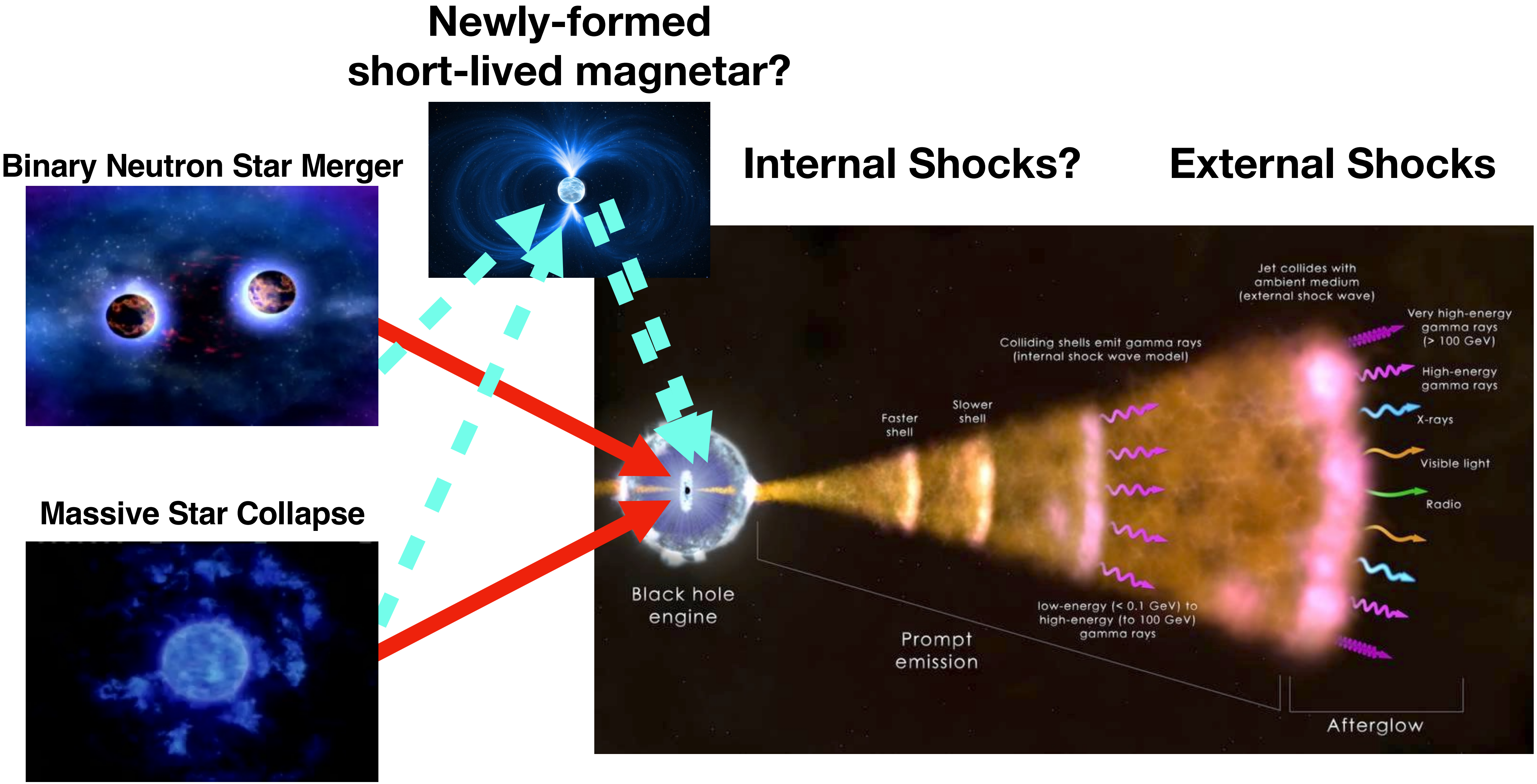
Gamma-ray Burst Science in the context of Multimessenger Observations

Judy Racusin
NASA/GSFC

Fermi Summer School 2022

GRB Formation



Newly-formed short-lived magnetar?

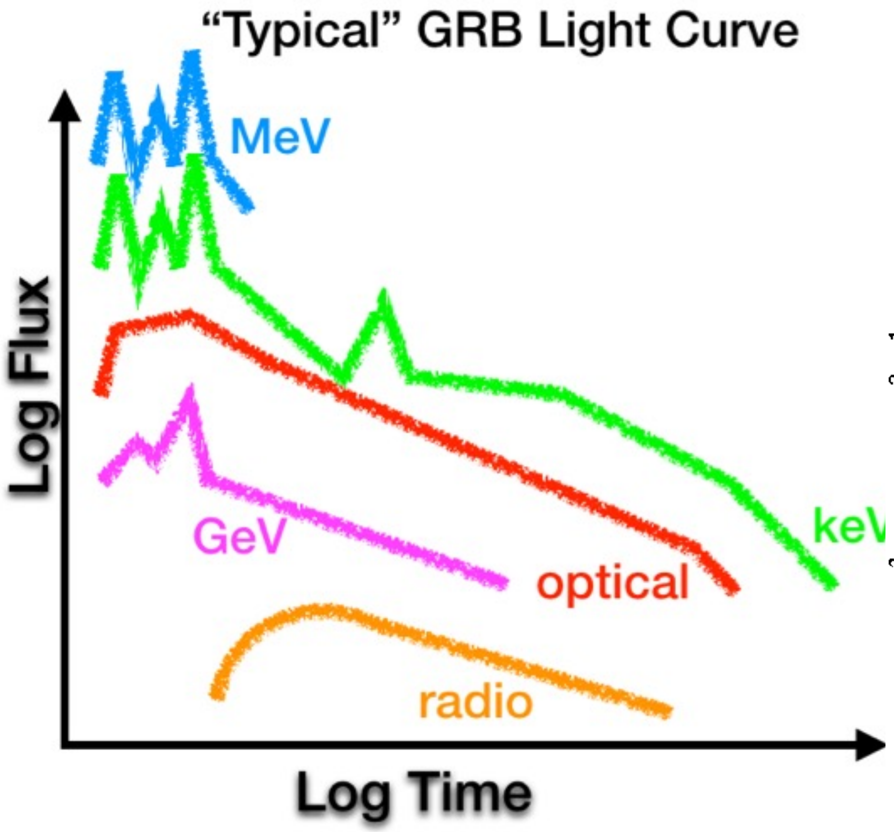
Binary Neutron Star Merger

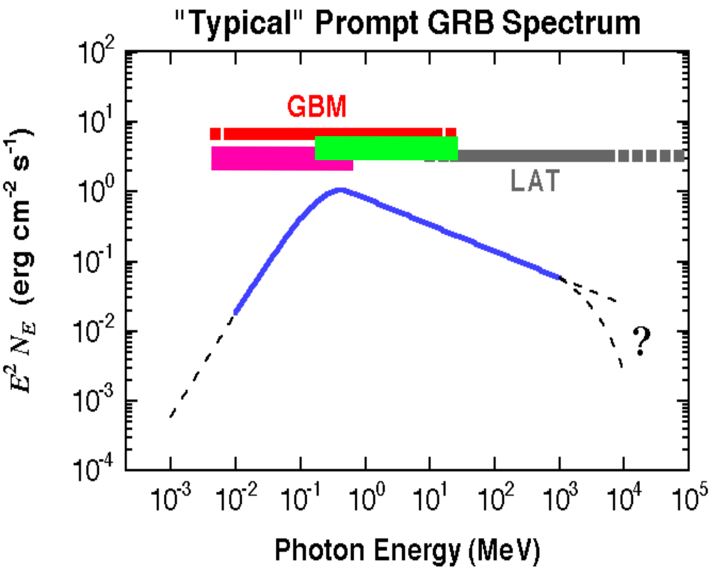
Internal Shocks?

