中性子捕獲反応で迫る宇宙の重元素合成

中性子星合体の可視赤外線スペクトルで探る r-process元素合成の痕跡

土本 菜々恵 (東北大学)

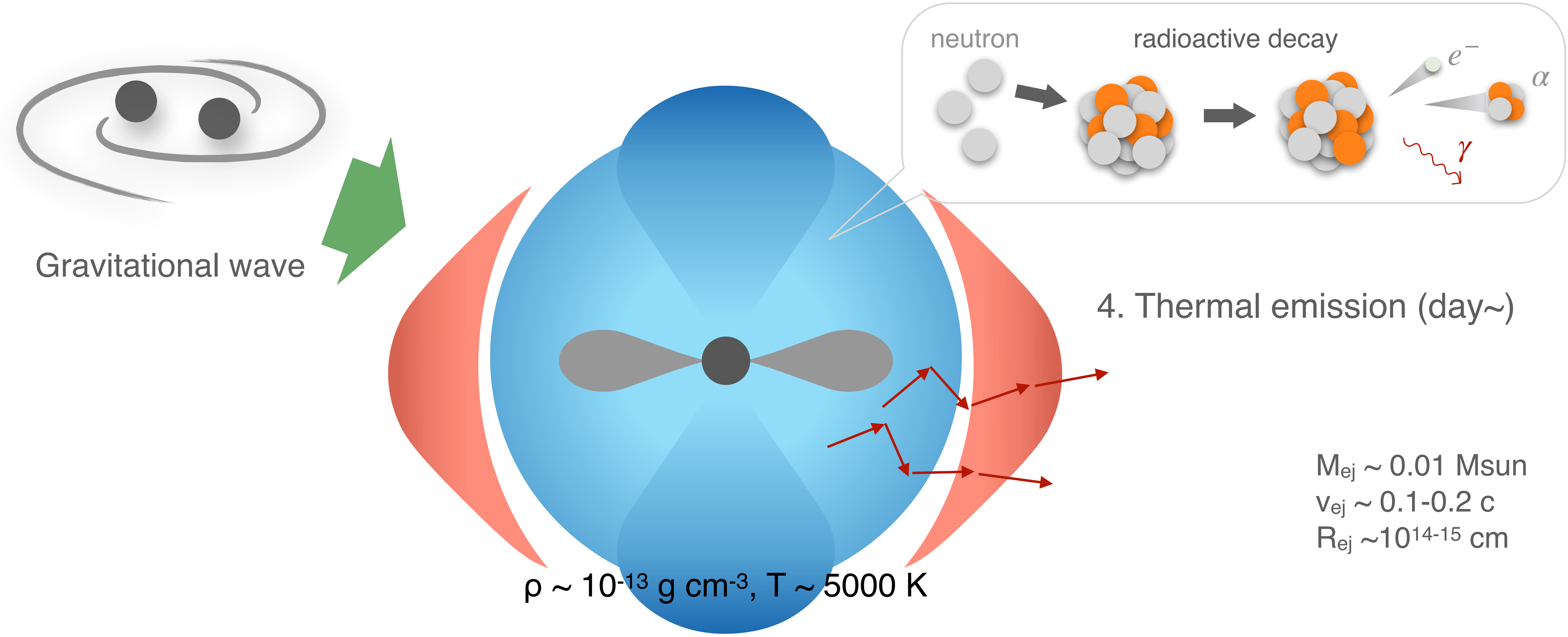
田中雅臣 (東北大学)、加藤太治 (核融合研)、川口恭平 (東大宇宙線研)、
仏坂健太 (東大RESCEU)、和南城伸也 (マックスプランク/AEI)

Domoto et al. 2021, ApJ, 913, 26
Domoto et al. 2022, ApJ, 939, 8

Binary neutron star merger

- One promising site for r-process nucleosynthesis
- One of the most important targets of multi-messenger astronomy

1. Merger (~ms)
2. Mass ejection (~s)
3. Nucleosynthesis (~s)
4. Thermal emission (day~)



$\rho \sim 10^{-13}$ g cm^{-3}, T ~ 5000 K

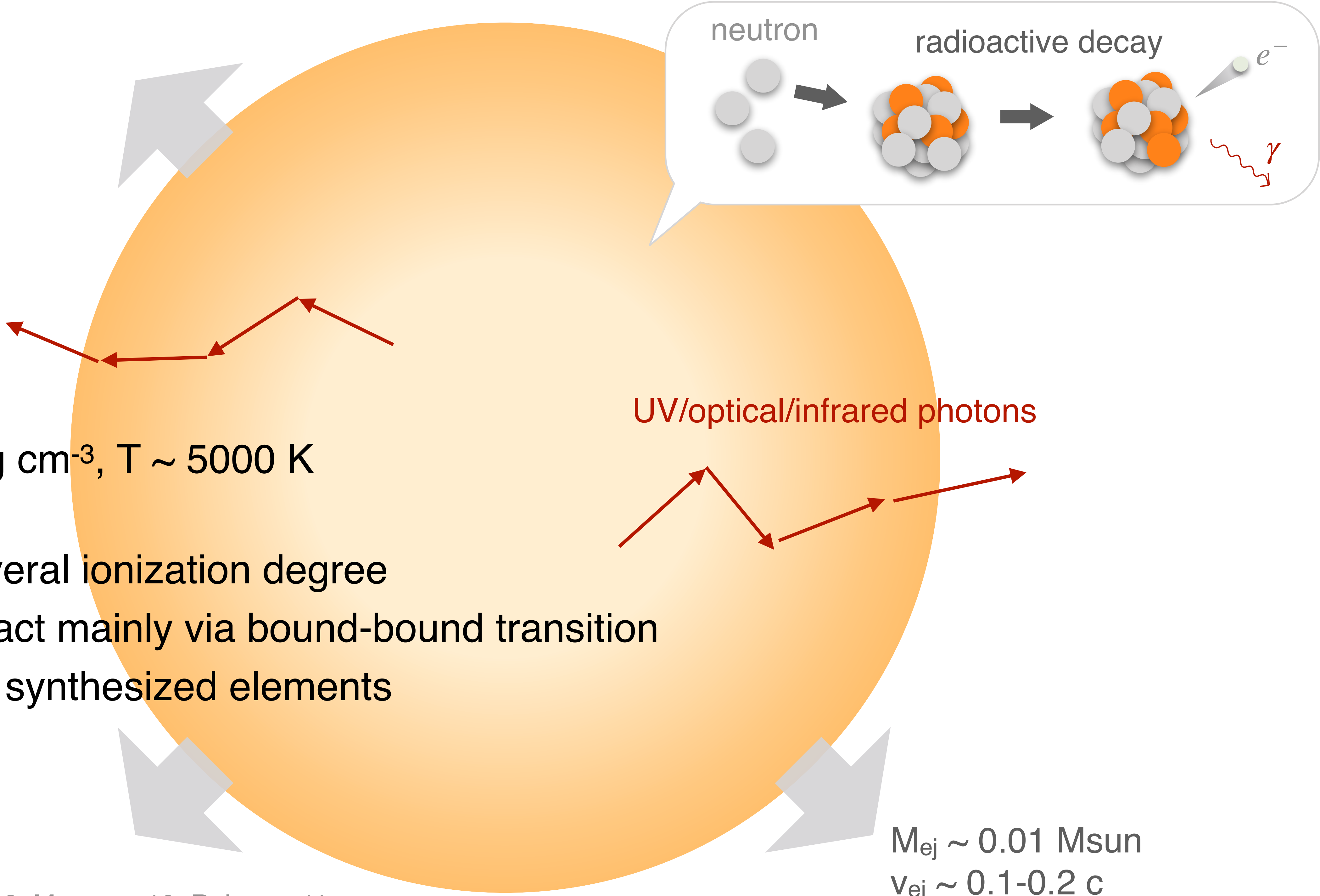
M_{ej} ~ 0.01 Msun
v_{ej} ~ 0.1-0.2 c
R_{ej} ~10^{14-15} cm

e.g., Lattimer & Schramm 74, Eichler+89, Li & Paczynski 98, Freiburghaus+99, Metzger+10, Goriely+11, Roberts+11,Tanaka & Hotokezaka 13…

Kilonovae

~day-week

Radioactively-powered UV/optical/infrared emission



$\rho \sim 10^{-13}$ g cm^{-3}, T ~ 5000 K

Neutral to several ionization degree

Photons interact mainly via bound-bound transition

→ Imprints of synthesized elements

$M_{ej} \sim 0.01$ Msun
$v_{ej} \sim 0.1\text{-}0.2$ c
$R_{ej} \sim 10^{14\text{-}15}$ cm

