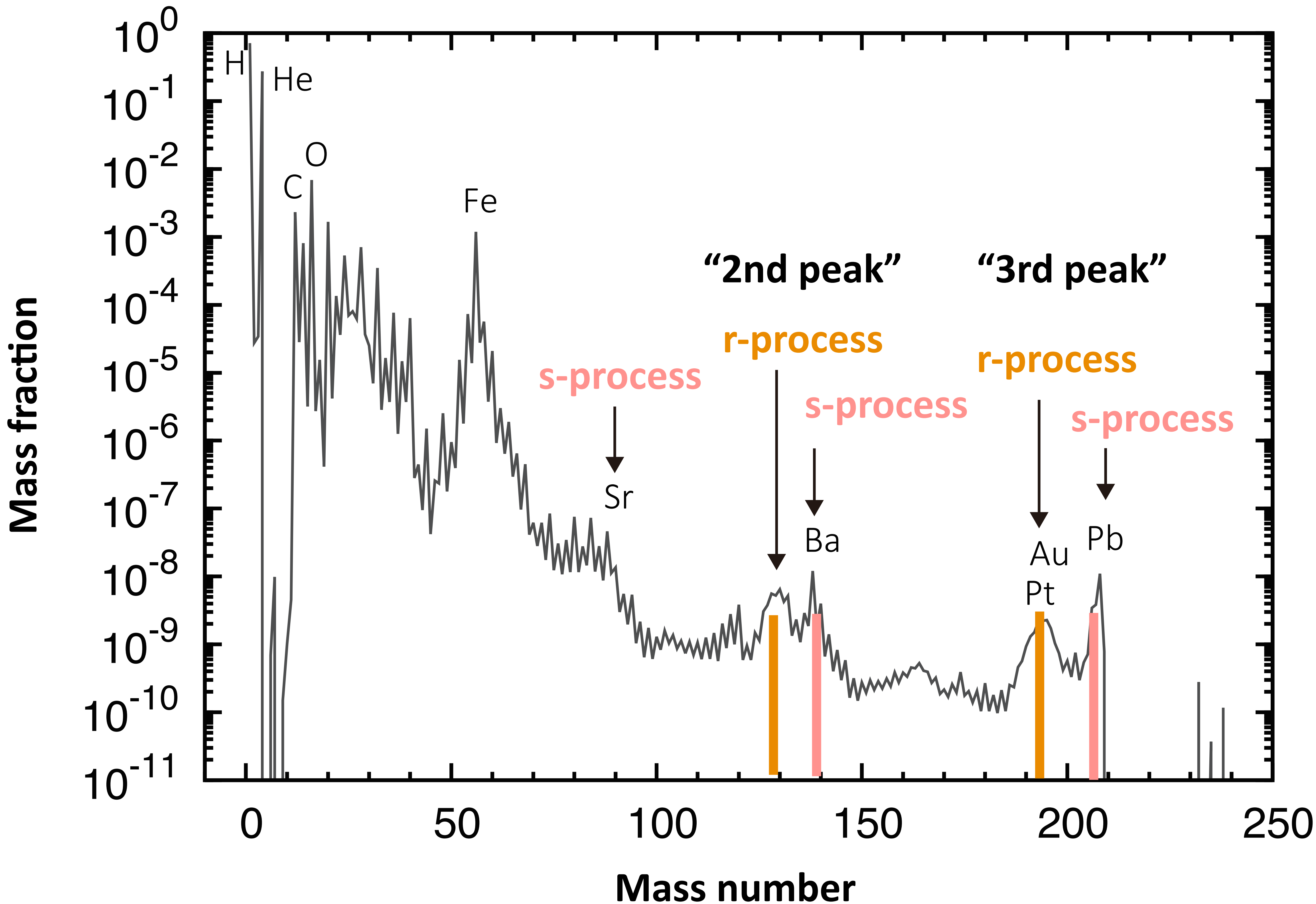
Section 11.
Neutron star merger

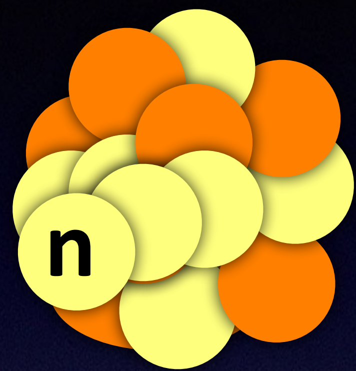
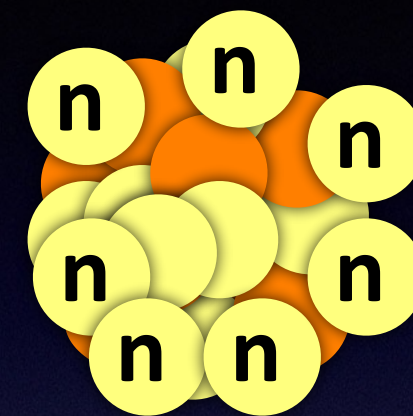
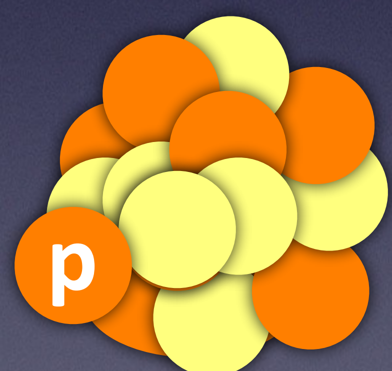
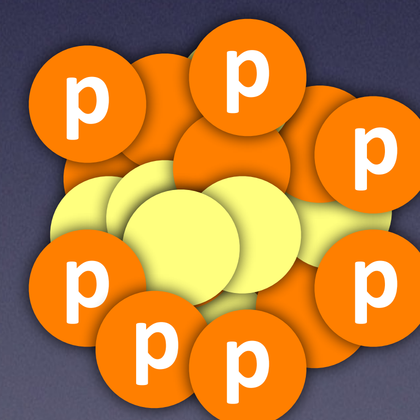
11.1 Neutron star merger

11.2 Observations of gravitational wave sources

Cosmic abundances



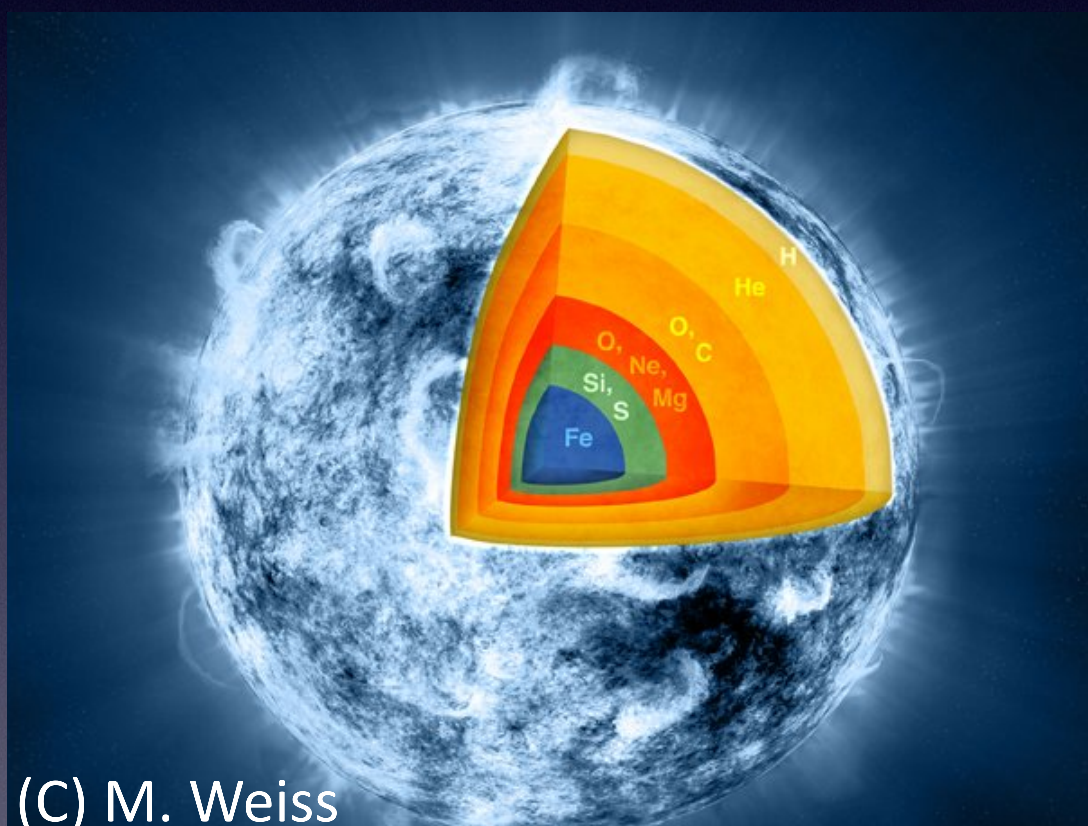
Neutron-capture nucleosynthesis

s (slow)-process	r (rapid)-process
	
Decay	Decay
	
Ba, Pb, …	Au, Pt, U, …
Inside of stars	SN? NS merger?

