Exploring the multi-messenger nature of FRBs: insights from gamma-ray and gravitational-wave searches

G. Principe[1,2,3]

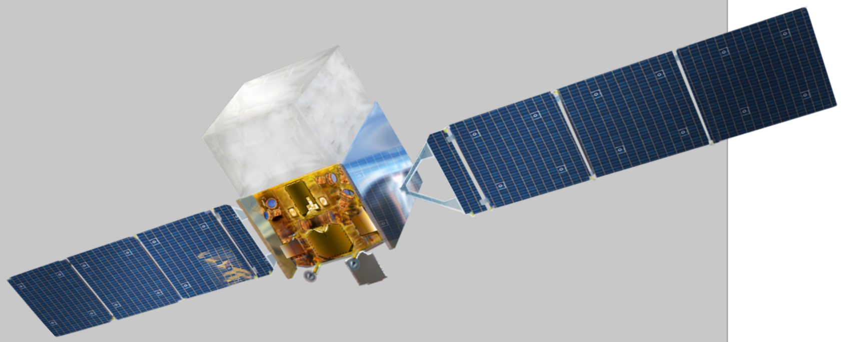
for the Fermi-LAT and LVK collaborations

[1]University of Trieste, Trieste, Italy; [2]INFN-Trieste, Trieste, Italy; [3]IRA-INAF, Bologna, Italy;

Content

Gamma-ray searches from FRB sources with Fermi-LAT [Principe et al., 2023]

1. Gamma-ray expectations
2. Sample of selected Fast Radio Bursts
3. Fermi-LAT: analysis description and results
   - the periodic FRB 180916
   - all individual sources
   - stacking analysis
   - triplets photons counting analysis



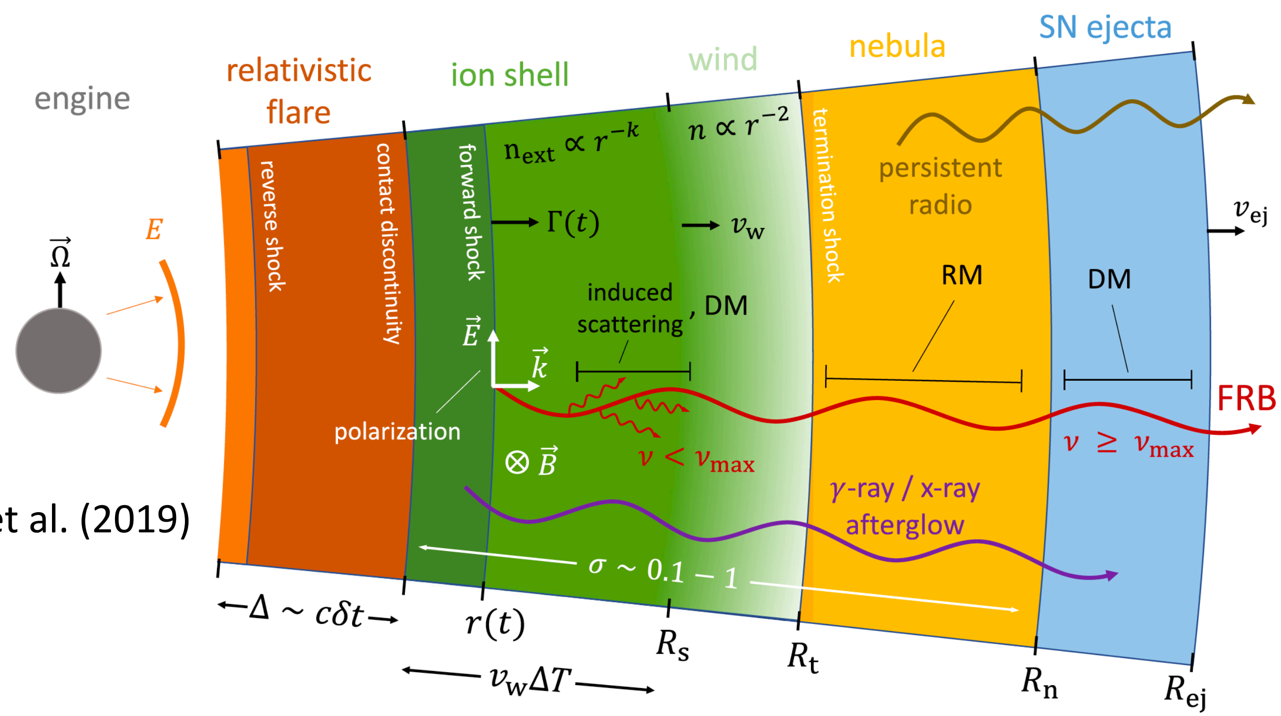
Gravitational Wave searches from FRB sources (a special focus on SGR 1935+2154) [LVK coll., 2024]

1. GW expectations
2. Previous GW searches during O3a [LVK et al, 2023]
3. SGR 1935+2154 events
4. GW (GEO 600) analysis description and results

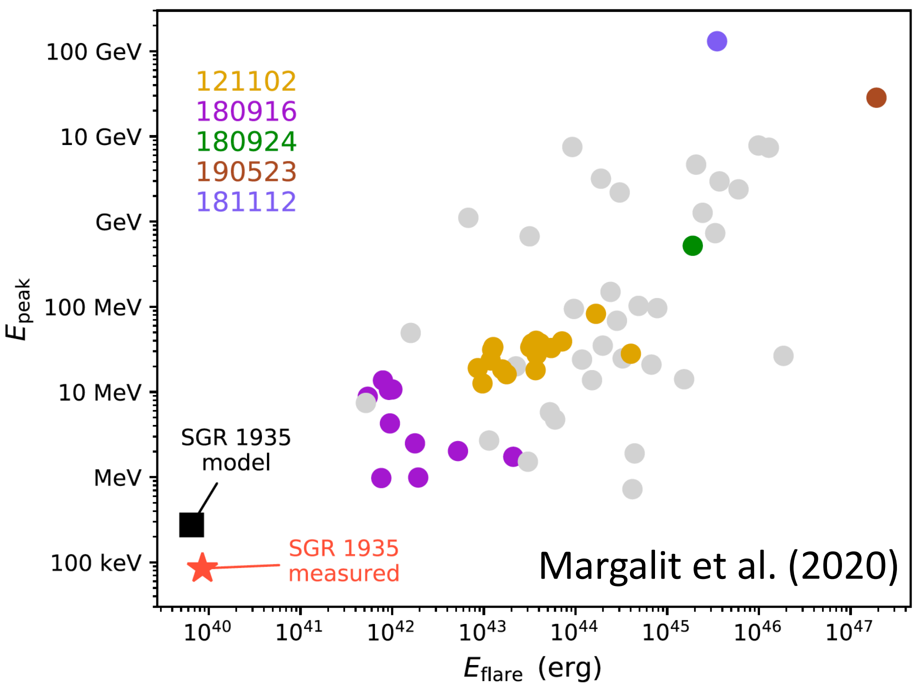
Summary

Gamma-ray expectations from FRB

Synchrotron maser emission from *decelerating relativistic blast waves (FRBs from magnetar origin)*



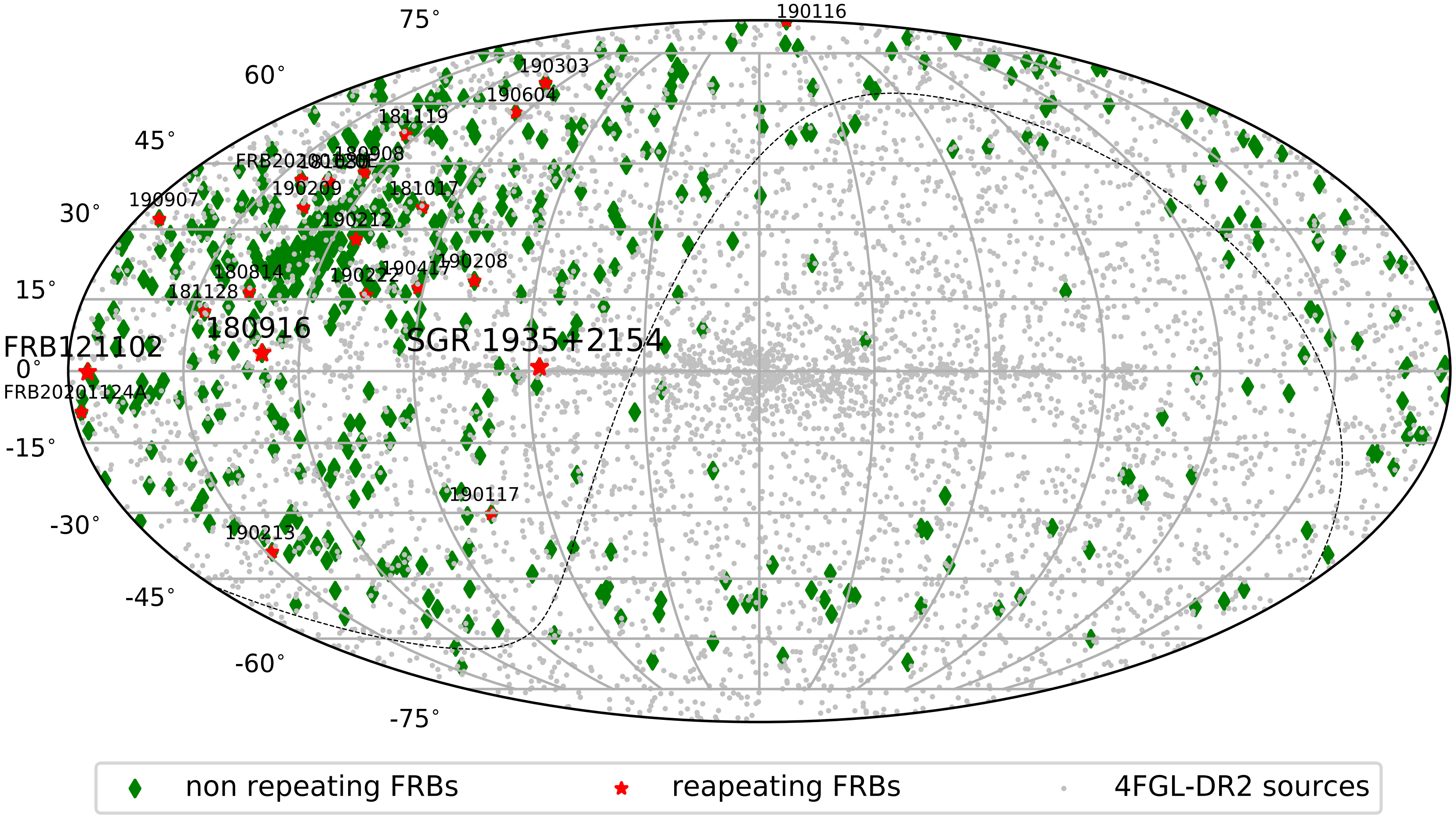
Metzger et al. (2019)

