Atomic opacities for kilonovae

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Tanaka, Kato, Gaigalas, Kawaguchi 2019, arXiv:1906.08914

Atomic opacities for kilonovae

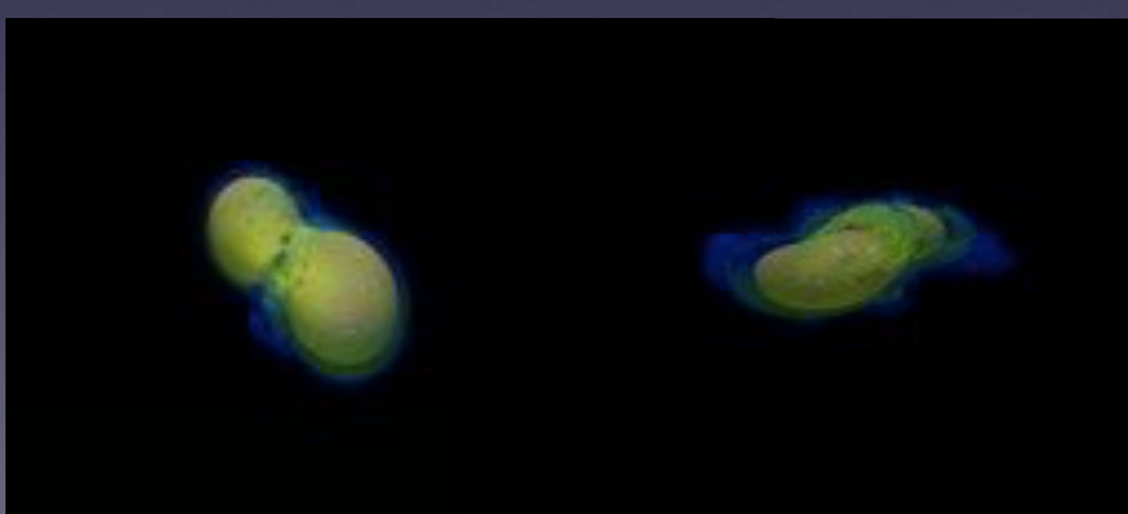
- Why atomic opacity?
- Systematic opacity calculations

Timescales in NS mergers

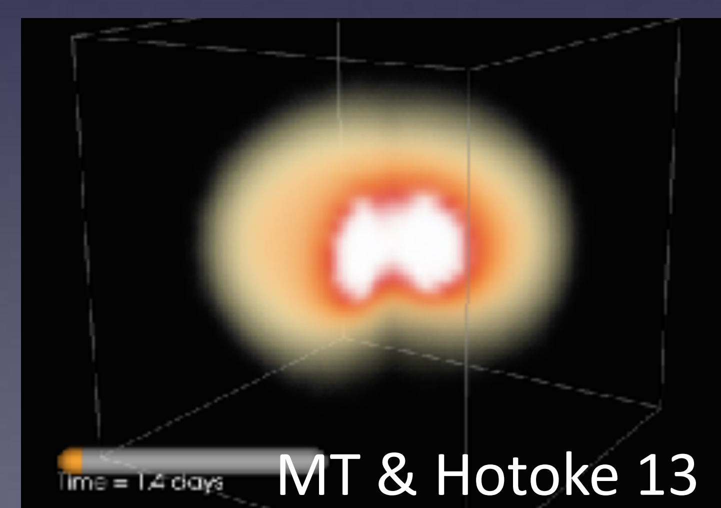
Merger → **r-process nucleosynthesis** → **Radioactive decay => kilonova** → **Chemical enrichment**

Mass ejection

ms - seconds	1-10 seconds	days - weeks	> Myr



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



MT & Hotoke 13

Physics involved in kilonova

See Jennifer Barnes's talk

Mass ejection

Dynamical ejecta, post-merger ejecta

Mej, v, Ye, Xi

R-process nucleosynthesis and radioactive decays

β decay, α decay, and fission

Energy deposition ("thermalization")

γ-rays, electrons, α particles, fission fragments

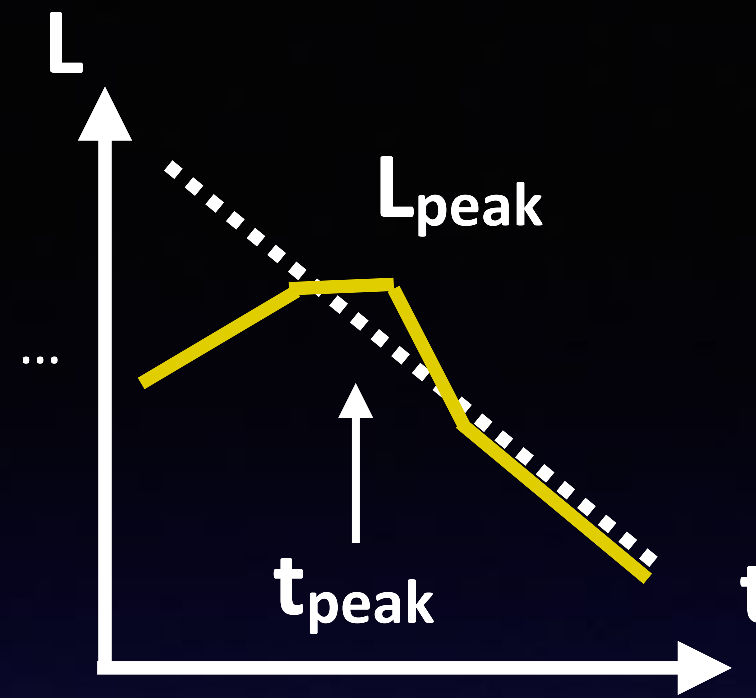
Photon propagation

Atomic opacities (mainly bound-bound transitions)

Observations (light curves and spectra)

“Kilonova/Macronova"

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



See Iair Arcavi’s talk

Timescale

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

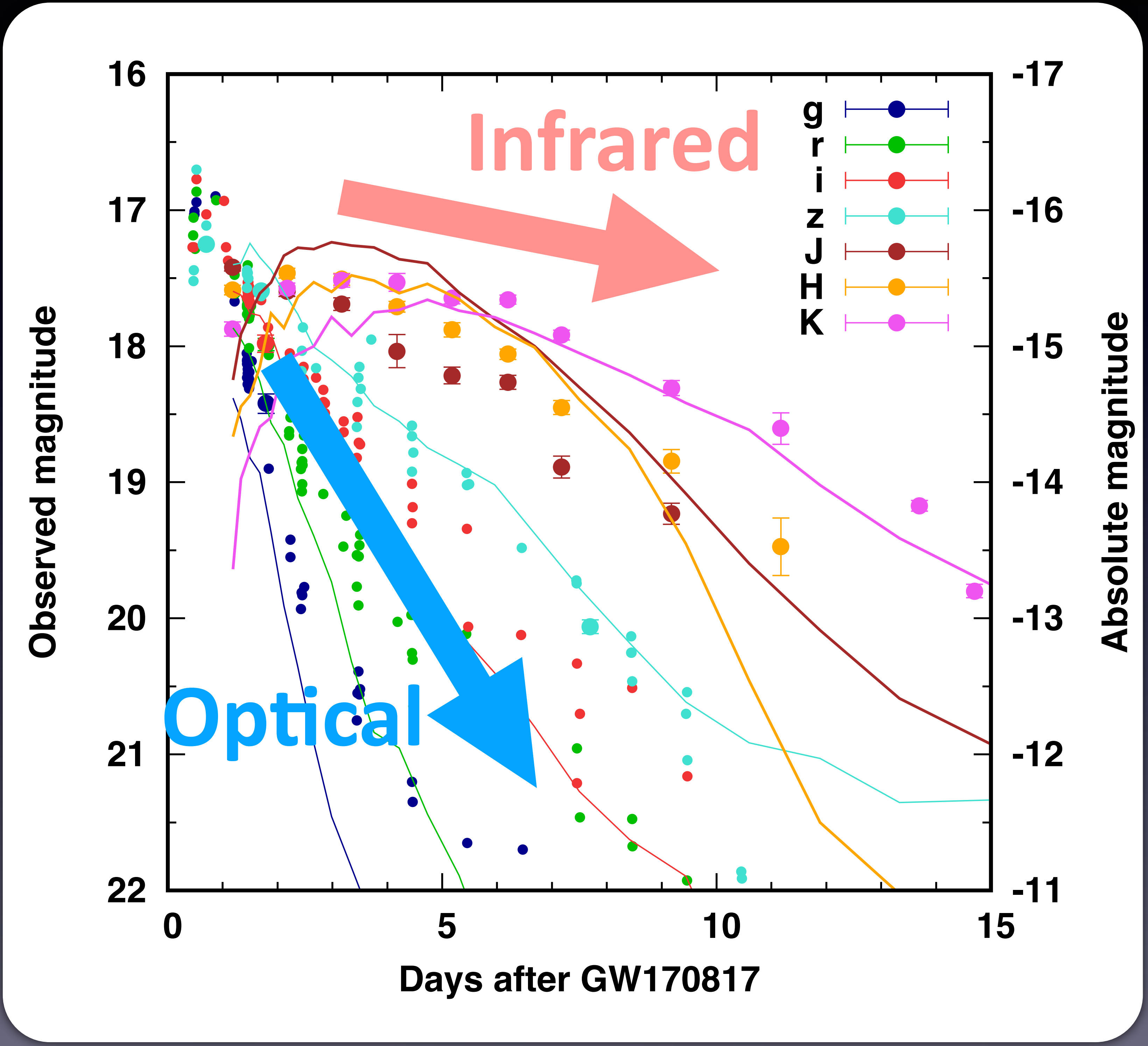
Luminosity

*assuming 50% thermalization

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

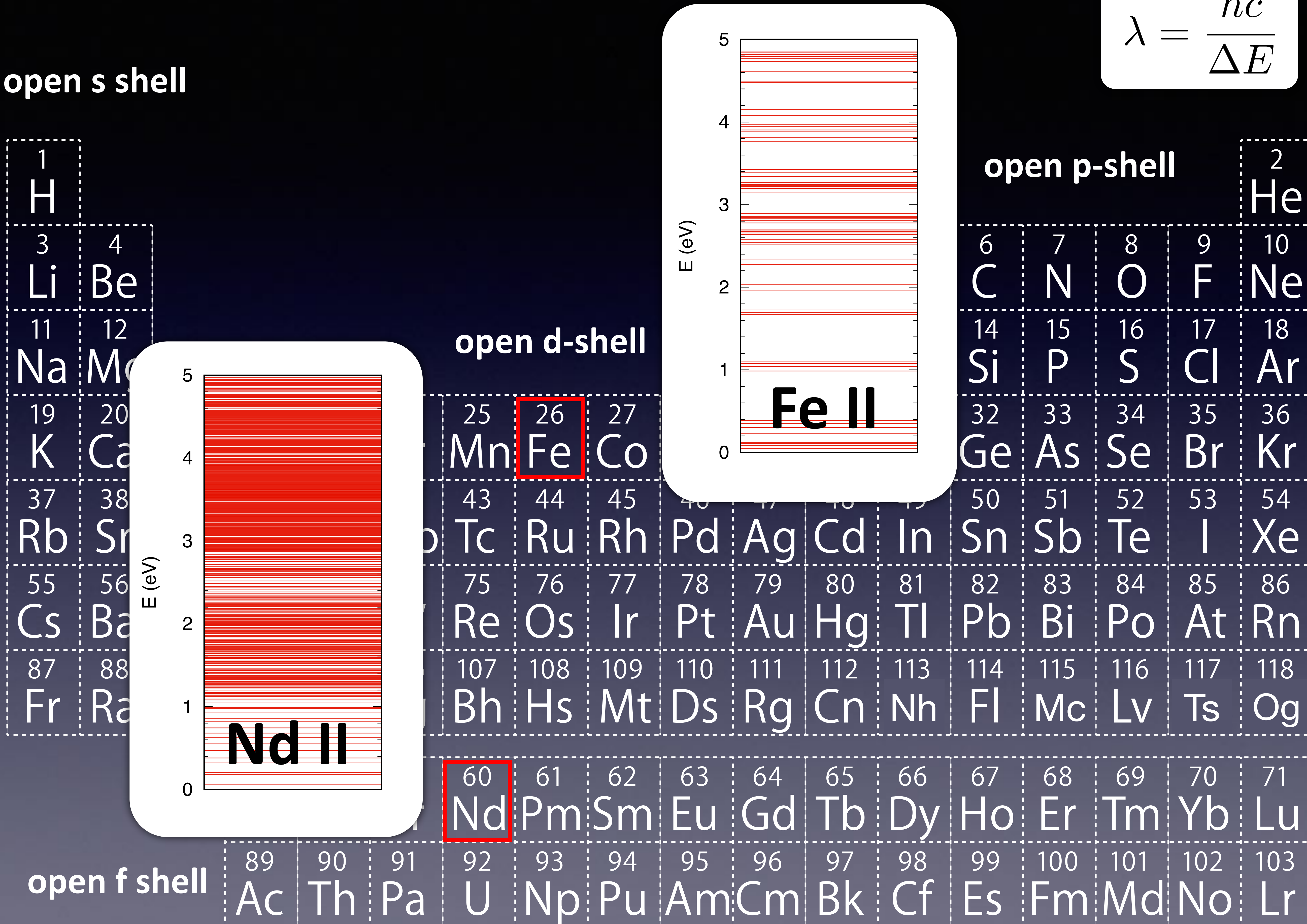
Temperature ~ 5000 K => Optical and infrared wavelengths

