Exploring the origin of heavy elements with multimessenger astronomy

マルチメッセンジャーで探る重元素の起源

(C) Tohoku University

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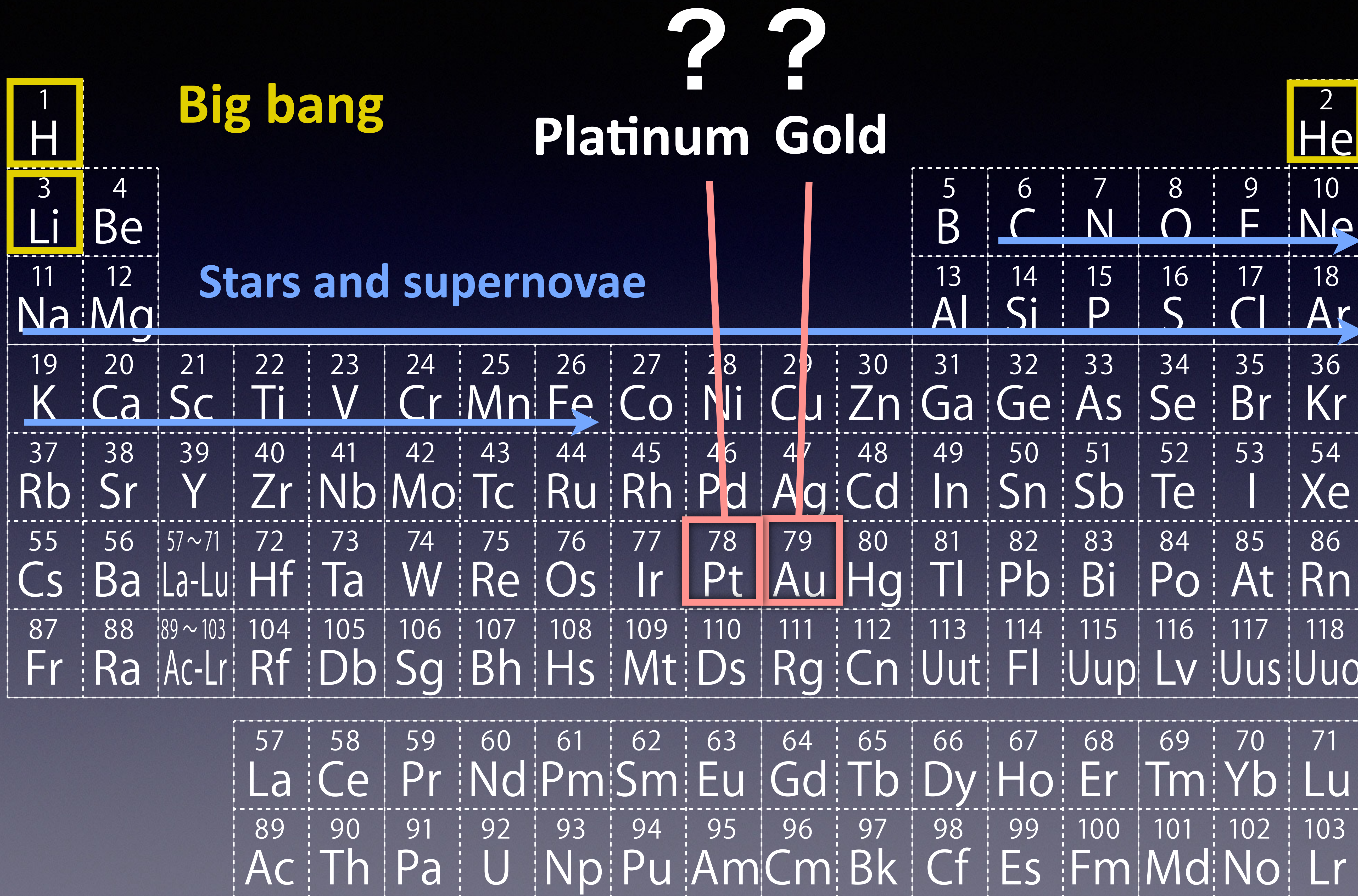
Exploring the origin of heavy elements with multimessenger astronomy

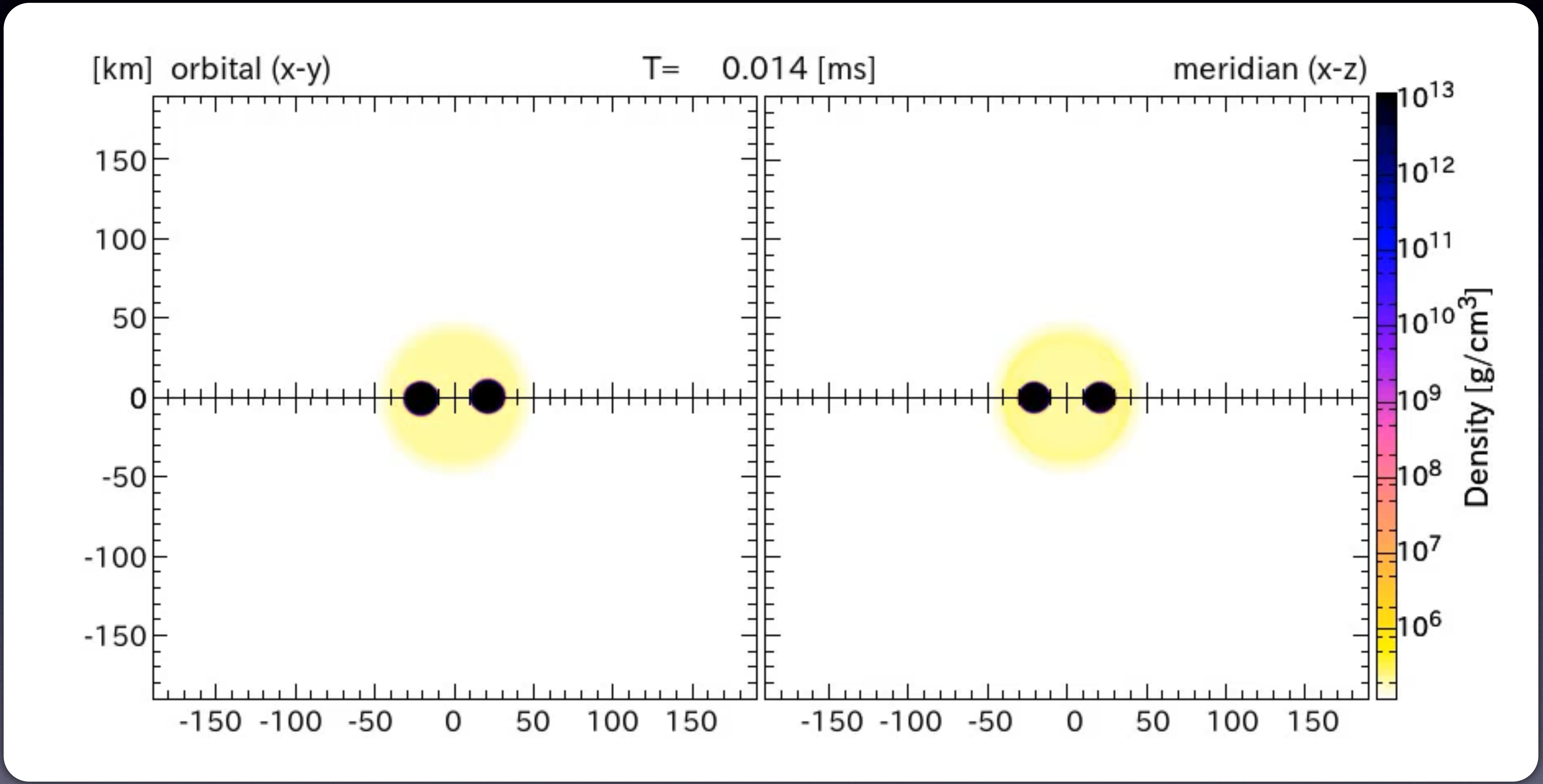
- Neutron star mergers, heavy elements, and kilonovae
- Decoding signals from kilonovae
- O4, O5, and beyond

