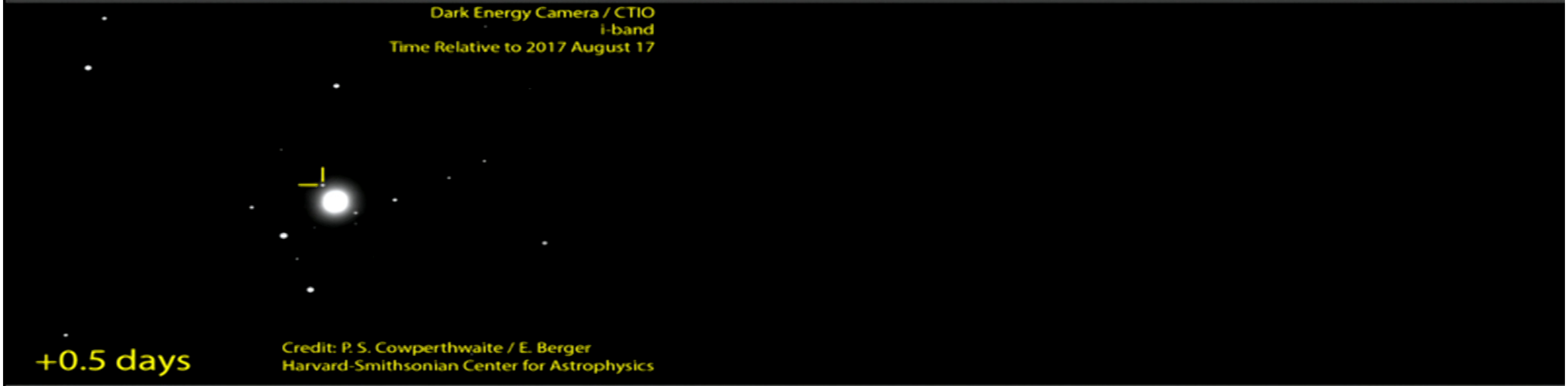
Title: Rattle and Shine: Joint Detection of Gravitational Waves and Light from the Binary Neutron Star Merger GW170817

Date: Nov 06, 2017 02:00 PM

URL: http://pirsa.org/17110067

Abstract: <p>The much-anticipated joint detection of gravitational waves and electromagnetic radiation was achieved for the first time on August 17, 2017, for the binary neutron star merger GW170817.  This event was detected by Advanced LIGO/Virgo, gamma-ray satellites, and dozens of telescopes on the ground and in space spanning from radio to X-rays.  In this talk I will describe the exciting discovery of the optical counterpart, which in turn led to several detailed studies across the electromagnetic spectrum.  The results of the observations carried out by our team include the first detailed study of a "kilonova", an optical/infrared counterpart powered by the radioactive decay of r-process nuclei synthesized in the merger, as well as the detection of an off-axis jet powering radio and X-ray emission.  These results provide the first direct evidence that neutron star mergers are the dominant site for the r-process and are the progenitors of short GRBs.  I will also describe how studies of the host galaxy shed light on the merger timescale, and describe initial constraints on the Hubble Constant from the combined GW and EM detection.        </p>

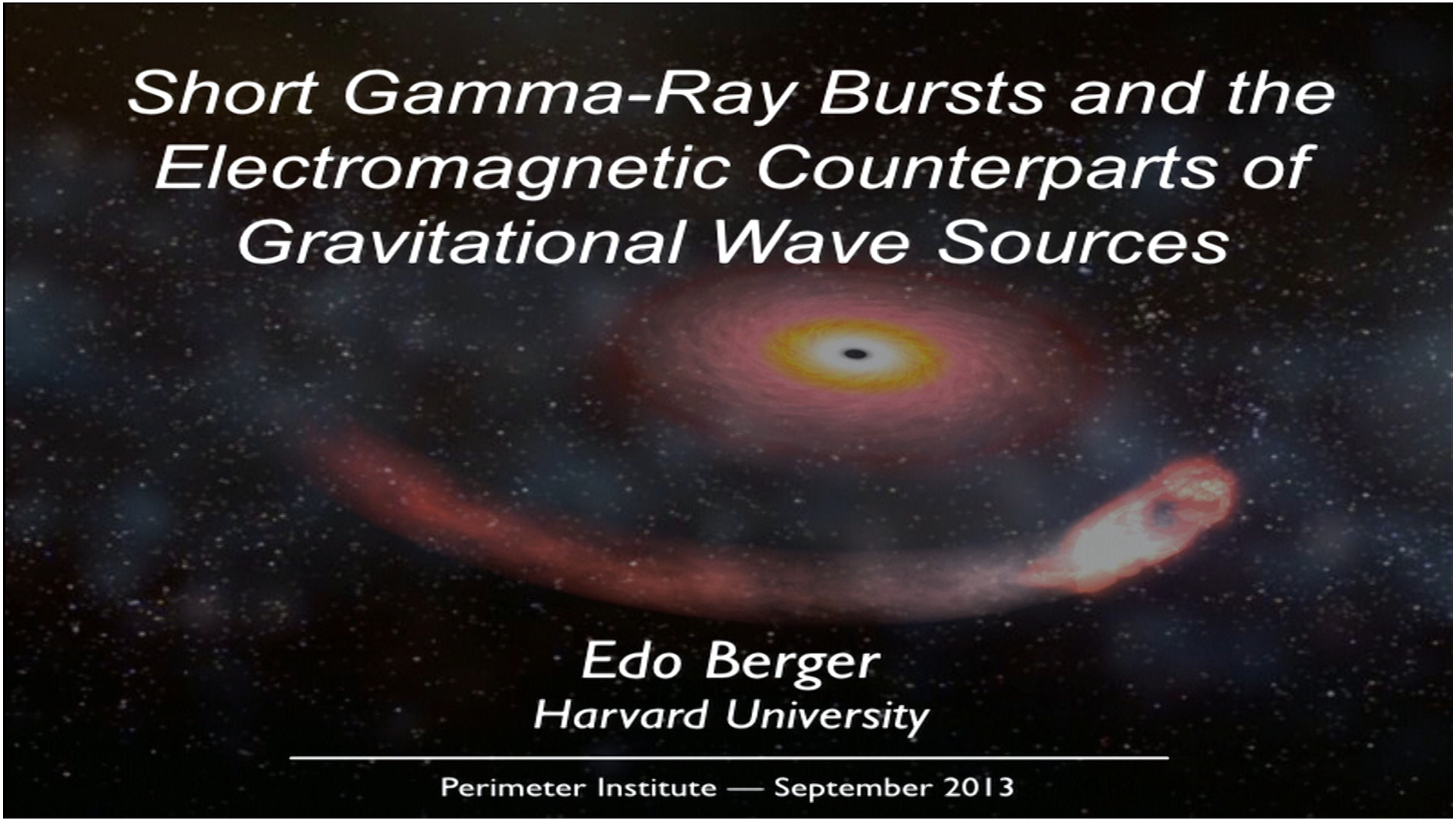
# Rattle and Shine: The Joint Detection of Gravitational Waves and Light form the Binary Neutron Star Merger GW170817



Credit: P. S. Cowperthwaite / E. Berger
Harvard-Smithsonian Center for Astrophysics

**Edo Berger** *(Harvard University)*

K. Alexander, P. Blanchard, R. Chornock, P. Cowperthwaite, T. Eftekhari, W. Fong, D. Kasen,
R. Margutti, B. Metzger, M. Nicholl, M. Soares-Santos, P. Williams, +DES

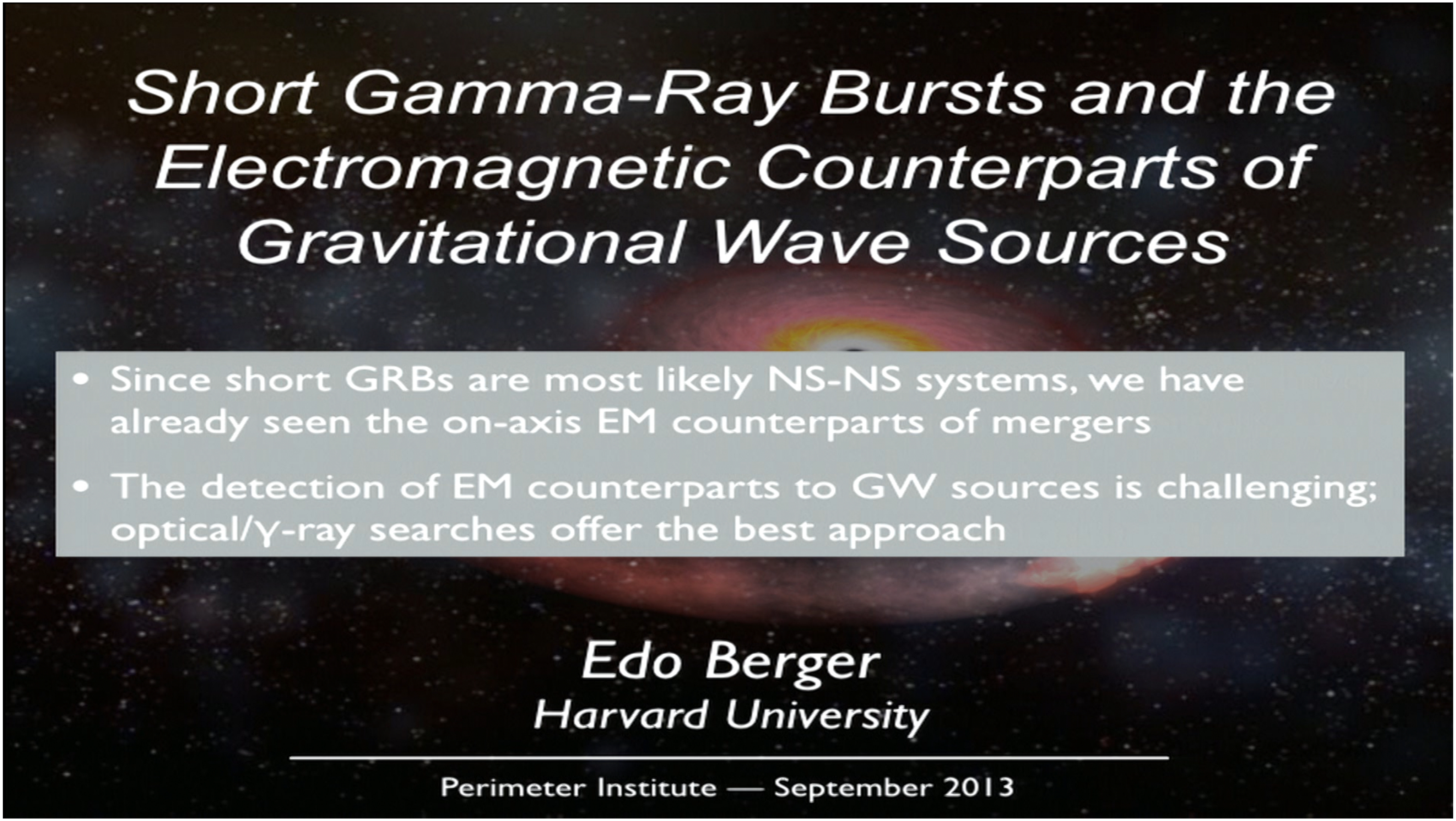


# Short Gamma-Ray Bursts and the Electromagnetic Counterparts of Gravitational Wave Sources

**Edo Berger**

*Harvard University*

Perimeter Institute — September 2013



# Short Gamma-Ray Bursts and the Electromagnetic Counterparts of Gravitational Wave Sources

- Since short GRBs are most likely NS-NS systems, we have already seen the on-axis EM counterparts of mergers
- The detection of EM counterparts to GW sources is challenging; optical/γ-ray searches offer the best approach

*Edo Berger*

*Harvard University*

Perimeter Institute — September 2013

# The Key Players


Ashley Villar


Kate Alexander


Phil Cowperthwaite


Peter Blanchard


Tarraneh Eftekhari

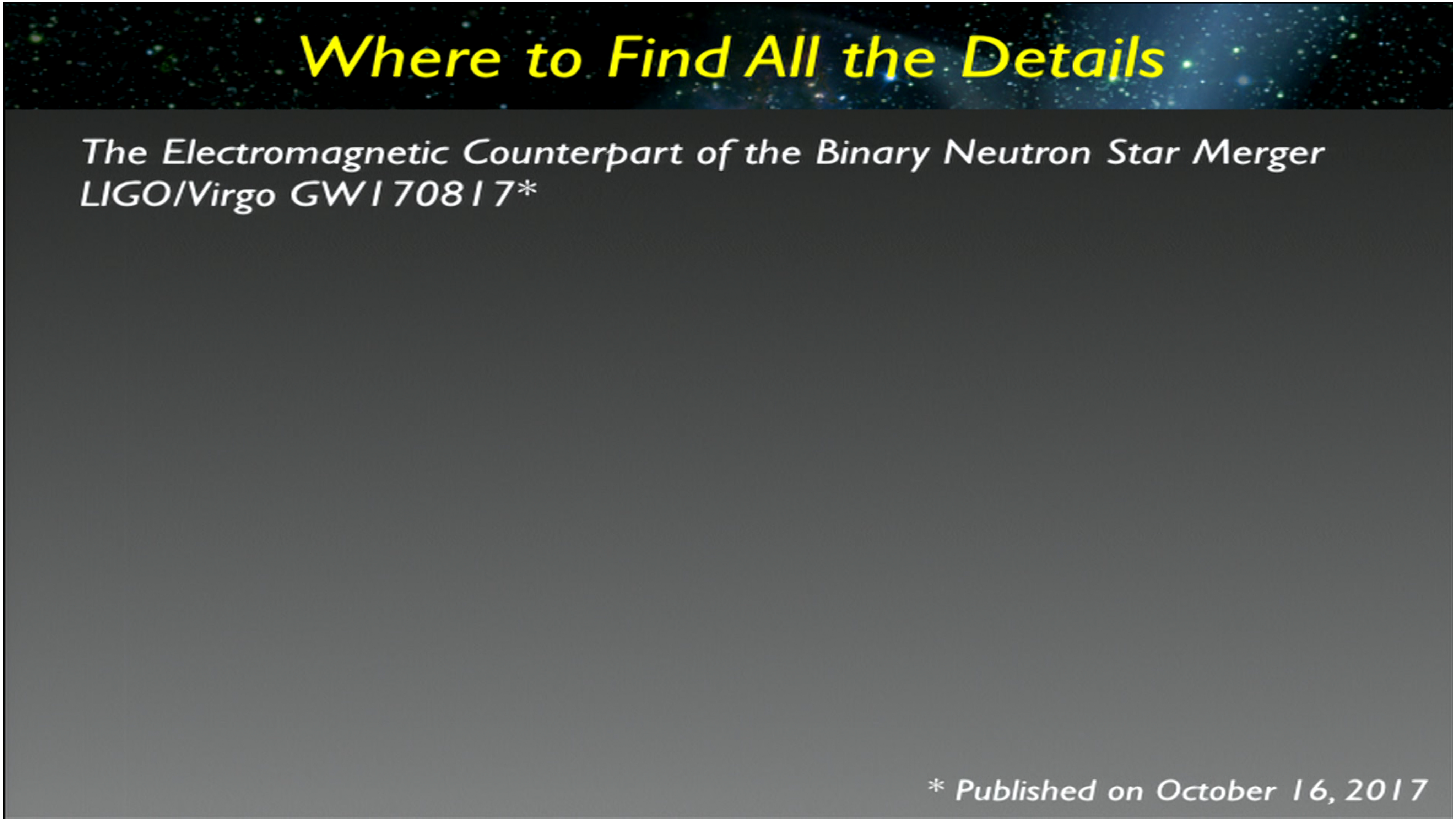
Matt Nicholl


Peter Williams


Wen-fai Fong
(Northwestern)


Raffaella Margutti
(Northwestern)

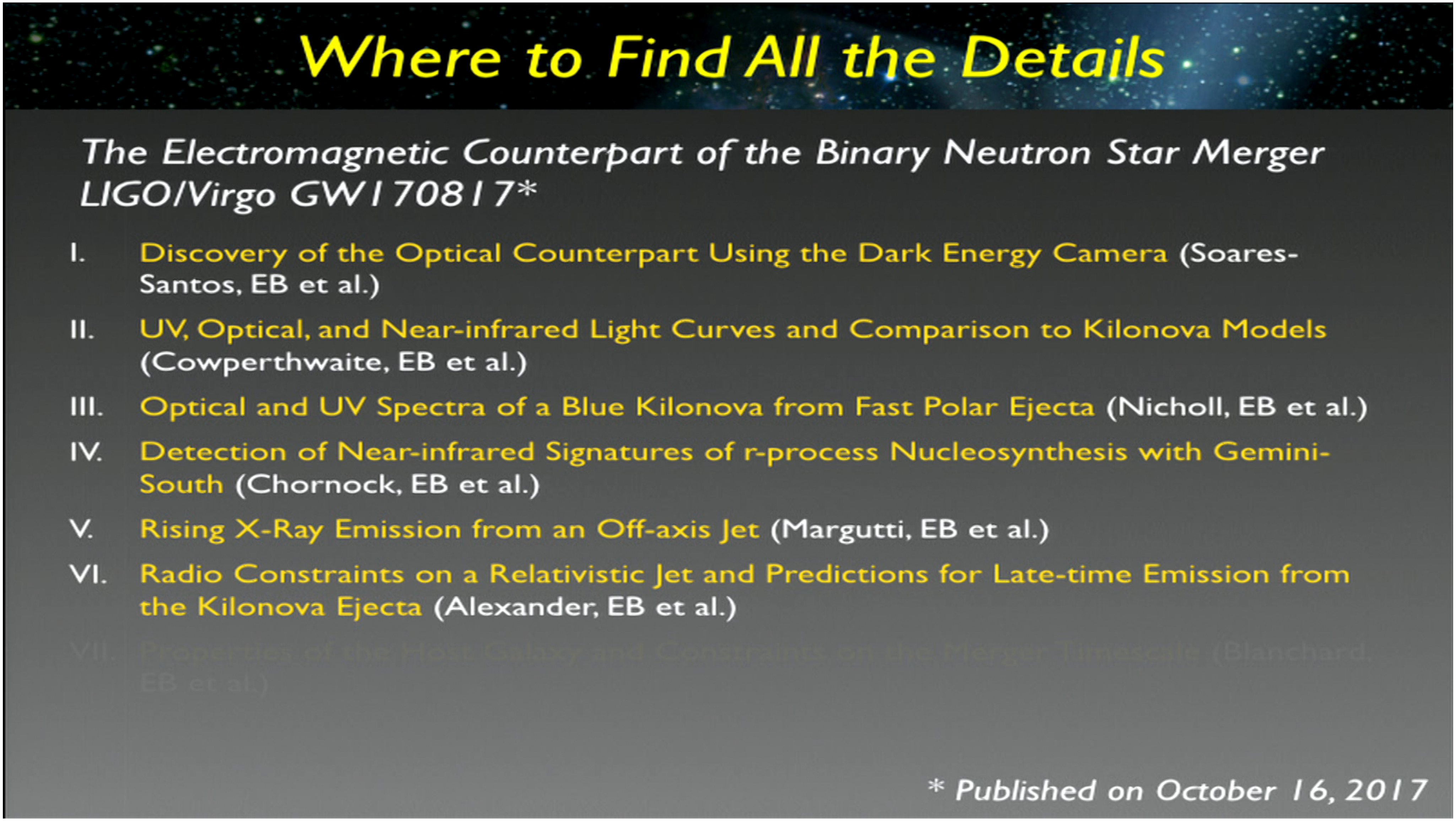

Ryan Chornock
(Ohio University)

# Where to Find All the Details

*The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817**

** Published on October 16, 2017*



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*The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817**

I. Discovery of the Optical Counterpart Using the Dark Energy Camera (Soares-Santos, EB et al.)

II. UV, Optical, and Near-infrared Light Curves and Comparison to Kilonova Models (Cowperthwaite, EB et al.)

III. Optical and UV Spectra of a Blue Kilonova from Fast Polar Ejecta (Nicholl, EB et al.)

IV. Detection of Near-infrared Signatures of r-process Nucleosynthesis with Gemini-South (Chornock, EB et al.)

V. Rising X-Ray Emission from an Off-axis Jet (Margutti, EB et al.)

VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejecta (Alexander, EB et al.)

VII. Properties of the Host Galaxy and Constraints on the Merger Timescale (Blanchard, EB et al.)

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VIII. A Comparison to Cosmological Short-duration Gamma-Ray Bursts (Fong, EB et al.)

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# Where to Find All the Details

- How Many Kilonovae Can Be Found in Past, Present, and Future Survey Datasets? (Scolnic, EB et al.)
- Multi-messenger Observations of a Binary Neutron Star Merger (Abbott et al. + EB)
- A gravitational-wave standard siren measurement of the Hubble constant (Abbott et al. + EB)

- Improved constraints on $H_0$ from a combined analysis of gravitational-wave and electromagnetic emission from GW170817 (Guidorzi et al.)
- The Complete Ultraviolet, Optical, and Near-Infrared Light Curves of the Kilonova Associated with the Binary Neutron Star Merger GW170817: Homogenized Data Set, Analytic Models, and Physical Implications (Villar et al.)

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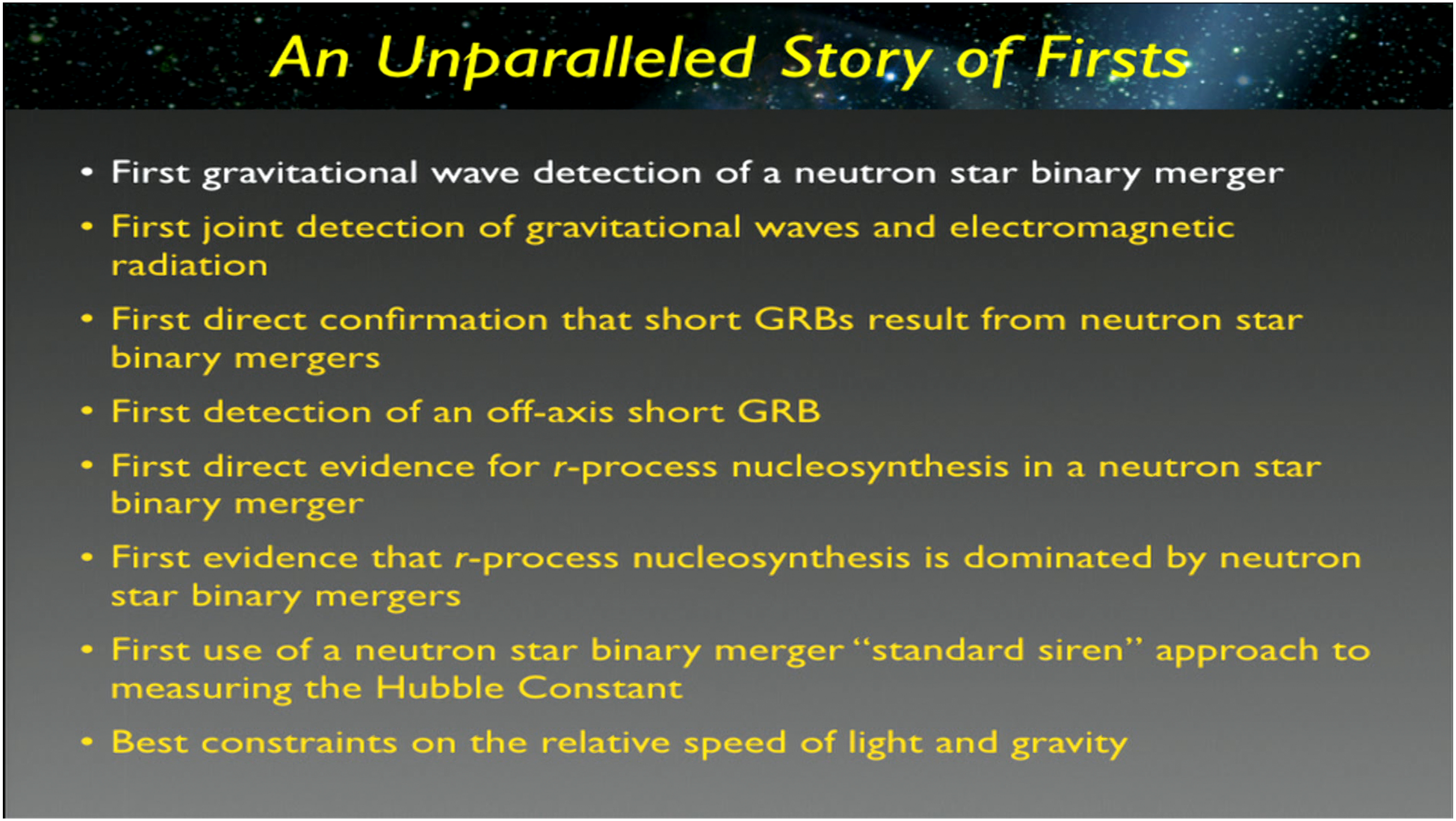
`http://kilonova.org`

Papers, popular level and technical materials, data

# An Unparalleled Story of Firsts

- First gravitational wave detection of a neutron star binary merger
- First joint detection of gravitational waves and electromagnetic radiation
- First direct confirmation that short GRBs result from neutron star binary mergers



# An Unparalleled Story of Firsts

- First gravitational wave detection of a neutron star binary merger
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- First direct confirmation that short GRBs result from neutron star binary mergers
- First detection of an off-axis short GRB
- First direct evidence for *r*-process nucleosynthesis in a neutron star binary merger
- First evidence that *r*-process nucleosynthesis is dominated by neutron star binary mergers
- First use of a neutron star binary merger "standard siren" approach to measuring the Hubble Constant
- Best constraints on the relative speed of light and gravity

# Outline

- What can we learn from EM counterparts?
- What can we learn about EM counterparts from short GRBs?
- What kinds of EM counterparts do we expect?
- GW170817 from radio to gamma-rays
  - *Discovery of the optical counterpart*
  - *UV/optical/IR light curves: multiple ejecta components + origins*
  - *Optical/IR spectroscopy: r-process nucleosynthesis*
  - *Radio / X-ray detections: off-axis jet + connection to short GRBs*
  - *Host galaxy properties: merger timescale*
  - *Hubble constant constraints*
- Future directions

# Electromagnetic Counterparts: Why & What

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

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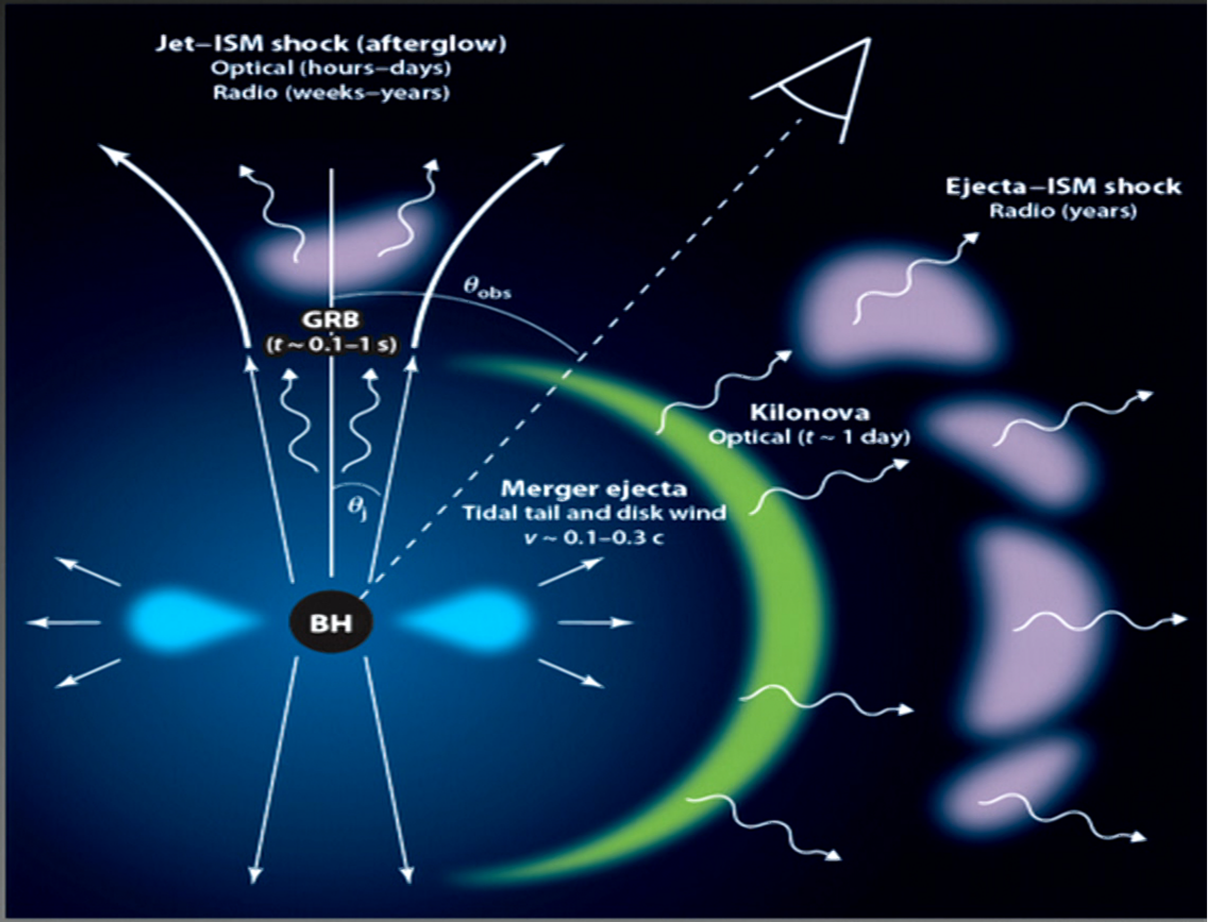
Predicted EM emission beamed and isotropic, relativistic and non-relativistic, multi-$\lambda$.

