Neutron star mergers and kilonovae

Masaomi Tanaka (Tohoku University)

in collaboration with
Nanae Domoto, Ayari Kitamura, Salma Rahmouni (Tohoku U.), Daiji Kato (NIFS),
Gediminas Gaigalas, Laima Kitovienė, Pevel Rynkun (Vilnius U.),
Kyohei Kawaguchi (AEI), Kenta Hotokezaka (U. Tokyo)

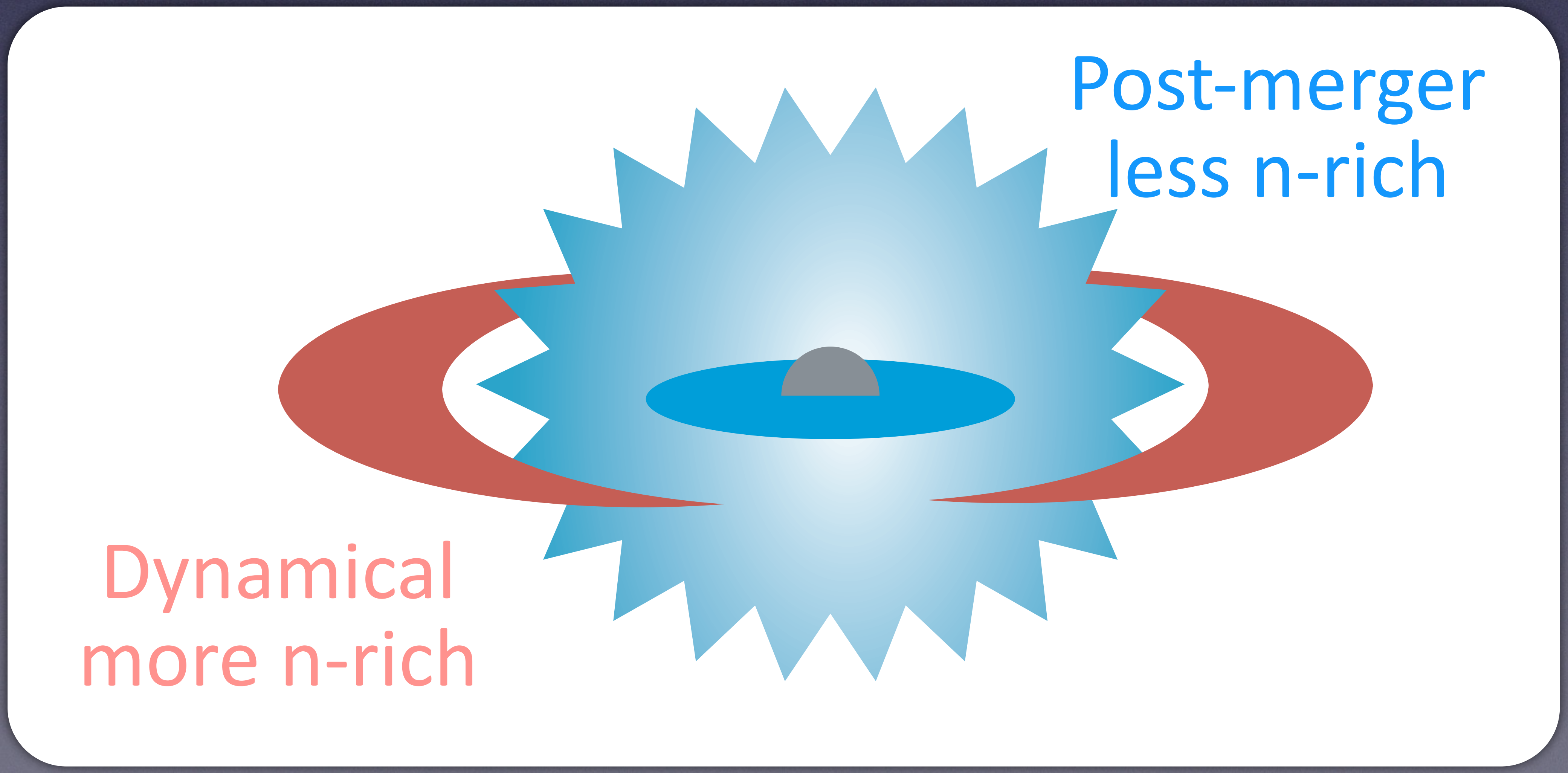
Neutron star mergers and kilonovae

- (Very) brief overview
- Kilonova light curves
- Kilonova spectra

Neutron star mergers

Merger ⇨ **r-process nucleosynthesis** ⇨ **Radioactive decay => kilonova (thermal emission)**

Dynamical mass ejection	post-merger ejection		Optically think	Optically thin
~< 100 ms		**< 1 sec**	**~> days**	**~10 days**



Mej ~ 0.01 Msun
v ~ 0.1 c

NS merger => dynamical mass ejection (< 0.1 sec)
=> “wind” from disk (~ 1 sec)

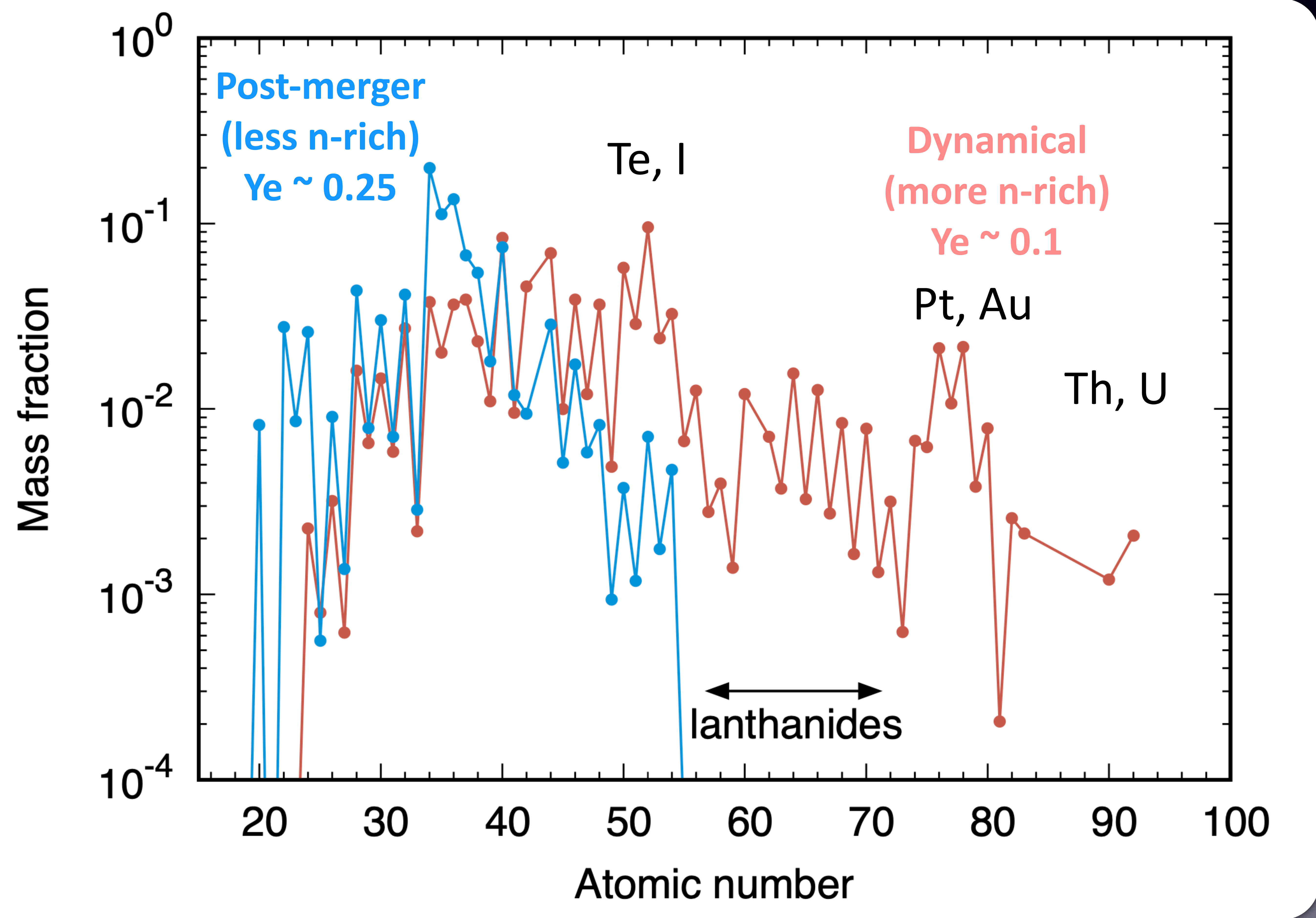
Ye **Density** **B field**

Kiuchi+23

r-process nucleosynthesis

Lattimer & Schramm 1974, Eichler et al. 1989, Goriely et al. 2011, Korobkin et al. 2012, Bauswein et al. 2013, Wanajo et al. 2014, …

