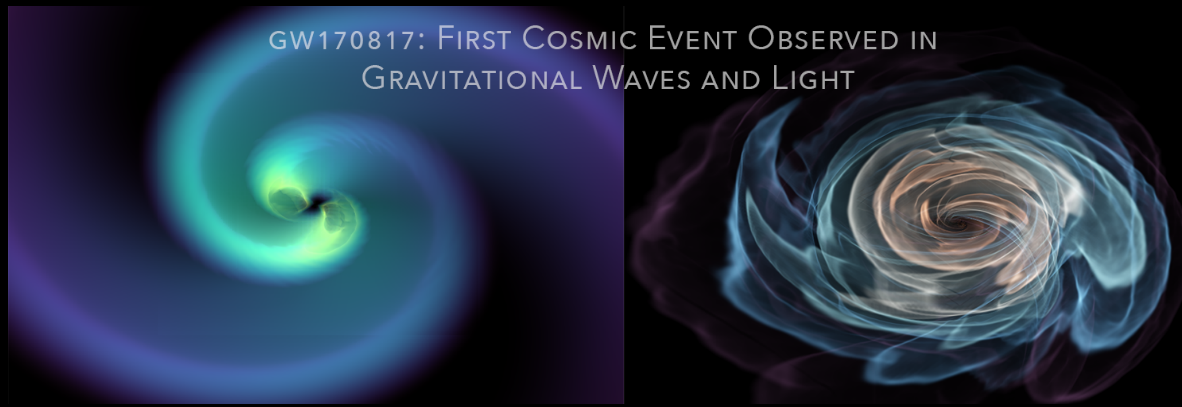


Mansi M. Kasliwal

ASSISTANT PROFESSOR OF ASTRONOMY

CALIFORNIA INSTITUTE OF TECHNOLOGY

ON BEHALF OF THE MMA SWG

GROWTH

Global Relay of Observatories Watching Transients Happen

NSF

PIRE

Multi-Messenger Astrophysics Discovery Engines

Gravitational Waves: LIGO, Virgo, LIGO-India, Kagra, LISA, PTA

Neutrinos and UHECRs: Icecube, Pierre Auger, Antares, SuperK

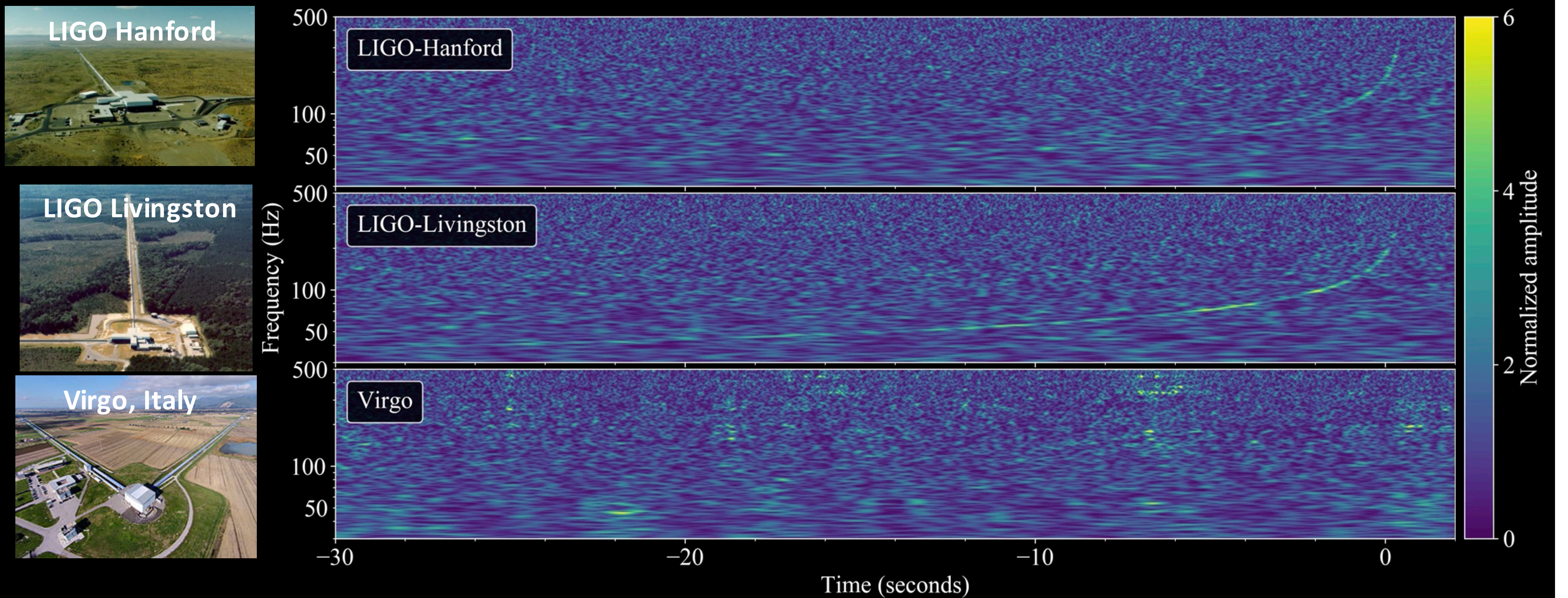
Optical: Evryscope, ASASSN, HATPI, ZTF, CSS-II, PS2, Blackgem, ATLAS, DECAM, HSC (and soon, LSST)

Gamma-Rays Fermi, Swift, Integral

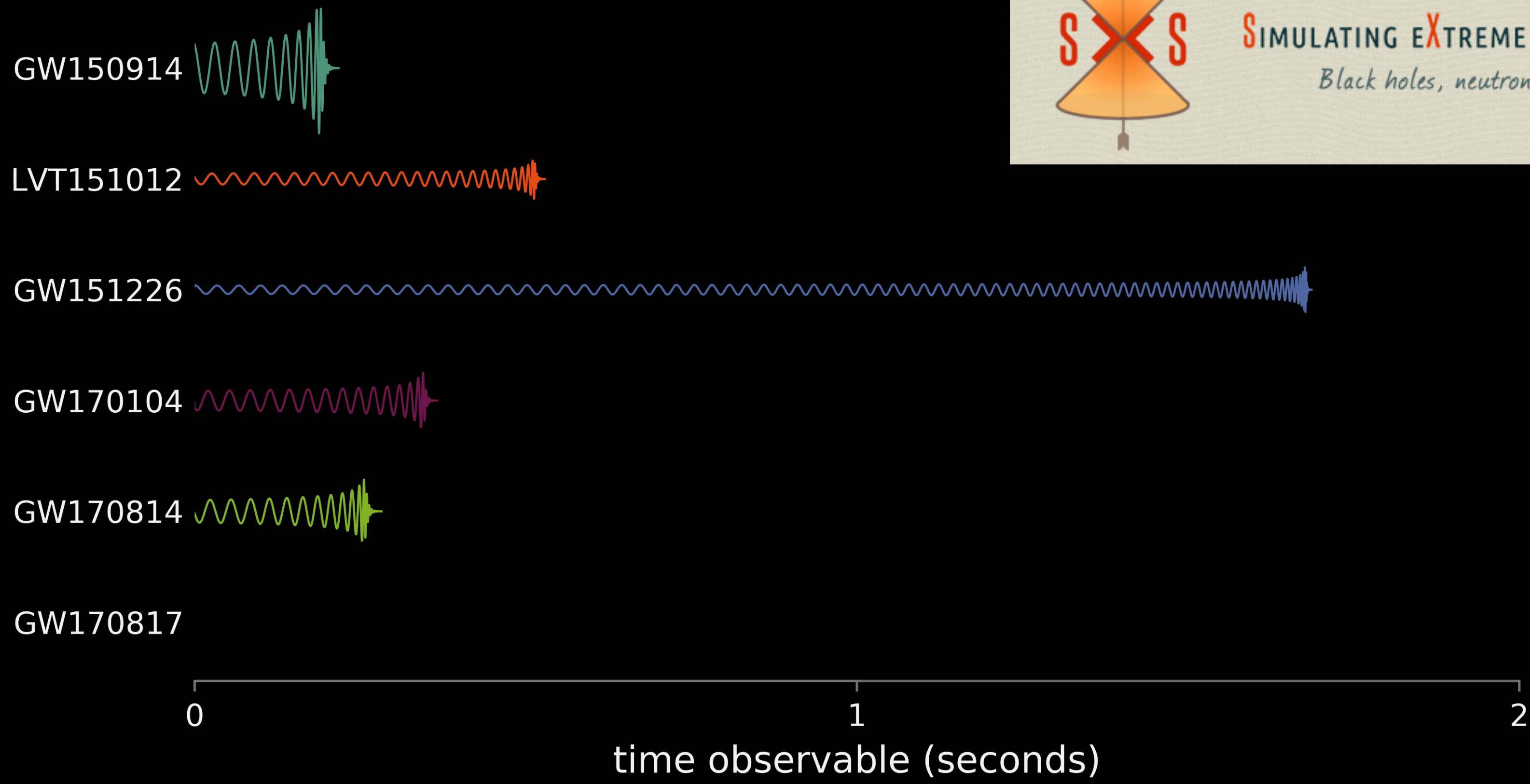
Radio: LOFAR, MWA, LWA, Apertif, Meerkat, Askap, VLASS

MISSING: Wide-field Infrared, Ultraviolet, X-rays

August 17, 2017, 12:41:04 UTC

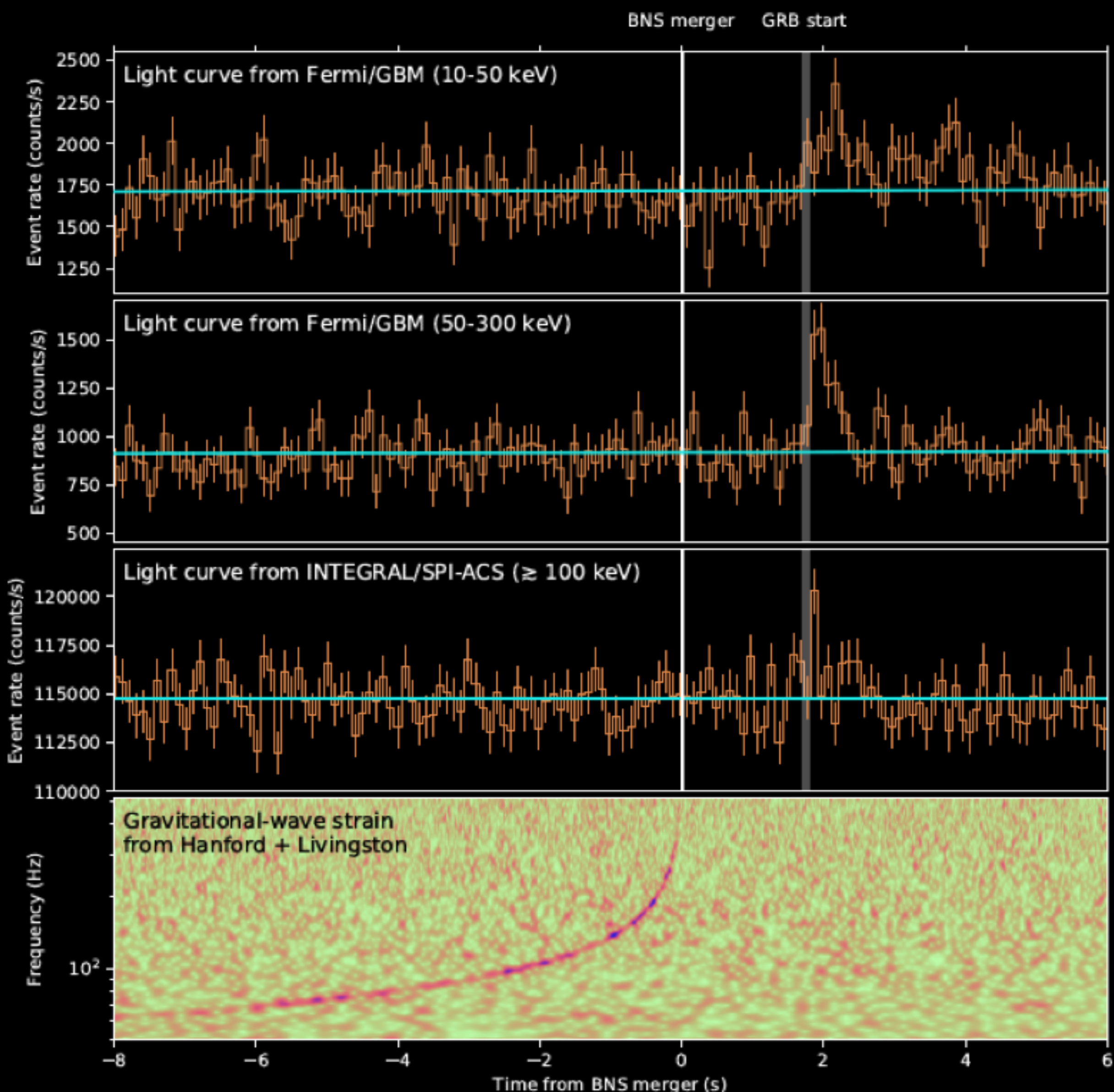


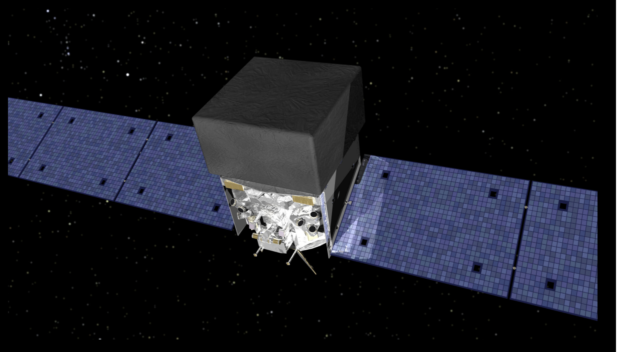
LVC, *Phys. Rev. Lett.* 119, 161101 (2017)

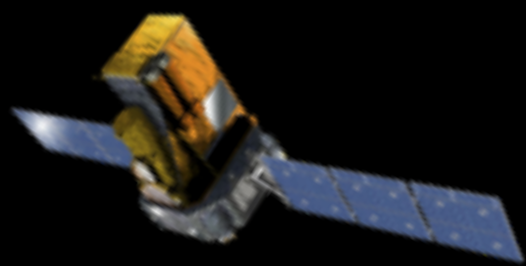


	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–$1.60\ M_\odot$	1.36–$2.26\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$	0.86–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Just 1.7 seconds later:
a burst of gamma-rays!

