Fast Localization of Gamma-Ray Bursts: Implications of a Technical Challenge

Eric Burns

Louisiana State University

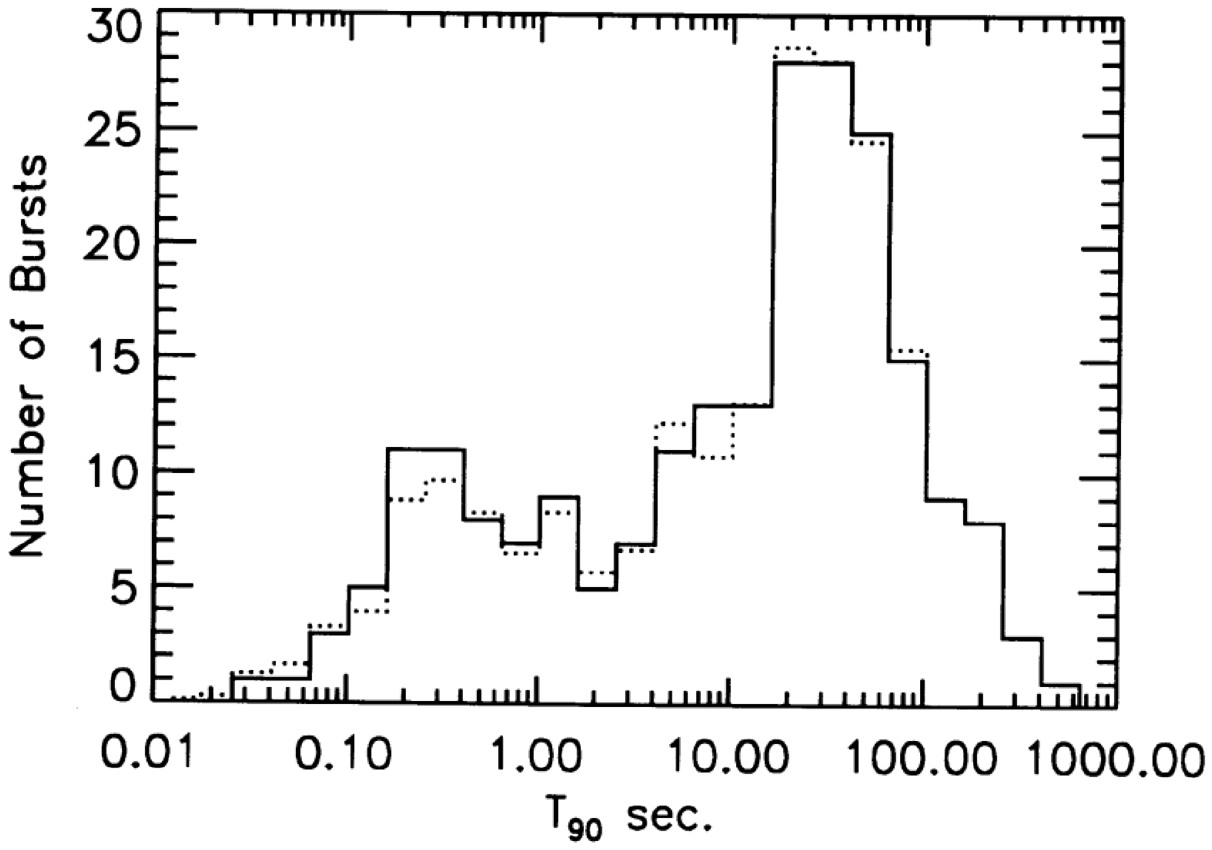
Gamma-Ray Bursts

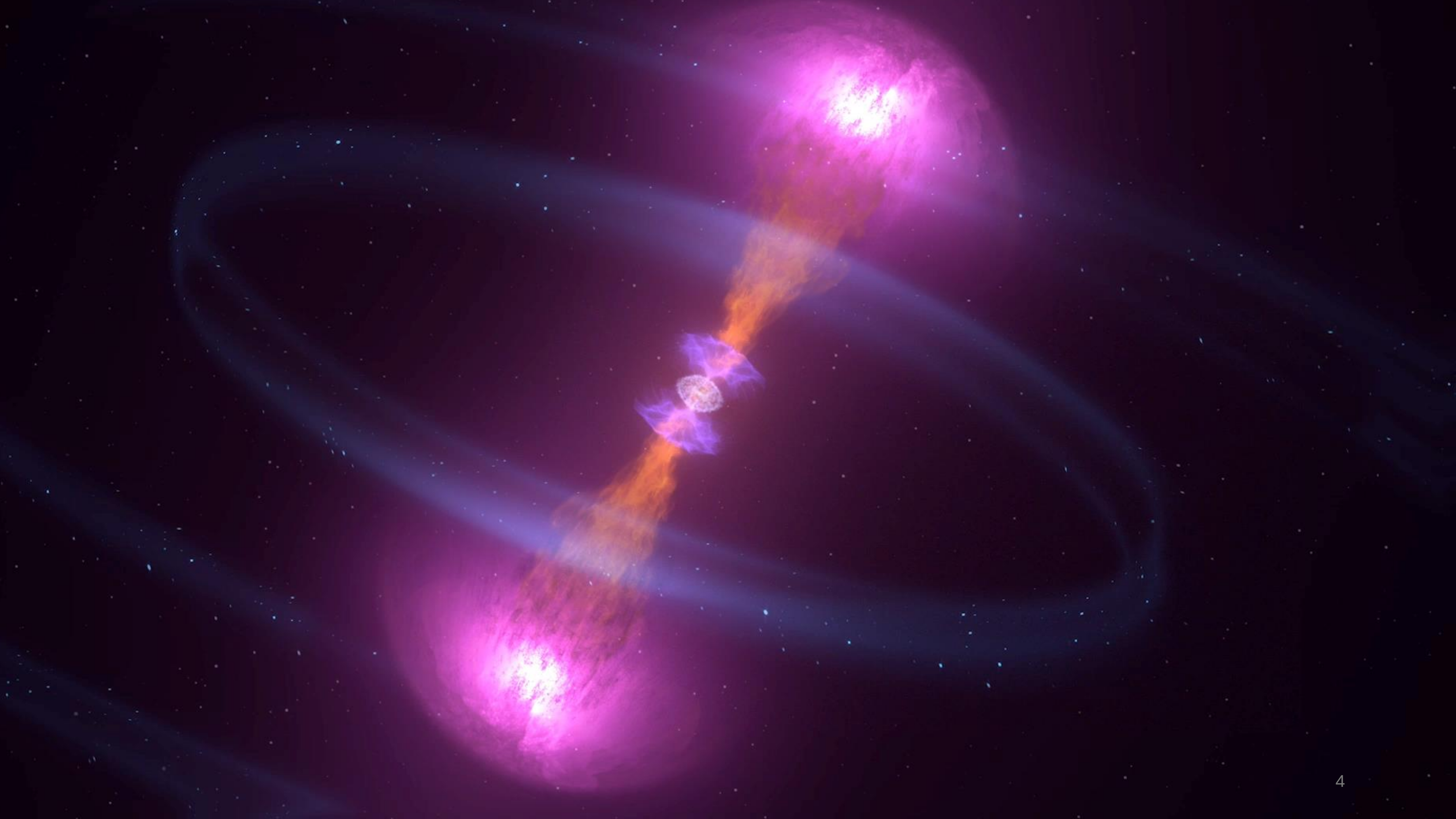
- Neutron Star Mergers
- Collapsars
- Magnetar Giant Flares
- Magnetar Short Bursts
- Tidal Disruption Events
- White Dwarf Mergers
- Accretion Induced Collapse of a magnetized white dwarf
- Etc