External Shocks

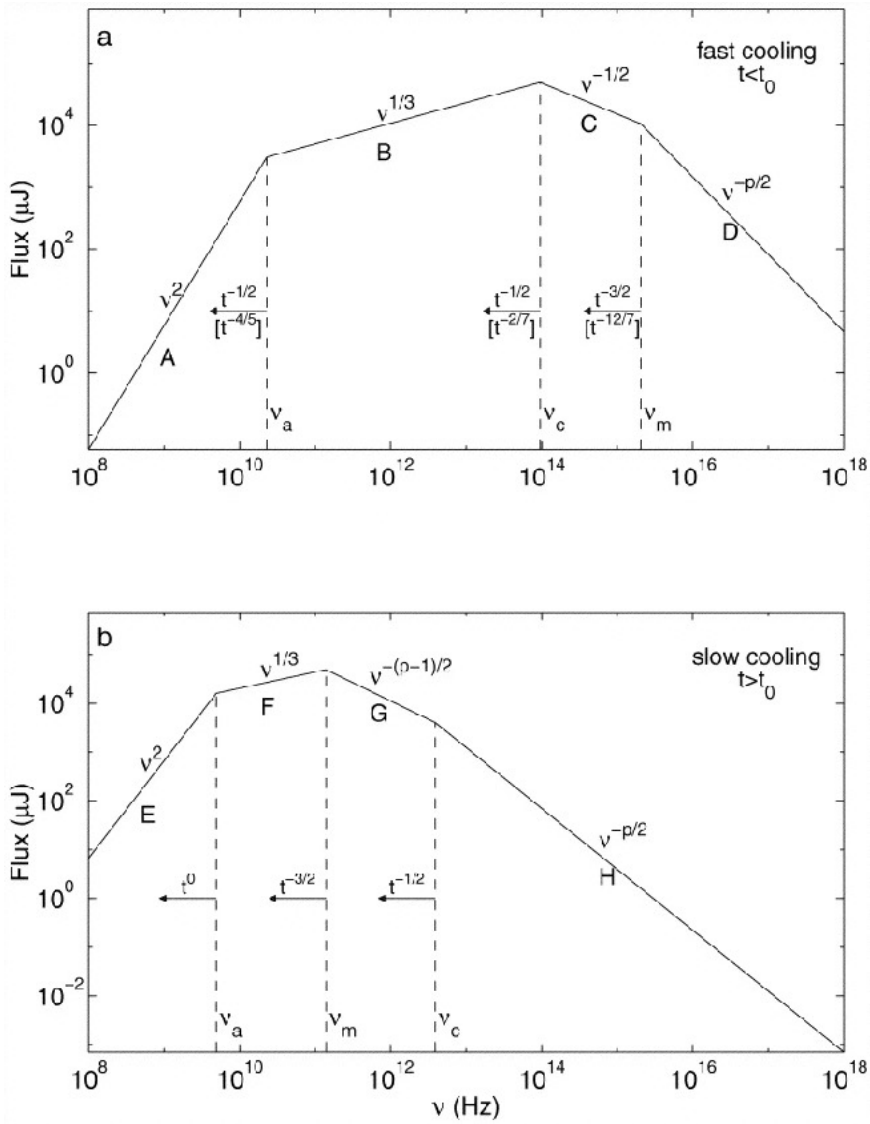
Massive Star Collapse

Broadband Observations of GRBs



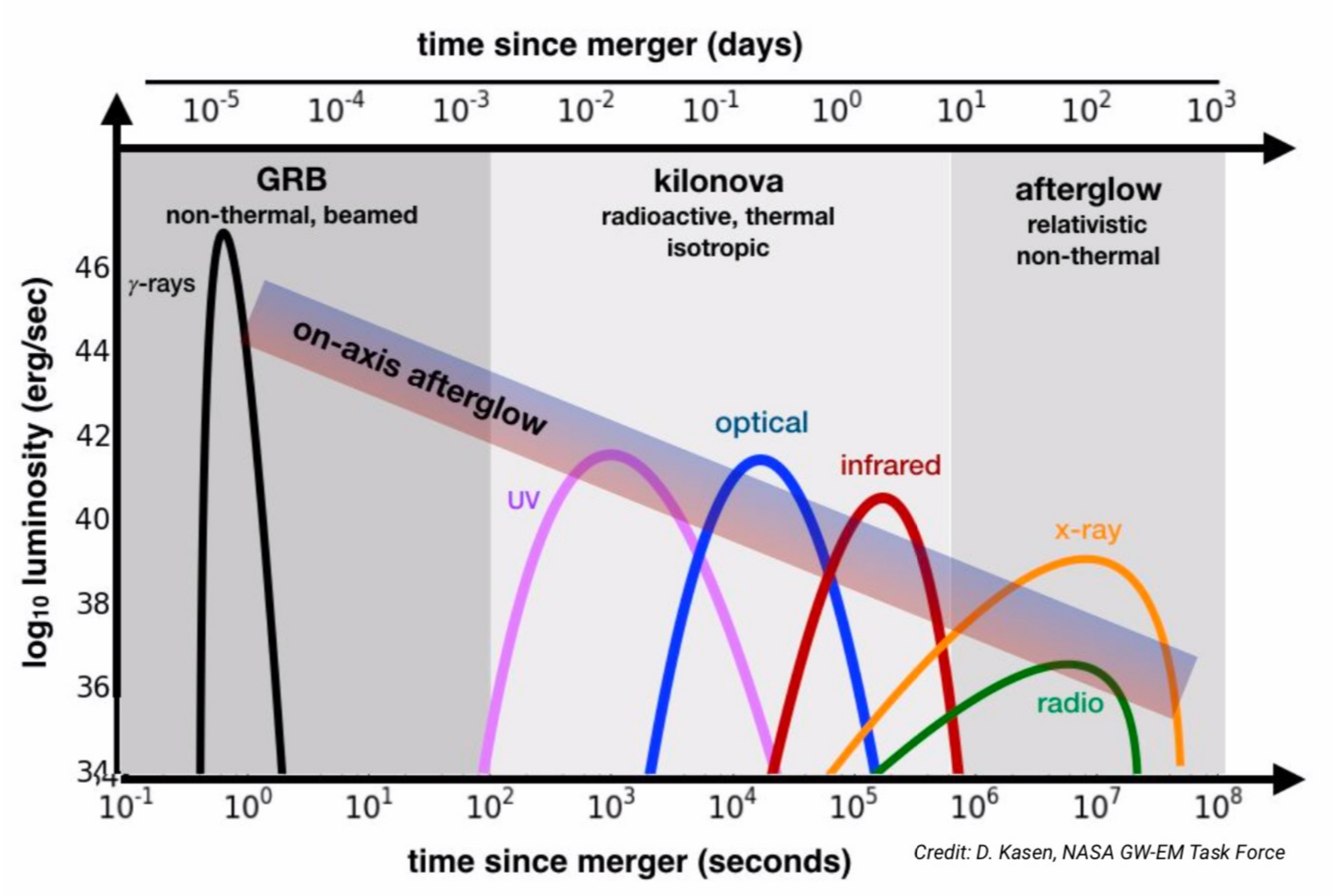


GRB Afterglow Synchrotron Spectra

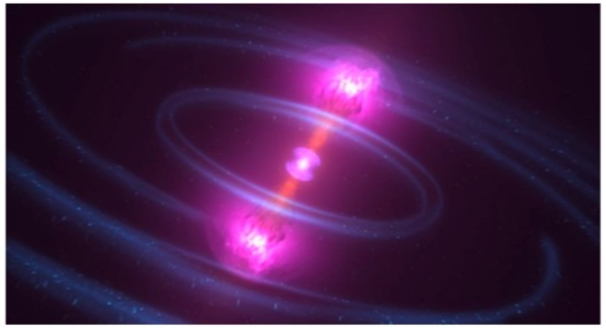


Sari 1998

BNS Merger Counterparts



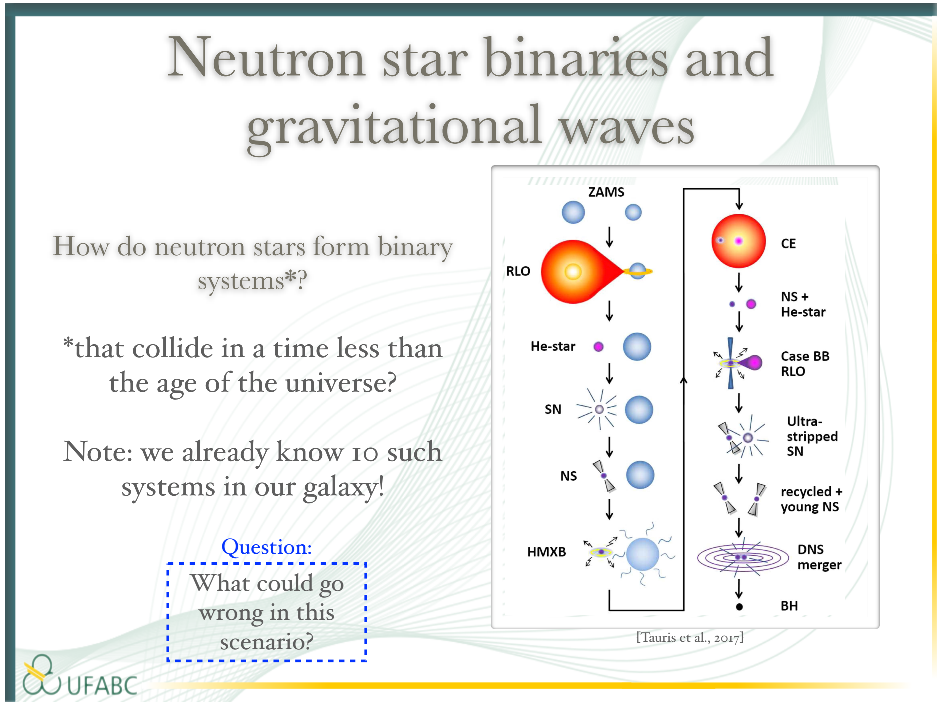
Credit: D. Kasen, NASA GW-EM Task Force



- Gamma-ray burst (GRB) and On-Axis Afterglow: Relativistic jet viewed within cone
- Kilonova: Radioactive glow from heavy elements, isotropic
- Off-Axis Afterglow: Relativistic jet viewed after lateral spreading
- **Panchromatic phenomenon with a variety of time scales**

Borrowed from NASA GW-EM Task Force Report - https://pcos.gsfc.nasa.gov/gw-em-taskforce/gw-em-taskforce.php

What have you already learned about binary neutron star mergers?



Neutron star binaries and gravitational waves

How do neutron stars form binary systems*?

*that collide in a time less than the age of the universe?

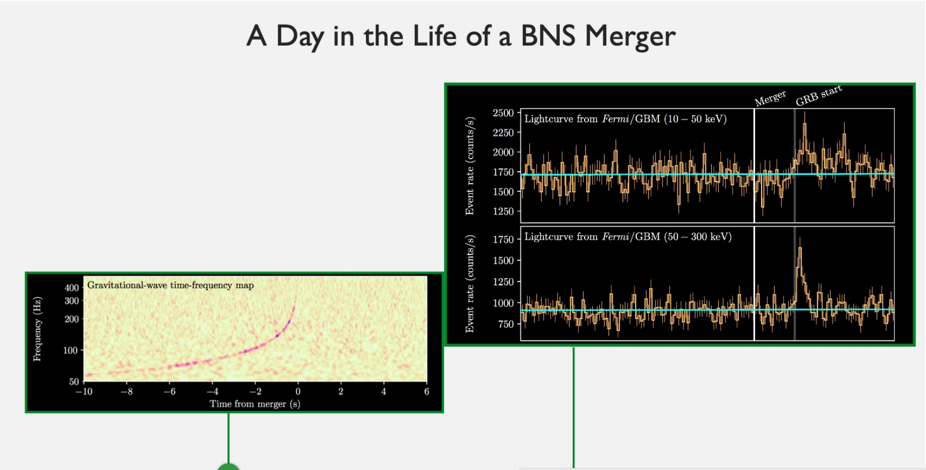
Note: we already know 10 such systems in our galaxy!

Question:
What could go wrong in this scenario?

[Tauris et al., 2017]

From Cecilia's Talk, also:

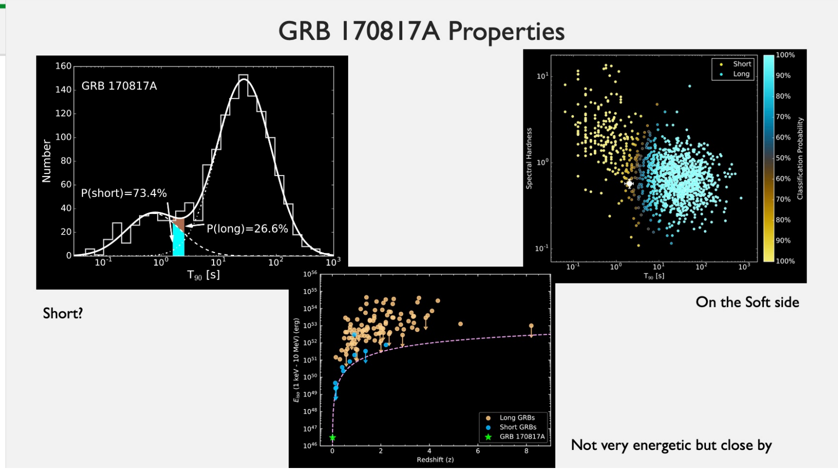
- rates of BNS, 2 GW detections so far
- BNS rates
- NS EOS
- Hubble Constant
- Lots of other great stuff!



A Day in the Life of a BNS Merger

From Josh's talk:

- analysis tutorial of GRB 170817A



GRB 170817A Properties

Short?

On the Soft side

Not very energetic but close by

From Cori's talk:

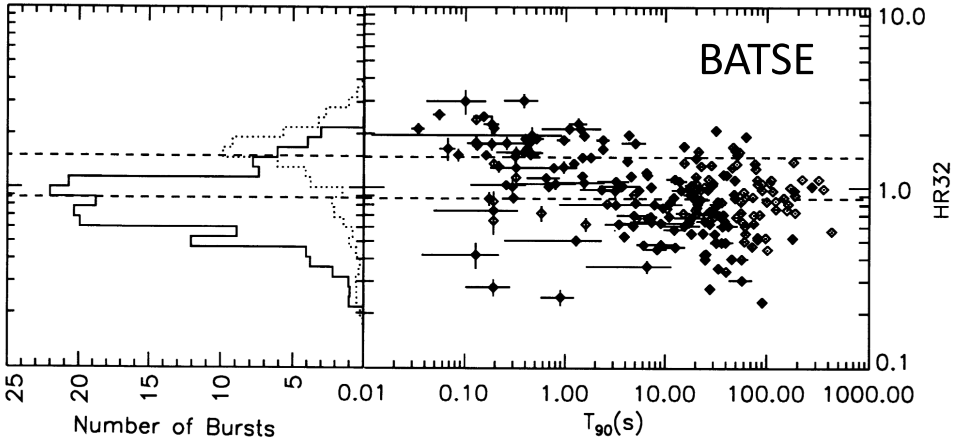
- GRB 170817A observational sequence, properties
- Lots of other great stuff!

Did our understanding of binary neutron star mergers start with GW 170817?

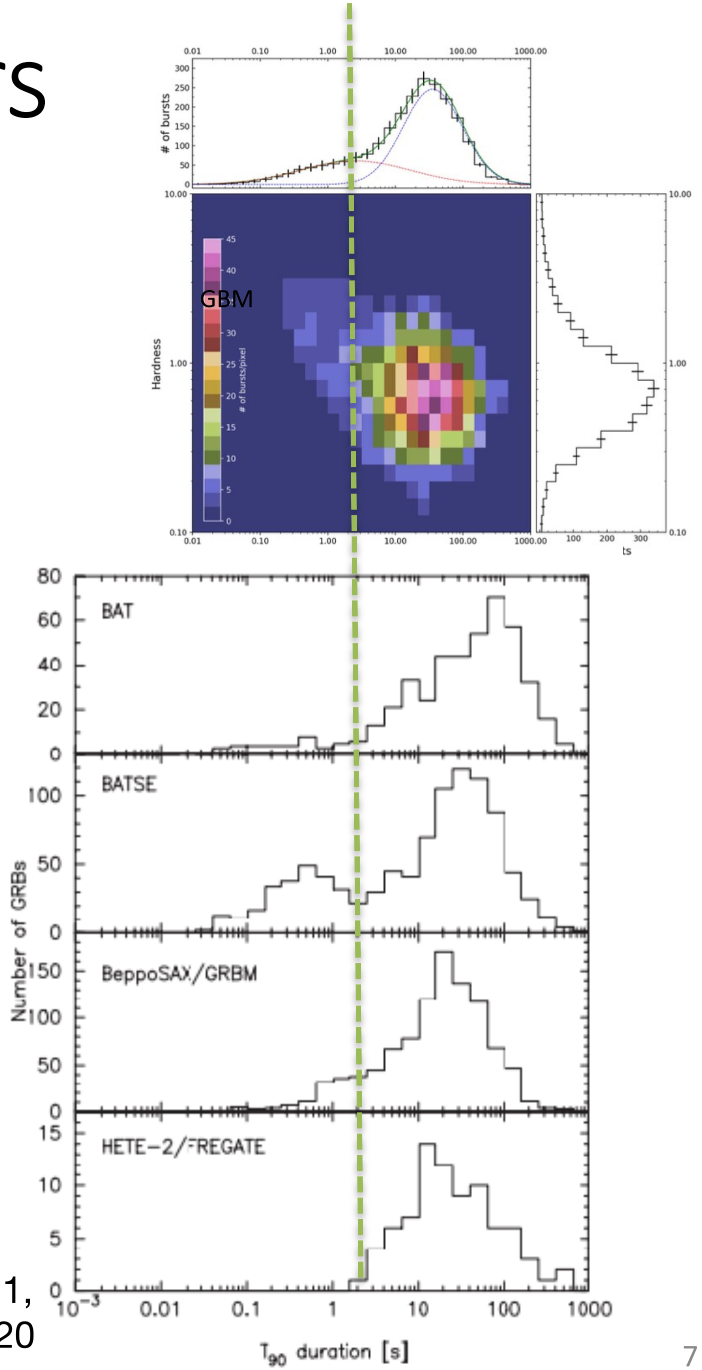
NO

What did we know about BNS mergers before GW detection?

