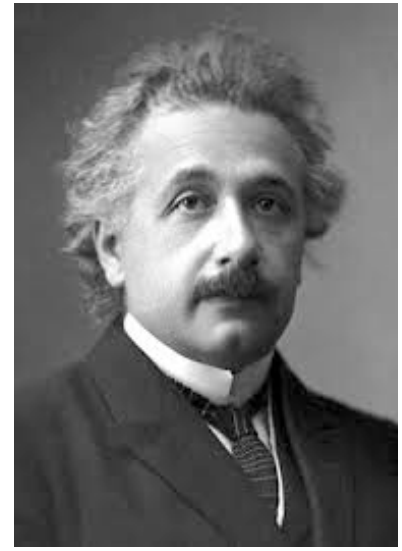
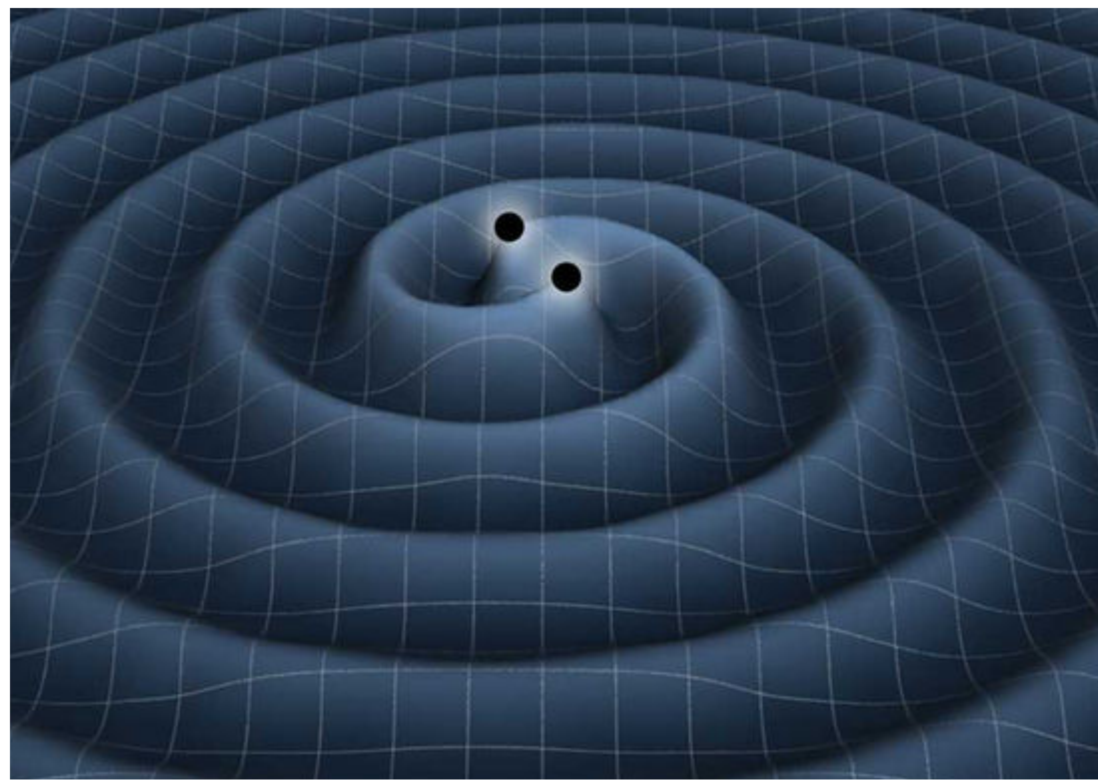
LIGO and gravitational-wave Astrophysics at UO

Gravitational Waves (GWs)

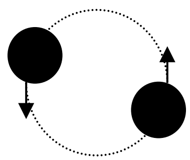


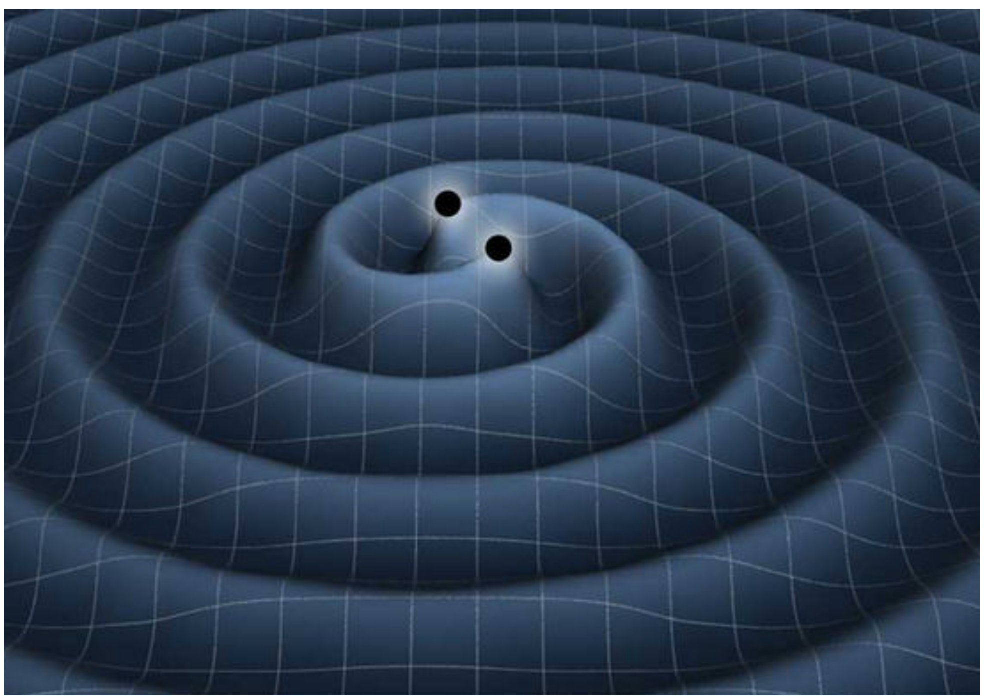
- The waves of the electromagnetic force are realized as (electric and magnetic) fields which propagate through space and time. [Maxwell, 1865]
- General Relativity describes gravity in terms of a spacetime which is deformable. [Einstein, 1915]
- GWs are oscillations of that spacetime. [Einstein, 1916]
- “ripples in spacetime”



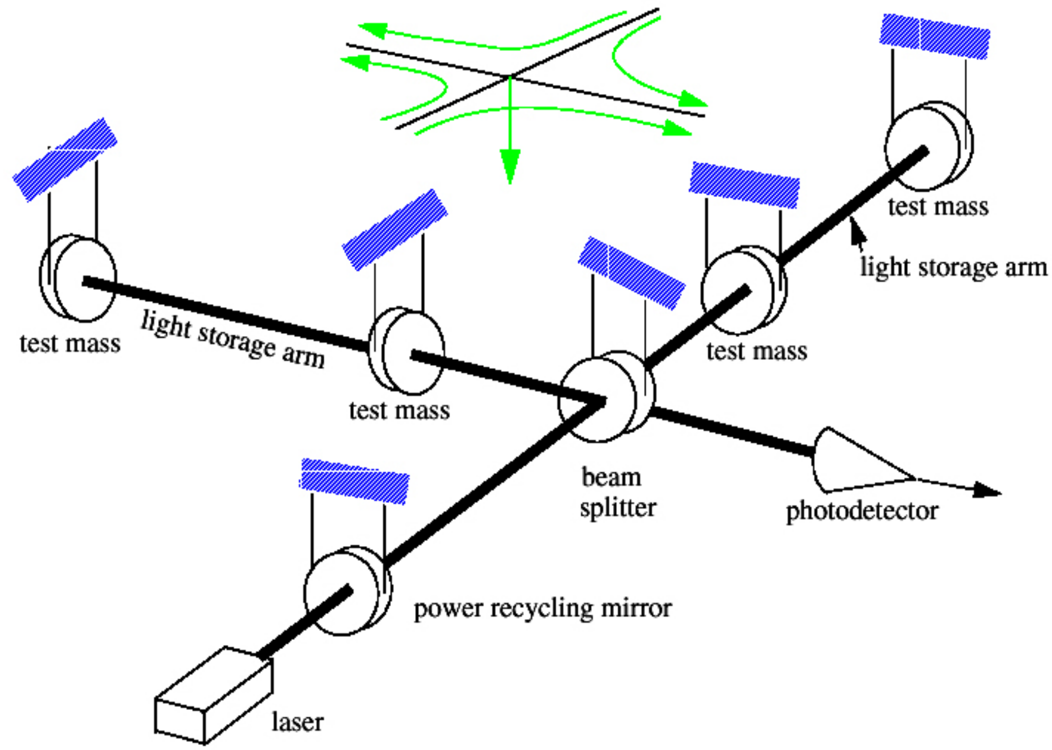
Gravitational waves and LIGO: short version

Binary black hole system





As detected by LIGO:

