Kilonova

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Kilonova

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

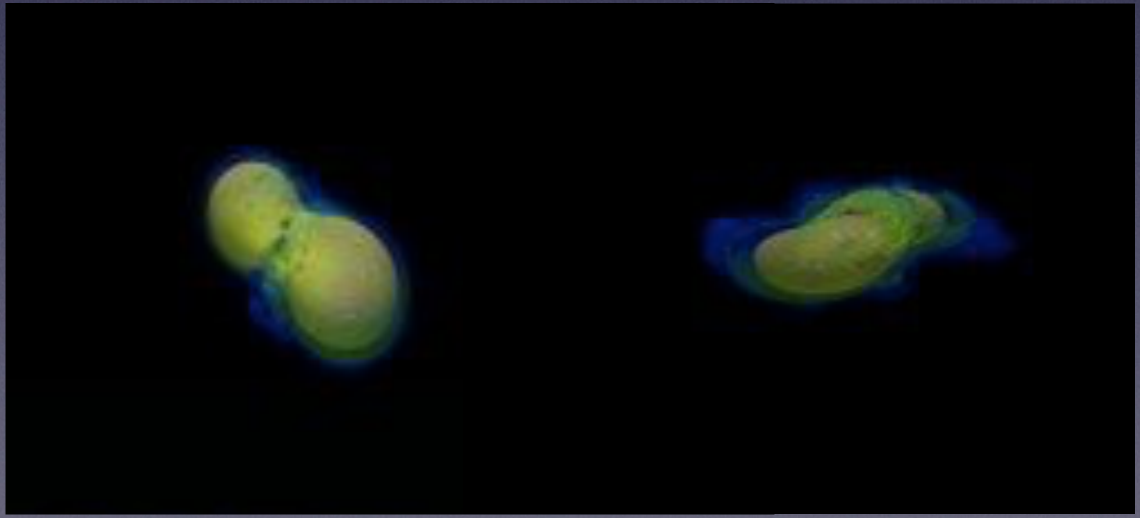
- キロノバの物理
- 重元素の構造とopacity
- 輻射輸送計算

Timescales of NS mergers

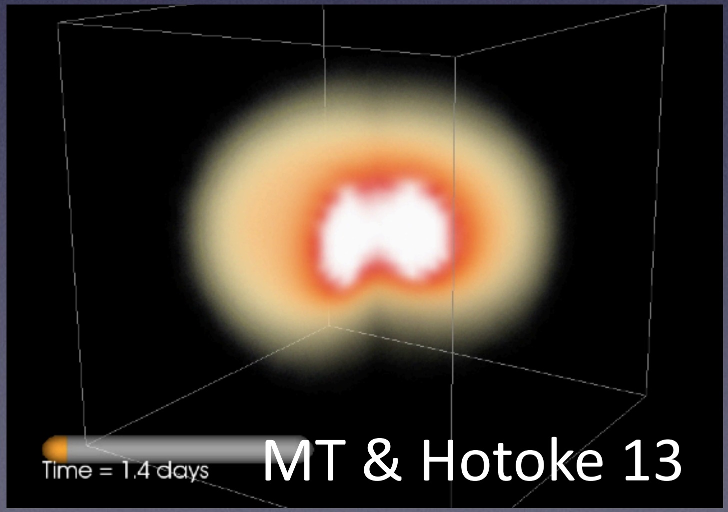
Merger → r-process nucleosynthesis → Radioactive decay => kilonova → Chemical enrichment