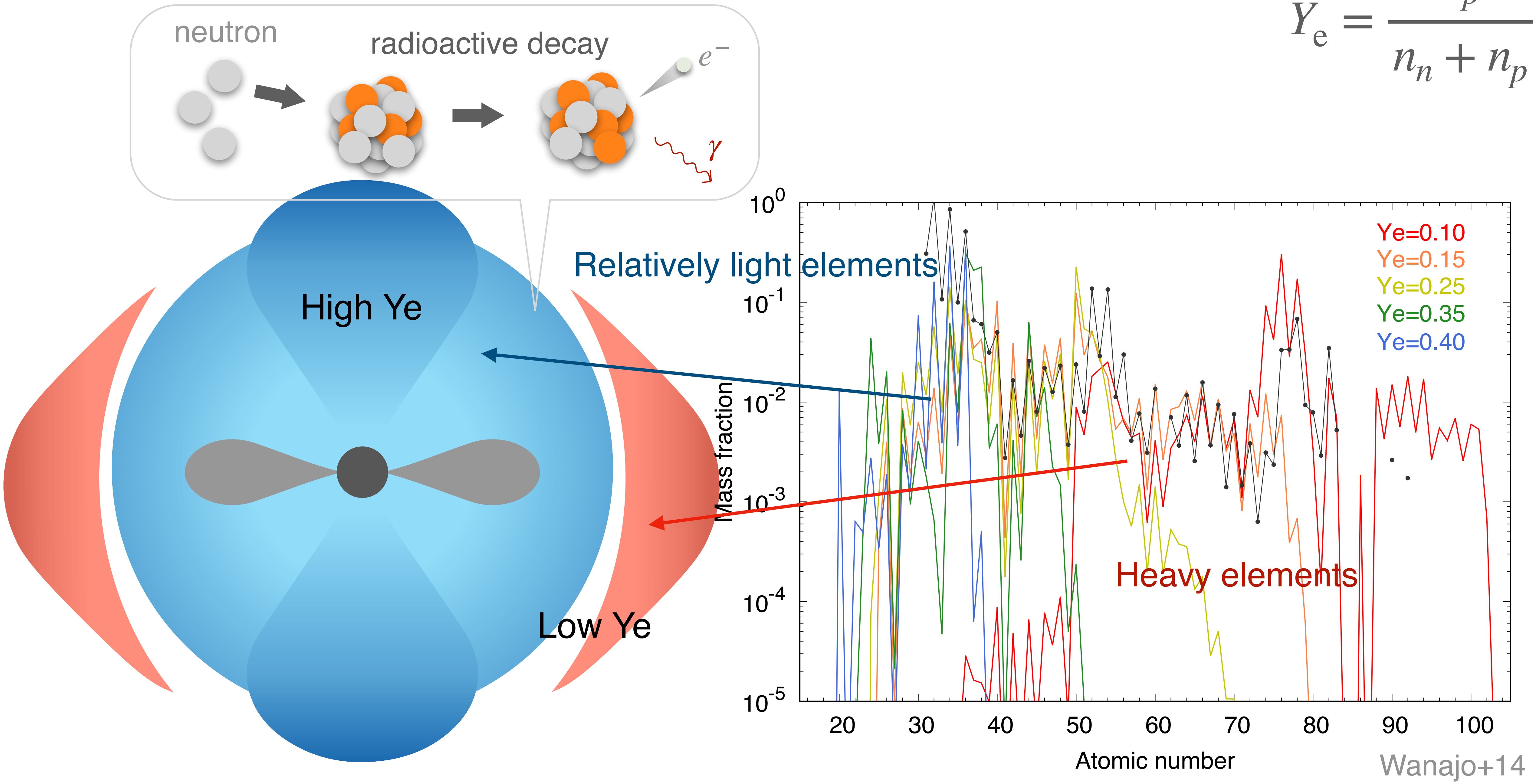
e.g., Li & Paczynski 98, Metzger+10, Roberts+11,
Tanaka & Hotokezaka 13, Kasen+13, 17, Fontes+20,
Tanaka+20, Banerjee+20, 22, Kawaguchi+18, 20, …

Nucleosynthesis/Abundances

~1 s

Physical conditions are reflected to synthesized elements

$$Y_{\mathrm{e}} = \frac{n_p}{n_n + n_p}$$



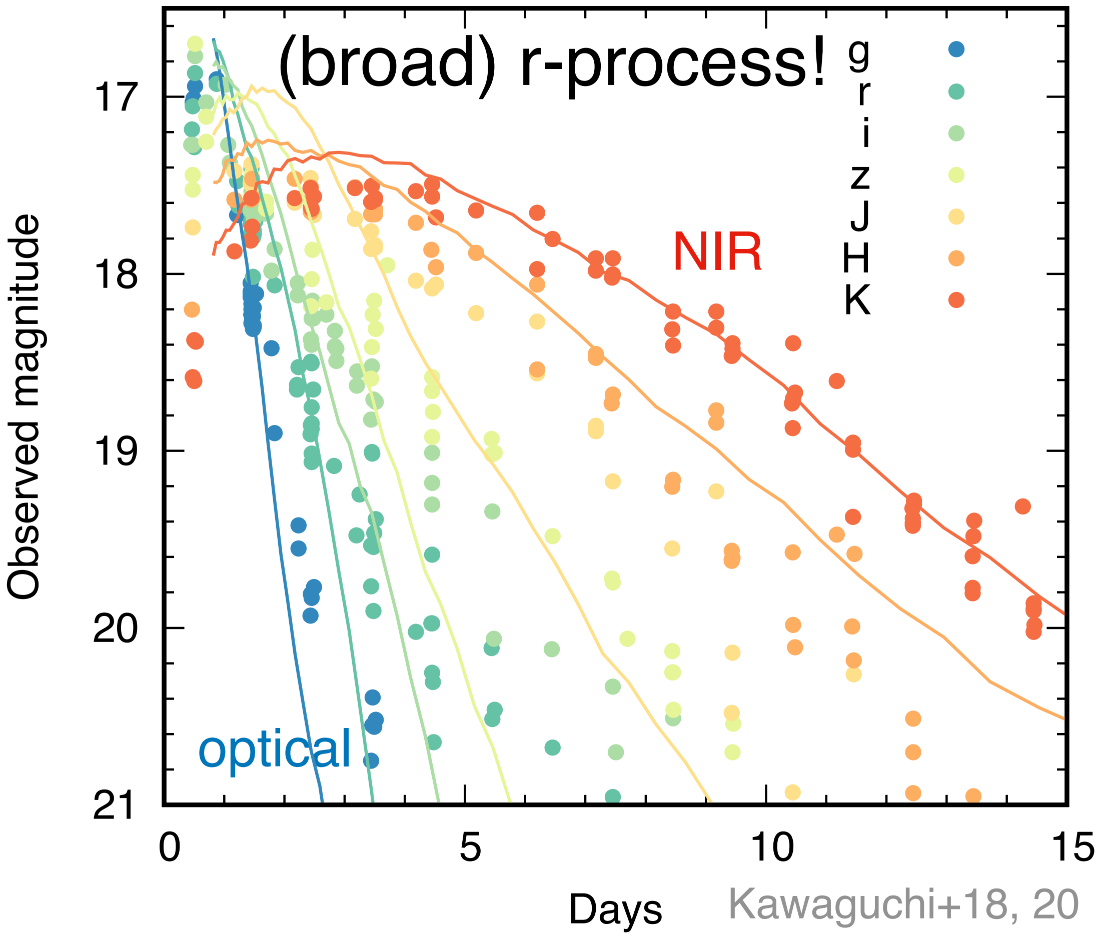
Wanajo+14

e.g., Wanajo+14, Just+15, Martin+15, Lippuner+17, …

Kilonova in GW170817

e.g., Arcavi+17, Smartt+17, Kasen+17, Kilpatrick+17, Perego+17, Rosswog+17, Shibata+17, Tanaka+17, Toroja+17, …

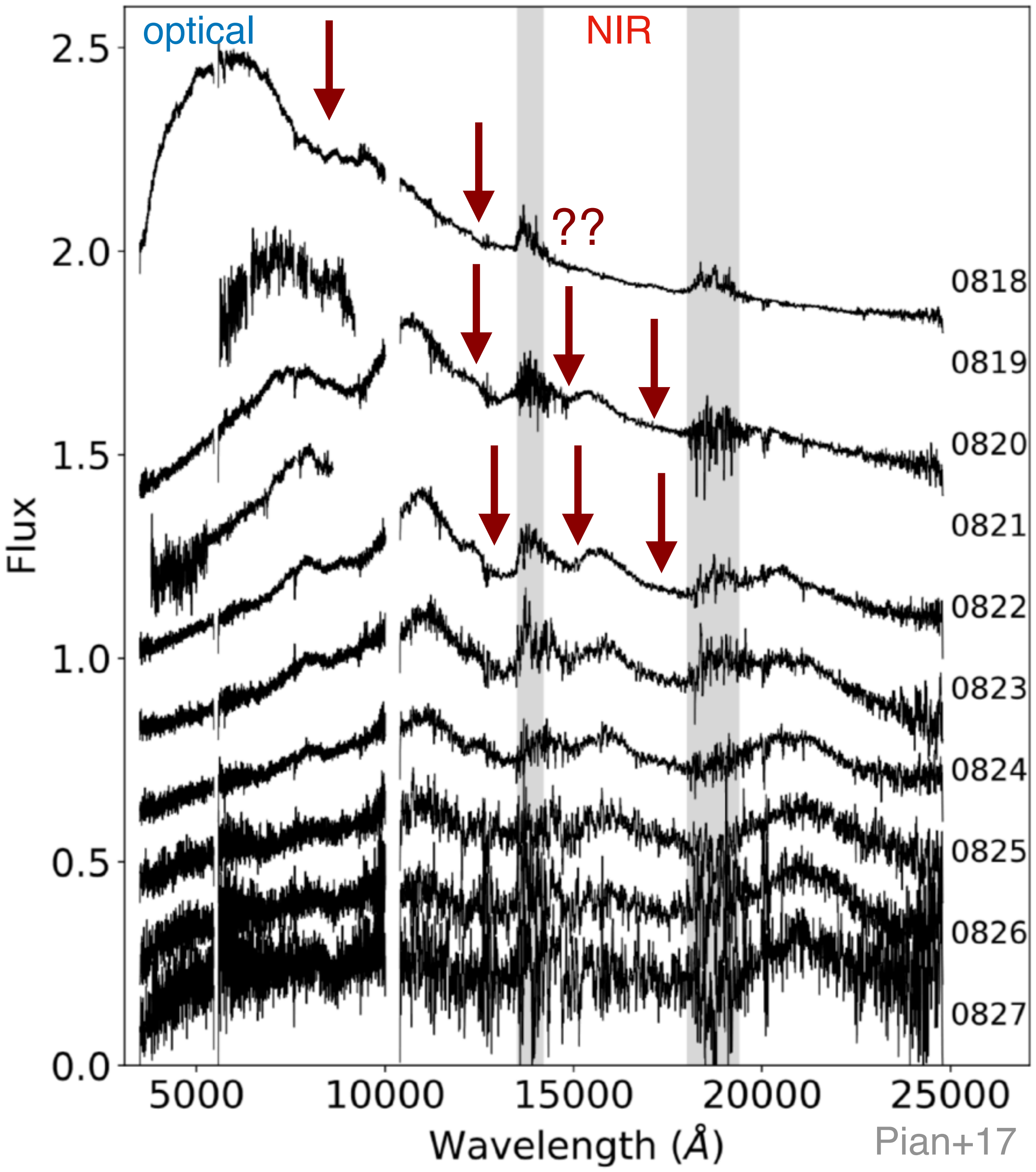
Utsumi+17



Kawaguchi+18, 20

Which and how much elements?

Sr II Watson+19, Domoto+21, Gillanders+22



Pian+17

Why difficult?

