A Kilonova Following Gravitational Waves From Merging Neutron Stars

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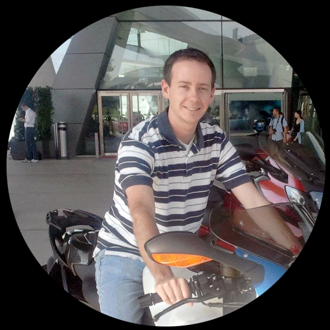

Curtis McCully
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Network Operations Scientist,
LCO

Arcavi et al. 2017a (Nature), Arcavi et al. 2017b (ApJL),
McCully et al. 2017 (ApJL) & ~80 other papers listed on kilonovae.org

August 17, 2017

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First gravitational wave signal from **merging neutron stars**

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Closest and best localized gravitational wave event

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August 17, 2017

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Closest and best localized gravitational wave event

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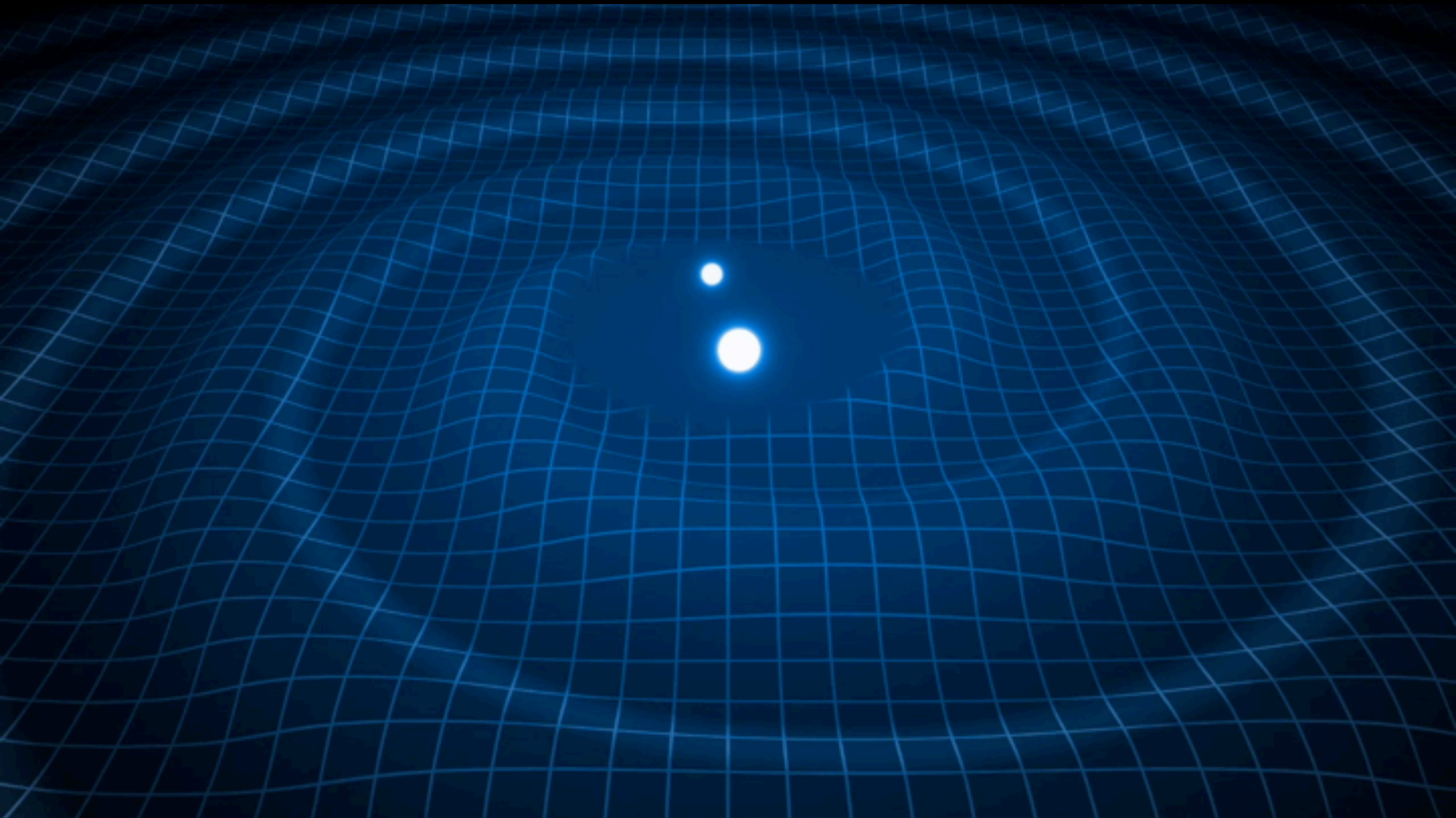
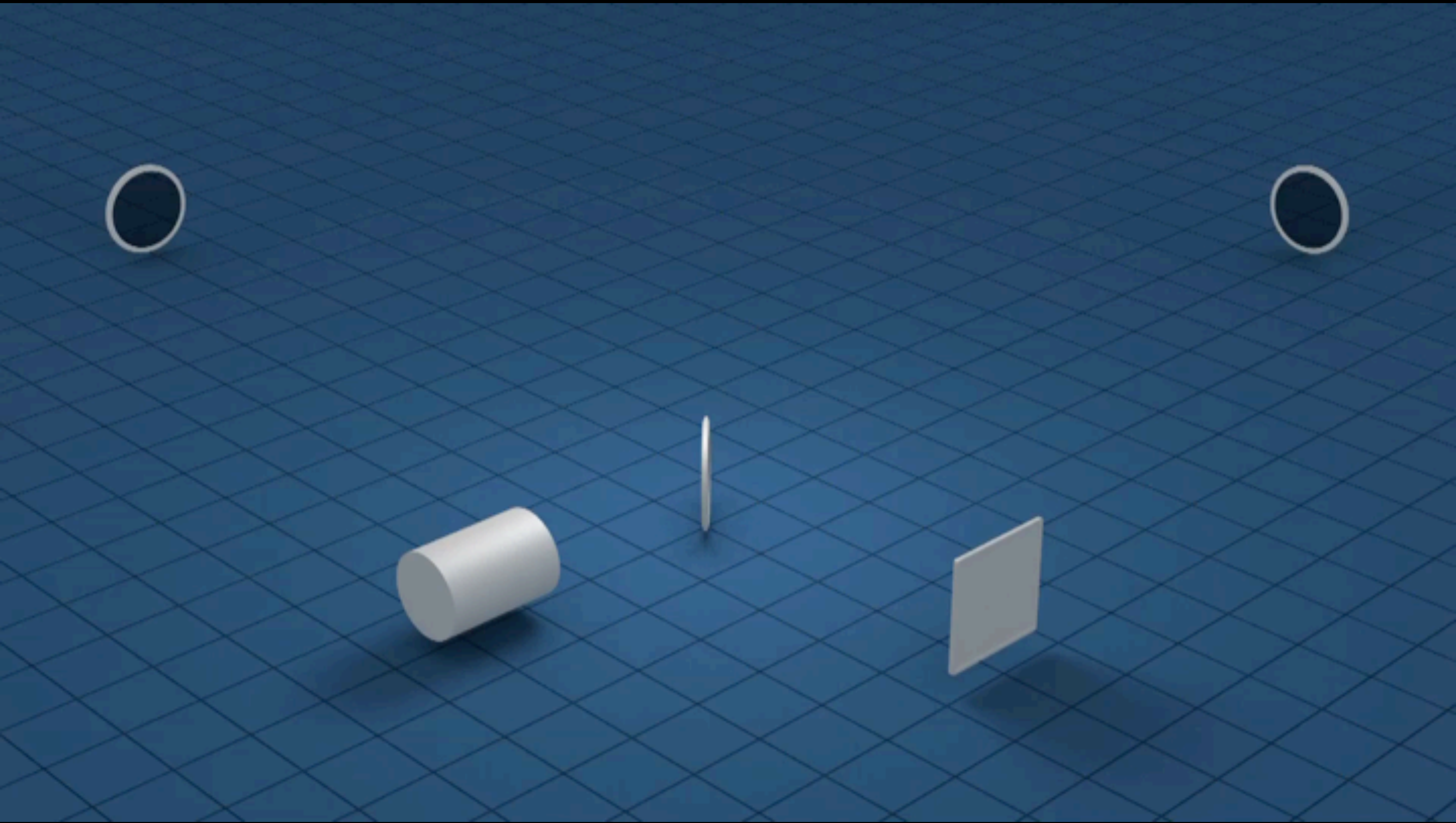
First time **gravitational waves and electromagnetic radiation** were observed from the same event

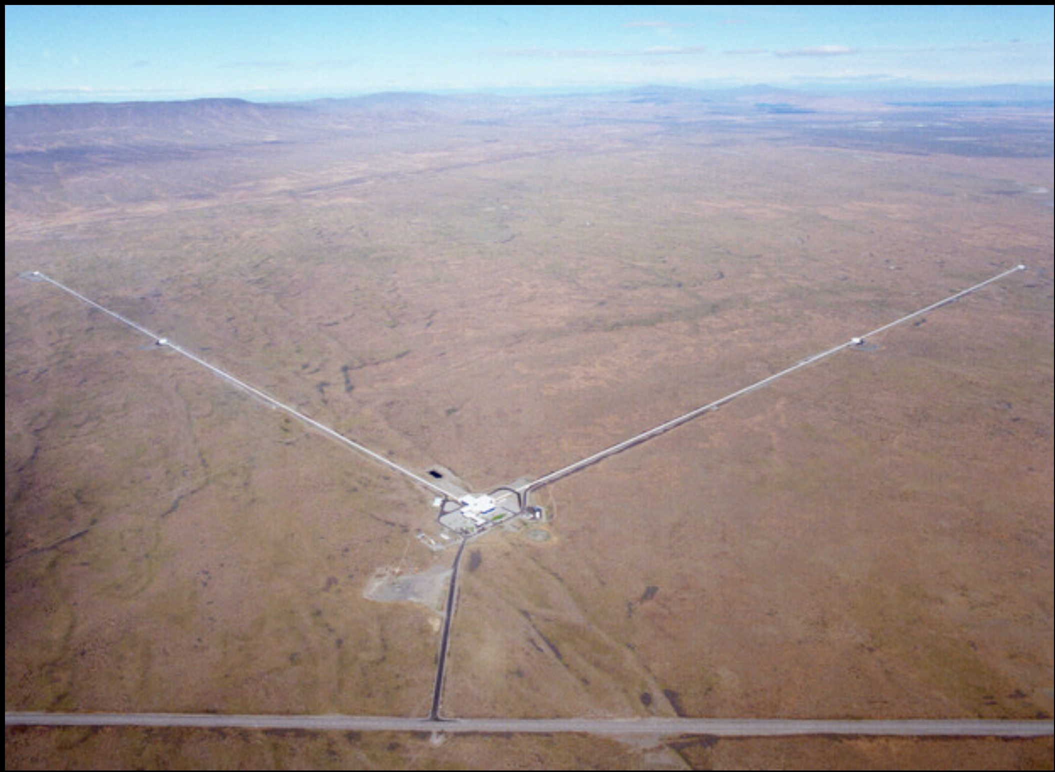
First detection of a **kilonova**

First identification of the **host galaxy** of a gravitational wave event.





LIGO: Laser Interferometer Gravitational-wave Observatory



Merging Neutron Stars Could Produce EM Emission

Simulation: D. Link, L. Rezzolla, M. Koppitz

Merging Neutron Stars Could Produce EM Emission

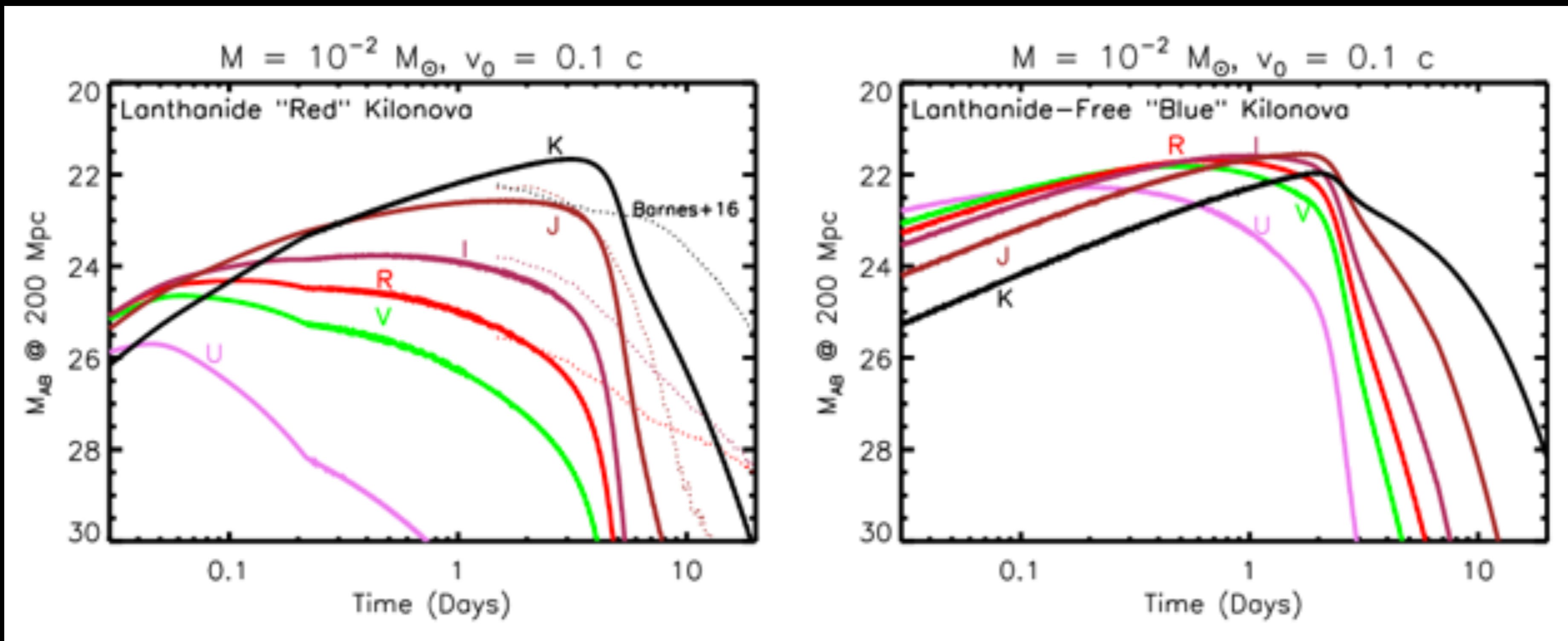
Short gamma-ray burst (Curtis)

Kilonova - light from the radioactive decay of heavy elements synthesized in the neutron-rich ejected material:

Solar masses of ejected material: 0.001-0.1
Velocity of ejected material: 0.1c-0.3c
Electron fraction: low (<0.25)

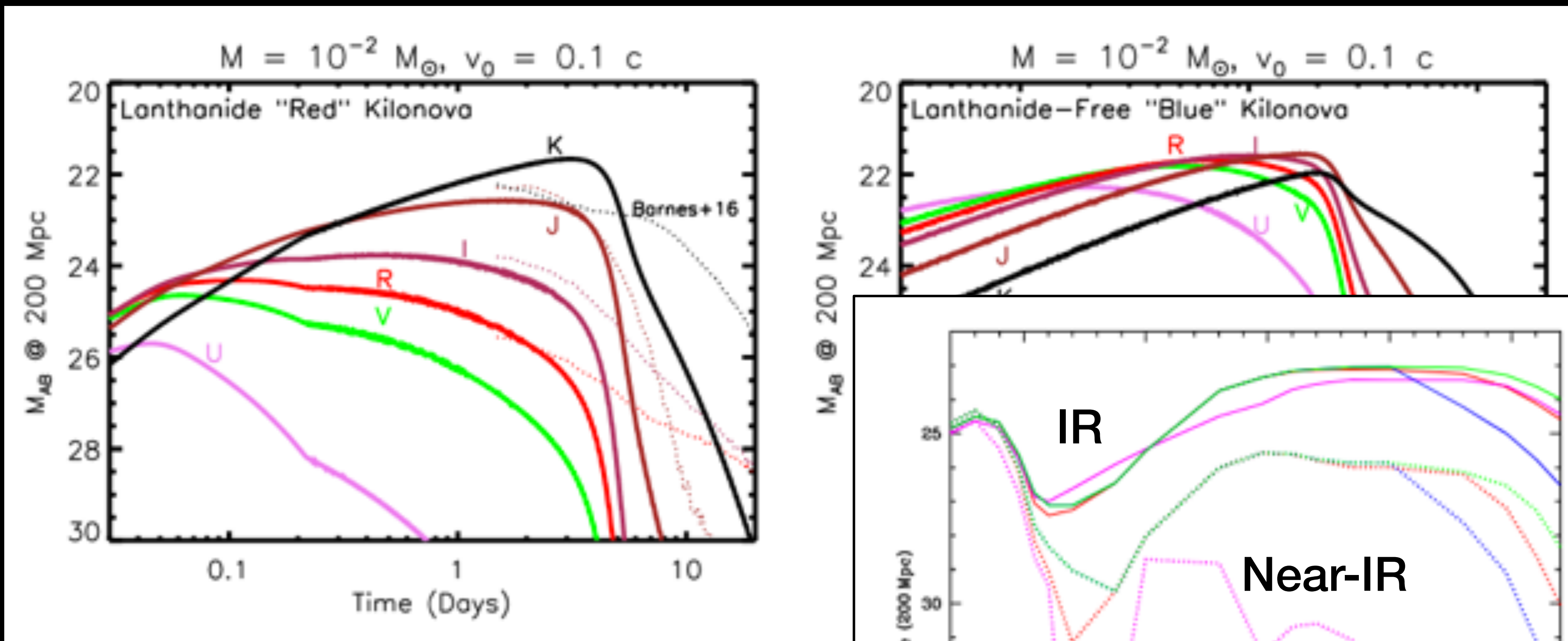
Result: r-process nucleosynthesis

Not so Basic Kilonova Predictions = Opacity Effects

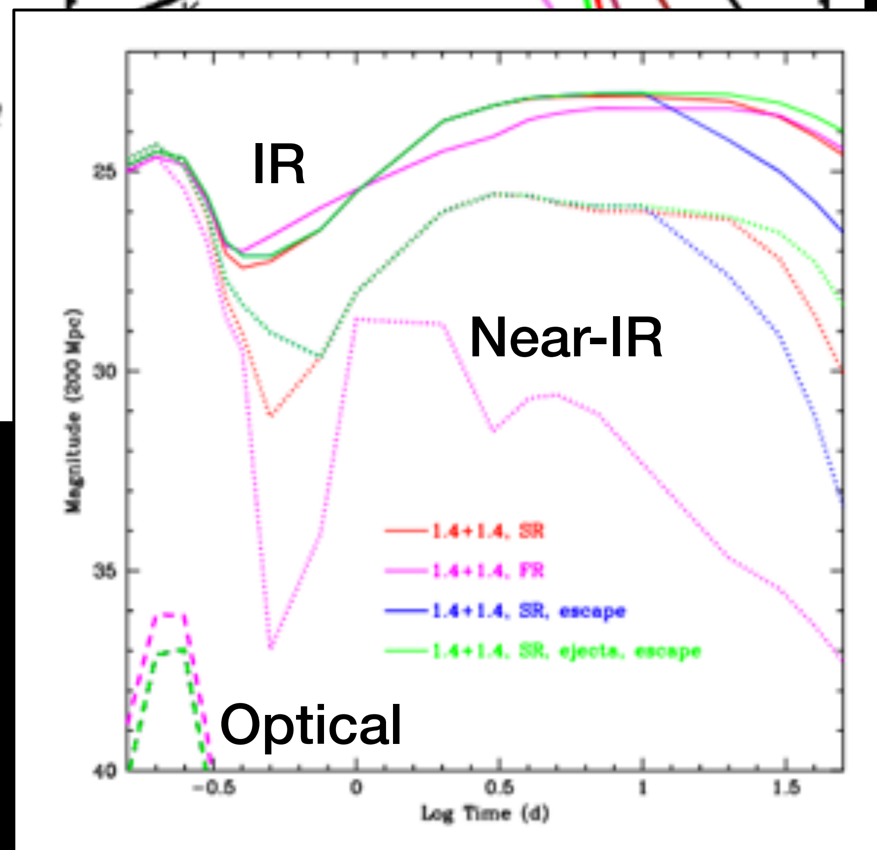


Metzger 2017

Not so Basic Kilonova Predictions = Opacity Effects

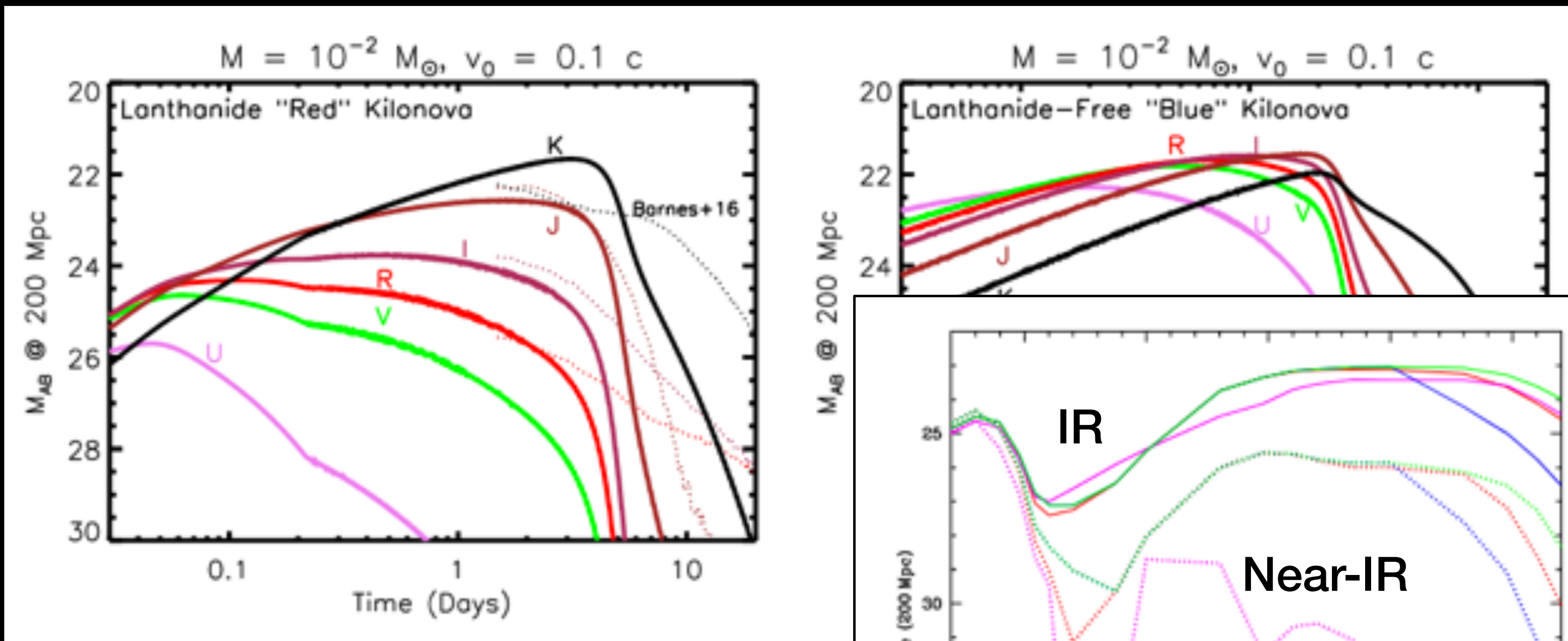


Metzger 2017



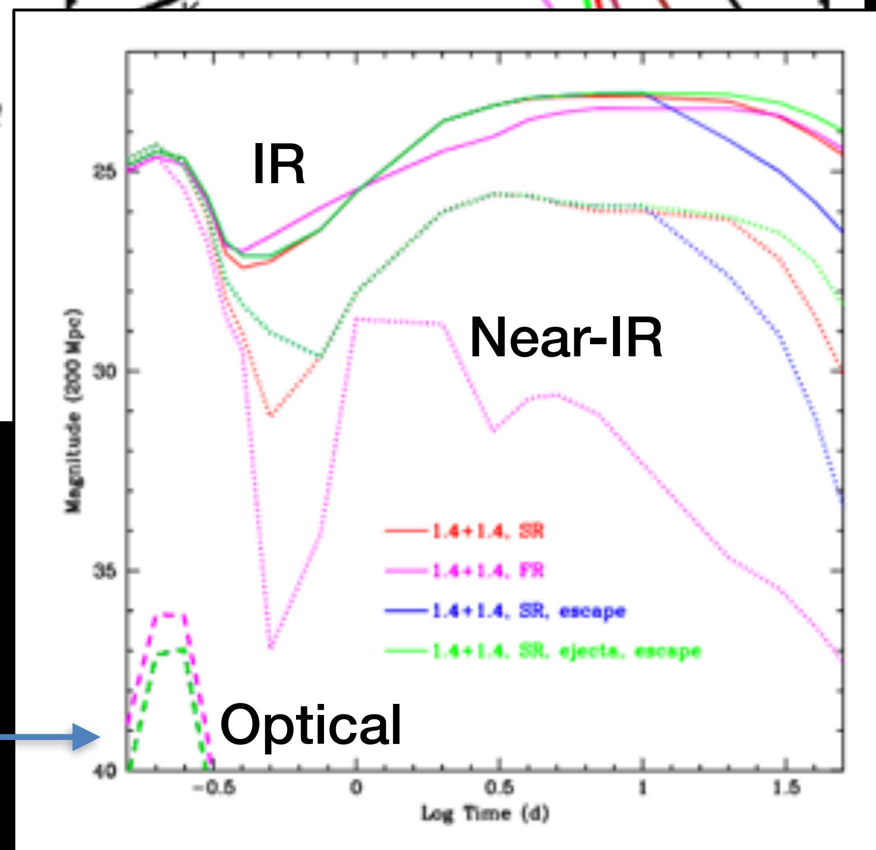
Fontes+ 2017

Not so Basic Kilonova Predictions = Opacity Effects



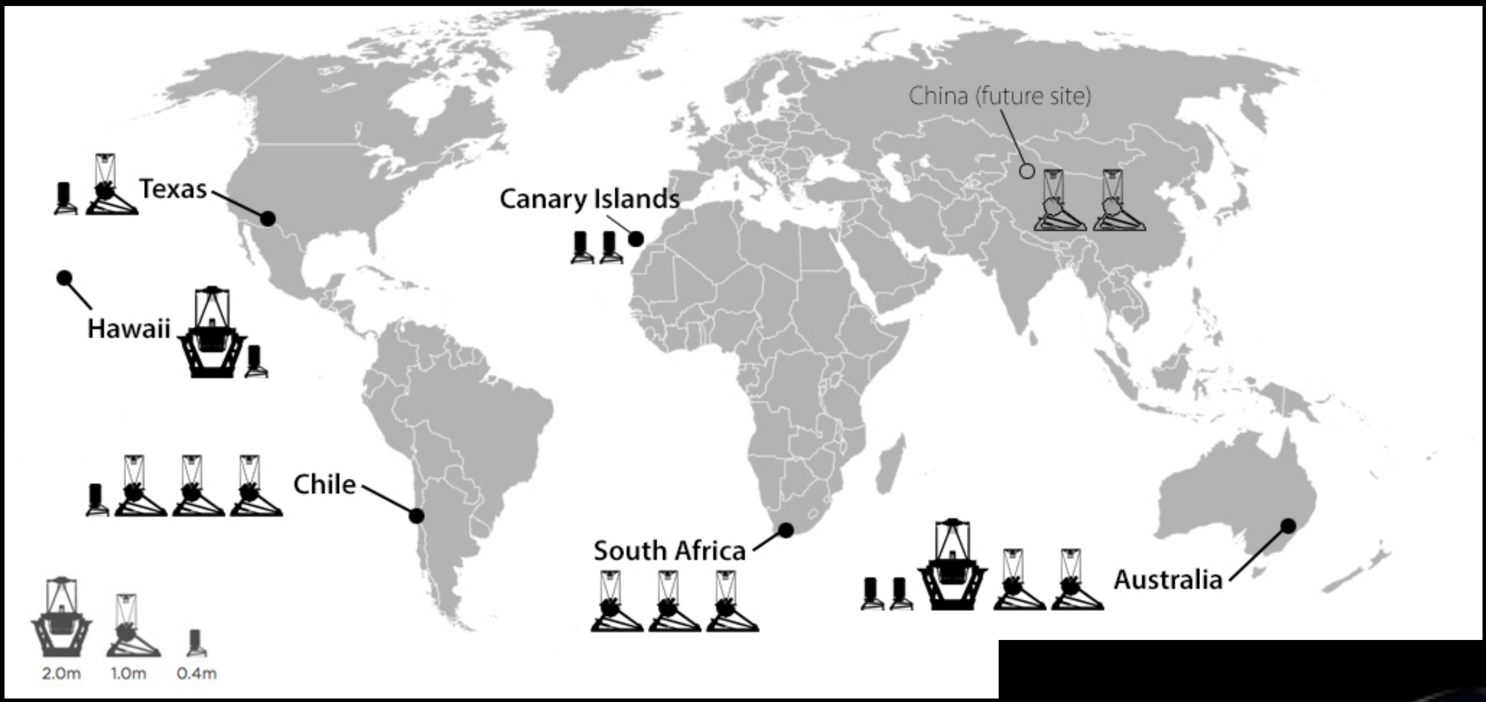
Metzger 2017

Factor of ~10,000 in flux!

