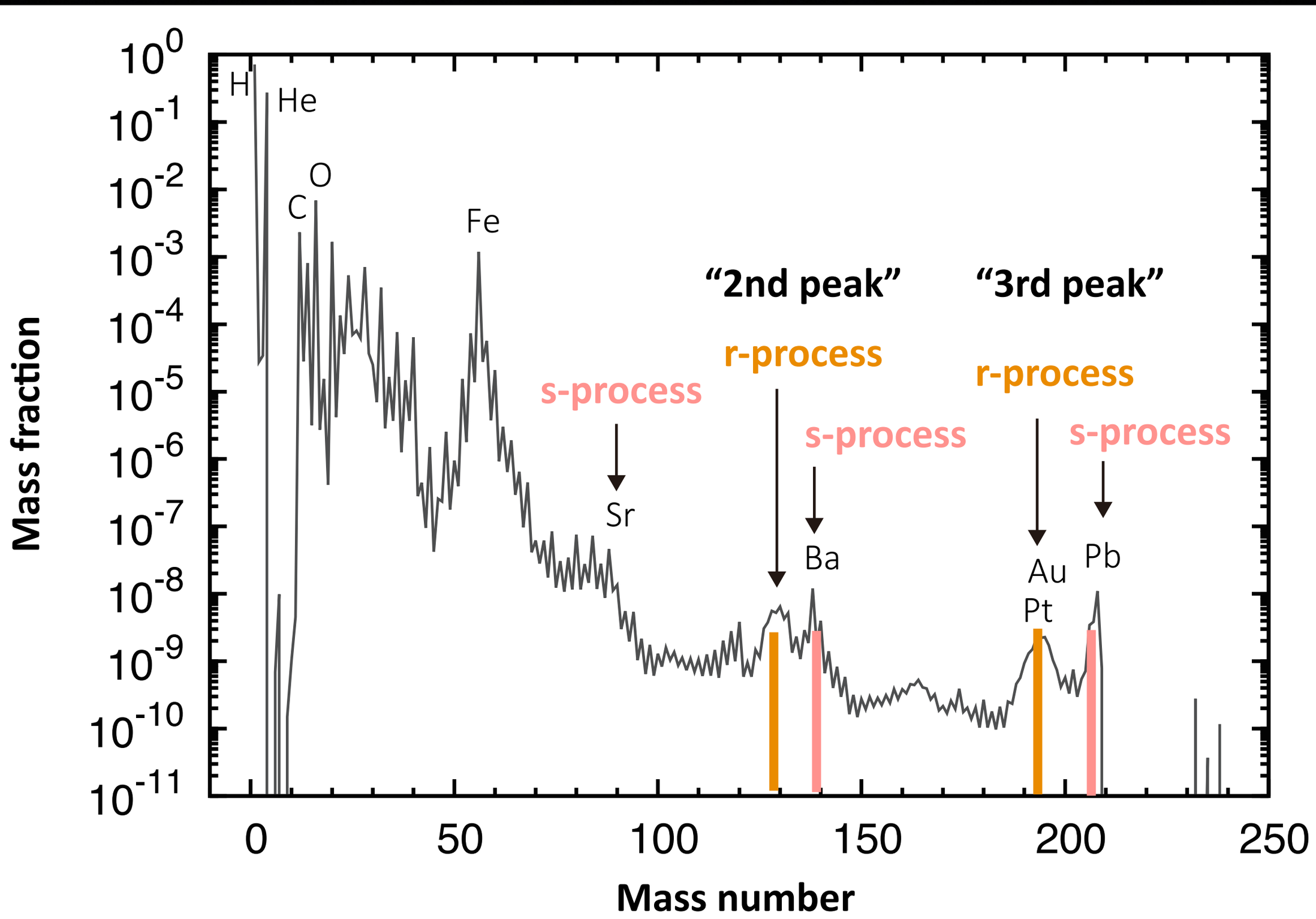
Section 10.
Neutron star merger

10.1 Neutron star merger

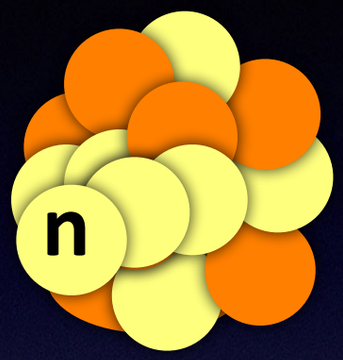
10.2 Observations of gravitational wave sources

Cosmic abundances



Neutron-capture nucleosynthesis

s (slow)-process



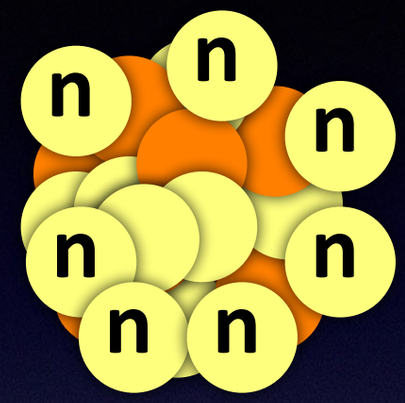
Decay



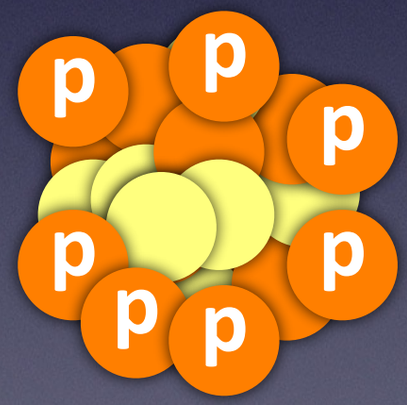
Ba, Pb, …

Inside of stars

r (rapid)-process



Decay



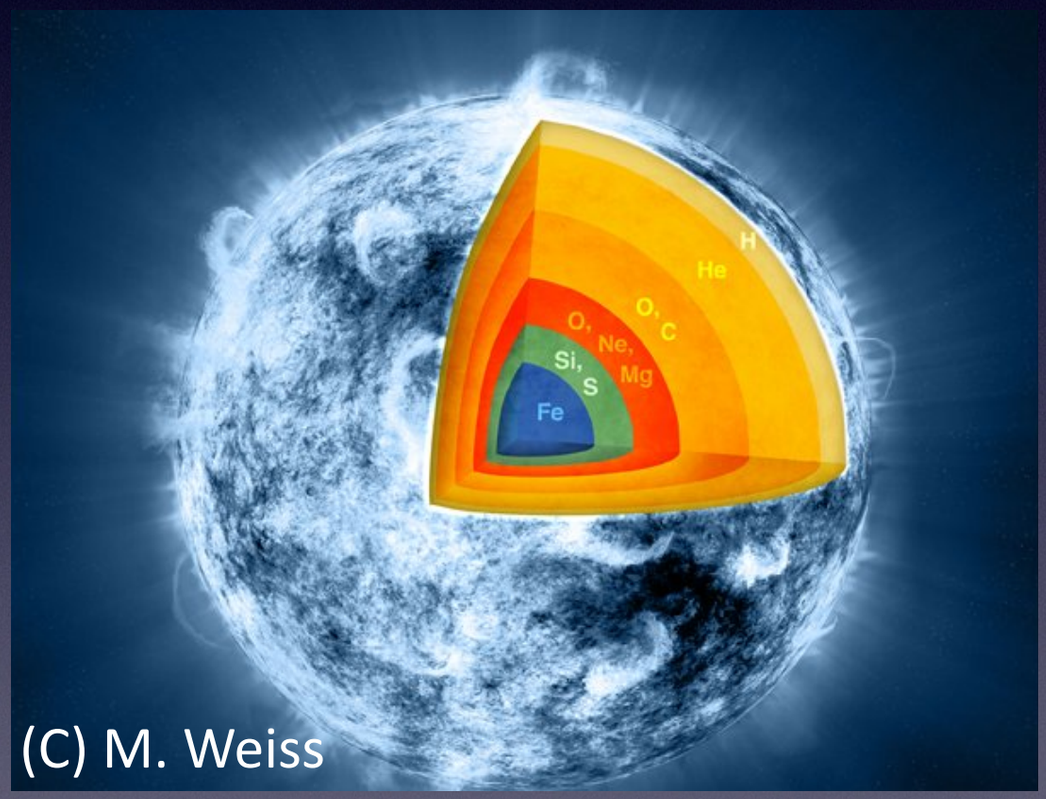
Au, Pt, U, …

SN? NS merger?

Origin of r-process elements?