(*short GRB, kilonova, ejecta/ISM interaction, speculative components*)



Metzger & EB 2012

# Short GRBs as BNS Merger Counterparts

- No SNe / elliptical hosts $\Longrightarrow$ old progenitor population
- Host galaxy demographics $\Longrightarrow$ broad delay-time distribution ($P \propto \tau^{-1}$; consistent with Galactic BNS)
- Spatial offset distribution $\Longrightarrow$ natal kicks of $\sim 10-10^2$ km/s
- Afterglows $\Longrightarrow$ $E_K \sim$ few $\times 10^{49}$ erg, $n \sim 0.01$ cm$^{-3}$, $\theta_{jet} \sim 10°$

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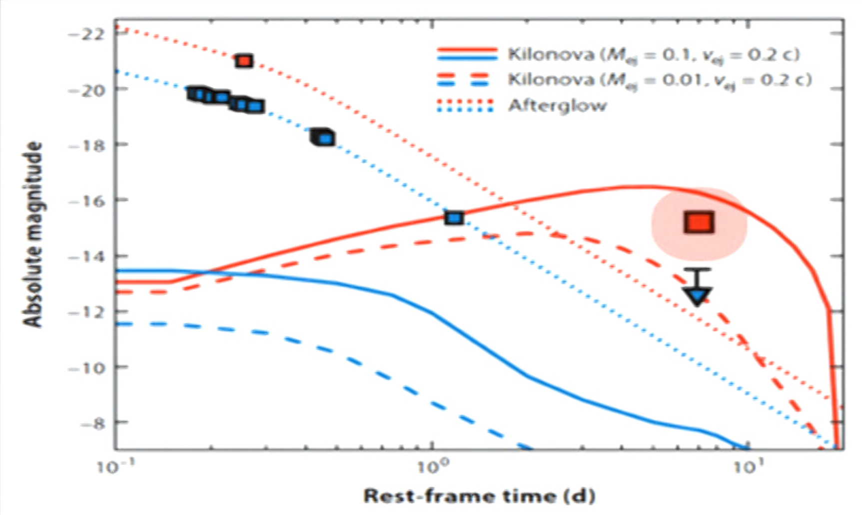
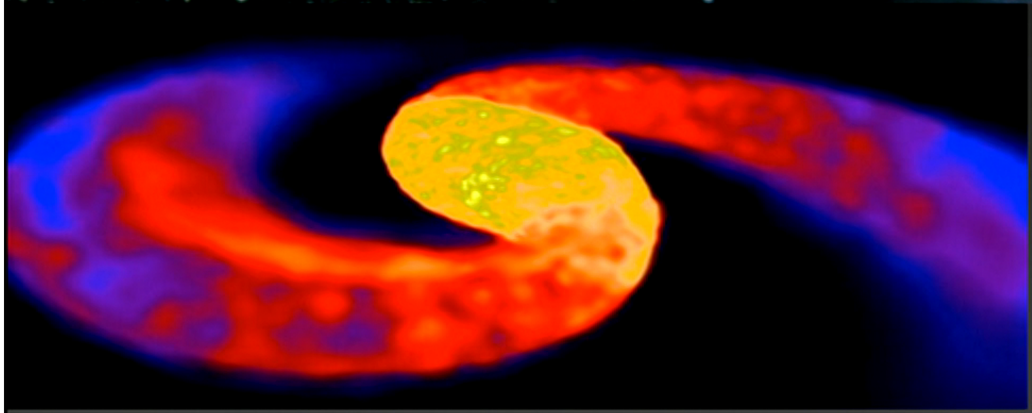
- Afterglows ⟹ $E_K \sim$ few $\times 10^{49}$ erg, $n \sim 0.01$ cm$^{-3}$, $\theta_{jet} \sim 10°$
- GRB130603B ⟹ signature of *r*-process nucleosynthesis?



EB et al. 2013; Tanvir et al. 2013

# r-Process Nucleosynthesis: "Kilonova"



- Tidal tails
- Shocked interface
- Accretion disk outflows

Li & Paczynski 1998; Metzger et al. 2008; Rosswog et al. 2012; Kasen et al. 2013

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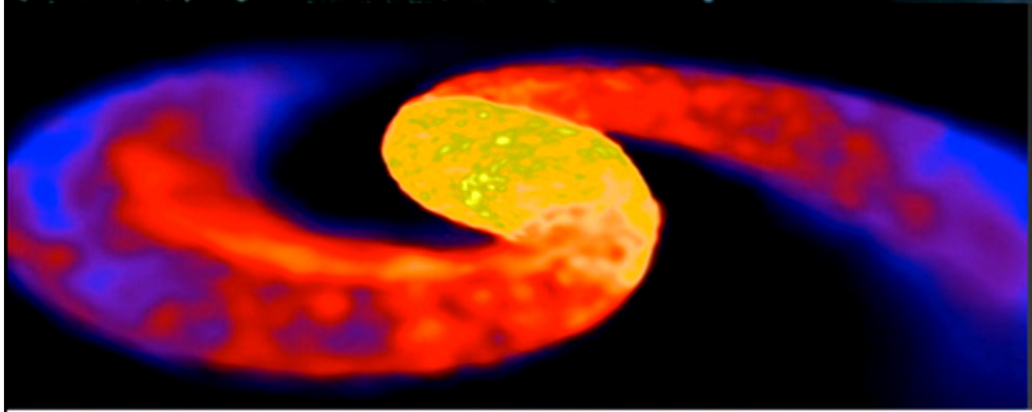

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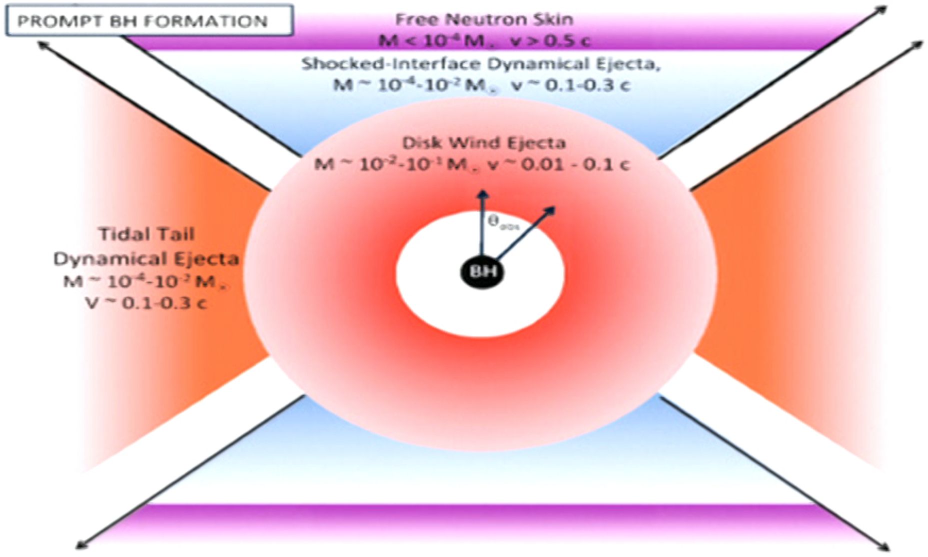
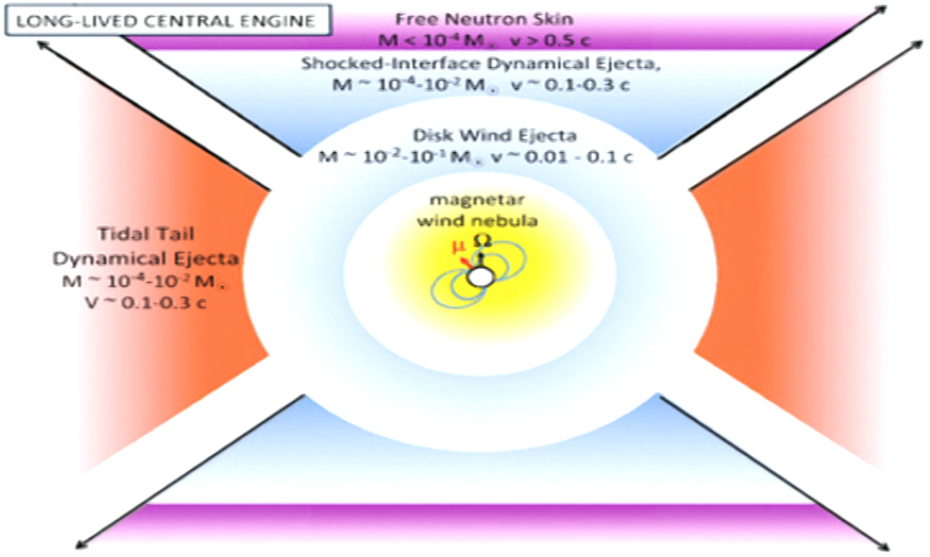
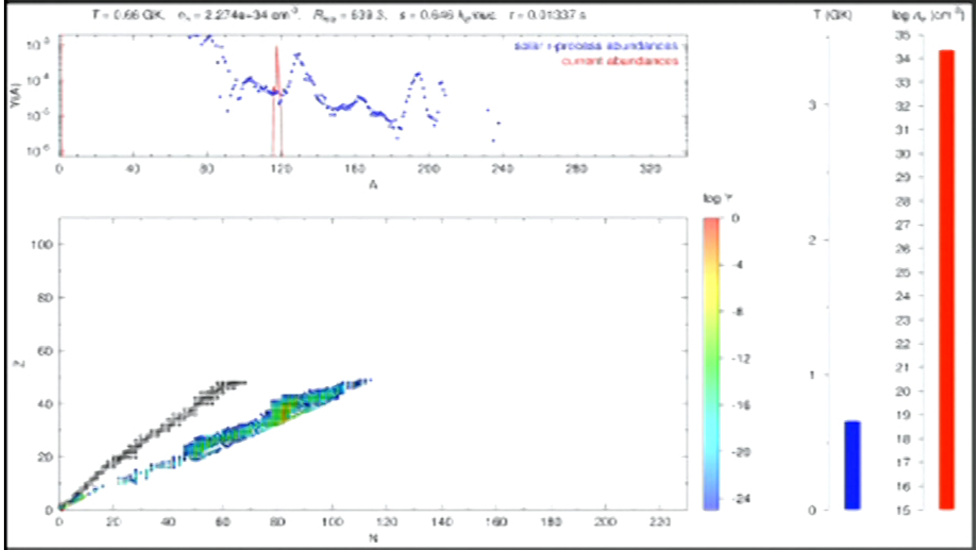
Metzger 2017





# *r*-Process Nucleosynthesis: "Kilonova"

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



Gabriel Martinez Pindeo

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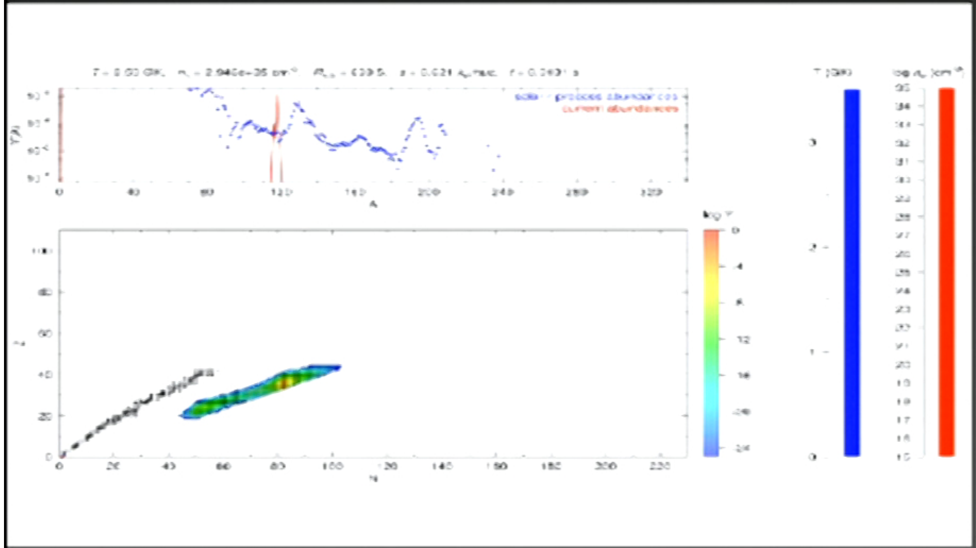
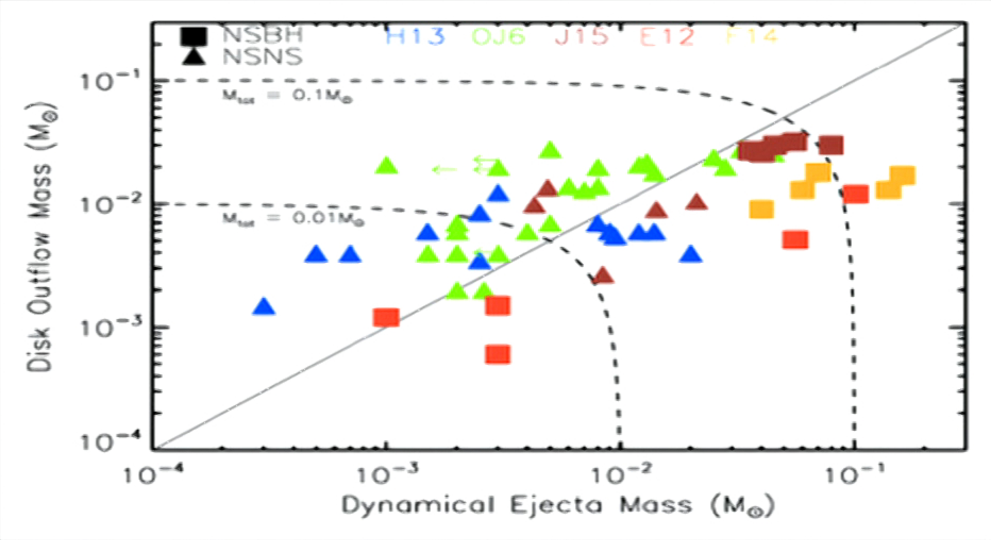
Ejecta mass: $\sim 10^{-3} - 0.1\ M_\odot$

Metzger 2017





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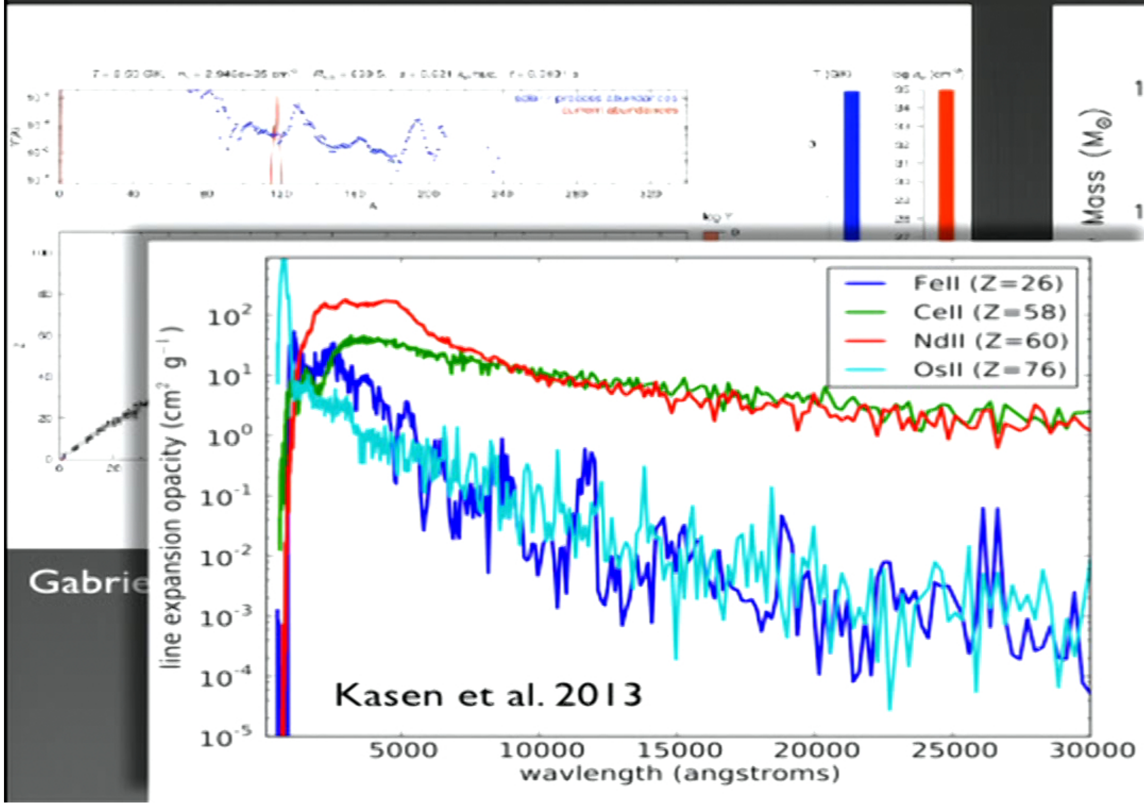
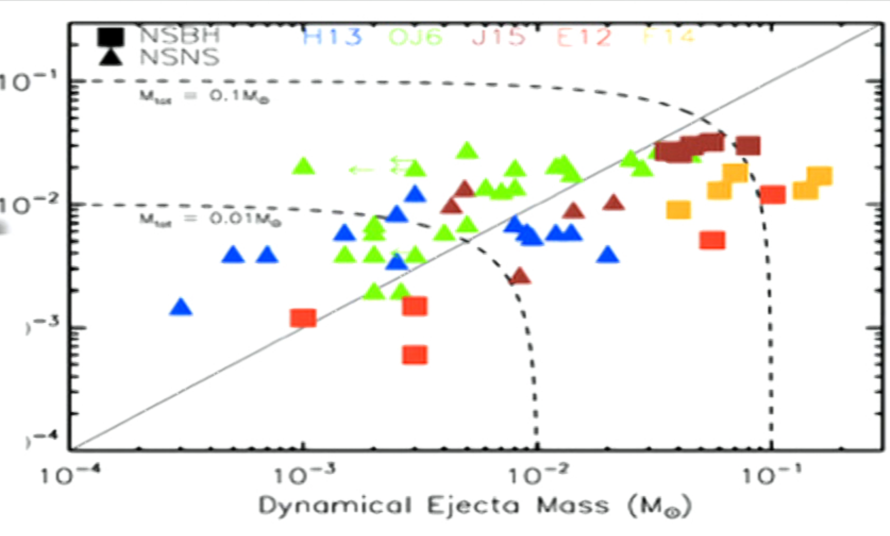
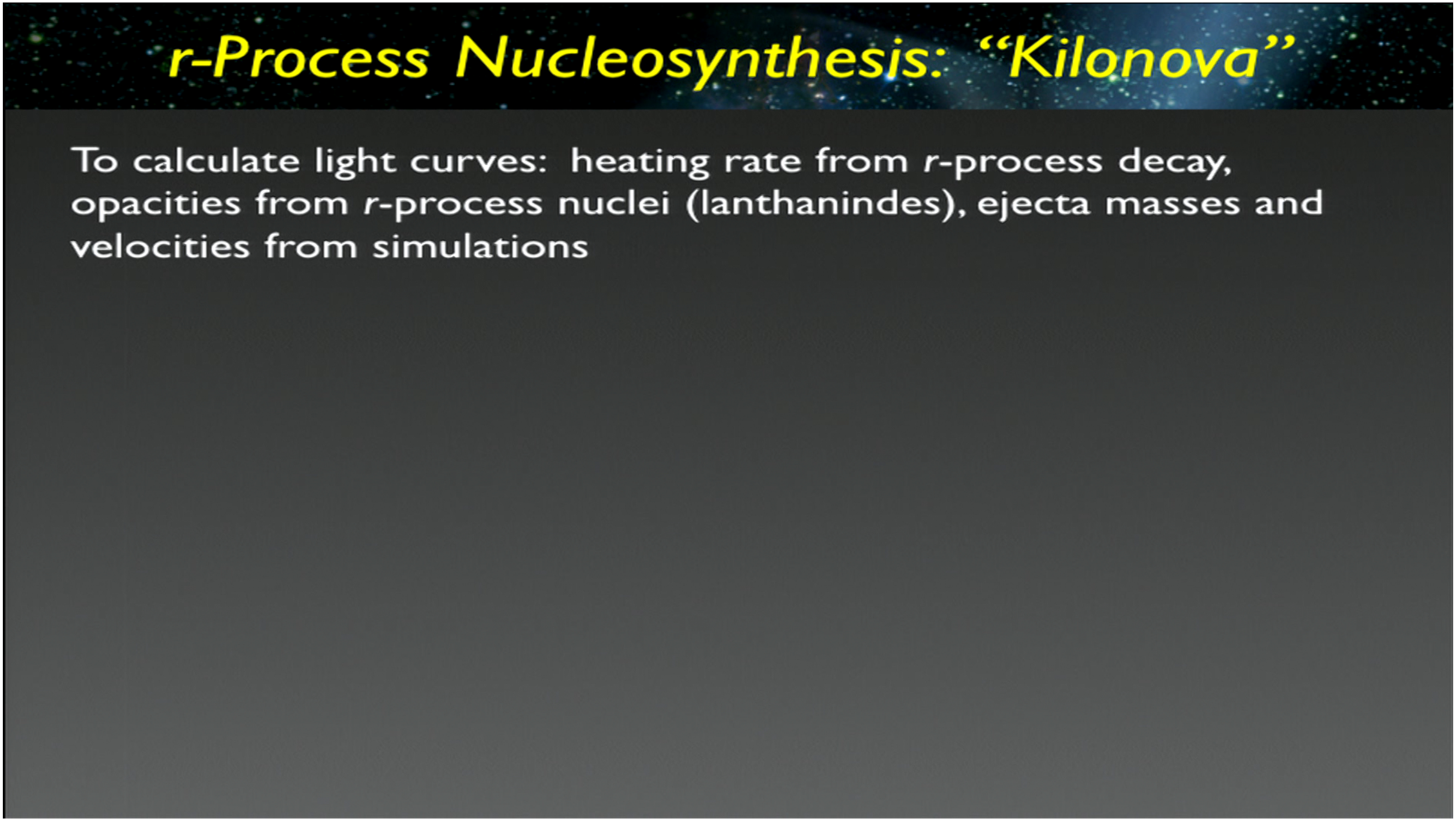


Kasen et al. 2013

Gabrie



Opacity: ~100×$\kappa_{Fe}$ (10–100 cm²/g in optical) if lanthanides are present



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To calculate light curves: heating rate from *r*-process decay, opacities from *r*-process nuclei (lanthanindes), ejecta masses and velocities from simulations

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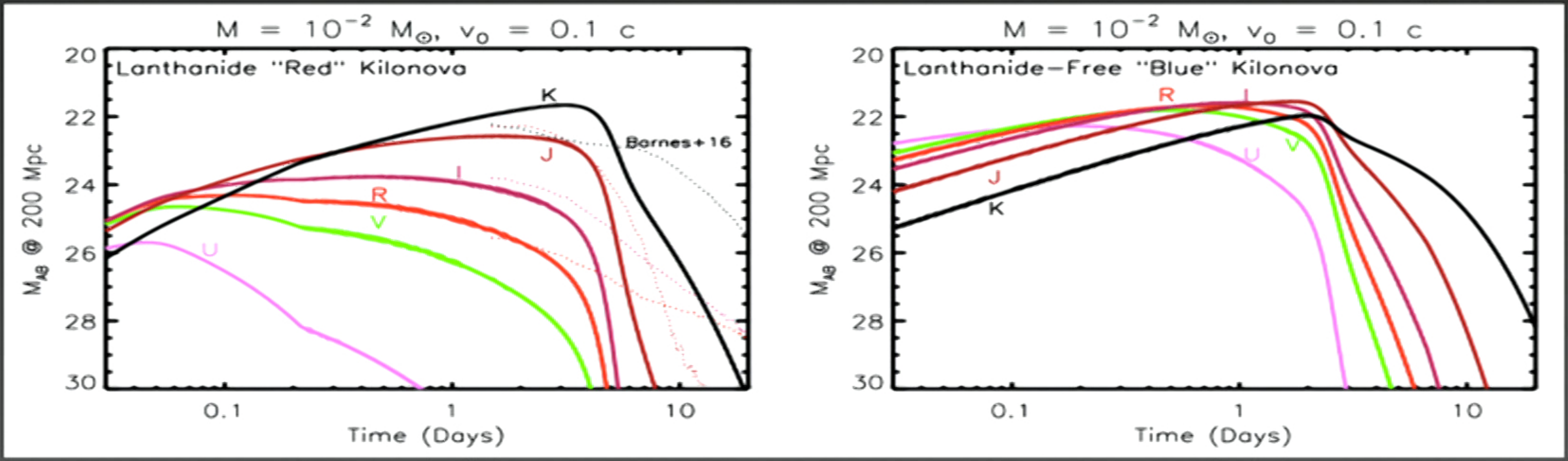

IR-peaked; ~1 week

Optical-peaked; ~1 day

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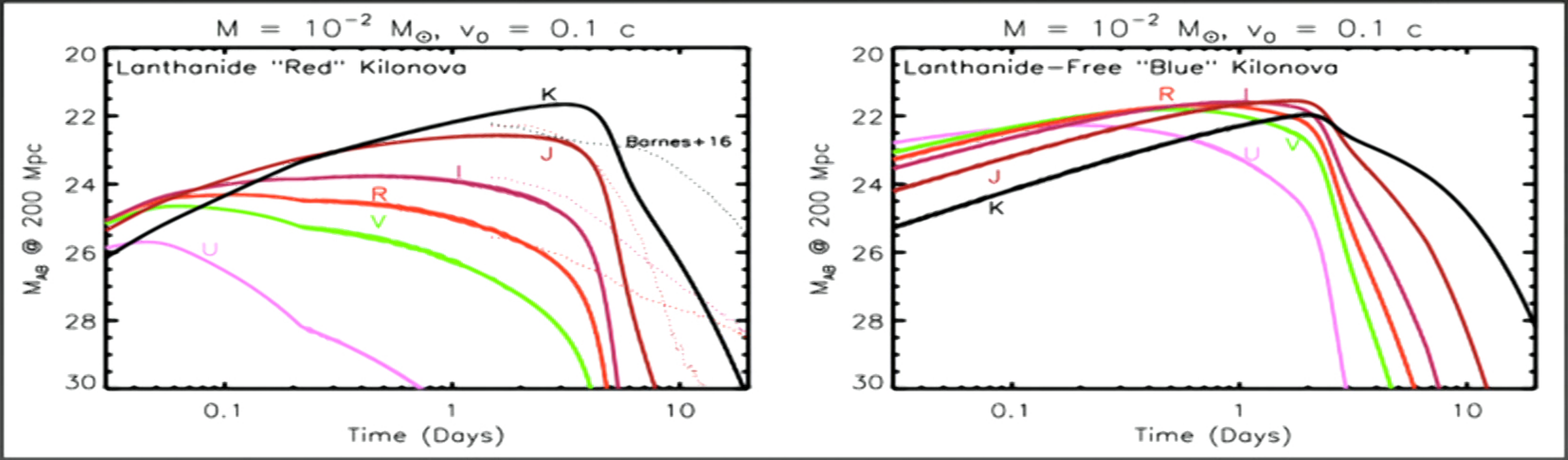