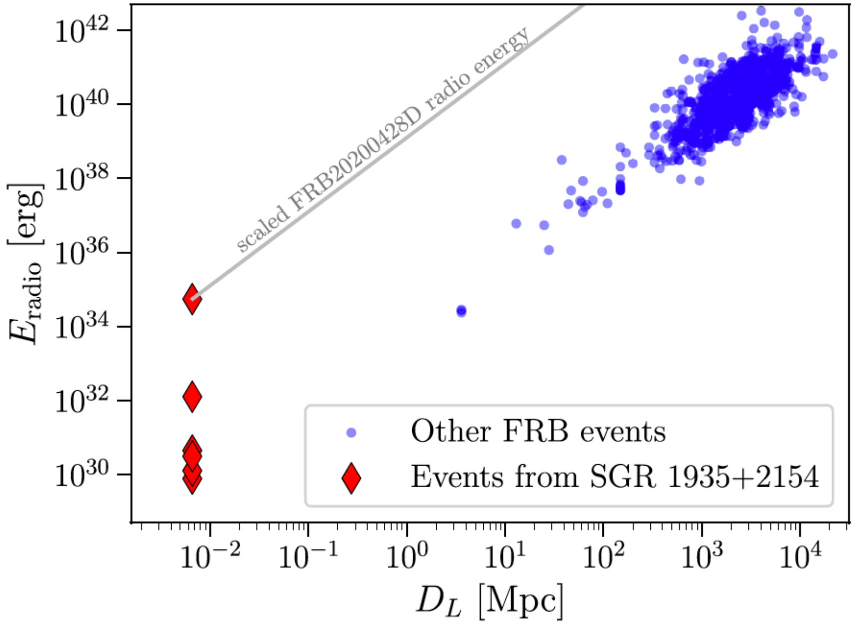


- Any FRB should be accompanied by **gamma-ray emission** with energy at least a factor $\boldsymbol{\eta \gtrsim 10^4}$ larger than the emitted radio energy [Margalit et al. (2020)]
- Predicted gamma-ray luminosities $\mathbf{L_\gamma \sim 10^{45}}$**–**$\mathbf{10^{46}}$ **erg s**$^{-1}$ on FRB time-scale (0.1–10 ms) [Metzger et al. (2019)]
- The detection of high GeV emission from a magnetar giant flare in the *Sculptor* galaxy also motivated the search for gamma-ray counterparts to the FRBs [Fermi-LAT coll., (2021)]

Searching gamma rays from FRB with Fermi-LAT

Thanks to over 13 years of Fermi-LAT data and to more than 1000 published FRBs (*1020 FRBs: 560 non repeating and 21 repeating ones presenting 465 events*), we aim to perform the largest and deepest systematic search for gamma-ray emission from all the reported repeating and non-repeating bursts.





Analysis description

Analysis plan:

1. Fermipy / Likelihood analysis on each individual FRB:
   - on time intervals ranging from 10 s up to 10000 s
2. Fermipy / Likelihood analysis on the repeating FRBs:
   - stacking analysis on 10s,100s,.. windows
   - analysis on 13yrs for a search of possible steady emission
3. Special attention is given to the periodic FRB 180916:
   - *folding analysis* on the 0.6d (5.4d) phase windows on 13yrs
4. Stacking analysis for all the FRBs
5. triplets photon counting analysis to study the coincidence of triplet events with the time and position of the FRBs in our sample.

Data Selection	Values
IRFs	P8R3_SOURCE_v3
PSF Classes	All , [no PSF0 and PSF1, E < 300 MeV] [no PSF0, 300 MeV < E < 1 GeV]
Time Intervals	**10 s / 100 s/ 1000 s /… / years**
Energy Range	100 MeV (1 GeV) – 1 TeV
Zenith angle	< 105°/ [< 85°, E < 300 MeV] / [< 95°, 300 MeV < E < 1 GeV]
Pixel Size	0.1°

Diffuse models: galdiff (gll_iem_v07.fits), isodiff: (iso_P8R3_SOURCE_V3_v1.tx)
Model for the Fermi-LAT extend sources: LAT_extended_sources_10years.fits
Catalog: 4FGL-DR2 (gll_psc_v27.fit)

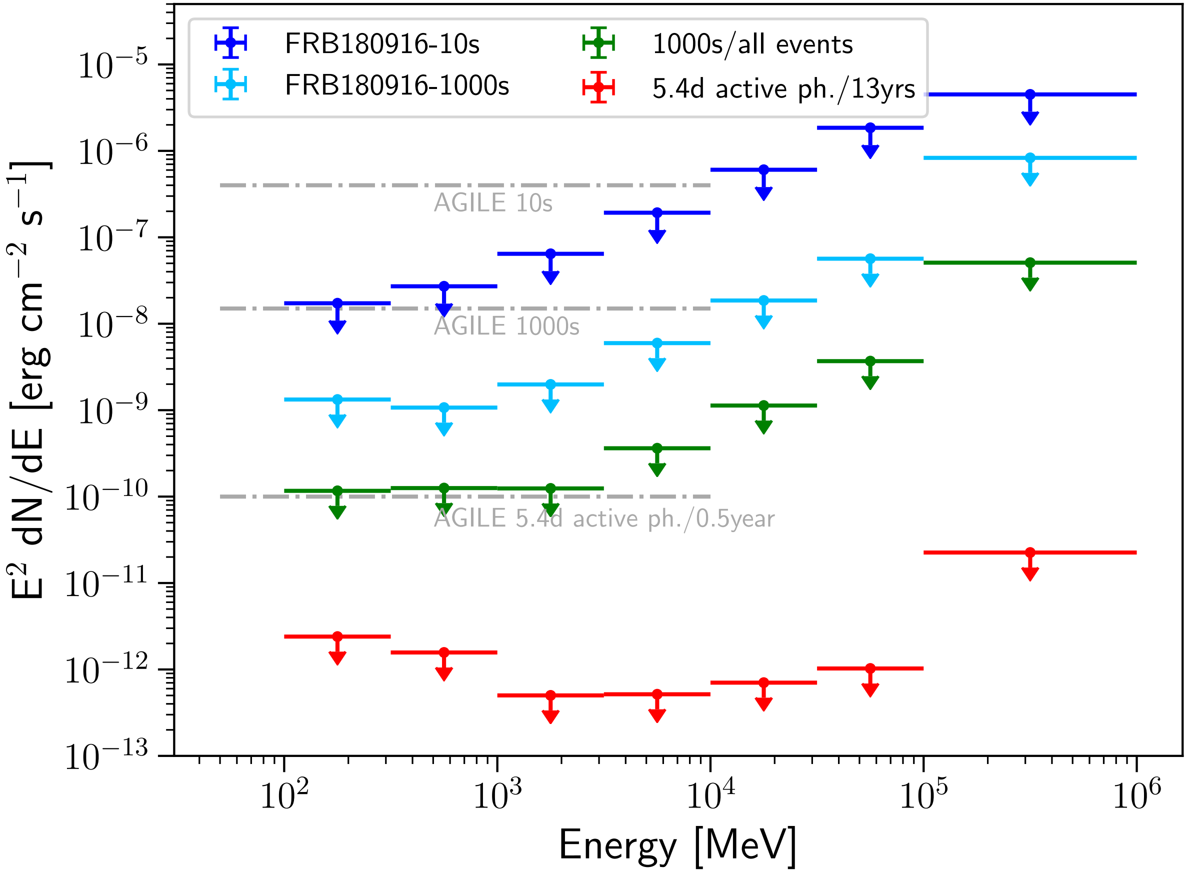
The periodic FRB 180916

We search for high-energy emission from the periodic FRB 180916 (z=0.0337) with Fermi-LAT.
We analysed LAT data:

- 10 s and 1000 s time intervals centred on the first observed burst (MJD=58377.42972096).
- 73 detected bursts using time intervals of 1000 s centred on each event, as well as on the 5.4-day active phase windows of the periodic FRB, using 13 years of available LAT data.

We did not find any significant gamma-ray emission from the periodic FRB 180916. We report 95% upper limits on the FRB energy flux above 100 MeV:

- 10 s: $F < 7.8 \times 10^{-8}$ erg cm^{-2} s^{-1}
- 1000 s: $F < 1.4 \times 10^{-9}$ erg cm^{-2} s^{-1}
- folding 1000 s: $F < 1.7 \times 10^{-10}$ erg cm^{-2} s^{-1}
- 5.4-d active phase: $F < 2.1 \times 10^{-12}$ erg cm^{-2} s^{-1}

