

GW170817: FIRST COSMIC EVENT OBSERVED IN  
GRAVITATIONAL WAVES AND LIGHT



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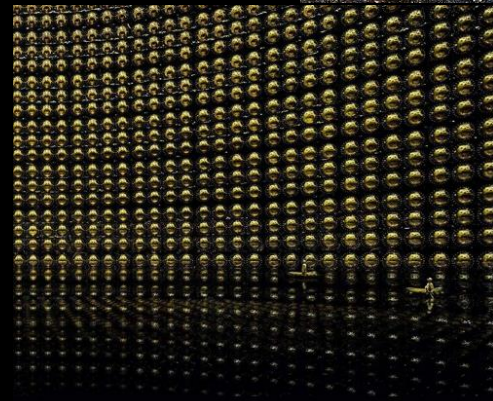
(MAJOR HELP FROM PROF. MANSI KASLIWAL, CALTECH)



# When Did Multi-Messenger Astronomy Begin?

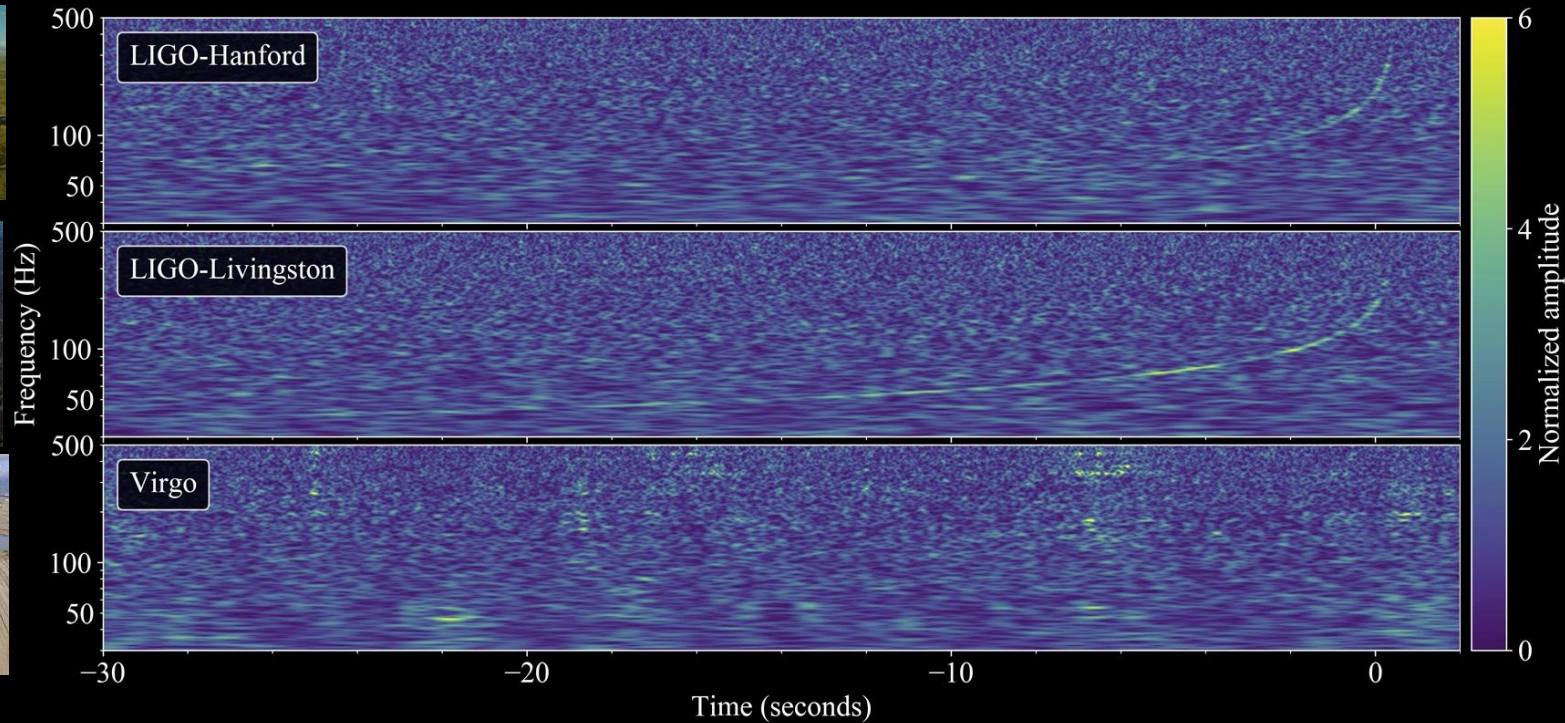
On February 24, 1987 Ian Shelton and Oscar Duhalde, at the Las Campanas Observatory in Chile, looked up in the sky and saw a supernova in the Large Magellanic Cloud.

