Radiative transfer simulations for light curves and spectra of kilonovae

Masaomi Tanaka (Tohoku University)

in collaboration with
Nanae Domoto (Tohoku U.), Daiji Kato (NIFS),
Gediminas Gaigalas, Laima Radziute, Pevel Rynkun (Vilnius U.),
Smaranika Banerjee (Stockholm U.),
Kyohei Kawaguchi (AEI), Kenta Hotokezaka (U. Tokyo)

What can we learn from kilonova?

Light curves

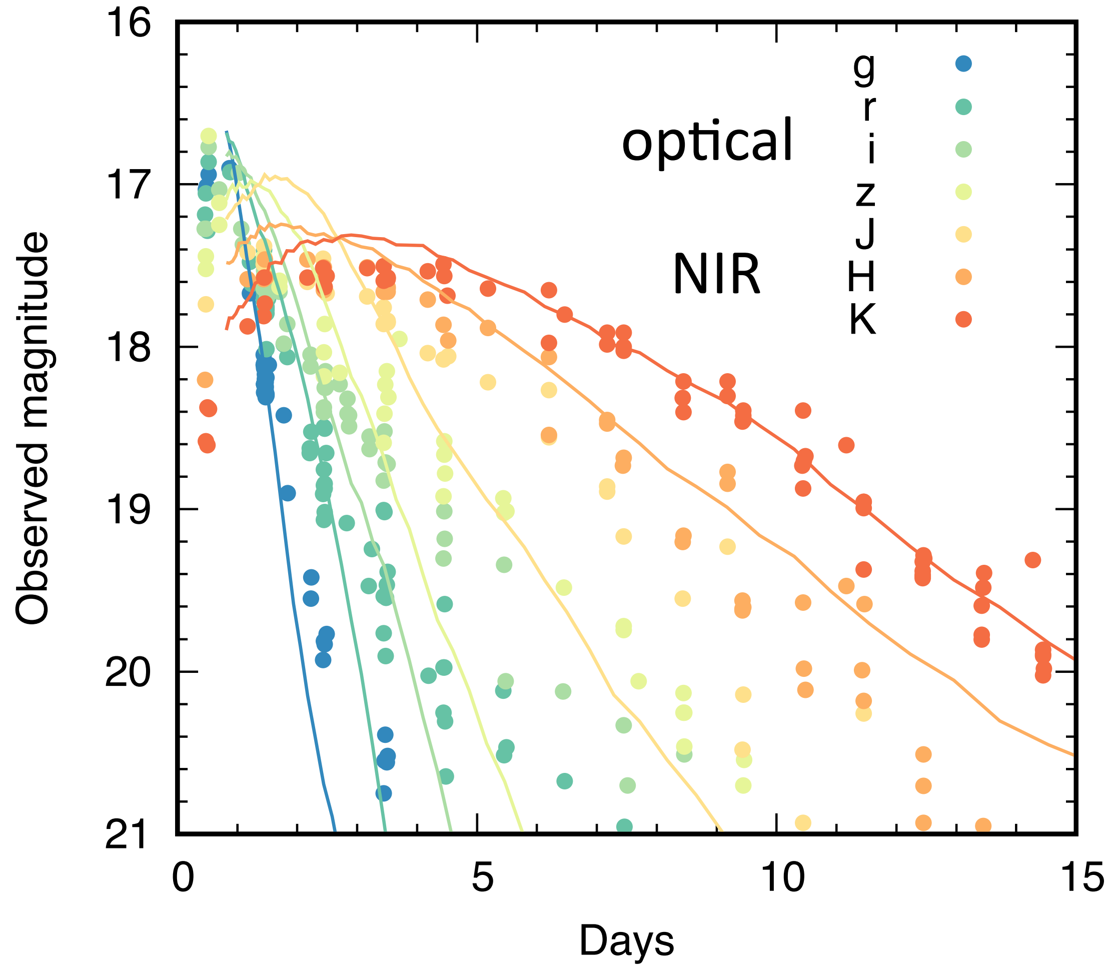


Figure from Kawaguchi+2018, 2020

Ejected mass and (rough) composition

Spectra

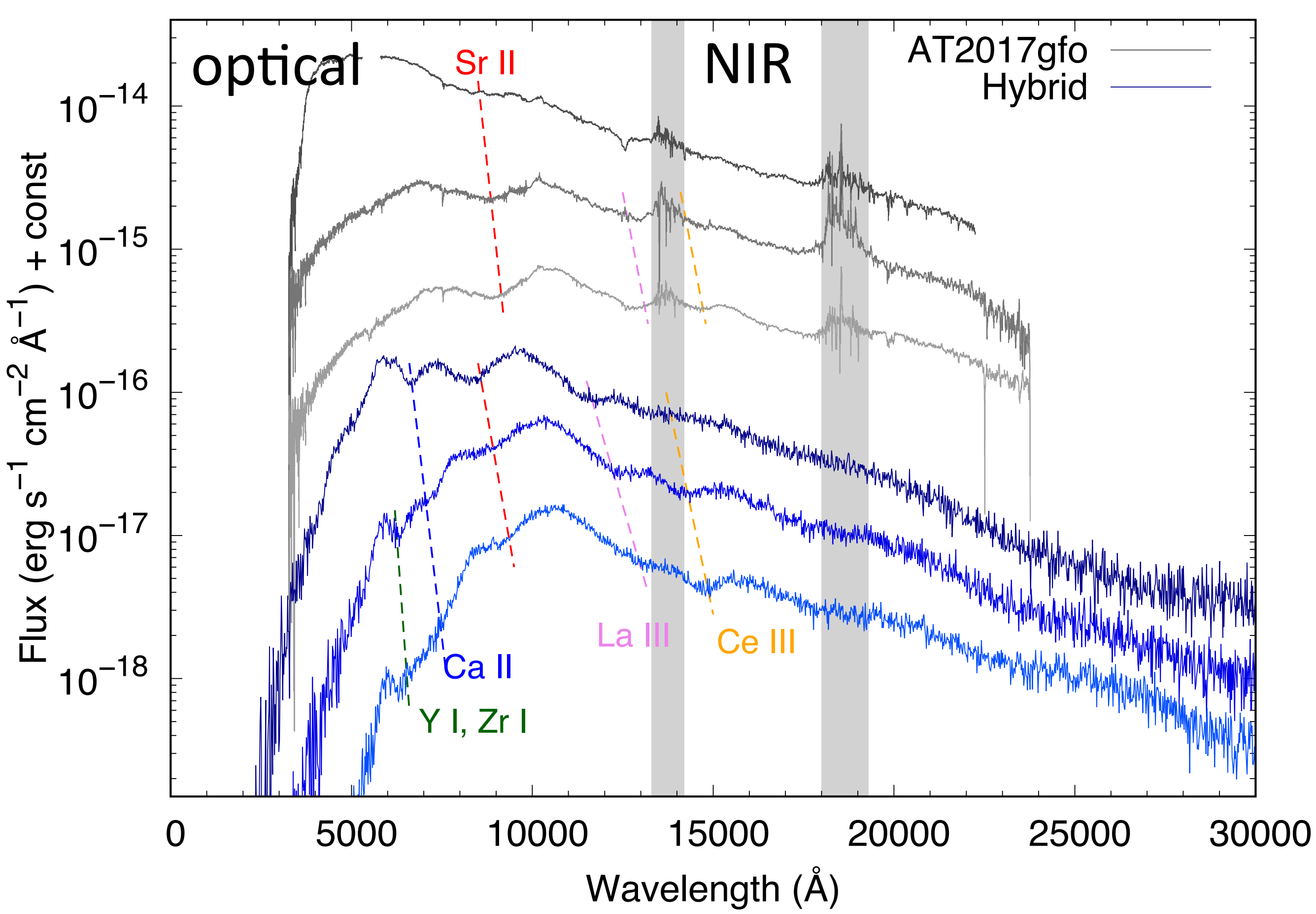


Figure from Domoto+2020,2022

Detailed composition

Origin of r-process elements

Physics of neutron star mergers

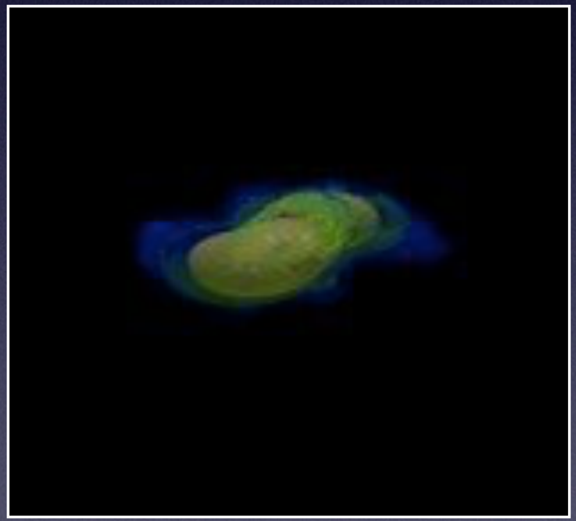
Role of kilonova radiative transfer

Numerical relativity + nucleosynthesis ⟺ **Radiative transfer** ⟺ **Kilonova observations**

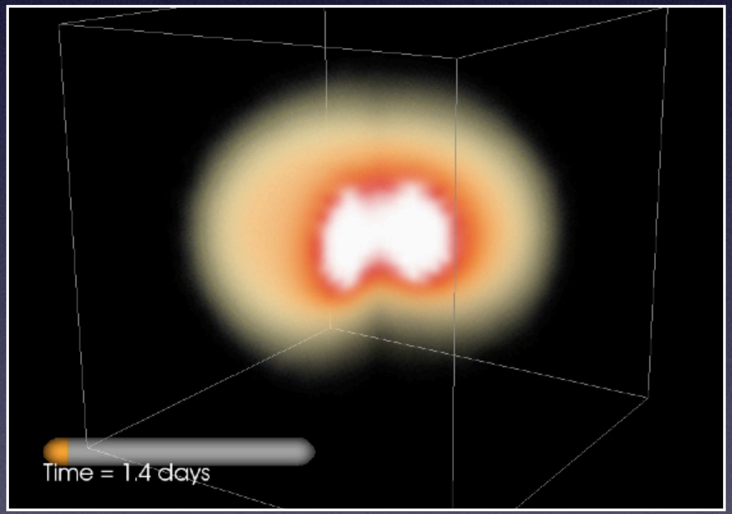
dynamical ejection => post-merger ejection

optically thick => thin

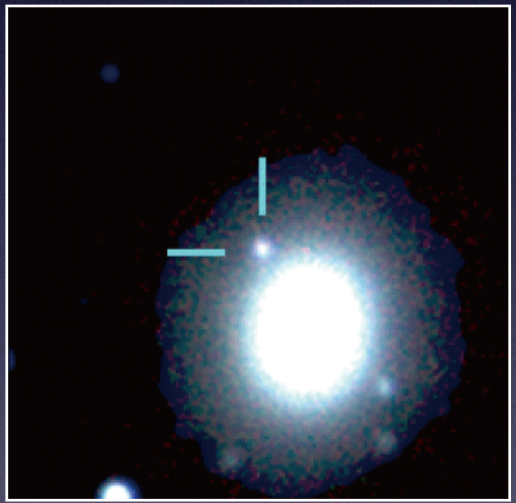
Light curves
Spectra



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



MT & Hotokezaka 13

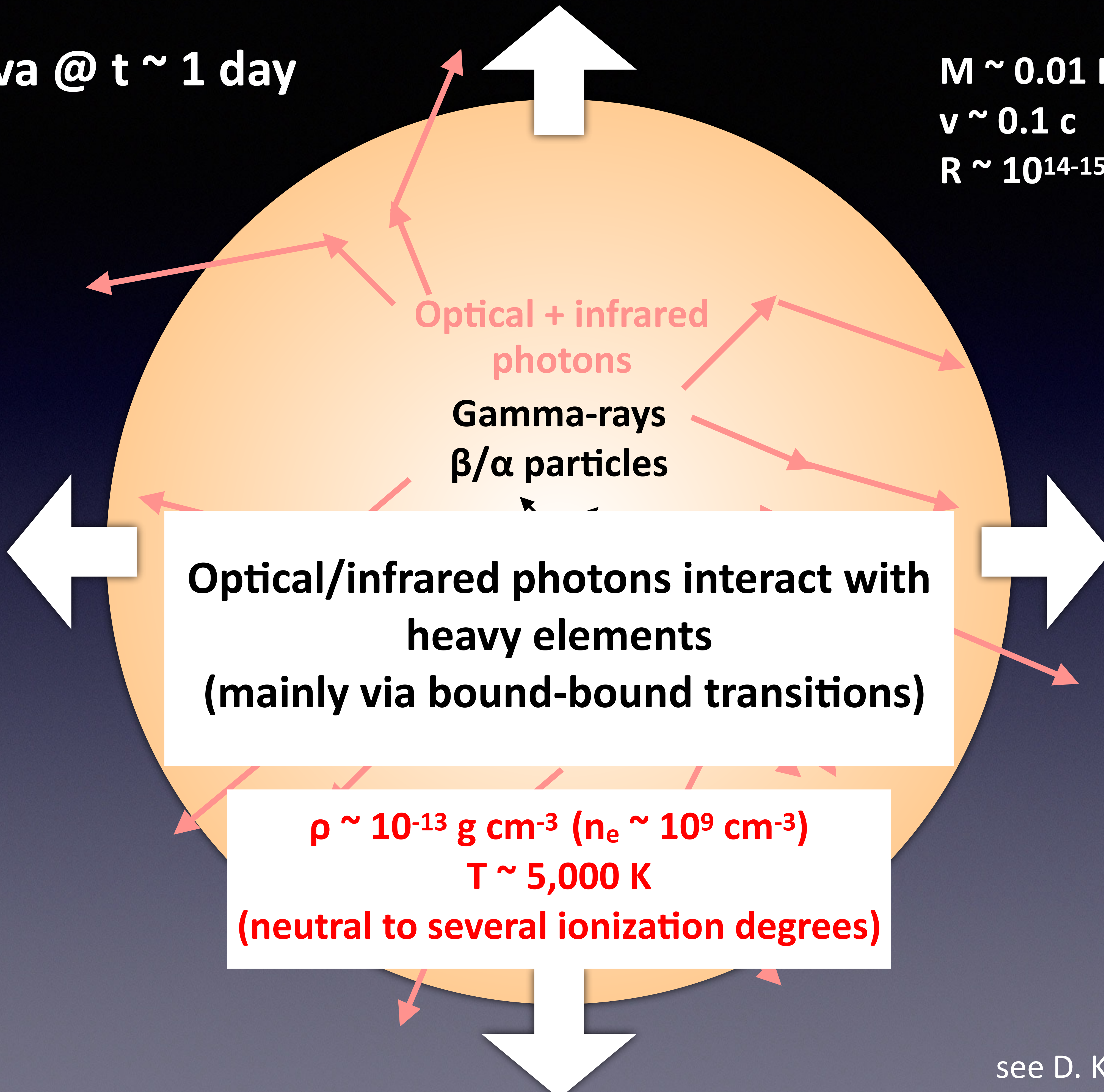


(C) NAOJ

What is necessary ingredients (= atomic data)?
What is necessary for future improvement?

