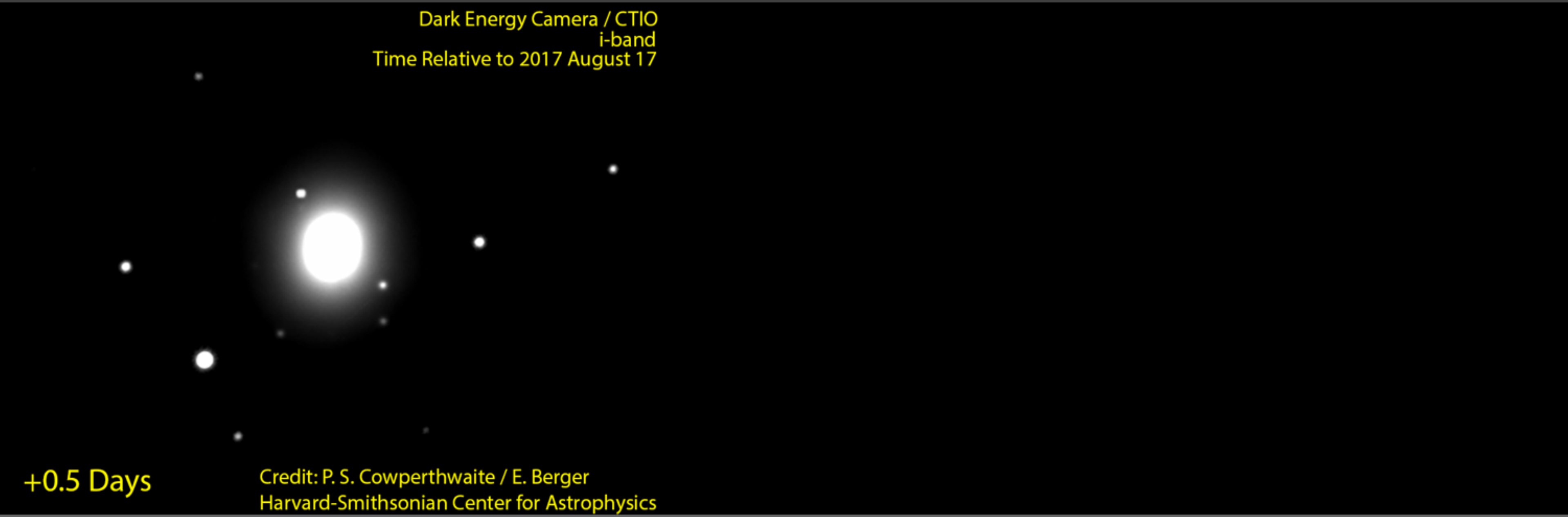
Rattle and Shine: Joint Detection of Gravitational Waves and Light from the Binary Neutron Star Merger GW170817



Edo Berger (Harvard University)

Universität Bern – April 2018

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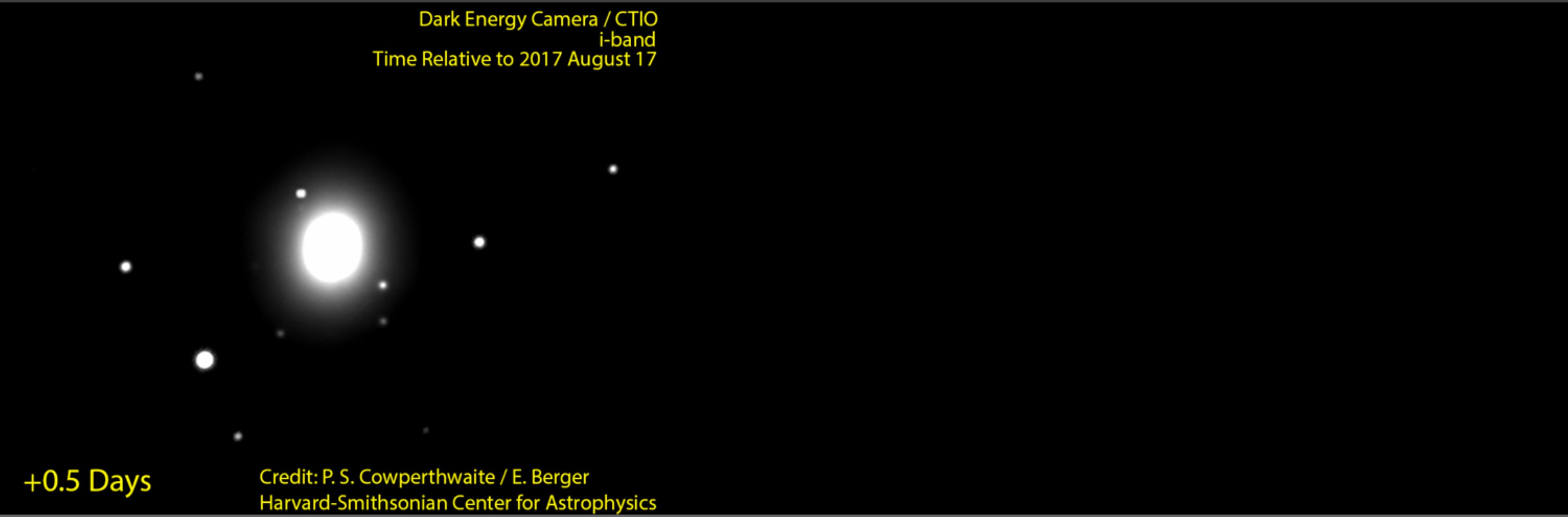

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The Key Players





Ashley Villar | Kate Alexander | Phil Cowperthwaite | Peter Blanchard | Tarraneh Eftekhari

Matt Nicholl | Peter Williams | Wen-fai Fong | Raffaella Margutti | Ryan Chornock





Where to Find All the Details

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2. UV/Optical/Near-IR Light Curves
3. UV/Optical Spectra
4. Near-IR Spectra
5. X-Ray Observations
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7. Host Galaxy Properties
8. Comparison to Short GRBs

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The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VIII. A Comparison to Cosmological Short-duration Gamma-Ray Bursts

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Key words: gamma-ray burst: general – gravitational waves – stars: neutron

1. Introduction

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+200 papers by other authors…

An Unparalleled Story of Firsts

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- First gravitational wave detection of a neutron star binary merger
- First joint detection of gravitational waves and light
- First direct confirmation that short gamma-ray bursts result from neutron star binary mergers
- First direct evidence that *r*-process nucleosynthesis is dominated by neutron star binary mergers
- First constrains on the remnant of a neutron star binary merger
- First use of a neutron star binary merger to measure the Hubble Constant
- …

A Confluence of Physics Research Areas

A Confluence of Physics Research Areas

This single event brings together and impacts multiple disparate field of physics:

- Gravity / General Relativity (gravitational waves)
- Nuclear physics (*r*-process nucleosynthesis; NS equation of state)
- Atomic physics (opacities of *r*-process elements)
- High-energy astrophysics (origin of gamma-ray bursts)
- Stellar and binary evolution (NS binary properties)
- Cosmology (Hubble constant)

Outline

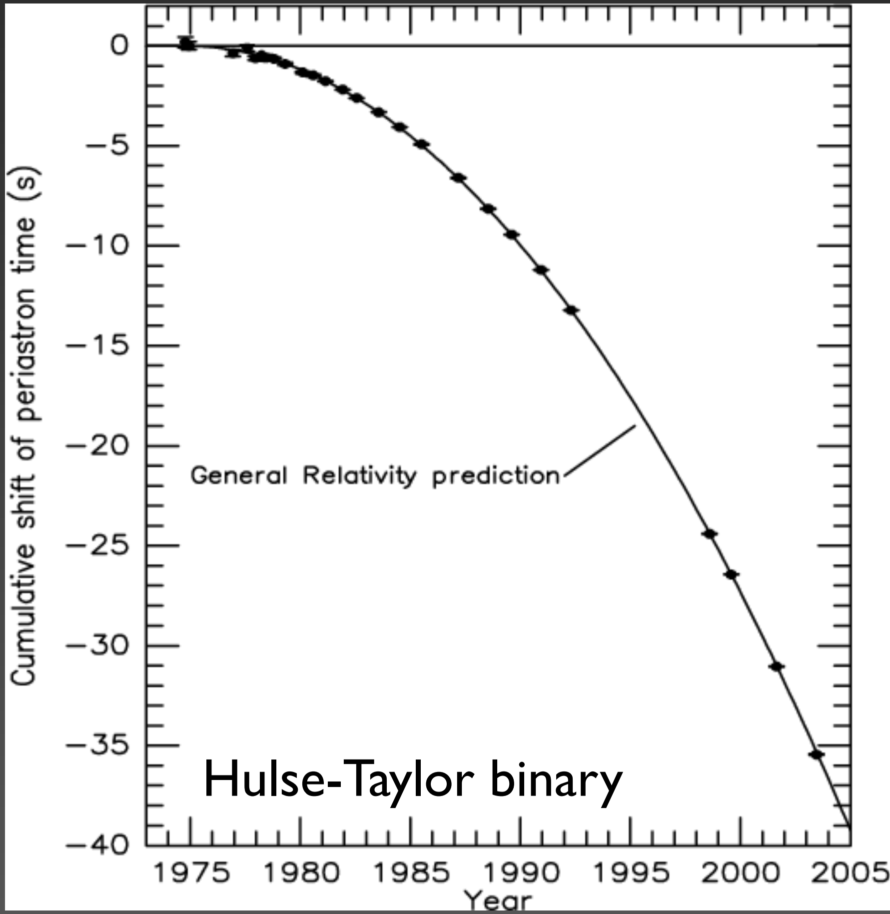
Outline

- Gravitational wave sources and detectors
- Electromagnetic counterparts: Why and what?
- GW170817 in gravitational waves
- GW170817 in electromagnetic radiation
    - *Discovery of the optical counterpart*
    - *Complex ejecta structure and the origin of the heavy elements*
- The future of gravitational wave astronomy

Gravitational Wave Sources

Strain: $$h \sim \frac{G}{c^4}\frac{\ddot{Q}}{d}$$

Frequency: $$f \sim \sqrt{G\rho}$$



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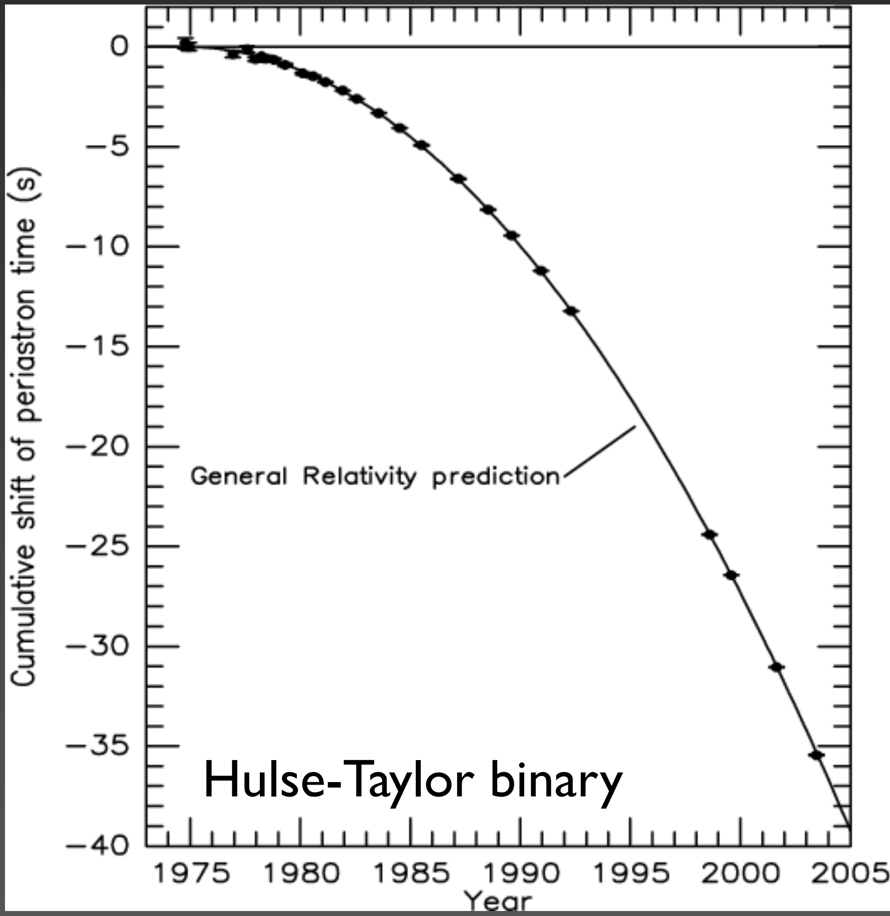

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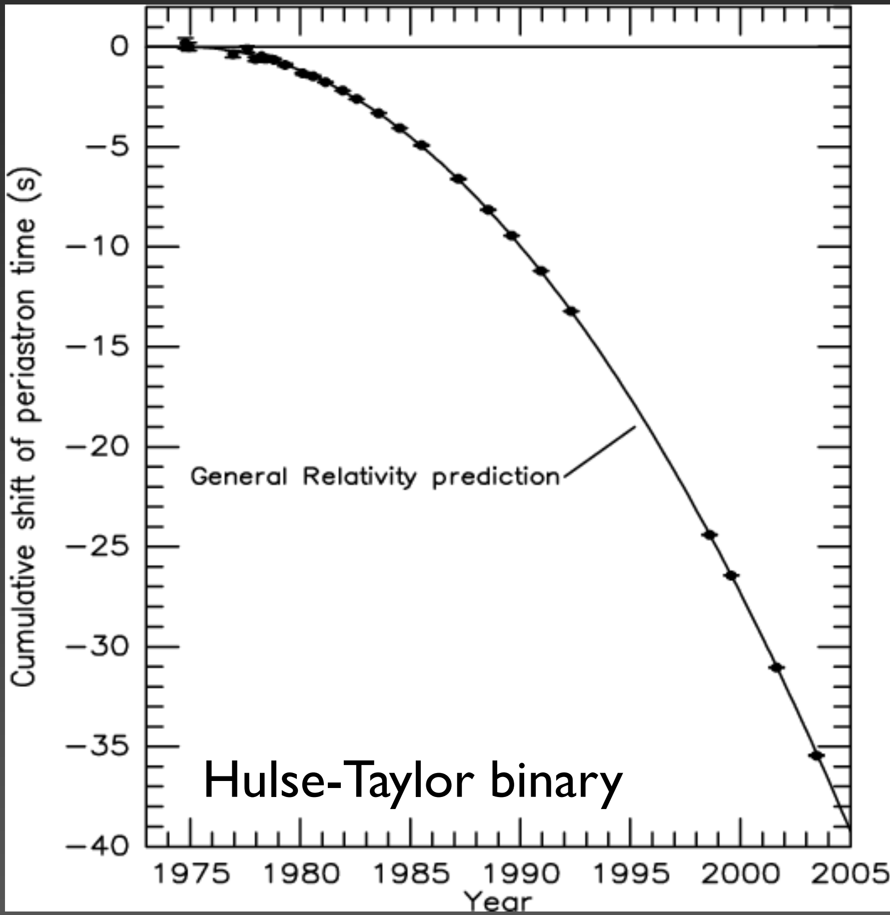
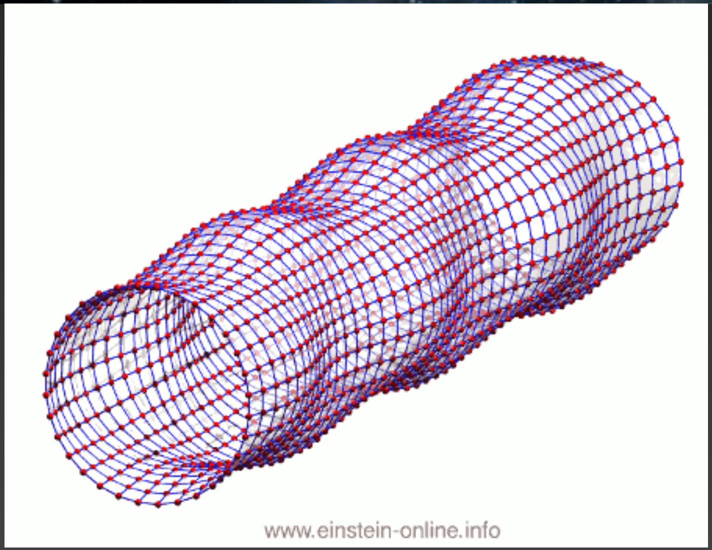


