Radiation from supernovae and neutron star mergers

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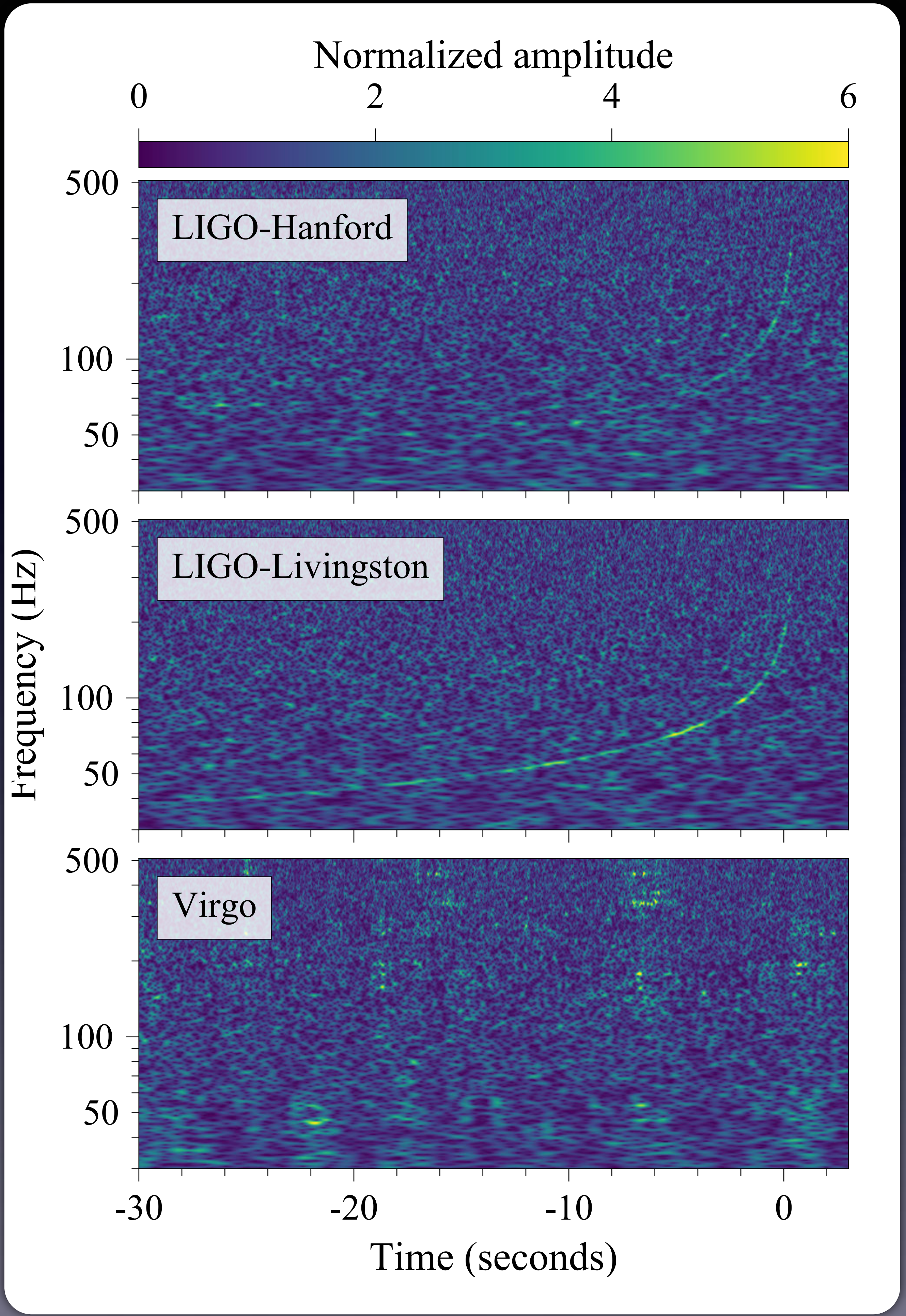
Goals of this lecture

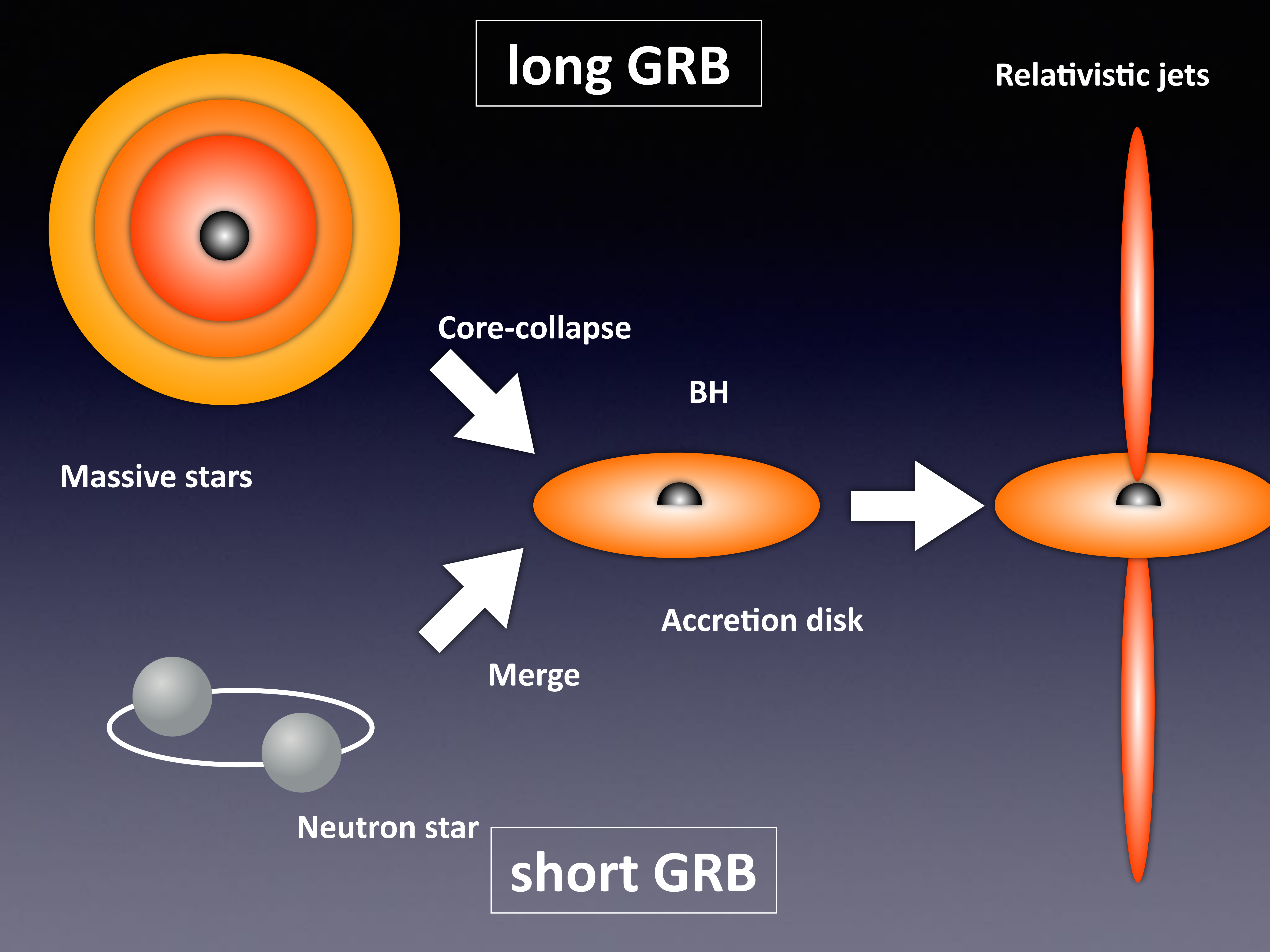
- Why do supernovae (SNe) emit huge luminosity?
- Why does emission from SNe evolve with time?
- What can we learn from observations of SNe?

- Why do NS mergers emit electromagnetic emission?
- What can we learn from observations of NS merger?

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



LIGO Scientific Collaboration
and Virgo Collaboration, 2017, PRL



long GRB
Relativistic jets
Core-collapse
BH
Massive stars
Accretion disk
Merge
Neutron star
short GRB

Summary: explosive transients

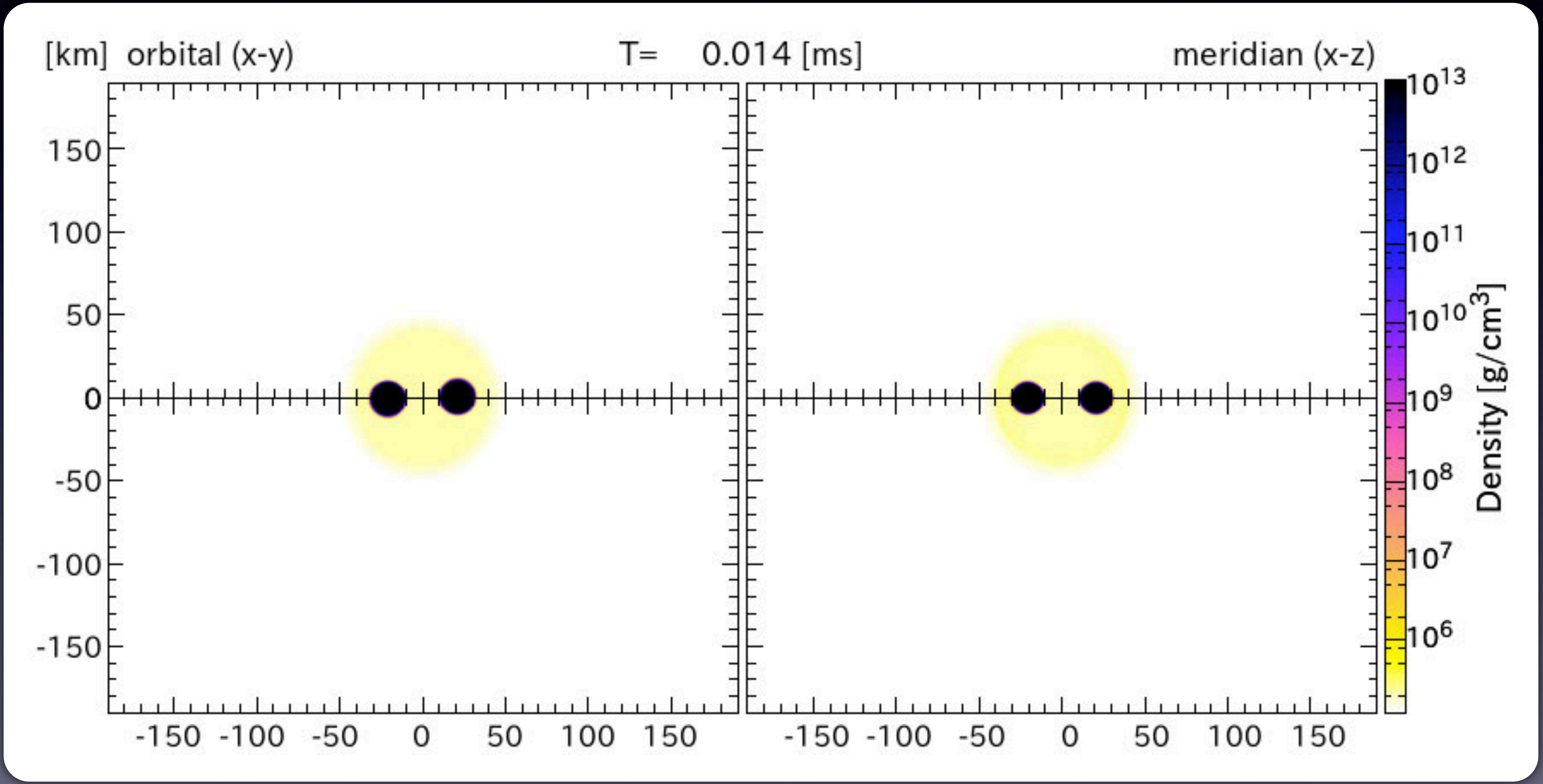
	Spectrum	Galaxy	Progenitor	Ejecta mass	Kinetic energy
Type Ia	No H	Elliptical Spiral	White dwarfs	~ 1.4 Msun	10^{51} erg
Type II	H	Spiral	Massive stars	~10 Msun	10^{51} erg
Type Ib/Ic	No H/He	Spiral	Massive stars	~3-5 Msun	10^{51} erg
Long GRBs	Type Ic Broad line	Spiral	Massive stars (rotating?)	~10 Msun	10^{52} erg
Short GRBs	??	Elliptical Spiral	Neutron stars?	??	??