GW170817: optical/infrared light curves

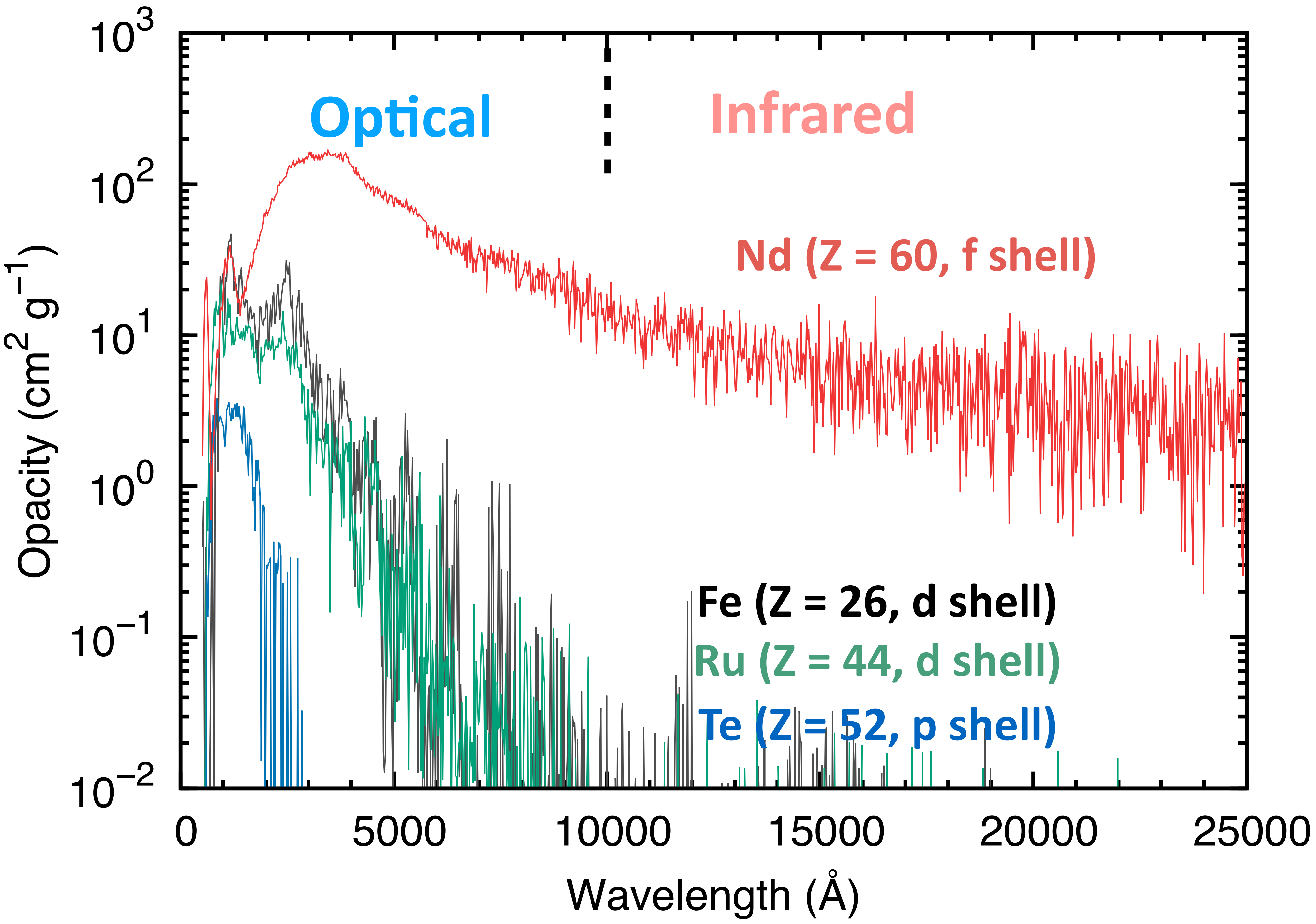


Arcavi+17, Cowperthwaite+17, Diaz+17, Drout+17,Evans+17, Kasliwal+17,Pian+17, Smartt+17, Tanvir+17, Troja+17, Utsumi, MT+17, Valenti+17

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



Bound-bound opacity



MT, Kato, Gaigalas, Ryunkun, Radzuite et al. 2018, ApJ, 852, 109

Status of atomic calculations for kilonova

No gold is observed??
=> No gold in the model!

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

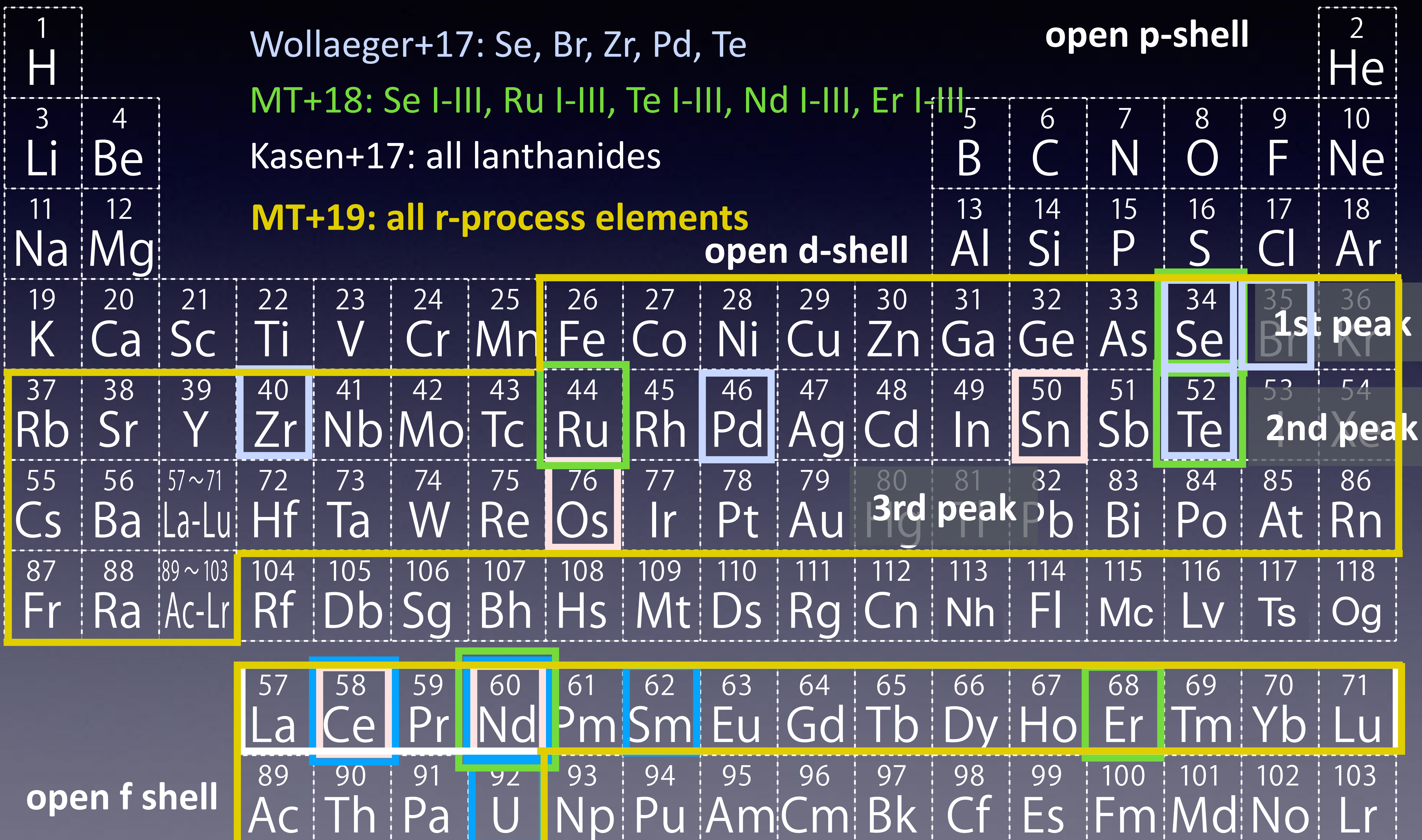
Fontes+17: Ce I-IV, Nd I-IV, Sm I-IV, U I-IV

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: all lanthanides

MT+19: all r-process elements



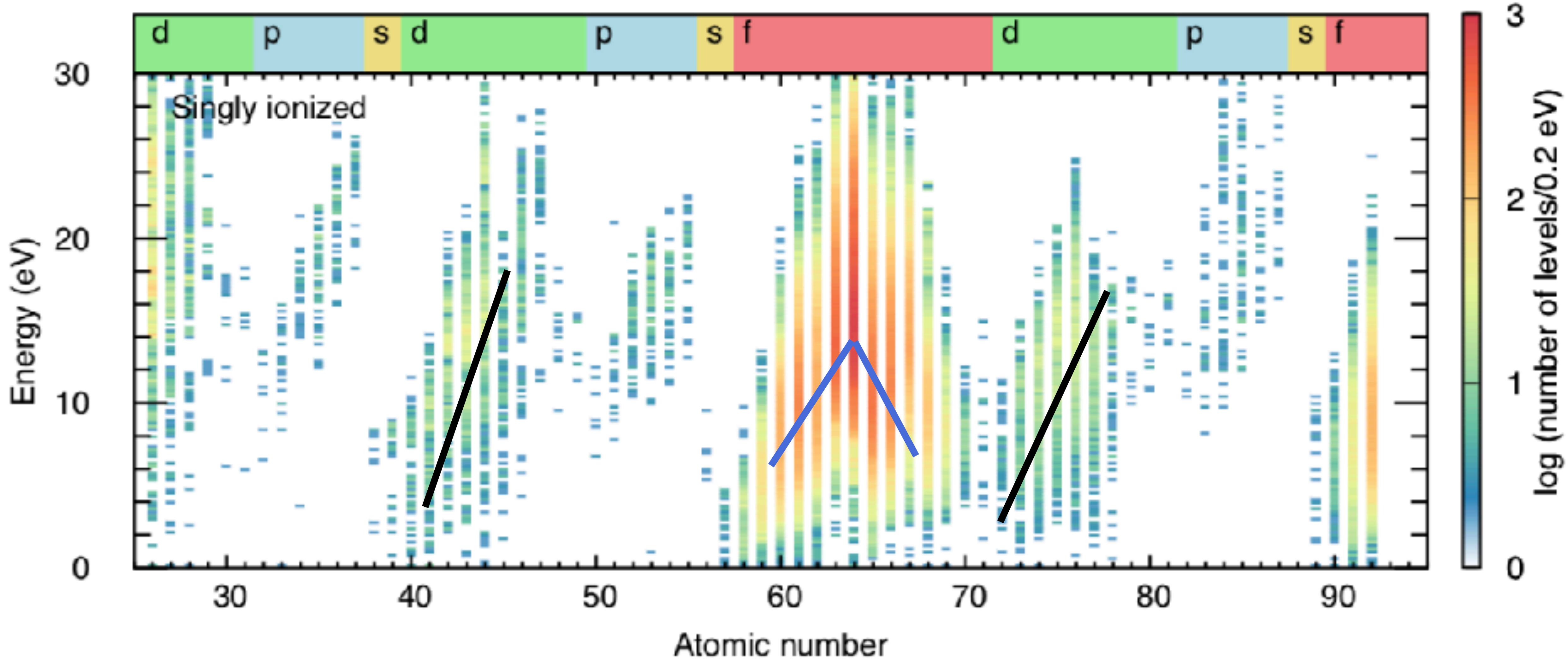
Atomic opacities for kilonovae

- Why atomic opacity?
- Systematic opacity calculations

Systematic calculations of atomic structure ~7 x 10⁵ levels in total

Using HULLAC code (with parametric radial potential) (I, II, III, IV)

Energy levels (singly ionized)



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)