Approximately two to three hours before the visible light from SN 1987A reached Earth, a burst of neutrinos was observed at Kamiokande II (as well as 2 other neutrino detectors). Neutrino emission, is a by-product of core collapse, but occurs before visible light is seen as it takes time for the shock wave to reach the stellar surface and for the supernova to emit light.



KAMIOKANDE

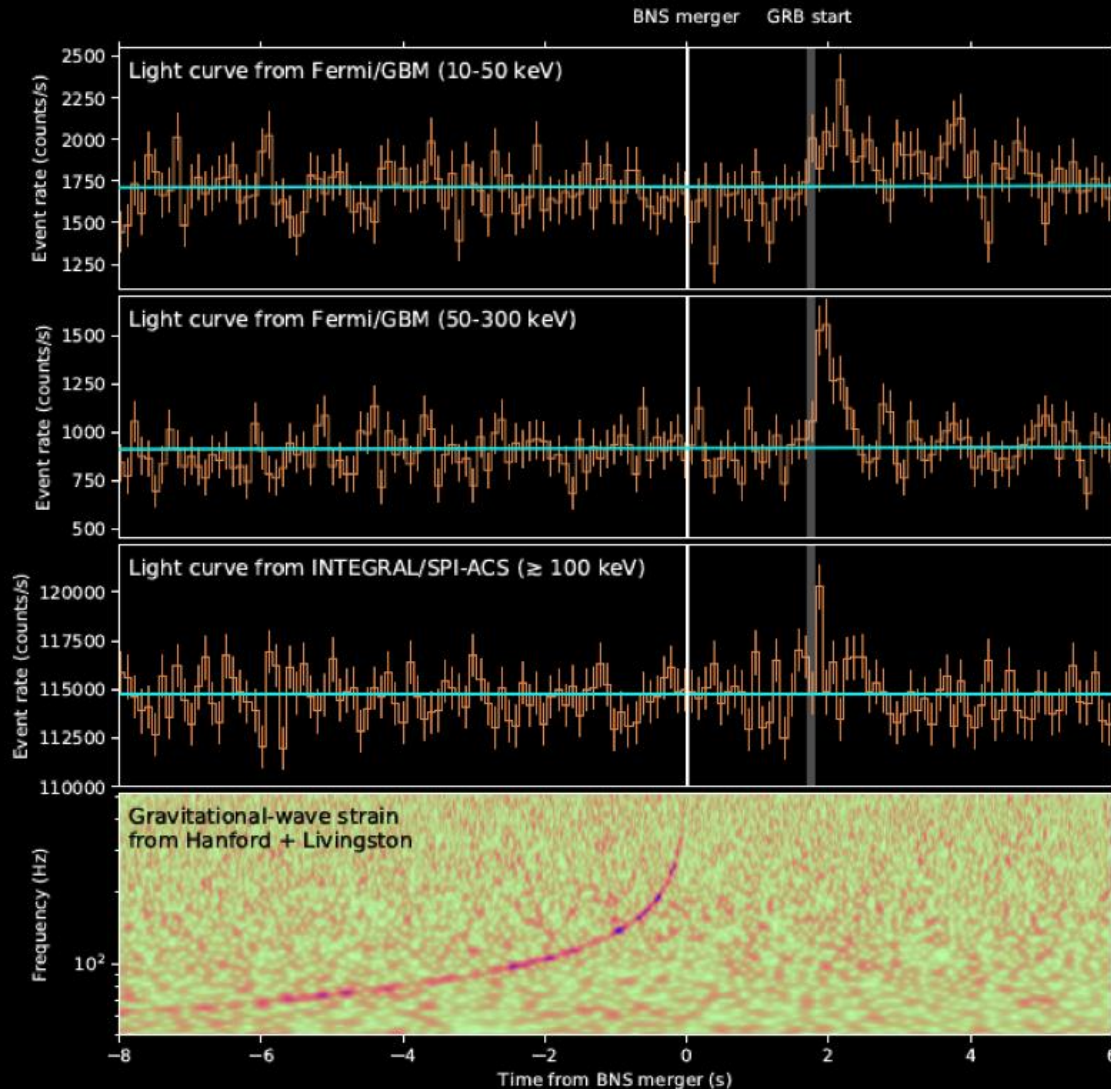
August 17, 2017, 12:41:04 UTC



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

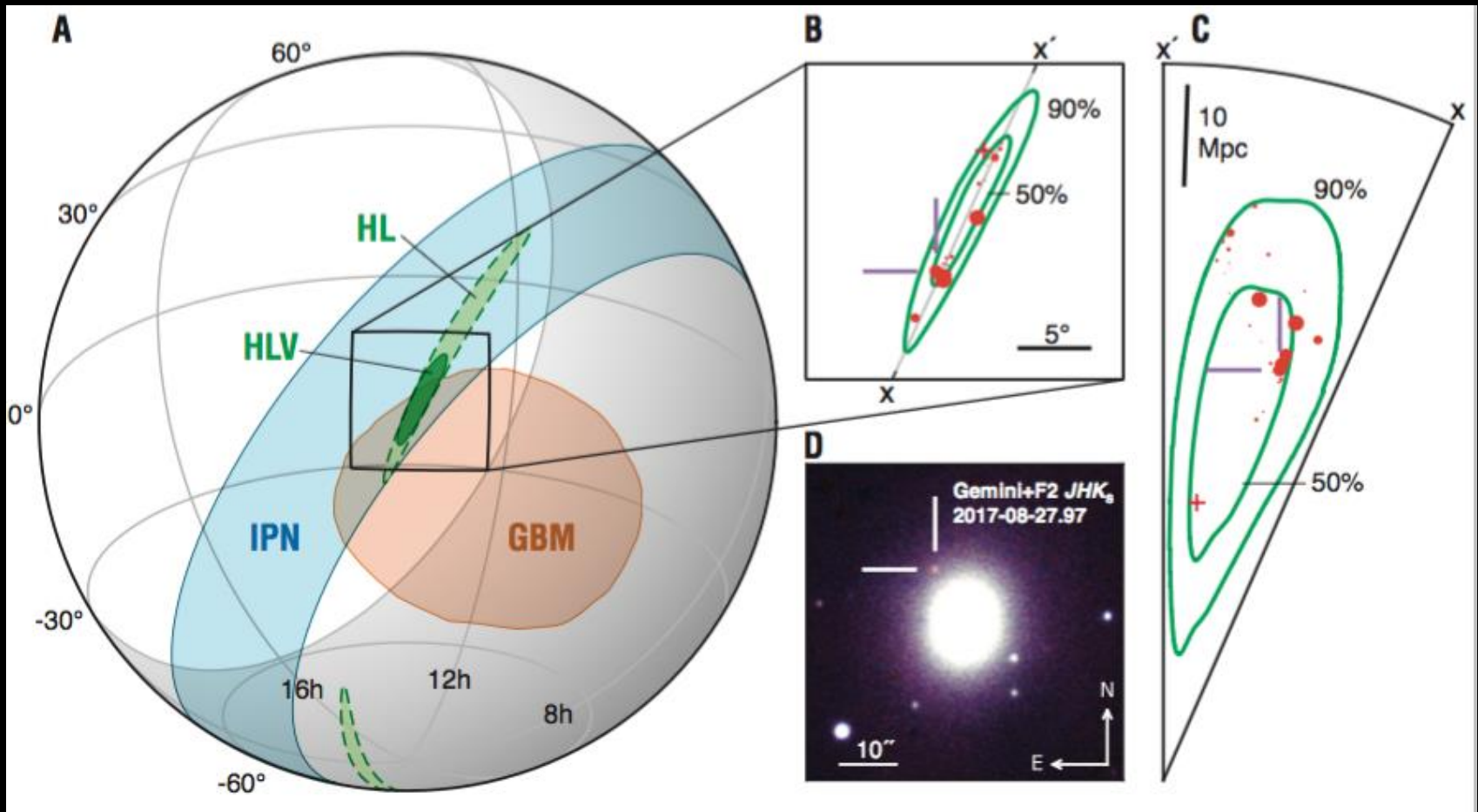
The **longest** ( $\sim 100$  s), **loudest** ( $\text{SNR} \sim 32$ ), **closest** (40 Mpc) signal we've ever observed!

