中性子星合体とキロノバ

Neutron Star Mergers and Kilonovae

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Neutron Star Mergers and Kilonovae

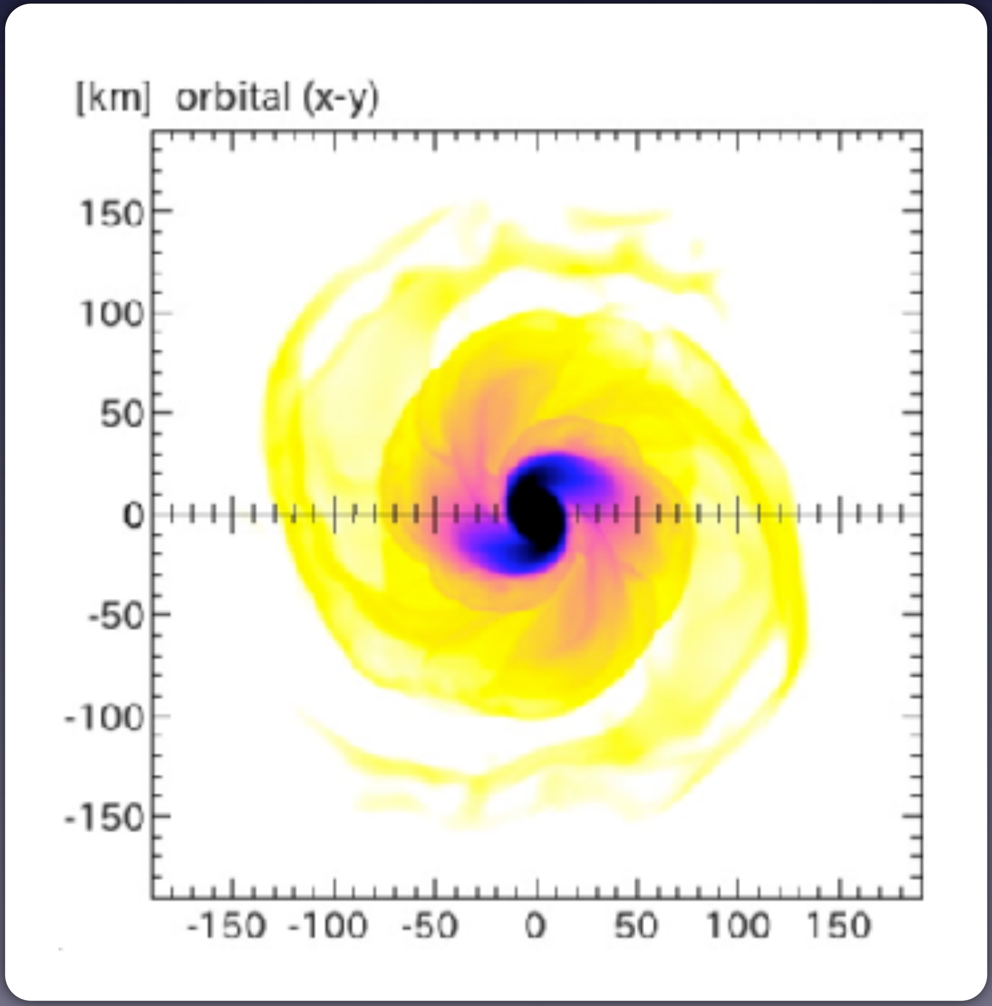
- Kilonova and the origin of heavy elements
- Lessons learned from GW170817

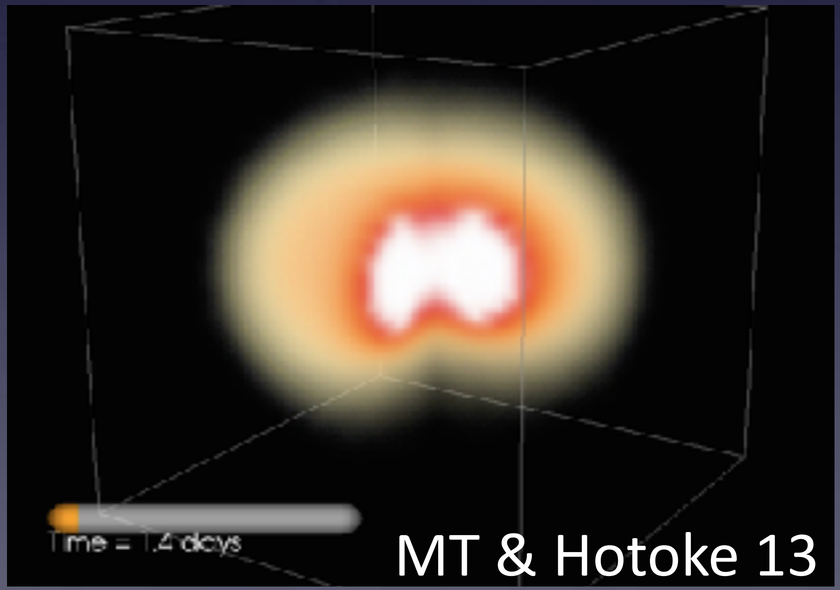
Merger → r-process nucleosynthesis → Radioactive decay => kilonova