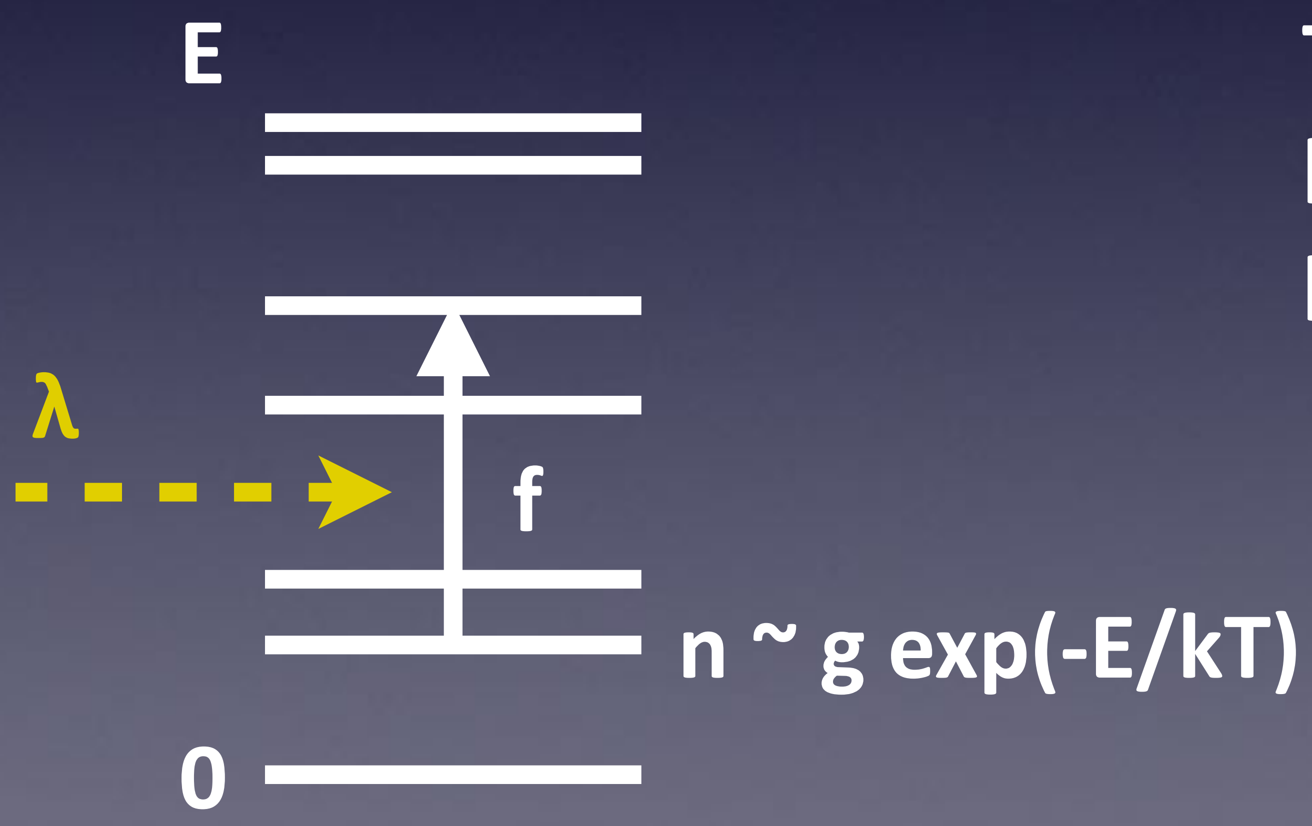
Bound-bound transition

See Jennifer Barnes's talk

Sobolev optical depth

f: oscillator strength

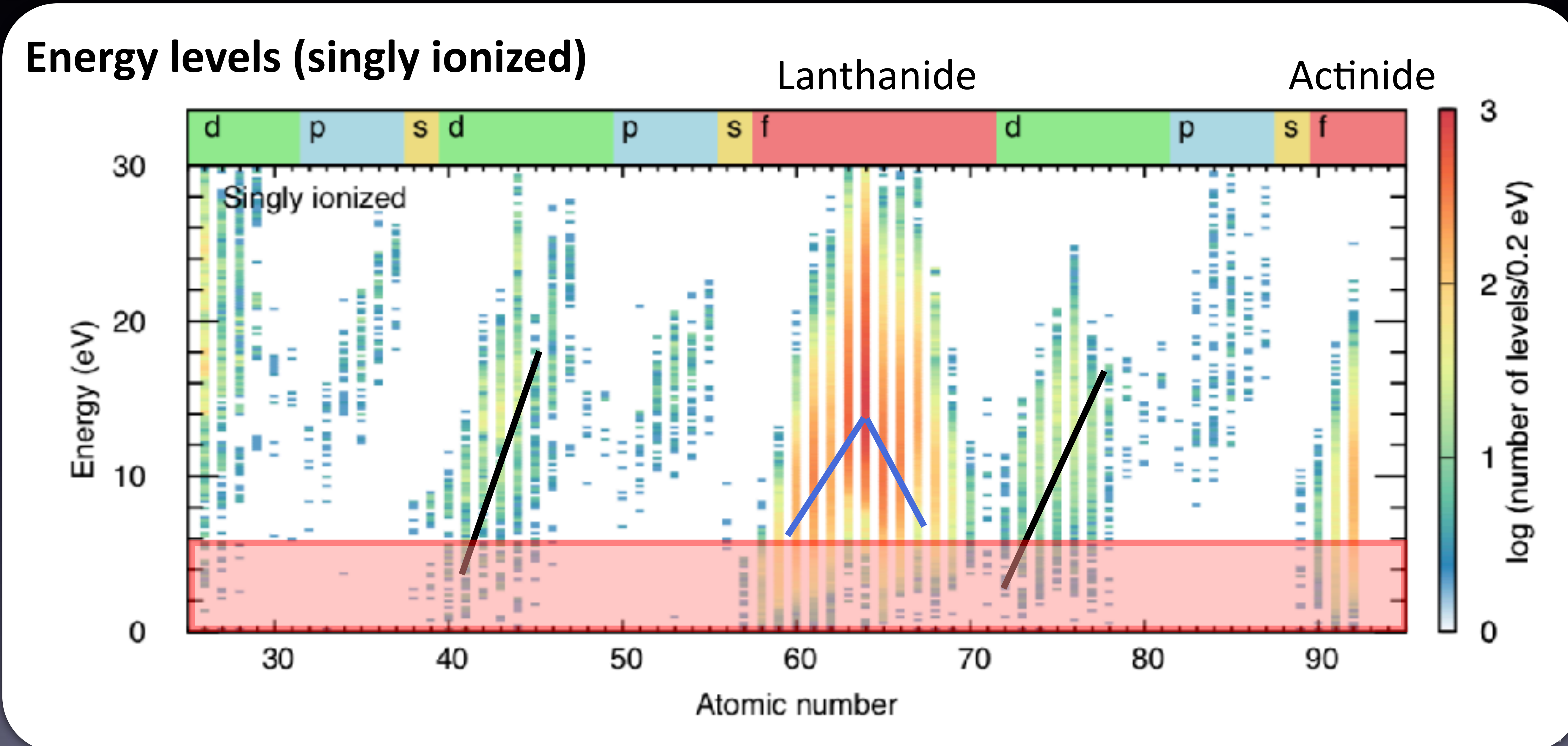
$$\tau_l = \frac{\pi e^2}{m_e c} f n t \lambda \propto g f \exp(-E/kT)$$



Transitions from
low-lying energy levels
have larger contributions

Systematic calculations of atomic structure ~7 x 10^5 levels in total

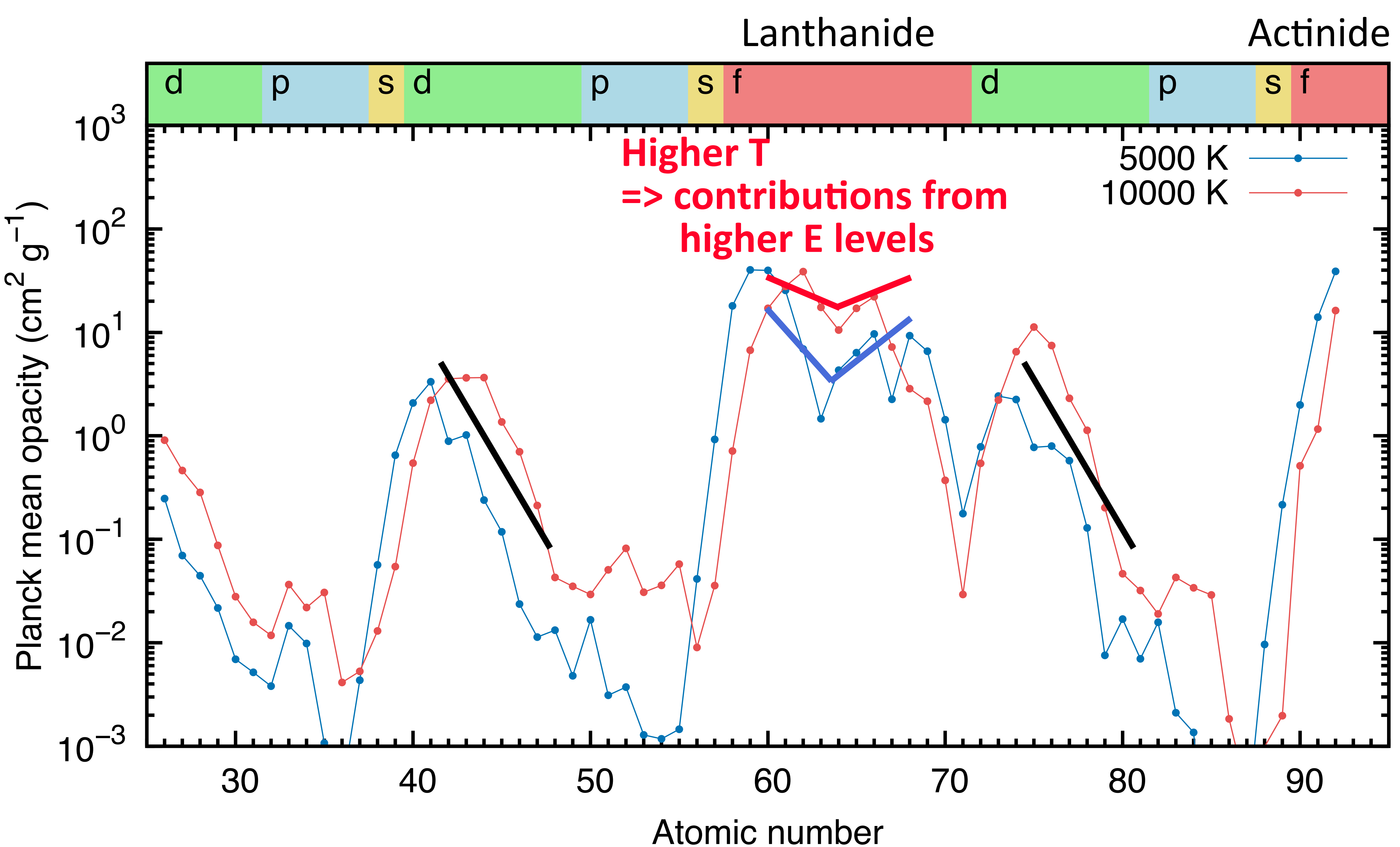
Using HULLAC code (with parametric radial potential) (I, II, III, IV)