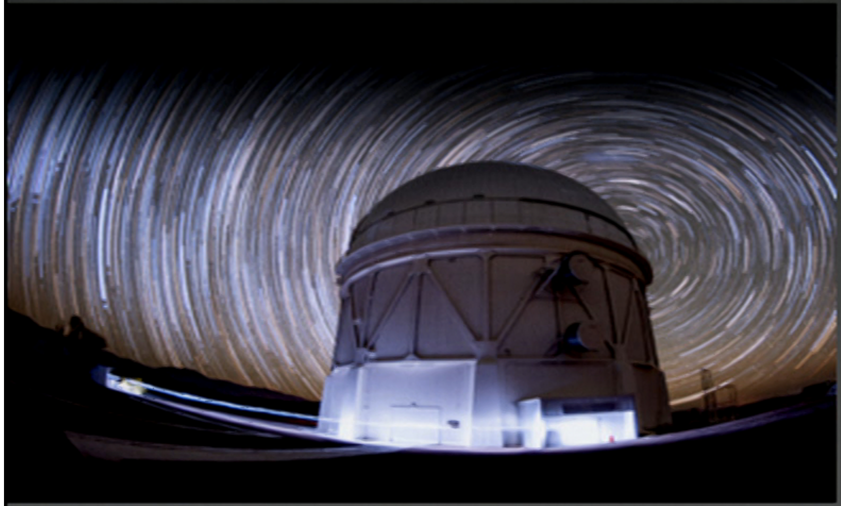
IR-peaked; ~1 week

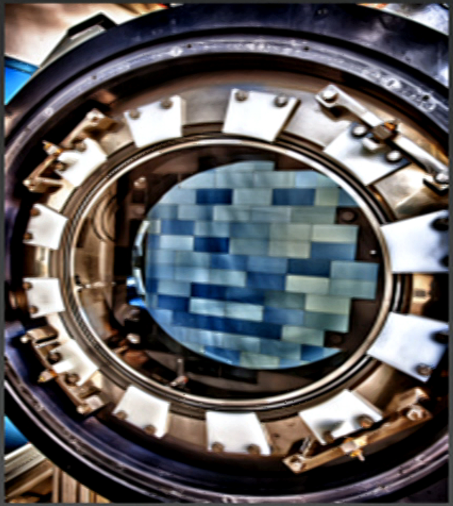
Optical-peaked; ~1 day

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

# Our Follow-up Program

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





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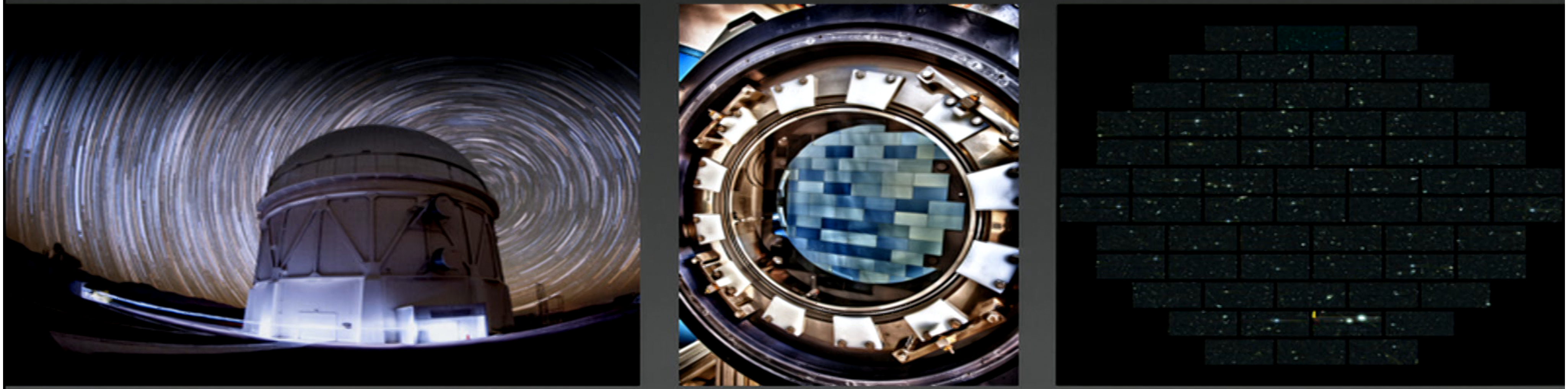

Upon detection: Optical/IR light curves & spectra (DECam, Gemini, Magellan, HST), radio/mm (VLA, ALMA), X-rays (Chandra)

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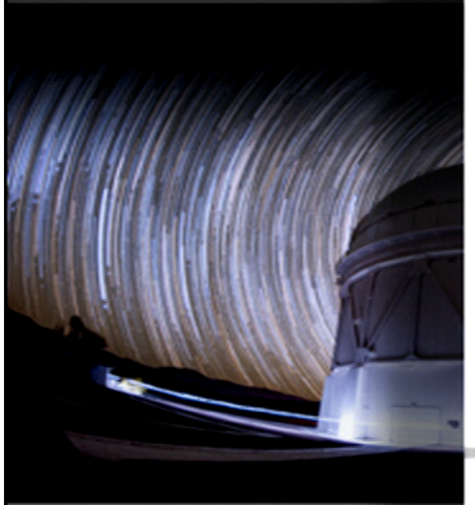


**Edo Berger**
PI of Berger Time-Domain Research Group at Harvard

*Signature*

*Date* April 14, 2014

**David Reitze**
Director of LIGO Laboratory

*Signature*

*Date* April 5, 2014

**Gabriela Gonzalez**
LSC Spokesperson

*Signature*

*Date* April 5, 2014

**Bernard Schutz**
GEO 600 Principal Investigator for Data Analysis

*Signature*
Bernard F Schutz

*Date* April 5, 2014

*LIGO-M1400047, VIR-0150-14* 5

**Jean-Yves Vinet**
Virgo Spokesperson

*Signature*

*Date* April 5, 2014

**Federico Ferrini**
Director of EGO

*Signature*

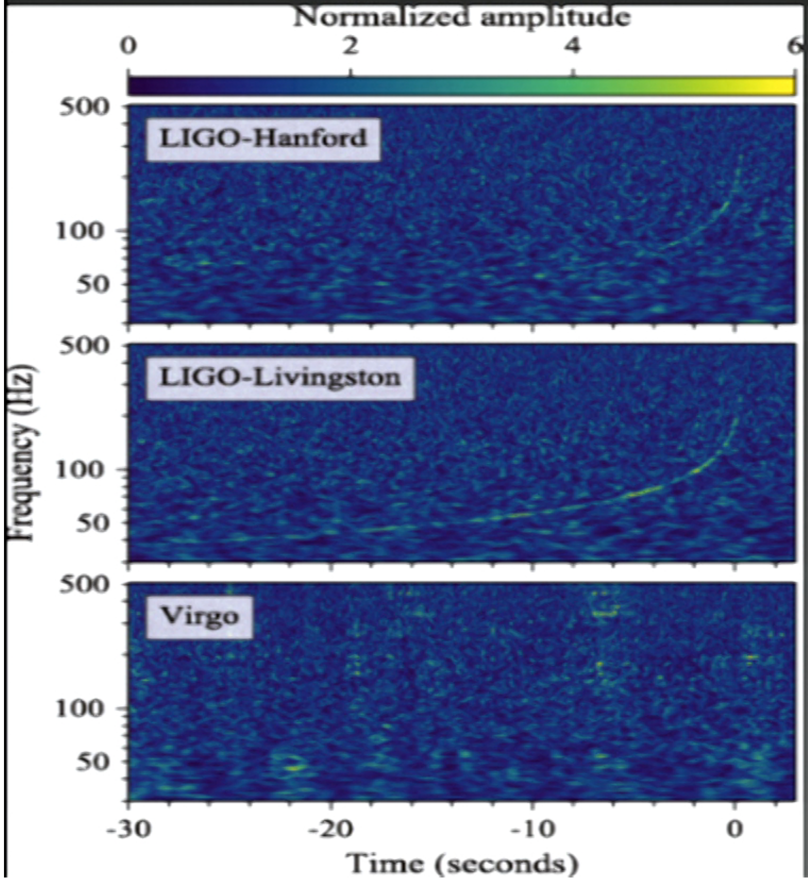
*Date* April 5, 2014

Upon detecti am, Gemini, Magellan, HST),

*Previous follow V170814*

# GW170817: The Chirp Heard Around the World

2017 August 17 12:41:04 UT



Abbott et al. 2017

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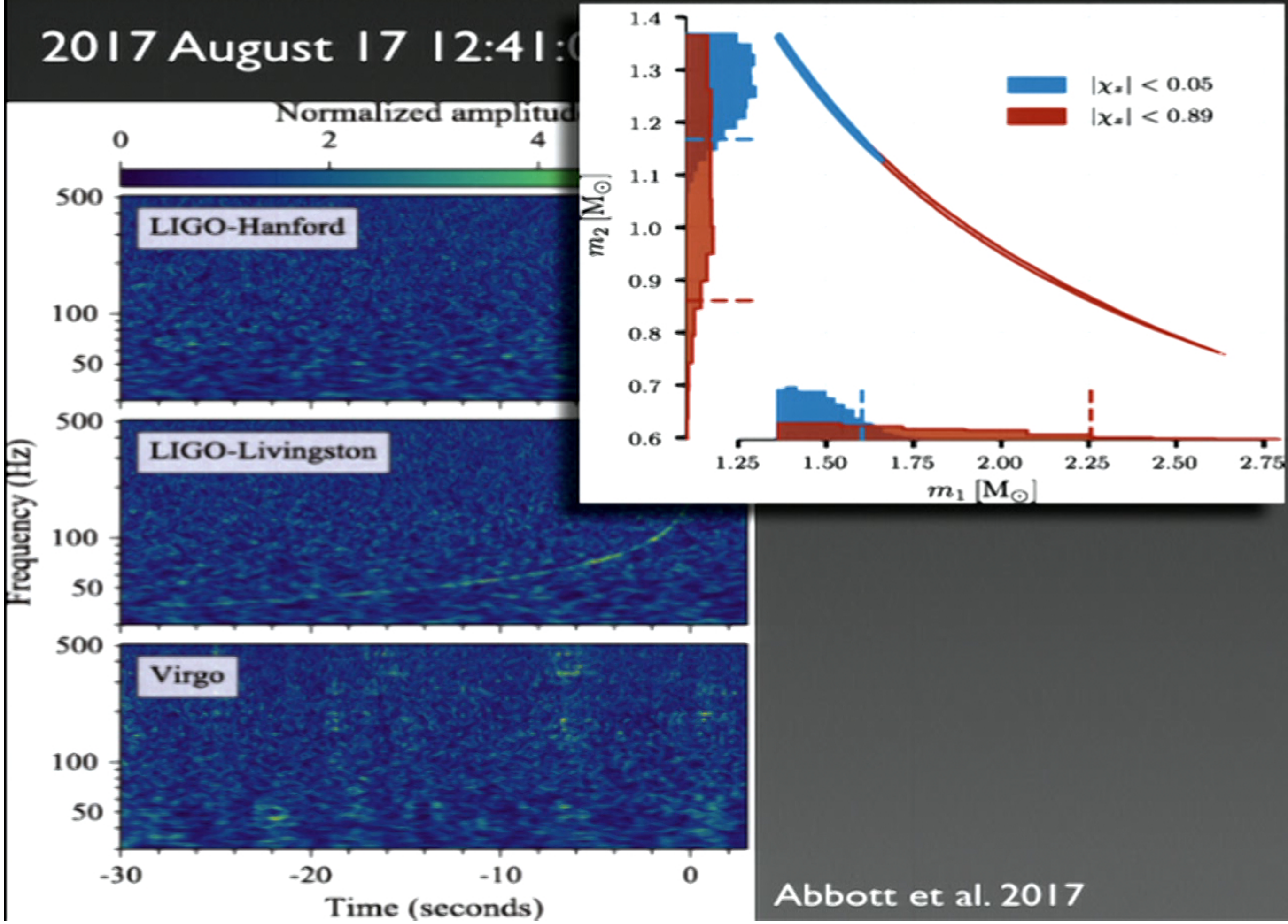

$M_1 \approx 1.36$–$1.60\ \mathrm{M}_\odot$

$M_2 \approx 1.17$–$1.36\ \mathrm{M}_\odot$

$q \approx 0.7$–$1$

$M_{tot} \approx 2.74\ \mathrm{M}_\odot$

Abbott et al. 2017

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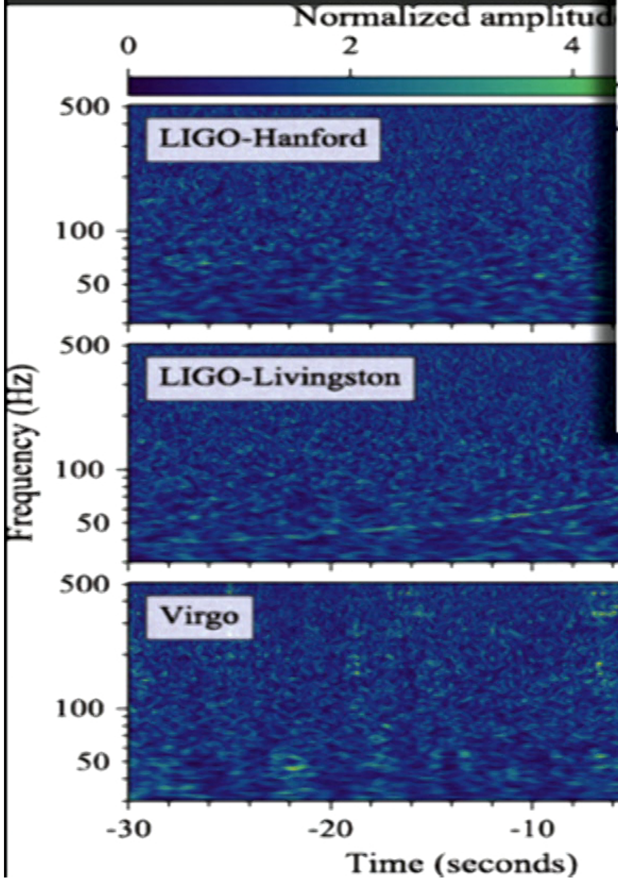

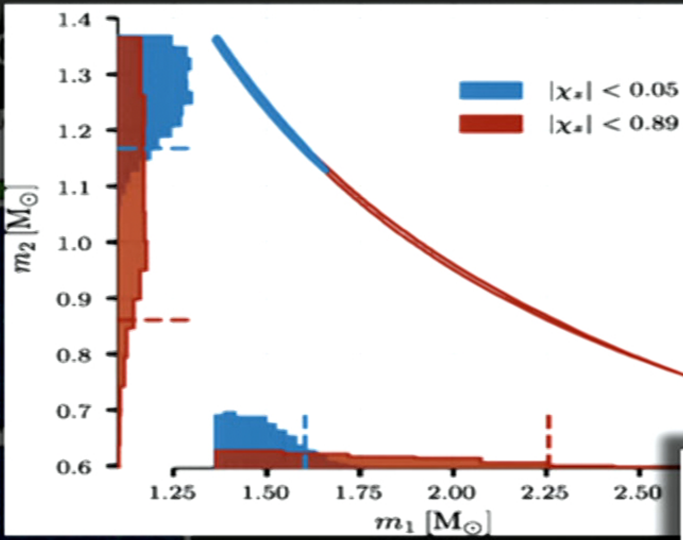

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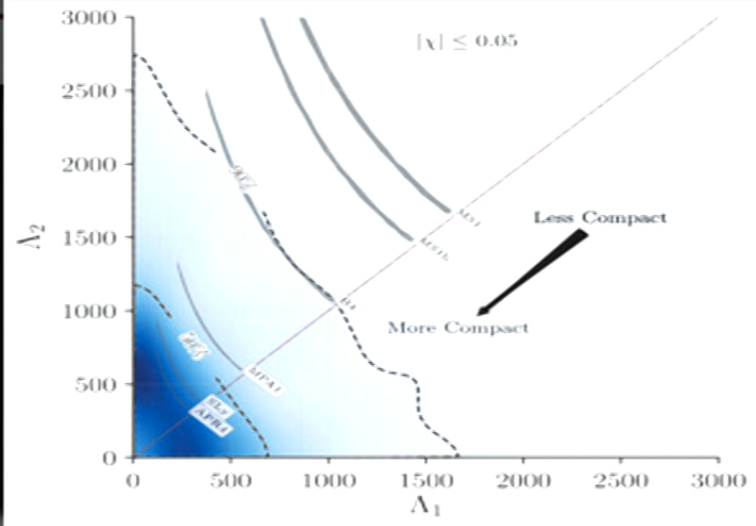
Tidal deformability



$\Lambda \lesssim 10^3$

Abbott et al. 2017

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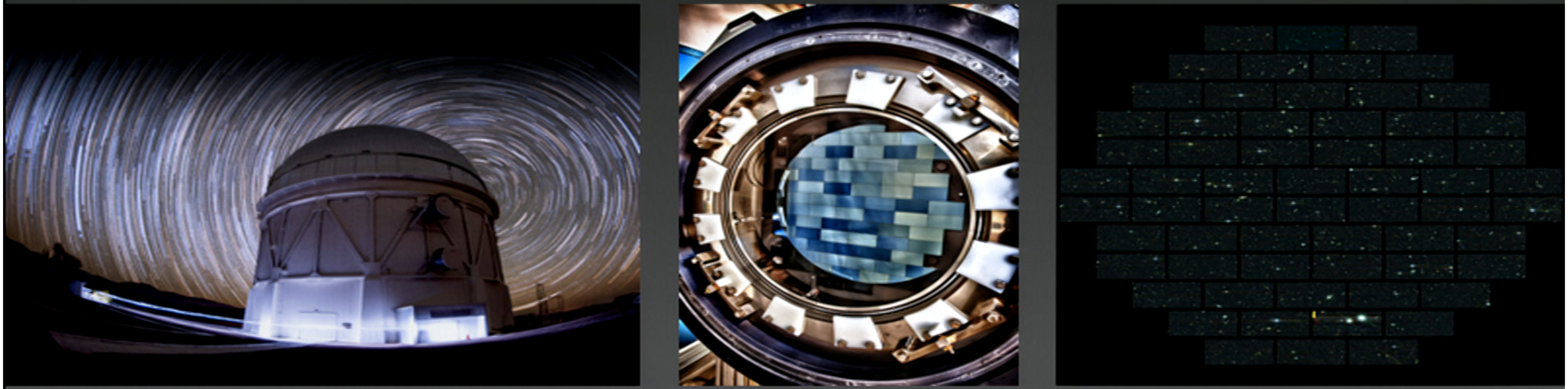

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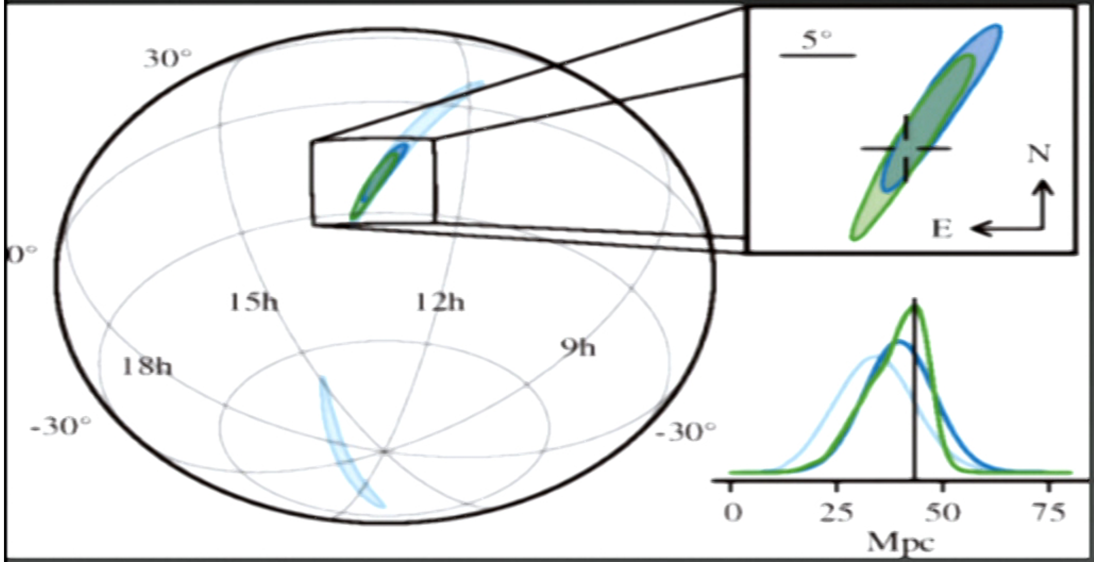
Abbott et al. 2017



[12:41:04 UT: Merger time]

13:08:16 UT: Online single-detector trigger

13:21:42 UT: GCN Circular

17:54:51 UT: First LIGO/Virgo map

23:54:40 UT: Revised map

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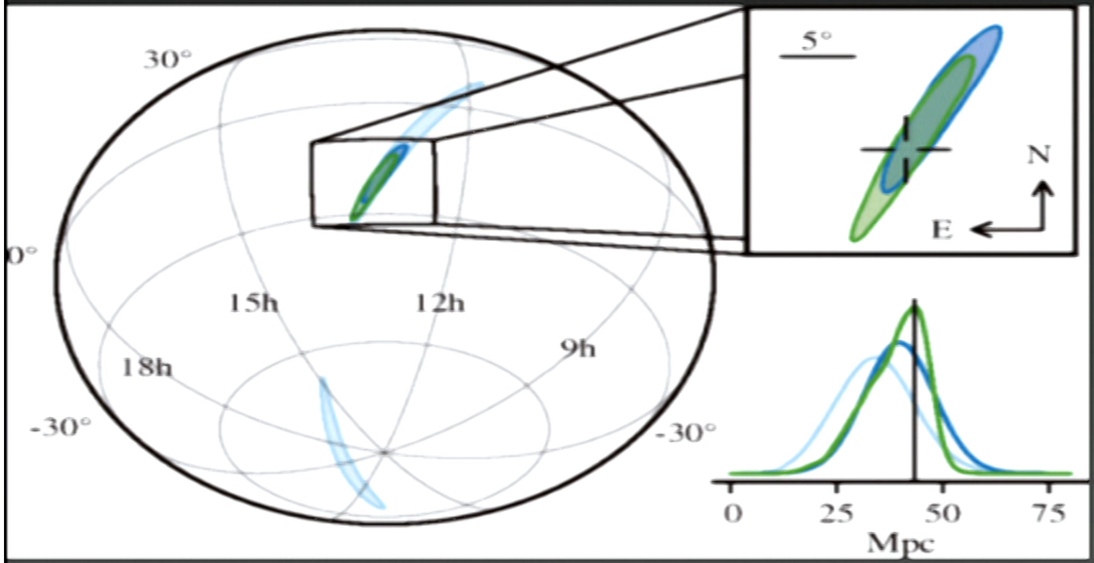

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Decl. = $-25°37'$

$A \approx 30$ deg$^2$

$d \approx 24-48$ Mpc

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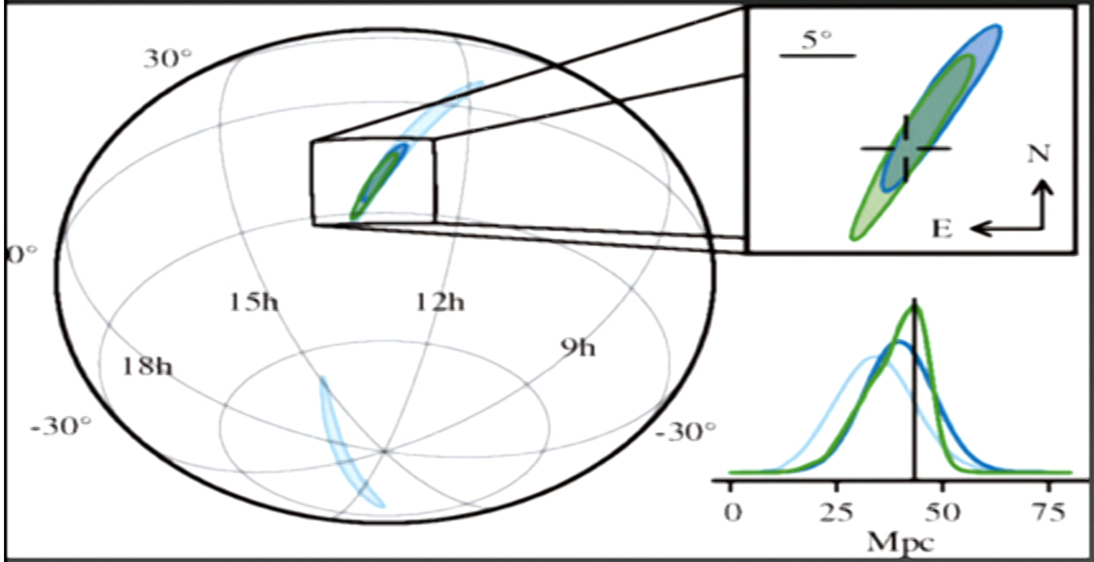
Abbott et al. 2017



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$A \approx 30$ deg$^2$
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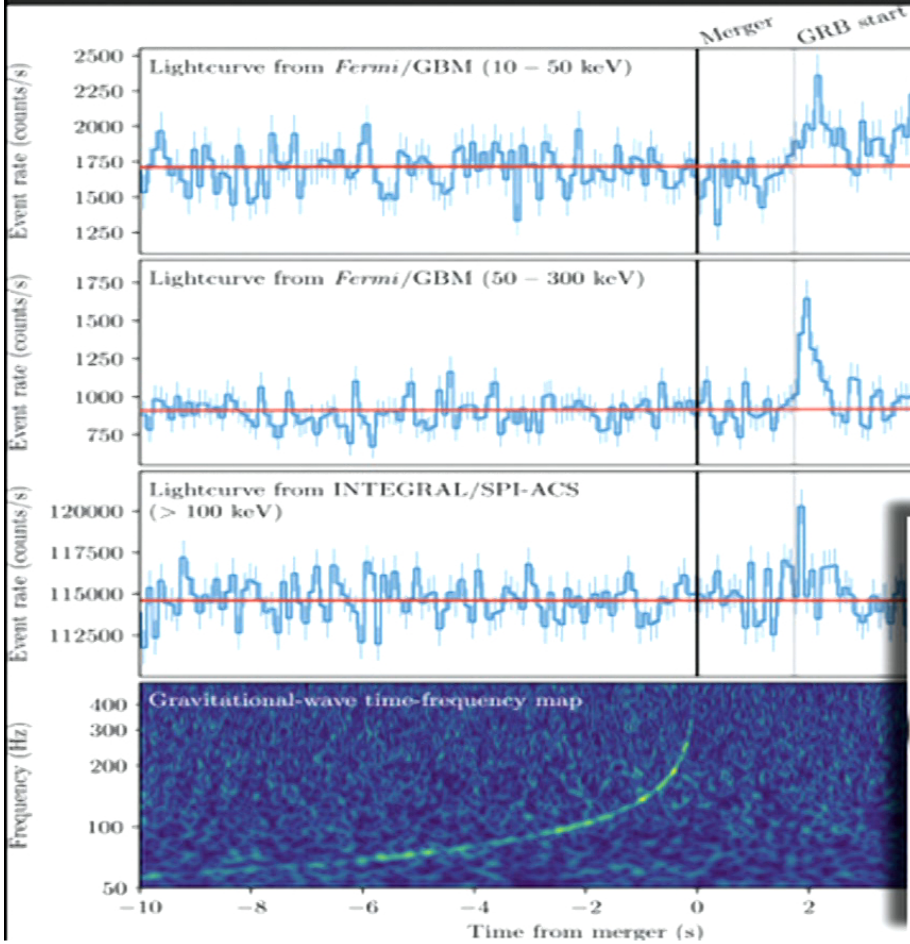
A near-miss: 3 weeks earlier (no Virgo); 10 days later (no LIGO/Virgo); >15 deg further west (too close to Sun)

# GRB170817

Abbott et al. 2017



12:41:06 UT: *Fermi* detection

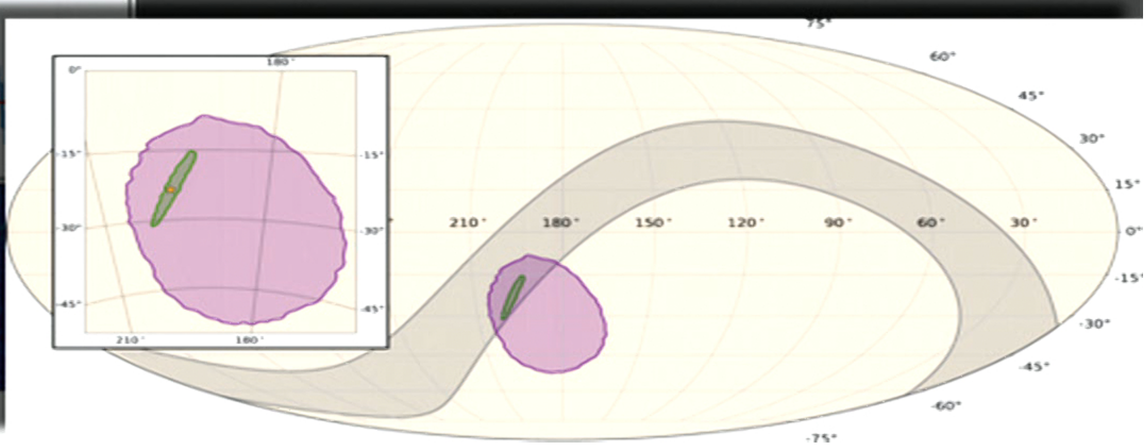
12:41:20 UT: GCN notice

$P_{cc} \approx 5\times10^{-8}$

$T_{90} \approx 2.0$ sec

$F_{\gamma} \approx 1.4\times10^{-7}$ erg/cm$^2$

$E_{\gamma,iso} \approx 2.6\times10^{46}$ erg



# GRB170817

1.7 sec delay between merger and GRB: Could be due to internal shock shell collision time or deceleration time (if external shock)