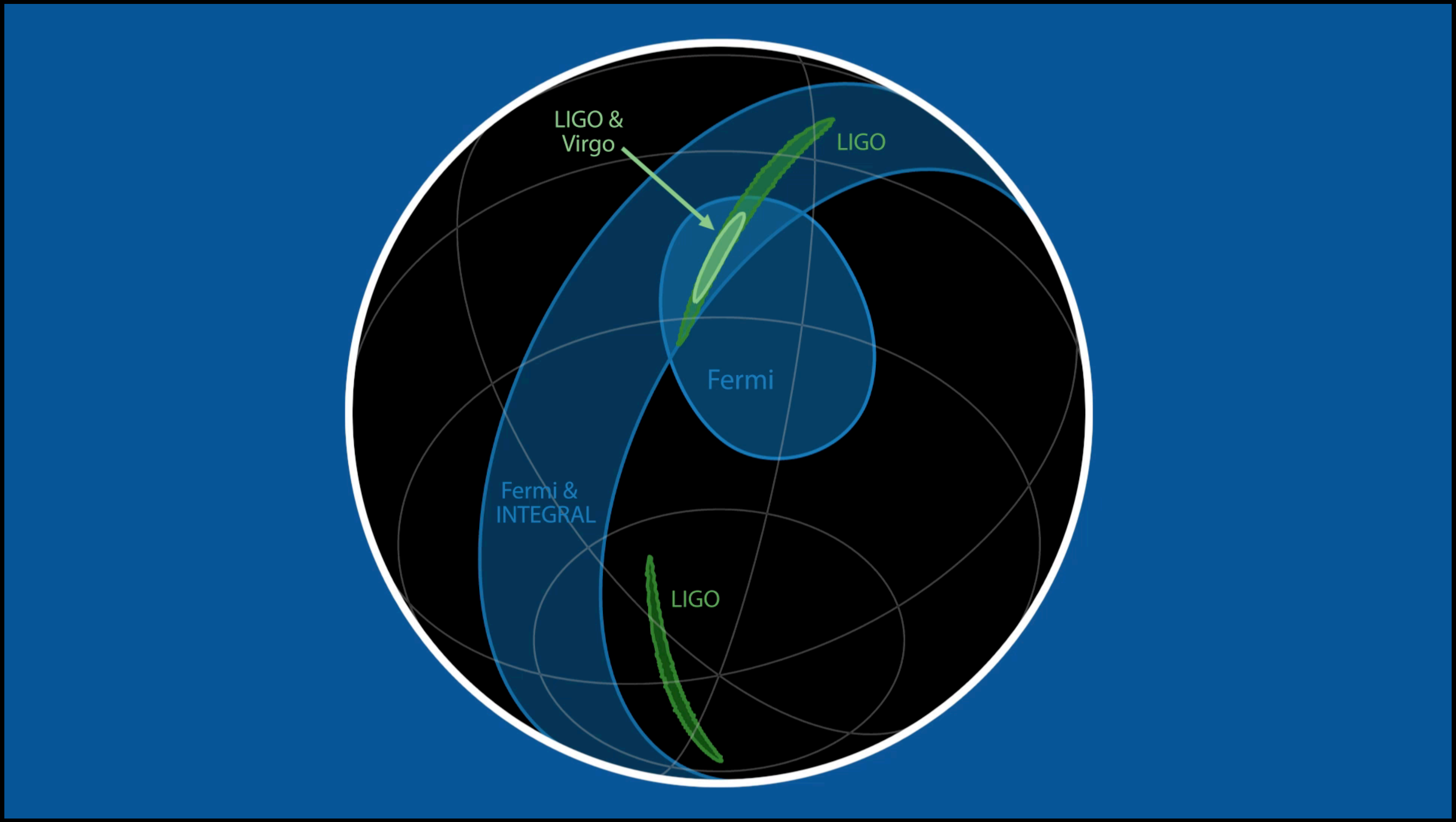






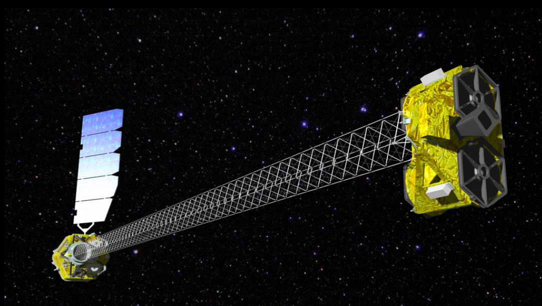
LVC, Fermi, Integral *Astrophys. J. Lett., 2017; Goldstein et al. 2017*

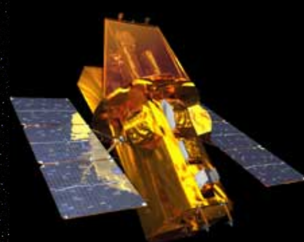
Localization



Credit: R. Hurt

A Panchromatic Hunt





Six
Optical
Telescopes

NuSTAR
Hard X-ray

Neil Gehrels Swift Obs.
Soft X-ray & Ultraviolet

Evans et al. 2017

Gemini-South & VISTA
Infrared

Tanvir et al. 2017
Kasliwal et al. 2017

Very Large Array
Radio

Hallinan et al. 2017
Mooley et al. 2017

8 Independent Searches in Chile

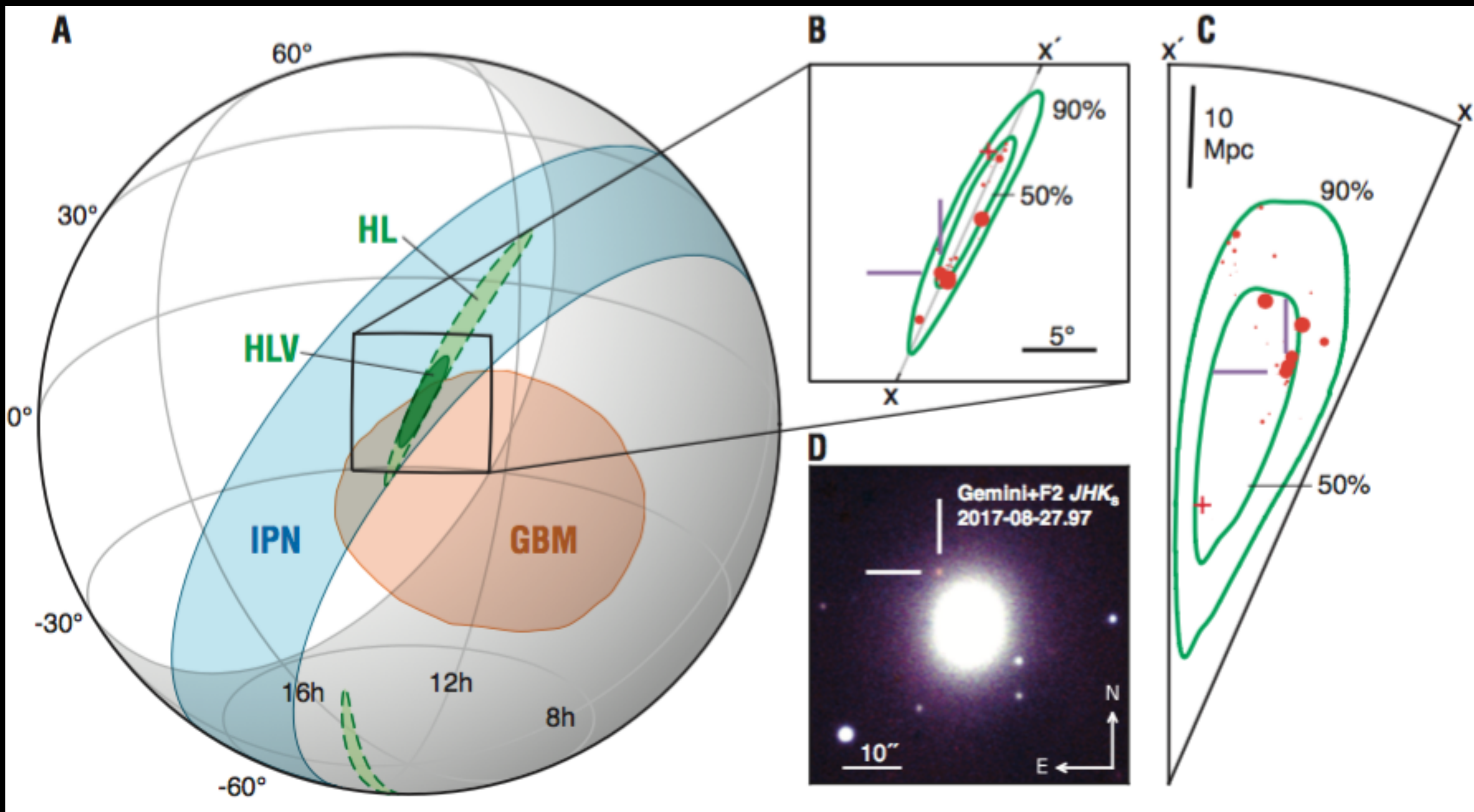
Optical:

1. Swope 40” Las Campanas Telescope (Coulter et al. 2017)
2. MASTER (Lipunov et al. 2017)
3. DLT40 (Valenti et al. 2017)
4. DECam on Blanco Telescope (Soares-Santos et al. 2017)
5. Las Cumbres Observatory (Arcavi et al. 2017)
6. REM (Pian et al. 2017)

Infrared:

1. ESO VISTA (Tanvir et al. 2017)
2. Gemini-South (Kasliwal et al. 2017)

Role of Galaxy Catalogs



Kasliwal et al. 2017c

3rd highest priority galaxy in the Census of the Local Universe (CLU) list!

Read more about CLU galaxy catalog in Cook et al. 2017;

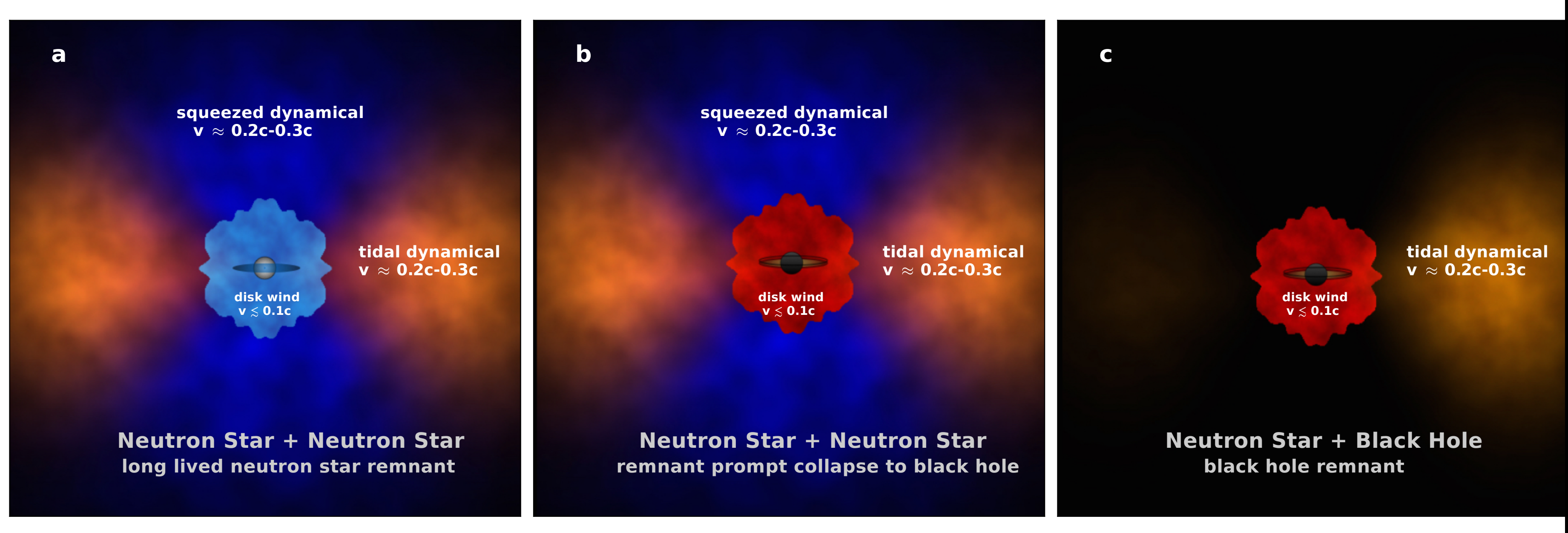
Read about search strategy in Nissanke et al. 2013, Gehrels et al. 2016

Is ZTF Unique?

1. ZTF can respond instantly given the location of Palomar Observatory and GW quadrupolar antenna pattern
2. ZTF mapping speed allows us to follow-up all events, including the majority which will be coarse two-detector events
3. ZTF 600s depth allows us to be sensitive to events fainter than GW170817 by factor of 10 (at 120 Mpc in O3).
4. ZTF sequence sensitive to both the fast-blue and slow-red (e.g., if we do ggg_0, gr_1, ri_2, ri_4, ri_6, gri_15)
5. GROWTH's panchromatic approach complements ZTF to paint a complete astrophysical picture

ZTF is a powerful discovery engine.

Why 600s?