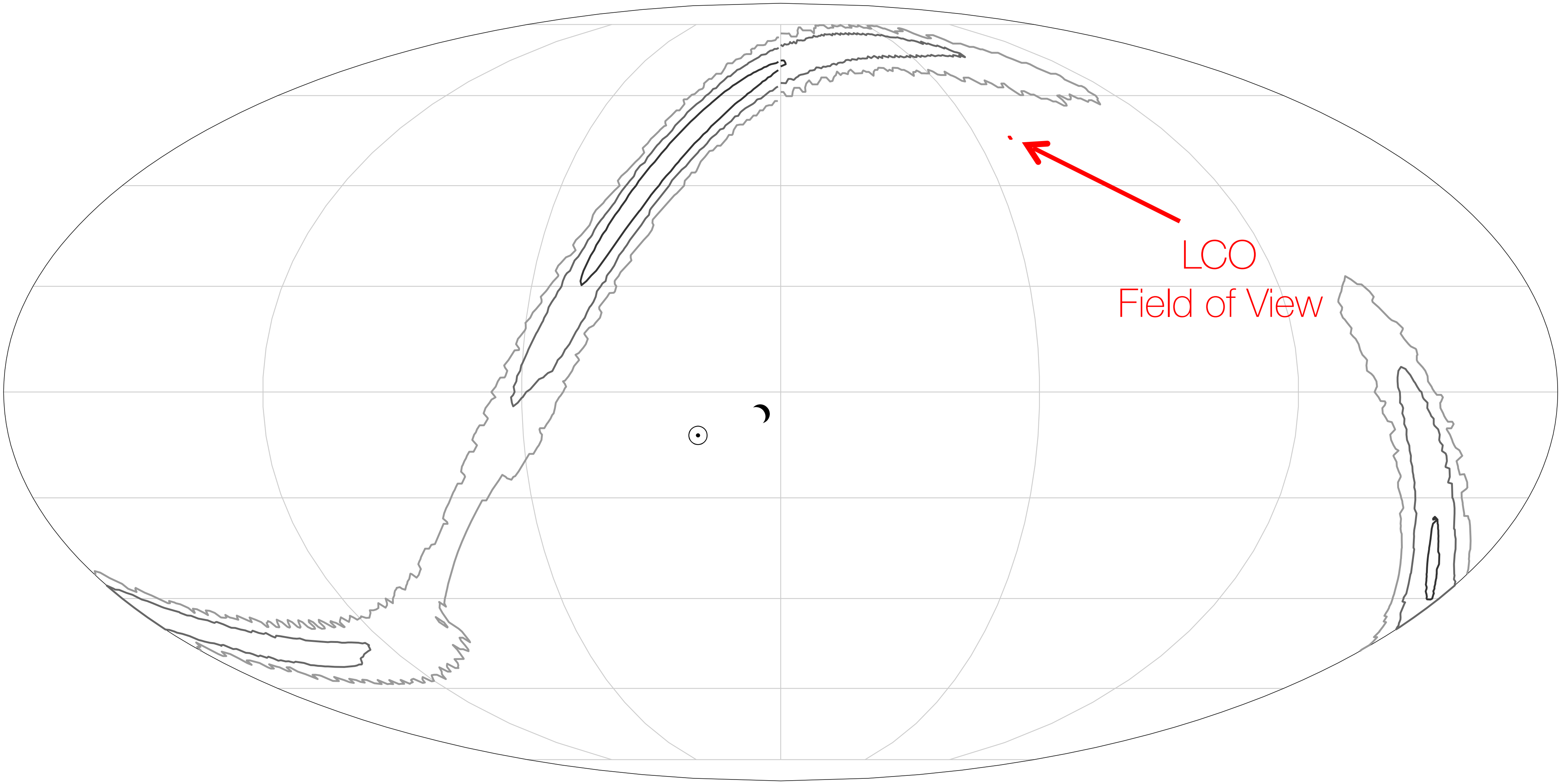


Fontes+ 2017

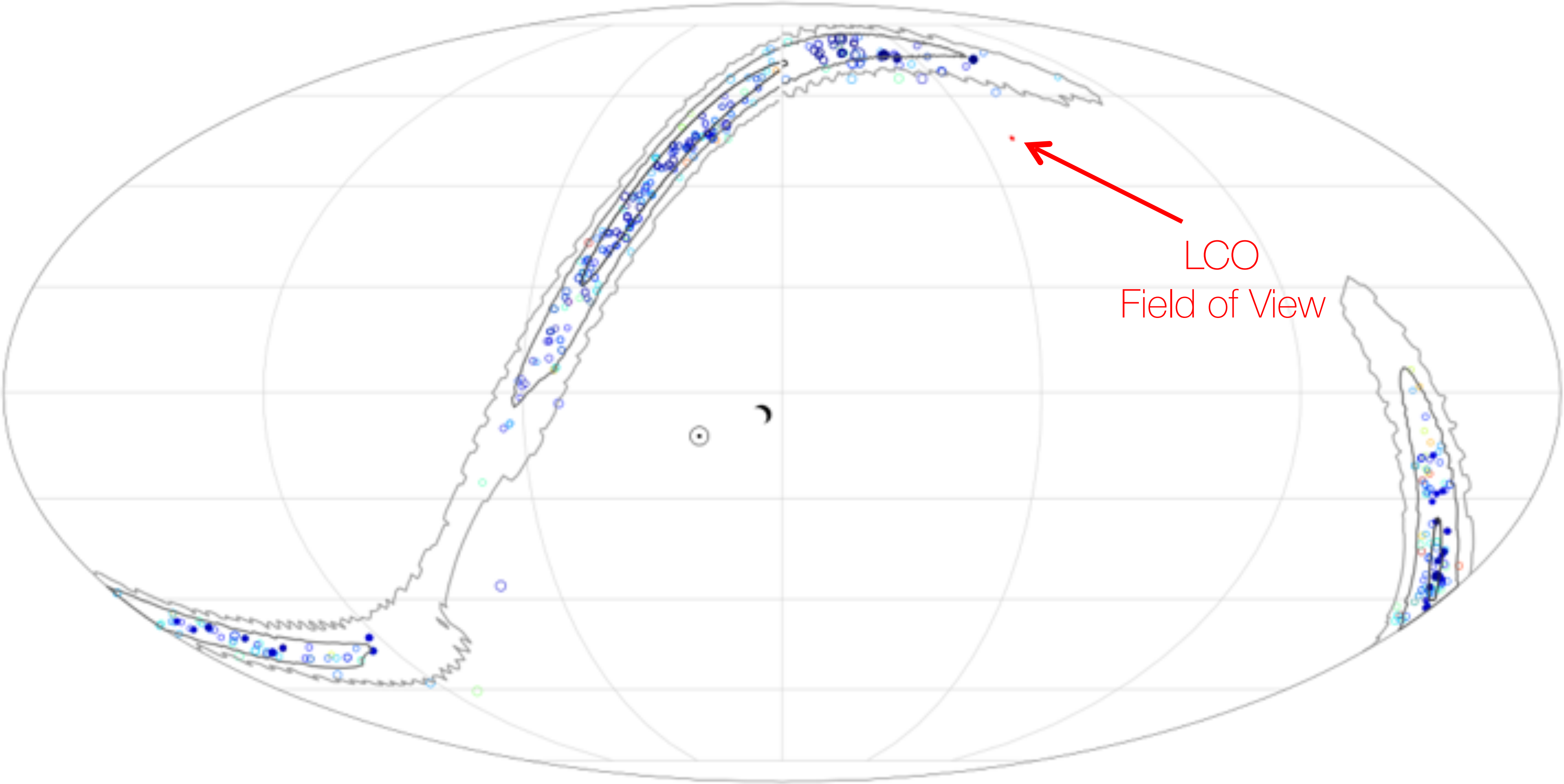
LCO: Las Cumbres Observatory



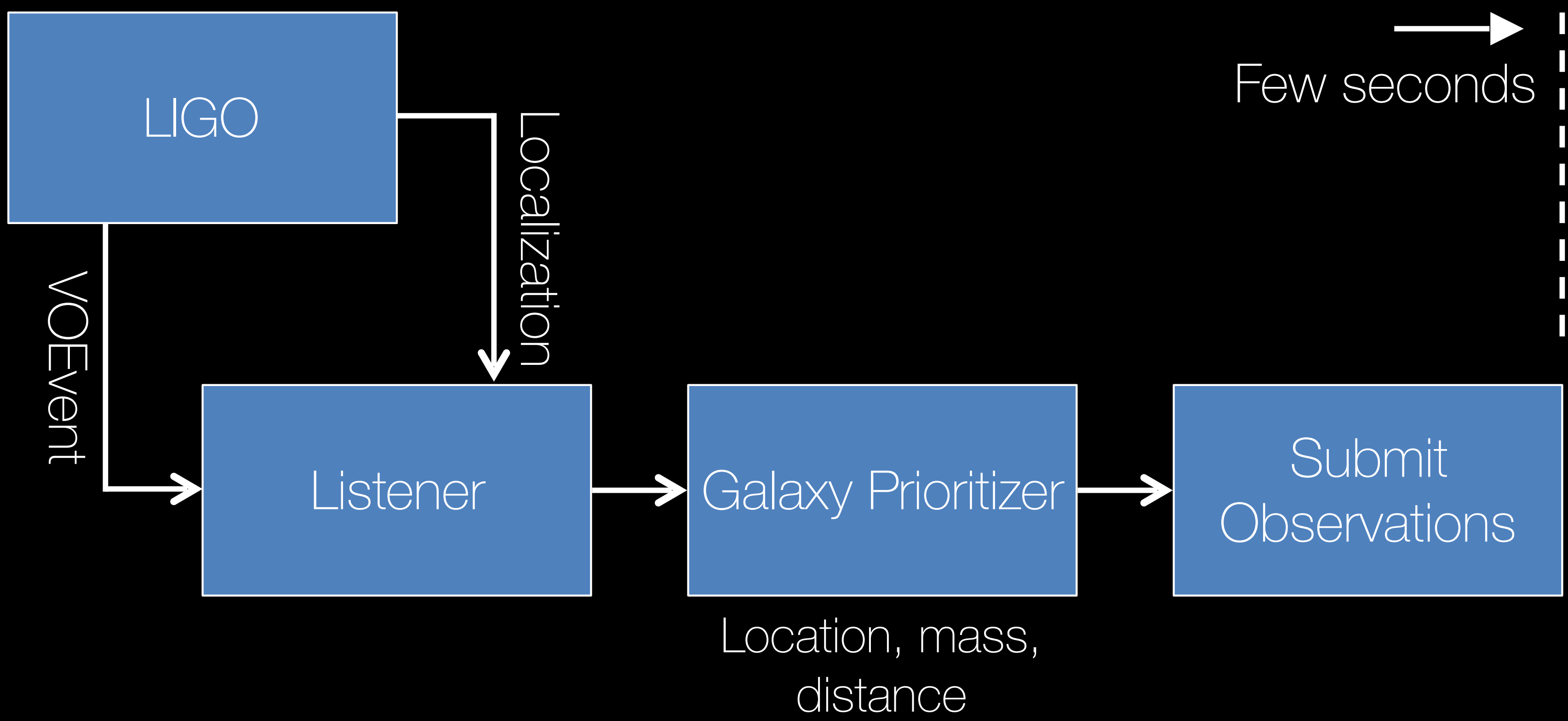
LIGO Localizations ~ 100's-1000's sq. deg.



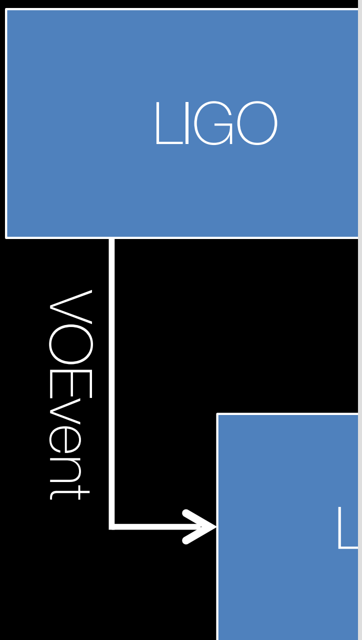
Target Galaxies Instead of Tiling the Full Region

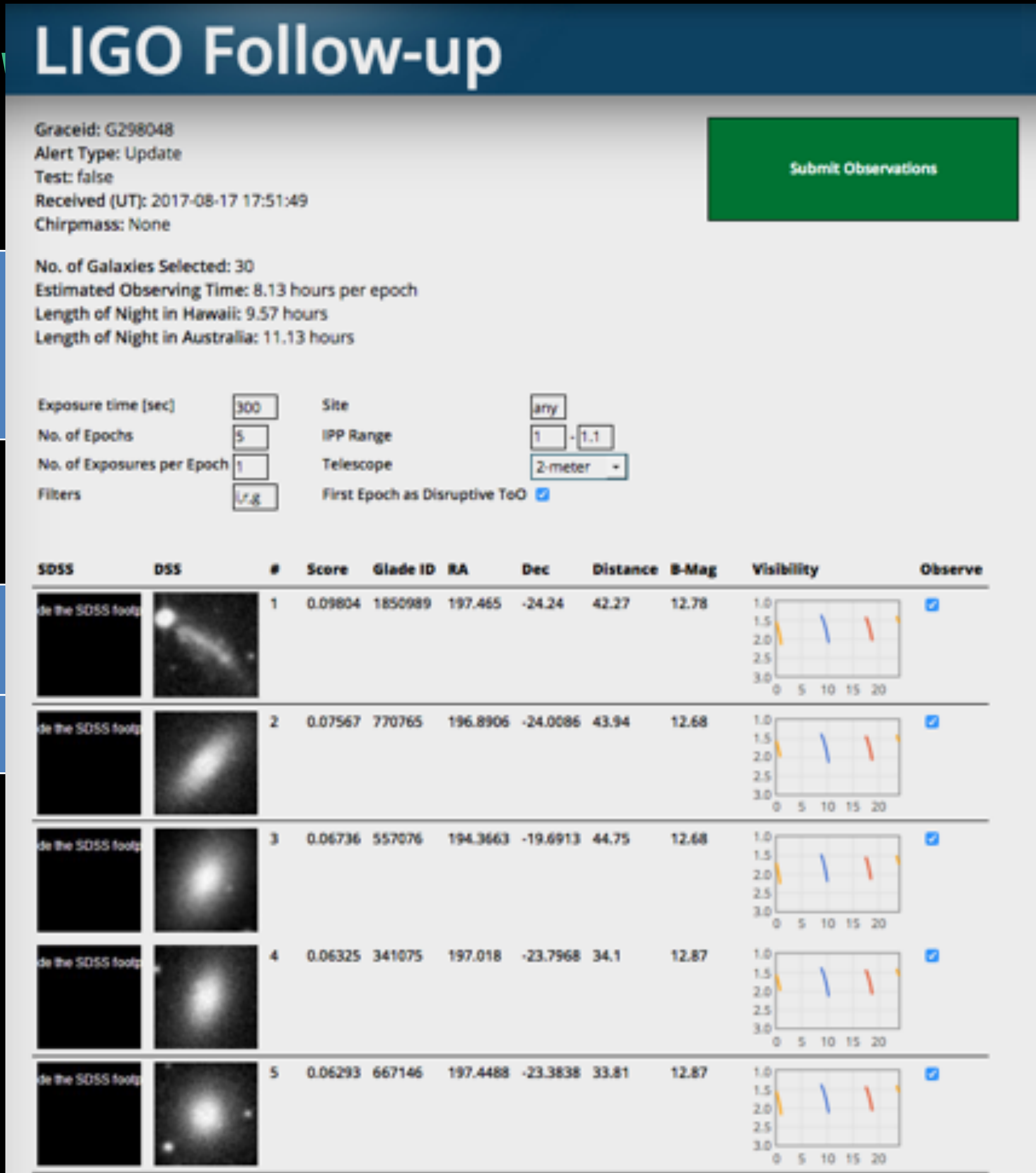


The LCO GW Follow-up Strategy



The LCO G





LIGO Follow-up

Graceid: G298048
Alert Type: Update
Test: false
Received (UT): 2017-08-17 17:51:49
Chirpmass: None

Submit Observations

No. of Galaxies Selected: 30
Estimated Observing Time: 8.13 hours per epoch
Length of Night in Hawaii: 9.57 hours
Length of Night in Australia: 11.13 hours

Exposure time [sec]	300	Site	any
No. of Epochs	5	IPP Range	1 - 1.1
No. of Exposures per Epoch	1	Telescope	2-meter
Filters	r,g	First Epoch as Disruptive ToO	

SDSS	DSS	#	Score	Glade ID	RA	Dec	Distance	B-Mag	Visibility	Observe
de the SDSS footp		1	0.09804	1850989	197.465	-24.24	42.27	12.78		
de the SDSS footp		2	0.07567	770765	196.8906	-24.0086	43.94	12.68		
de the SDSS footp		3	0.06736	557076	194.3663	-19.6913	44.75	12.68		
de the SDSS footp		4	0.06325	341075	197.018	-23.7968	34.1	12.87		
de the SDSS footp		5	0.06293	667146	197.4488	-23.3838	33.81	12.87		

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Sergiy Vasylyev
UCSB

Stefano Valenti
UC Davis

Leo Singer
U Maryland

Dovi Poznanski
Tel Aviv U

Michael Zaltzman
Tel Aviv U

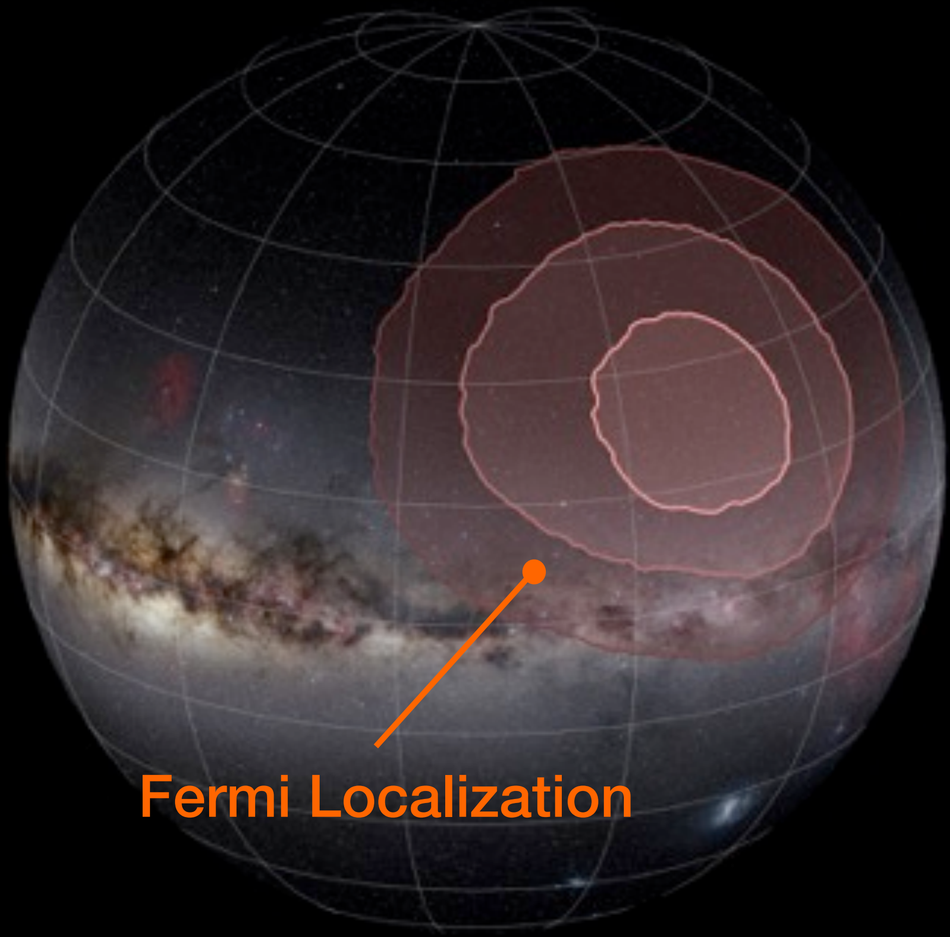
Wen-Fai Fong
U of A

Tsvi Piran
Hebrew U

Dan Kasen
UC Berkeley

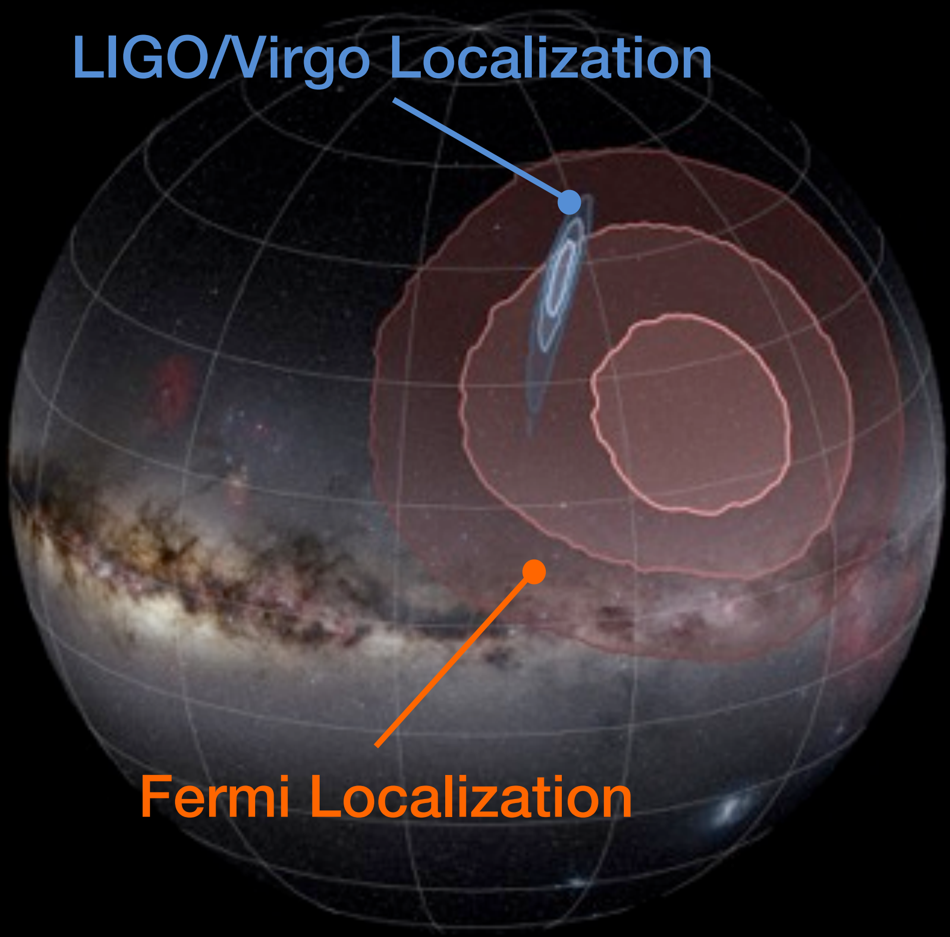
Jennifer Barnes
UC Berkeley

Finding the Kilonova on Aug 17, 2017



Arcavi+ 2017a, Nature

Finding the Kilonova on Aug 17, 2017



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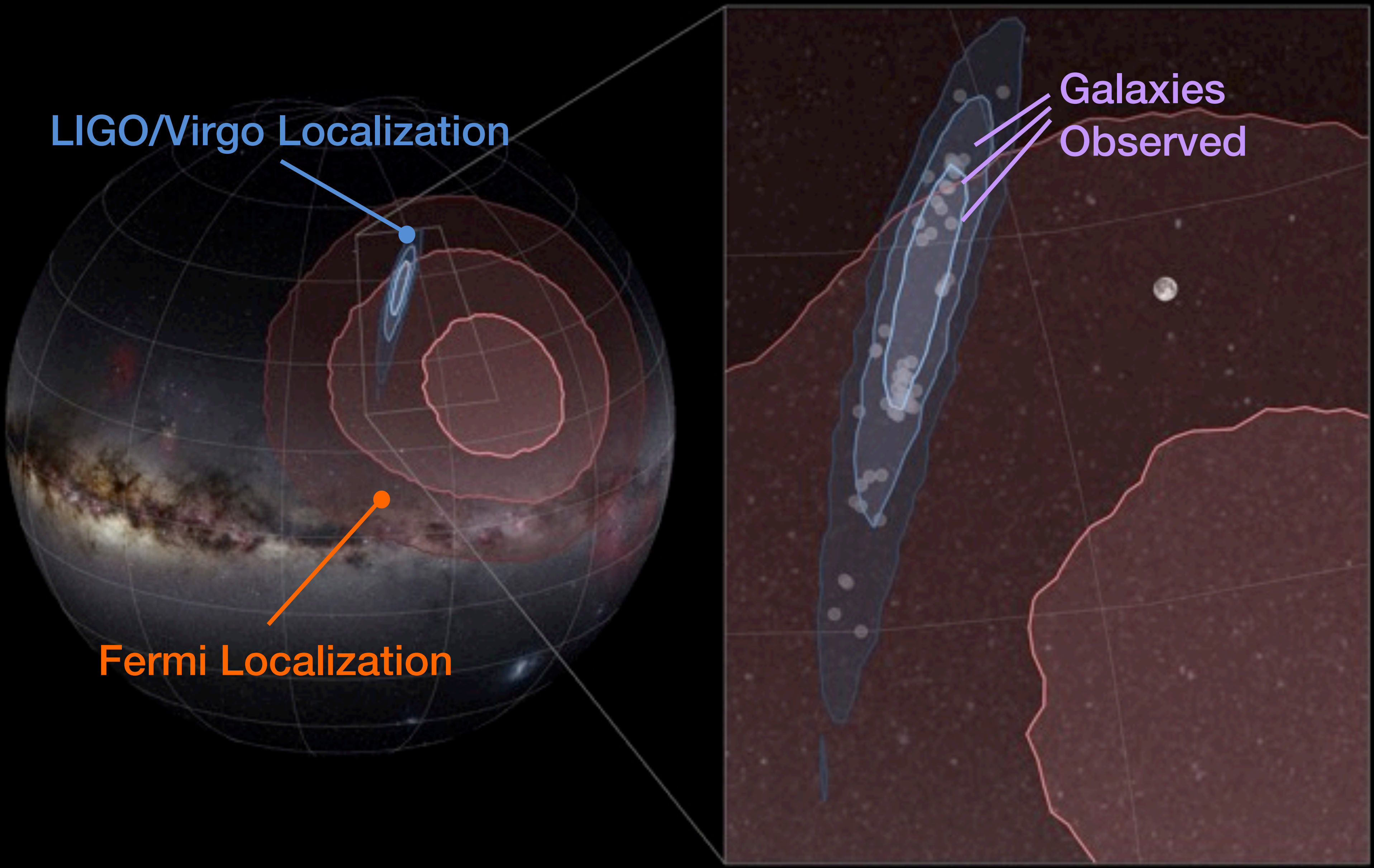