- GRBs can be separated into 2 distributions in T90, even better including hardness ratio
- Short GRBs are shorter and harder than long GRBs
- Overlap in distributions, but reasonable separation
- Lots of studies looking for a 3rd intermediate population, some claims, but they look like like long bursts

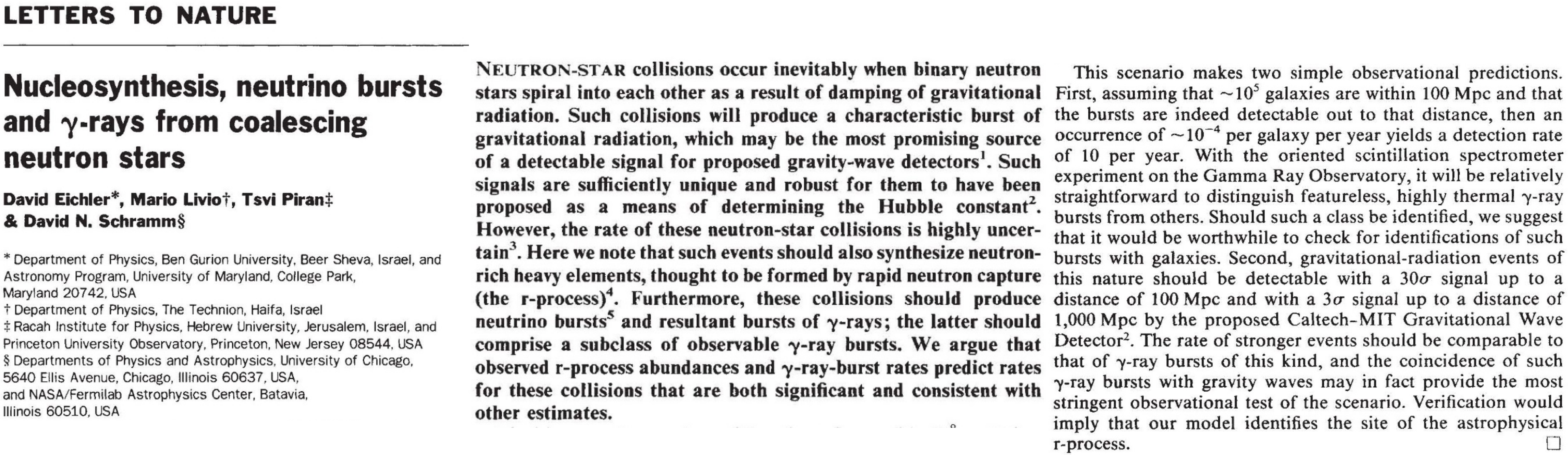


Kouveliotou et al. 1993



Sakamoto et al. 2011,
von Kienlin et al. 2020

BNS Mergers produce sGRBS – Predictions tested



LETTERS TO NATURE

Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

David Eichler*, Mario Livio†, Tsvi Piran‡ & David N. Schramm§

* Department of Physics, Ben Gurion University, Beer Sheva, Israel, and Astronomy Program, University of Maryland, College Park, Maryland 20742, USA
† Department of Physics, The Technion, Haifa, Israel
‡ Racah Institute for Physics, Hebrew University, Jerusalem, Israel, and Princeton University Observatory, Princeton, New Jersey 08544, USA
§ Departments of Physics and Astrophysics, University of Chicago, 5640 Ellis Avenue, Chicago, Illinois 60637, USA, and NASA/Fermilab Astrophysics Center, Batavia, Illinois 60510, USA

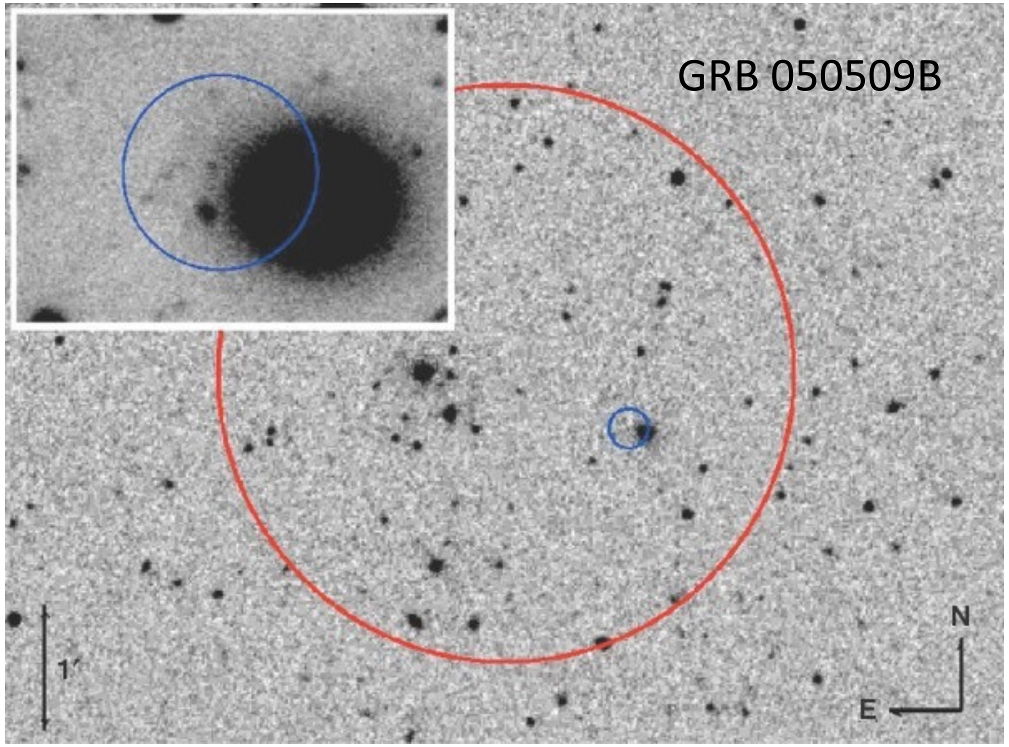
NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

This scenario makes two simple observational predictions. First, assuming that $\sim 10^5$ galaxies are within 100 Mpc and that the bursts are indeed detectable out to that distance, then an occurrence of $\sim 10^{-4}$ per galaxy per year yields a detection rate of 10 per year. With the oriented scintillation spectrometer experiment on the Gamma Ray Observatory, it will be relatively straightforward to distinguish featureless, highly thermal γ-ray bursts from others. Should such a class be identified, we suggest that it would be worthwhile to check for identifications of such bursts with galaxies. Second, gravitational-radiation events of this nature should be detectable with a 30σ signal up to a distance of 100 Mpc and with a 3σ signal up to a distance of 1,000 Mpc by the proposed Caltech–MIT Gravitational Wave Detector[2]. The rate of stronger events should be comparable to that of γ-ray bursts of this kind, and the coincidence of such γ-ray bursts with gravity waves may in fact provide the most stringent observational test of the scenario. Verification would imply that our model identifies the site of the astrophysical r-process. ☐

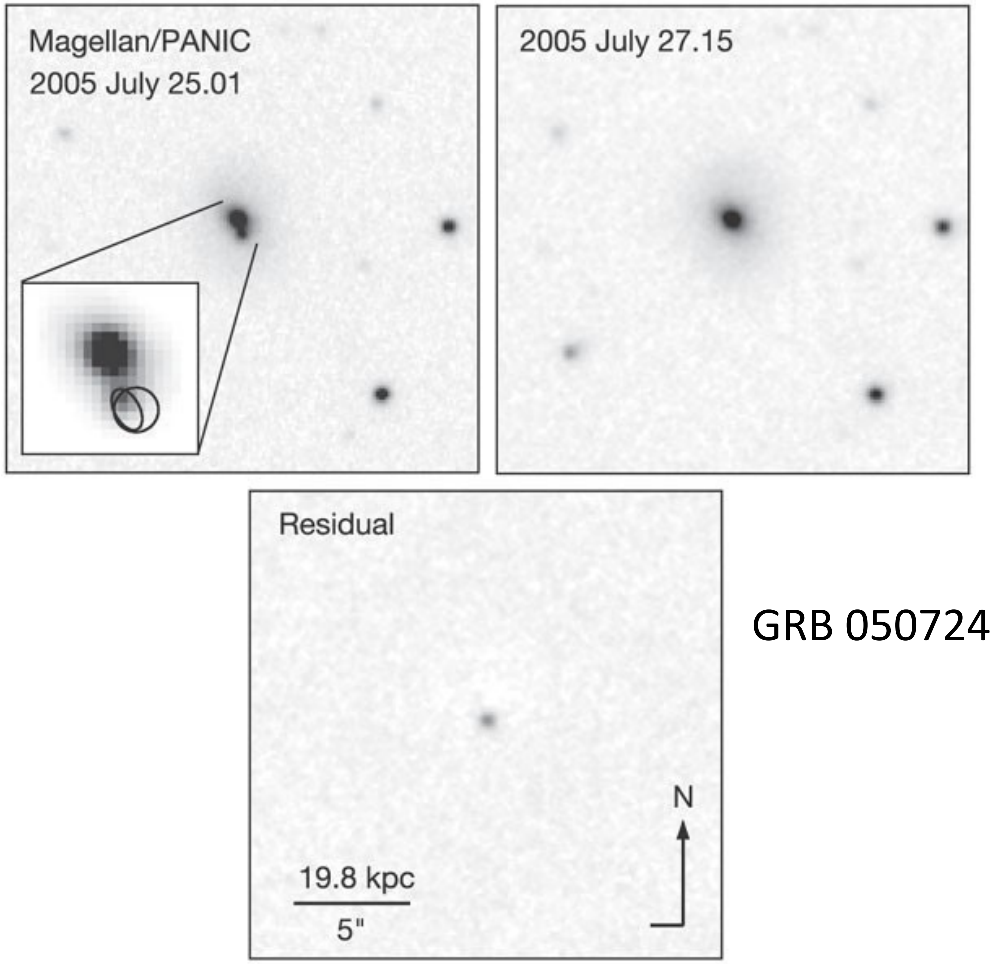
Eichler et al. 1989

sGRBs live in old stellar populations

First afterglows of a sGRBs just outside elliptical galaxies with low star formation rates