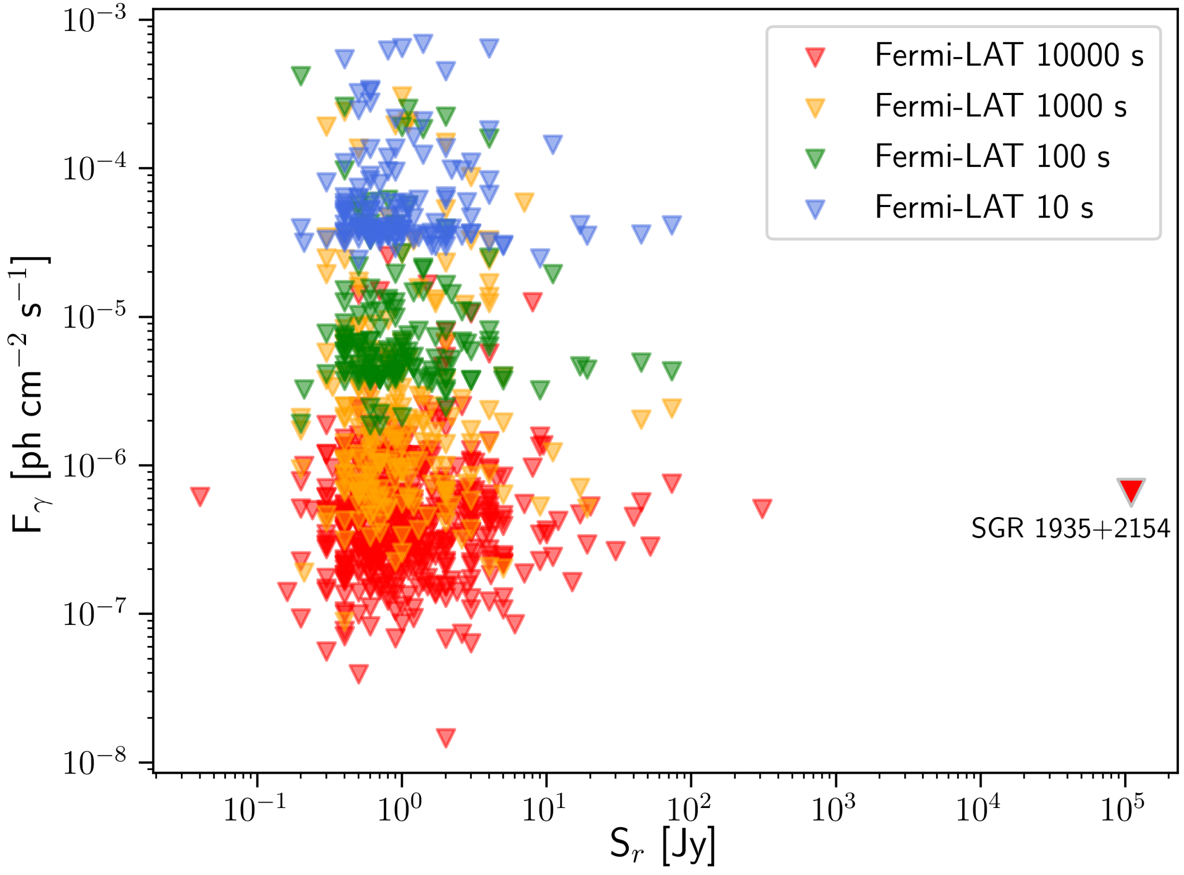


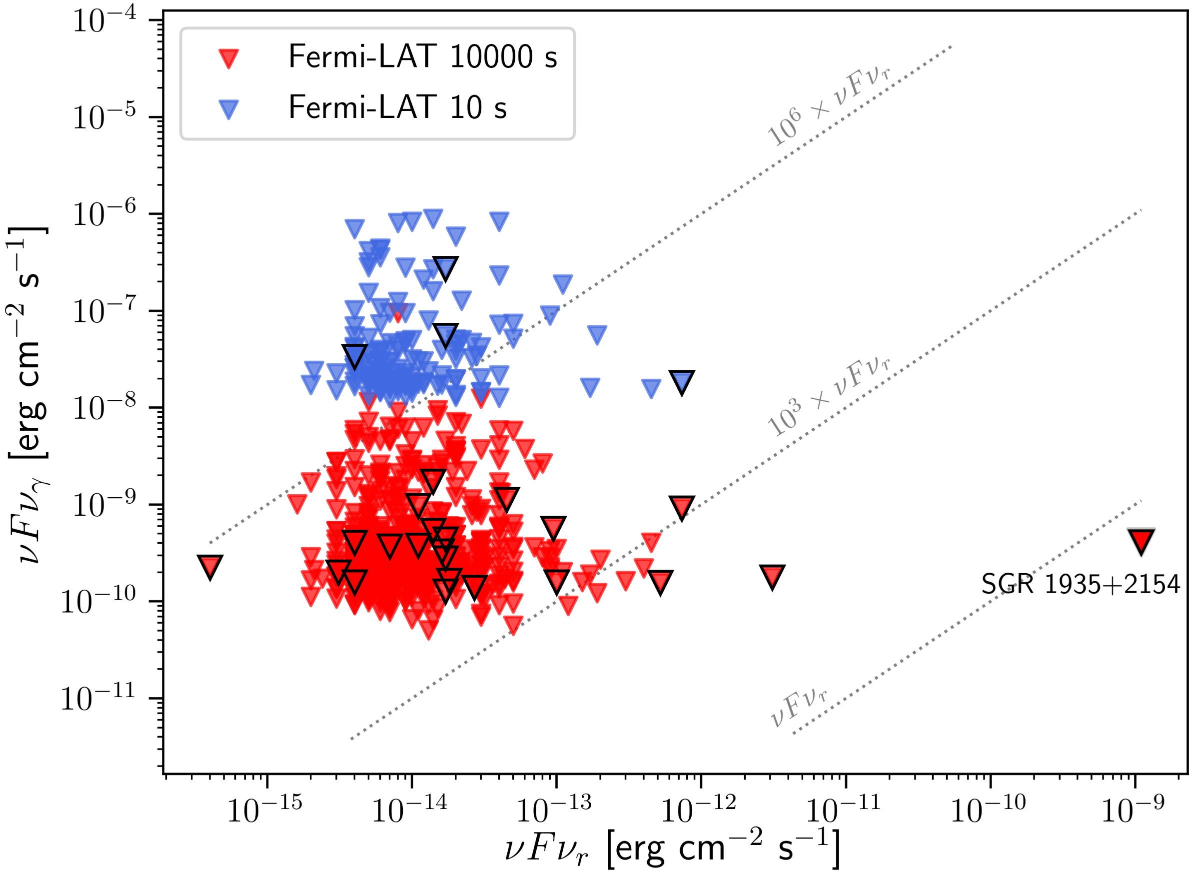
Individual limits on flux and energy flux

Flux

Energy flux

Gamma-ray UL



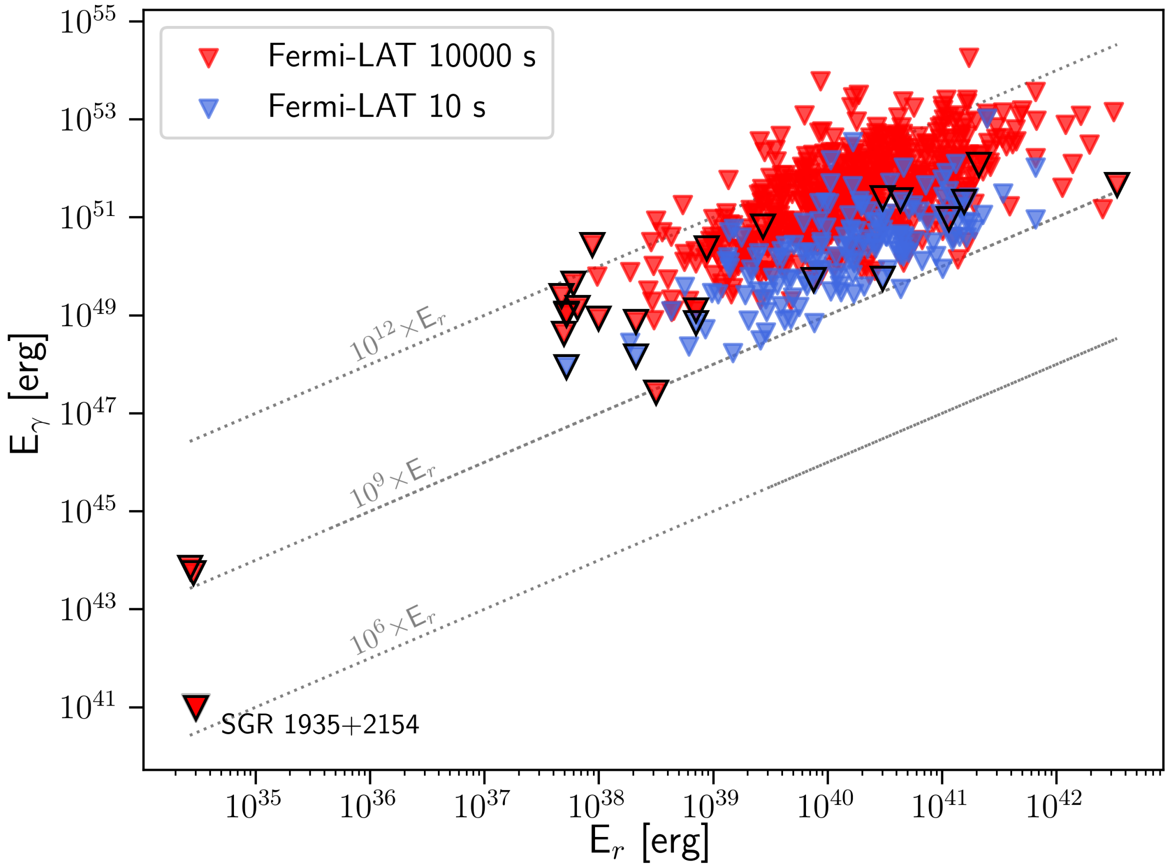


Radio emission

Radio emission

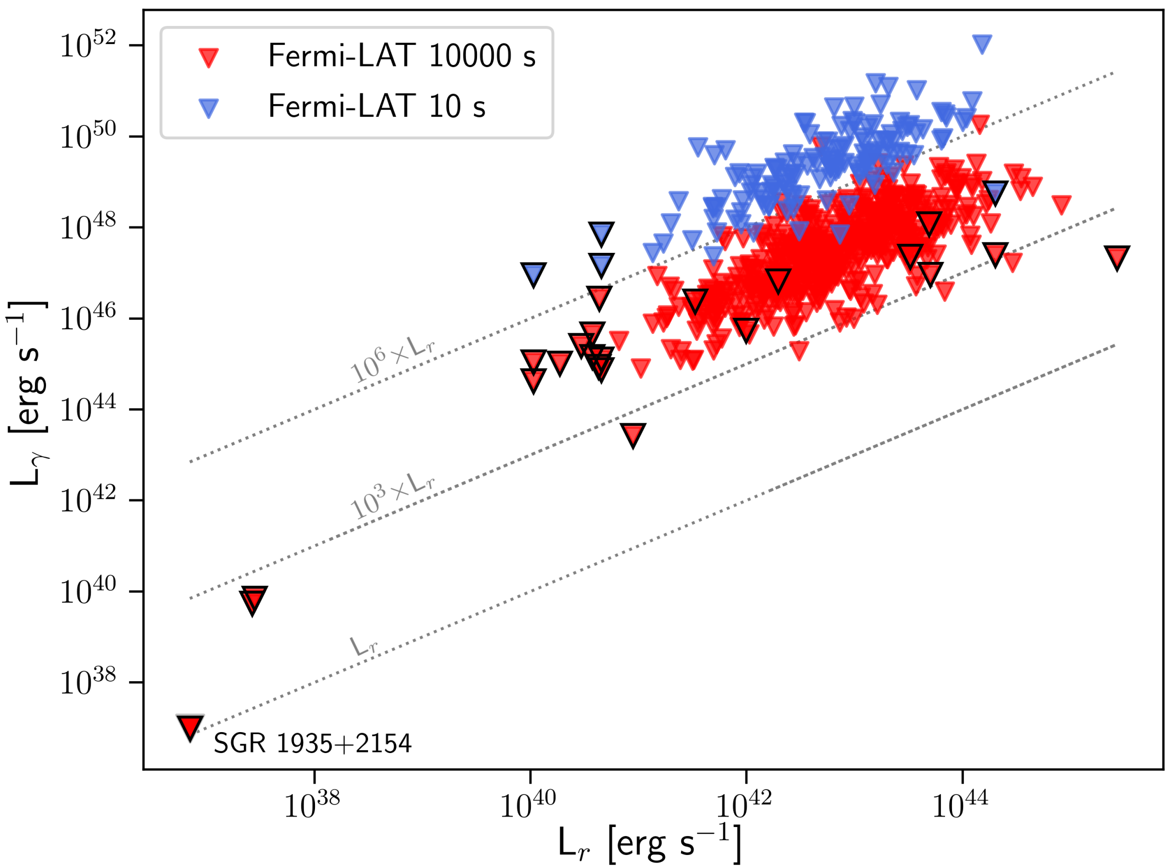
Limits on Energy and Luminosity

Energy



Predicted gamma-ray emission with energy $\eta \gtrsim 10^4$ larger than the emitted radio energy (Margalit et al. 2020)

Luminosity



Predicted gamma-ray luminosity $L_\gamma \sim 10^{45}$–10^{46} erg s^{-1} on ms time-scale (Metzger et al. 2019)