Arcavi+ 2017a, Nature

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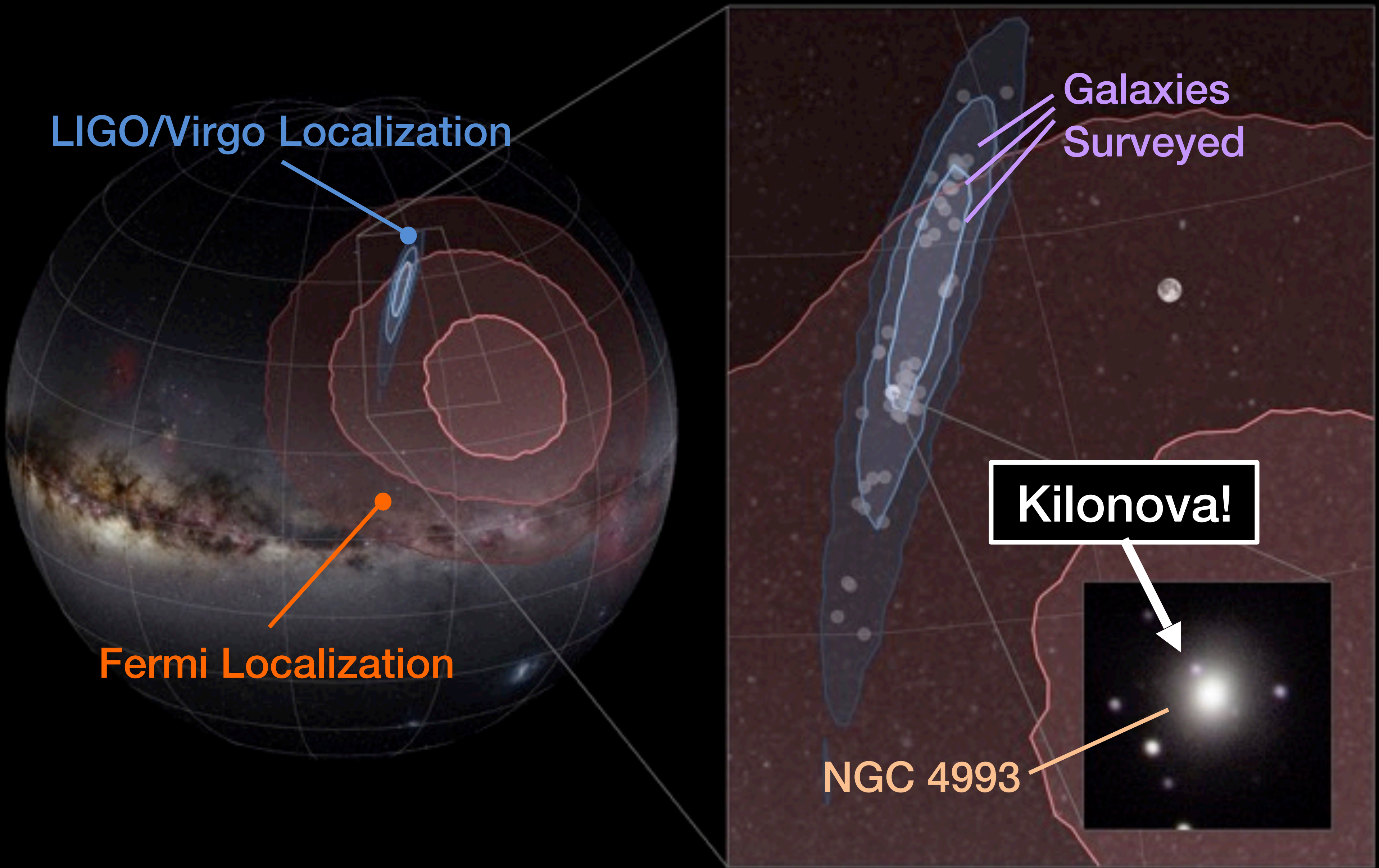
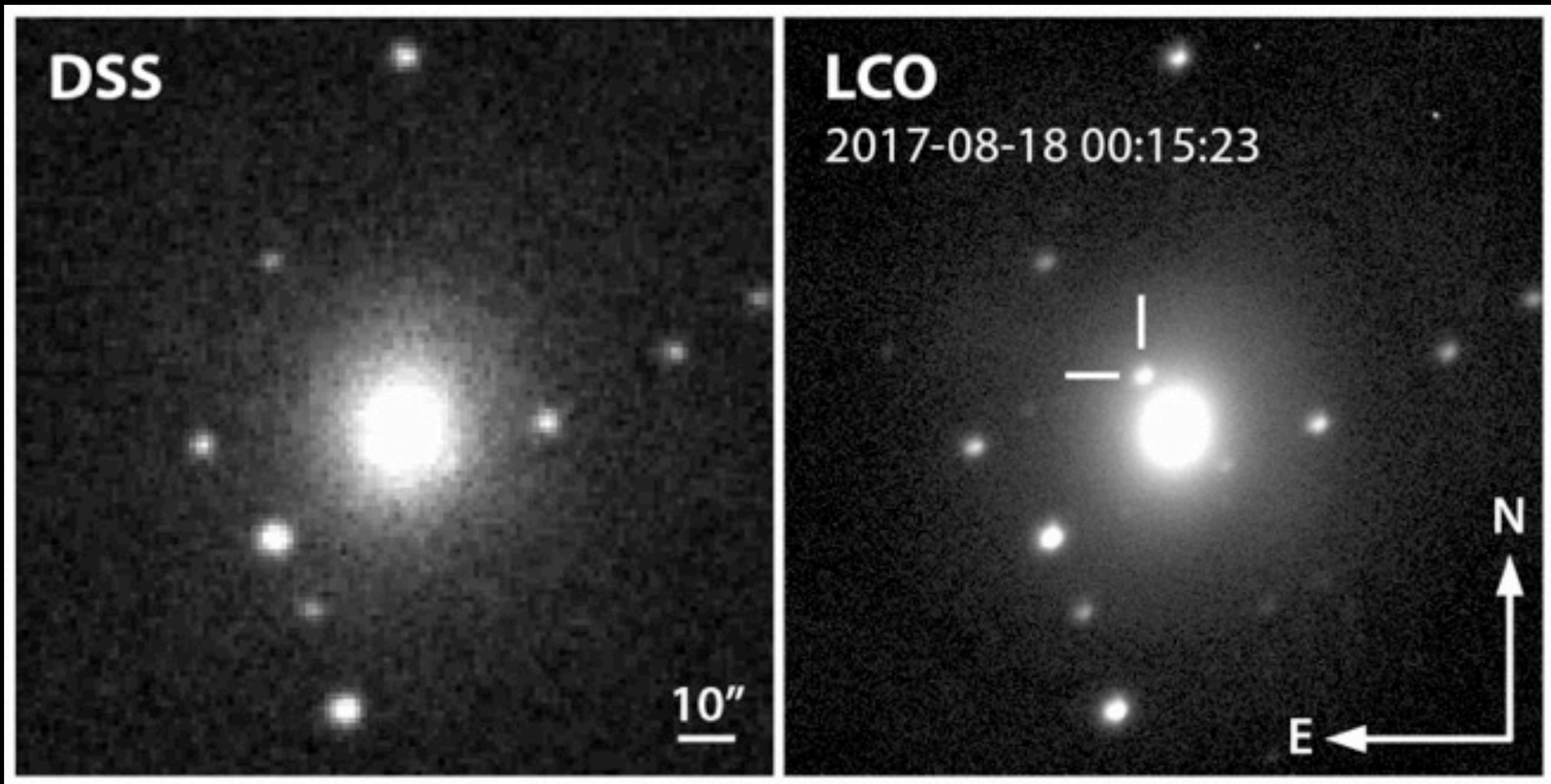


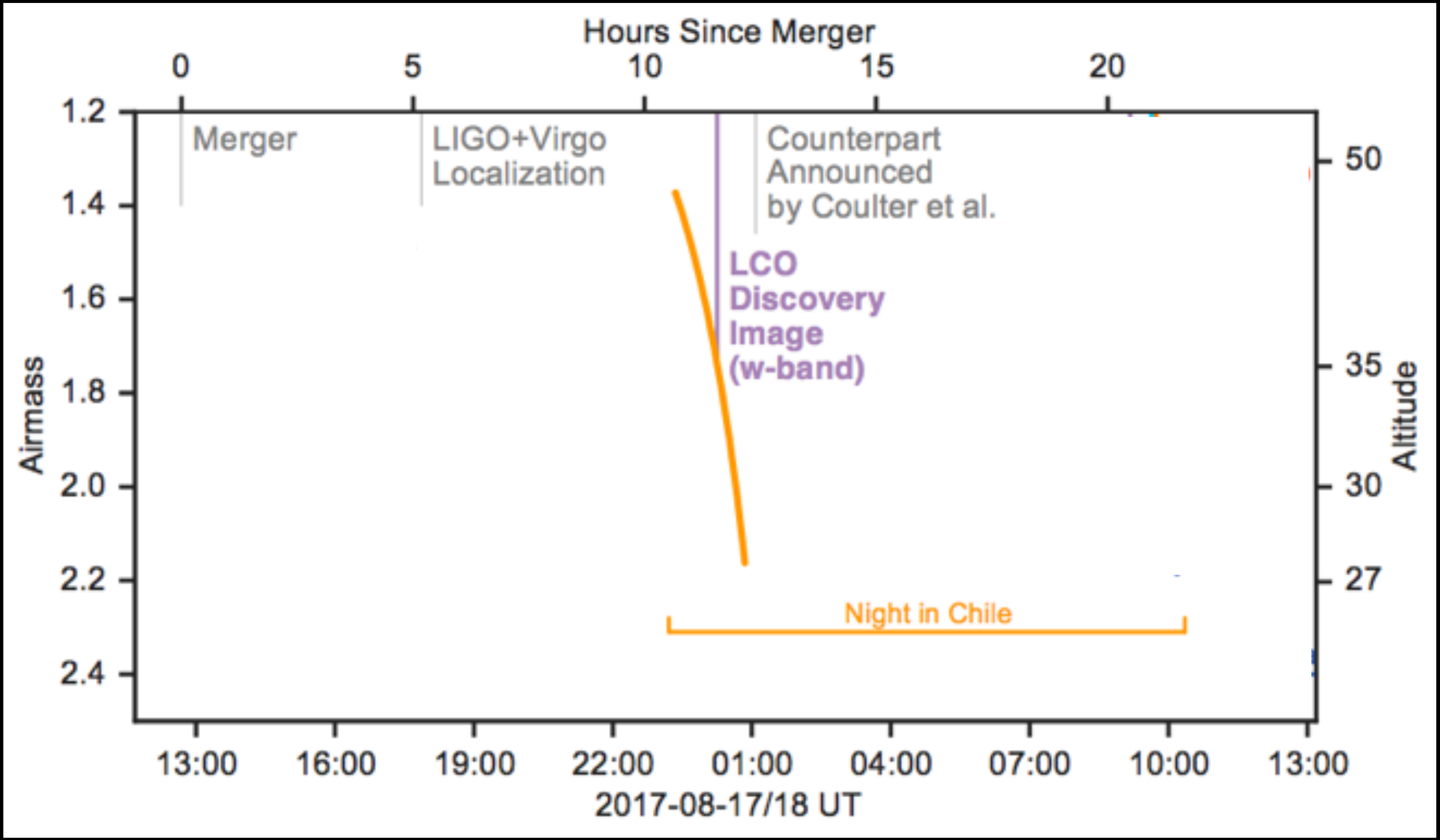
Arcavi+ 2017a, Nature

Las Cumbres Discovery Image of the Kilonova



Arcavi+ 2017a, Nature

Las Cumbres 3x Daily Visibility of the Kilonova



Arcavi+ 2017a, Nature

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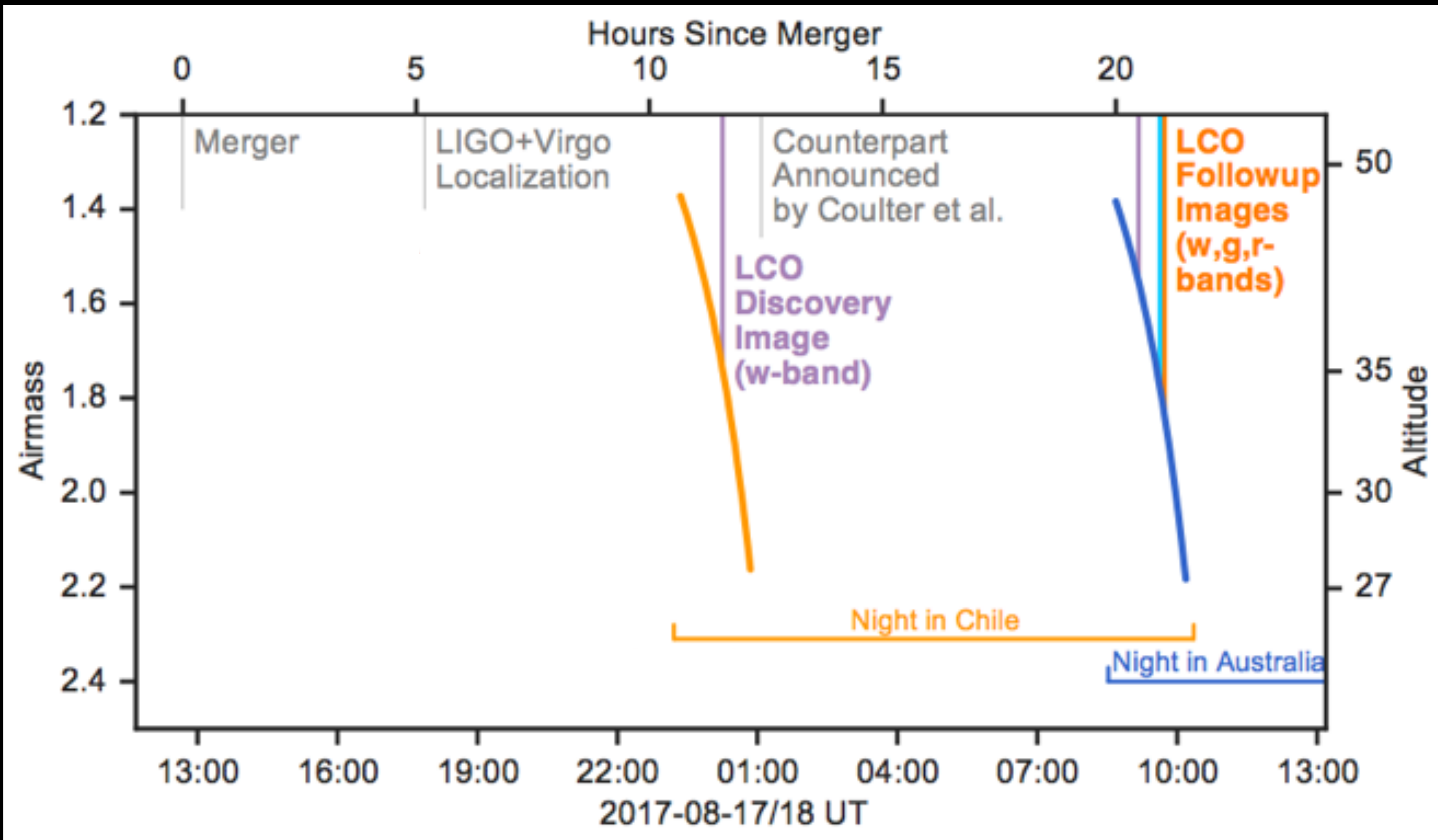

Arcavi+ 2017a, Nature

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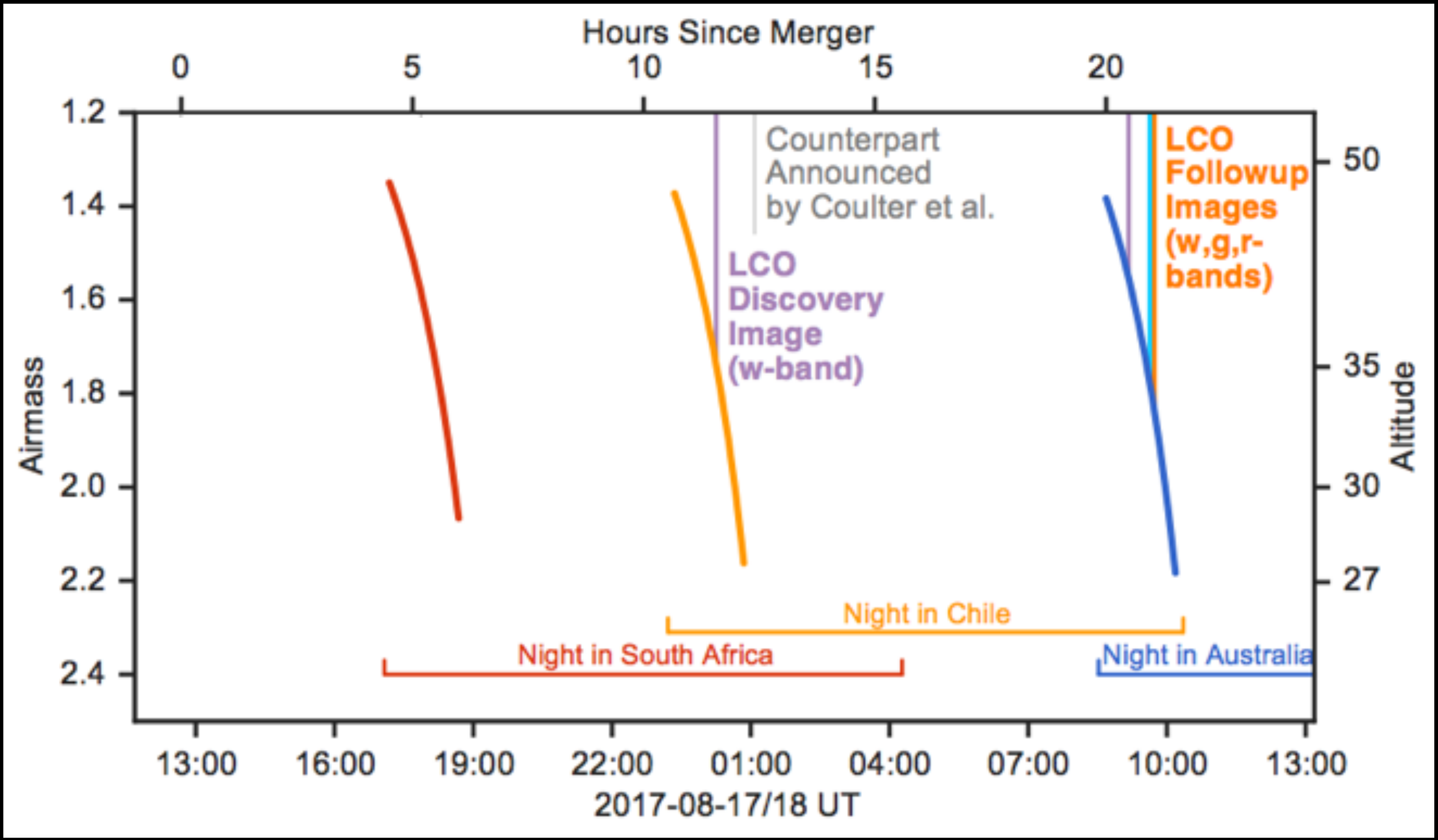
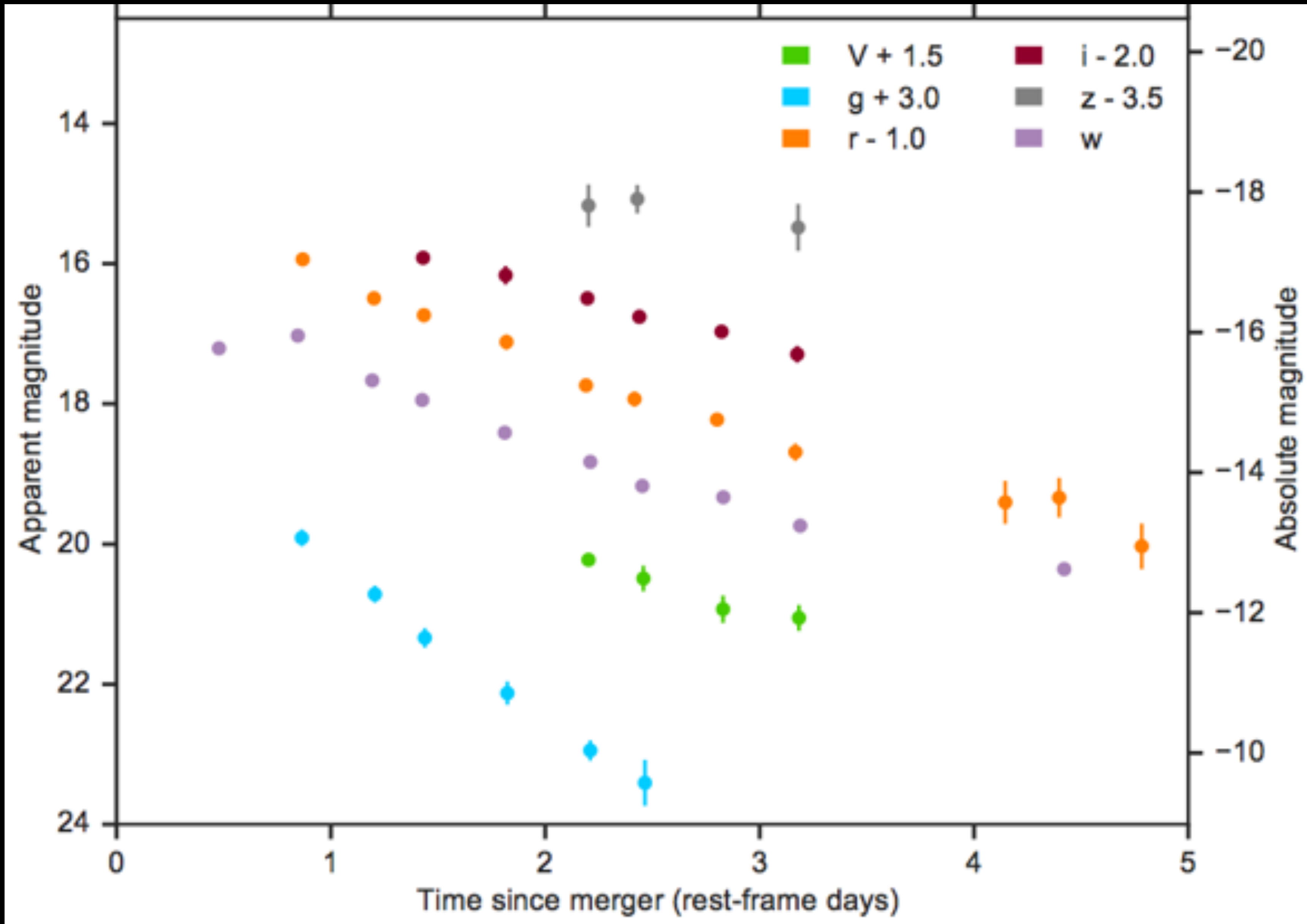