The origin of elements in the Universe



Mass ejection from NS merger

Top view | **Side view**

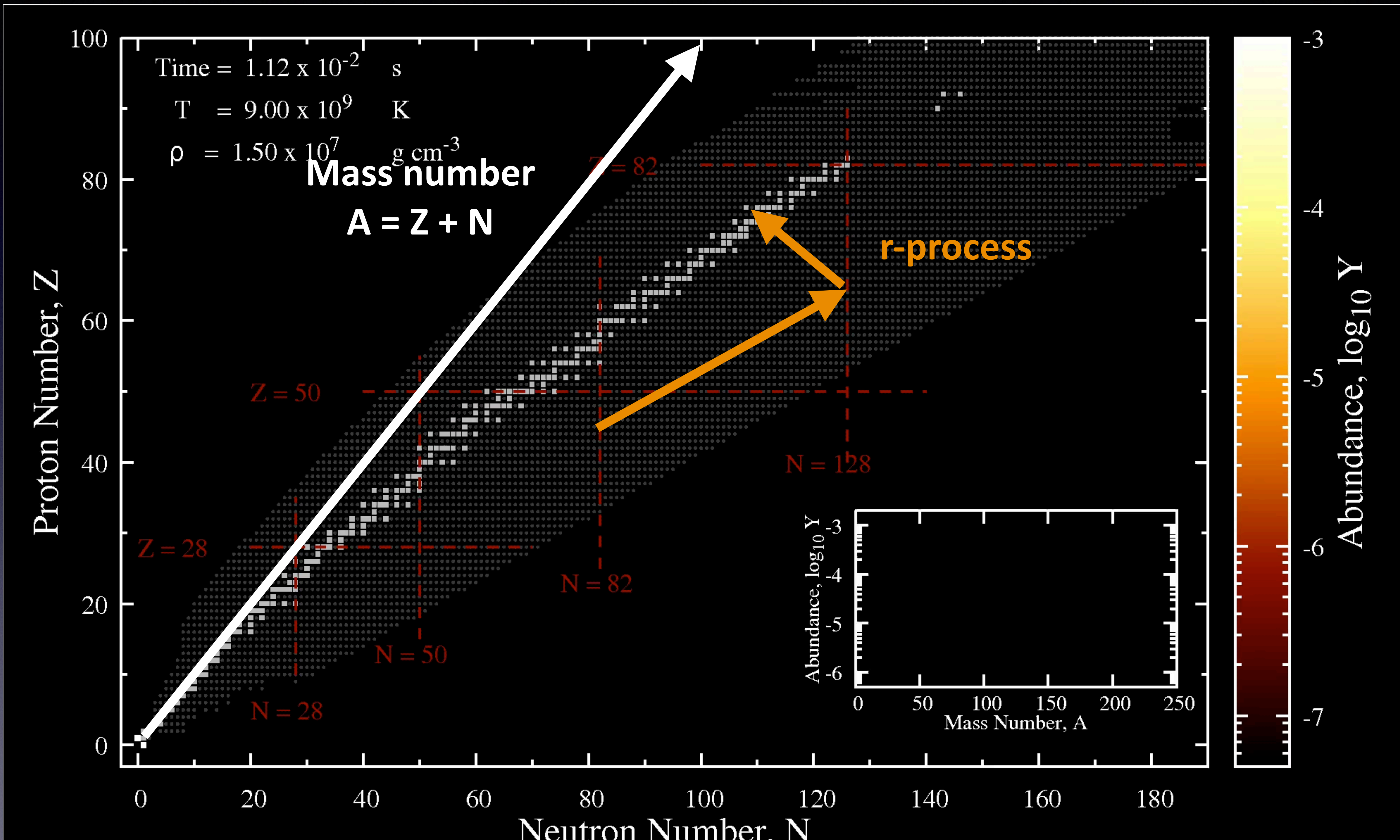


Sekiguchi+15, 16

$M \sim 10^{-3}$ - 10^{-2} Msun

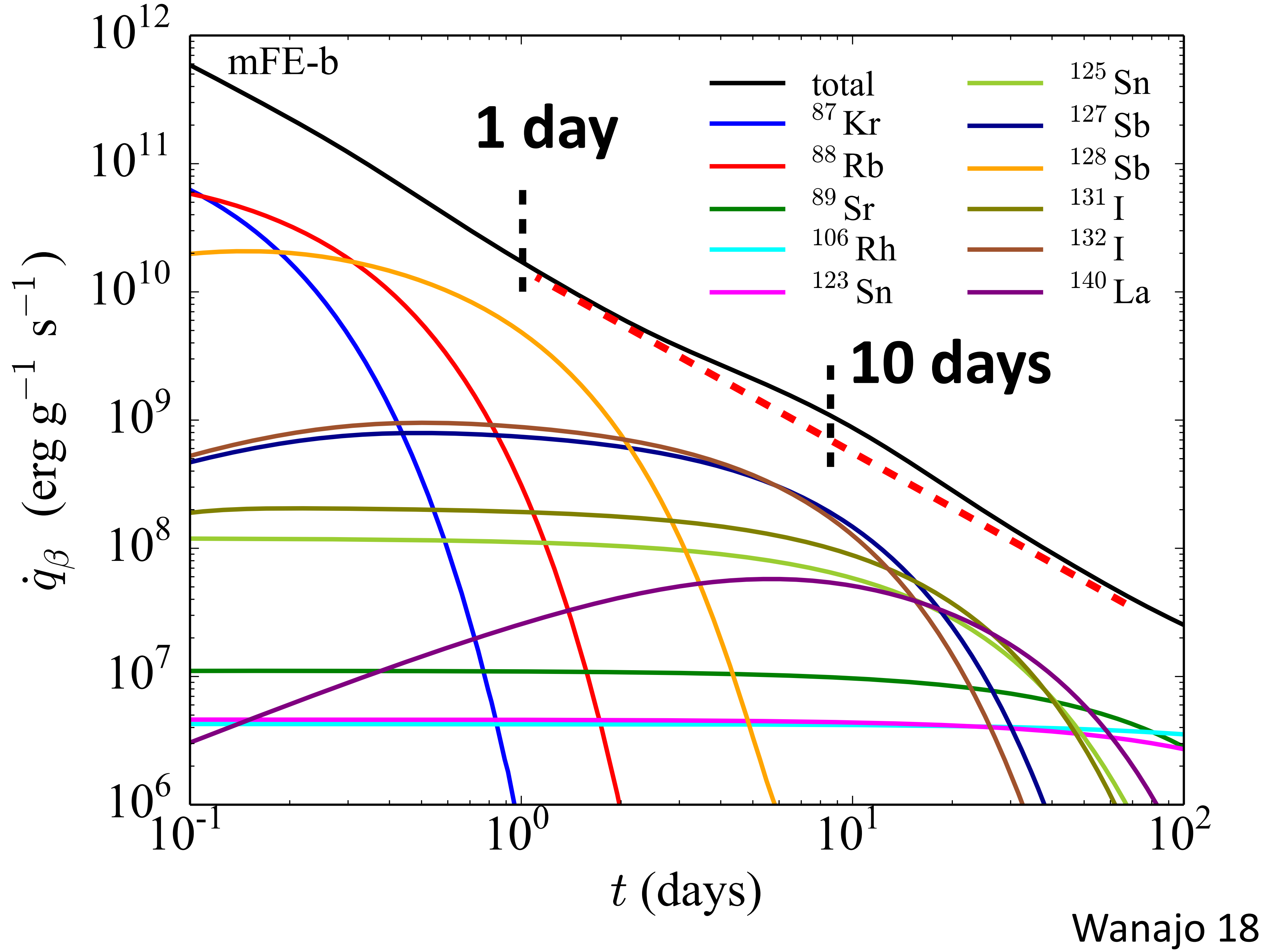
v ~ 0.1 - 0.2 c

r-process nucleosynthesis in NS merger



(C) Nobuya Nishimura

Radioactive decay luminosity (β-particles, γ-rays, neutrinos)

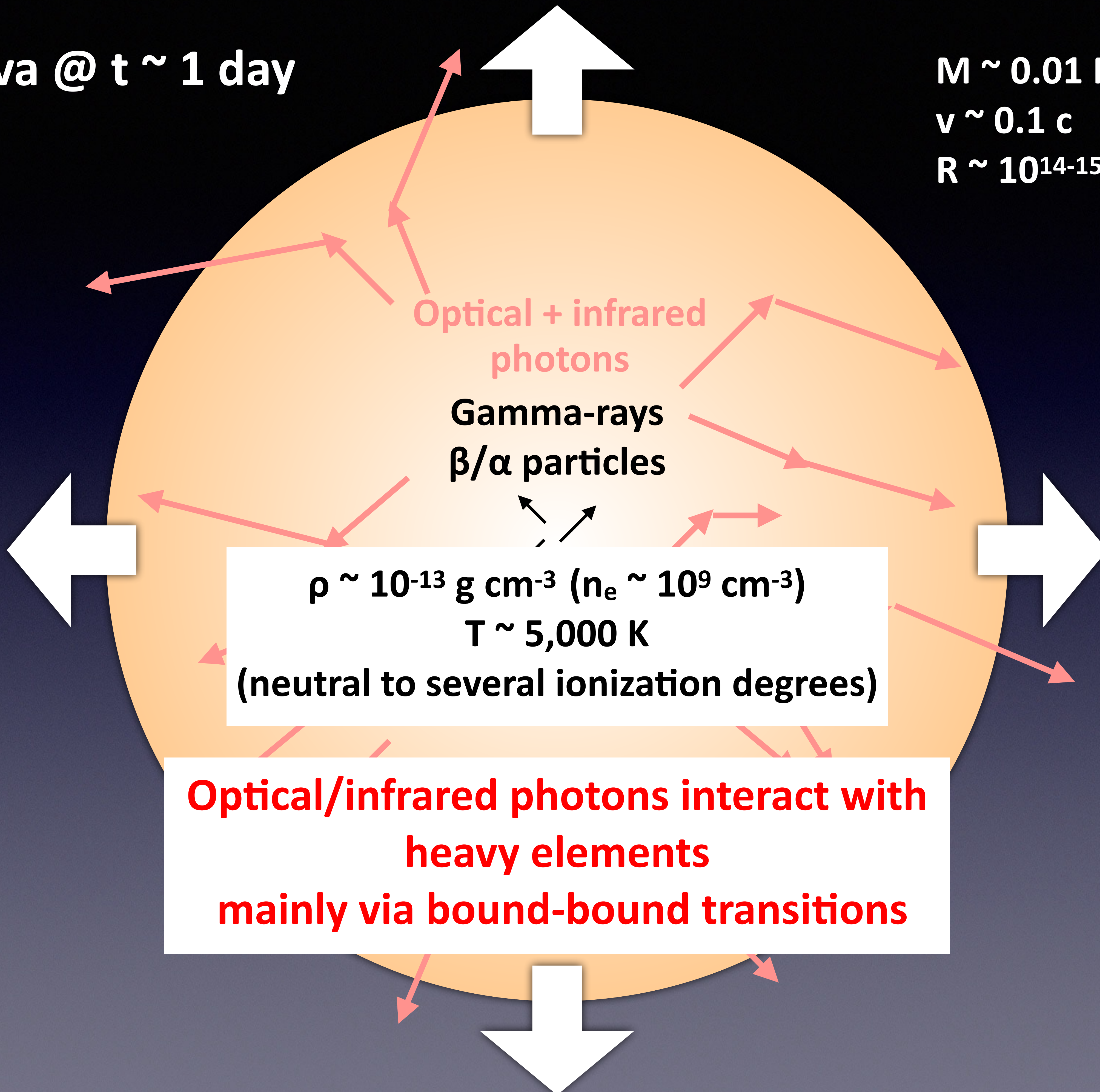


$$q \sim 2 \times 10^{10}\ t_{\rm day}^{-1.3}\ \mathrm{erg\ s^{-1}\ g^{-1}}$$

Metzger+10
Lippuner+15
Hotokezaka+16, 17

Kilonova @ t ~ 1 day

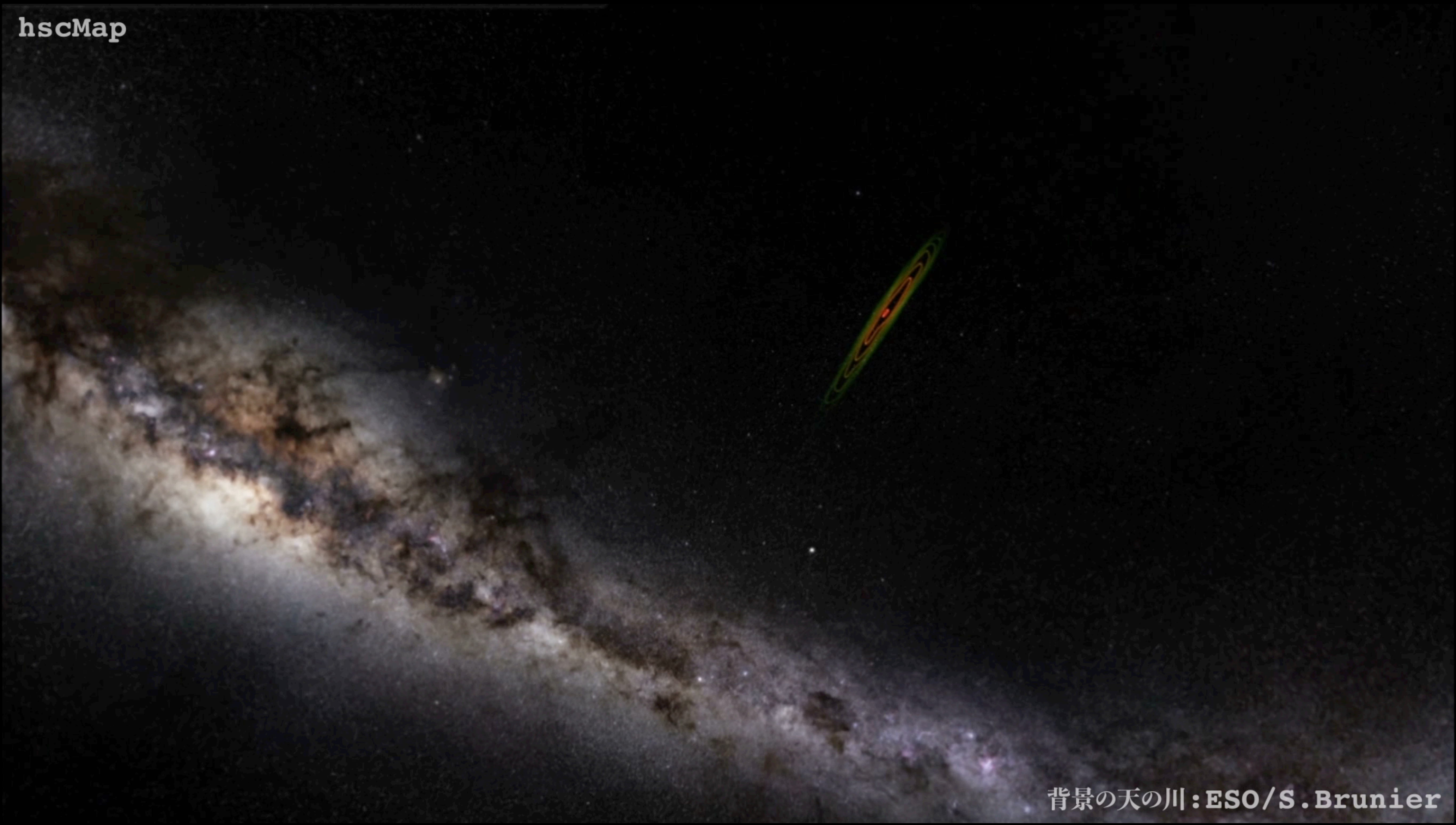
M ~ 0.01 Msun
v ~ 0.1 c
R ~ 10^{14-15} cm



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

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

Optical counterpart of GW170817



(C) Michitaro Koike (NAOJ/HSC)

What can we learn from observations of kilonova?