Neutron star mergers

1. Neutron star mergers
2. Radiation from neutron star mergers
3. Observations of neutron star mergers

NS merger => mass ejection

Top view **Side view**

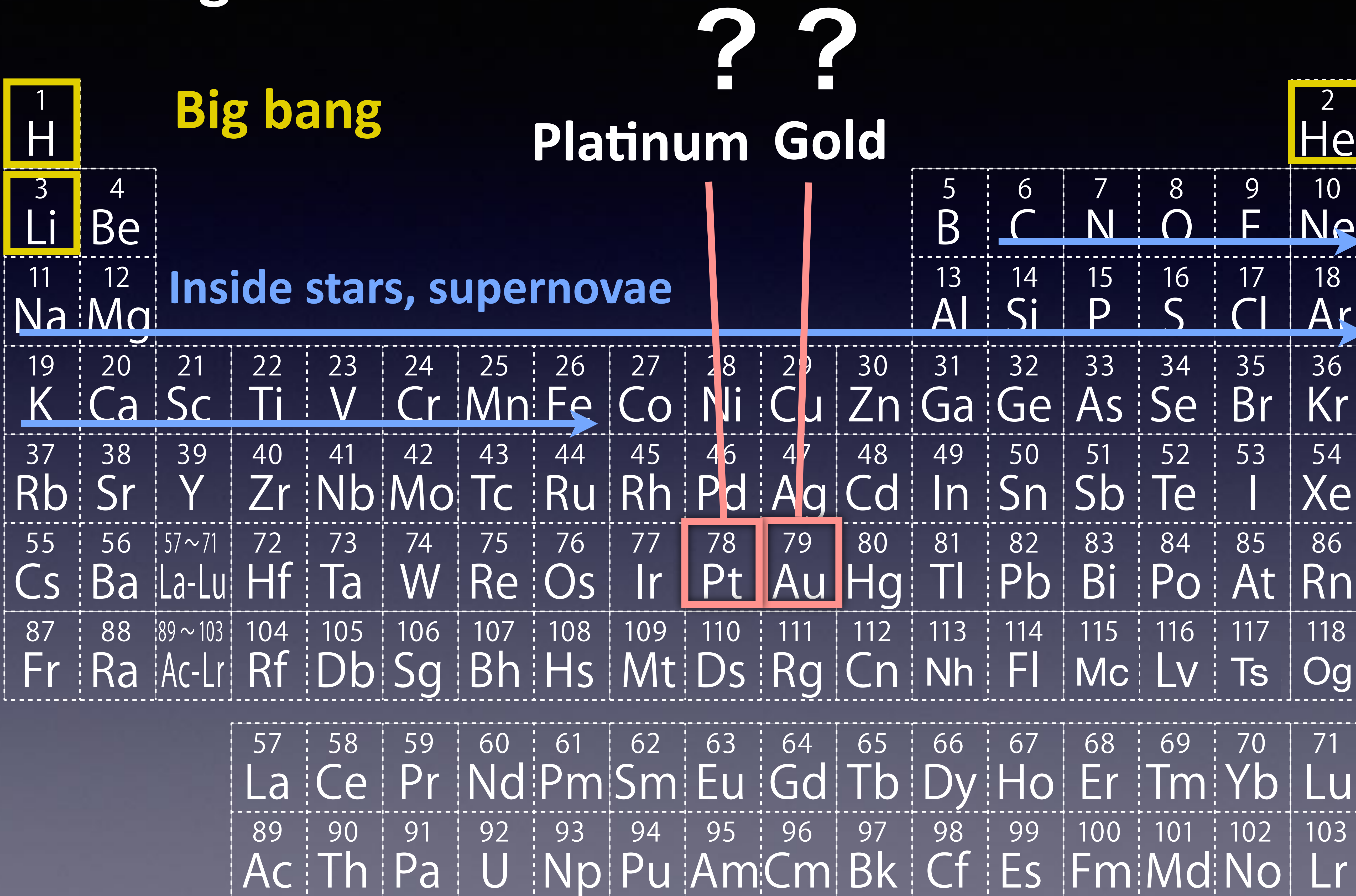


Sekiguchi+15, 16

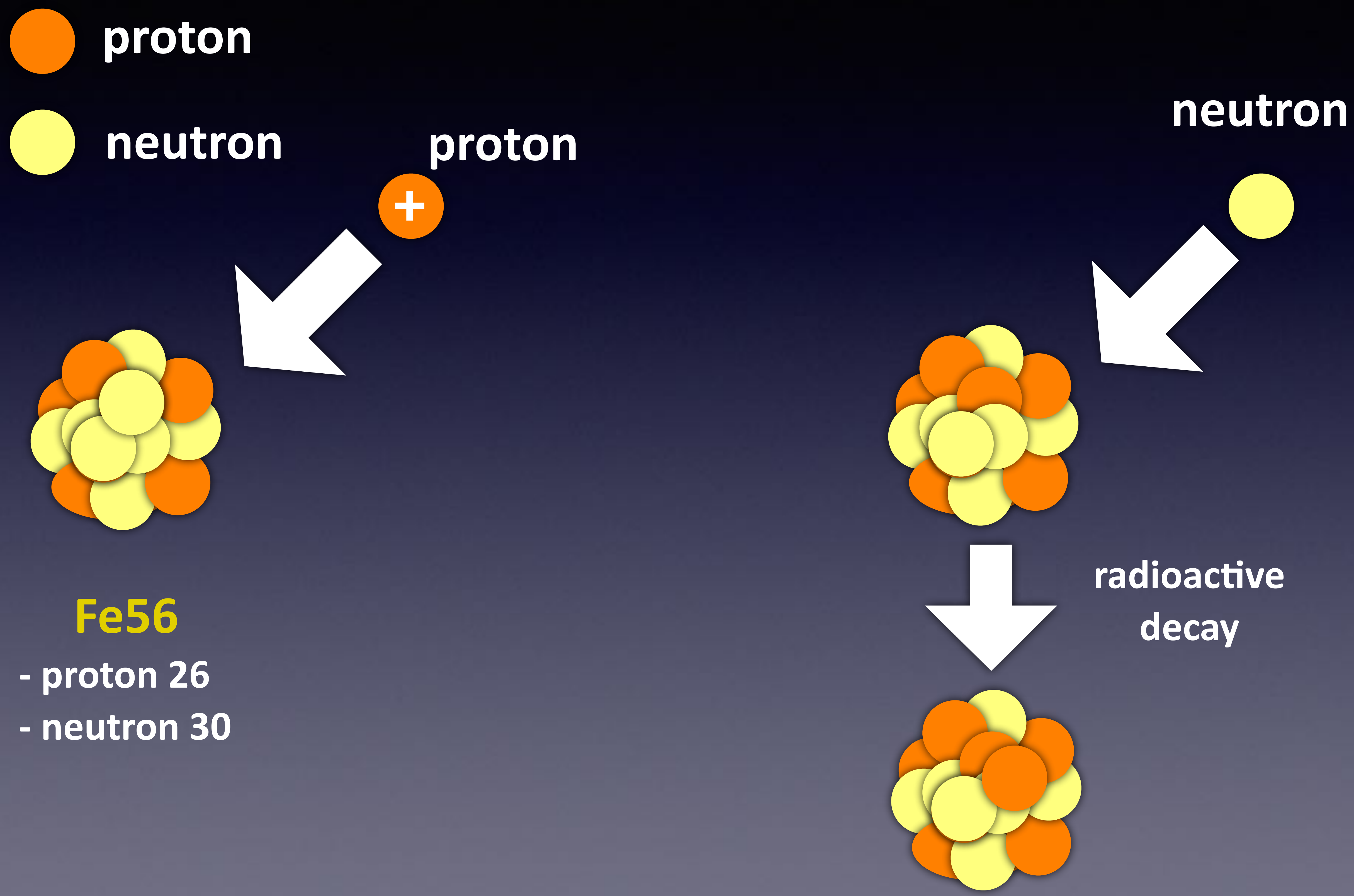
M ~ 10^{-3} - 10^{-2} Msun

v ~ 0.1 - 0.2 c

The origin of elements

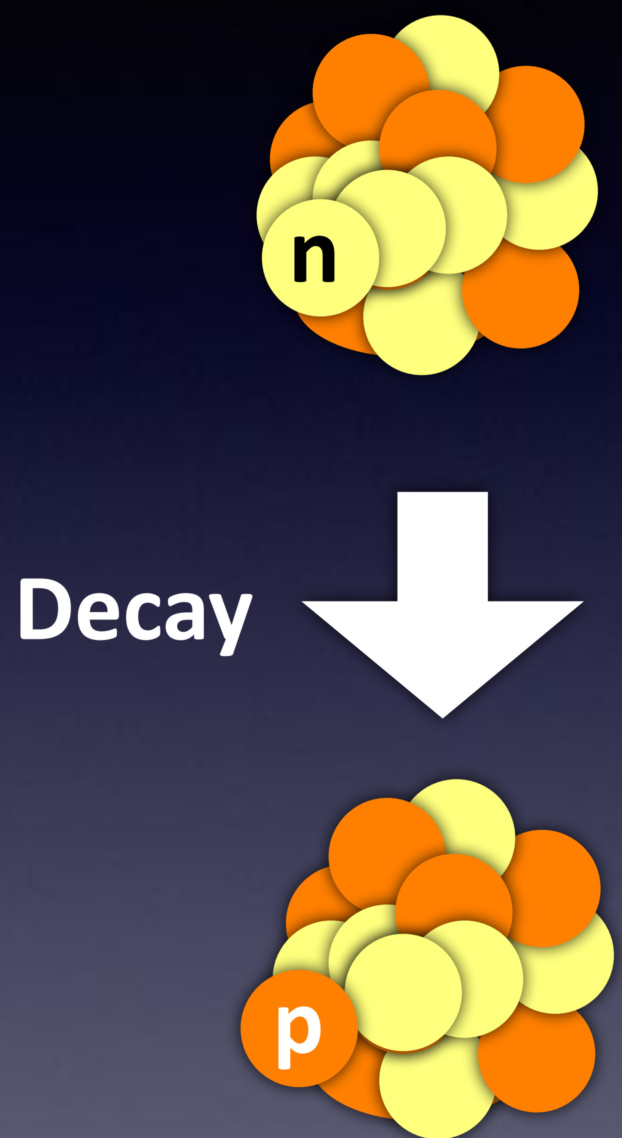


Key player: Neutron



Neutron-capture nucleosynthesis

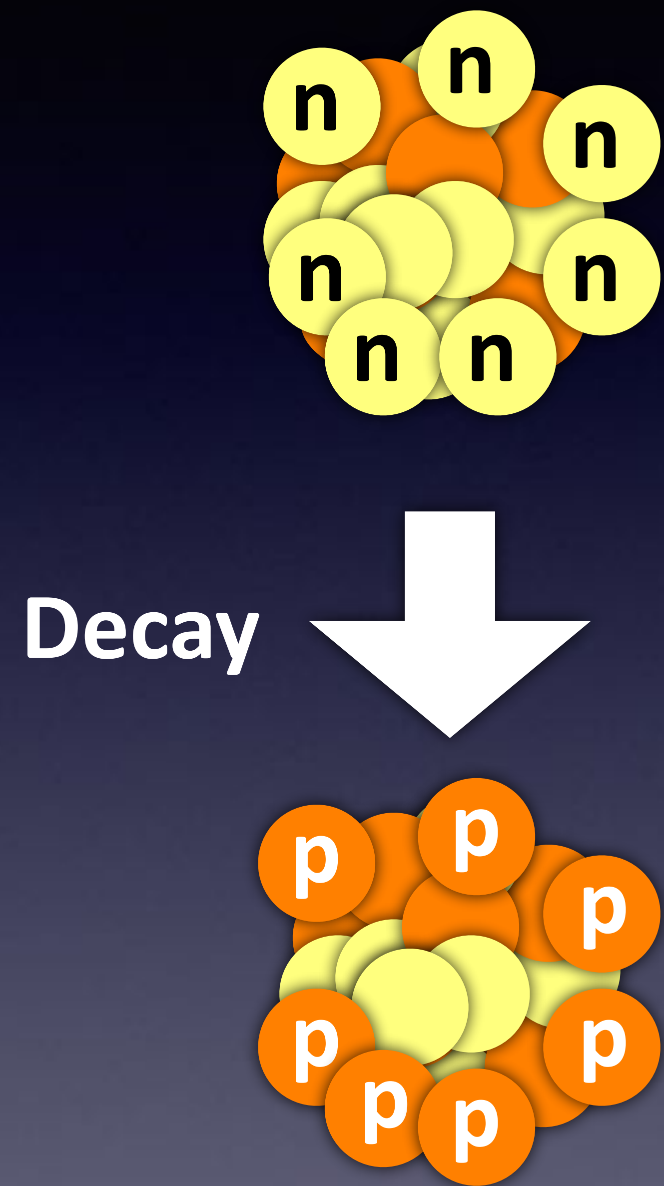
s (slow)-process



Ba, Pb, …

Inside of stars

r (rapid)-process

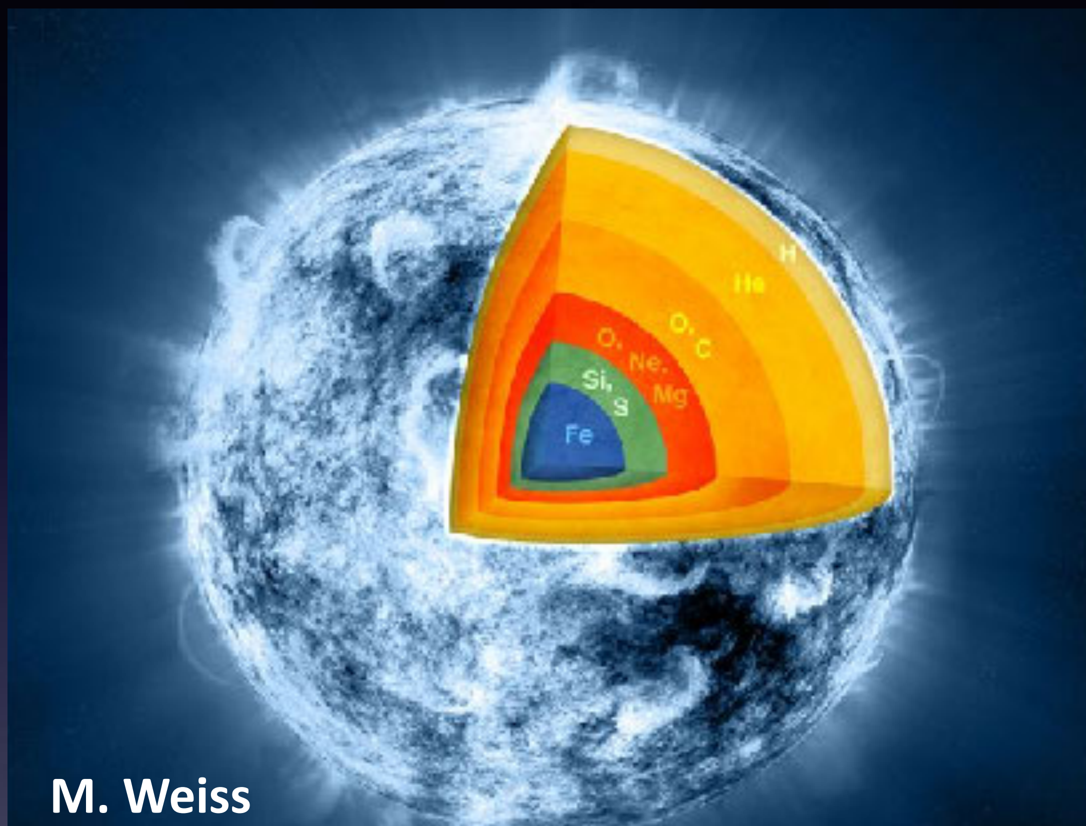


Au, Pt, U, …

??

Explosive phenomena near the neutron star

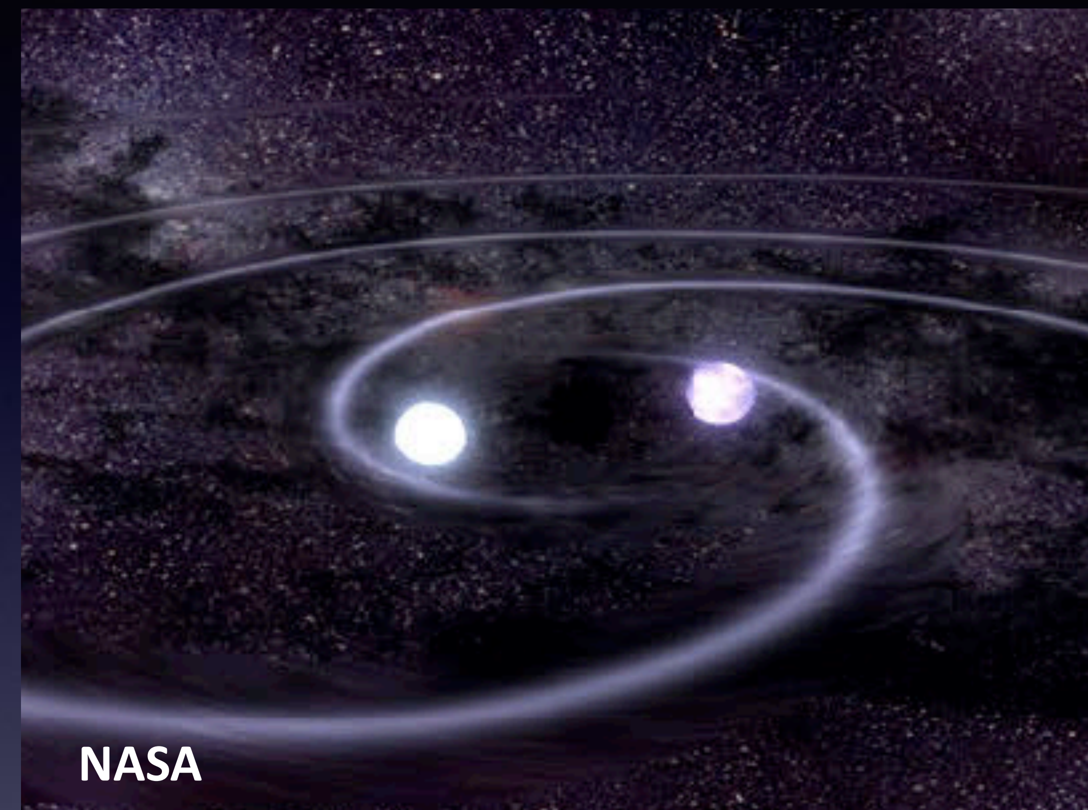
Core-collapse supernova



Moderately neutron rich

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

NS merger



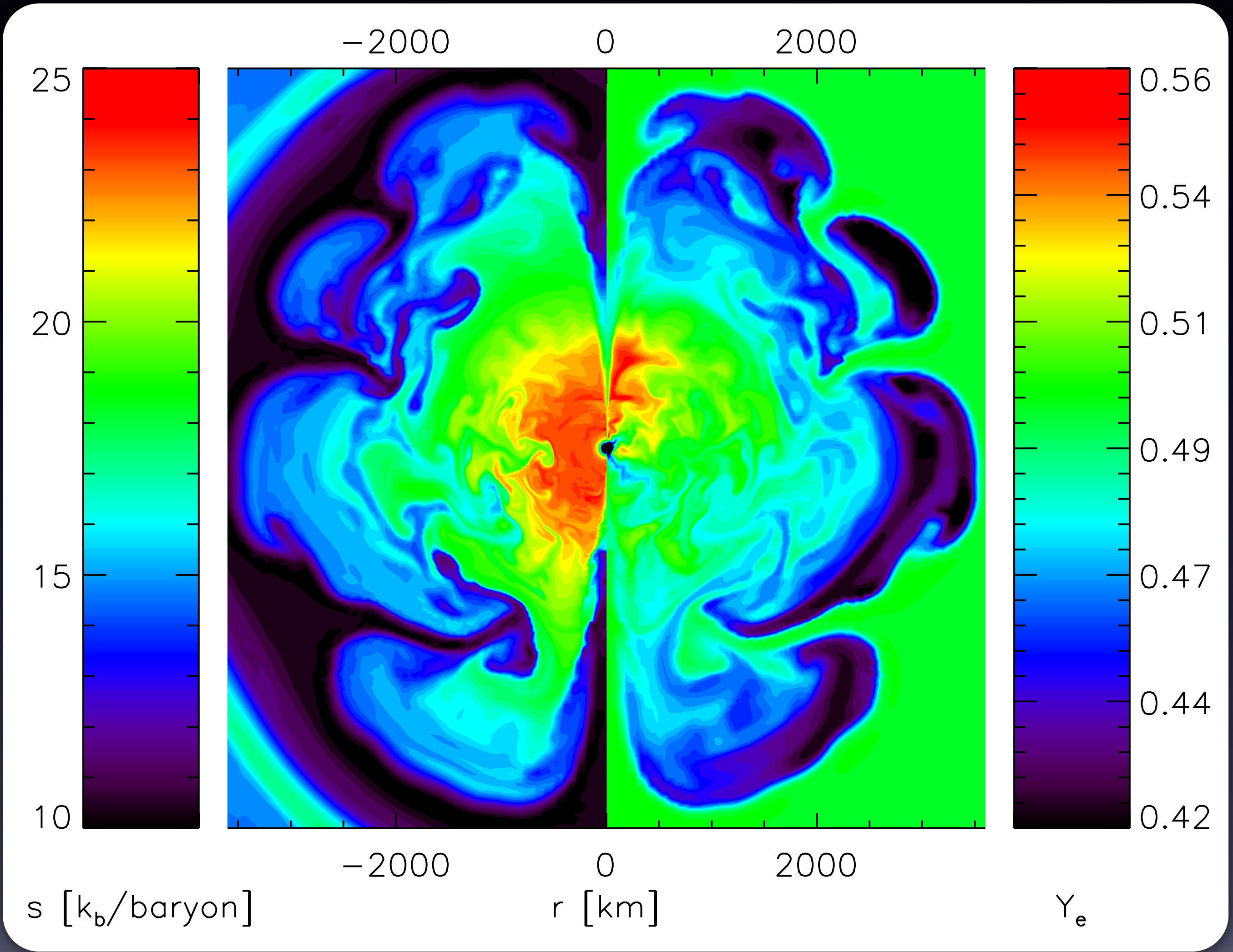
Very neutron rich

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

Core-collapse supernovae



Wanajo+11, Wanajo 14

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

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

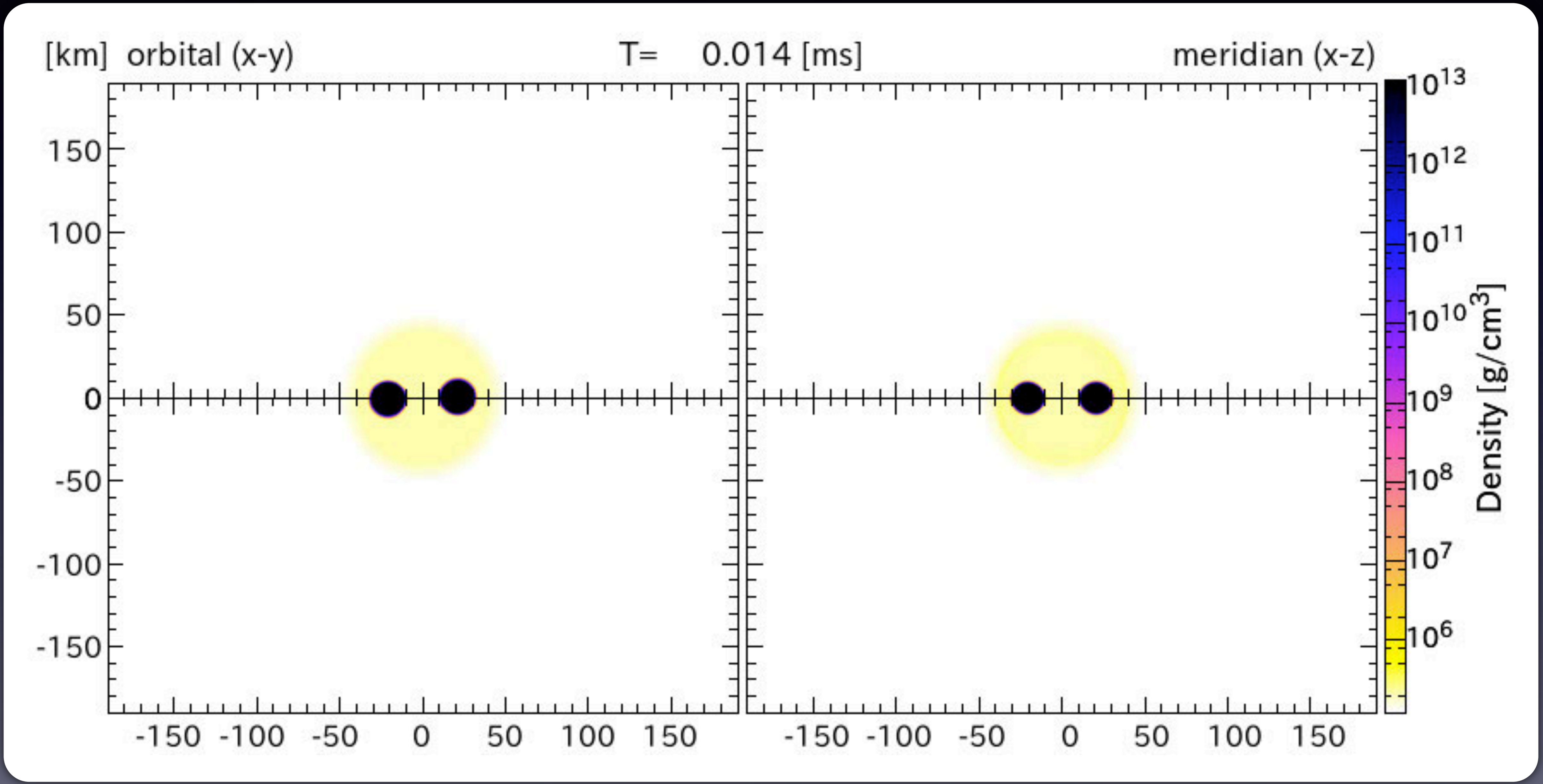
$$\epsilon_{\bar{\nu}_e} > \epsilon_{\nu_e}$$

Probably neutron rich but only moderately

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

Neutron star merger

Top view **Side view**



Sekiguchi+15, 16

Very neutron rich (Composition of neutron star

Ye ~ 0.10 (n_n ~ 9 n_p)