Arcavi+ 2017a, Nature

LCO High-Cadence Light Curve of the Kilonova



Arcavi+ 2017a, Nature

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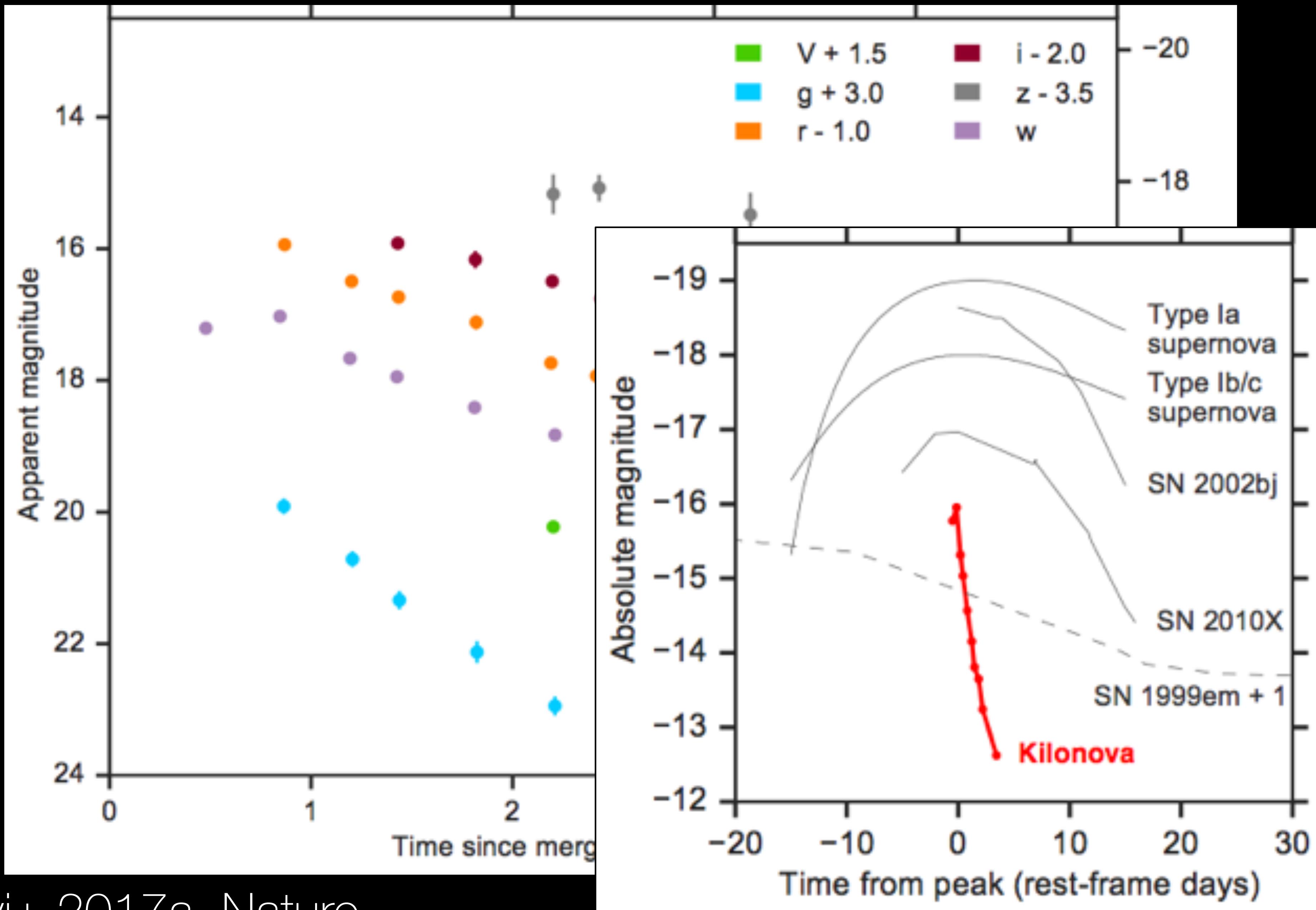

Arcavi+ 2017a, Nature

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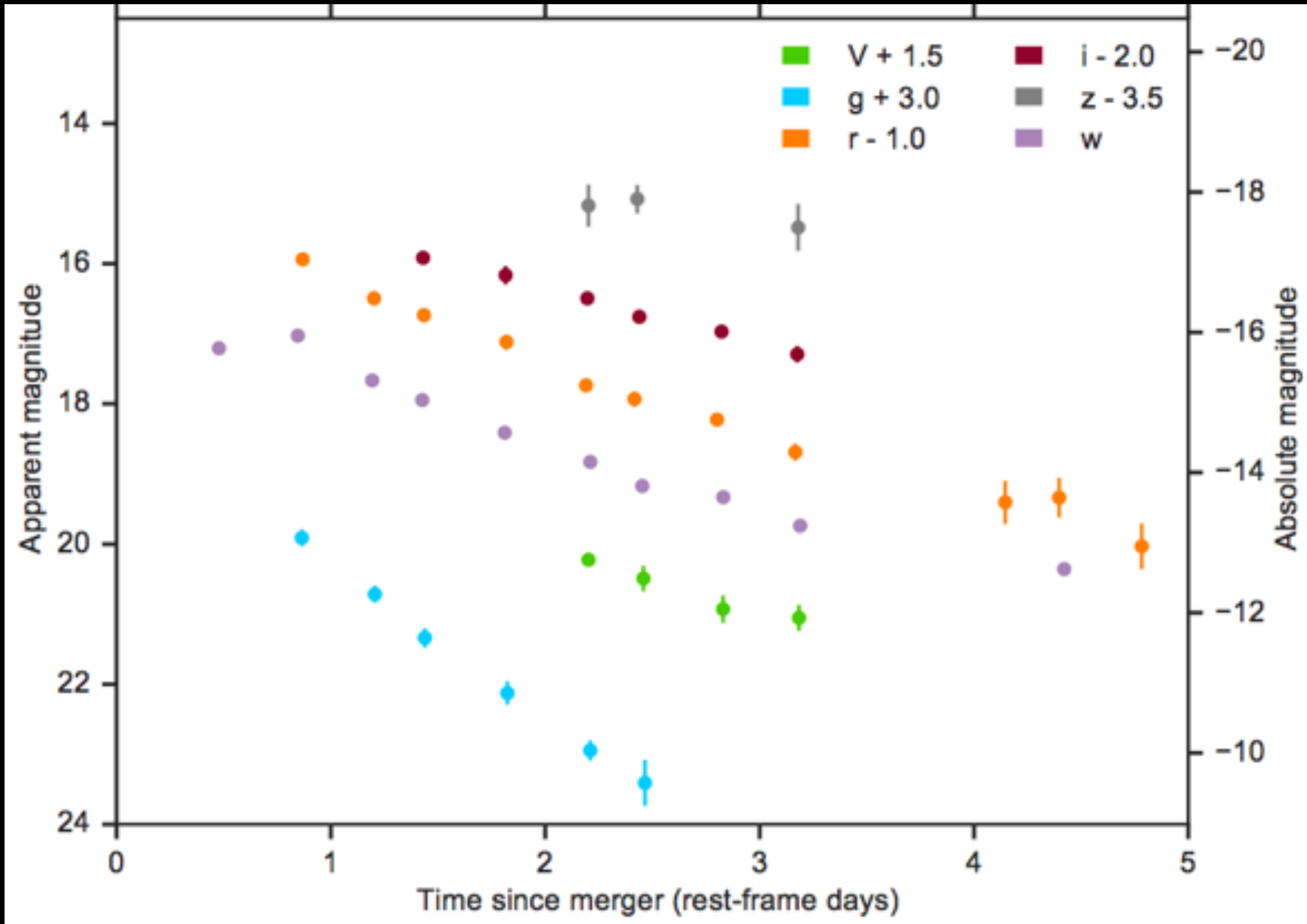
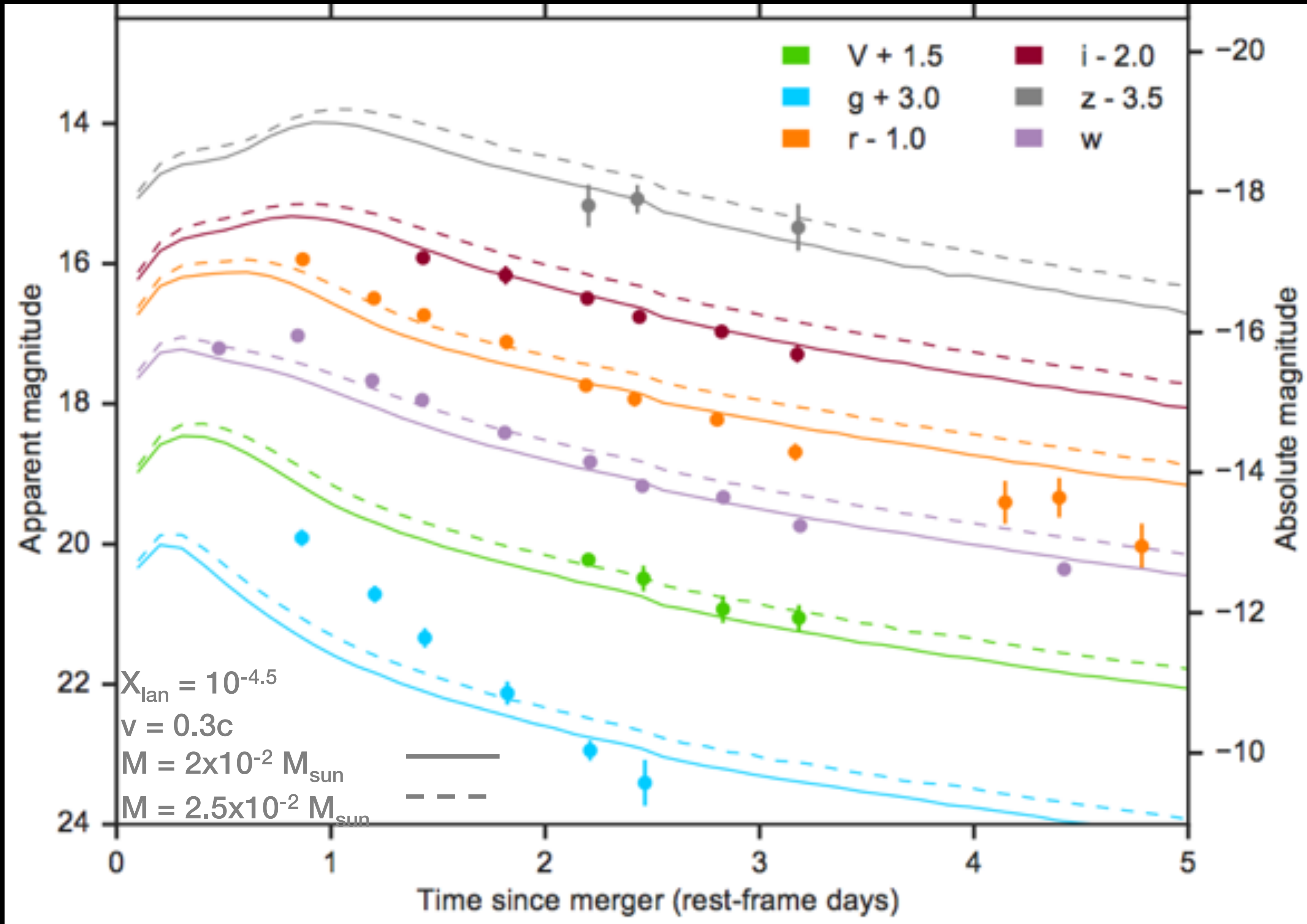


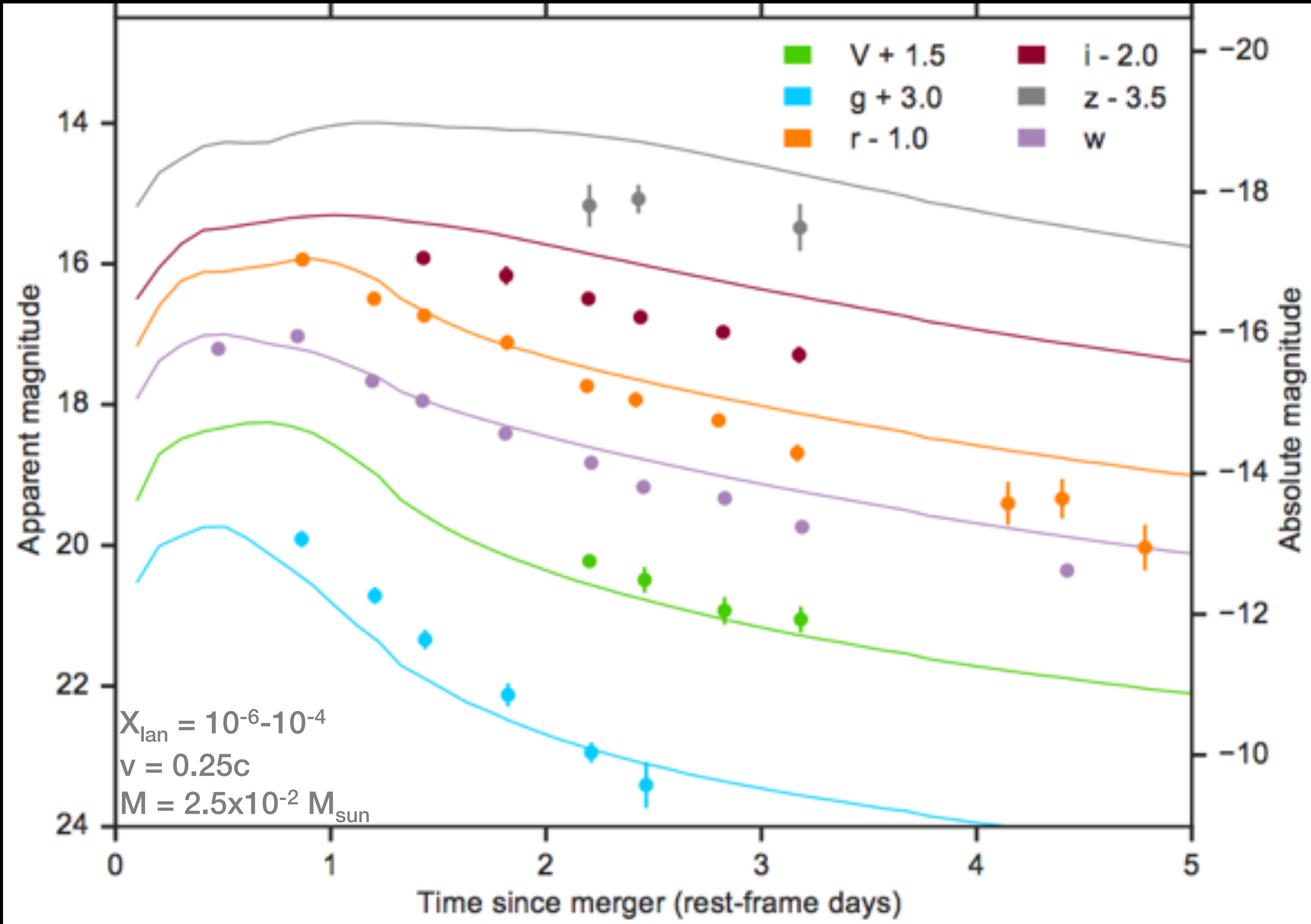
Arcavi+ 2017a, Nature

LCO Data Constrains Ejecta Mass / Composition



Arcavi+ 2017a, Nature (models from Kasen+ 2017, Nature)

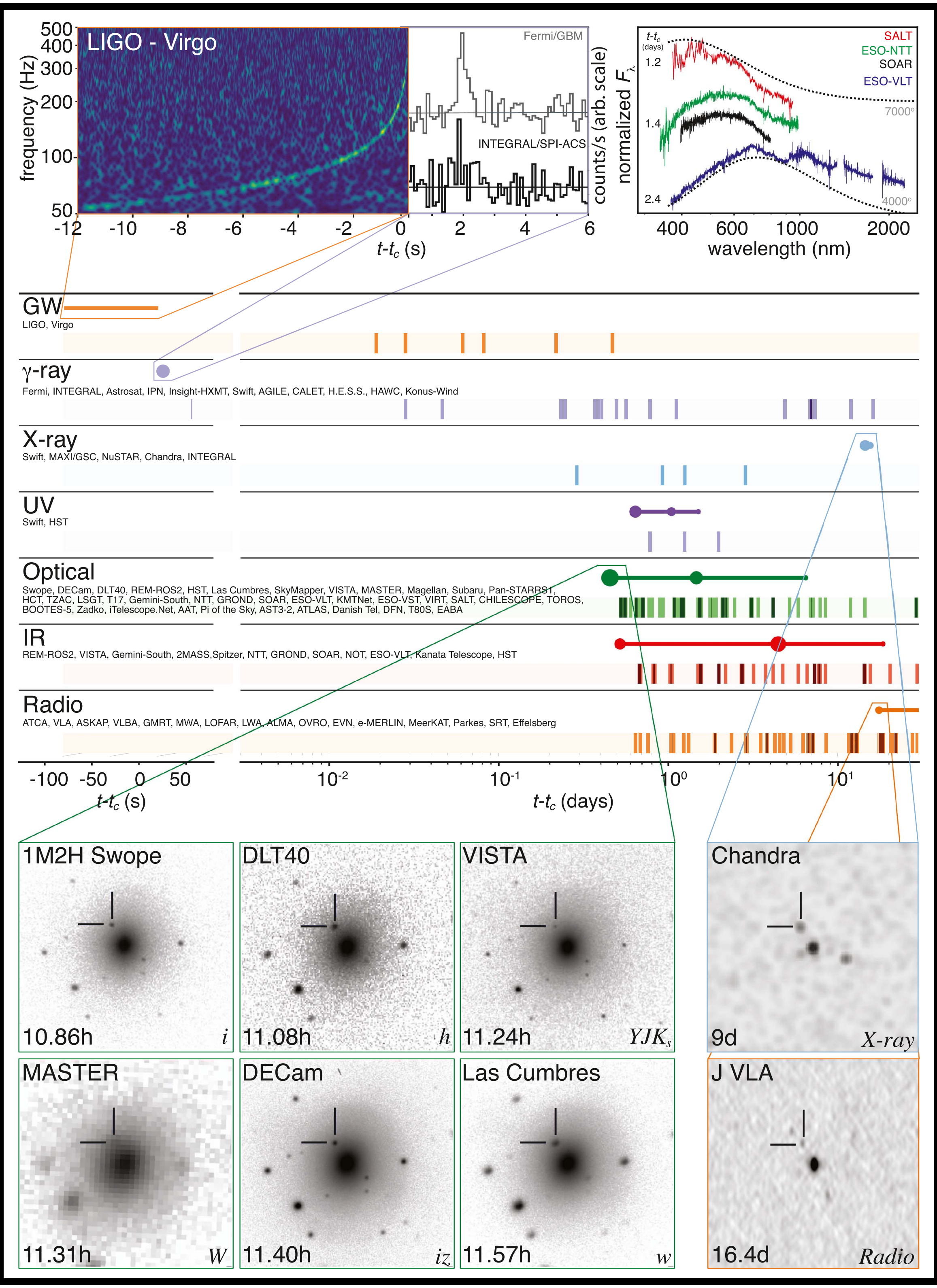
LCO Data Constrains Ejecta Structure!



(models from Kasen+ 2017, Nature)

Electromagnetic Followup of GW170817

This event was one of the most observed transients in history and was observed across the full electromagnetic spectrum from **γ**-rays to radio.

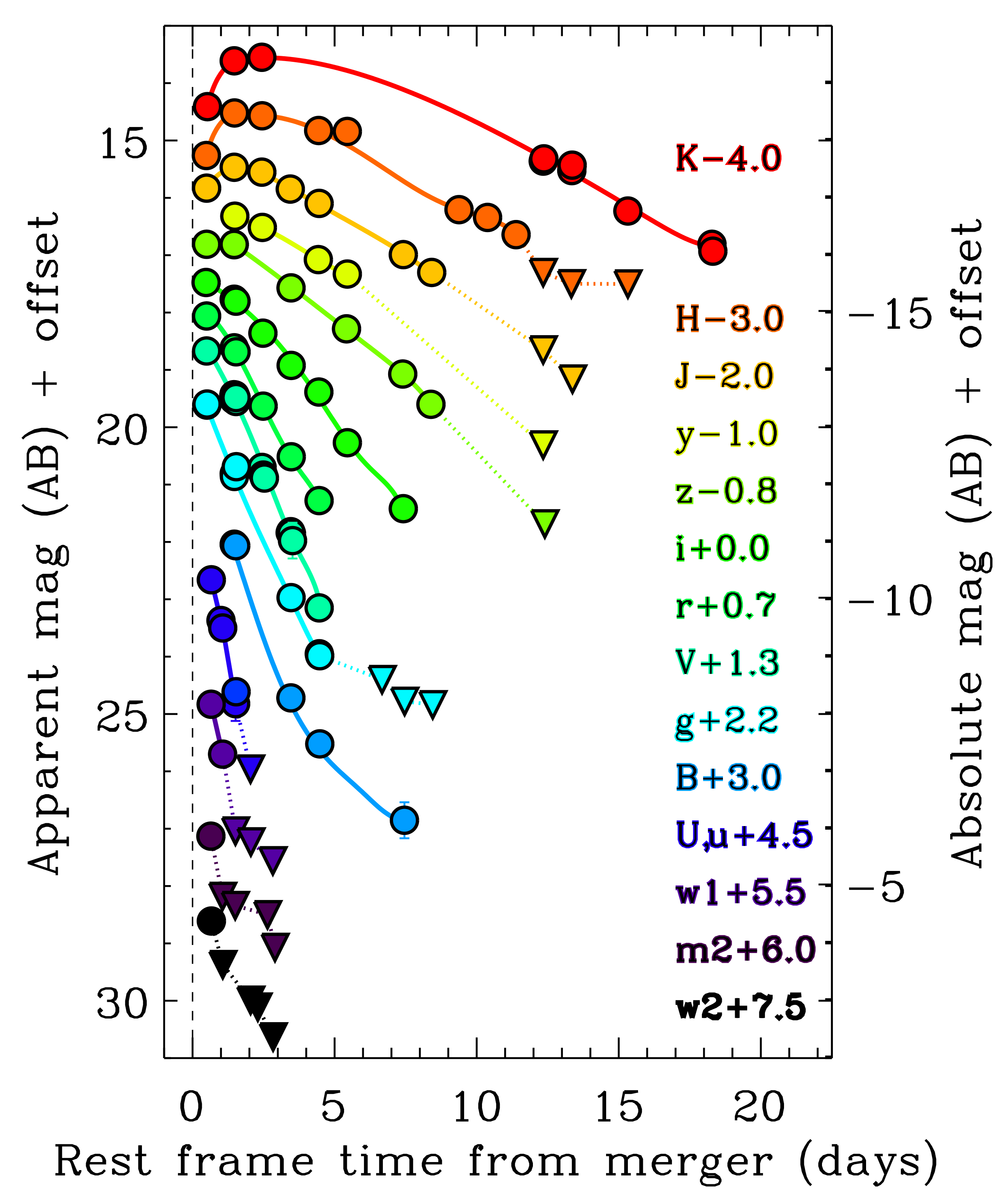


LIGO Virgo EM collaboration, ApjL, 2017

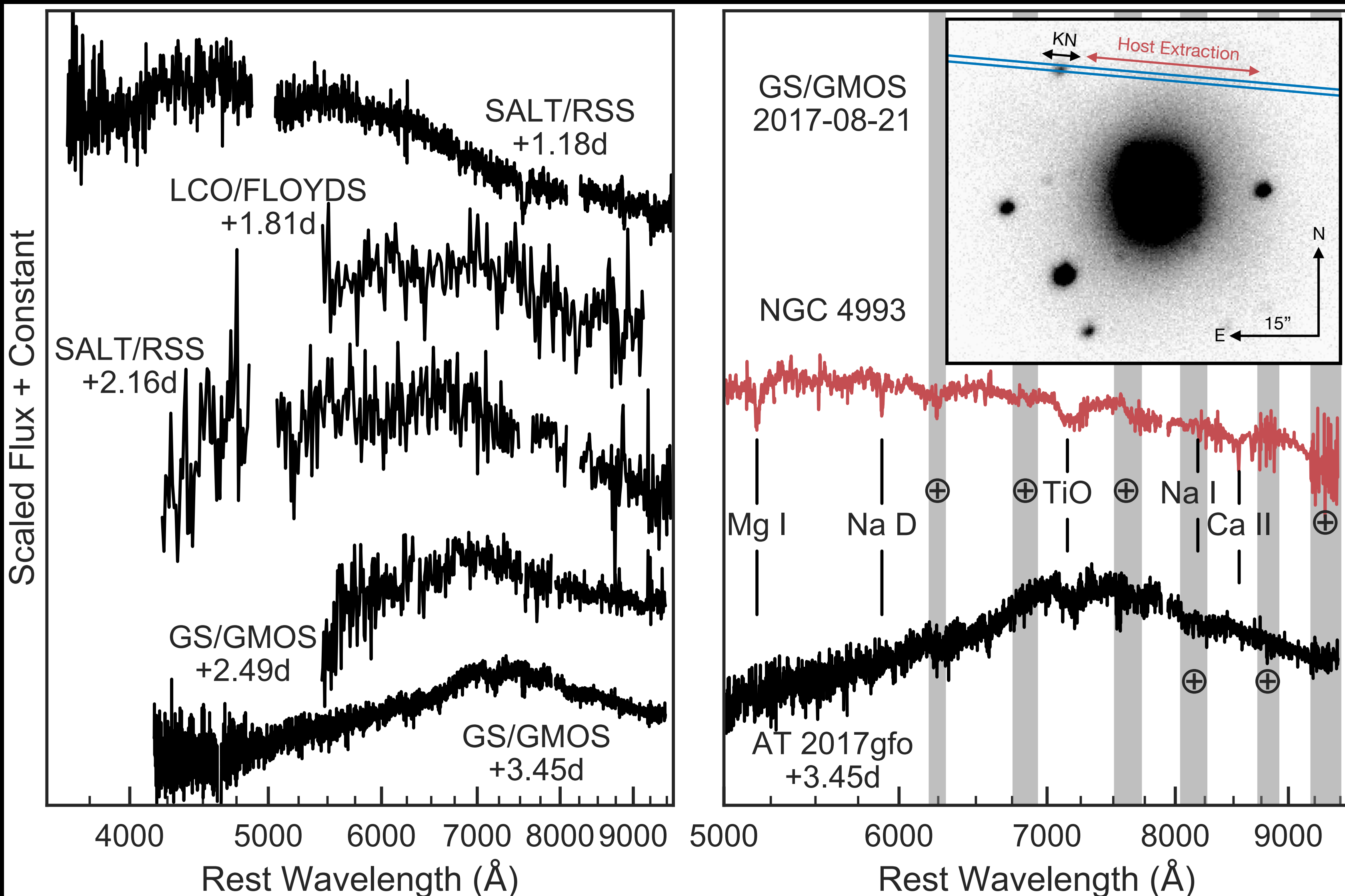
Observations of a kilonova from UV to IR

The optical/IR counterpart of GW170817 faded rapidly, factors of a hundred over two weeks in the red, and even more in the blue. The UV light became undetectable just a few days after the merger.

