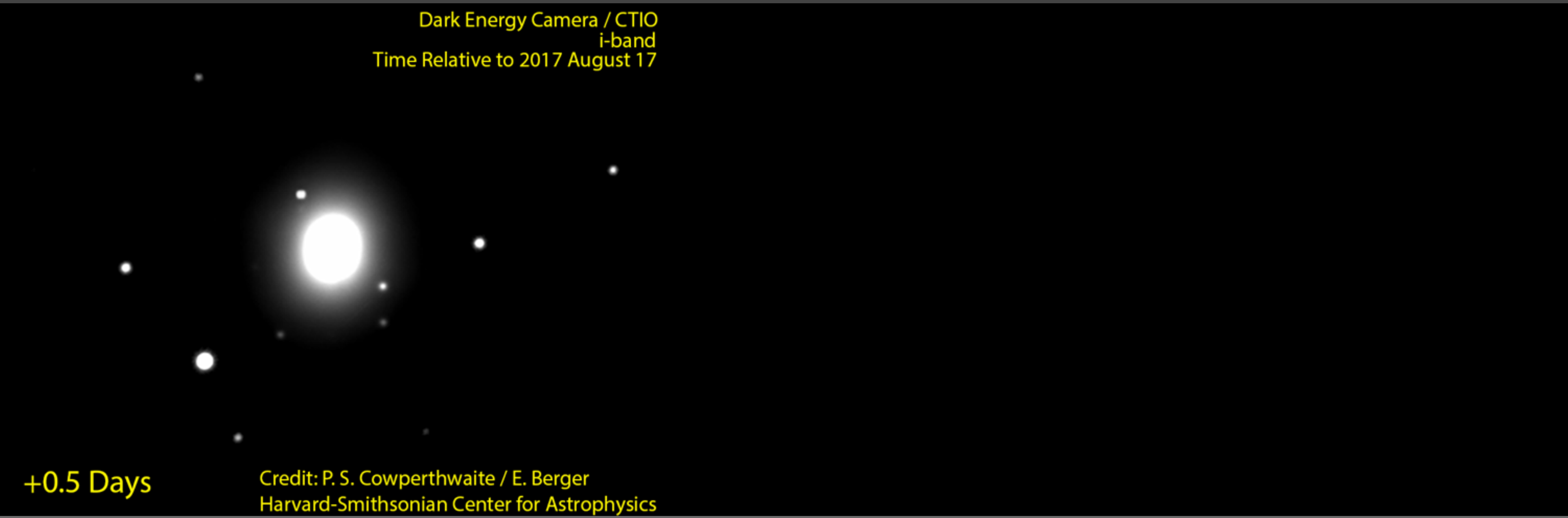
Combining Gravitational Waves and Electromagnetic Radiation to Decipher the Properties and Outcome of a Binary Neutron Star Merger



Edo Berger *(Harvard University)*

Universität Bern – April 2018

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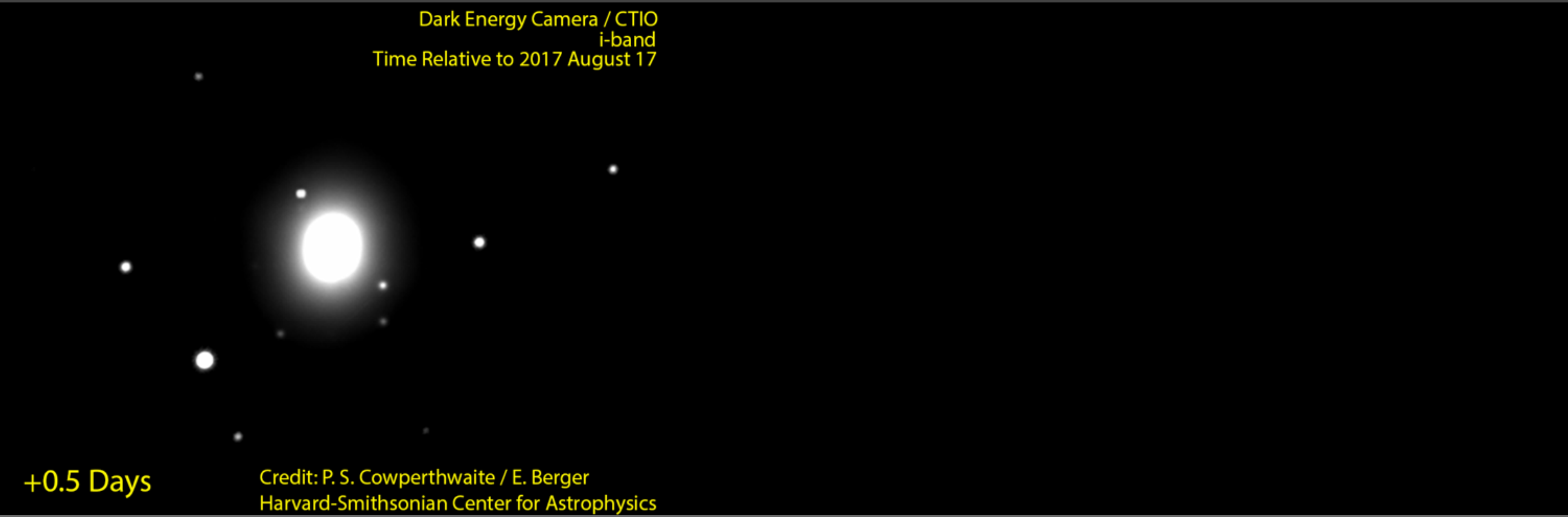

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Outline

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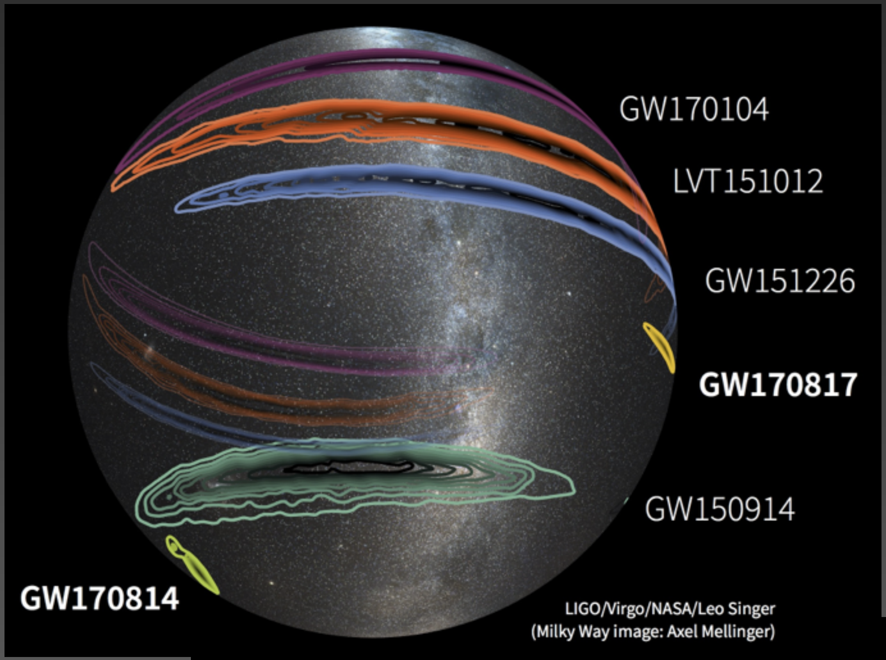
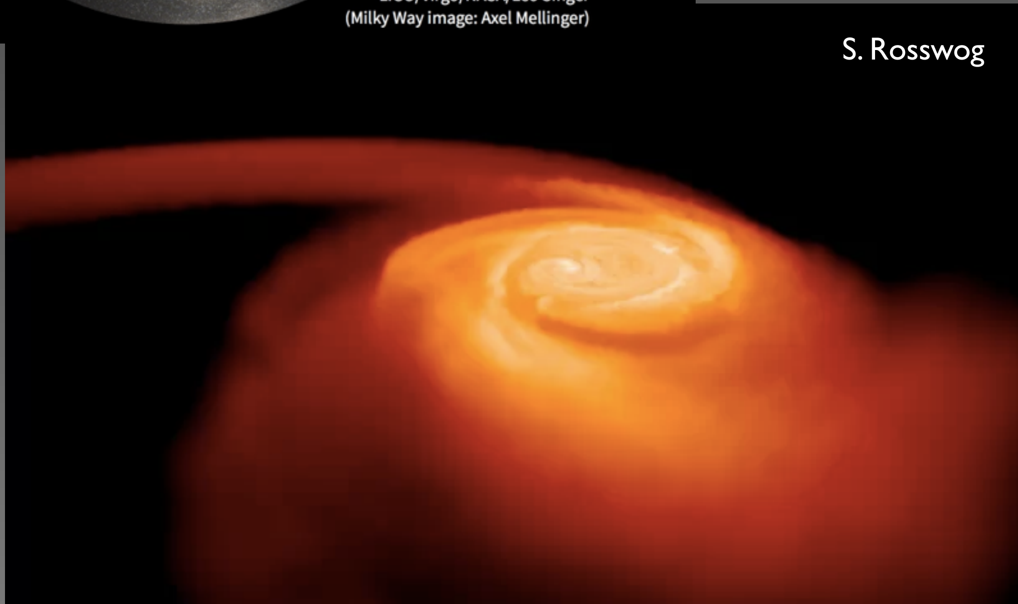
- Electromagnetic counterparts: Why and what?
- Short gamma-ray bursts as neutron star binary mergers
- GW170817 from radio to gamma-rays
    - *UV/optical/IR: r-process nucleosynthesis*
    - *Radio/X-ray emission: off-axis jet & connection to short GRBs*
    - *Host galaxy properties: merger timescale*

Electromagnetic Counterparts: Why & What

- Precise position
- Distance
- Host / context
- Behavior of matter
- Nature of remnant





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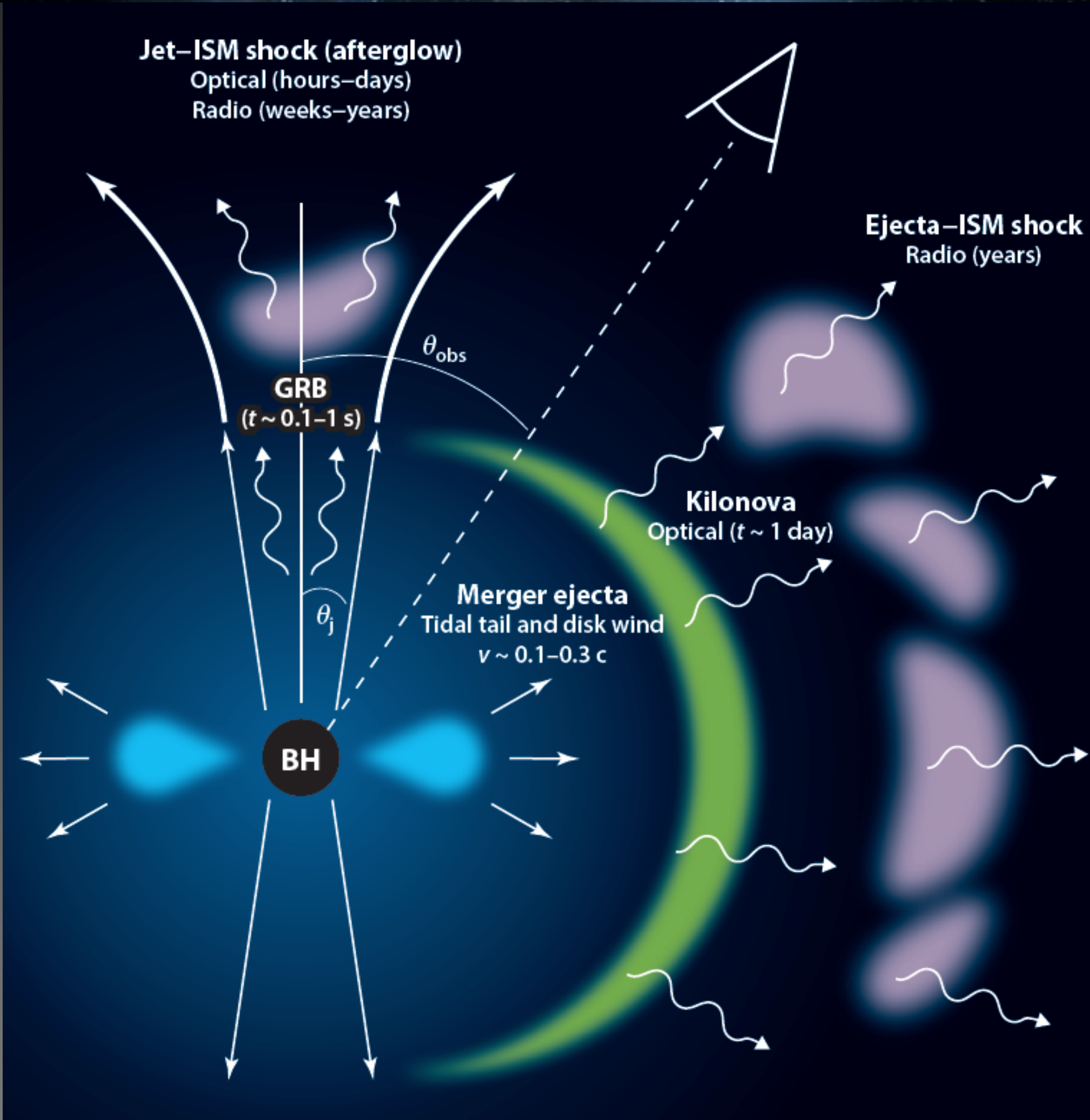
Predicted emission:

- Beamed & isotropic
- Relativistic & non-relativistic
- Multi-wavelength



Metzger & EB 2012

Short GRBs as BNS Merger Counterparts

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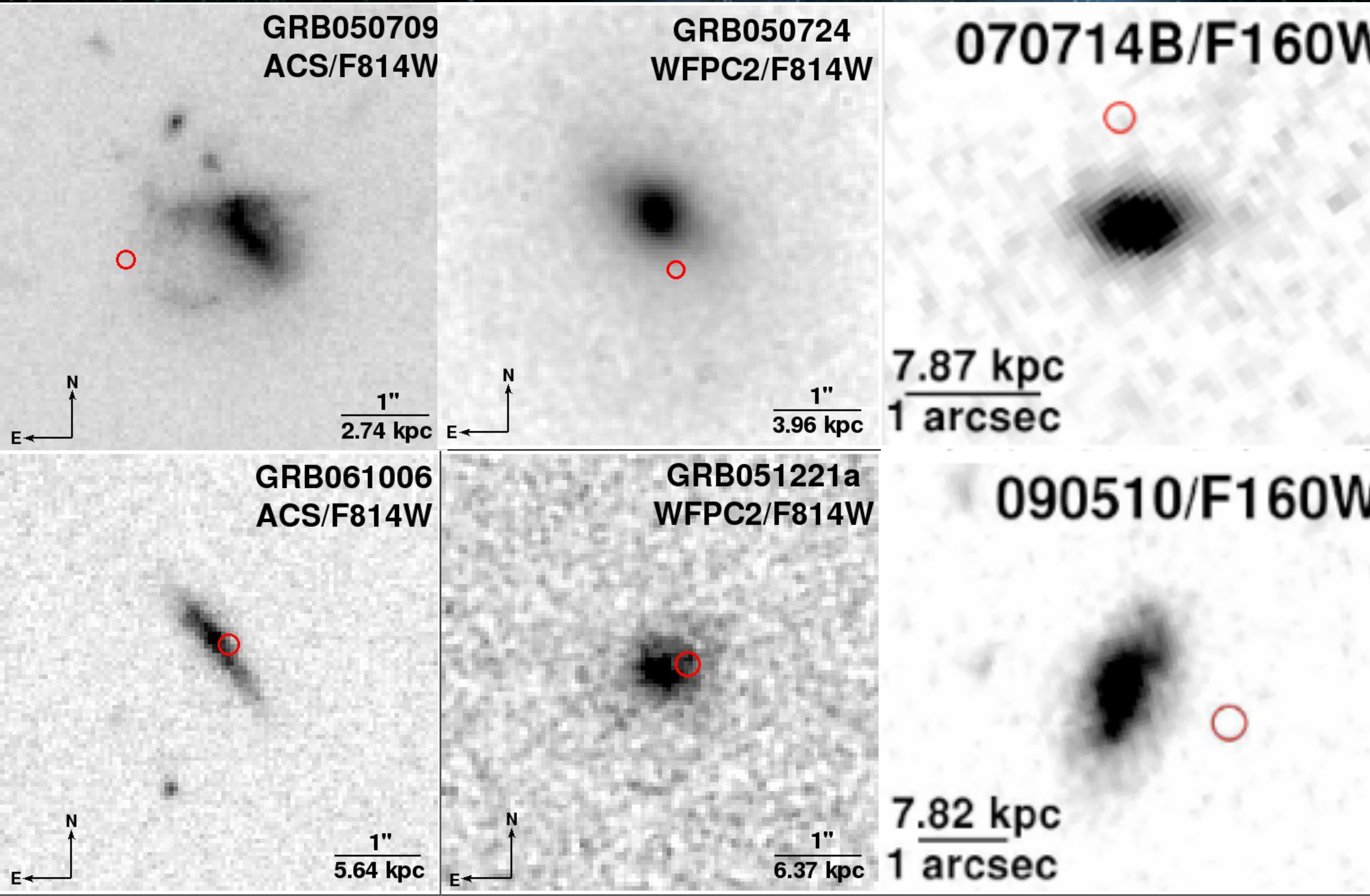