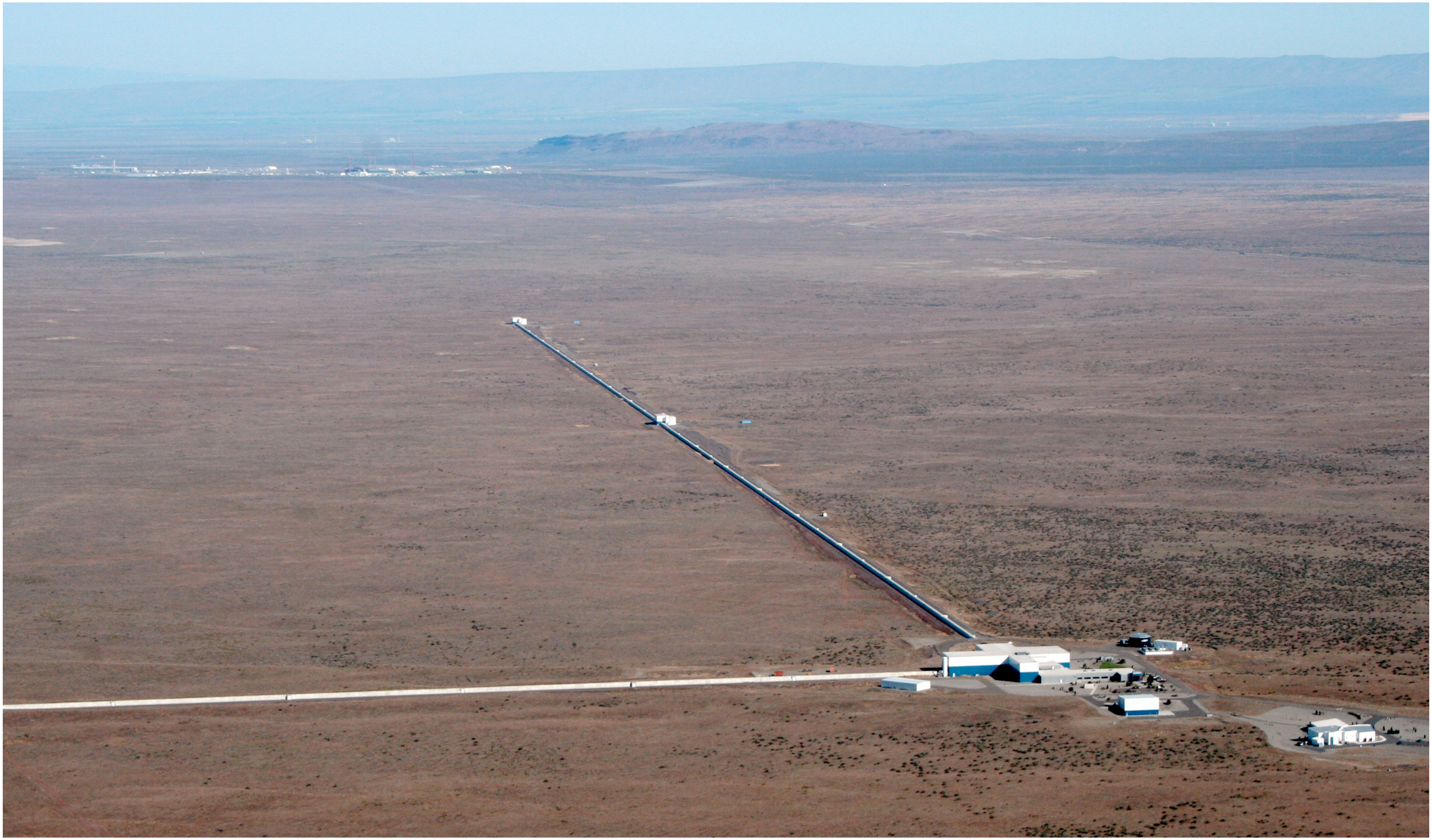


GW ripples manifest as a space strain h, where $h = \Delta L / L$

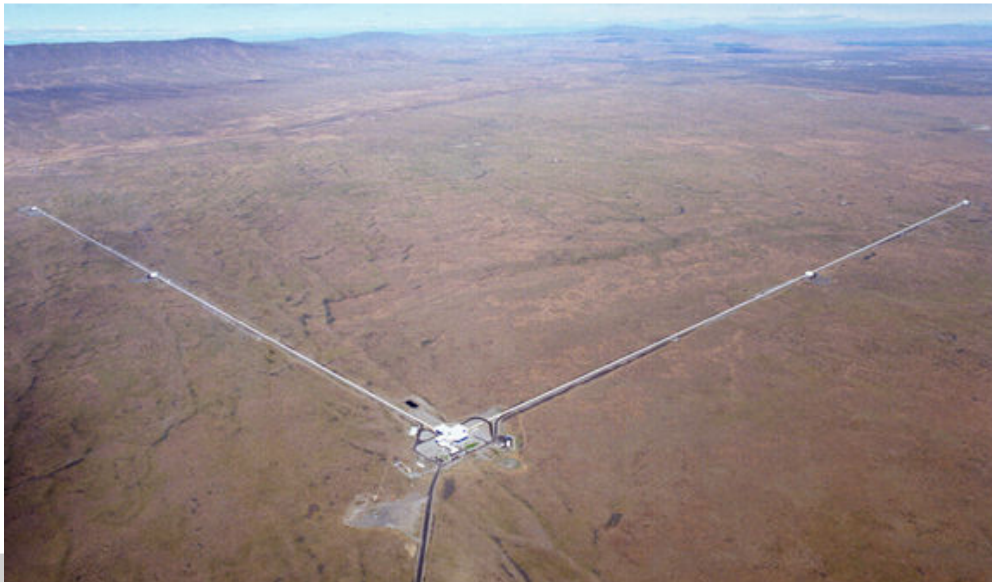
Realistic sources: $h \sim 10^{-23}$

$\Rightarrow \Delta L \sim 10^{-19}$ m (Yikes !)

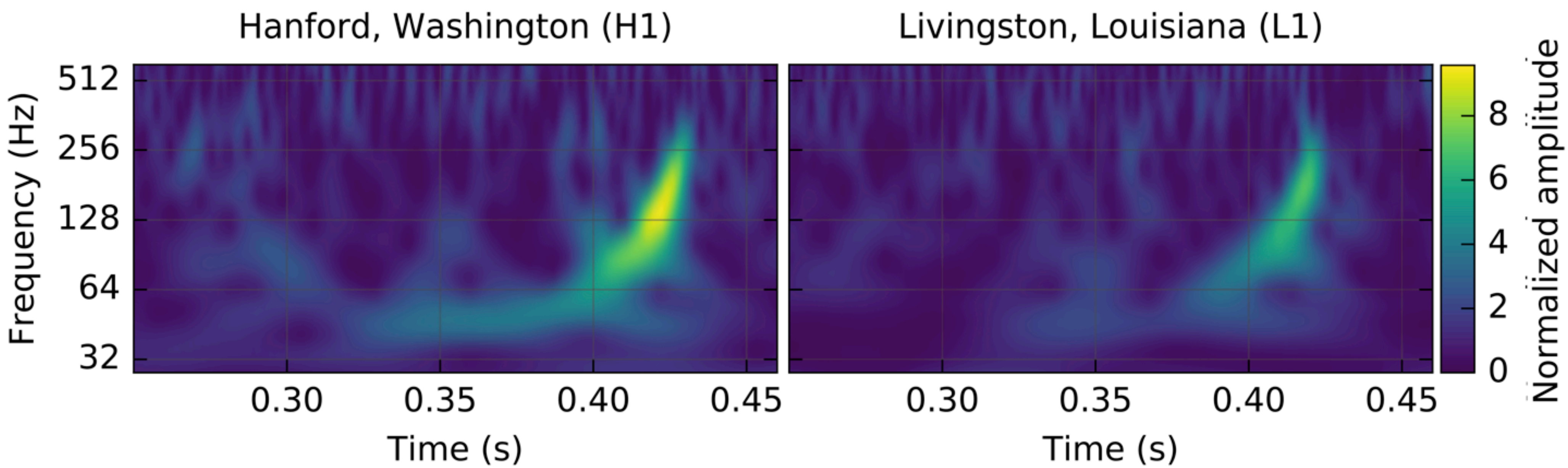
LIGO Hanford Observatory



observatories



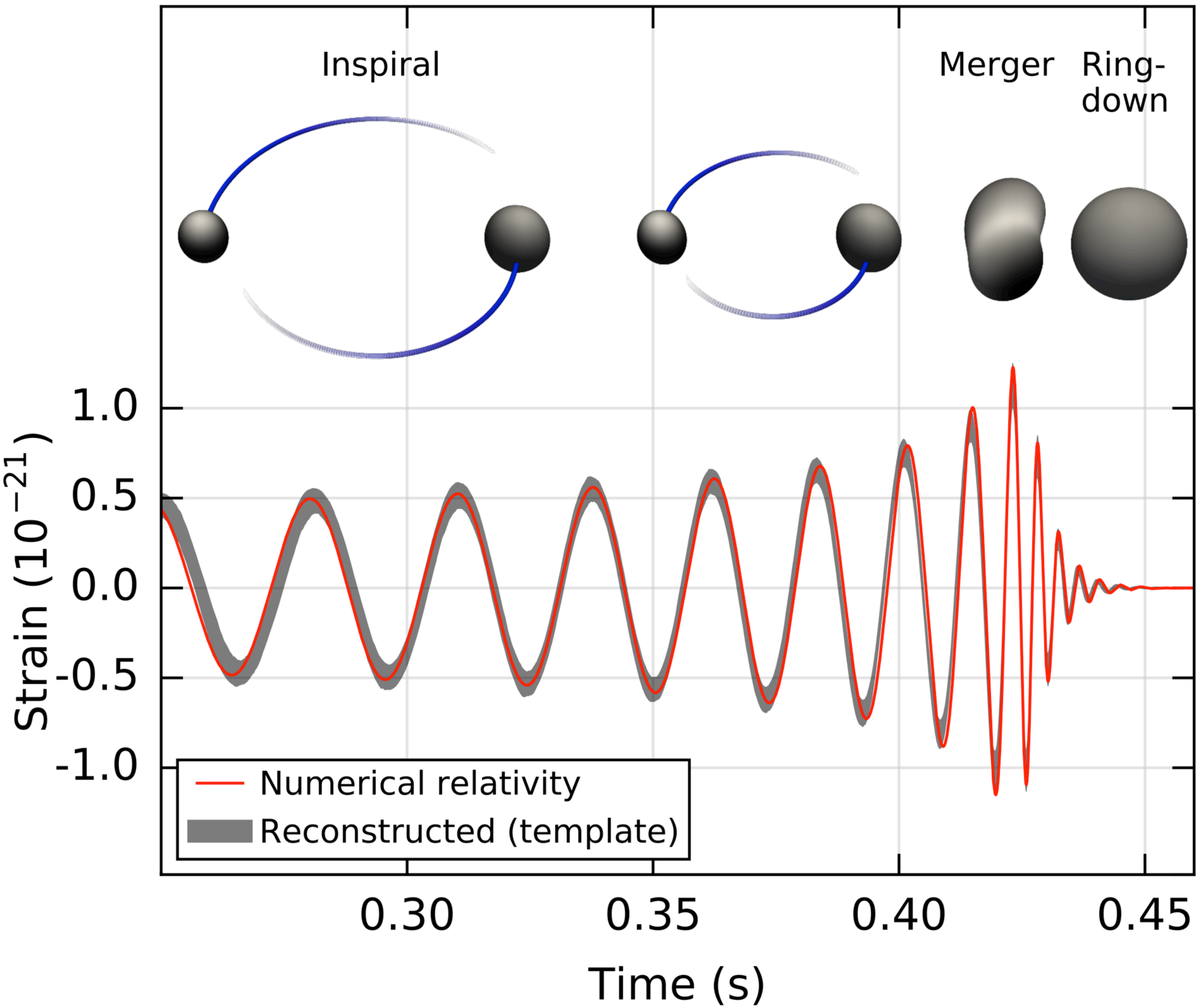
Boom !