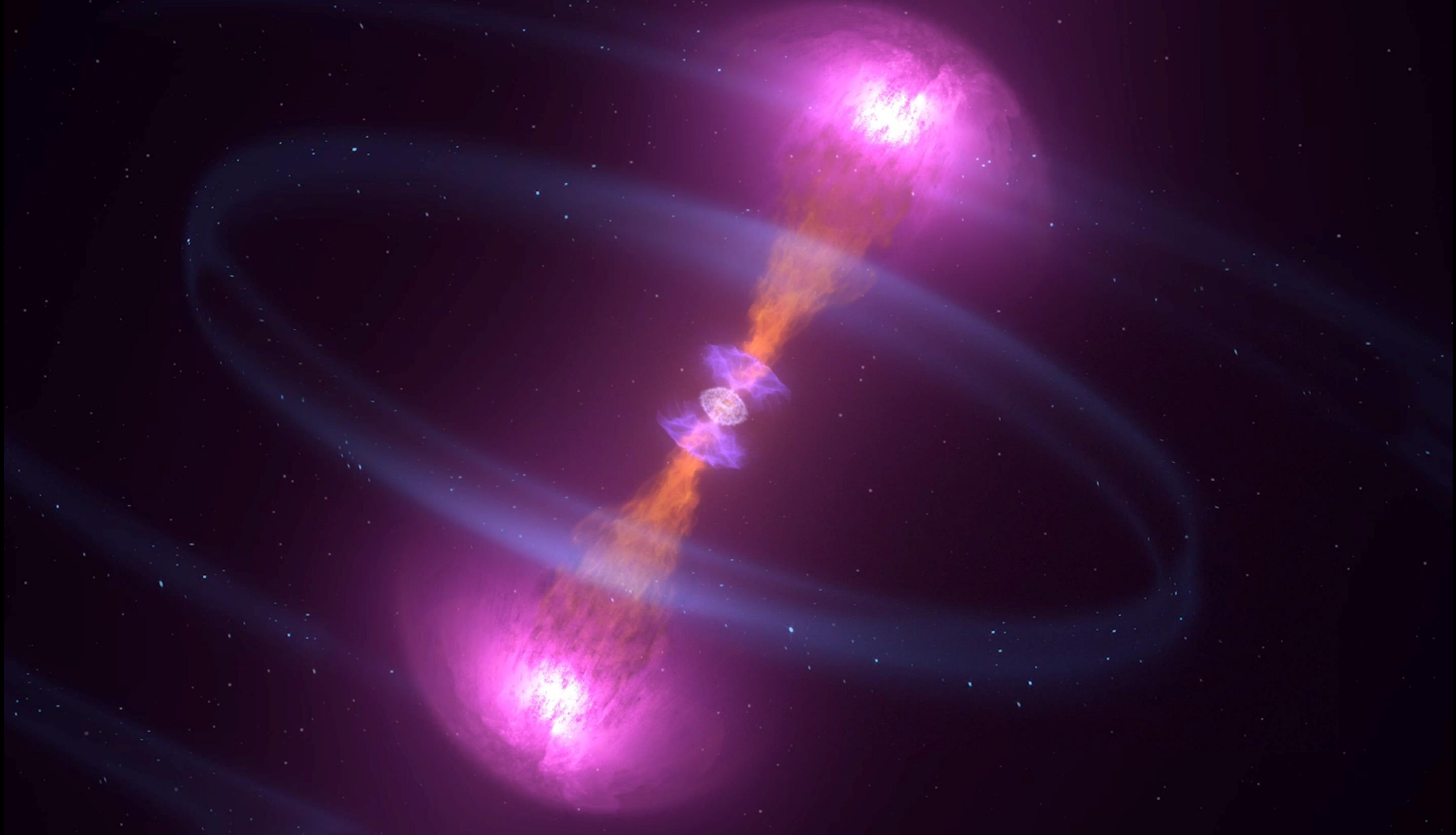
Short and Long Gamma-Ray Bursts

- GRBs were split into short and long classes based on their duration
- Follow-up observations have confirmed they have distinct physical origin
  - Short GRBs arise predominantly from neutron star mergers, and a subset from magnetar giant flares
  - Long GRBs come from collapsars, a rare type of massive star death

