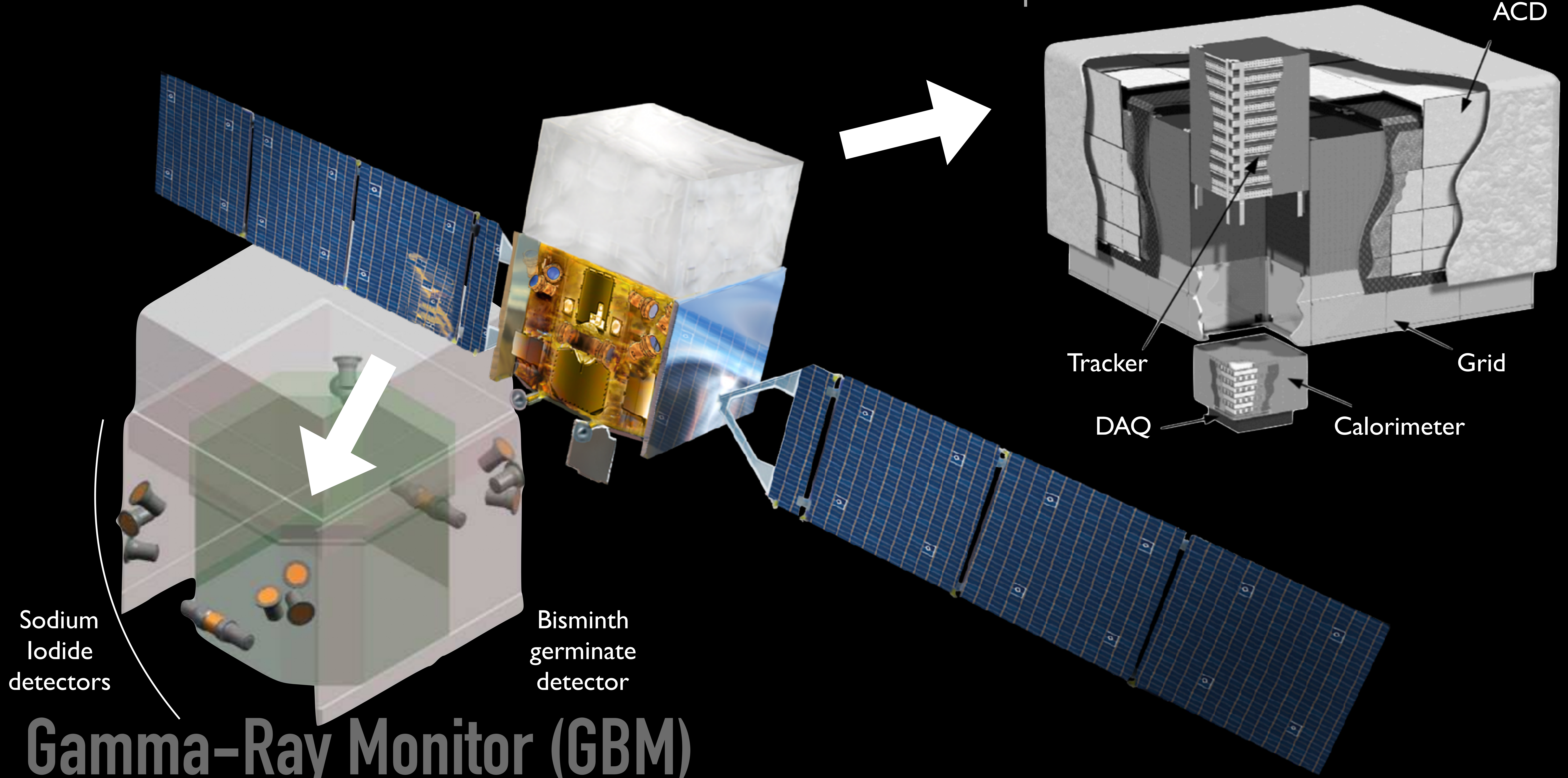
Identification of a local sample of gamma-ray bursts consistent with a magnetar giant flare origin — E. Burns et al. +MN
Ap. J. Letters 907(2):L28, jan 2021 • DOI: 10.3847/2041-8213/abd8c8

BACKUP

FERMI

Large Area Telescope (LAT)