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

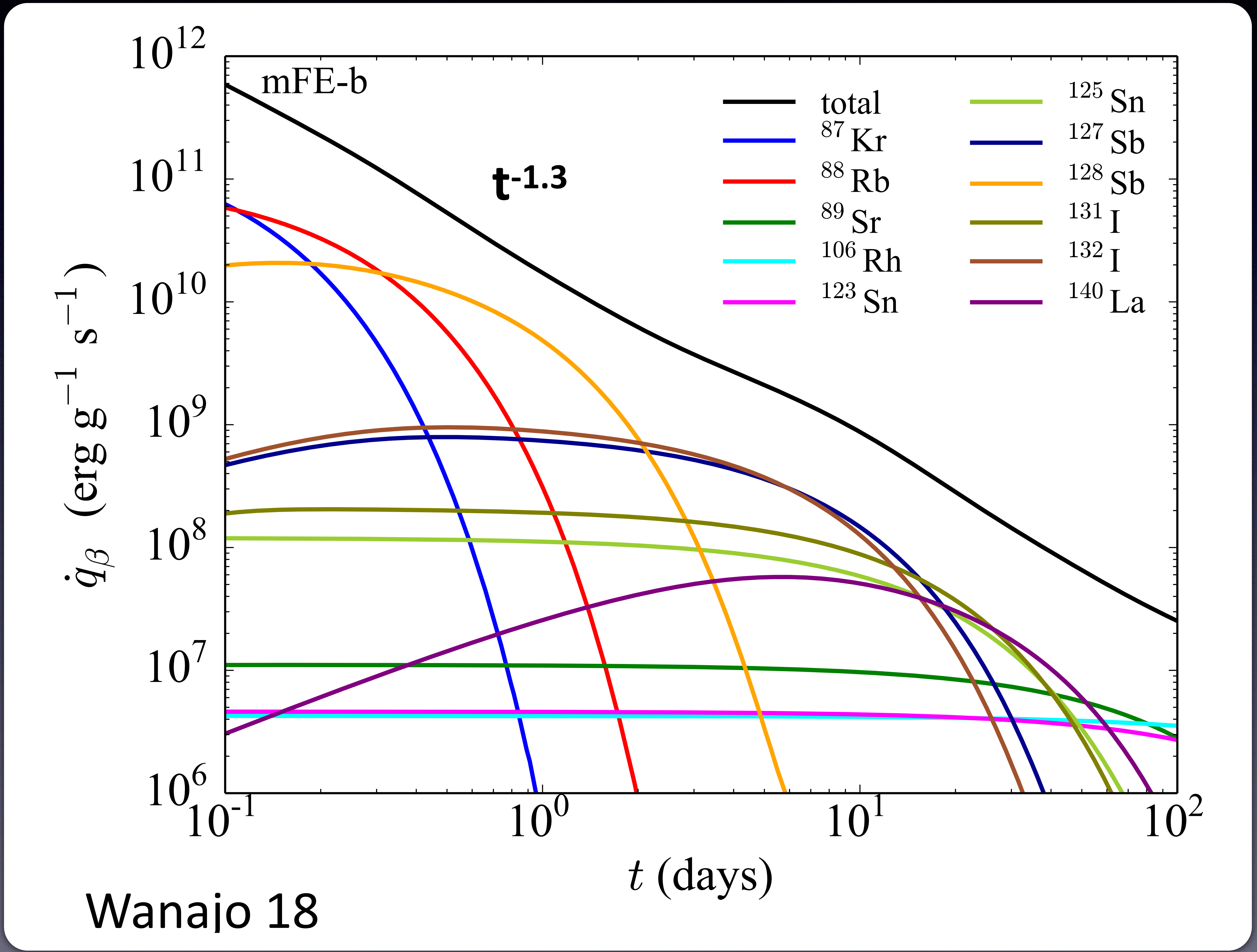


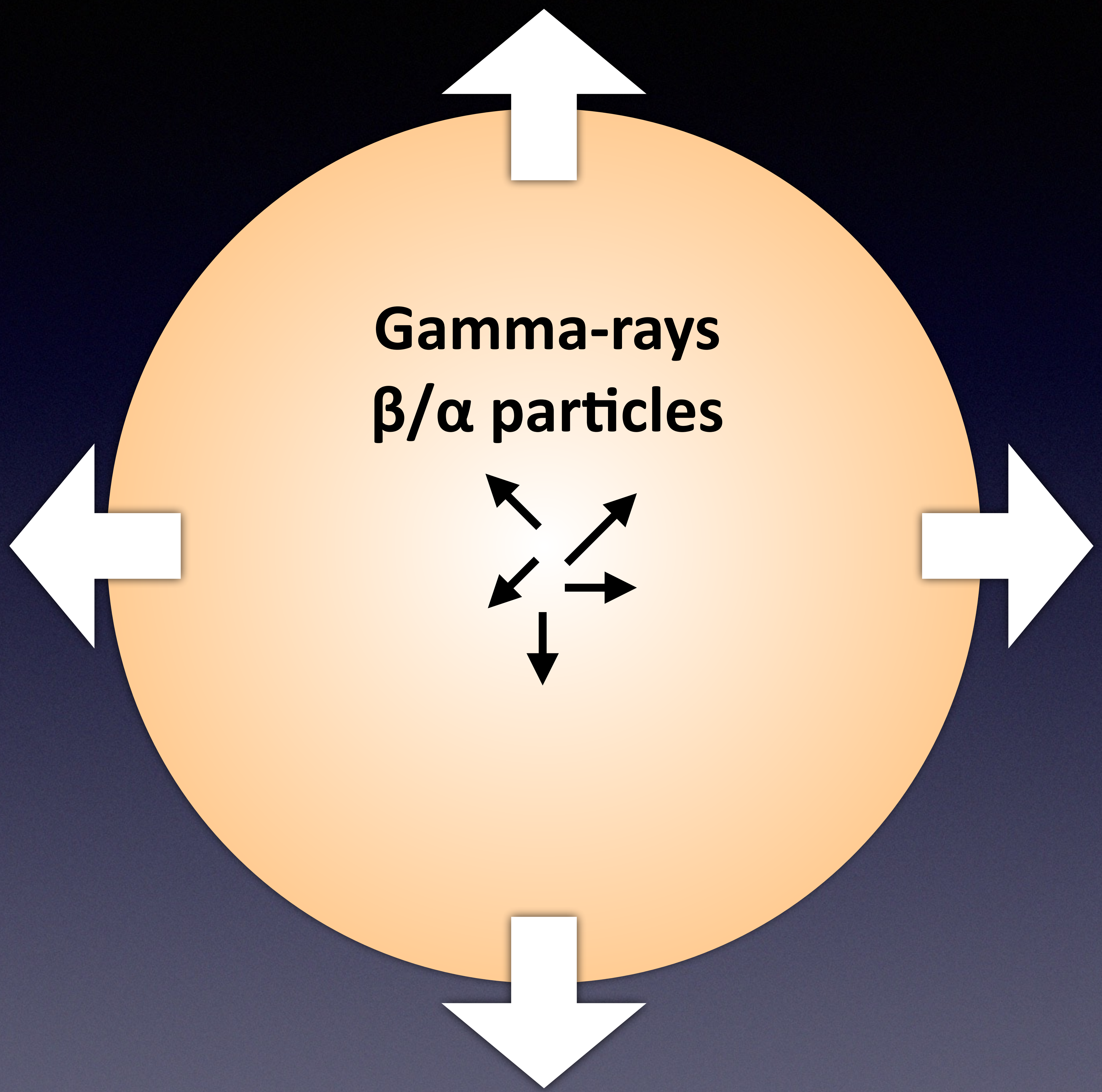
Fujibayashi+23

* mass fraction is normalized for each component

Radioactive heating

Metgzer+10, Lippuner+15, Wanajo18, …

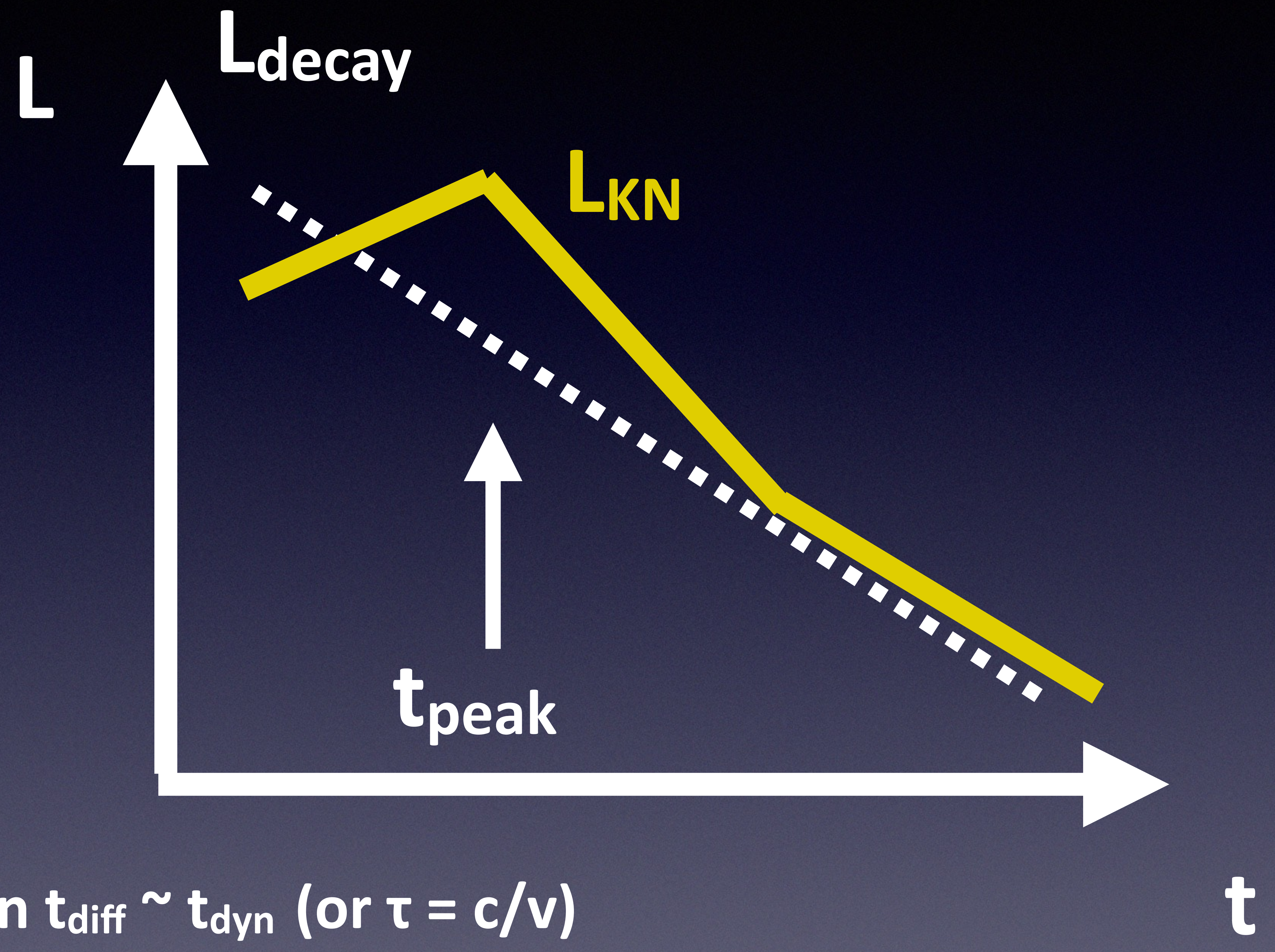




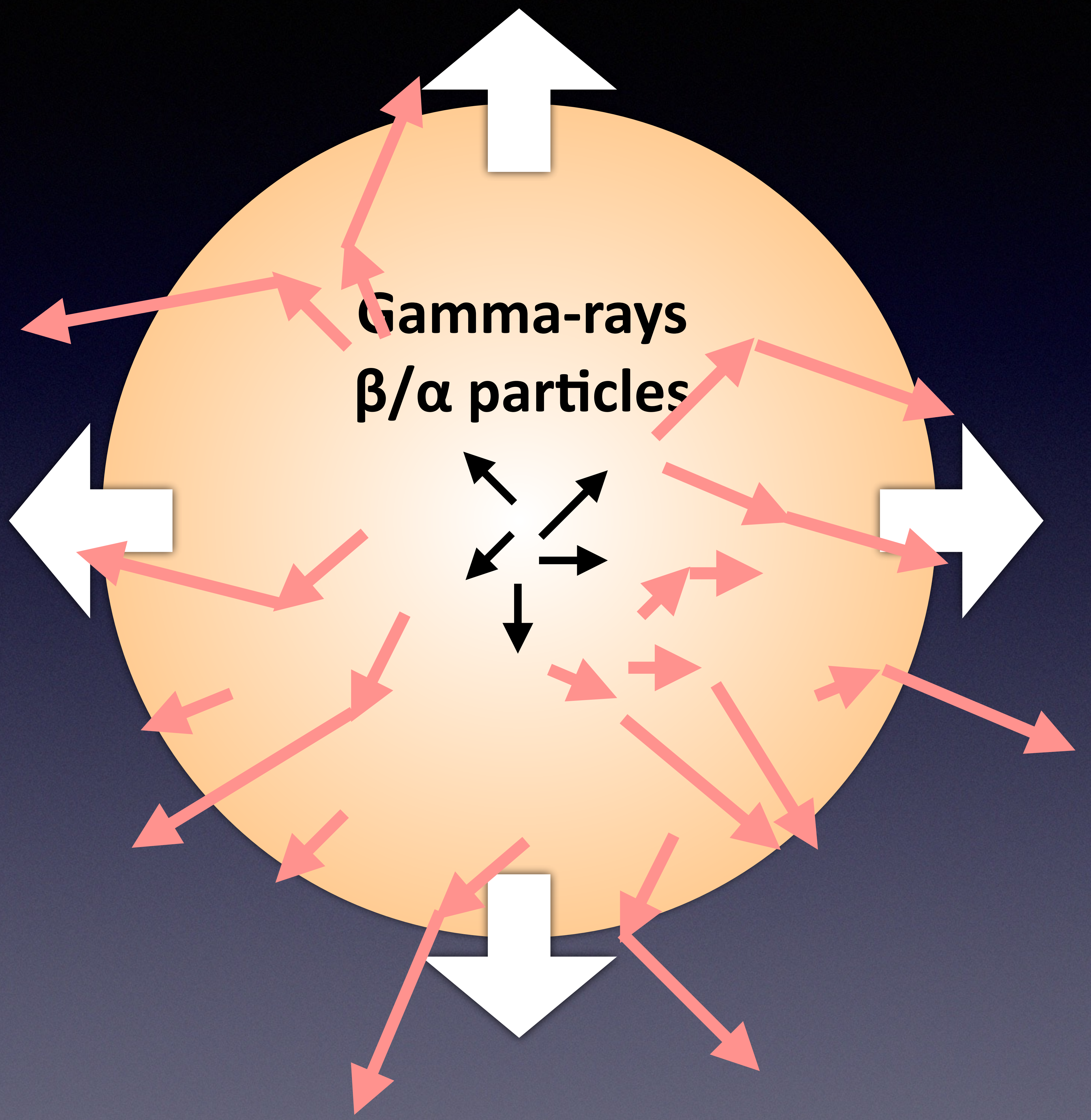
MeV particles are "stopped" => thermalization (energy deposition) e.g., Barnes+16

Thermal photon diffusion

Arnett 82, Li & Paczynski 98, Metgzer+10



Optical + infrared photons



When $t_{diff} \sim t_{dyn}$ (or $\tau = c/v$)

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

$$\simeq 8 \text{ days} \left(\frac{M_{\rm ej}}{0.01\ M_\odot}\right)^{1/2} \left(\frac{v_{\rm ej}}{0.1\ c}\right)^{-1/2} \left(\frac{\kappa(\lambda;\rho,T,X)}{10\ {\rm cm^2\ g^{-1}}}\right)^{1/2}$$

Opacity (atomic properties)

Main source of opacity:
Bound-bound transitions of heavy elements

What can we learn from observations of kilonova?

