Decoding light curves and spectra of kilonovae

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in collaboration with

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Decoding light curves and spectra of kilonovae

- (Very) brief overview
- Kilonova light curves
- Kilonova “photospheric” spectra

Neutron star mergers

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

Dynamical mass ejection

post-merger ejection

Optically think

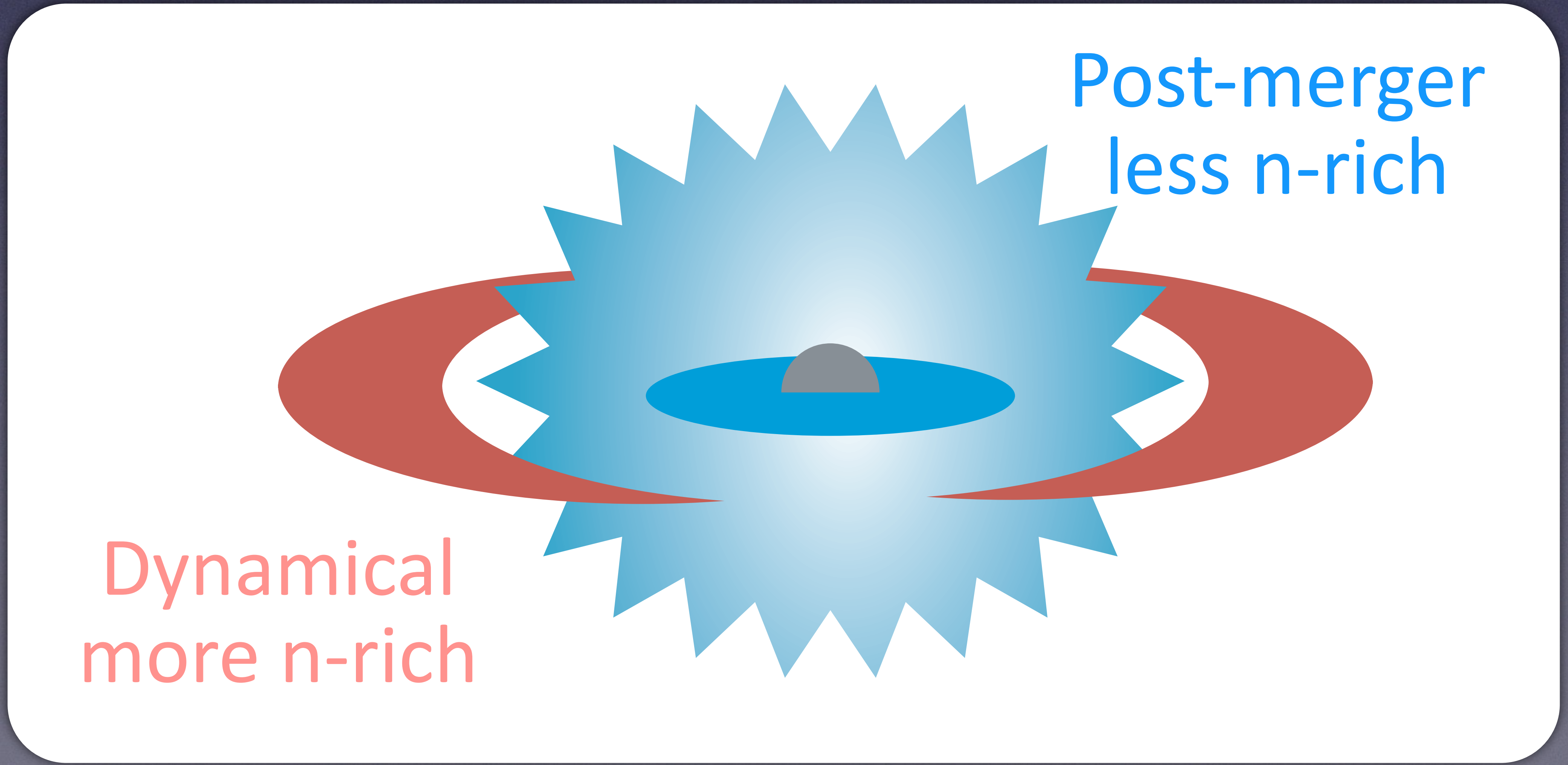
Optically thin

~< 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)

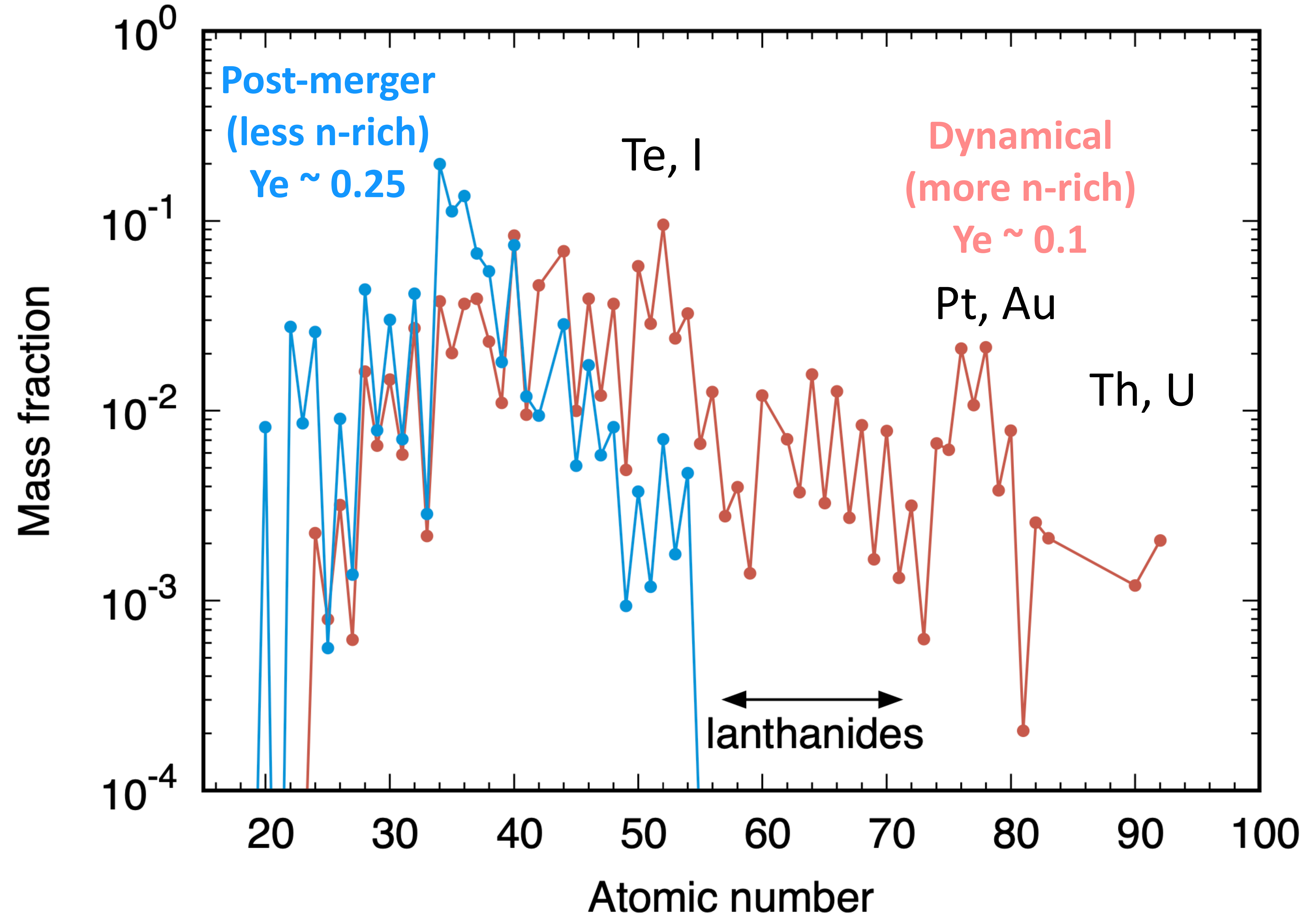
Ye **Density** **B field**

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, …

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

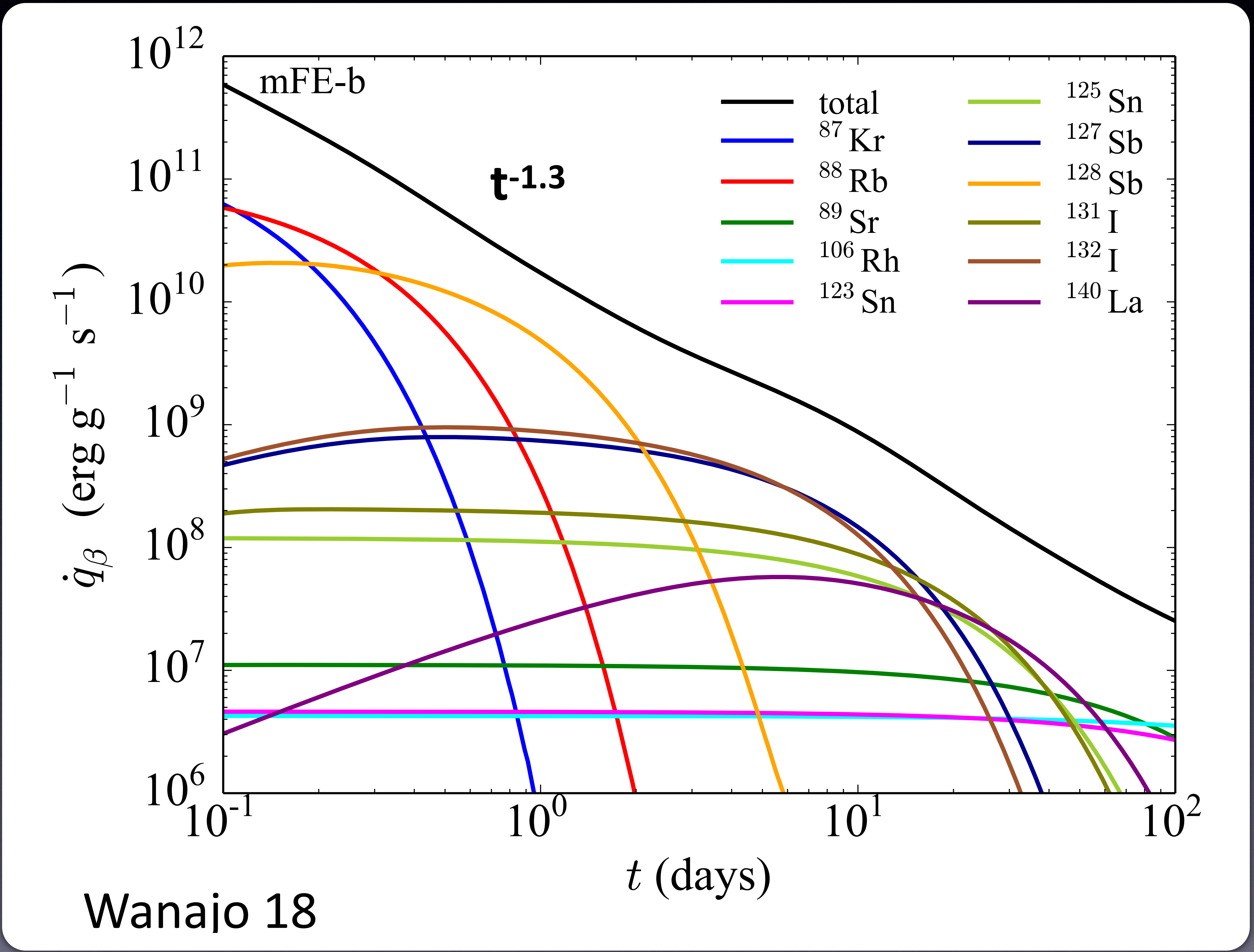


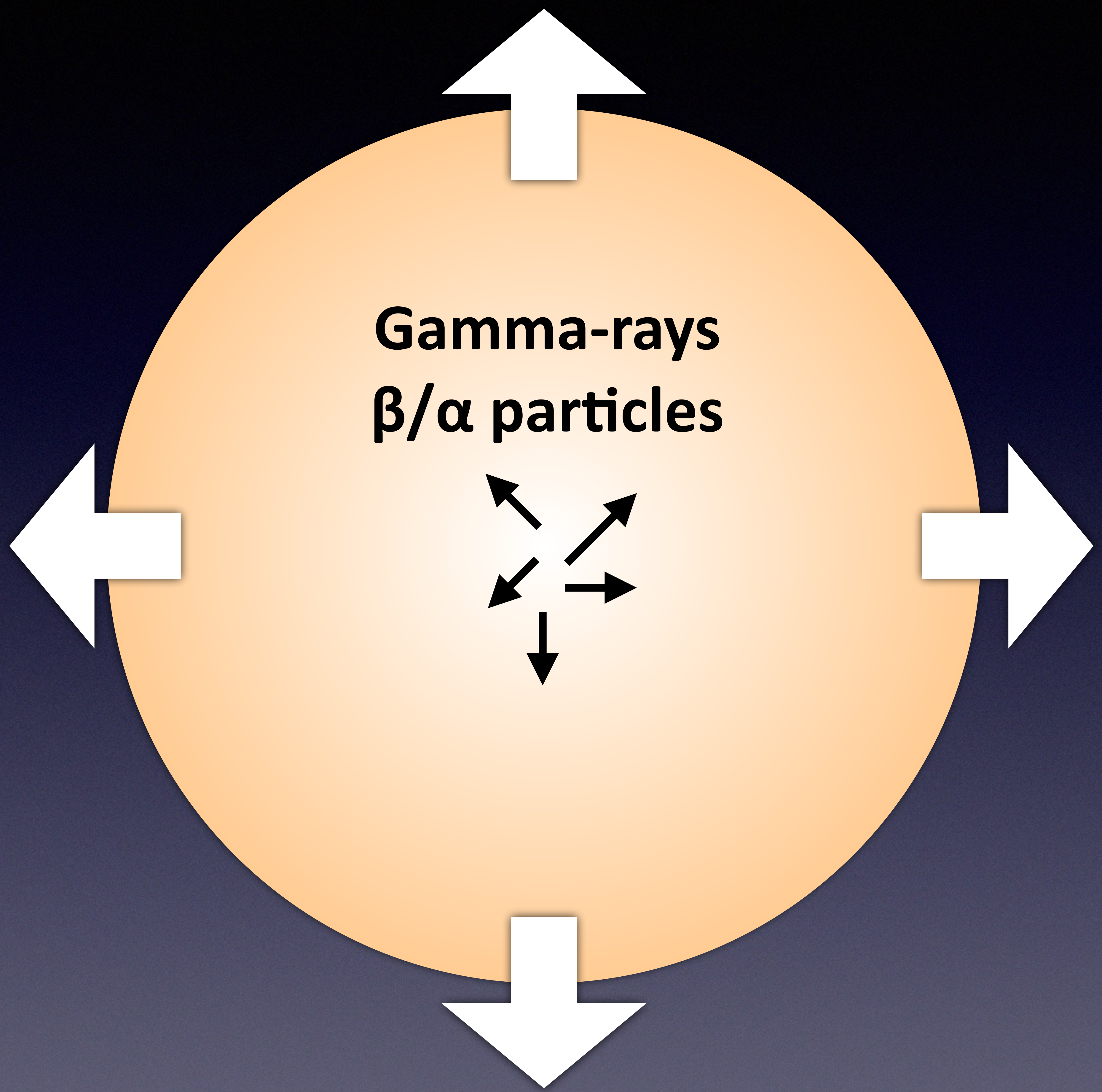
Fujibayashi+23

* mass fraction is normalized for each component

Radioactive heating

Metgzer+10, Lippuner+15, Wanajo18, …

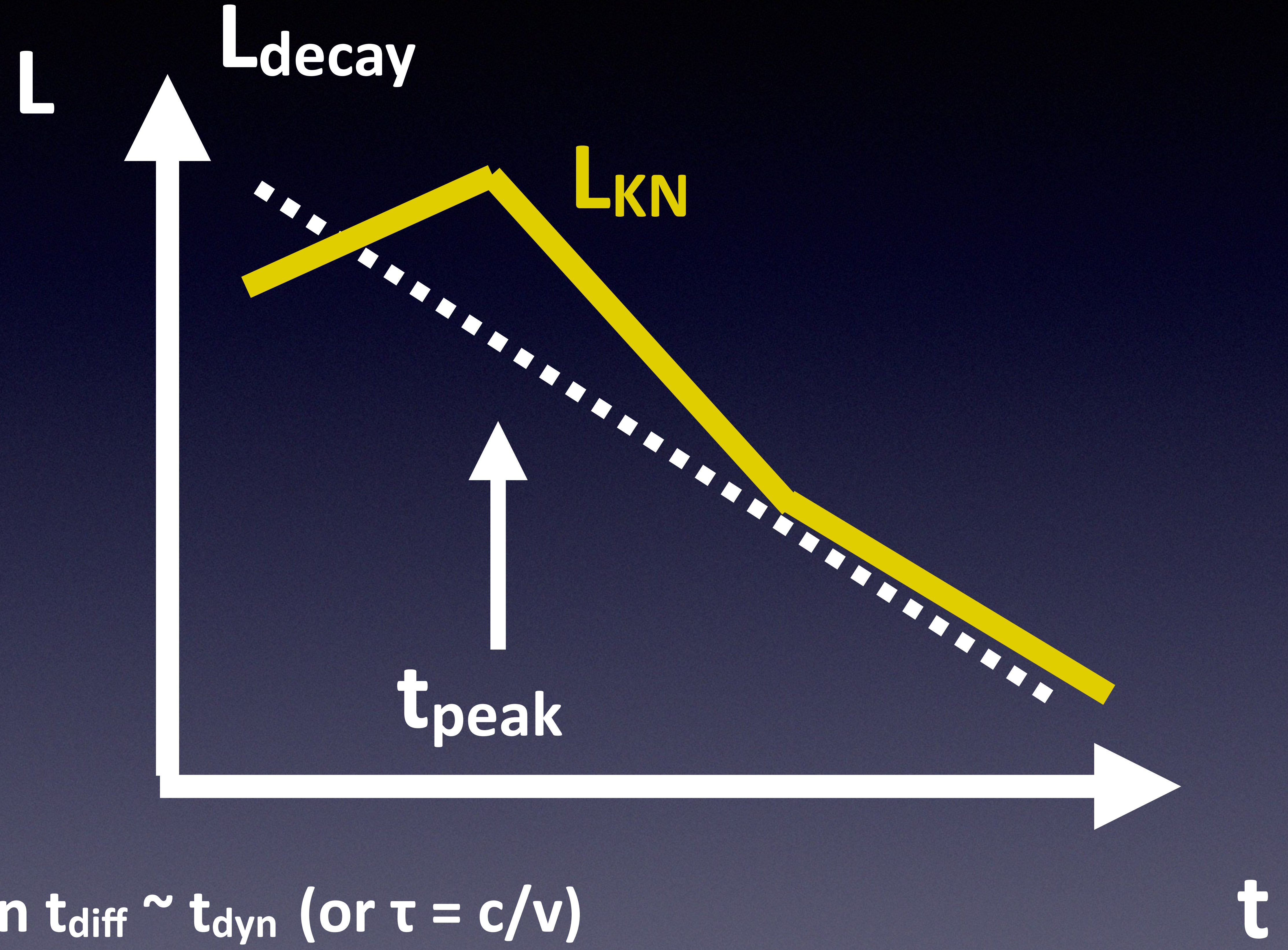




MeV particles are "stopped" => thermalization (energy deposition) e.g., Barnes+16

Thermal photon diffusion

Arnett 82, Li & Paczynski 98, Metgzer+10

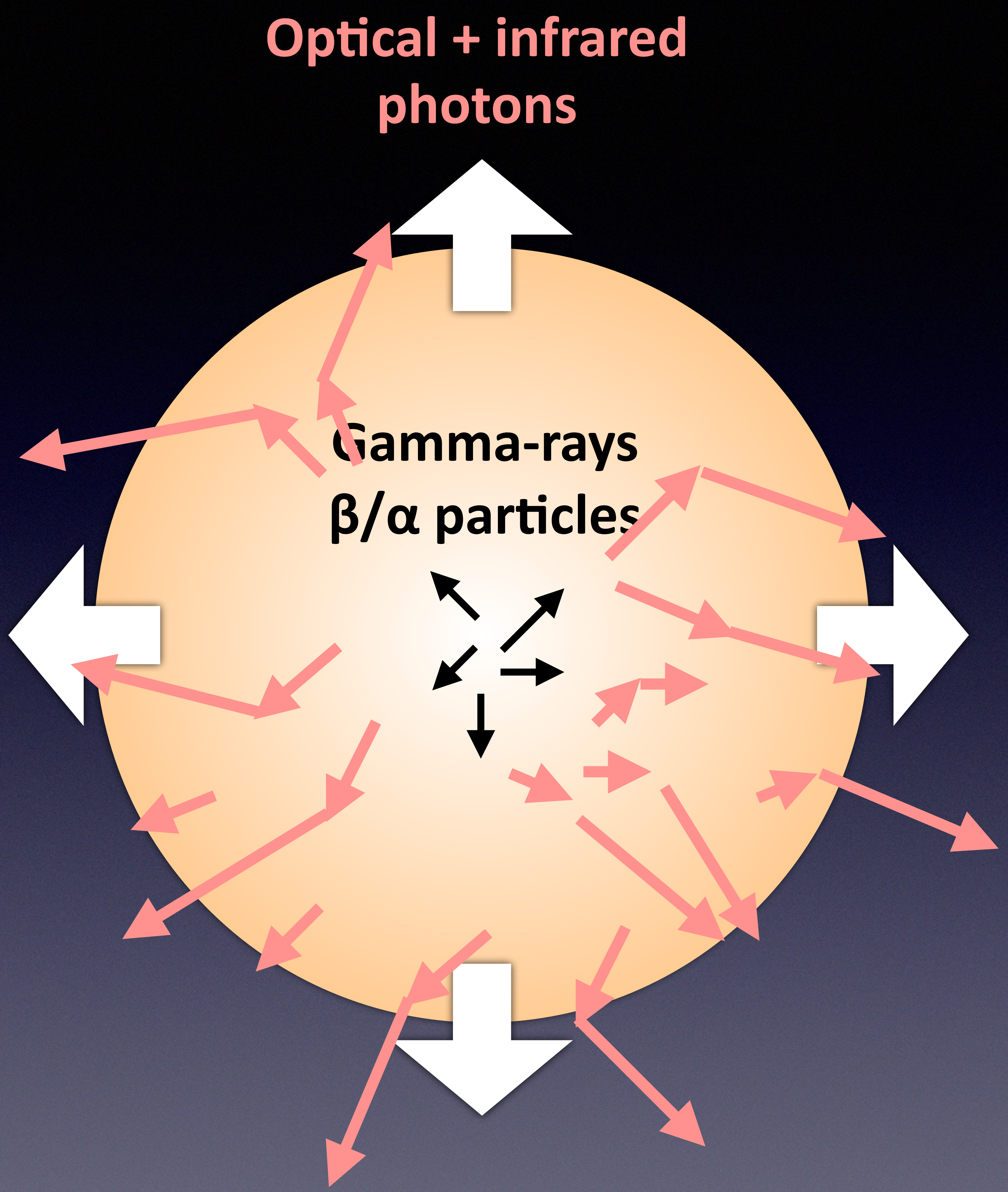


When $t_{diff} \sim t_{dyn}$ (or $\tau = c/v$)

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

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

Opacity (atomic properties)



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

What can we learn from observations of kilonova?