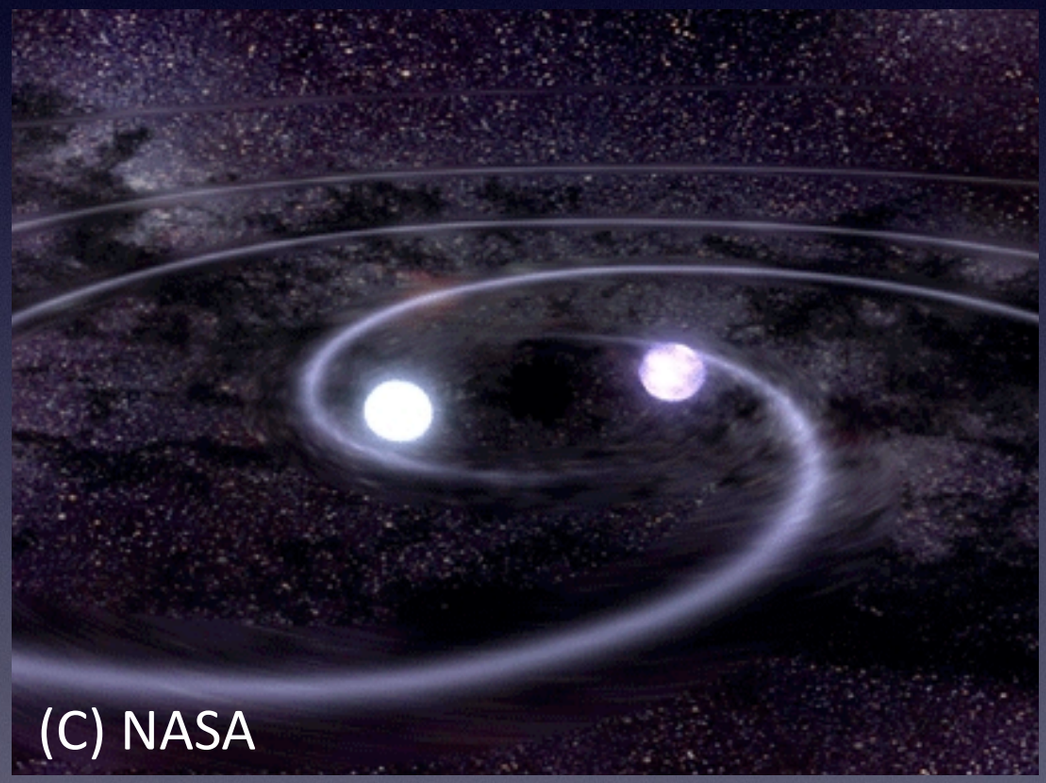
Some phenomena related to neutron star

Supernova



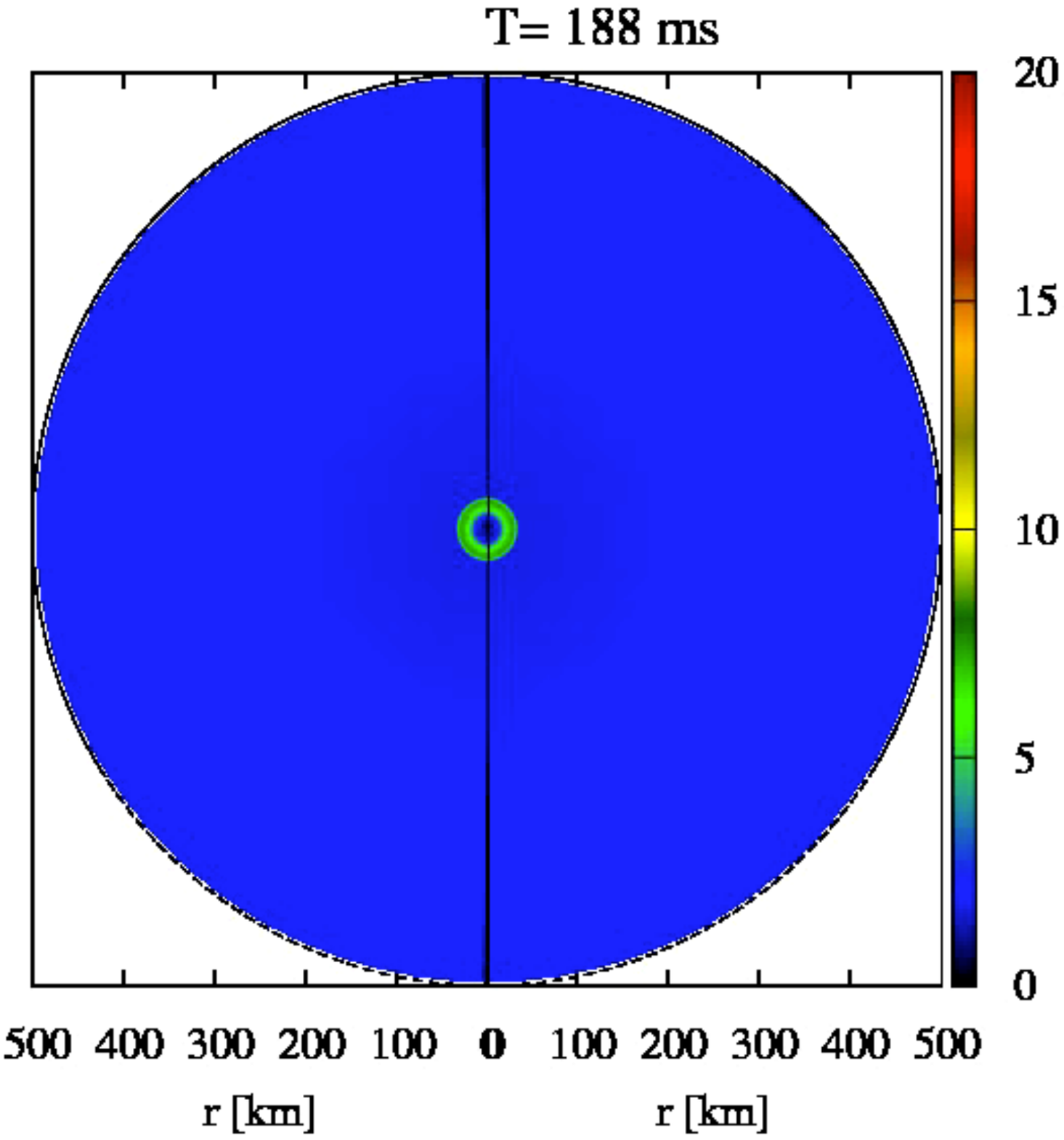
~ 1 event per 100 yr in a galaxy
($R \sim 10^{-2}$ yr-1)

Neutron star merger



~ 1 event per 10,000 yr in a galaxy
($R \sim 10^{-4}$ yr-1)

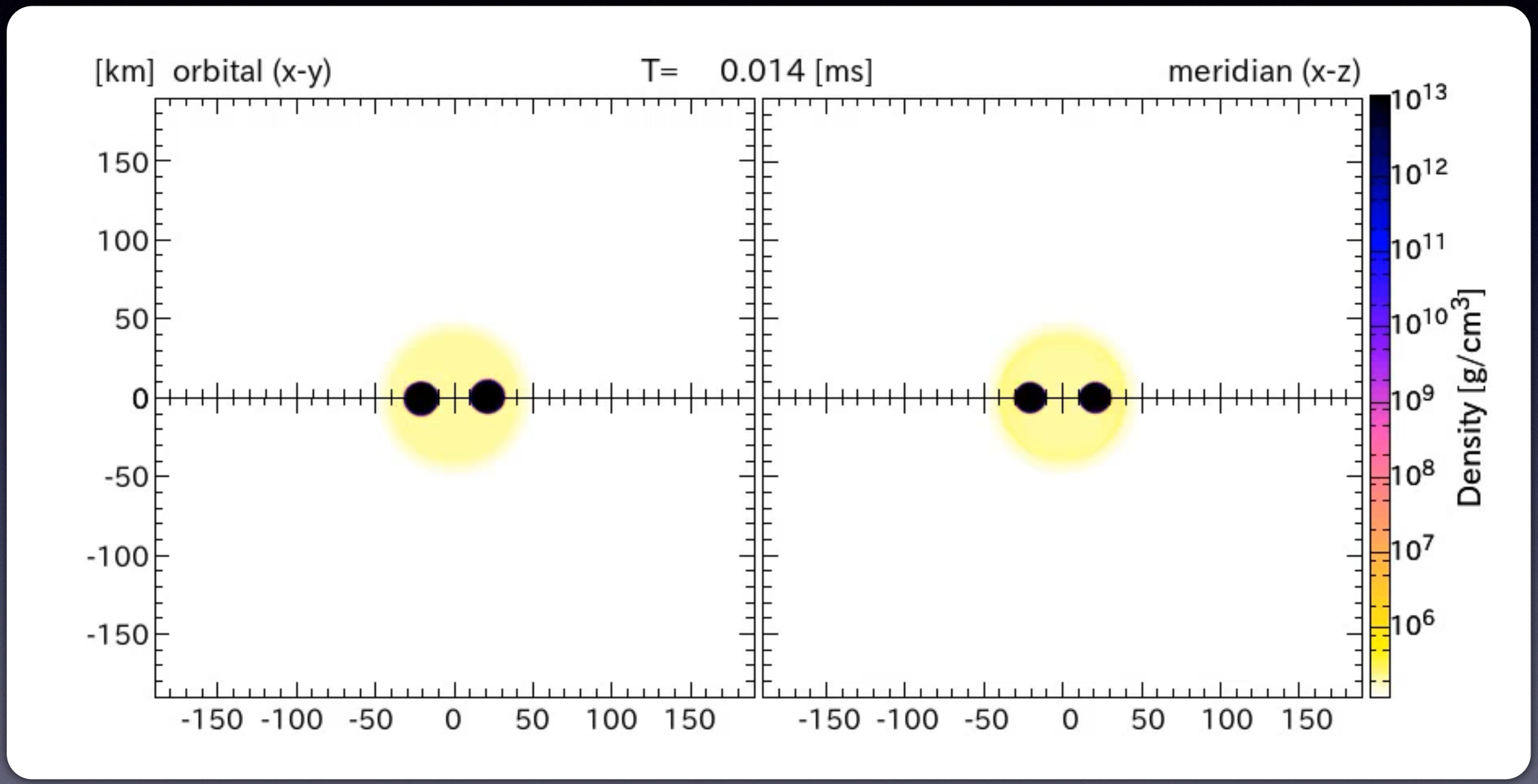
Suwa et al. 2011



NS merger => mass ejection

Top view

Side view



Sekiguchi+15, 16

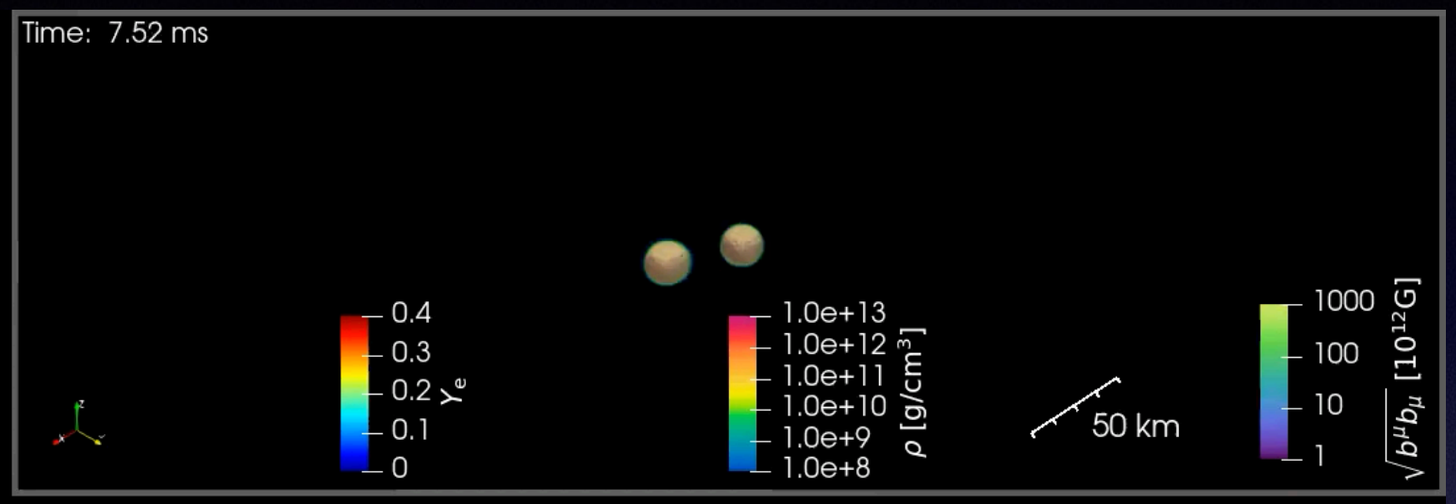
M ~ 10^{-3} - 10^{-2} Msun

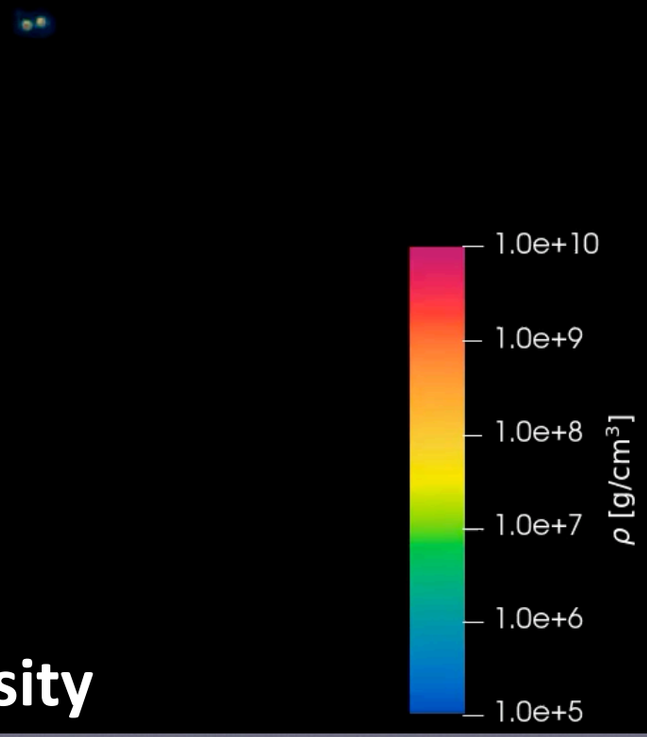
v ~ 0.1 - 0.2 c

NS merger => dynamical mass ejection (< 0.1 sec)