Systematic calculations of opacities

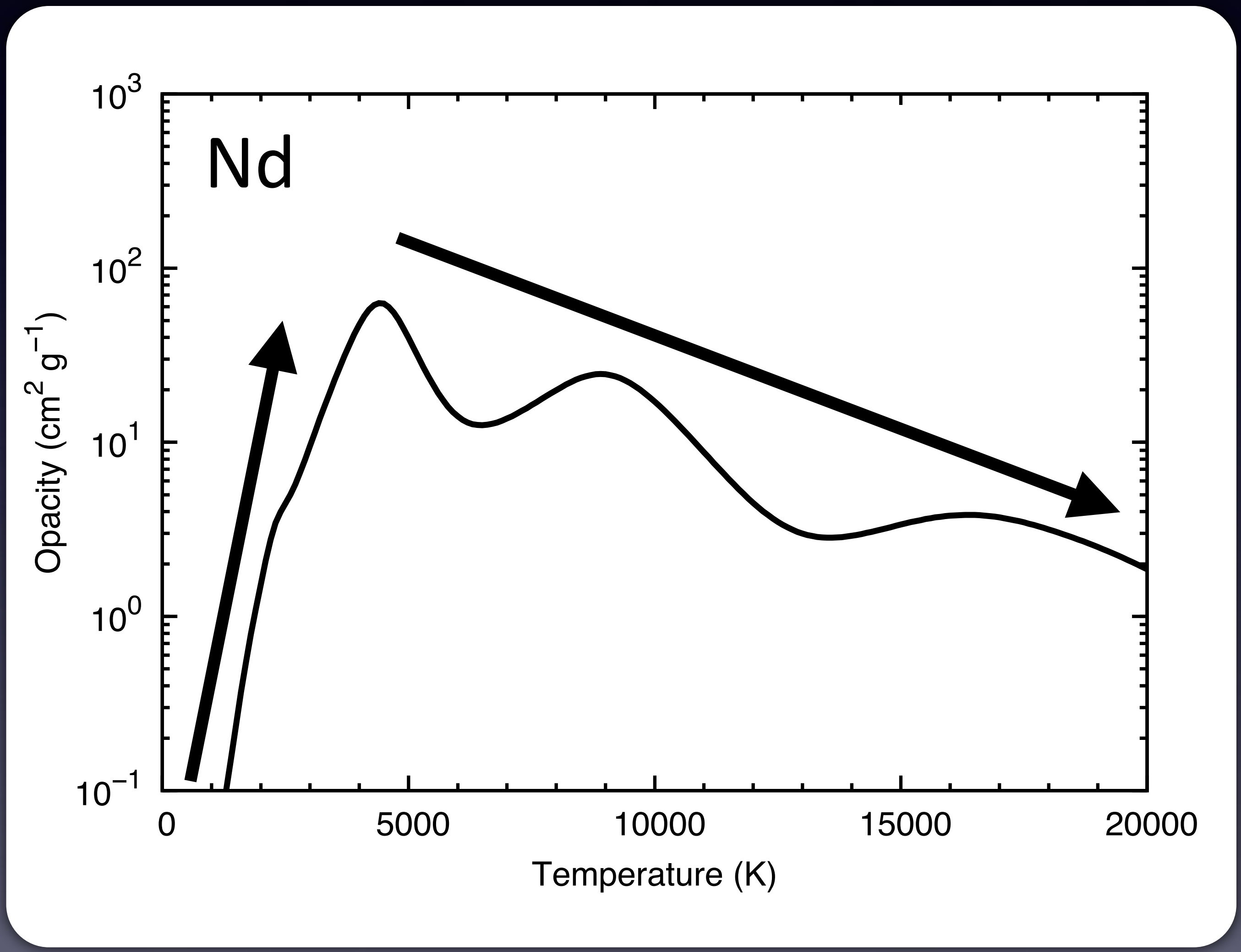
~2 x 10^9 transitions in total

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

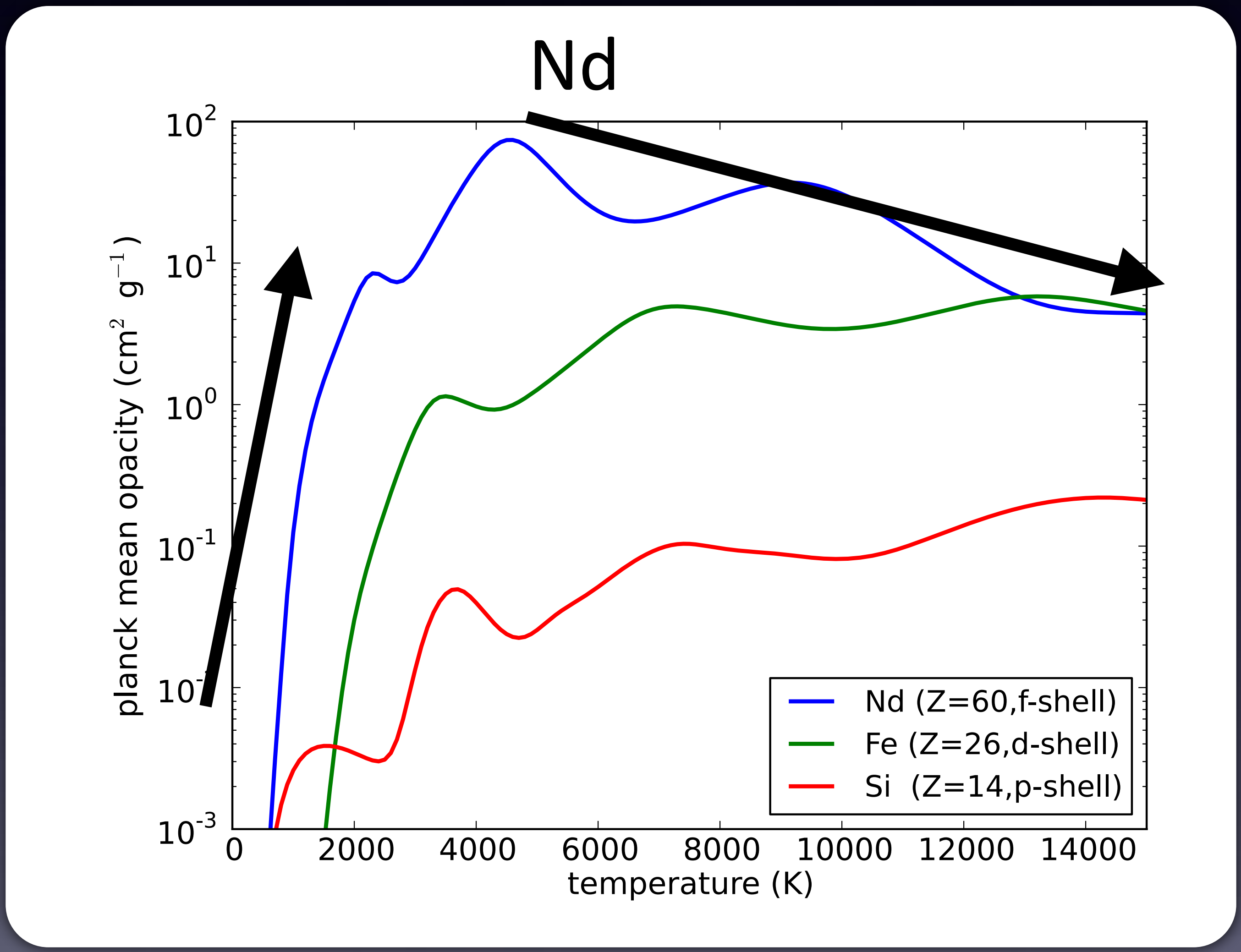


Results (1/2) Temperature dependence

$\rho = 10^{-13}$ g cm^{-3}



Tanaka+18



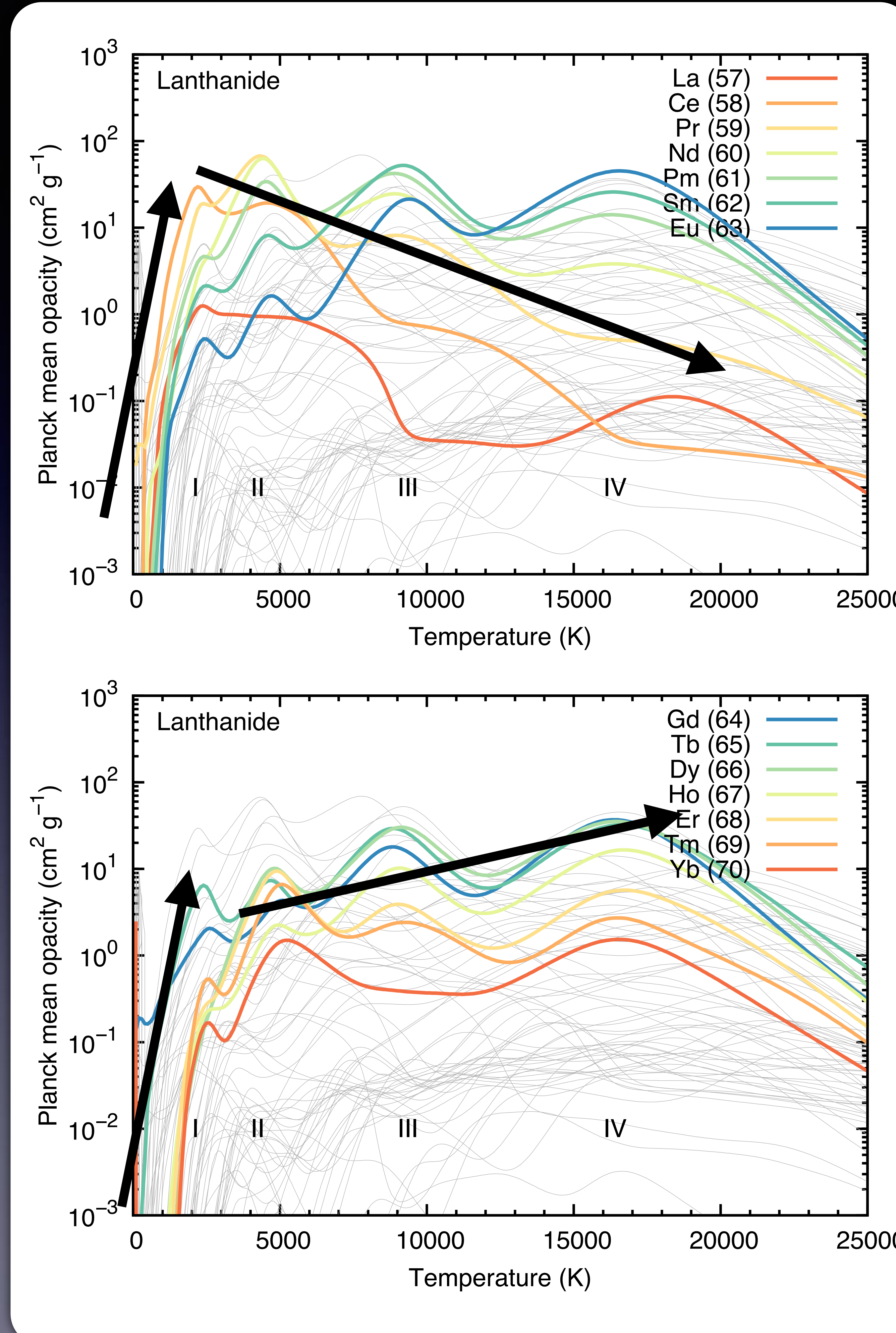
Kasen+13

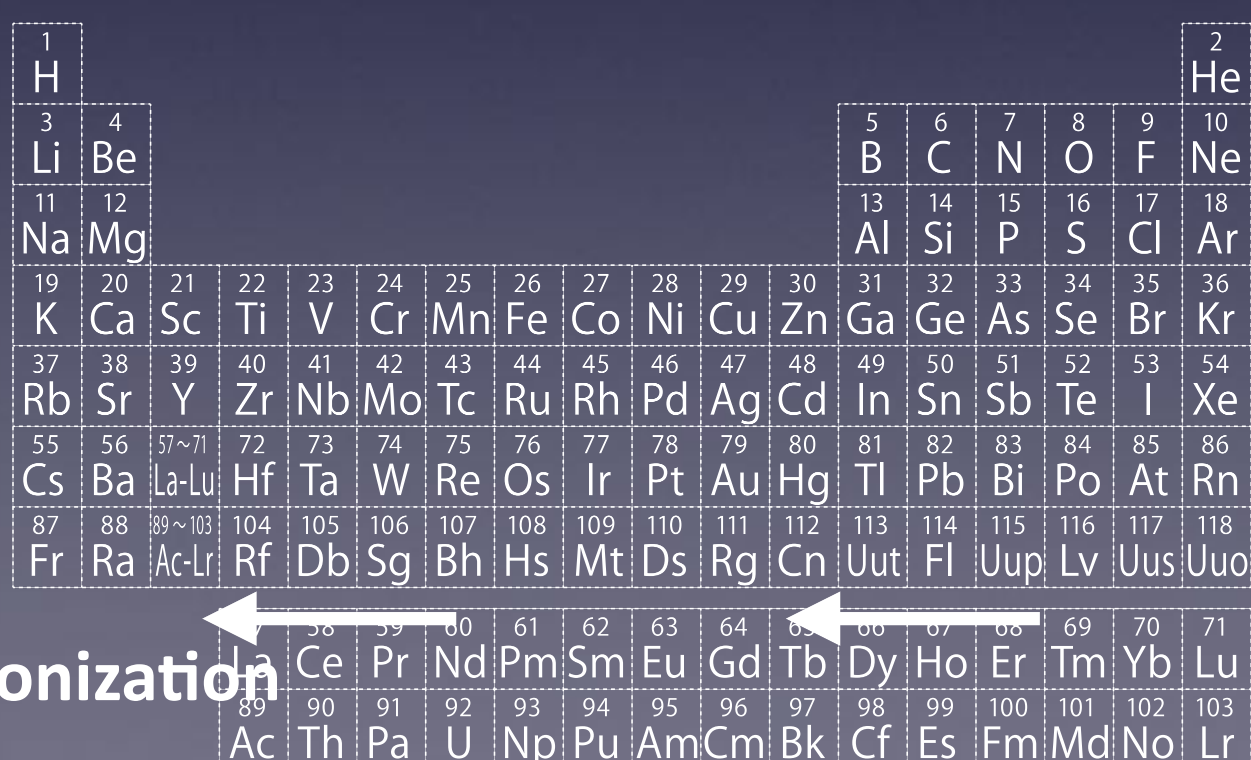
Is this behavior universal??