- Much high expansion velocity, v~0.2 c
- Really metal rich
- Luminous in near infrared

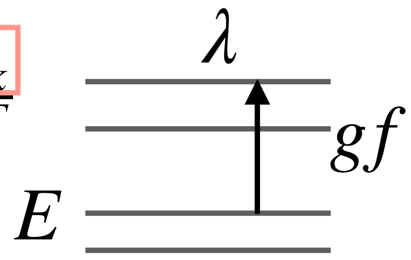
=> need “atomic data” of heavy elements in near infrared

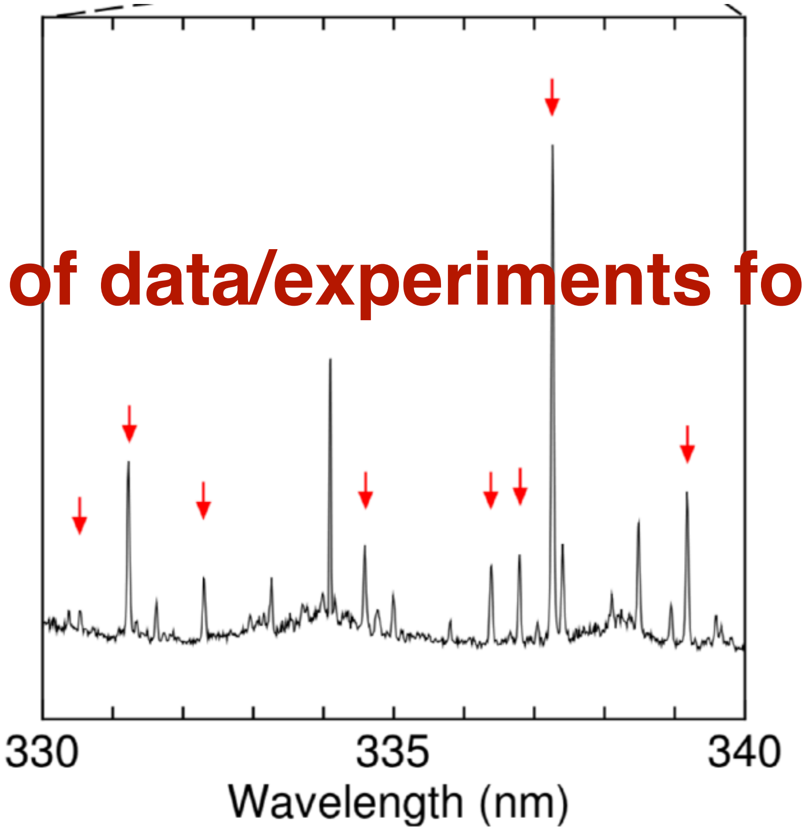
cf. supernovae

- v~10000 km/s
- up to Fe-group
- keep luminous in optical

Strength of lines: “Sobolev optical depth”

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \boxed{\lambda_l} \frac{\boxed{g_k f_l}}{g_0} e^{-\frac{\boxed{E_k}}{kT}}$$

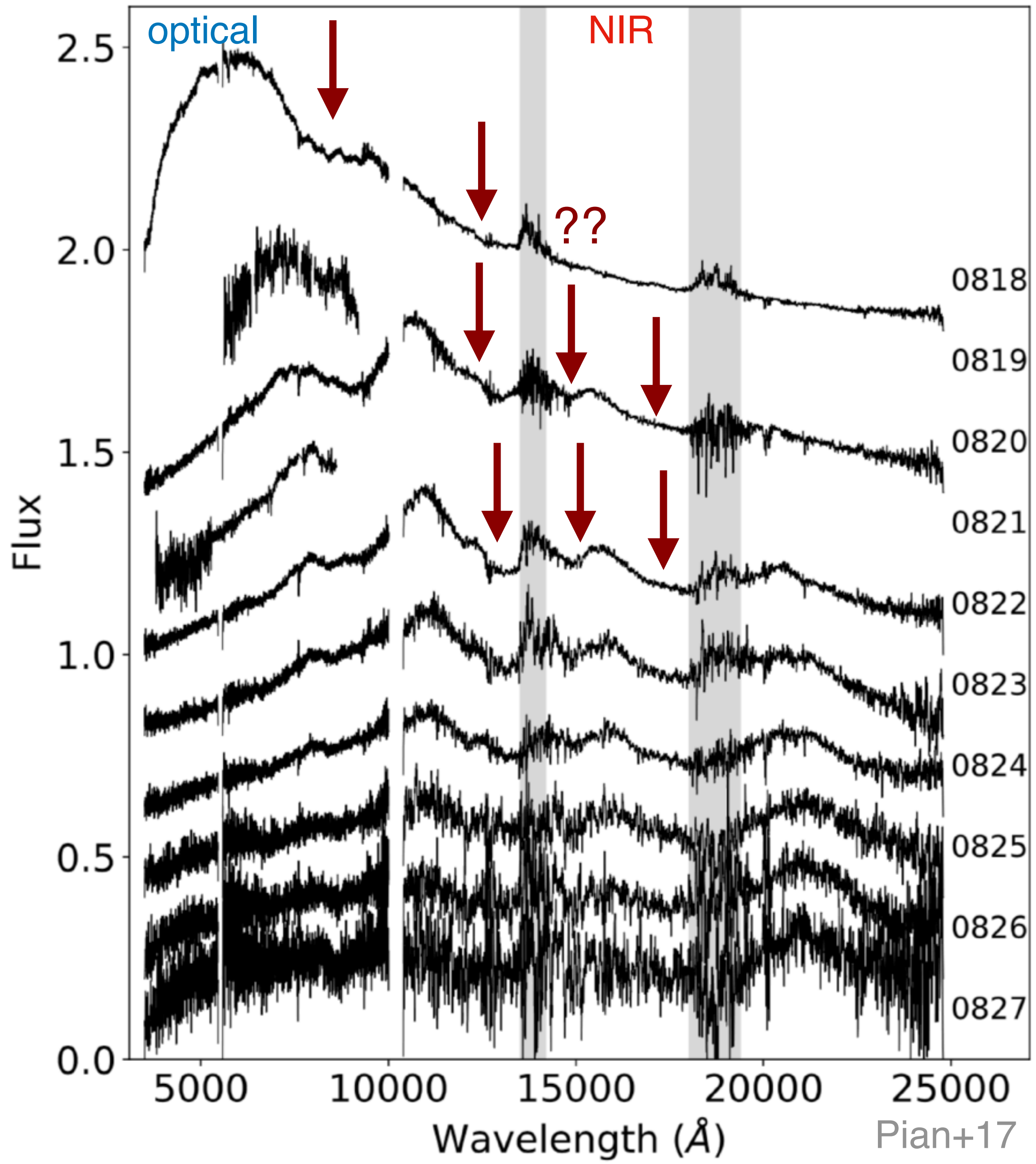




Lack of data/experiments for NIR

lab experiment, Naoi+22

Sr II Watson+19, Domoto+21, Gillanders+22

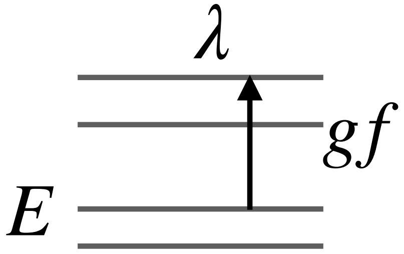


Pian+17

Situation on atomic data

Strength of lines: “Sobolev optical depth”

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \boxed{\lambda_l} \frac{\boxed{g_k f_l}}{g_0} e^{-\frac{\boxed{E_k}}{kT}}$$



	Theoretically constructed list *high completeness e.g., Kasen+17, Tanaka+20, Fontes+20, Banerjee+20, 22	Experimentally calibrated list *spectroscopically accurate e.g., NIST, VALD, DREAM
Transition wavelength	low accuracy	✔
Energy level	low accuracy	✔
Transition probability	aveilable	unavailable (especially for NIR)

Light curve calculations

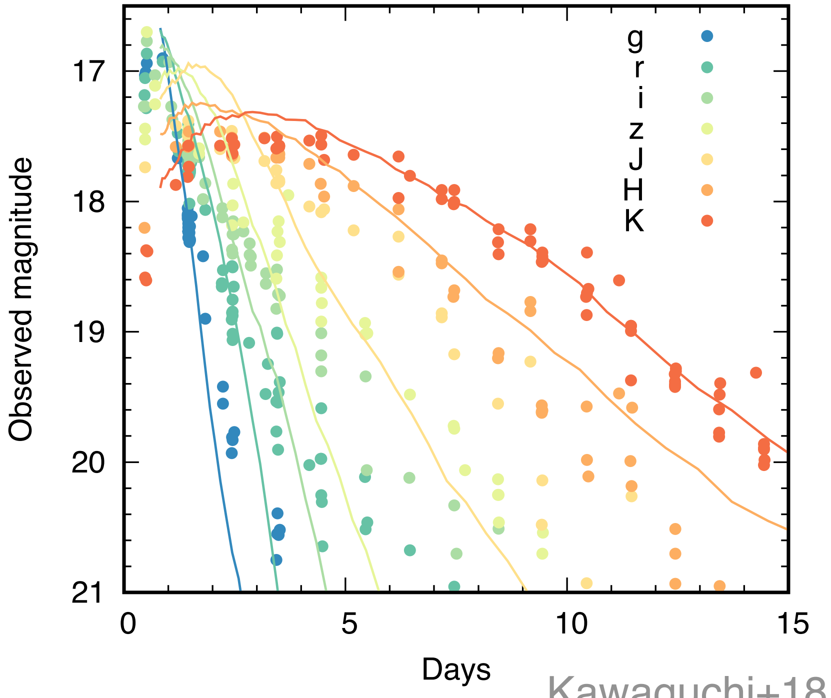
Need for discussion of spectra

So, what we did?