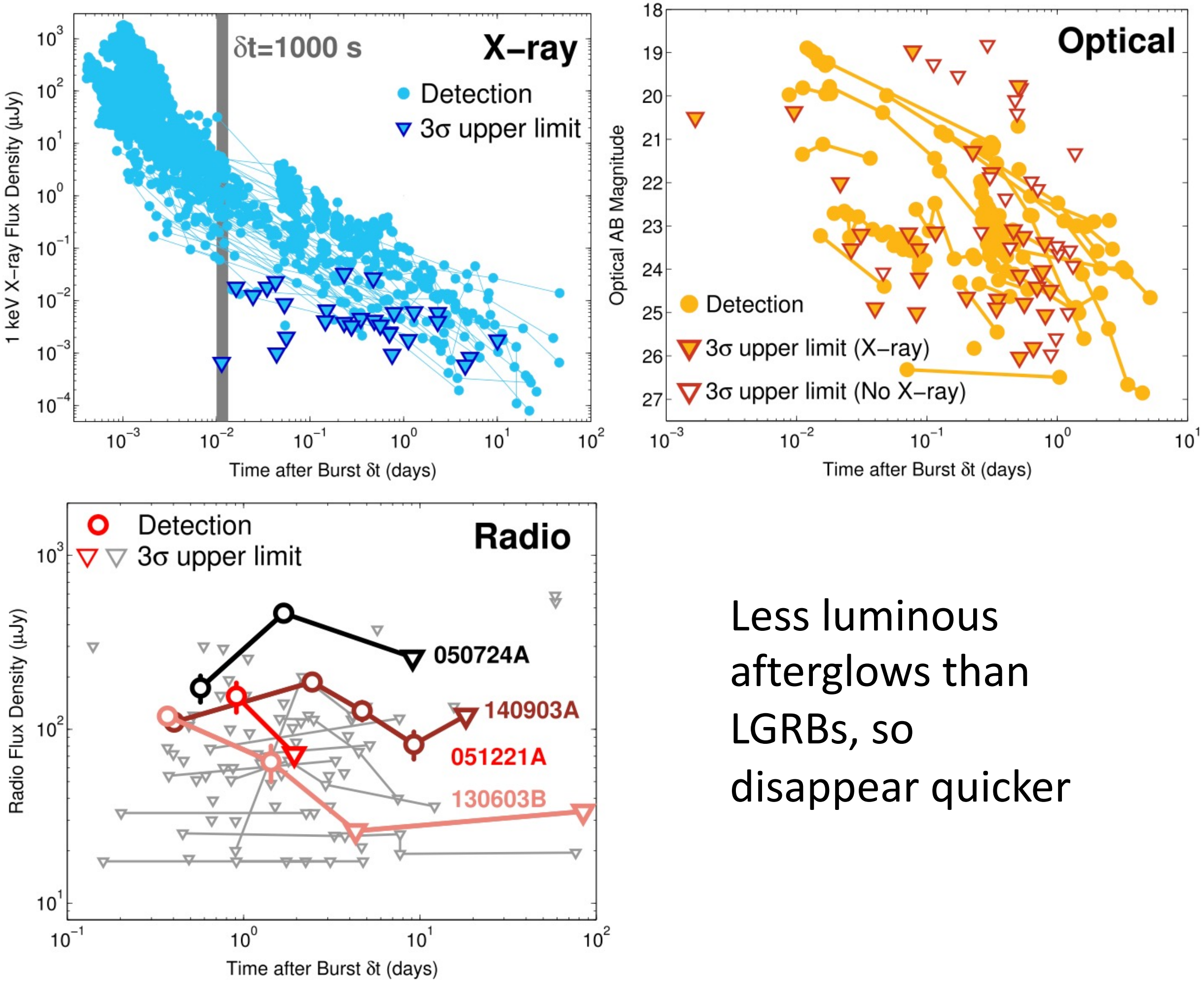
Gehrels et al. 2005



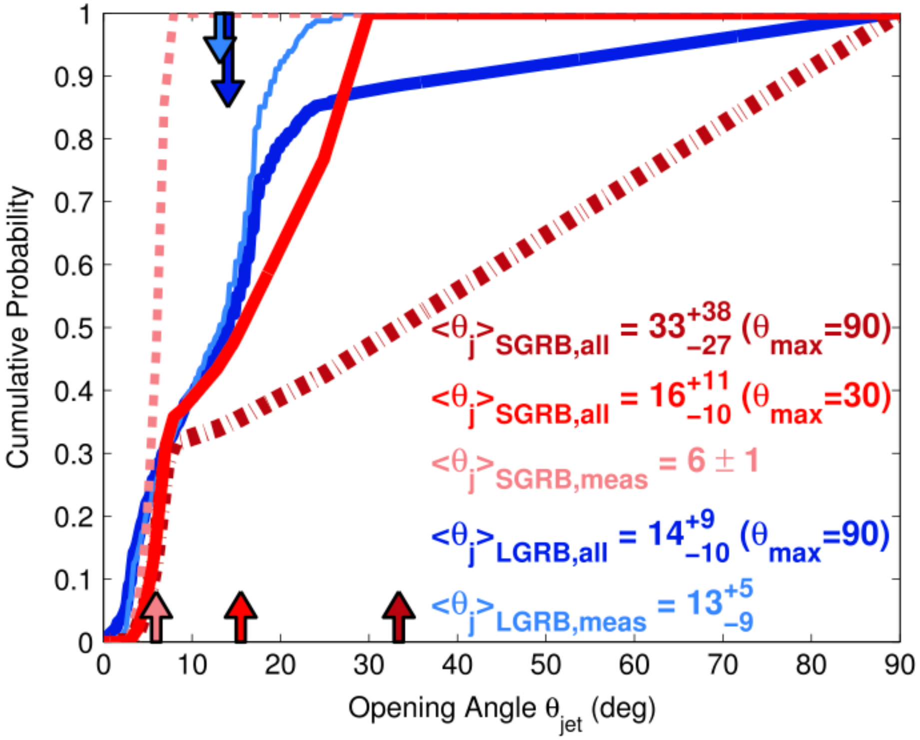
GRB 050724

Berger et al. 2005

sGRBs have afterglows and wider jets



Less luminous afterglows than LGRBs, so disappear quicker

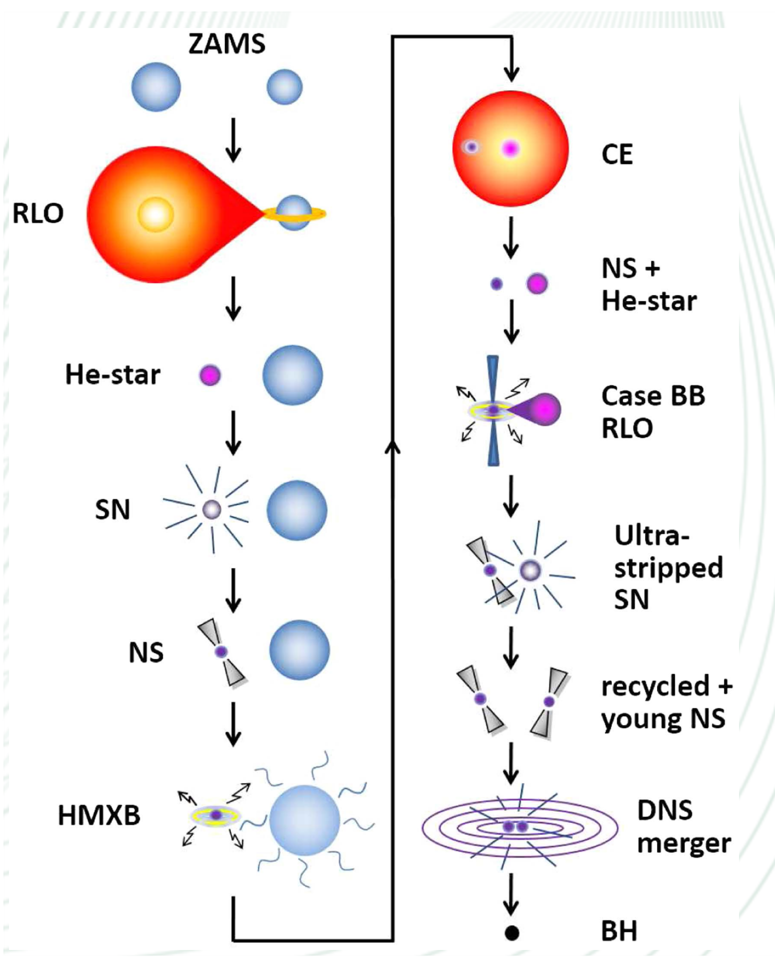


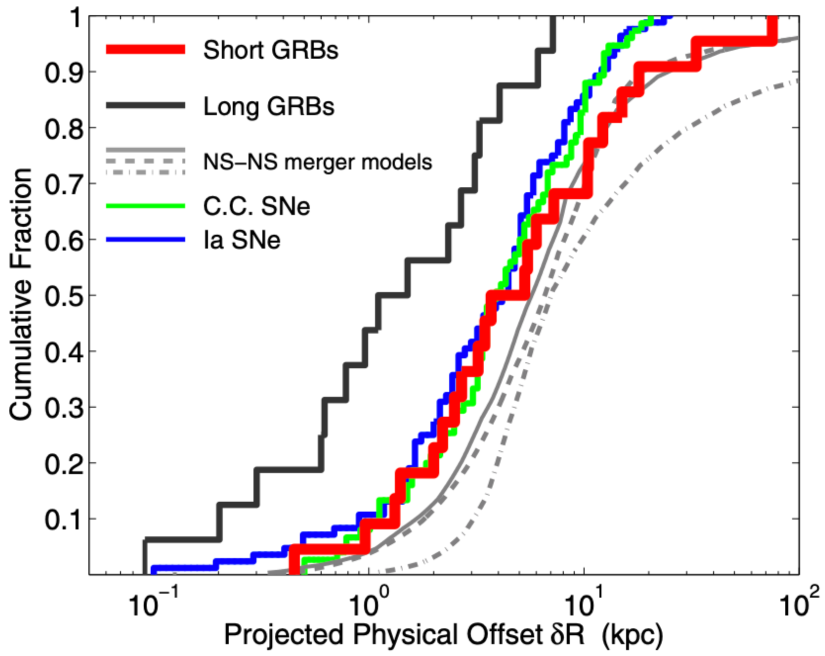
Maybe they have wider jet opening angles?
Lots of selection effects

Fong et al. 2015

Host Galaxies and Environments

- mass, stellar population age, specific star formation rate and metallicity are significant different between the hosts of short and long GRBs
- short GRBs are associated with a mixed population of early and late-type host galaxies





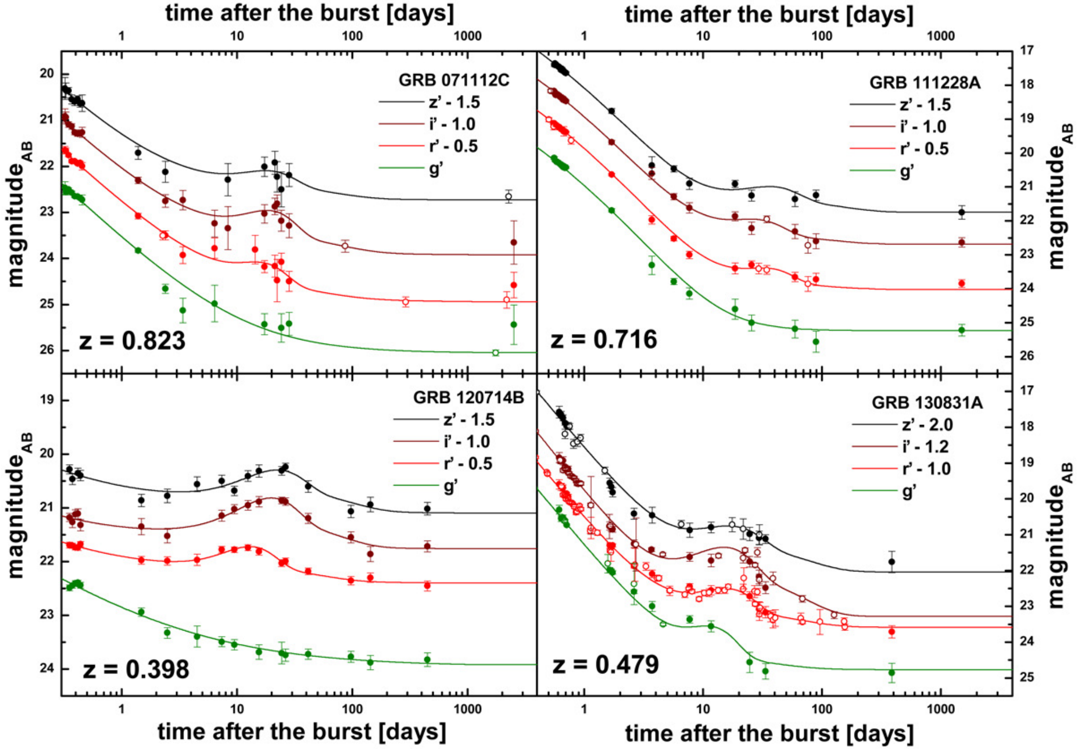
D'Avanzo et al. 2015

Tauris et al. 2017

Fong et al. 2013

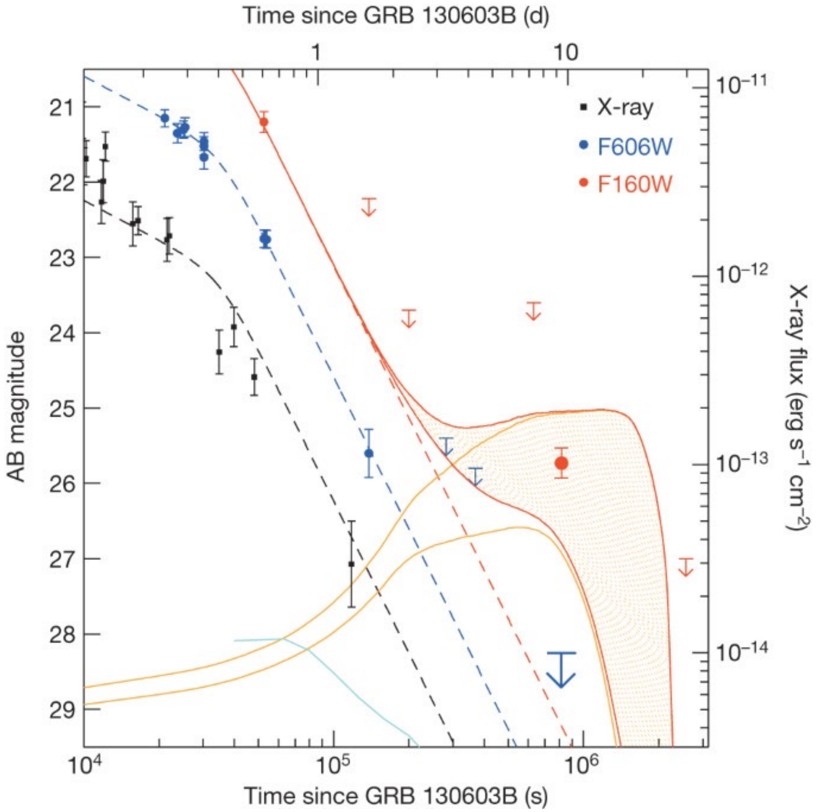
SN/KN Bumps Identify Progenitor Type

late-time bump in optional/IR afterglow light curves consistent with broadline SN Ic -> Collapsar



Klose et al. 2019

late-time bump in optional/IR afterglow light curves consistent with KNe -> BNS merger



Tanvir et al. 2013

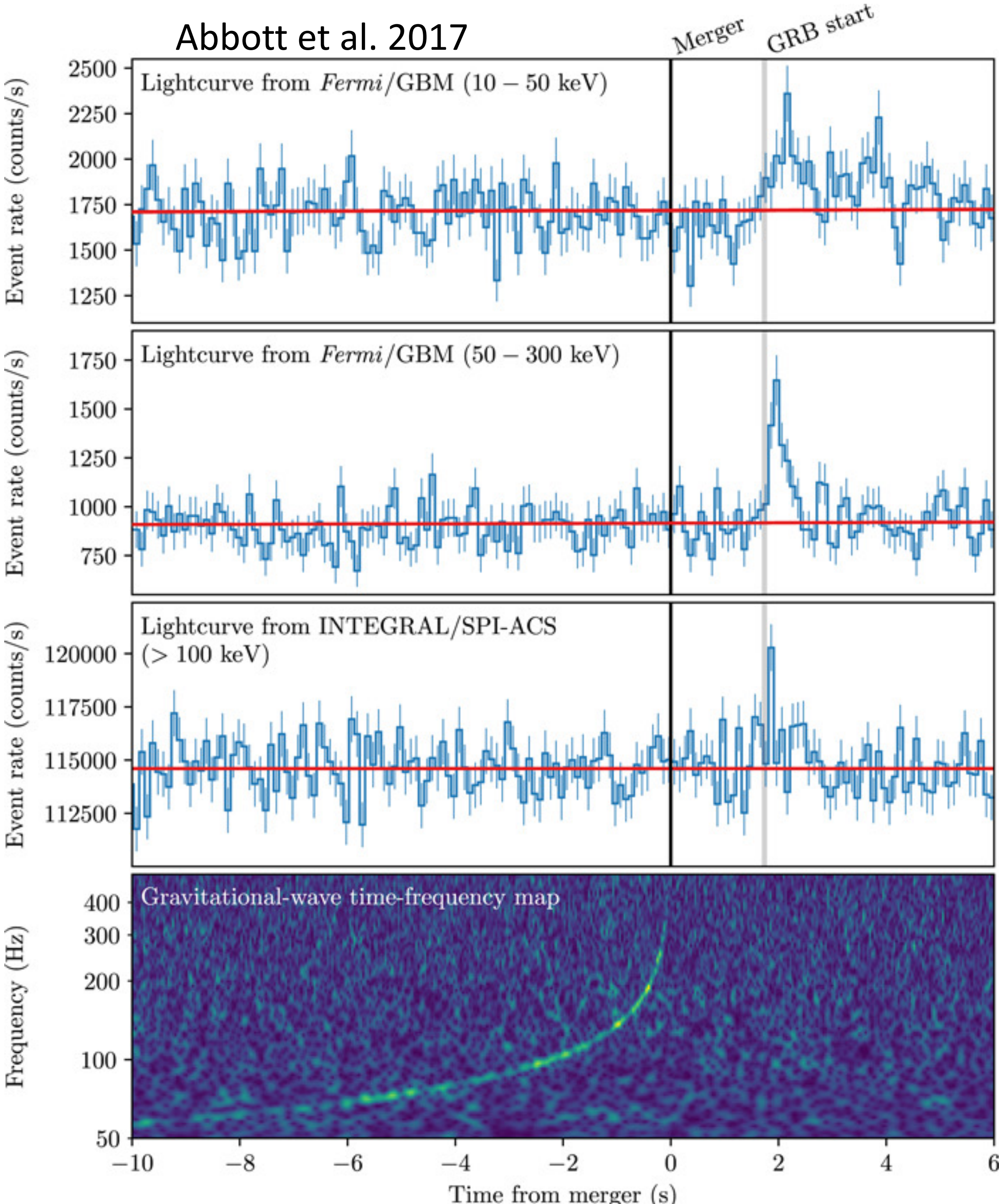
What was actually new with 170817?

