New Constraints on Short GRBs and Their Host Galaxies

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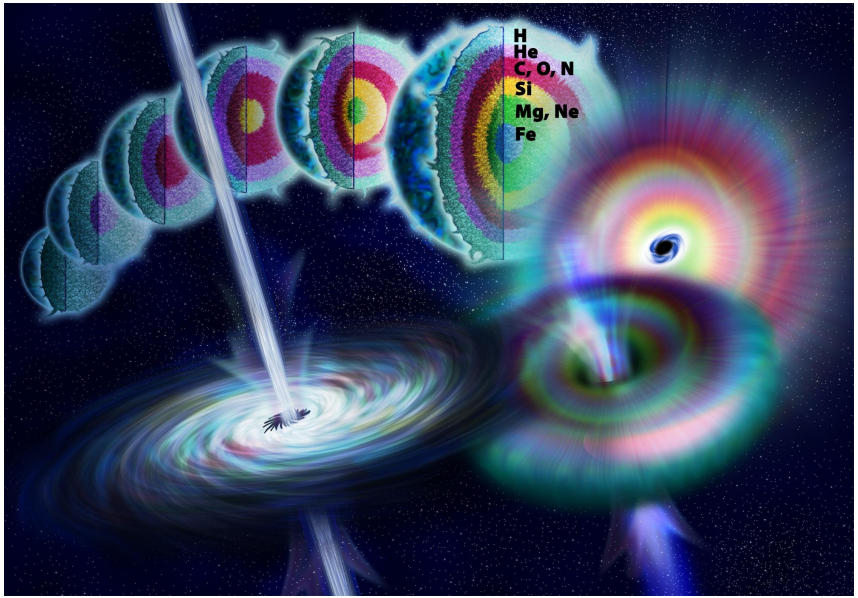
What are Gamma Ray Bursts? (GRBs)



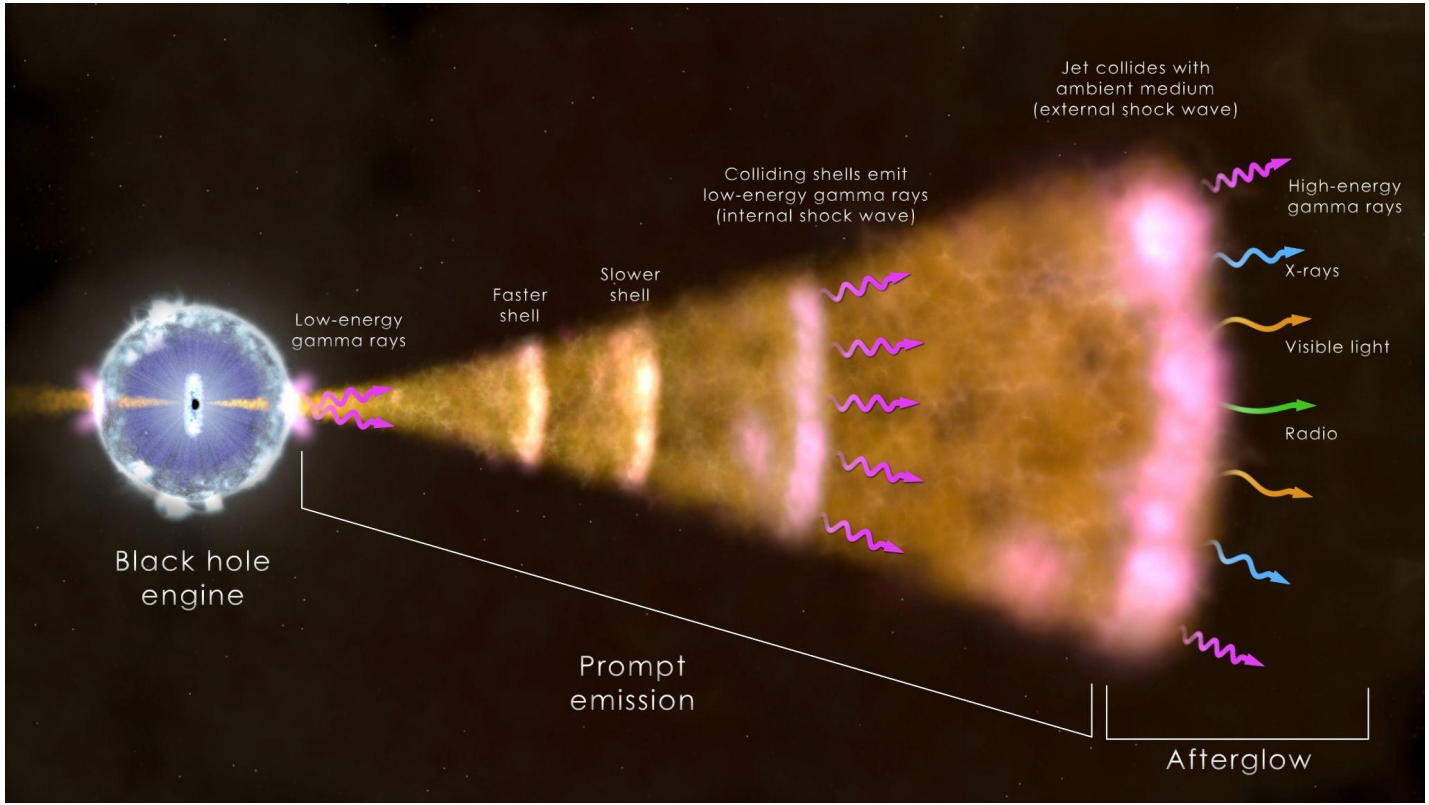
Long GRBs

Credit: National Science Foundation Press Release 05-156: Gamma-Ray Burst Smashes a Record

