

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

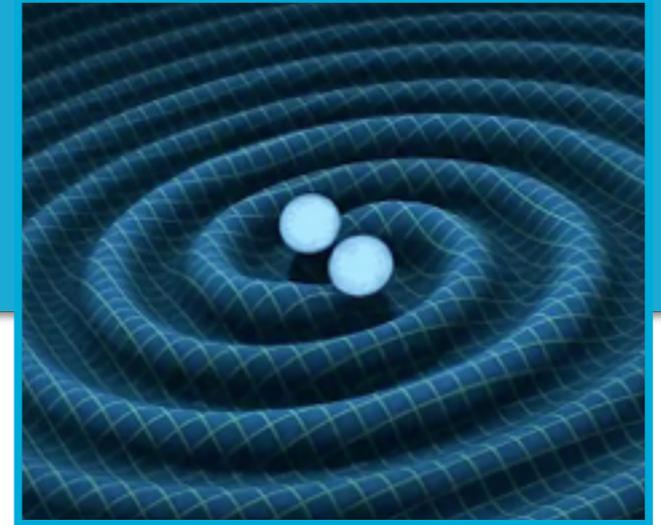
When Neutron Stars Collide

Mustafa A. Amin



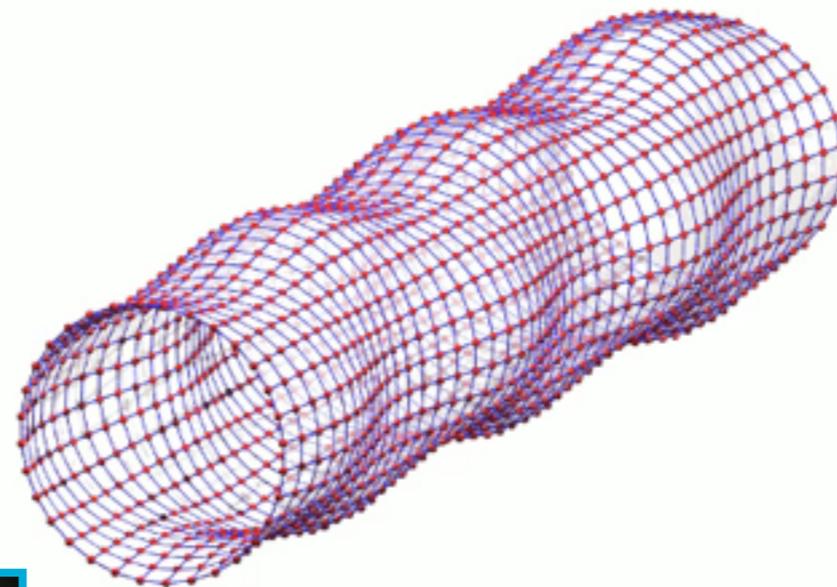
preliminaries

gravitational waves and their detection

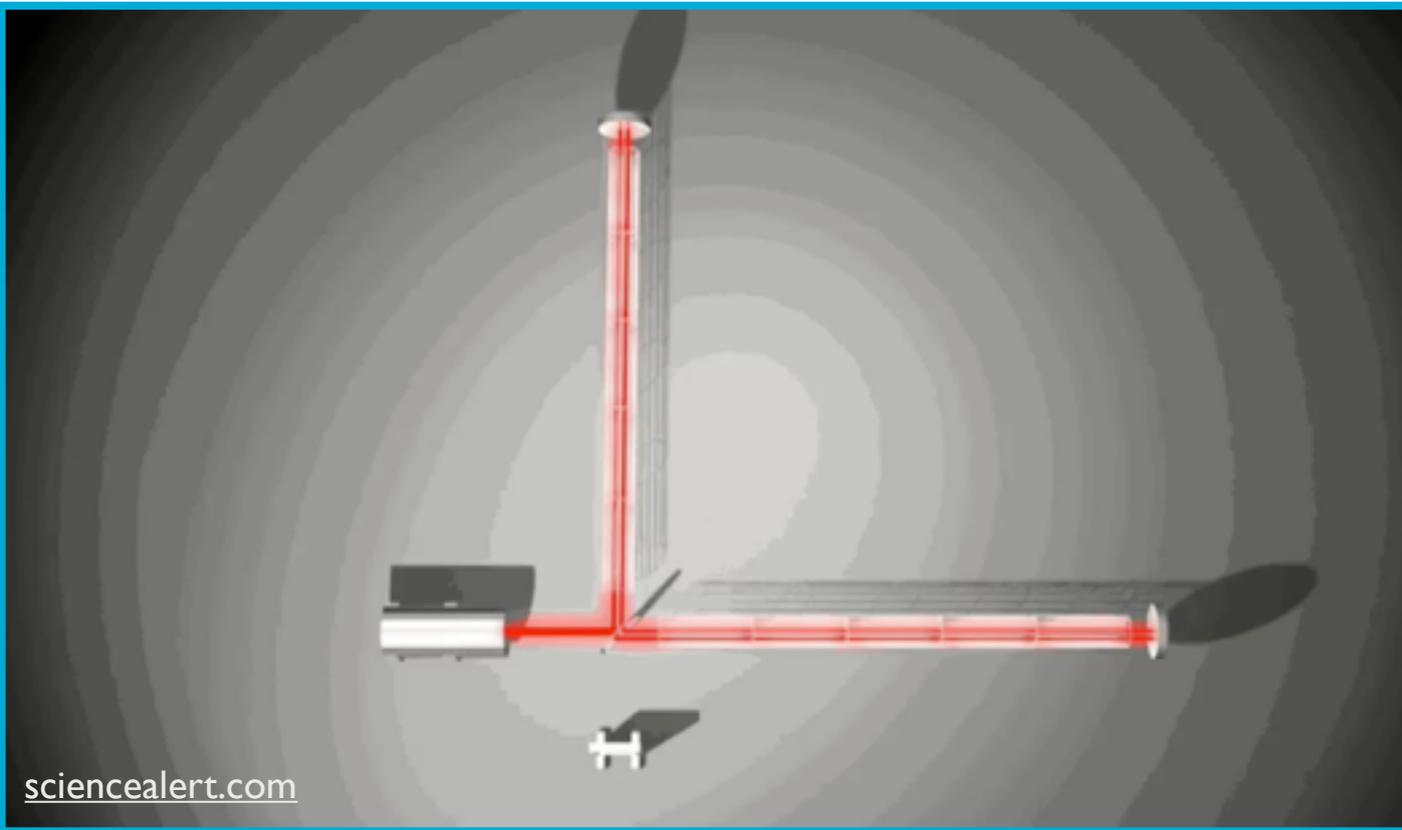


$$\mathbf{G}[h] = 8\pi G\mathbf{T}$$

$$[\partial_t^2 - \nabla^2] h(t, \mathbf{x}) = 0$$

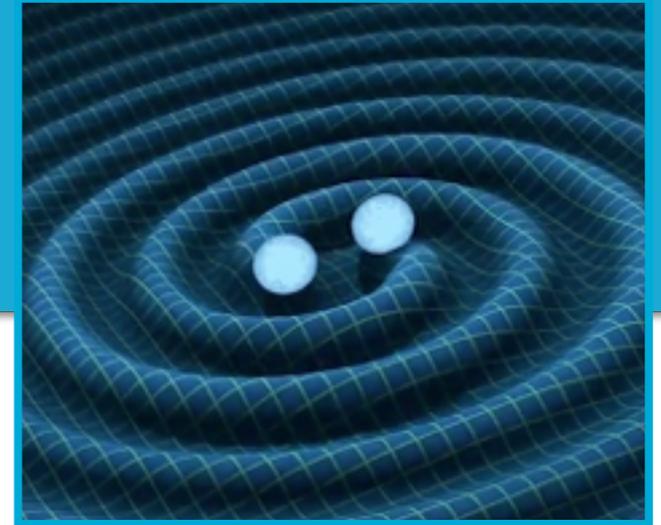


www.einstein-online.info



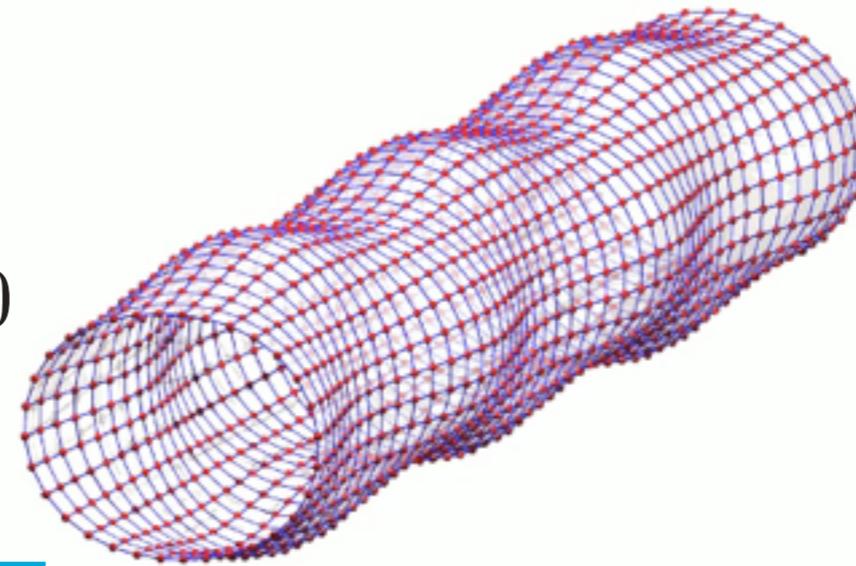
$$h(t) \sim \frac{\Delta L}{L} \quad \text{strain}$$

gravitational waves and their detection

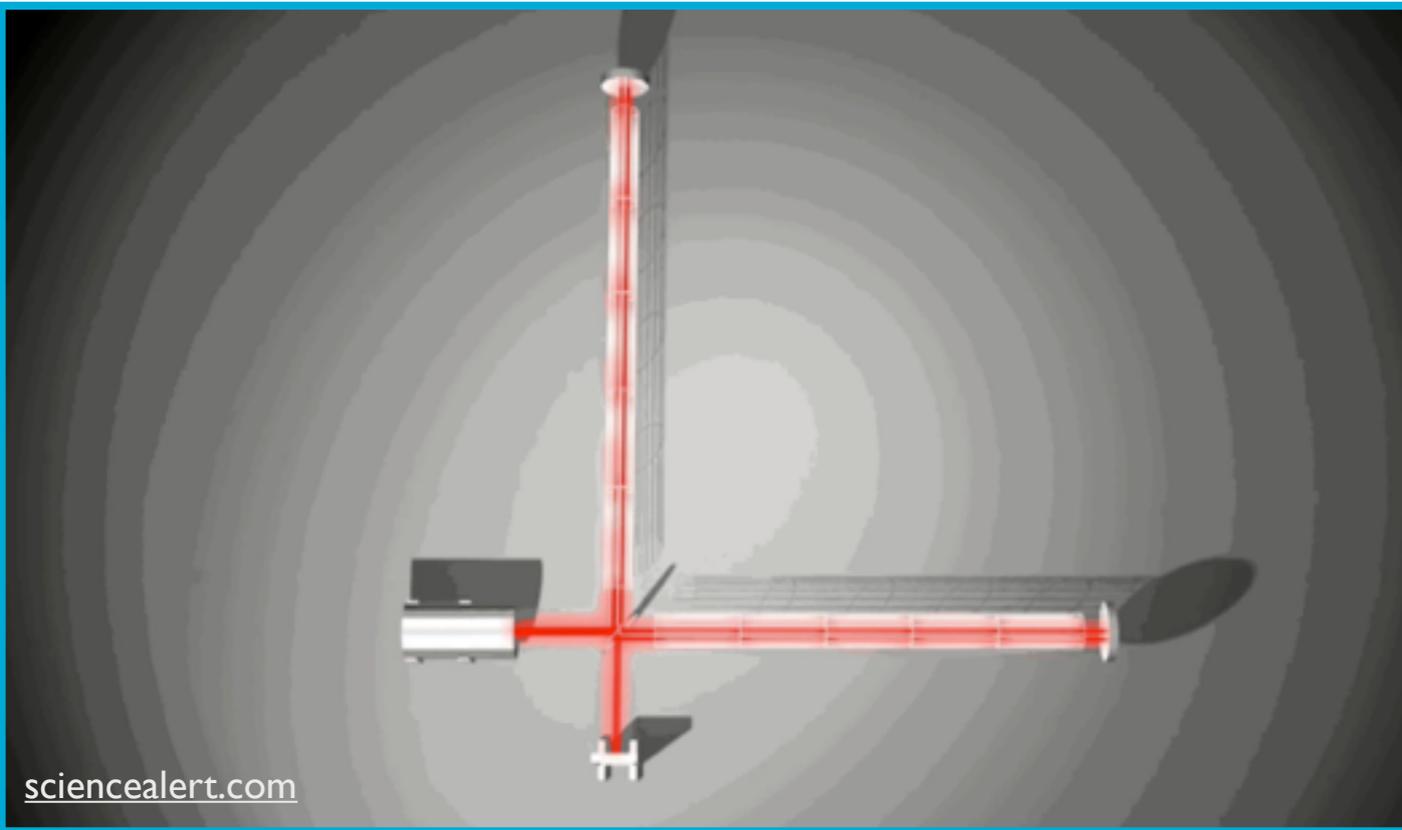


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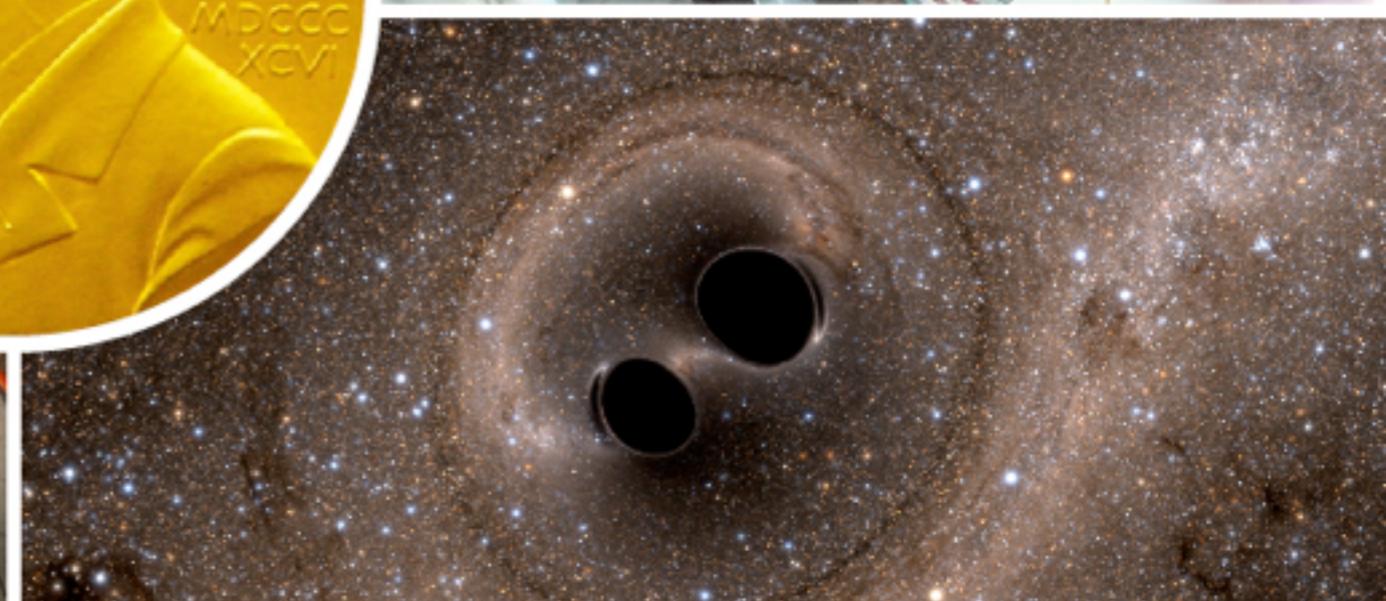
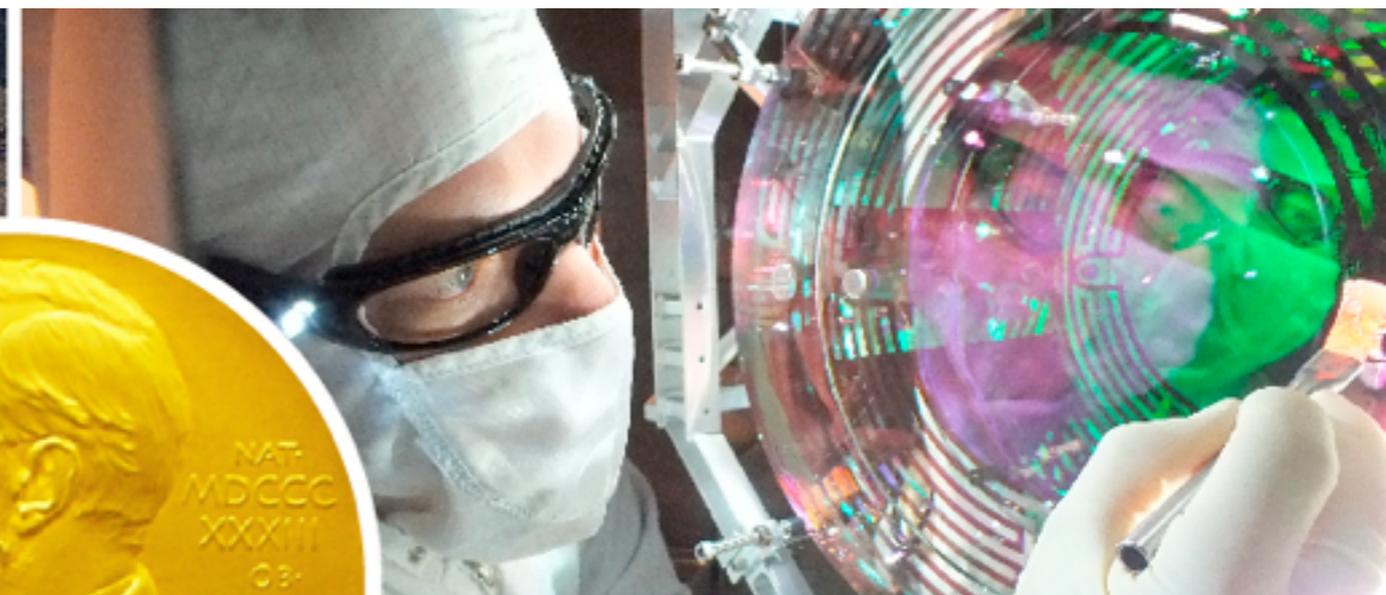