Origin of r-process elements?

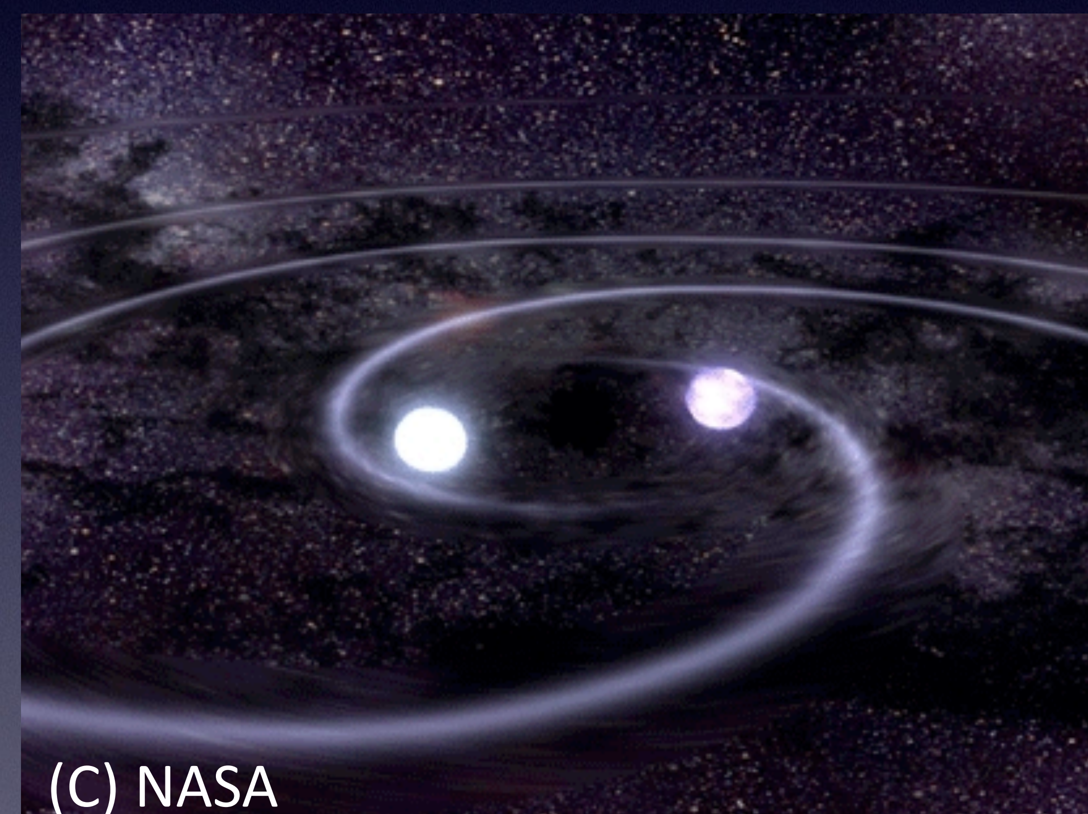
Some phenomena related to neutron star

Supernova

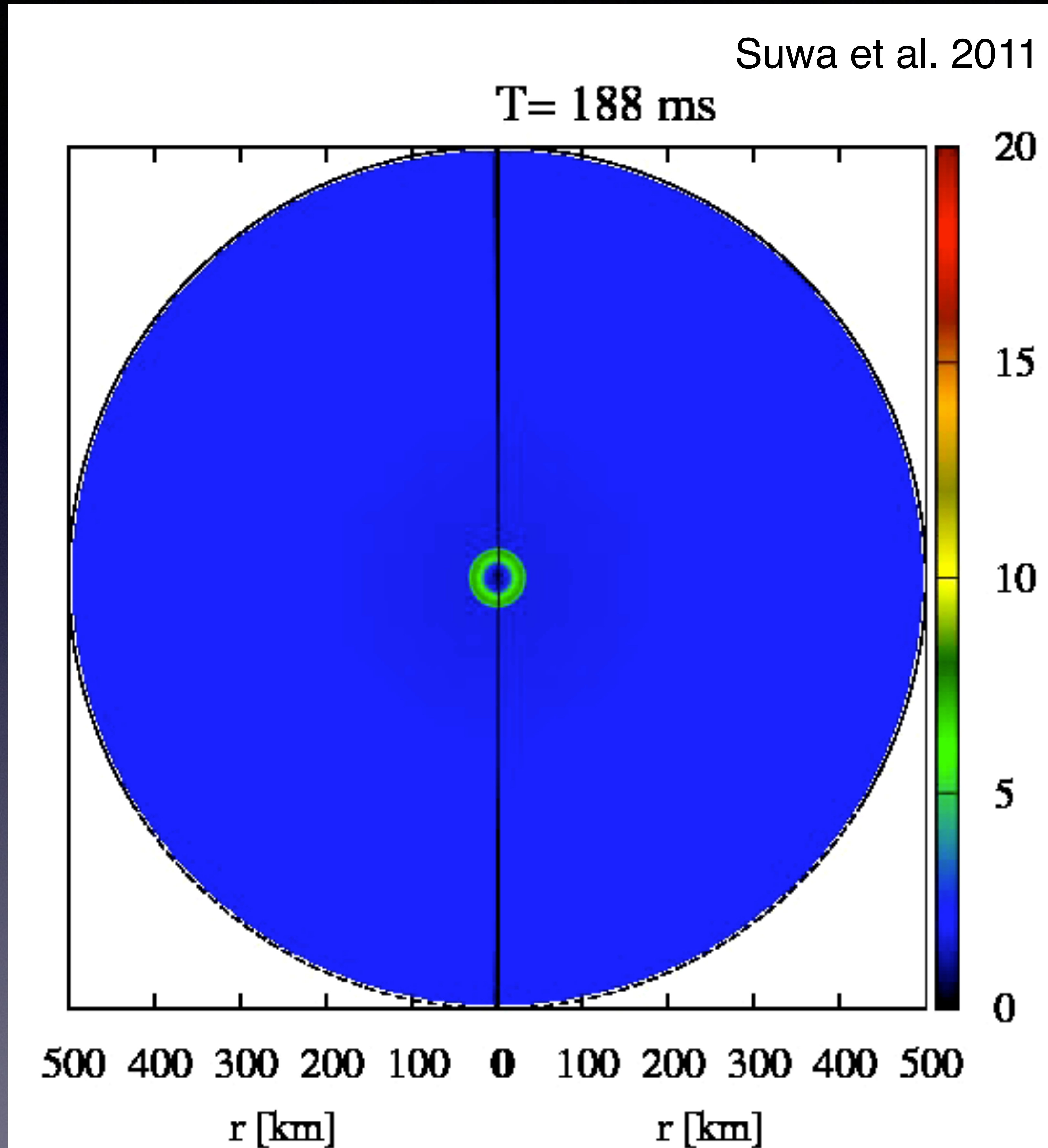


~ 1 event per 100 yr in a galaxy
(R ~ 10^{-2} yr-1)

