

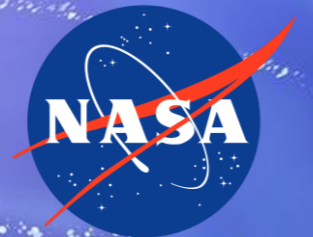
Fermi LAT and GBM collaborations results on GRB 200415A

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Papers

- Fermi-LAT Collaboration “High-energy emission from a magnetar giant flare in the Sculptor galaxy”, Nature Astronomy volume 5, pages 385–391 (2021)
- Roberts O. J. et al. “Rapid spectral variability of a giant flare from a magnetar in NGC 253”, Nature volume 589, pages 207–210 (2021)



High-energy emission from a magnetar giant flare in the Sculptor galaxy

The Fermi-LAT Collaboration

Magnetars are the most highly magnetized neutron stars in the cosmos (with magnetic field 10^{13} – 10^{15} G). Giant flares from magnetars are rare, short-duration (about 0.1 s) bursts of hard X-rays and soft γ rays^{1,2}. Owing to the limited sensitivity and energy coverage of previous telescopes, no magnetar giant flare has been detected at gigaelectronvolt (GeV) energies. Here, we report the discovery of GeV emission from a magnetar giant flare on 15 April 2020 (refs. 3^a and A. J. Castro-Tirado et al., manuscript in preparation). The Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope detected GeV γ rays from 19 s until 284 s after the initial detection of a signal in the mega-electronvolt (MeV) band. Our analysis shows that these γ rays are spatially associated with the nearby (3.5 megaparsecs) Sculptor galaxy and are unlikely to originate from a cosmological γ -ray burst. Thus, we infer that the γ rays originated with the magnetar giant flare in Sculptor. We suggest that the GeV signal is generated by an ultra-relativistic outflow that first radiates the prompt MeV-band photons, and then deposits its energy far from the stellar magnetosphere. After a propagation delay, the outflow interacts with environmental gas and produces shock waves that accelerate electrons to very high energies; these electrons then emit GeV γ rays as optically thin synchrotron radiation. This observation implies that a relativistic outflow is associated with the magnetar giant flare, and suggests the possibility that magnetars can power some short γ -ray bursts.

On 15 April 2020, the Fermi Gamma-ray Burst Monitor (GBM) triggered and located γ -ray burst (GRB) 200415A^a, which was initially classified as a short (duration <2 s) γ -ray burst (SGRB). The Interplanetary Network of γ -ray detectors (IPN, <http://isil.berkeley.edu/ipn3/index.html>) reduced the uncertainty on the GBM position to 20 square arcmin, suggesting that the GRB originated from the nearby Sculptor galaxy^b, located at a distance of about 3.5 megaparsecs^c. This, with the resemblance of the GBM sub-MeV light curve (E. Burns, manuscript in preparation) to the extragalactic soft gamma repeater (SGR) giant flare candidates GRB051103^{b,c} and GRB070201^d, and the detection of quasi-periodic oscillations by the Atmosphere-Space Interaction Monitor (A. J. Castro-Tirado et al., manuscript in preparation), led to the identification of GRB200415A as a magnetar giant flare (MGF) in Sculptor. GRB 200415A was 43° from the LAT boresight at the GBM trigger time T_0 (08:48:05.563746 UTC) and remained well within the LAT field of view (FOV) until 500 seconds after T_0 . Three γ rays were detected by the LAT, allowing the localization of GRB200415A at high energies (>100 MeV); this detection of high-energy γ -ray emission from an MGF suggests that magnetars can power the relativistic outflows observed in some SGRBs.

To study the localization of the γ -ray signal observed by the LAT we perform a likelihood analysis and compute a test statistic (TS)

for the presence of the source at different positions. The best position is obtained from the maximum of the TS ($TS_{\text{max}} = 29$, corresponding to a detection significance close to 5 σ ; see the Methods and Extended Data Fig. 1 for the numerical value of the best-fit model). Then, the variation of the TS around this position provides the map of localization contours shown in Fig. 1. The iso-counts in red encompass localization probabilities of 68% and 90%.

Four galaxies (IC1576, IC1578, IC1582 and NGC253) from the NGC 2000 catalogue^e are located within a circular region of radius r_{90} , whose area is equivalent to the 90% confidence level, and which is centred on the maximum of the TS map at right ascension (RA) = 11.13° and declination (dec.) = -24.97° (J2000). NGC 253, also known as the Sculptor galaxy, has already been detected as a steady source in γ rays^{b,d} with a flux integrated between 100 MeV and 100 GeV of $(1.3 \pm 0.2) \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$. The γ -ray emission is powered by cosmic rays accelerated by supernova remnants interacting with the interstellar gas, and the enhanced massive star-formation activity in the galaxy also favours the presence of stellar remnants like magnetars. The centre of the galaxy lies on the contour containing a localization probability of 72%.

We apply the likelihood ratio (LR) method¹¹ to quantify the reliability of a possible association of the γ -ray source with Sculptor. This method can distinguish between two situations: the true counterpart associated with a γ -ray emitter, which appears to lie a certain distance away owing to localization uncertainties; or a background object which, by chance, happens to lie close to the γ -ray position. Our analysis takes into account the angular size of the counterpart candidate and the elongated shape of the LAT localization contours shown in Fig. 1. Since the LR method takes into account the magnitude of the galaxy, we find that the Sculptor galaxy is the most likely host galaxy of the source detected by the LAT with a LR value approximately 60 times larger than the values for other galaxies. To evaluate the statistical significance of this association, we compare the LR values obtained in these analyses with the same analyses repeated over a sample of random locations in the sky. The P values range from 3.2×10^{-4} to 2.9×10^{-3} depending on the particular analysis (see details in the Methods and Extended Data Figs. 3 and 4). Both analyses suggest a positional association between Sculptor and the LAT γ -ray detection. Assuming that the emission detected by the LAT is from an SGRB, our calculation of the false alarm rates (FARs) ranges from $5.4 \times 10^{-4} \text{ yr}^{-1}$ to $4.7 \times 10^{-3} \text{ yr}^{-1}$.

We perform a detailed maximum likelihood spectral analysis of the LAT emission by modelling GRB200415A as a point source with a power-law spectrum. As part of our analysis we estimate the probability that each photon detected by the LAT is associated with the point source, as opposed to any of the other model components. The list of events is shown in Extended Data Fig. 2. Three events are associated with the source with a probability greater than 90%. The arrival times (after T_0) of these events are 19 s, 180 s and 284 s, with

Article

Rapid spectral variability of a giant flare from a magnetar in NGC 253

<https://doi.org/10.1038/s41586-020-03077-8>

Received: 18 August 2020

Accepted: 26 October 2020

Published online: 13 January 2021

Check for updates

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Magnetars are neutron stars with extremely strong magnetic fields (10^{13} to 10^{15} gauss)^{1,2}, which episodically emit X-ray bursts approximately 100 milliseconds long and with energies of 10^{49} to 10^{50} erg. Occasionally, they also produce extremely bright and energetic giant flares, which begin with a short (roughly 0.2 s), intense flash, followed by fainter, longer-lasting emission that is modulated by the spin period of the magnetar^{3,4} (typically 2 to 12 seconds). Over the past 40 years, only three such flares have been observed in our local group of galaxies^{5–7}, and in all cases the extreme intensity of the flares caused the detectors to saturate. It has been proposed that extragalactic giant flares are probably a subset⁸ of short γ -ray bursts, given that the sensitivity of current instrumentation prevents us from detecting the pulsating tail, whereas the initial bright flash is readily observable out to distances of around 10 to 20 million parsecs. Here we report X-ray and γ -ray observations of the γ -ray burst GRB 200415A, which has a rapid onset, very fast time variability, flat spectra and substantial sub-millisecond spectral evolution. These attributes match well with those expected for a giant flare from an extragalactic magnetar⁹, given that GRB 200415A is directionally associated¹⁰ with the galaxy NGC 253 (roughly 3.5 million parsecs away). The detection of three-mega-electronvolt photons provides evidence for the relativistic motion of the emitting plasma. Radiation from such rapidly moving gas around a rotating magnetar may have generated the rapid spectral evolution that we observe.

On 15 April 2020 at 08:48:05.563746 UTC, the Gamma-ray Burst Monitor (GBM) onboard the Fermi Gamma-Ray Space Telescope (Fermi) was triggered by an extremely bright, short and spectrally hard event, initially classified as a short γ -ray burst (GRB), GRB 200415A^a, which was also detected by several other instruments (refs. 13^b–15^c; A. J. Castro-Tirado et al., manuscript in preparation). An offline search using time-tagged event data from the Burst Alert Telescope (BAT) onboard the Neil Gehrels Swift Observatory (Swift), obtained with the Gamma-ray Urgent Archiver for Novel Opportunities (GUANO)¹⁶ pipeline, also found the event. Using the light travel time of photons detected by the Inter-Planetary Network of satellites, GRB 200415A was triangulated to a 17-arcmin² region centred at a right ascension (RA) and declination (dec.) (J2000) of 11.88° (00 h 47 m 32 s) and -25.263° (-25° 15' 46"), respectively¹⁷. The relatively small error box of the localization overlaps significantly with the Sculptor galaxy (NGC 253) – an

active star-bursting intermediate spiral galaxy located about 3.5 Mpc away¹⁸ – which strongly suggests that GRB 200415A originated from this galaxy.

