

Kilonova

田中 雅臣 (東北大学)

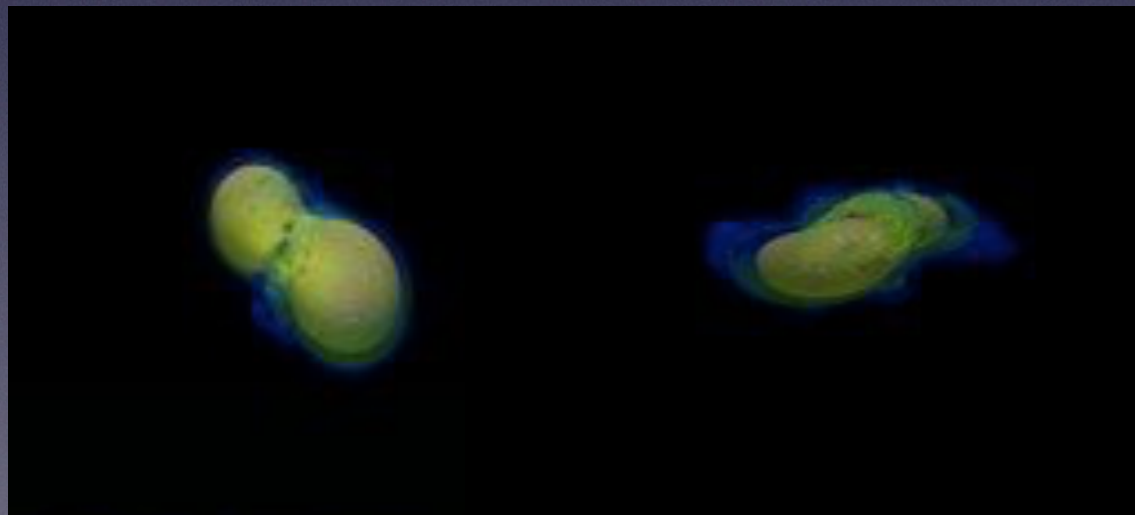
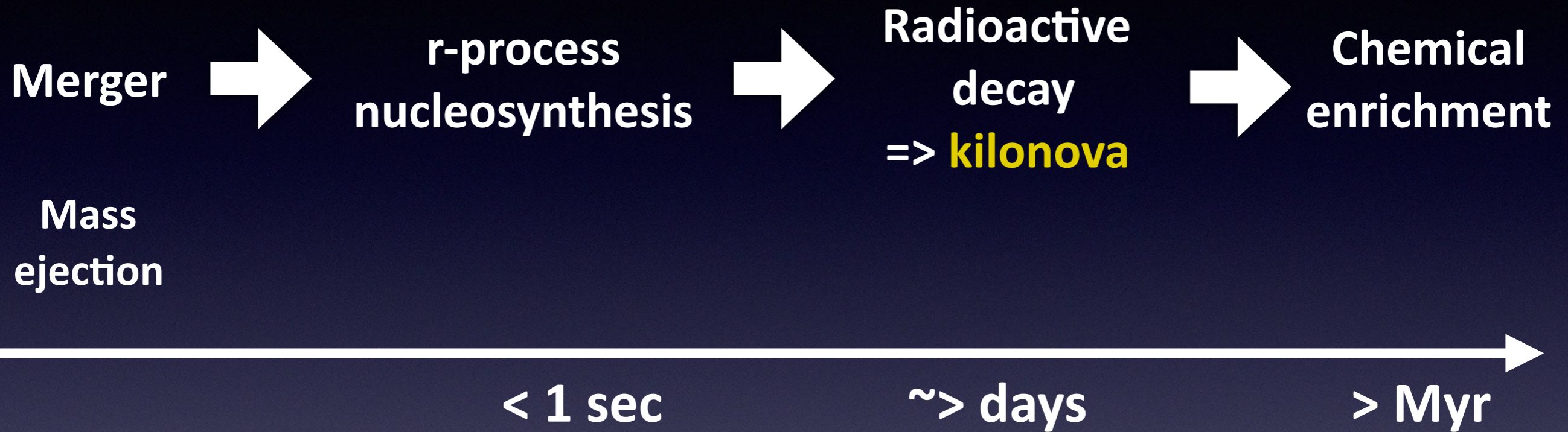
**Smaranika Banerjee (東北大学)、土本 菜々恵 (東北大学)、川口 恭平 (東京大学)、
加藤 太治 (核融合科学研究所)、Gediminas Gaigalas (Vilnius大学)**

Kilonova

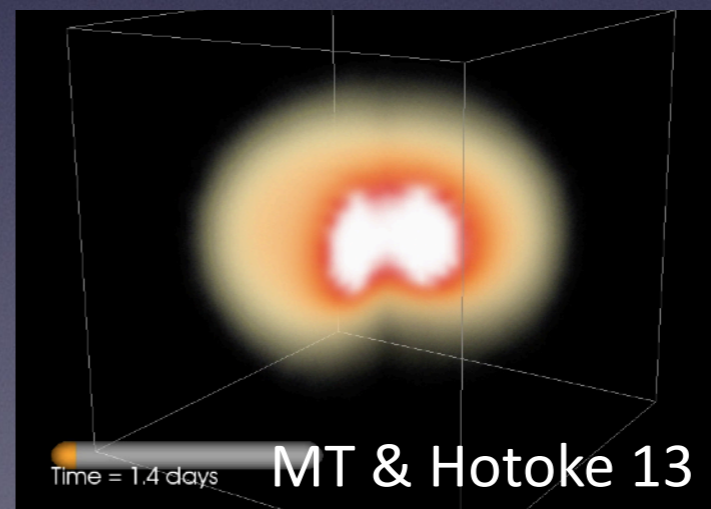
= radioactively-powered thermal radiation from
very metal-rich ($Z > 30$), expanding outflow ($v \sim 0.1c$)

- キロノバの物理
- 重元素の構造とopacity
- 輻射輸送計算

Timescales of NS mergers



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



$M \sim 0.01 M_{\text{sun}}$

$v \sim 0.1c$

$R \sim 10^{14-15} \text{ cm}$

Optical + infrared
photons

Gamma-rays
 β/α particles

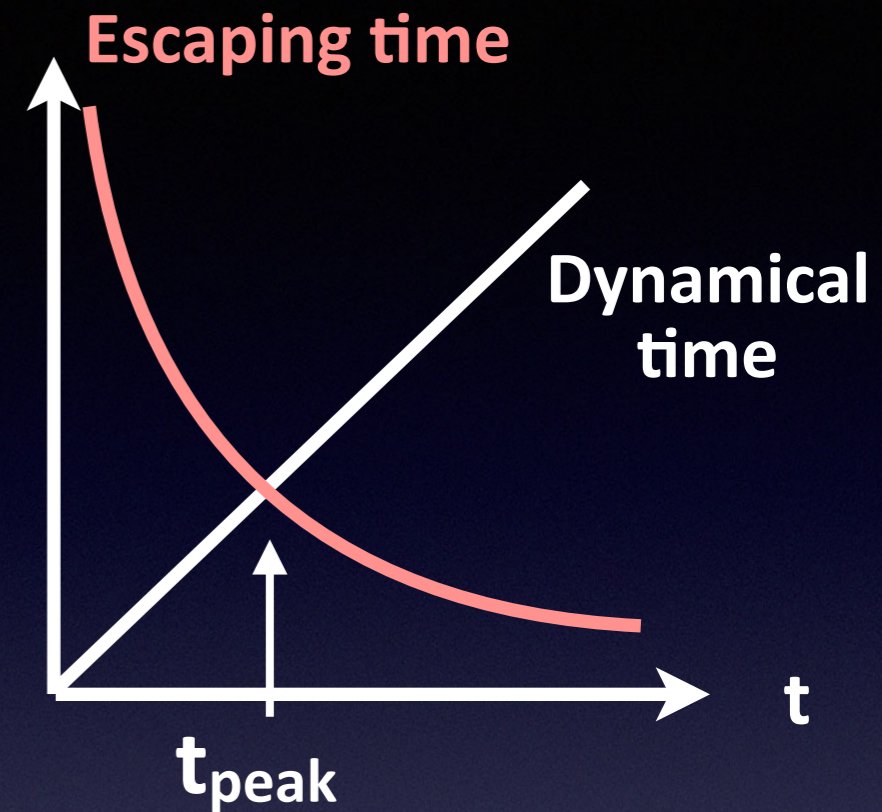
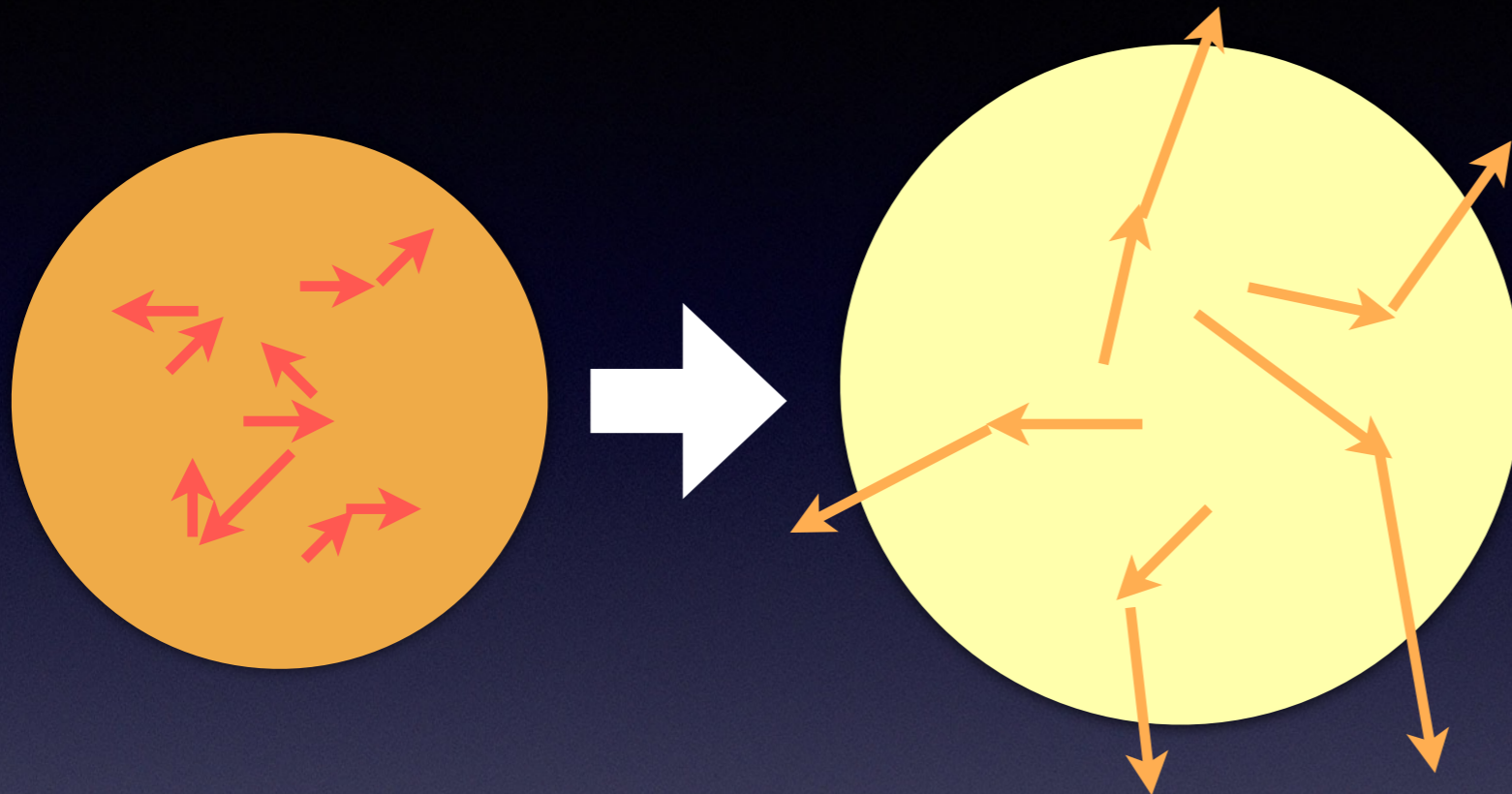
Optical/infrared photons interact with
heavy elements
(mainly via bound-bound transitions)