Light curves

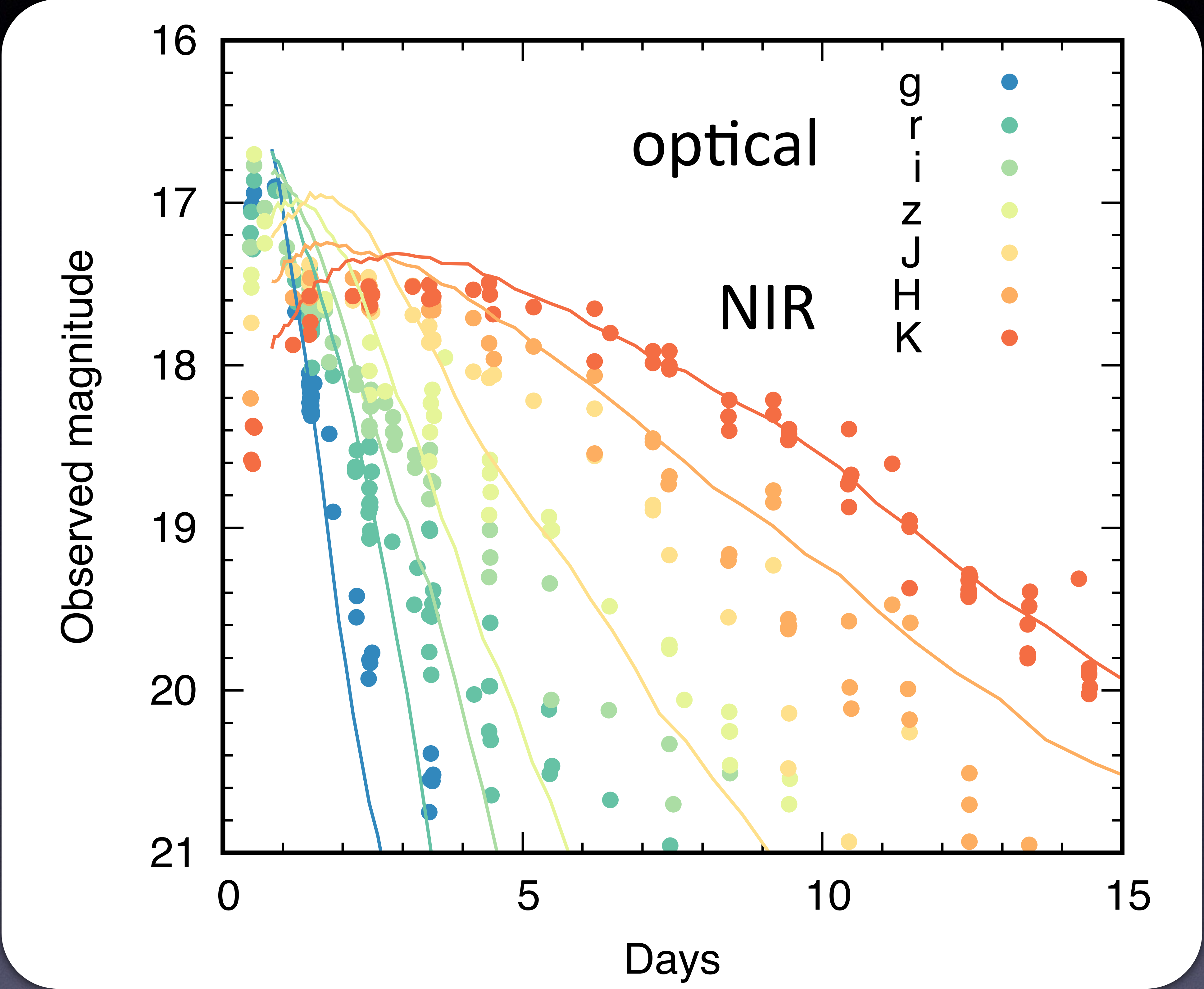


Figure from Kawaguchi+2018, 2020

Ejected mass and (rough) composition

Spectra

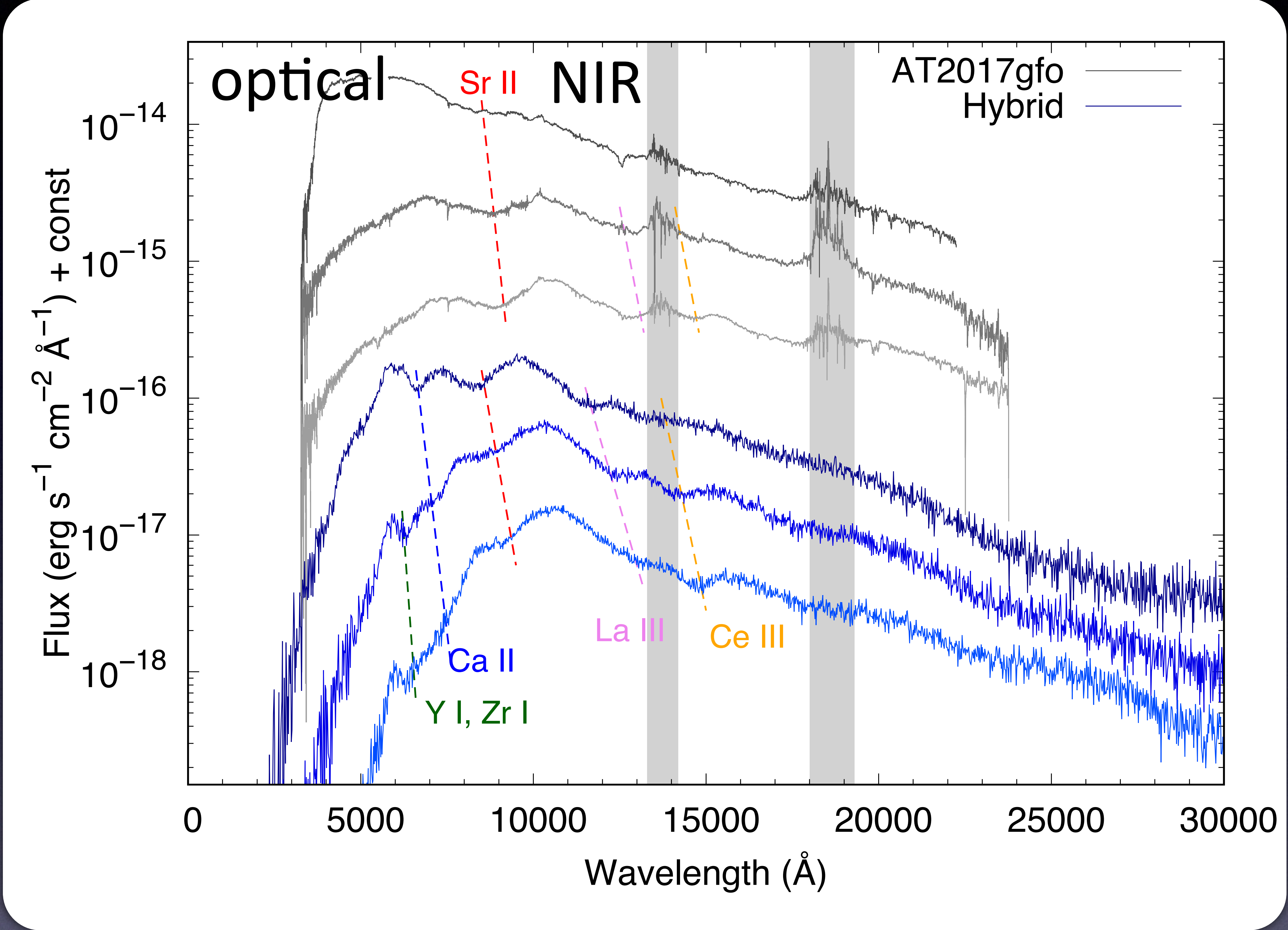


Figure from Domoto+2020,2022

Detailed elemental compositions

Origin of r-process elements

Physics of neutron star mergers

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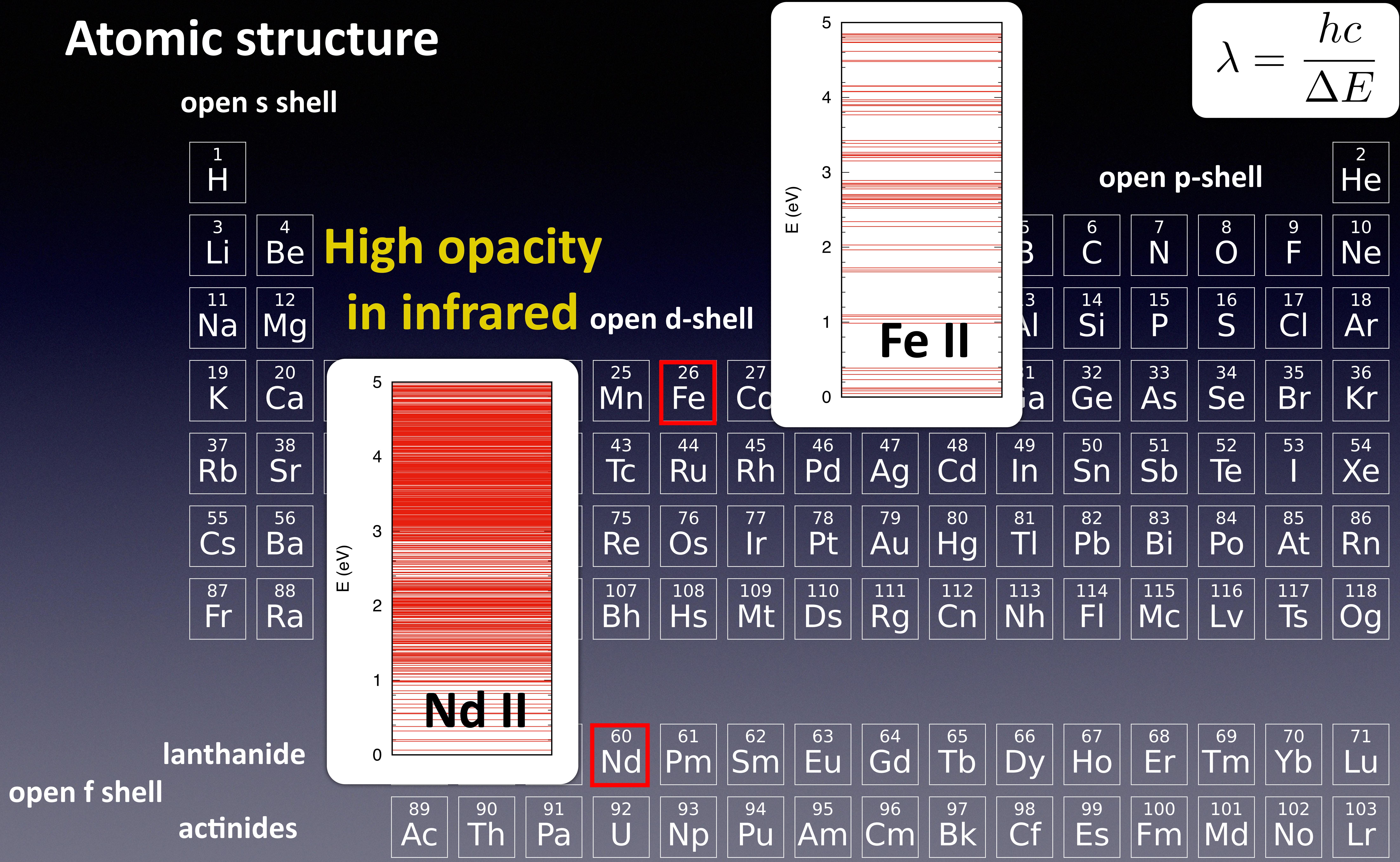
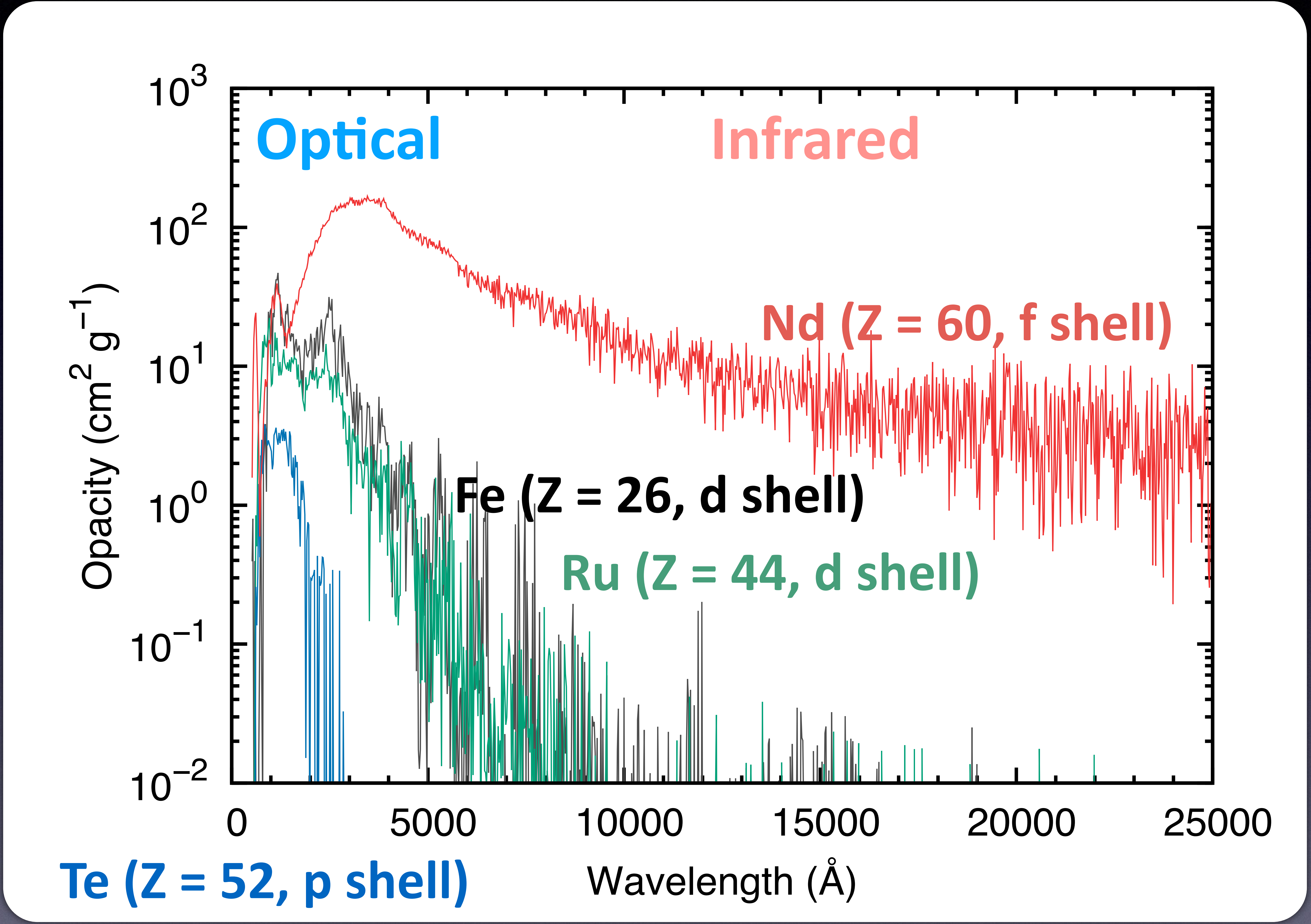
Atomic structure

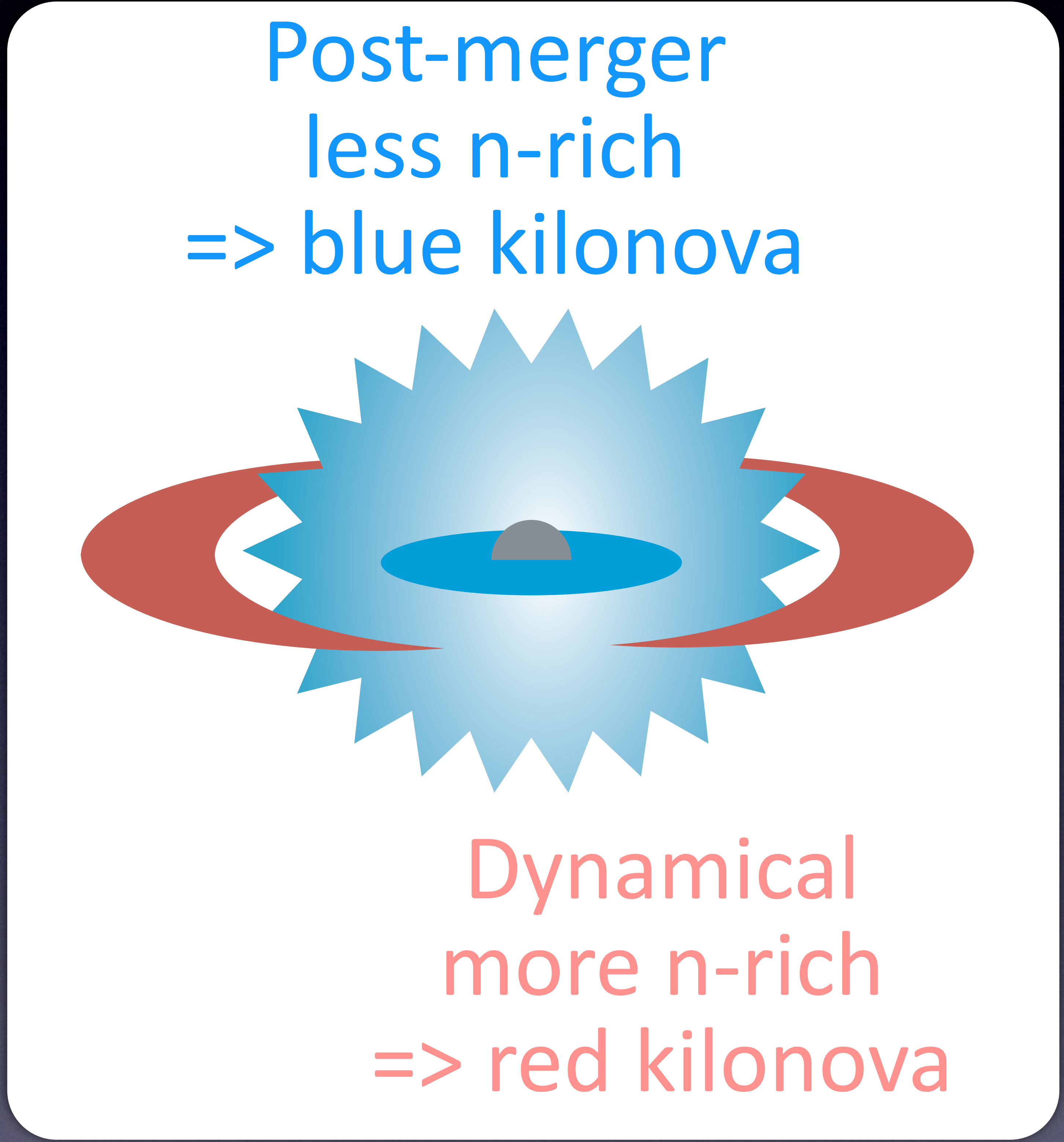
$$\lambda = \frac{hc}{\Delta E}$$



Opacity in kilonova

Kasen+13, MT & Hotokezaka 13,
Kasen+17, MT+18, 20, Wollaeger+18, Fontes+20, Banerjee+20,22…





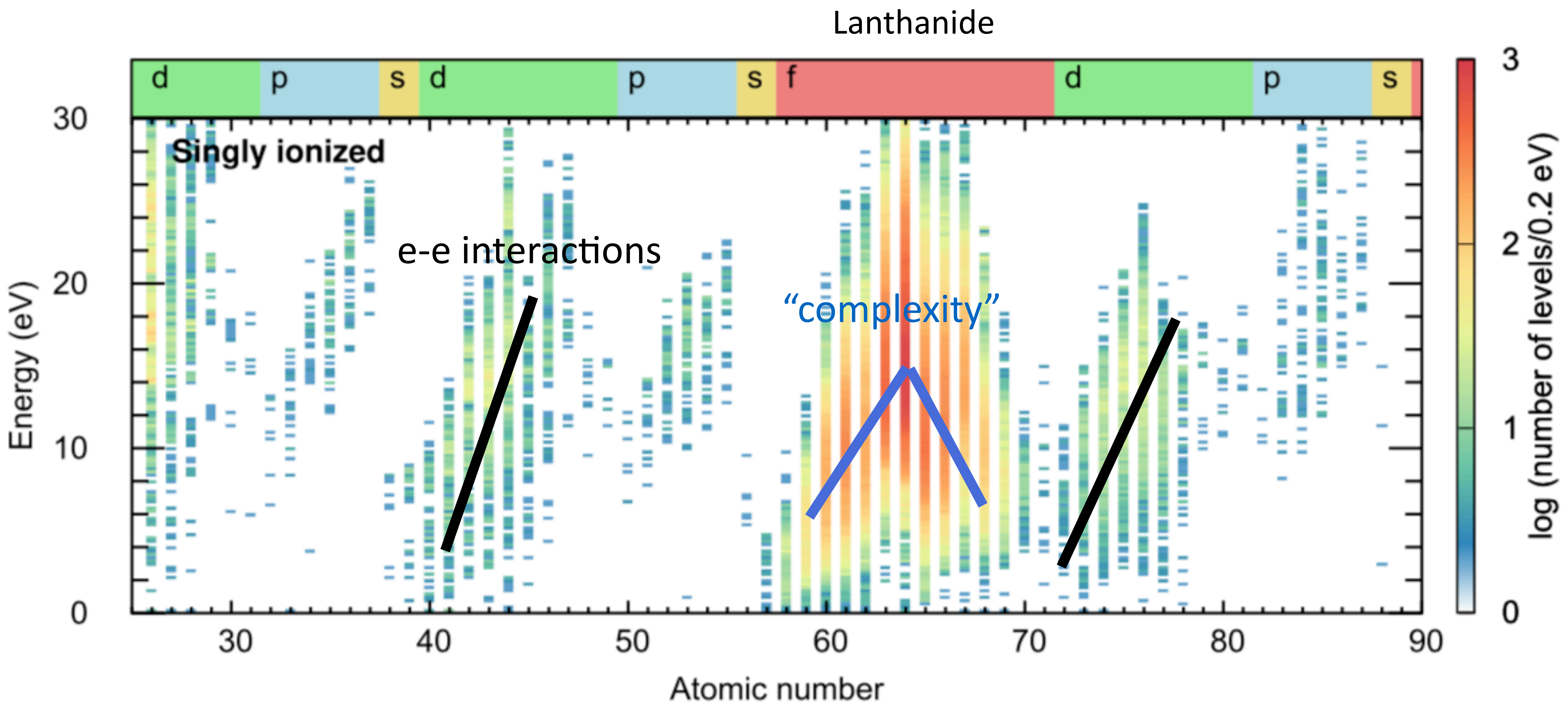
Lanthanide-poor => “Blue” kilonova

Lanthanide-rich => “Red” kilonova

Metzger+14,
Fernandez & Metzger 15,
Wollaeger+18, MT+18, …

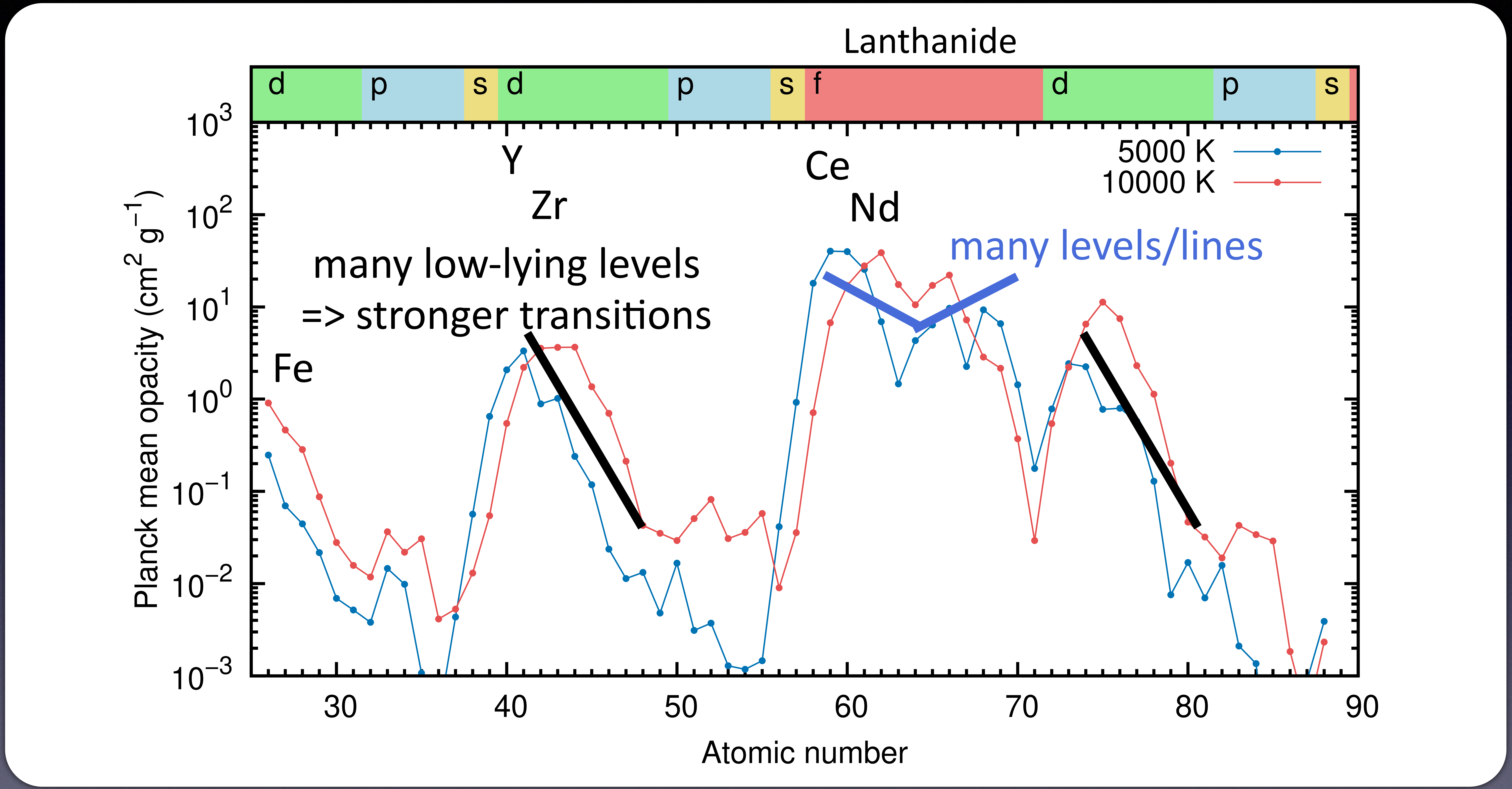
Energy level distributions (all the elements)

MT, Kato, Gaigalas, Kawaguchi 20



Opacities (all the elements)

MT, Kato, Gaigalas, Kawaguchi 20



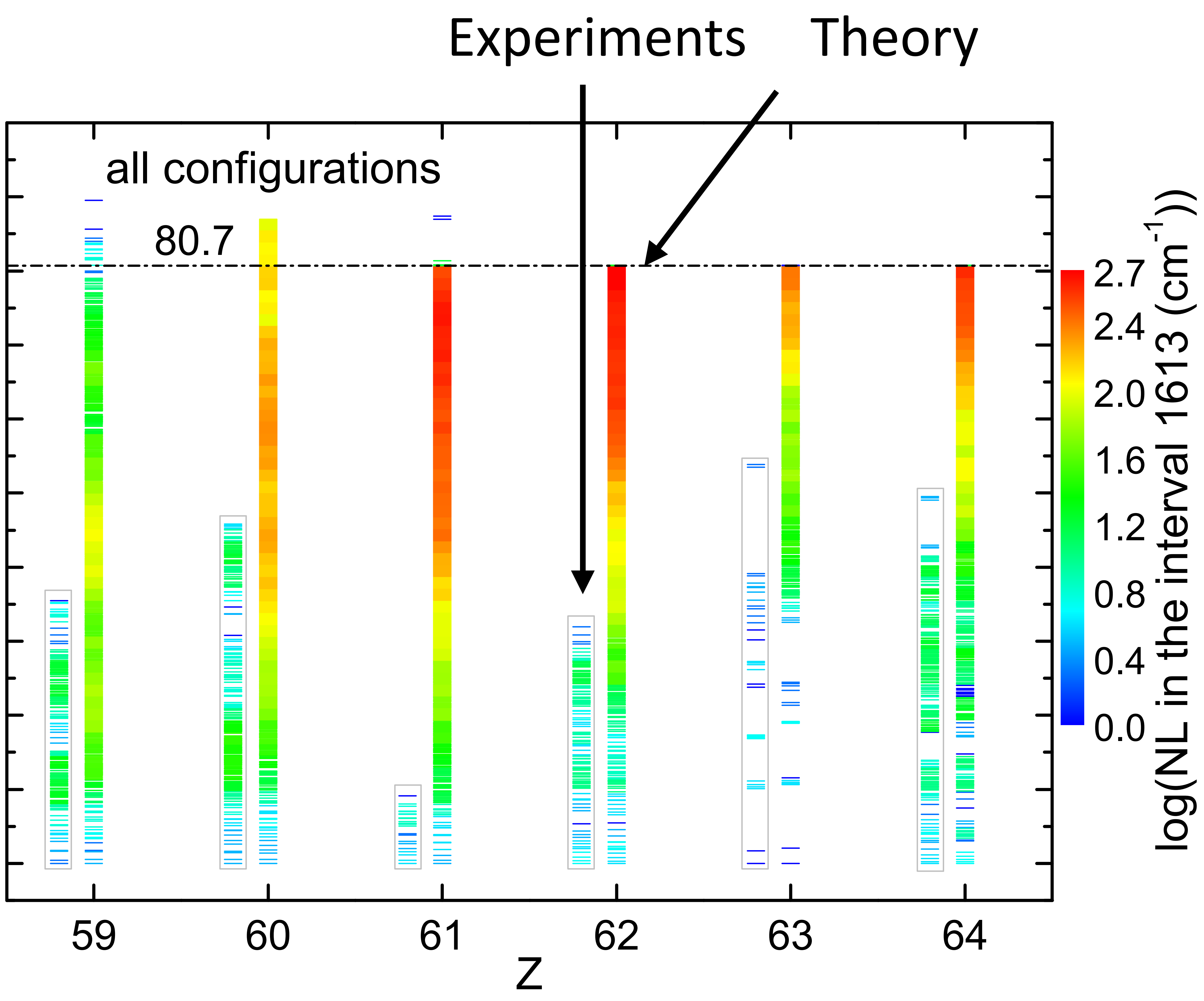
Lanthanide-rich ejecta κ ~ 10-30 cm² g⁻¹

