Sometimes What Glitters is Gold

The Detection of an Optical Counterpart to a Neutron Star-Neutron Star Merger

Ben Shappee & Maria Drout

CSP

October 28, 2017

GW170817 Papers

Query Results from the ADS Database

Go to bottom of page

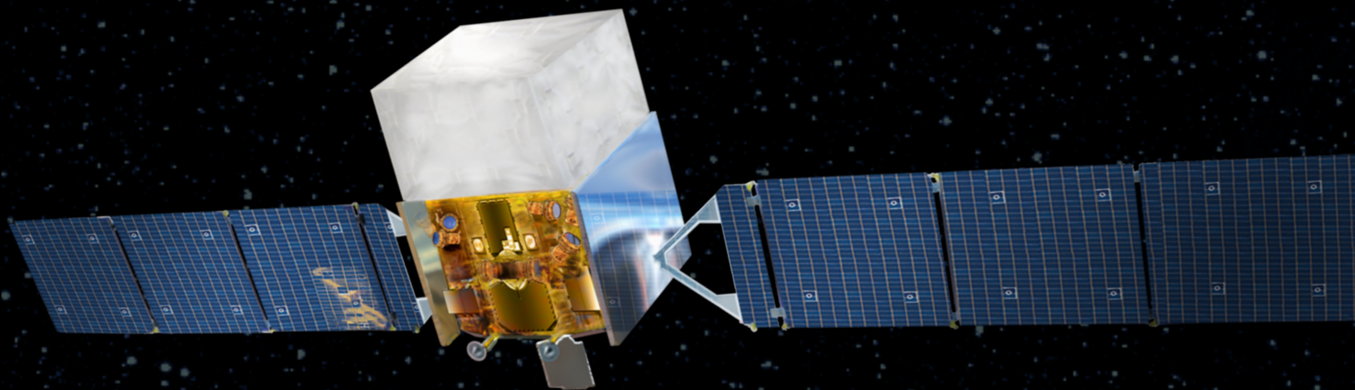
Selected and retrieved 77 abstracts. Total citations: **19**

Sort options

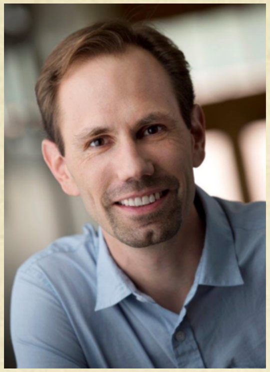
#	Bibcode / Authors	Cites	Date	List of Links / Title
1	2017arXiv171005432S Shappee, B. J.; Simon, J. D.; Drout, M. R.; Piro, A. L.; Morrell, N.; Prieto, J. L.; Kasen, D.; Holoien, T. W.-S.; Kollmeier, J. A.; Kelson, D. D.; and 26 coauthors	3.000	10/2017	A Z X R C U Early Spectra of the Gravitational Wave Source GW170817: Evolution of a Neutron Star Merger
2	2017arXiv171005452C Coulter, D. A.; Foley, R. J.; Kilpatrick, C. D.; Drout, M. R.; Piro, A. L.; Shappee, B. J.; Siebert, M. R.; Simon, J. D.; Ulloa, N.; Kasen, D.; and 7 coauthors	2.000	10/2017	A Z X R C U Swope Supernova Survey 2017a (SSS17a), the Optical Counterpart to a Gravitational Wave Source
3	2017arXiv171005443D Drout, M. R.; Piro, A. L.; Shappee, B. J.; Kilpatrick, C. D.; Simon, J. D.; Contreras, C.; Coulter, D. A.; Foley, R. J.; Siebert, M. R.; Morrell, N.; and 34 coauthors	2.000	10/2017	A Z X R C U Light Curves of the Neutron Star Merger GW170817/SSS17a: Implications for R-Process Nucleosynthesis
4	2017arXiv171005434K Kilpatrick, Charles D.; Foley, Ryan J.; Kasen, Daniel; Murguia-Berthier, Ariadna; Ramirez-Ruiz, Enrico; Coulter, David A.; Drout, Maria R.; Piro, Anthony L.; Shappee, Benjamin J.; Boutsia, Konstantina; and 11 coauthors	2.000	10/2017	A Z X R C U Electromagnetic Evidence that SSS17a is the Result of a Binary Neutron Star Merger
5	2017arXiv171005901M	1.000	10/2017	A Z X R C U

Column headings as printed: # Bibcode / Authors; Cites; Date; List of Links / Access Control Help; Title

The Discovery Actors



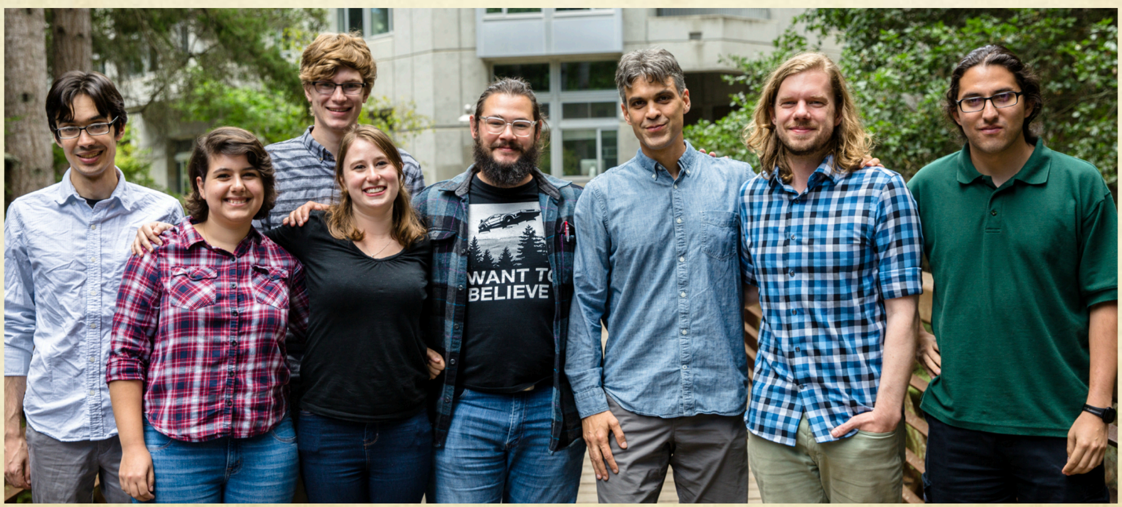
Carnegie Observatories





+ Juna, Barry, Carlos, Konstantina, Francesco, David
and observations from 12 other OCIW/LCO scientists and 18 other scientists

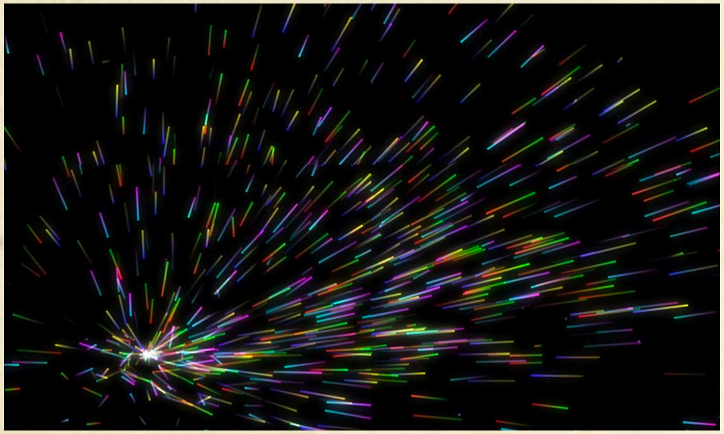
UC Santa Cruz



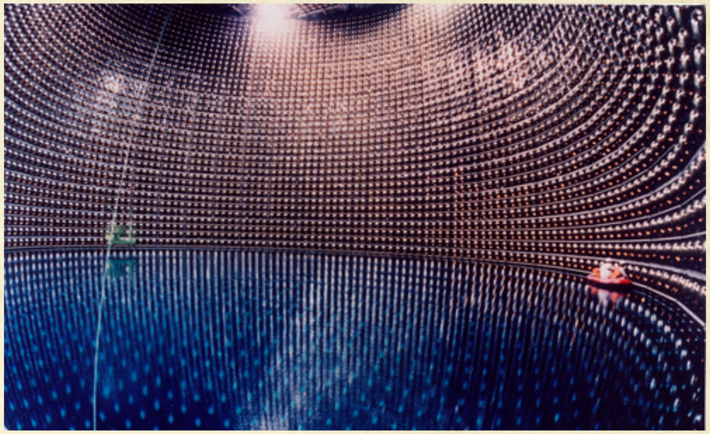
+ 70 observatories and 1500 physicists/astronomers around the world

Multi-messenger Astronomy

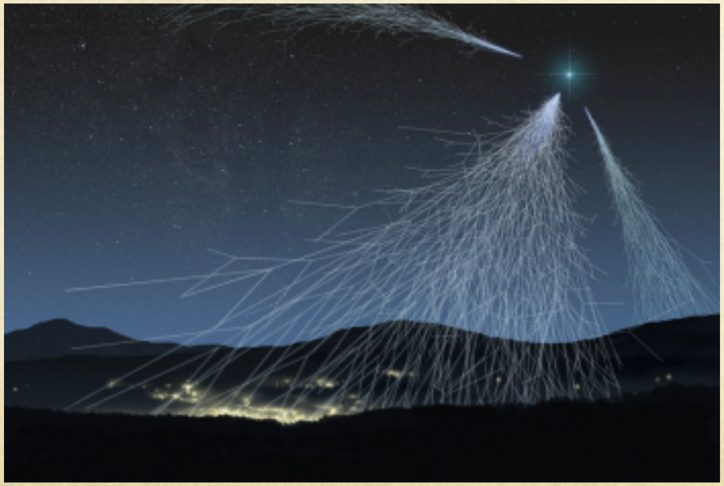
Multi-messenger Astronomy



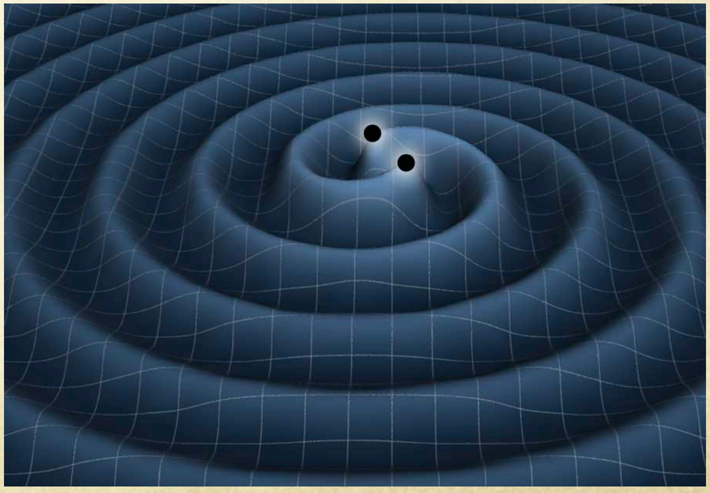
Photons



Neutrinos



Cosmic-Rays



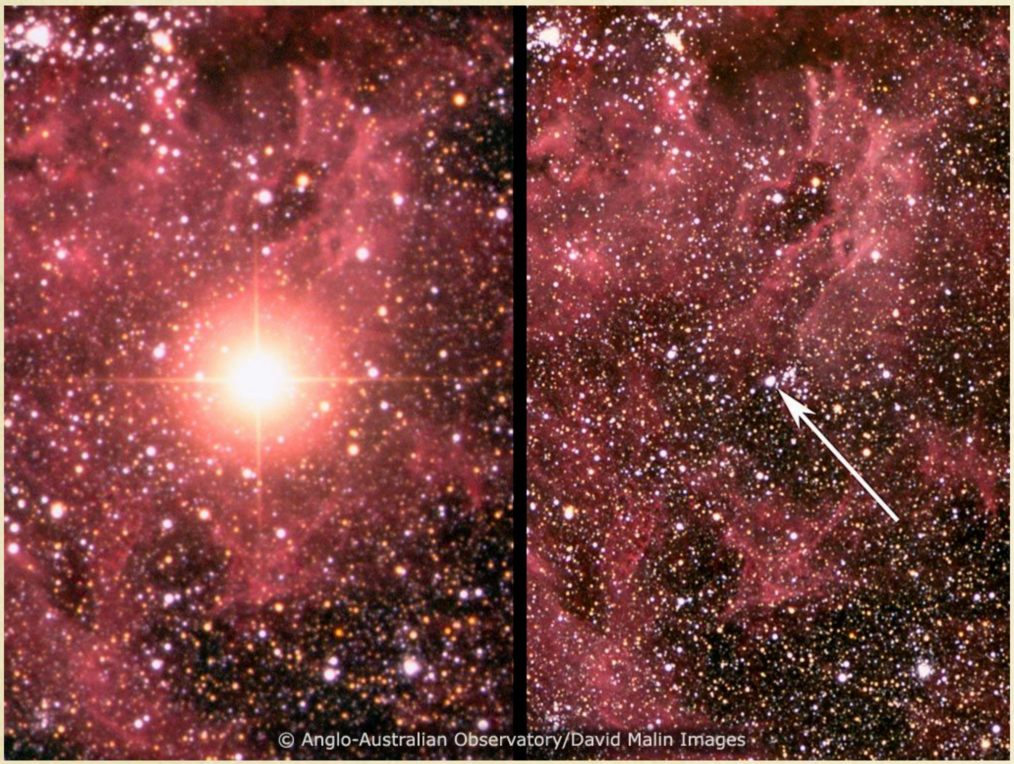
Gravitational Waves

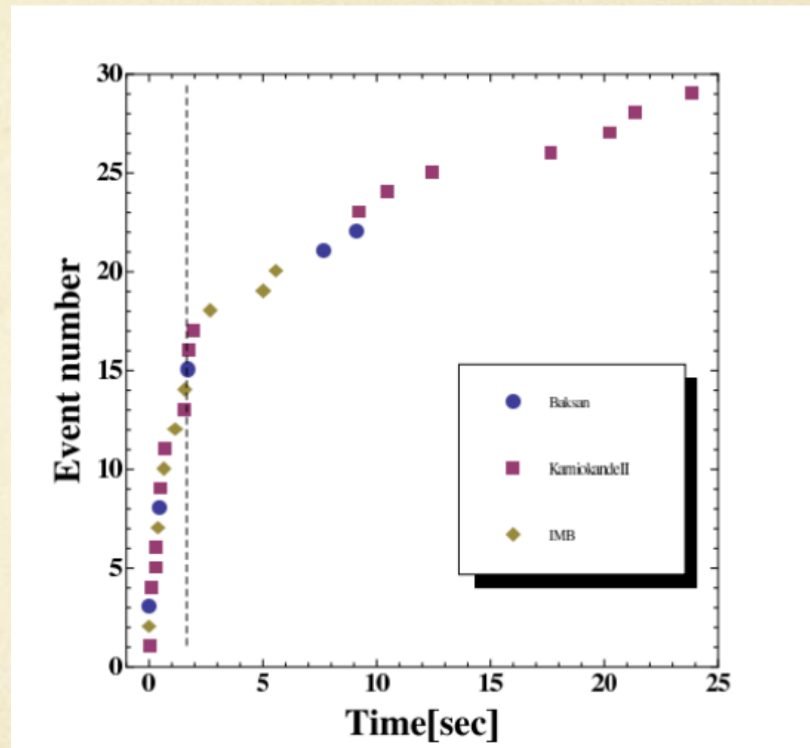
Multi-messenger Astronomy

Success Stories

Multi-messenger Astronomy
Success Stories

SN1987A: photons + neutrinos





Vissani et al. (2010)

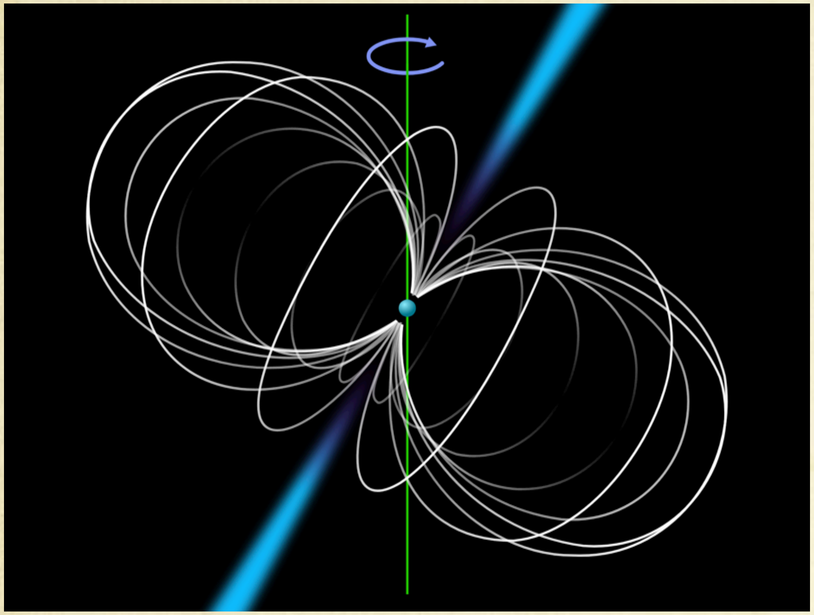
Multi-messenger Astronomy

Gravitational Wave

Gravitational Waves

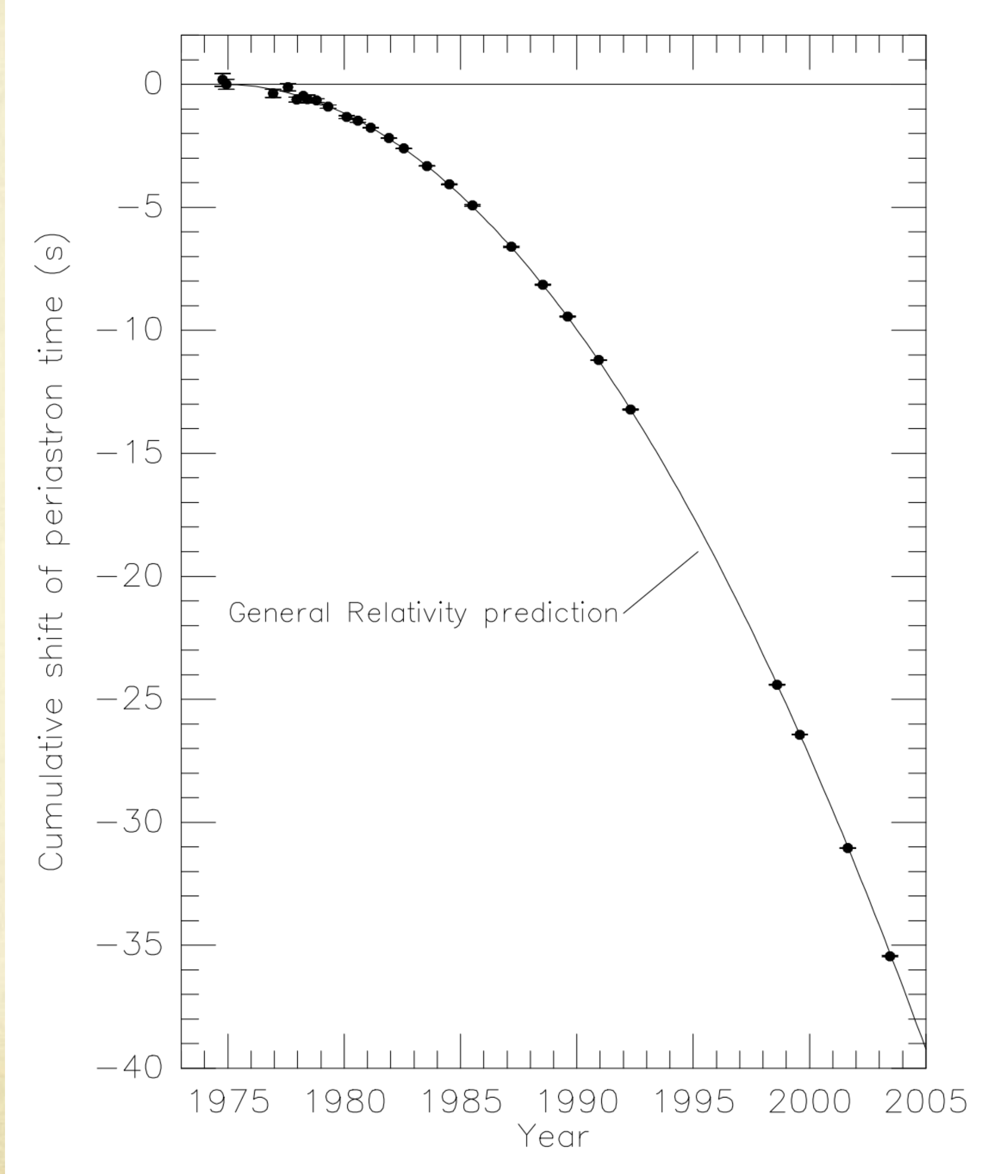
$$t_{\rm GW} = \frac{3}{85}\frac{a_1}{c}\left(\frac{a_1^3 c^6}{G^3 m_0 m_1 M}\right)(1-e_1^2)^{7/2}$$
$$\simeq 1.6\times 10^{13}\,{\rm yr}\left(\frac{2\,M_\odot^3}{m_0 m_1 M}\right)\left(\frac{a_1}{0.1\,{\rm AU}}\right)^4(1-e_1^2)^{7/2},$$

Hulse-Taylor binary



Measured Orbital Parameters for PSR B1913+16

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)



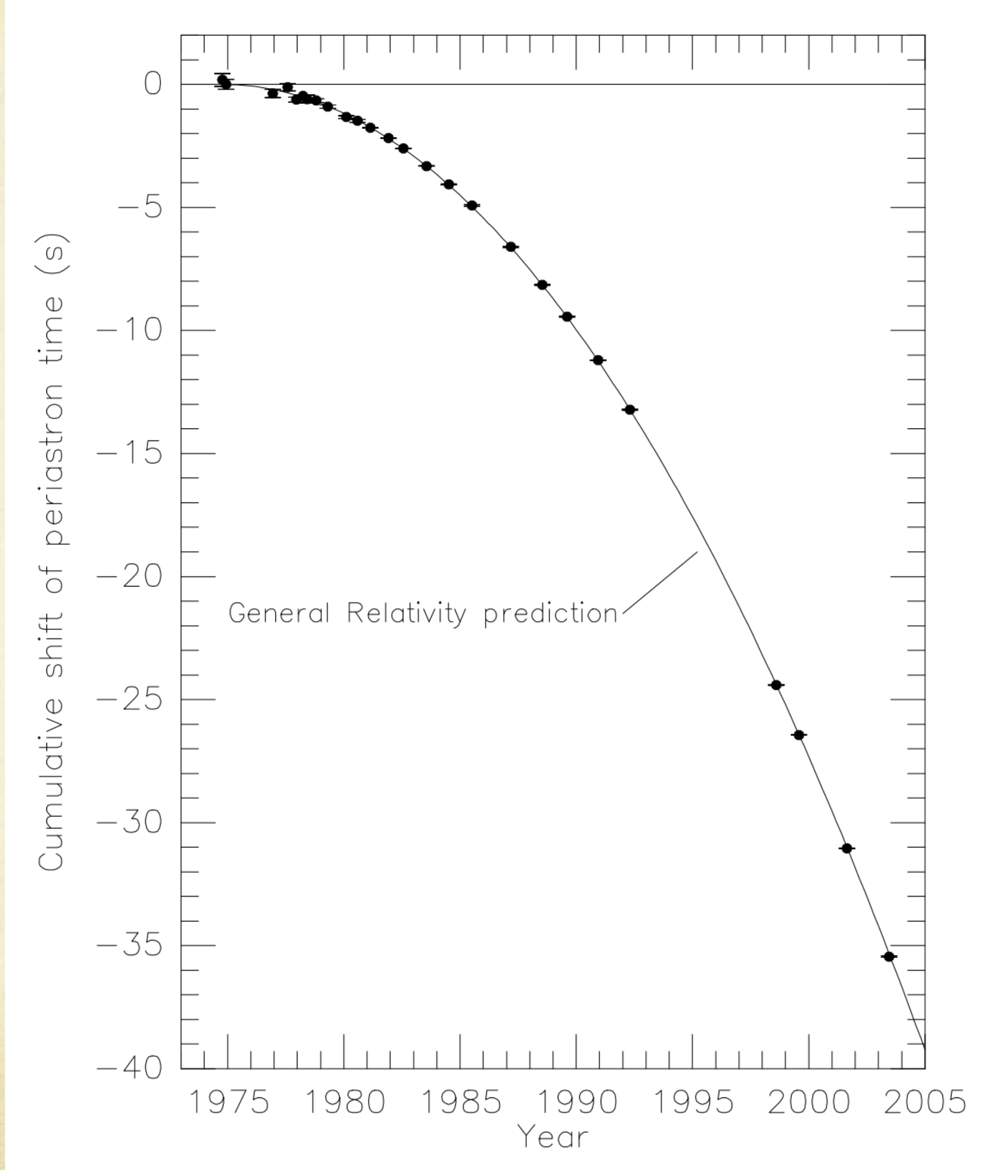
Hulse & Taylor 1975, Weisberg and Taylor 2005

Hulse-Taylor binary

$$t_{\rm GW} = \frac{3}{85}\frac{a_1}{c}\left(\frac{a_1^3 c^6}{G^3 m_0 m_1 M}\right)(1-e_1^2)^{7/2}$$
$$\simeq 1.6\times 10^{13}\,{\rm yr}\left(\frac{2\,M_\odot^3}{m_0 m_1 M}\right)\left(\frac{a_1}{0.1\,{\rm AU}}\right)^4(1-e_1^2)^{7/2},$$

Measured Orbital Parameters for PSR B1913+16

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)

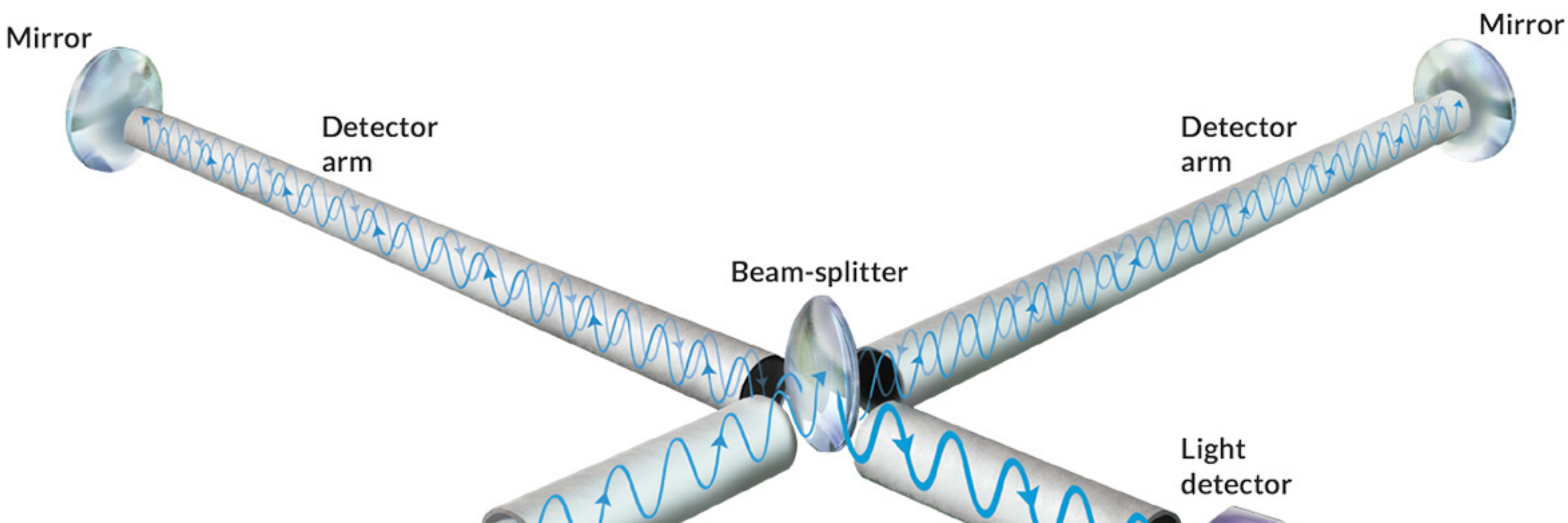


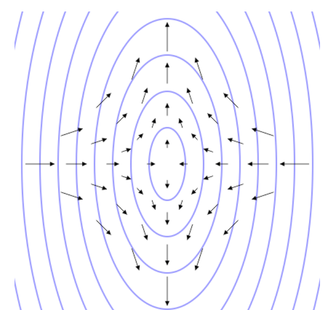
Hulse & Taylor 1975, Weisberg and Taylor 2005

Detecting Gravitational Waves

Detecting Gravitational Waves

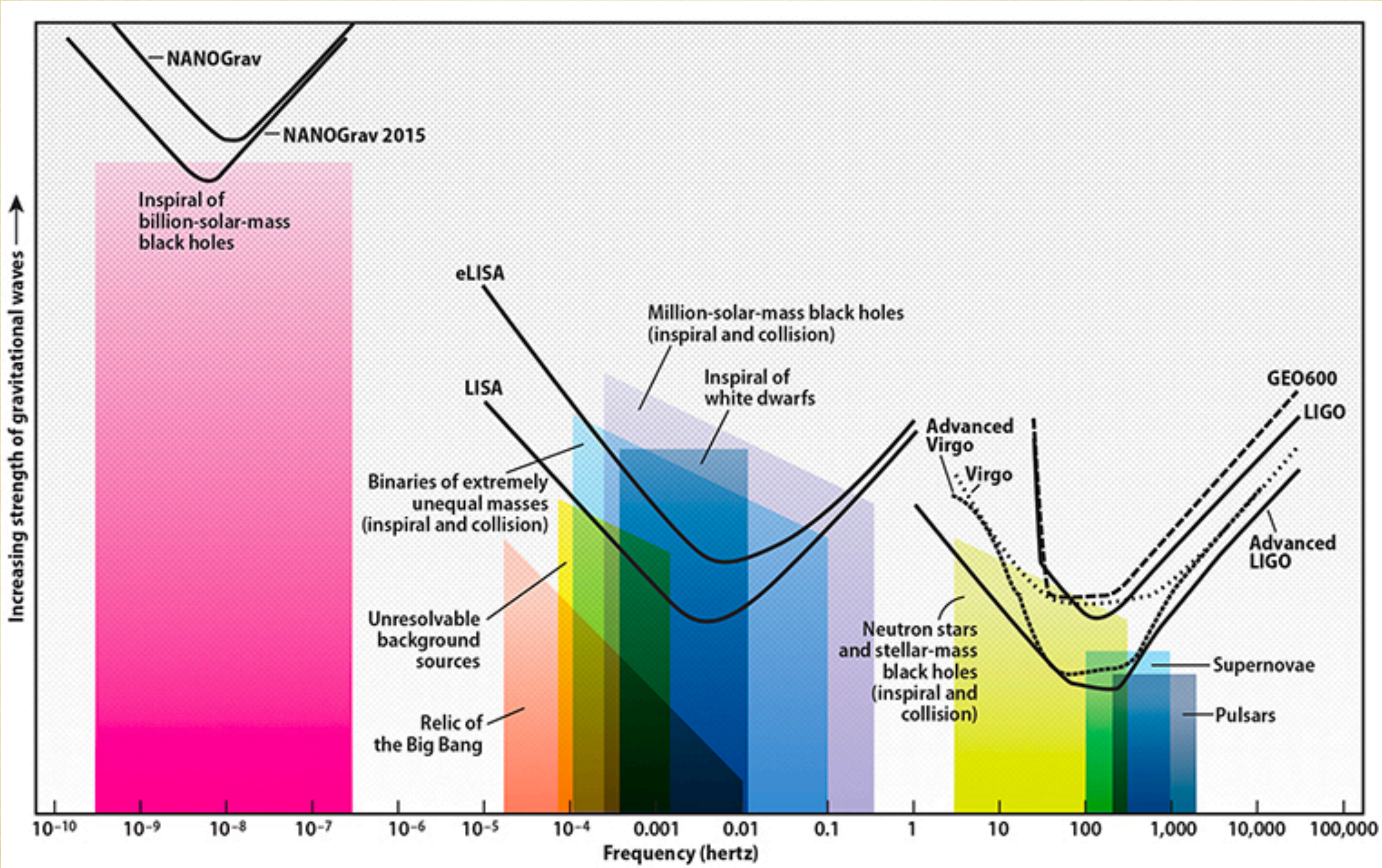
Fabry-Perot-Michelson Interferometers





LIGO + Virgo

Detecting Gravitational Waves



Astronomy: Roen Kelly, after C. Moore, R. Cole, and C. Berry (Institute of Astronomy, Univ. of Cambridge

Multi-messenger Astronomy

Motivation

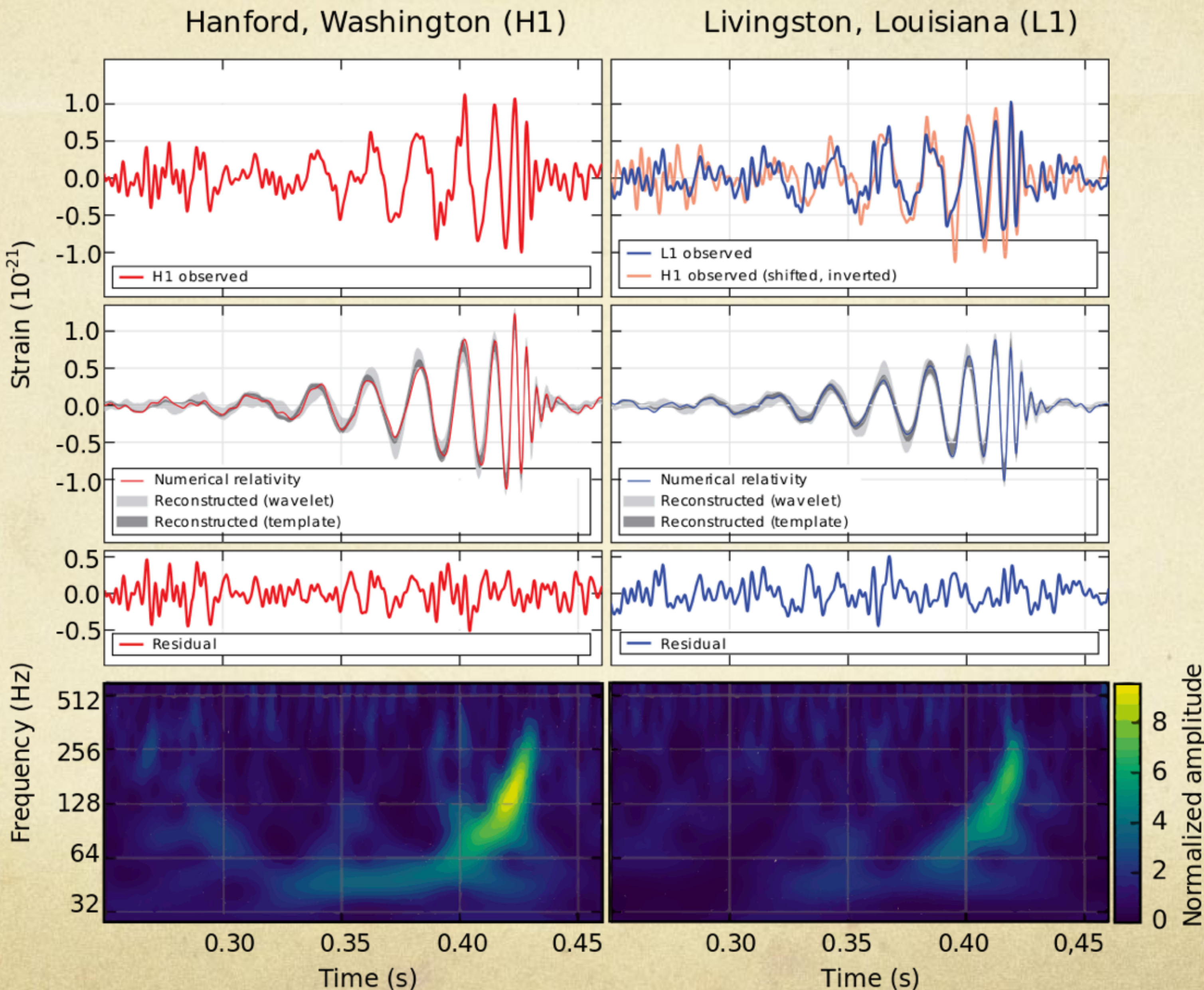
Multi-messenger Astronomy

Motivation

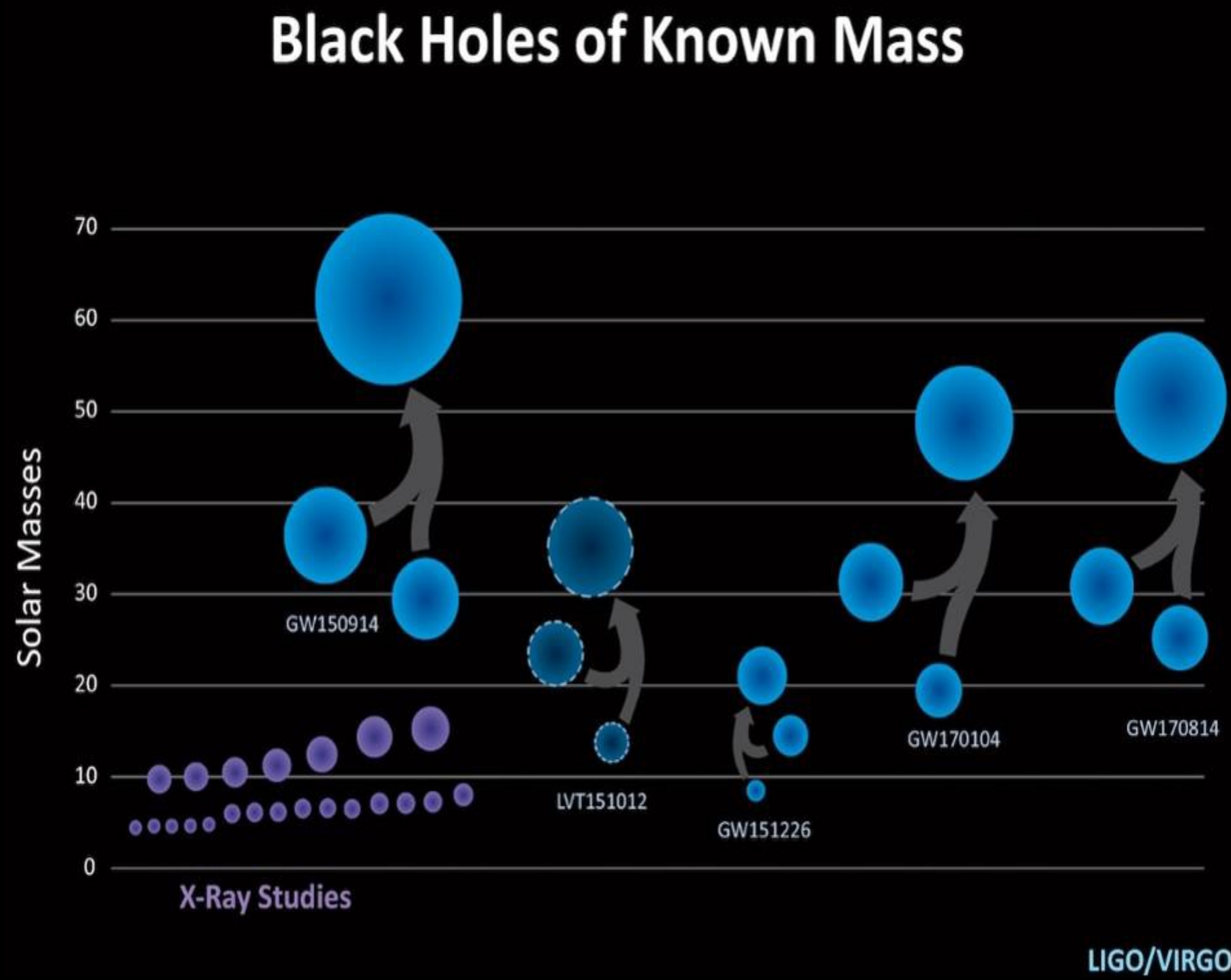
Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