Short GRBs

Credit: NASA/Swift/Dana Berry

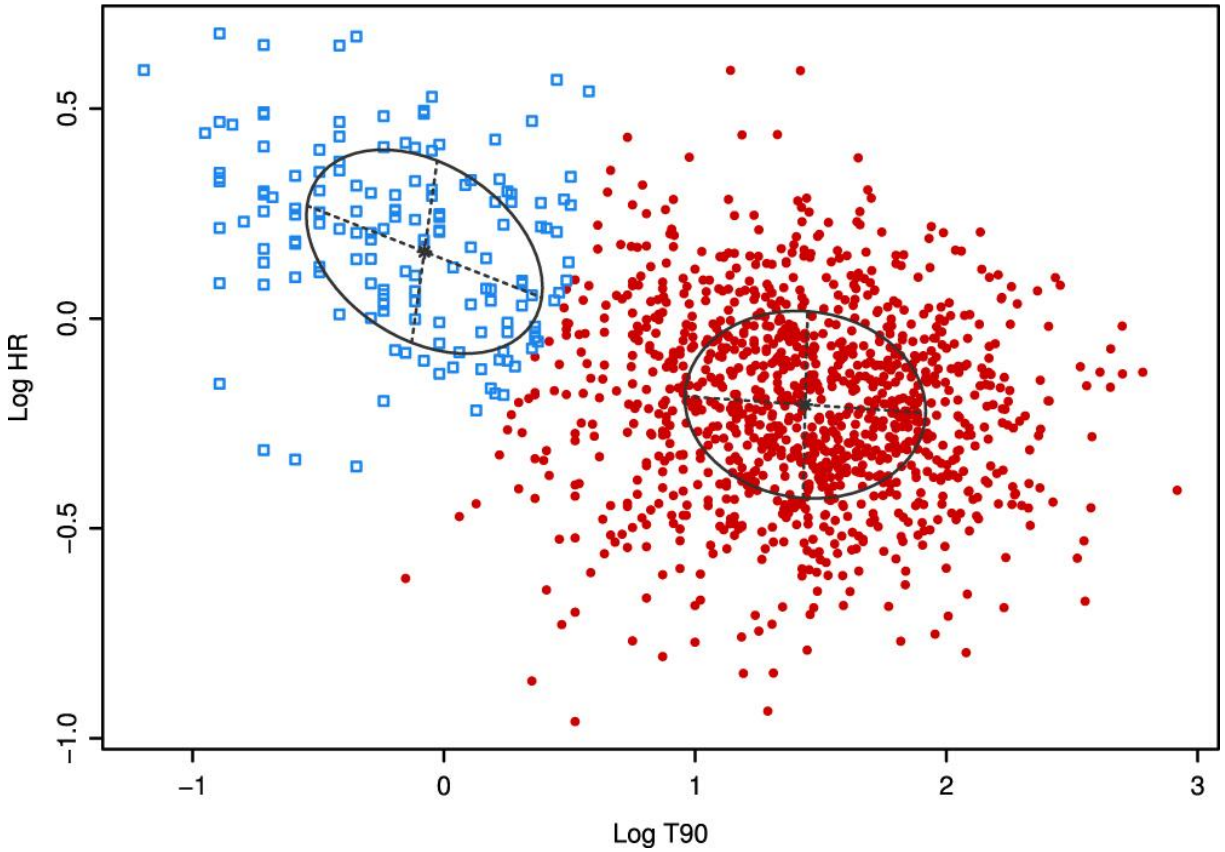
What are Gamma Ray Bursts? (GRBs)



Credit: NASA's Goddard Space Flight Center

What are Gamma Ray Bursts? (GRBs)

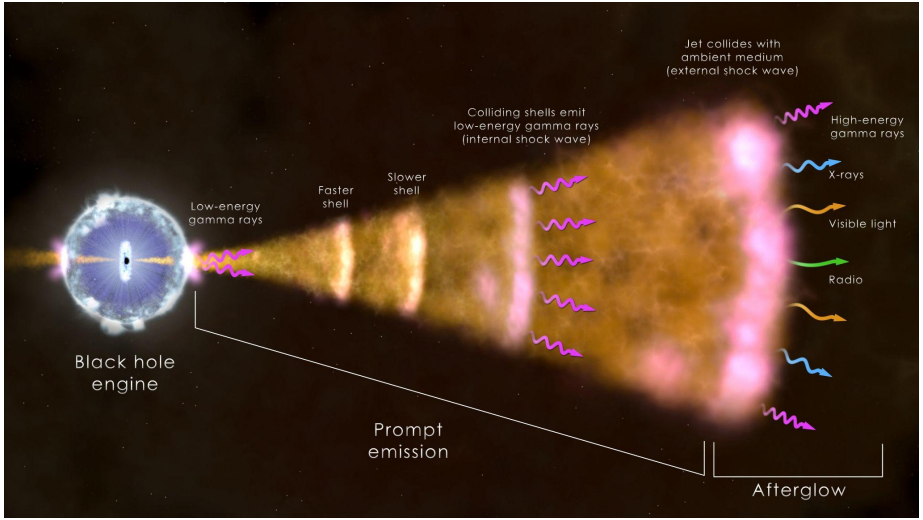
- Short GRBs are shorter in duration
- Short GRBs are fainter
- Few radio detections



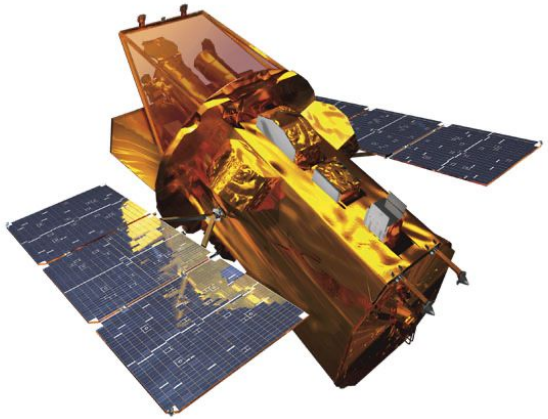
(Right) P. Narayana Bhat et al. "The Third Fermi GBM Gamma-Ray Burst Catalog: The First Six Years". ApJS 223.2, 28 (Apr. 2016), p. 28

Short GRB Follow-up

- Initial Alerts from Neil Gehrels Swift Observatory
- Afterglow confirmation
- Observations from Fermi-GBM and others



