Radio View on Gamma-Ray Burst Extremes

Alexander van der Horst

THE GEORGE WASHINGTON UNIVERSITY

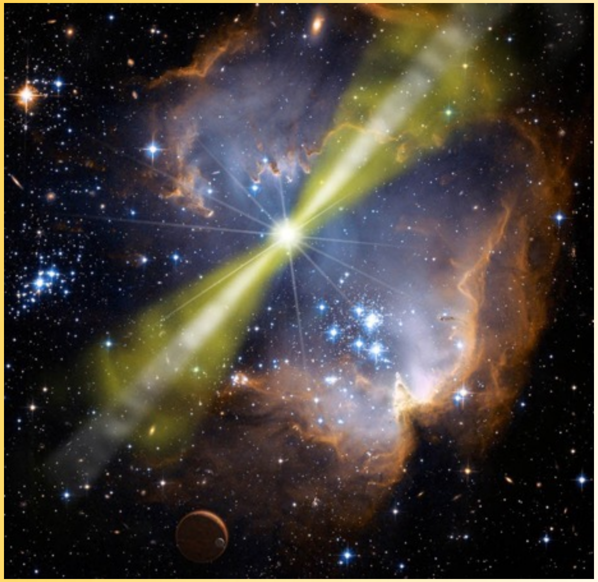
WASHINGTON, DC

NTNU – Department of Physics

22 February 2023

Explosive Transients Galore

Gamma-Ray Bursts



Stellar deaths

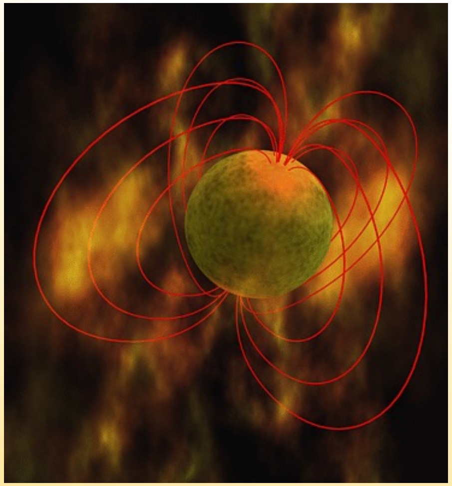
Neutron stars

Black holes

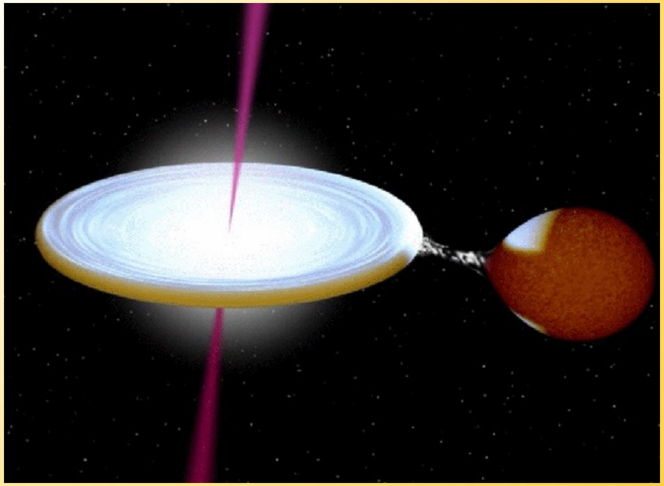
(and more…)

Supernovae

Compact binary mergers



Magnetars



X-ray binaries

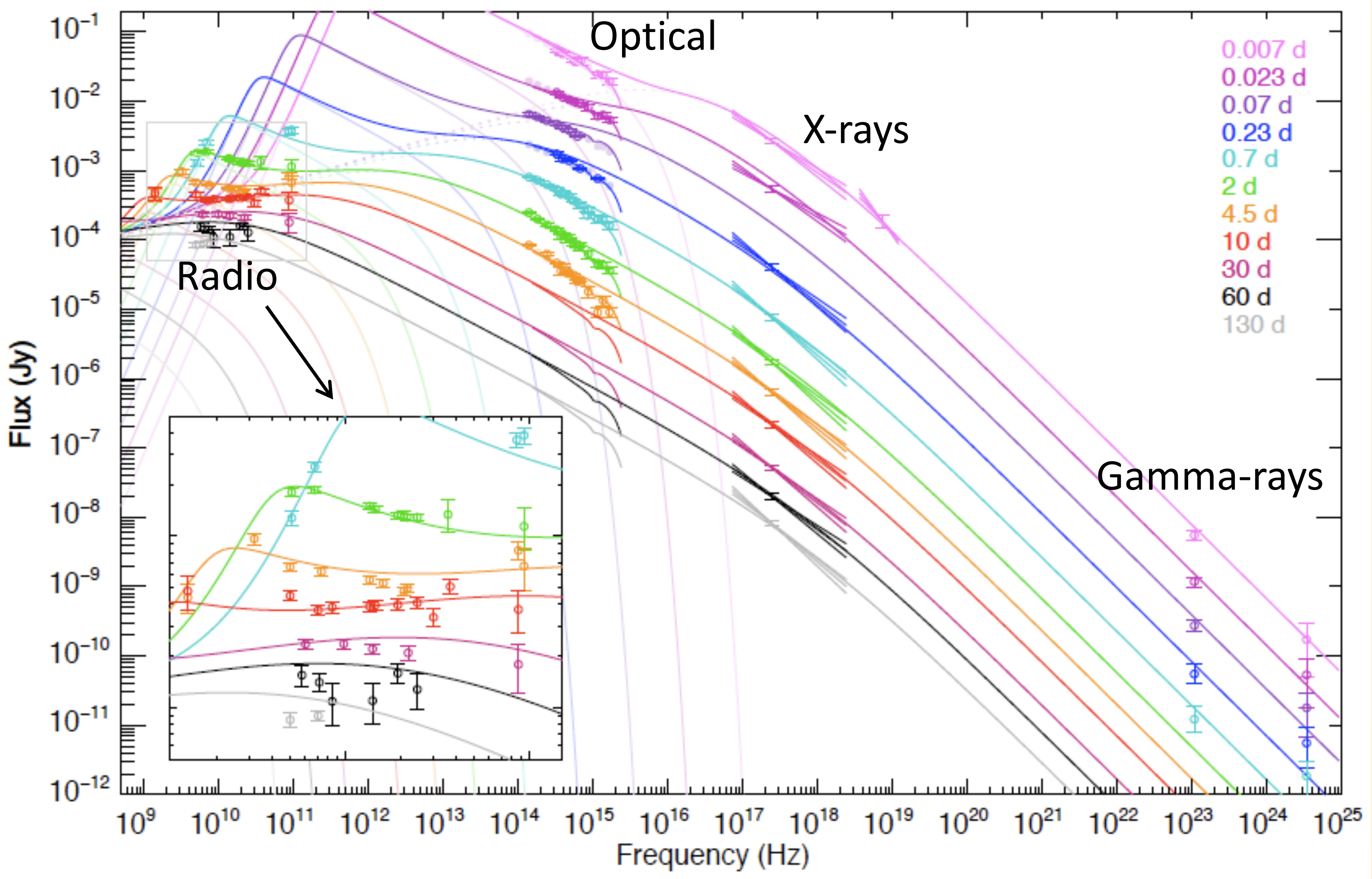
Physics of Explosive Transients

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!

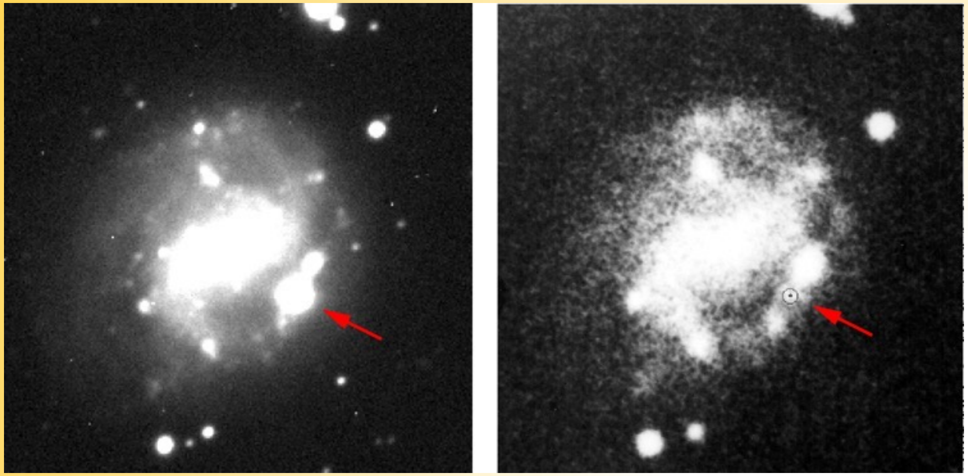
GRBs: Multi-Wavelength Transients

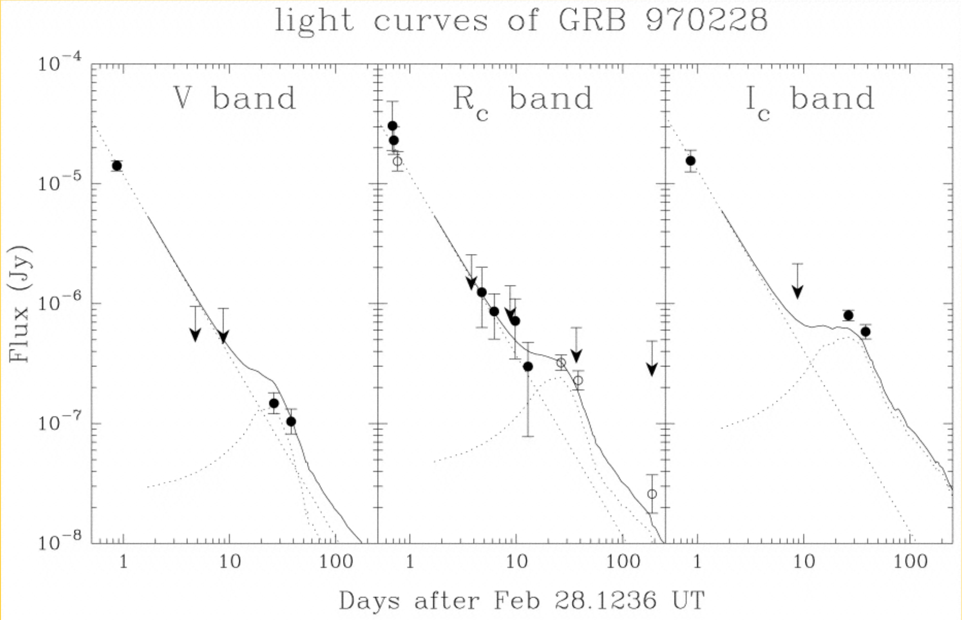


GRB 130427A (Perley et al. 2014)