BATSE GRB Catalog

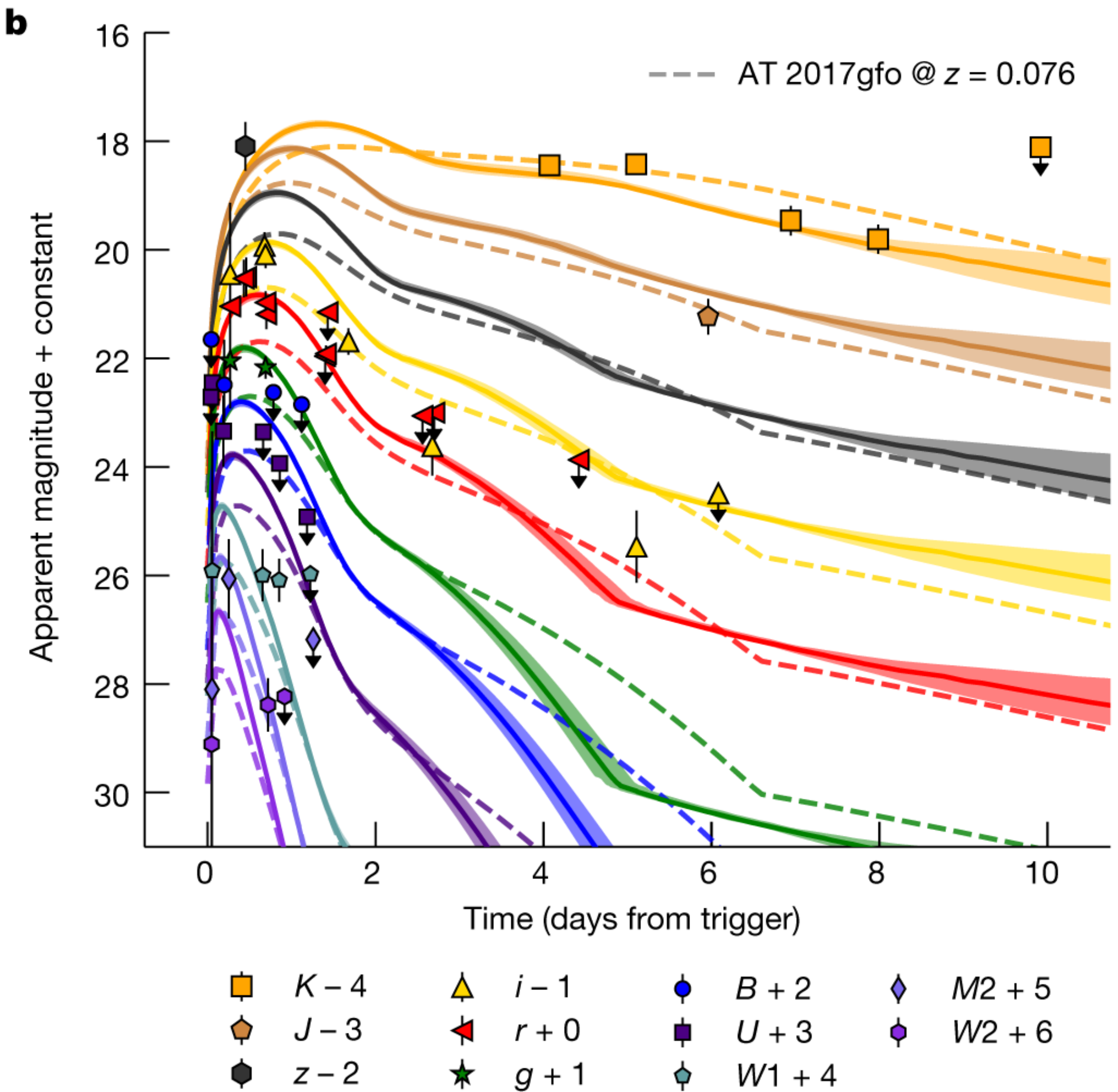






Rastinejad et al. 2022 Nature 612 223-227

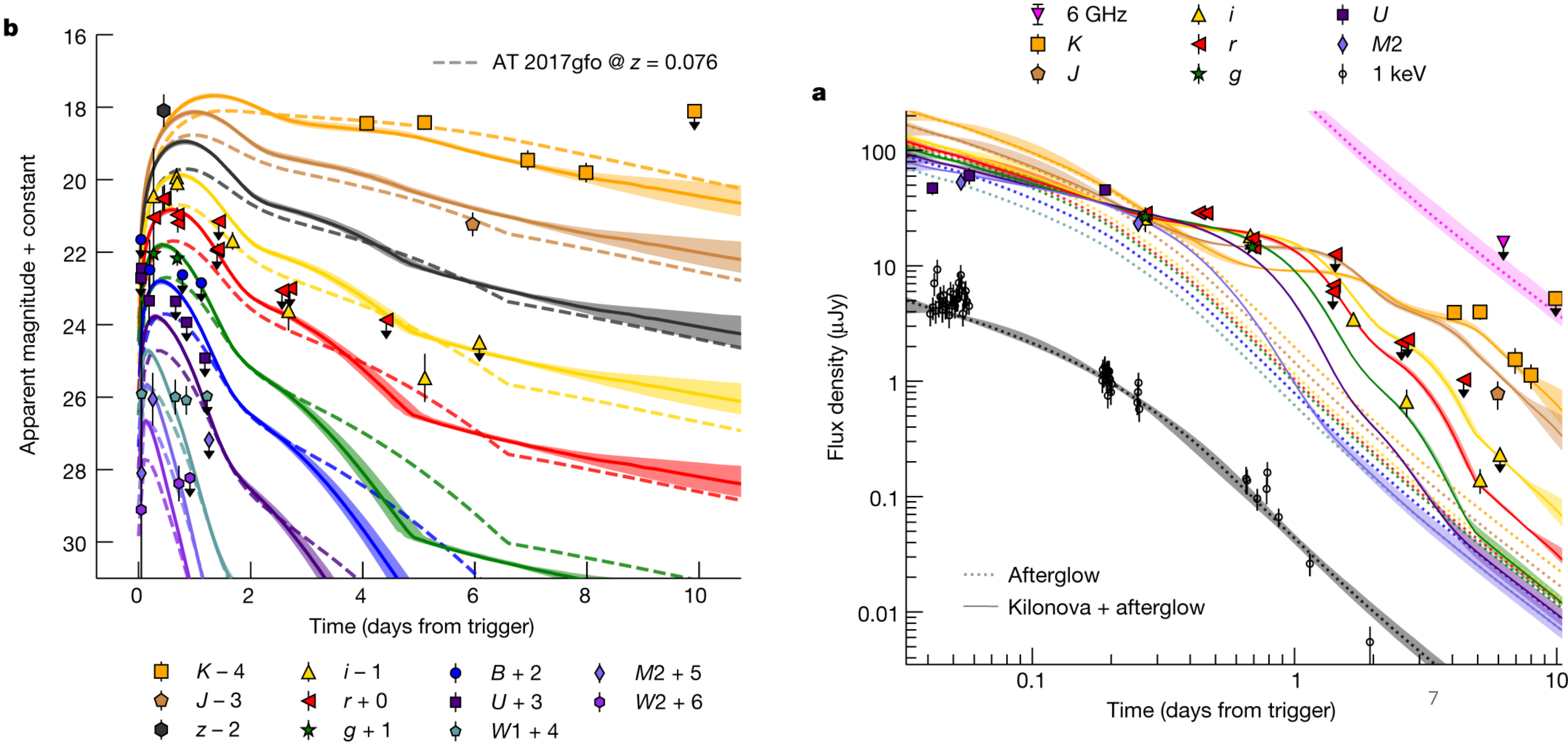
Afterglow + Kilonova



- Kilonova are thermal transients which emit over ultraviolet, optical, and infrared wavelengths
- Photometric observations in these bands give you some insight into the ejecta mass, velocity distribution, and composition
- The earliest signals of interest occur in ~10 minutes, then a few hours