Light curves

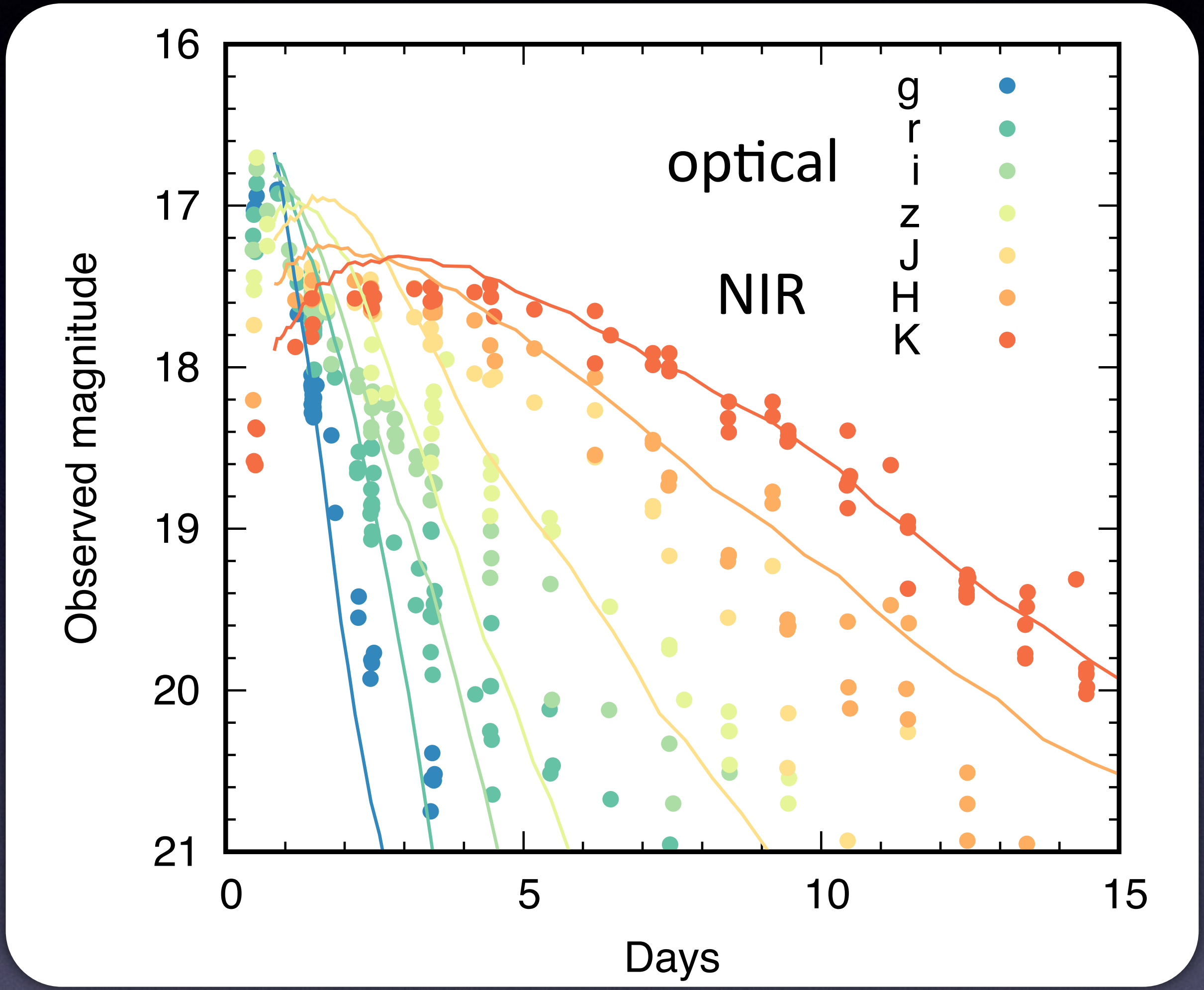


Figure from Kawaguchi+2018, 2020

Ejected mass and (rough) composition

Spectra

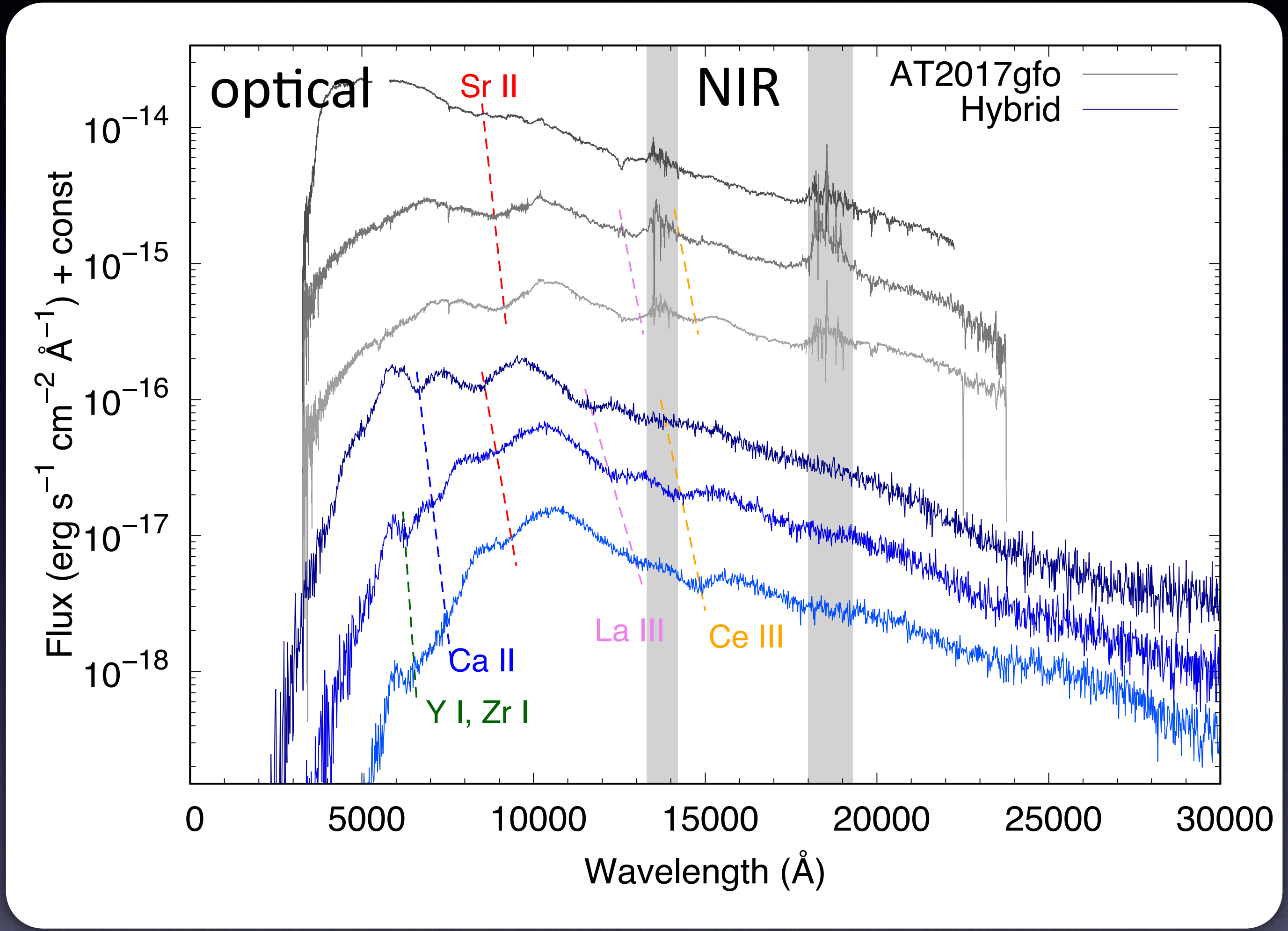


Figure from Domoto+2021,2022

Detailed composition

Origin of r-process elements

Physics of neutron star mergers

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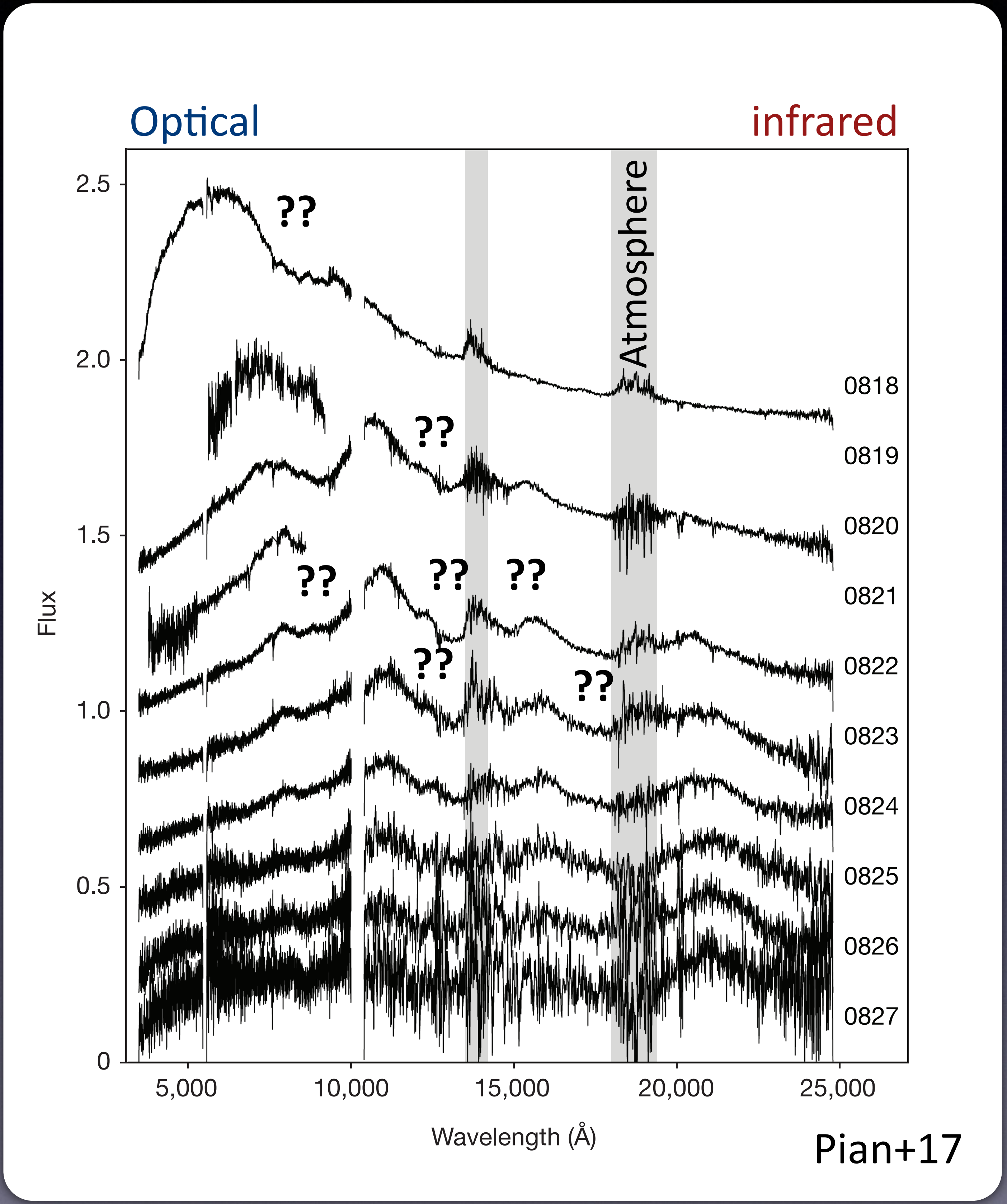
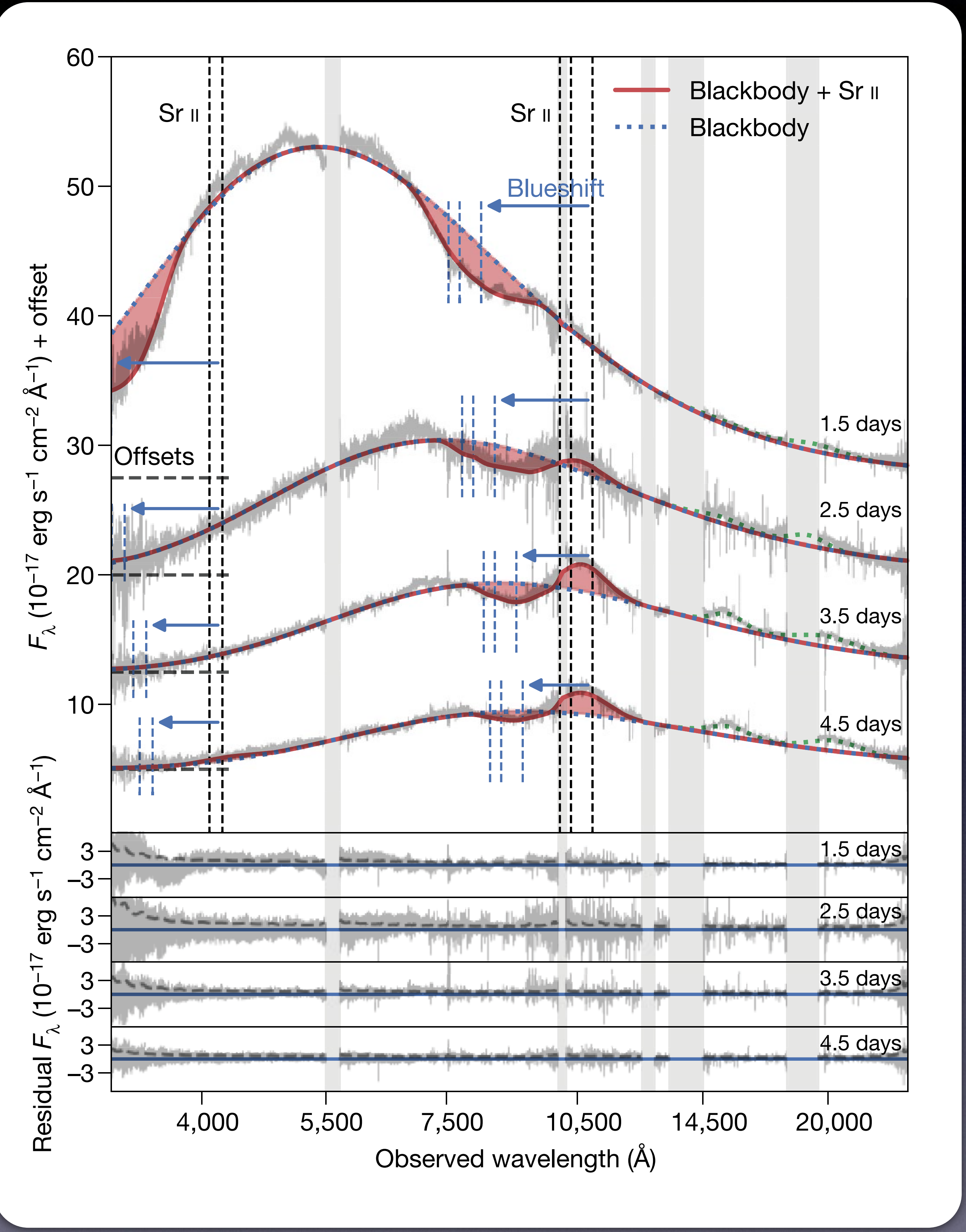
Challenges in kilonova spectra

- Many absorption features
- Large Doppler shift
  (velocity ~ 0.1 - 0.2 c)
- Lack of atomic data

Neither gold nor platinum are identified!!