Opacities of lanthanides

First half

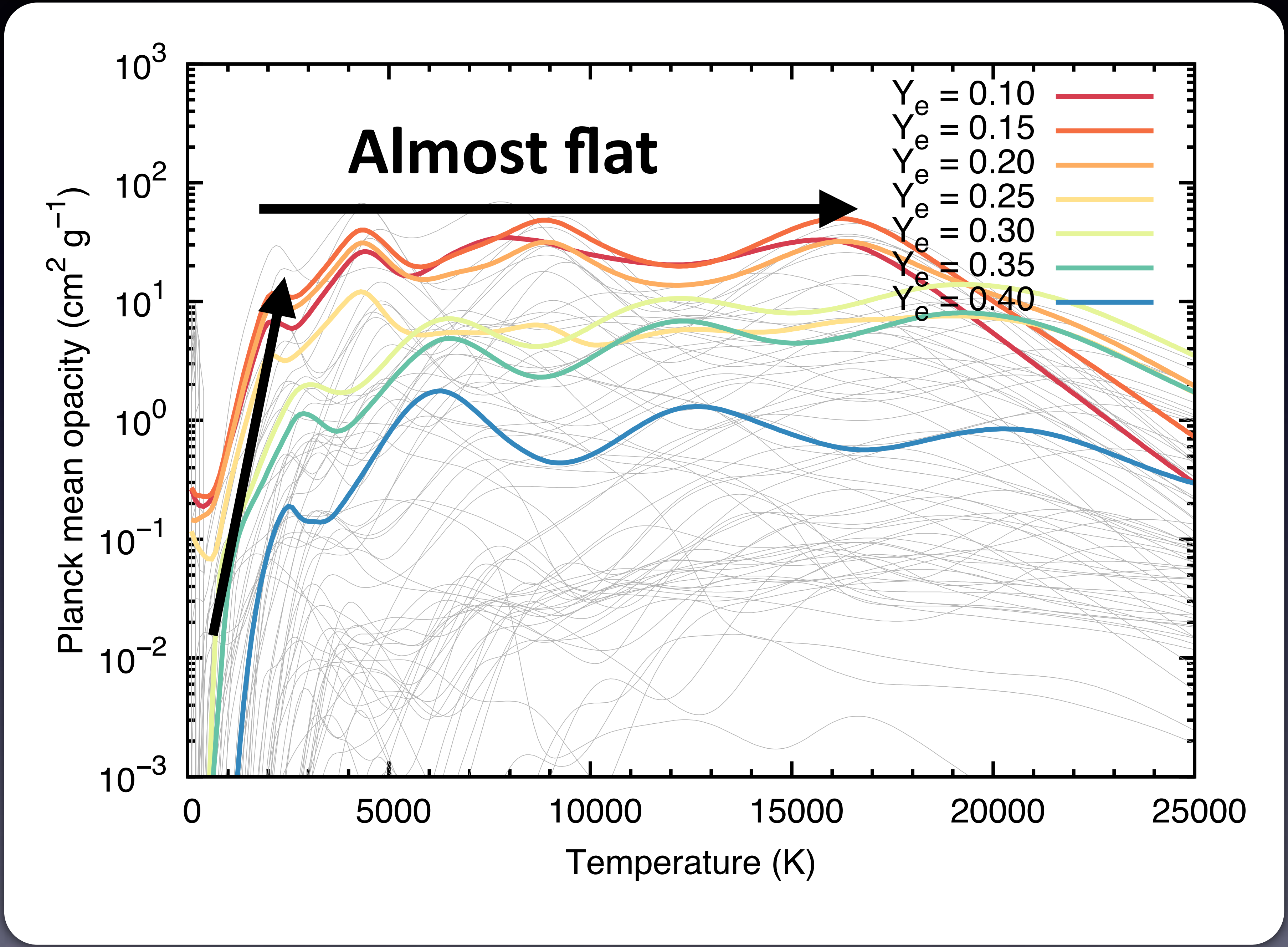
Latter half





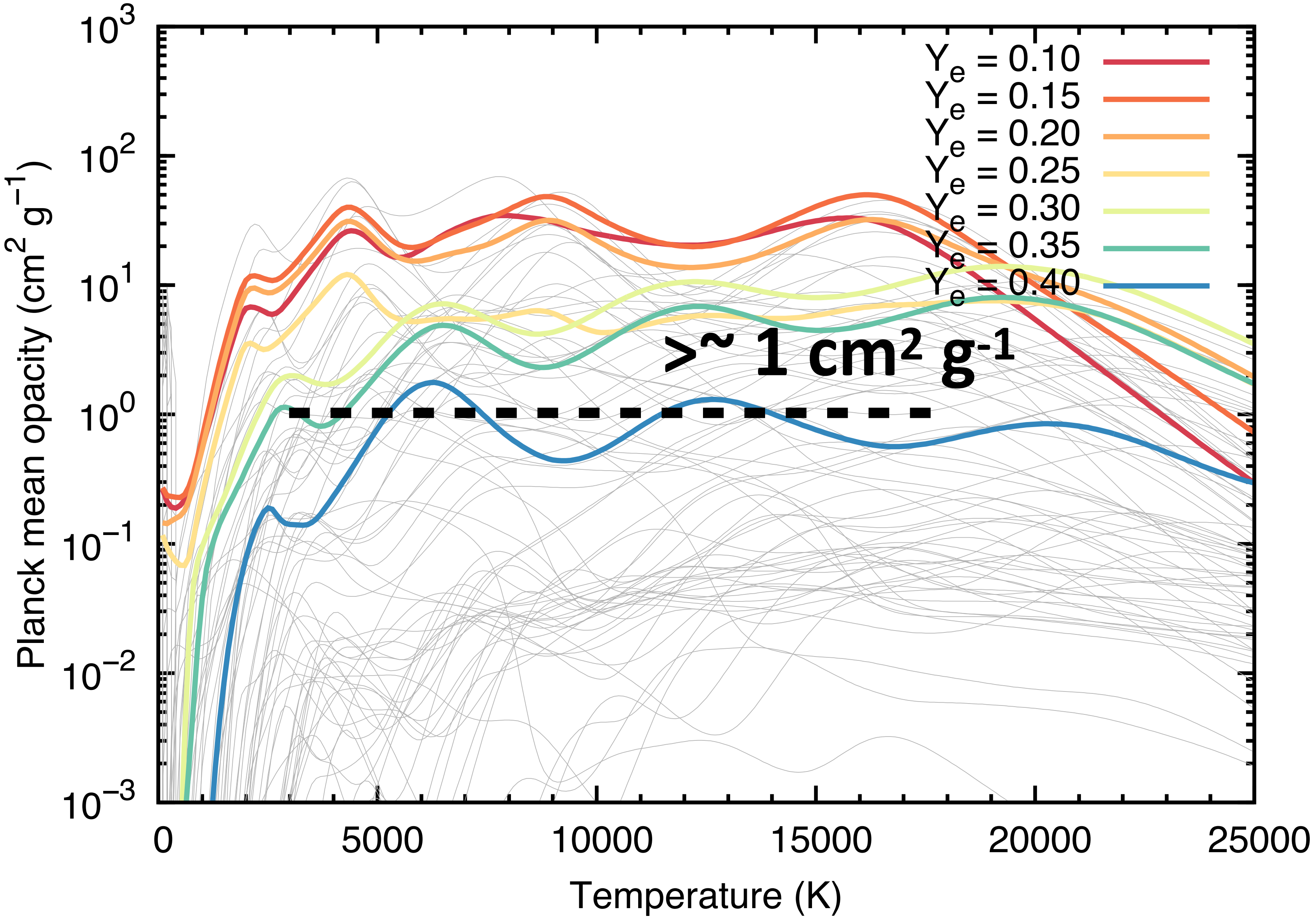
ionization

Opacity of element mixture



Strong temperature dependence at low T (caveats for “constant-opacity” approach)