1. Construct new bound-bound transition atomic data ("line list")

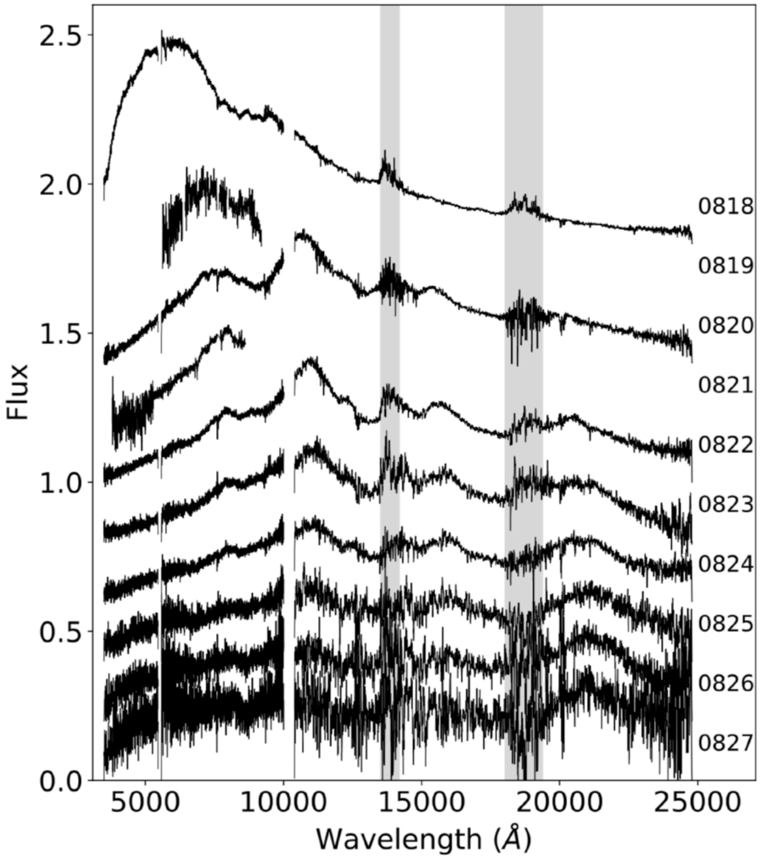
✓ "complete" atomic data by theory
(-> light curve)

Kasen+17, Tanaka+18,20,
Fontes+20,22, Banerjee+20,22



Kawaguchi+18, 20

"accurate" data by experiments
(-> spectra)



Pian+17

- Which species are important? <- searchable thanks to "complete" set
- Calibrate and extend "accurate" data using available experimental data

2. Perform radiative transfer simulation to obtain self-consistent results

Radiative transfer simulations

Tanaka & Hotokezaka 2013, Tanaka+14, 17, Kawaguchi+18, 20

Calculate realistic synthetic spectra considering ejecta structure

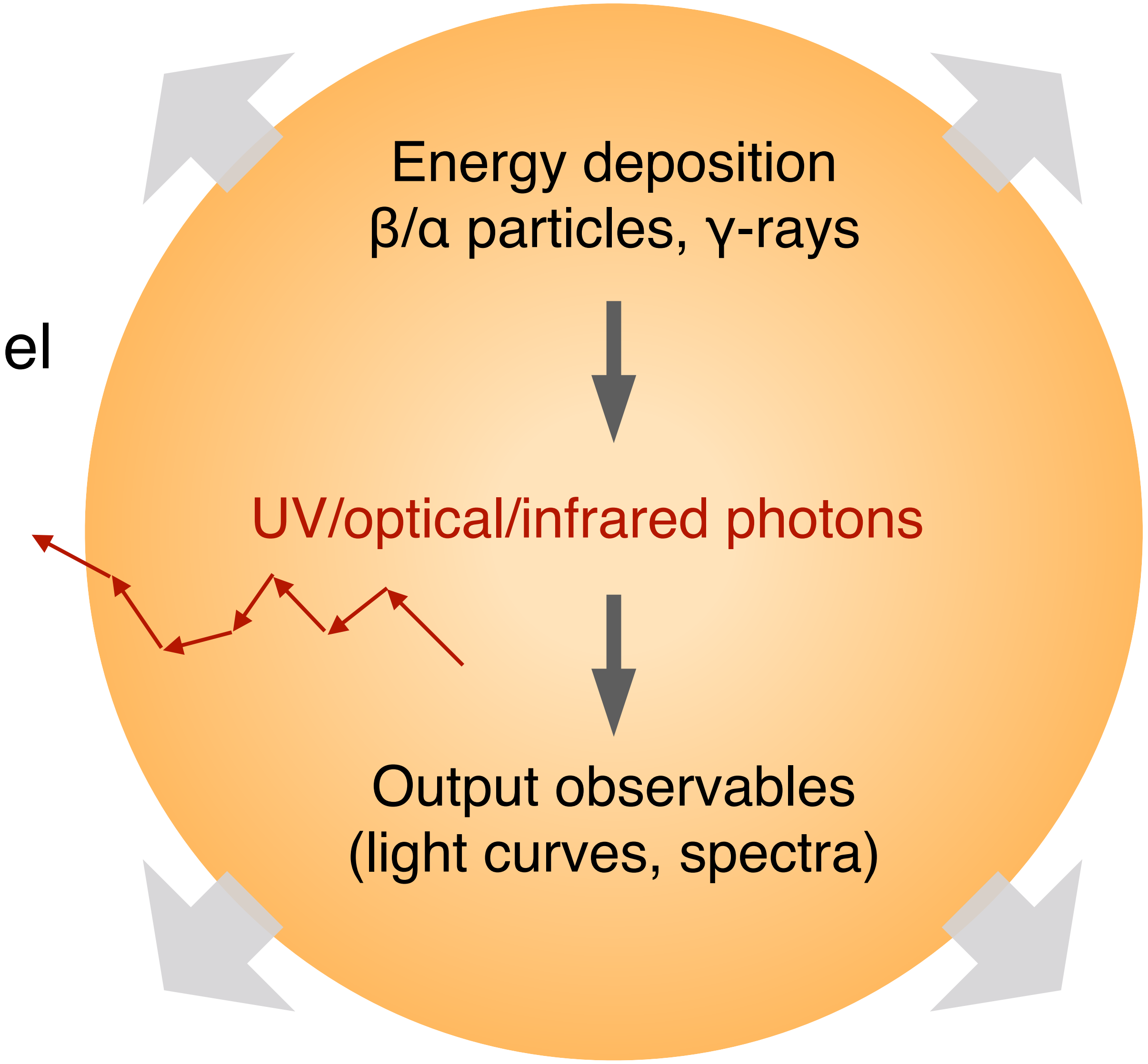
Ejecta model:

- Mass: Mej = 0.03 Msun
- Velocity: v = 0.05-0.3 c
- Density: 1D power law ($\rho \propto r^{-3}$)
- Assume solar-r-like abundance pattern model (homogeneous distribution)

Ionization/population:
LTE (Saha eq. + Boltzmann dist.)

Atomic data: new hybrid line list

Monte Carlo radiative transfer
→ Realistic spectral shapes & features by self-consistent simulation

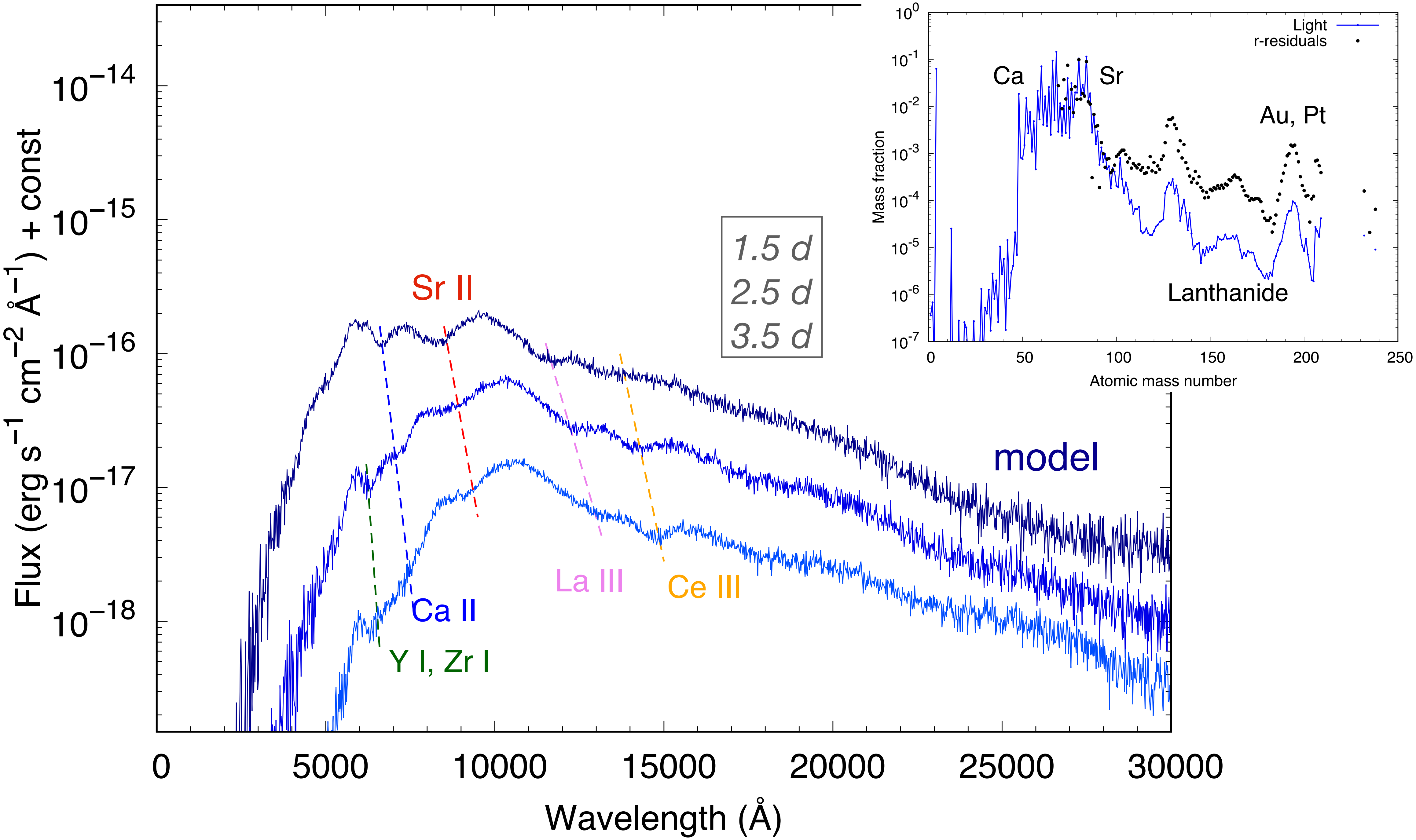


Energy deposition
β/α particles, γ-rays

UV/optical/infrared photons

Output observables
(light curves, spectra)