Identification of Sr II (Z=38)

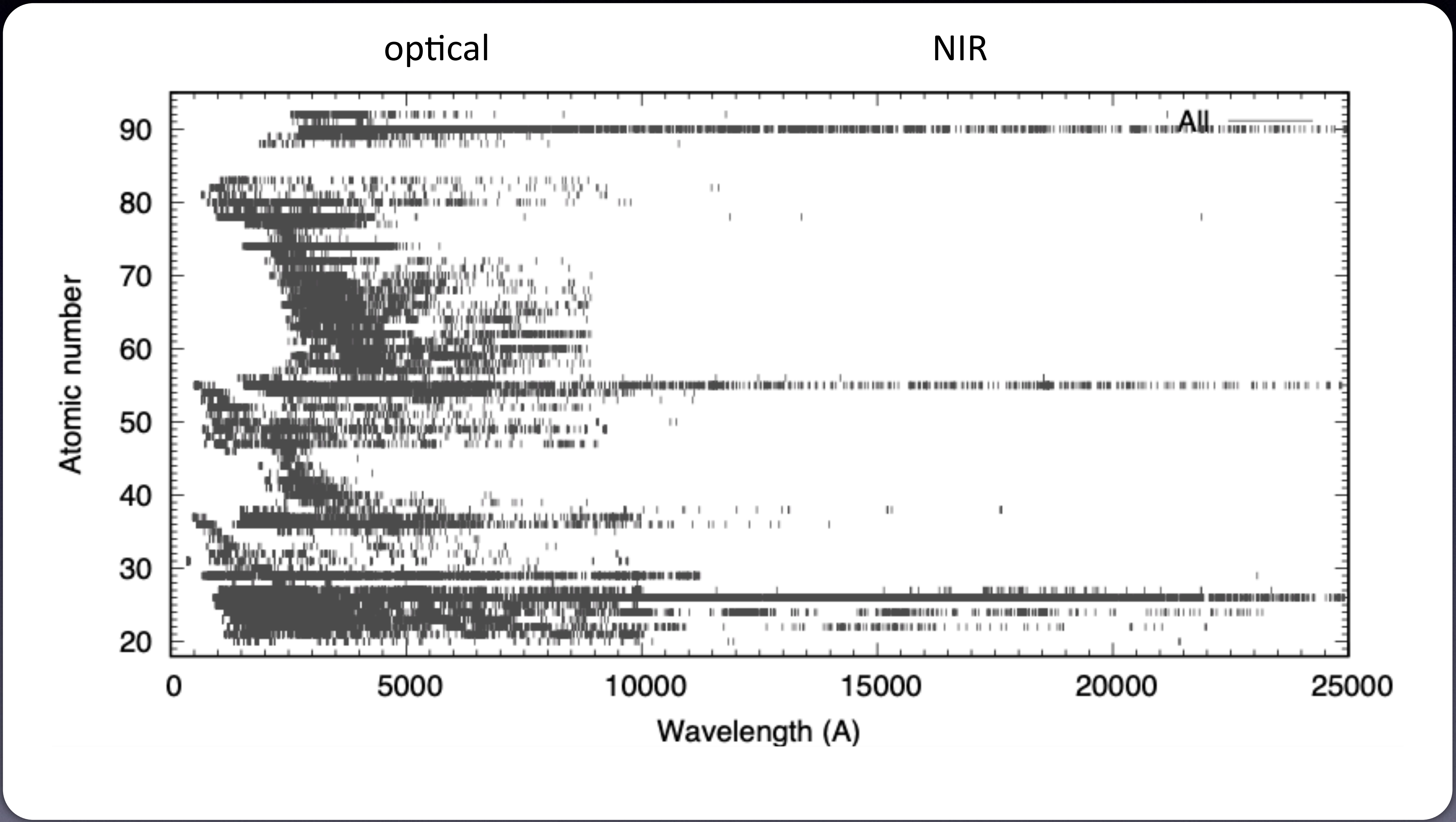


Watson+19, Domoto+21, Gillanders+22

Available atomic data

Data from the NIST ASD

Transitions with known wavelengths



Accurate transition data are highly incomplete (in particular NIR)

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)

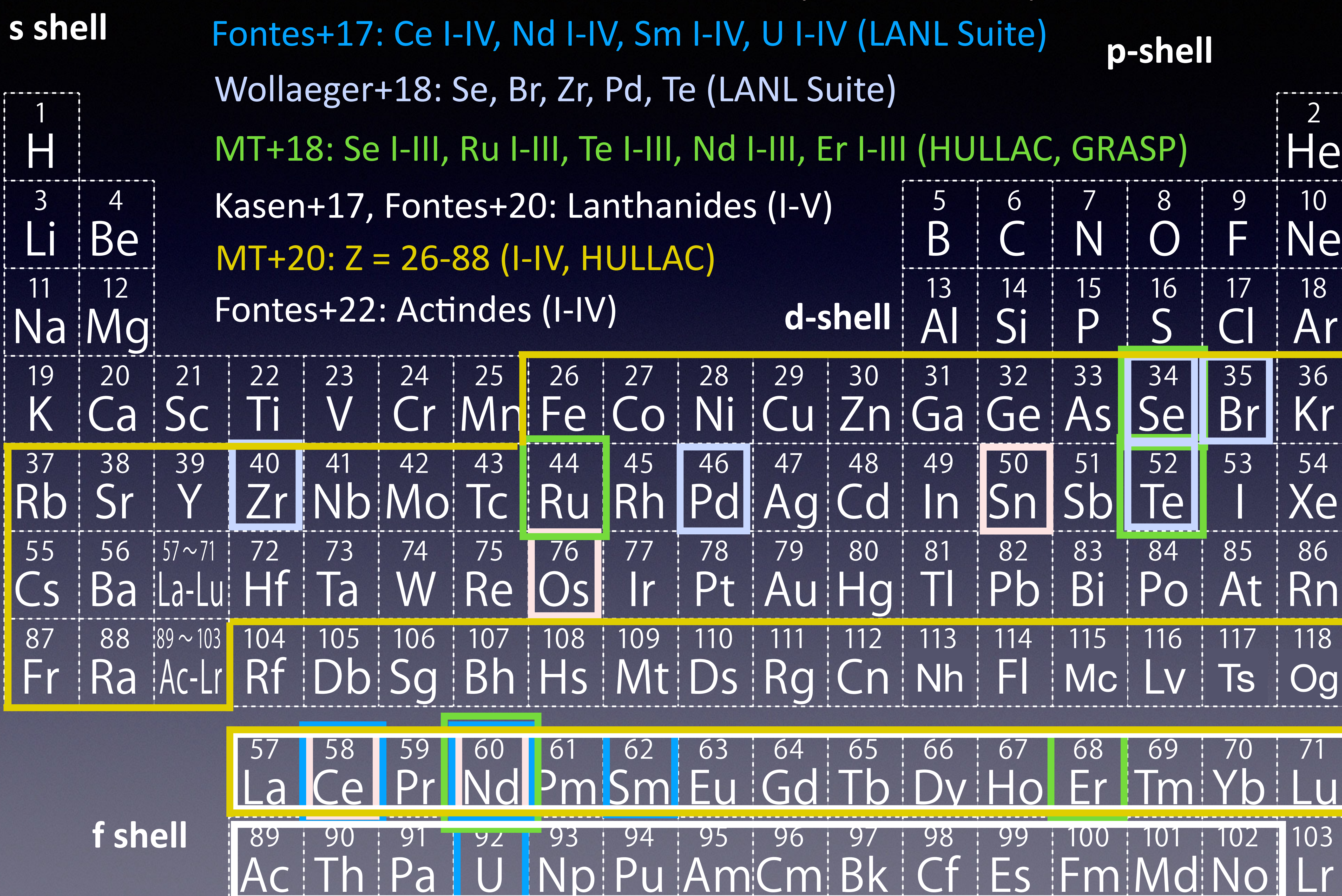
Wollaeger+18: Se, Br, Zr, Pd, Te (LANL Suite)

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)

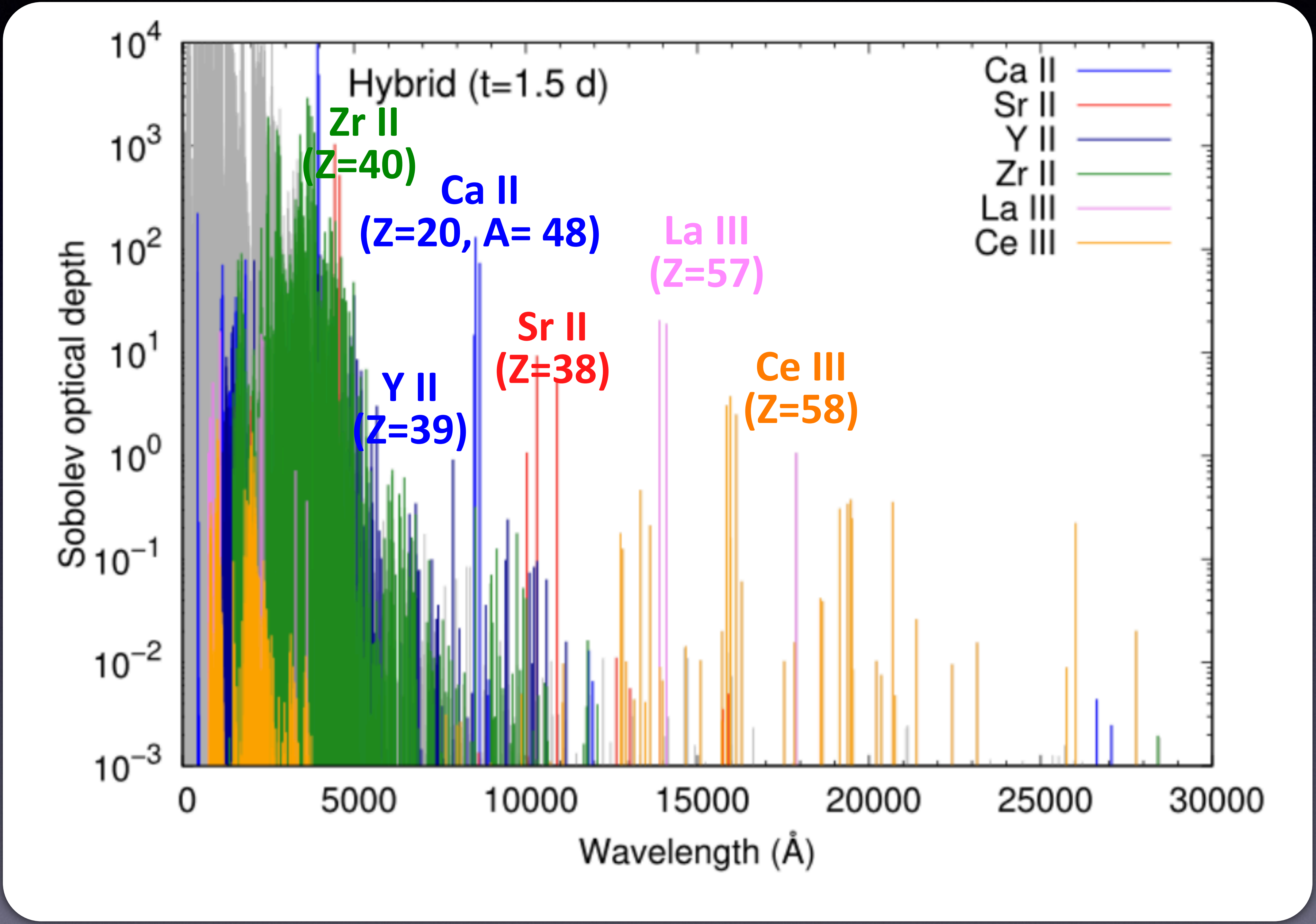
Fontes+22: Actindes (I-IV)