Credit: NASA's Goddard Space Flight Center



Swift, Credit: NASA E/PO, Sonoma State University

Short GRB Follow-up

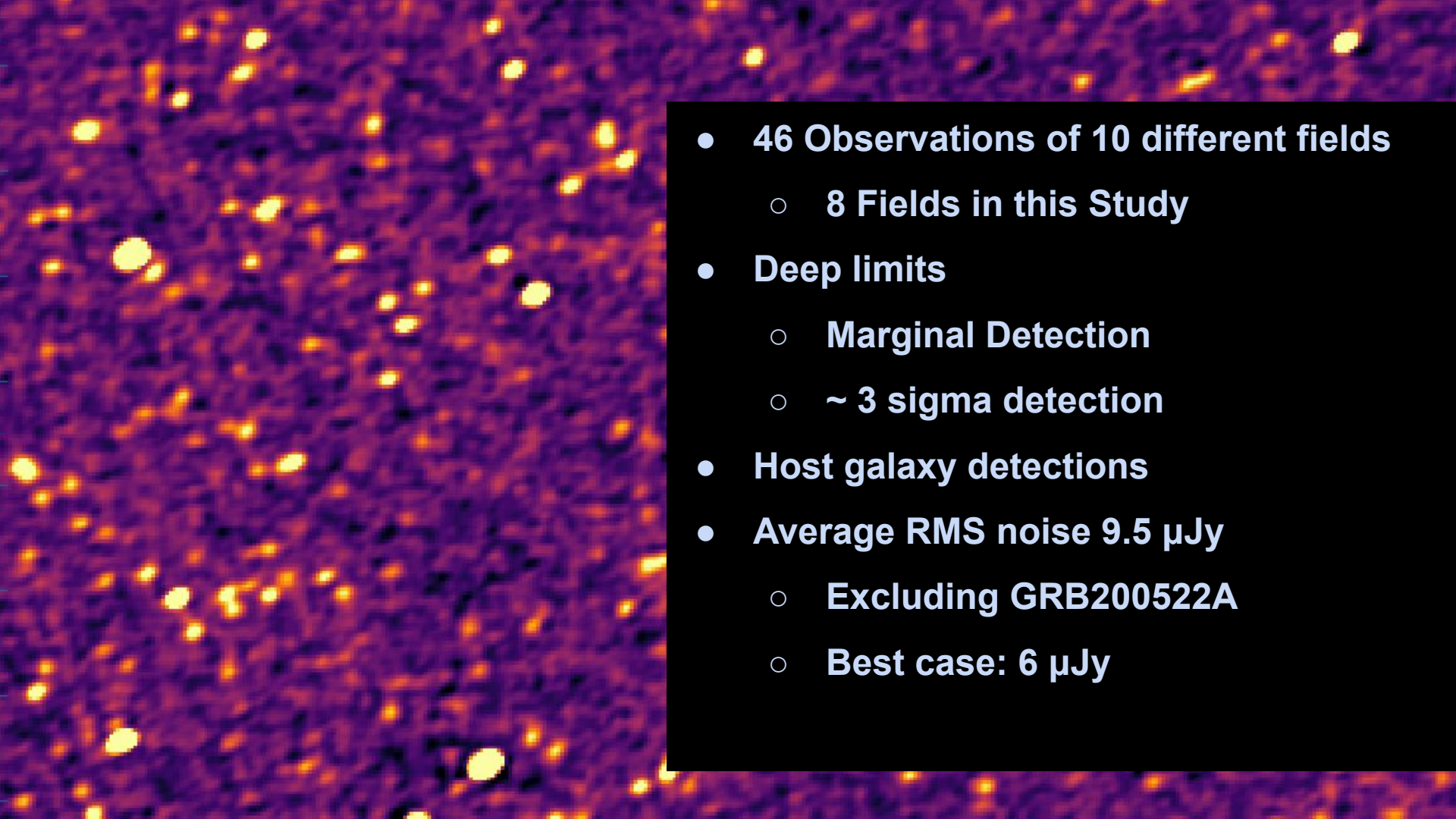
- ThunderKAT
  - Large Survey Project using MeerKAT
  - Studying radio transients
    - SGRB follow-up
    - Commensal searches
- MeerKAT
  - Started operations in summer 2018
  - Operates in 3 bands spanning 544 MHz and 3499 MHz with excellent sensitivity
    - L-band (856-1711 MHz)

image: SARAO

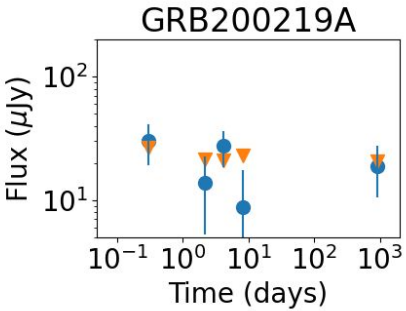
Short GRB Follow-up

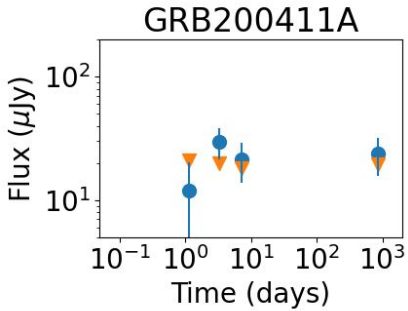
- ATCA
  - Part of a rapid response program for SGRB
    - PI: G. E. Anderson
    - Anderson et al. 2021
  - 4 of the 8 GRBs observed with MeerKAT
- *e*-MERLIN
  - 2 of the 8 GRBs
  - One GRB with nearly continuous coverage from 1 to 10 days

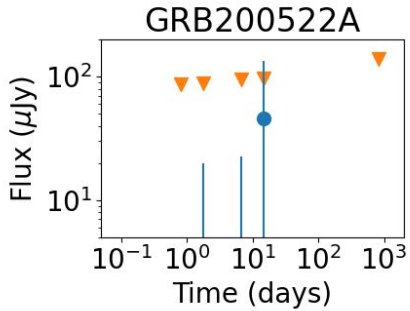
image: Paul Edwards

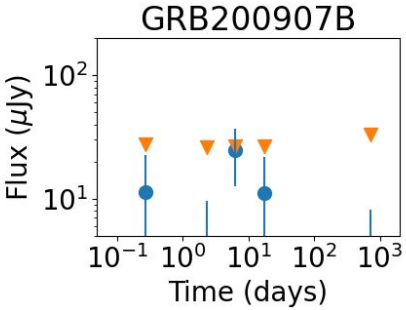


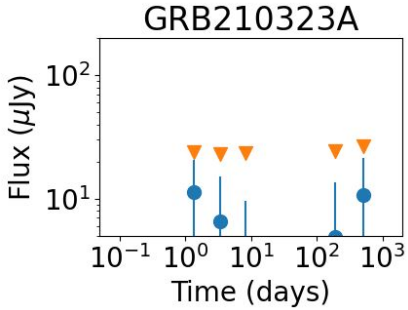
- 46 Observations of 10 different fields
  - 8 Fields in this Study
- Deep limits
  - Marginal Detection
  - ~ 3 sigma detection
- Host galaxy detections
- Average RMS noise 9.5 μJy
  - Excluding GRB200522A
  - Best case: 6 μJy

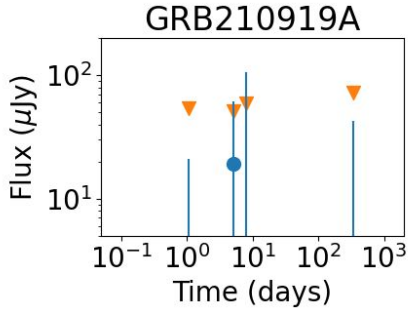

GRB200219A
Flux (μJy)
Time (days)

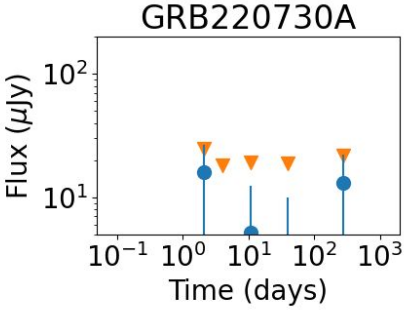

GRB200411A
Flux (μJy)
Time (days)

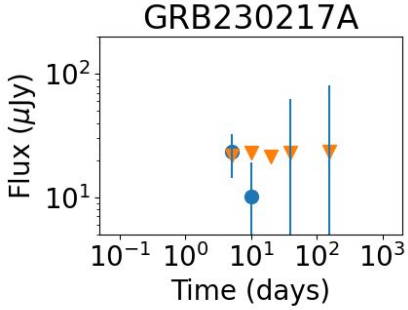

GRB200522A
Flux (μJy)
Time (days)


GRB200907B
Flux (μJy)
Time (days)


GRB210323A
Flux (μJy)
Time (days)


GRB210919A
Flux (μJy)
Time (days)


GRB220730A
Flux (μJy)
Time (days)


GRB230217A
Flux (μJy)
Time (days)

Host Galaxy Measurements

- Combined observations
  - 12-16 hours
- 4 detections
  - Previous efforts found 1 out of 16 at higher frequencies (Klose et al. 2019)