- GW provided
  - precise time of merger (and delay between merger and GRB of 1.7 s, used e.g. speed of gravity)
  - NS progenitor masses, and final mass
  - independent measure of distance (used e.g. for hubble constant)
- kilonova
  - precise localization (and every telescope on earth pointed at it) provided amazing dataset of evolving kilonova
- off-axis afterglow
  - extremely nearby distance allowed for detection of off-axis afterglow
- GRB appeared relatively normal and boring, except it’s very nearby

GRB 170817A and it’s counterpart GW 170817

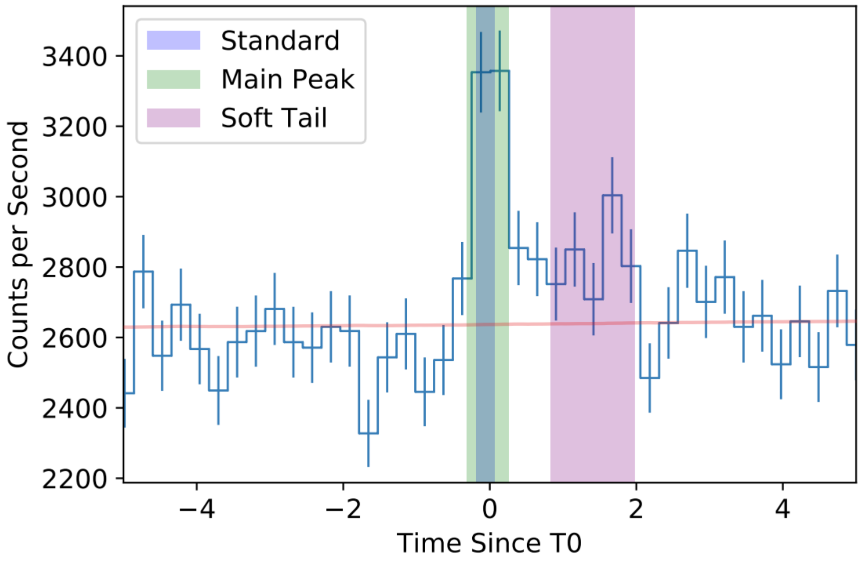
- Distance of 40 Mpc (z=0.01)
- GRB 1.7s after GW merger signal
- GRB was extremely sub-luminous
- It was viewed slightly off axis
- We got really really lucky

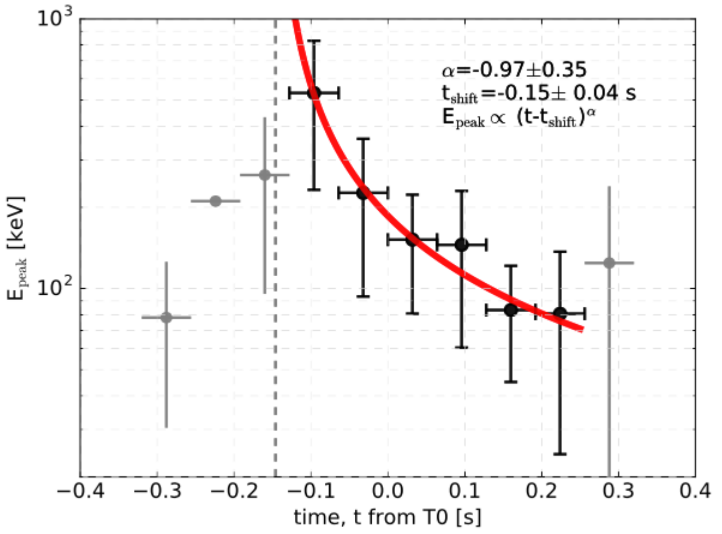
Abbott et al. 2017



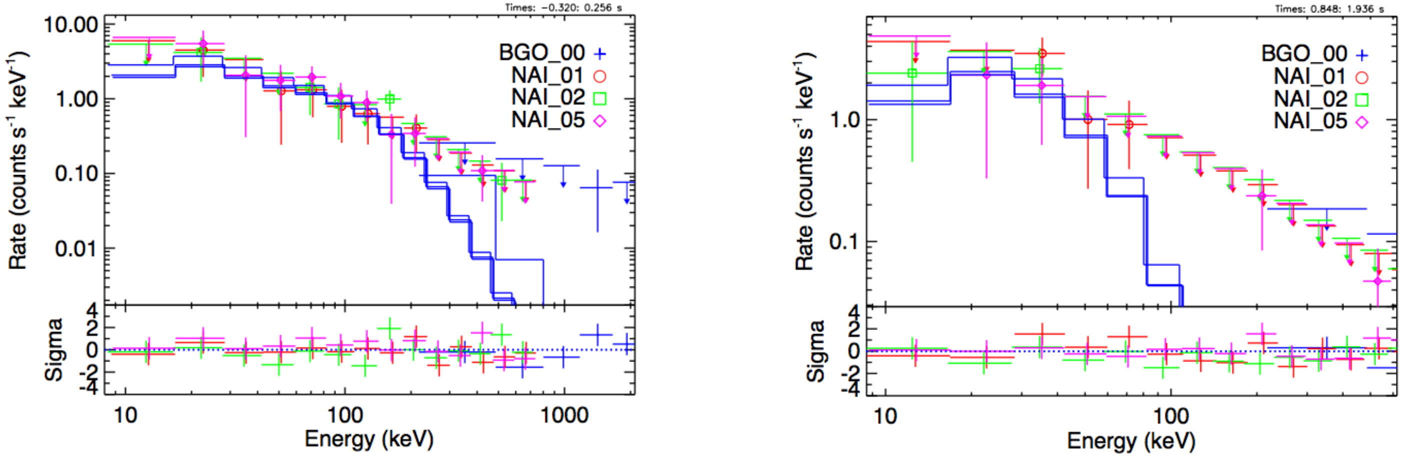
GRB 170817A Spectral Components

- Typical short (~0.5 s) hard spike
  - $\alpha = -0.62 \pm 0.40$
  - $E_{peak} = 185 \pm 62$ keV
- Longer (~1 s) soft thermal tail
  - $kT = 10.3 \pm 1.5$ keV