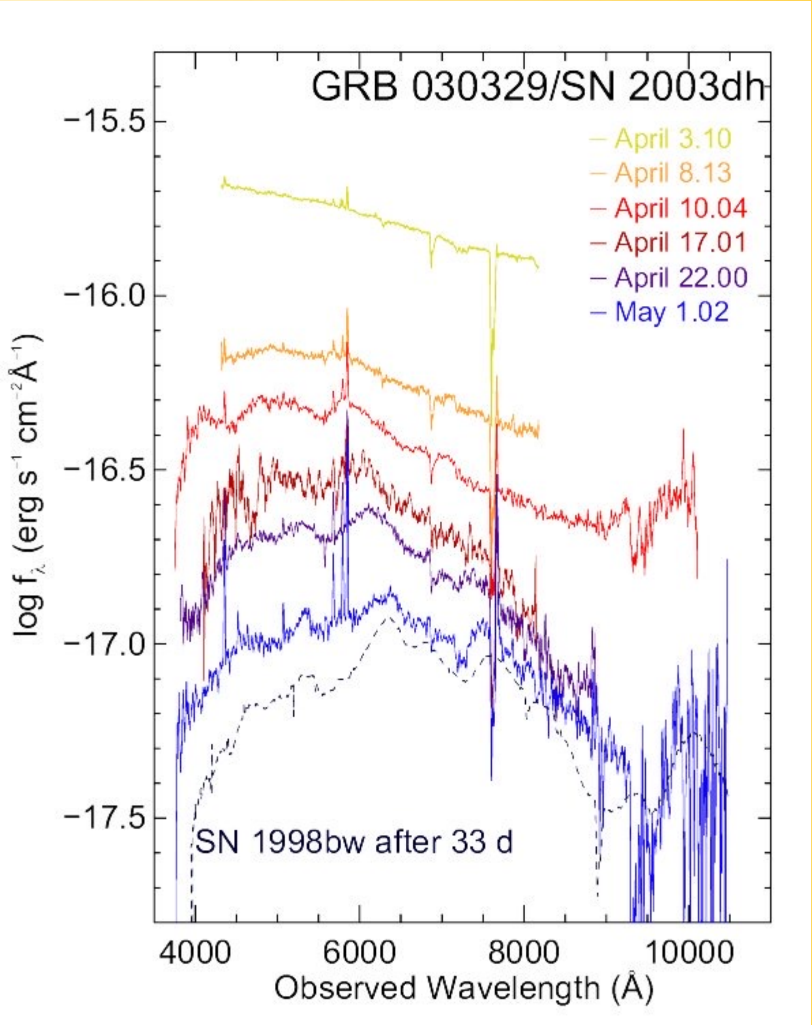
Long GRBs: Massive Stellar Explosions

Galama et al. 1998



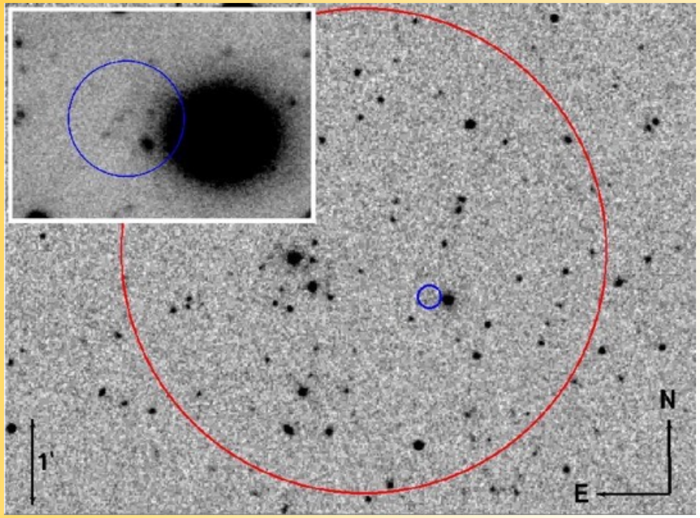


Galama et al. 1999

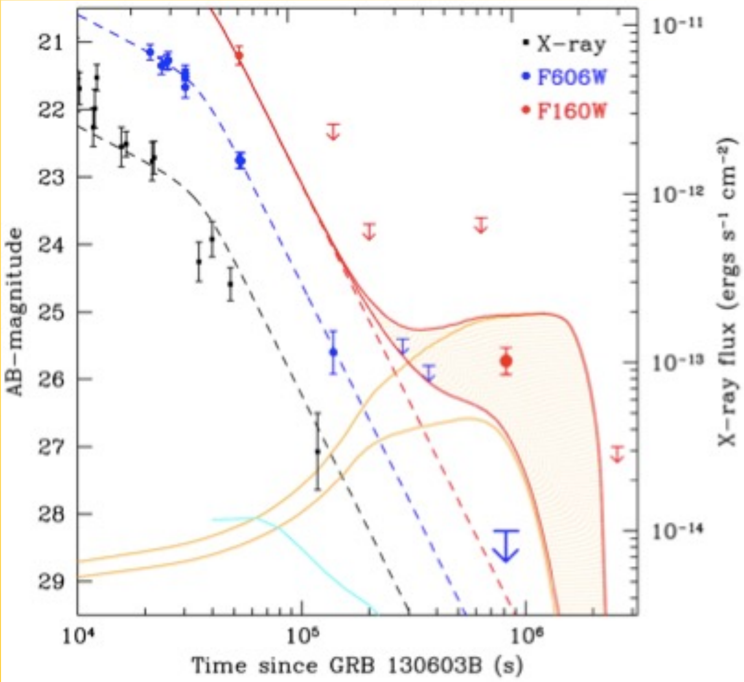


Hjorth et al. 2003

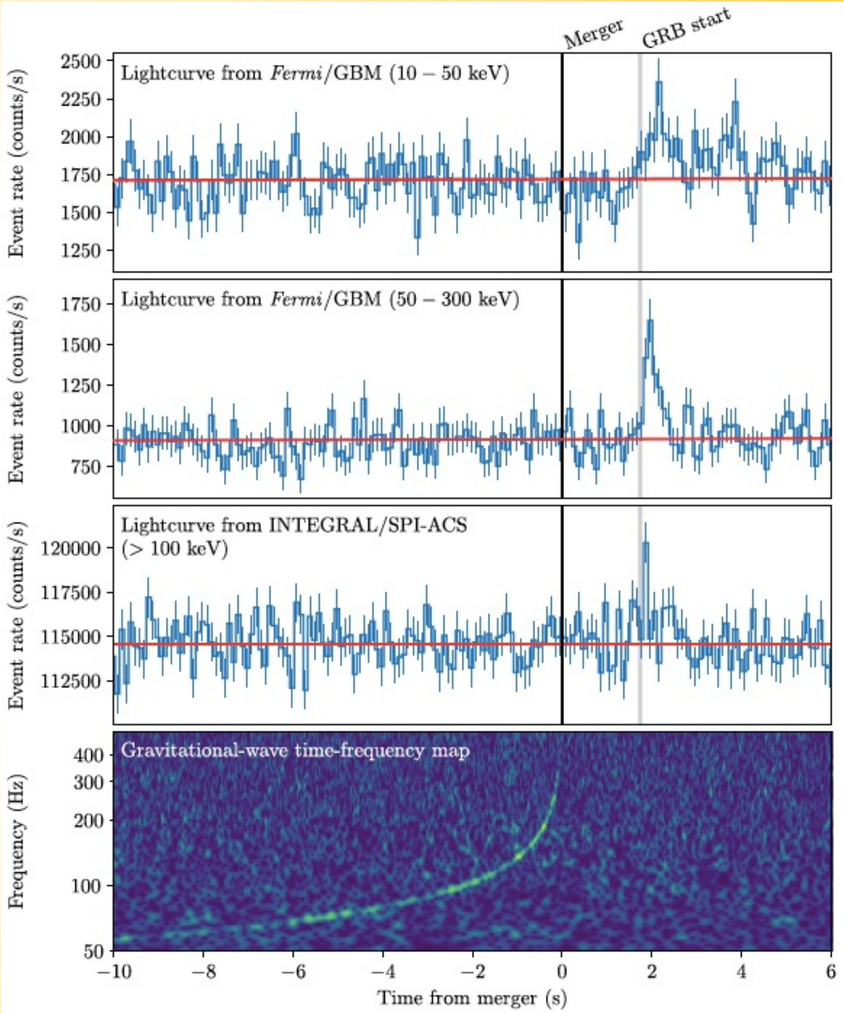
Short GRBs: Compact Binary Mergers



Gehrels et al. 2005



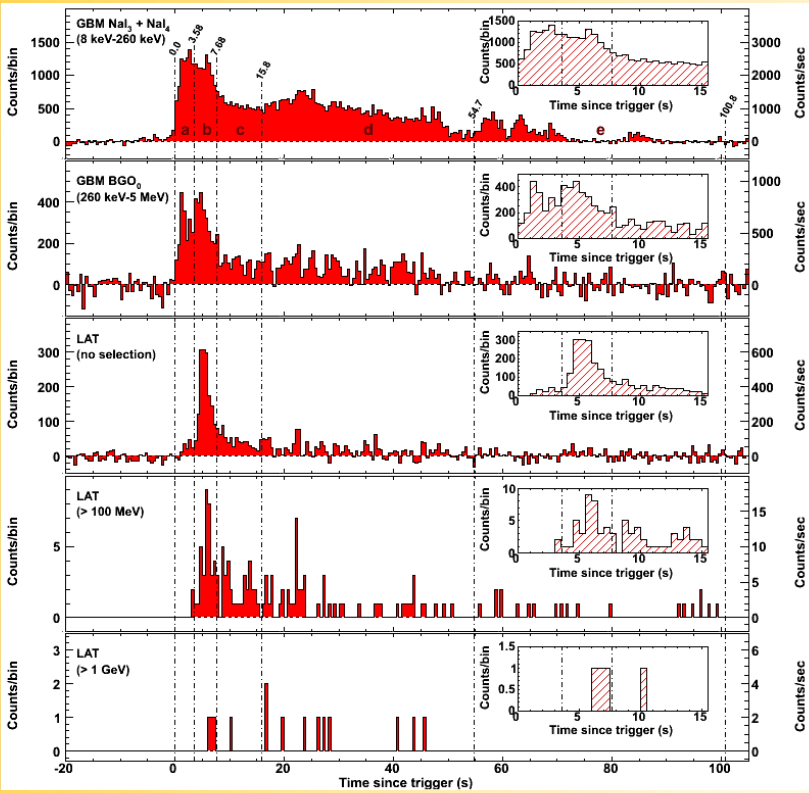
Tanvir et al. 2013



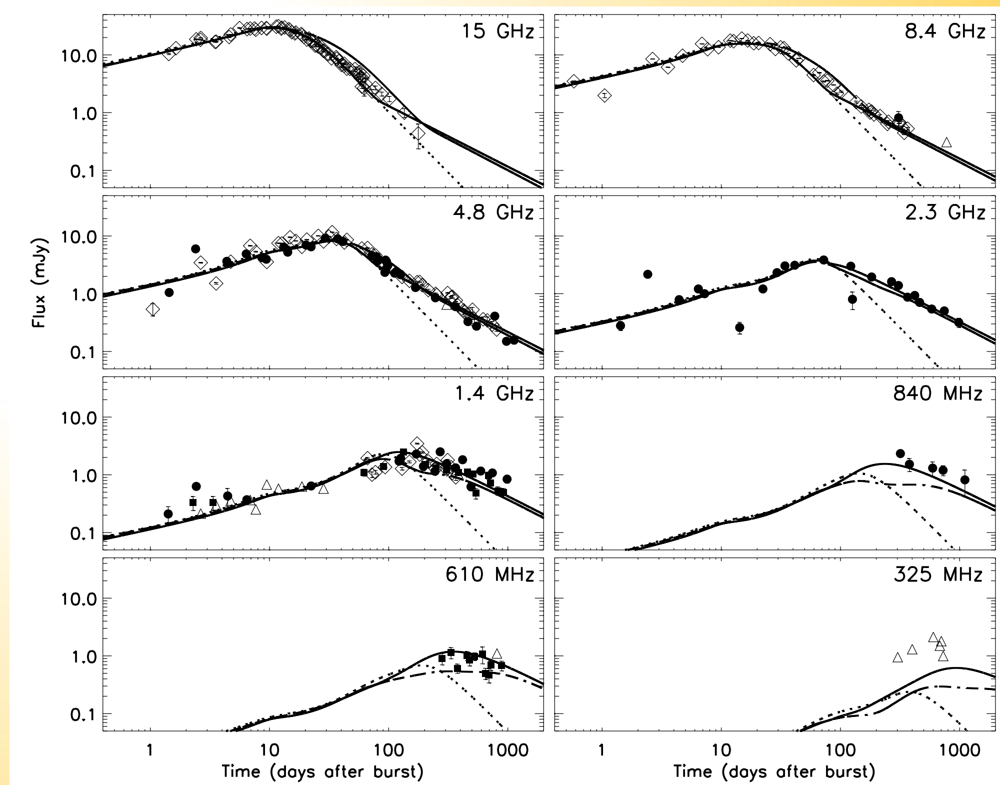
LIGO & Virgo Collaborations, Fermi GBM, INTEGRAL

