Extreme Transients in the Radio Sky

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THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

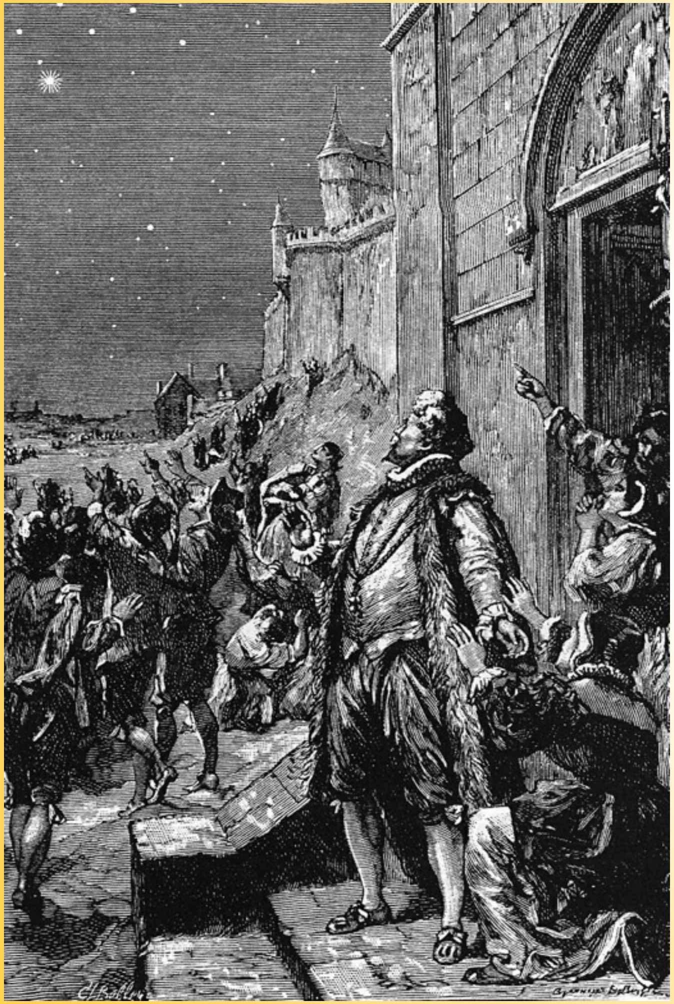
RAS Science Talk

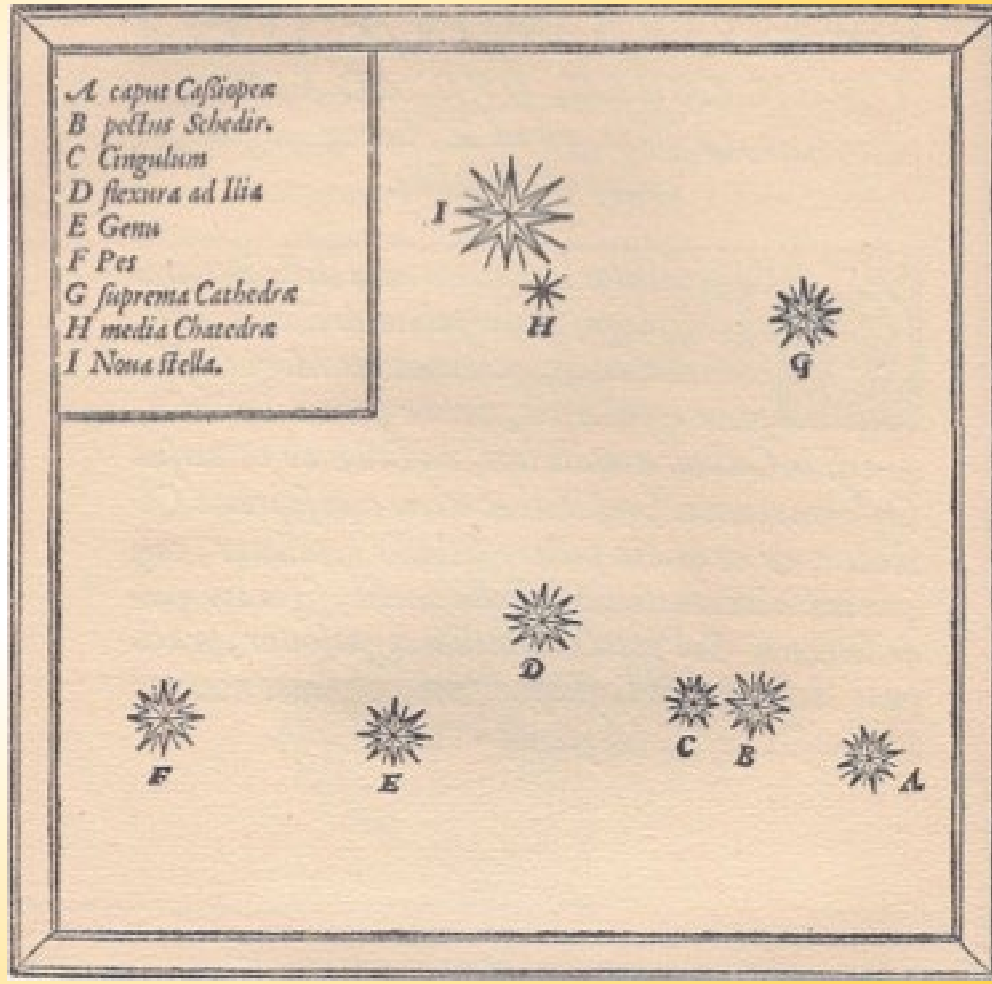
CORF – 8 May 2025

Image credit: Danielle Futselaar

"De Nova Stella"

Tycho Brahe (1572)





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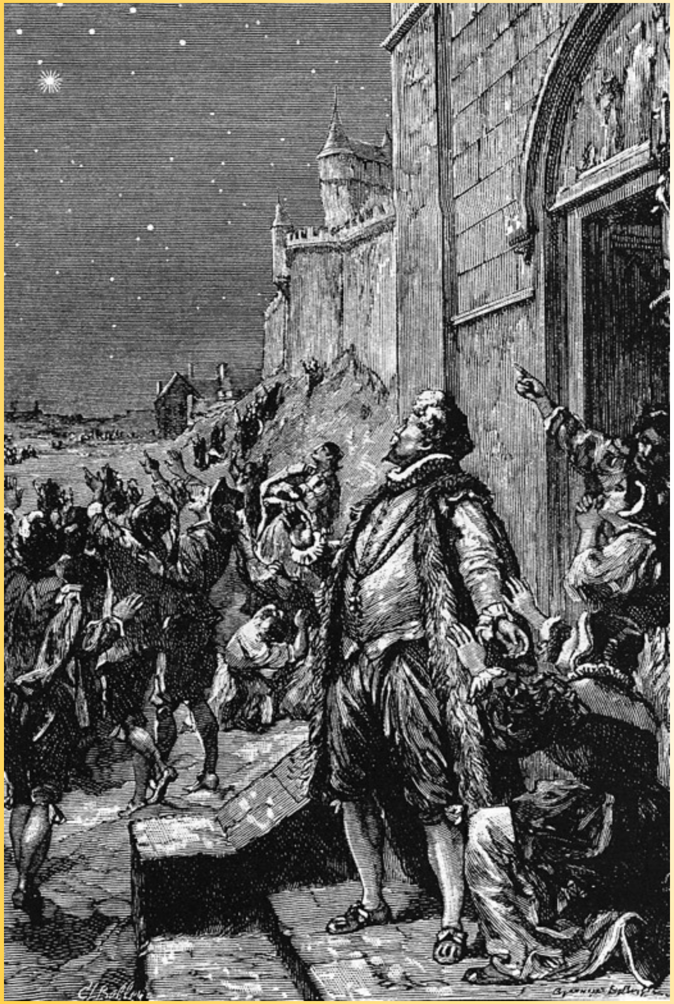
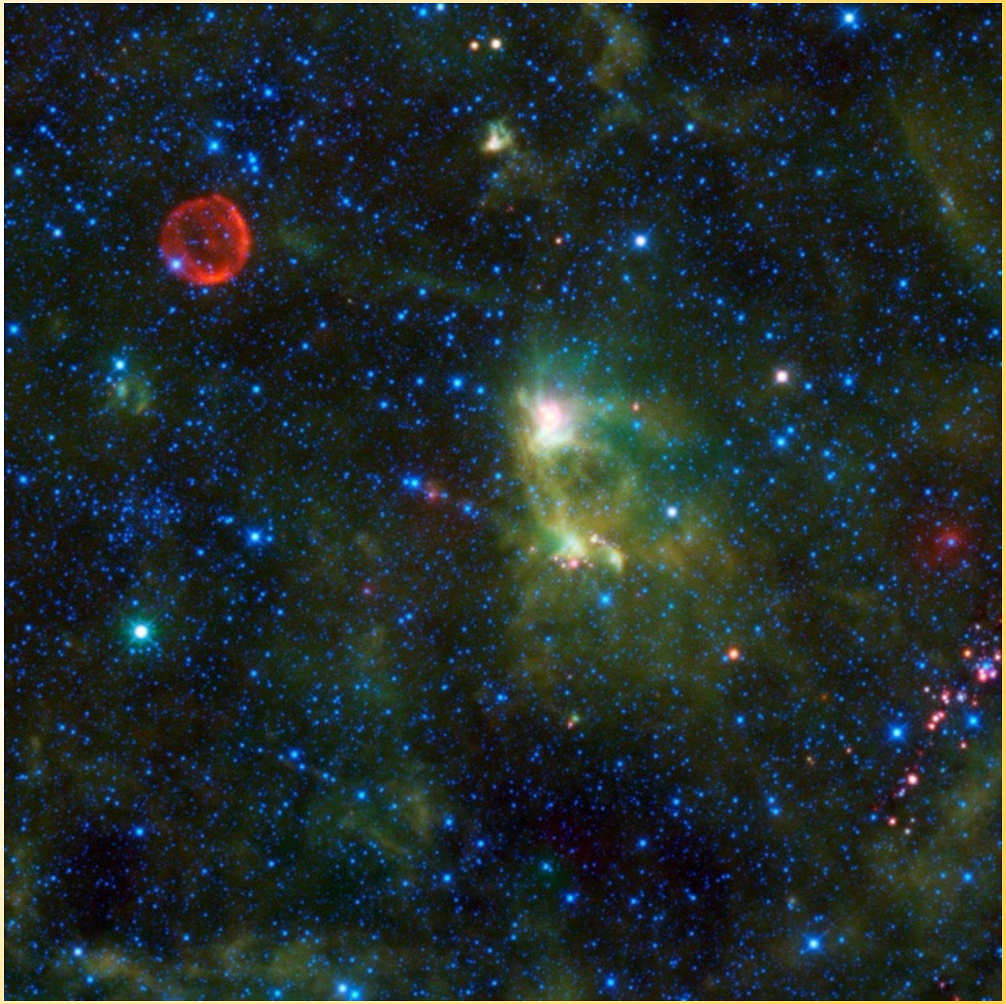
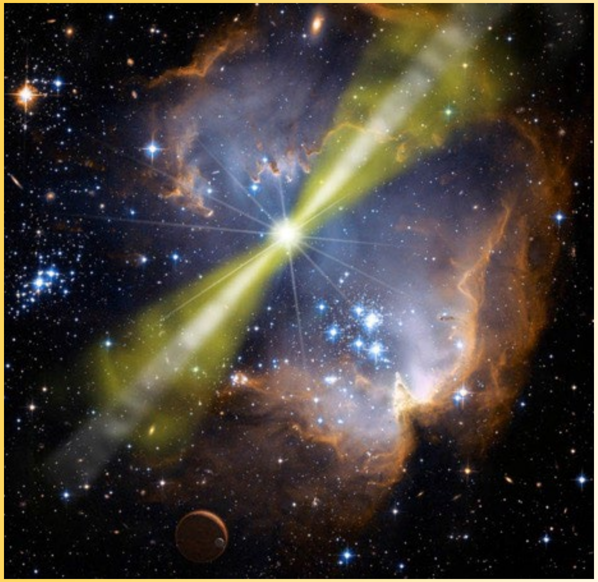