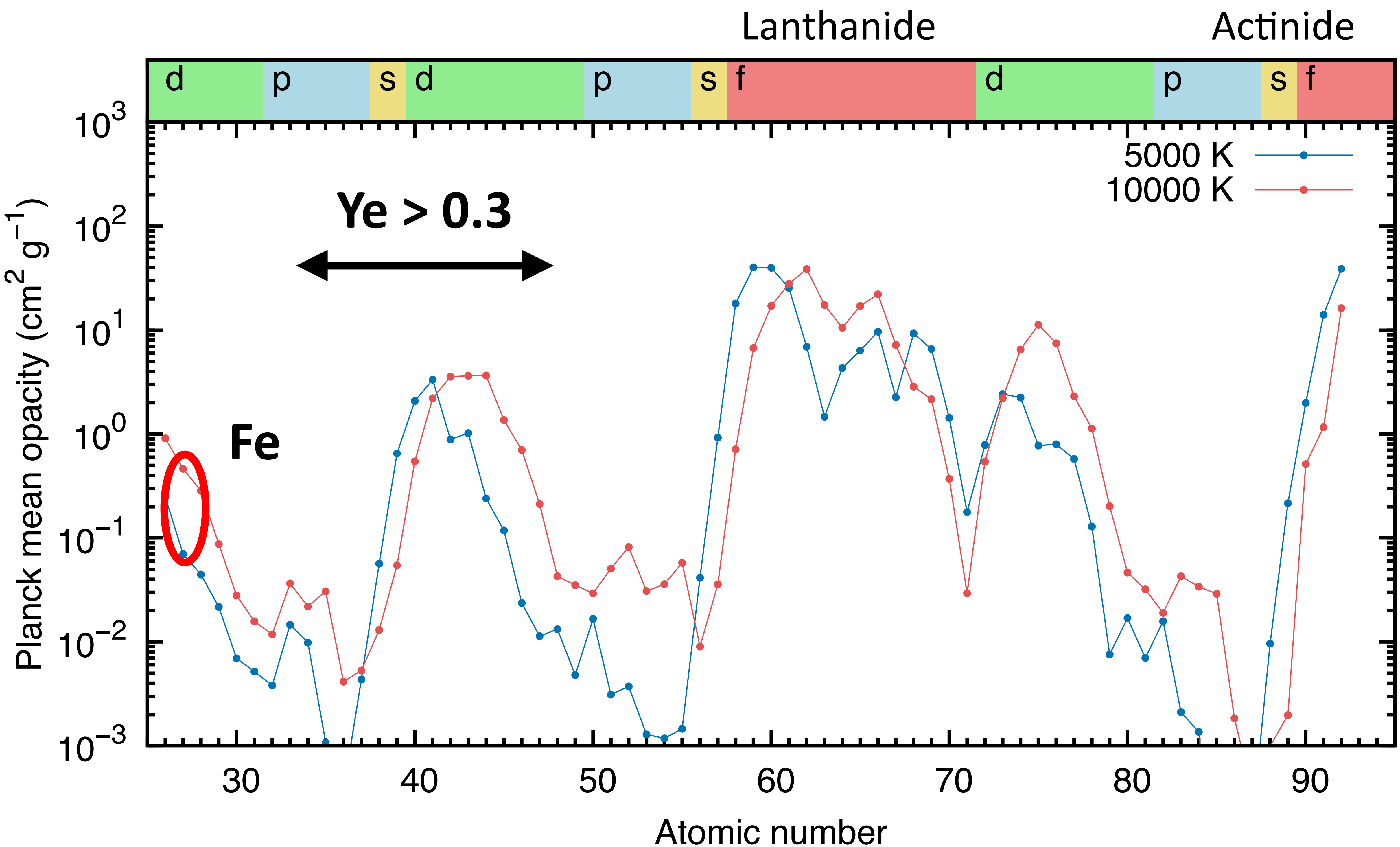
Results (2/2) Opacity of blue kilonova



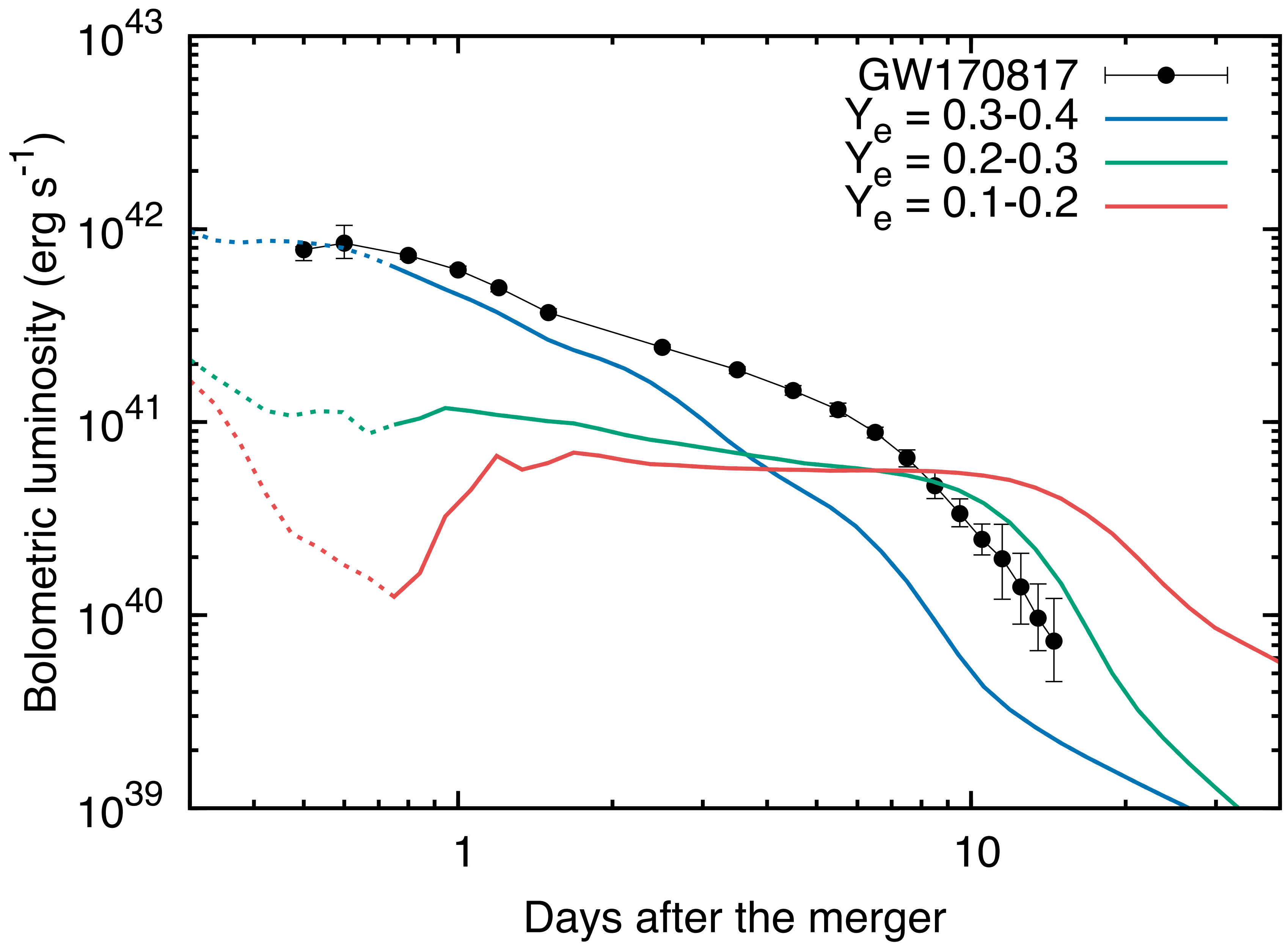
Higher than the commonly assumed value (~ 0.1 cm^2 g^{-1})

Element dependence

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



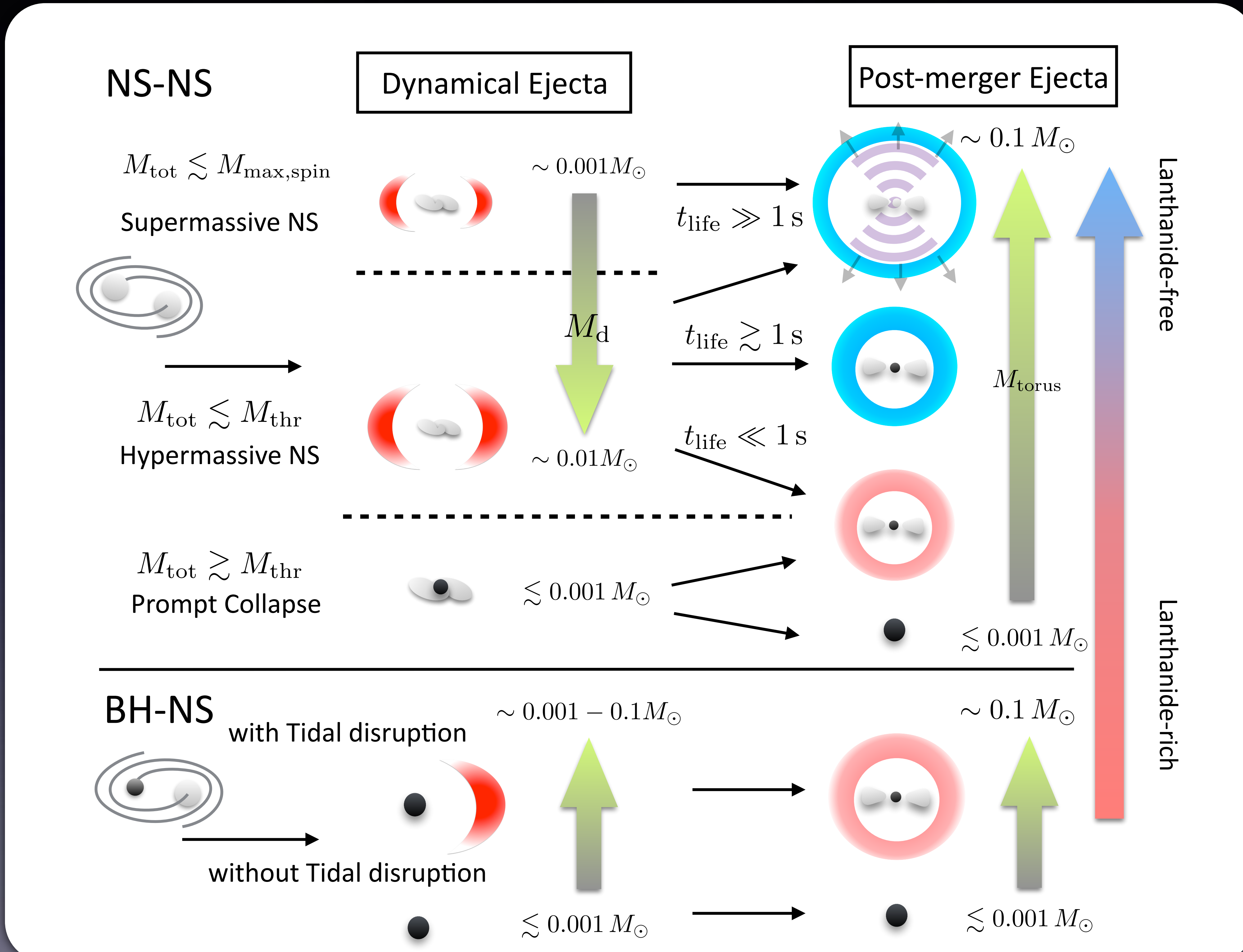
Application: GW170817



Confirm that general interpretations are OK (Red/blue components and their masses)

Application: variety of kilonova

See Francois Foucart's and Rodrigo Fernandez's talks

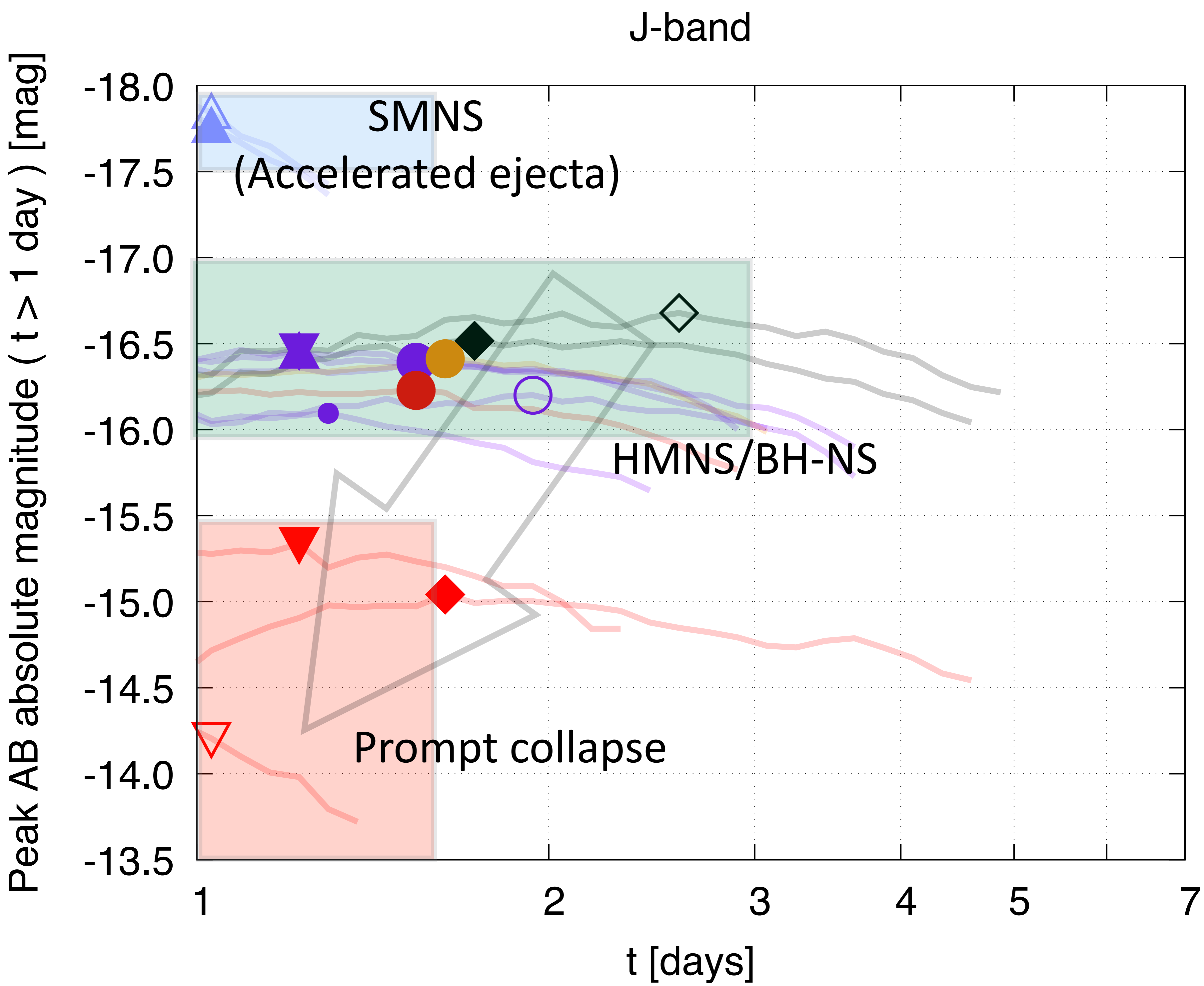


Kawaguchi, Shibata, Tanaka 2019, arXiv:1908.05815

Variety of kilonova

See Kyohei Kawaguchi's talk (next week)