GW150914

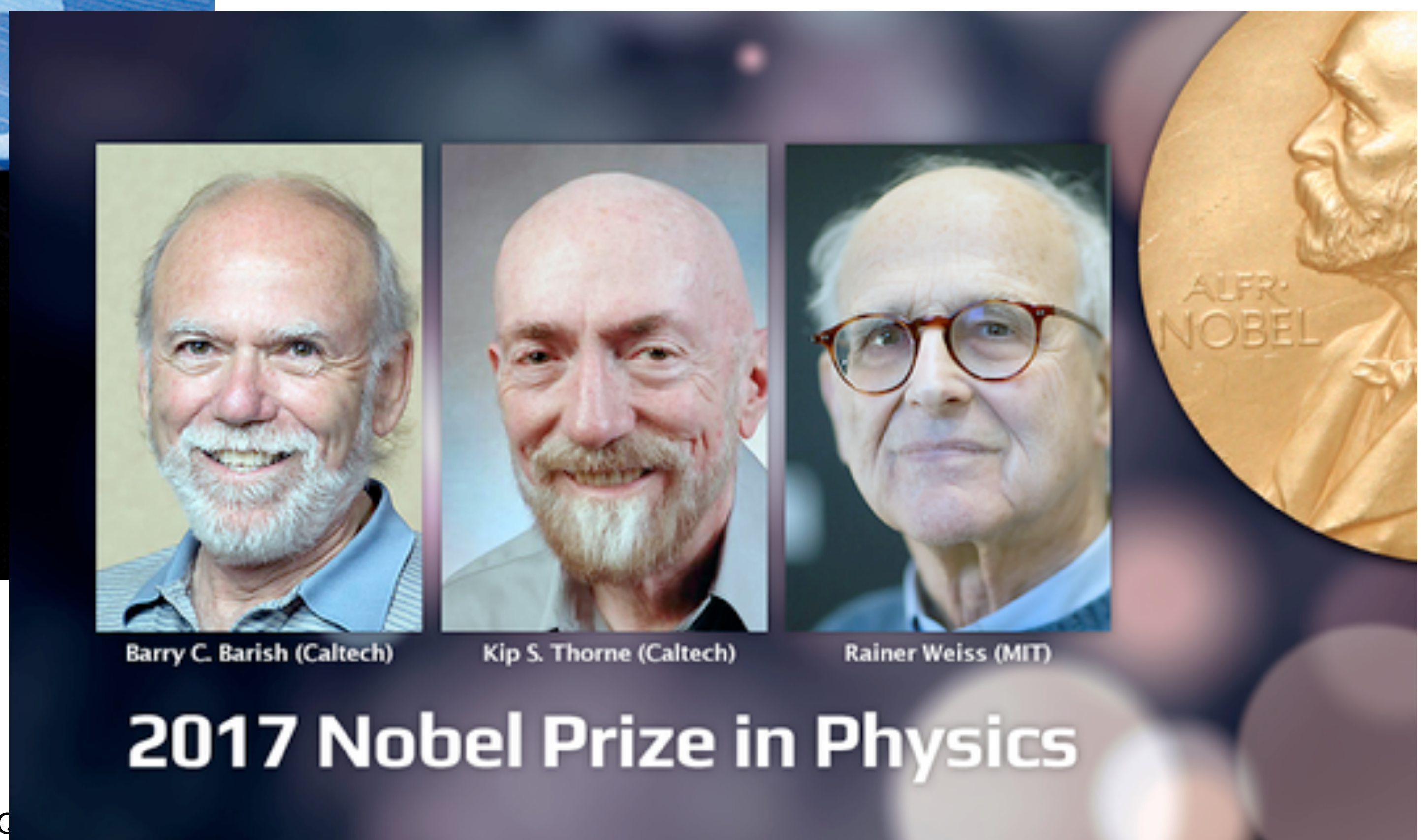
- First observation of GWs
- First direct observation of black holes

Binary black hole inspiral, merger, ringdown

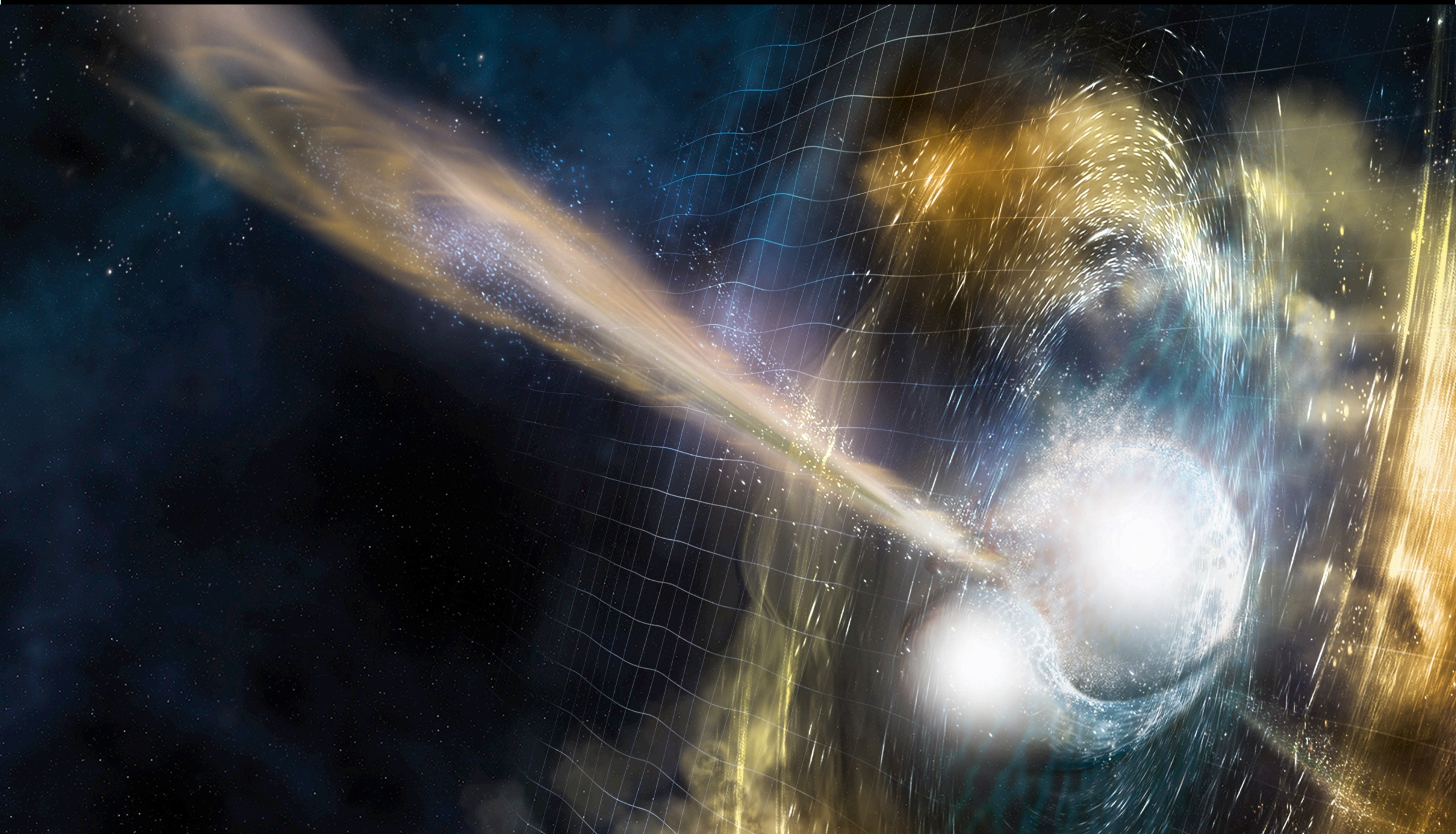


LIGO

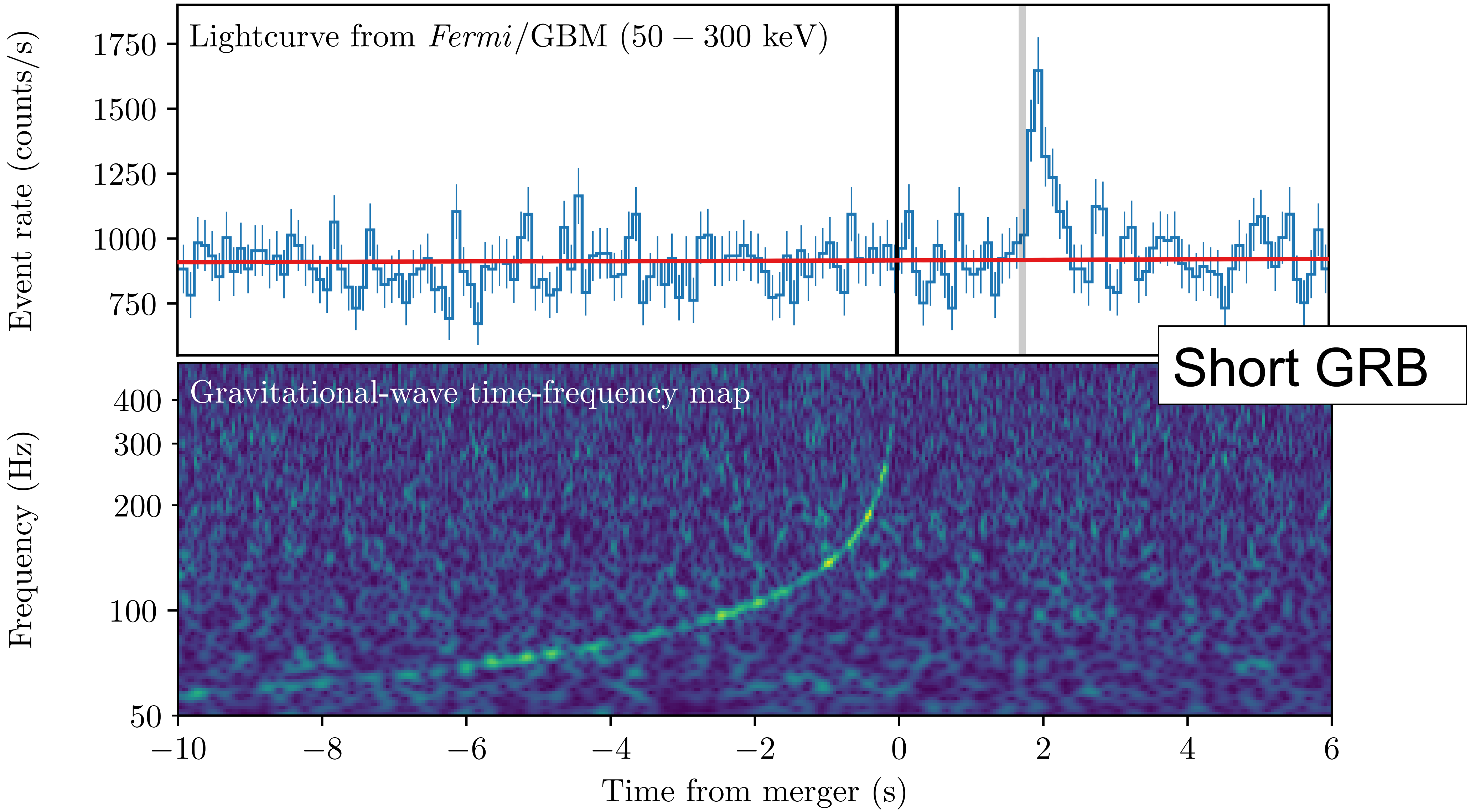
GW Discovery Accolades



Boom II:
Binary neutron-star merger August 17, 2017



August 17, 2017: LIGO+Fermi



$\Delta t = 1.74 \pm 0.05$ s

Speed of gravity

$$\Delta t = 1.74 \pm 0.05\,\mathrm{s} = \Delta t_{\mathrm{astro}} + \frac{D}{c^2}(c_g - c)$$

- Δt_astro ~2 s is very reasonable
  - Our prior based on astrophysics of SGRBs was Δt = [0,4] s
  - jet with γ ~ 50 is delayed by ~2 s (relative to v=c) at a photospheric radius of ~30 AU ✔