WISE satellite (2010)



Explosive Transients Galore

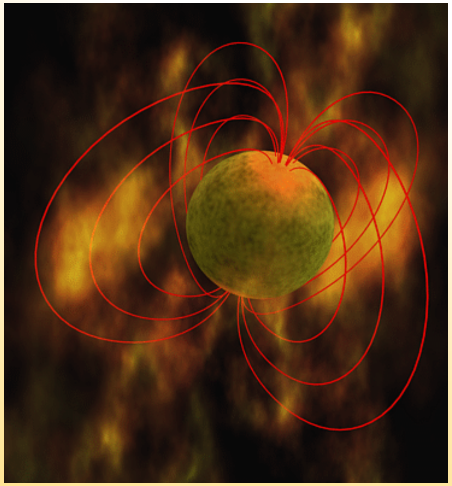
Gamma-Ray Bursts



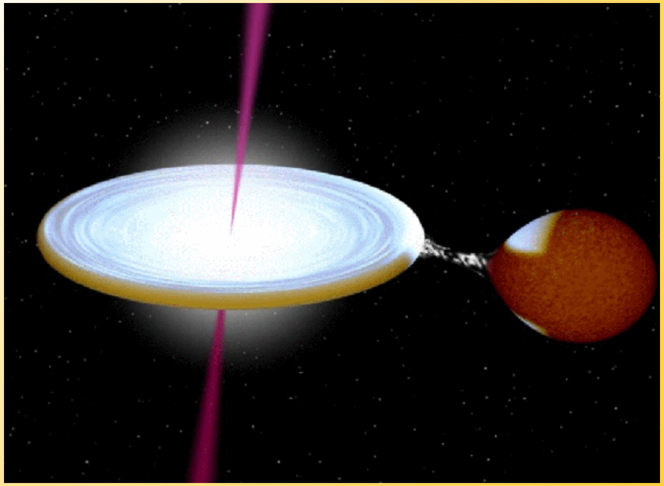
Stellar deaths
Neutron stars
Black holes
(and more…)

Supernovae

Compact binary mergers



Magnetars



X-ray binaries

Physics of Explosive Transients

Physics in extreme conditions:

- Extreme gravity → black holes
- Extreme densities → neutron stars
- Extreme magnetic fields → magnetars
- Extreme energies → stellar explosions
- Extreme outflow velocities → jets
- Extreme particle acceleration → shocks

Time-Domain, Multi-Wavelength
& Multi-Messenger Astronomy!

Transient Radio Sky

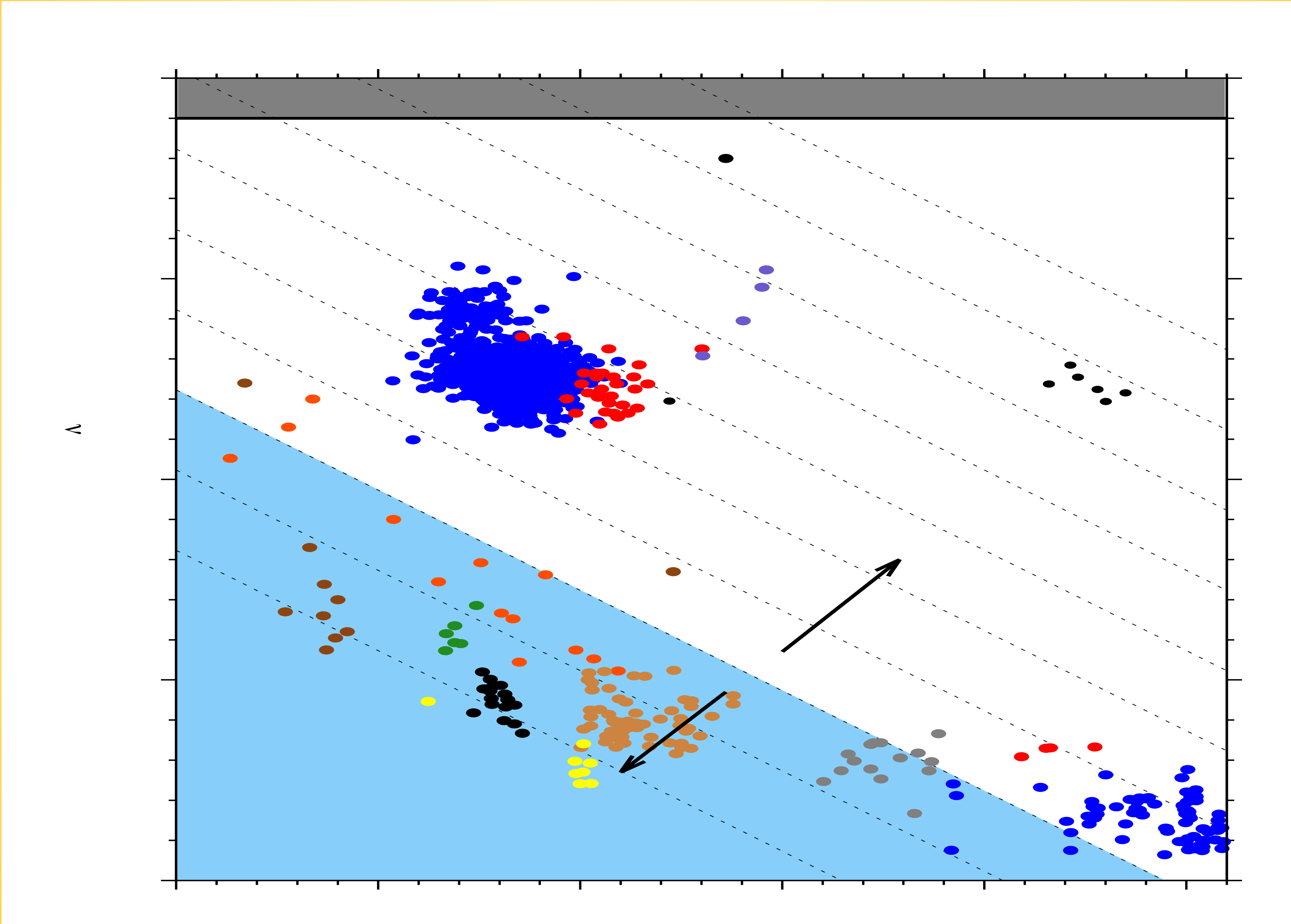
Incoherent emission:

- Relatively slow variability
- Low brightness temperature
- Flat or inverted spectra
- Found mostly in images
- Explosive events & jets
  - Gamma-ray bursts, tidal disruption events, X-ray binaries, supernovae

Coherent emission:

- Relatively fast variability
- High brightness temperature
- Steep spectra
- Found mostly in time series
- Largely unexplored
  - Theory (gamma-ray bursts, magnetars)
  - Possibly fast radio bursts

Observational Phase Space



Pietka et al. 2015

Searching for Transients

- Many observations of same field → transient searches
- Long observations → searches on various timescales
- Imaging and Transients Pipeline on High-Performance Computers across the globe

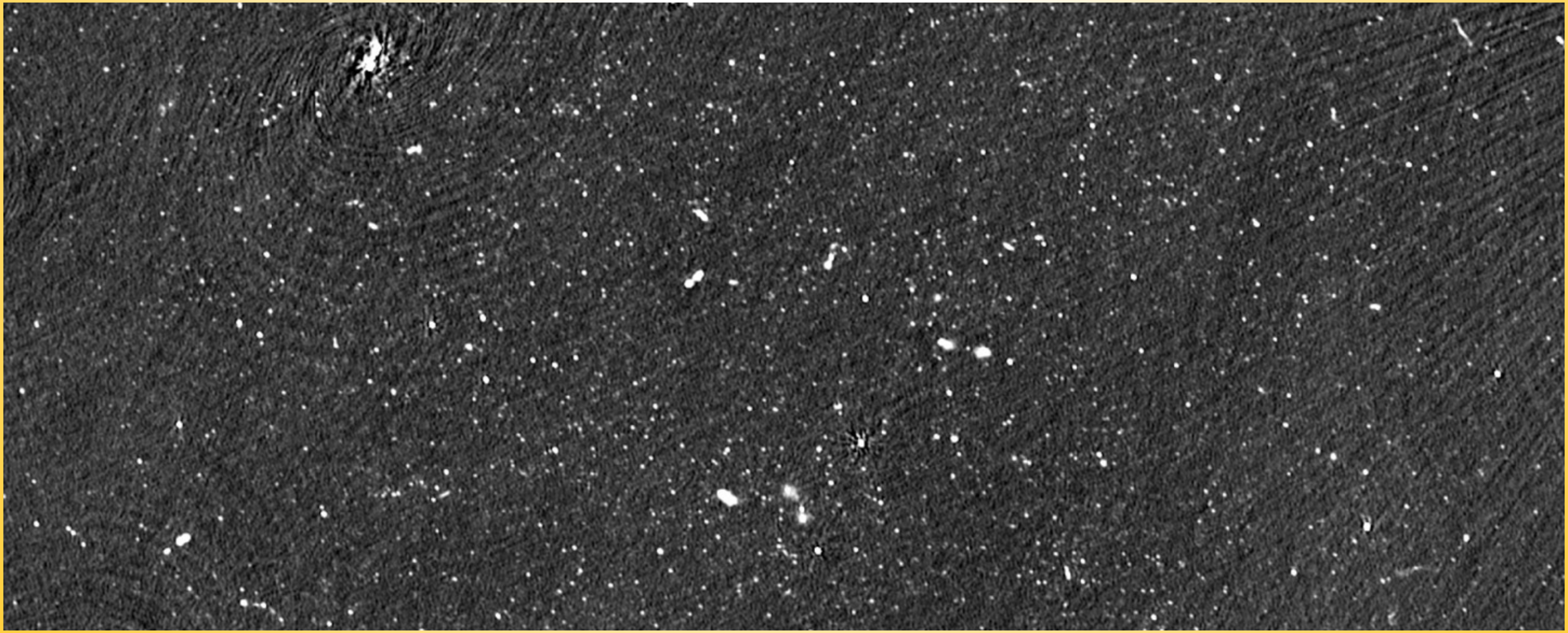


Image credit: Sarah Chastain

Searching for Transients: Objectives

- Find interesting and/or rare transients
- Study populations of variables and transients
- Characterize radio transient sky → transient rate
- Probe timescales from months/years to seconds