(1) Dynamical ejection

(2) Post-merger ejection

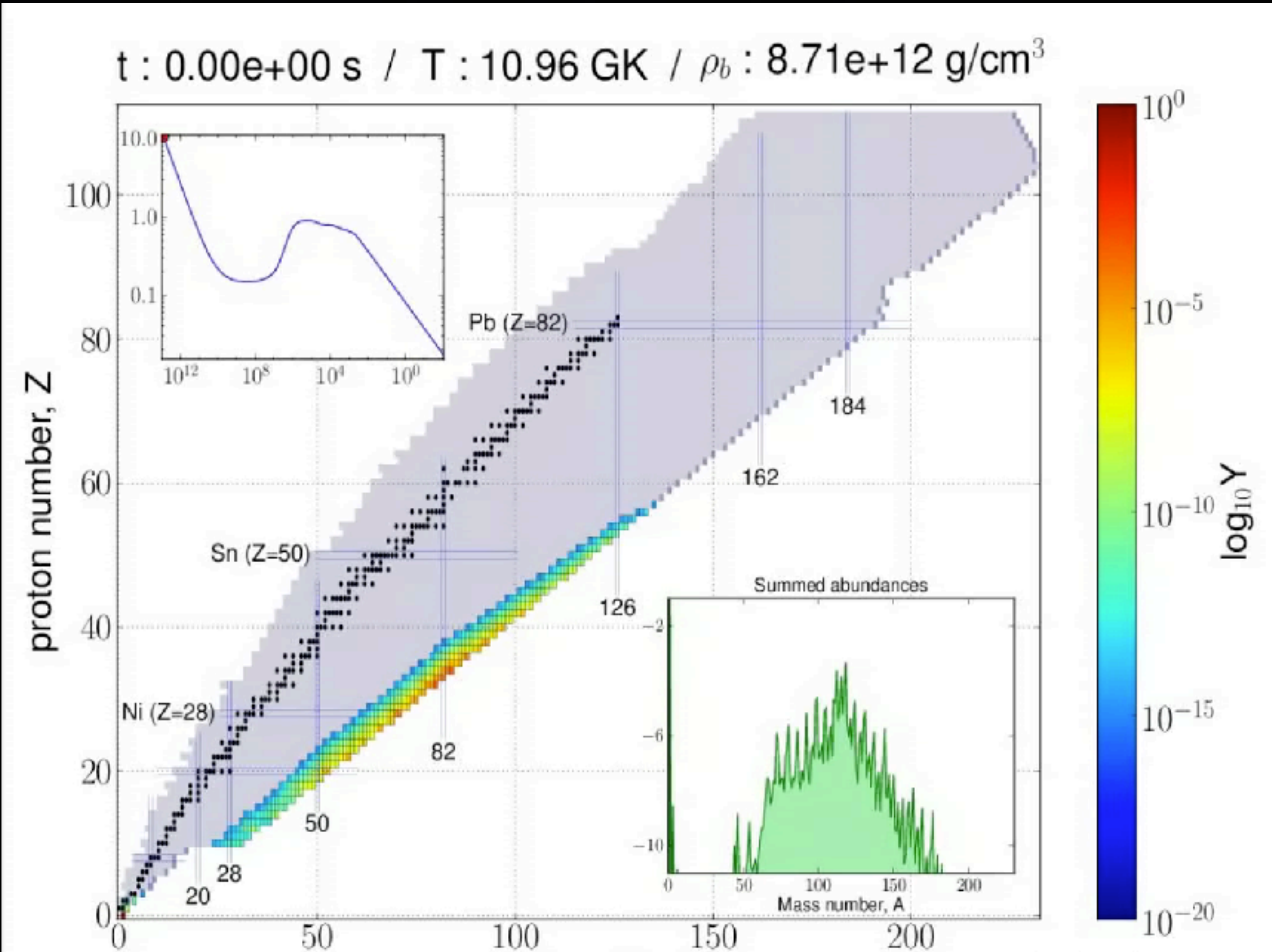
< 10 ms | ~< 100 ms | < 1 sec | ~> days





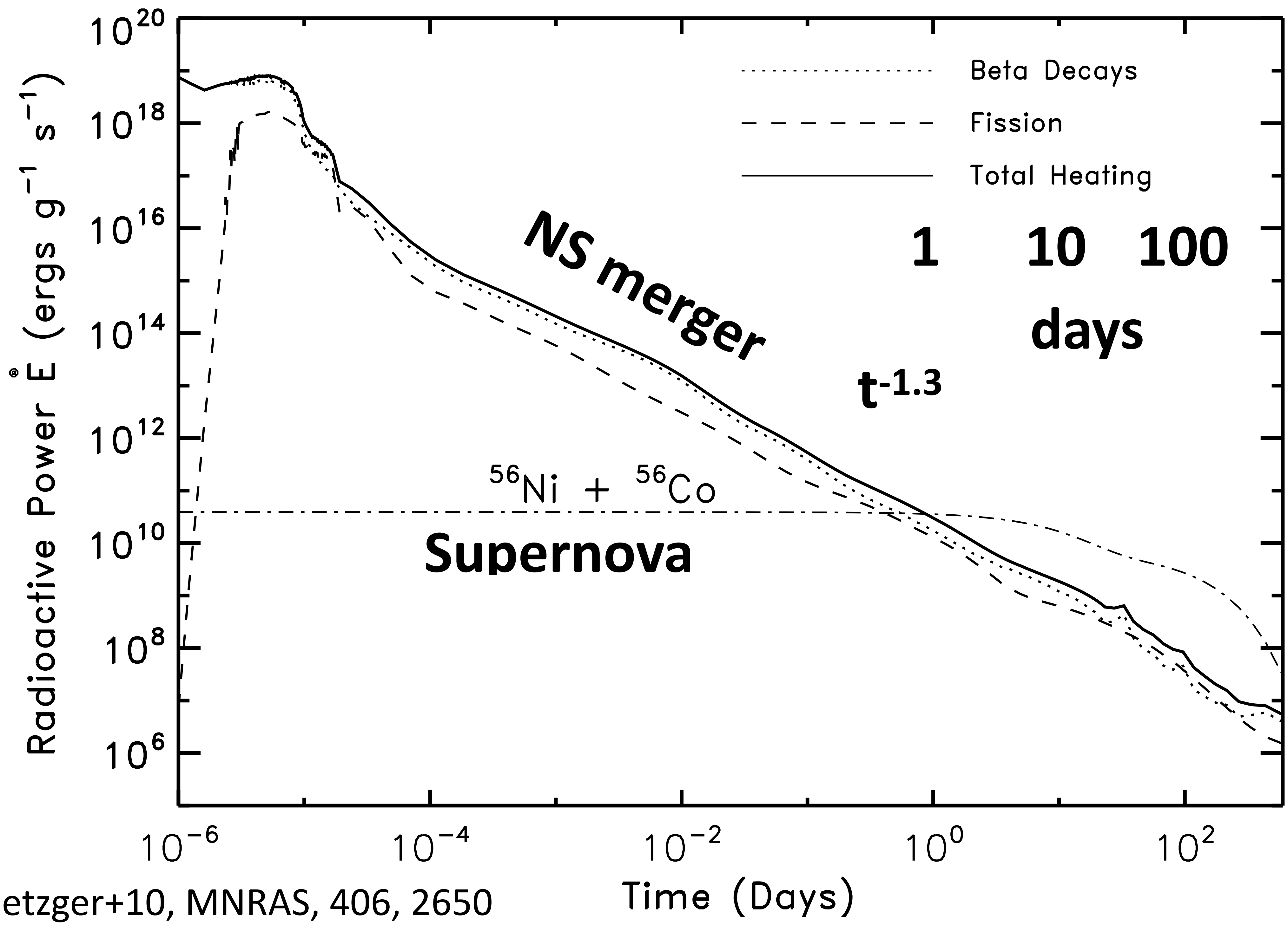
Sekiguchi+15,16

r-process nucleosynthesis in NS merger



O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

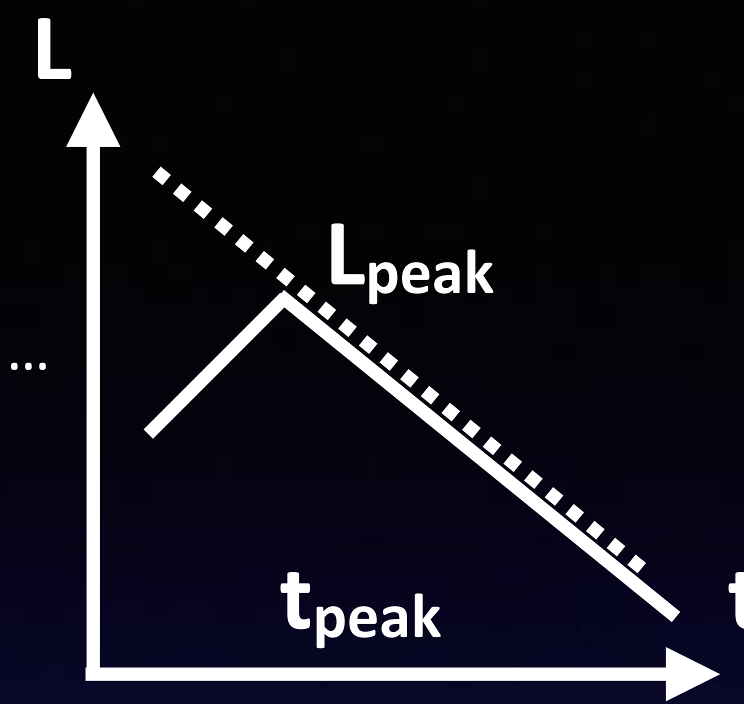
Radioactive energy => optical emission



Metzger+10, MNRAS, 406, 2650

“Kilonova/Macronova"

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



Timescale

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

bound-bound transitions of heavy elements

Luminosity

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

*assuming 50% thermalization

open s shell
(l=1)

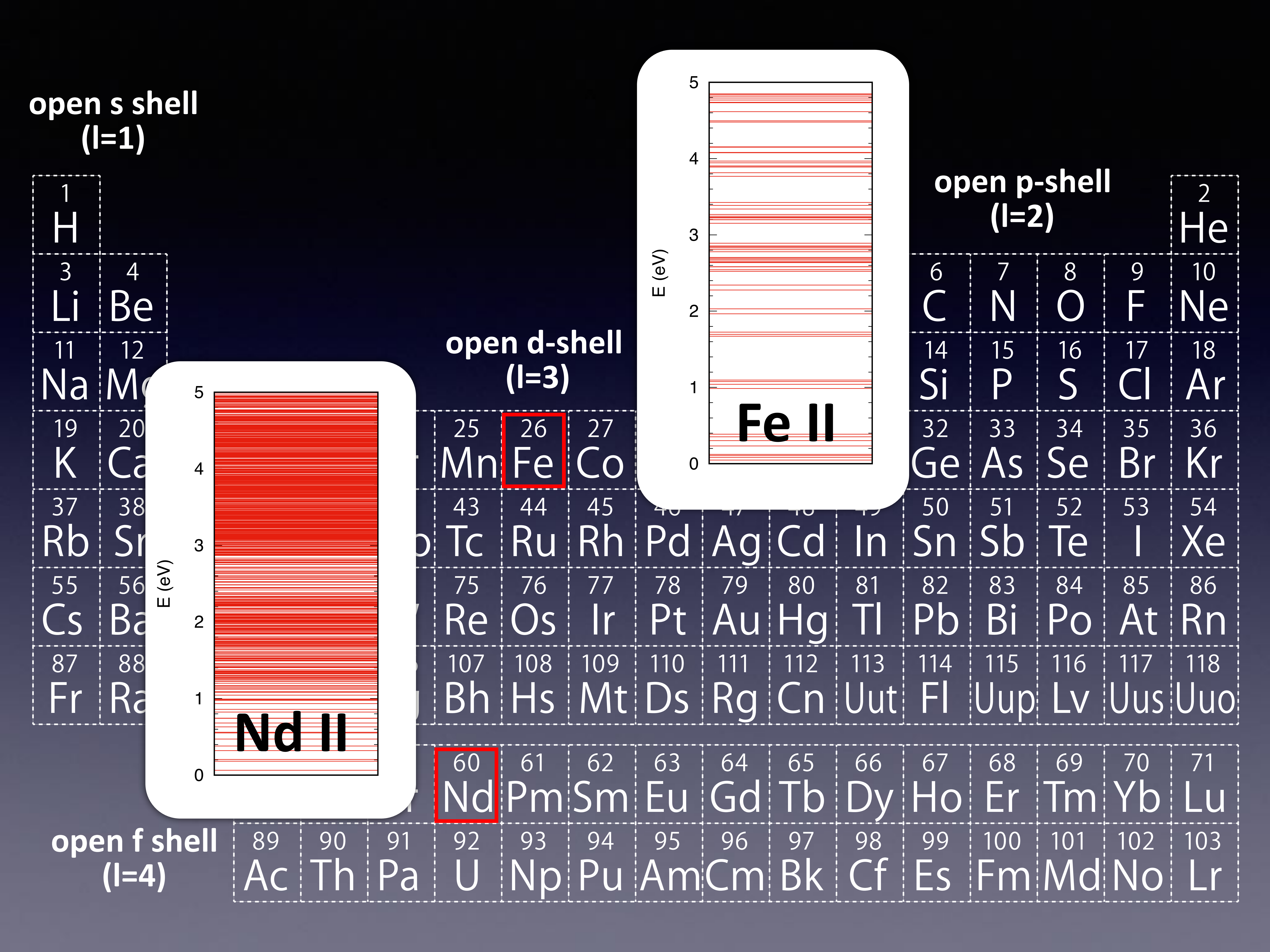
open p-shell
(l=2)

open d-shell
(l=3)