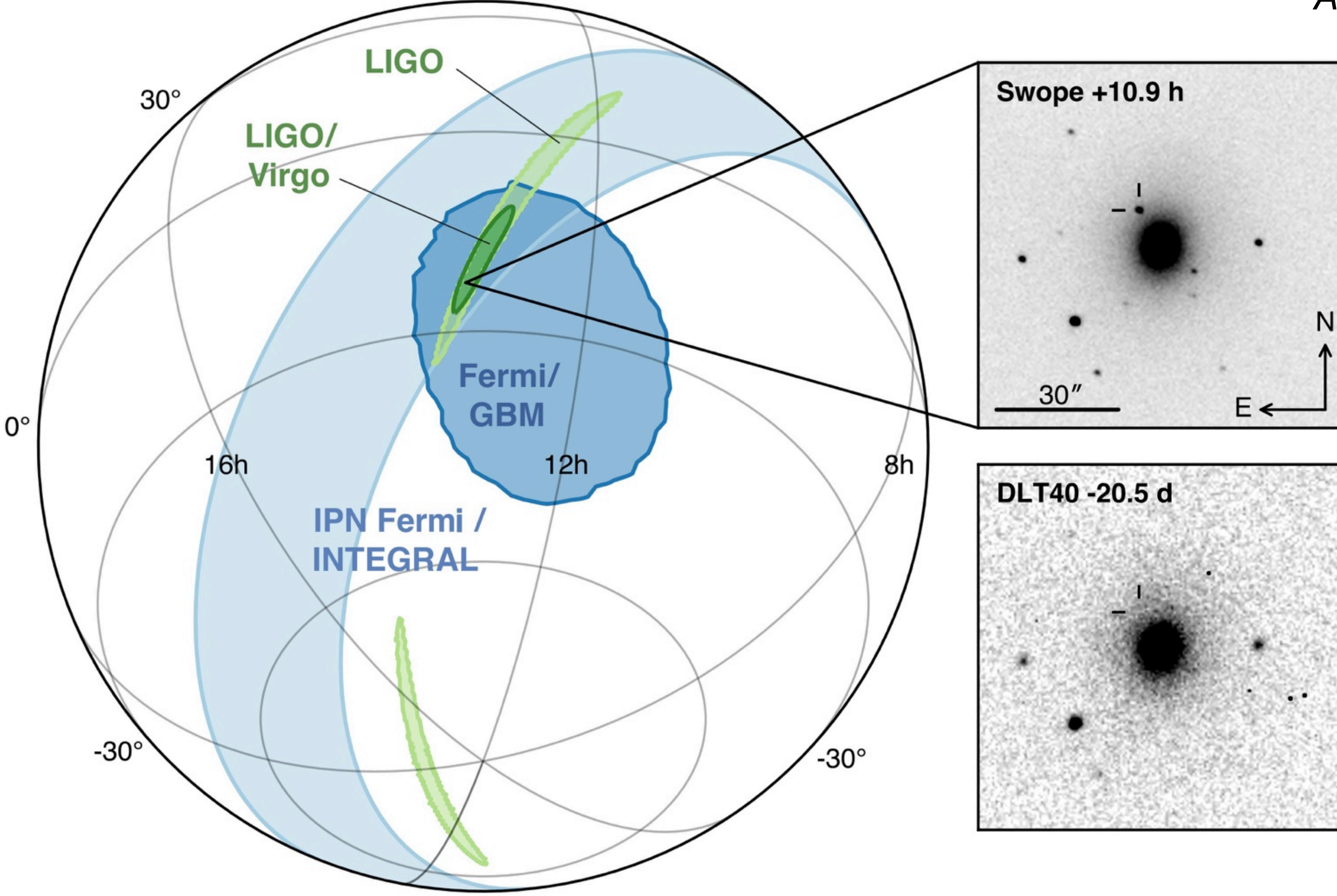
- Limits: (1) Let Δt_astro = 0; (2) Let Δt_astro = 10 s:

$$-3 \times 10^{-15} < \frac{c_g - c}{c} < 7 \times 10^{-16}$$

- Future measurements at different distances can improve this

GW localization allows ID of afterglow (kilonova)

ApJL **848** L12

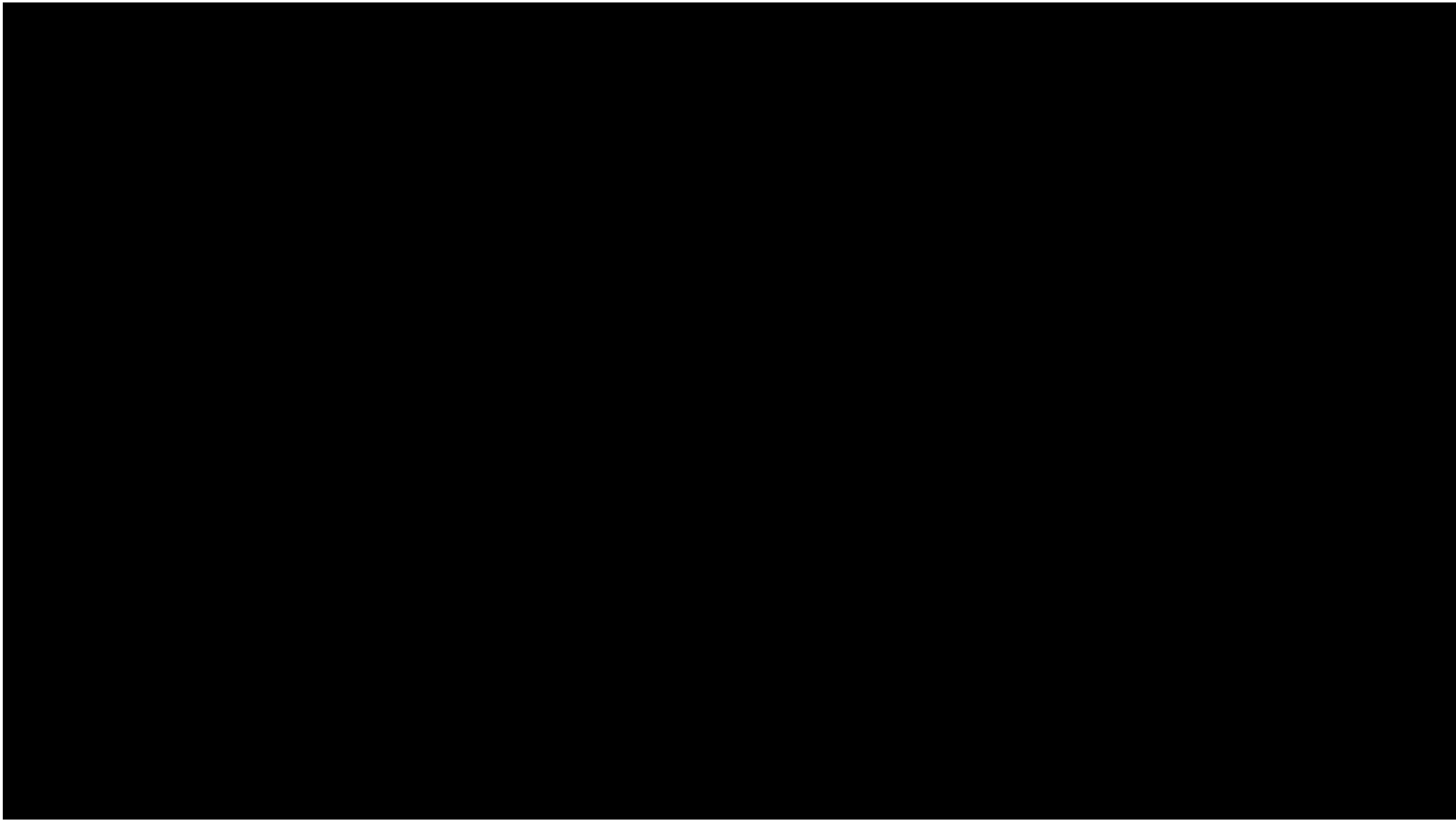


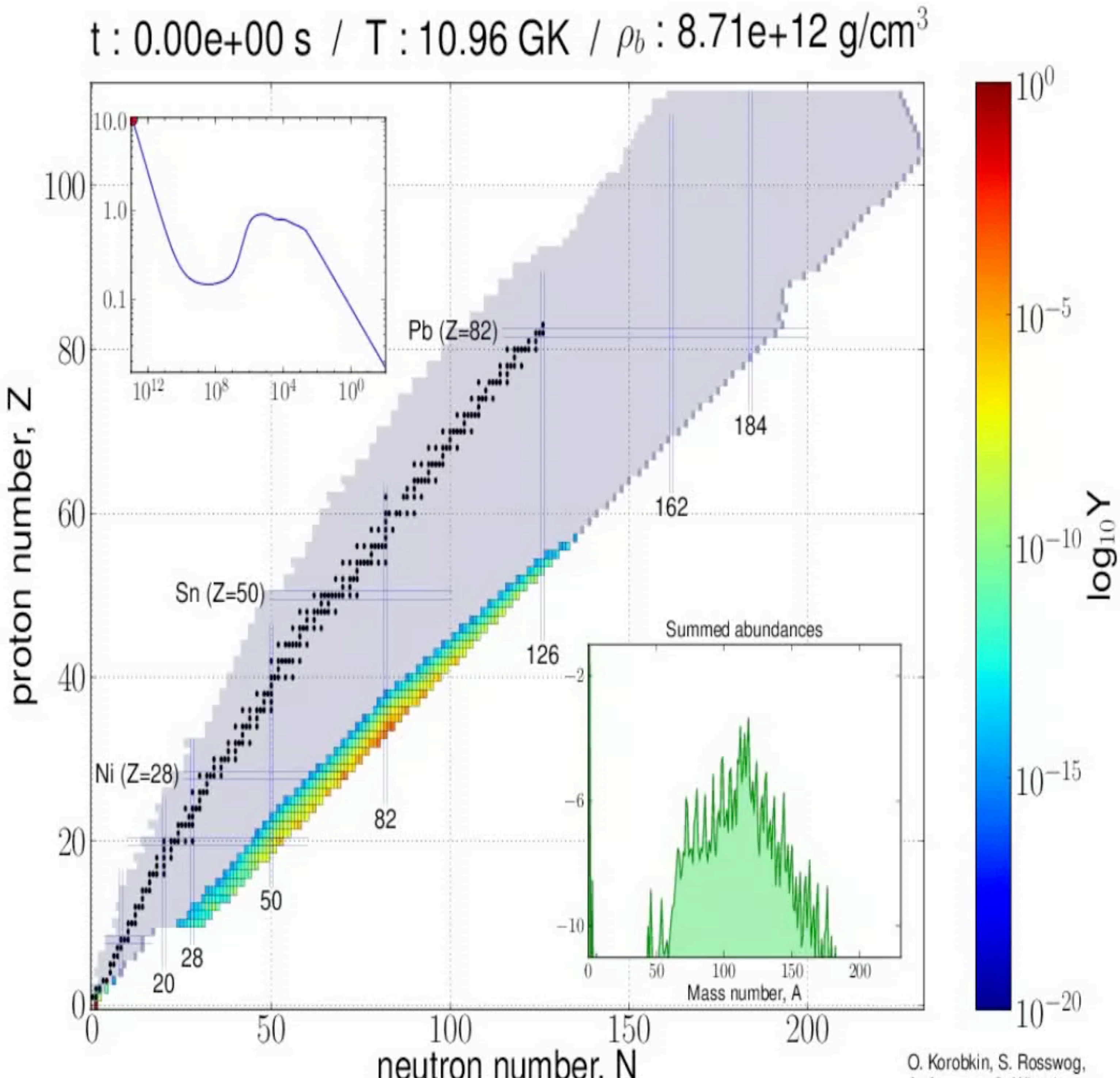
NGC 4993
43 ± 3 Mpc

offset of 2 kpc – typical of kicks

"Multimessenger Astronomy"