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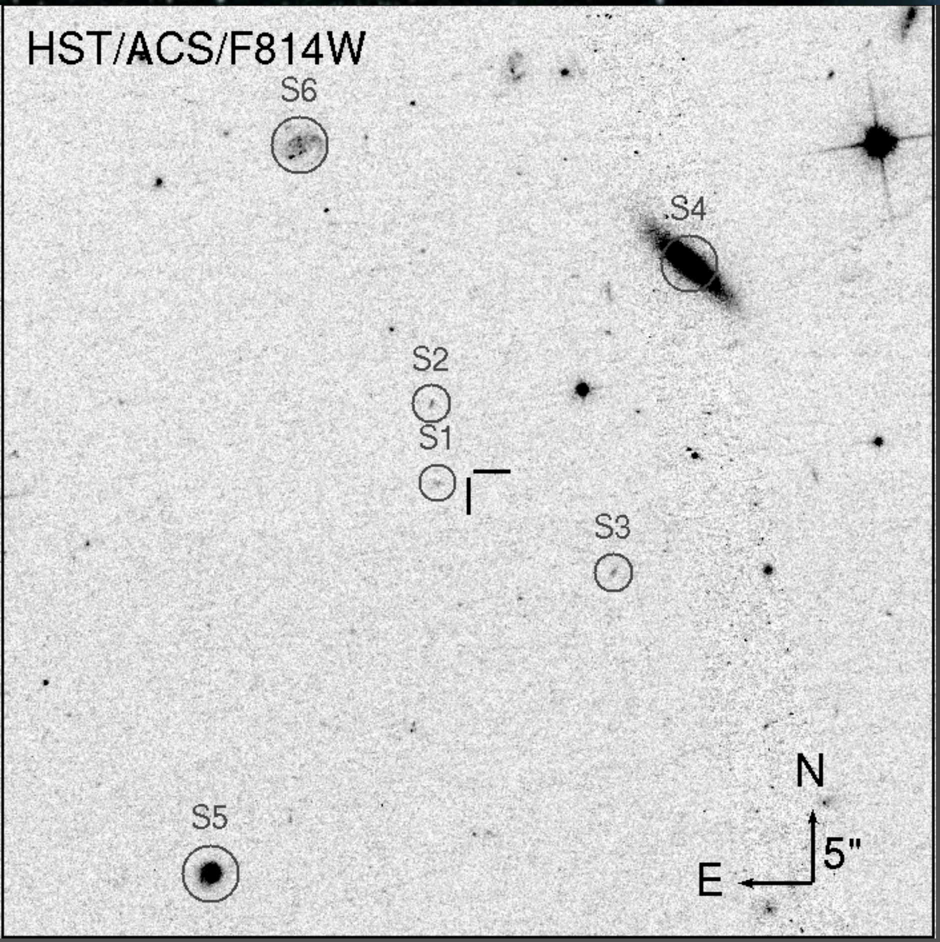
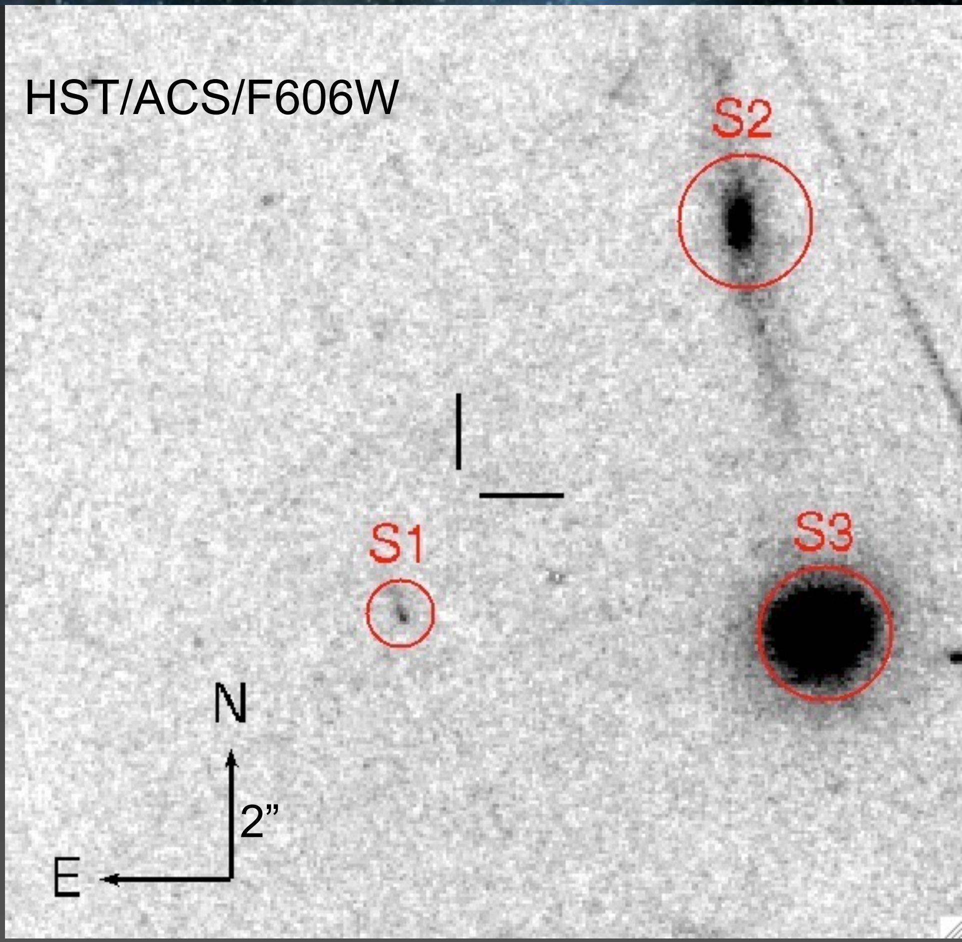
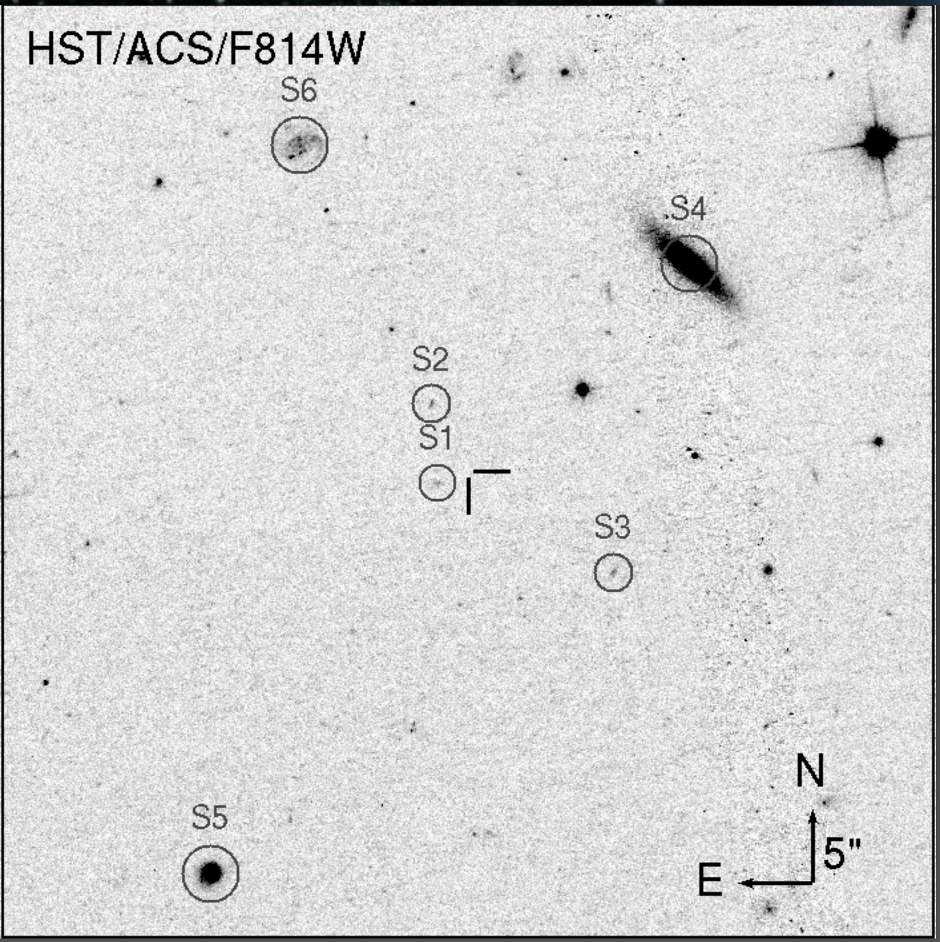




EB 2010

~25% of short GRBs with optical afterglows have no coincident hosts to >27th mag in optical/NIR.

Short GRB Environments



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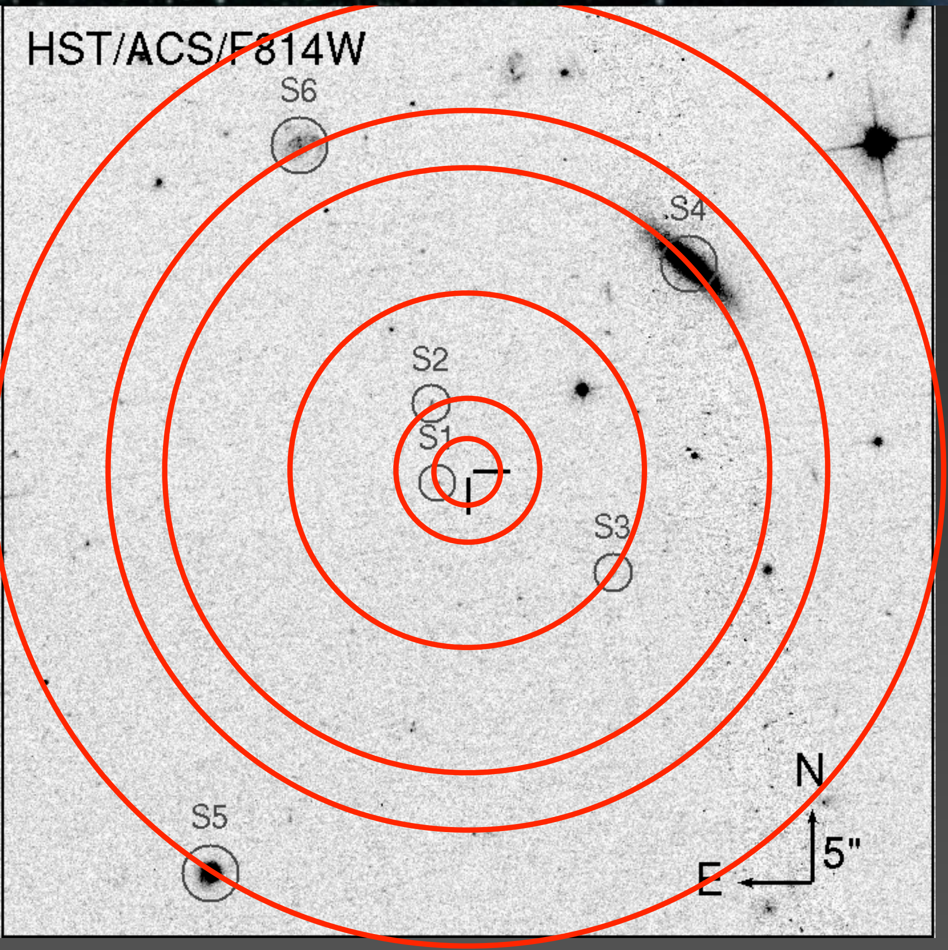
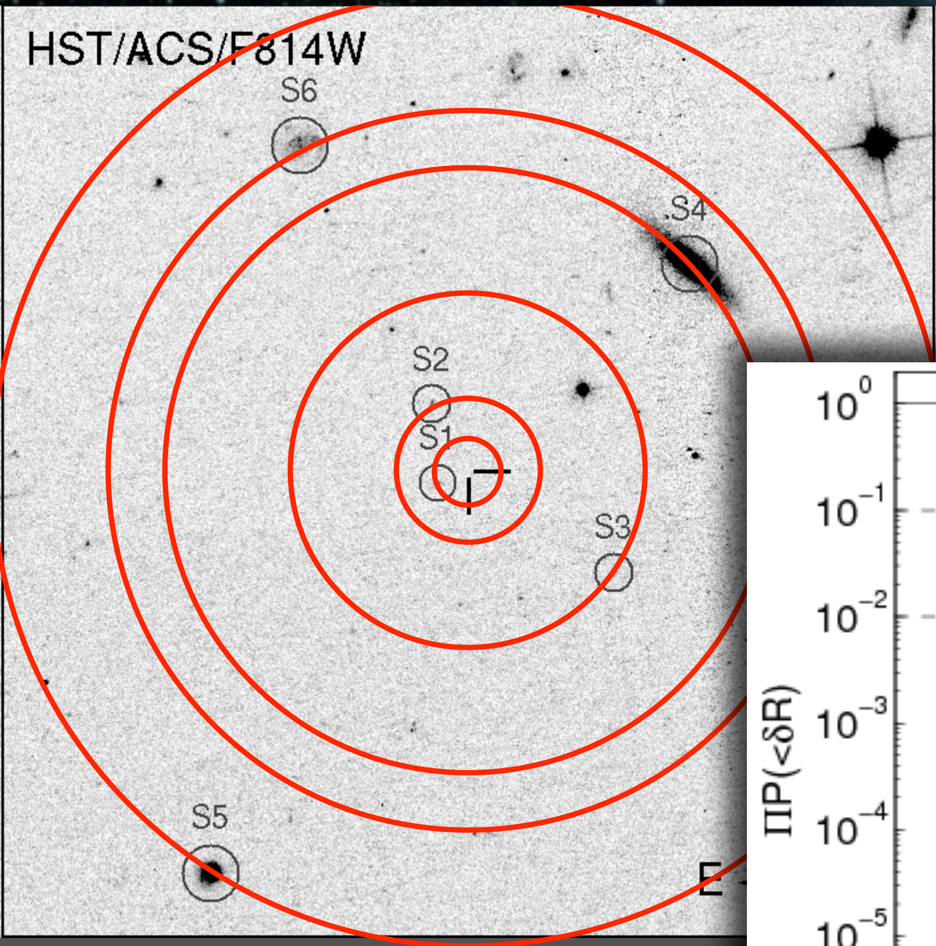


EB 2010

$$P(\leq \delta R) = 1 - e^{-\pi(\delta R)^2 \Sigma(\leq m)}$$

Short GRB Environments



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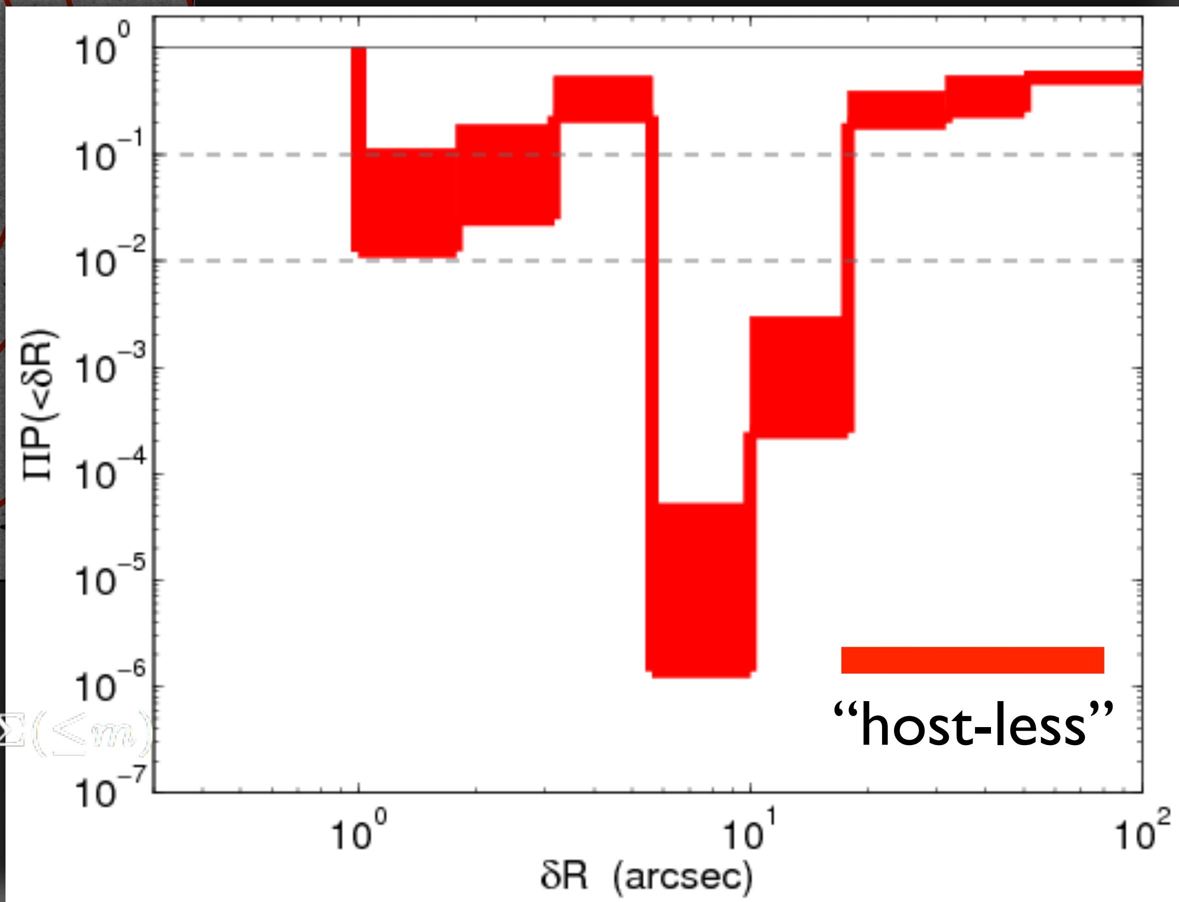

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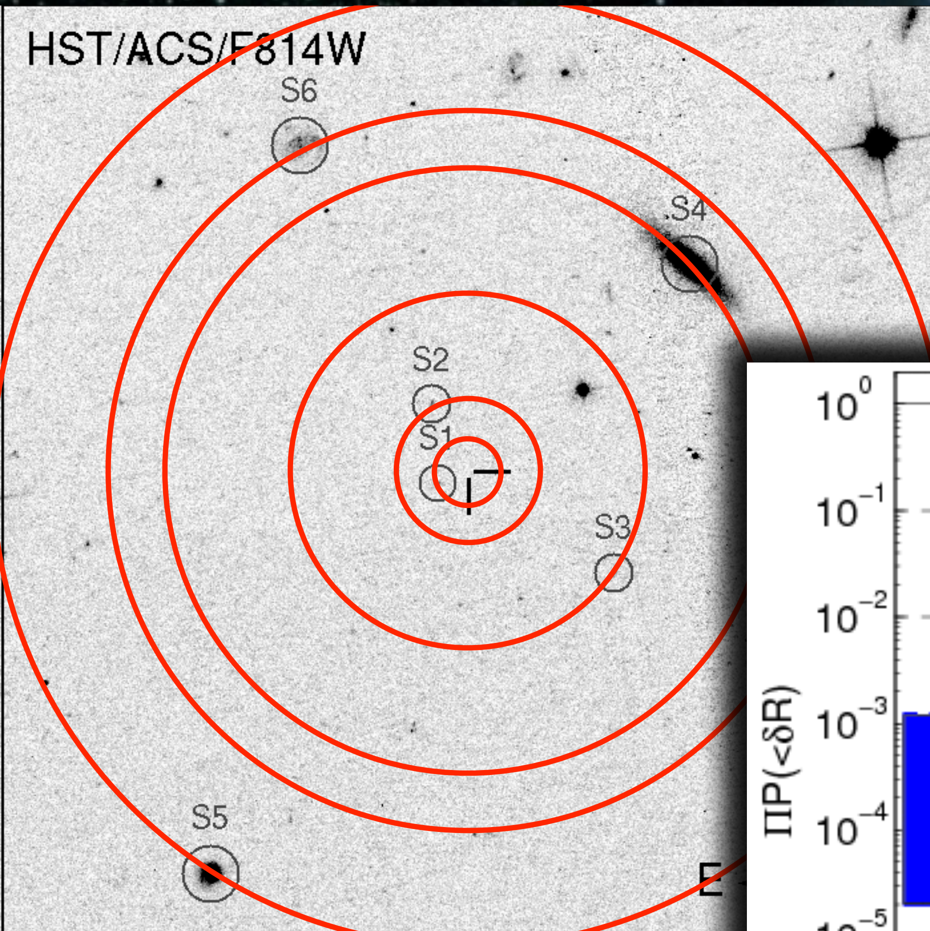

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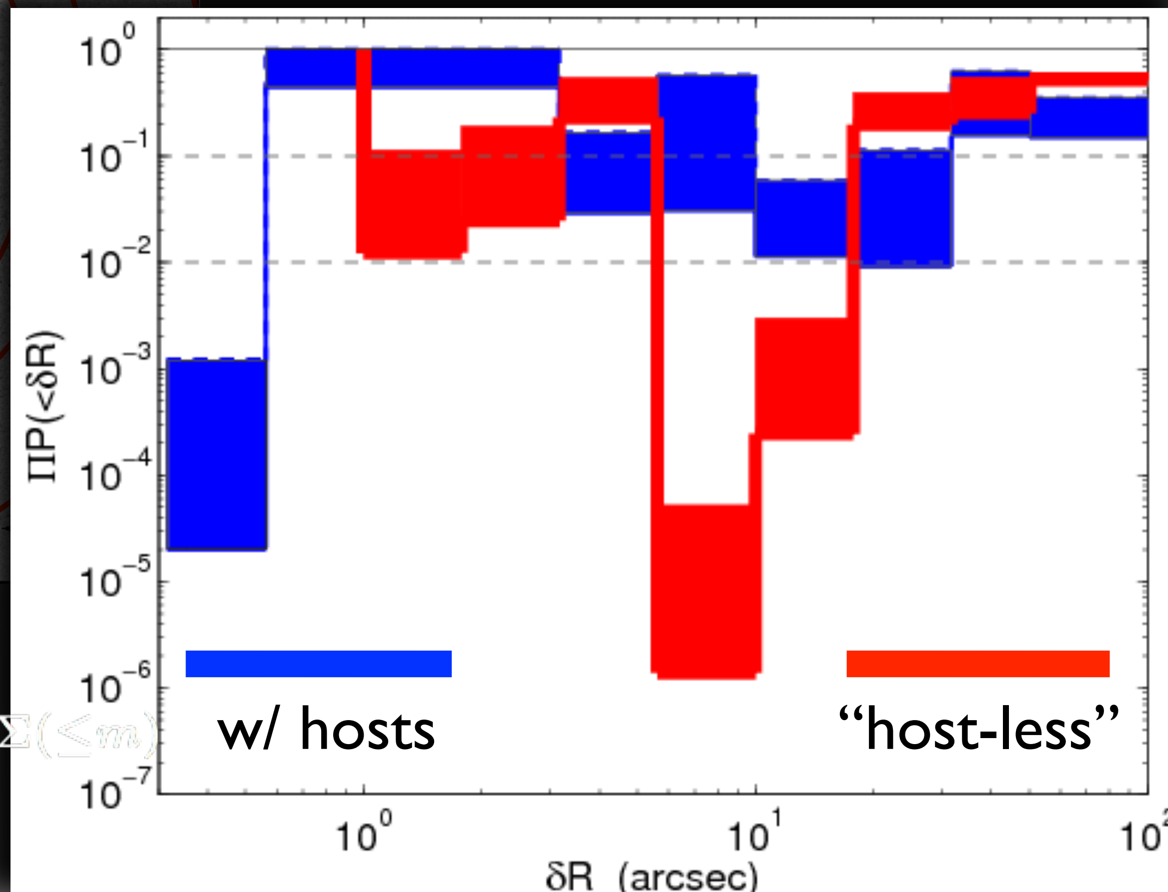