Mass ejection

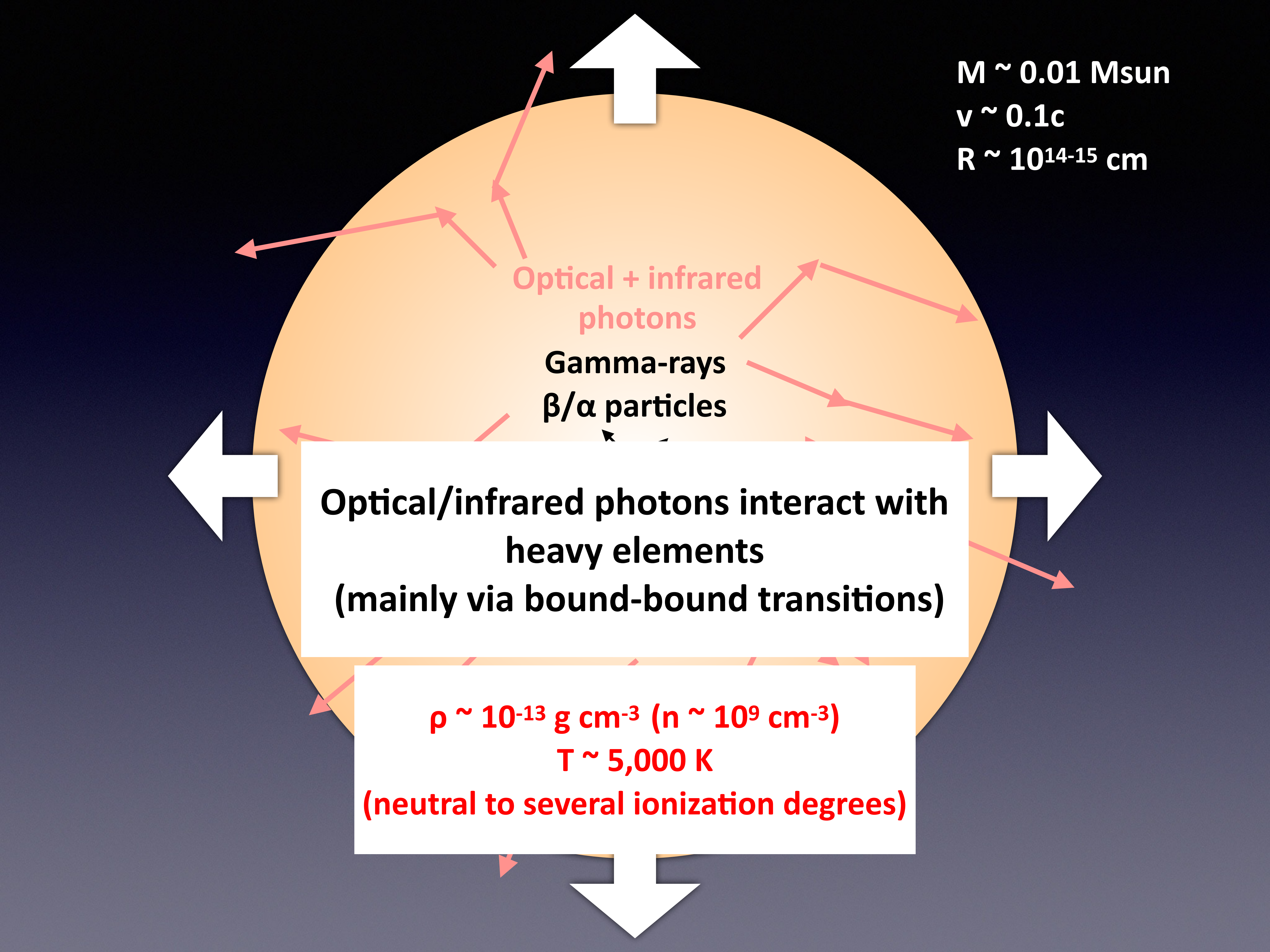
< 1 sec   ~> days   > Myr



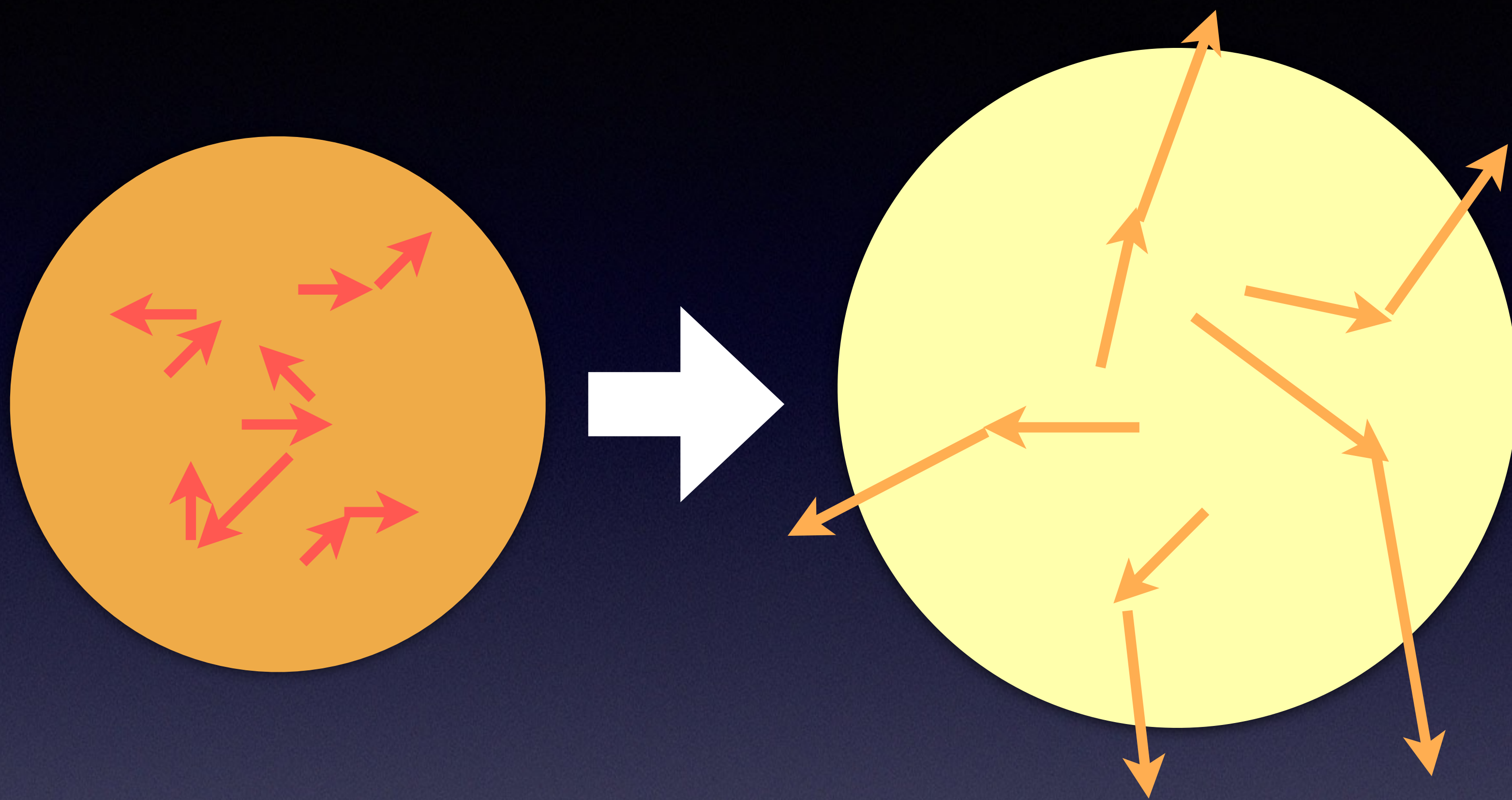
http://www.aei.mpg.de/comp-rel-astro

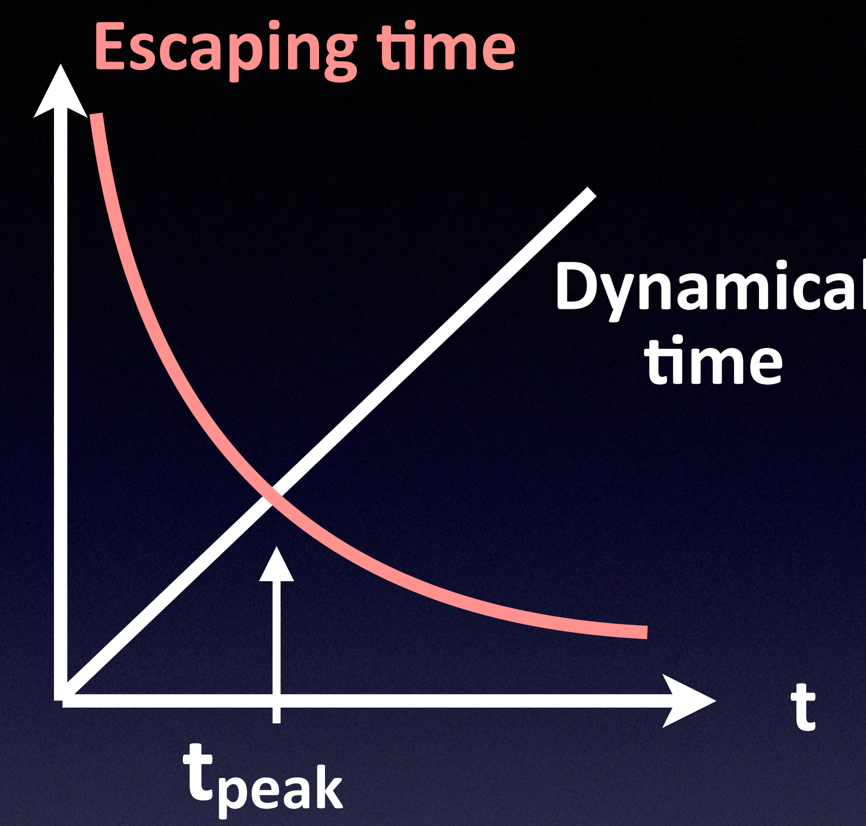


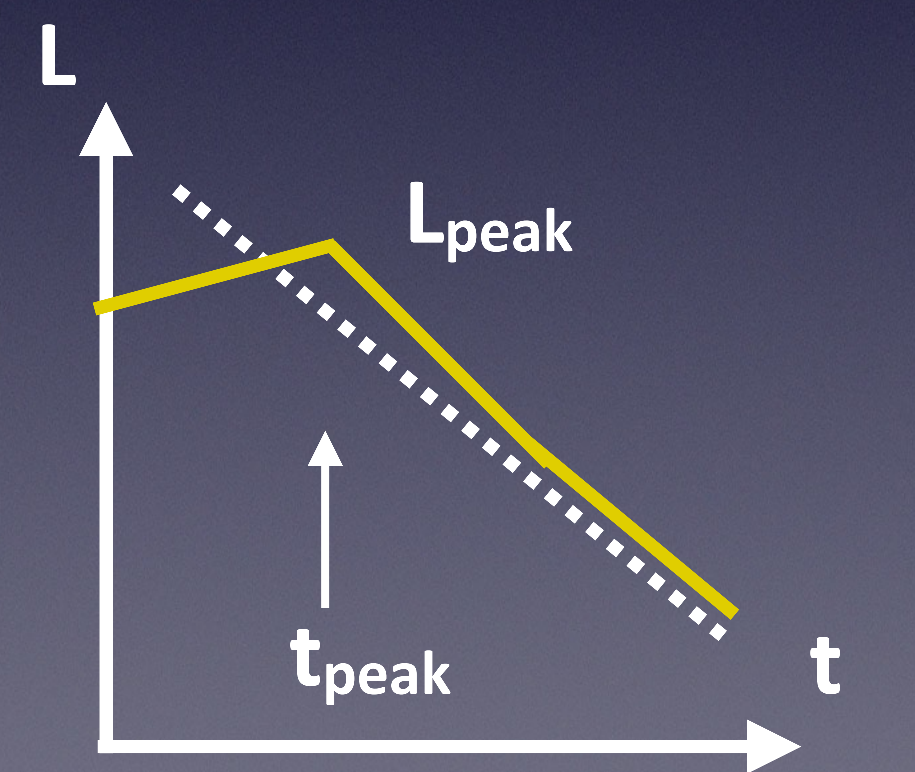
MT & Hotoke 13


M ~ 0.01 Msun
v ~ 0.1c
R ~ 10^14-15 cm
Optical + infrared photons
Gamma-rays
β/α particles
Optical/infrared photons interact with heavy elements
(mainly via bound-bound transitions)
ρ ~ 10^-13 g cm^-3 (n ~ 10^9 cm^-3)
T ~ 5,000 K
(neutral to several ionization degrees)

Timescale





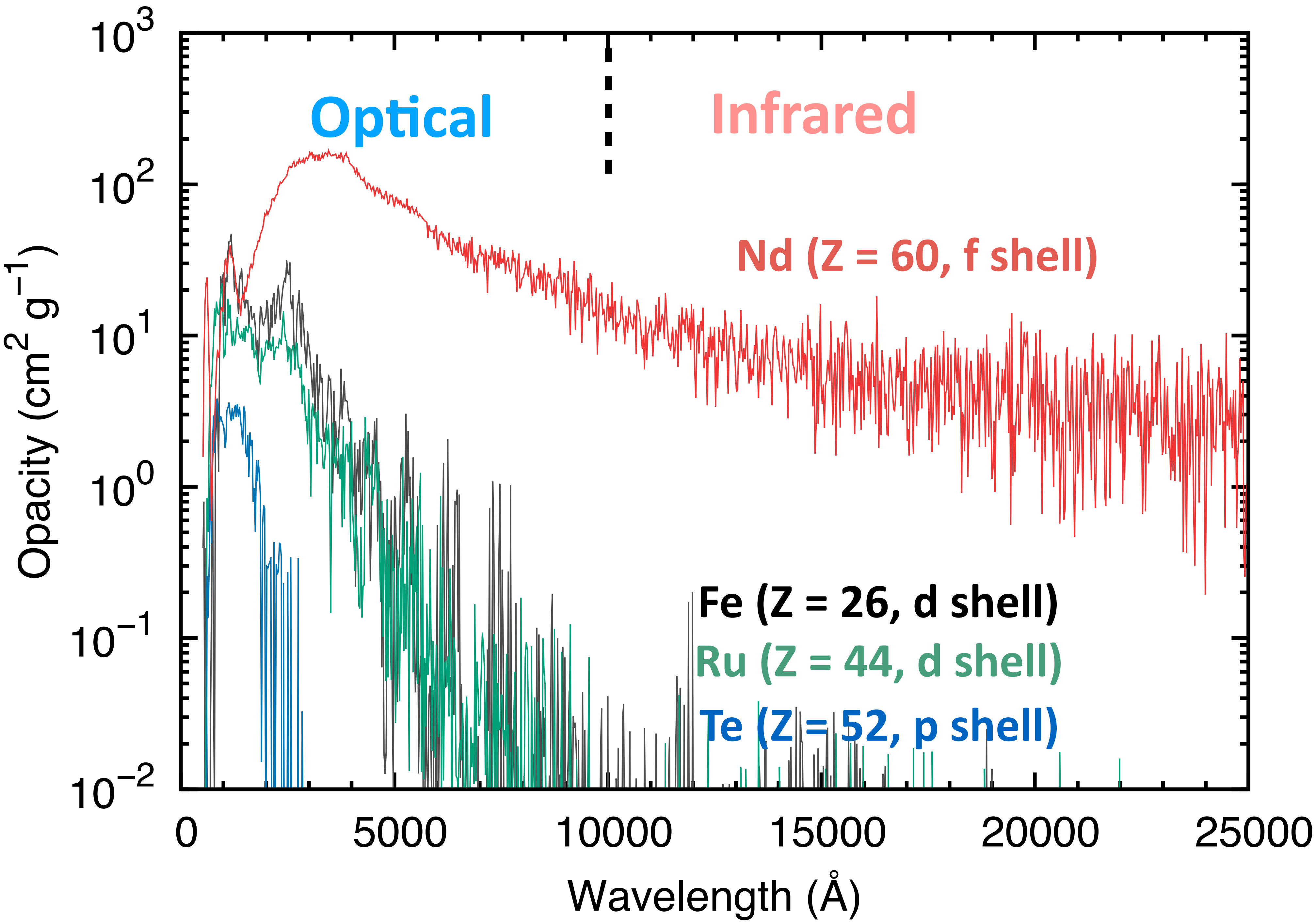


$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$

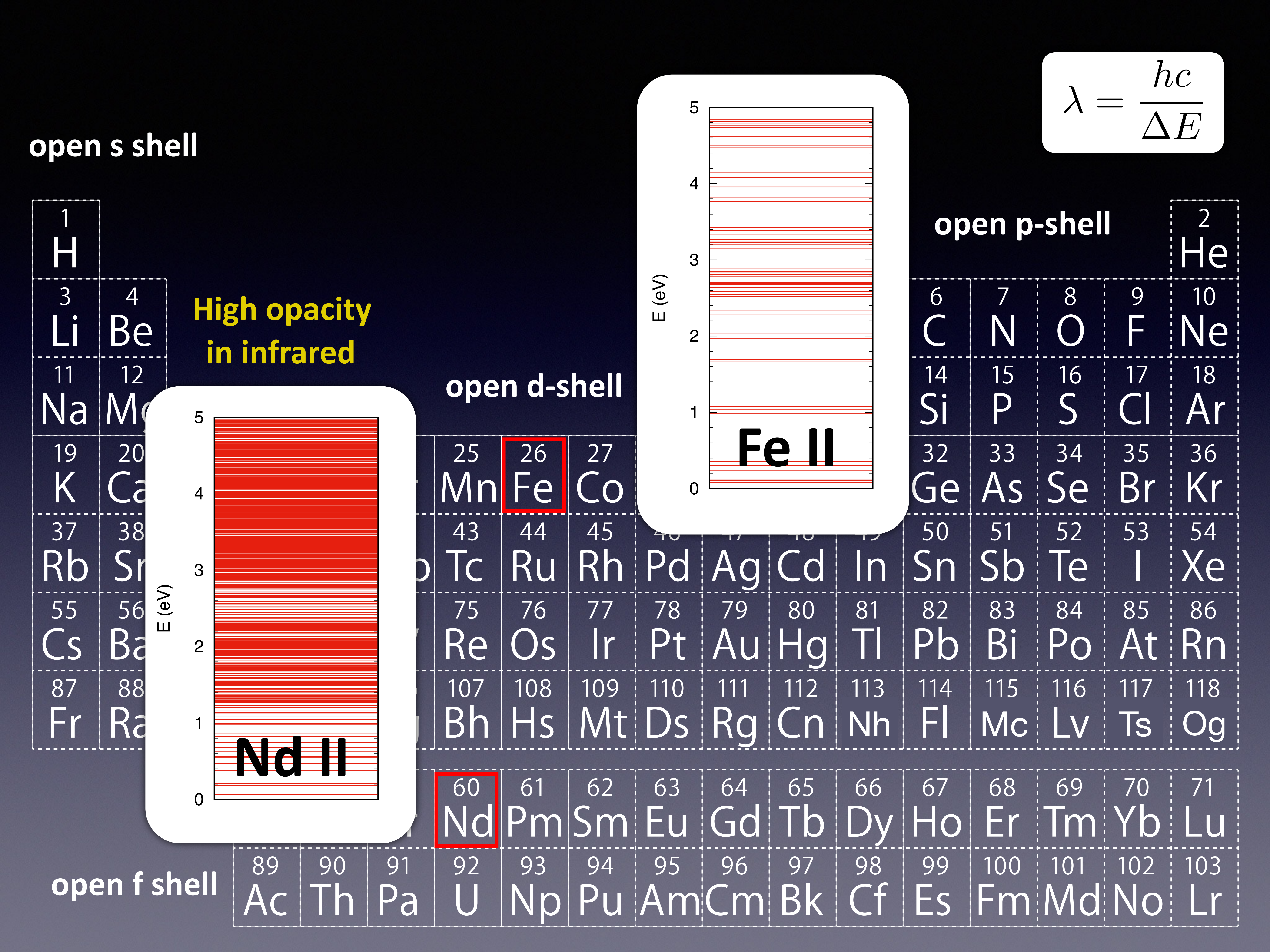
$$\simeq 8.4 \text{ days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}$$