Light curves

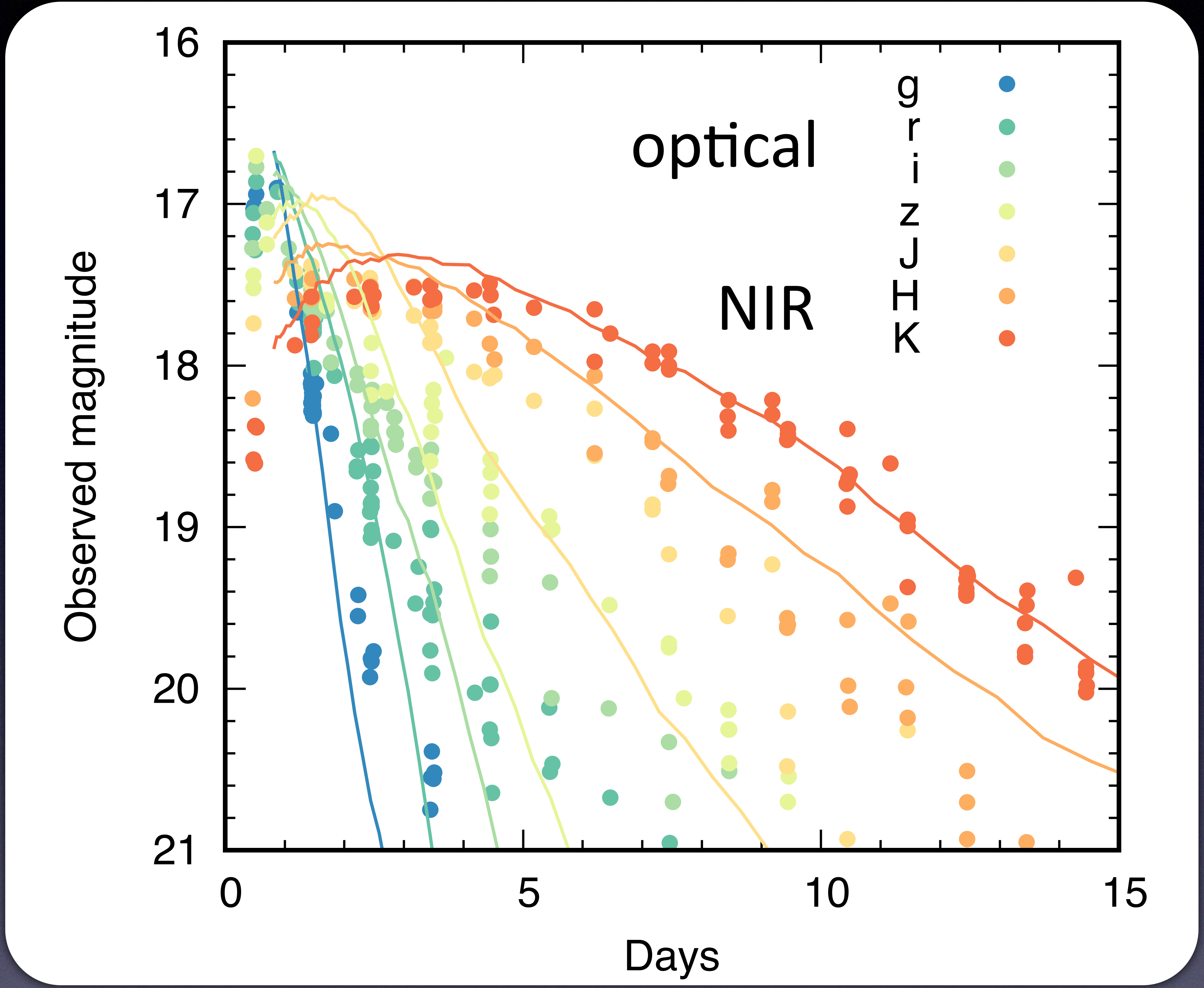


Figure from Kawaguchi+2018, 2020

Ejected mass and (rough) composition

Spectra

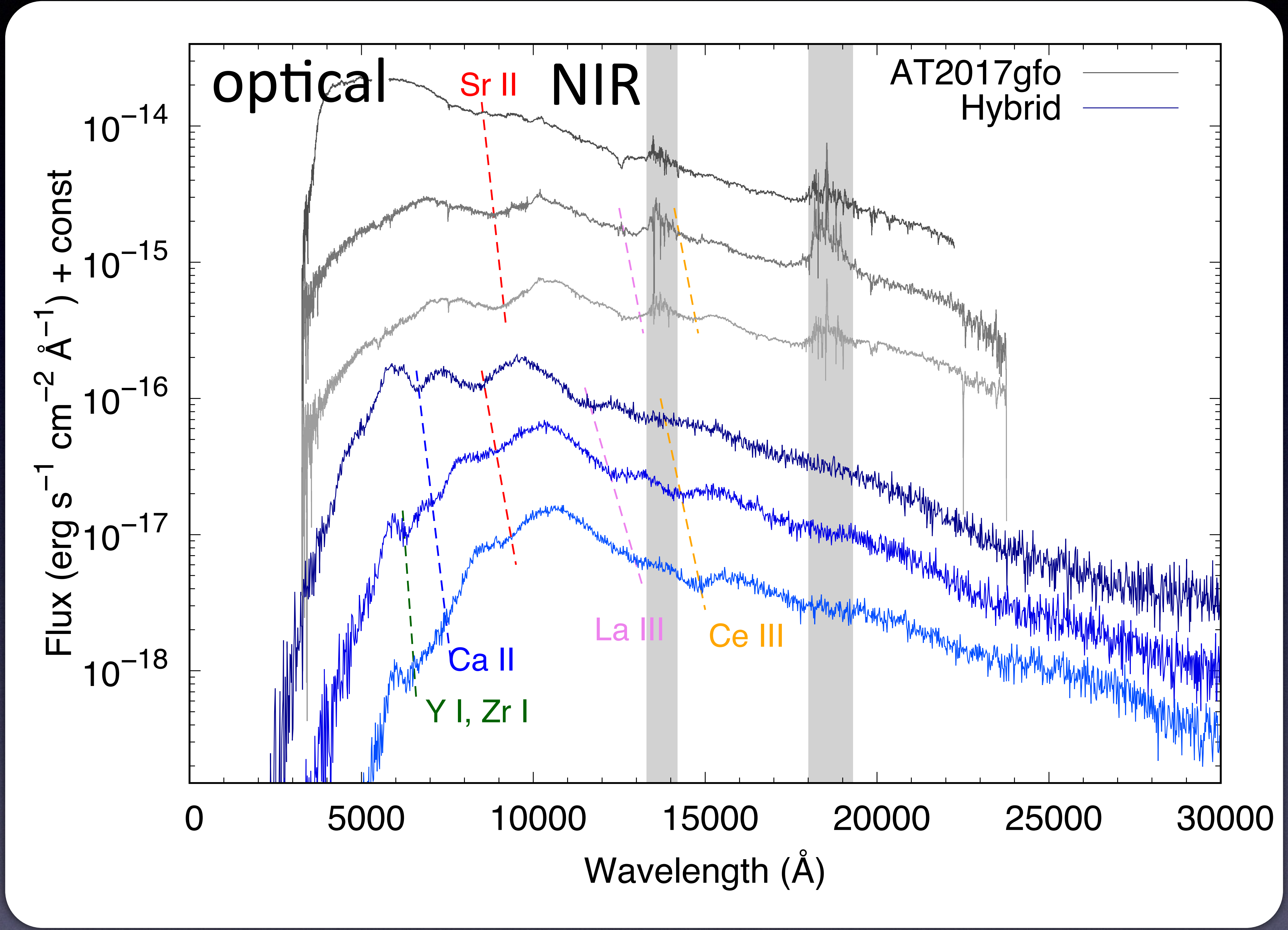


Figure from Domoto+2020,2022

Detailed elemental compositions

Origin of r-process elements

Physics of neutron star mergers

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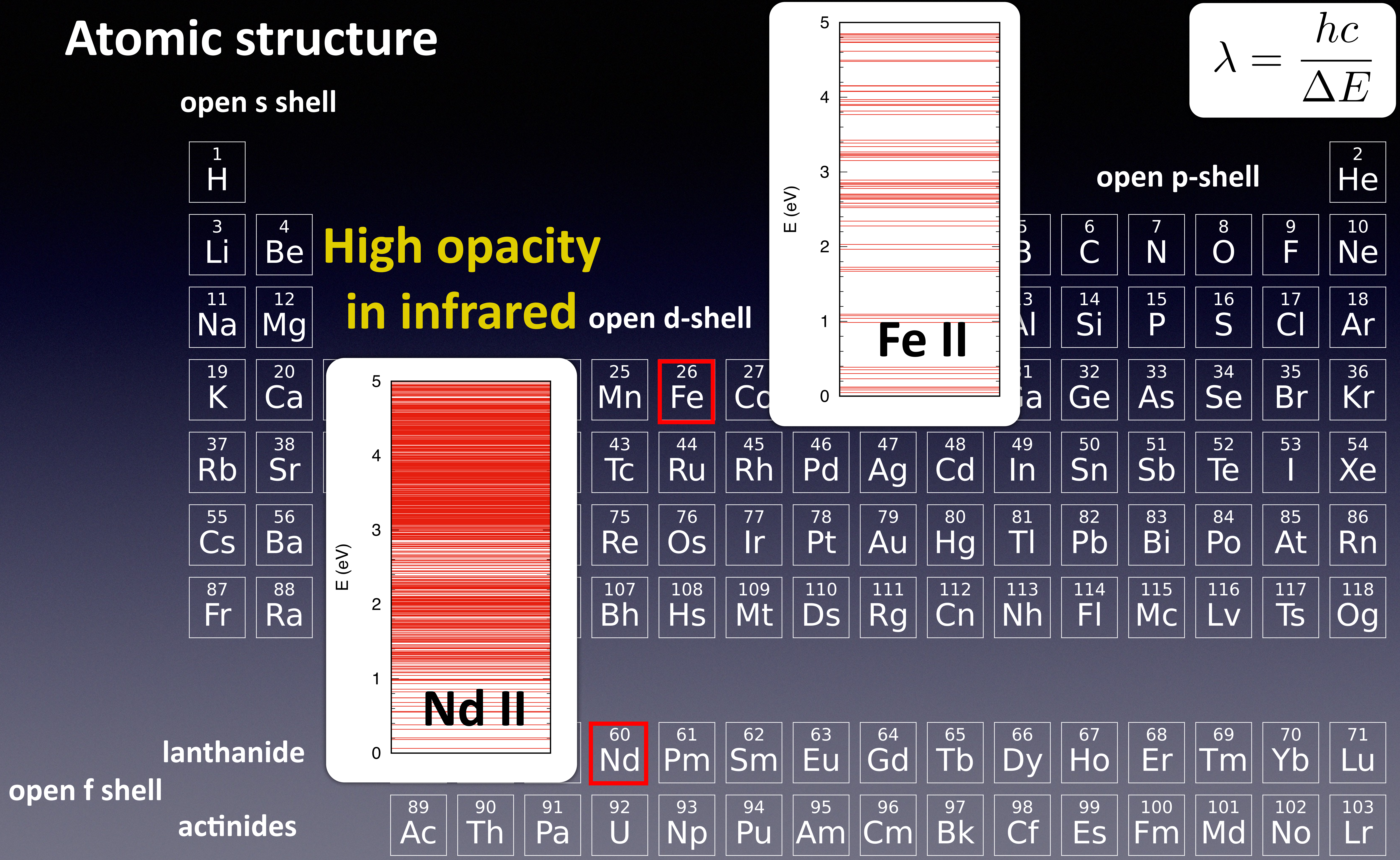
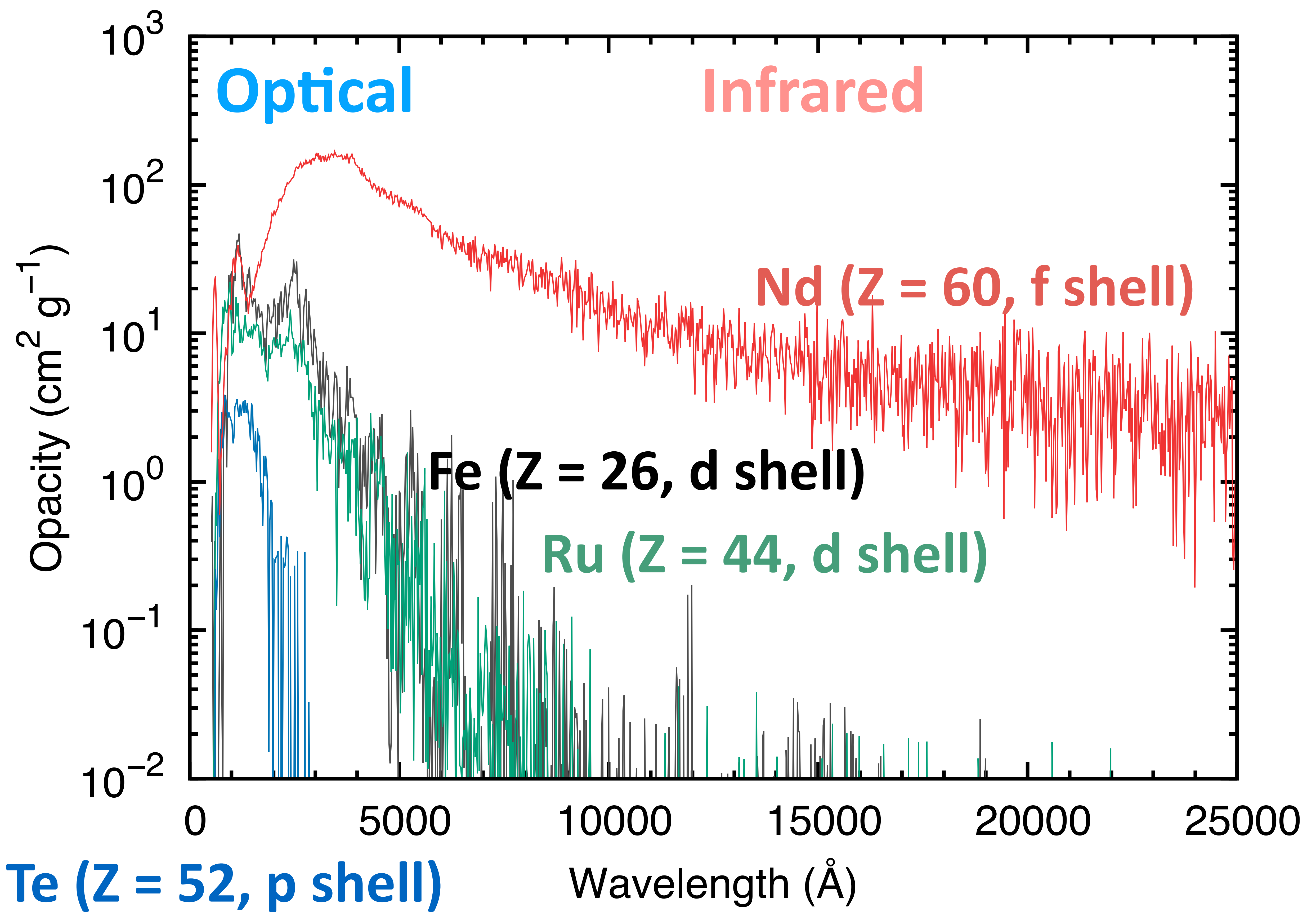
Atomic structure