=> “wind” from disk (~ 1 sec)

General relativity



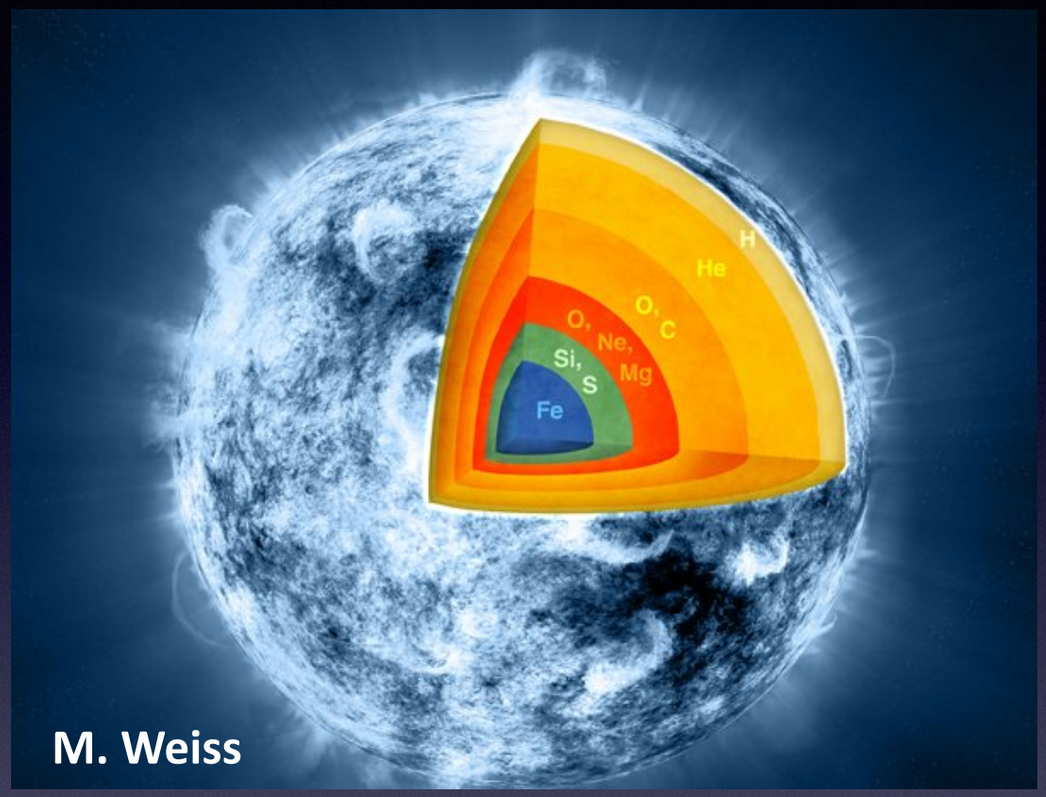


Density

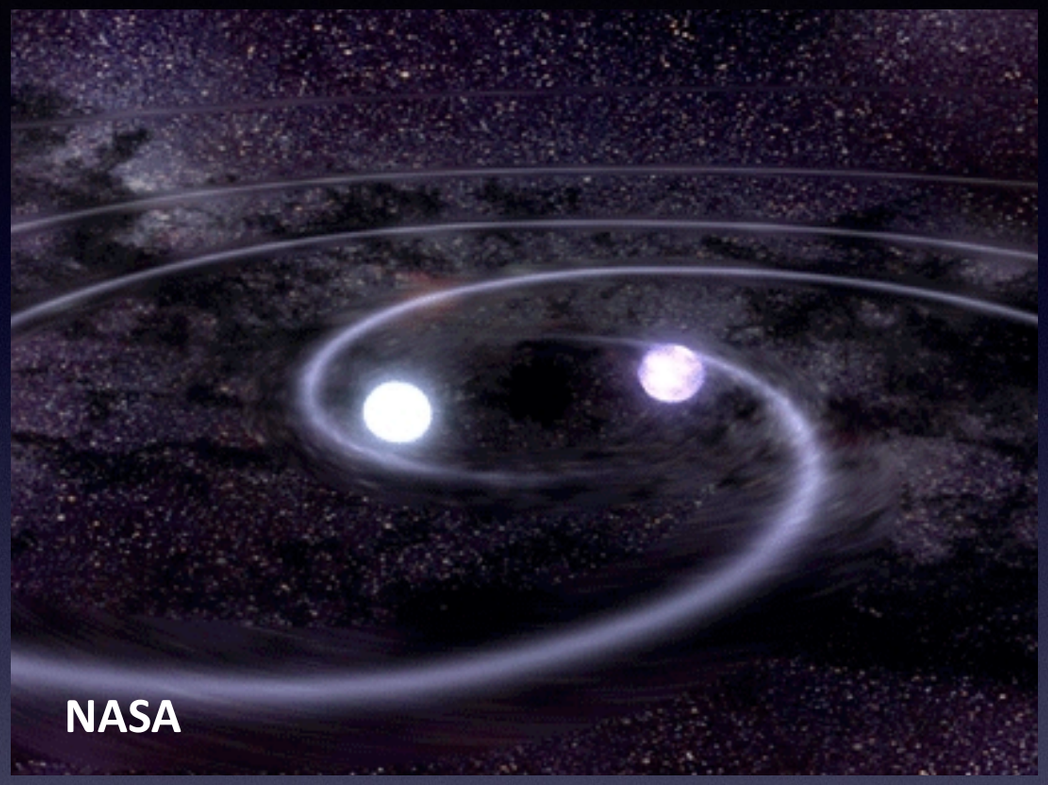
B field

Explosive phenomena around the neutron star

Core-collapse supernova



NS merger



Moderately neutron rich

Ye ~ 0.45 ($n_n \sim 1.2 n_p$)

Very neutron rich

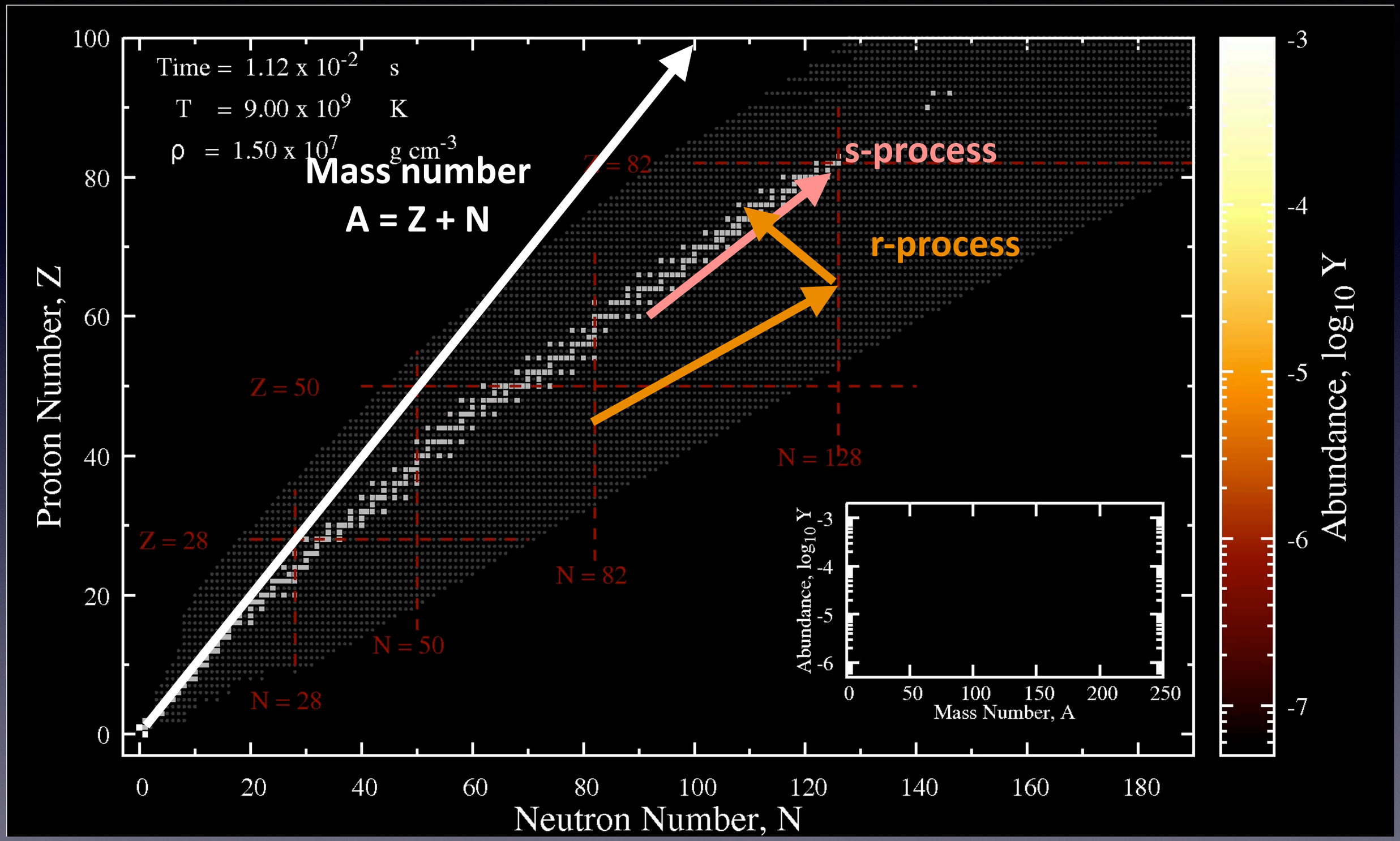
Ye ~ 0.10 ($n_n \sim 9\ n_p$)