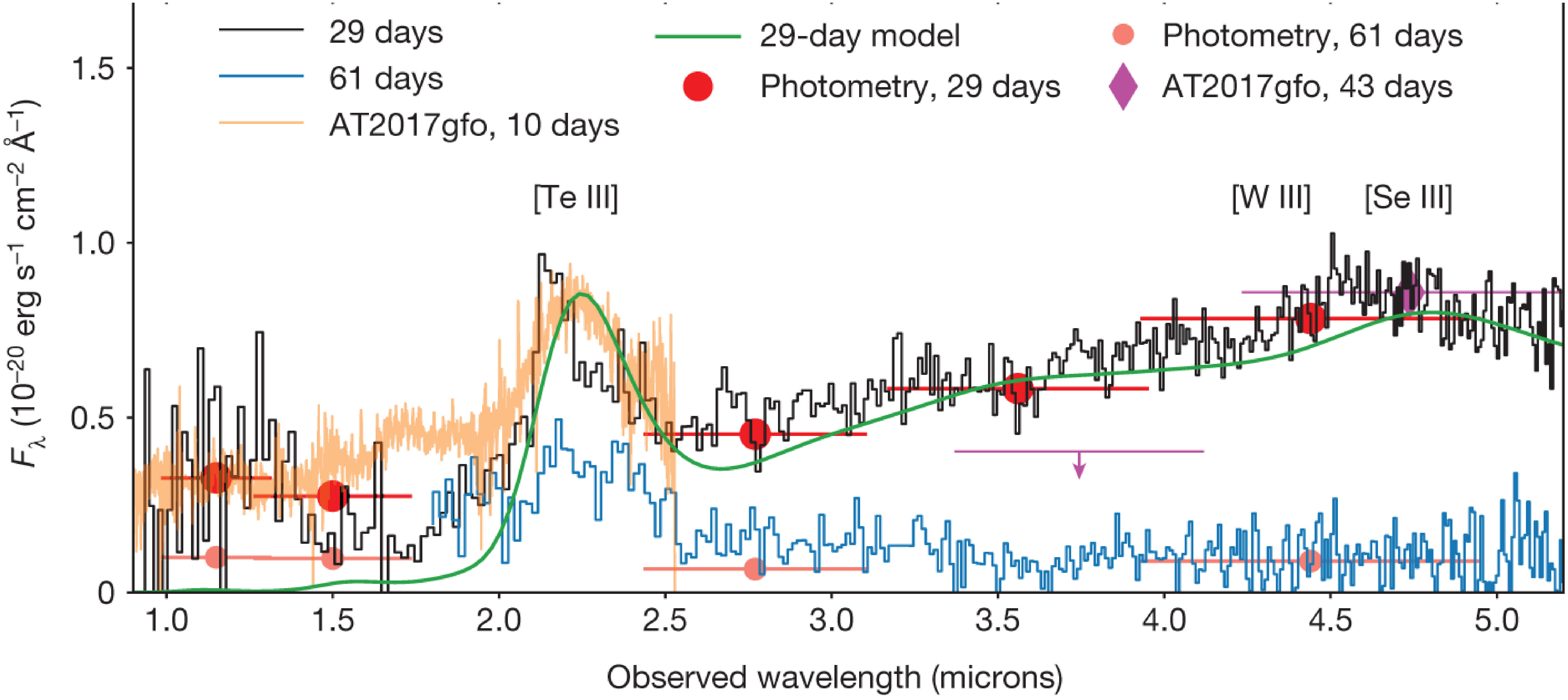
Rastinejad et al. 2022 Nature 612 223-227