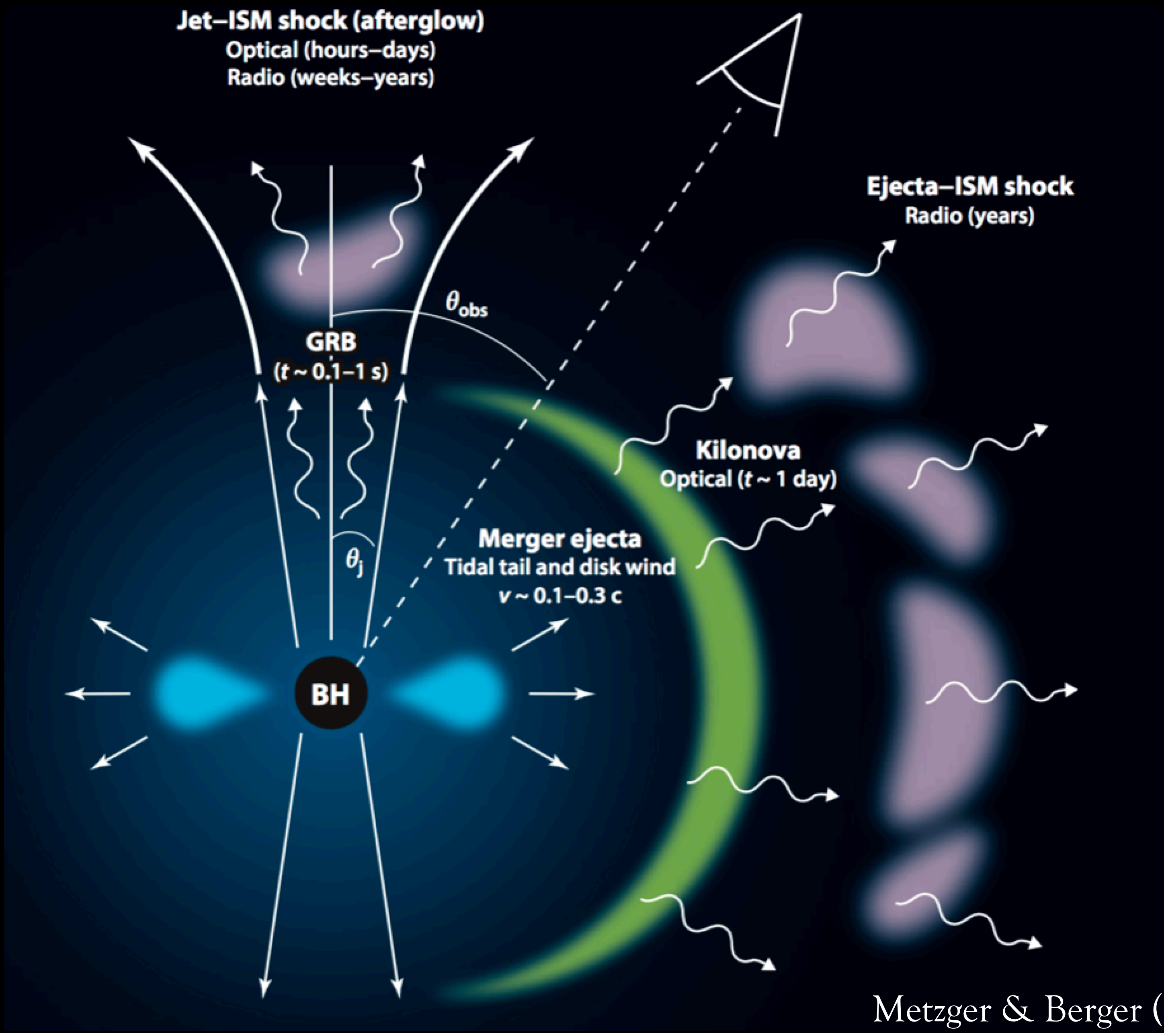
GW150914


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
0,45
Time (s)
Normalized amplitude
8
6
4
2
0

GW150814

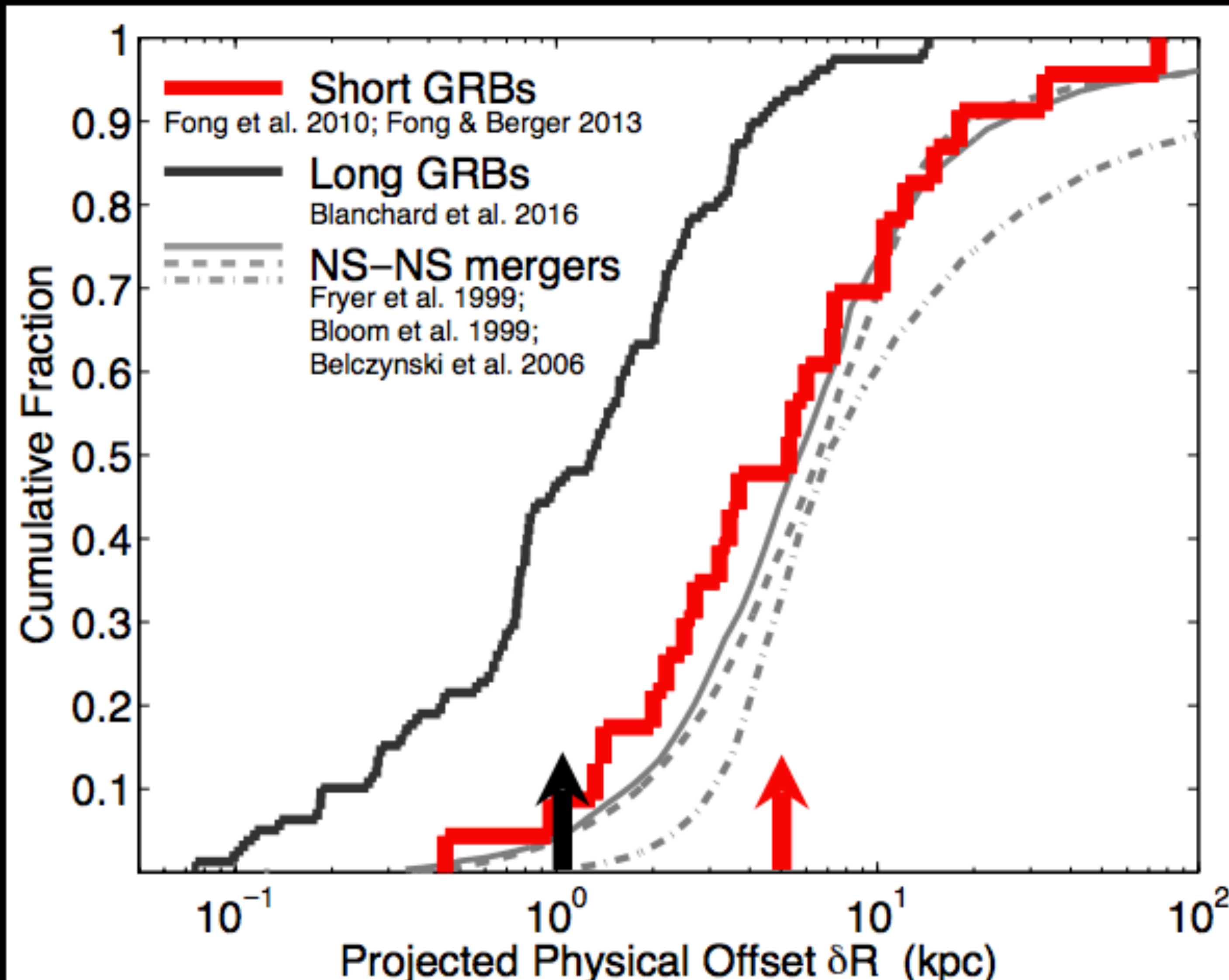

Black Holes of Known Mass
70
60
50
40
30
20
10
0
Solar Masses
GW150914
LVT151012
GW151226
GW170104
GW170814
X-Ray Studies
LIGO/VIRGO

EM Signals from Neutron-Star Mergers



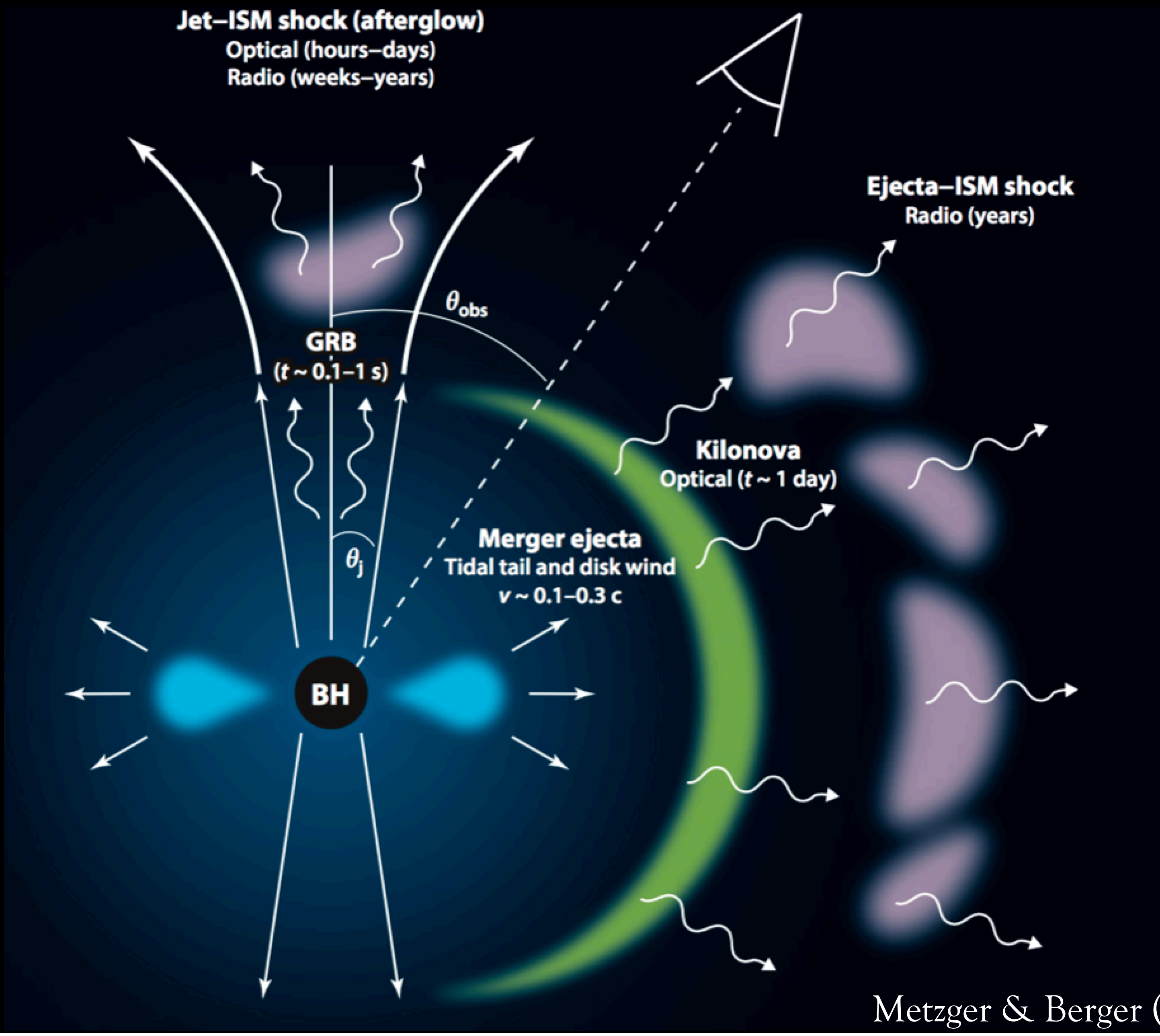
Metzger & Berger (2012)

Short-duration GRBs as NS mergers



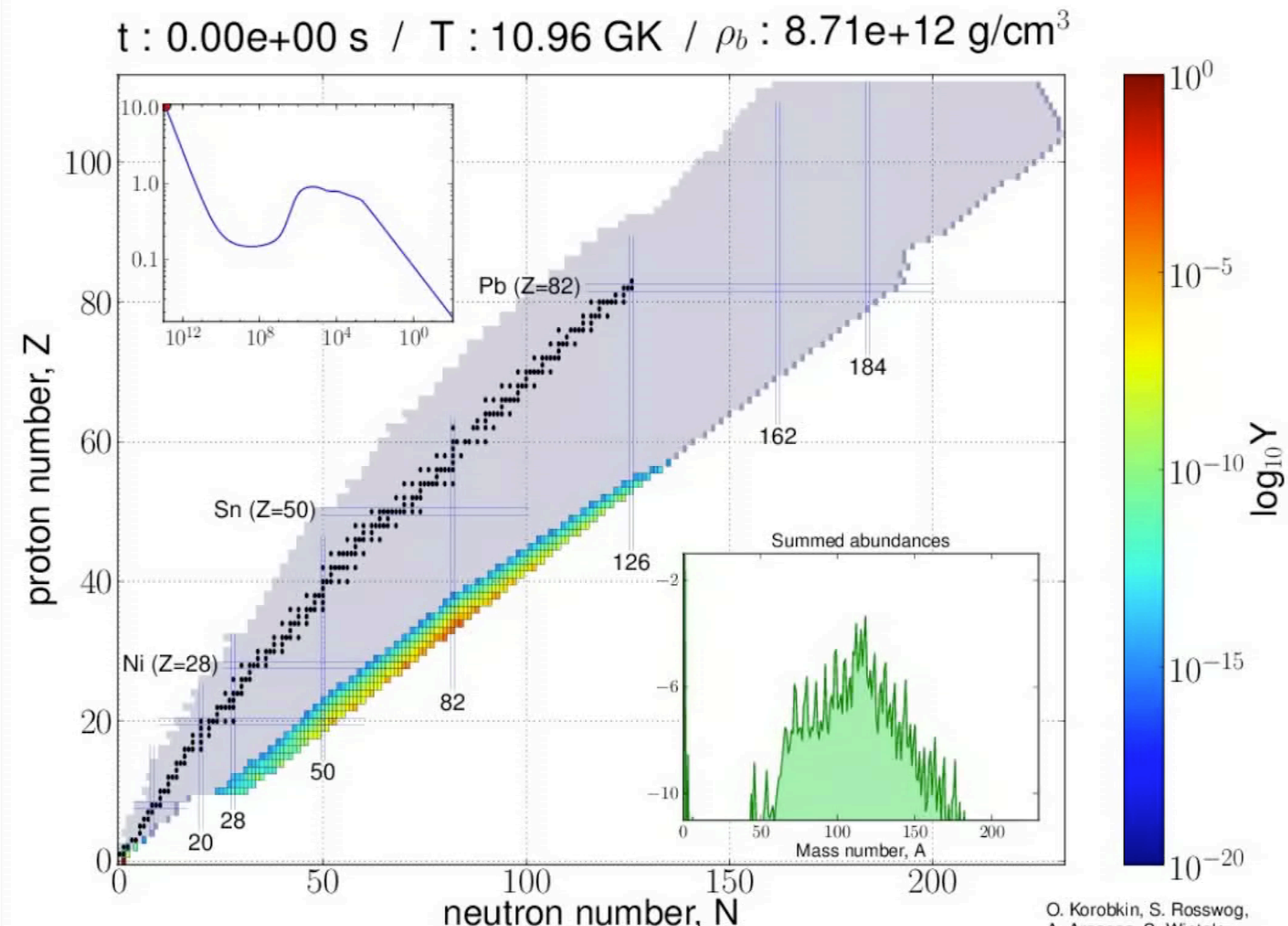
Fong et al. 2010; Fong & Berger 2013

EM Signals from Neutron-Star Mergers



Metzger & Berger (2012)

r-process nucleosynthesis



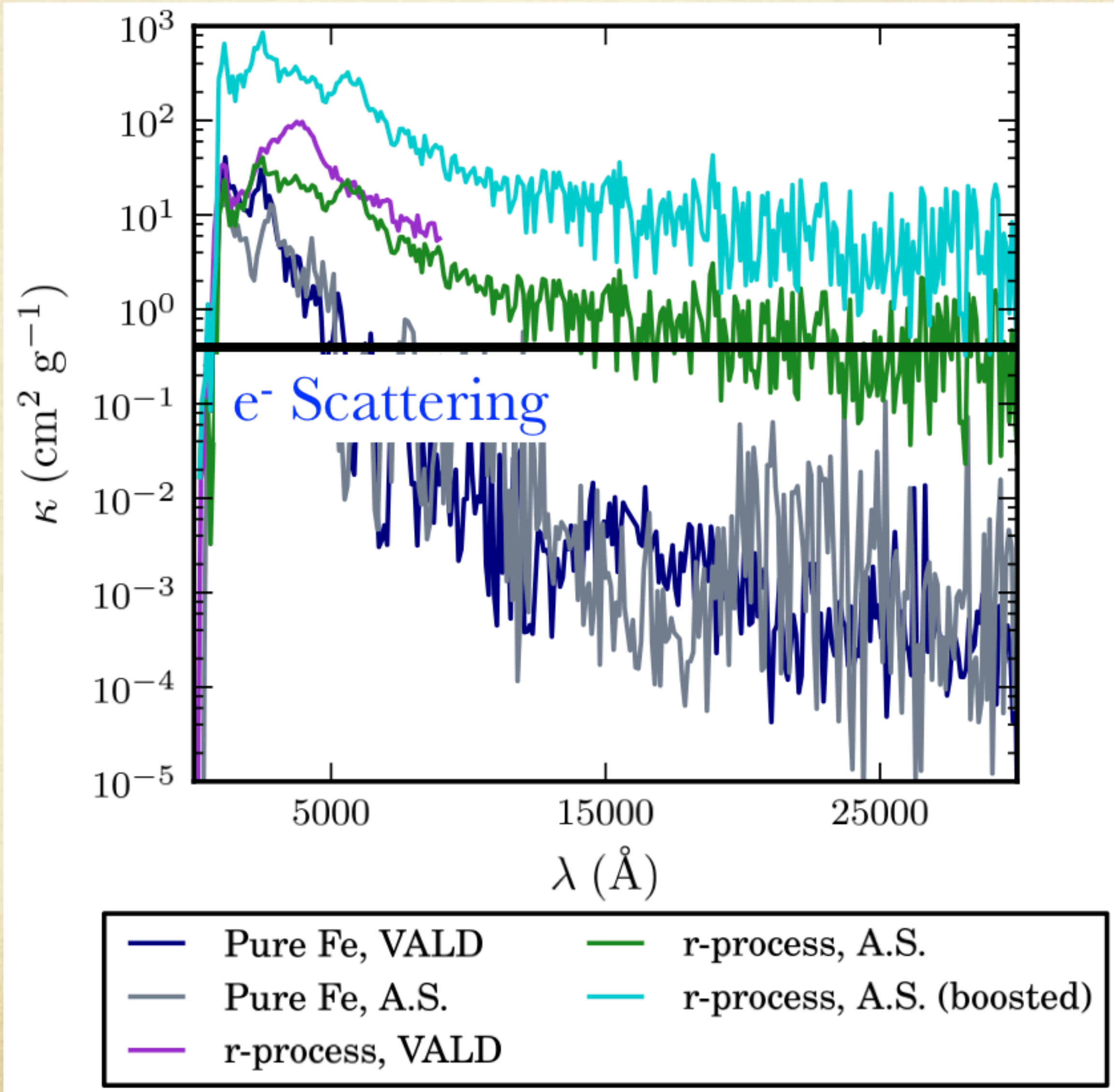
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

Kilonova

What will they look like?

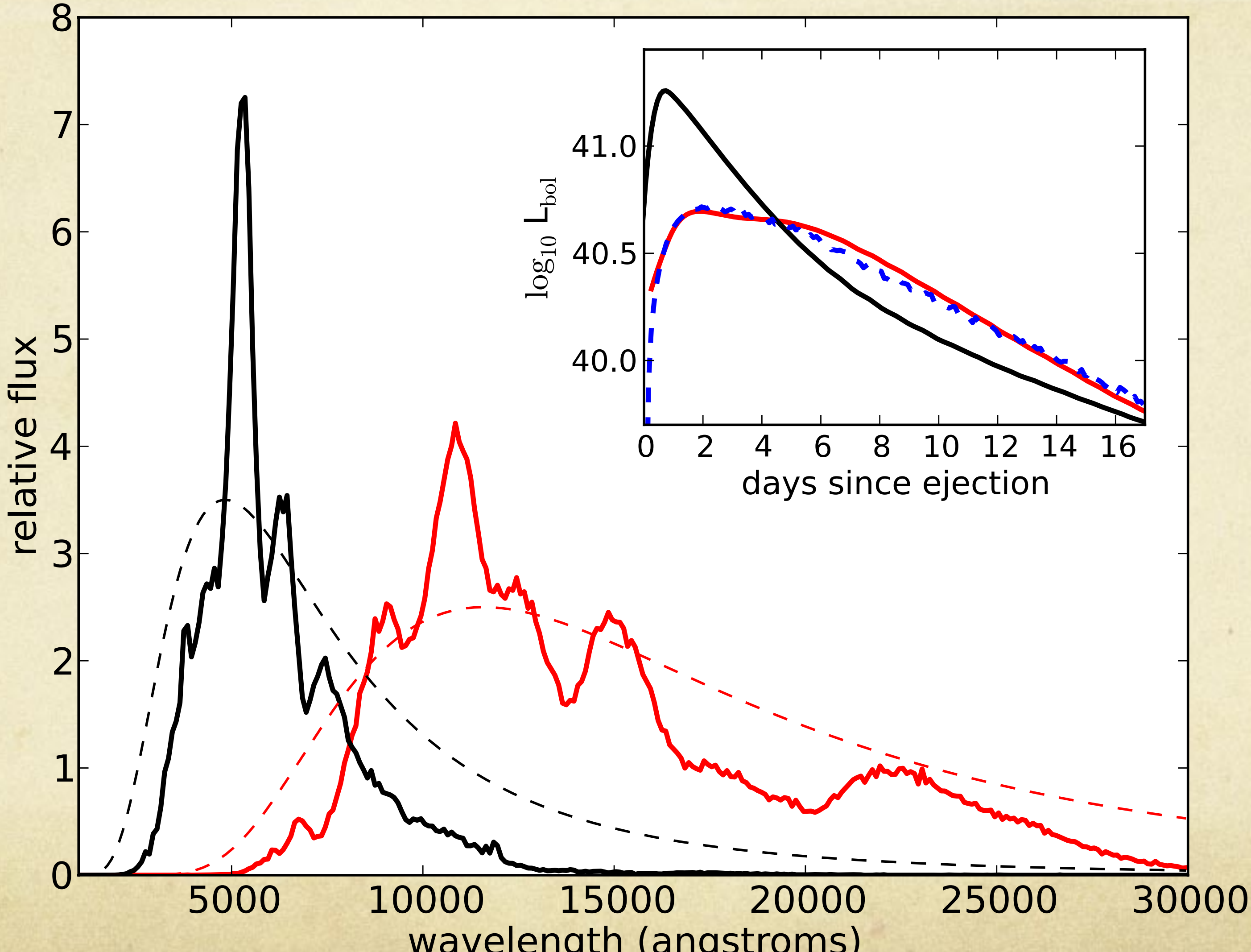
Kilonova

What will they look like?



Kilonova

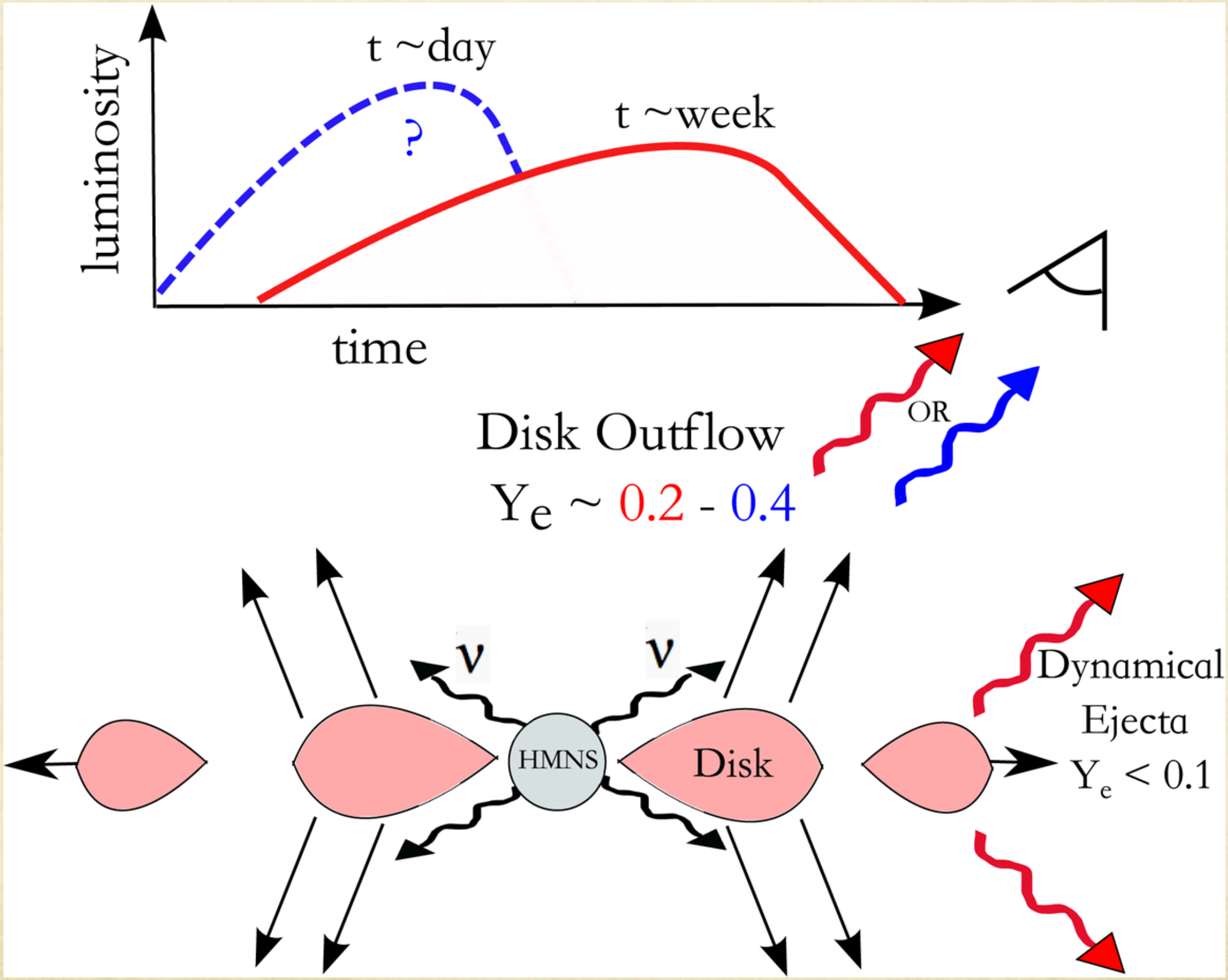
What will they look like?



Kasen, Badnell, & Barnes 2013

Kilonova

What will they look like?



Metzger & Fernández 2014

Multi-messenger Astronomy

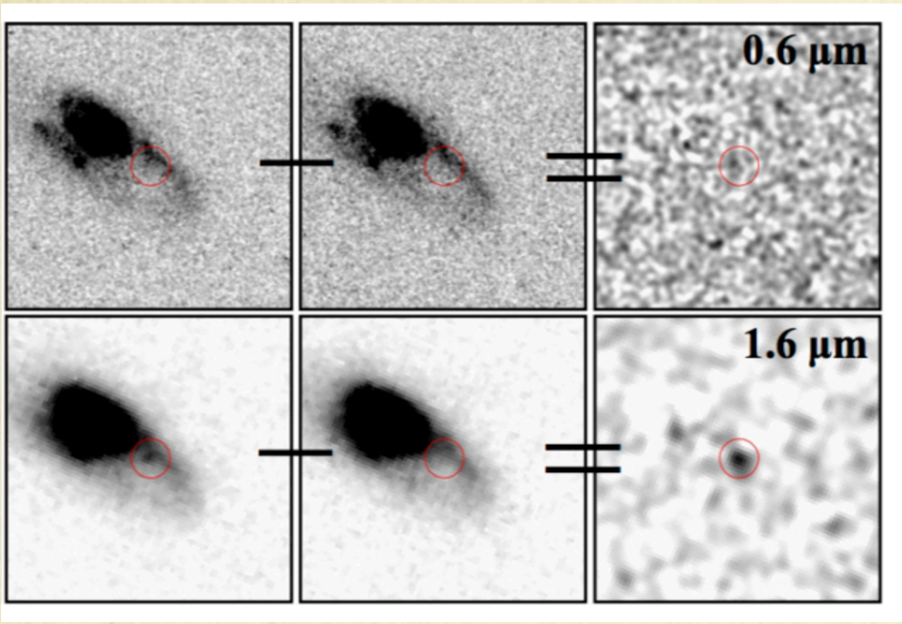
Motivation

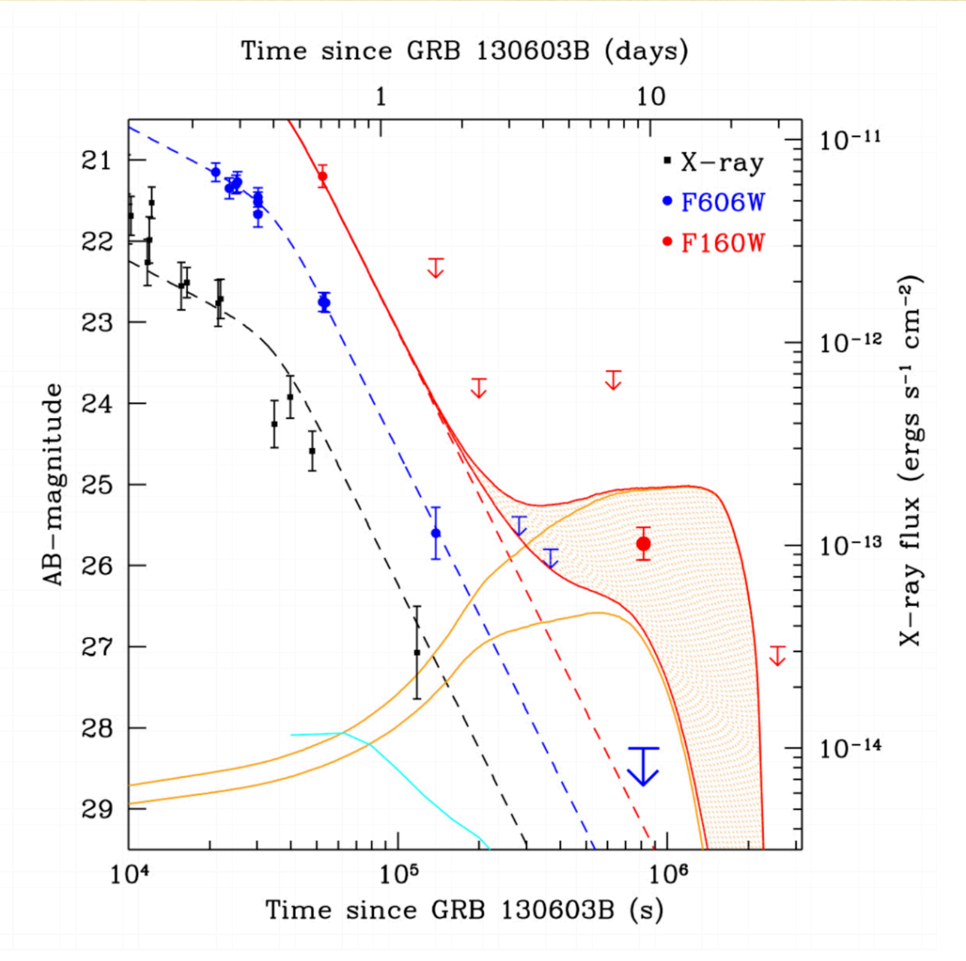
Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

Aug 17th, 2017

GRB 130603B a Kilonova?





