Physics and astrophysics of kilonovae

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Brief CV

1983: Born in Nagoya, Japan
2009: PhD at U. Tokyo
2009-2011: Postdoc at U. Tokyo
2011-2018: Assis. prof. at NAOJ
2018- : Assoc. prof. at Tohoku U. (Sendai)

2008: First visit to Bangalore
(IIA: Indian Institute of Astrophysics)
2008: Darjeeling
2015: Bangalore (IIA)
2017: Mysore
2019: Bangalore (IIA)

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Research topics

- Time-domain astronomy
- Transients (e.g., supernovae,
  neutron star mergers,
  or anything variable)
- Observations and theory

Supercomputer@NAOJ

Subaru telescope

Kiso observatory

Physics and astrophysics of kilonovae

1. Brief overview
2. Mass ejection and r-process nucleosynthesis
3. Heating of the ejecta

May 21

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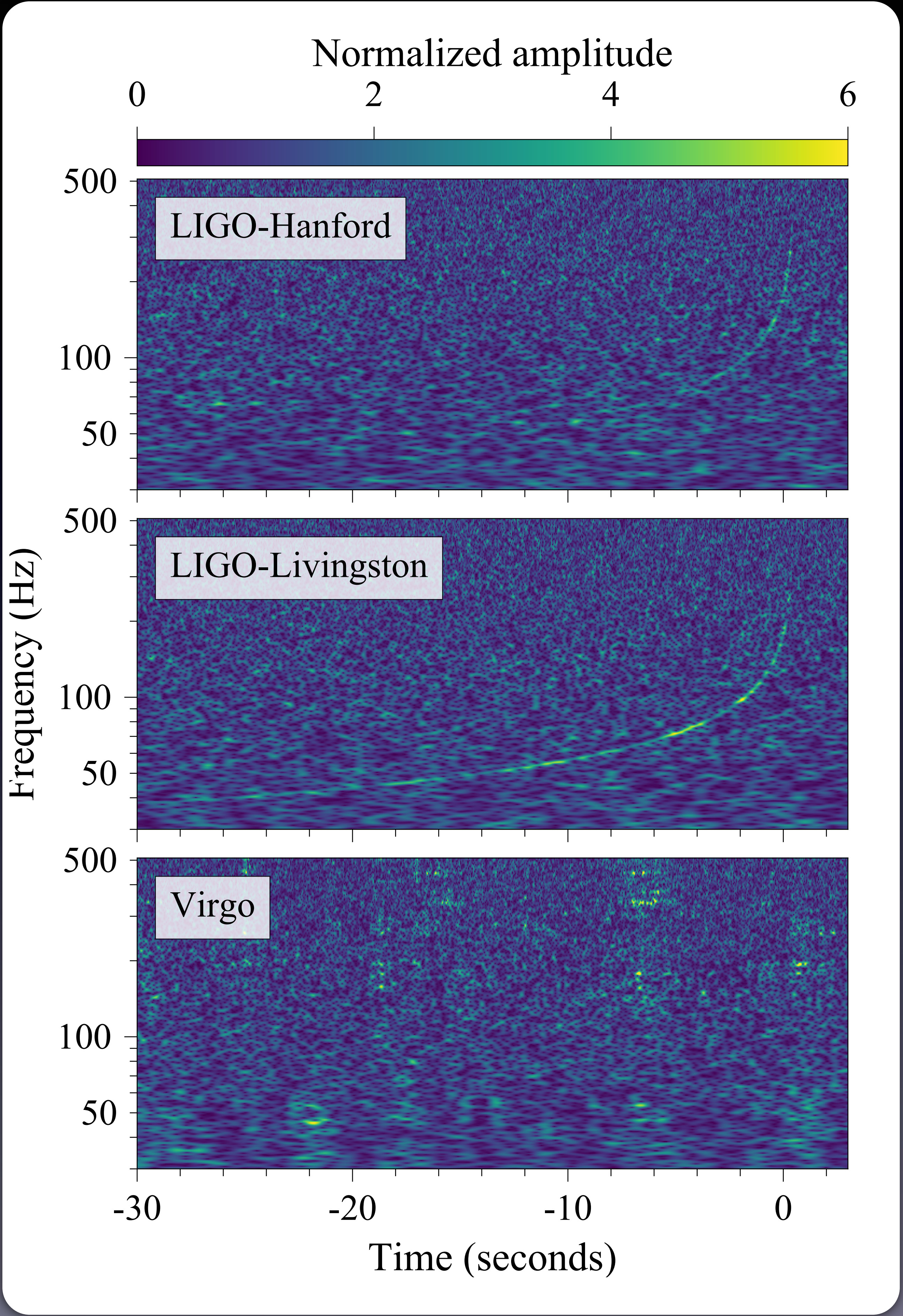
4. Photon transfer => kilonova
5. Comparison with observations
6. Recent topics and future prospects

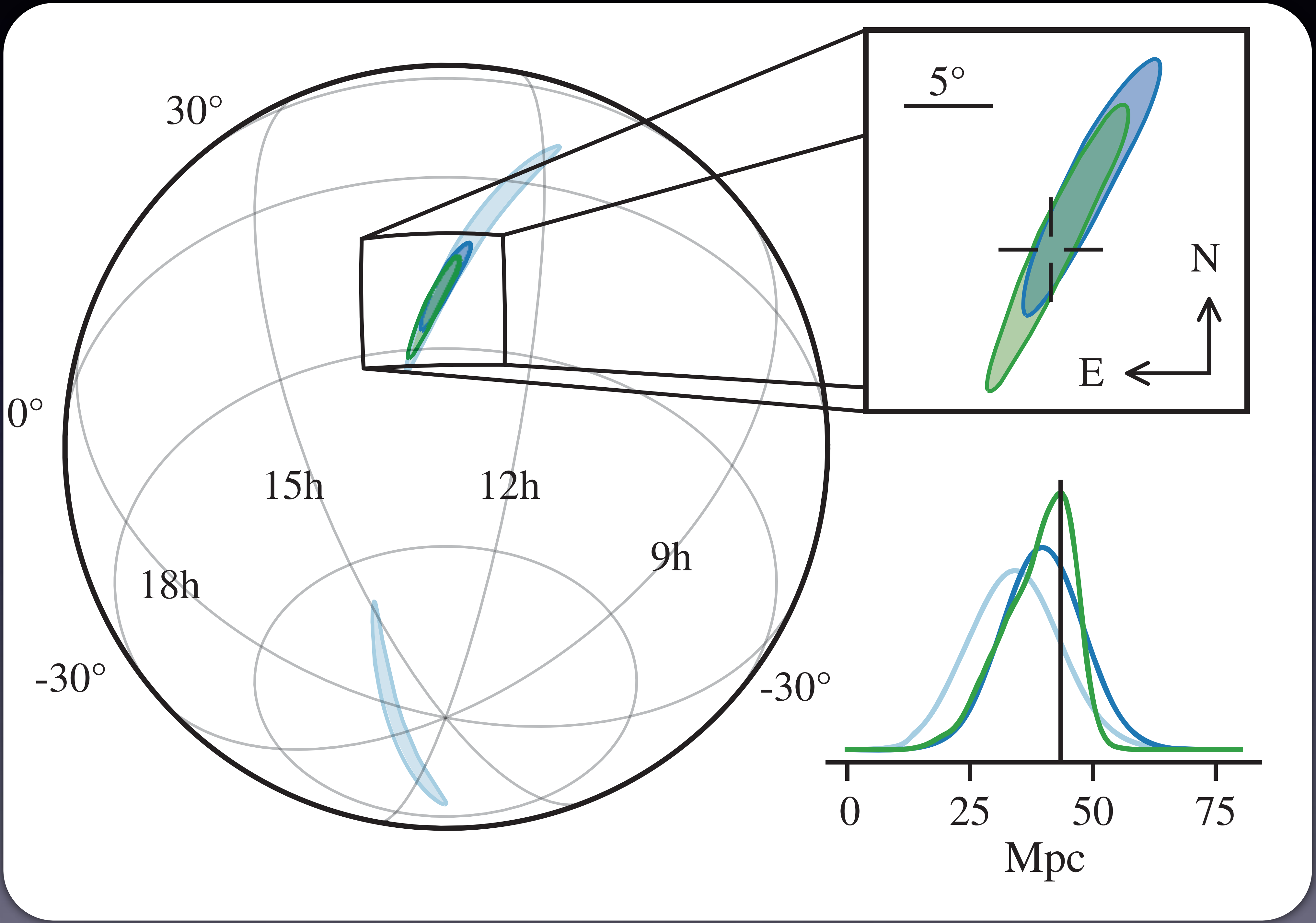
May 22

GW170817
Gravitational waves (GWs) from neutron star (NS) merger



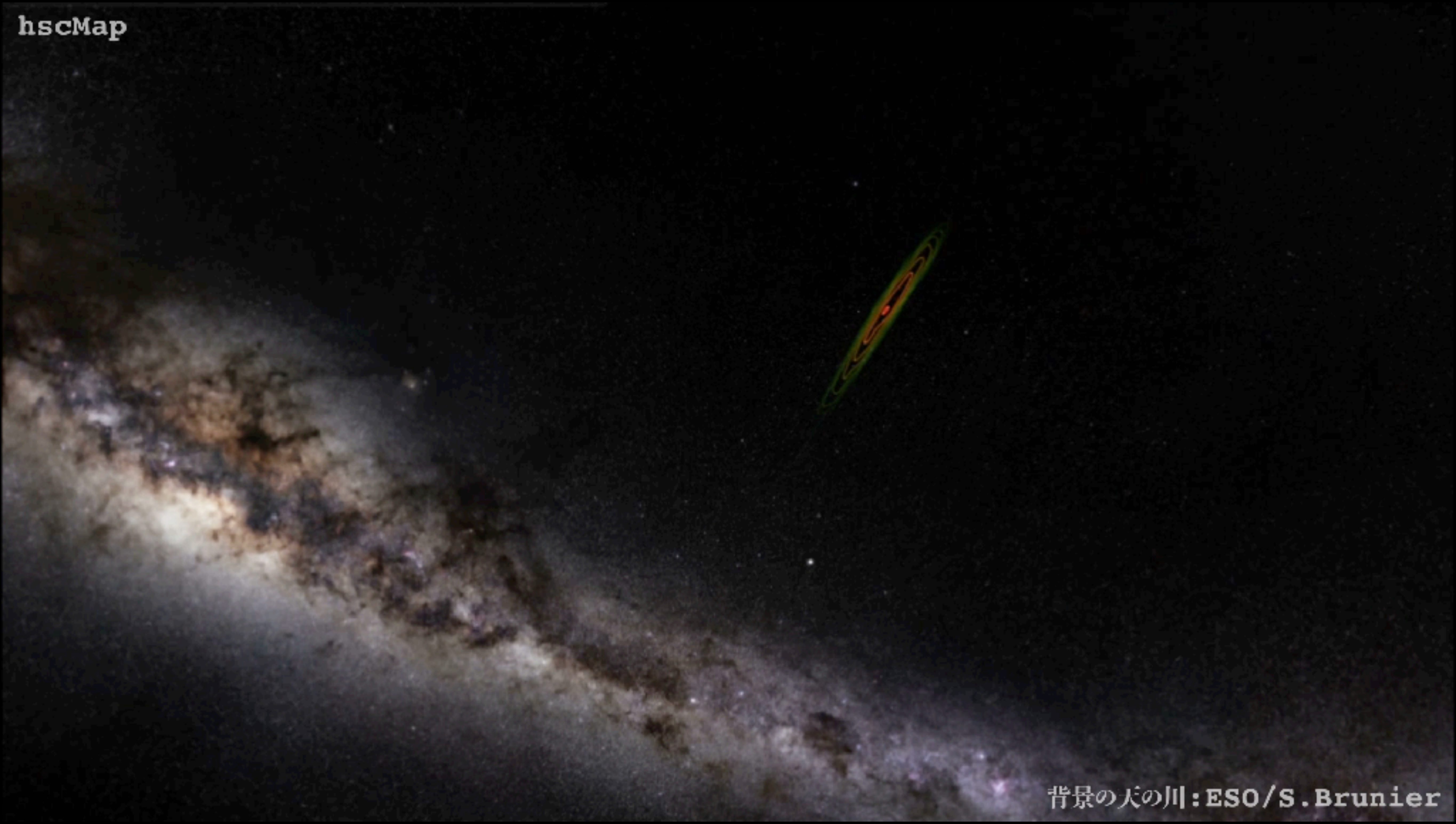
LIGO Scientific Collaboration
and Virgo Collaboration, 2017, PRL

Sky localization with 3 detectors (LIGO x 2 + Virgo) ==> 30 deg² (~40 Mpc)



LIGO Scientific Collaboration and Virgo Collaboration, 2017

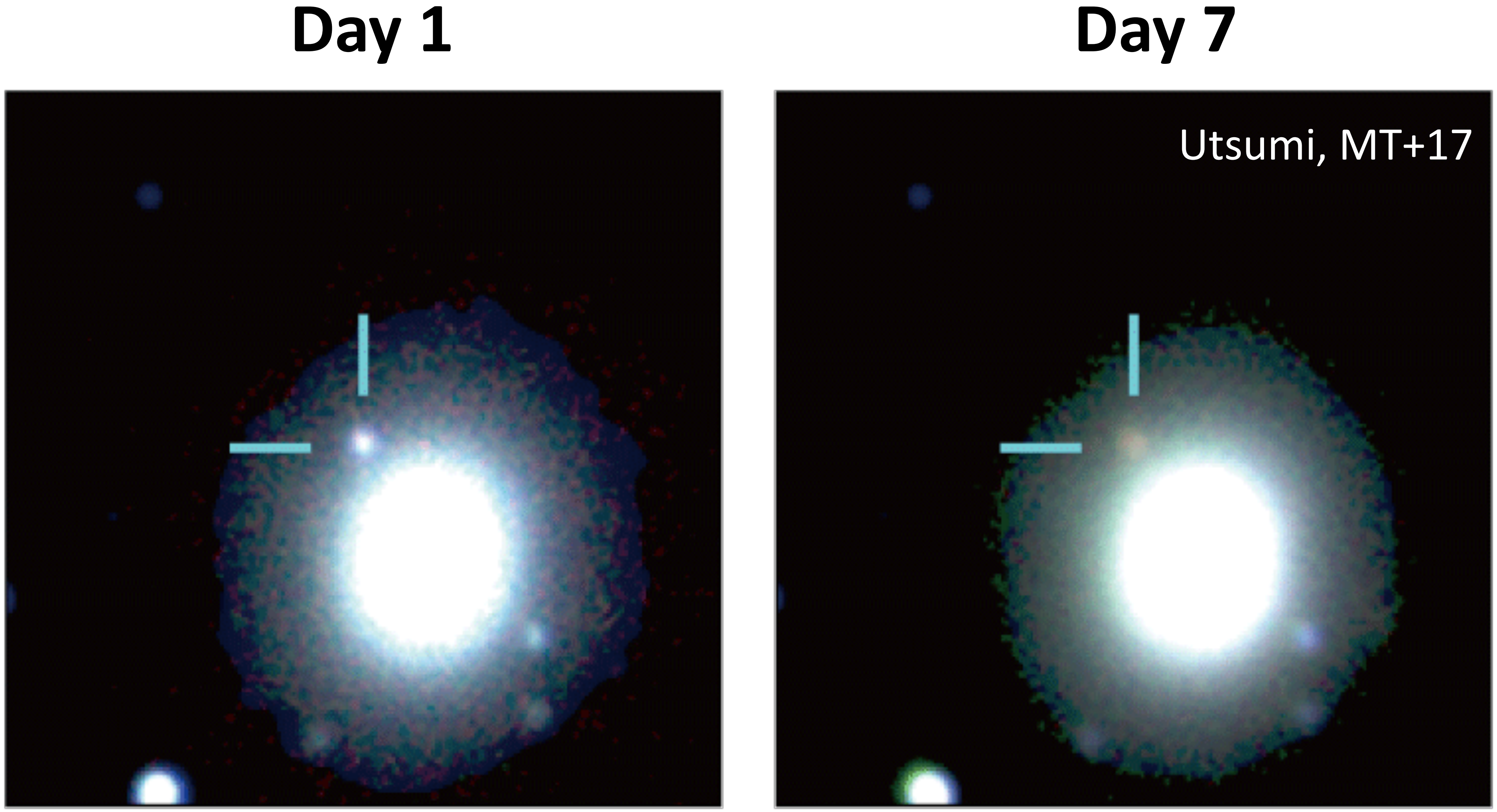
Search for electromagnetic (EM) counterpart



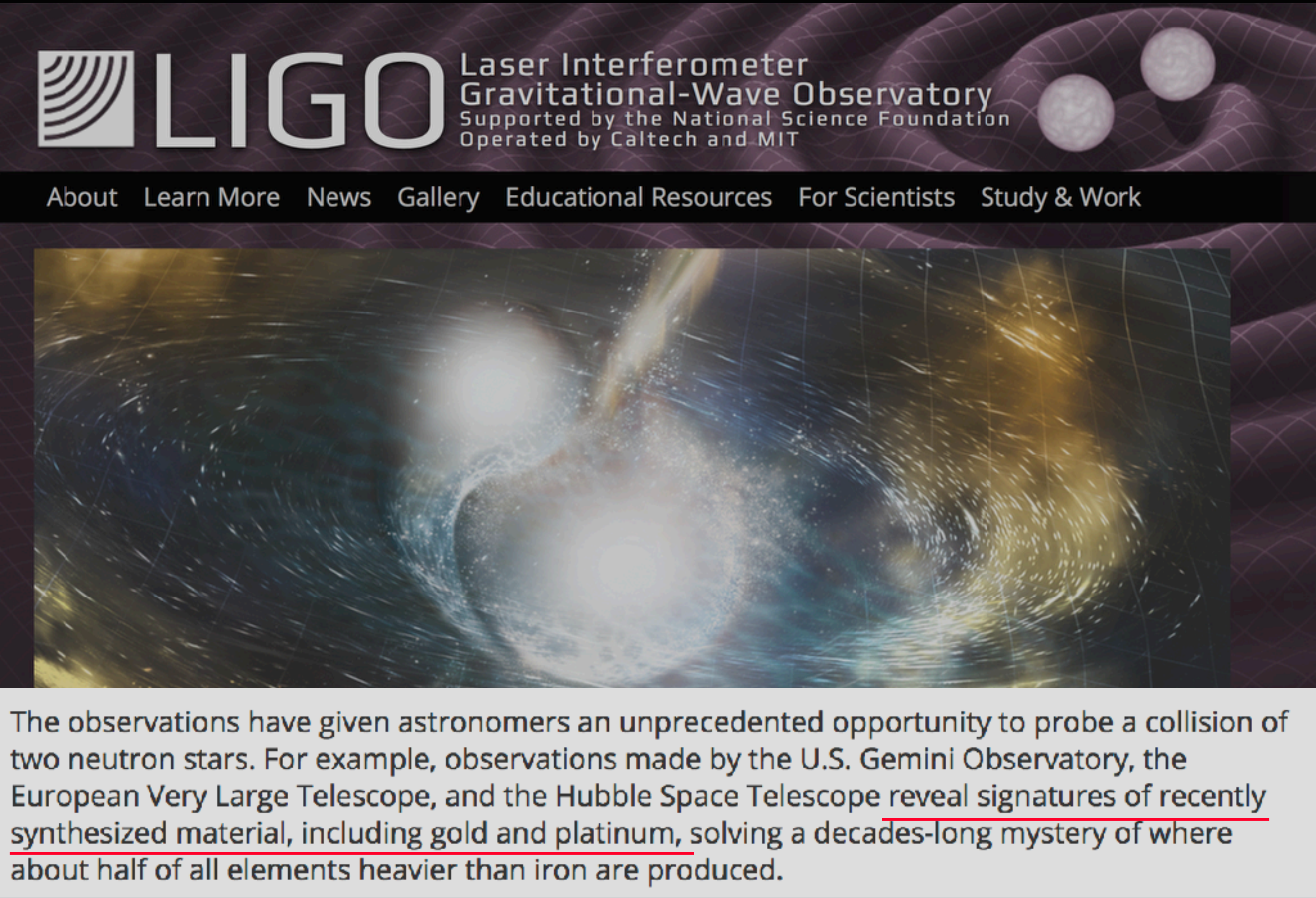
Coulter+17, Soares-Santos+17, Valenti+17,
Arcavi+17, Tanvir+17, Lipunov+17

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

EM counterpart of GW170817 @ 40 Mpc
=> “Kilonova” (ultraviolet, optical, and infrared)



Optical (z) near IR (H) near IR (Ks)



The observations have given astronomers an unprecedented opportunity to probe a collision of two neutron stars. For example, observations made by the U.S. Gemini Observatory, the European Very Large Telescope, and the Hubble Space Telescope reveal signatures of recently synthesized material, including gold and platinum, solving a decades-long mystery of where about half of all elements heavier than iron are produced.

https://www.ligo.caltech.edu/page/press-release-gw170817

Questions to be answered in this lecture

- What is kilonova?
- Why does NS merger produce emission?
- What determines the properties of kilonova?
- Why is it related to the origin of elements?
- What did we learn from kilonova?
- What can we learn in the future?
- ...