Pair-production instrument



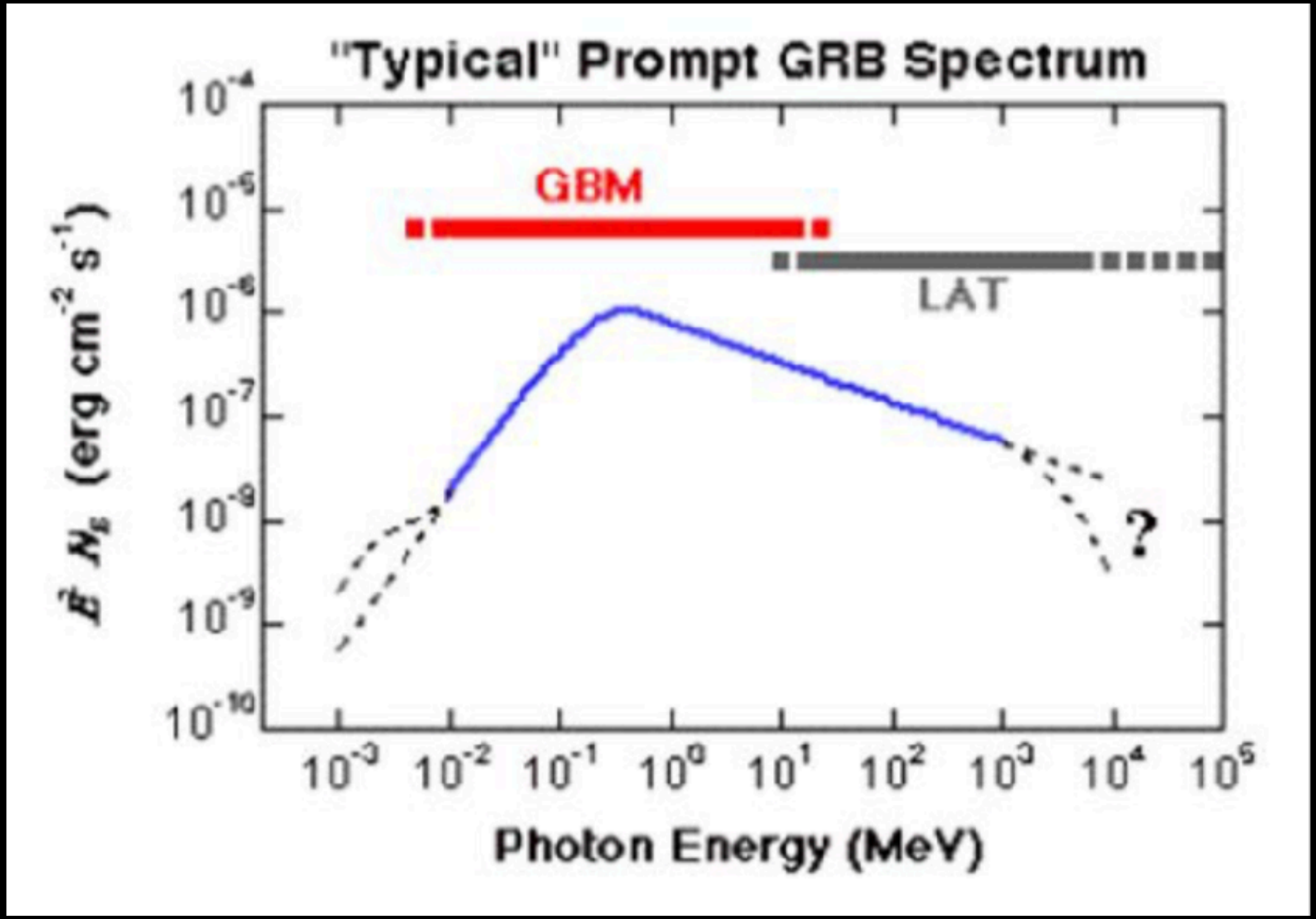
Gamma-Ray Monitor (GBM)