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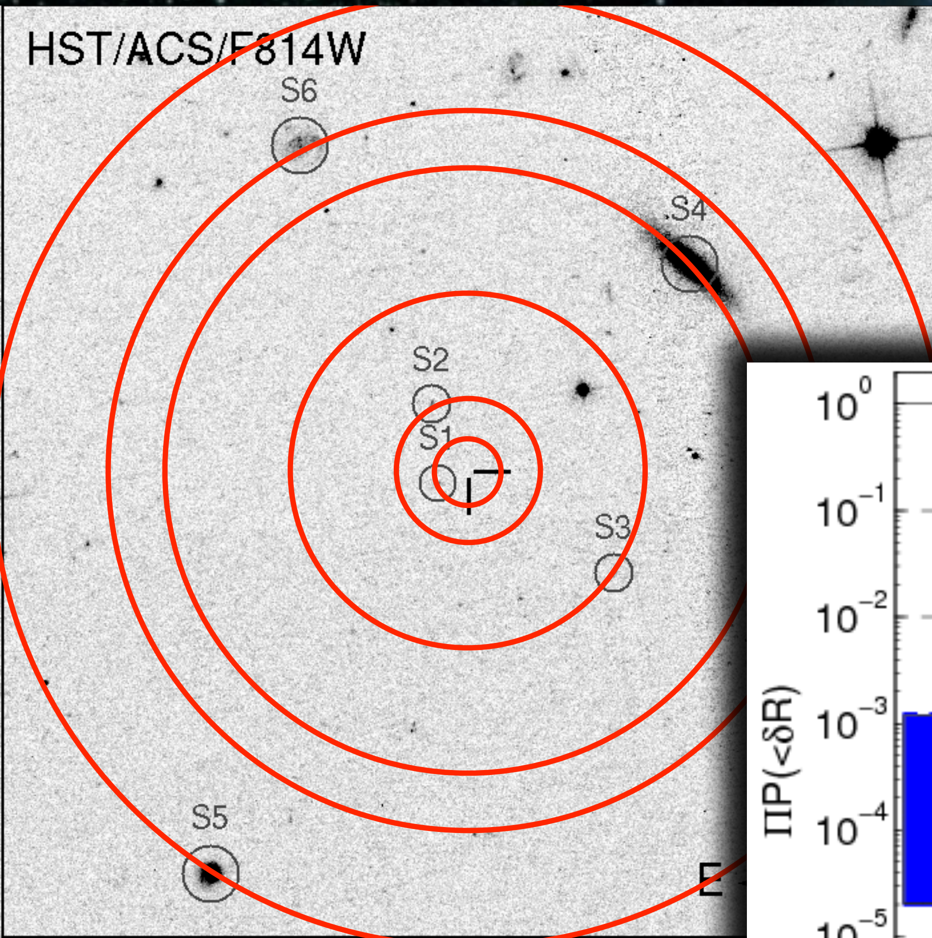

z ~ 0.1-0.5 ⇒ ~10” = 50-100 kpc

EB 2010

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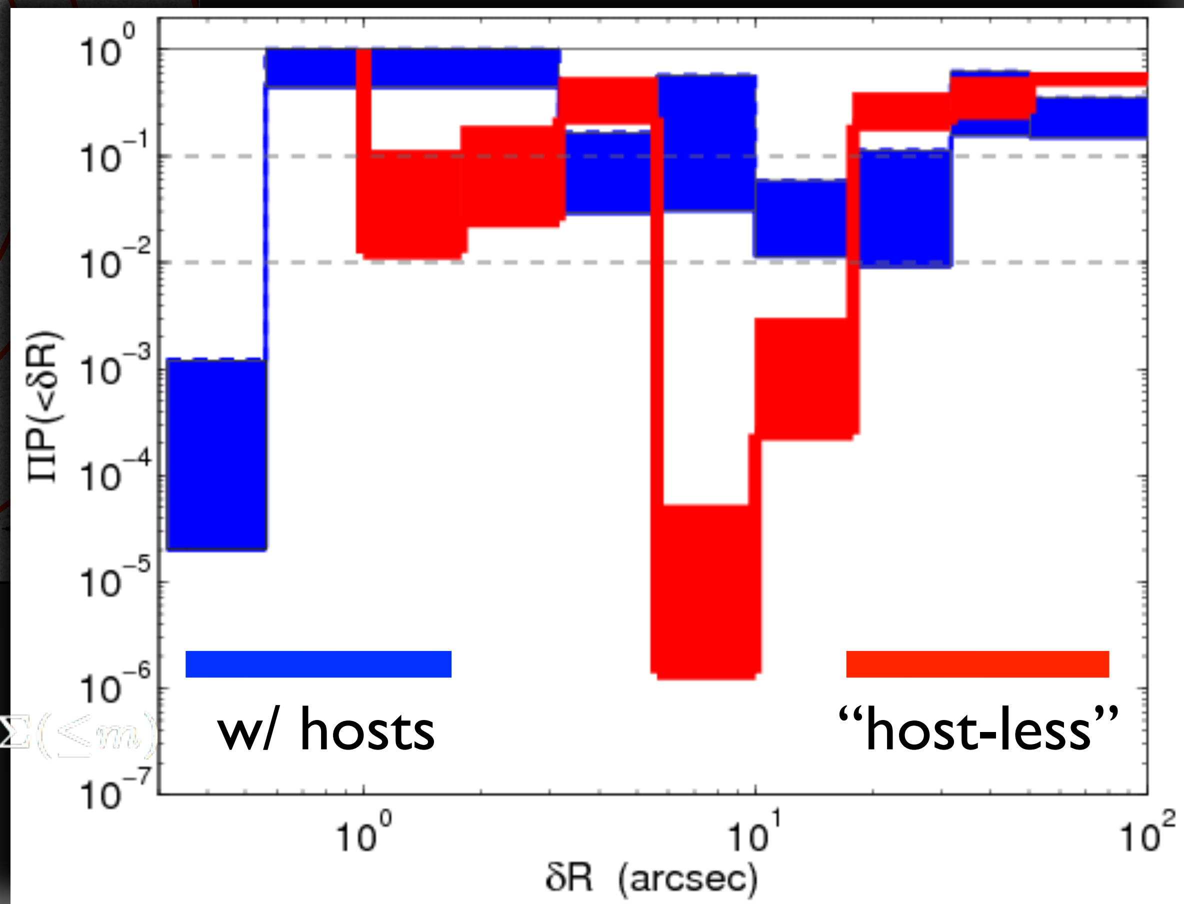

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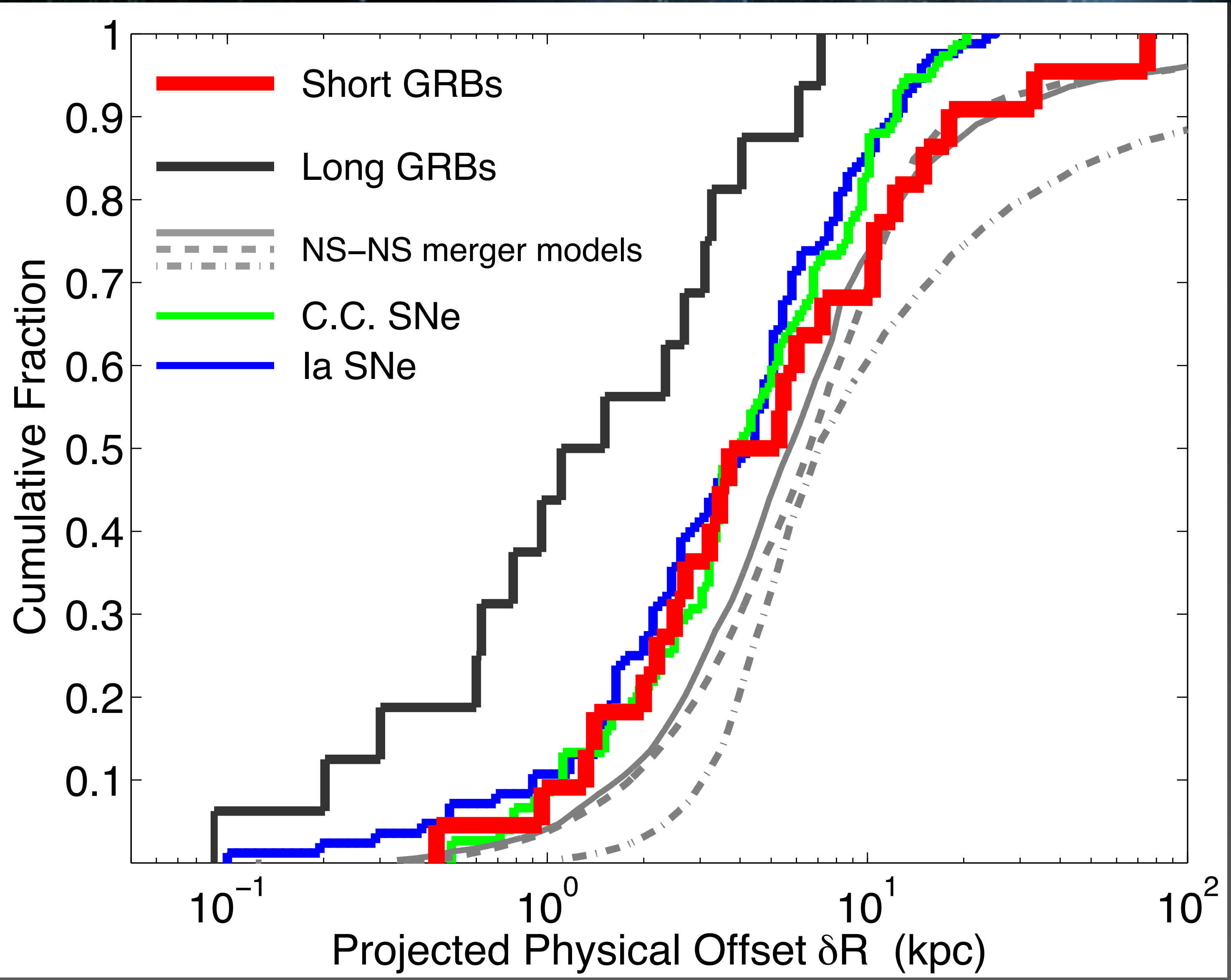

Fong et al. 2010; EB 2010; Fong & EB 2013

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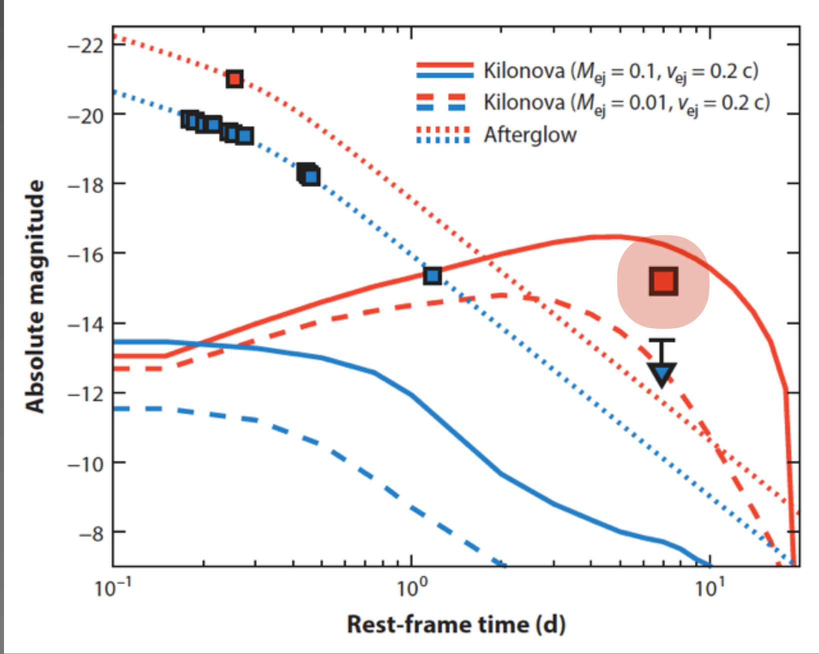
- Afterglows ⟹ E_K ~ few ×10^{49} erg, n ~ 0.01 cm^{-3}, θ_{jet} ~ 10°
- GRB130603B ⟹ signature of *r*-process nucleosynthesis?



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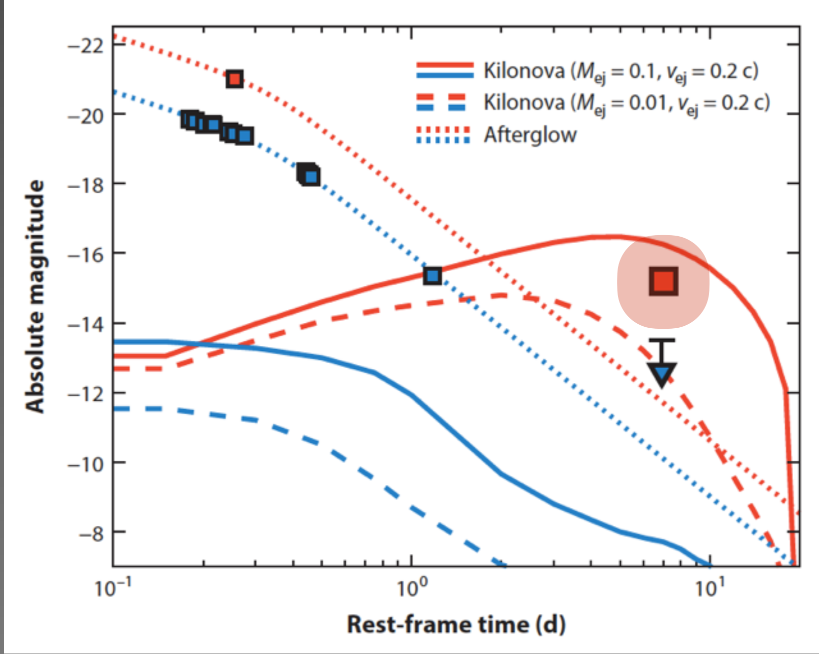
EB 2014, ARA&A, 52, 43



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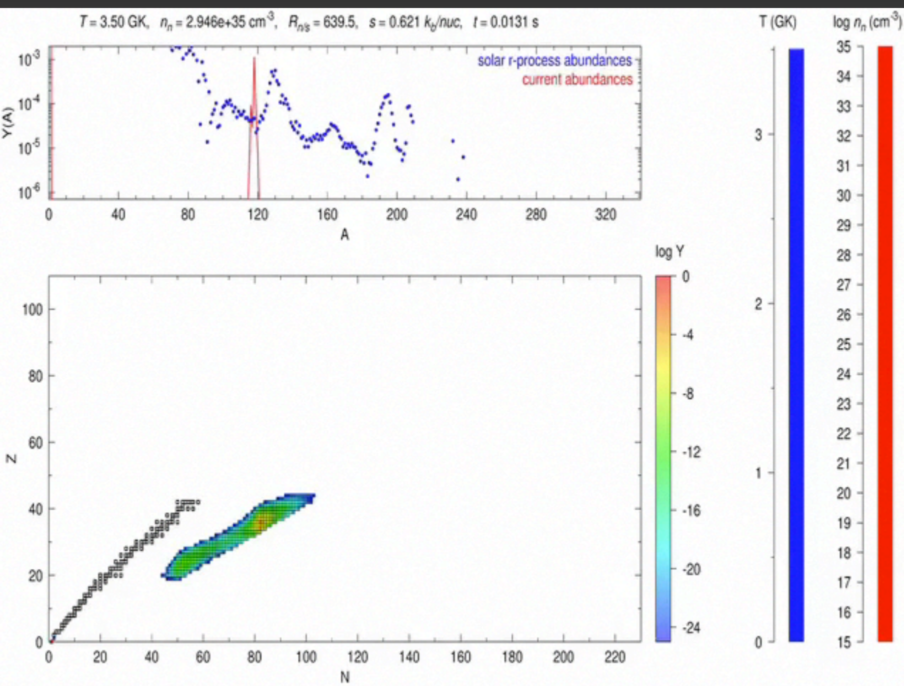
r-Process Nucleosynthesis: "Kilonova"

Decompressed n-rich ejecta
⇒ *r*-process (A > 130)



Gabriel Martinez Pindeo

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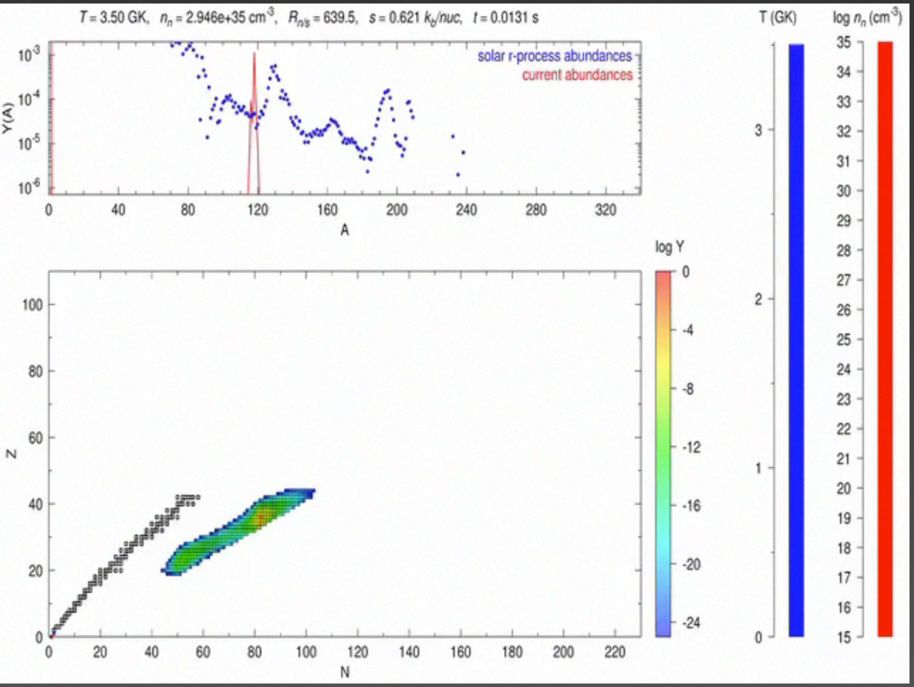

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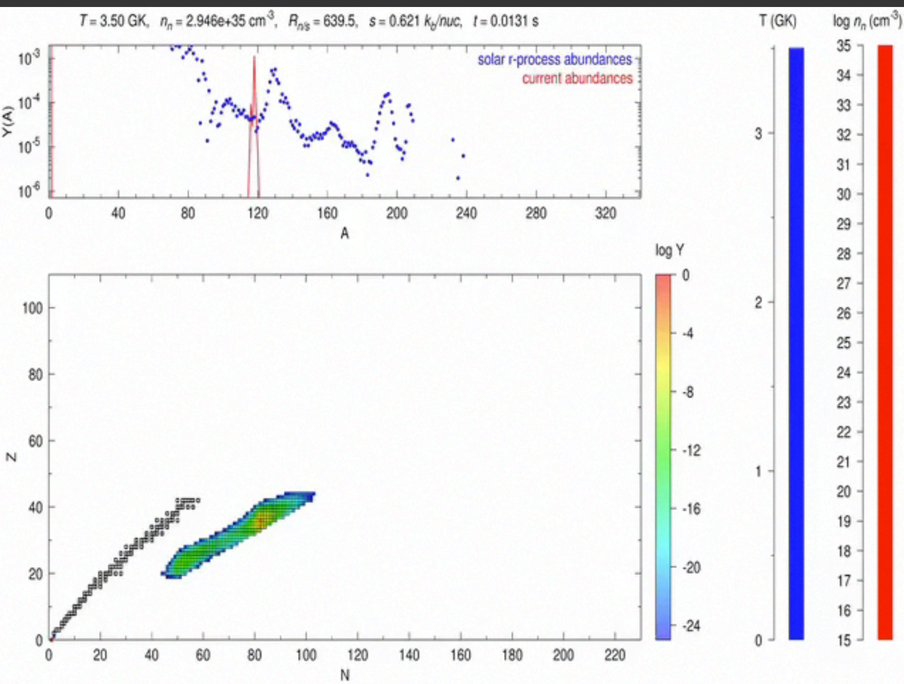
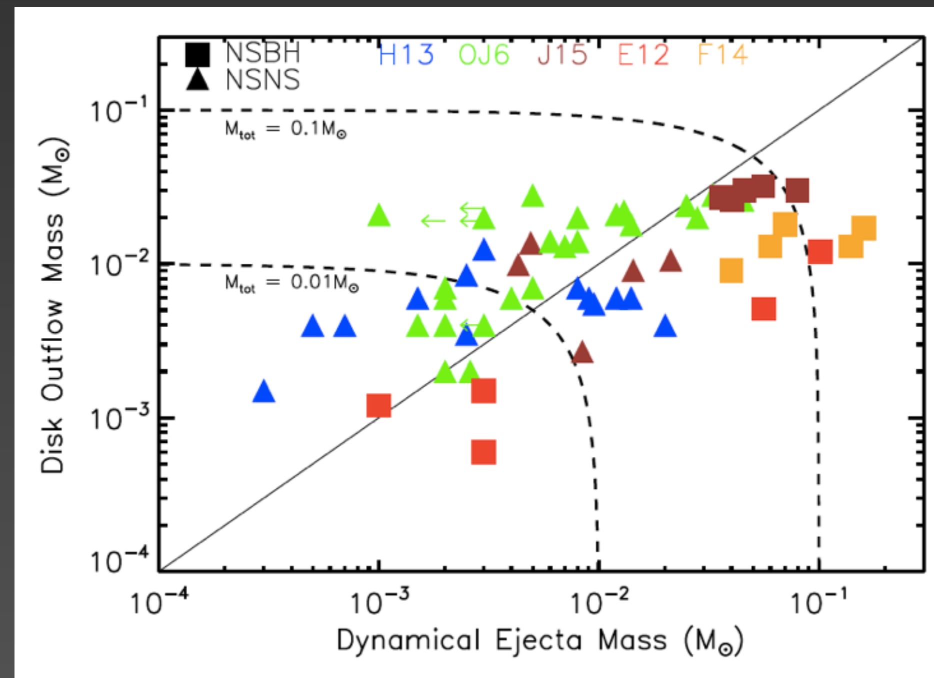
Metzger 2017