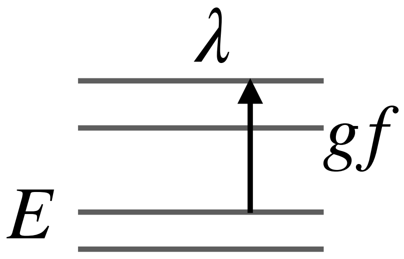
Results: synthetic spectra

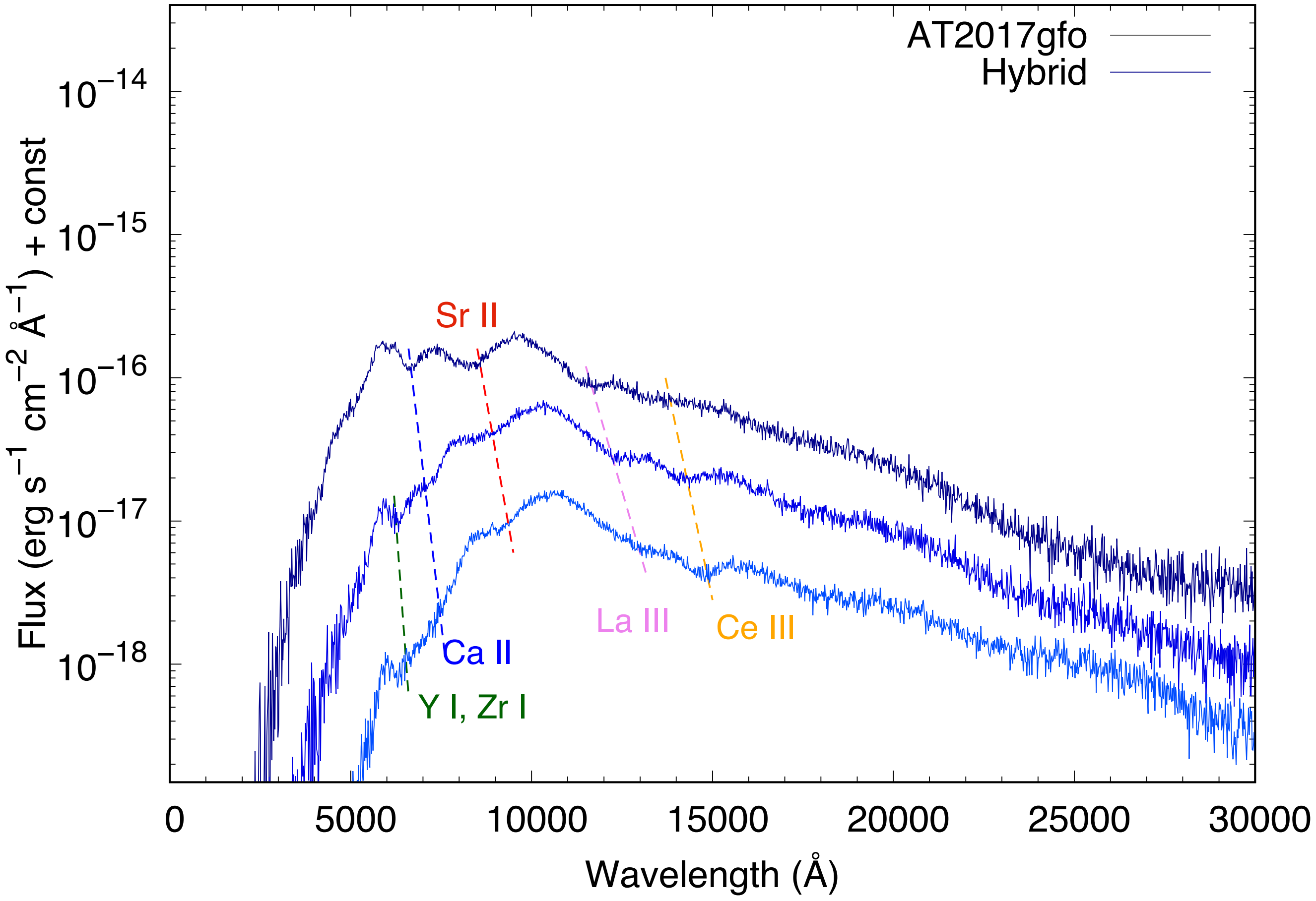


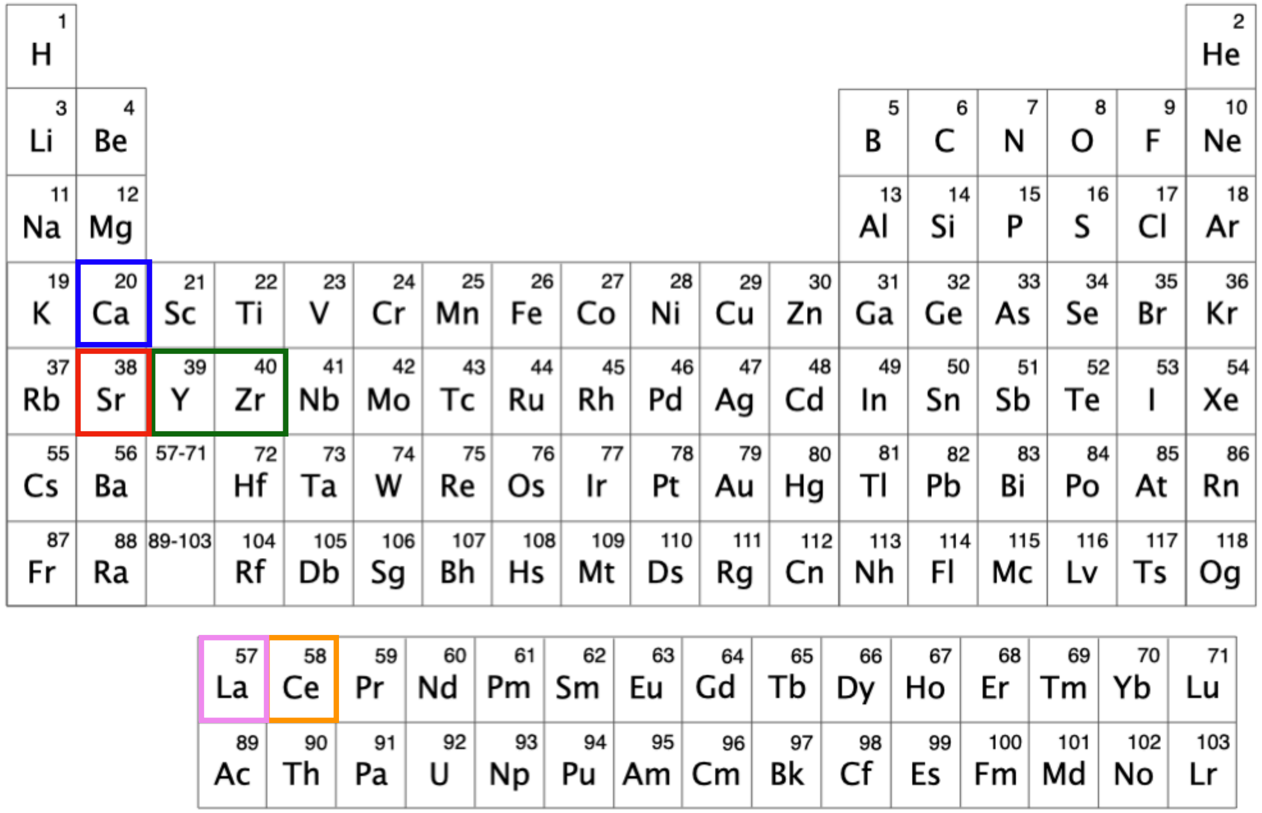
(Only) several elements produce absorption features

Important species for spectral features

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \boxed{\lambda_l} \frac{\boxed{g_k f_l}}{g_0} e^{-\frac{\boxed{E_k}}{kT}}$$