$\rho \sim 10^{-13} \text{ g cm}^{-3}$ ($n \sim 10^9 \text{ cm}^{-3}$)

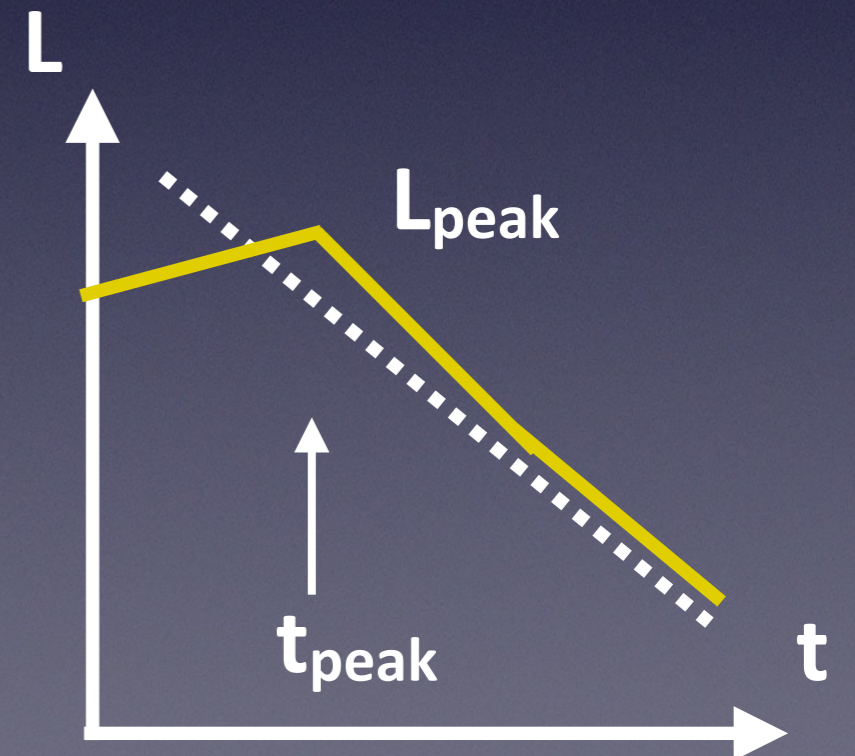
$T \sim 5,000 \text{ K}$

(neutral to several ionization degrees)

Timescale

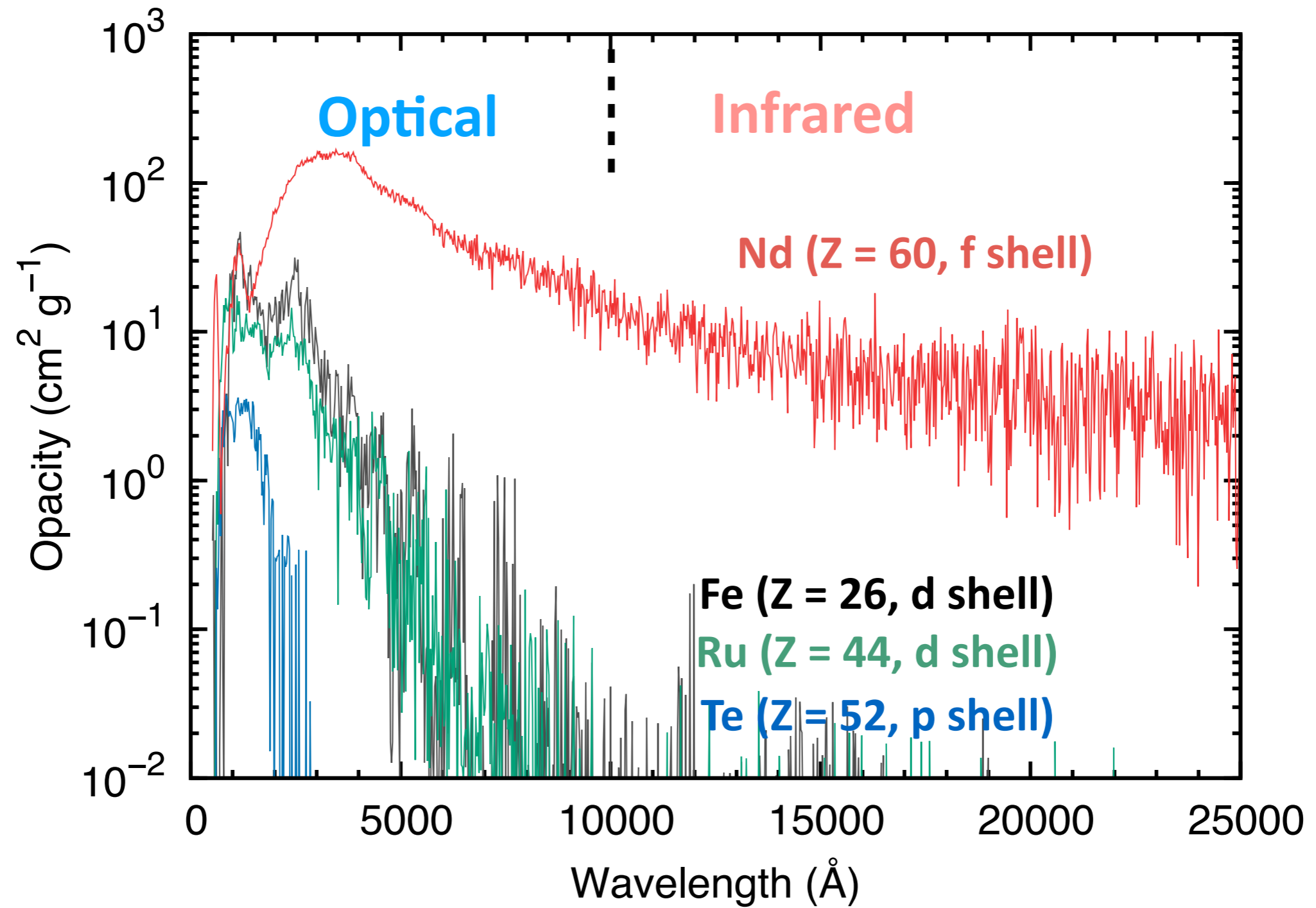


$$t_{\text{peak}} = \left(\frac{3\kappa M_{\text{ej}}}{4\pi c v} \right)^{1/2}$$
$$\approx 8.4 \text{ days} \left(\frac{M_{\text{ej}}}{0.01 M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{-1/2} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2}$$



Bound-bound opacity

Kasen+13, MT & Hotokezaka 13,
MT+18, 20, Fontes+20

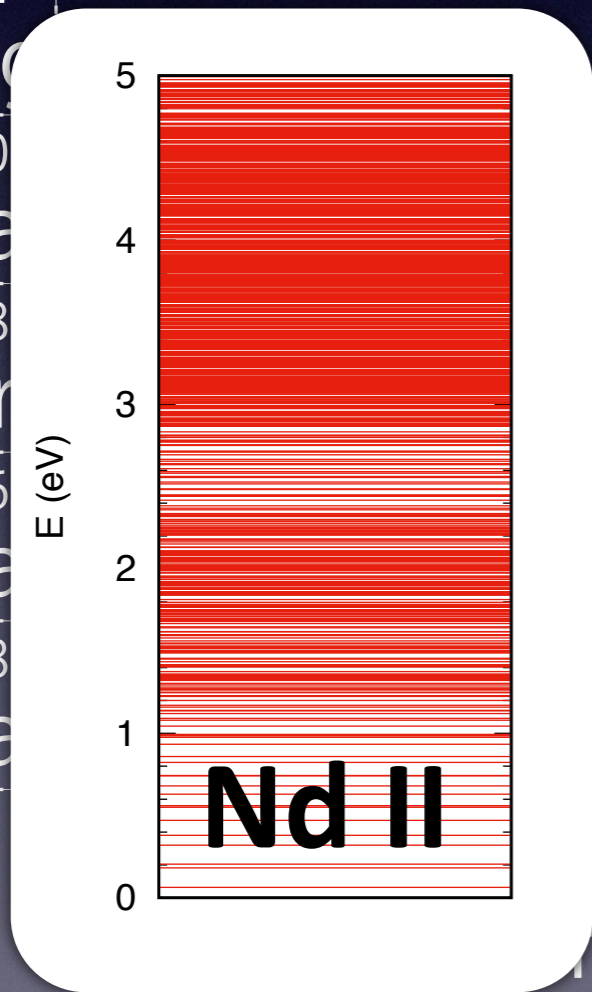


$$\lambda = \frac{hc}{\Delta E}$$

open s shell

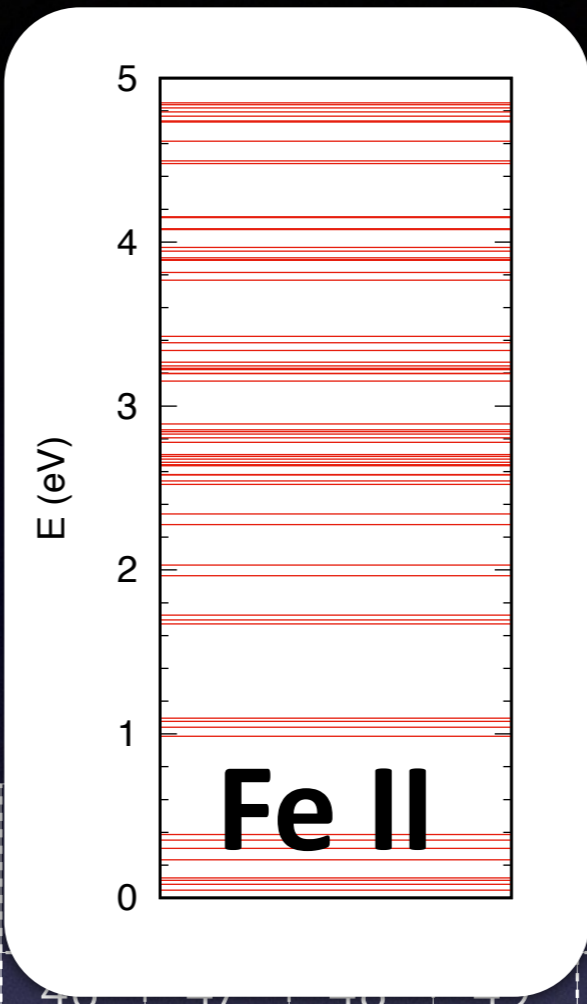
1	H		
3	Li	4	Be
11	Na	12	Mg
19	K	20	Ca
37	Rb	38	Sr
55	Cs	56	Ba
87	Fr	88	Ra

High opacity
in infrared



open d-shell

25	Mn	26	Fe	27	Co																								
43	Tc	44	Ru	45	Rh	46	Pd	47	Ag	48	Cd	49	In	50	Sn	51	Sb	52	Te	53	I	54	Xe						
75	Re	76	Os	77	Ir	78	Pt	79	Au	80	Hg	81	Tl	82	Pb	83	Bi	84	Po	85	At	86	Rn						
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