Conditions for r-process

High n/seed ratio after step

$$A_{\mathrm{final}} = A_{\mathrm{seed}} + \mathrm{n/seed}$$

~200 ~50-100

n/seed ~> 100-150

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

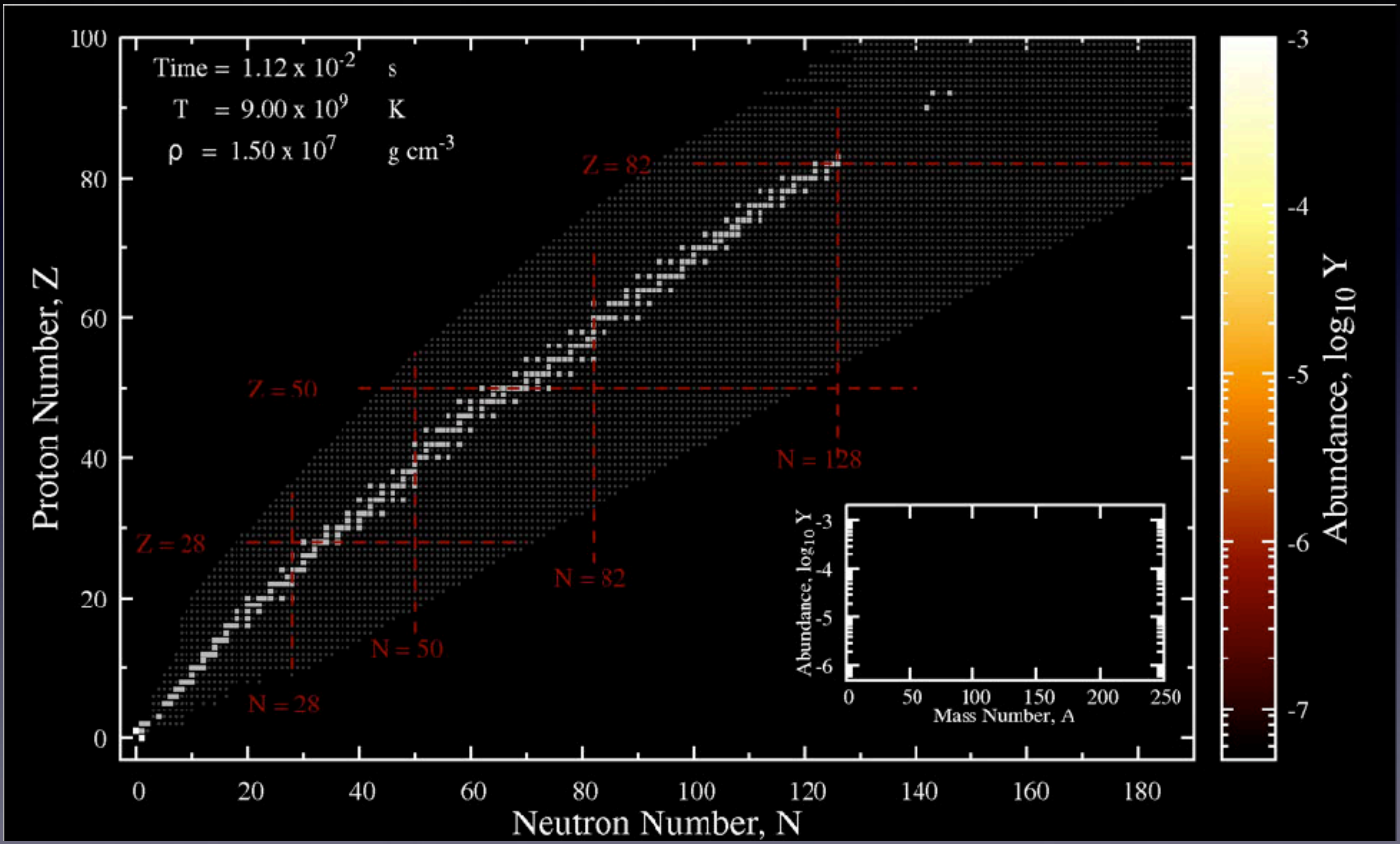
Neutron star merger

(ex) Ye = 0.1 (n_n ~ 9 n_p)

1 seed ^{56}Ni (Z = 28, N = 28) + ~200 free neutron

=> n/seed ~ 200

r-process nucleosynthesis in NS merger



(C) Nobuya Nishimura

Summary: Neutron star 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

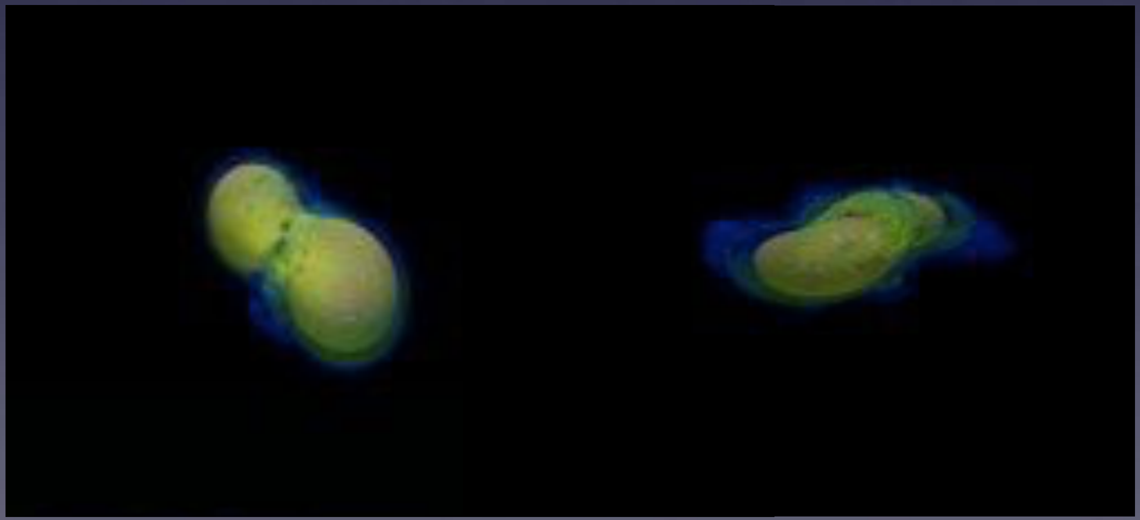
Neutron star mergers

1. Neutron star mergers
2. Radiation from neutron star mergers
3. Observations of neutron star mergers

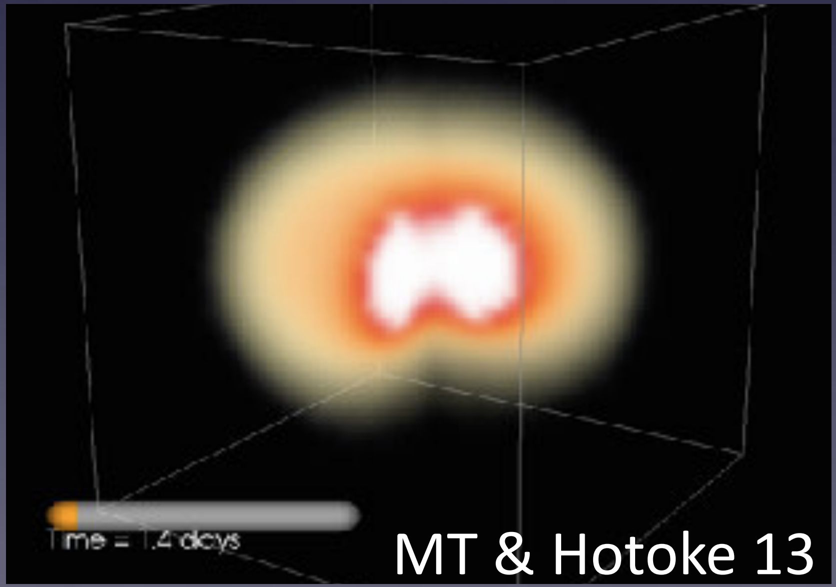
Merger → **neutron-capture (r-process) nucleosynthesis** → **Radioactive decay => kilonova**

Mass ejection

~< 100 ms   < 1 sec   ~> days

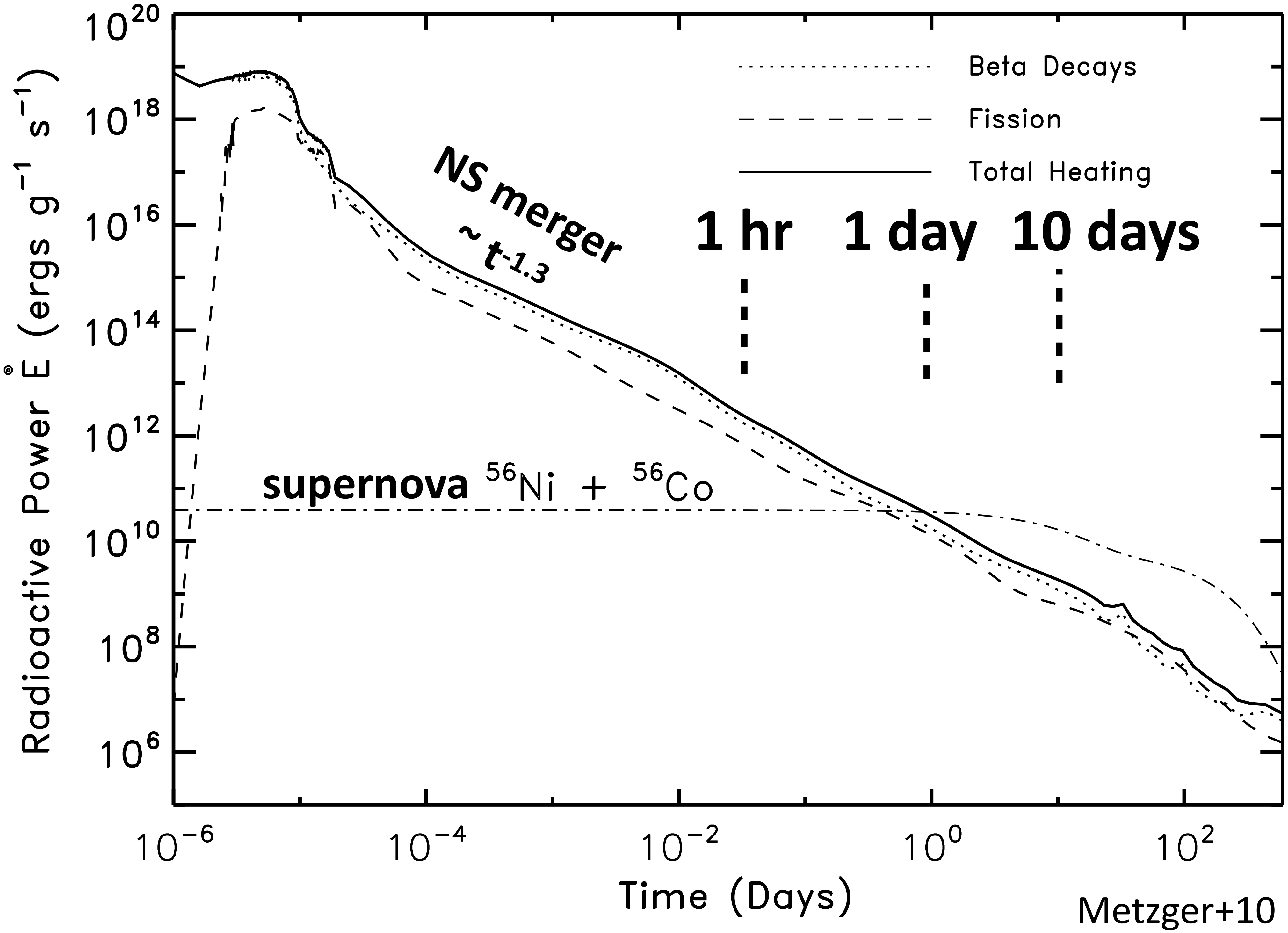


http://www.aei.mpg.de/comp-rel-astro

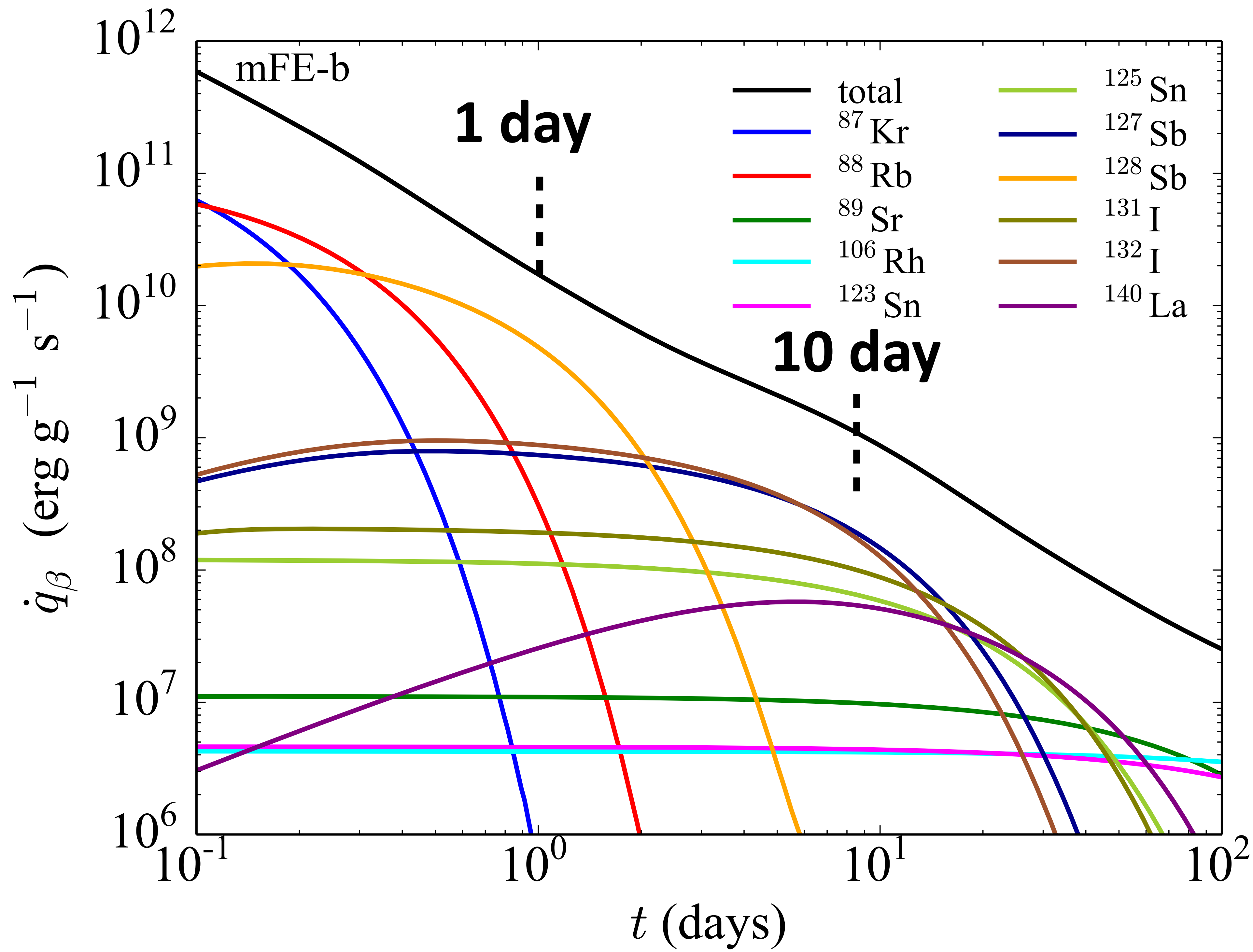


MT & Hotoke 13

Power source



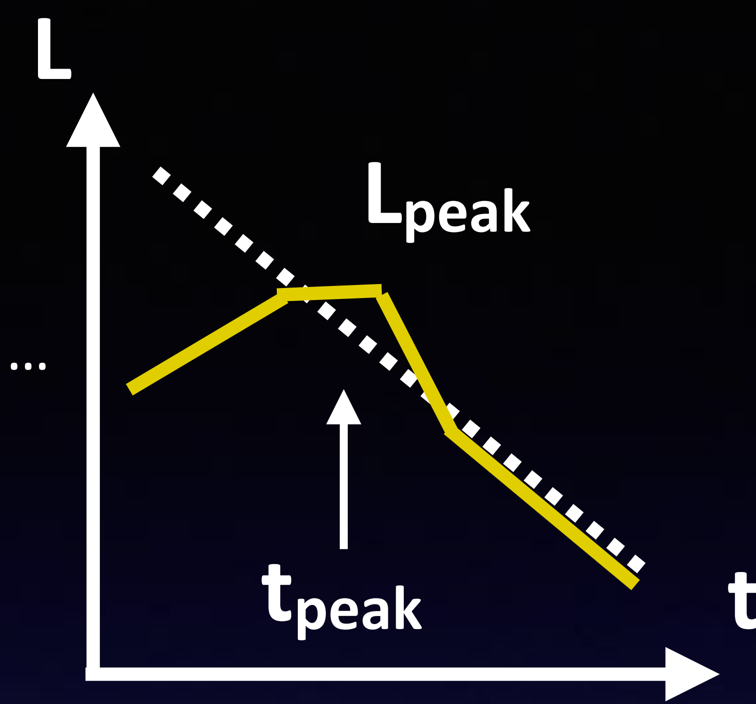
Radioactive decay luminosity



Wanajo 18

“Kilonova/Macronova"

Initial works: Li & Paczynski 98, Kulkarni 05, Metzger+10, Goriely+11, …
High opacity: Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13, …



Timescale

$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2} \simeq 8.4 \ {\rm days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10 \ {\rm cm^2 \ g^{-1}}}\right)^{1/2}$$

Luminosity

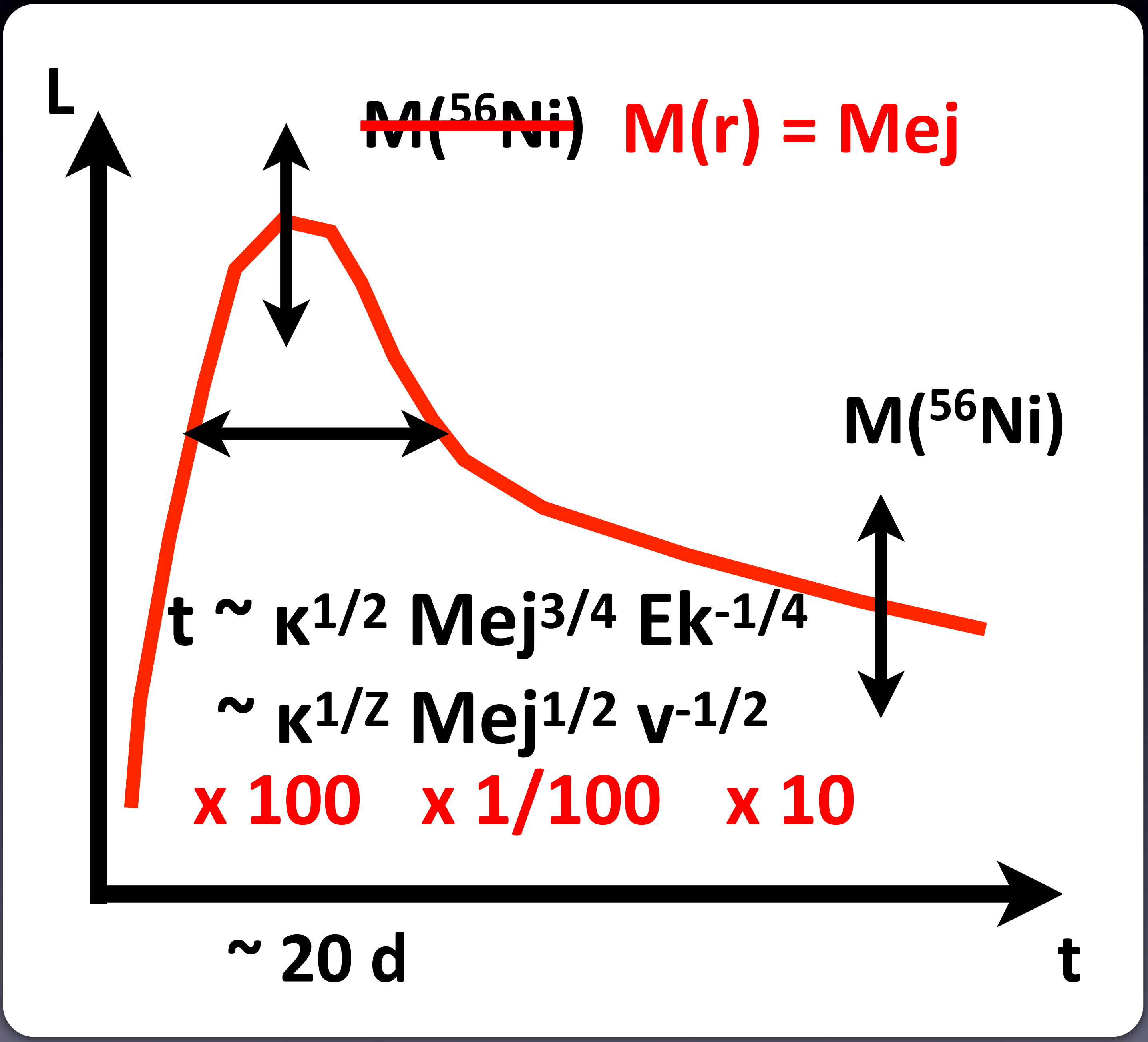
$$L_{\rm peak} = L_{\rm dep}(t_{\rm peak}) \simeq 1.3 \times 10^{40} \ {\rm erg \ s^{-1}} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{10 \ {\rm cm^2 \ g^{-1}}}\right)^{-0.65}$$