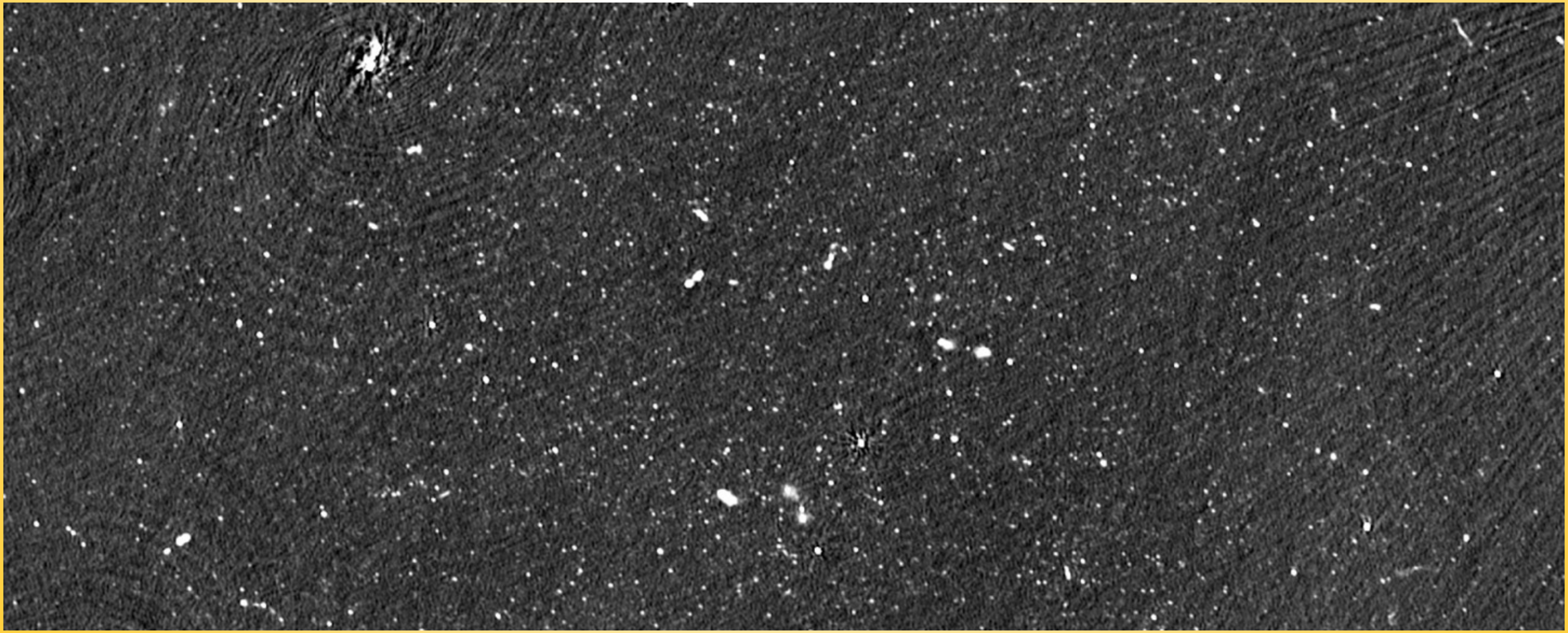
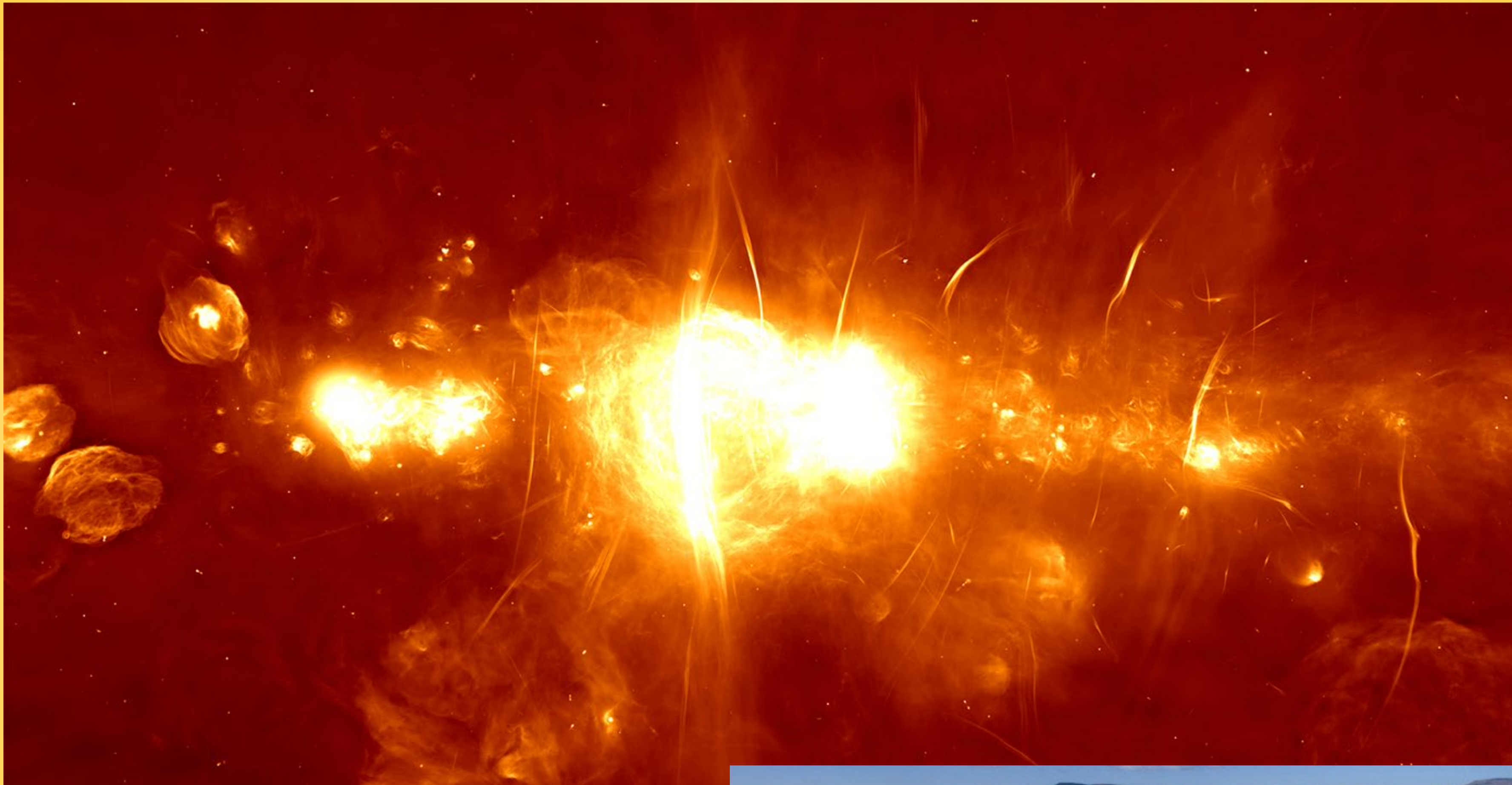


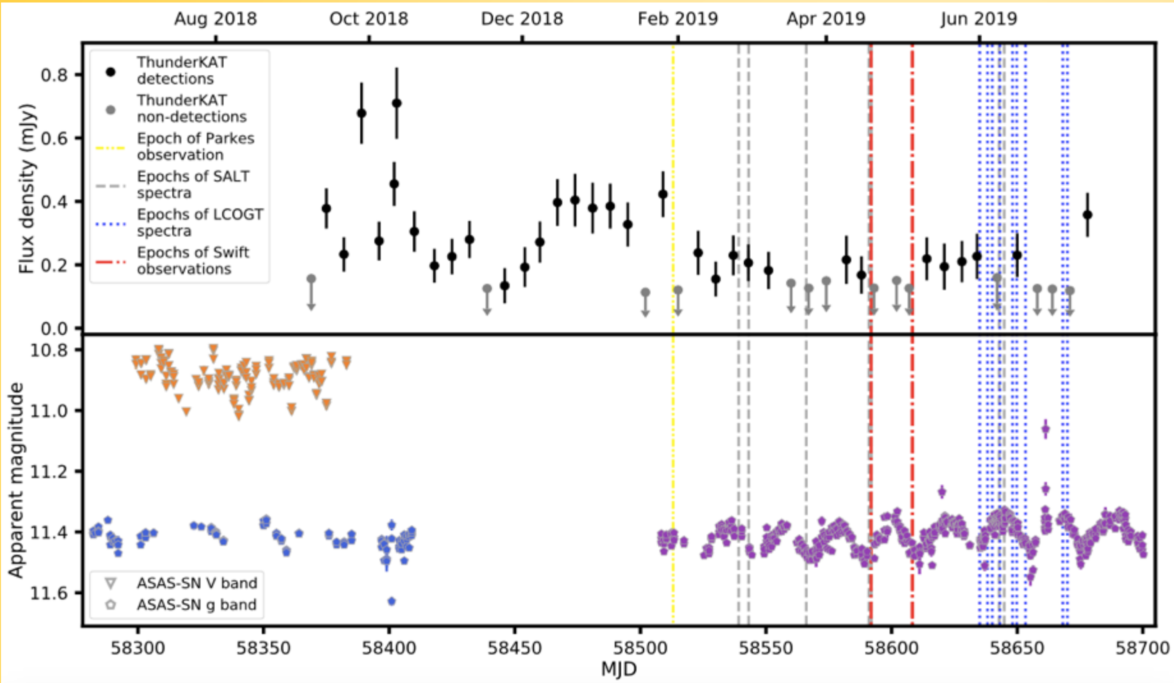
Image credit: Sarah Chastain

MeerKAT in South Africa



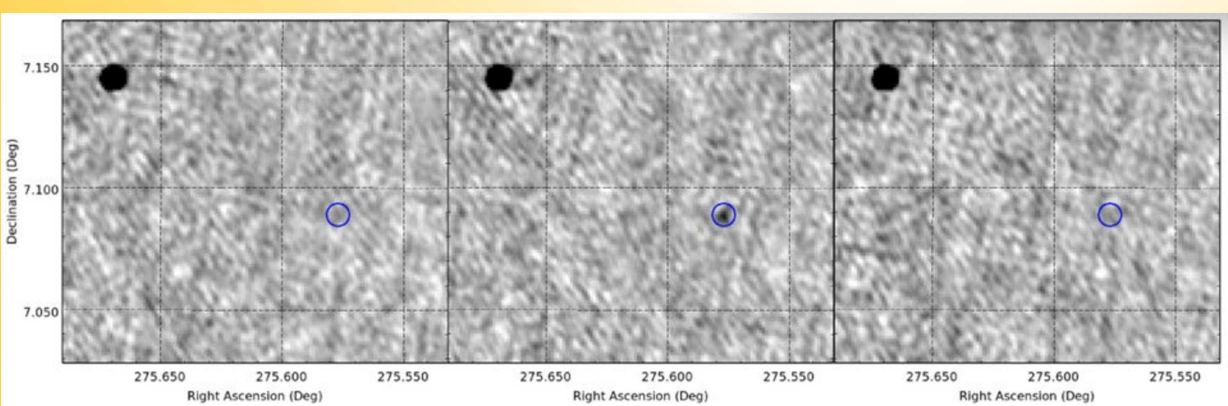
Galactic Center: MeerKAT first light in 2018