Multi-Wavelength & Multi-Timescale

GRB 080916C (Abdo et al. 2009)



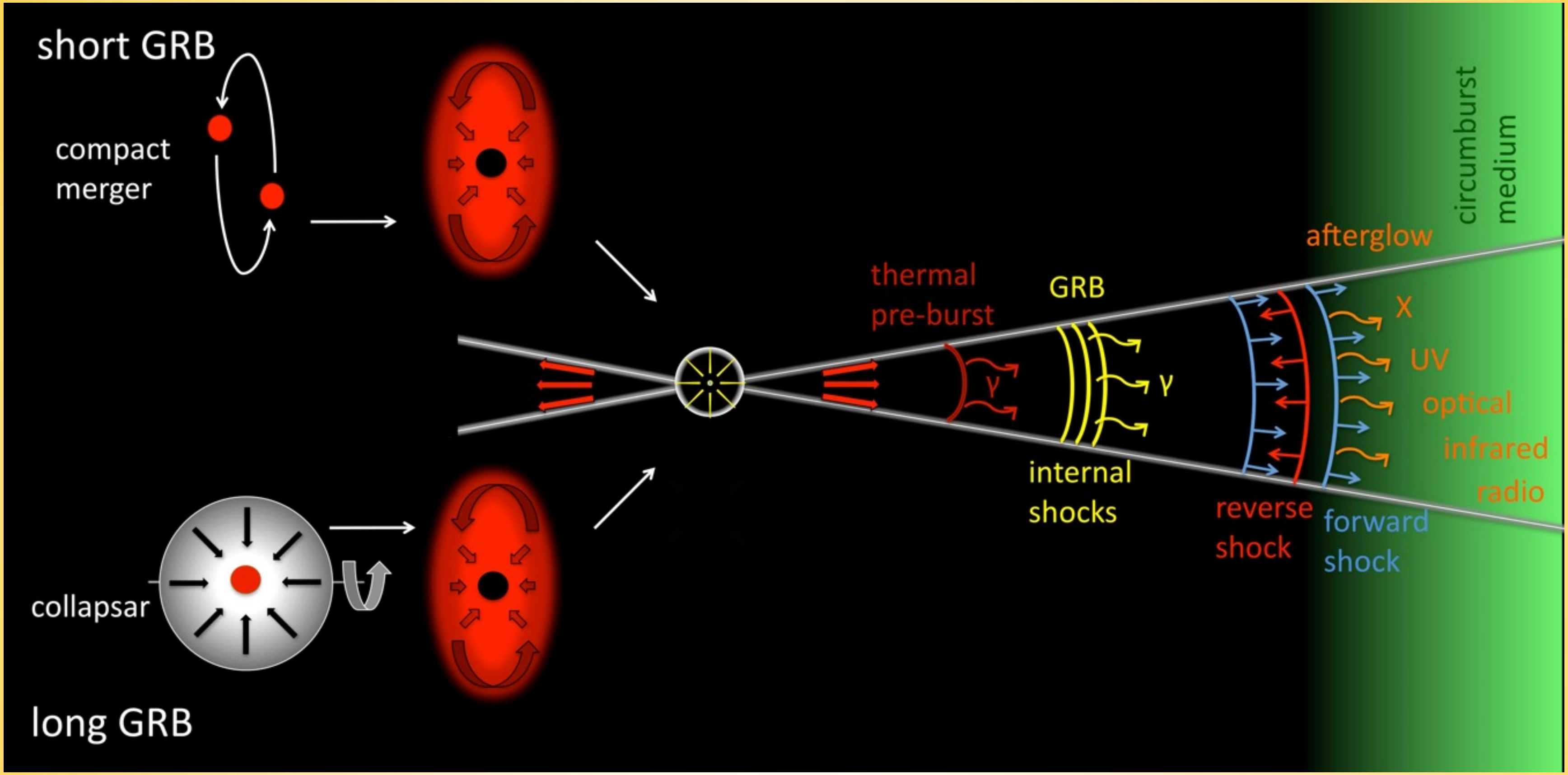
Seconds – Years



GeV – GHz

GRB 030329 (van der Horst et al. 2008)

Relativistic Blast Wave Model

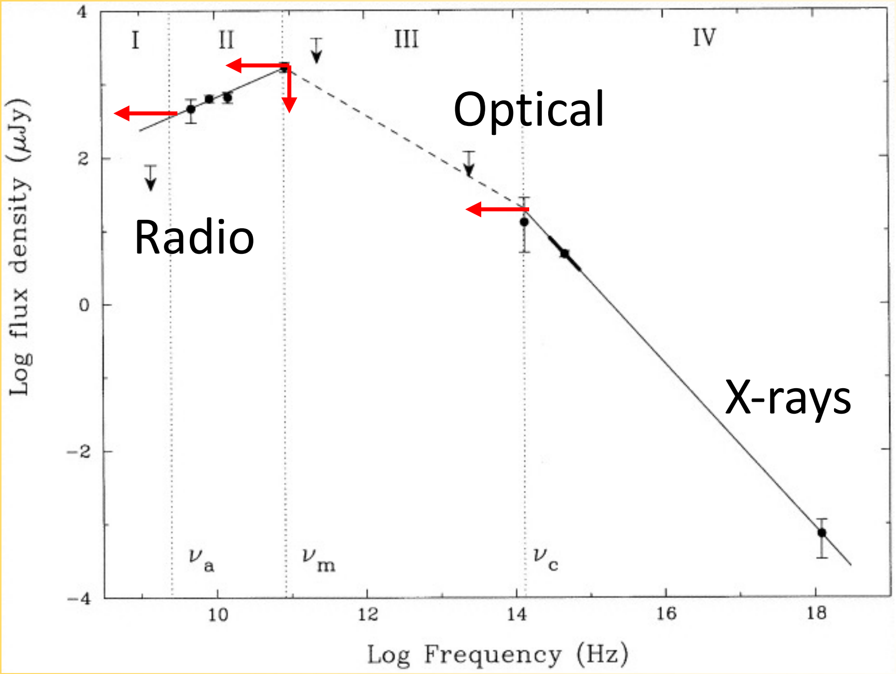


Meszaros & Rees 1992; Rees & Meszaros 1992 (Figure: Gomboc 2012)

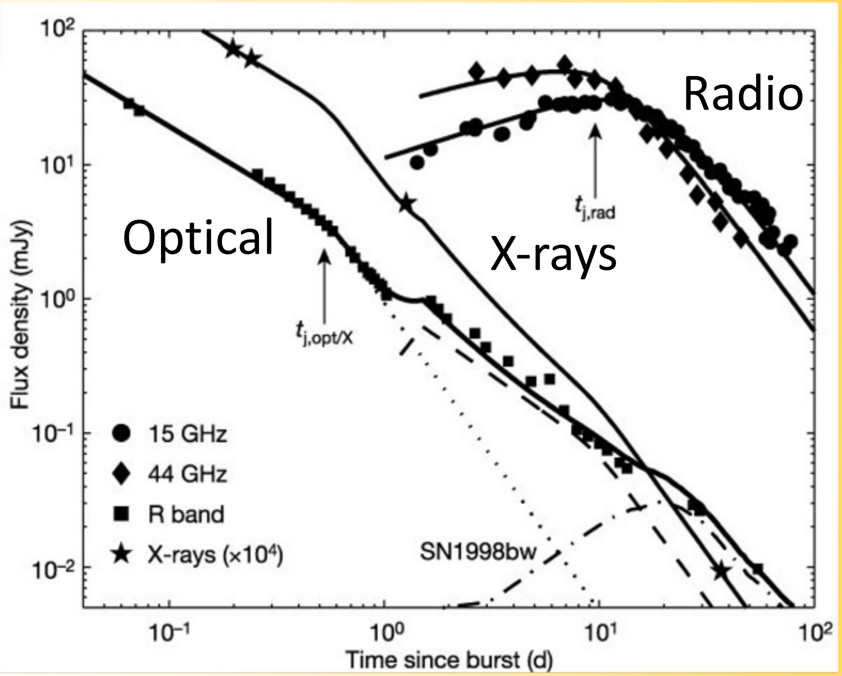
- Afterglow synchrotron emission → relativistic beaming: $\vartheta_{rel} = 1/\Gamma$
- Collimated relativistic outflow → jet opening angle: ϑ_0
- Initially $\vartheta_{rel} << \vartheta_0$, but blast wave decelerating

Modeling Spectra & Light Curves

Evolving spectrum ⟶ Light curves



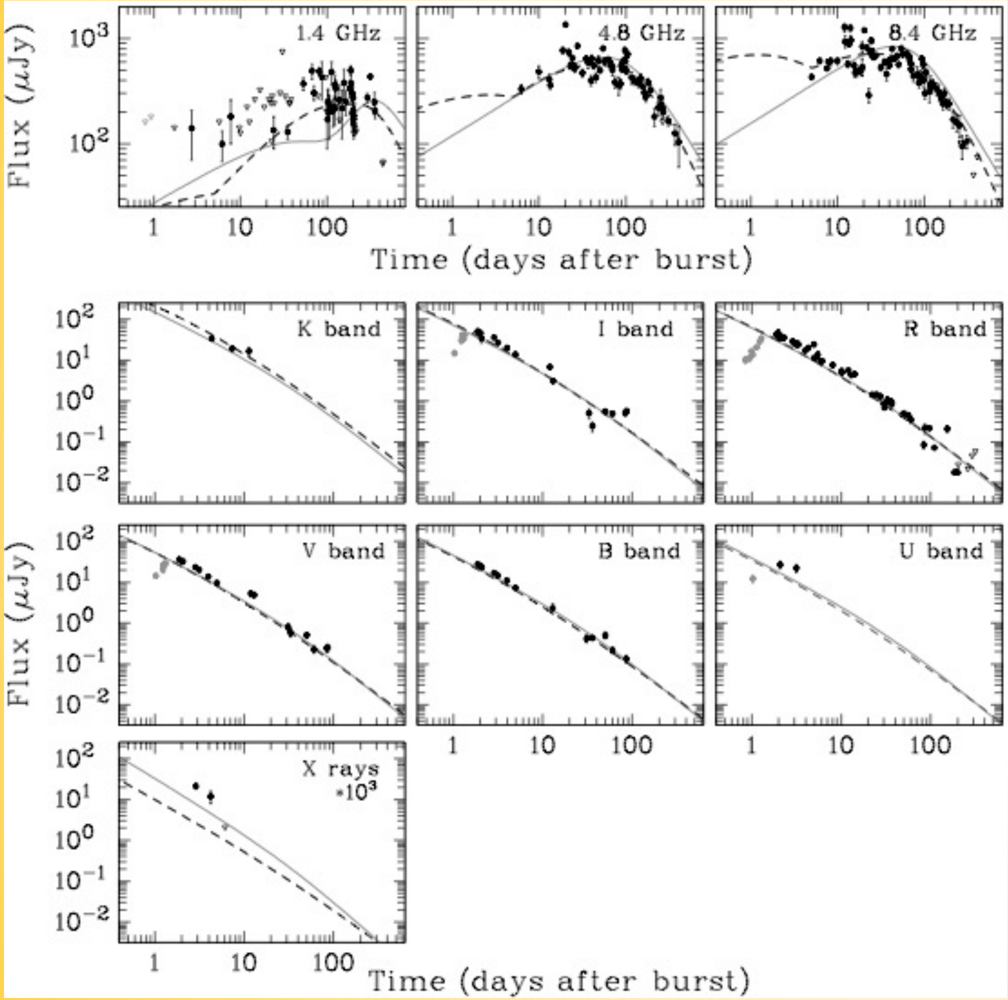
GRB 970508 (Wijers & Galama 1999)