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



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

# GW170817: Binary Neutron Star Merger



Kasliwal et al. 2017c, Science

# Some wagers are fine to lose....

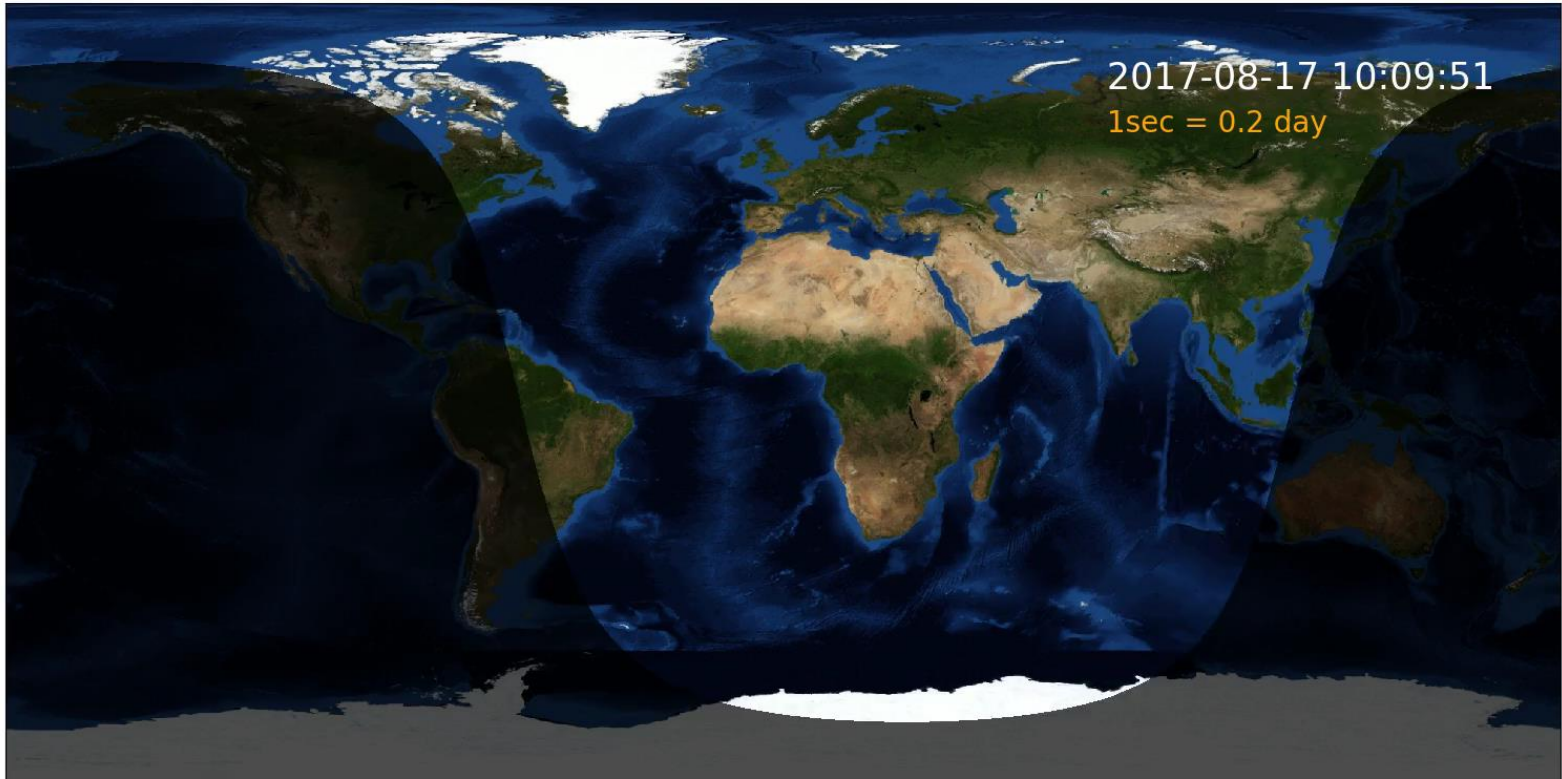
I bet a nice, and appropriately named, bottle of wine on the fact that what was identified as potentially being associated with the NS-NS merger, was in fact just a plain old supernova....

The wine, which I was unloading at the time into my cellar when the first candidates were coming through is called *Syzygy*.

Deinfition: the nearly straight-line configuration of three celestial bodies such as the sun, moon, and earth during a solar or lunar eclipse. A pair, or more, of connected or corresponding things.