Drout+ 2017



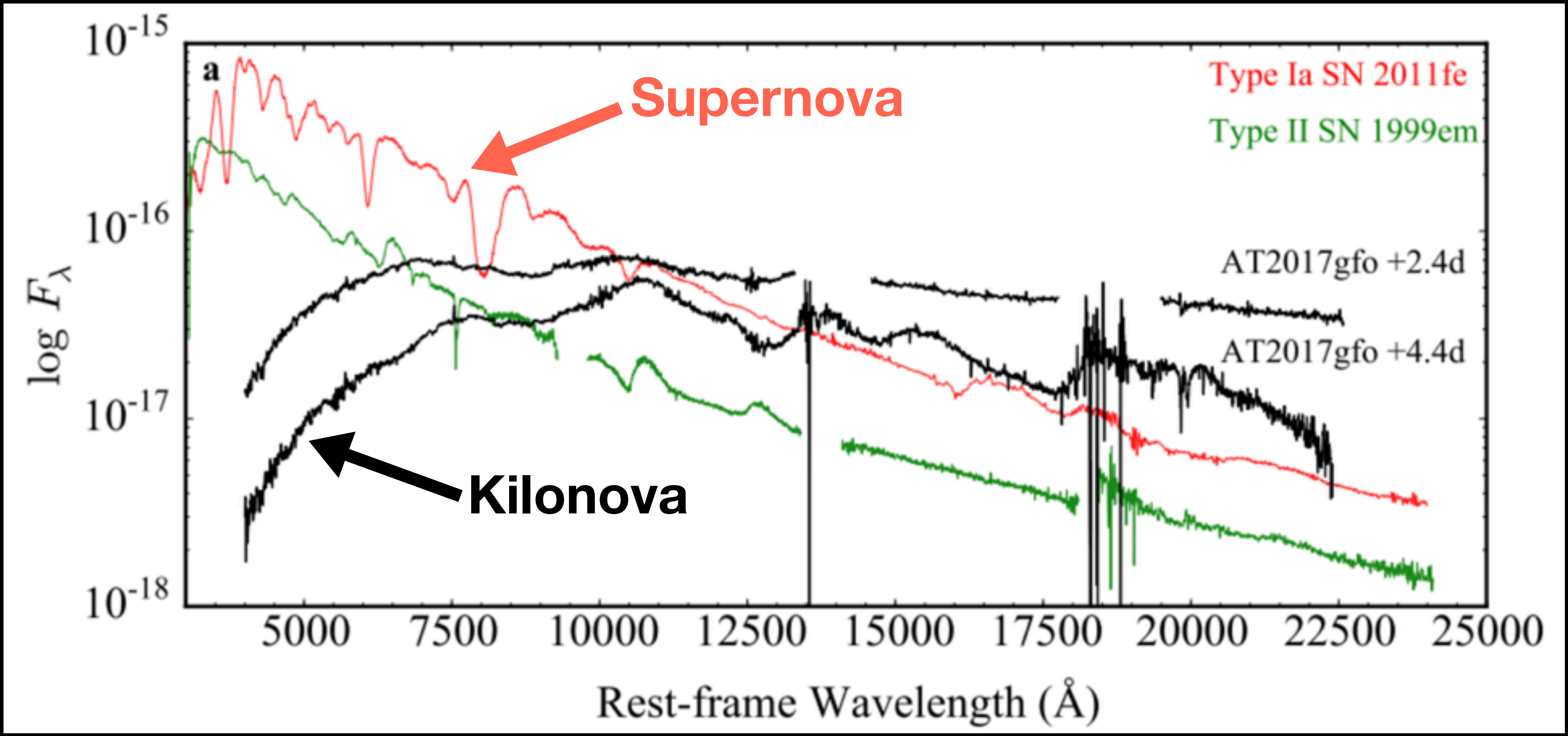
Our Spectra of the Kilonova



McCully+ 2017

Because this is a totally new type of transient, it is difficult to distinguish which features are intrinsic to the kilonova. Many of the features we see are due to the host galaxy.

Spectra of the kilonova compared to supernovae



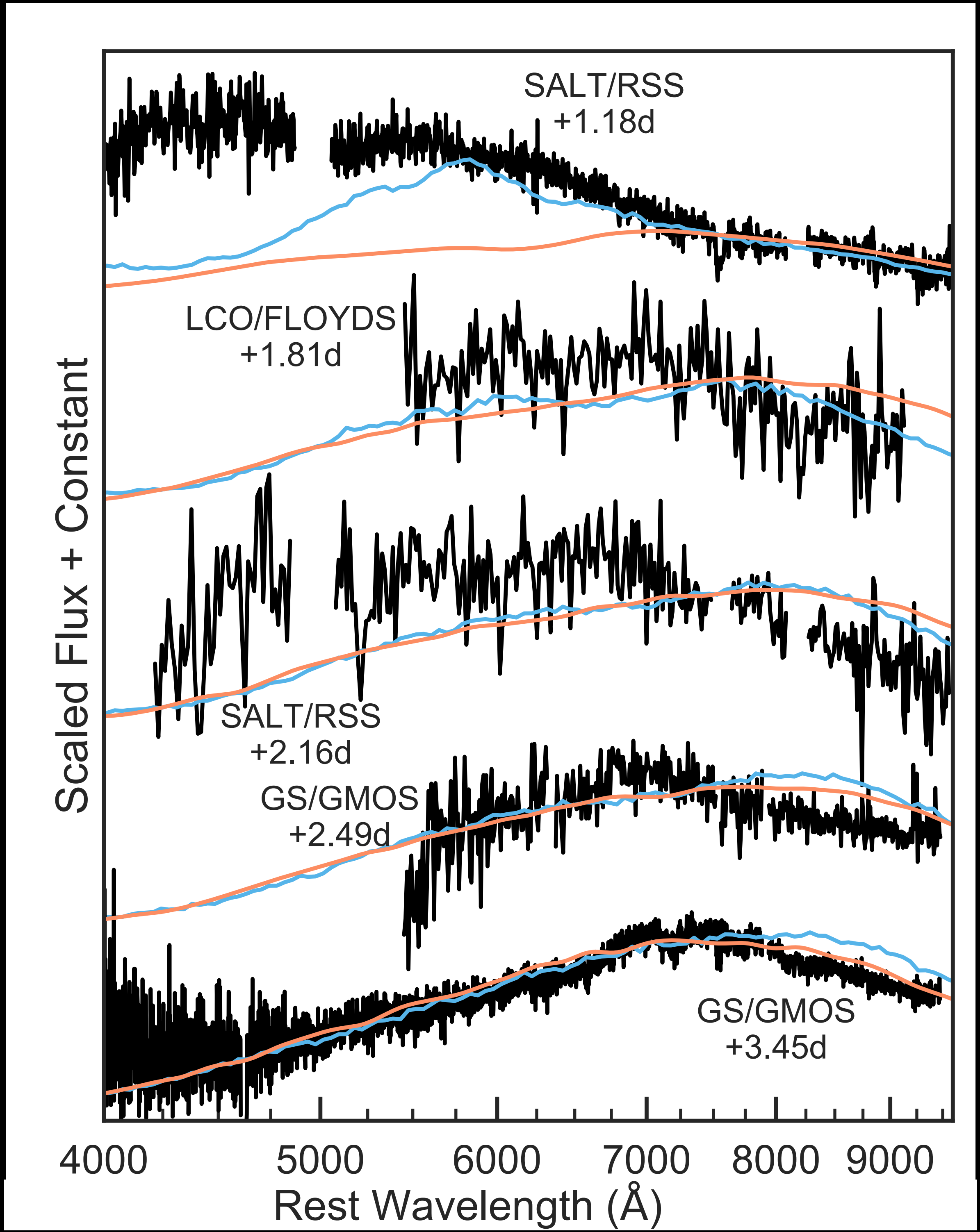
Smartt+ 2017

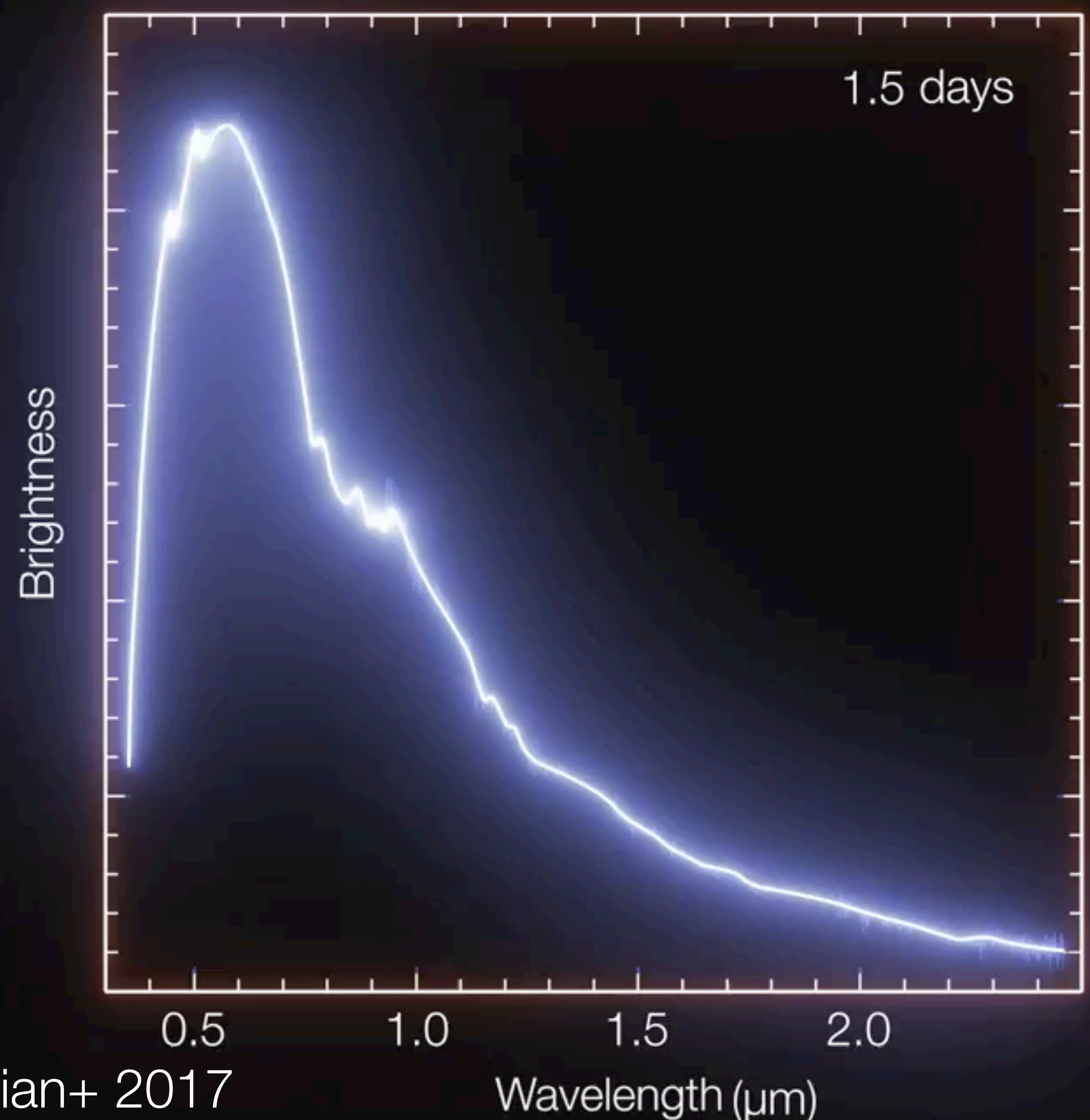
Generally, spectra can tell us about the composition of material of transients, but this was challenging for EM counterpart of GW170817.

Our spectra compared to kilonova models

As we found with the light curves, simple models agree with the observed spectra at late times, but the earliest spectrum is bluer than the models predict. Models with a lower abundance of r-process elements produce more flux in the blue but still not enough.

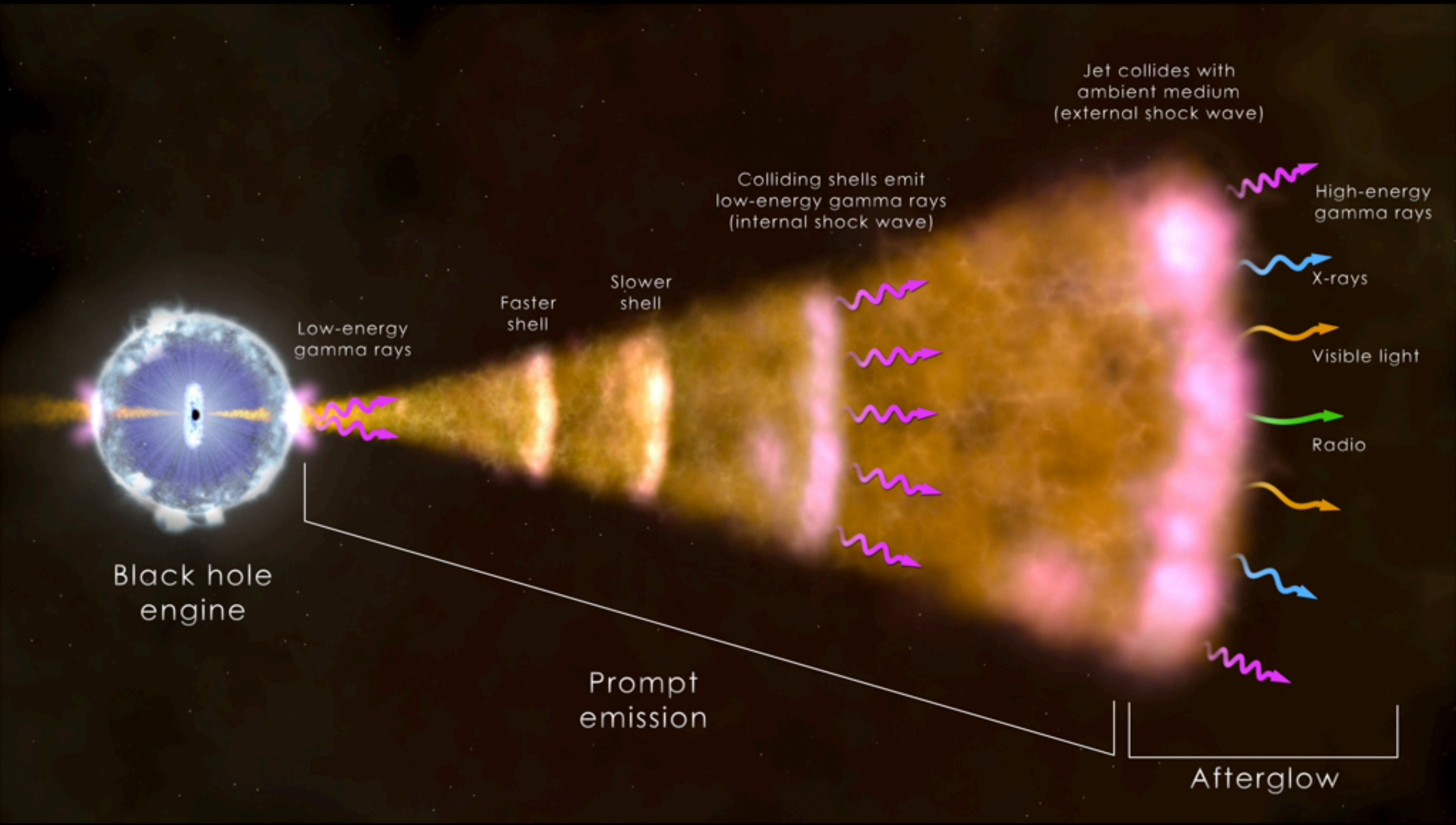
McCully+ 2017





Data from Pian+ 2017
Credit: ESO

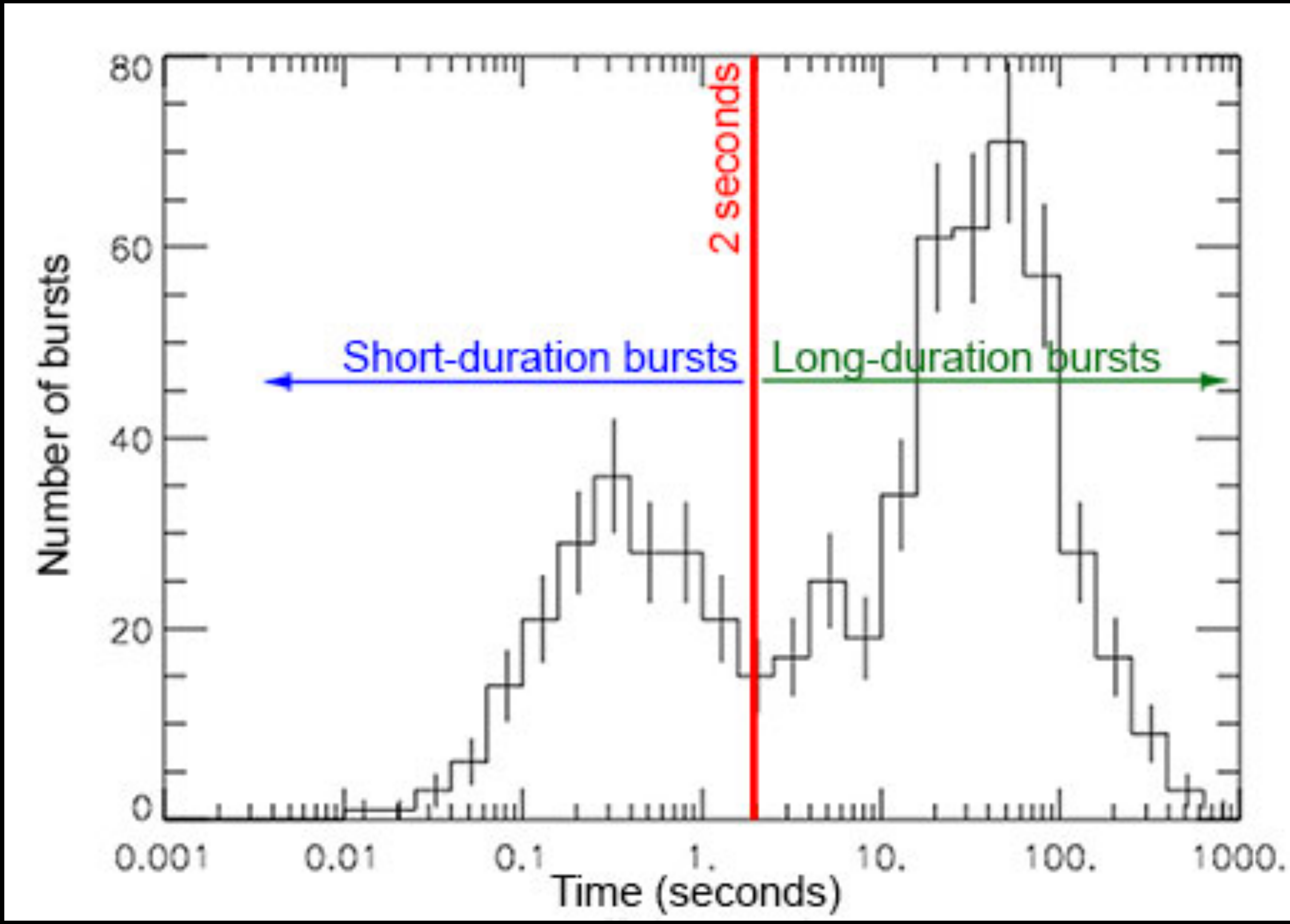
What are γ-ray Bursts (GRBs)?



Credit: NASA's Goddard Space Flight Center

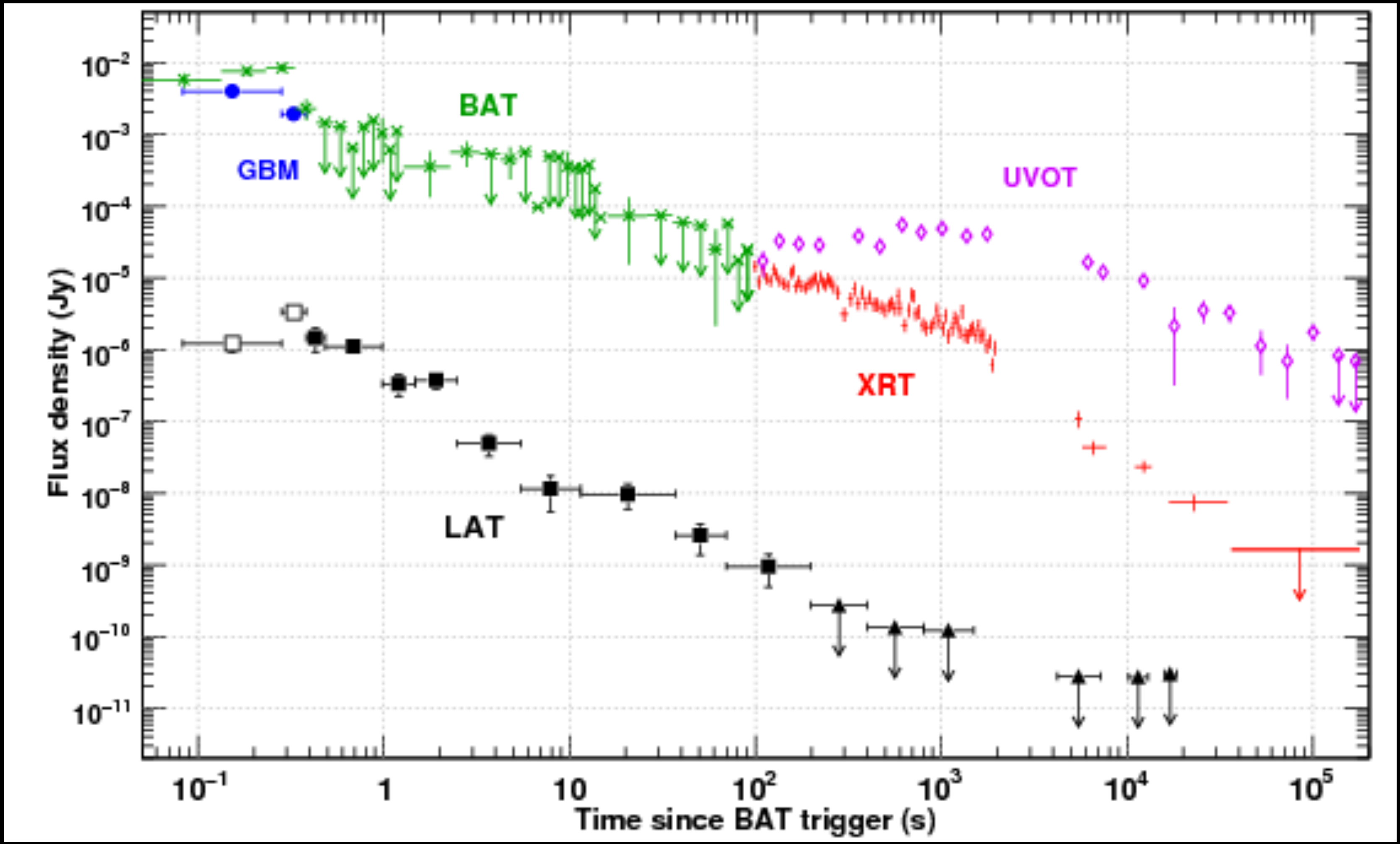
Long vs. Short γ-ray Bursts (GRBs)

Long **γ**-ray bursts come from young stellar populations and are associated with the explosions of massive stars. Short GRBs come from old stellar populations and were thought to be associated with merging neutron stars.



Credit NASA Swift

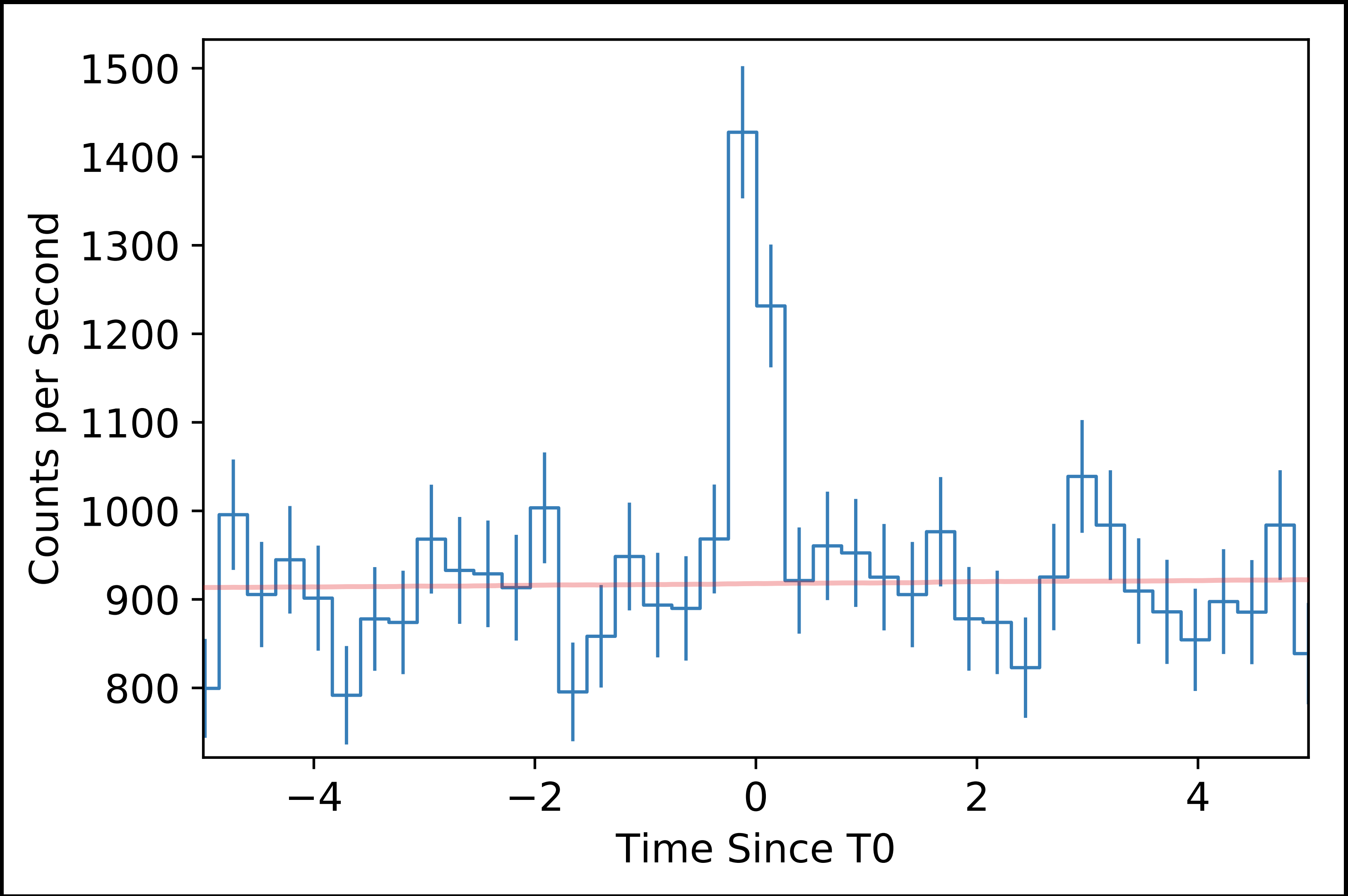
Observations of GRBs and their Afterglows



Pelassa+ 2010

GRBs follow a power-law decline. The afterglow emission starts in the X-rays and later peaks at longer wavelengths.