*assuming 50% thermalization

Temperature ~ 5000 K => Optical and infrared wavelengths

Radiation from NS merger

Light curves

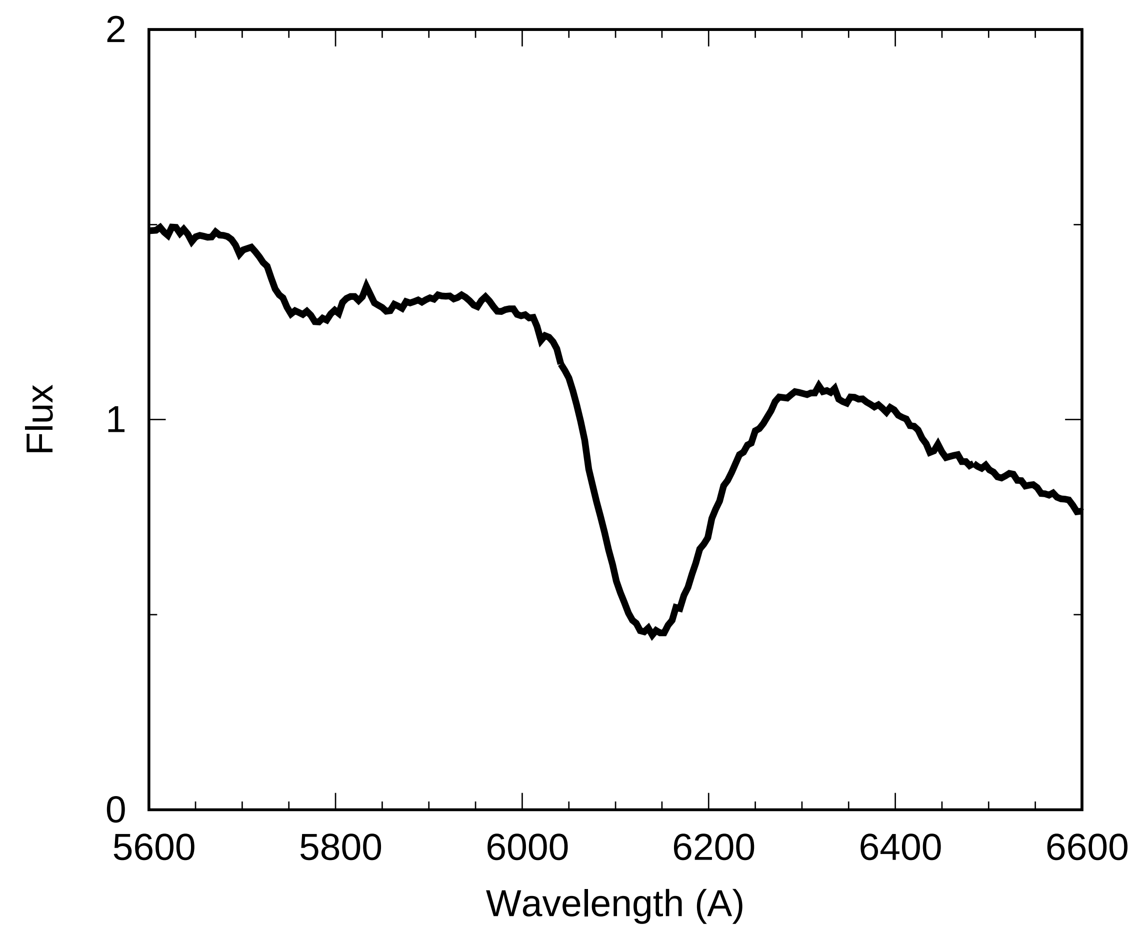


Fainter and faster than supernovae

Spectra

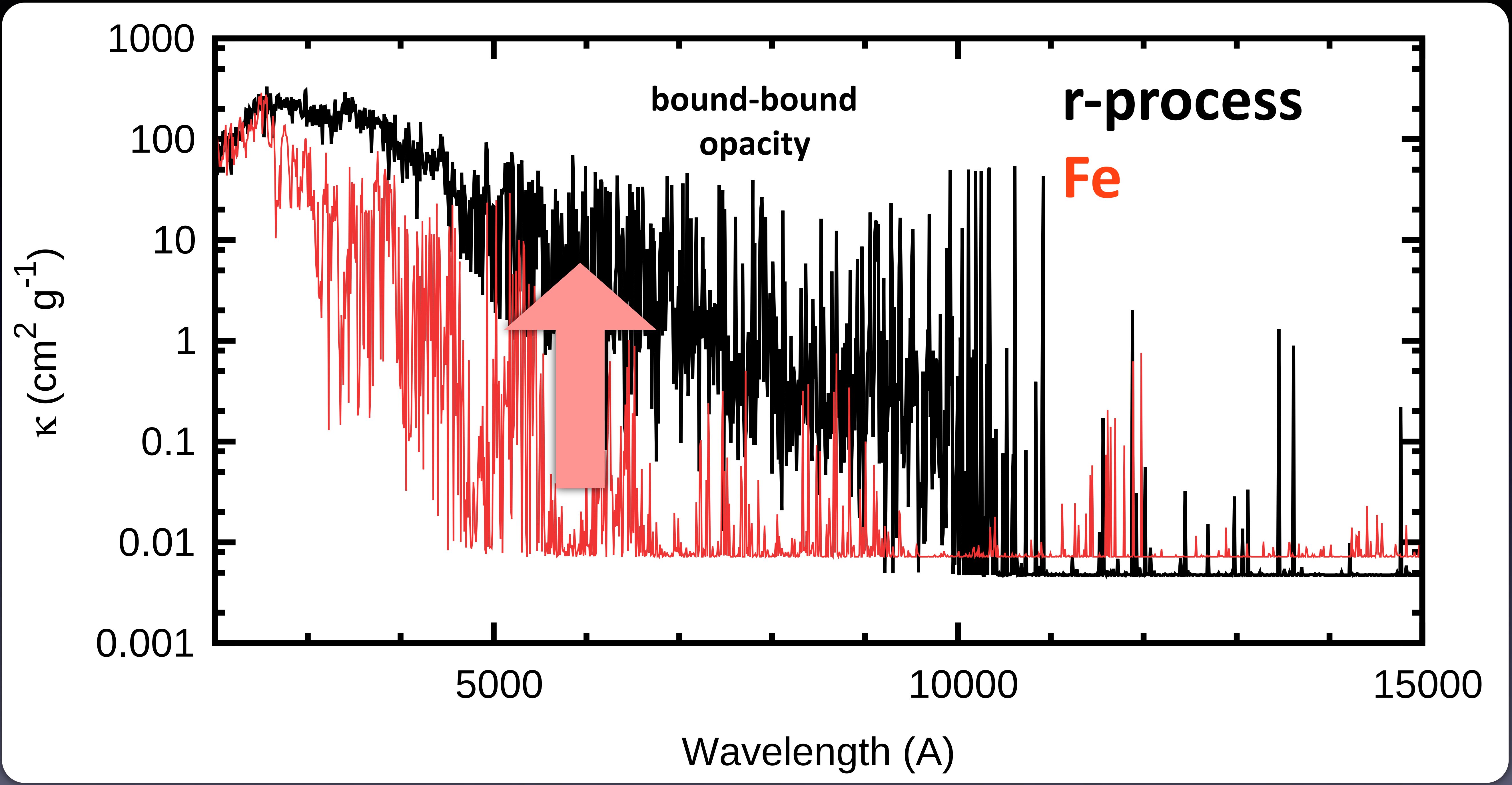
$v \sim E^{1/2} Mej^{-1/2}$

+ Chemical composition



Higher velocities than supernovae

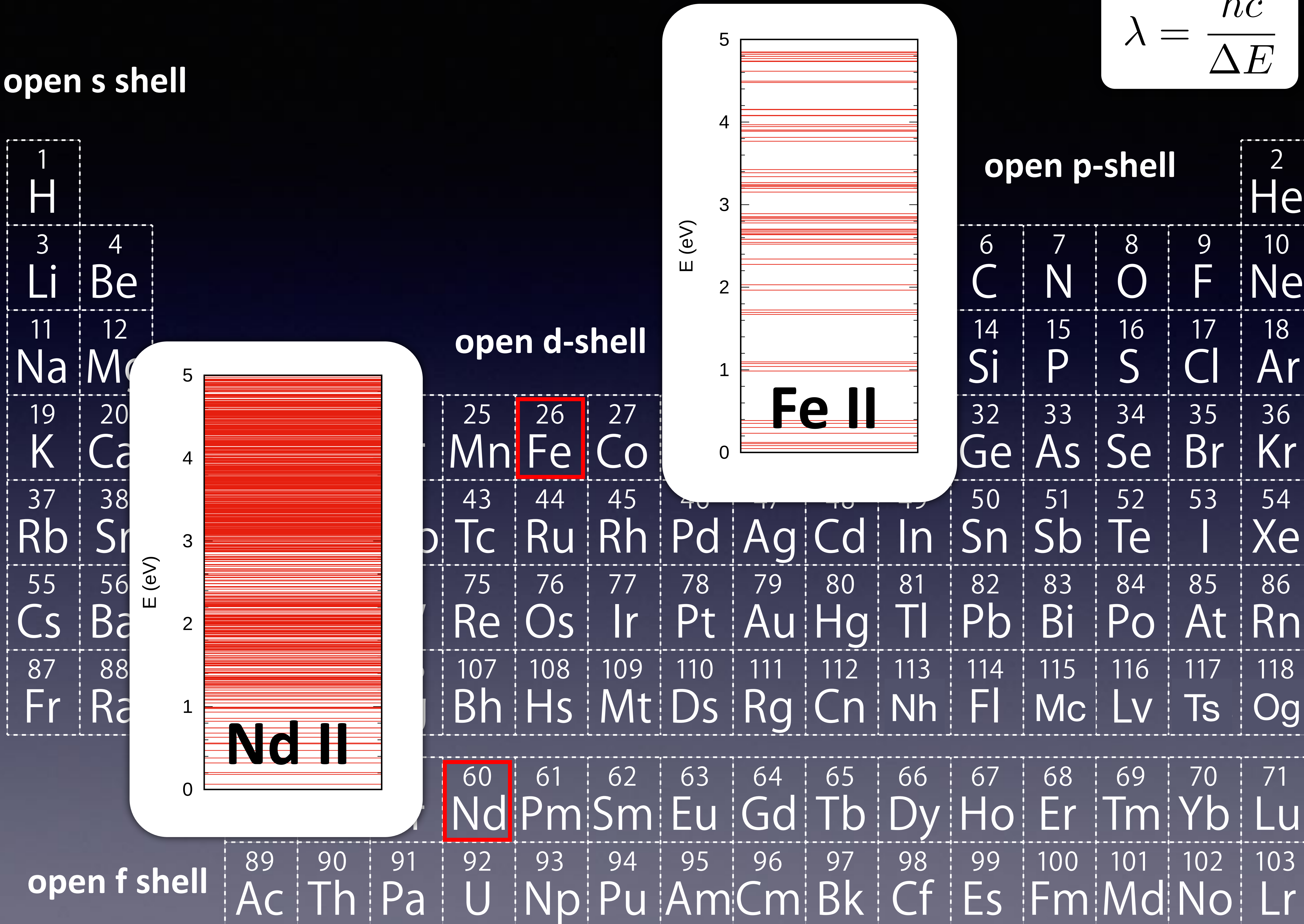
Opacity



Higher opacity by factor of 100

(Kasen+13, Tanaka & Hotokezaka 13)

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



Statistical weight

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

(different combinations of m_l and m_z)

$$g = 2(2l+1)$$

m_z (spin) m_l (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)

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

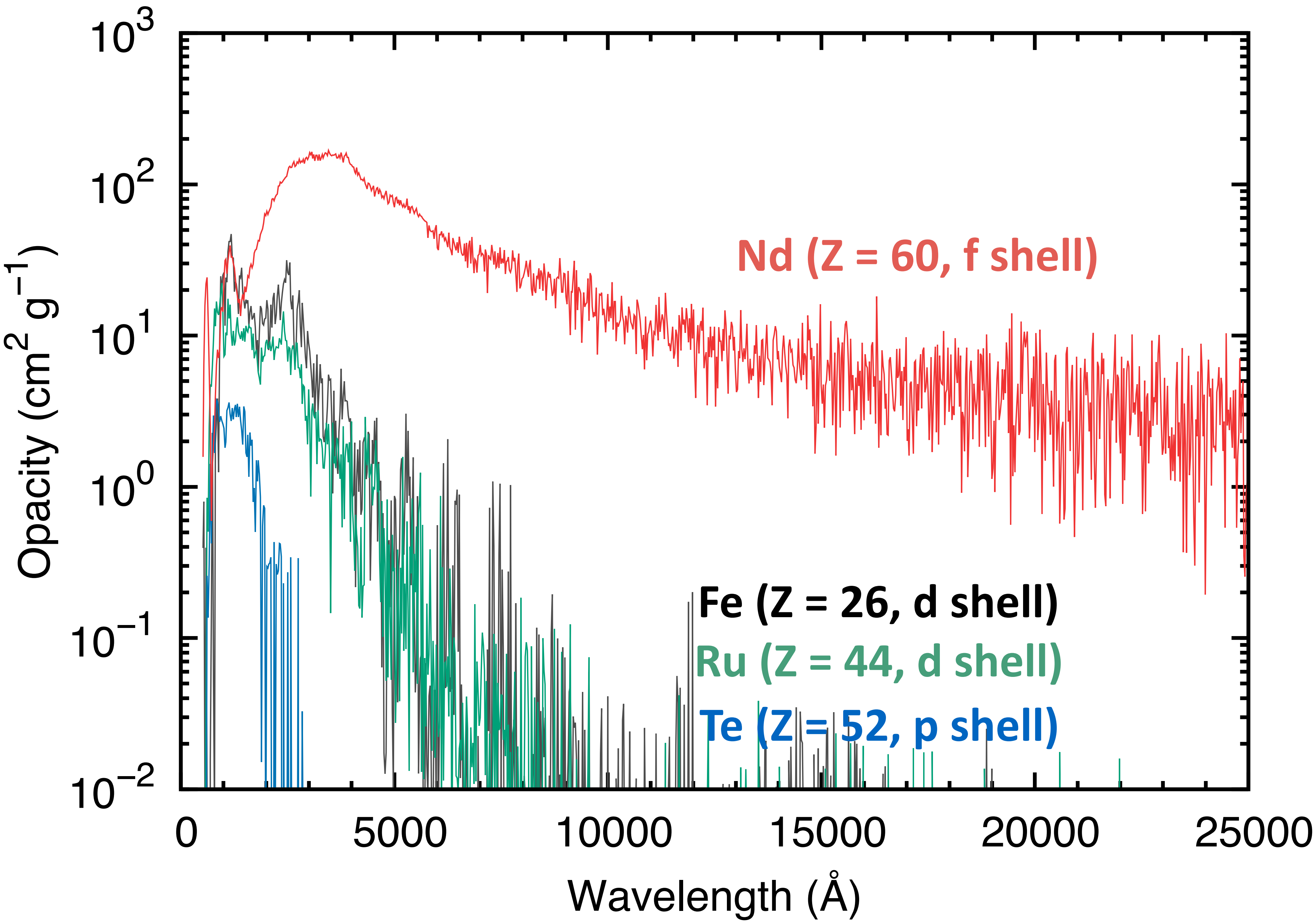
(ex)