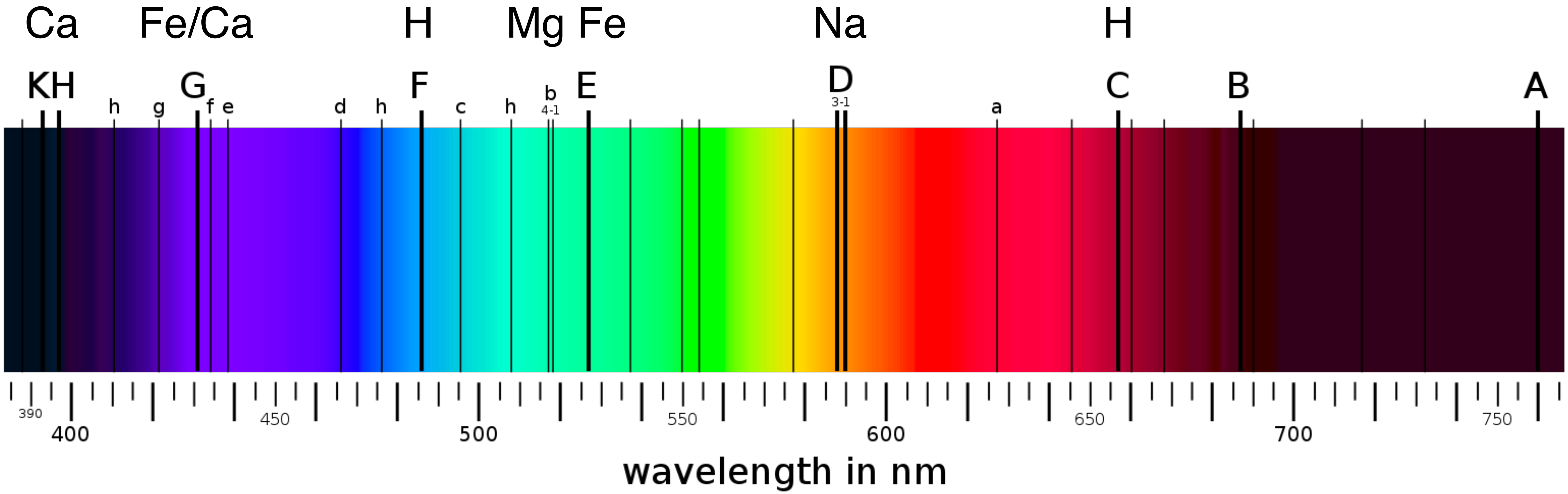


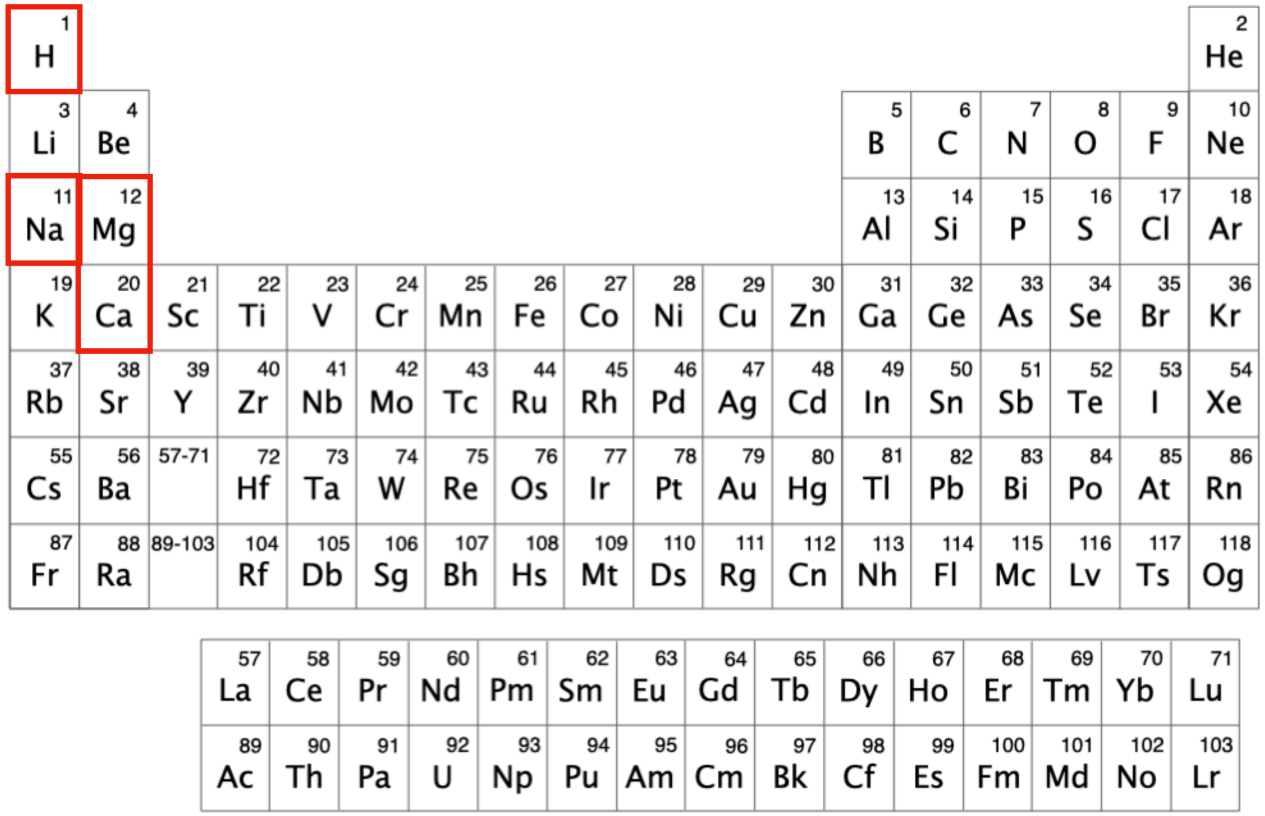
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	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	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	

Ca II, Sr II, Y II, Zr II, La III, and Ce III are strong absorption sources

- Small number of transitions -> higher transition probability (sum rule)
- Low-lying energy levels -> higher population

Counterintuitive? but we know the Sun





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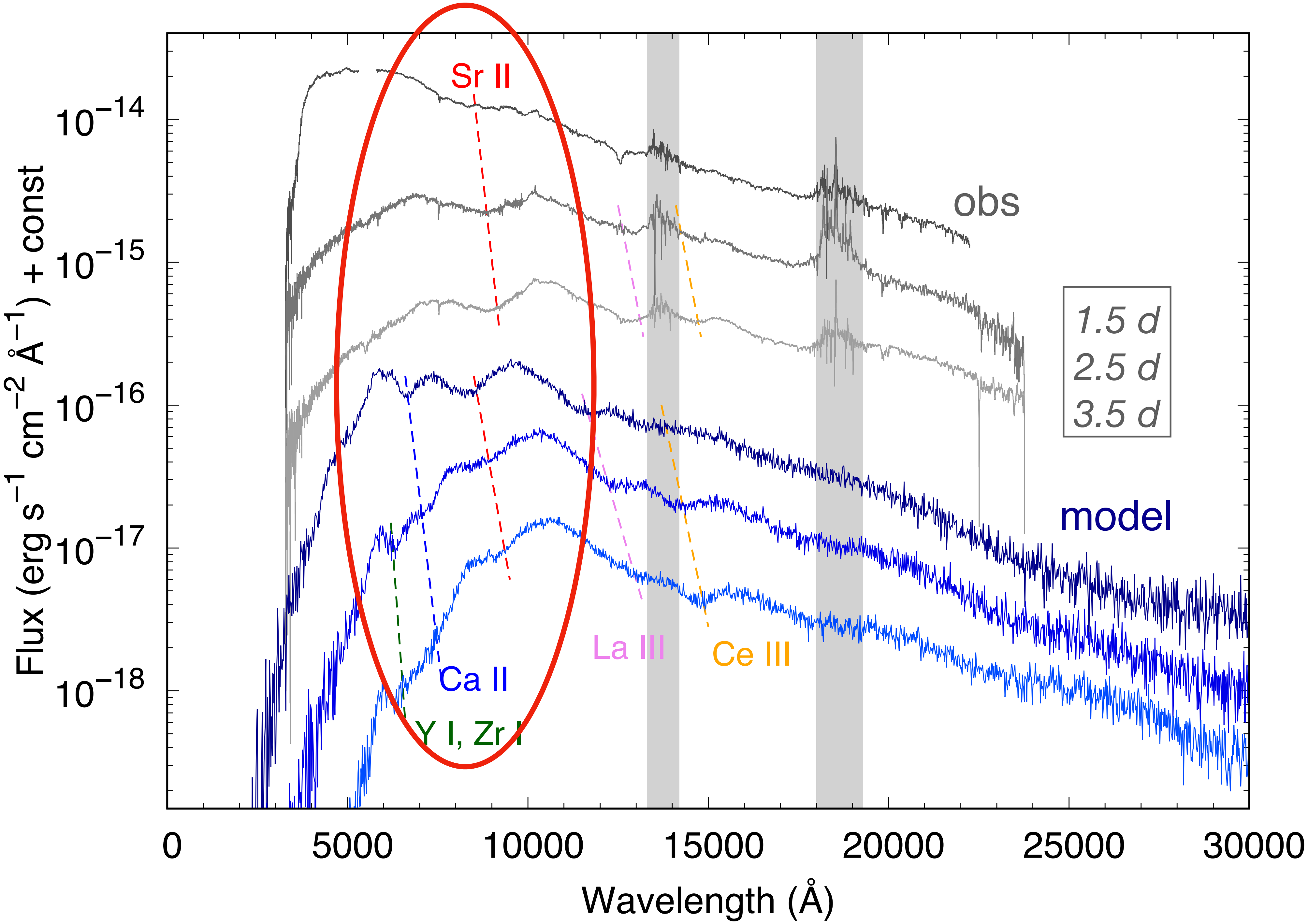
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

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

Comparison with observations (1)



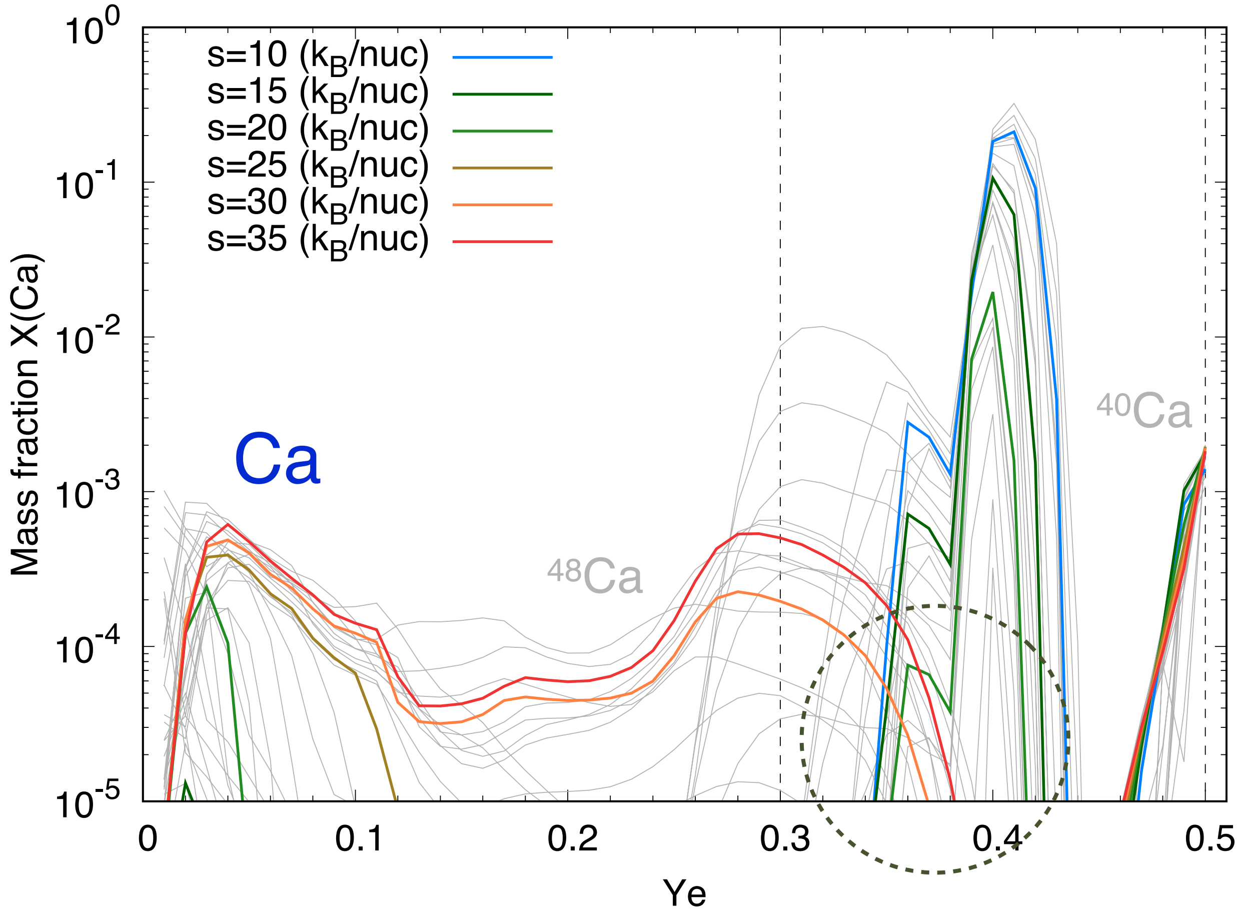
Sr and Ca have similar atomic structures and transitions