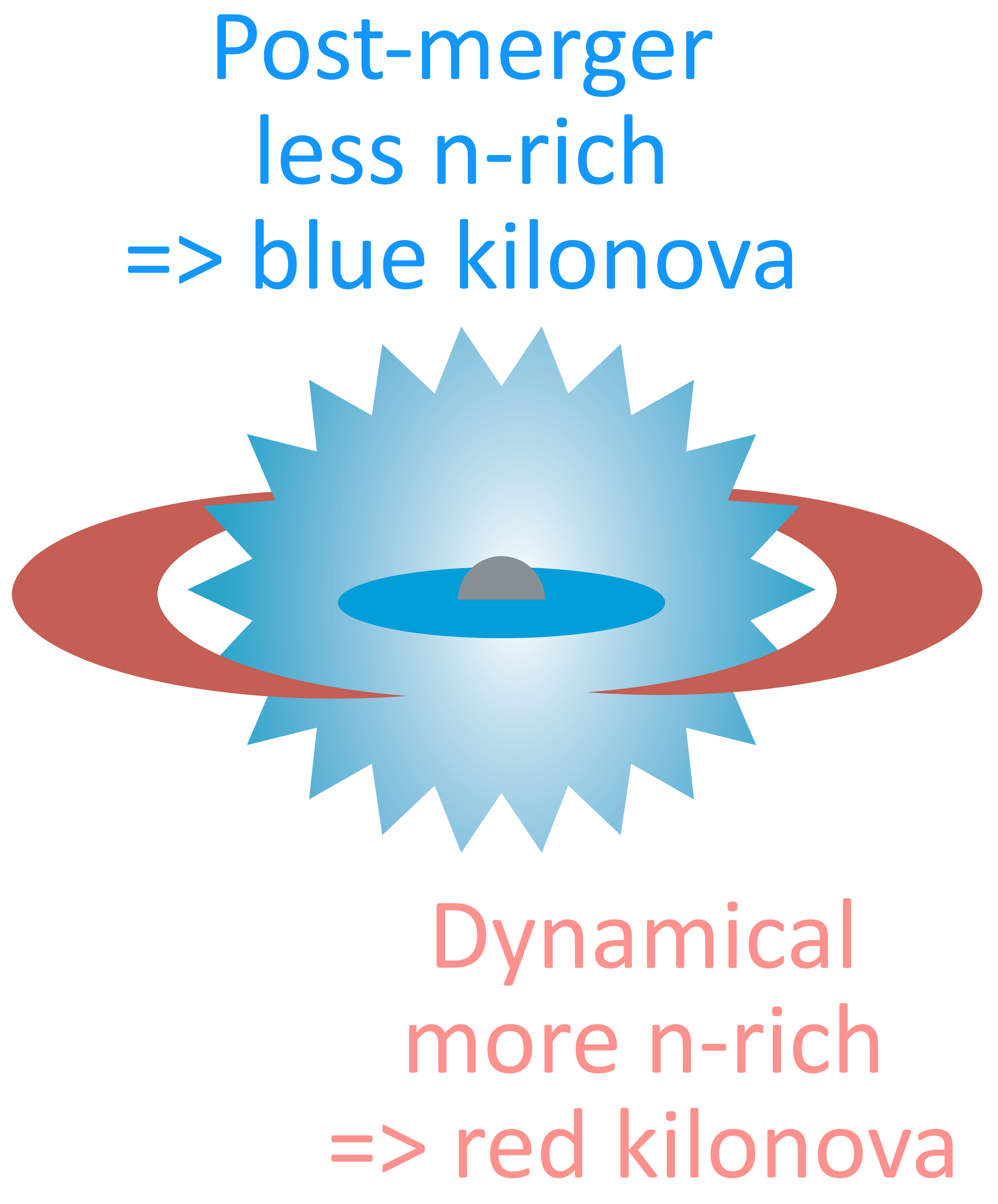
$$\lambda = \frac{hc}{\Delta E}$$



Opacity in kilonova

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





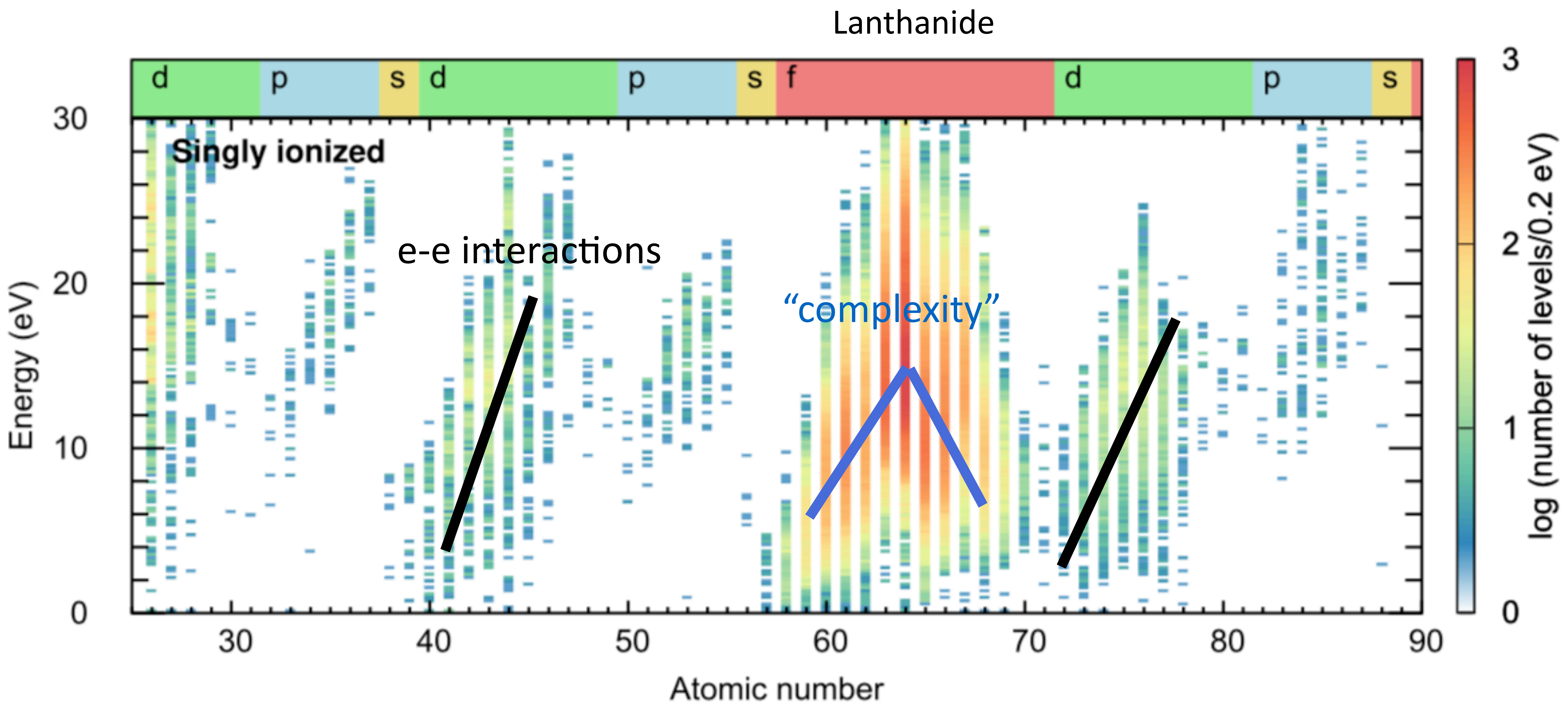
Lanthanide-poor => "Blue" kilonova

Lanthanide-rich => "Red" kilonova

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

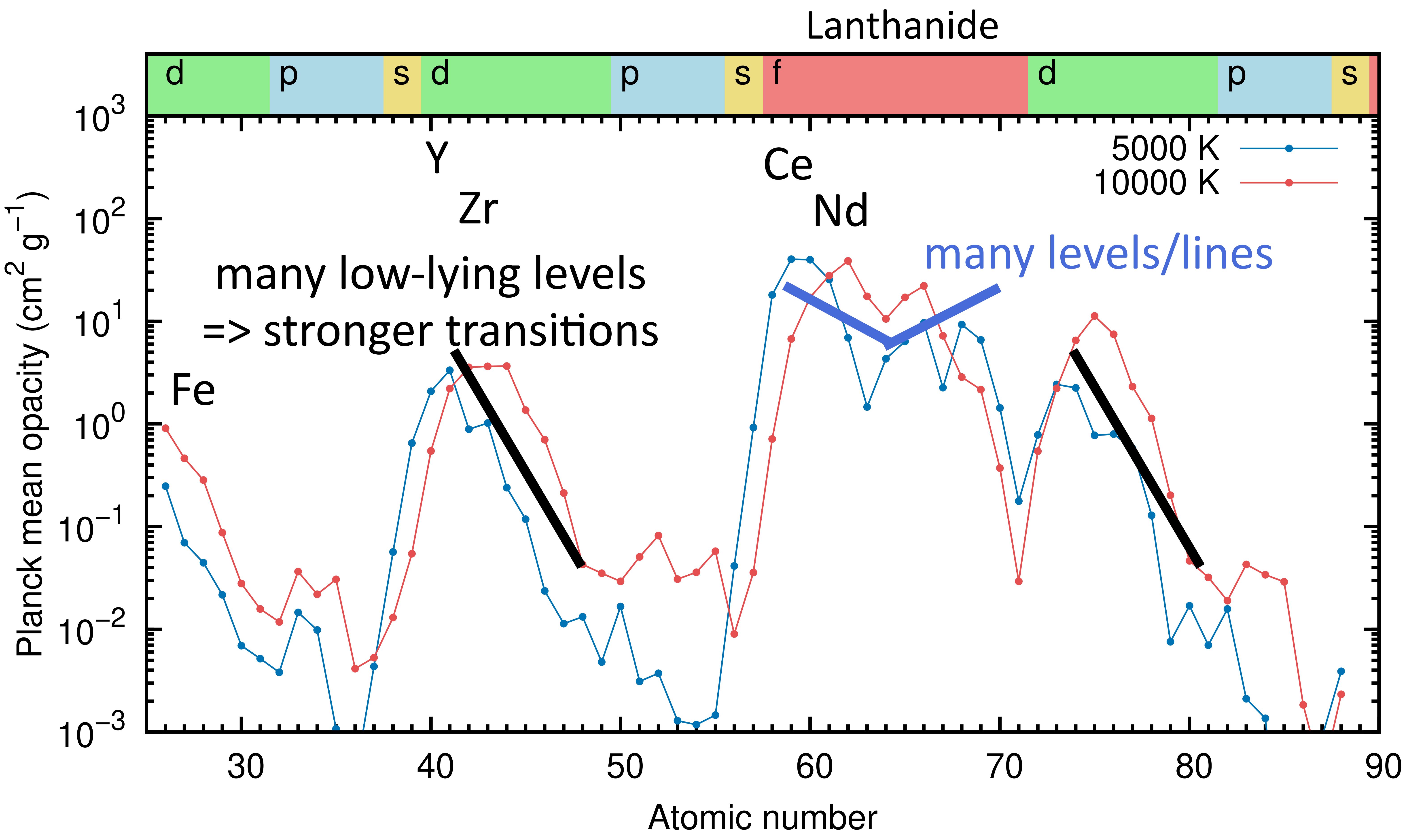
Energy level distributions (all the elements)

MT, Kato, Gaigalas, Kawaguchi 20



Opacities (all the elements)

MT, Kato, Gaigalas, Kawaguchi 20

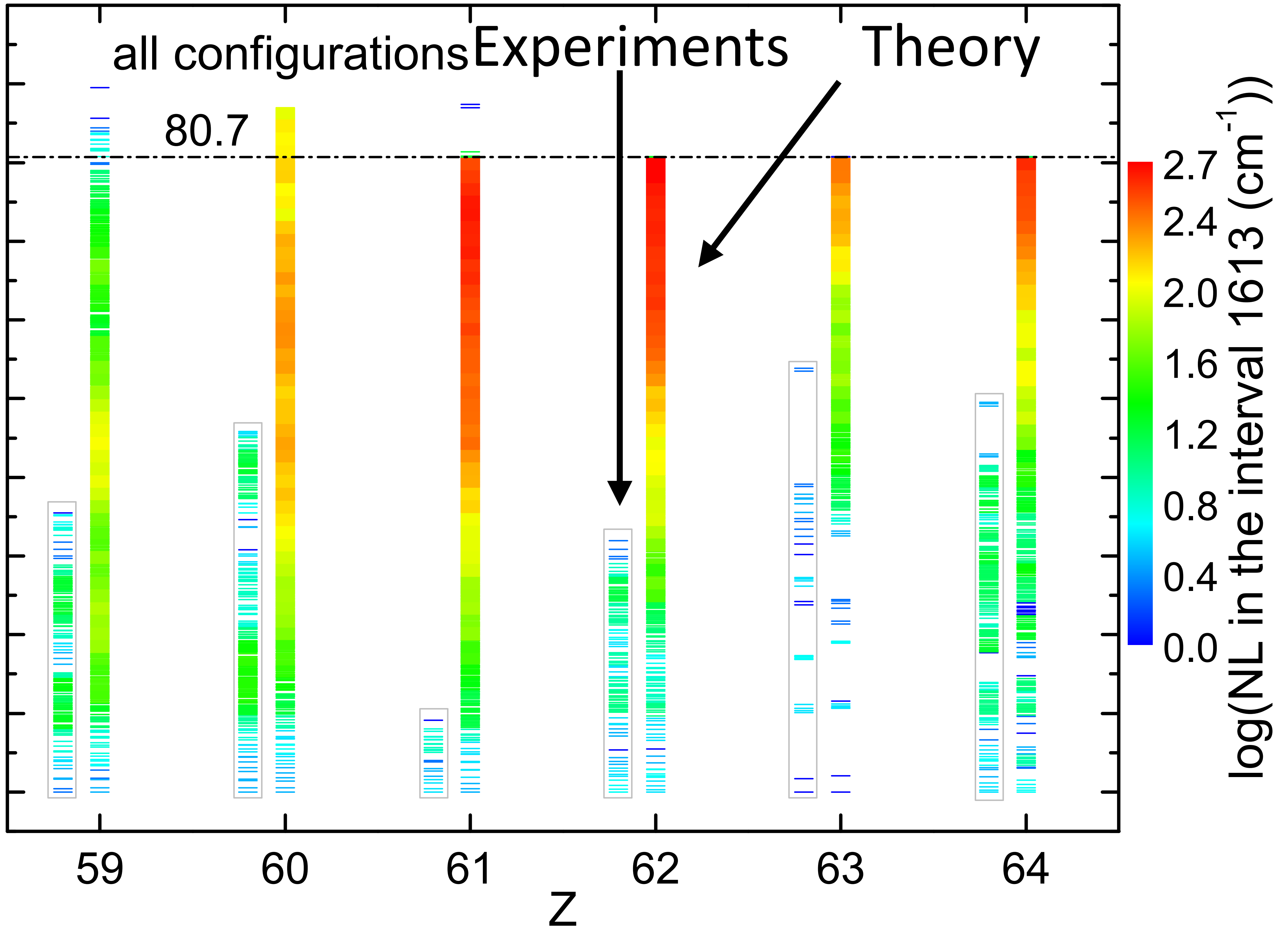


Lanthanide-rich ejecta κ ~ 10-30 $cm^2\ g^{-1}$

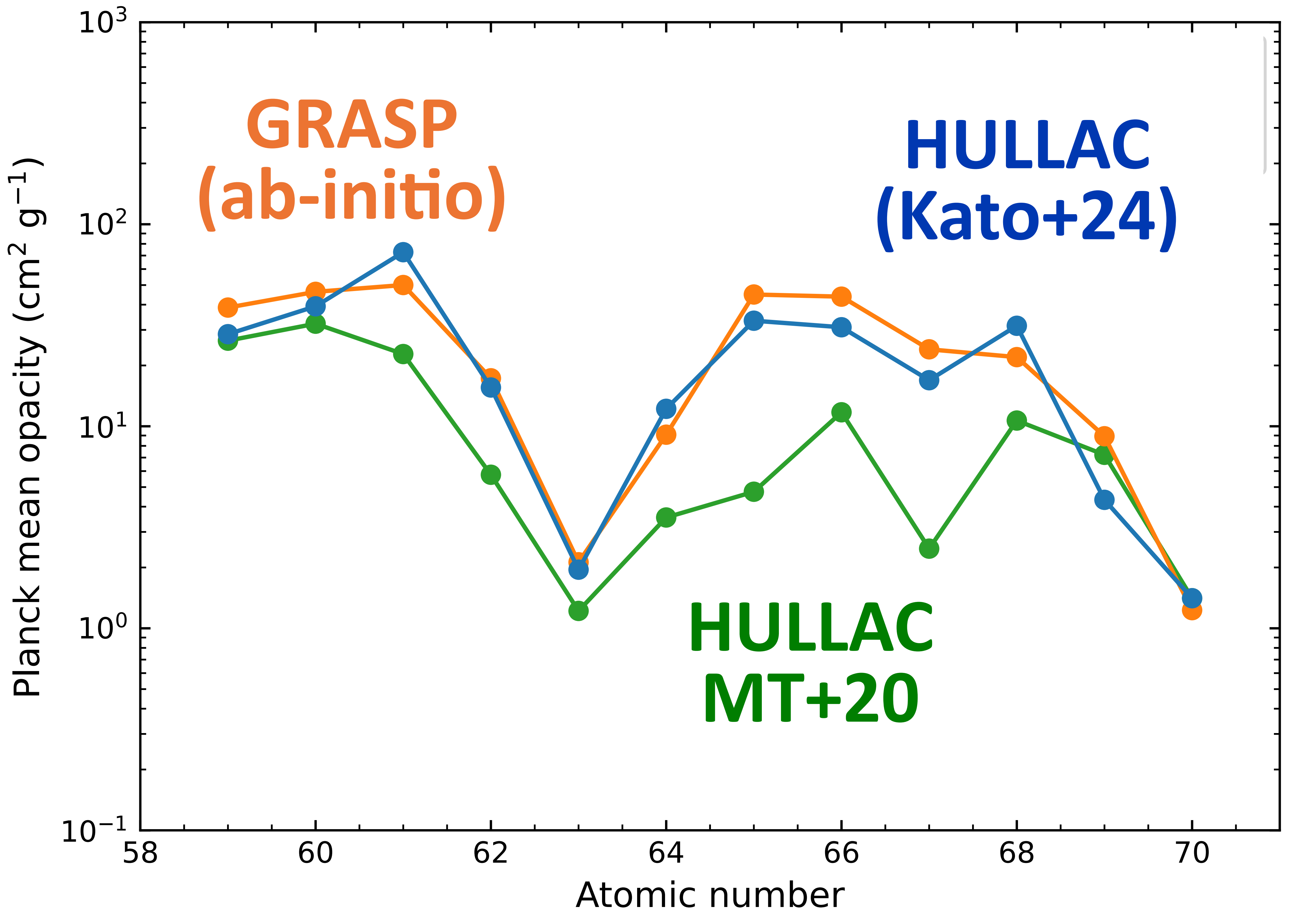
Lanthanide-free ejecta κ ~ 1 $cm^2\ g^{-1}$

Ab-initio atomic structure calculations (singly ionized lanthanides)

GRASP (Gaigalas+19, Radziute+20,21)



HULLAC (Kato+24)

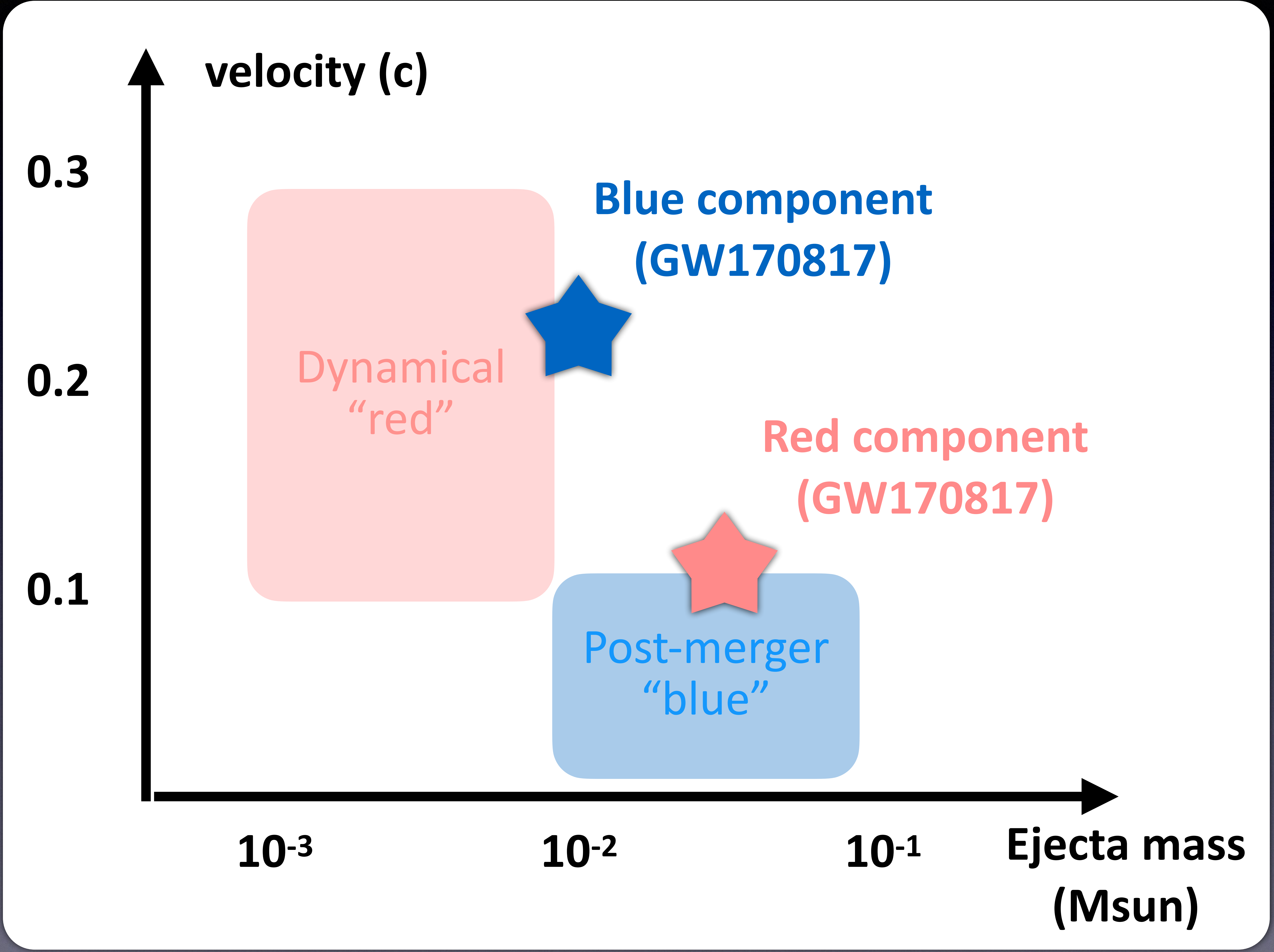


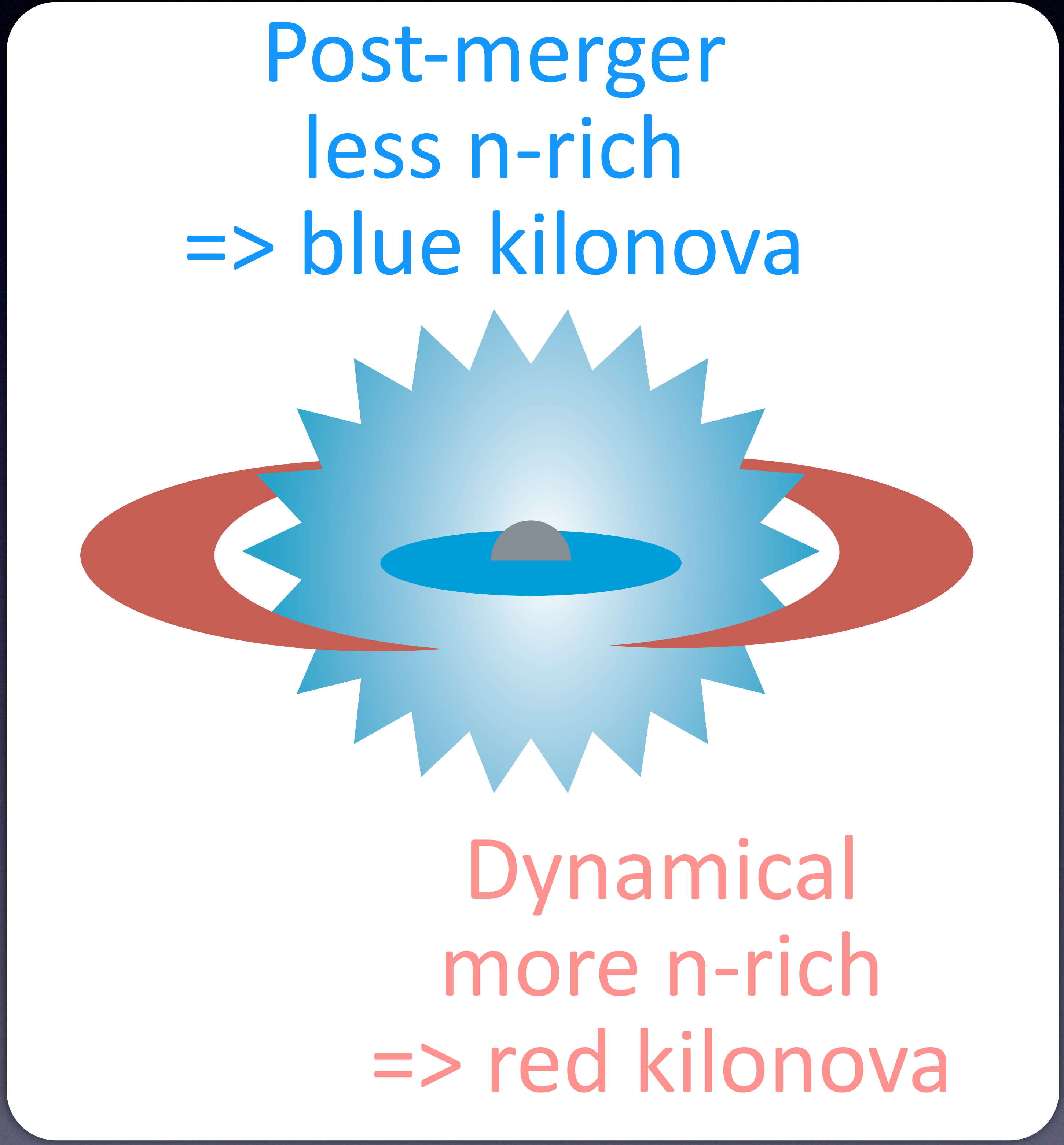
~10 % accuracy in the energy levels

factor of ~ 3 in the opacity

see also Floers+23, Deprince+24

Ejecta components in GW170817?