Kasen et al. 2017

Future events could be less luminous than GW170817 if:

Ejecta Mass is Lower or

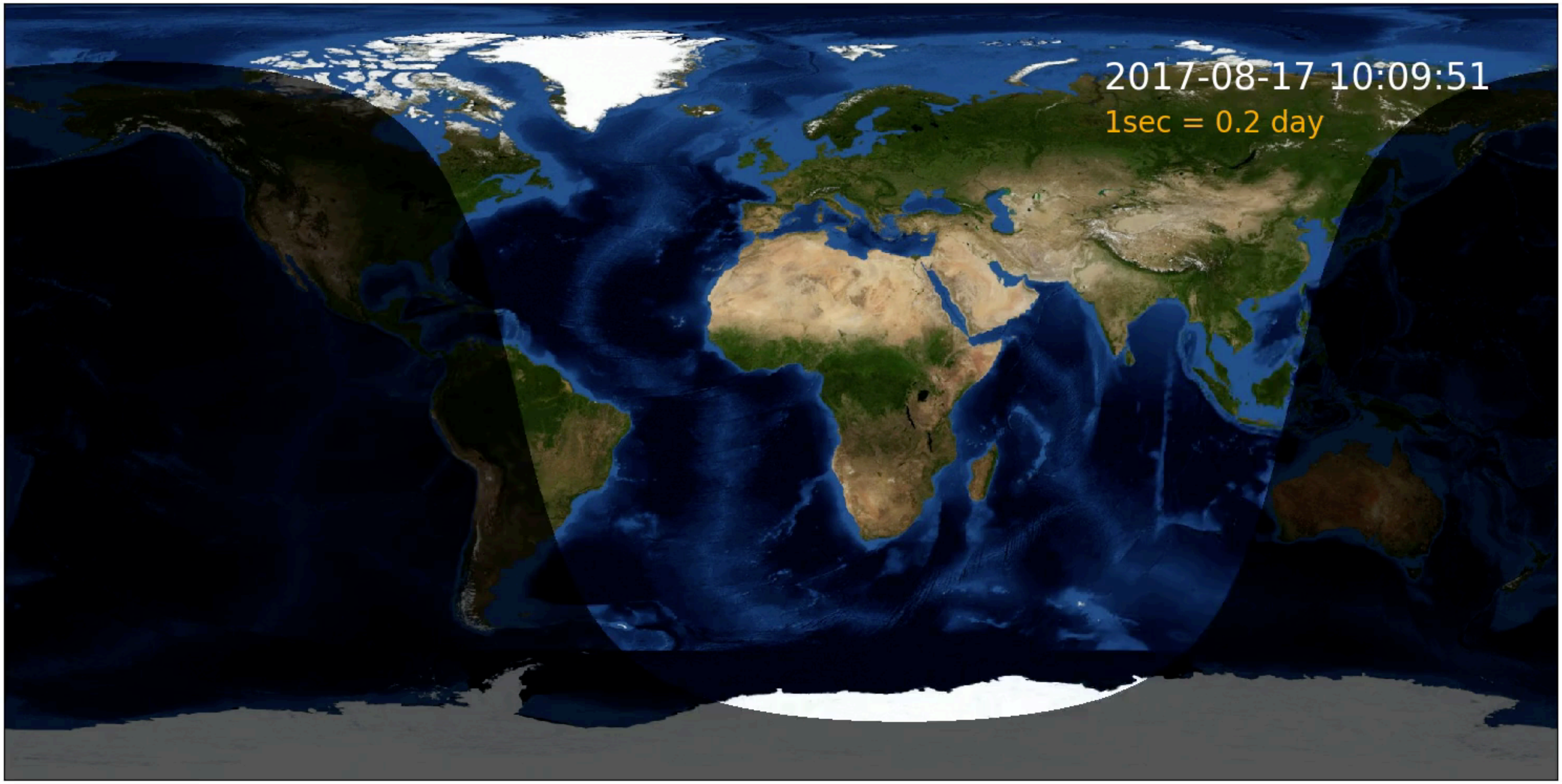
Ejecta Velocity is Lower or

Mass ratio is larger or

Remnant Lifetime is shorter or

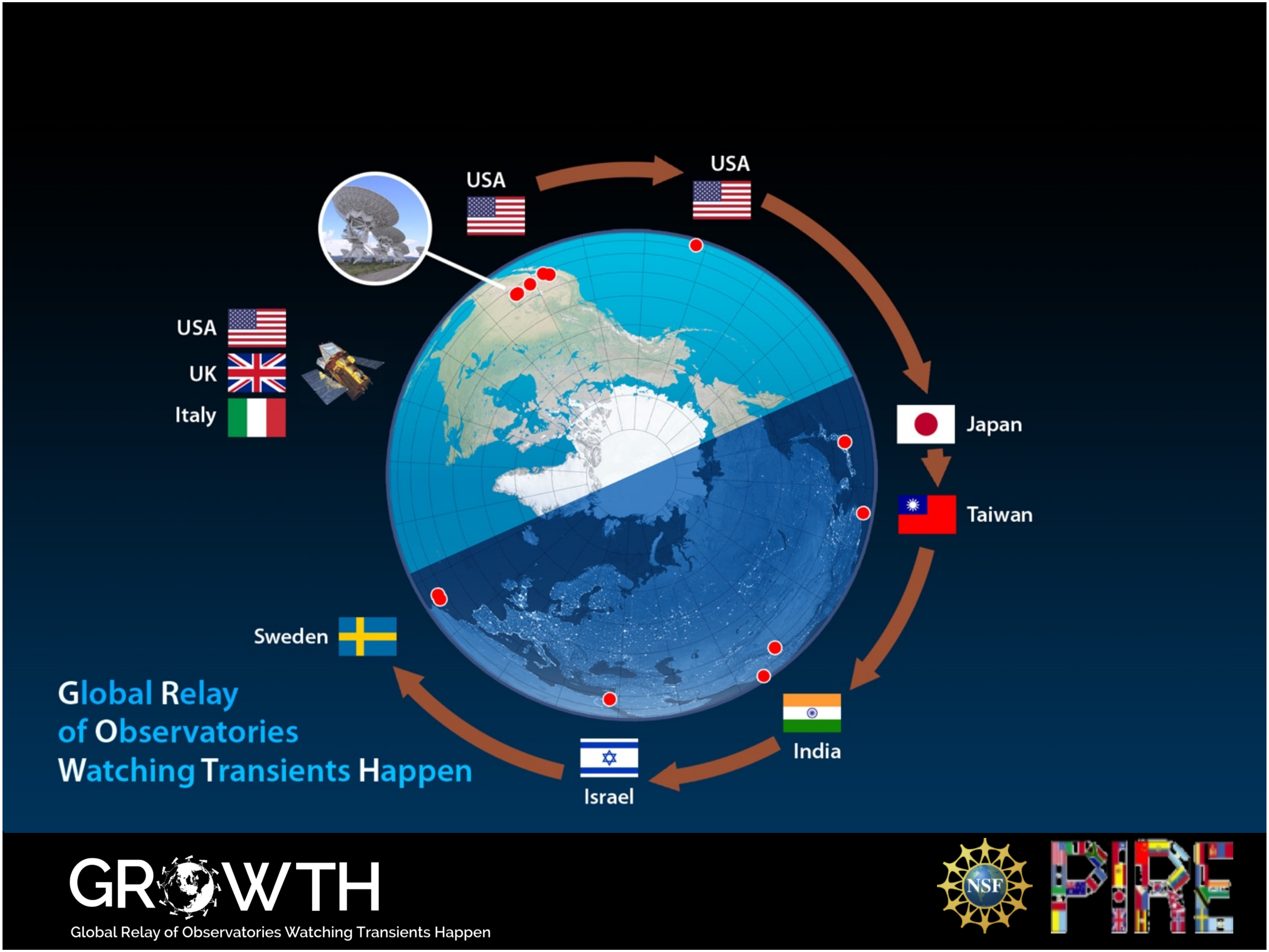
Viewing angle is more equatorial

GW170817: A Global Effort

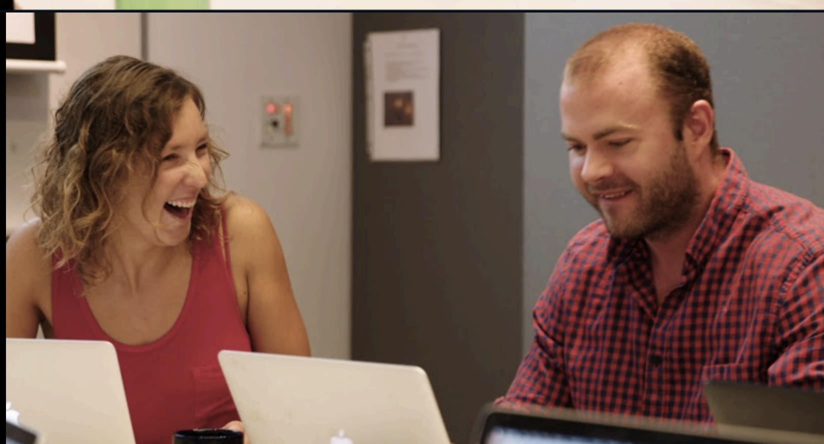


Movie Credit: V. Bhalerao

Total 70 ground-based telescopes + 7 space telescopes
(The GROWTH Team: 18 telescopes, 6 continents, 100+ people)


USA
USA
USA
UK
Italy
Japan
Taiwan
Sweden
India
Israel
Global Relay
of Observatories
Watching Transients Happen
GROWTH
Global Relay of Observatories Watching Transients Happen
NSF
PIRE

Students and Postdocs



GROWTH

Global Relay of Observatories Watching Transients Happen

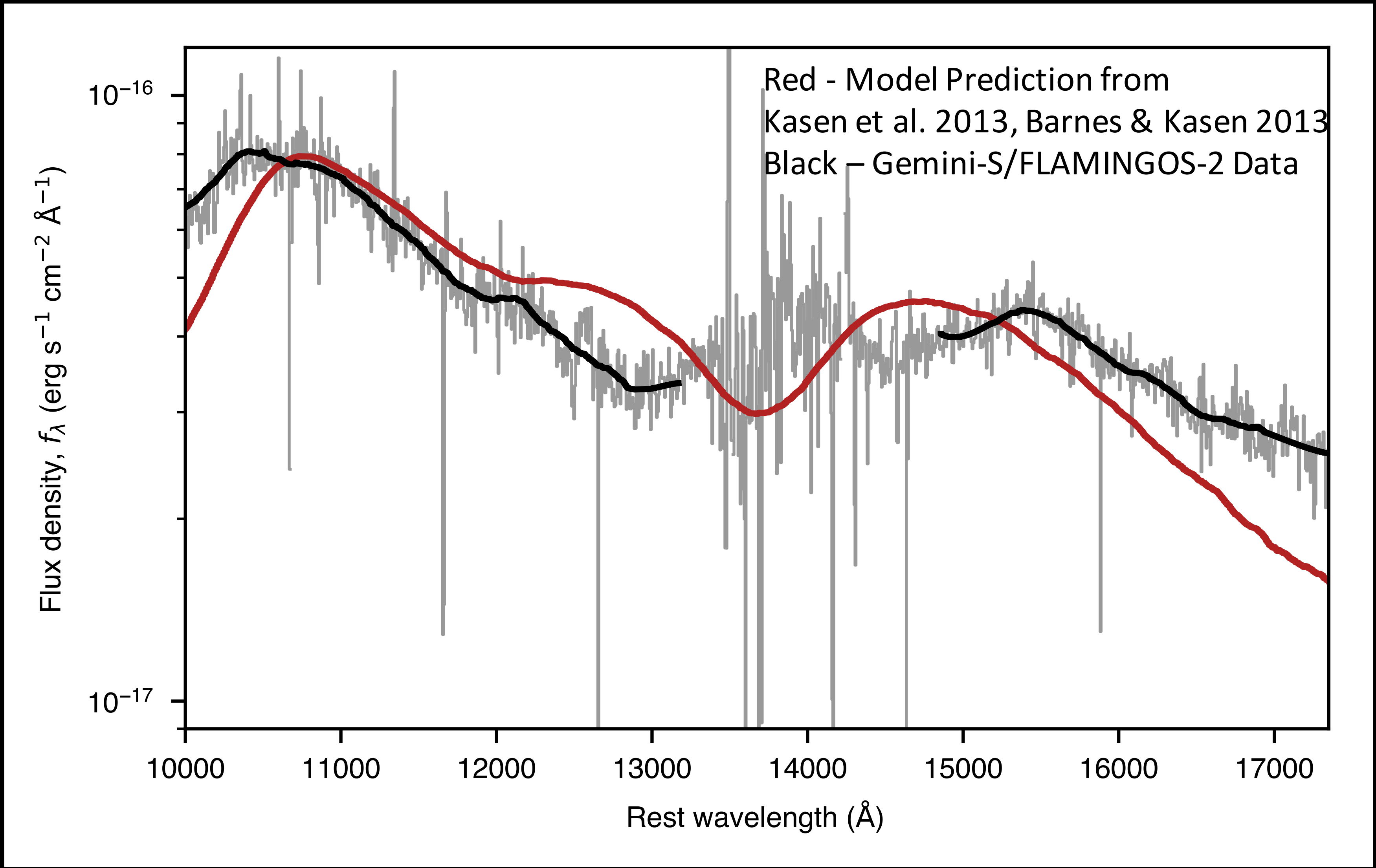
Celebrating a trio of papers in journal Science:
Evans et al. 2017, Kasliwal et al. 2017, Hallinan et al. 2017
Gottlieb et al. 2017, Rosswog et al. 2017, Mooley et al. 2017

I. Nucleosynthesis

Are neutron star mergers the long-sought sites of heavy element production?

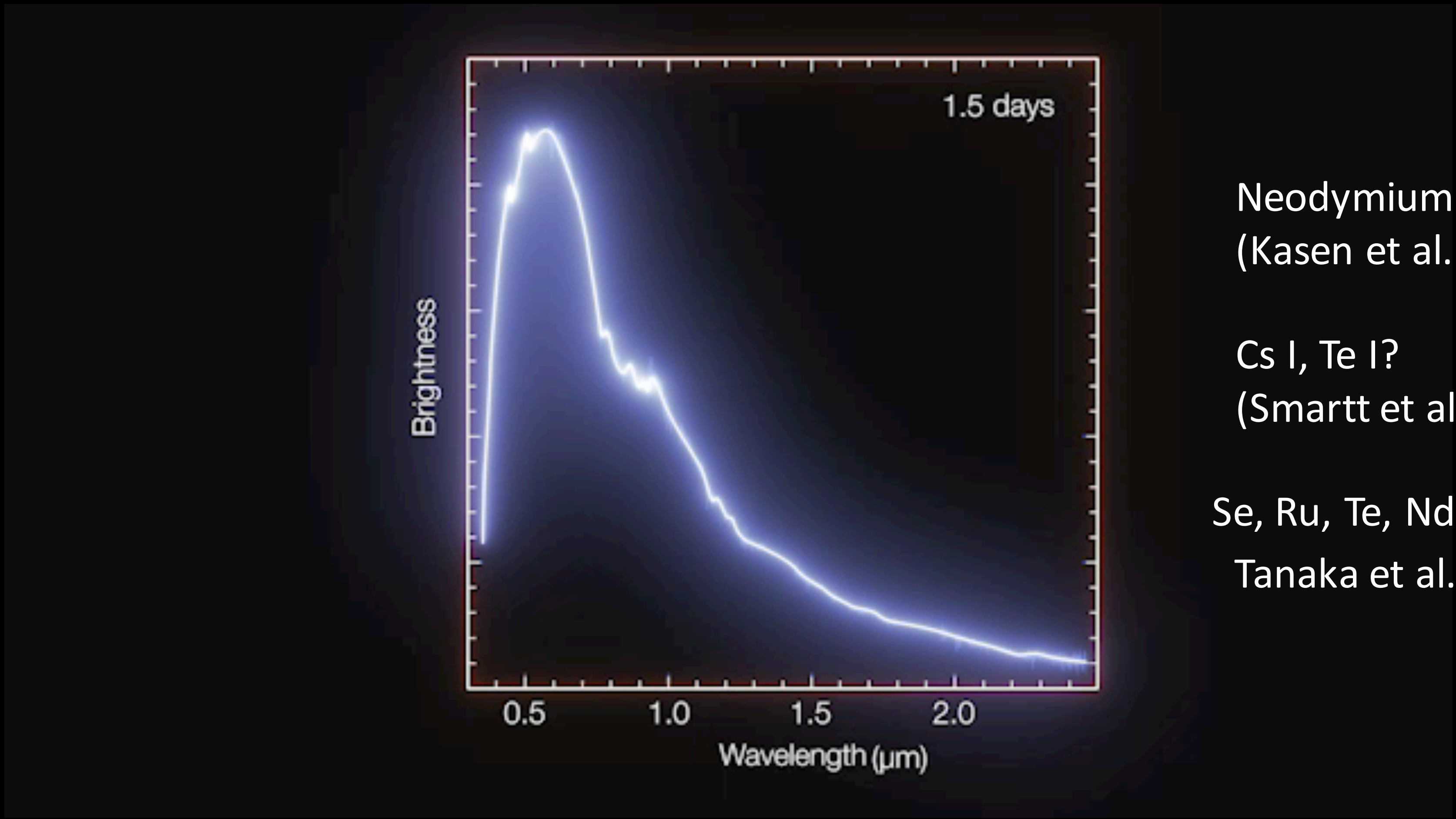
Lattimer & Schramm 1974

Kilonovae: Heavy Element Thumbprint



Kasliwal et al. 2017c
See also Chornock et al. 2017, Troja et al. 2017

Spectroscopic Evolution



Neodymium?
(Kasen et al. 2017)