Lanthanide-free ejecta κ ~ 1 cm² g⁻¹

(> 0.1 cm² g⁻¹ for Type Ia SN, Fe)

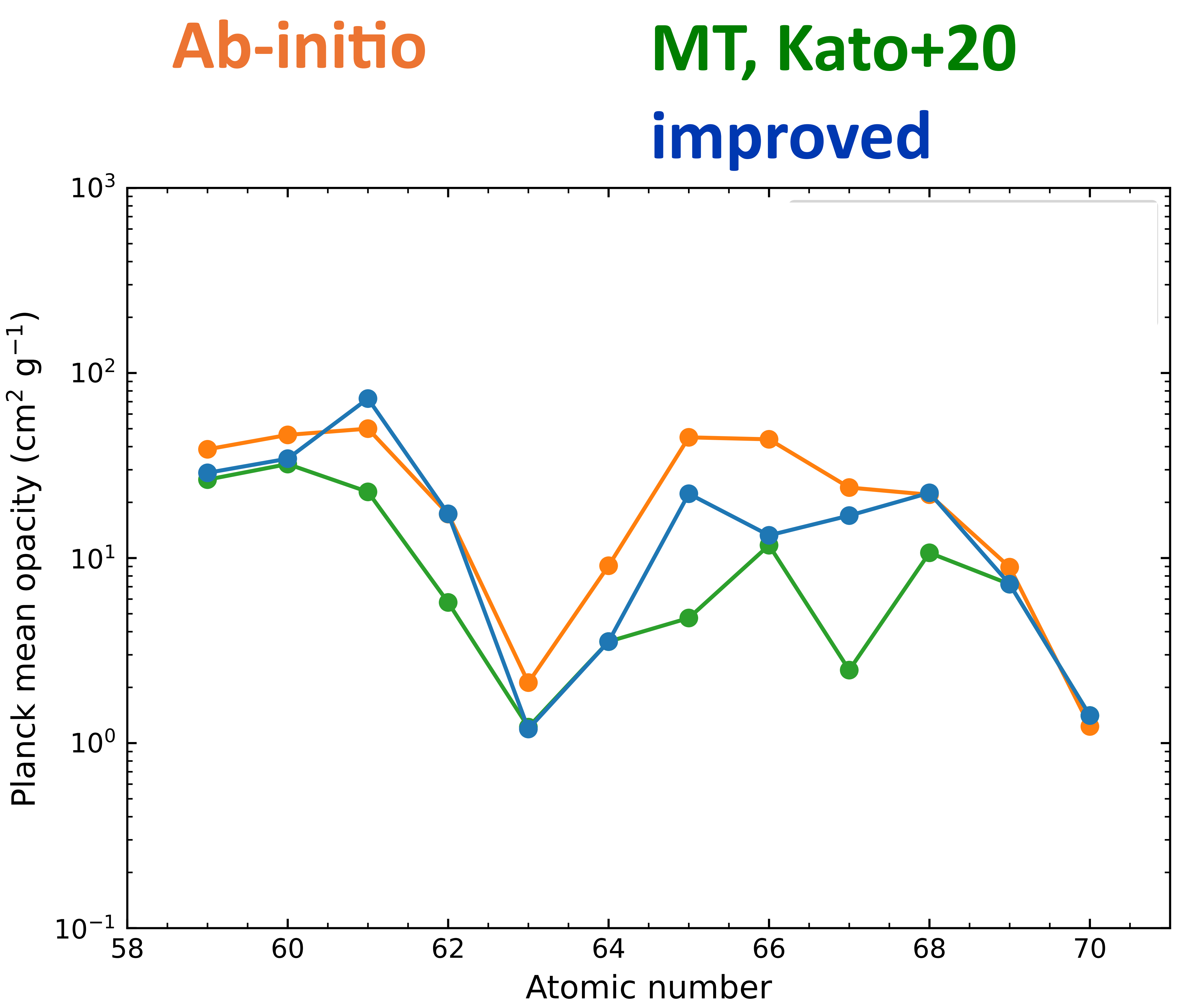
Ab-initio atomic structure calculations (singly ionized lanthanides)

Gaigalas+19, Radziute+20,21



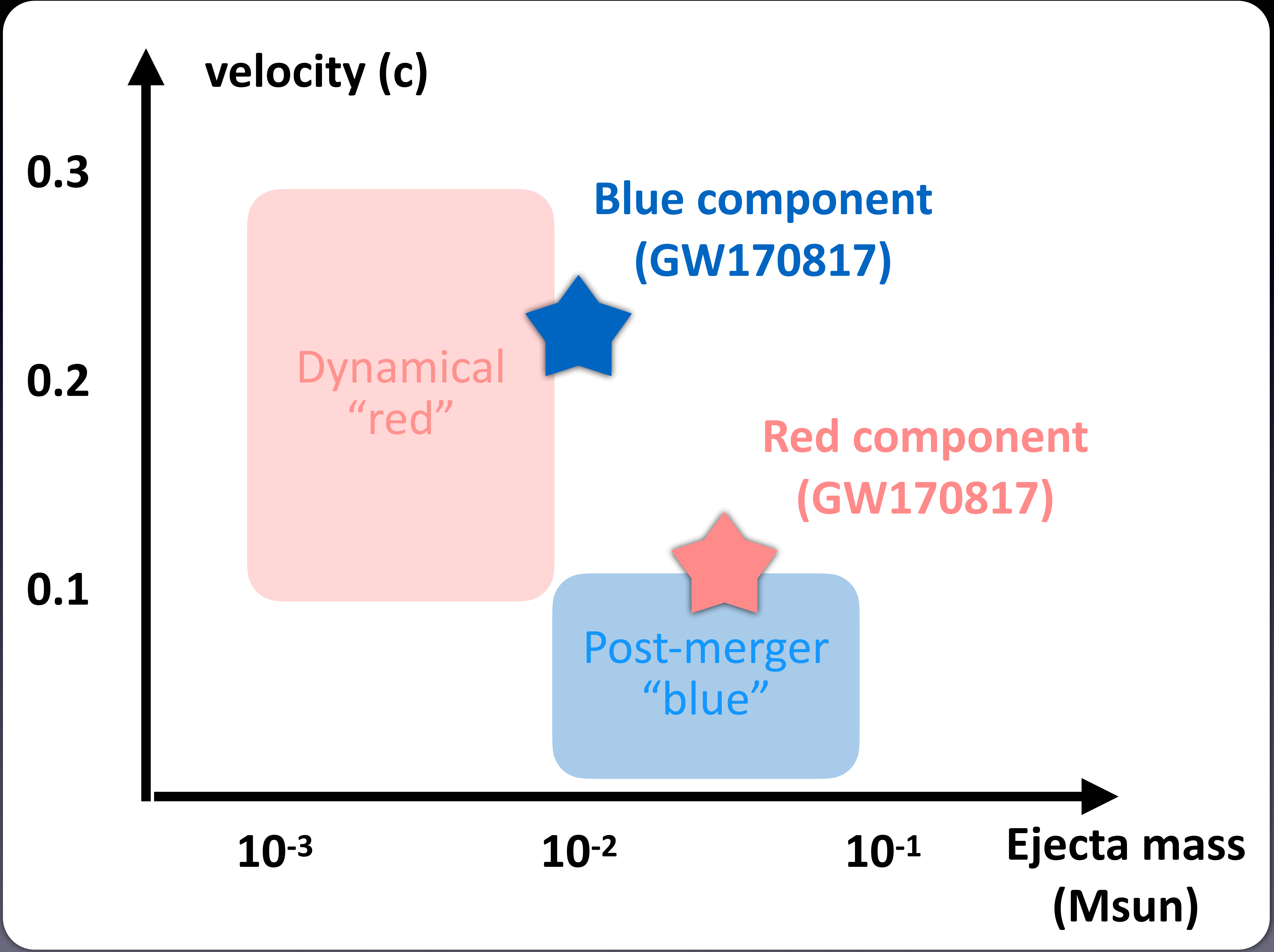
~10 % accuracy in the energy levels

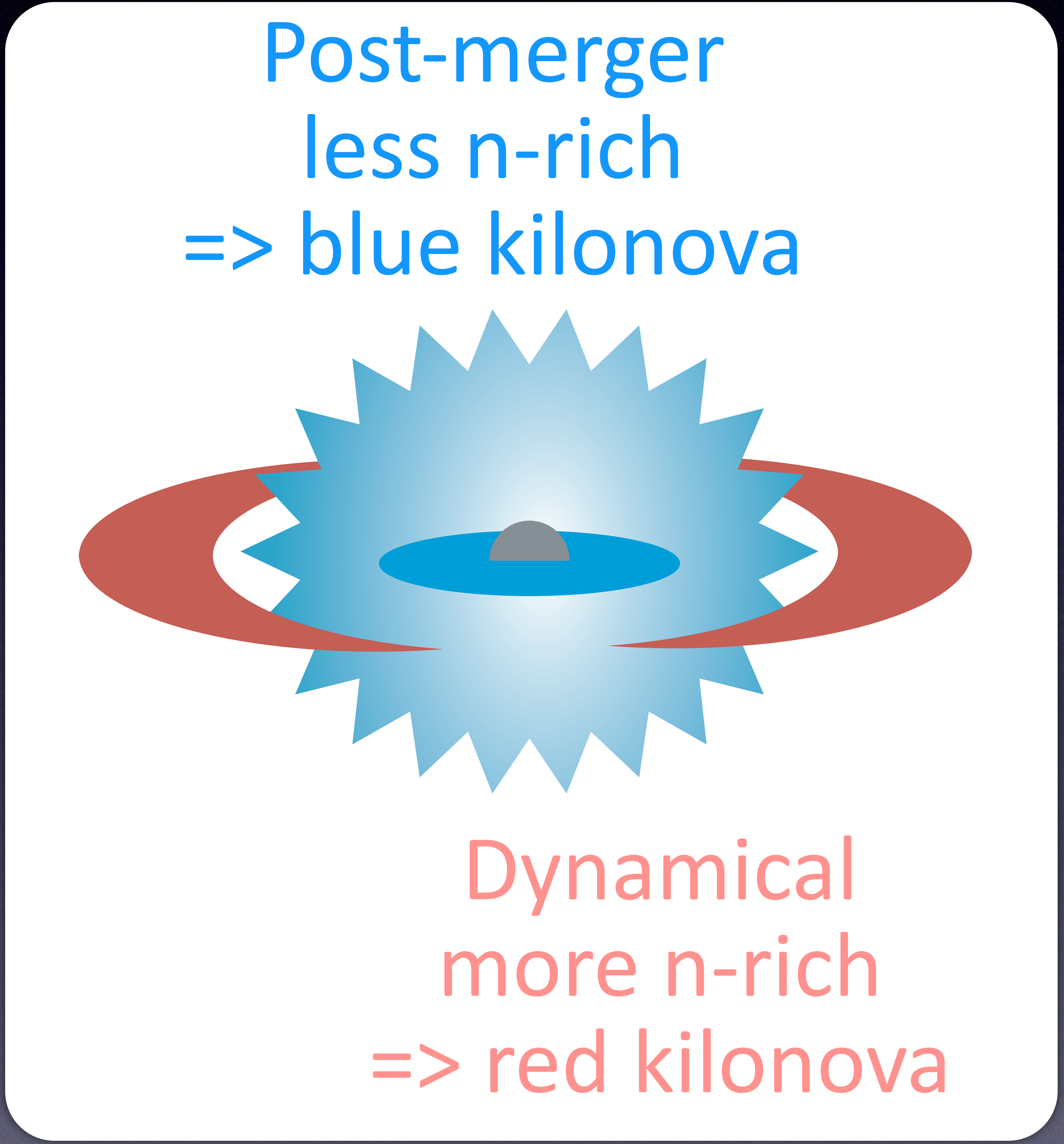
Kato, MT+ in prep.



factor of ~ 3 in opacity

Ejecta components in GW170817?