GRB 030329 (Berger et al. 2003)

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

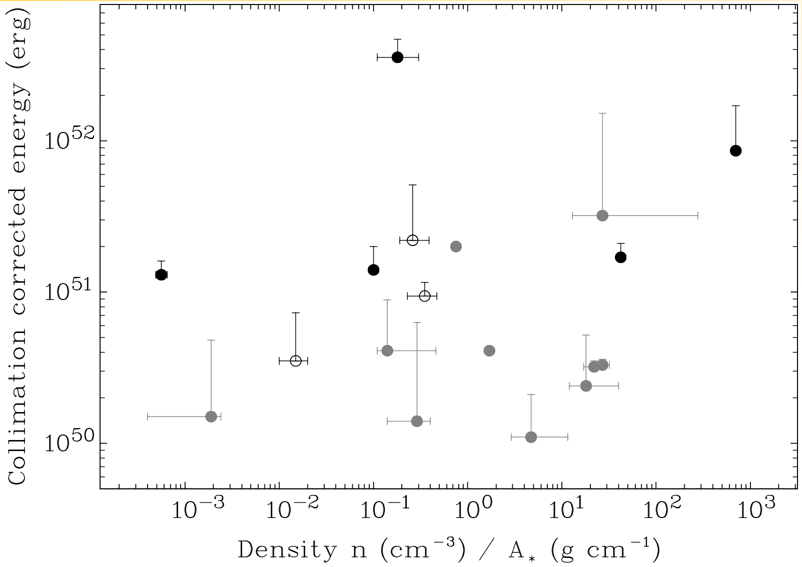
Physical Parameters



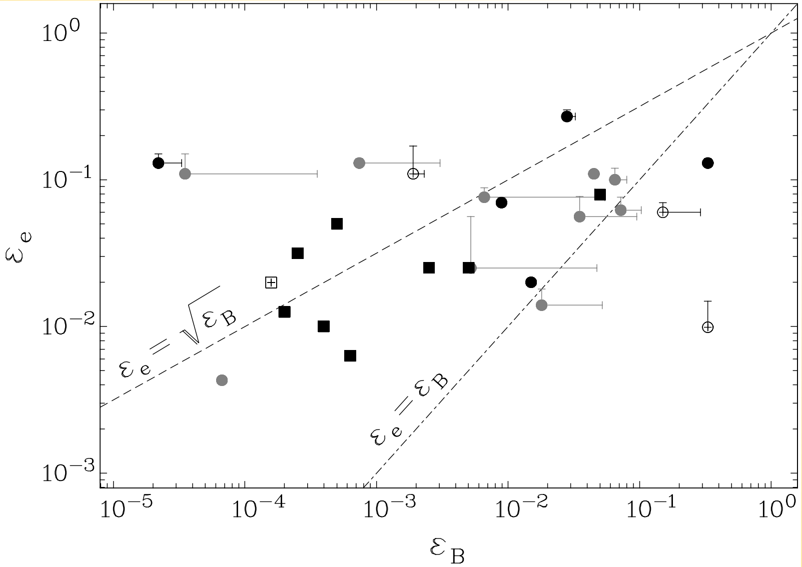
GRB 970508 (Leventis, van der Horst, van Eerten & Wijers 2013)

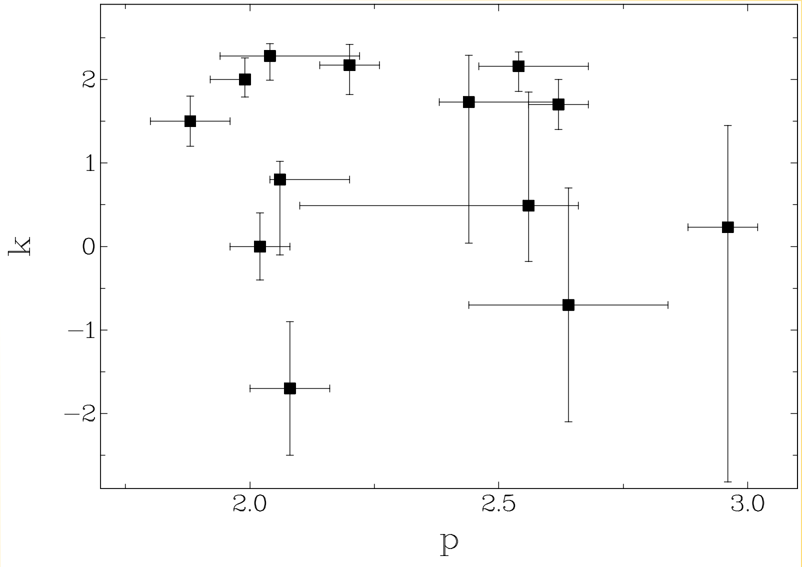
- Explosion parameters
  - Blast wave energy
  - Density of ambient medium
  - Structure of ambient medium
  - Jet opening angle
- Radiation parameters
  - Electron energy distribution
  - Energy in electrons
  - Energy in magnetic field
- Observer parameters
  - Observing angle
  - Redshift & luminosity distance
  - Observer time & frequency

Physical Parameter Distributions



- Broadband modeling: large spread, between and within various studies
- Only optical & X-rays: *p* and density structure not universal



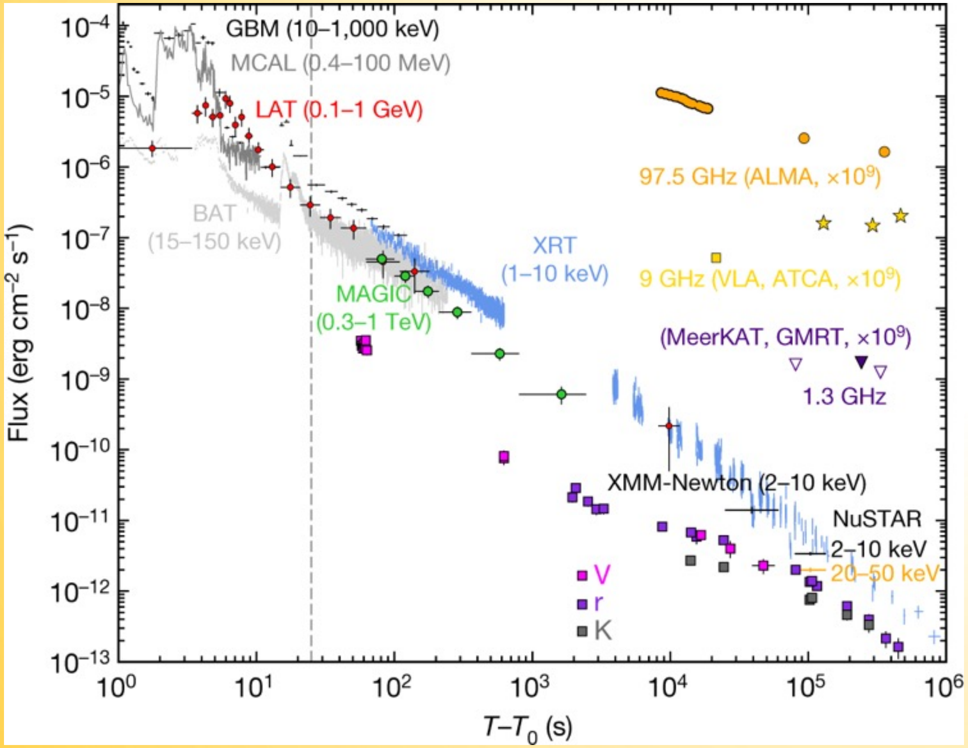


Cenko et al. 2011;

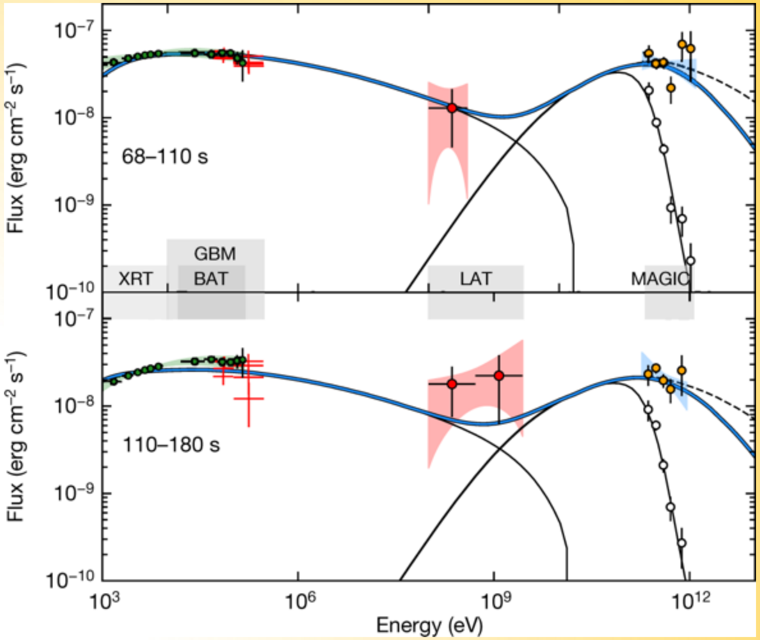
Granot & van der Horst 2014

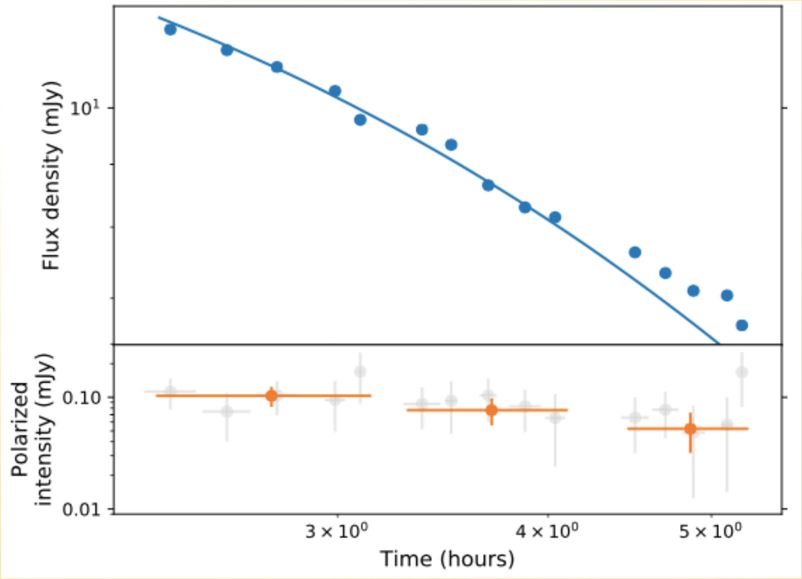
GRB 190114C: GHz to TeV

- 17 orders of magnitude in frequency: synchrotron & synchrotron self-Compton
- ALMA polarization detection