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**

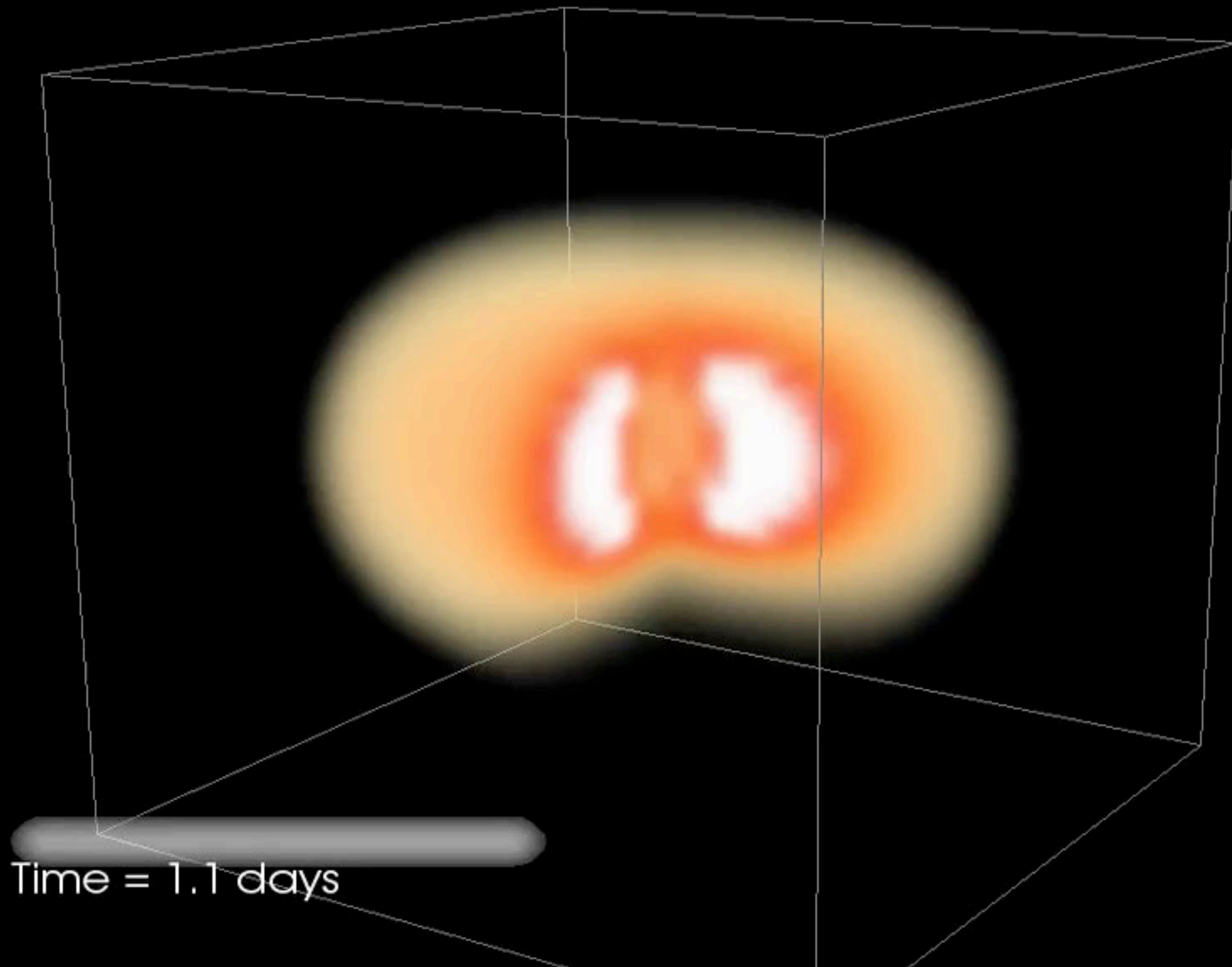
Opacity



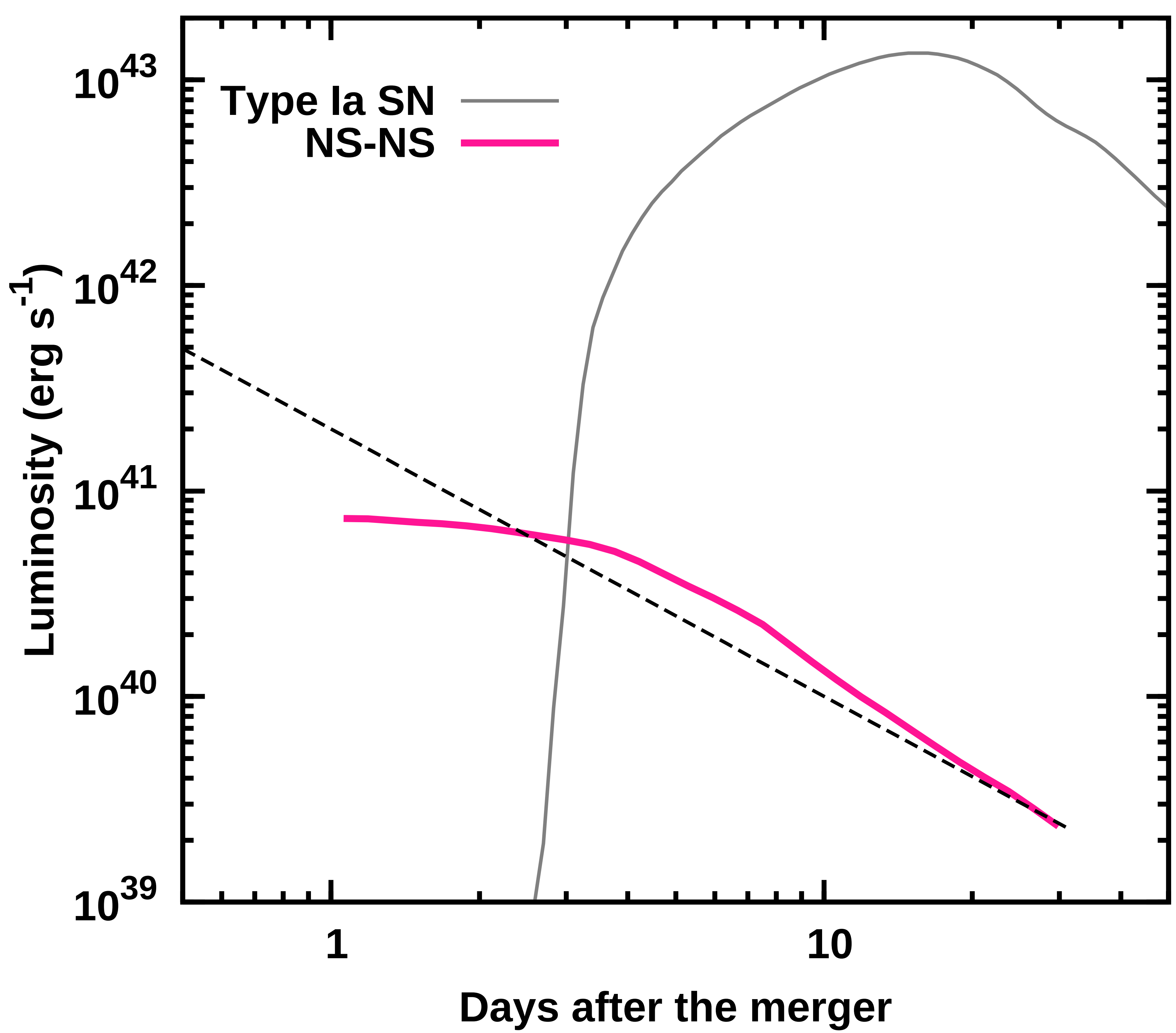
MT, Kato, Gaigalas+18

Radiation transfer simulations of kilonova

(MT & Hotokezaka 13, MT+14, MT 16)



Light curve: Fainter and faster than SNe



MT 16

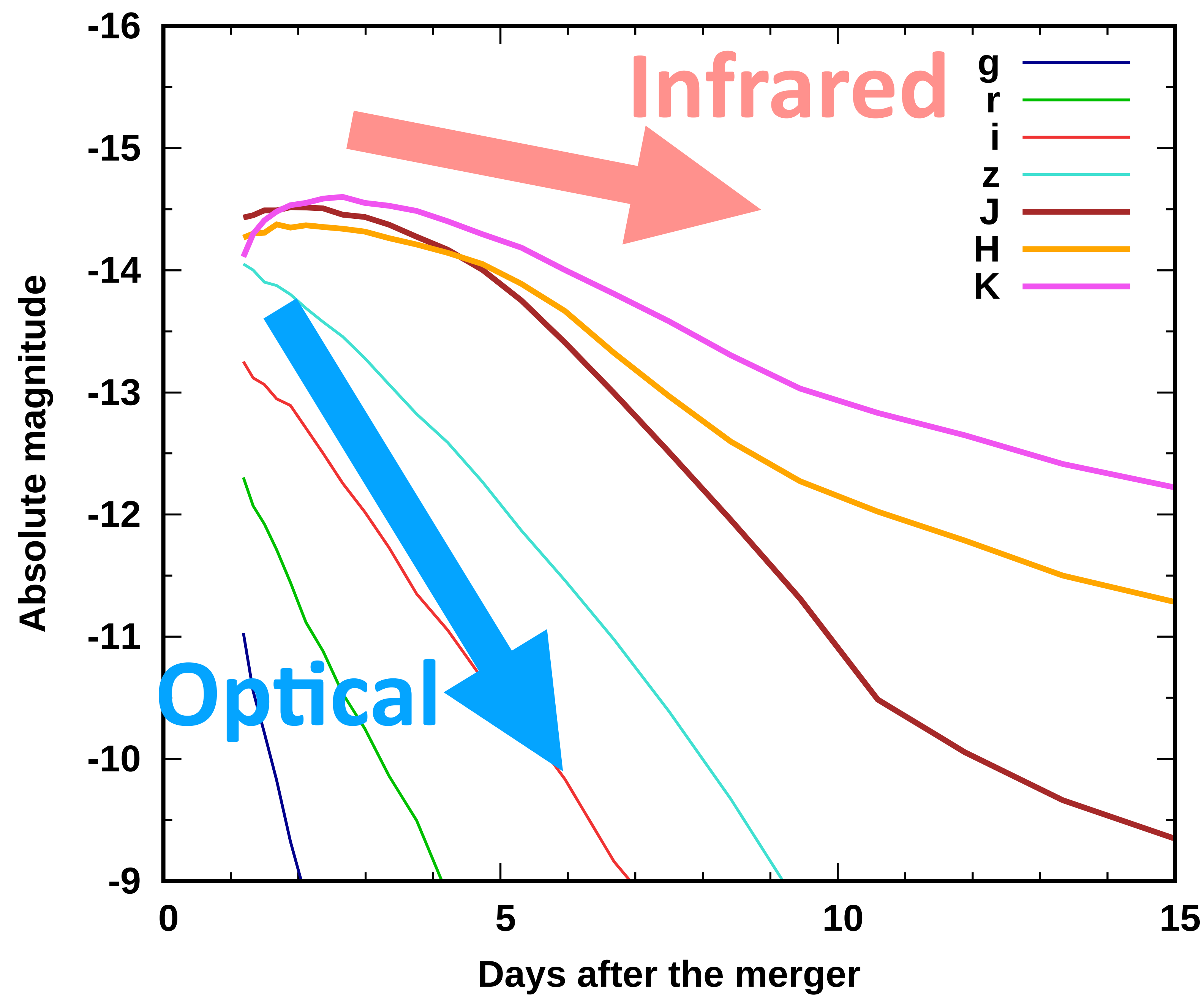
Light curves of kilonova

Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13

$L \sim 10^{40}$-10^{41} erg s^{-1}

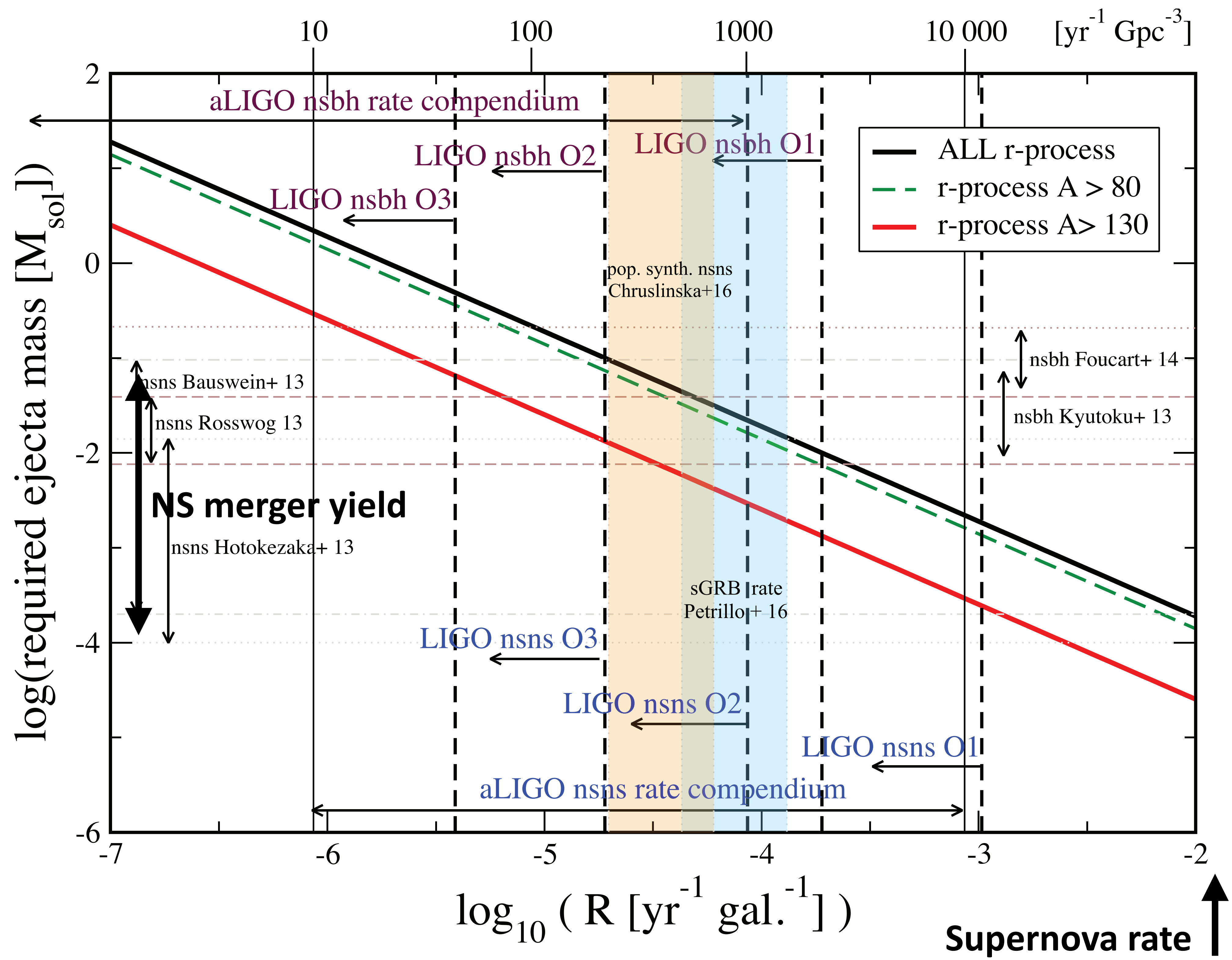
t ~ weeks

NIR > Optical



Model: MT+17a

Constraints from the total amount in our Galaxy



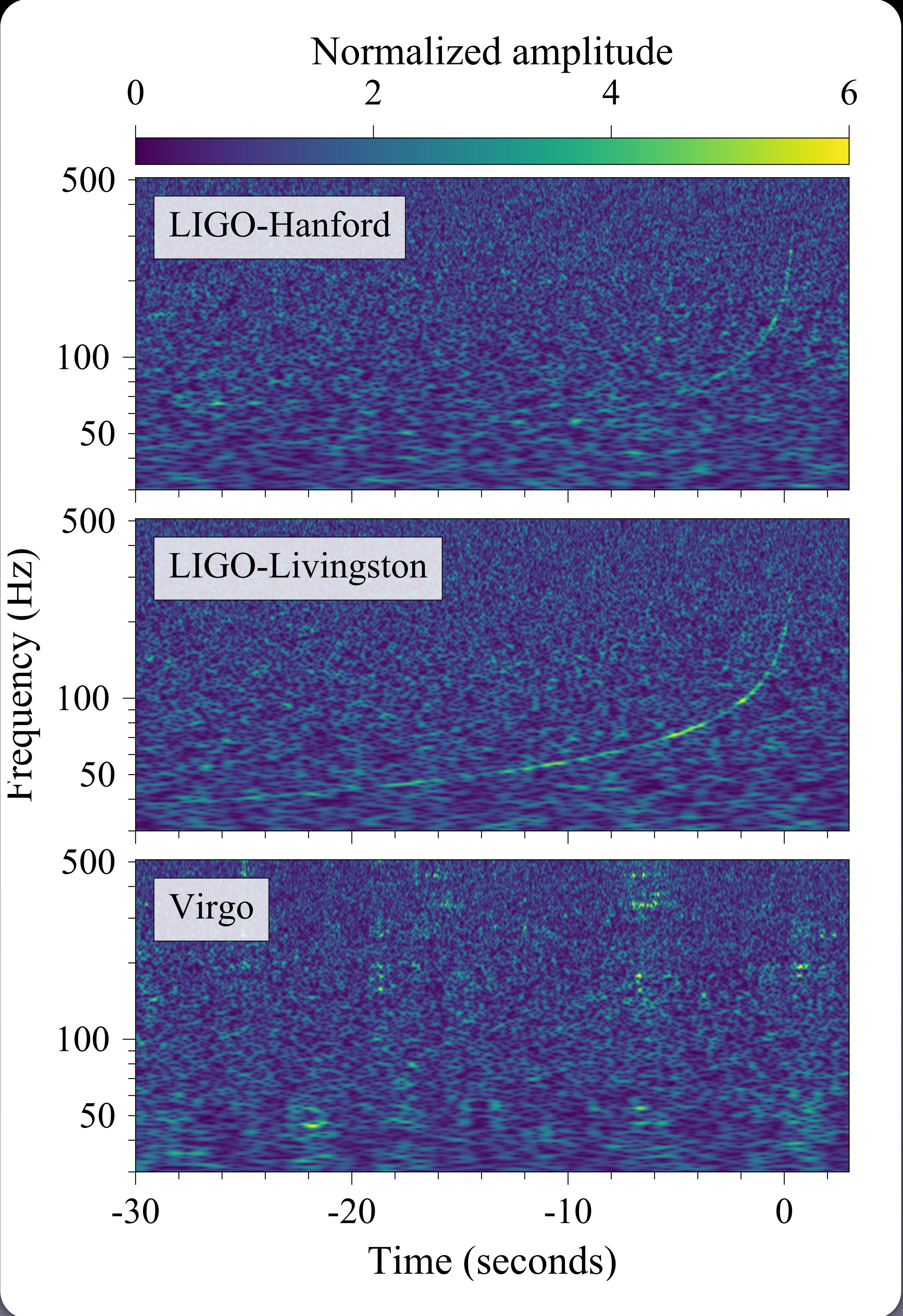
Rosswog+17, Hotokezaka+15, 18

Neutron star mergers

1. Neutron star mergers
2. Radiation from neutron star mergers
3. Observations of neutron star mergers

2017 Aug 17

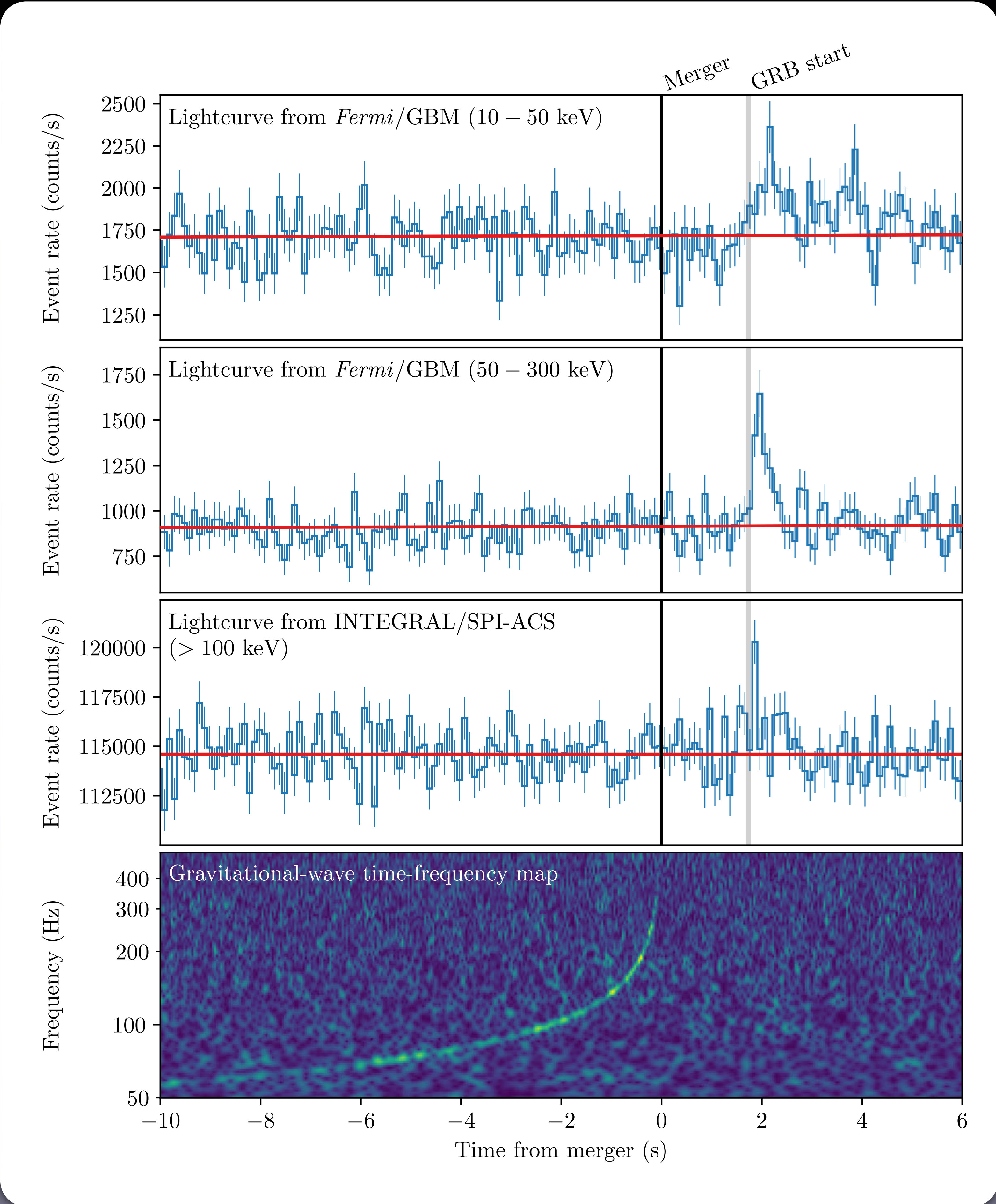
GW170817:
The first detection of GWs from a NS merger