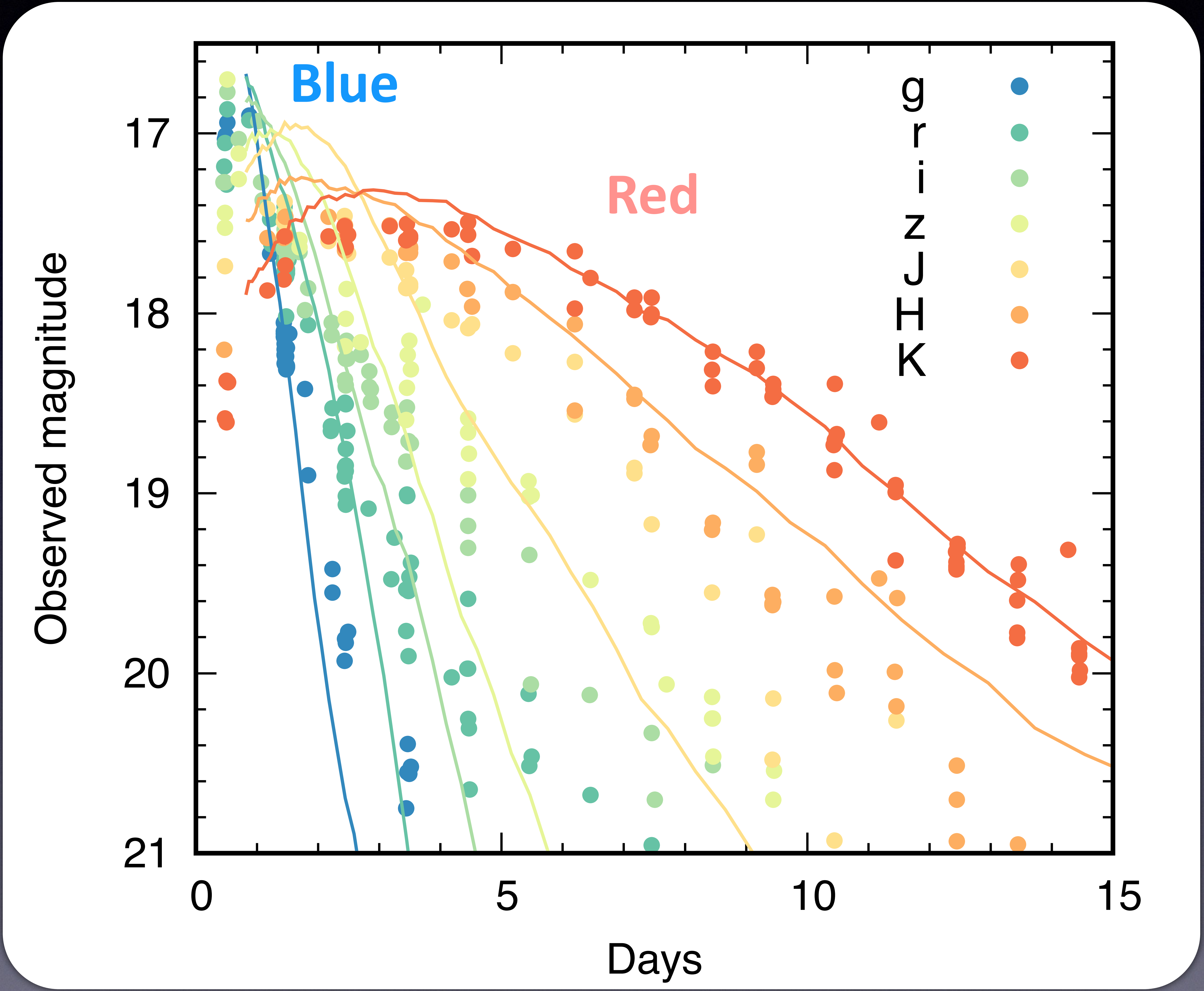


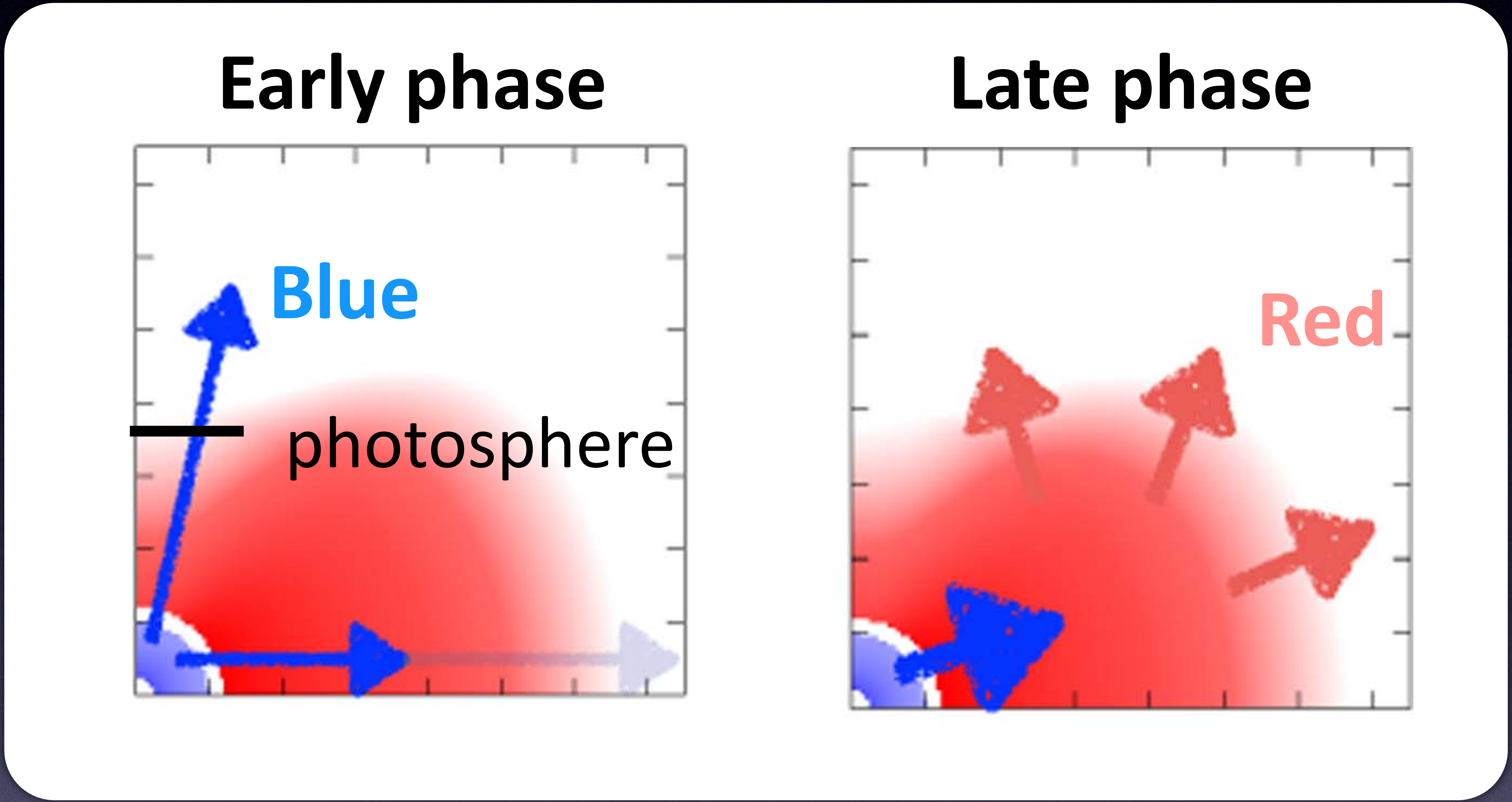


Tension with theoretical prediction??

End-to-end simulations based on numerical relativity simulations

Kawaguchi+2018, 2020 (see also Perego+17, Wollaeger+18, Bulla 19, Just+23, Fryer+24…)





Post-merger ejecta = heating source
Dynamical ejecta = reprocessing photons

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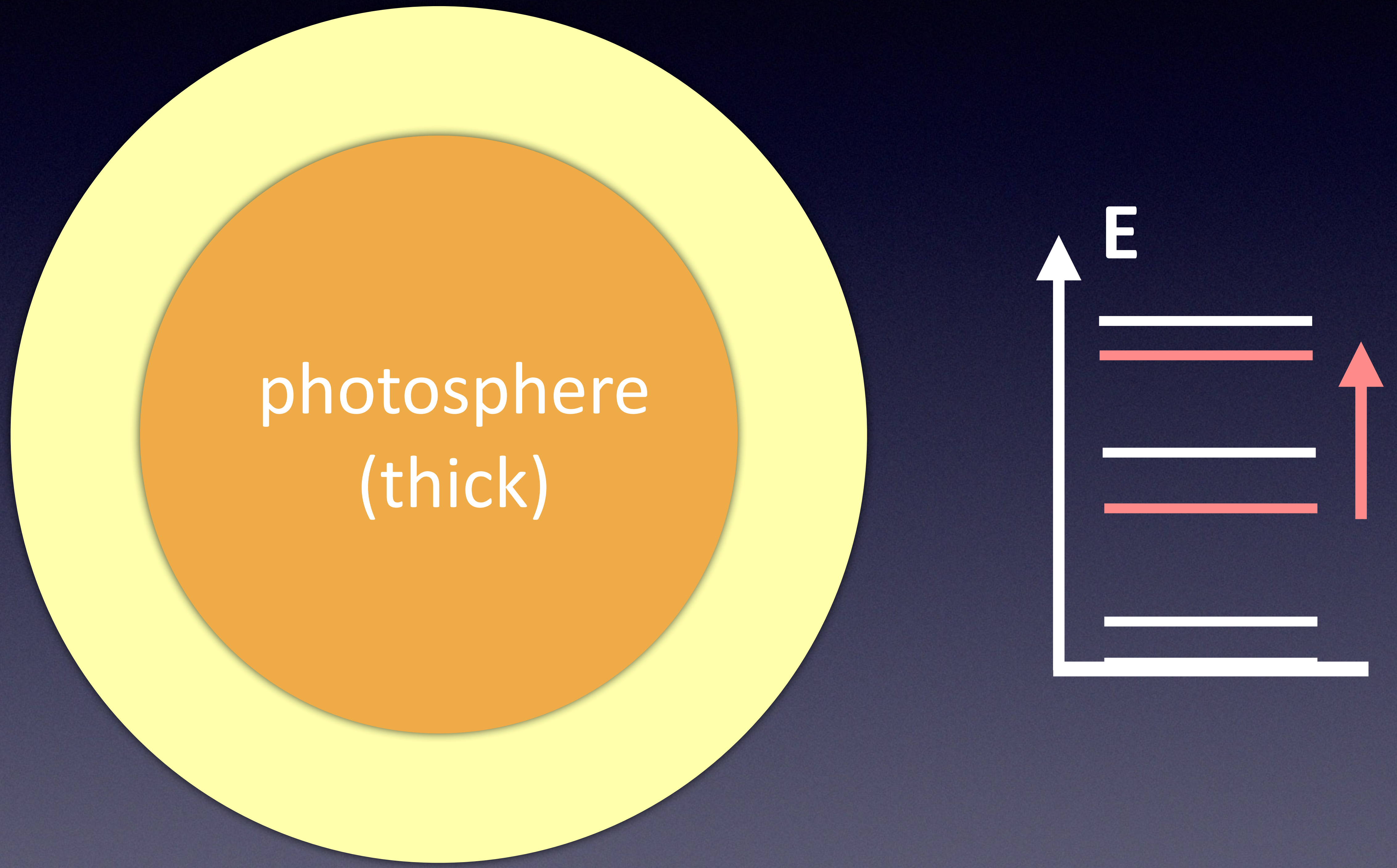
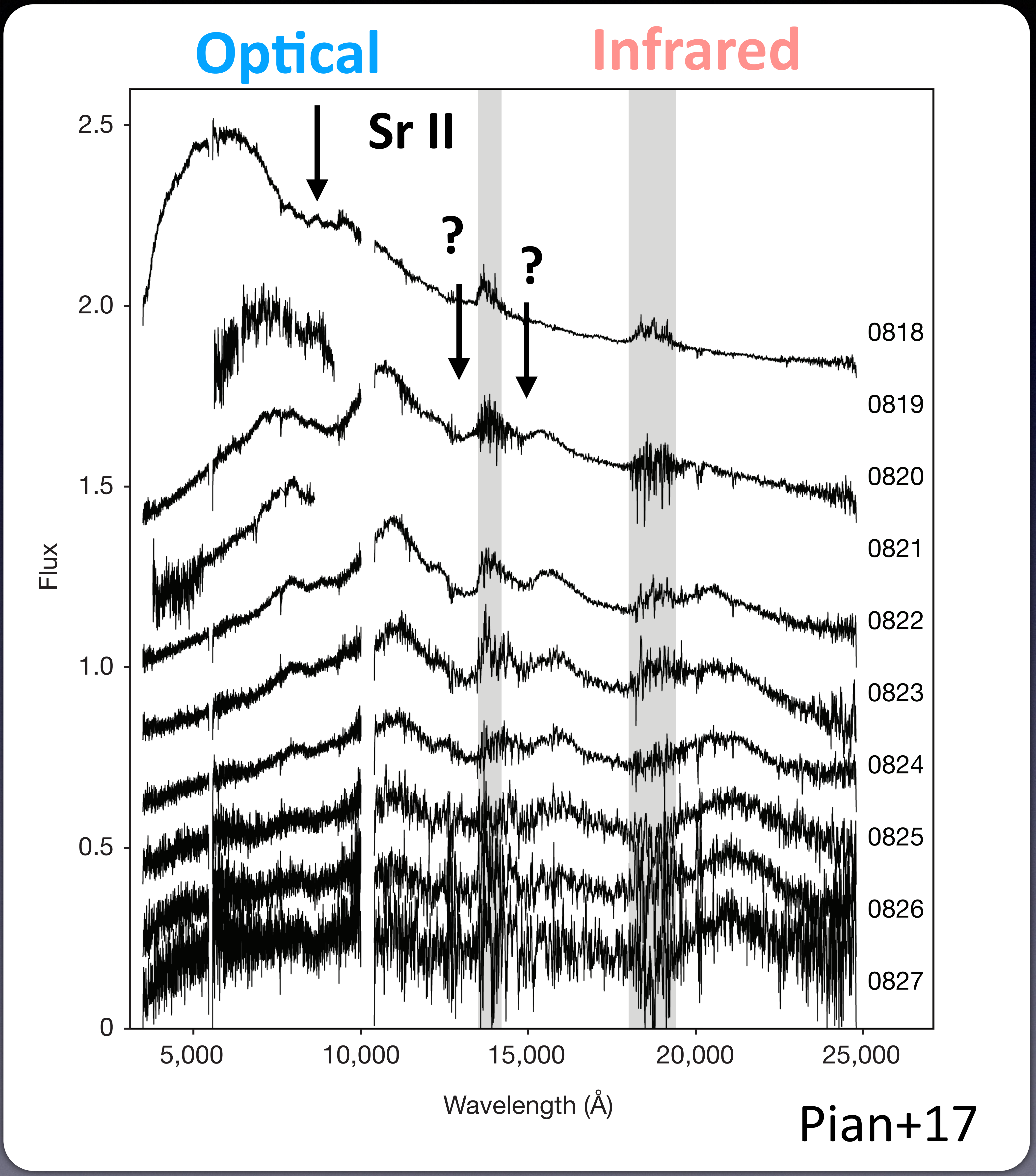
Spectral features in kilonova spectra

absorption feature



GW170817/AT2017gfo

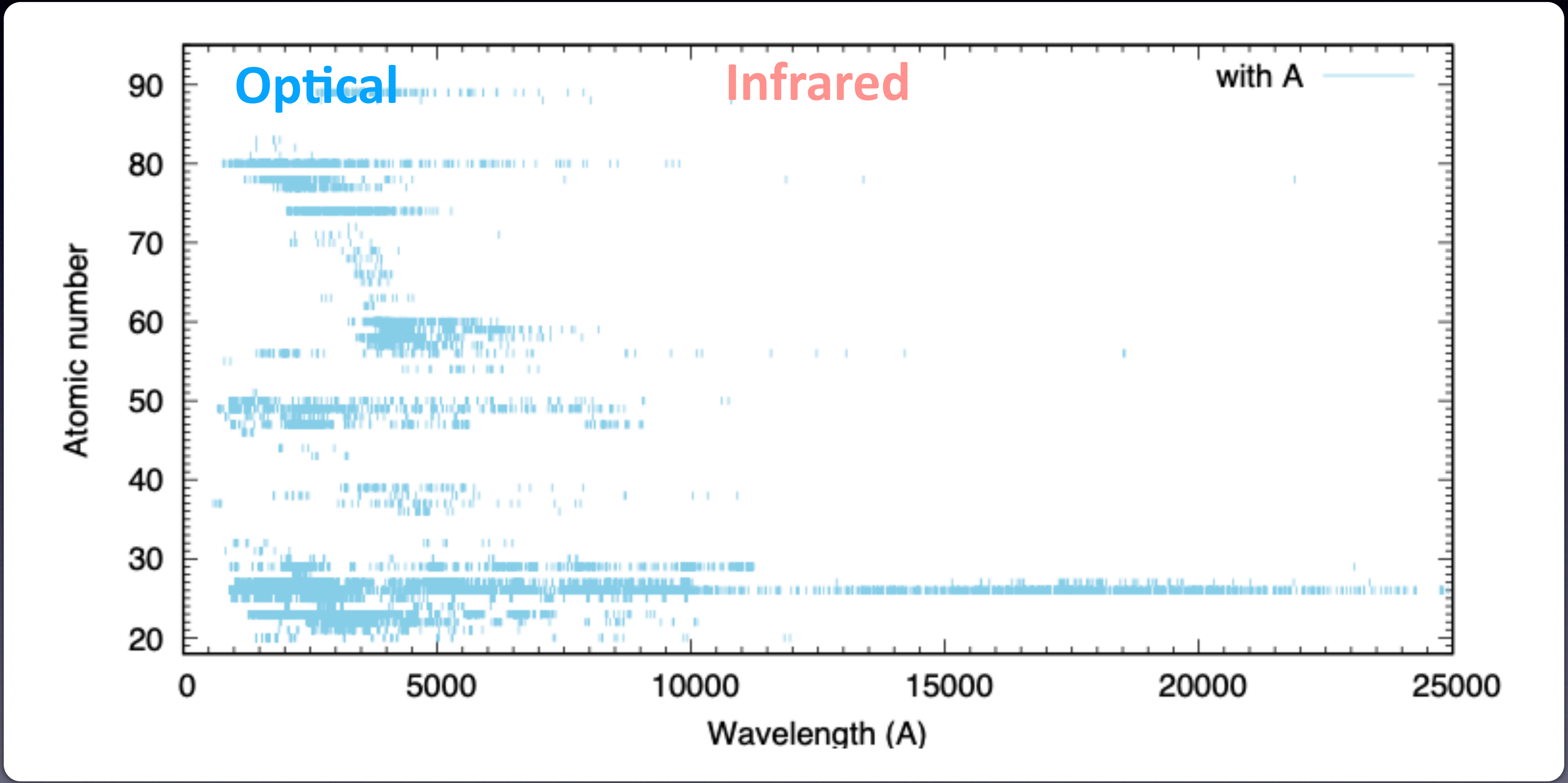


Need accurate atomic data for important transitions

Available atomic data

Data from the NIST database
(singly ionized)