# A Global Effort



Movie Credit: GROWTH co-I V. Bhalerao

The GROWTH Team: 18 telescopes, 6 continents, 100+ people

# Q1. Nucleosynthesis

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

Lattimer & Schramm 1974

# Element Origins

# Element Origins

1 H																	2 He	
3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			89 Ac	90 Th	91 Pa	92 U												

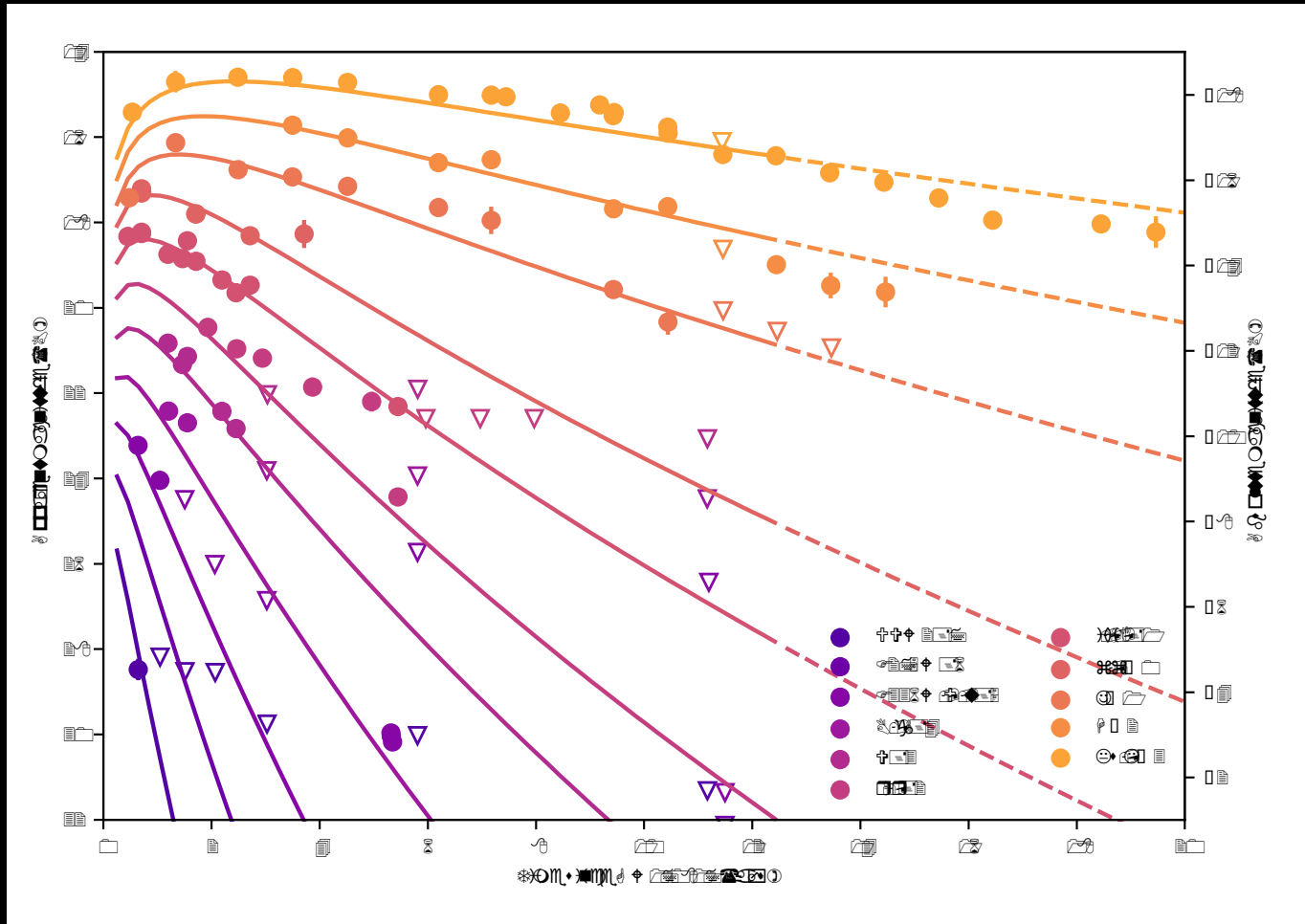
**Merging Neutron Stars**  
**Dying Low Mass Stars**