Bound-bound opacity

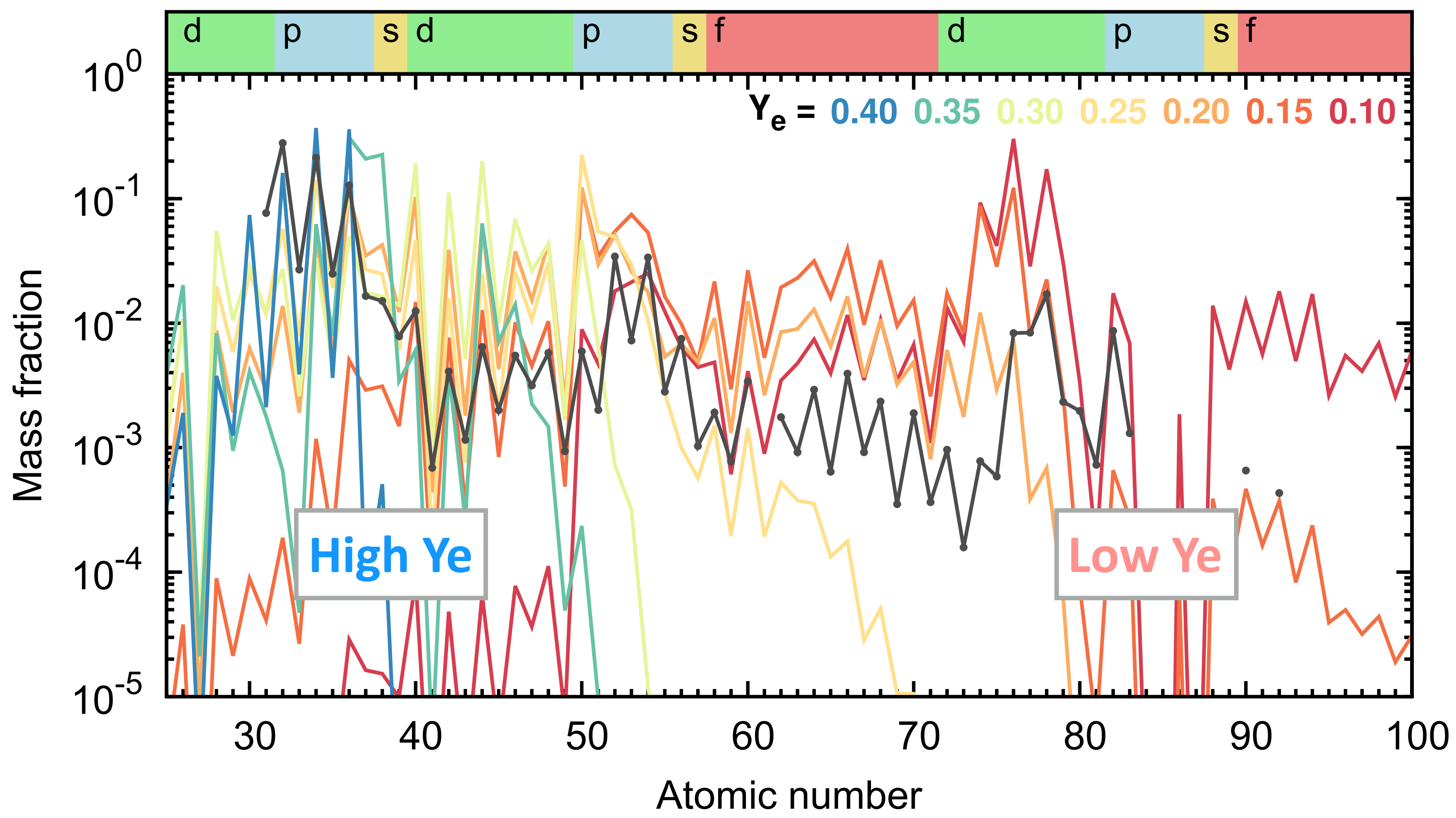
Kasen+13, MT & Hotokezaka 13,
MT+18, 20, Fontes+20



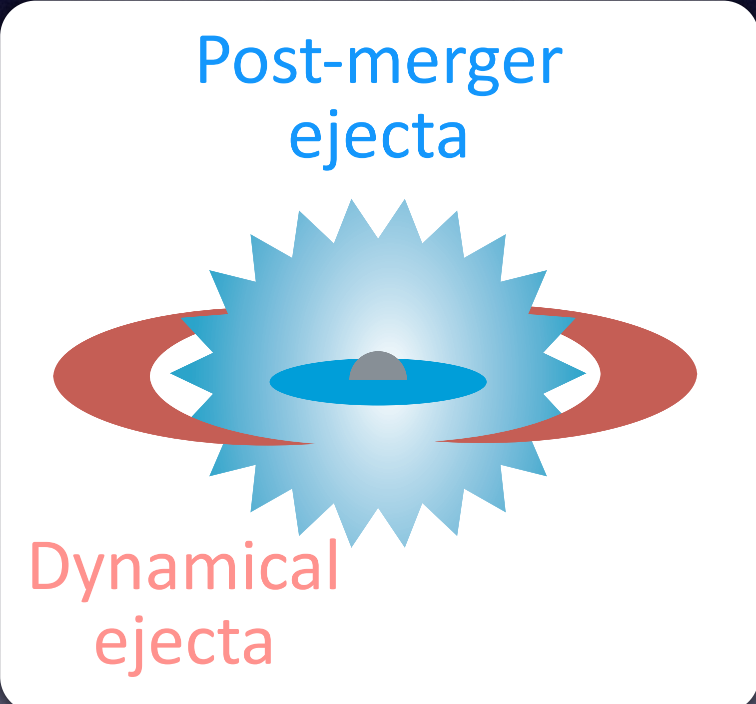
MT, Kato, Gaigalas, et al. 2018


$\lambda = \frac{hc}{\Delta E}$
open s shell
High opacity
in infrared
open d-shell
open p-shell
open f shell
Fe II
Nd II
E (eV)
0
1
2
3
4
5