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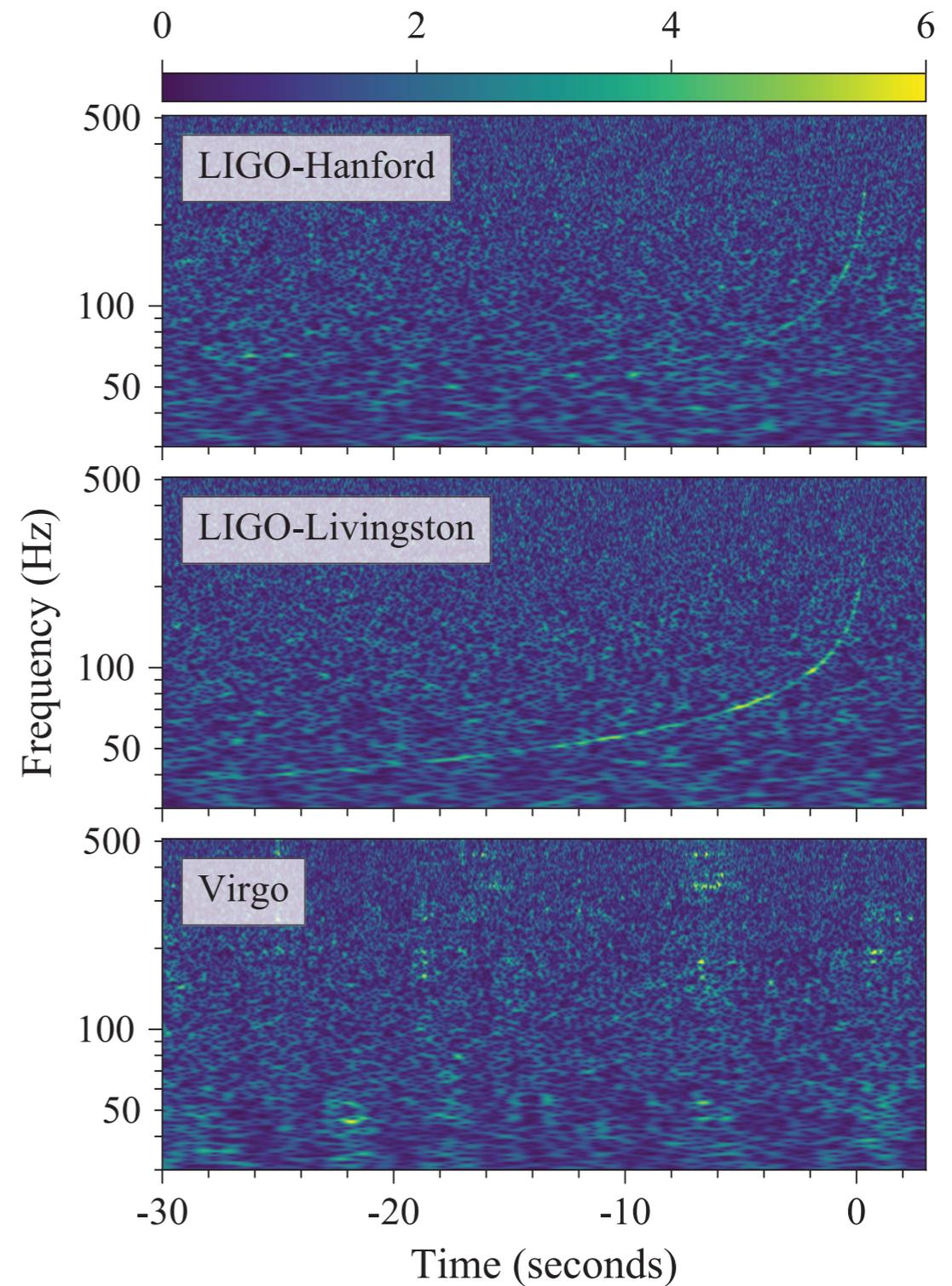
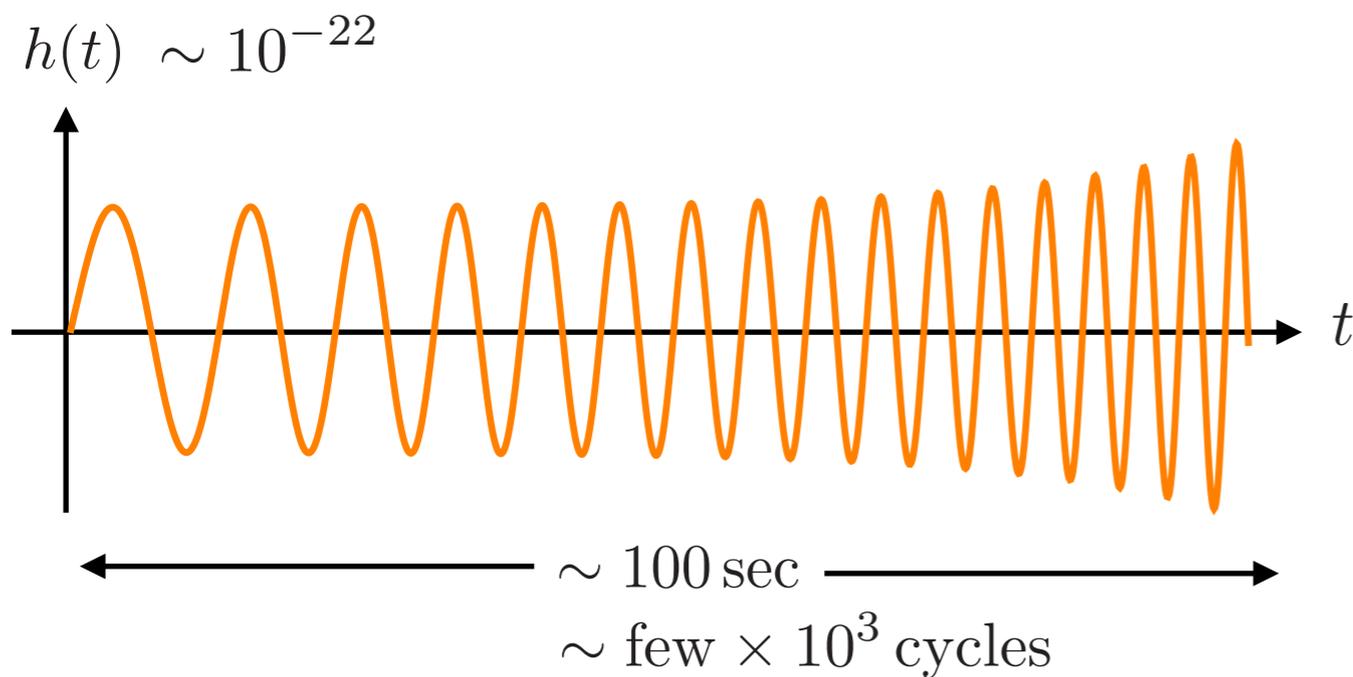
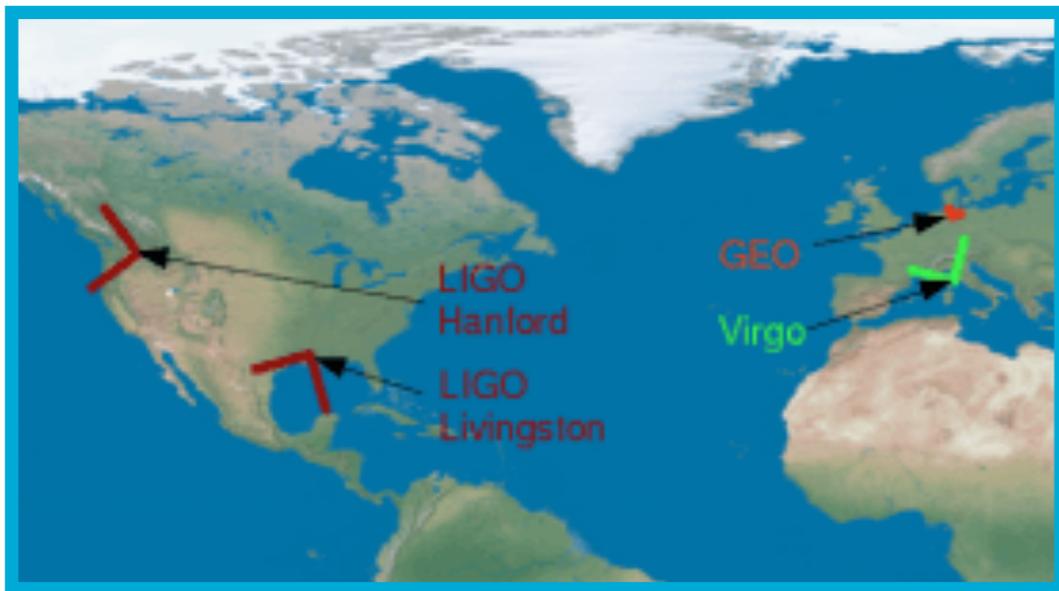
g-waves from $\sim 30 M_{\odot}$ binary Black Holes



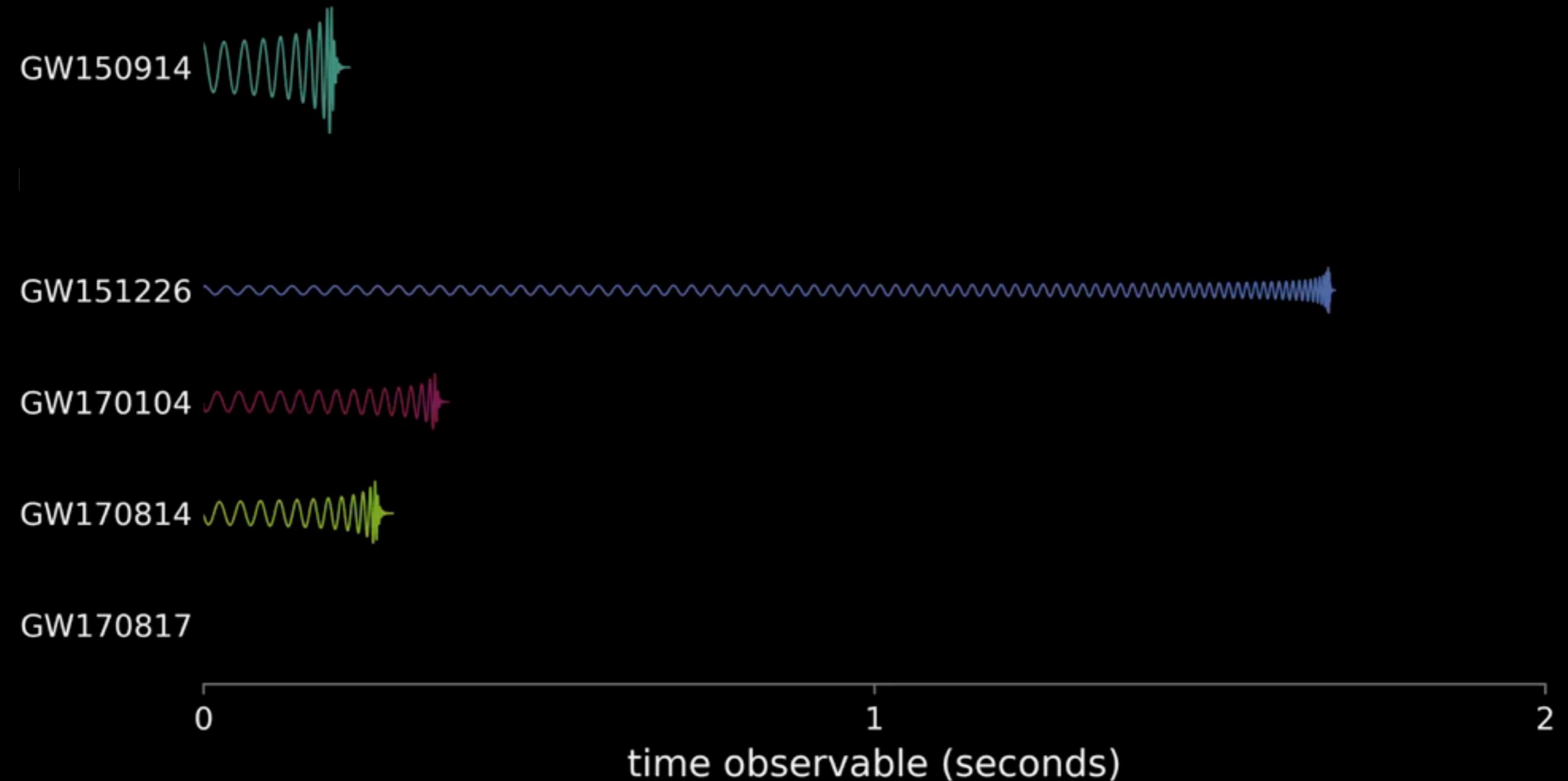
Aug 17, 2017

7:40 am (Houston time)