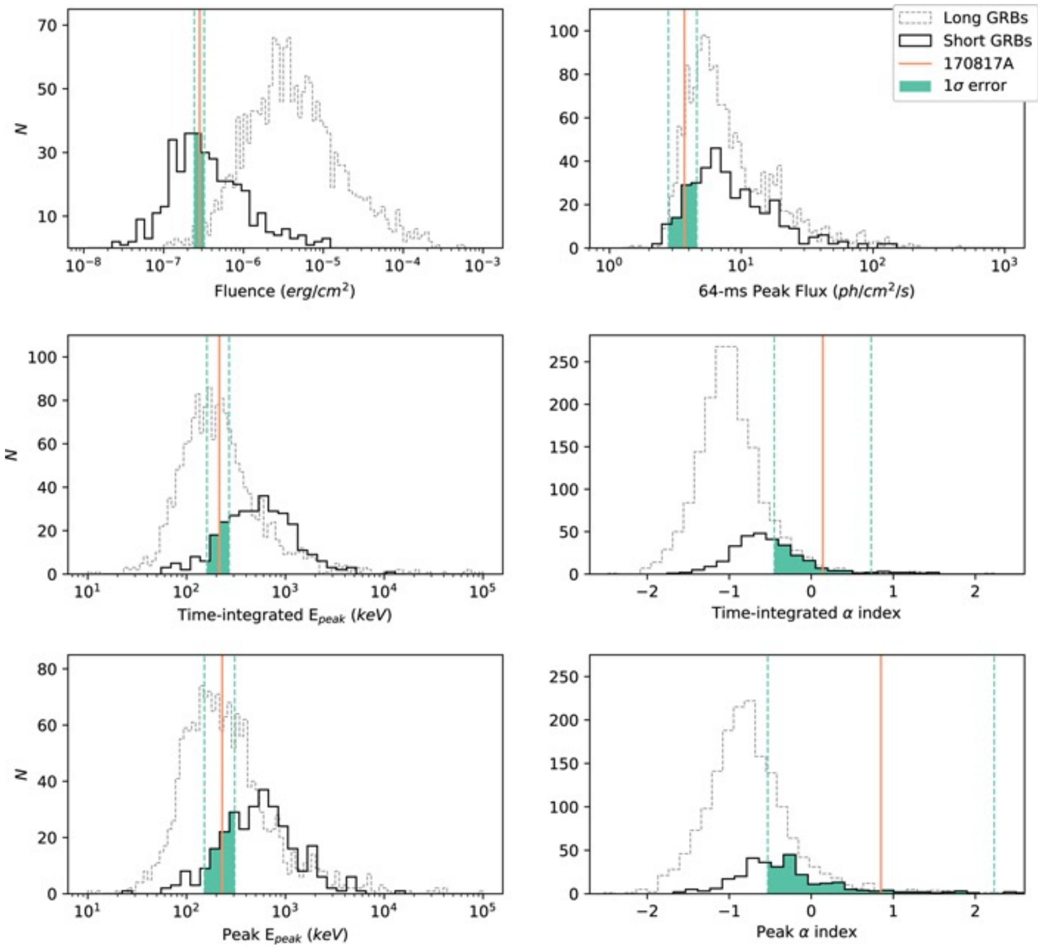
Veres et al. 2018



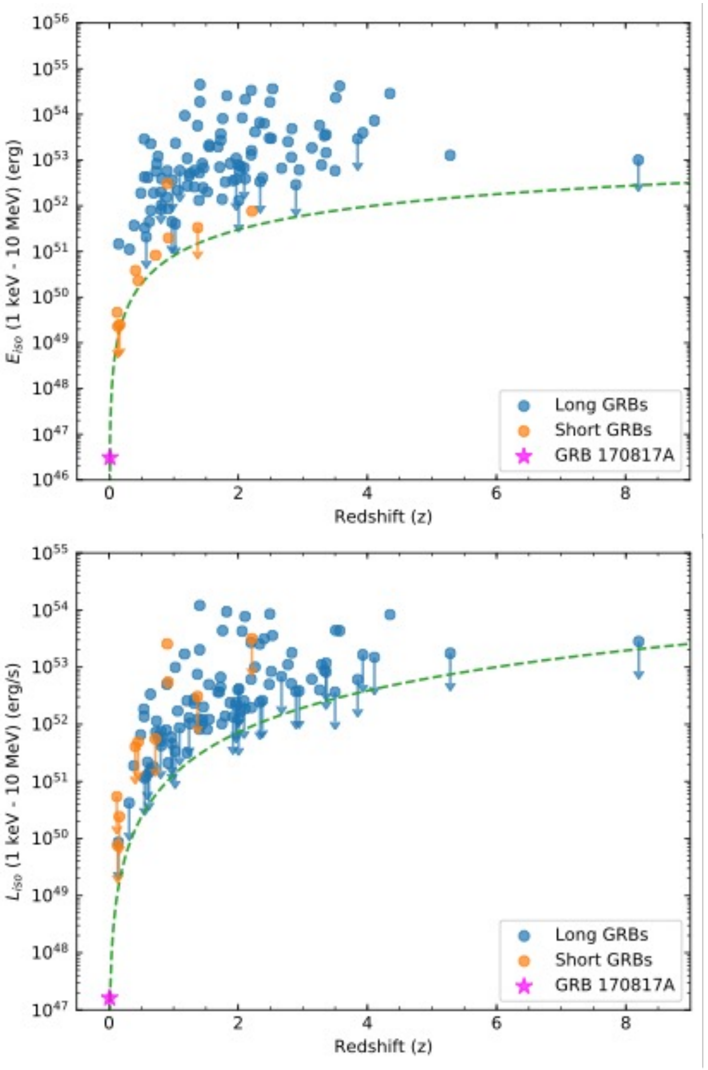
Goldstein et al. 2017

GRB 170817A Properties

GW170817 looks like a normal short GRB in observed properties



Goldstein et al. 2017

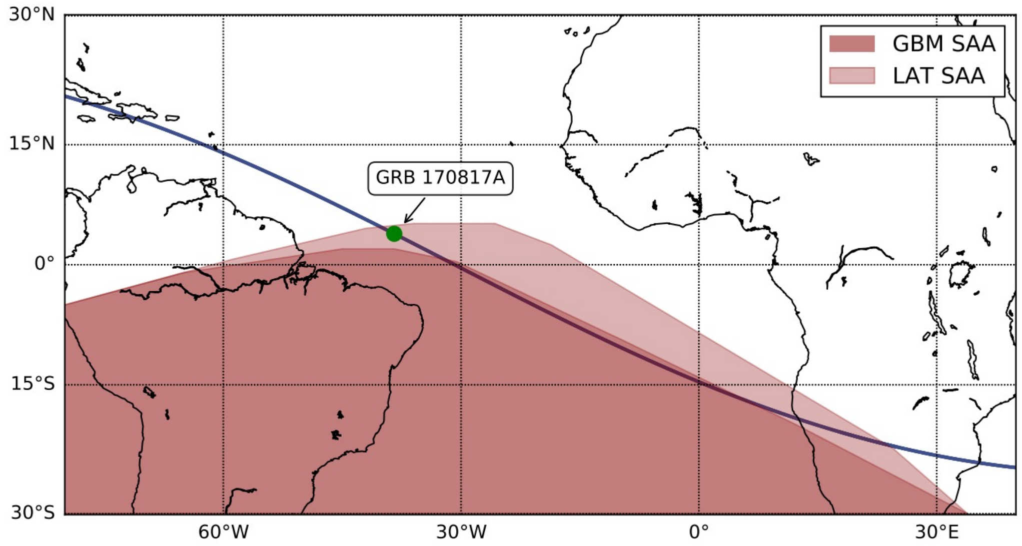


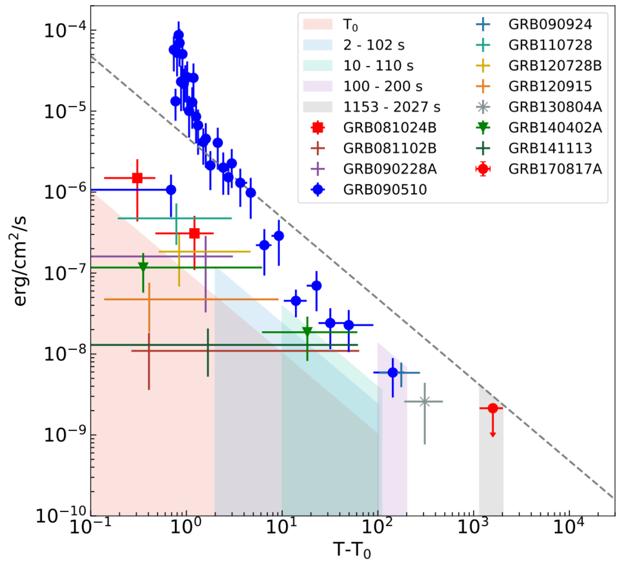
Abbott et al. 2017

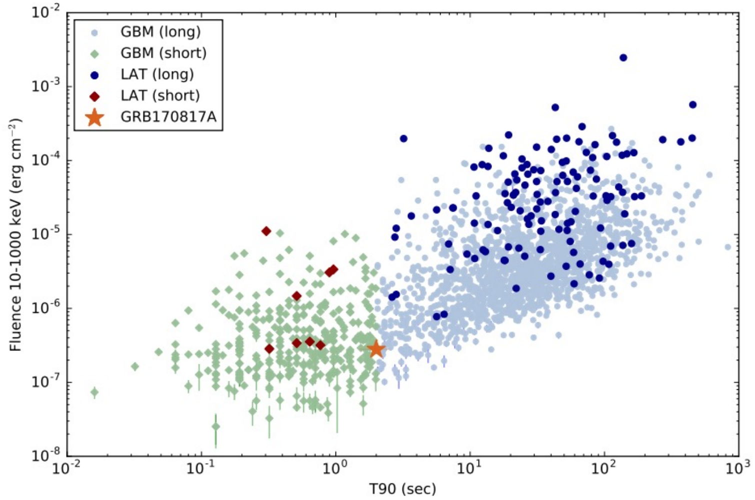
GW170817 several orders of magnitude weaker than other GRBs when accounting for distance

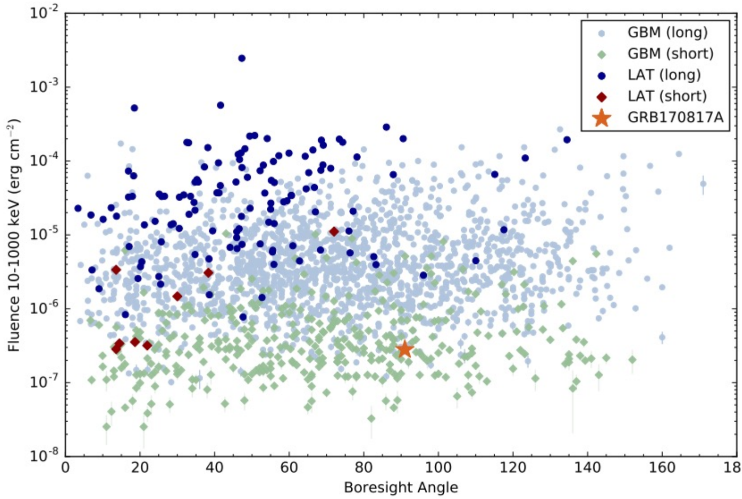
LAT Observations of GW170817/GRB 170817A

- LAT was not taking data at merger time (SAA)
- Upper limit from first observation perhaps in realm of detections of other LAT short GRBs
- LAT & GBM both shrinking SAA polygons









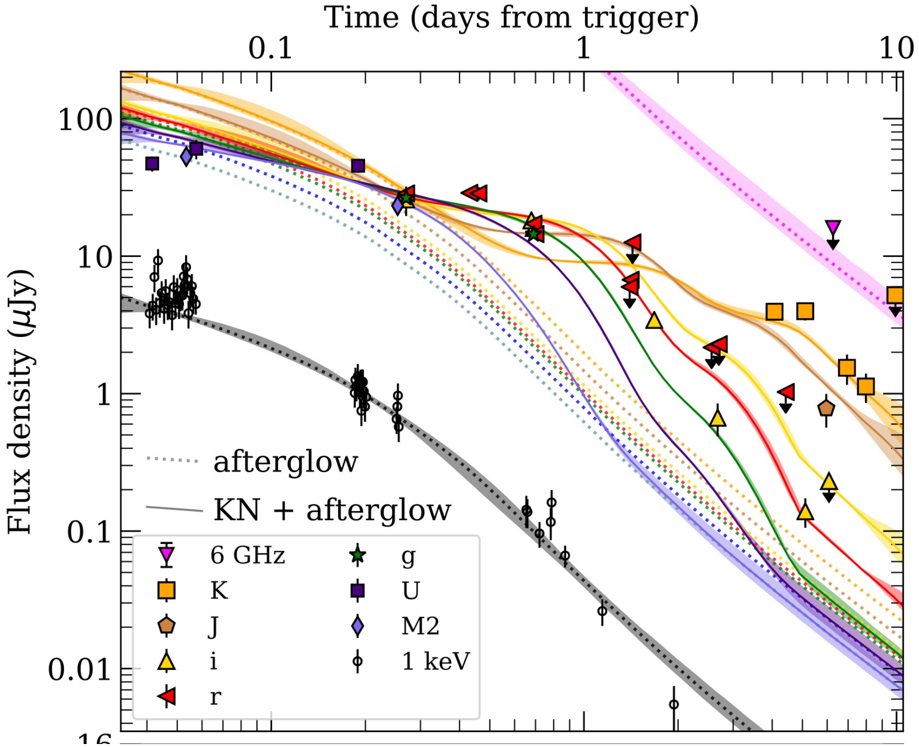
Ajello et al., 2018, ApJ, 861, 85

How do we identify BNS mergers in GRBs?

- Hardness and duration, right?

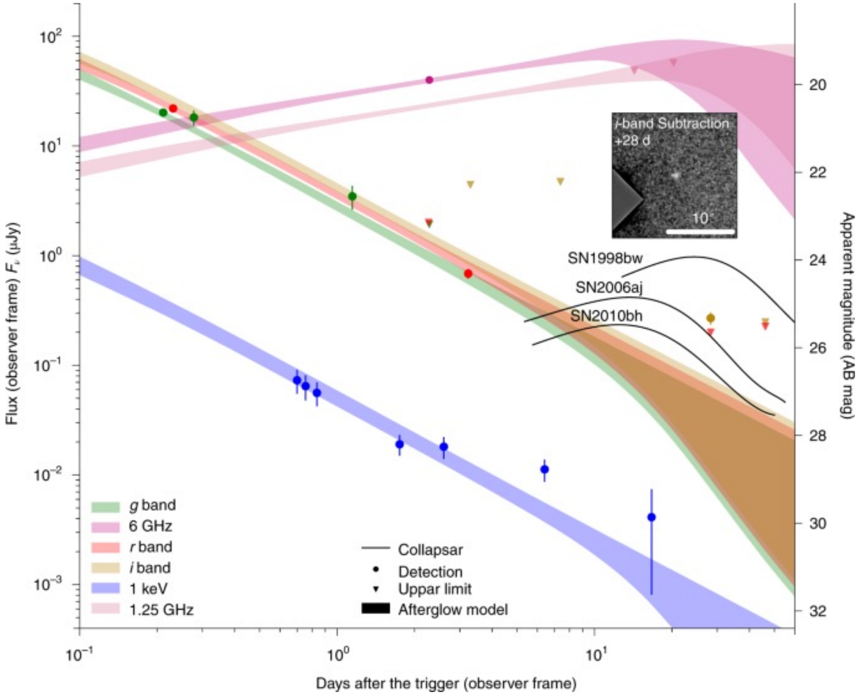
- long-short burst
- short-long bursts
- sGRBs with soft component

Long GRB with a KN
GRB 211211A
T_{90} = 43 s
350 Mpc, z=0.076



Rastinejad et al. 2022
See also Yang et al. 2022

Short GRB with SN
GRB 200826A
T_{90} = 0.65 s
5 Gpc, z = 0.748

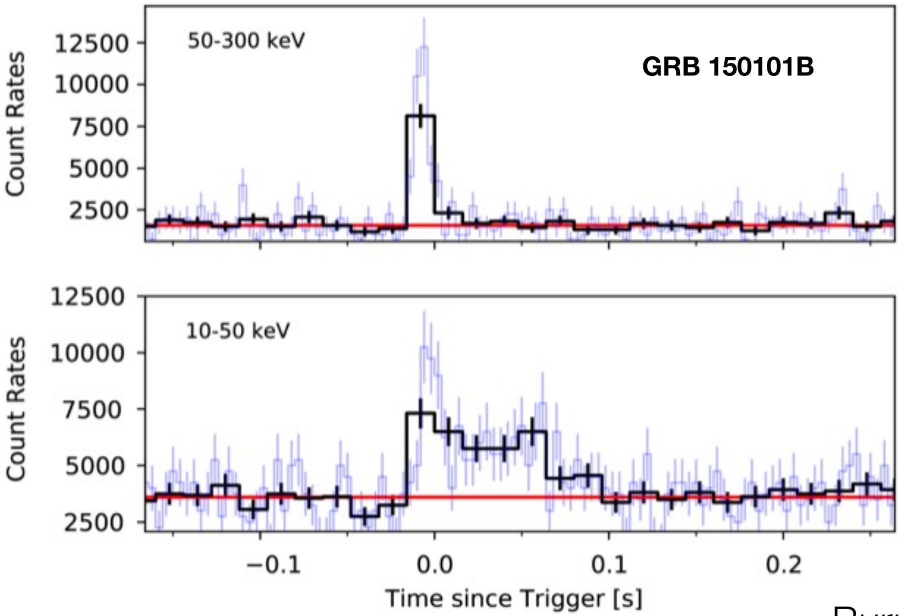


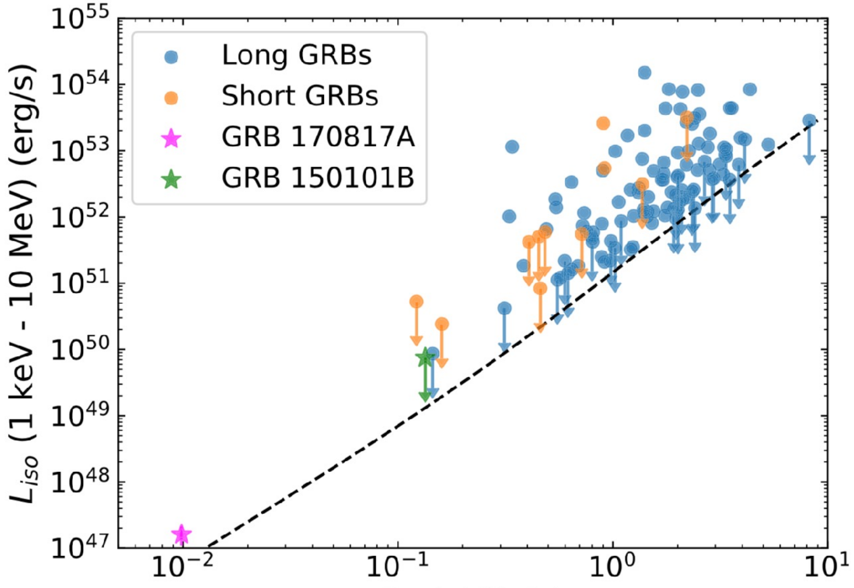
Ahumada et al. 2021

GRB 150101B - A Cousin of GW170817?