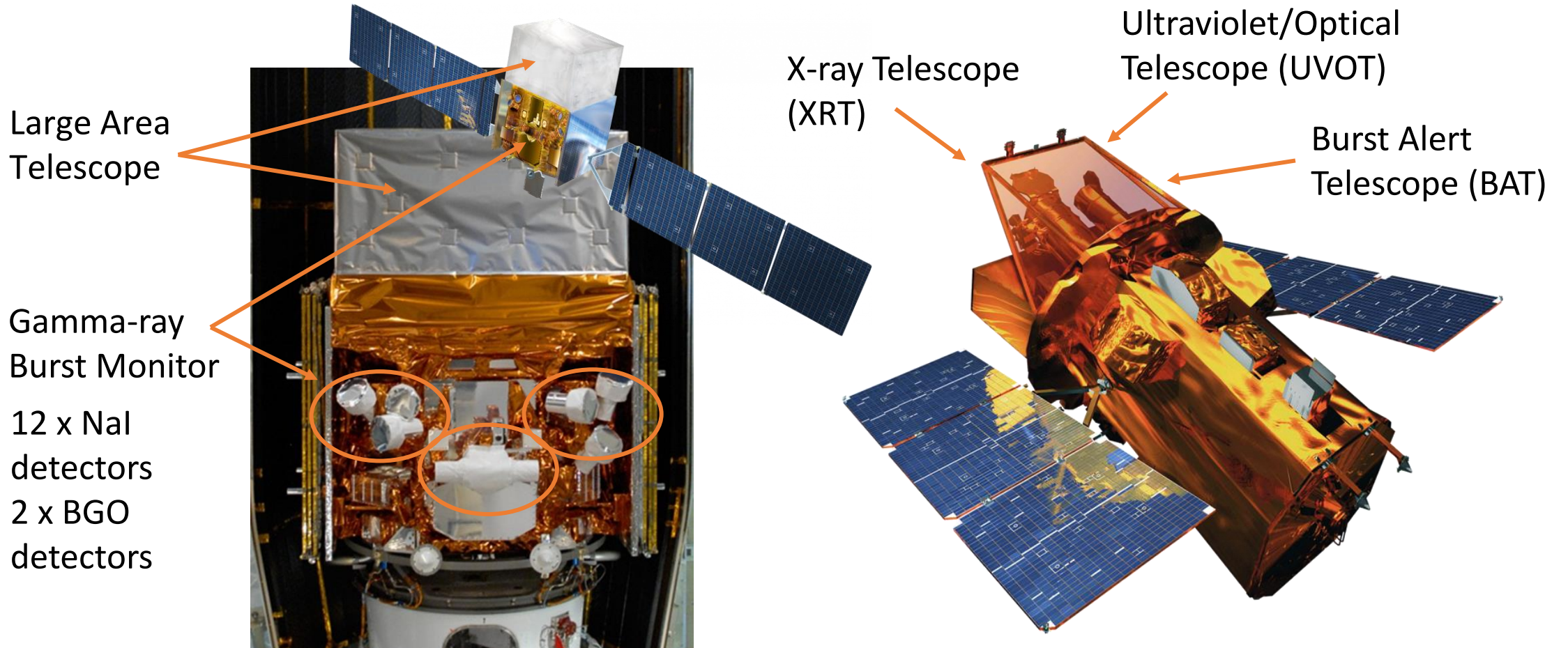
We use the BAT time-tagged event data to determine the duration due to bandwidth saturation of the high-time-resolution GBM time-tagged event data (Methods). We find the T_{90} duration of GRB 200415A (the time interval over which 5%–95% of the total counts were accumulated¹⁹) to be 140.8^{+10.0}_{-10.0} ms (1 σ). Correspondingly, the T_{50} duration of the event (over which 25%–75% of the total counts were accumulated) is 54.7^{+2.3}_{-2.3} ms (1 σ). Our detailed temporal analysis of the event lightcurve shows that the rise time (0%–90%) of the first pulse is $T_{\text{rise}} = 77 \pm 23 \mu\text{s}$ (1 σ) (Fig. 1e).

We performed a timing analysis on the GBM lightcurve to search for a rotational frequency in the range 0.02–50 Hz, but found no clear pulse. We also searched the 40–4,000-Hz window for quasi-periodic

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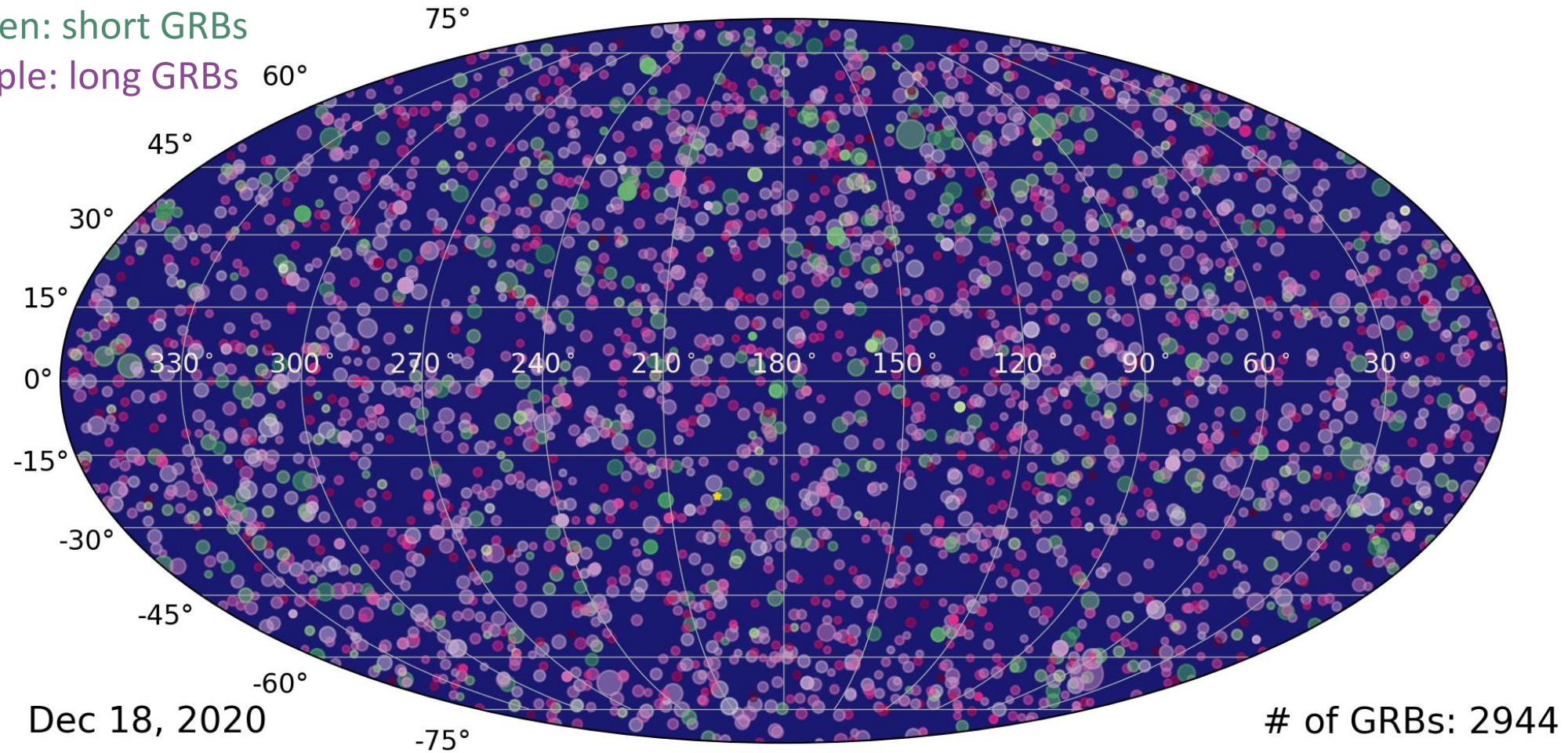
Fermi and Swift