Acciari et al. 2019

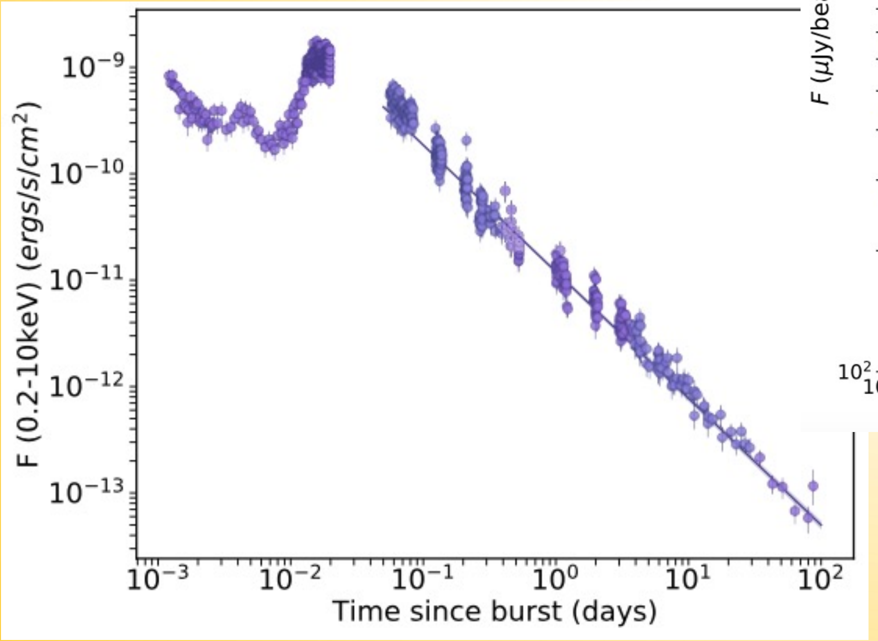


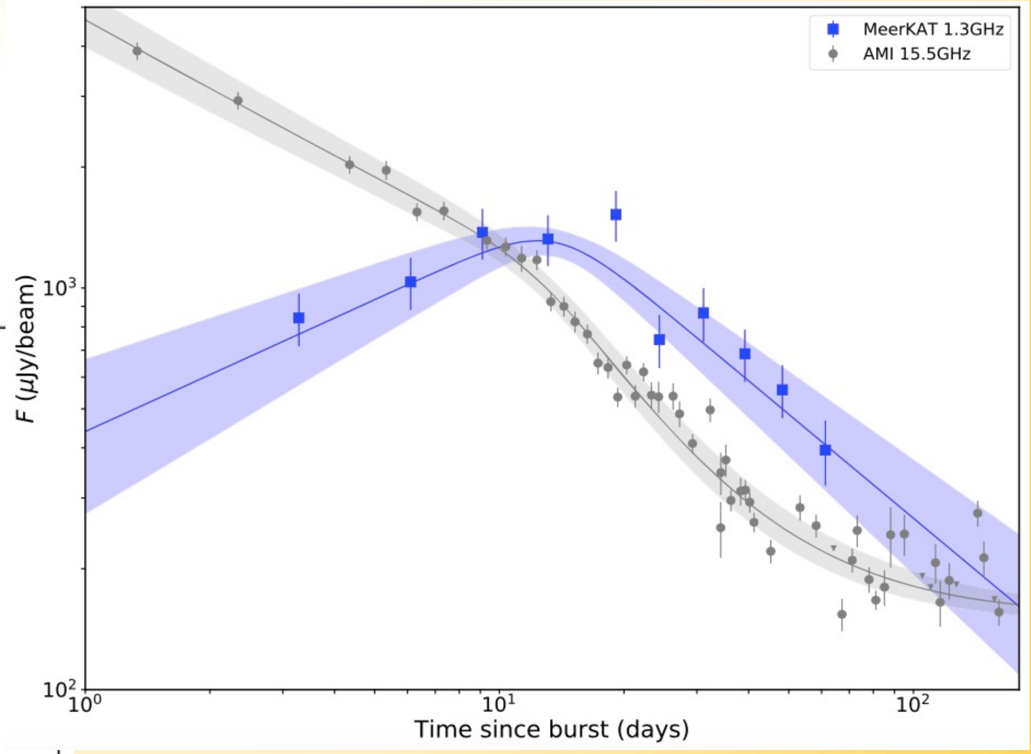


Laskar et al. 2019

GRB 190829A: GHz to TeV

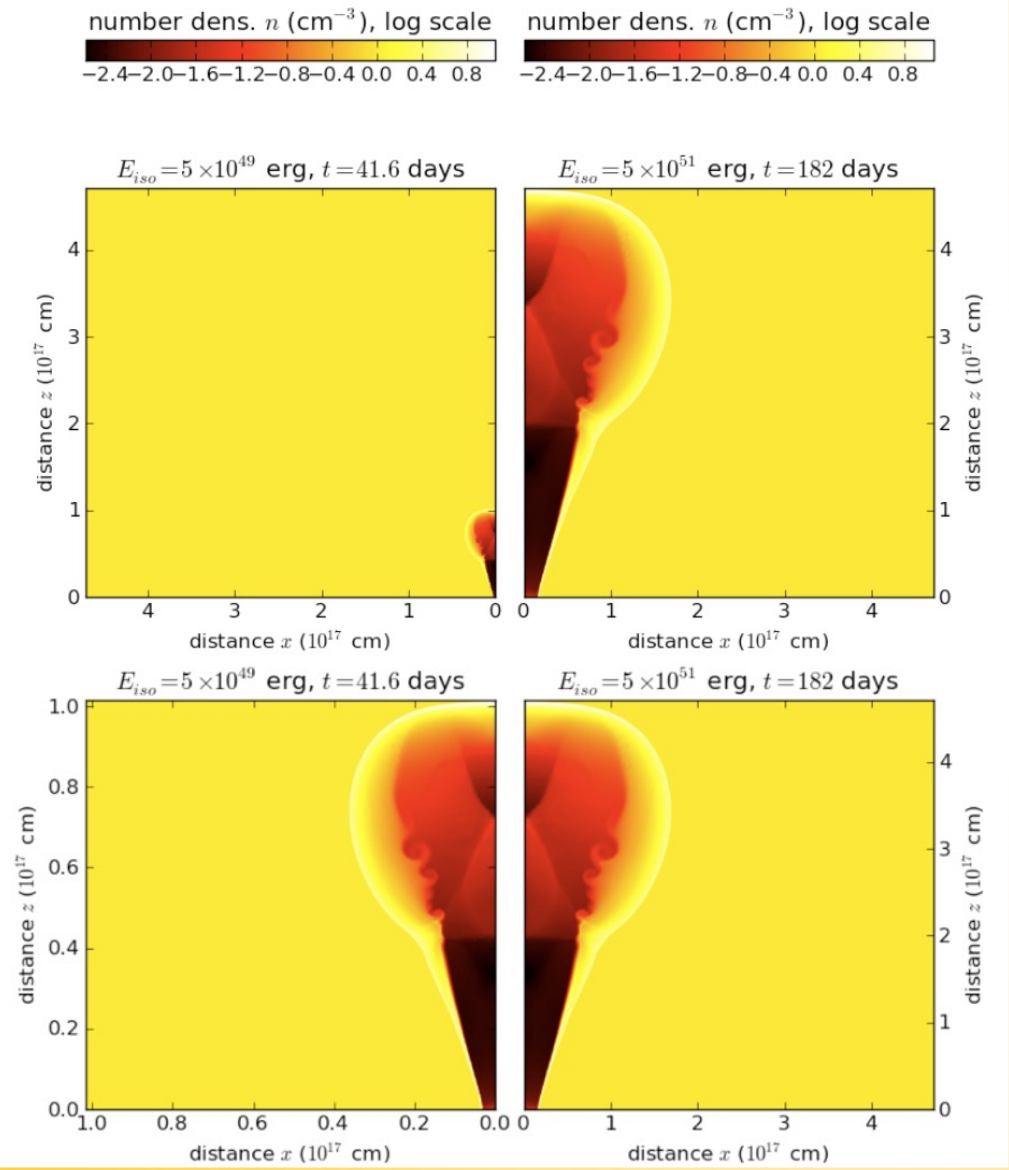
- Well-sampled radio light curves: forward & reverse shock
- Very-high energy emission GRBs: same parent distribution as other radio-detected GRBs





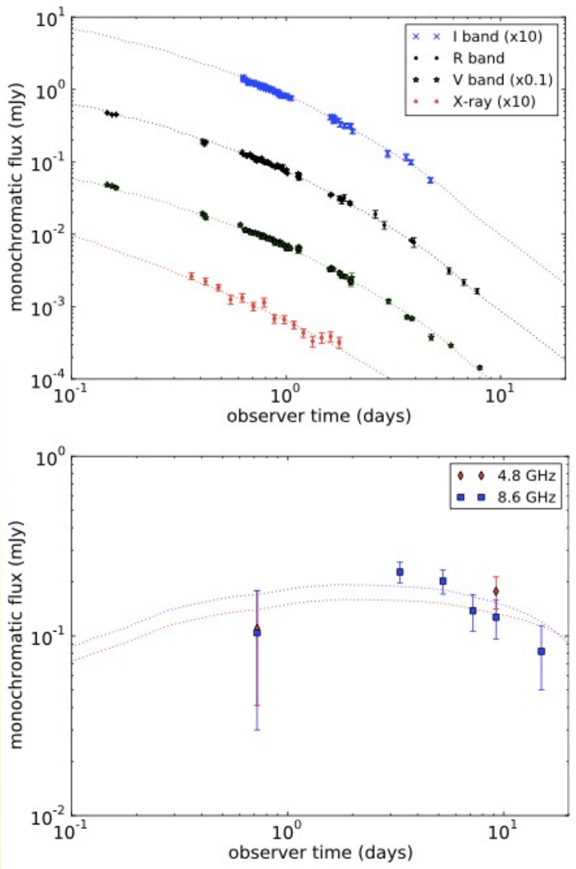
Rhodes et al. 2020

Breakthroughs in Modeling



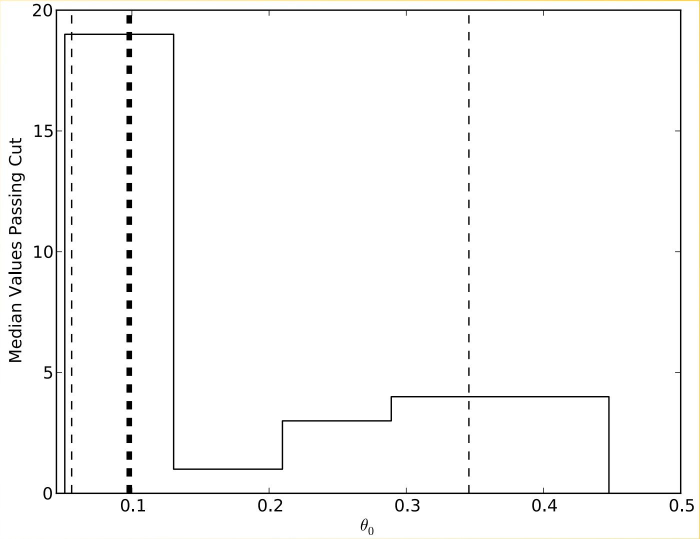
van Eerten, van der Horst & MacFadyen 2012