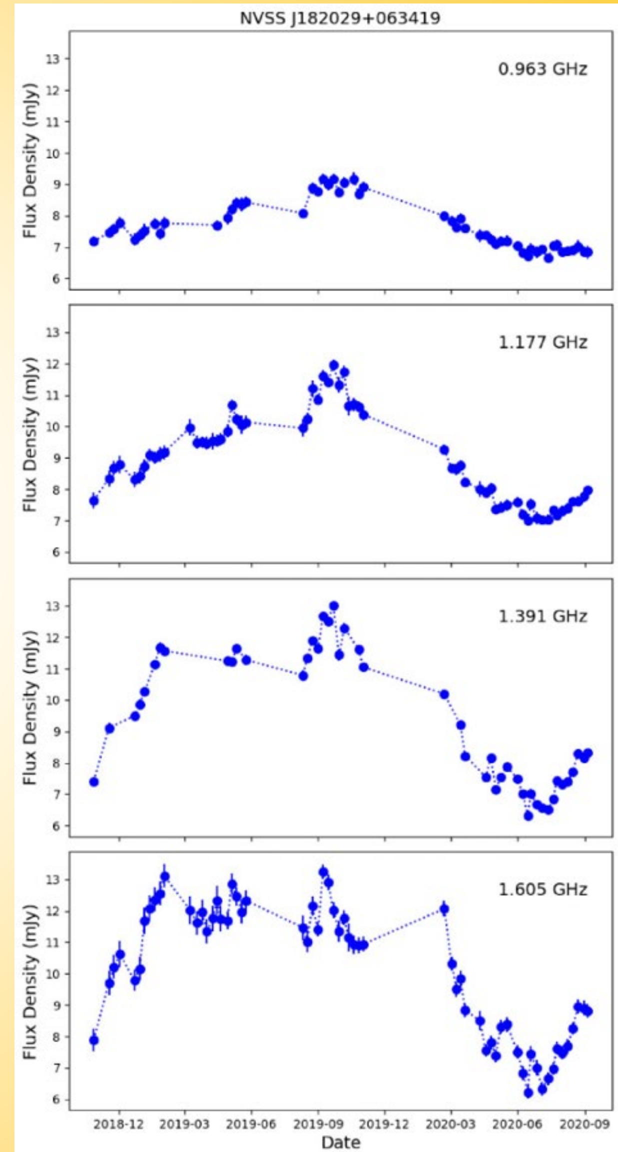
MeerKAT & Commensal Transients



Driessen et al. 2019

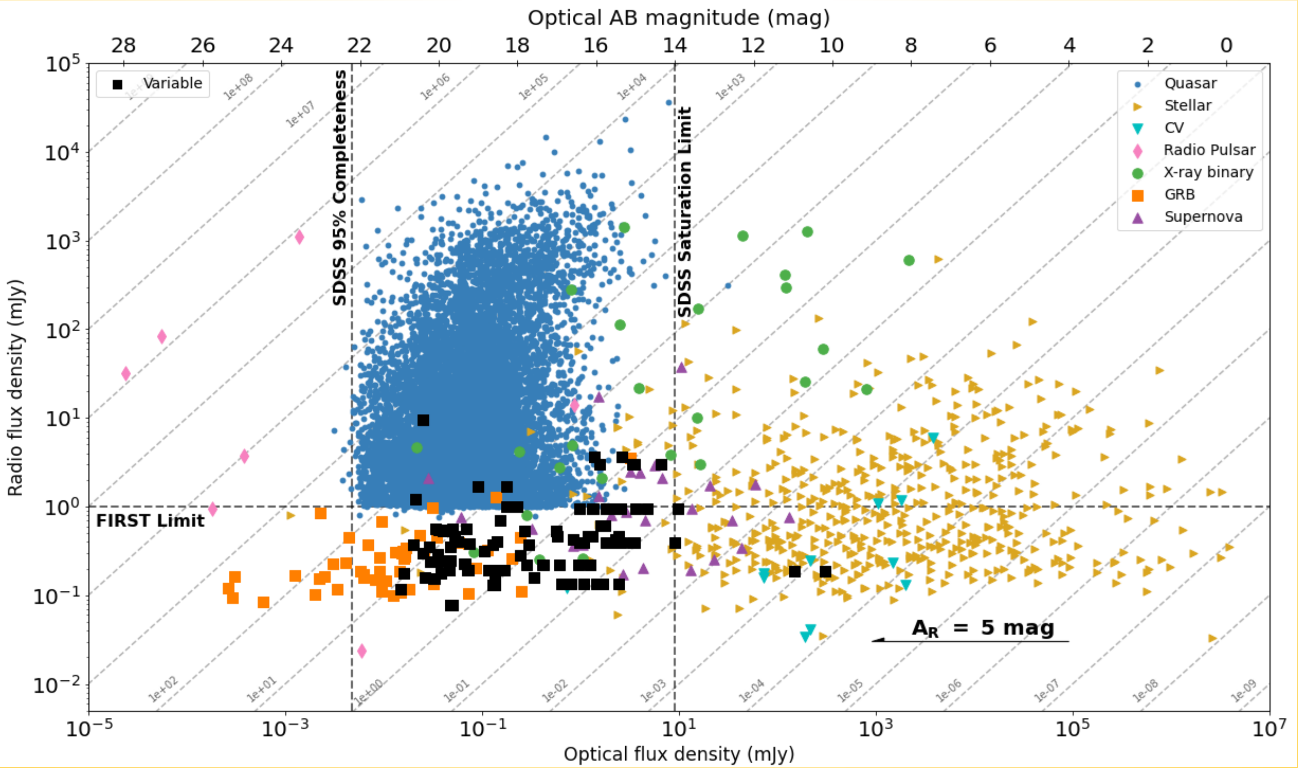
Rowlinson et al. 2022





Statistics: Long-Observation Fields

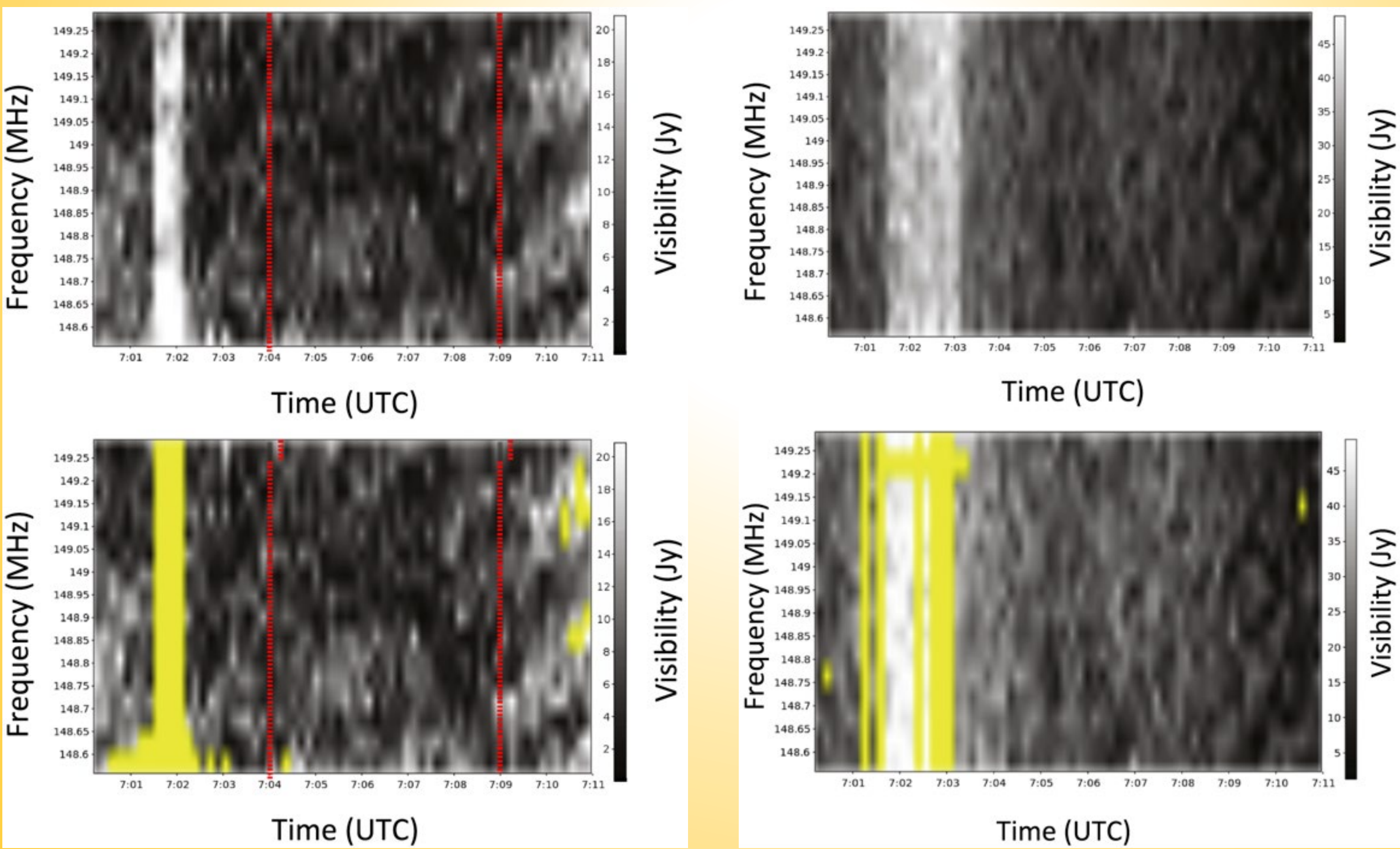
- 120 variables on long timescales (8 fields, >100 hours)
  - 52 likely scintillating known AGN
  - 66 unclassified but likely scintillating AGN
  - 2 cannot be scintillation, potentially stellar flares