GBM Gamma-ray Bursts

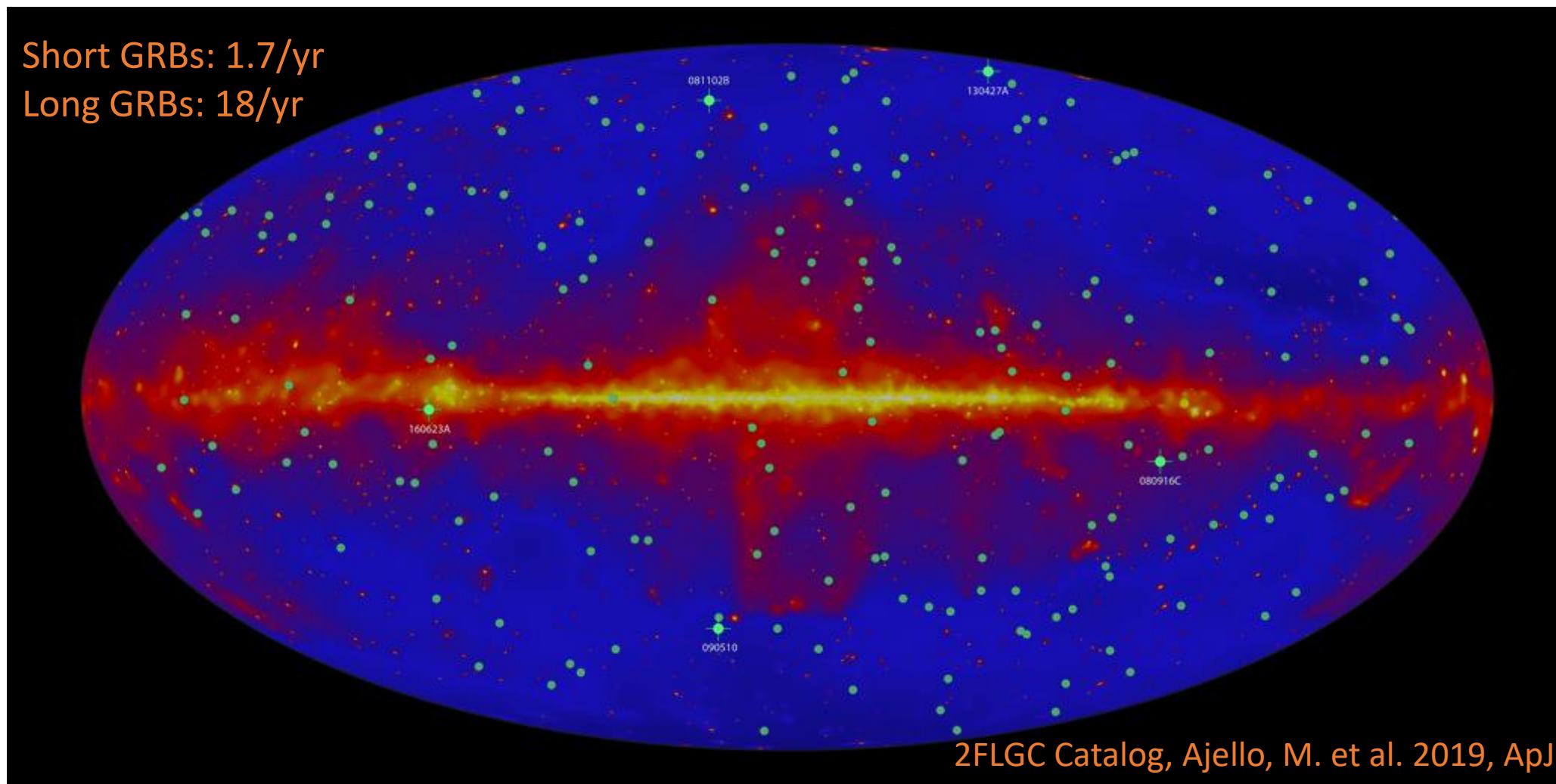
Green: short GRBs

Purple: long GRBs



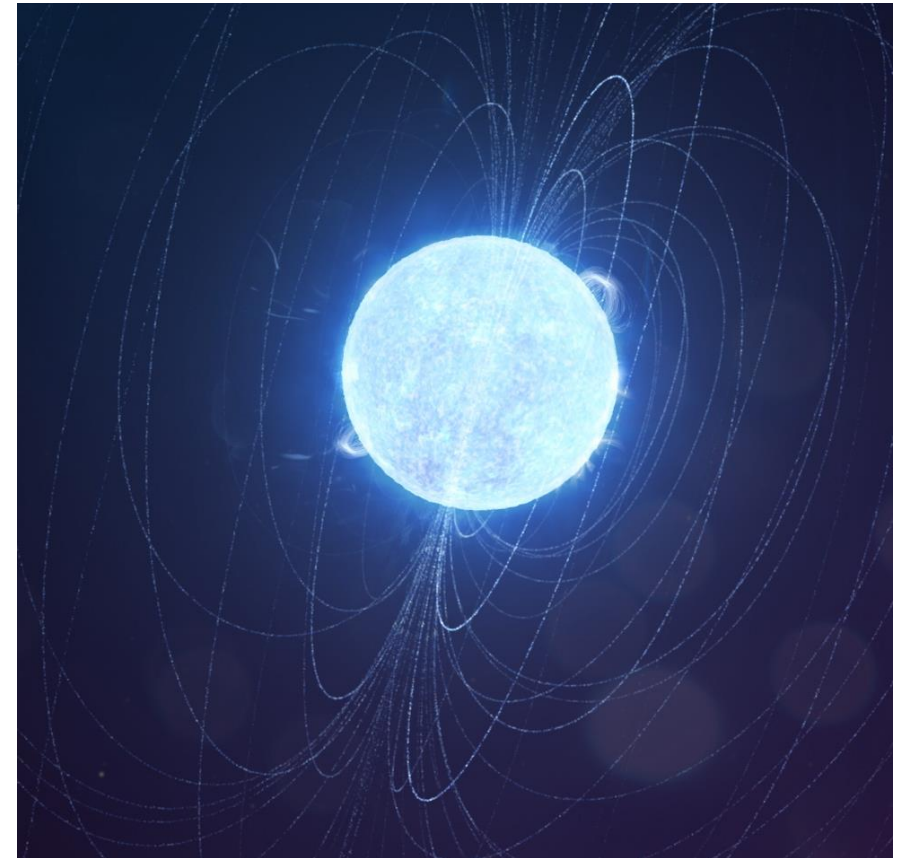
LAT Gamma-ray sky and GRBs

Short GRBs: 1.7/yr
Long GRBs: 18/yr



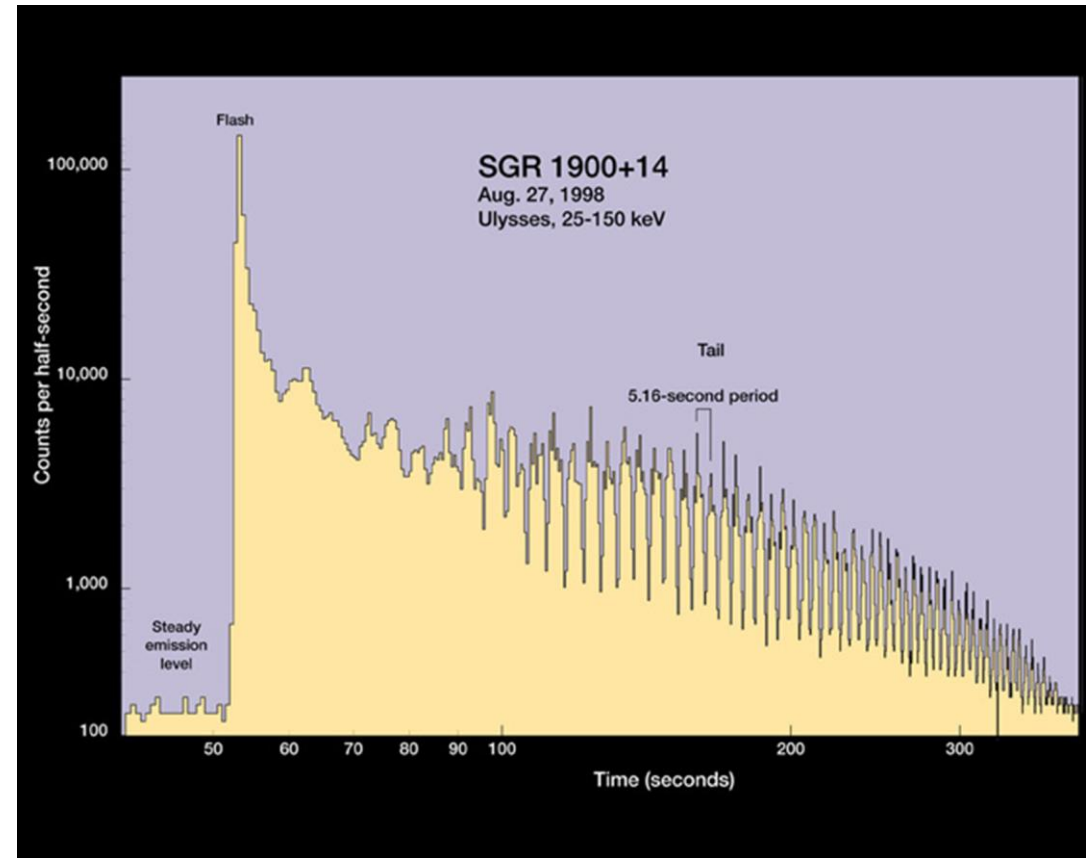
Magnetars

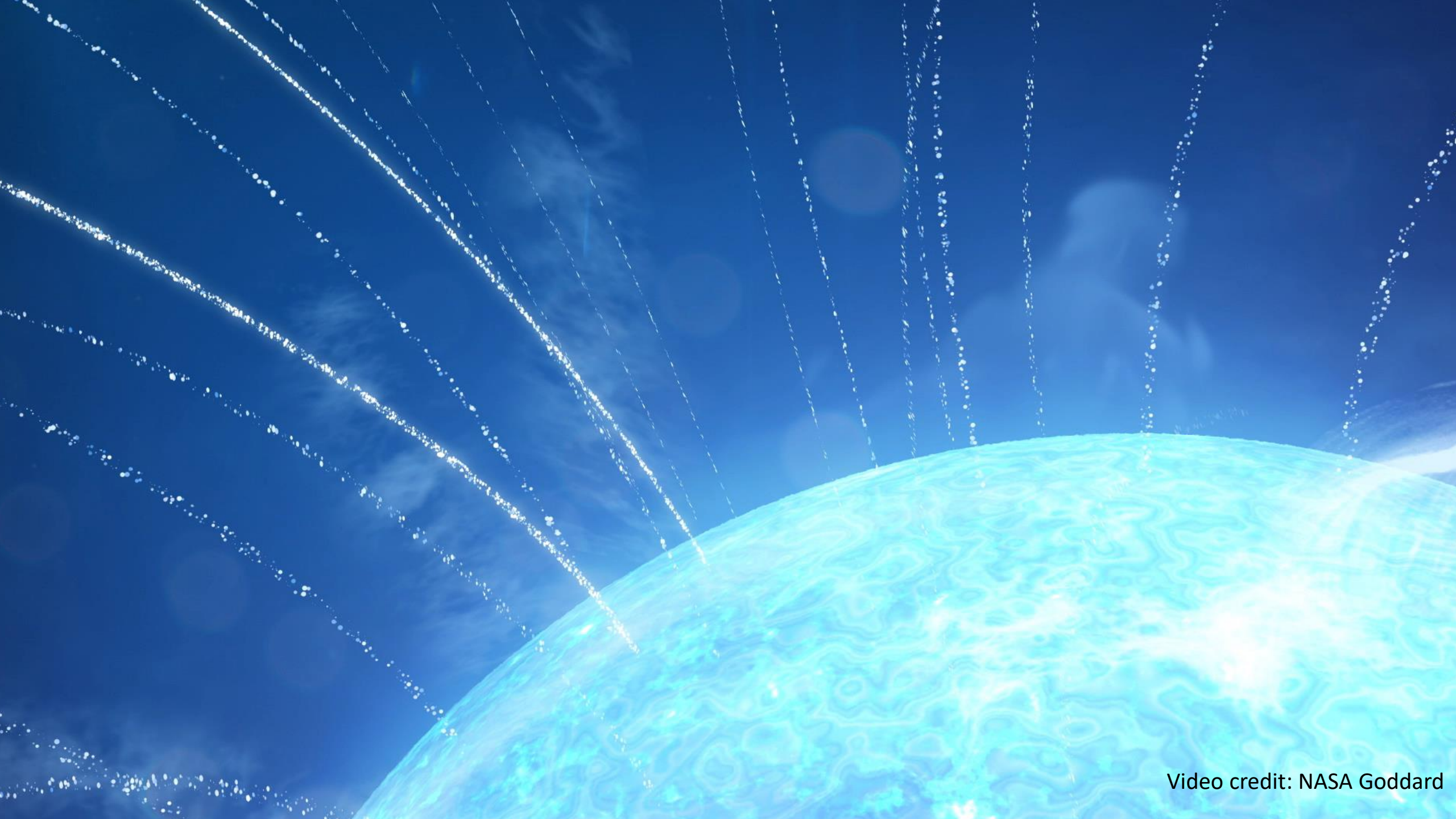
- Strongly magnetized neutron star:
 - Magnetic field $\sim 10^{13-15}$ G
 - Rotation period of 0.1-10 s
 - Steady X-ray luminosity $L_x \sim 10^{31-36}$ erg/s
- Magnetars can manifest:
 - Recurrent short duration bursts $L \sim 10^{36-41}$ erg/s and period ~ 0.1 s