Neutron star merger



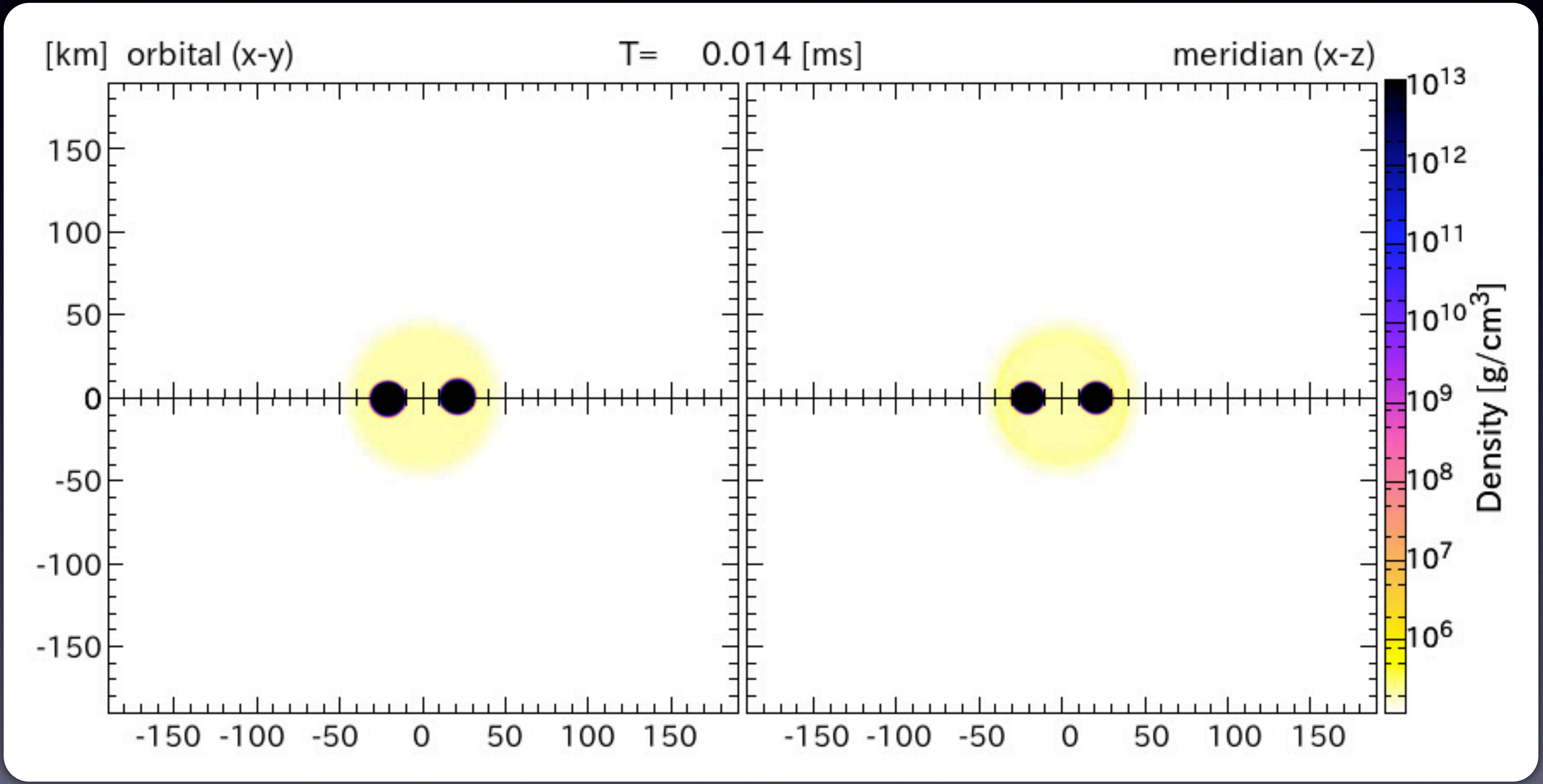
~ 1 event per 10,000 yr in a galaxy
(R ~ 10^{-4} yr-1)



Suwa et al. 2011
T= 188 ms
20
15
10
5
0
500 400 300 200 100 0 100 200 300 400 500
r [km]
r [km]

NS merger => mass ejection

Top view **Side view**



Sekiguchi+15, 16

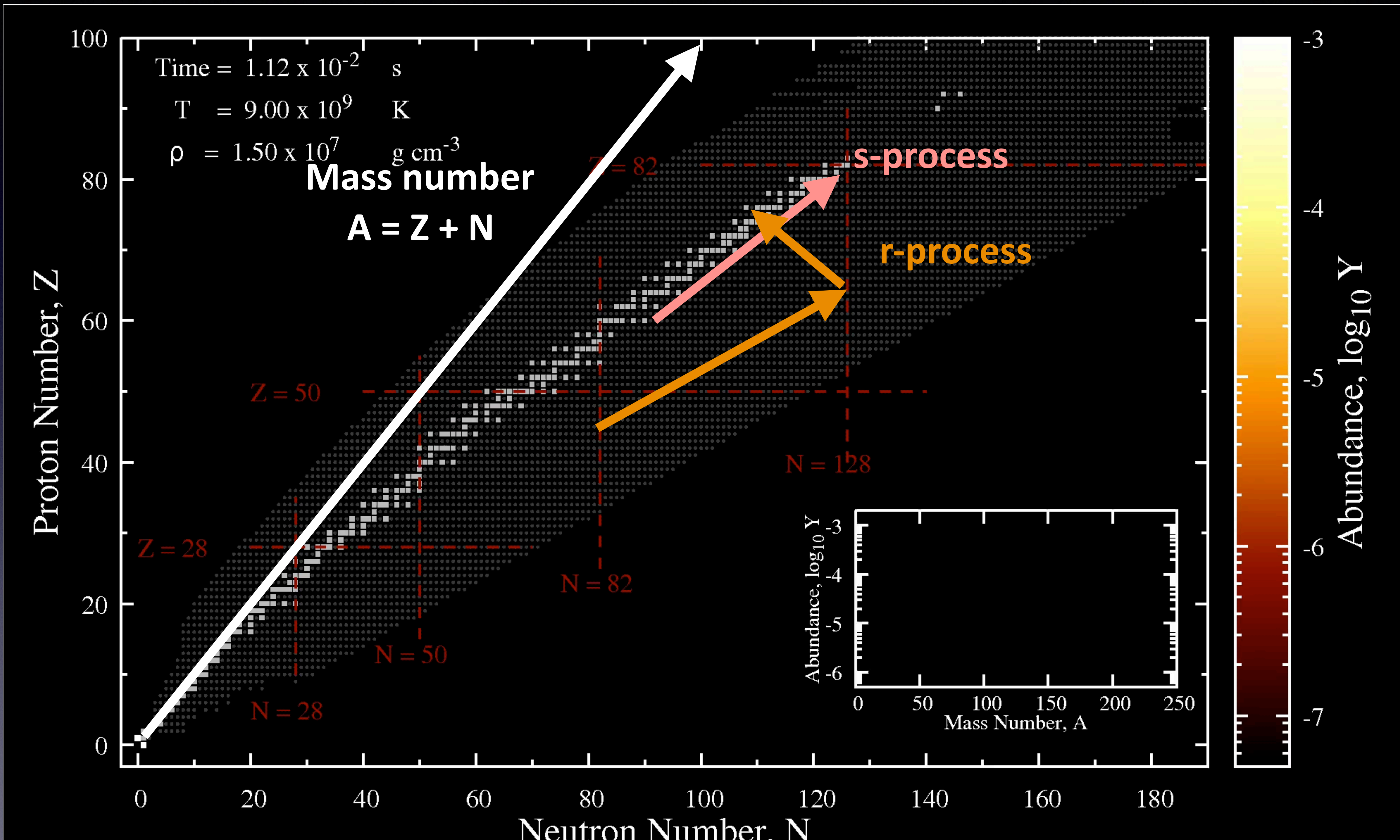
$M \sim 10^{-3} - 10^{-2}$ Msun

v ~ 0.1 - 0.2 c

Why some material are ejected?

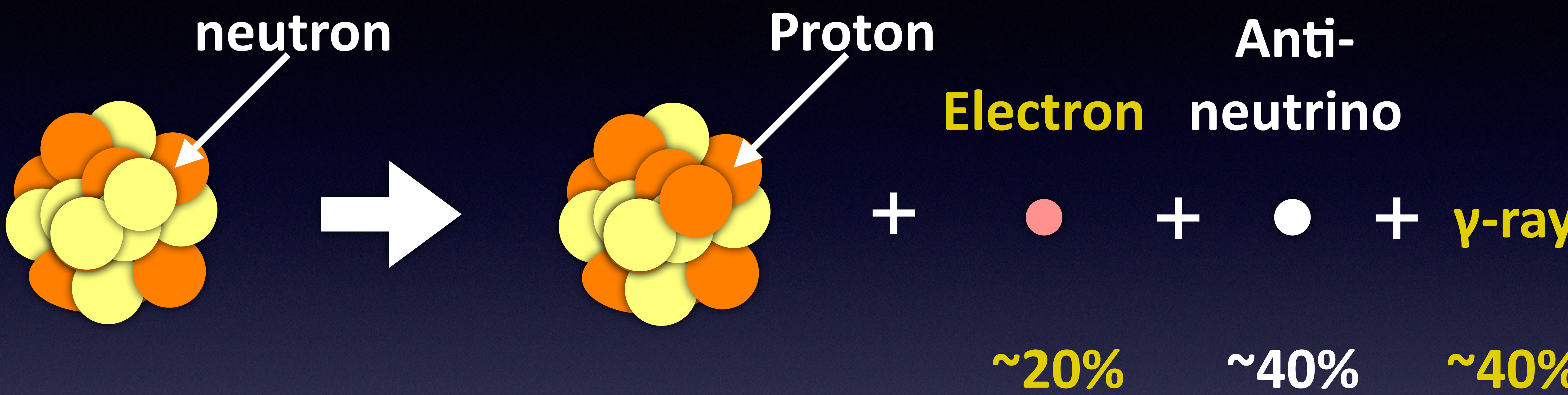
(NS has an extremely strong gravity!)

r-process in NS merger



(C) Nobuya Nishimura

Radioactive decay (Beta decay)



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

Radioactively powered transients similar to SN (56Ni)

=> "kilonova"

How to find NS merger??