Probing Nucleosynthesis via opacity



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

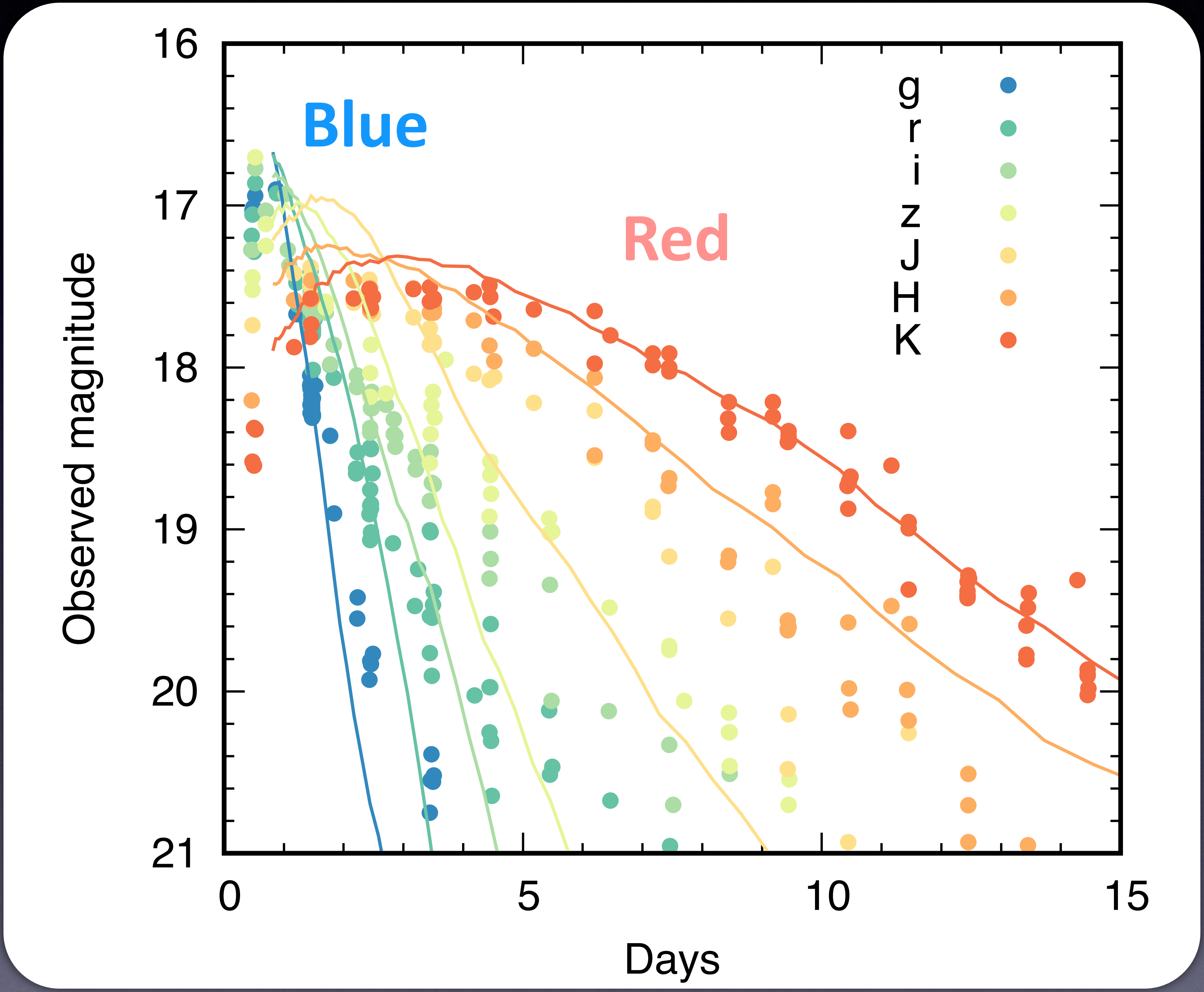


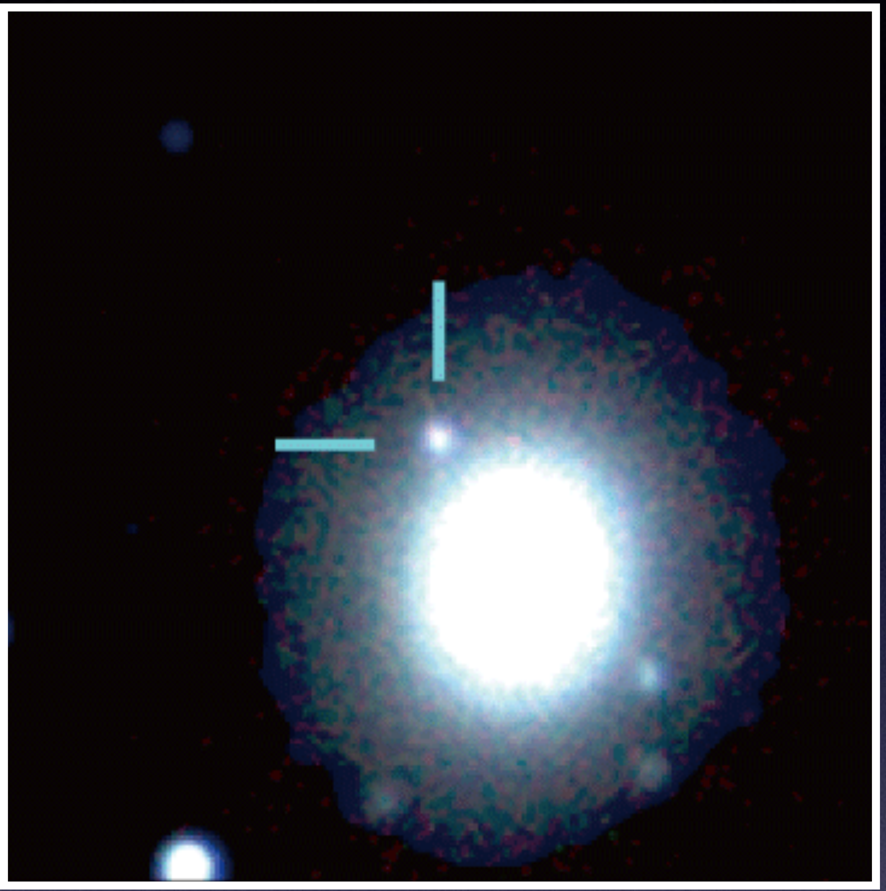
Ye >~ 0.25 ==> "blue" kilonova

Ye ~< 0.25 ==> "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

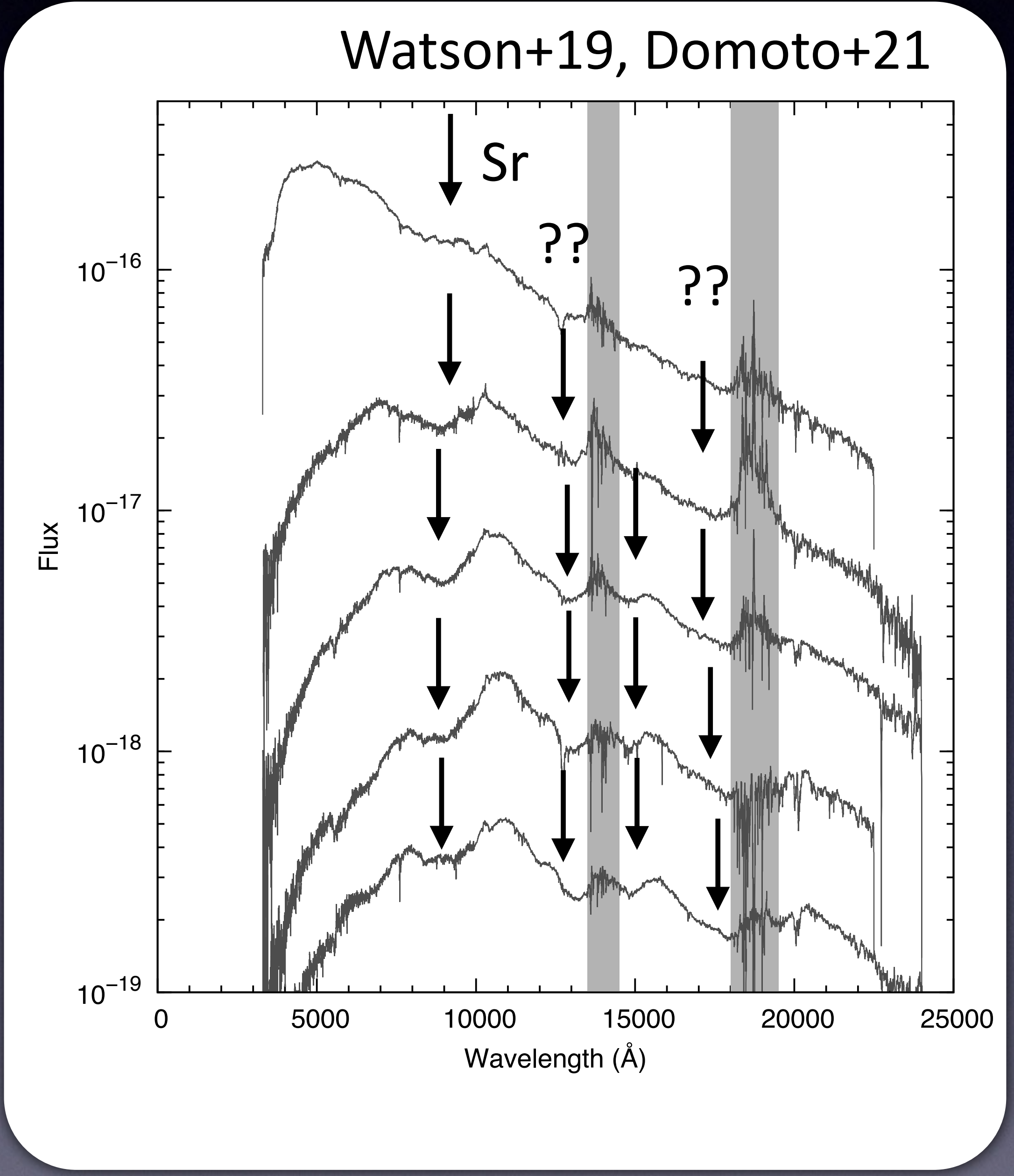
- どの元素がどれぐらいいるのか？
  スペクトルは「解読」できるか？
- エジェクタの多次元構造の影響は？

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

- …



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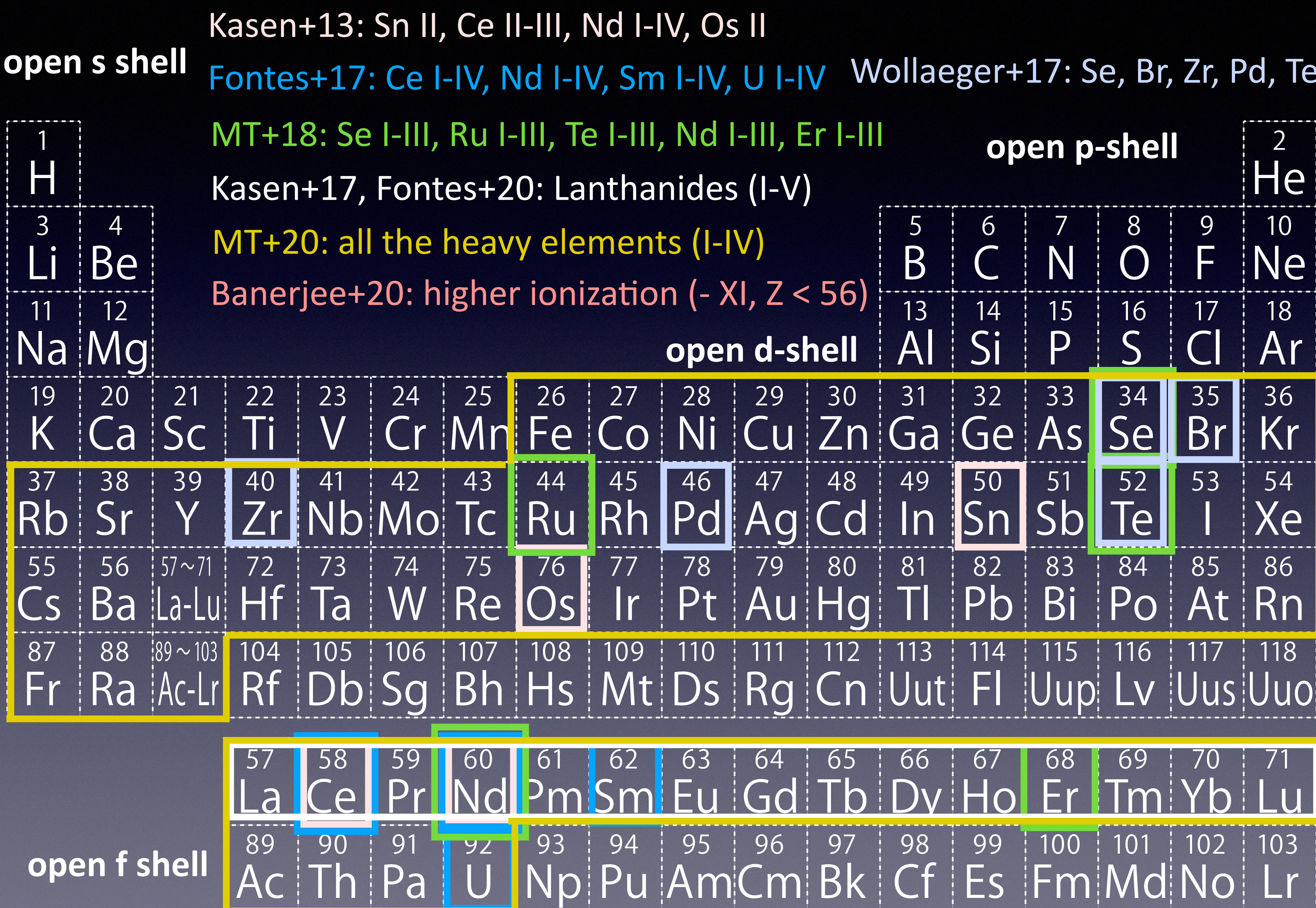
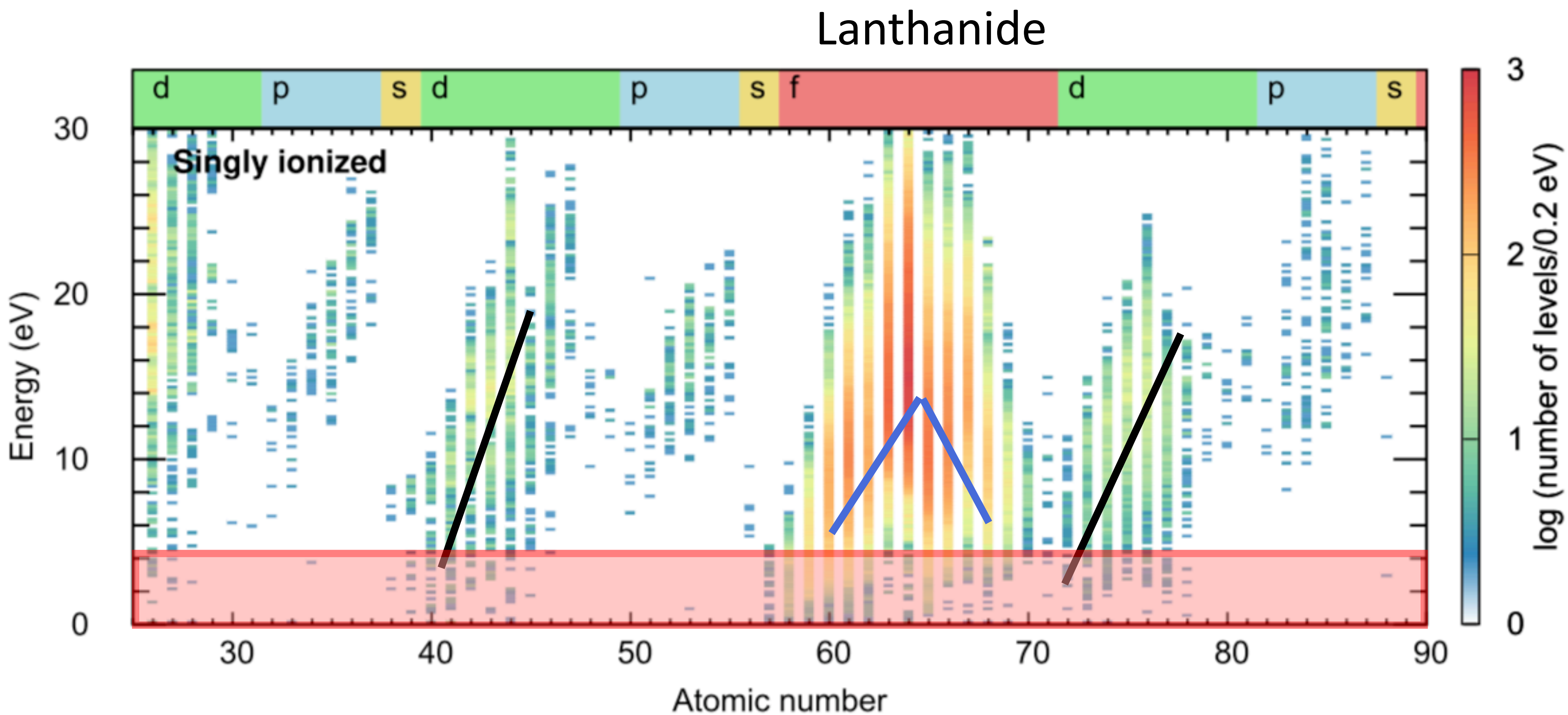
Atomic calculations for kilonova

MT, Kato, Gaigalas, Kawaguchi 2020



Energy level structure



Spin-orbit interaction (increases with Z)

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

k = j +1/2

Complexity (max at half closed)

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

g = 2(2l + 1)