(eLISA, operating at 0.001-0.1 Hz, will be sensitive to supermassive binary black hole mergers & white dwarf binary mergers)

LIGO/Virgo



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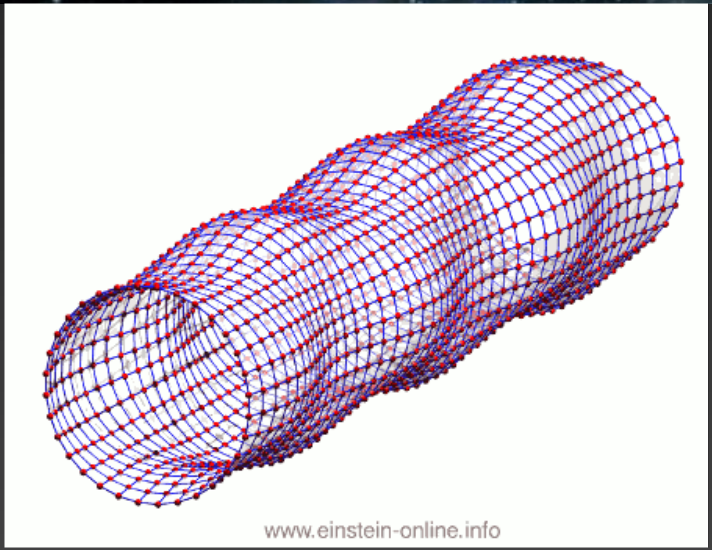

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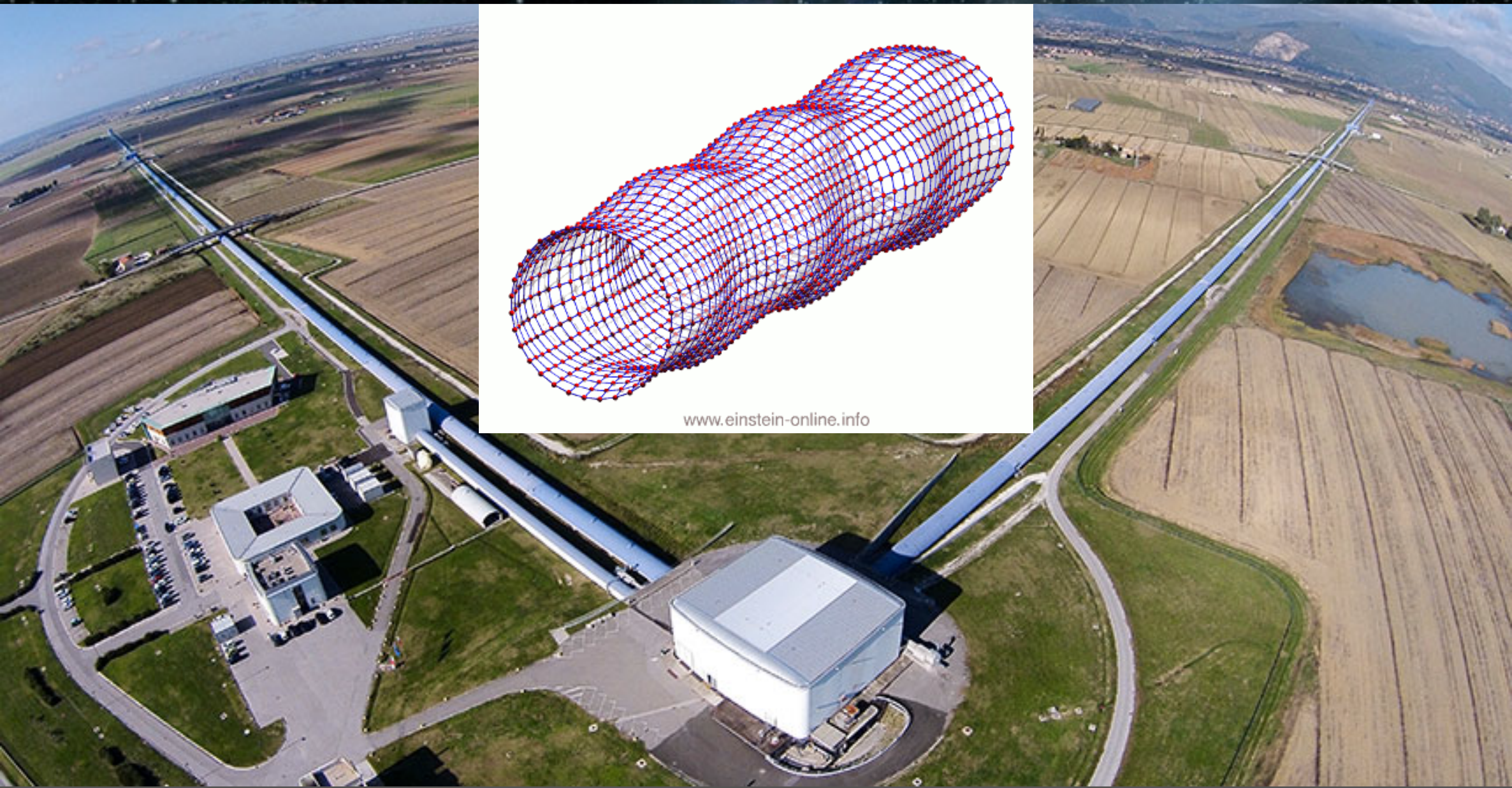

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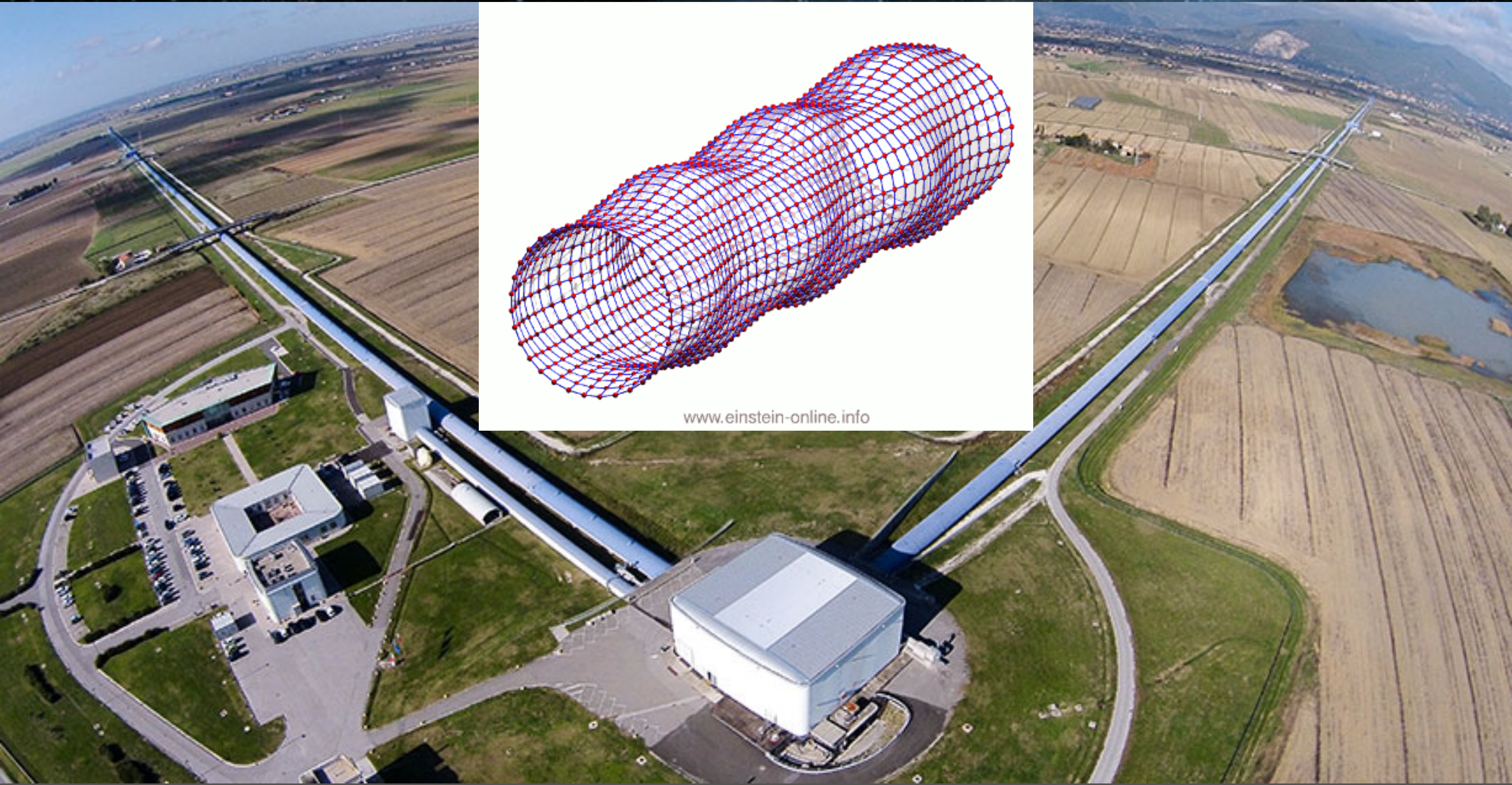
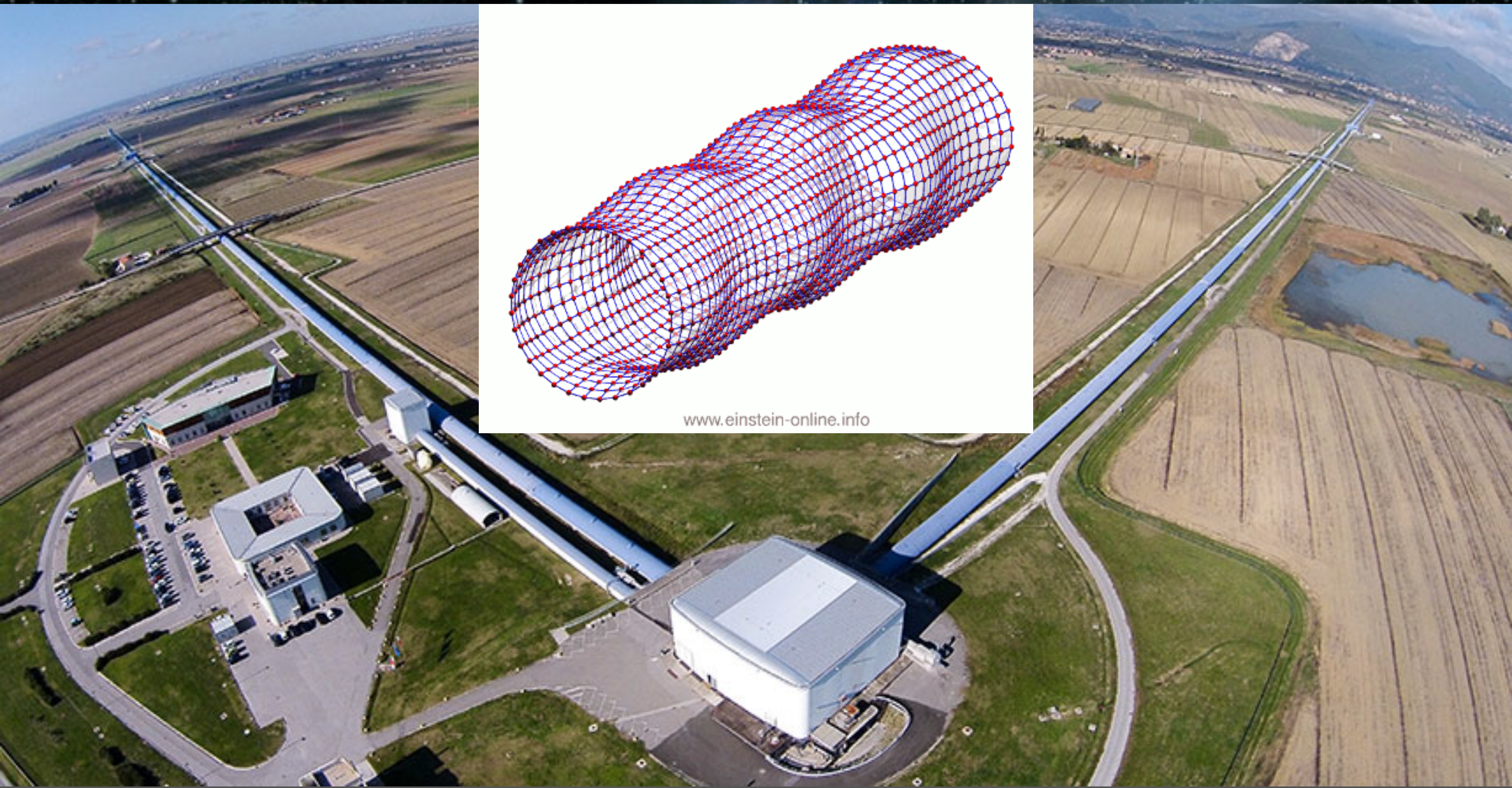


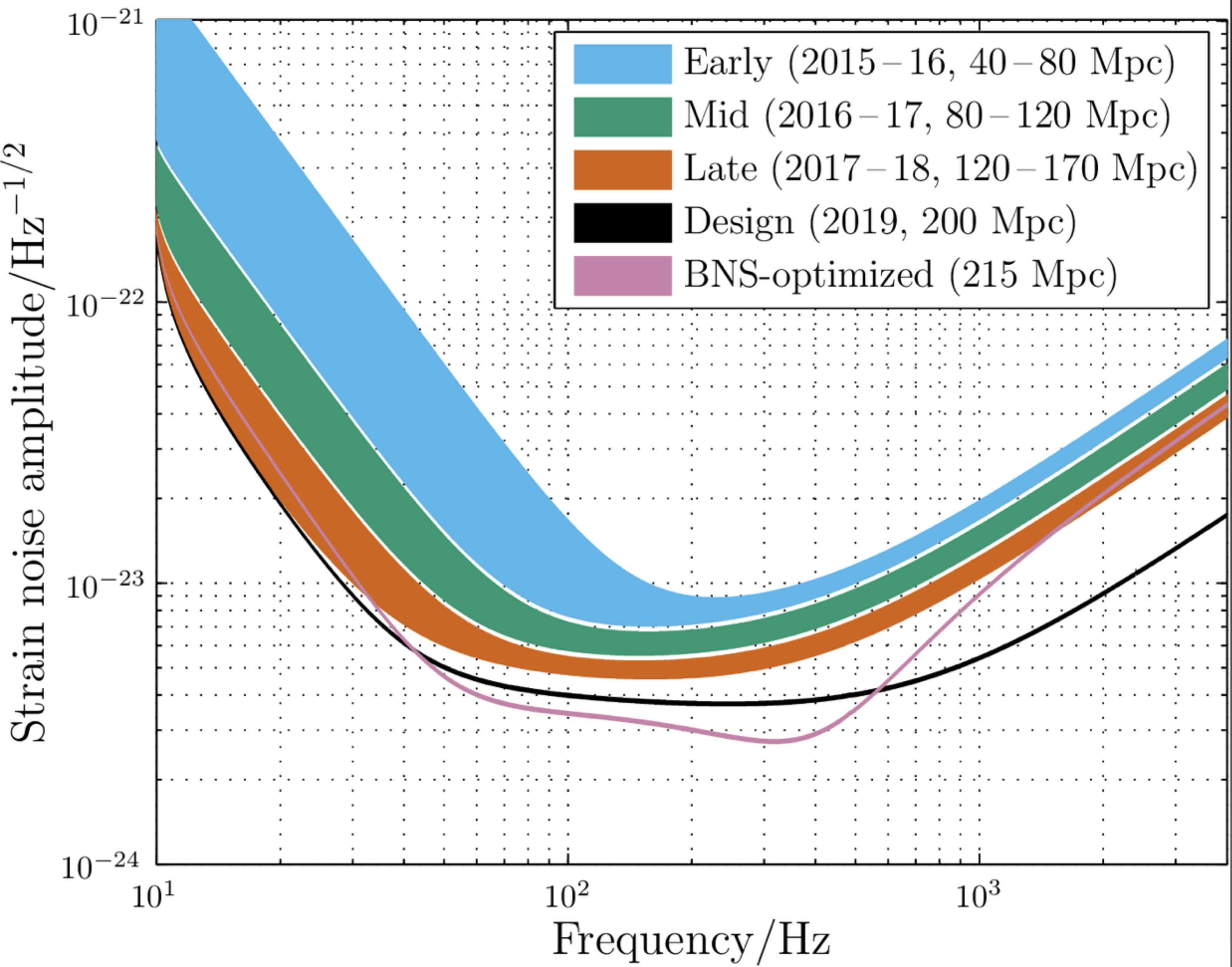
To detect gravitational waves need to measure the arm lengths to $h = \Delta L/L \sim 10^{-22}$