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

$n_n = n_p$ for Ye = 0.50

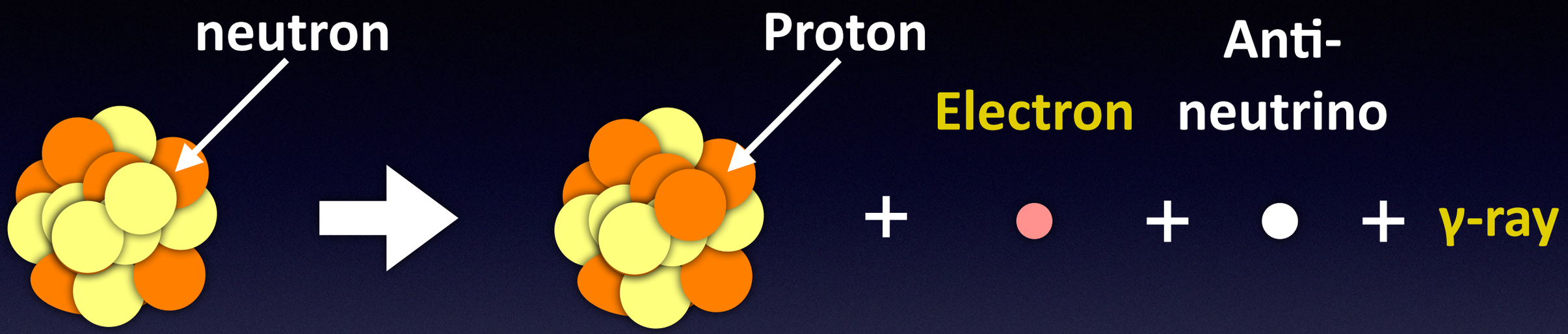
Why some material are ejected?
(NS has an extremely strong gravity!)

r-process in NS merger



(C) Nobuya Nishimura

Radioactive decay (Beta decay)



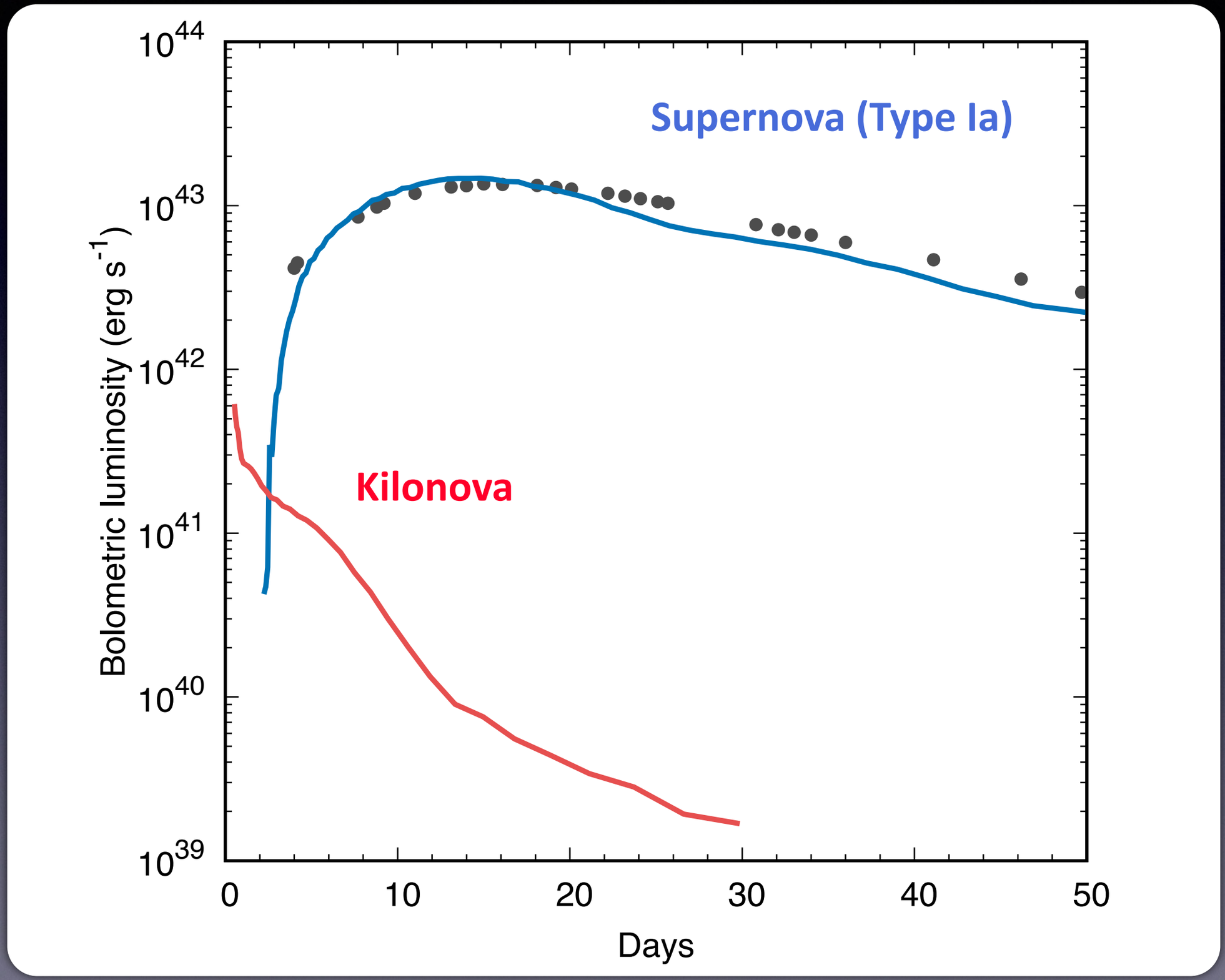
$$\mathrm{n} \rightarrow \mathrm{p}^{+} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

Radioactively powered transients similar to SN (56Ni)
=> “kilonova”

Supernova vs NS merger

	Supernova	NS merger
Power source	^{56}Ni	r-process elements
Ejecta mass	1-10 Msun	0.01 Msun
Ejecta velocity	5,000-10,000 km/s	30,000-60,000 km/s (0.1c-0.2c)
Kinetic energy	10^{51} erg	1-5 x 10^{50} erg
Composition	H, He, C, O, Ca, Fe-group	r-process elements

Supernova and kilonova



Section 10.
Neutron star merger

10.1 Neutron star merger

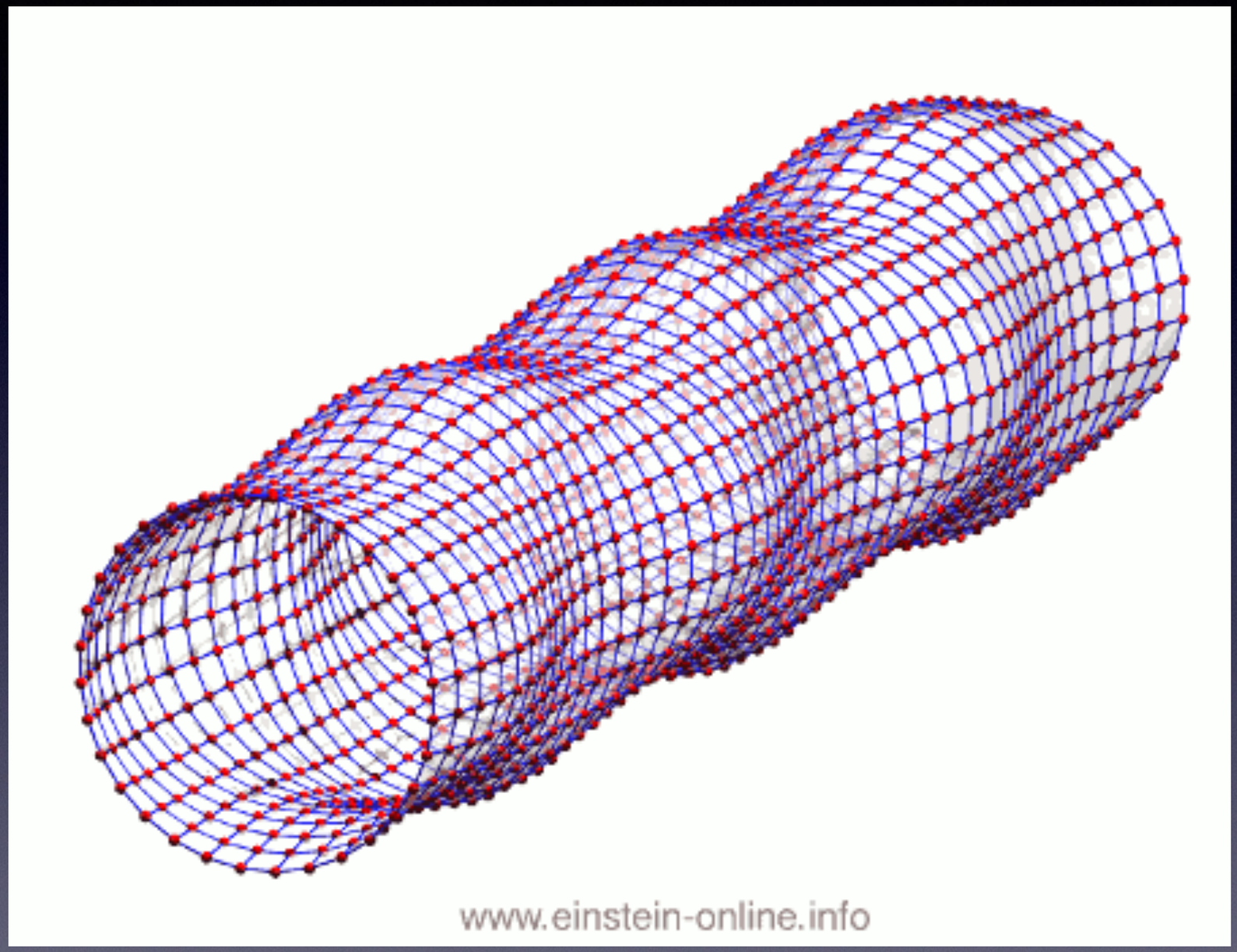
10.2 Observations of gravitational wave sources

How to find NS merger??