 - Long lasting active phases $L > 10^{36}$ erg/s lasting years
 - Rare Magnetar Giant Flares



Magnetar Giant Flares

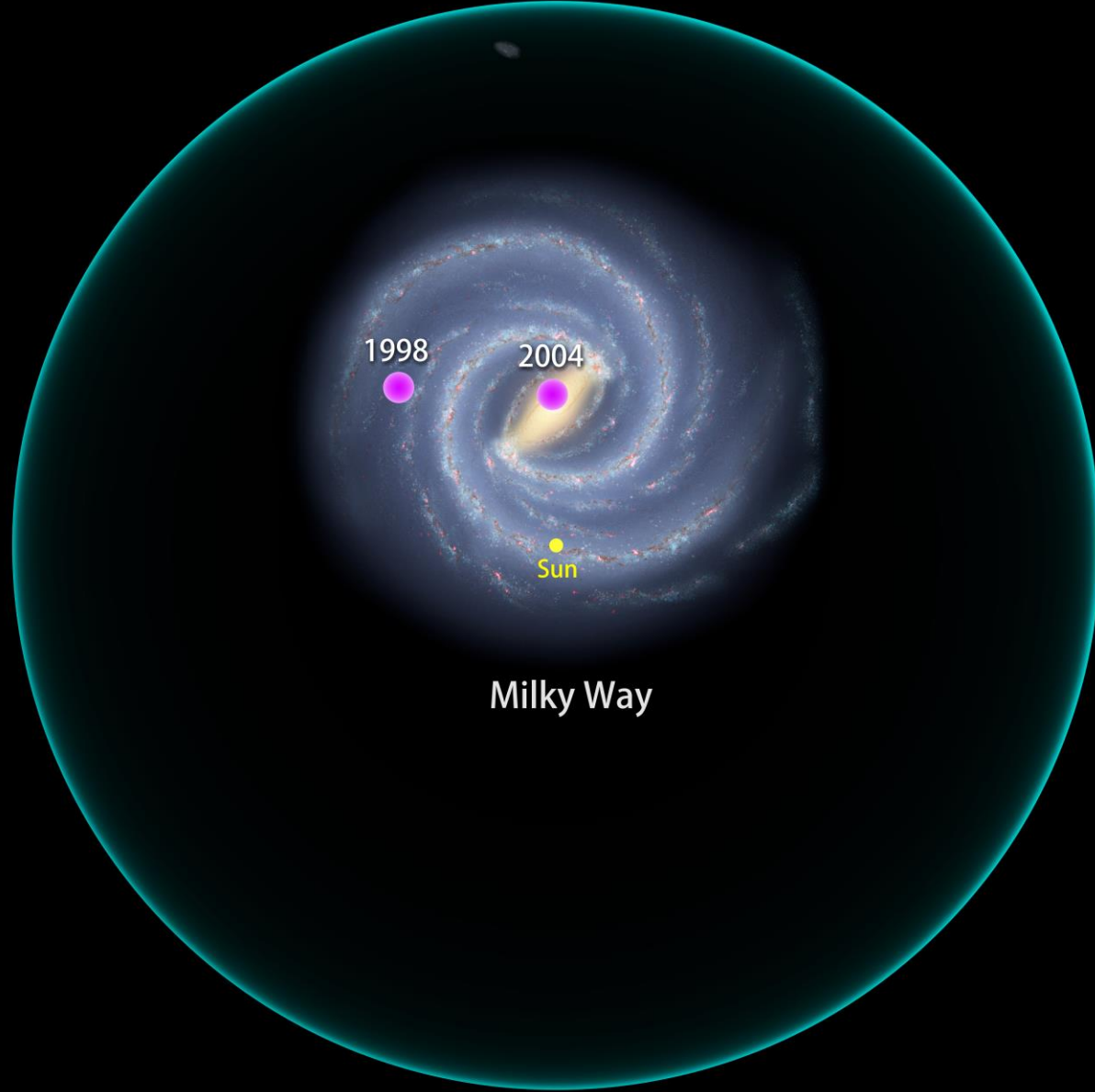
- Rare, short duration bursts of hard X-rays and soft gamma-rays with luminosity $\sim 10^{44-47}$ erg/s:
 - Bright and variable initial spike lasting a few tenths of a second
 - Dimmer pulsating tail lasting a few hundred of seconds
- Triggered by extreme starquakes:
 - Induced by the extreme magnetic field which causes crustal fractures and the release of hot plasma