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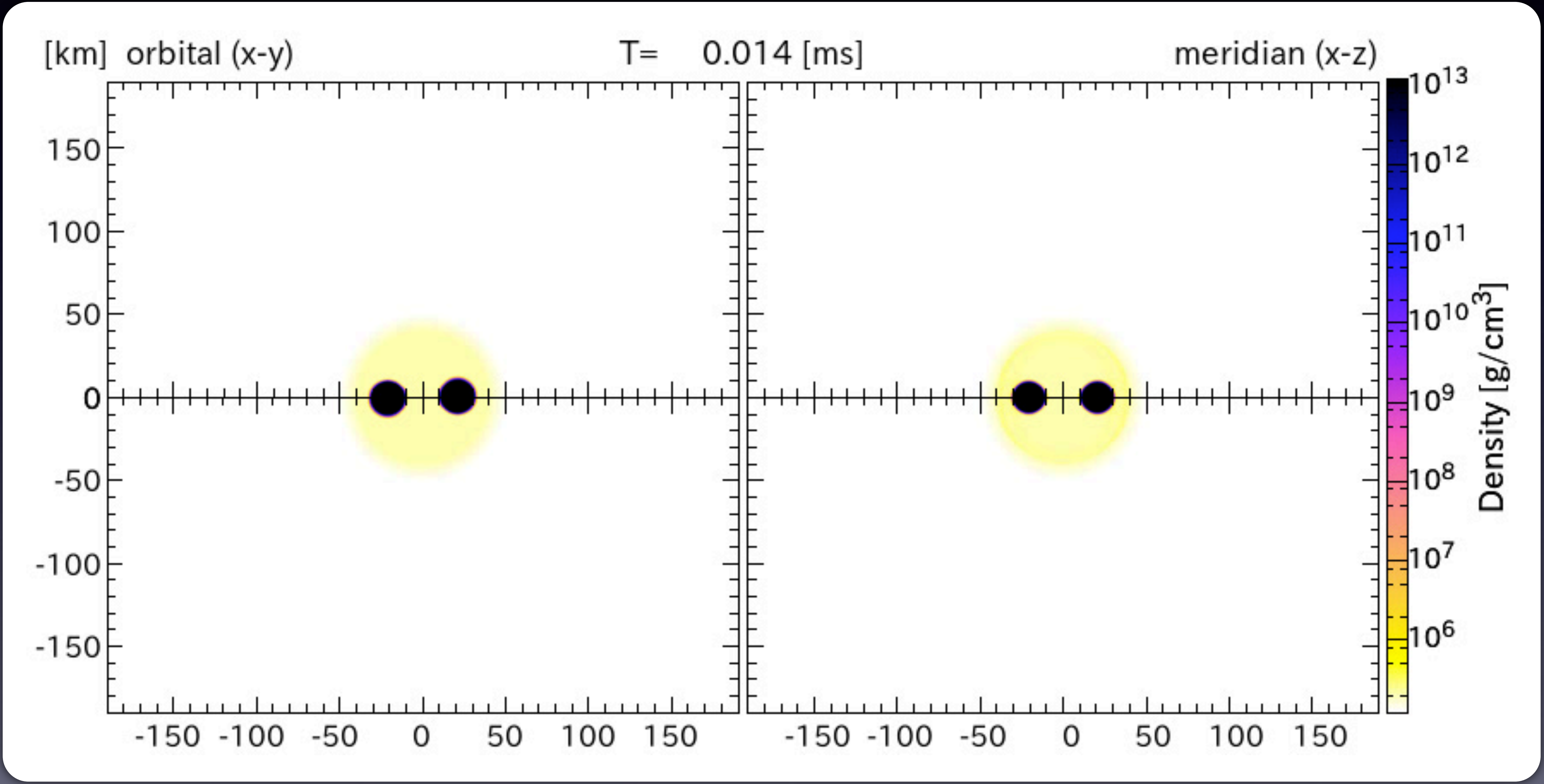
NS merger => mass ejection

Top view **Side view**

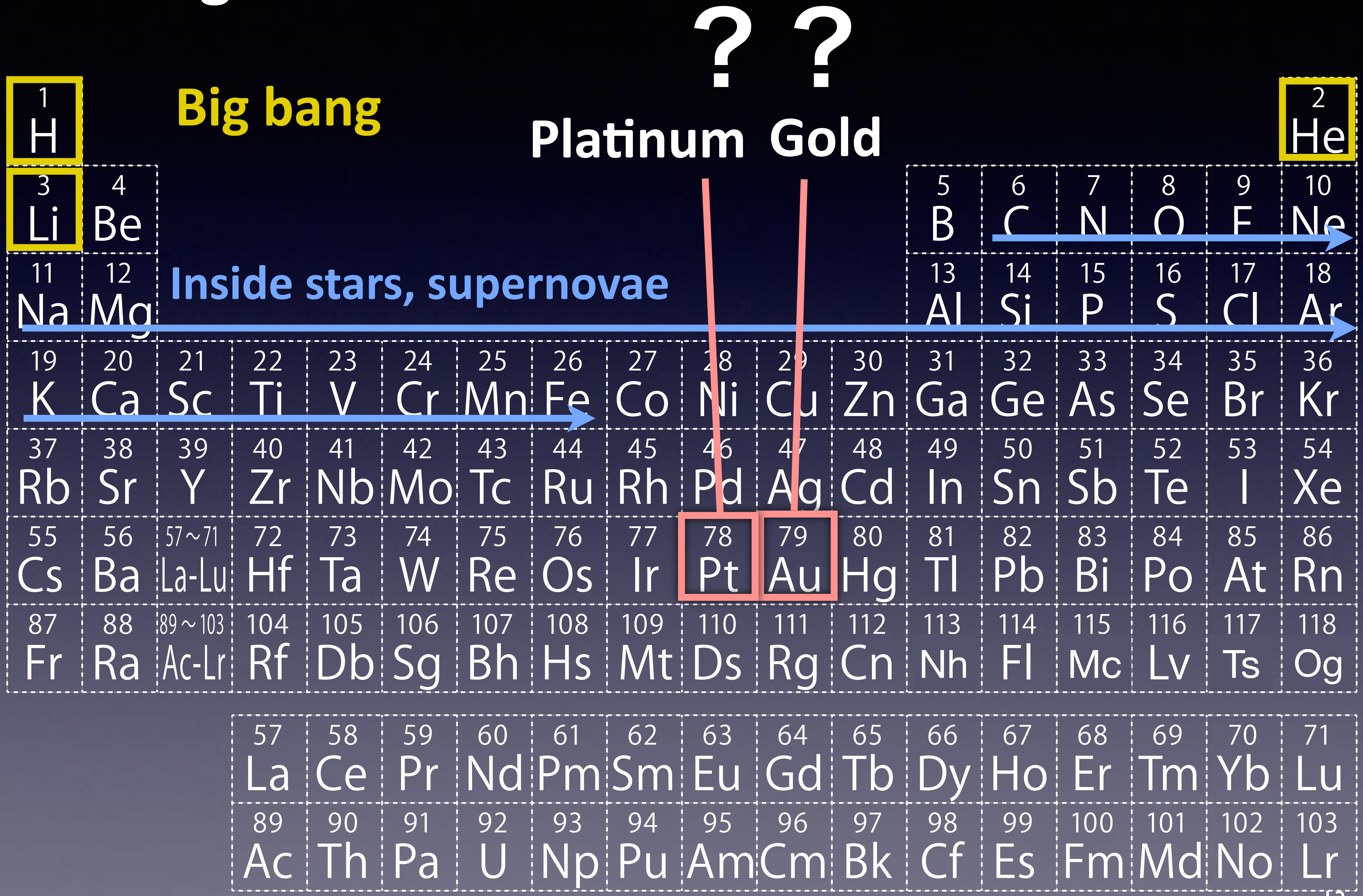


Sekiguchi+15, 16

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

v ~ 0.1 - 0.2 c

The origin of elements



? ?

Platinum Gold

Big bang

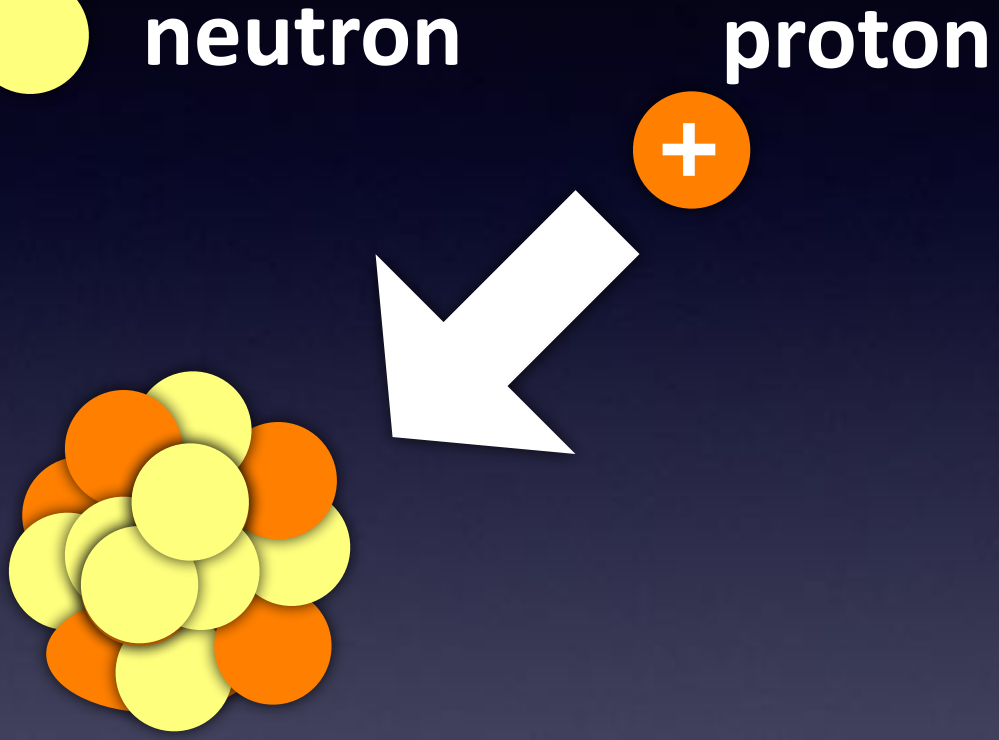
Inside stars, supernovae

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	57～71 La-Lu	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	89～103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			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	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Key player: Neutron

● proton

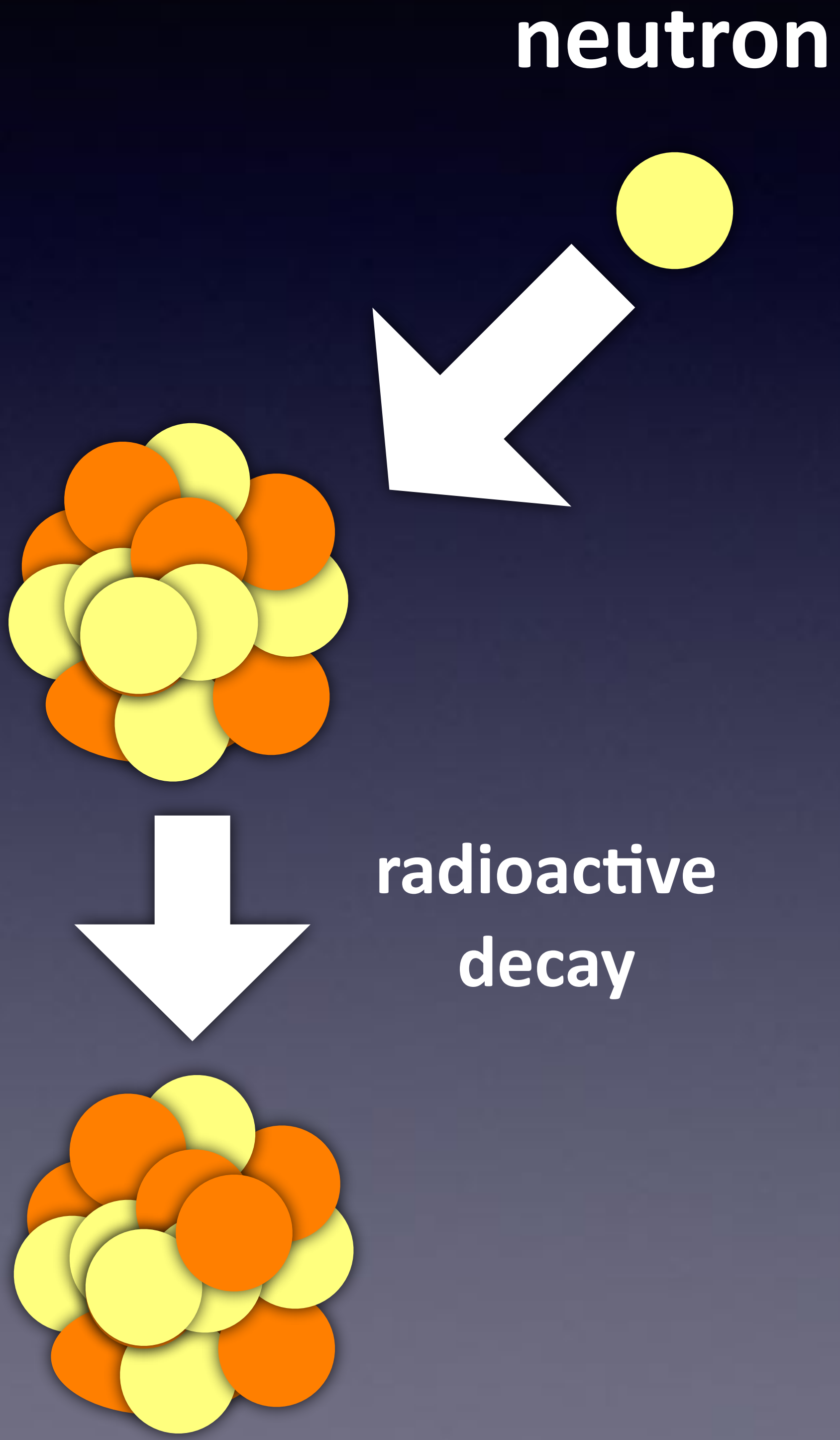
● neutron



proton

Ni56

- proton 28
- neutron 28



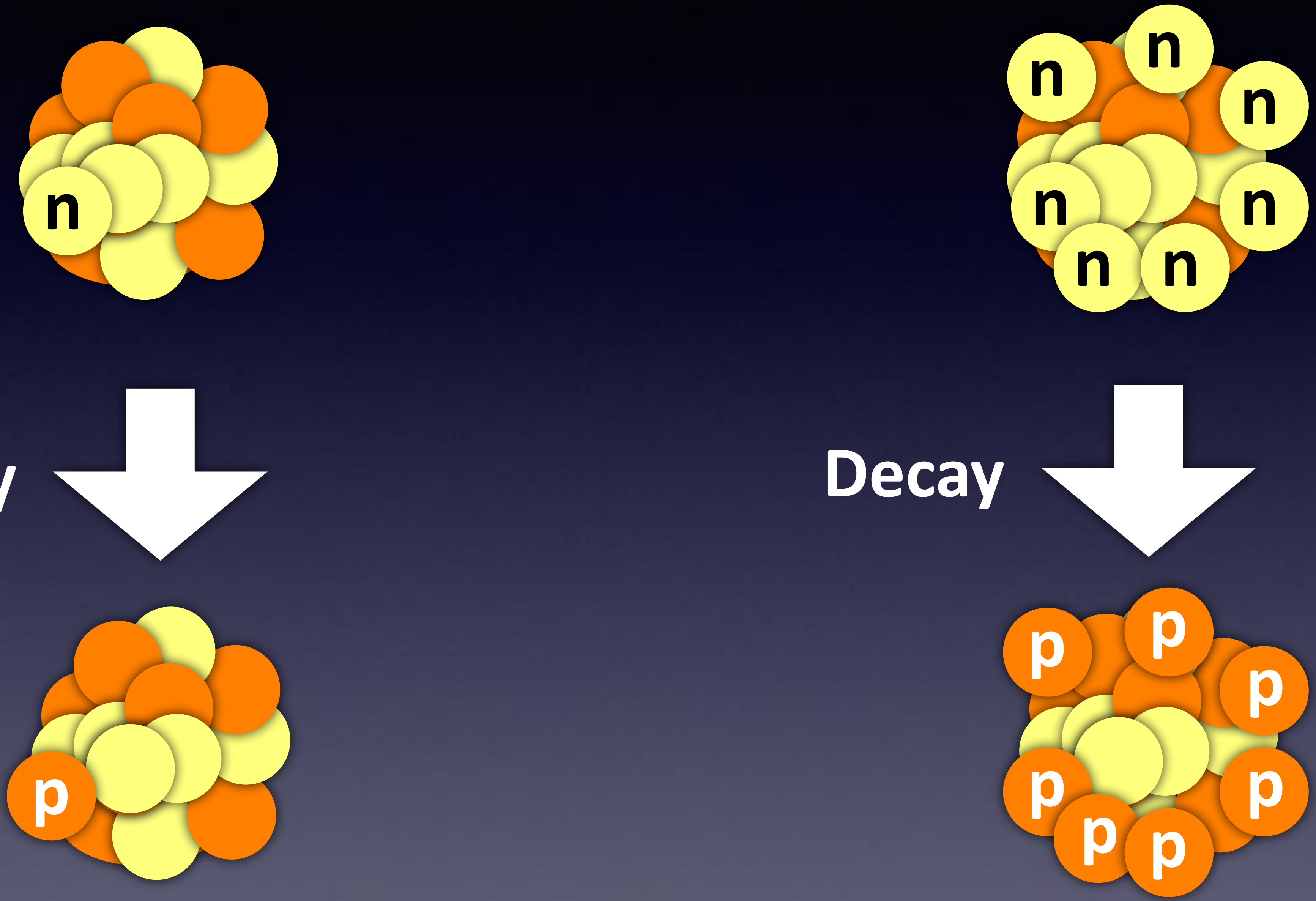
neutron

radioactive decay

Neutron-capture nucleosynthesis

s (slow)-process

r (rapid)-process



Decay

Decay

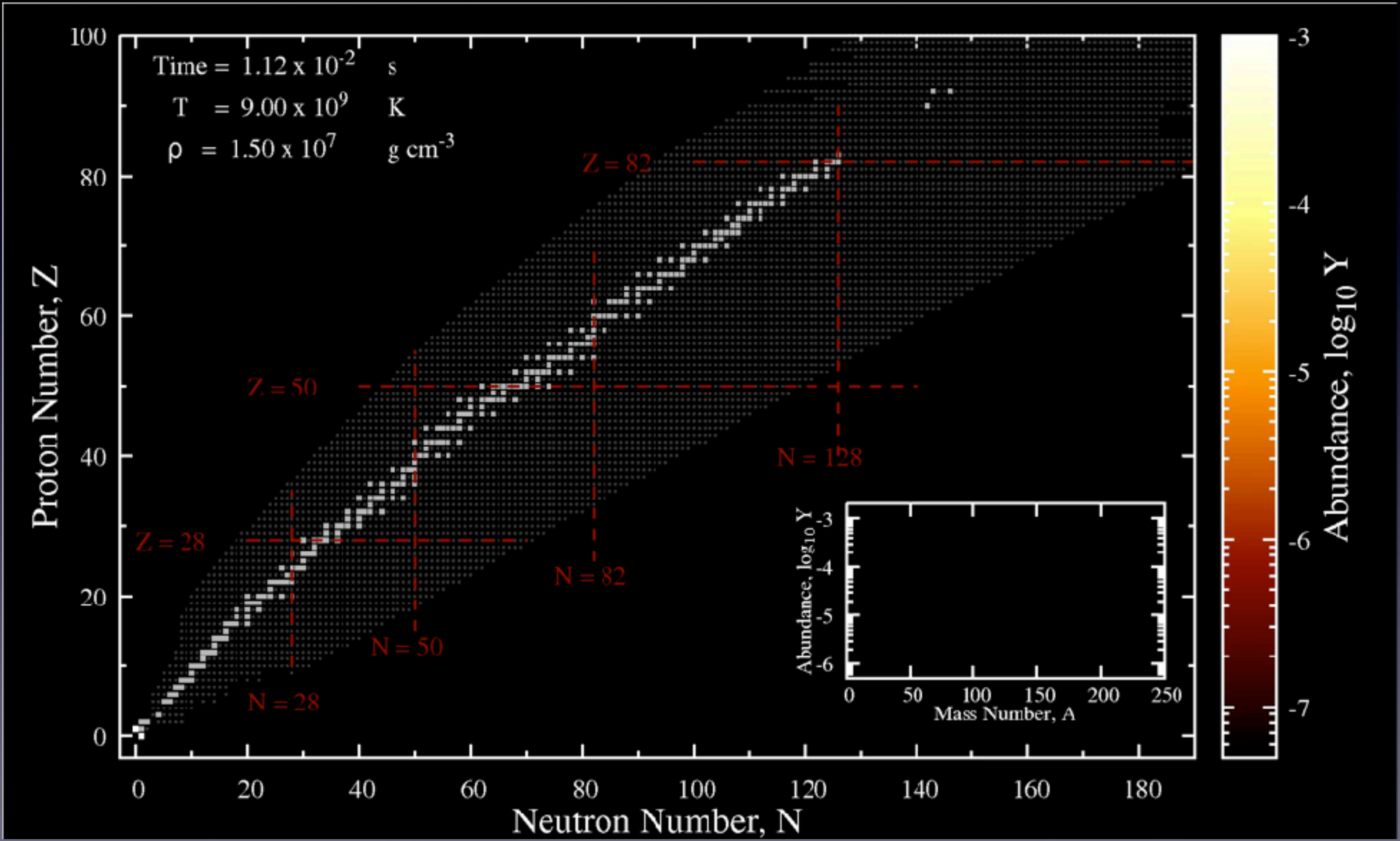
Ba, Pb, …

Inside of stars

Au, Pt, U, …

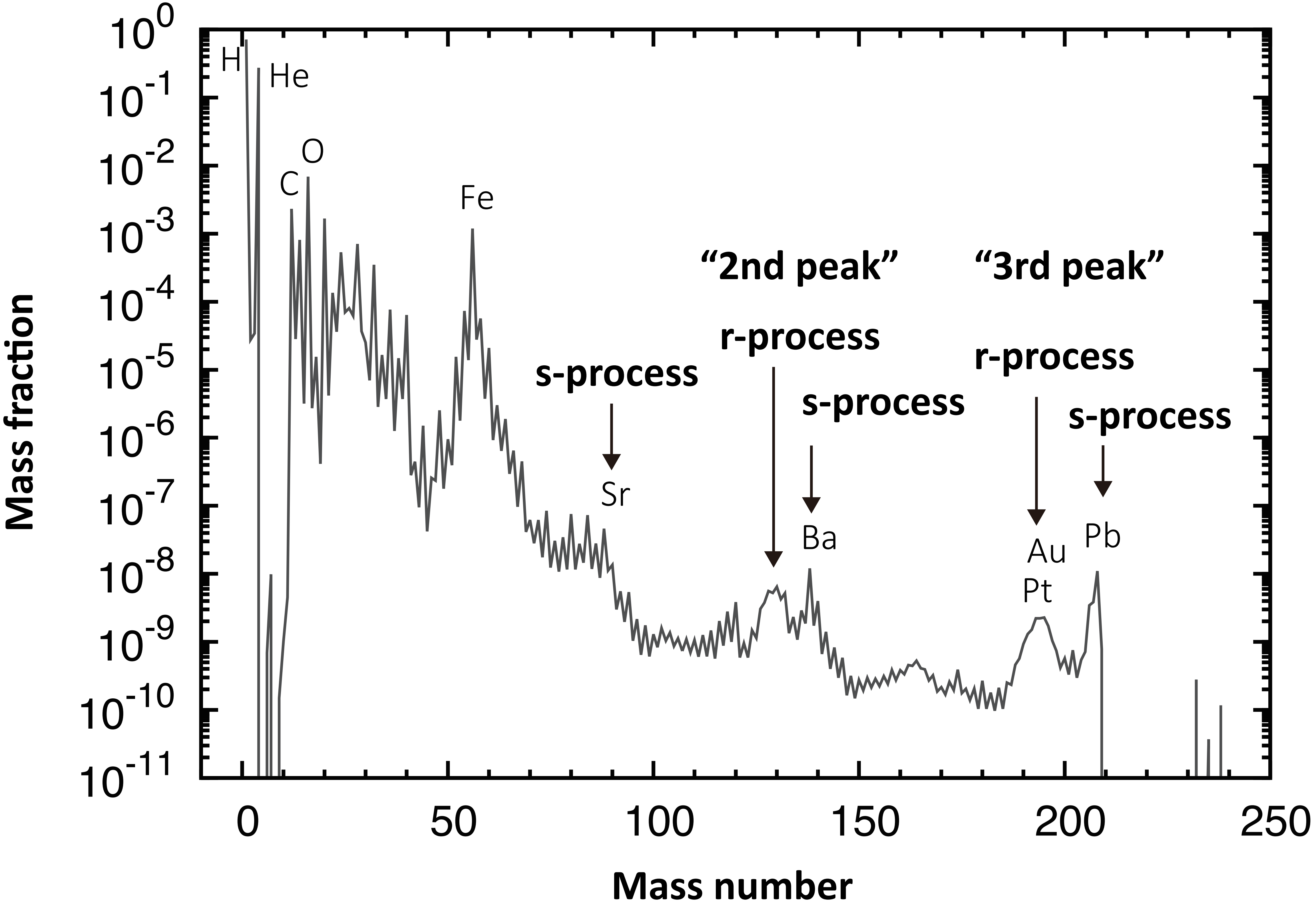
??