Stacking on all individual FRBs

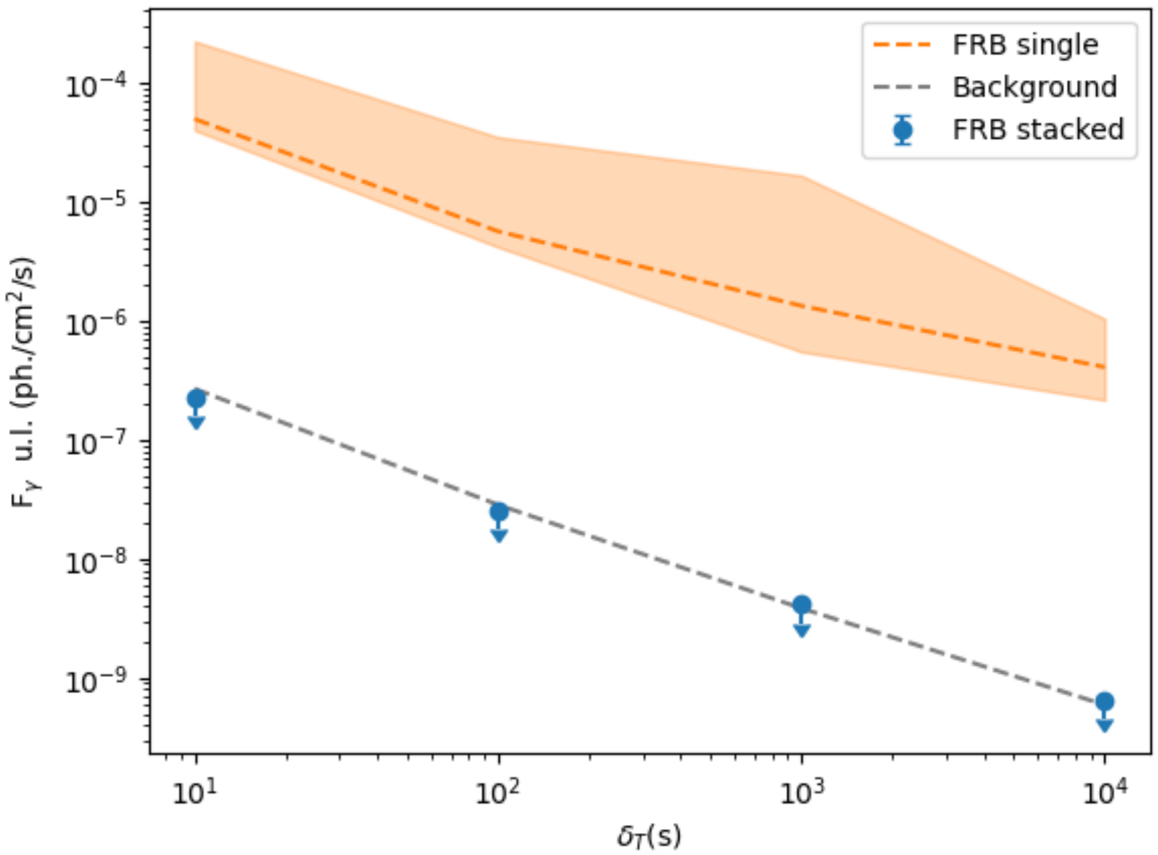
Stacking method tested in: *Principe et al. 2021*

We do not find any significant emission from each individual FRBs.
-> UL provided strongly depends on the exposure to each FRBs events region.

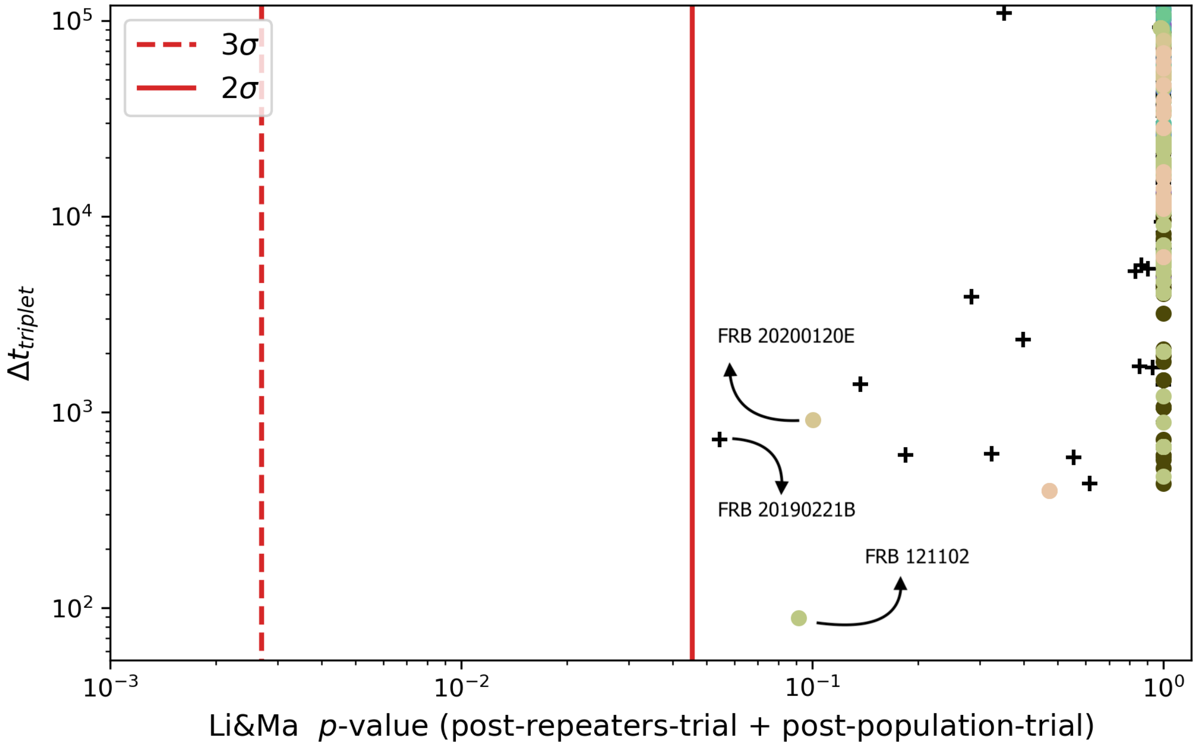
We performed the first stacking analysis on all the analysed FRB events (1020 events).

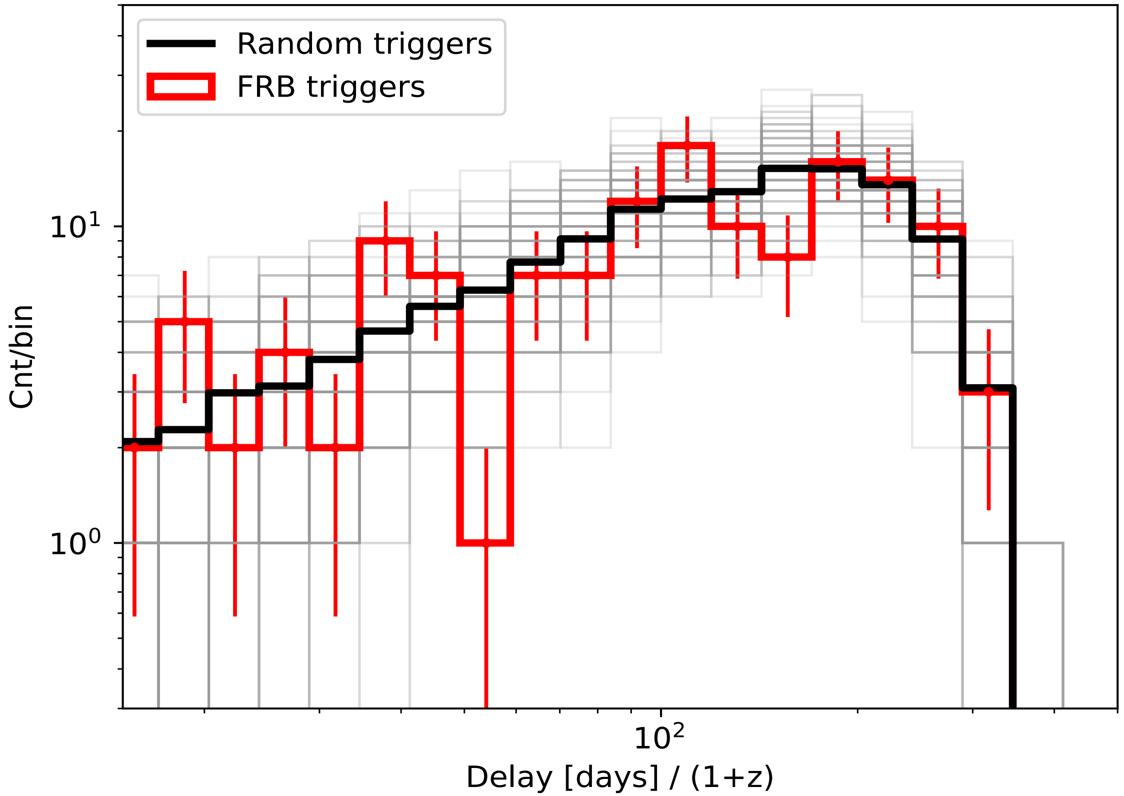
No significant emission has been detected also for the stacking analysis.

This provides the most stringent UL on the gamma-ray emission from a sample of FRBs.



Individual and Triplet photon counting analysis





No significant triplet events found. The most significant FRB is the non-repeating event FRB 20190221B with a Li&Ma p-value of 0.055 (~2σ).

Most significant triplet delay distribution

UL on individual photons study

$$L_{\gamma,\delta_T=1\mathrm{ms}} \lesssim 10^{50} \left(\frac{\mathrm{D}_L}{150\,\mathrm{Mpc}}\right)^2 \mathrm{erg\,s^{-1}}$$

Summary gamma-ray searches

We perform the largest and deepest systematic search of gamma-ray emission from FRBs using a sample of 1020 burst events and 13 years of Fermi-LAT data.

Results

- No significant emission has been found in the 10, 100, 1000 and 10000 s analyses
- We provide the so-far most stringent upper limits on the gamma-ray emission from the FRB 180916 source during its 5.4-day active-phase window ($F_{\gamma\text{-ray}} < 2.3 \times 10^{-12}$ erg cm^{-2} s^{-1}, $L_{\gamma\text{-ray}} < 7.5 \times 10^{42}$ erg s^{-1}).
- Constraints on gamma-ray luminosity and energy on individual FRBs
- First stacking analysis on a large sample of FRBs, no significant emission found:
    - resulting ULs are on average more than two orders of magnitude smaller than those on single events.
- Triplets photon counting analysis indicate no significant cluster of photons close in time with FRB events.
- We also investigated a possible delay possibly connected to the FRB distance.

Our results provide crucial information on constraining the origin of FRBs and modelling their emission mechanisms.