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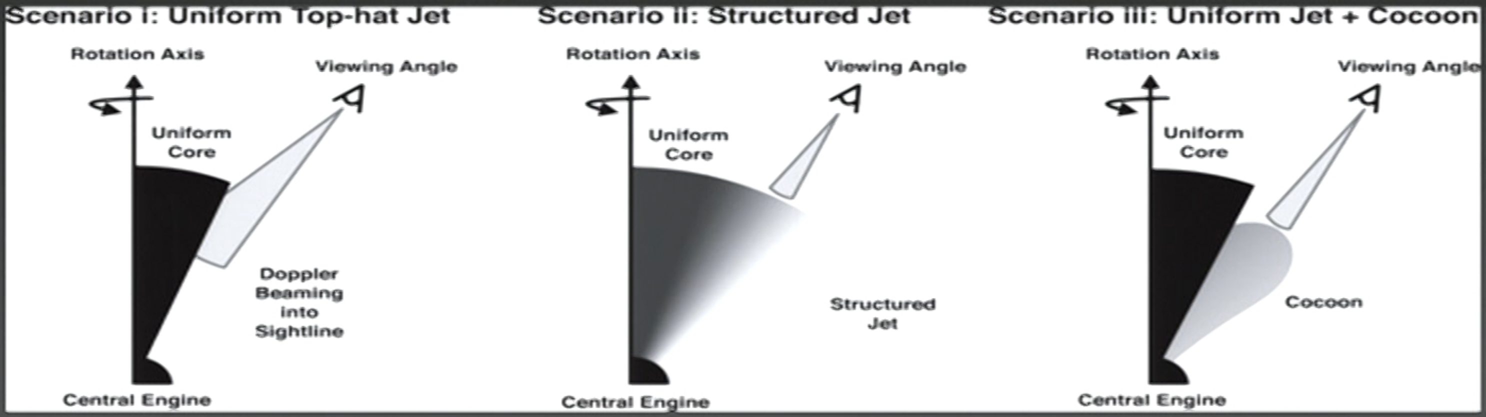

*γ−ray data alone cannot distinguish origin of the emission*

Abbott et al. 2017

# GRB170817

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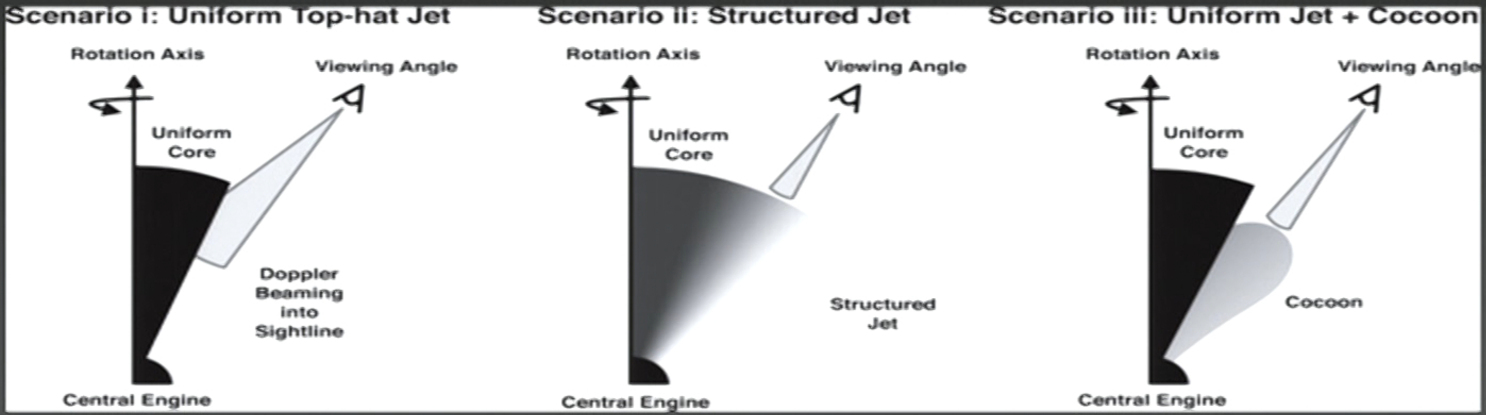


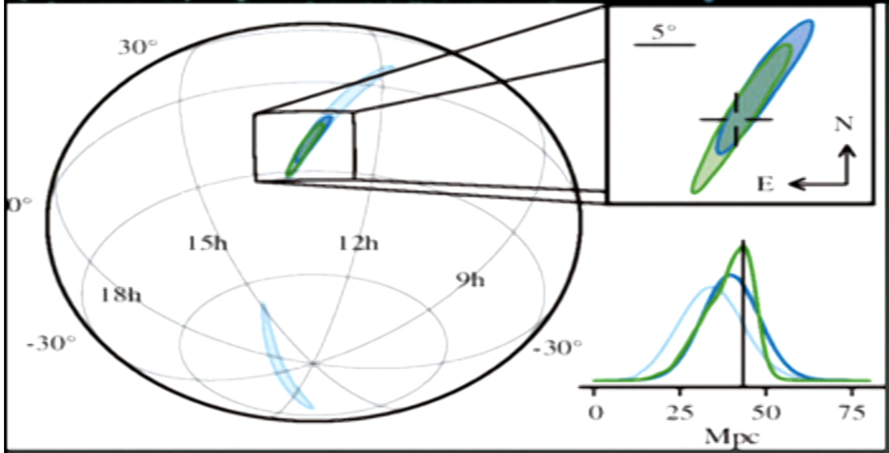
*γ−ray data alone cannot distinguish origin of the emission*

Abbott et al. 2017

Speed of gravity: $\Delta v/v_{EM} \lesssim 7\times10^{-16}$

Equivalence principle (Shapiro delay): $\gamma_{EM} - \gamma_{GW} \lesssim 1.2\times10^{-6}$

# DECam Discovery of Optical Counterpart



[17:54:51 UT: First GW sky-map]

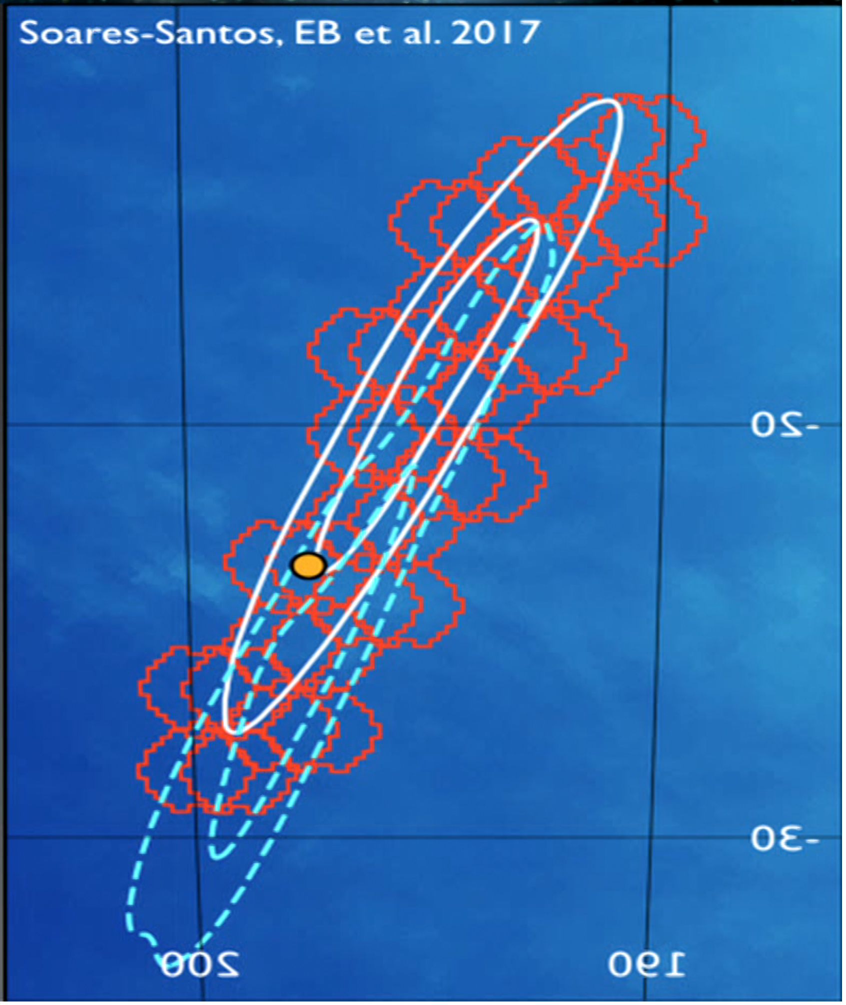
23:13 UT: DECam start

[23:54:40 UT: Revised sky-map]

00:05 UT: NGC4993 imaged

18(×2) pointings; 30 sec in $i + z$

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


Soares-Santos, EB et al. 2017

# DECam Discovery of Optical Counterpart

**From:** Ryan Chornock <chornock@ohio.edu>
**Subject: Re: All Eyes! G298048. Images will be downloadable here**
**Date:** 18 August 2017 at 02:42:00 CEST

Holy shit.

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

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

Galaxy is at 40 Mpc.

-R

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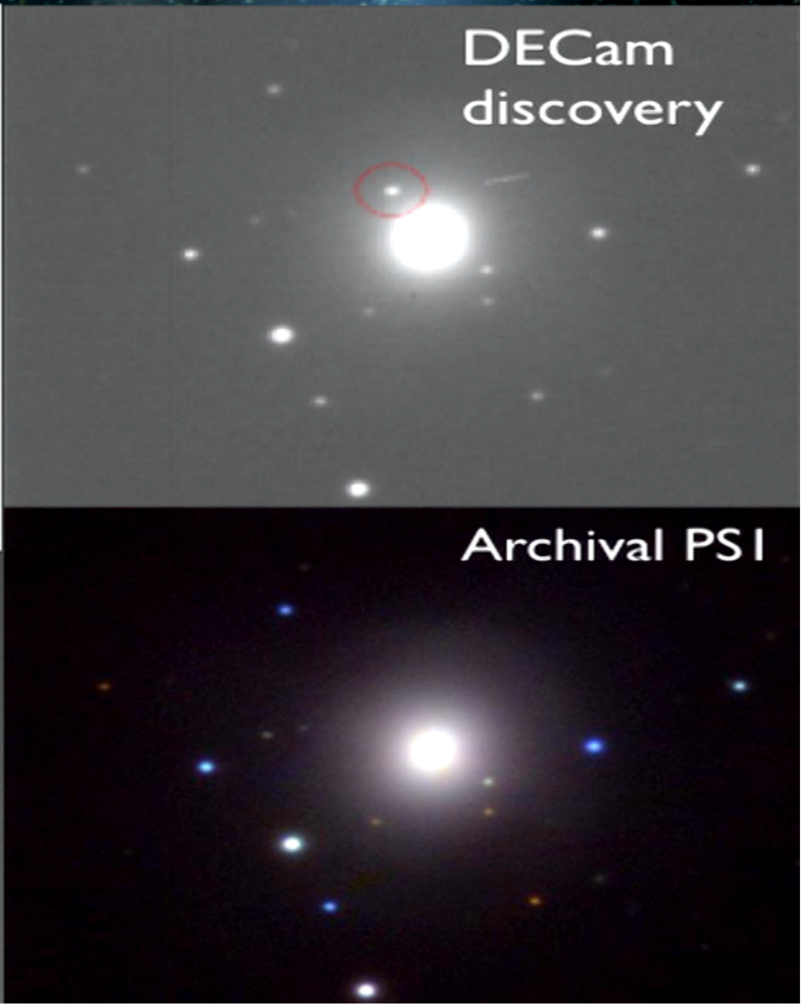

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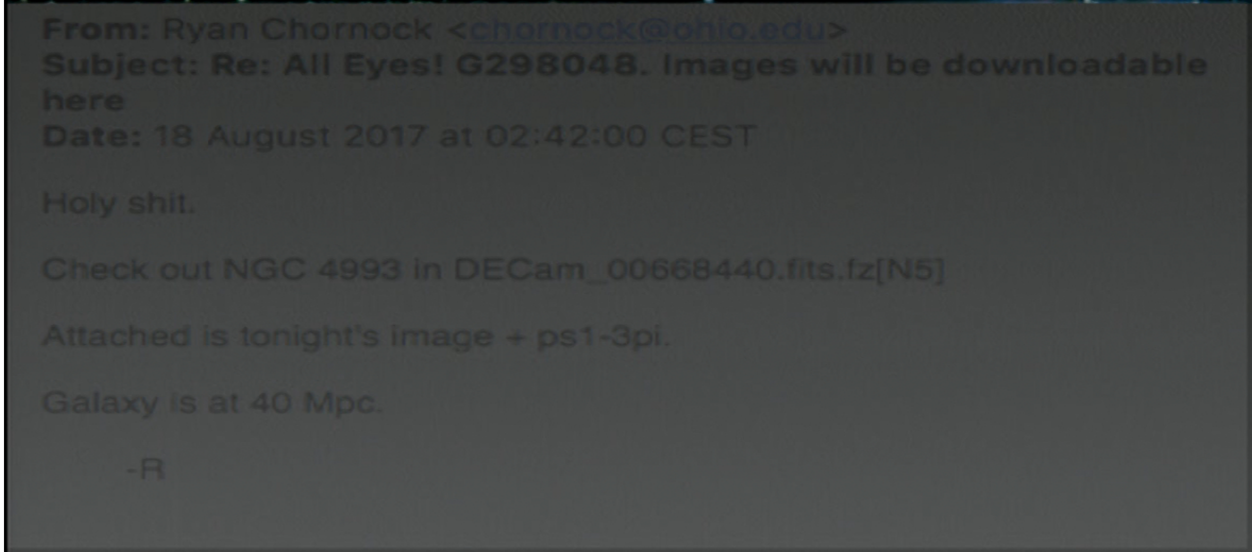

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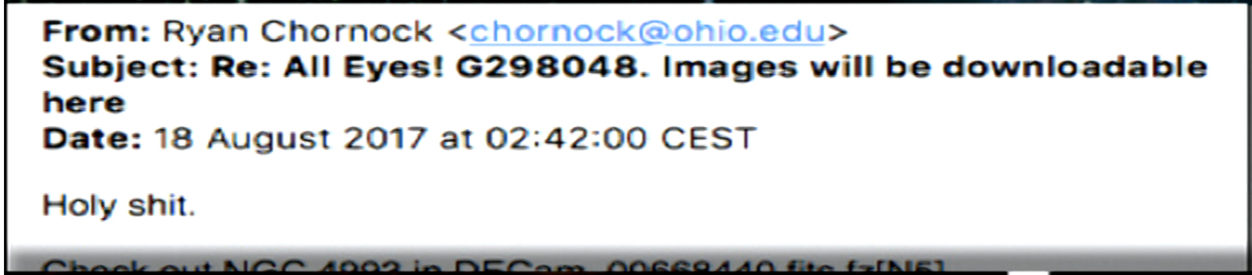
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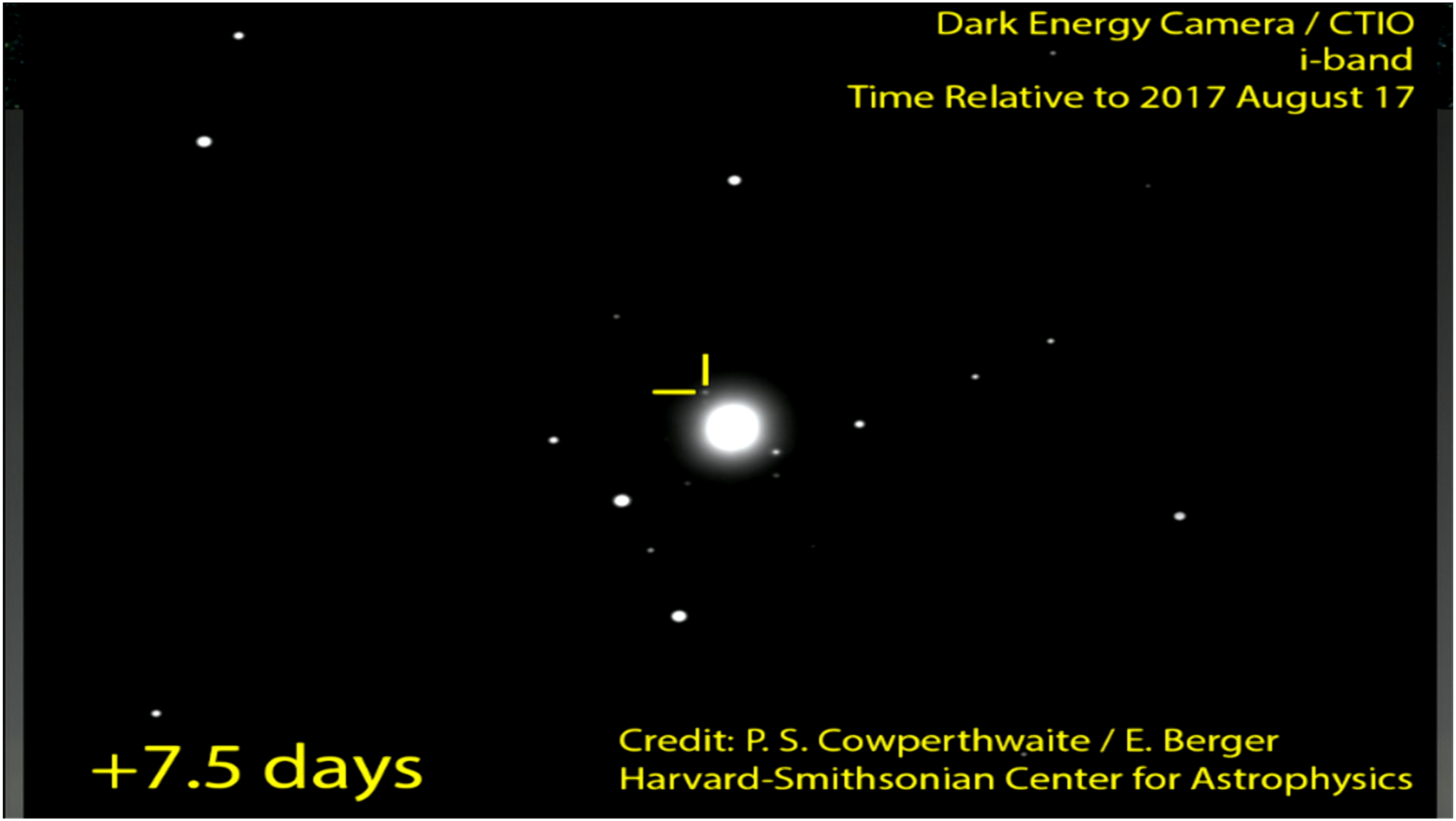
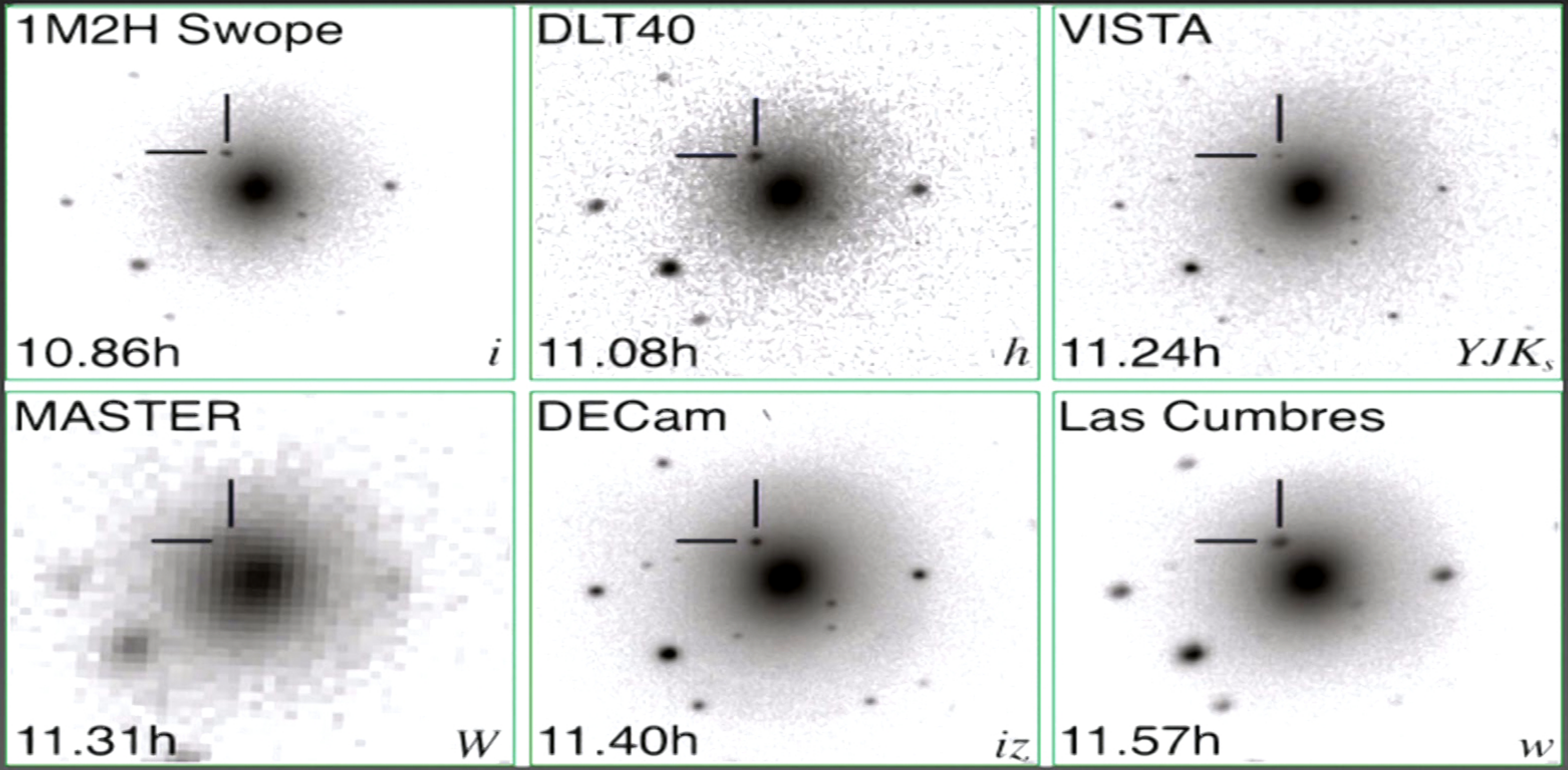


Credit: P. S. Cowperthwaite / E. Berger
Harvard-Smithsonian Center for Astrophysics

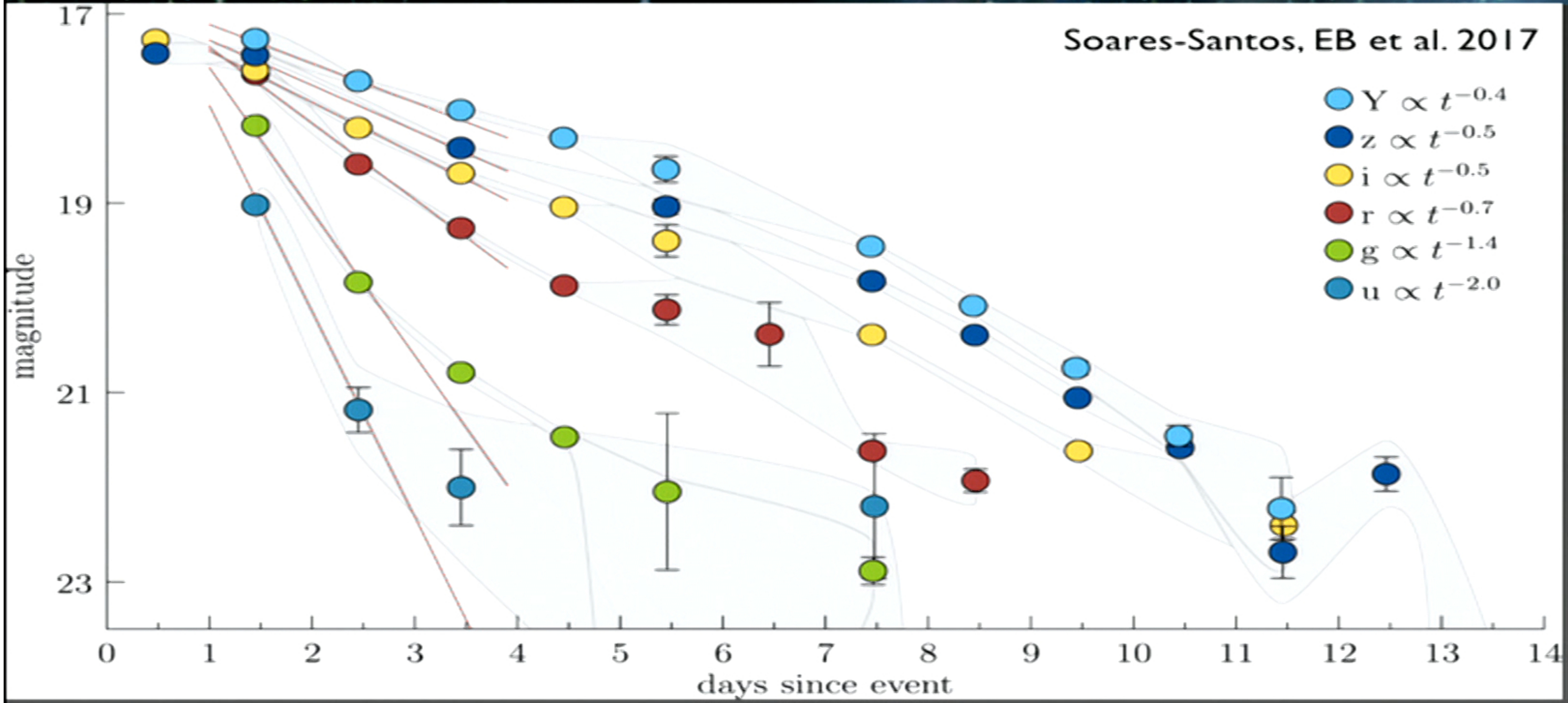
# Discovery of the Optical Counterpart

Abbott et al. 2017



Independently imaged by 6 telescopes before detection was announced

# DECam Discovery of Optical Counterpart



Soares-Santos, EB et al. 2017

Rapid fading and reddening with time

Tracked to ~2 weeks thanks to 4-m aperture telescope

# DECam Discovery of Optical Counterpart

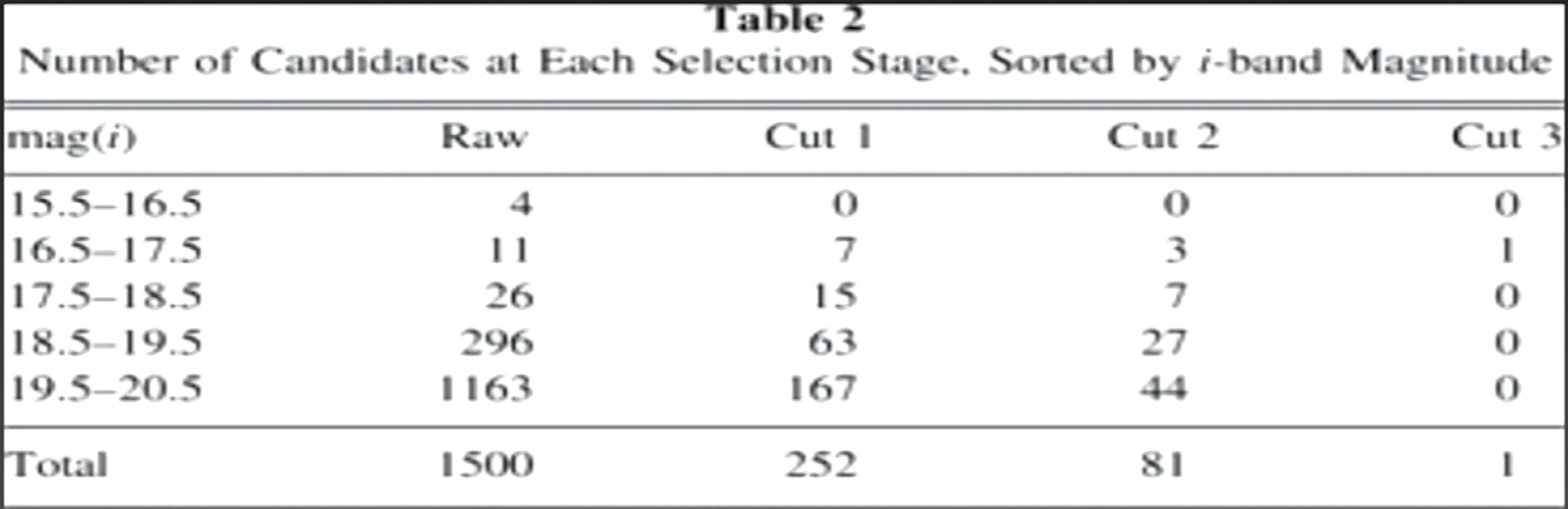


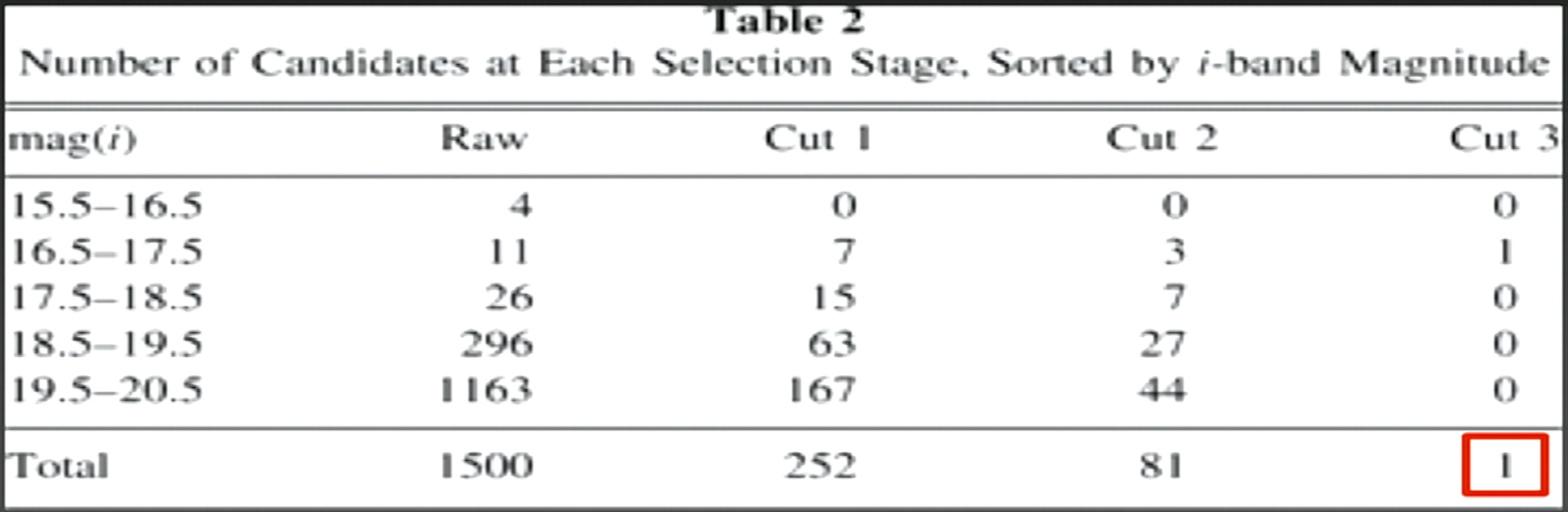
**Table 2**
Number of Candidates at Each Selection Stage, Sorted by *i*-band Magnitude

| mag($i$) | Raw | Cut 1 | Cut 2 | Cut 3 |
|---|---|---|---|---|
| 15.5–16.5 | 4 | 0 | 0 | 0 |
| 16.5–17.5 | 11 | 7 | 3 | 1 |
| 17.5–18.5 | 26 | 15 | 7 | 0 |
| 18.5–19.5 | 296 | 63 | 27 | 0 |
| 19.5–20.5 | 1163 | 167 | 44 | 0 |
| Total | 1500 | 252 | 81 | 1 |