Afterglow + Kilonova



JWST Spectrum of a Kilonova – GRB 230307A

Levan et al. 2024 Nature 626 737-741

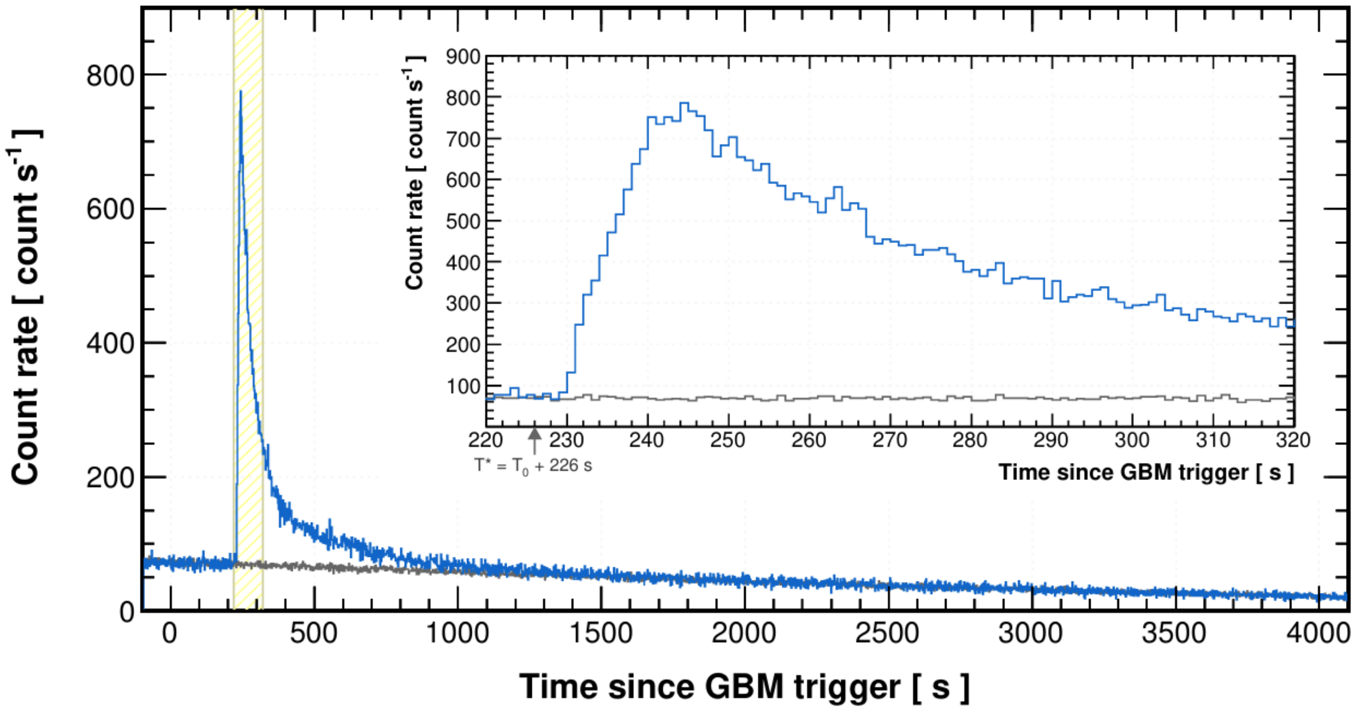


Kilonova and GRB Monitors

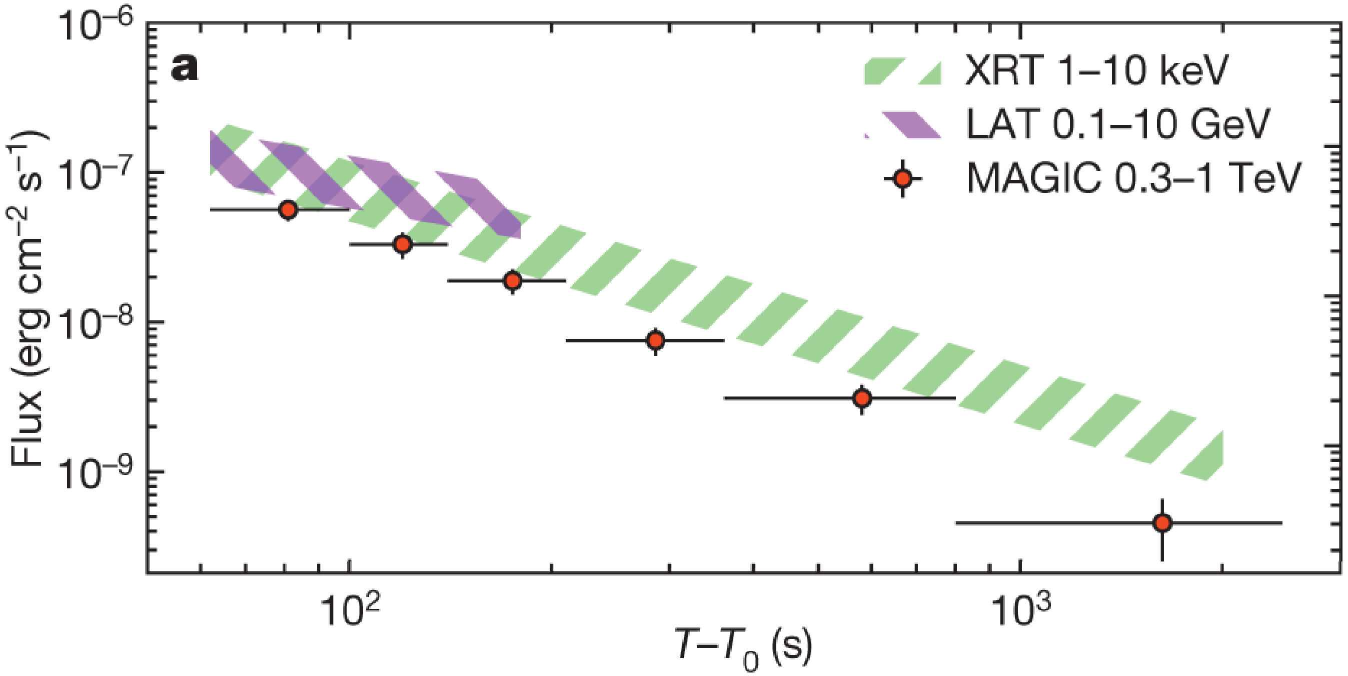
- All kilonovae which have been observed were identified through their prompt GRB signal (one also through the gravitational wave signal).
- Early observations after merger are required to properly interpret kilonovae data
- The most likely counterpart to GWs will be gamma-ray bursts
- Both examples used here were long gamma-ray bursts, which should not arise from neutron star mergers. Are they a different progenitor?

Very-High Energy Detections of GRBs

- IACTs
  - GRB 160821B - ~10,000 s
  - GRB 180720B – 40,000 s
  - GRB 190114C – 2,500 s
  - GRB 190829A – 200,000 s
  - GRB 201015A - ~10,000 s
  - GRB 201216C – 1,200 s
- Water Cherenkov Telescopes
  - GRB 970417A - ~10 s
  - GRB 221009A – 226-4,000 s