Chastain et al. 2023

Searching for Transients: Challenges

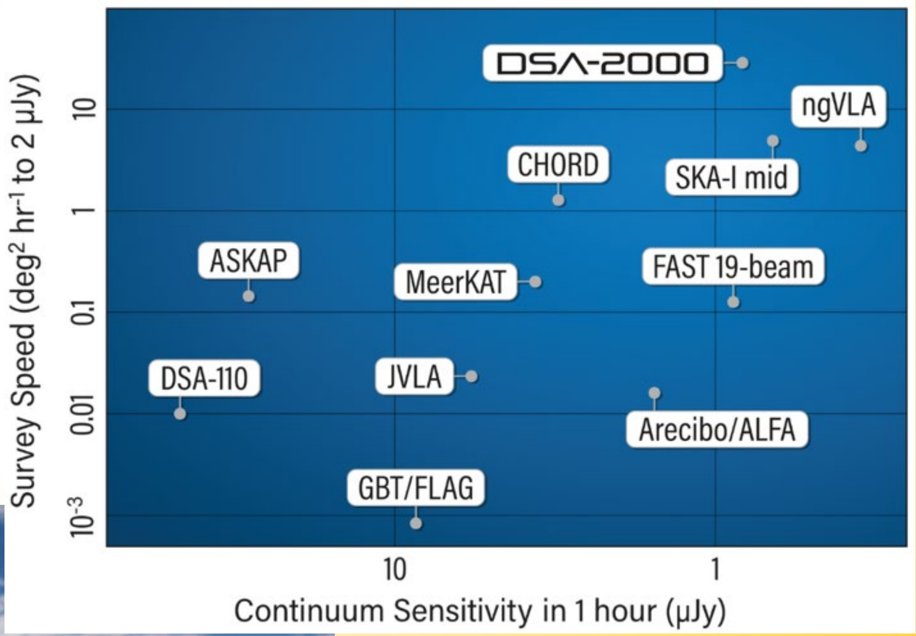
- New RFI flagging tools: stand-alone or in other software
- Flagging RFI → potentially remove transients
- Commensal transient searches → different strategies



LOFAR (Cendes et al. 2018)

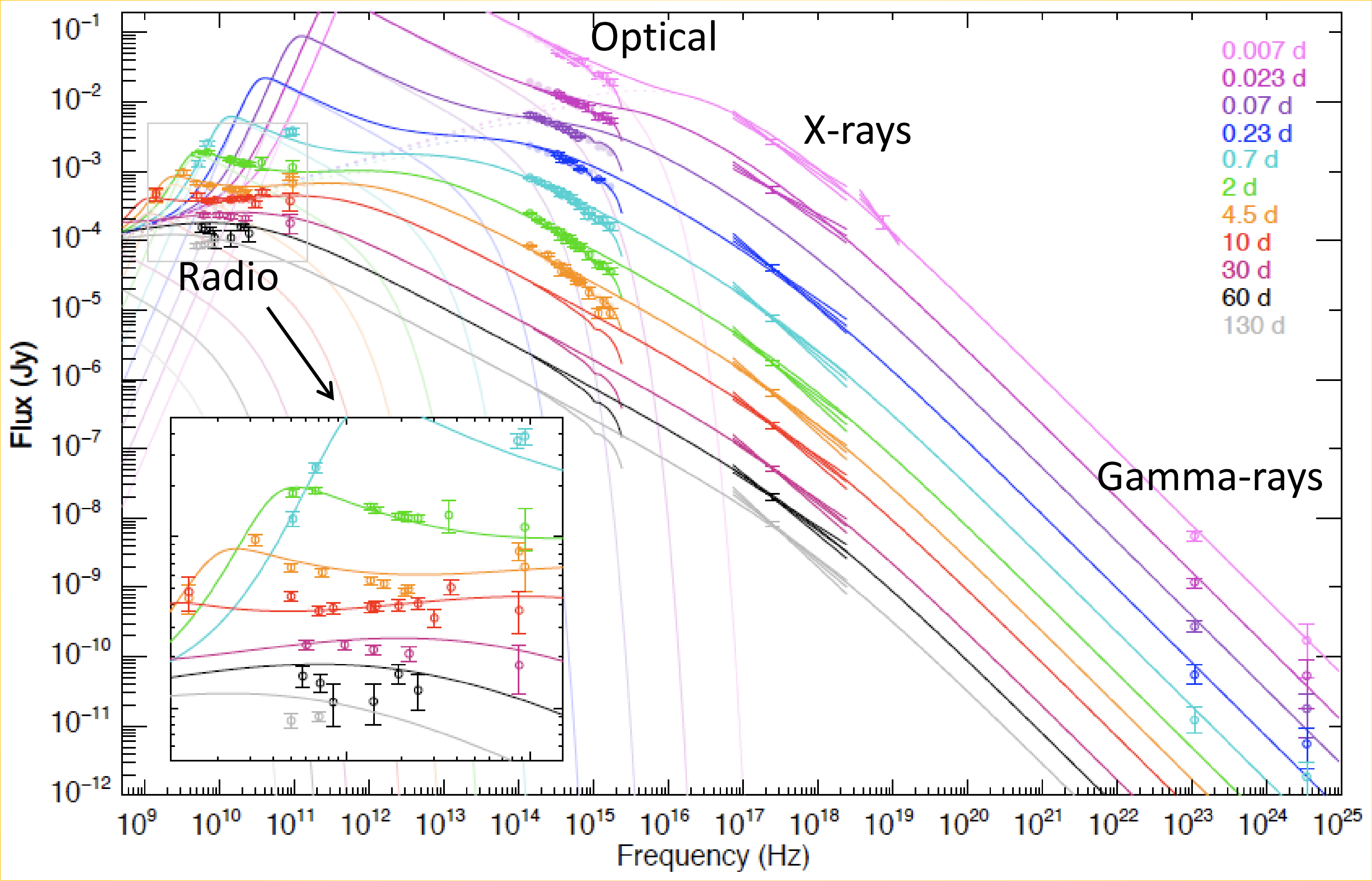
Searching for Transients: Opportunities

- In the US: DSA-2000 (Deep Synoptic Camera)
  - Survey radio camera → great opportunity for transients
  - Provides images, not visibilities → RFI under control (?)
- Internationally: SKA



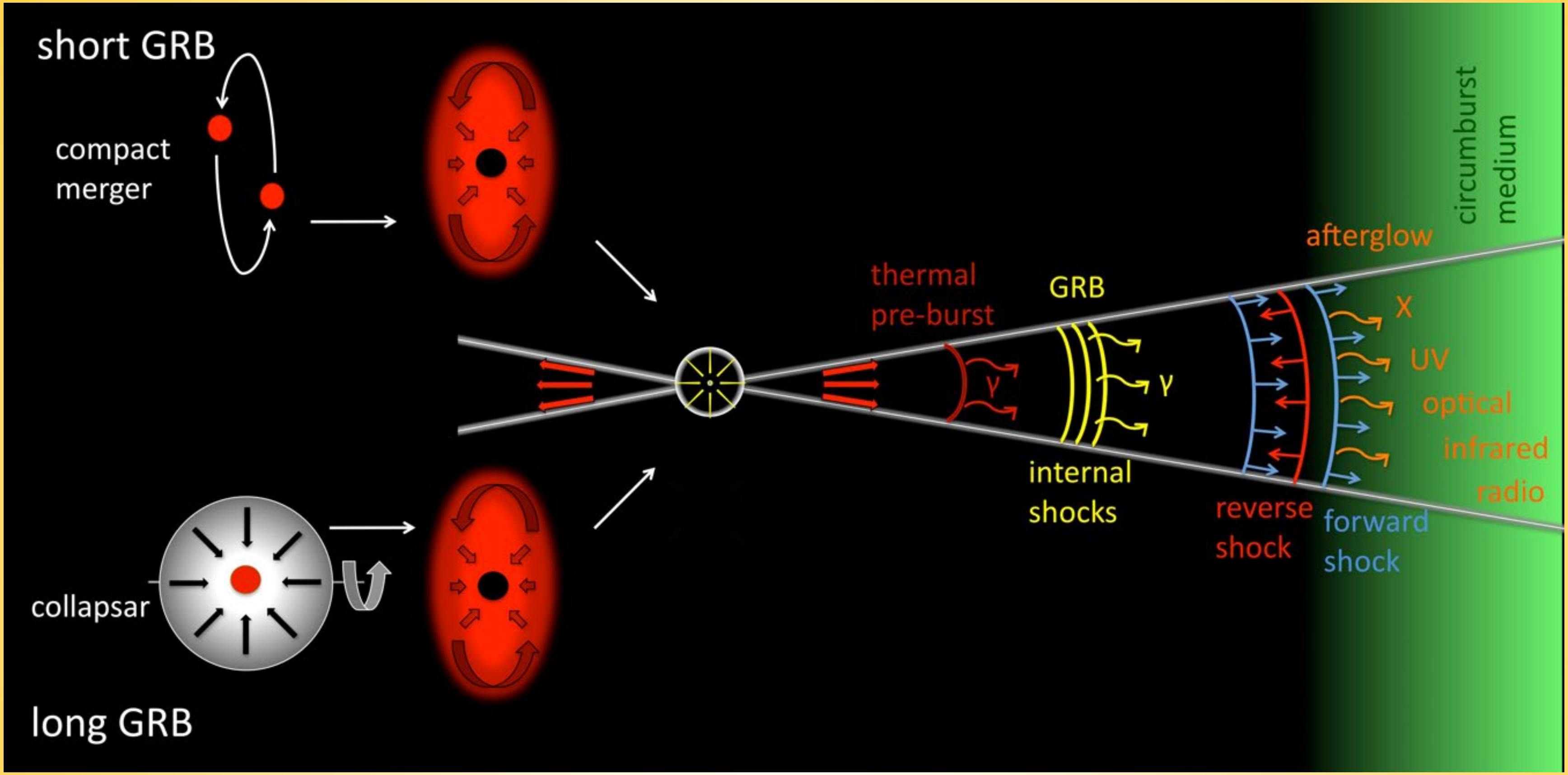
DSA-2000

Multi-Wavelength Gamma-Ray Bursts



GRB 130427A (Perley et al. 2014)

Relativistic Blast Wave Model

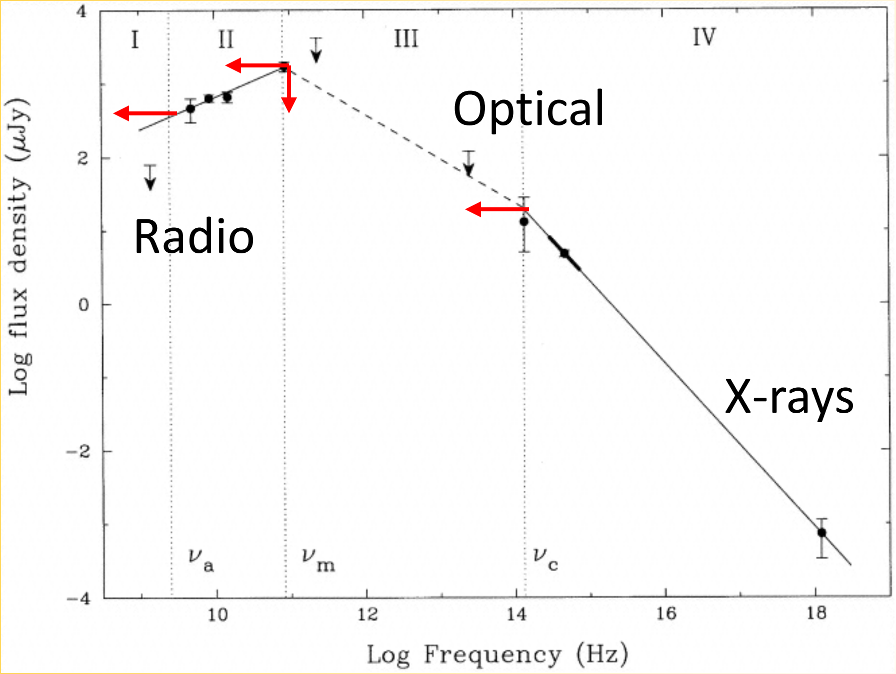


Meszaros & Rees 1992; Rees & Meszaros 1992 (Figure: Gomboc 2012)