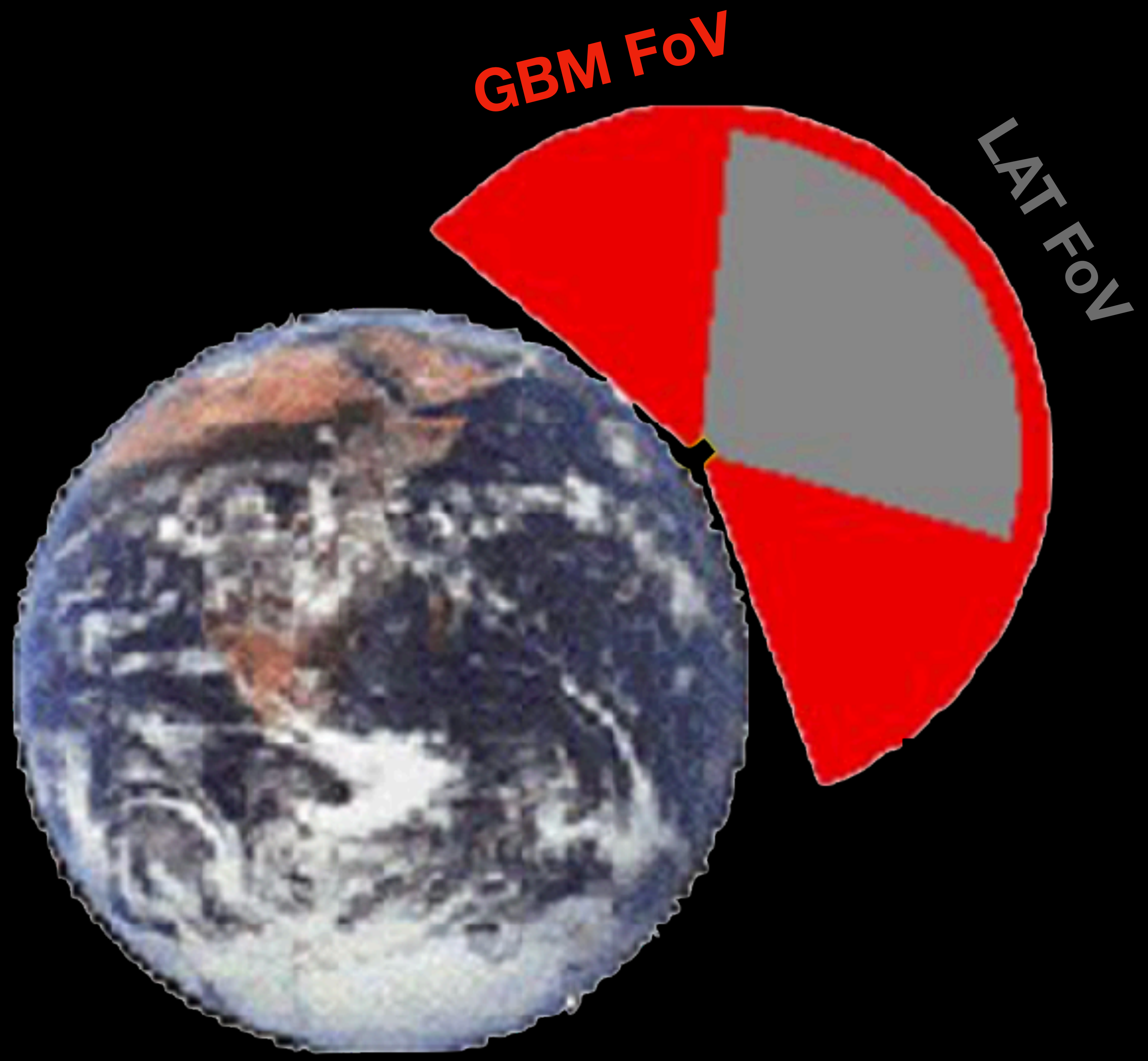
NaI and BGO scintillators

FERMI

LAT
- ✳ Energy range: 20 MeV to > 300 GeV
- ✳ Field of view: 2.4 steradians
- ✳ Single photon angular resolution: <1° at 1 GeV