Gravitational waves!

(C) LIGO/T. Pyle

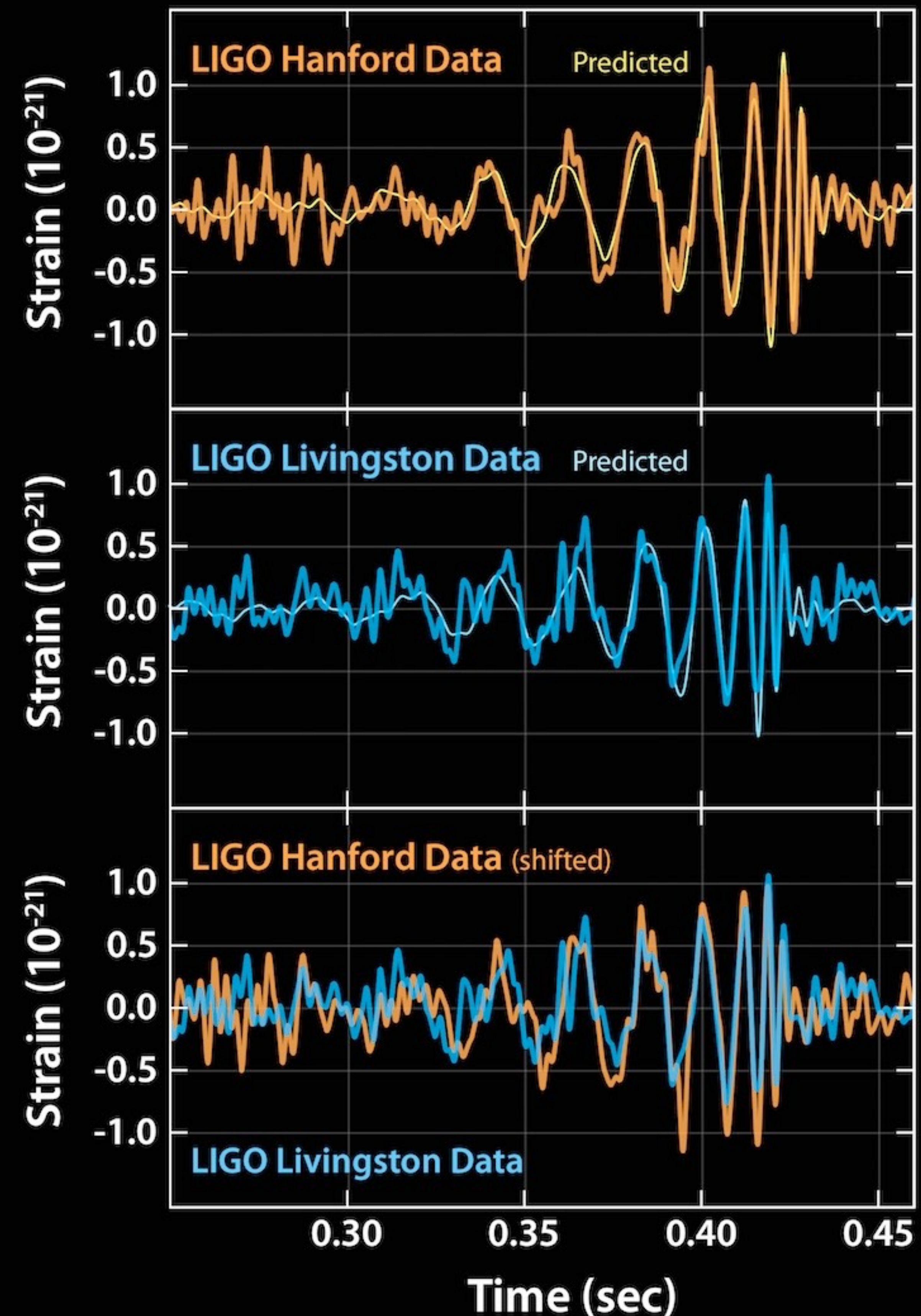
Section 11.
Neutron star merger

11.1 Neutron star merger

11.2 Observations of gravitational wave sources

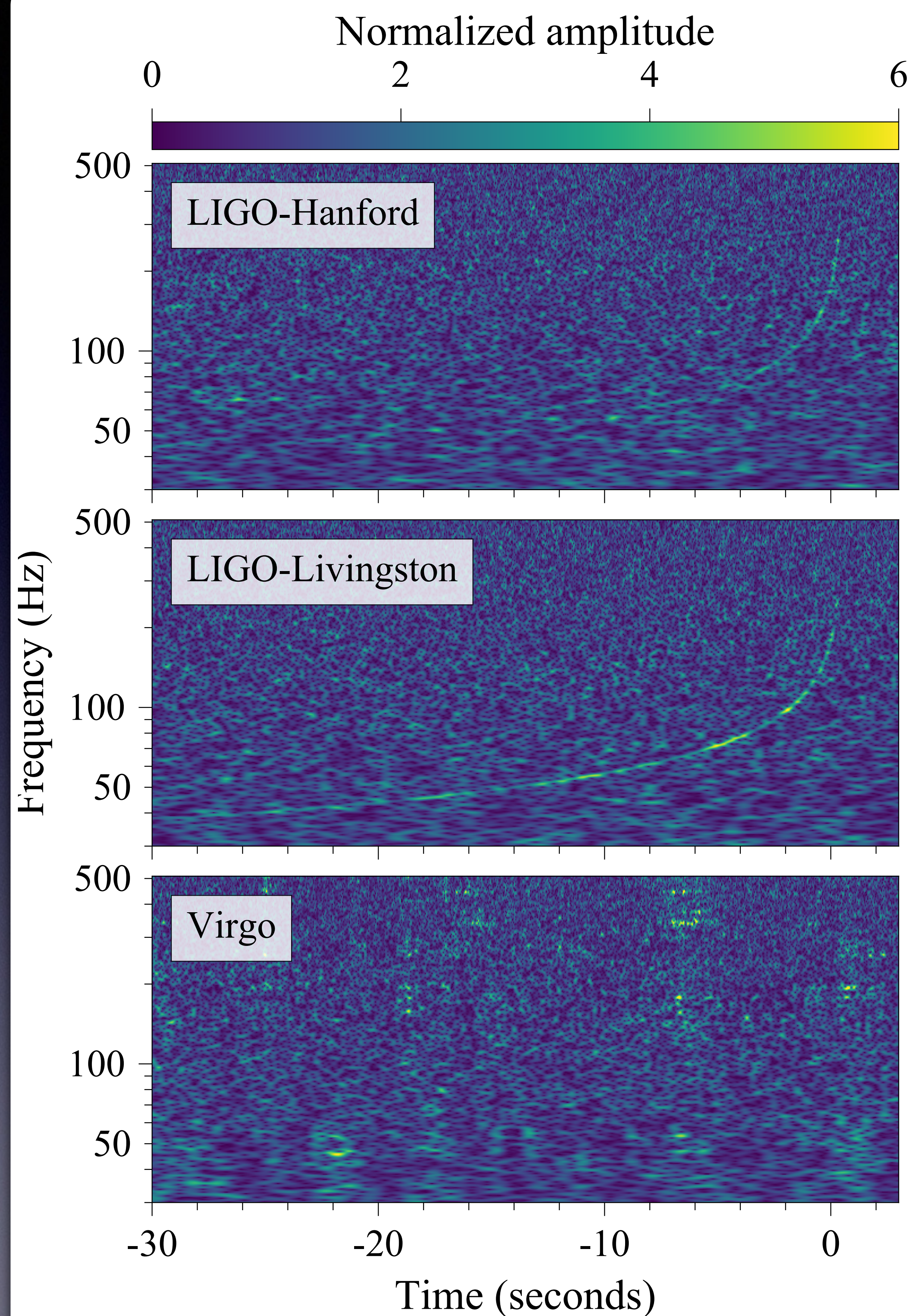
The first GW detection (GW150914)

Merger of binary black hole



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

The first GW detection
From NS merger (GW170817)