LIGO/Virgo



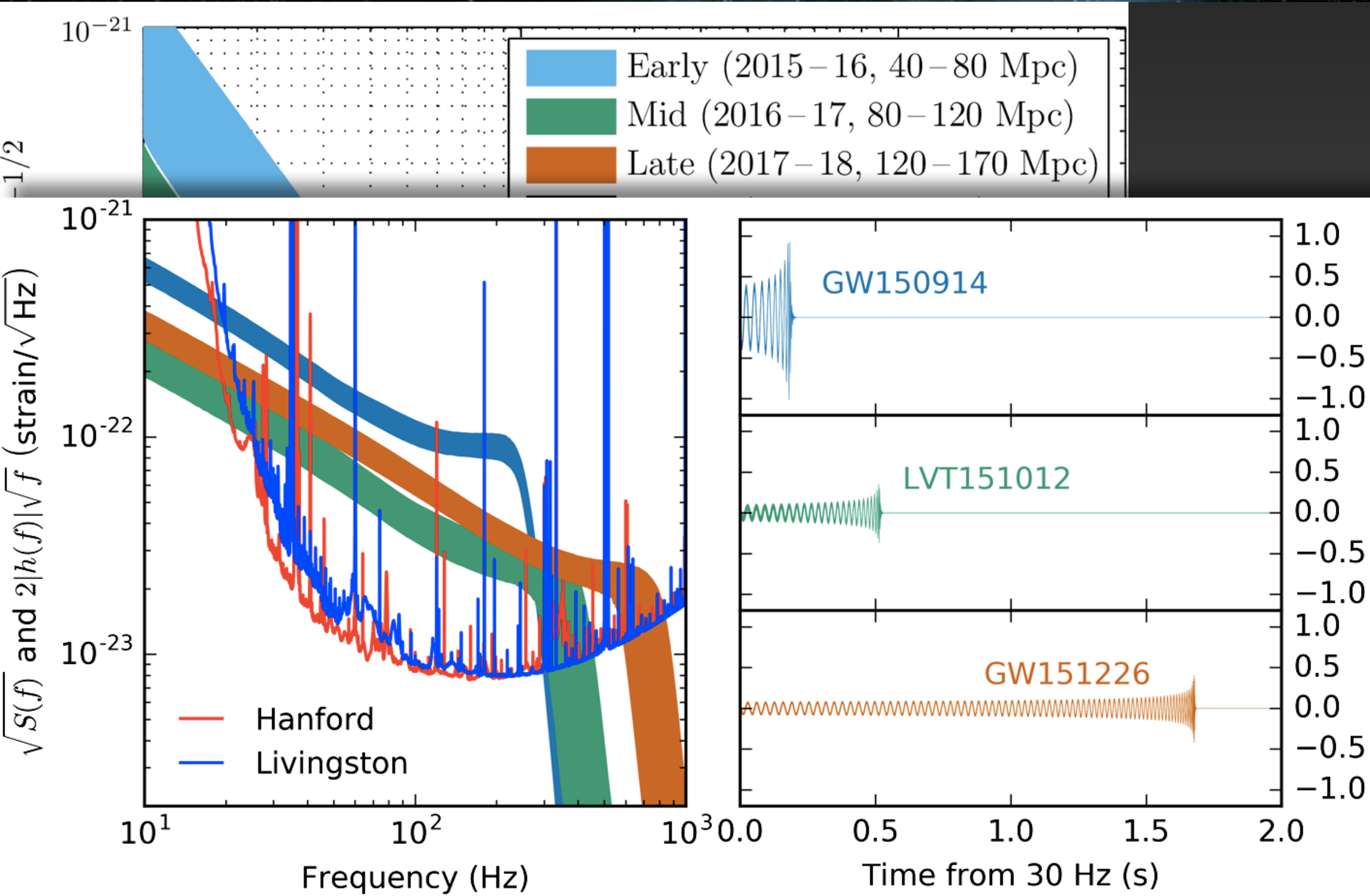
To detect gravitational waves need to measure the arm lengths to
$h = \Delta L/L \sim 10^{-22}$ $\Rightarrow 10^{-3}$ size of proton; nearest star to 10 μm

LIGO/Virgo



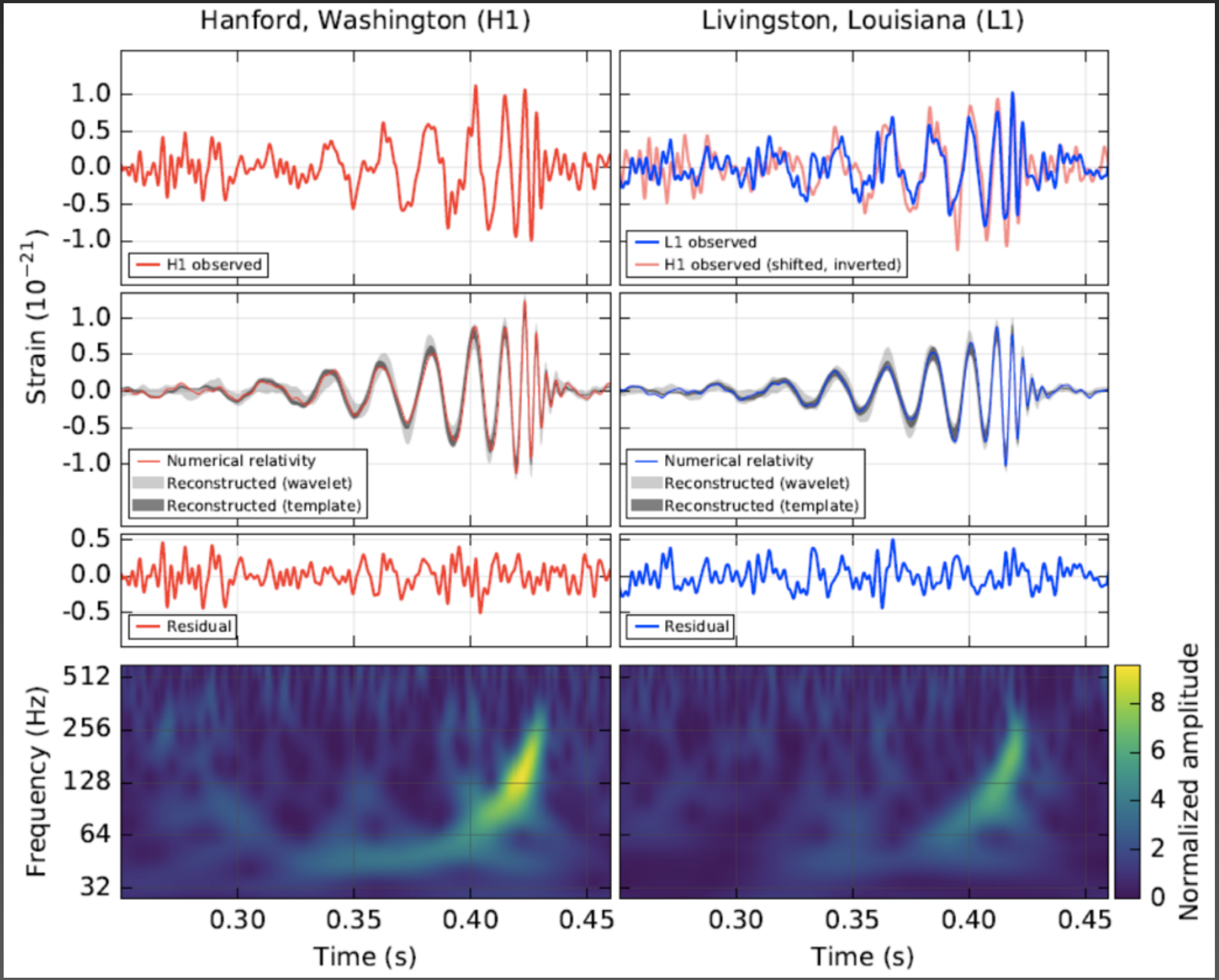
Early (2015 – 16, 40 – 80 Mpc)
Mid (2016 – 17, 80 – 120 Mpc)
Late (2017 – 18, 120 – 170 Mpc)
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Strain noise amplitude/$\mathrm{Hz}^{-1/2}$
Frequency/Hz

LIGO/Virgo



Early (2015 – 16, 40 – 80 Mpc)
Mid (2016 – 17, 80 – 120 Mpc)
Late (2017 – 18, 120 – 170 Mpc)
$\sqrt{S(f)}$ and $2|h(f)|\sqrt{f}$ (strain/$\sqrt{\text{Hz}}$)
Frequency (Hz)
Hanford
Livingston
GW150914
LVT151012
GW151226
Time from 30 Hz (s)

LIGO/Virgo: First Detection (BBH)