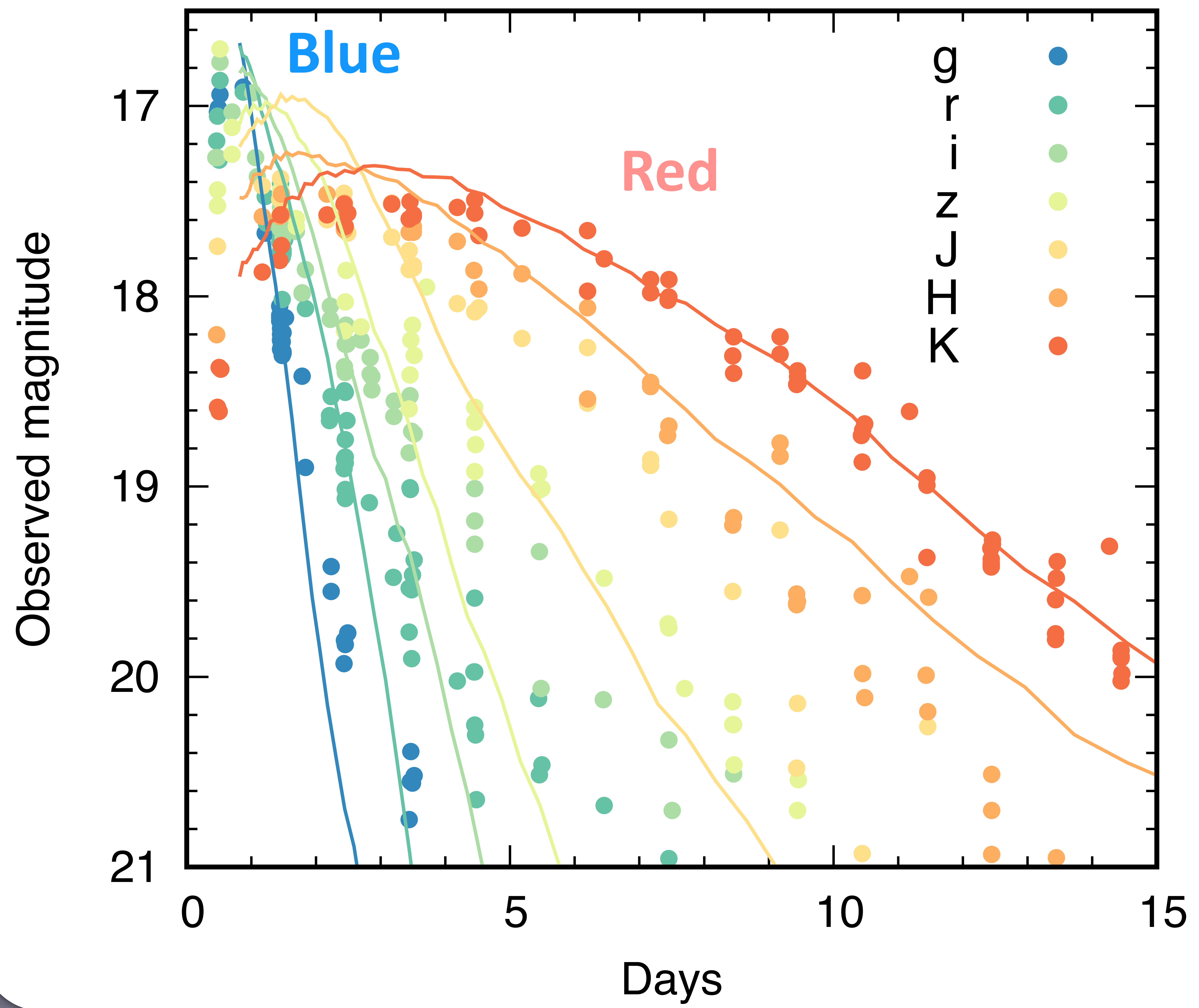


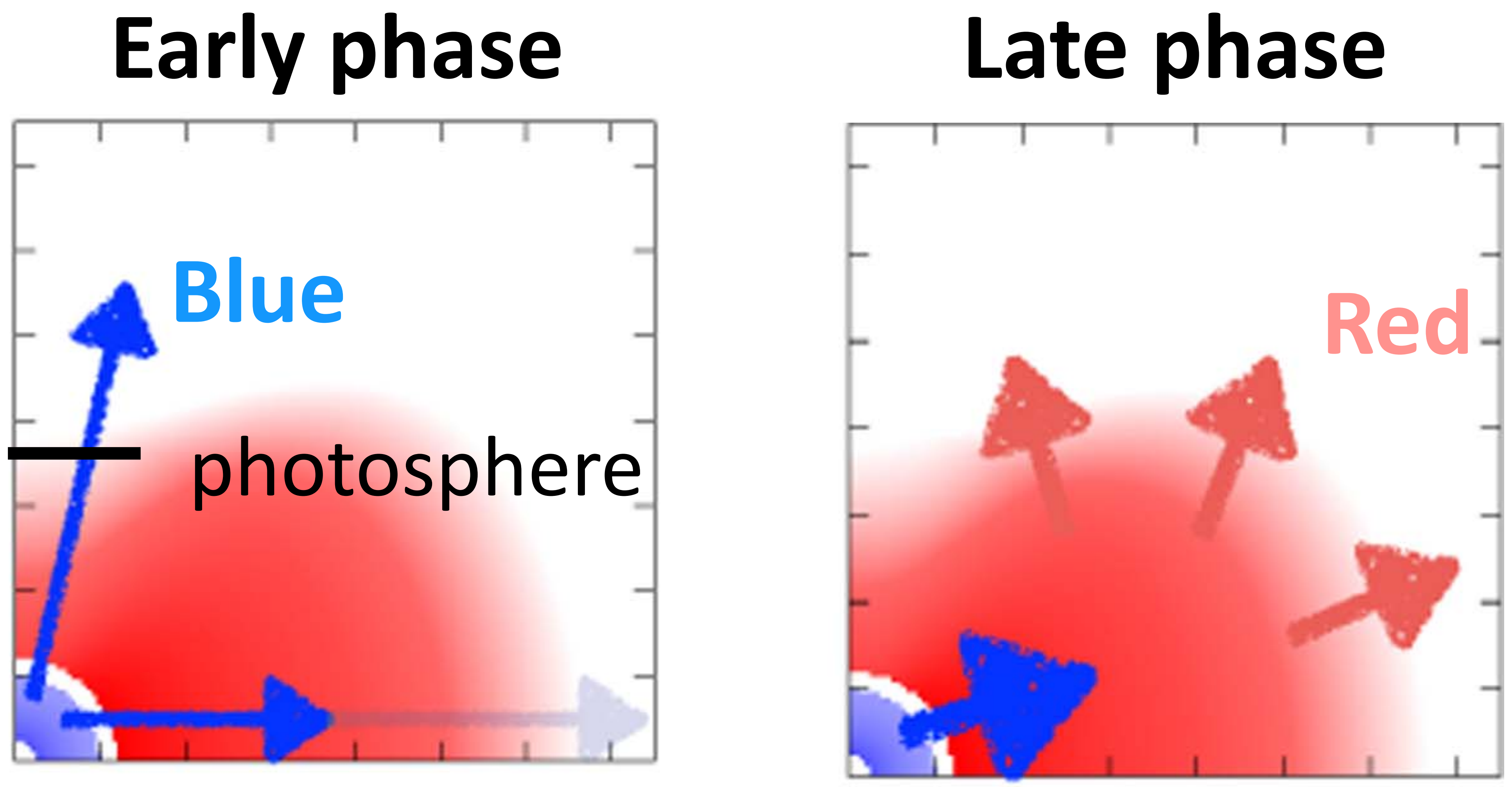


Tension with theoretical prediction??

“End-to-end” simulations based on numerical relativity simulations

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



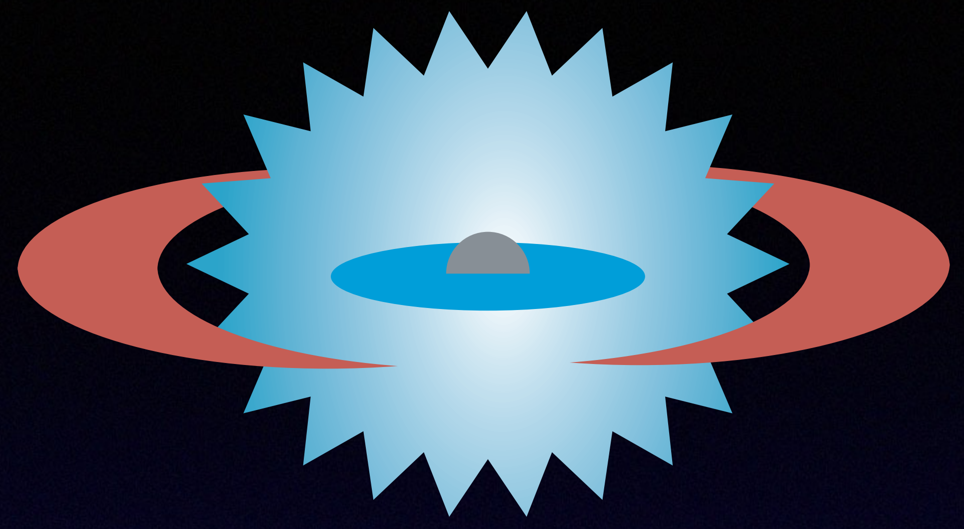


Post-merger ejecta = heating source

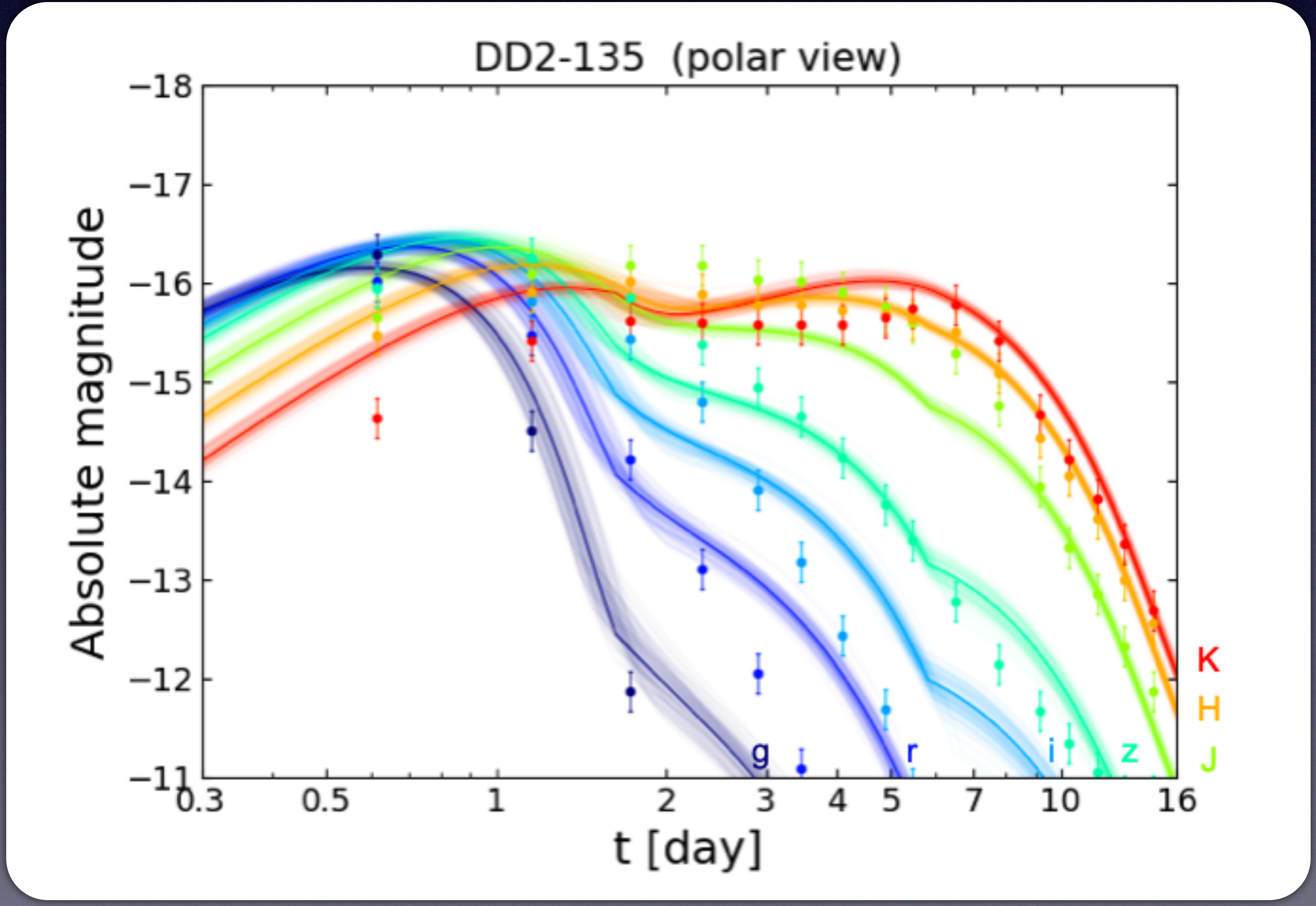
Dynamical ejecta = reprocessing photons

Interpretation of the blue/red components

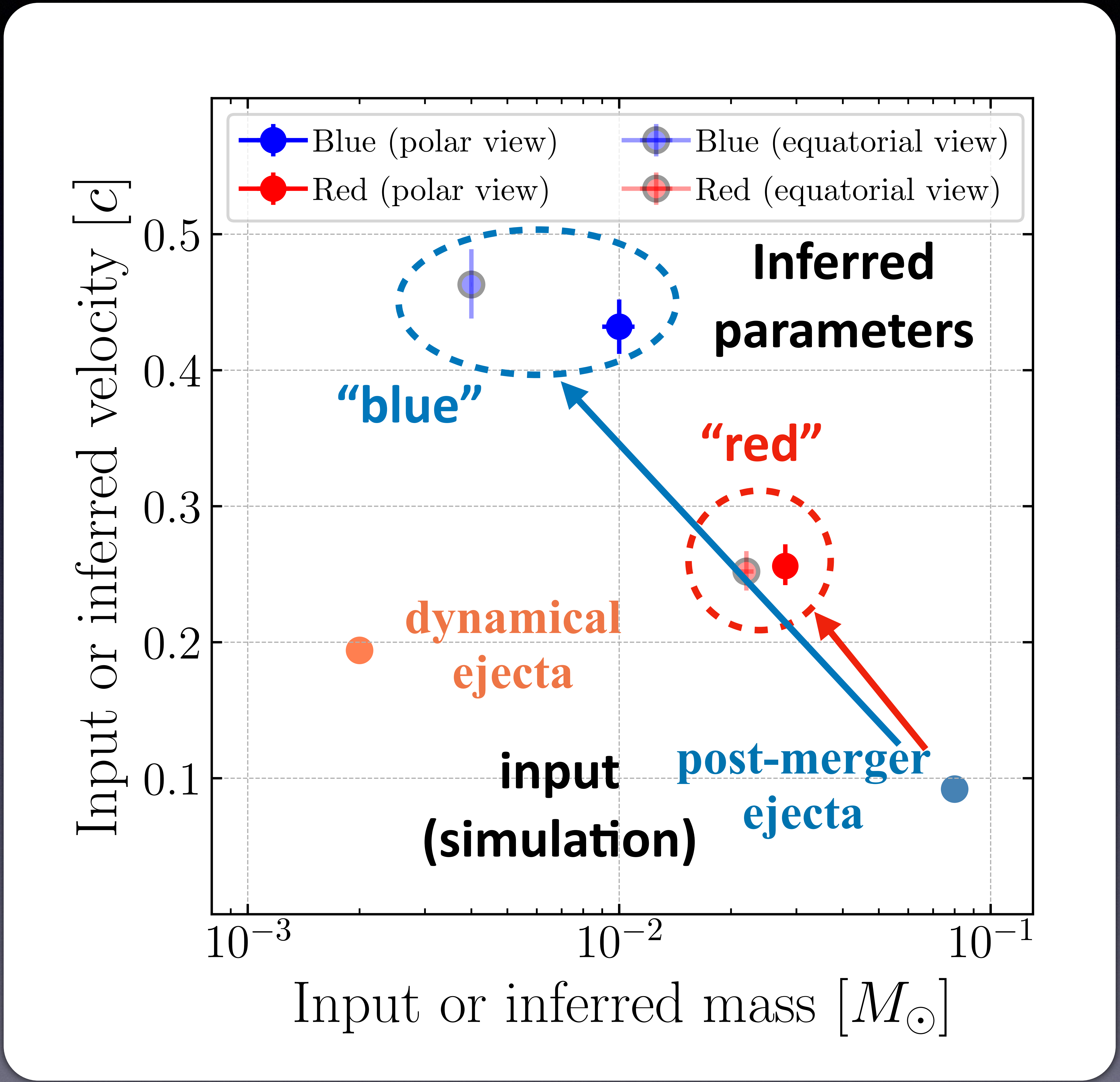
Kitamura, Kawaguchi, MT+25
(arXiv: TODAY)



simulation data = "observations"



Model fitting



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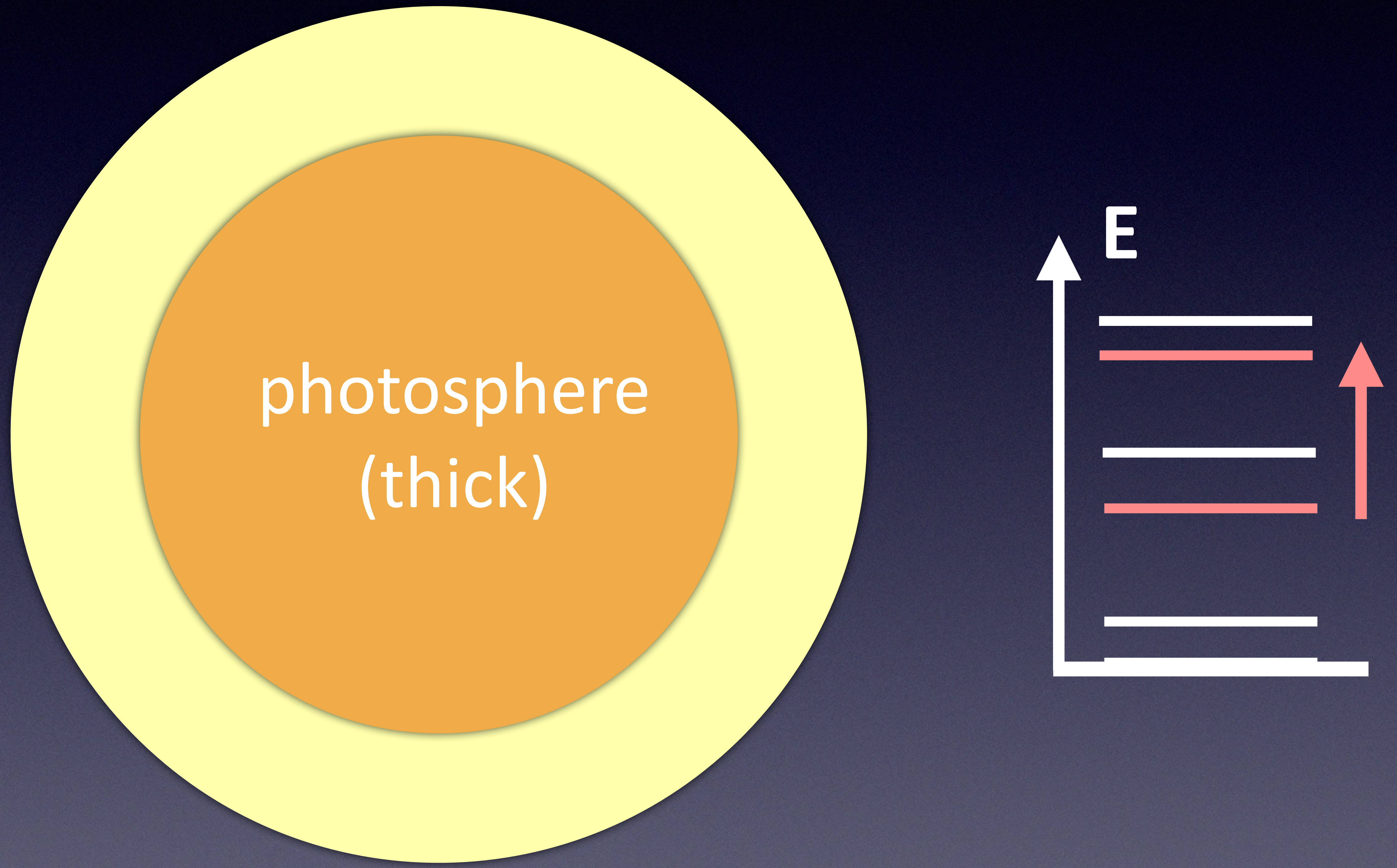
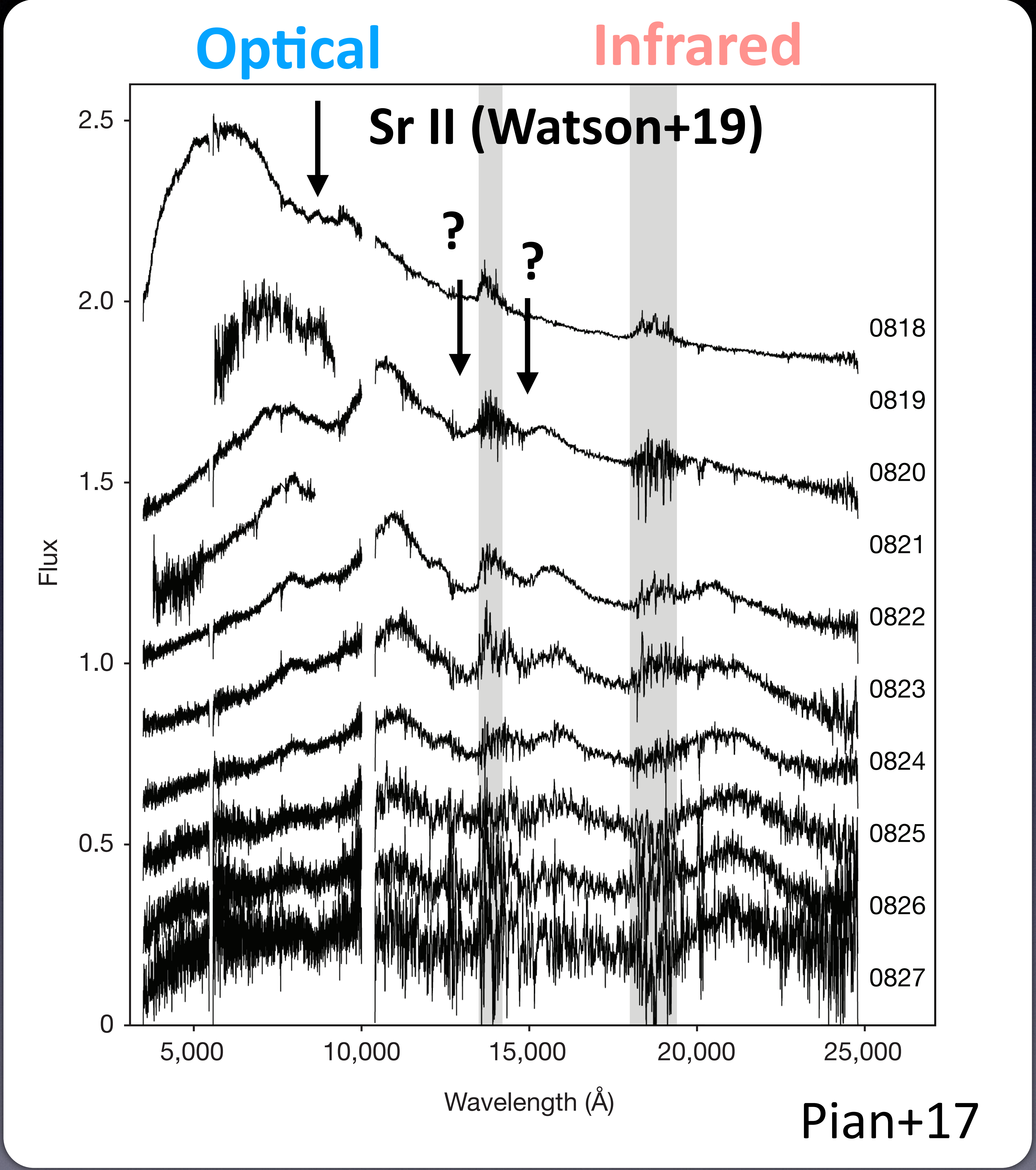
Spectral features in kilonova photospheric spectra