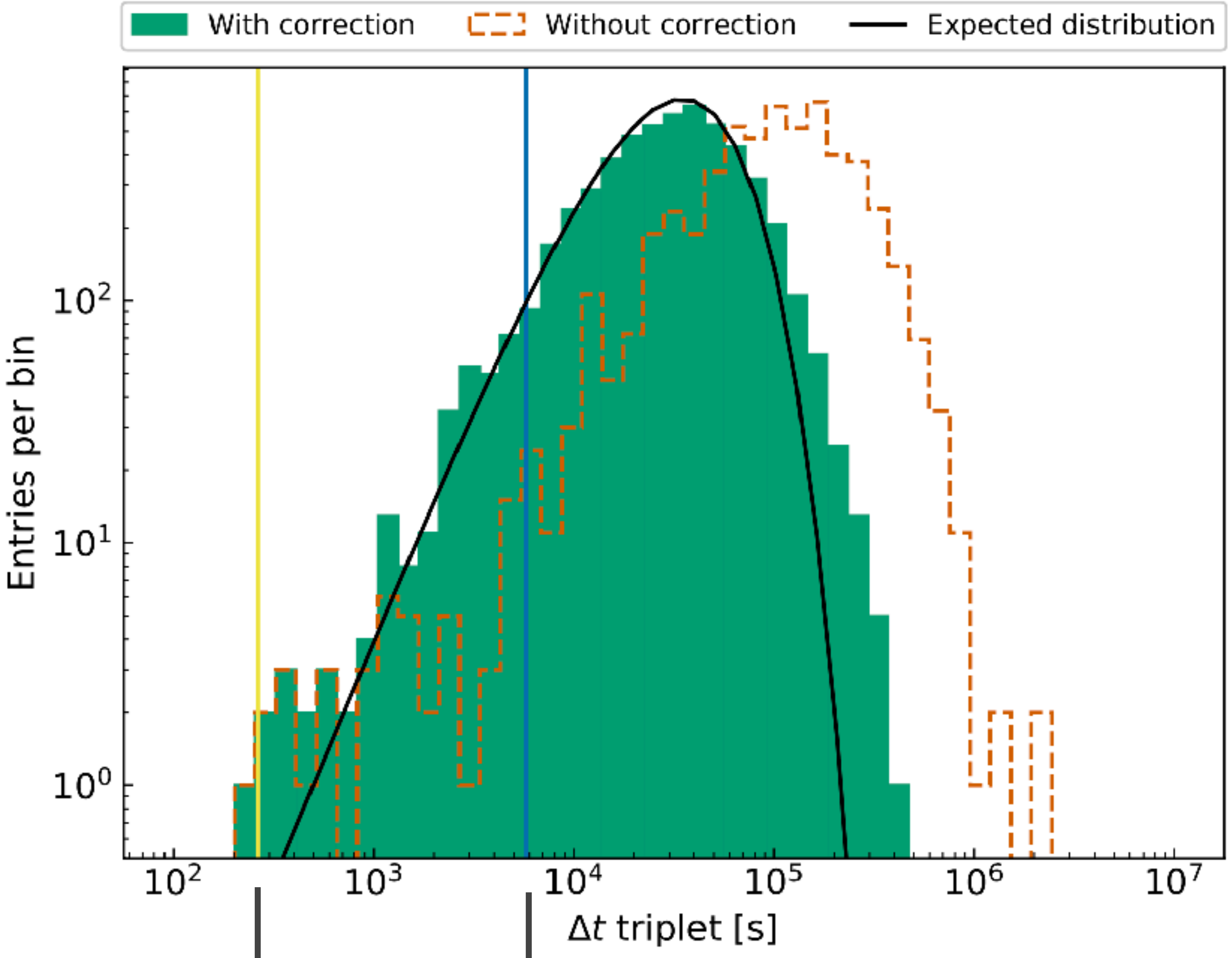
GBM
- ✳ Energy range: 8 keV to 40 MeV
- ✳ Field of view: 9.5 steradians
- ✳ Gamma-ray burst localization: typical 3°