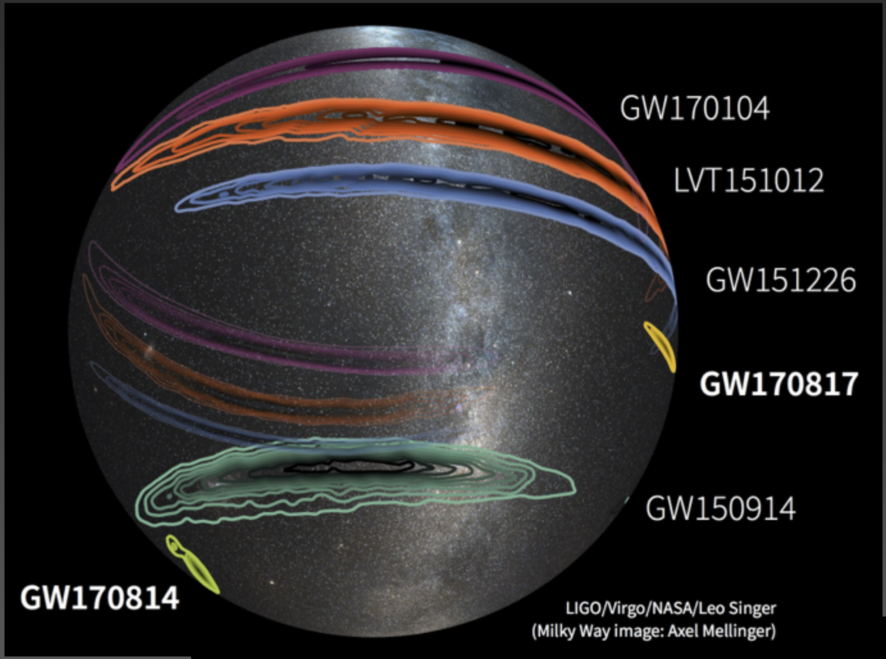


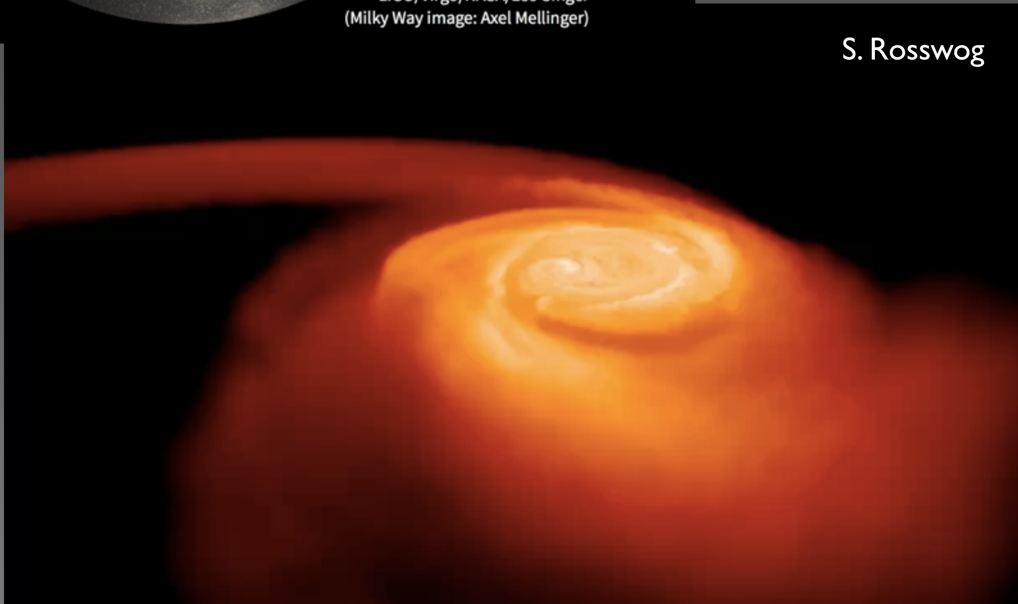
Abbott et al. 2015

35+30 $M_\odot$ black hole binary at 450 Mpc, with 3 $M_\odot$ radiated in GW

Electromagnetic Counterparts: Why & What

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



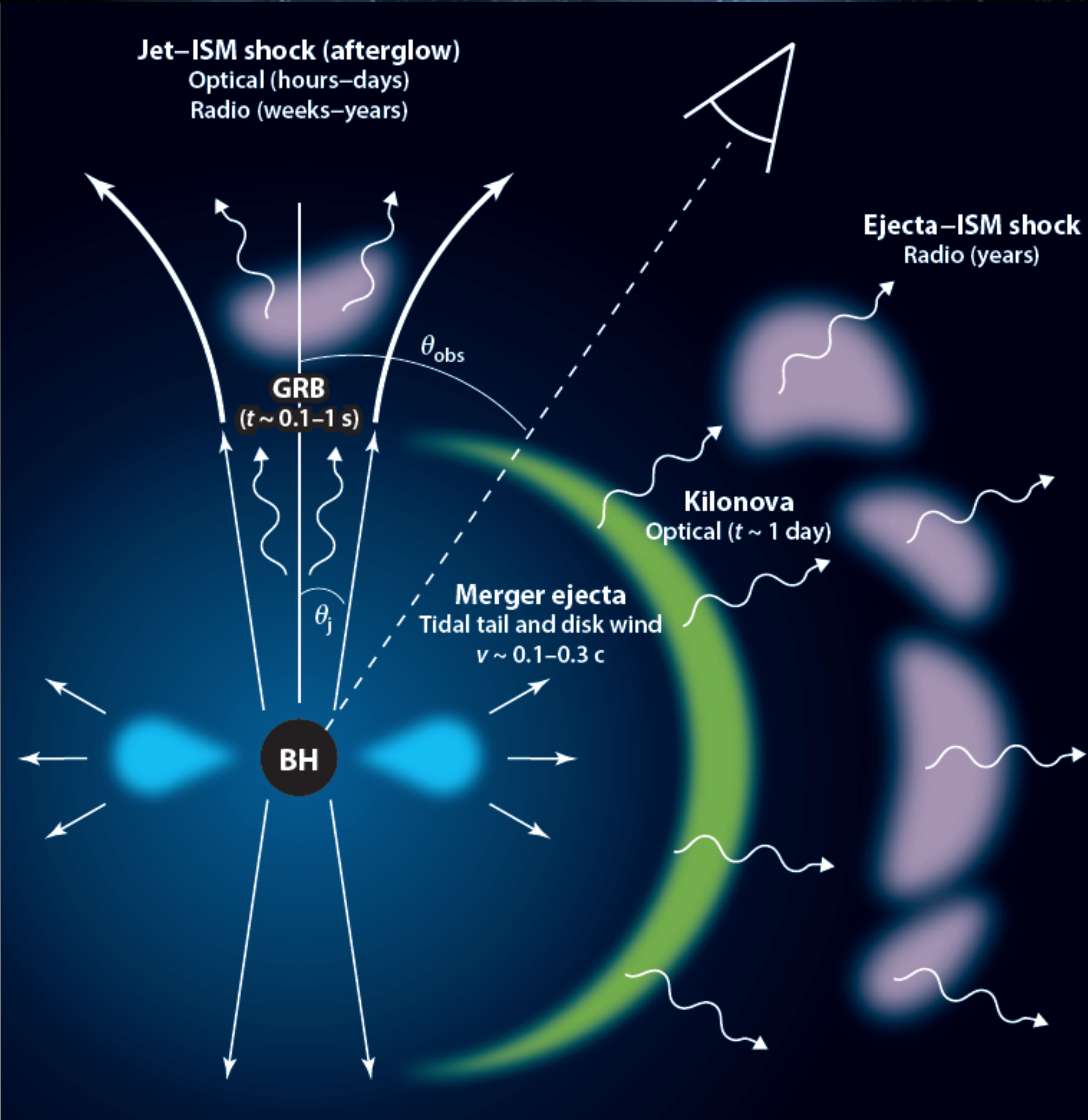


Electromagnetic Counterparts: Why & What

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

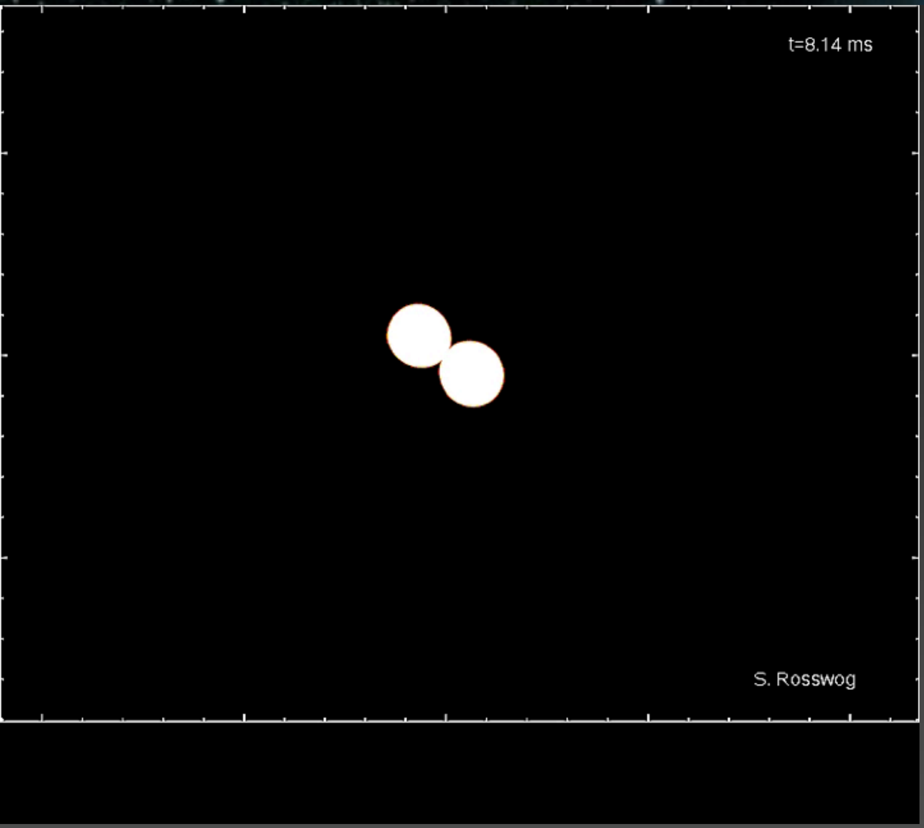
Predicted emission:

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



Metzger & EB 2012

r-Process Nucleosynthesis: "Kilonova"



- Tidal tails (NS-NS/NS-BH)
- Accretion disk wind (NS-NS/NS-BH)
- Shocked interface (NS-NS)

e.g. Lattimer & Schramm 1974; Li & Paczynski 1998; Rosswog et al. 1999; Freiburghaus et al. 1999; Metzger et al. 2008; Kasen et al. 2013; Metzger 2017

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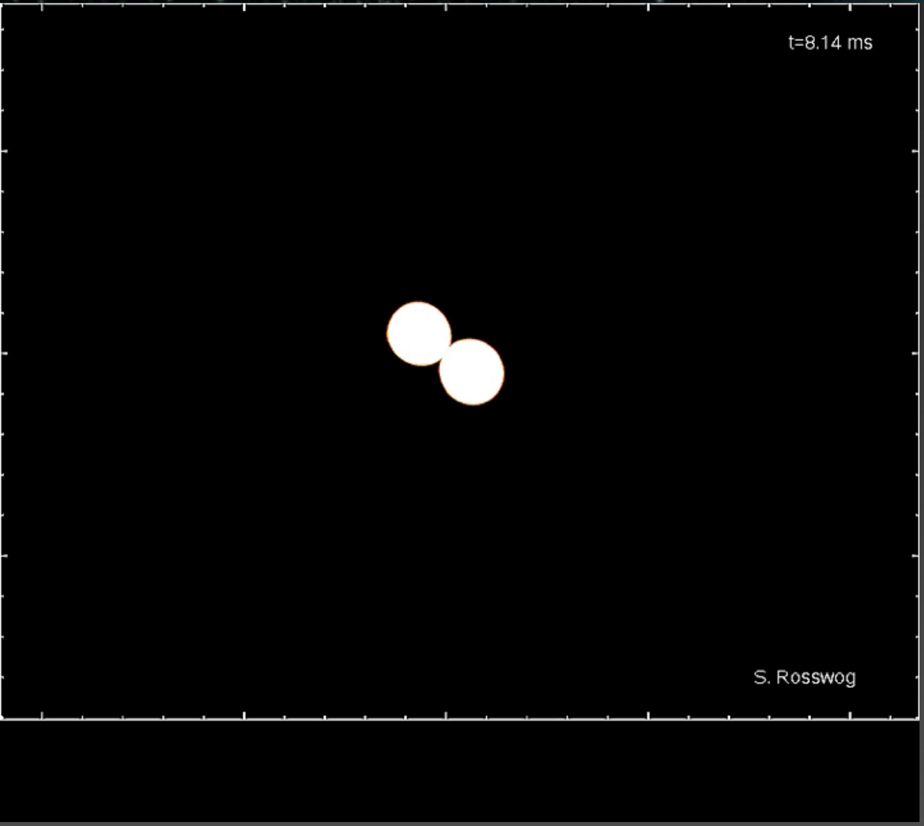

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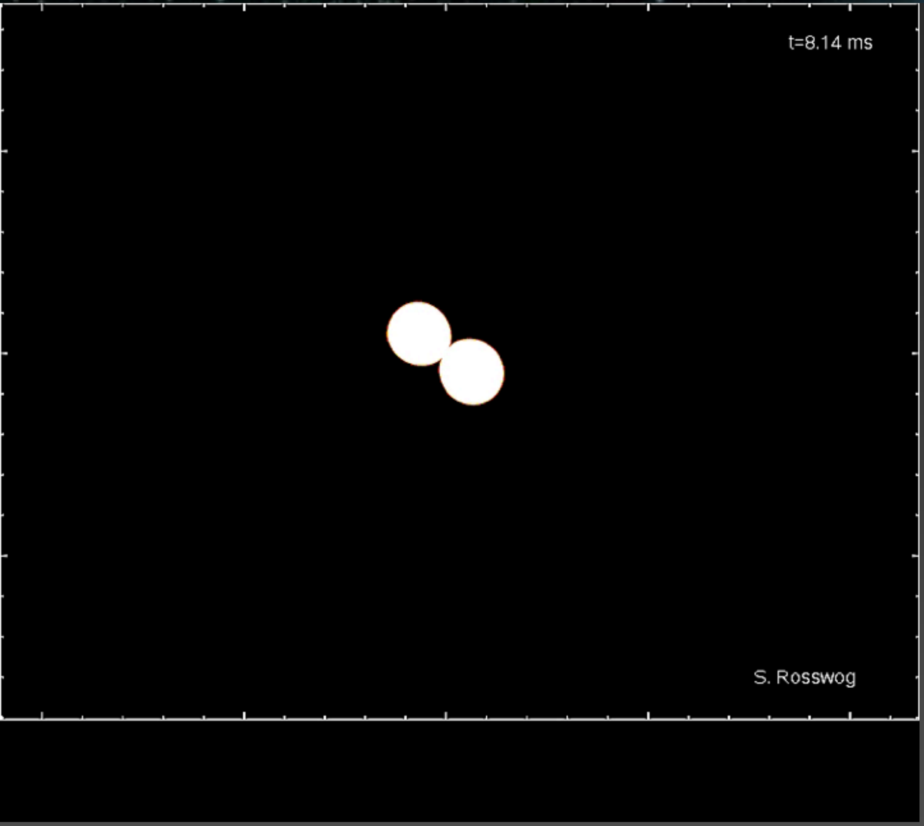

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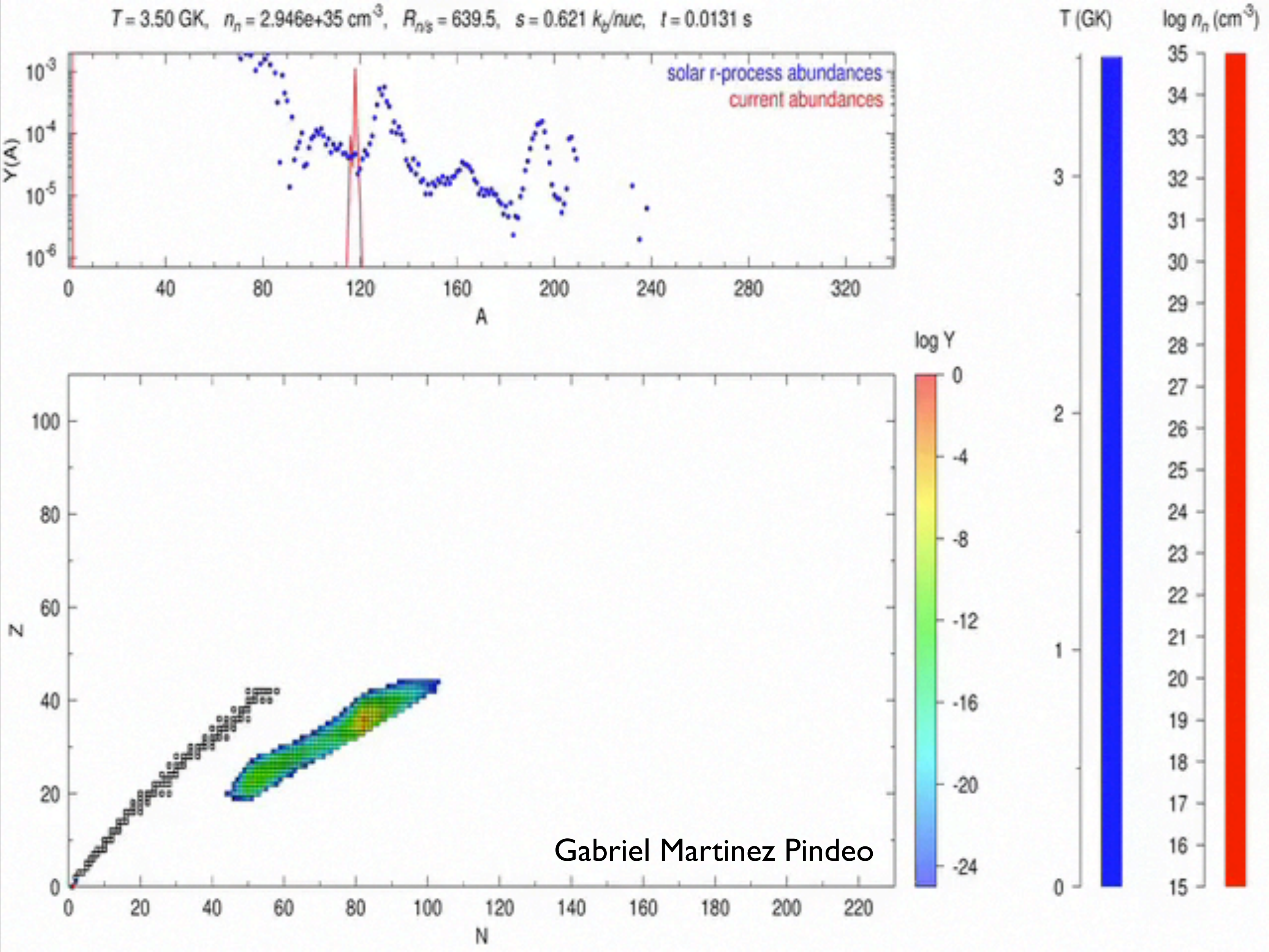
The presence, mass, velocity of these components depend on the nature of the merging objects (NS-NS vs. NS-BH, mass ratio) and the remnant (prompt BH, delayed BH, stable NS)

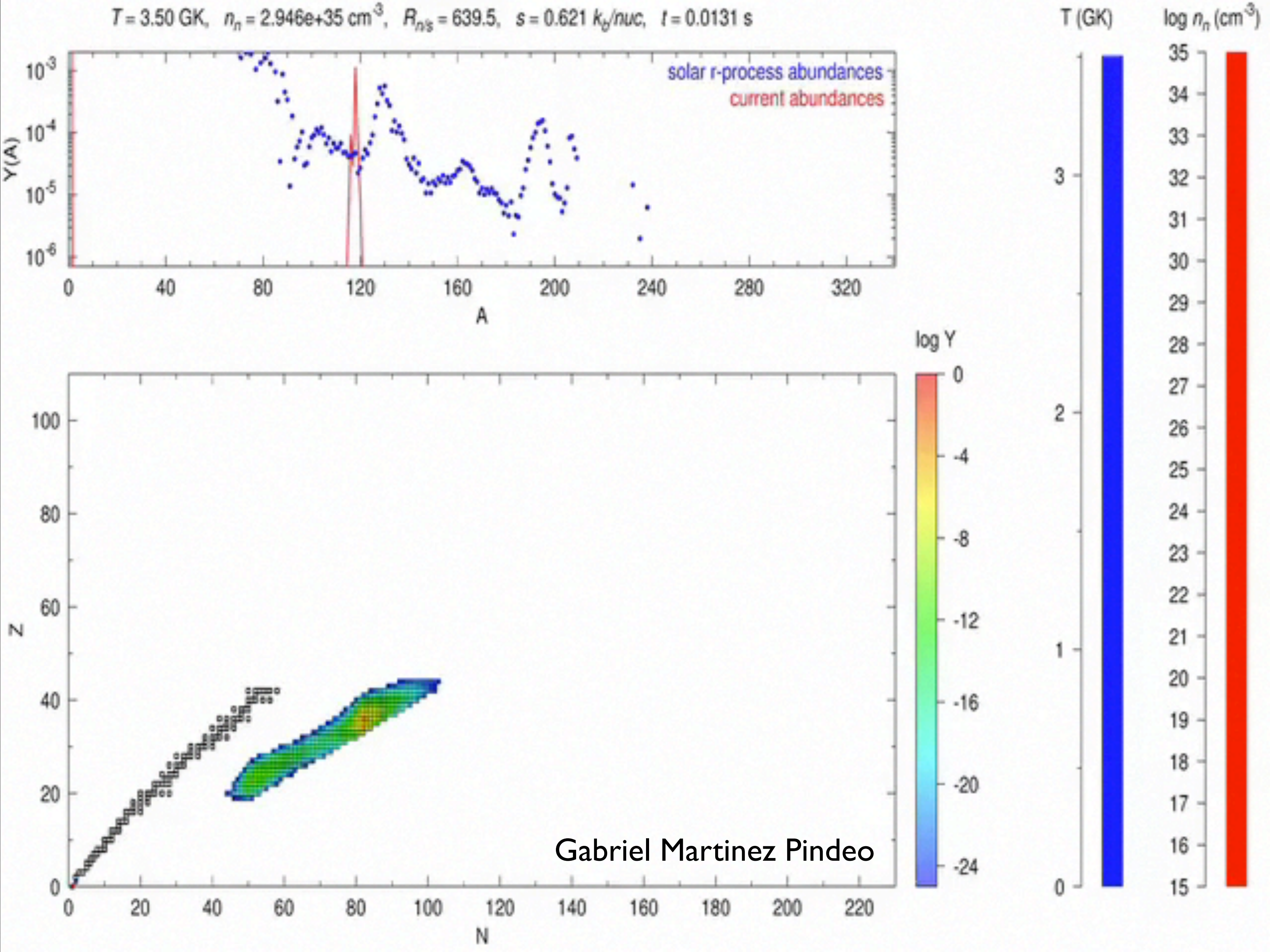
The observational manifestation also depends on nucleosynthesis

r-Process Nucleosynthesis: "Kilonova"



Gabriel Martinez Pindeo

r-Process Nucleosynthesis: "Kilonova"



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Brightness and spectrum depend on heating rate & opacity