absorption feature



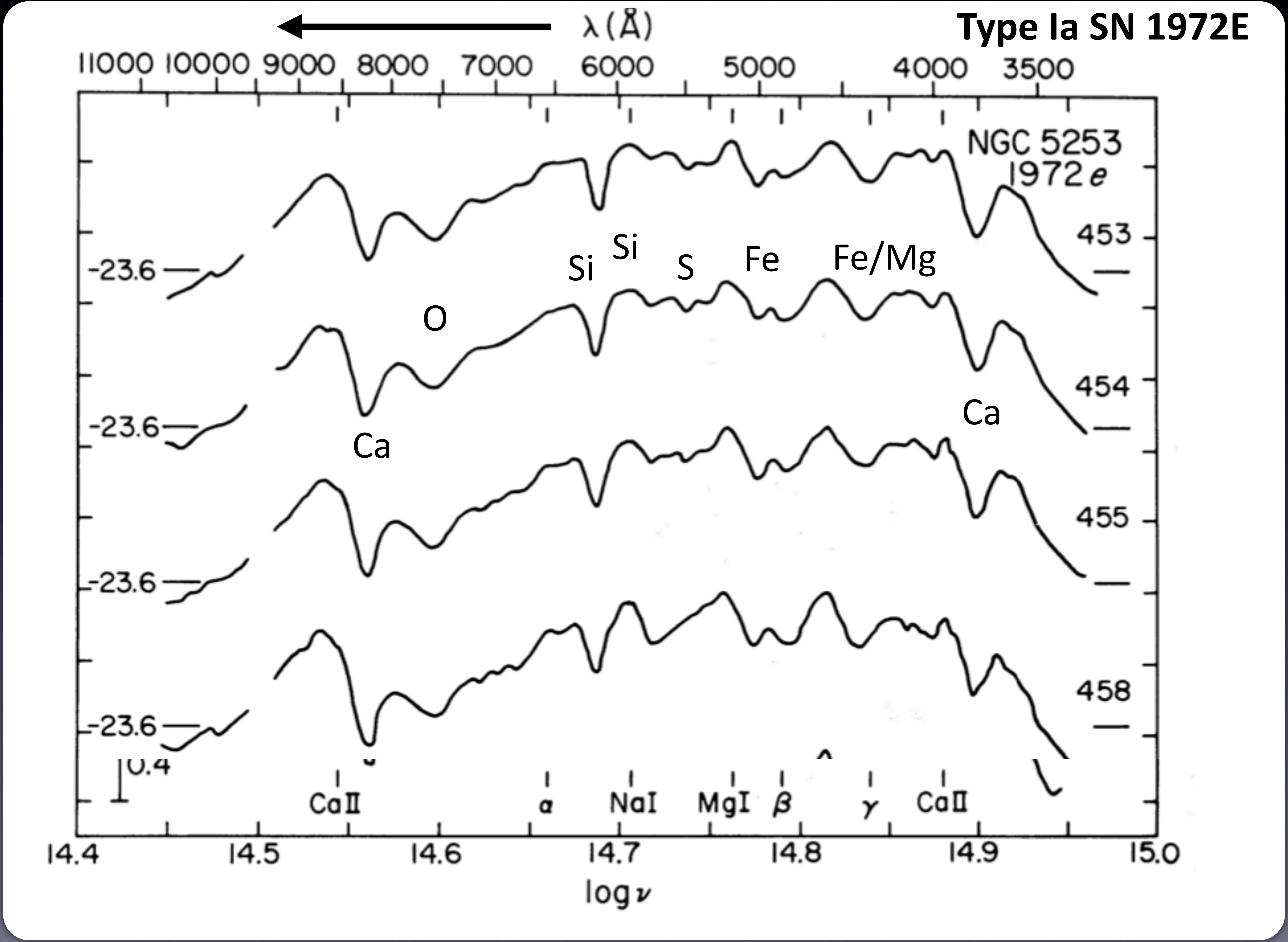
GW170817/AT2017gfo



Need accurate atomic data for important transitions

Supernova spectra in 1970s

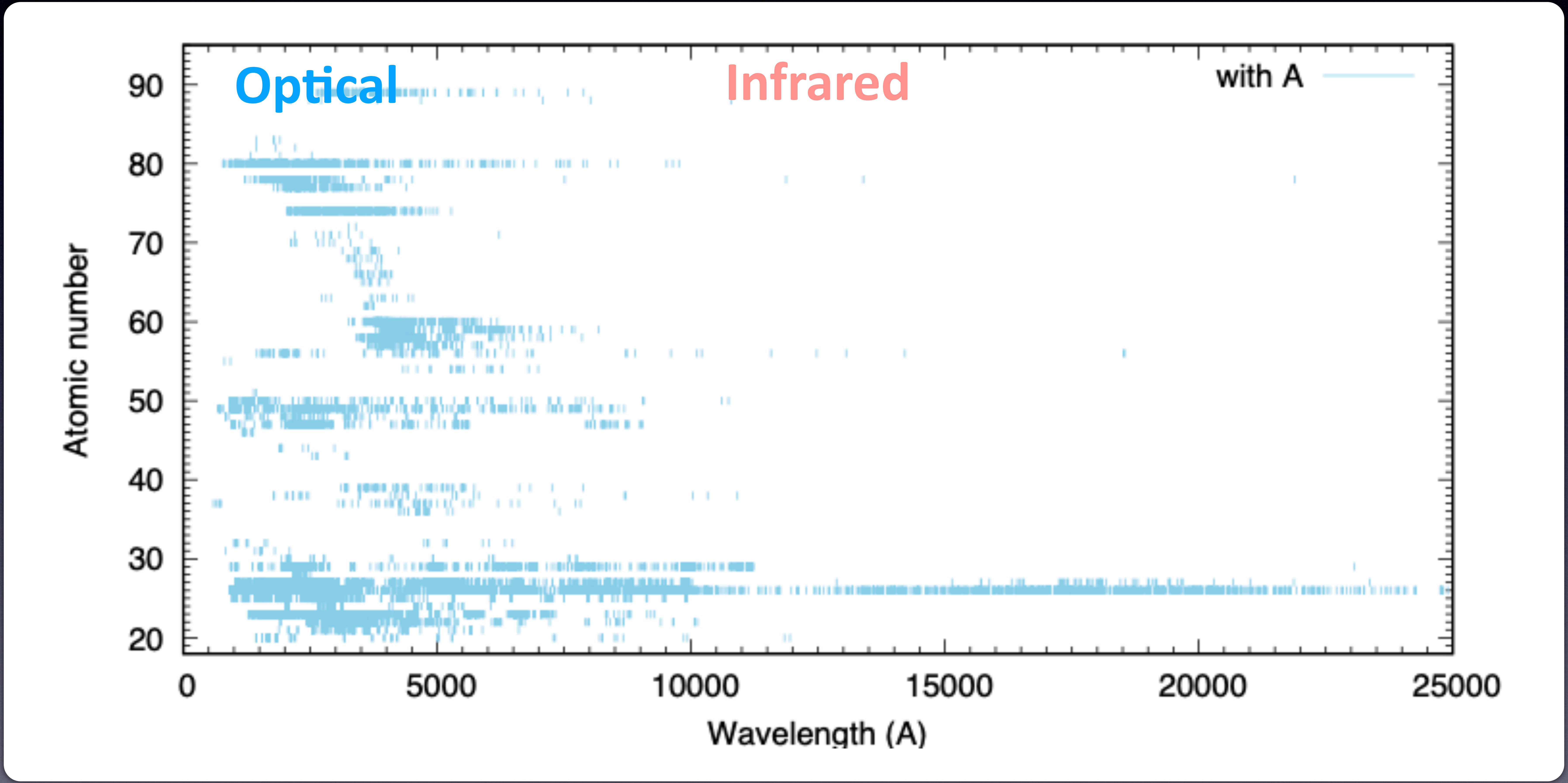
Kirshner+73



Available atomic data

Data from the NIST database
(singly ionized)

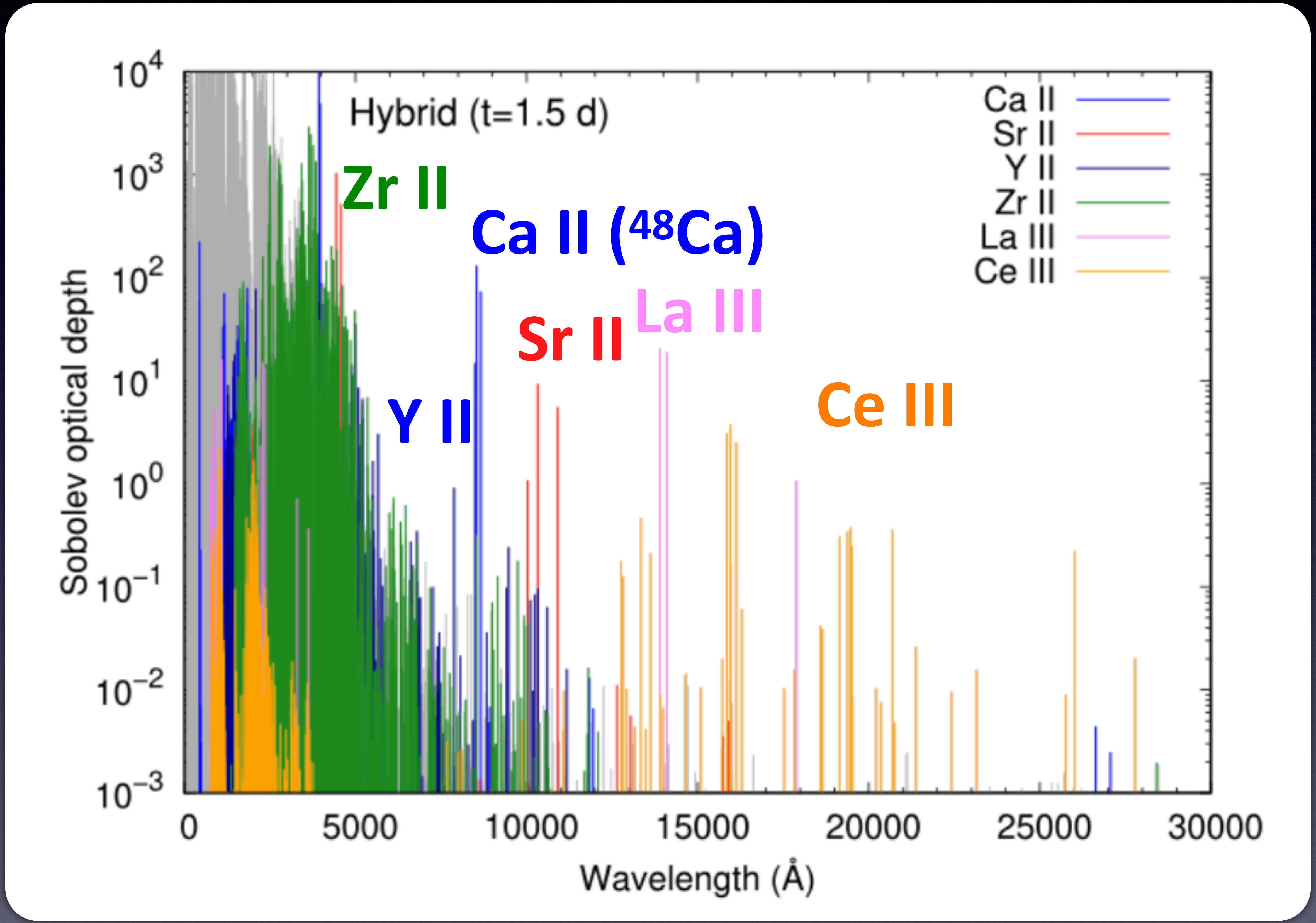
Transitions with known transition probability

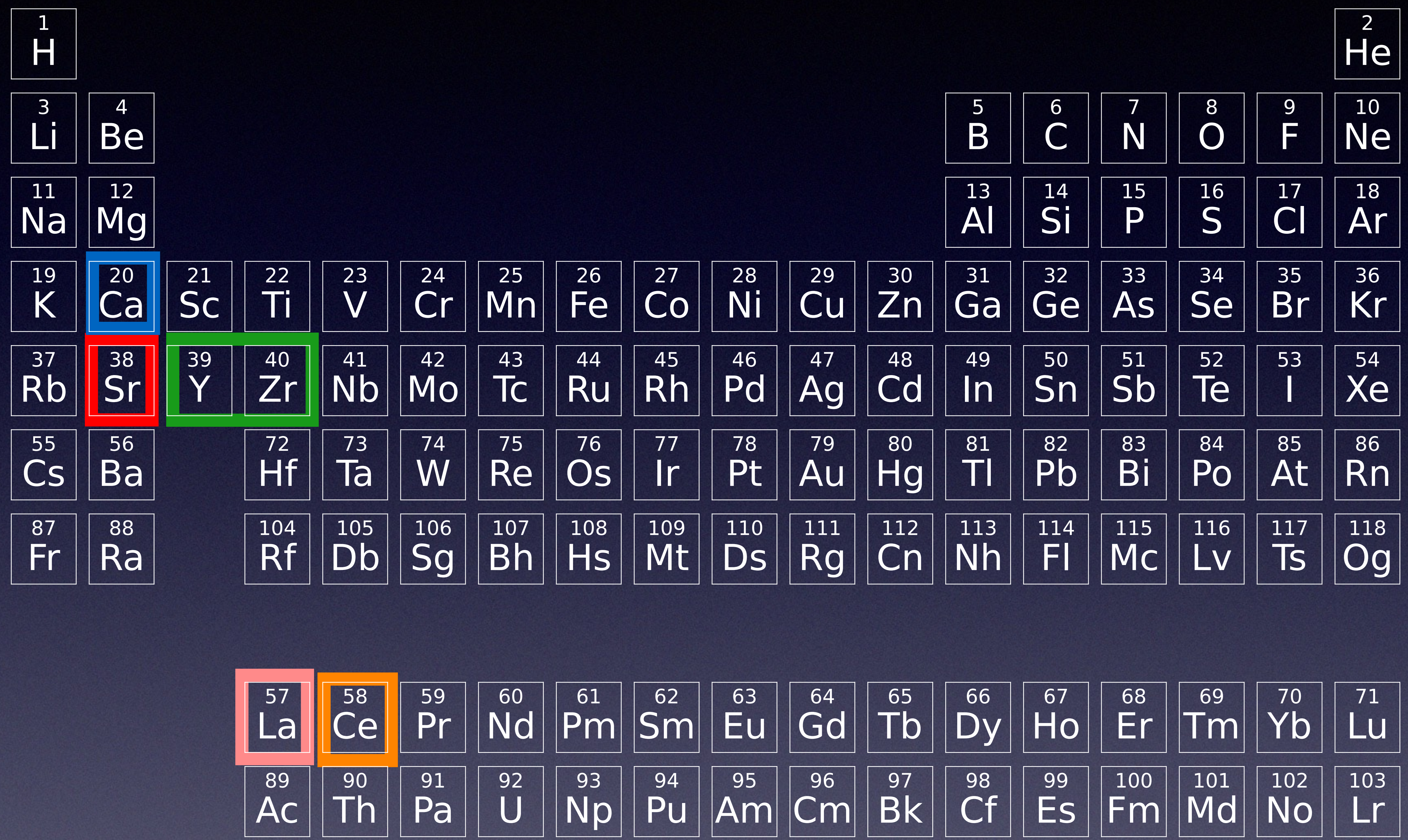


Accurate transition data are highly incomplete (in particular NIR)

Important element for spectral features

Domoto+22



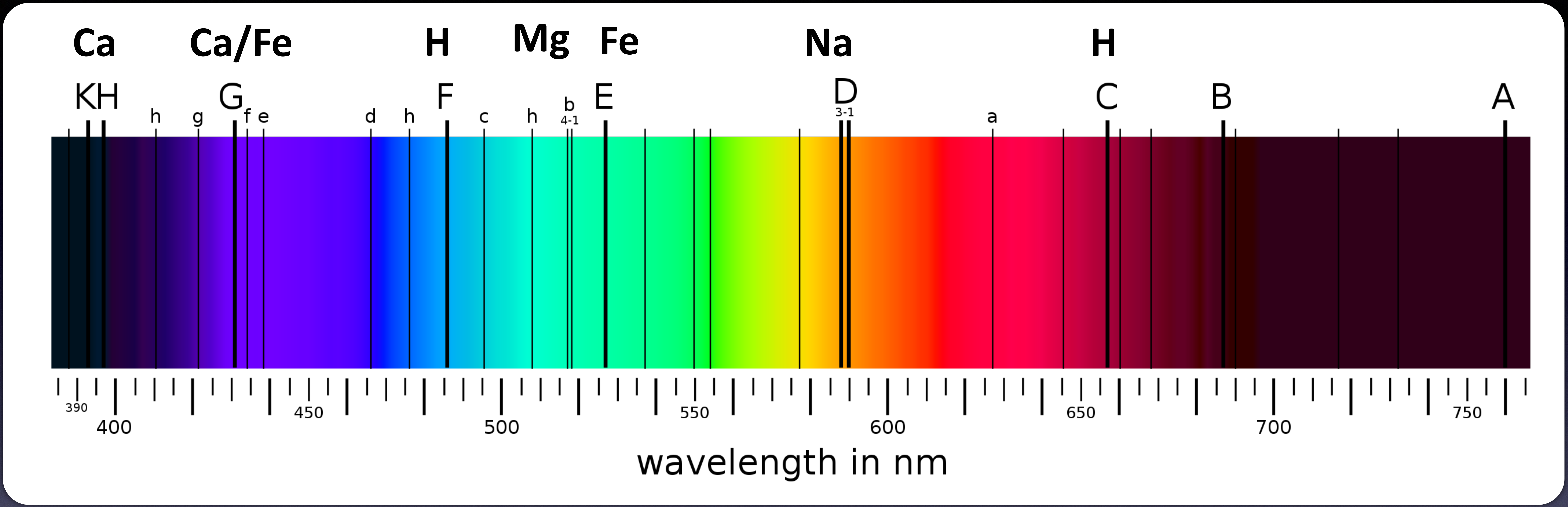


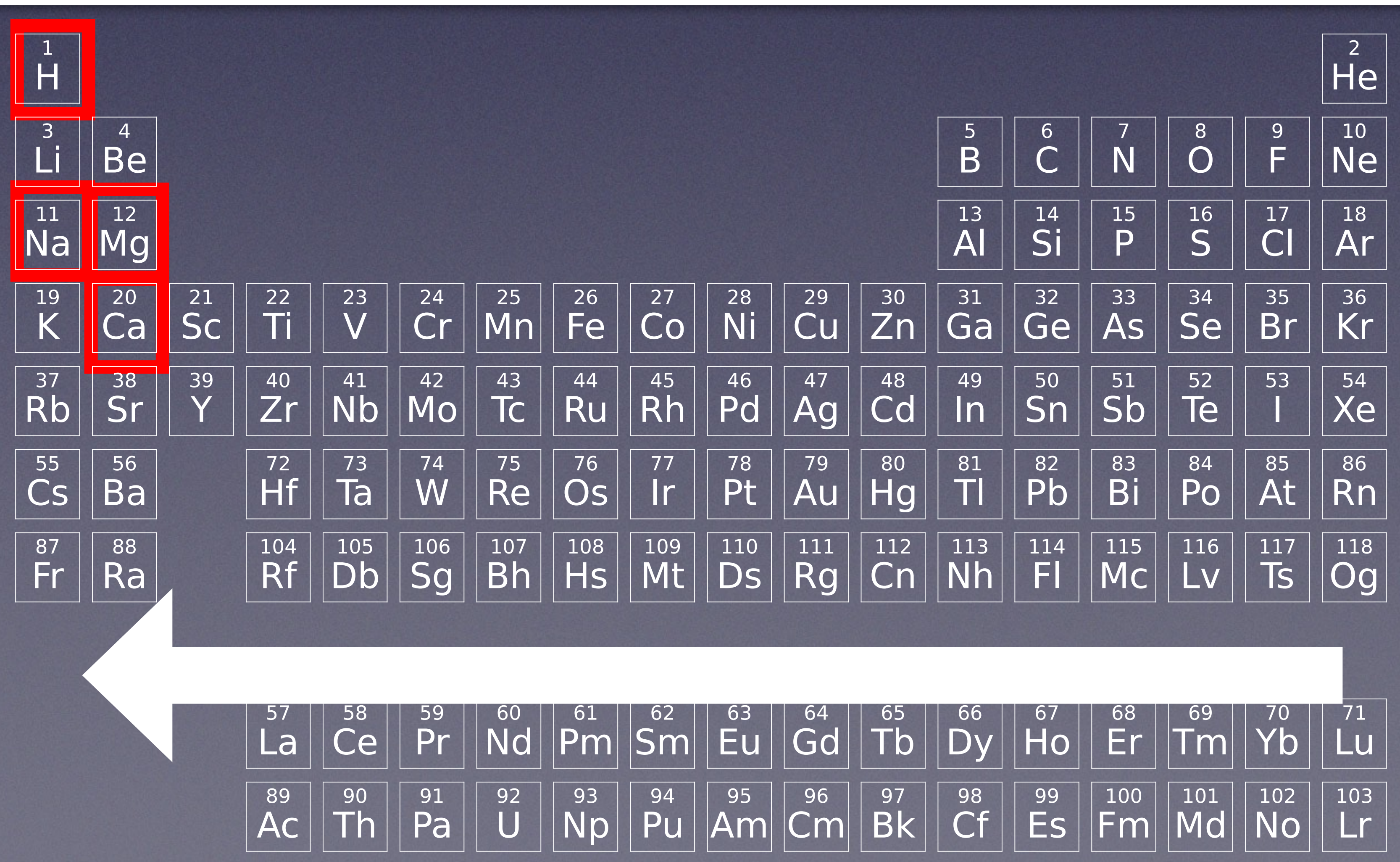
$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l \frac{g_k f_l}{\Sigma} e^{-E_k/kT}$$

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

Solar spectrum

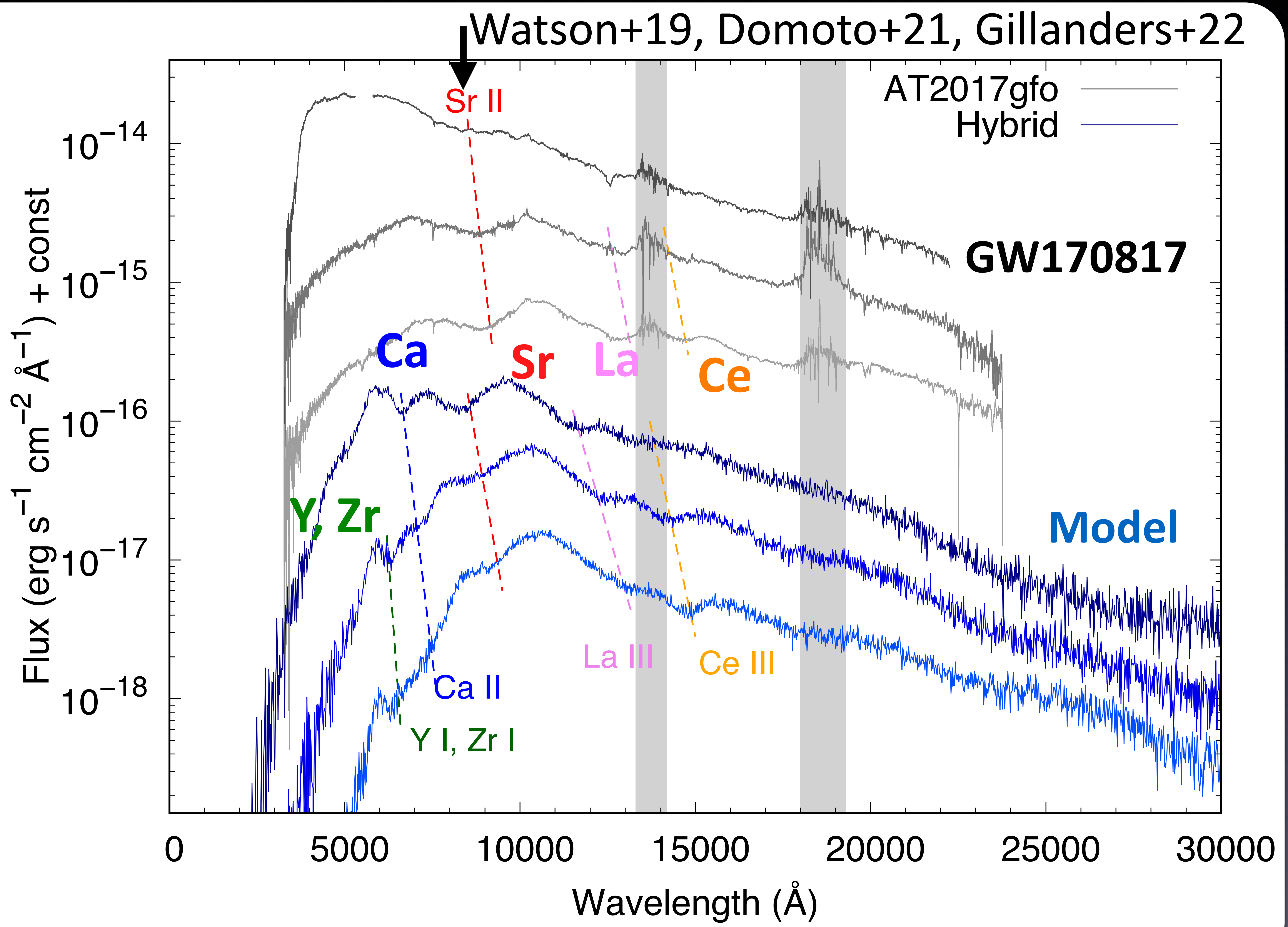
https://en.wikipedia.org/wiki/Fraunhofer_lines