Kilonova @ t ~ 1 day

M ~ 0.01 Msun
v ~ 0.1 c
R ~ $10^{14\text{-}15}$ cm



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

ρ ~ 10^{-13} g cm^{-3} (n_e ~ 10^{9} cm^{-3})
T ~ 5,000 K
(neutral to several ionization degrees)

see D. Kasen's talk

Radiative transfer simulations for light curves and spectra of kilonovae

- **Light curves**
- Spectra

Two different demands on atomic data

Light curves

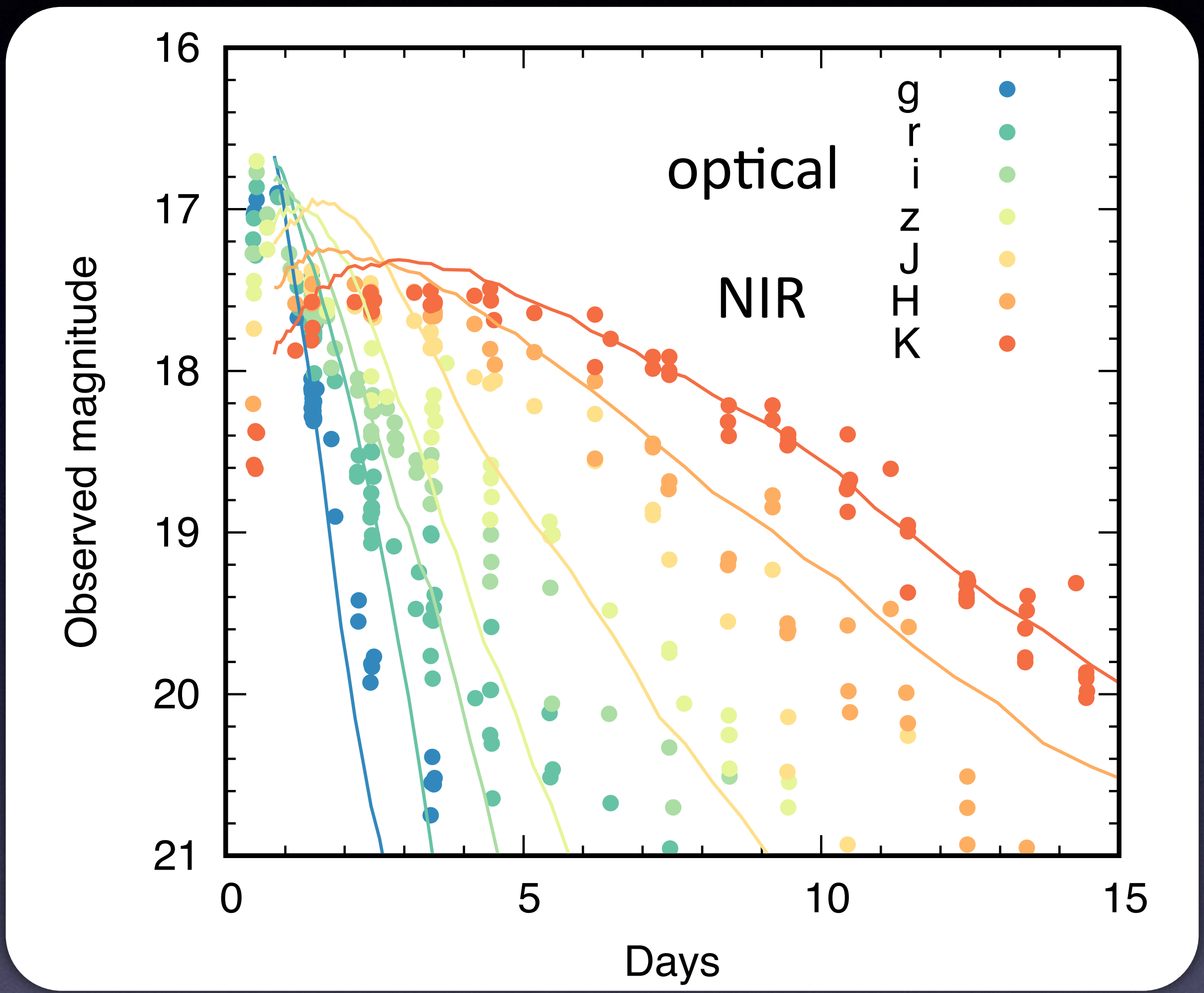


Figure from Kawaguchi+2018, 2020

Complete data for (even weak) transitions => total opacity

Spectra

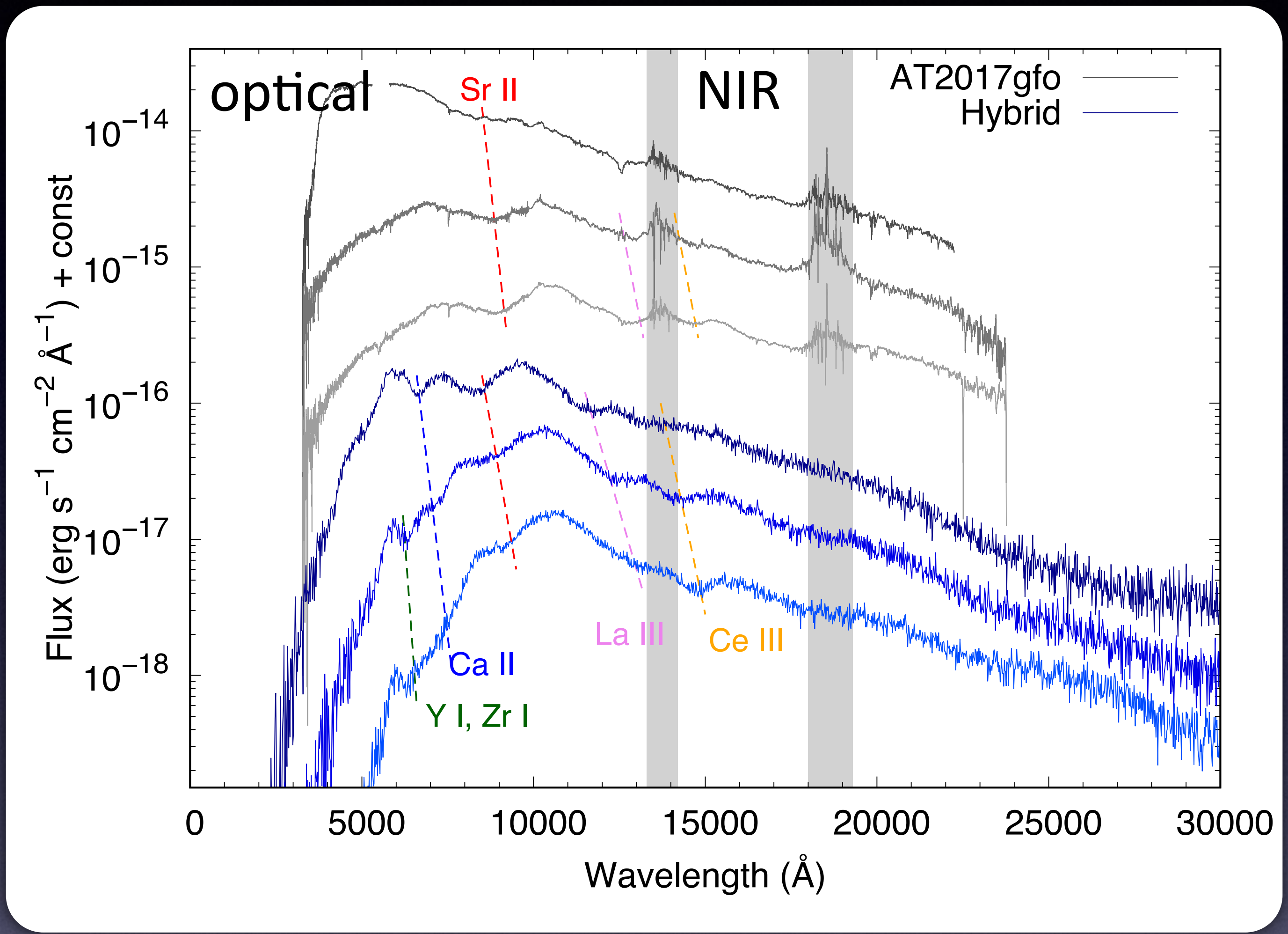


Figure from Domoto+2020,2022

Accurate data for important transitions => spectral feature

see also talks by D. Kasen, C. Fryer, A. Floers, R. Ferreira da Silva, C. Fontes, S. Banerjee, P. Palmeri, …

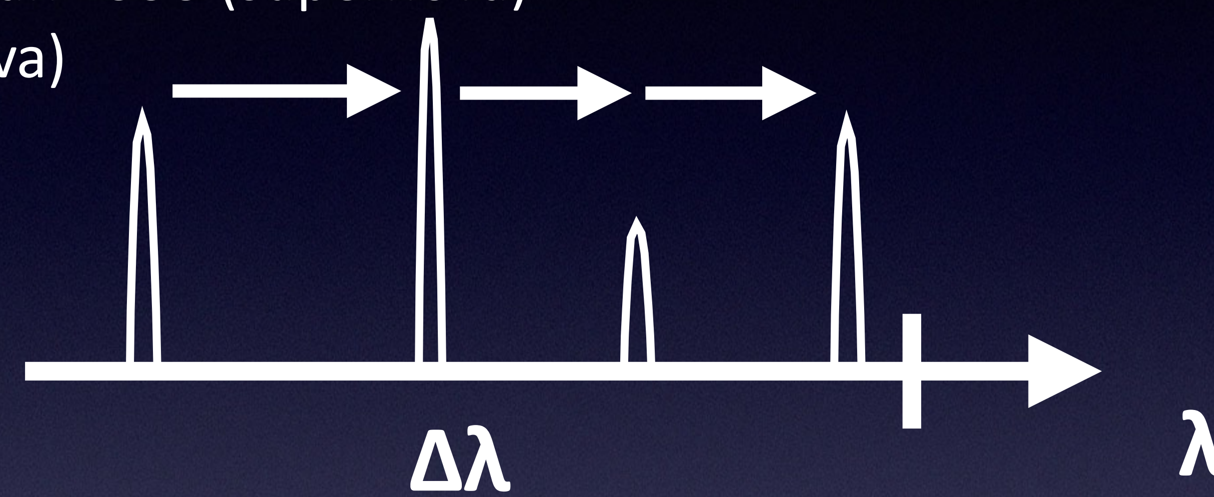
“Minimum” atomic data for NS merger opacity (LTE)

see talks by D. Kasen, Q. Pognan, K. Hotokezaka, N. Badnell for non-LTE cases

Expansion opacity

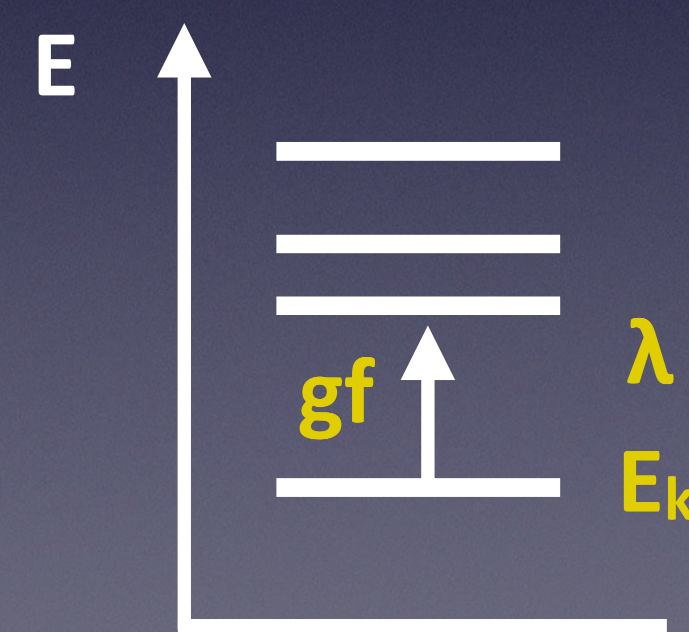
Friend & Castor 1983 (stellar wind), Pinto & Eastman 1993 (supernova)
Kasen+06, Kasen+13, MT & Hotokezaka 13 (kilonova)

$$\kappa_{\mathrm{exp}}(\lambda) = \frac{1}{ct\rho}\sum_l \frac{\lambda_l}{\Delta\lambda}\left(1 - e^{-\tau_l}\right)$$



Sobolev optical depth (homologous expansion)

$$\begin{aligned}\tau_l &= \int \alpha dr \\ &= \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l f_l \frac{g_k}{g_0} e^{-\frac{E_k}{kT}},\end{aligned}$$



No systematic, experimentally-evaluated data

Status of atomic calculations for kilonova

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

Fontes+17: Ce I-IV, Nd I-IV, Sm I-IV, U I-IV (LANL Suite)

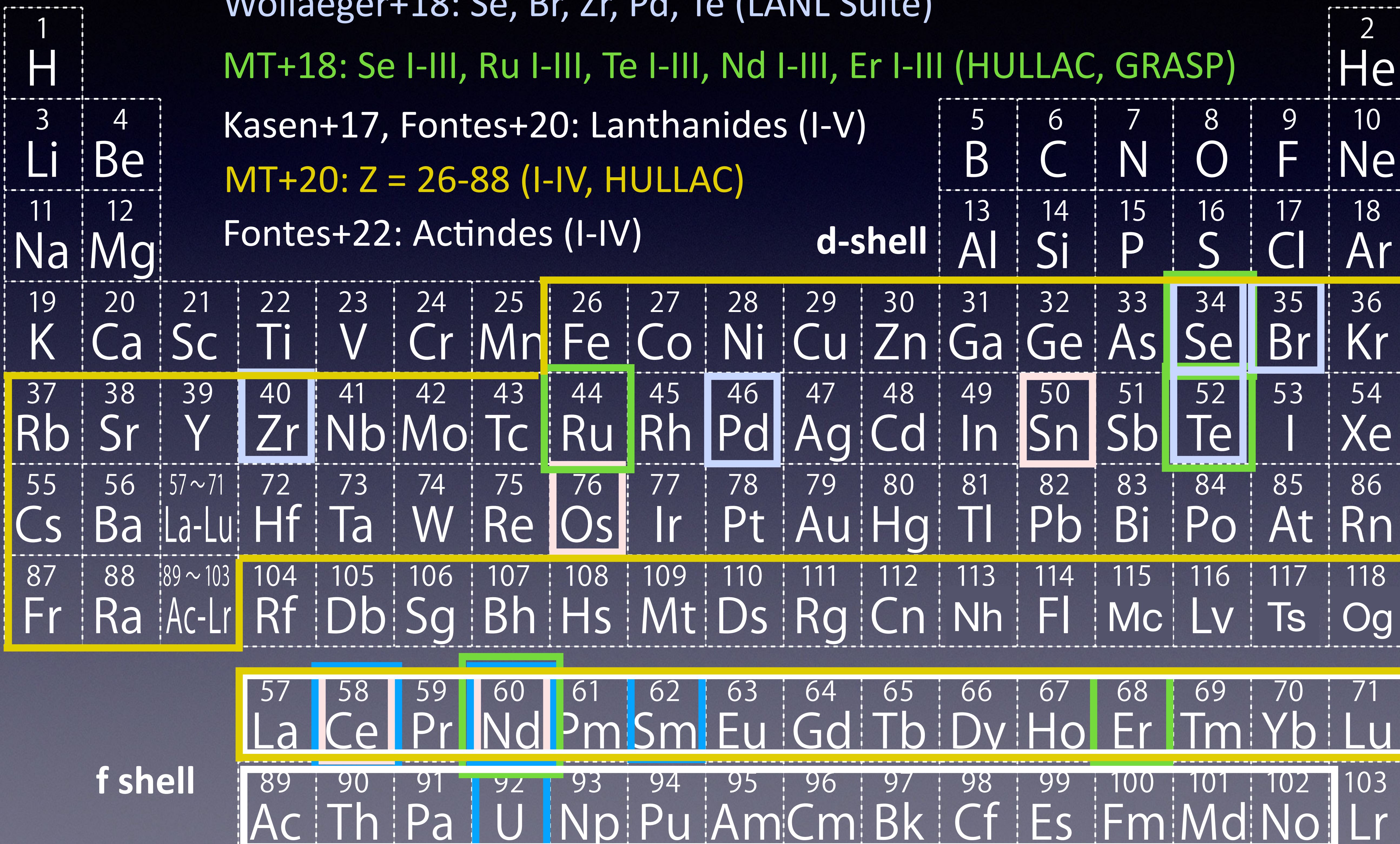
Wollaeger+18: Se, Br, Zr, Pd, Te (LANL Suite)

MT+18: Se I-III, Ru I-III, Te I-III, Nd I-III, Er I-III (HULLAC, GRASP)

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

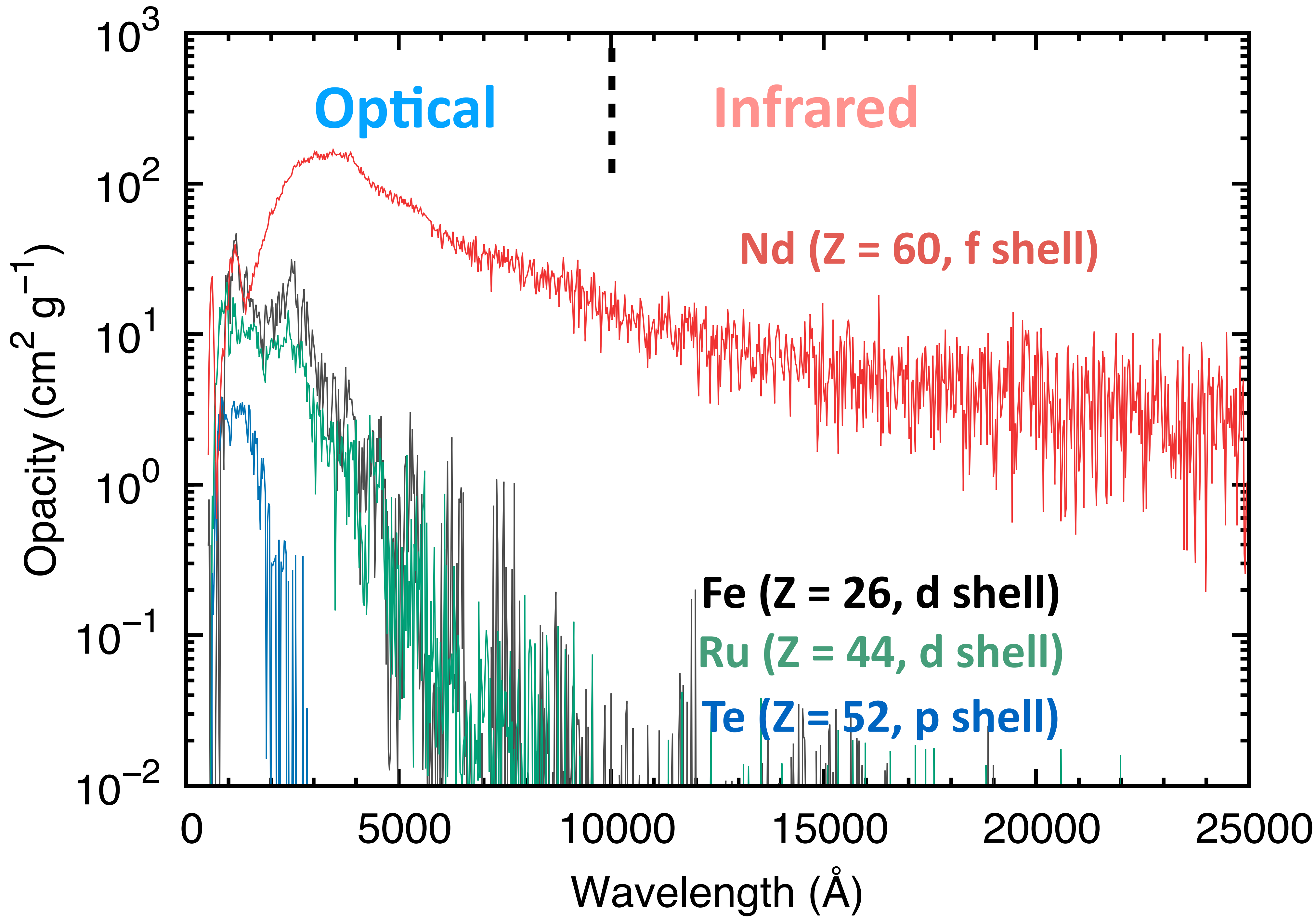
MT+20: Z = 26-88 (I-IV, HULLAC)