Tanvir et al. 2013, Berger et al. 2013

Aug 17th, 2017

Aug 17, 2017

```
////////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of
a possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary
identification of a GW candidate associated with the time
 of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47
 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.

The candidate is consistent with a neutron star binary coalescence with
False Alarm Rate of ~1/10,000 years.

An offline analysis is ongoing. Any significant updates will be provided
by a new Circular.

[GCN OPS NOTE(17aug17): Per author's request, the LIGO/VIRGO ID
was added to the beginning of the Subject-line.]
```

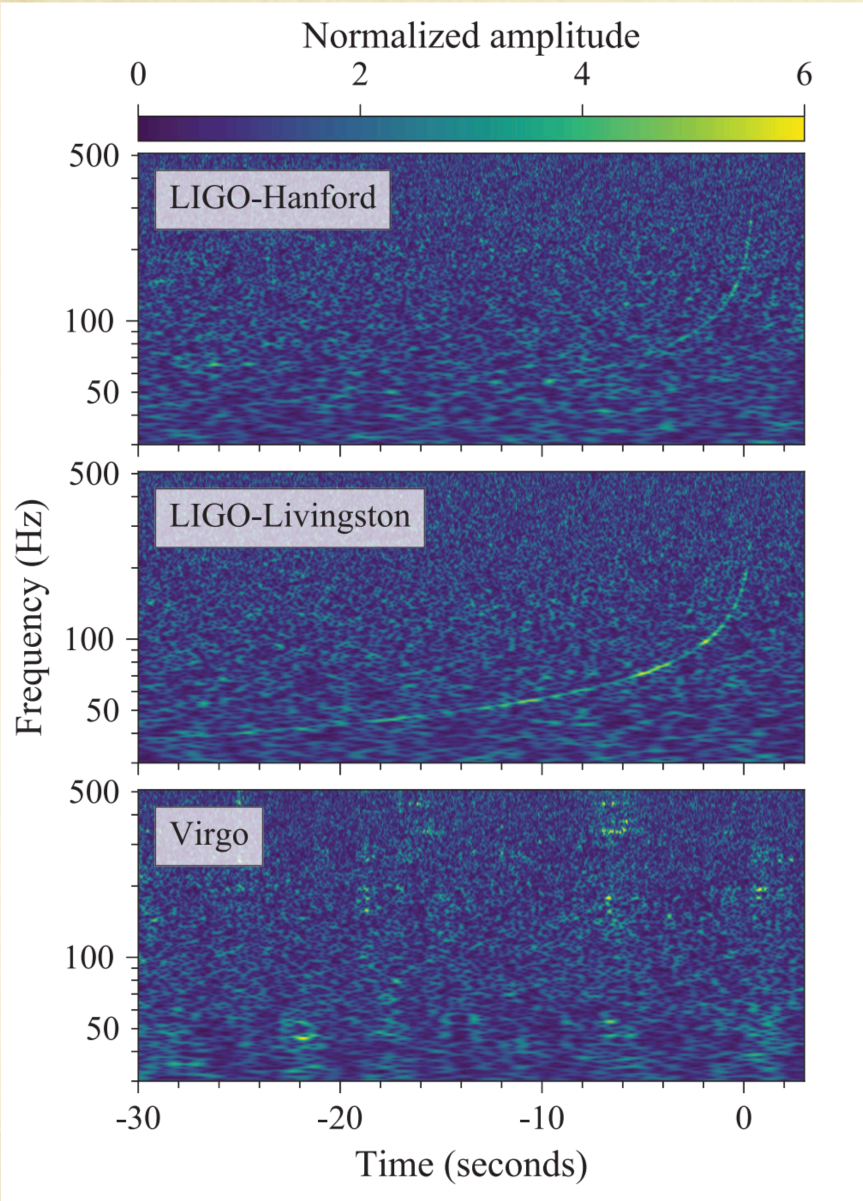
Aug 17, 2017

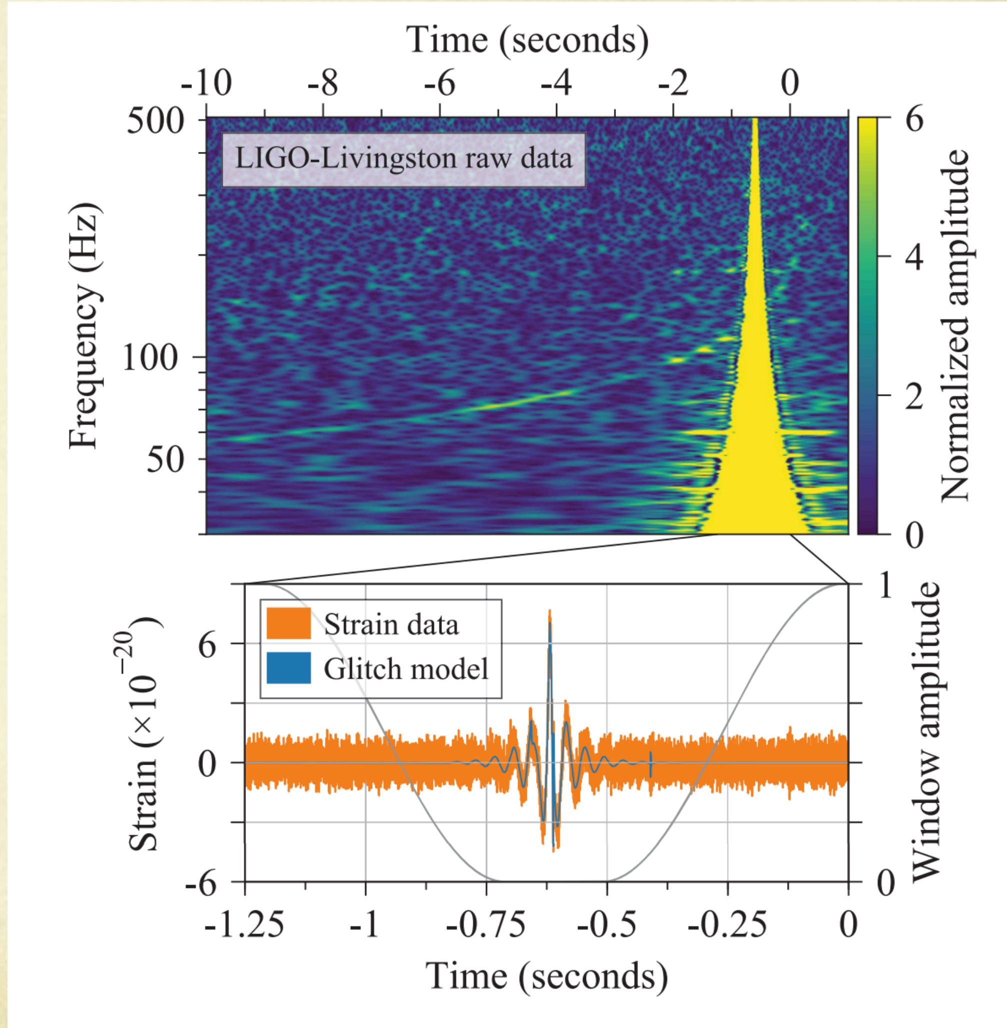
```
//////////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of
a possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary
identification of a GW candidate associated with the time
 of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47
 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.

The candidate is consistent with a neutron star binary coalescence with
False Alarm Rate of ~1/10,000 years.

An offline analysis is ongoing. Any significant updates will be provided
by a new Circular.

[GCN OPS NOTE(17aug17): Per author's request, the LIGO/VIRGO ID
was added to the beginning of the Subject-line.]
```

Aug 17, 2017

```
//////////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of
a possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary
identification of a GW candidate associated with the time
 of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47
 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.

The candidate is consistent with a neutron star binary coalescence with
False Alarm Rate of ~1/10,000 years.

An offline analysis is ongoing. Any significant updates will be provided
by a new Circular.

[GCN OPS NOTE(17aug17): Per author's request, the LIGO/VIRGO ID
was added to the beginning of the Subject-line.]
```

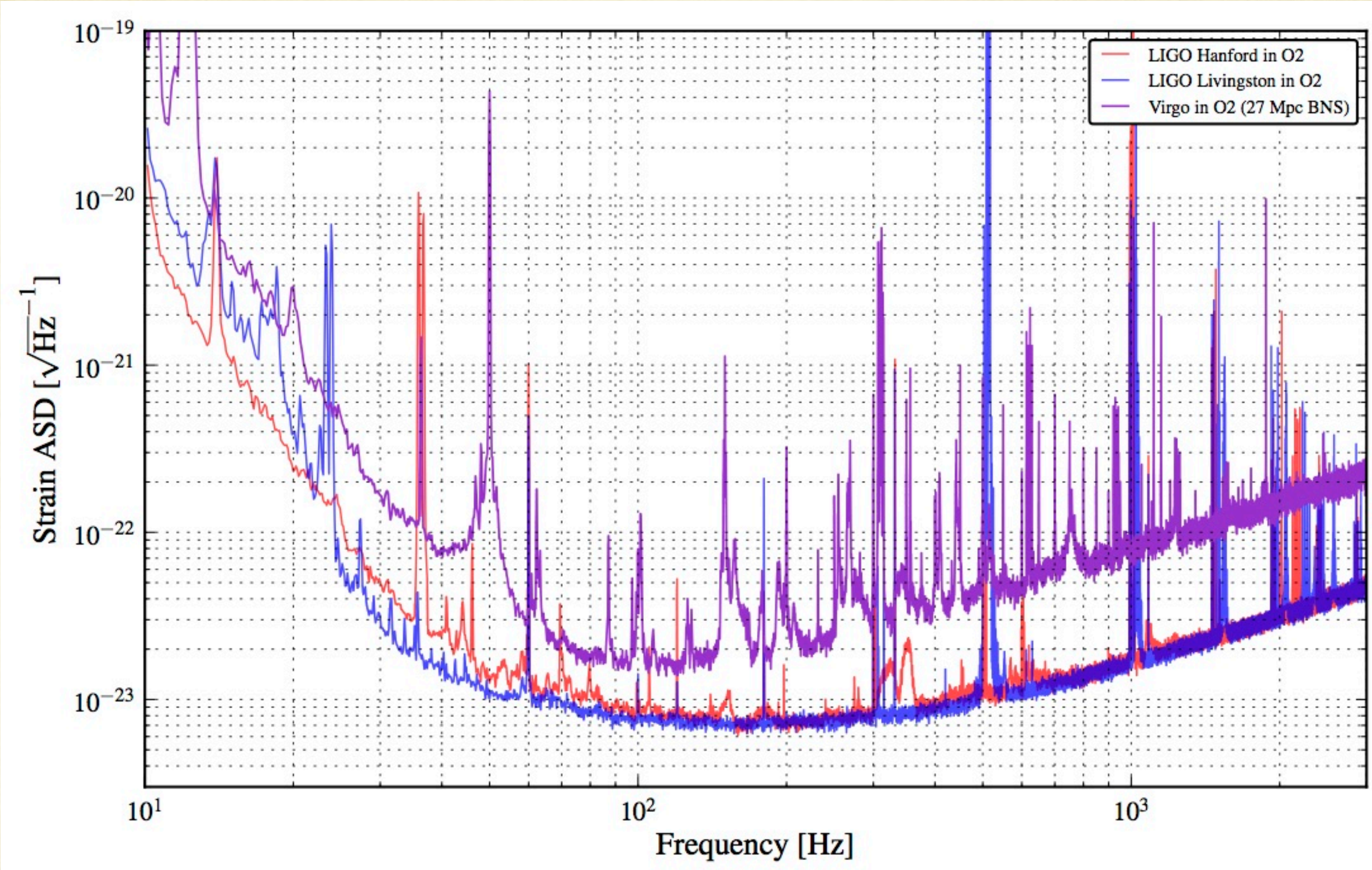
Gravitational Waves





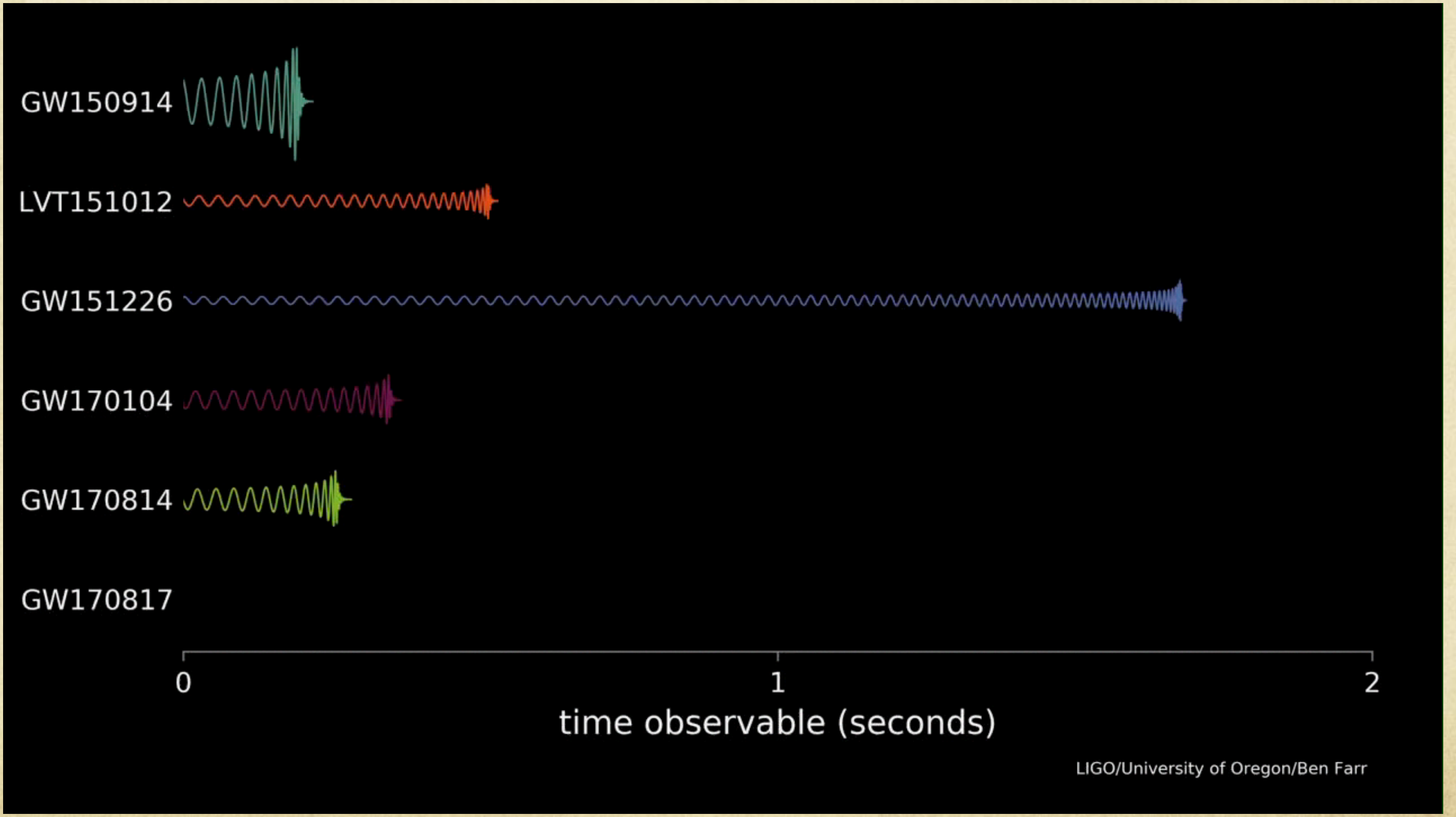
Abbot et al. 2017

LIGO + Virgo



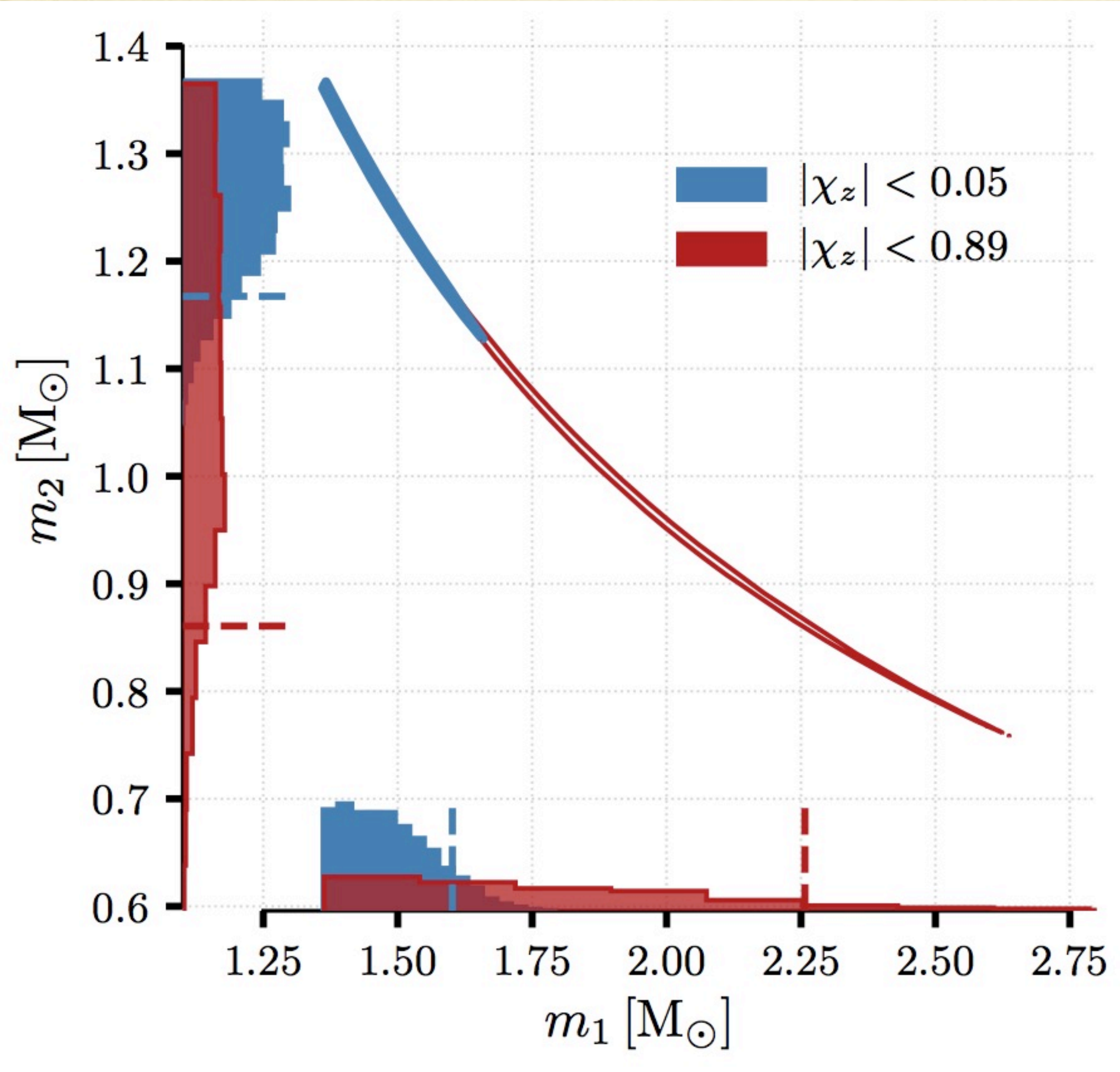
LIGO + Virgo

Gravitational Waves



Gravitational Waves

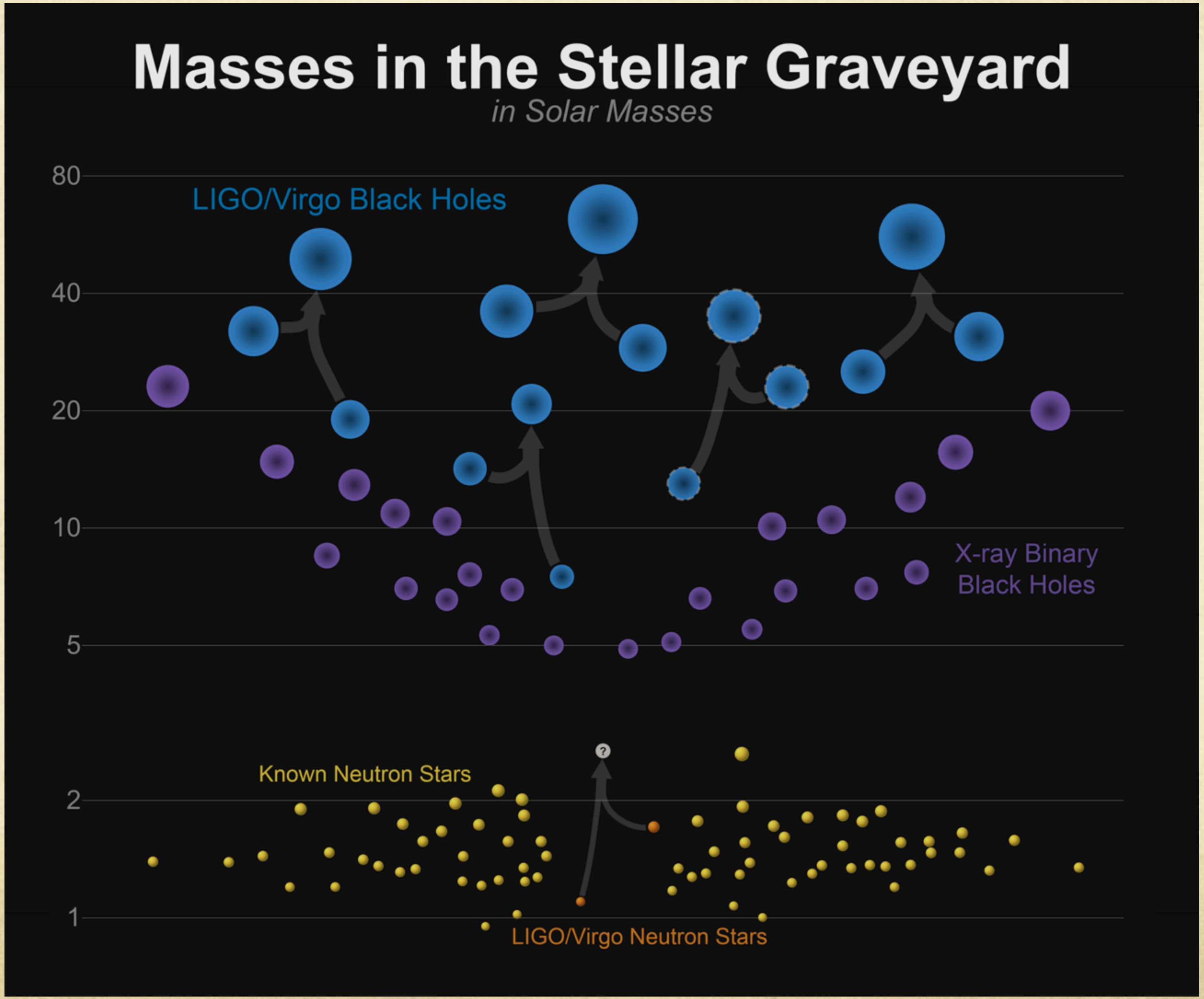
Component Masses



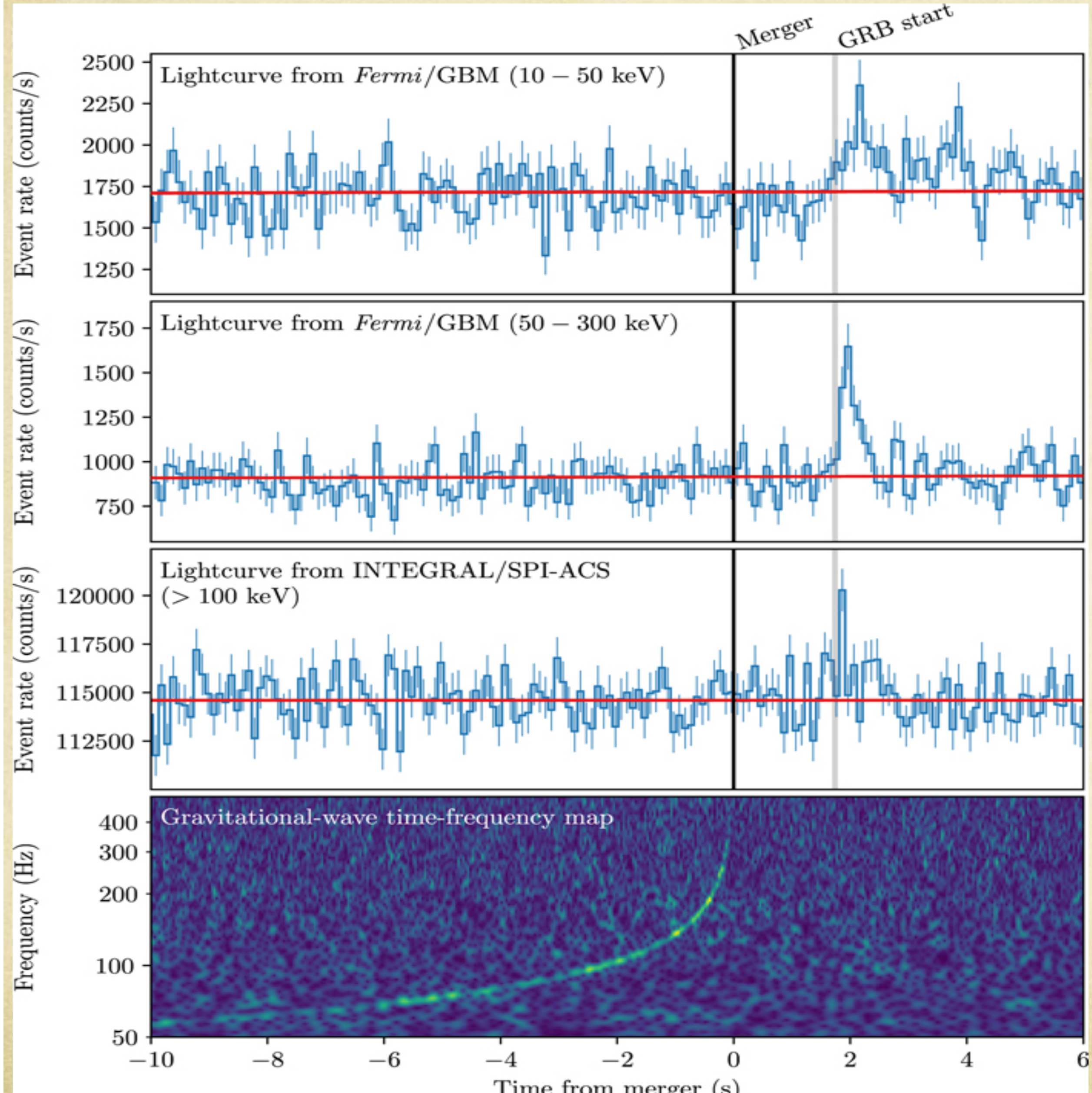
m1 = 1.36 – 1.60 Msun
m2 = 1.17 – 1.36 Msun
Mtot = 2.74 Msun
Mass ratio = 0.7 – 1.0

Abbott et al (2017)

Gravitational Waves



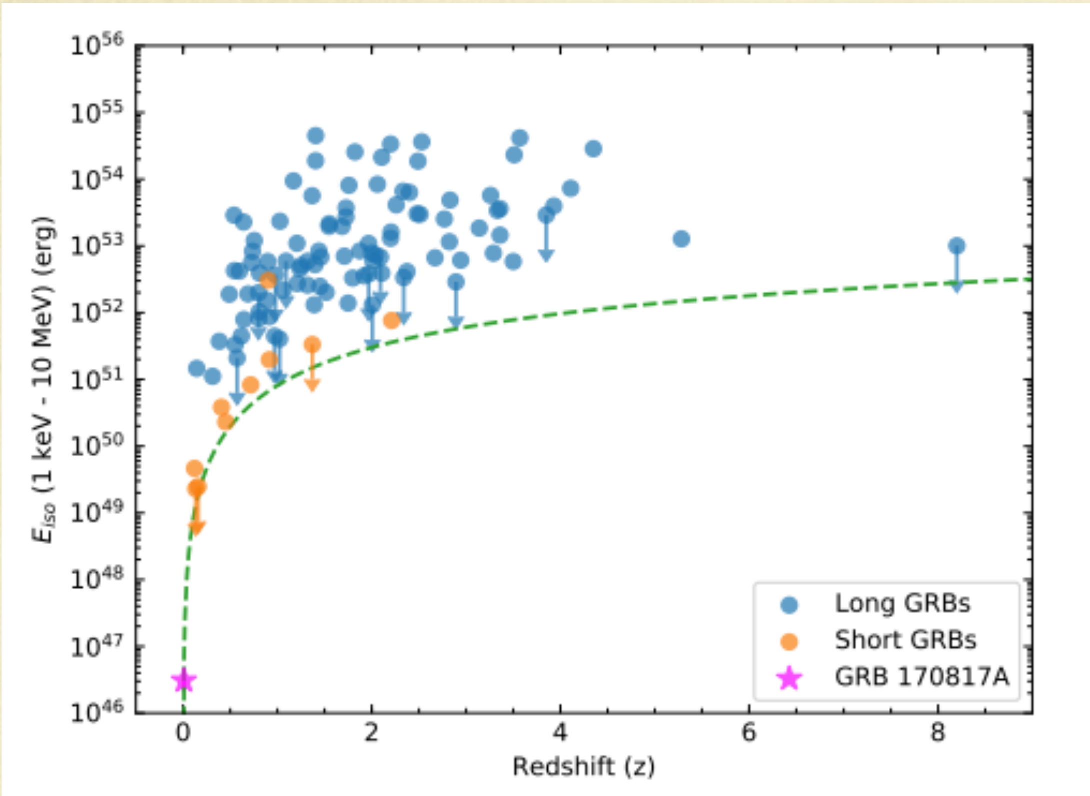
Gamma-rays



- 1.74 +/- 0.05s
- 4-6 orders of mag less than a typical Swift sGRB (Gehrels et al. 2009).
- X-ray emission 6-8 orders of mag less than typical Swift sGRB (Gehrels et al. 2009).

Abbot et al. 2017b

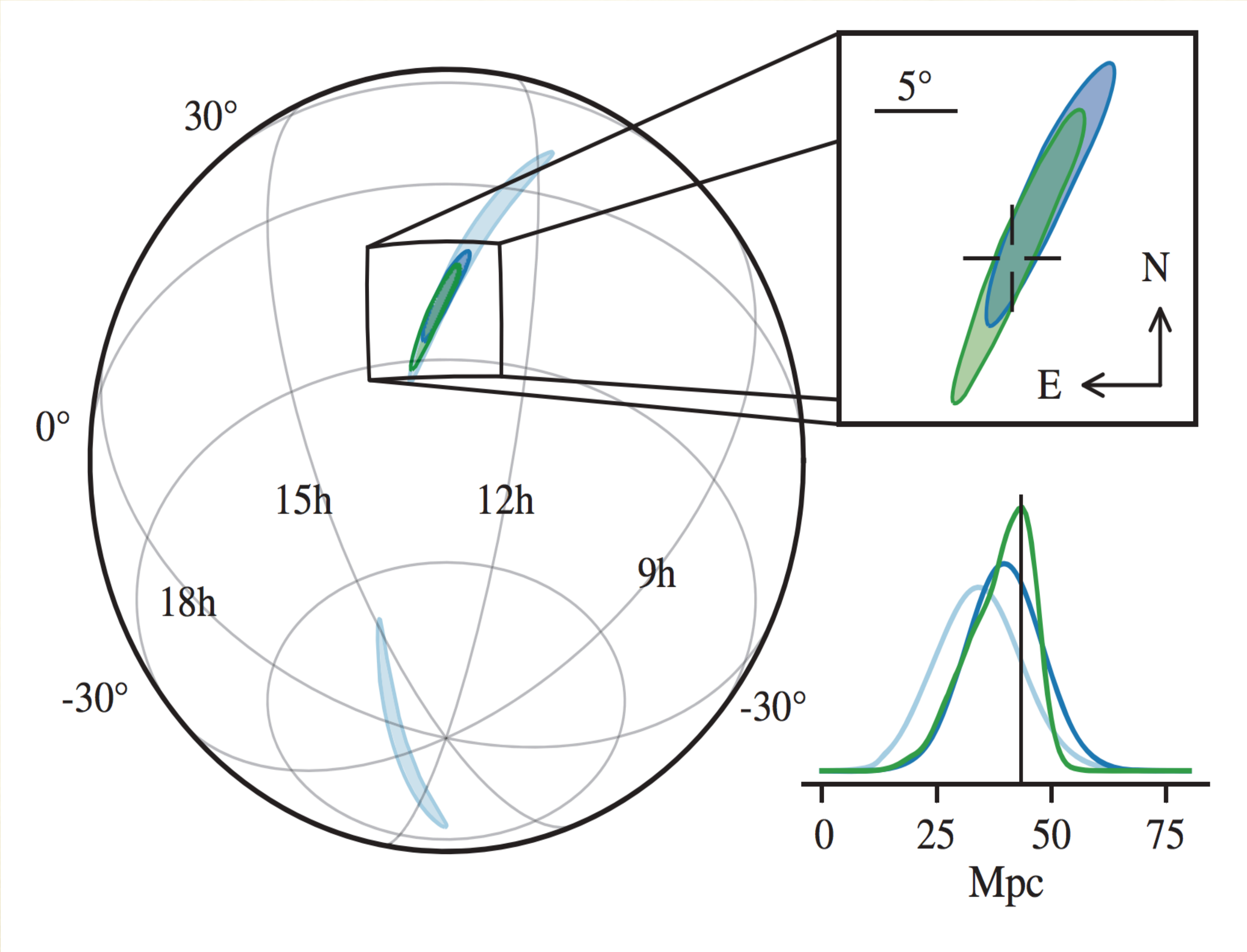
Gamma-rays



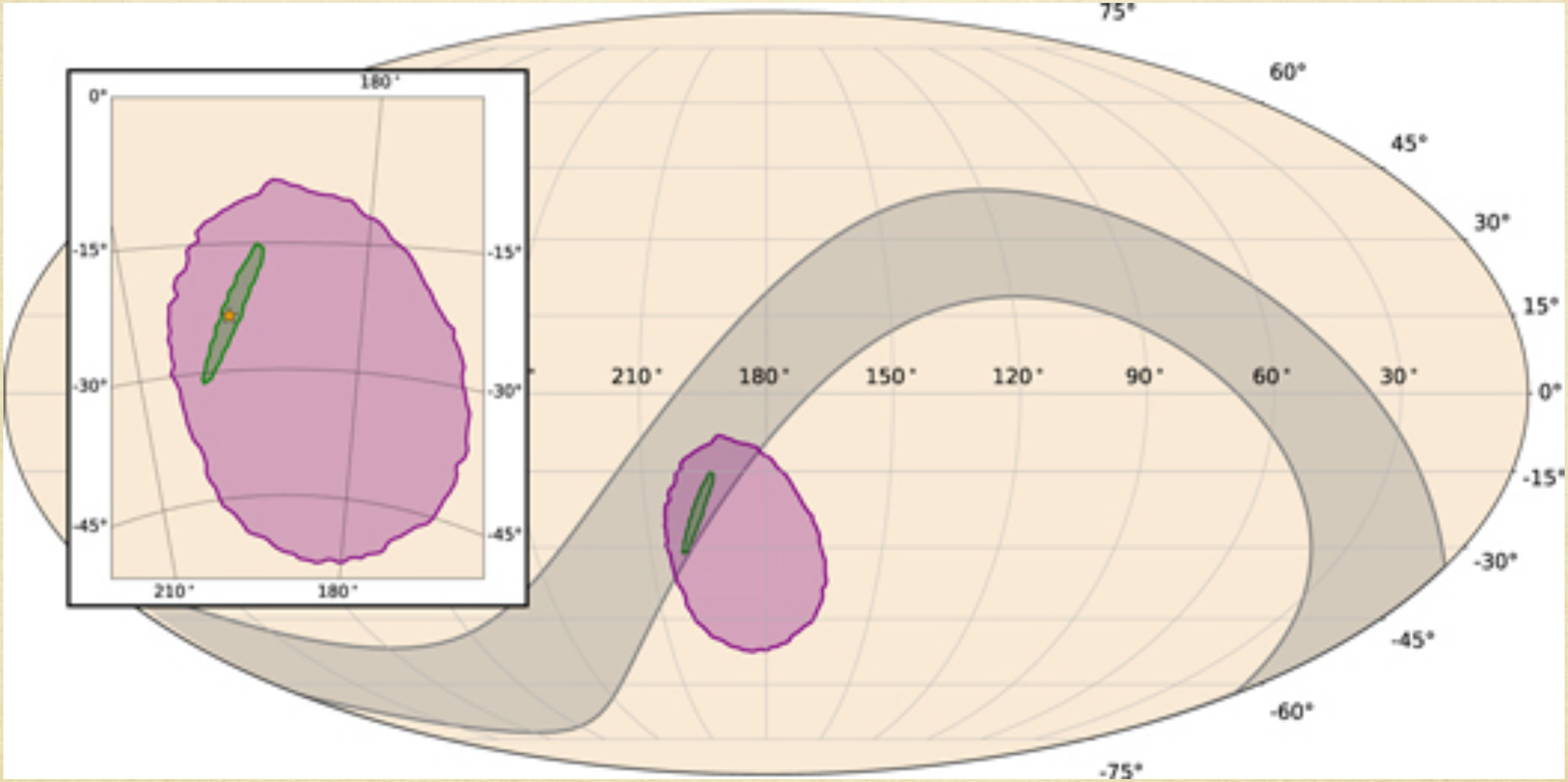
- 1.74 +/- 0.05s
- 4-6 orders of mag less than a typical Swift sGRB (Gehrels et al. 2009).
- X-ray emission 6-8 orders of mag less than typical Swift sGRB (Gehrels et al. 2009).