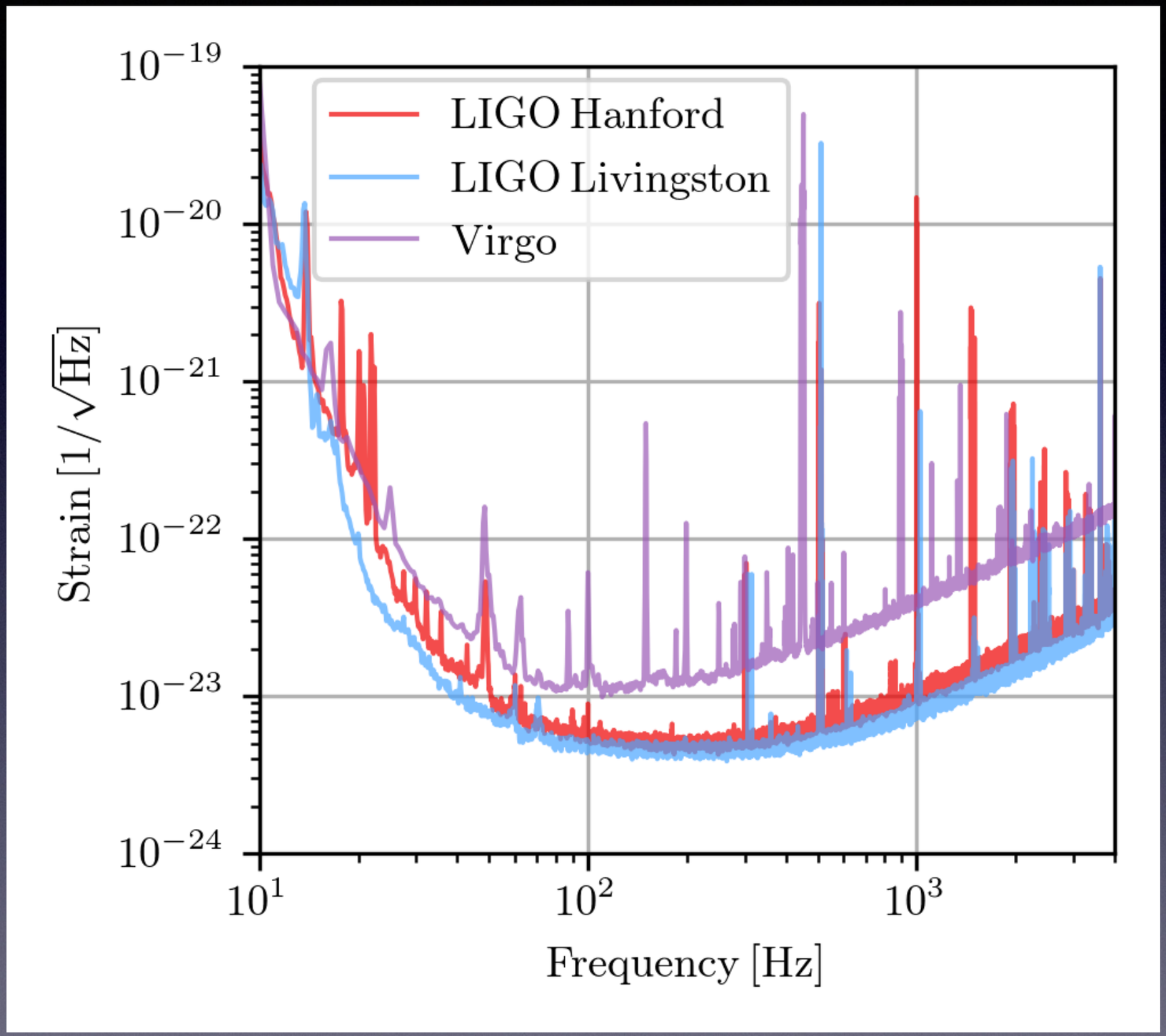


What is the expected amplitude of GW waves?

Visualization of GWs



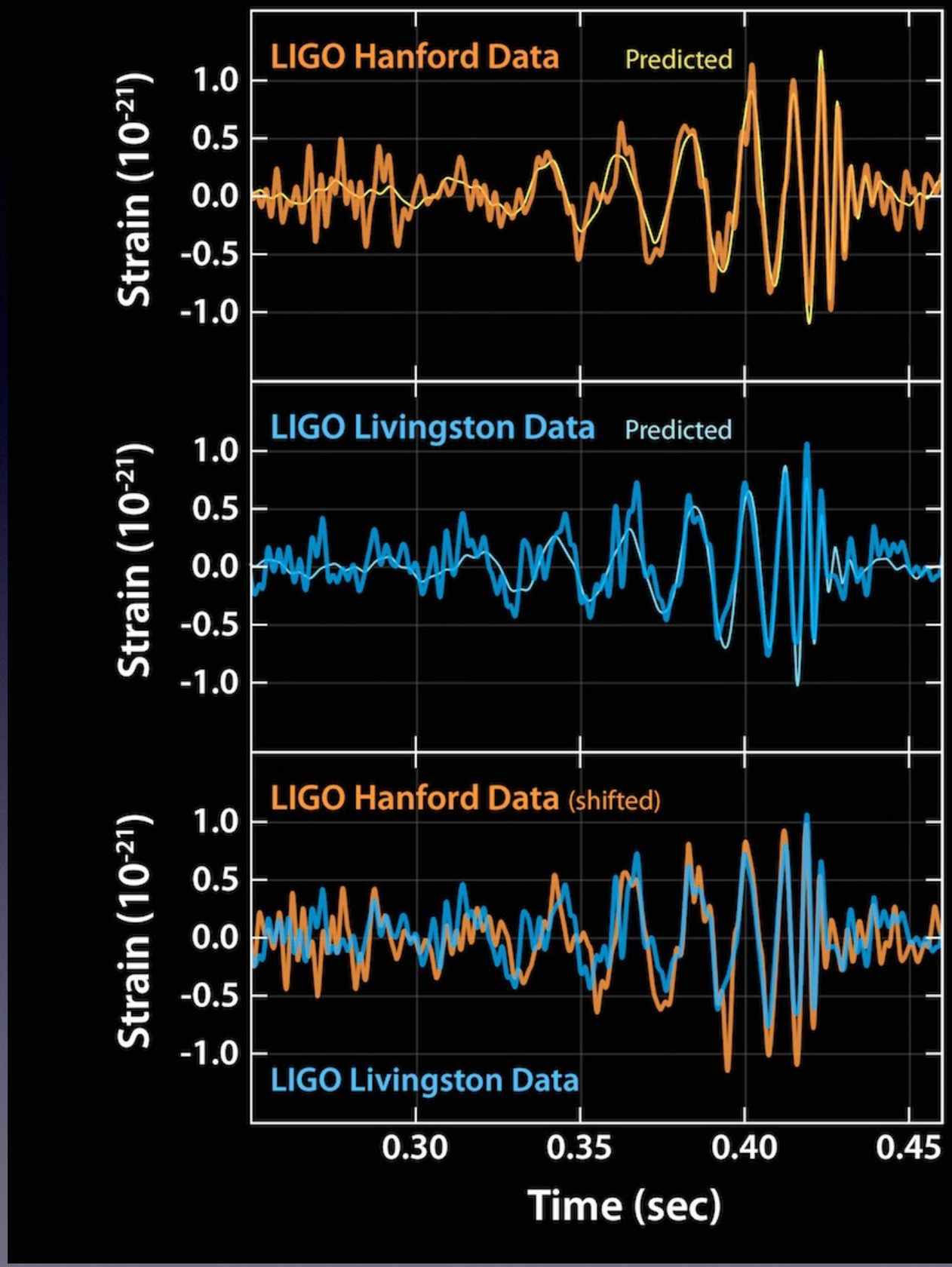
Sensitivity of GW detectors



https://gwosc.org/O3/o3speclines/

The first GW detection (GW150914)