GRB	RA	Dec	Host Galaxy References	F_{peak} (μJy)	SFR ($M_\odot/yr$)
GRB200219A	342.63795	-59.11988	Schlegel et al. (2021); Fong et al. (2022)	20 ± 4	12 ± 2
GRB200411A	47.66306	-52.31654	Schlegel et al. (2021); Fong et al. (2022)	46 ± 3	48 ± 3
GRB200907B	89.02896	6.90629	Fong et al. (2022)	<36	<17
GRB210323A	317.94717	25.36944	Fong et al. (2022)	18 ± 6	2 ± 2
GRB210919A	80.25814	1.31112	Schlegel et al. (2021); Fong et al. (2022)	67 ± 16	11 ± 2

Host Galaxy Measurements

- Upper Limits on SFR
- Other contributions including neutral hydrogen
- Rates are higher than Nugent et al 2022
- GRB 210323A: redshift too high for neutral hydrogen

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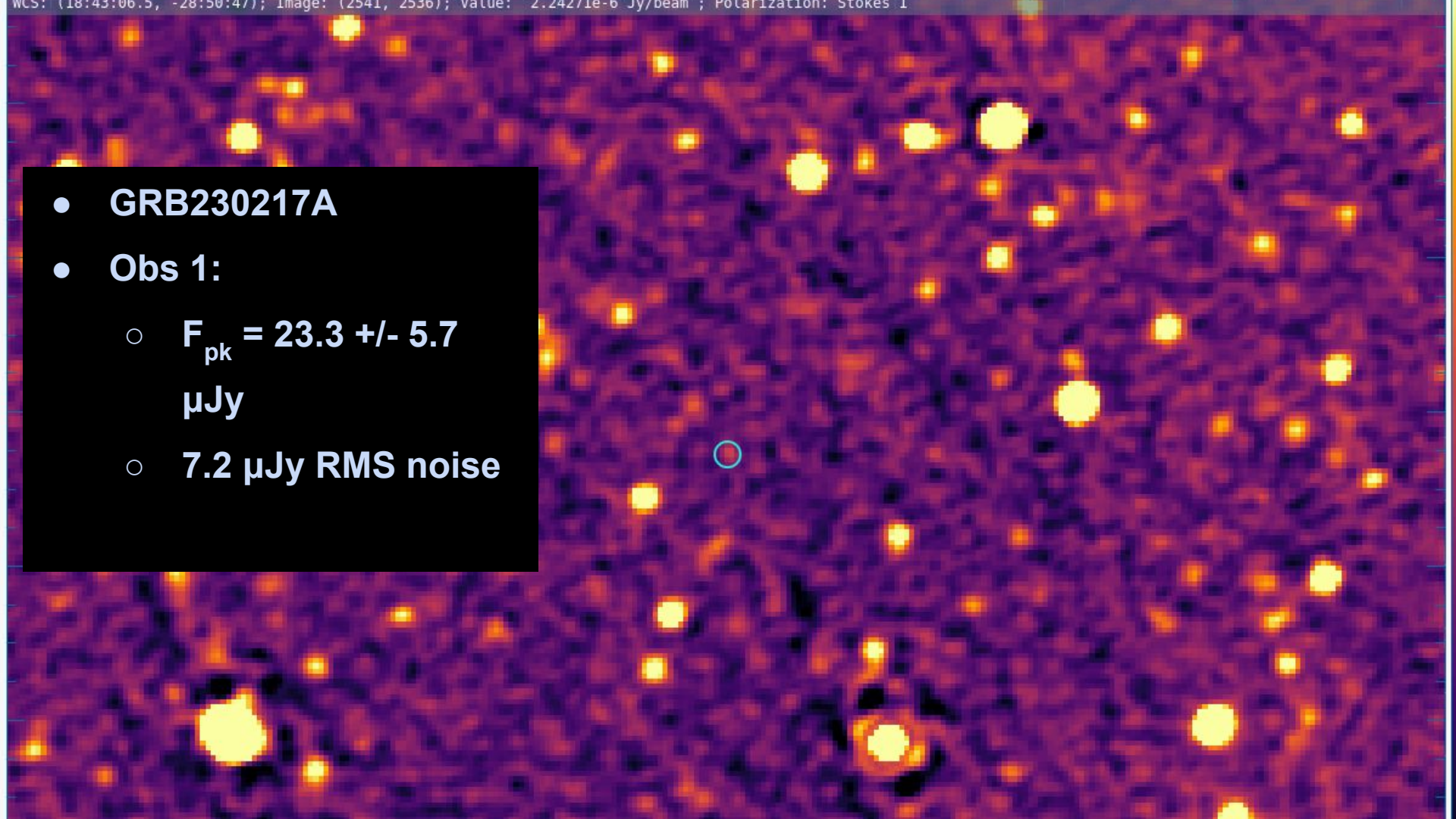
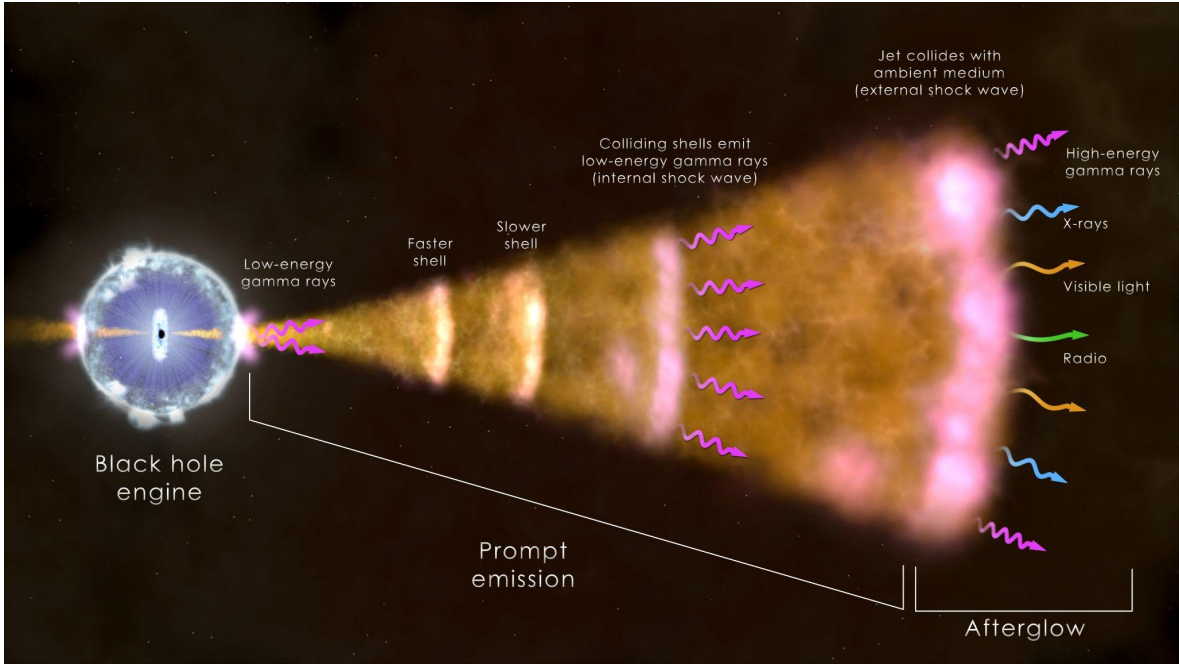