r-process nucleosynthesis in NS merger



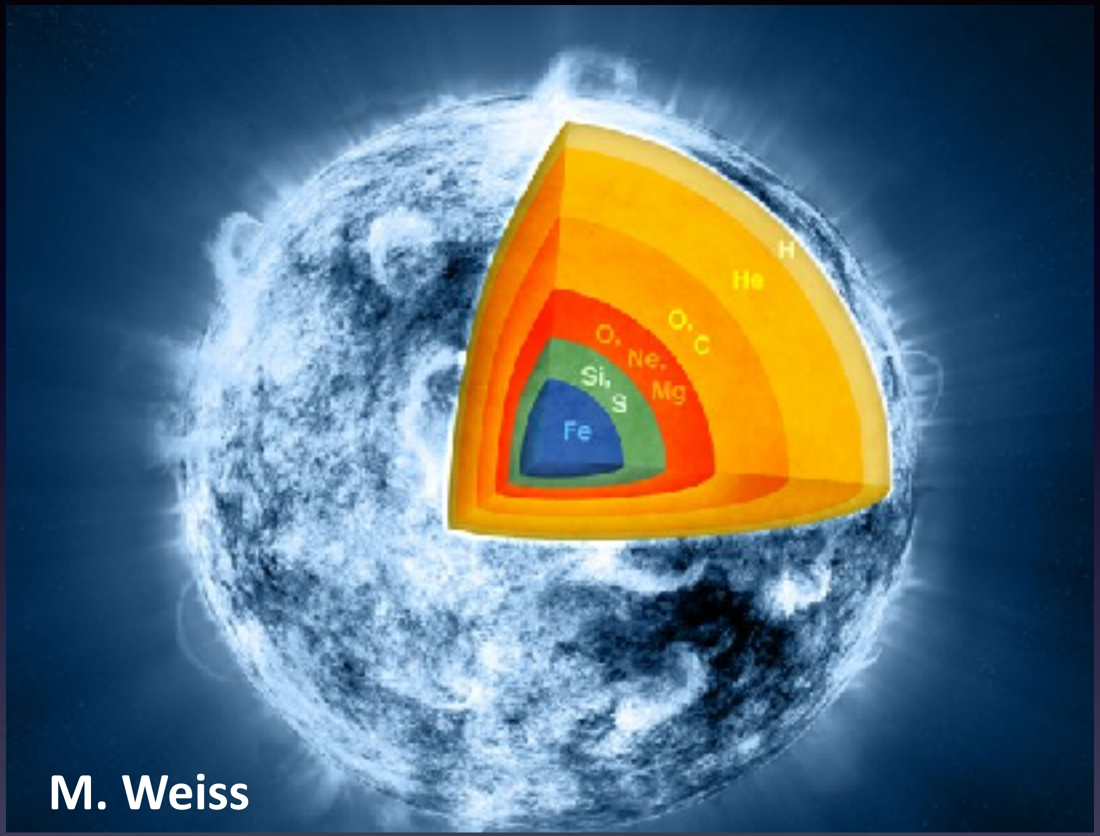
(C) Nobuya Nishimura

Cosmic abundances



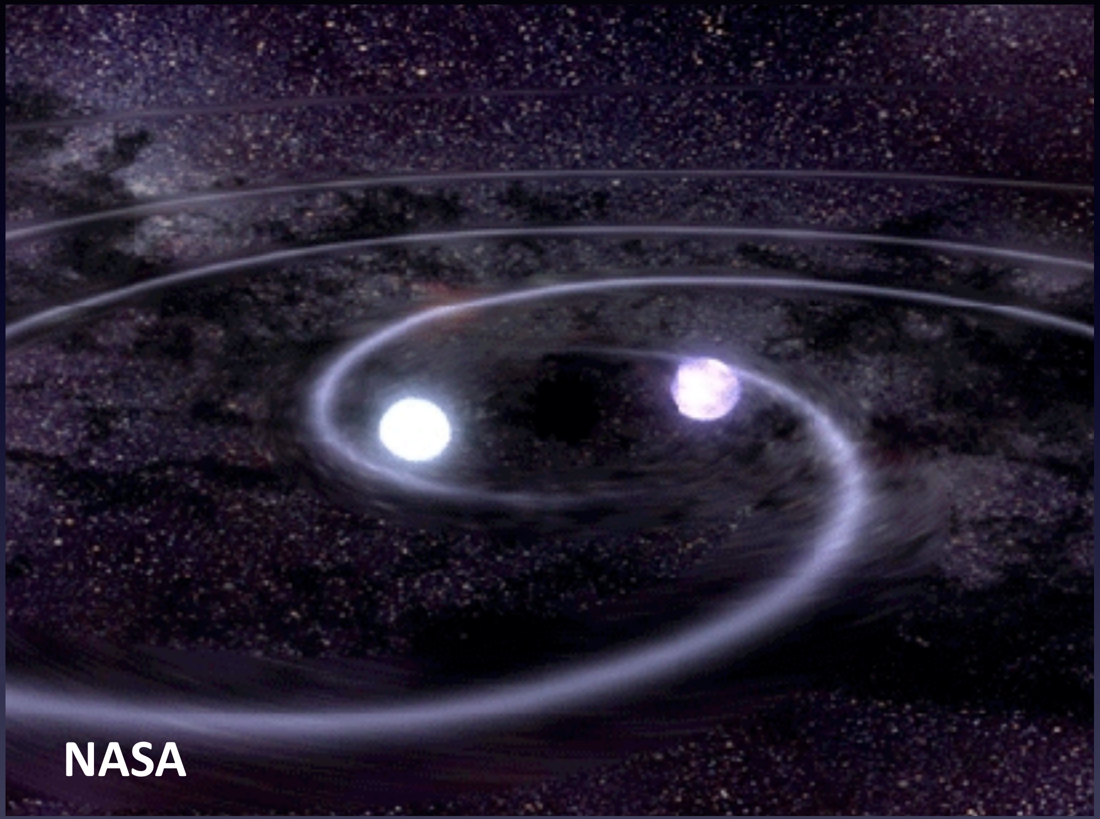
Explosive phenomena around the neutron star

Core-collapse supernova



M. Weiss

NS merger



NASA

Moderately neutron rich

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

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

Outcome of r-process nucleosynthesis

$$A_{\mathrm{final}} = \underbrace{A_{\mathrm{seed}}}_{\sim 50\text{-}100} + \mathrm{n/seed}$$

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

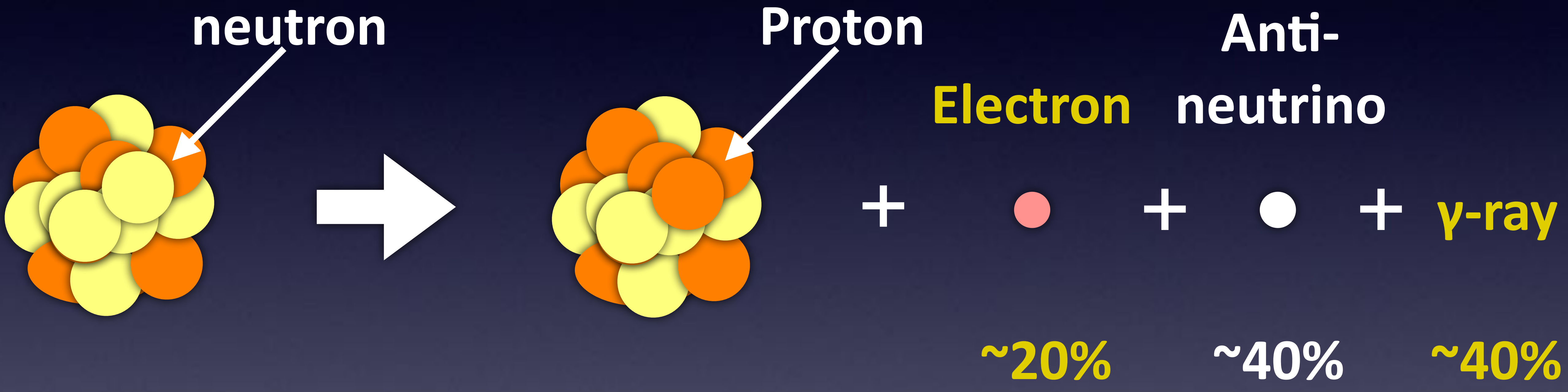
Example 1: Ye = 0.1

$n_n \sim 9\, n_p$
=> 1 seed ^{56}Ni (Z = 28, N = 28) + ~250 free neutron
=> n/seed ~ 250 => A(final) ~ 50 + 200 = 250

Example 2: Ye = 0.25

$n_n \sim 3\, n_p$
=> 1 seed ^{56}Ni (Z = 28, N = 28) + ~60 free neutron
=> n/seed ~ 60 => A(final) ~ 50 + 60 = 110

Beta decay



neutron

Proton

Electron

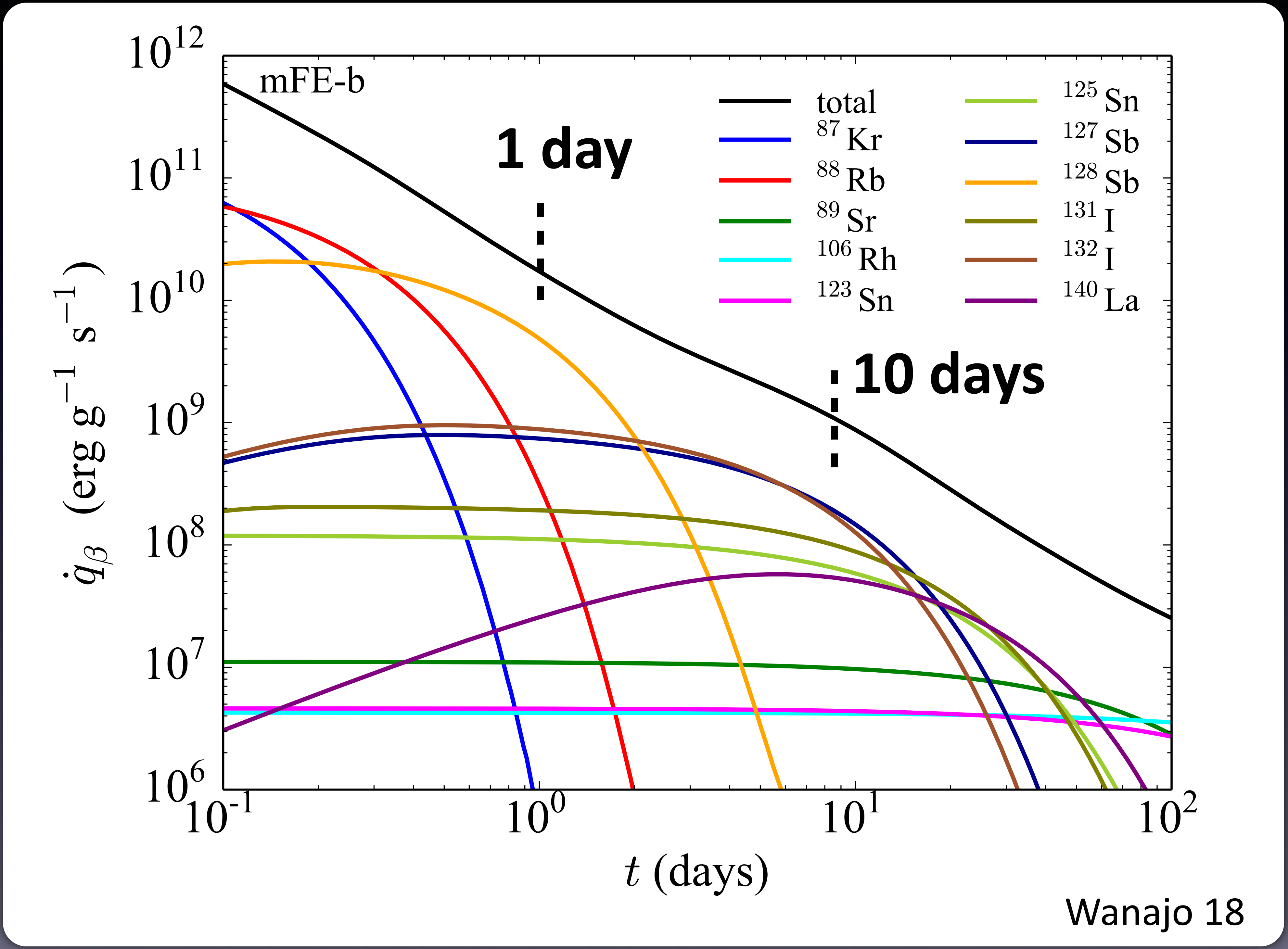
Anti-neutrino

\+ ● + ● + γ-ray

~20% ~40% ~40%

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

Radioactive decay luminosity (β-particles, γ-rays, neutrinos)



Wanajo 18

$$q \sim 2 \times 10^{10}\ t_{\rm day}^{-1.3}\ {\rm erg\ s^{-1}\ g^{-1}}$$

Metzger+10
Lippuner+15
Hotokezaka+16, 17

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Timescale

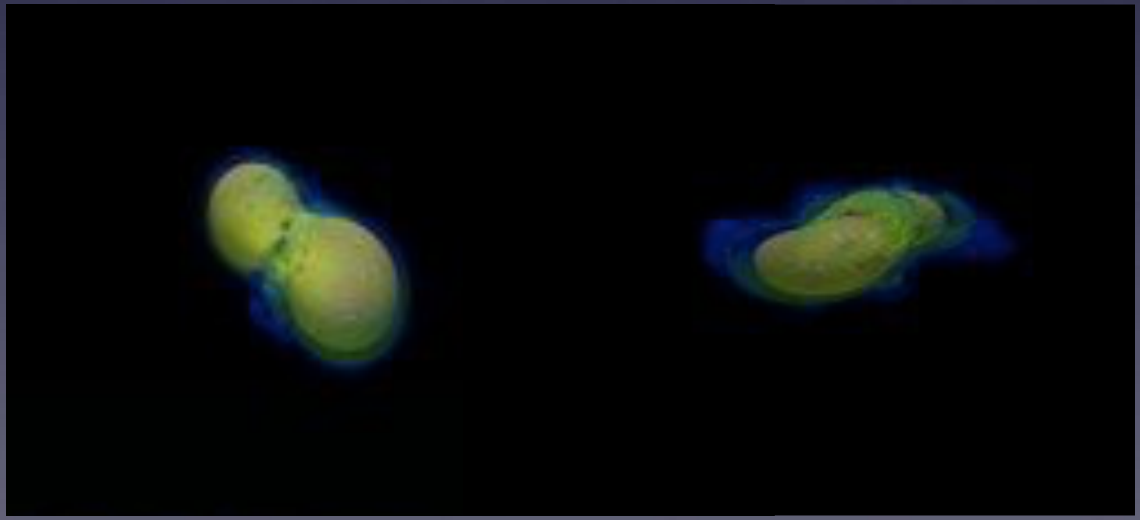
Merger → **neutron-capture (r-process) nucleosynthesis** → **Radioactive decay => kilonova**