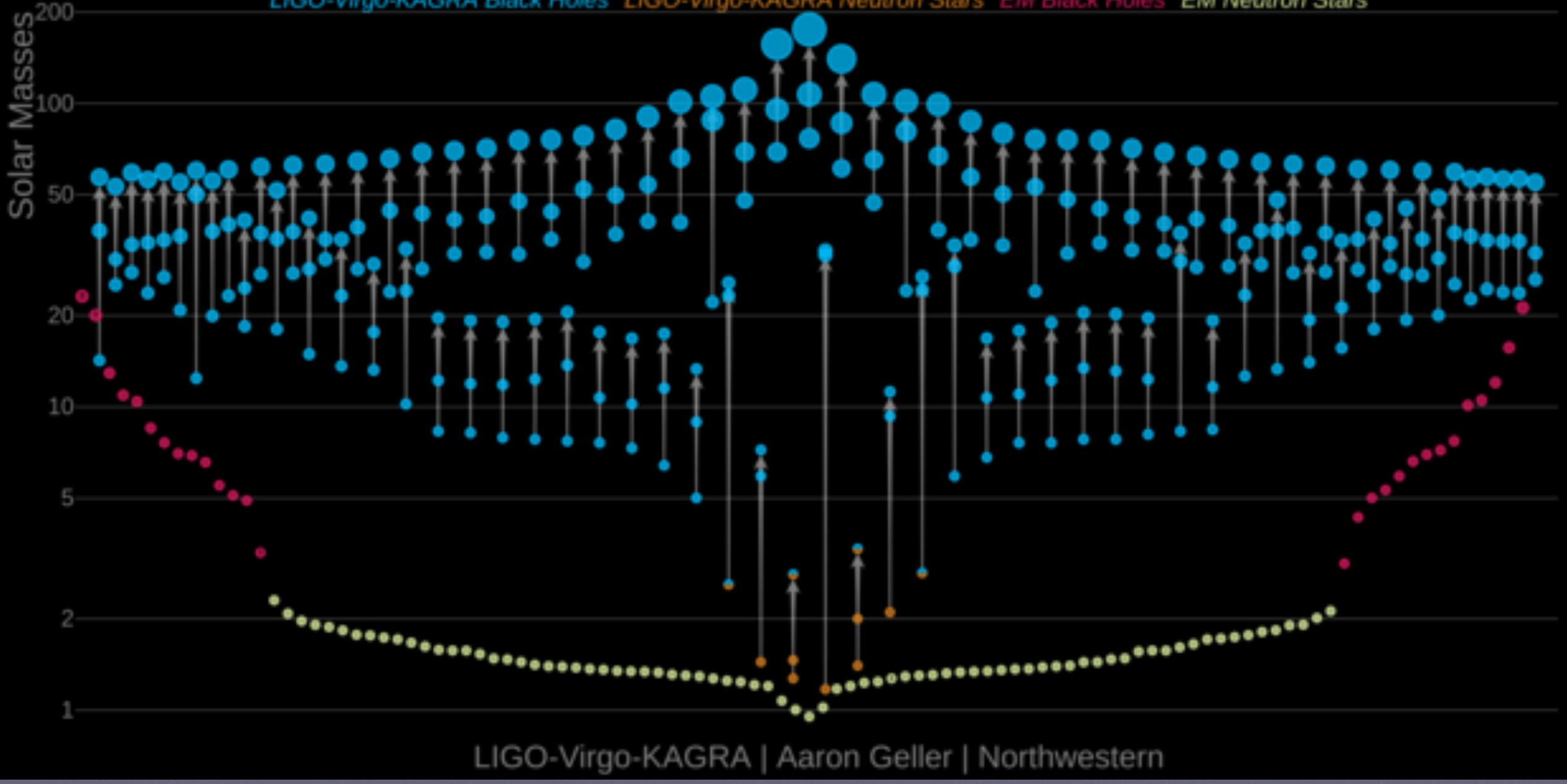
Merger of binary black hole



LIGO Scientific Collaboration
and Virgo Collaboration, 2016, PRL, 061102

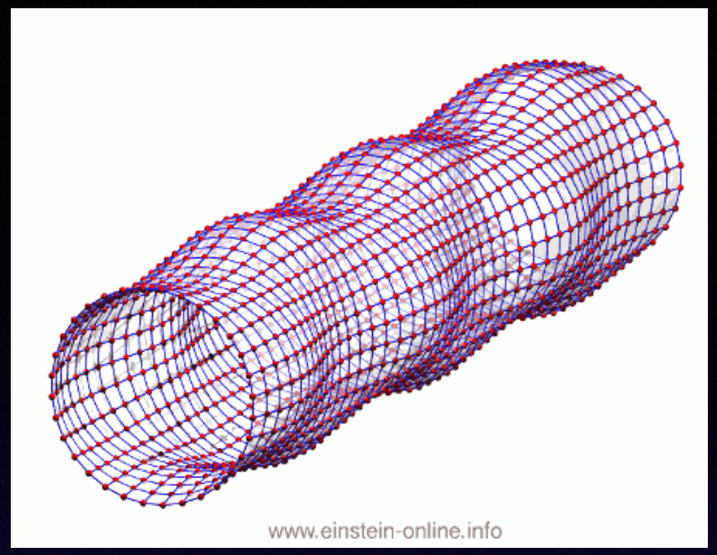
Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars

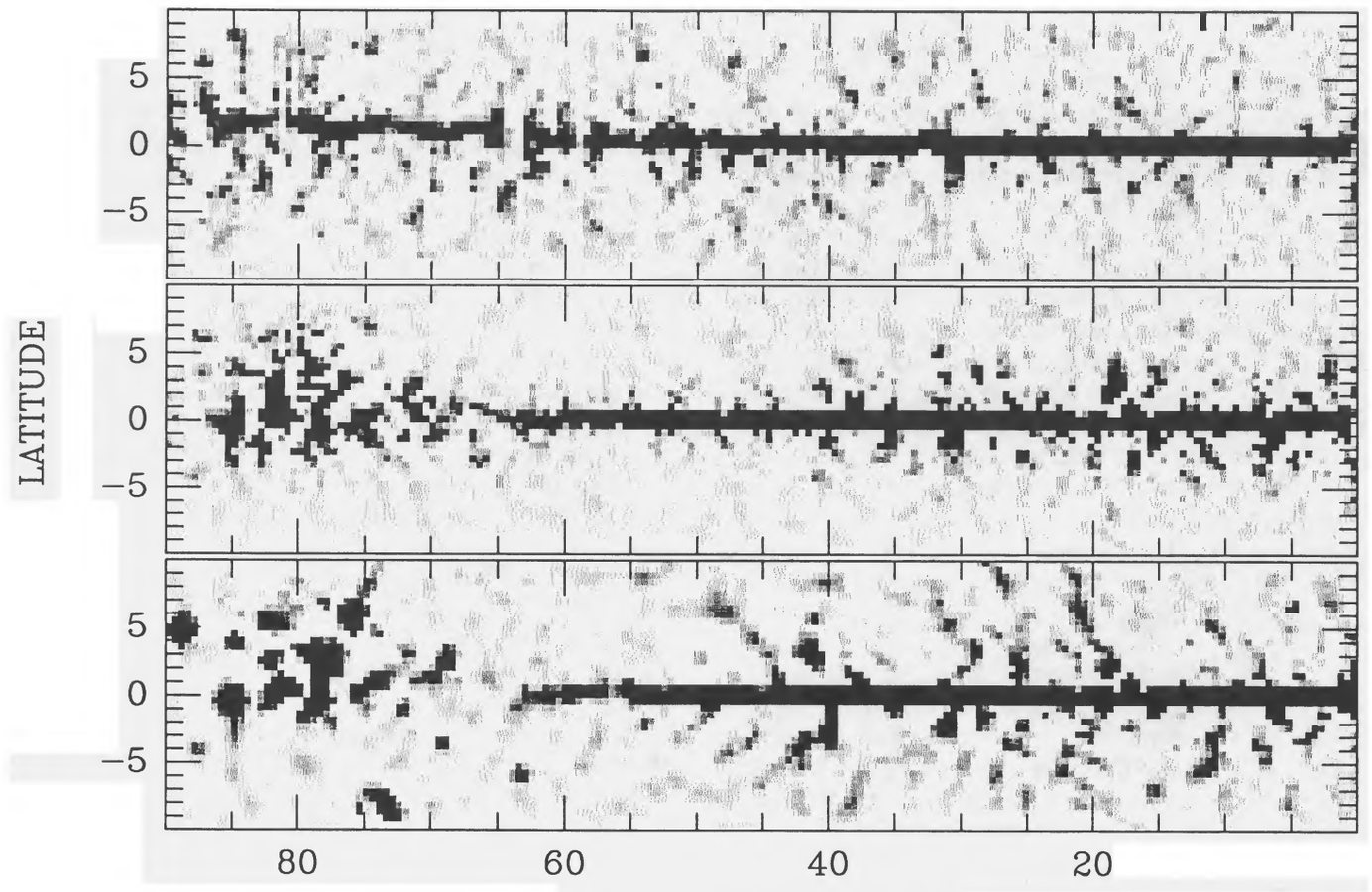


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Gravitational wave



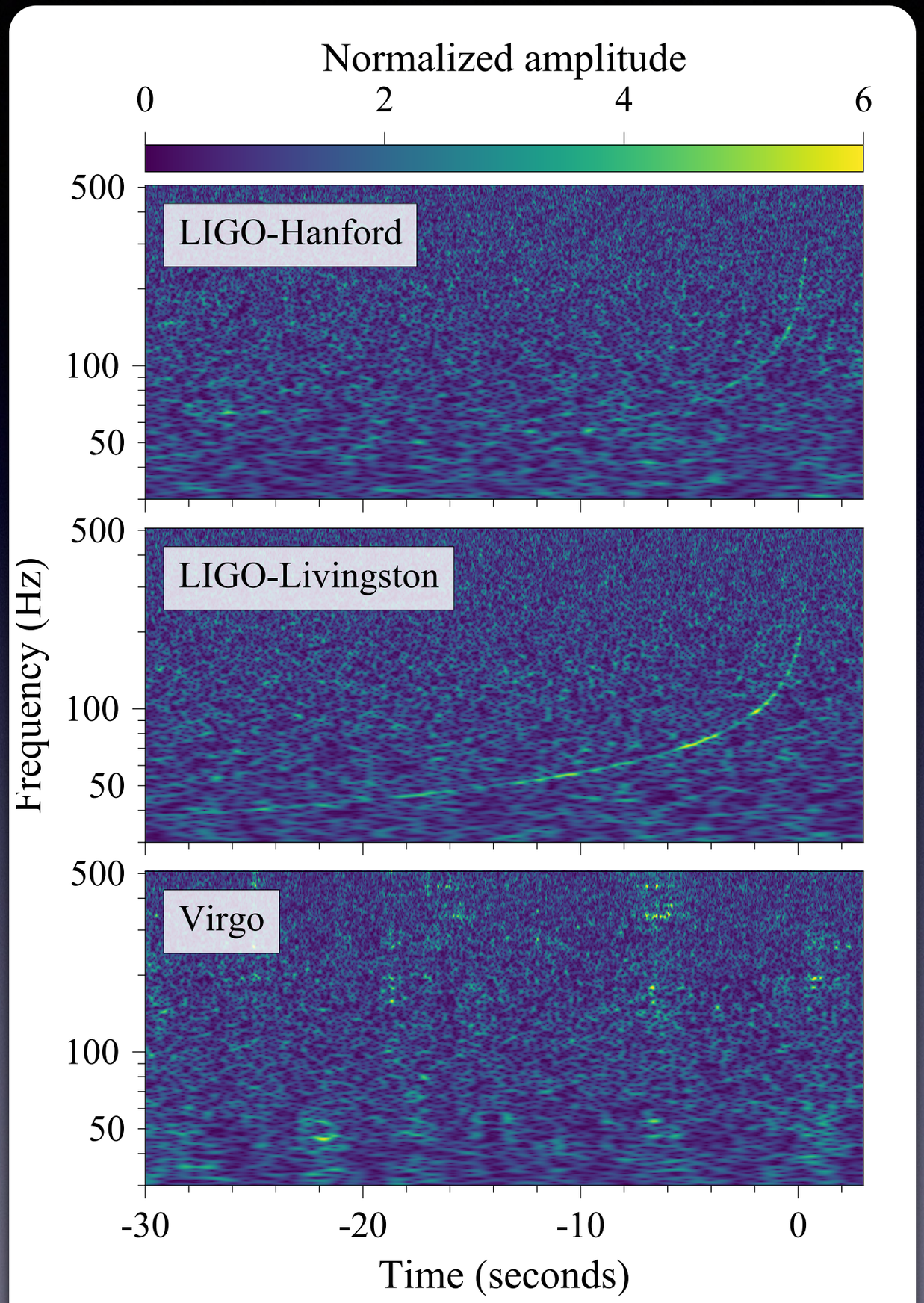
“Galactic worms”



Number (1)	Name (2)	Δl (deg) (3)	Δb (deg) (4)
64	GW 175.8−2.5	13.0	4.5
65	GW 177.3+1.4	3.0	1.0
66	GW 192.0+8.7	2.5	3.0
67	GW 193.8+2.7	1.0	1.5
68	GW 195.7+4.5	5.5	6.5
69	GW 211.5+6.9	5.0	7.5
70	GW 213.4+1.4	2.0	1.0
71	GW 216.6+1.3	2.5	1.0
72	GW 220.0+3.6	3.0	5.0
73	GW 230.8+5.2	6.5	8.5
74	GW 239.2+7.4	4.5	6.5
75	GW 239.9+3.4	7.5	5.5
76	GW 243.9+2.1	1.5	2.5
77	GW 247.9+4.6	3.5	8.0