LIGO Scientific Collaboration
and Virgo Collaboration, 2017, PRL

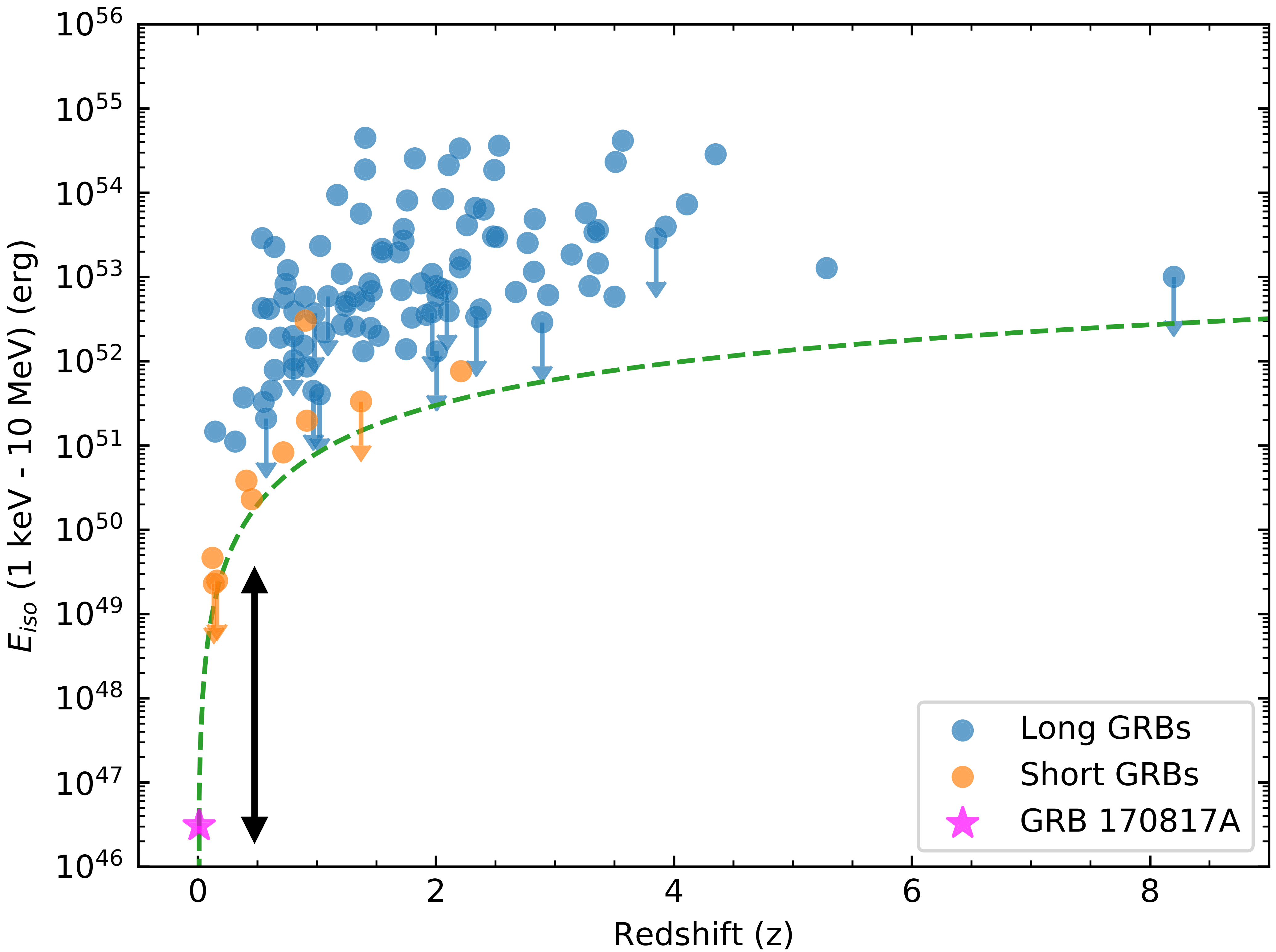
Detection of short GRBs

Short GRB - NS merger connection



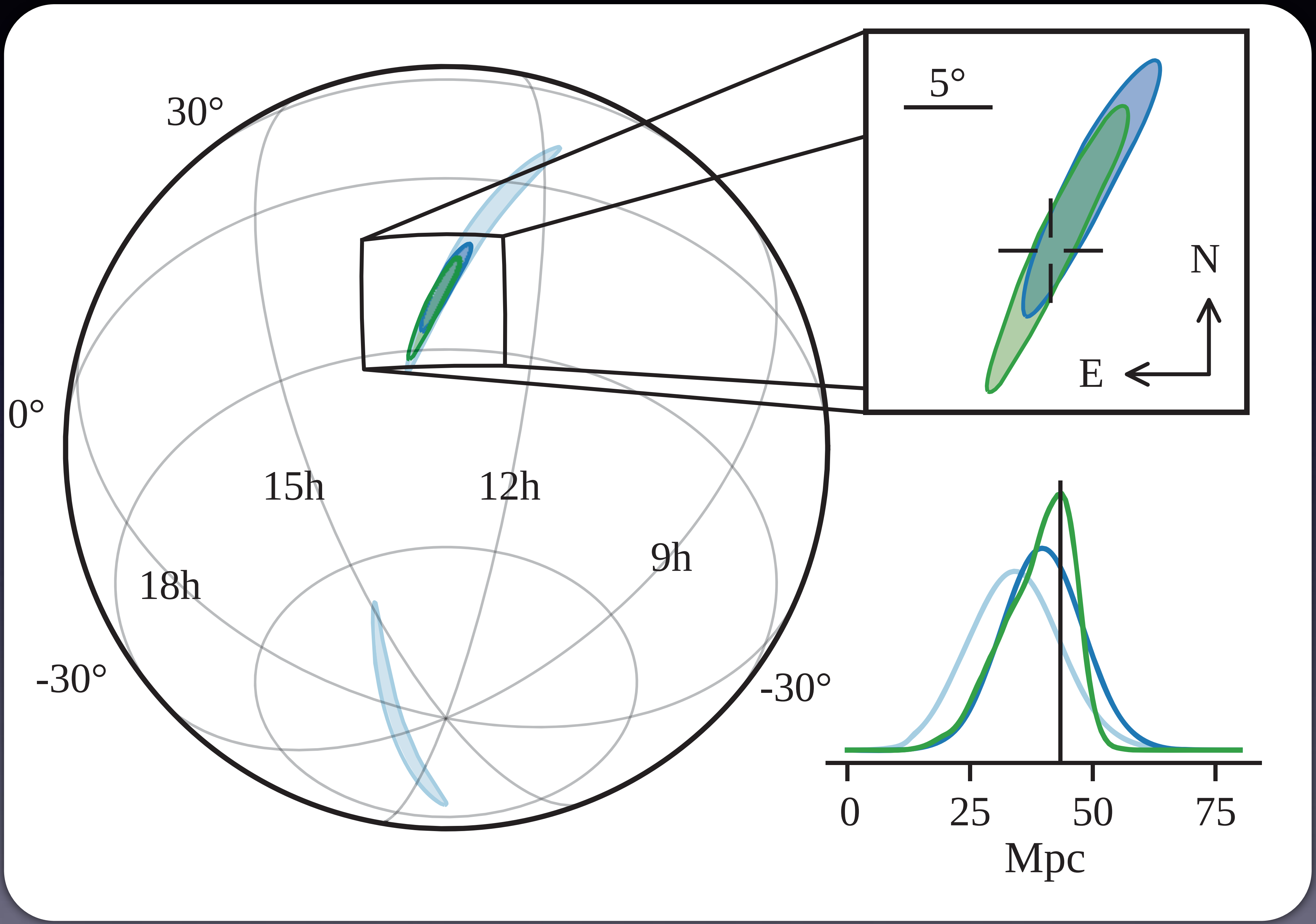
LIGO Scientific Collaboration
and Virgo Collaboration, 2017, ApJ

Extremely weak gamma-rays



Abbott et al. 2017

Skymap from 3 detectors (LIGO x 2 + Virgo)
==> 30 deg^2 (~40 Mpc)

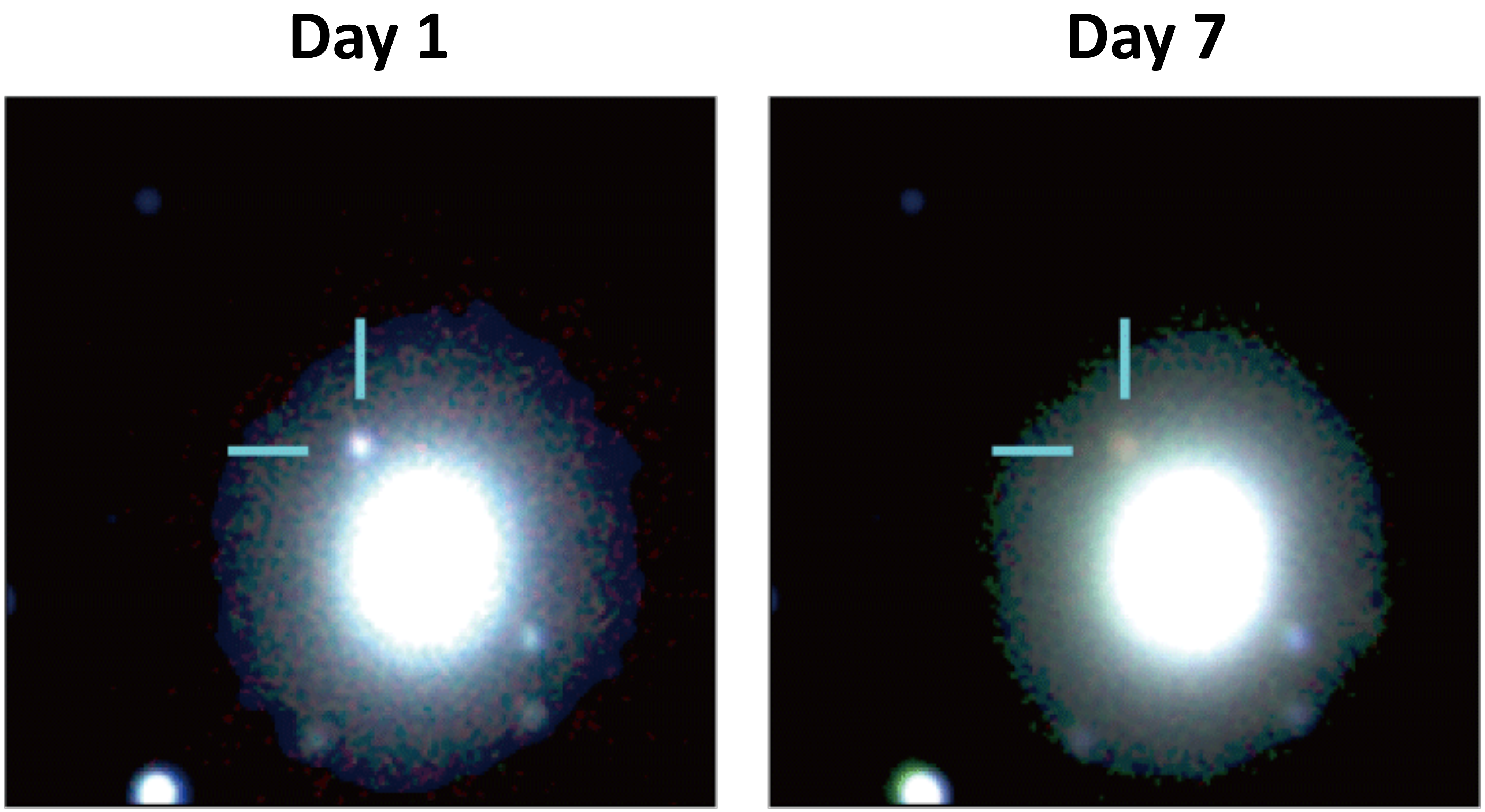


LIGO Scientific Collaboration and Virgo Collaboration, 2017

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

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

Electromagnetic counterpart of GW170817 @ 40 Mpc

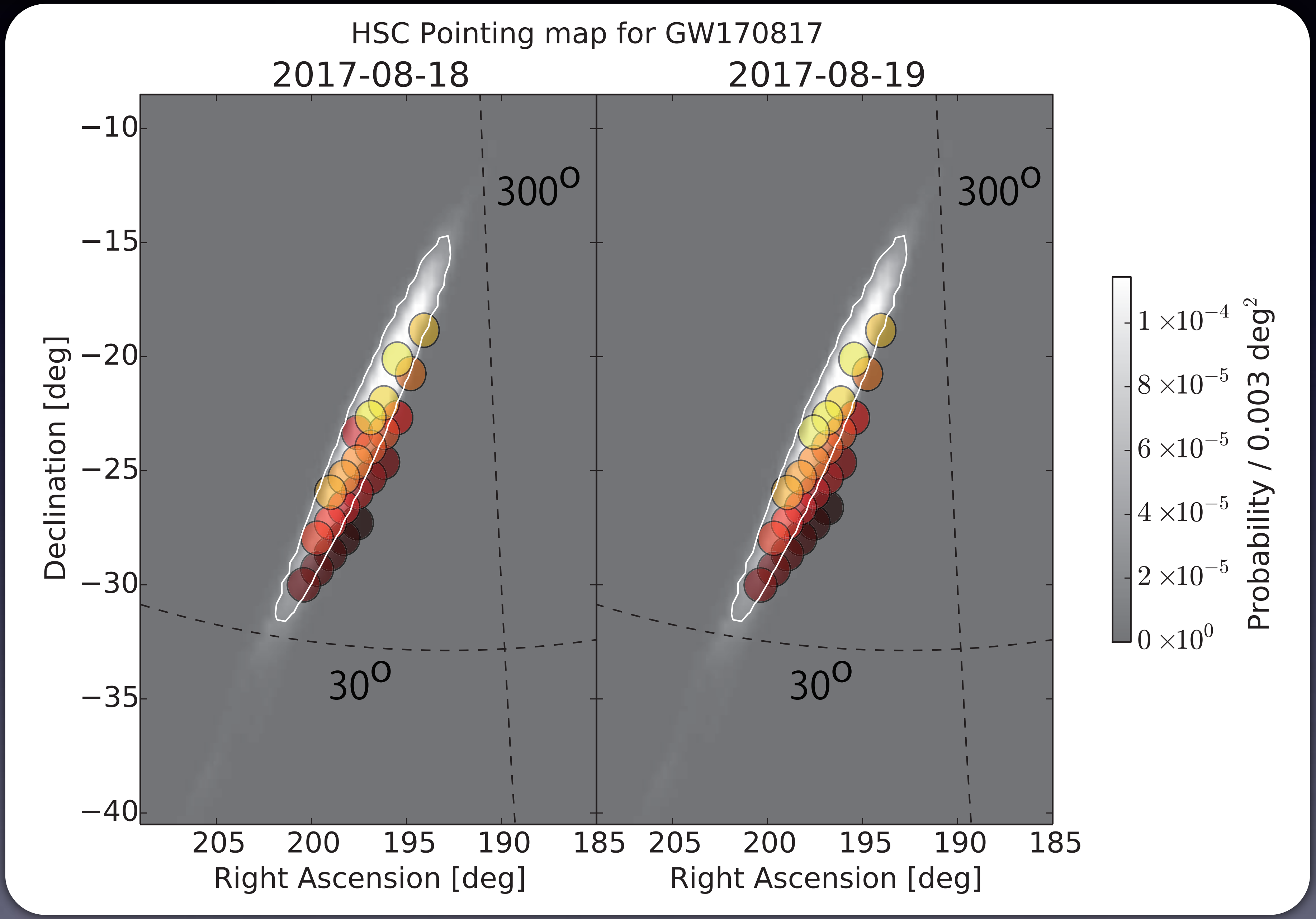


Optical (z) near IR (H) near IR (Ks)