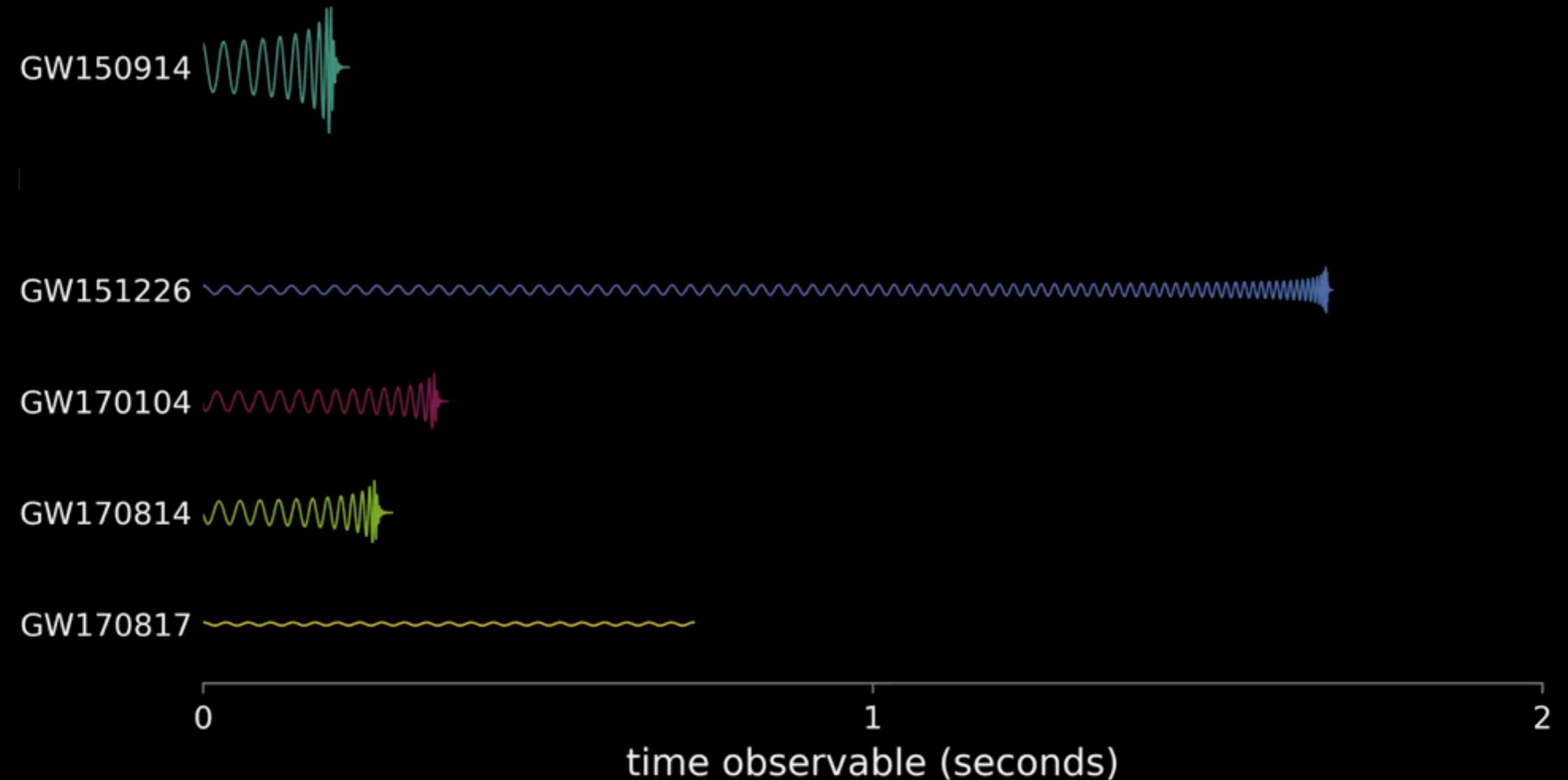
LIGO/VIRGO gravitational waves



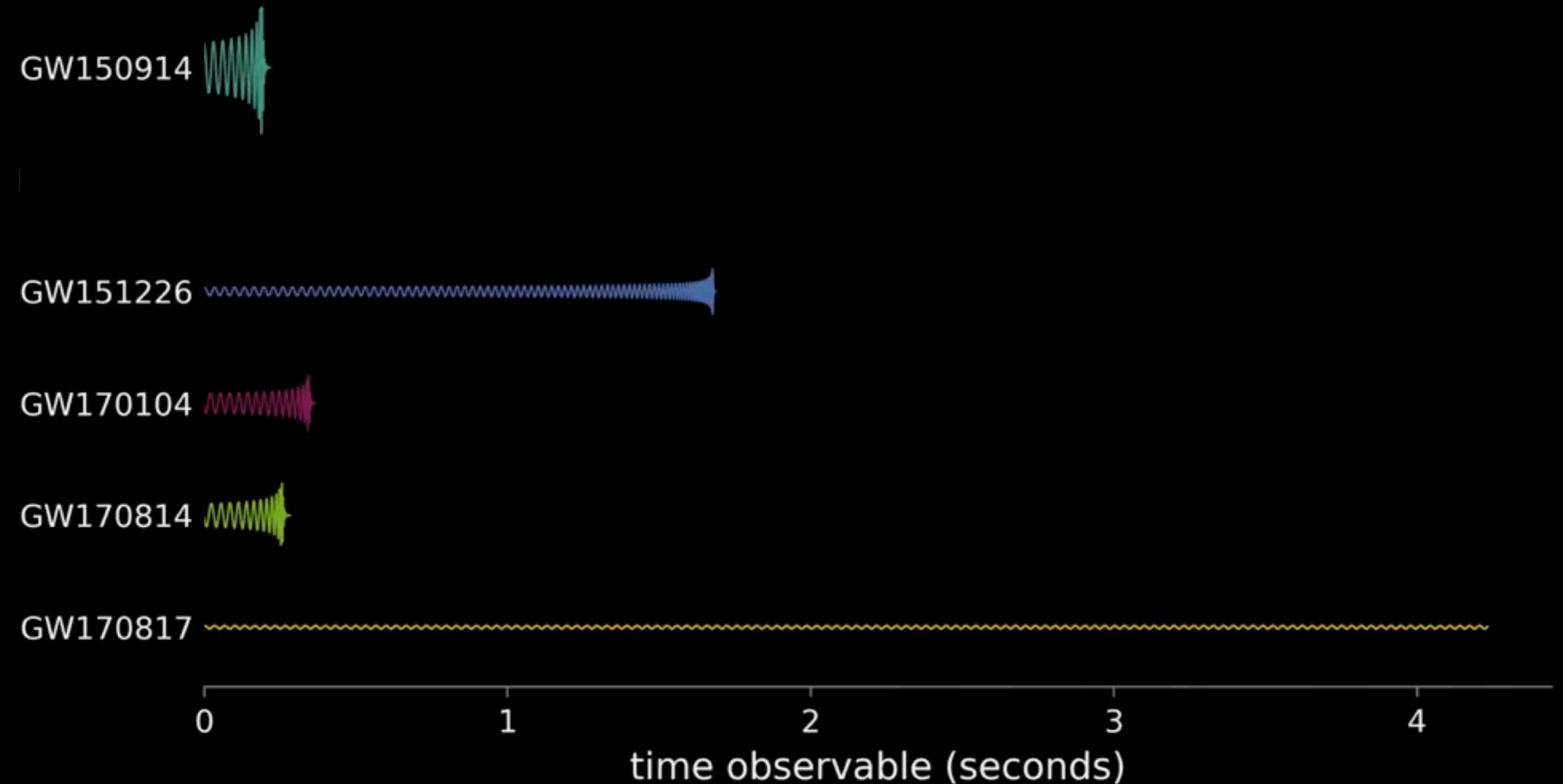
how was this signal different ?



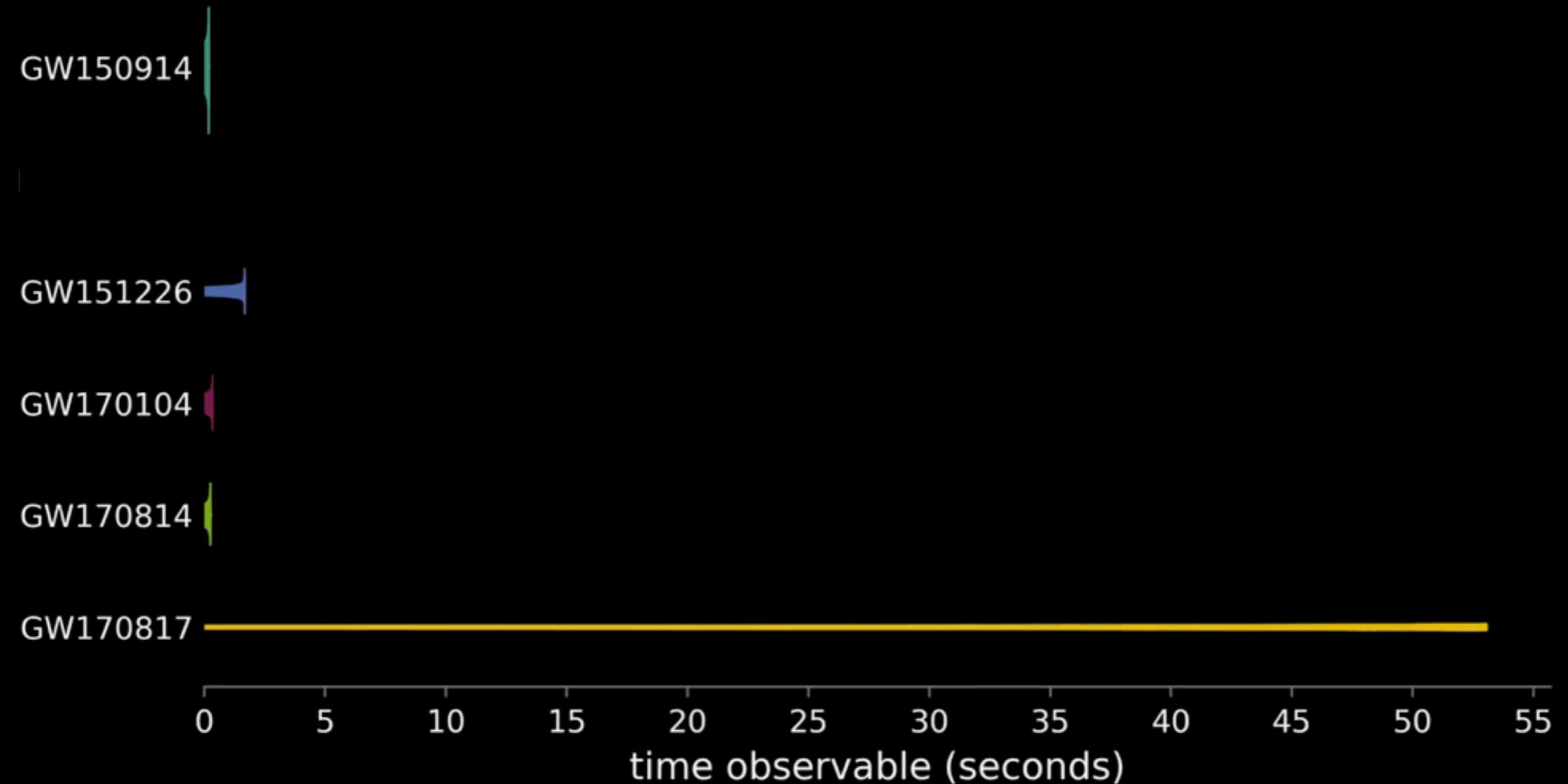
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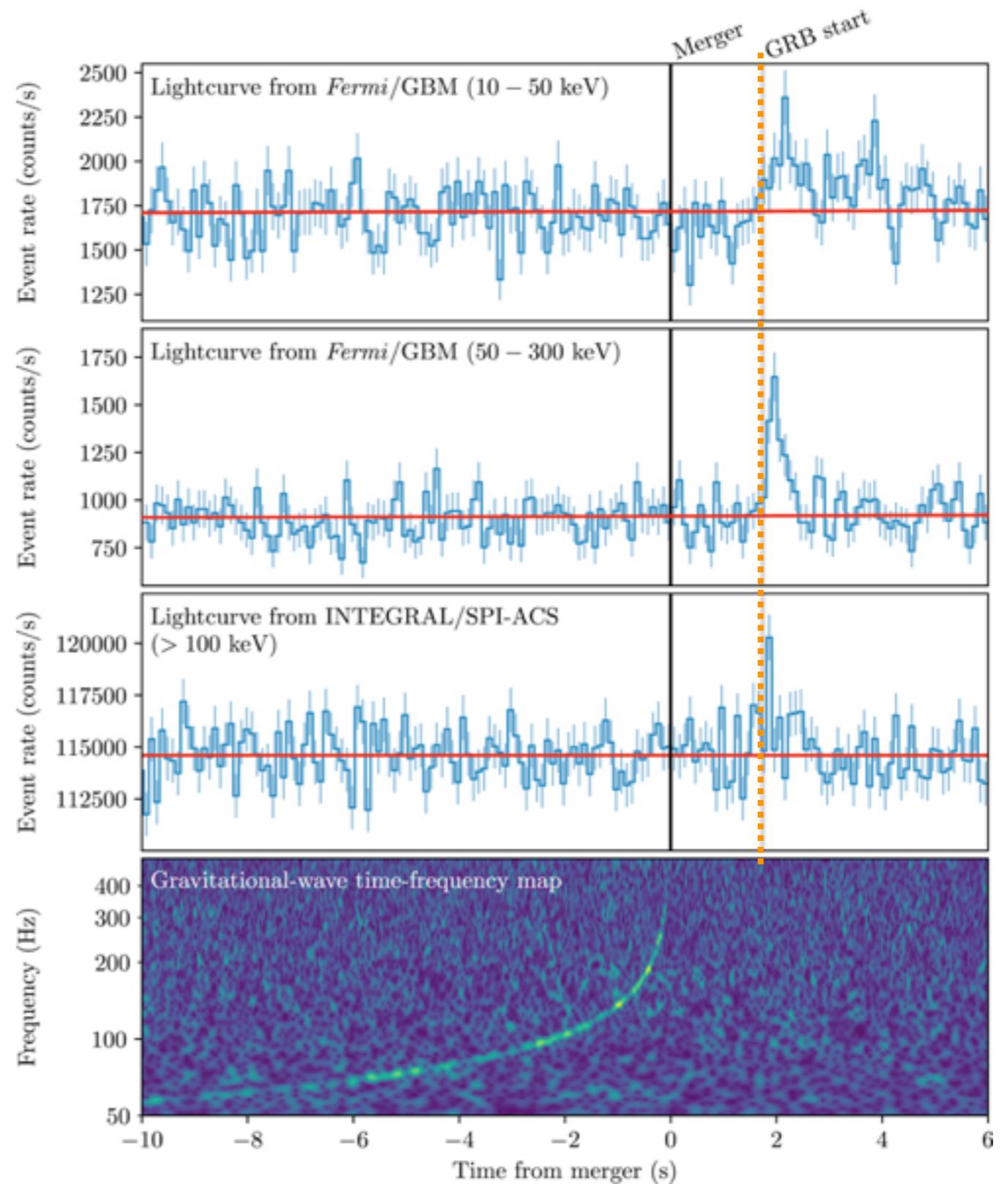
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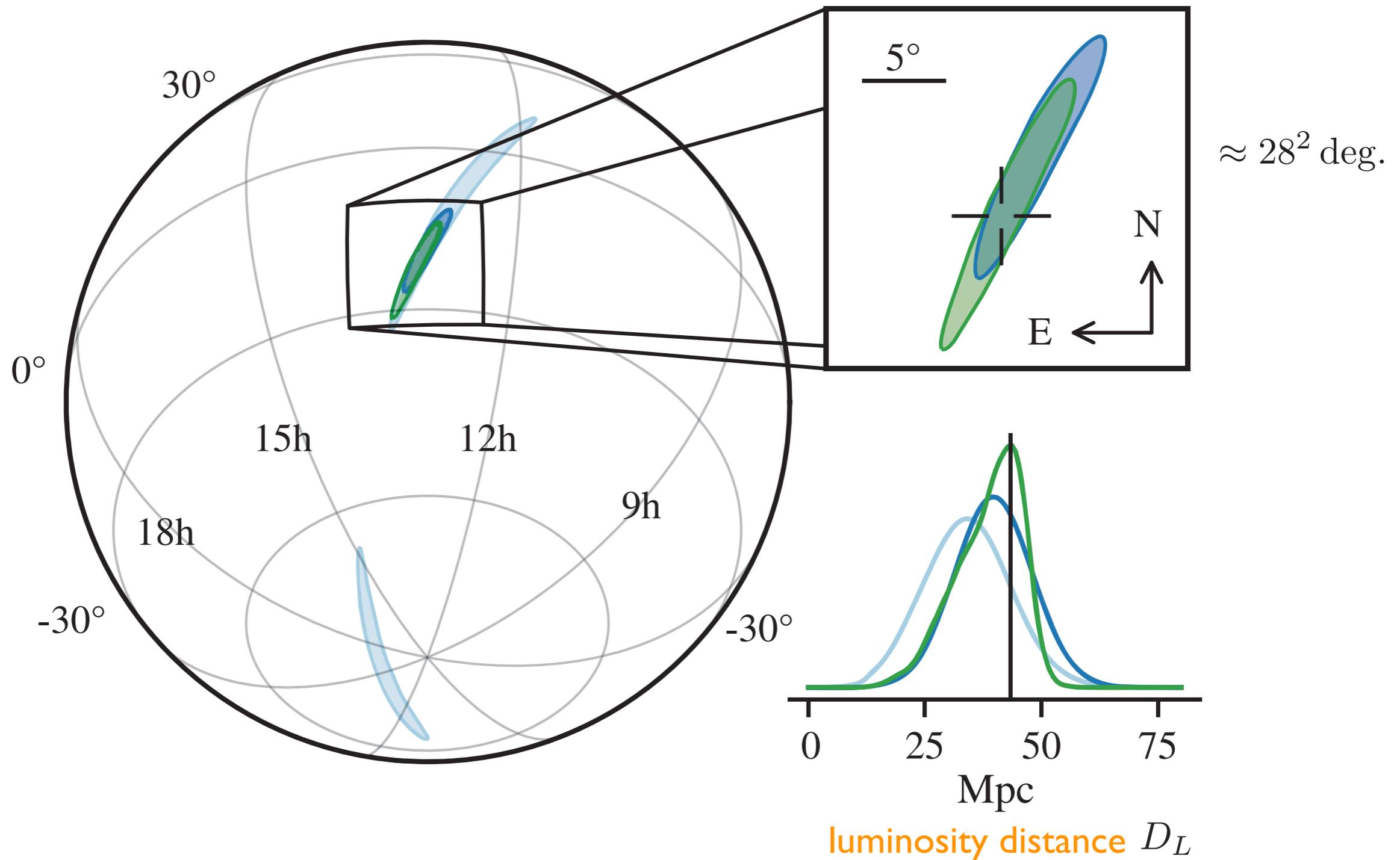
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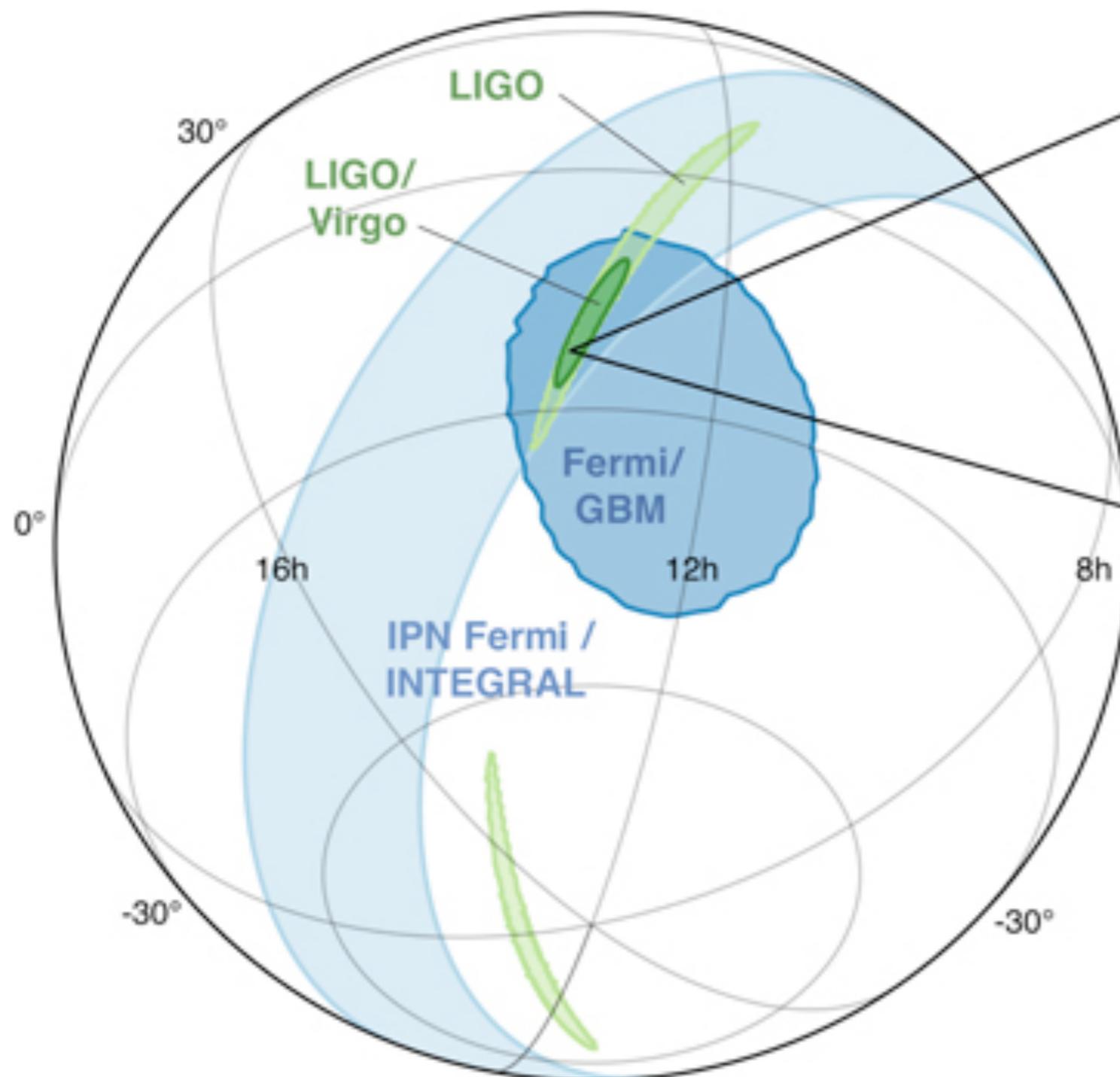
(short) gamma ray burst