GRB 170817A

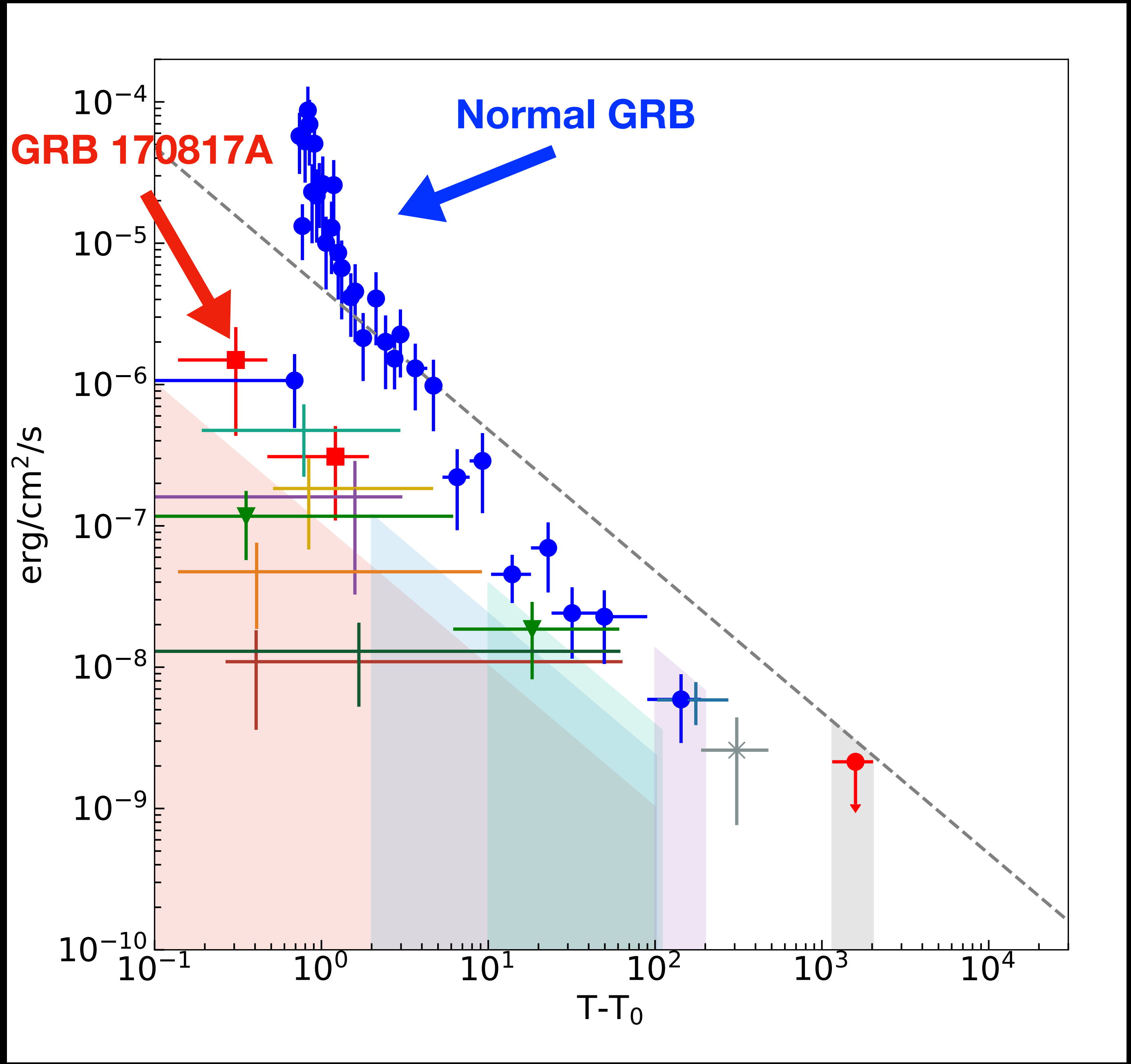


Goldstein+ 2017

Two seconds after GW170817 Fermi-LAT detected GRB 170817A. The GRB was initially classified as a normal short GRB.

Not such a Normal Short GRB After All

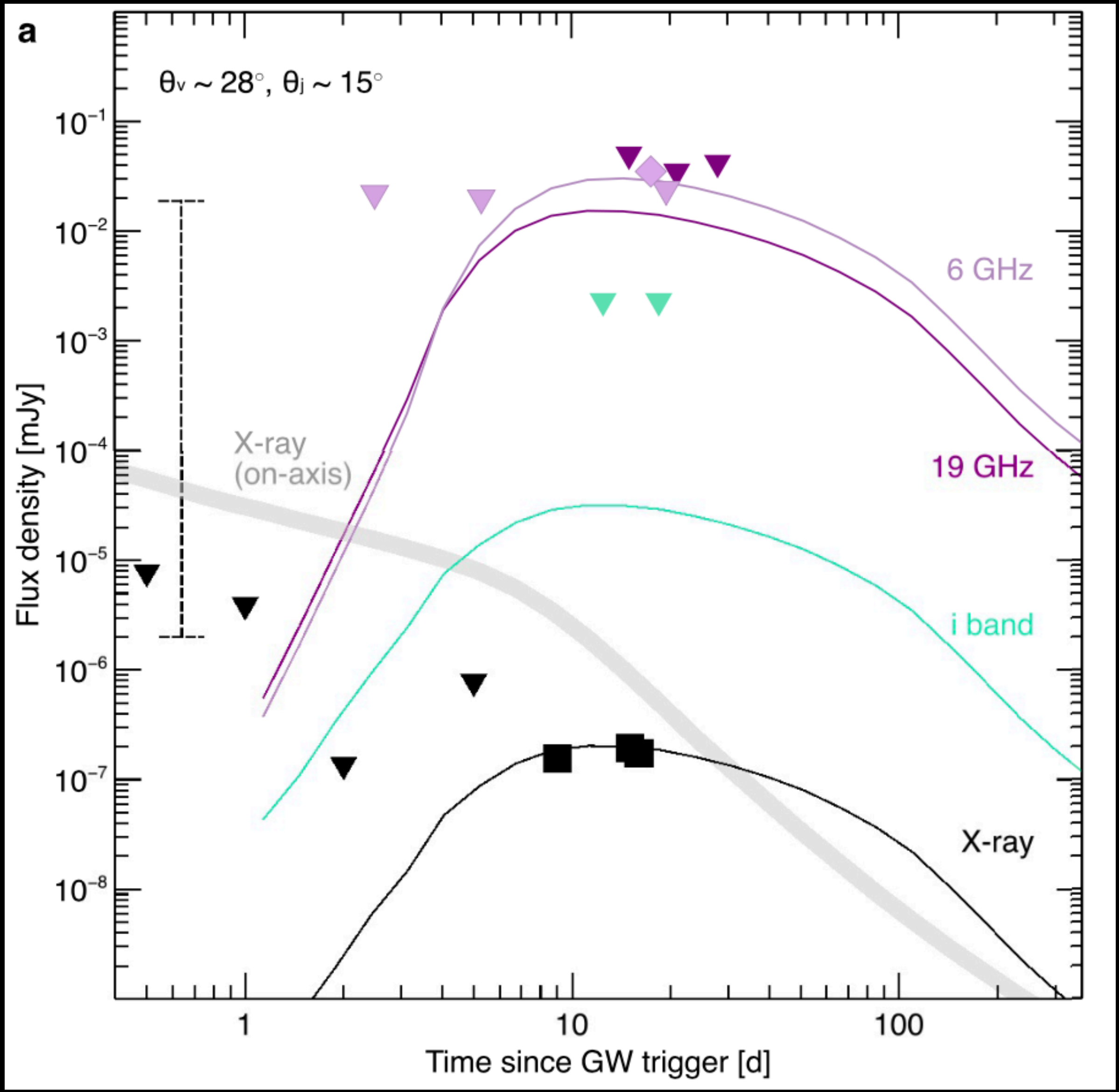
Once the distance was determined, it was realized that this GRB was about a hundred times fainter than previous short GRBs.



Fermi-LAT Team+ 2017

X-ray and Radio Observations of the Afterglow of GRB 170817A

Unlike normal short GRBs, the X-rays and radio appeared about a week after the **γ**-rays were detected.

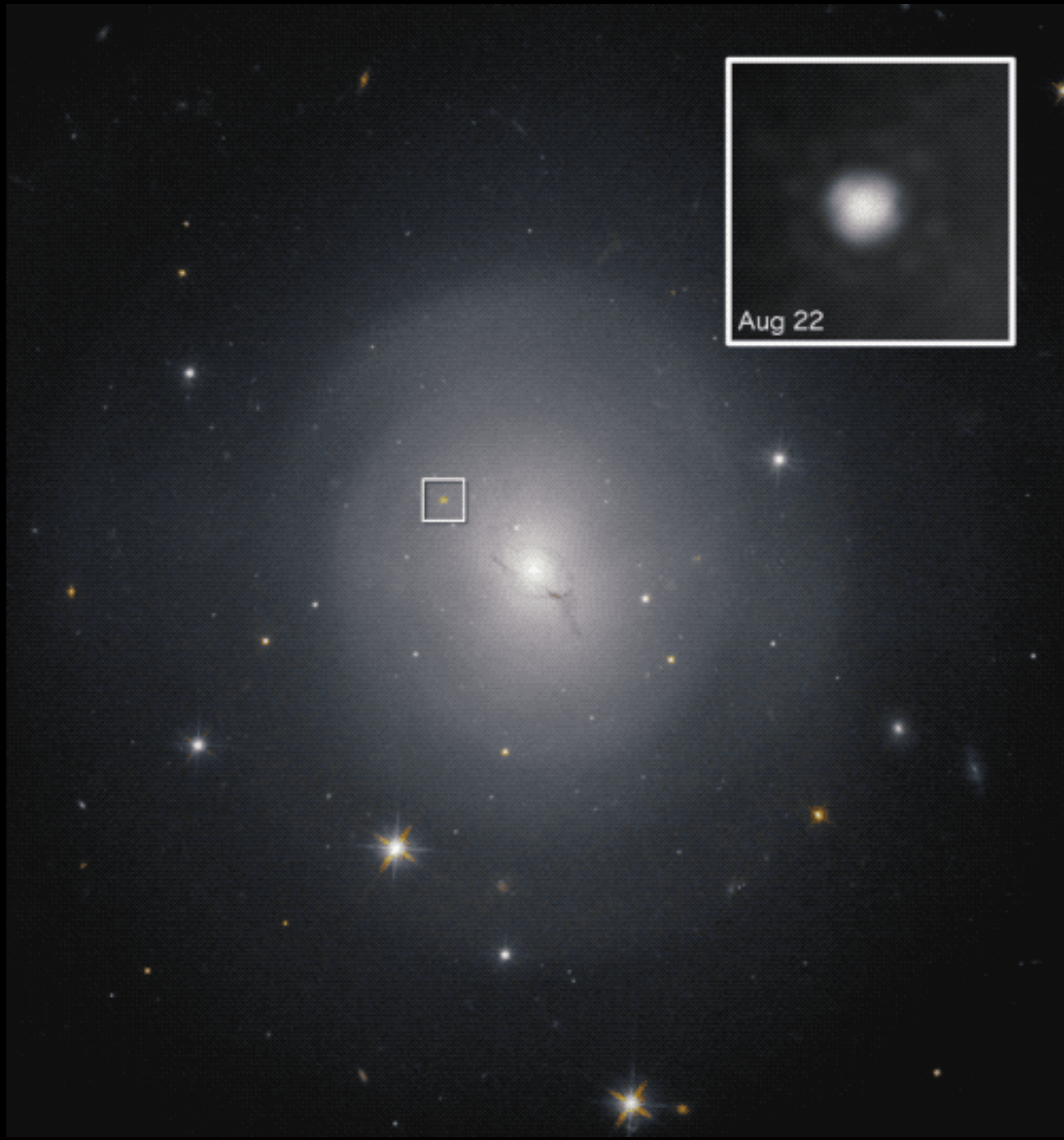


Troja+ 2017

Host Galaxy of the Kilonova

The counterpart was discovered in an elliptical galaxy with an old stellar population, similar to previous counterparts of short GRBS. No massive star was detected in pre-explosion images.

Credit: NASA and ESA



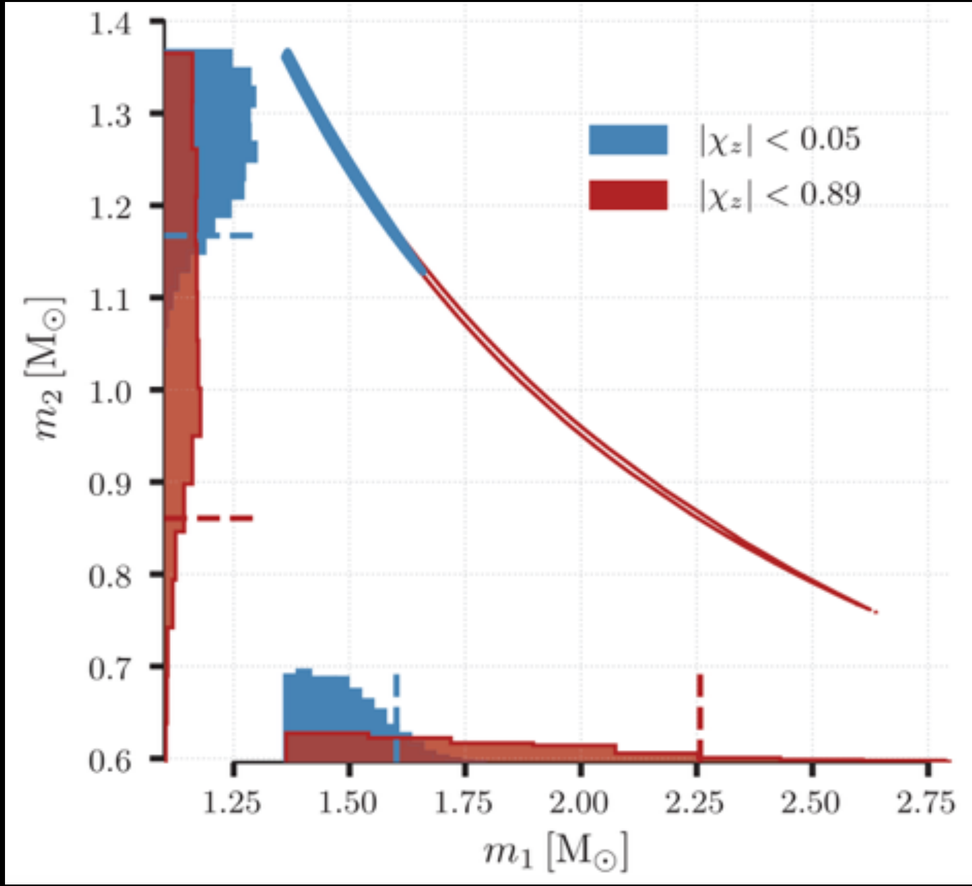
Inferred neutron star parameters from gravitational waves

LIGO/Virgo Collaboration, 2017, PRL, 119, 61

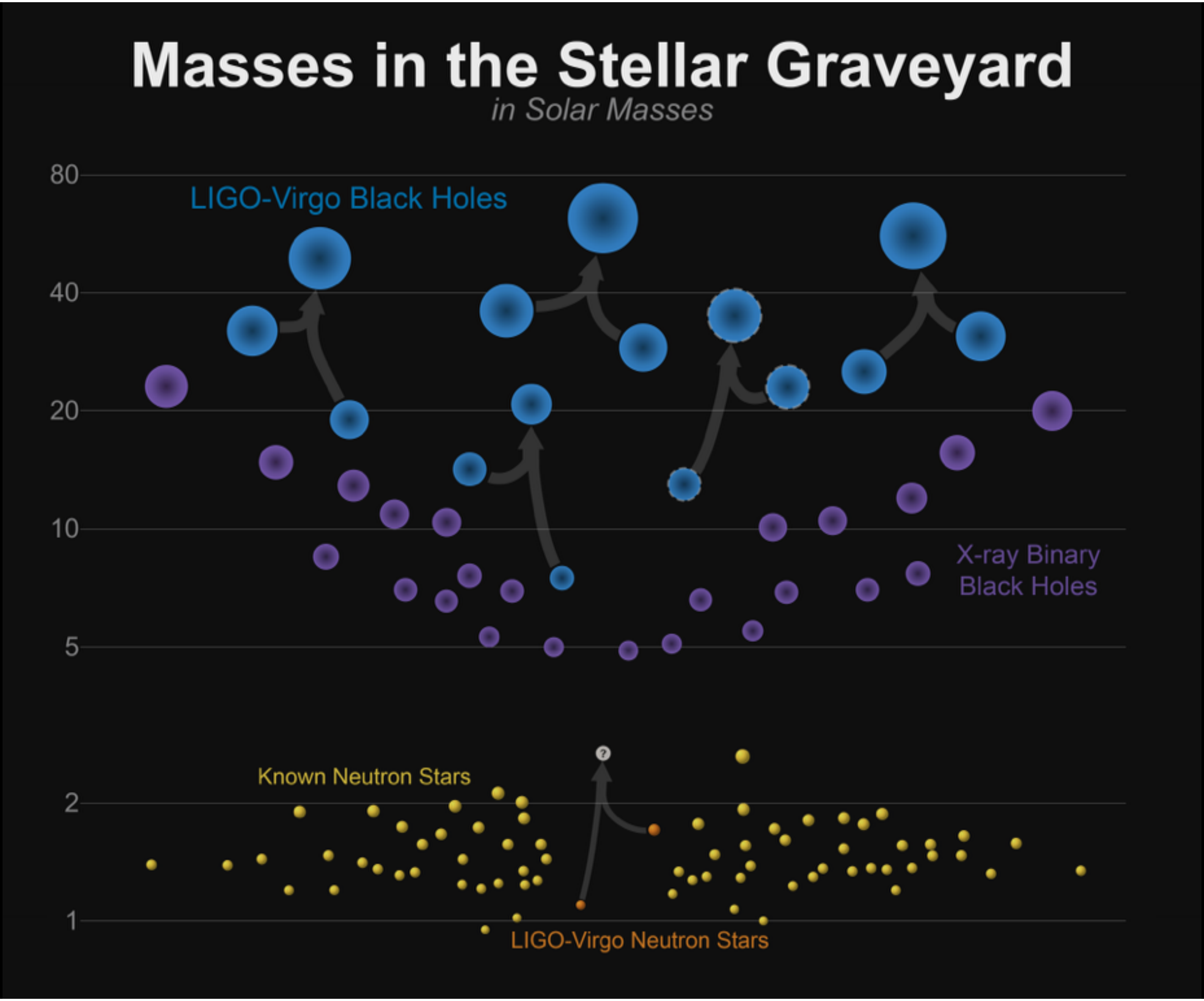
Chirp mass:

$$\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$$

Degeneracy between mass ratio and aligned spin components



	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 $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	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



Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars
?

Powering a kilonova

Theory: Kasen, Metzger, Barnes, Quataert, Ramirez-Ruiz 2017, Nature

Heating: Expanding cloud of ejecta kept warm (10^3-10^4 K) by decay of r-process isotopes with heating rate of ($\alpha \approx 1.3$):

$$\dot{\varepsilon}_{\rm nuc} \approx 10^{10} \left(\frac{t}{\rm days} \right)^{-\alpha} {\rm erg\ s^{-1}\ g^{-1}}$$

Power law: statistical consequence of multiple isotopes with half-lives roughly uniformly distributed in log time. Overall level uncertain to factor of 5 (uncertain composition, nuclear data inputs).

$$t_{\rm lc} \approx \left(\frac{3\kappa M}{4\pi c v} \right)^{\frac{1}{2}} \approx 2.7{\rm days} \left(\frac{M}{0.01 M_\odot} \right)^{\frac{1}{2}} \left(\frac{v}{0.1c} \right)^{-\frac{1}{2}} \left(\frac{\kappa}{1{\rm cm^2\ g^{-1}}} \right)^{\frac{1}{2}}$$

Lightcurve timescale: Thermal radiation released when photon diffusion time matches elapsed time.

Luminosity: Radioactive heating rate at escape timescale.

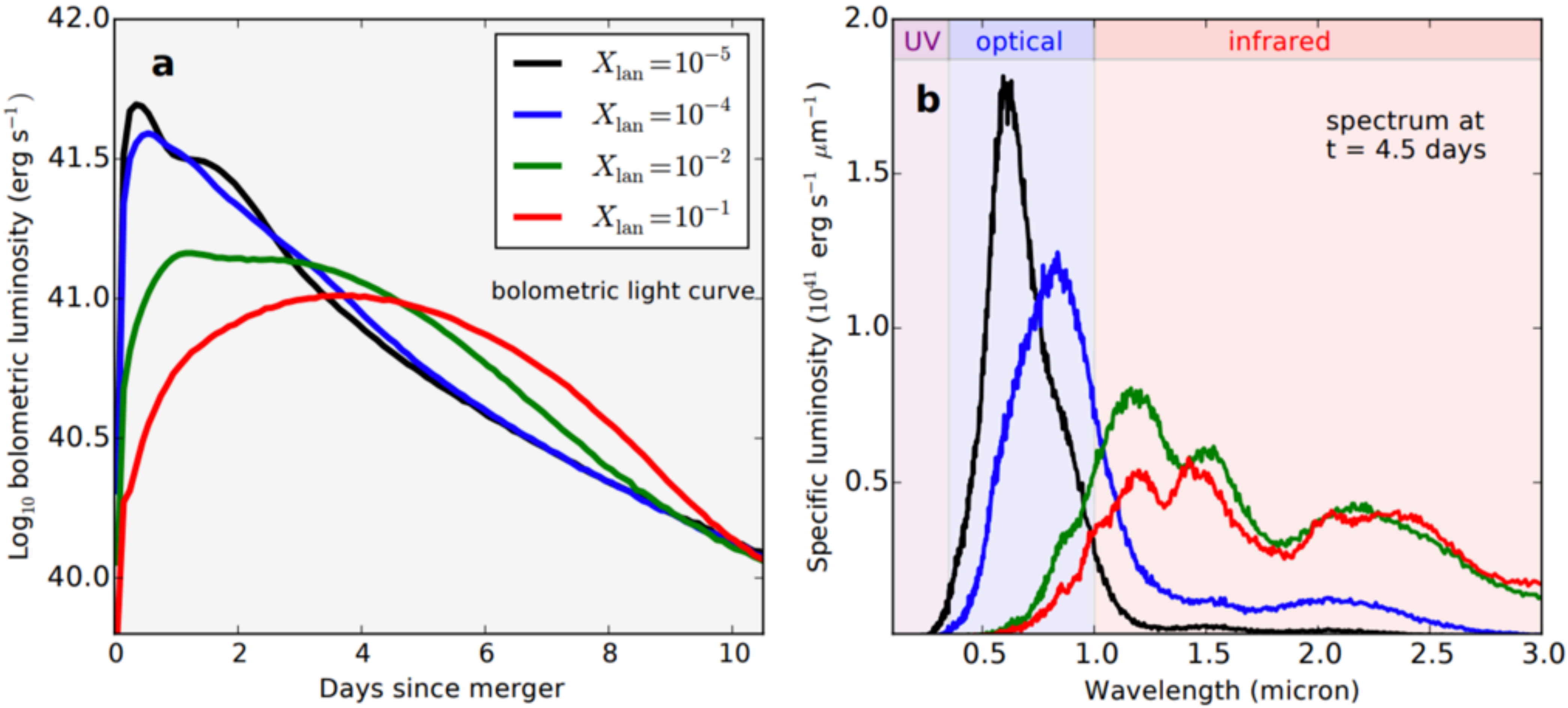
$$L_{\rm lc} \approx M \dot{\varepsilon}_{\rm nuc}(t_{\rm lc}) \approx 5 \times 10^{40} {\rm erg\ s^{-1}} \left(\frac{M}{0.01 M_\odot} \right)^{1-\frac{\alpha}{2}} \left(\frac{v}{0.1c} \right)^{\frac{\alpha}{2}} \left(\frac{\kappa}{1{\rm cm^2\ g^{-1}}} \right)^{-\frac{\alpha}{2}}$$

More ejected mass: brighter, longer kilonova.

Higher velocity: brighter, briefer kilonova.

Lanthanides block optical emission

Theory: Kasen, Metzger, Barnes, Quataert, Ramirez-Ruiz 2017, Nature

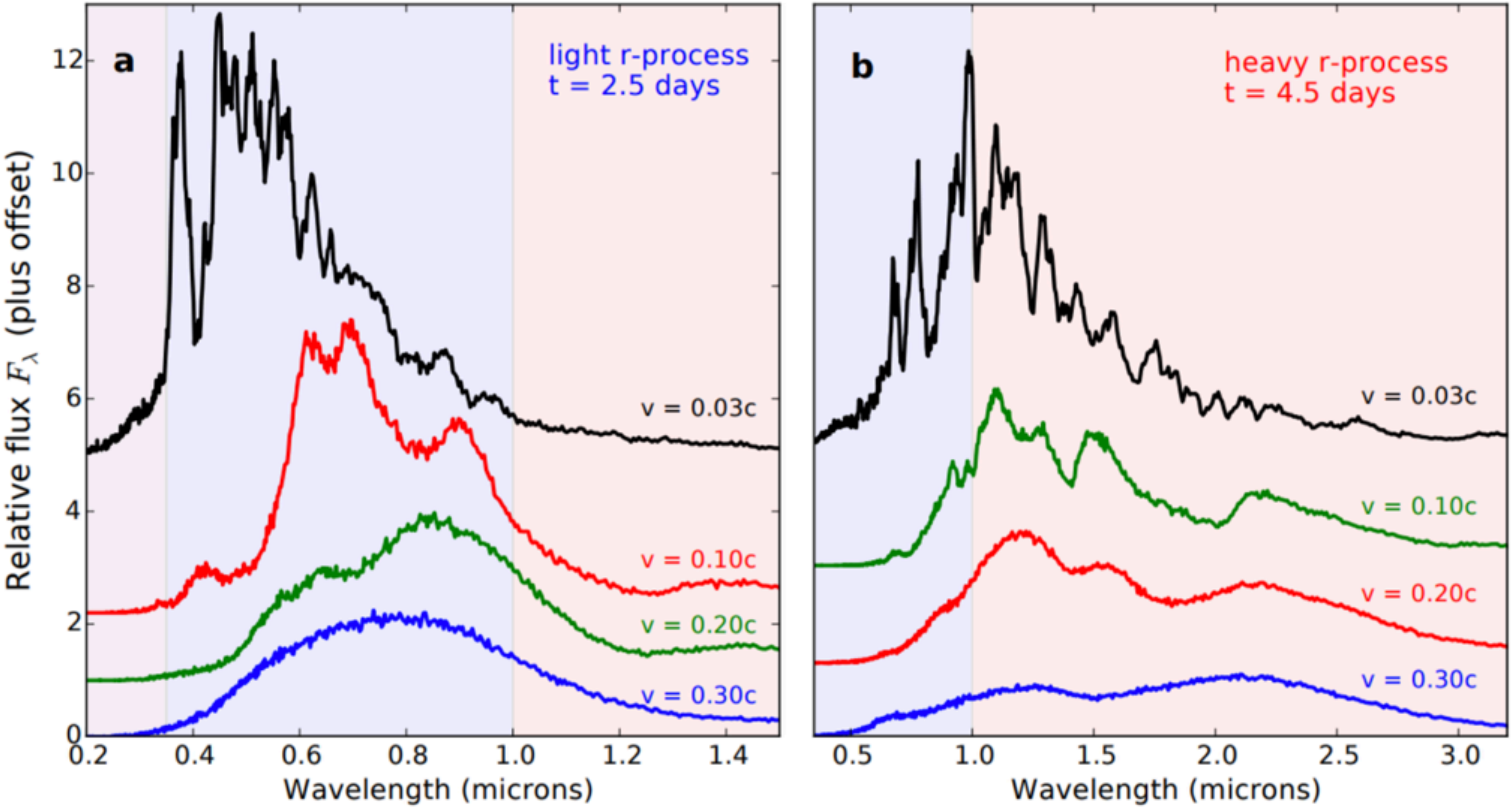


Light r-process: most lines from iron-group homologues with d-shell valence electrons.