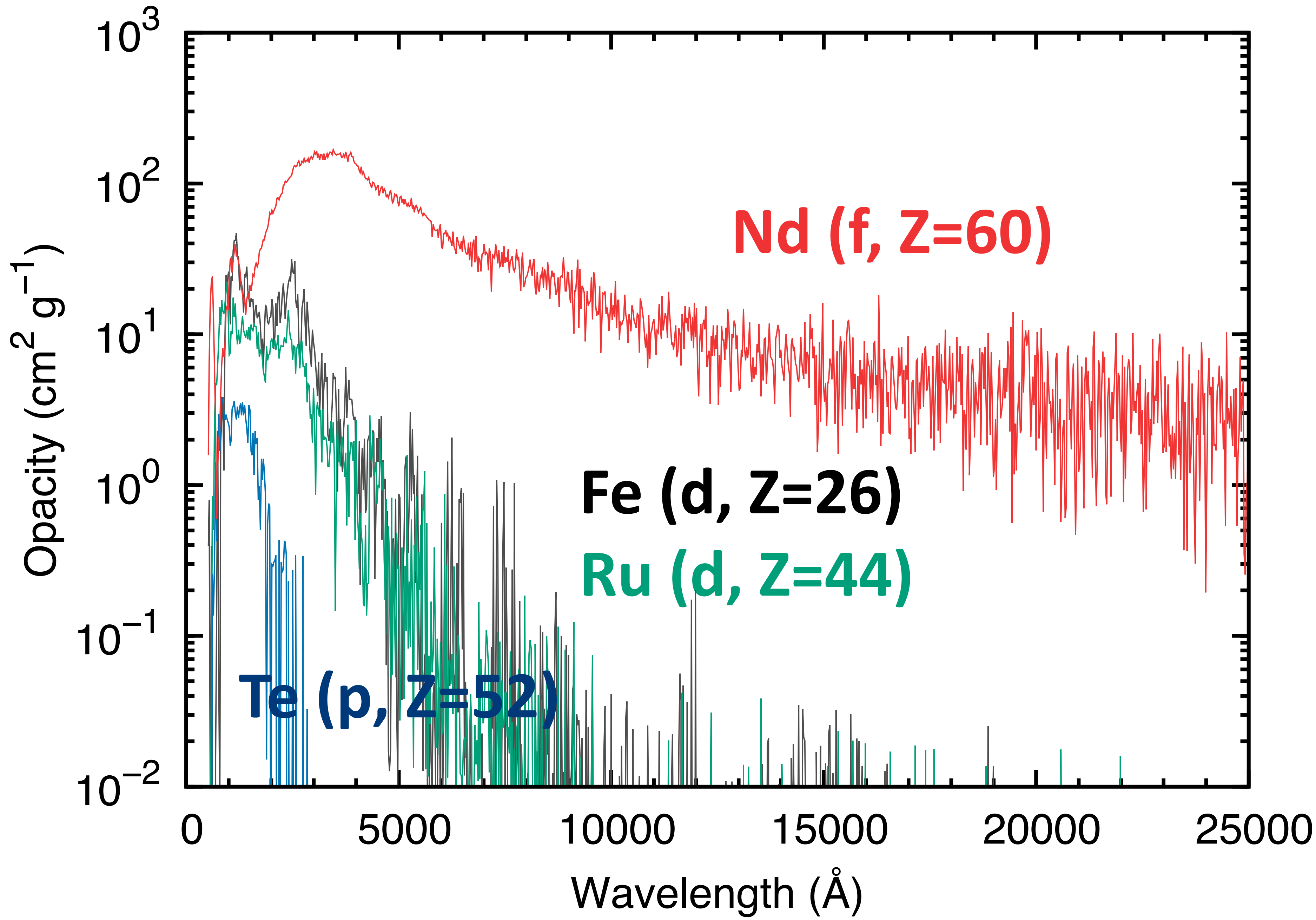
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 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 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

open f shell
(l=4)

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


open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
Fe II
Nd II
E (eV)
26 Fe
60 Nd

Bound-bound opacities of lanthanide elements



MT+18

κ (p shell) << κ (d shell) << κ (f shell)

Expected light curves of kilonova

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

t ~ weeks

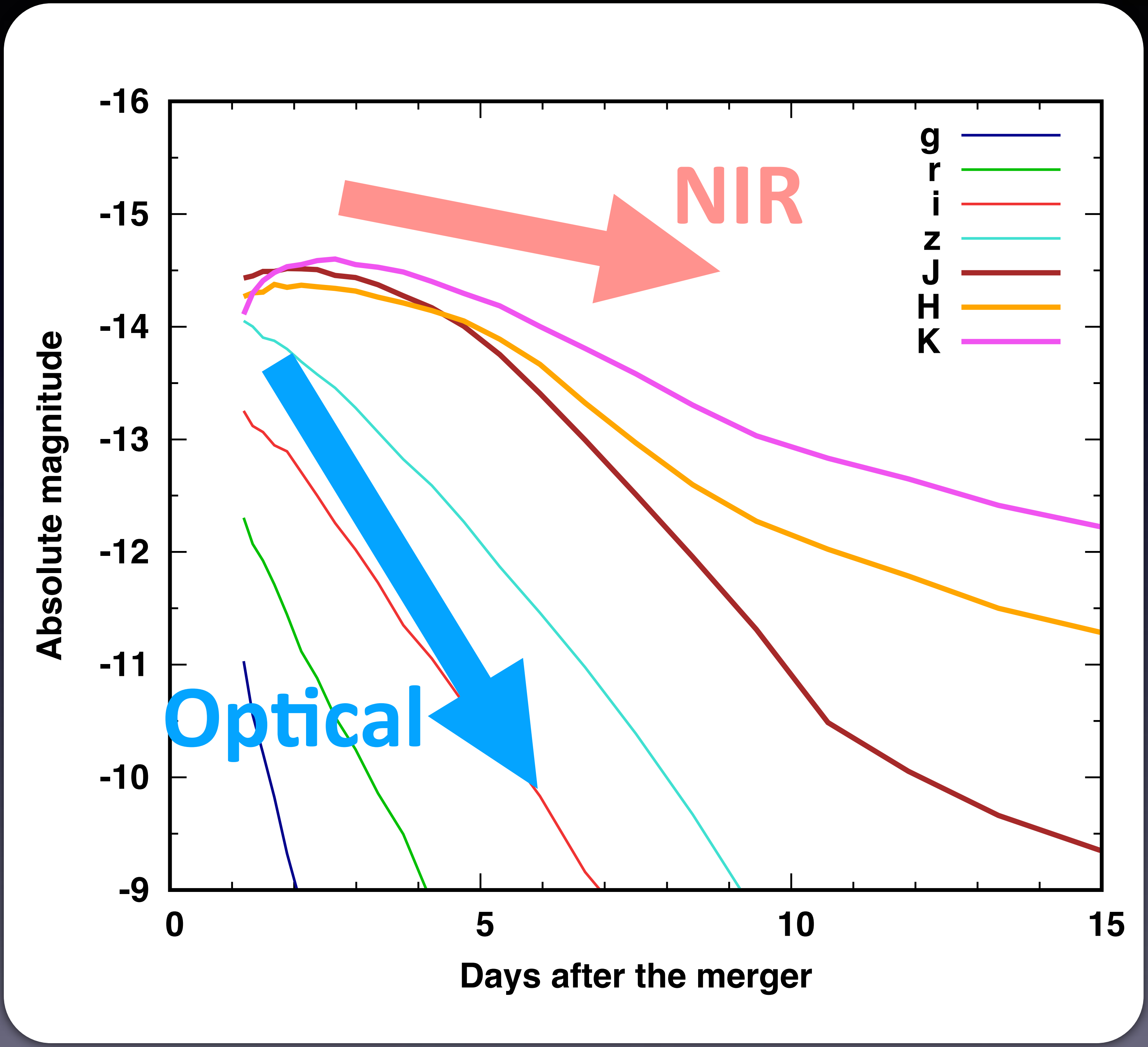
NIR > Optical

Smooth spectra

(high velocity)