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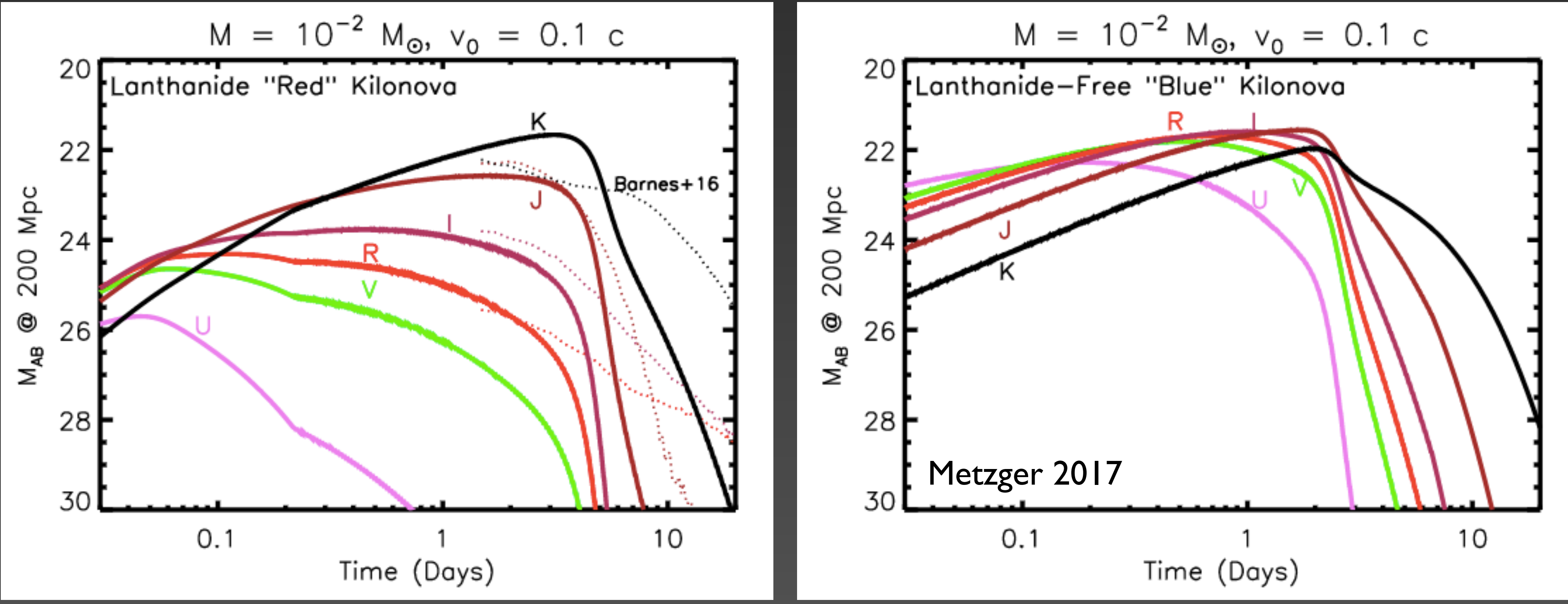

IR-peaked; ~1 week

Optical-peaked; ~1 day

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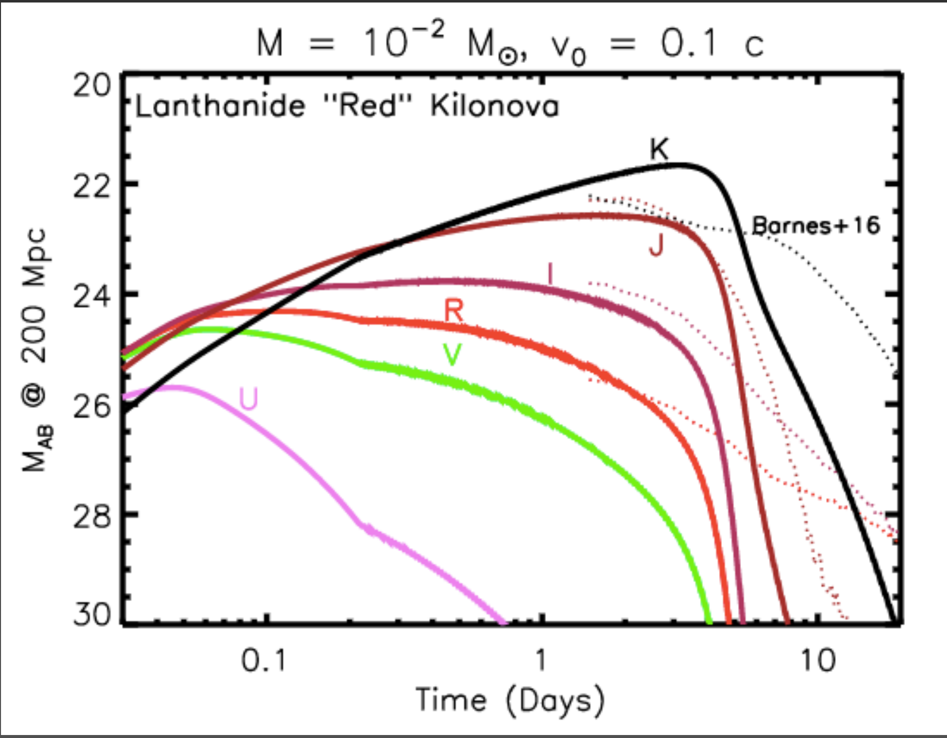

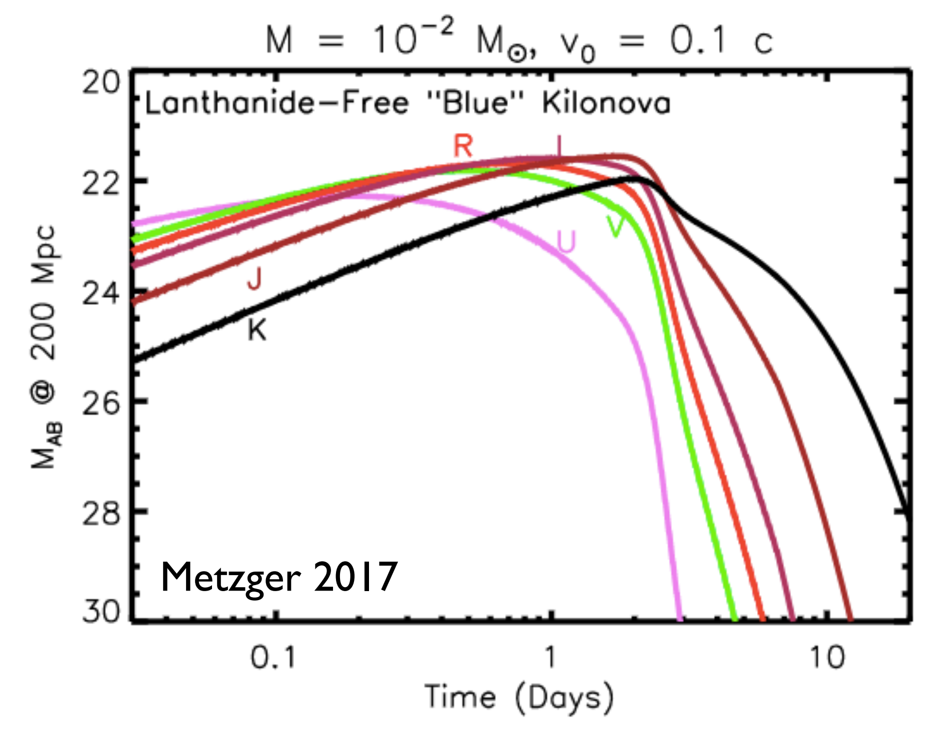

IR-peaked; ~1 week

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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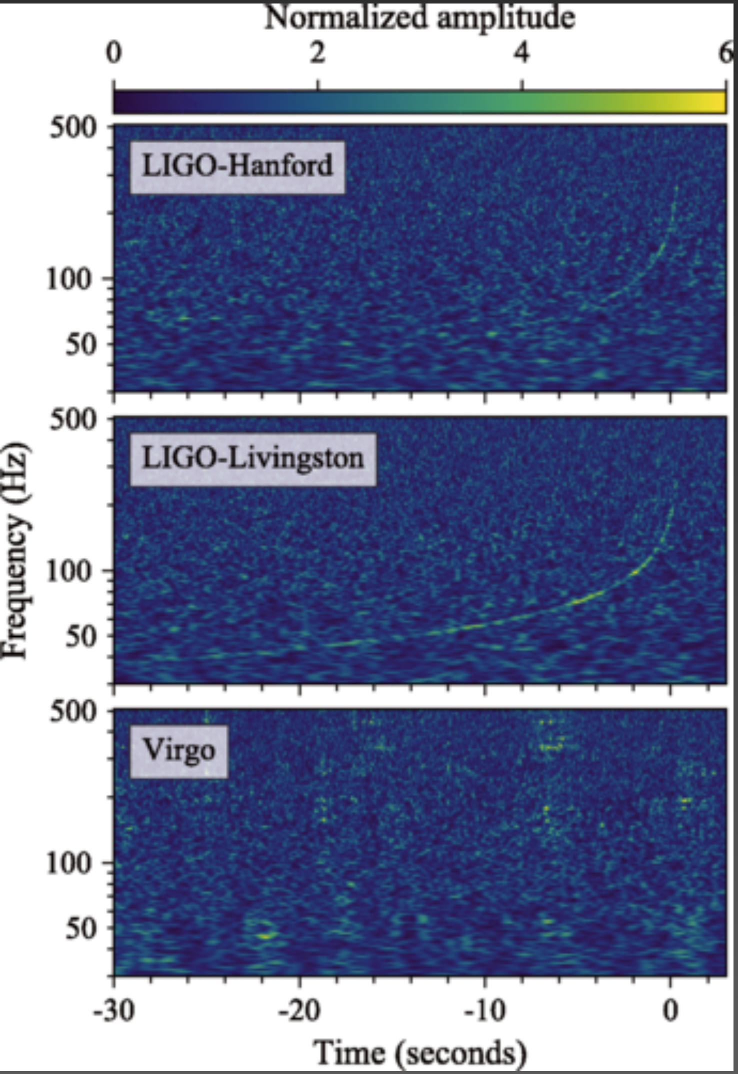
GW170817: The First BNS Merger

Abbott et al. 2017



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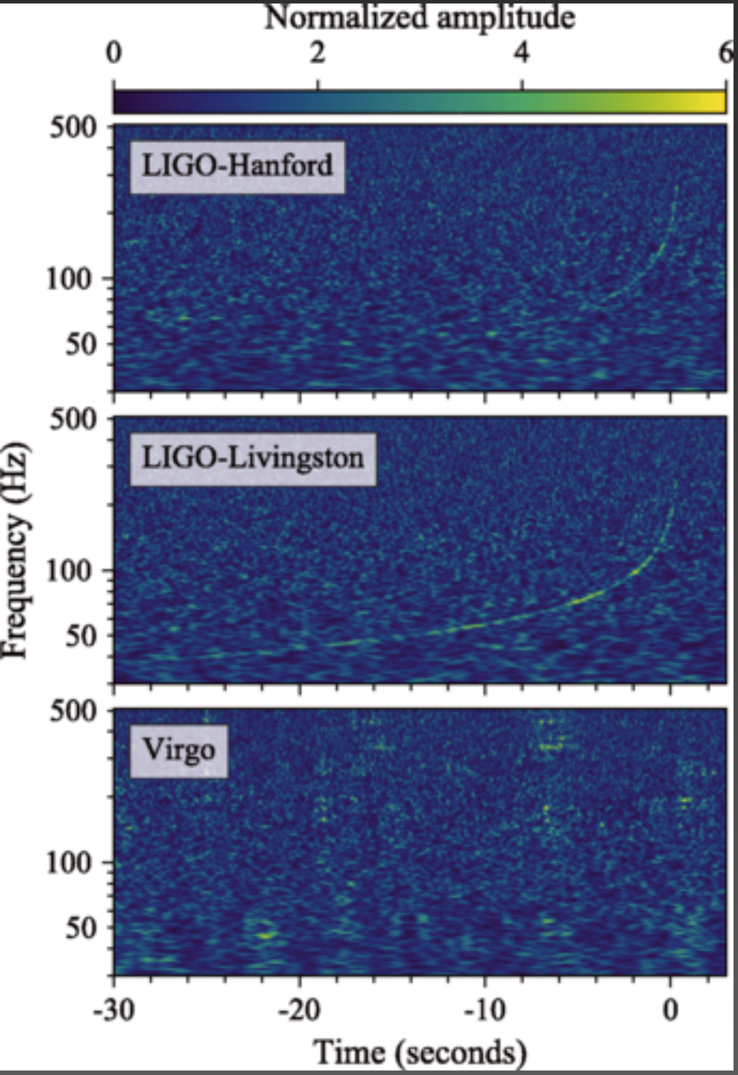

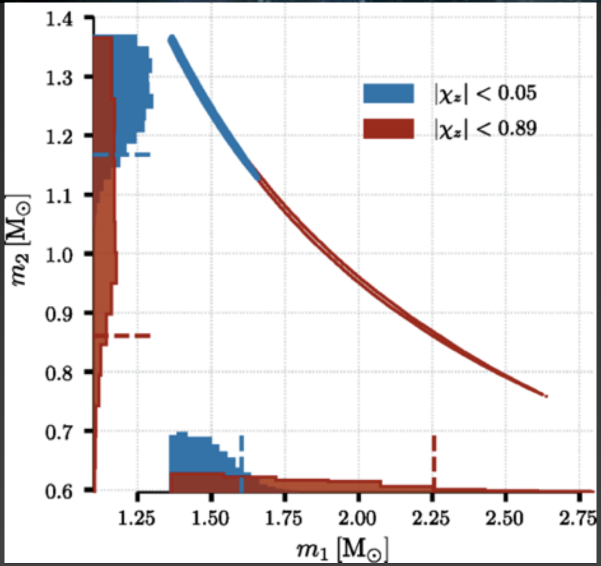

$M_1 \approx 1.4\text{–}1.6\ M_\odot$

$M_2 \approx 1.2\text{–}1.4\ M_\odot$

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

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

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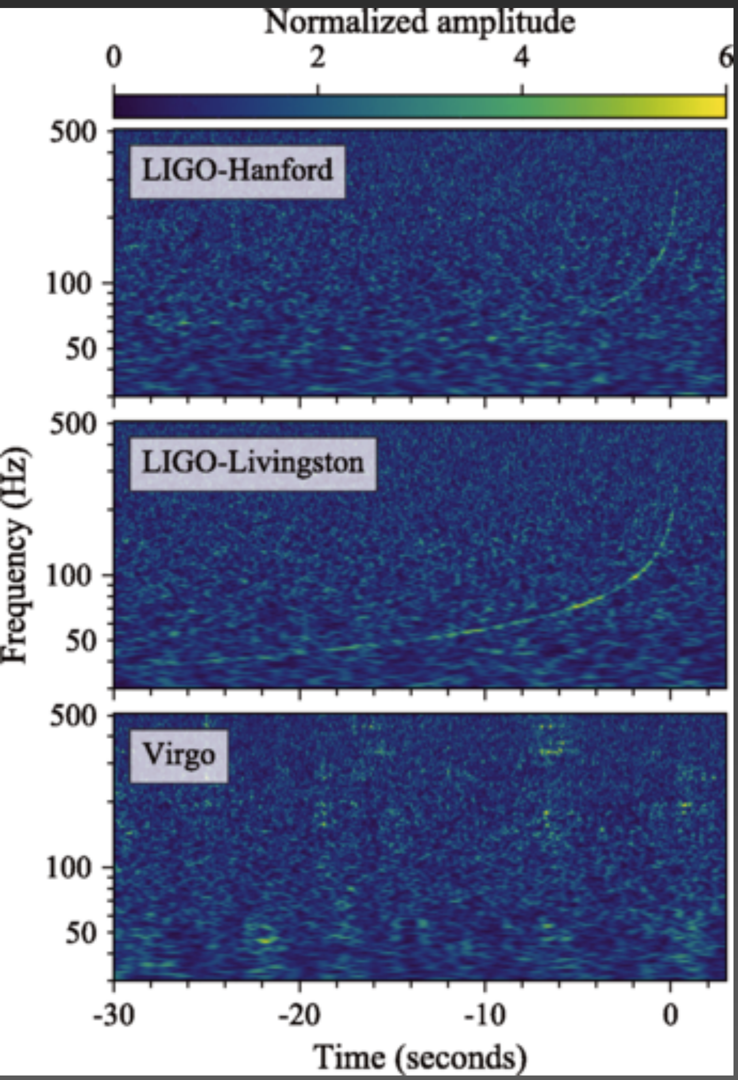