Energy levels of lanthanides

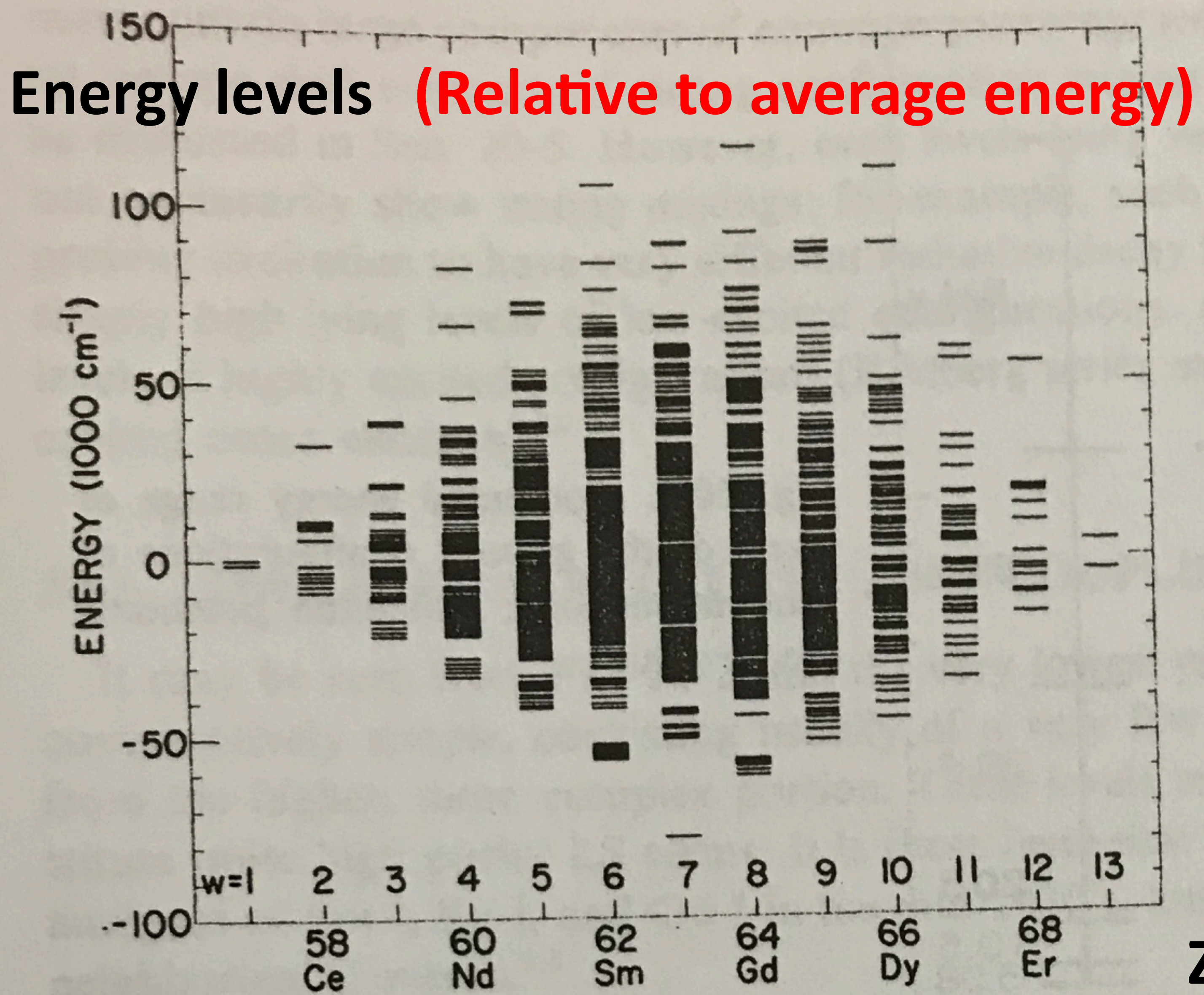
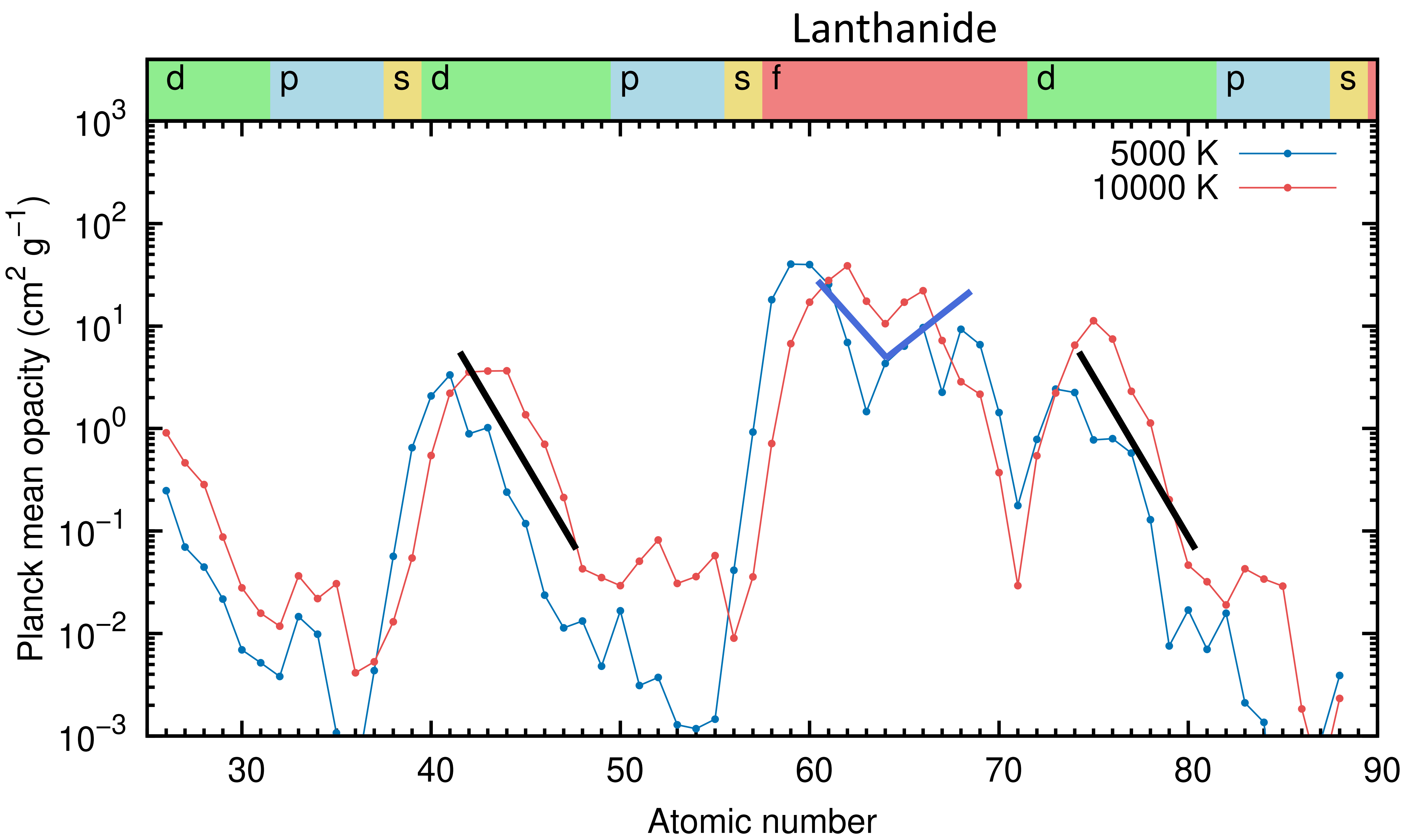


Fig. 20-2. Theoretical energy levels of configurations $4f^w6s^2$ of neutral lanthanide atoms, relative to the center-of-gravity energy E_{av}. The density of levels within each solid block is too great for the levels to be drawn separately.

The Theory of Atomic Structure and Spectra
(Cowan 1981)

Opacity (Planck mean)

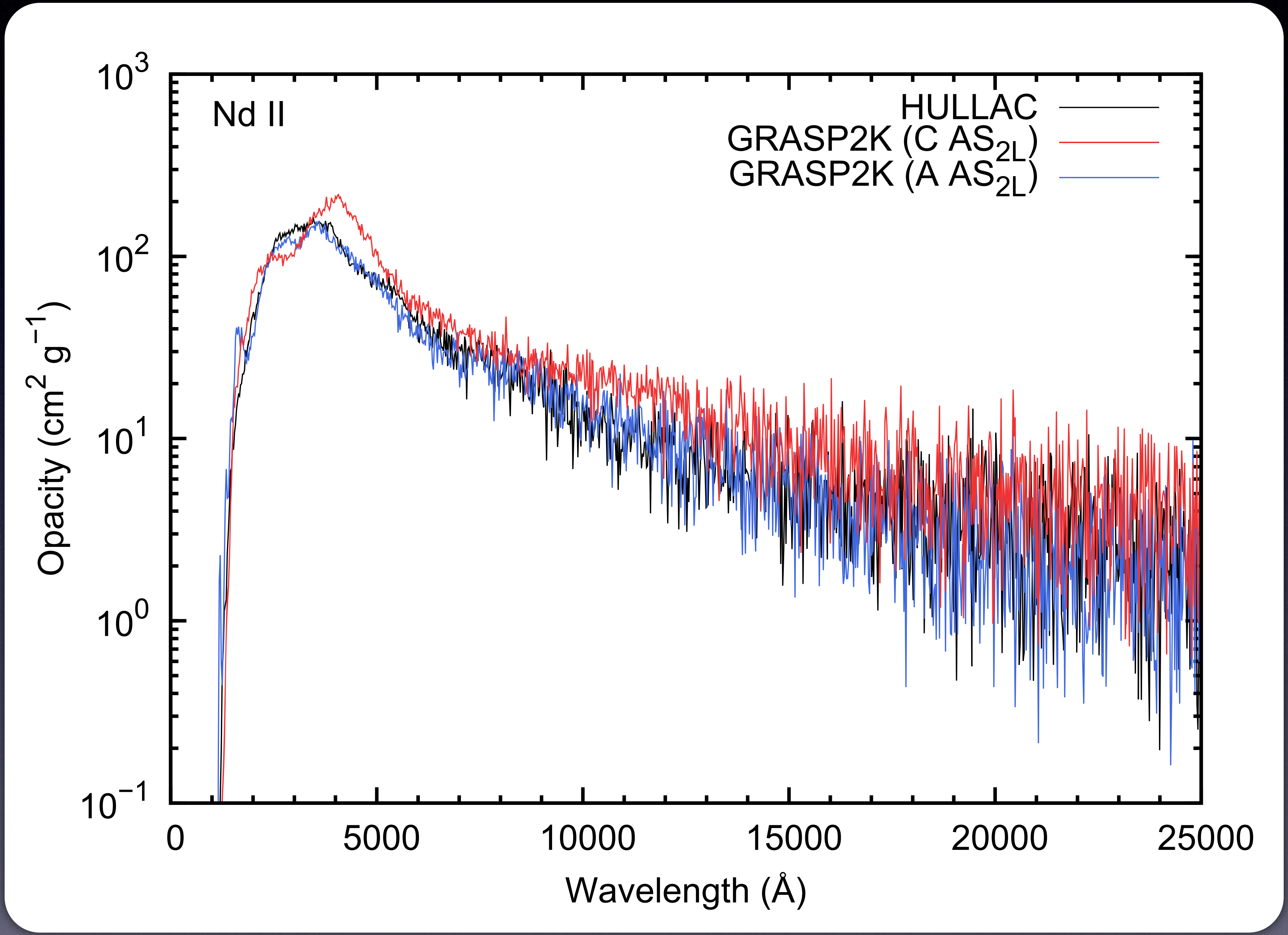
$$\kappa_{Pl} = \frac{\int_0^\infty \kappa_\nu B_\nu(T) d\nu}{\int_0^\infty B_\nu(T) d\nu}$$



Systematic uncertainty?