Transitions with known transition probability

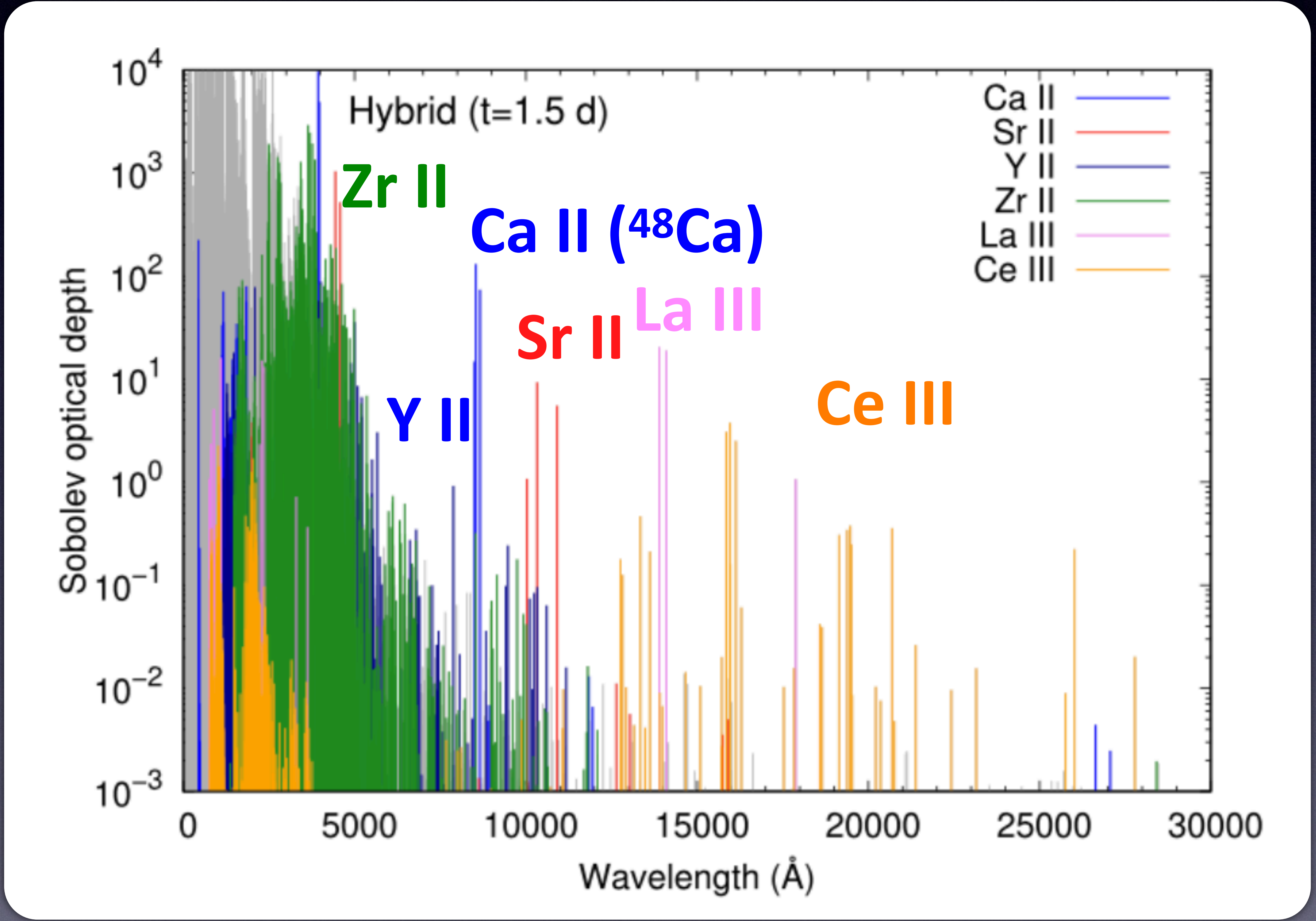


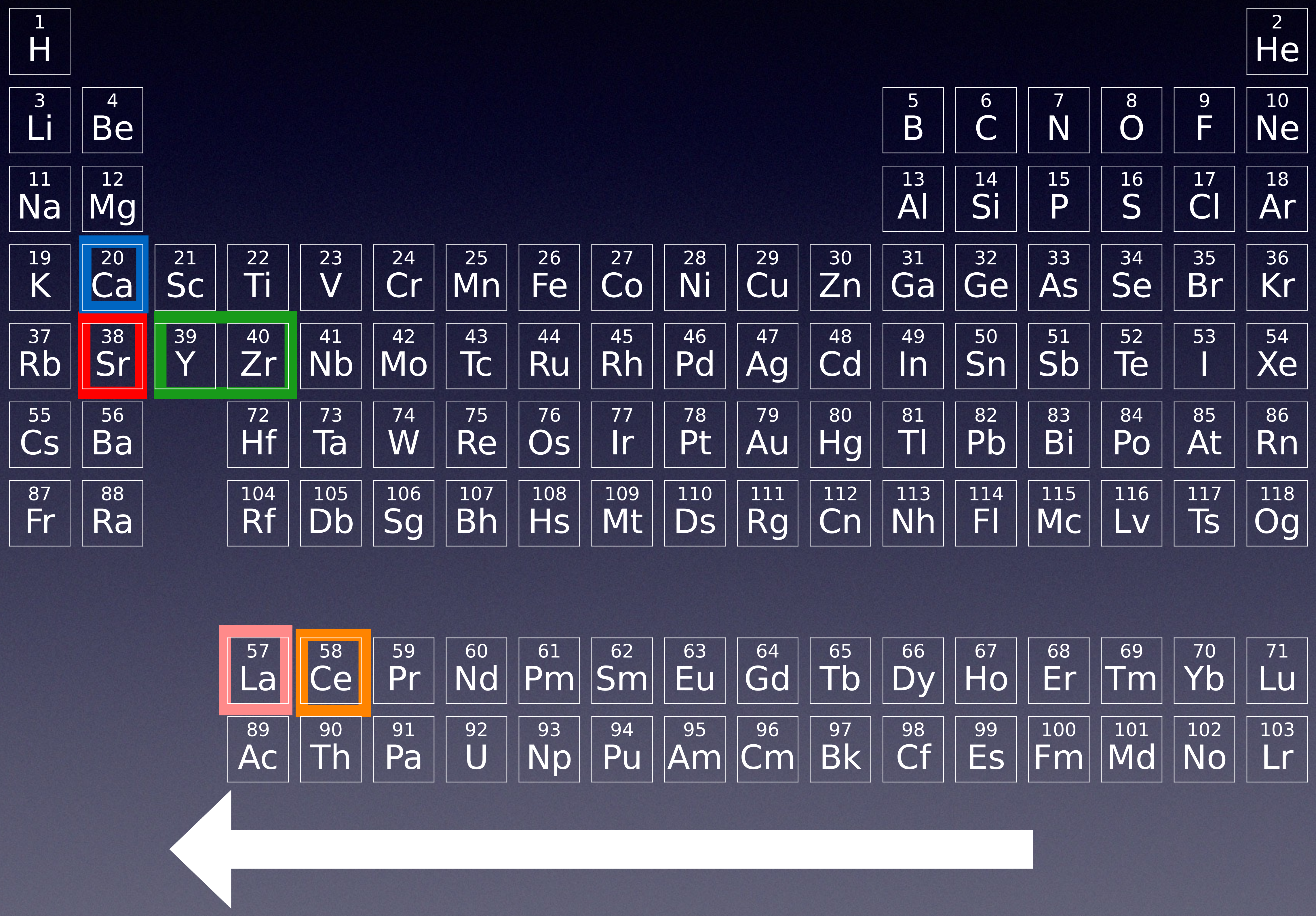
Accurate transition data are highly incomplete (in particular NIR)

Important element for spectral features

Talk by Nanae Domoto

Domoto, MT+22



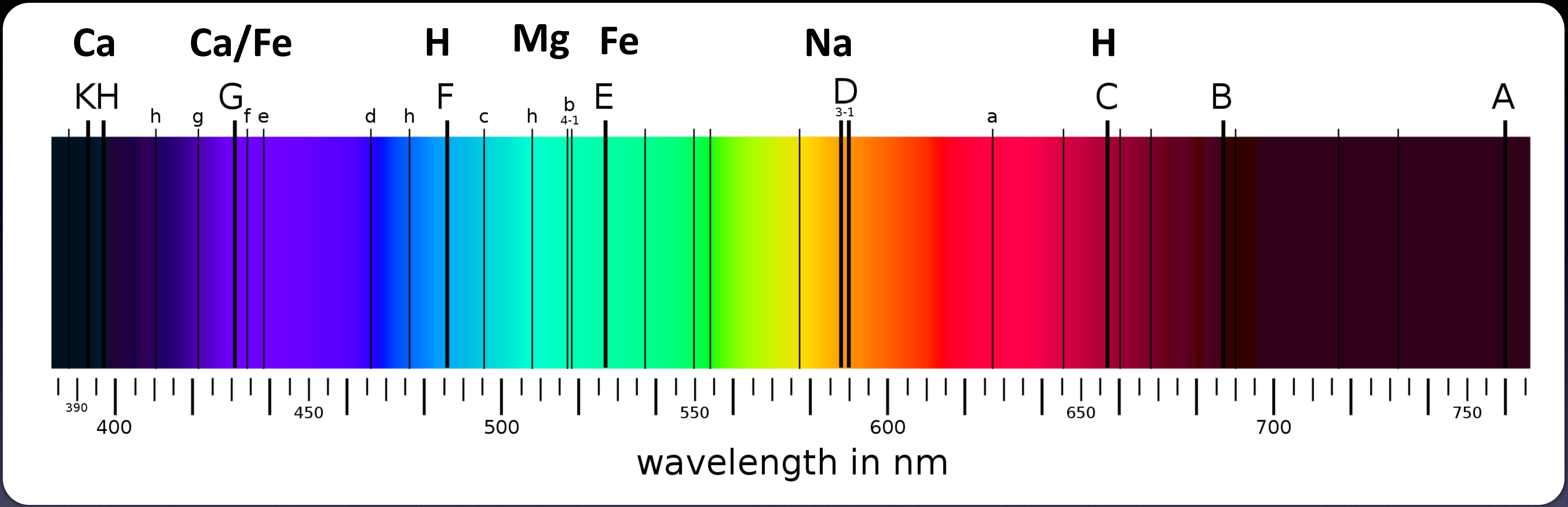


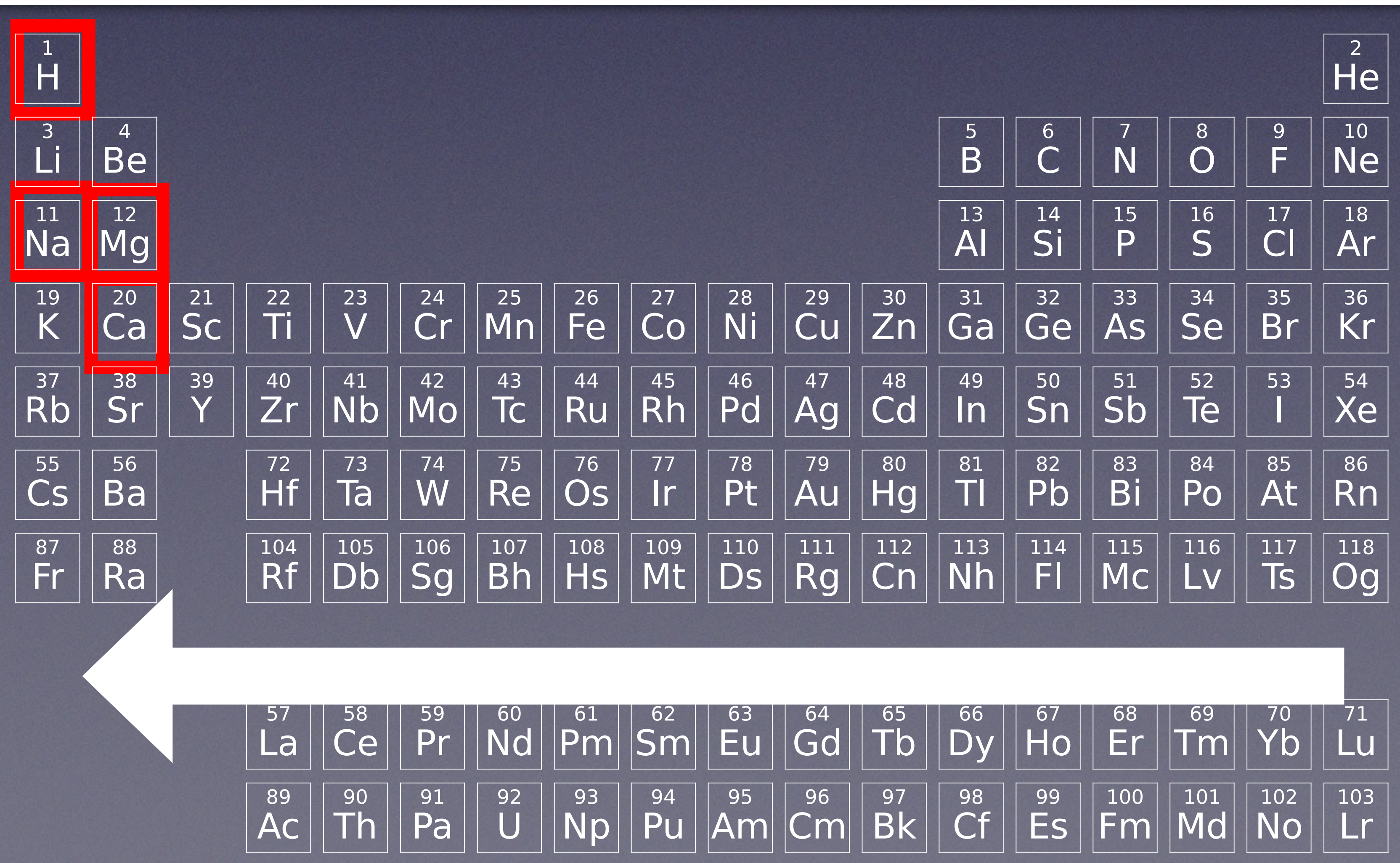
$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l \frac{g_k f_l}{\Sigma} e^{-E_k/kT}$$

Elements with (1) low-lying energy levels = higher population
(2) relatively simple structure
= small number of transitions = high transition probability

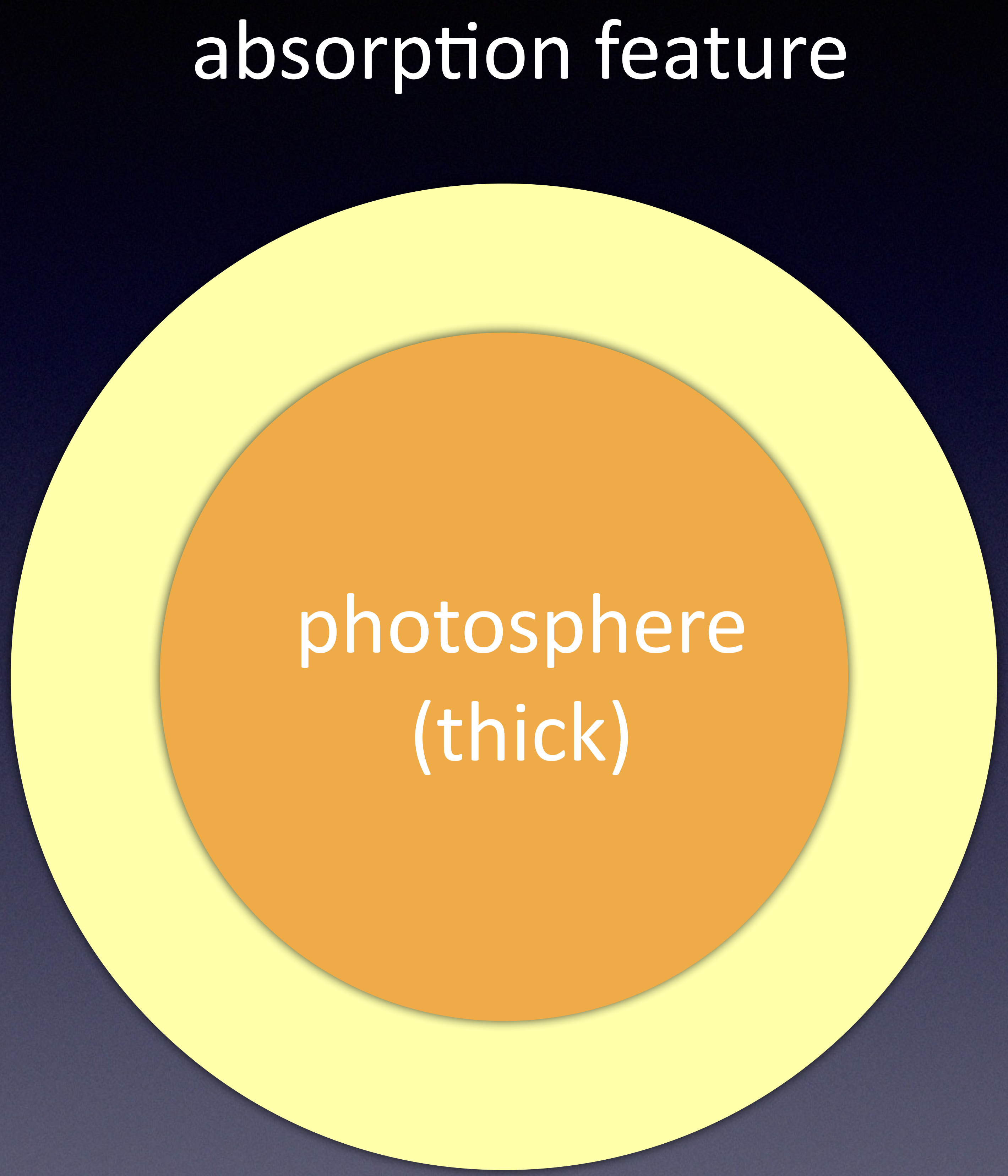
Solar spectrum

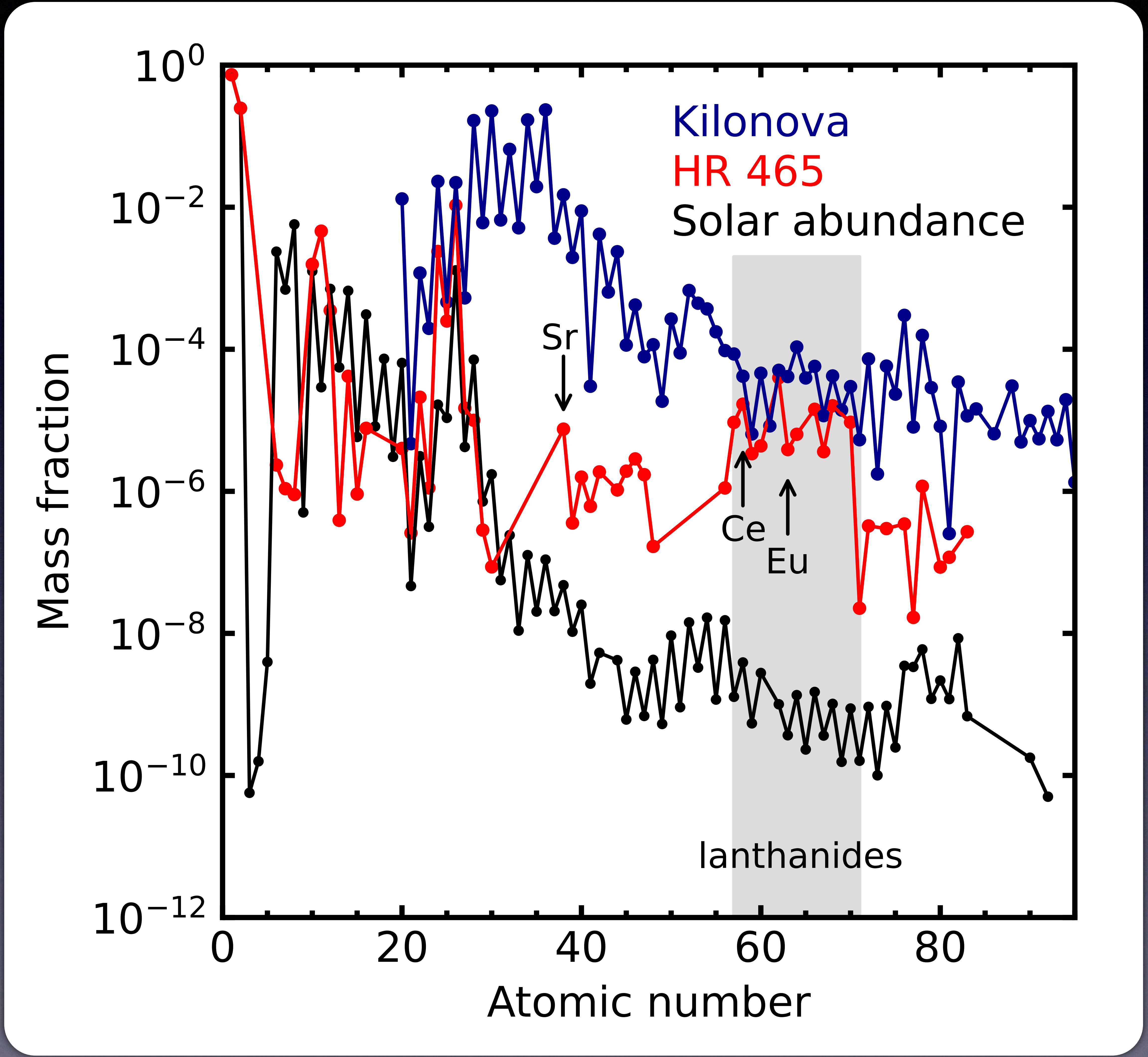
https://en.wikipedia.org/wiki/Fraunhofer_lines