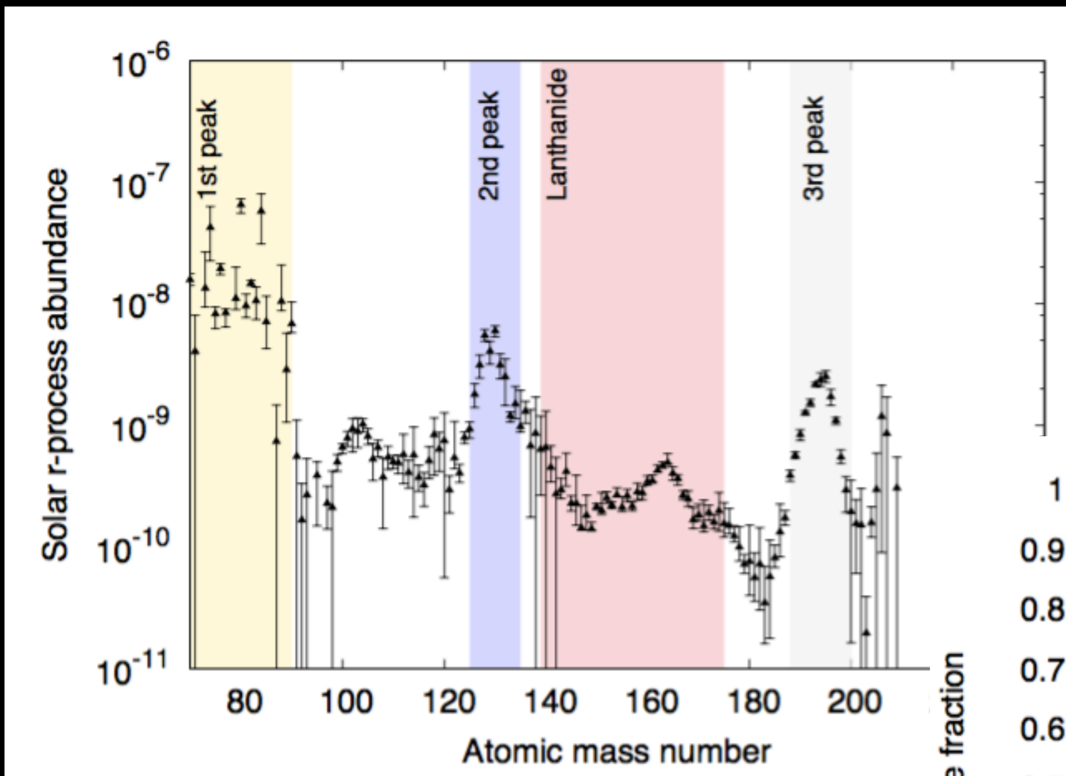
Cs I, Te I?
(Smartt et al. 2017)

Se, Ru, Te, Nd, and Er
Tanaka et al. 2017

Pian et al. 2017, Nature

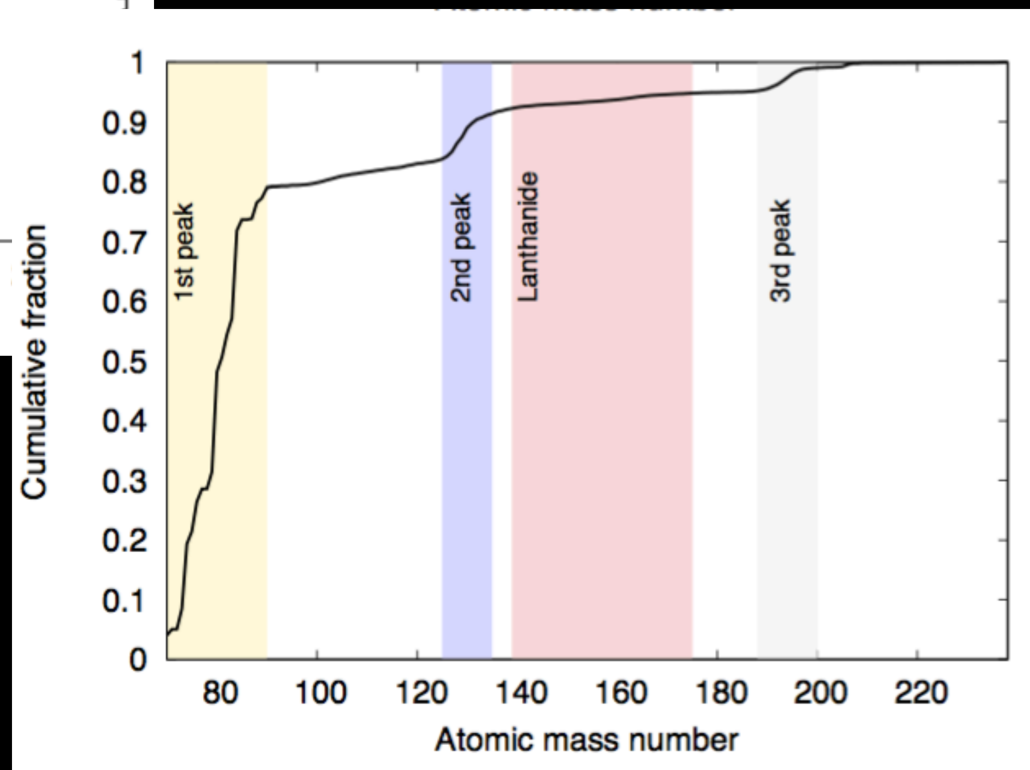
Additional spectroscopic evolution datasets:
Shappee et al . 2017, Chornock et al. 2017, Smartt et al. 2017, Nicholl et al. 2017
McCullly et al. 2017, Buckley et al. 2017, Kasliwal et al. 2017

Solar abundance of Heavy Elements

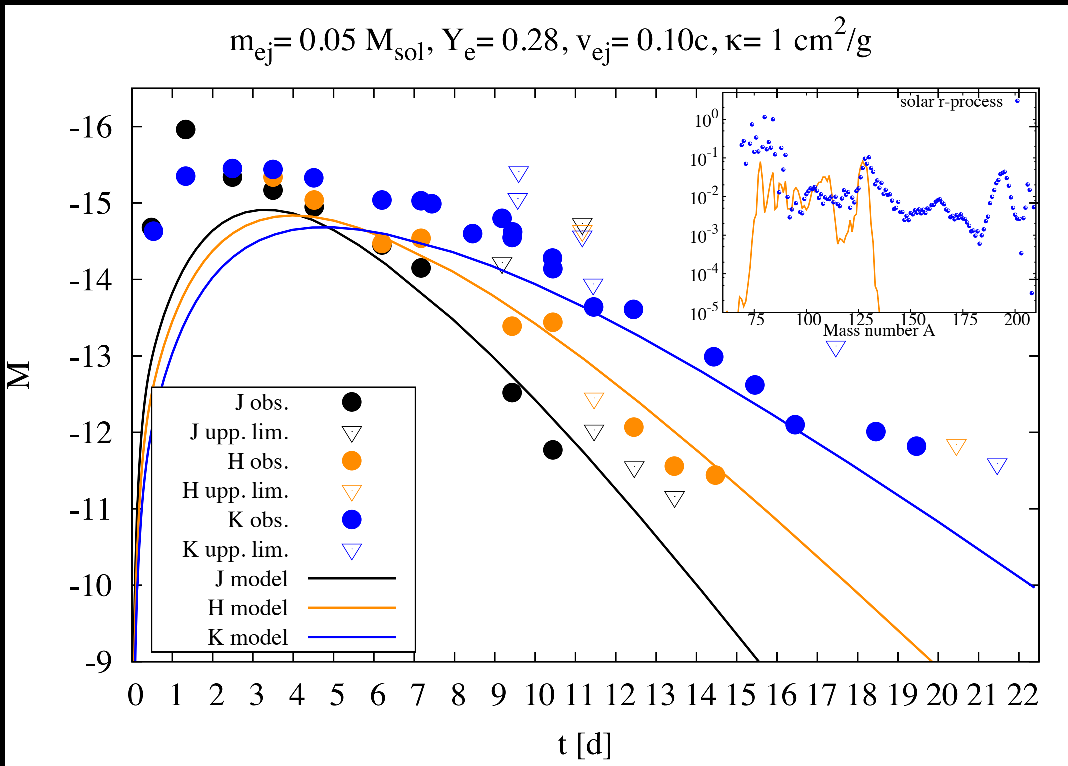


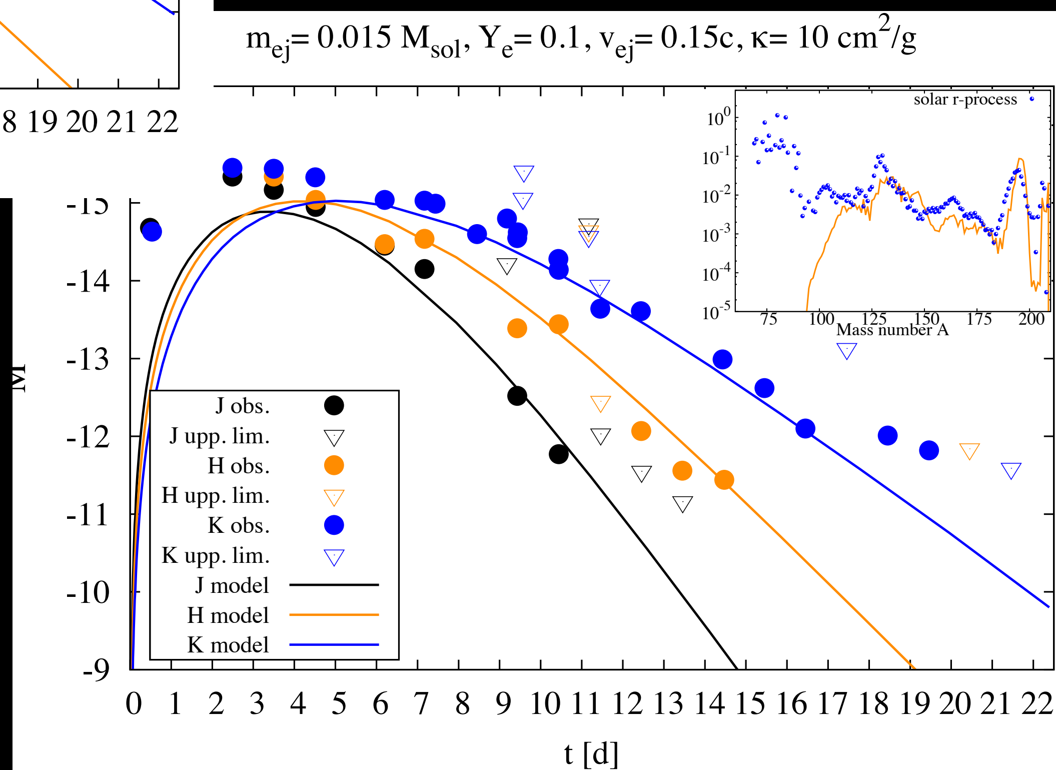
Rate / 500 Gpc^-3 yr^-1
X Ejecta / 0.05 Msun
= Observed Solar Abundance

LIGO lower limit: > 320 / Gpc^3 / yr
PTF upper limit: < 800 / Gpc^3 / yr



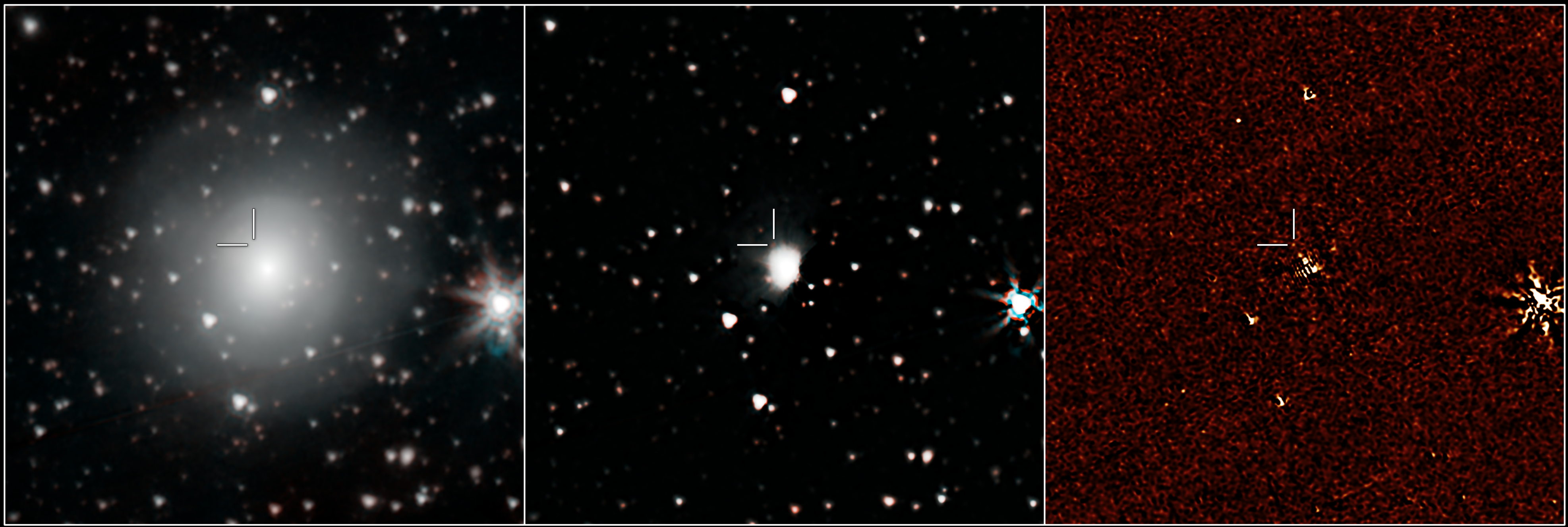
A Site or The Site?
e.g. Hotokezaka et al. 2018