WCS: (18:43:06.5, -28:50:47); Image: (2541, 2536); Value: 2.24271e-6 Jy/beam ; Polarization: Stokes I
GRB230217A
Obs 1:
F_{pk} = 23.3 +/- 5.7 µJy
7.2 µJy RMS noise

Learning from the Observations

- Energy
  - E_{iso}, isotropic energy
  - ε_{γ}, energy efficiency of the prompt
    - $E_{\gamma,iso} / (E_{\gamma,iso} + E_{K,iso})$
- Properties of electrons
  - p, power law index of accelerated electrons
  - ξ_e, fraction of accelerated electrons
- EM field properties
  - ε_e, E field shock energy/total energy
  - ε_B, B field shock energy/total energy
- Surrounding Environment
  - n_0, ambient medium density



Credit: NASA's Goddard Space Flight Center

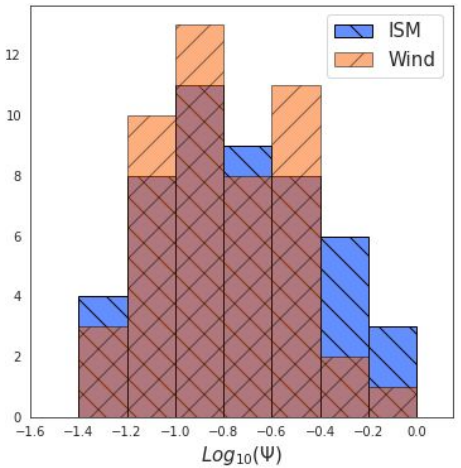
Learning from the Observations

- Use Ψ from Duncan et al. 2023
  - From equations for peak flux
  - In typical radio regime
- Assume:
  - ξ_e and ε_e same for long and short GRBs
  - p should also be similar
- Compare Ψ values
- Particularly interested in:
  - n_0, ambient medium density
  - ε_γ, energy efficiency of the prompt

$$\Psi_{\rm ISM} = \left(\frac{261.4\,(1+z)^{1/2}\,\nu_p\,t_p^{3/2}\,E_{\gamma,iso,53}^{1/2}}{10^{15}\,d_{28}^2\,F_{\nu_p}\,\max(1,t_p/t_j)^{1/2}} \right)^{1/2}$$

$$= \frac{(p-2)}{0.177\,(p-1)} \left(\frac{p-0.67}{p+0.14} \right)^{1/2}$$

$$\times \left(\frac{1-\epsilon_\gamma}{\epsilon_\gamma} \right)^{-1/4} n_0^{-1/4} \epsilon_e\,\xi_e^{-3/2}$$



Duncan et al. 2023

Constraining GRB physical parameters with Radio Peaks

- Use lower limits to place constraints on ε_γ and n_0
- Ψ should approximately be the same
- Lower limits on Ψ has implications on peak flux

$$\Psi_{\rm ISM} = \left(\frac{261.4\,(1+z)^{1/2}\,\nu_p\,t_p^{3/2}\,E_{\gamma,iso,53}^{1/2}}{10^{15}\,d_{28}^2\,F_{\nu_p}\,\max(1,t_p/t_j)^{1/2}} \right)^{1/2}$$

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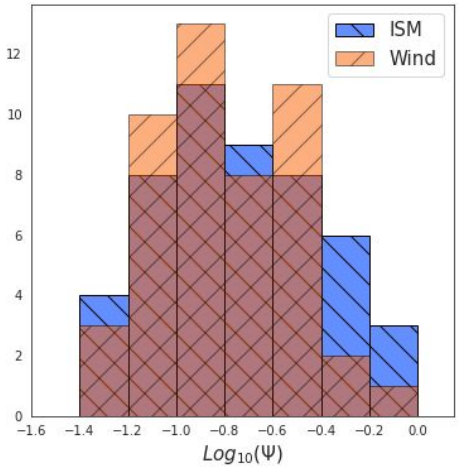
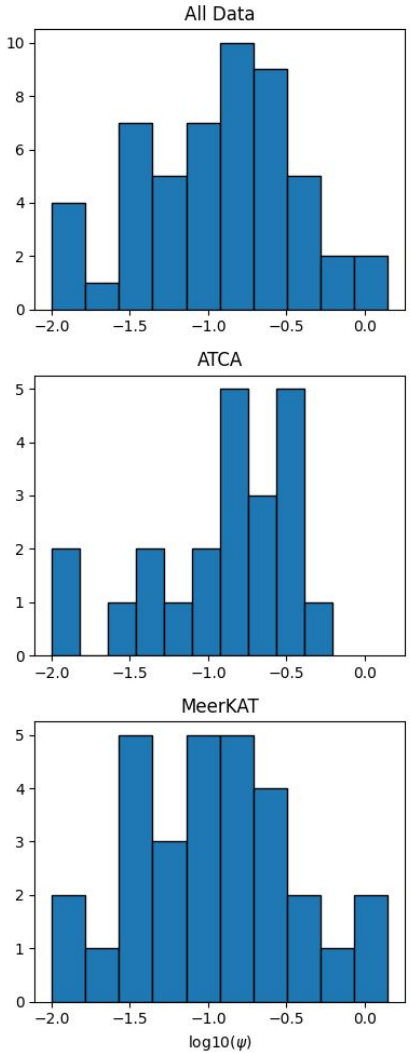
$$\Psi \propto (\epsilon_\gamma/n_0)^{1/4} \text{ for } \epsilon_\gamma << 1$$



Duncan et al 2023



Constraining GRB physical parameters with Radio Peaks

- Gamma-ray efficiency
  - Aksulu et al. 2022 show very low values
  - Fan and Piran 2006; Beniamini et al 2015, 2016 claim a consistent value ~ 0.15
- Electron density
  - How low can it get?

$$\Psi_{\rm ISM} = \left(\frac{261.4\,(1+z)^{1/2}\,\nu_p\,t_p^{3/2}\,E_{\gamma,iso,53}^{1/2}}{10^{15}\,d_{28}^2\,F_{\nu_p}\,\max(1,\,t_p/t_j)^{1/2}} \right)^{1/2}$$

$$= \frac{(p-2)}{0.177\,(p-1)} \left(\frac{p-0.67}{p+0.14} \right)^{1/2}$$

$$\times \left(\frac{1-\epsilon_\gamma}{\epsilon_\gamma} \right)^{-1/4} n_0^{-1/4} \epsilon_e\,\xi_e^{-3/2}$$

$$\Psi \propto (\epsilon_\gamma/n_0)^{1/4} \text{ for } \epsilon_\gamma << 1$$

Review

- 4 New GRB Host Galaxy detections
- 1 Marginal GRB Afterglow Detection
  - Low Densities?
  - Gamma Ray Efficiences?
    - ngVLA and SKA