“Spectroscopic experiments” with a chemically peculiar star





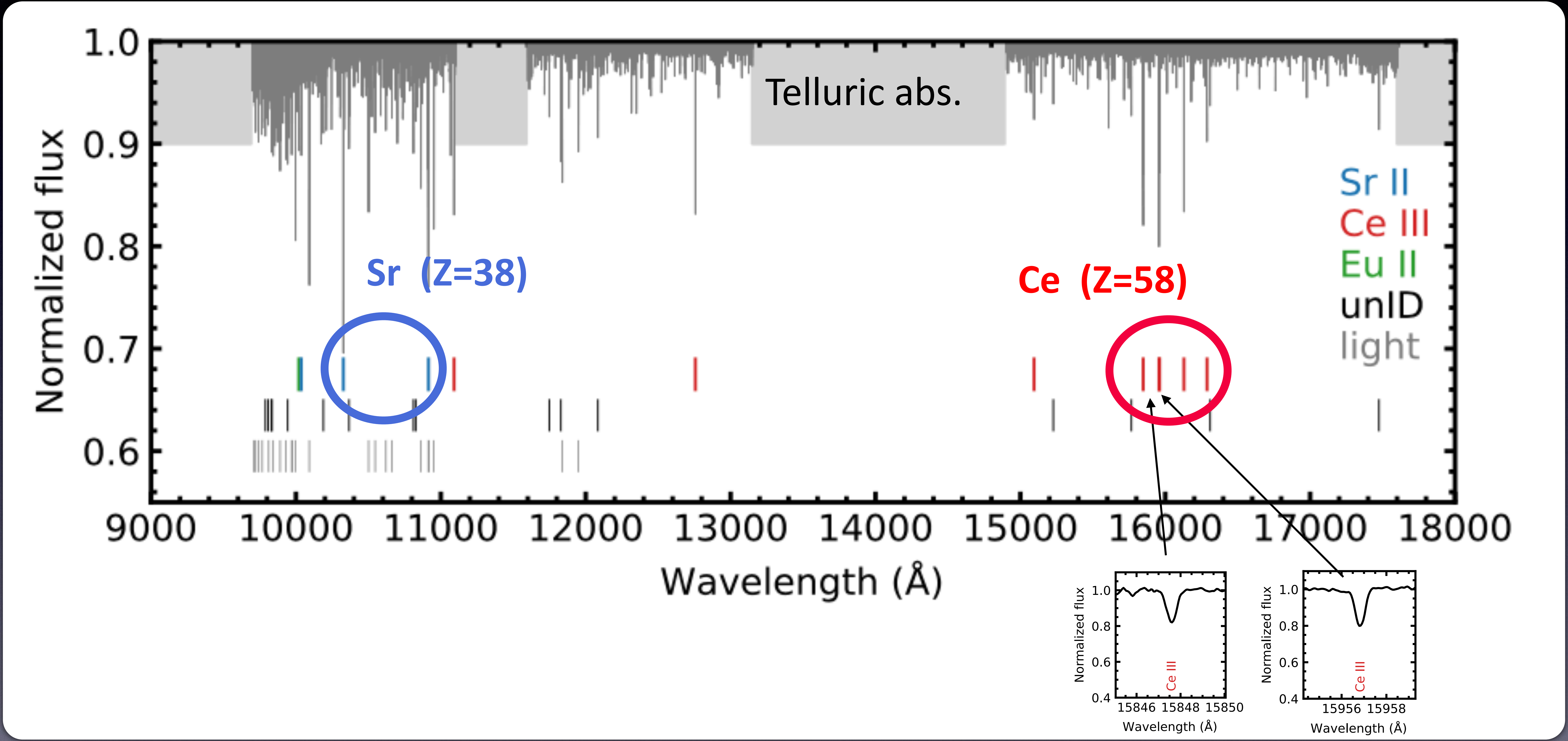
MT, Domoto, Aoki et al. 2023

Similar lanthanide abundances (and ionization degrees) with NS merger

NIR spectrum of chemically peculiar star

MT, Domoto, Aoki et al. 2023

Subaru/IRD (R ~ 70,000)

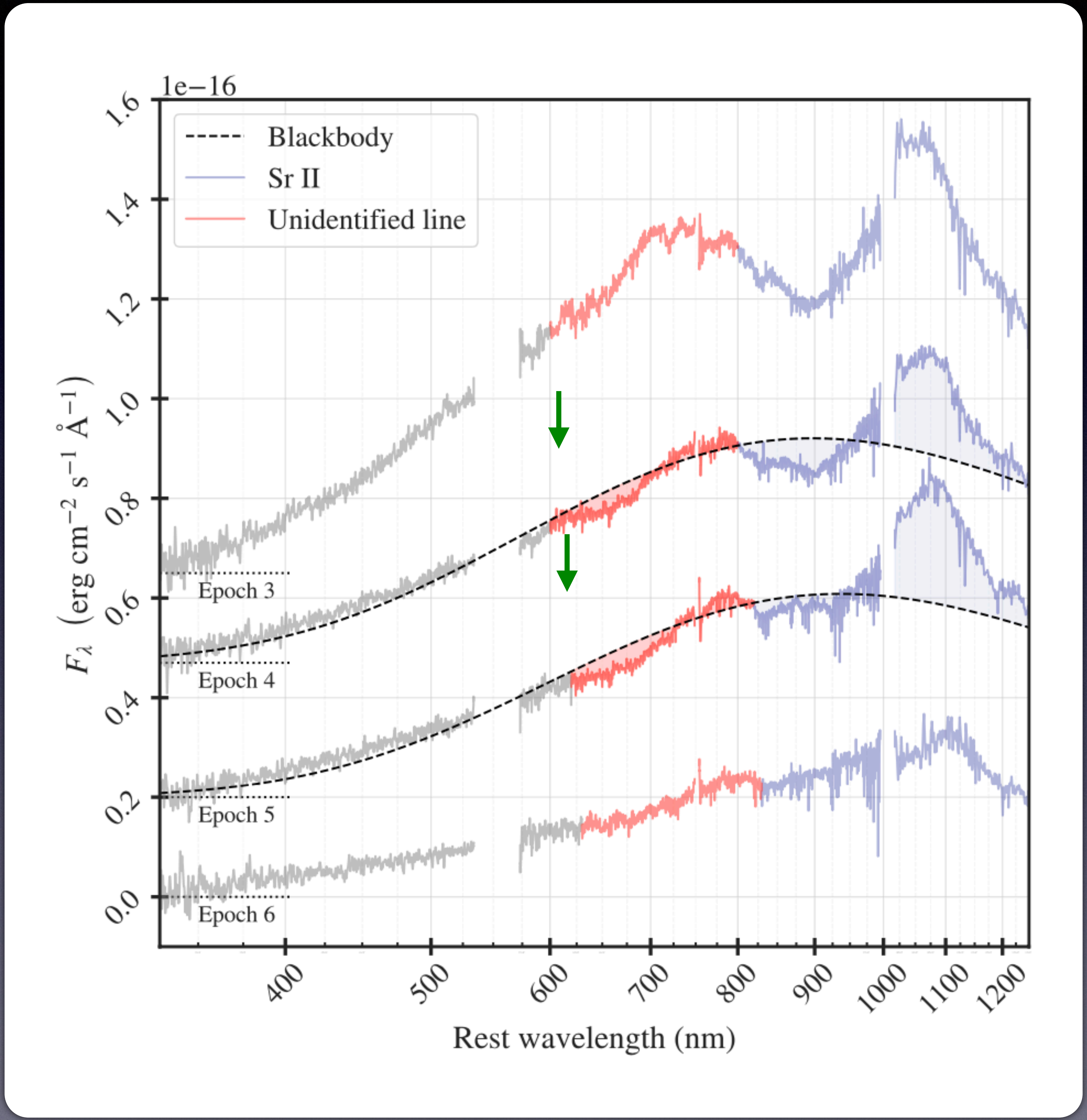


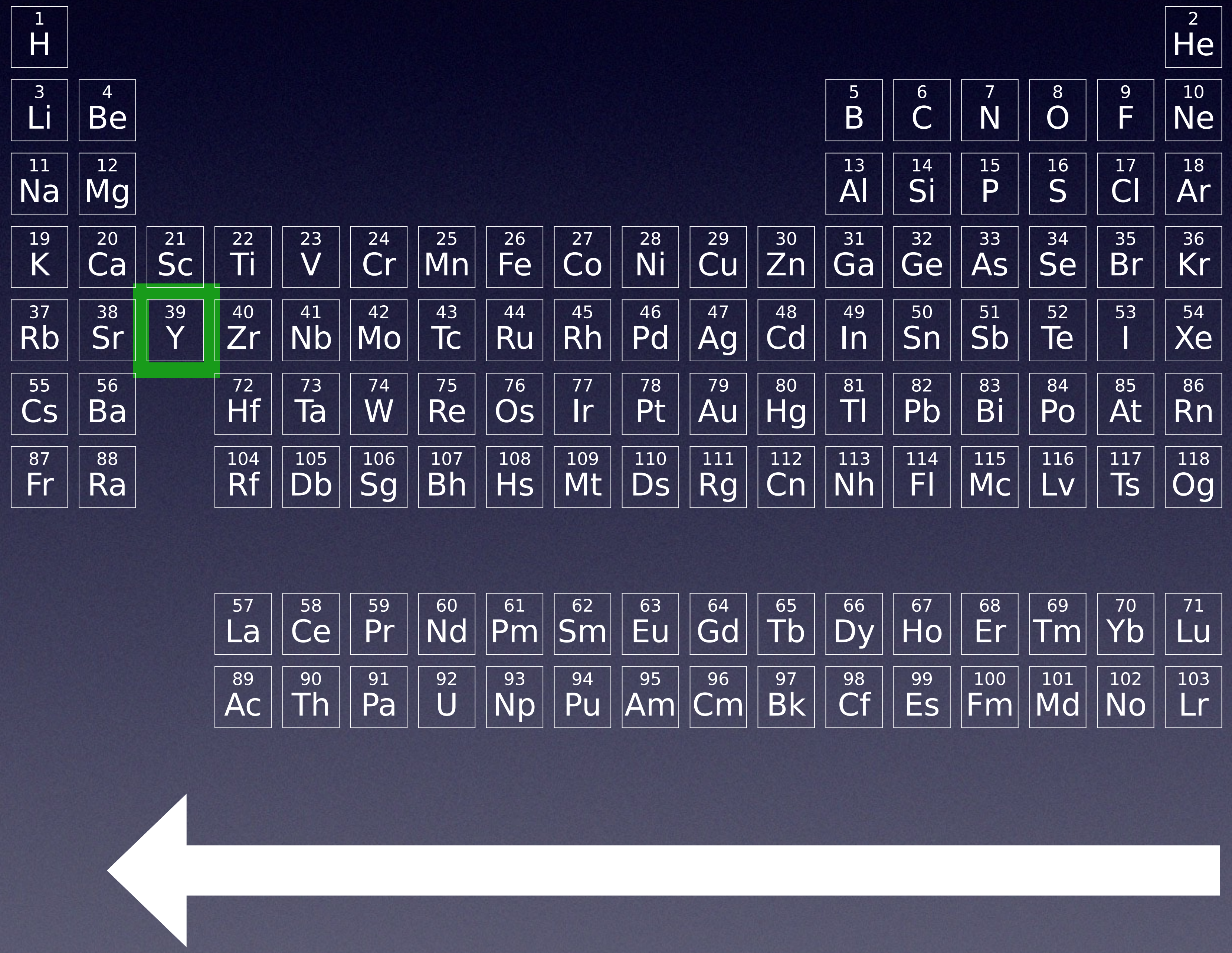
Strongest lines = Ce III and Sr II

No other comparably strong lines = uniqueness of the identification

Identification of Y II (Z=39)

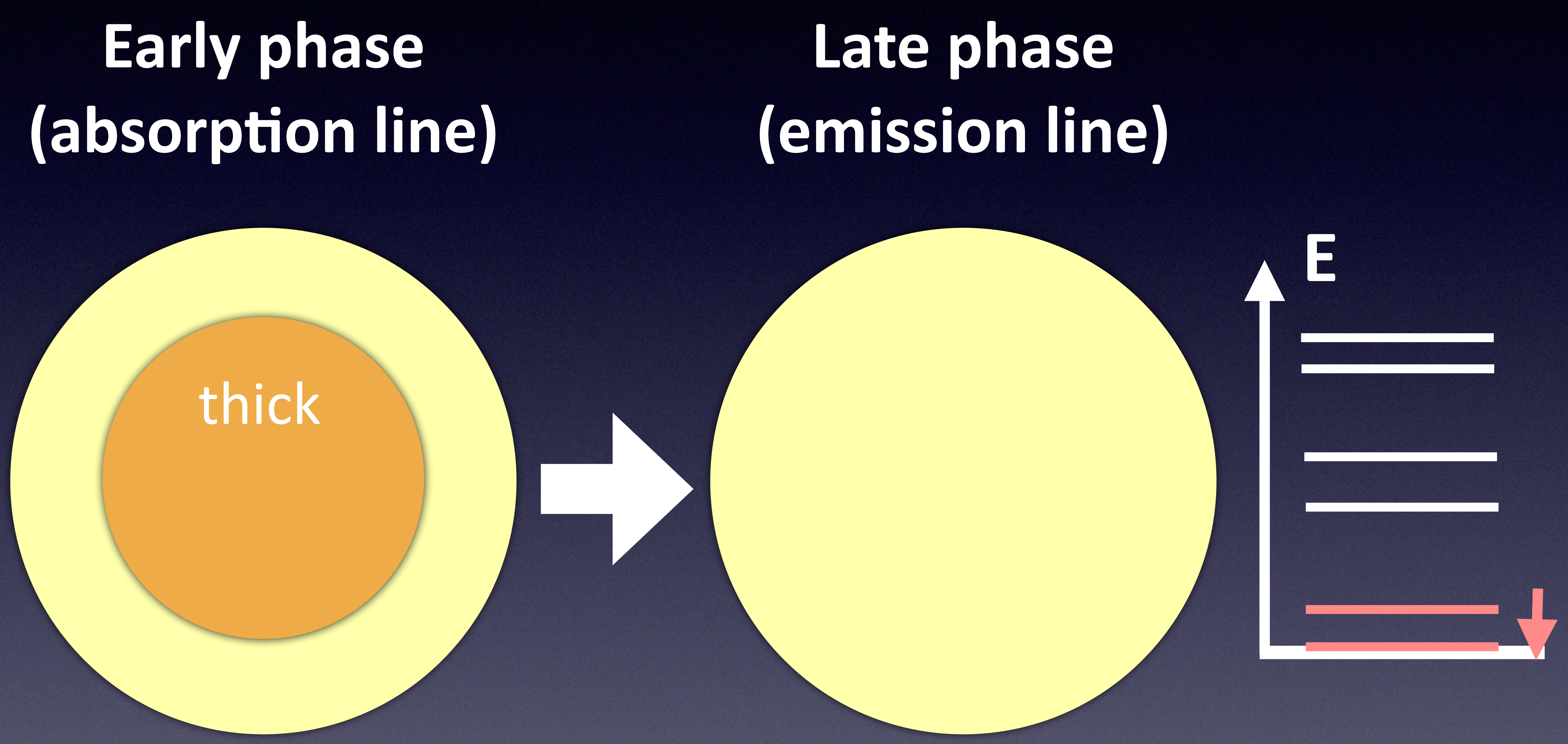
Sneppen & Watson 23

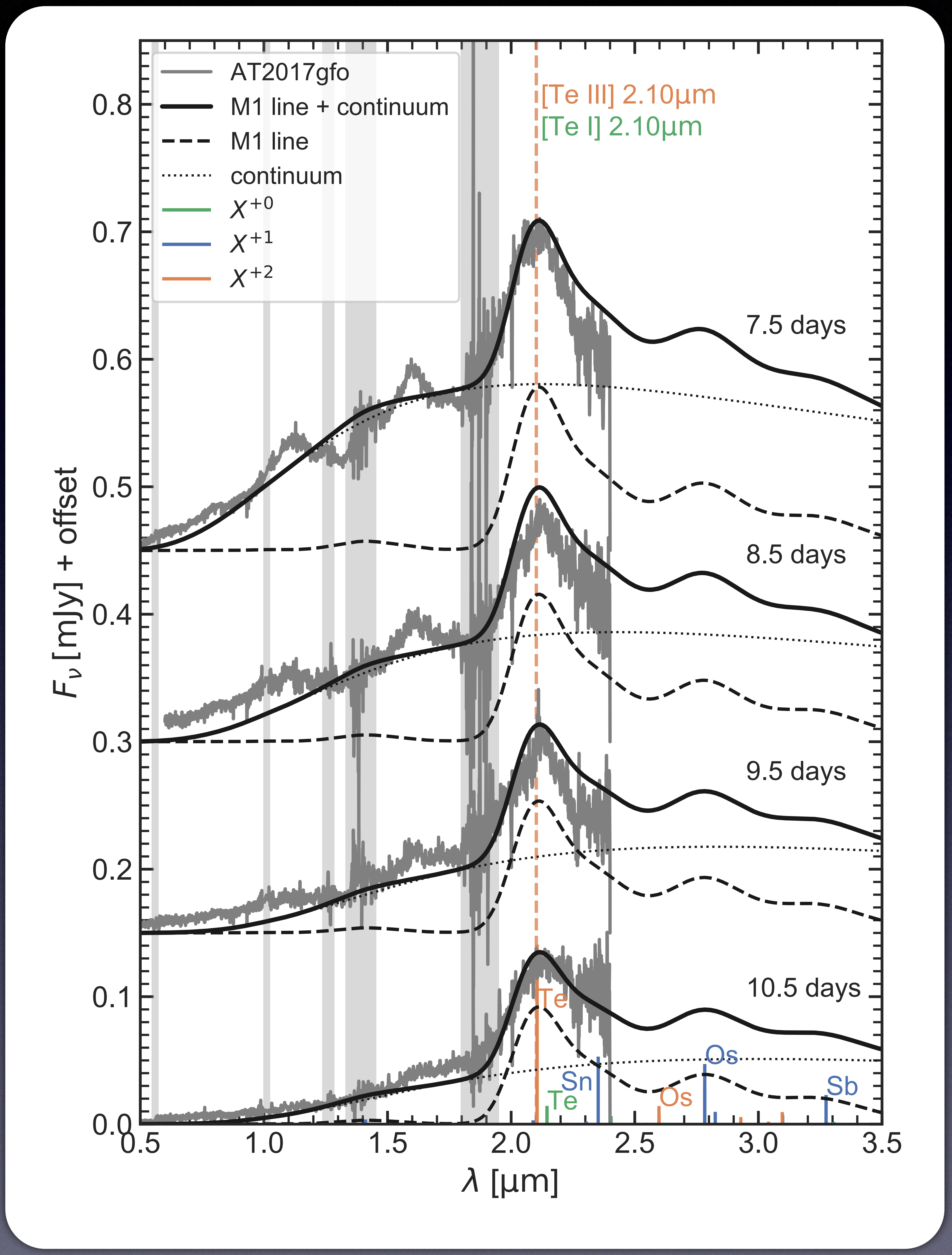




Emission line of Te III (Z=52) at late phase (inner ejecta)