Just the first two peaks can explain the ground-based IR light curve?
Rosswog et al. 2017

Reddest detection with Spitzer



Infrared Image (3.6–4.5 μm) Filtered Image (3.6–4.5 μm) Galaxy-Subtracted Image (4.5 μm)

Afterglow of Neutron Star Merger in galaxy NGC 4993

NASA / JPL-Caltech / R. Lau, M. Kasliwal (Caltech), E. Ofek (Weizmann)

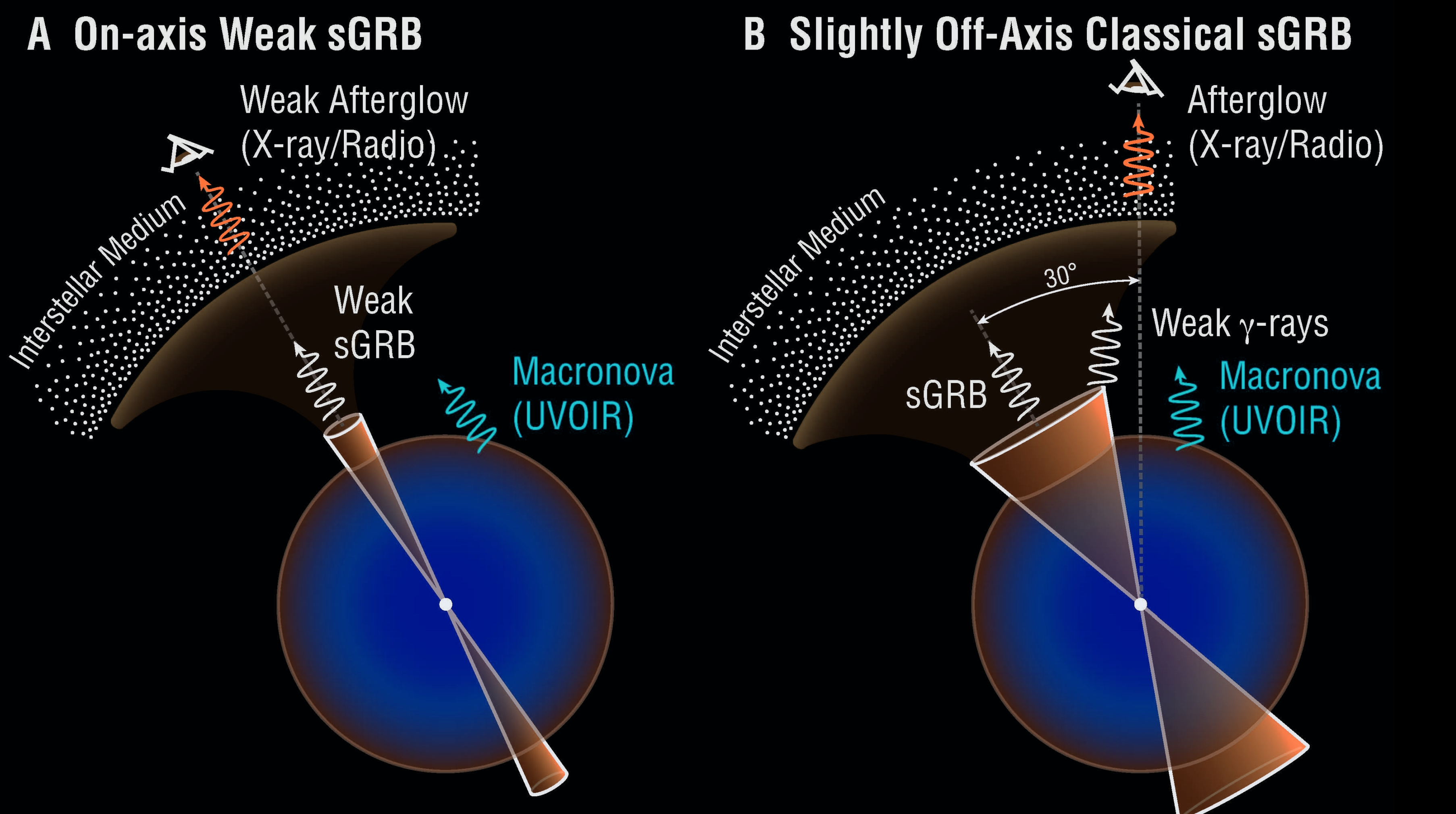
Spitzer Space Telescope • IRAC

II. Jet Physics

Are neutron star mergers progenitors of short hard gamma-ray bursts?

Eichler et al. 1989, Paczynski 1989

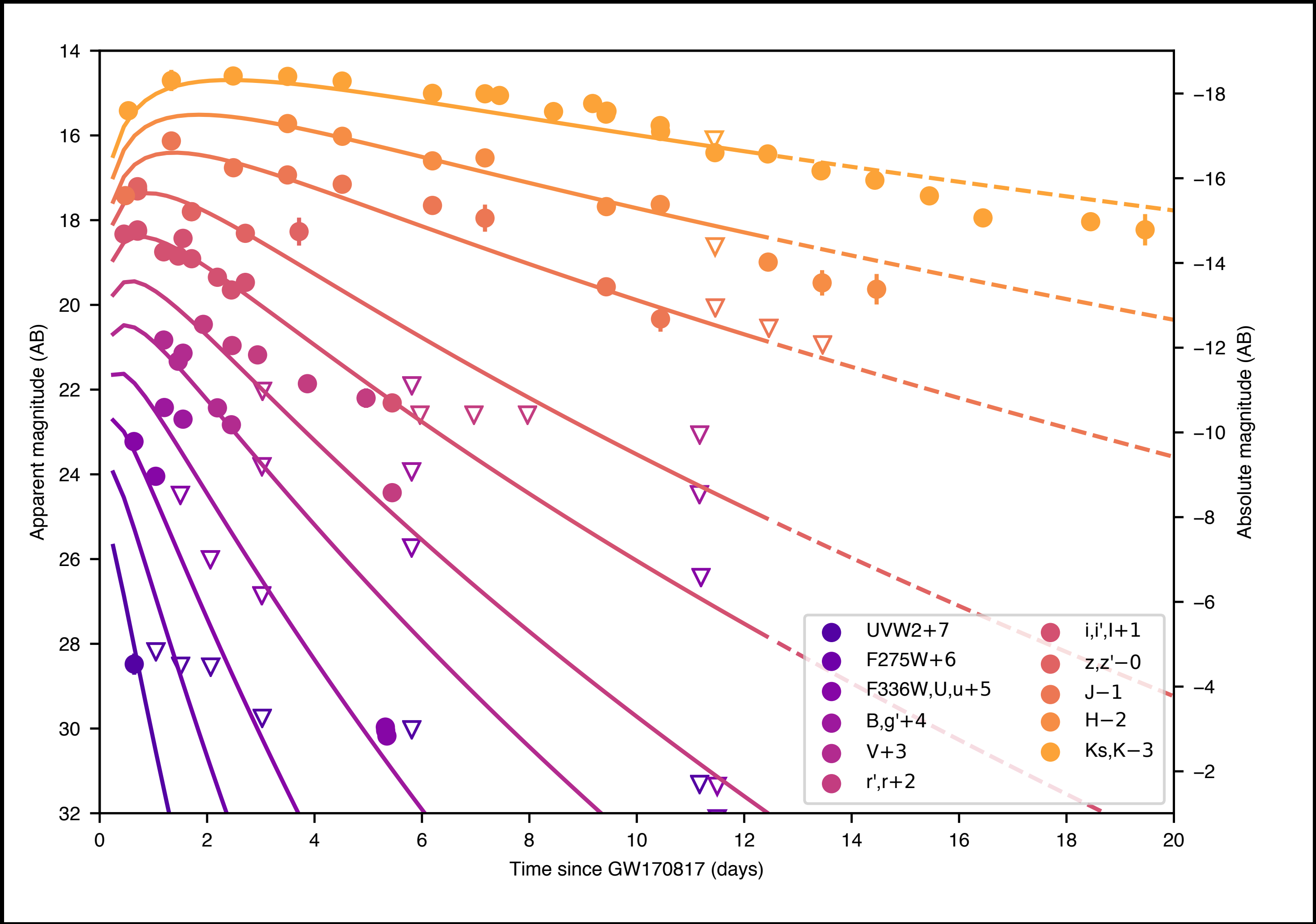
What it is not



Surprise # 1: Weaker than a sGRB by 10,000x

Surprise # 2: Delayed onset of Radio/X-rays

UVOIR Light Curve

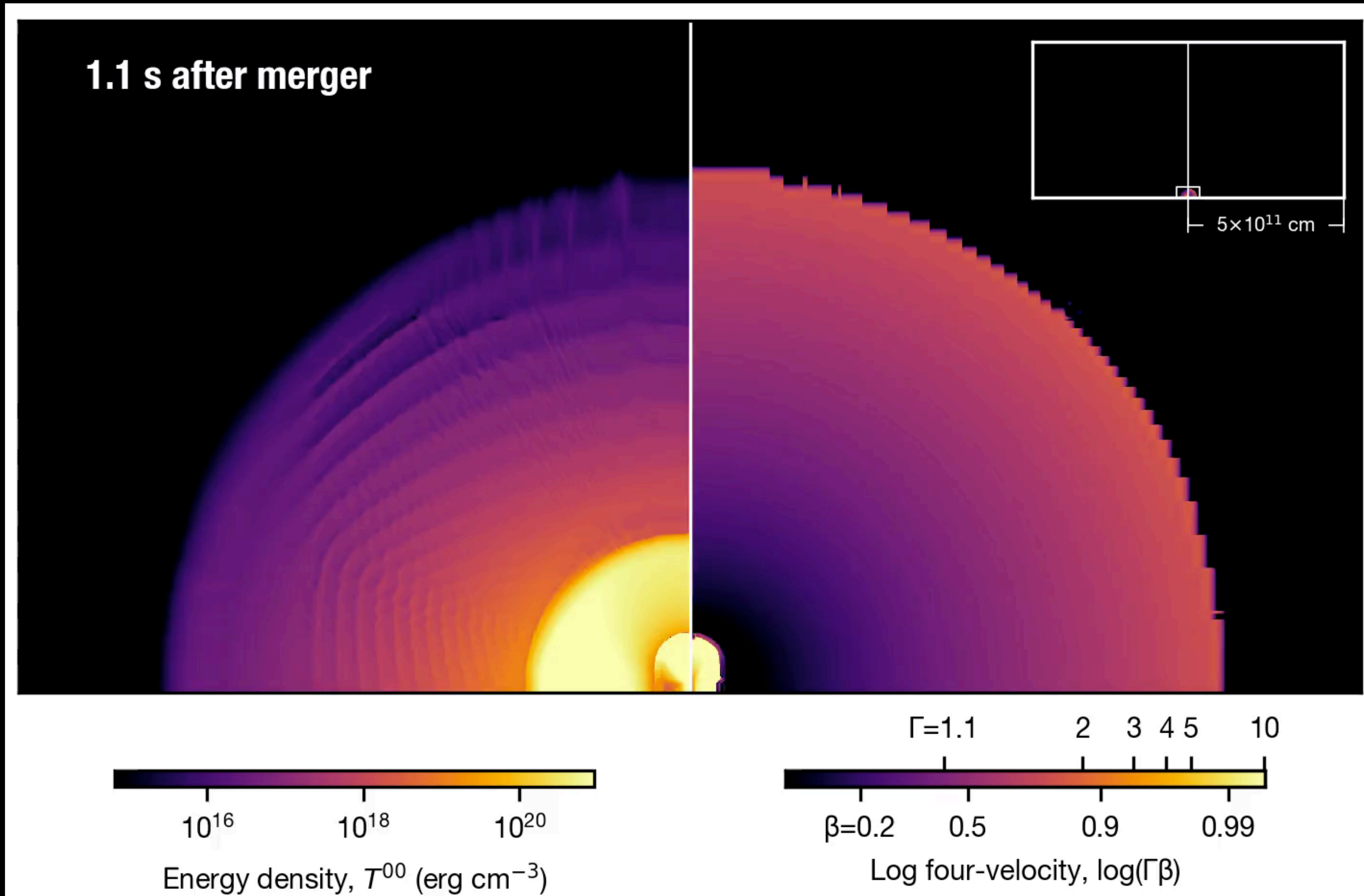


See also:
Andreoni et al. 2017
Arcavi et al. 2017
Cowperthwaite et a.
Coulter et al. 2017
Drout et al. 2017
Lipunov et al. 2017
Lyman et al. 2017
Pian et al. 2017
Soares-Santos et al. 2
Smartt et al. 2017
Tanvir et al. 2017
Utsumi et al. 2017
Villar et al. 2017