Gravitational wave expectations from FRB

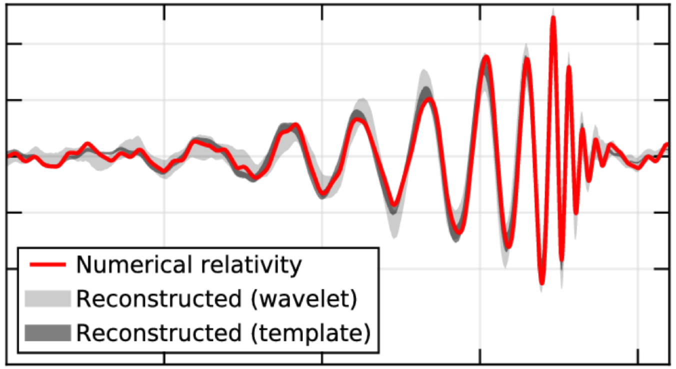
- Most GW-relevant models are for **Compact Binary Coalescences**
  - merging of compact (BH or NS) objects

  (which is not the case for repeating FRBs or SGR 1935+2154)
- **Magnetar GW models**
  - from *quasi-periodic oscillations, crustal f-modes* (around 2 kHz)

    [Levin & van Hoven 2011, Quitzow-James et al. 2017, Glampedakis & Gualtieri 2018, Ho+ 2020]
  - SGR 1935+2154 confirms the magnetar association for at least some FRBs
- **Neutron star glitches** (< 10^{45} erg GW emission) [*Prix+ 2011, Abadie+ 2011*]

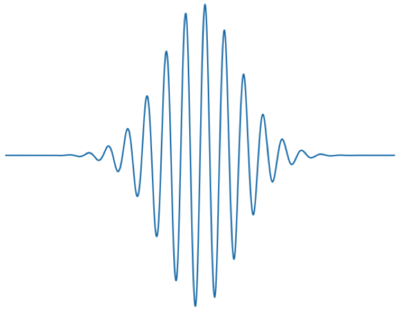
Gravitational wave searches during O3a

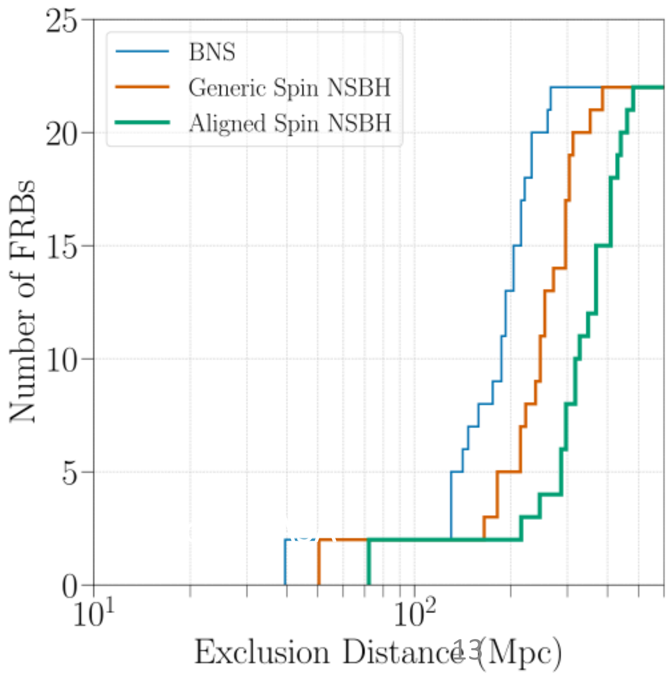
[*LVK 2023 ApJ* ***955*** *155*]



Based on 22 (40) FRB events during O3a (April 1 – October 1, 2019)

- [PyGRB] **matched-filtering analysis**
  - on 22 non repeating FRB events
  - search window [-10, 2] s
  - search for CBC (BNS, NSBH, BBH) signals [0.001 - 10] s
- [X-Pipeline] **generic transient searches analysis**
  - on 40 FRB events
  - search window [-120, 120] s
  - search for burst events [0.3 - 300] ms



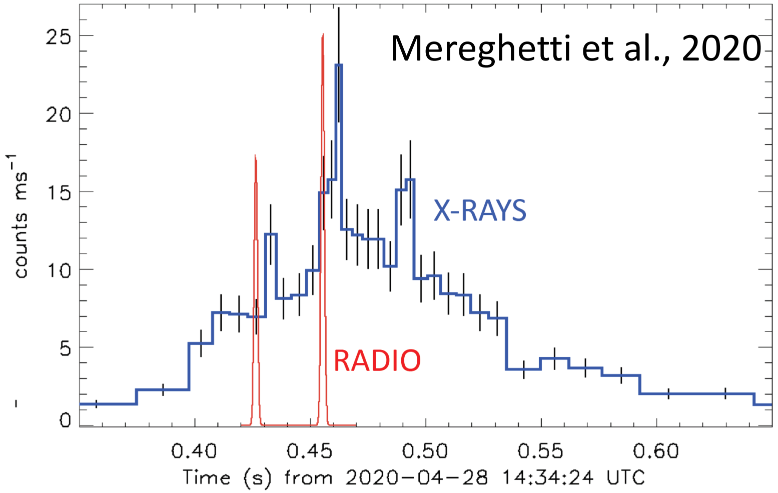


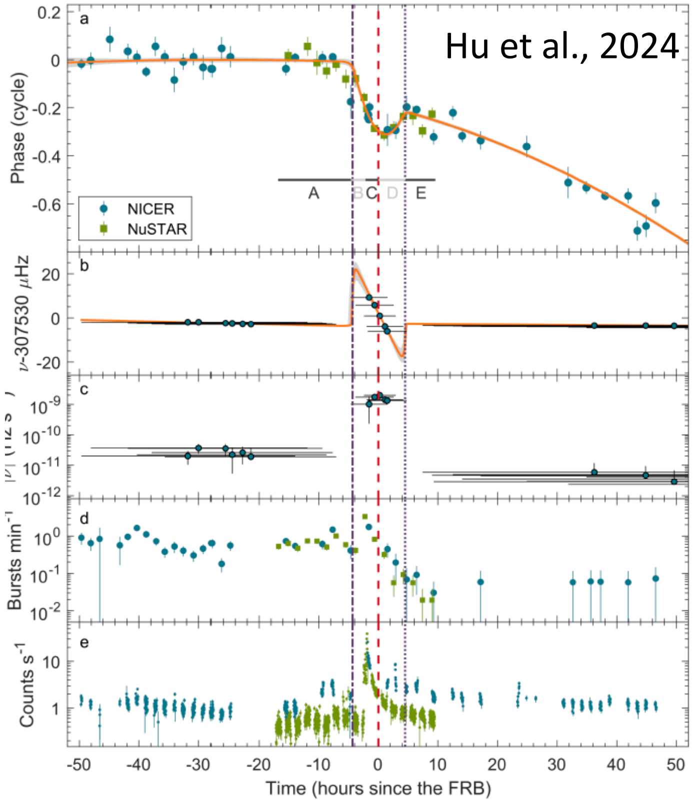
No GW detected

- Best UL: emitted GW energy < 10^{54} erg at 2 kHz (< 10^{52} erg at 300 Hz)

Selected SGR 1935+2154 events

Perform searches for the 4 FRBs, and 3 X-ray events





April 28, 2020
First event!
CHIME/FRB + STARE2 + X-ray

First observation of simultaneous FRB + X-ray

October 8, 2020
CHIME/FRB and Green Bank Telescope

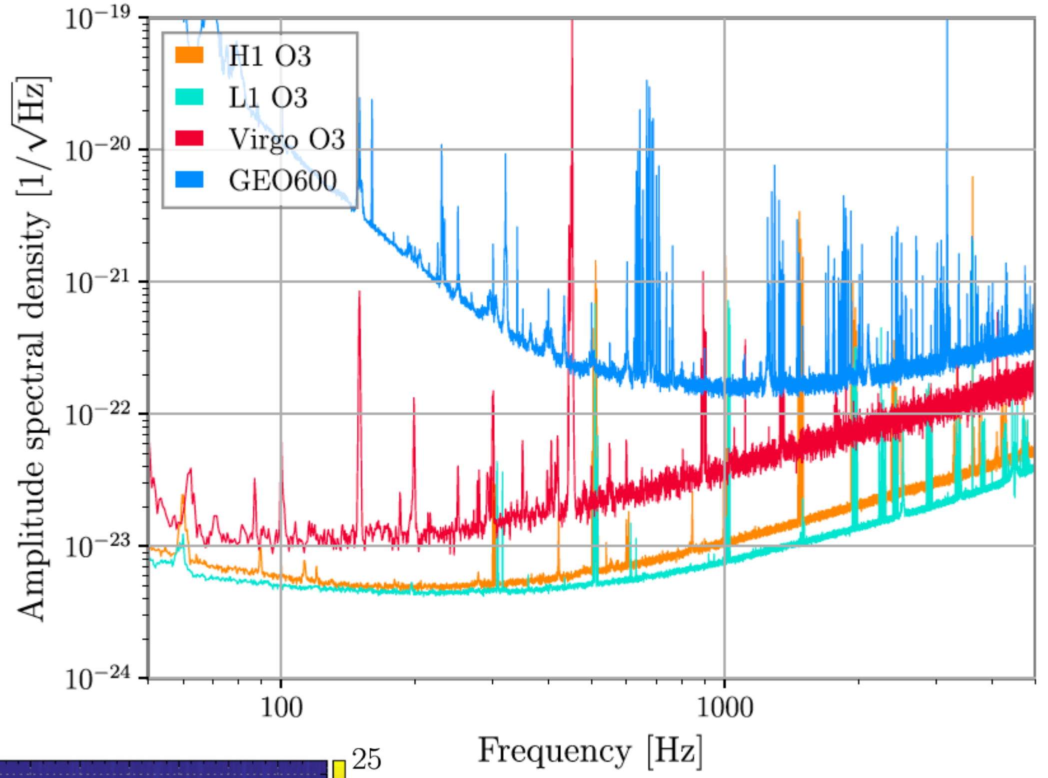
October 14, 2022
CHIME/FRB

Two *X-ray spin-up glitches* (~4 hours before/after FRB), one *X-ray burst peak* (2.5 hours before)