**Exploding Massive Stars**  
**Exploding White Dwarfs**

**Big Bang**  
**Cosmic Ray Fission**

Based on graphic created by Jennifer Johnson

# UVOIR Light Curve

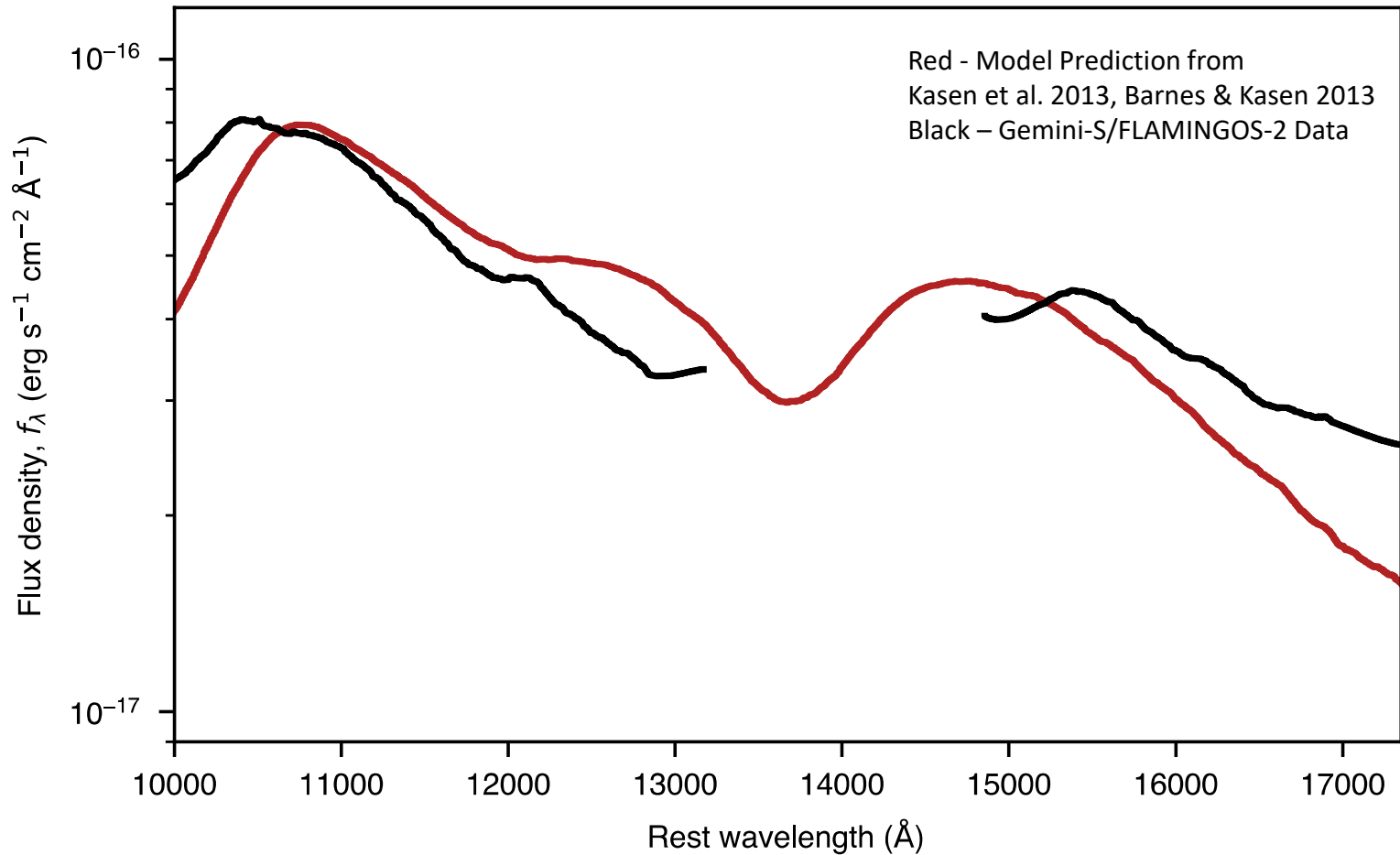


See also:  
 Andreoni et al. 2017  
 Arcavi et al. 2017  
 Cowperthwaite et al. 2017  
 Coulter et al. 2017  
 Drout et al. 2017  
 Lipunov et al. 2017  
 Lyman et al. 2017  
 Pian et al. 2017  
 Soares-Santos et al. 2017  
 Smartt et al. 2017  
 Tanvir et al. 2017  
 Utsumi et al. 2017  
 Villar et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