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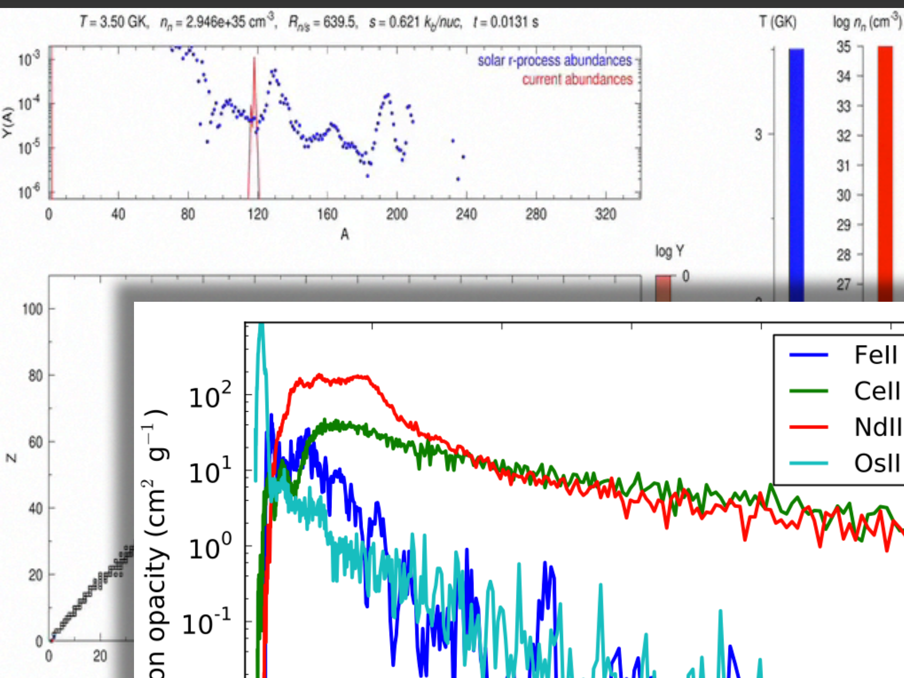
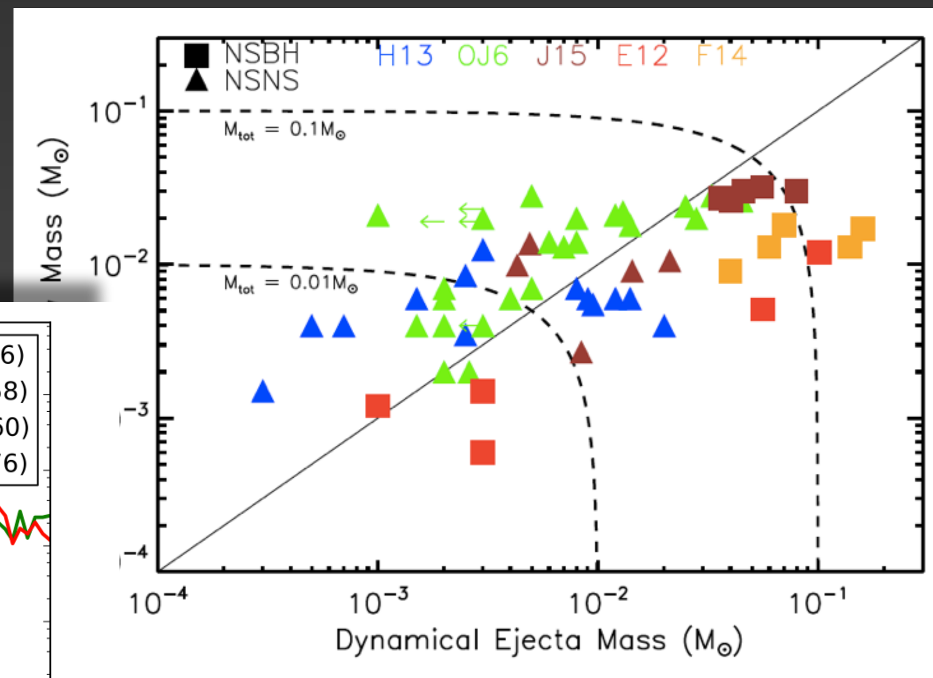
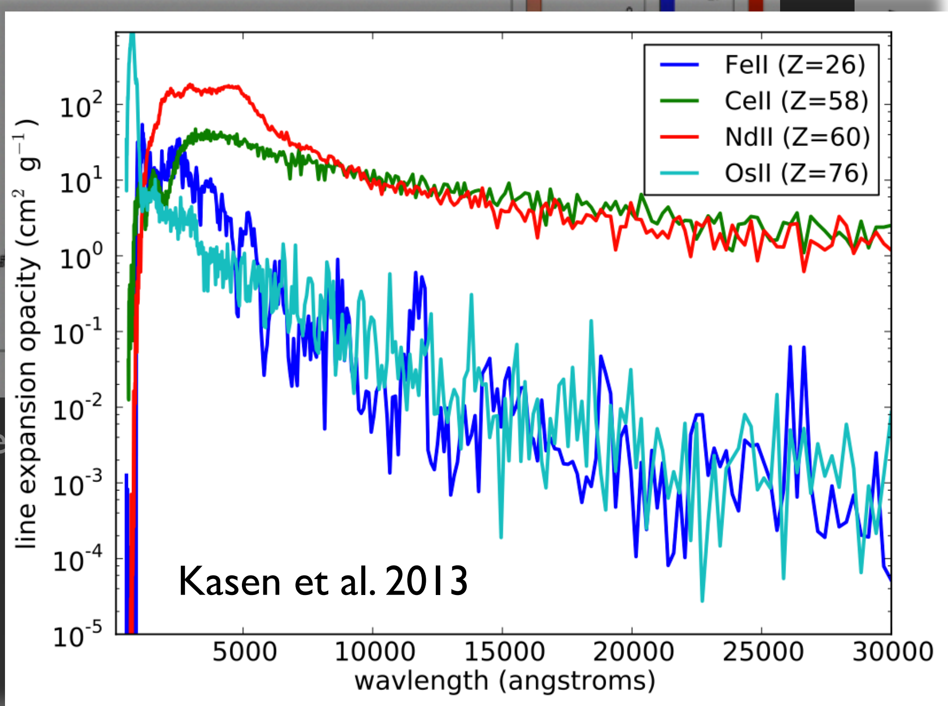


Gabrie





Opacity: ~100×κ_{Fe} if
lanthanides are present

r-Process Nucleosynthesis: "Kilonova"

To calculate light curves: heating rate from *r*-process radioactive decay, opacities from *r*-process nuclei (lanthanides), ejecta masses & velocities from numerical simulations

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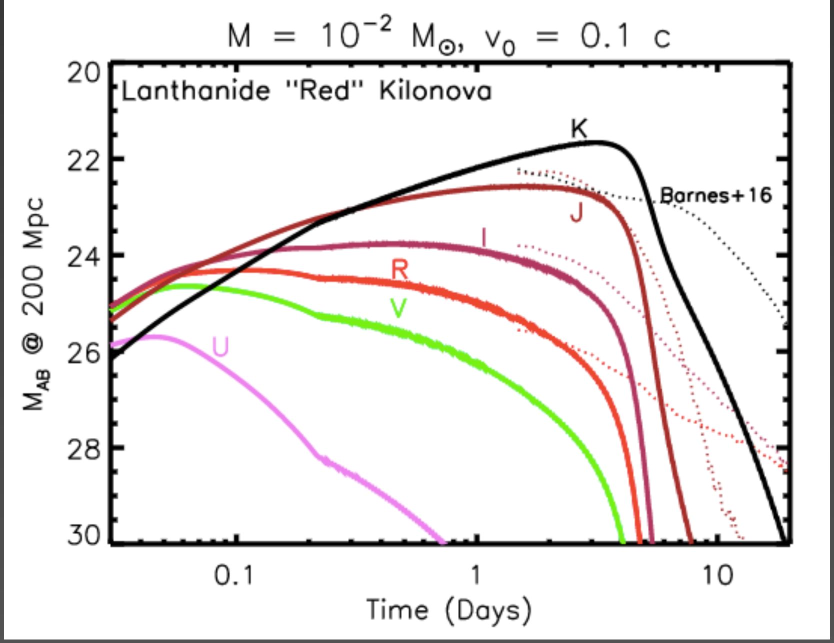
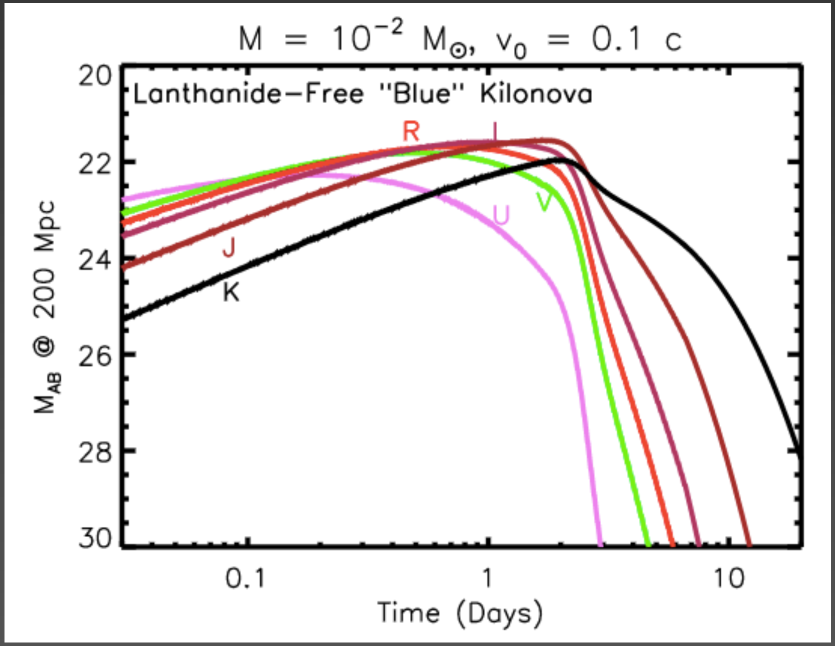


IR-peaked; ~1 week



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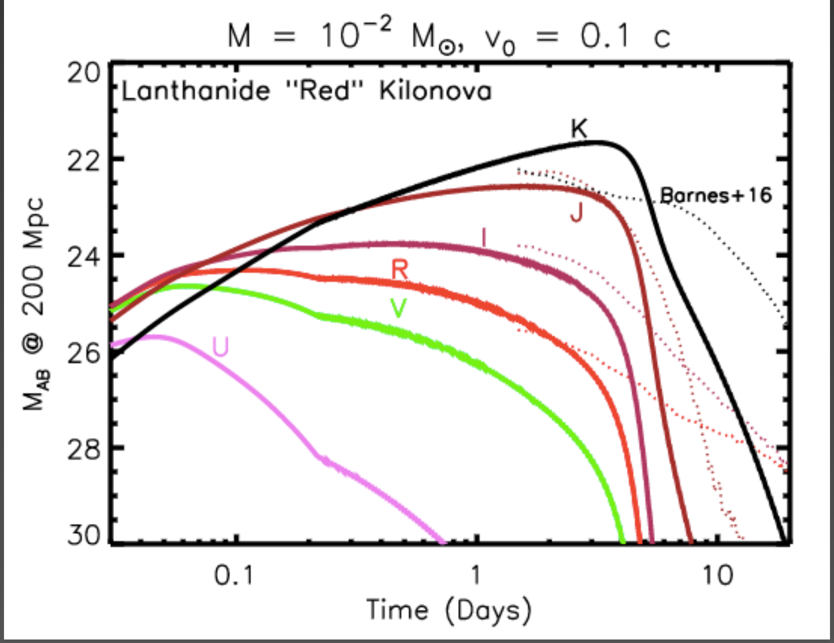

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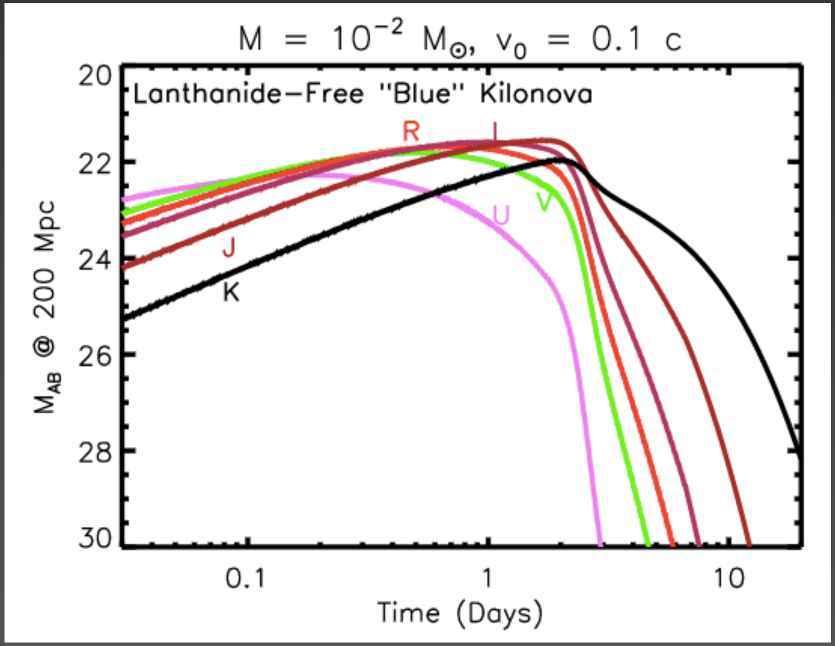

Optical-peaked; ~1 day

Challenge: faint, rapid, (potentially red) transient in ~100 deg^2

Our Follow-up Program: Radio to X-rays

Deep, red, wide-field imaging: Dark Energy Camera on the Blanco 4-m telescope at CTIO

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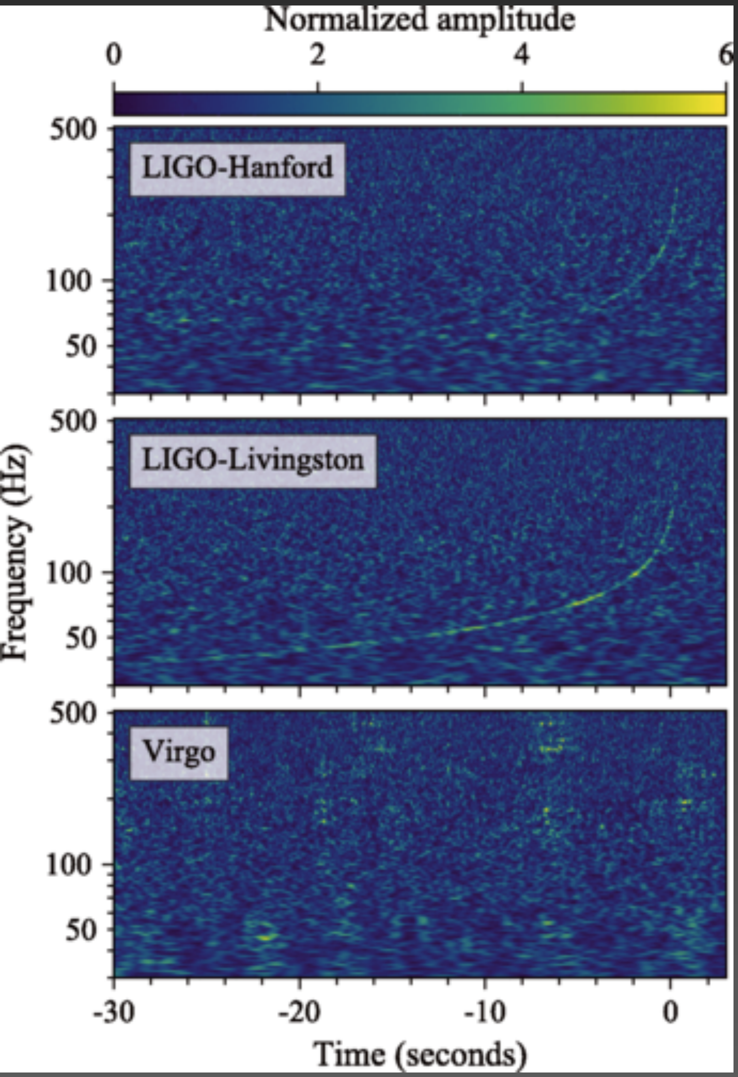
GW170817

Abbott et al. 2017



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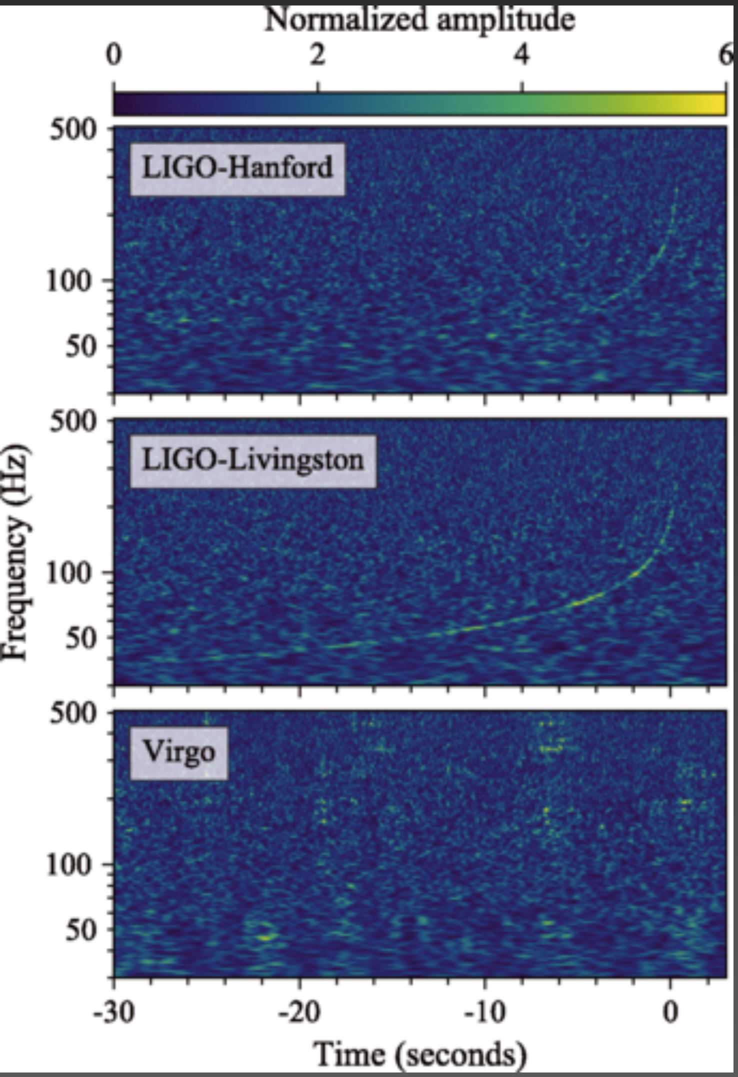
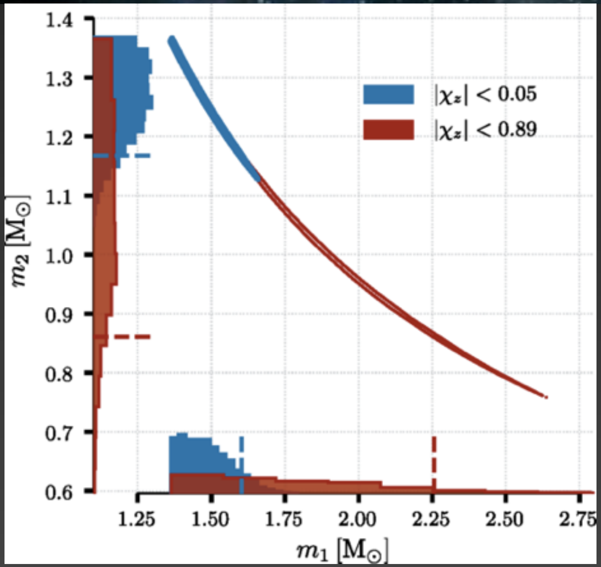