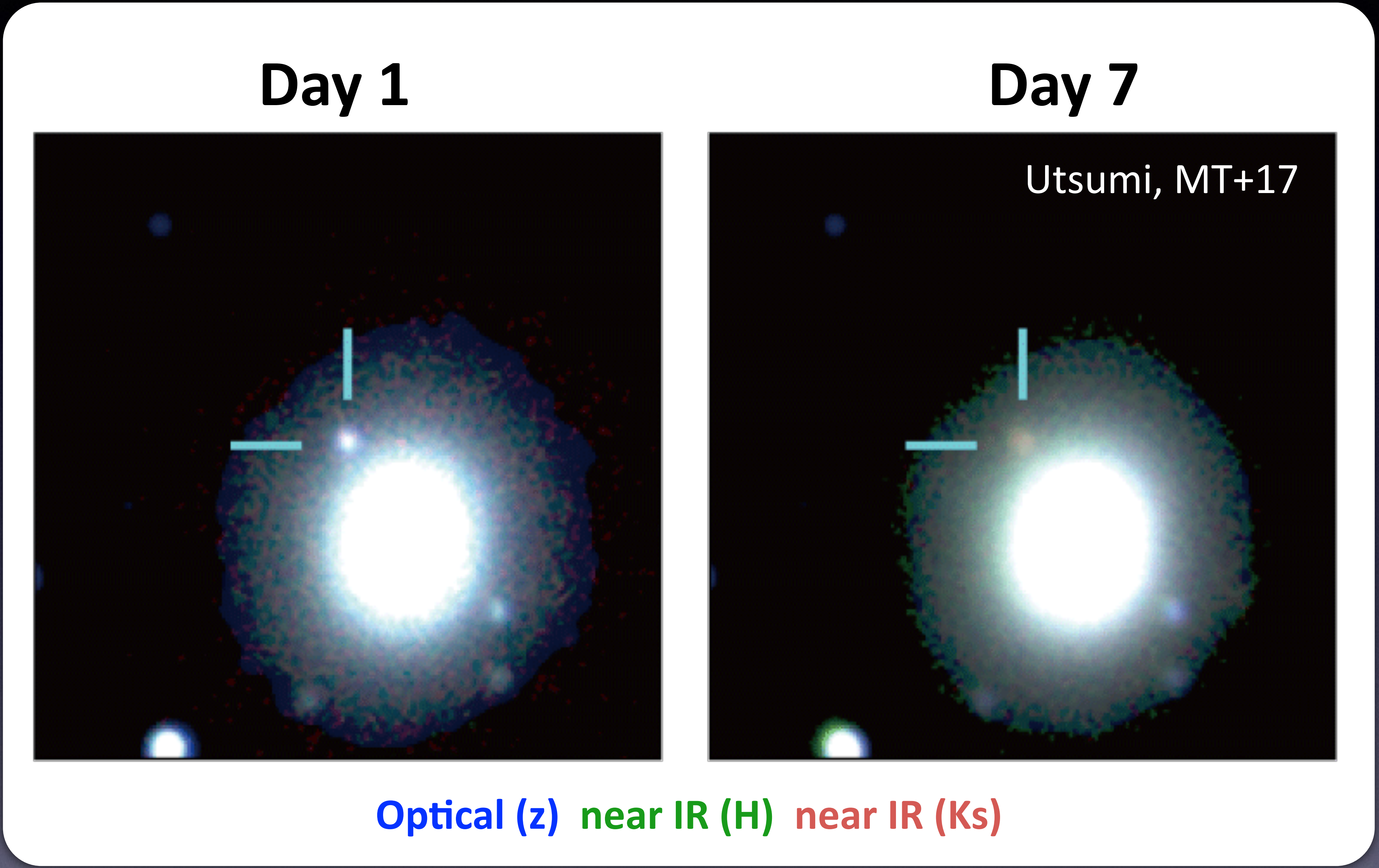
LIGO Scientific Collaboration
and Virgo Collaboration, 2017, PRL

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”



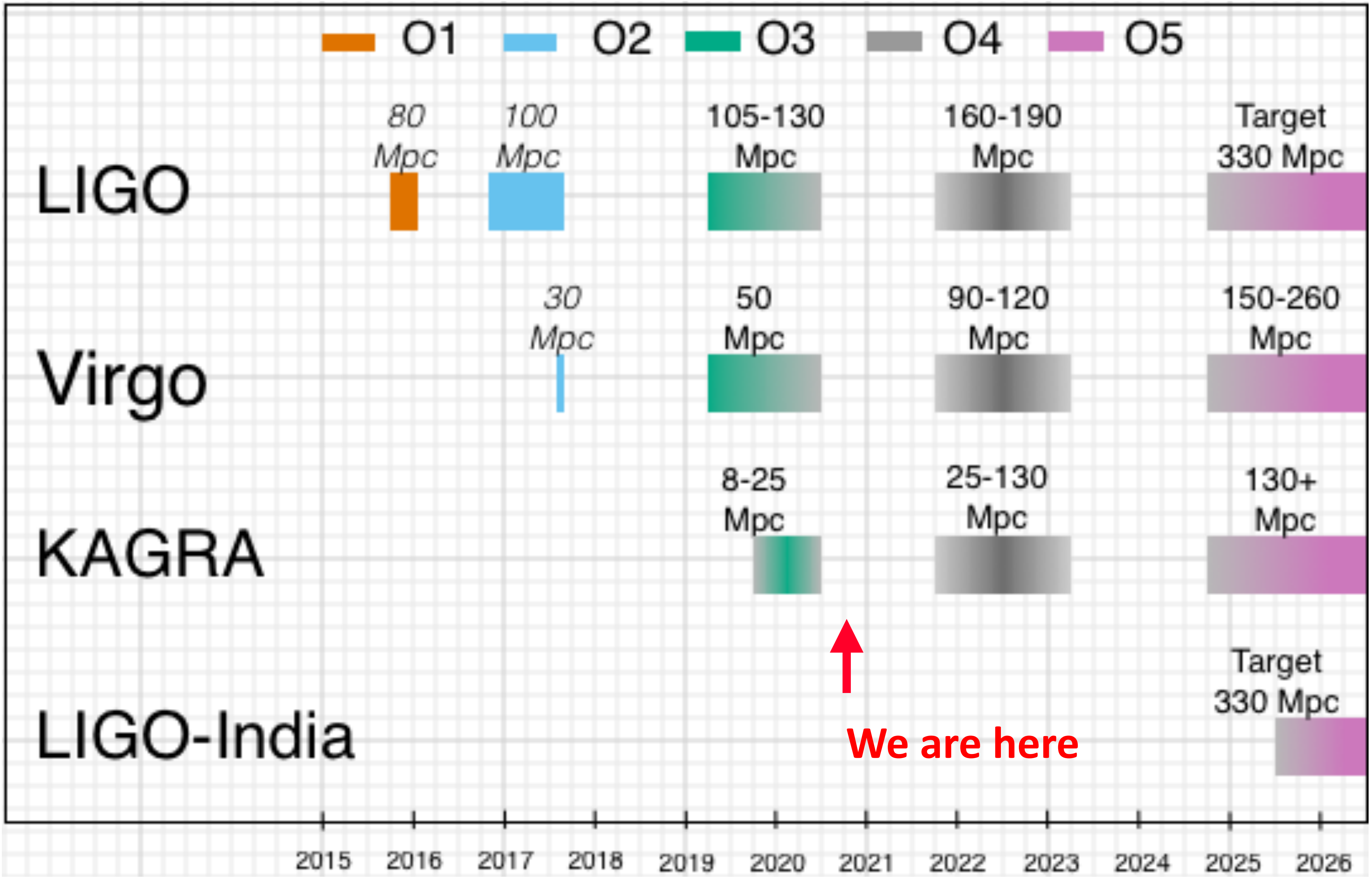
Mej ~ 0.05 Msun

Enough to explain the total mass of r-process elements
(if R ~ 10^{-4} yr^{-1} Gal^{-1})