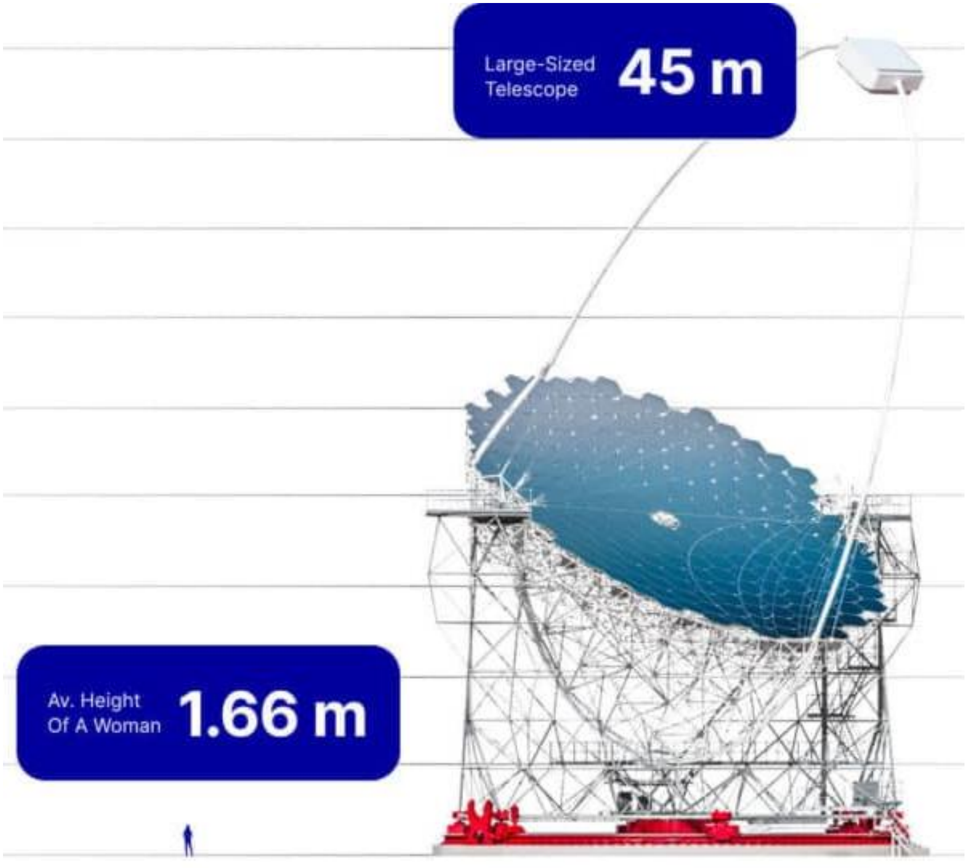
LHAASO 2023 Science 380 6652



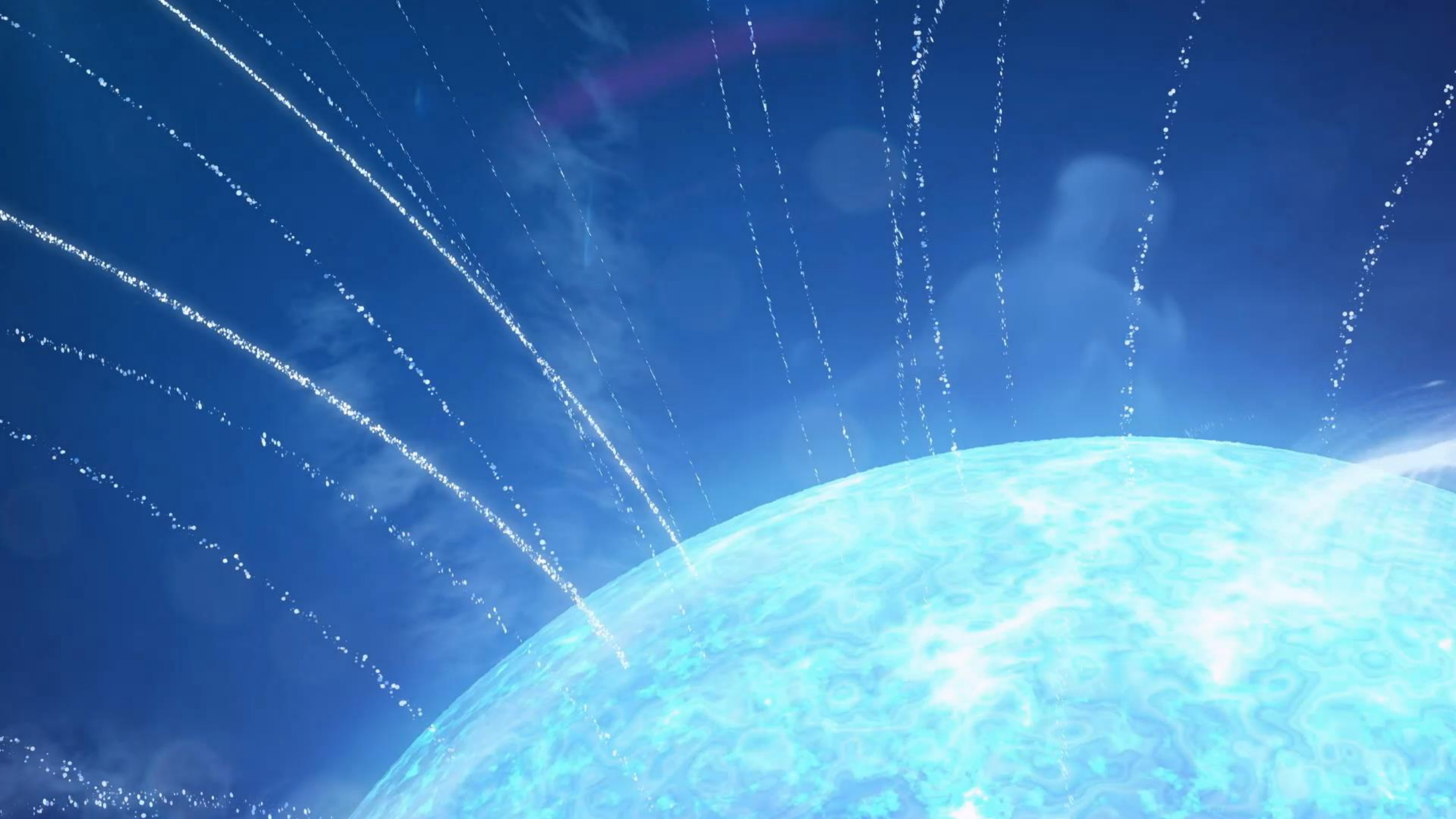
MAGIC 2019 Nature 757 455

Cherenkov Telescope Array

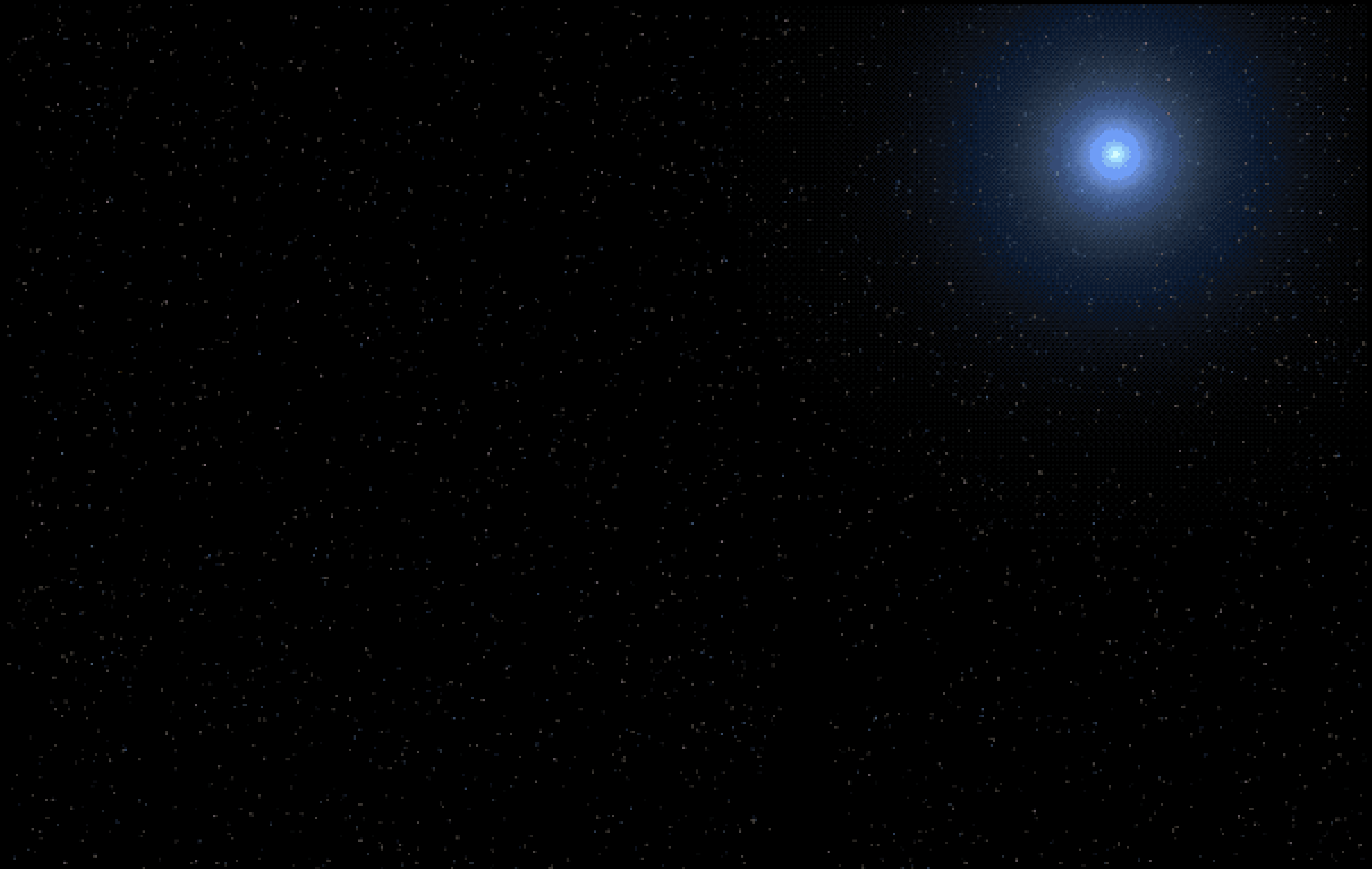
- Ashkar et al. 2024 ApJ 964 1: Current rate of VHE detections of GRBs is <1/year; rough rate with the CTA is ~4/year.
- CTA could target larger localization regions, but the best observations and results still rely on rapid reporting
- CTA will provide a comprehensive sample to understand the origins of the VHE emission in GRBs
  - Synchrotron Self Compton?
  - External Inverse Compton?
  - Both?