$M_1 \approx 1.4–1.6\ M_\odot$

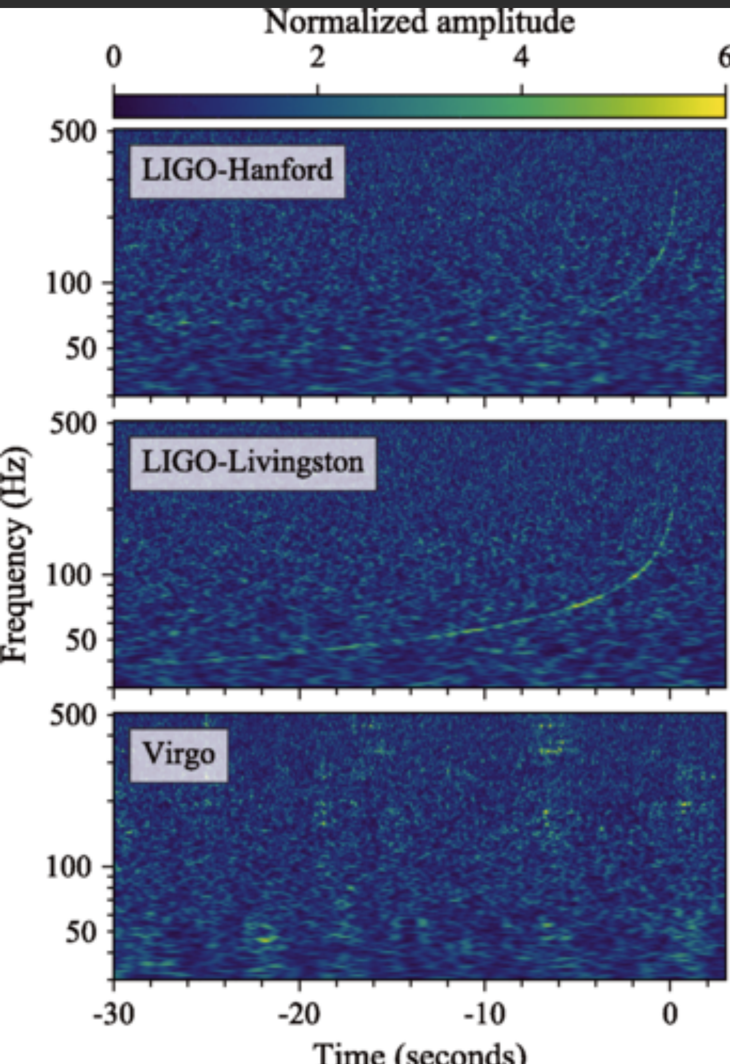
$M_2 \approx 1.2–1.4\ M_\odot$

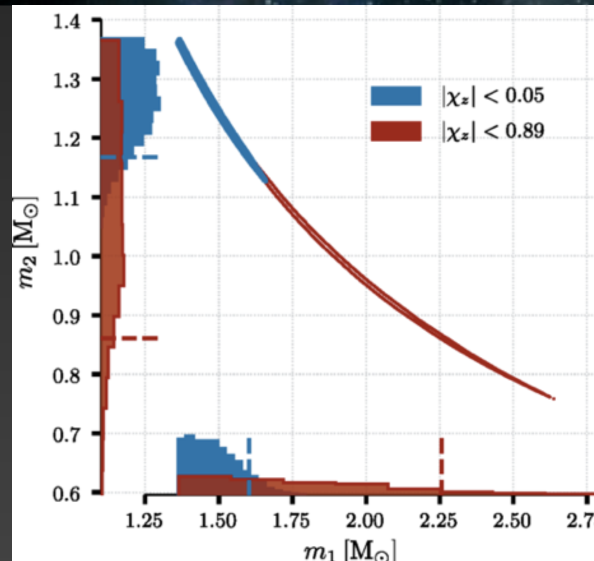
$M_{tot} \approx 2.74\ M_\odot$

Tidal deformability:
$\Lambda \lesssim 10^3$

GW170817

Abbott et al. 2017





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Tidal deformability:
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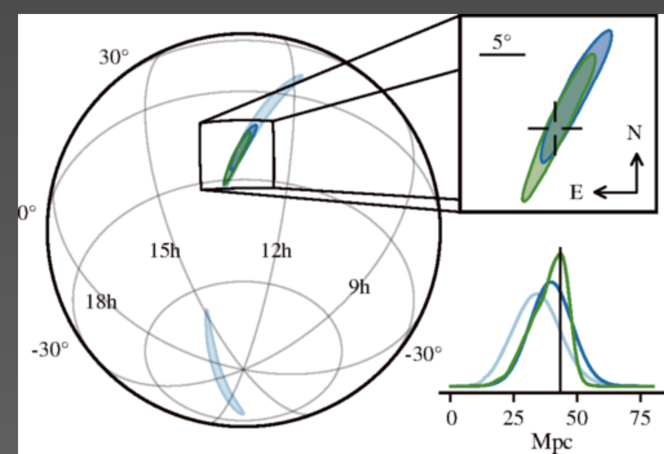
R.A. = 13^h09^m

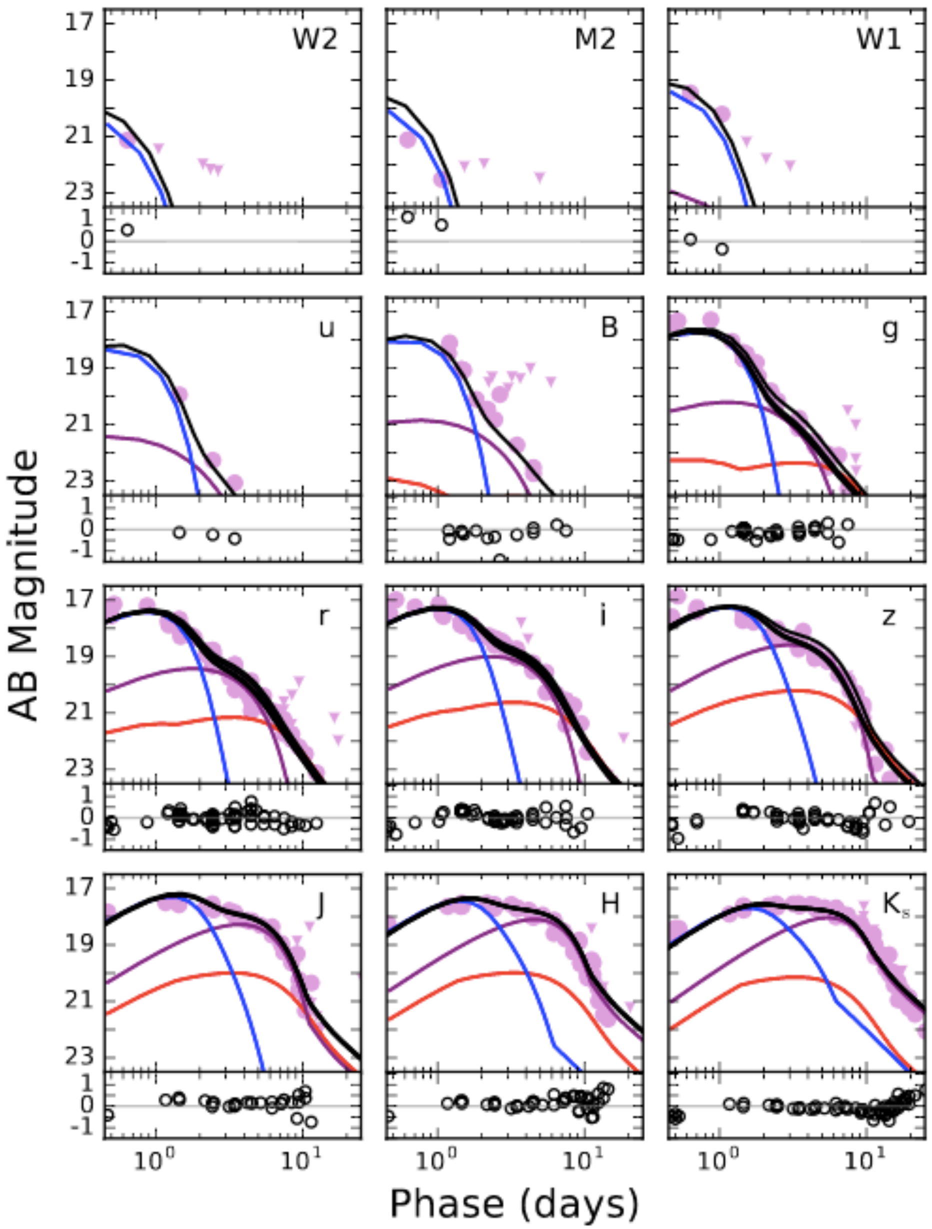
Dec. = $-25°37'$

$A \approx 30\ \text{deg}^2$

$d \approx 24\text{–}48$ Mpc



Light Curves & Kilonova Models



Three-component model:

Blue: $M_{ej} \approx 0.016\ M_\odot$ / $v_{ej} \approx 0.27c$

Purple: $M_{ej} \approx 0.040\ M_\odot$ / $v_{ej} \approx 0.14c$

Red: $M_{ej} \approx 0.009\ M_\odot$ / $v_{ej} \approx 0.08c$

Villar, EB et al. 2017

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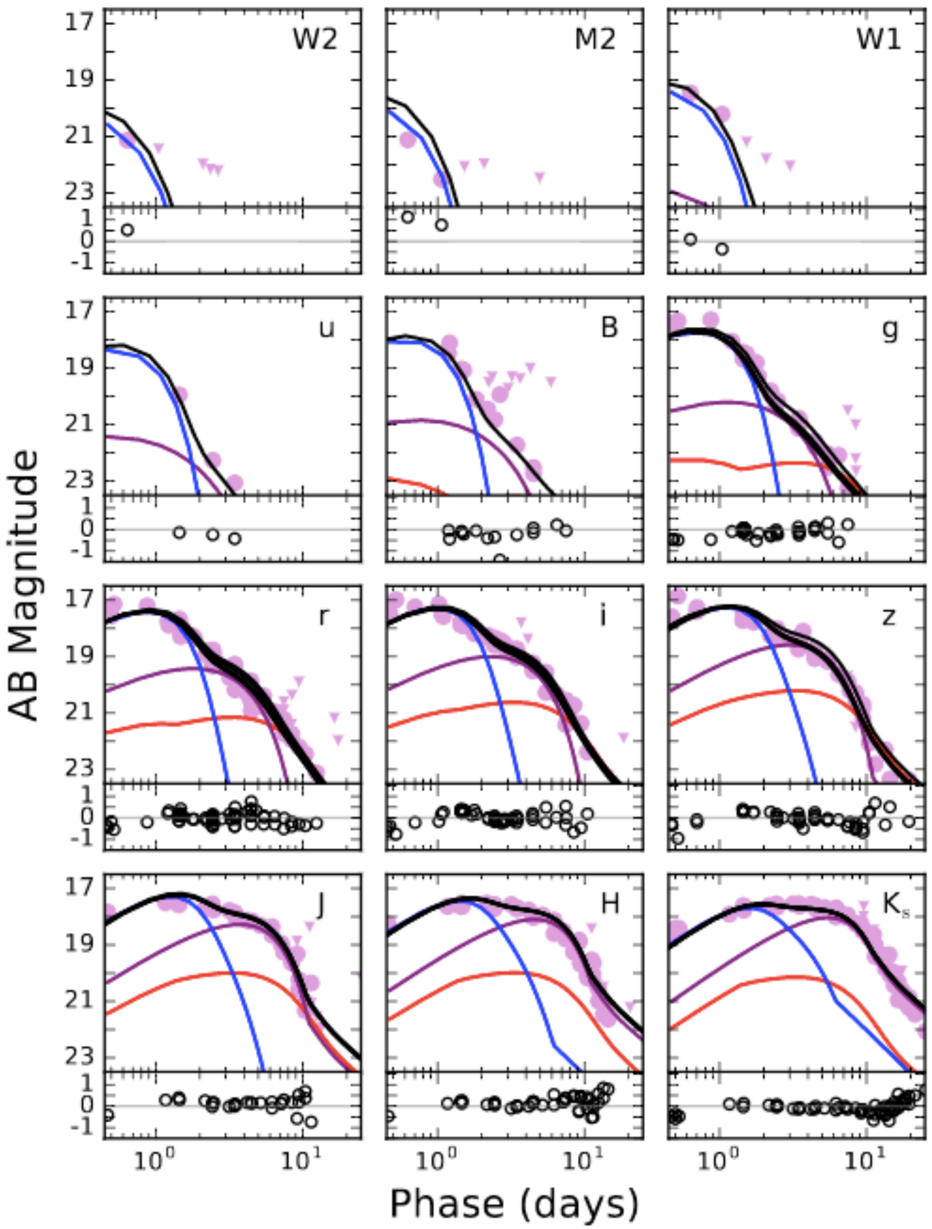

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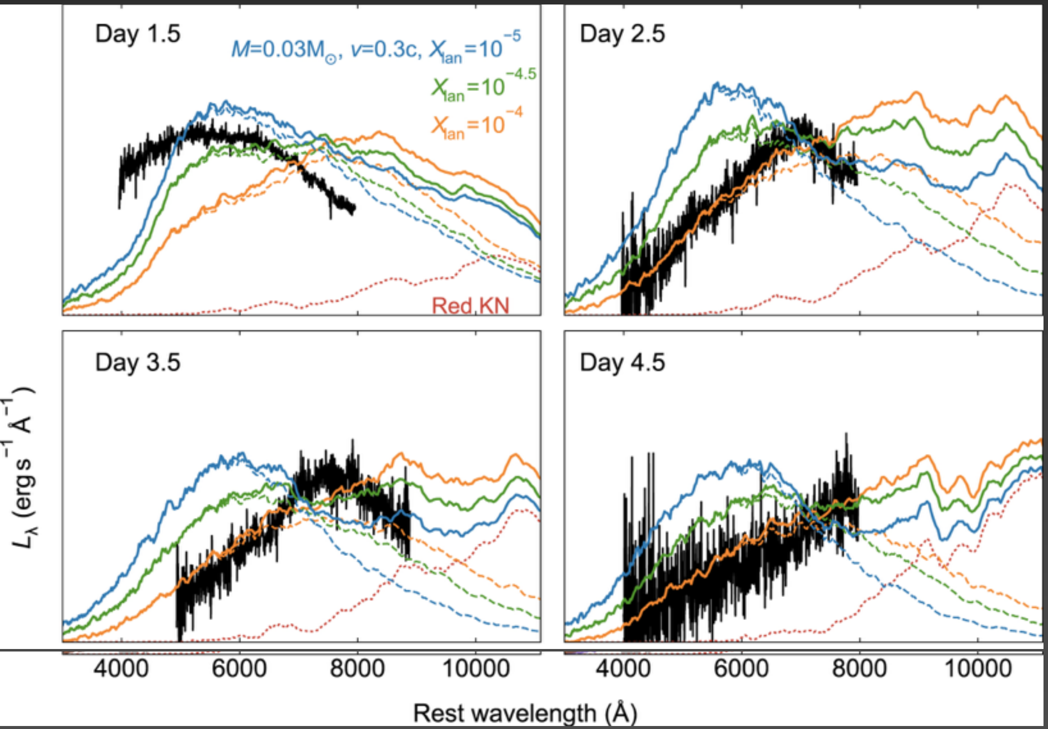
A range of ejecta properties with different nucleosynthesis, velocity, ejecta mass (geometry?)

Villar, EB et al. 2017

Spectroscopy

Nicholl, EB et al. 2017



Optical spectra featureless (high velocity)

M_{ej} ~ 0.03 $M_\odot$ / v_{ej} ~ 0.3c

X_{lan} ≲ 10^{-5} (1 day) / ~10^{-4} (2−4 days)

Spectroscopy

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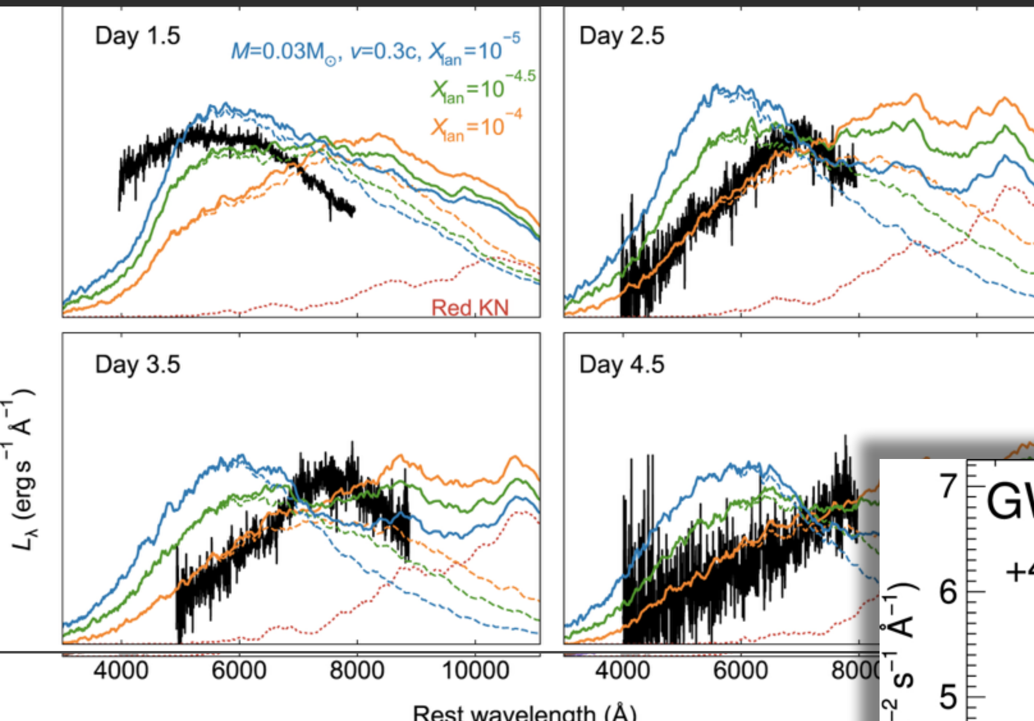

NIR spectra show distinct features (lower velocity)

M_{ej} ~ 0.04 $M_\odot$ / v_{ej} ~ 0.1c

X_{lan} ~ 10^{-2} (5–9 days)

Chornock, EB et al. 2017

Optical spectra featureless (high

M_{ej} ~ 0.03 $M_\odot$ / v_{ej} ~ 0.3c

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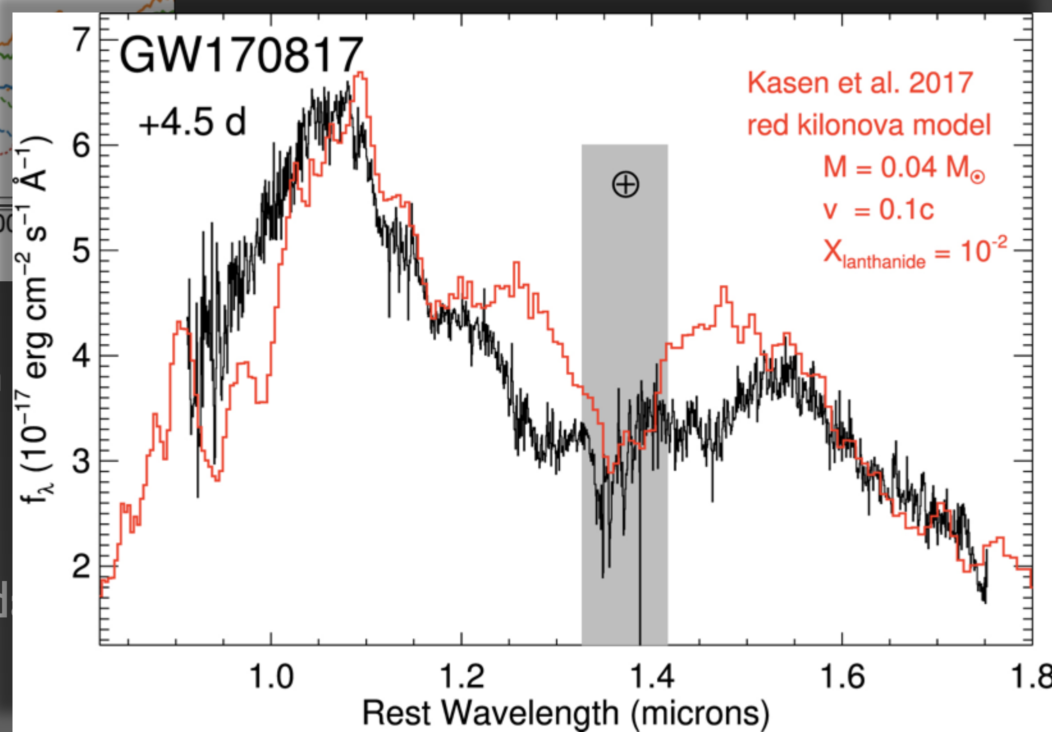

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  (breaks ambiguity from GW data)