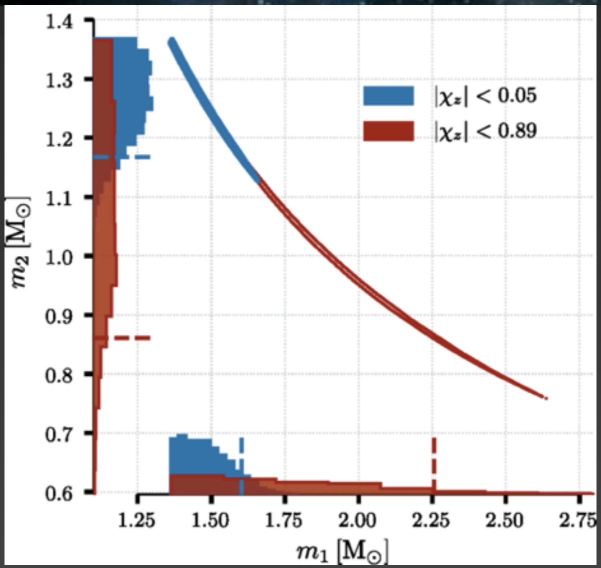

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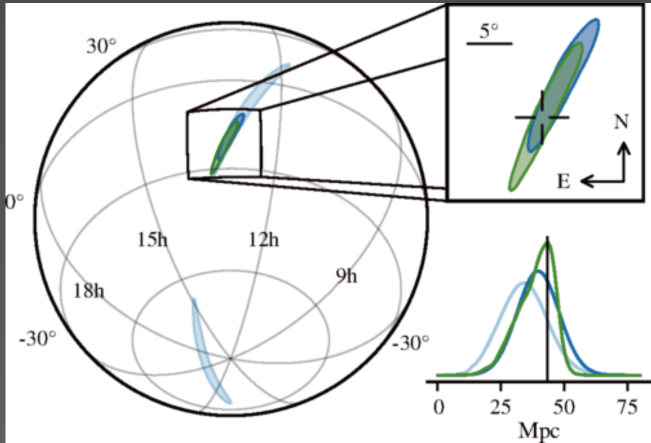
R.A. = 13^h09^m

Dec. = $-25°37'$

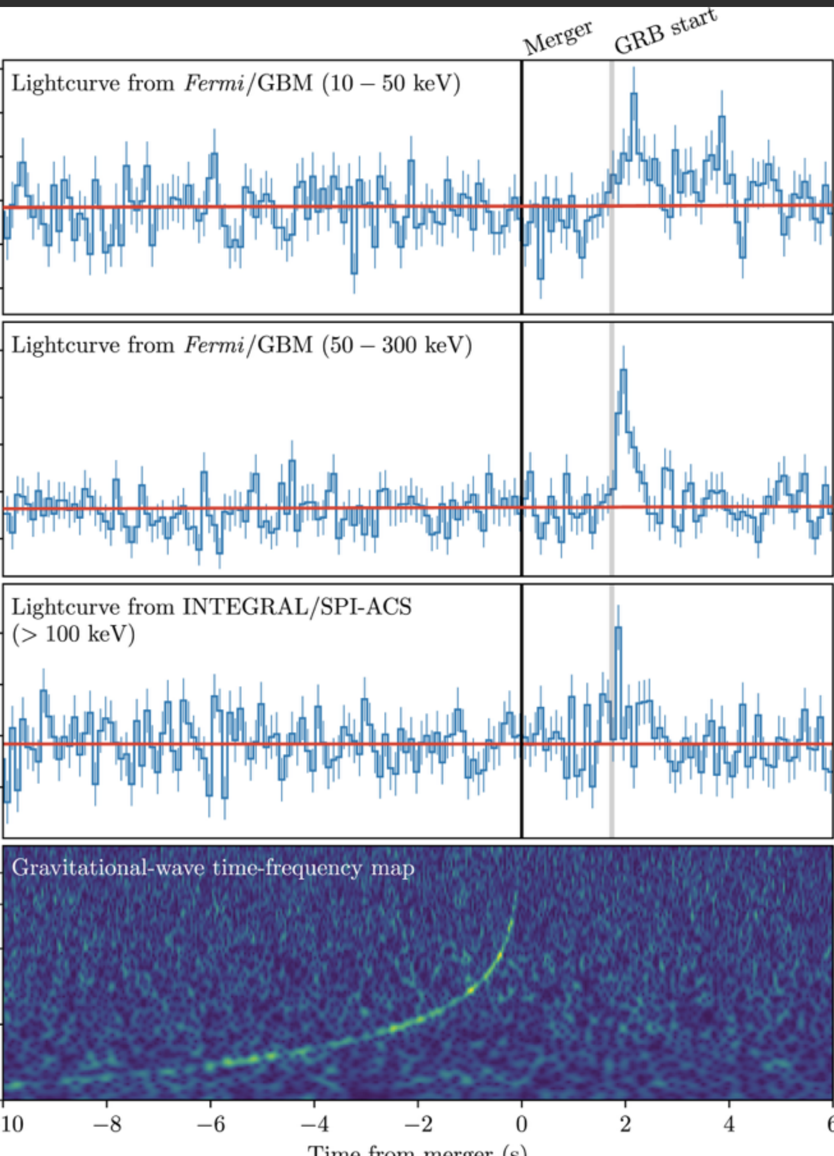
$A \approx 30\ \text{deg}^2$

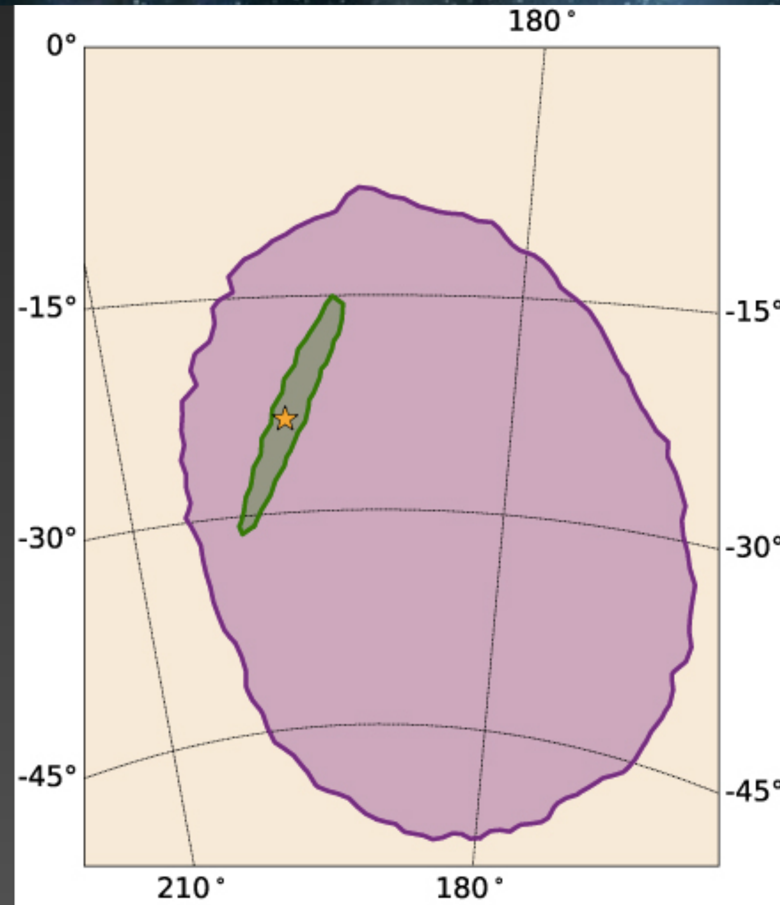
$d \approx 24\text{–}48$ Mpc



GRB170817

Abbott et al. 2017

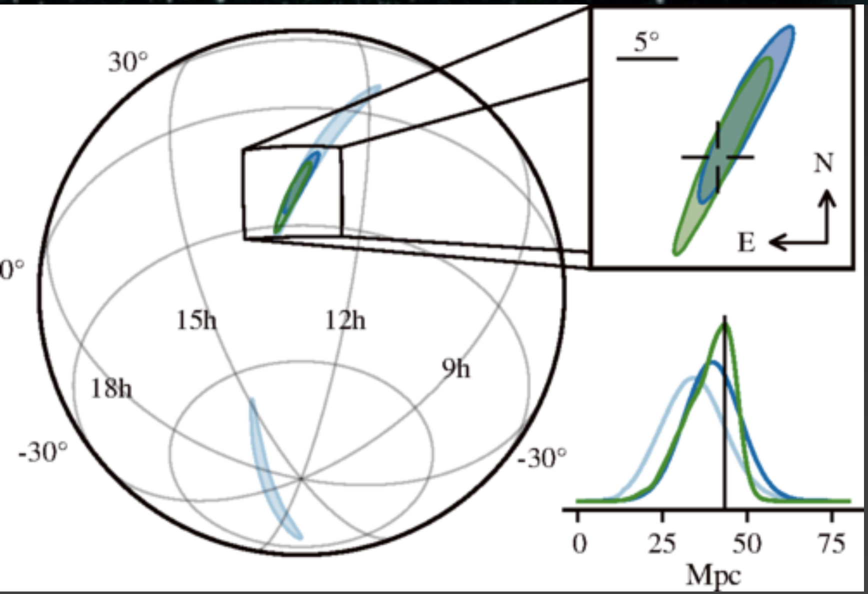




1.7 sec delay between GW and GRB

E_γ is ~10^5 times smaller than in typical short GRBs

DECam Discovery of Optical Counterpart



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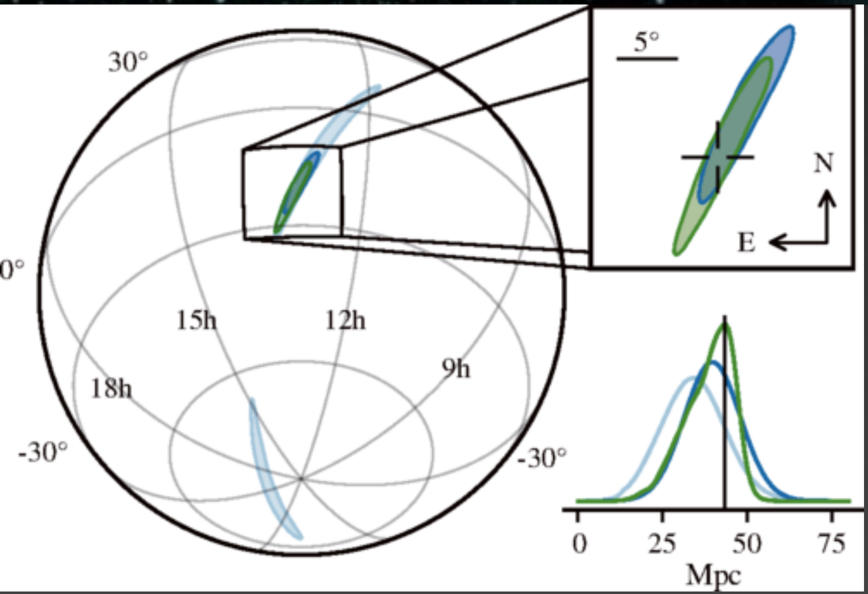

08:41 EDT Merger/GRB

09:21 LIGO Notification

13:54 Initial sky-map

19:13 DECam observations

19:54 Revised sky-map

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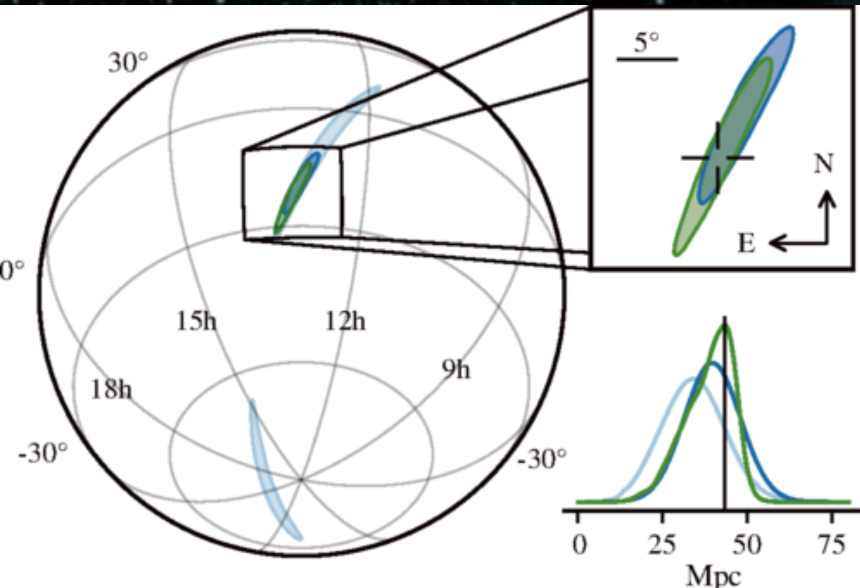
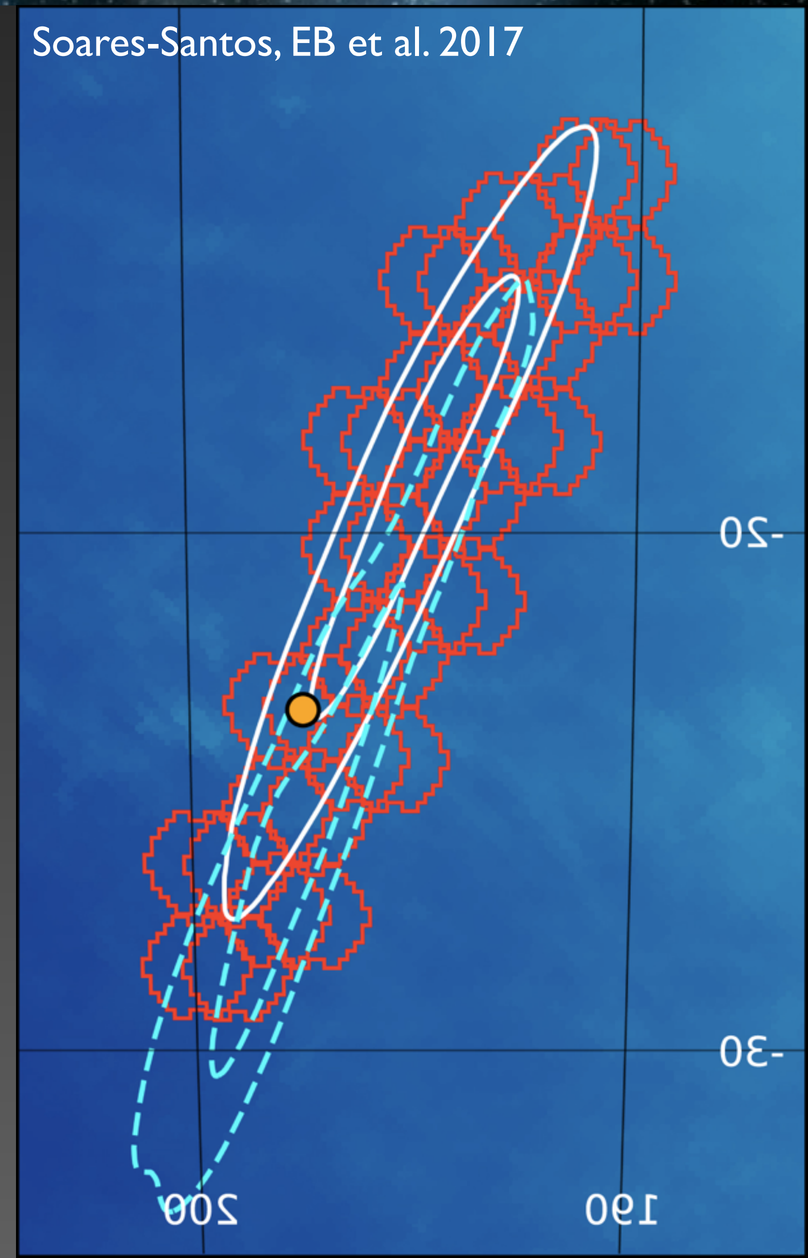




08:41 EDT	Merger/GRB
09:21	LIGO Notification
13:54	Initial sky-map
19:13	DECam observations
19:54	Revised sky-map

93% of initial map (81% of final map)

DECam Discovery of Optical Counterpart

From: **Ryan Chornock** <chornock@ohio.edu>
Date: Thu, Aug 17, 2017 at 8:42 PM
Subject: Re: All Eyes! G298048. Images will be downloadable here
To: Sahar Allam <sallam@fnal.gov>, "Berger, Edo" <eberger@cfa.harvard.edu>, Douglas L Tucker <dtucker@fnal.gov>
Cc: "Philip S. Cowperthwaite" <pcowperthwaite@cfa.harvard.edu>, Dillon Brout <dbrout@physics.upenn.edu>, Marcelle Soares Santos <marcelle@fnal.gov>, Dan Scolnic <dscolnic@kicp.uchicago.edu>, des-gw <des-gw@fnal.gov>

Holy s[redacted]t.