Fontes+22: Actindes (I-IV)

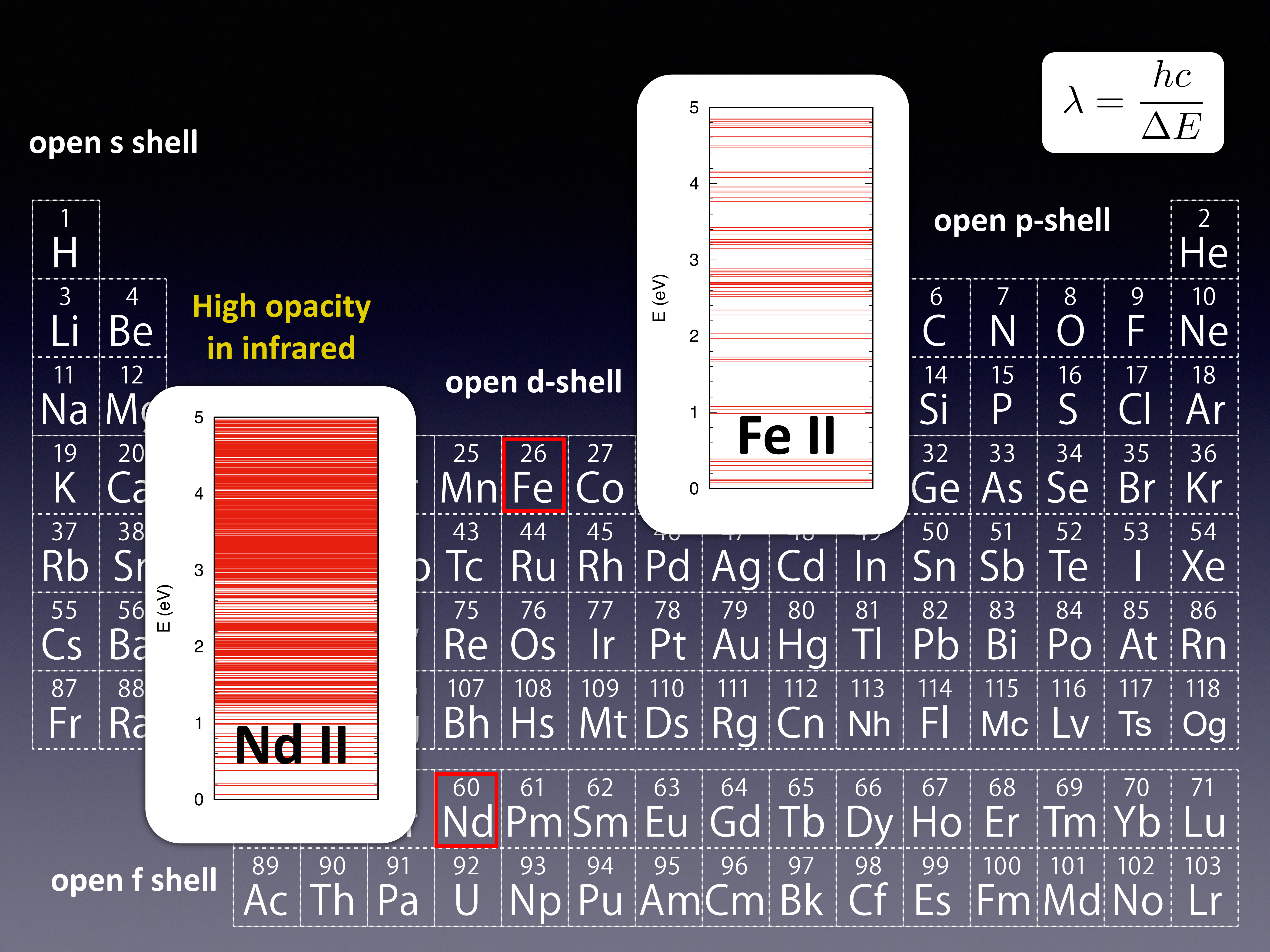


Bound-bound opacity

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



MT, Kato, Gaigalas, et al. 2018

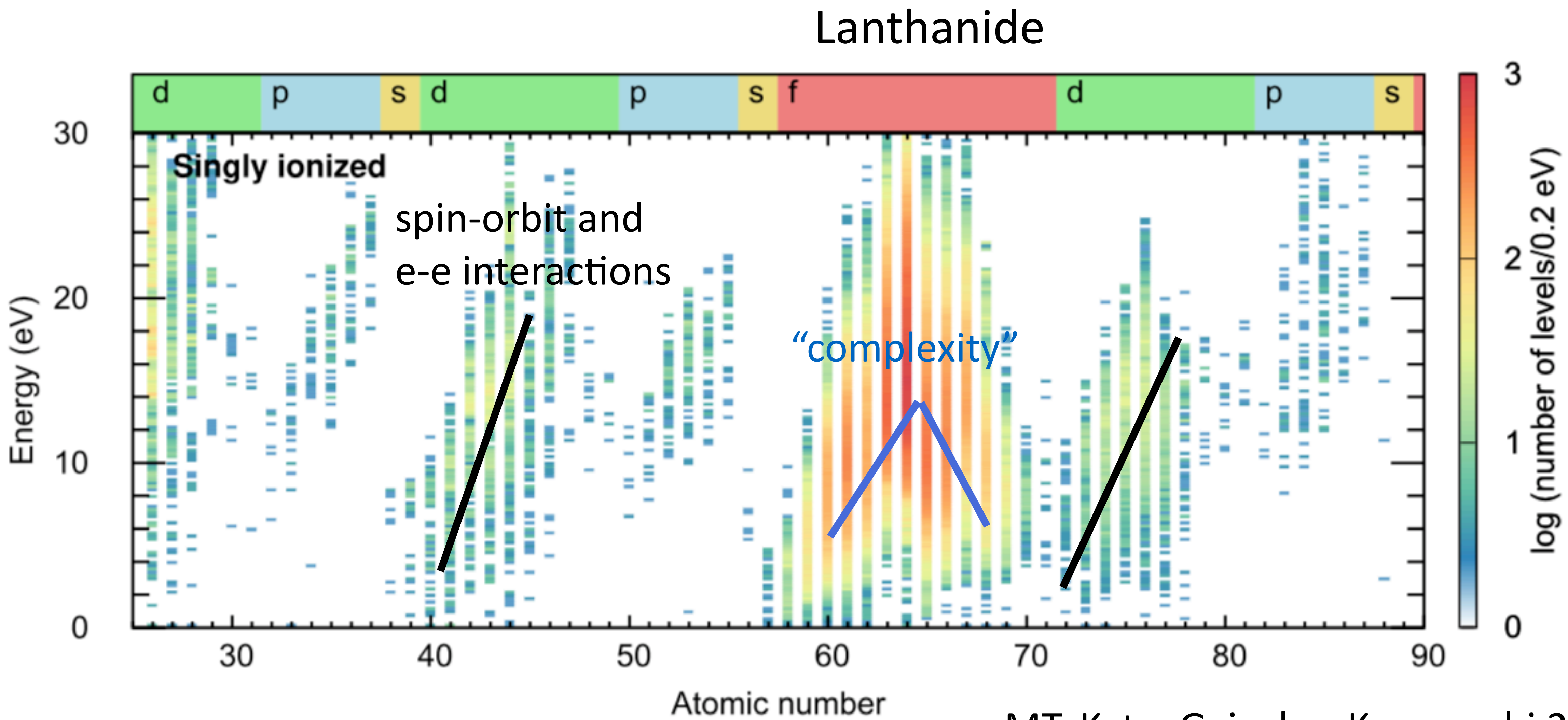


open s shell
open p-shell
open d-shell
open f shell
High opacity
in infrared
$\lambda = \frac{hc}{\Delta E}$
Fe II
Nd II
E (eV)
E (eV)

Energy level distribution

calculated with HULLAC code

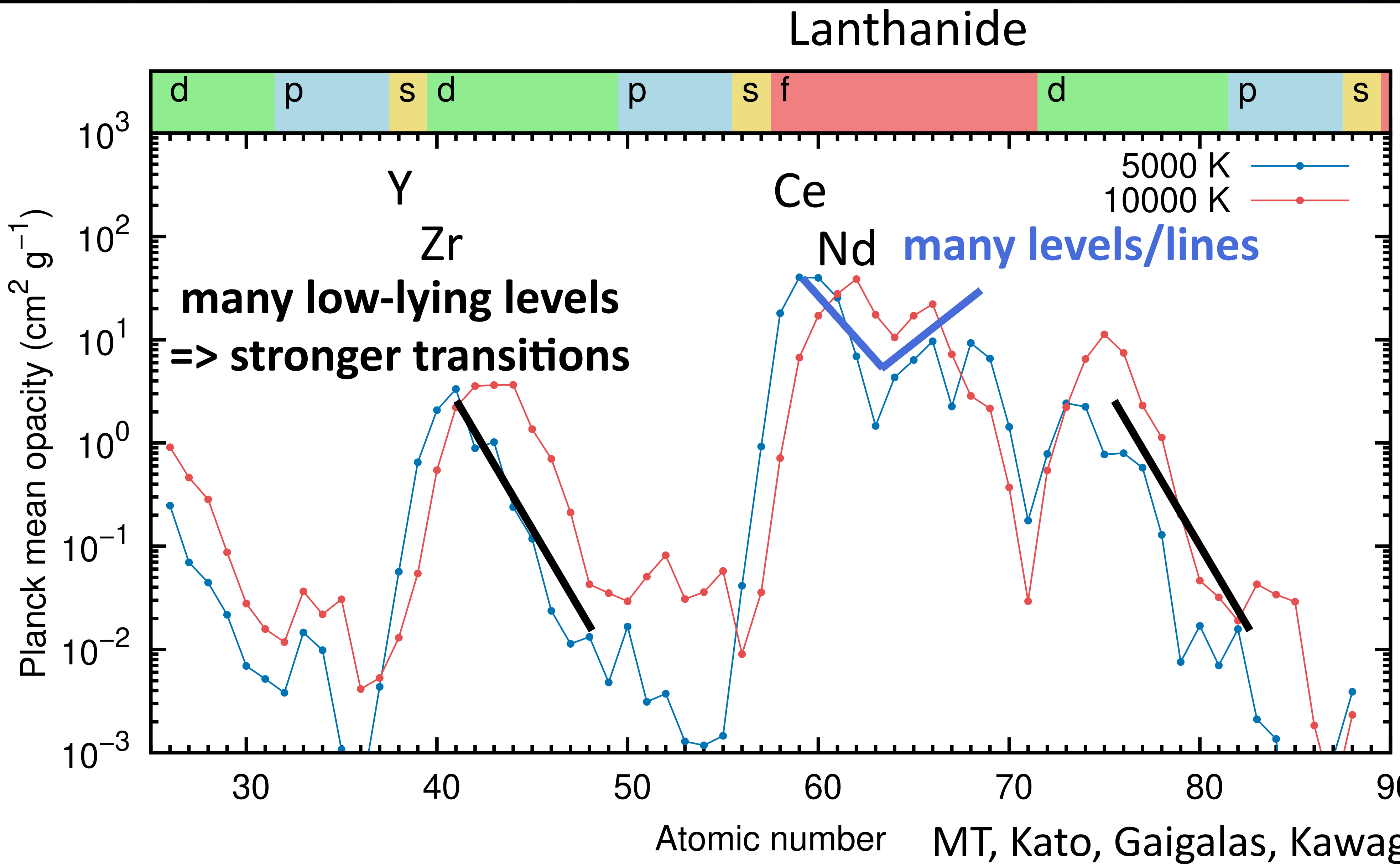
All the data are available at
http://dpc.nifs.ac.jp/DB/Opacity-Database/



MT, Kato, Gaigalas, Kawaguchi 20

Opacity (Planck mean)

All the data are available at
http://dpc.nifs.ac.jp/DB/Opacity-Database/



MT, Kato, Gaigalas, Kawaguchi 20

$$\kappa_{\rm exp}(\lambda) = \frac{1}{ct\rho}\sum_l \frac{\lambda_l}{\Delta\lambda}(1-e^{-\tau_l})$$

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l f_l \frac{g_k}{g_0} e^{-\frac{E_k}{kT}}$$

Understanding the impact of accuracy in atomic calculations

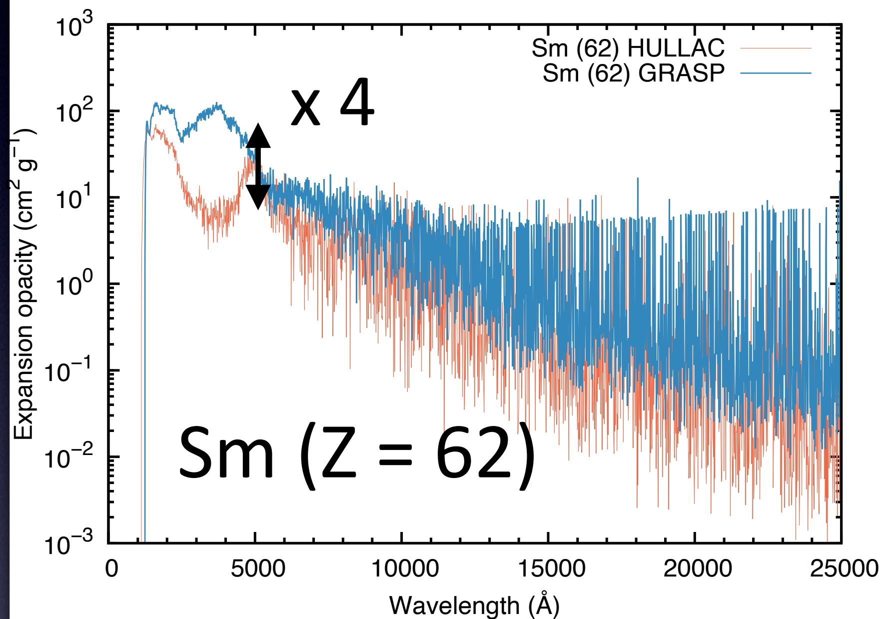
see Gaigalas+19 for Nd (see also Floers+23)