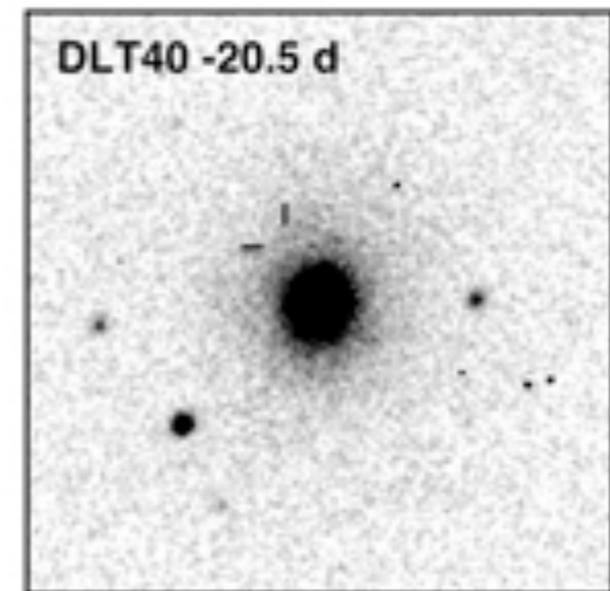
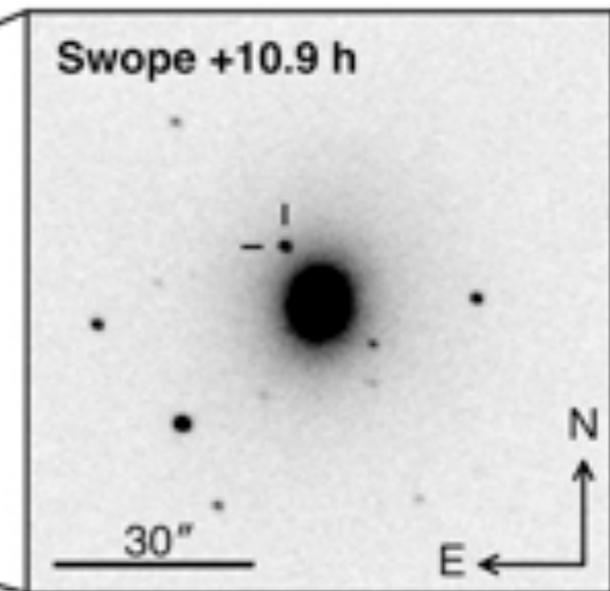
source localization (from LIGO/VIRGO)



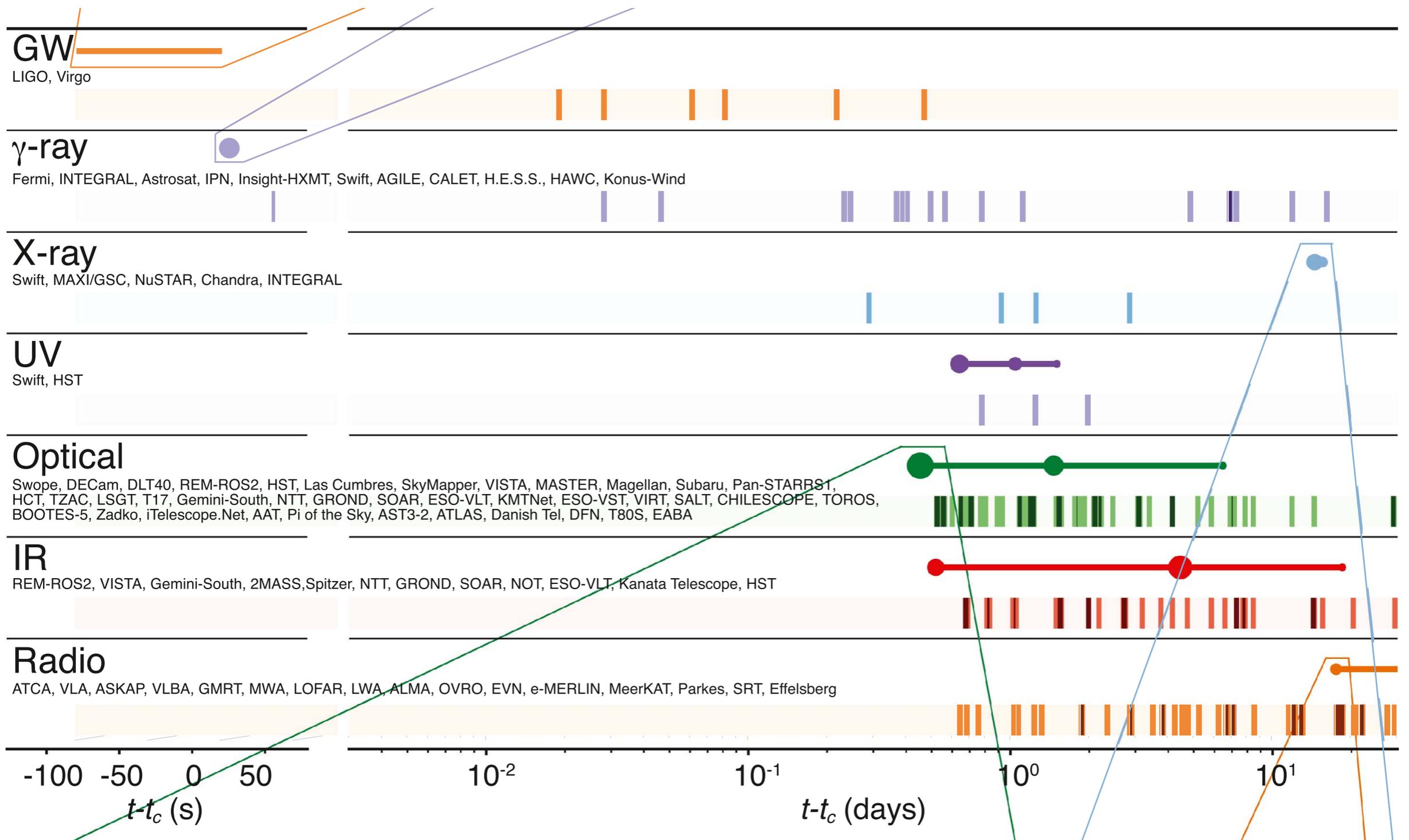
source localization



optical transient near **NGC 4993**
 $z \approx 0.01$



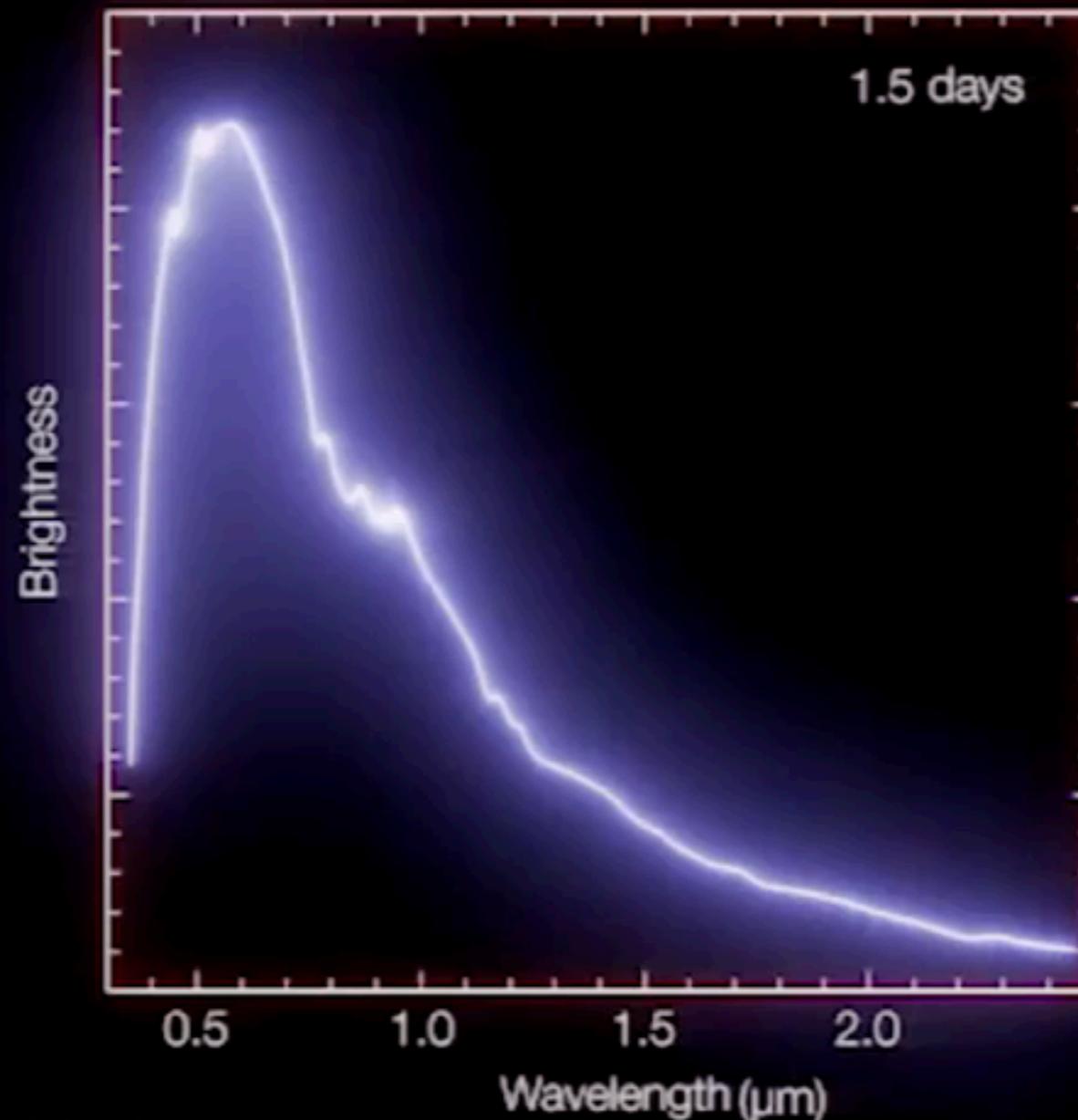
“the signal that launched ~70 follow-ups”



*no neutrinos detected

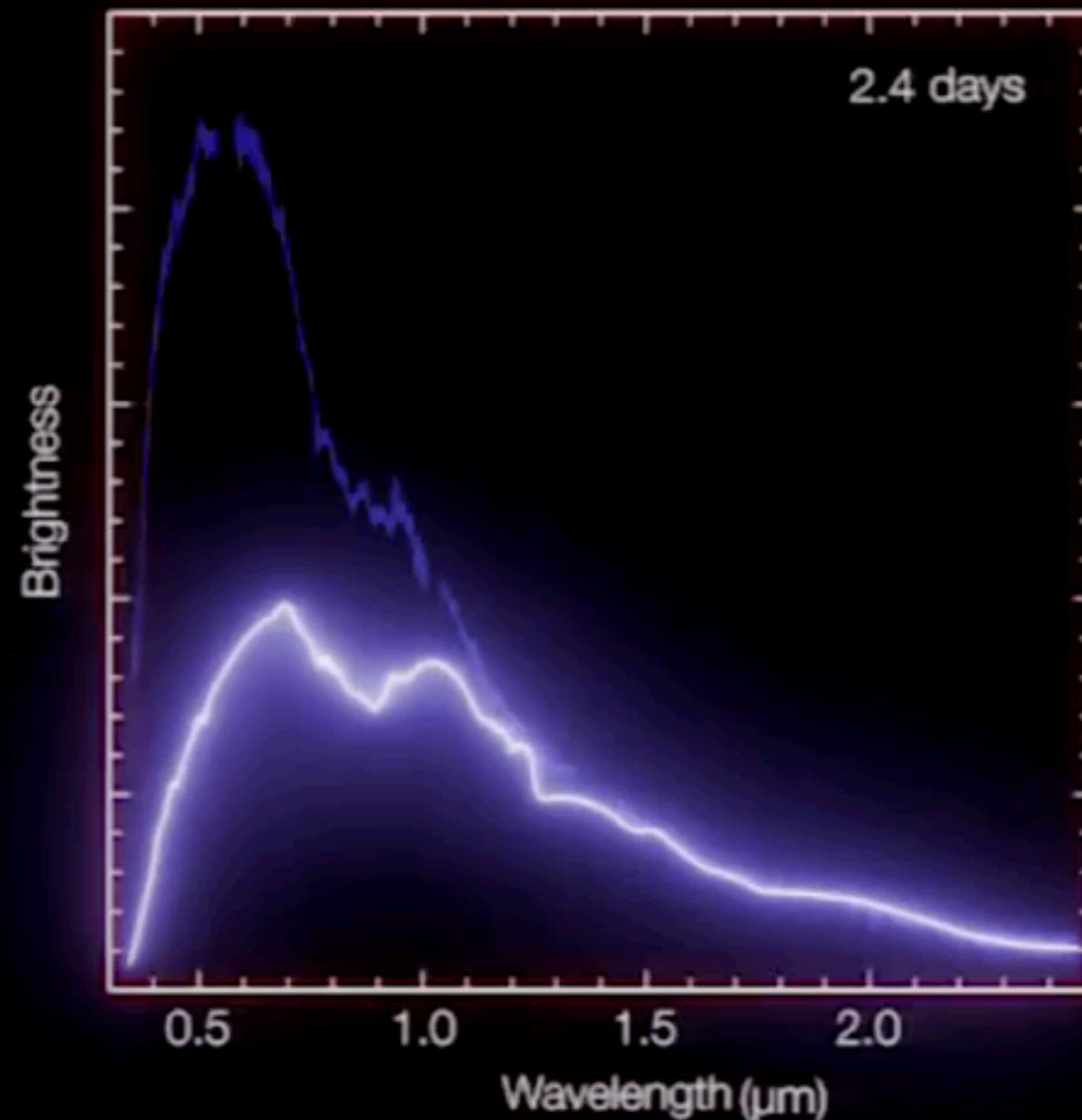
kilonova: r-process element formation/decay