Element identification in NIR spectra

Domoto+22

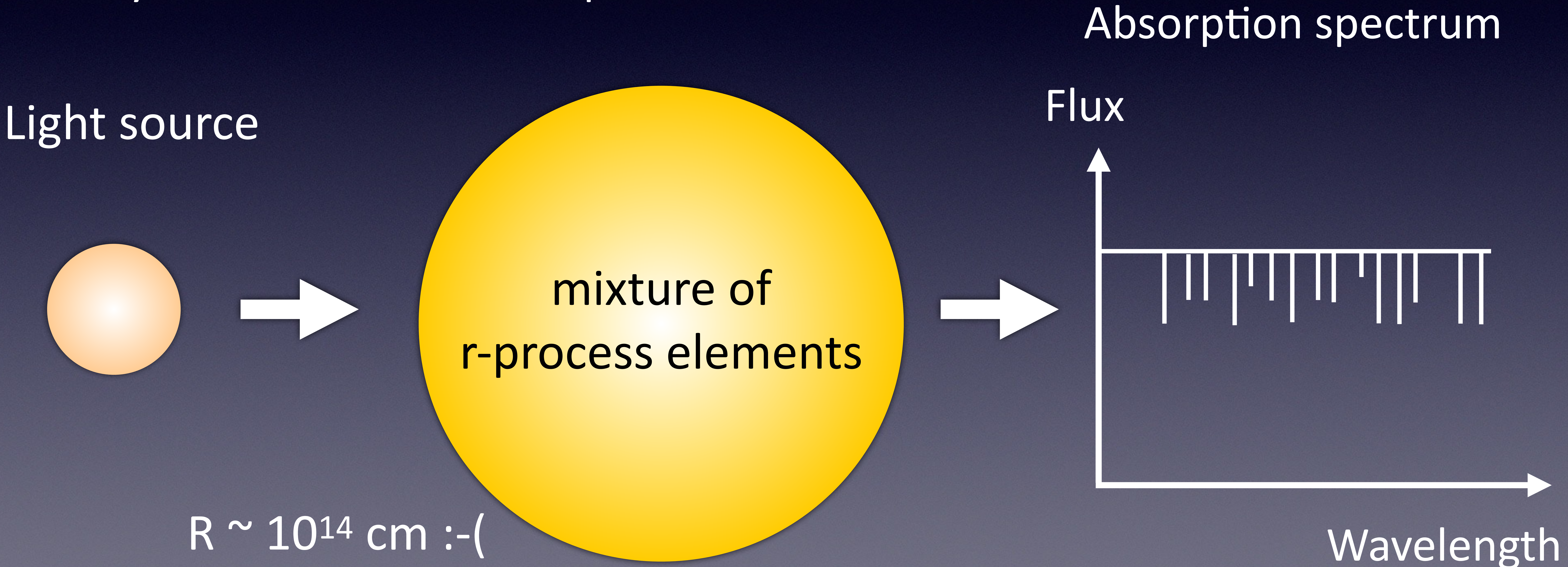


La (Z=57) and Ce (Z=58): direct confirmation of lanthanide production

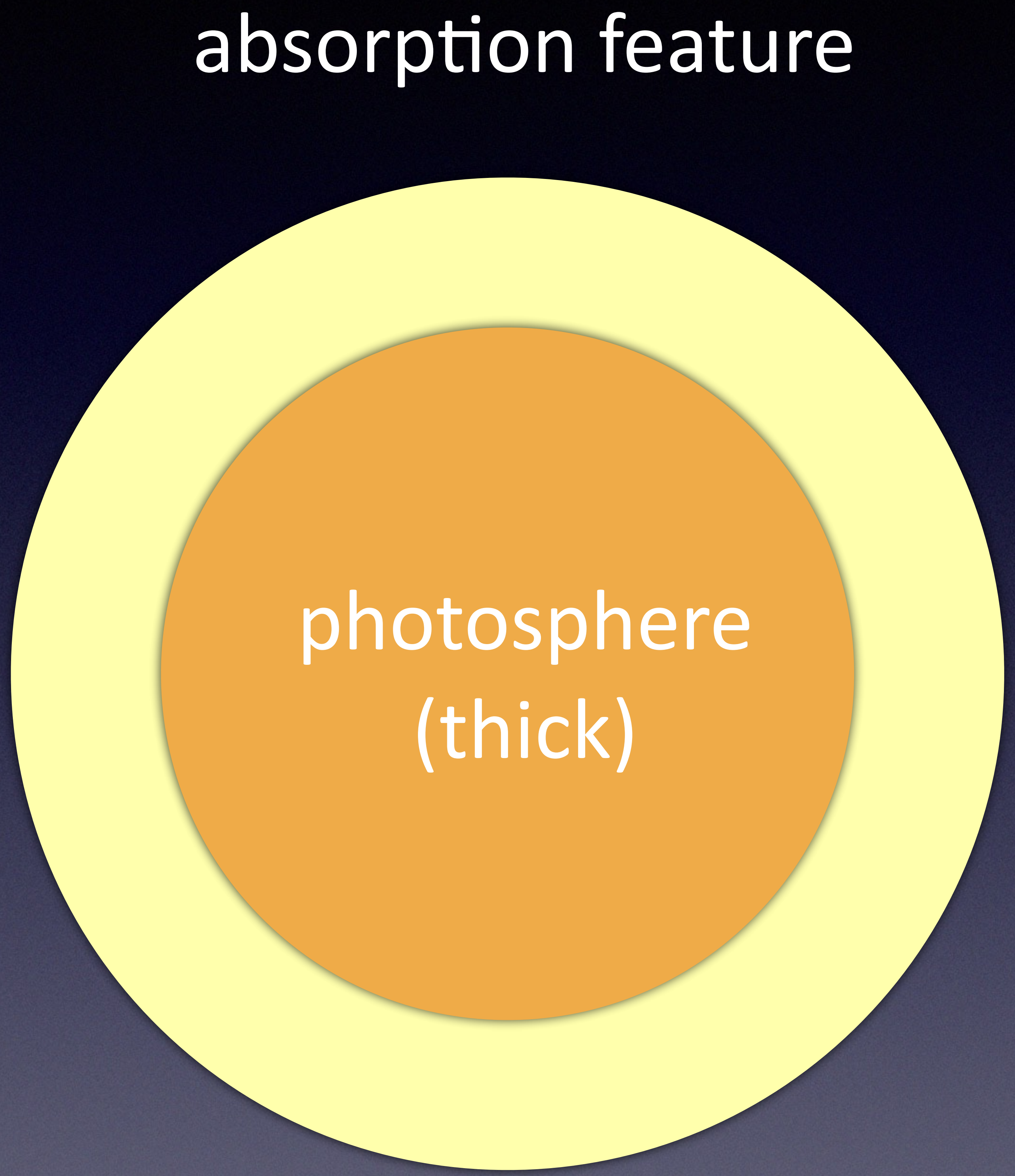
How to test the completeness of the strong transitions??

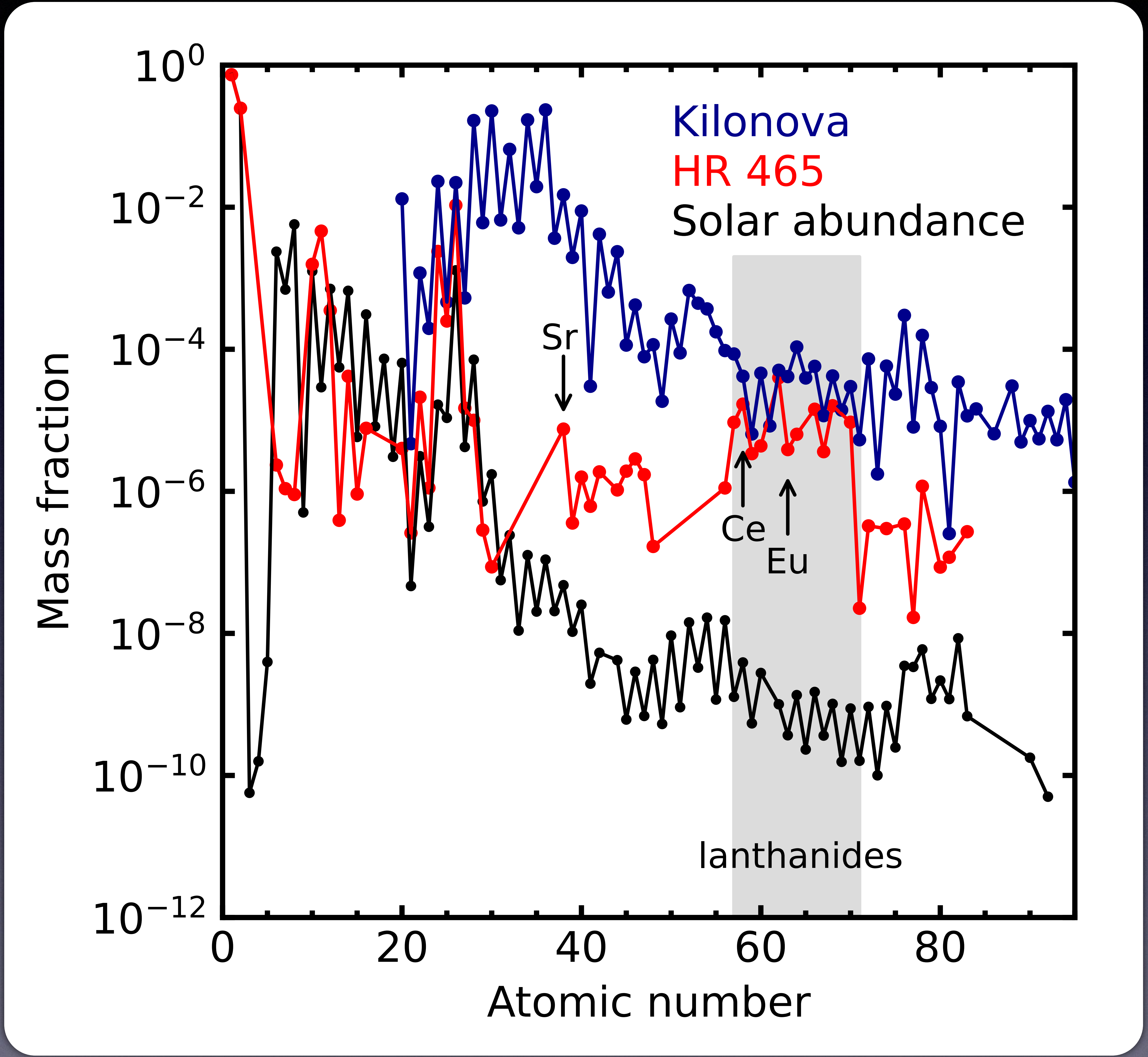
The best spectroscopic experiment...

- $T \sim 5{,}000$ K, $\rho \sim 10^{-15}$ g cm^{-3} ($n \sim \rho / A\, m_p \sim 10^{7}$ cm^{-3})
- Heavy elements dominated plasma



“Spectroscopic experiments” with a chemically peculiar star





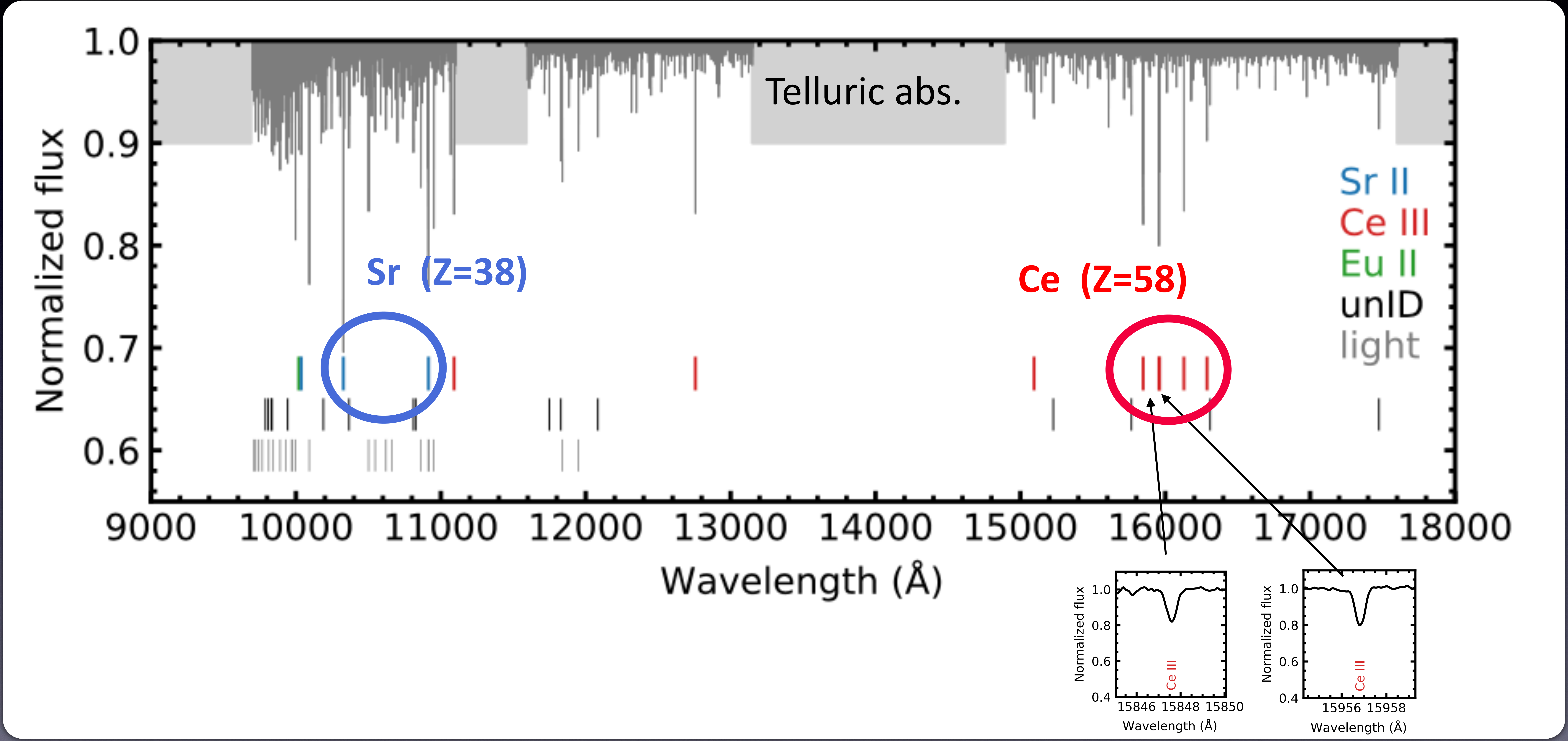
MT, Domoto, Aoki et al. 2023

Similar lanthanide abundances (and ionization degrees) with NS merger

NIR spectrum of chemically peculiar star

MT, Domoto, Aoki+23

Subaru/IRD (R ~ 70,000)

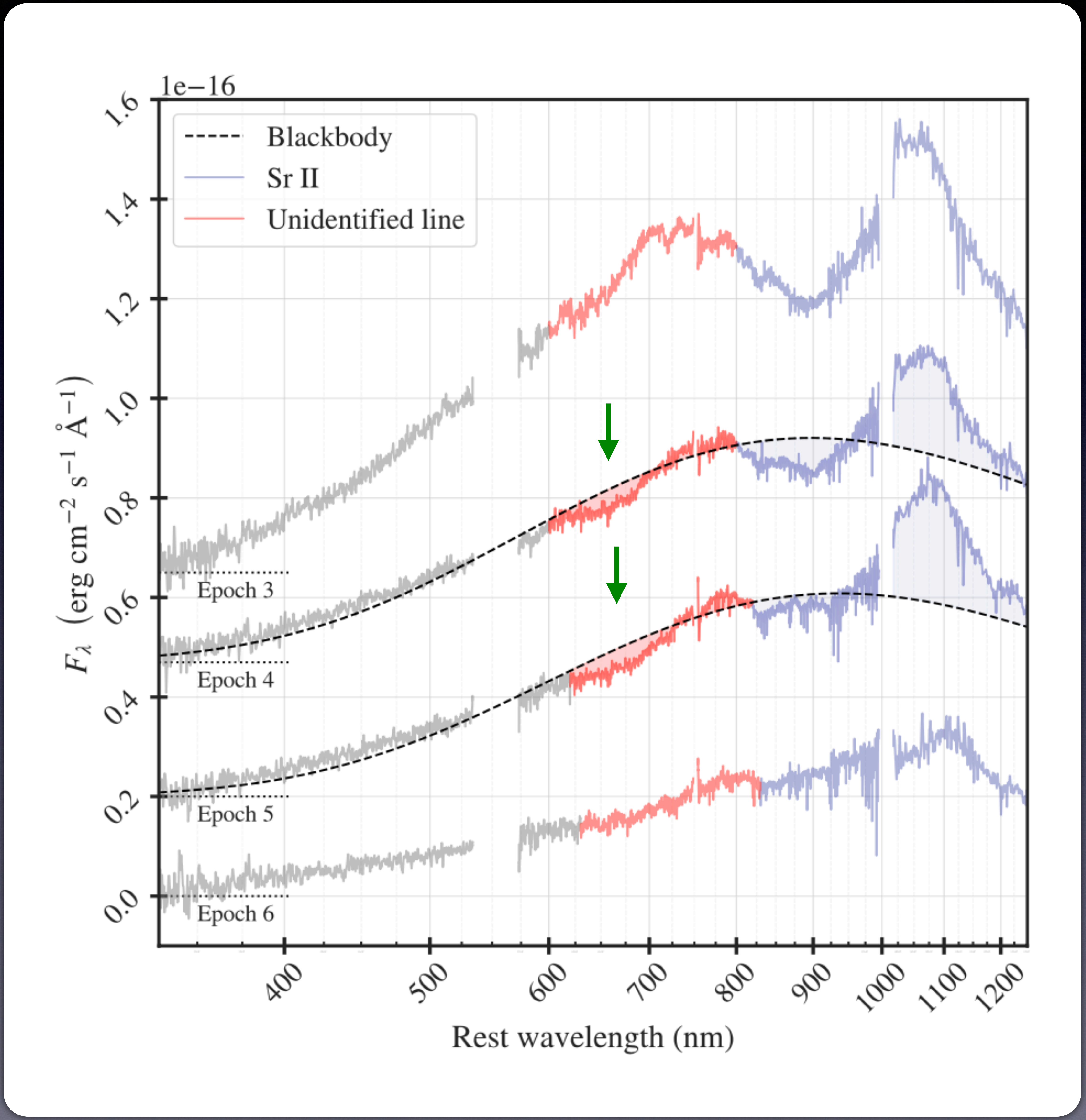


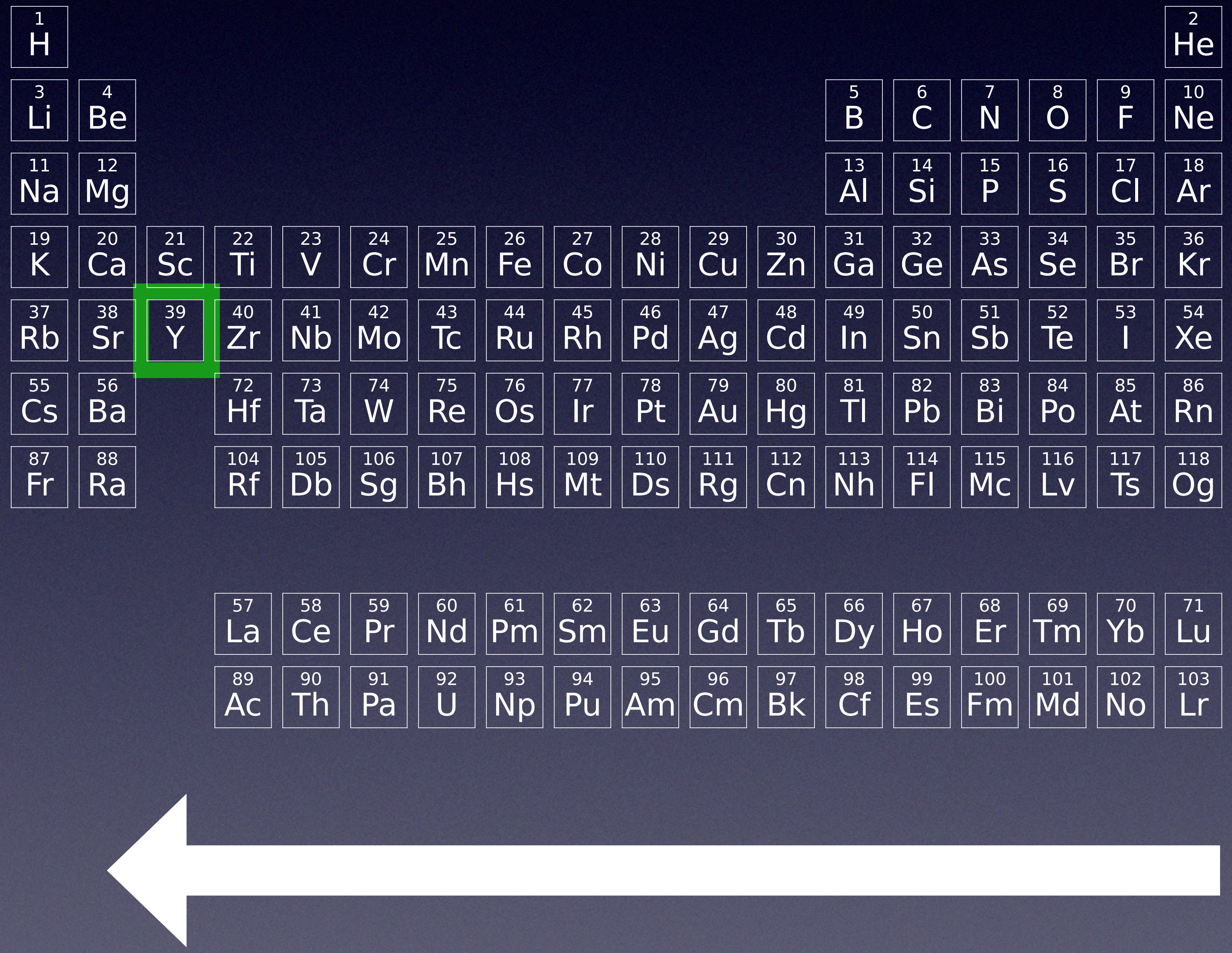
Strongest lines = Ce III and Sr II

No other comparably strong lines = uniqueness of the identification

Identification of Y II (Z=39)