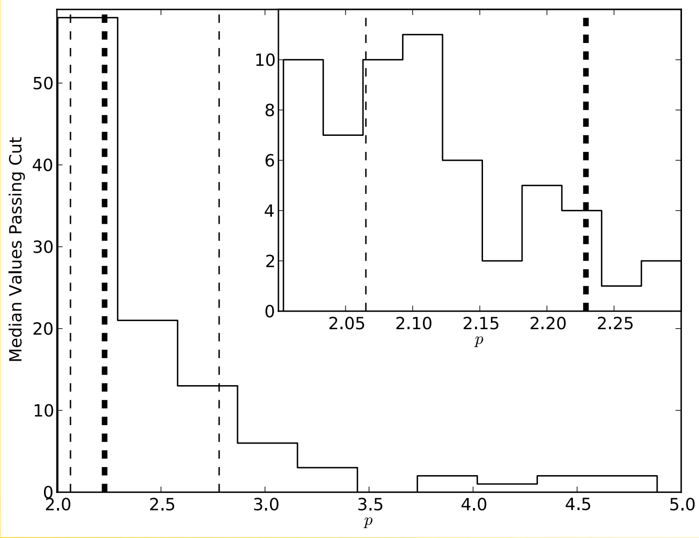
- Modeling based on 2D hydrodynamic simulations
- 2D dynamics scale invariant
- Valid for entire evolution



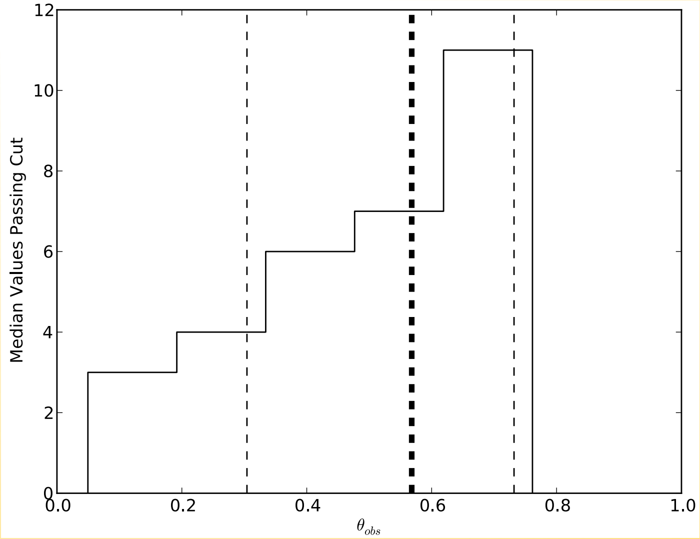
Constraints from X-Ray Light Curves

- Using simulations-based modeling: p and ϑ_0 not universal
- ϑ_0 / ϑ_{obs} broad distribution
  - Two jet breaks instead of one
  - Smearing of (or missing) jet breaks
  - Beaming-corrected energetics incorrect



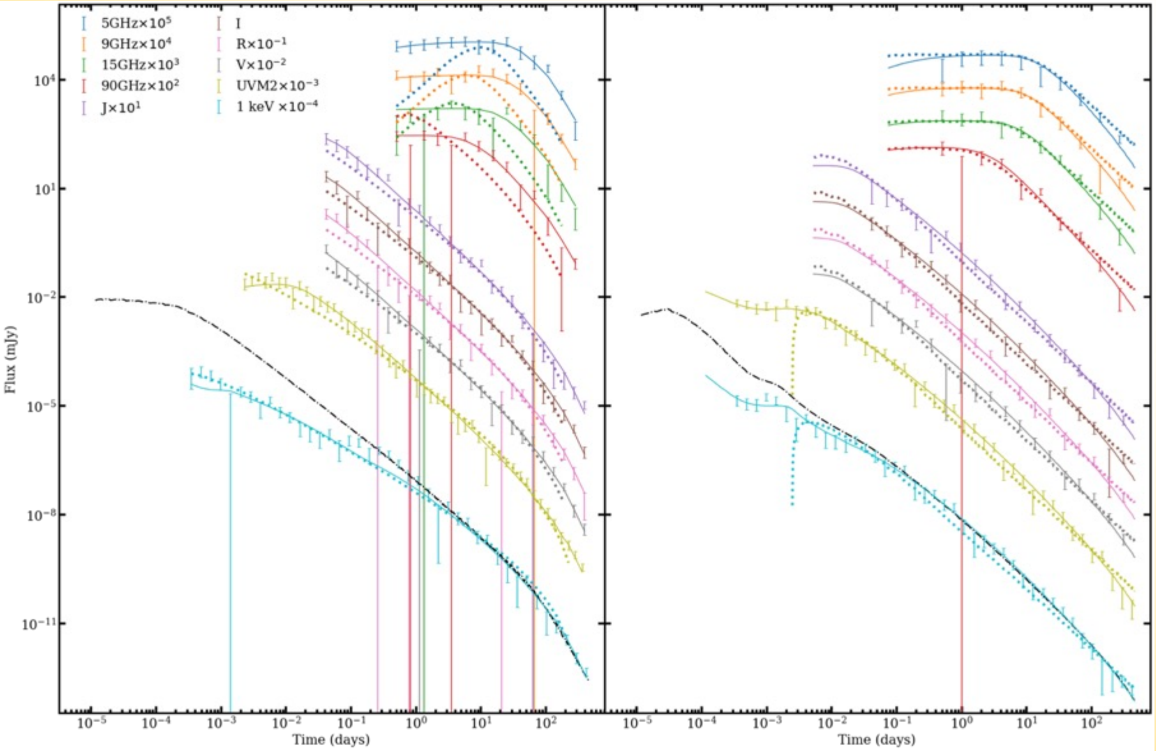


Ryan et al. 2015

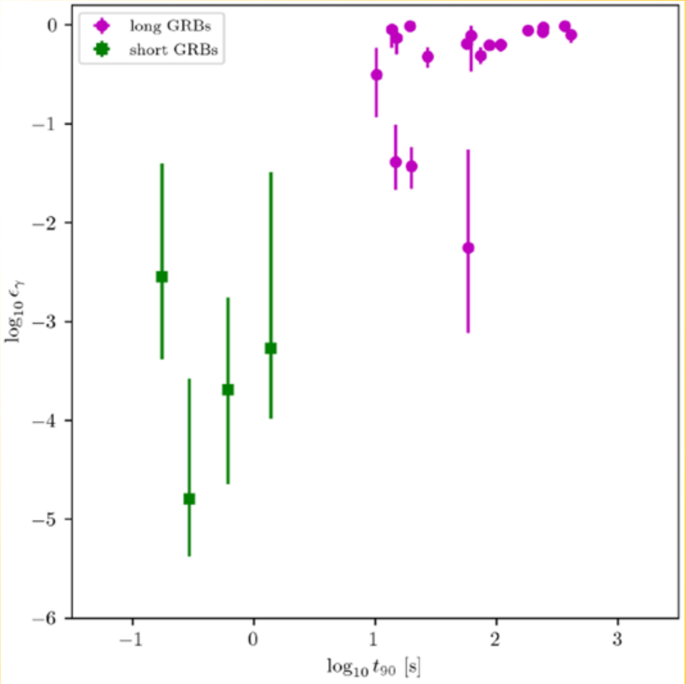


Advanced Modeling Methodology

- Include various jet structures, driven by GW 170817
- Include more cooling mechanisms, e.g., Synchrotron Self-Compton
- New statistical techniques, e.g., Gaussian Processes → take systematics in the data into account



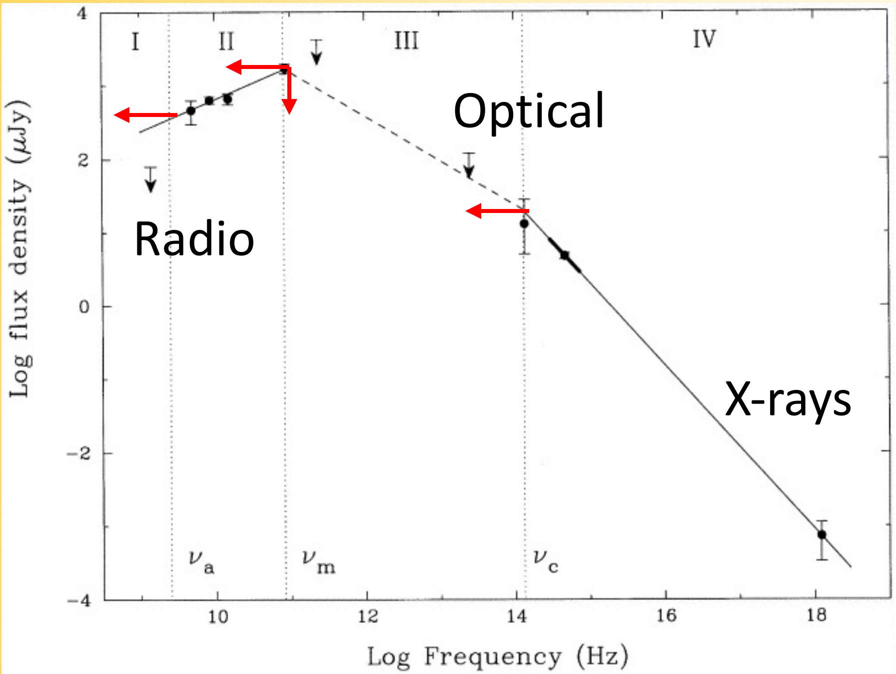
Jacovich, Beniamini & van der Horst 2020



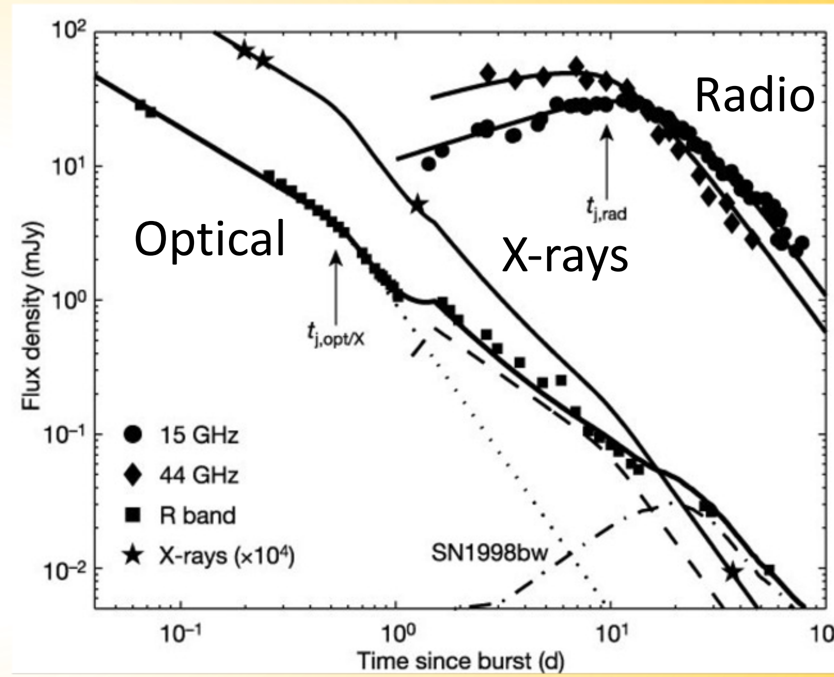
Aksulu et al. 2022

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
- Scintillation: source size constraints, but with caveats