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

## Heavy Elements were Synthesized.

# Thumbprint of Heavy Elements



Kasliwal et al. 2017c, Science

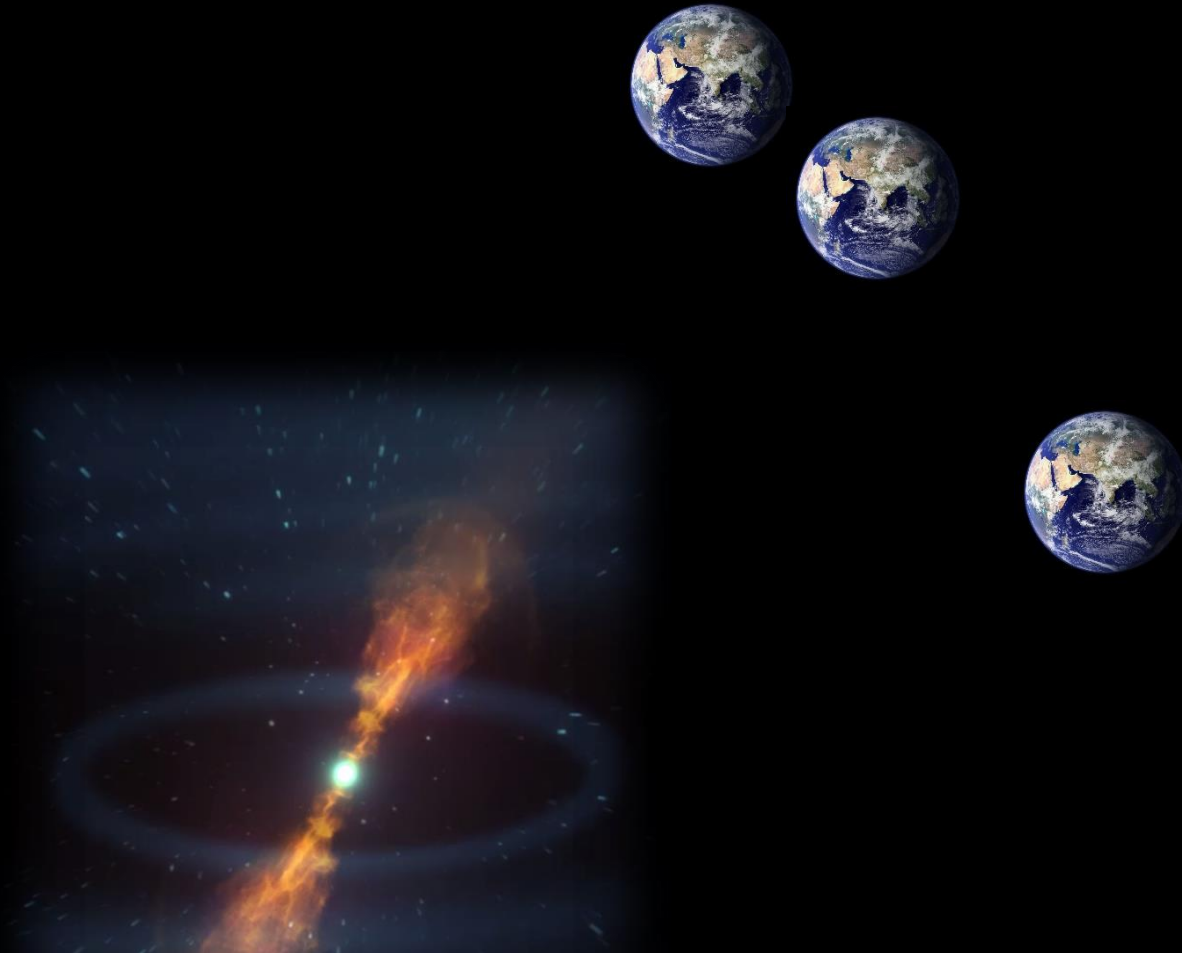
See also Chornock et al. 2017, Troja et al. 2017