Sneppen & Watson 23

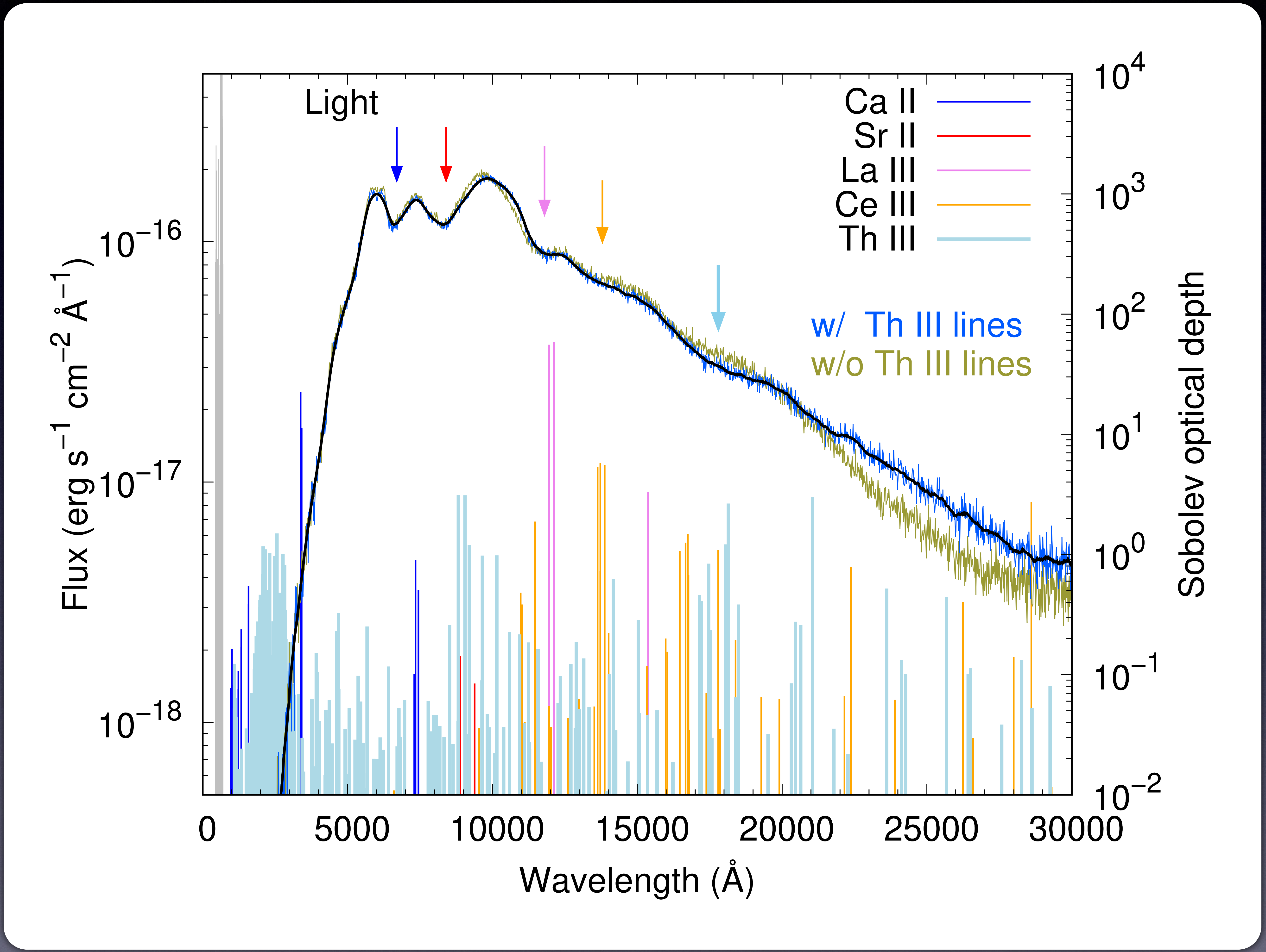


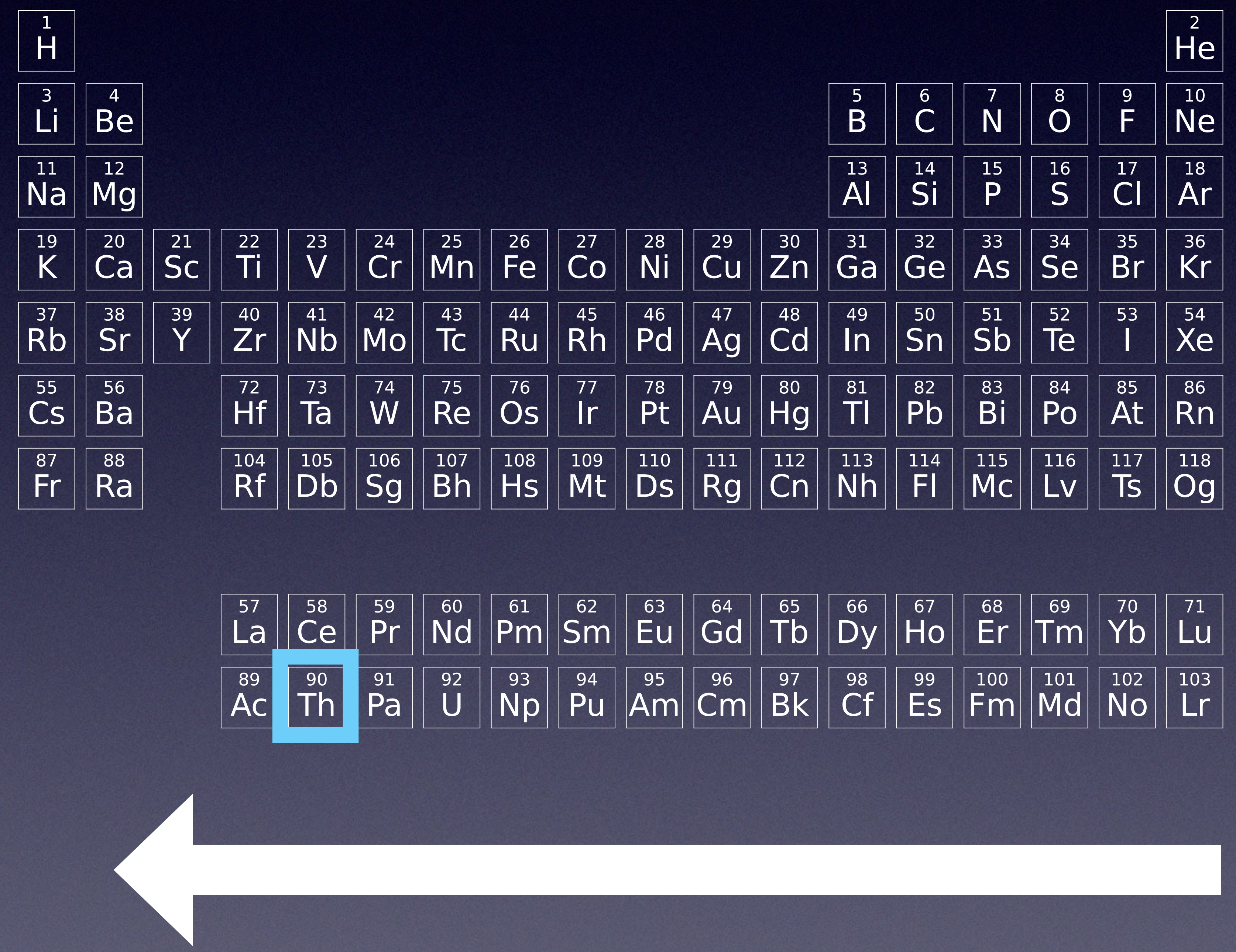


Th (Z=90): Heaviest detectable element?

Poster by Nanae Domoto

Domoto+25





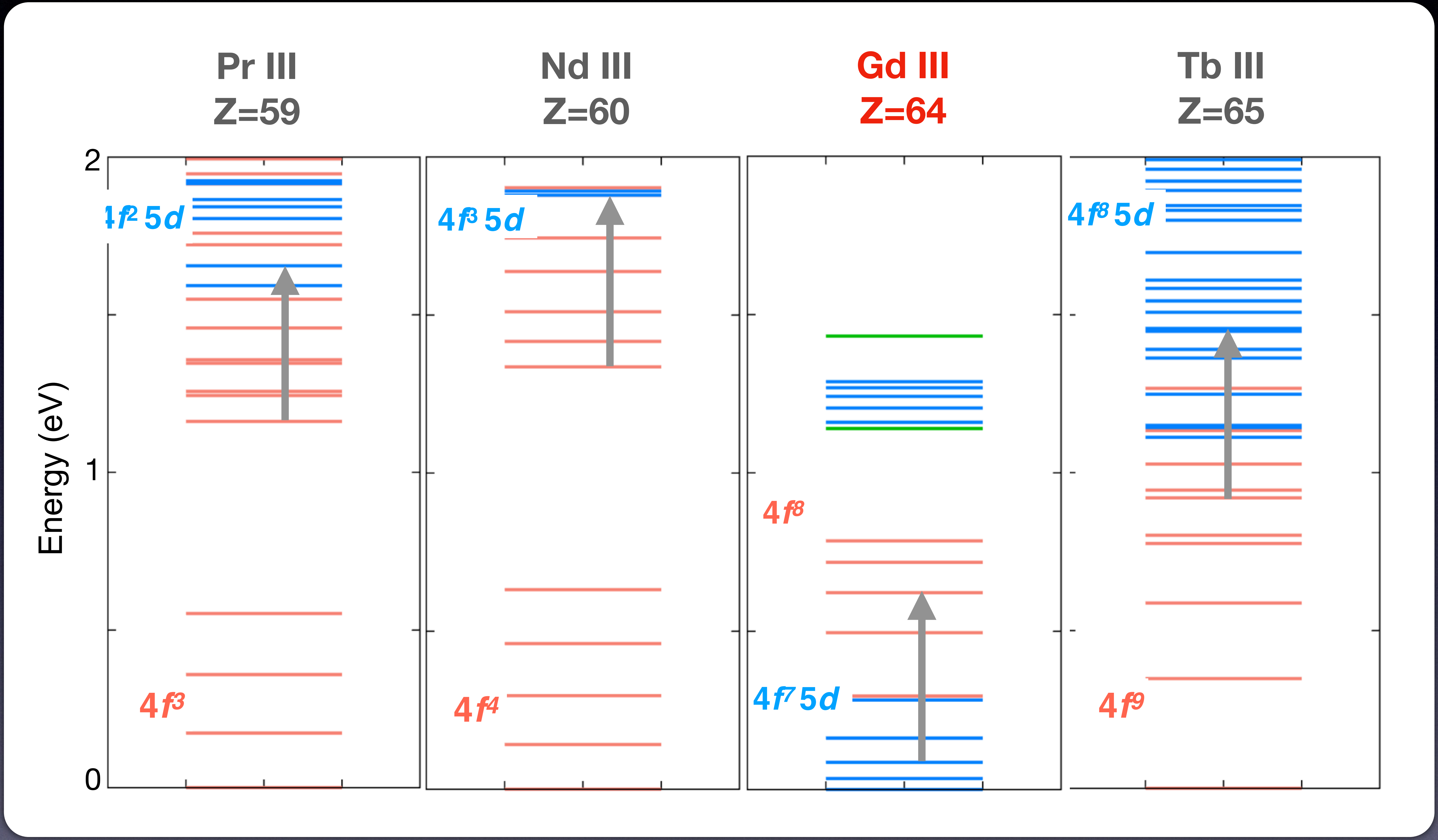
Future observations with HST/JWST

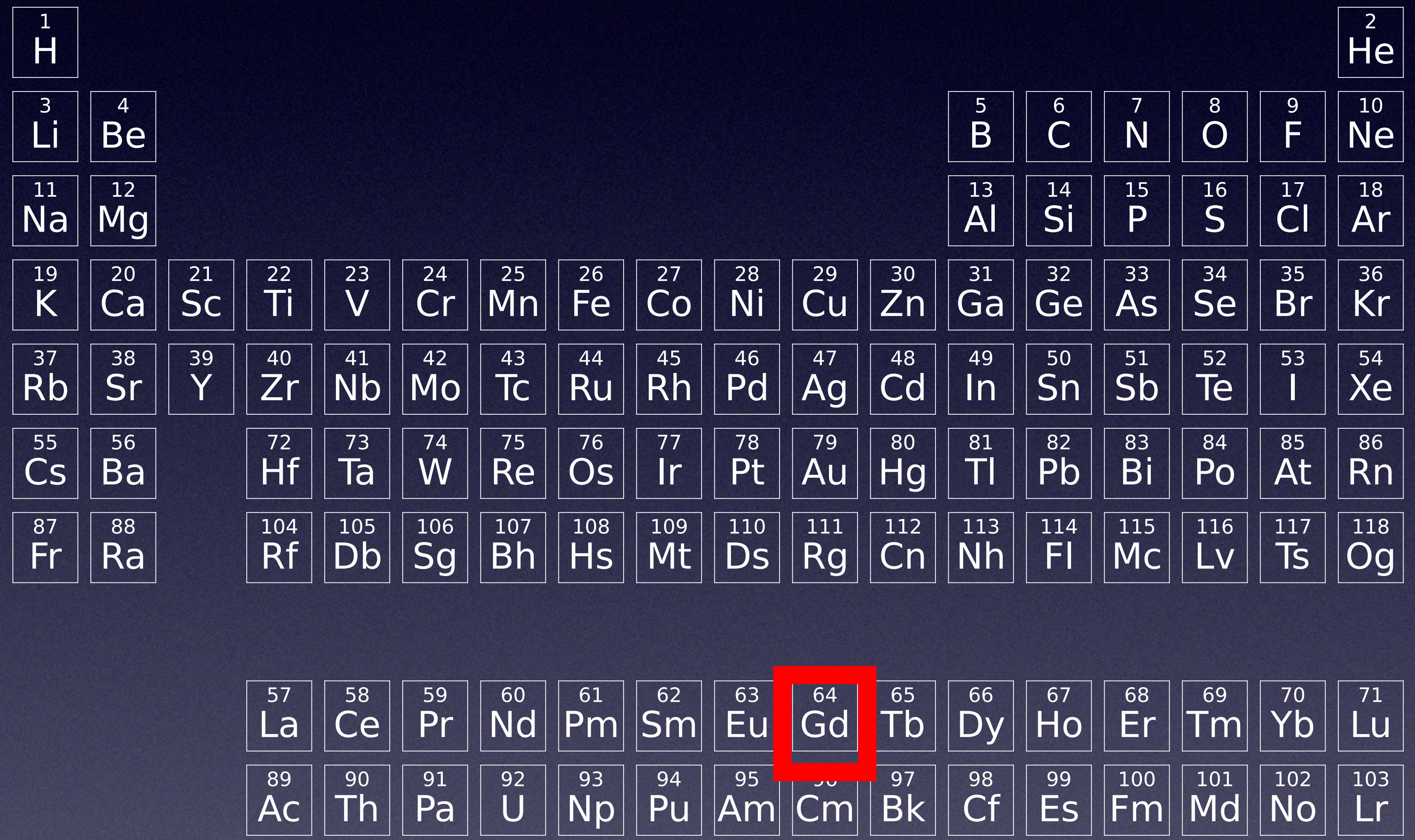
Th (Z=90) on the way to RIKEN

An interesting exception: Gd (Z=64)

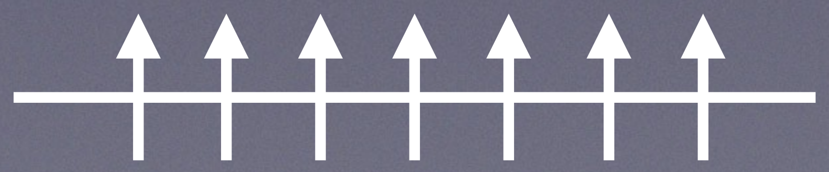
Poster by Salma Rahmouni

Rahmouni+25





$4f^7\,5d$ (4f half closed) has lower energy than $4f^8$

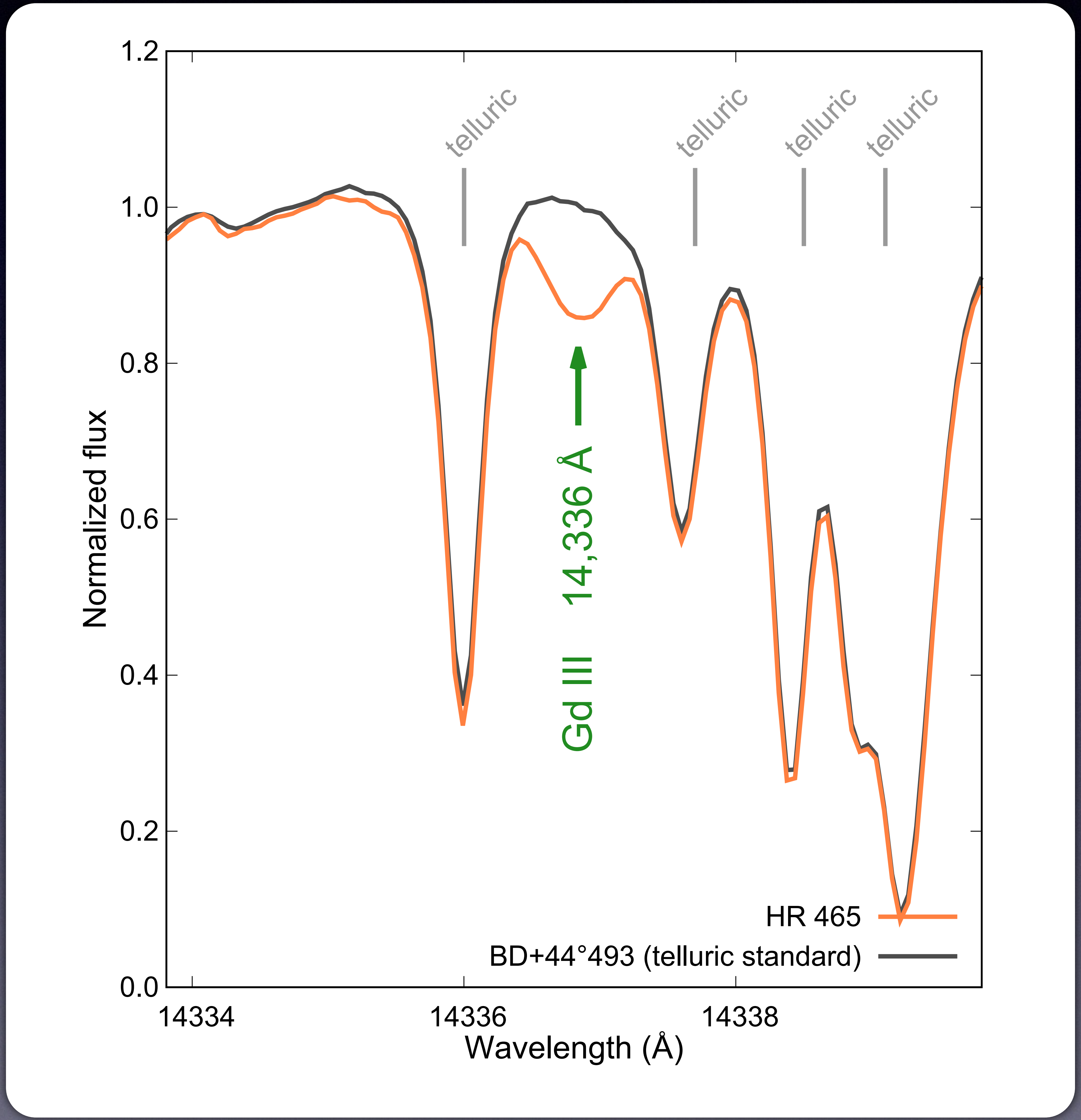


Importance of Gd features (Z=64)