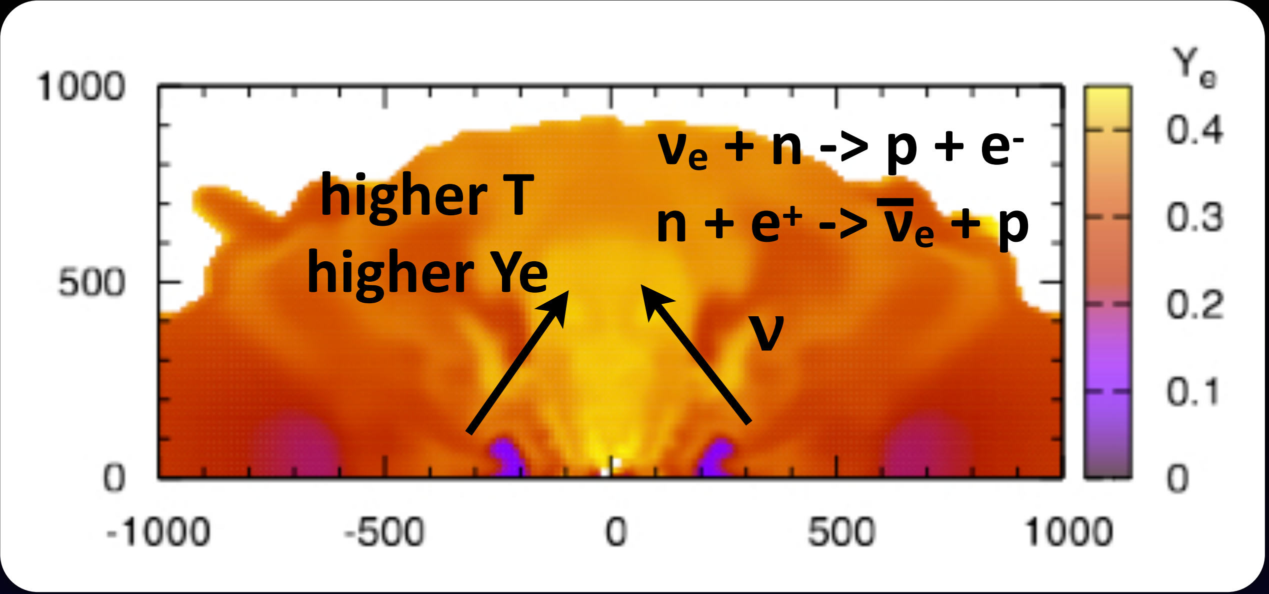
Kasen+13, Barnes & Kasen 13

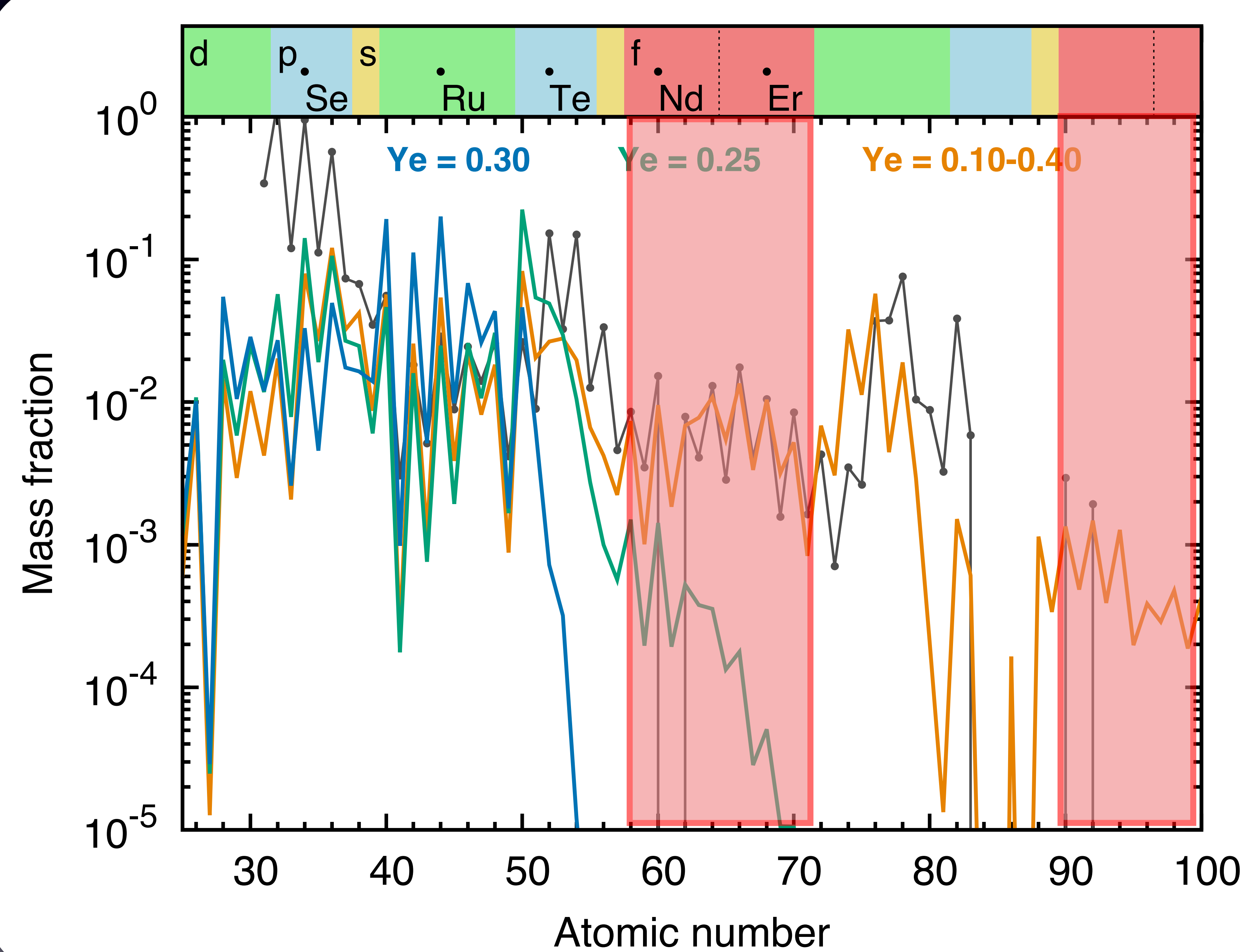
MT & Hotokezaka 13, MT+14,



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

- Low Ye => stronger r-process
- Neutrino absorption increases Ye





Nucleosynthesis are imprinted in the spectra

"Blue kilonova"

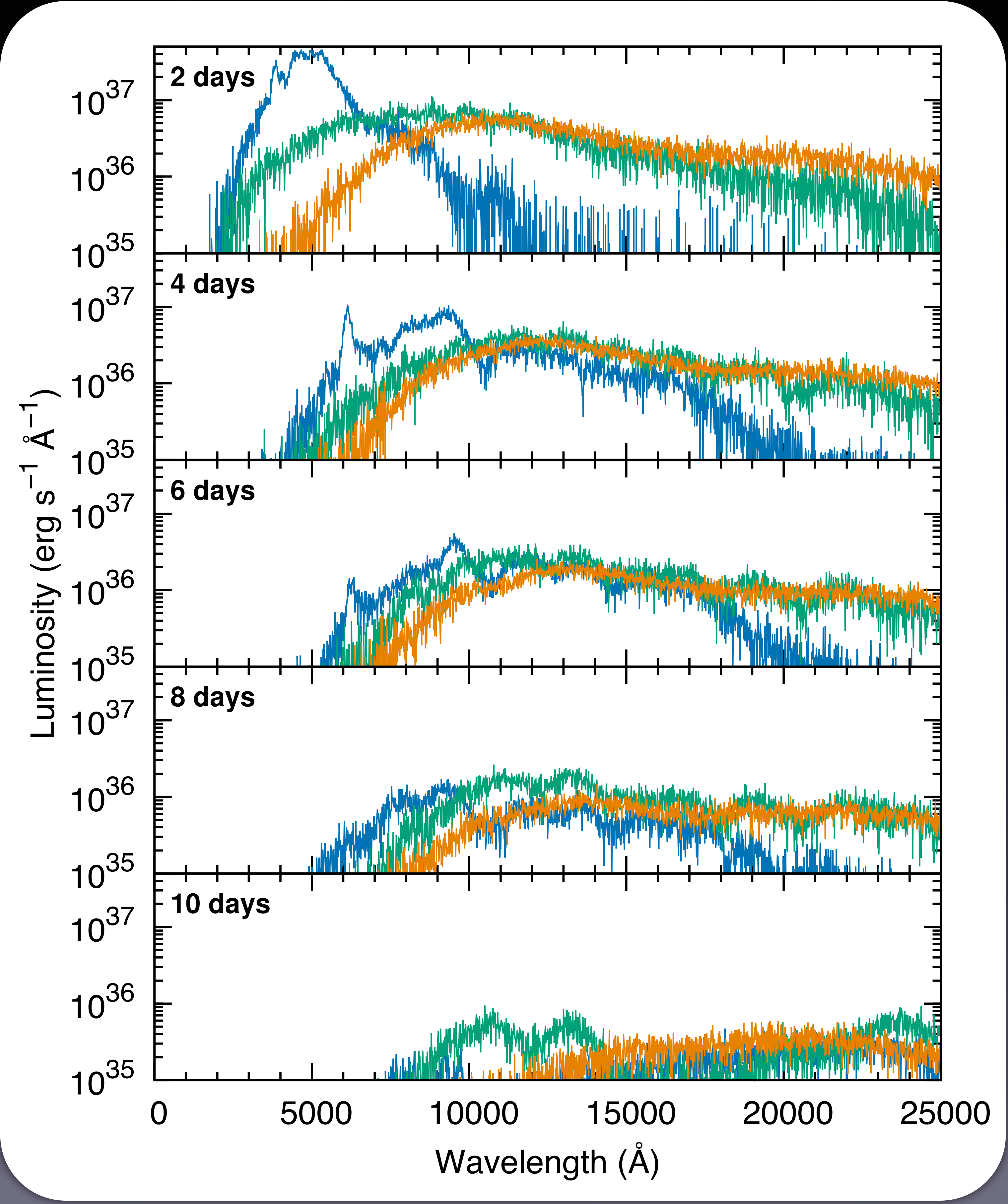
High Ye (Ye = 0.30)
(Lanthanide-free)