Hotokezaka, MT+ 23





[Te III]: Fine structure lines
= more direct probe of high-abundance elements

Also in GRB 230307A (Levan+23, Gillanders+23)

"Direct" constraints on nucleosynthesis so far

Sr: Watson+19, Sr, Ca: Domoto+21, La, Ce: Domoto+22, Y: Sneppen+23, Te: Hotokezaka+23

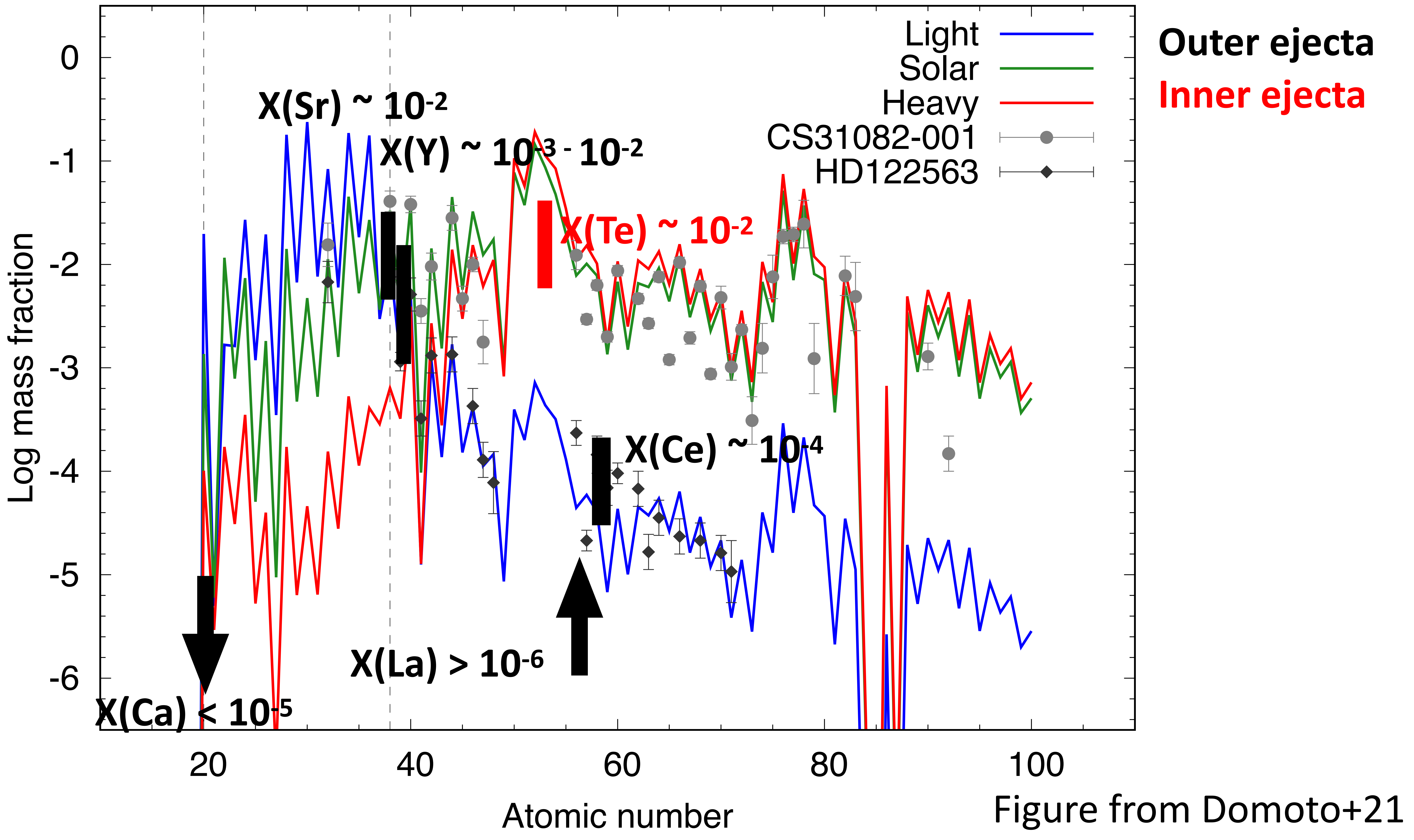
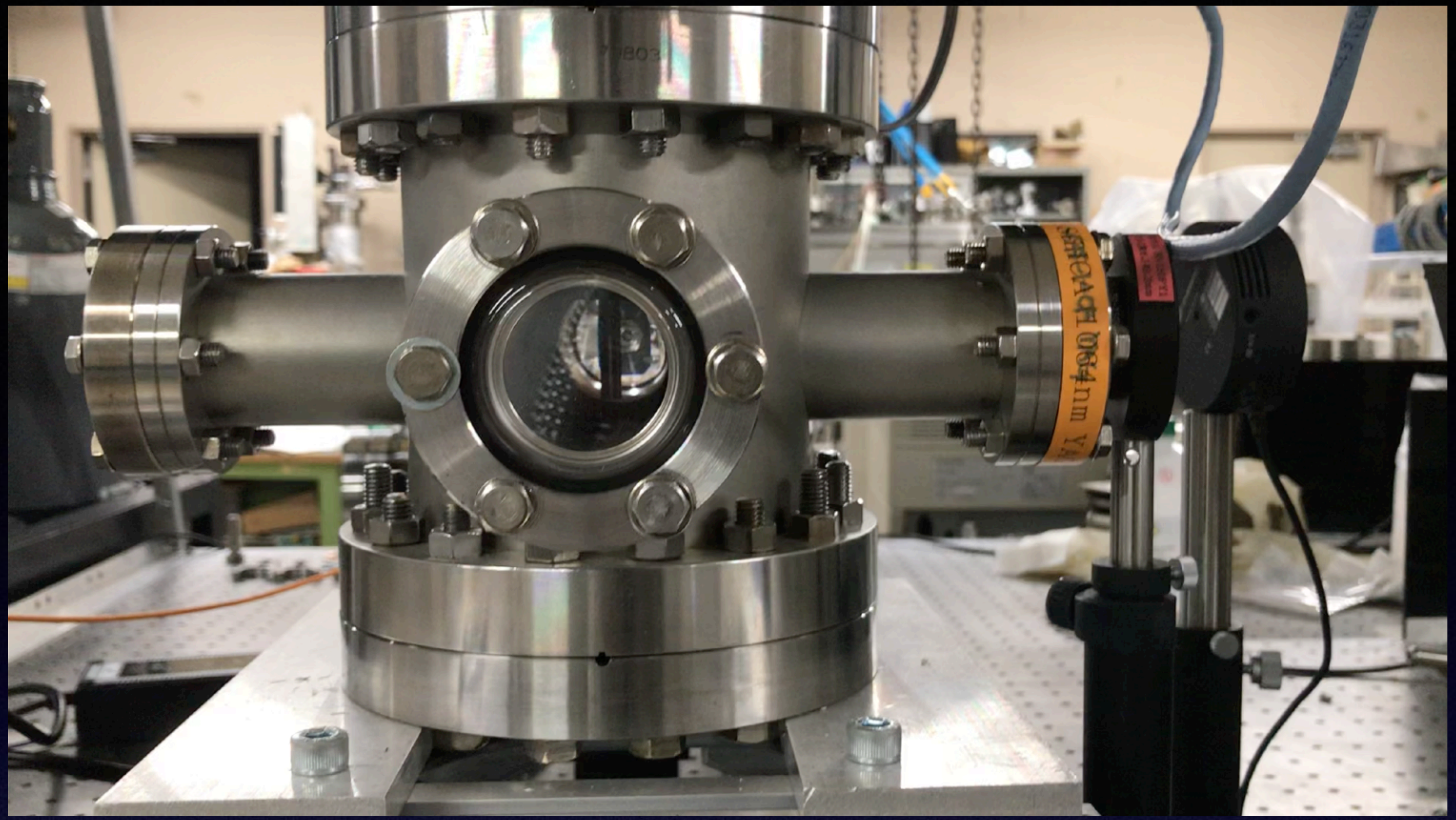


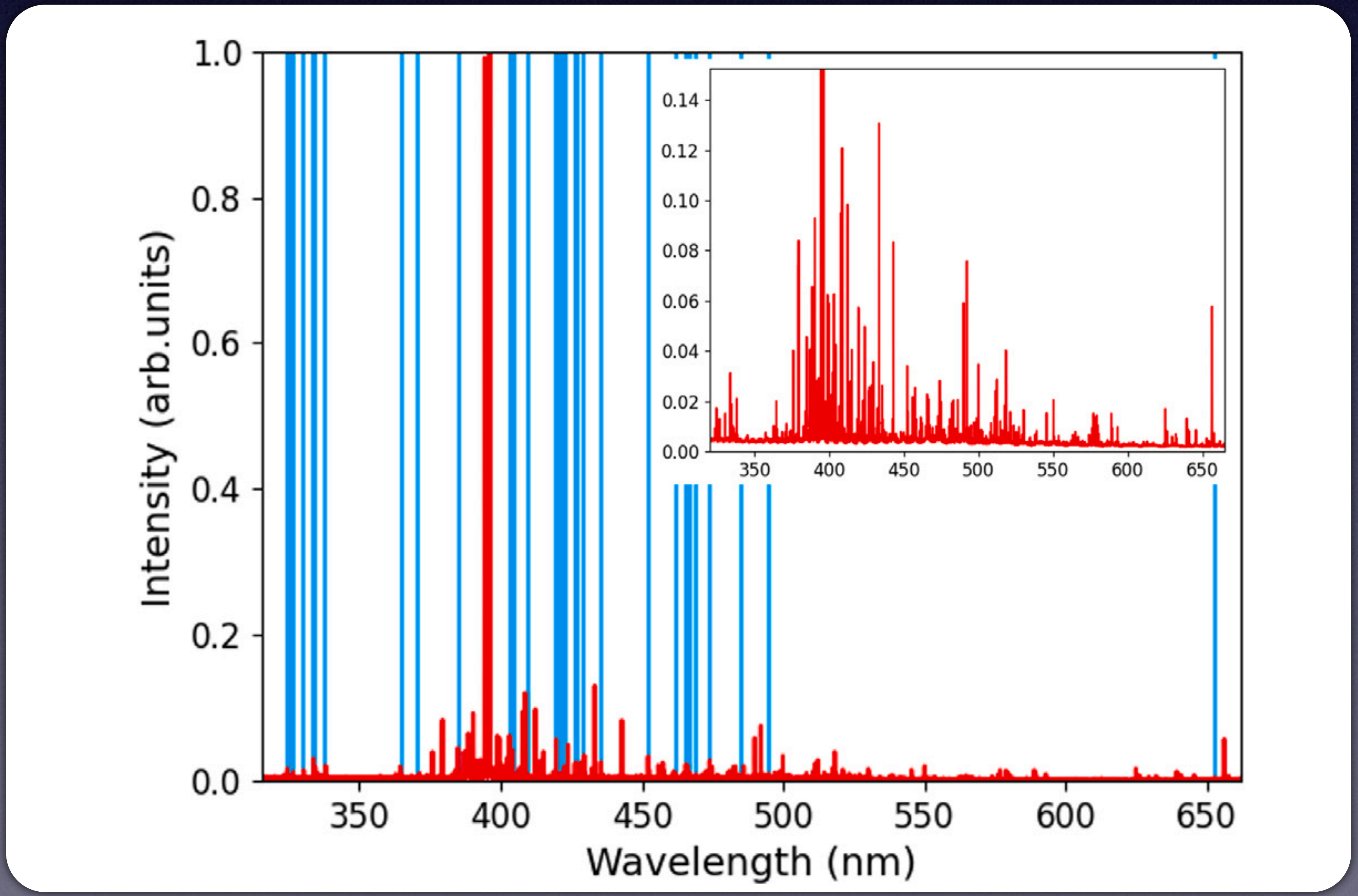
Figure from Domoto+21

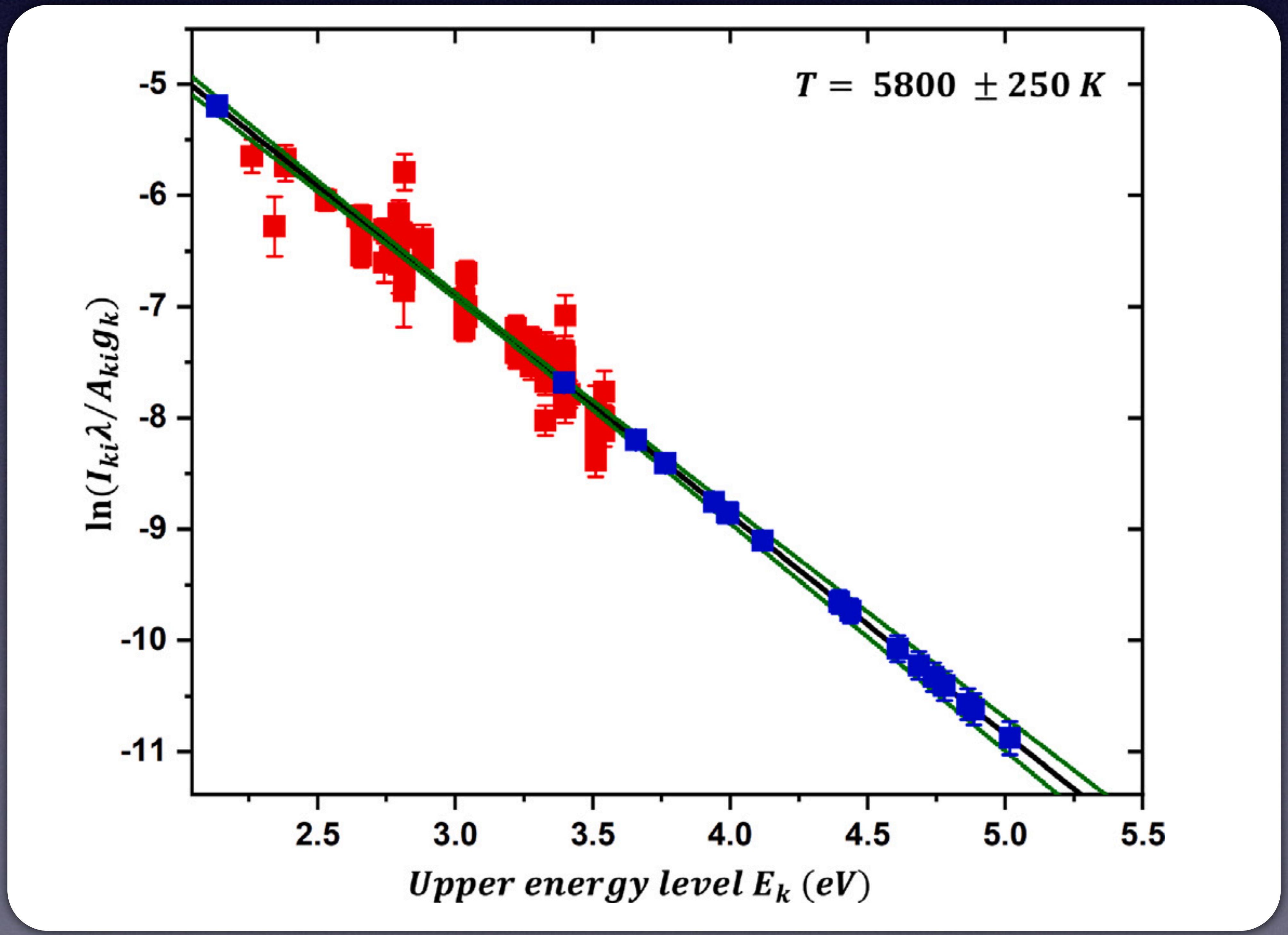
Spectroscopic experiments

Laser induced breakdown spectroscopy
(R ~ 10,000 in optical) at UEC
led by Nobuyuki Nakamura



Kodangil, Domoto, MT+2024





Summary

- **Kilonova light curves**
  - Systematic opacity data are now available
    => Ready for light curve modeling
  - Assessment of accuracy in progress (uncertainty by a factor of ~3)
  - **Future: "end-to-end" simulations, non-thermal effects, …**
- **Kilonova spectra**
  - Several elements have been directly identified:
    Absorption: Sr (Z=38), Y (Z=39), La (Z=57), Ce (Z=58), and Gd (Z=64)
    Emission: Te (Z=52),
  - Direct constraints on r-process nucleosynthesis
  - **Future: MIR features (JWST), late-phase emission lines, lab measurements, …**