Spectroscopic Evolution



kilonova: r-process element formation/decay

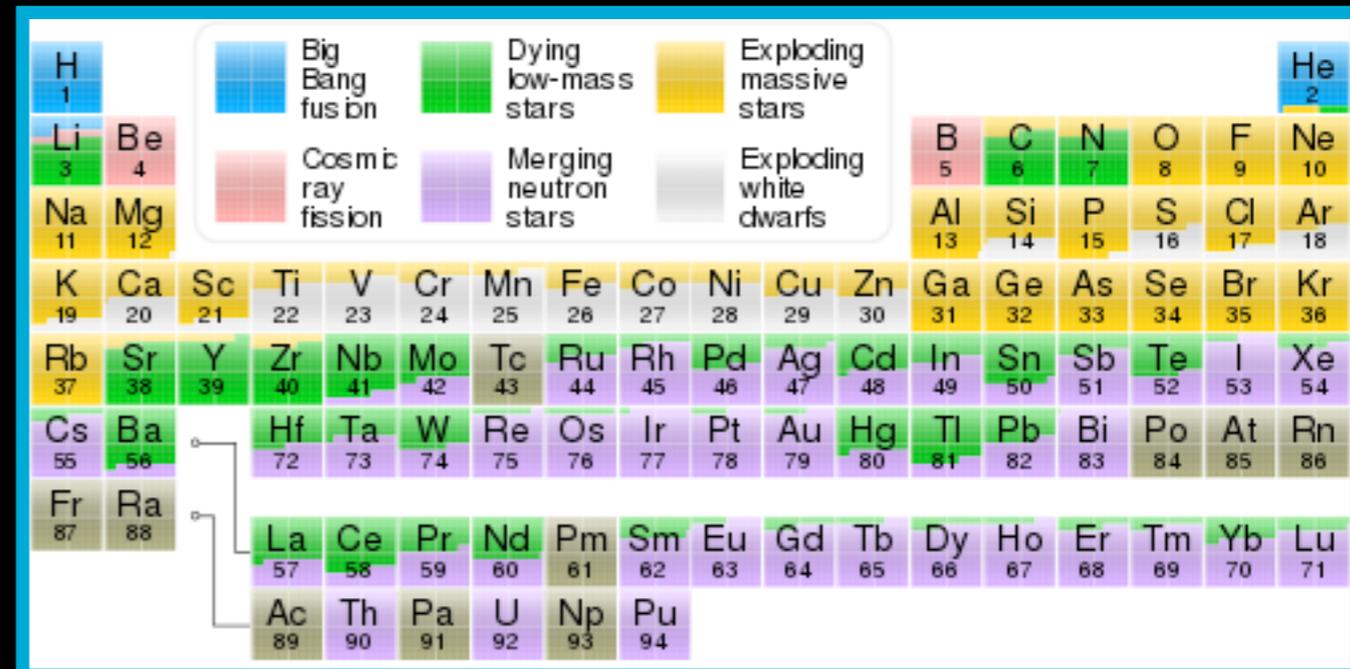
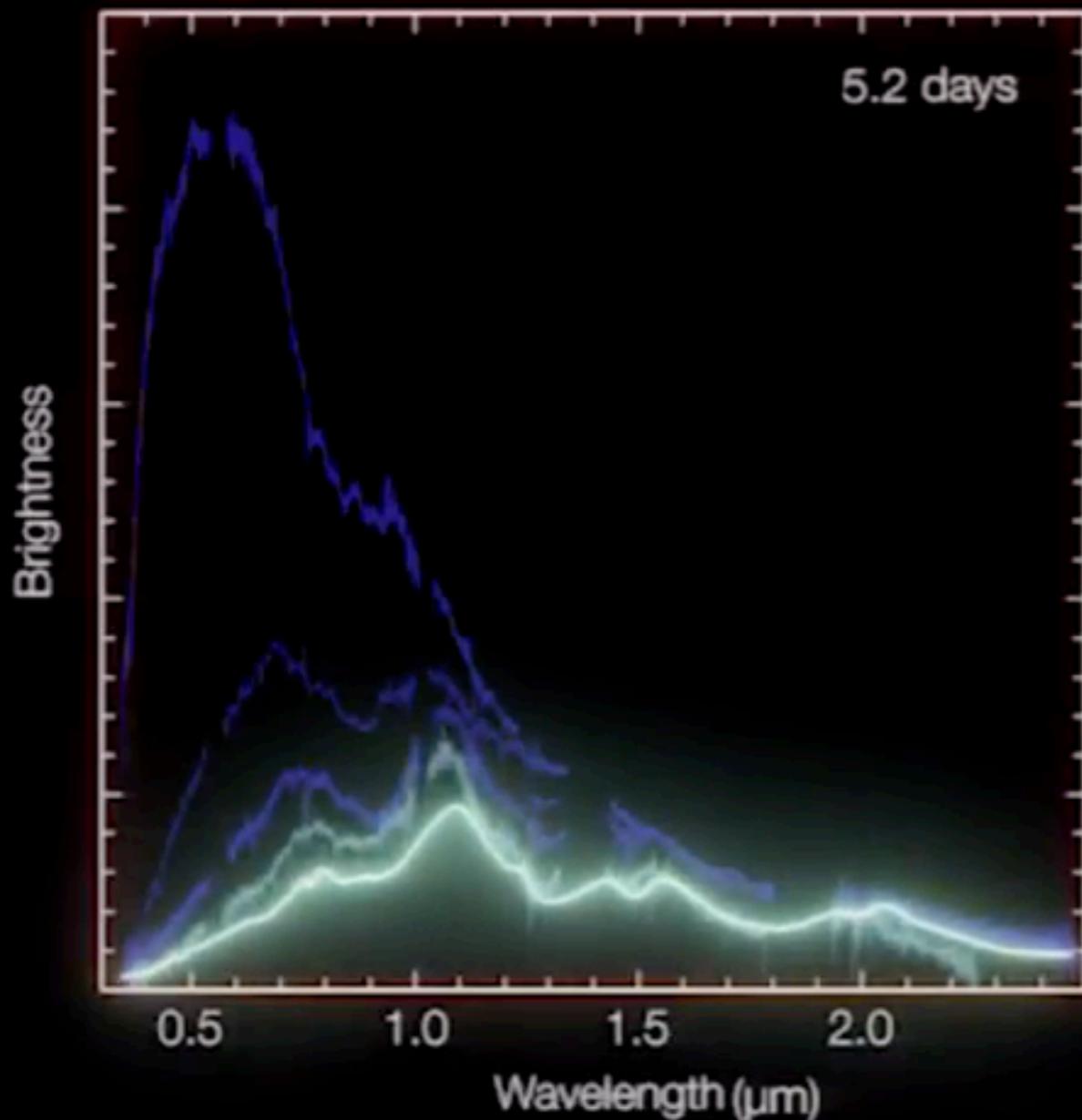
Spectroscopic Evolution



kilonova

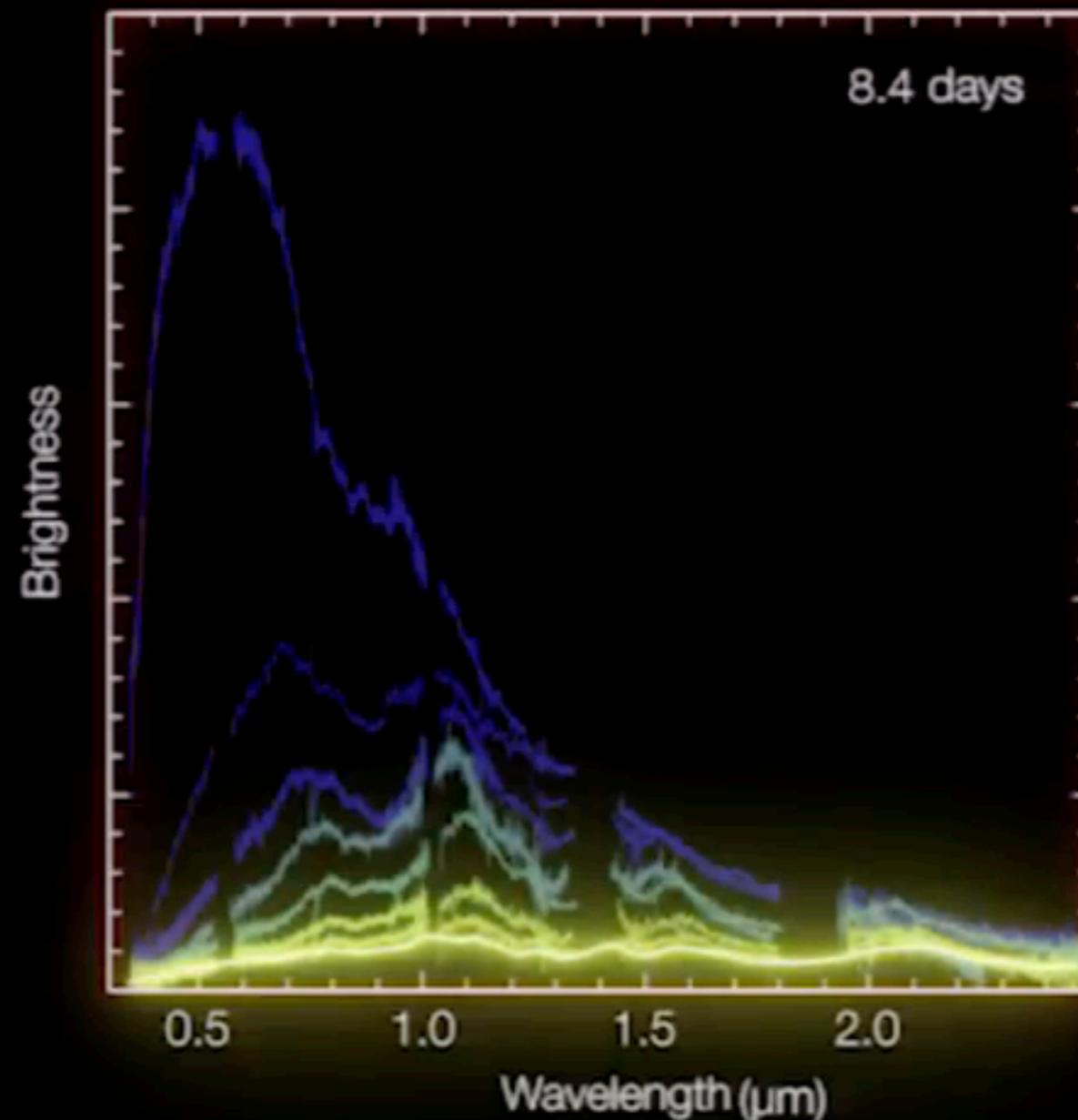


Spectroscopic Evolution



kilonova: r-process element decay

Spectroscopic Evolution



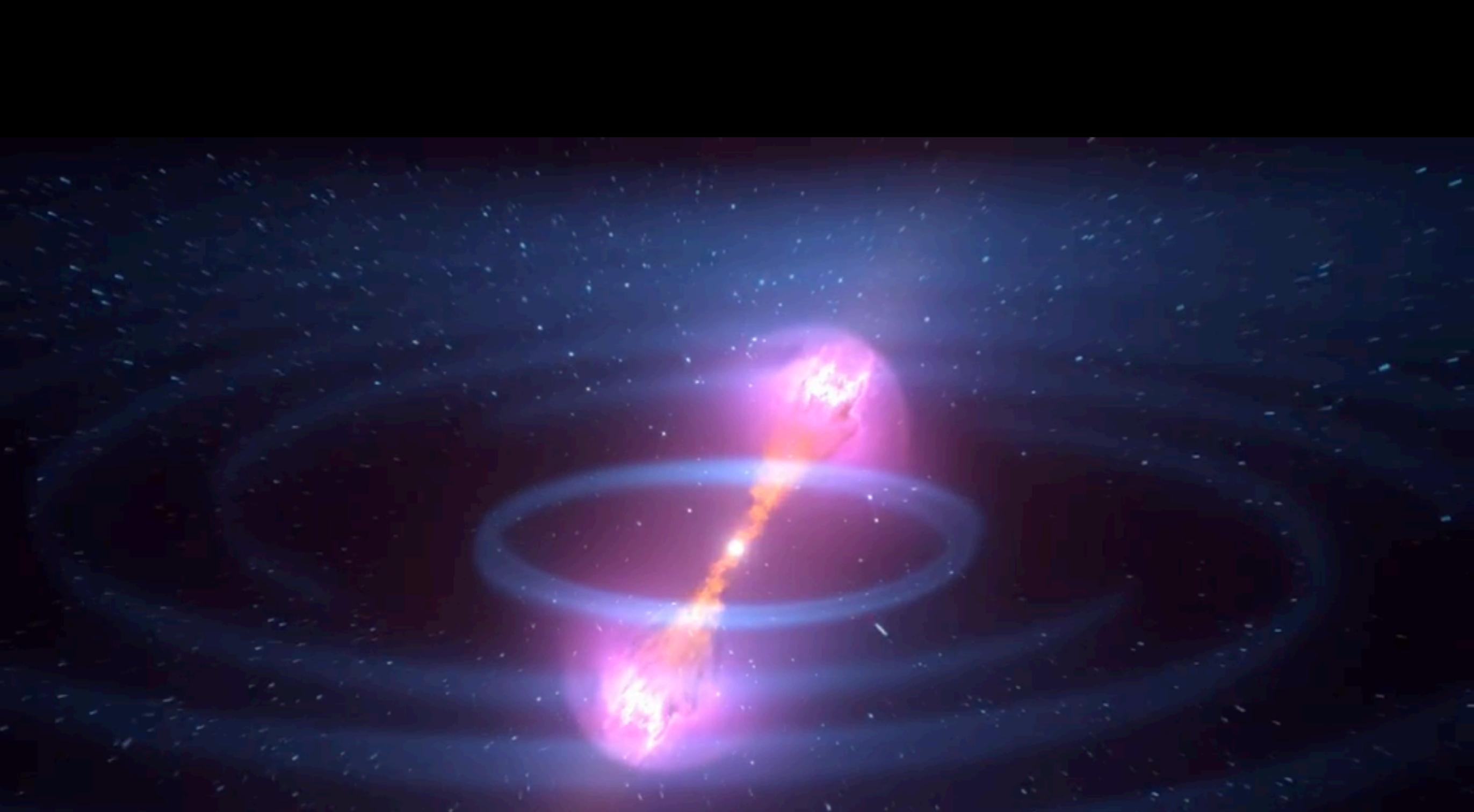


**RIPPLES OF GRAVITY,
FLASHES OF LIGHT:**

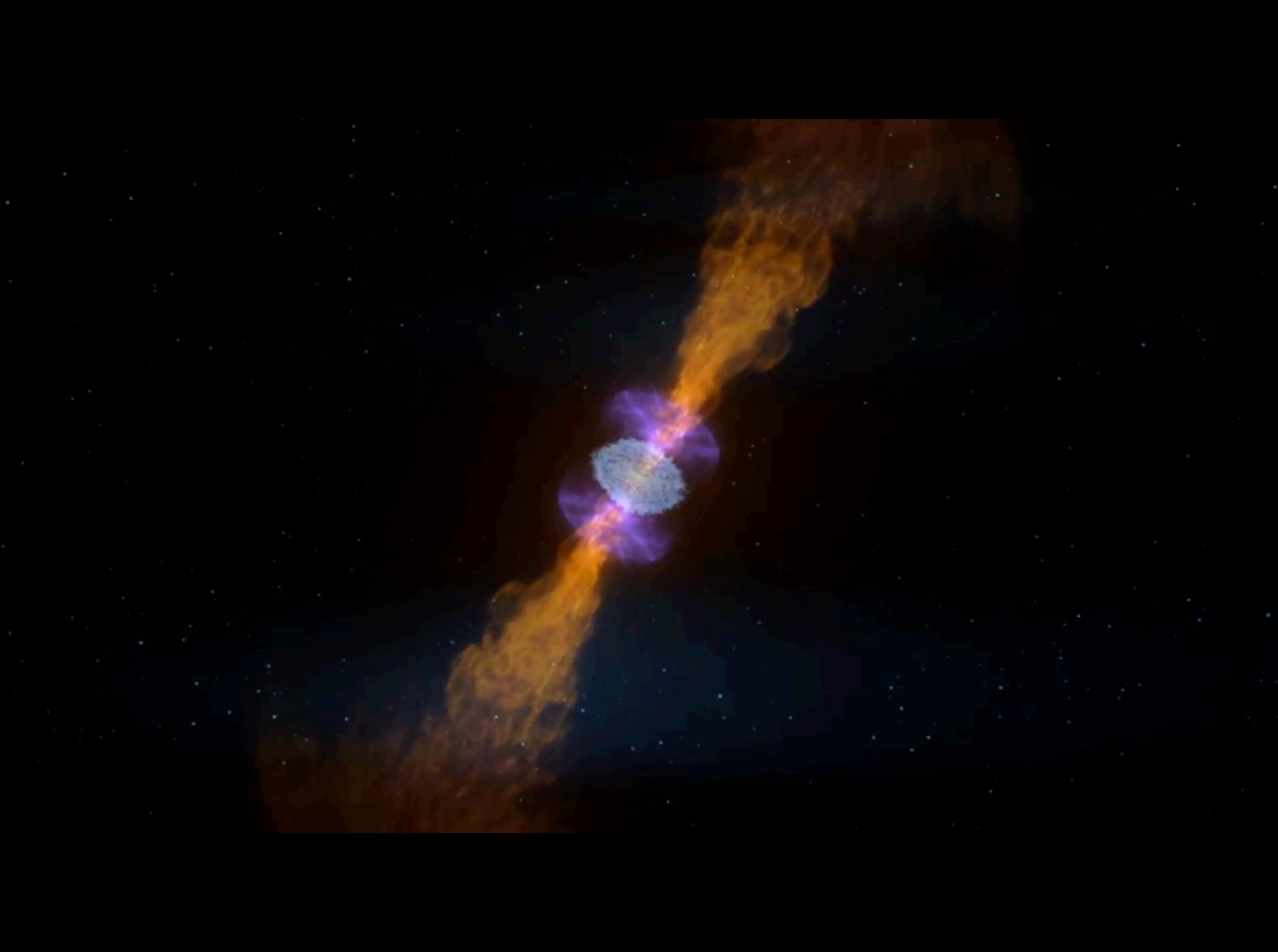
**WORLD'S OBSERVATORIES
WITNESS A COSMIC CATAclySM**