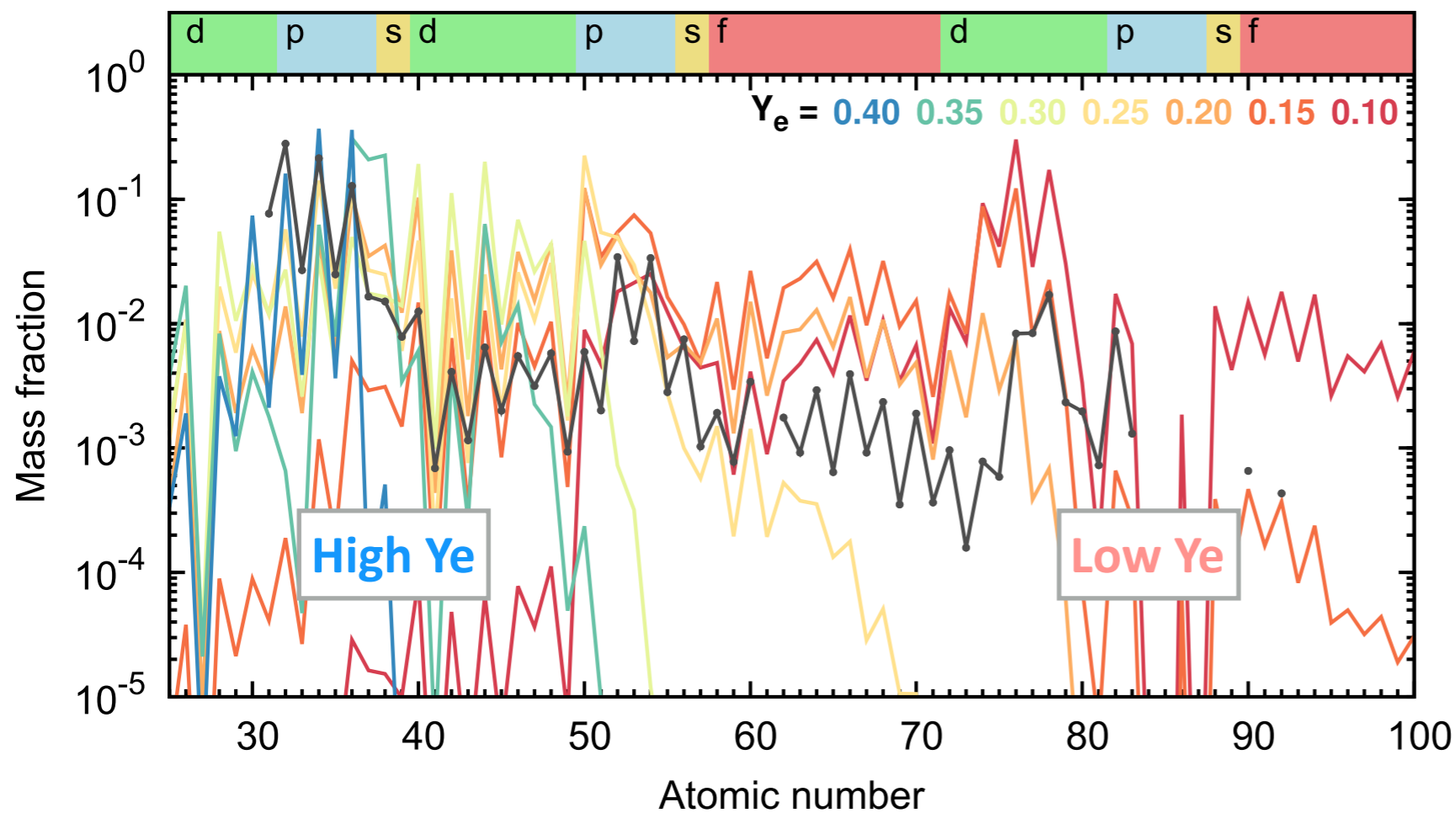


open p-shell

6	C	7	N	8	O	9	F	10	Ne
14	Si	15	P	16	S	17	Cl	18	Ar
32	Ge	33	As	34	Se	35	Br	36	Kr
50	Sn	51	Sb	52	Te	53	I	54	Xe
82	Pb	83	Bi	84	Po	85	At	86	Rn
114	Fl	115	Mc	116	Lv	117	Ts	118	Og

open f shell

Probing Nucleosynthesis via opacity



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

Post-merger
ejecta



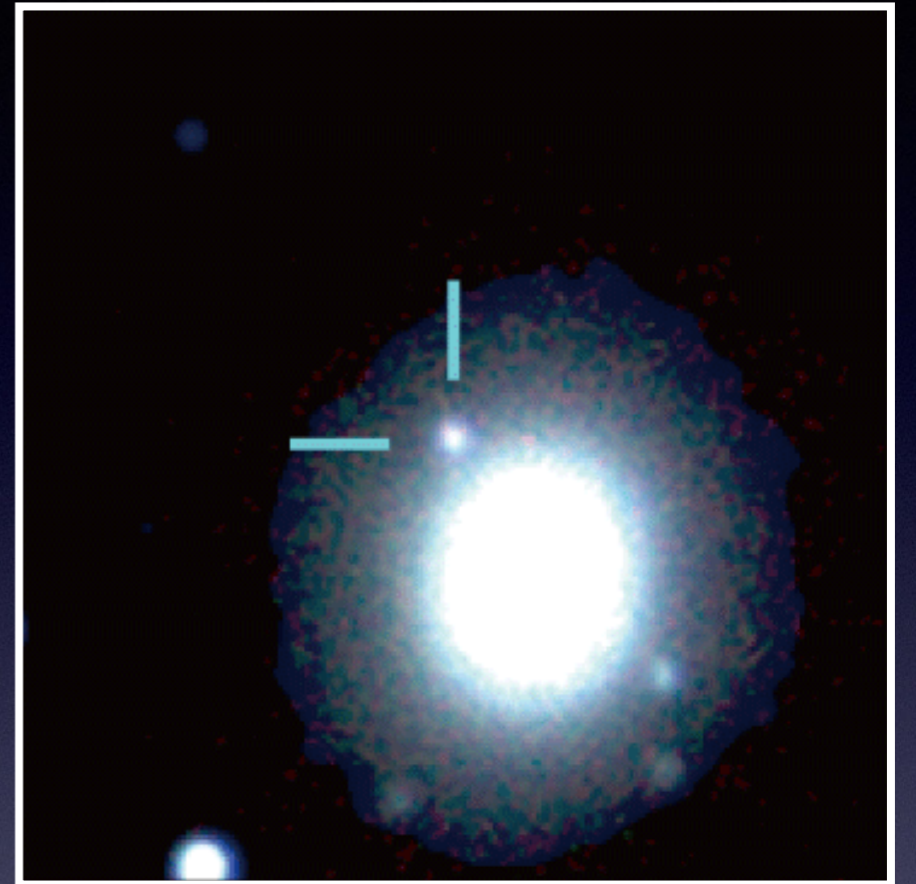
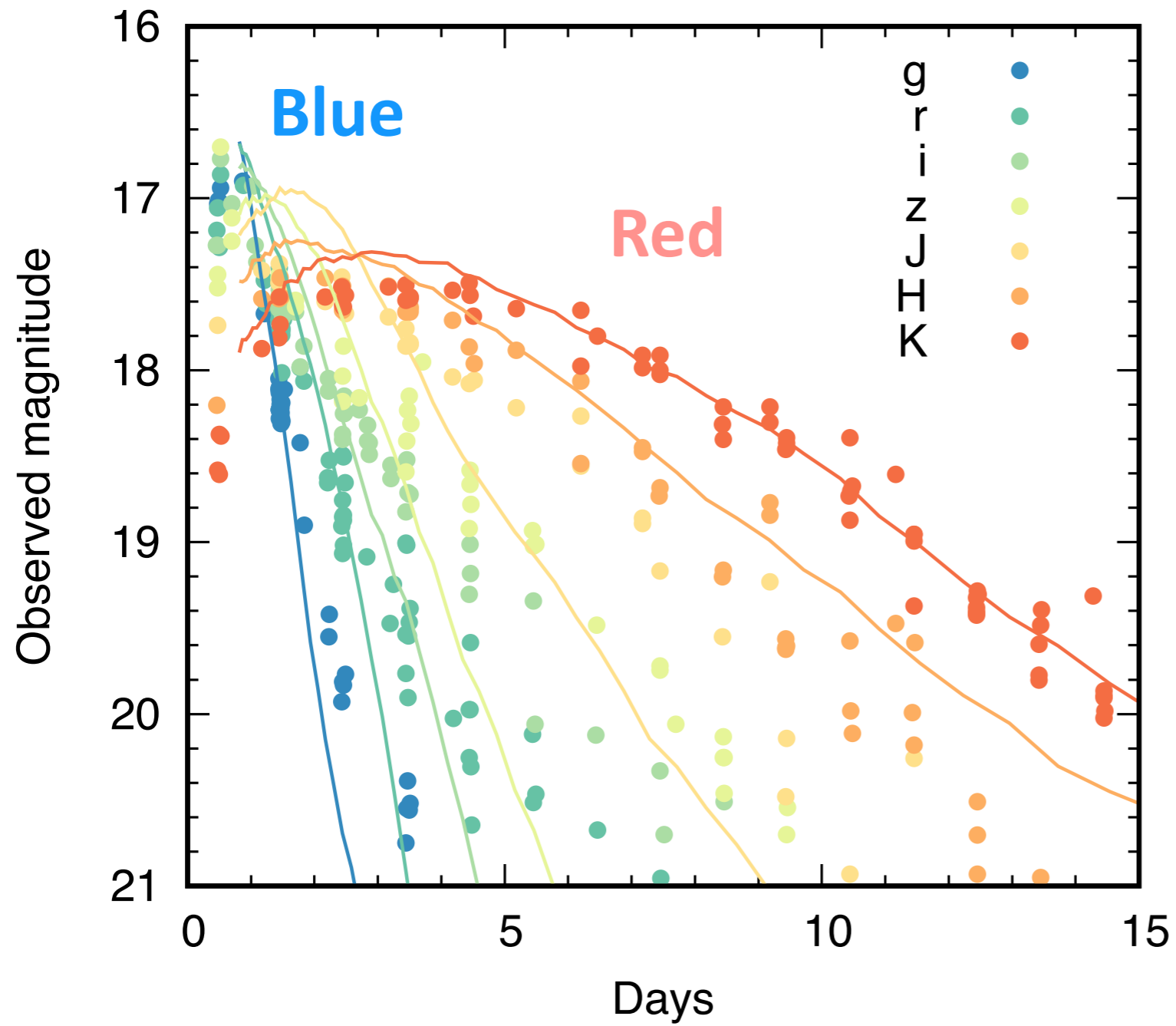
Dynamical
ejecta