Mass ejection

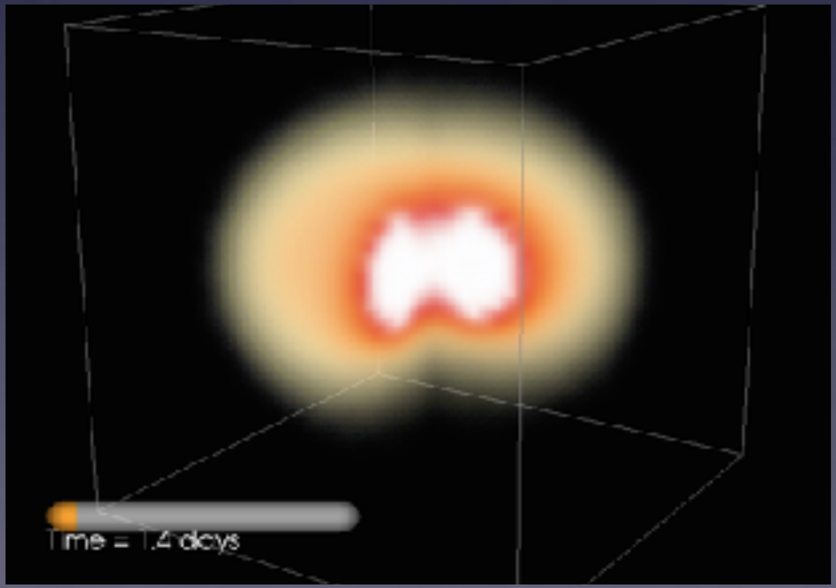
~< 100 ms

< 1 sec

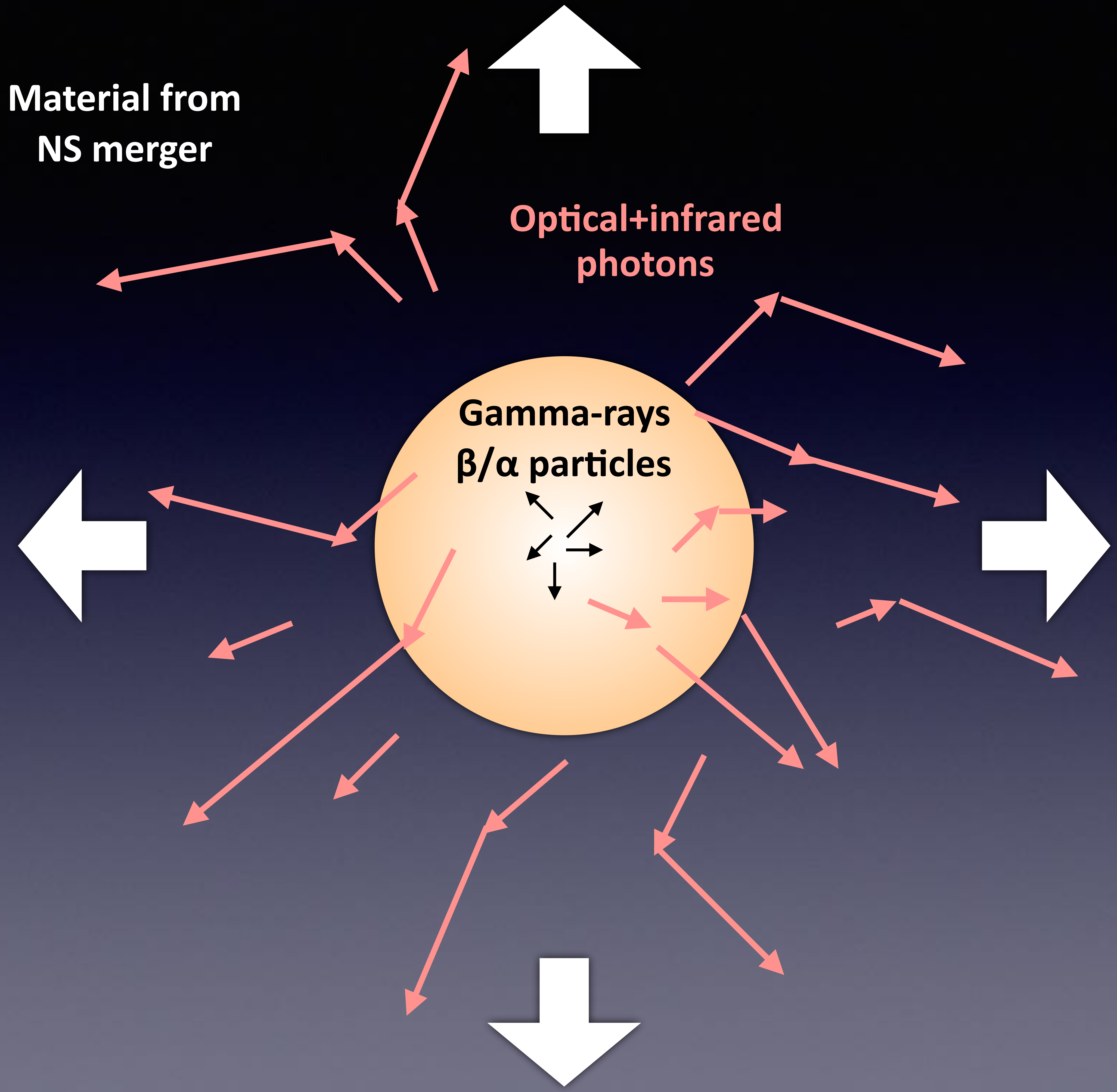
~> days



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



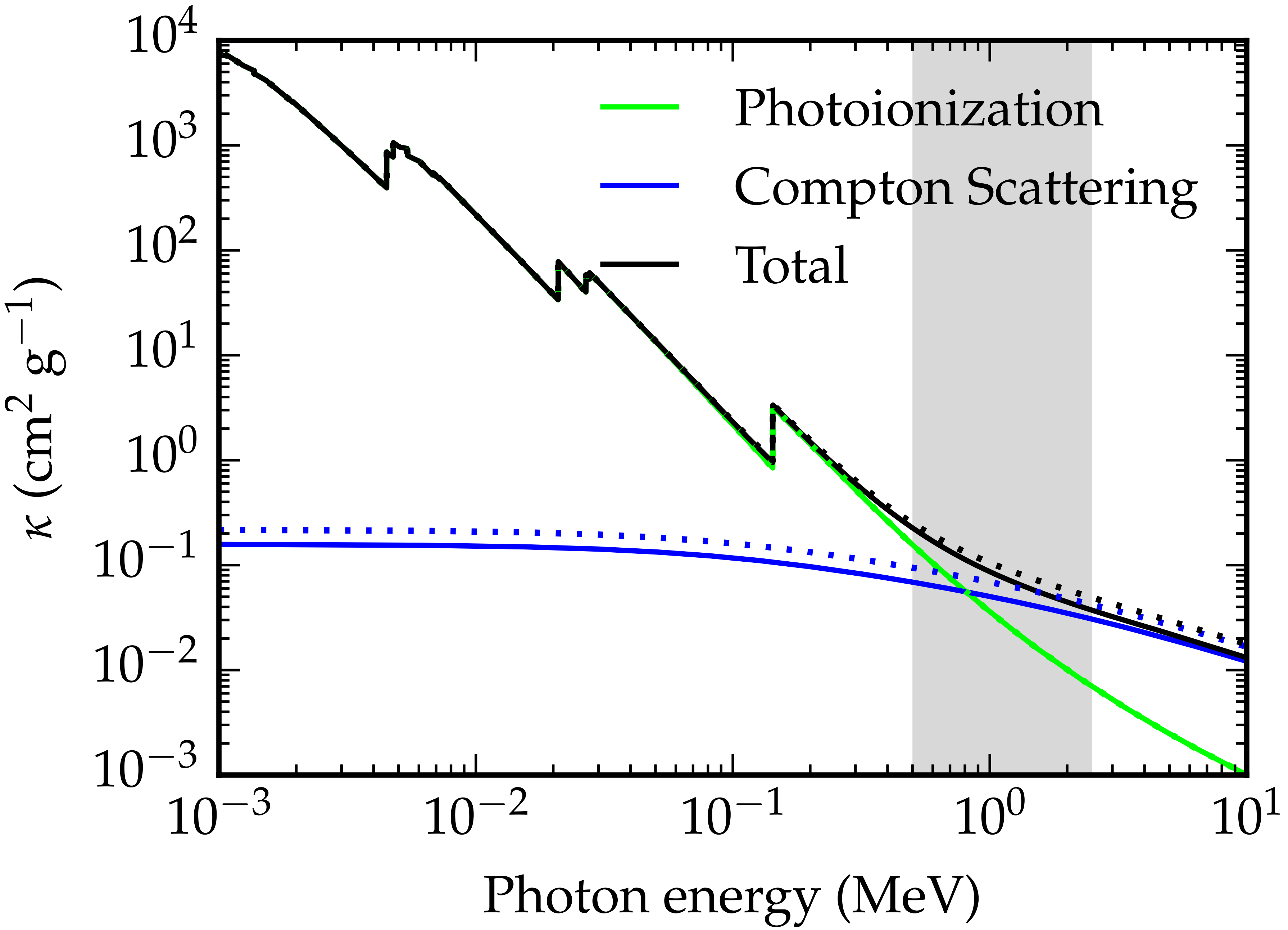
MT & Hotokezaka 13



Material from NS merger
Optical+infrared photons
Gamma-rays
β/α particles

Gamma-rays (~ 1 MeV)

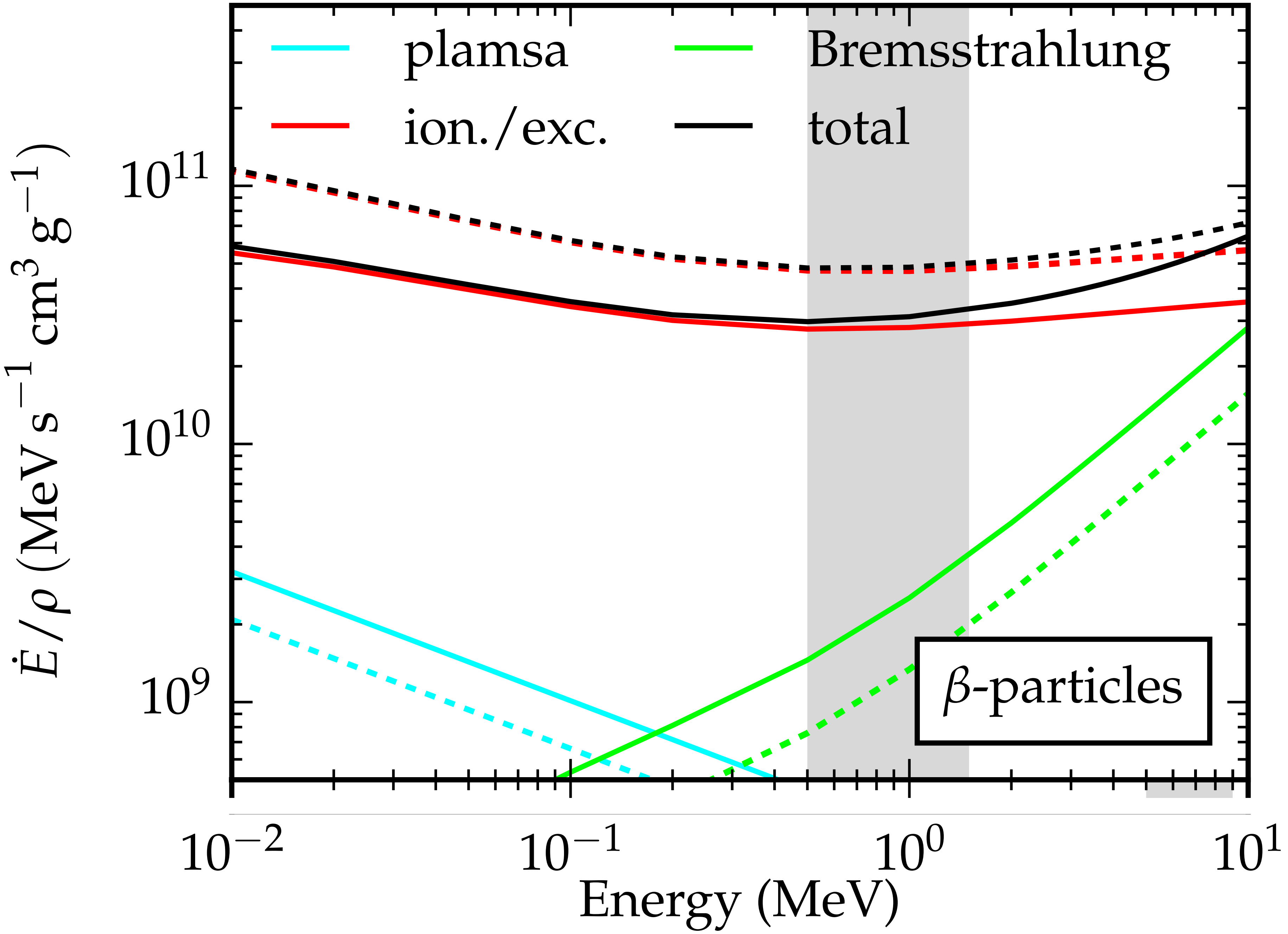
Absorption by photo-ionization



Barnes+16

Beta particles (~ 1 MeV)

Energy loss by ionization/excitation



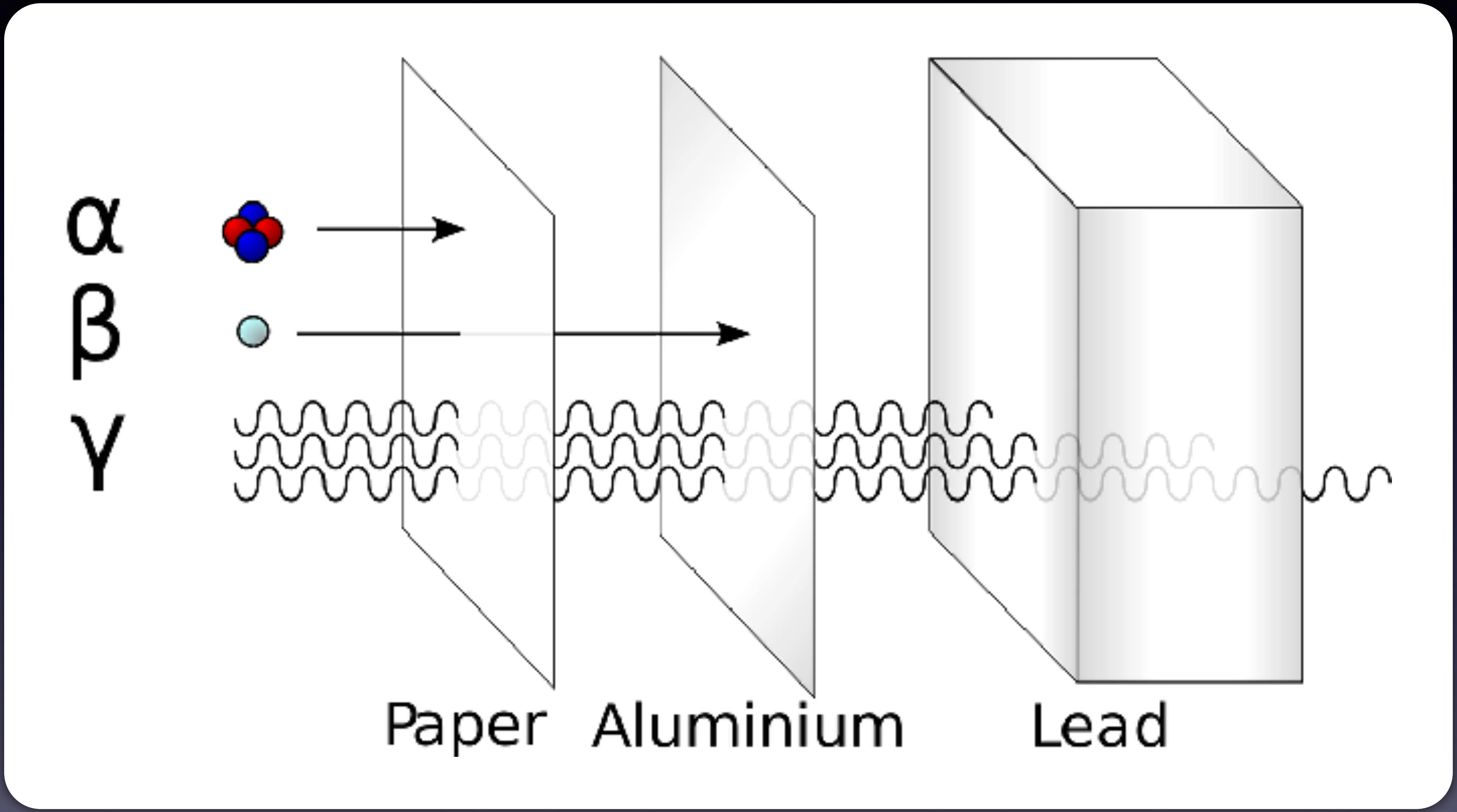
Barnes+16

See Quantum Theory of Radiation (Heitler, W.)

Can NS merger ejecta “stop” gamma-rays and electrons?

= Can radioactive energy be “deposited” to the ejecta?

Penetrating power



https://en.wikipedia.org/wiki/Radiation

*** α decay becomes important (A >~ 200)**

*** fission may also play roles (A >~ 250)**

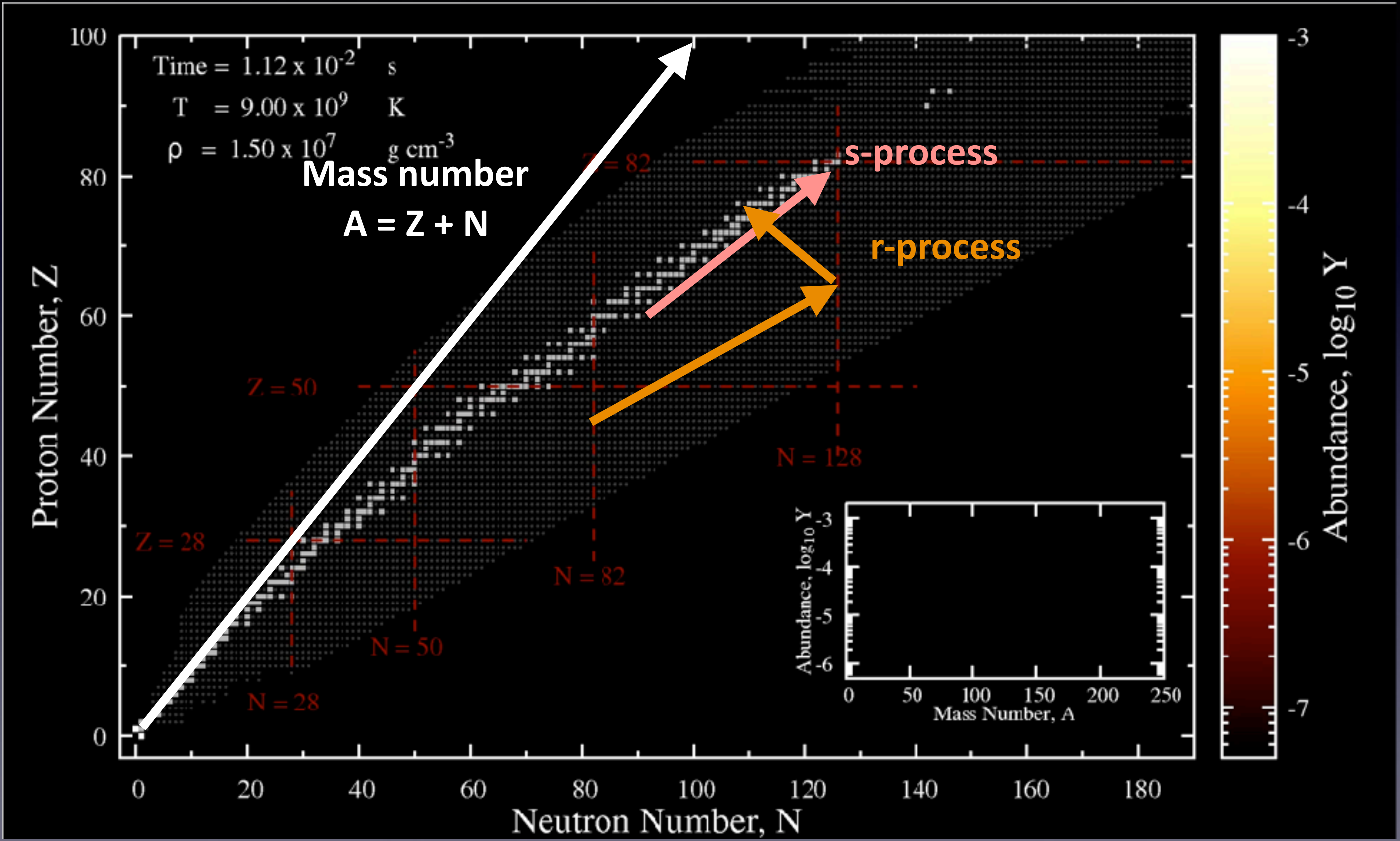
Short summary

- Mass ejection from NS merger
  - M ~ 0.01 Msun, v ~ 0.1c (dynamical ejection)
  - Neutron rich (Ye ~ 0.1)
  - Promising site for r-process nucleosynthesis
- NS merger ejecta
  - Rapidly expanding, metal-dominant, partially-ionized gas ($\rho \sim 10^{-13}$ g cm^{-3}, T ~ 10^4 K)
  - Radioactive decay energy (mainly beta decay)
  - Fast electrons (+ some γ-rays) are stopped => energy deposition (or thermalization)
  - Thermal emission is expected: “kilonova”

Q & A

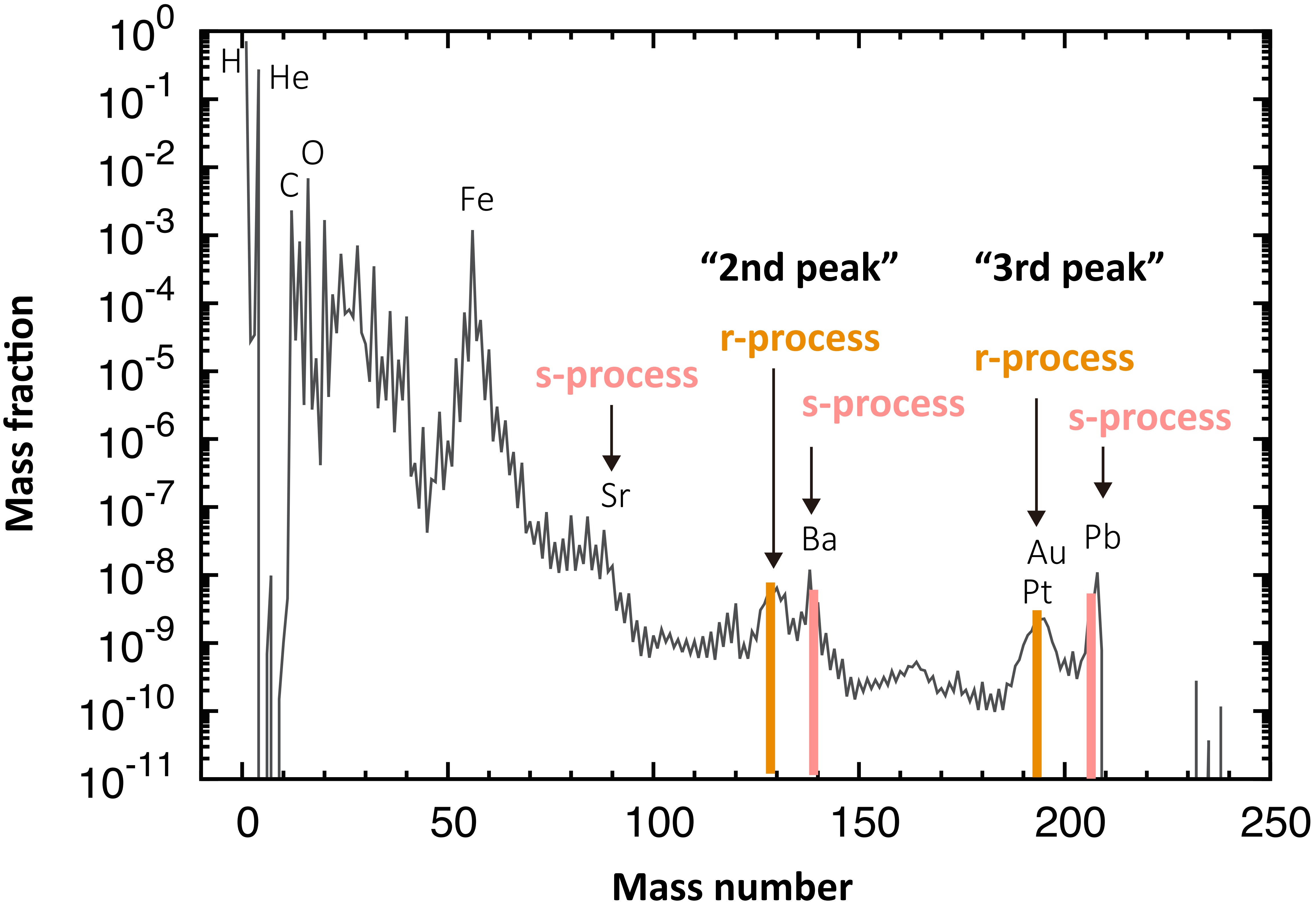
https://www.astr.tohoku.ac.jp/~masaomi.tanaka/icts2020/

★ s-process and r-process?



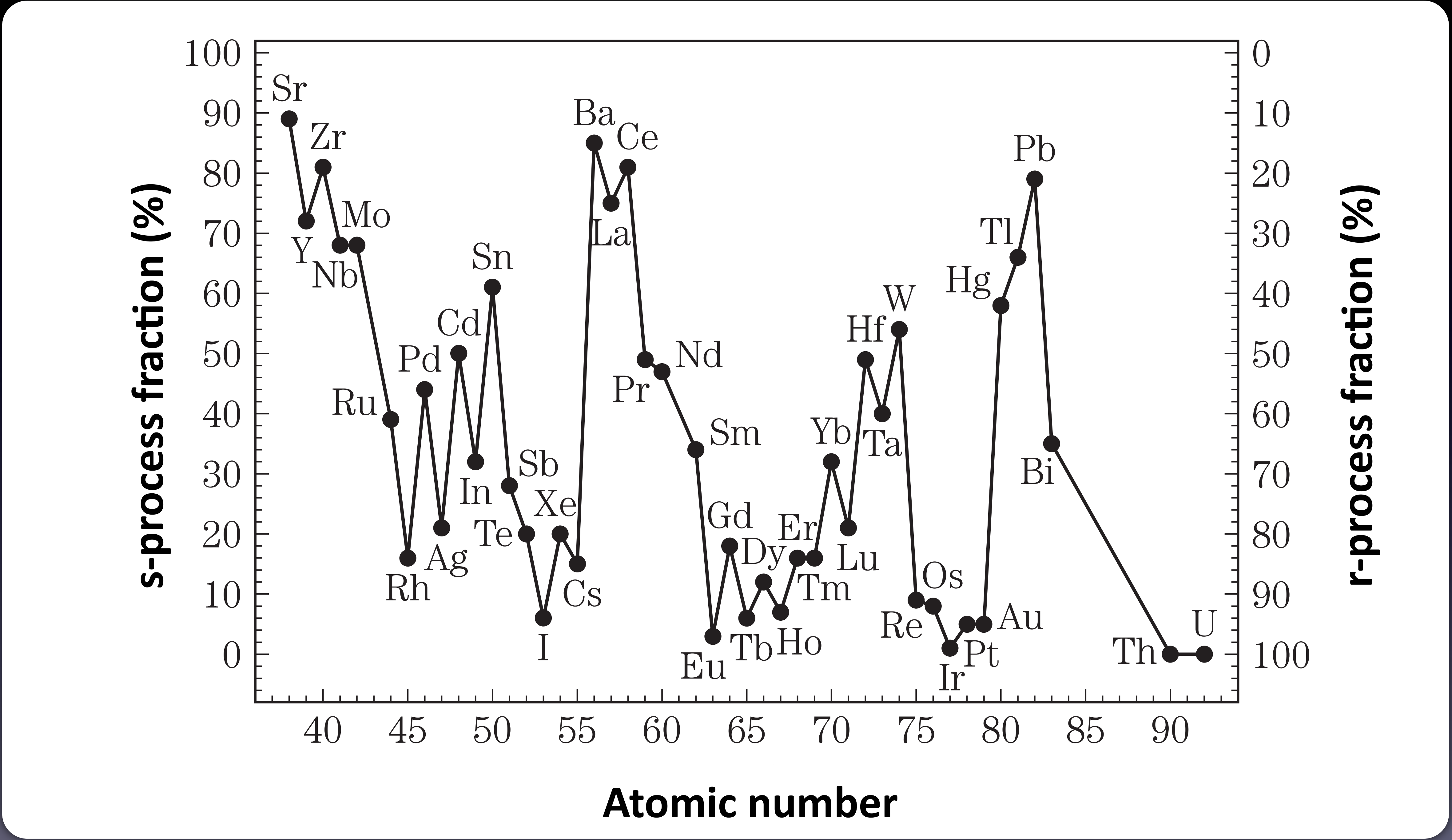
(C) Nobuya Nishimura

Cosmic abundances



★ Relative contribution?