Video credit: NASA Goddard

100,000 light-years from Sun



1998

2004

Sun

Milky Way

1979

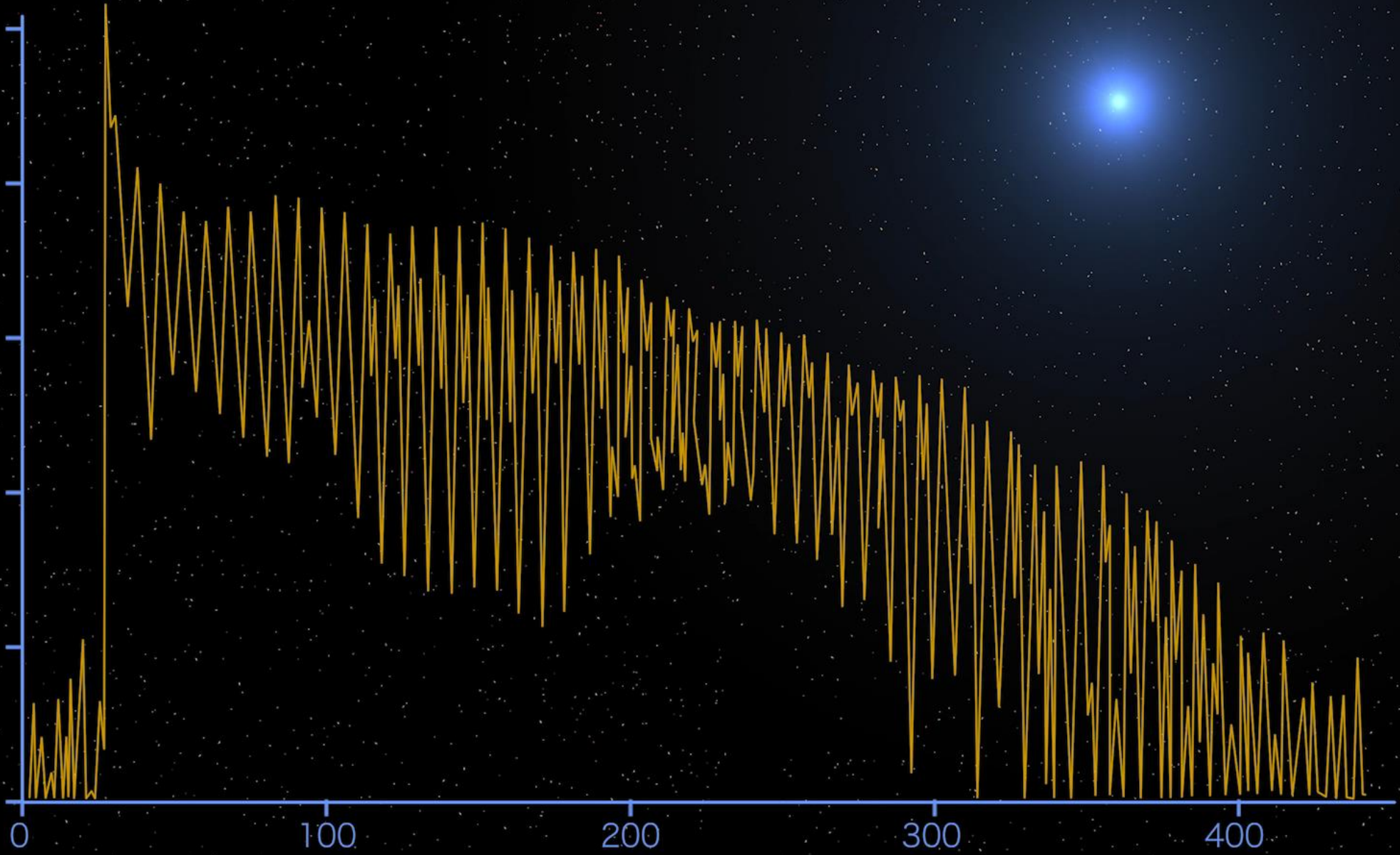
Large Magellanic Cloud





Video credit: NASA
Goddard

Photons
per
second



Time in seconds

Video credit: NASA Goddard

15 million light-years from Sun



There should be many more MGFs in the Universe than short GRBs!

Michela Negro's talk

July 14th at 6 PM
Berlin Time [[link](#)]



ONLINE ICRC 2021



Virtually in Berlin,
14 July 2021

Detection of the third class of gamma-ray bursts
Magnetar giant flares

Michela Negro, CRESST-GFSC/UMBC (mnegro1@umbc.edu)
- On behalf of the working team -



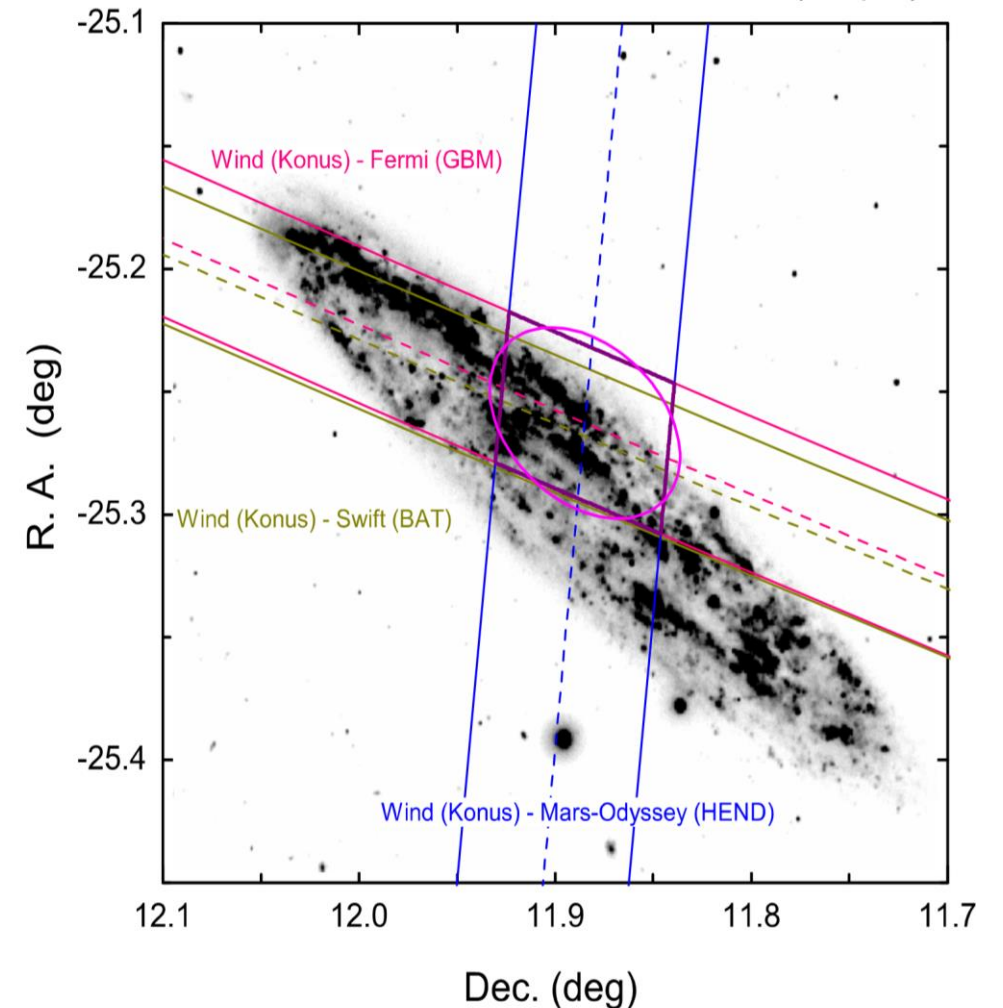
NGC 253

Sculptor galaxy

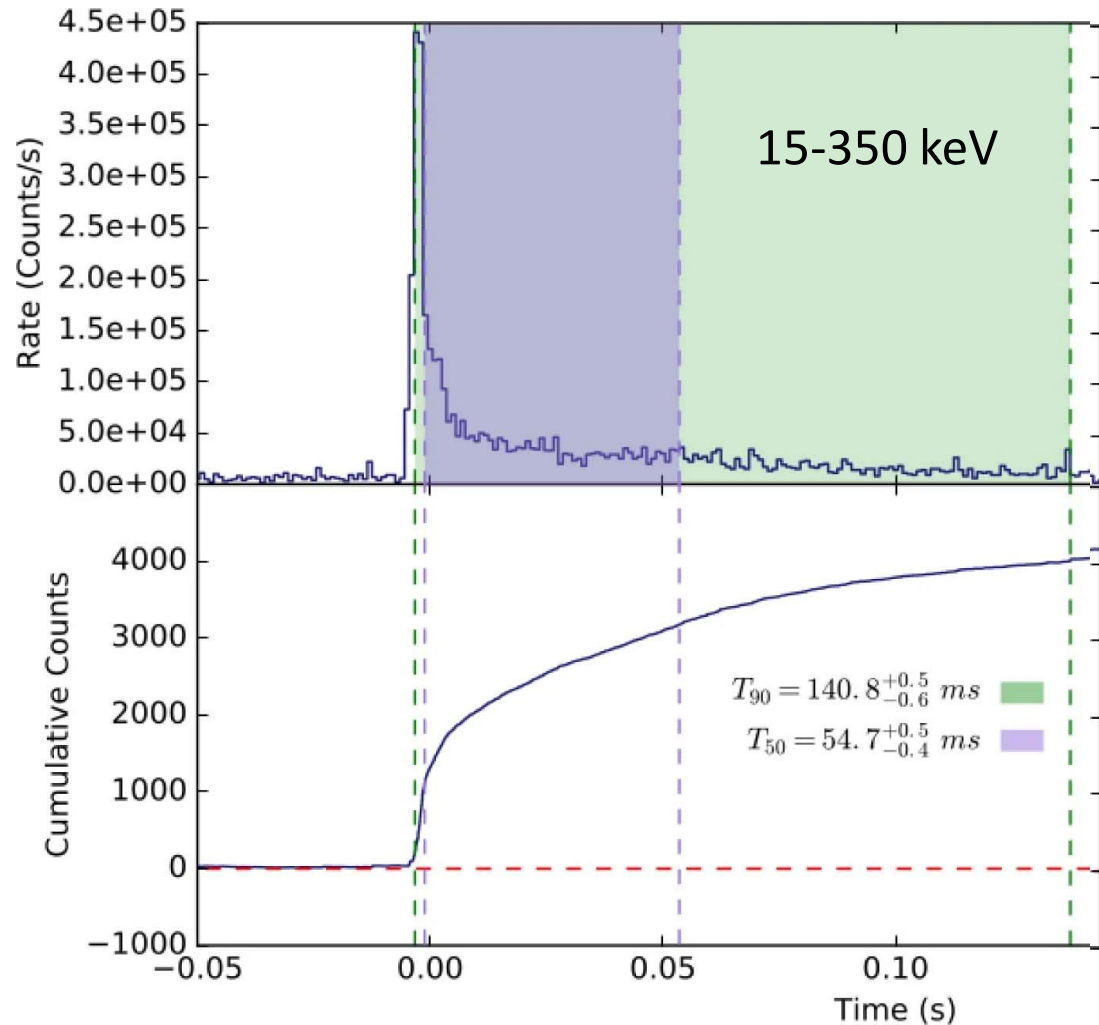
Video credit: NASA Goddard

GRB 200415A

- Bright transient on April 15th 2020:
 - GBM triggered at 08:48:05.56 UTC
 - O. Roberts et al., Nature Vol. 589, 207 (2021)
 - Localized by the Inter-Planetary Network in a 17 arcmin² region overlapping with NGC 253,
 - D. Svinkin, et al., Nature Vol.589, 211 (2021)
 - Active star-bursting spiral galaxy at a distance of 3.5 Mpc
- Chance coincidence with NGC 253:
1 in 230,000
 - E. Burns et al., ApJL 907 L28 (2021)