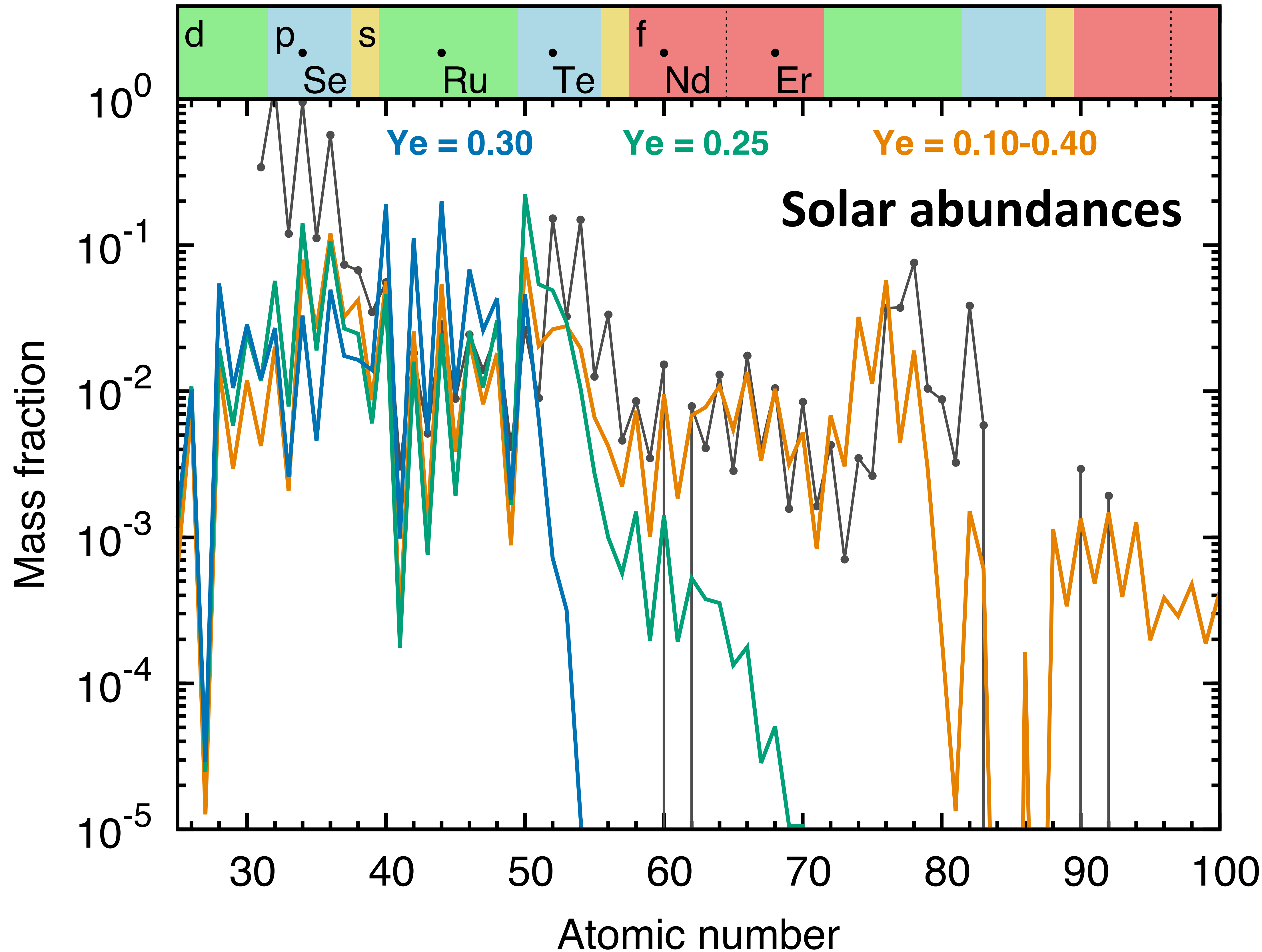
Medium Ye (Ye = 0.25)

Low Ye
(Ye = 0.1)

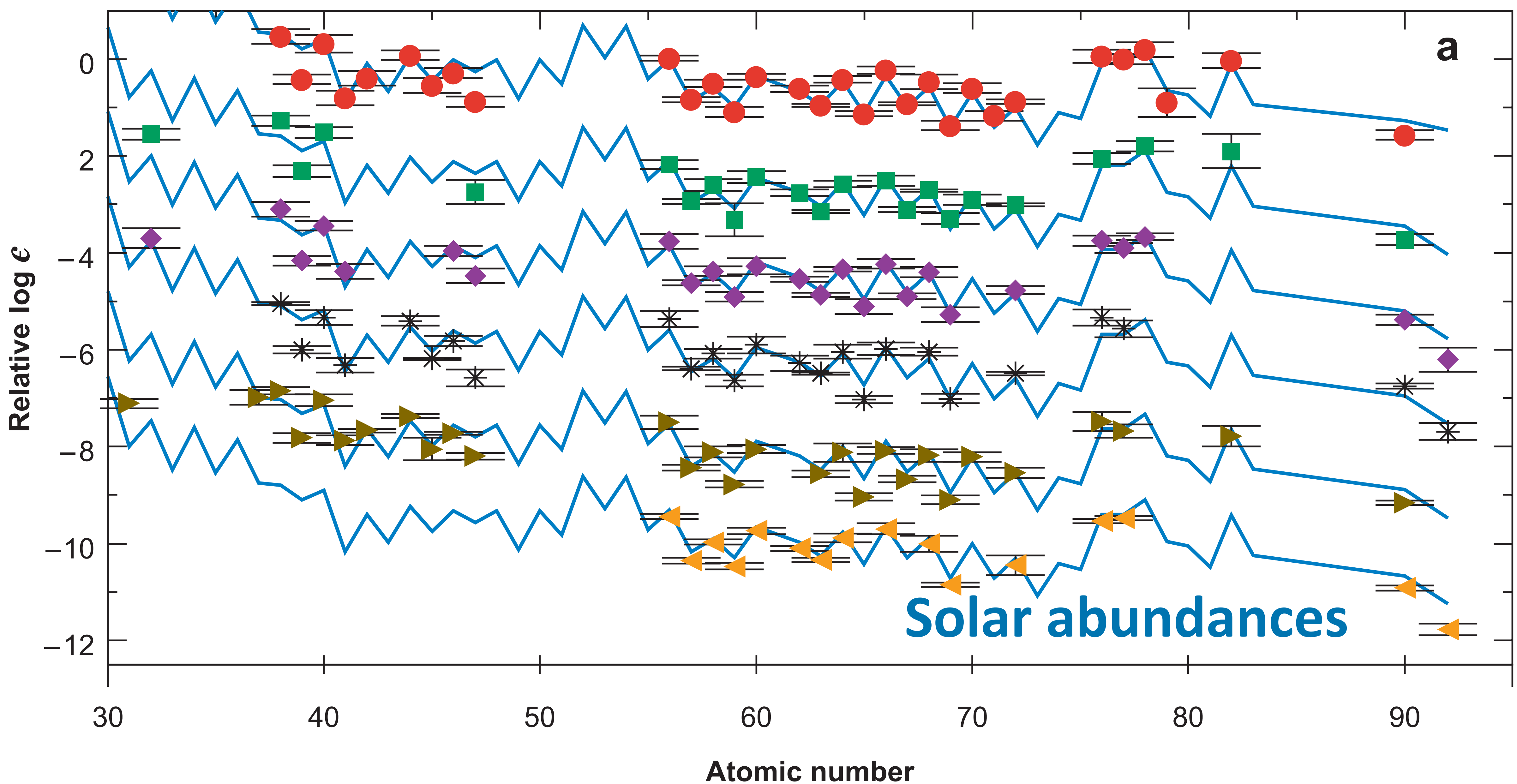
"Red kilonova"

MT+17

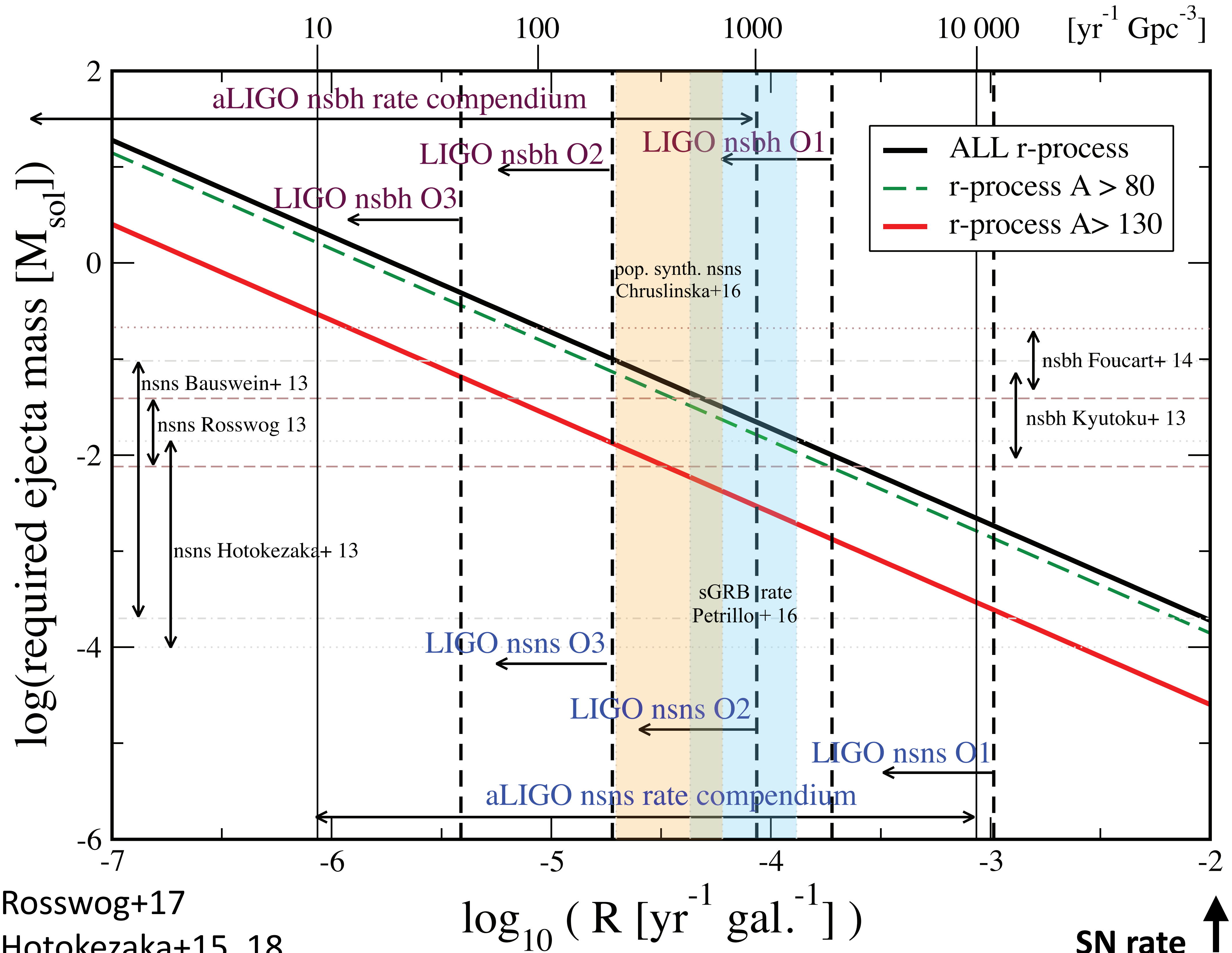



d
p
s
f
Se
Ru
Te
Nd
Er
Ye = 0.30
Ye = 0.25
Ye = 0.10-0.40
Solar abundances
Mass fraction
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
30
40
50
60
70
80
90
100
Atomic number