Abbot et al. 2017b

Sky Localization

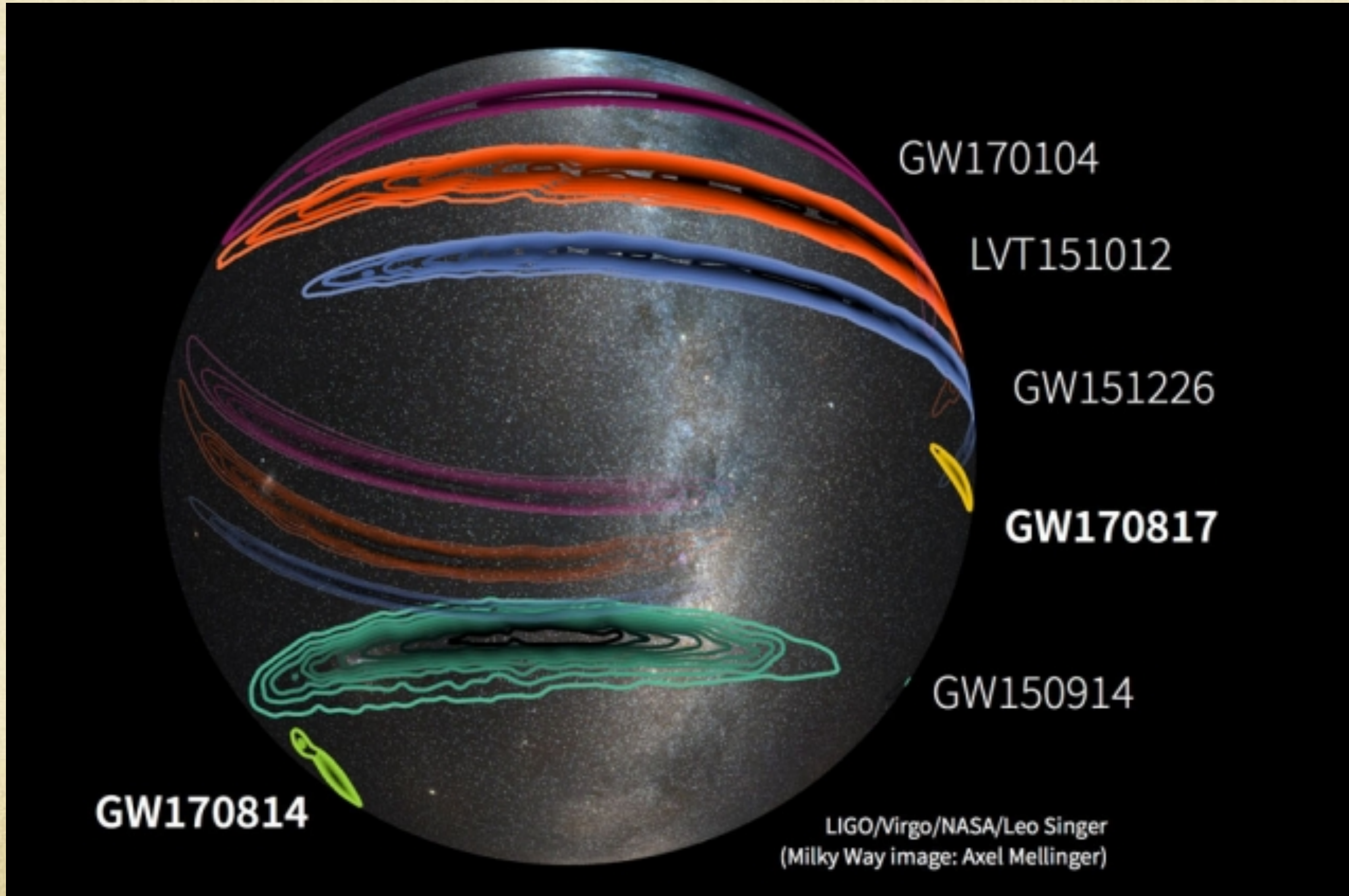


Not a better localization



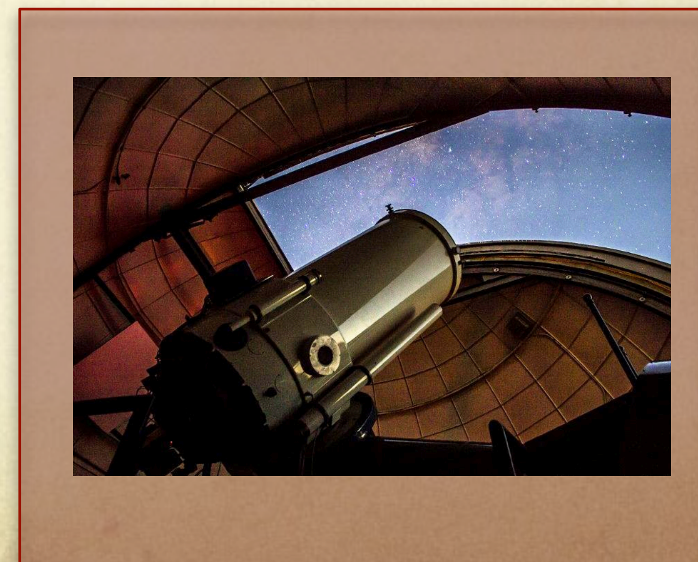
Abbot et al. 2017b

Sky Localization



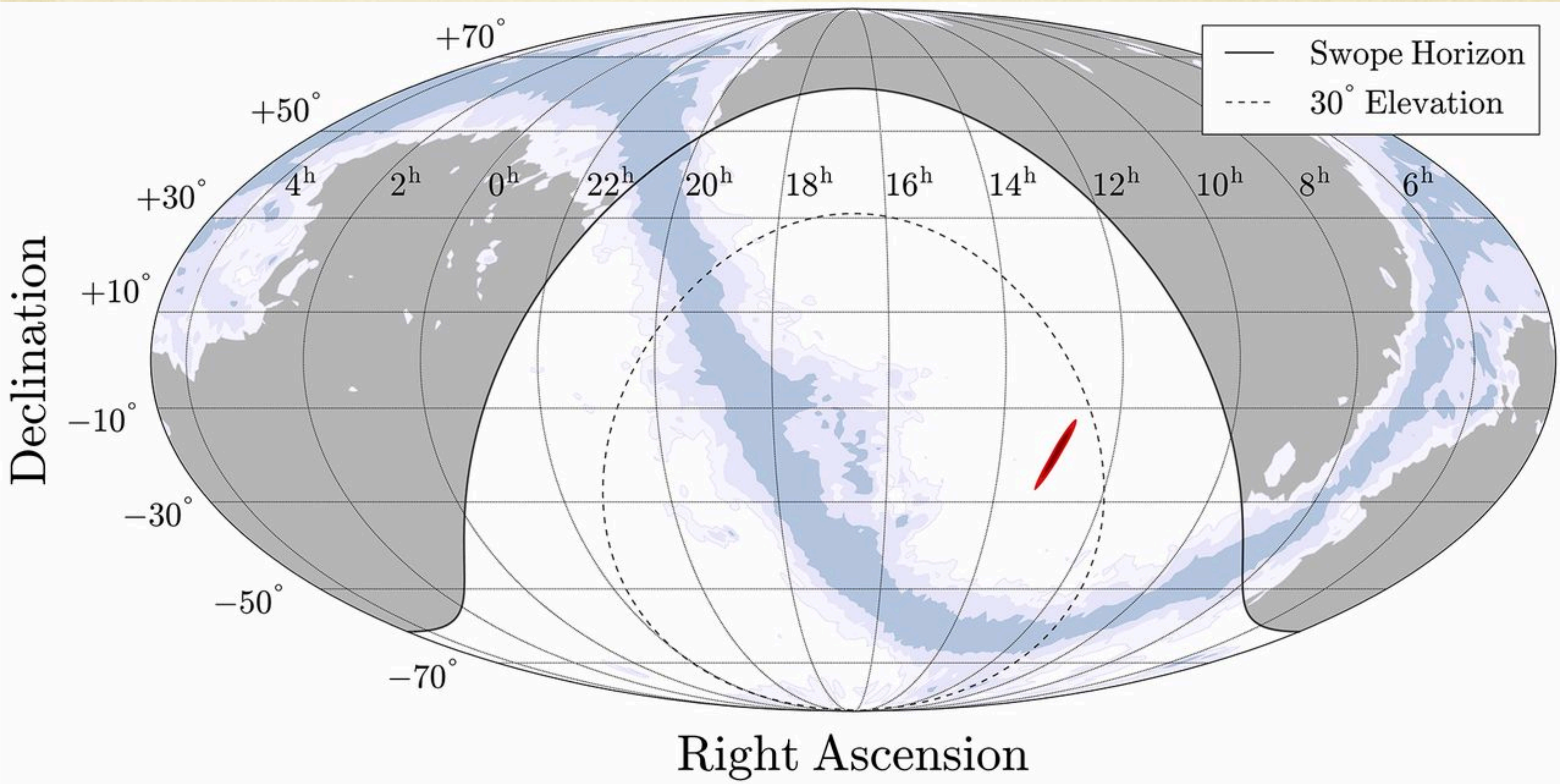
1M2H

1M2H



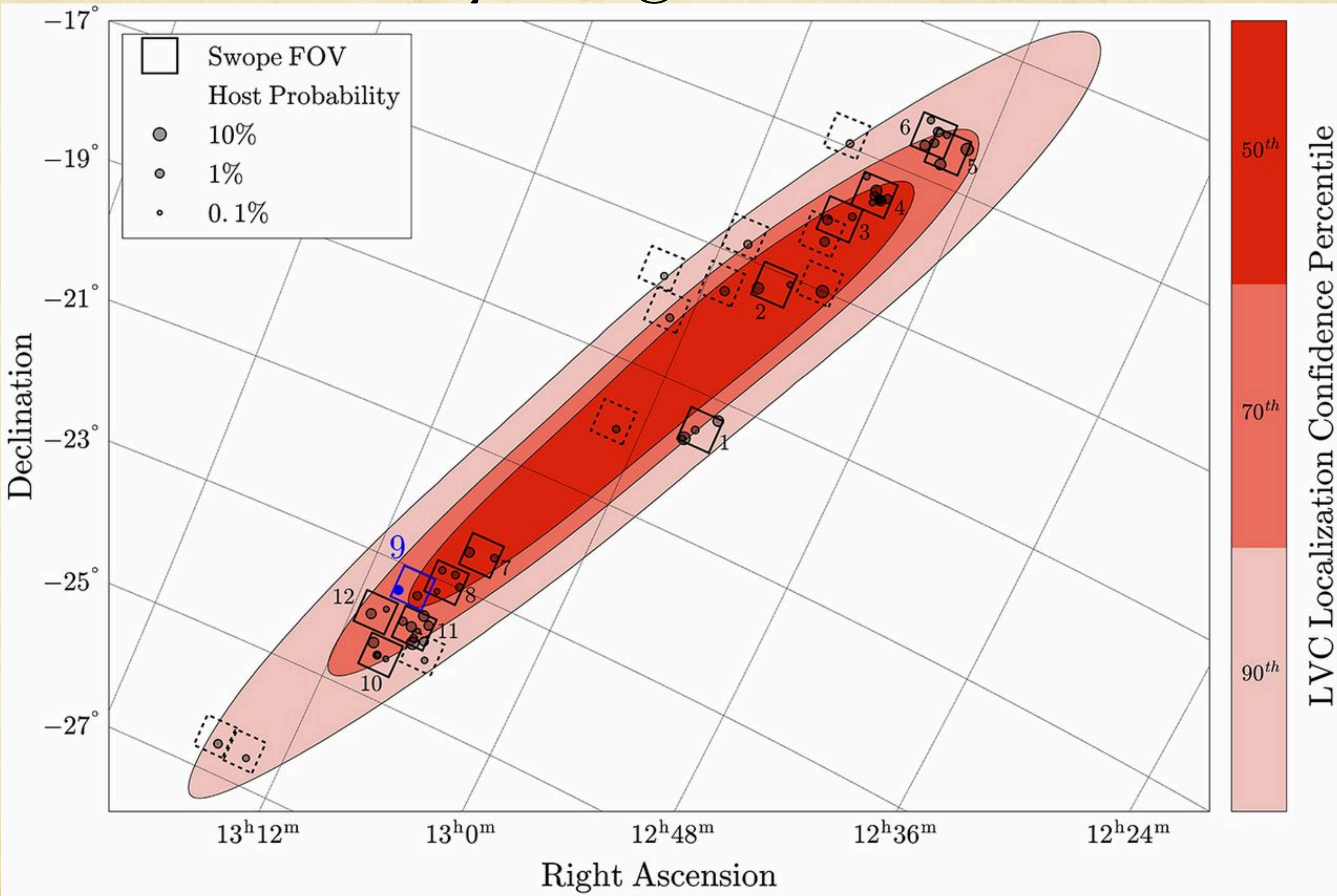
1M2H

1M2H



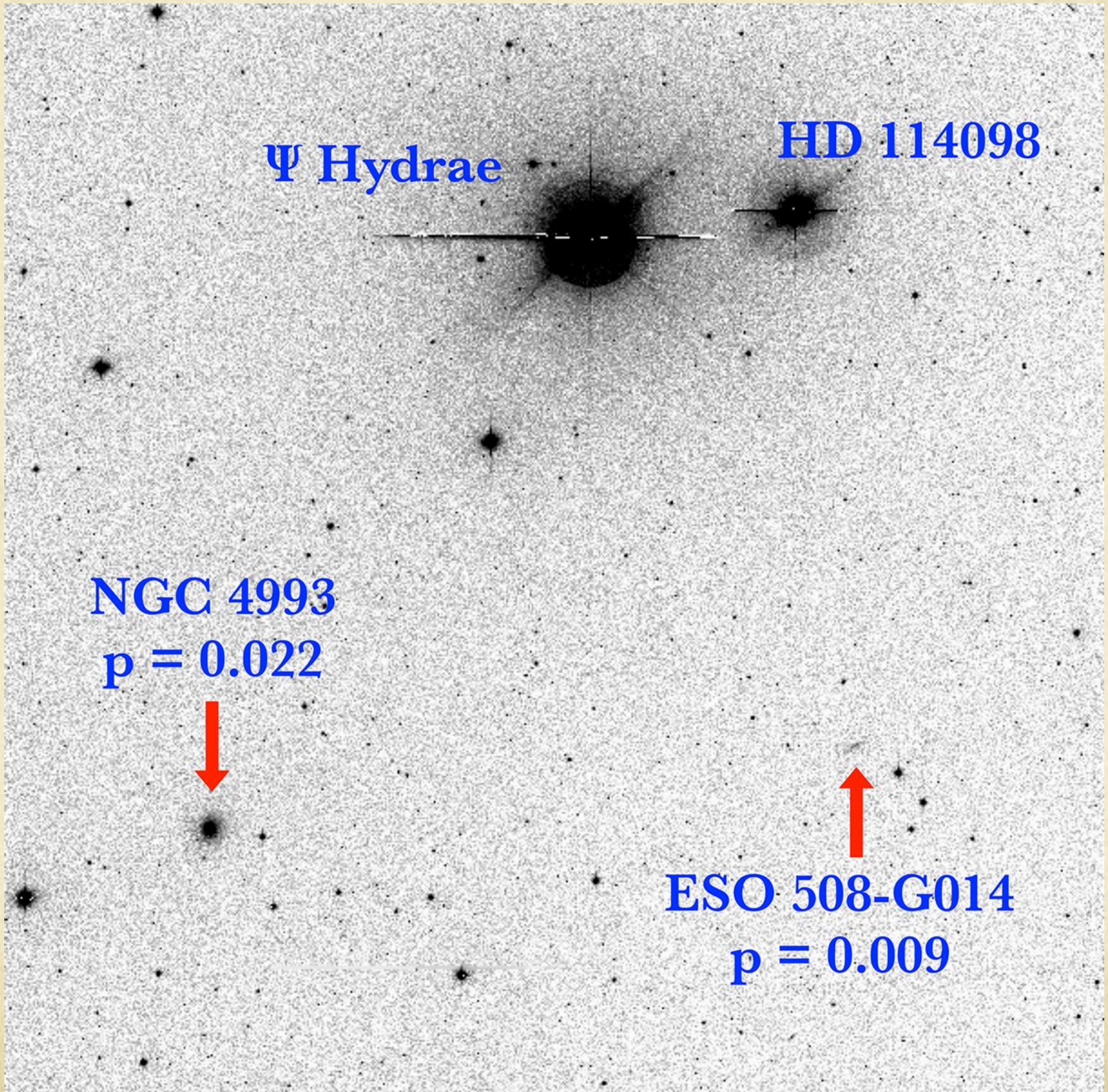
Coulter et al. (2017)

Galaxy-Targeted Search



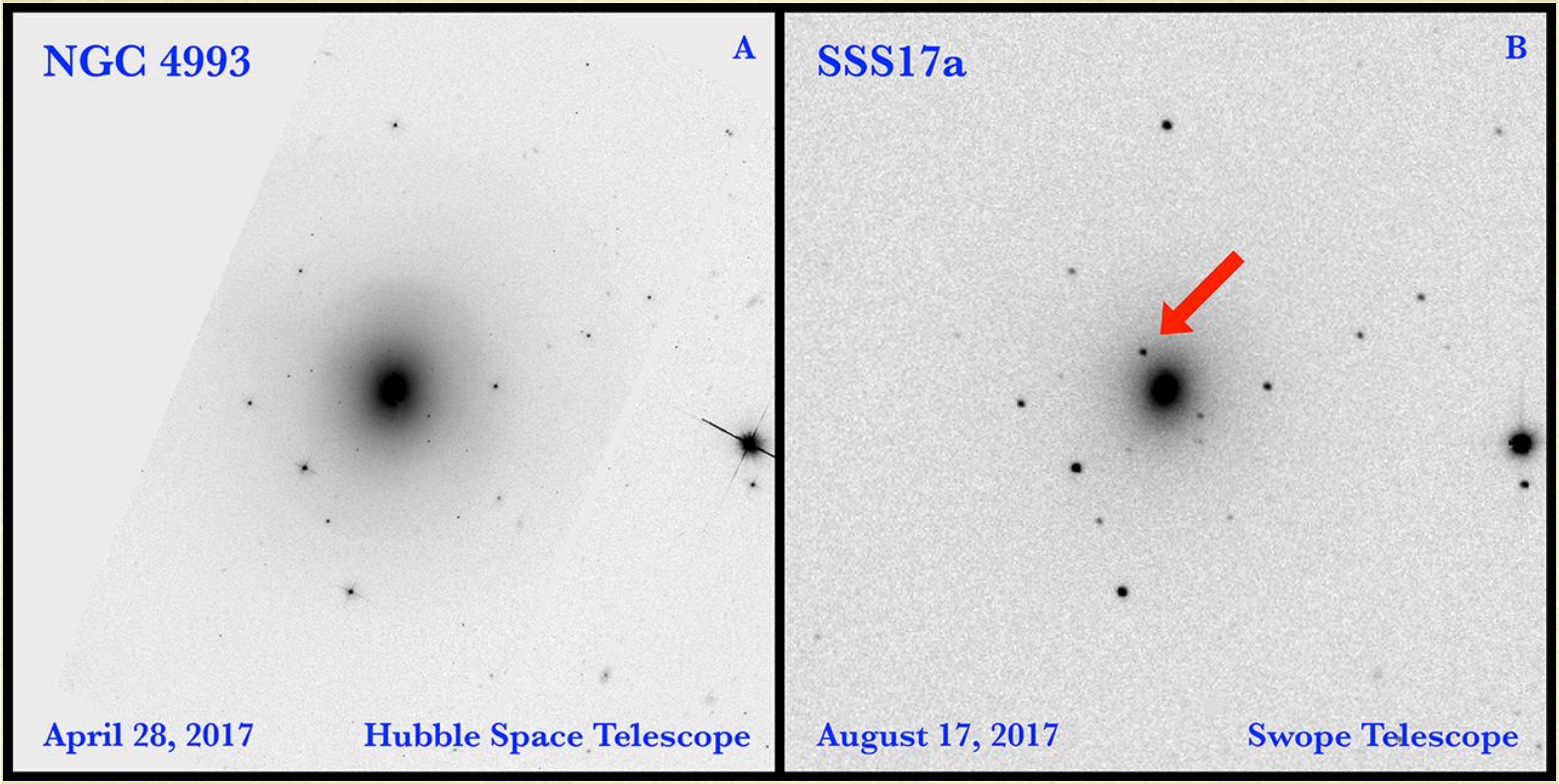
Coulter et al. 2017

The 9th Image

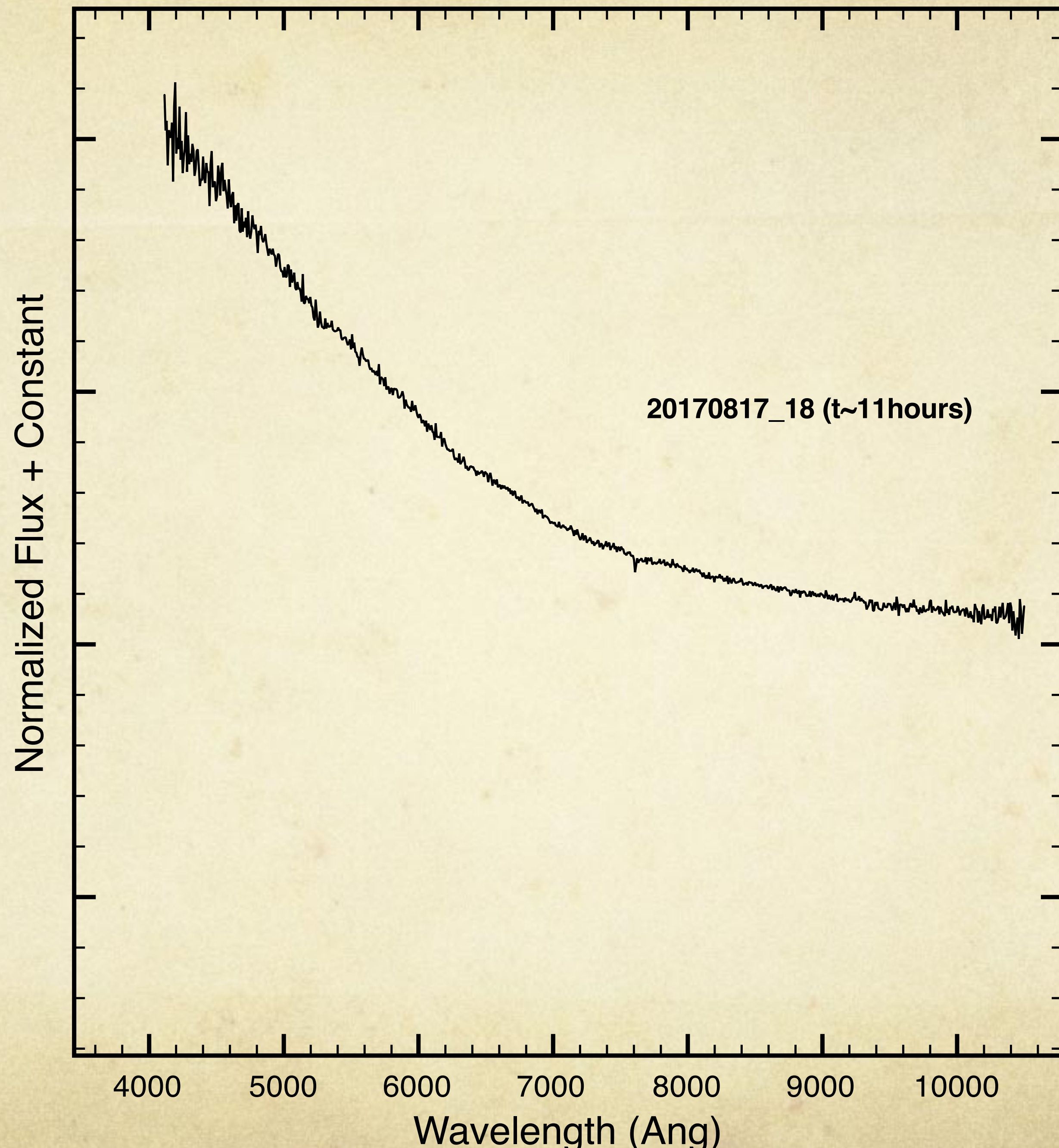


Coulter et al. 2017

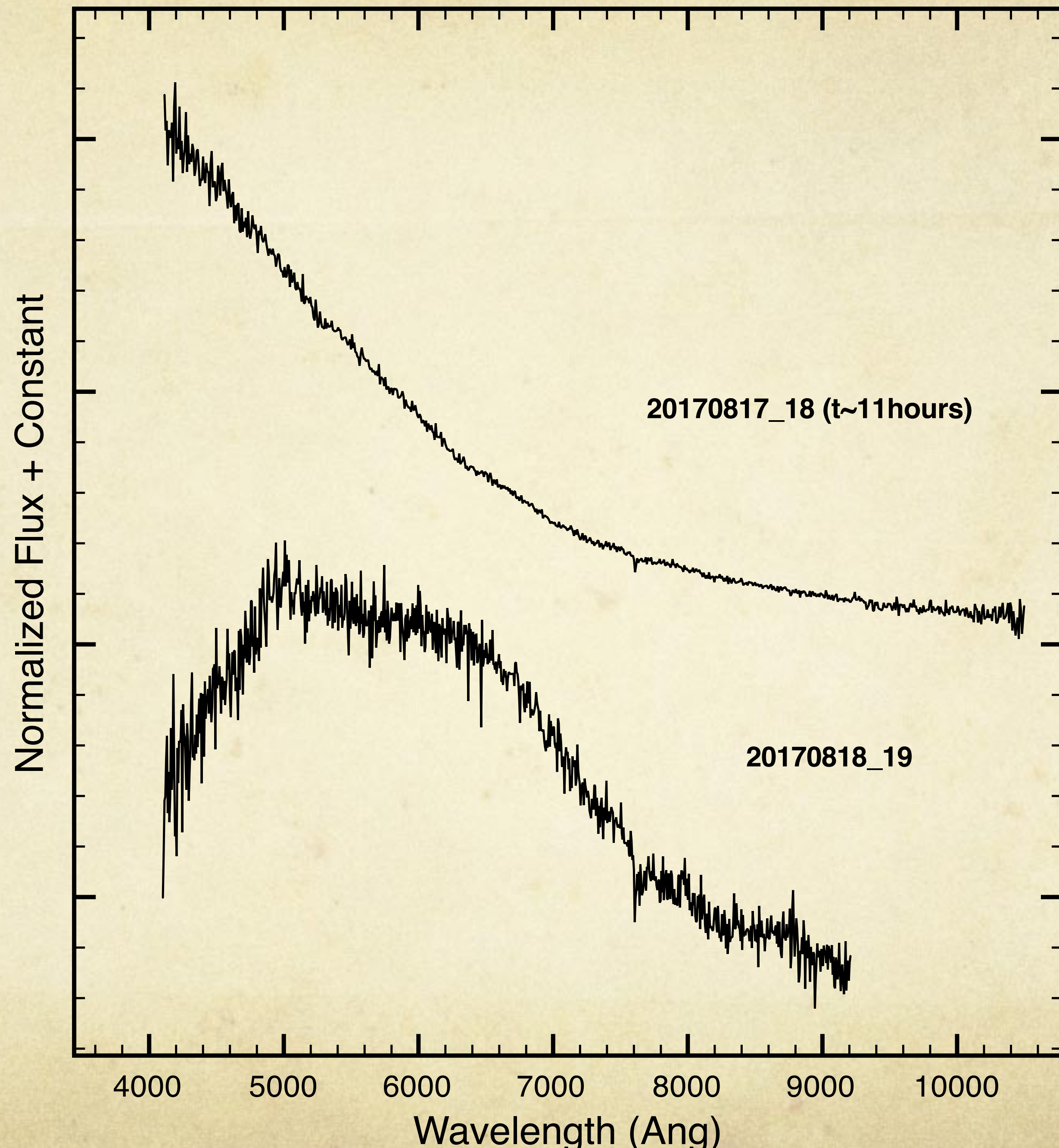
SSS17a



Coulter et al. 2017

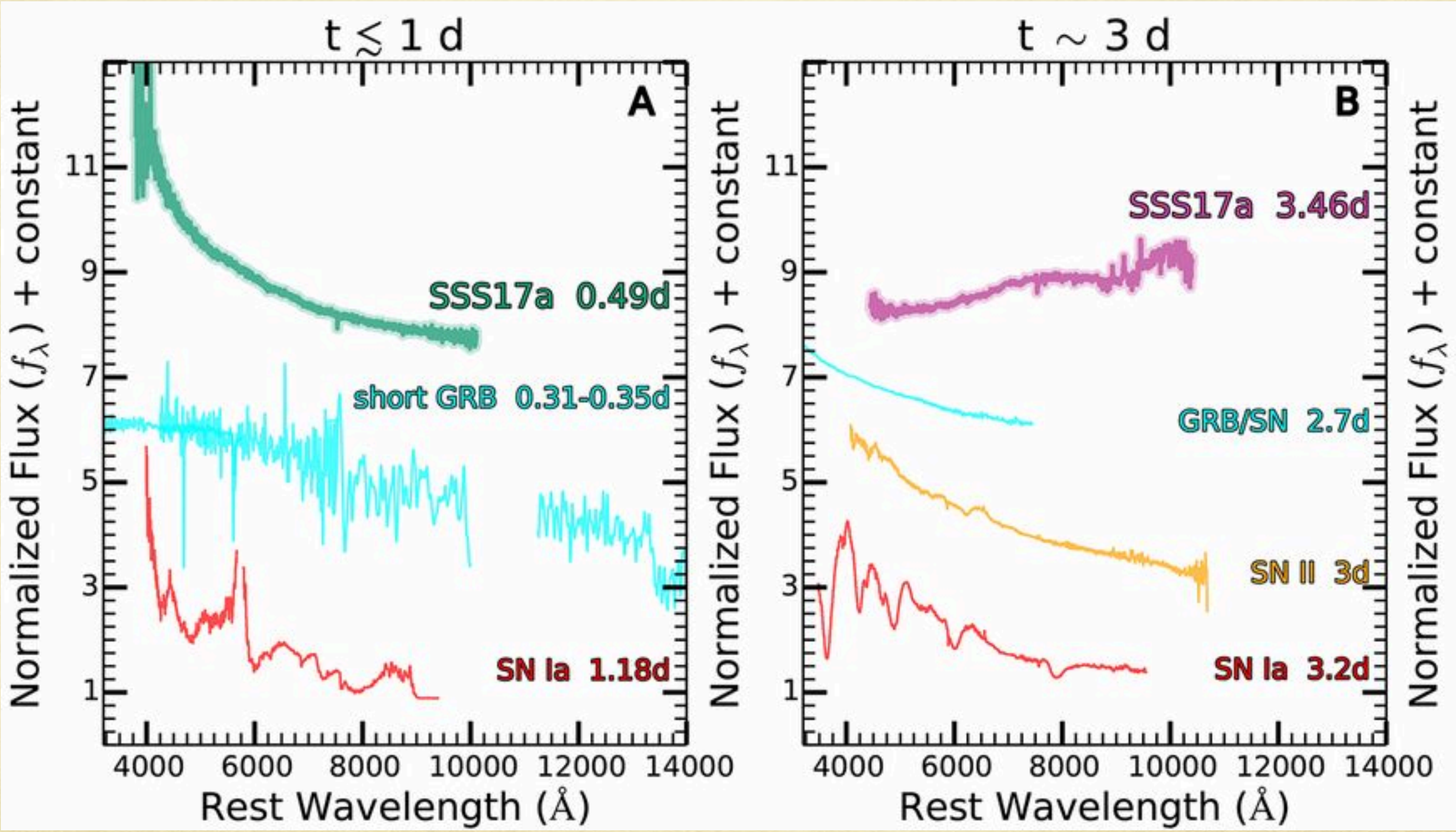


20170817_18 (t~11hours)
Normalized Flux + Constant
4000
5000
6000
7000
8000
9000
10000
Wavelength (Ang)



Normalized Flux + Constant
20170817_18 (t~11hours)
20170818_19
4000
5000
6000
7000
8000
9000
10000
Wavelength (Ang)

SSS17a vs. Other Transients



Shappee, et al. 2017

SSS17a: Follow-Up

<u>Swope 1-m:</u>
Optical
Photometry

<u>du Pont 2.5-m</u>:
Near-IR
Photometry

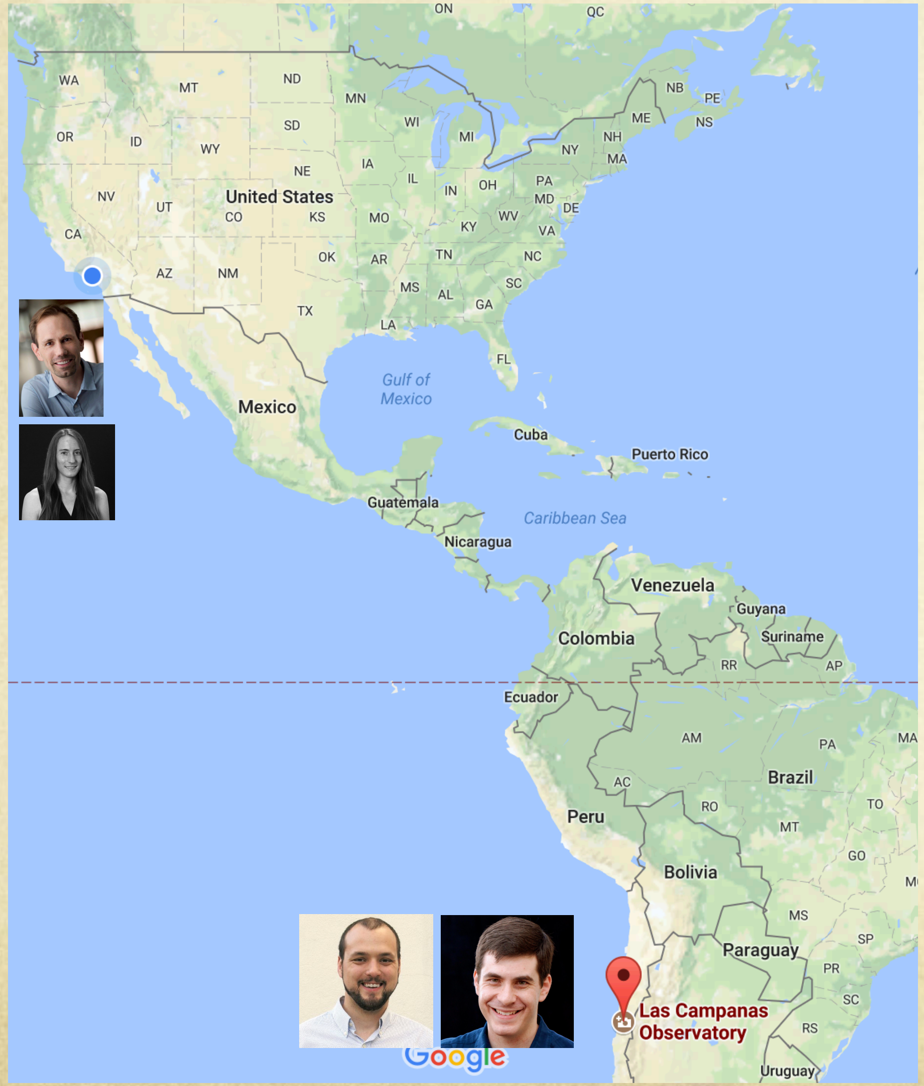
<u>Magellan/Clay and</u>
<u>Magellan/Baade 6.5m:</u>
Optical Photometry
NIR Photometry
Optical Spectroscopy

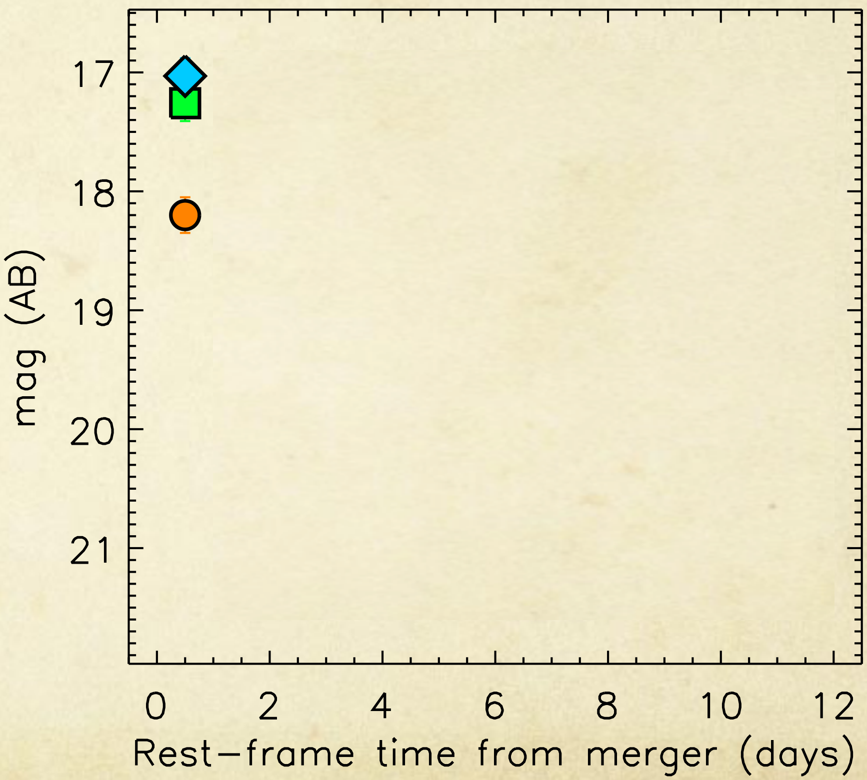
Where in the World are...
Carnegie Scientists

Where in the World are...

Carnegie Scientists

+0.5 days (Thurs.)

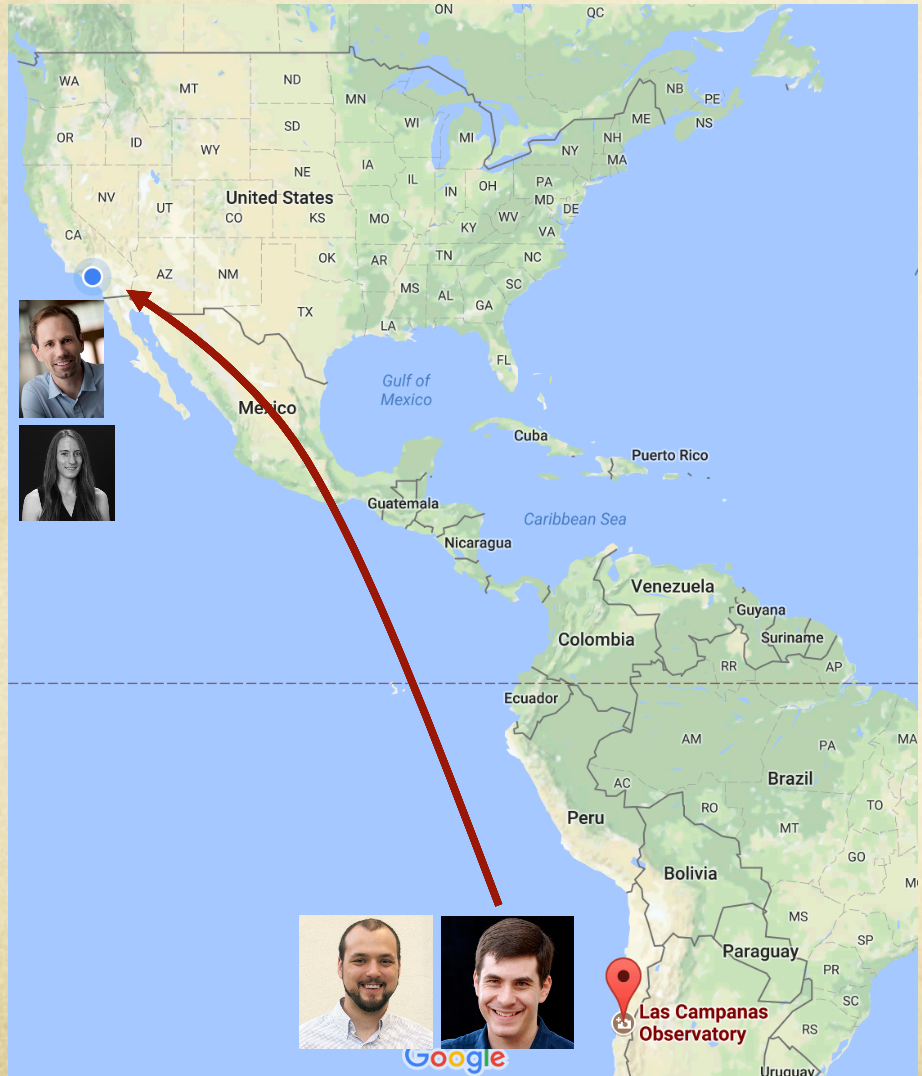


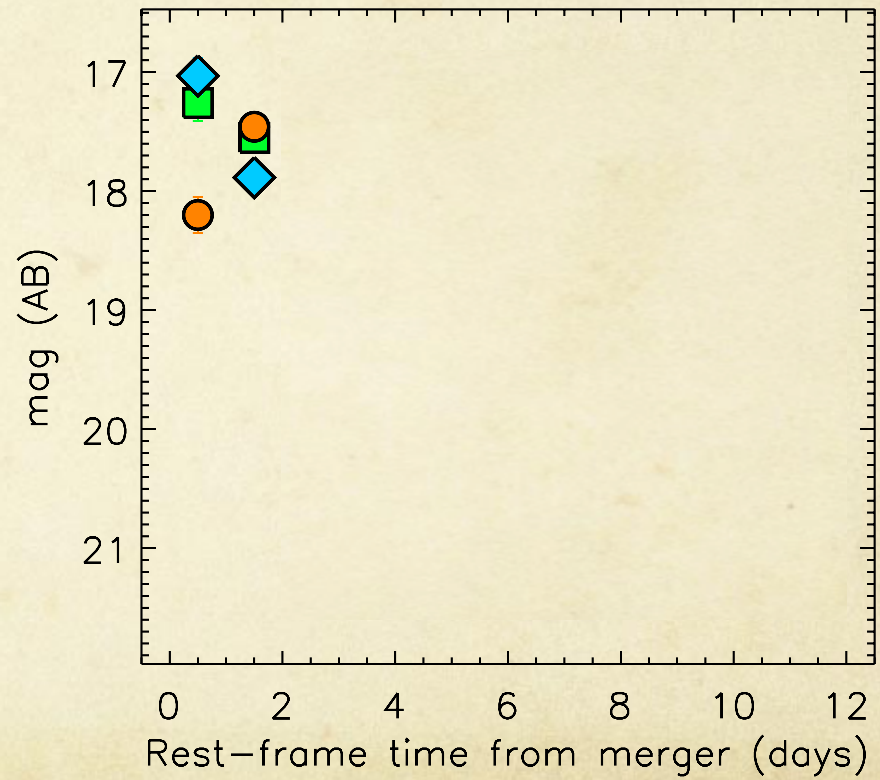


Where in the World are...

Carnegie Scientists

+1.5 days (Fri.)