Gaigalas, Kato, Ruykun et al. 2019

Opacity using different atomic codes (w/ different assumptions)

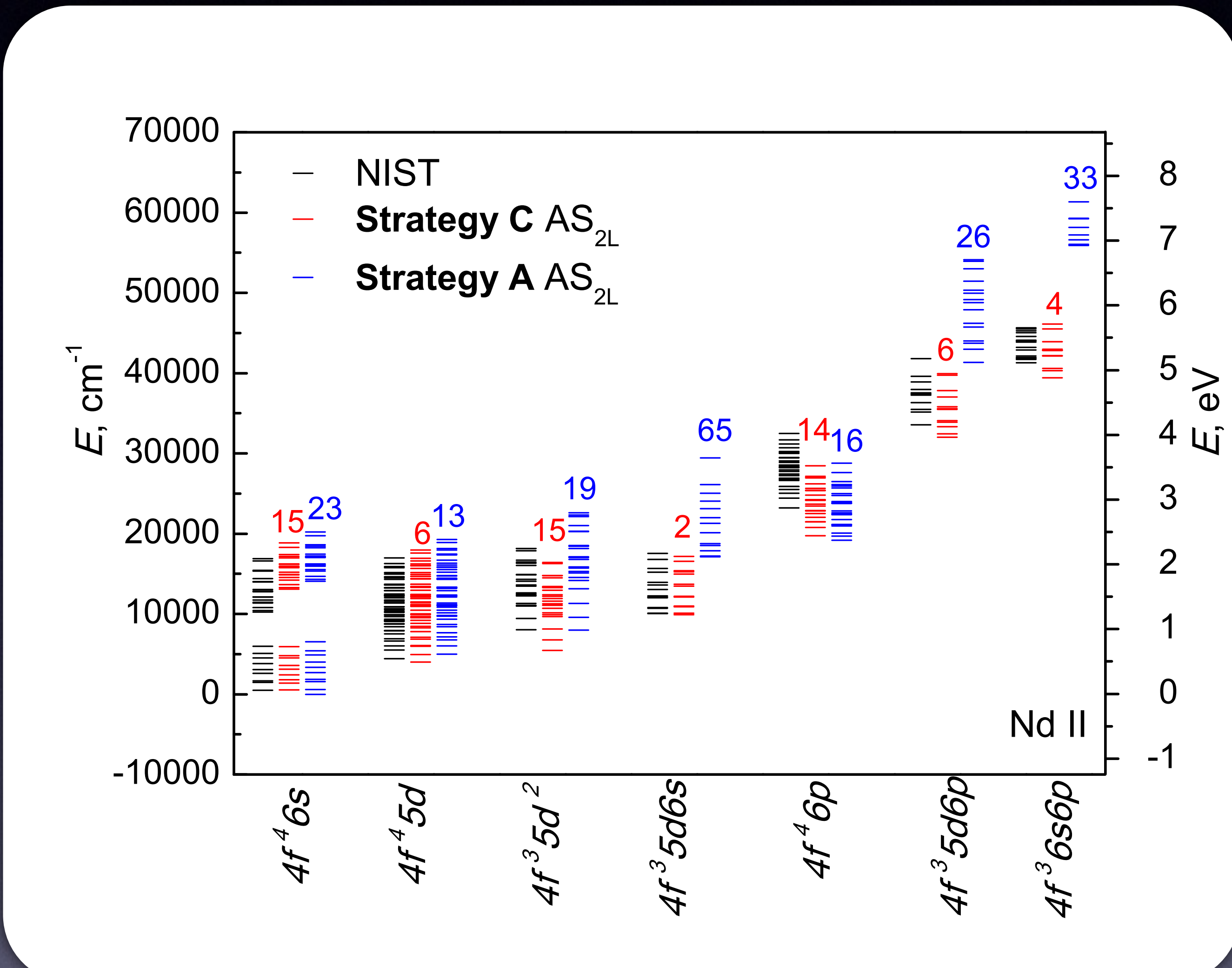


Planck mean opacity: agreement within a factor of ~1.5

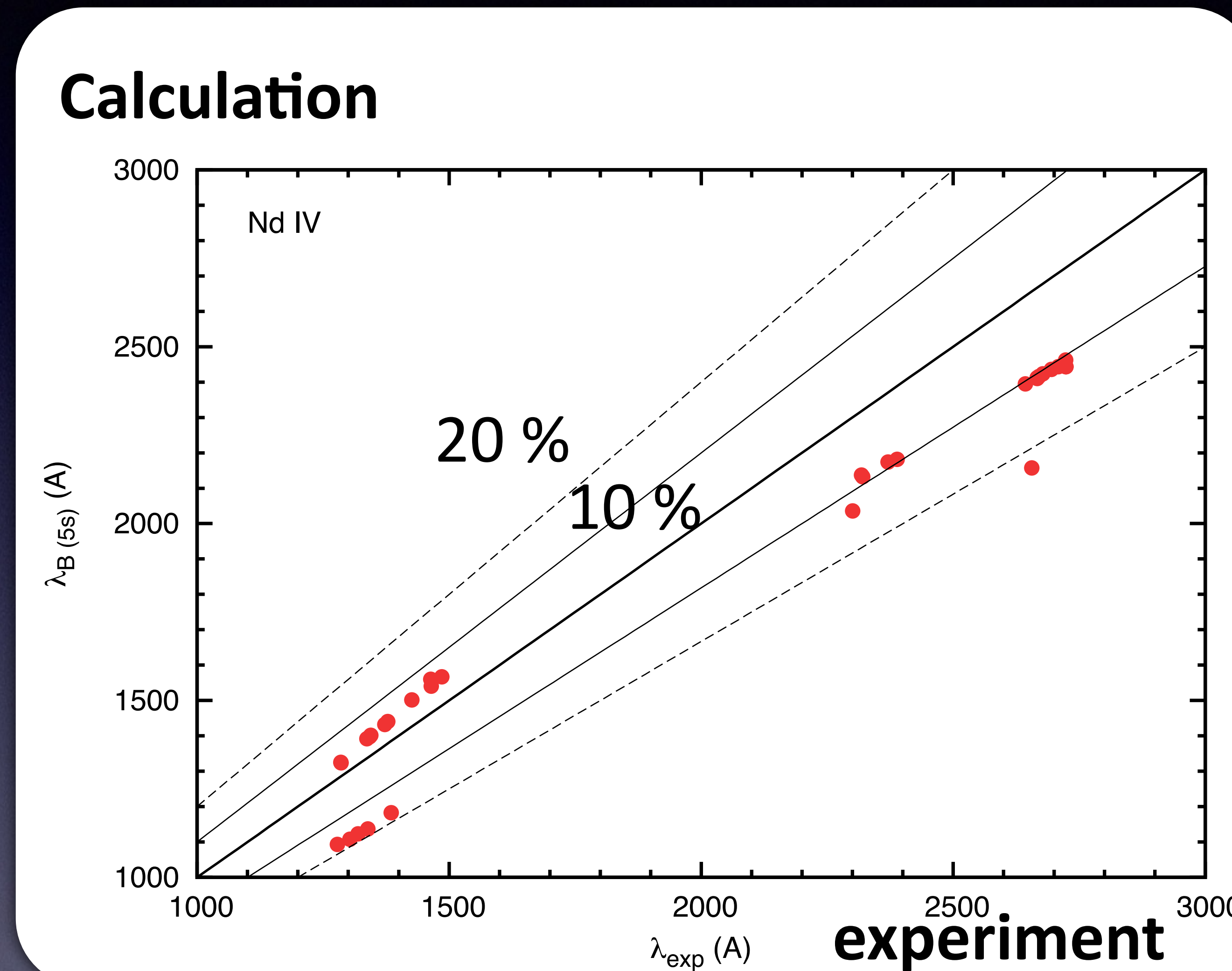
Good accuracy for light curve

Spectral accuracy?

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



10 % accuracy for energy levels



20 % accuracy for transition wavelengths

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

土本さん

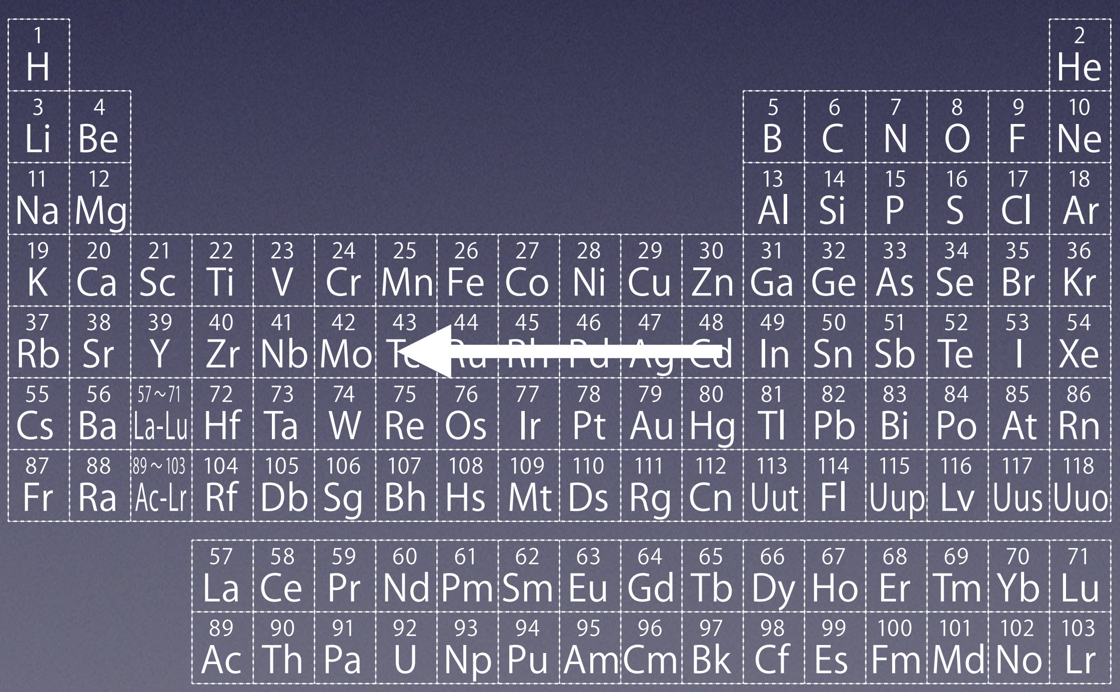
Opacity at early time (t < 1 day)?

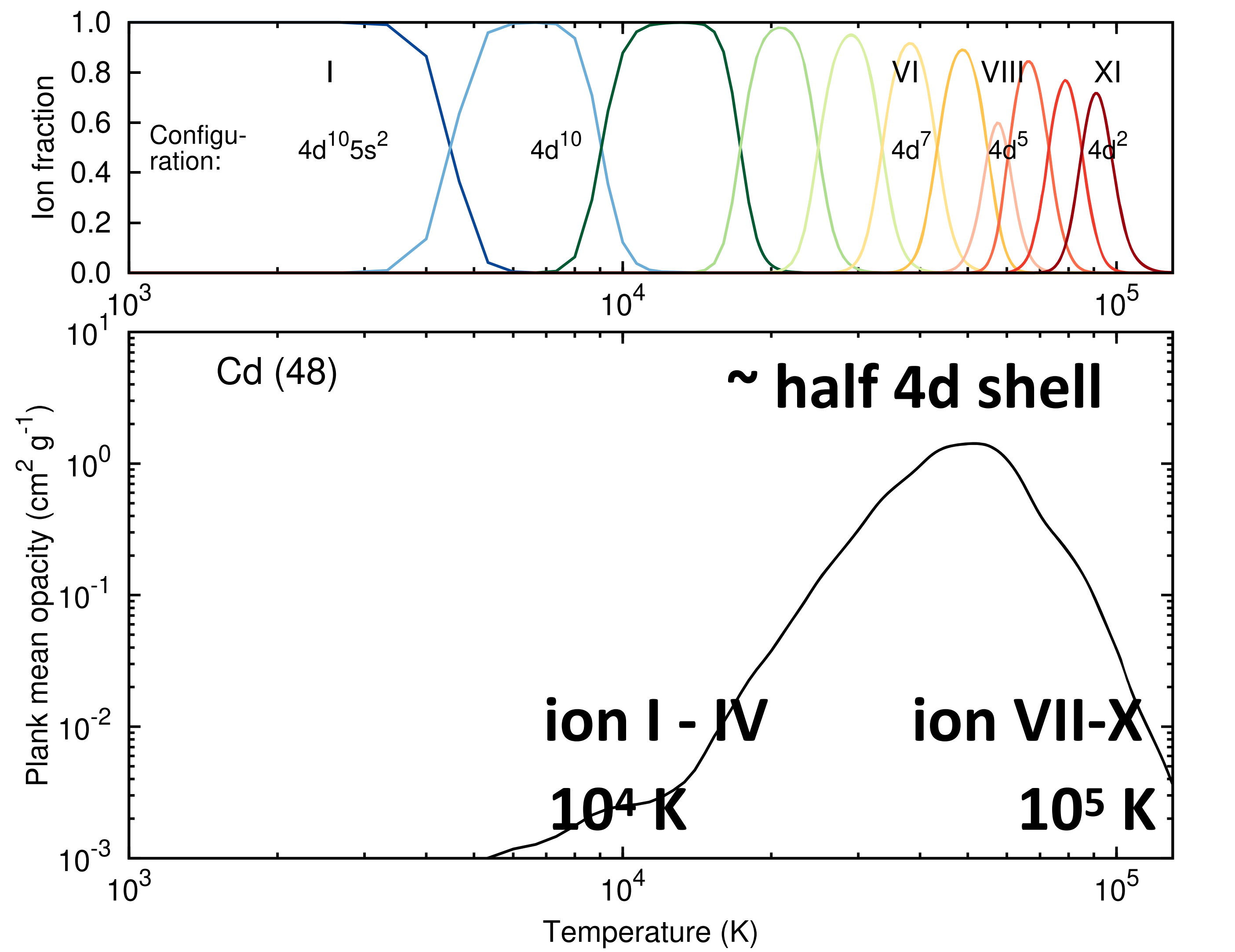
Banerjee, MT, Kawaguchi et al. 2020
(blue kilonova at early time)