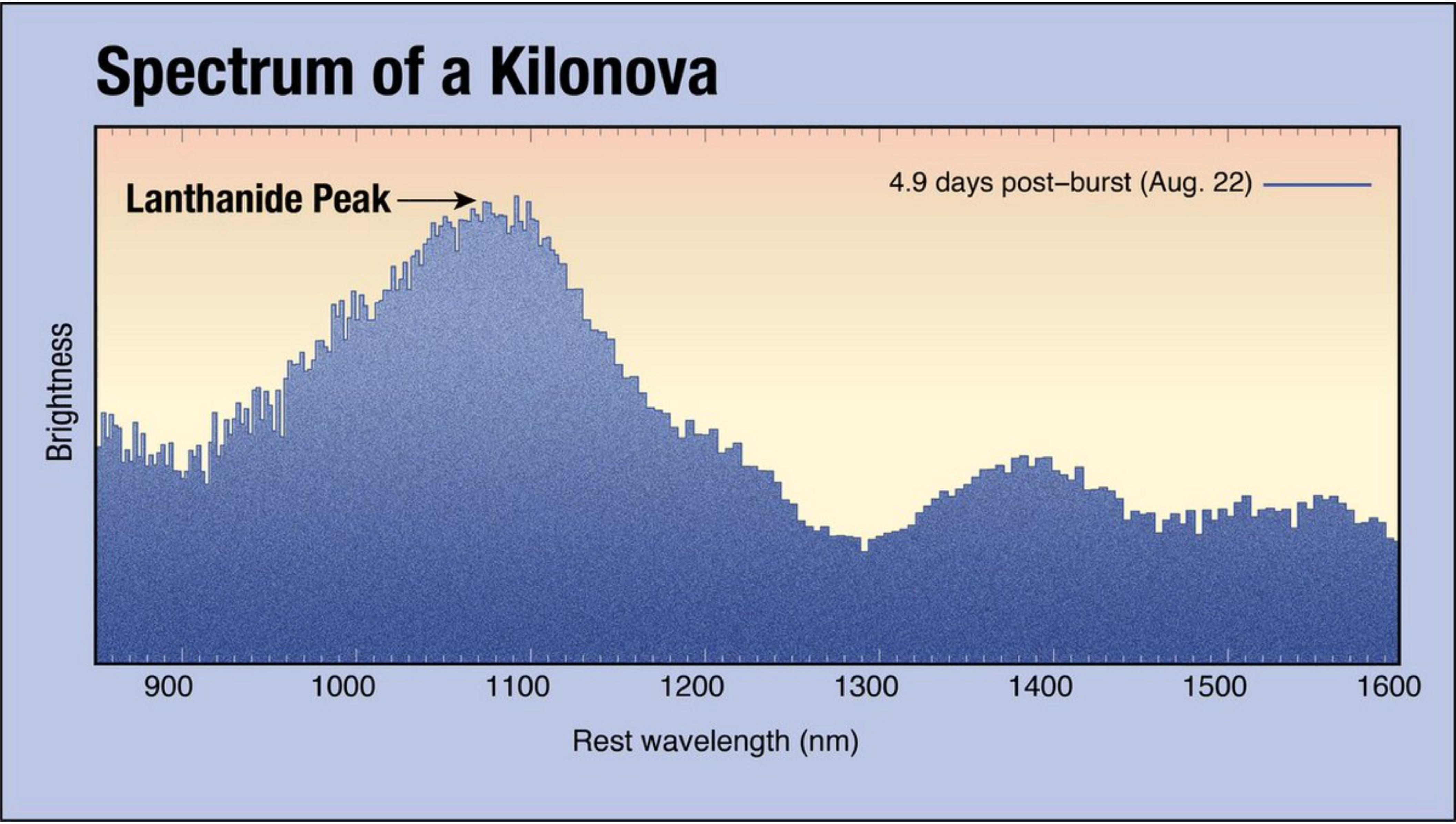
Merger, gamma-ray burst, afterglow (“kilonova”)



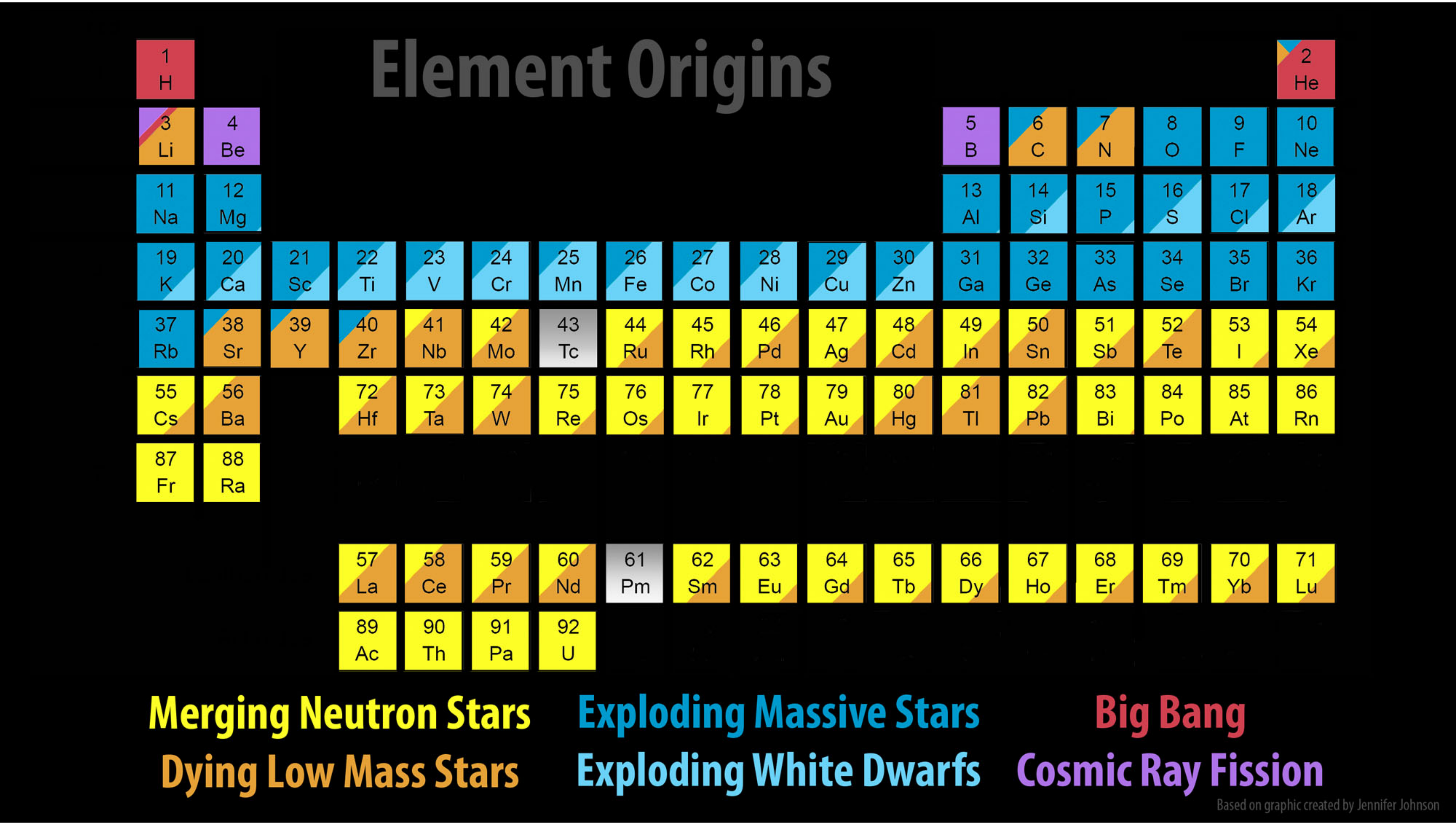


O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

Observed afterglow ("kilonova") spectrum

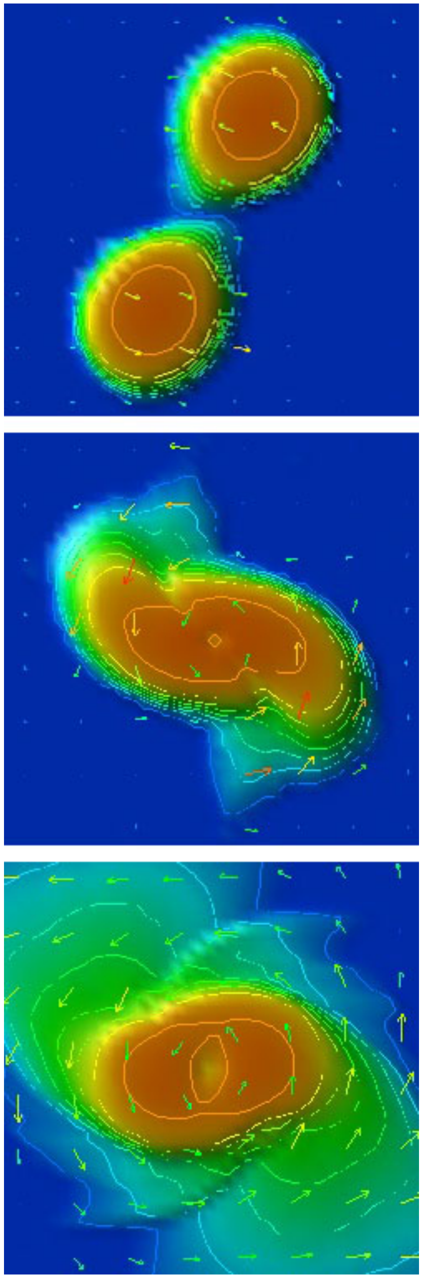


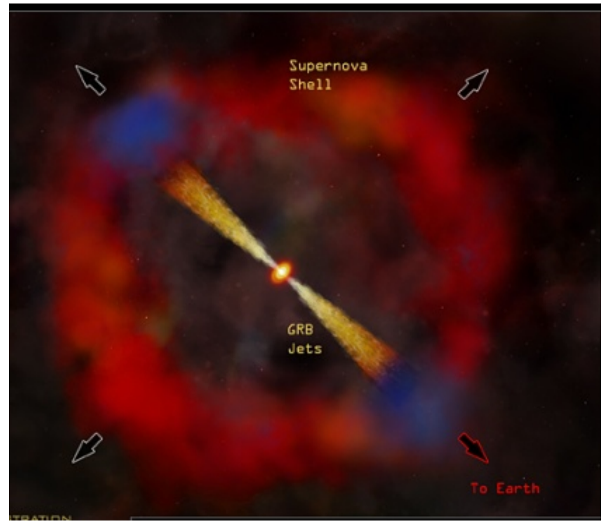
Origins of elements: Major Update



NS-NS or NS-BH mergers, NS equation of state, EM afterglows (kilonova), Gamma-ray Bursts