- The third closest SGRB with known redshift - GRB 150101B
- Very hard initial pulse with E_{peak} =1280±590 keV followed by a soft thermal tail with kT~10 keV
- Unlike GRB 170817, 150101B was not under luminous and can be modeled as on-axis
- Suggests that the soft tail is common, but generally undetectable in more distant events
- Thermal tail can be explained as GRB photosphere, but degeneracy with the cocoon model still exists

See also Troja et al. 2018 on GRB 150101B, and von Kienlin et al. 2019 for additional candidates

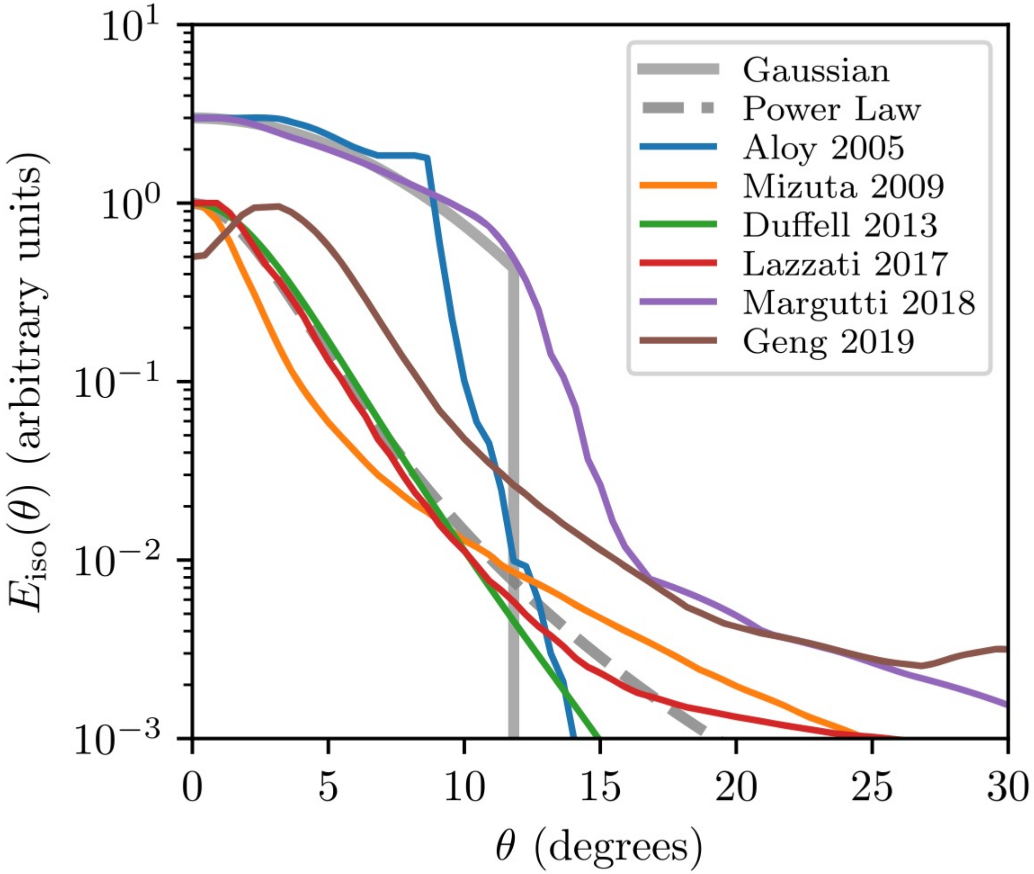




Burns et al 2018

What have we learned and could learn with more GW-GRBs?

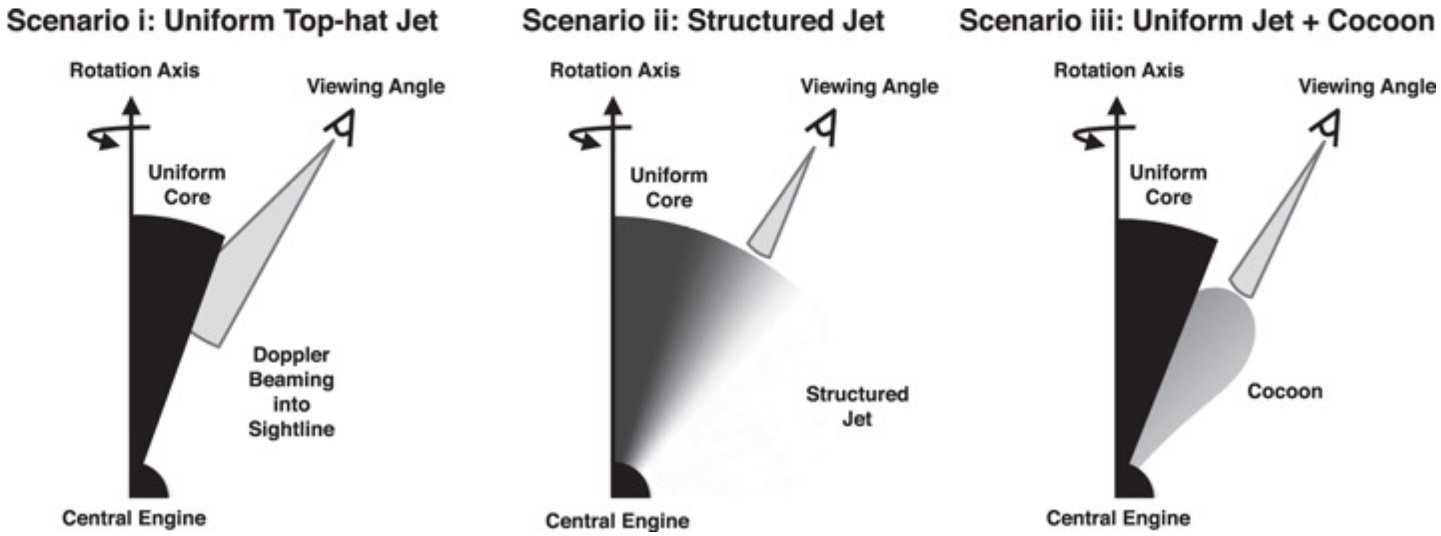
- sub-energetic population of nearby sGRBs
    - Is the intrinsic population not normally accessible or viewing angle geometry?
- jet structure
    - How does that affect visibility?
- progenitor and remnant objects
    - How do the binary component masses and mass ratio affect the final merged object?

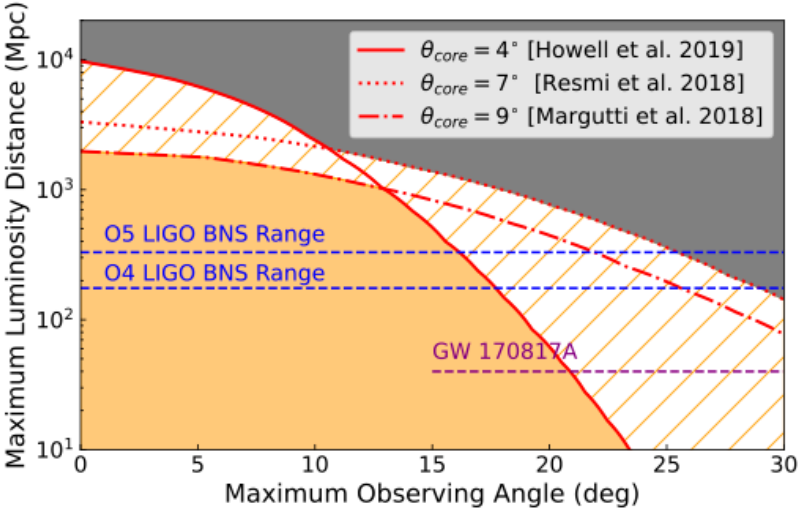


Ryan et al. 2020

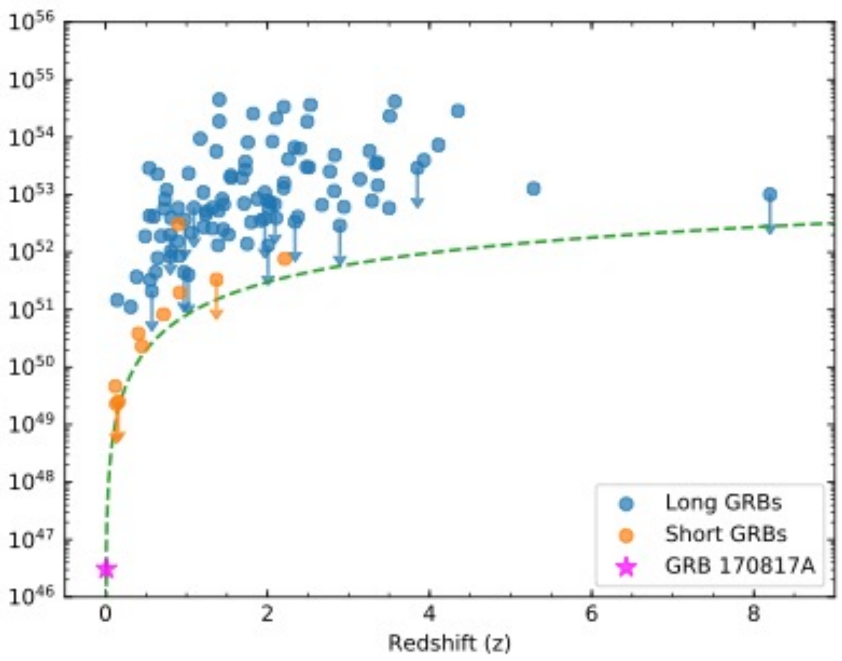
Jet Structure

- evidence for off-axis viewing
  - GW parameterization
  - low-luminosity GRB
  - rising X-ray/radio afterglow + afterglow modeling
- Population of good observations of GW detections of BNS can constrain jet structure models





Adapted from Howell et al. 2019

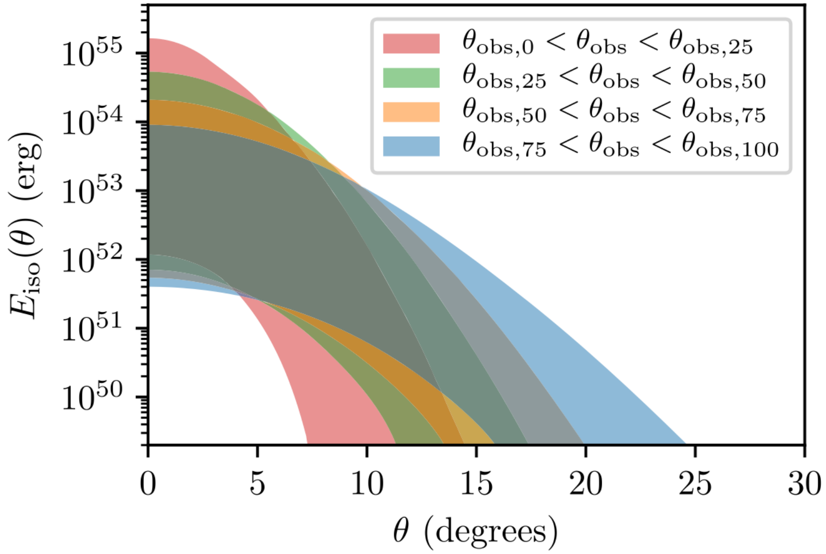


Abbott et al. 2017

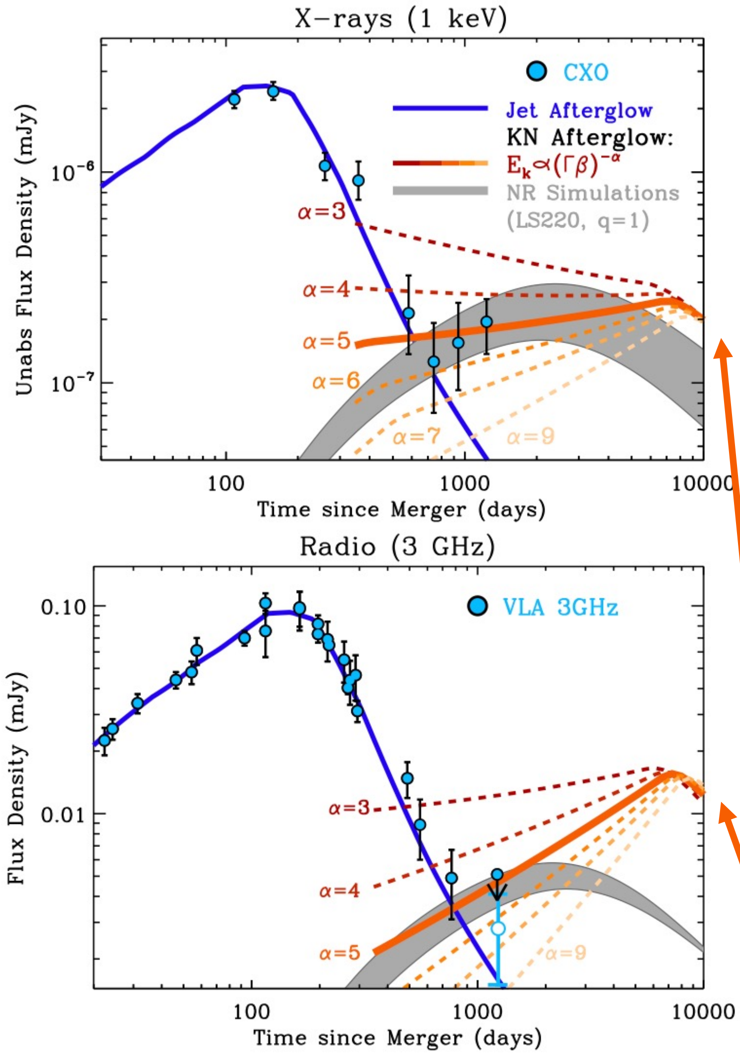
Afterglow Modeling Constrains Jet Opening Angle and Jet Viewing Angle