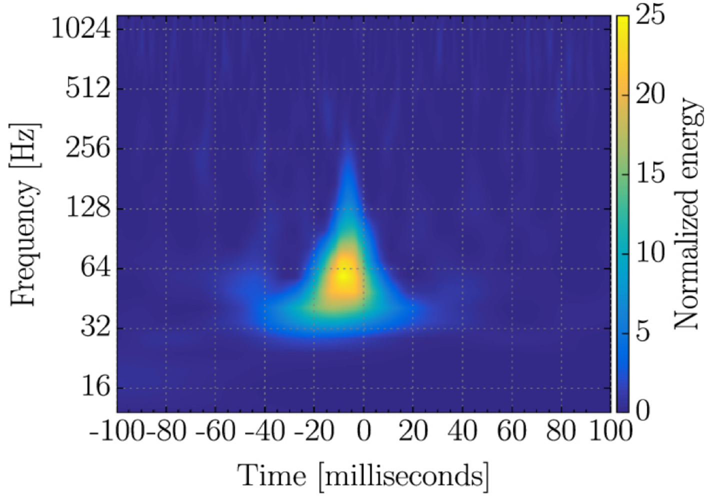
December 1, 2022
CHIME/FRB

GW searches from SGR 1935+2154

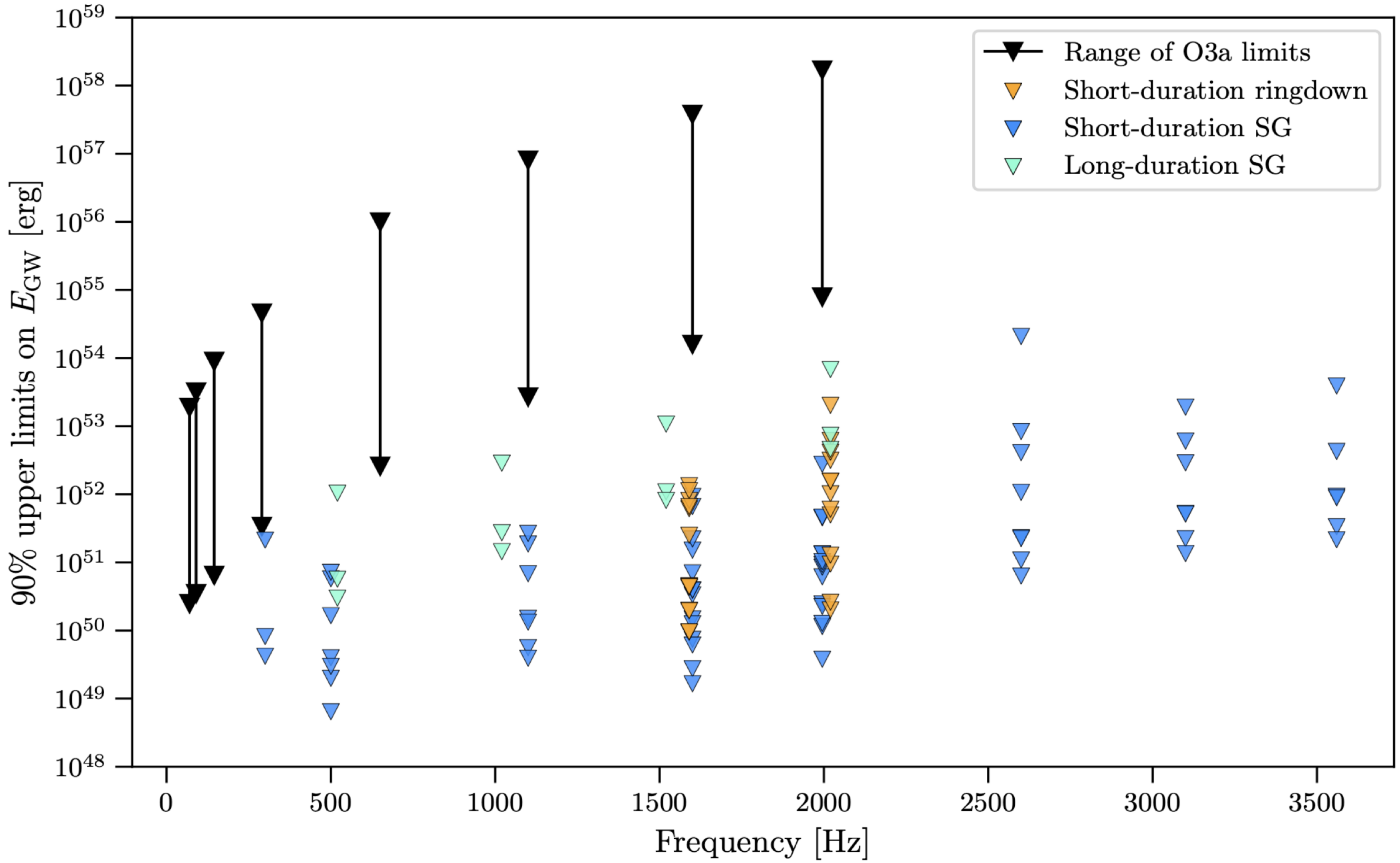
GEO600
- 600m arms GW interferomenter built in Hanover, Germany
- *Astrowatch* mode,
- <u>online between O3 and O4</u>
- 1 Mpc BNS range
  - LIGO ~ 160 Mpc
  - But only 1.5 orders of magnitude worse at 1-2 kHz compared to LIGOs



We searched for generic / burst GW events
(Finds candidates from clustered time-frequency maps – excess power)
- PySTAMP:
  - long-duration signals (1-10 s)
  - search window [-1200, 120] s
- X-Pipeline:
  - short-duration signals (<1 s)
  - search window [-4,4] s / [-1200, 120] s

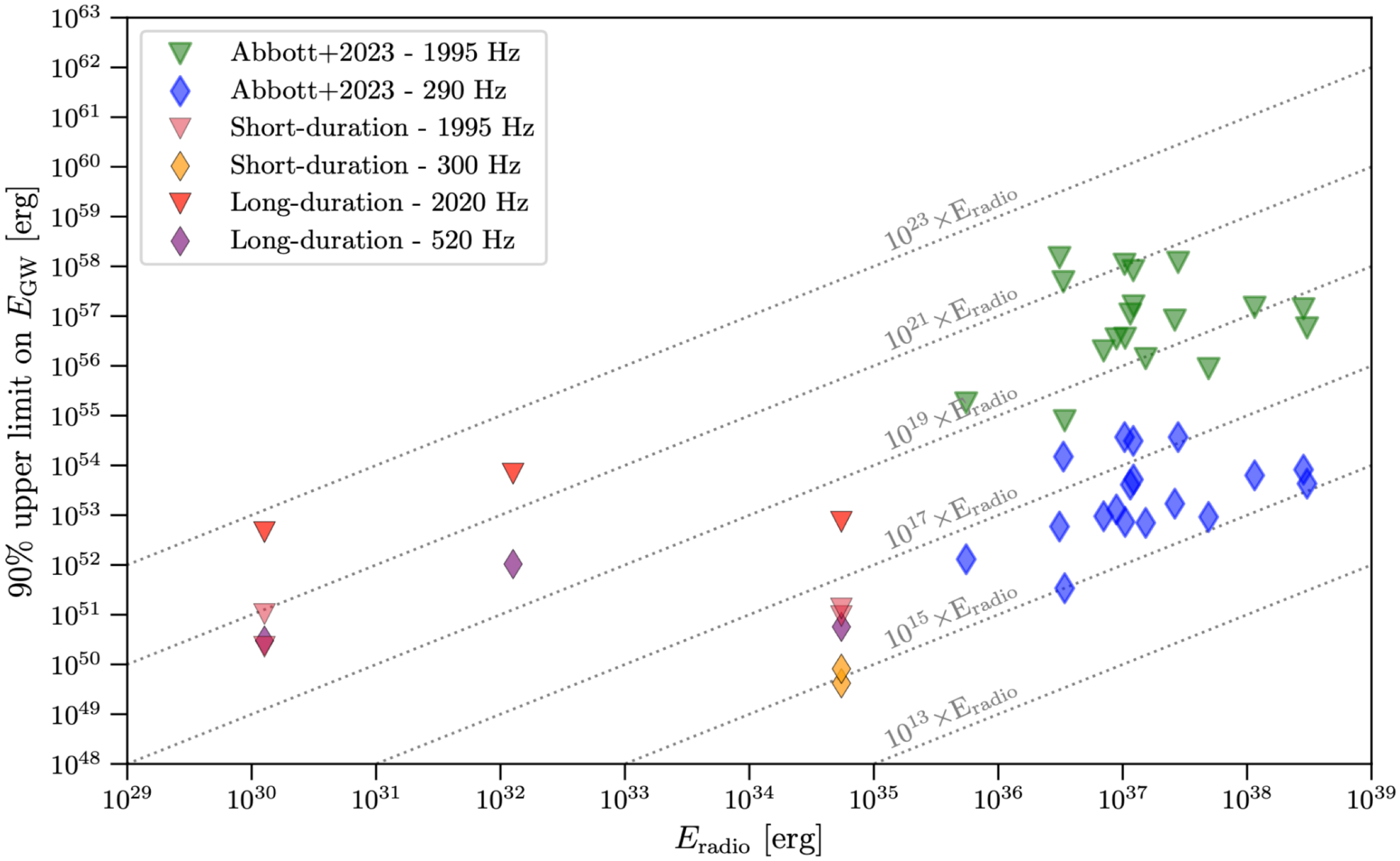


UL on the emitted GW energy



- Best limits on FRB emission coincident with GWs
- Improvement of 5 orders of magnitude near f-mode (~2 kHz)

UL on the GW/radio energy ratio



- Best limits on E_{GW} / E_{radio}
- Smaller improvement than in just E_{GW}, since SGR 1935 FRBs are weaker

Summary GW searches

- First systematic search for GW emision from FRBs during O3a [LVK et al, 2023]

SGR 1935+2154 – GEO 600 [LVK coll., 2024]

- Best GW + FRB constraints! (Distance matters: $E_{\mathrm{GW}} \propto D_L^2$)
- First long-duration GW constraints on FRBs
- Not the most constraining on magnetars SGR 1935+2154
  - Magnetar search with LIGO UL~10^{47} erg (
- Single detector limits background trials + sensitivity

Outlook

- LVK FRB O3b paper will be submitted soon to ApJ
- Currently working on the O4 FRB project

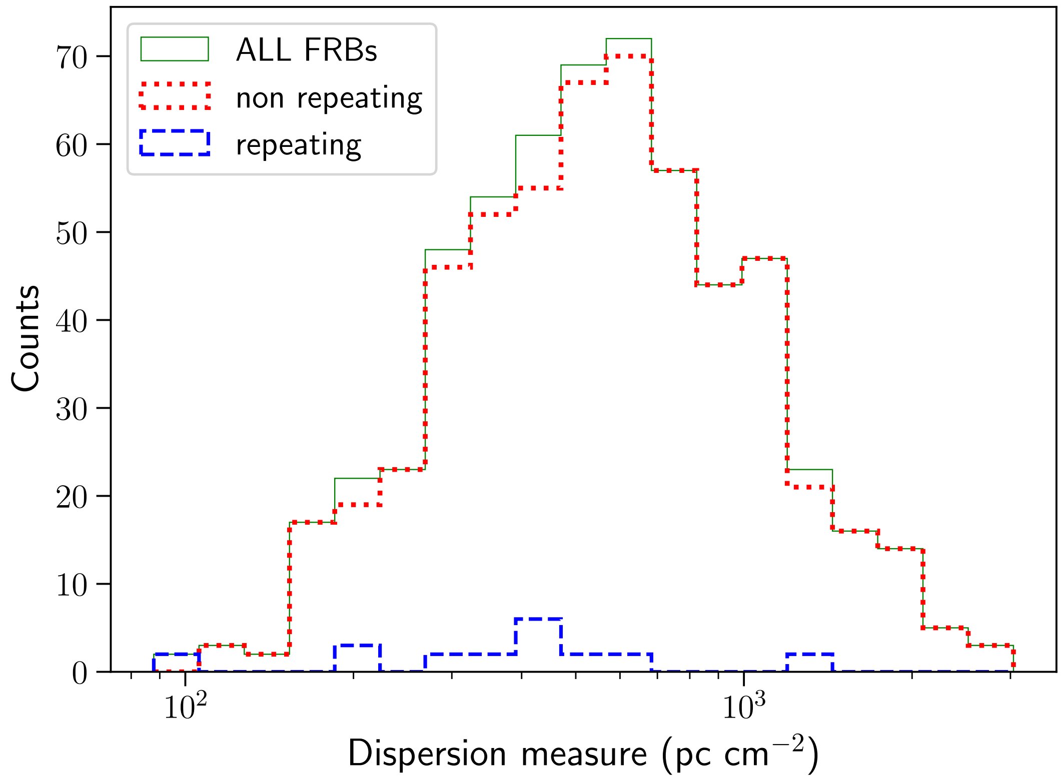
Thanks for your attention!