Shibata



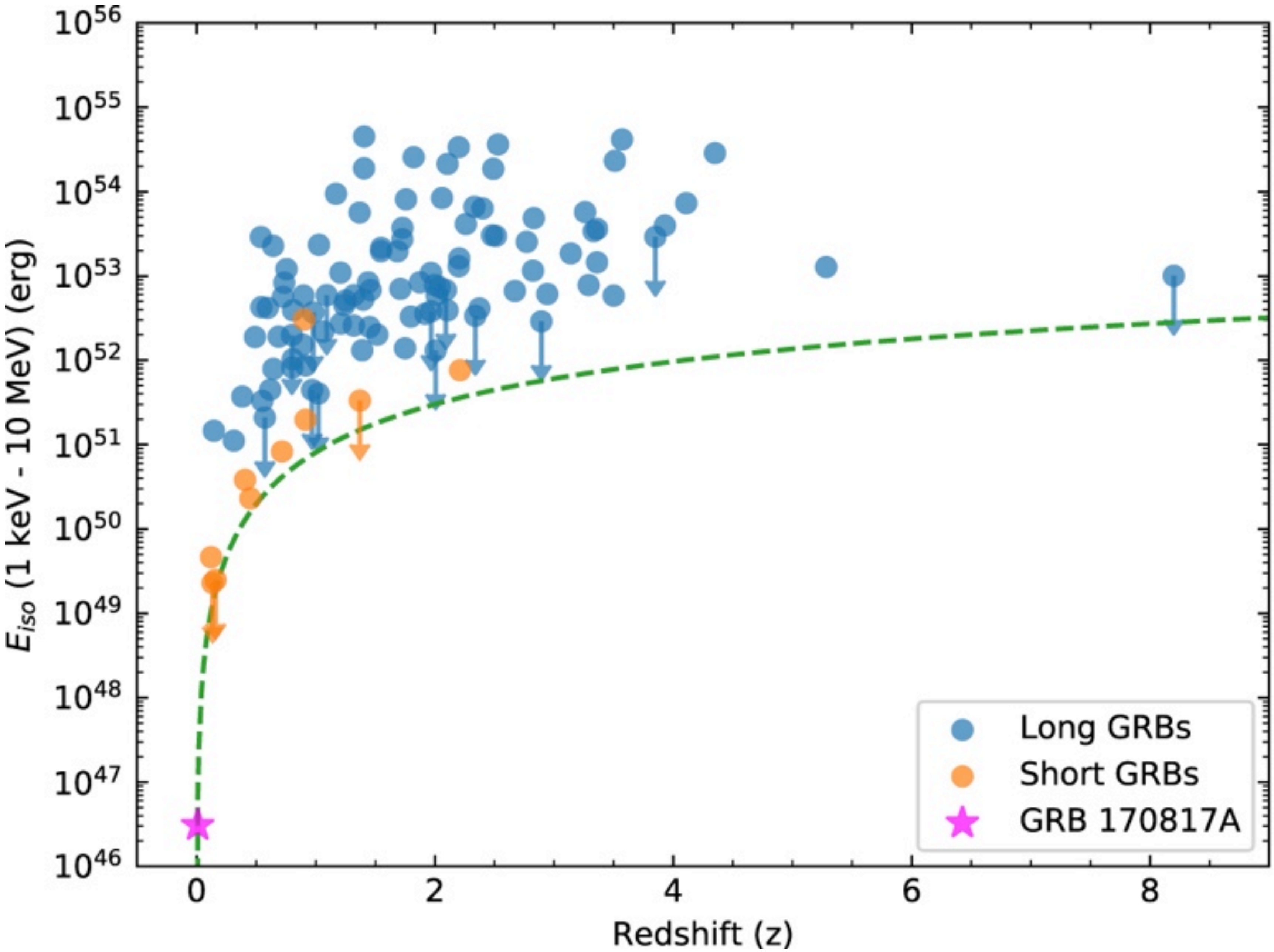


GW waveform ➔ stiffness of NS (EOS)

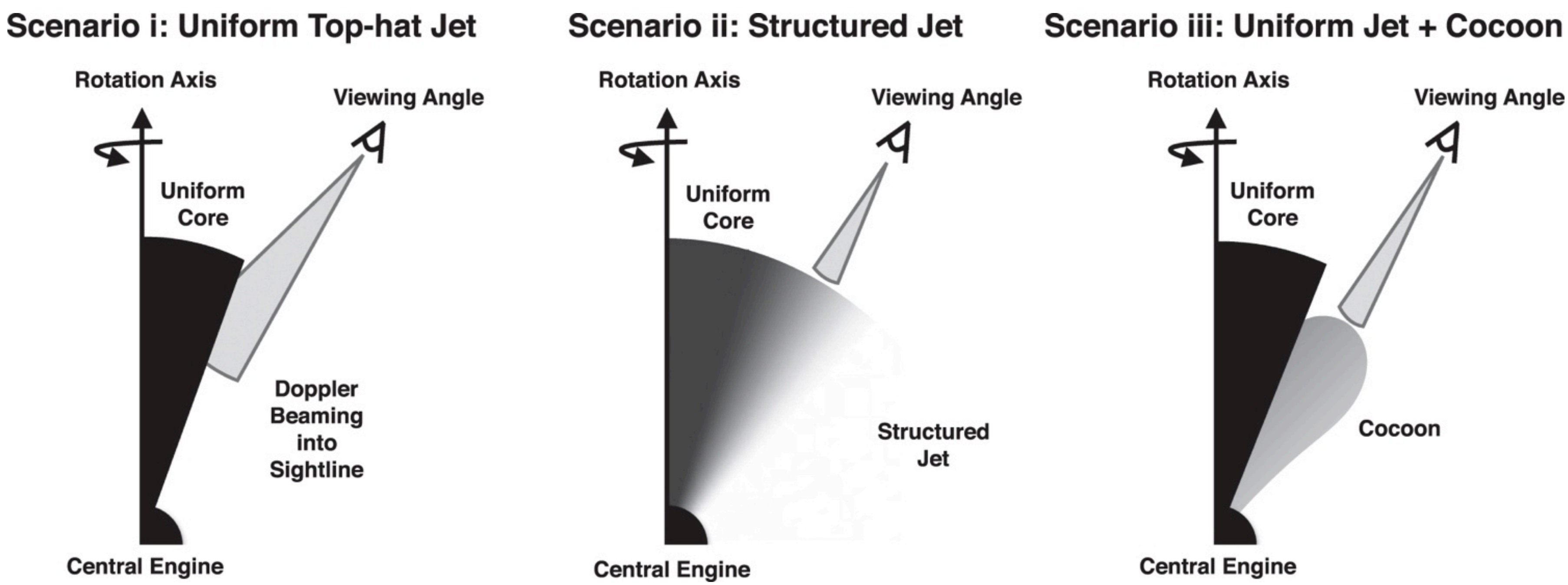
GRB astrophysics

Measure distance (GW) and redshift (EM)
➔independent Hubble plot
➔ accelerating universe

GRB 170817A: a dim outlier



Evidence implies the GRB is viewed off axis - I



$$h_+ = h_o \boxed{\frac{1+\cos^2\iota}{2}} \cos 2\Phi(t)$$

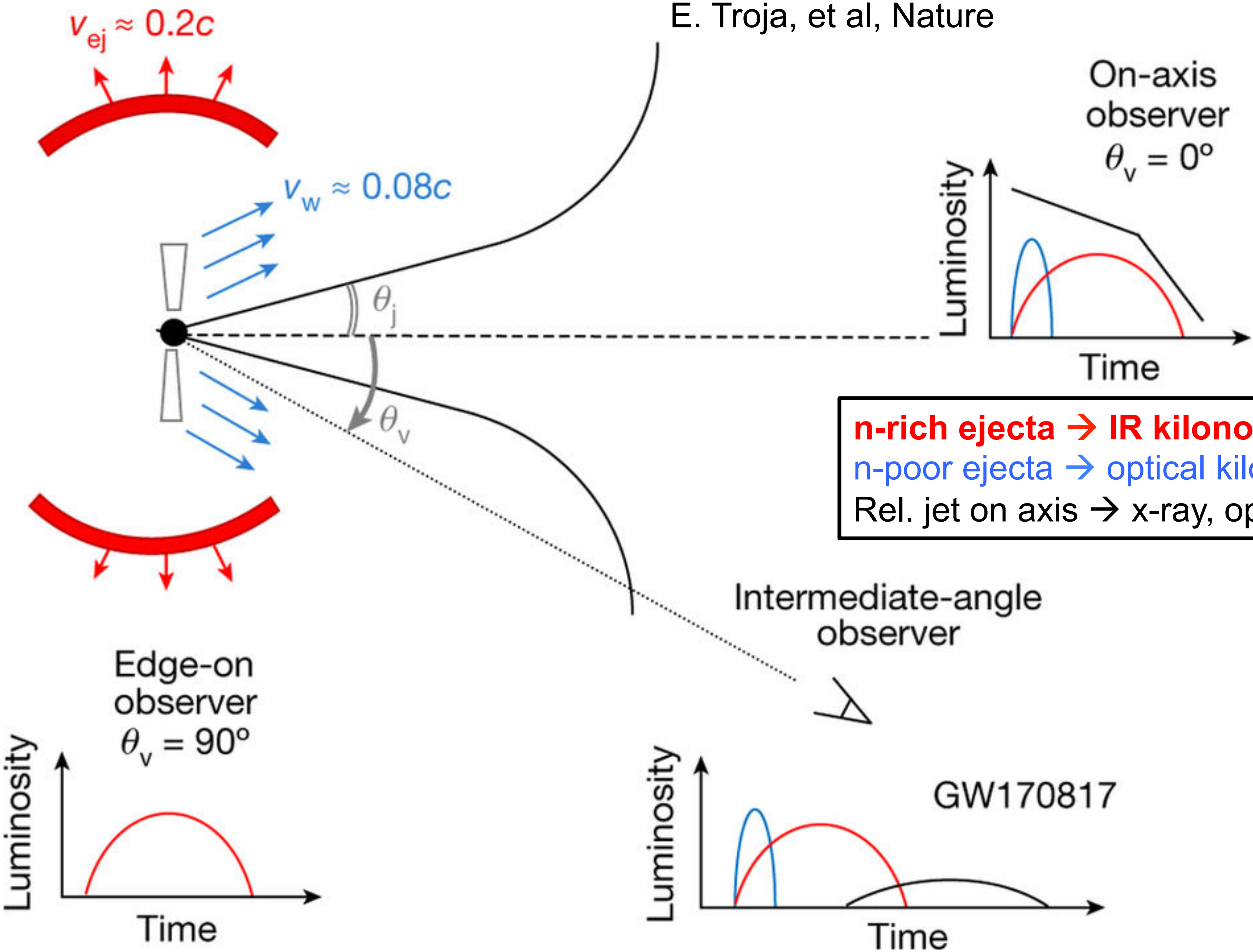
$$h_\times = -h_o \boxed{\cos\iota} \sin 2\Phi(t)$$