Utsumi, MT+17

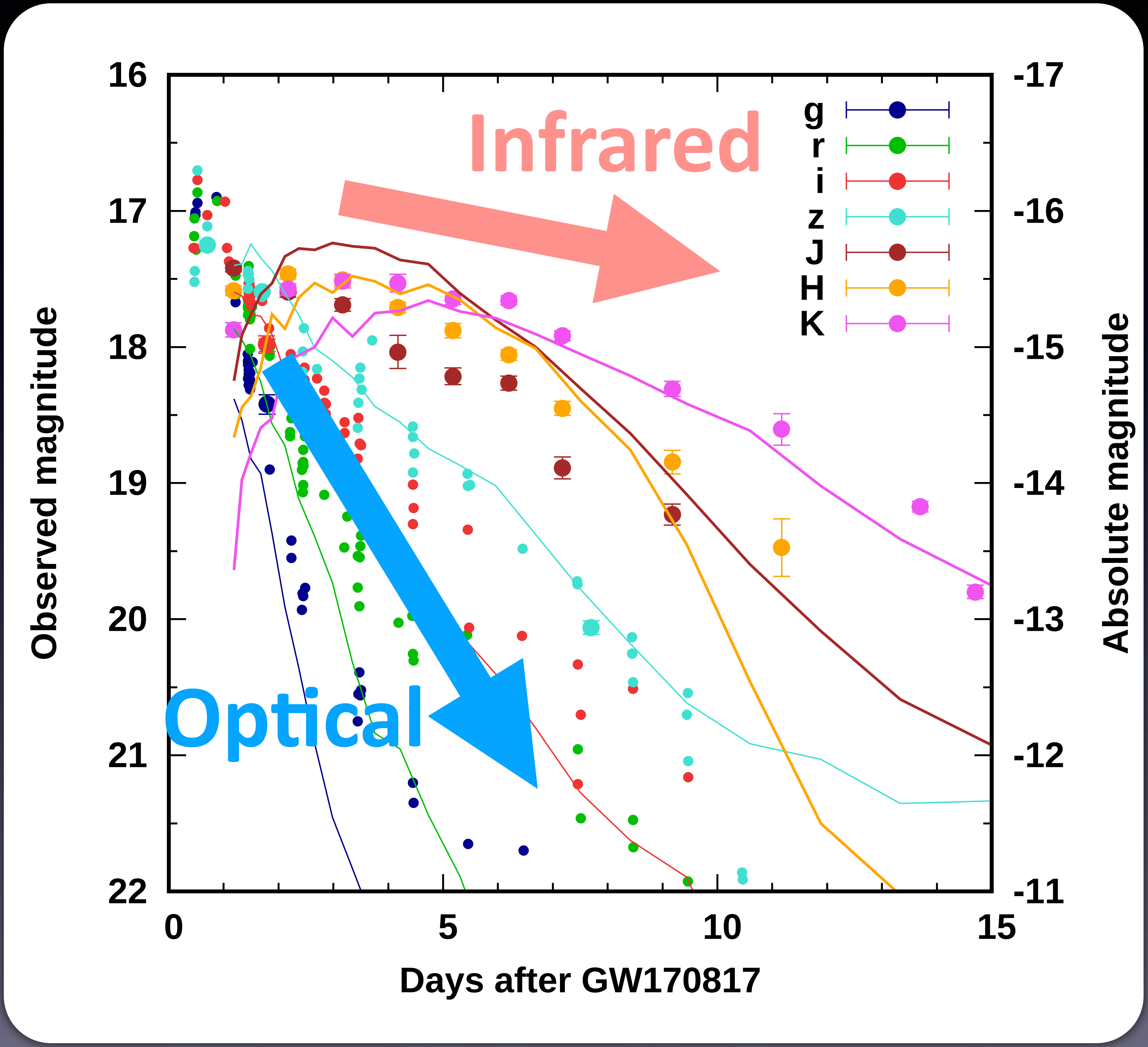
Wide-field survey with Subaru/HSC

➡ No other transient within 40 Mpc distance



Tominaga, MT et al. 2018

GW170817: optical/infrared light curves

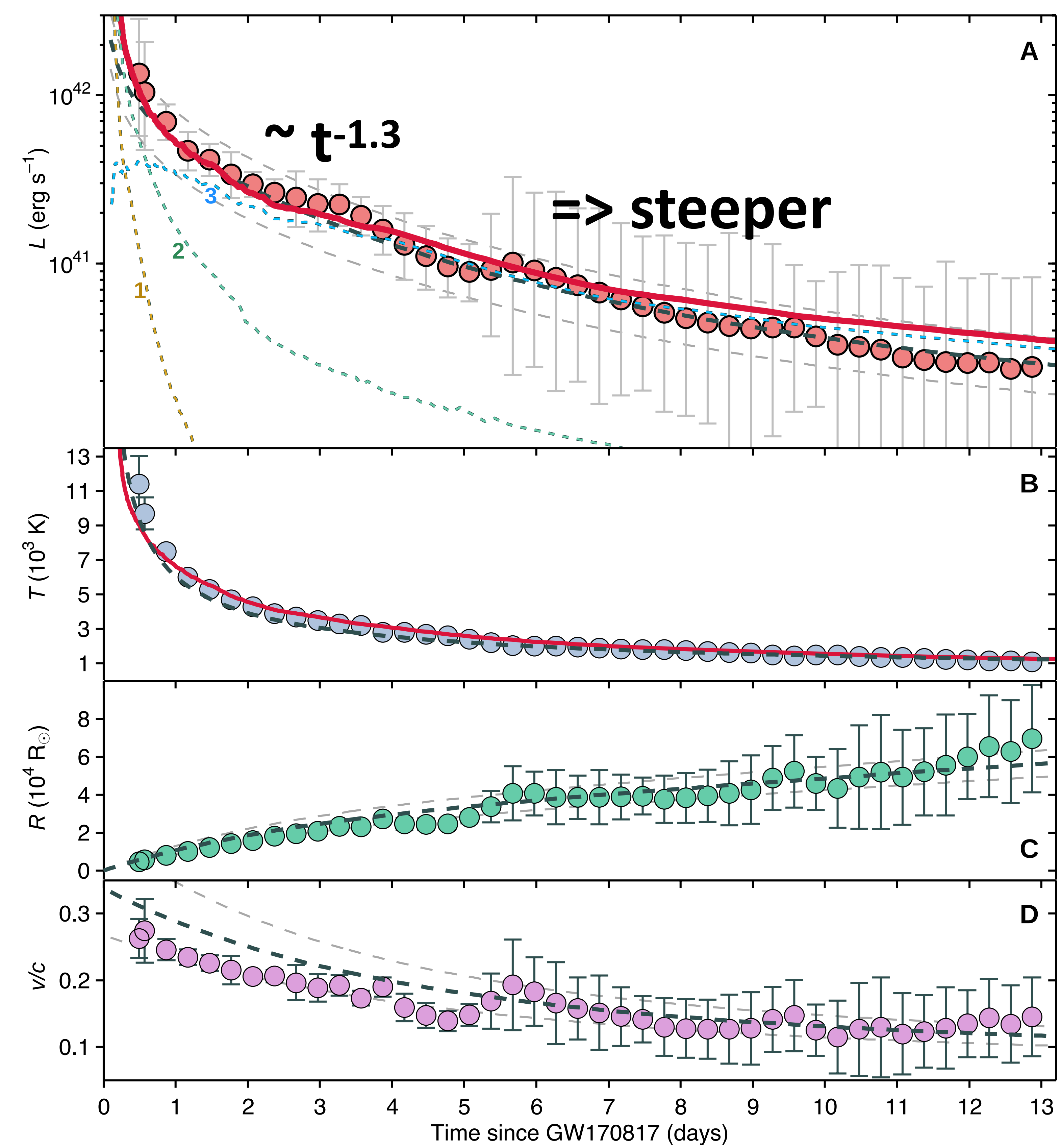


Arcavi+17, Cowperthwaite+17, Diaz+17, Drout+17,Evans+17, Kasliwal+17,Pian+17, Smartt+17, Tanvir+17, Troja+17, Utsumi, MT+17, Valenti+17

Signature of lanthanide elements
Ejecta mass ~0.03 Msun (w/ ~1% of lanthanides)

Bolometric light curves

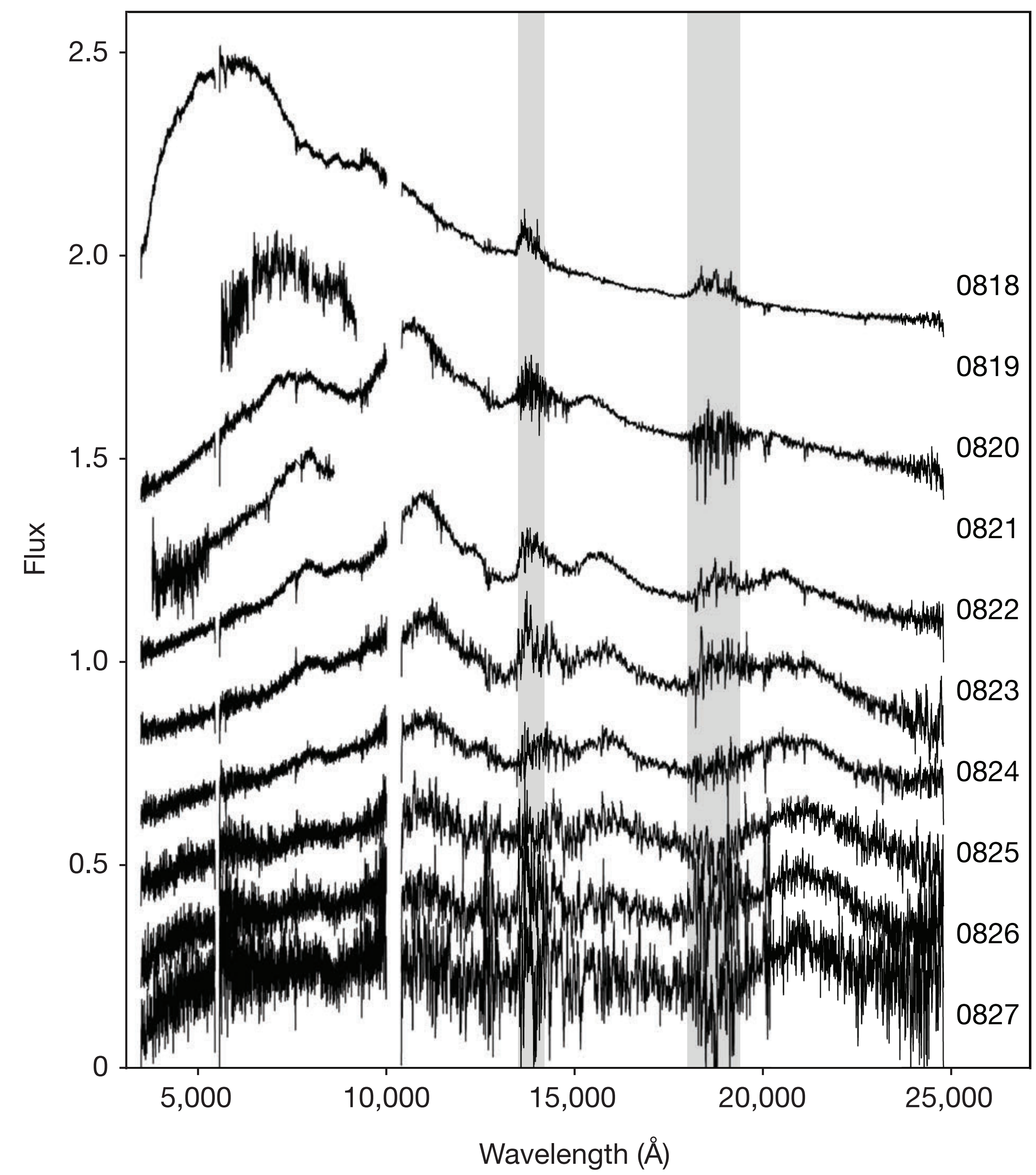
Heating rate ~ $t^{-1.3}$



Kasliwal+17

GW170817: Spectra

- Smooth spectra
  (high velocity)
- Not similar to
  known transients

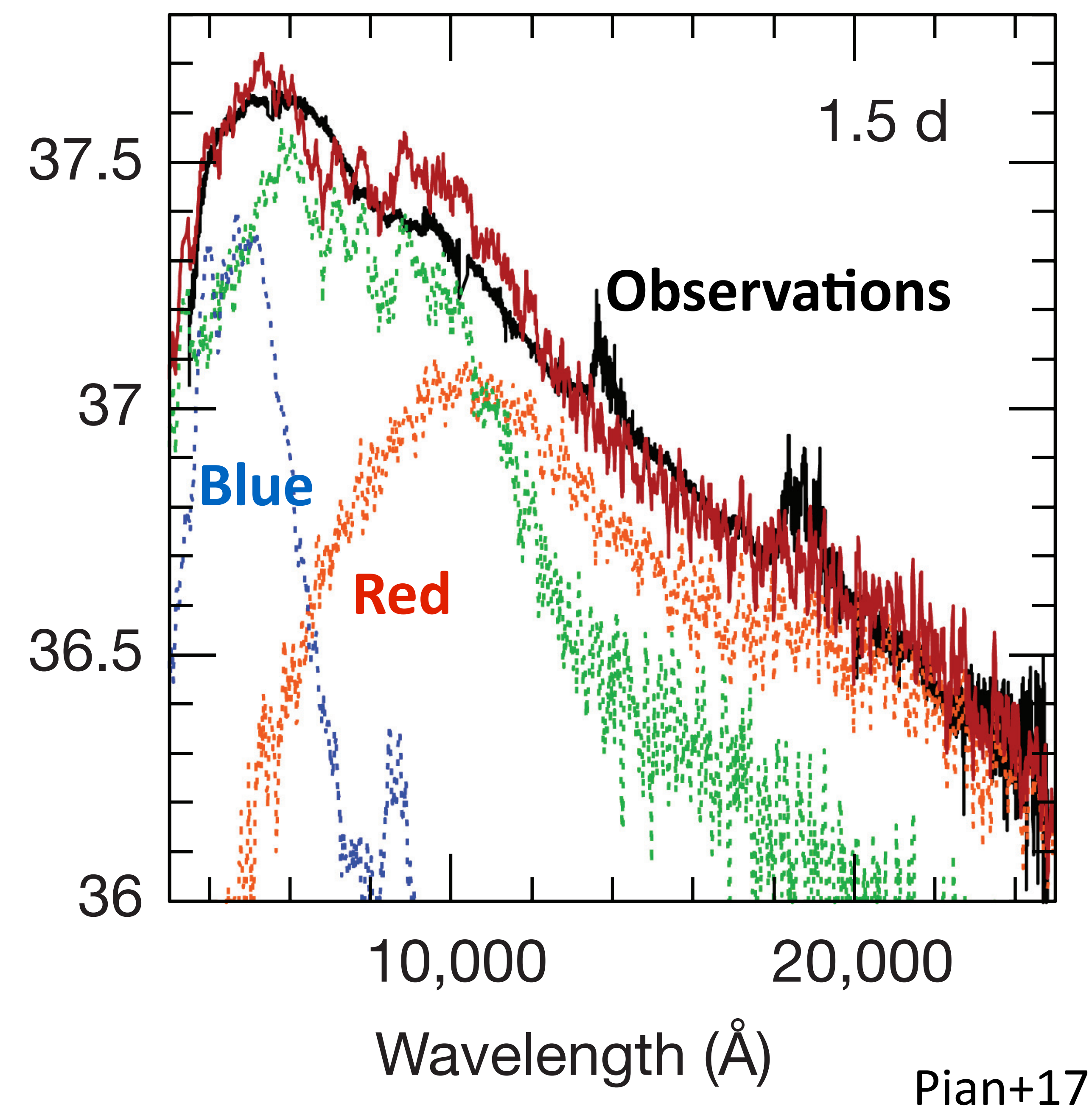


Andreoni+17, Chornock+17, Kilpatrick+17
McCully+17, Nicholl+17, Pian+17,
Shappee+17, Smartt+17

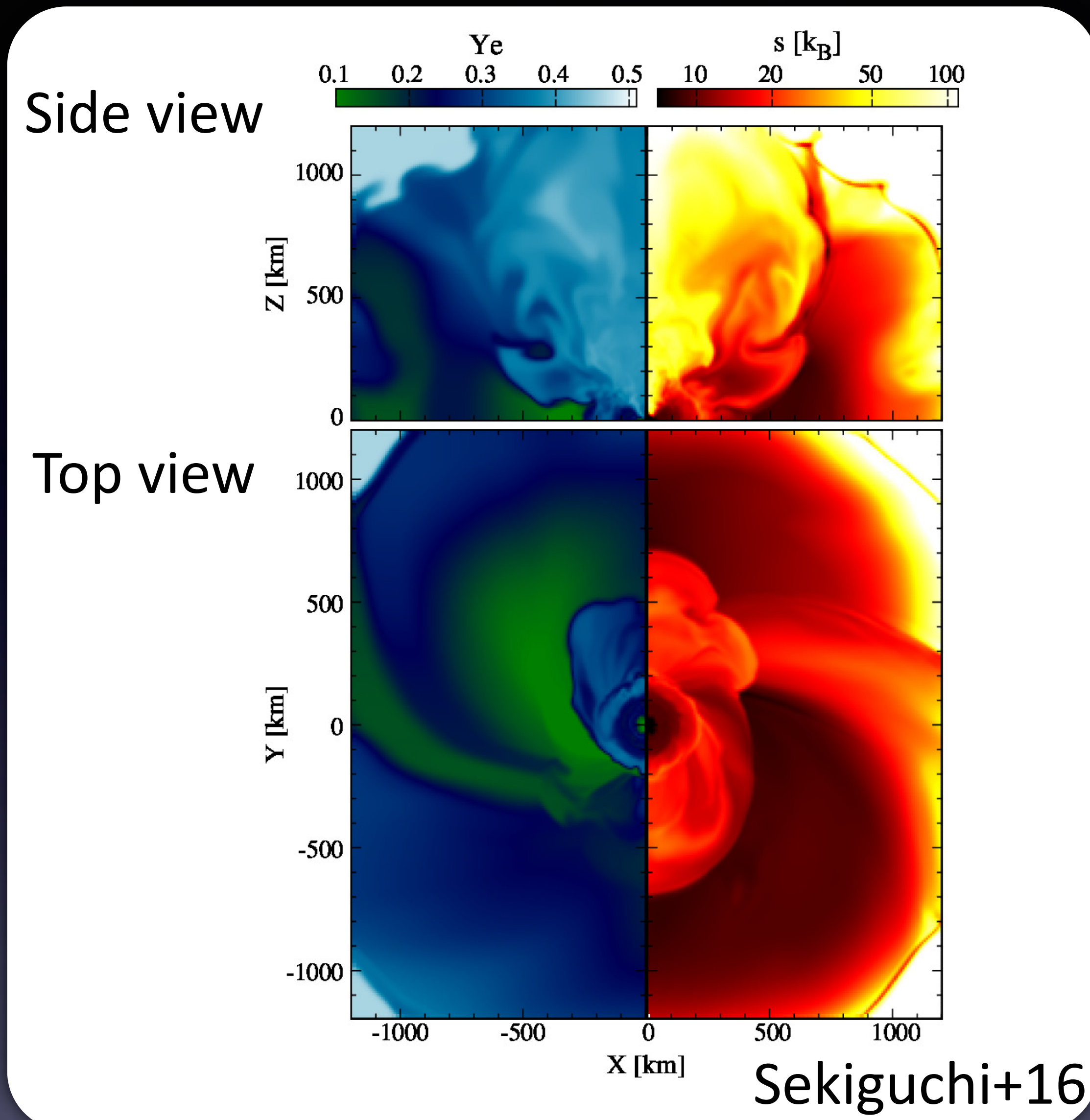
Pian+17

Presence of blue component

Kasen+17, Metzger 17, MT+17

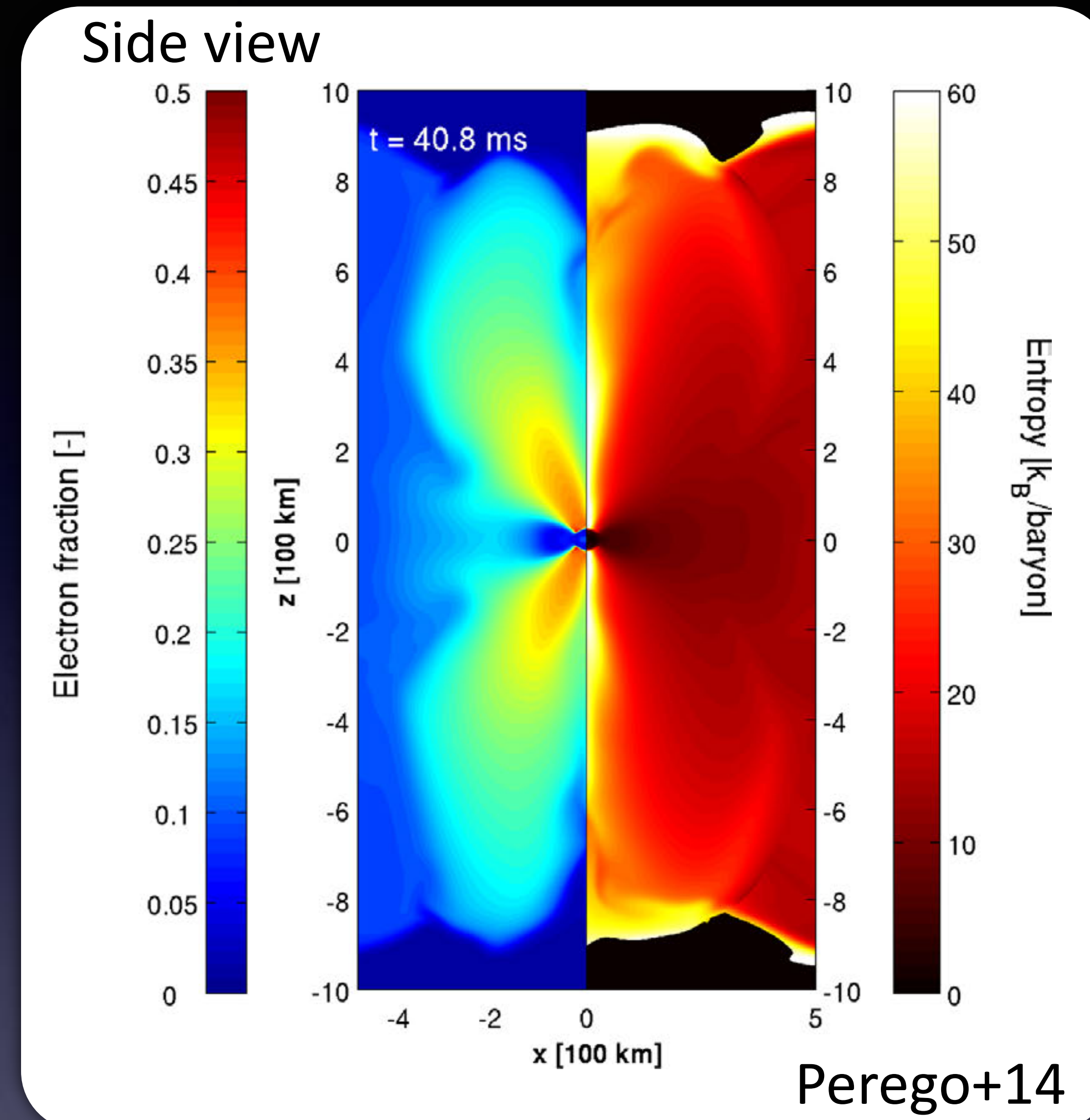


Dynamical ejecta (~< 10 ms)



Mej ~ 10^{-3} - 10^{-2} Msun
v ~ 0.1-0.2 c
Low Ye (wide distribution)

Post-merger ejecta (~< 100 ms)