(C) Shinya Wanajo

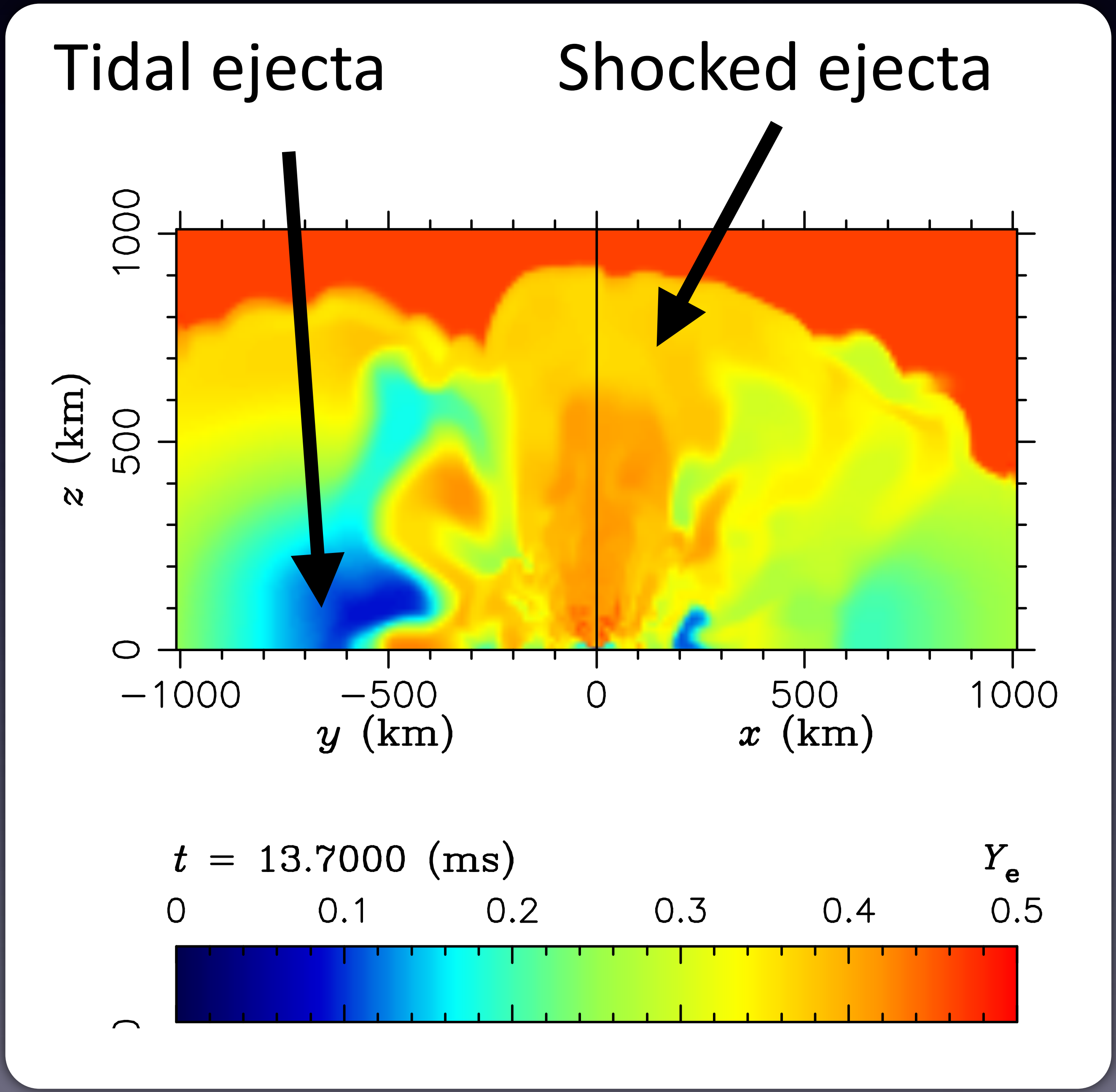


Why ~50:50??
=> just by chance…

s-process: evolved low-mass stars
r-process: NS merger (massive star binary evolution)
or special supernova (non neutrino-driven)

★ Calculating Ye in NS merger?

Hydrodynamics + neutrino radiation transport (weak interaction)



Tidal ejecta

Shocked ejecta

Wanajo+14

Relatively Ye even in NS merger

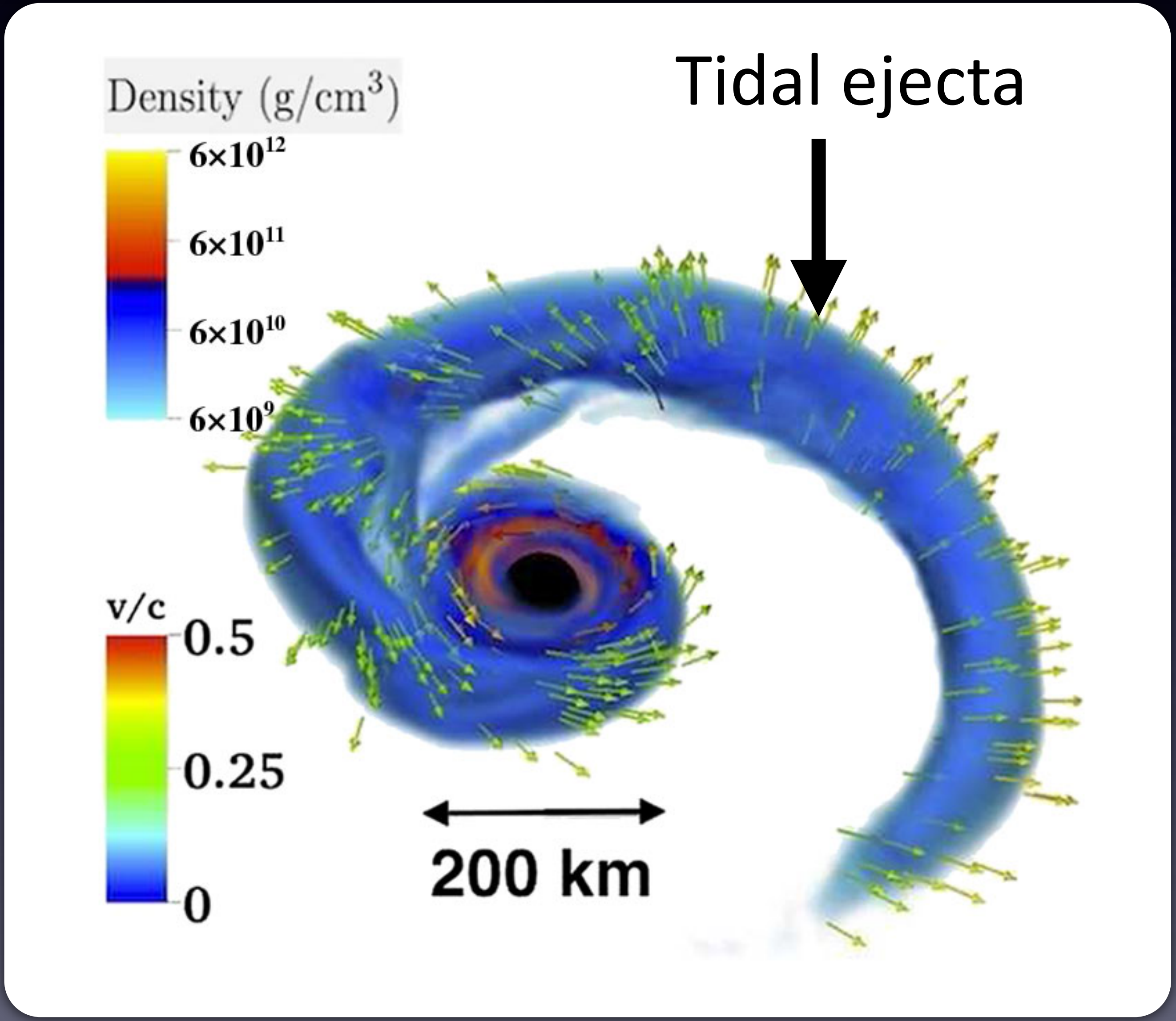
- Shocked ejecta
  => high temperature (e- e+)

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

- Wind from the accretion disk
  around massive neutron star

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

★ Mass ejection from BH-NS merger?



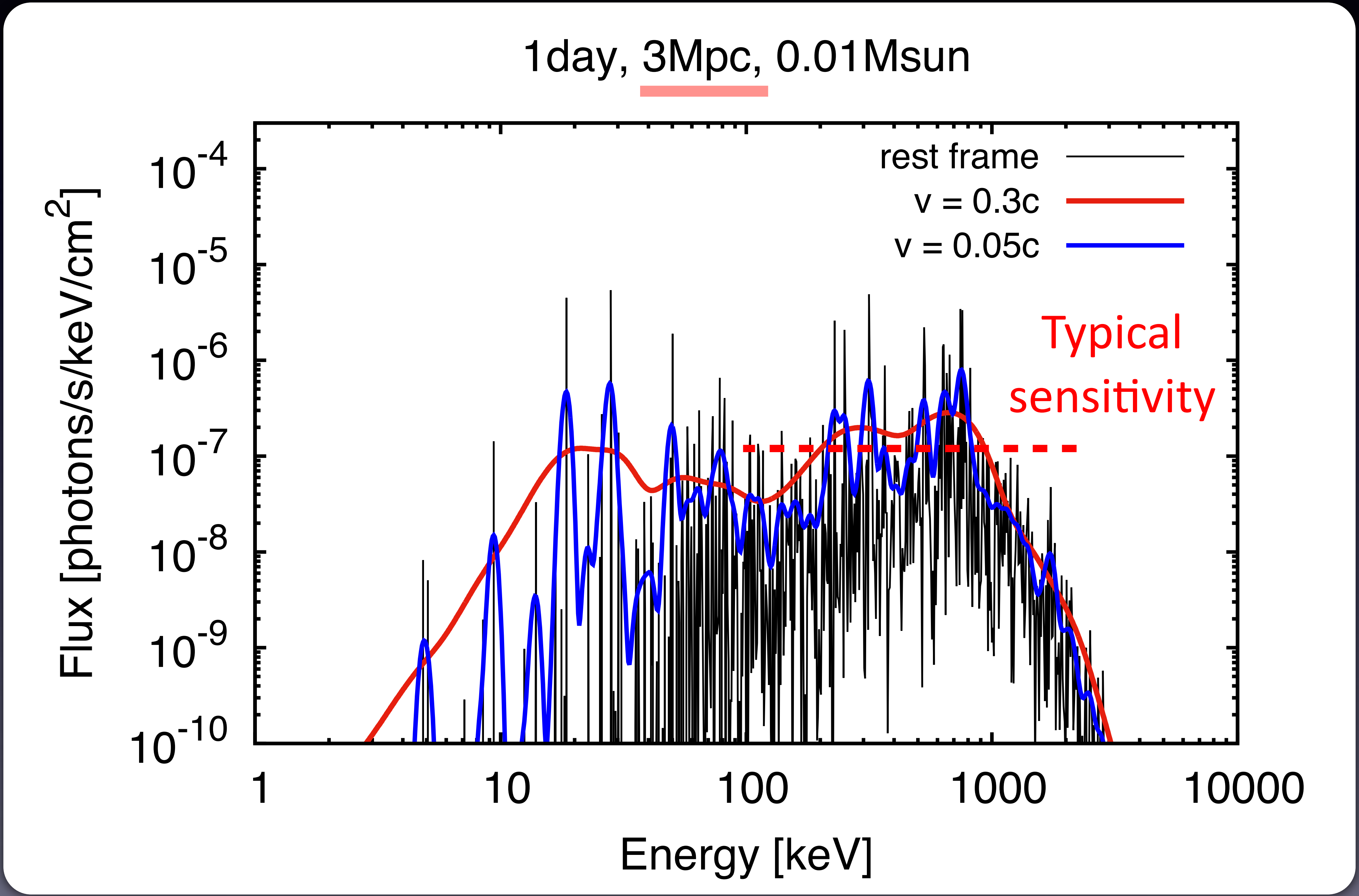
Foucart+14

Mass ejection occurs when
R(tidal) > R(ISCO)
ISCO: innermost stable circular orbit

See e.g., Shibata & Taniguchi 2008

More mass ejection for
- smaller M(BH) <= smaller R(ISCO)
- higher BH spin <= smaller R(ISCO)
- smaller M/R of NS <= larger R(tidal)

gamma-ray signals from NS merger?



Hotokezaka+16

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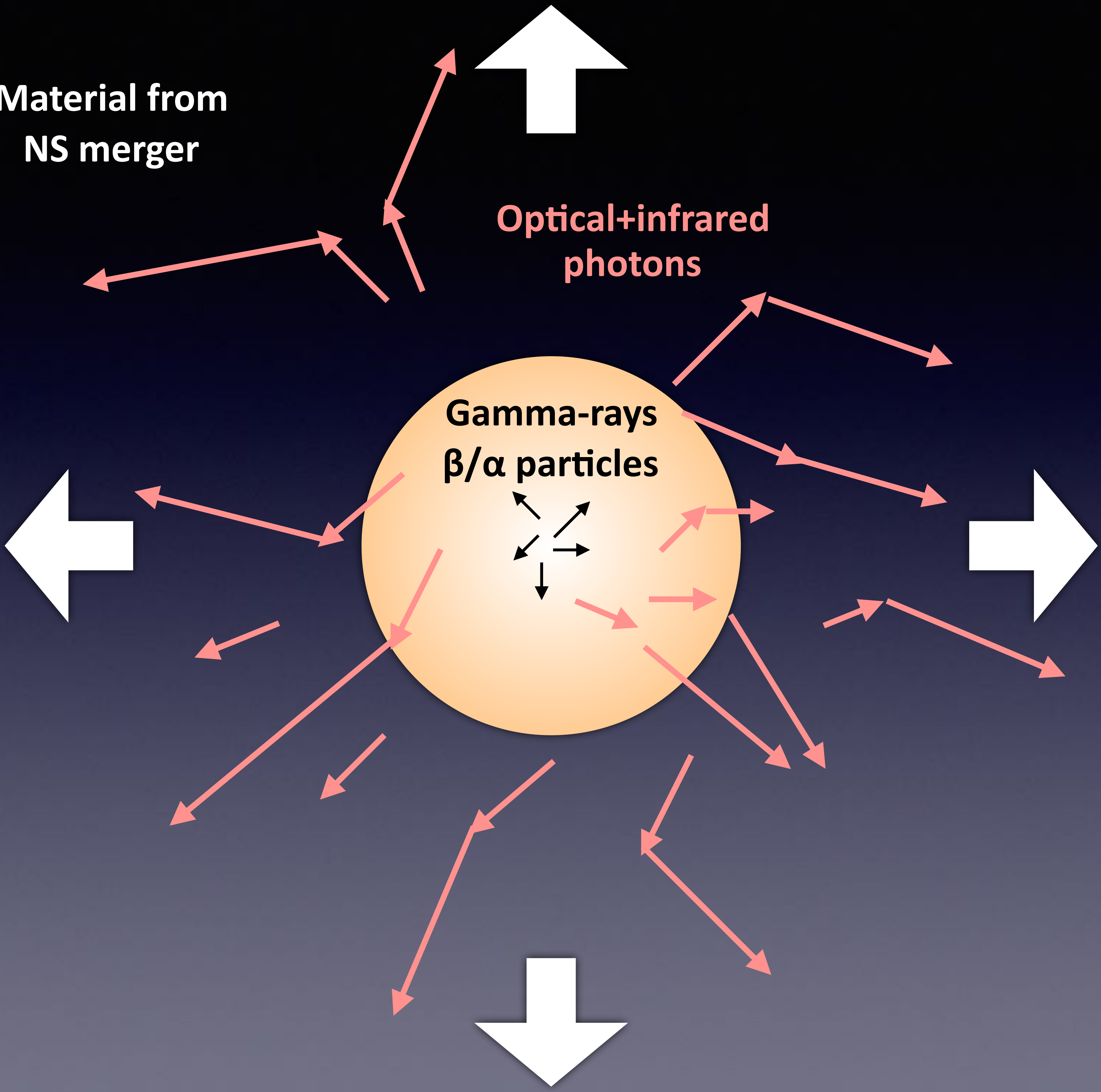


Material from NS merger

Optical+infrared photons

Gamma-rays

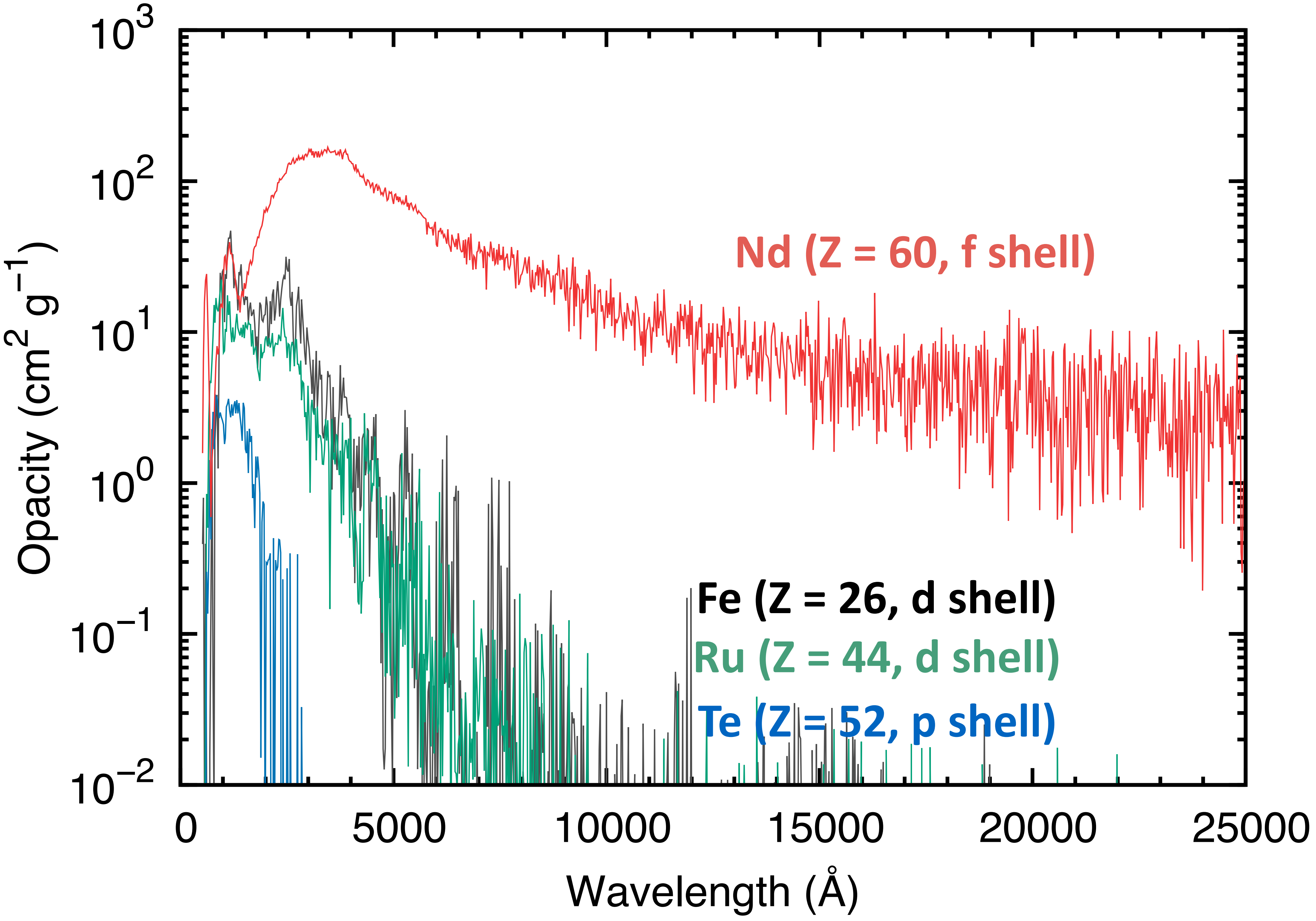
β/α particles

What is the properties of thermal emission (kilonova)?