65 deg$^2$: 1500 candidates with detection in *i* or *z* to ~20.5 mag

Soares-Santos, EB et al. 2017

# DECam Discovery of Optical Counterpart



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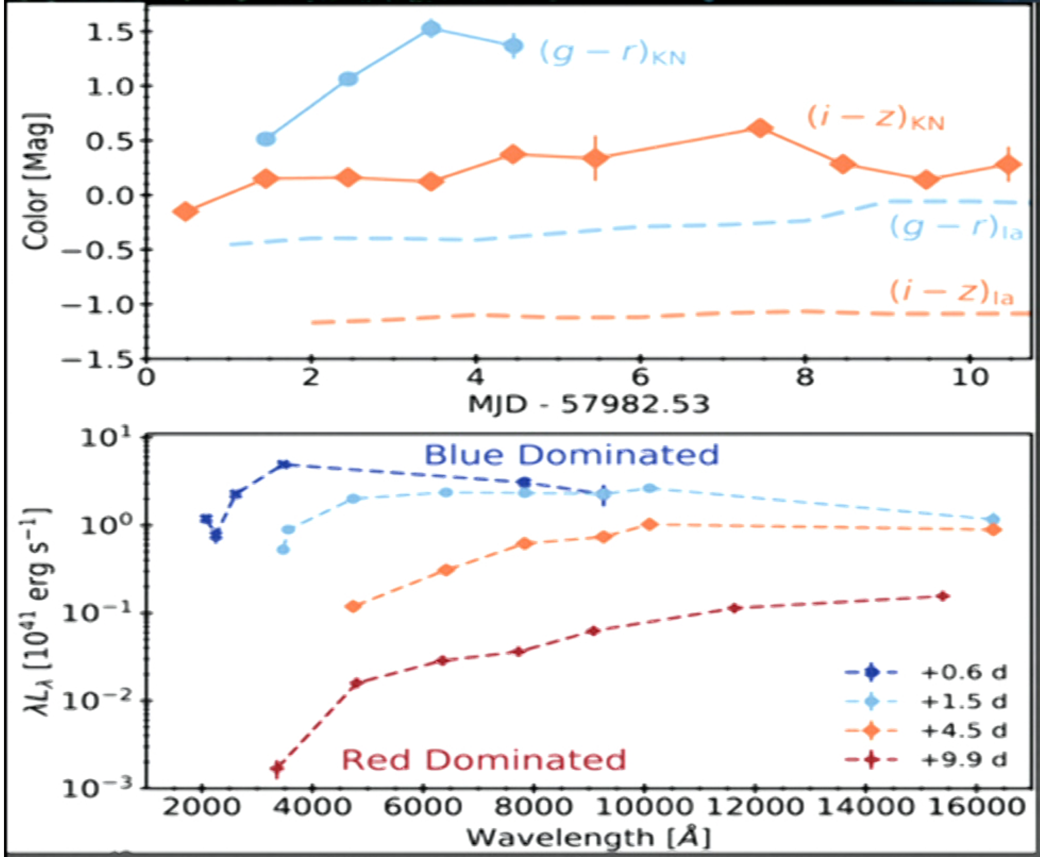
65 $\text{deg}^2$: 1500 candidates with detection in *i* or *z* to ~20.5 mag

1. Astrophysical
2. *i* + *z* detection
3. faded by >5-sigma in 2 weeks

} 1 candidate

Soares-Santos, EB et al. 2017

# Light Curves & Kilonova Models



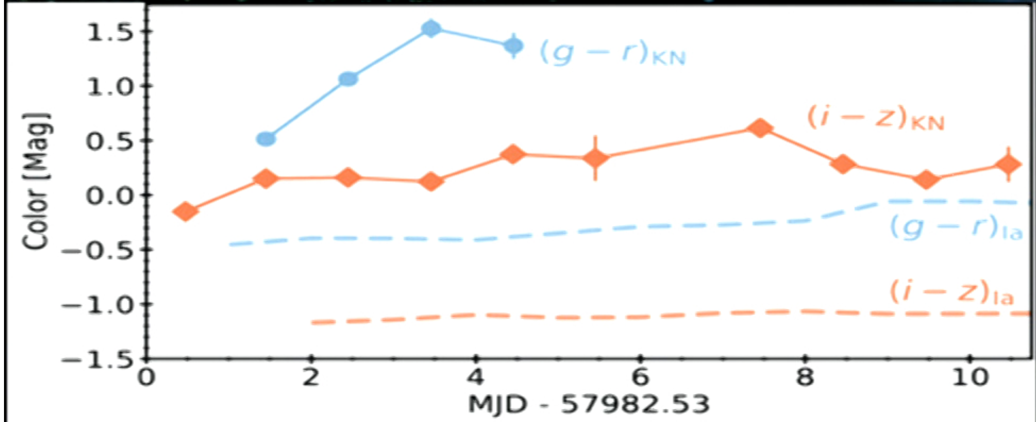
Cowperthwaite, EB et al. 2017

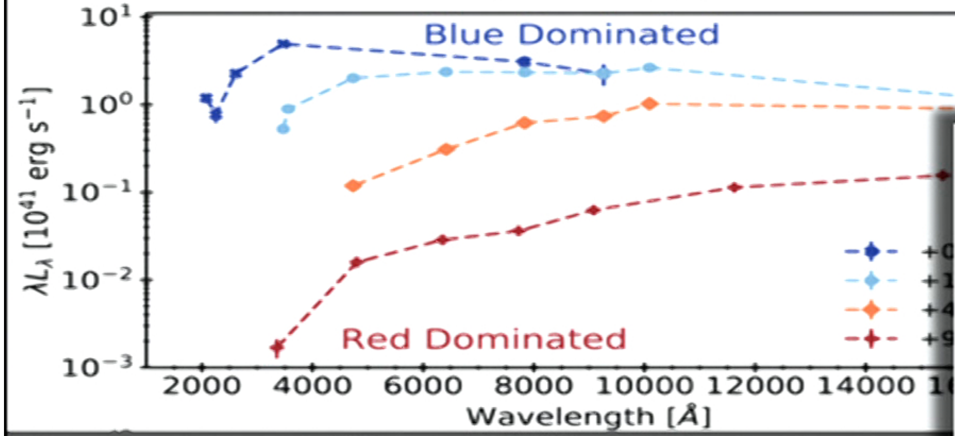
*DECam, Gemini, Swift, Hubble*

Transient significantly redder than a normal SN

Rapidly reddens from ~0.4 μm (0.5 days) to ~1 μm (4.5 days)

# *Light Curves & Kilonova Models*





Cowperthwaite, EB et al. 2017

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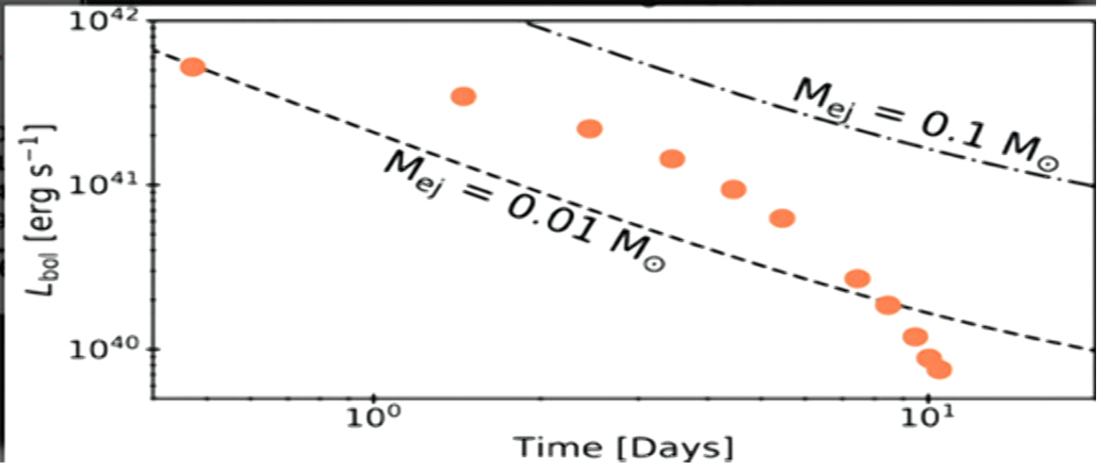
Rapidly reddens from ~0.4 μm (0.5 days) to ~1 μm (4.5 days)

$L_{bol} \sim E_{r\text{-process}}$ ($M_{ej} \sim$ few % $M_\odot$)



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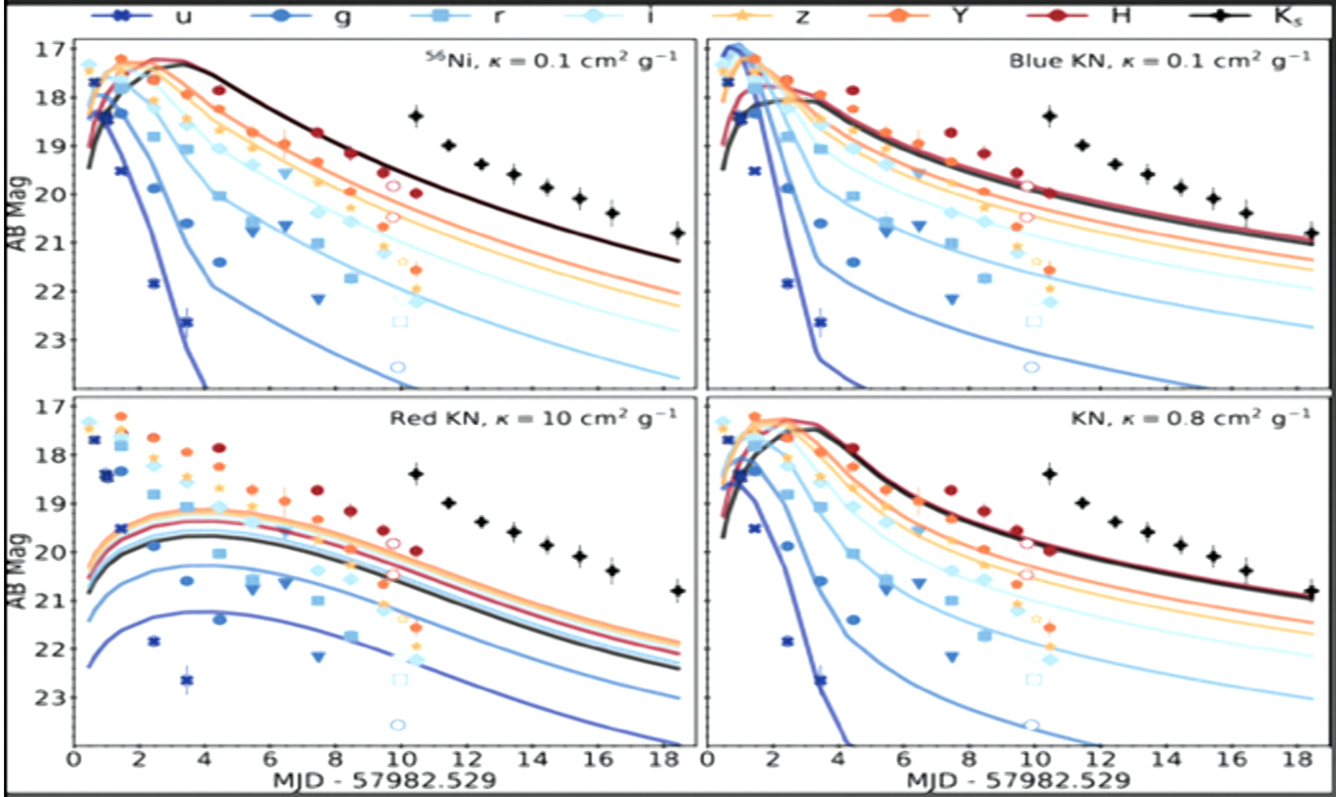
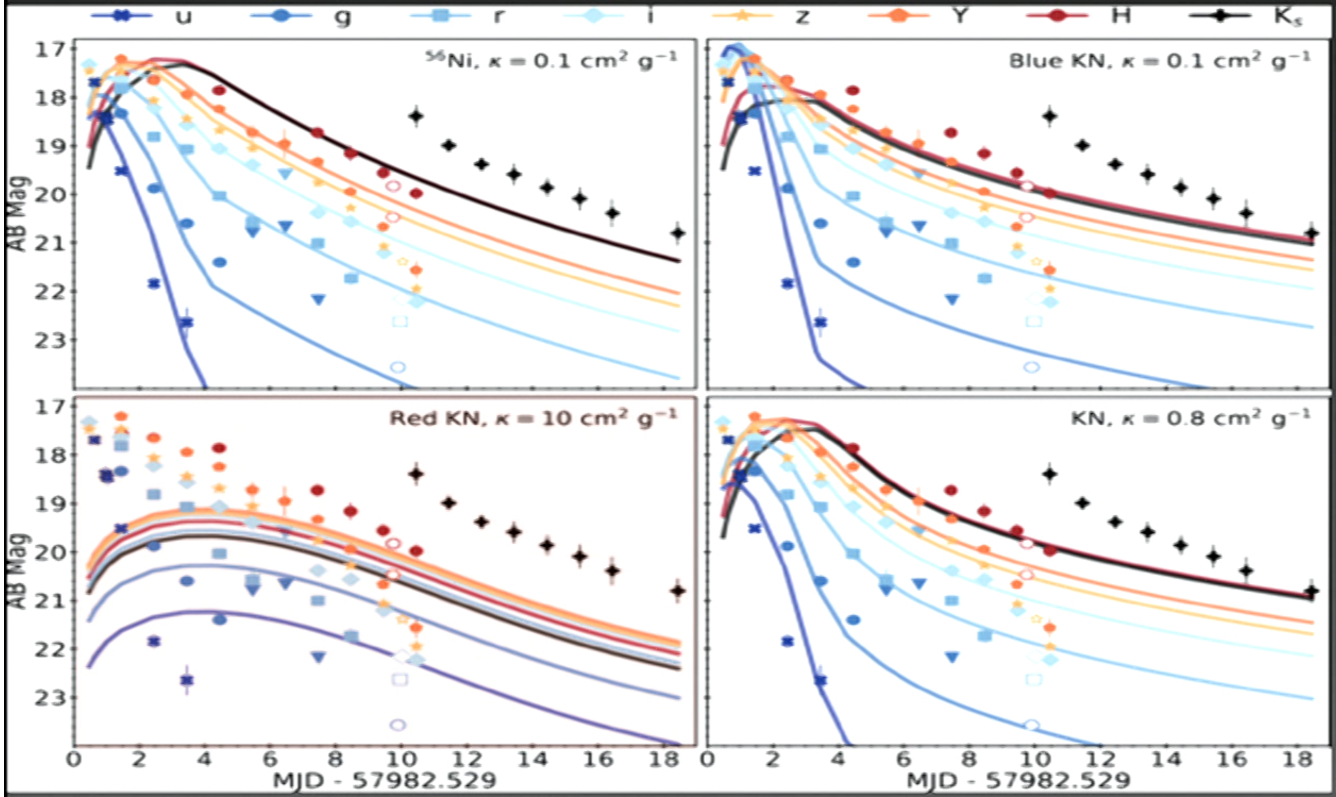


Cowperthwaite, EB et al. 2017

Ruling out models:

# Light Curves & Kilonova Models



Cowperthwaite, EB et al. 2017

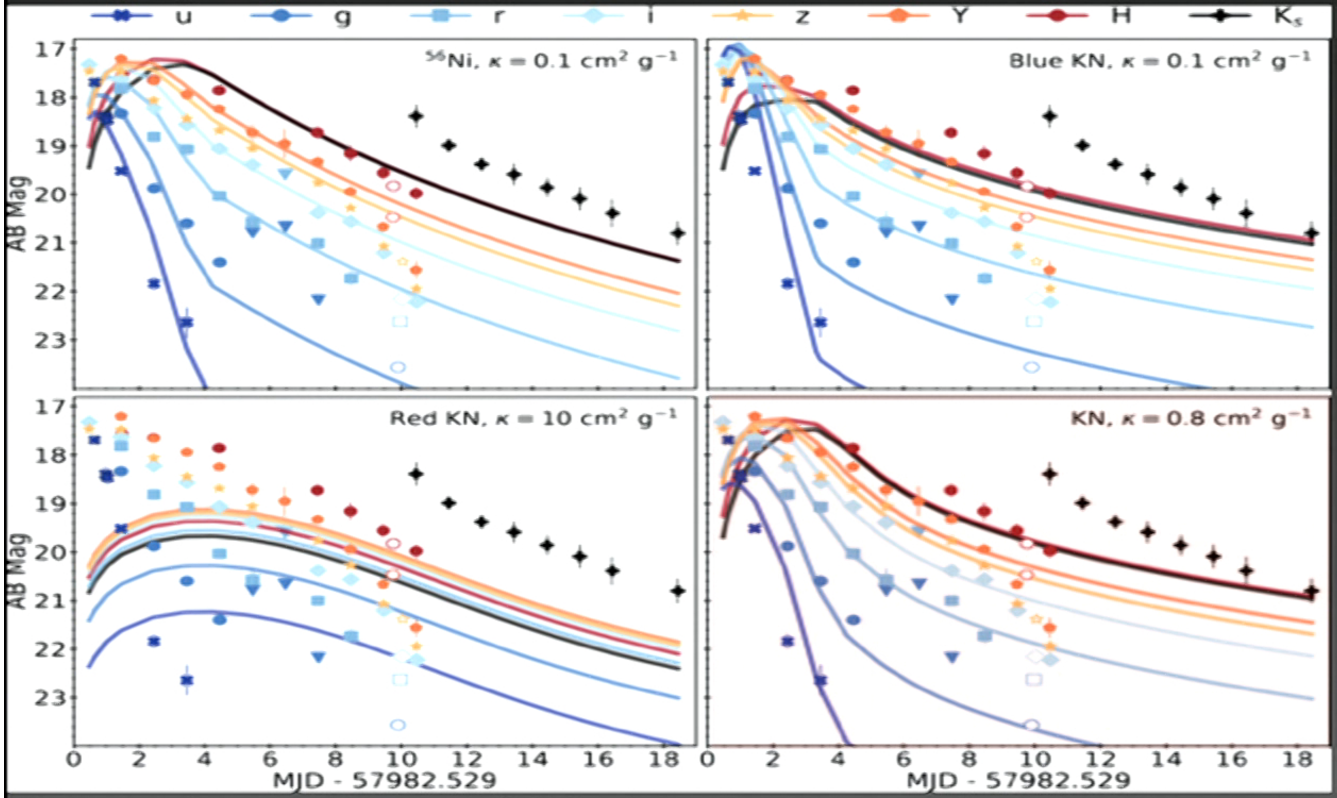
Ruling out models:

$^{56}$Ni radioactivity and Fe-peak opacity

*r*-process radioactivity and Fe-peak opacity

*r*-process radioactivity and lanthanide opacity

# Light Curves & Kilonova Models



Cowperthwaite, EB et al. 2017

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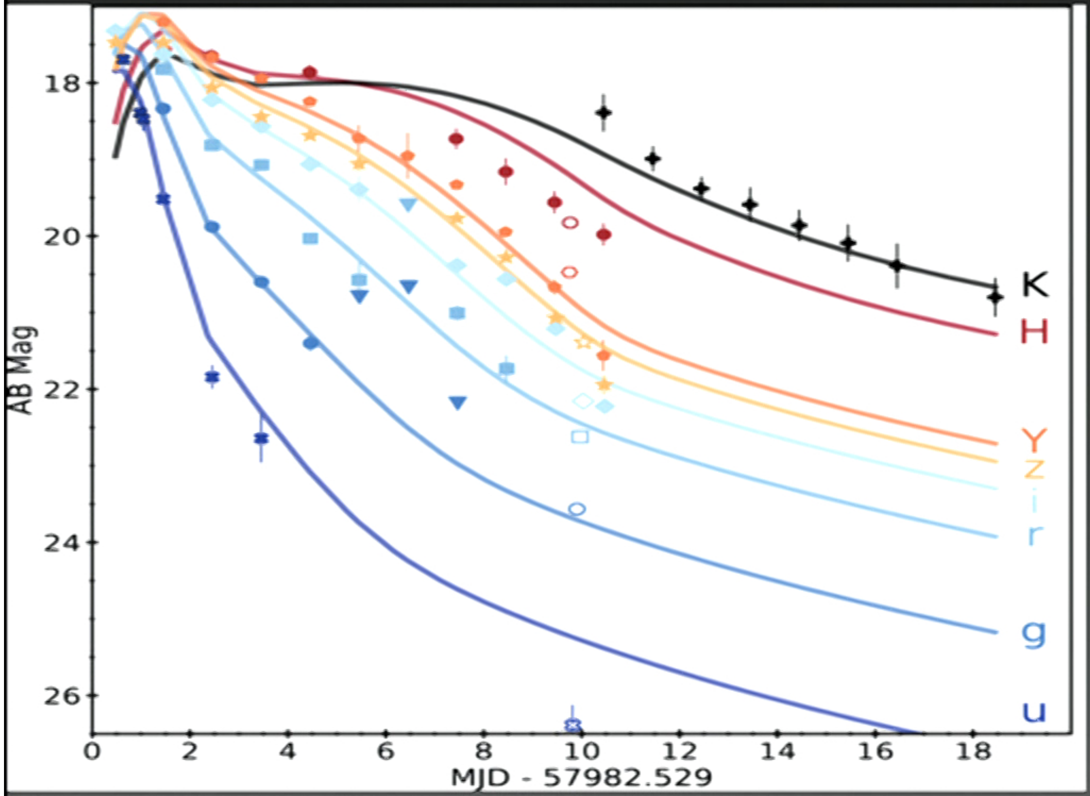
*r*-process radioactivity and variable opacity

# Light Curves & Kilonova Models

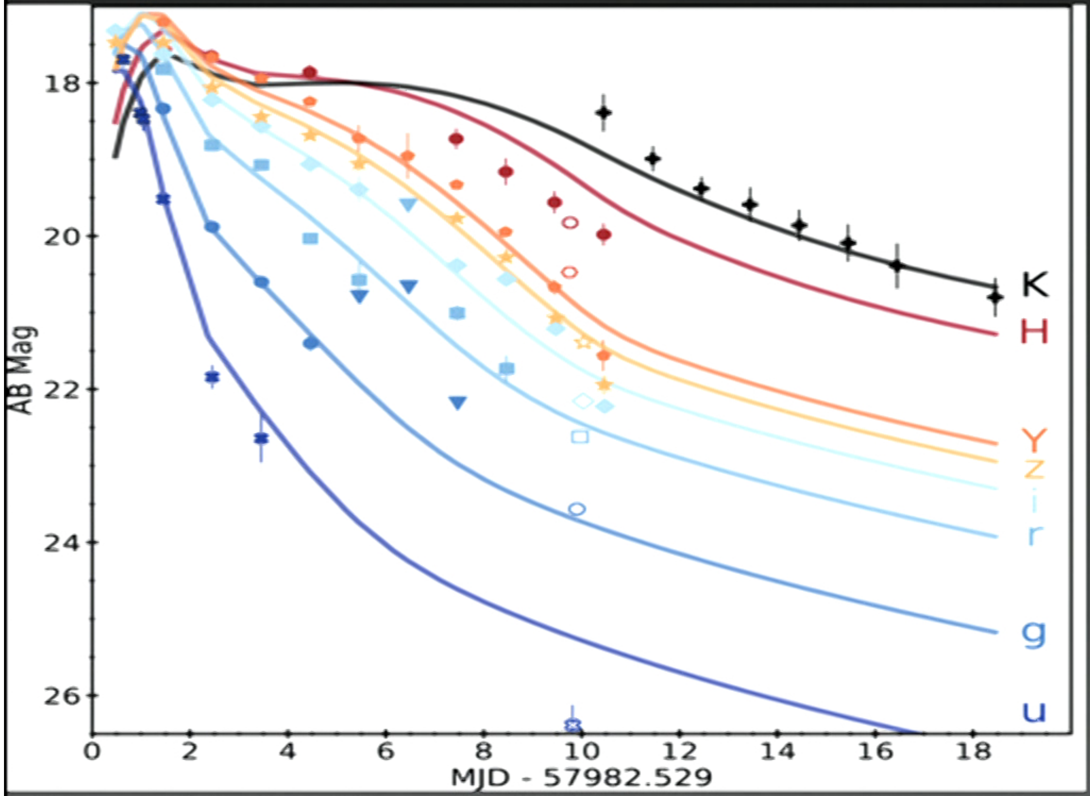


Cowperthwaite, EB et al. 2017

What does work?

**All models use the modular open source code MOSFiT; all data and model setups are public*

# Light Curves & Kilonova Models



Cowperthwaite, EB et al. 2017

What does work?