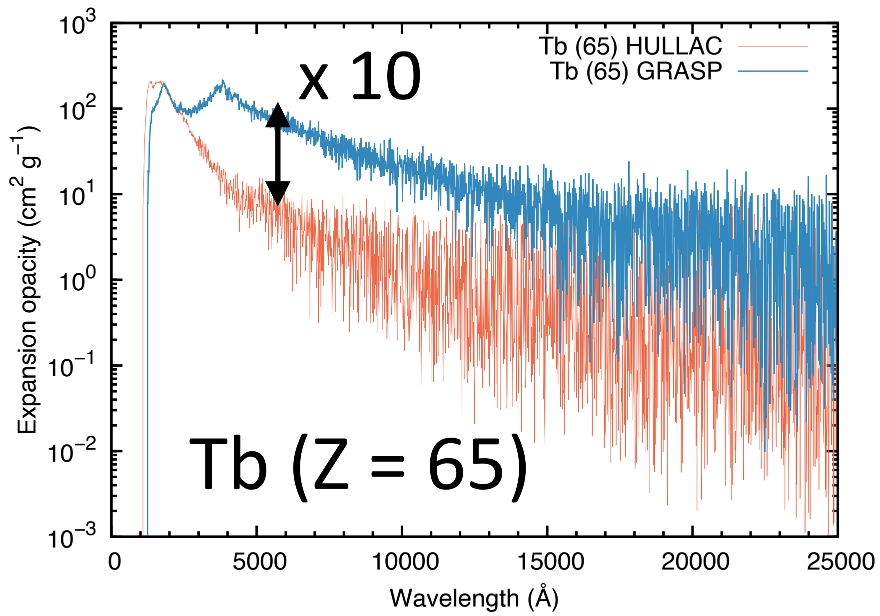
Singly ionized lanthanides

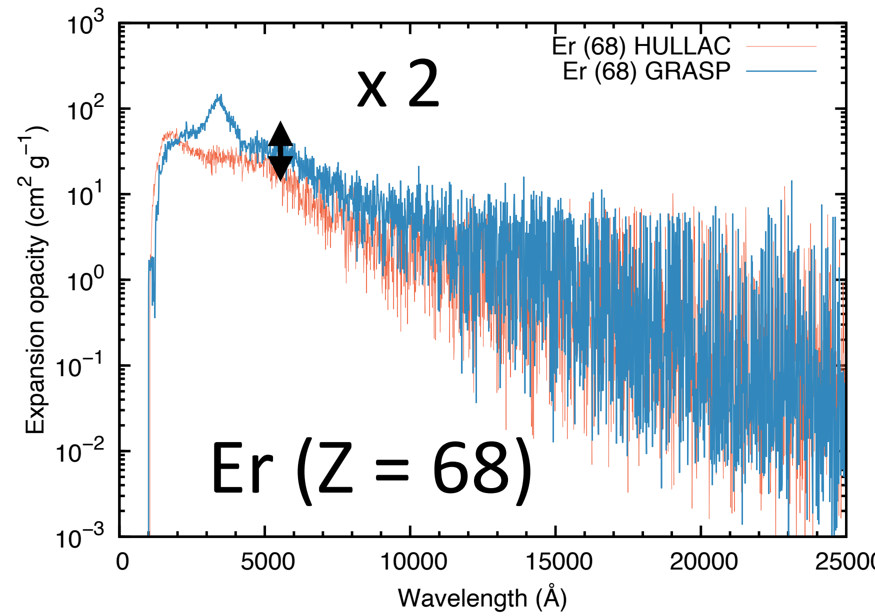
GRASP (Radziute+20, 21) see P. Jonsson's talk

HULLAC (Tanaka+20)

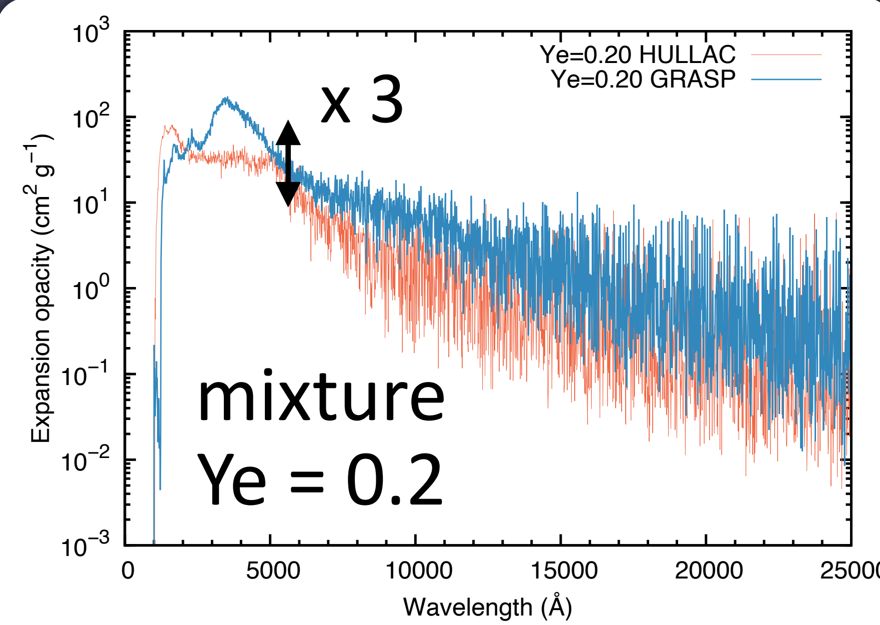
T = 5000 K



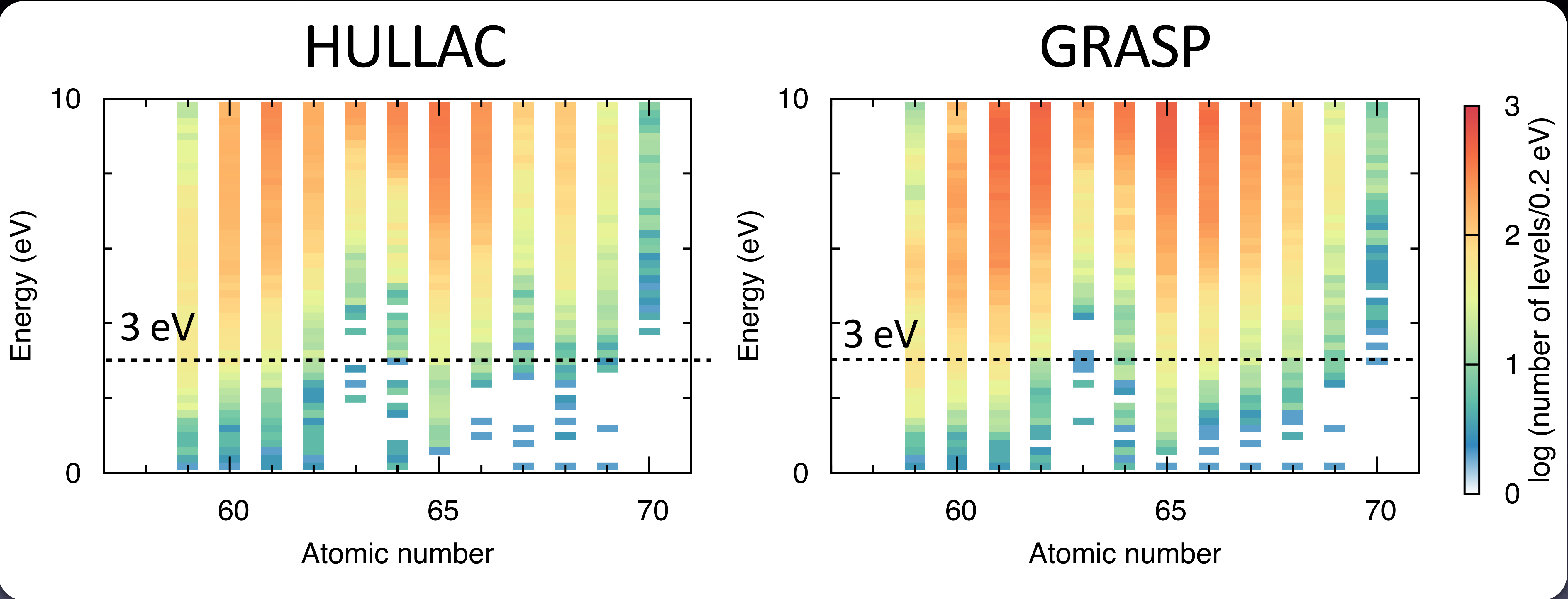




Largest difference in the most complex ions



Energy level distributions

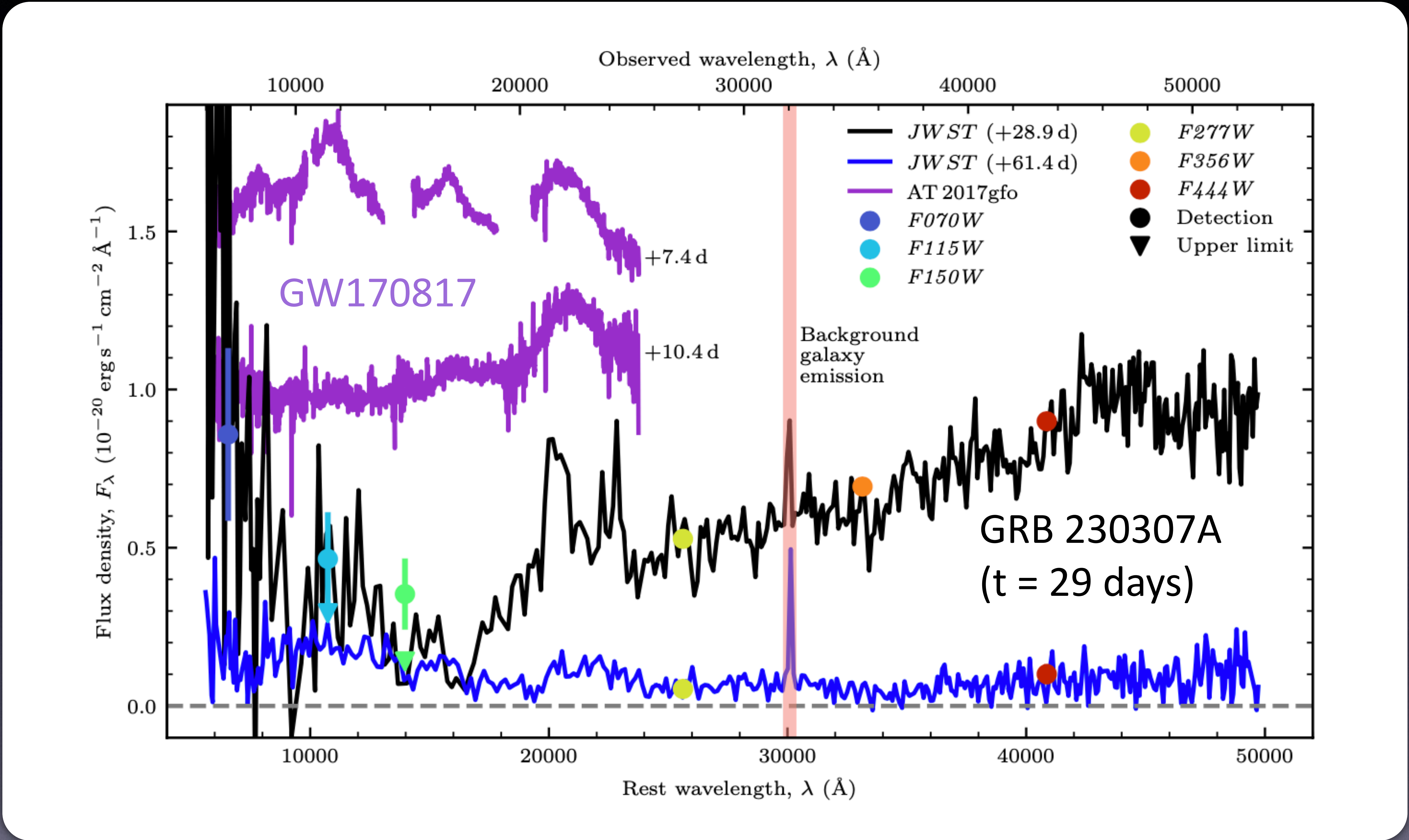


HULLAC results tend to show upward energy level distribution

(Main difference is in $4f^n$ 5d 6s configurations)

Kilonova in GRB230307A?

Levan+23, Gillanders+23

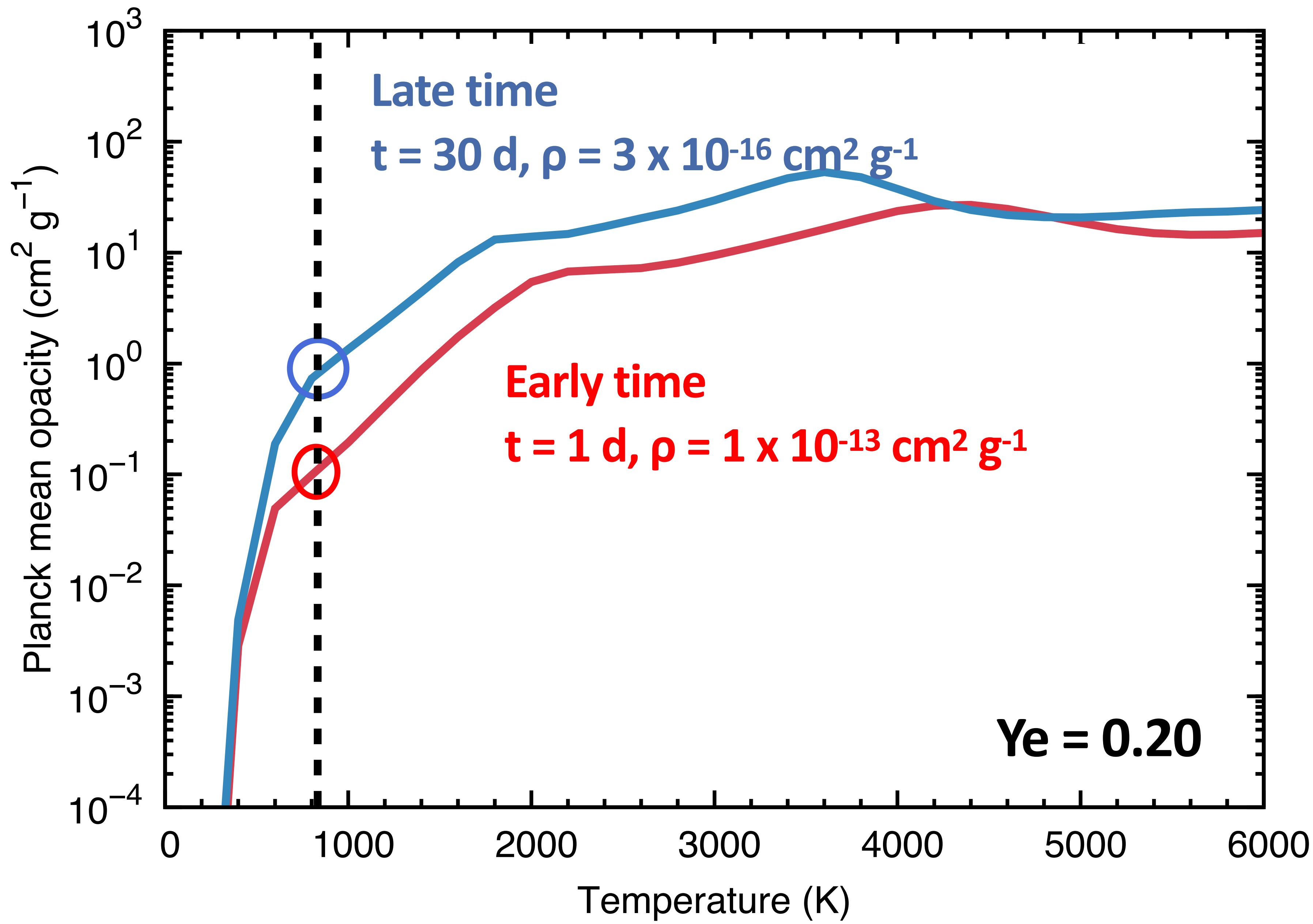


κ >~ 5 cm^2 g^{-1} to keep the photosphere

High opacity at late time?

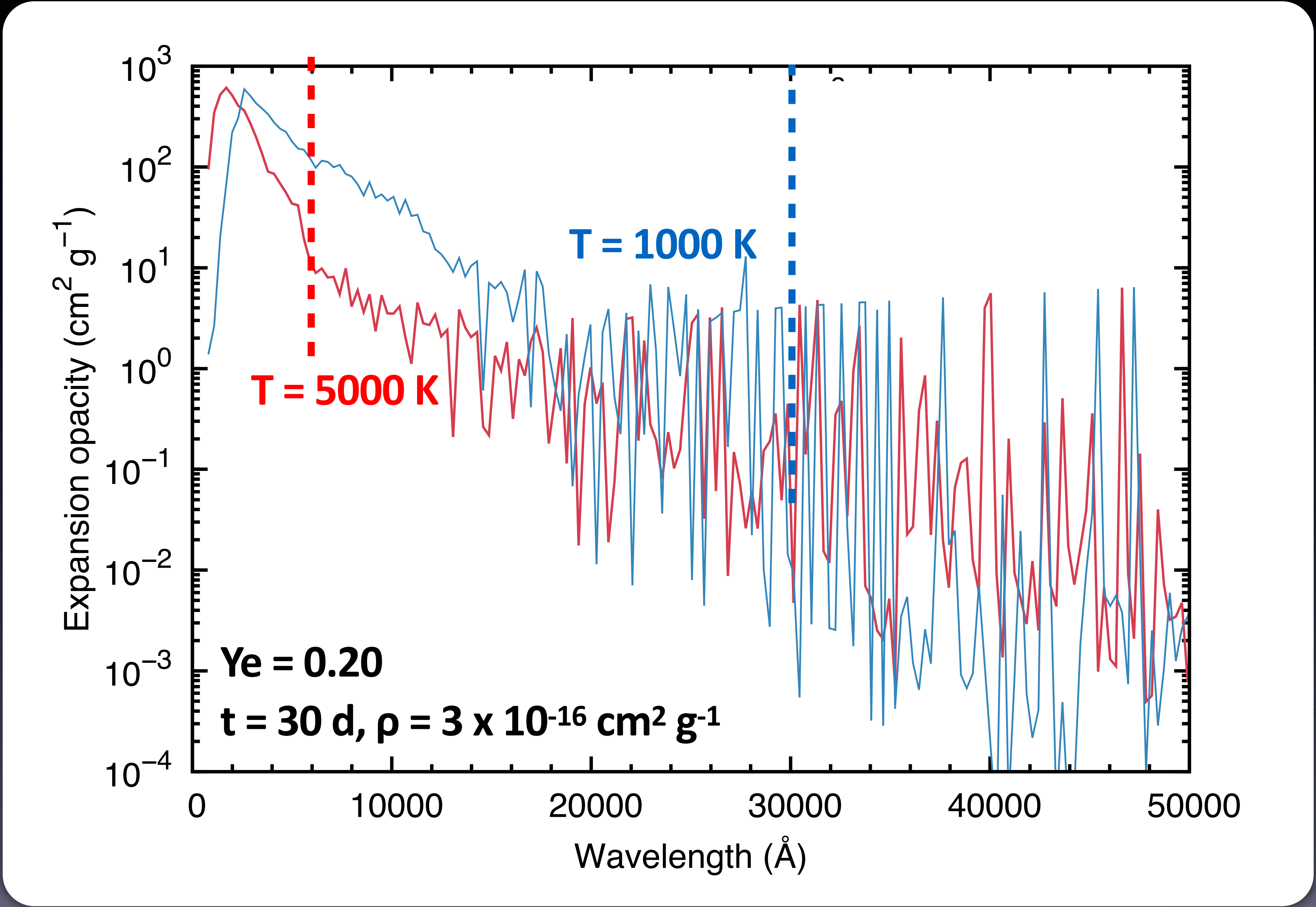
$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l f_l \frac{g_k}{g_0} e^{-\frac{E_k}{kT}}$$

$$\kappa_{\rm exp}(\lambda) = \frac{1}{ct\rho} \sum_l \frac{\lambda_l}{\Delta\lambda}(1 - e^{-\tau_l})$$



κ >~ 5 cm^2 g^{-1} at t = 30d is difficult with T ~ 800 K (under LTE)

High opacity at late time?