Constraining GRB physical parameters with Radio Peaks

- Parameters are the same:
  - Should be detecting or marginally detecting
- Gamma-ray efficiencies differ:
  - Lower densities
  - Close to detecting
- Or possibly: much lower densities

$$\Psi_{\rm ISM} = \left(\frac{261.4\,(1+z)^{1/2}\,\nu_p\,t_p^{3/2}\,E_{\gamma,iso,53}^{1/2}}{10^{15}\,d_{28}^2\,F_{\nu_p}\,\max(1,\,t_p/t_j)^{1/2}} \right)^{1/2}$$

$$= \frac{(p-2)}{0.177\,(p-1)} \left(\frac{p-0.67}{p+0.14} \right)^{1/2}$$

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$$\Psi \propto (\epsilon_\gamma/n_0)^{1/4} \text{ for } \epsilon_\gamma << 1$$

Commensal Transient Searches

- 8 GRB Fields, 30 observations
- Multiple timescales
  - 4 hour
  - 15 minute
  - 8 seconds

- 8 SNe fields, 8 GRB fields, 28 observations
  - All 4-5 hours
- Multiple timescales
  - 30 minutes
  - 8 seconds
- SN2021qvv and SN2021smj overlap

Images Used

- MeerKAT Images
  - 0.8 Degree search radius
- 208 30 minutes images after QC
  - Shown in background
  - 35 μJy median noise
- 98035 total 8 second images
  - Split L-band in half
  - 200-400 μJy median noise for depending on the field

Search Strategy

- LOFAR Transients Pipeline (TraP)[1]
  - Light curves
  - Low threshold
- Further restrictions
  - Threshold
  - Source Density
  - Compute V and η
  - η cuts
- Make animations

$$V_\nu = \frac{1}{\bar{I}_\nu}\sqrt{\frac{N}{N-1}(\bar{I^2_\nu} - \bar{I_\nu}^2)}$$

$$\eta = \frac{1}{N-1}\sum_{i=1}^{N}\frac{(I_{\nu,i} - \xi_{I_\nu})^2}{\sigma^2_{\nu,i}}$$

[1]Swinbank et al. "The LOFAR Transients Pipeline" Astronomy and Computing. vol. 11, June 2015

Further Reduction

- 30 minute images
  - 814 sources left after automated cuts
    - 57 noise
    - 28 single image
    - 24 potentially astrophysical
    - 477 need further investigation
  - Force fit 477 sources + 28 sources
    - 52 with eta > 2
  - 52 sources, including the previous 24
    - Beam shape 2 to 1 issues
    - Noise, bright sources
    - 14 sources left total

Further Reduction

- 30 minute images
  - 14 sources
    - 1 source, intra-observational variability, possibly noise
    - 3 sources had variability within the 4-5 hour observation
    - 10 sources had obs-to-obs variability
  - Leaves 13 sources

Variables in 30 minute images

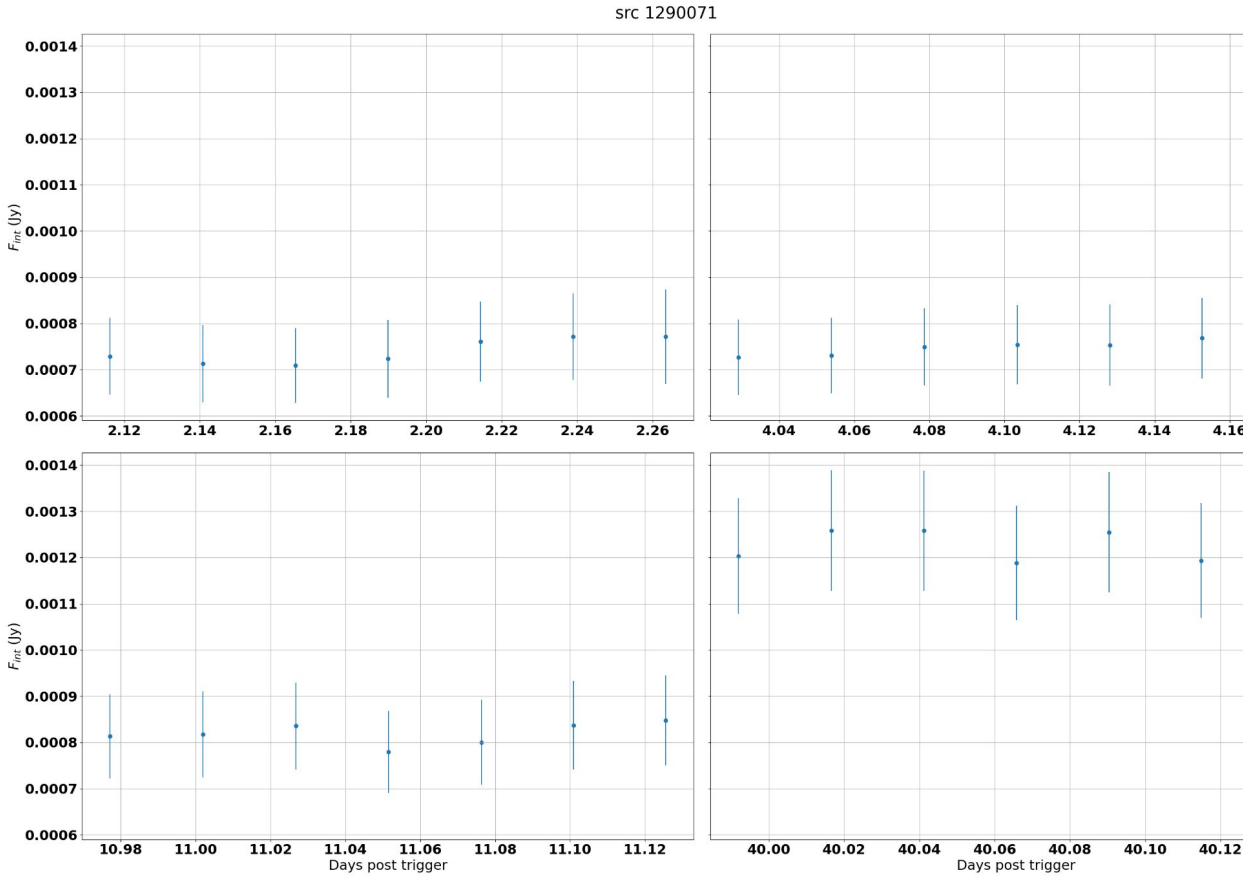
- Seven sources reported in radio catalogs
  - RACS and VLASS
  - six with a counterpart
  - forced measurement w/ PySE on the rest
  - all have optical and NIR
- src 1267266
  - Bright, variable
  - 7-10 mJy
  - also NVSS and FIRST