Many open issues

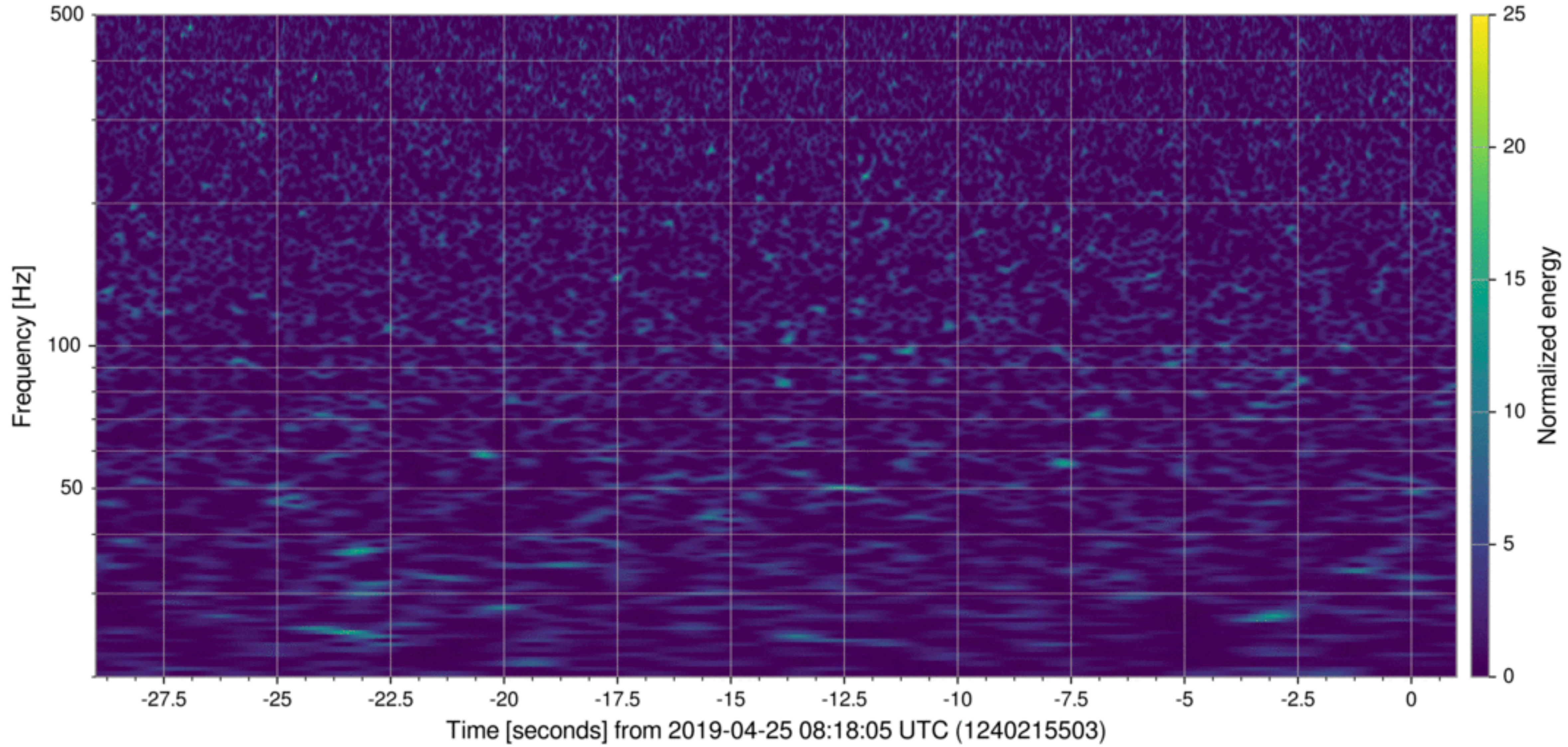
- **Physical origin of the ejecta**
  - Dynamical ejecta and disk ejecta?
- **Production rate**
  - Event rate? => more GW events
  - Are kilonova (mass ejection) always the same?
- **Elemental abundances**
  - Which elements are produced?
  - How massive elements? Fission?
  - Similar to solar abundance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

GW observing runs



https://www.ligo.org/scientists/GWEMalerts.php

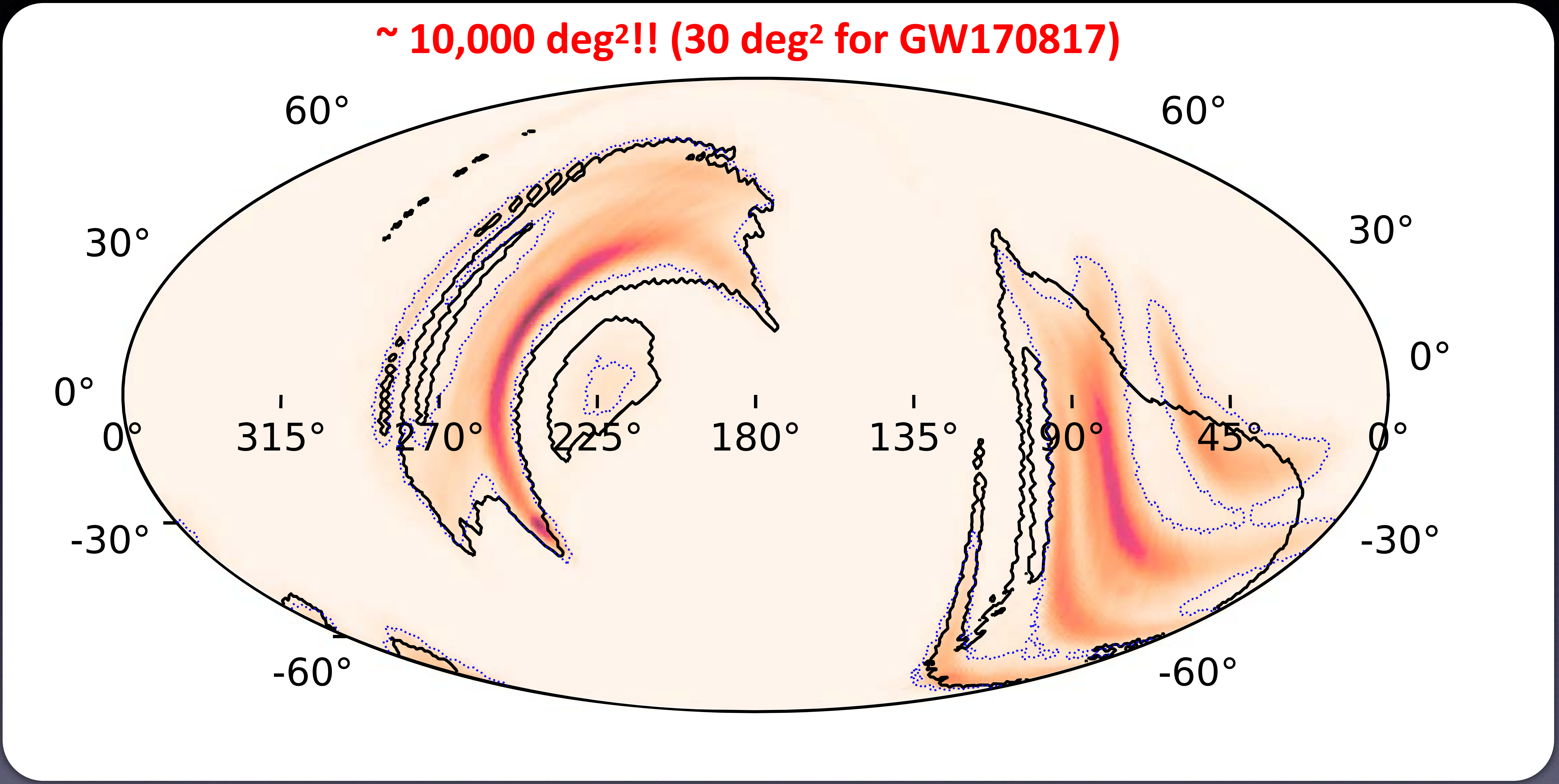
GW190425: 2nd NS-NS merger event



https://www.ligo.org/detections/GW190425.php

What is the kilonova signal?

Skymap of GW190425



LVC 2020

No convincing counterpart was identified...

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

Let's **understand** these questions with the word of physics

Knowing ≒ Understanding

- Why do some stars explode?
- Why don't normal star explode?
- Why do stars show L ~ M^4?
- Why do stars evolve?
- Why does the destiny of stars depend on the mass?
- Why does stellar core collapses?
- Why is the energy of supernova so huge?
- ...