- Timescale

- Luminosity

Bound-bound opacity of heavy elements



MT, Kato, Gaigalas+18

$$\lambda = \frac{hc}{\Delta E}$$

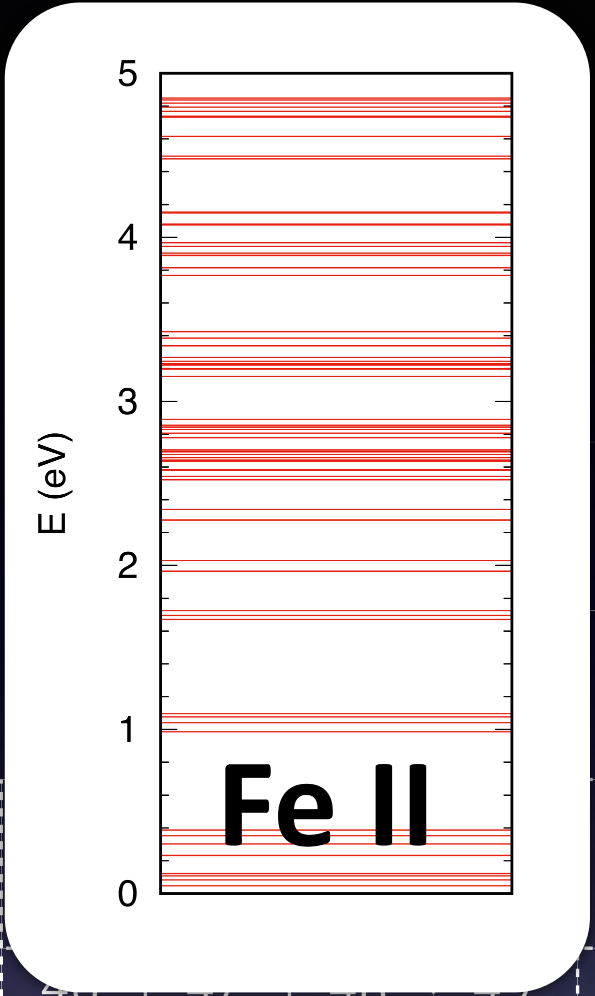
s shell (l = 0)

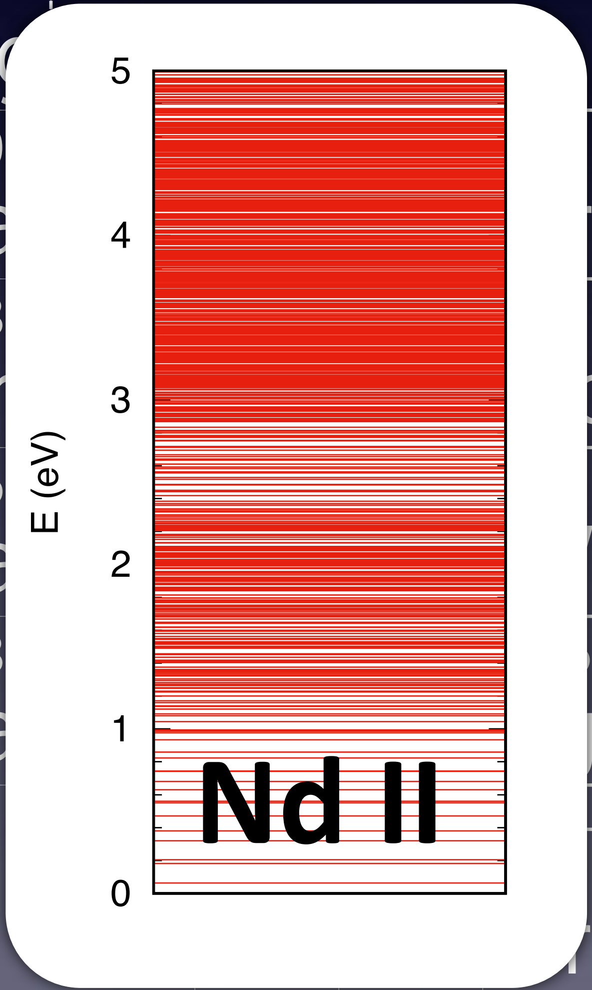
p-shell (l = 1)

d-shell (l = 2)

f shell (l = 3)

1 H																	2 He
3 Li	4 Be												6 C	7 N	8 O	9 F	10 Ne
11 Na	12 M												14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca					25 Mn	26 Fe	27 Co					32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr					43 Tc	44 Ru	45 Rh	Pd	Ag	Cd	In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba					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					107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
						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	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr





Statistical weight

= Number of state for a given l (1 electron)

(different combinations of m_l and m_z)

$$g = \underbrace{2}_{m_z \text{ (spin)}}\underbrace{(2l + 1)}_{m_l \text{ (orbital)}}$$

g = 2 (l = 0, s shell)
g = 6 (l = 1, p shell)
g = 10 (l = 2, d shell)
g = 14 (l = 3, f shell)

Number of state per configuration (n electrons)

$${}_gC_n = \frac{g!}{n!(g-n)!}$$

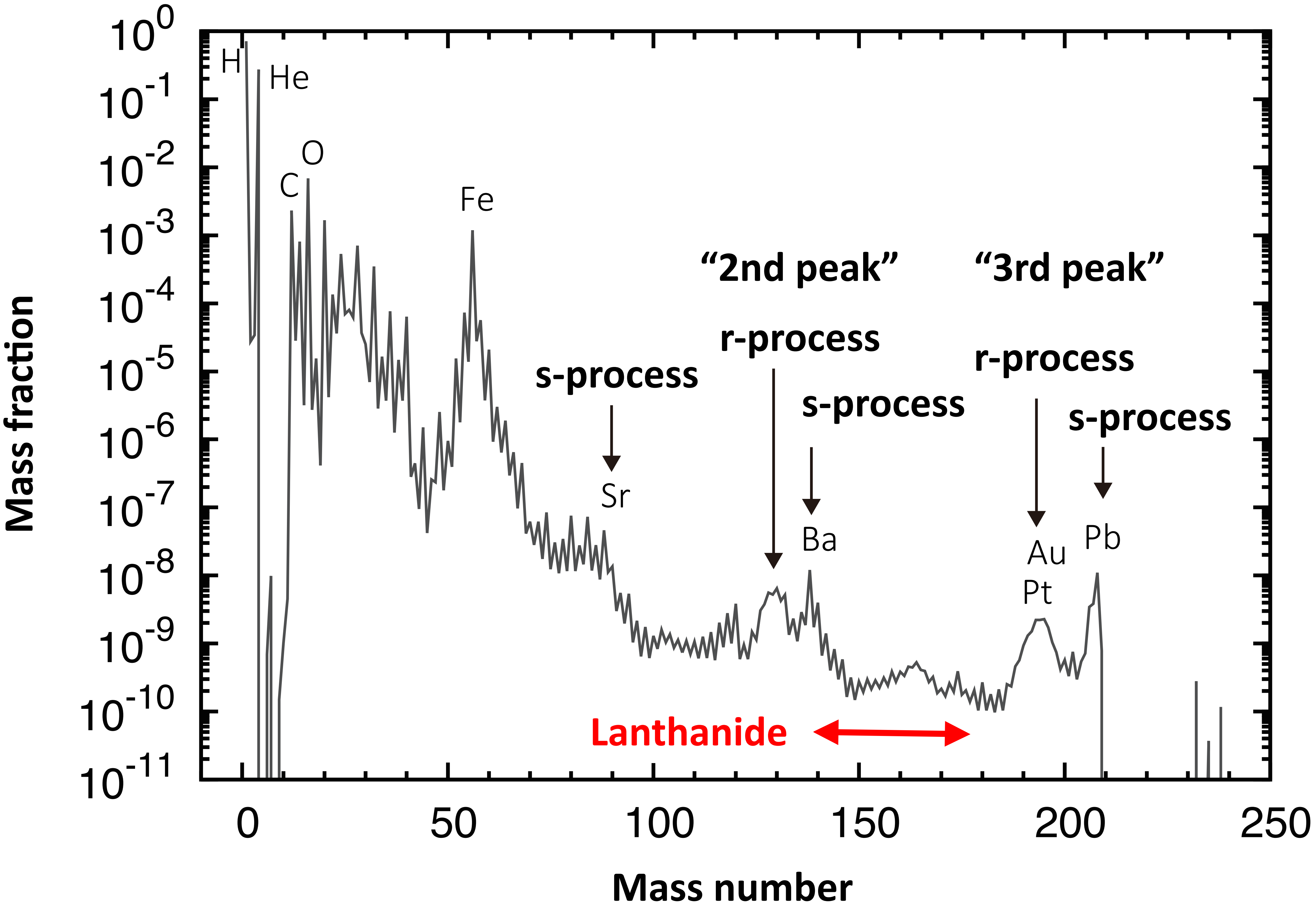
(ex)

Si I: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$ **${}_6C_2$ = 15**

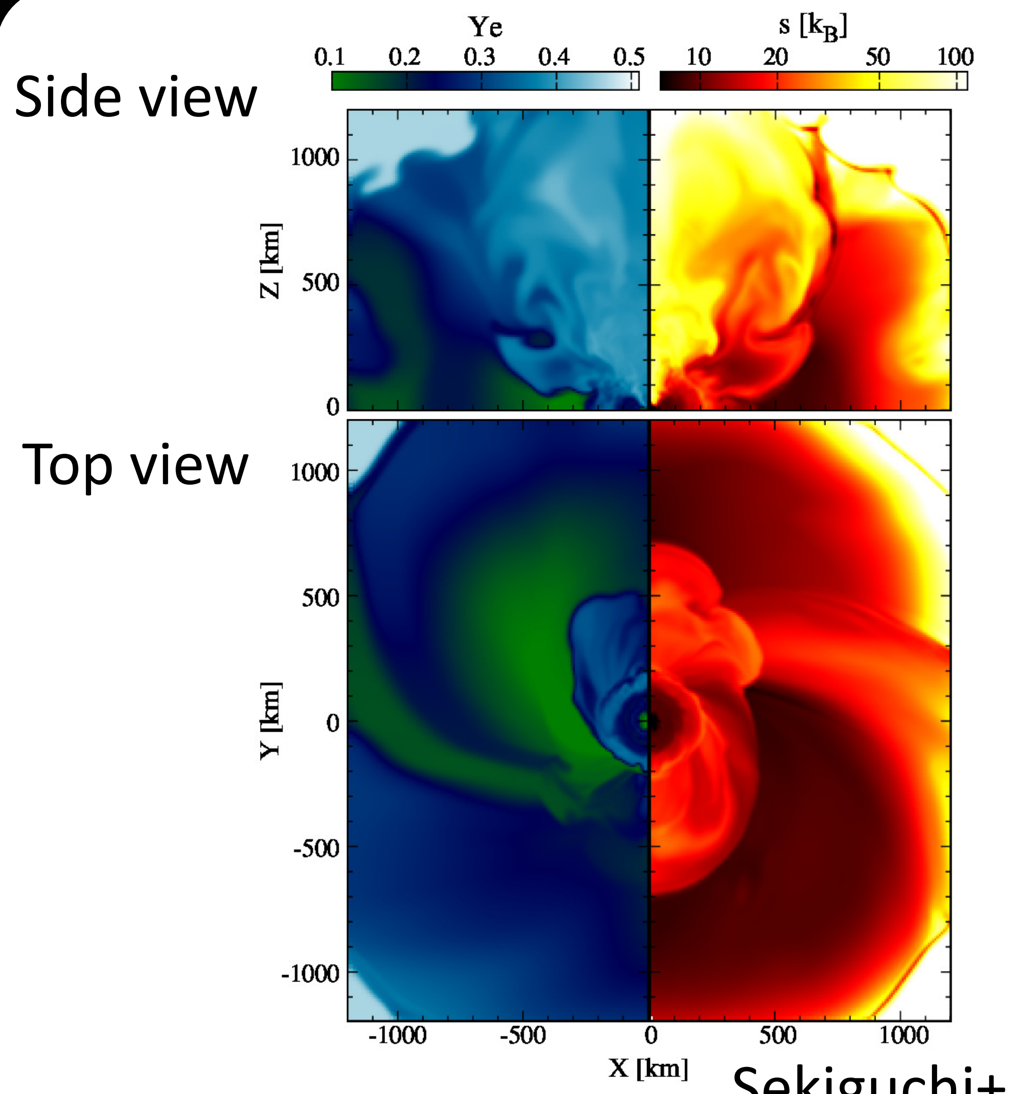
Fe I: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^6$ **${}_{10}C_6$ = 219**

Nd I: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 4d^{10}\ 5s^2\ 4f^4$ **${}_{14}C_4$ = 1001**

Cosmic abundances

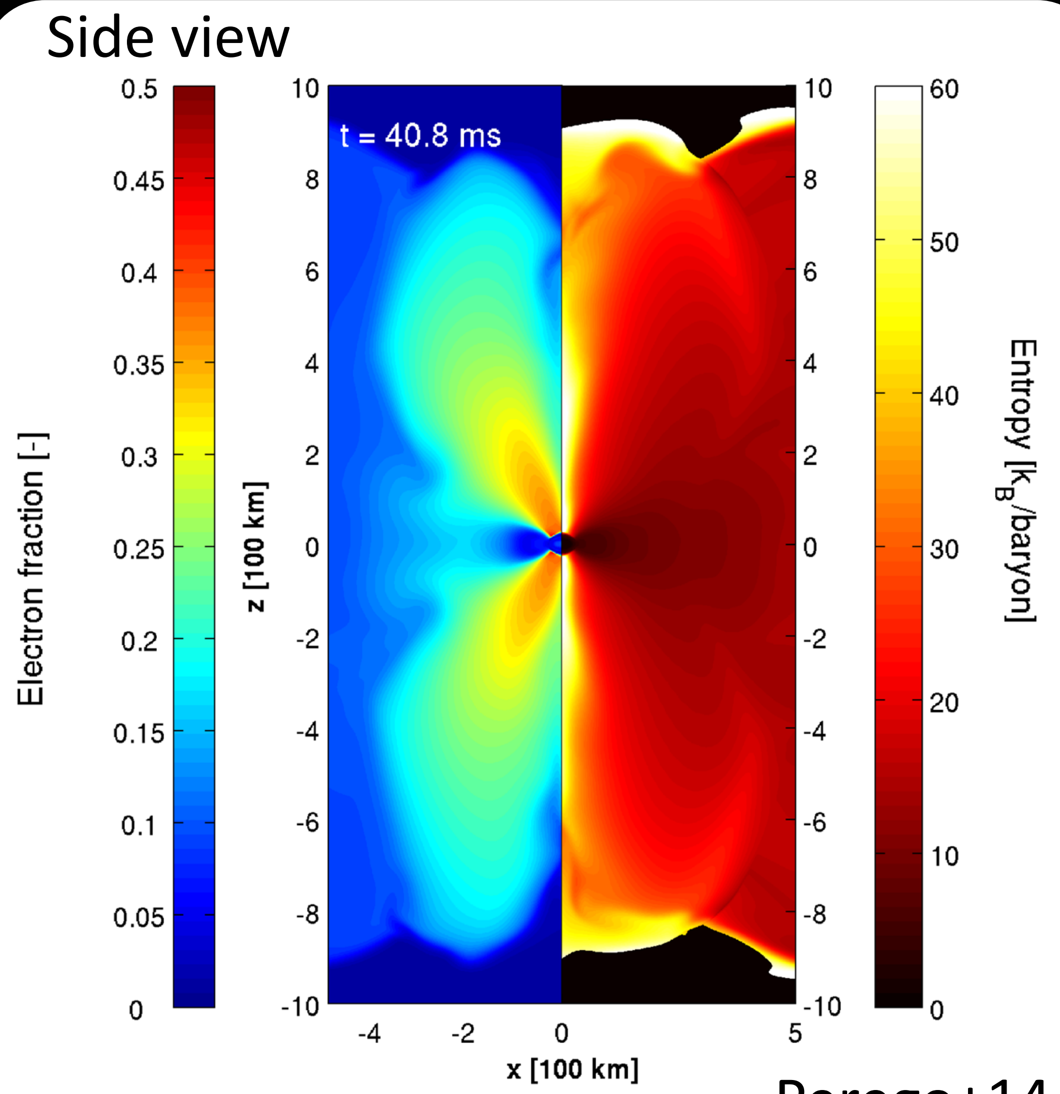


Dynamical ejecta (~< 10 ms)



Sekiguchi+16

Post-merger ejecta (~< 100 ms)



Perego+14

Low Ye (~0.1-0.3)
=> lanthanide-rich
=> high opacity
=> **faint and red kilonova**

High Ye (~ 0.3)
=> lanthanide-poor
=> low opacity
=> **luminous and blue kilonova**

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

Kilonova = Probe of heavy element production

Exercise: solve the following equations and calculate kilonova light curve

Parameters: Mej, vej, κ(opt)

Initial condition: $E_{\rm int} = 0$ at t ~ 0.01 days

$$\frac{dE_{\rm int}(t)}{dt} = -\underbrace{L_{\rm KN}(t)}_{\text{Outgoing luminosity}} - \frac{E_{\rm int}(t)}{\underbrace{t_{\rm dyn}}_{\text{Adiabatic loss}}} + \underbrace{f_{\rm dep}(t)}_{\sim 0.5}\underbrace{L_{\rm decay}(t)}_{\text{Deposited luminosity}}$$

$$L_{\rm SN} \simeq \frac{E_{\rm int}}{t_{\rm esc}} \longleftarrow t_{\rm esc} = \tau\frac{R_{\rm ej}}{c} = \frac{3\kappa M_{\rm ej}}{4\pi c R_{\rm ej}} = \frac{3\kappa M_{\rm ej}}{4\pi c v_{\rm ej} t}$$

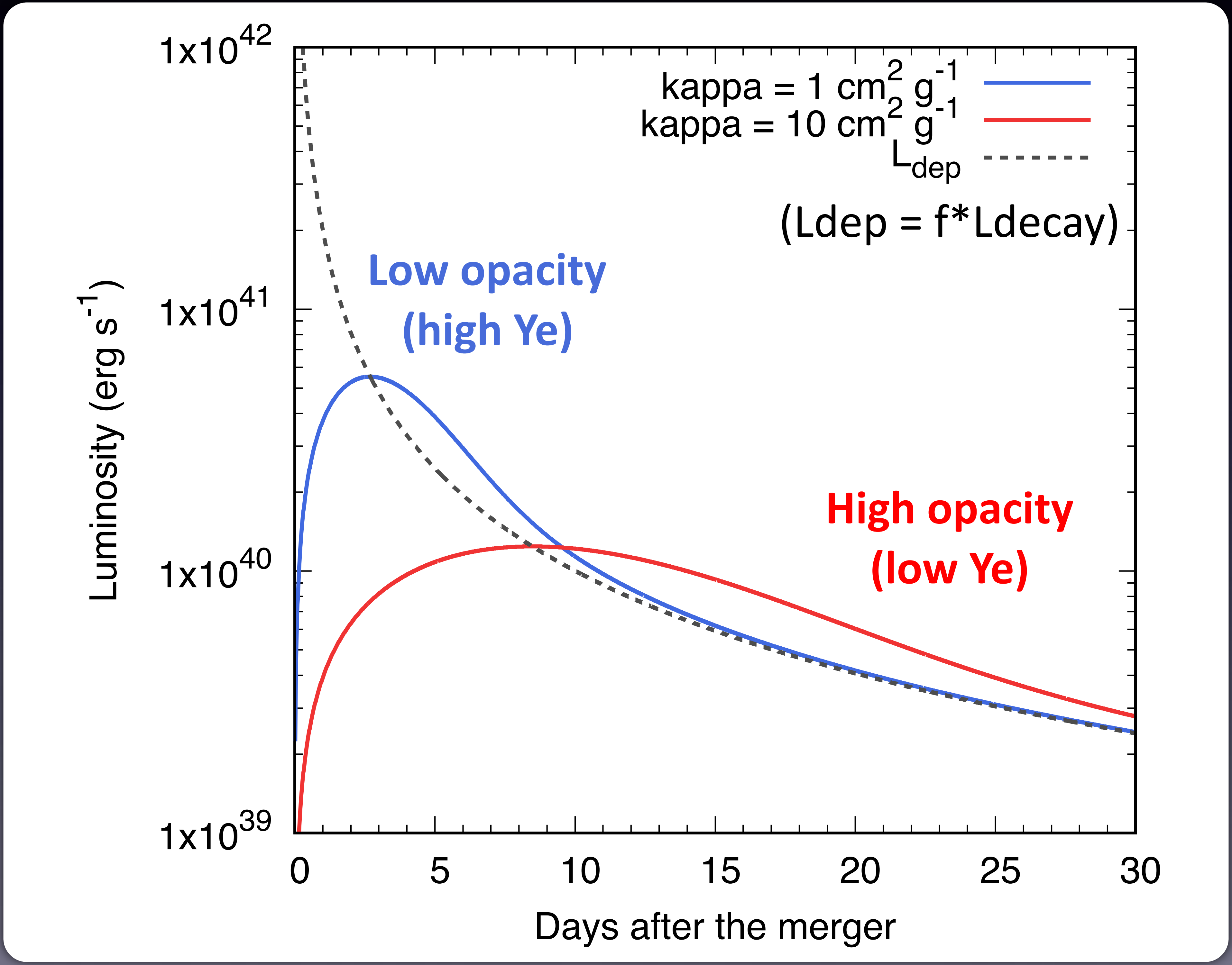
$$t_{\rm dyn} = R_{\rm ej}/v \longleftarrow R_{\rm ej} = \underbrace{R_0}_{\text{initial radius} \sim 0} + v_{\rm ej} t$$

$$L_{\rm decay} = M_{\rm ej}\dot{q} \longleftarrow \dot{q} = 2.0 \times 10^{10} (t/{\rm day})^{-1.3}\ {\rm erg\ s^{-1}\ g^{-1}}$$