$Y_e > \sim 0.25 \implies$ “blue” kilonova

$Y_e \sim < 0.25 \implies$ “red” kilonova

MT, Kato, Gaigalas,
Kawaguchi 2020

GW1701817



Utsumi, MT, Tominaga et al. 2017

Kawaguchi+2018, 2020

気になること

土本さん

- どの元素がどれぐらいいるのか？
スペクトルは「解読」できるか？
- エジェクタの多次元構造の影響は？

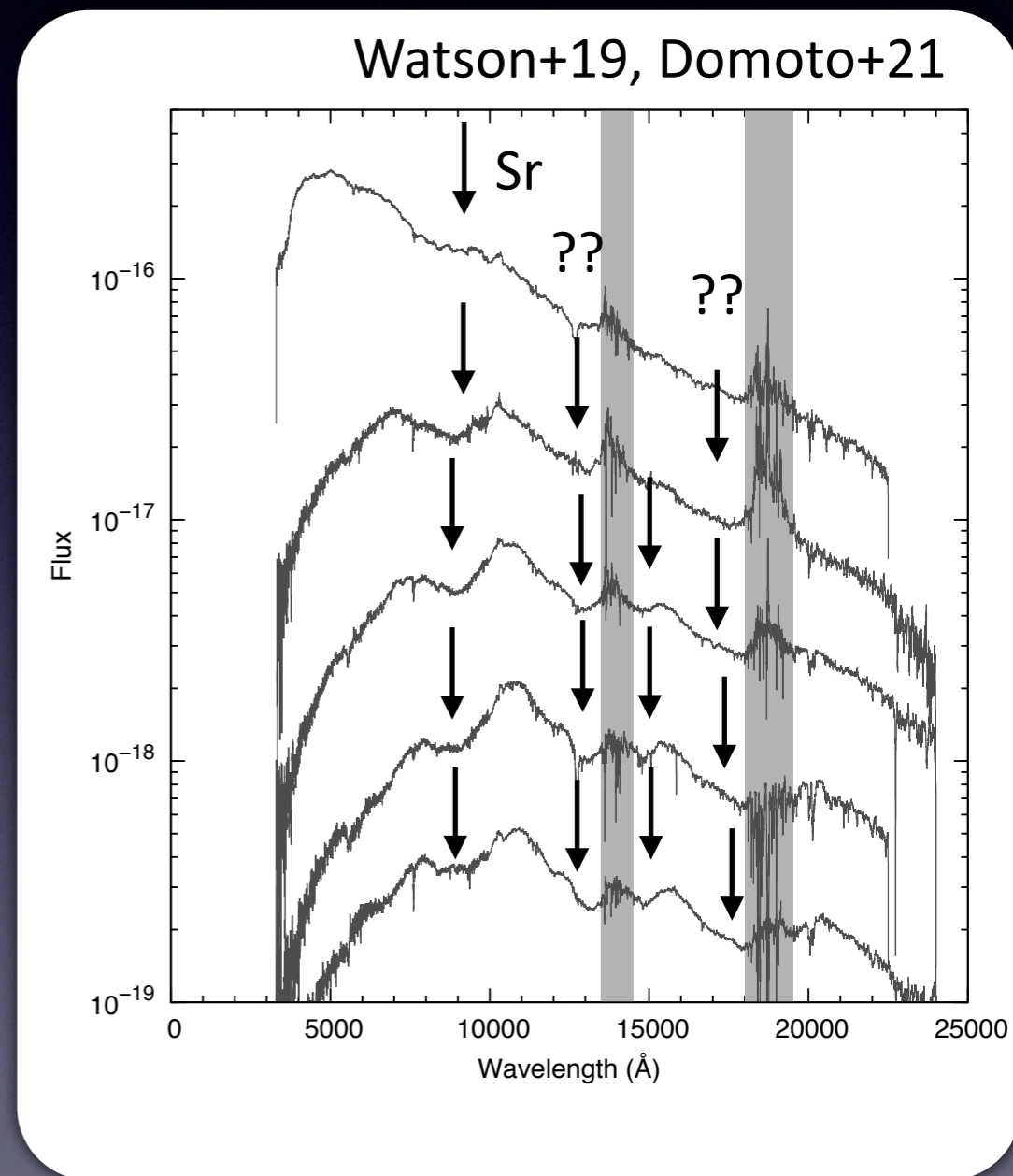
川口さん

- 原子物理の不定性は？
- 放射の計算方法は？

- Nebular phase (後期スペクトル)？

仏坂さん

- ...



Kilonova

= radioactively-powered thermal radiation from
very metal-rich ($Z > 30$), expanding outflow ($v \sim 0.1c$)

- キロノバの物理
- 重元素の構造とopacity
- 輻射輸送計算

Atomic calculations for kilonova

MT, Kato, Gaigalas, Kawaguchi 2020

Kasen+13: Sn II, Ce II-III, Nd I-IV, Os II

open s shell

Fontes+17: Ce I-IV, Nd I-IV, Sm I-IV, U I-IV Wollaeger+17: Se, Br, Zr, Pd, Te

MT+18: Se I-III, Ru I-III, Te I-III, Nd I-III, Er I-III

Kasen+17, Fontes+20: Lanthanides (I-V)

MT+20: all the heavy elements (I-IV)

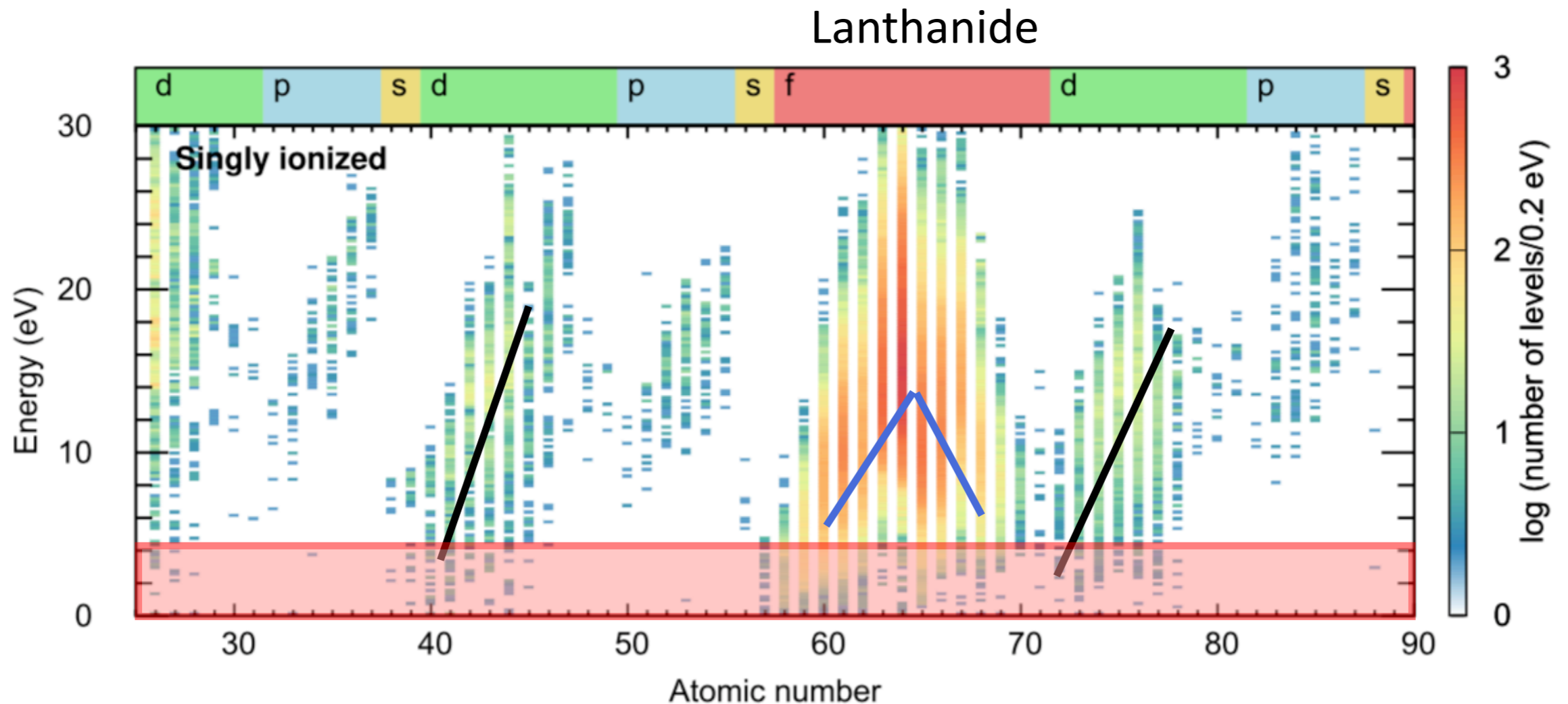
Banerjee+20: higher ionization (- XI, $Z < 56$)

1 H																2 He	
3 Li	4 Be															10 Ne	
11 Na	12 Mg															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
			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
open f shell			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 p-shell

open d-shell

Energy level structure



Spin-orbit interaction (increases with Z)

$$E \sim -\frac{Z^2}{2n^2} \text{Ry} - \frac{\alpha^2 Z^4}{4n^4} \left(\frac{4n}{k} - 3 \right) \text{Ry} + \dots$$

Complexity (max at half closed)

$${}_g C_n = \frac{g!}{n!(g-n)!} \quad \begin{array}{l} k = j + 1/2 \\ g = 2(2l + 1) \end{array}$$

Energy levels of lanthanides

Energy levels (Relative to average energy)

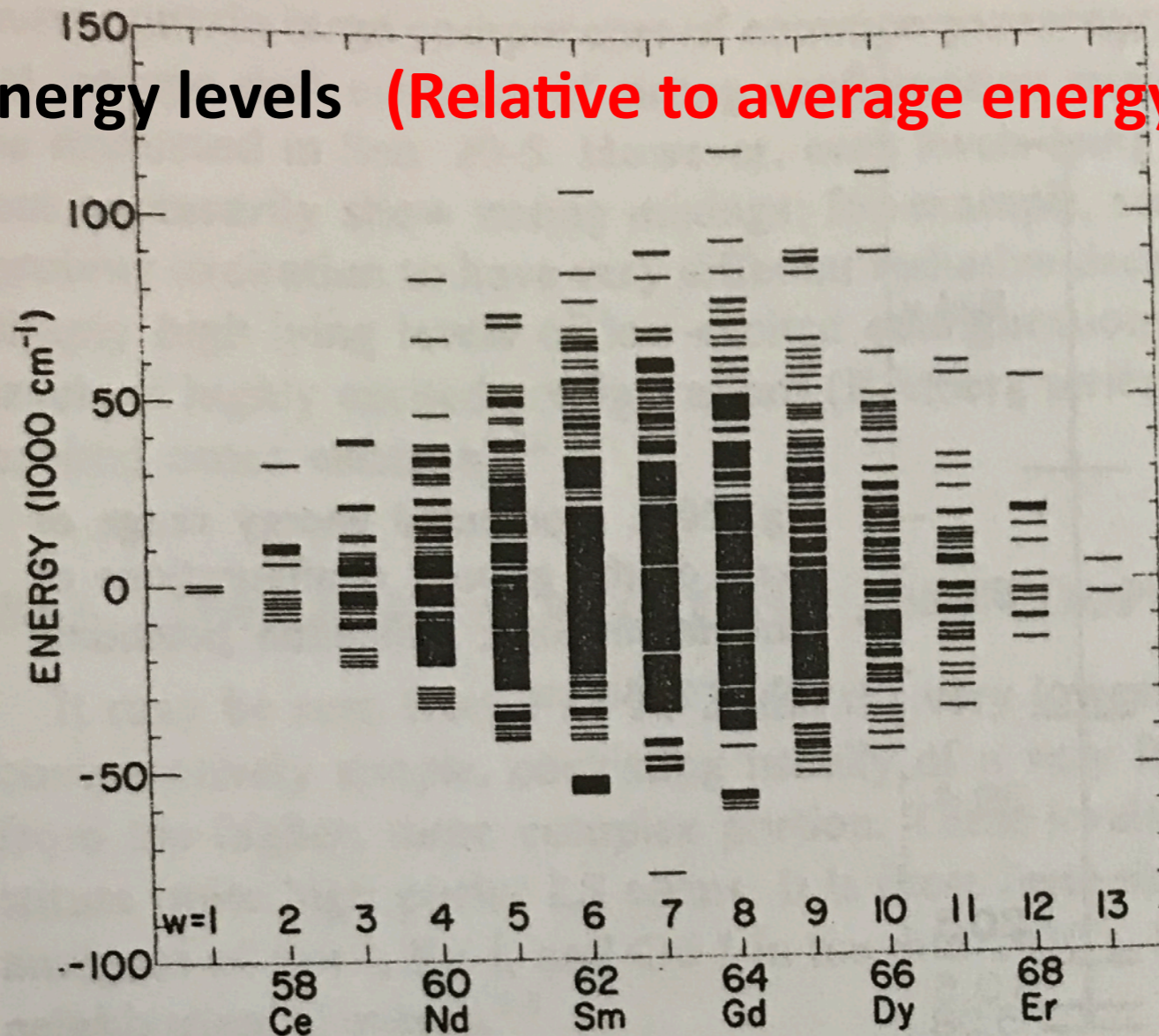
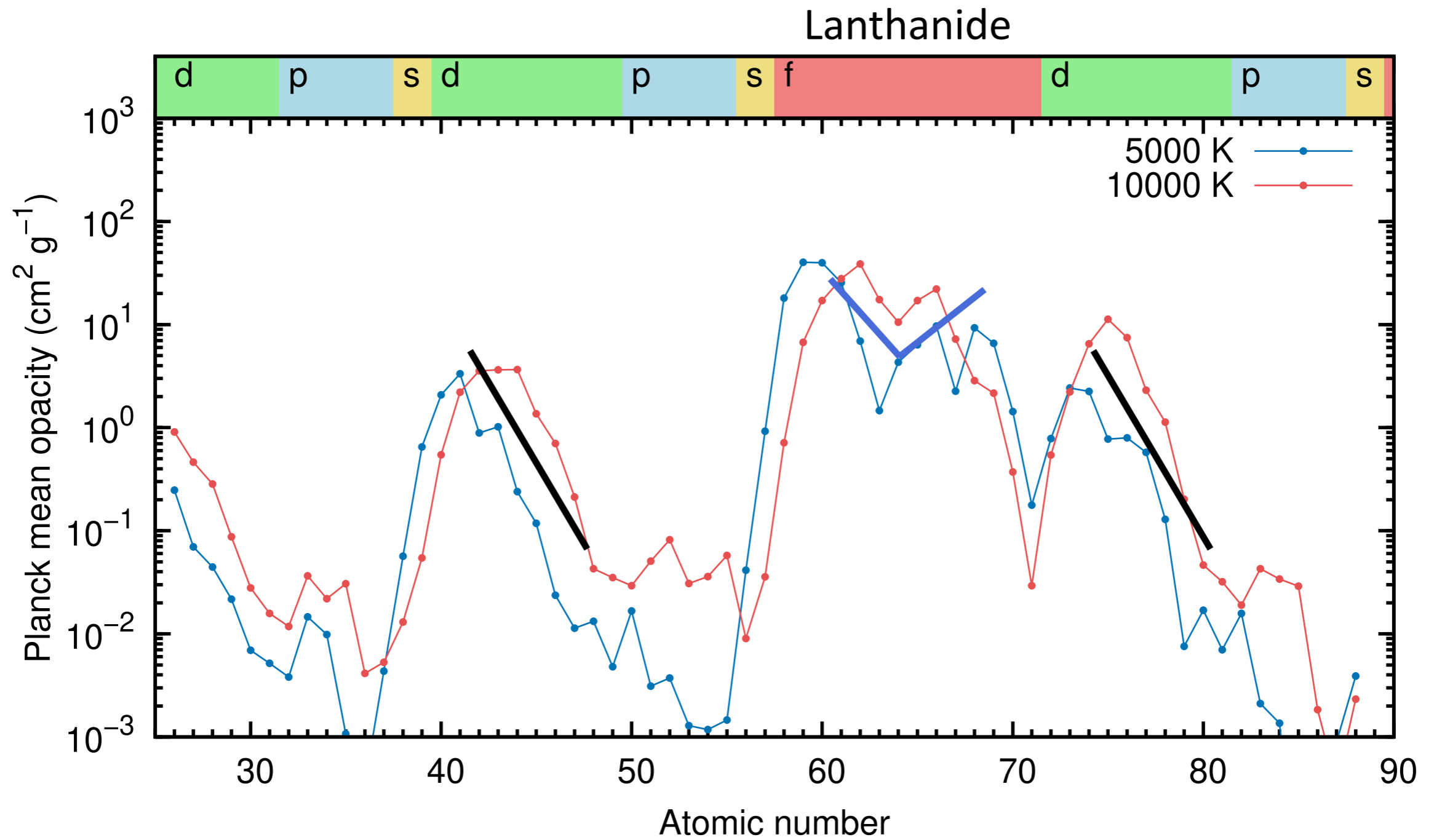