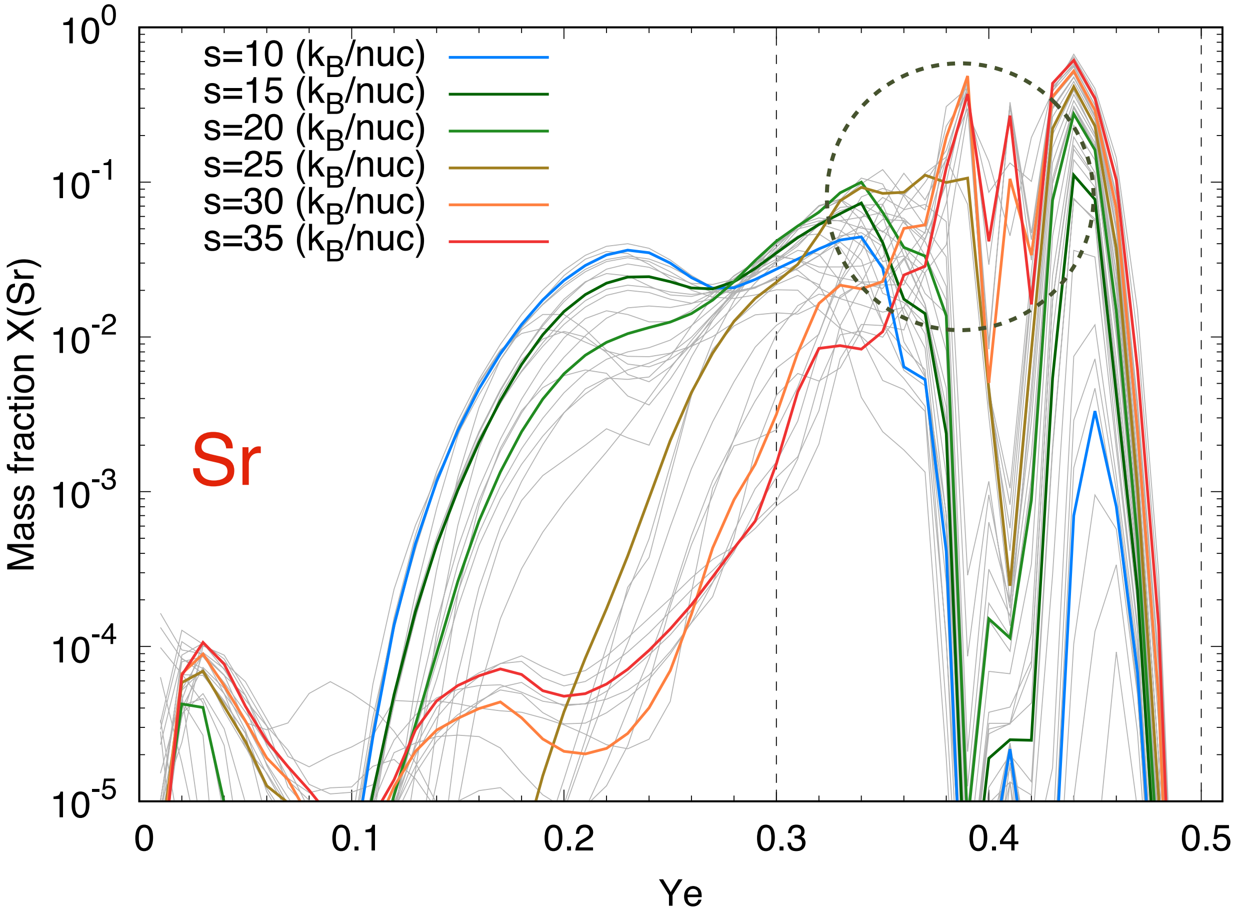
X(Ca)/X(Sr) < 0.002 in GW170817

Physical conditions

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

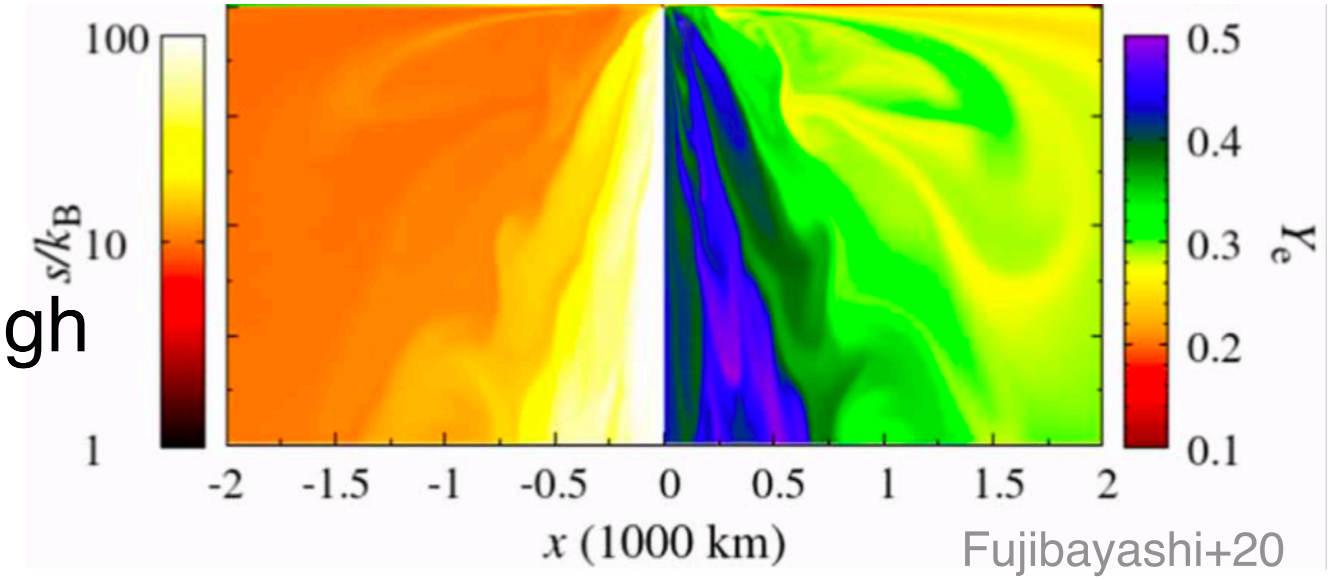
color: v=0.2 c & different entropies





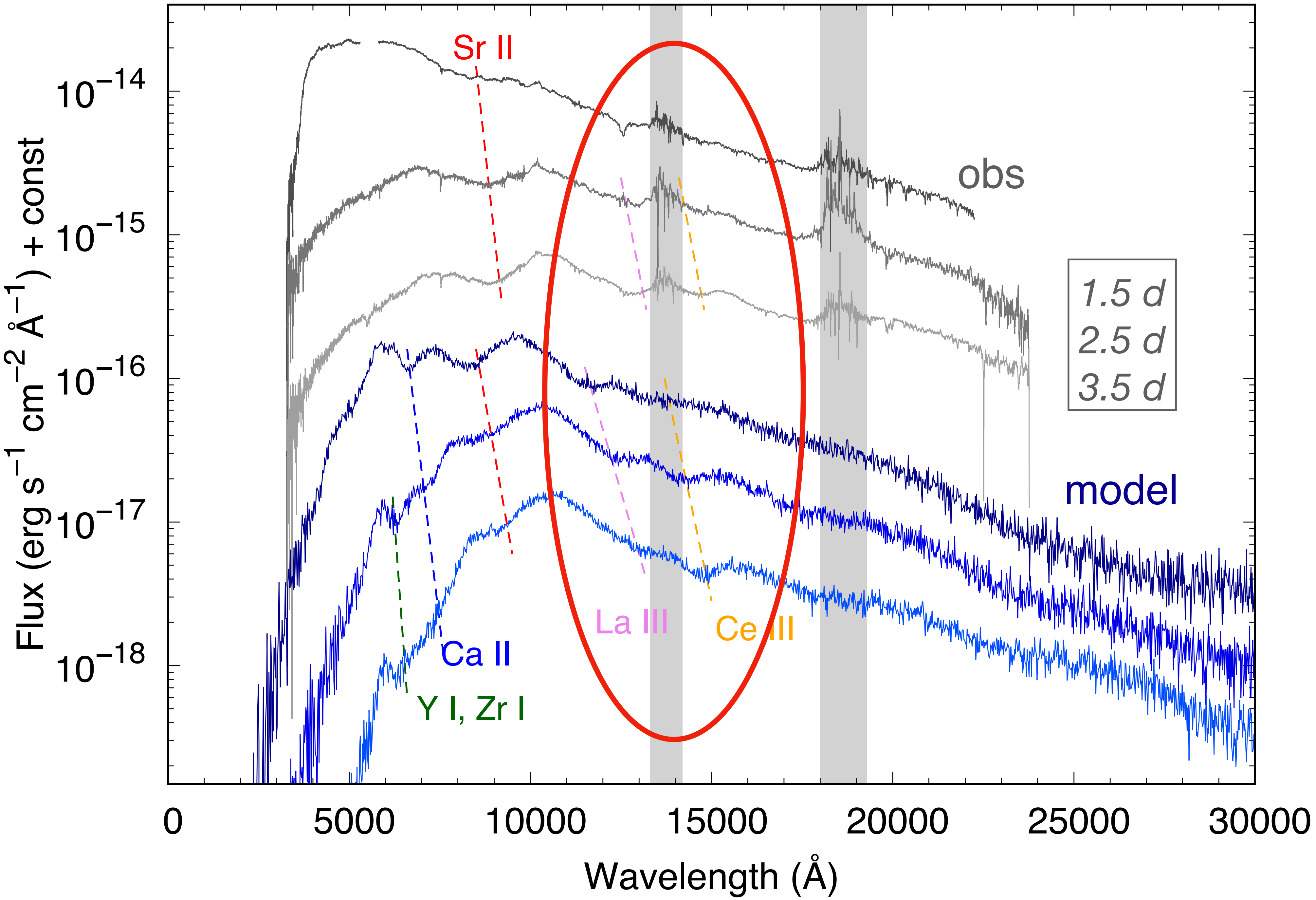
$X(Ca)/X(Sr) < 0.002$

→Velocity and entropy of high-Ye component is relatively high for GW170817.