Light curves of kilonova

- One-zone ejecta
- constant opacity

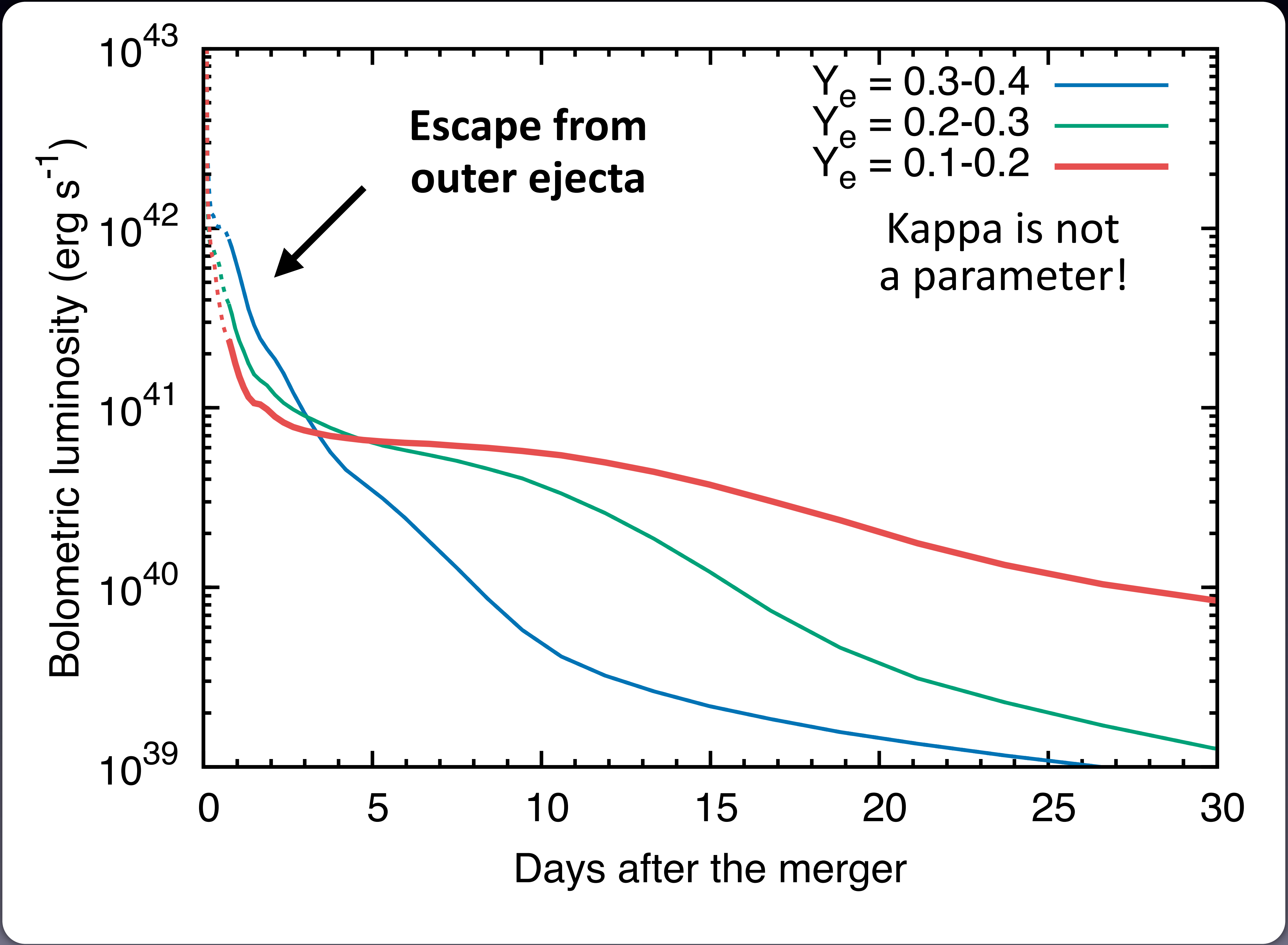
Mej = 0.01 Msun



More realistic calculations

- Ejecta structure
- Opacity from atomic data
- Ye dependent thermalization

Mej = 0.03 Msun



Escape from outer ejecta

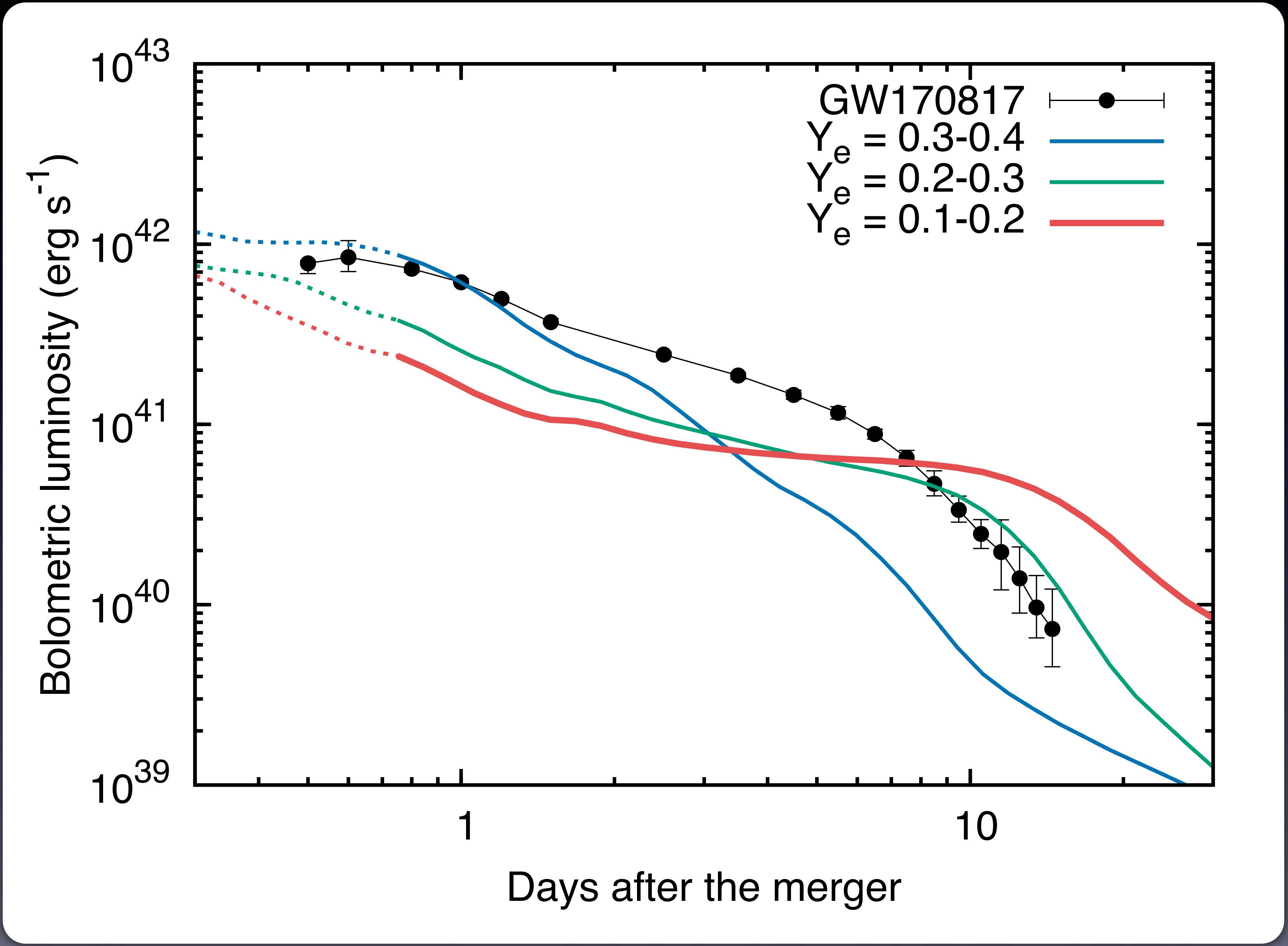
Kappa is not
a parameter!

MT+19

Physics and astrophysics of kilonovae

1. Brief overview
2. Mass ejection and r-process nucleosynthesis
3. Heating of the ejecta
4. Photon transfer => kilonova
5. Comparison with observations
6. Recent topics and future prospects

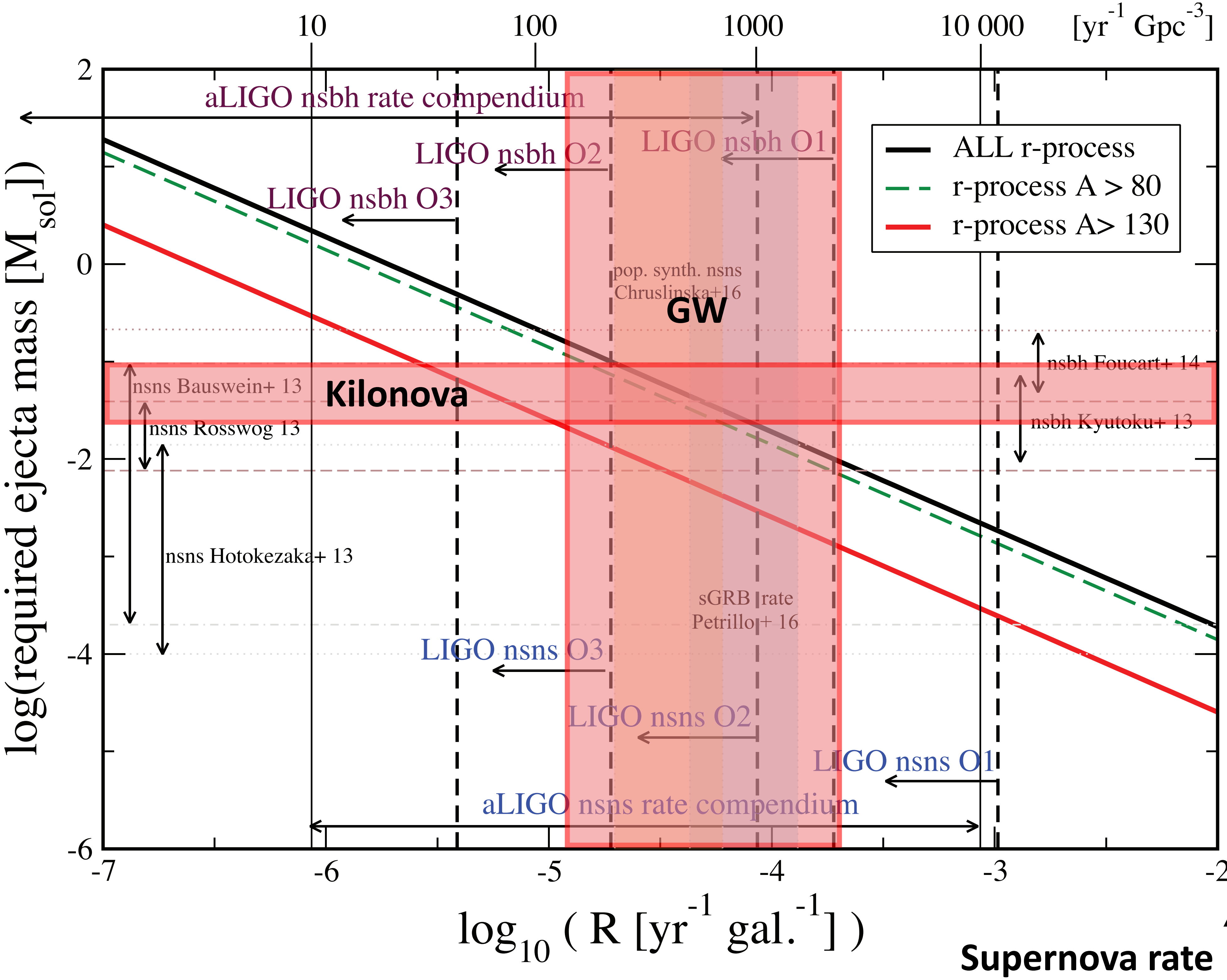
Comparison with GW170817



MT+19

Presence of both luminous/blue and faint/red components
Total ejecta mass ~0.05 Msun

Production rate of heavy elements



Supernova rate

Rosswog+17, Hotokezaka+15, 18

What we have learned from GW170817

- Red kilonova => production of lanthanide elements
- Blue kilonova => production of lighter r-process elements
- Production rate (rate x yield) explains the total abundance

Great achievement in physics!

(relativity, hydrodynamics, nuclear physics, atomic physics, …)

- Gravitational force
- Strong force
- Weak force
- Electromagnetic force

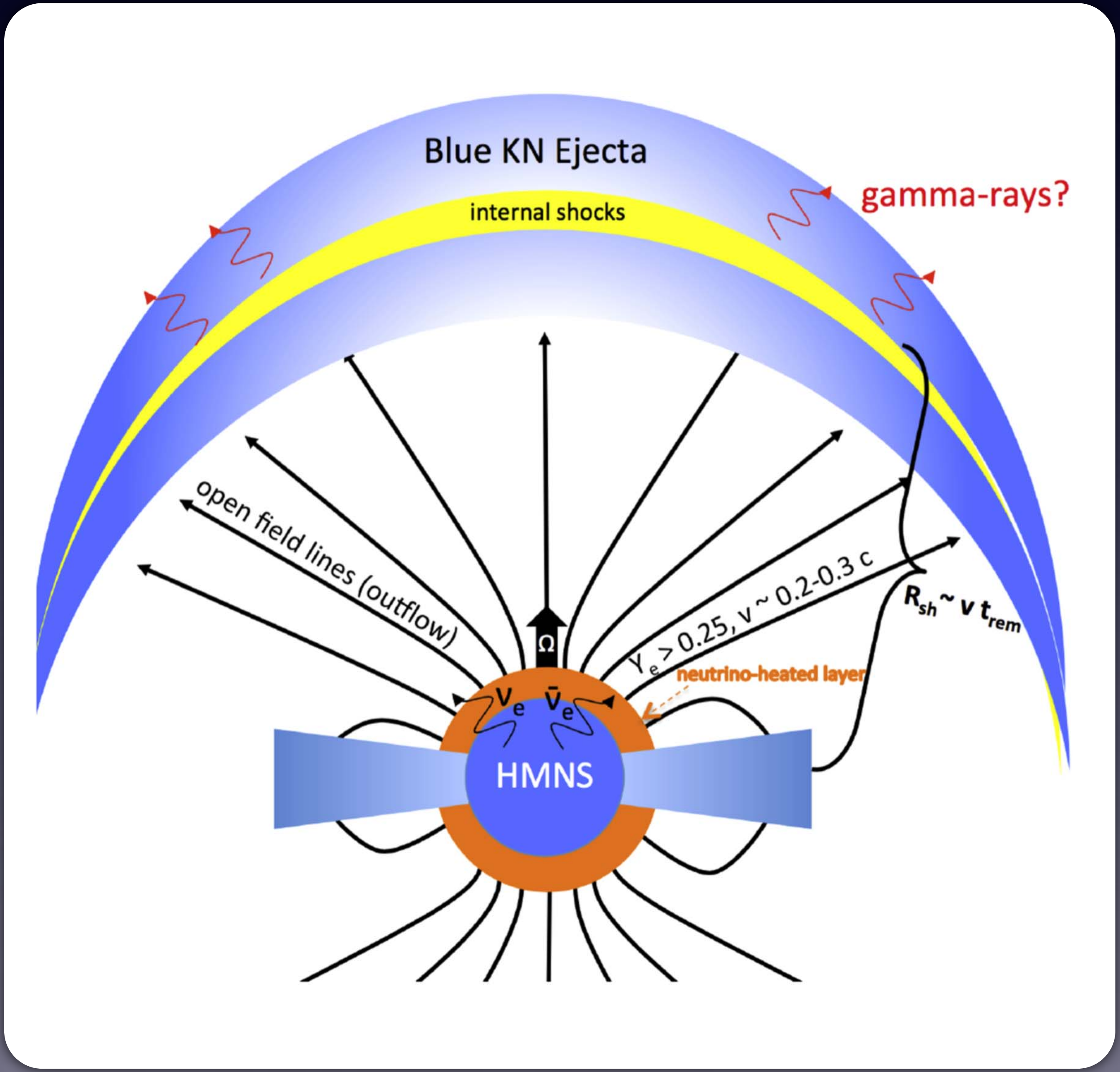
Open issues

- **Physical origin of the ejecta**
  - Blue component <= disk wind ejecta?
  - Red component <= dynamical 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?

★ Presence of magnetar?

Observed blue component

- M ~ 0.03 Msun
- v ~ 0.2 c <= higher than expectation from disk wind (~ 0.05 c)



Metzger+18

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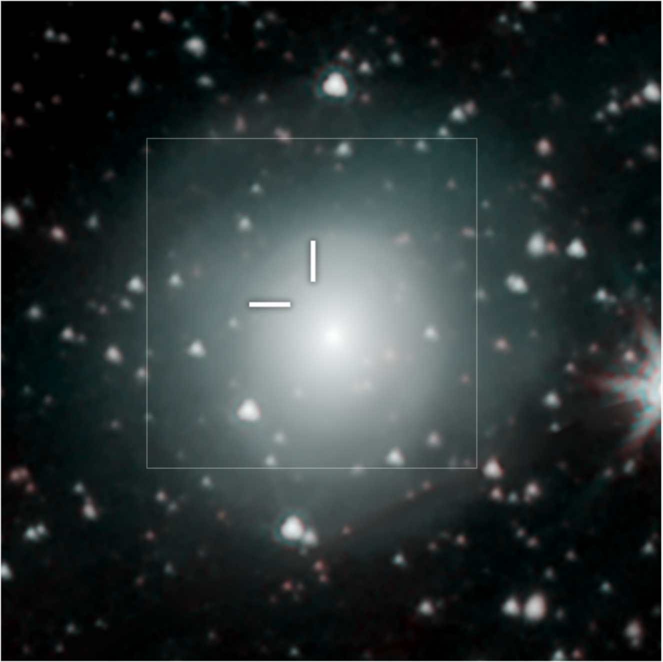
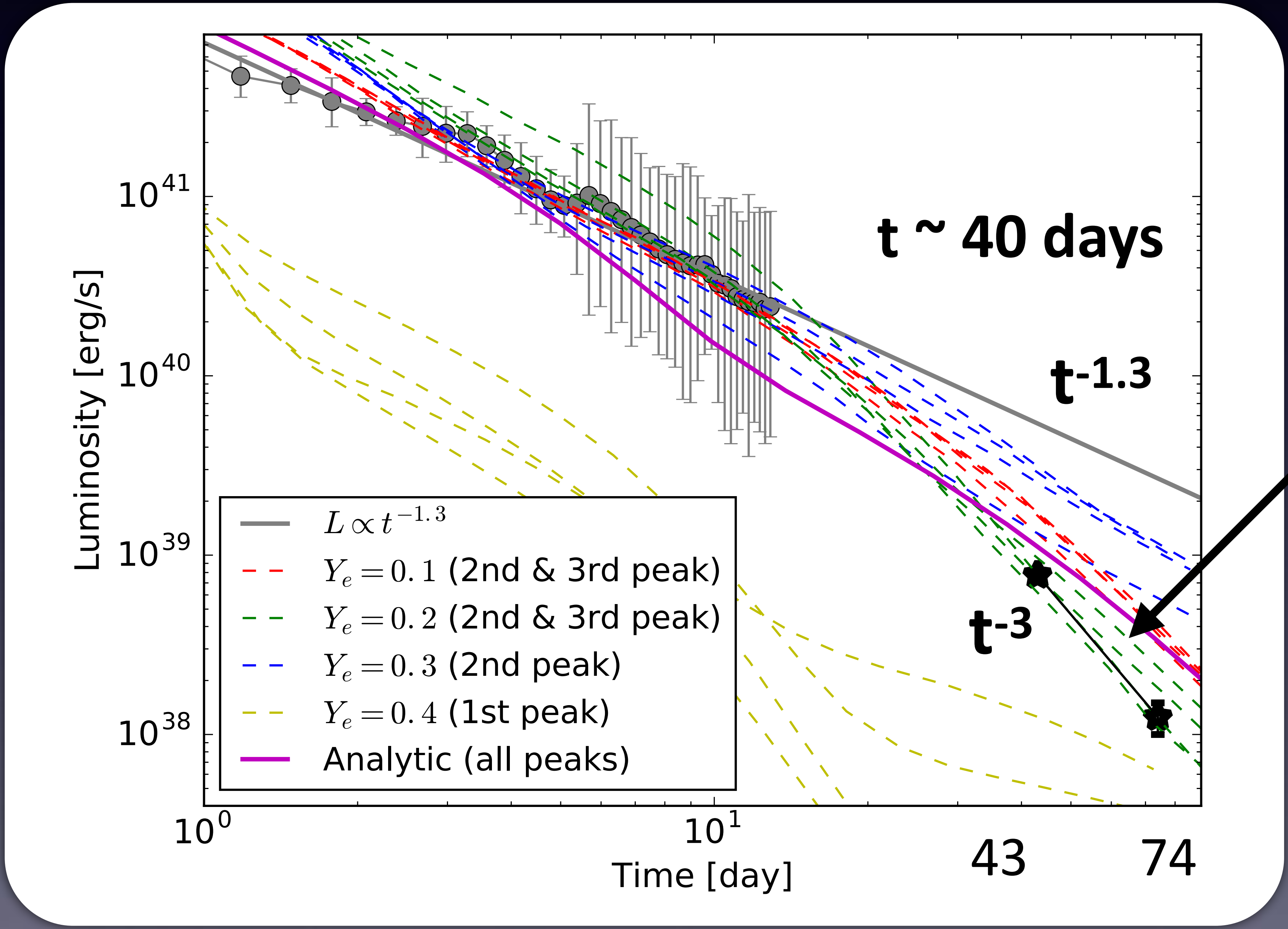
Clues of 3rd peak elements



Late-time observations in mid infrared (4 um)



Dominated by several isotopes in the 3rd peak? (Ye ~ 0.1-0.2)

Kasliwal+18

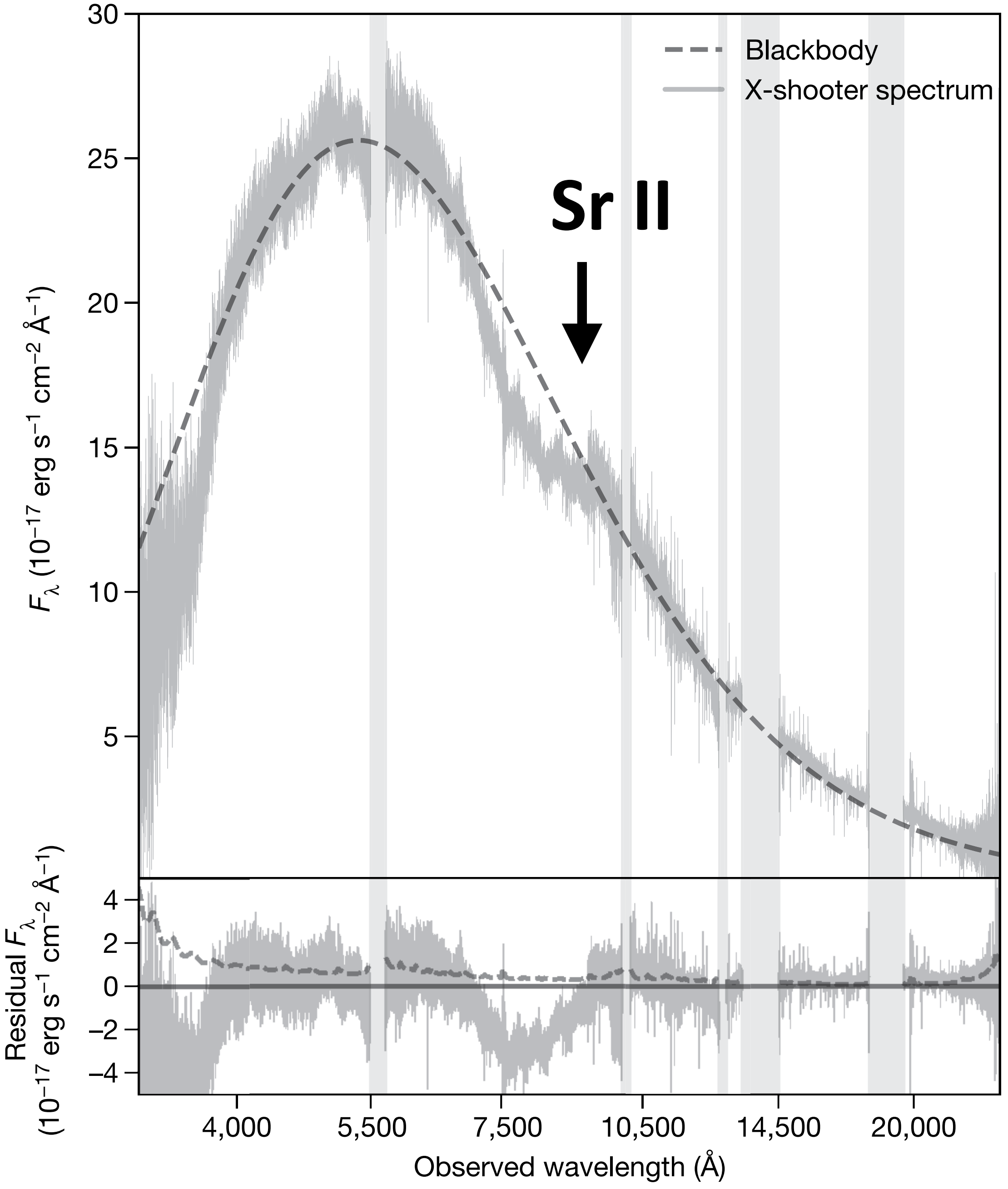
Clues of fission?