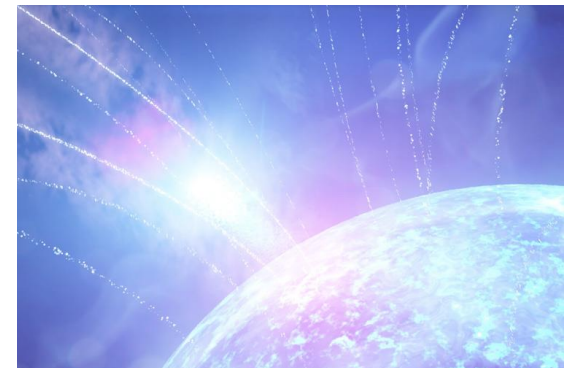
Swift BAT light curve



Short
GRB

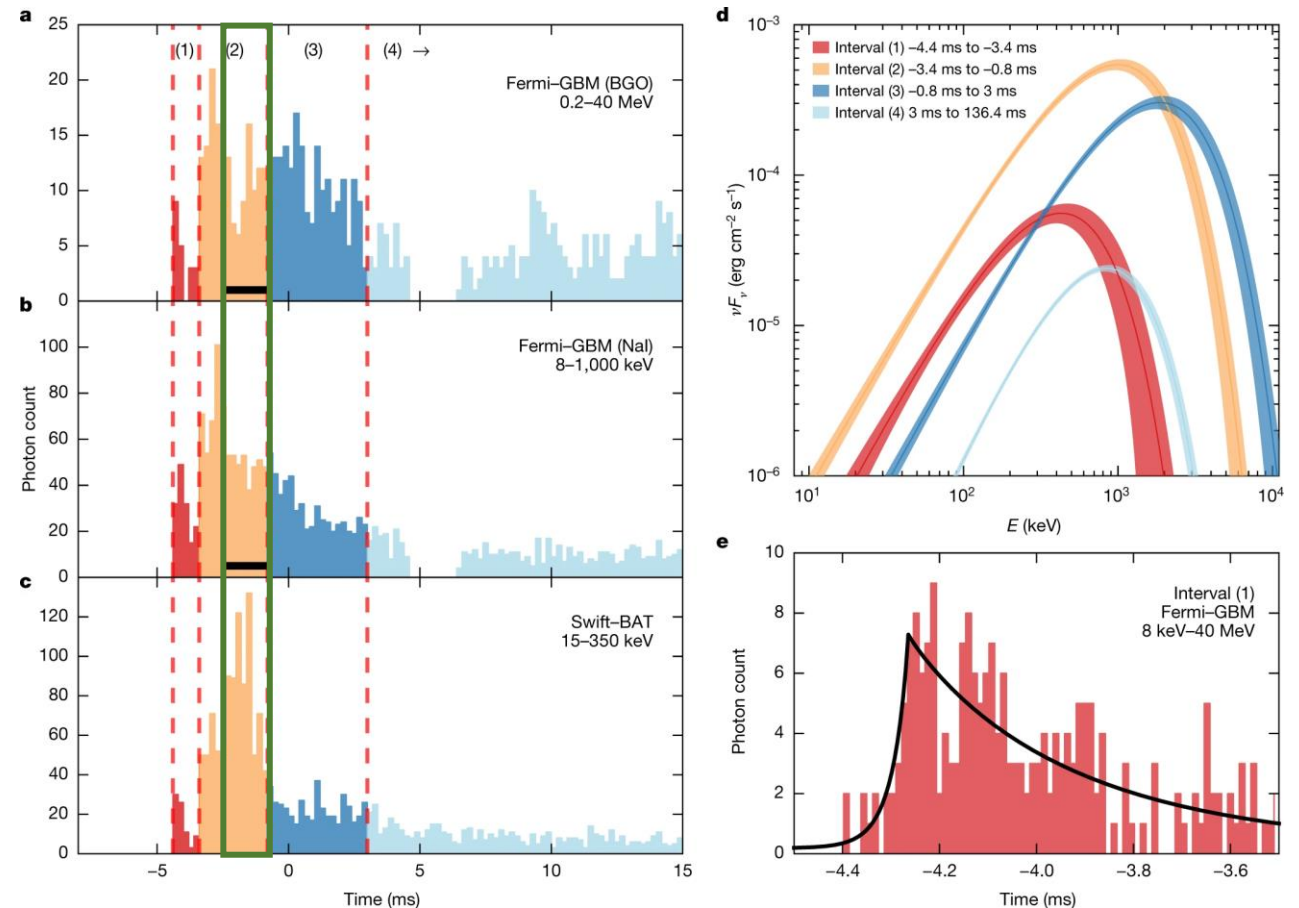


MGF



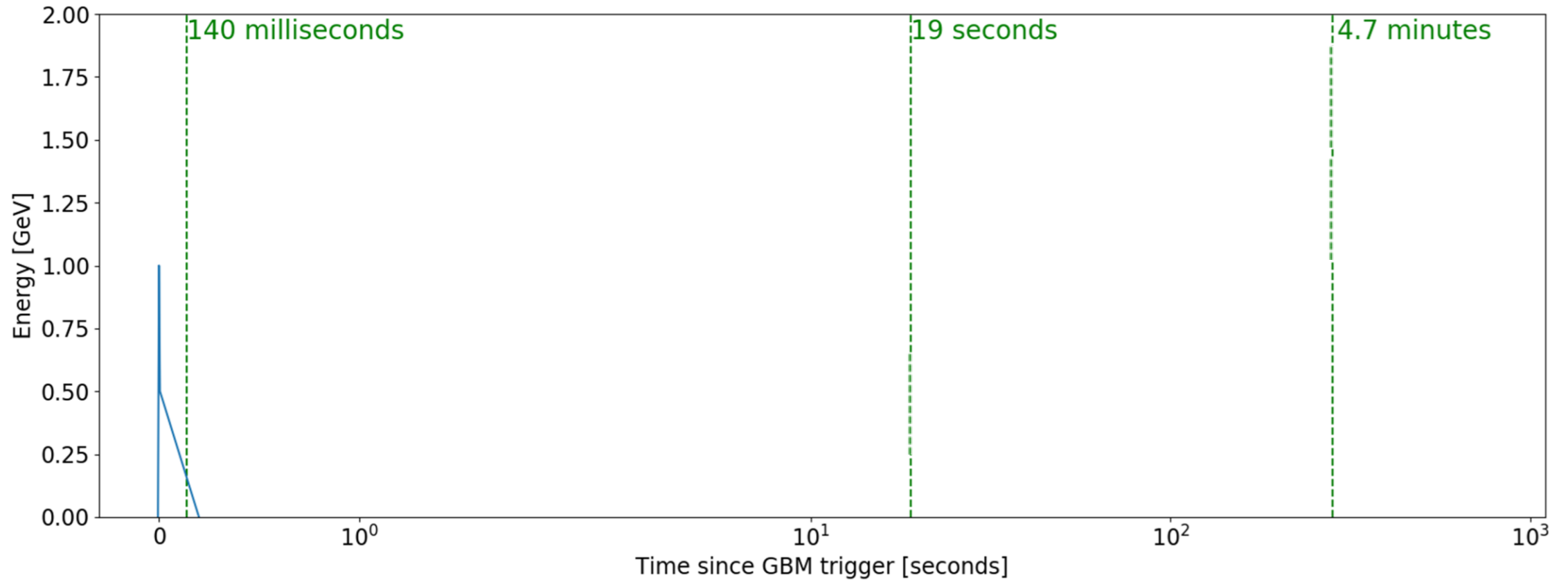
Fermi GBM observation

- Flux and spectral shape unusual for a short GRB:
 - 77 μs rise time
 - Sub-ms spectral evolution
 - Flat spectrum ($\alpha \sim 0$), $E_p \sim \text{MeV}$
 - 180 Hz QPO at 2.5σ in the burst decay
- Very bright and very energetic:
 - $E_{\text{iso}} = 1.5 \times 10^{46}$ erg
 - $L_{\text{iso}} = 1.1 \times 10^{47}$ erg/s
 - Highest energy photon: 3 MeV
- No radio counterpart (VLA) or GW emission (KAGRA)