Gravitational Waves





Electromagnetic Waves



consistent with:

neutron star inspiral & merger

first ever detected !

short gamma ray burst

first confirmed association with neutron star merger!

kilonova

production/decay of heavy elements!

interaction with surrounding

radio, X-rays

so what ?

if you ask, you have no physics soul

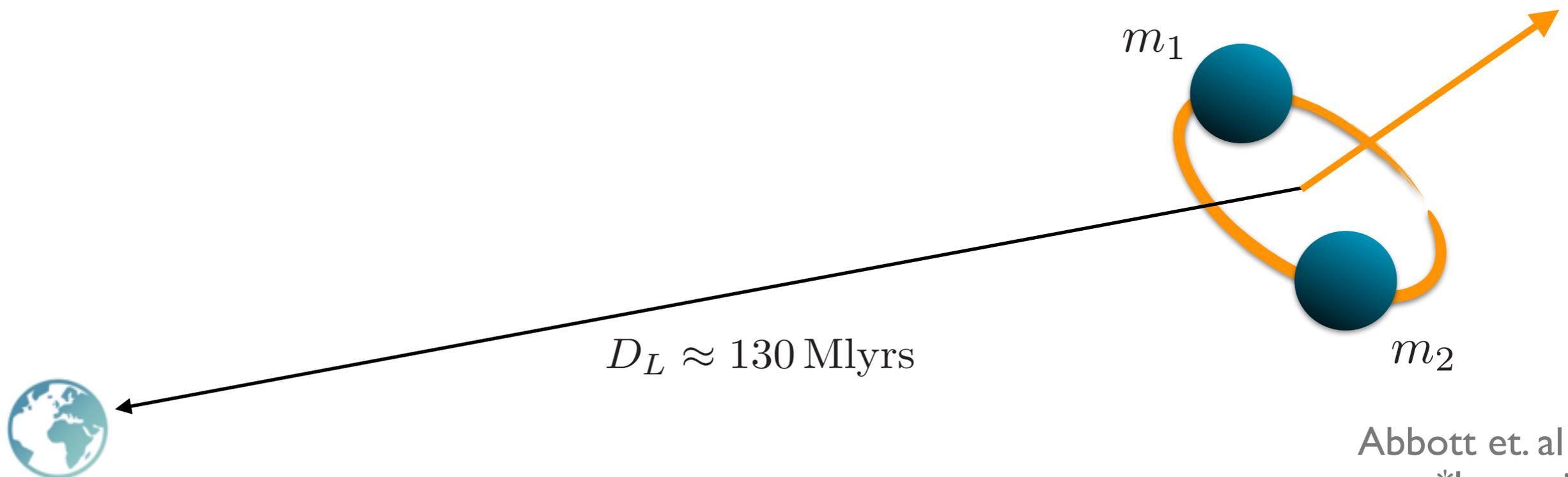
selected implications

1. General Relativity (GR) works in extreme environments
2. properties of ultra-dense matter
3. many theories that modify GR are dead *
4. cosmology — Hubble constant



inferred system parameters (from g-wave signal)

Primary mass m_1	1.36–1.60 M_\odot
Secondary mass m_2	1.17–1.36 M_\odot
Chirp mass $\mathcal{M} = \left(\frac{(m_1 m_2)^3}{m_1 + m_2} \right)^{1/5}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc

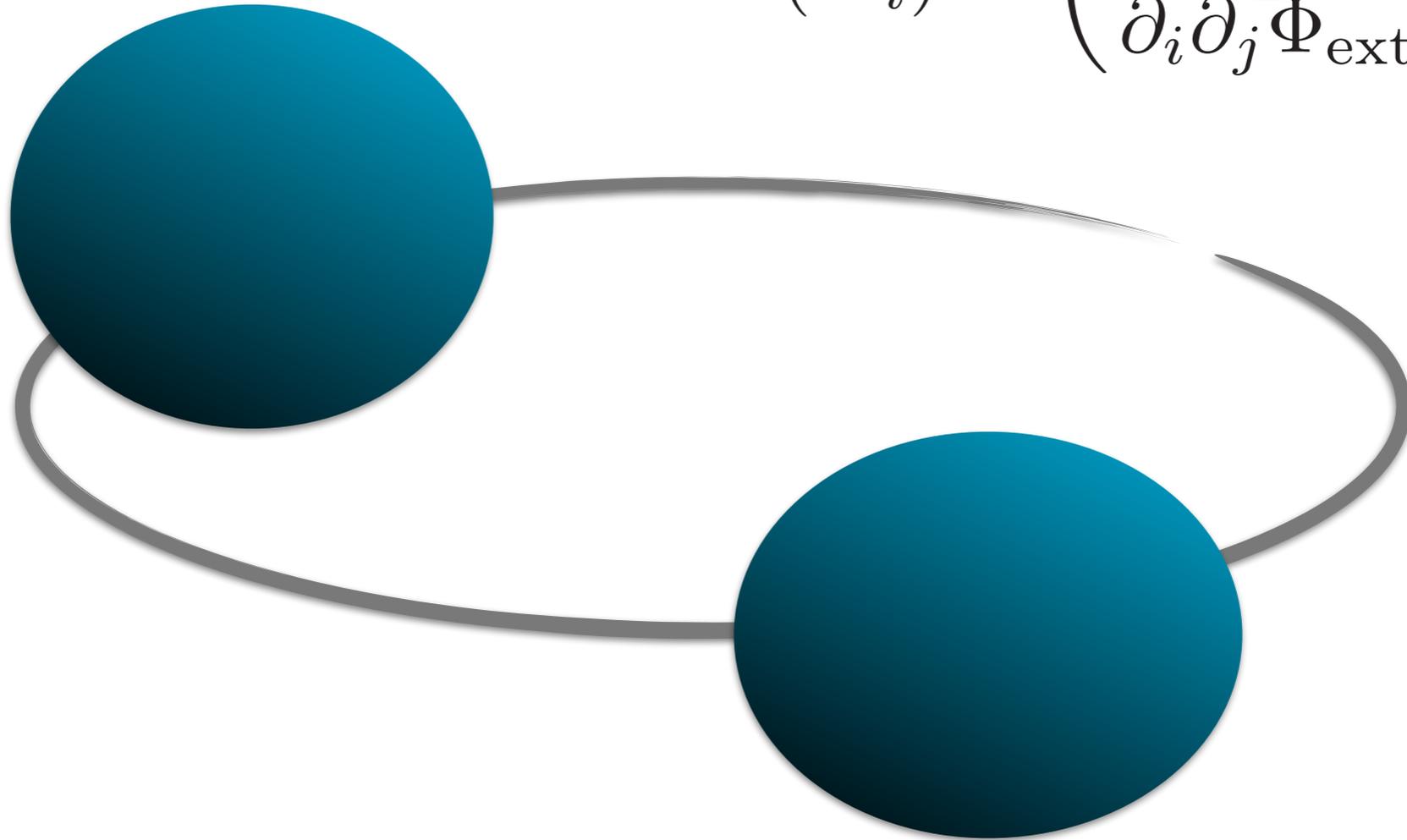


Abbott et. al (2017)
*low spin prior

tidal deformability

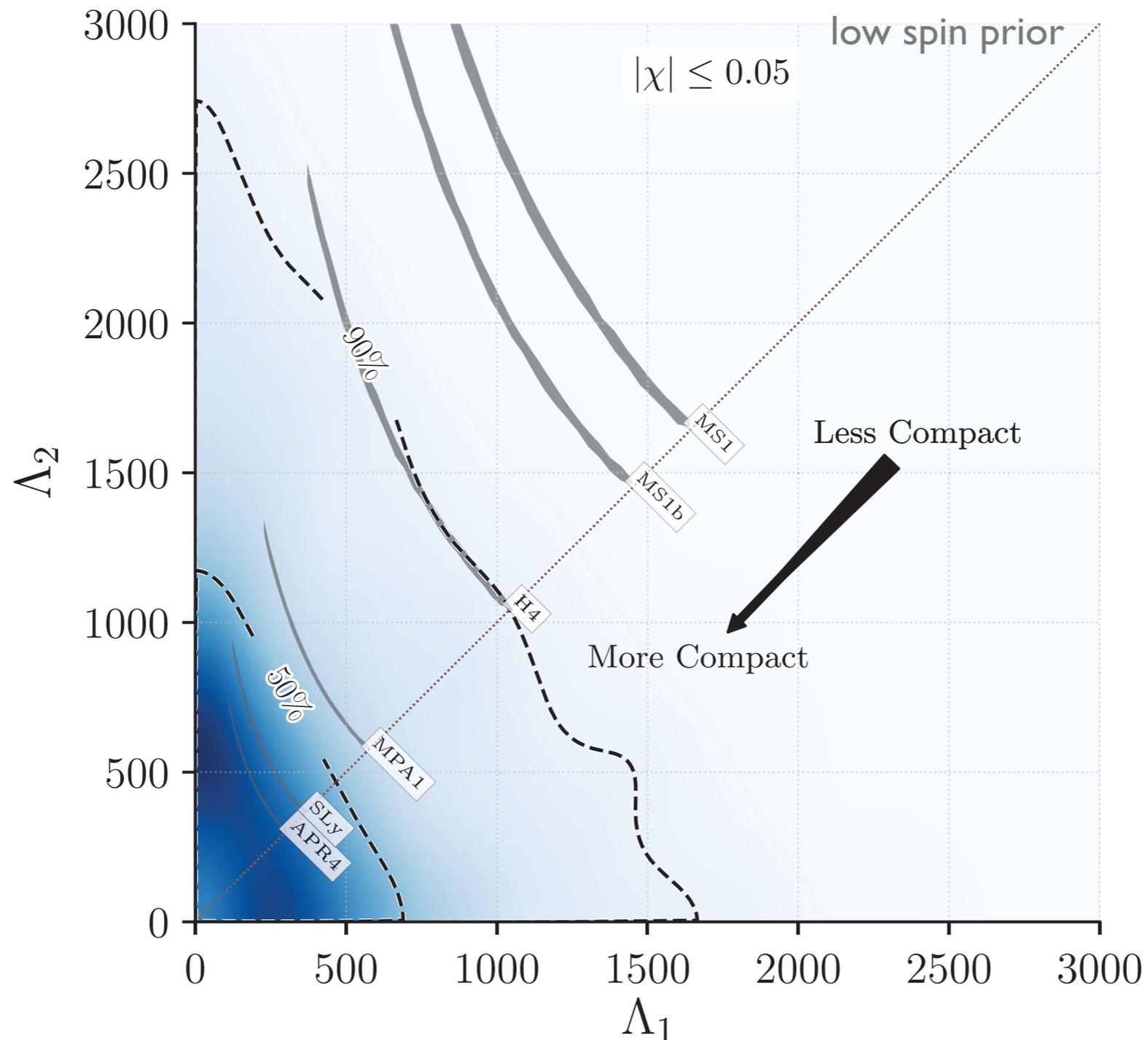
induced quadrupole moment

$$\Lambda(m_i) \sim \left(\frac{Q_{ij}}{\partial_i \partial_j \Phi_{\text{ext}}} \right) r_i^{-5}$$

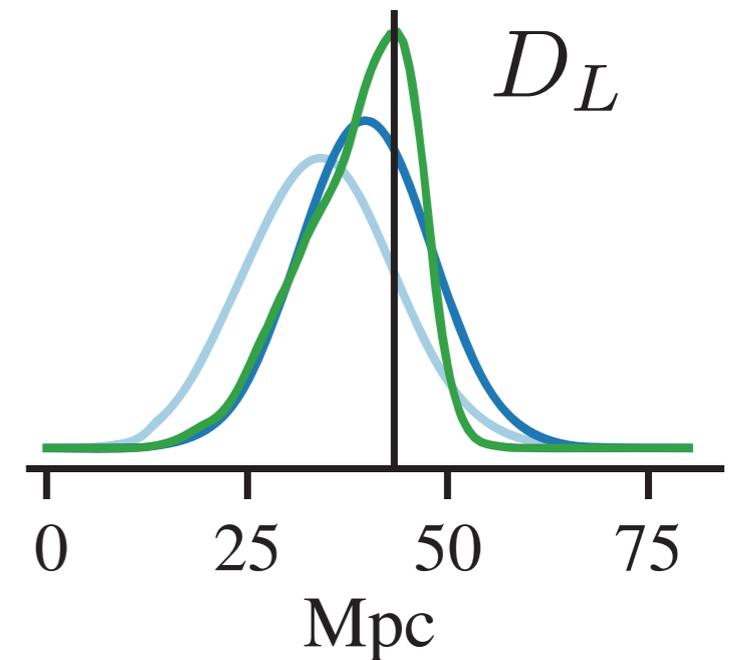
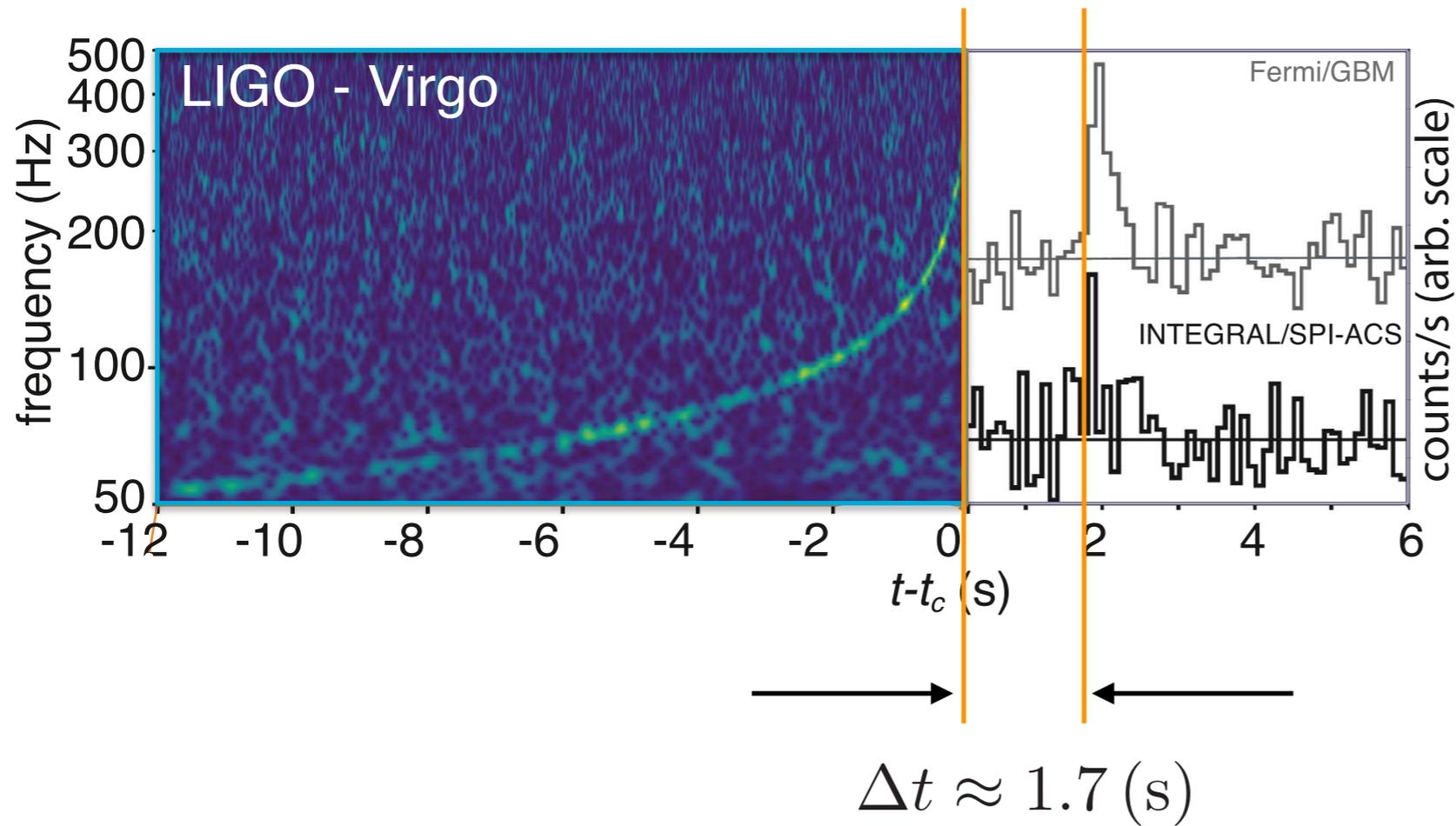