Variables in 30 minute images

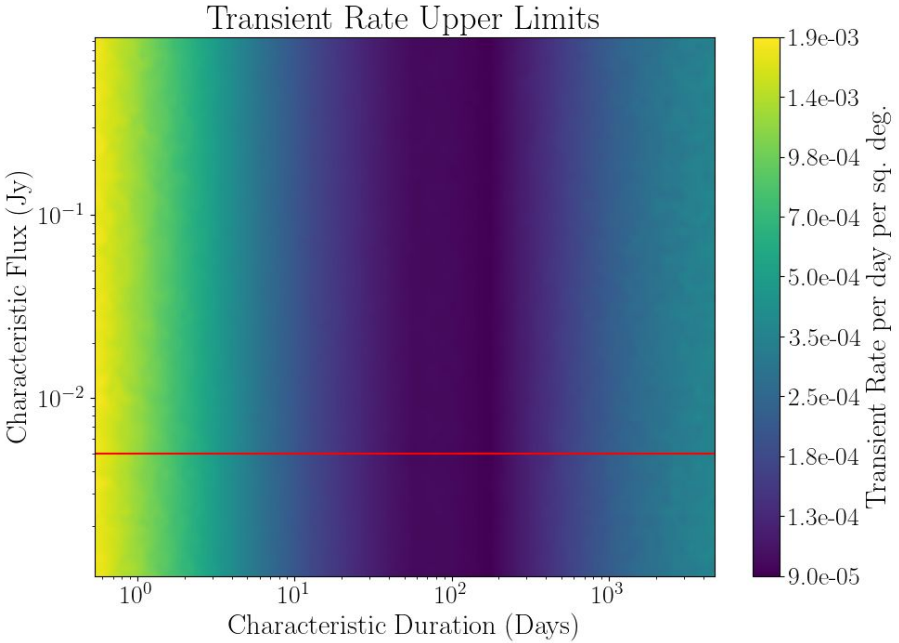
- src 1278651
  - Should have been detected in VLASS
  - 0.77 degrees from center of FOV
  - PB correction? Scintillation?
  - Chandra source
    - Conflicting distance 1.3 kpc? 12 Mpc?
  - Possible AGN

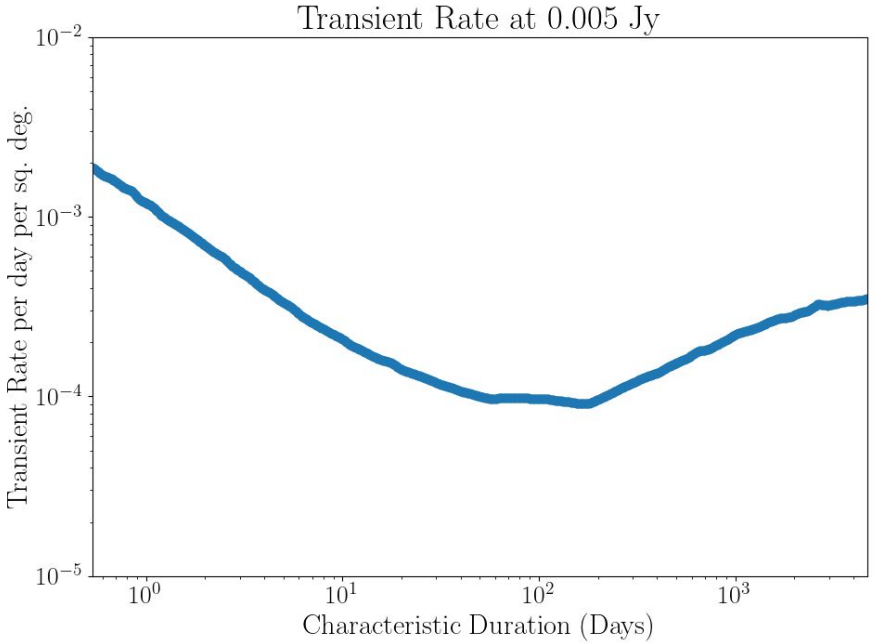
Variables in 30 minute images

- src 1290071
  - Inconsistent with scintillation
    - Unless assumed scattering screen is much less
  - RACS counterpart at 890 MHz is remarkably stable



Transient Rate Limits from 30 minute images





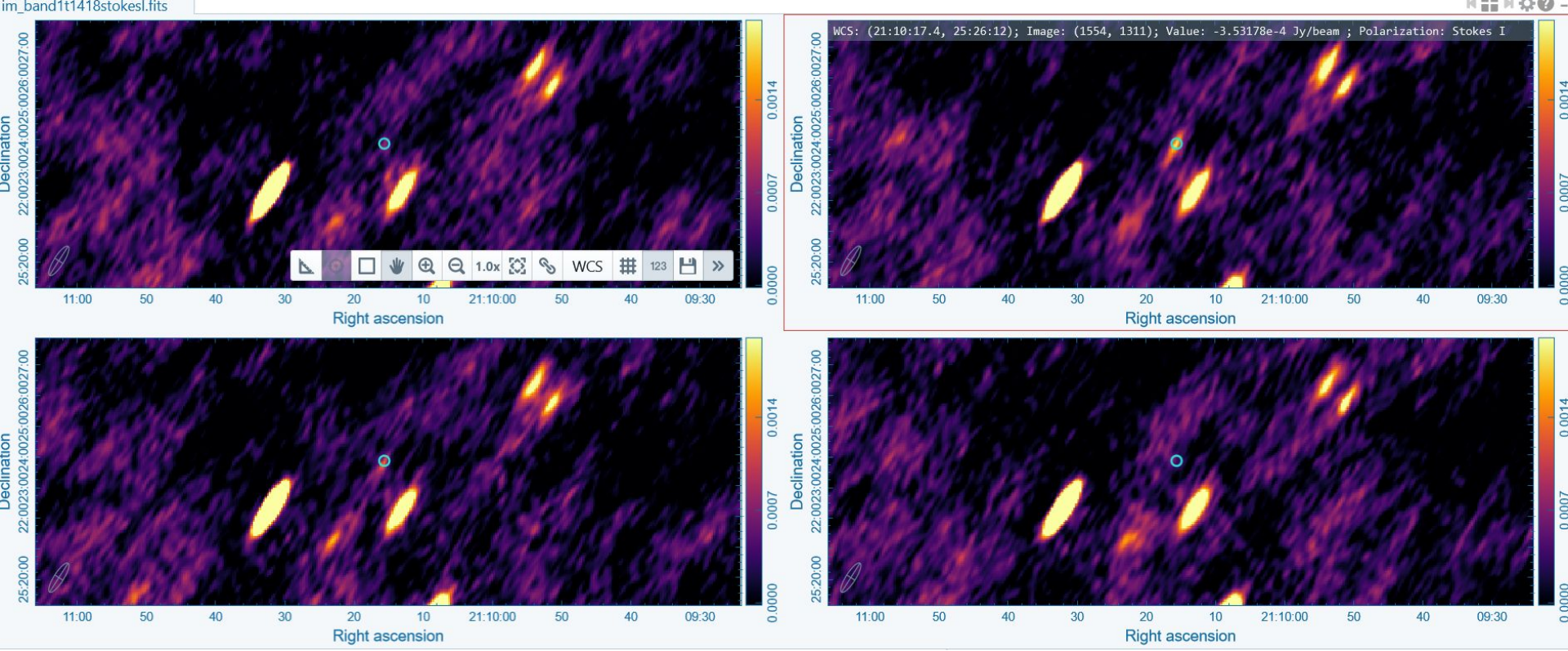
- Transient Rate Limits computed using https://github.com/dentalfloss1/transients-simulations
- Half of previous limits
- More total hours
- Better quality