Heavy r-process: 1-10% by mass lanthanides (*Z:* 58-71), which have f-shell valence electrons with more densely spaced energy levels and orders of magnitude more line transitions. They are 100x more opaque than iron-like elements in the optical.

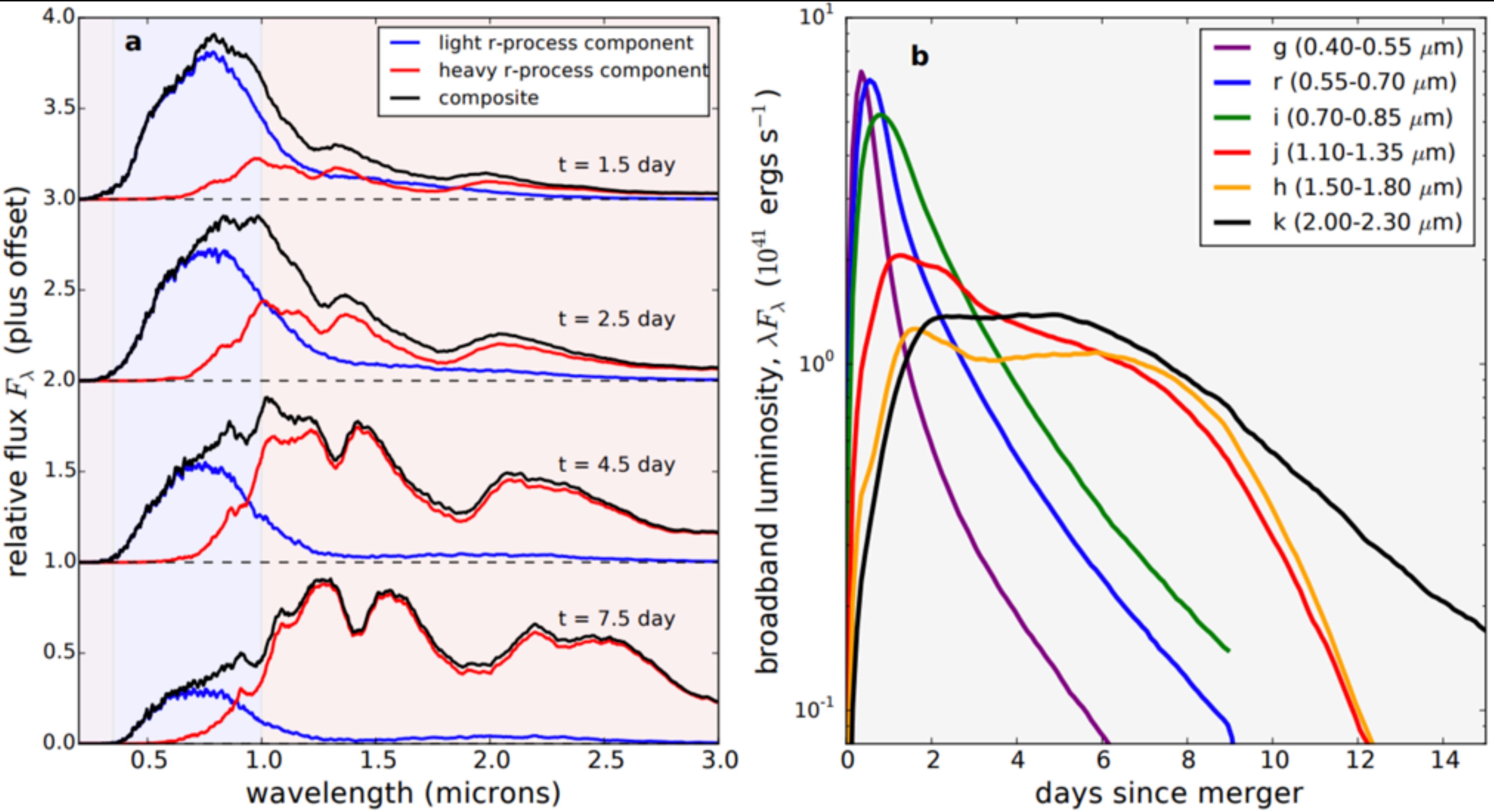
High velocities smear out lines

Theory: Kasen, Metzger, Barnes, Quataert, Ramirez-Ruiz 2017, Nature



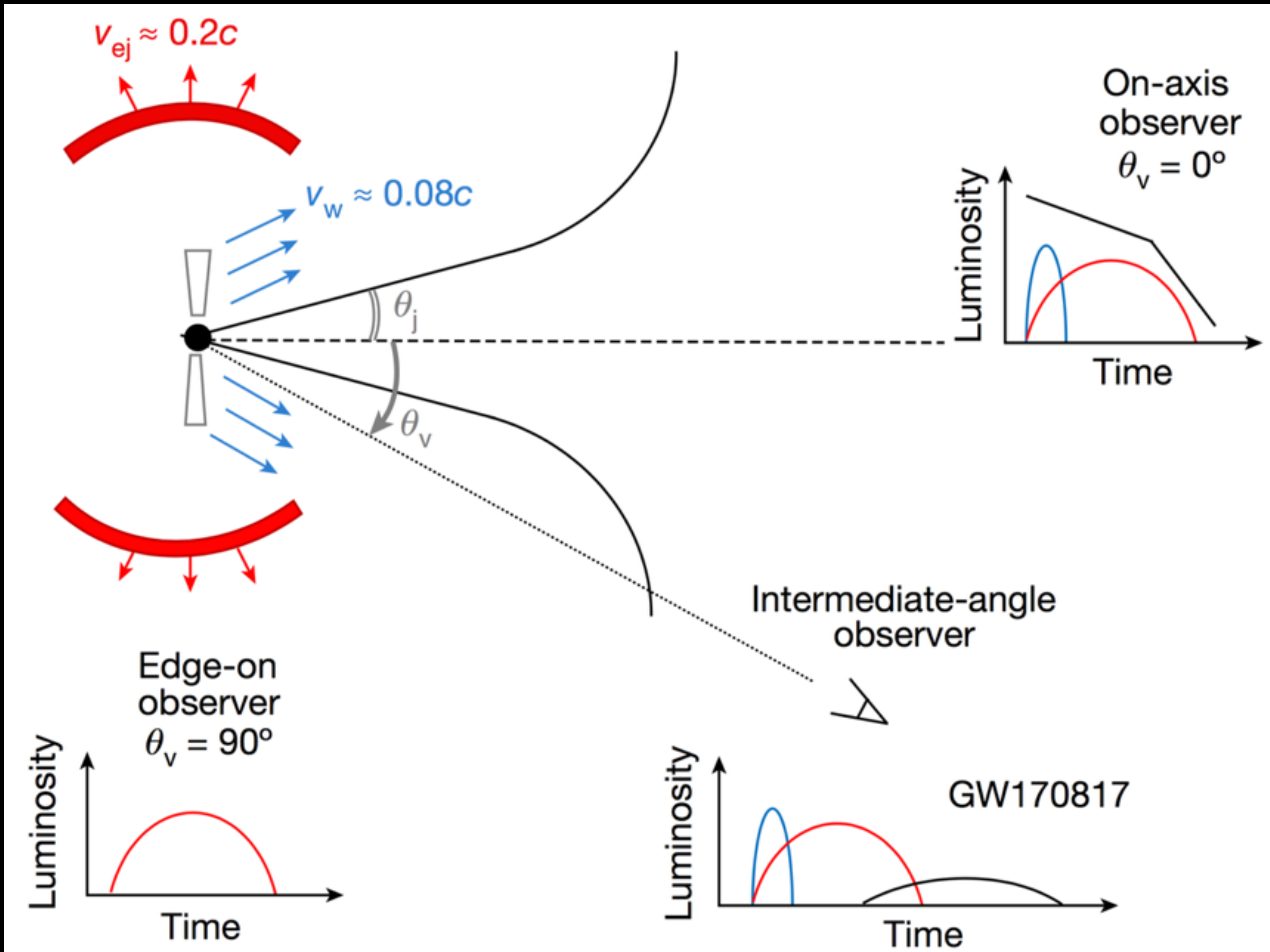
Hybrid blue-red model

Theory: Kasen, Metzger, Barnes, Quataert, Ramirez-Ruiz 2017, Nature



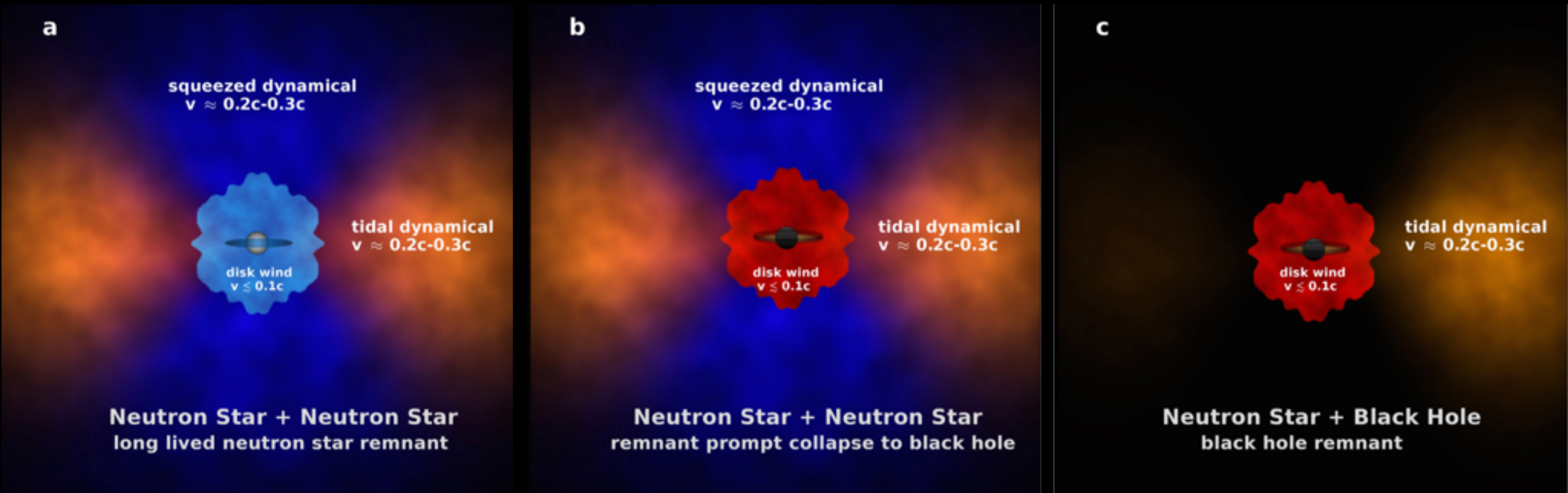
Delay in X-rays and radio from off-axis jet

Troja et al. 2017: viewing angle has strong effect



Merger remnant

Theory: Kasen, Metzger, Barnes, Quataert, Ramirez-Ruiz 2017, Nature



Blue: light r-process Red: heavy r-process

1. Cold tidal tails thrown off (red).
2. As NSs come into contact, later matter thrown off squeezed into polar regions by shock heating at interface.
3. Disk winds

If a hot neutron star survives for tens of milliseconds, neutrino irradiation causes weak interaction lowering the neutron fraction and producing a blue accretion disk wind.

Cocoon model

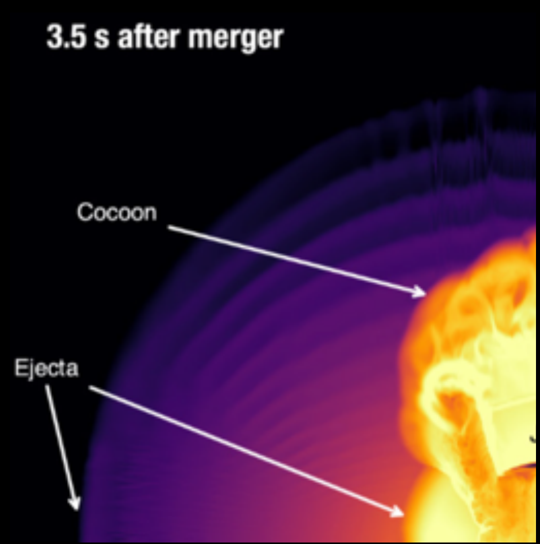
Piro & Kollmeier 2017, see also Nakar & Piran (2017), Gottlieb et al. (2017)

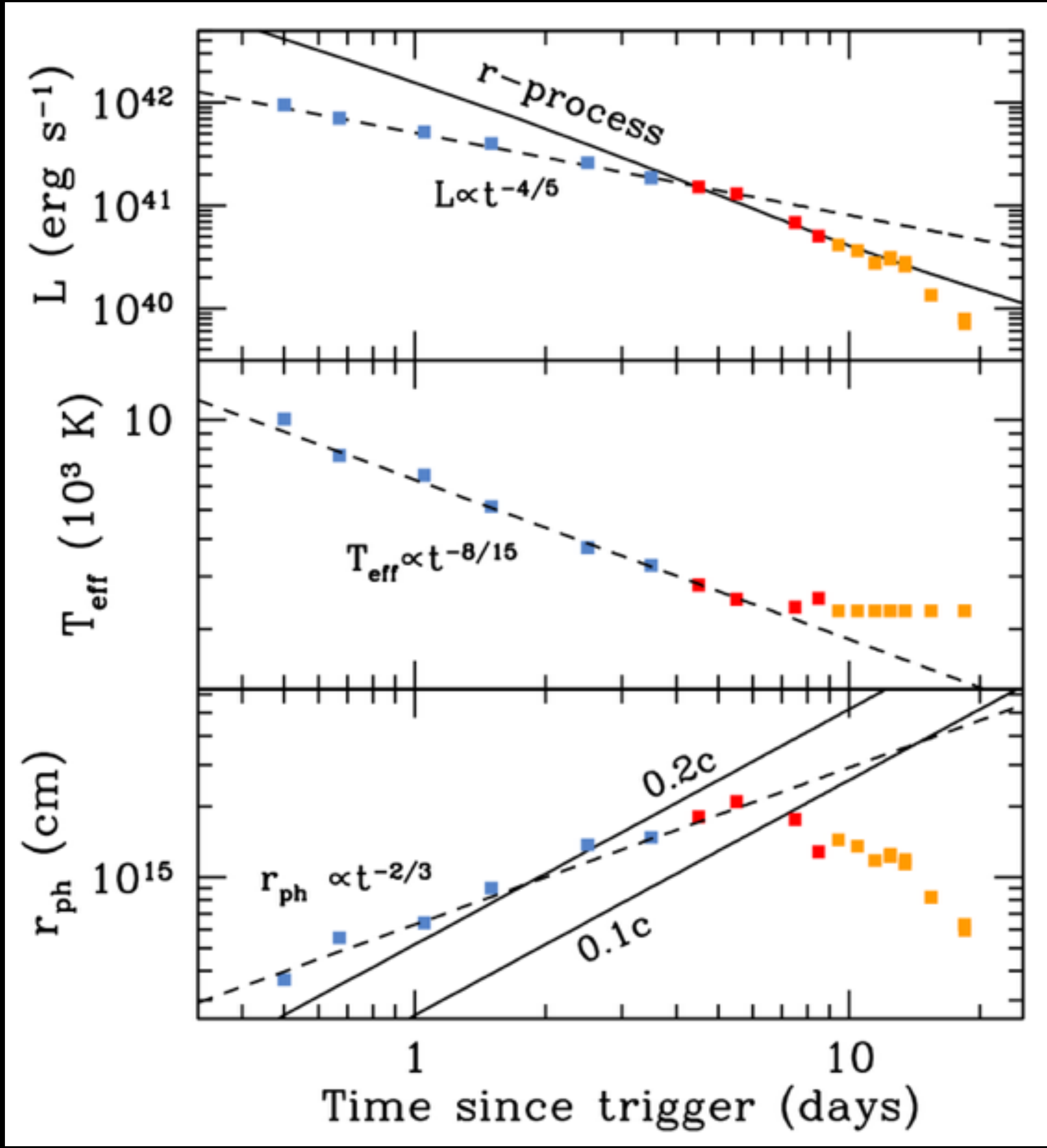
Power-law evolution of luminosity, temperature, photospheric radius early on explained by cooling of shock heated material, heated by interaction of GRB jet and merger debris.

Dashed: shock-heated ejecta: *s = -d ln E / d ln v ~ 3*

Solid: r-process heating

Implications:
It is possible the gamma rays are from shock breakout and not a jet.





Simulation: Kasliwal et al. 2017, Science

Polarization

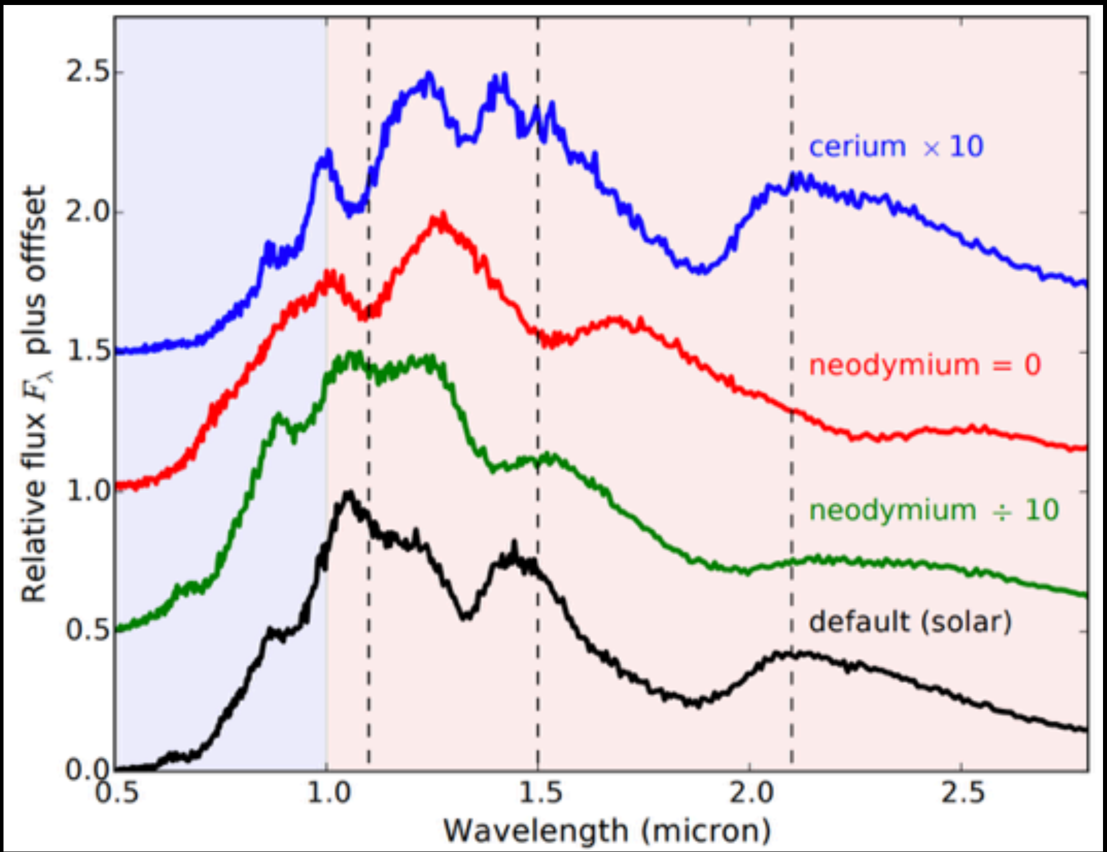
Covino et al 2017: Polarization is consistent with Milky Way stars along the line of sight, indicating it is caused by MW dust, and intrinsic polarization of the blue component is zero.

This implies a non-asymmetric blue component.

T-T$_{GW}$	Q/I	U/I	Polarization	Position Angle	Magnitude
(days)			(%)	(deg)	(AB)
1.46	-0.0021 ± 0.0008	$+0.0046 \pm 0.0007$	0.50 ± 0.07	57 ± 4	17.69 ± 0.02
2.45	-0.0025 ± 0.0016	$+0.0044 \pm 0.0032$	< 0.58	-	18.77 ± 0.04
3.47	-0.0009 ± 0.0015	$+0.0034 \pm 0.0024$	< 0.46	-	19.27 ± 0.01
5.46	-0.0029 ± 0.0033	$+0.0026 \pm 0.0050$	< 0.84	-	20.39 ± 0.03
9.48	$+0.0412 \pm 0.0216$	-0.0095 ± 0.0126	< 4.2	-	20.69 ± 0.11

Signatures of r-process elements

Kasen et al. 2017 (theory): High velocities make seeing individual absorption lines difficult, but in principle it is possible.



Signatures of r-process elements

Smartt et al. 2017: Evience for Cesium (Z=55), and Tellurium (52)

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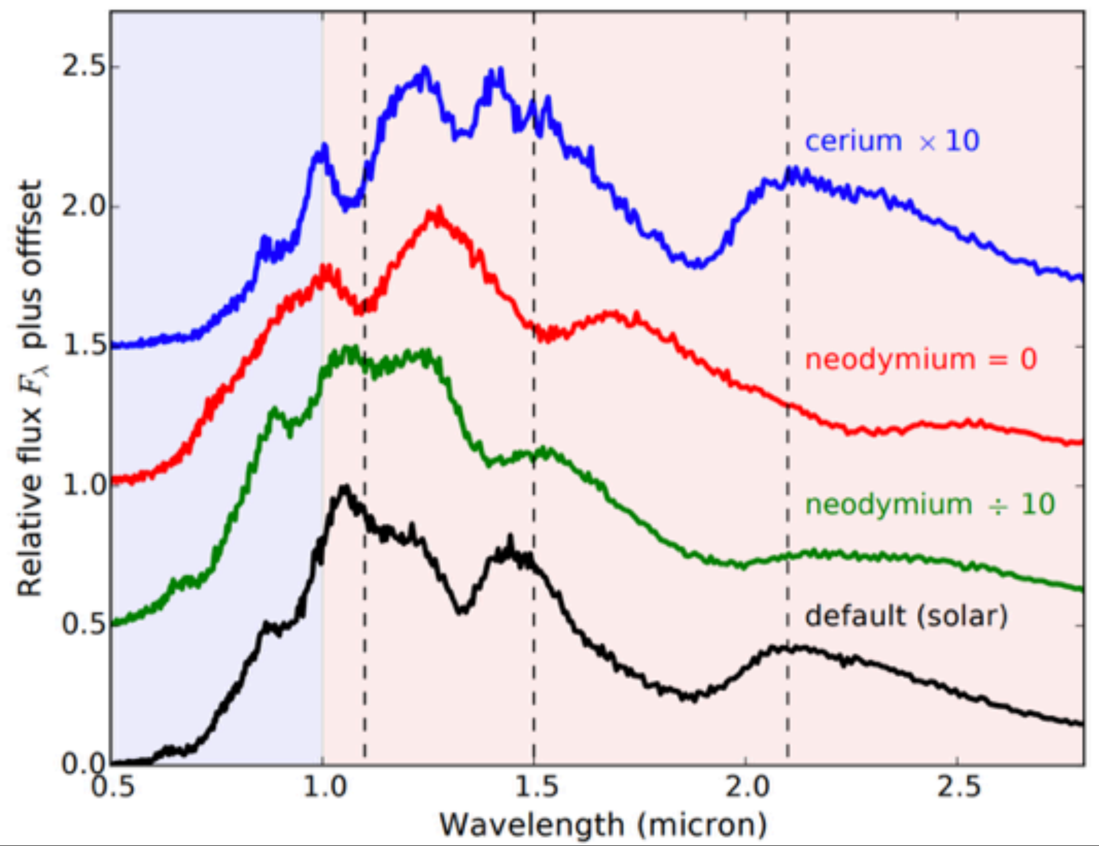
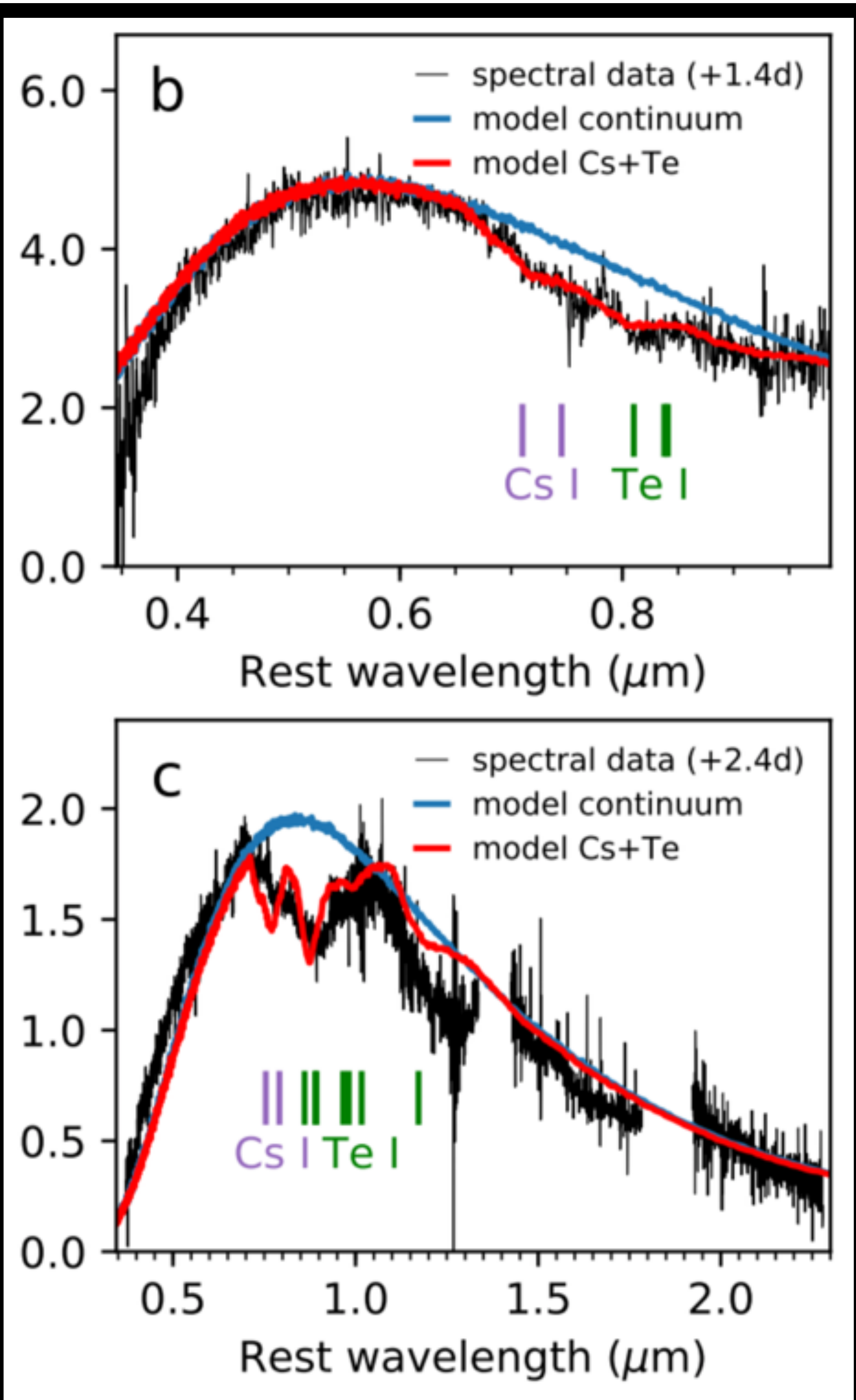