GW: ι < 56 degrees

Consistent with GRB viewed 20-30 degrees off axis

Expected behavior of EM emissions

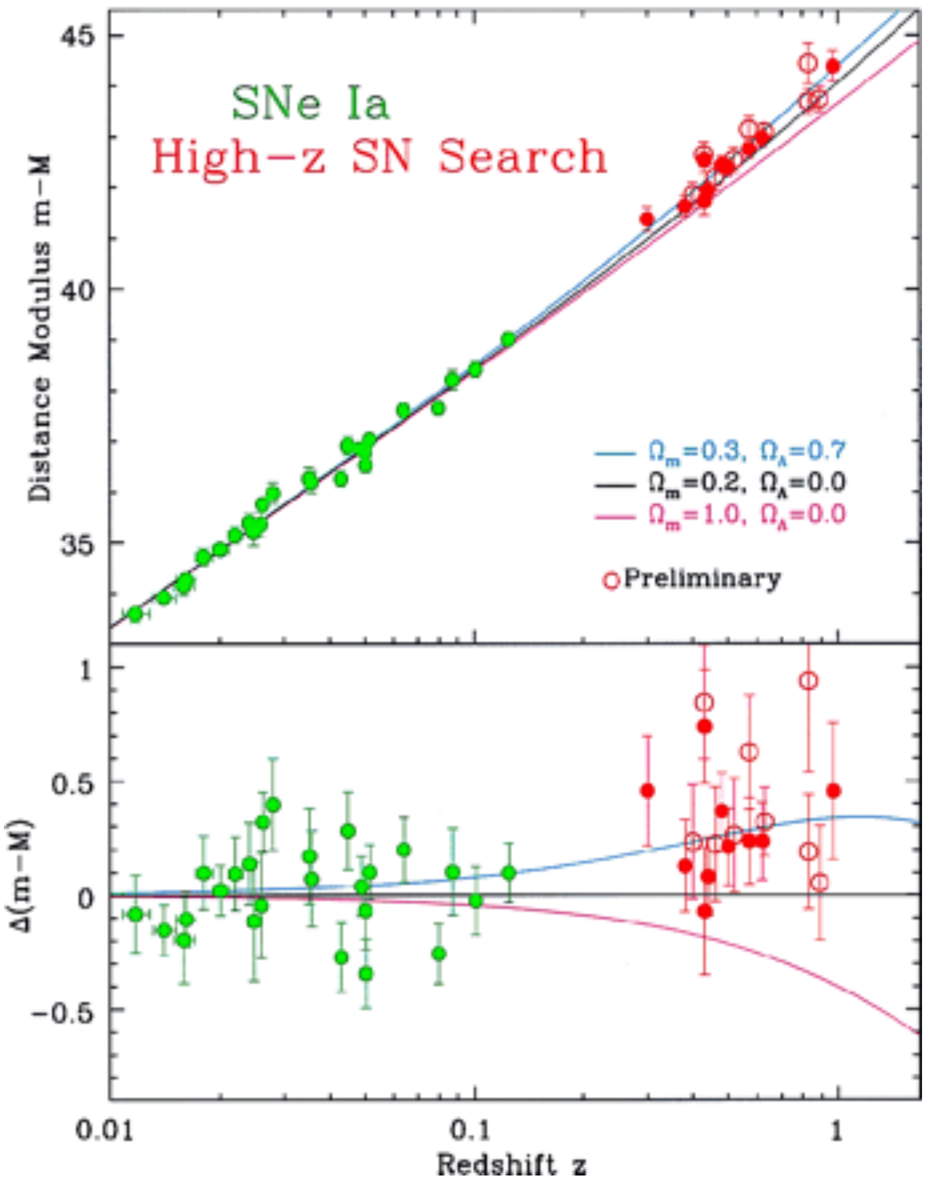
E. Troja, et al, Nature

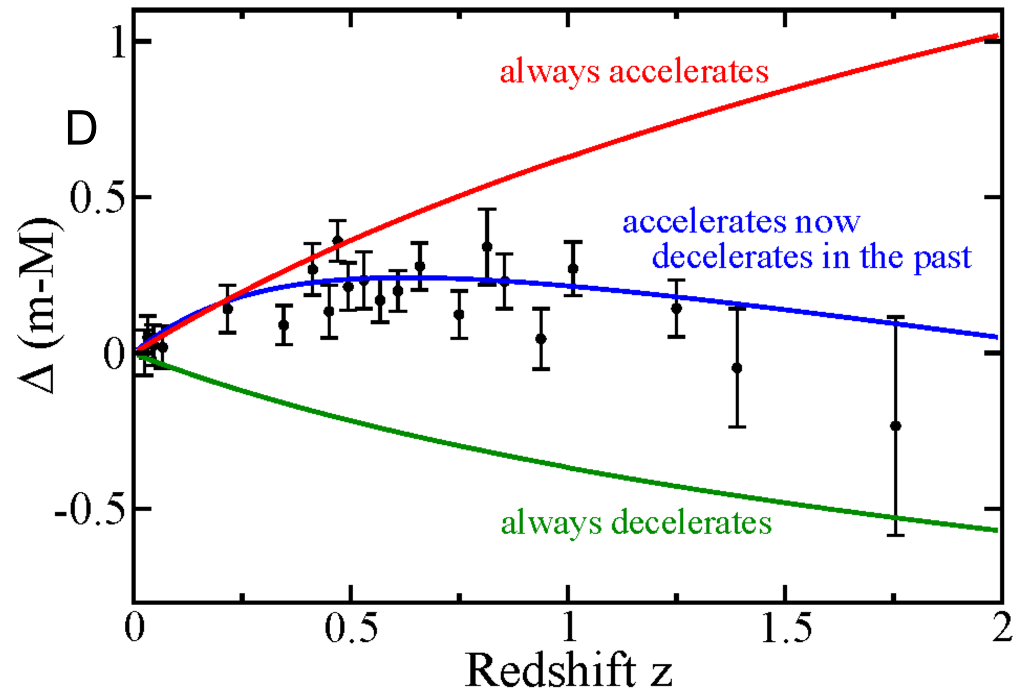


n-rich ejecta → IR kilonova
n-poor ejecta → optical kilonova
Rel. jet on axis → x-ray, optical, radio

GW Measurement of Hubble Flow

$$\dot{R} = H R$$



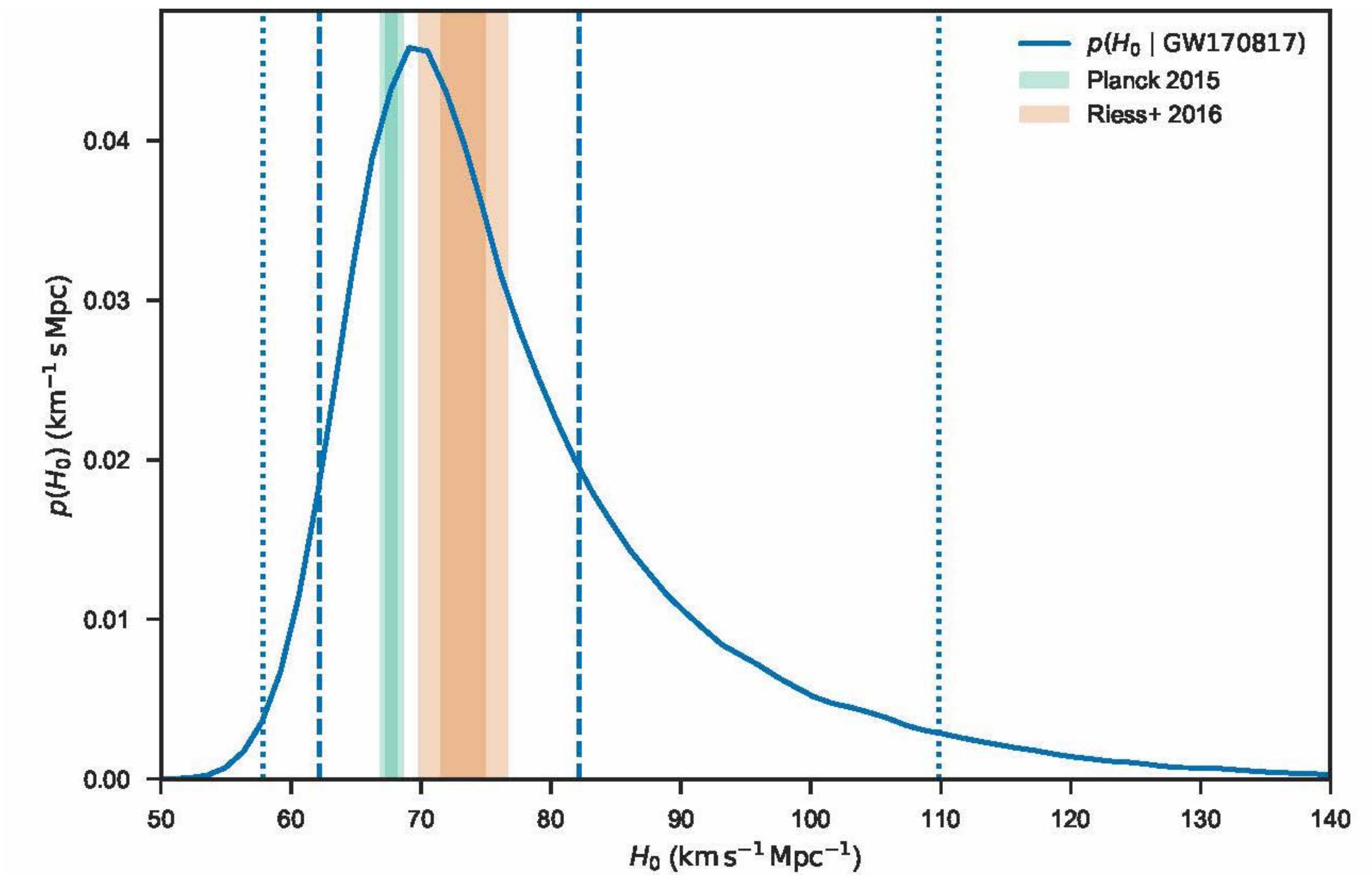


$$D_C(z) = \frac{c}{H_0} \int_0^z dz' \frac{H_0}{H(z')} \, .$$

- Need to measure D and z
- EM: does not measure D directly, but GW does
- SGRBs (z) + BNS (D from GW)