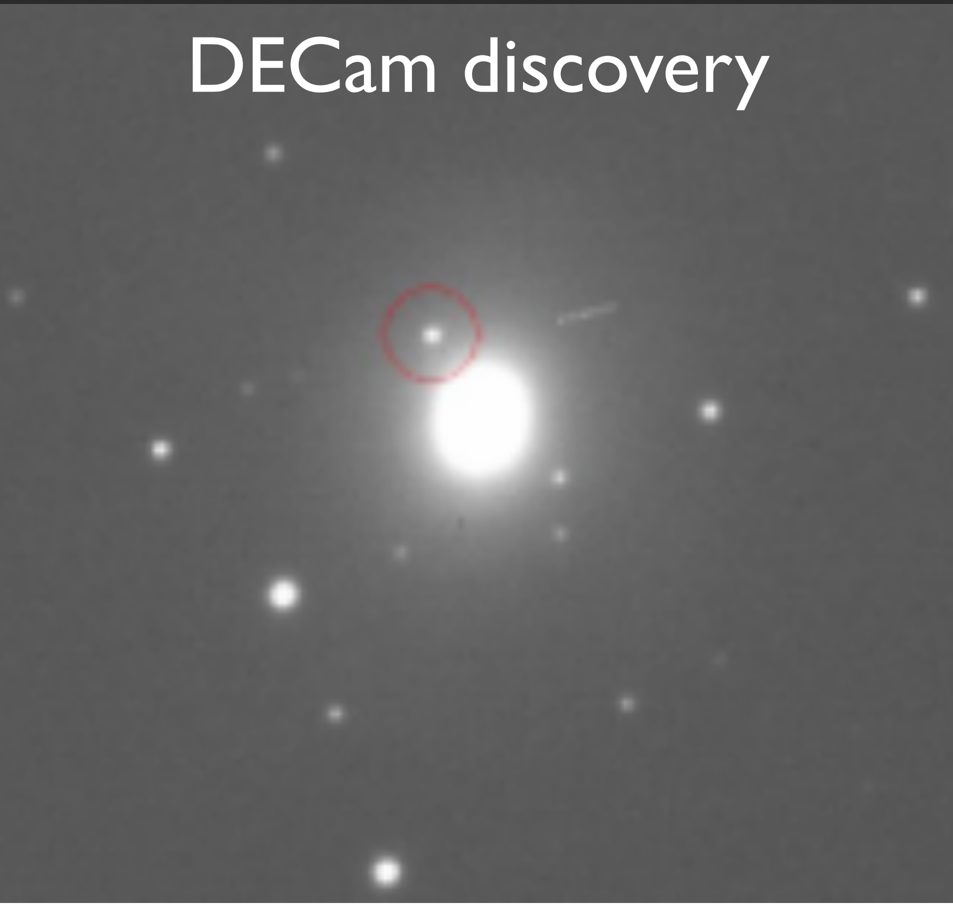
Check out NGC 4993 in DECam_00668440.fits.fz[N5]

Attached is tonight's image + ps1-3pi.

Galaxy is at 40 Mpc.

-R

DECam Discovery of Optical Counterpart



DECam discovery

Archival image

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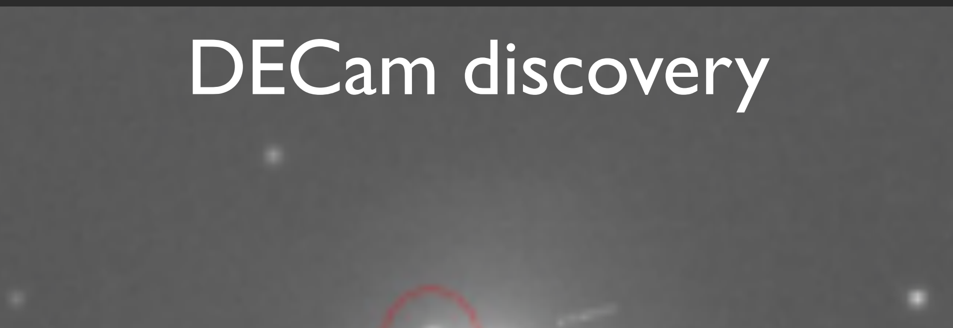
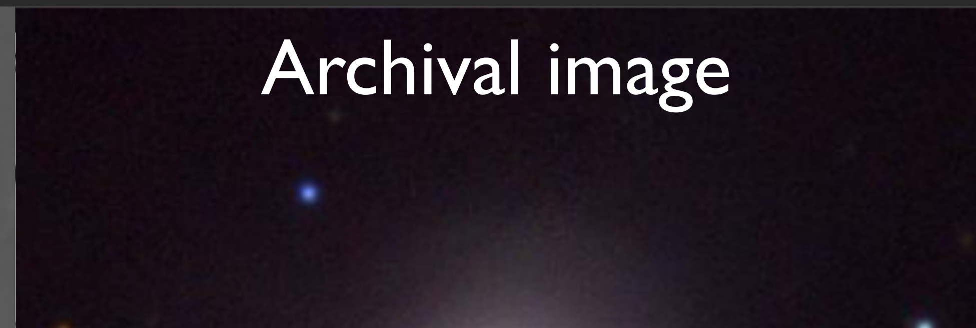
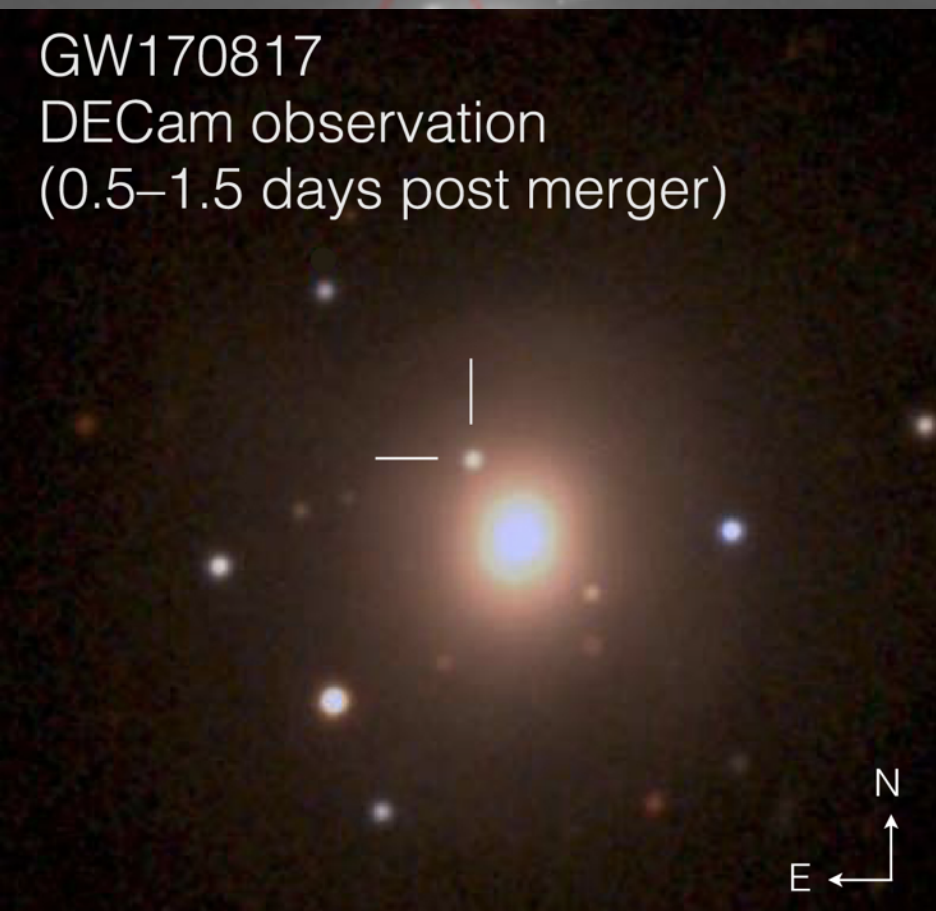
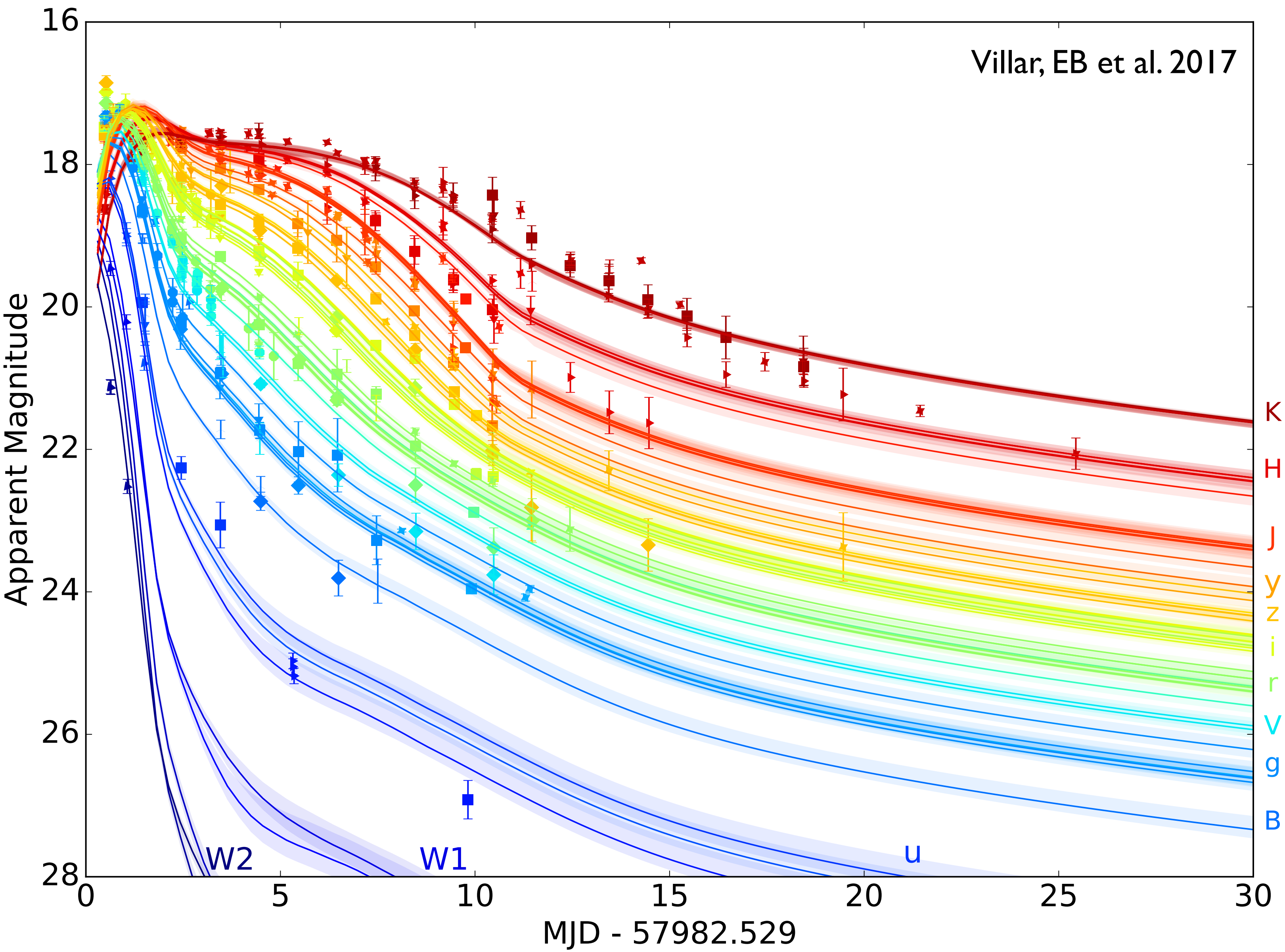






Light Curves & Kilonova Models



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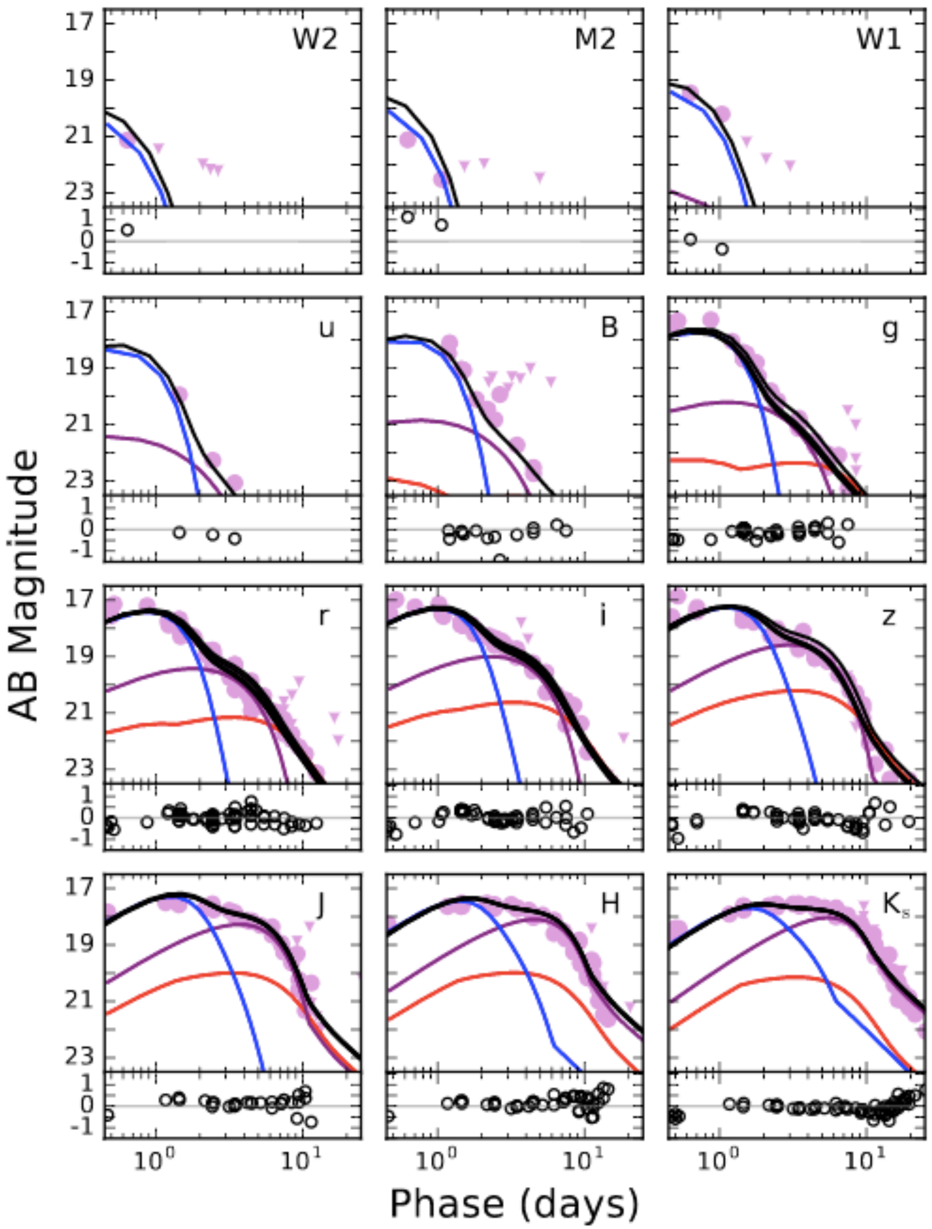

<u>Multi-component model:</u>

Gradient from fast (~0.3c) "blue" (lanthanide-poor) ejecta to slow (~0.1c) "red" (lanthanide-rich) ejecta with ≈0.06 $M_\odot$