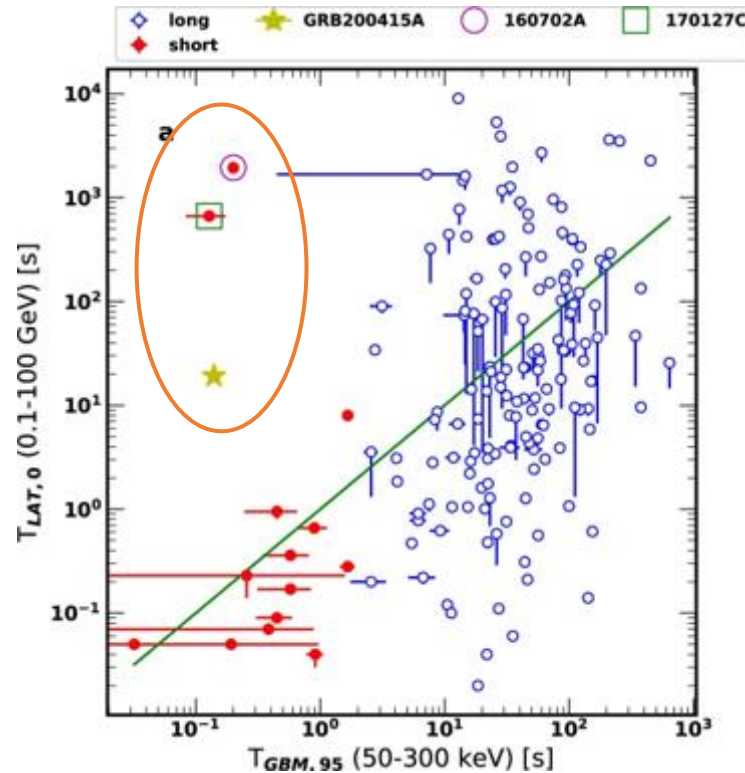


Fermi LAT light curve

GRB200415A was well **within the LAT FoV** until 500s after the GBM emission



A peculiar LAT GRB?



GRB 200415A is the only LAT sGRB within the FoV that was detected much later the end of the GBM prompt emission

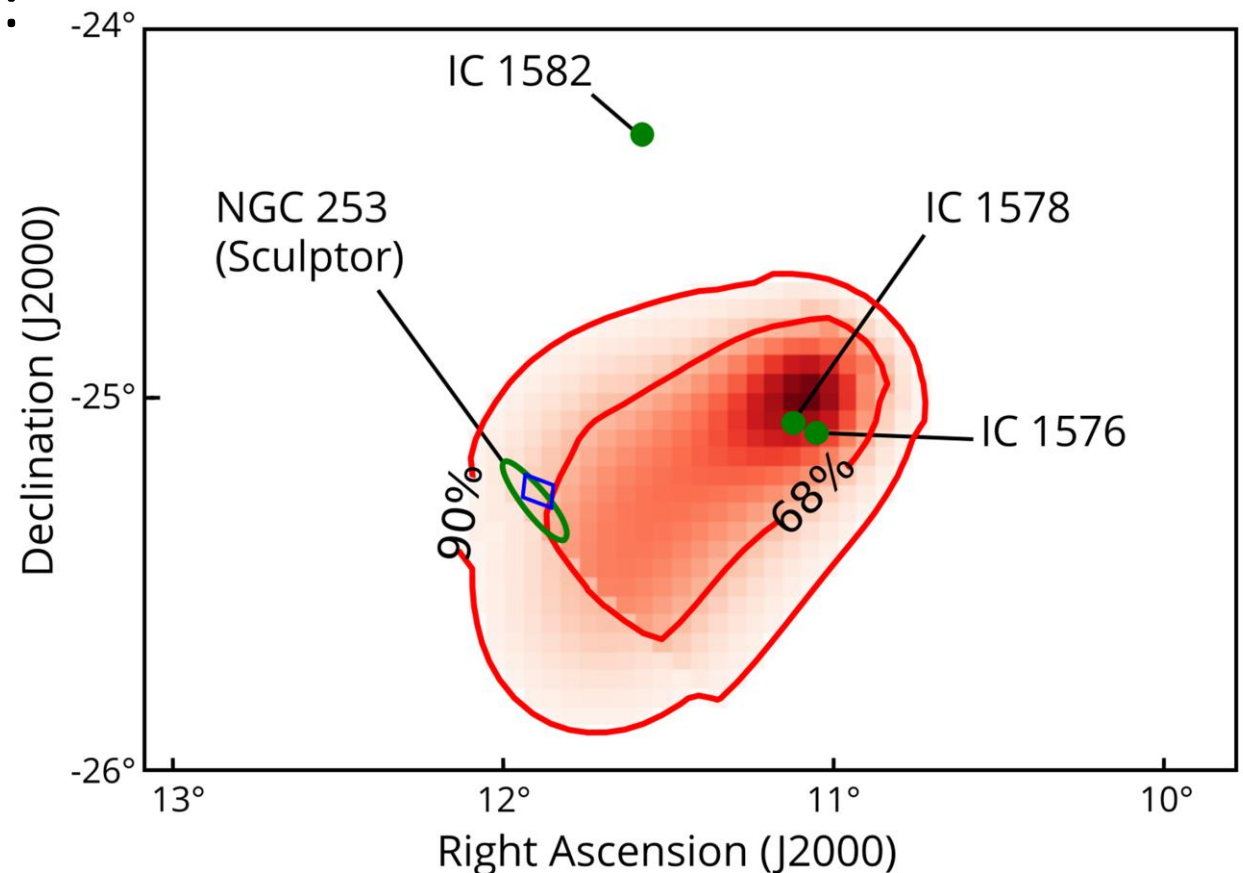
LAT Localization map

- Likelihood analysis and TS map:

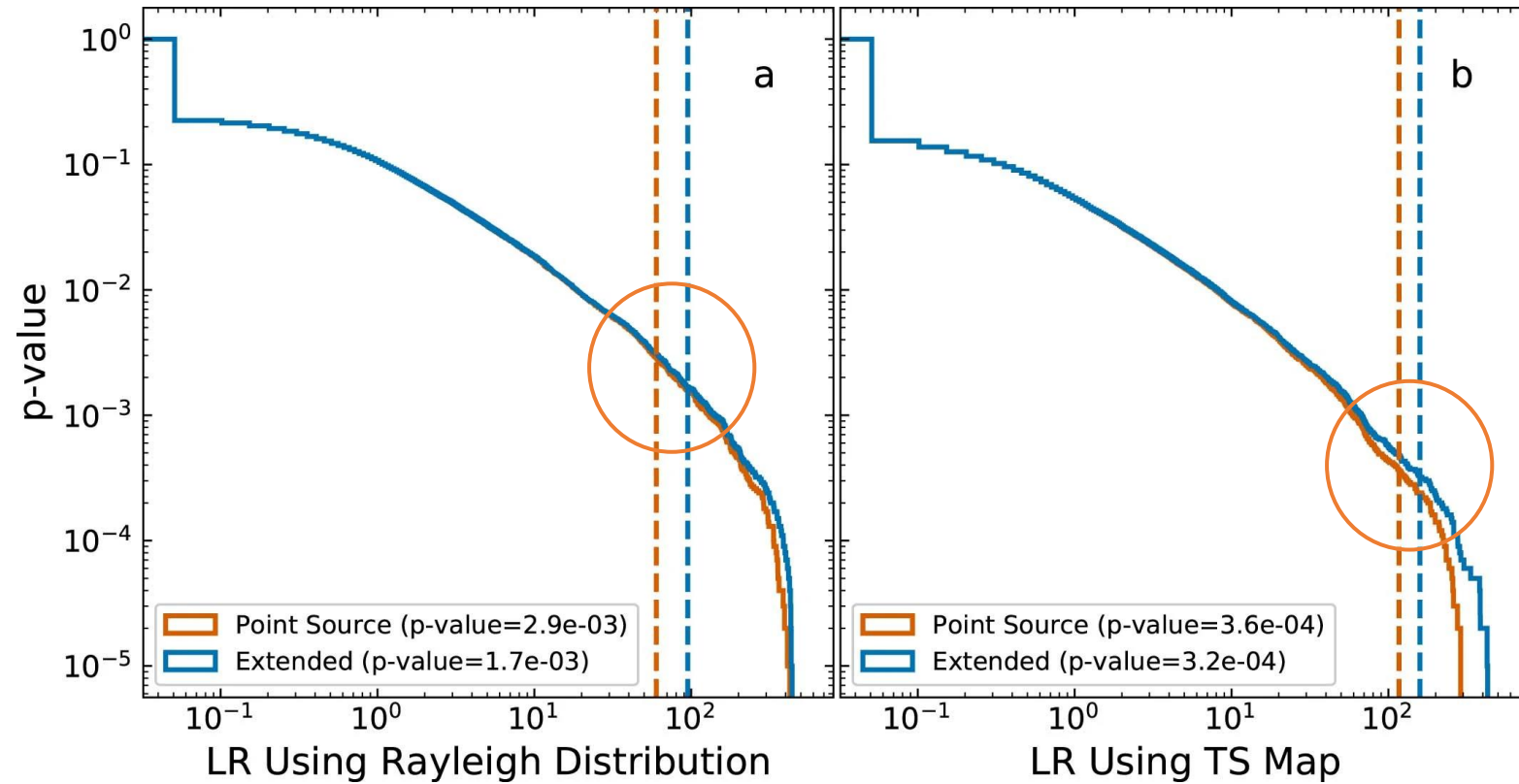
- Maximum TS = 29 at
RA = 11.13°, dec = -24.97°
- 4 NGC 2000 galaxies in the
3° x 3° ROI
- NGC 253 at 72% localization CL