“Universality” of r-process abundances



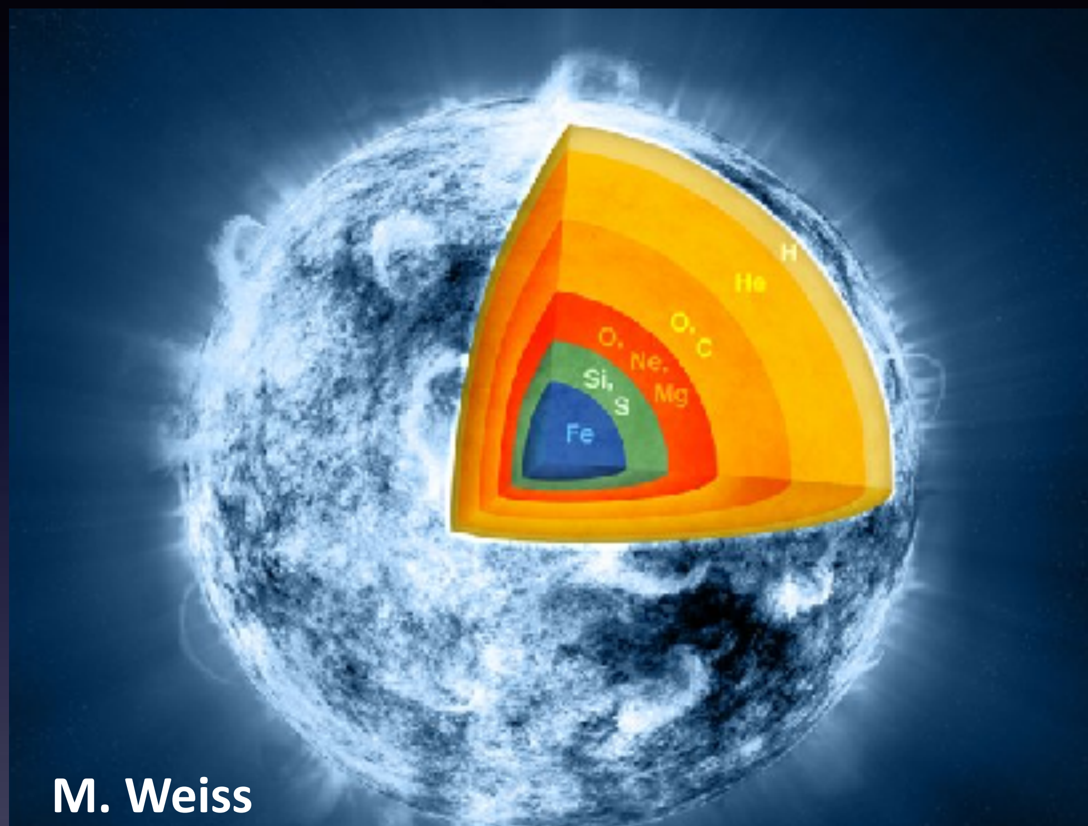
Sneden+2008



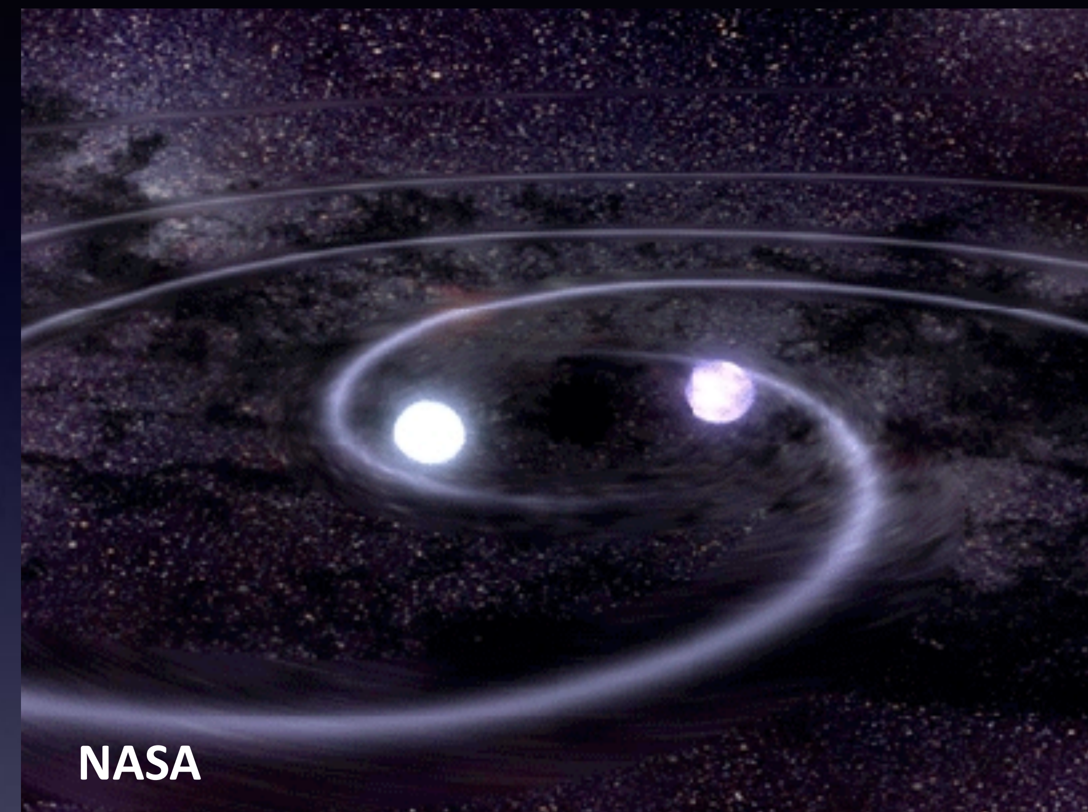
Rosswog+17
Hotokezaka+15, 18

Origin of r-process elements

Supernova



NS merger



Well known event rate

Robust r-process

Difficult to have r-process?