Two-component model:

Blue: $M_{ej} \sim 0.02\ M_{\odot}$ / $v_{ej} \sim 0.3c$

Red: $M_{ej} \sim 0.04\ M_{\odot}$ / $v_{ej} \sim 0.1c$

Three-component model:

Blue: $M_{ej} \sim 0.02\ M_{\odot}$ / $v_{ej} \sim 0.3c$

Purple: $M_{ej} \sim 0.03\ M_{\odot}$ / $v_{ej} \sim 0.1c$

Red: $M_{ej} \sim 0.01\ M_{\odot}$ / $v_{ej} \sim 0.1c$

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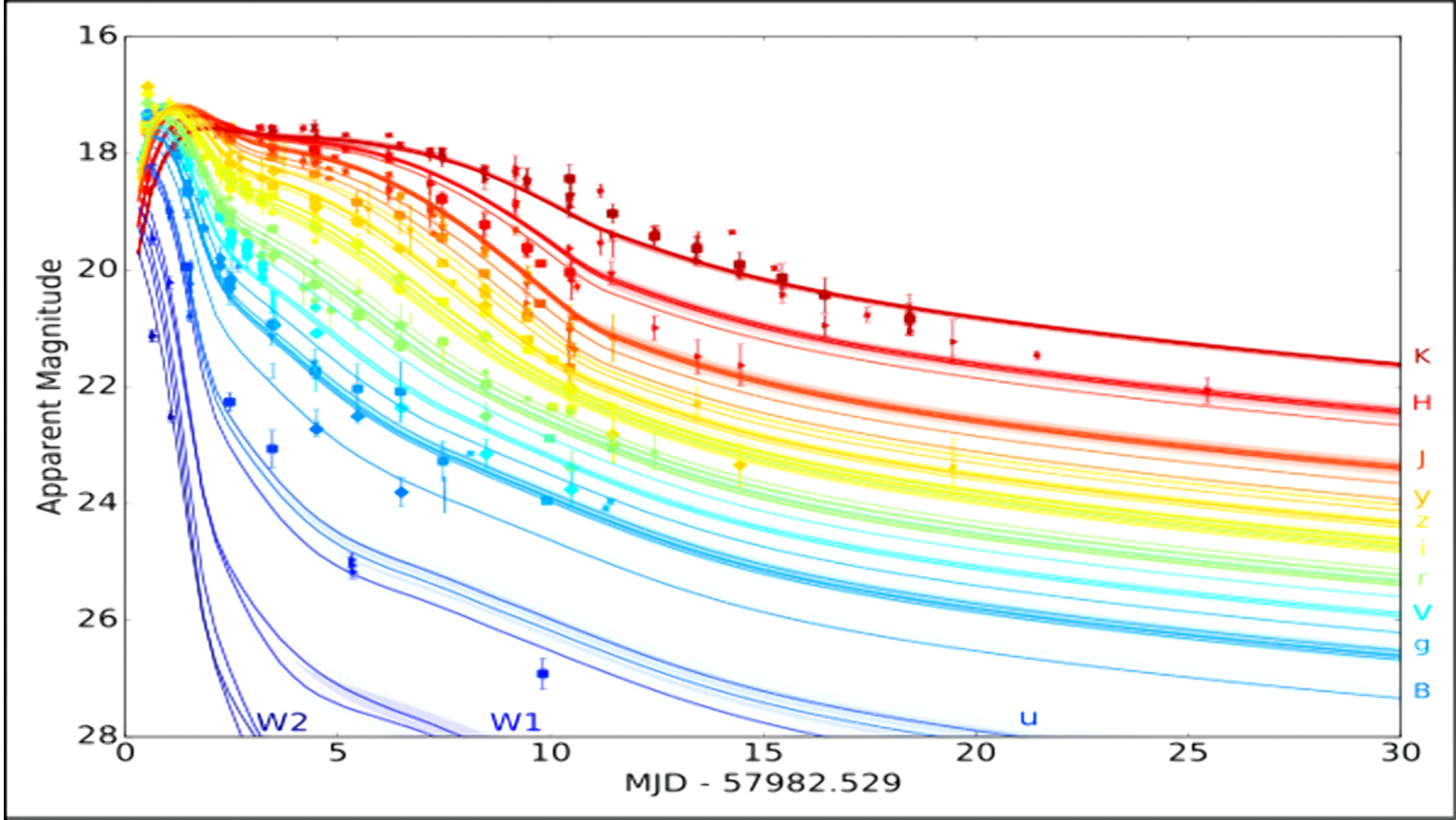
# Light Curves & Kilonova Models

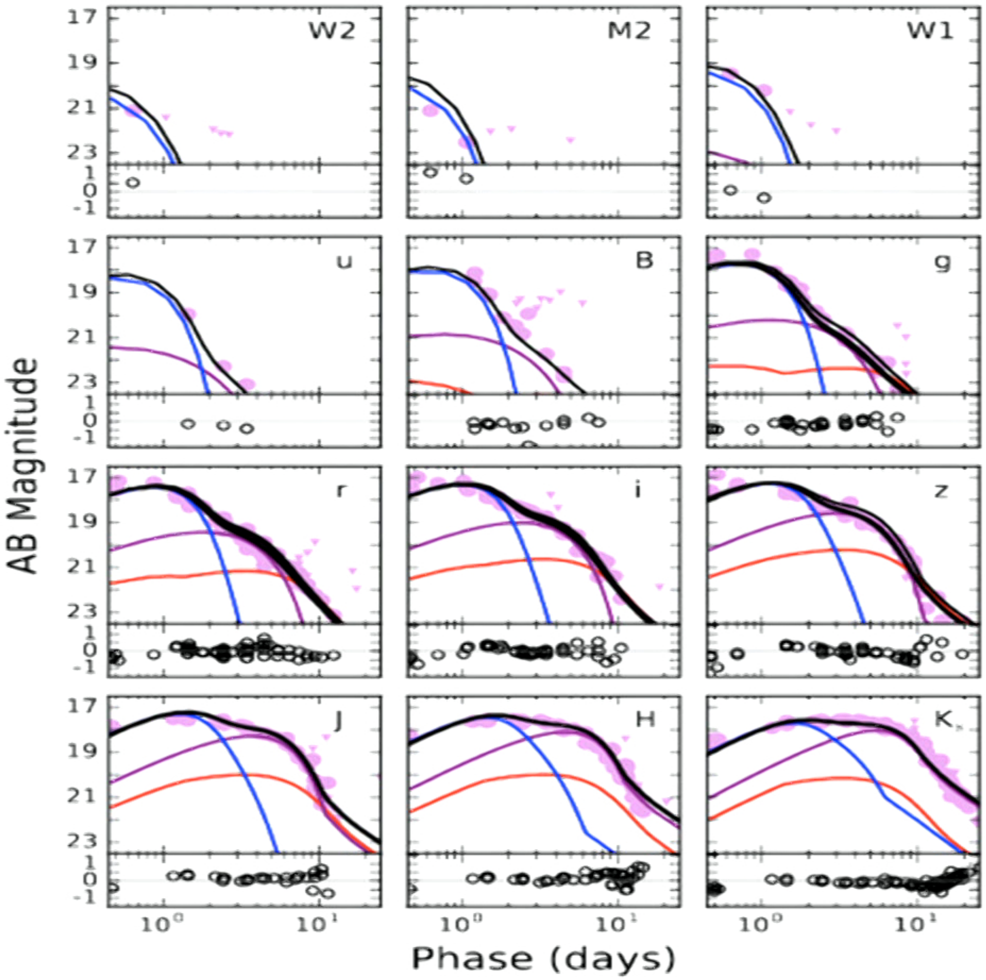
Villar, EB et al. 2017



Aggregated, homogenized & public (625 data points!)

16 individual data sets; 38 instruments; 35 filters. About 10% of the data had to be corrected or discarded due to inadequate photometry

# Light Curves & Kilonova Models



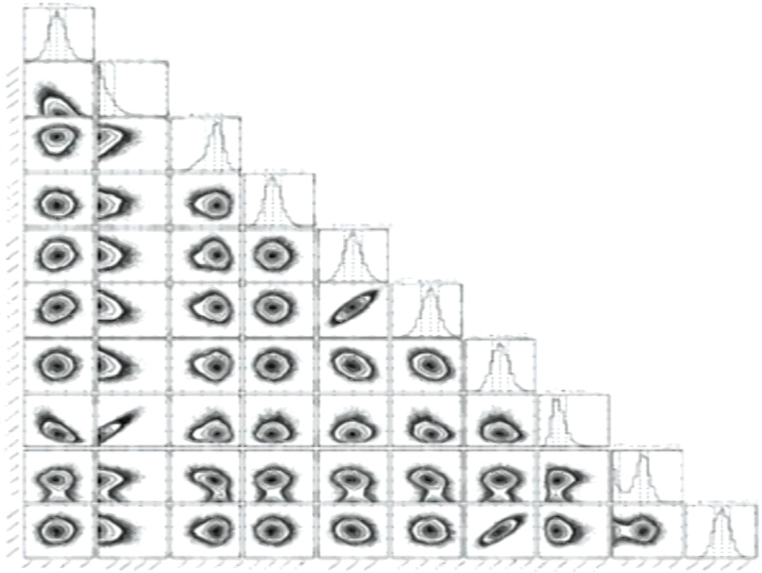
## Three-component model:

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

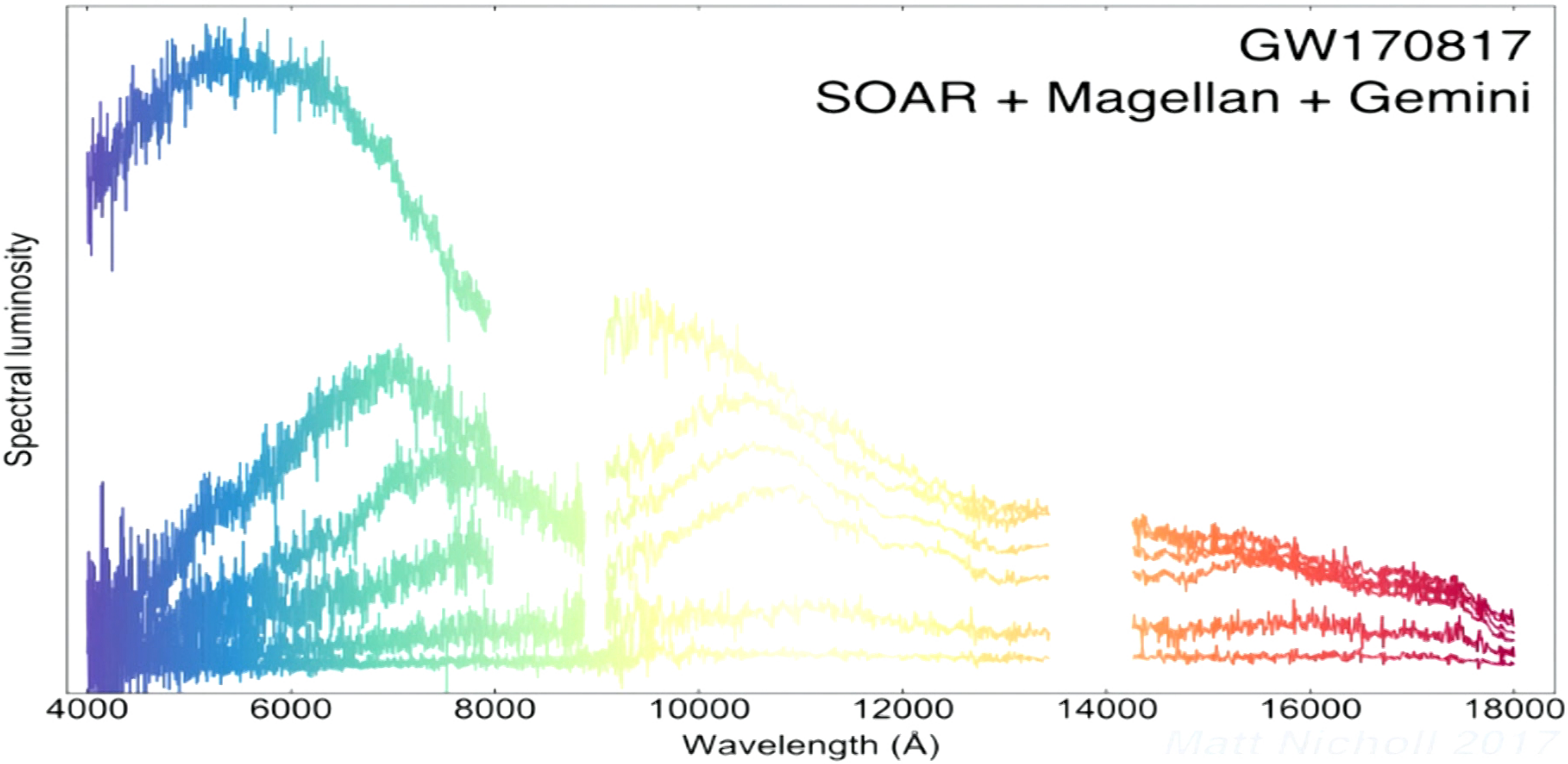
Purple: $M_{ej} \approx 0.040\ M_\odot$ / $v_{ej} \approx 0.14c$

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

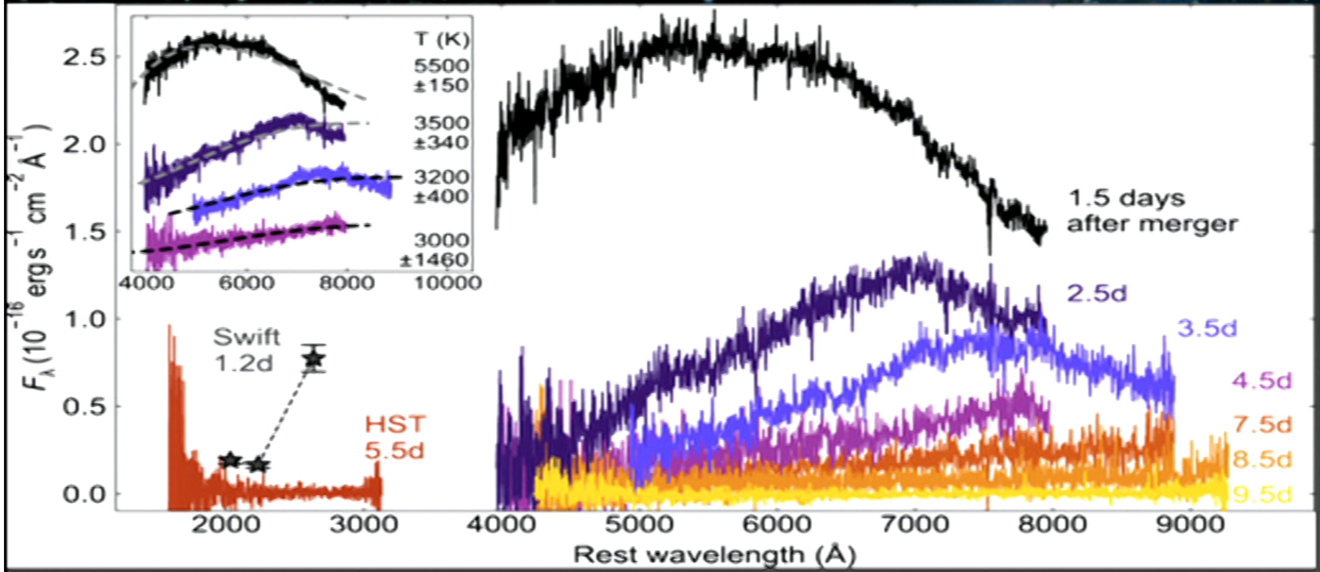
Villar, EB et al. 2017



# Spectroscopy



# Spectroscopy: Optical



Nicholl, EB et al. 2017

Optical spectra rapidly evolve from blue to red

At >2 days significant absorption in blue relative to blackbody emission

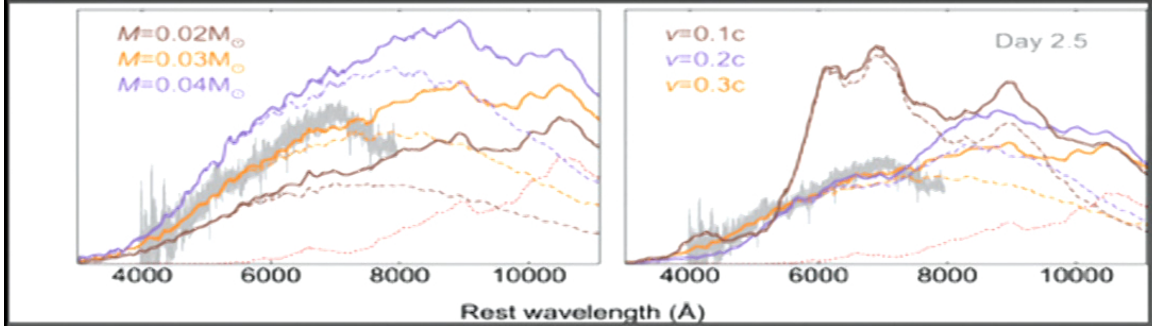
# Spectroscopy: Optical

Nicholl, EB et al. 2017

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

*Light curve modeling*

*Blue:* $M_{ej} \sim 0.02\ M_\odot$ / $v_{ej} \sim 0.3c$



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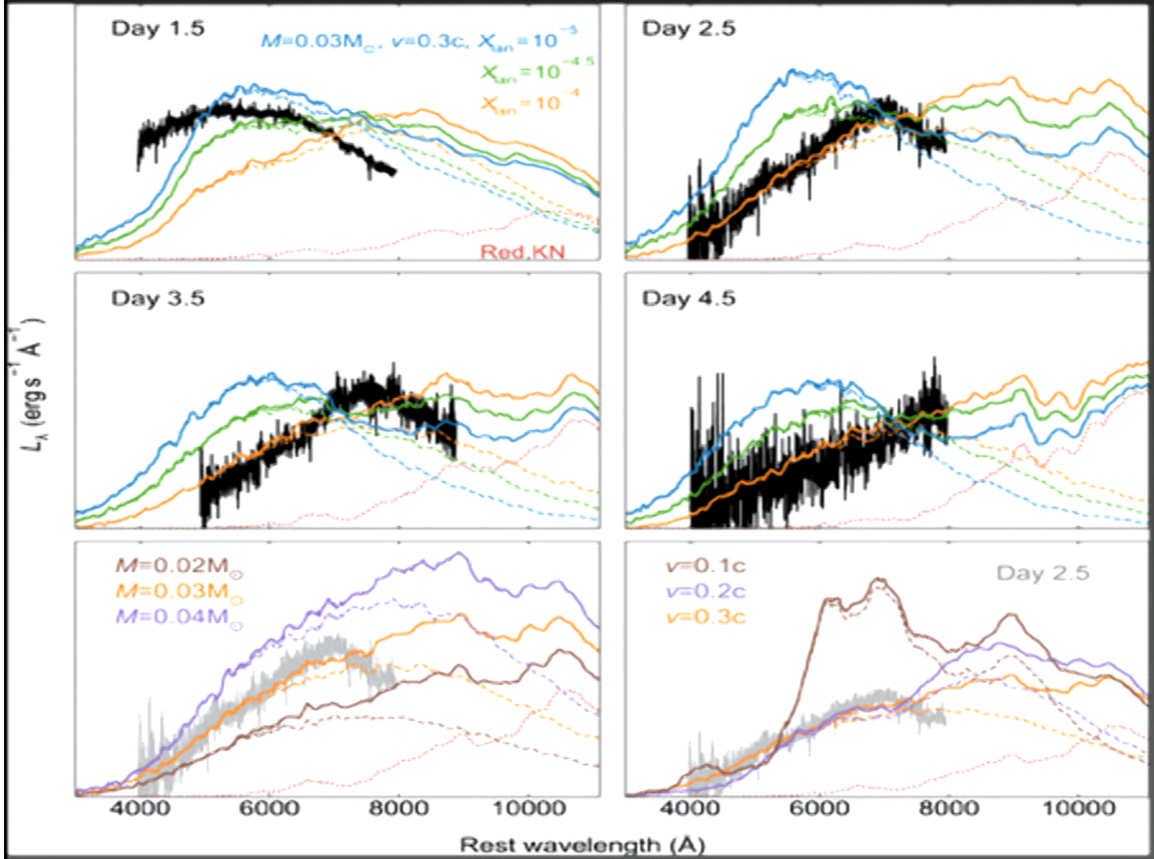
Nicholl, EB et al. 2017



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*Light curve modeling*

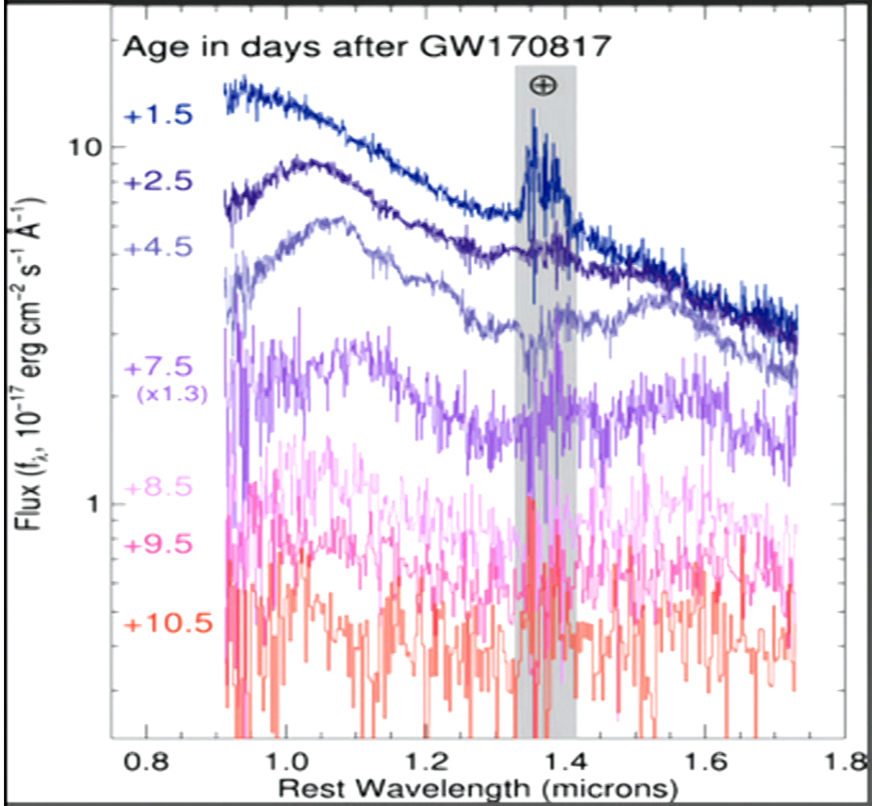
*Blue:* $M_{ej} \sim 0.02\ M_\odot$ / $v_{ej} \sim 0.3c$

Lanthanide fraction from spectra at 2.5-4.5 days is low, $\sim 10^{-4}$

Even lower at 1.5 days (chemical gradient?)

# Spectroscopy: Near-IR

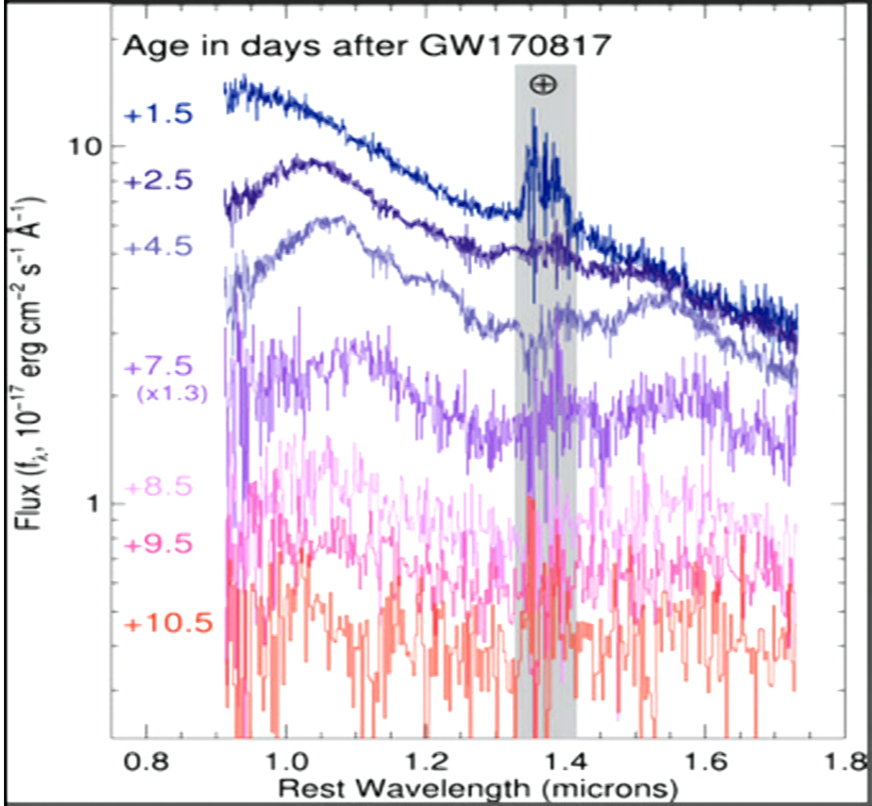
Chornock, EB et al. 2017



Unlike in the optical, the near-IR spectra show clear spectral features (i.e. lower velocity)

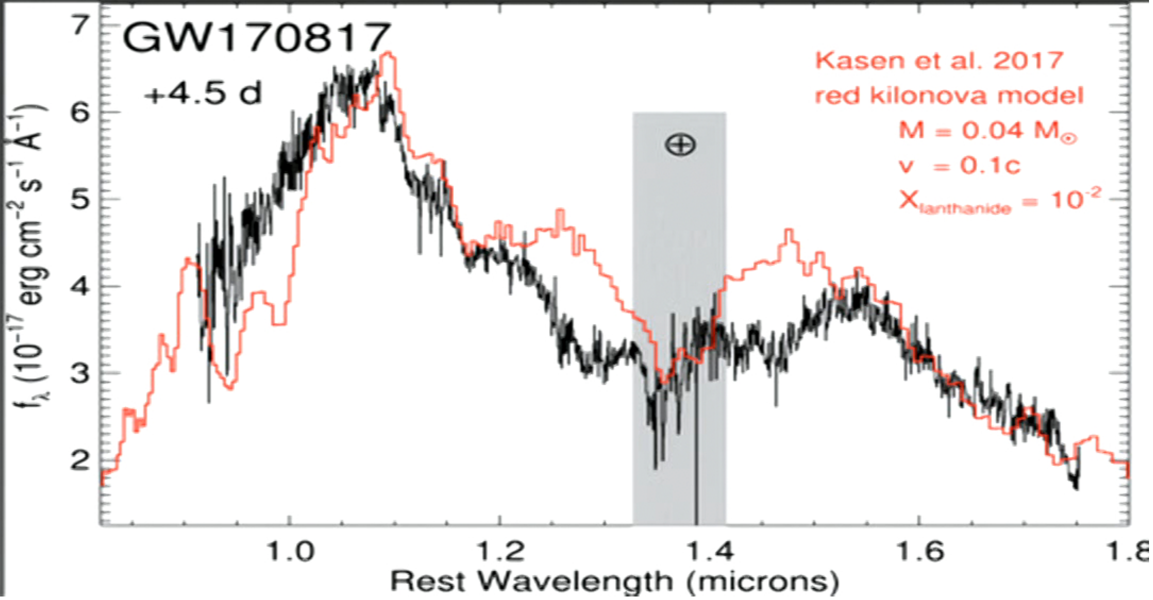
# Spectroscopy: Near-IR

Chornock, EB et al. 2017



Unlike in the optical, the near-IR spectra show clear spectral features (i.e. lower velocity)

Spectra well matched by red kilonova model



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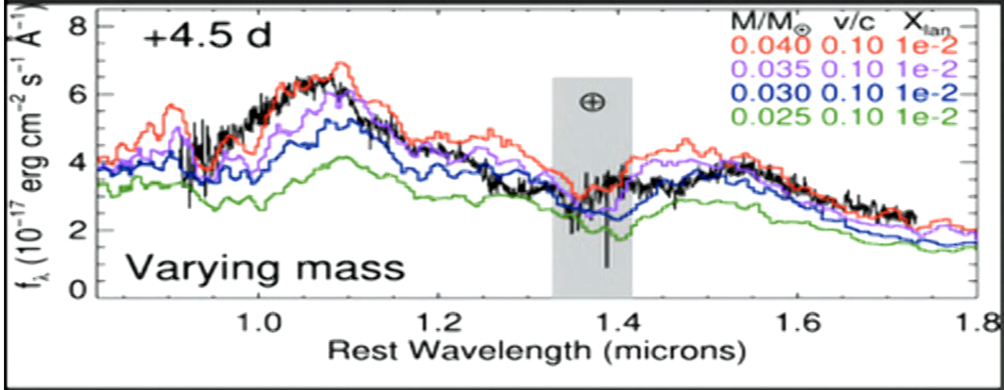
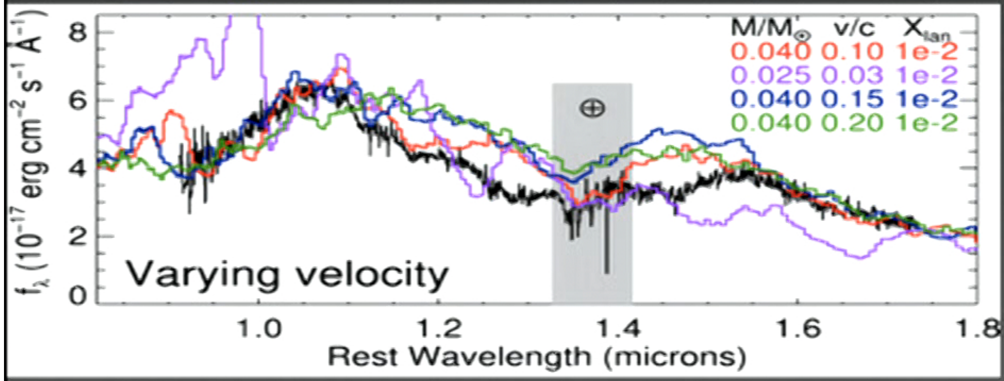