2D radiative transfer simulations with multiple ejecta components

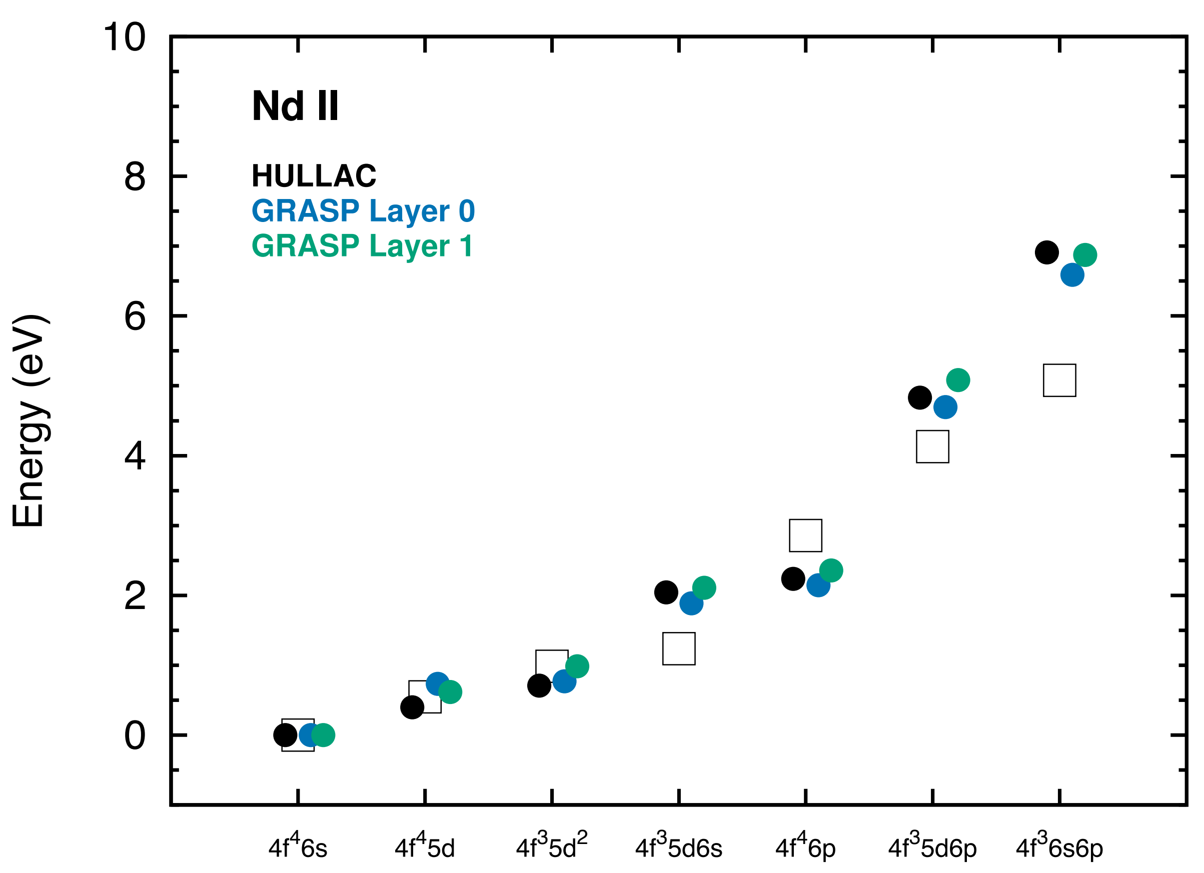


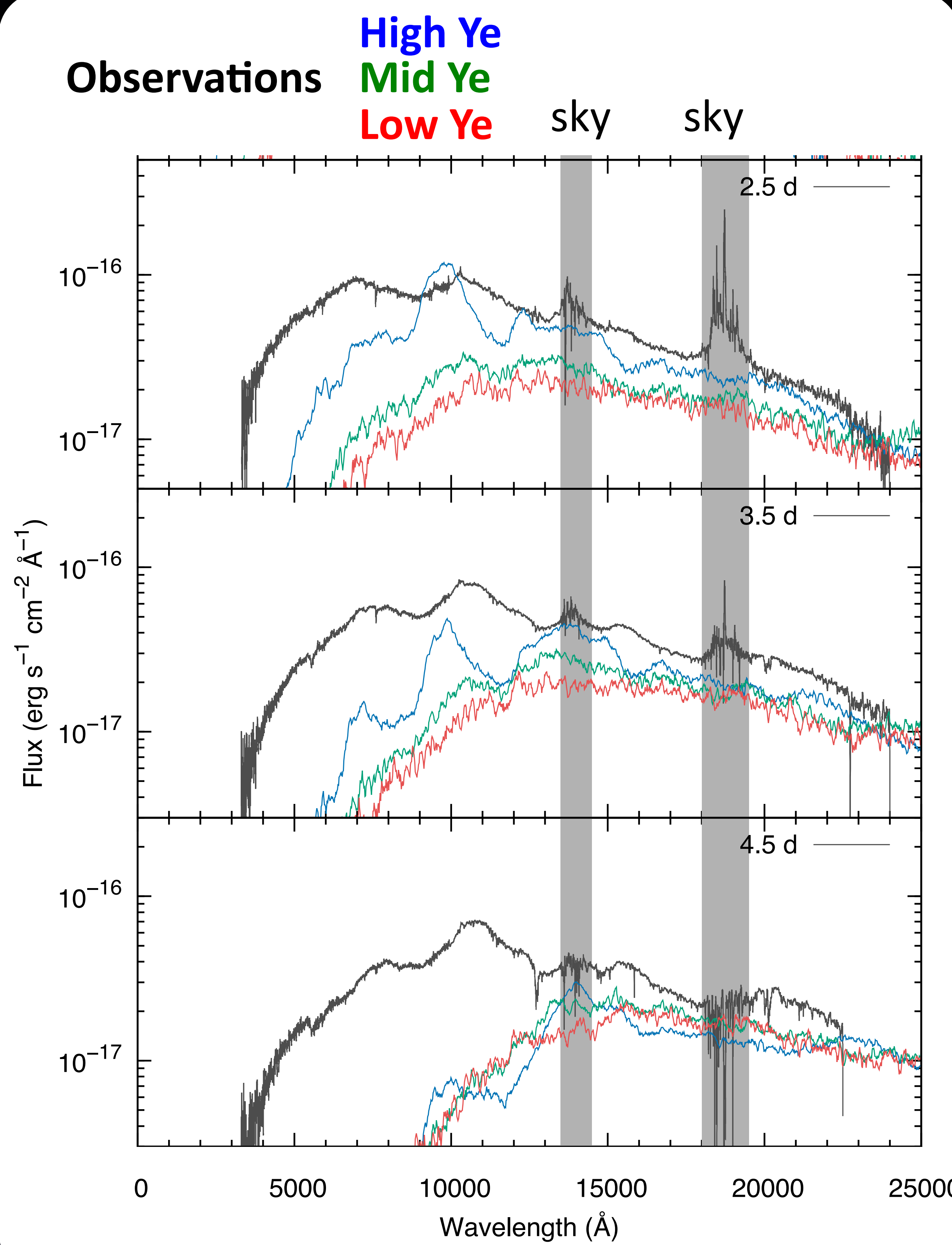
Kawaguchi, Shibata, Tanaka 2019, arXiv:1908.05815

Spectral features?

Atomic calculations are not accurate enough (by <30-50% in energy)

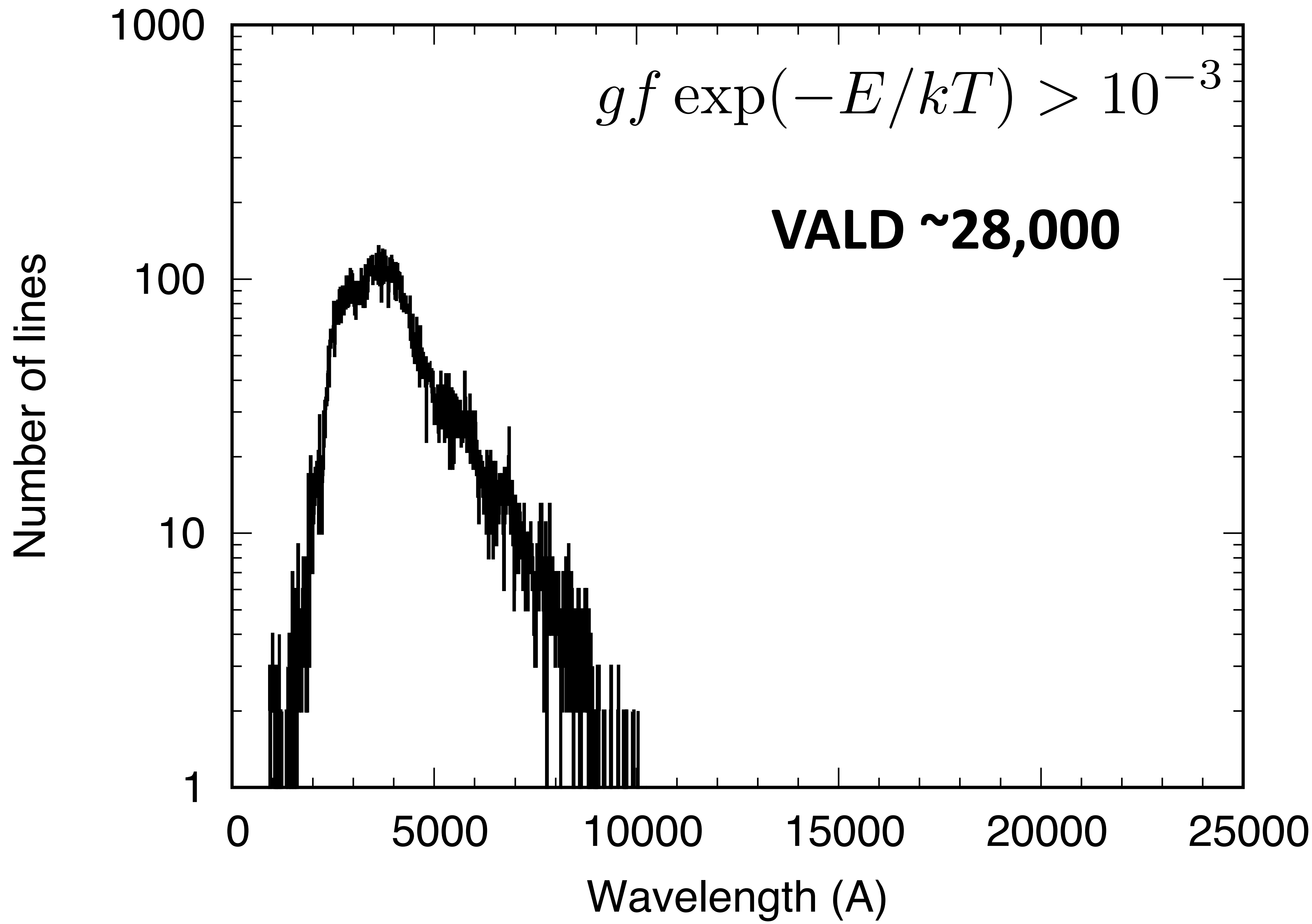
Tanaka+18, see also Kasen+13



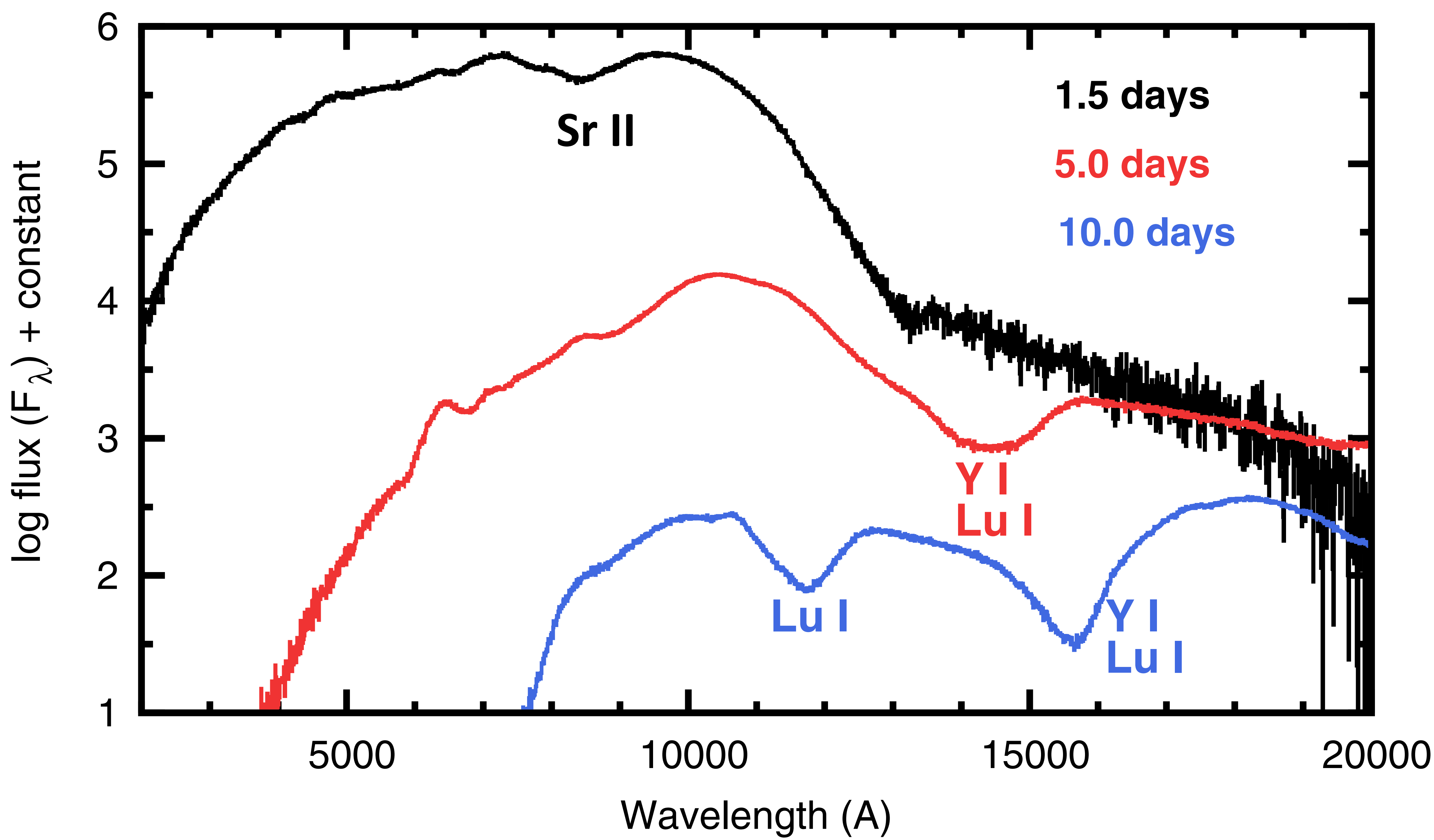


Accurate transition data
(VALD database)