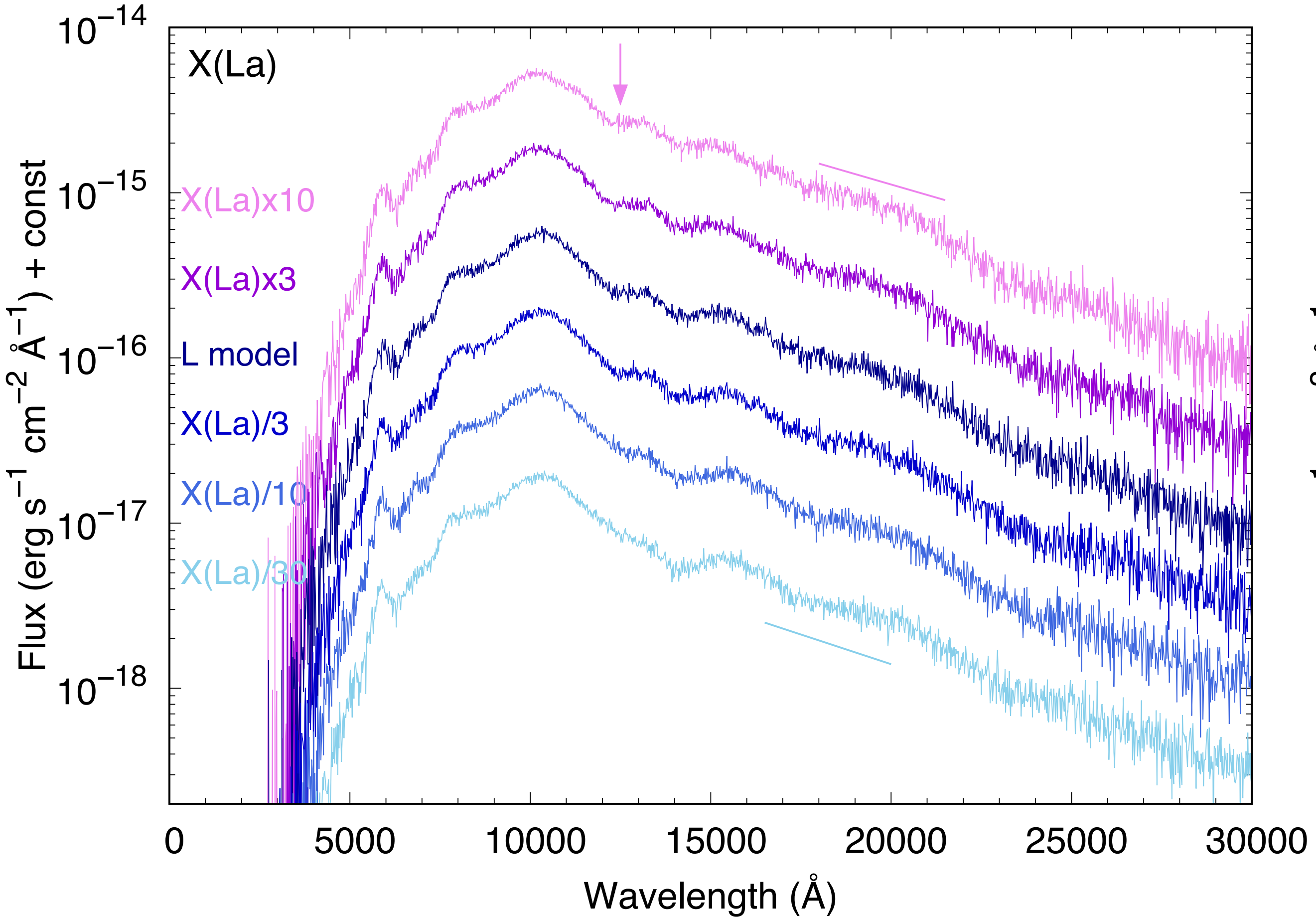
Fujibayashi+20

Comparison with observations (2)

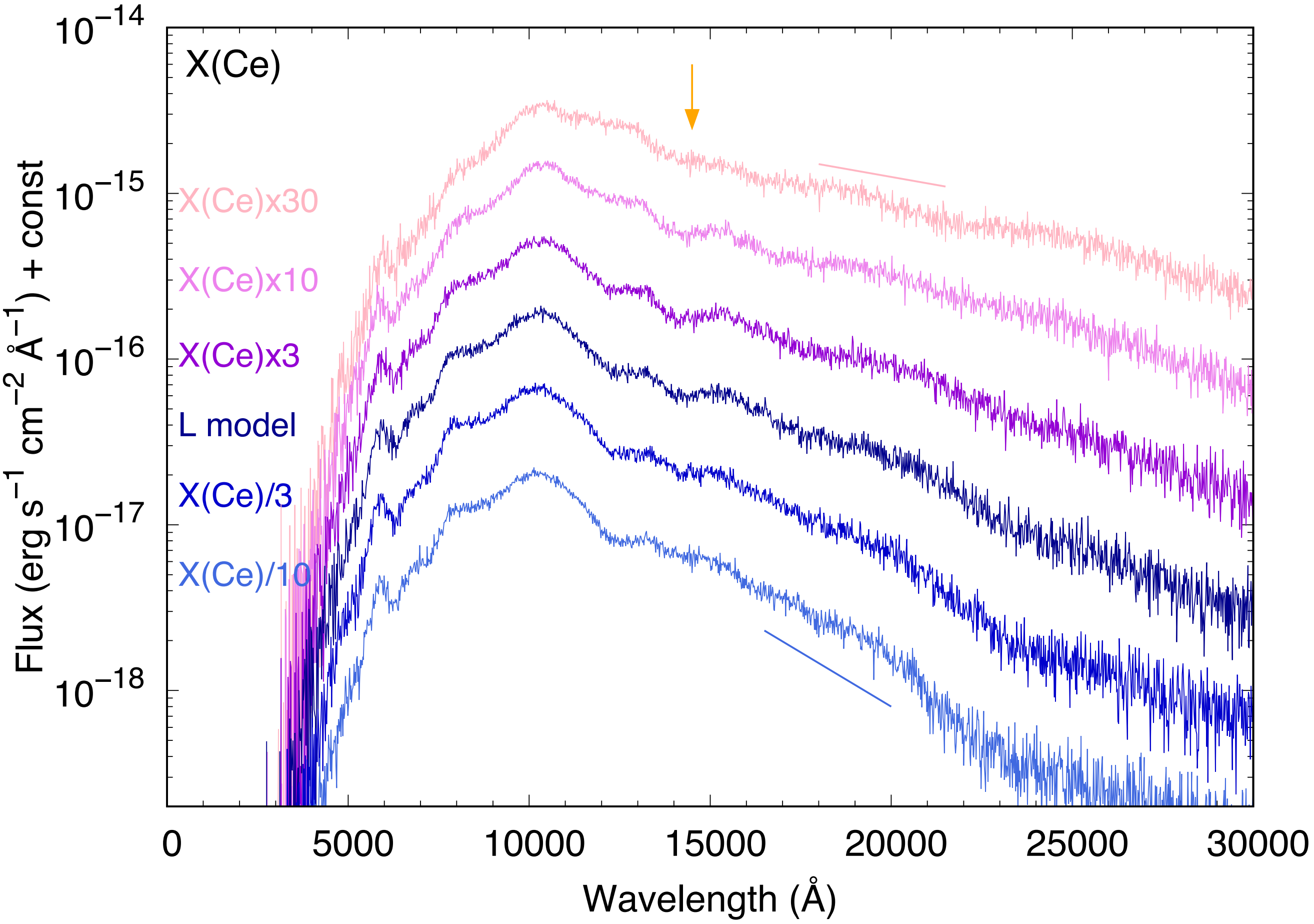


La III and Ce III lines can explain the NIR observed features

Mass fraction of lanthanides



$X(La) > 2 \times 10^{-6}$



$X(Ce) \sim 10^{-5} - 10^{-3}$

Lanthanide fraction ~ $2 \times (10^{-4} \sim 10^{-2})$
(if abundance pattern is similar to solar pattern)

cf. previous estimation (blue component): $\sim 10^{-5} - 10^{-3}$

Arcavi+17, Kilpatric+17, Nicholl+17, Gillanders+22

Summary

- Binary neutron star merger: origin of r-process elements?
  An important event for multi-messenger astronomy

- Kilonova: imprints of r-process nucleosynthesis

- Identification of elements in spectra is
  direct way to study synthesized elements

- New atomic data by taking advantages
  of both experimental (accurate) and theoretical (complete) data

- Elements that can appear in spectra: Ca, Sr, Y, Zr, La, and Ce
  - Understandable by atomic properties

- Ca, Sr can be used to infer physical condition of high-Ye ejecta

- Observed NIR features can be explained by rare-earth: La and Ce
  Mass fraction of La and Ce in GW170817 are estimated to be
  $< 2\times10^{-6}$ and $\sim 10^{-3}$-10^{-5} (direct estimation)

Next GW observing run (O4) plans (currently) to be from May 2023 (for 1.5 yr)