Important elements for spectral features

Domoto+22

Complete theoretical atomic data + **Accurate** data for important elements

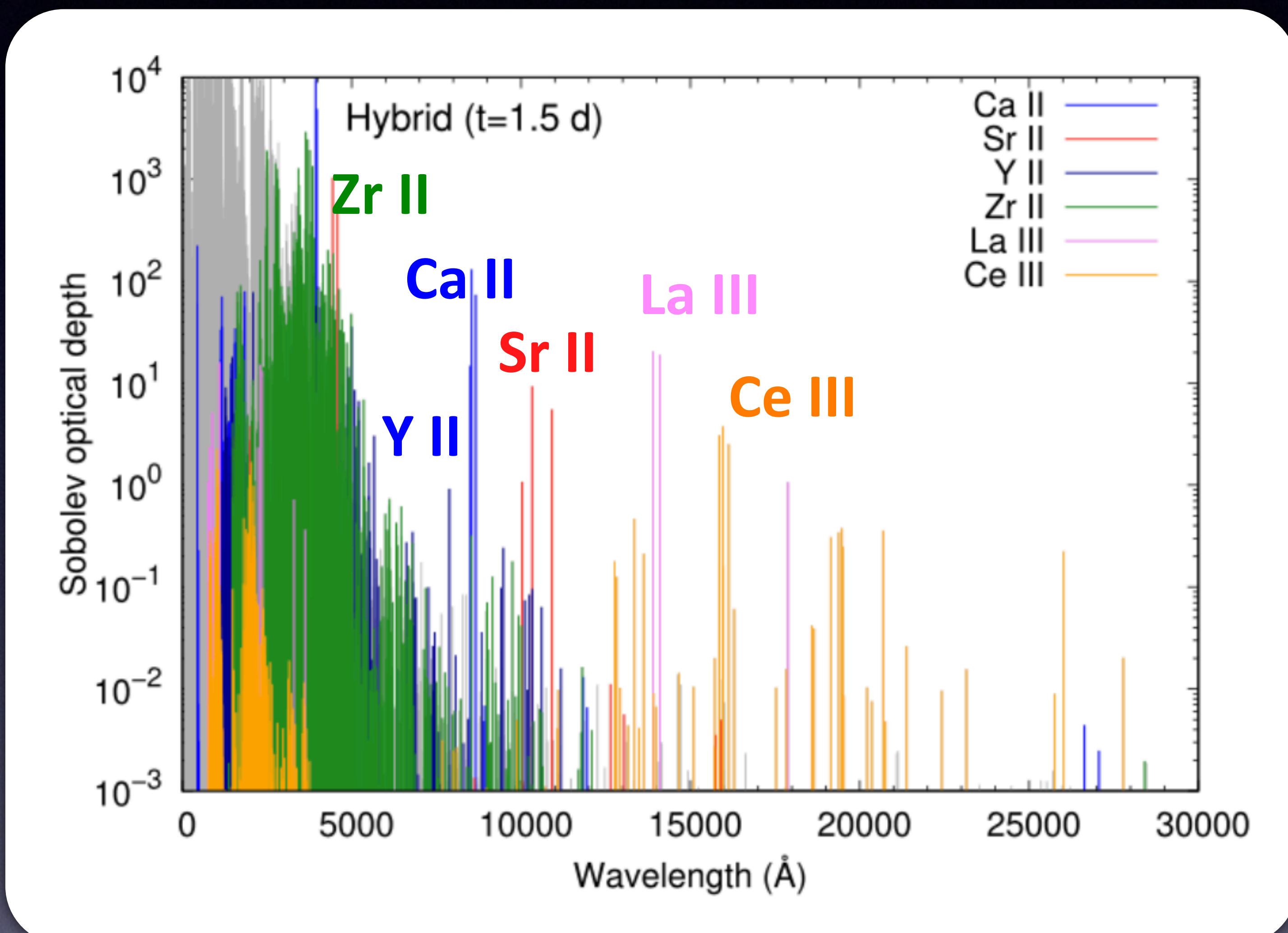


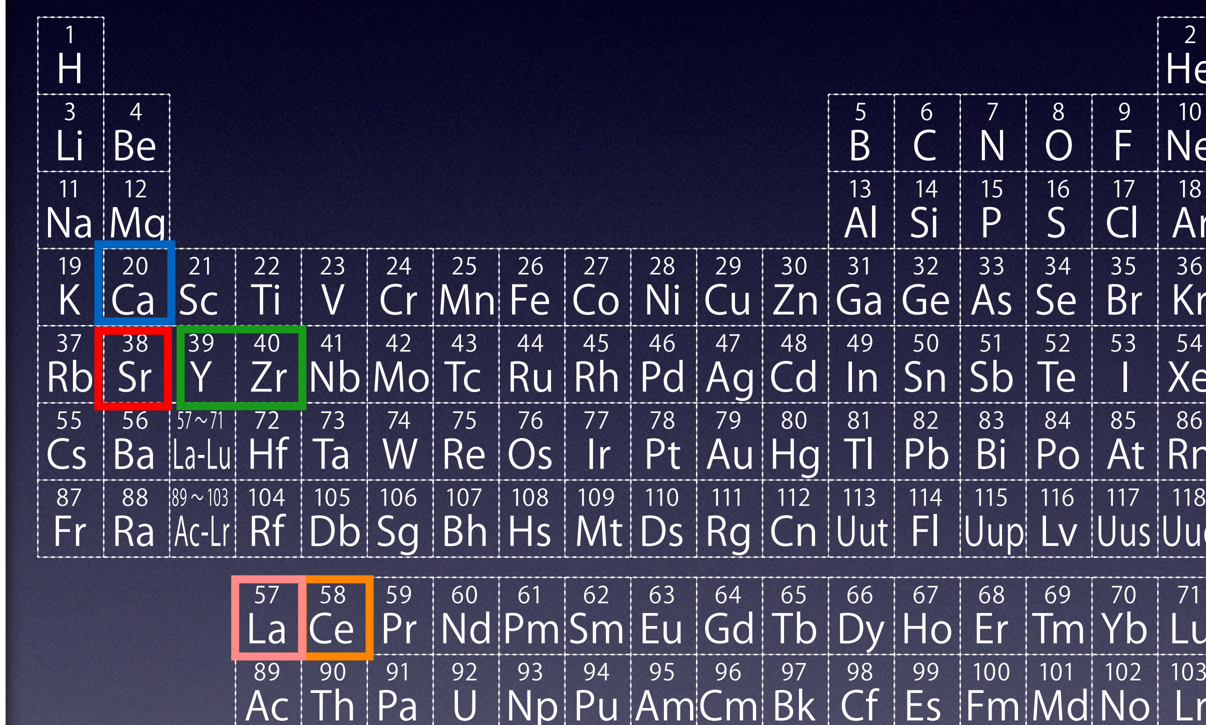
Relatively small number of elements are important

Important elements for spectral features

Domoto+22

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



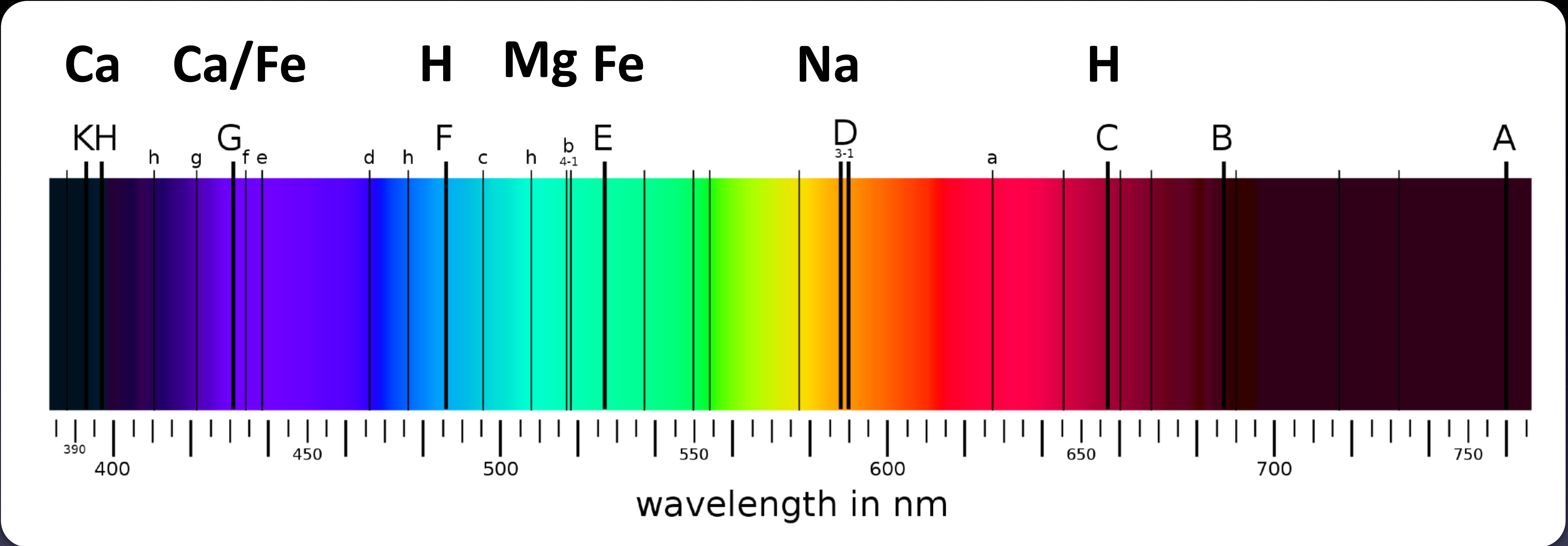


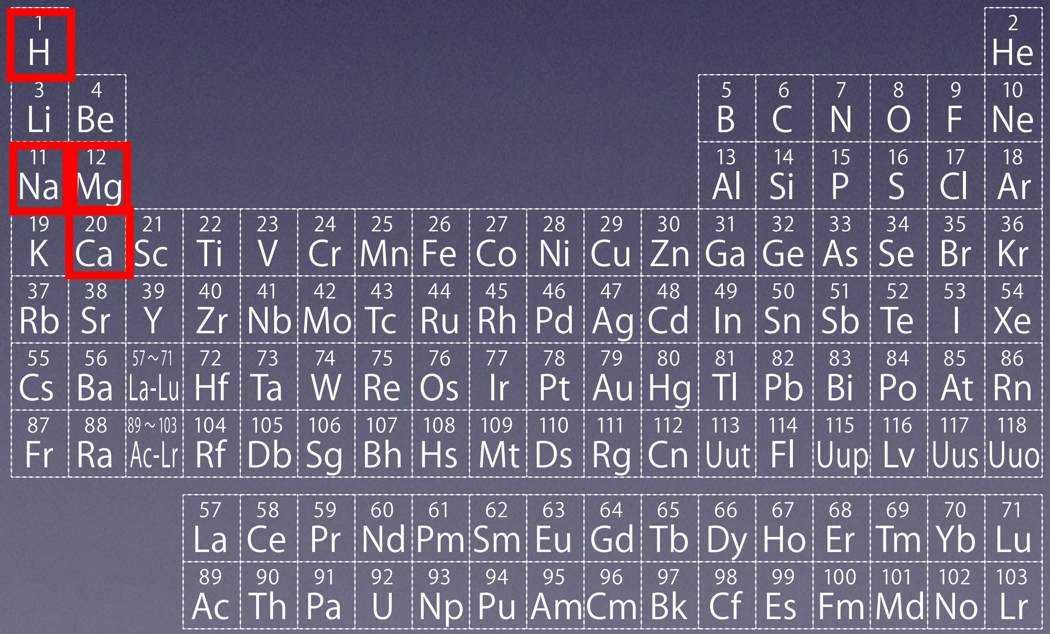
Elements with

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

Solar spectrum

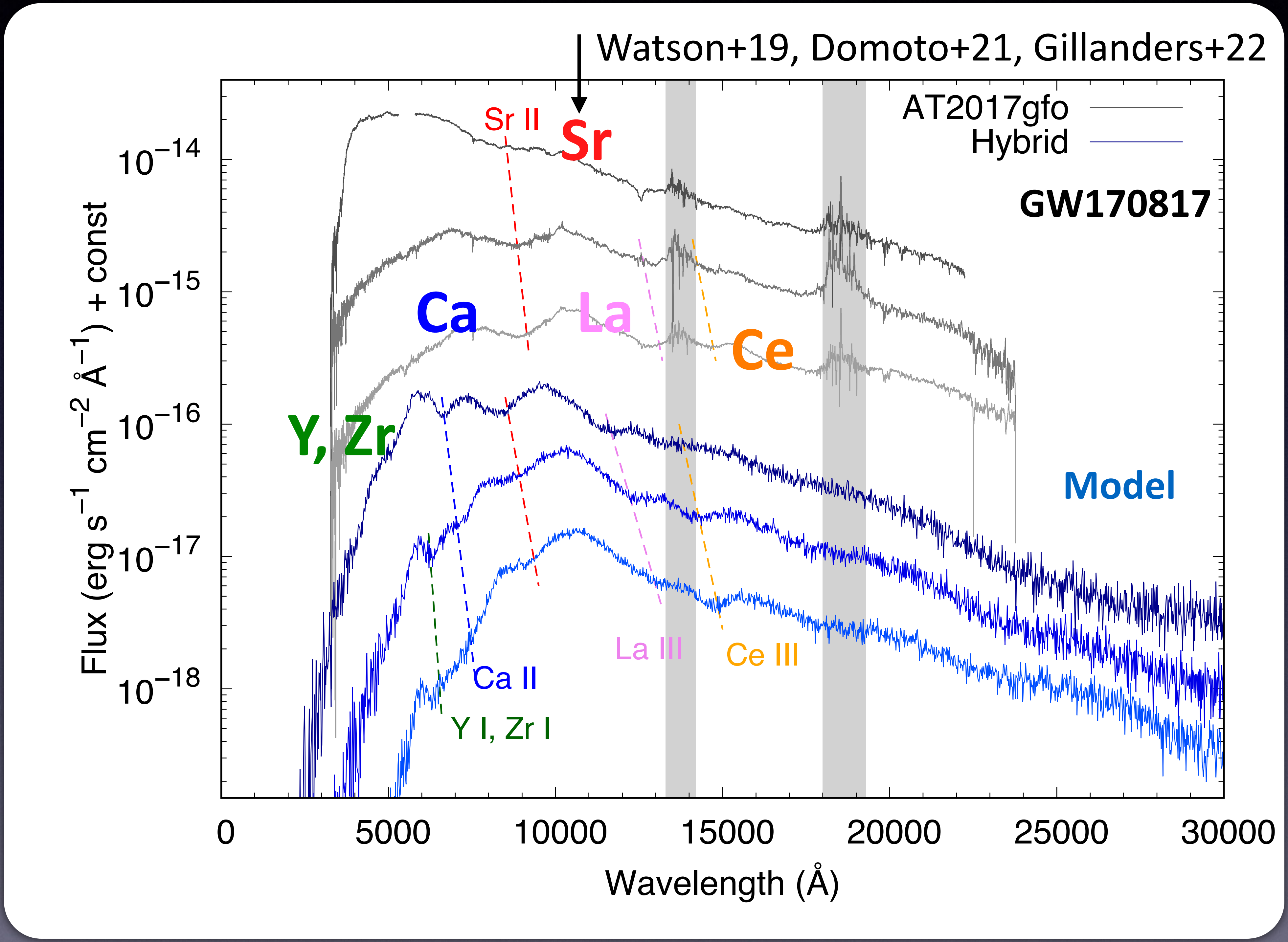
https://en.wikipedia.org/wiki/Fraunhofer_lines