Non-LTE => T ~ 5,000 K?

Optical photons can still be absorbed

Radiative transfer simulations for light curves and spectra of kilonovae

- Light curves
- Spectra

Two different demands on atomic data

Light curves

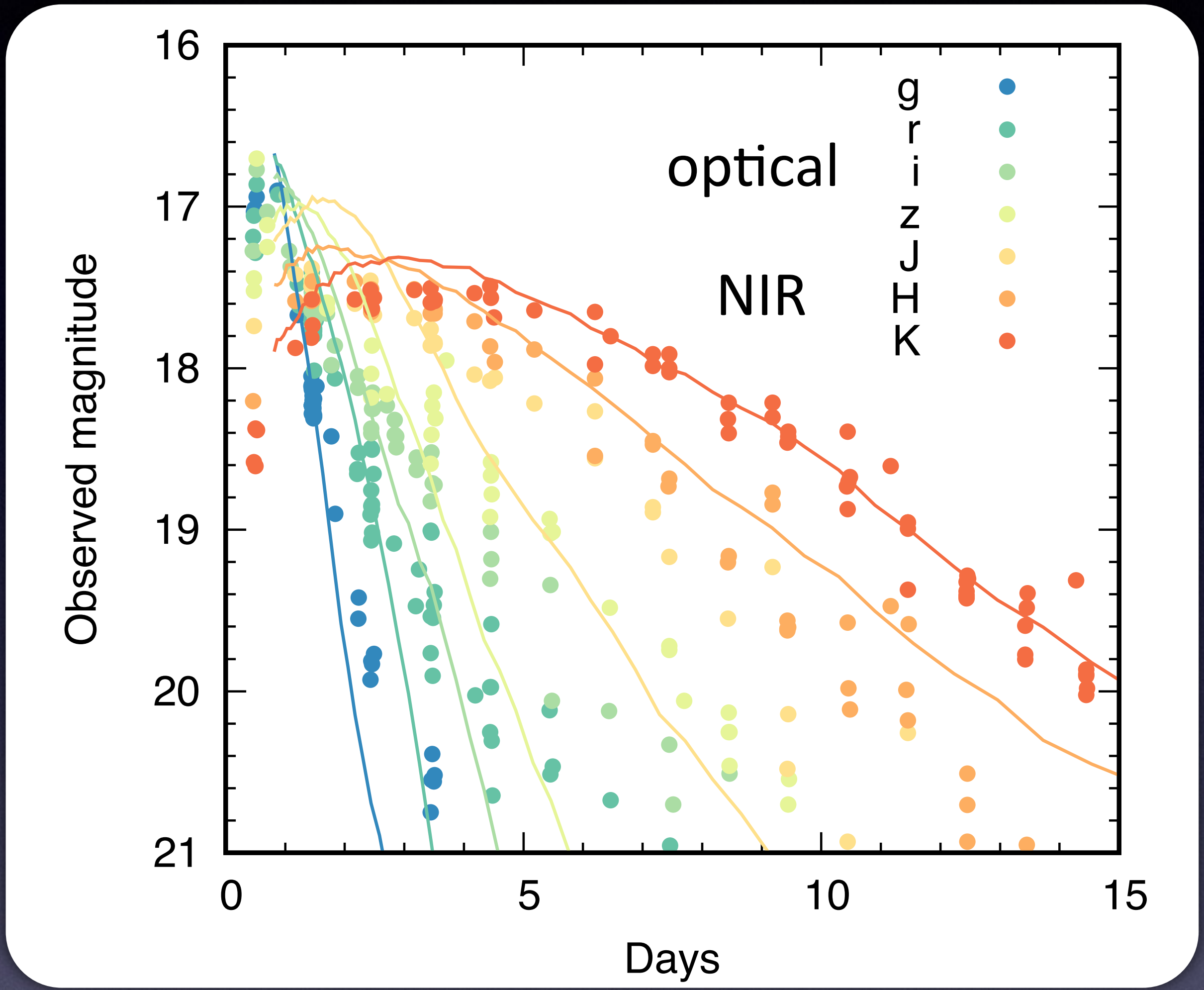


Figure from Kawaguchi+2018, 2020

Complete data
for (even weak) transitions
=> total opacity

Spectra

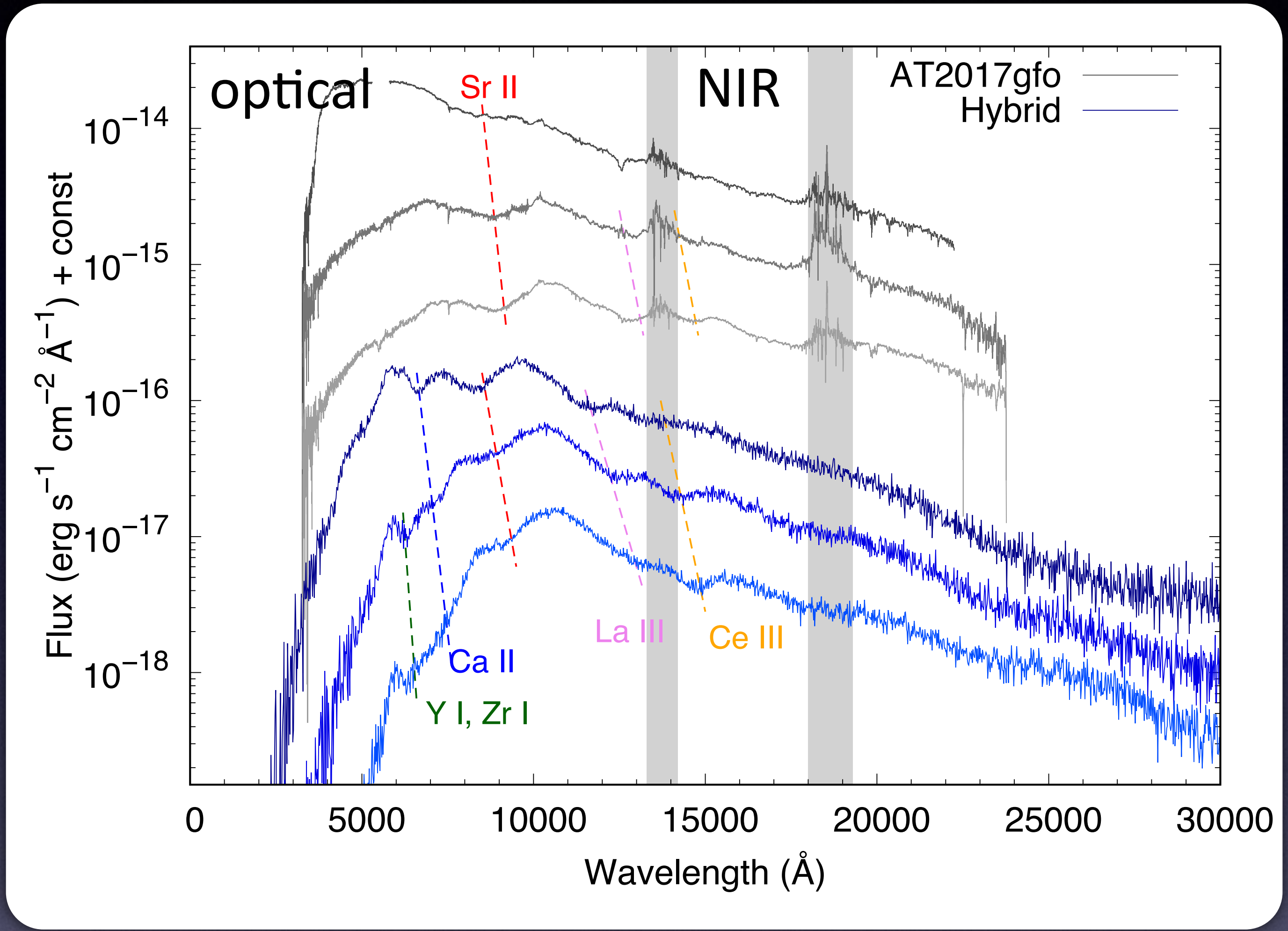


Figure from Domoto+2020,2022

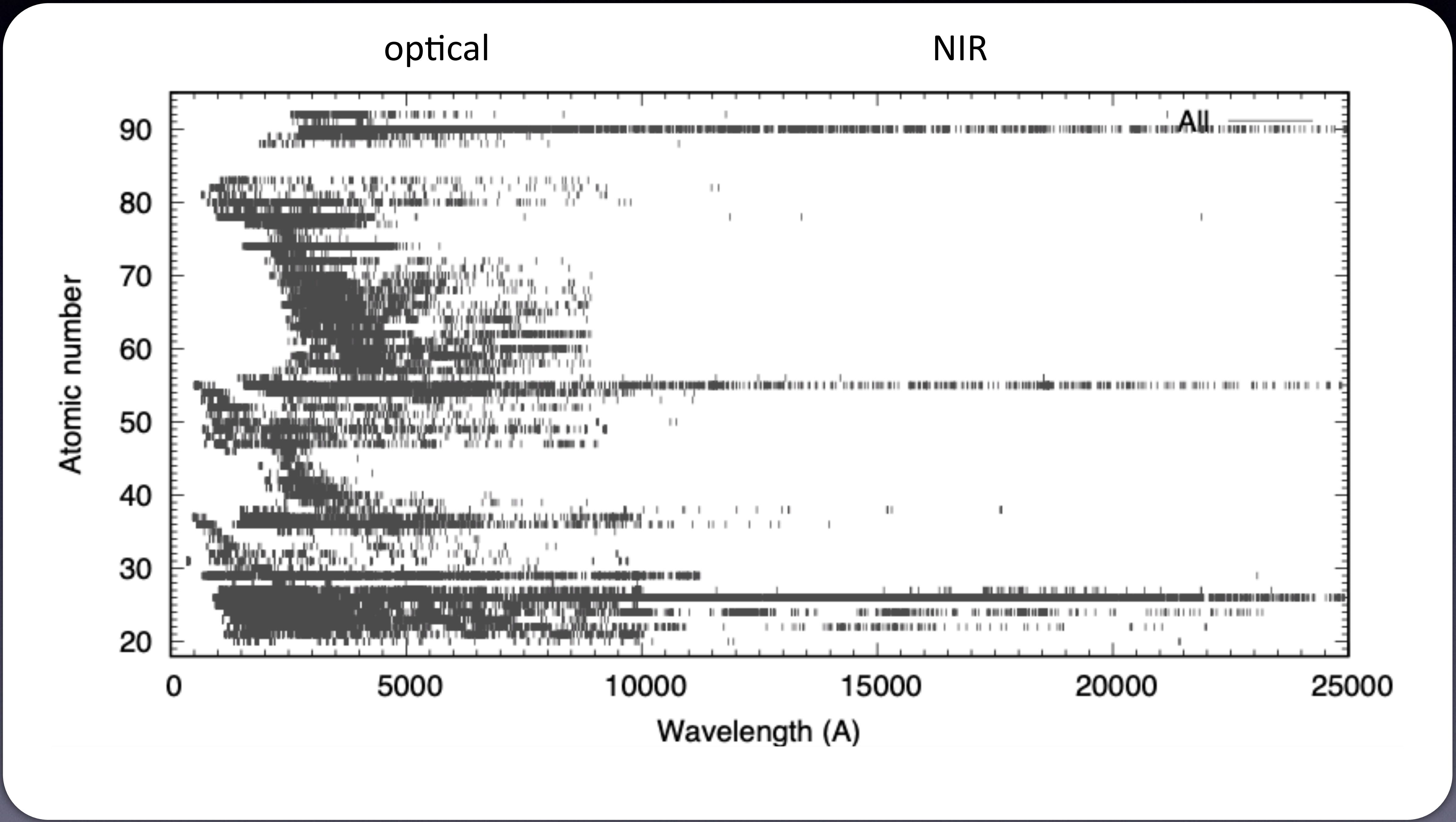
Accurate data for
important transitions
=> spectral feature

see also talks by N. Domoto, A. Sneppen, N. Vieira, …

Available atomic data

Data from the NIST ASD

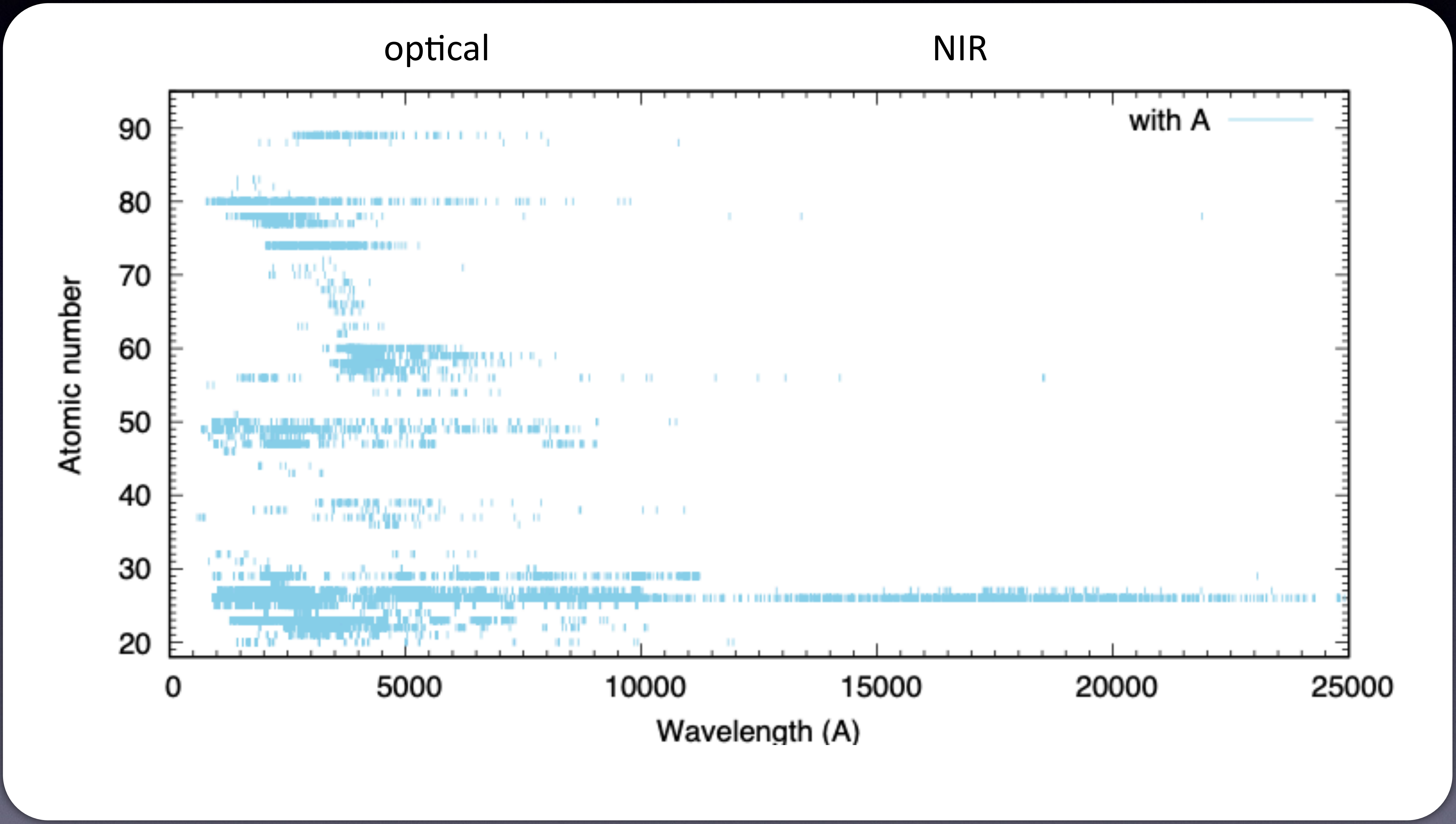
Transitions with known wavelengths



Available atomic data

Data from the NIST ASD

Transitions with known transition probability



Accurate transition data are highly incomplete (in particular NIR)