8 Second Transients

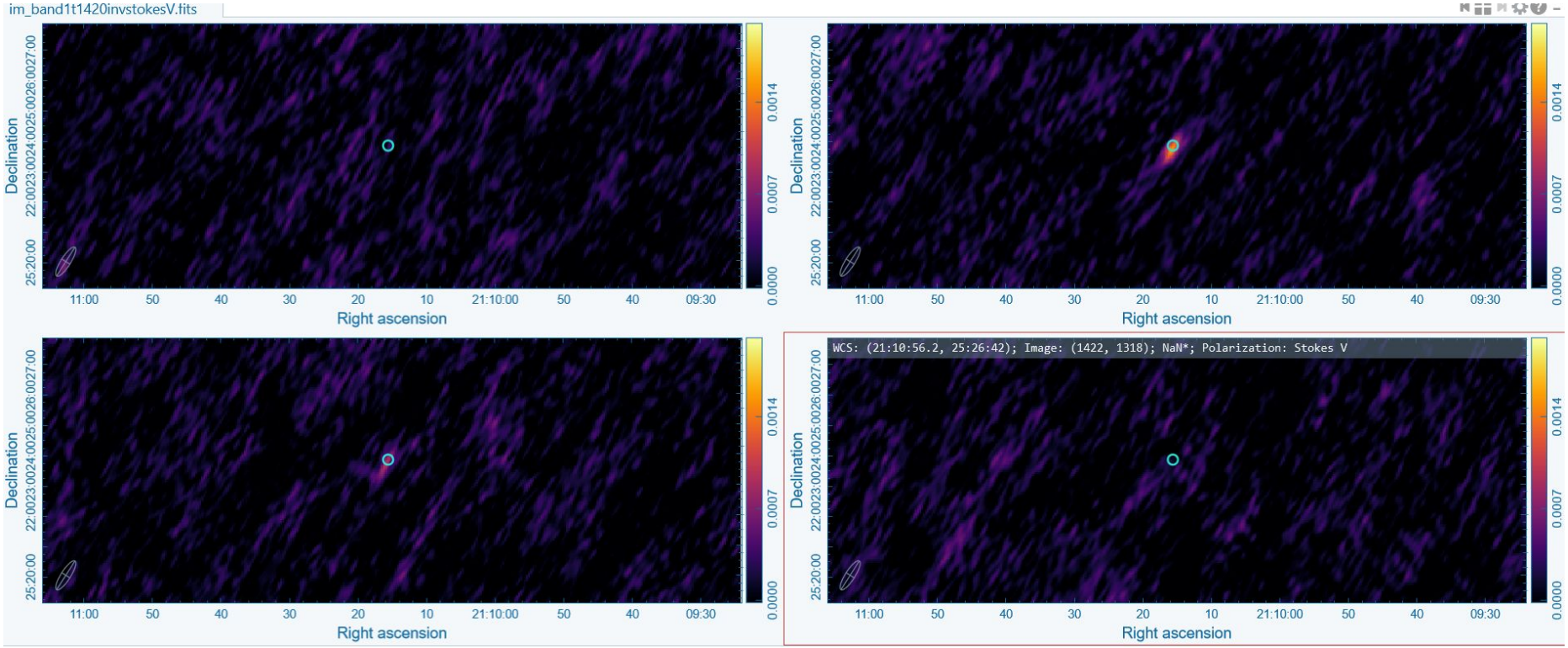
- Separate TraP run for each band and field
- One band/field remaining
- Sliding window for eta
    - 14 images long
- One promising source

8 Second Transients

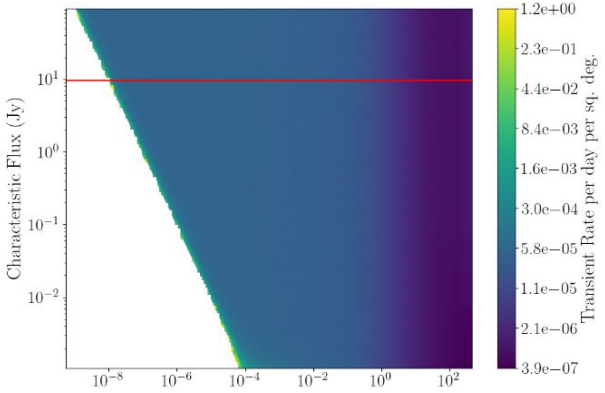
- src 96178
  - Re-split bandwidth, brightest < 1000 MHz
  - 8-16 second duration
  - Nearby deep image counterpart (22 +/- 8 μJy)
  - TESS red dwarf counterpart
  - Polarization?

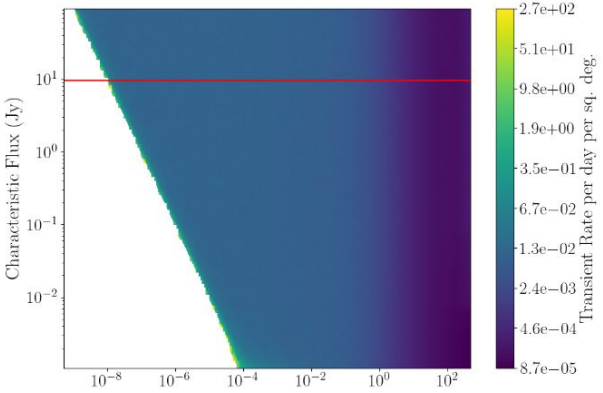


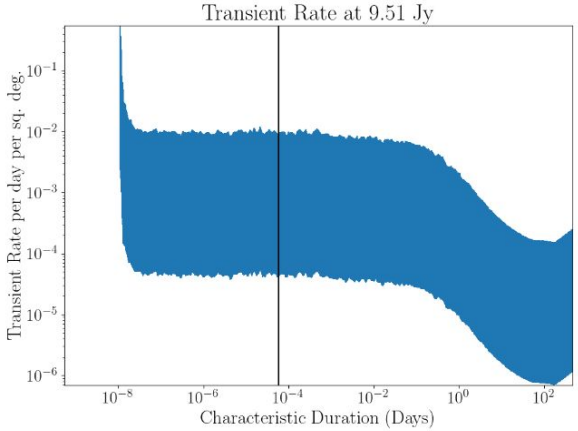
src 96178 stokes I at 990 MHz



src 96178 stokes V at 990 MHz


Characteristic Flux (Jy)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}
Transient Rate per day per sq. deg.
1.2e+00
2.3e−01
4.4e−02
8.4e−03
1.6e−03
3.0e−04
5.8e−05
1.1e−05
2.1e−06
3.9e−07


Characteristic Flux (Jy)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}
Transient Rate per day per sq. deg.
2.7e+02
5.1e+01
9.8e+00
1.9e+00
3.5e−01
6.7e−02
1.3e−02
2.4e−03
4.6e−04
8.7e−05


Transient Rate at 9.51 Jy
Transient Rate per day per sq. deg.
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}
Characteristic Duration (Days)

Review

- 4 New GRB Host Galaxy detections
- 1 Marginal GRB Afterglow Detection
  - Low Densities?
  - Gamma Ray Efficiences?
    - ngVLA and SKA
- Transient Searches
  - Likely scintillating sources on longer timescales
  - 8 to 16 second transient with ~100% circular polarization