* for relativistic cases, see for example Bennington & Poisson (2009)

tidal deformability — NS eq. of state



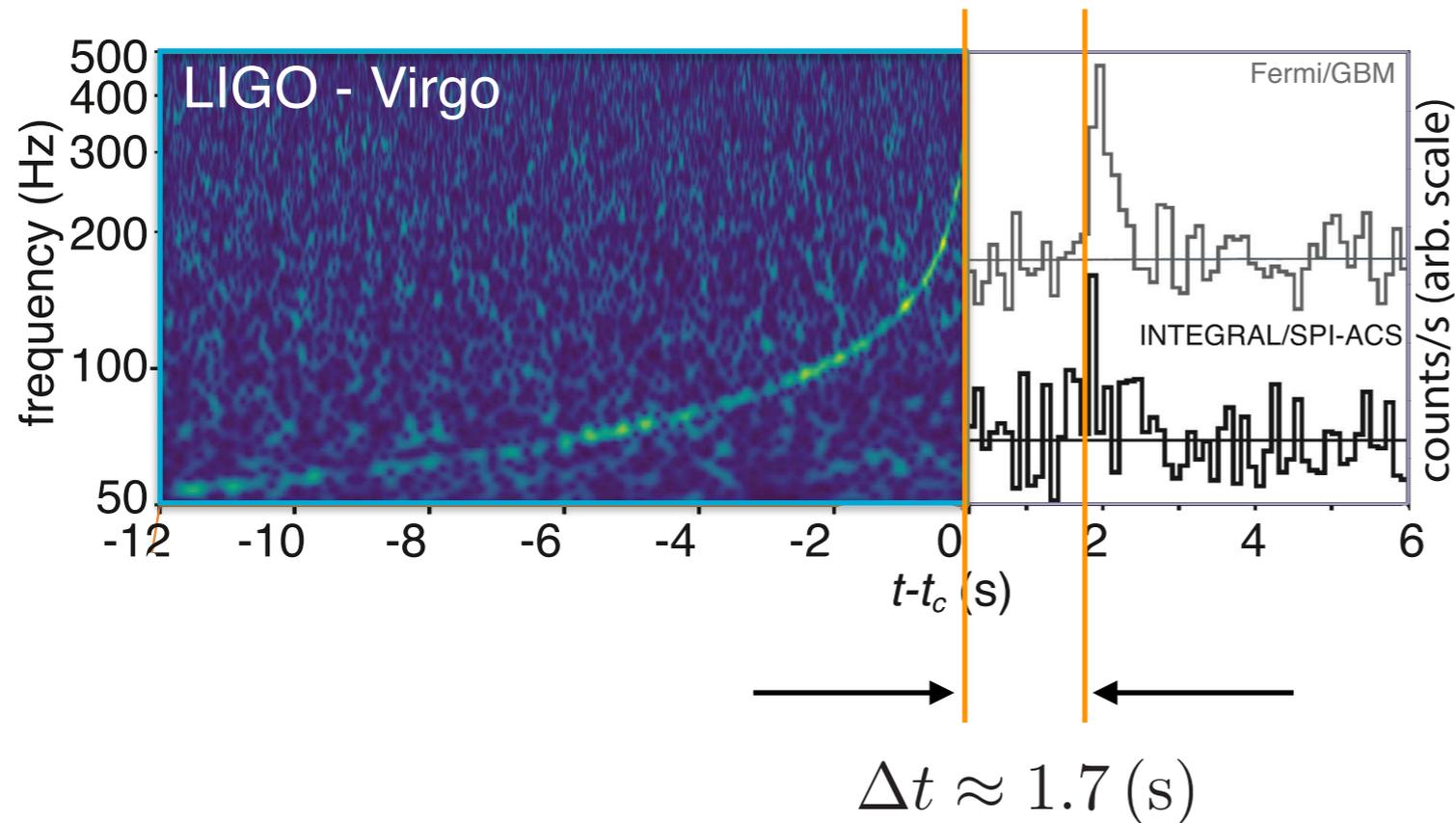
“speed” of gravity = speed of light ?



$$\underset{\sim 2 \text{ s}}{\Delta t} \approx \underset{\sim 40 \text{ Mpc}}{D_L} \left(\frac{1}{v_g} - \frac{1}{c} \right) \implies \left| \frac{c - v_g}{c} \right| \lesssim \text{few} \times 10^{-15}$$

*also test equivalence principle

mass of the graviton ?



$$f \sim \text{few} \times 10^2 \text{ Hz}$$

$$\implies k \sim 10^{-5} \text{ meters}^{-1}$$

$$\left(\frac{c - v_g}{c} \right) \lesssim 10^{-15}$$

$$\omega = c \sqrt{k^2 + (m_g c^2 / \hbar)^2}$$

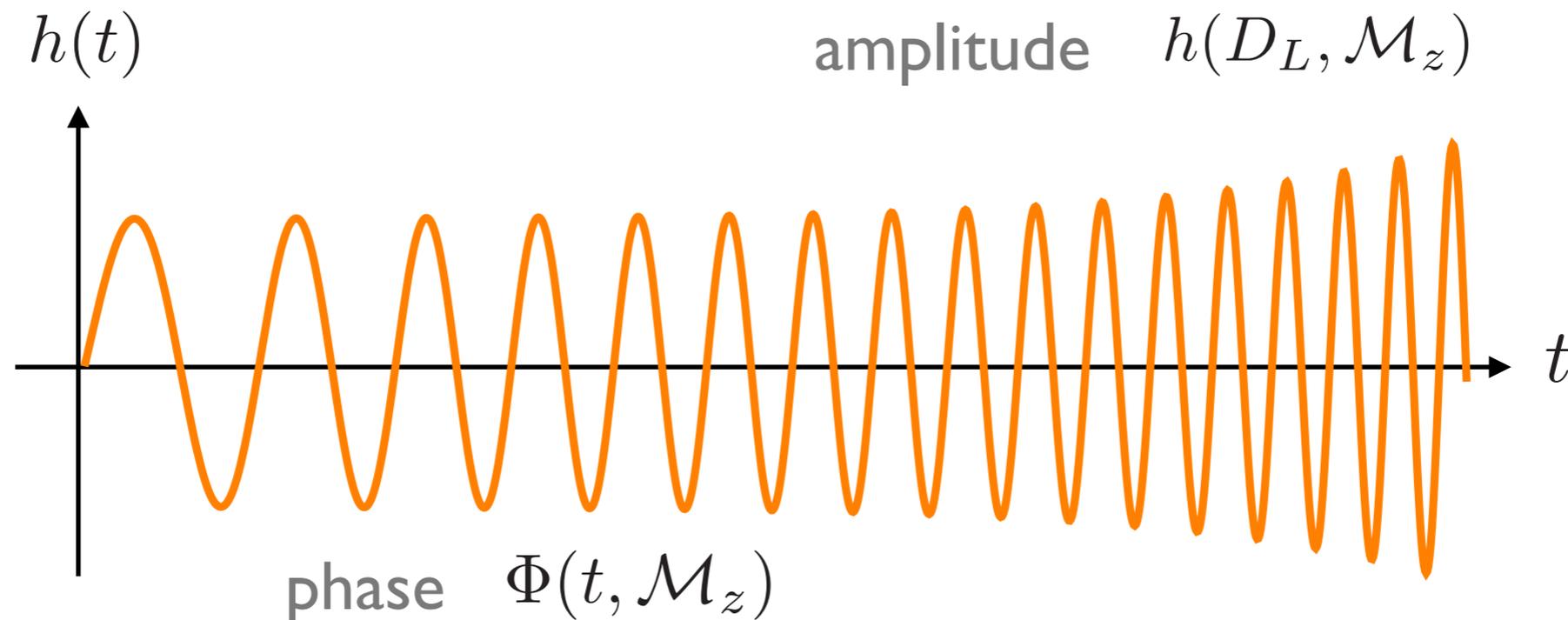
$$v_g = \frac{d\omega}{dk} \approx c \left[1 - \frac{1}{2} \left(\frac{m_g c}{\hbar k} \right)^2 + \dots \right] \implies m_g c^2 \lesssim 10^{-22} \text{ eV}$$



Standard Sirens — distances

measure phase & amplitude — yields distance !

$$\mathcal{M}_z = \mathcal{M}(1 + z) \quad \mathcal{M} = \left(\frac{(m_1 m_2)^3}{m_1 + m_2} \right)^{1/5} \quad \text{“chirp mass”}$$



Schutz (1986)

Holz & Hughes (2005)

Hubble constant from Standard Sirens

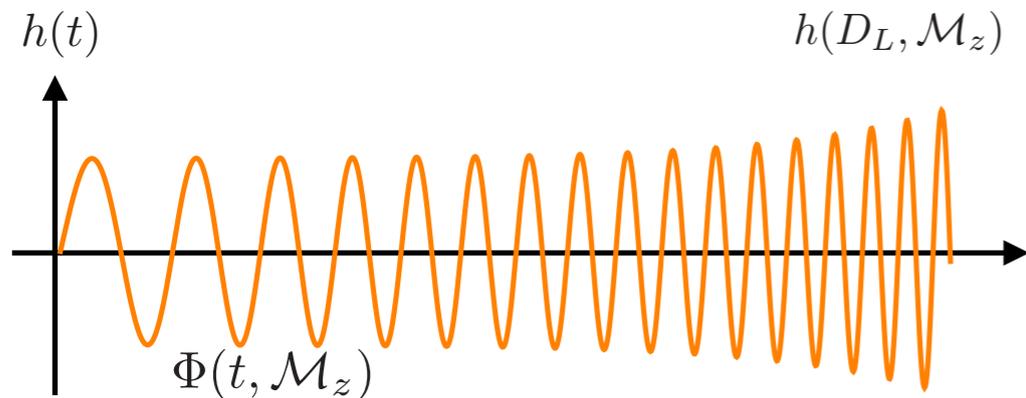


NGC 4993

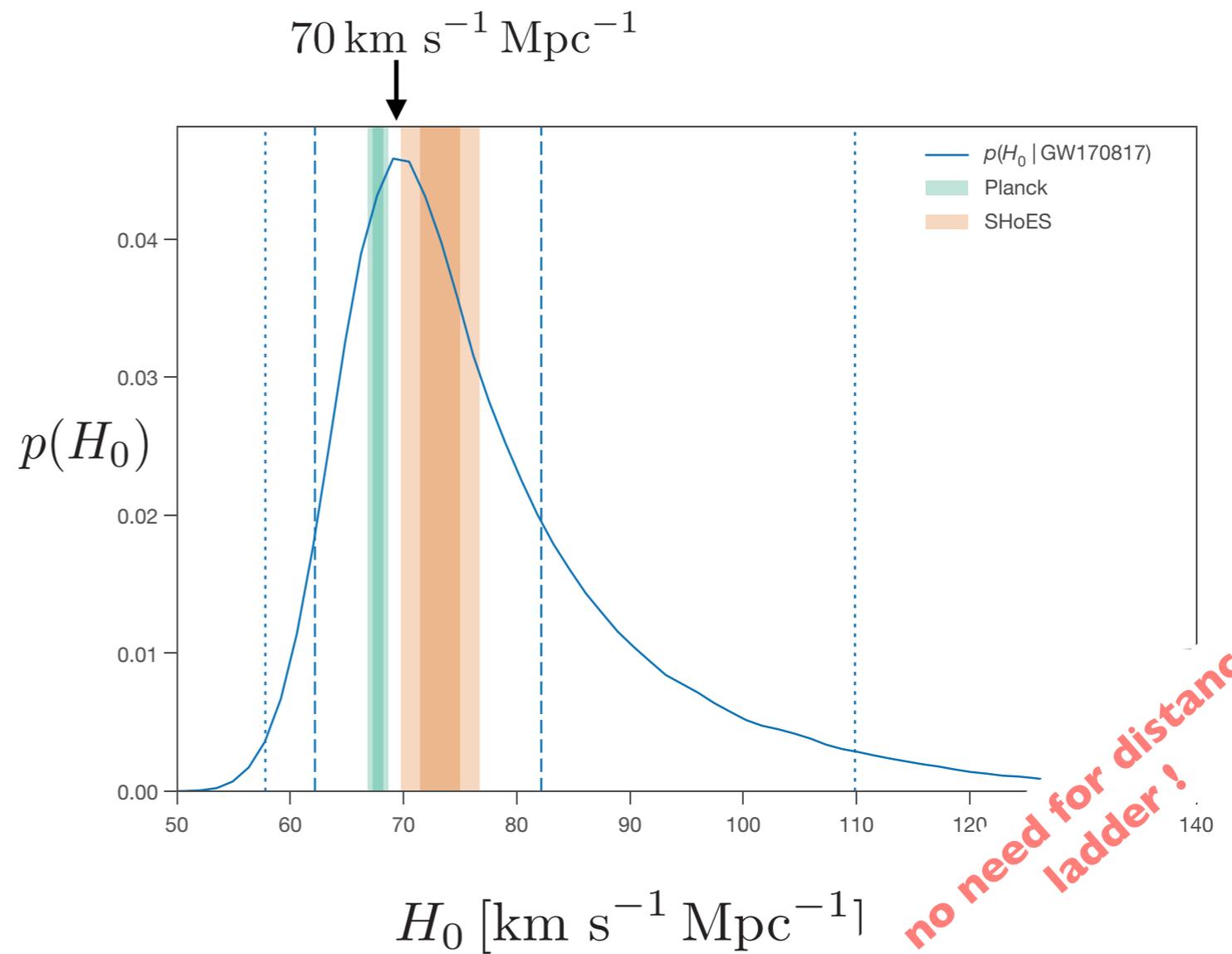
$$v \approx 3 \times 10^3 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$v \approx H_0 D_L$$

$$40 \text{ Mpc}^{-1}$$



• A gravitational-wave standard siren measurement of the Hubble constant, nature, 2017