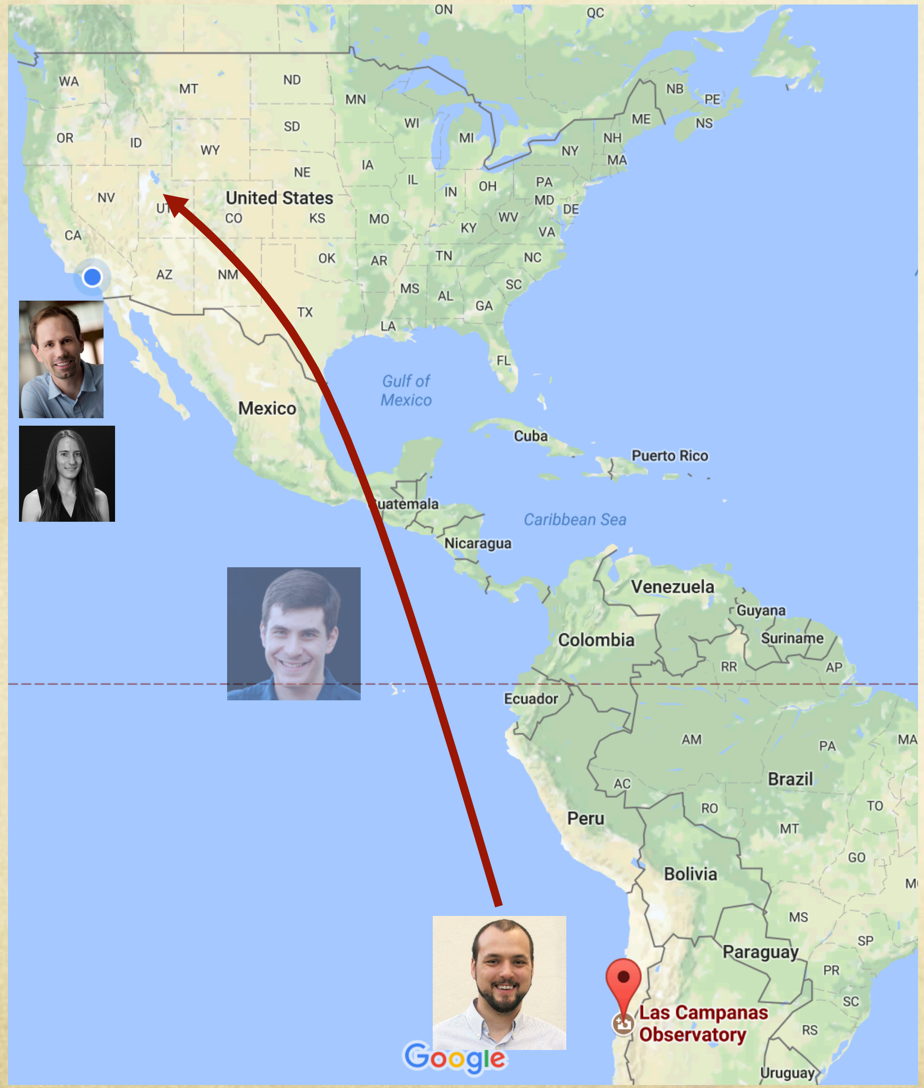


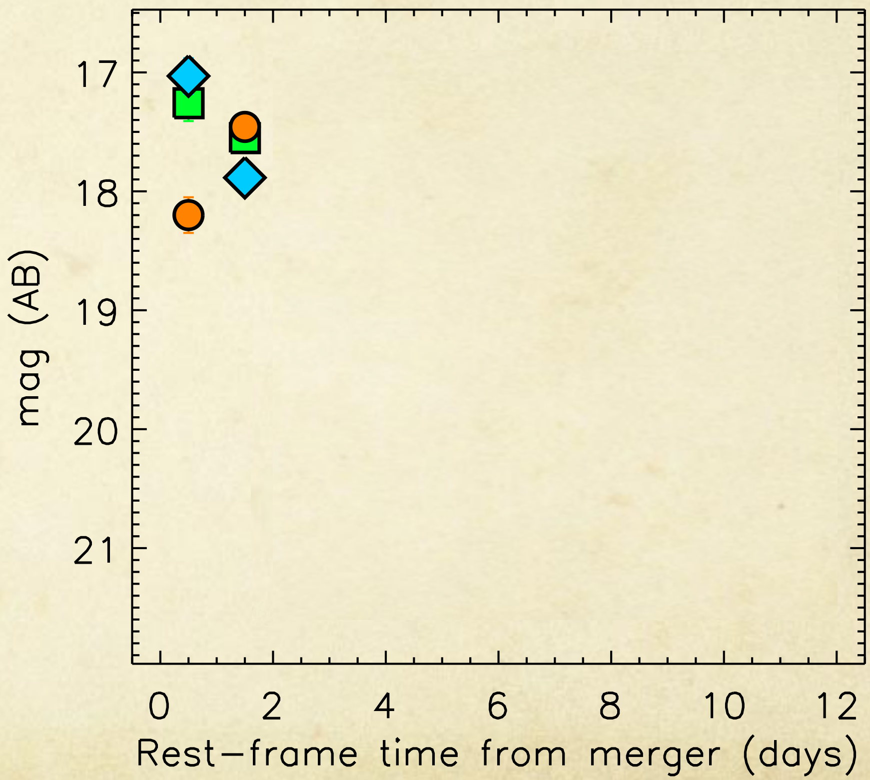


Where in the World are...

Carnegie Scientists

+2.5 days (Sat.)

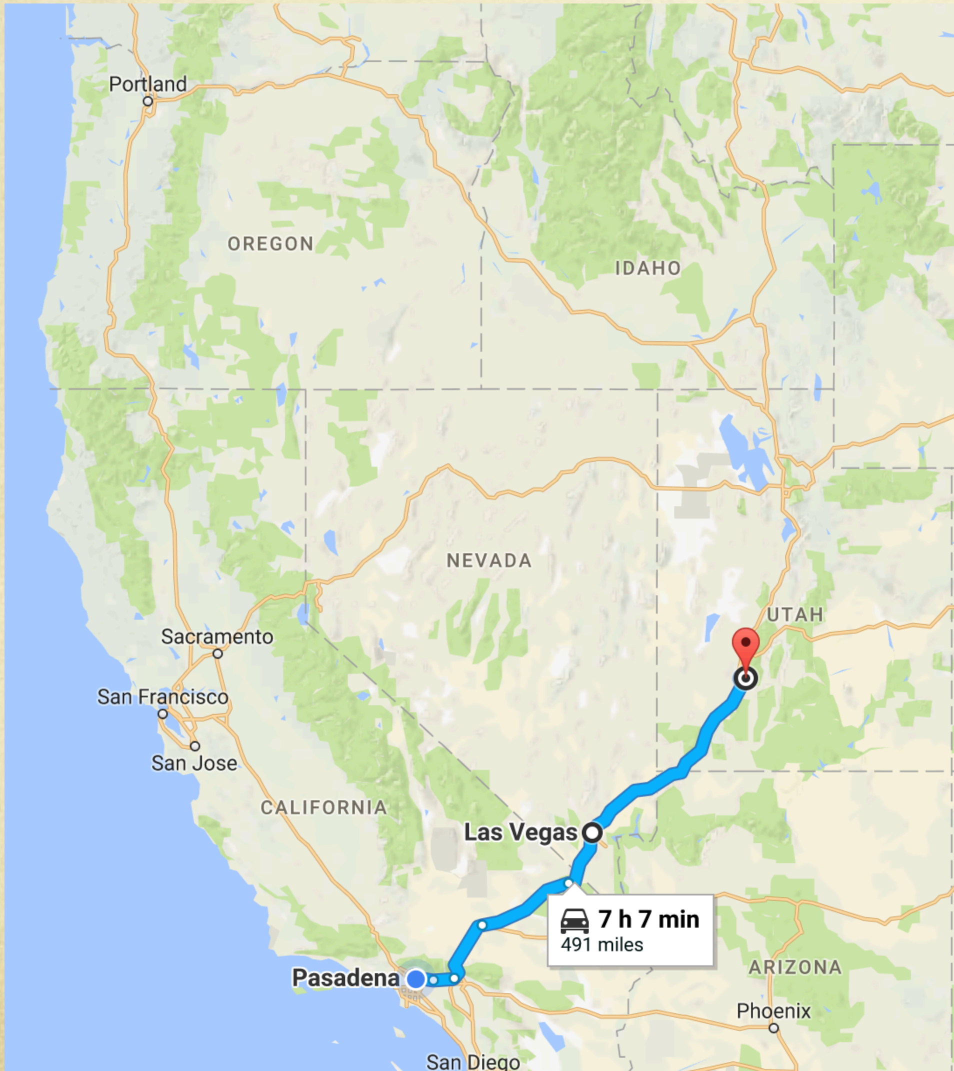


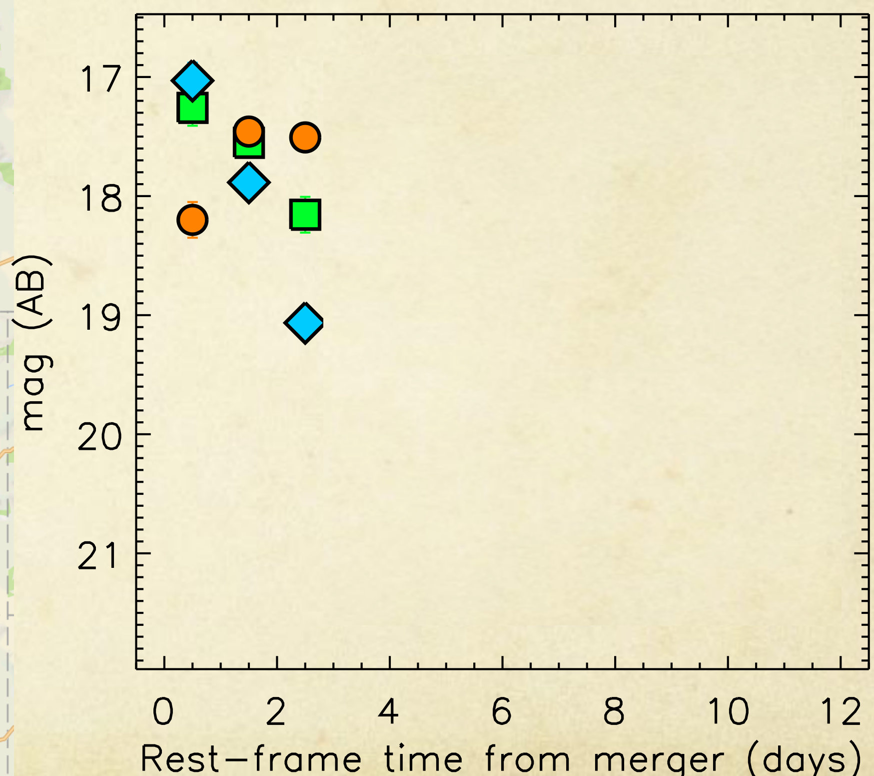


Where in the World are...

Carnegie Scientists

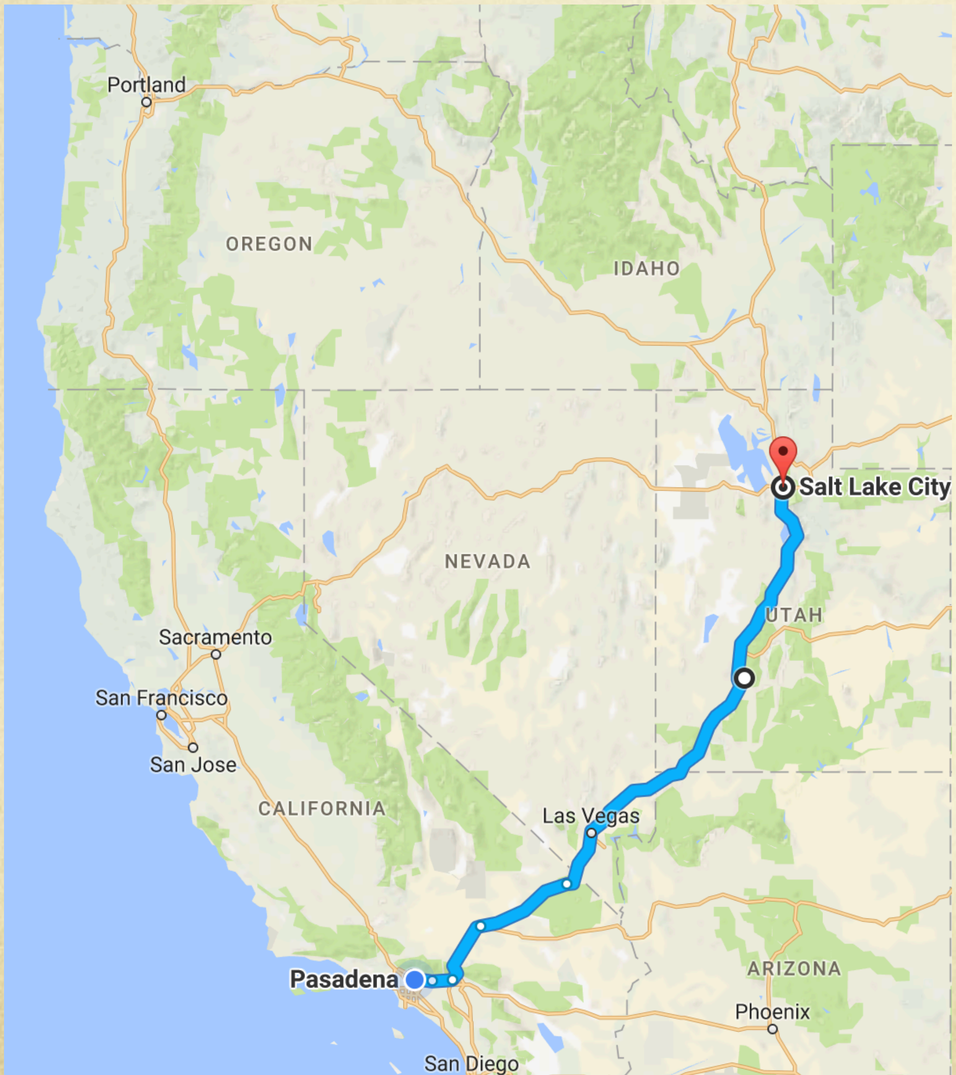
+2.5 days (Sat.)

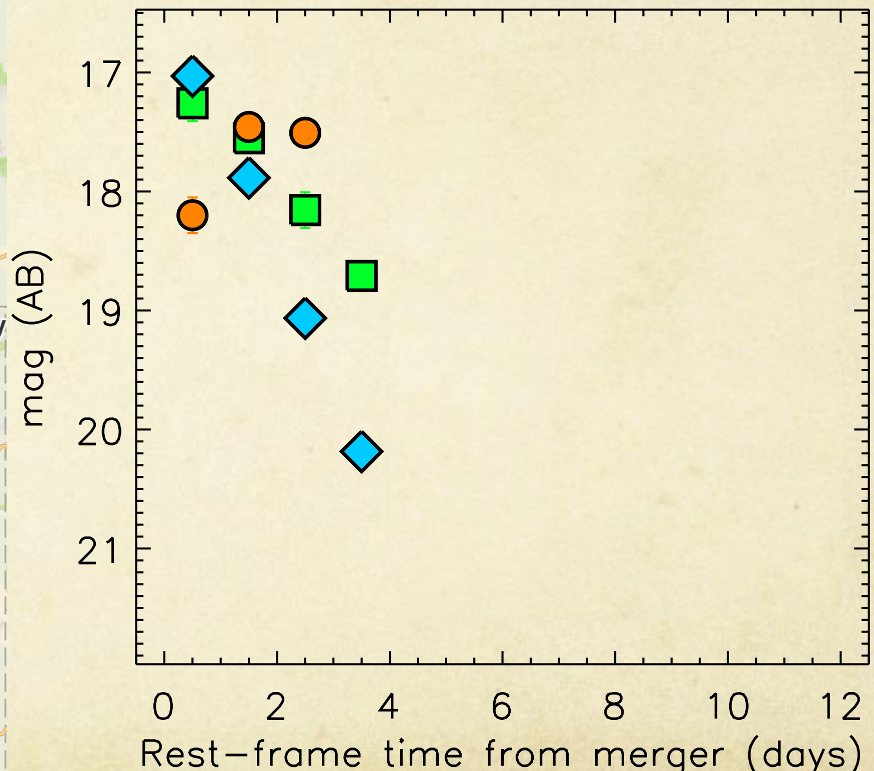




Where in the World are...
Carnegie Scientists

+3.5 days (Sun.)

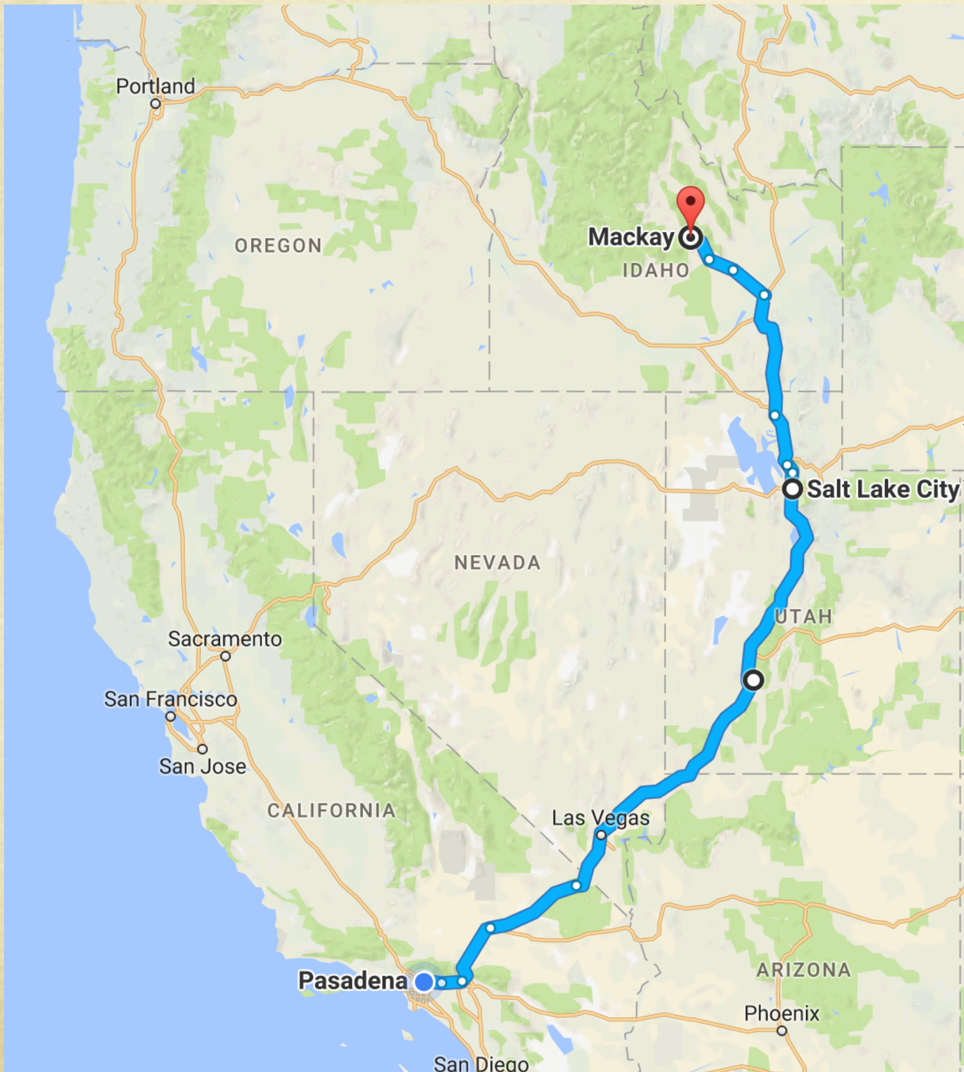


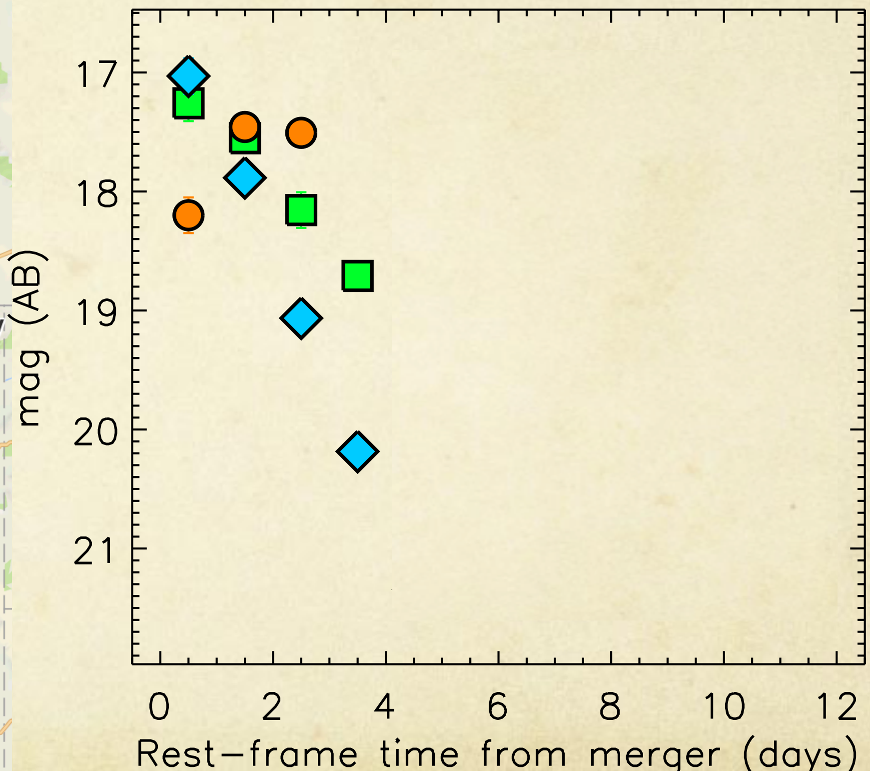


Where in the World are...

Carnegie Scientists

+3.5 days (Sun.)

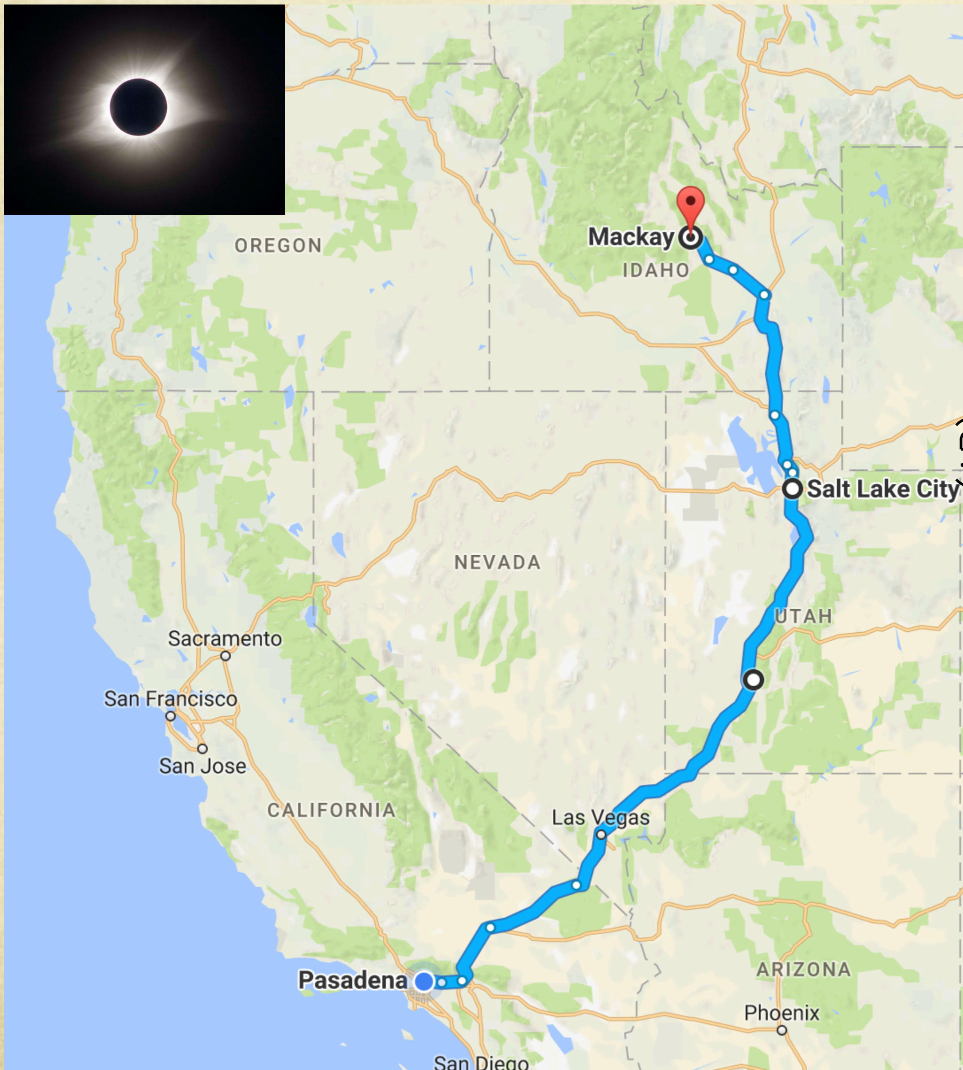


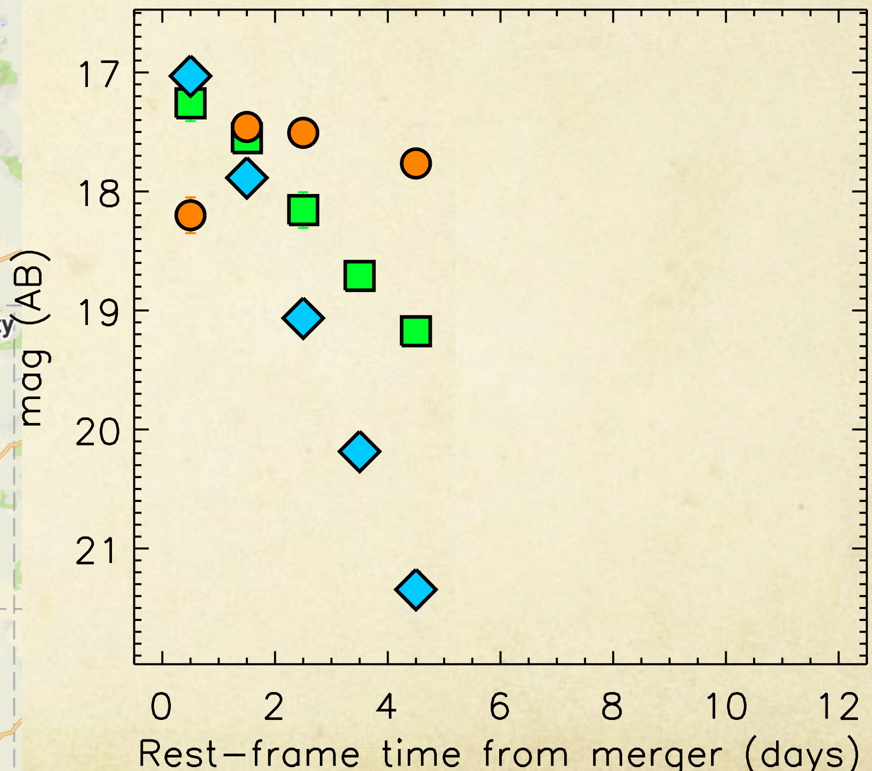


Where in the World are...

Carnegie Scientists

+4.5 days (Mon.)

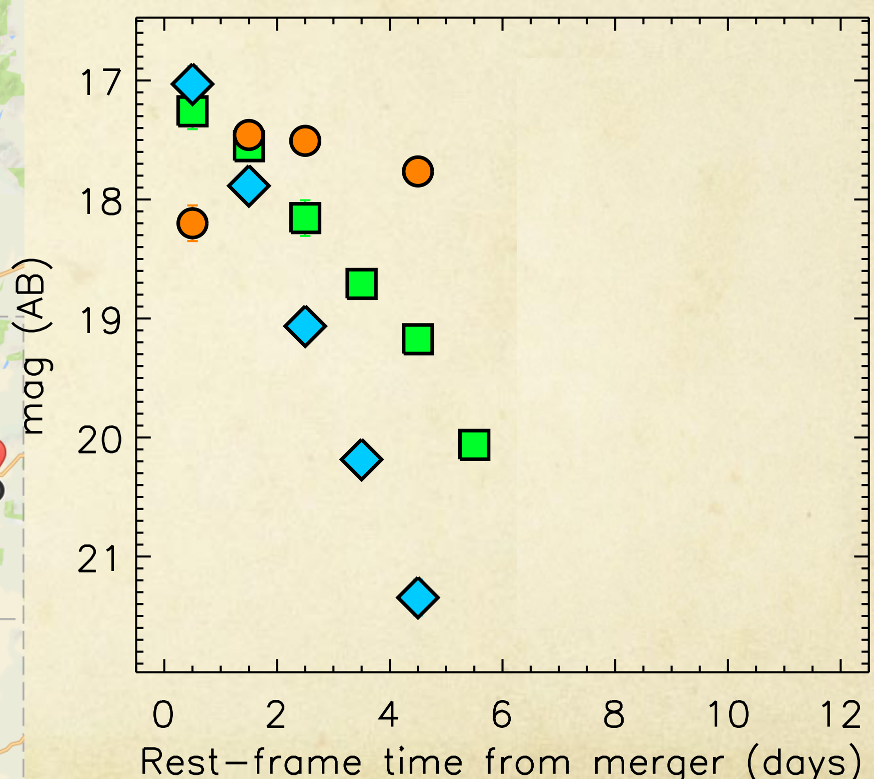




Where in the World are...

Carnegie Scientists

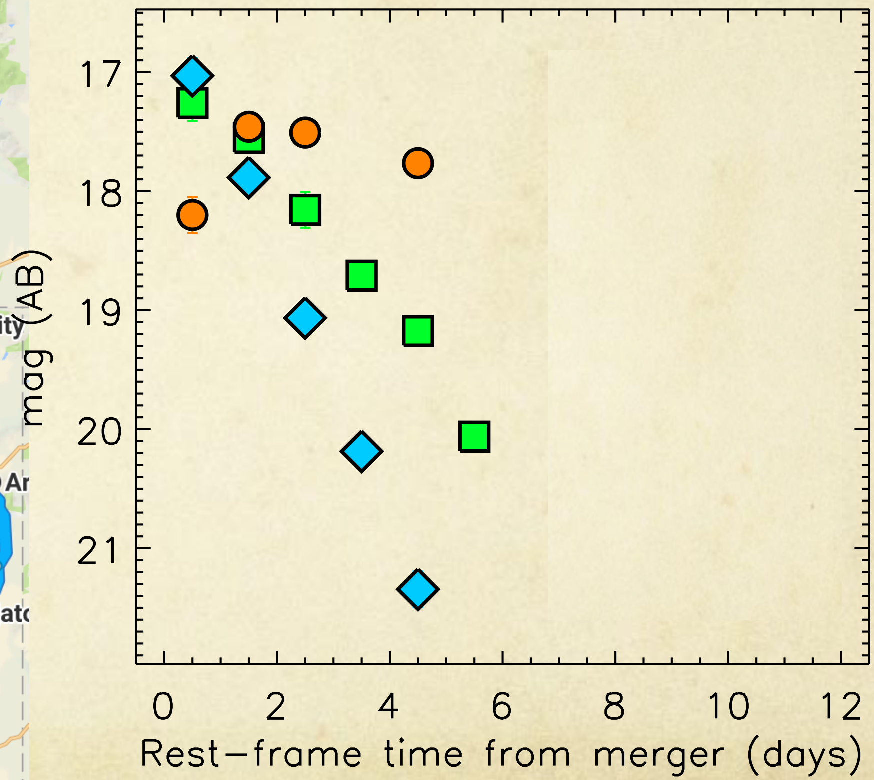
+5.5 days (Tues.)



Where in the World are...

Carnegie Scientists

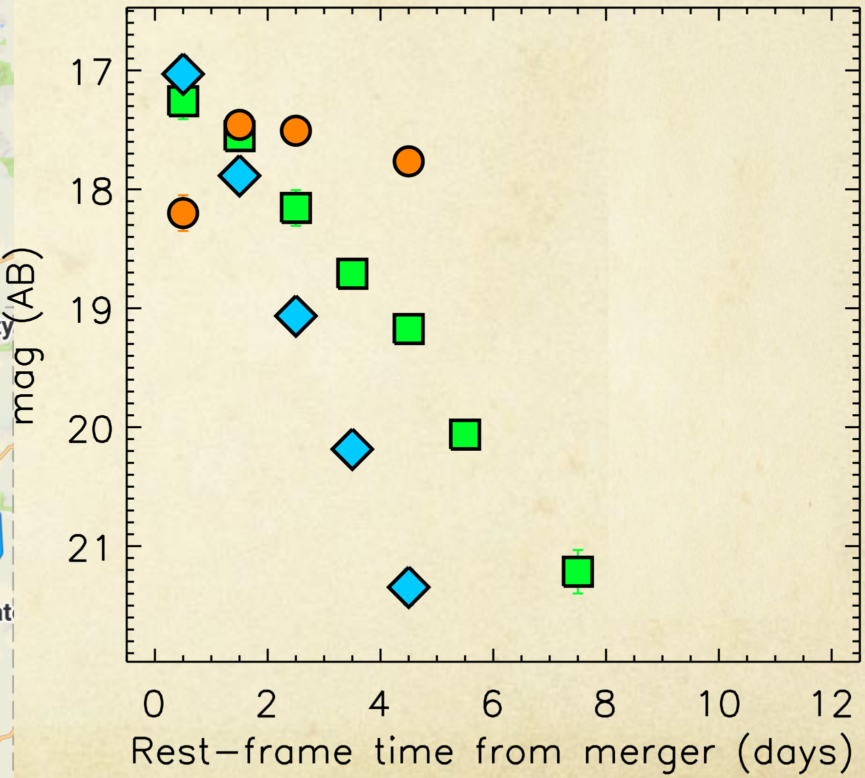
+6.5 days (Wed.)



Where in the World are...

Carnegie Scientists

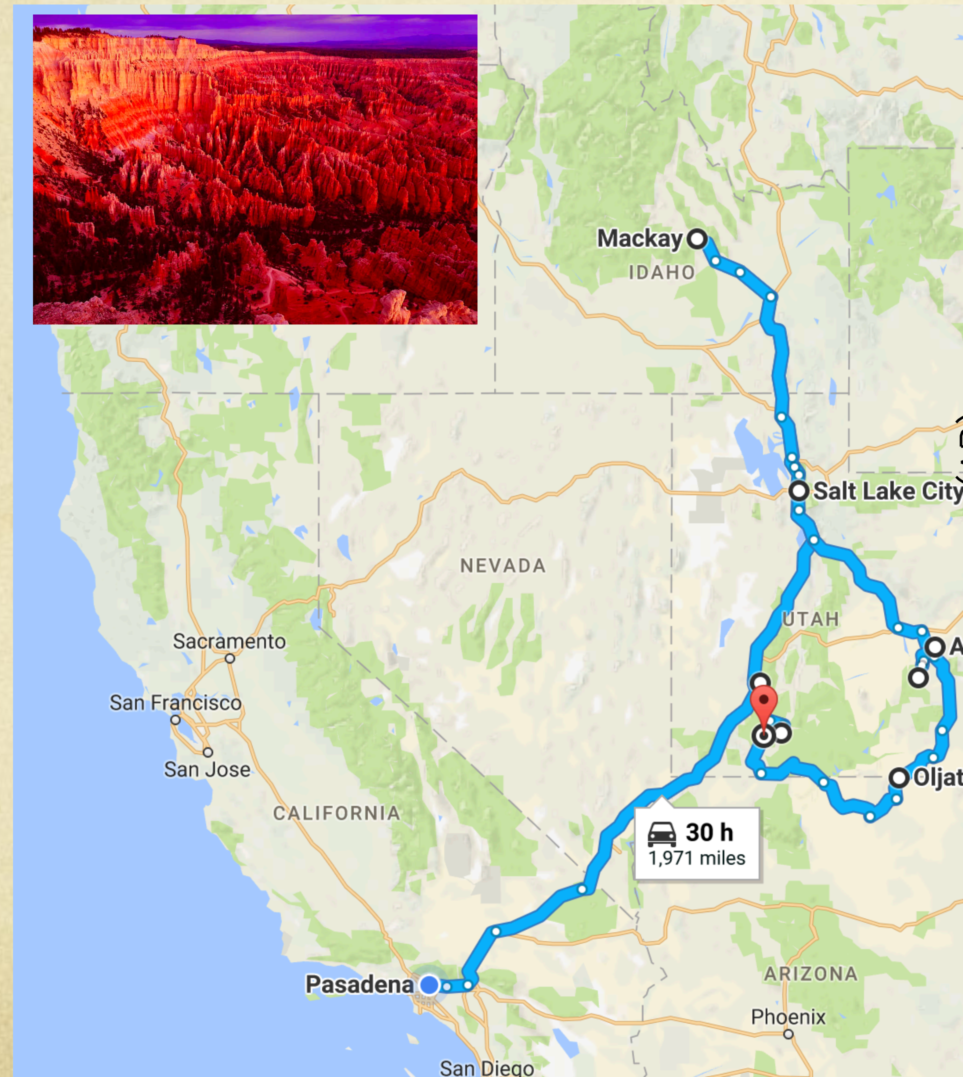
+7.5 days (Thurs.)

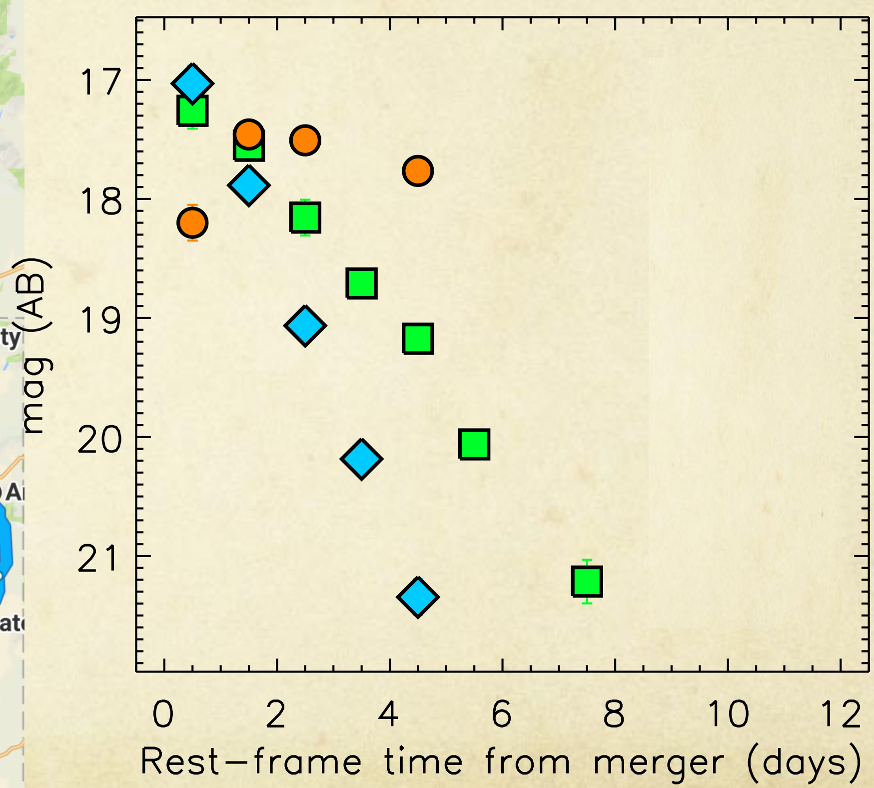


Where in the World are…

Carnegie Scientists

+8.5 days (Fri.)