Identification of La III (Z=57) and Ce III (Z=58) in NIR spectra

Domoto+22

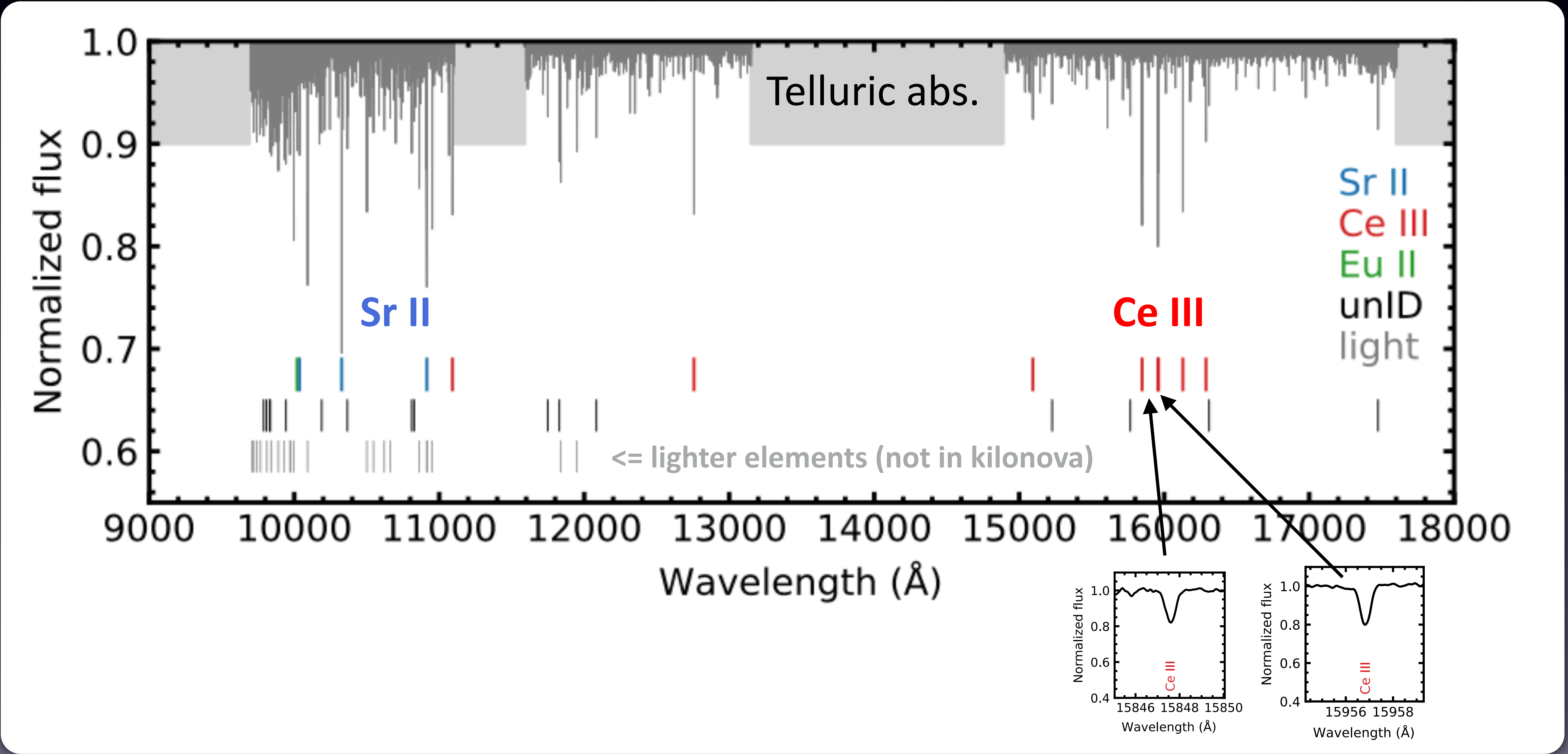


X(Ca) < 10^{-5}   **X(Sr) ~ 10^{-2}**   **X(La) > 10^{-6}**   **X(Ce) ~ 10^{-4}**

Test with the spectrum of a chemically peculiar star (= metal rich plasma!)

Tanaka, Domoto, Aoki et al. 2023

Subaru/IRD (R ~ 70,000)

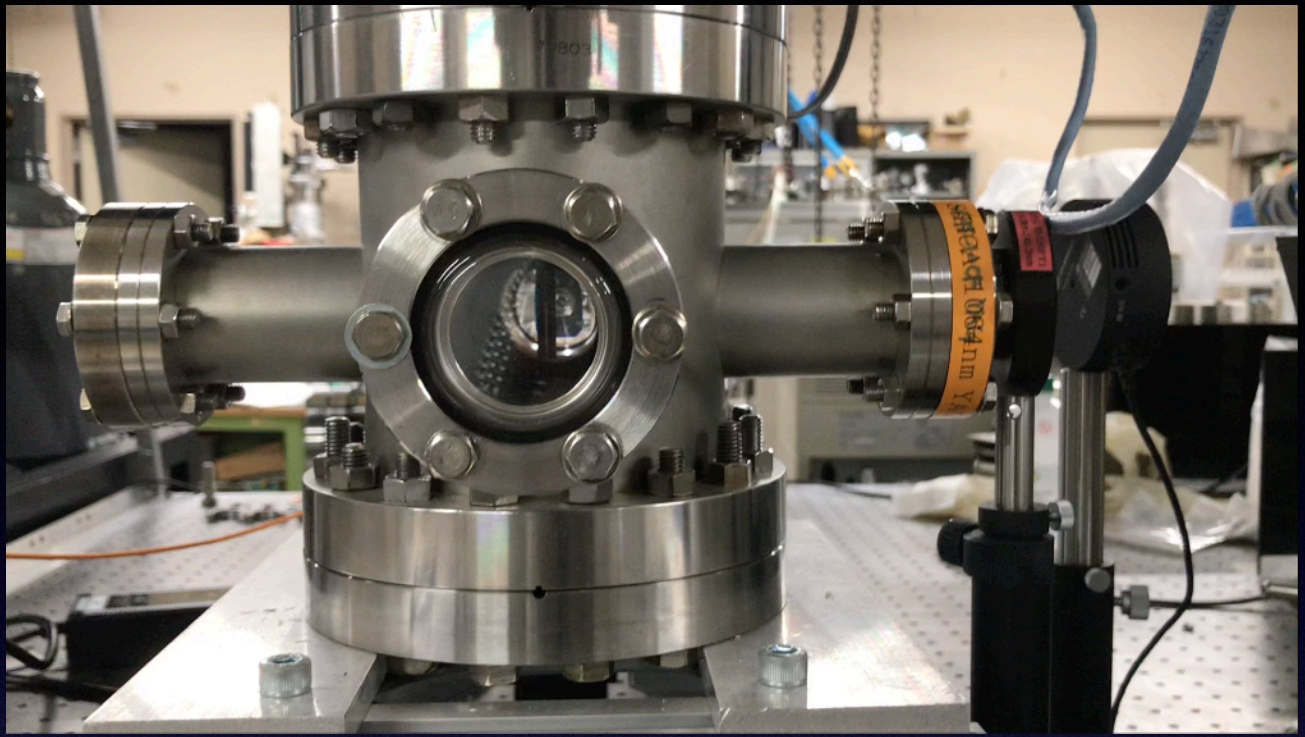


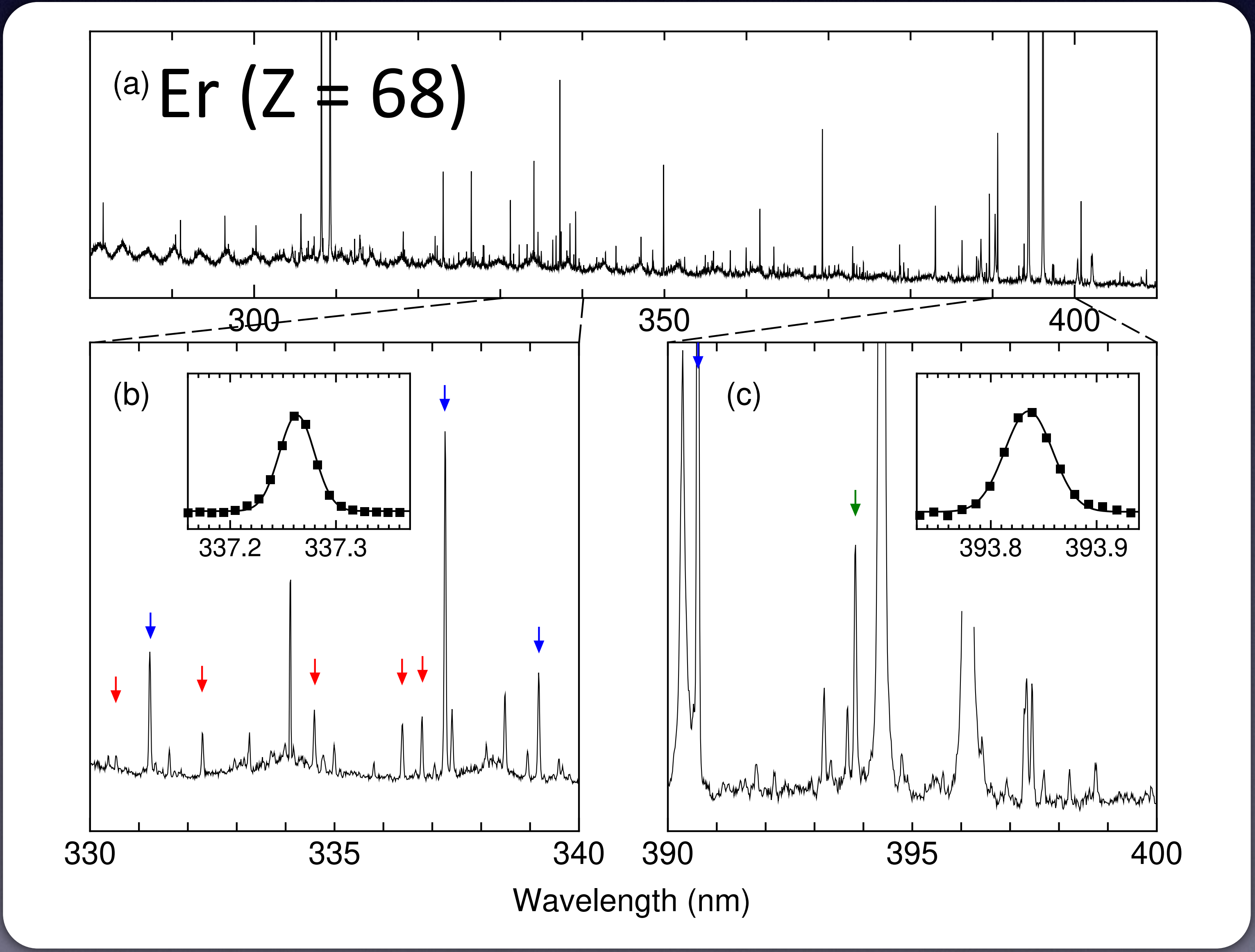
Strongest lines = Ce III, Sr II

No other comparably strong lines = Uniqueness!