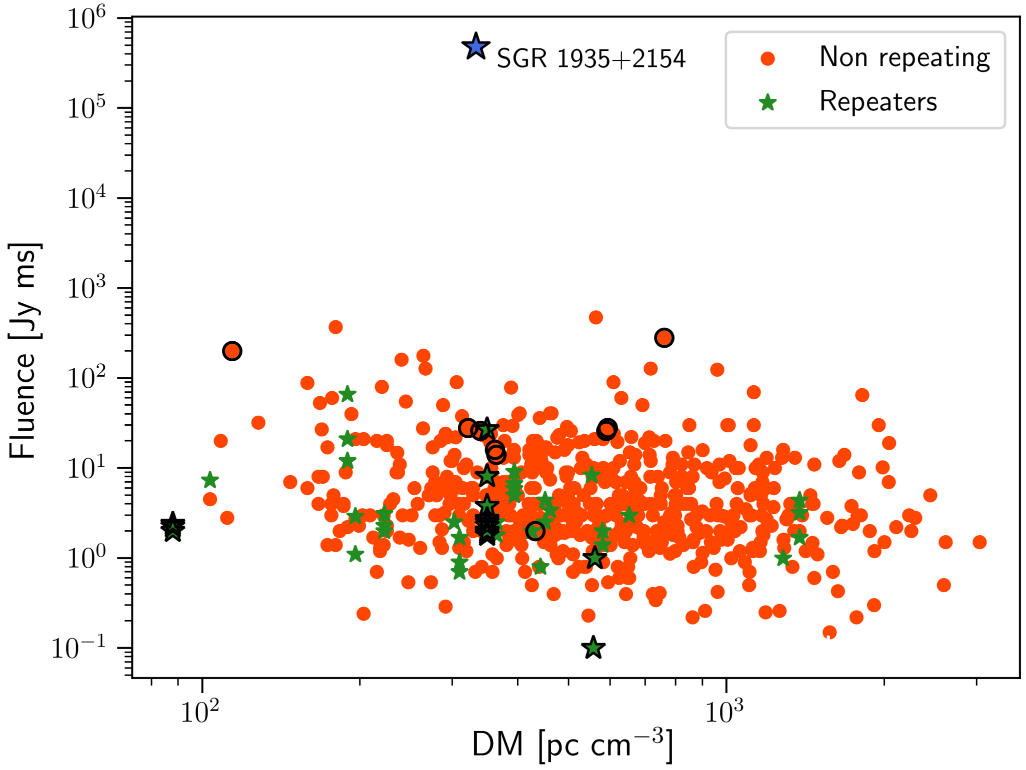
Backup slides

FRB Sample

Our sample consists of **1020 FRBs** (560 non repeating and 21 repeating ones presenting 465 events) selected from the following resources:

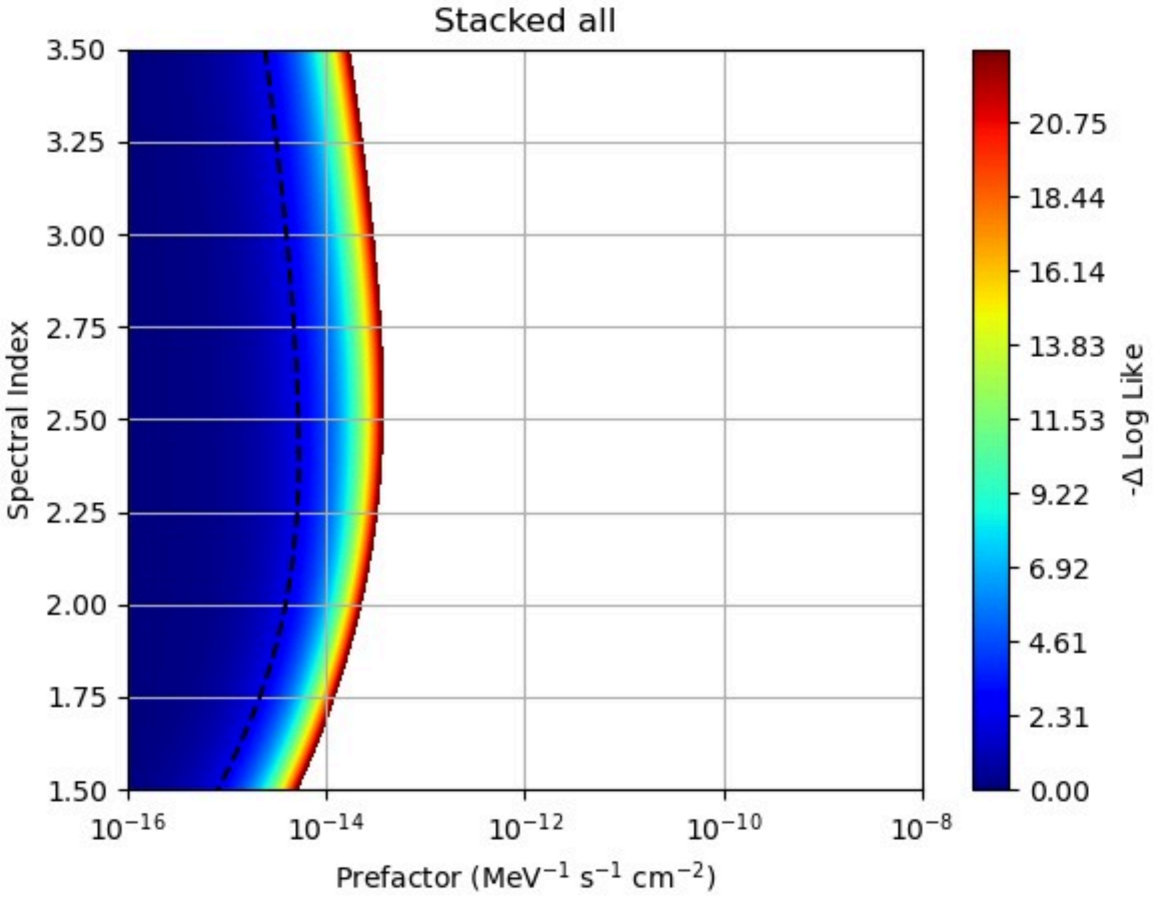
- 535 repeating and non-repeating FRBs reported in the first CHIME/FRB catalog;
- 230 bursts from 20 repeating FRBs reported by the CHIME/FRB collaboration (http://www.chime-frb.ca/repeaters) as of June 15, 2021, including 73 bursts from the periodic FRB 180916;
- 235 bursts from FRB 121102 collected by Rajwade et al. 2021.
- 118 events from the FRBCAT (Petroff. et al. 2016);