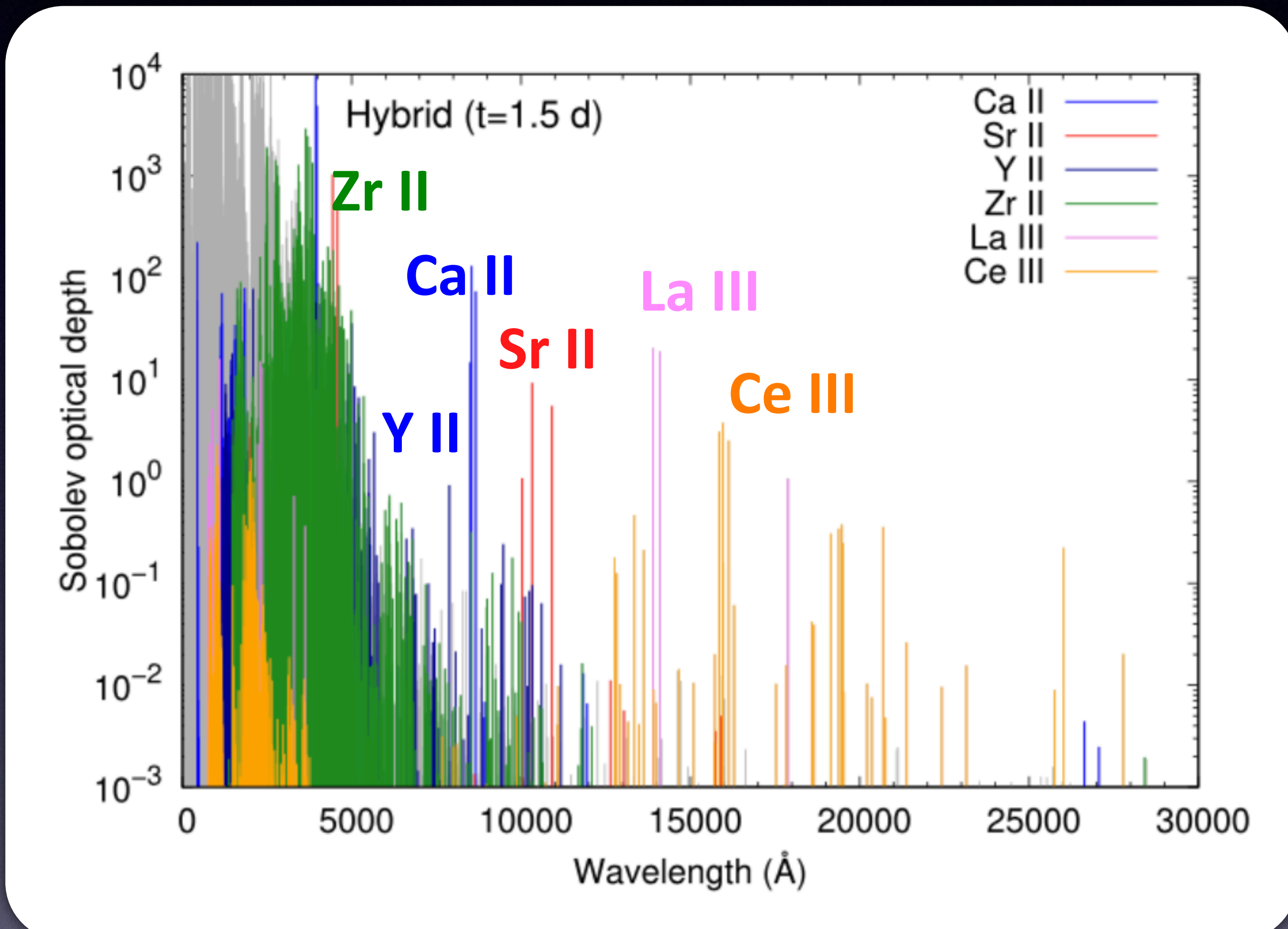
Important elements for spectral features

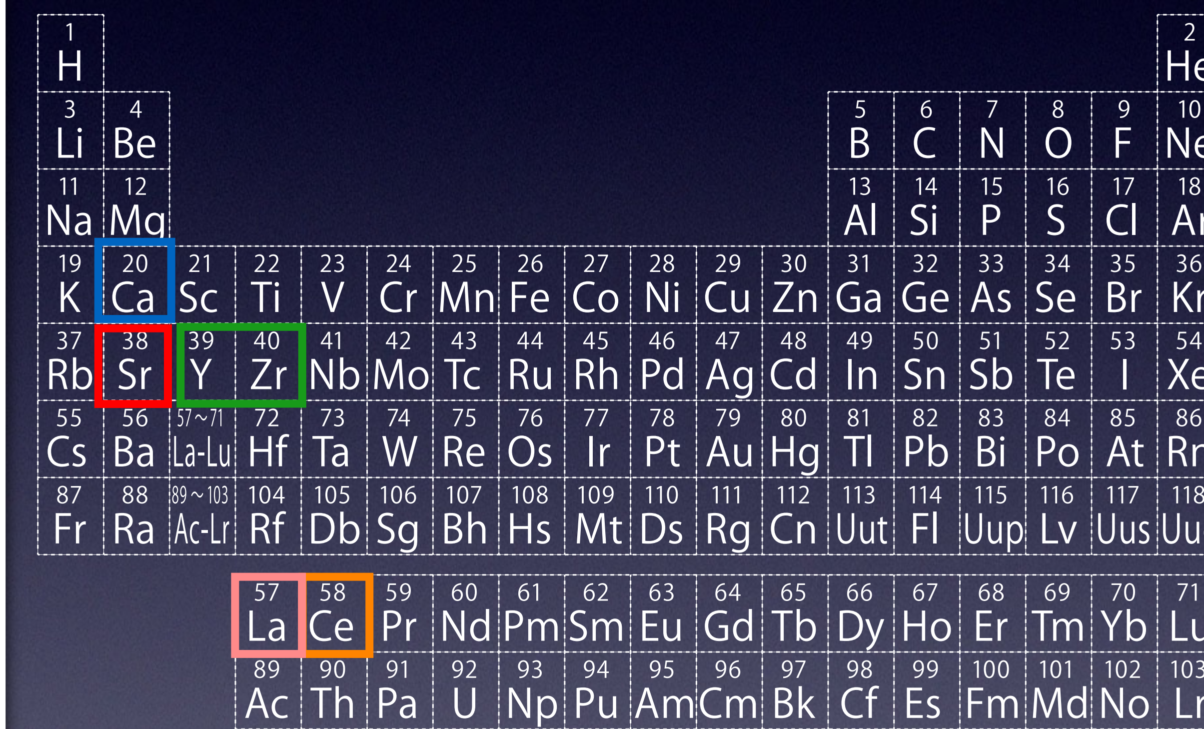
see N. Domoto's talk

Domoto+22

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l f_l \frac{g_k}{g_0} e^{-\frac{E_k}{kT}}$$

Constructed from complete data (MT+20)



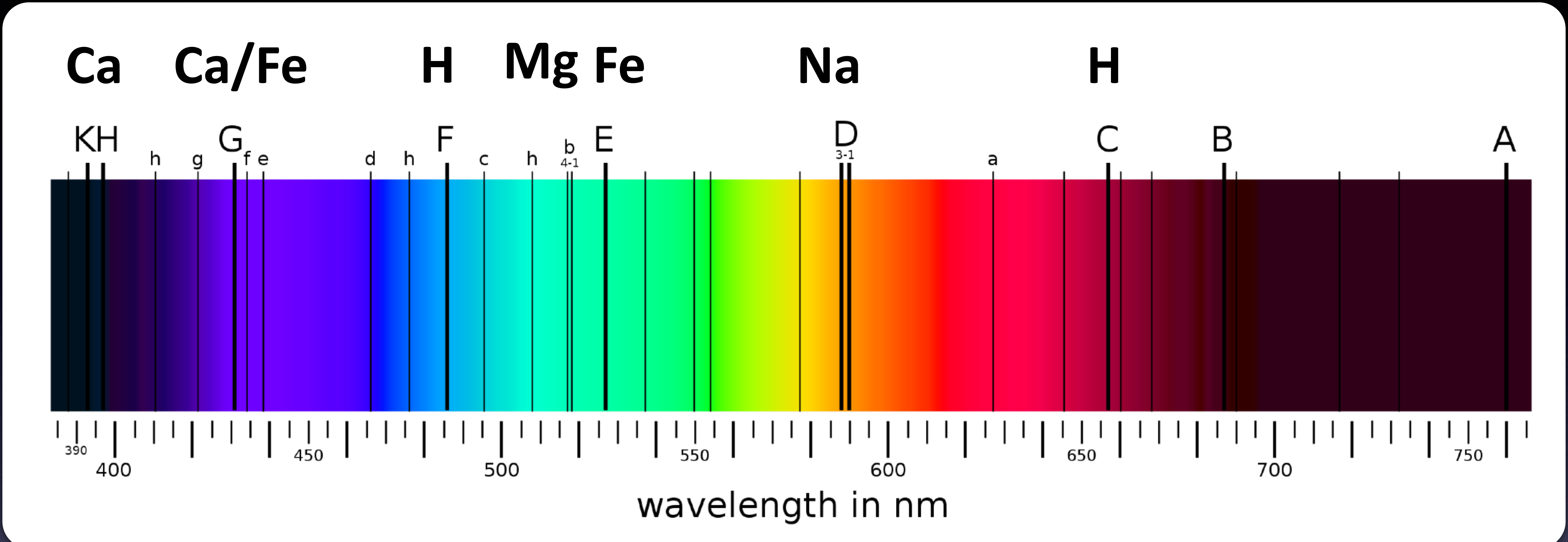


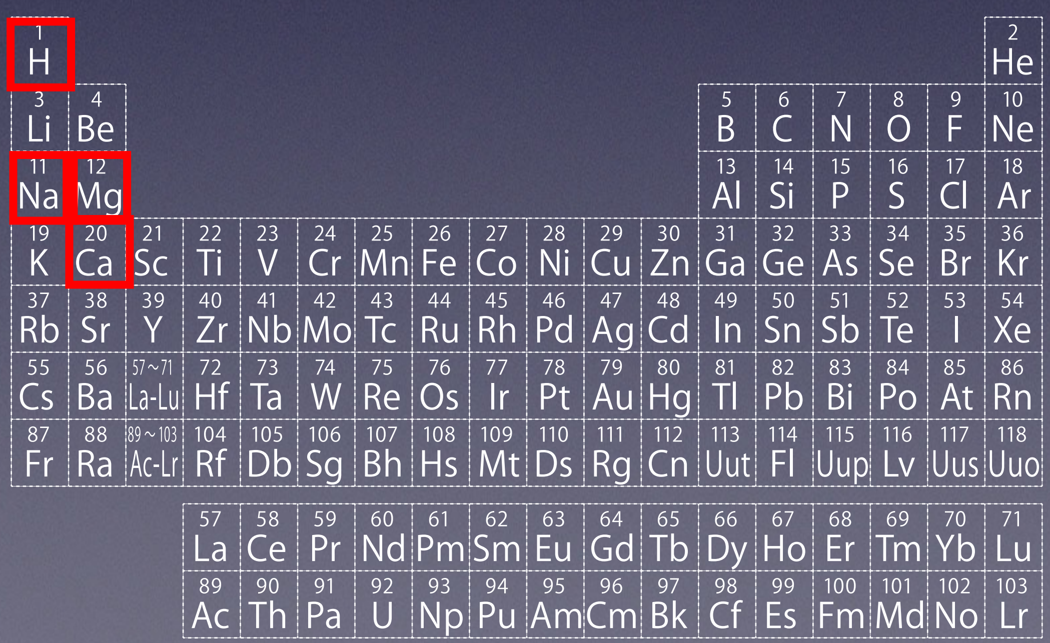
Elements with

- **low-lying energy levels (higher population)**
- **relatively simple structure = small number of transitions**
  = high transition probability (sum rule)

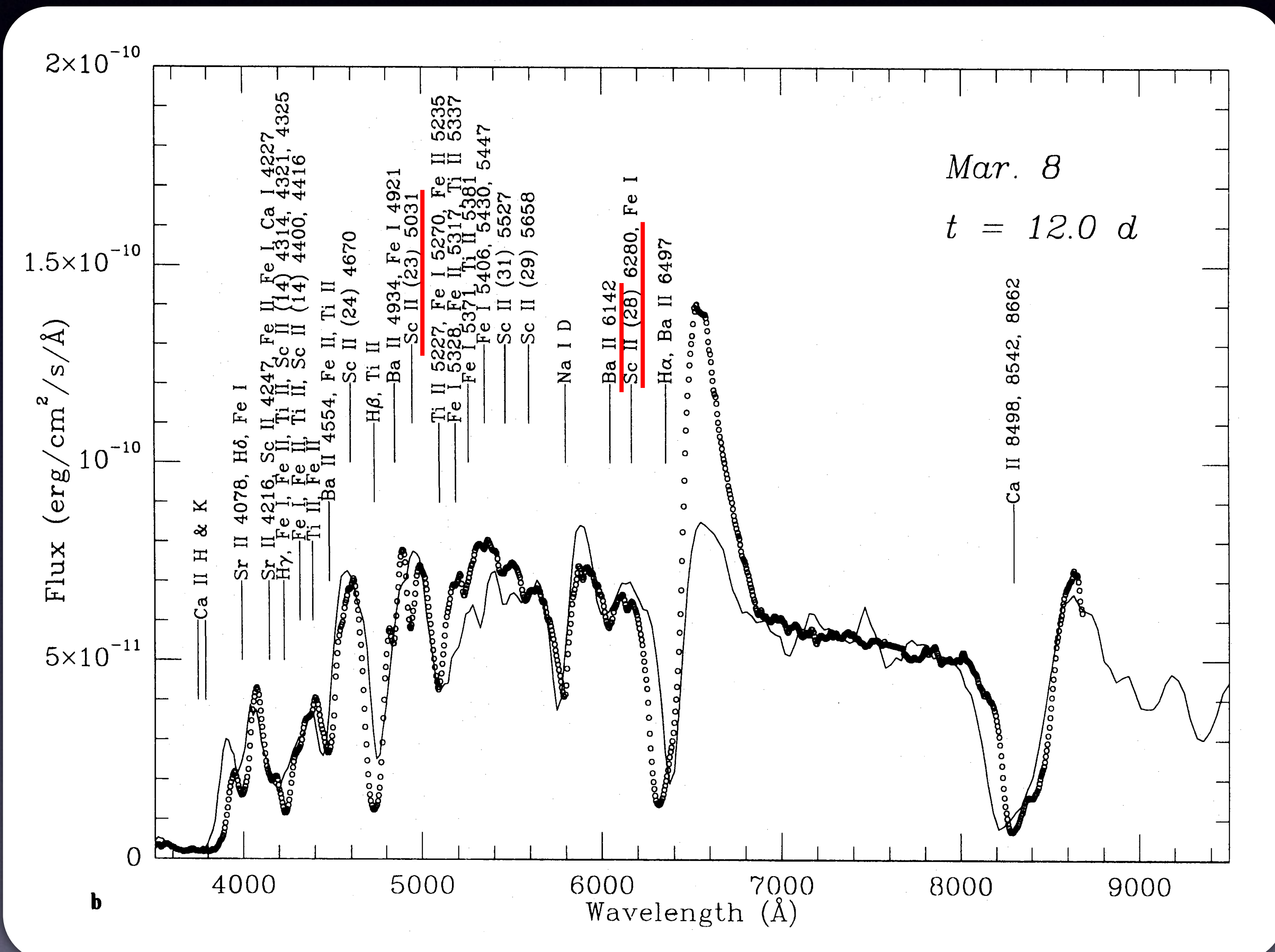
Solar spectrum

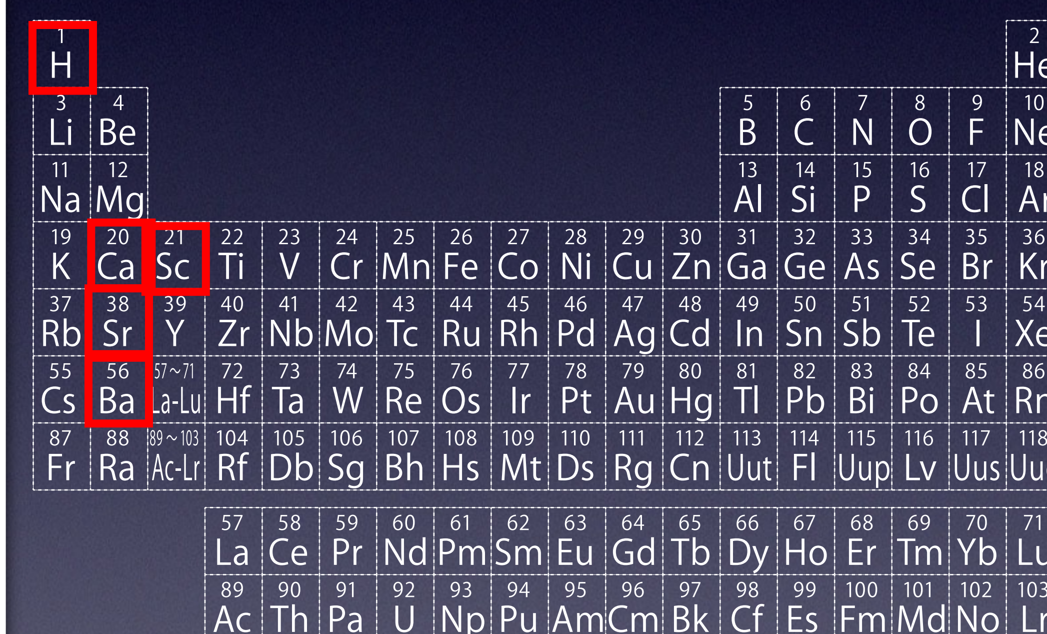
https://en.wikipedia.org/wiki/Fraunhofer_lines