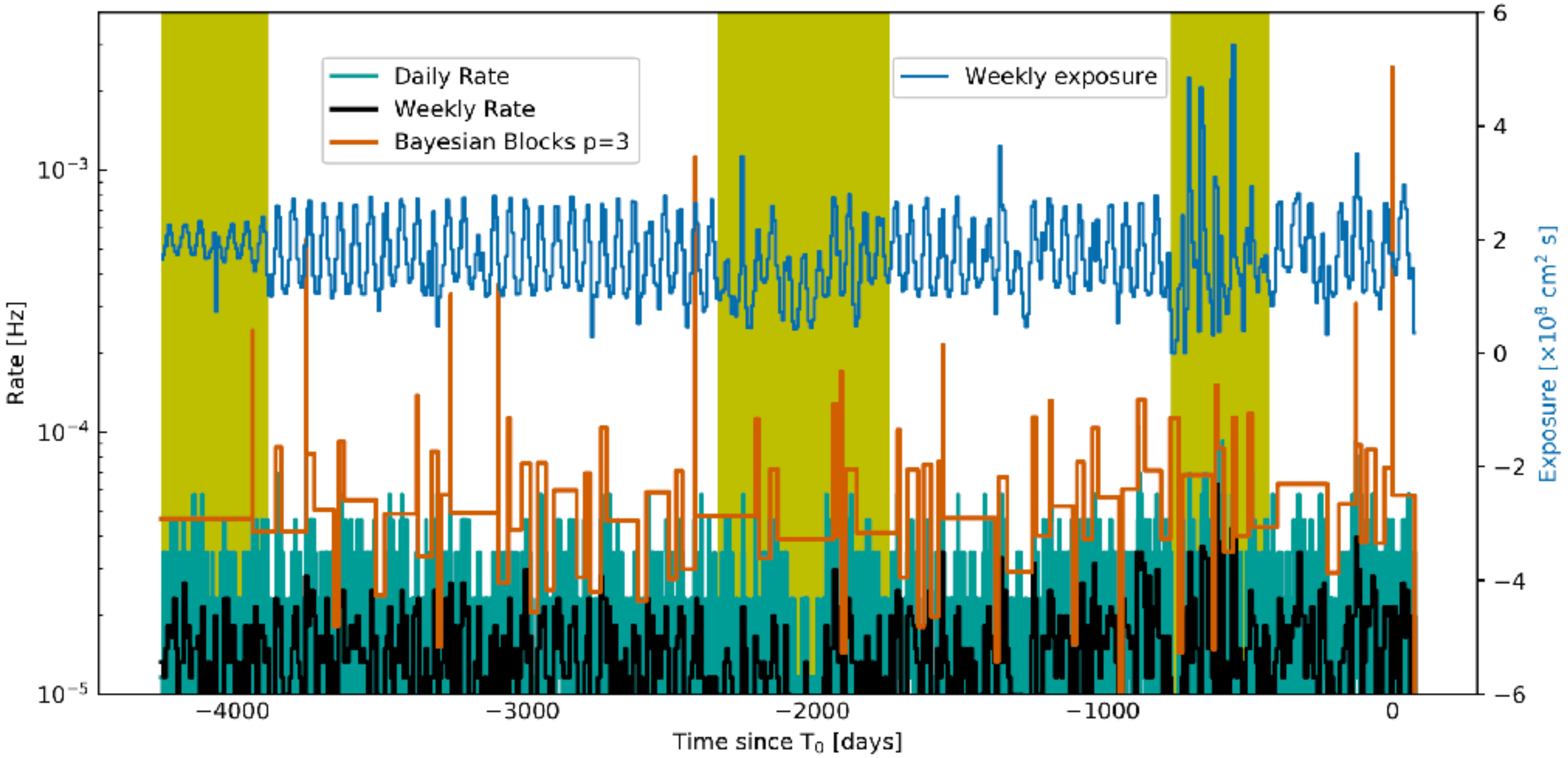
What did trigger the LAT

How often did we observed a triplet of photons above 100 MeV in a 500 second time window in the past 12 years?



Δt = 264.87 s

Period of the Fermi orbit (5,790 s)



Analysis	p-value	FAR (yr^{-1})
Temporal Association with GRB 200415A		
Triplet Analysis	8.3×10^{-7} (Li & Ma)	1.6×10^{-7}
Bayesian Blocks	2.3×10^{-3} (Poisson)	6.3×10^{-8}

LAT Collab (MN). 2021, Published in Nature Astronomy

Summary of MGF sample today

	Known			Extragalactic			
MGF Event	790305B	980827	041227	200415A	070222	051103	070201
Origin							
False Alarm Rate	0	0	0	4.9×10^{-6}	7.8×10^{-6}	1.5×10^{-5}	1.2×10^{-4}
BNS Excl. [Mpc]					6.7	5.2	3.5
Galaxy Properties							
Catalog Name	LMC	MW	MW	NGC253	M83	M82	M31
Distance [Mpc]	0.054	0.0125	0.0087	3.5	4.5	3.7	0.78
SFR [$M_{\odot}/yr$]	0.56	1.65	1.65	4.9	4.2	7.1	0.4
GRB Properties							
Duration [s]	<0.25	<1.0	<0.2	0.100	0.038	0.138	0.010
Rise Time [ms]	~2	~4	~1	2	4	2	24
$L_{\rm iso}^{Max}$ [10^{46} erg/s]	0.65	2.3	35	140	40	180	12
$E_{\rm iso}$ [10^{45} erg]	0.7	0.43	23	13	6.2	53	1.6
Index			-0.7	0.0	-1.0	-0.2	-0.6
$E_{\rm peak}$ [keV]	500	1200	850	1080	1290	2150	280

Why have we not identified MGFs to greater* distances?

*they were thought to be detectable to tens of Mpc)

18th century…

Nicolas Louis de Lacaille introduces Sculptor Contellation