Evans et al. 2017, Kasliwal et al. 2017c

Surprise # 3: Too Bright and Blue at Early Time

A New Model: The Cocoon Breakout



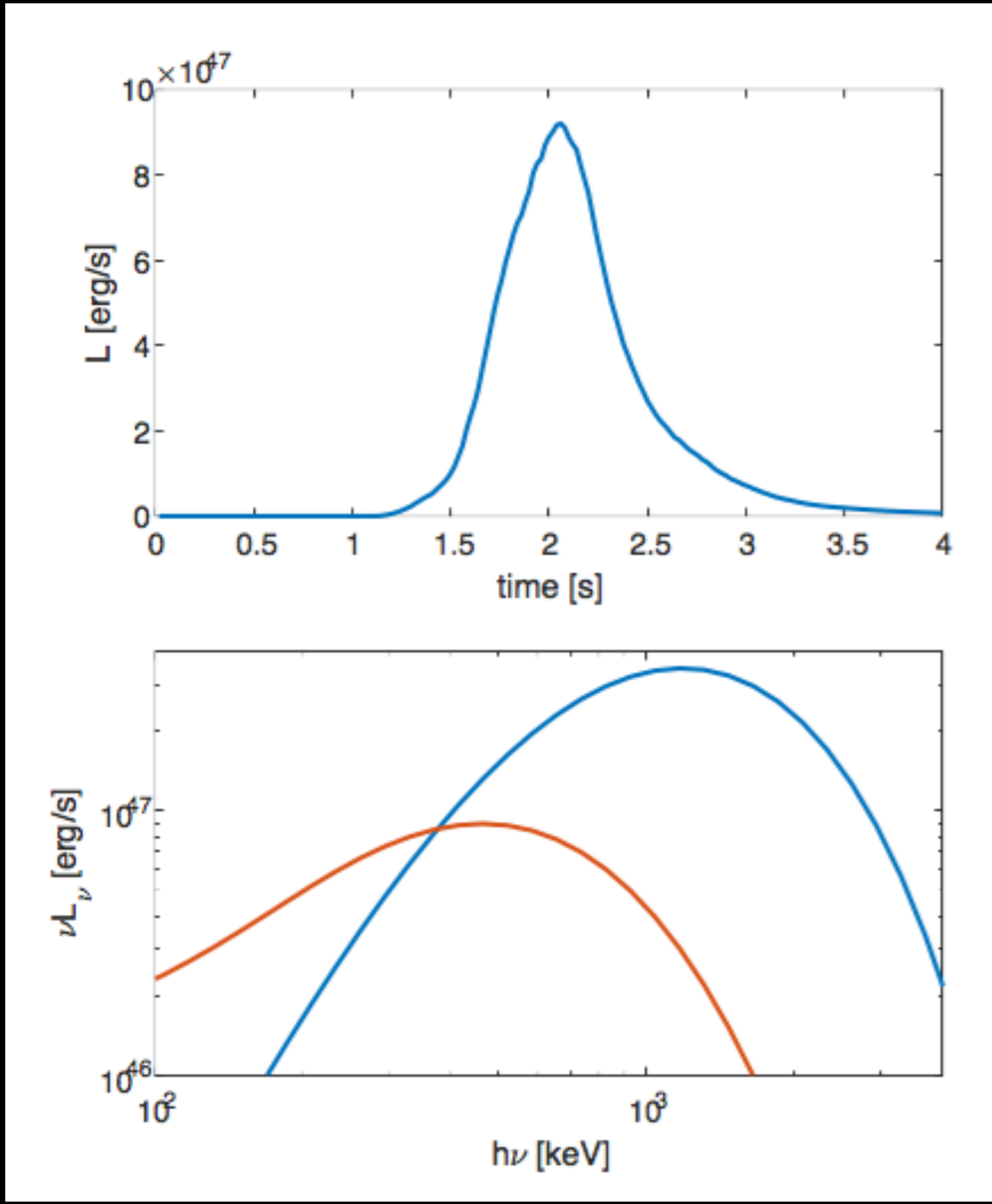
Kasliwal et al. 2017c

Gamma-ray Modeling in Gottlieb et al. 2017b; More analytics in Piro & Kollmeier 2017

Cocoon for NS mergers: Lazzati et al. 2017a,b, Gottlieb et al. 2017a, Hotokezaka et al. 2015

Simulations: Aloy et al. 2005, Nagakura et al. 2014, Murguia-Berthier et al. 2014 , Duffell et al. 201

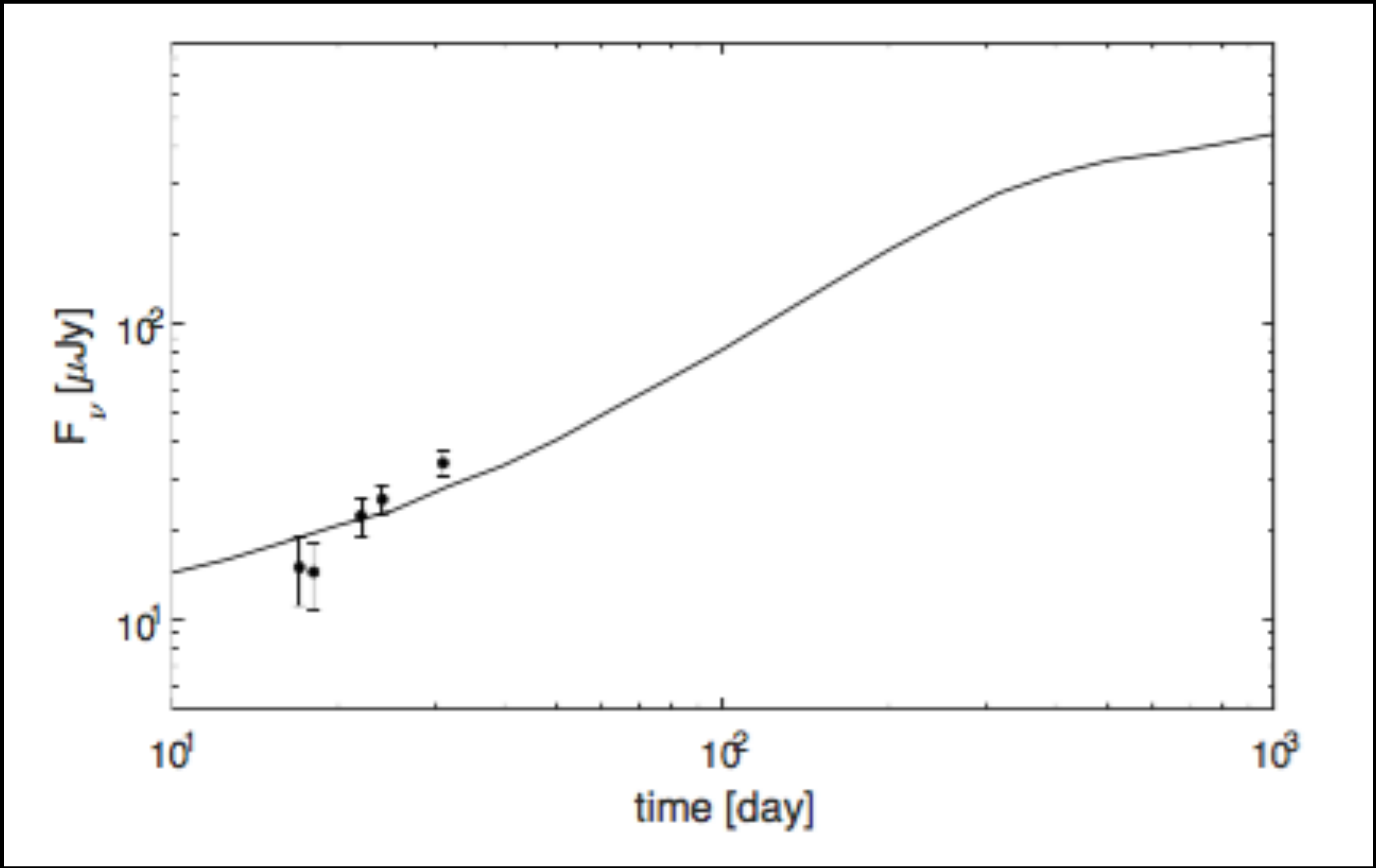
Cocoon Explains Gamma-Rays



1. Smooth Profile
2. Two Spectral Components
3. Low luminosity
4. Time lag

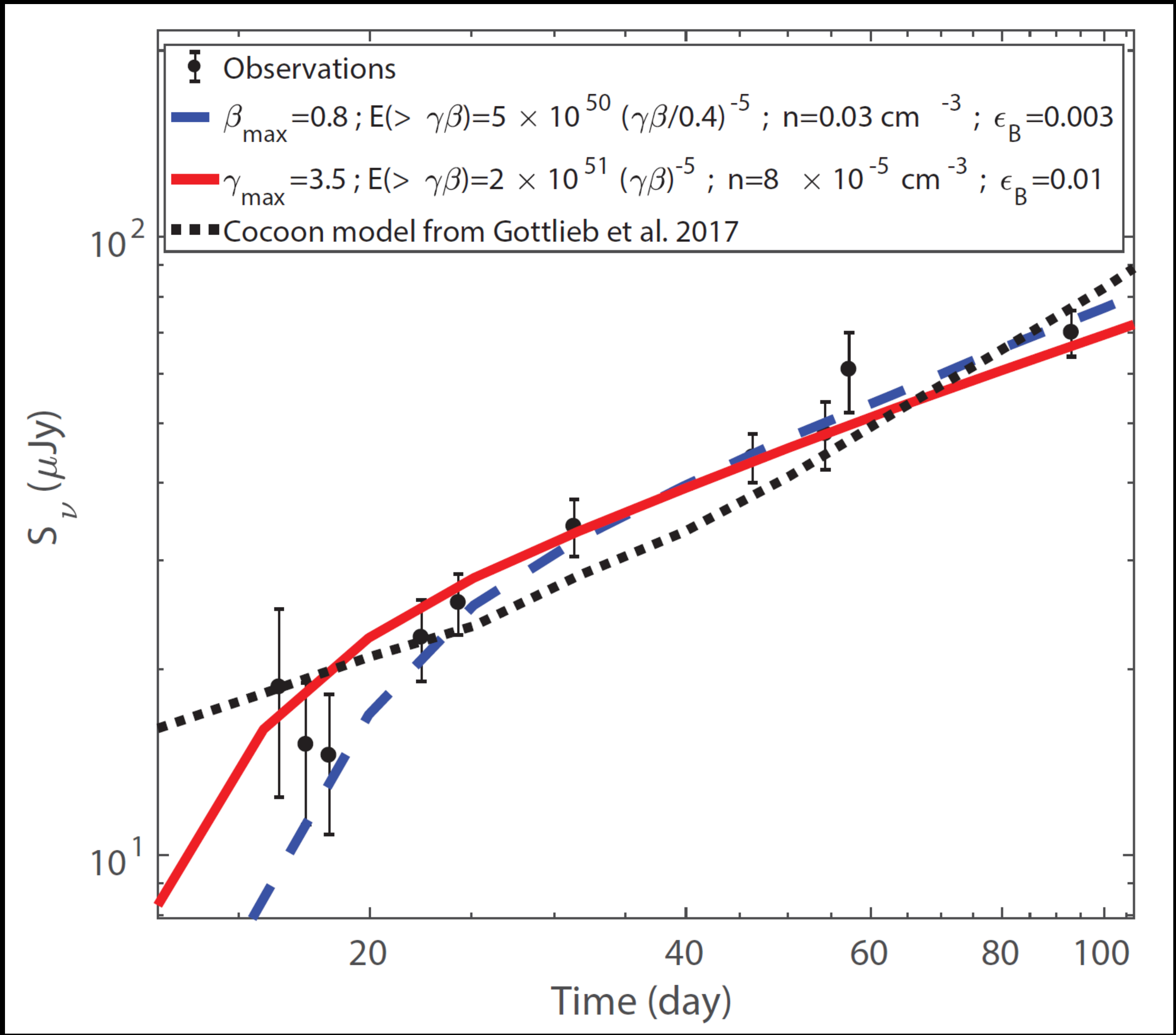
Gottlieb et al. 2017b

Radio Prediction on Oct 16



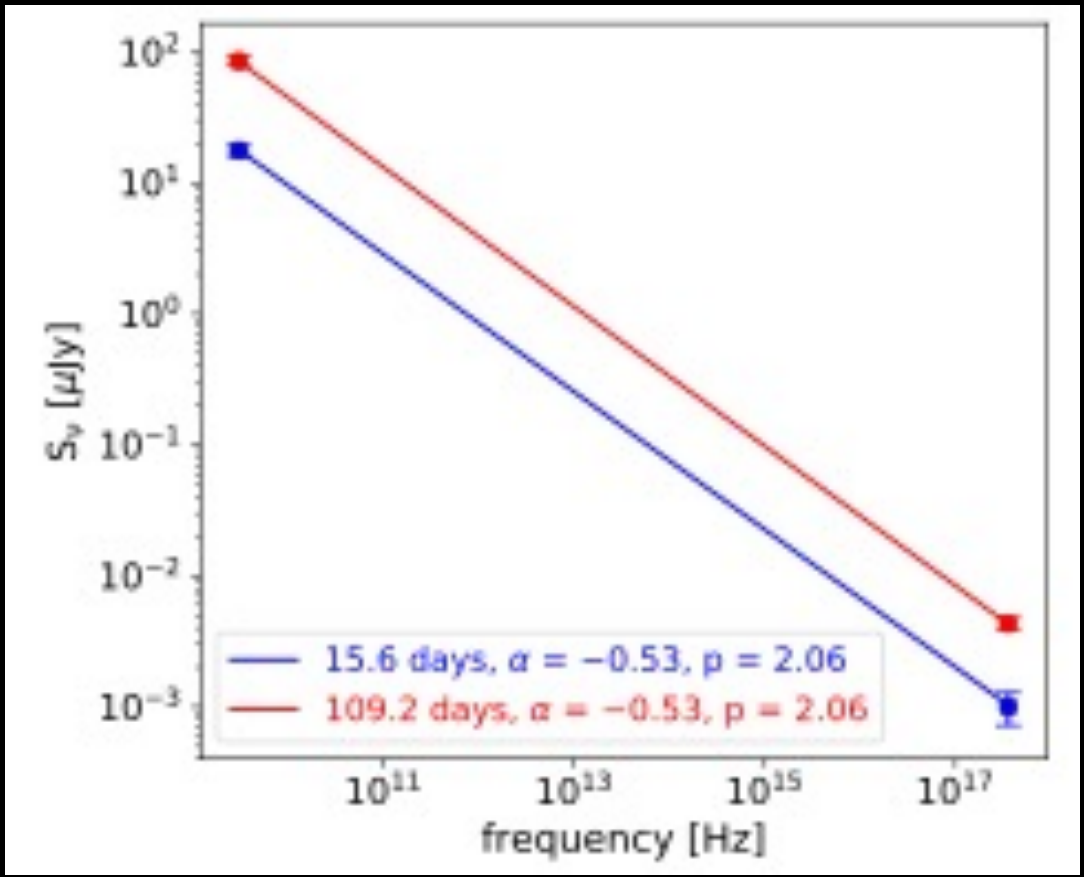
Prediction: Gottlieb et al. 2017b, Data: Hallinan et al. 2017