X-ray afterglow of GRB 170817A still being detected after 3.3 years

Afterglow evolution is subject to both viewing geometry and jet geometry

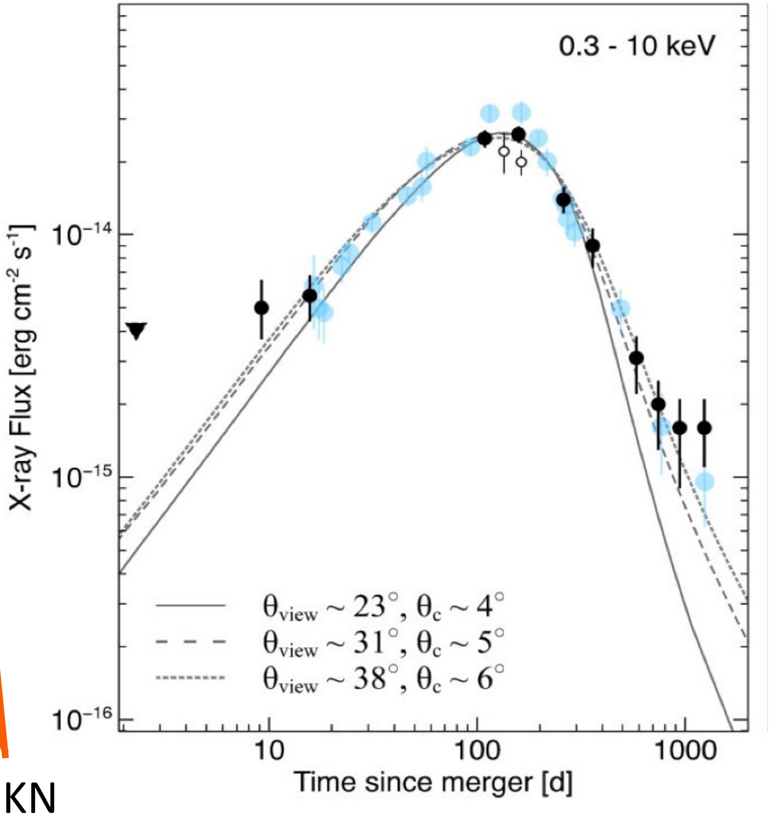


Ryan et al. 2020



Hajela et al. 2022

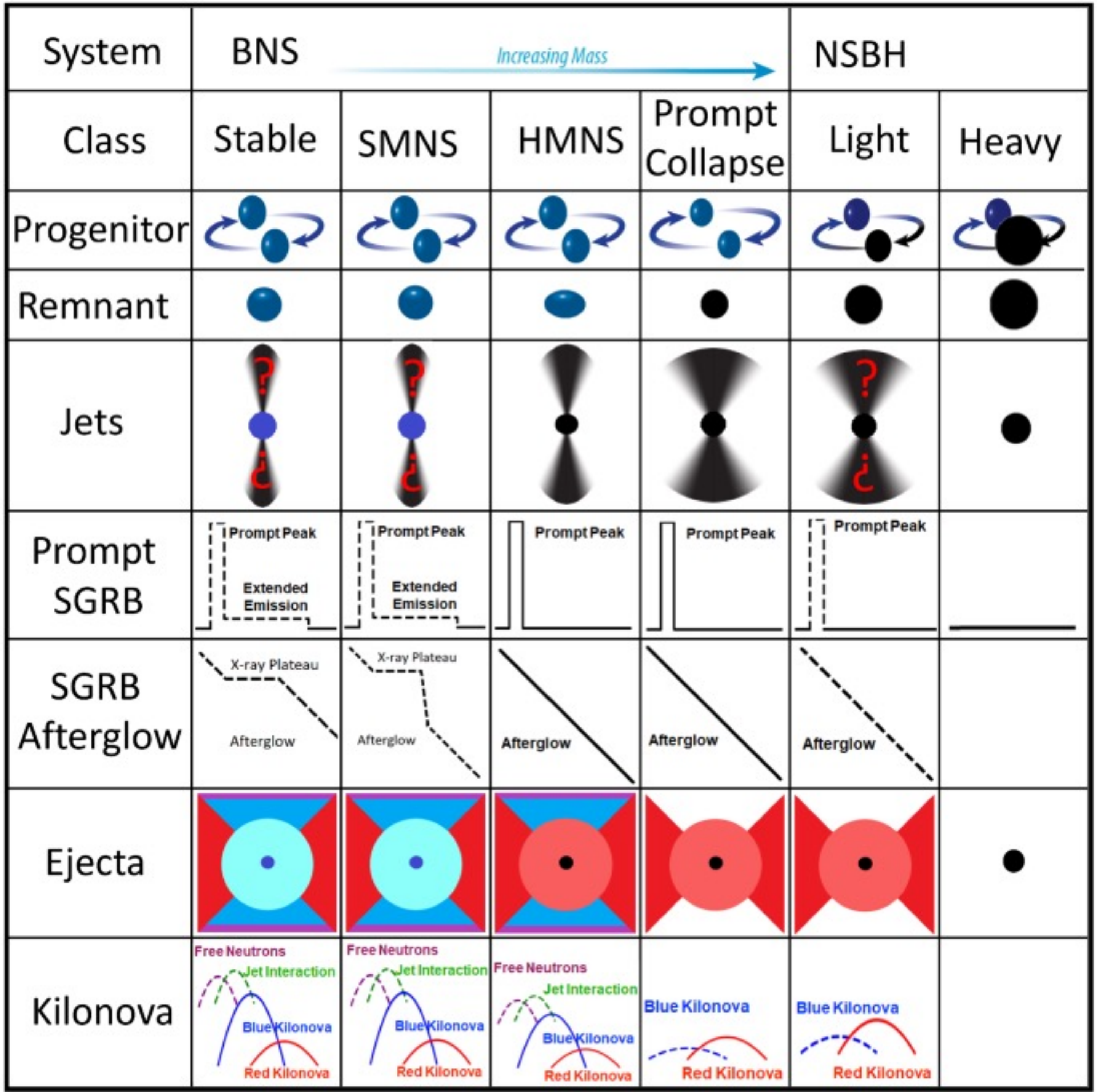
KN afterglow



Troja et al. 2022

Progenitor Objects

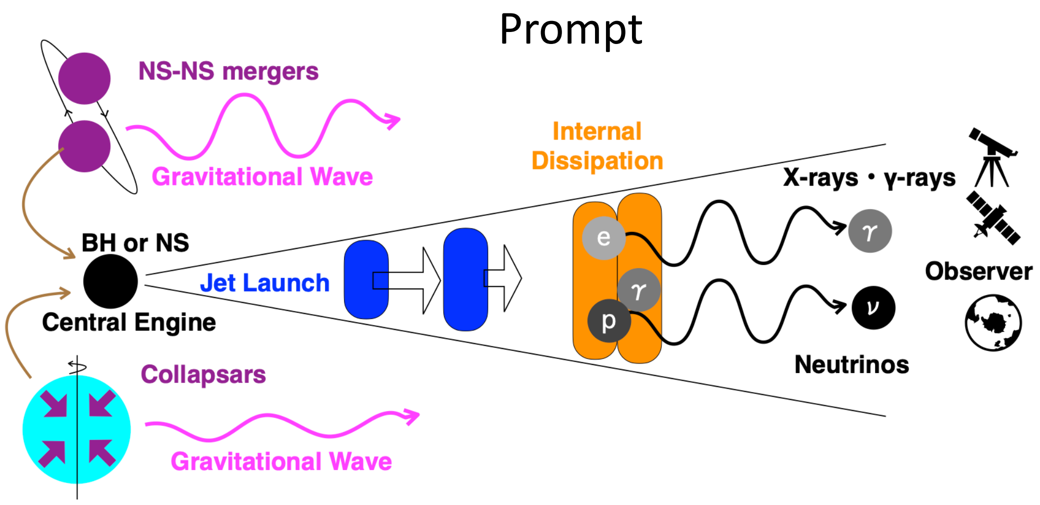
Good observations of GW, GRB, KN, afterglow can constrain the merger remnant and properties of the binary system



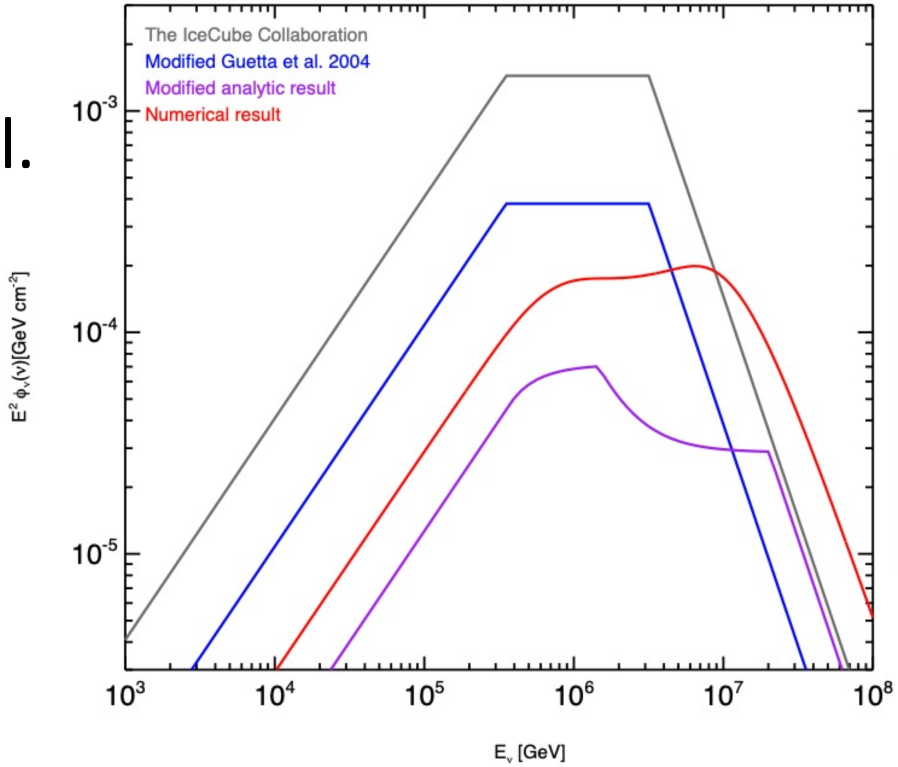
Burns et al. 2020 (originally from Nimble proposal)

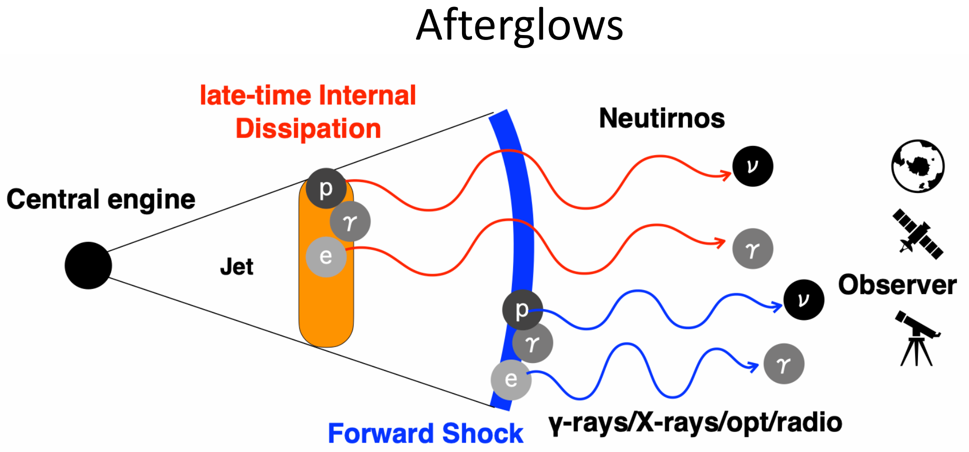
Neutrinos and GRBs

- GRB jets accelerate non-thermal protons, which are expected to produce high-energy neutrinos via photohadronic interactions.
- See Kimura et al. 2022 for a comprehensive review



Prompt





Afterglows

What’s next?

- Watershed GRB 170817A taught us a lot about BNS mergers and all of its counterparts (GW, GRB prompt, KN, GRB afterglow)
- The future will likely bring more events, but not nearly as close and exquisitely observable as 170817. We need to learn from those too.
- We need GRB monitors to provide measures of prompt temporal and spectral properties, delay time from merger, confirmation of signal/type, and localizations, and broadband afterglow observations.
- In addition to GBM, many more small GRB detectors coming (e.g. BurstCube, Glowbug, StarBurst, BlackCat, …), and many others proposed