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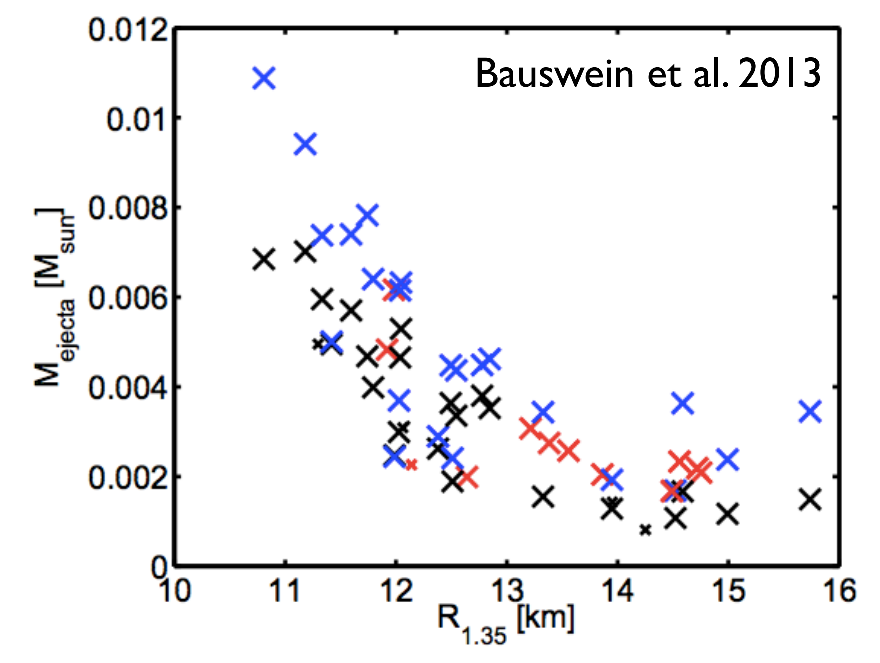
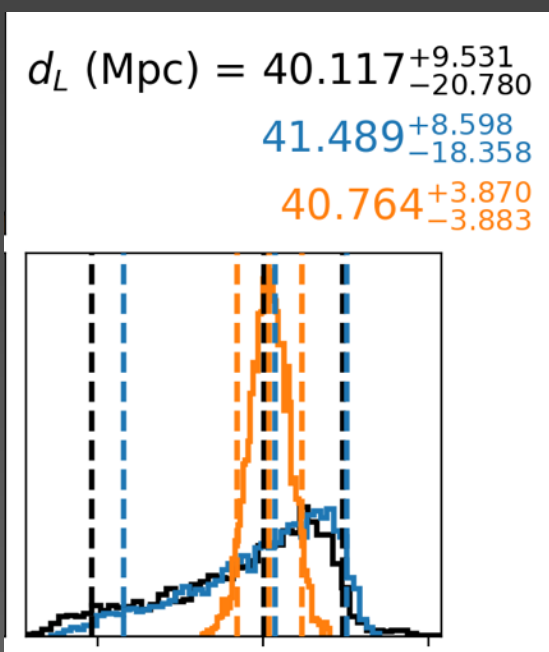
- Lanthanide-poor (blue) ejecta large M_{ej} indicates small NS radius of ~11 km



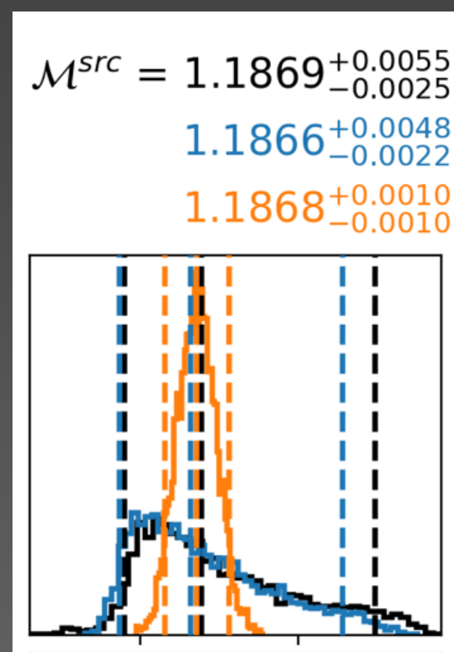
Optical/Near-IR: Implications

Finsted, De, Brown & EB submitted

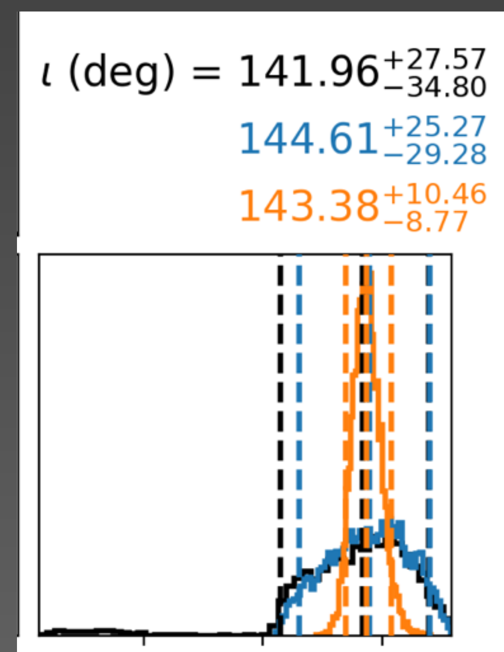
$\delta(d_L)$: 30.3 → 7.7 Mpc



$\delta(M_c)$: 0.008 → 0.002 $M_\odot$



$\delta(i)$: 62.4 → 19.3 deg



Optical/Near-IR: Implications

- Lanthanide-rich (red) ejecta $v \approx 0.1c \Rightarrow$ accretion disk wind

Finsted, De, Brown & EB submitted

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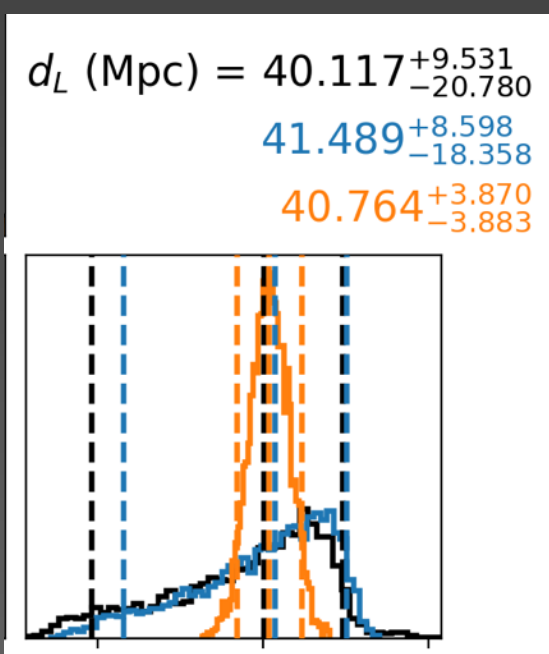

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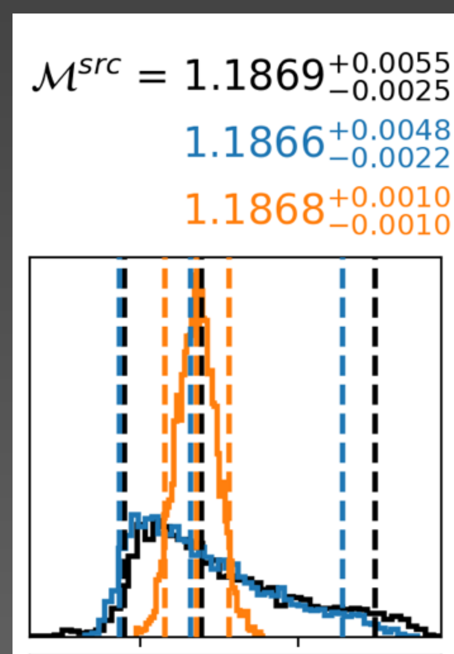

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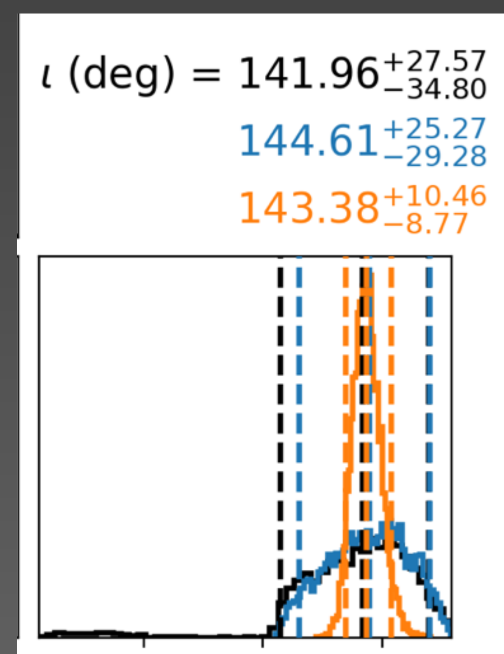
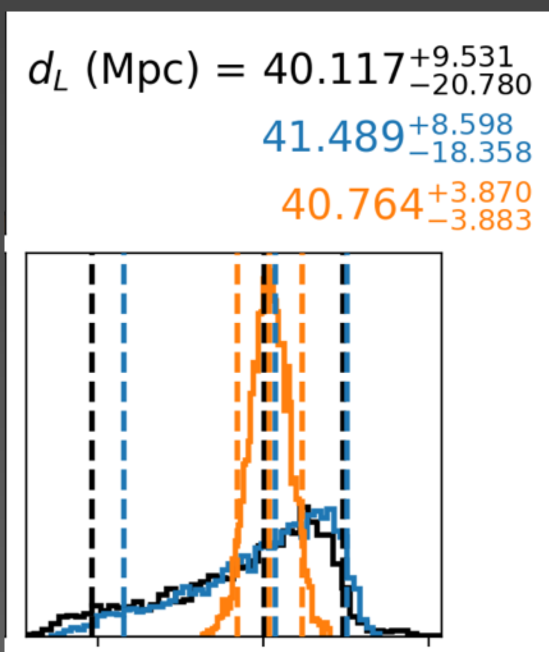


Optical/Near-IR: Implications

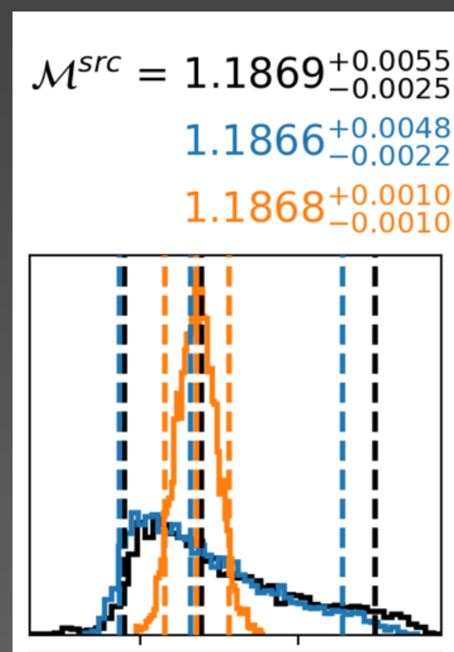
- Lanthanide-rich (red) ejecta $v \approx 0.1c \Rightarrow$ accretion disk wind
- High lanthanide fraction indicates short HMNS phase ($\lesssim$0.1 sec) $\Rightarrow$ final state is BH

Finsted, De, Brown & EB submitted

$\delta(d_L)$: 30.3 → 7.7 Mpc



$\delta(M_c)$: 0.008 → 0.002 $M_\odot$



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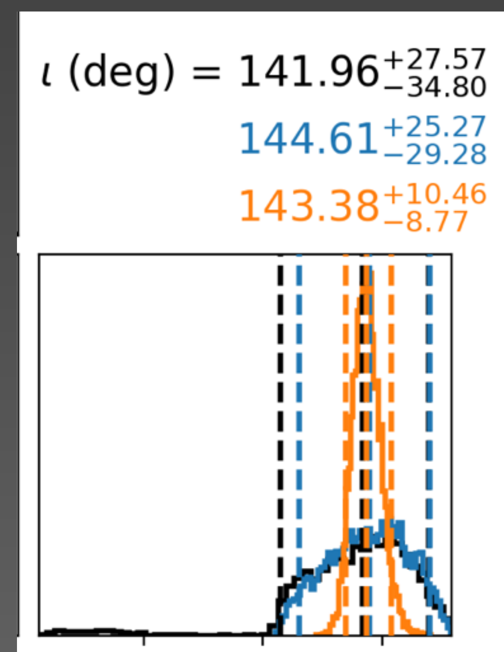

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- First analysis directly combining GW and EM data

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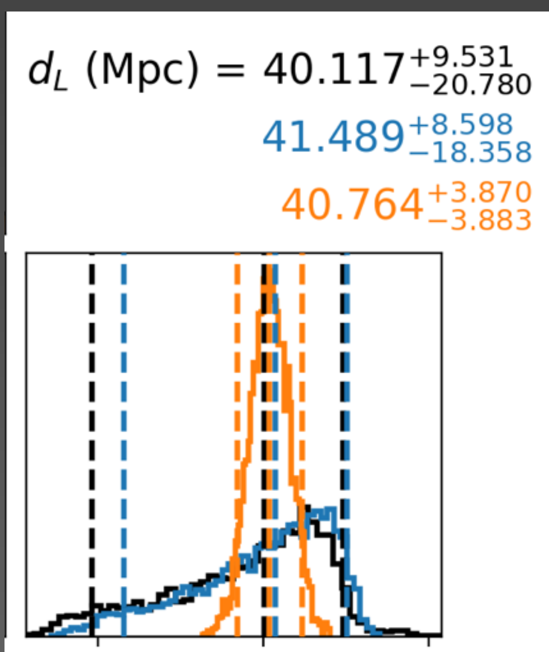

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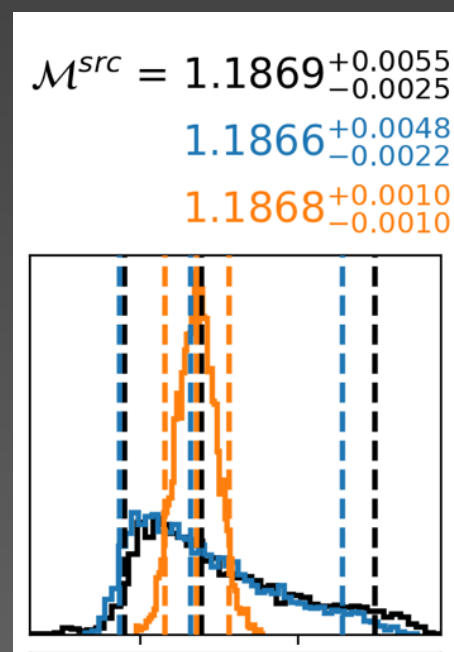

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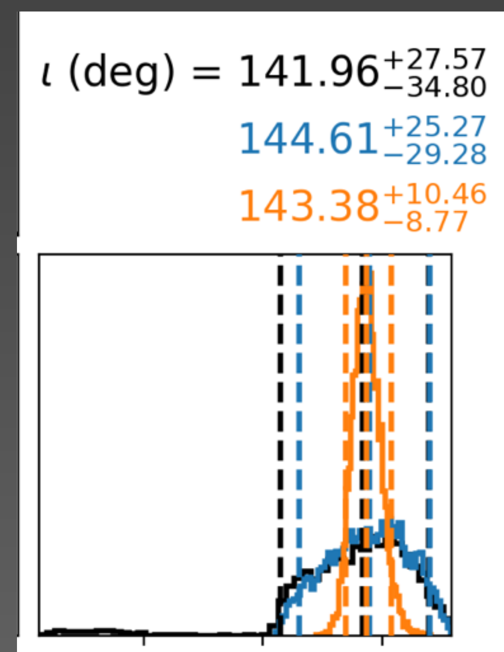
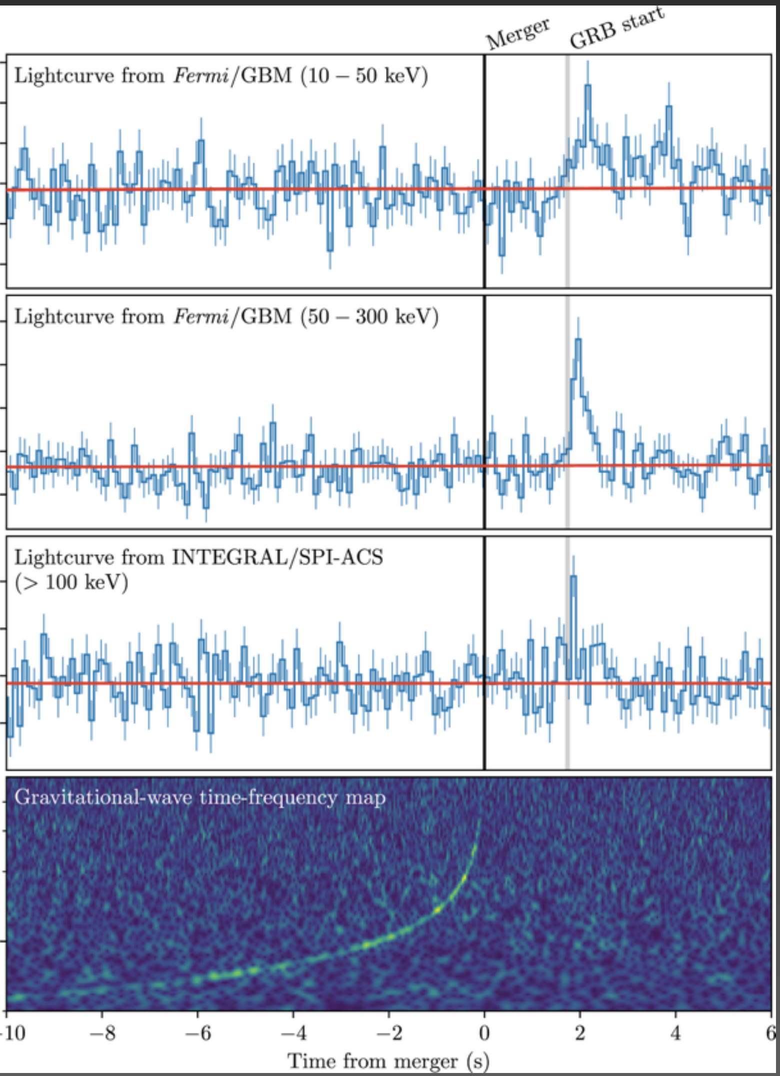
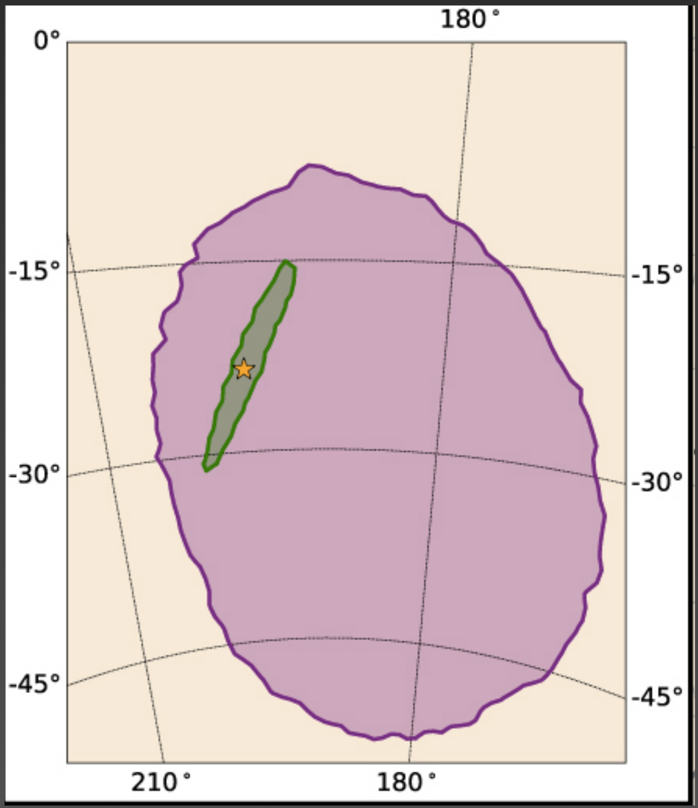