Z > 31 (I and II)



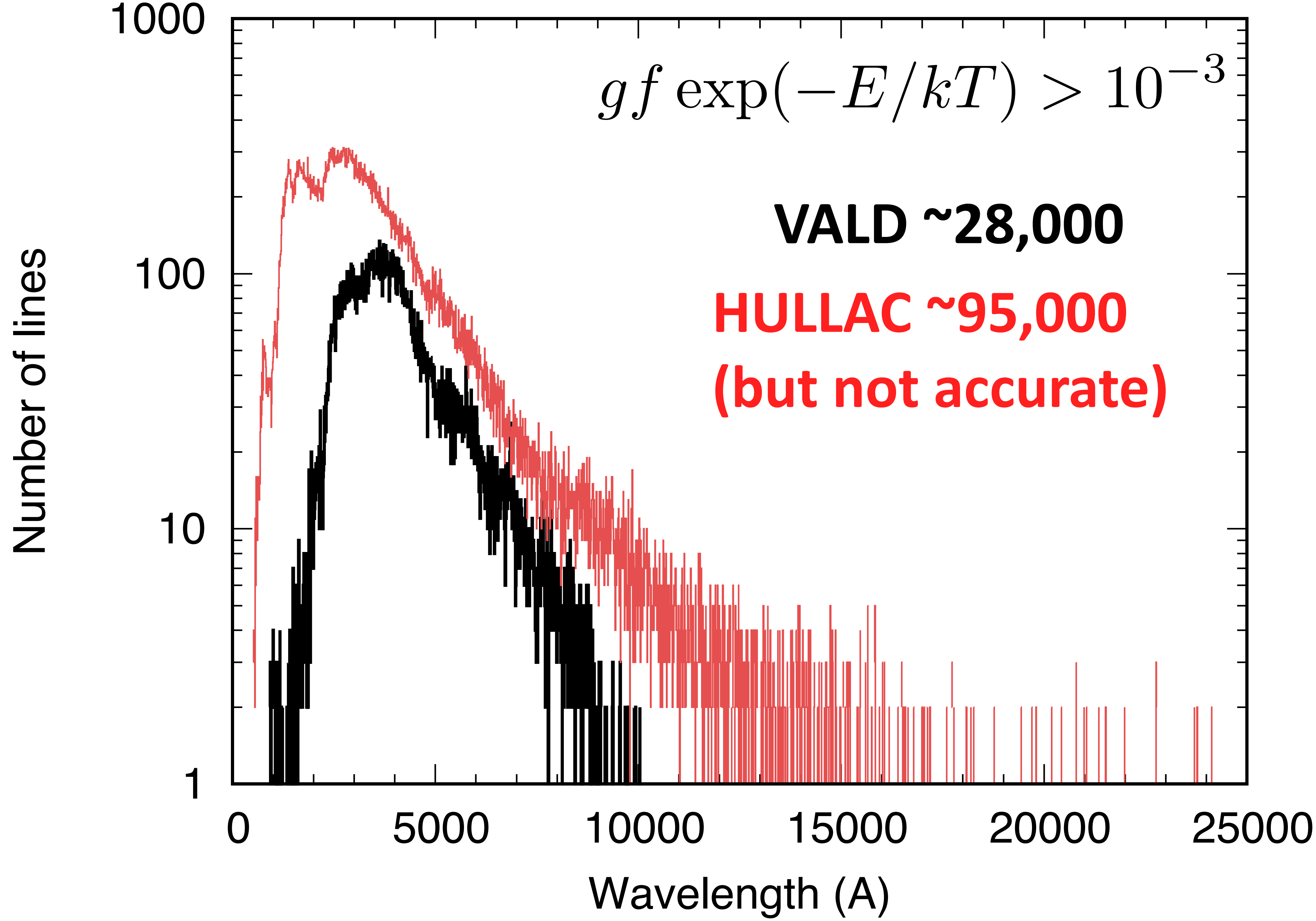
Spectral calculations using accurate data



Tanaka & Hotokezaka 2013

Accurate transition data
(VALD database)

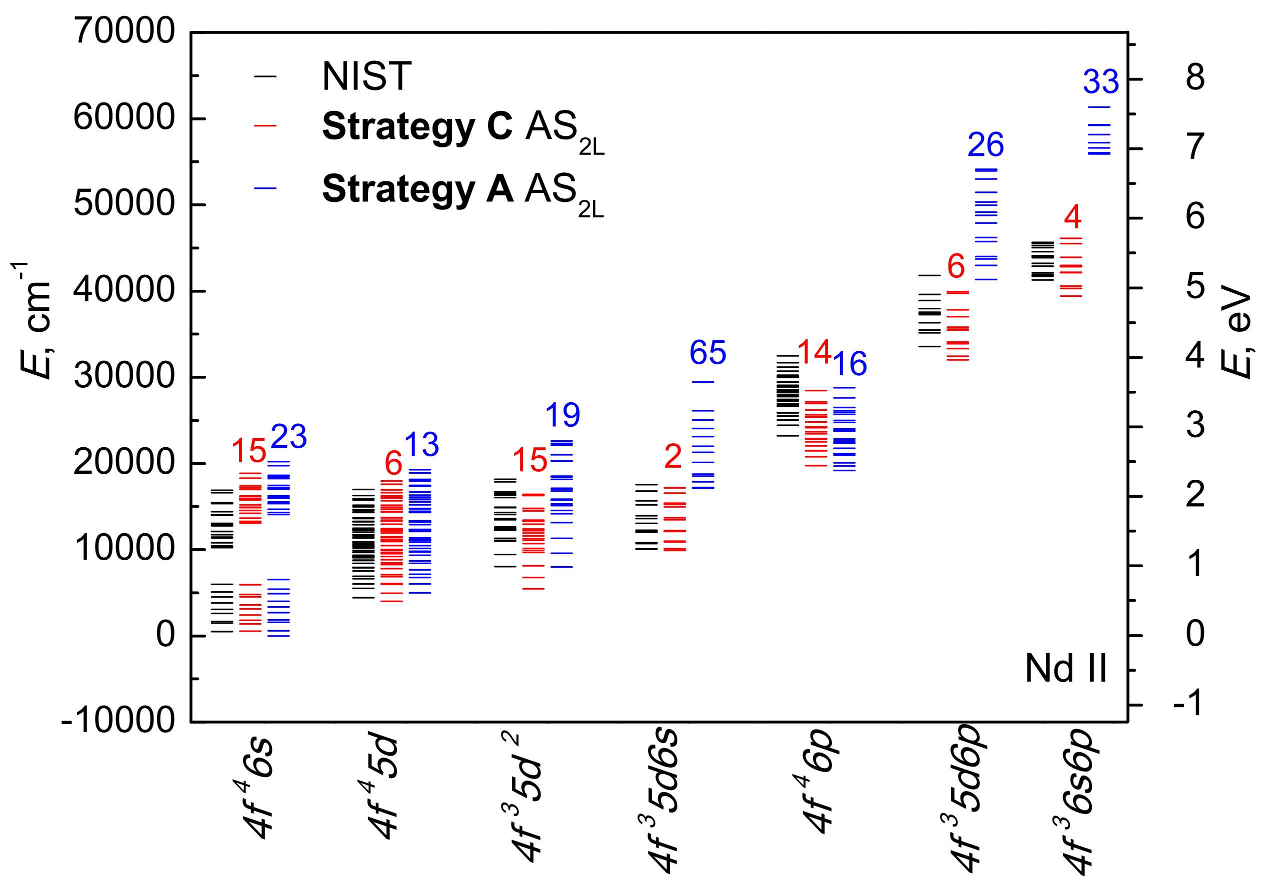
Z > 31 (I and II)

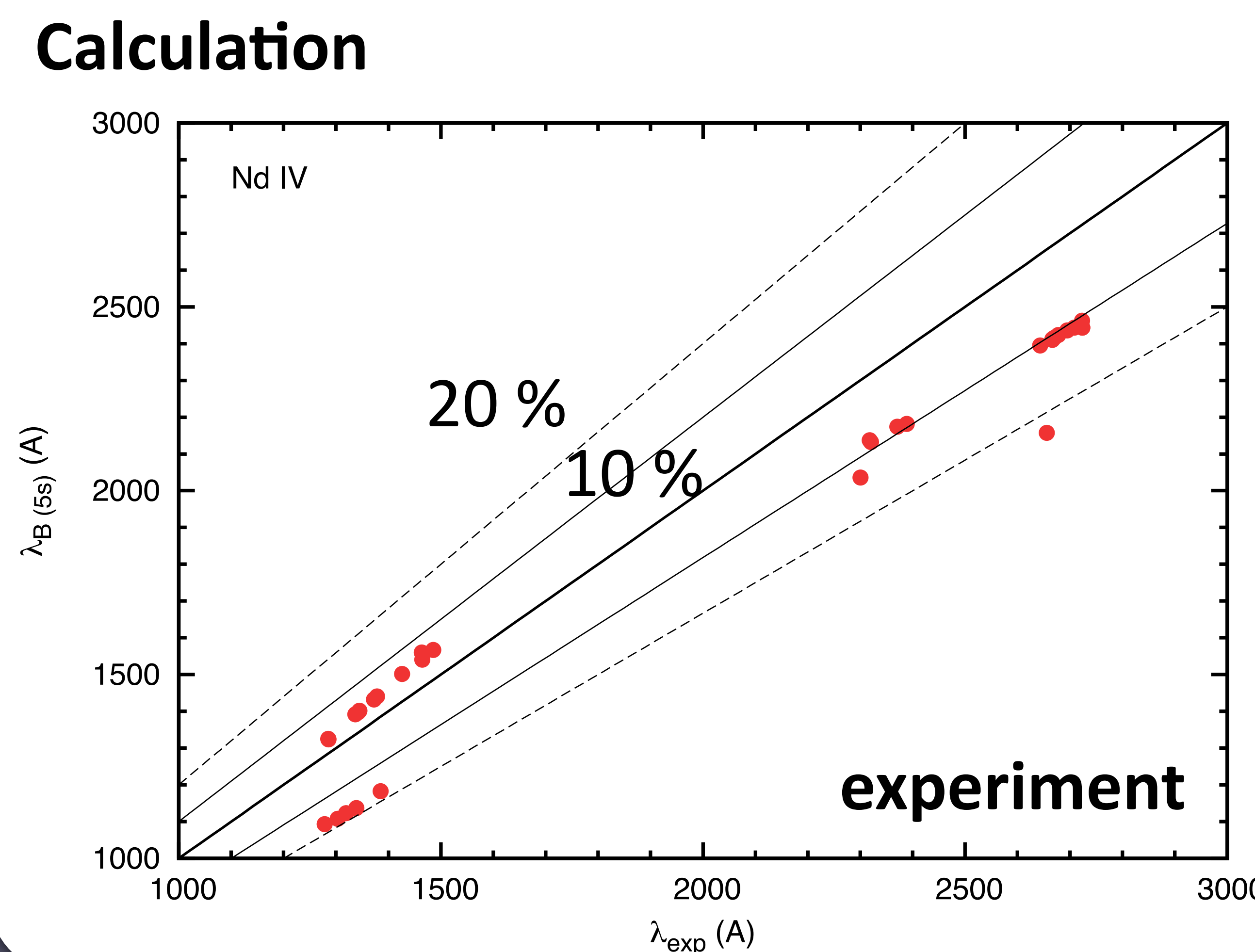


	Astro data (Kurucz, VALD, ...)	Systematic calculations	Systematic calculations calibrated with experiments
Accuracy	✓	✗	✓
Completeness	✗	✓	✓

Accurate atomic calculations for element identification

Using ab-initio calculations (GRASP2K code)





10 % accuracy for energy levels

20 % accuracy for transition wavelengths

Gaigalas, Kato, Rynkun, Radziute, MT 2019, ApJS

Summary

- **Systematic opacity calculations**
  - All the elements from Z=30 to 92 (I, II, III, IV)
  - Energy level distribution is determined by complexity and spin-orbit interaction (+ e-e interaction)
  - Opacity trend with temperature depends strongly on temperature
  - Ready to calculate light curves with realistic models (Kawaguchi+)
- **Room for improvement**
  - Higher temperature (earlier phase) => highly ionized ions
  - Accuracy/completeness for spectral identification (IR in paticular)
  - Departure from LTE => Kenta Hotokezaka's talk

Tanaka, Kato, Gaigalas, Kawaguchi 2019, arXiv:1906.08914

Gaigalas, Kato, Rynkun, Radziute, Tanaka 2019, ApJS

Kawaguchi, Shibata, Tanaka 2019, arXiv:1908.05815