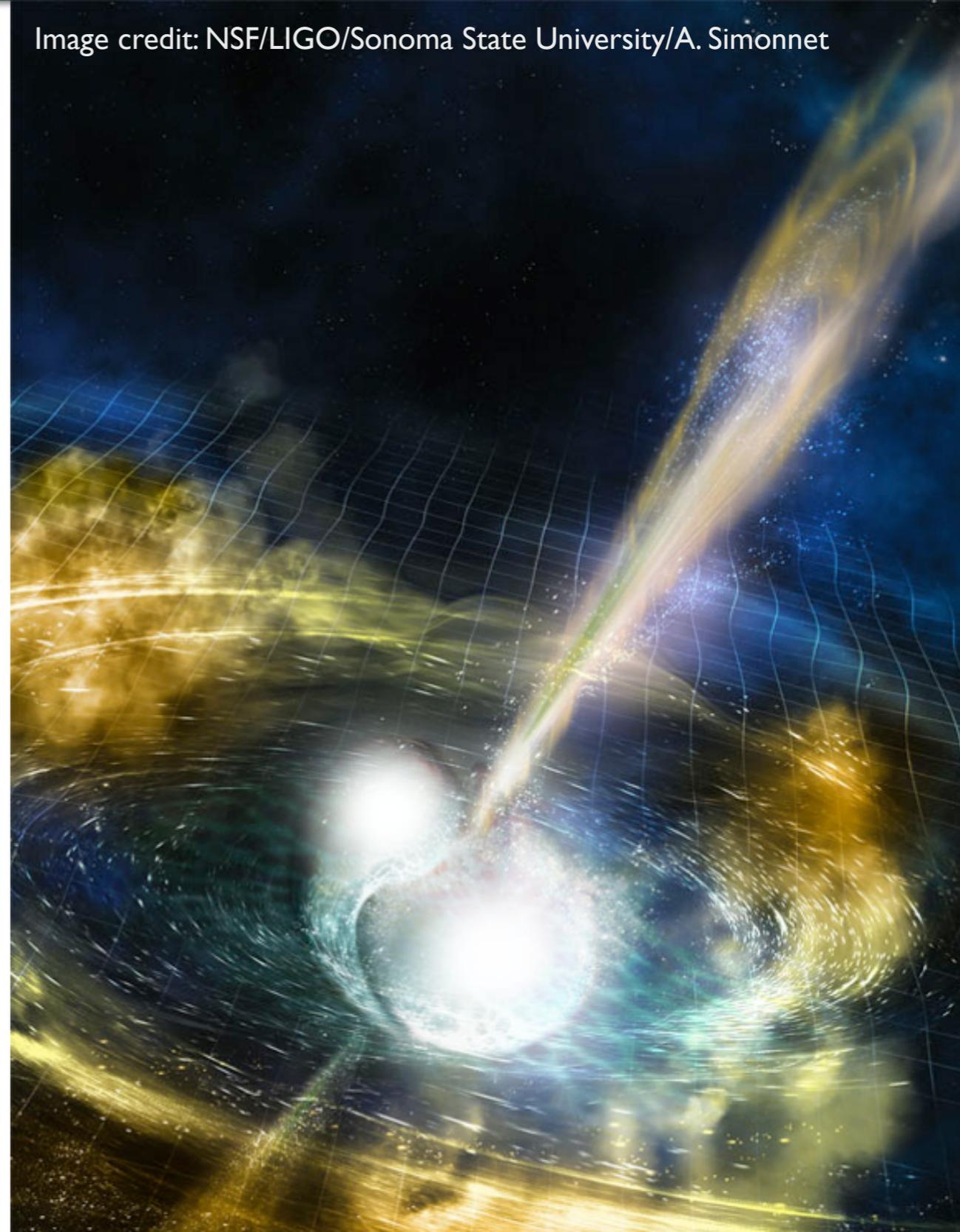


*degeneracy with viewing angle

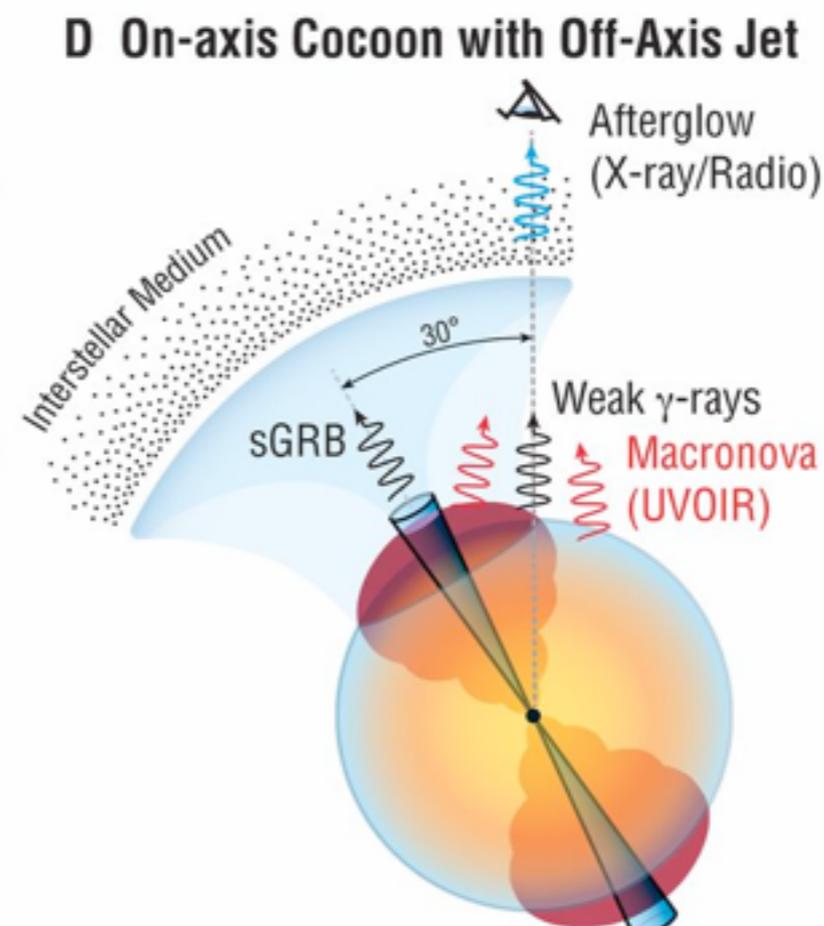
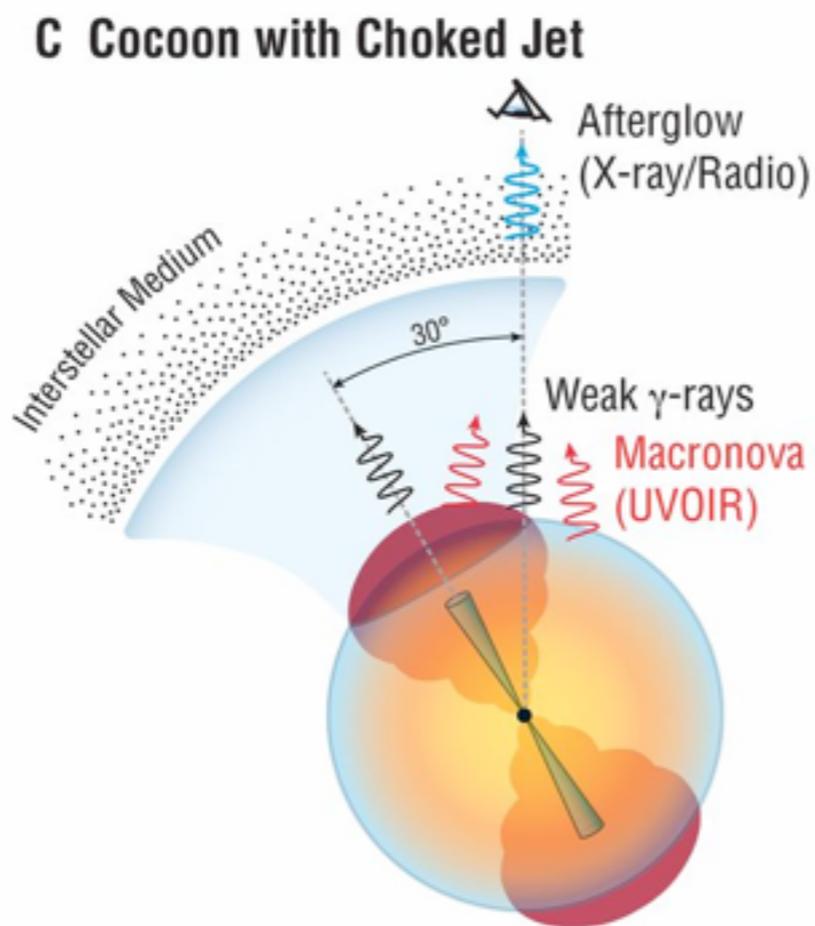
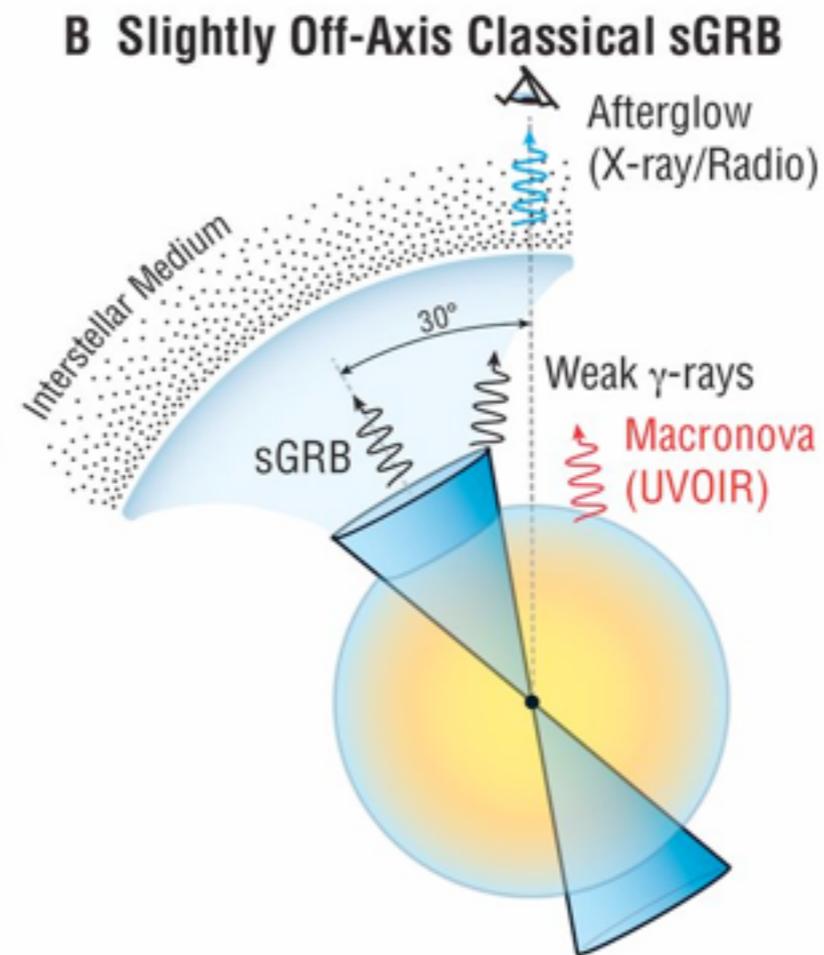
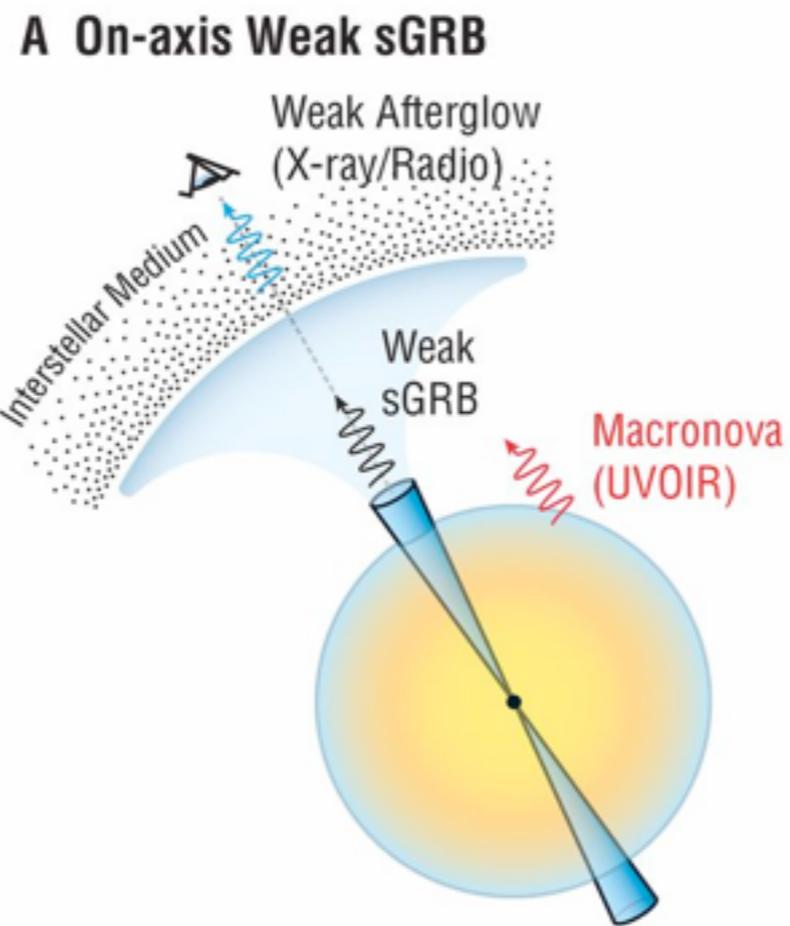
should we be excited ?

- beginning of **multi-messenger astronomy** with G & EM waves
- constraints on **rates** of formation, evolution etc. of progenitors
- **cosmology** with G-waves
- ability to test “**fundamental**” **physics** in extreme environments
 - * theories of gravity
 - * ultra-dense matter
- exotica — anticipation for the **unexpected** !

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

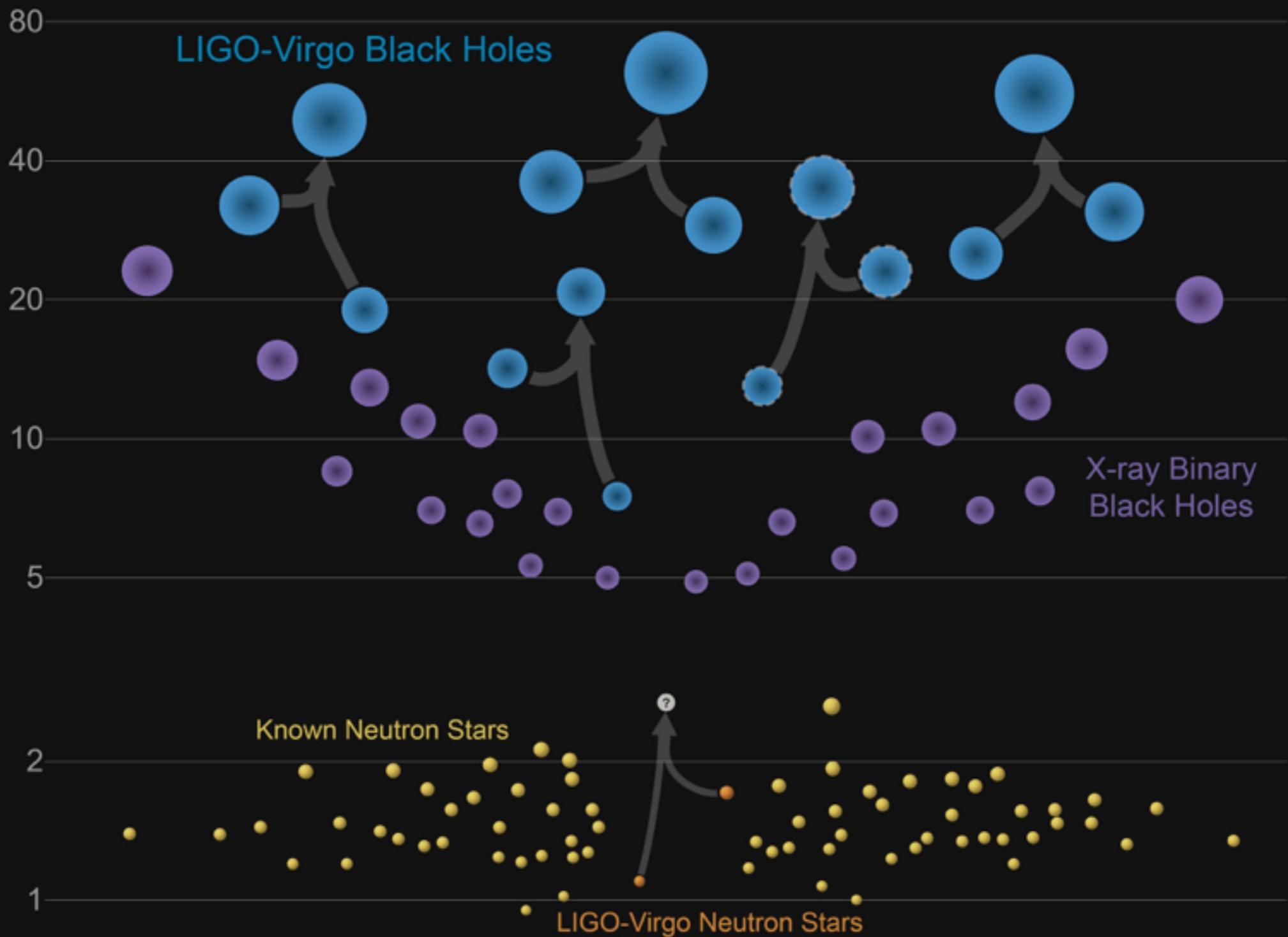


extra slides



Masses in the Stellar Graveyard

in Solar Masses



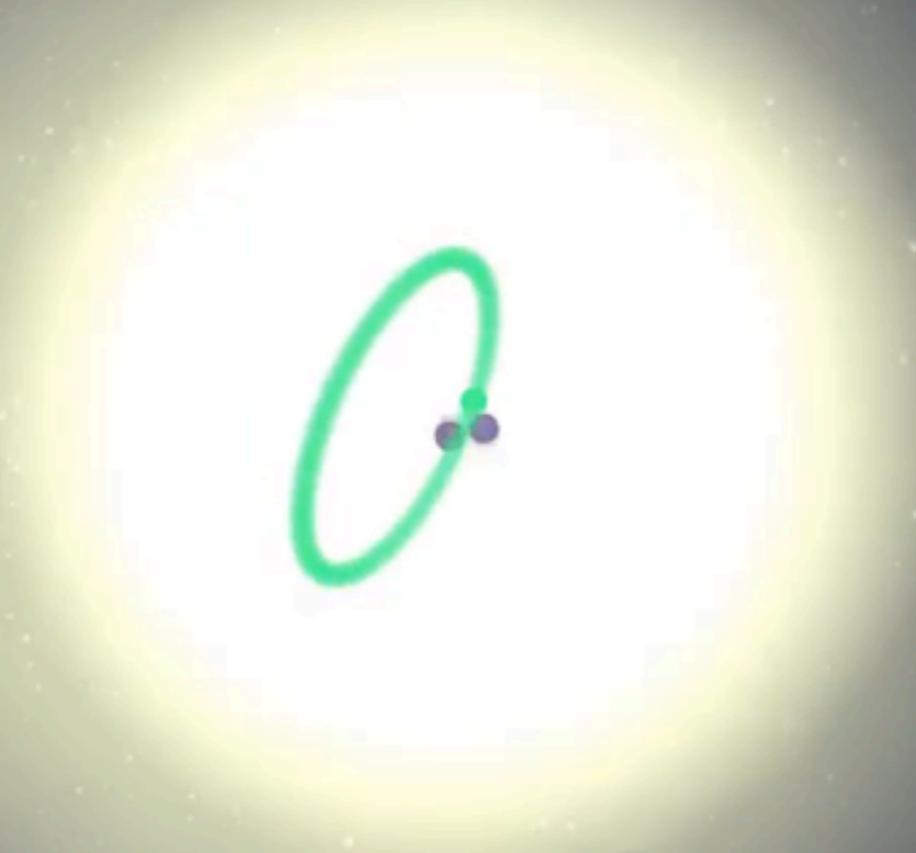
Time Until
Merger

quiescent orbit



Time Until
Merger

SN kick



final position before merger ?