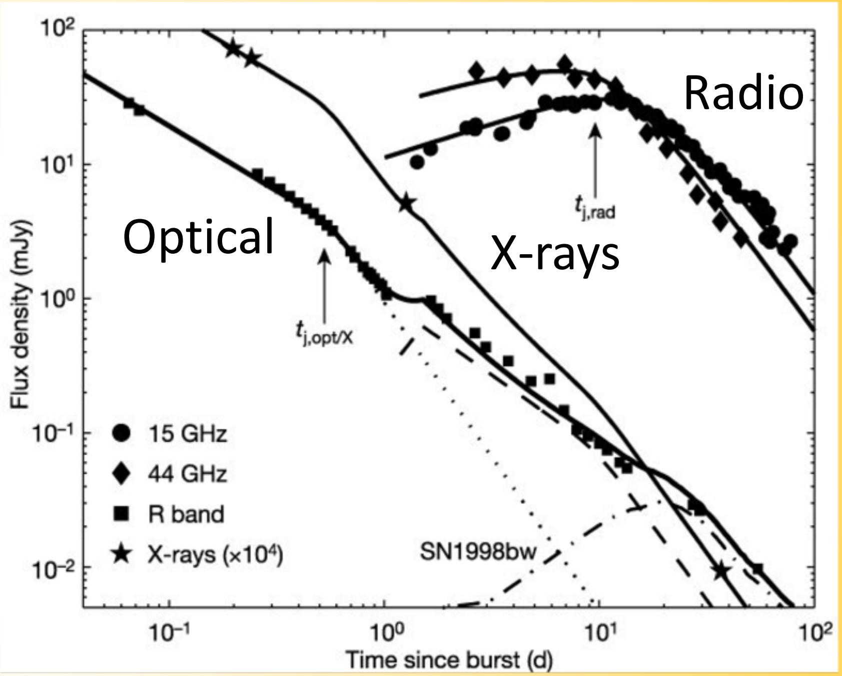
- Afterglow synchrotron emission → relativistic beaming: $\vartheta_{rel} = 1/\Gamma$
- Collimated relativistic outflow → jet opening angle: ϑ_0
- Initially $\vartheta_{rel} << \vartheta_0$, but blast wave decelerating

Modeling Spectra & Light Curves

Evolving spectrum ⟶ Light curves



GRB 970508 (Wijers & Galama 1999)

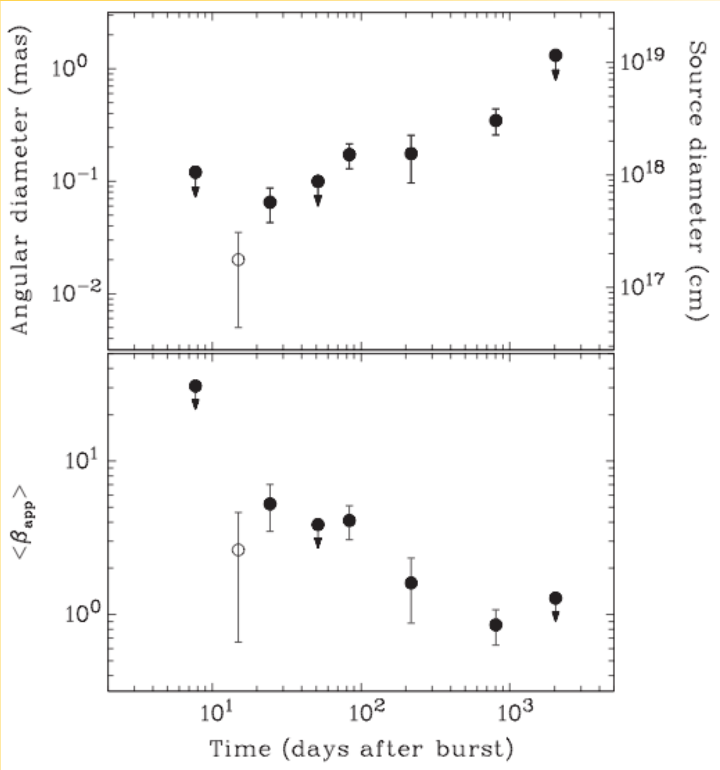


GRB 030329 (Berger et al. 2003)

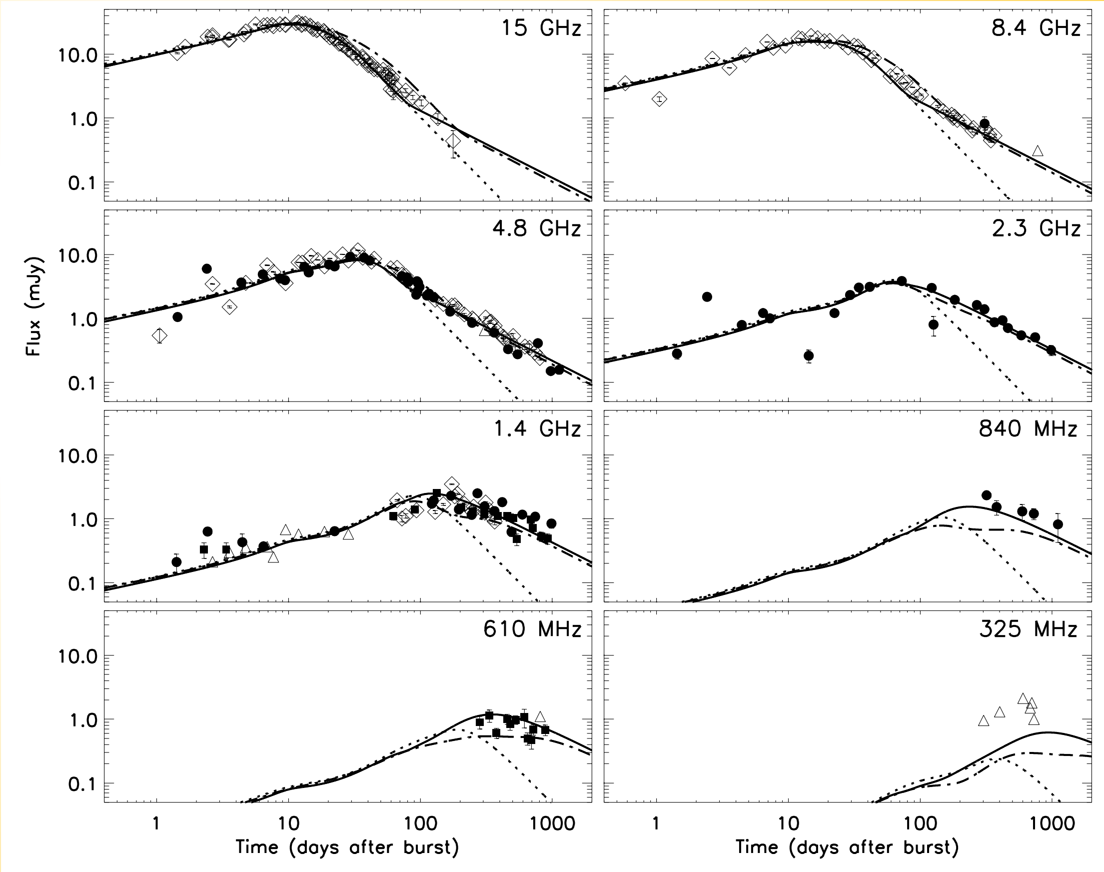
- Radio crucial: pin down evolution of peak flux, peak frequency, self-absorption frequency
- Radio scintillation: source size constraints, but with caveats

GRB 030329: Long Radio Follow-Up

- Blast wave evolution: from relativistic to non-relativistic
- Sideways spreading → (quasi-)spherical at late(?) times



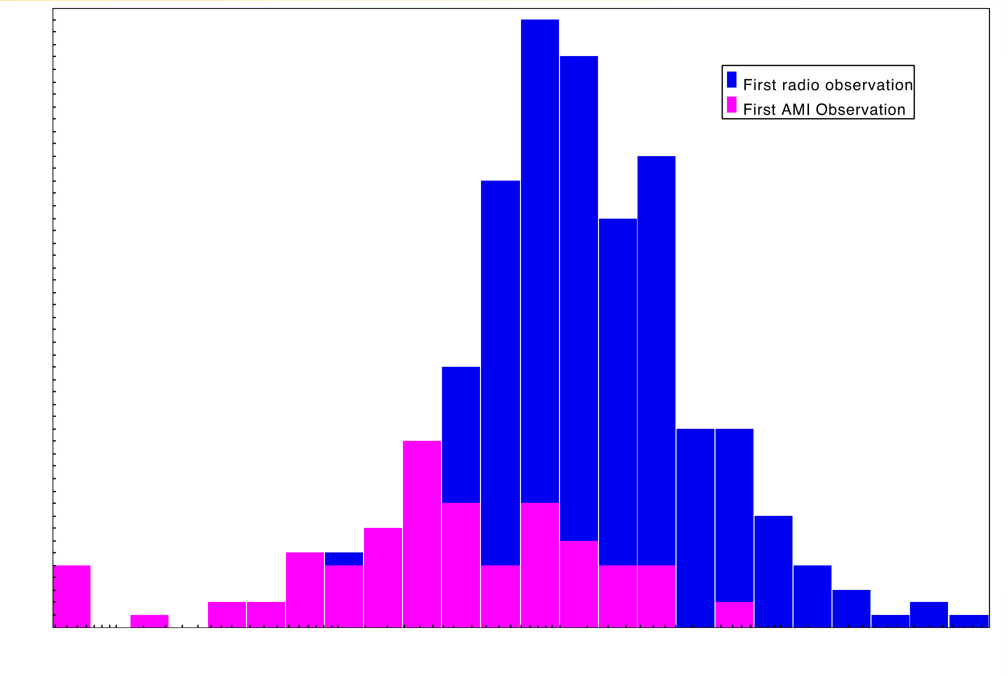
Taylor et al. 2004, 2005;
Pihlstrom et al. 2007;
Granot & AJvdH 2014



Frail et al. 2005; AJvdH et al. 2005, 2008

Fast & Systematic Radio Follow-Up

- AMI Large Array at 15 GHz → first responses: 4-5 minutes
- System developed for other (new) radio observatories