Fig. 20-2. Theoretical energy levels of configurations $4f^w6s^2$ of neutral lanthanide atoms, relative to the center-of-gravity energy E_{av} . The density of levels within each solid block is too great for the levels to be drawn separately.

The Theory of Atomic Structure and Spectra
(Cowan 1981)

Opacity (Planck mean)

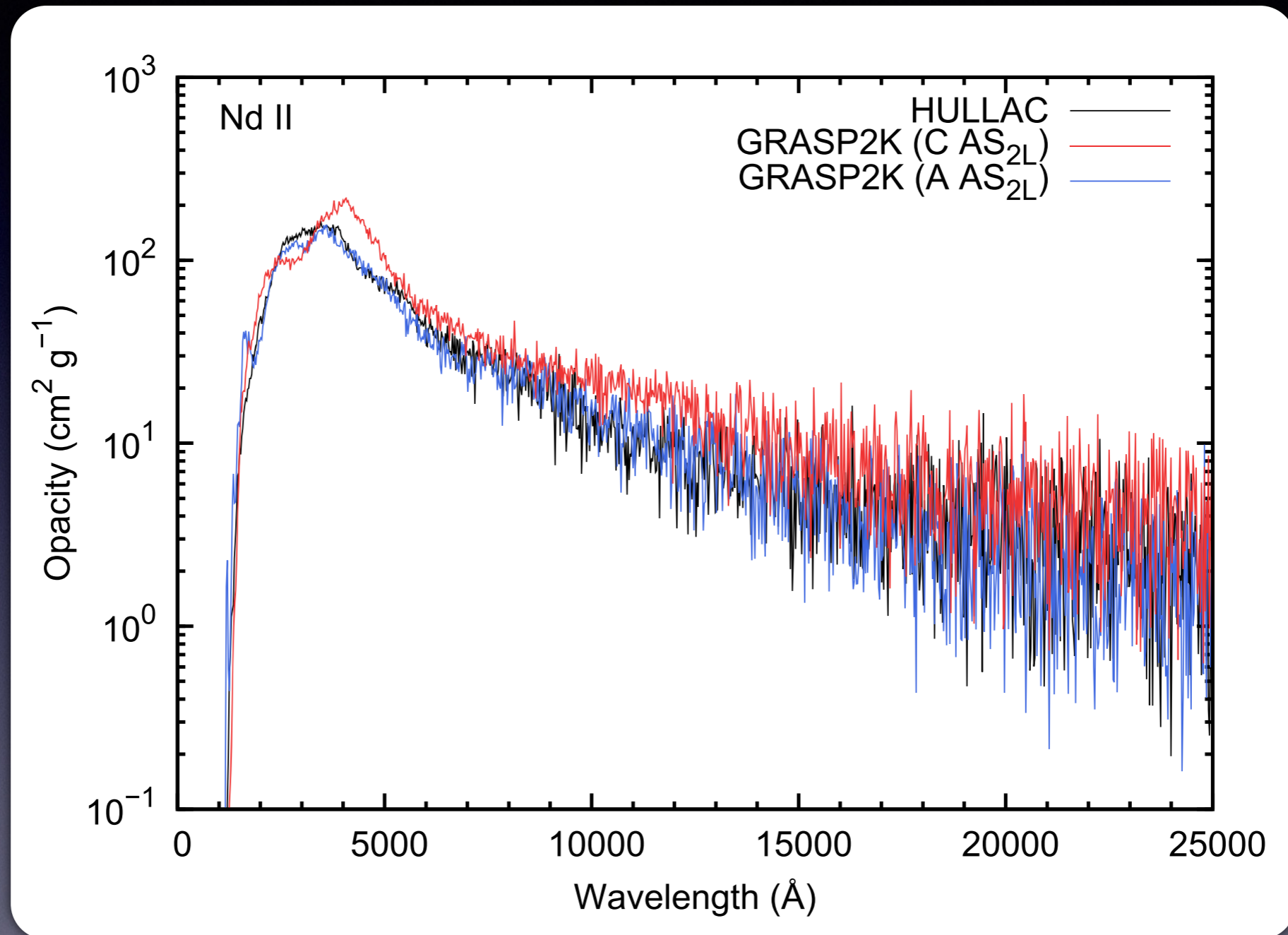
$$\kappa_{Pl} = \frac{\int_0^\infty \kappa_\nu B_\nu(T) d\nu}{\int_0^\infty B_\nu(T) d\nu}$$



Systematic uncertainty?

Gaigalas, Kato, Ruykun et al. 2019

Opacity using different atomic codes (w/ different assumptions)