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

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

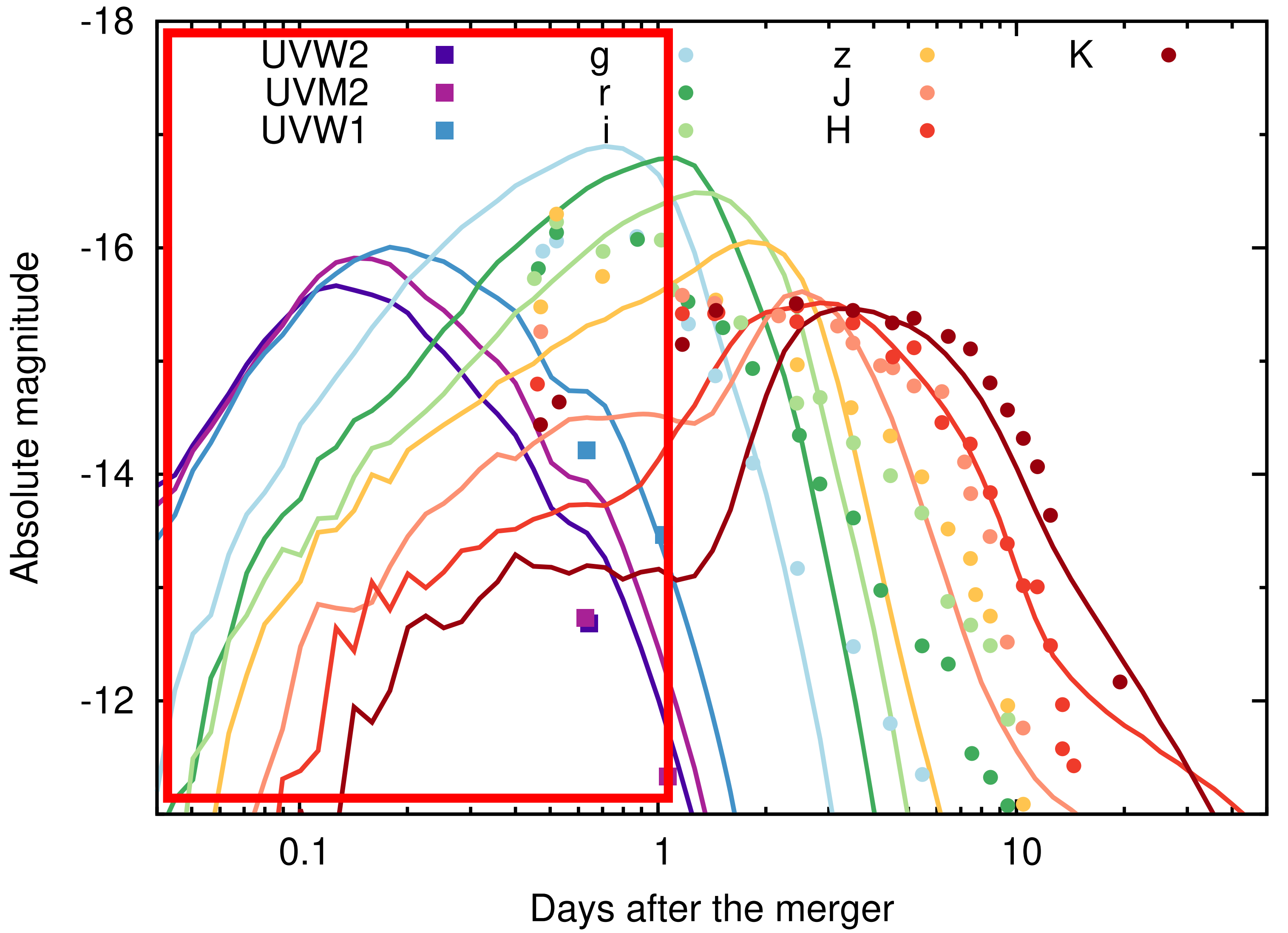
=> atomic calculations up to 10 th ionization

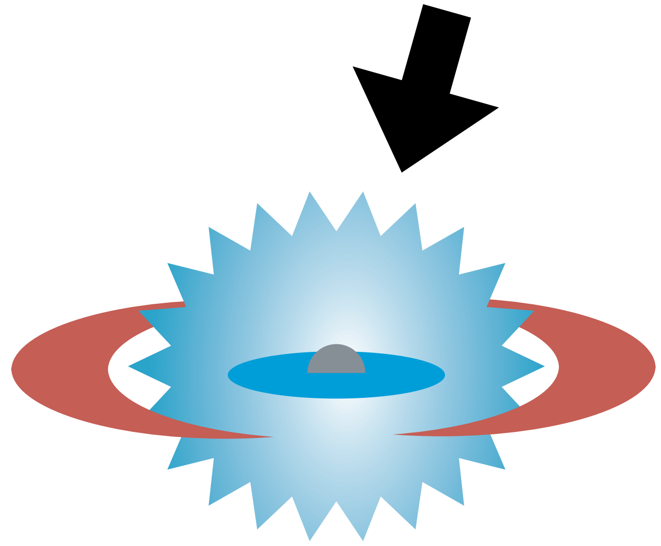




UV emission at t ~ hours

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





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

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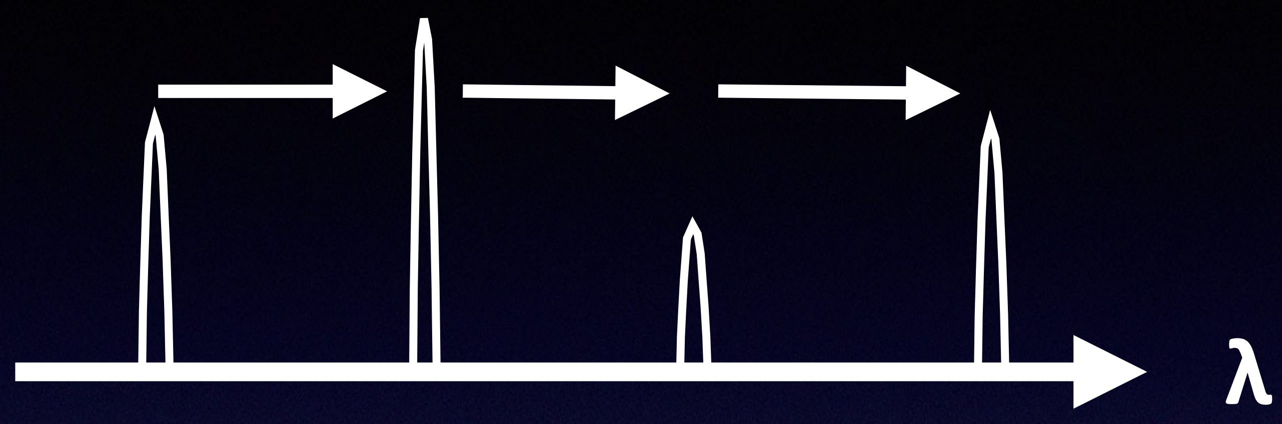
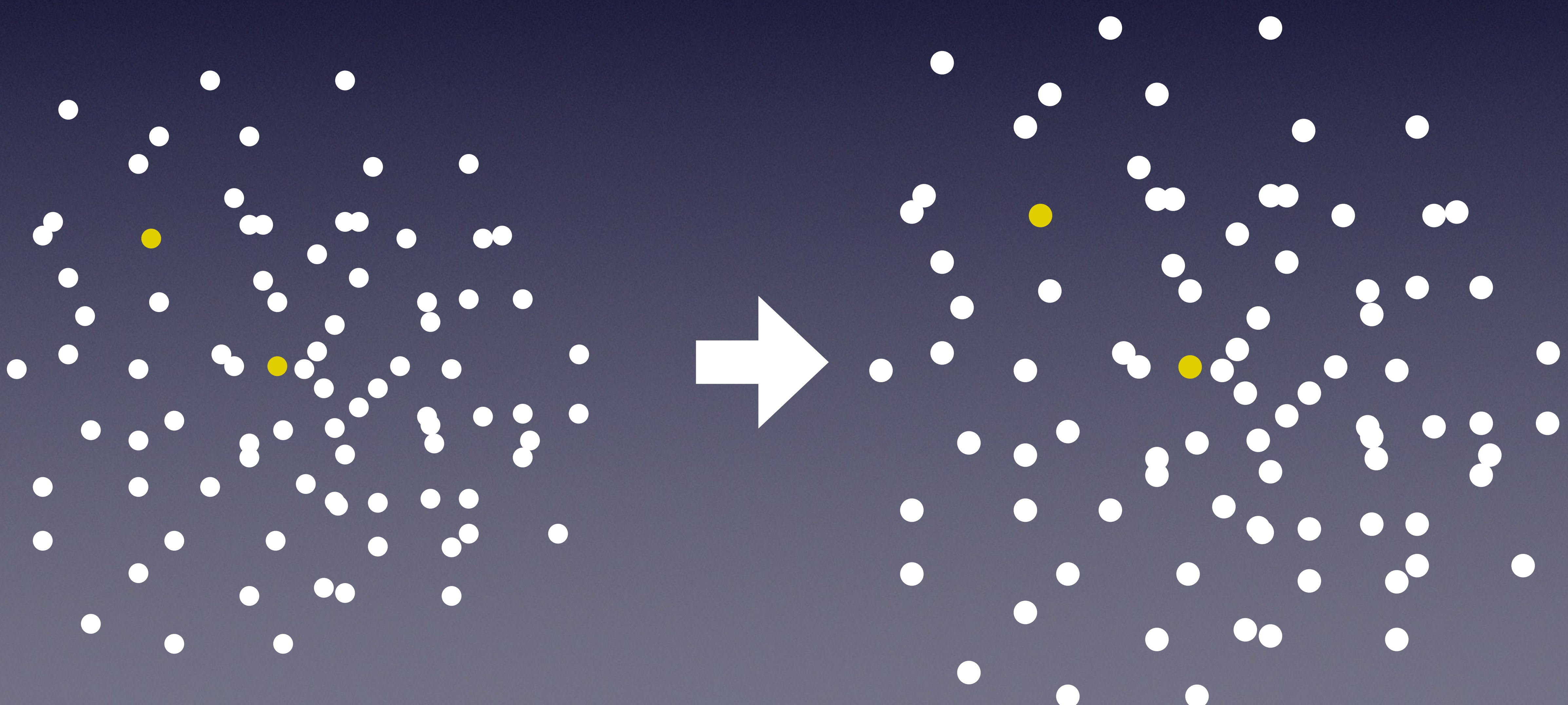
Radiative transfer in metal-rich expanding medium