Electron Acceleration in GRB Shocks

- Basic assumptions (most relevant for radio regime):
  - Synchrotron emission from relativistic electrons
  - Electrons accelerated by relativistic shock
  - Power-law energy / Lorentz factor distribution
- Physical & observed parameters:
  - ε_e : fraction of shock energy in accelerated electrons
  - ξ_e : fraction of electrons in power-law energy distribution
  - γ_m : minimum Lorentz factor of the power-law distribution
  - ν_m : peak frequency, depends on shock Lorentz factor (and thus time) and physical parameters (as does peak flux)
- Radio peaks (light curves and/or SEDs) → strong and unique constraints on electron acceleration in relativistic shocks

Beniamini & van der Horst 2017; Duncan, van der Horst & Beniamini 2023

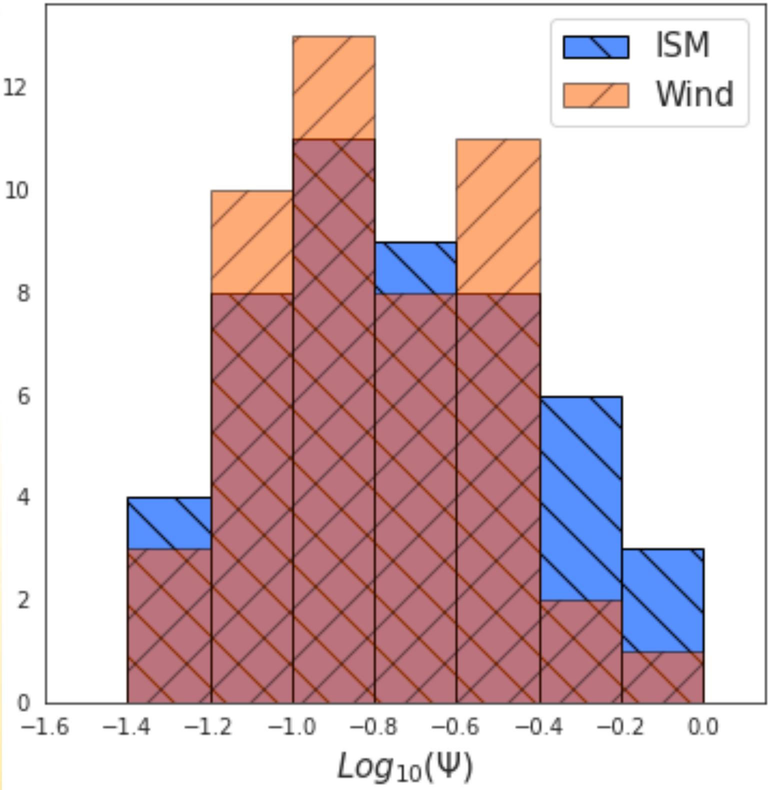
GRB Microphysics from Radio Peaks

- Peak flux, time & frequency → strong constraints on electron acceleration in GRB blast waves
- Parameter ψ strongly depends on ε_e and ξ_e (weakly on others)
- $\varepsilon_e \xi_e^{-3/2}$ = 0.16 (ISM) / 0.21 (Wind)
- $\sigma_{\psi,log}$ = 0.32 (ISM) / 0.28 (Wind)
- Microphysics universal in GRBs?

  (*caution: possible selection bias*)

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

$$= \frac{(p-2)}{0.177\,(p-1)} \left(\frac{p-0.67}{p+0.14} \right)^{1/2} \times \left(\frac{1-\epsilon_\gamma}{\epsilon_\gamma} \right)^{-1/4} n_0^{-1/4} \epsilon_e\,\xi_e^{-3/2}$$



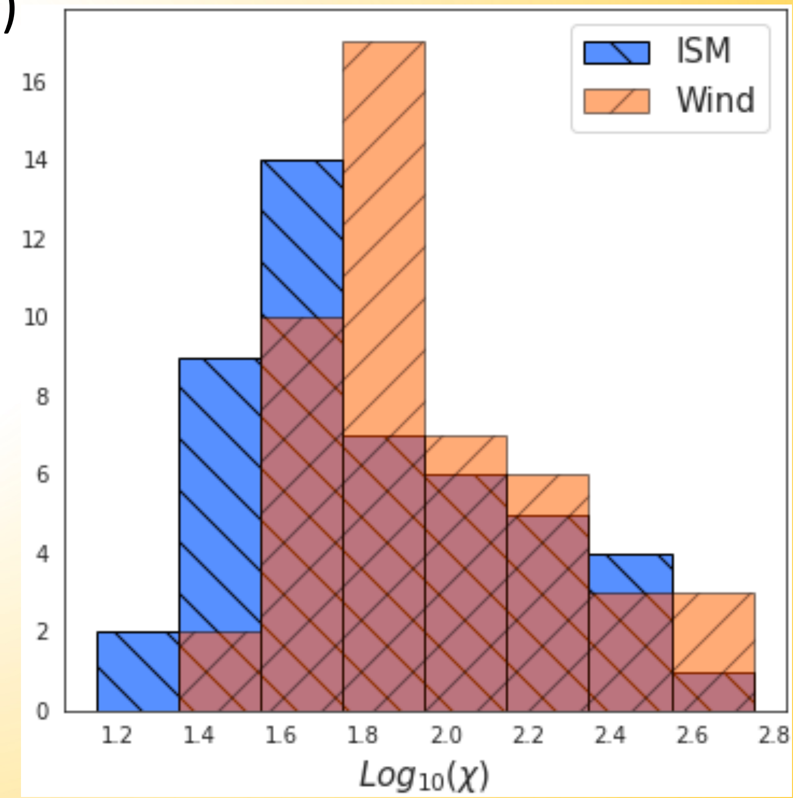
Beniamini & van der Horst 2017; Duncan, van der Horst & Beniamini 2023

GRB Microphysics from Radio Peaks

- Peak flux, time & frequency → strong constraints on electron acceleration in GRB blast waves
- Parameter χ strongly depends on γ_m and ξ_e (weakly on others)
- $\gamma_m \xi_e^{-1/2} = 53\ t_d^{-3/8}$ (ISM) / $96\ t_d^{-1/4}$ (Wind)
- $\sigma_{\chi,log} = 0.36$ (ISM) / 0.29 (Wind)
- Determining γ_m in GRBs unique

  (ν_m *not accessible in other sources*)

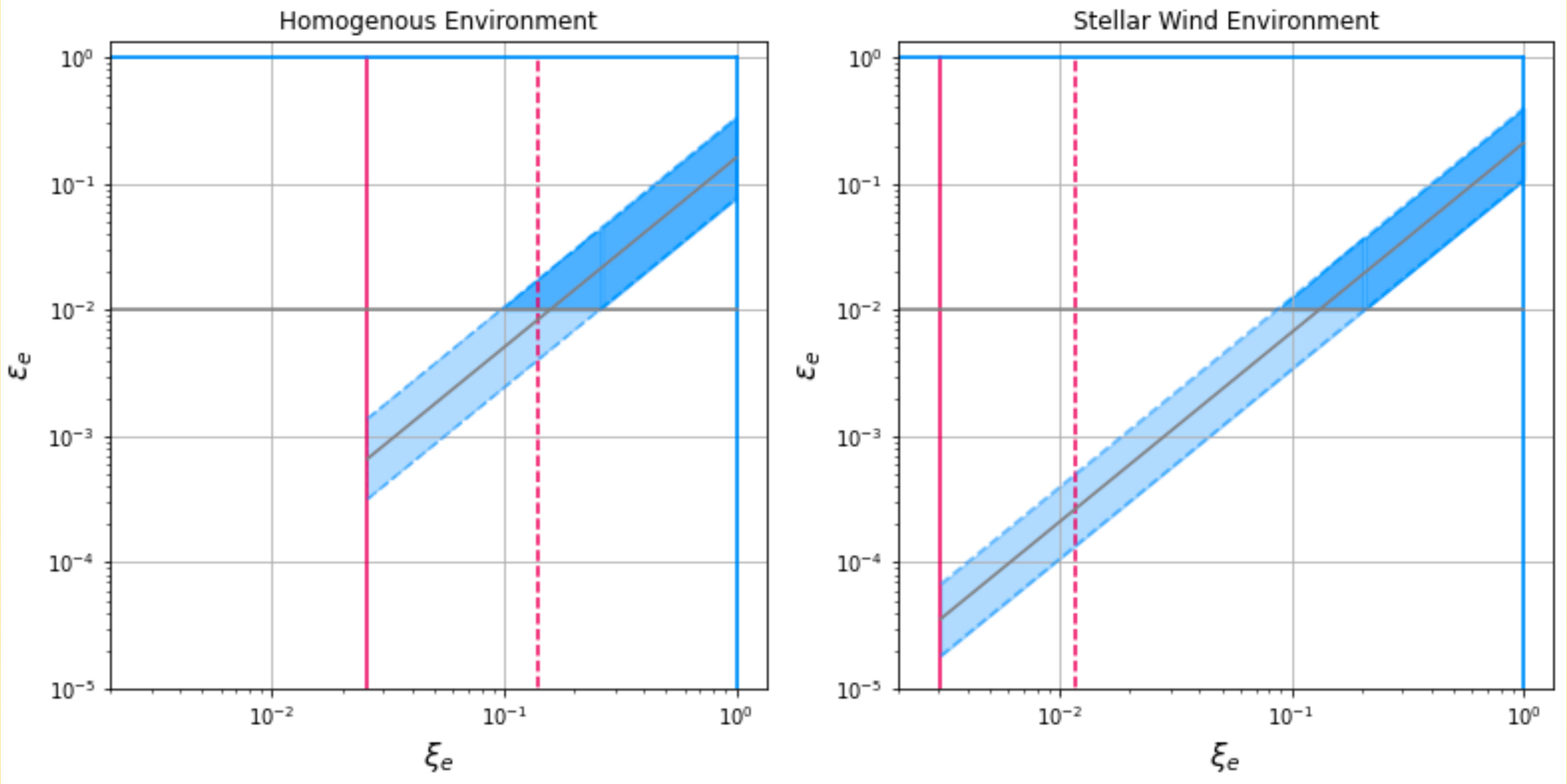
$$\chi_{\rm ism} = 266\ \Psi_{\rm ism}\ E_{\gamma,{\rm iso},53}^{1/8}\ (z+1)^{3/8}\ t_d^{-3/8}$$
$$= \left(\frac{p-0.67}{0.66\,(p+0.14)}\right)^{1/2} \left(\frac{\epsilon_\gamma}{1-\epsilon_\gamma}\right)^{3/8} n_0^{-1/8}\ \gamma_m\ \xi_e^{-1/2}$$