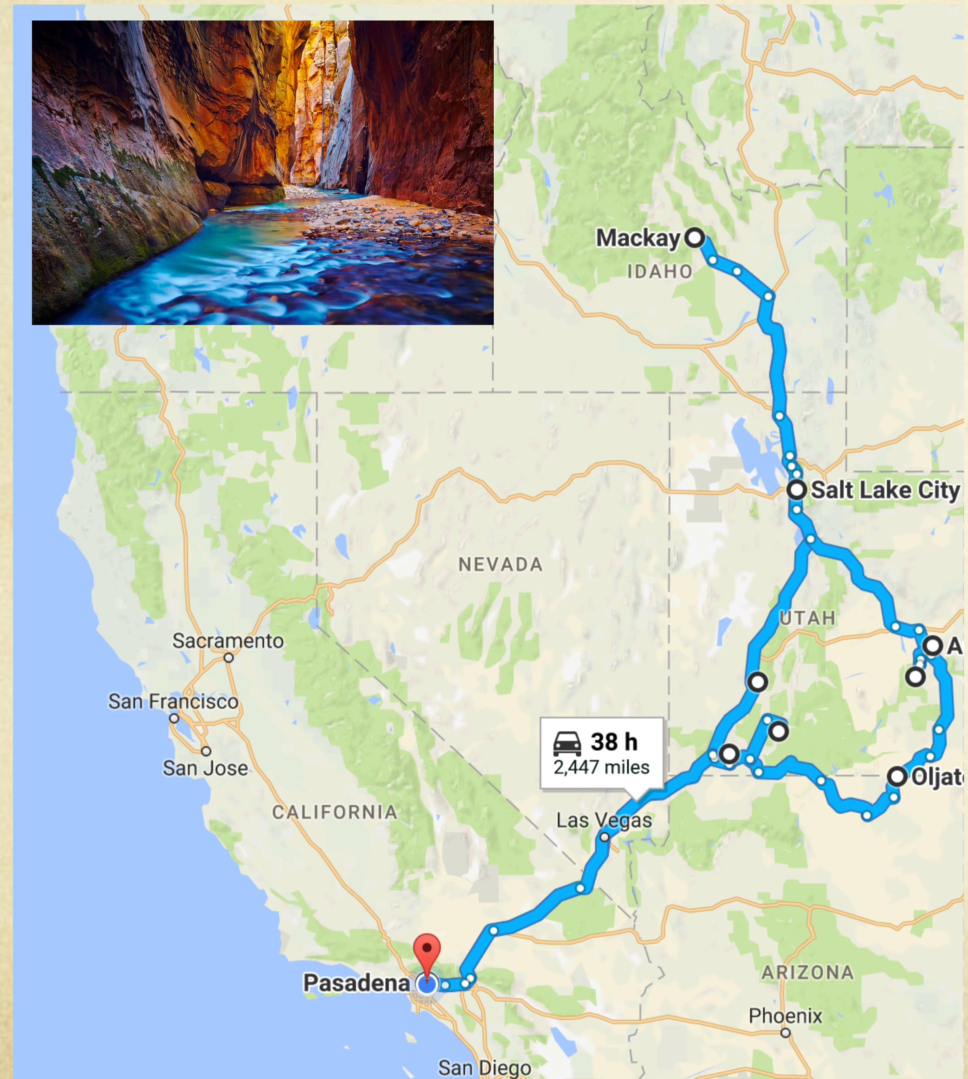


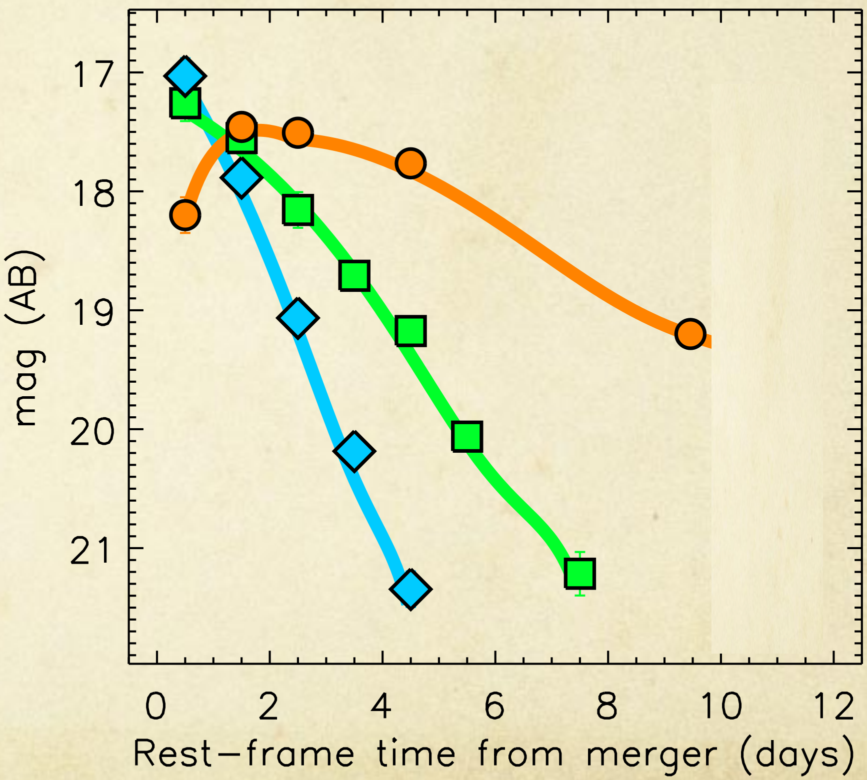


Where in the World are...

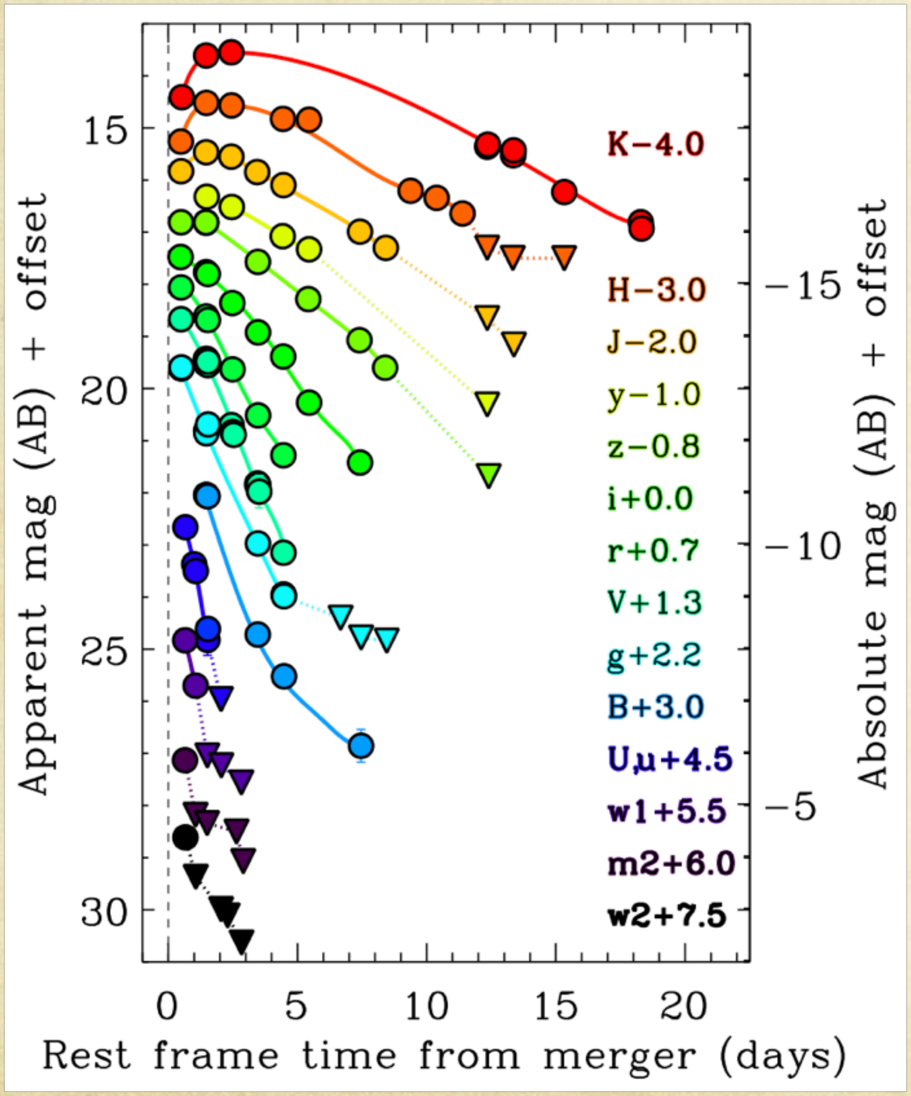
Carnegie Scientists

+9.5 days (Sat.)

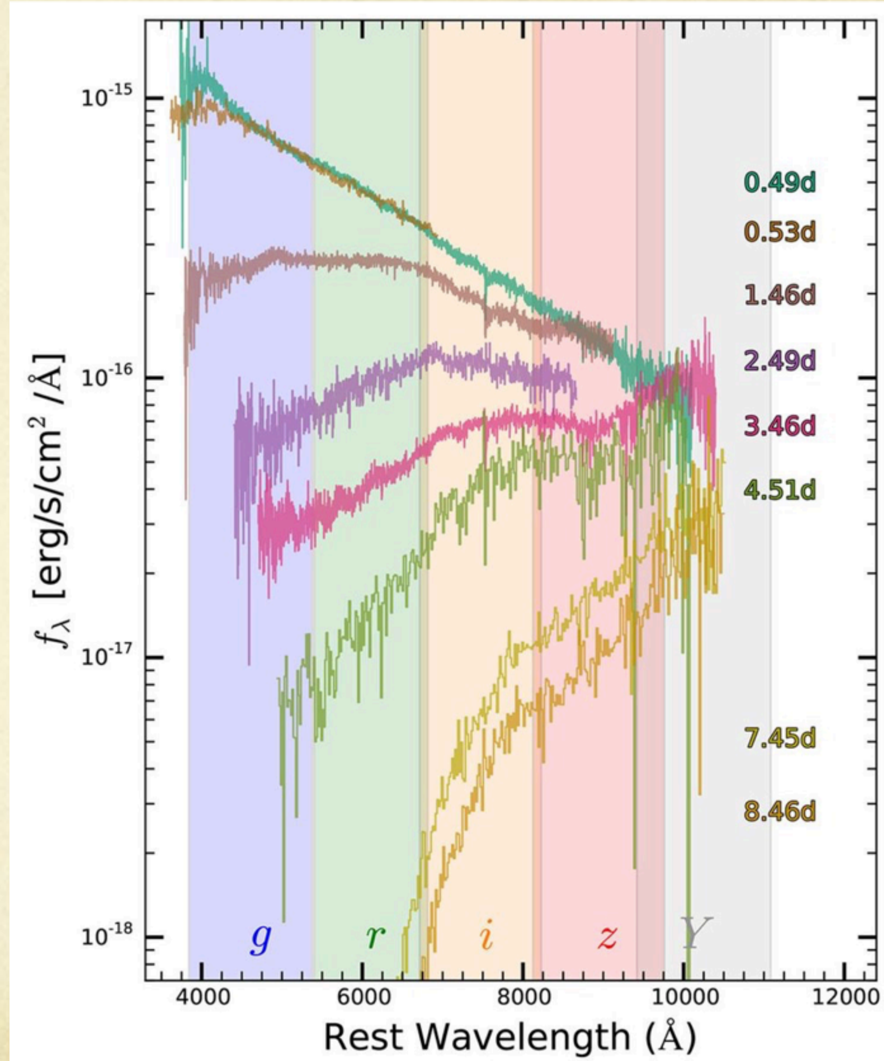




SSS17a: Observations

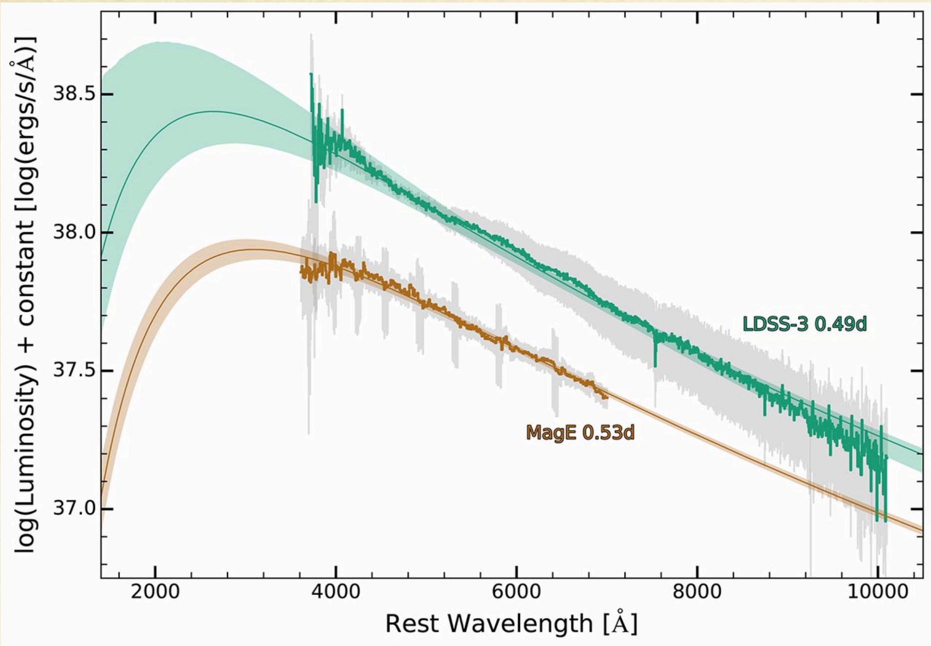


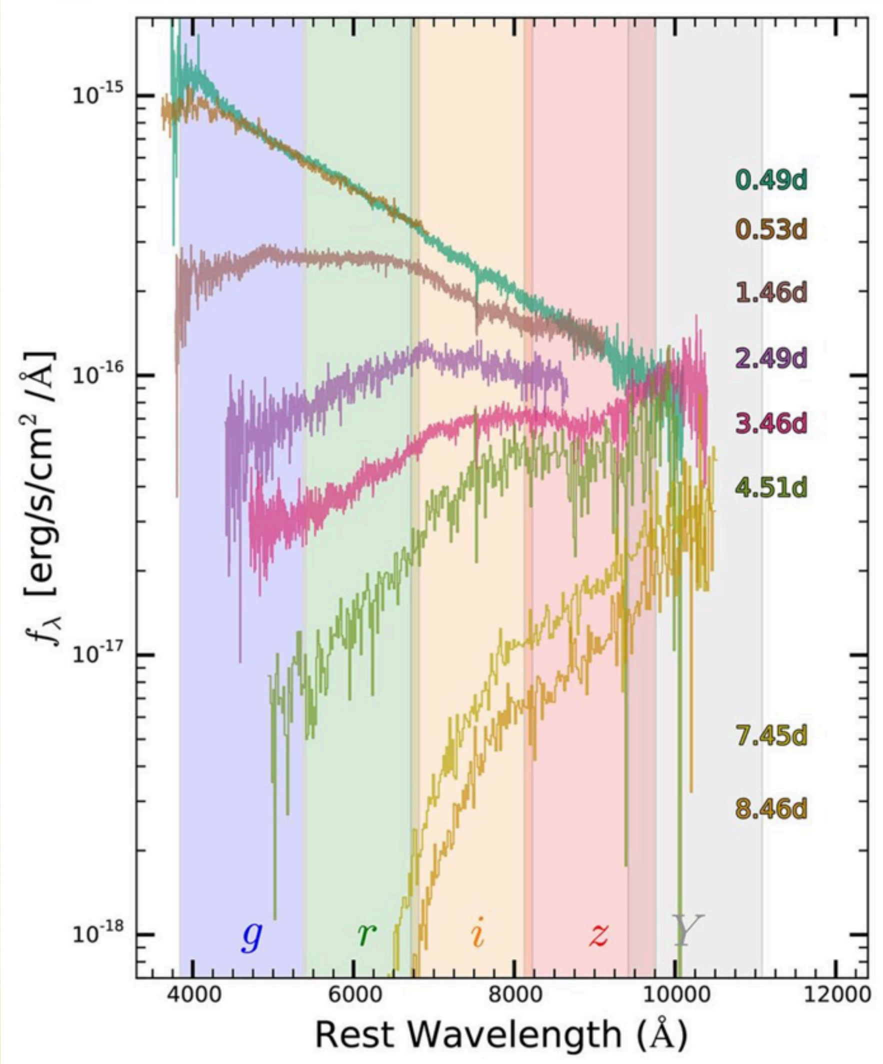
Drout et al. (2017)



Shappee et al. (2017)

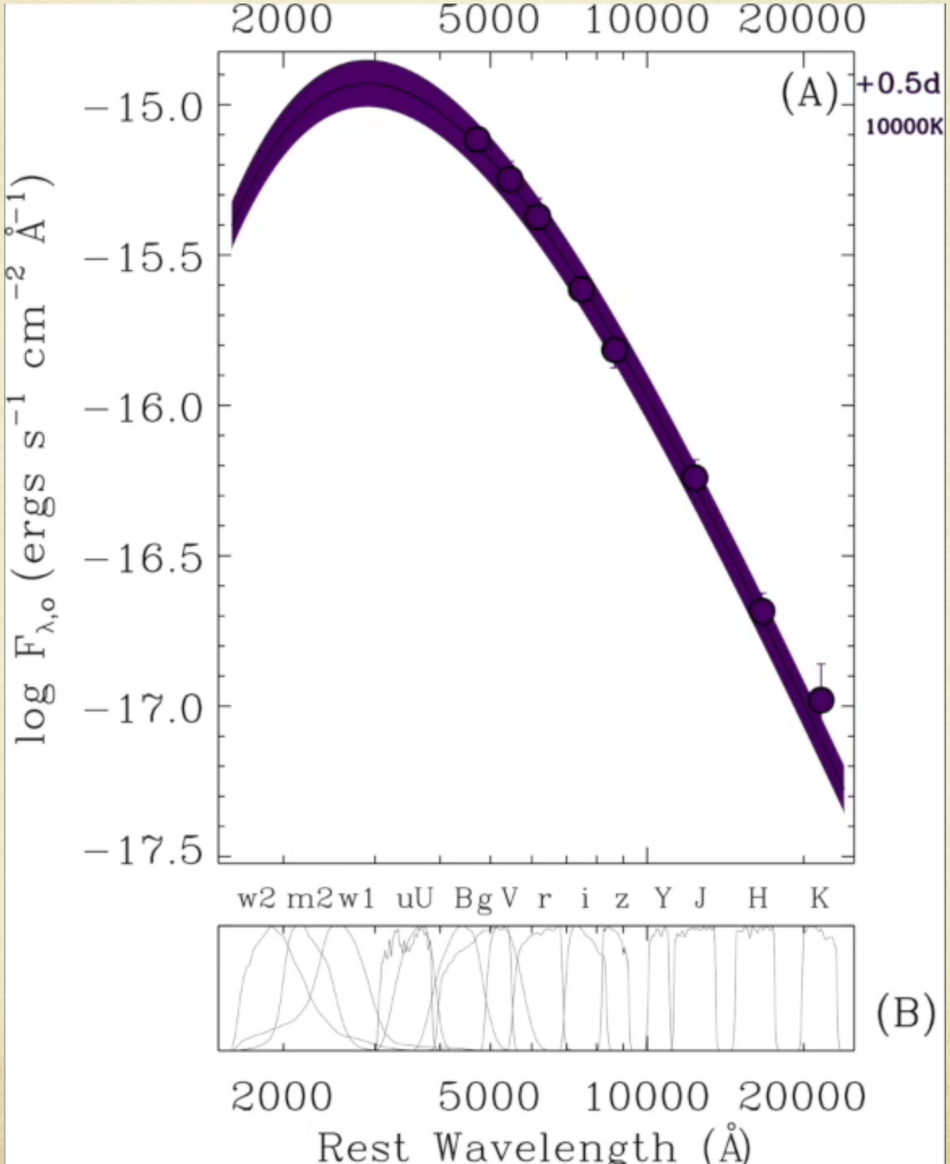
SSS17a Evolution





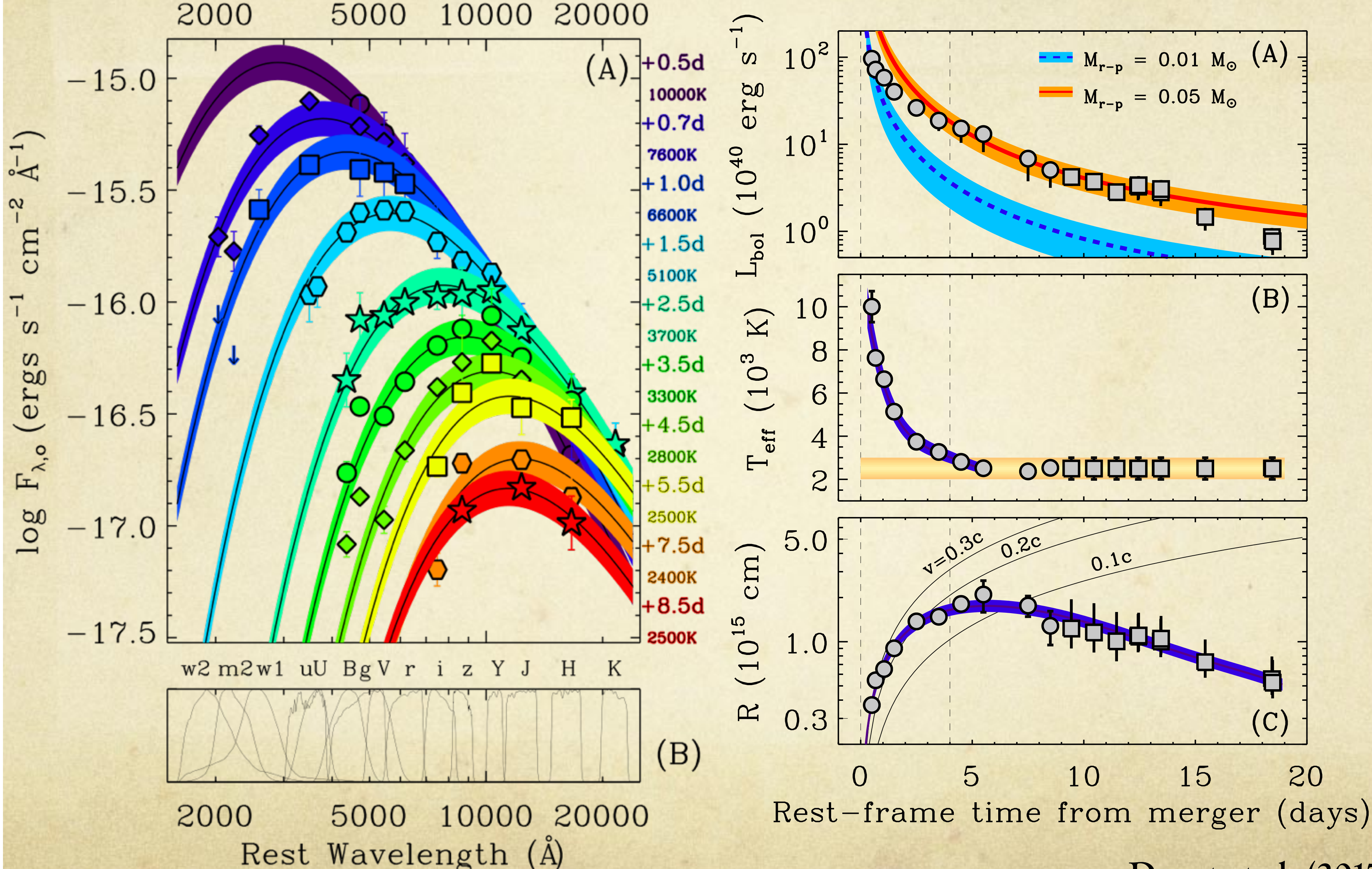
Shappee et al. (2017)

SSS17a: Observations



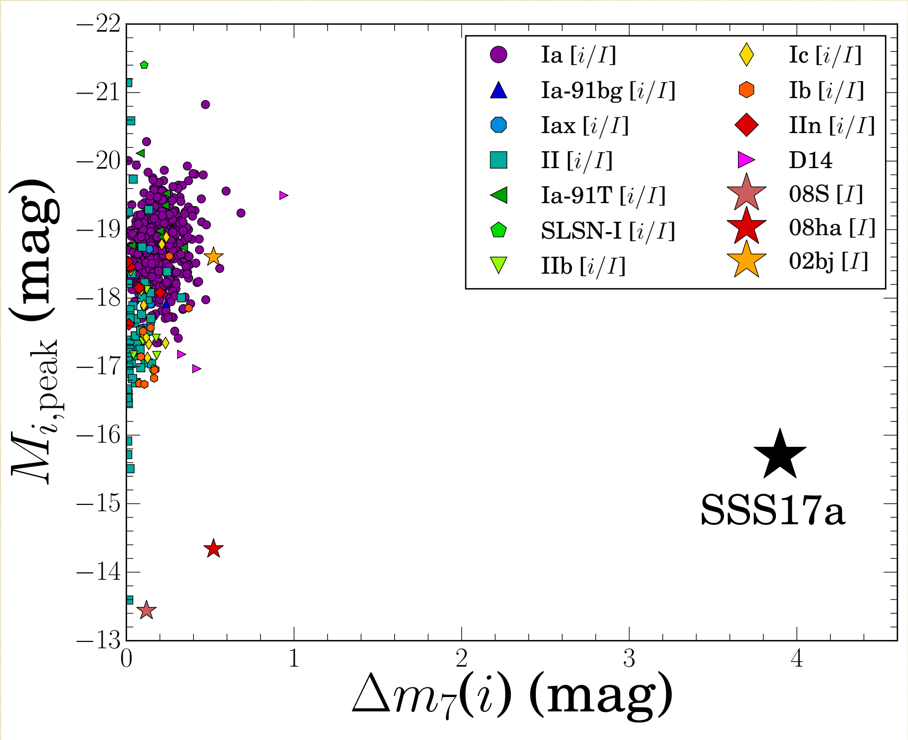
Drout et al. (2017)

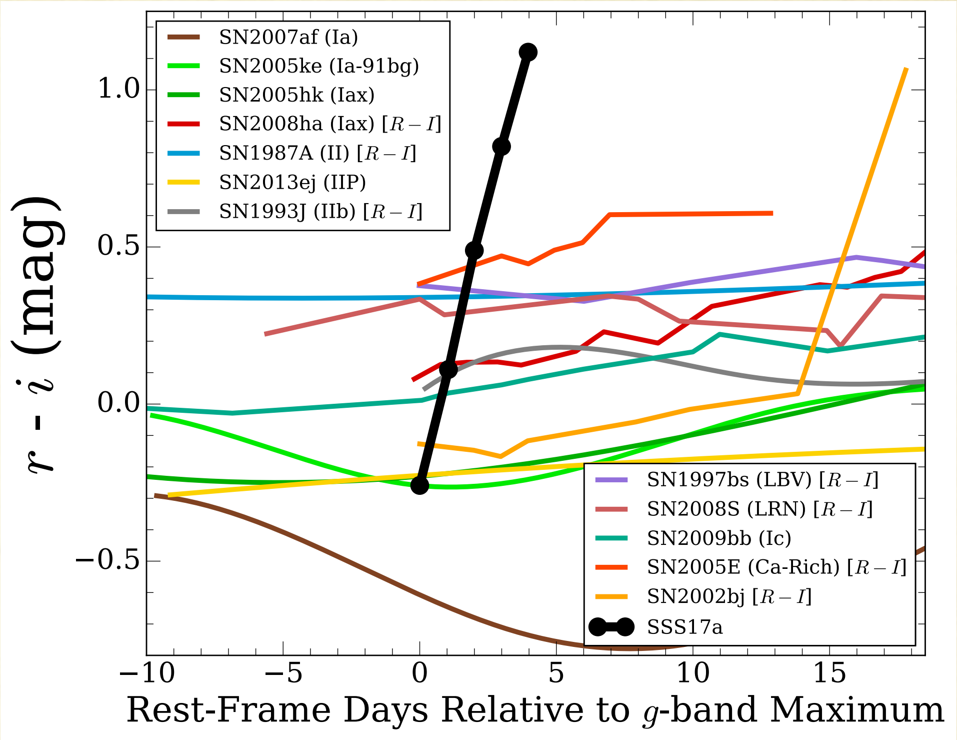
SSS17a: Observations



Drout et al. (2017)

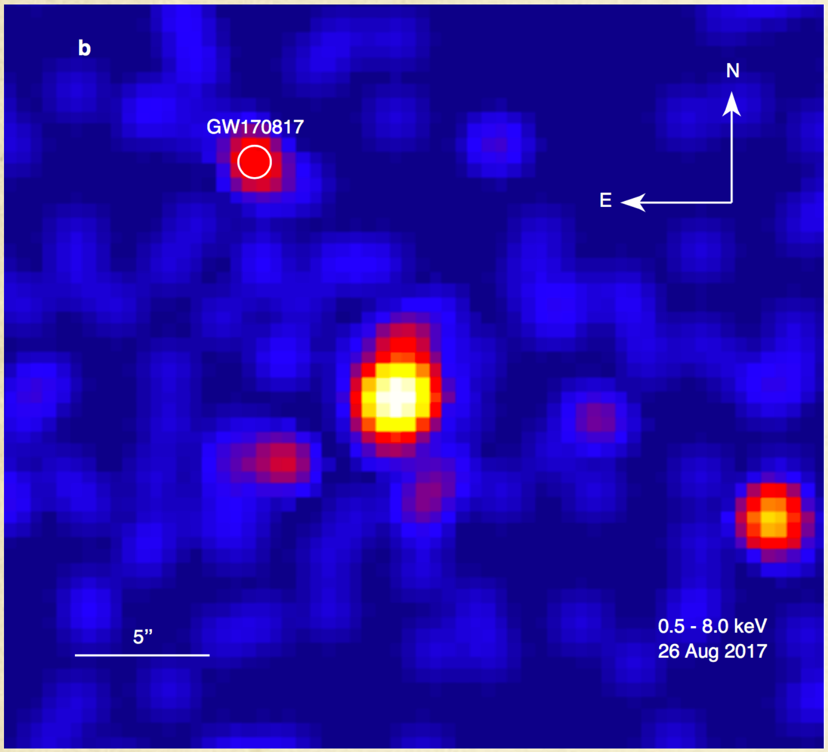
SSS17a is Unique

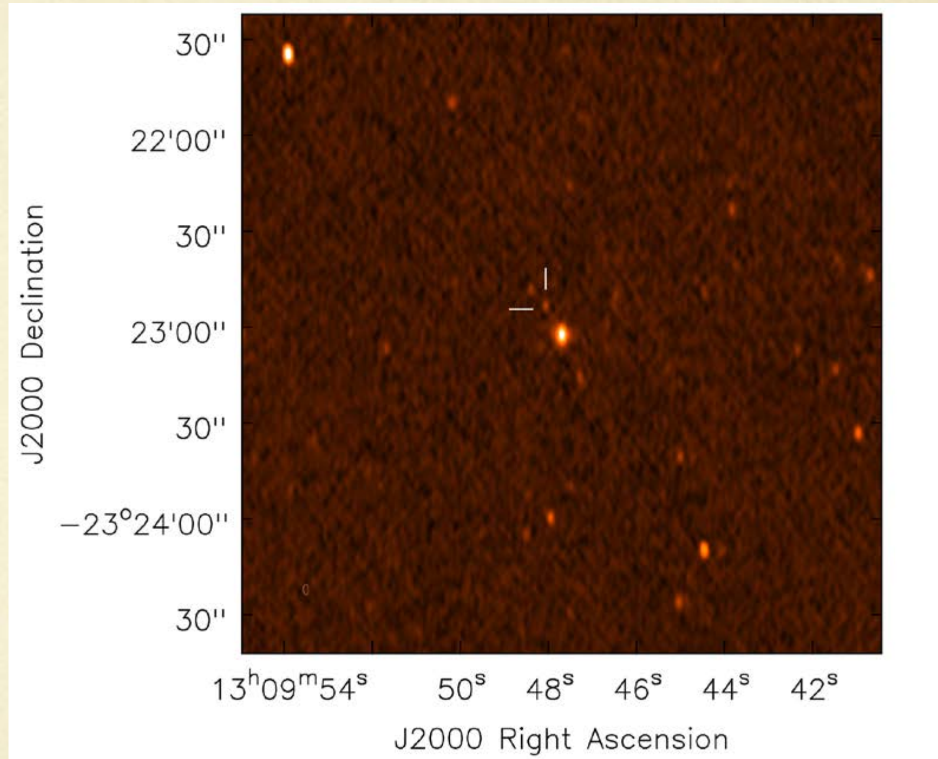




Siebert et al. 2017

X-ray and Radio Emission

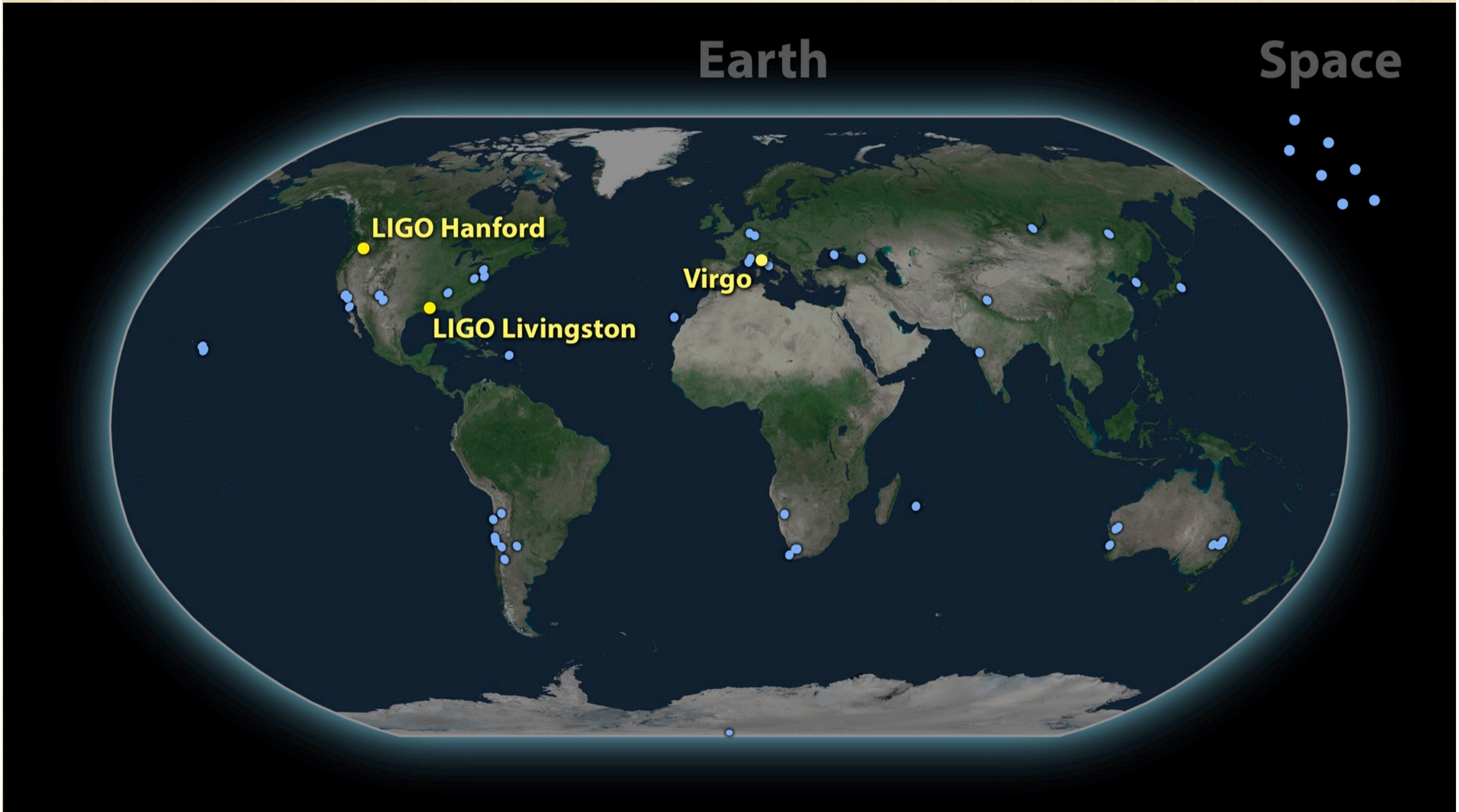




Chandra +9d; (Troja et al. 2017)

JVLA +16.4d; (Hallinan et al. 2017)

All Together:



What does it all mean?

Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

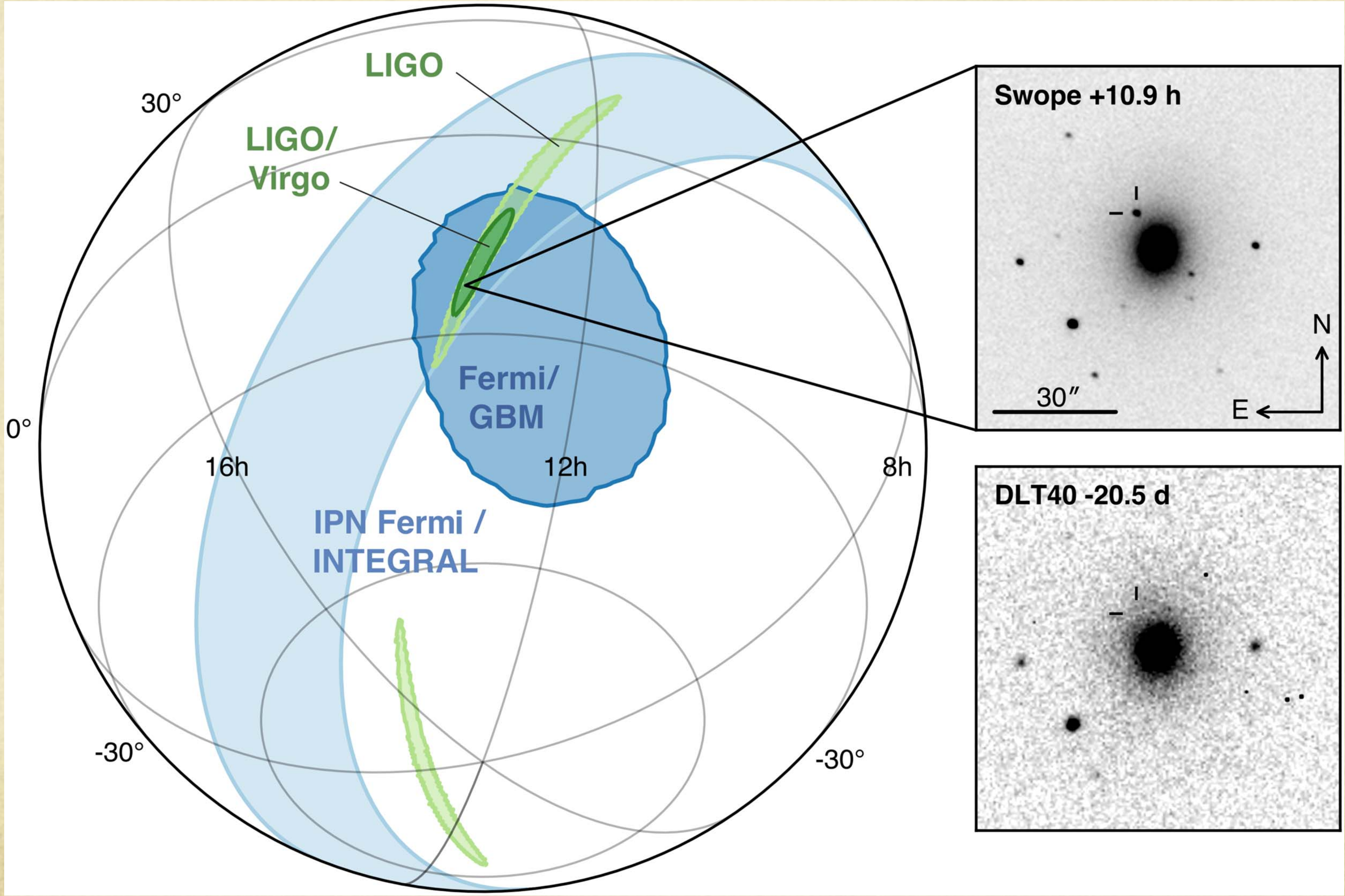
Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

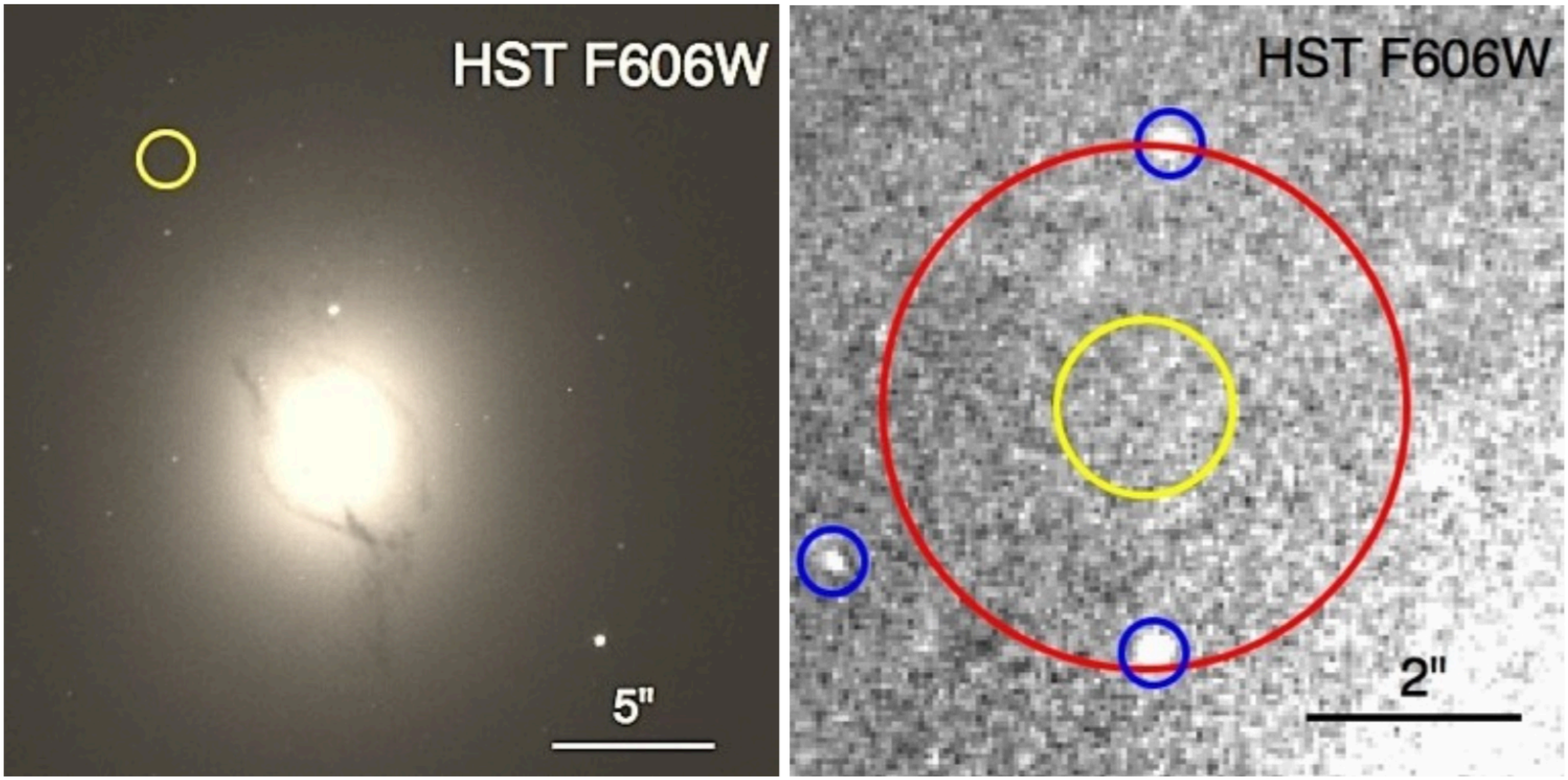
1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

Precise Localization



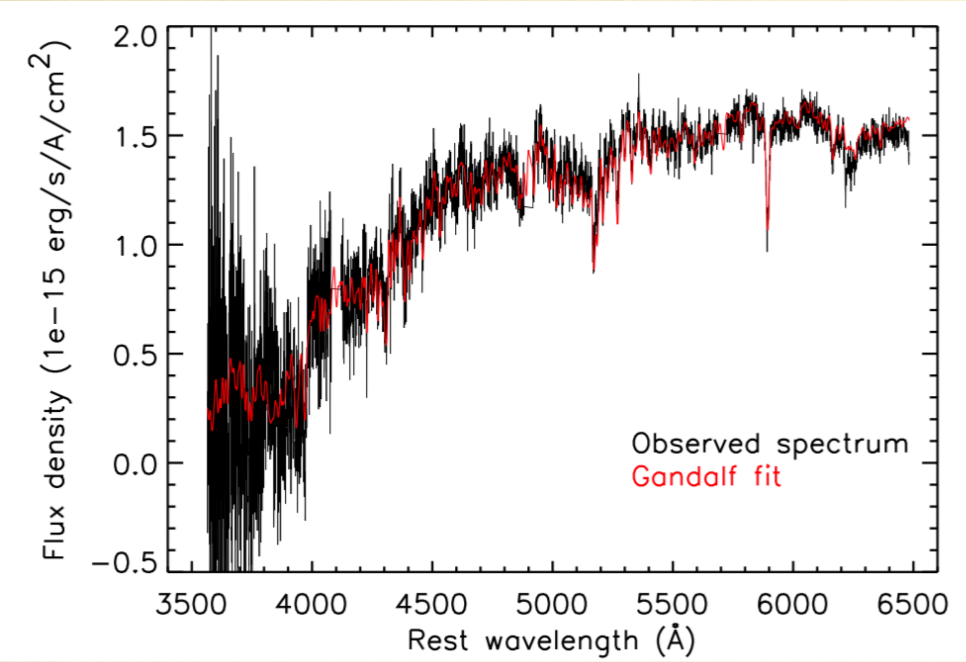
Host Environment

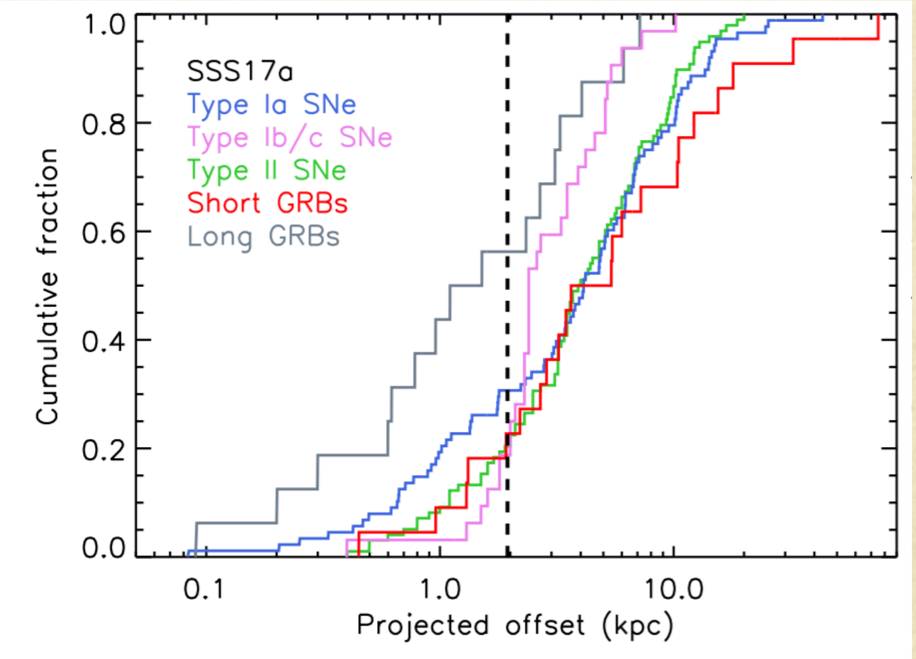
No Progenitor



Host Environment

Old Population, Similar to SGRB Hosts





Pan et al. 2017

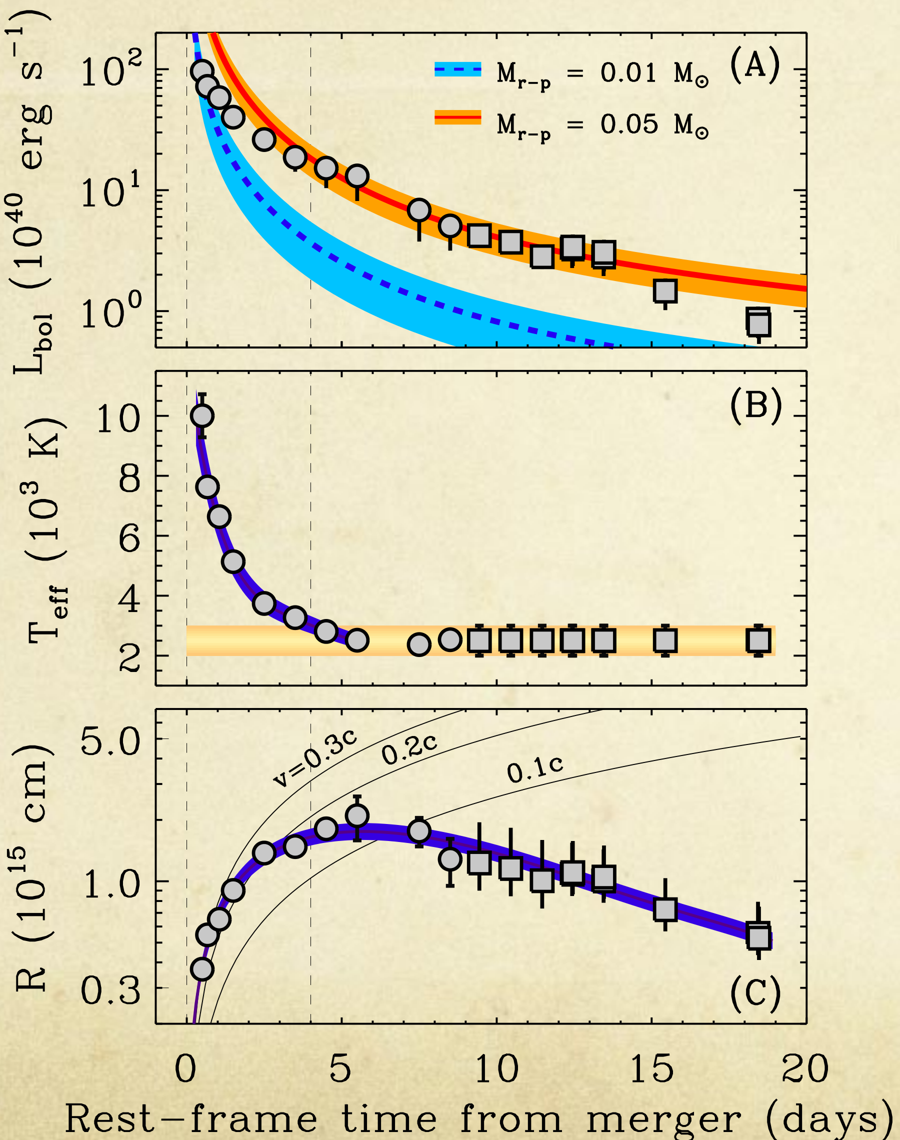
Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - “Standard Siren” Hubble diagram

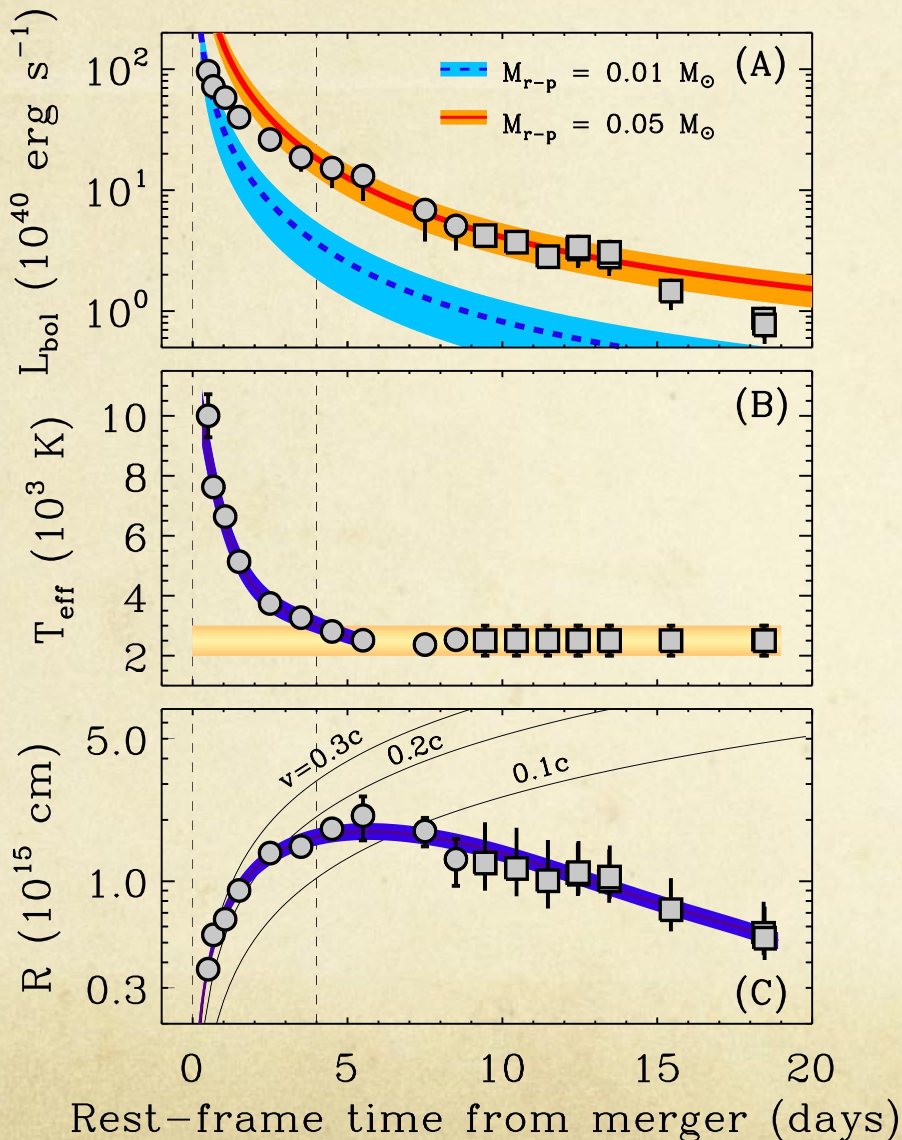
SSS17a: Physical Parameters



Drout et al. (2017)

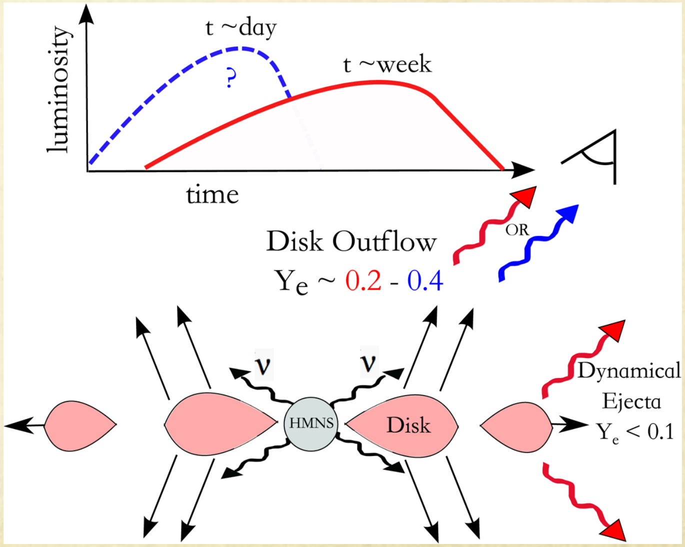
- r-process heating goes as $t^{-1.3}$

SSS17a: Physical Parameters

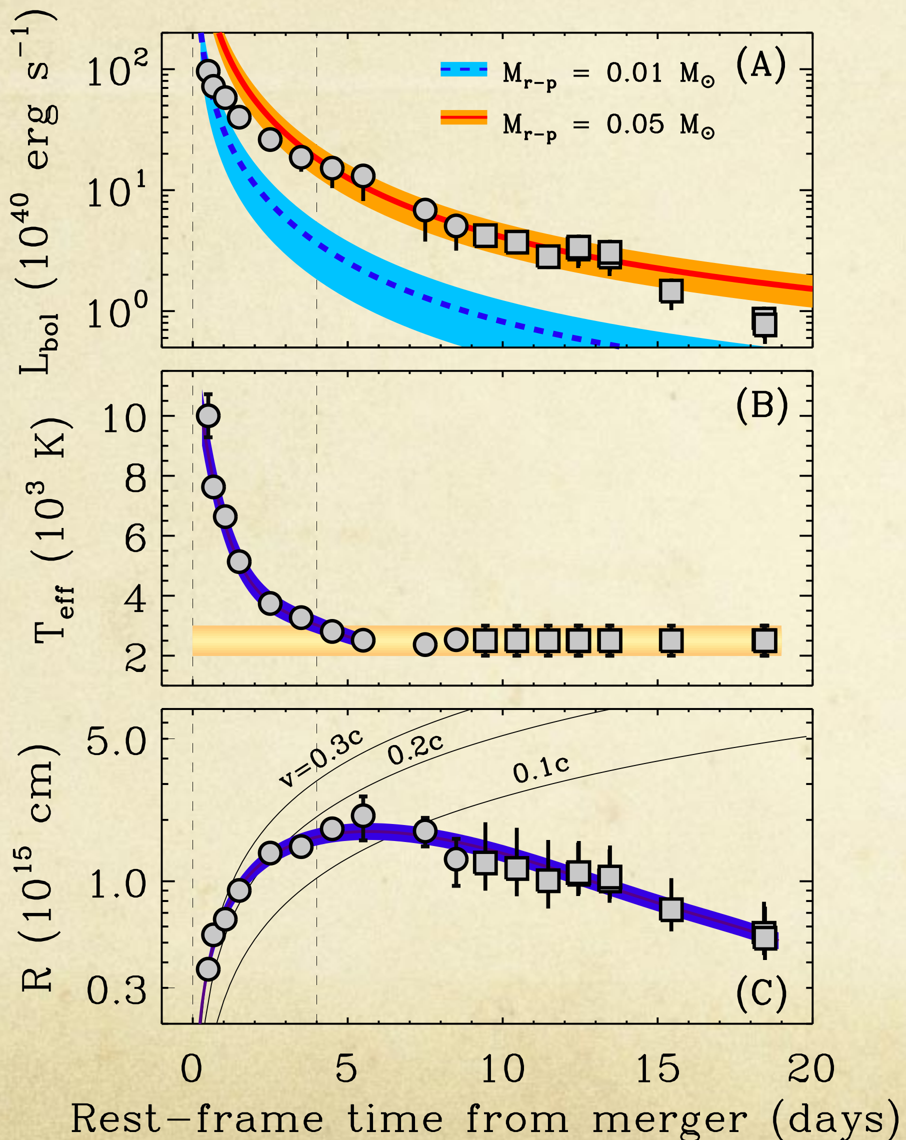


Drout et al. (2017)

- r-process heating goes as $t^{-1.3}$
- two components are required



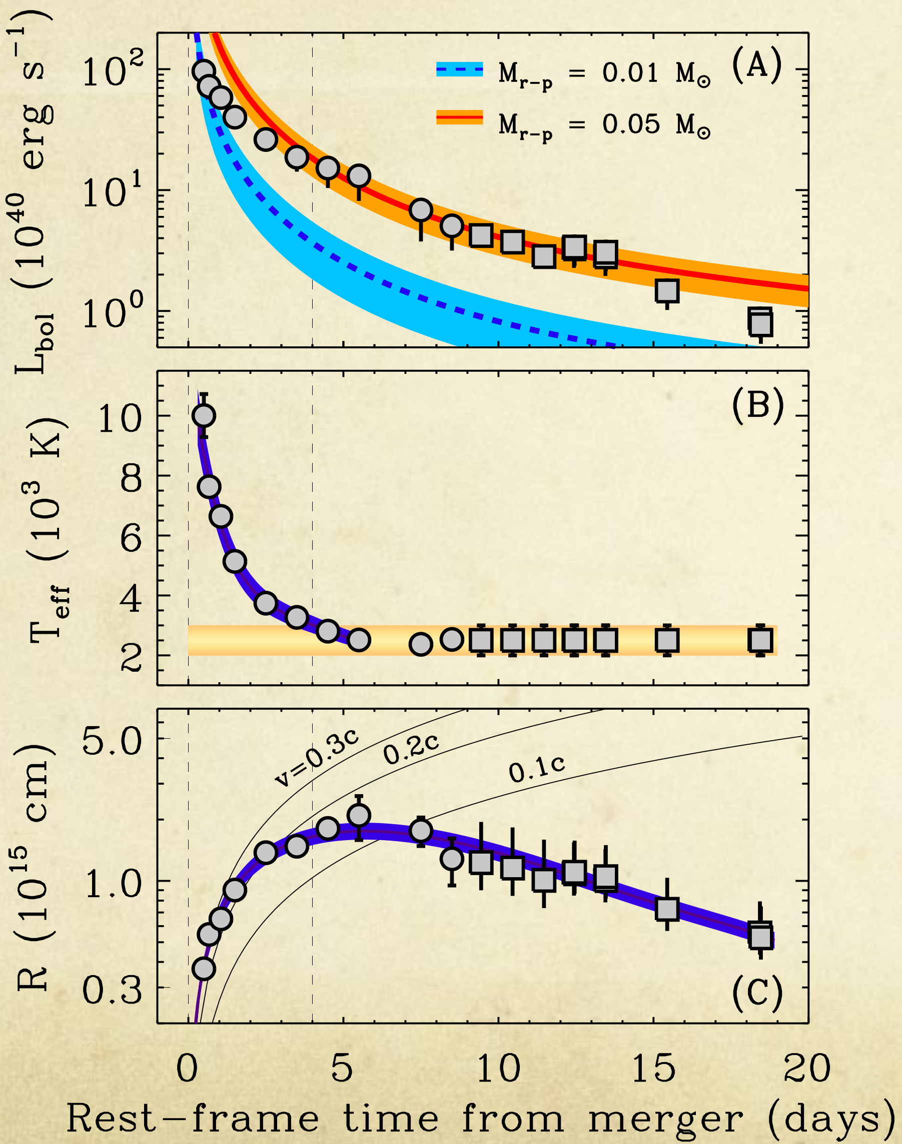
SSS17a: Physical Parameters



Drout et al. (2017)

- r-process heating goes as $t^{-1.3}$
- two components are required

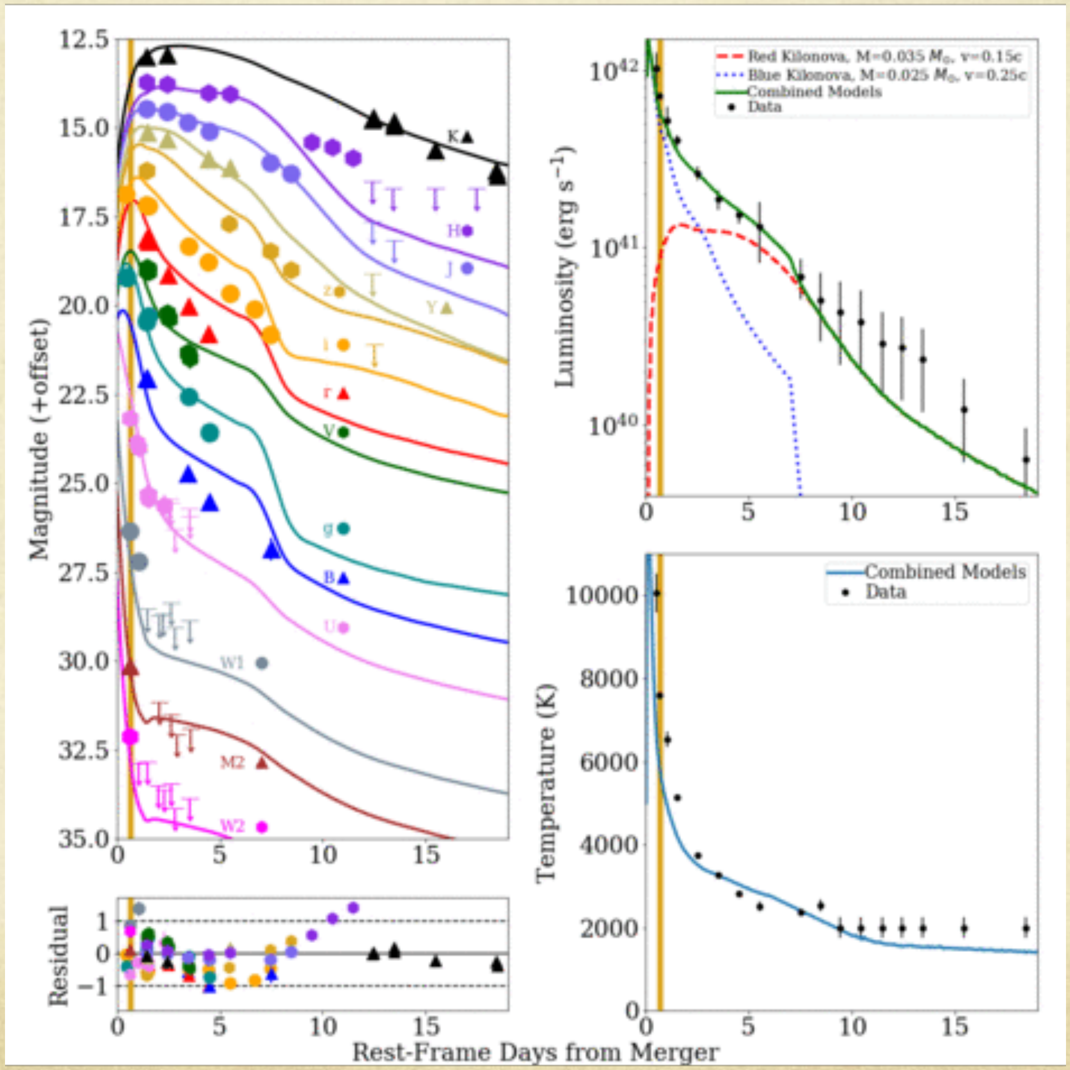
SSS17a: Physical Parameters



Drout et al. (2017)

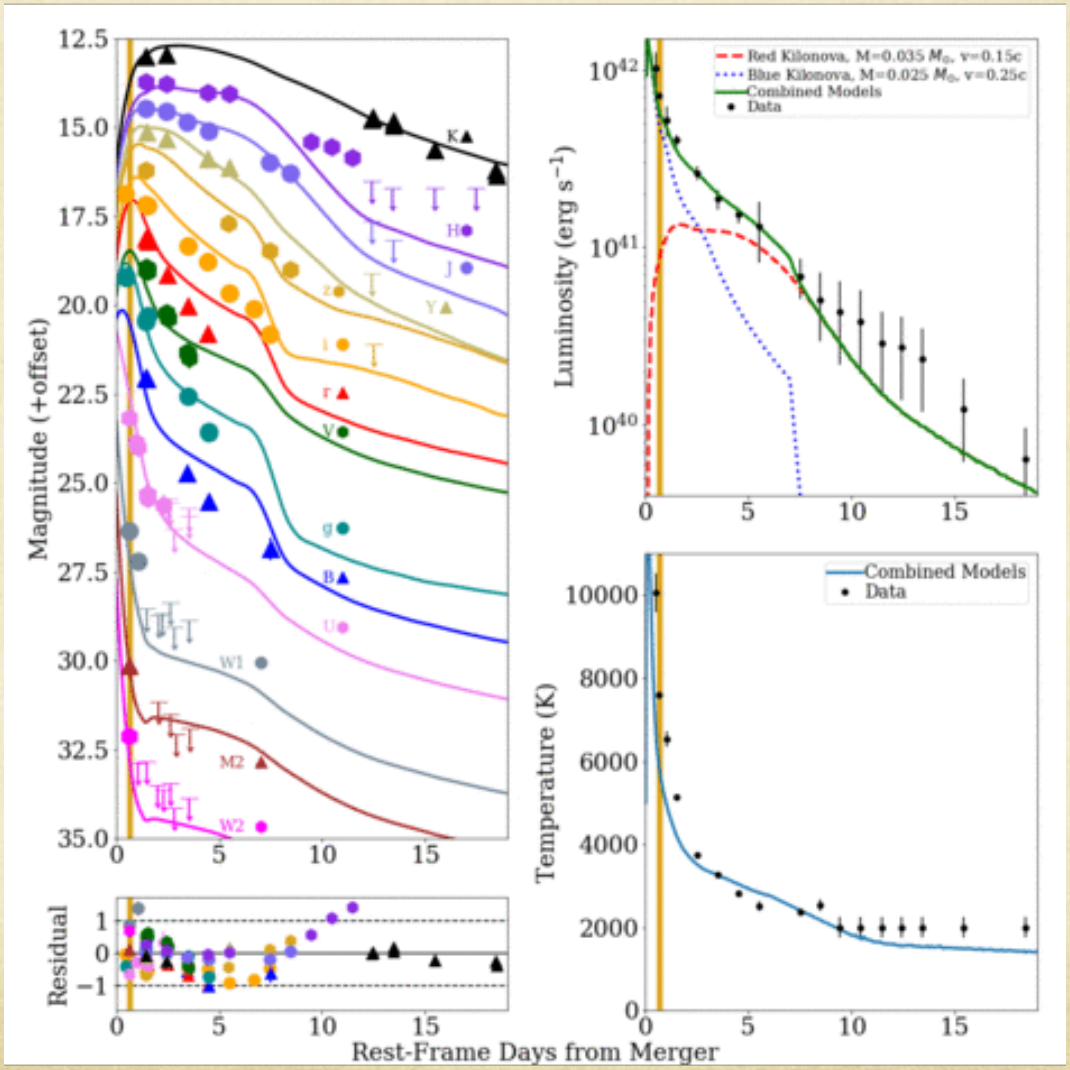
- r-process heating goes as $t^{-1.3}$
- two components are required
- temperature evolution consistent with lanthanide recombination

Kilonova Modeling



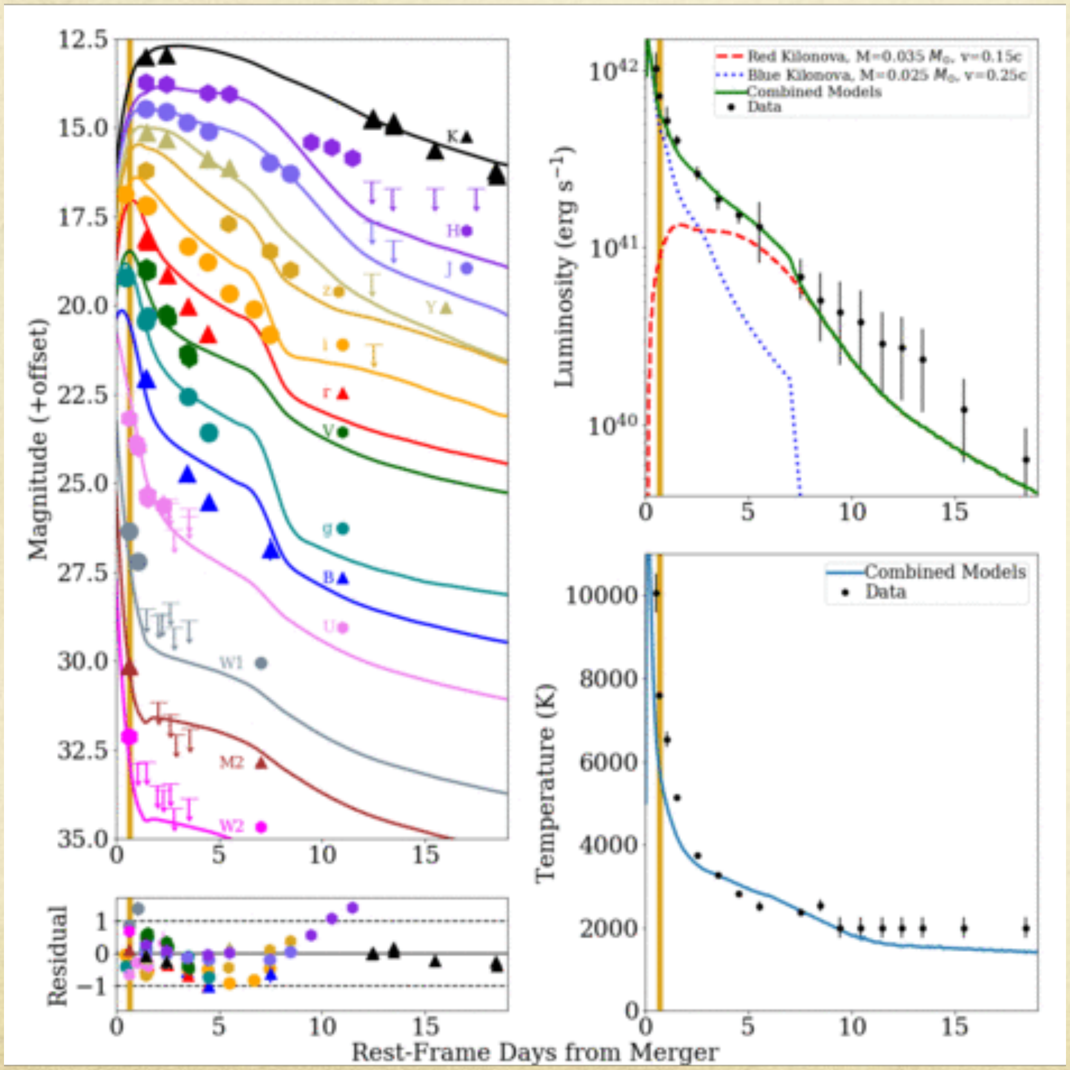
Kilpatrick et al. (2017), Kasen et al. (2017)

Kilonova Modeling



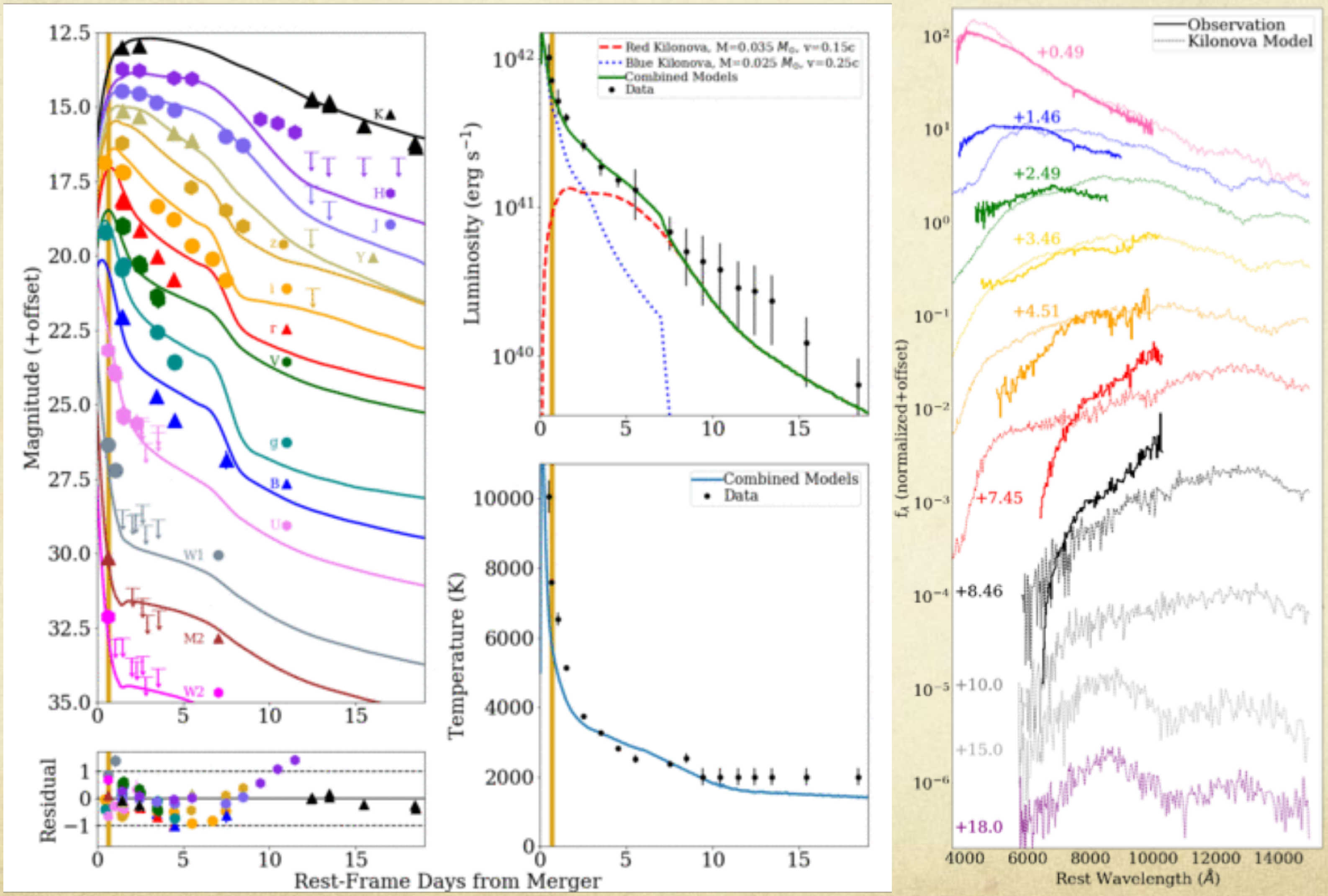
Kilpatrick et al. (2017), Kasen et al. (2017)