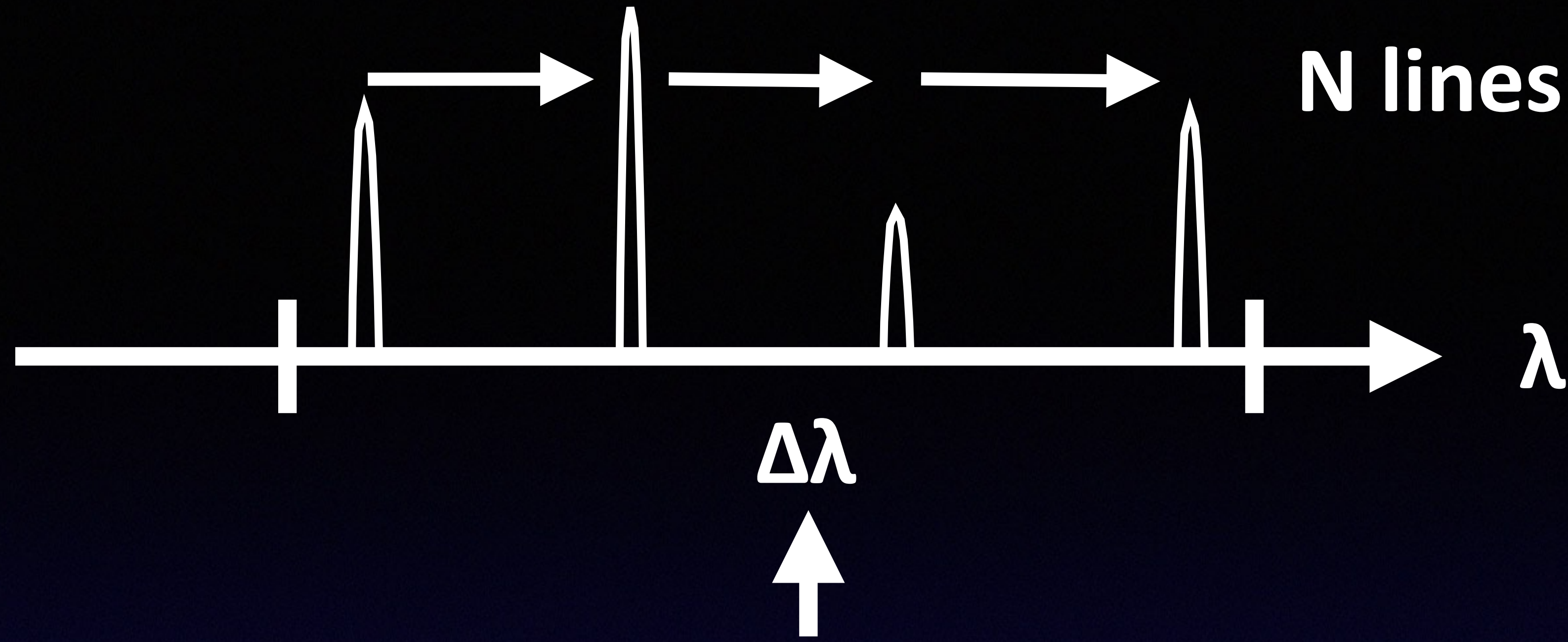
Photons are always redshifted in comoving frame





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

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

Effective mean free path

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

Effective absorption coefficient $\alpha_{\rm exp}$ (cm^{-1})

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

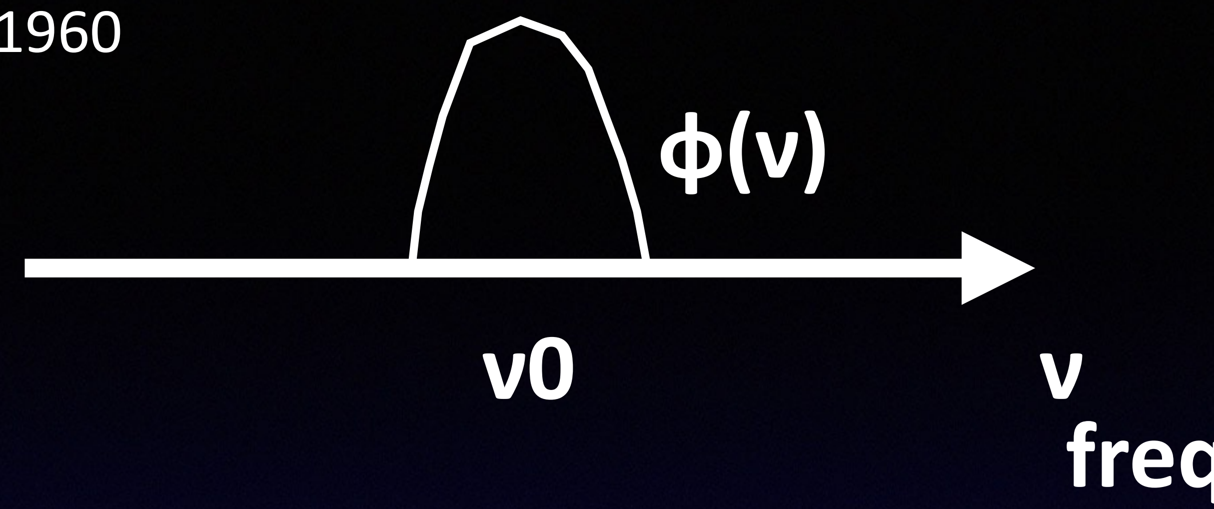
This does not depend on the line strength
(if lines are strong enough)

By including weak lines
(τ_sob = Sobolev optical depth)

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

Sobolev optical depth

Sobolev 1960



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

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

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

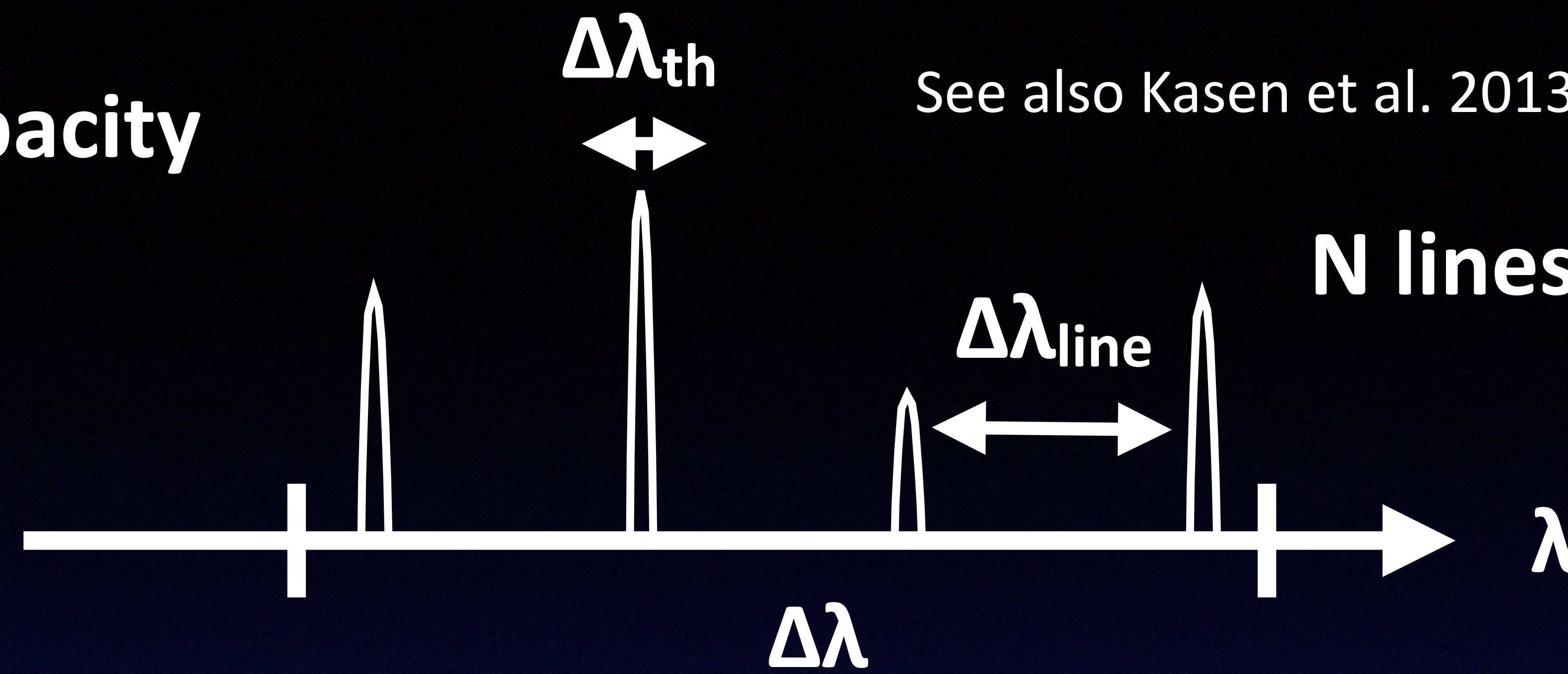
if velocity dominated by radial motion ($v_{th} << v_{rad}$)

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

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

Validity of expansion opacity

See also Kasen et al. 2013



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

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

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

→

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

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

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

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

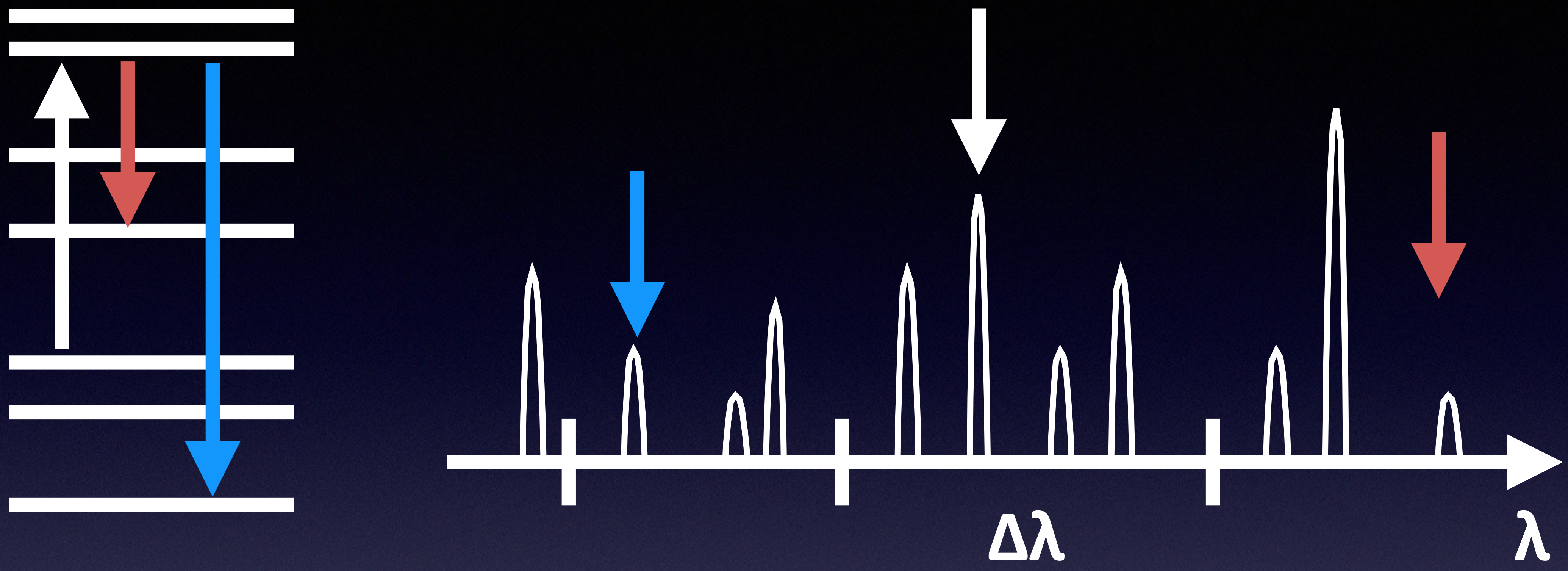
v_th ~ $T^{-1/2} \sim t^{-1/2}$

κ_crit ~ 10^3 cm^2 g^{-1} $(t/1\ day)^{2.5}$

~ 3 cm^2 g^{-1} @ t = 0.1 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