Beniamini & van der Horst 2017; Duncan, van der Horst & Beniamini 2023

GRB Microphysics from Radio Peaks

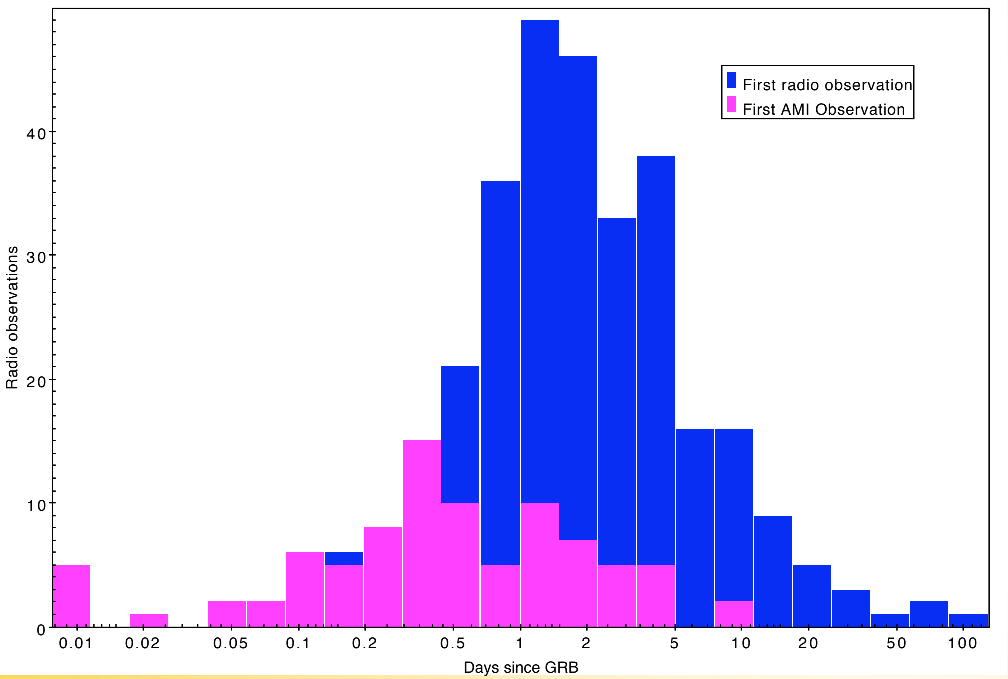
- Peak flux, time & frequency → strong constraints on electron acceleration in GRB blast waves
- Constraints: $0.01 < \varepsilon_e < 0.2$ and $0.1 < \xi_e < 1$ (with dependence)



Beniamini & van der Horst 2017; Duncan, van der Horst & Beniamini 2023

Fast & Systematic Radio Follow-Up

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

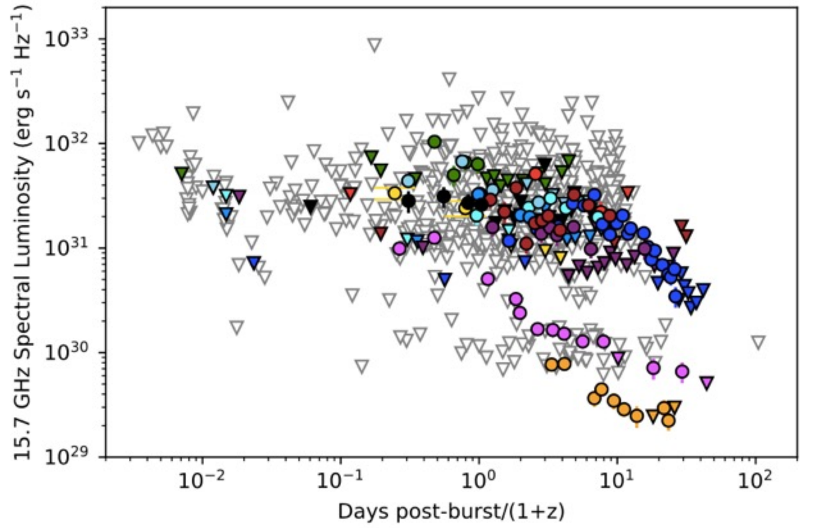


Chandra & Frail 2012;

Staley et al. 2013;

Anderson et al. 2016

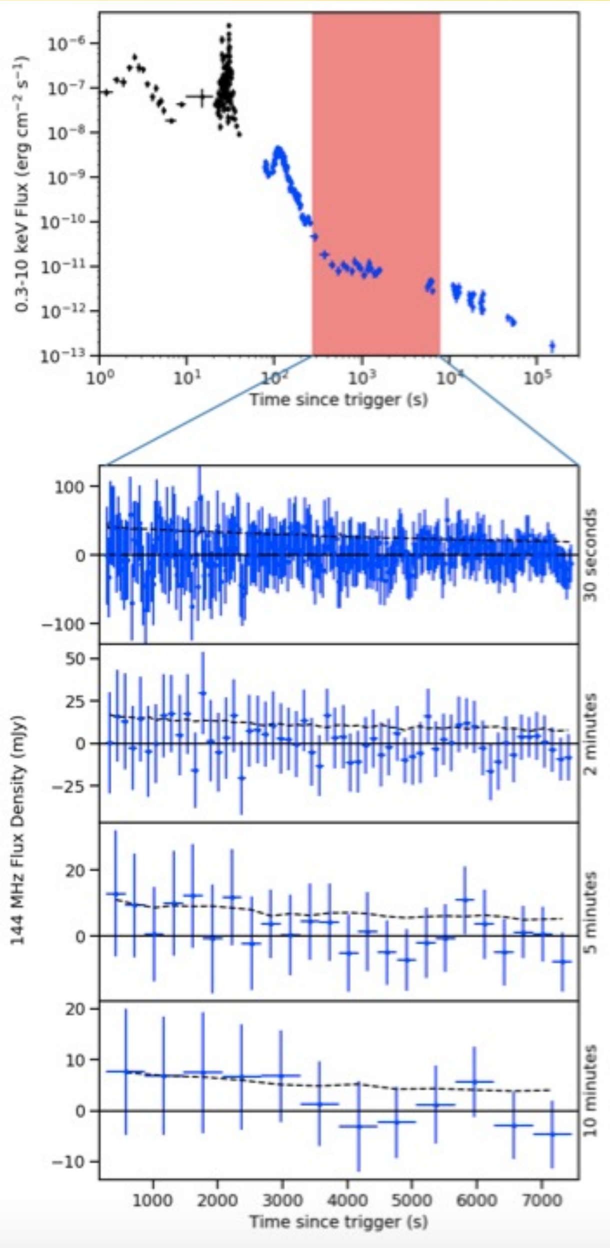
Anderson et al. 2018



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

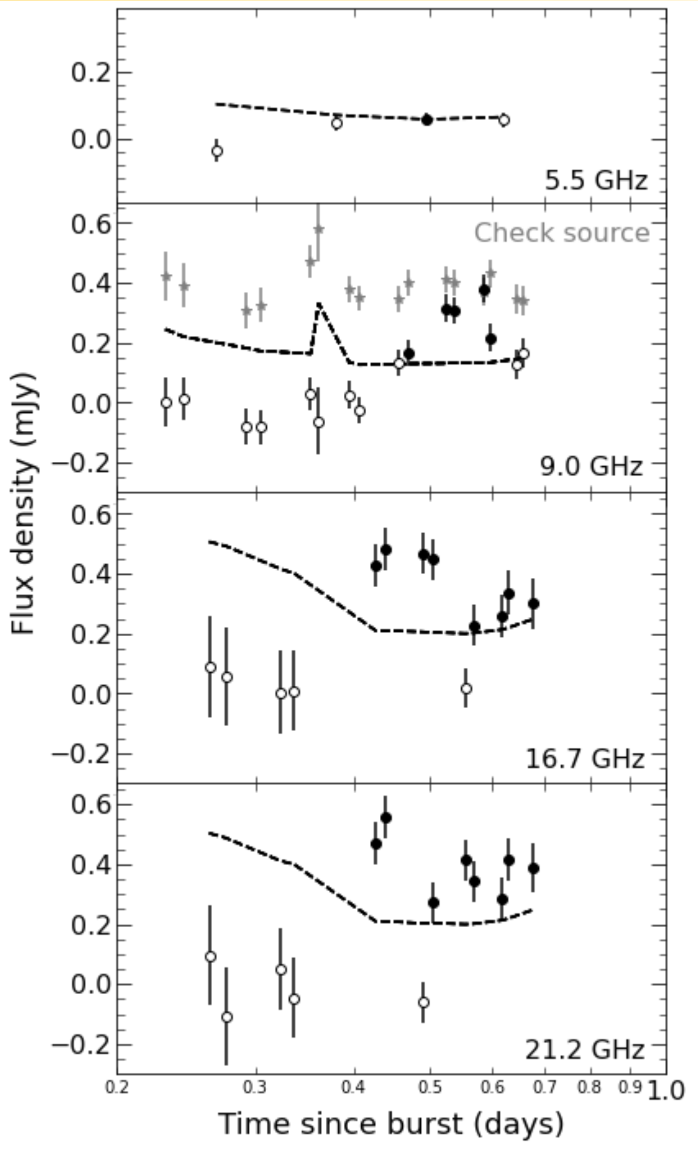
Searching for Coherent Radio Emission

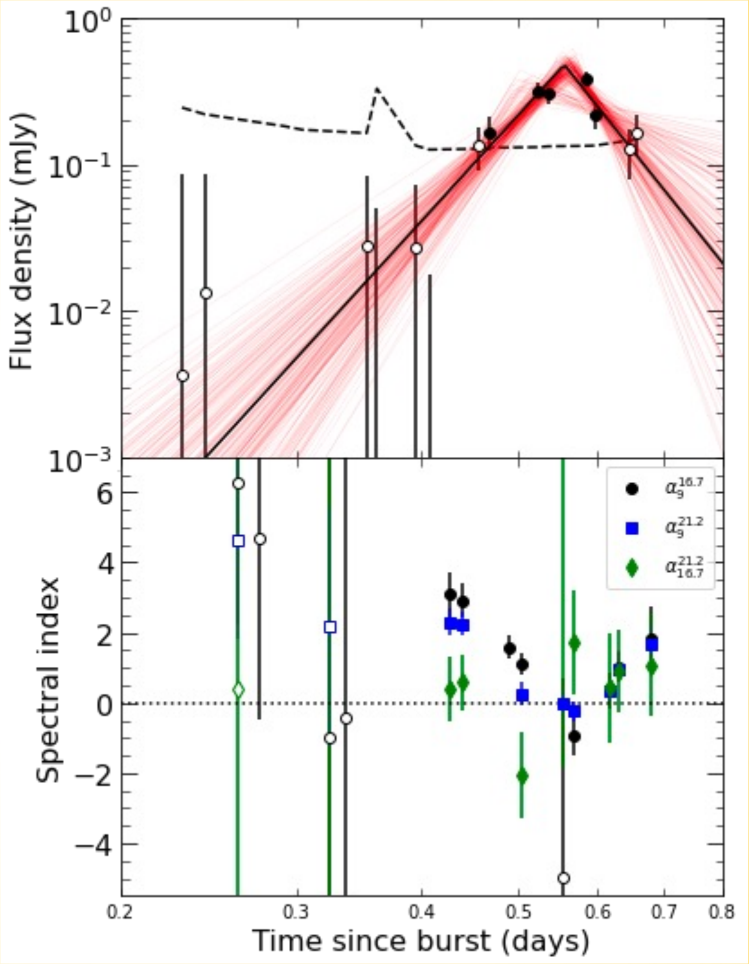
- LOFAR observations starting few minutes after trigger of GRB 180706A
- Search for coherent emission, FRBs, etc.
- Propagation effects important
- Complementary to searches in AARTFAAC (very large field of view, core of LOFAR)
- Similar efforts for MWA (GRB 150424A; Kaplan et al. 2015) and LWA (GRB 170112A)
- Various models proposed, but large uncertainties in predicted flux levels



Rowlinson et al. 2019

GRB 210702A: Early Radio Brightening





- ATCA: 11-hours, starting after 5.4 hours
- Extreme brightening & spectral variations
- Scintillation → earliest source size limit

Anderson et al. 2022

Conclusions

- Gamma-ray bursts: multi-timescale, multi-wavelength, and multi-messenger
- Recent developments in observations
  - Better spectral and temporal coverage
  - High-energy gamma-ray (>1 TeV) detections
  - Automated early radio observations (with long integrations)
- Recent developments in modeling
  - Fitting hydrodynamics simulations to broadband data
  - Advanced statistical/modeling methodologies
  - Incorporating more emission mechanisms
  - New diagnostic tools for parameter estimation
  - (Quasi-)universality of electron acceleration?