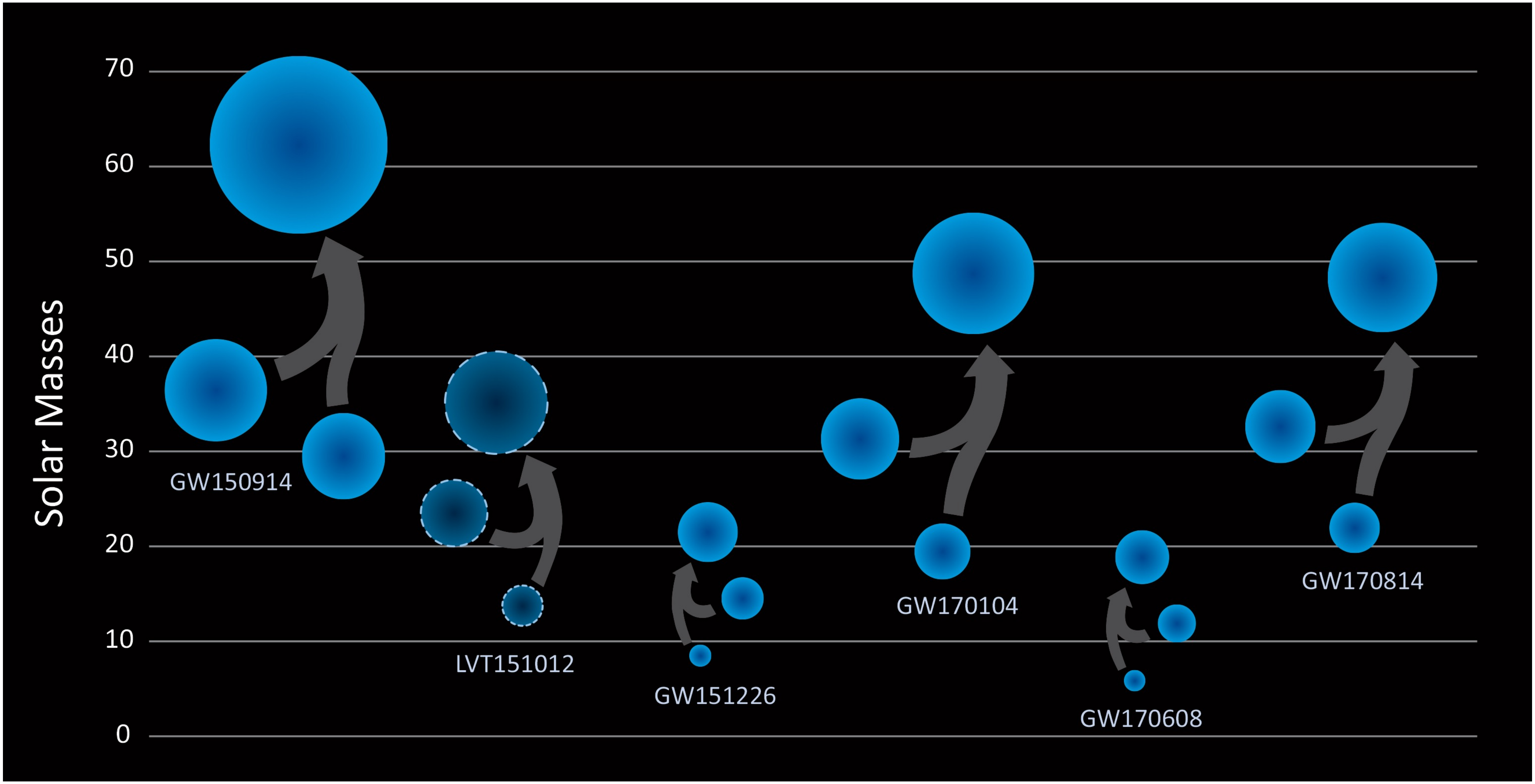
H0 with 1 event (!)

LIGO-Virgo: Nature 551, 85–88



Can the string continue??

Binary black hole astrophysics



What is the origin of these systems? Pop III ? Clusters? Primordial?

UO-LIGO

- Ray Frey, Professor
- Ben Farr, Assistant Professor
- Robert Schofield, Research Professor
- Jim Brau, Professor
- Vinny Roma, 6th-year grad student
- Sudarshan Karki, 6th-year grad student
- Jordan Palamos, 5th-year grad student
- Paul Schale, 5th-year grad student
- Philippe Nguyen, 2nd-year grad student
- Kara Merfeld, 1st-year grad student

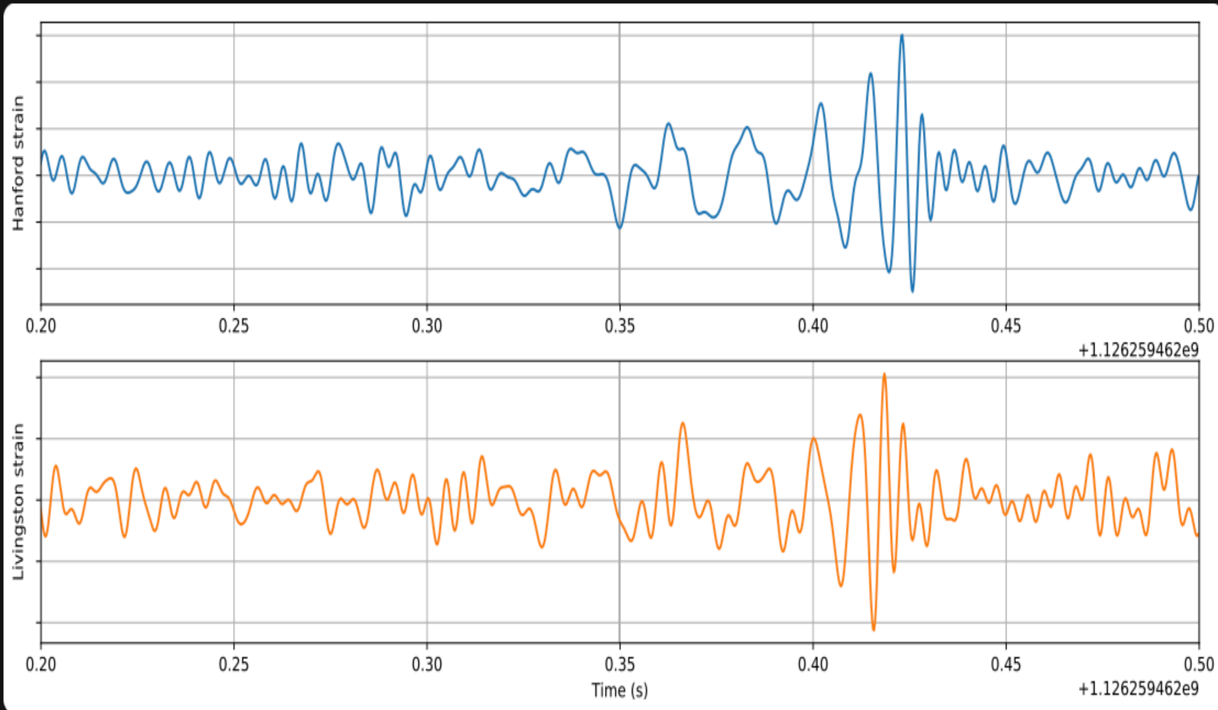
LIGO

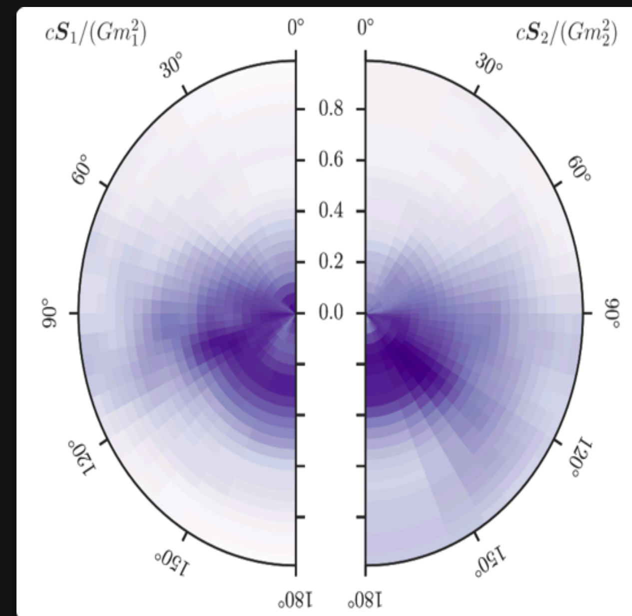
What UO Does?

- The non-GW environment – are the GW signals astrophysical?
  - Sensors and data analysis; time at Hanford Observatory
  - Traditional starting point for new graduate students
- GWs associated with gamma-ray bursts (GRBs)
  - First GW + EM detection; many new astrophysics questions!
  - New way to measure Hubble expansion/acceleration
- GWs from stellar collapse (supernovae), magnetar flares, …

- Farr: Astrophysics of compact binaries (BH-BH, NS-BH, NS-NS)
  - LIGO can use BBHs to trace the star formation history of the universe
  - Using the measured waveforms to determine the parameters of these systems: masses, distances, spins
  - How and where are these systems formed?

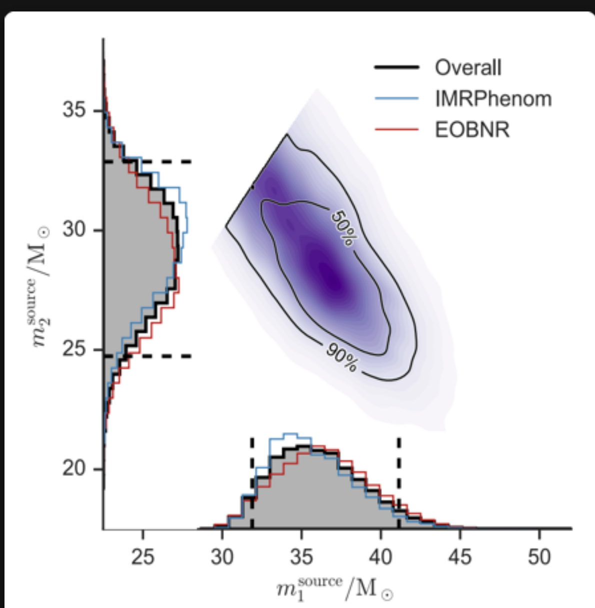
Parameter Estimation

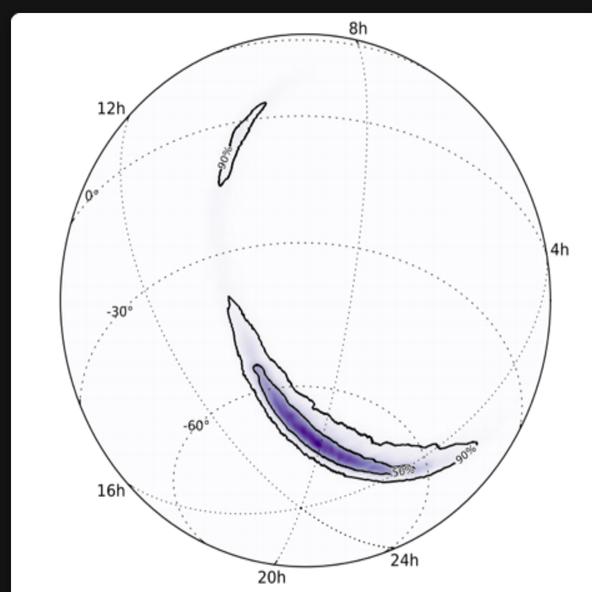




Masses

Location





Spins

(e.g., GW150914)