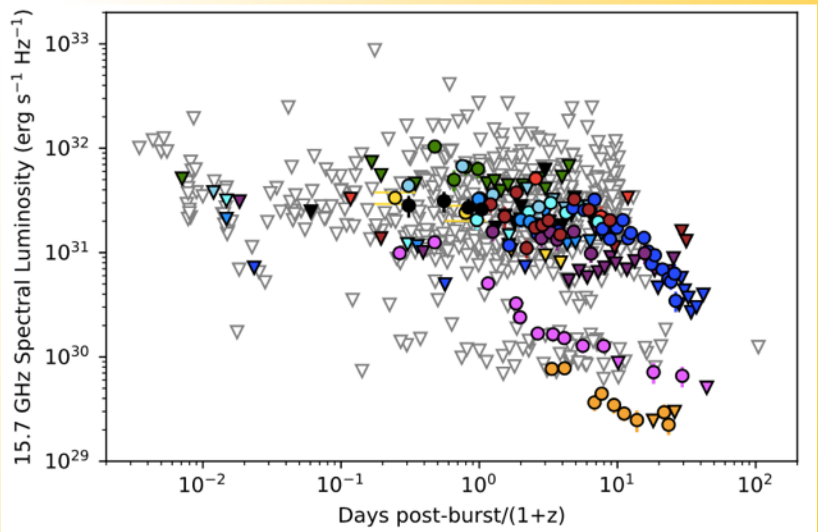


Chandra & Frail 2012;

Staley, Titterington et al. 2013;

Anderson, Staley, AJvdH et al. 2018

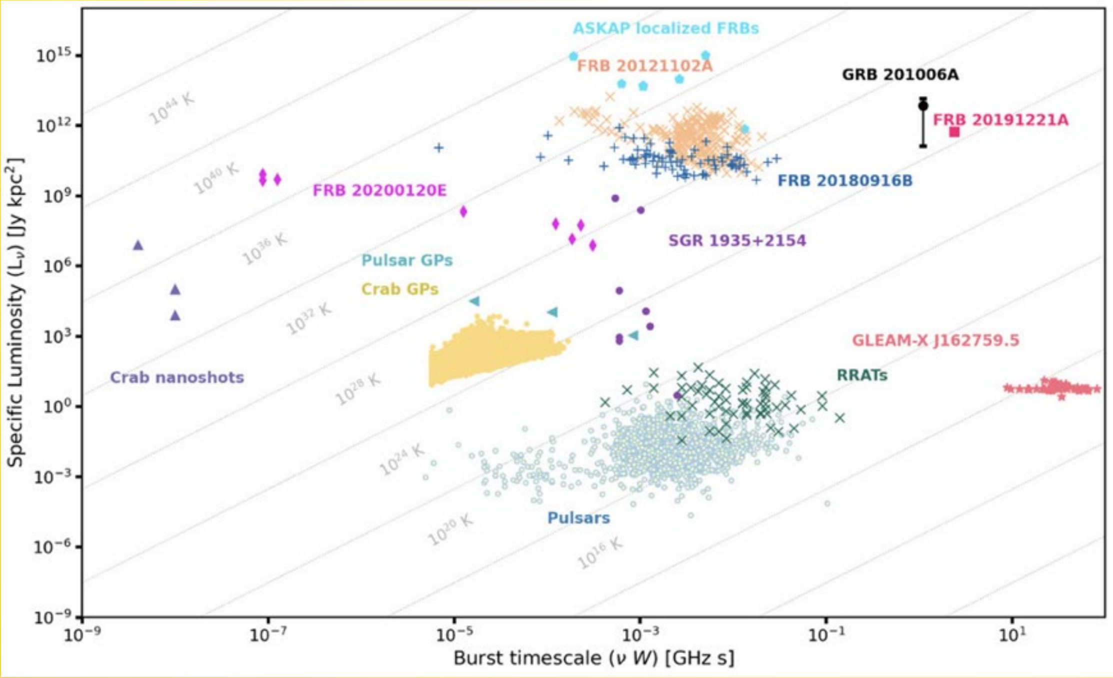
Anderson, Staley, AJvdH et al. 2018



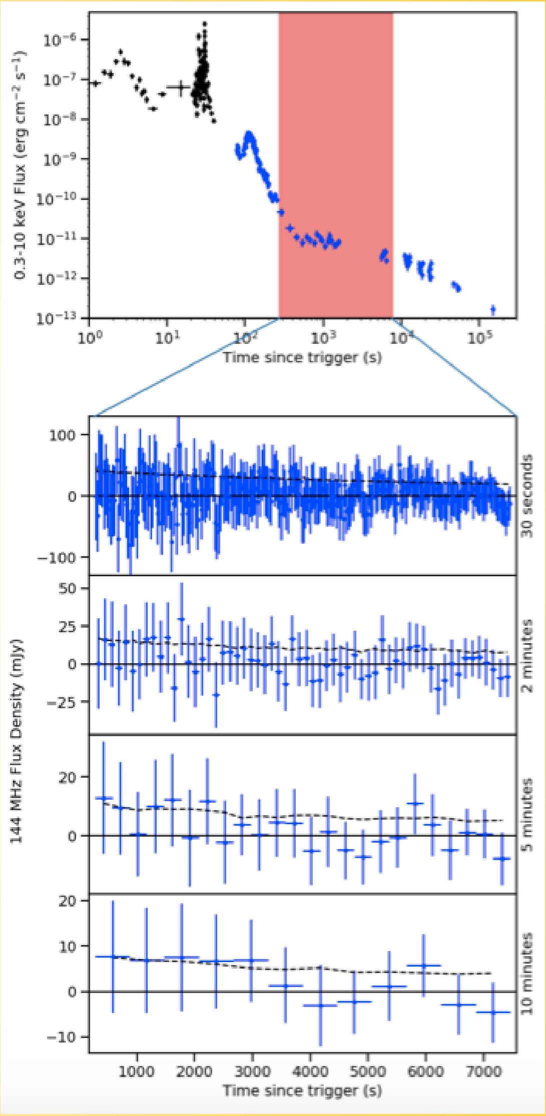
- Systematic AMI follow-up → 50% of Swift GRBs detected to 0.10 – 0.15 mJy

Searching for Coherent Radio Emission

- LOFAR observations starting few minutes after GRB triggers (similar for MWA)
- Various models proposed, but large uncertainties in predicted flux levels
- Candidate coherent radio flash



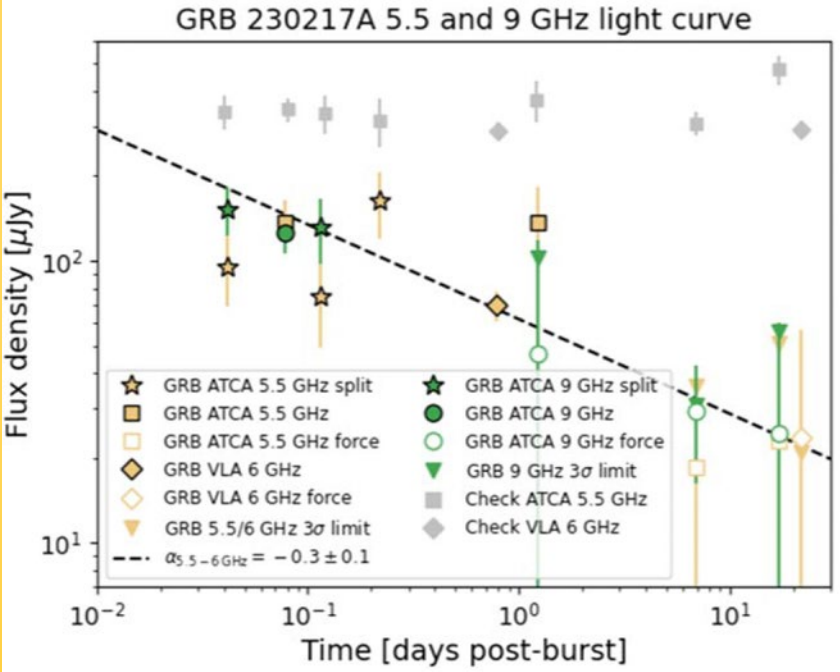
GRB 201006A (Rowlinson, de Ruiter et al. 2024)

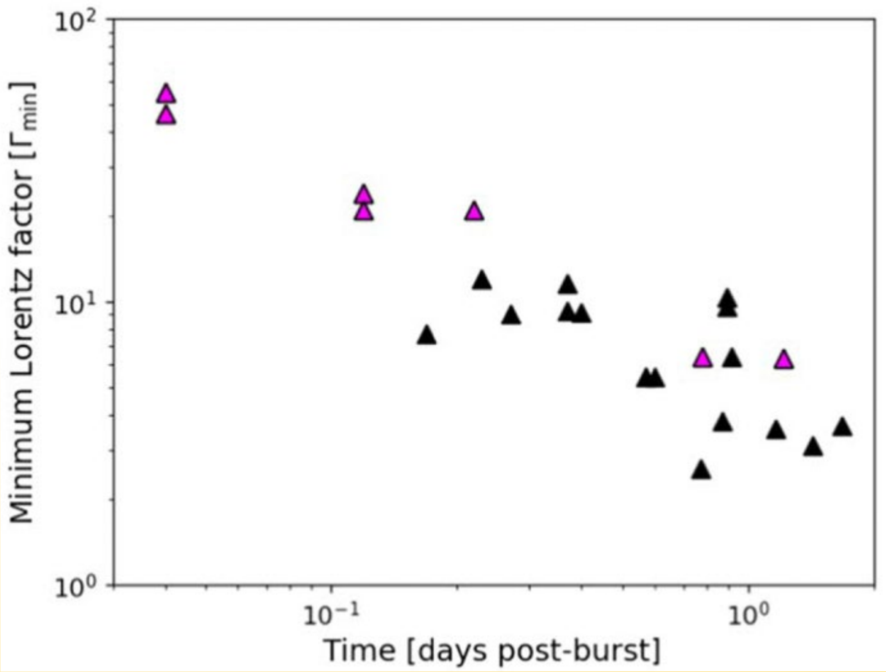


GRB 180706A (Rowlinson, Gourdji et al. 2019)

PanRadio GRB

- Large, multi-year program on ATCA (PI: Gemma Anderson)
- Systematic & unbiased: automated triggering & follow-up
- Observations starting after minutes to tens of minutes
- Earliest radio detections: from hours down to minutes!