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

Unknown event rate
and ejection per event

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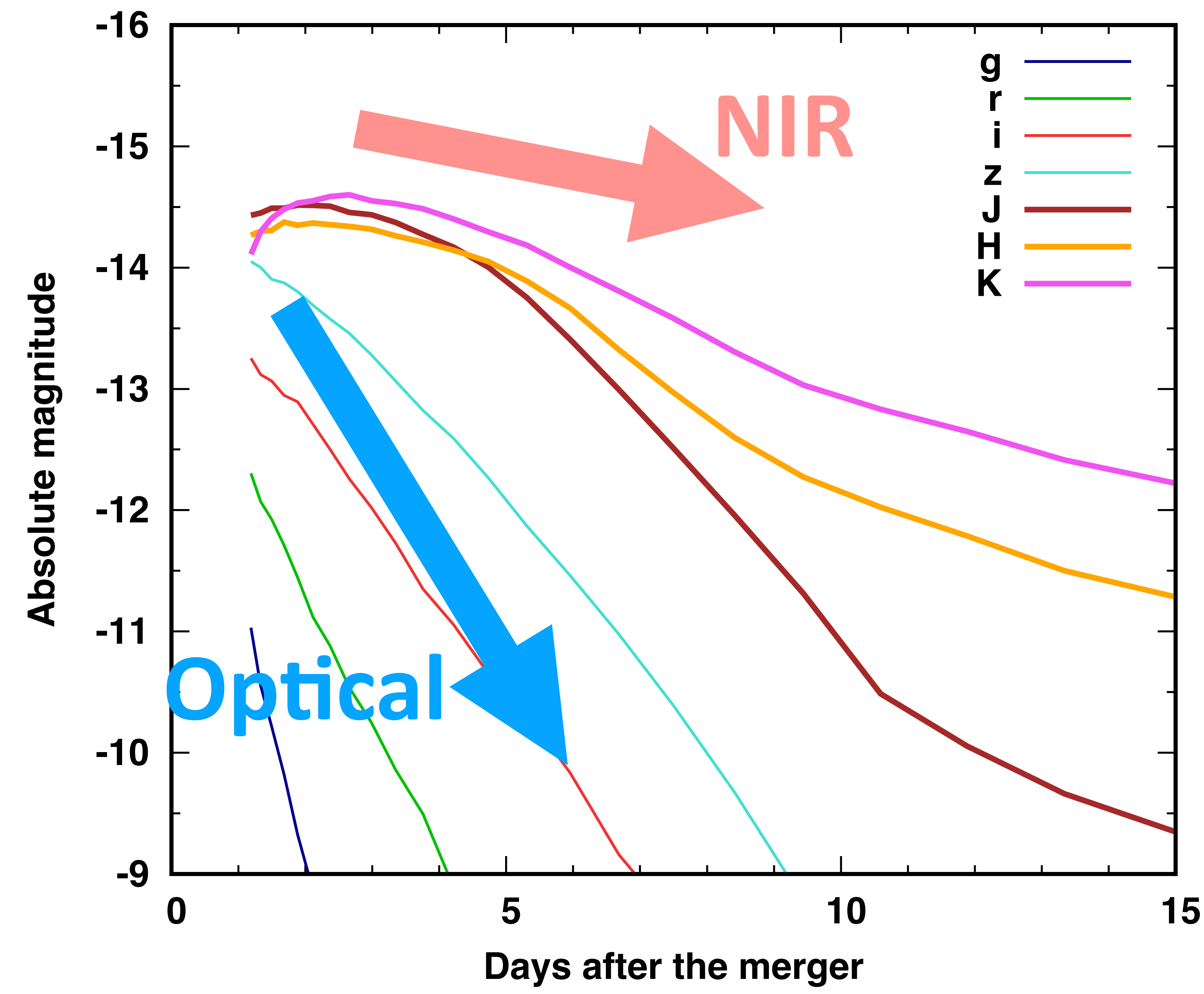
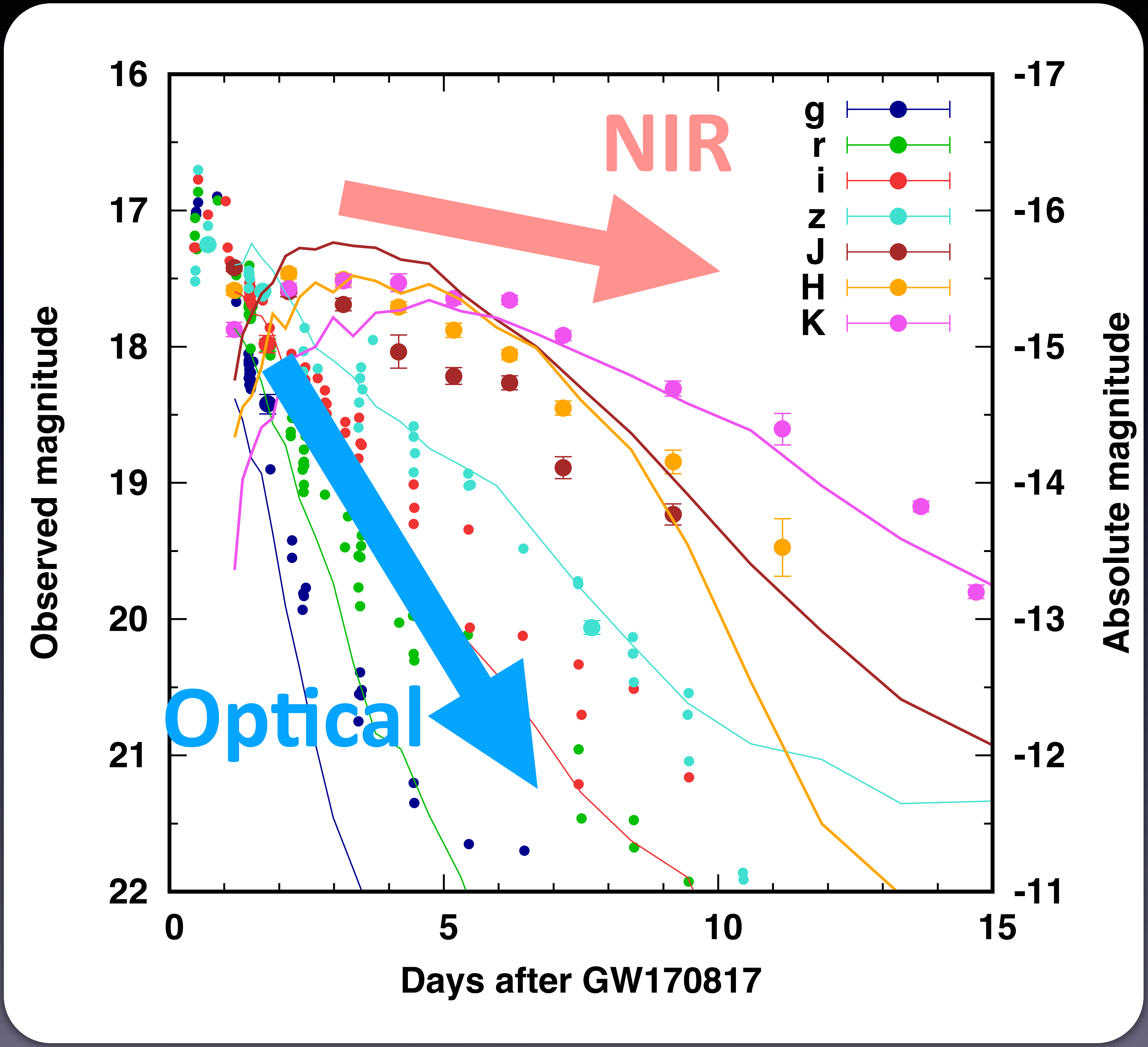


GW170817: light curves

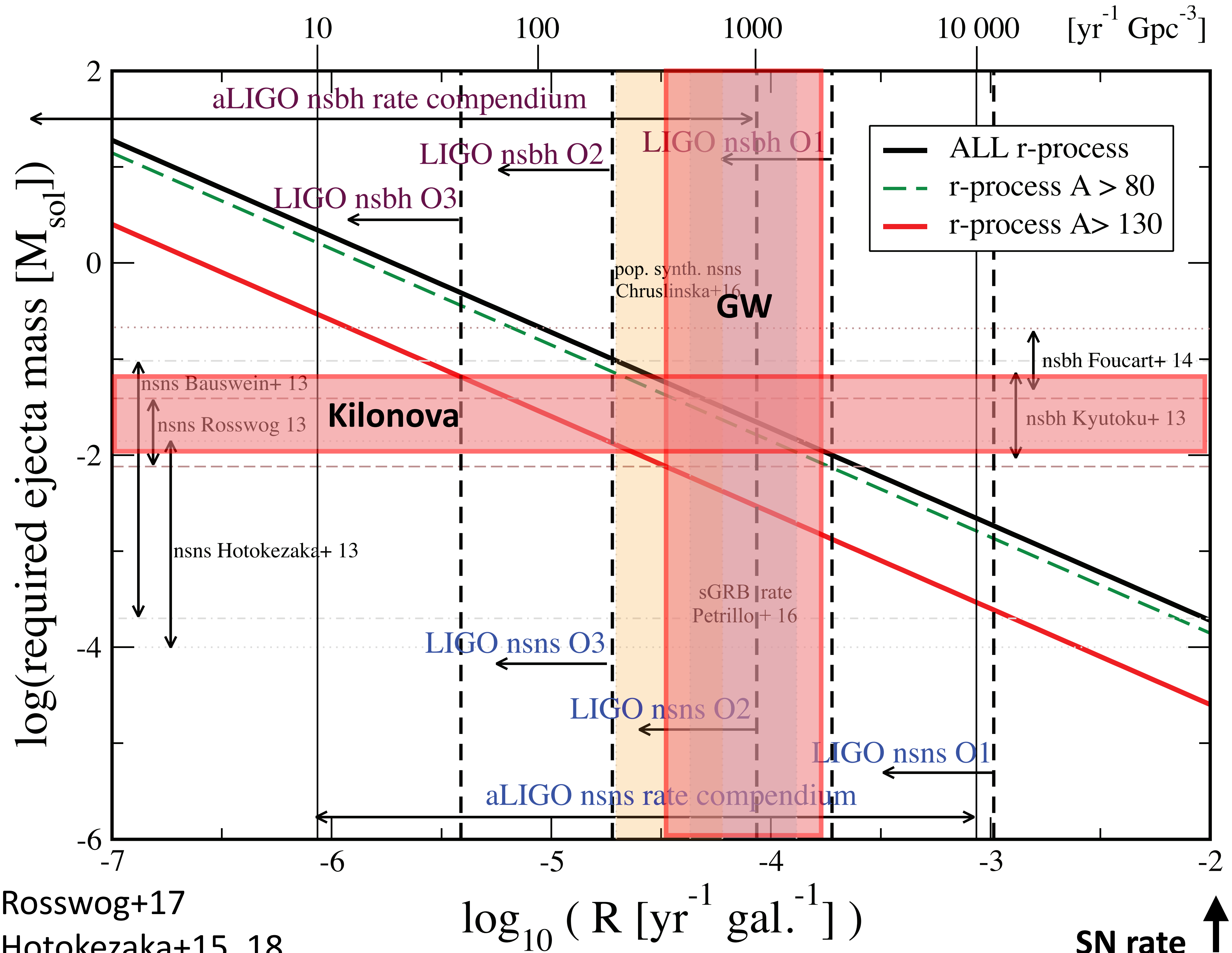
Single component model
- Mej = 0.03 Msun
- <v> = 0.1c
- Ye = 0.25