Lab measurements for transition probabilities

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

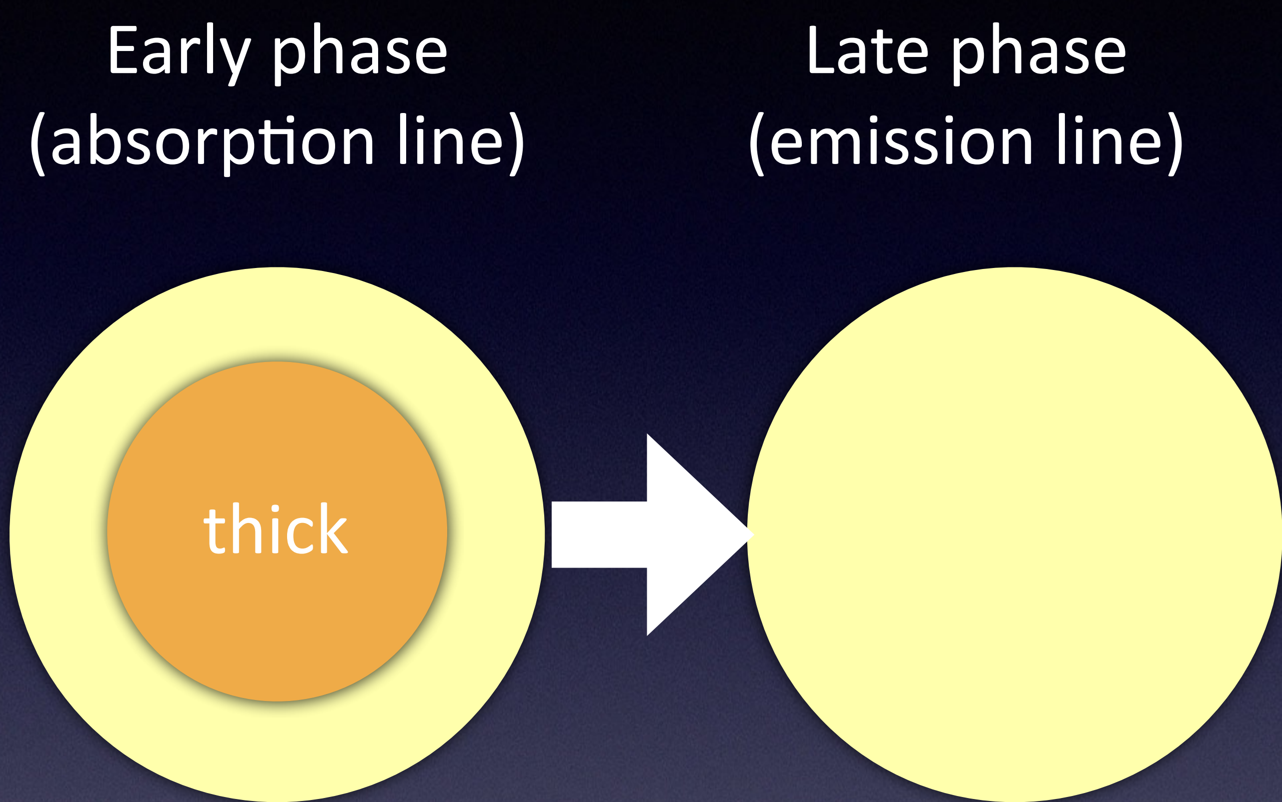




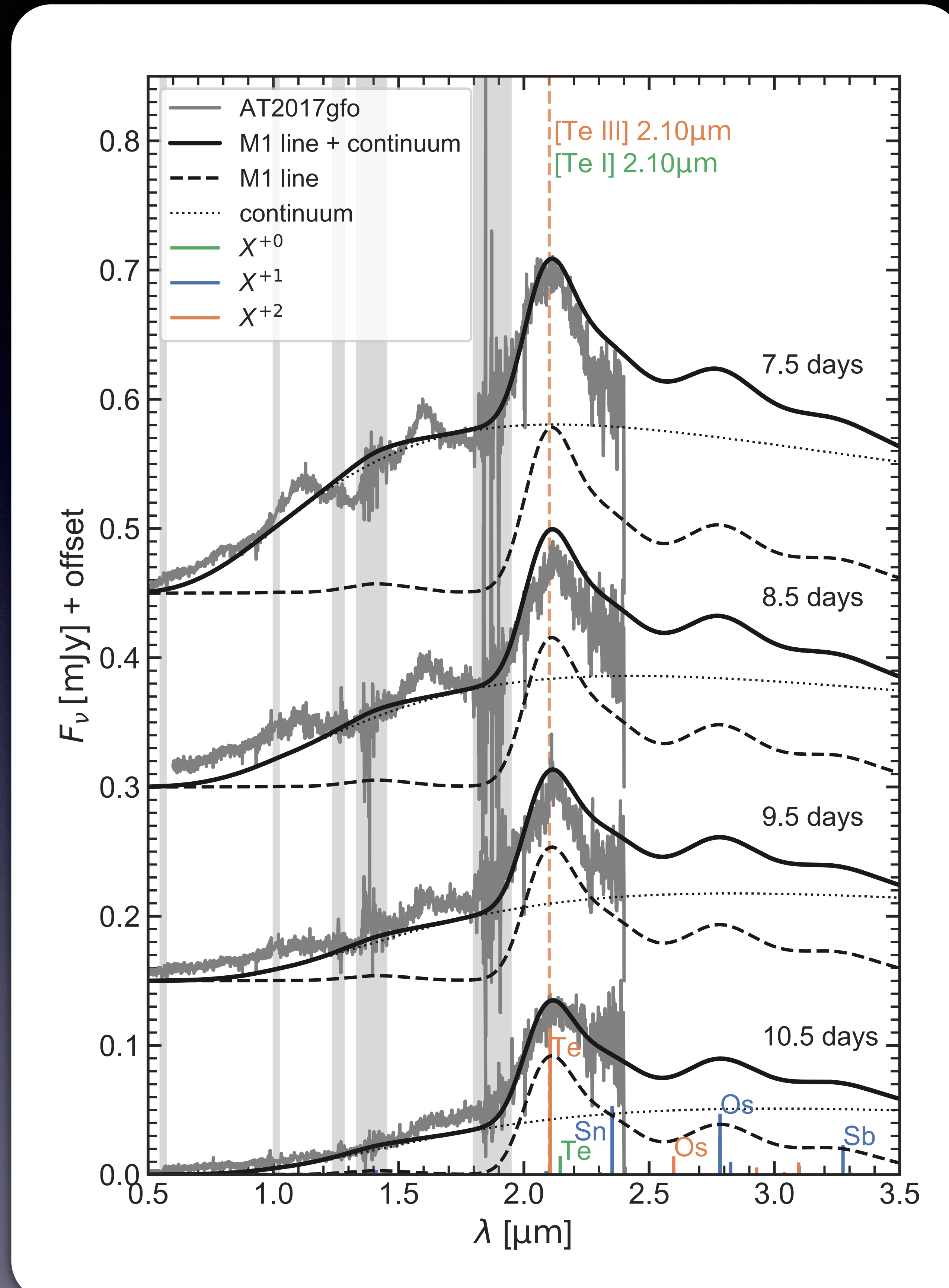
Measurements of Ce and La in optical
=> extension to NIR (2024)

Naoi (including MT)+22

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



M (Te III) ~ 10^{-3} Msun at v < 0.07 c
=>
M(Te) ~ 3 x 10^{-3} Msun
X(Te) ~ 10^{-2}



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

Constraints on the nucleosynthesis so far

Sr, Ca: Domoto+21, La, Ce: Domoto+22, He: Tarumi+23, Y: Sneppen+23, Te: Hotokezaka+23

X(He) ~ 10^{-3}

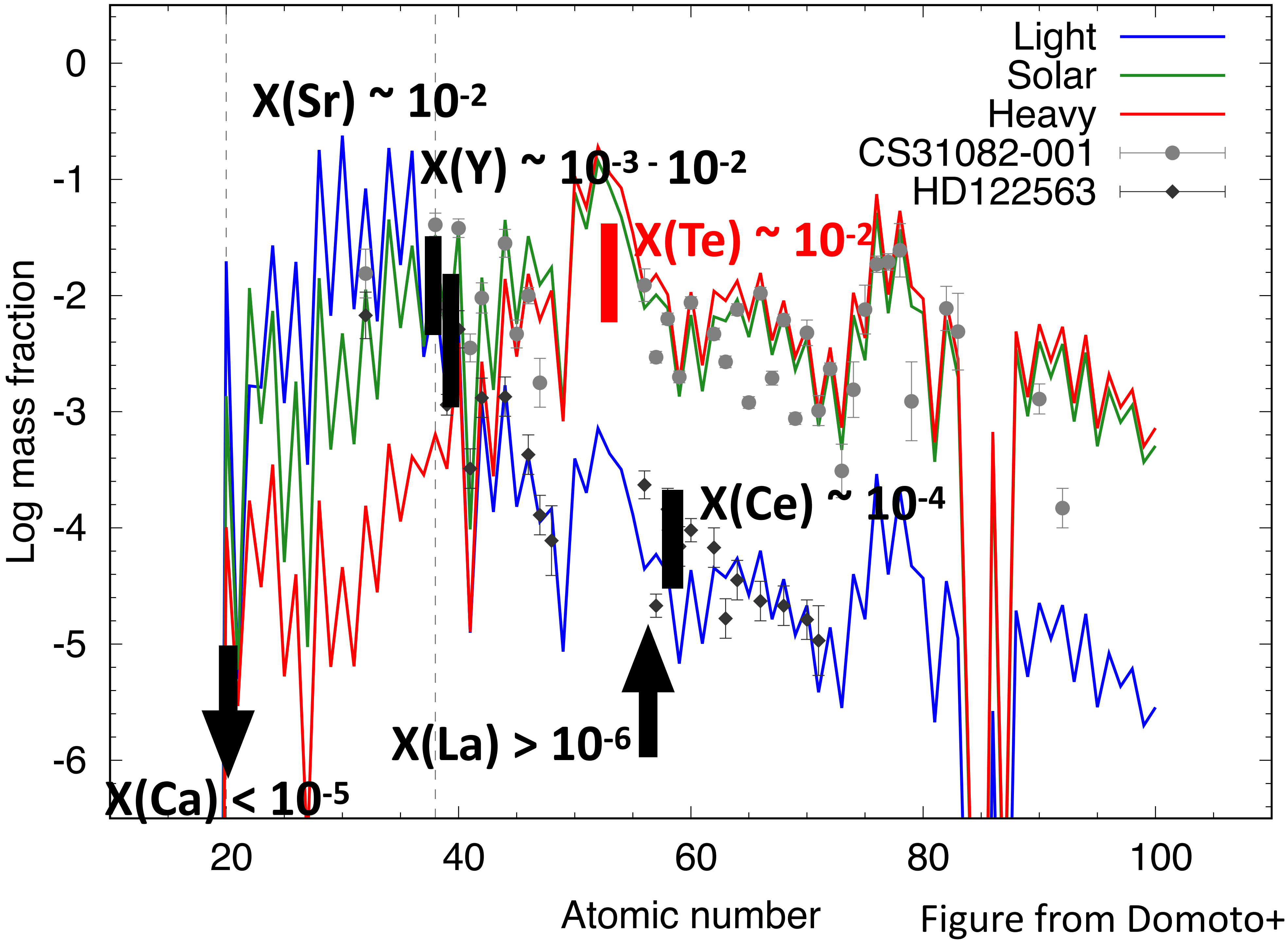


Figure from Domoto+21

Unique constraints also on the physics of NS mergers

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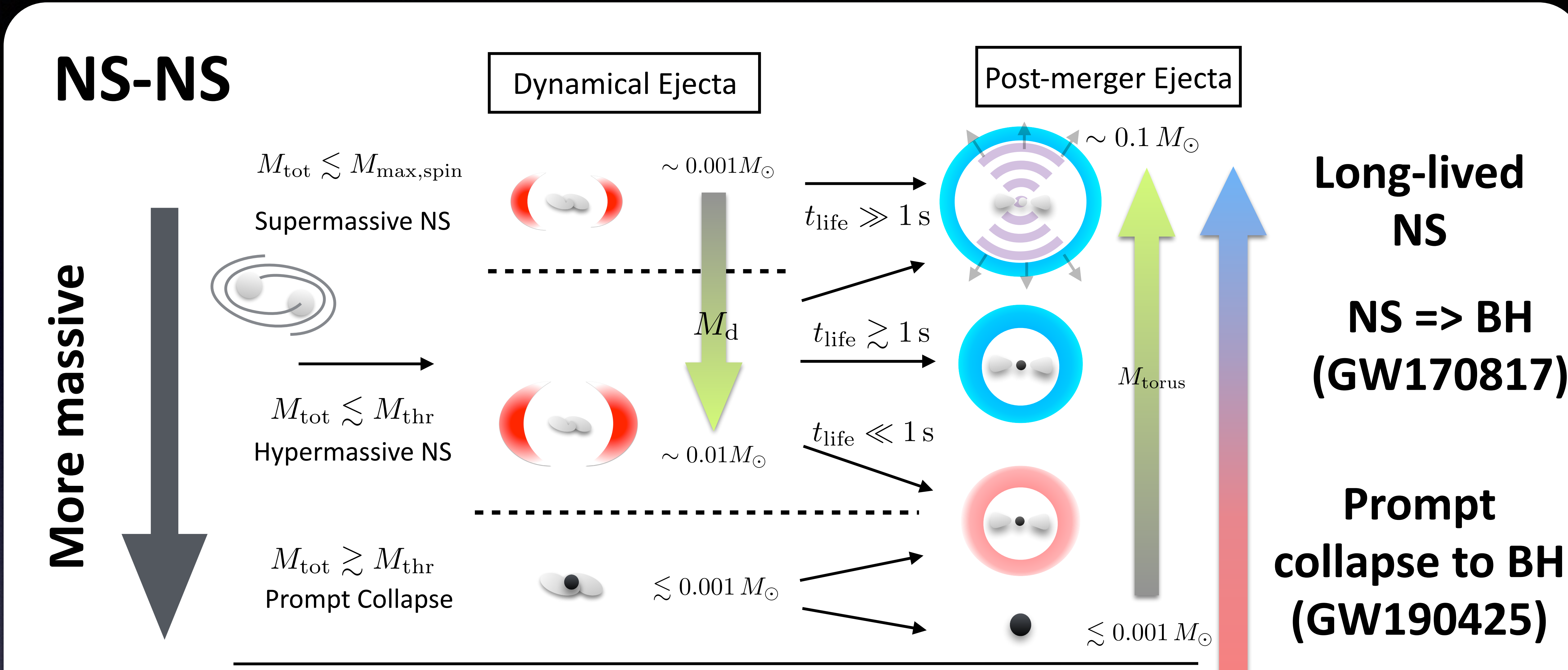
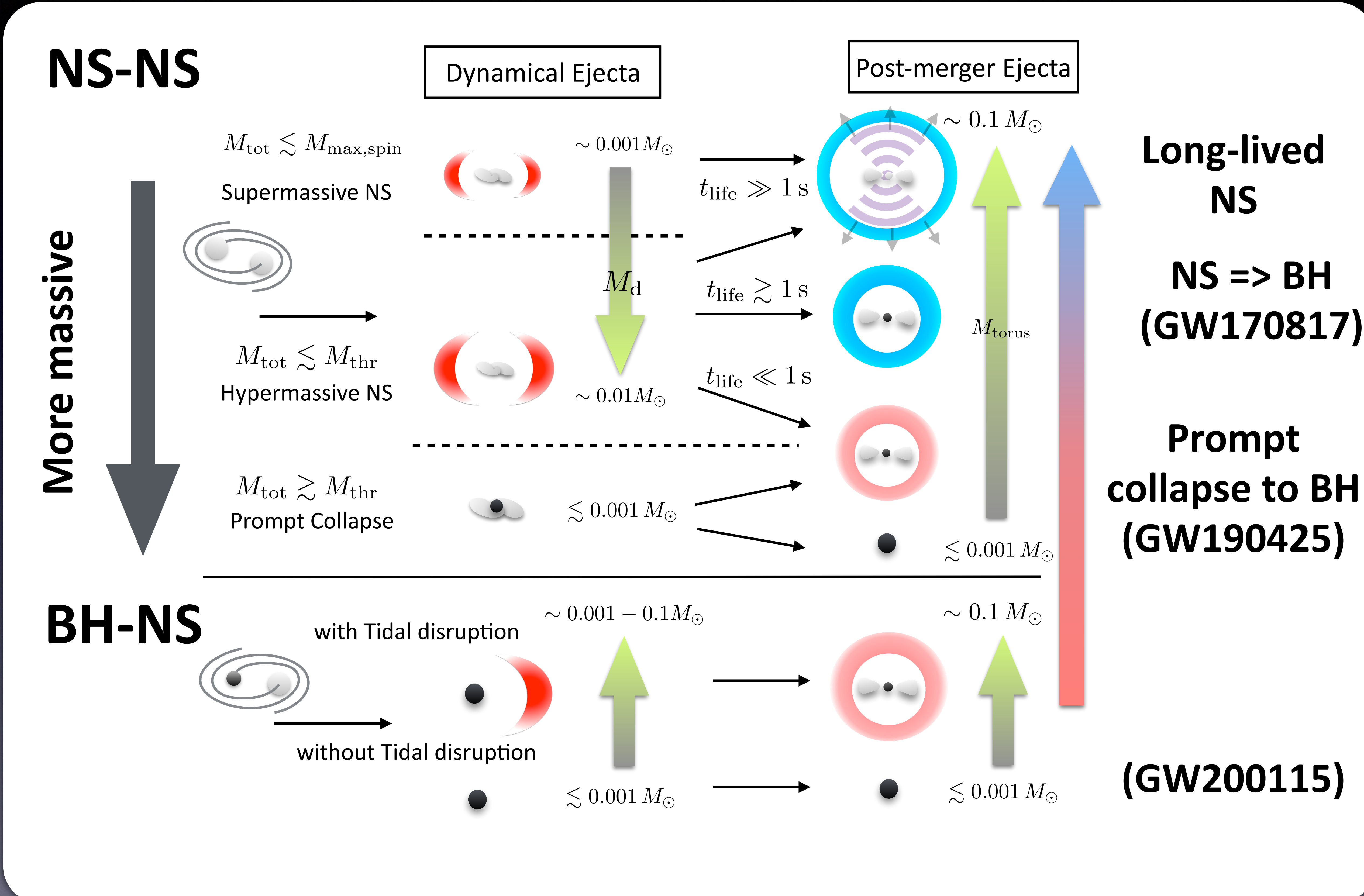
Diversity of neutron star mergers