https://www.ctao.org/emission-to-discovery/telescopes/



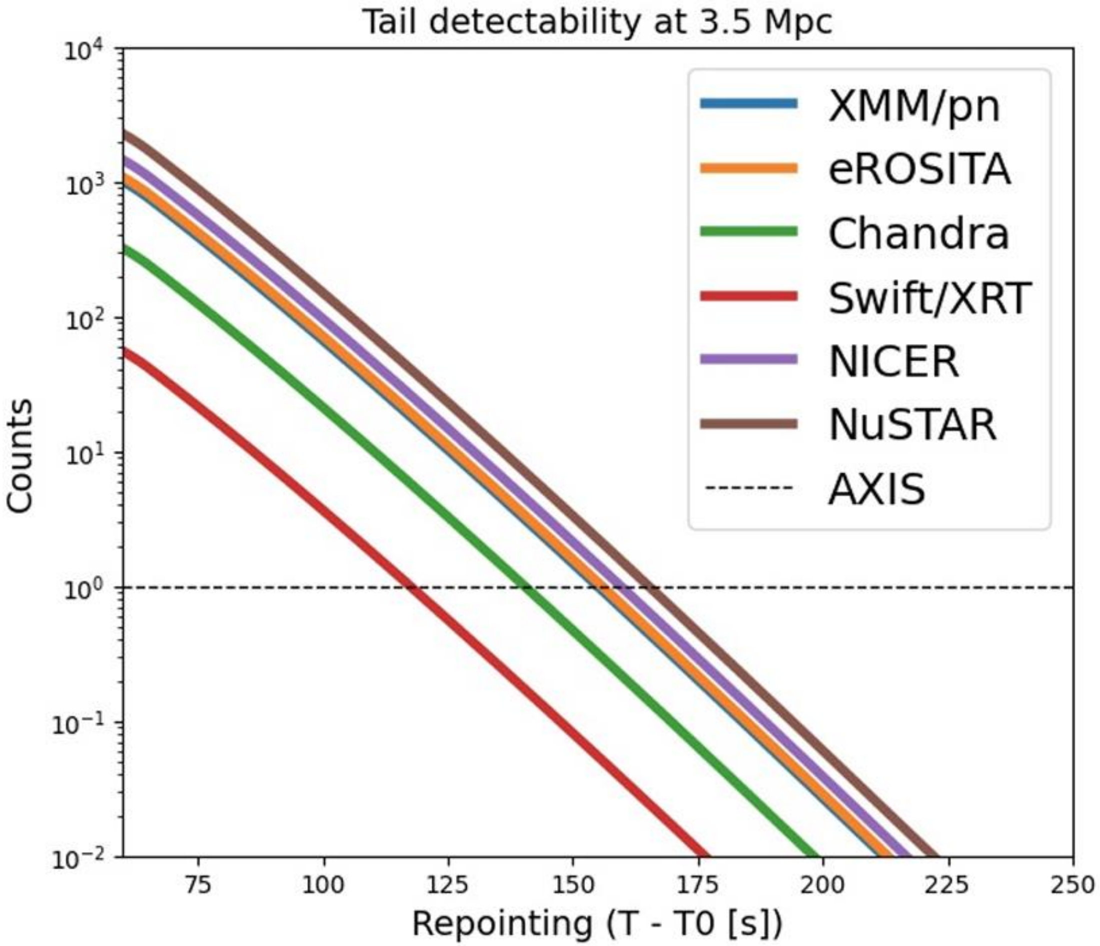
What if a giant flare occurred outside the Milky Way?



Magnetar Giant Flares: X-ray Tails

Negro, et al. 2020 Front. Astron. Space Sci. Sec. Comsology 11

- There are now ~9 MGFs
- GRB 231115A was the first rapidly identified (S. Mereghetti, Session 6)
- However, we did not automatically alert the community
- Swift could have recovered the X-ray tail, as could NICER (with technical improvements)
  - 'Smoking-gun' signature



Magnetar Giant Flares and heavy elements

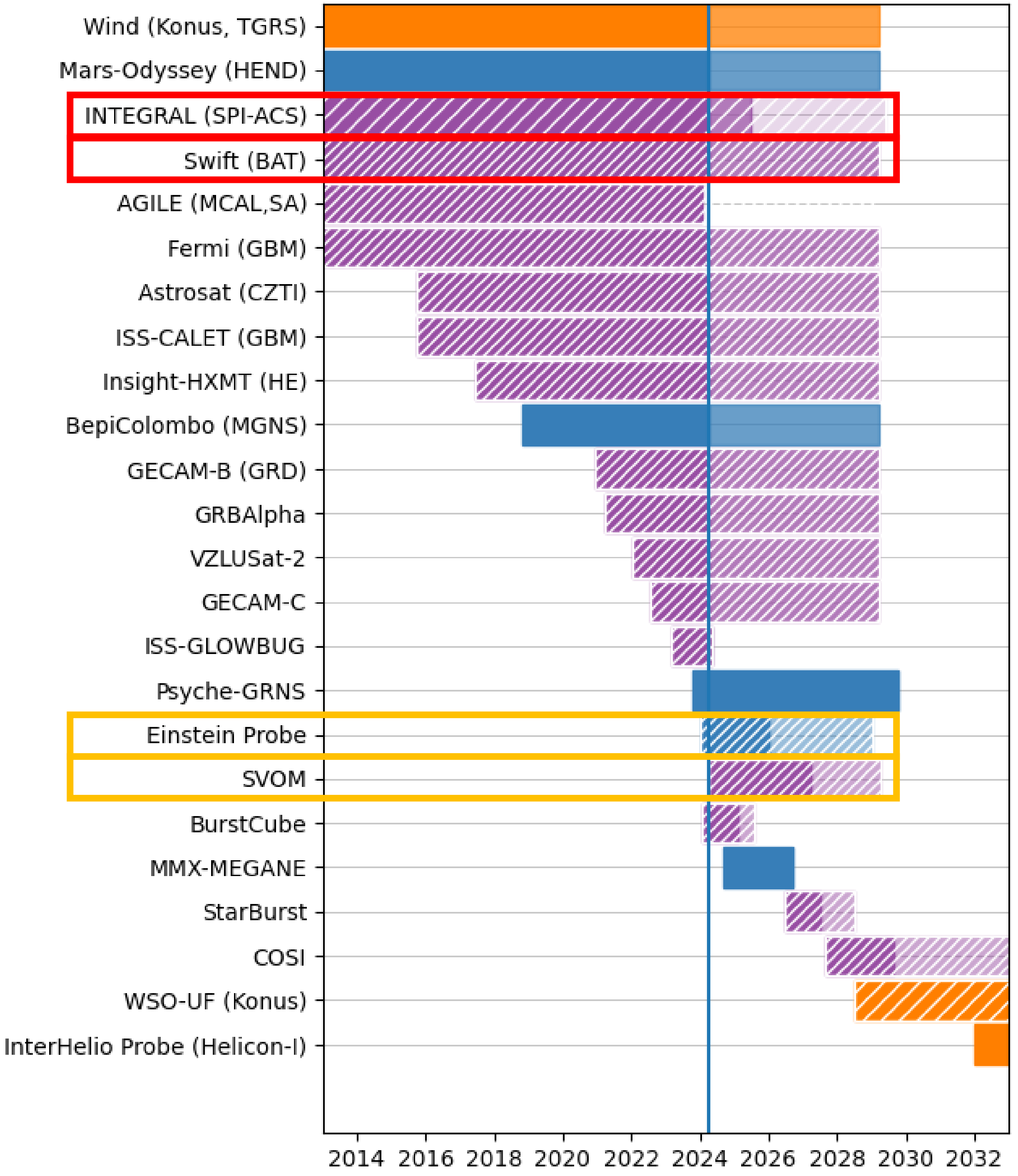
$$t_{\rm pk} \approx \sqrt{\frac{M_{\rm ej}\kappa}{4\pi v_{\rm ej}c}} \simeq 300{\rm s}\left(\frac{M_{\rm ej}}{10^{26}{\rm g}}\right)^{1/2}\left(\frac{v_{\rm ej}}{0.3c}\right)^{-1/2}\left(\frac{\kappa}{3\,{\rm cm^2\,g^{-1}}}\right)^{1/2},$$