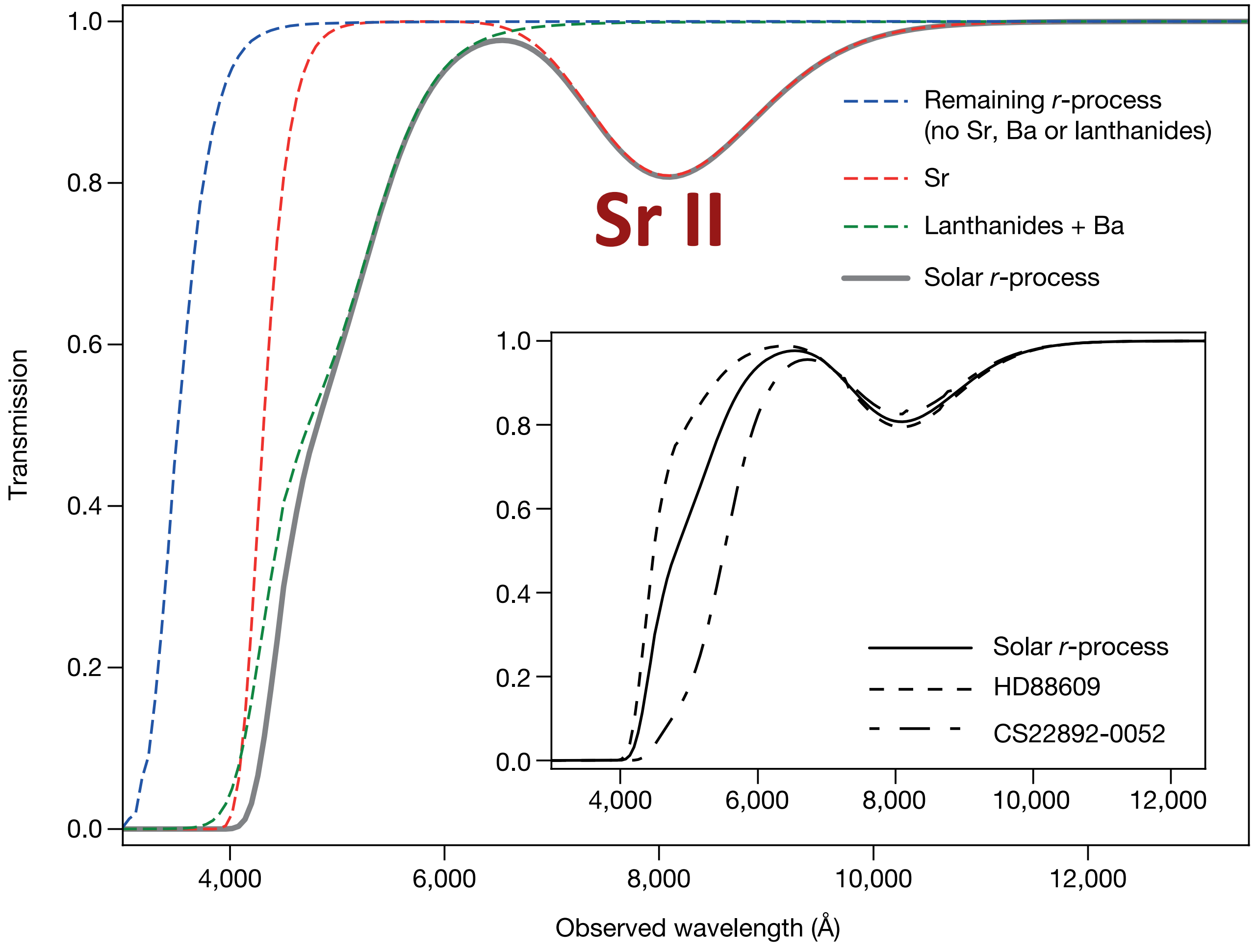
Wu+18, Zhu+18, Eichler+19

Caveats: not total (bolometric) luminosity

Clues of light r-process elements (Sr, Z=38)

Optical spectrum

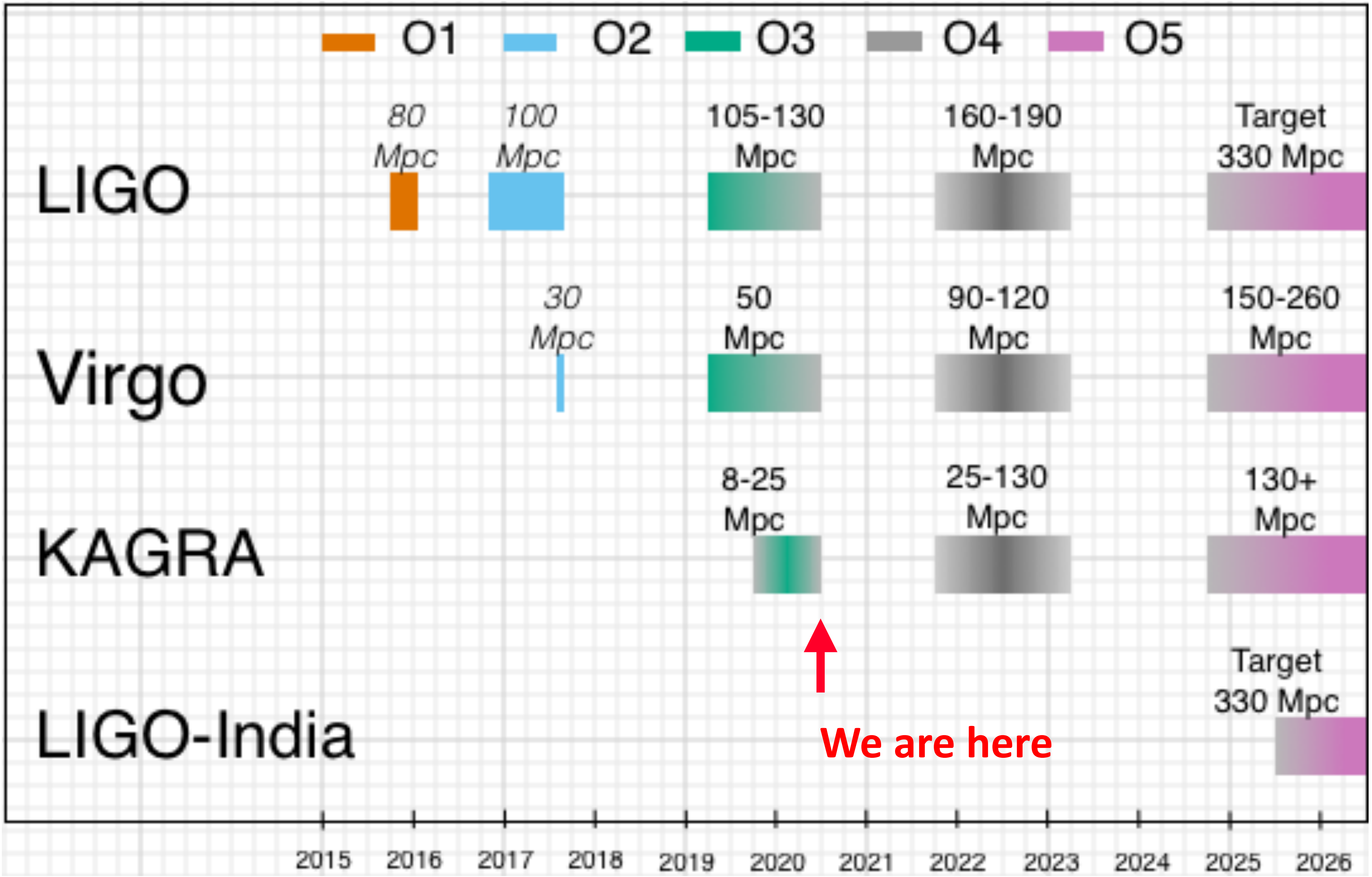




How about other elements?

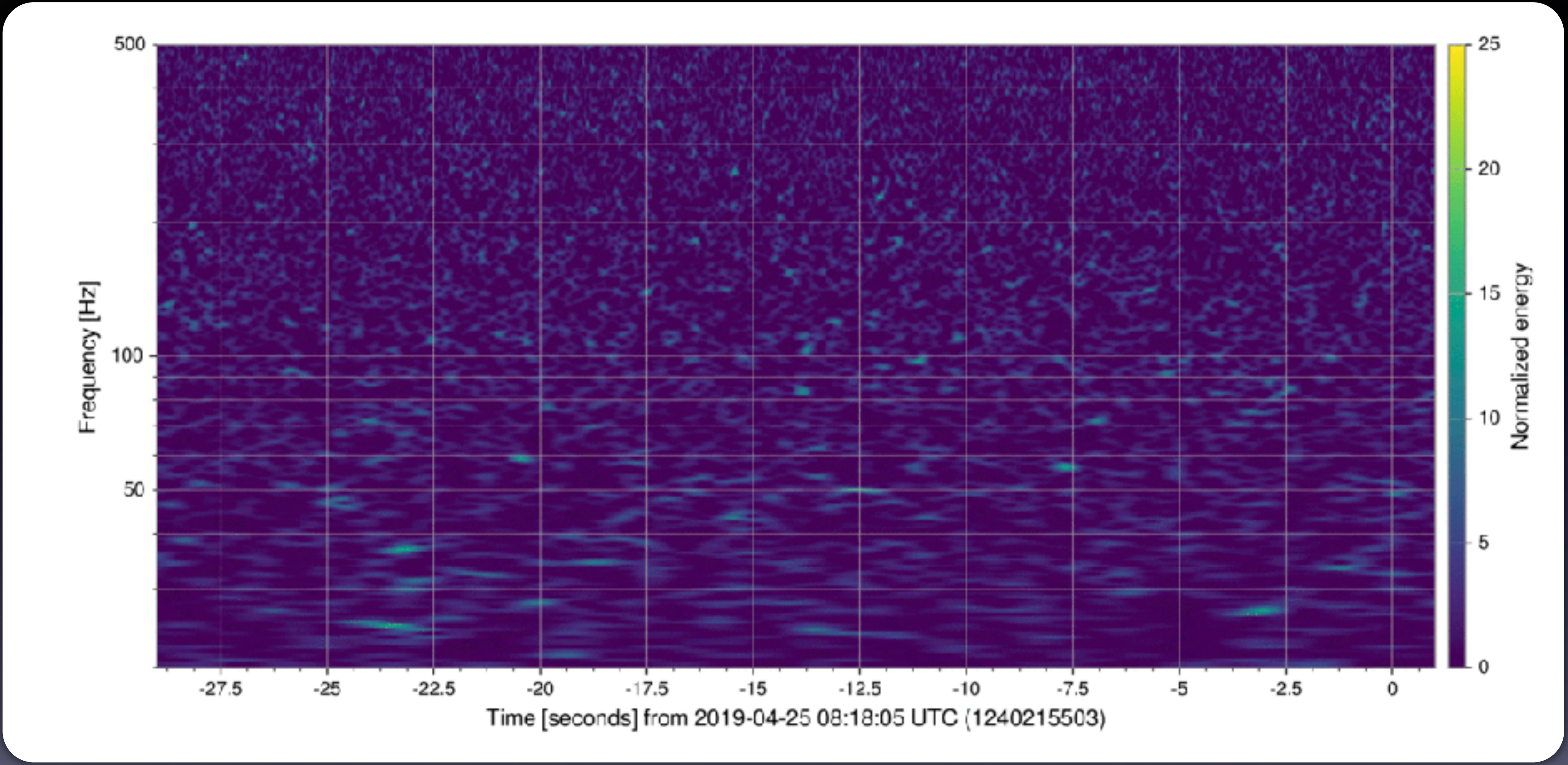
Watson+19

GW observing runs



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

GW190425: 2nd NS-NS merger event



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

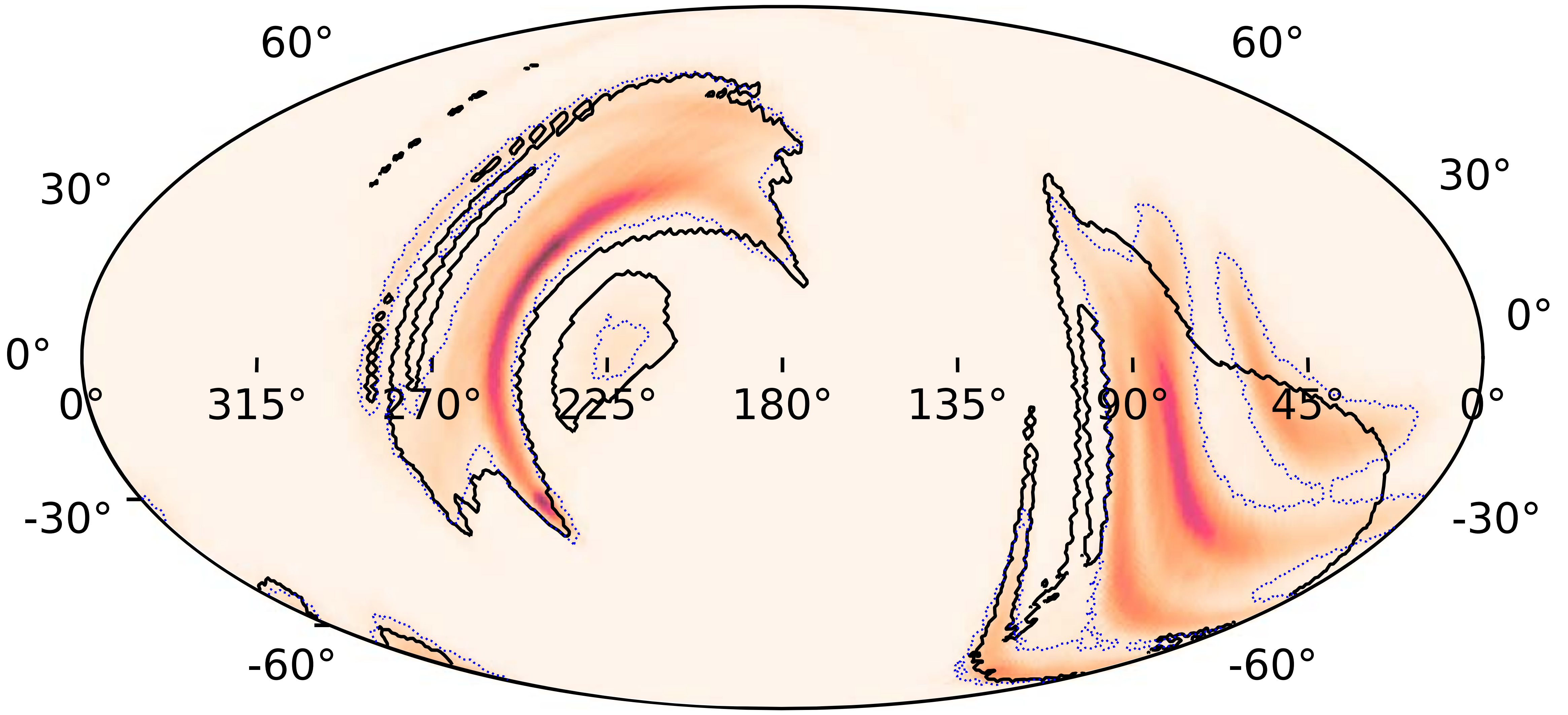
Total mass ~ 3.4 Msun!!

(2.7 Msun for GW170817)

What is the kilonova signal?

Skymap of GW190425

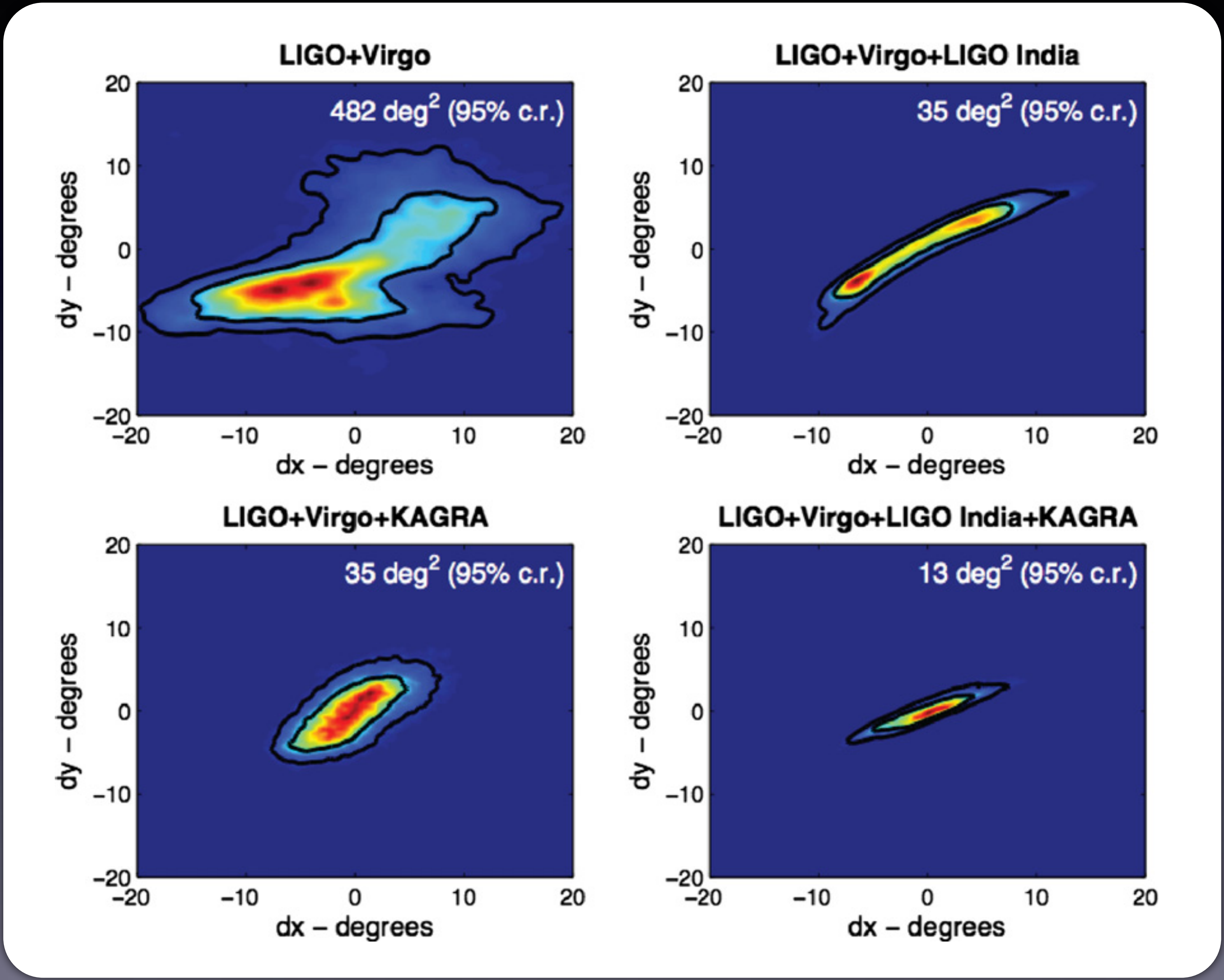
~ 10,000 deg²!! (30 deg² for GW170817)



LVC 2020

No convincing counterpart was identified…

Improving localization with KAGRA and LIGO India



Nissanke+13

Summary

- **Kilonova**
  - Thermal emission powered by r-process decay
  - Probe of heavy element production
- **Observations of GW170817**
  - Kilonova is confirmed (both blue and red components)
  - Production of lanthanide and lighter elements
  - Production rate fulfills the necessary condition
- **Future**
  - Identification of elements or abundance pattern
  - Understanding the variety (production rate)
  - More events with better localization!

Questions to be answered in this lecture

- What is kilonova?
- Why does NS merger produce emission?
- What determines the properties of kilonova?
- Why is it related to the origin of elements?
- What did we learn from kilonova?
- What can we learn in the future?
- …