Kawaguchi, Shibata, MT 2020

Diversity of neutron star mergers



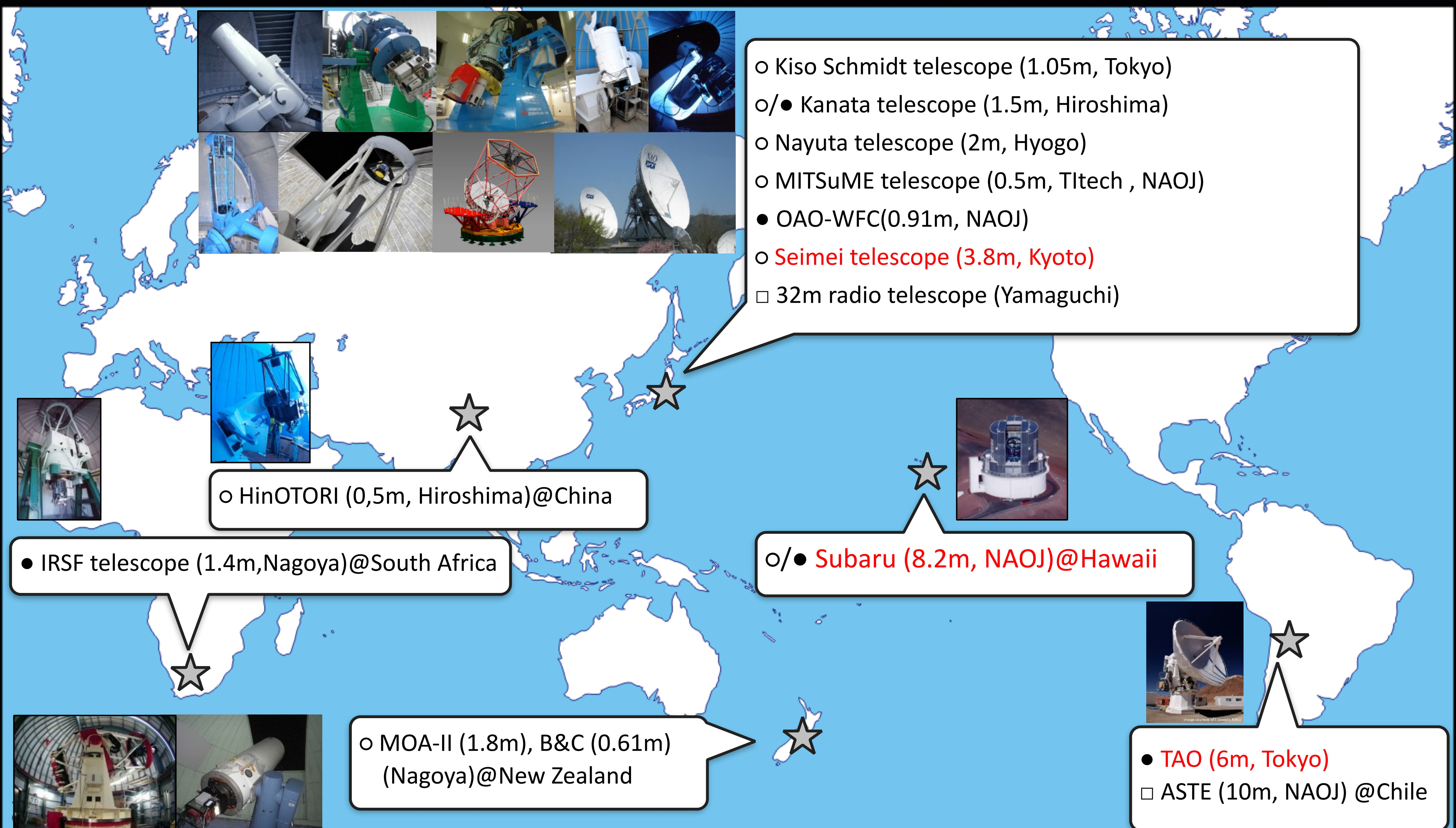
Kawaguchi, Shibata, MT 2020

Event rate of NS mergers at < 40 Mpc
~ 1 event in 30 years
(see Asano-san's talk)

Need to observe NS merger events at larger distances!
d = 100 Mpc => volume x 10   (1 event in 3 yr)
d = 200 Mpc => volume x 100 (1 event in 0.3 yr)

Optical/IR follow-up observations

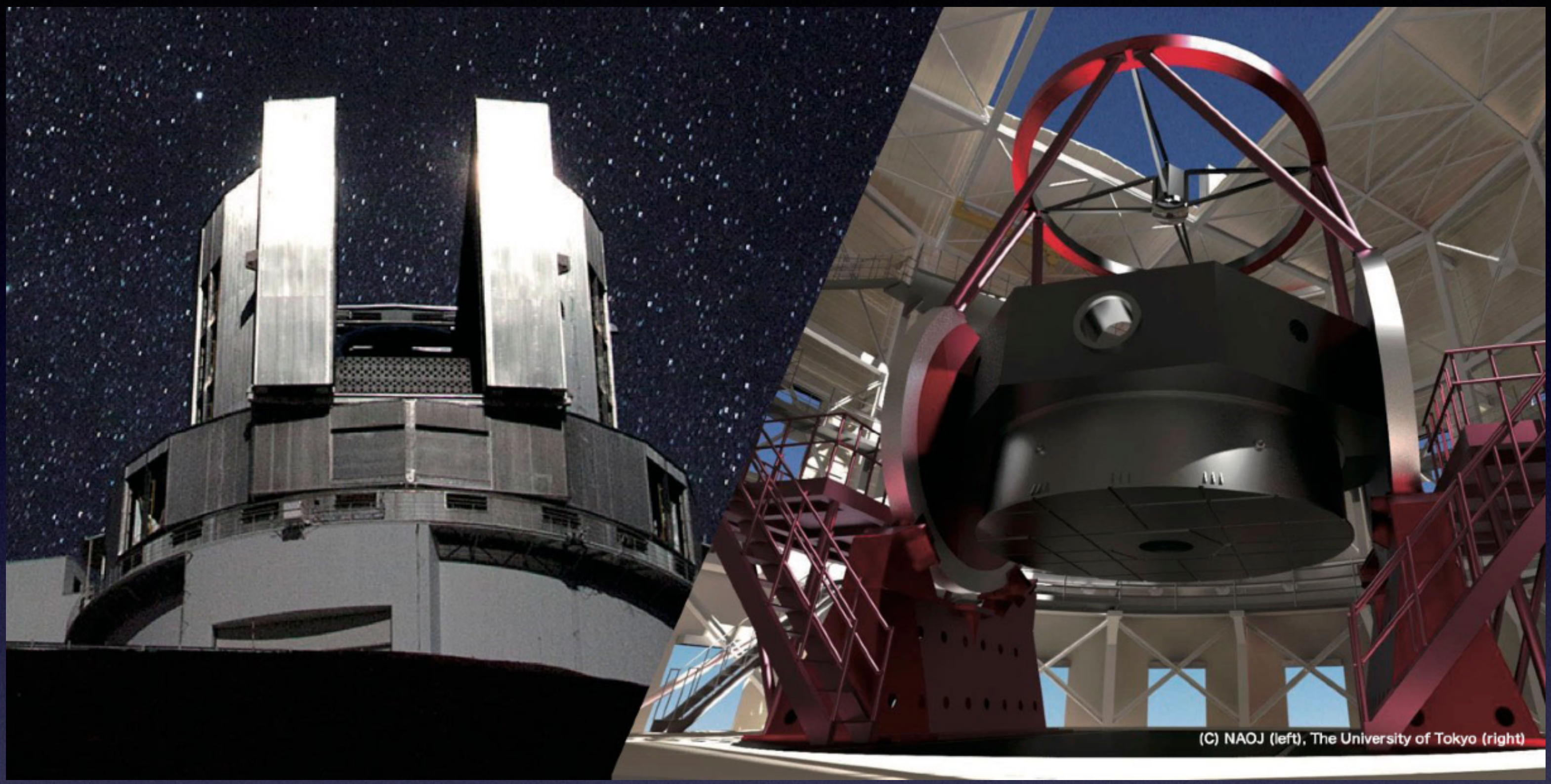
J-GEM: Japanese Collaboration for Gravitational Wave ElectroMagnetic Wave Follow-up



○ Optical ● Infrared □ Radio

Upgrades for spectroscopic observations

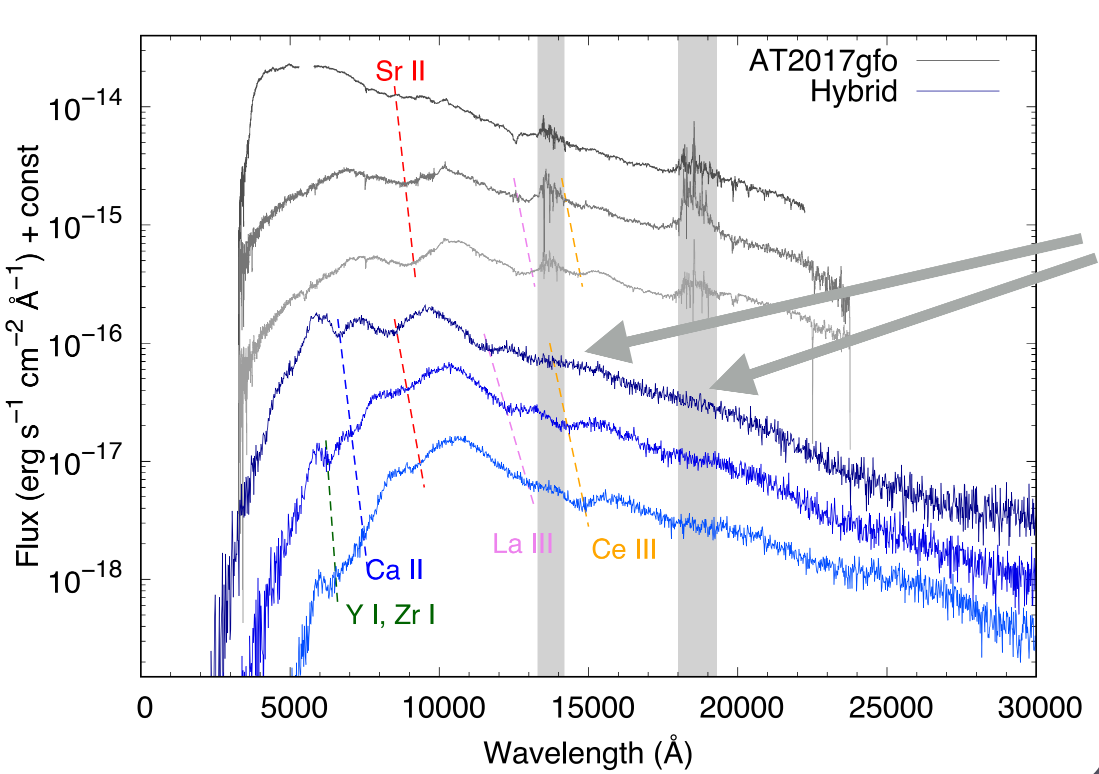
Subaru (north) **TAO (south)**



(C) NAOJ/U. Tokyo

NINJA

High sensitivity observations with (laser tomography) adoptive optics
=> fainter objects



SWIMS

Continuous spectra opening the atmospheric windows (5500 m altitude!)

Summary

- **Multimessenger observations of NS mergers**
  - Kilonovae: probe of heavy element nucleosynthesis
  - Progress in decoding spectral features of kilonovae
  - Sr II (or He I), Ce III, La III, Y II, Te III have been suggested (more works in progress)
- **Future**
  - More events with different masses and different line of sights => Comprehensive pictures of NS mergers
  - Optical/IR follow-up: upgrades for spectroscopic facilities