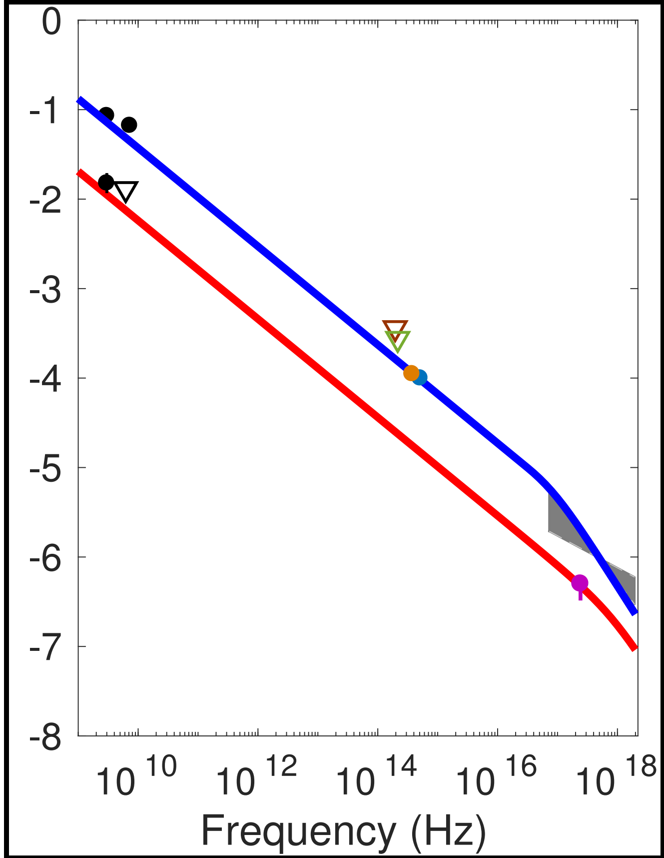
Cocoon Explains Radio



Mooley et al. 2017, Hallinan et al. 2017
See also: Alexander et al. 2017

Cocoon Explains X-ray and Optical

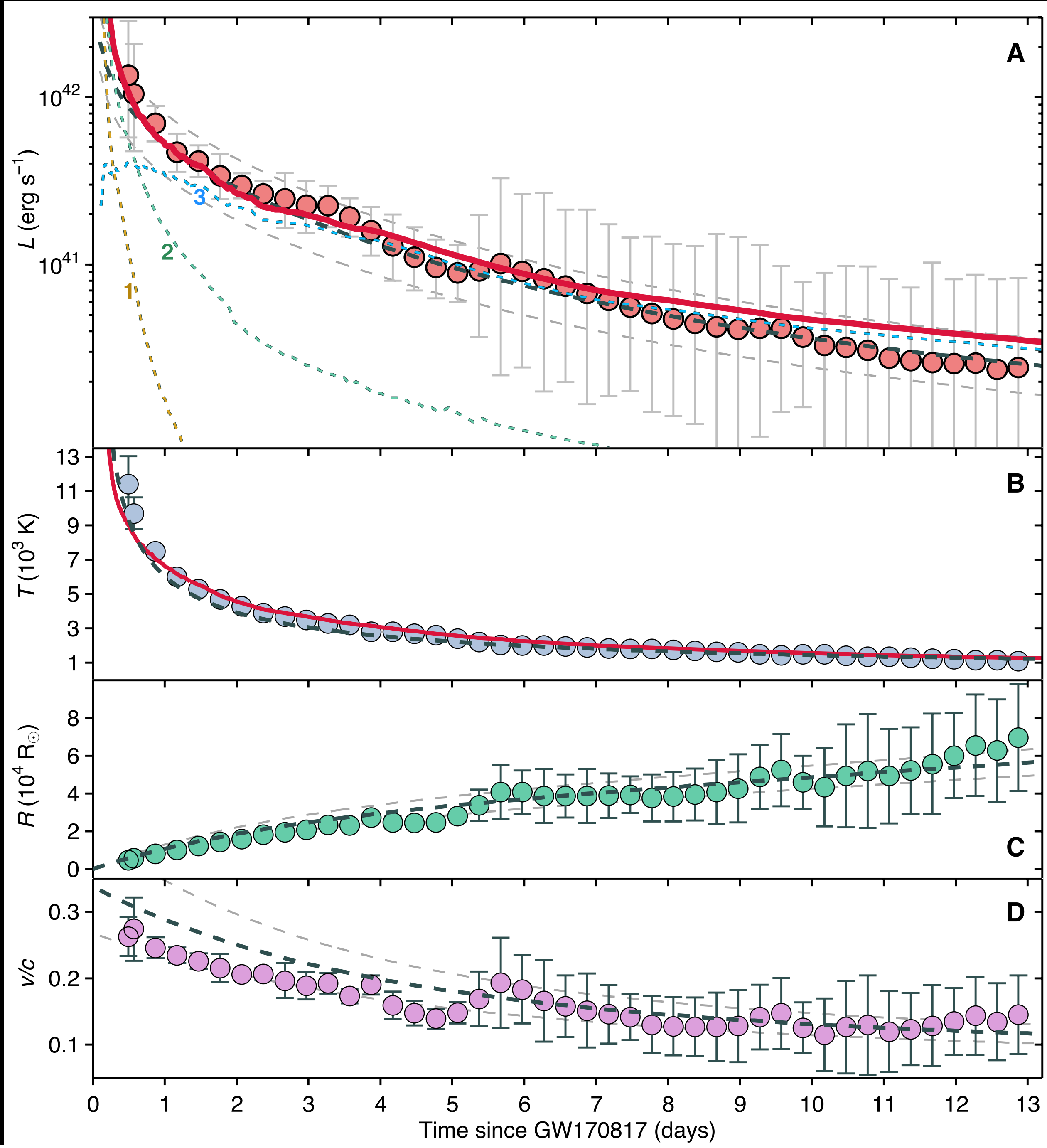




Ruan et al. 2017, Pooley et al. 2017
Troja et al. 2017, Haggard et al. 2017, Margutti et al. 2017

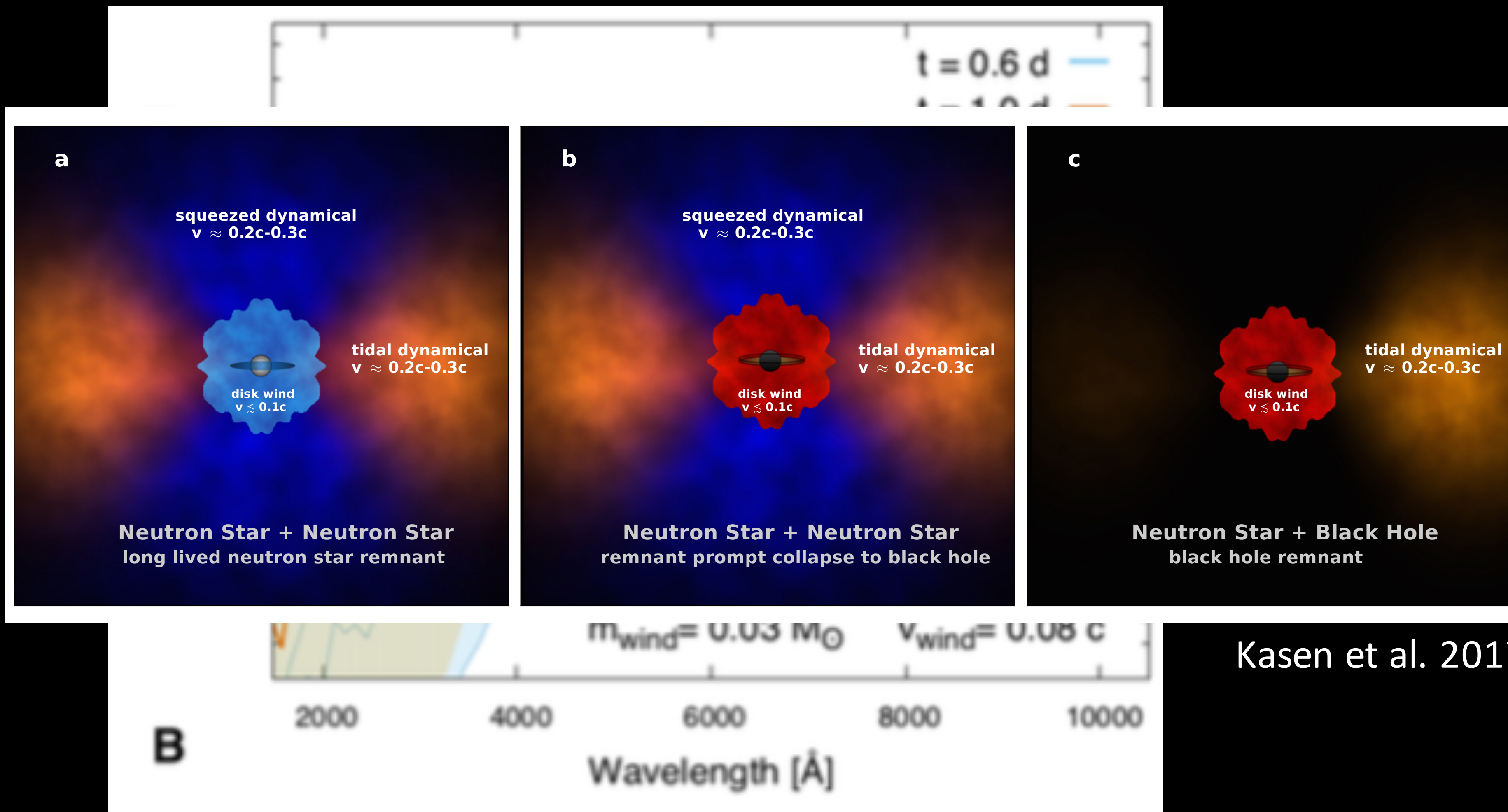
Lyman et al. 2018
Margutti et al. 2018

Cocoon Explains Early Blue Emission



Kasliwal et al. 2017c

Alternate: Geometry and Ye?

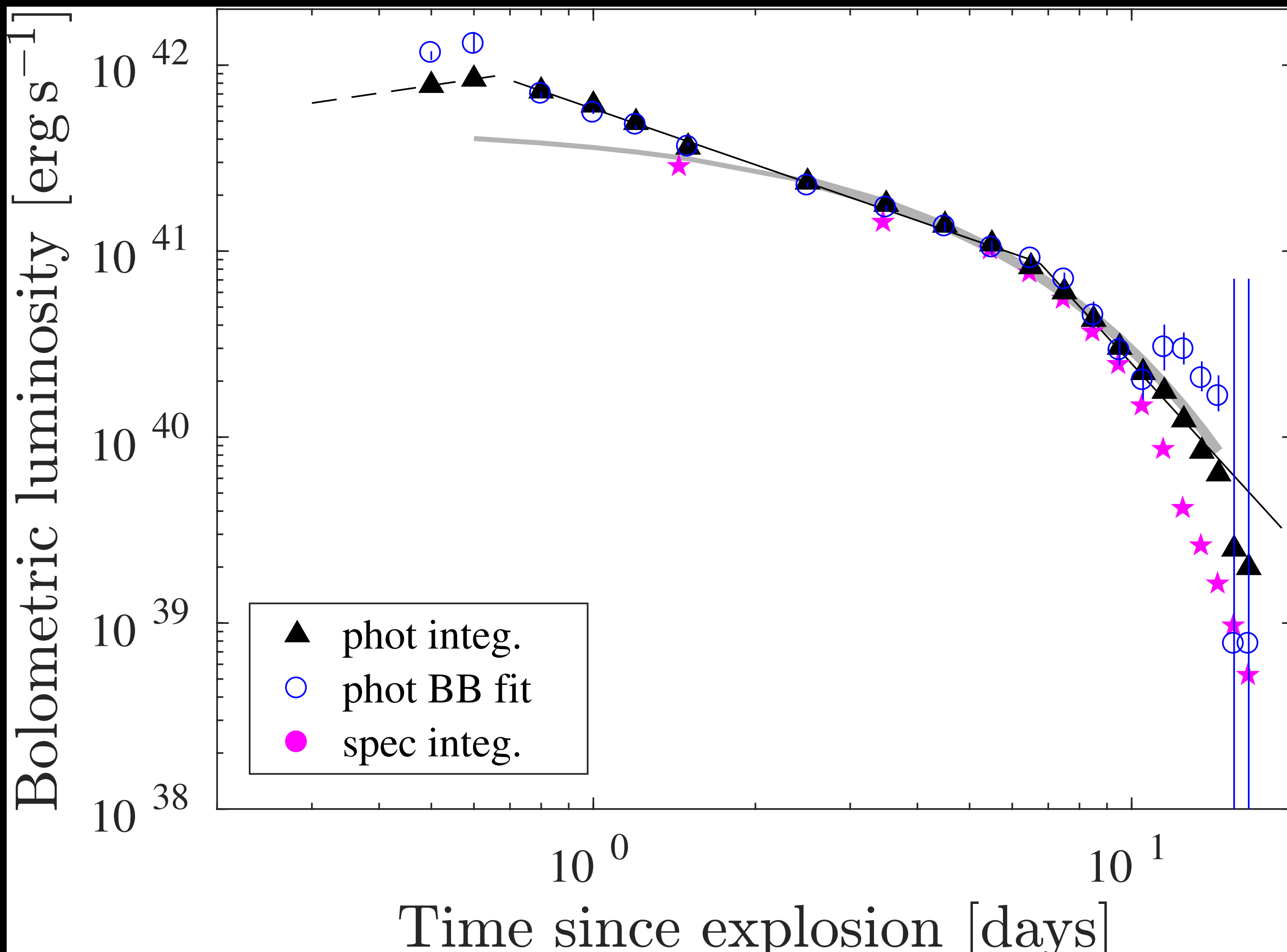


Kasen et al. 2017

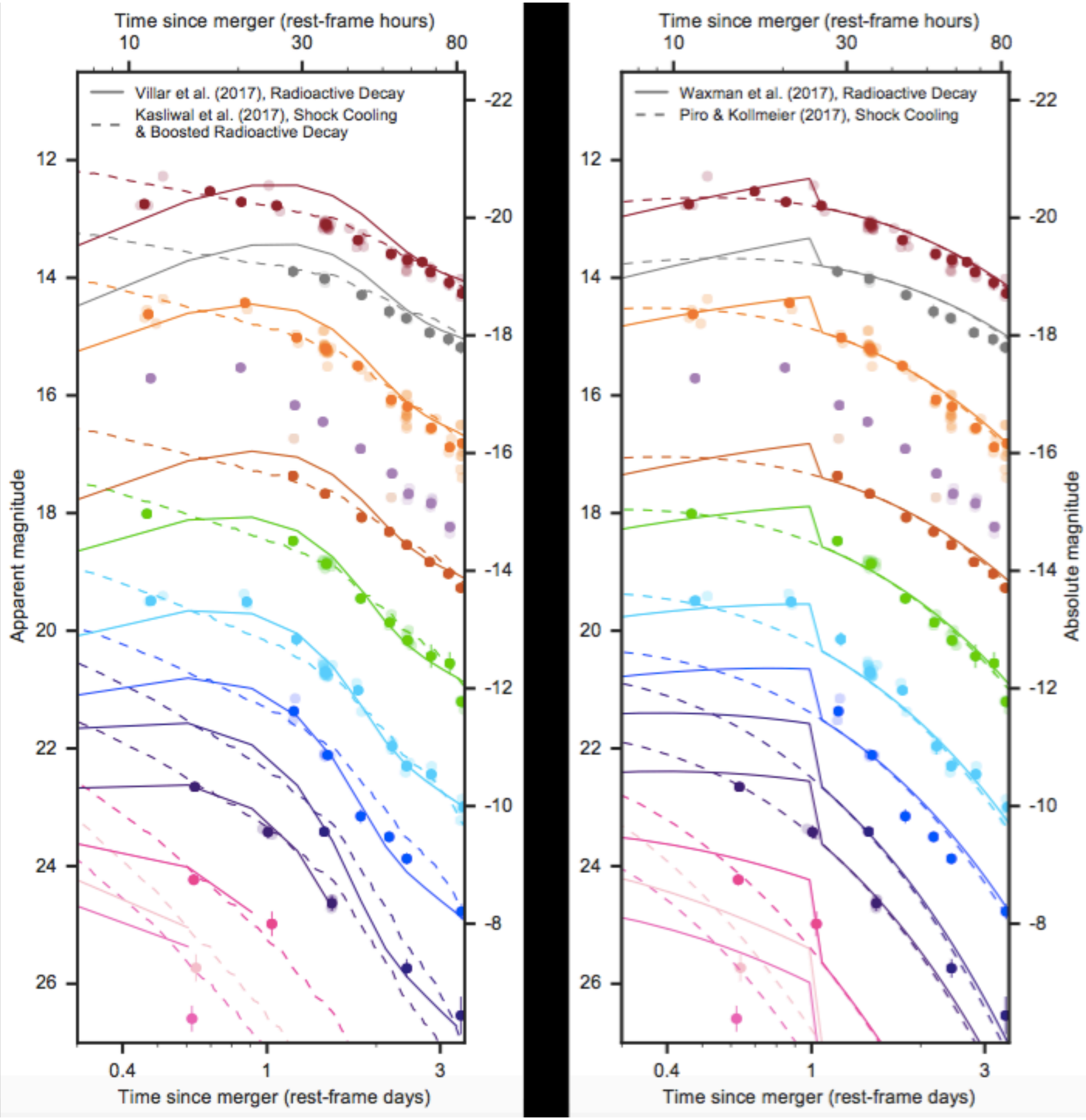
Evans et al. 2017

See also Kasen et al. 2017, Metzger 2017, Cowperthwaite et al. 2017, Villar et al. 2017

Alternate: A single-component model?