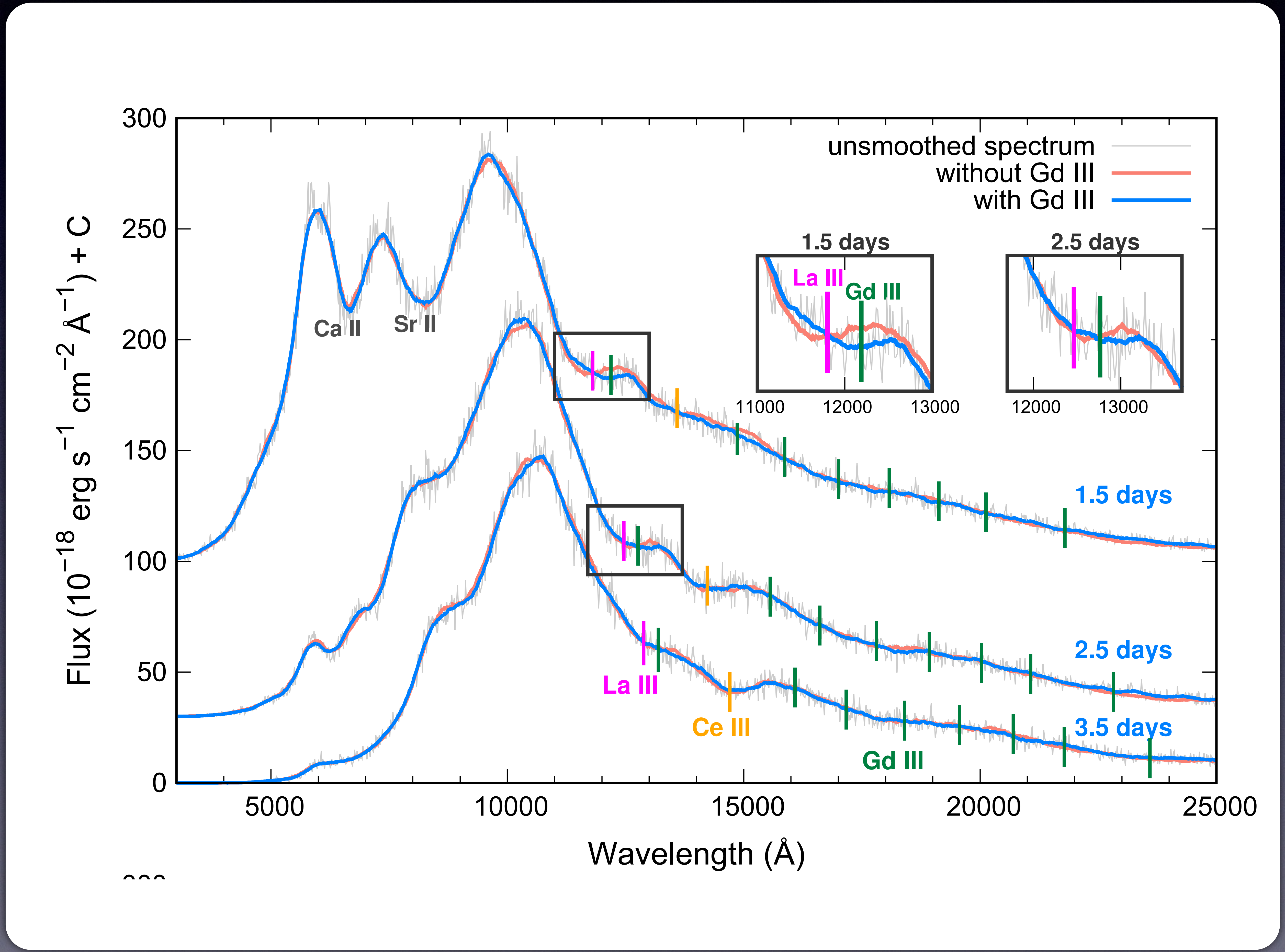
Poster by Salma Rahmouni

Rahmouni+25

Chemically peculiar star



Kilonovae



Testable with future observations with HST/JWST

“Direct” constraints on nucleosynthesis so far

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

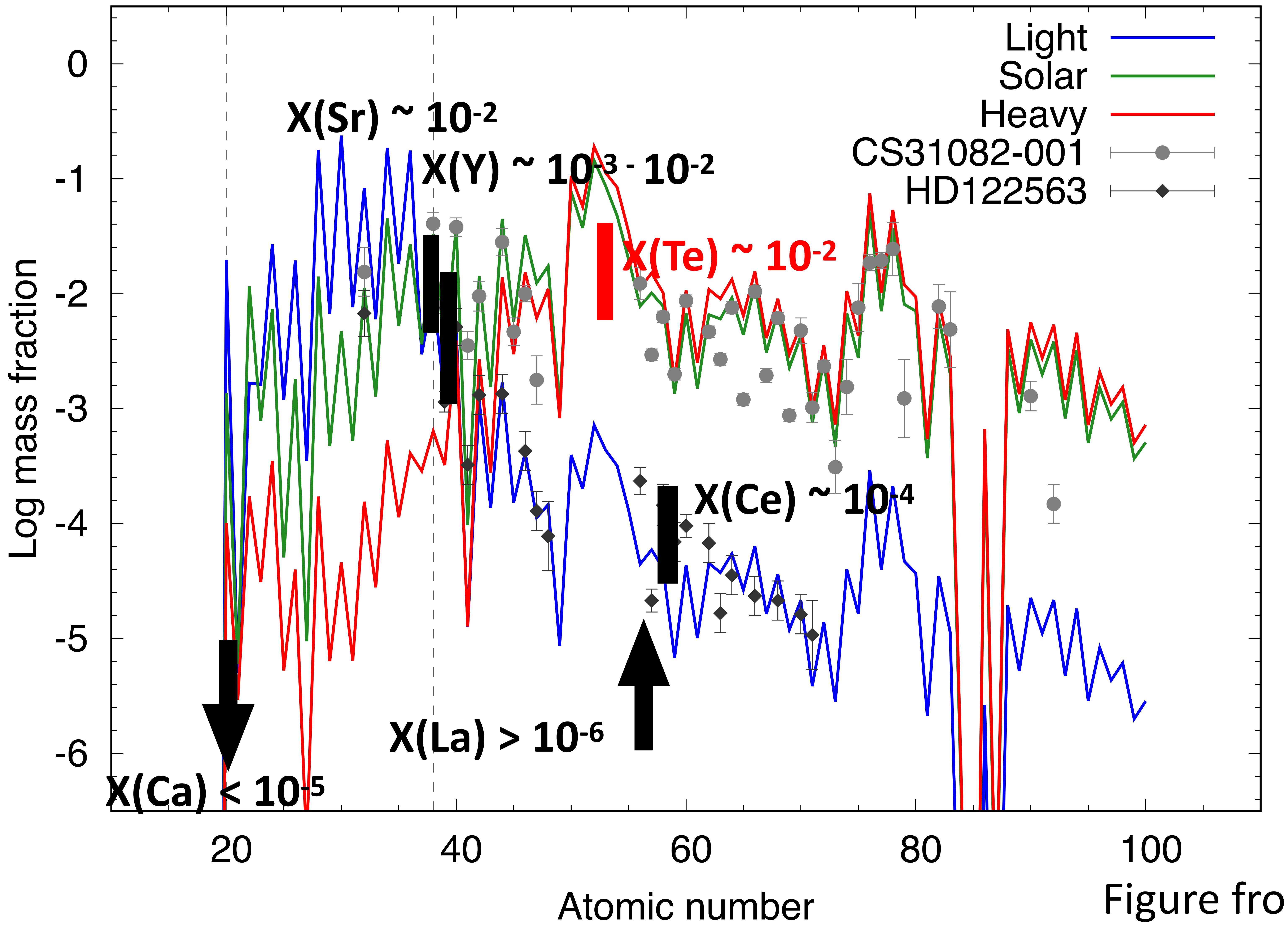


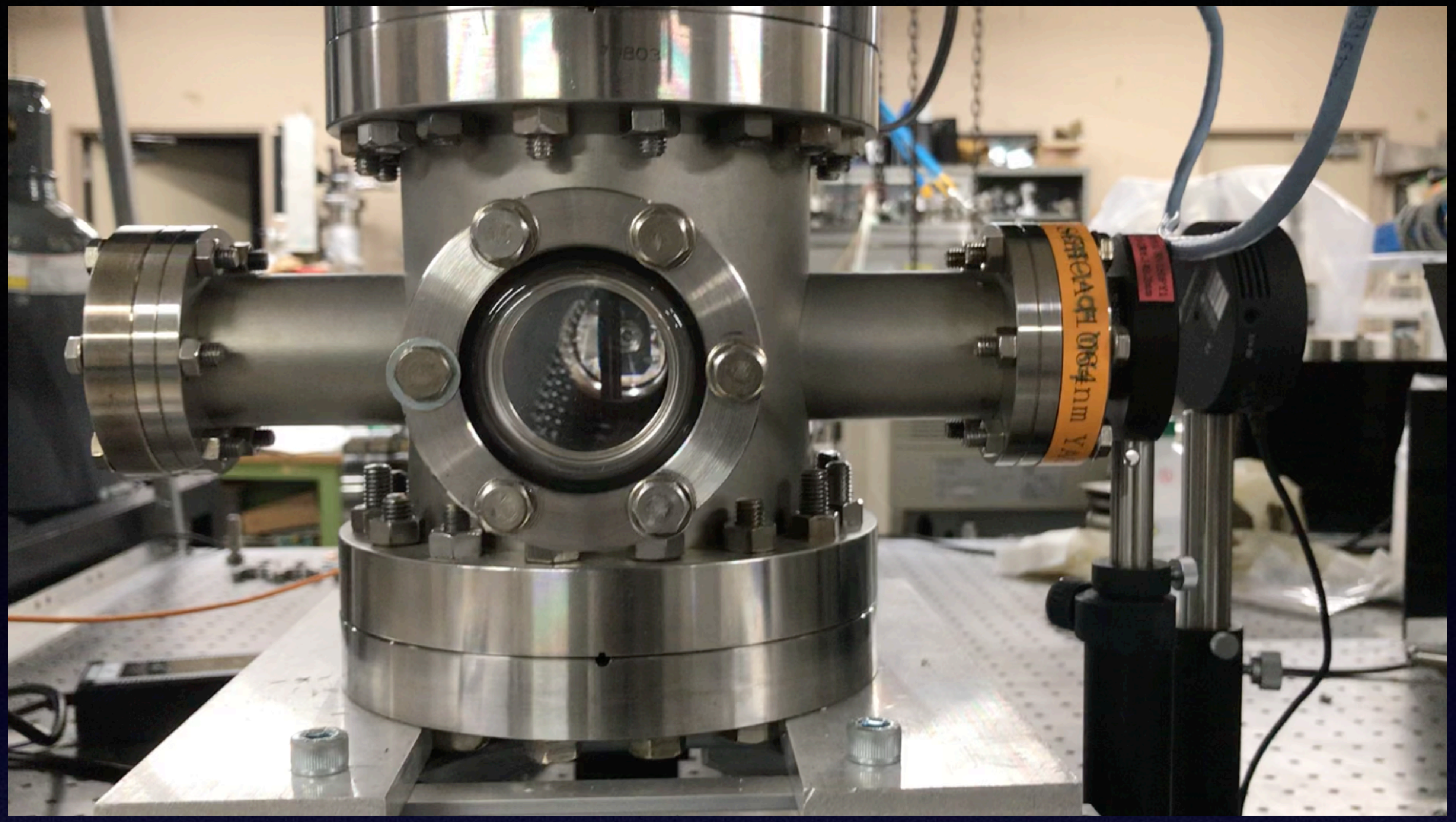
Figure from Domoto+21

Outer ejecta
Inner ejecta

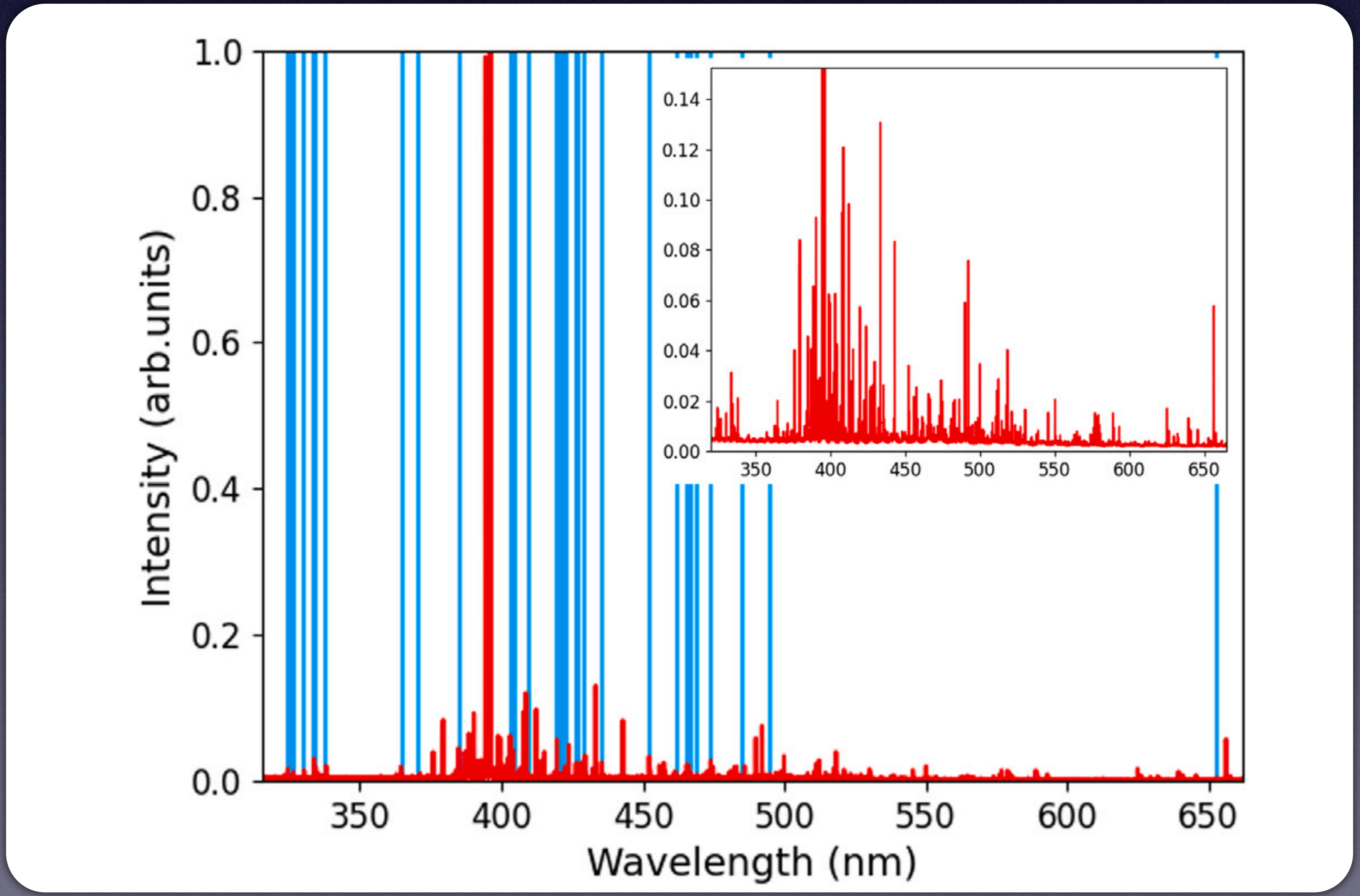
He:
Tarumi+23
Sneppen+24a,24b
(see the poster
by Albert Sneppen)

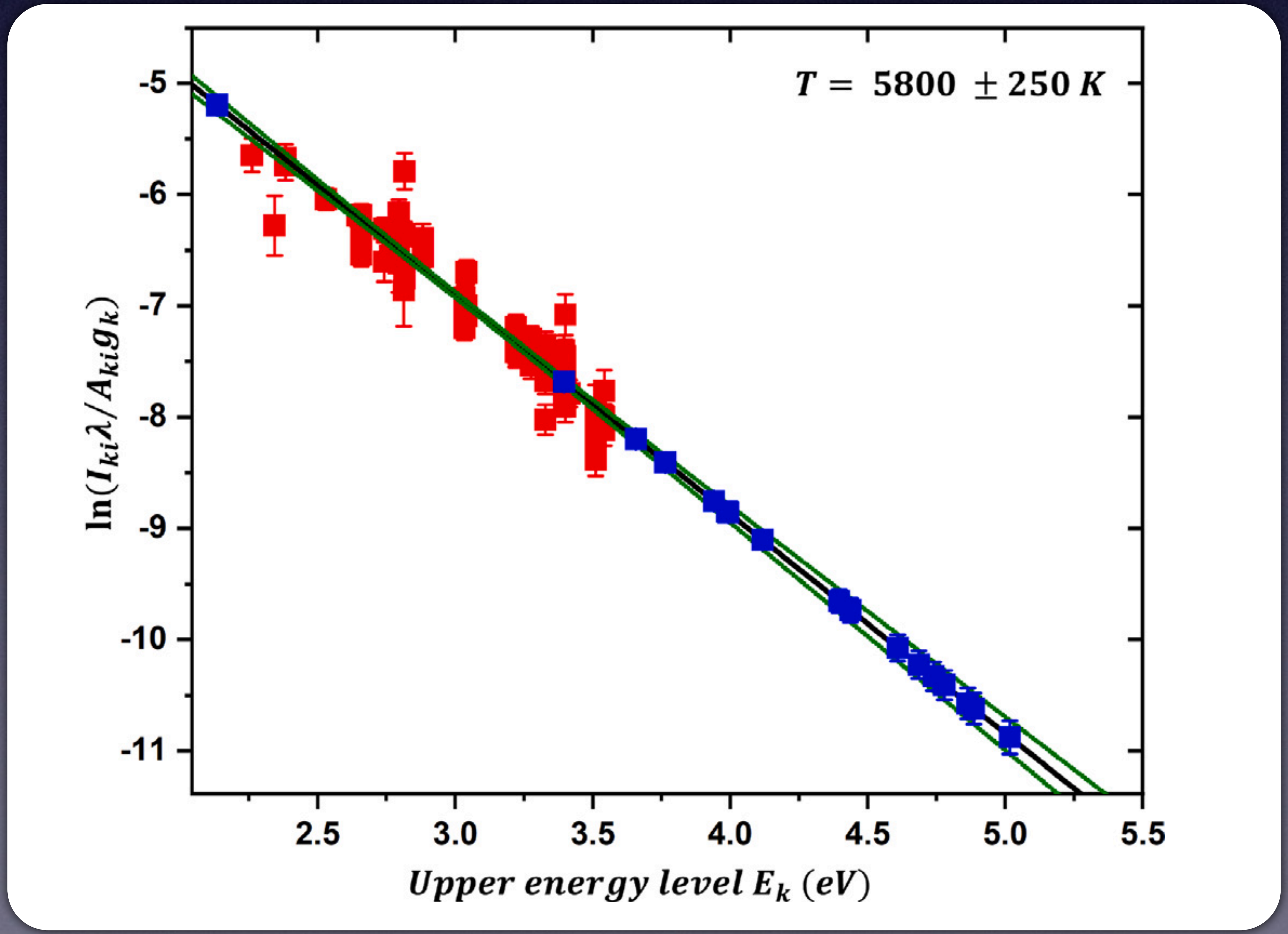
Spectroscopic experiments

Laser induced breakdown spectroscopy
(R ~ 10,000 in optical) at UEC



Kodangil, Domoto, MT+2024



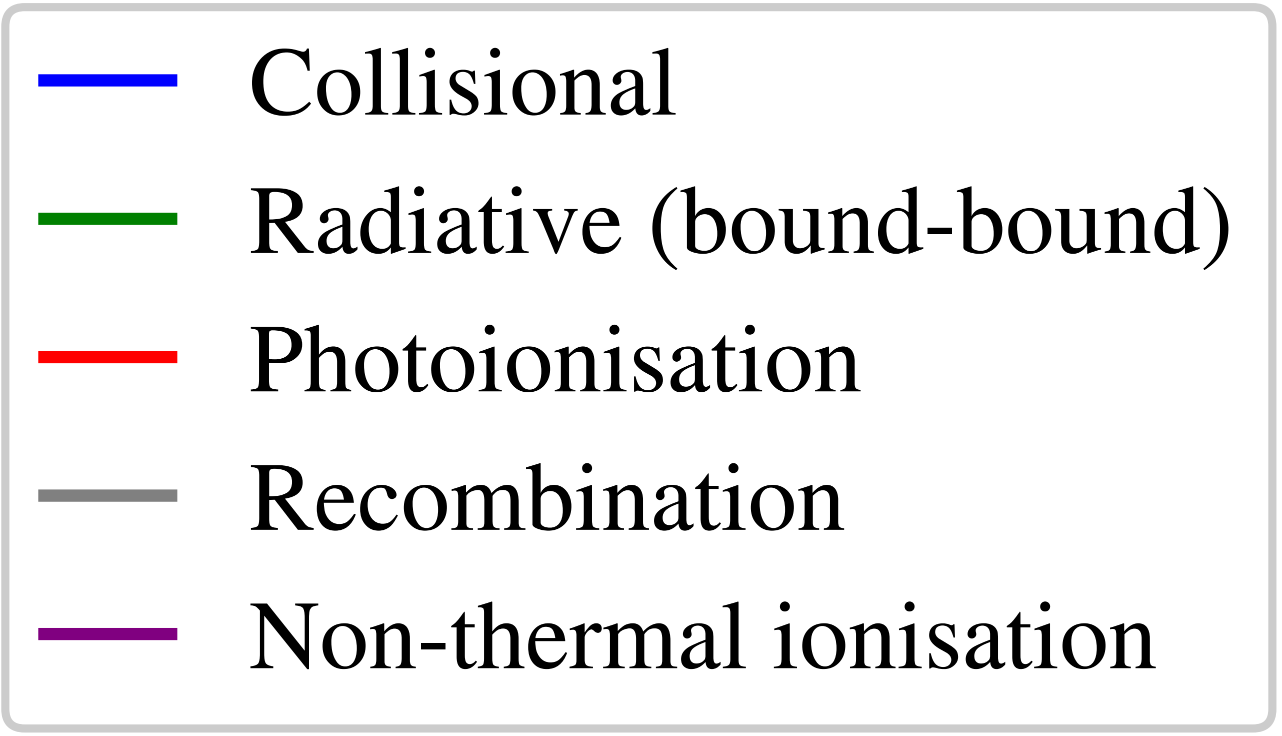


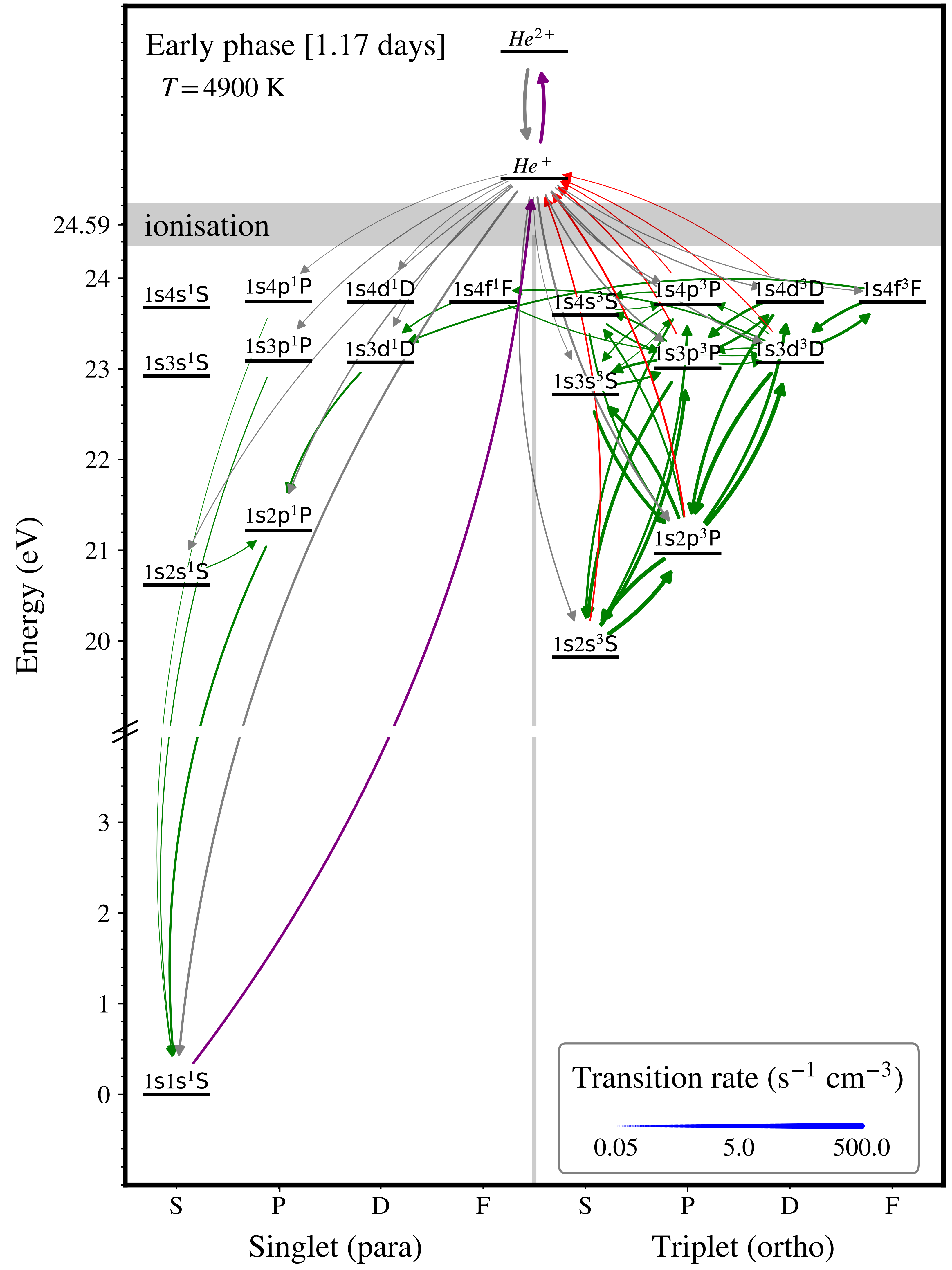
More demand for atomic data: Non-LTE plasma modeling

Need atomic data to solve
the ionization/thermal balance

- Bound-bound (Allowed + Forbidden)
- Photoionization
- Electron collision
- Recombination (Radiative + Dielectric)

Example for He





Sneppen+24

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-LTE modeling, ...**
- **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, ...**