Villar, EB et al. 2017

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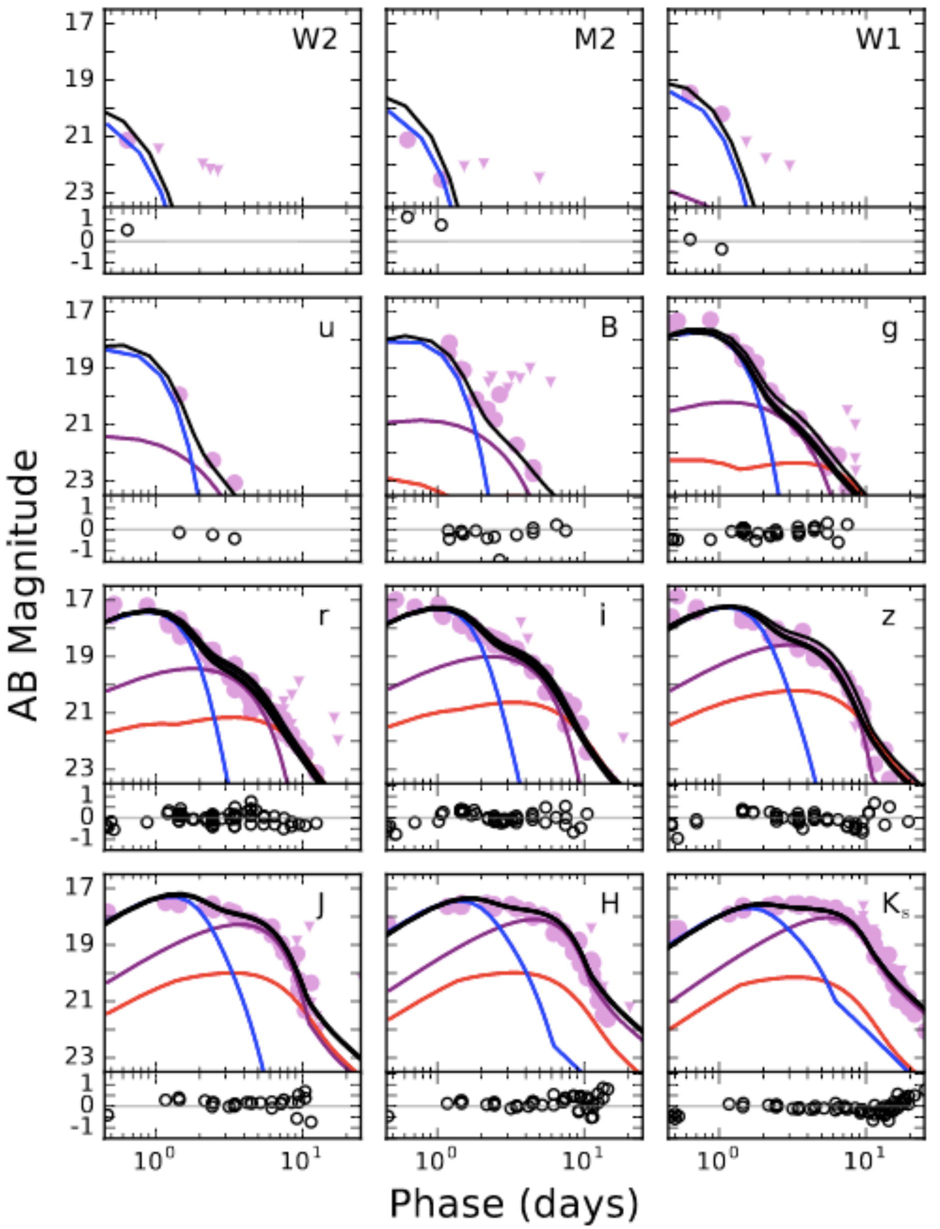

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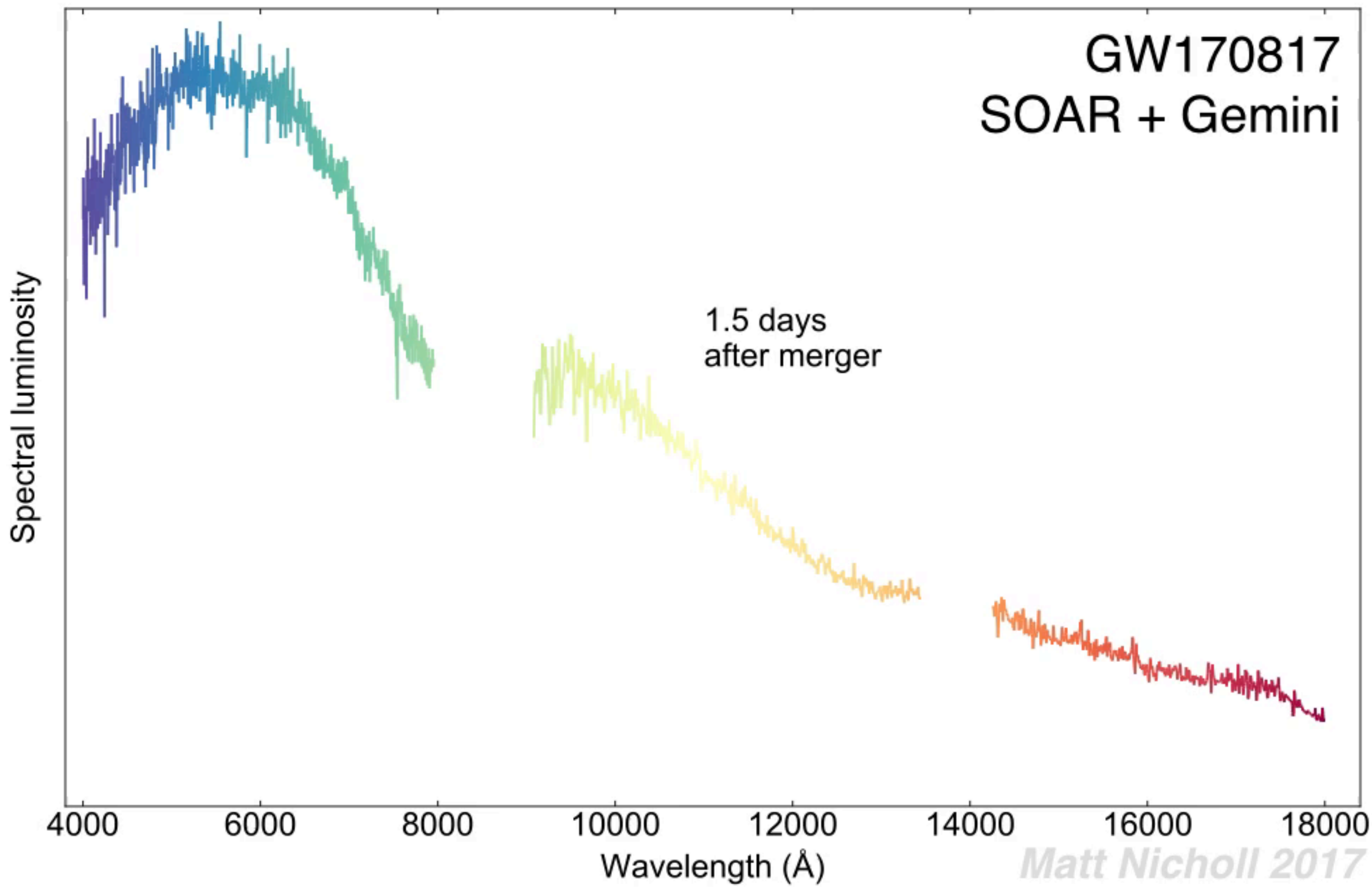
A range of nucleosynthesis and velocity (geometry?) point to distinct origins for the ejecta components

Villar, EB et al. 2017

Optical/Near-IR Spectroscopy



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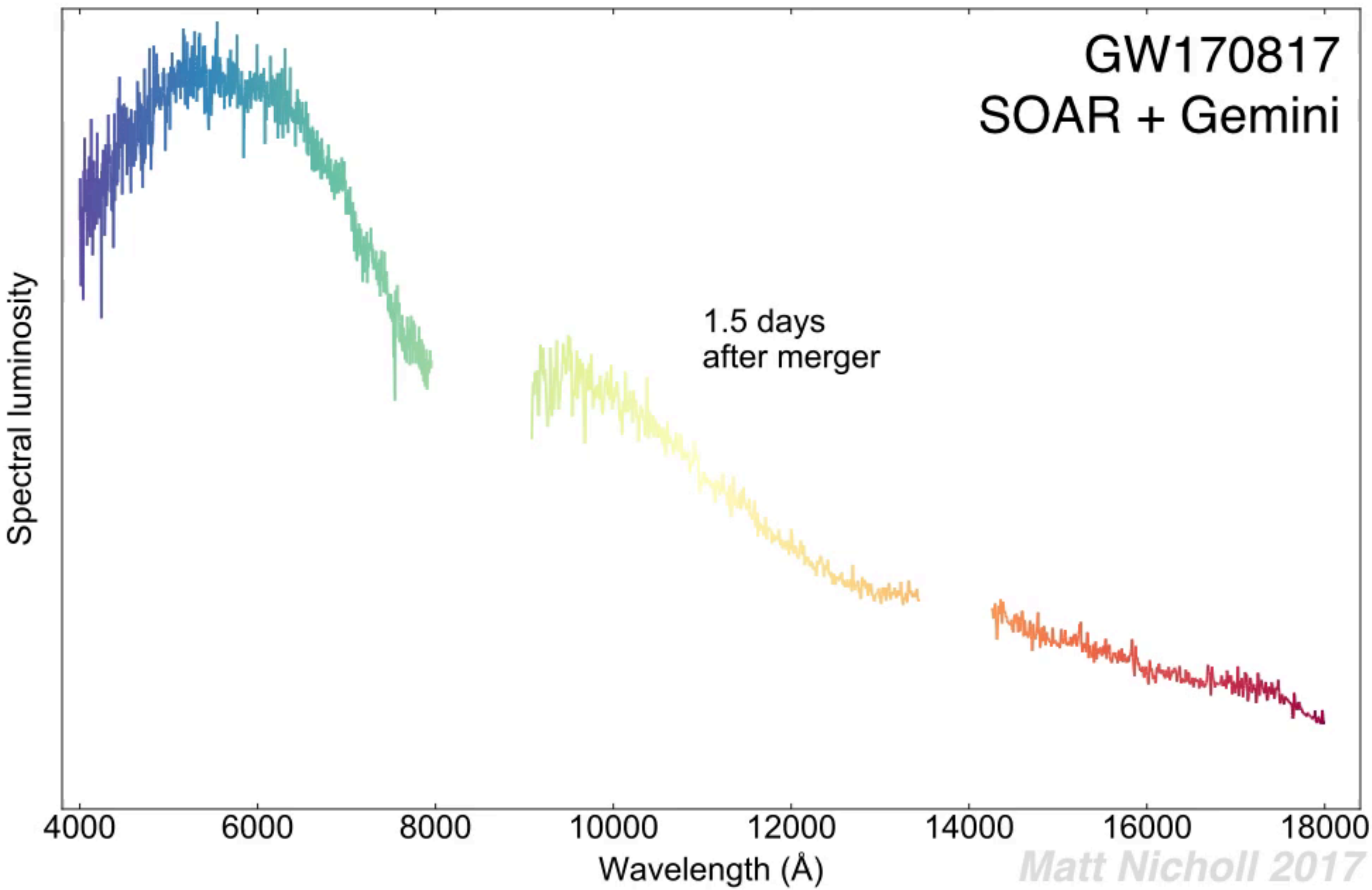

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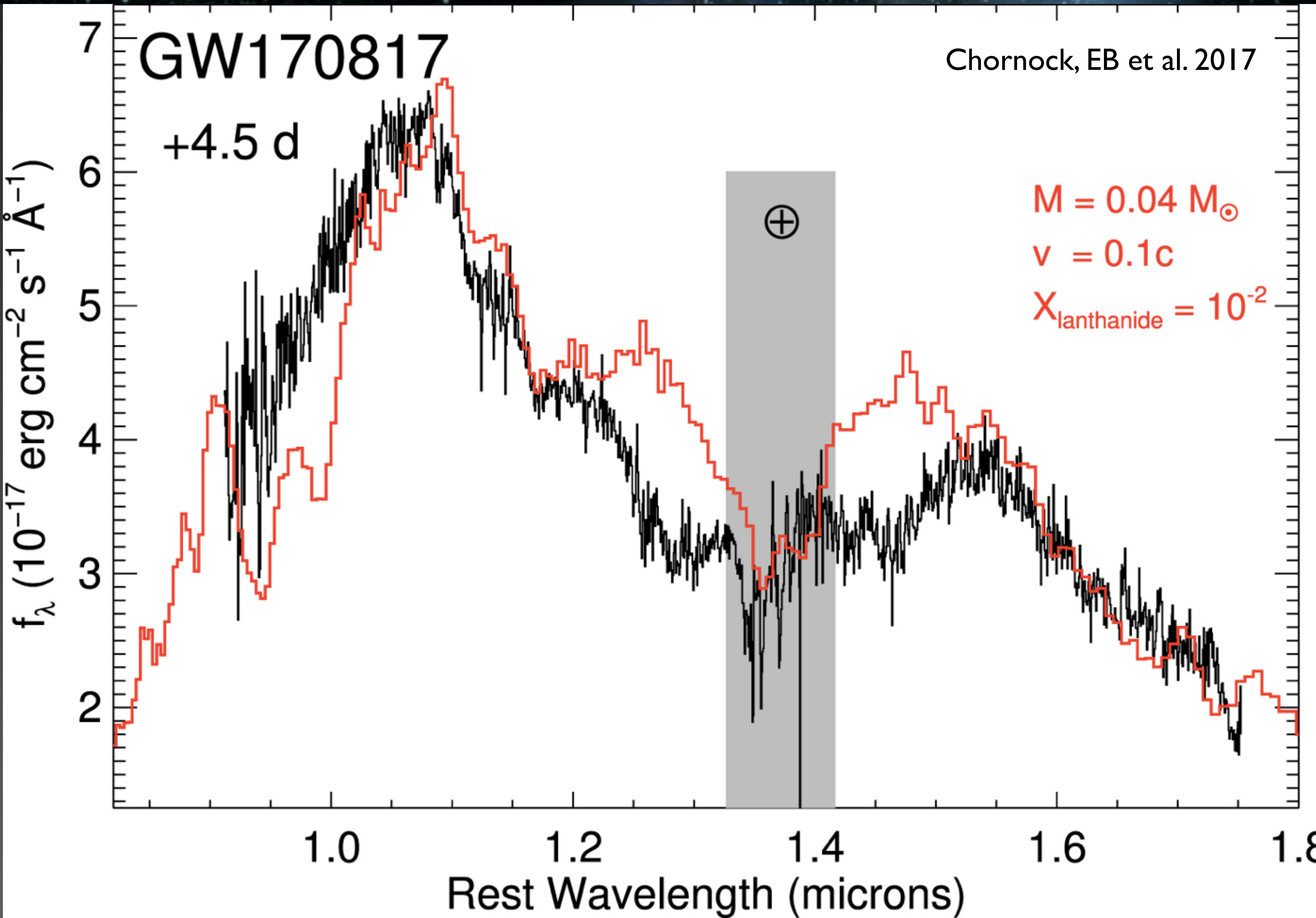

UV/Optical/NIR: Implications

- Direct (spectroscopic) evidence for *r*-process nucleosynthesis
- $M_{ej} \times R_{BNS}$ accounts for Galactic *r*-process production rate
- $M_{ej,\text{lan-rich}} / M_{ej,\text{lan-poor}} \approx 0.15 \approx R_{MW,A>140} / R_{MW,A<140}$

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- Lanthanide-rich ("red") ejecta $v \approx 0.1c \Rightarrow$ accretion disk wind & high lanthanide fraction $\Rightarrow$ NS for $\lesssim 0.1$ sec $\Rightarrow$ BH

The Future

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- LIGO/Virgo Observing Run 3 will span all of 2019.

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- Kagra and IndIGO in ~2022 & ~2025.
- Third generation detectors (US / Europe) in 2030s? Increased sensitivity by an order of magnitude (e.g. all BBH mergers).

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
- Optical/IR data suggest NS-NS → BH
- More observations and interpretation underway
- We expect multiple new detections in 2019 and up to few events per month by mid-2020s


2018
Prof. Dr. Edo Berger
UNIVERSITÄT
BERN
CSH
CENTER FOR SPACE AND
HABITABILITY
CSH Distinguished
Lecturer