- L.R. association results:

Galaxy	IC 1576	IC 1578	IC 1582	NGC 253
L.R.	2.1	2.9	0.3	60



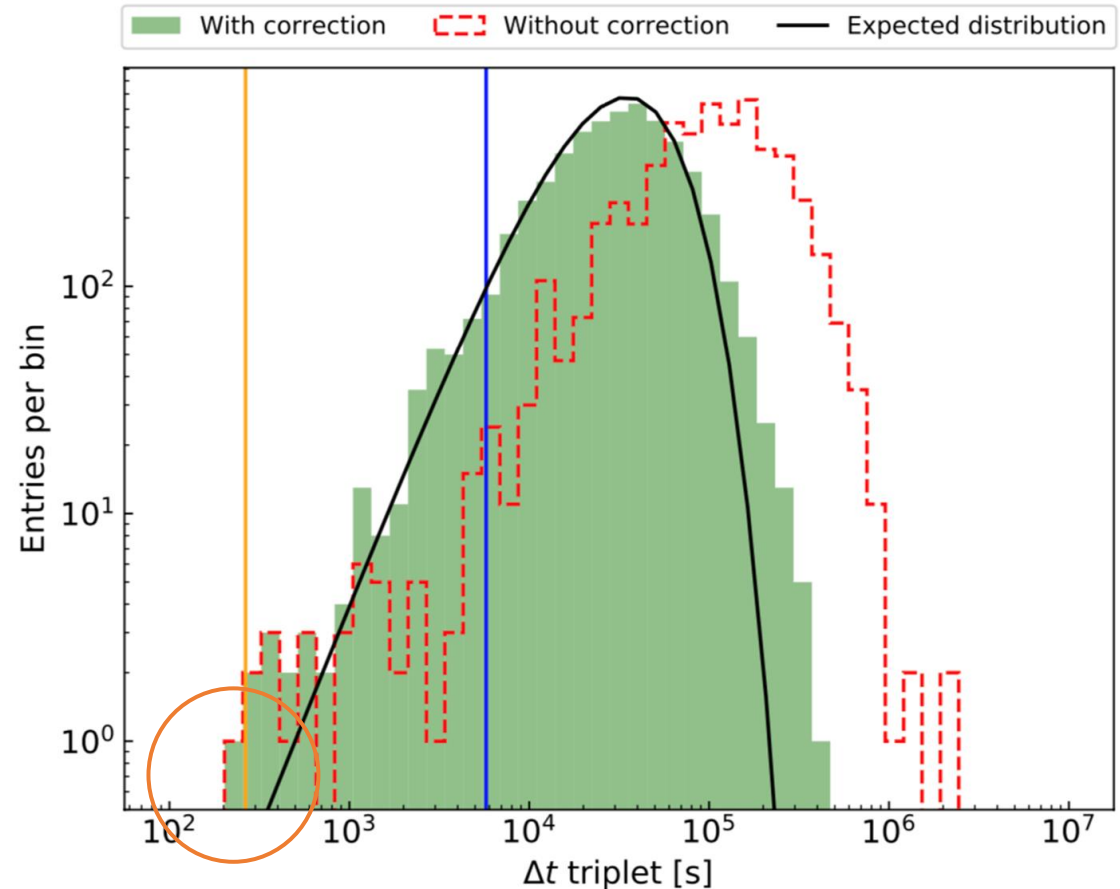
Spatial association

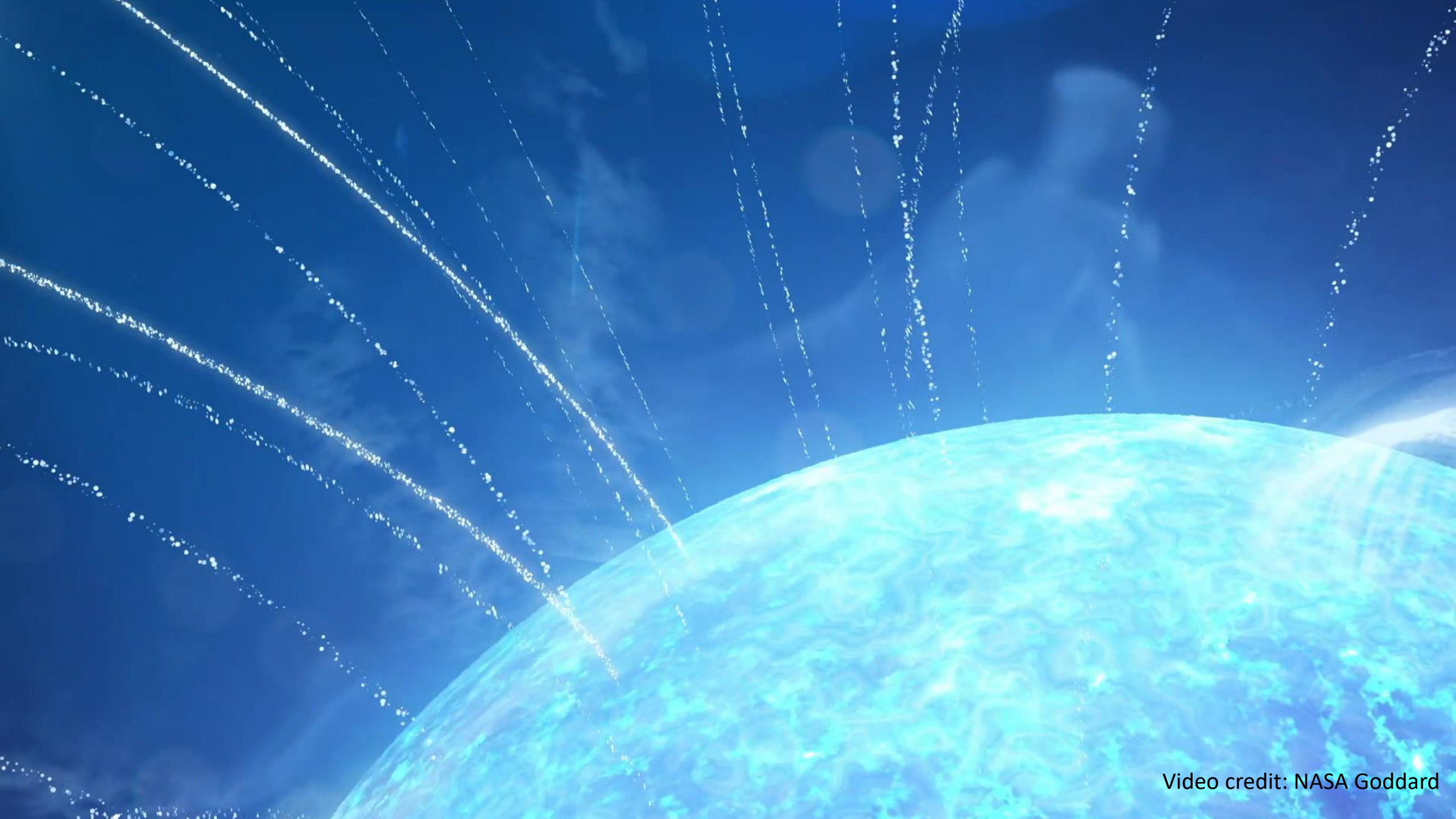


False Alarm Rate \sim 1 chance coincidence in 200-1800 years

Temporal association

- Significance 5.3σ :
 - 3 events in ~ 300 seconds in the Sculptor region [Li&Ma, 1983]
- $\Delta t_i = t_{i+2} - t_i$
- Expected distribution:
 - Obtained using the Poisson statistics
- In 12 years of LAT data:
 - 3 years of livetime
 - Only 1 triplet has a smaller Δt (TS=16)
- Probability of chance coincidence with GBM signal: 1 in million years





Video credit: NASA Goddard

Case closed?

- Not yet:
 - Clear detection of pulsations is needed to absolutely prove magnetar origin
 - Repeating burst to ensure a not cataclysmic event
 - But do MGFs repeat?
- But clear fingerprint at the crime scene:
 - Burst morphology (in star-forming galaxy):
 - Initial spike, spectral evolution and properties
 - Absence of gravitational waves yet so nearby
- With an unexpected discovery:
 - Delayed high energy gamma rays seen by the LAT
 - Do all MGF produce GeV emission? Is the delay a constant?



Conclusions

- Fermi LAT and GBM Collaborations reported the high-energy detection of a magnetar giant flare coming from NGC 253:
 - The first detection at GeV energies!
- Simple physical model explains the observations
- MGFs may constitute a fraction of current short GRB samples
- Further details:
 - The Fermi LAT Collaboration, Nature Astronomy [[link](#)]
 - GBM/Swift results, Roberts et al. Nature [[link](#)]
 - IPN localization, Svinkin et al., Nature [[link](#)]
 - Population of Magnetar Giant Flares, Burnes et al., ApJL [[link](#)]