GRB170817

Abbott et al. 2017





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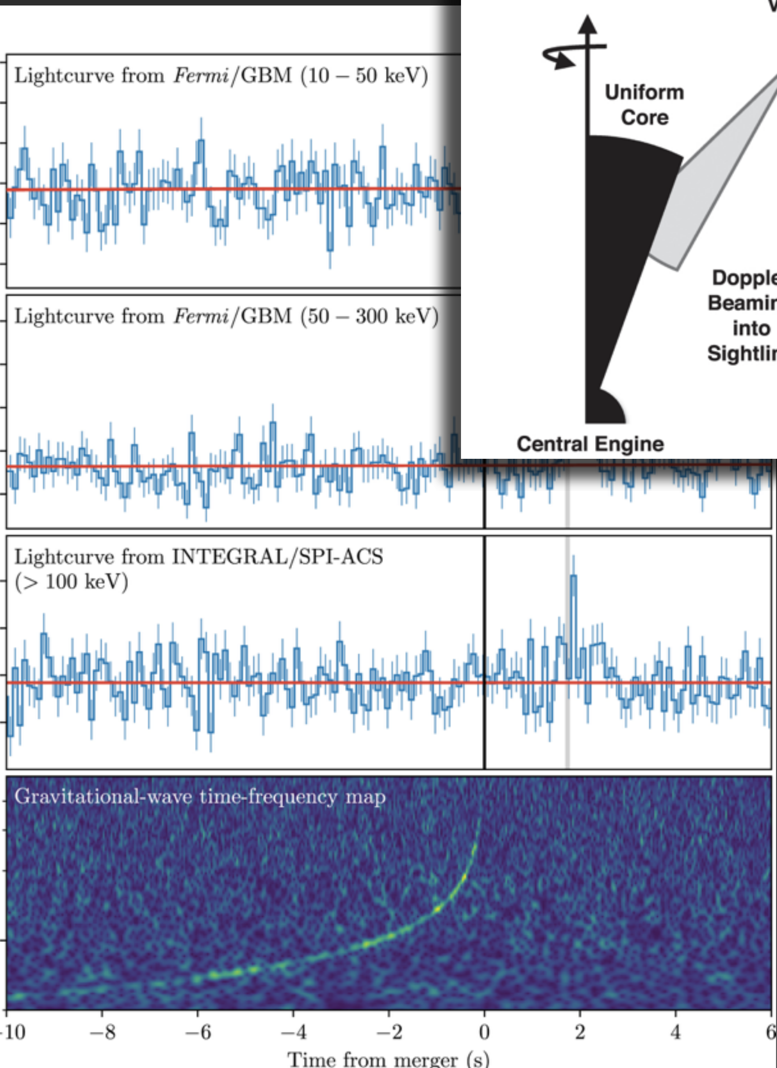
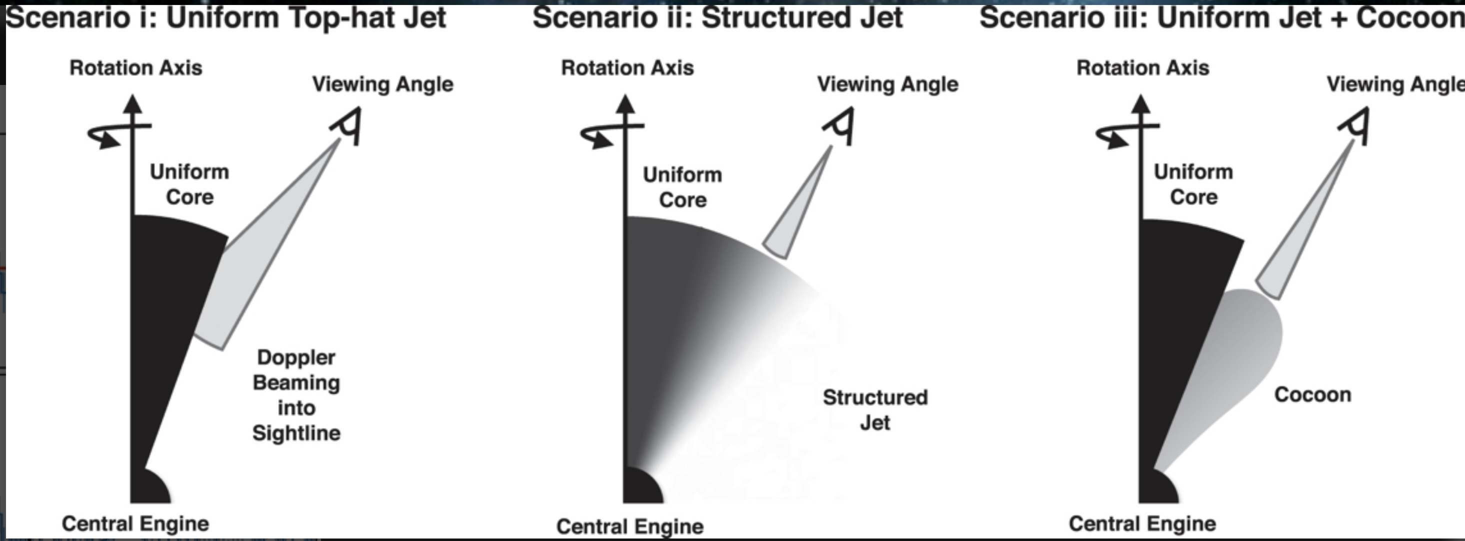




1.7 sec delay between merger and GRB

$E_{\gamma,iso}$ is ~10^5 times smaller than for cosmological short GRBs

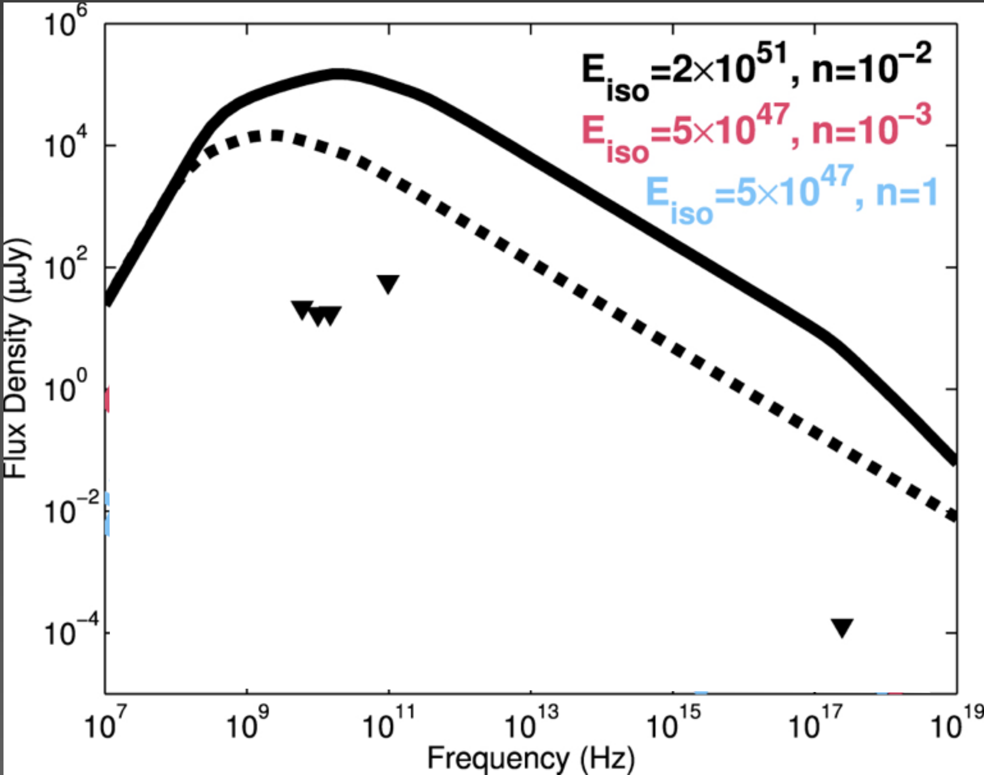
γ-ray emission alone does not distinguish between the various models

Radio/X-ray Emission

First radio observation (VLA by our group) 2.5 hours after optical discovery. Remained undetected until ~2 weeks later.

First deep X-ray observation (*Chandra* by our group) 2.3 days after optical discovery. The source remained undetected until ~1.5 weeks later.

Early non-detections rule out a typical short GRB on-axis



Alexander, EB et al. 2017; Margutti, EB et al. 2017, 2018; also, Haggard et al., Troja et al. 2017, 2018

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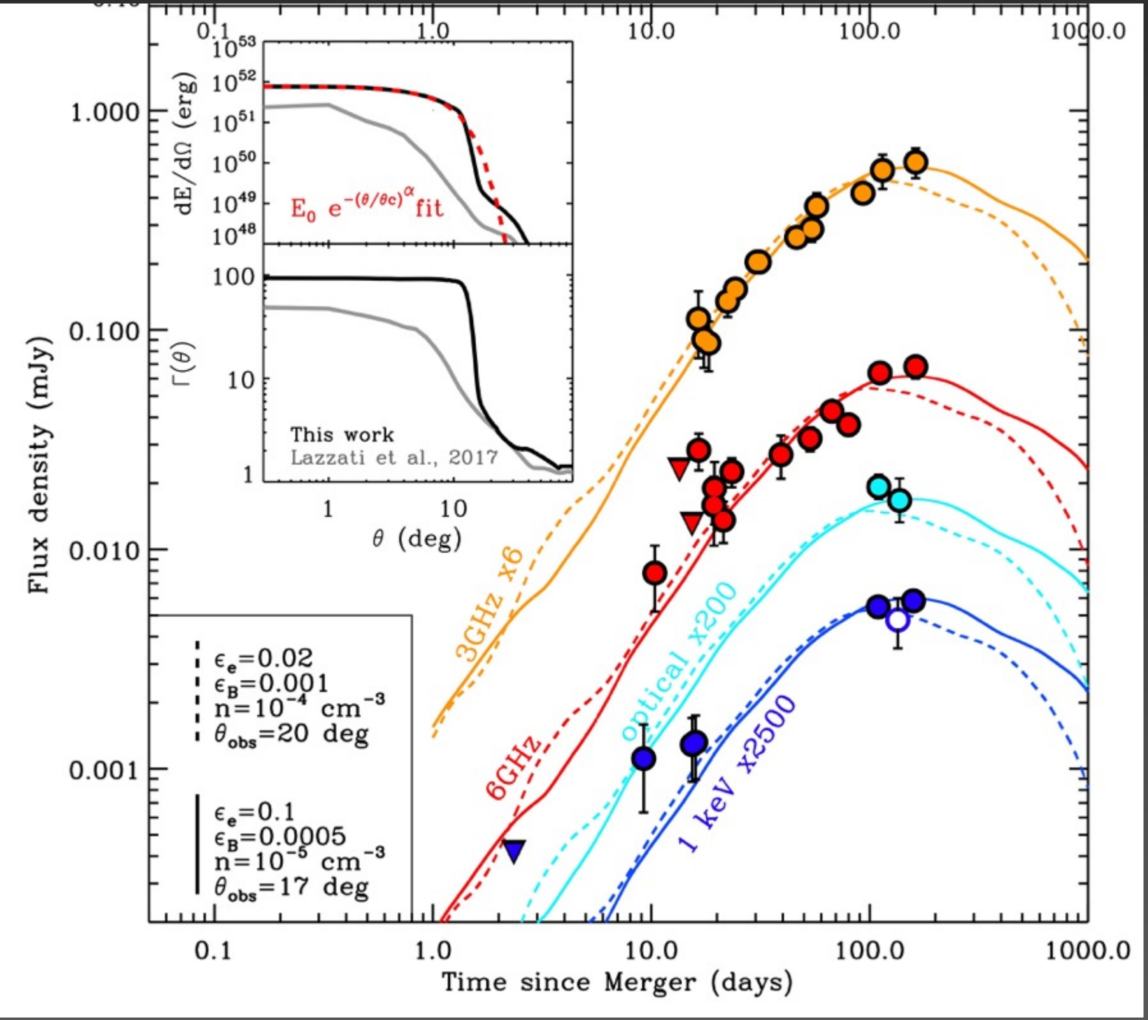
Alexander, EB et al. 2017; Margutti, EB et al. 2017, 2018



Radio / X-ray emission (and recent optical) are consistent with:

Structured GRB jet: relativistic core and angular structure with $E(\theta)$, $\Gamma(\theta)$ viewed from an off-axis angle of ~20°

Mildly-relativistic cocoon: Isotropic with $E(\Gamma)$; but ad-hoc

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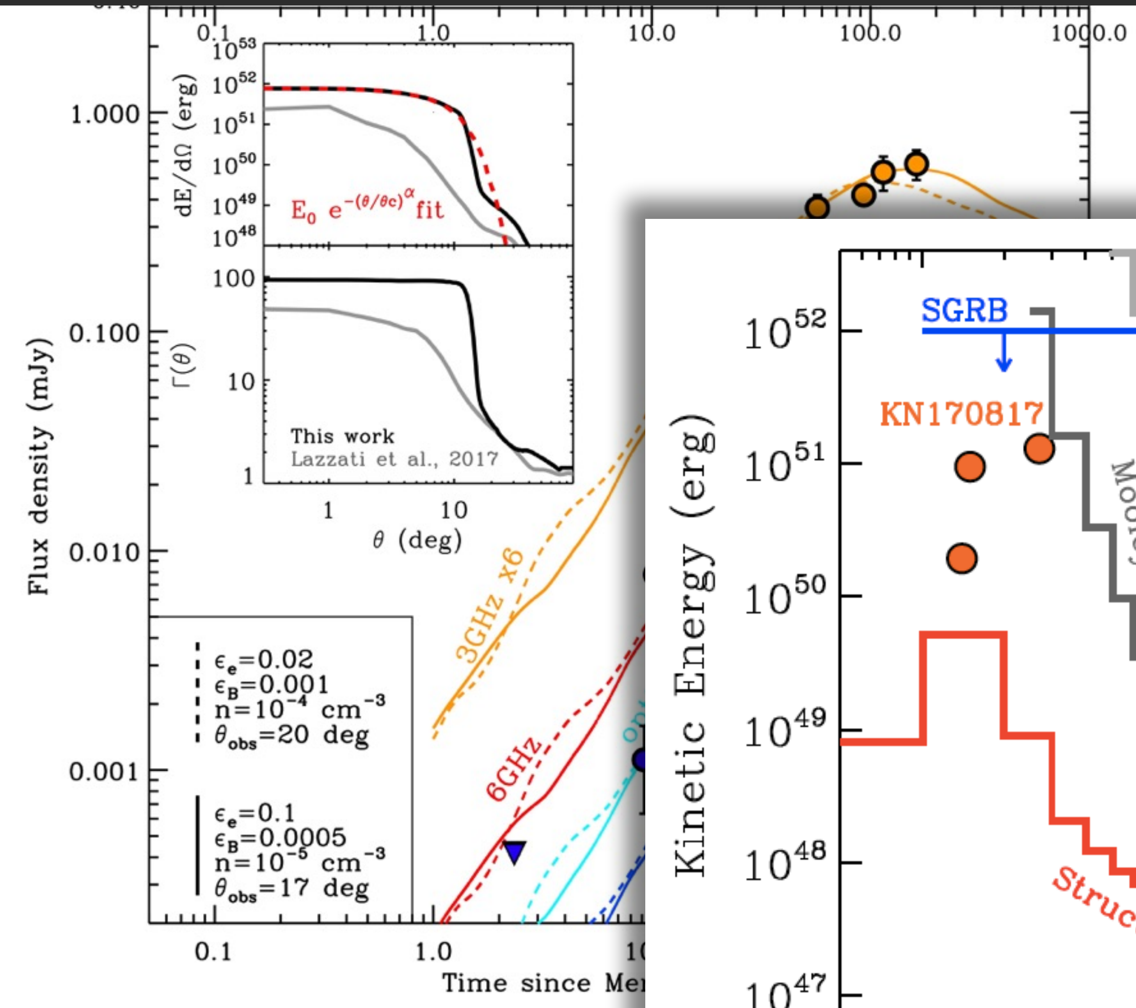

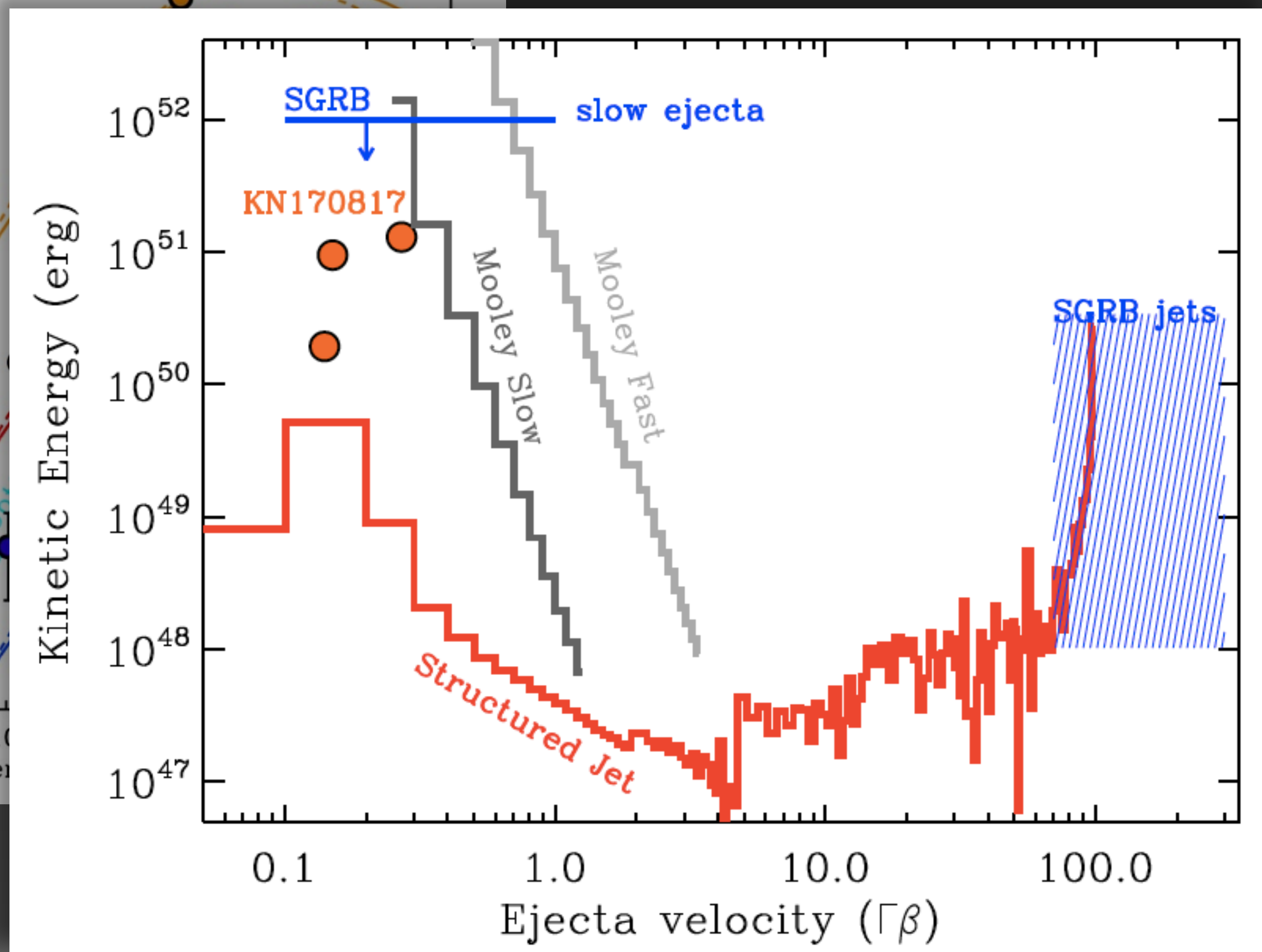

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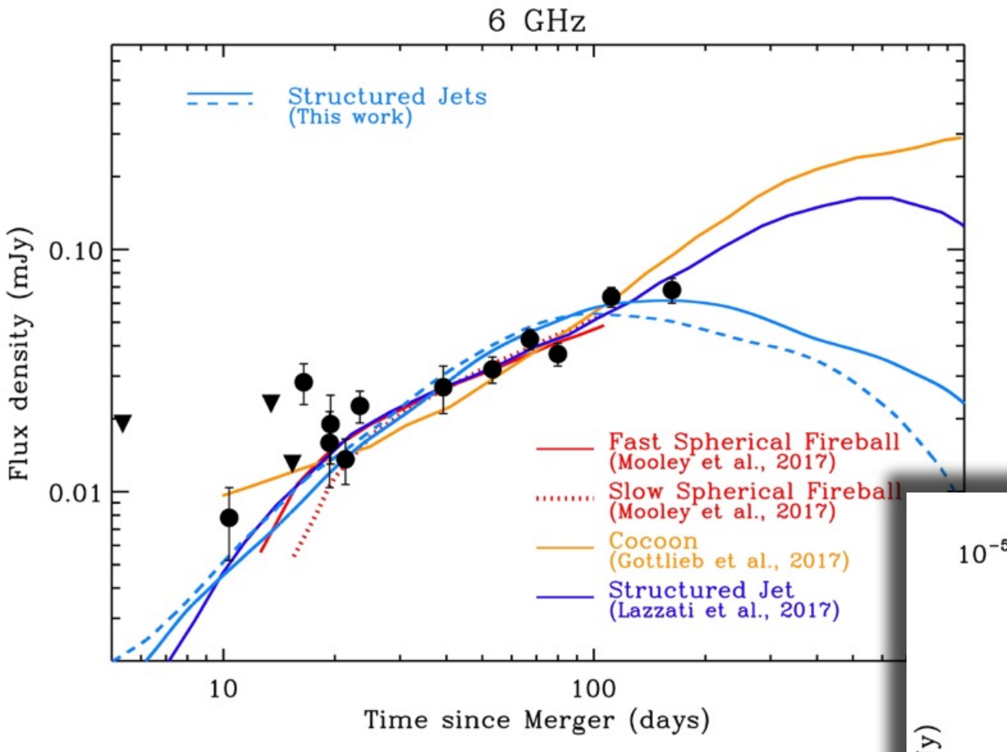
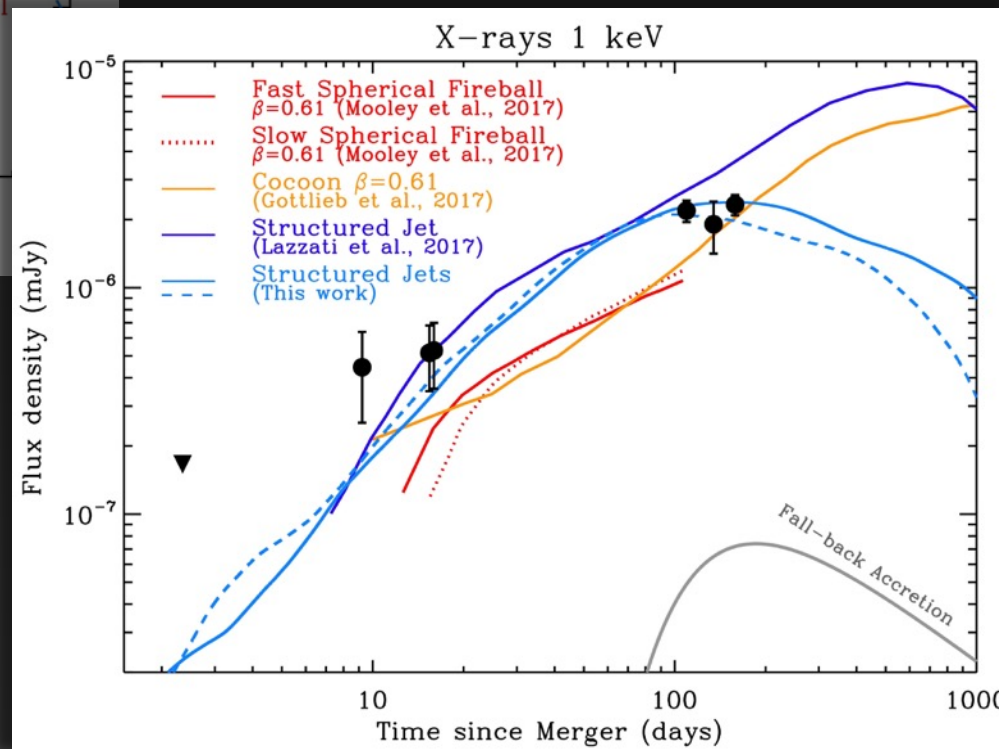