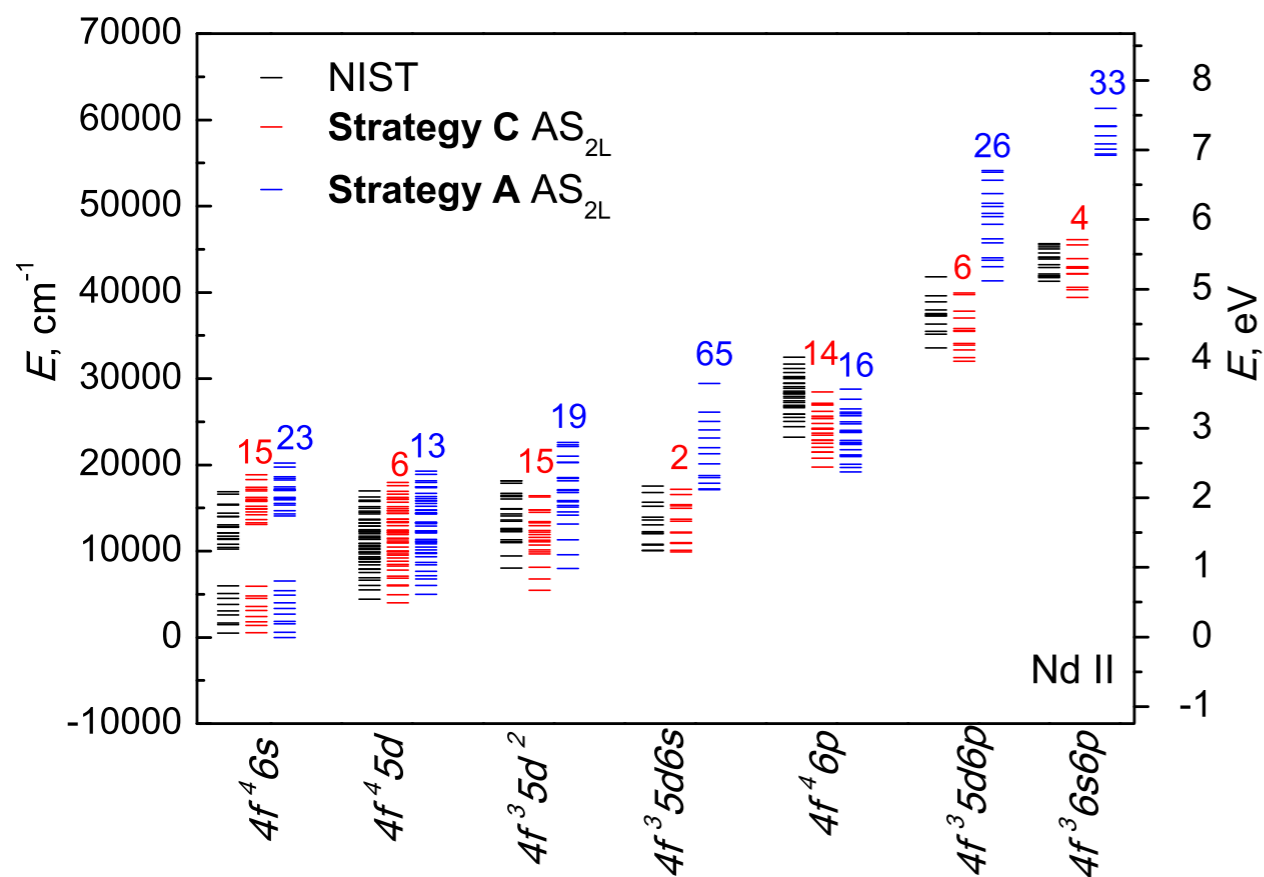


Planck mean opacity: agreement within a factor of ~1.5

Good accuracy for light curve

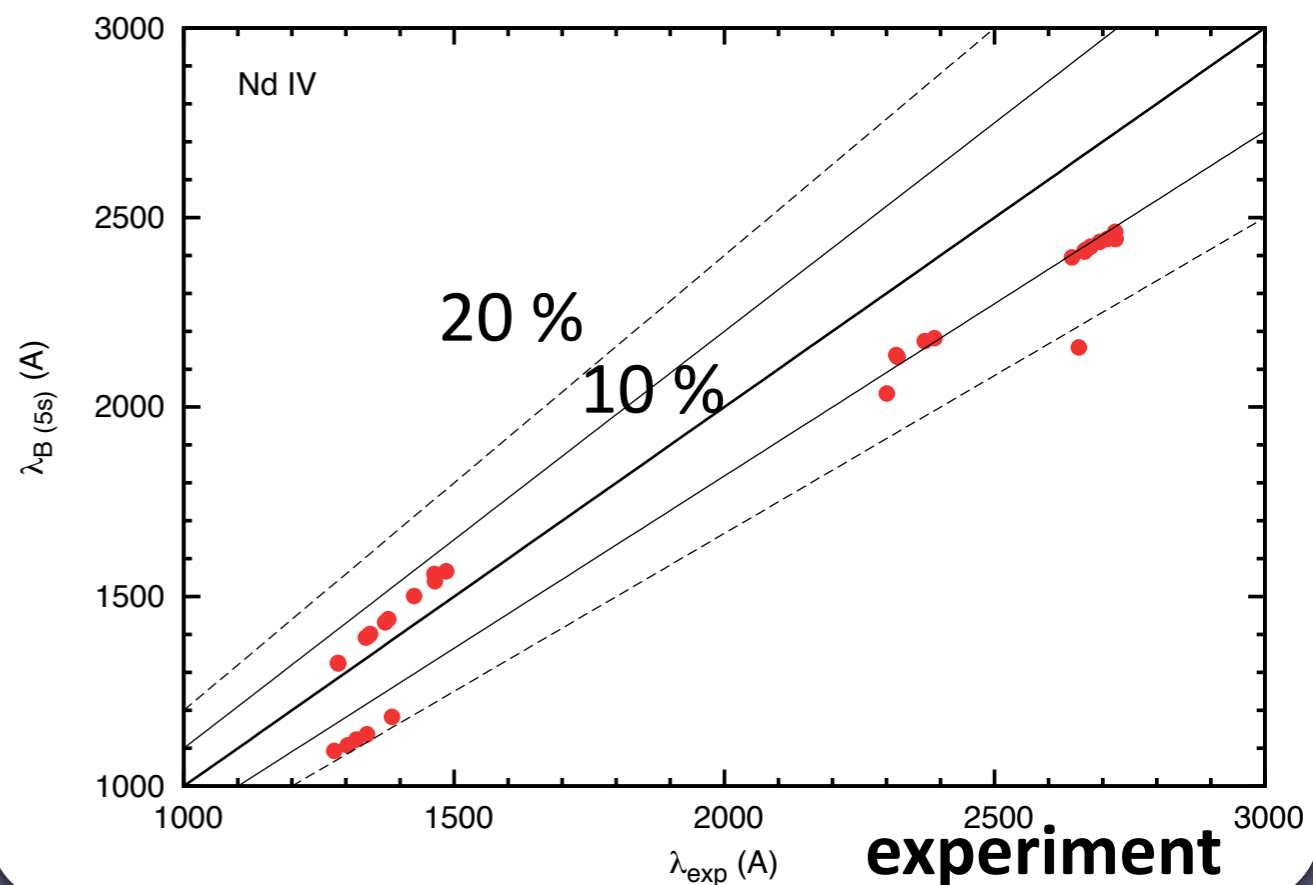
Spectral accuracy?

Gaigalas, Kato, Rynkun et al. 2019
 Radziute, Gaigalas, Kato et al. 2020, 2021



10 % accuracy for energy levels

Calculation



20 % accuracy for transition wavelengths

Not enough to discuss spectral features
 (Need experimentally calibrated data)

土本さん

Opacity at early time ($t < 1$ day)?

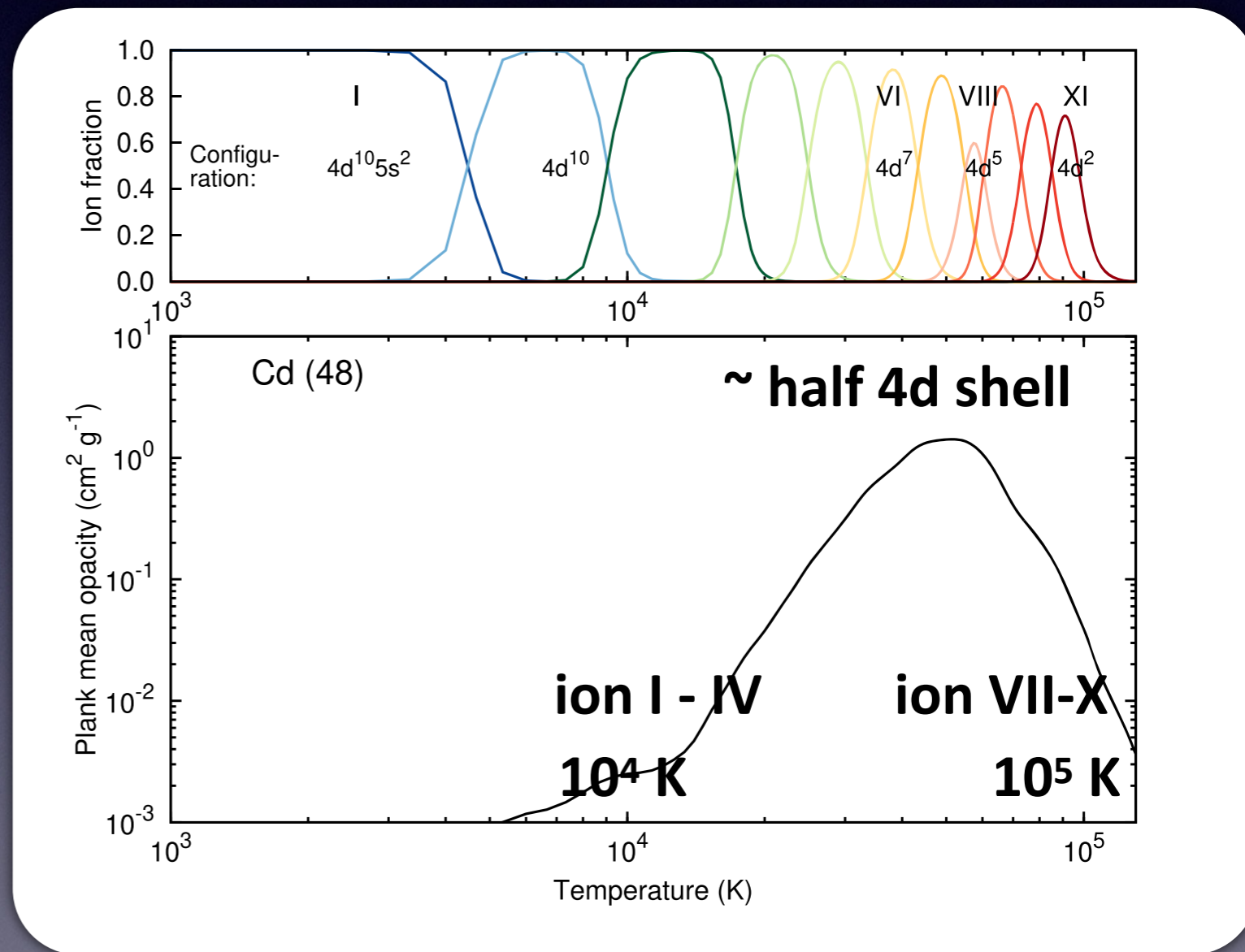
Banerjee, MT, Kawaguchi et al. 2020
(blue kilonova at early time)

$$T \sim 10^4 \text{ K } (t/1 \text{ day})^{-1}$$

$$\sim 10^5 \text{ K @ } t = 0.1 \text{ day}$$

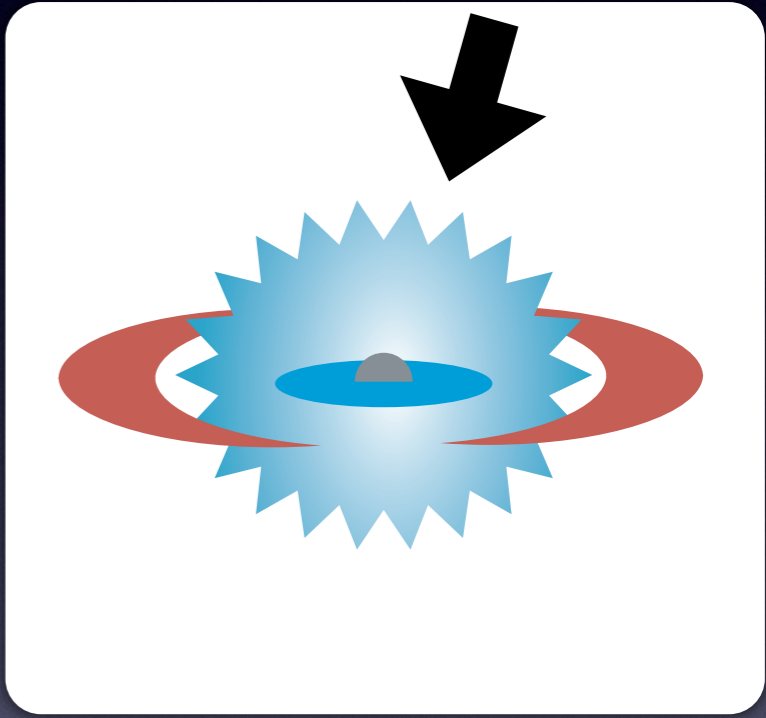
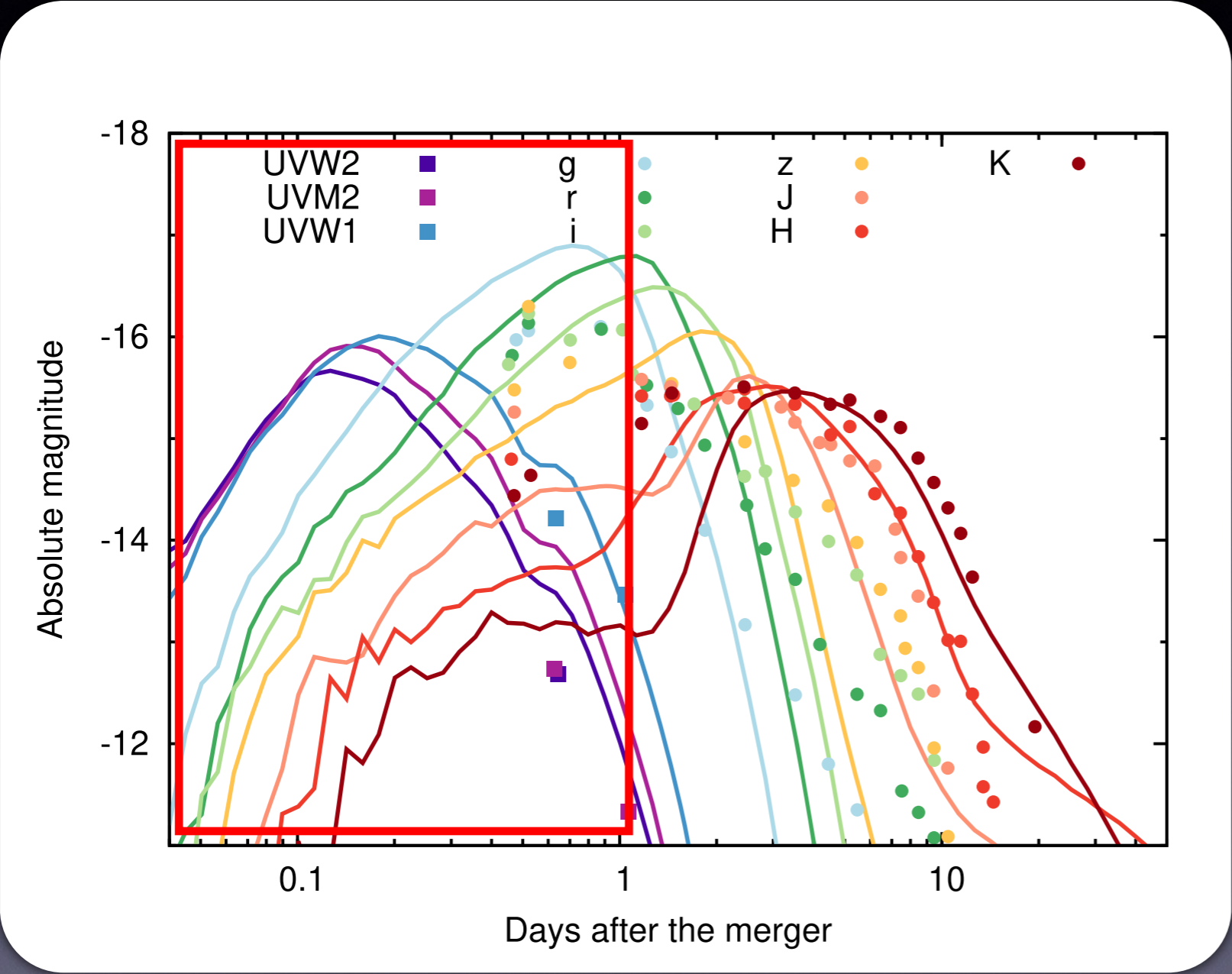
=> atomic calculations up to 10th ionization