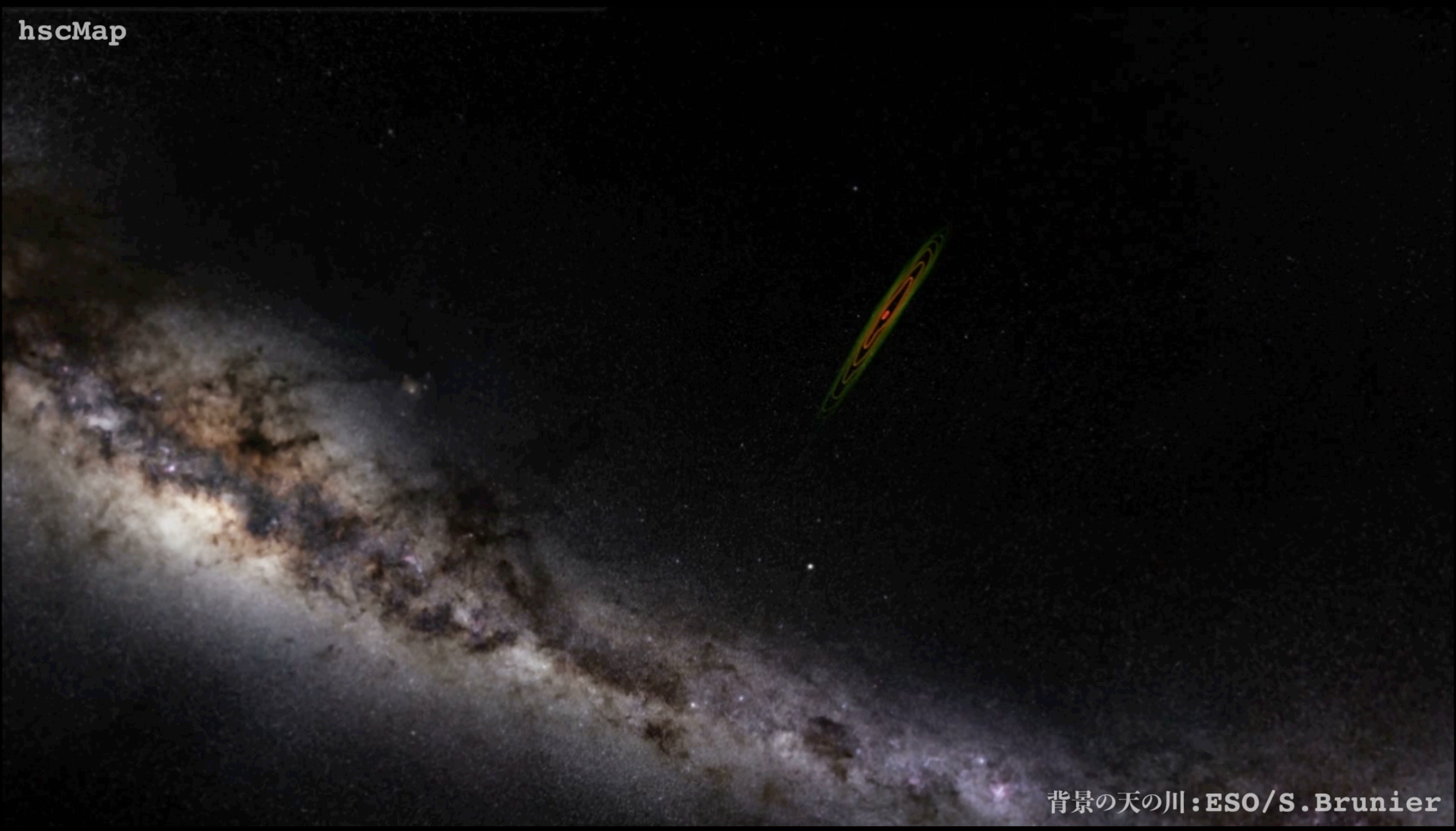
Koo+92

The first GW detection From NS merger (GW170817)



LIGO Scientific Collaboration and Virgo Collaboration, 2017, PRL

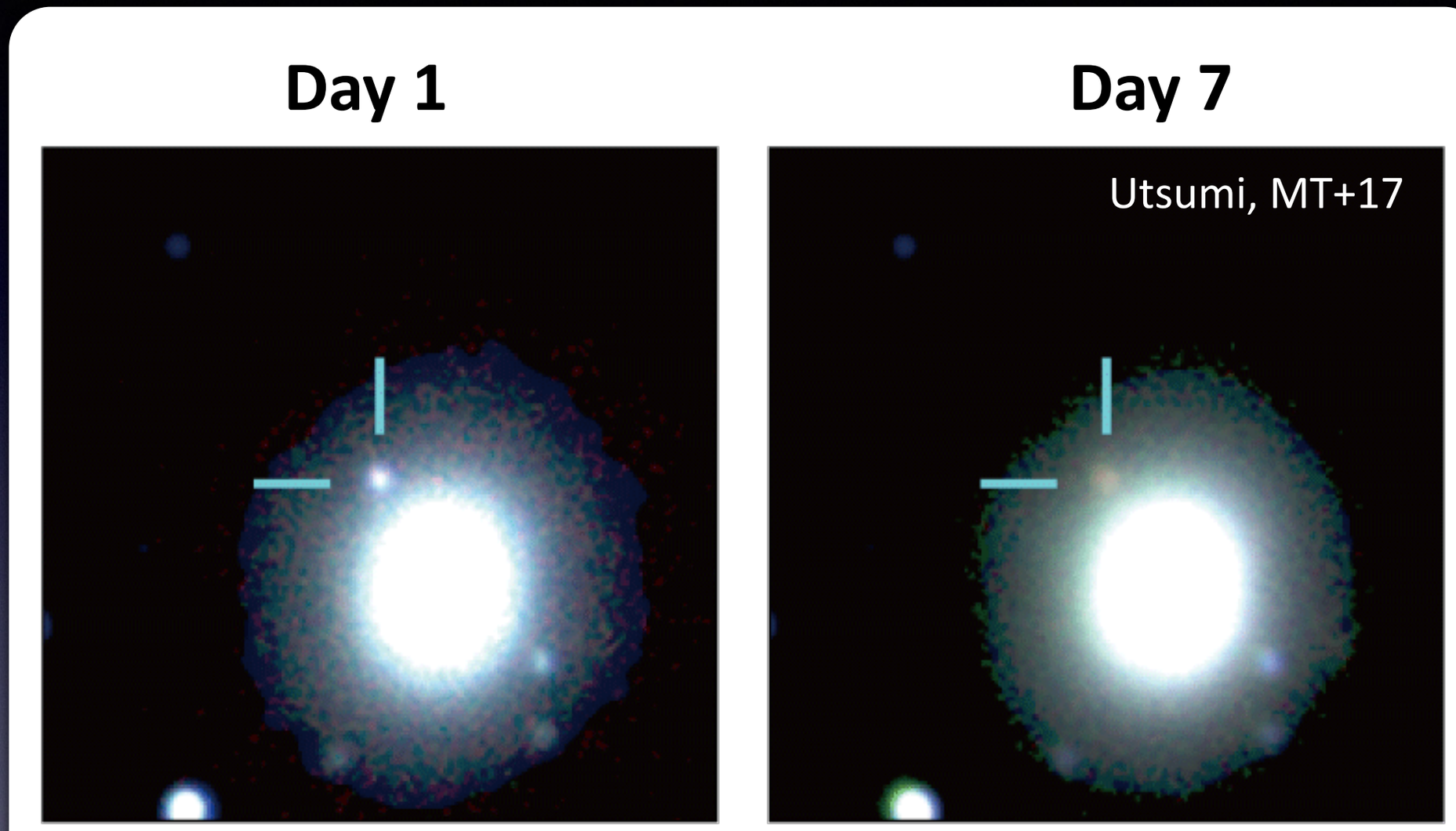
Search for electromagnetic (EM) counterpart



Coulter+17, Soares-Santos+17, Valenti+17,
Arcavi+17, Tanvir+17, Lipunov+17

Movie: Utsumi, MT+17, Tominaga, MT+18

EM counterpart of GW170817 @ 40 Mpc
= “Kilonova”

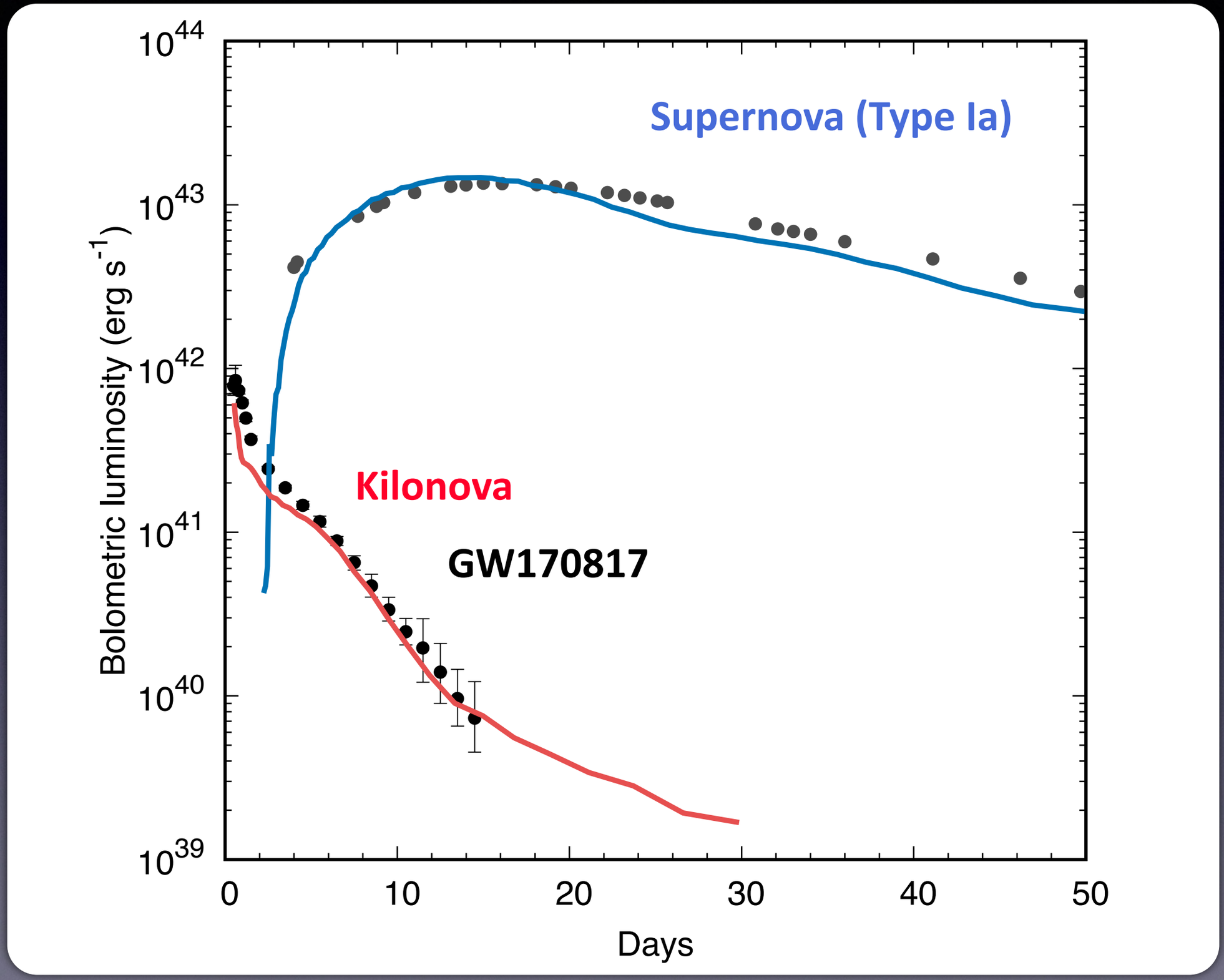


Mej ~ 0.05 Msun

Enough to explain the total mass of r-process elements

(if R ~ 10^{-4} yr^{-1} Gal^{-1})