Thermodynamics

Electromagnetism

Classical mechanics

Statistical mechanics

Astrophysics

Hydrodynamics

Quantum mechanics

Relativity

Nuclear physics

Appendix

Relavant timescales

Merger ➡ neutron-capture (r-process) nucleosynthesis ➡ Radioactive decay => **kilonova**

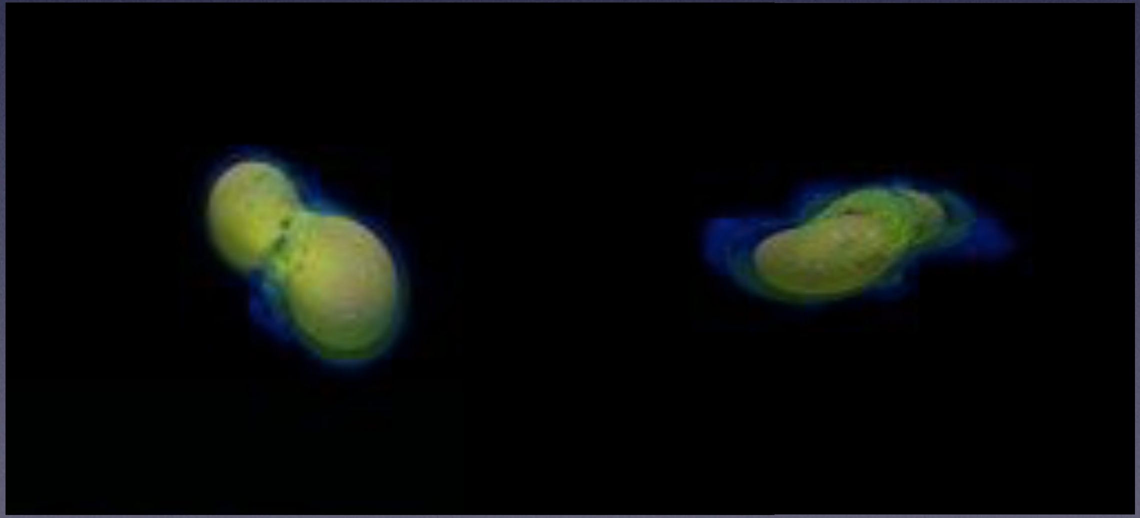
GW

Mass ejection

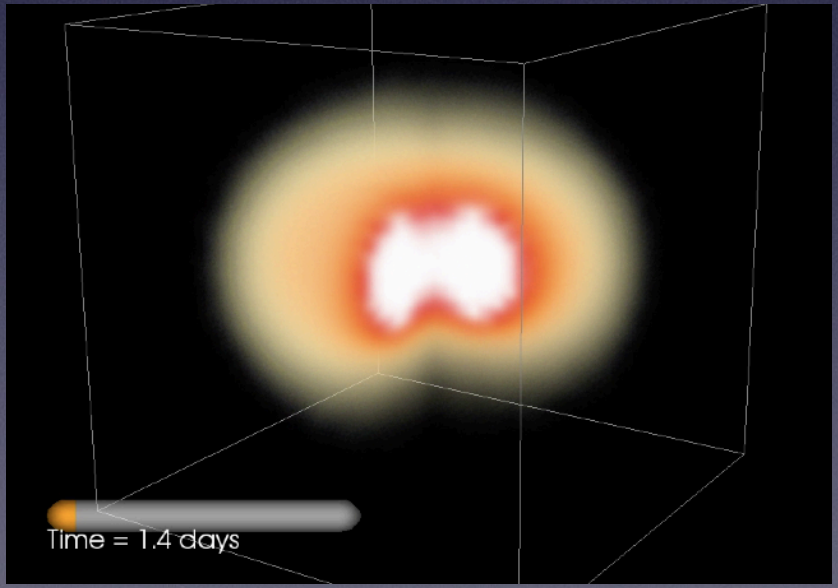
~< 100 ms

< 1 sec

~> days



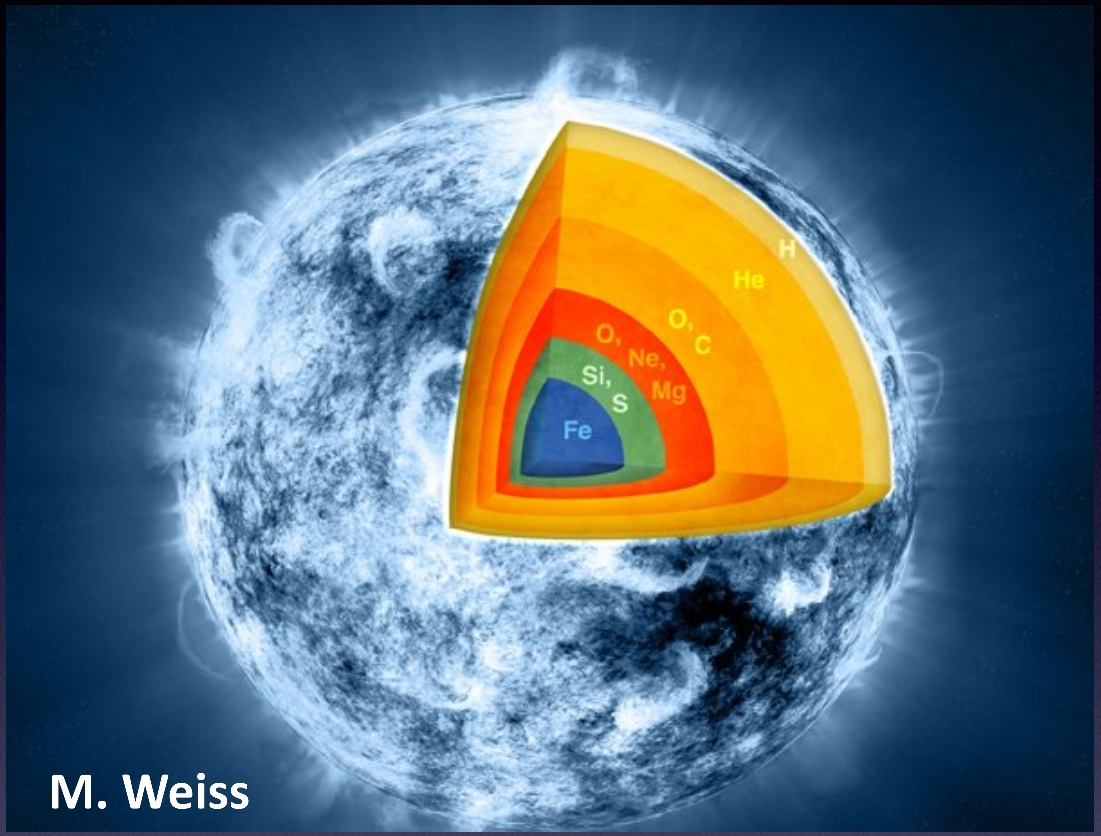
http://www.aei.mpg.de/comp-rel-astro



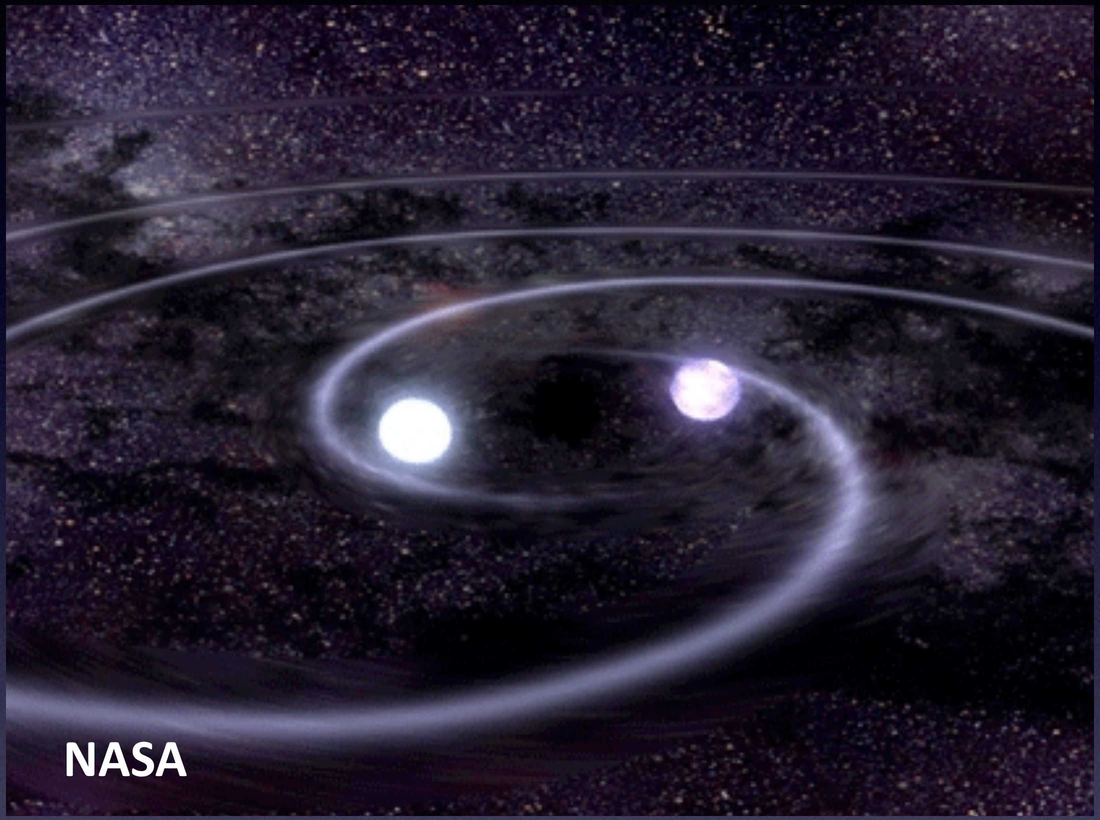
MT & Hotokezaka 13

Explosive phenomena around the neutron star

Core-collapse supernova



NS merger



Moderately neutron rich

Ye ~ 0.45 (n_n ~ 1.2n_p)