Summary of kilonova properties

Metzger 2017: some depend on model assumptions

Table 1: Key Properties of GW170817

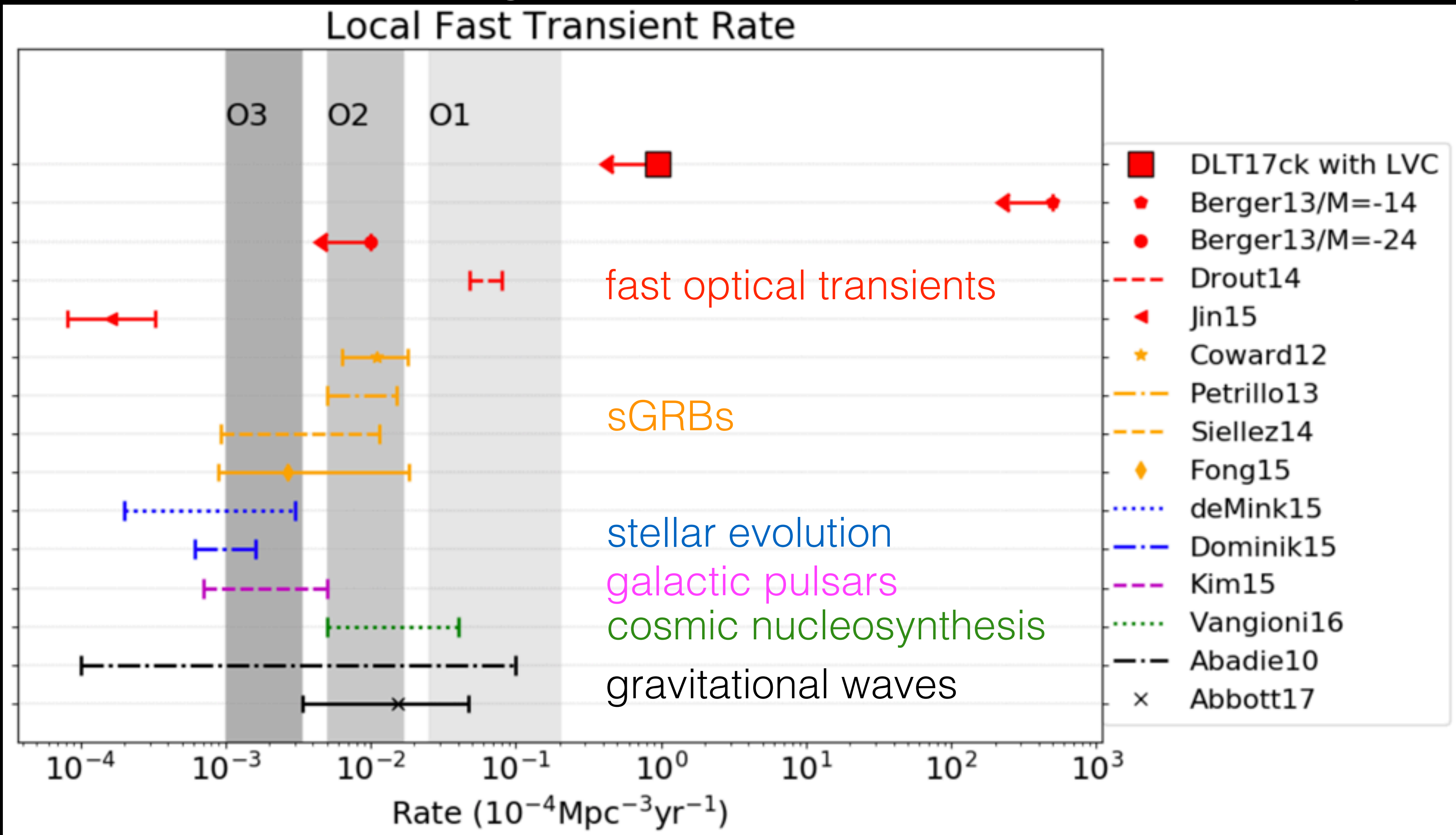
Property	Value	Reference
Chirp mass, $\mathcal{M}$ (rest frame)	$1.188^{+0.004}_{-0.002} M_\odot$	1
First NS mass, M_1	$1.36 - 1.60 M_\odot$ (90%, low spin prior)	1
Second NS mass, M_2	$1.17 - 1.36 M_\odot$ (90%, low spin prior)	1
Total binary mass, $M_{tot} = M_1 + M_2$	$\approx 2.74^{0.04}_{-0.01} M_\odot$	1
Observer angle relative to binary axis, θ_{obs}	$11 - 33^\circ$ (68.3%)	2
Blue KN ejecta ($A_{max} \lesssim 140$)	$\approx 0.01 - 0.02 M_\odot$	e.g., 3,4,5
Red KN ejecta ($A_{max} \gtrsim 140$)	$\approx 0.04 M_\odot$	e.g., 3,5,6
Light r-process yield ($A \lesssim 140$)	$\approx 0.05 - 0.06 M_\odot$	
Heavy r-process yield ($A \gtrsim 140$)	$\approx 0.01 M_\odot$	
Gold yield	$\sim 100 - 200 M_\oplus$	8
Uranium yield	$\sim 30 - 60 M_\oplus$	8
Kinetic energy of off-axis GRB jet	$10^{49} - 10^{50}$ erg	e.g., 9, 10, 11, 12
ISM density	$10^{-4} - 10^{-2}$ cm^{-3}	e.g., 9, 10, 11, 12

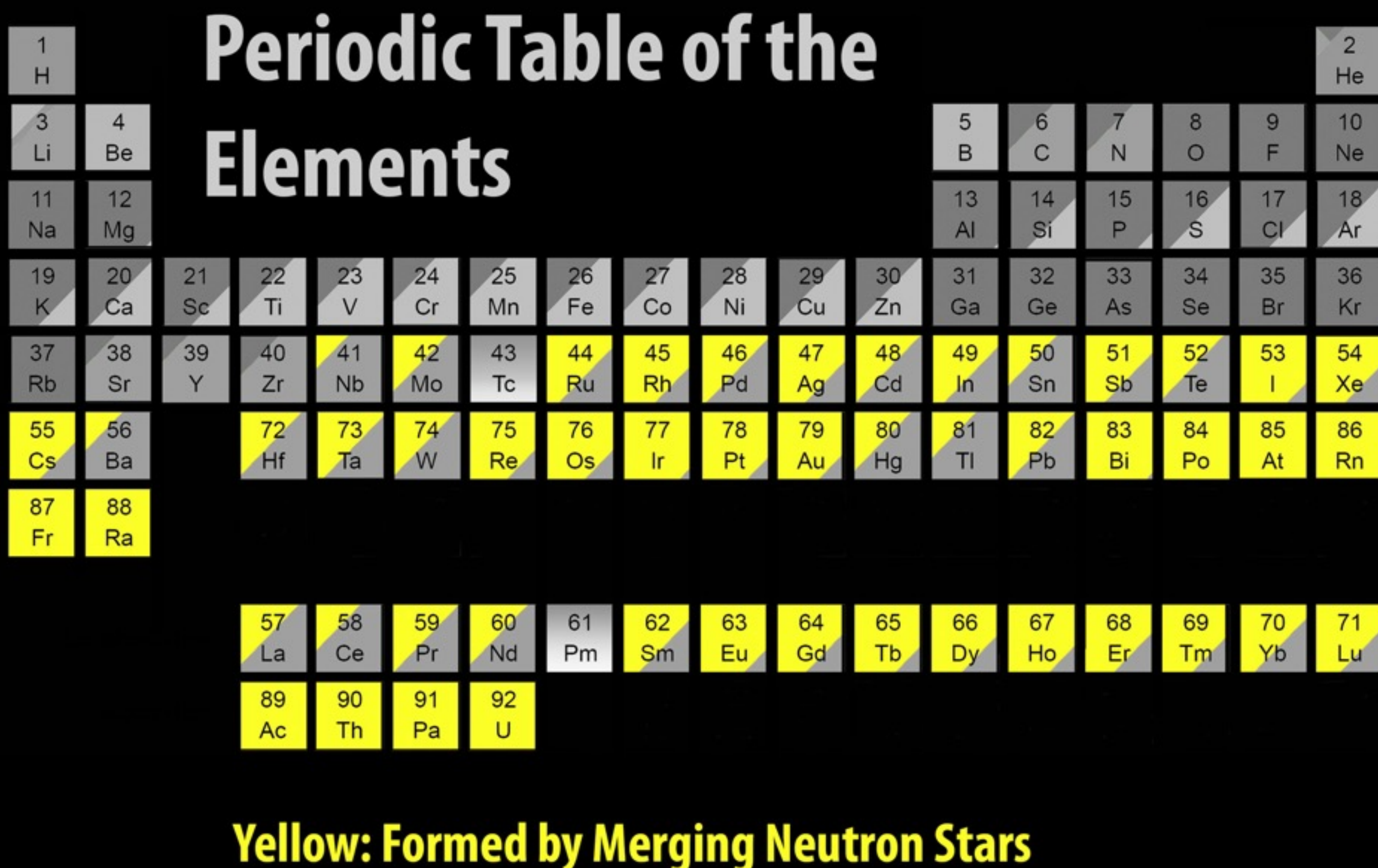
(1) LIGO Scientific Collaboration et al. 2017c; (2) depends on Hubble Constant, LIGO Scientific Collaboration et al. 2017d; (3) Cowperthwaite et al. 2017; (4) Nicholl et al. 2017; (5) Kasen et al. 2017; (6) Chornock et al. 2017; (8) assuming heavy r-process ($A > 140$) yields distributed as solar abundances (Arnould et al., 2007); (9)Margutti et al. 2017; (10) Troja et al. 2017; (11) Fong et al. 2017; (12) Hallinan et al. 2017

Rates

Upcoming 2018-2019 LIGO/Virgo run: expect 0.1 - 1.4 joint Fermi/LIGO detections, 0.3-1.7 at design sensitivity (LIGO/Virgo Collaboration, 2017, ApJ Letters, 848)

Yang et al. 2017: KN every 200 years in MW-size galaxy



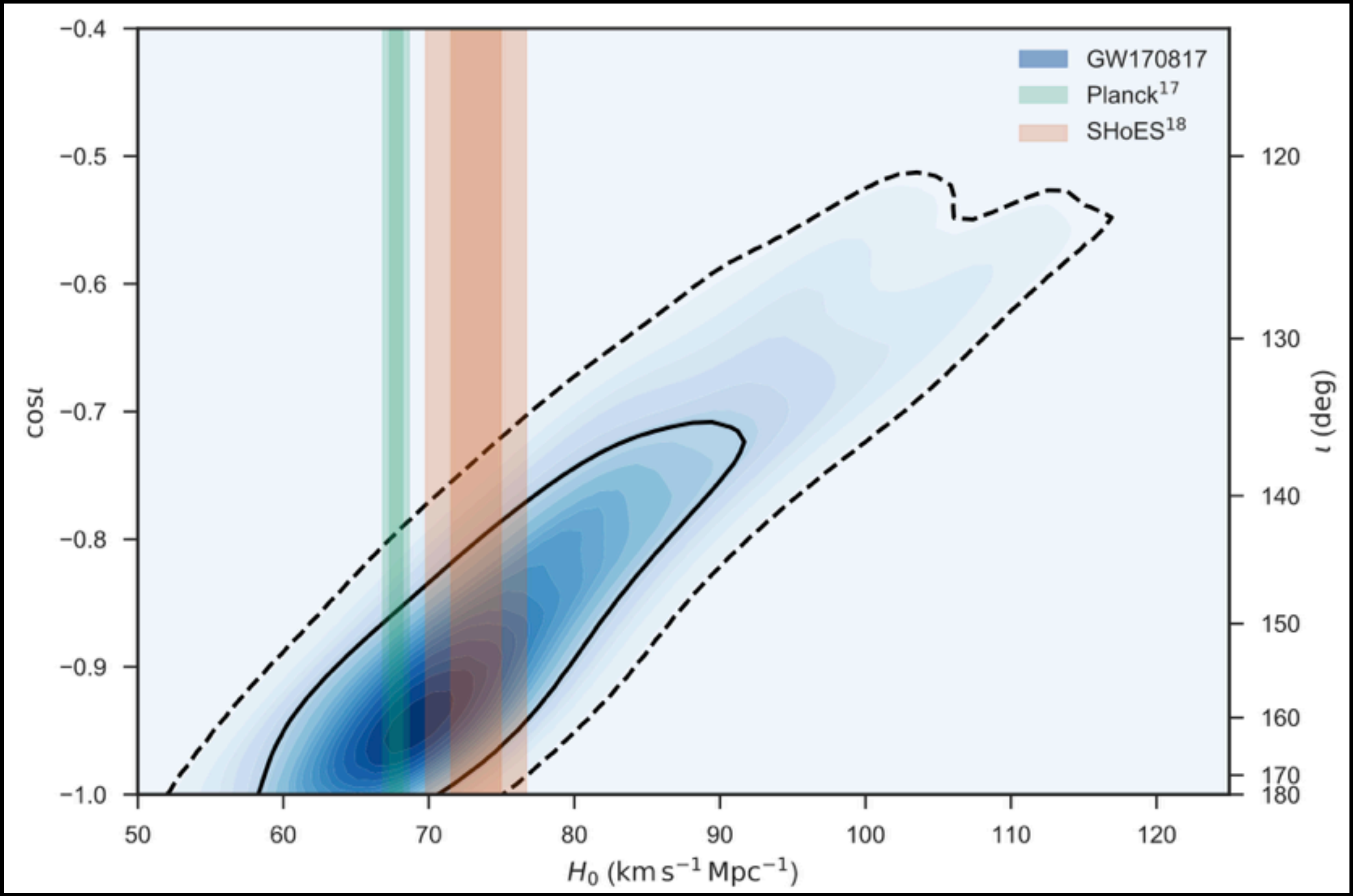


Given the amount of r-process elements created, the ejecta mass, and known rates, kilonovae can account for all the r-process elements

Hubble constant

LIGO-Virgo Collaboration et al. (including us) 2017, ApJ Letters

Gravitational waves are “standard sirens” — they can tell you luminosity distance. When paired with redshift from host galaxy, you can get the Hubble constant, H_0. They find $H_0 = 70^{+12}_{-8}$ km s^{-1} Mpc^{-1}



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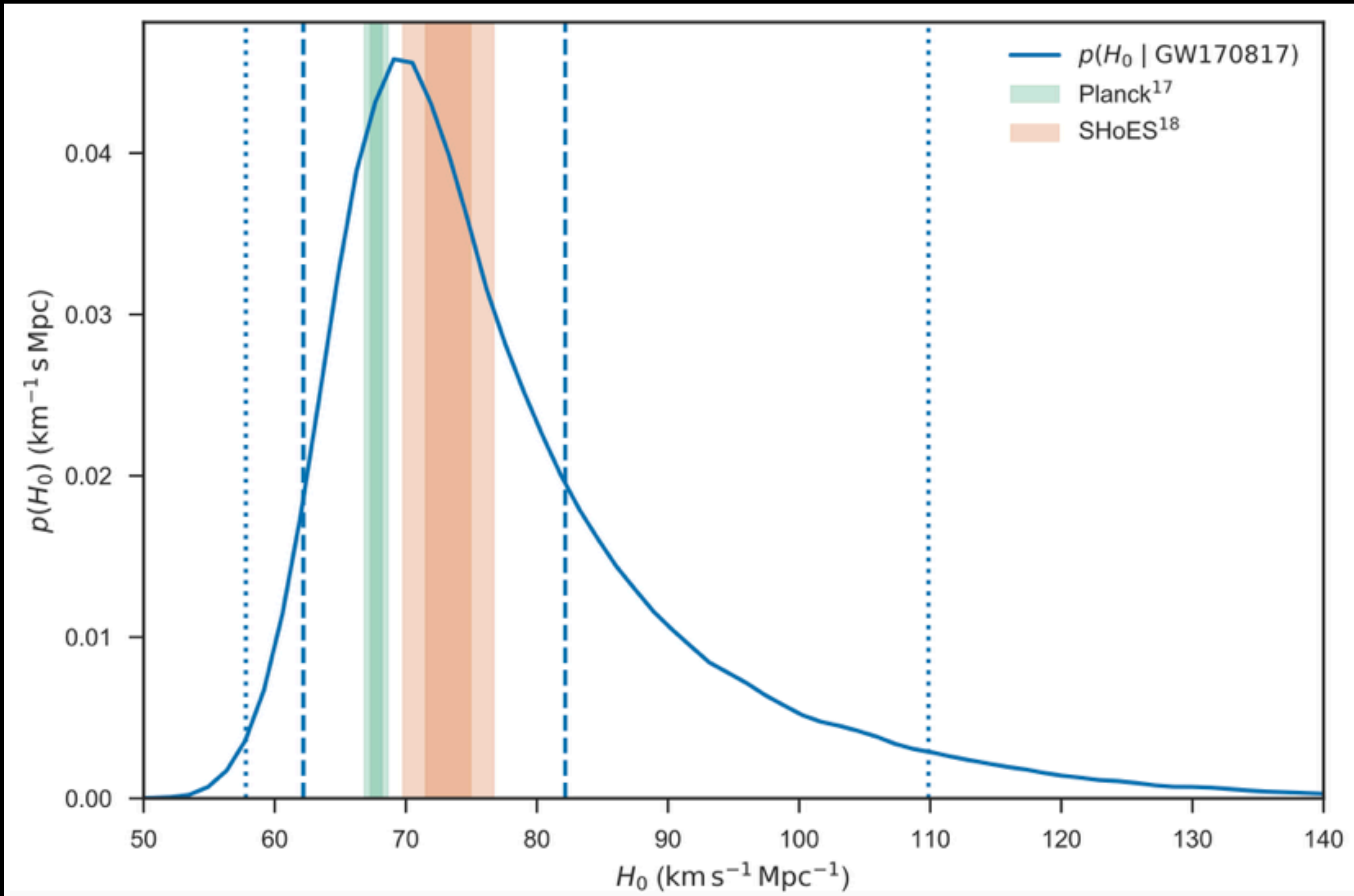


Conclusions

At least some short gamma ray bursts are associated with neutron star mergers as suspected.

Kilonova theory largely works! Given uncertainties in atomic data, different possible mass ratios, simplifications in models, and orientation effects, there is a remarkable agreement with what was expected.

The bright, blue part of the kilonova emission was largely a surprise. We need a multi-component kilonova model to explain the data. What we saw early had few lanthanides.

It is possible a massive neutron star survived for tens of milliseconds before collapsing to a black hole.

An off-axis jet can explain the late x-rays and radio, but does it have problems explaining polarization data? Shock cooling of a cocoon is an alternative.

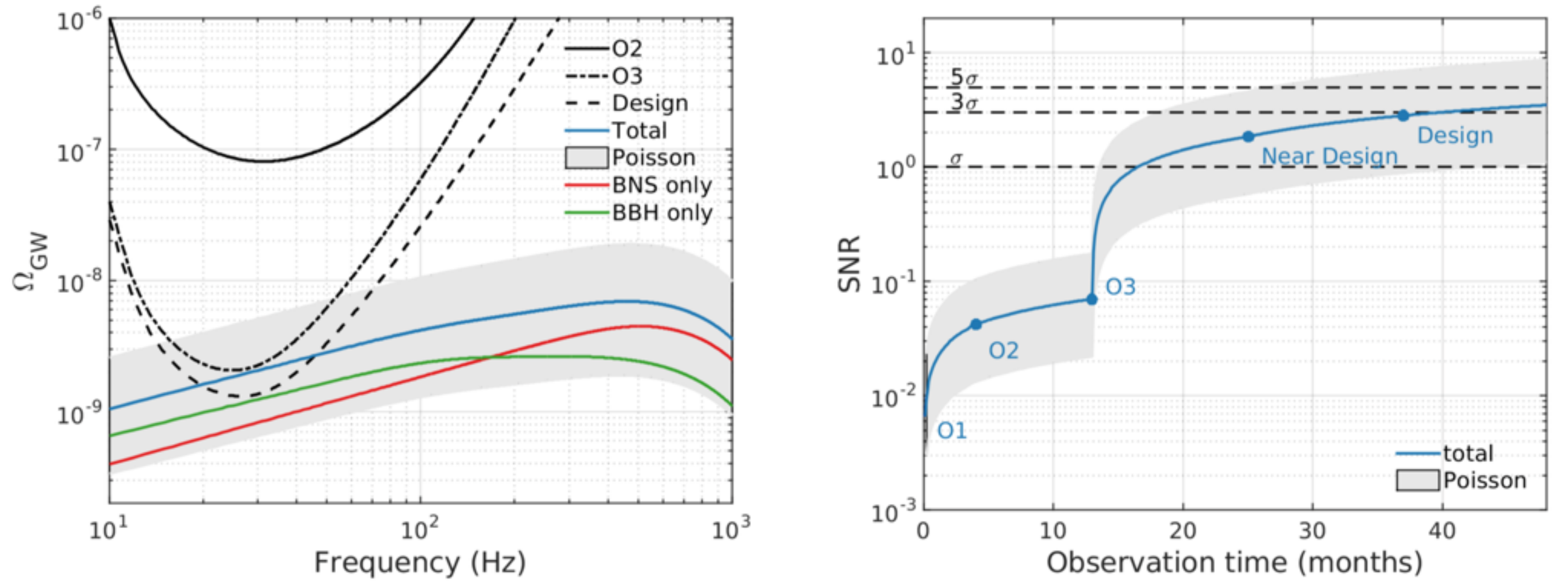
The era of gravitational wave cosmology is here.

We are in the multi messenger astronomy era, and Las Cumbres Observatory is well positioned to act quickly on future gravitational wave and neutrino alerts!

Questions

Should we have found these in the past? No. Average number of KNe expected in ASASSN, SDSS, PS1, SNLS, DES, and SMT is 0-0.3 (Scolnic et al. 2017).

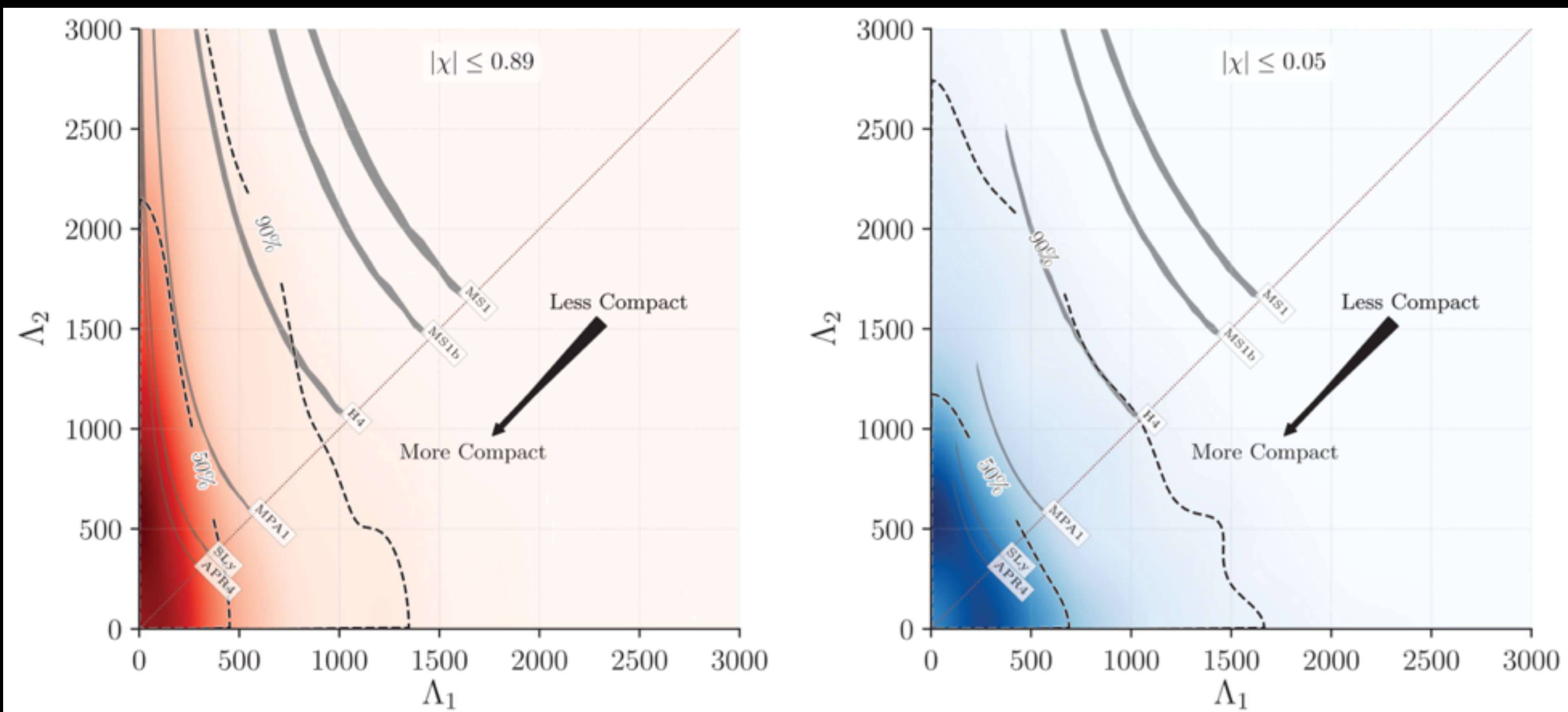
How long to reach the stochastic background?



Neutron star structure

Neutron star radius constrained to 11 km (Nicholl et al. 2017). See also Ligo Virgo Collaboration paper.

The details of the objects' internal structure become important as the orbital separation approaches the size of the bodies. For neutron stars, the tidal field of the companion induces a mass-quadrupole moment [99,100] and accelerates the coalescence [101]. The ratio of the induced quadrupole moment to the external tidal field is proportional to the tidal deformability (or polarizability) $\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$, where k_2 is the second Love number and R is the stellar radius. Both R and k_2 are fixed for a given stellar mass m by the equation of state (EOS) for neutron-star matter, with $k_2 \simeq 0.05$–0.15 for realistic neutron stars [102–104]. Black holes are expected to have $k_2 = 0$ [99,105–109], so this effect would be absent.



Angle definition

measurement [45]. The distance measurement is correlated with the inclination angle $\cos\theta_{JN} = \hat{\mathbf{J}} \cdot \hat{\mathbf{N}}$, where $\hat{\mathbf{J}}$ is the unit vector in the direction of the total angular momentum of the system and $\hat{\mathbf{N}}$ is that from the source towards the observer [140]. We find that the data are consistent with an antialigned source: $\cos\theta_{JN} \leq -0.54$, and the viewing angle $\Theta \equiv \min(\theta_{JN}, 180° - \theta_{JN})$ is $\Theta \leq 56°$. Since the luminos-