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
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			



UV emission at $t \sim$ hours

Banerjee, MT, Kawaguchi et al. 2020
(blue kilonova at early time)



**Probe of the outermost ejecta in NS merger
=> future UV satellites**

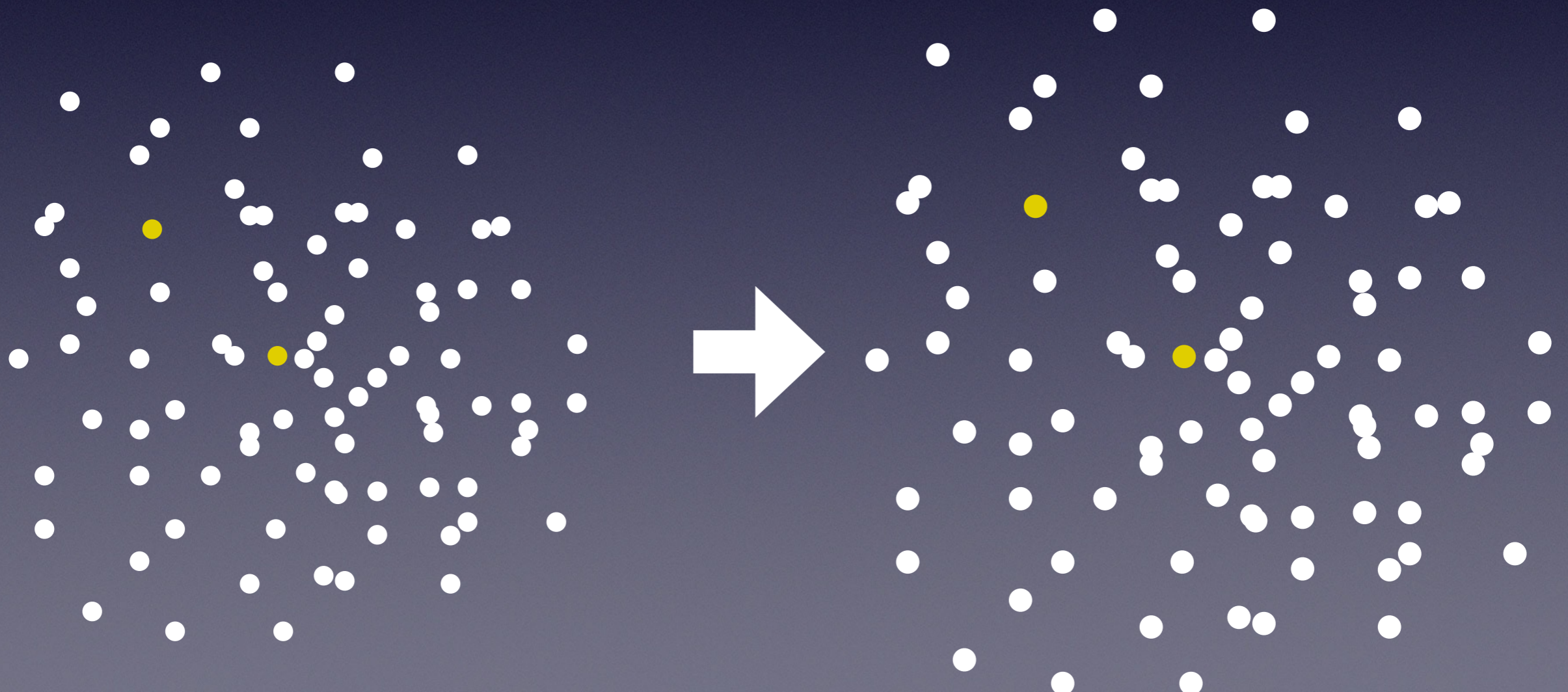
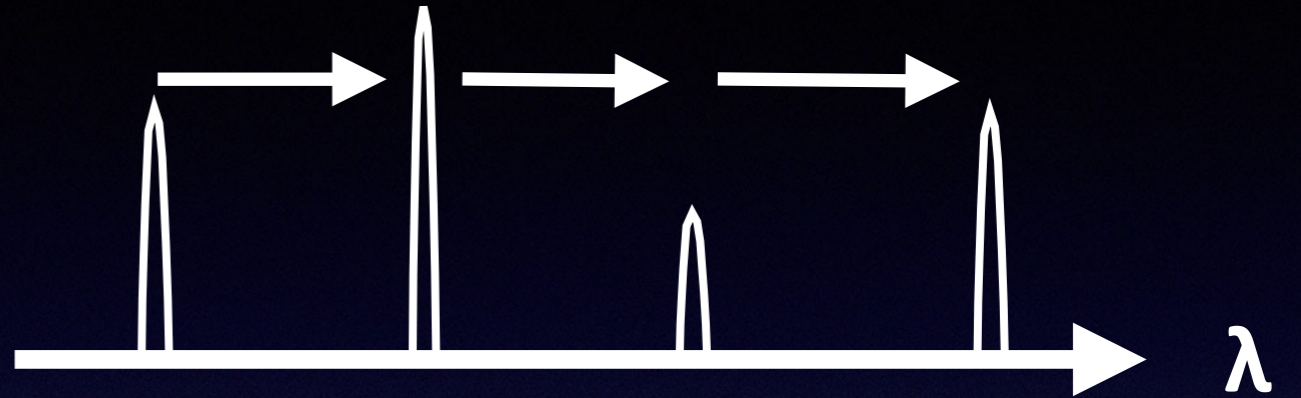
Kilonova

= radioactively-powered thermal radiation from
very metal-rich ($Z > 30$), expanding outflow ($v \sim 0.1c$)

- キロノバの物理
- 重元素の構造とopacity
- 輻射輸送計算

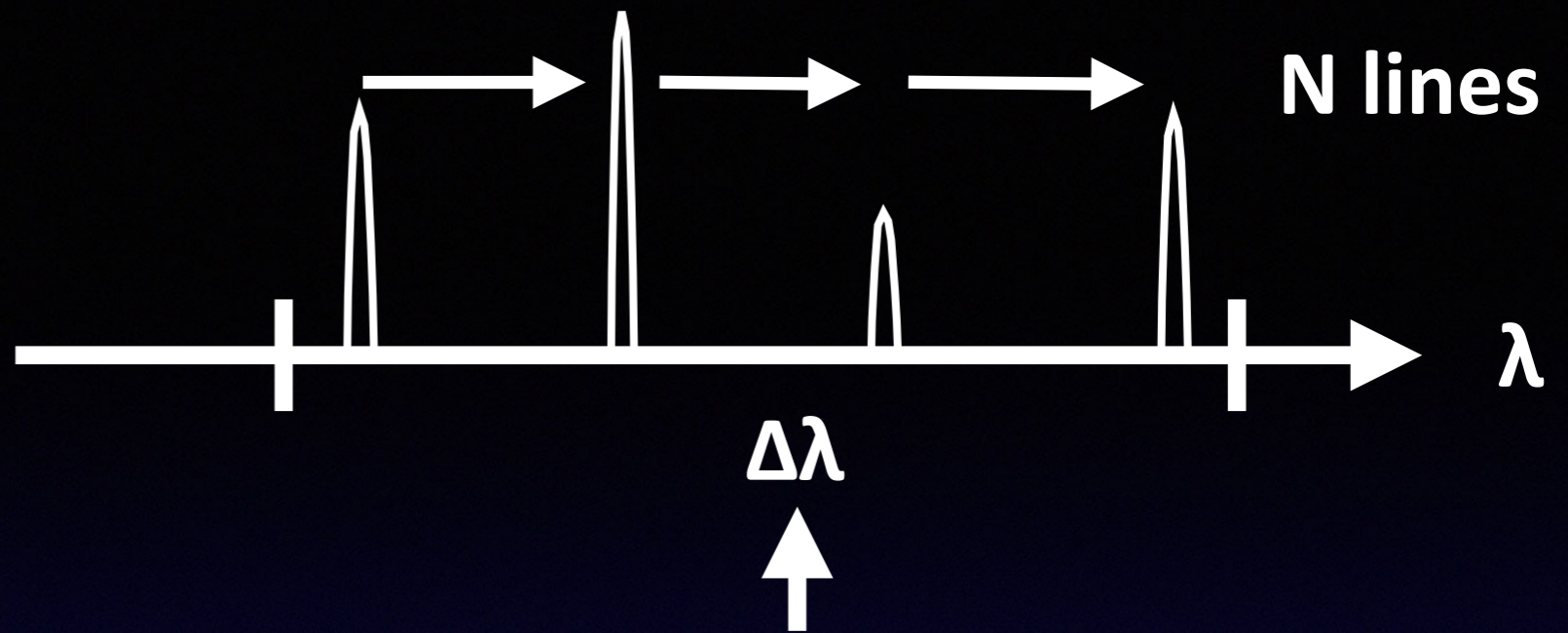
Radiative transfer in metal-rich expanding medium

Photons are always redshifted
in comoving frame



Expansion opacity

Friend & Castor 1983 (stellar wind)
Pinto & Eastman 1993 (supernova)
Kasen+06, Kasen+13 (kilonova)
MT & Hotokezaka 13 (kilonova)



How to define “effective” opacity in this bin?
(keeping each line info is not feasible)

Line spacing

$$\Delta\lambda_{\text{line}} = \frac{\Delta\lambda}{N}$$

Effective mean free path

$$l = \frac{\Delta\lambda_{\text{line}}}{\lambda} ct = \frac{\Delta\lambda}{\lambda} \frac{1}{N} ct$$

Effective absorption coefficient α_{exp} (cm^{-1})

$$\alpha_{\text{exp}} = \frac{1}{l} = \frac{\lambda}{\Delta\lambda} \frac{1}{ct} N$$

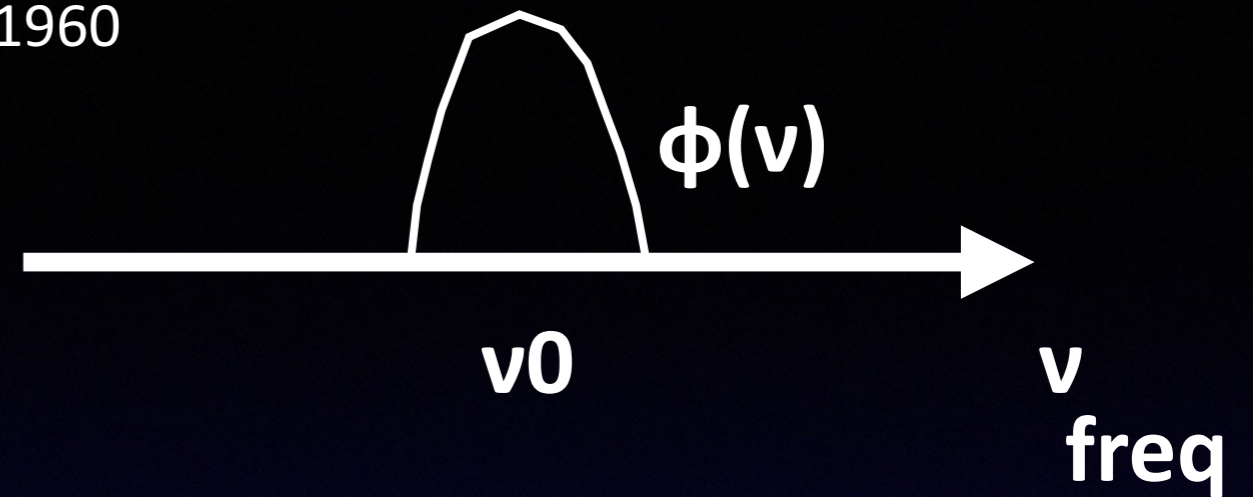
This does not depend on the line strength
(if lines are strong enough)