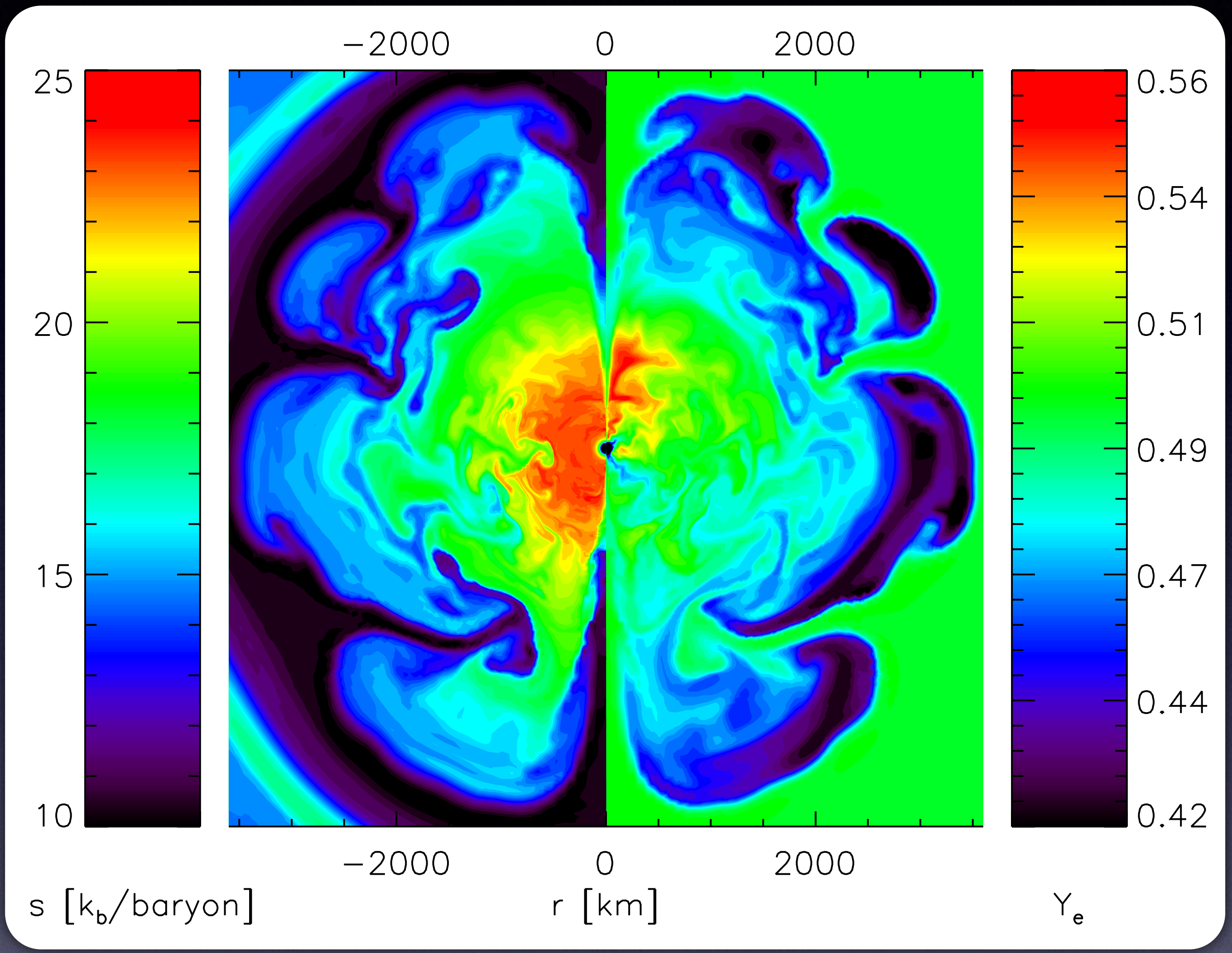
Very neutron rich

Ye ~ 0.10 (n_n ~ 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

Core-collapse supernovae



Wanajo+11, Wanajo 14

$$\nu_e + n \rightarrow p + e^-$$

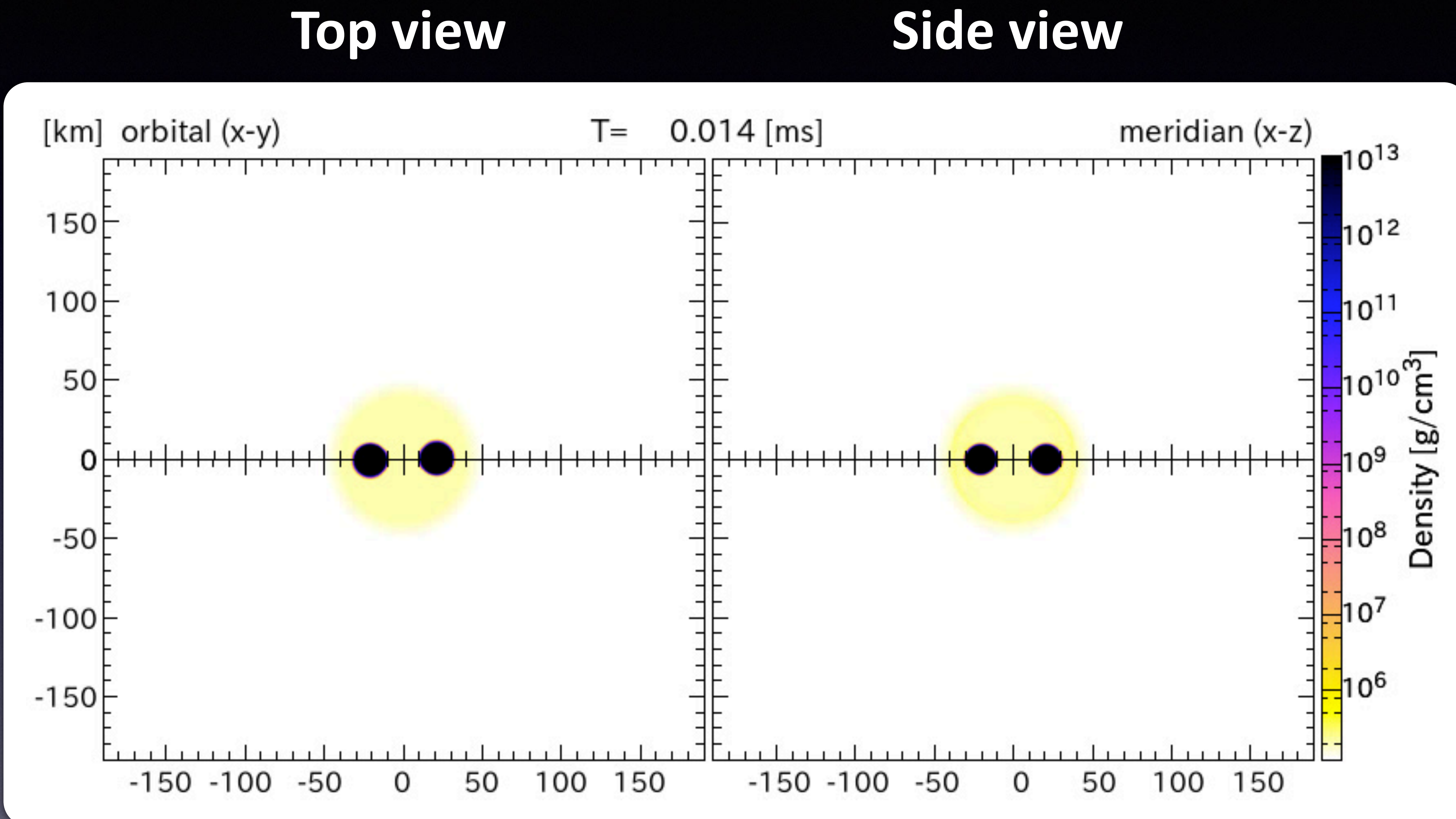
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$\epsilon_{\bar{\nu}_e} > \epsilon_{\nu_e}$$

Probably neutron rich but only moderately

Ye ~ 0.45 (n_n ~ $1.2n_p$)

Neutron star merger



Sekiguchi+15, 16

Very neutron rich (Composition of neutron star

Ye ~ 0.10 (n_n ~ 9 n_p)