Continued radio/X-ray/optical observations for the next ~3 years(!) will provide complete view of outflow's evolution and nature

Radio



X-ray

Margutti, EB et al. 2018

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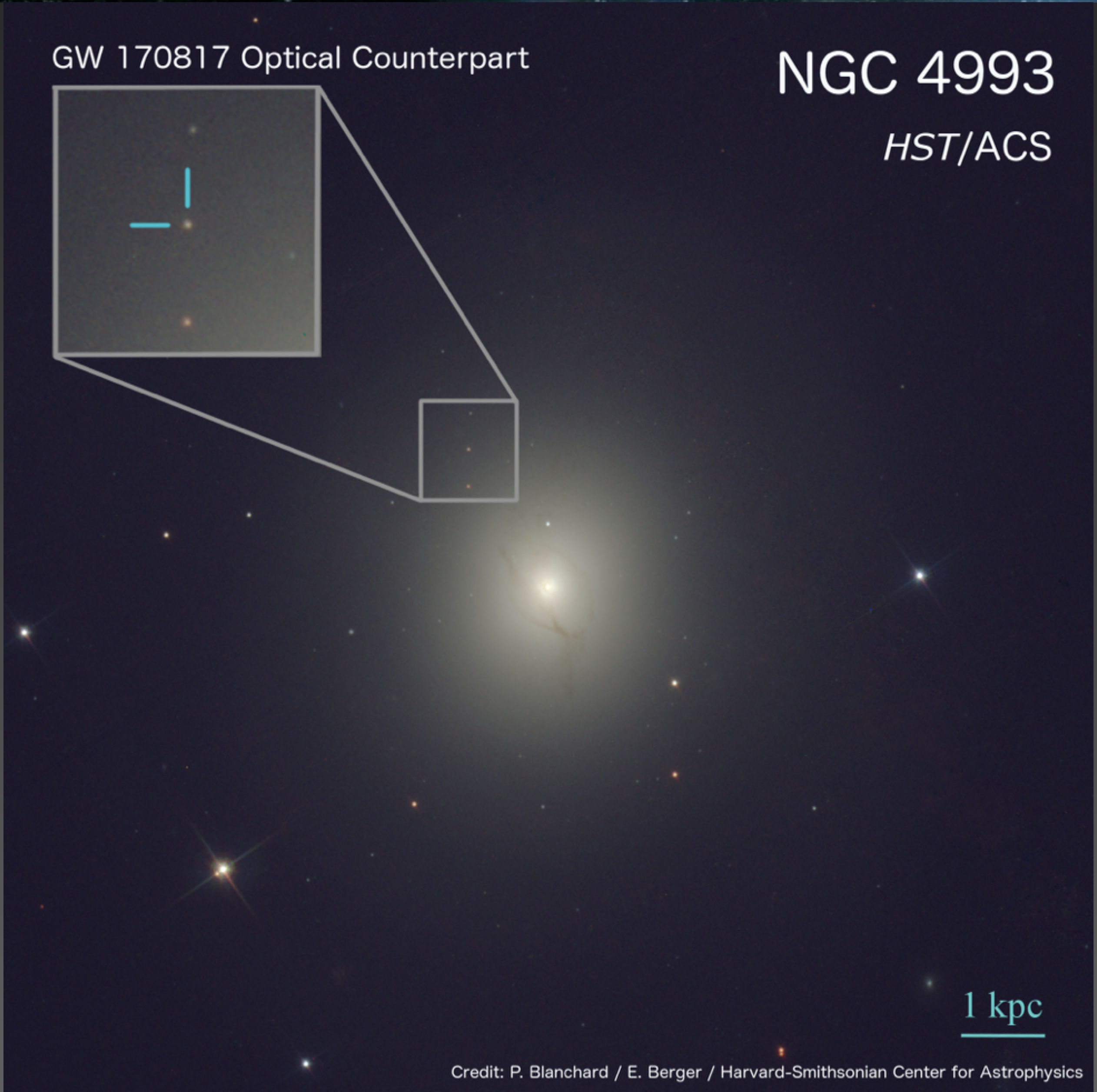
- Radio observations on a timescale of ~decade will reveal emission from the kilonova ejecta

Host Galaxy



Blanchard, EB et al. 2017

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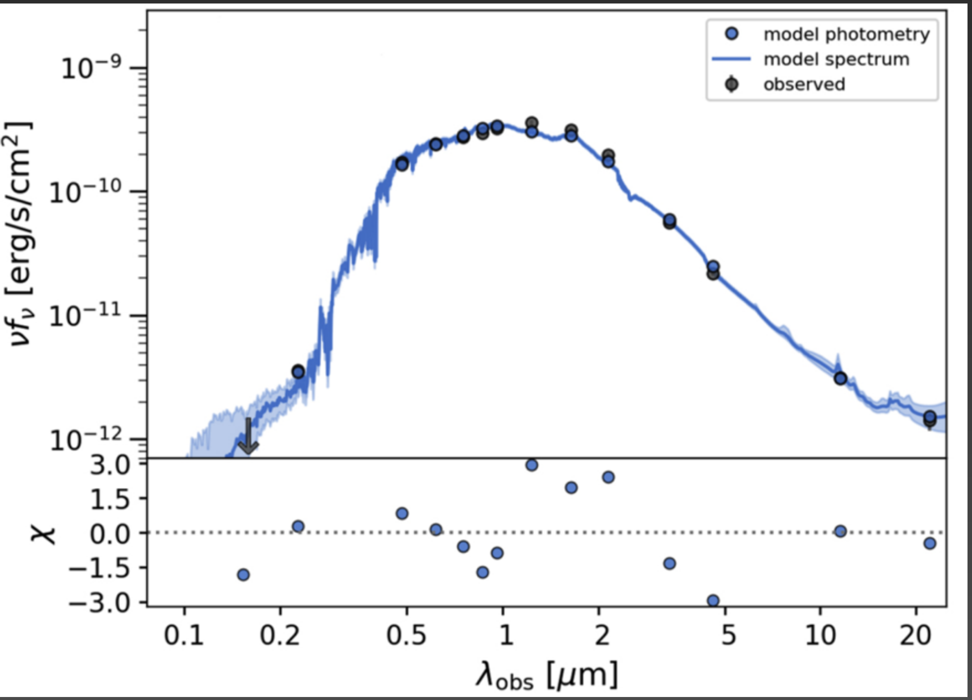

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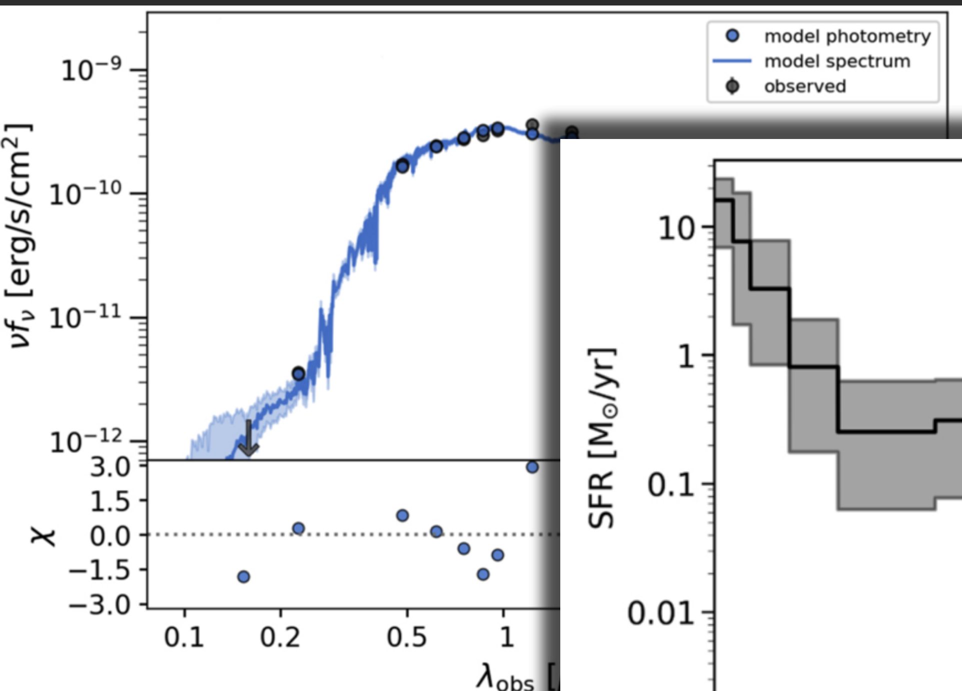
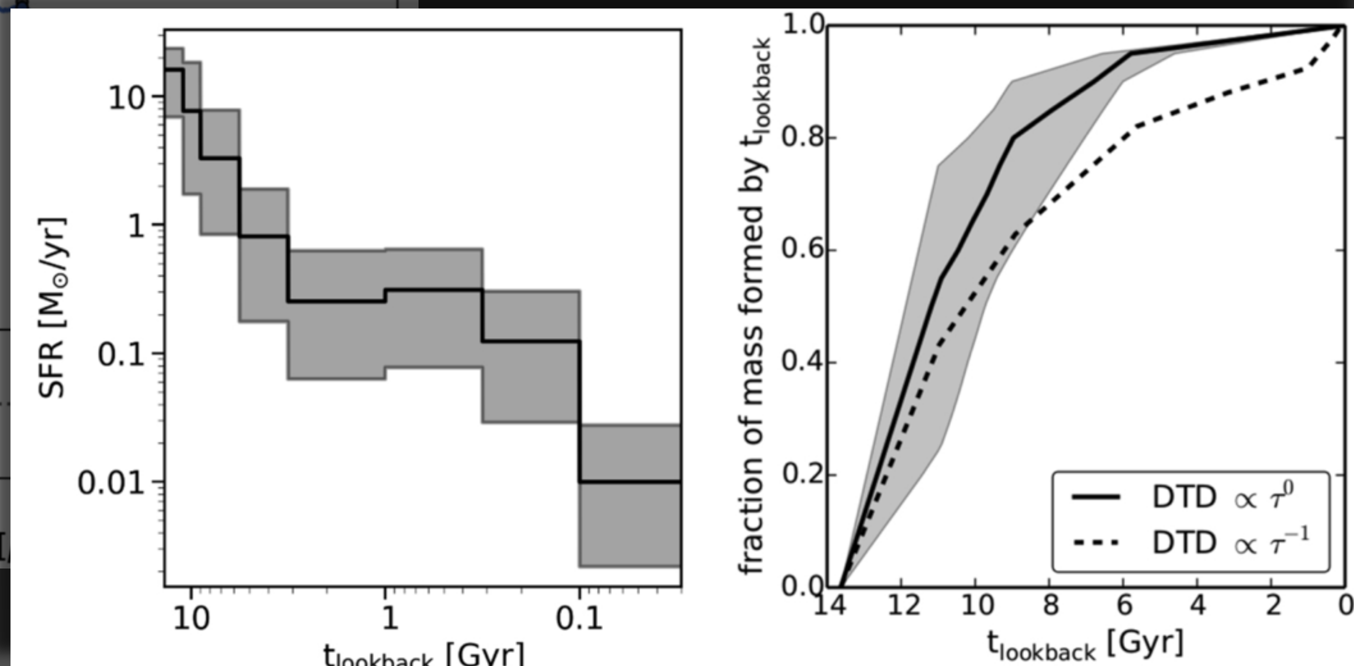
Blanchard, EB et al. 2017

$\langle \tau_{merger} \rangle \approx 11$ Gyr





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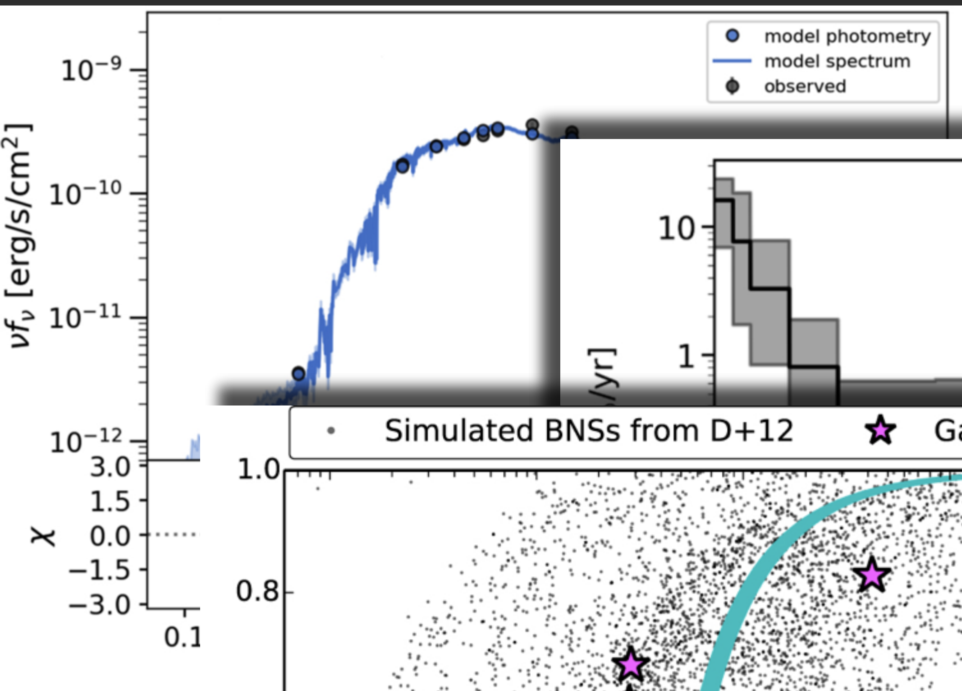

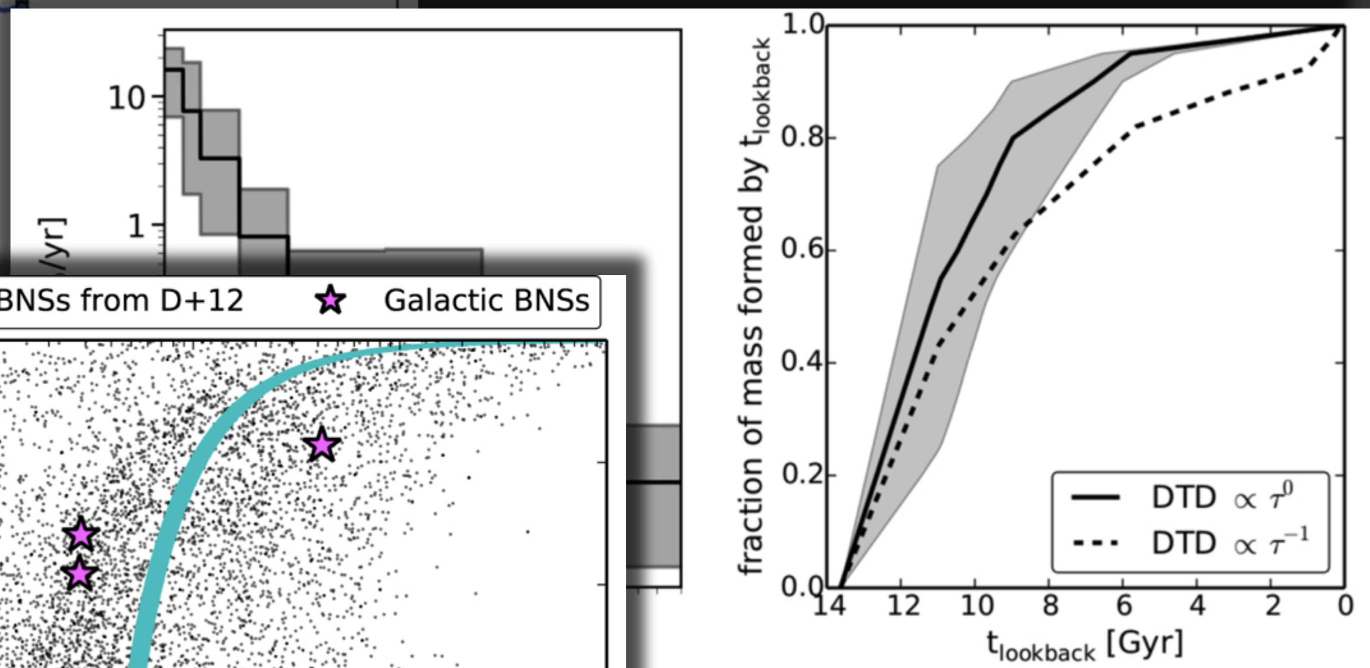

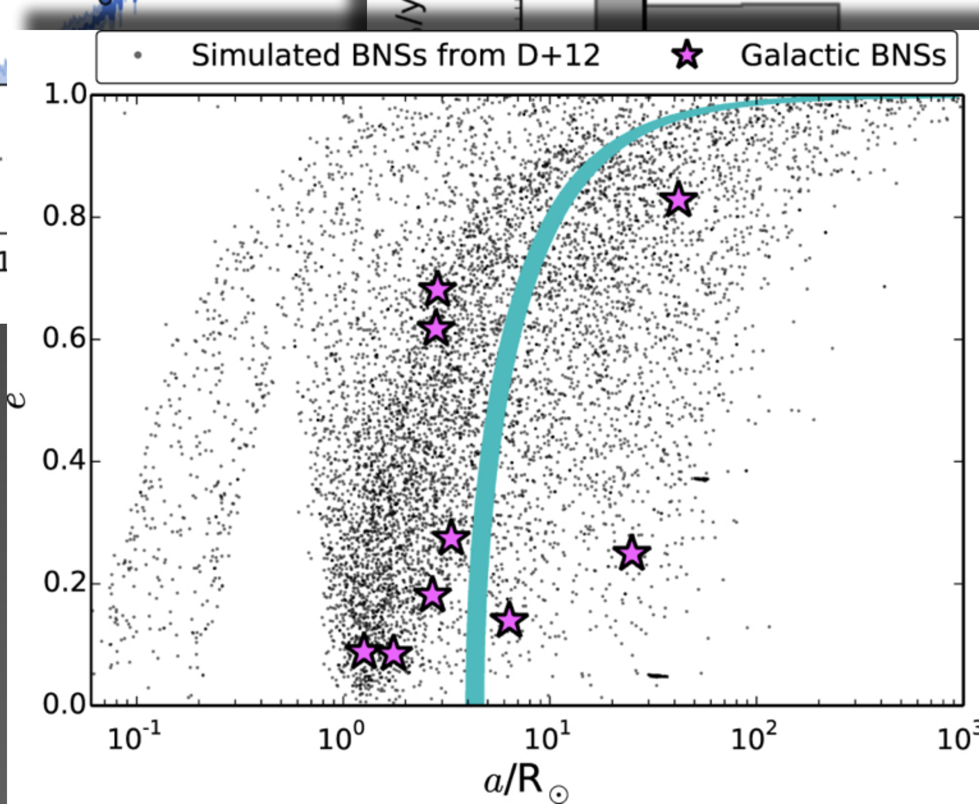

$\langle R_{initial} \rangle \approx 4.5\ R_\odot$

An Unparalleled Story of Firsts

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- The first joint detection of gravitational waves and light (γ−rays to radio)
- First direct evidence that *r*-process nucleosynthesis happens in, and is likely dominated by, BNS mergers
- Radio/X-ray observations consistent with a structured jet viewed off-axis
- Optical/IR data suggest NS-NS → BH
- More observations and interpretation underway