Model: MT+17b

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



Ejecta mass (La-rich) ~0.03 Msun => post-merger ejecta



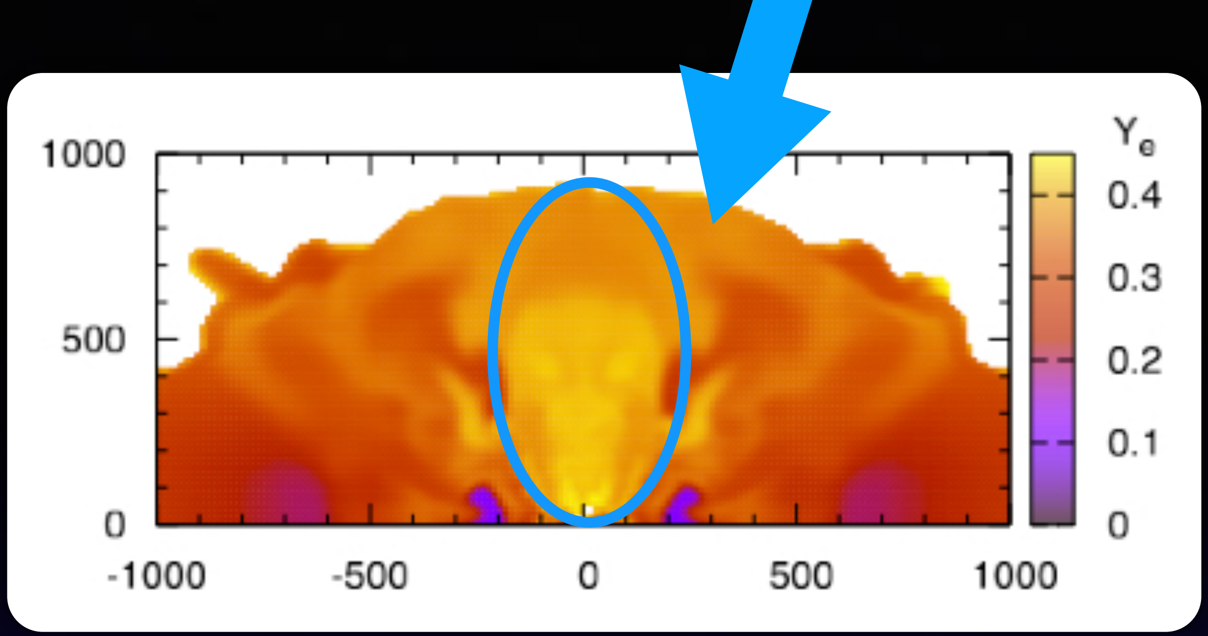
Rosswog+17

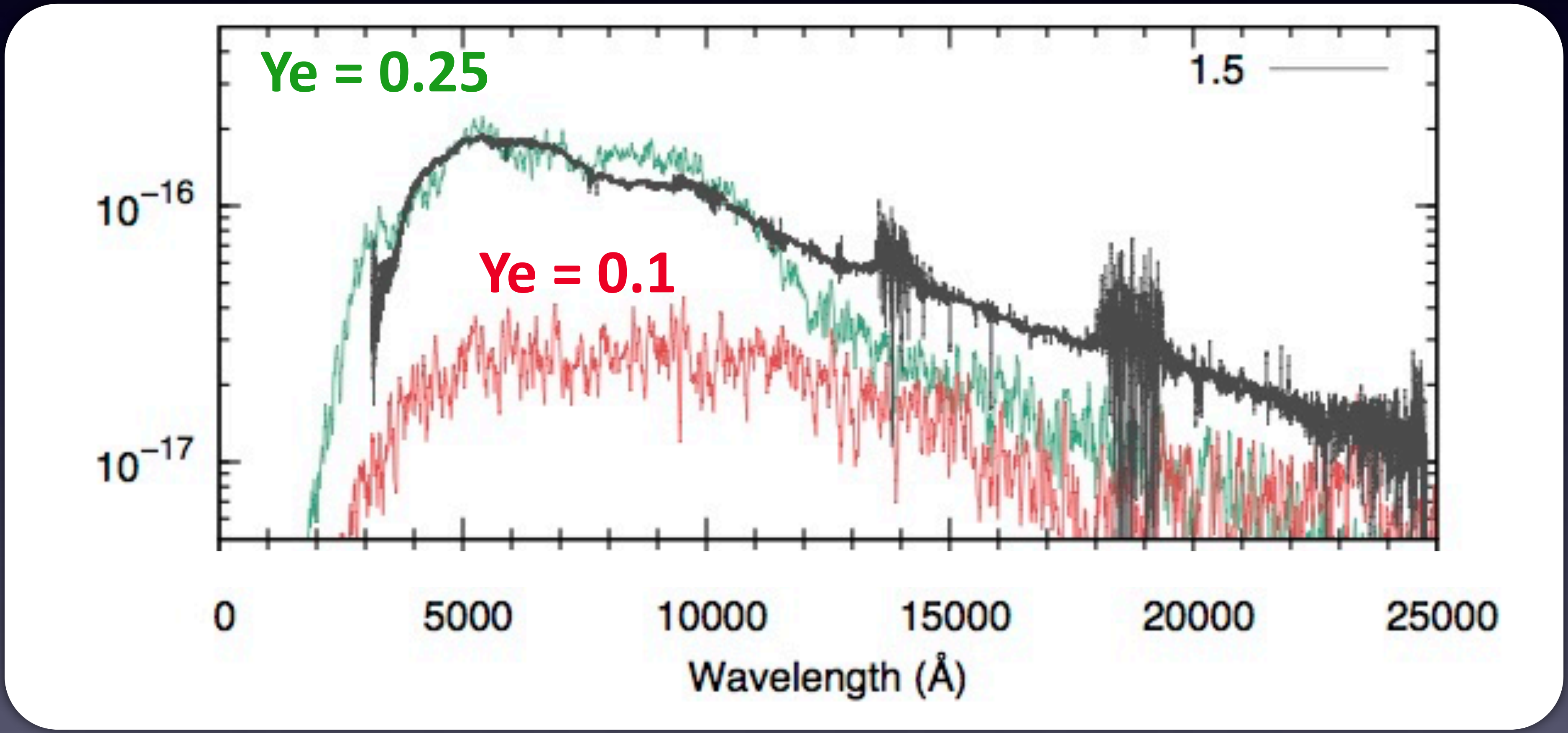
Hotokezaka+15, 18

CAVEATS: abundance ratios are not well constrained

Presence of “blue” kilonova

Cowperthwaite et al. 2017;
Drout et al. 2017; Nicholl et al. 2017;
Villar et al. 2017





MT+2017

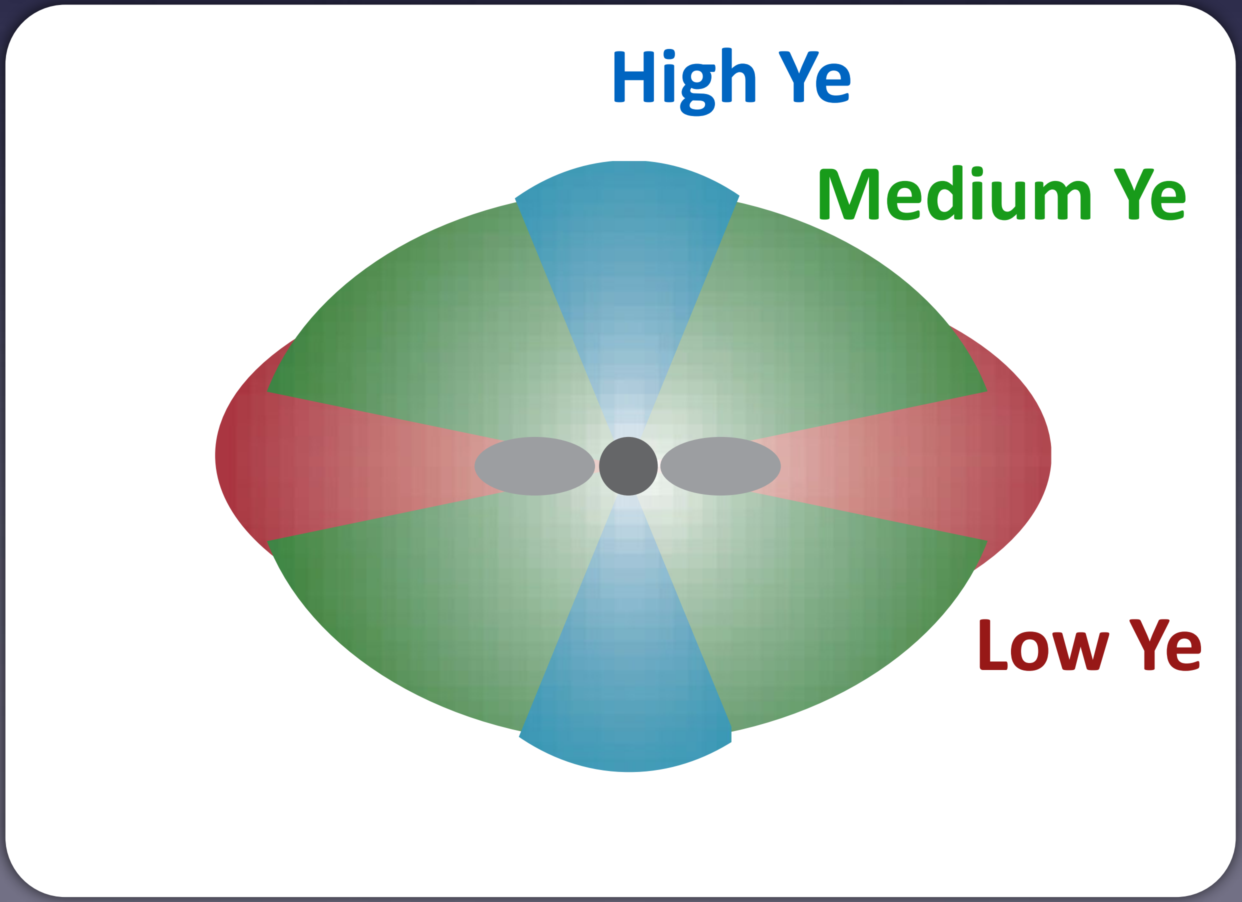
Mej (blue) ~ 0.02 Msun

too much for dynamical ejecta? => wind?

But v ~ 0.2c (difficult with wind ejecta)

Many open questions

- **Origin of ejecta? (Shibata-san's talk)**
  - Origin of "blue" and "red" component?
  - Blue component with high velocities?
- **Abundance pattern? Similar to solar abundances??**
  - 3rd peak?? (Au and Pt!)



Summary

- **NS mergers and kilonova**
  - Robust r-process nucleosynthesis
  - Radioactively powered EM emission
- **GW170817**
  - Red and blue components
    => Ye ~ 0.25 or X(Lan) ~ 10^{-3}-10^{-2} if single component
  - ~0.03 Msun ejection with Lanthanide
    => Enough to explain the origin of r-process elements
- **Open questions**
  - Ejecta mass: universal?
  - Abundance partners: solar abundance?
    => fraction of blue/red components