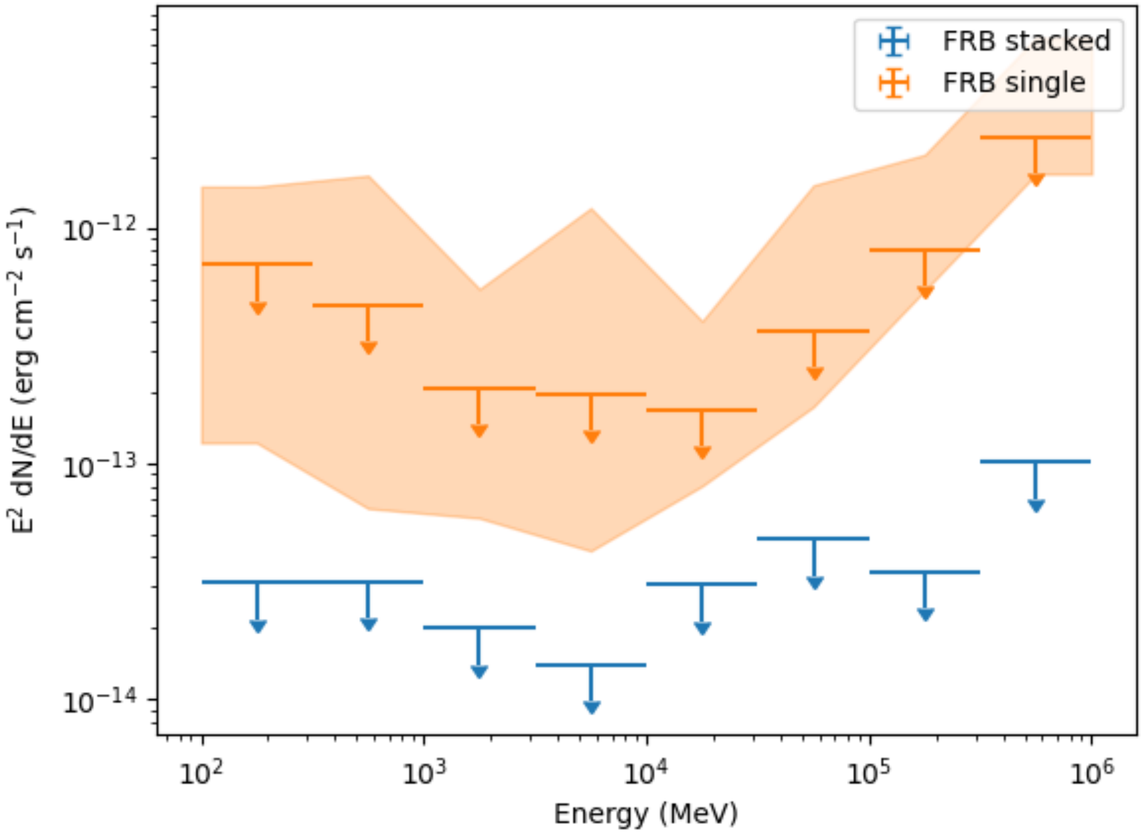




Stacking on repeating sources

21 repeating FRBs, analysed over 13 years

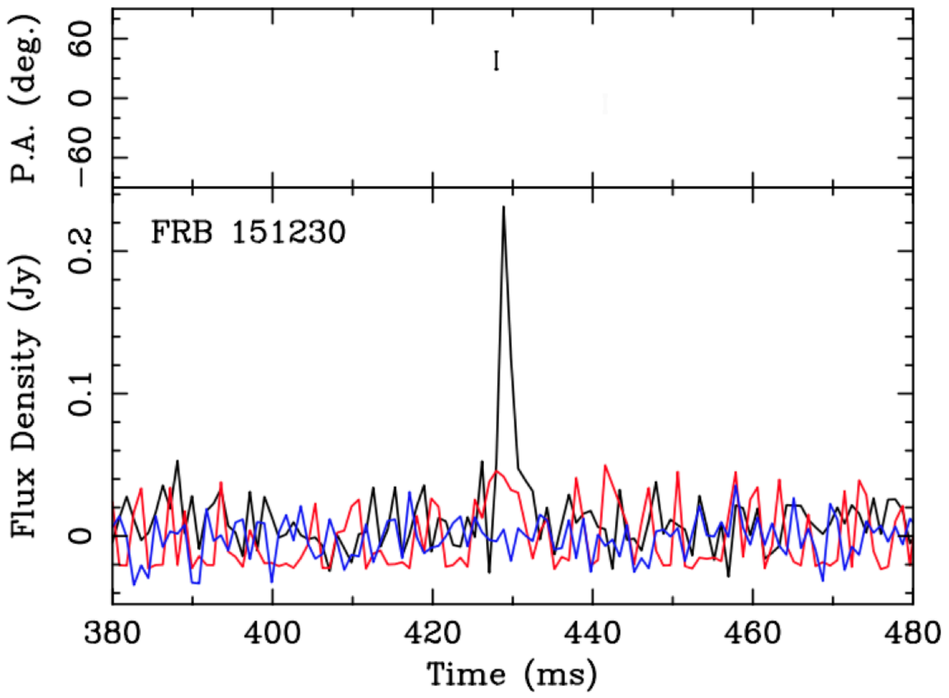




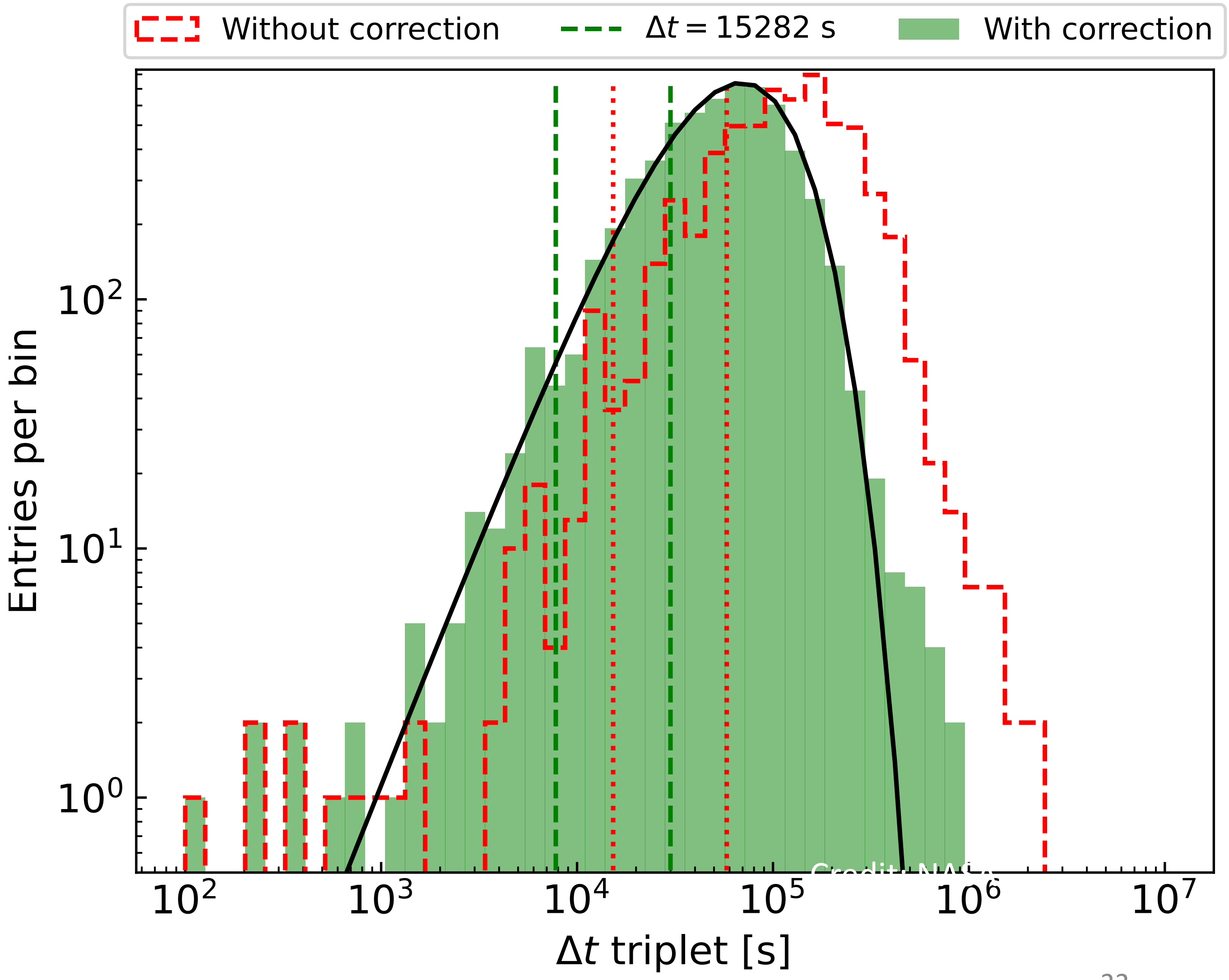
TS = 0.24   Flux (>100 MeV) UL = 9.3e-11 ph/cm2/s

Triplet photon counting analysis – FRBs results

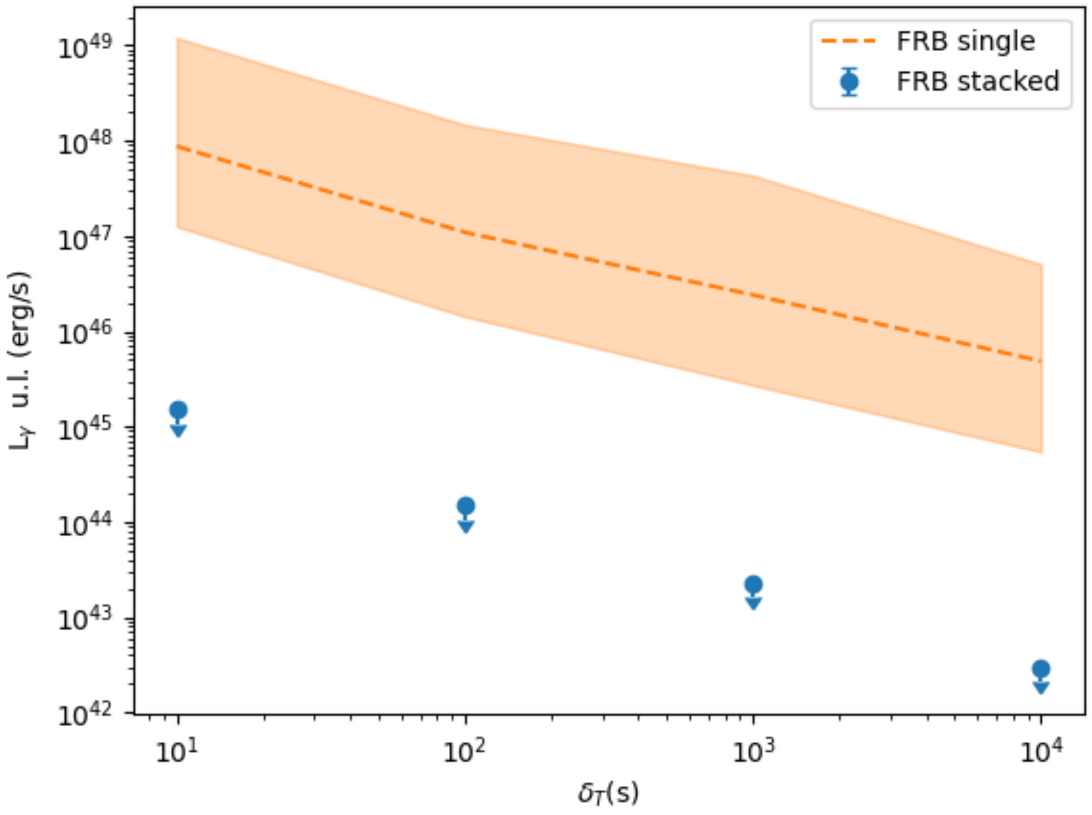
Example on individual FRB:
FRB151230:
- Repeater (two events seen)
- with linear polarized emission

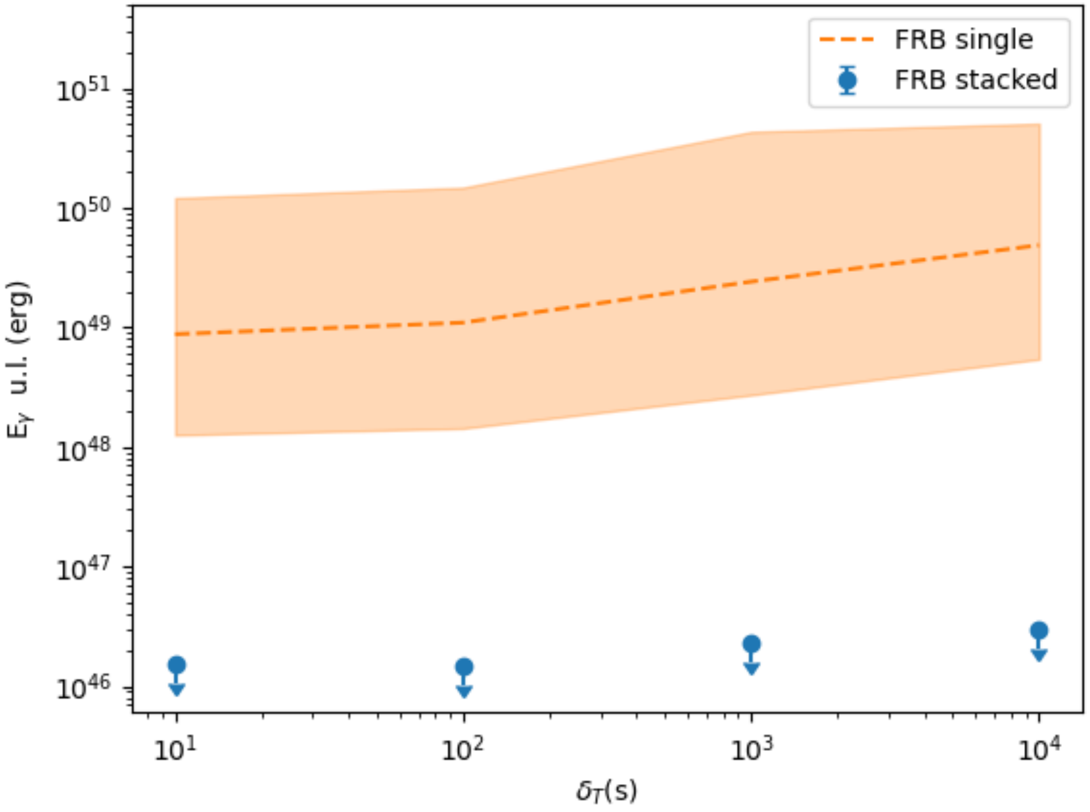


Caleb et al. (2018)



Stacking on luminosity and energy





LAT sensitivity on ms timescale

$$L_{\gamma,\delta_T=1\mathrm{ms}} \lesssim 10^{50} \left(\frac{\mathrm{D}_L}{150\,\mathrm{Mpc}}\right)^2 \mathrm{erg\,s}^{-1}$$