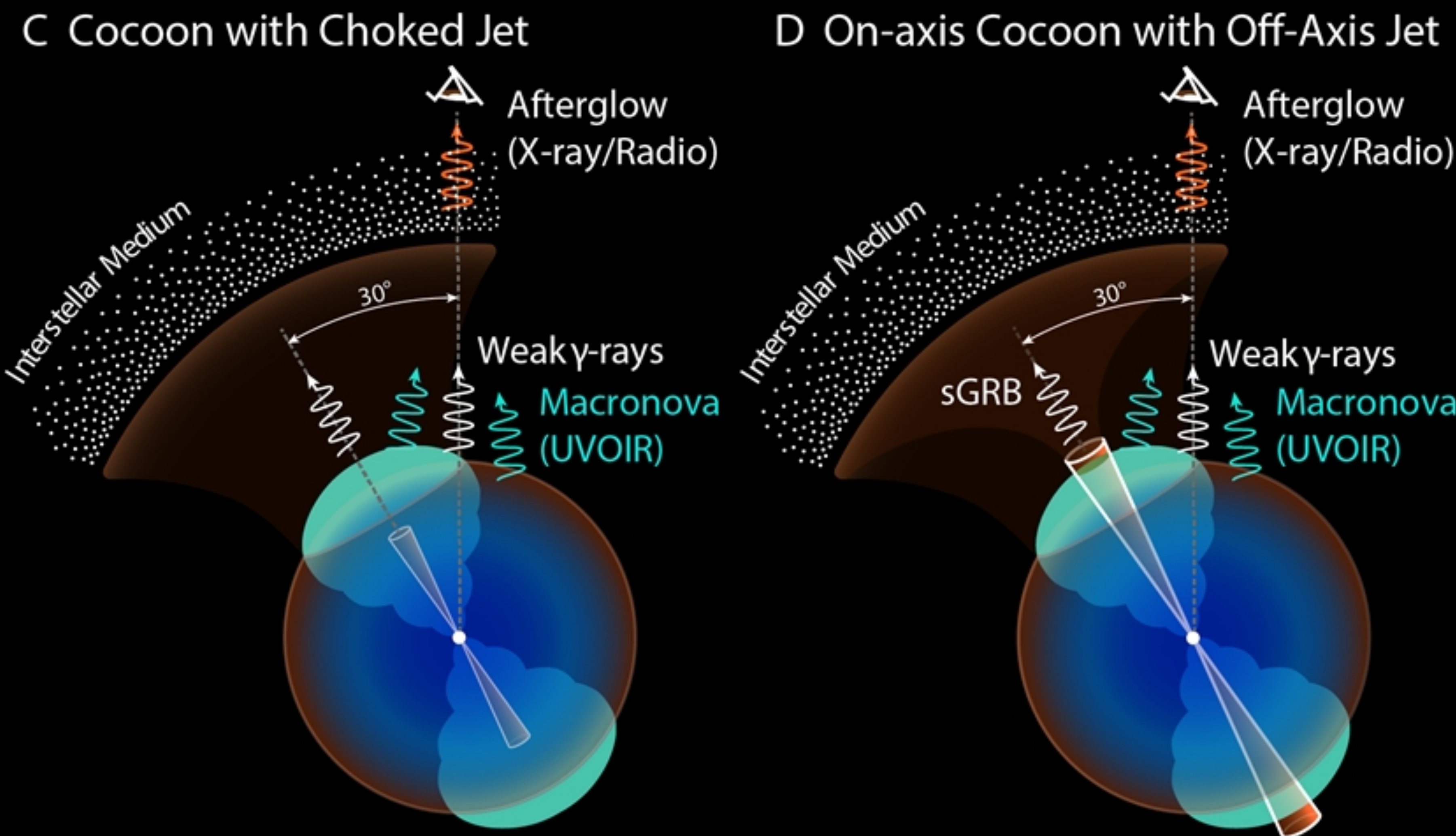
Waxman et al. 2017



Time since merger (rest-frame hours)
10
30
80
Villar et al. (2017), Radioactive Decay
Kasliwal et al. (2017), Shock Cooling & Boosted Radioactive Decay
Waxman et al. (2017), Radioactive Decay
Piro & Kollmeier (2017), Shock Cooling
Apparent magnitude
12
14
16
18
20
22
24
26
Absolute magnitude
-22
-20
-18
-16
-14
-12
-10
-8
0.4
1
3
Time since merger (rest-frame days)

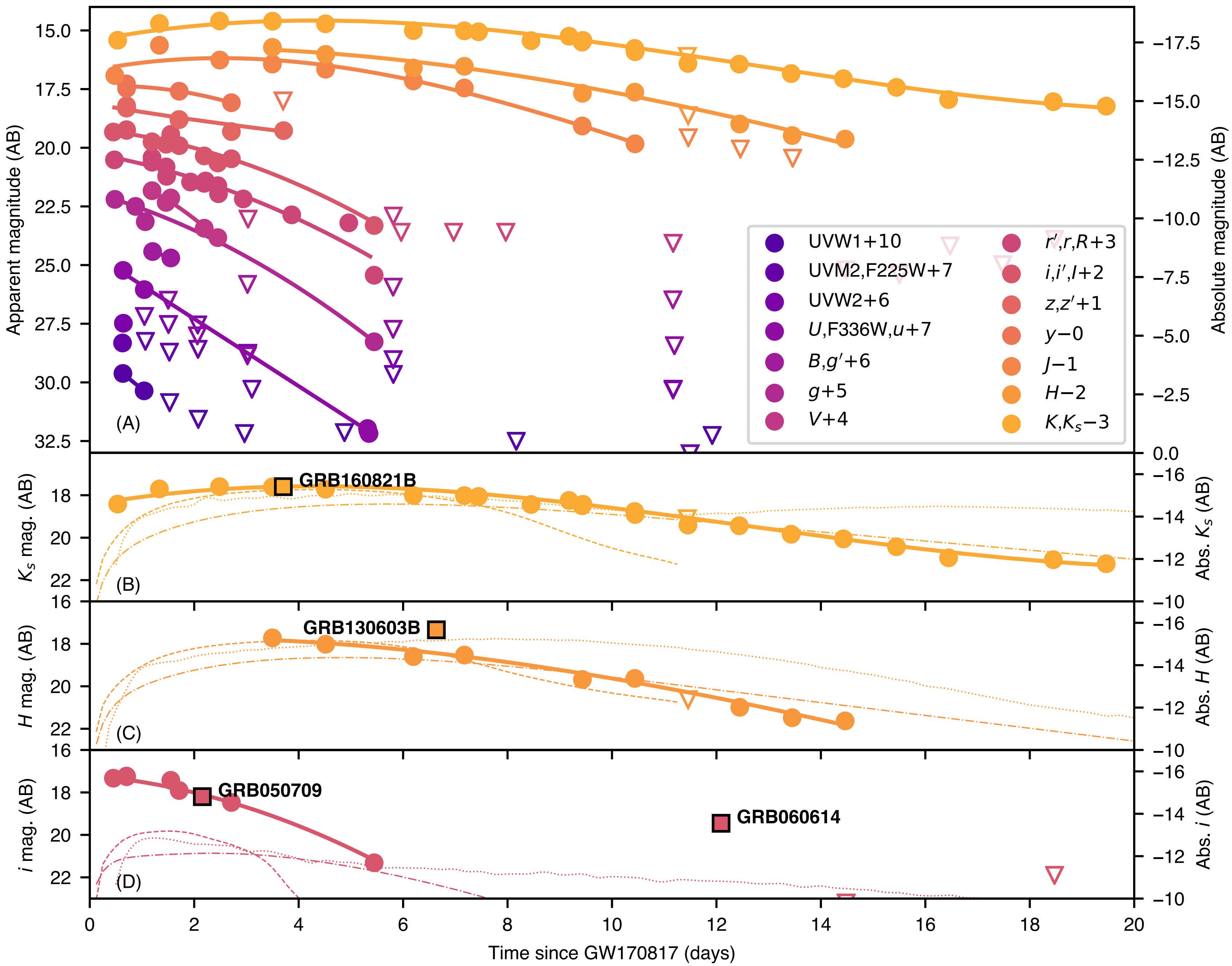
Arcavi 2018

The fate of the jet is not yet clear



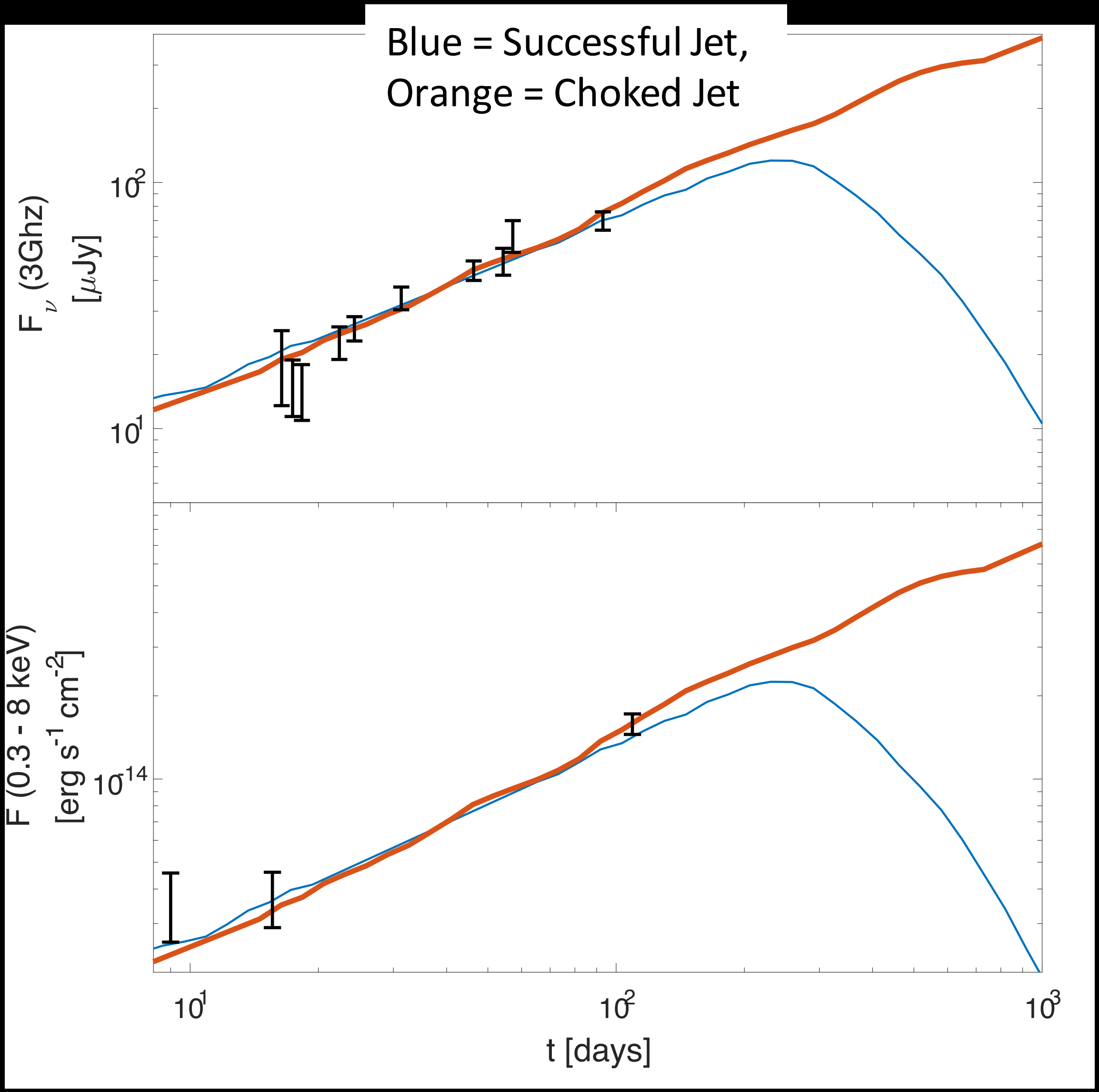
Kasliwal et al. 2017c

Also referred to as "structured jet"
e.g. Lazzati et al. 2017c, Lyman et al. 2018



Kasliwal et al. 2017c

Patience



Nakar et al., submitted

We have learned so much…

but this is just the beginning!

What is the rate of neutron star mergers?

Is this *the* source of heavy elements?

How bright, blue and ubiquitous is the early emission?

Does a cocoon accompany every neutron star merger?
What is the fate of the jet? Is there a connection to sGRB?

Can we directly infer the nature of the remnant?

What does a neutron star + black hole merger look like?

Best is that ZTF may find a kilonova even without a trigger from GW detectors…

Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	*60 – 100*	—	—	—
		Virgo	—	*25 – 30*	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.002 – 2	0.007 – 30	0.04 – 100	0.1 – 200	0.4 – 400
Actual BNS detections			0	—	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	median/deg^2		460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

LVC Living Review