Kilonova Modeling



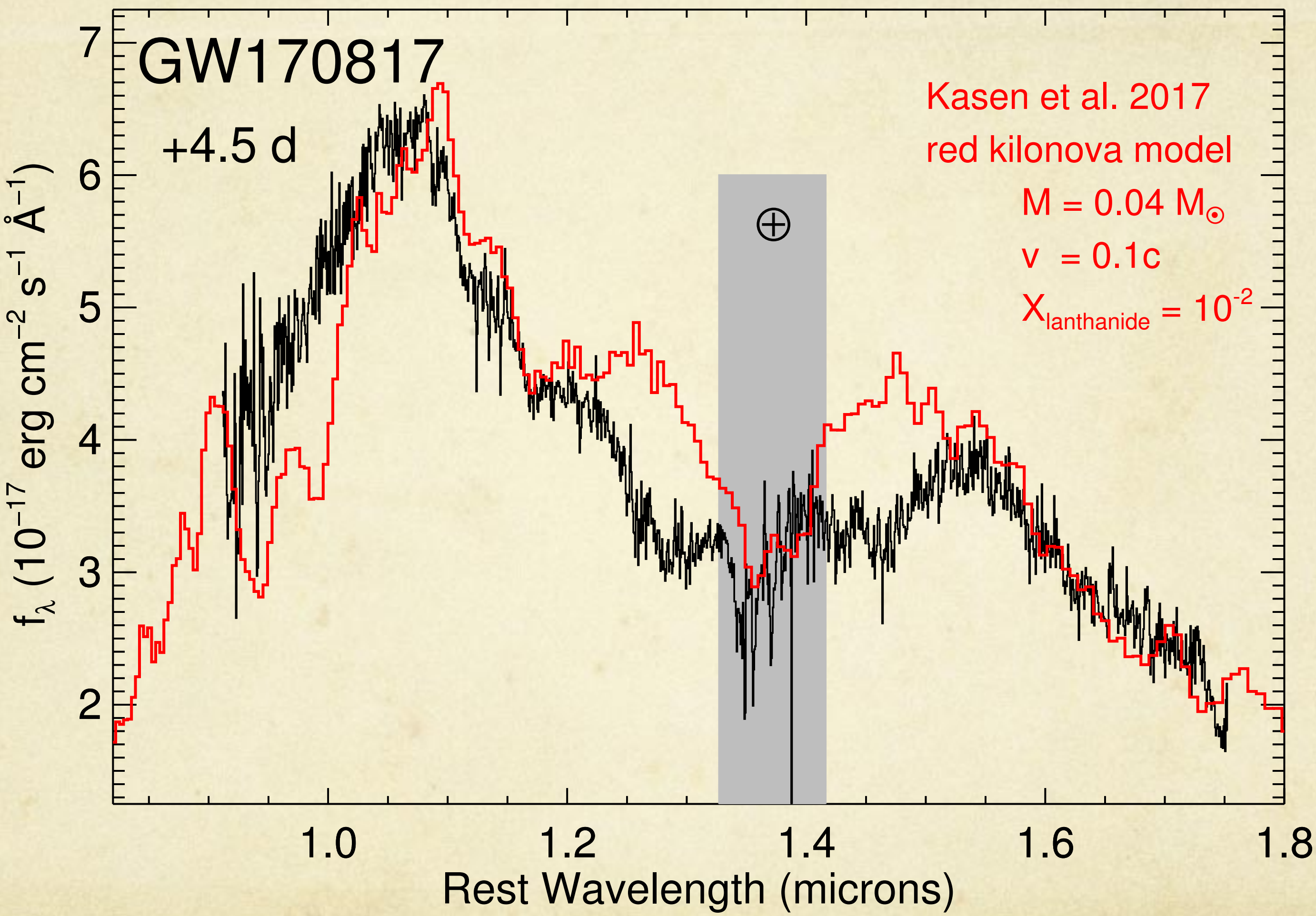
Kilpatrick et al. (2017), Kasen et al. (2017)

Kilonova Modeling



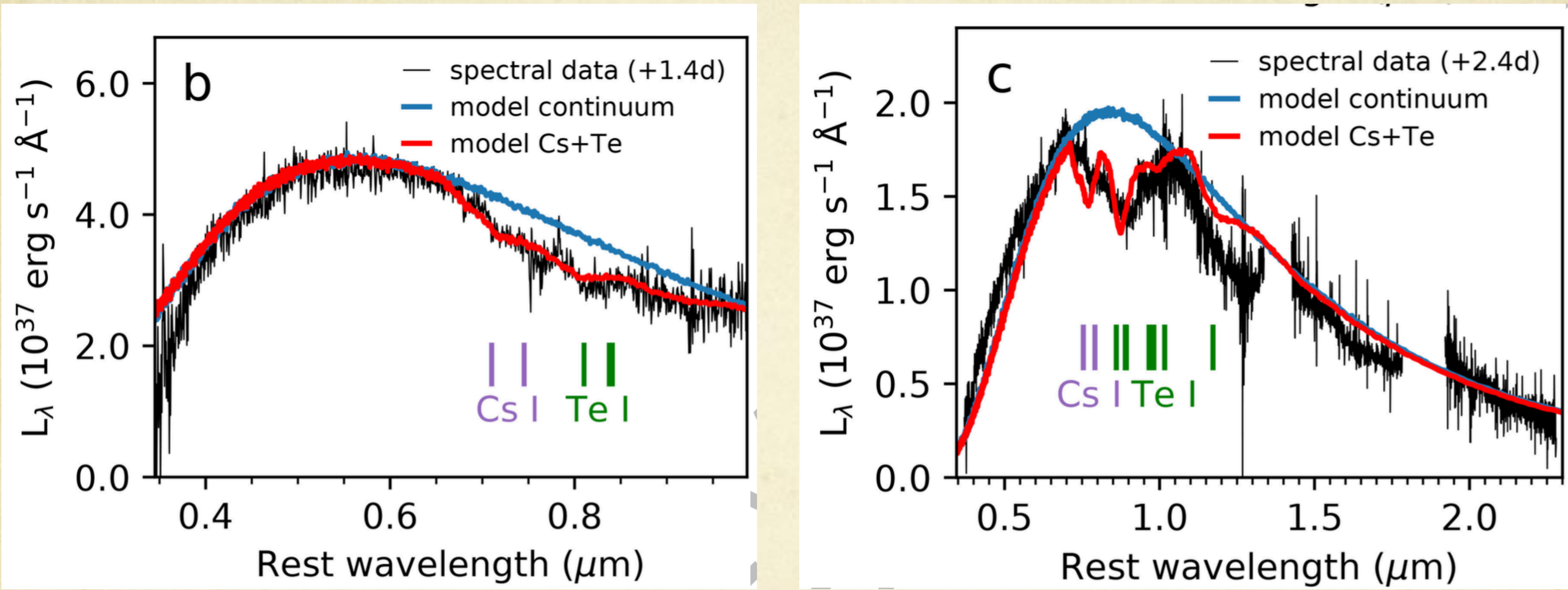
Kilpatrick et al. (2017), Kasen et al. (2017)

1 Micron Spectral Feature



Chornock et al. 2017

Elemental Spectral Feature?



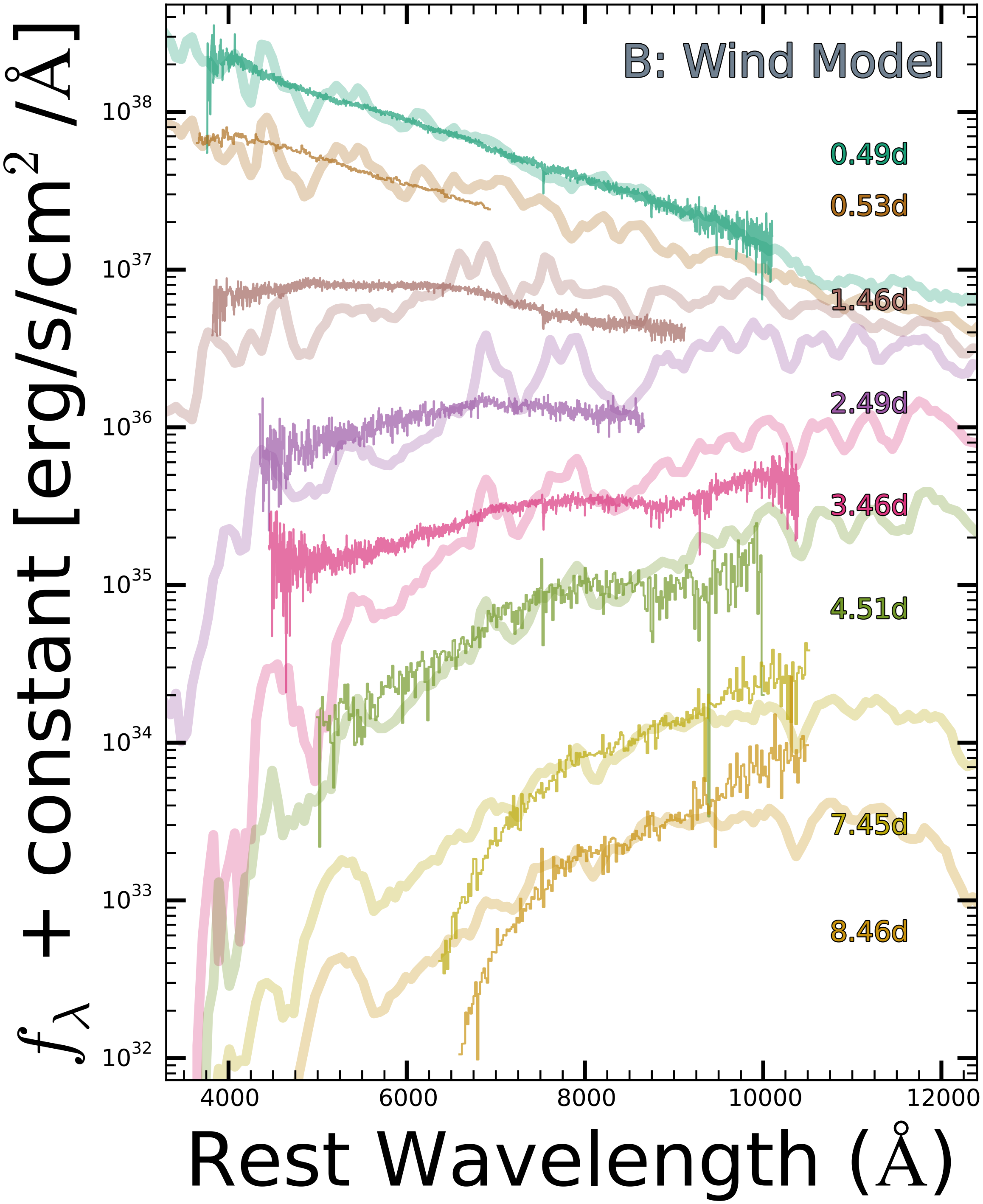
Smart et al. 2017

Consistent with an r-process powered transient in which approximately 0.05 solar masses of lanthanide-rich material is ejected

Consistent with an r-process powered transient in which approximately 0.05 solar masses of lanthanide-rich material is ejected

Nature of the blue component

(See Piro & Kollmeier 2017)



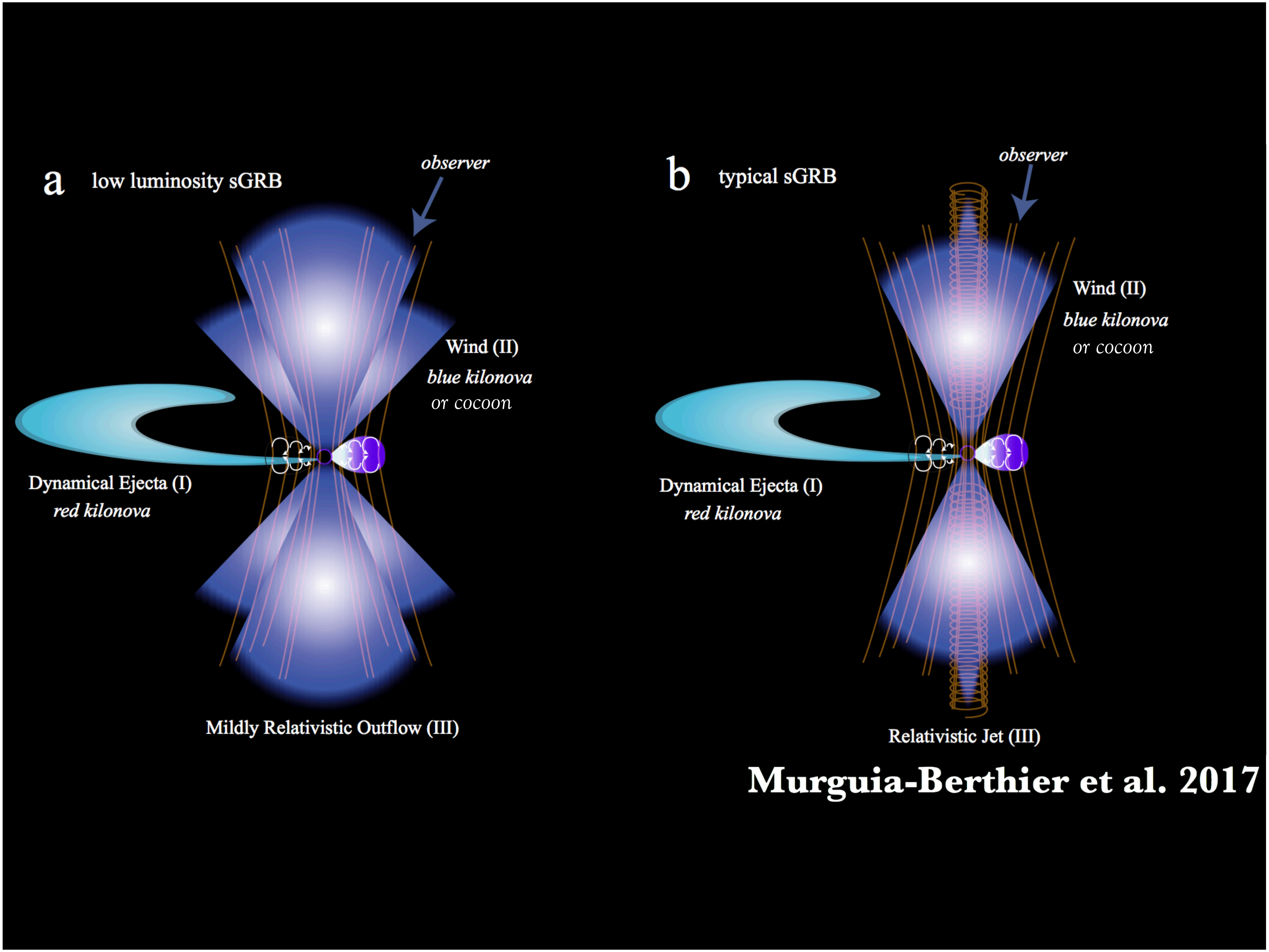
Shappee et al. 2017

Consistent with an r-process powered transient in which approximately 0.05 solar masses of lanthanide-rich material is ejected

Nature of the blue component

(See Piro & Kollmeier 2017)

Nature of the GRB/X-rays/radio


a
low luminosity sGRB
observer
Wind (II)
blue kilonova
or cocoon
Dynamical Ejecta (I)
red kilonova
Mildly Relativistic Outflow (III)
b
typical sGRB
observer
Wind (II)
blue kilonova
or cocoon
Dynamical Ejecta (I)
red kilonova
Relativistic Jet (III)
Murguia-Berthier et al. 2017

Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - “Standard Siren” Hubble diagram

Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

Difference is between -3×10^{-15} and $+7\times10^{-16}$ times the speed of light

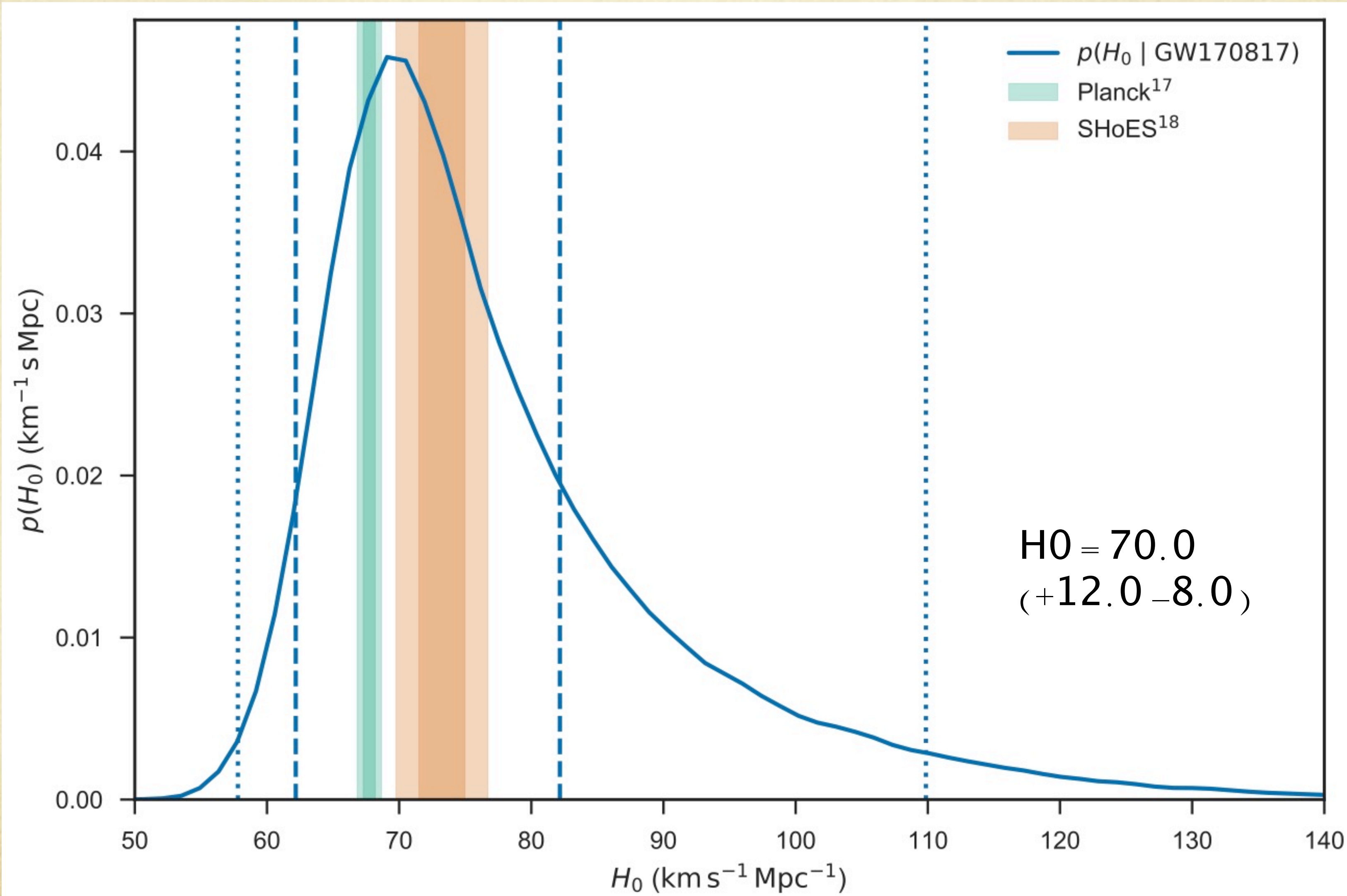
Multi-messenger Astronomy

Motivation

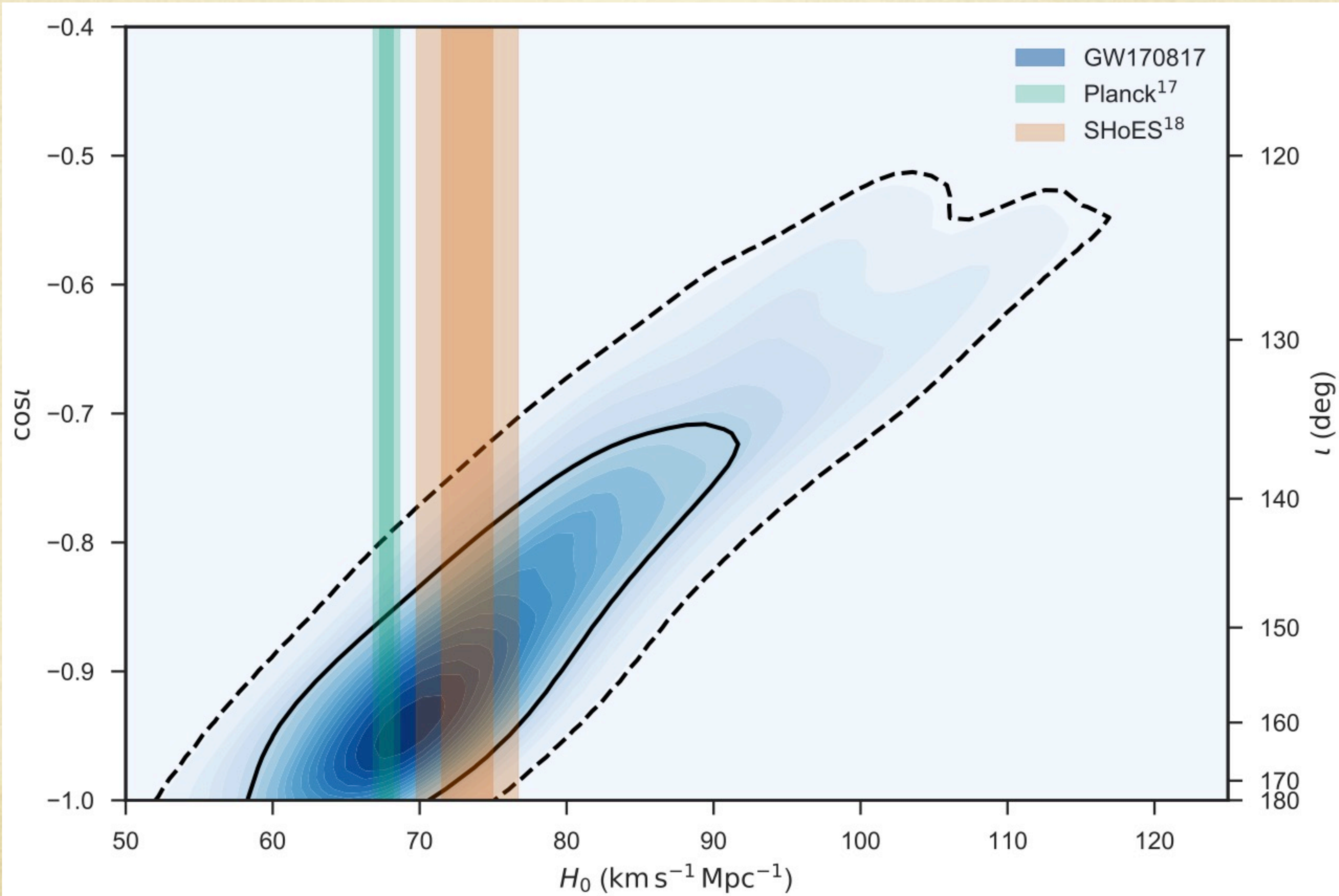
Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

“Standard Siren” Hubble Constant



“Standard Siren” Hubble Constant



Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

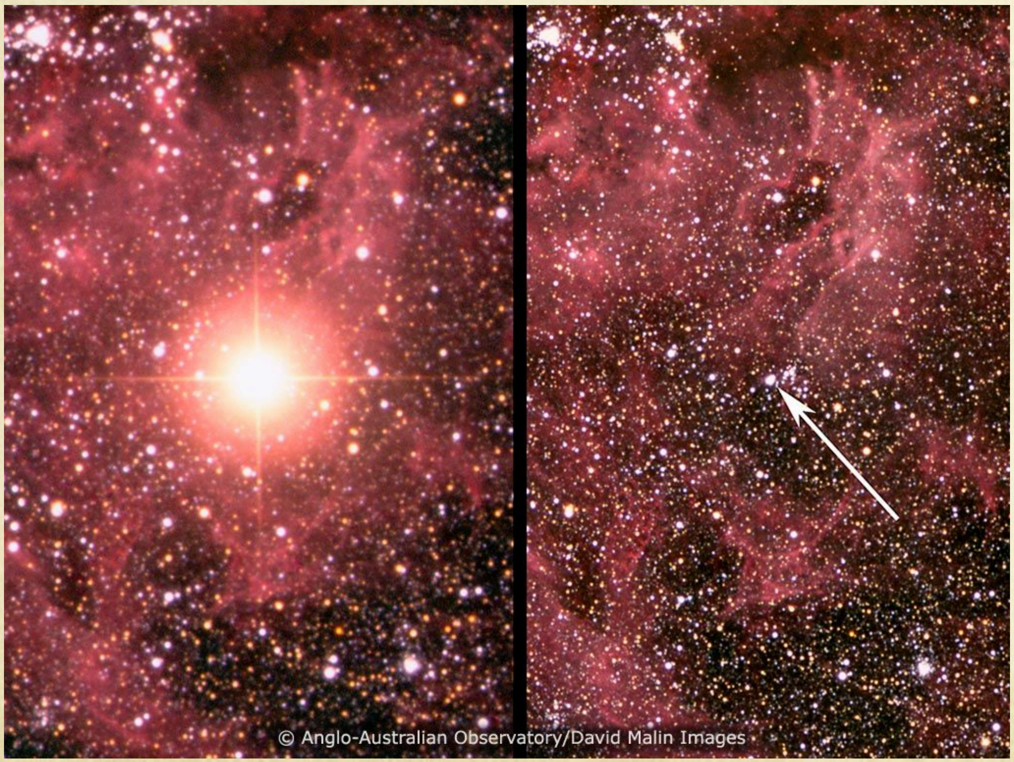
Summary

We discovered the first EM counterpart to a gravitational wave source

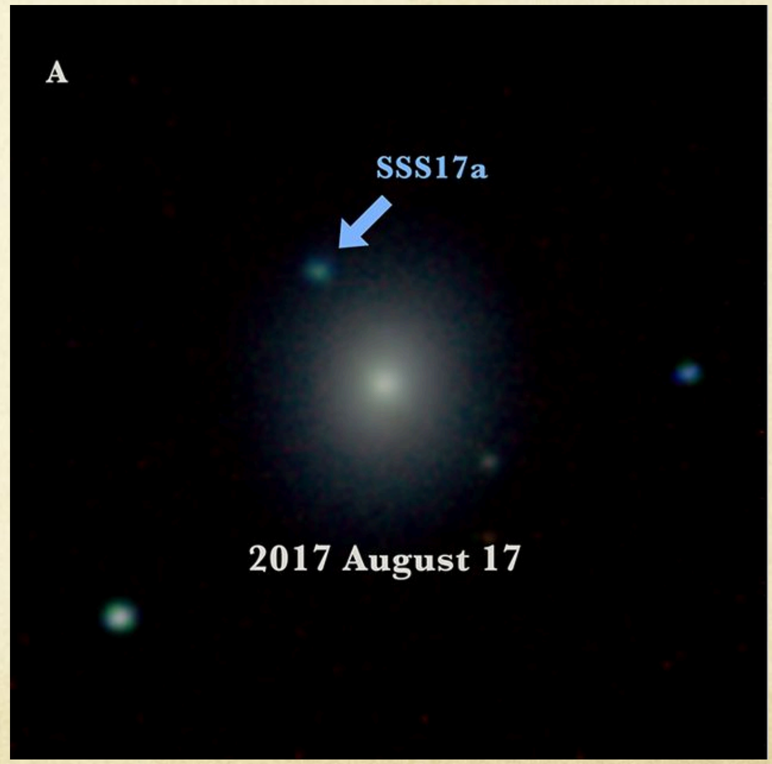
This begins the era of multi-messenger gravitational-waves astronomy, with implications across many areas of astronomy

Multi-messenger Astronomy
Success Stories

SN1987A:
photons + neutrinos



SSS17A:
photons + GWs



Multi-messenger Astronomy

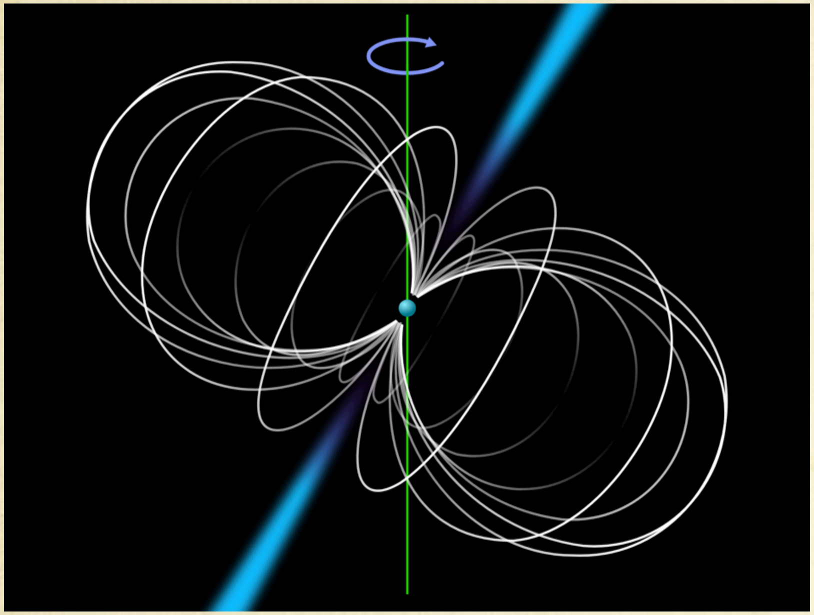
Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
   - Origin of short-duration GRBs
   - Origin of r-process elements
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - “Standard Siren” Hubble diagram

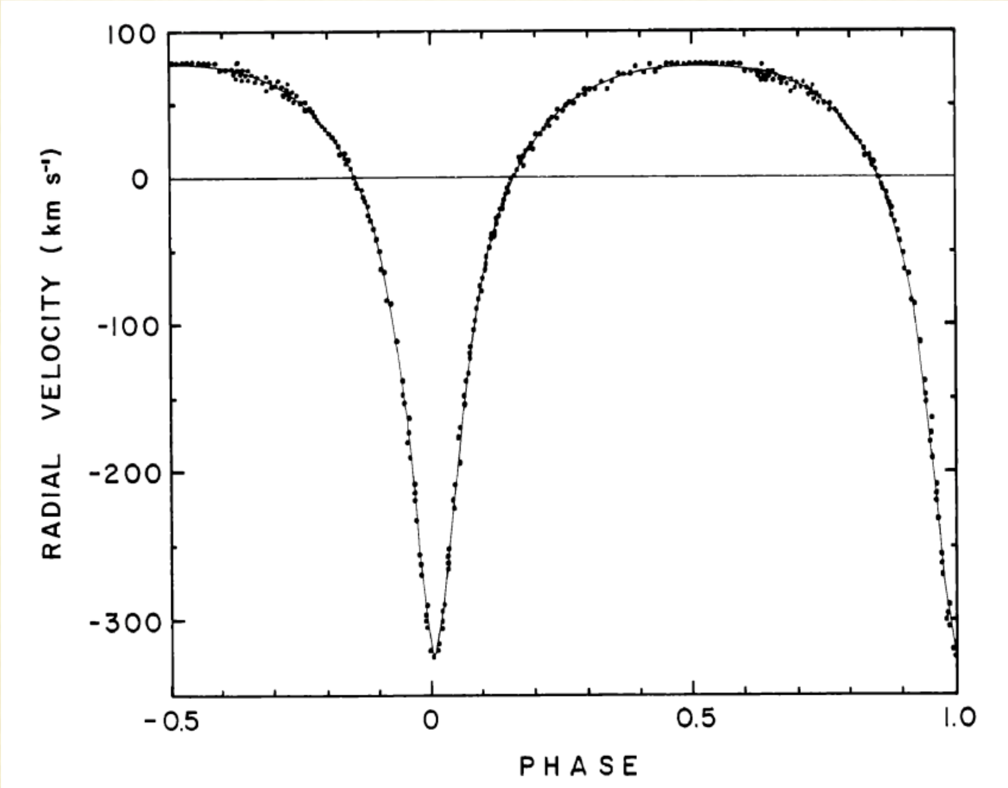
SSS17a: Follow-Up

Hulse-Taylor binary



Measured Orbital Parameters for PSR B1913+16

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)



Hulse & Taylor 1975, Weisberg and Taylor 2005

Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination

Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models

Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models

3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity

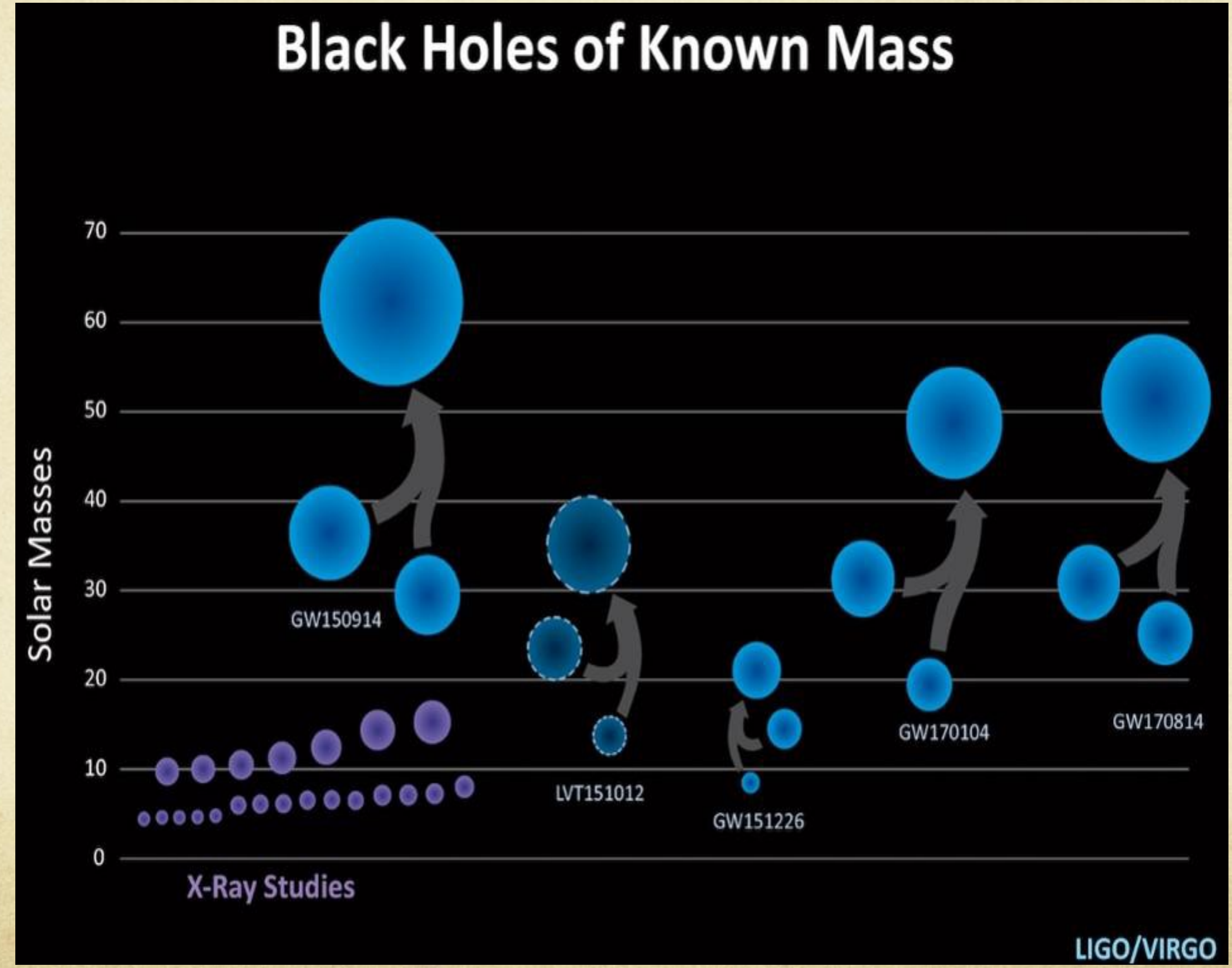
Multi-messenger Astronomy

Motivation

Gravitational Wave data only provides specific information

1. Precise Location/Distance Determination
   - Provides environmental information
   - Breaks degeneracy with inclination
2. Measure Influence/Test Merger Models
3. Fundamental Physics
   - Speed of gravity
   - Lorentz invariance, equivalence principle, non-GR gravity
4. Cosmology
   - "Standard Siren" Hubble diagram

GW150814



Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170814
X-Ray Studies
LIGO/VIRGO

Precise Localization