Supernova spectrum (Type II)





Mazzali+92
see also Dessart et al. 08, 11

Road to the line identification

"Candidate"

Wavelengths are consistent
(w/ reasonable Doppler shift)
=> Need transition wavelengths

Strong lines are expected
(in terms of abundances, ionization, excitation, …)
=> Need transition probabilities

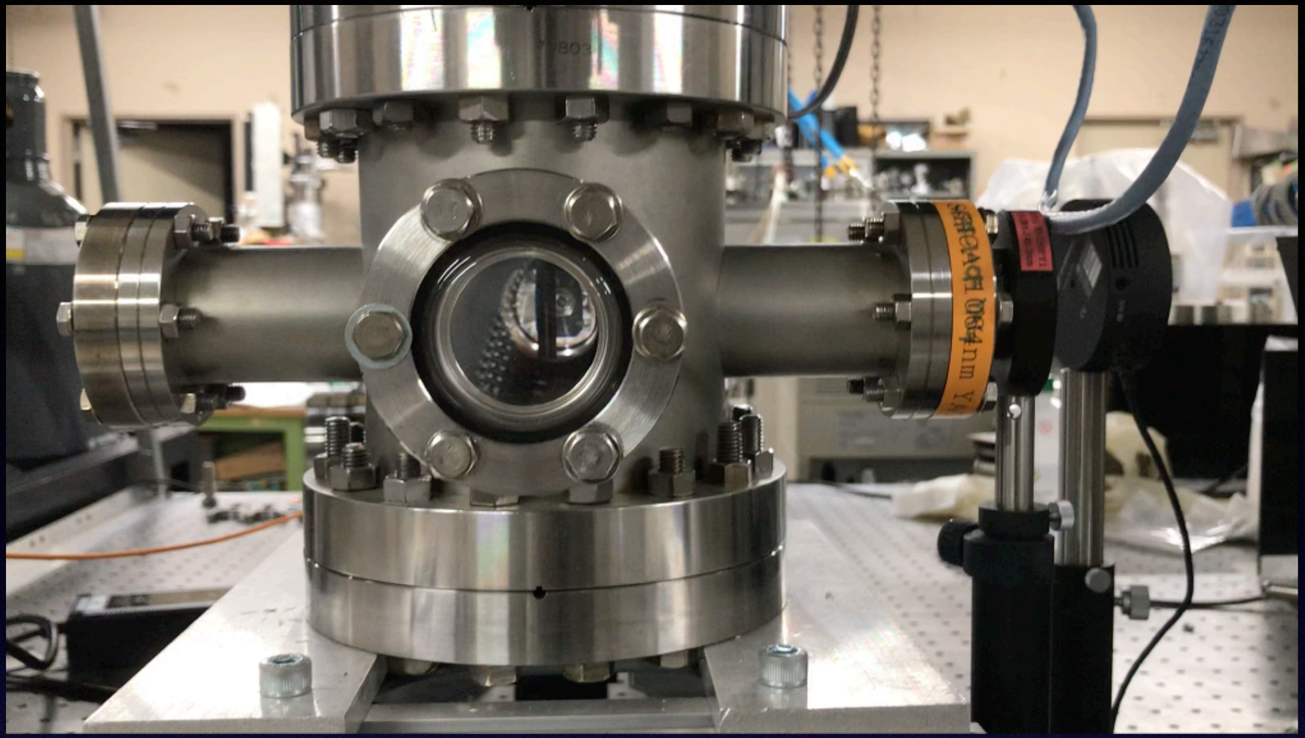
No other line can produce the feature
=> Need complete data for strong transitions

Line identification

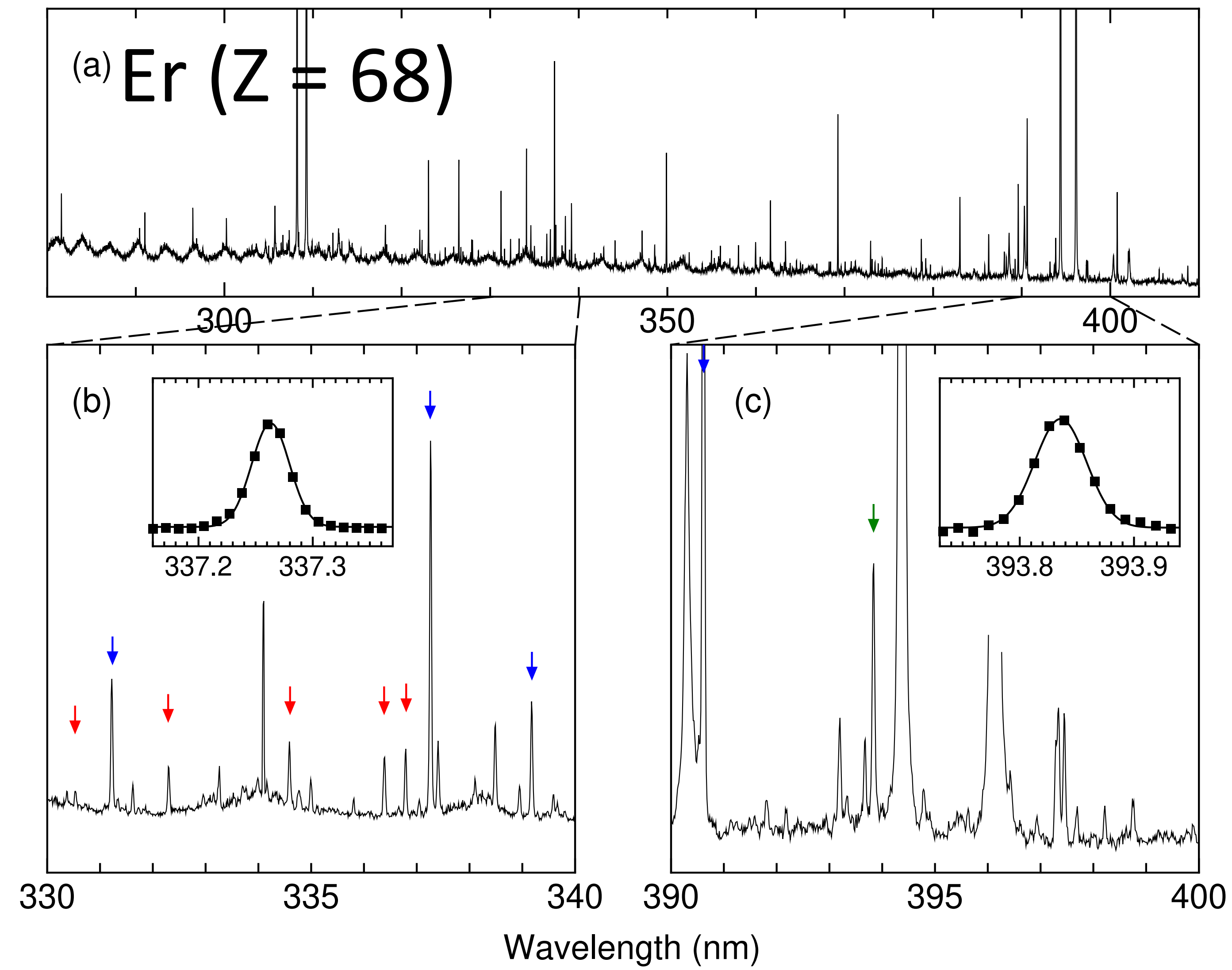
Spectroscopic measurements for transition probabilities

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

see P. Dunne's and H. Hartman's talk



Measurements of Ce and La in optical



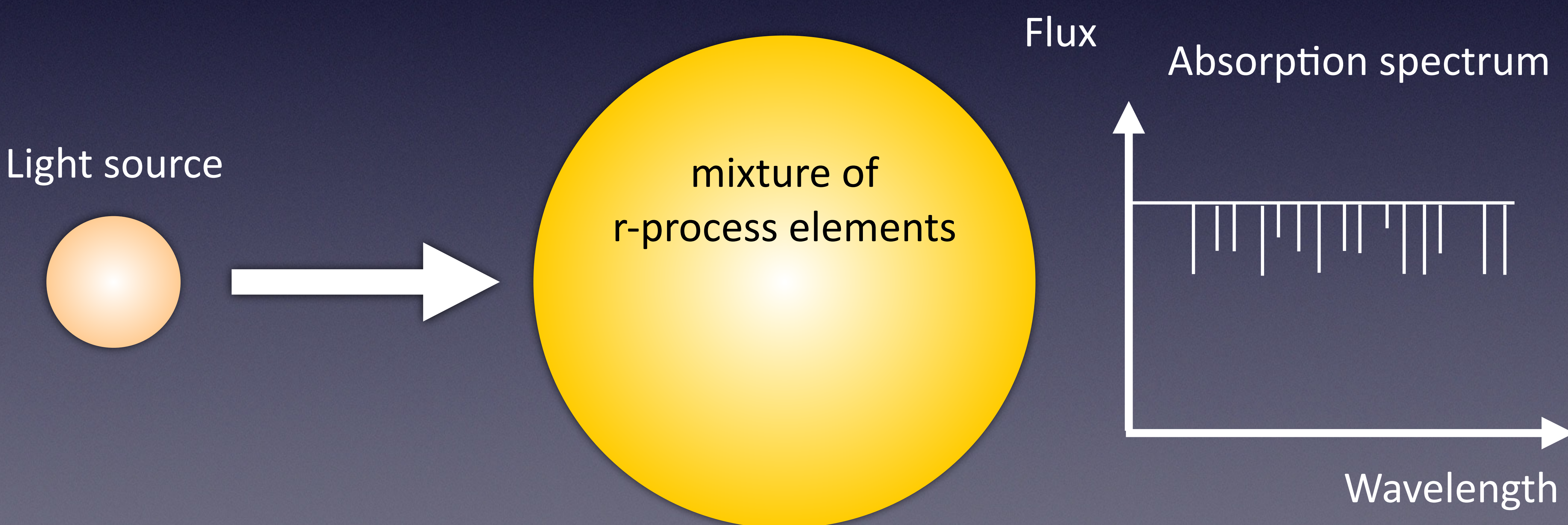
Naoi (including MT)+22

How to assure the completeness of the strong transitions?

Domoto et al. 2022: use theoretical data for the completeness

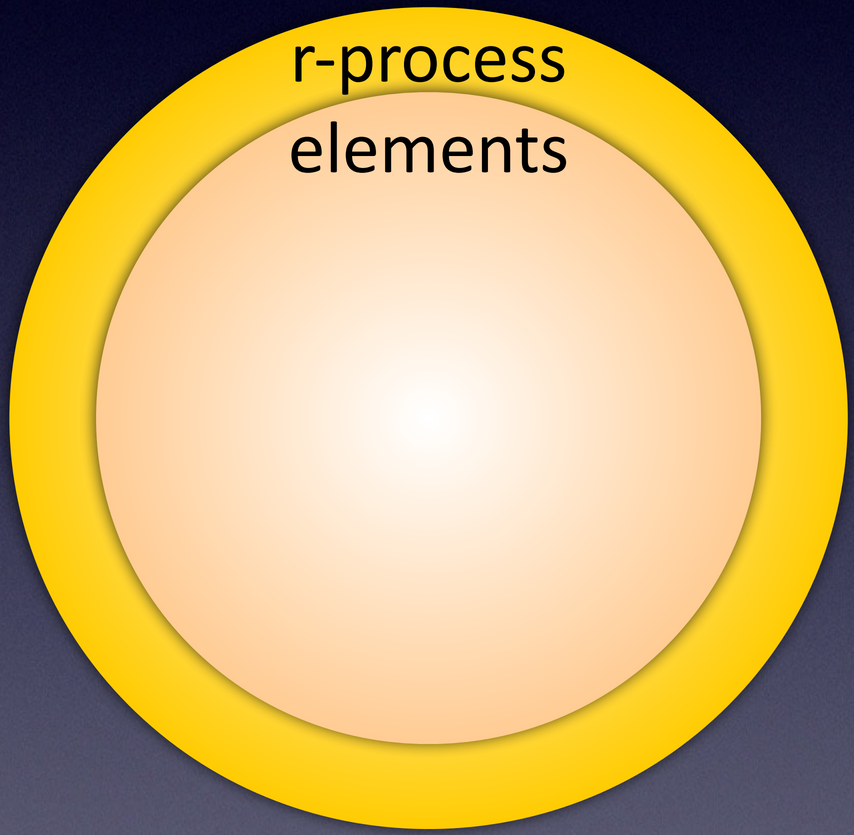
The best spectroscopic experiment…

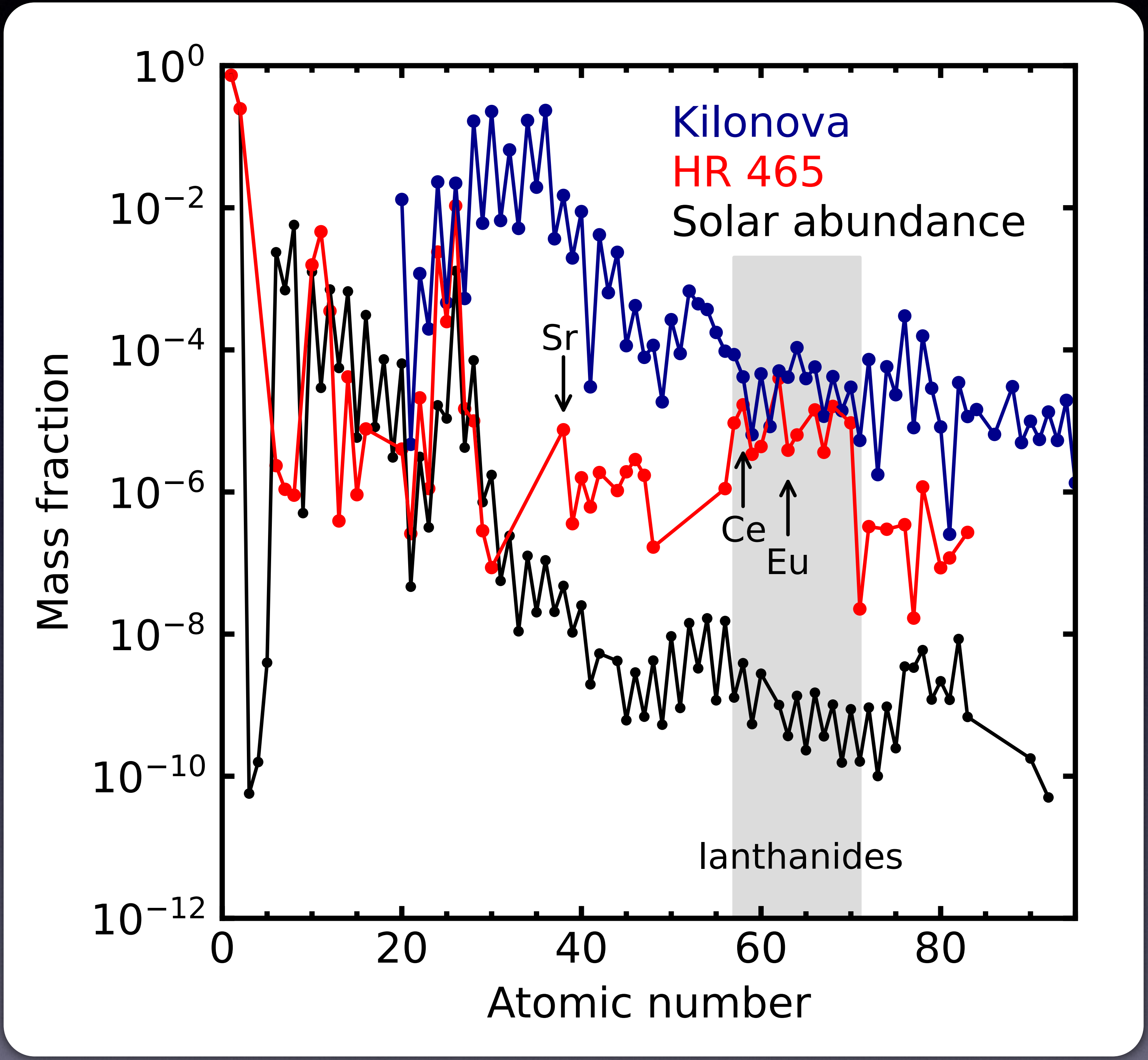
- T ~ 5,000 K, $\rho \sim 10^{-15}$ g cm^{-3}. (n ~ ρ /A m_p ~ 10^7 cm^{-3})
- Heavy elements dominated plasma



R ~ 10^{14} cm … :-(

How about using “chemically peculiar stars”?