$$L_{\rm pk} \approx 10^{39}\,{\rm erg\,s^{-1}}\left(\frac{M_{\rm ej}}{10^{26}\,{\rm g}}\right)^{0.35}\left(\frac{v_{\rm ej}}{0.3c}\right)^{0.65}\left(\frac{\kappa}{3\,{\rm cm^2\,g^{-1}}}\right)^{-0.65}.$$

- Expanding cold NS matter proposed and r process site by Lattimer and Schram 1974, Lattimer 1977
- Hot NS matter from MGFs revisited - Cehula et al. 2024 MNRAS 528 3
- Optical / ultraviolet observations within ~10 minutes could recover the signal, and is detectable to several Mpc
- Requires very rapid alerts, automatic giant flare identification, robotic follow-up

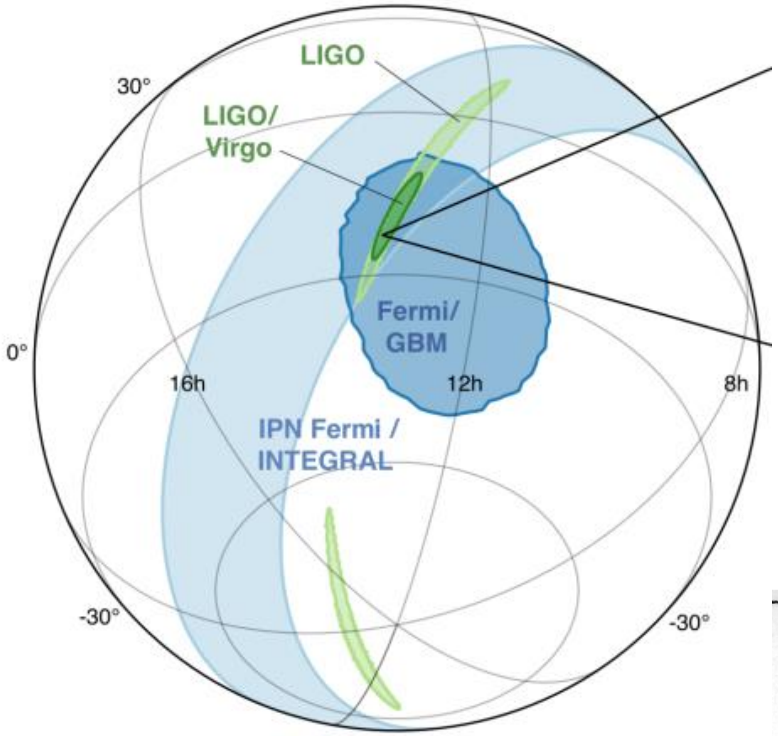
Rapid Localizers

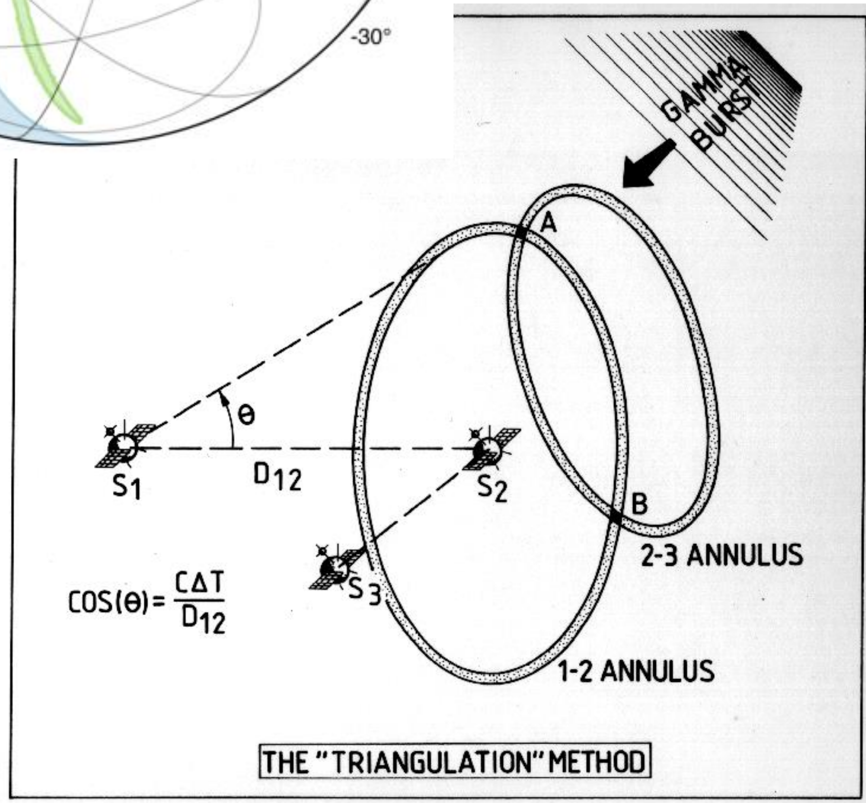
- Few GRB monitors provide rapid (~<1 hour) localizations at arcminute accuracy.
- INTEGRAL and Swift are 20+ years old and nearing mission end
  - Fermi is 16 years old
- Einstein Probe and SVOM are in commissioning, and could fill some of this gap, if they achieve design detection rates
- What else can we do?



InterPlanetary Network

- Geometric location determination, using detections in multiple satellites
- Key capability for other survey telescopes, but cannot (alone) provide rapid localizations for targeted follow-up
- We are working on rapid INTEGRAL-Fermi annuli, but its usefulness will be limited if/when INTEGRAL ends





New and Future Missions

- Session 12
  - THESEUS – Lorenzo Amati
  - Status of Einstein Probe – Erik Kuulkers
  - Status of SVOM – Stephane Schanne
- Session 13
  - COSI – Julien Malzac

- In the US, proposing a near-universe mission next year
  - True all-sky coverage with base scintillators (~20 keV – few MeV)
  - Coded aperture mask over ~30% of sky (~0.5-20 keV)

Conclusions

- GRB monitors have and will always play a crucial role in time-domain and multimessenger astronomy
- Rapid localization can be done, but requires significant design efforts and significant operational resources
- The field is in a transition period as the past generation of monitors begin to end, and new facilities launch
- We need to keep this momentum into the 2030s and beyond