Supernova and kilonova



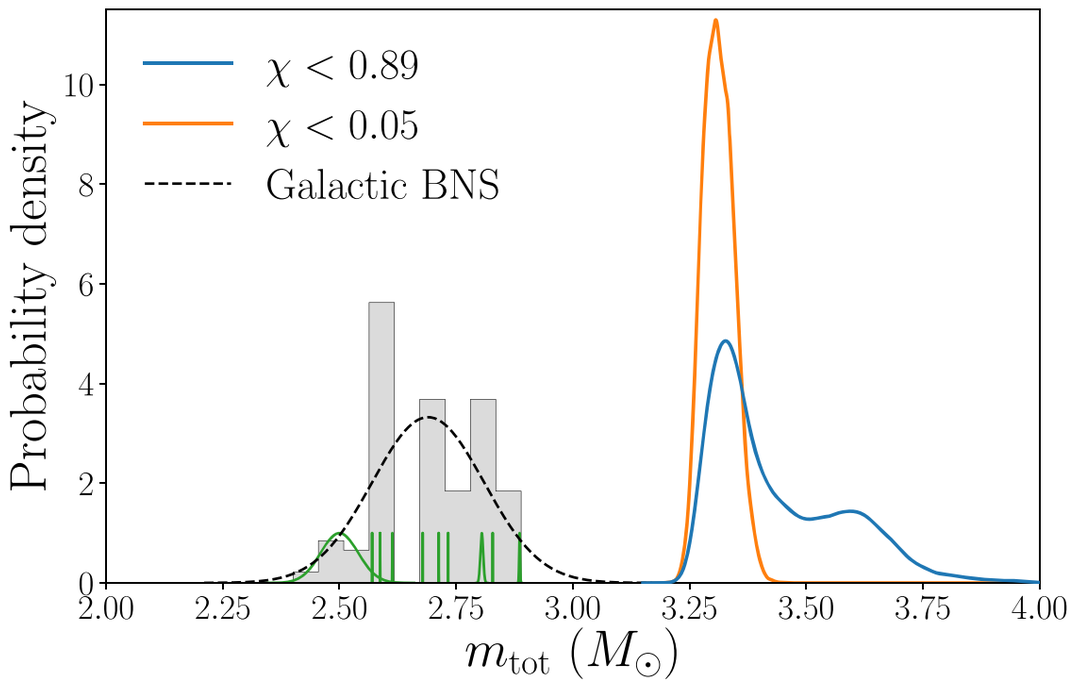
Many open issues

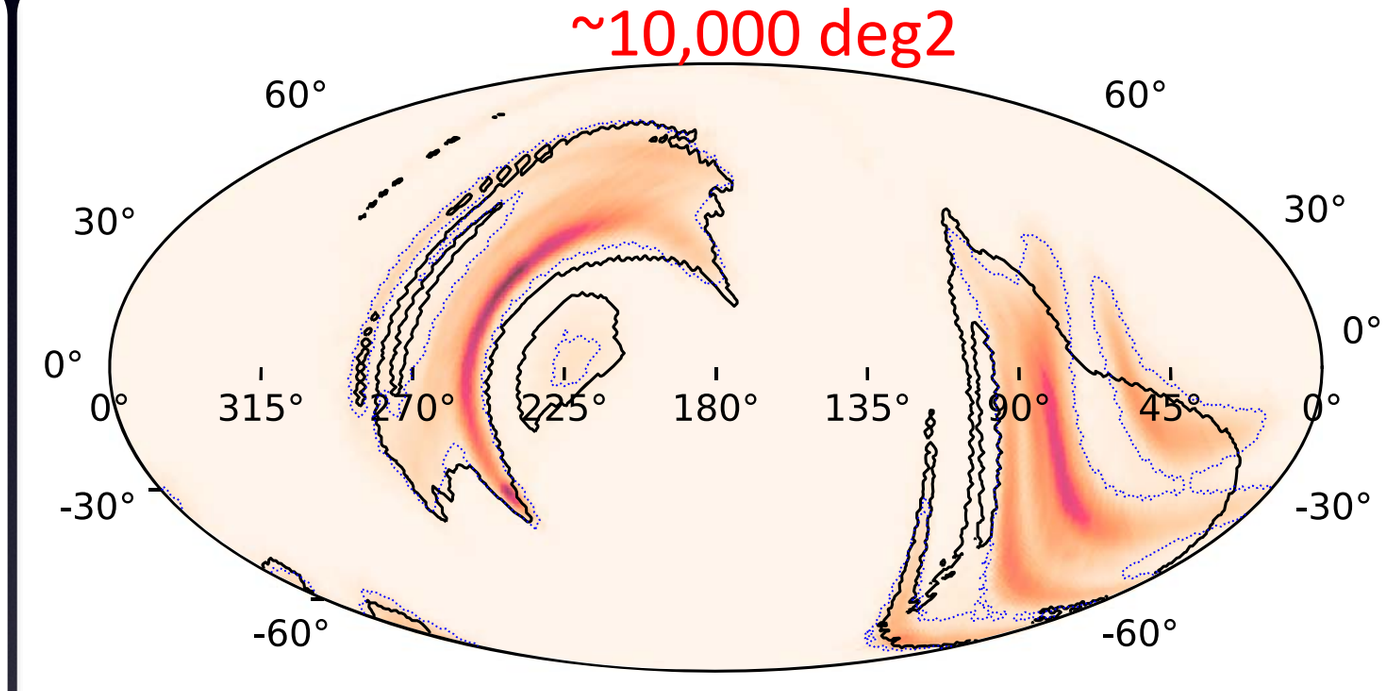
- **Physical origin of the ejecta**
  - Dynamical ejecta and disk ejecta?
- **Production rate**
  - Event rate? => more GW events
  - Are kilonova (mass ejection) always the same?
- **Elemental abundances**
  - Which elements are produced?
  - How massive elements? Fission?
  - Similar to solar abundance ratios?

GW190425: 2nd NS merger event

Total NS mass ~ 3.4 Msun

Abbott+2020

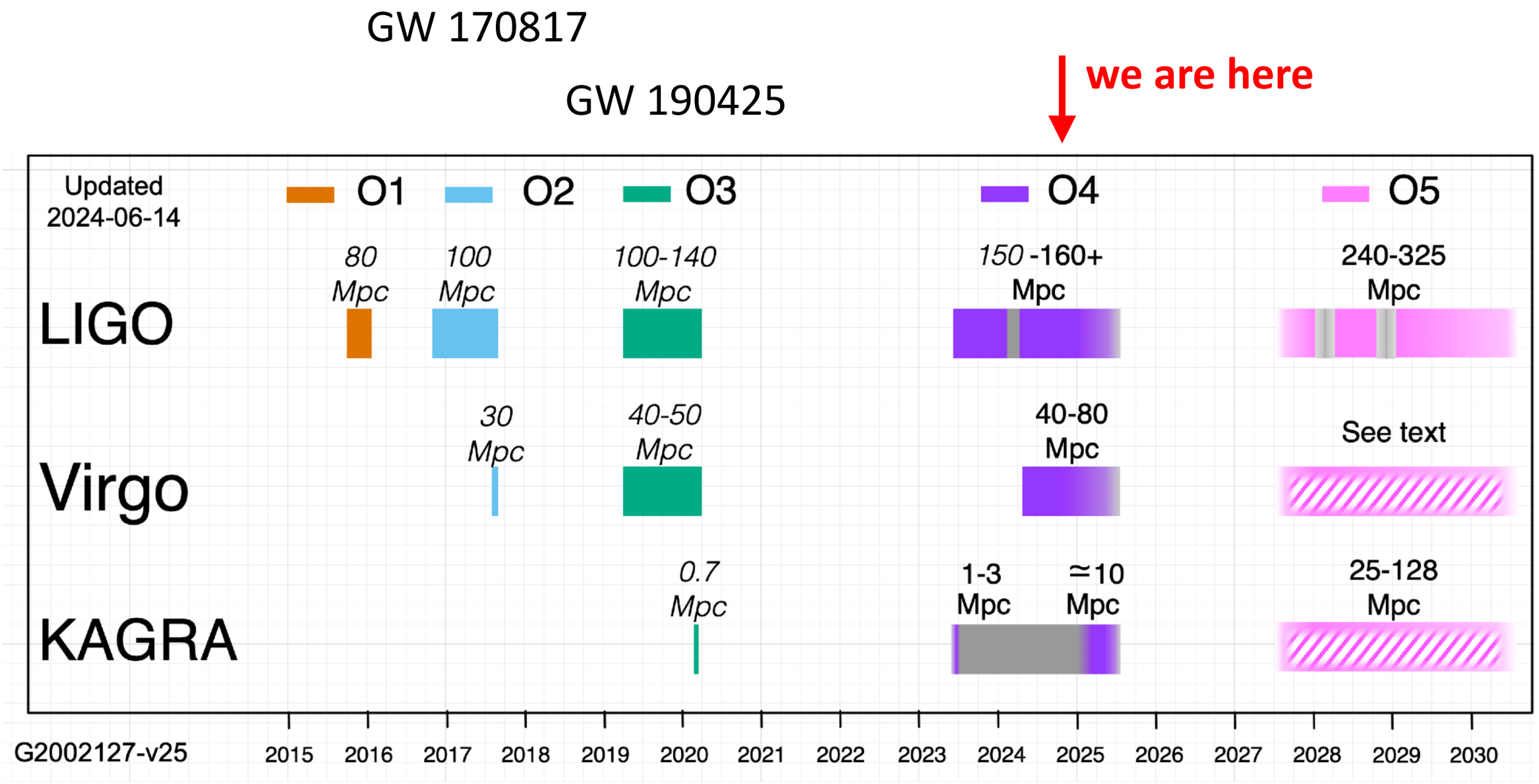




No kilonova… (d ~150 Mpc)

Diversity in neutron star masses
=> diversity in mass ejection

Schedule of GW observations



https://observing.docs.ligo.org/plan/

Summary

- **NS merger**
  - Ejection of material by tidal disruption
    (+ ejection from accretion disk)
  - r-process => radioactive decay => kilonova
- **Observations of GW sources**
  - Kilonova is observed
  - Production rate fulfills the necessary condition
- **Future**
  - Identification of elements or abundance pattern
  - Understanding the variety (production rate)
  - More events with better localization