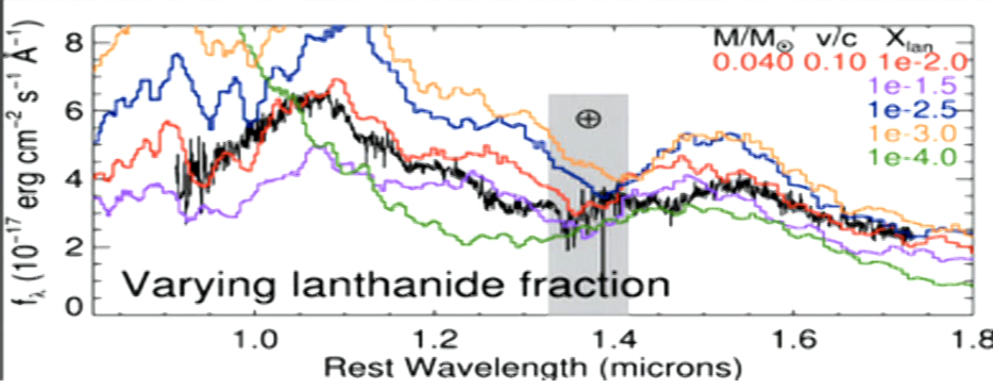


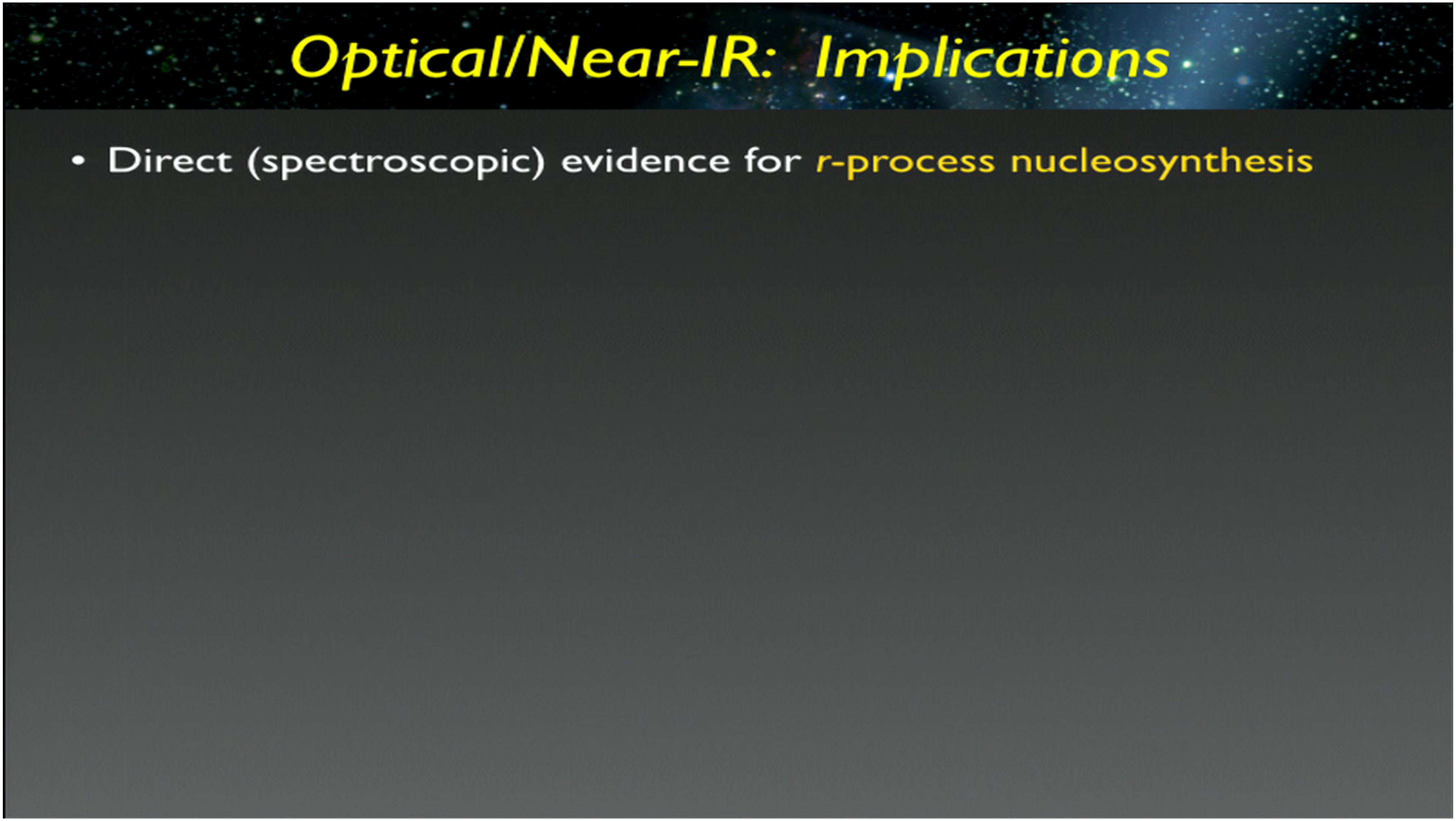
$M_{ej} \sim 0.04\ M_\odot$ / $v_{ej} \sim 0.1c$

*Light curve modeling*

*Red:* $M_{ej} \sim 0.05\ M_\odot$ / $v_{ej} \sim 0.1c$

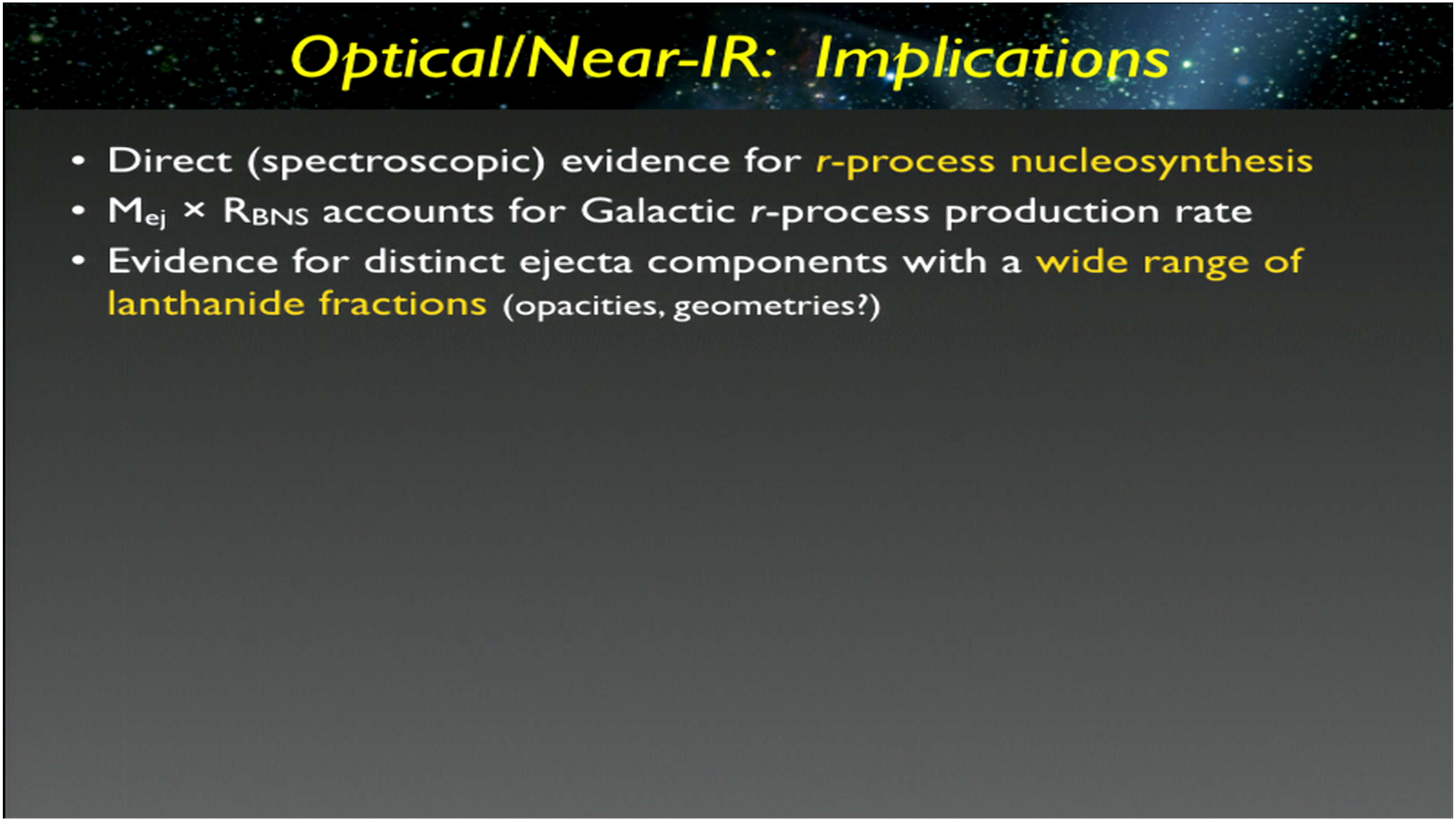
Lanthanide fraction inferred from near-IR spectra at >4.5 days is high, $\sim 10^{-2}$





# Optical/Near-IR: Implications

- Direct (spectroscopic) evidence for *r*-process nucleosynthesis



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- Evidence for distinct ejecta components with a wide range of lanthanide fractions (opacities, geometries?)

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- Blue component velocity indicates ejecta from collision interface $\Rightarrow$ NS-NS (not NS-BH or BH-BH; breaks ambiguity from GW data alone)

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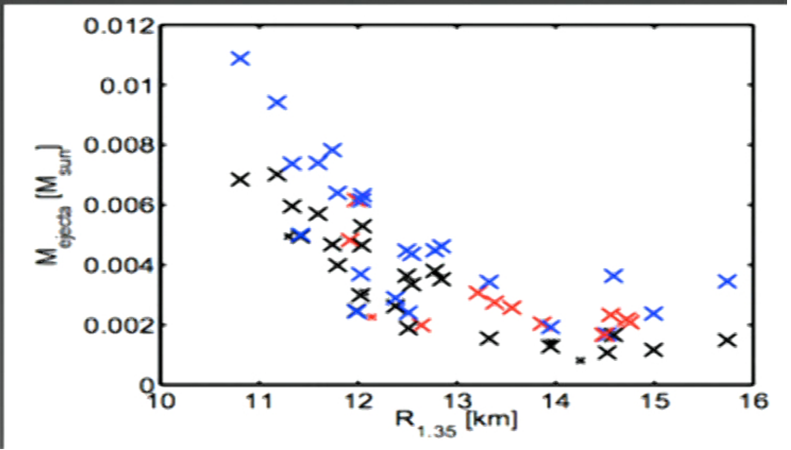

Bauswein et al. 2013

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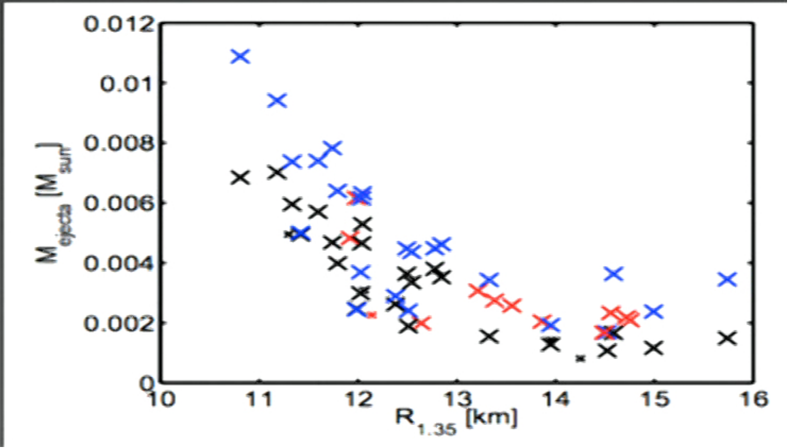
- Purple/red component velocity typical of accretion disk wind; distribution of opacity indicates short HMNS phase (≲30 ms) ⇒ final state is BH



Bauswein et al. 2013

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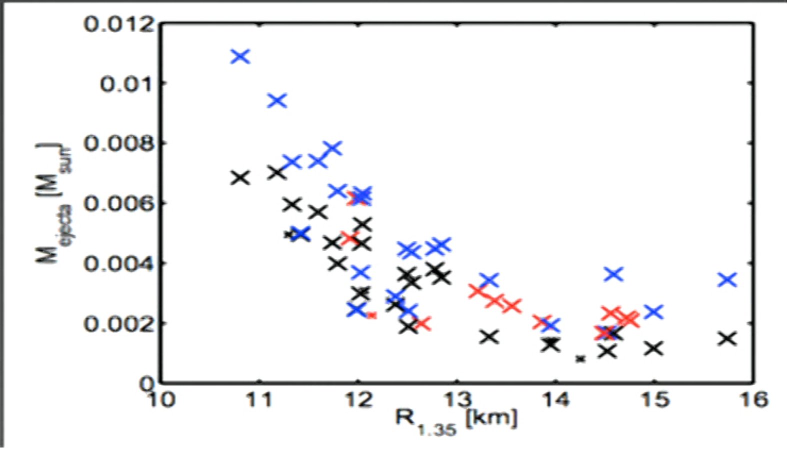
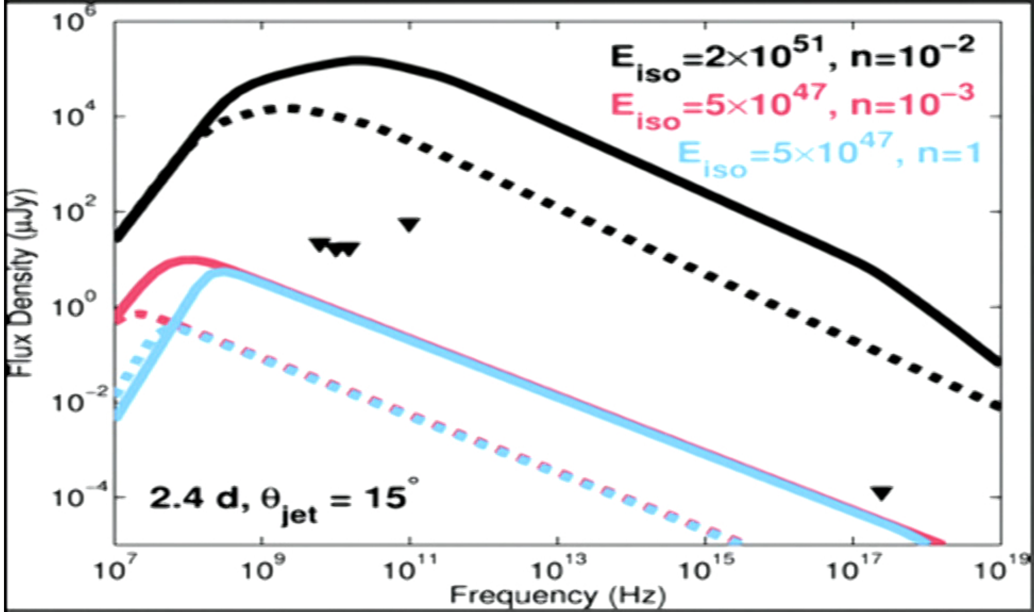
- Tidal tail component likely sub-dominant to disk wind



Bauswein et al. 2013

# Radio Counterpart: Off-axis Jet

Alexander, EB et al. 2017 (also Hallinan et al. 2017)

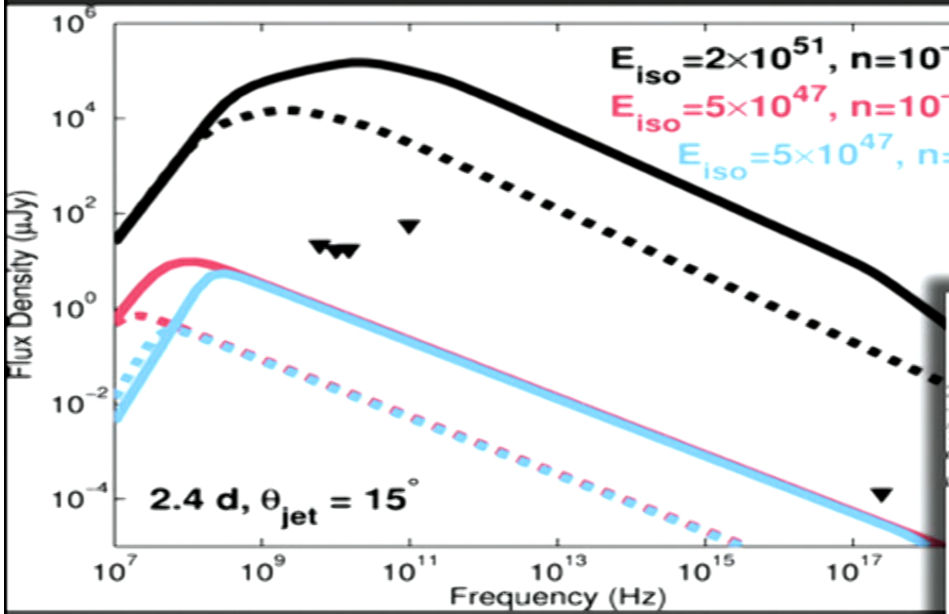


We obtained the first radio observation (VLA) 2.5 hours after discovering the optical counterpart. The source remained undetected until ~2 weeks post-merger

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

# Radio Counterpart: Off-axis Jet

Alexander, EB et al. 2017 (also Hallinan et al. 2017)



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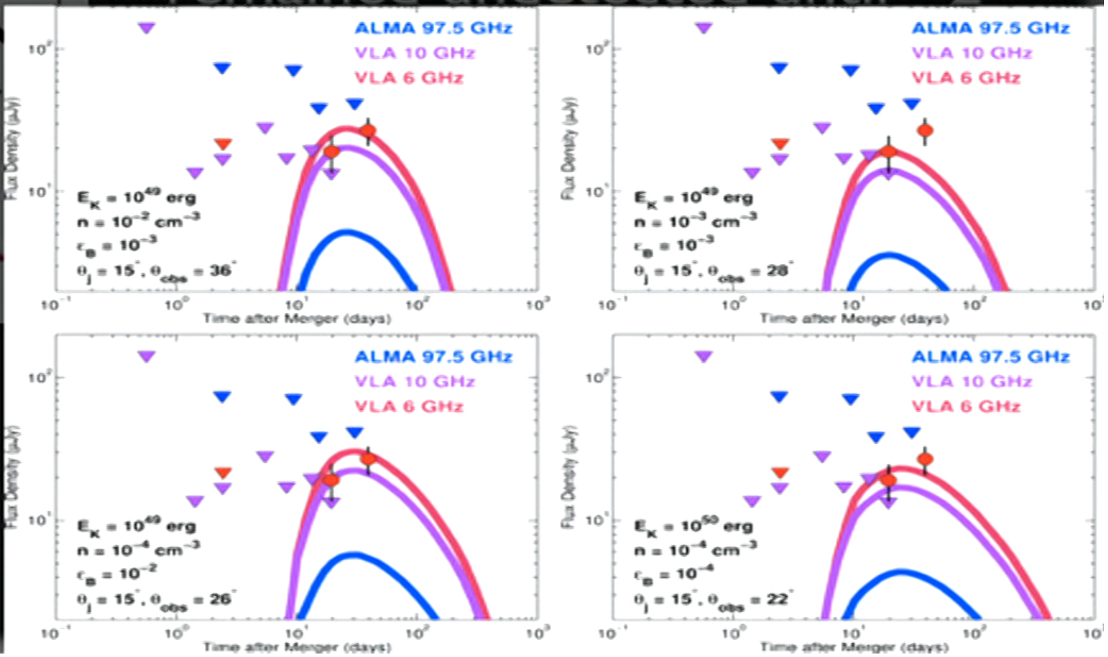
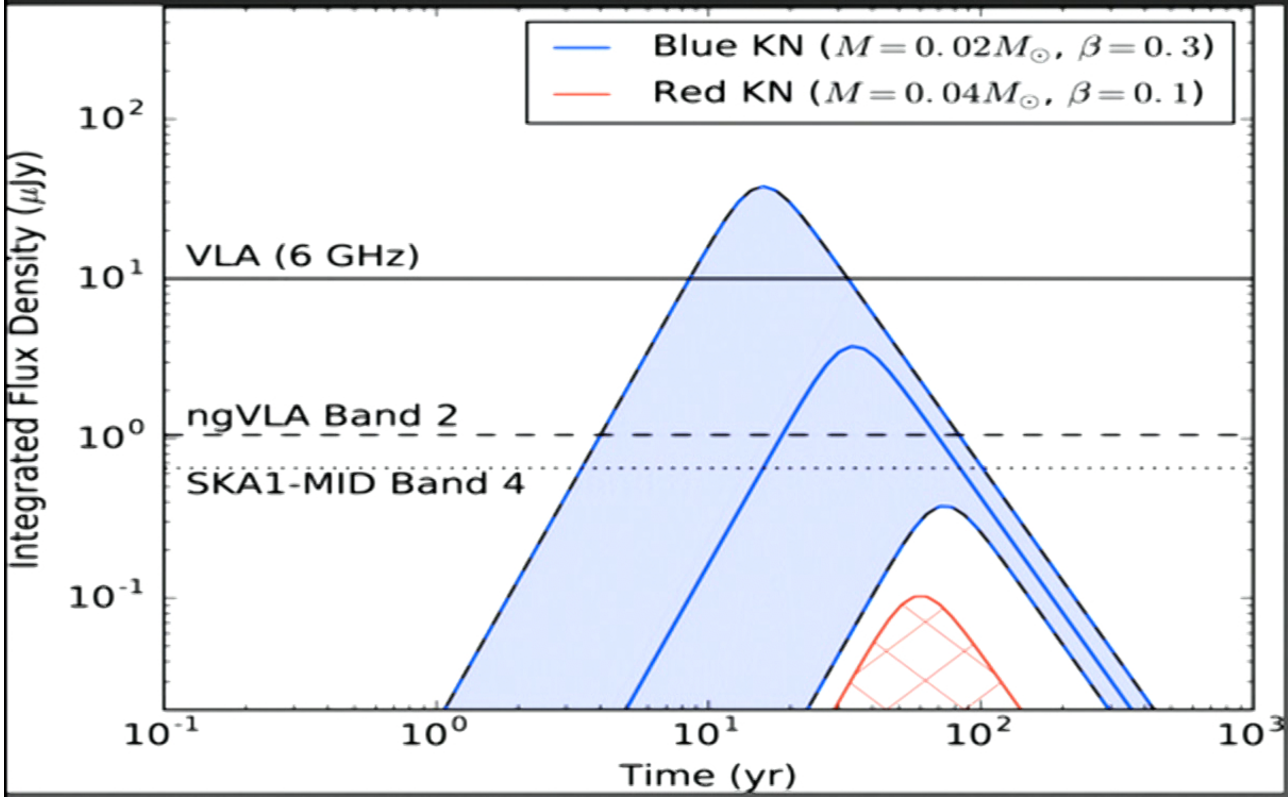


Late onset can be explained with an off-axis jet: $E_K \sim$ *few* $\times 10^{49}$ erg, $n \sim 0.01$ cm$^{-3}$, $\theta_{obs} \sim 20-40^\circ$

# Radio Counterpart: Kilonova

Alexander, EB et al. 2017

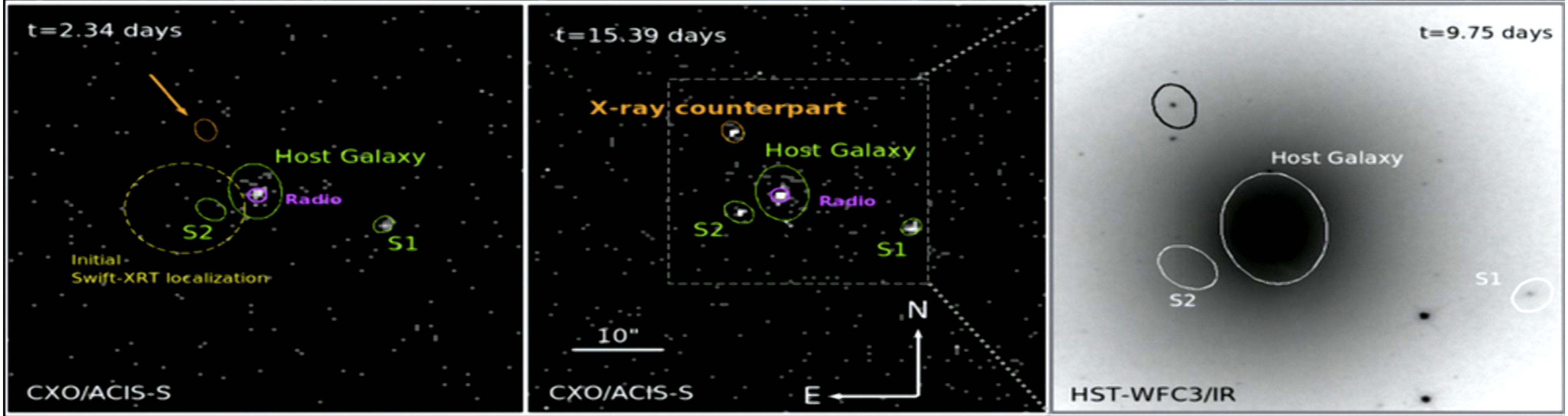


We also expect radio emission from the kilonova ejecta

The timescale is much longer since the ejecta mass is higher than for the relativistic jet

Weak (but detectable) emission in ~decade…

# X-ray Counterpart



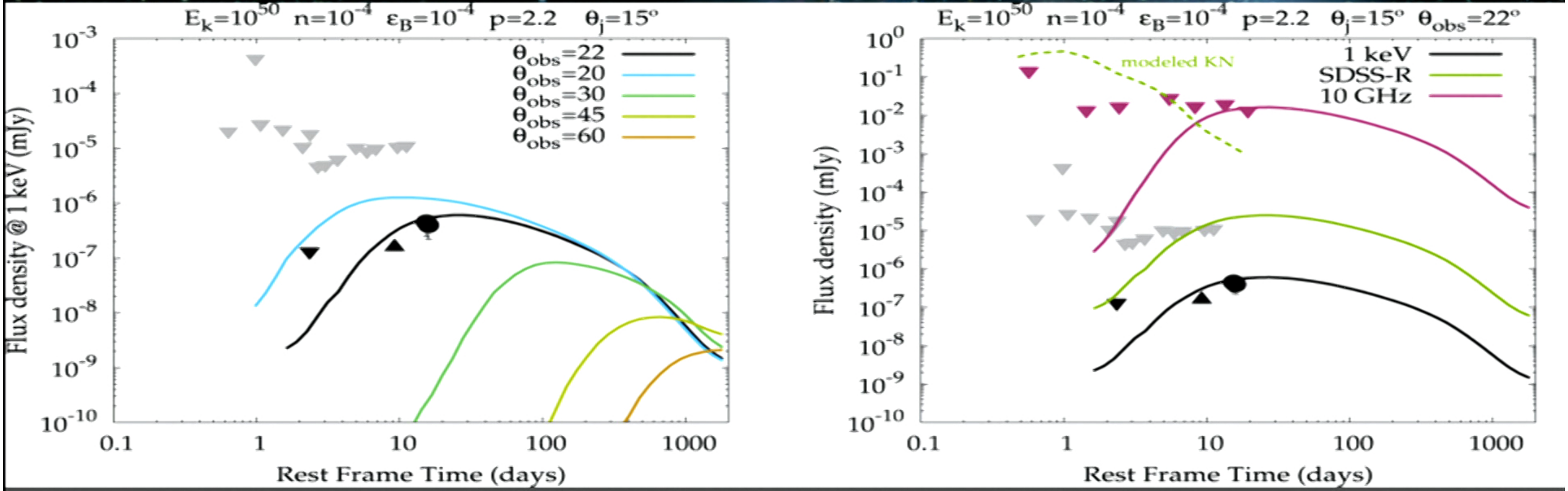
Margutti, EB et al. 2017 (also Troja et al. 2017)

First X-ray observations carried out with *Swift*/XRT ~4 hours after optical discovery (non-detection)

First deep observation with Chandra at 2.3 days (non-detection)

X-ray emission detected at ~10-15 days

# X-ray Counterpart: Off-axis Jet



The late-onset X-ray and radio emission are consistent with the same off-axis jet model

The off-axis optical emission is much fainter than the kilonova

Margutti, EB et al. 2017

# Radio/X-ray: Implications

- On-axis afterglow typical of short GRBs is ruled out
- A late (on-axis / isotropic) afterglow onset, due to deceleration of a mildly relativistic outflow can explain the X-ray data but violates the radio limits

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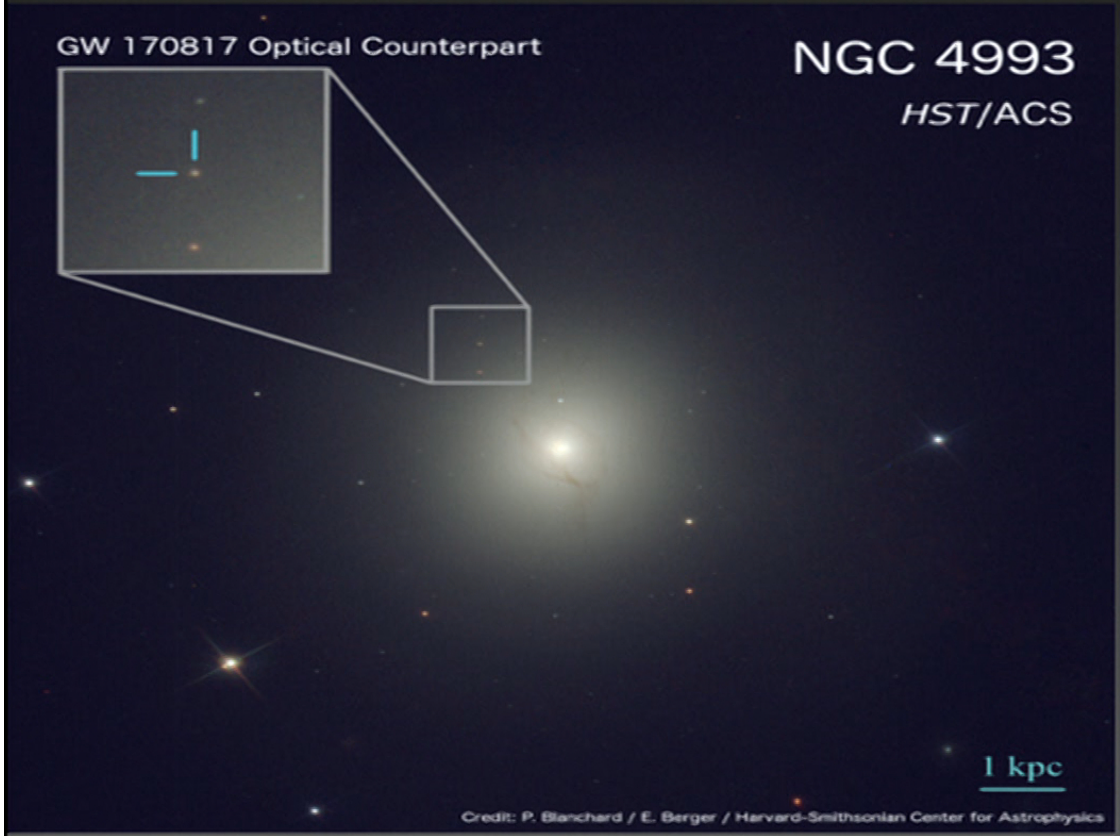
- A central engine origin of the X-ray emission is ruled out since the kilonova ejecta has an X-ray optical depth of $\sim 10^2$
- The radio and X-ray data are consistent with a relativistic jet with $E_K \sim few \times 10^{49}$ erg, $n \sim 0.01$ cm$^{-3}$, $\theta_{obs} \sim 20-40°$ typical of short GRBs