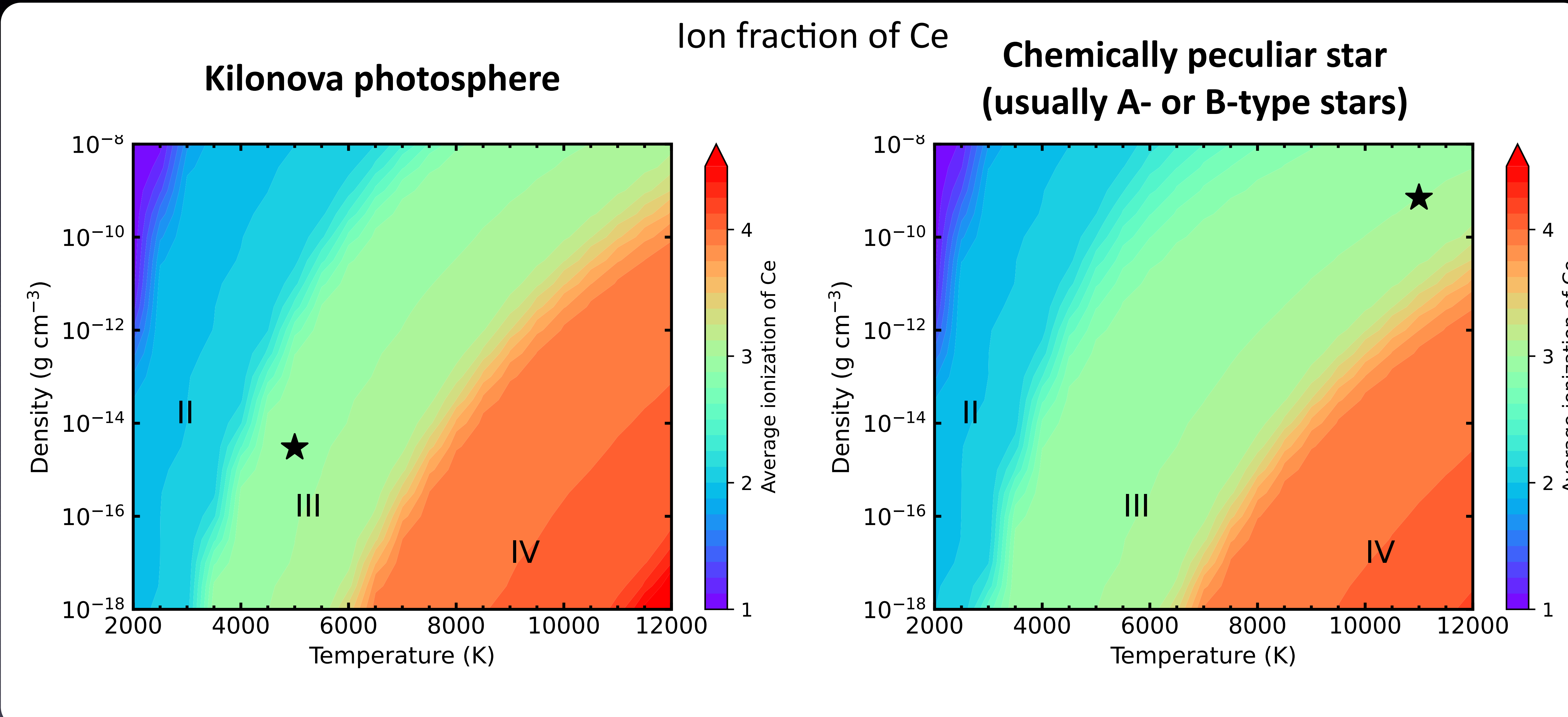




Similar lanthanide abundances

Tanaka, Domoto, Aoki et al. 2023

What about ionization states?



Ionization degrees are also similar

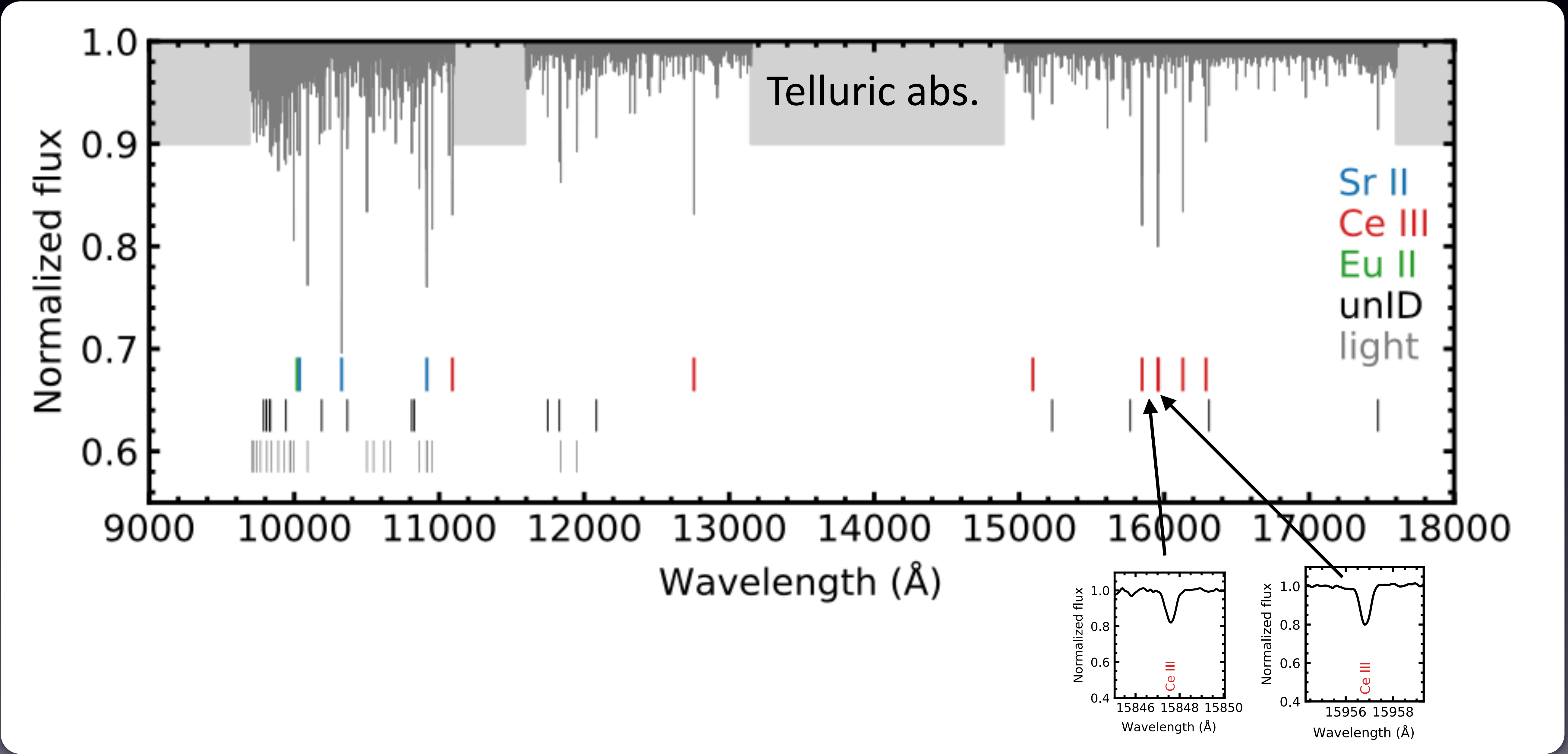
*** Excitation is higher in stellar atmosphere (higher T)**

Tanaka, Domoto, Aoki et al. 2023

NIR spectrum of a chemically peculiar star

Tanaka, Domoto, Aoki et al. 2023

Subaru/IRD (R ~ 70,000)

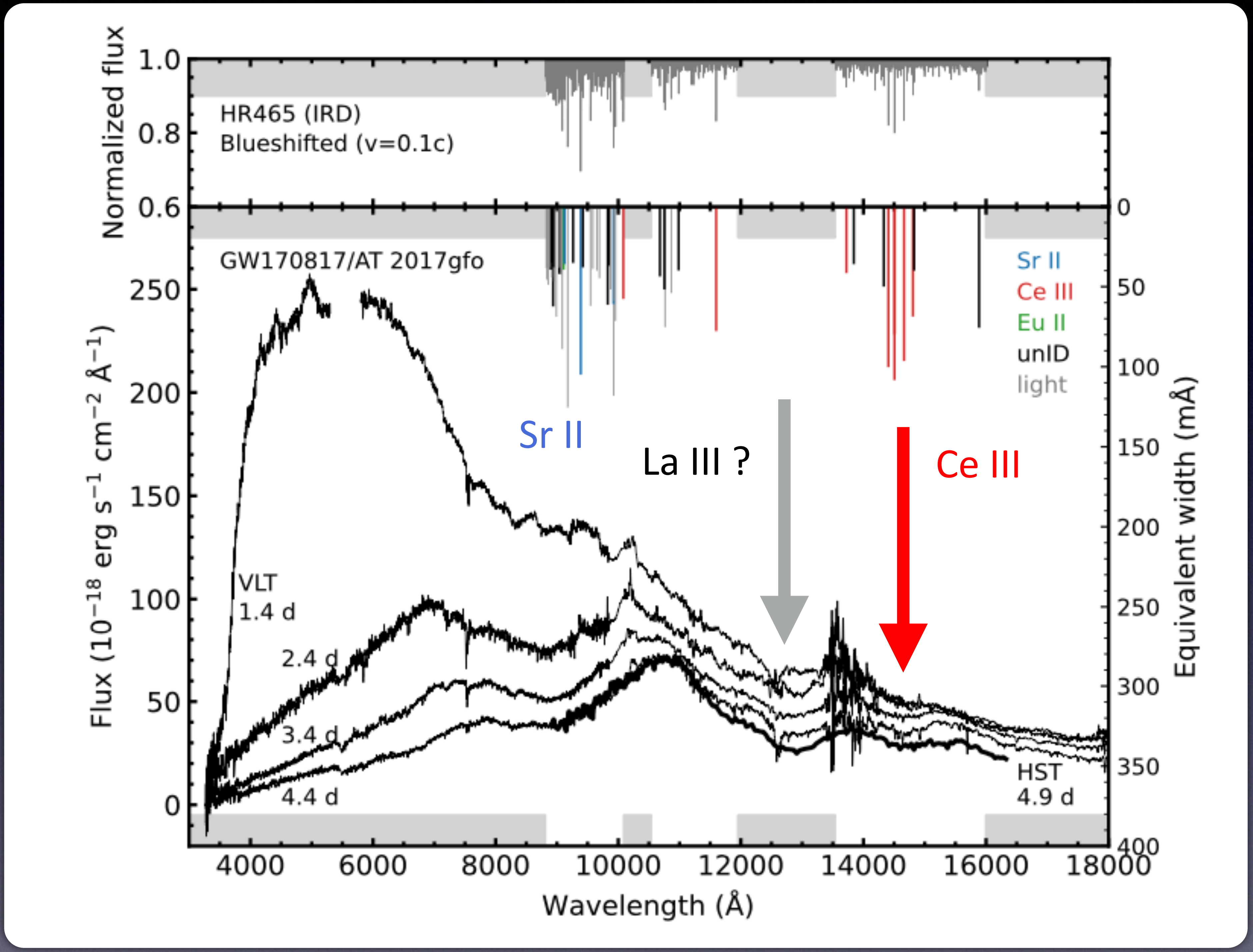


Strongest lines = Ce III, Sr II

No other comparably strong lines = completeness

Chemically peculiar stars vs kilonovae

Tanaka, Domoto, Aoki et al. 2023



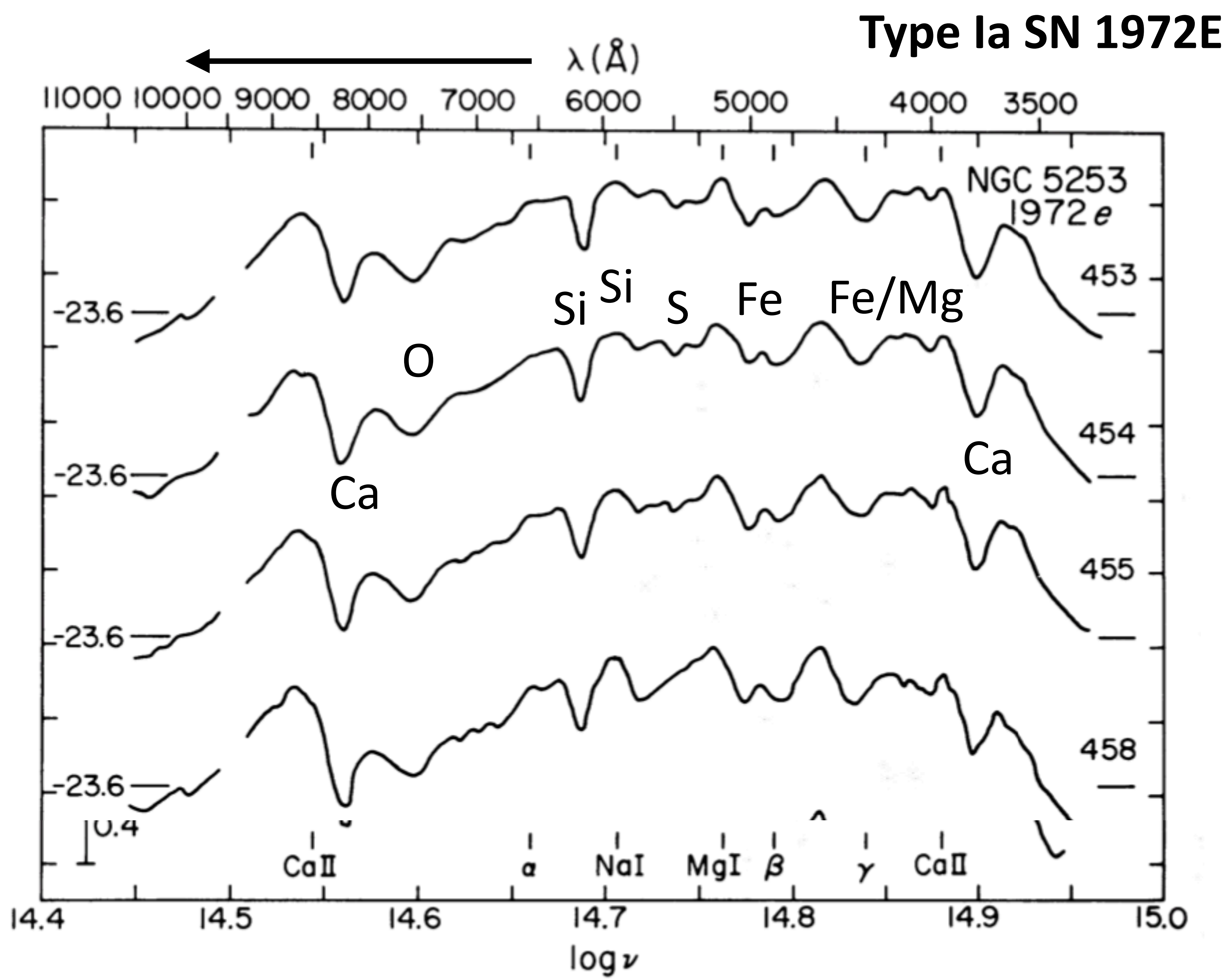
The most dominant feature around 14,500 A is Ce III (<= Domoto et al. 2022)

Another broad feature at 13,000 A (La III) is in the gap of the atmospheric windows…

Anders: “what we have learned from 50yr of SN studies? ”

Supernova spectra in 1970s

Kirshner+73



Summary: kilonova light curves and spectra

- **Atomic data for light curves**
  - Systematic atomic data for LTE are available
  - Need more evaluation of the accuracy (in progress)
- **Atomic data for spectra**
  - Accurate data for selected ions (w/ strong lines) are available
  - From “candidate” to “identification”
    - Need experimental transition probabilities (in progress)
    - Completeness for strong lines is also important
      (use of stellar spectrum is a possible way)