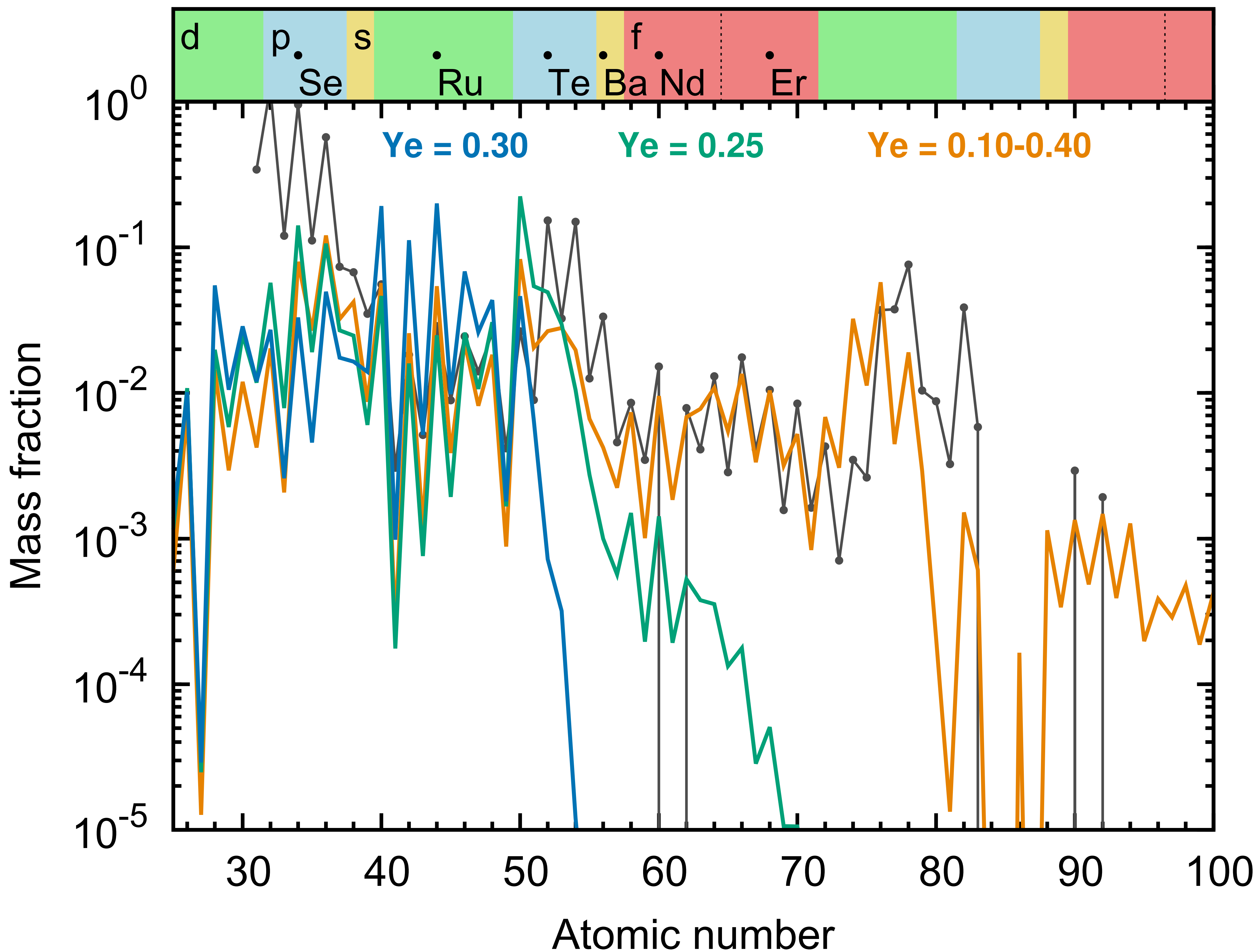


Mej >~ 10^{-2} Msun
v ~ 0.05 c
Relatively high Ye

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

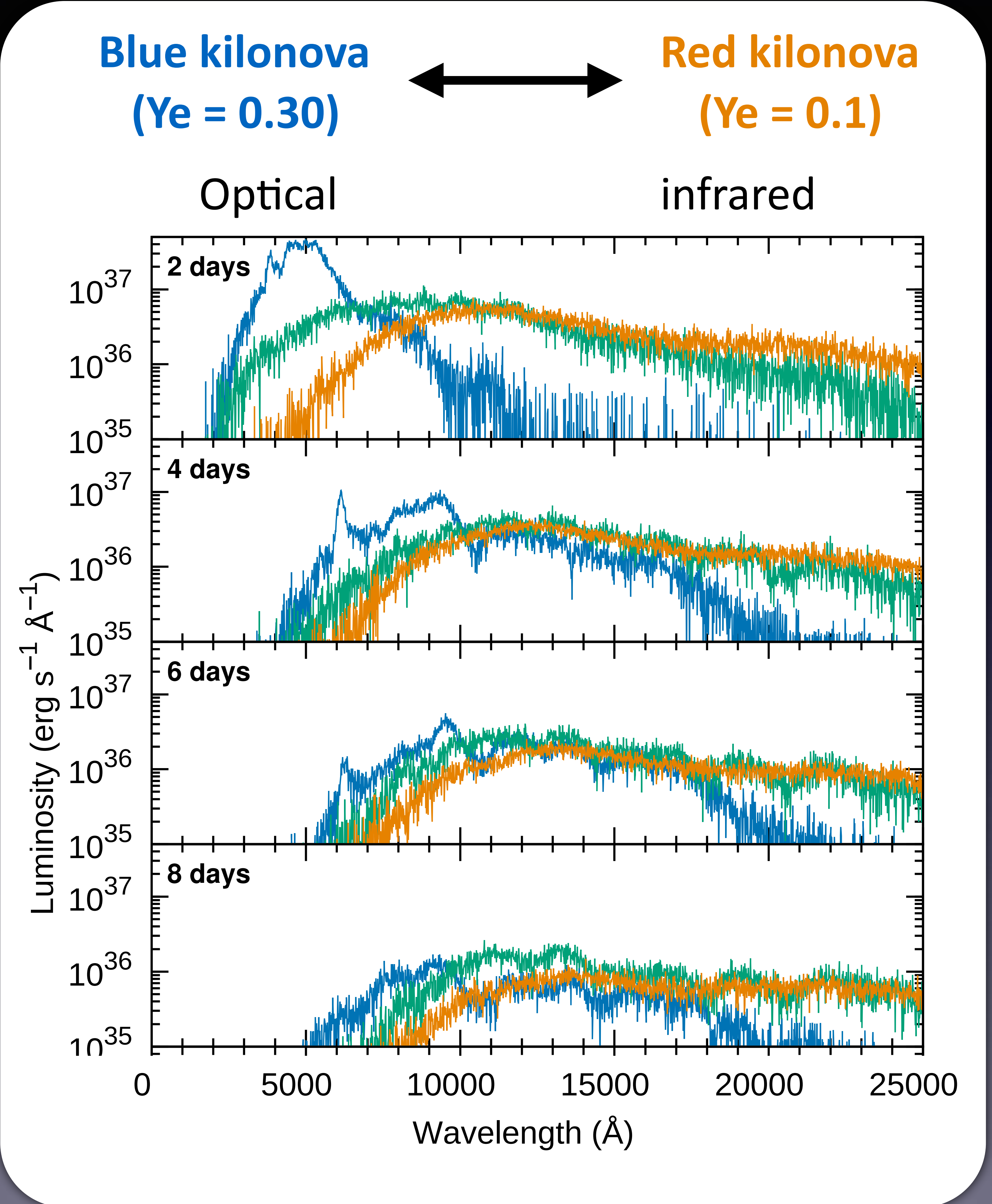
$$\nu_e + n \rightarrow p + e^-$$

High Ye => Suppression of heavy element production



MT+18

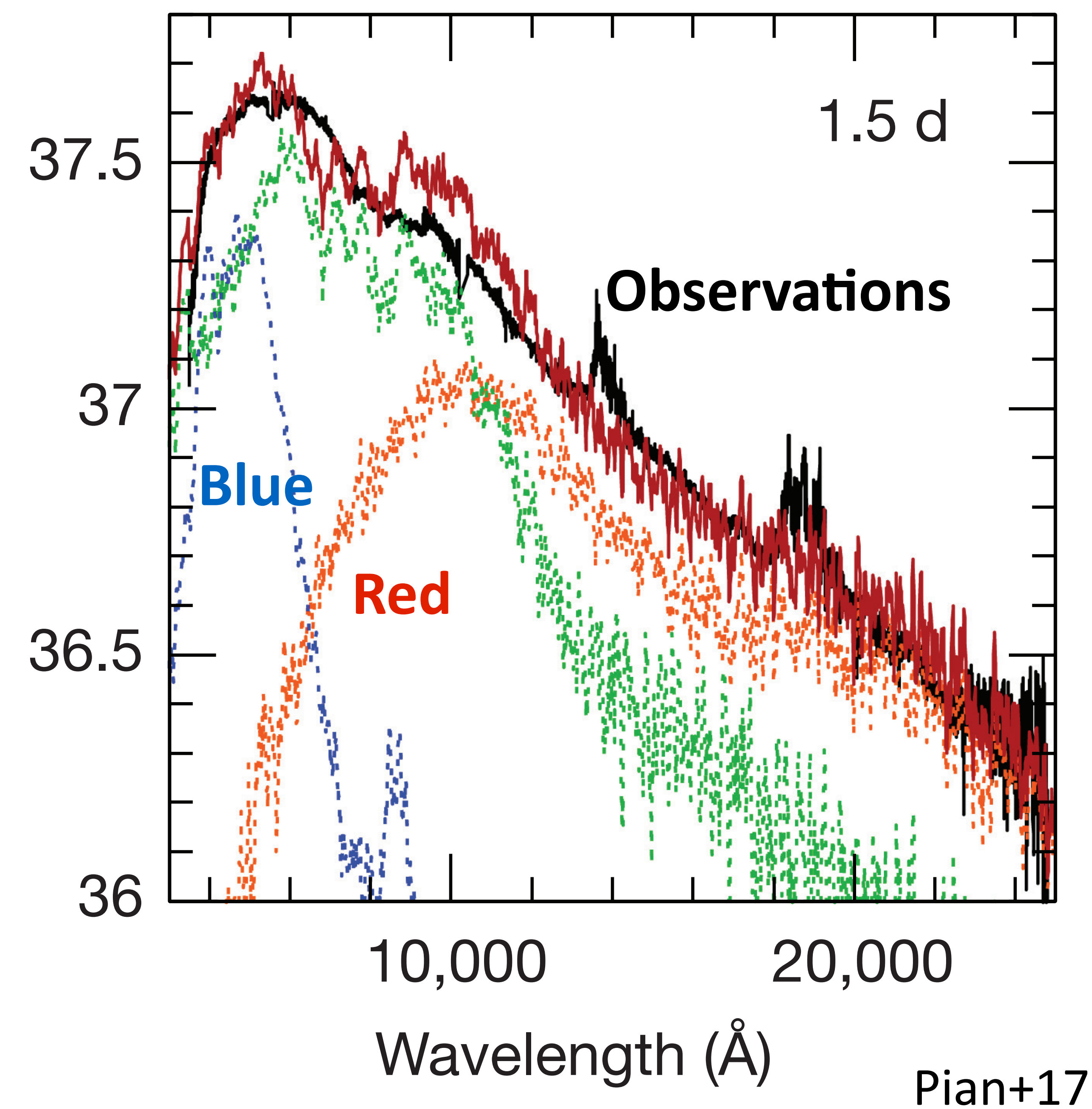
Nucleosynthesis is imprinted in the spectra



MT+18

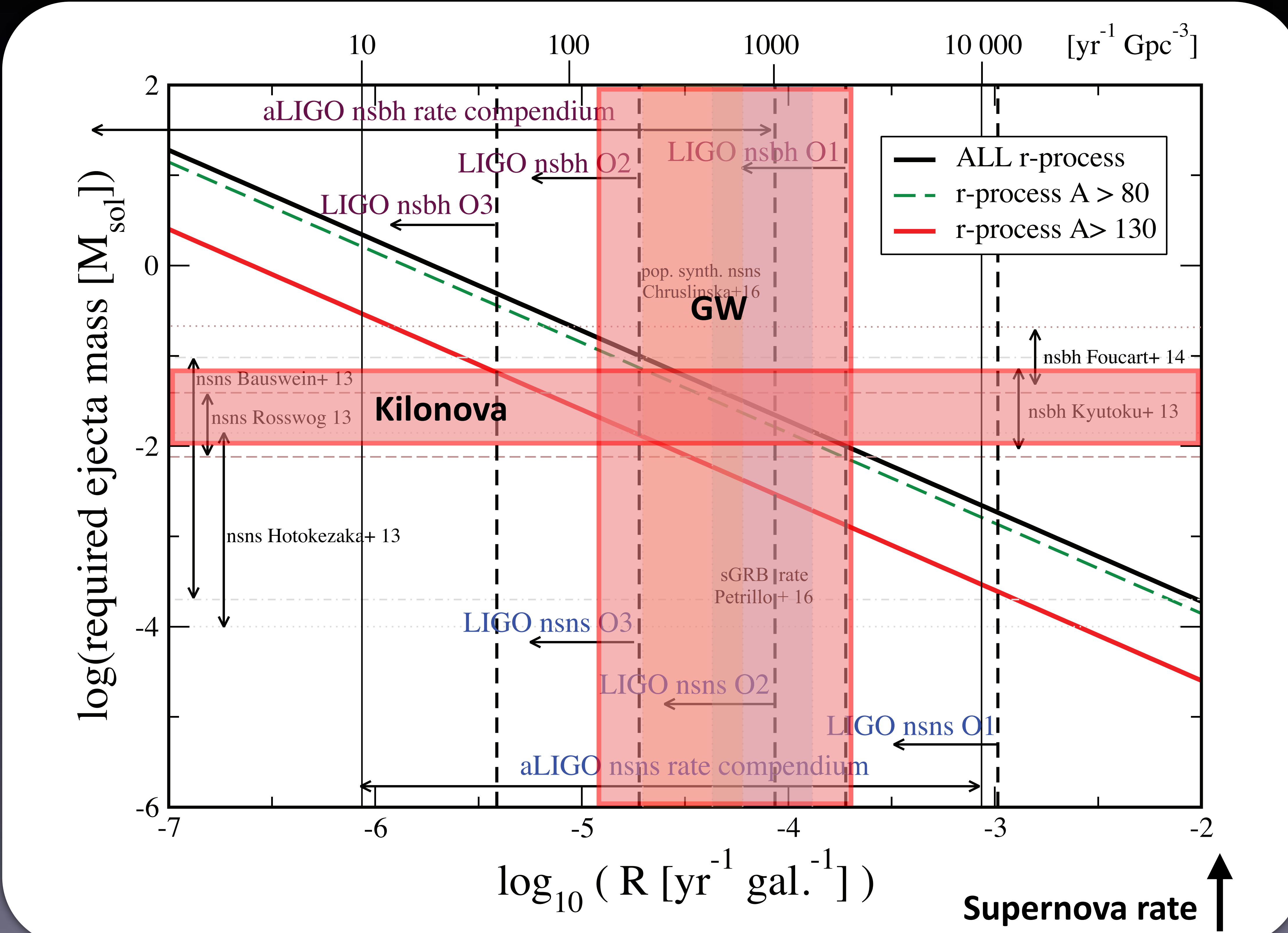
Presence of blue component

Kasen+17, Metzger 17, MT+17



Signature of lighter r-process elements
M ~ 0.02 Msun

Constraints from the total amount in our Galaxy



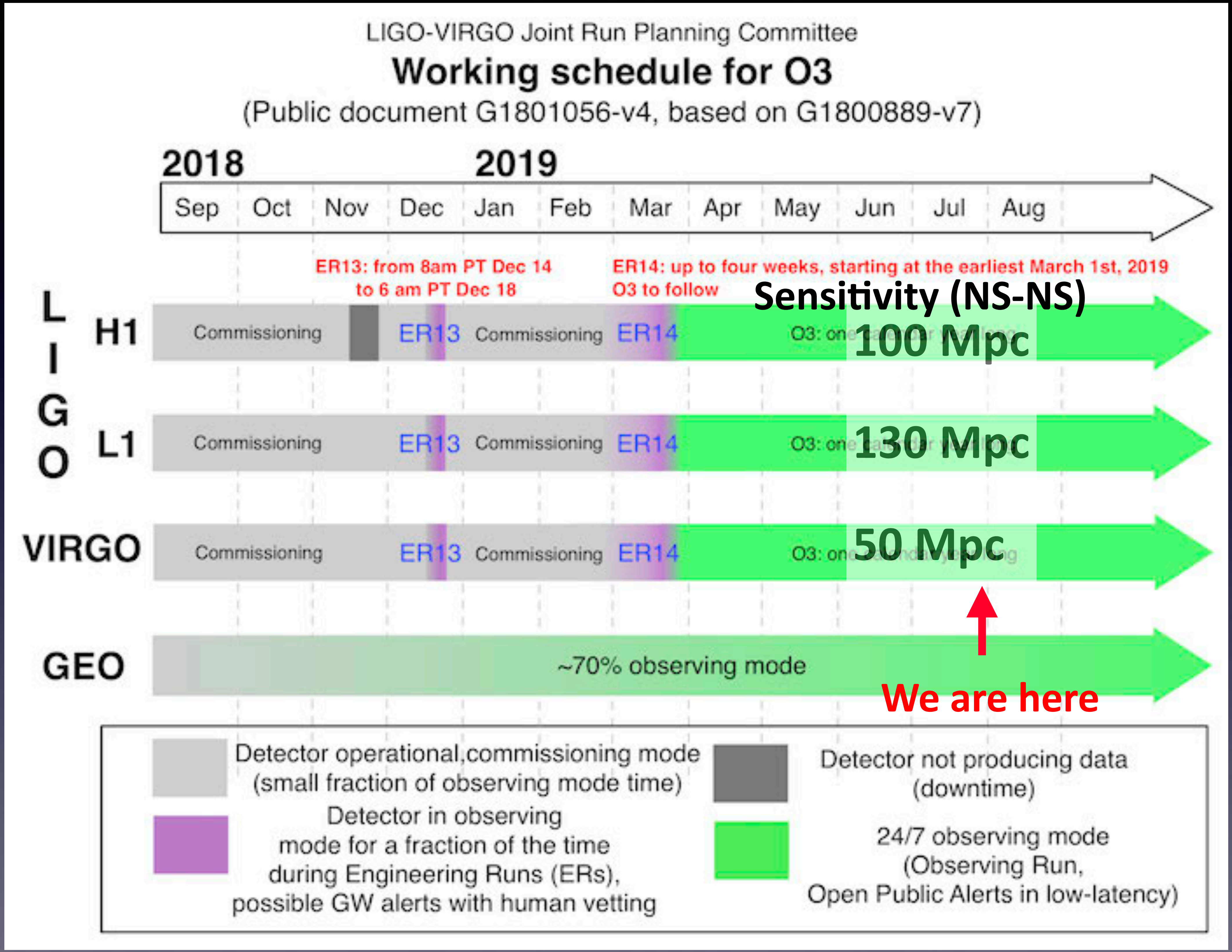
Rosswog+17, Hotokezaka+15, 18

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

Open issues

- Event rate?
- Which elements are produced?
  Similar to solar abundance ratios?



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

Expected event rate

R (NS-NS) ~ 100 - 4000 Gpc^{-3} yr^{-1}

$V \sim (4\pi/3)(100\ Mpc)^3 \sim 4 \times 10^{-3}\ Gpc^3$

$N \sim R \times V \sim 0.4 - 16\ yr^{-1}$

~ a few events/ yr

(0.4 event / yr - 1 event / 3 weeks)

Three events of interest so far

- S190425z: NS-NS (~150 Mpc, 7500 deg2)
- S190426c: NS-NS or BH-NS or noise (~380 Mpc, 1100 deg2
- S190510g: noise or NS-NS (~280 Mpc, 1200 deg2)

=> No convincing counterpart was identified

Summary: Neutron star merger

- **NS merger**
  - Possible origin of r-process elements
  - Radioactively powered transient: kilonova
- **Observations of neutron star mergers**
  - GW170817 and GRB 170817A
  - Both red and blue components
    => Production of lanthanide and lighter elements
  - Production rate fulfills the necessary condition
- **(Near) future**
  - Accurate event rate + production rate
  - Identification of elements

Goals of this lecture

- Why do supernovae (SNe) emit huge luminosity?
- Why does emission from SNe evolve with time?
- What can we learn from observations of SNe?

- Why do NS mergers emit electromagnetic emission?
- What can we learn from observations of NS merger?