By including weak lines
($\tau_{\text{sob}} = \text{Sobolev optical depth}$)

$$\alpha_{\text{exp}} = \frac{\lambda}{\Delta\lambda} \frac{1}{ct} \sum (1 - e^{-\tau_{\text{sob}}})$$

Sobolev optical depth

Sobolev 1960



$$\alpha = \frac{\pi e^2}{mc} n_1 f_{\text{osc}} \phi(\nu)$$

$$\begin{aligned} \tau_{\text{sob}} &= \int \alpha dr \\ &= \int \alpha \frac{dr}{d\nu} \frac{c}{\nu_0} d\nu \\ &= \int \frac{\pi e^2}{mc} n_1 f_{\text{osc}} \phi(\nu) \frac{dr}{d\nu} \frac{c}{\nu_0} d\nu \\ &= \frac{\pi e^2}{mc} n_1 f_{\text{osc}} \frac{dr}{d\nu} \frac{c}{\nu_0} \\ &= \frac{\pi e^2}{mc} n_1 f_{\text{osc}} t \lambda \end{aligned}$$

$$\frac{d\nu}{\nu_0} = \frac{d\nu}{c} = \frac{1}{c} \frac{d\nu}{dr} dr$$

if velocity dominated by
radial motion ($v_{\text{th}} \ll v_{\text{rad}}$)

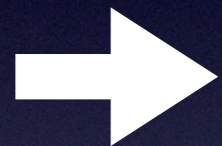
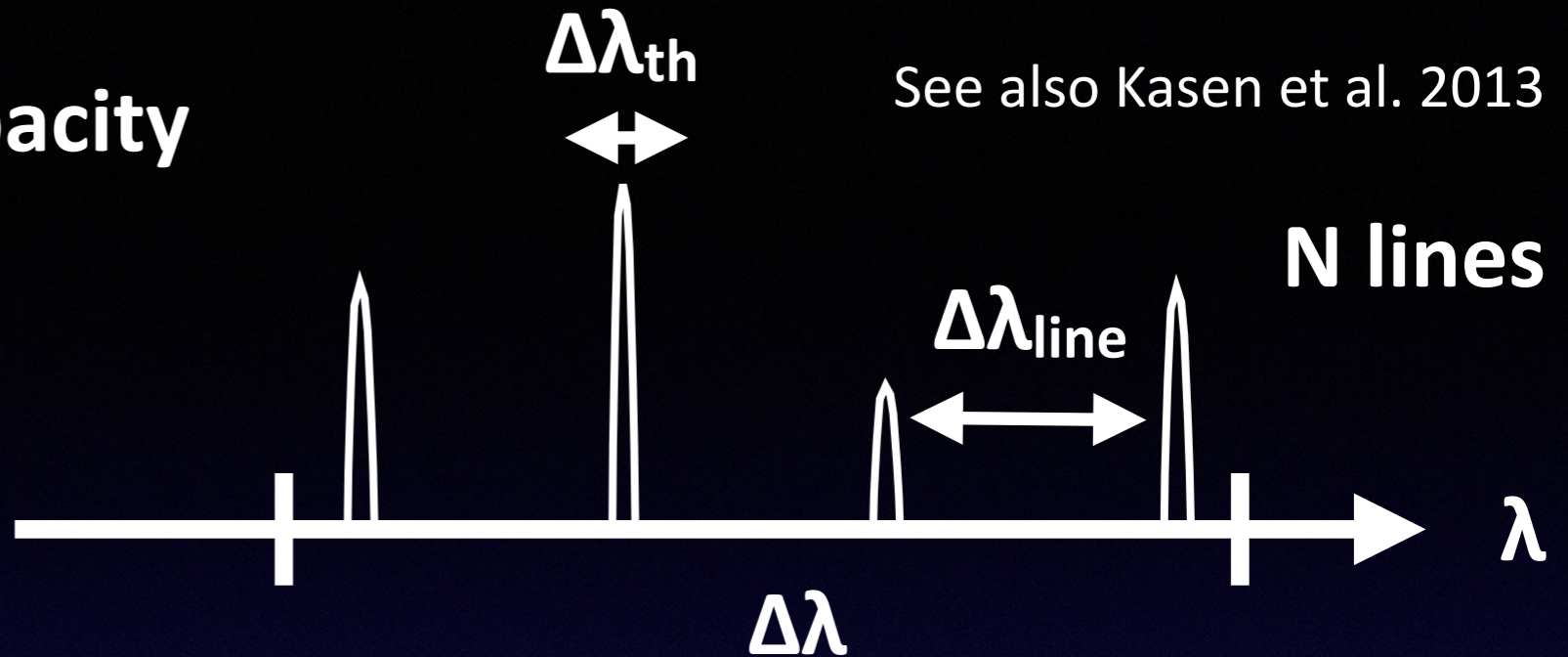
$$\int \phi(\nu) d\nu = 1$$

$$\alpha = \frac{\tau_{\text{sob}}}{t \lambda} \phi(\nu)$$

Validity of expansion opacity

See also Kasen et al. 2013

$$\Delta\lambda_{\text{line}} \gg \Delta\lambda_{\text{th}}$$



$$N_{\text{crit}} \equiv \frac{\Delta\lambda}{\lambda} \frac{c}{v_{\text{th}}}$$

$$\Delta\lambda_{\text{line}} = \frac{\Delta\lambda}{N}$$

$$\Delta\lambda_{\text{th}} = \frac{v_{\text{th}}}{c} \lambda$$

$$\alpha_{\text{crit}} = \frac{1}{ct} \frac{\lambda}{\Delta\lambda} N_{\text{crit}} = \frac{1}{v_{\text{th}} t}$$

$$\kappa_{\text{crit}} = \frac{\alpha_{\text{crit}}}{\rho} = \frac{1}{\rho v_{\text{th}} t}$$

$$\rho \sim t^{-3}$$

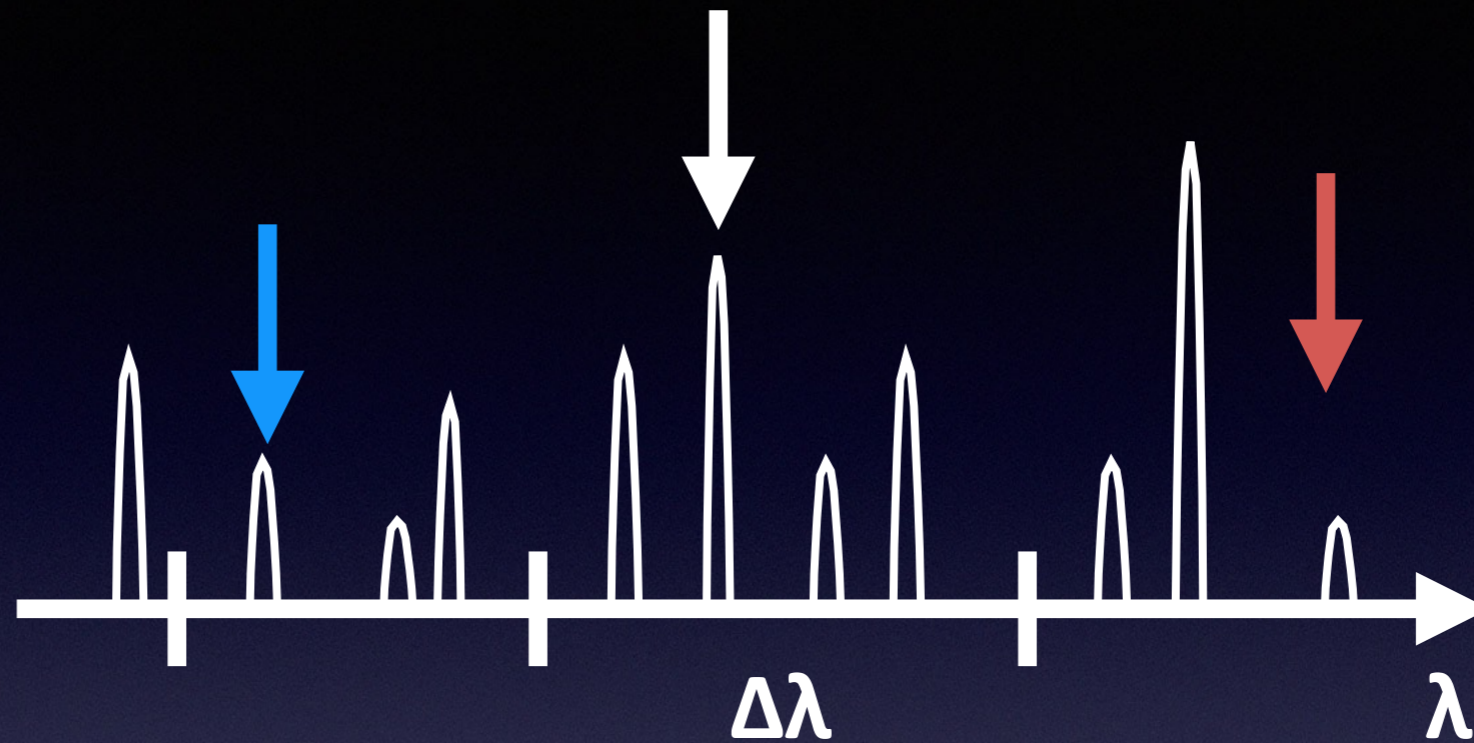
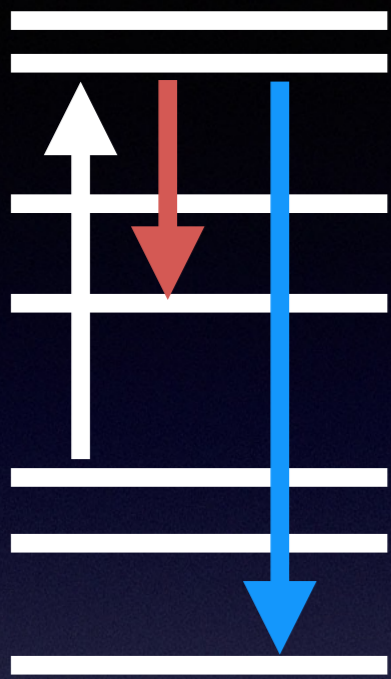
$$v_{\text{th}} \sim T^{-1/2} \sim t^{-1/2}$$

$$\kappa_{\text{crit}} \sim 10^3 \text{ cm}^2 \text{ g}^{-1} (t/1 \text{ day})^{2.5}$$

$$\sim 3 \text{ cm}^2 \text{ g}^{-1} @ t = 0.1 \text{ day}$$

Photon escape via fluorescence

See Lucy 1999, Pinto & Eastman 2000
for direct treatment in supernovae



(keeping each line info is not feasible)

Absorptive treatment

Redistribute photon energy
according to

thermal distribution $j = \alpha B(T)$

(adopted in kilonova simulations,
Kasen+13, MT & Hotokezaka 13,
Wollaeger+17)

Summary

- **Kilonova**

- Probe of nucleosynthesis via atomic properties (opacity)

- **Atomic calculations for kilonova**

- Almost done for low ionization ($t > 1$ day)
 - Good accuracy for light curves, but not for spectra
- Ongoing for high ionization ($t < 1$ day)
 - Predictions are available for early blue kilonova
 - Highly ionized lanthanides are very complicated
 - Different regime of radiative transfer