# Host Galaxy

Blanchard, EB et al. 2017



Credit: P. Blanchard / E. Berger / Harvard-Smithsonian Center for Astrophysics

Offset from the host center is 2.2 kpc

*Detected in radio/X-rays: weak AGN*

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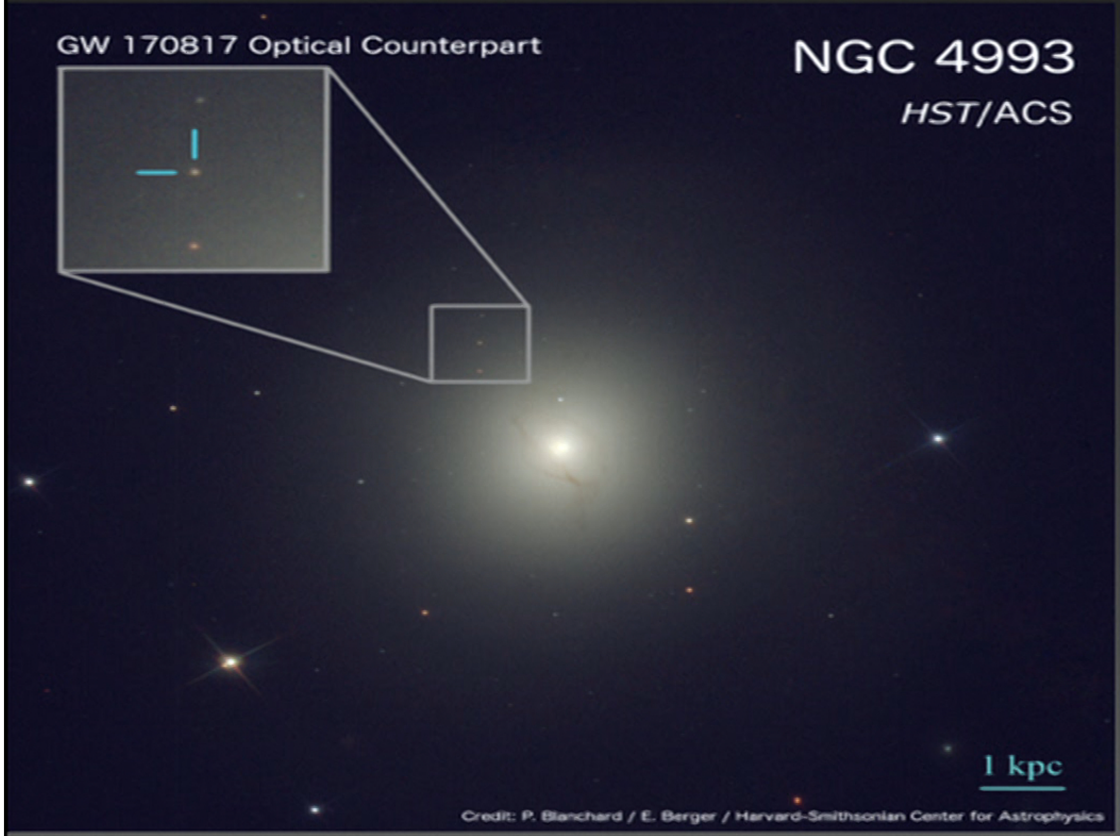

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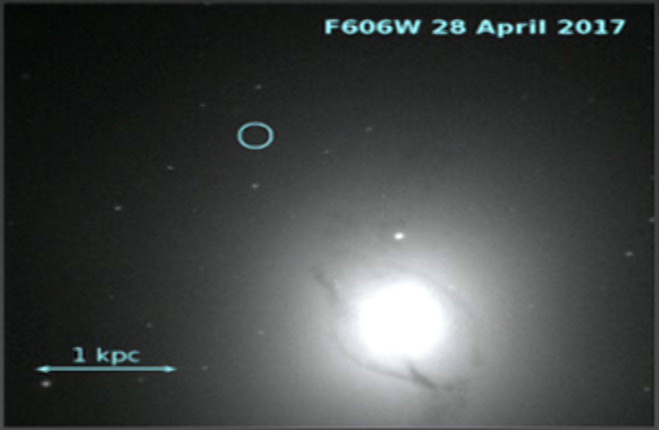

Limit from April 2017 HST data rules out globular cluster brighter than the median of the GC luminosity function

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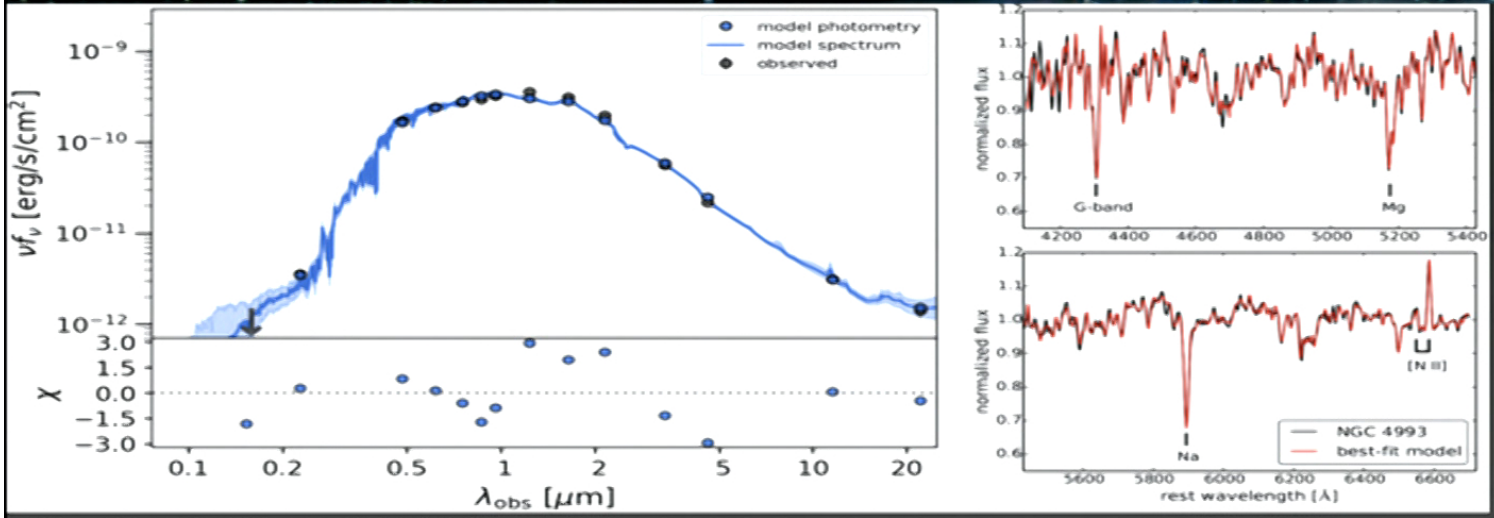

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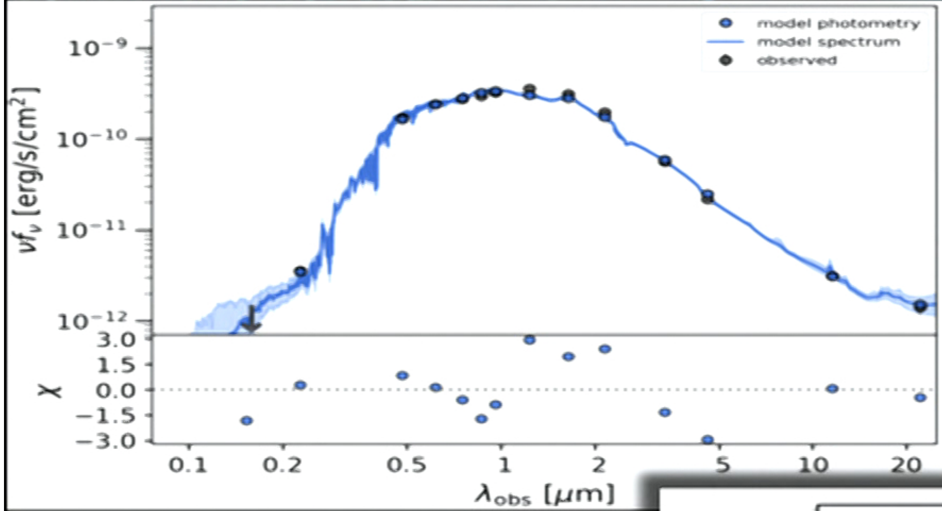
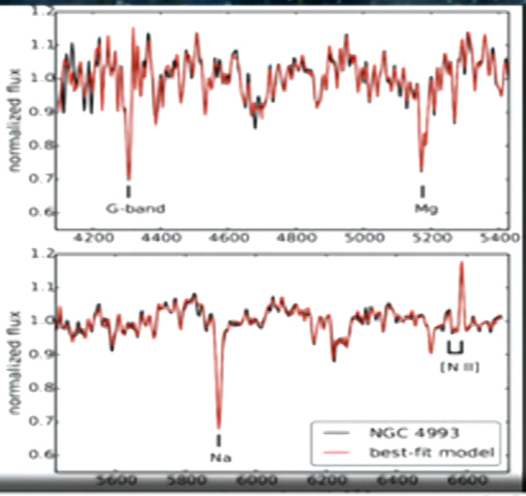
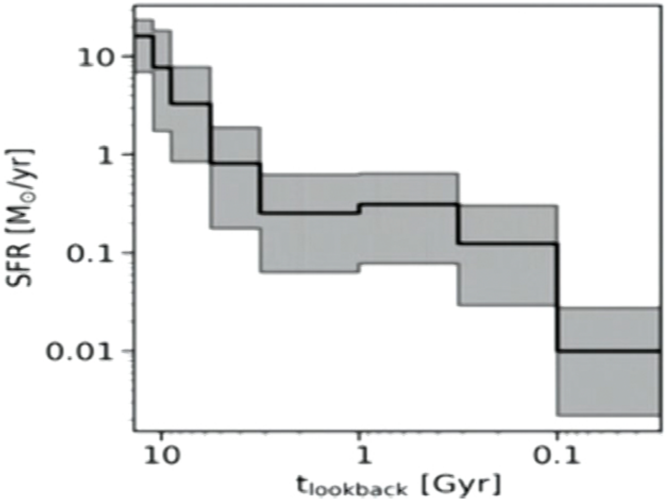
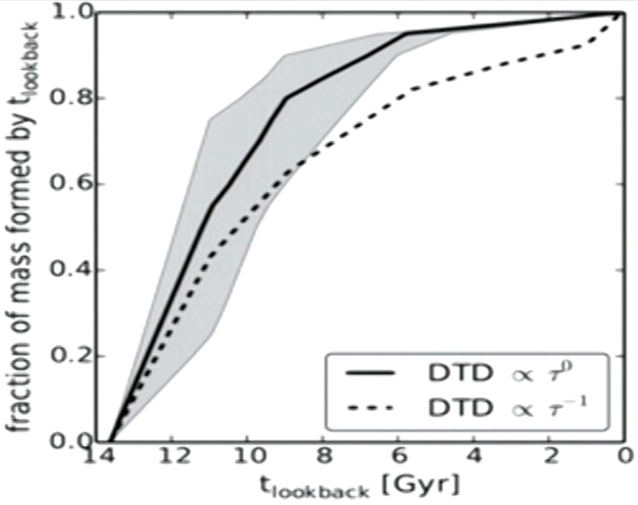




Blanchard, EB et al. 2017

Median stellar population age ~11 Gyr





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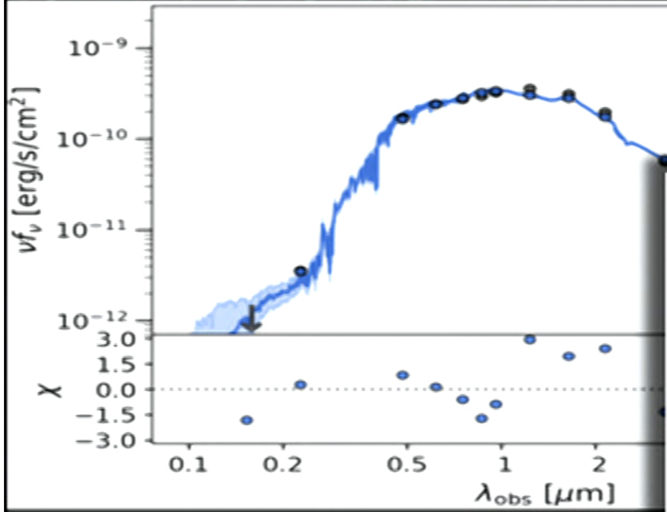

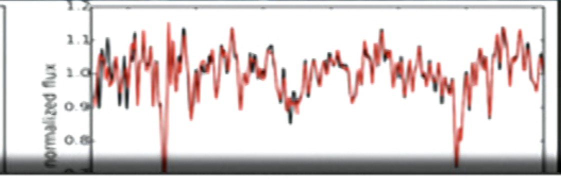

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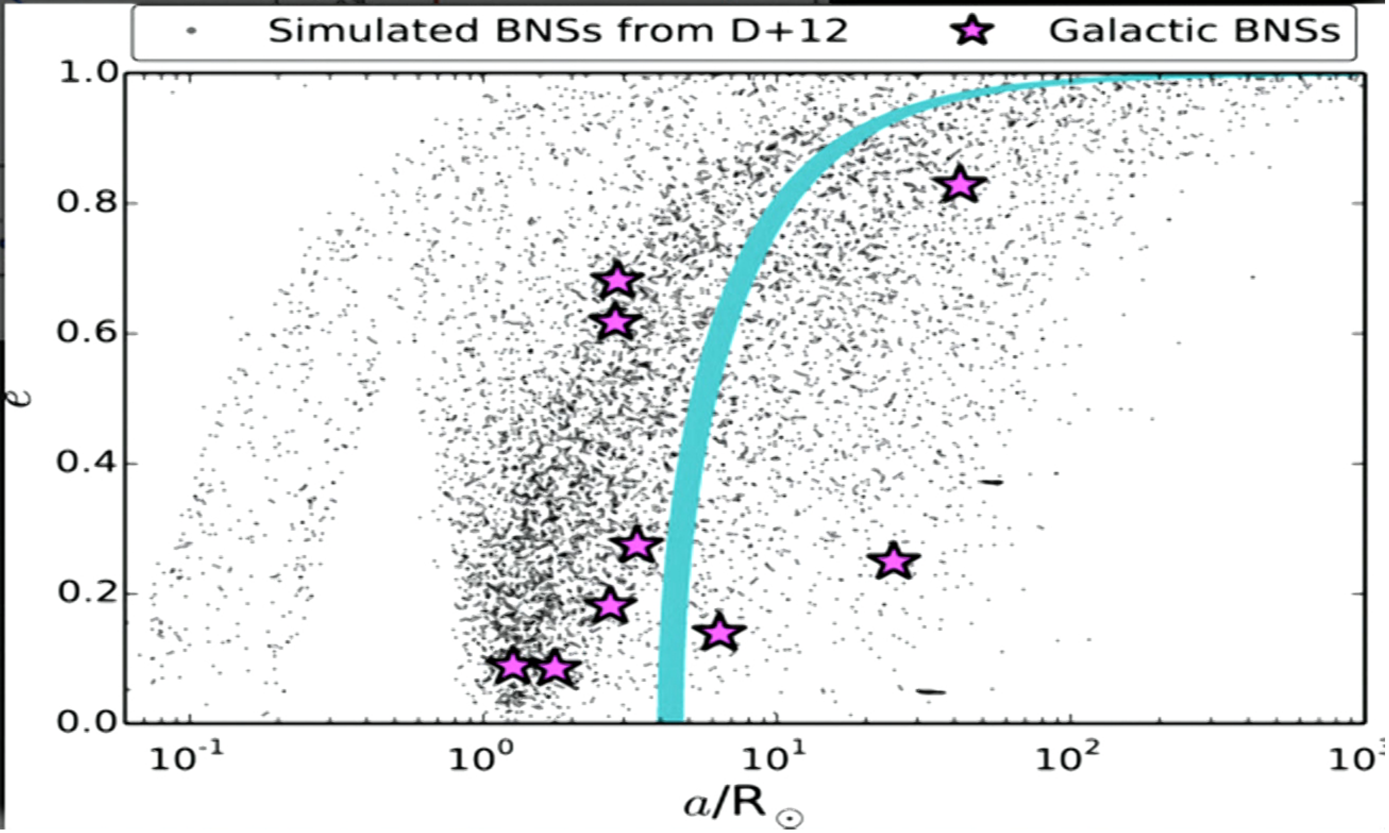
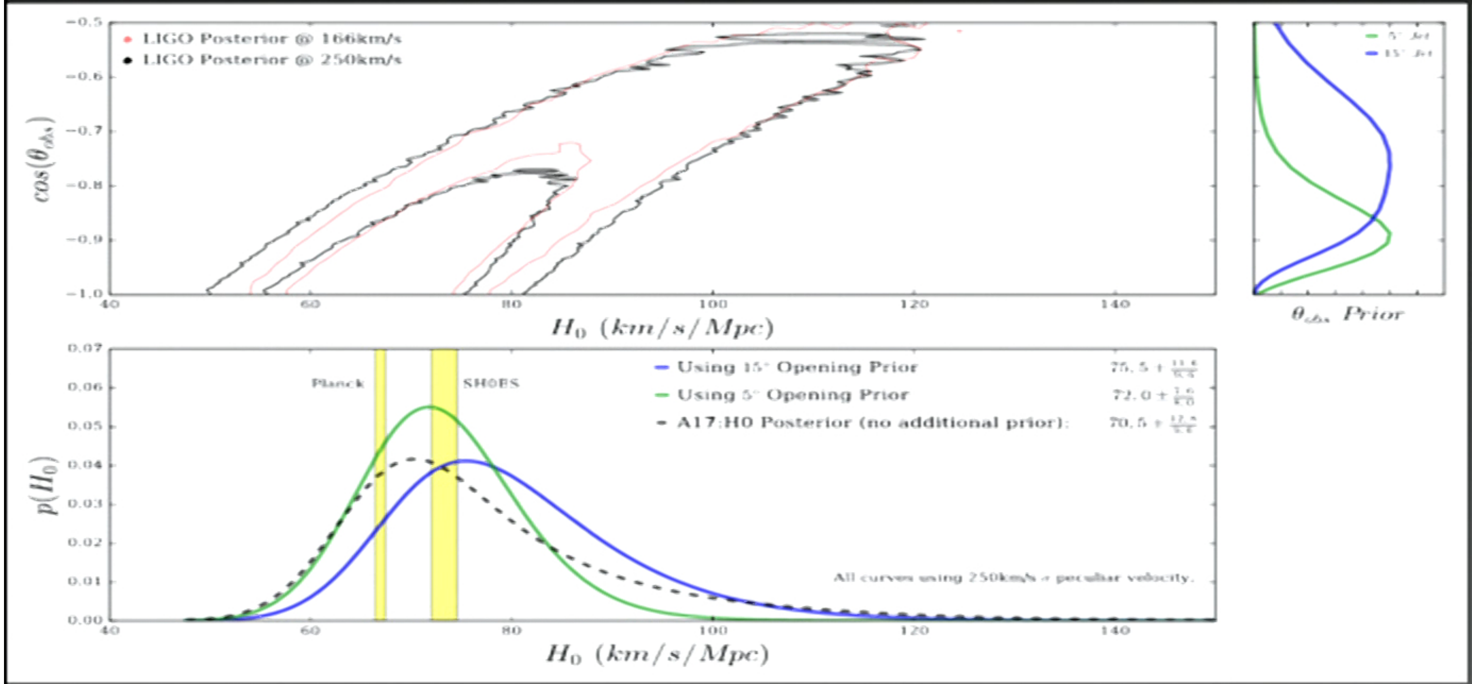


Initial binary separation was ~4.5 $R_\odot$

# Hubble Constant

Abbott et al. 2017 (+EB); Guidorzi, EB, et al. 2017



## *Standard Siren*:

The combination of distance (GW) and redshift (EM) can be used to measure the Hubble constant ($v = H_0 \times d$)

# Future Directions

Advanced LIGO/Virgo O3 should have 1.5× larger sensitivity
⇒ BNS detections to ~120 Mpc and 3.5× detection rate

Advanced LIGO/Virgo design will have 2.5× larger sensitivity
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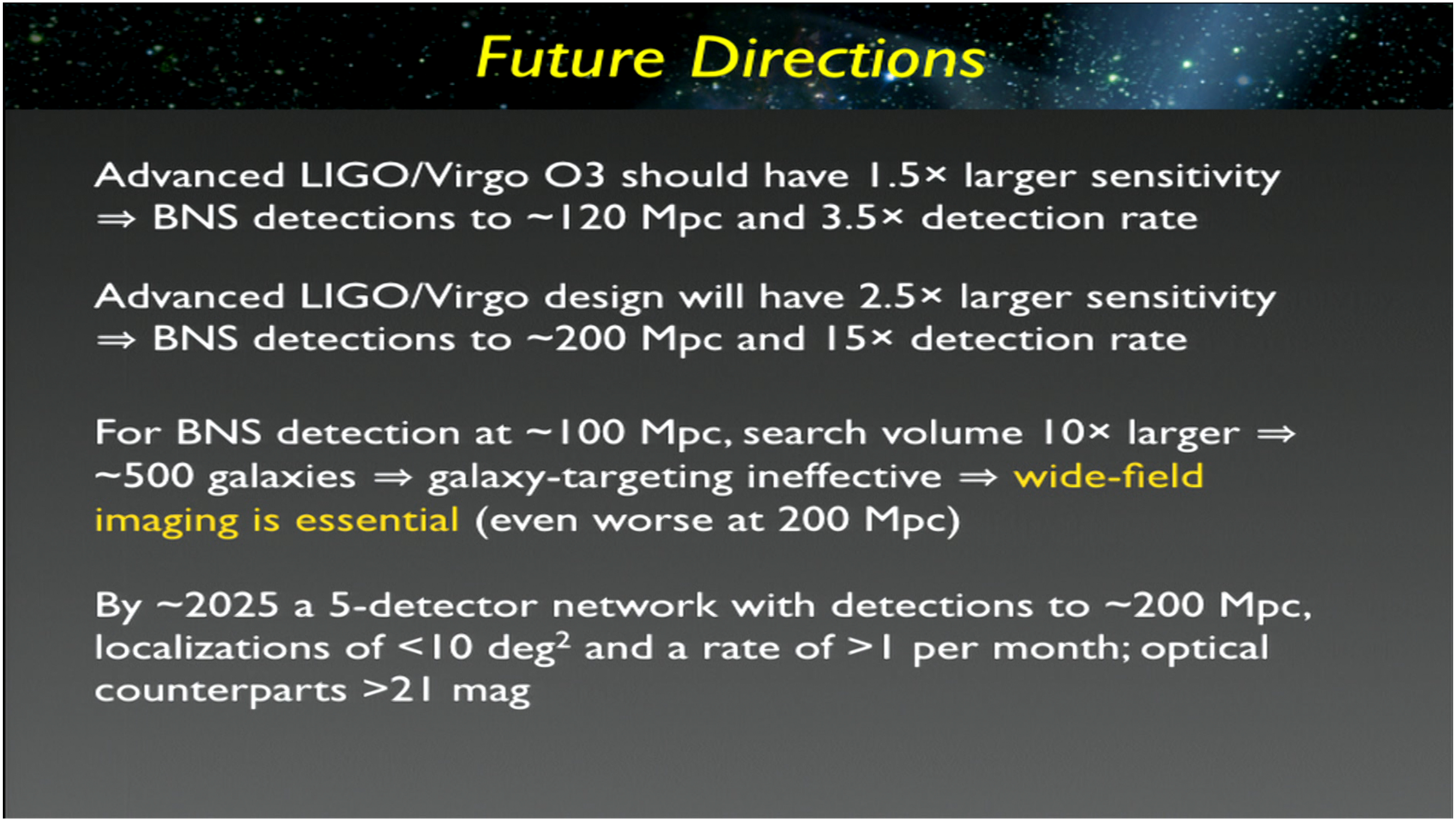

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By ~2025 a 5-detector network with detections to ~200 Mpc, localizations of <10 deg$^2$ and a rate of >1 per month; optical counterparts >21 mag

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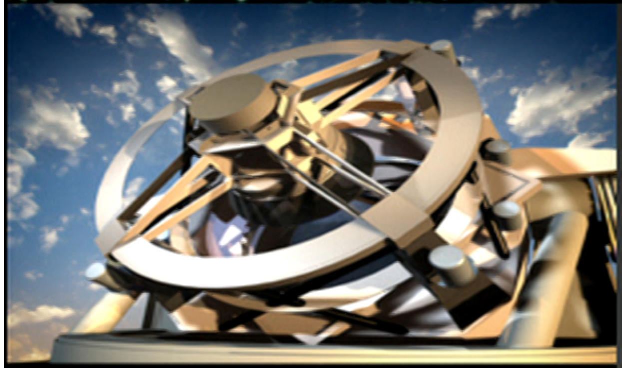
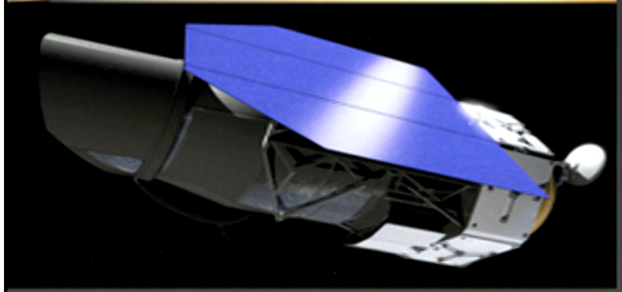


10 deg$^2$
0.35-1 micron
24 mag in 10 sec



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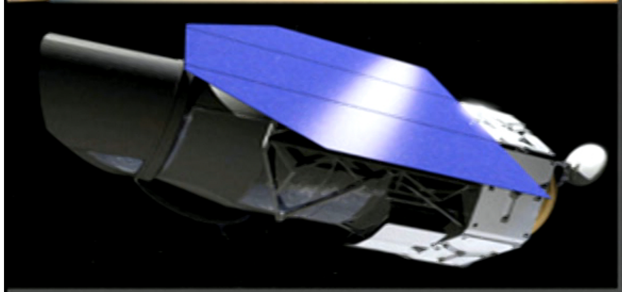

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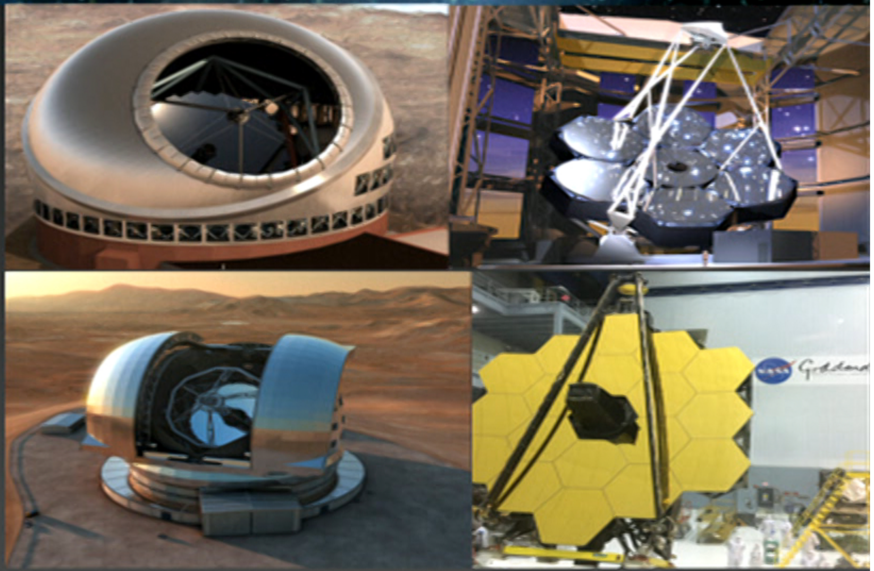

Spectra in photospheric phase to establish velocities & in the nebular phase to establish composition

# An Unparalleled Story of Firsts

- First gravitational wave detection of a neutron star binary merger
- First joint detection of gravitational waves and EM radiation
- First direct confirmation that short GRBs result from BNS mergers
- First detection of an off-axis short GRB
- First direct evidence for *r*-process nucleosynthesis in a neutron star binary merger
- First evidence that *r*-process nucleosynthesis is dominated by neutron star binary mergers
- First use of a neutron star binary merger "standard siren" approach to measuring the Hubble Constant
- Best constraints on the relative speed of light and gravity

`http://kilonova.org`