Anderson, Schroeder, AJvdH et al. 2024

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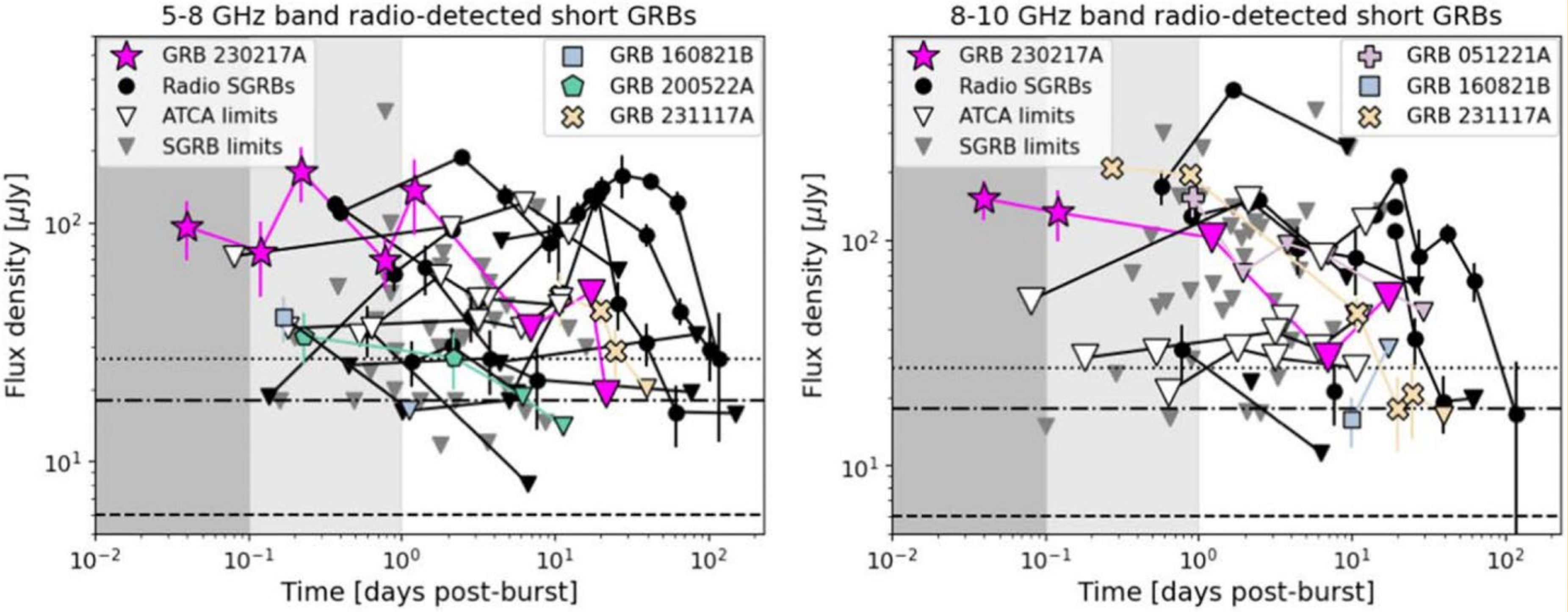
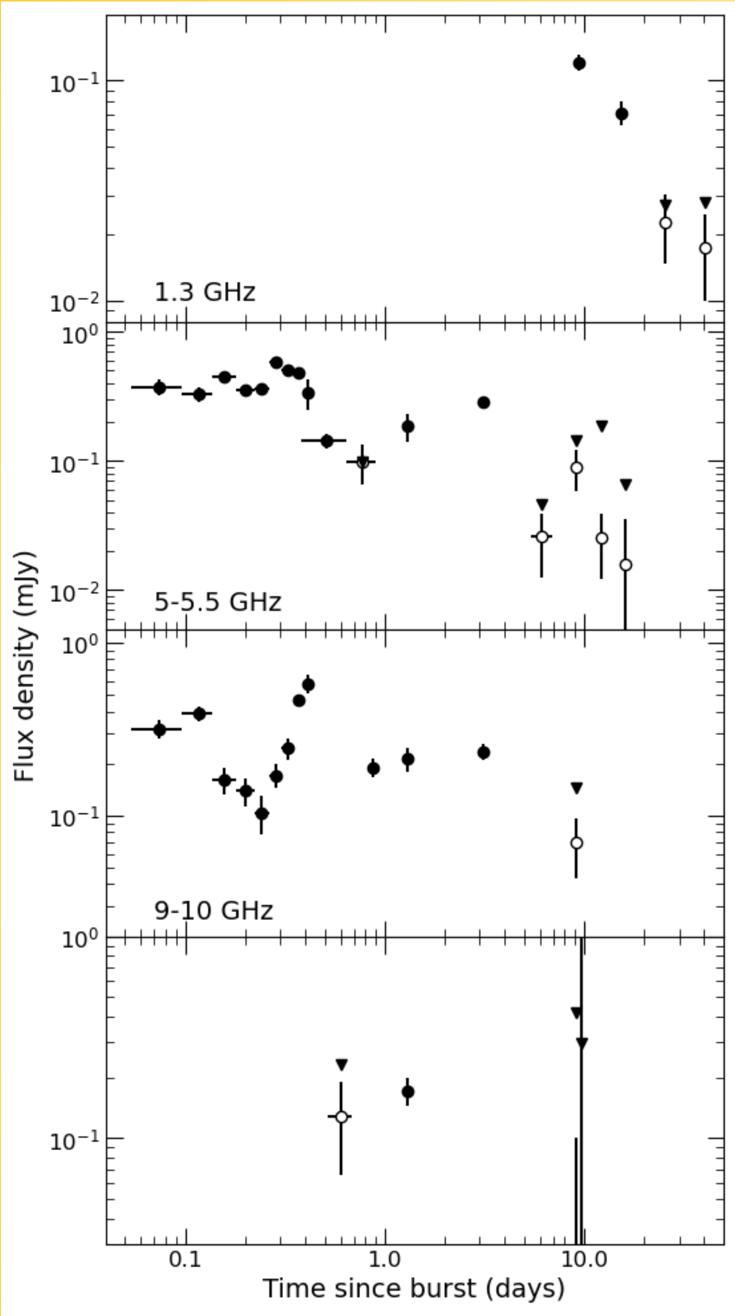
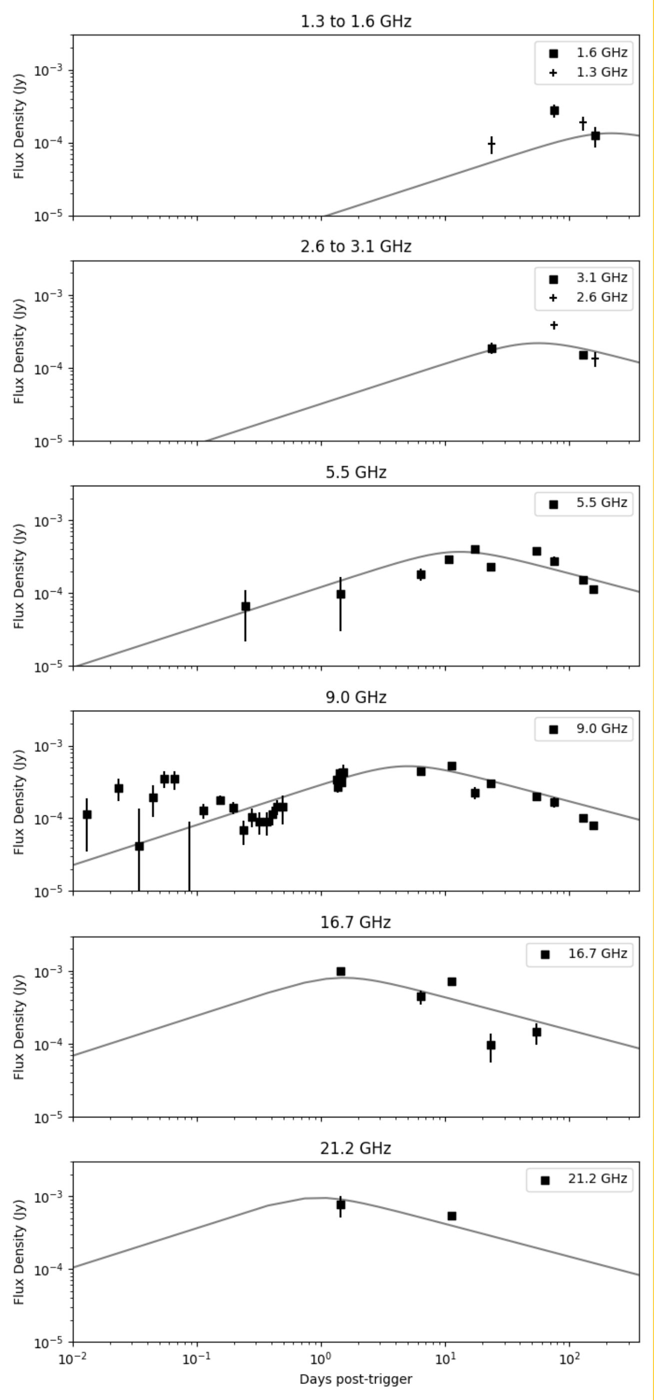


Anderson, Schroeder, AJvdH et al. 2024



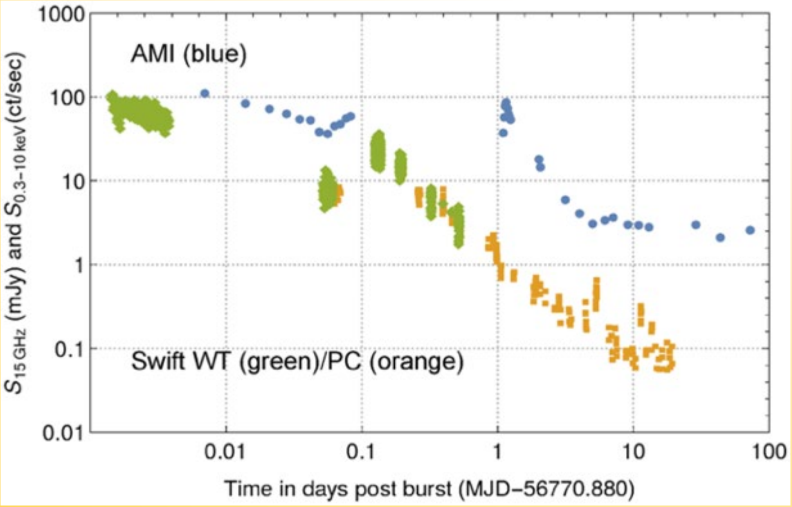
GRB 240205B (Chastain et al.,in prep.)



GRB 231117A (Anderson et al., in prep.)

Next Steps: VLA & ngVLA

- Automated triggering with the VLA
  - RSRO proposal accepted for 2025A semester (PI: AJvdH)
  - Focused on early GRB evolution, including polarization
  - Goals: great GRB science & new capability for general use
- Part of planning for ngVLA (?)
  - Sensitivity + time domain
  - Impact for many transient science cases



M dwarf binary DG CVn (gamma-ray superflare; Fender, Anderson et al. 2015)

Conclusions

- Radio astronomy at forefront of time-domain, multi-wavelength & multi-messenger astrophysics
  - Commensal image searches for new transients
  - Automated follow-up observations of fastest transients
- Imaging at timescales of seconds feasible
  - New observational phase space for discovery
  - Challenging if RFI not addressed properly and/or transient science not considered when planning RFI mitigation
- Great opportunities for time-domain radio astronomy
  - Sensitive large-field-of-view observatories, e.g., DSA-2000
  - More sensitive arrays for targeted observations, e.g., ngVLA