## Q2. Jet Physics

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

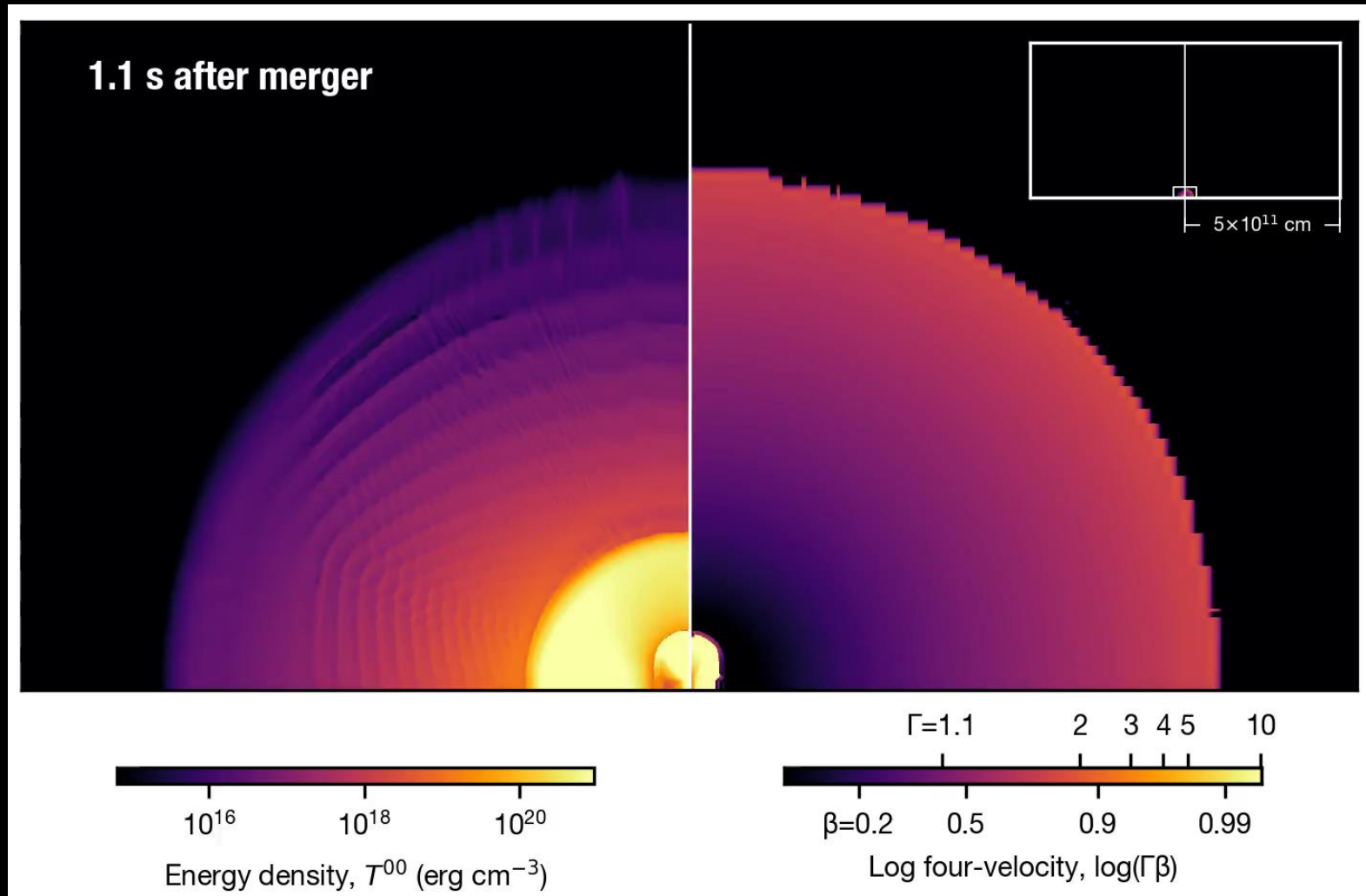
Eichler et al. 1989, Paczynski 1989

# A Gamma Ray Burst or a burst of gamma-rays?



Surprise # 1: Weaker than a sGRB by 10,000x  
Surprise # 2: Delayed onset of Radio/X-rays

# A New Model: The Cocoon Breakout



Kasliwal et al. 2017c. Science

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. 2015

# A Concordant Picture

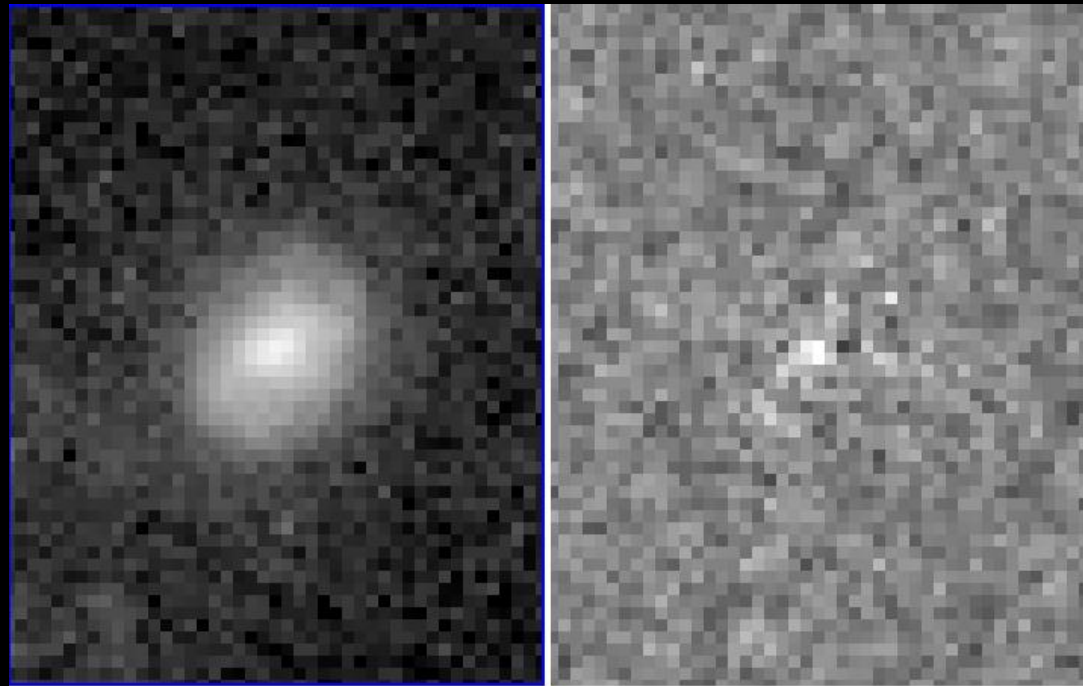
# The Rates of these events

Based on this **NOT** being a kilonova, we find a 3- $\sigma$  upper limit for these theoretical models of  $\sim 800$  events/yr/Gpc<sup>3</sup>

(Kasliwal *et al.*, Science, 2017)

Therefore, the large ejecta mass of EM170817 and the high rate estimates for GW170817 and EM170817 are consistent with NS-NS mergers being the main production sites of r-process elements in the Milky Way

The Zwicky Transient Facility should clean up on these events.



- Good candidate, met the criteria and declined quickly... not a nova!
- No other detections spanning 4 years.
- 150 other candidates vetted.

*"Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Networking and Information Technology Research and Development Program."*

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