

Multi-Messenger Astrophysics in the Dynamic Universe

Non-LTE Ionization Modeling for Helium and Strontium in Neutron Star Merger Ejecta

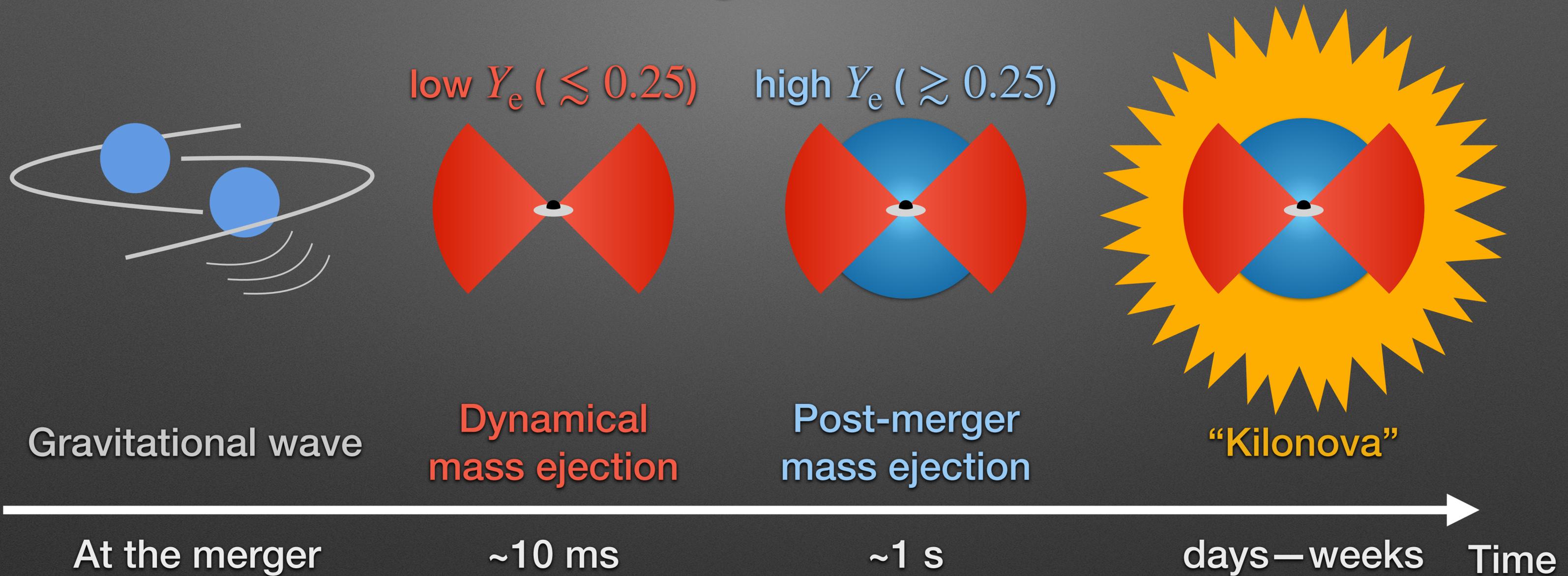
Koya Chiba

in collaboration with

Masaomi Tanaka (Tohoku U.), Shinya Wanajo (Kyoto U.),

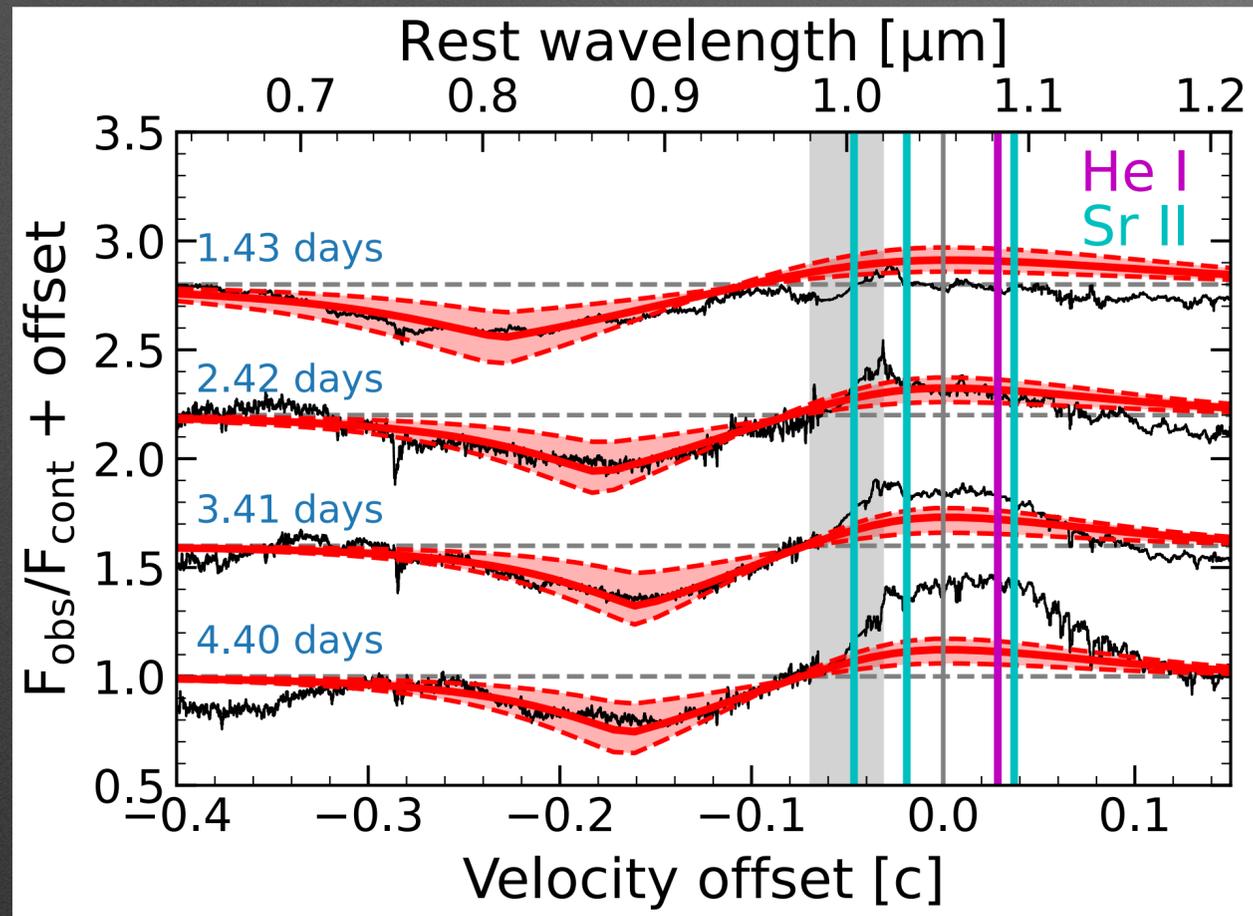
Sho Fujibayashi (Tohoku U.), Kyohei Kawaguchi (AEI), Kenta Hotokezaka (U. Tokyo)

From neutron star merger to “kilonova”



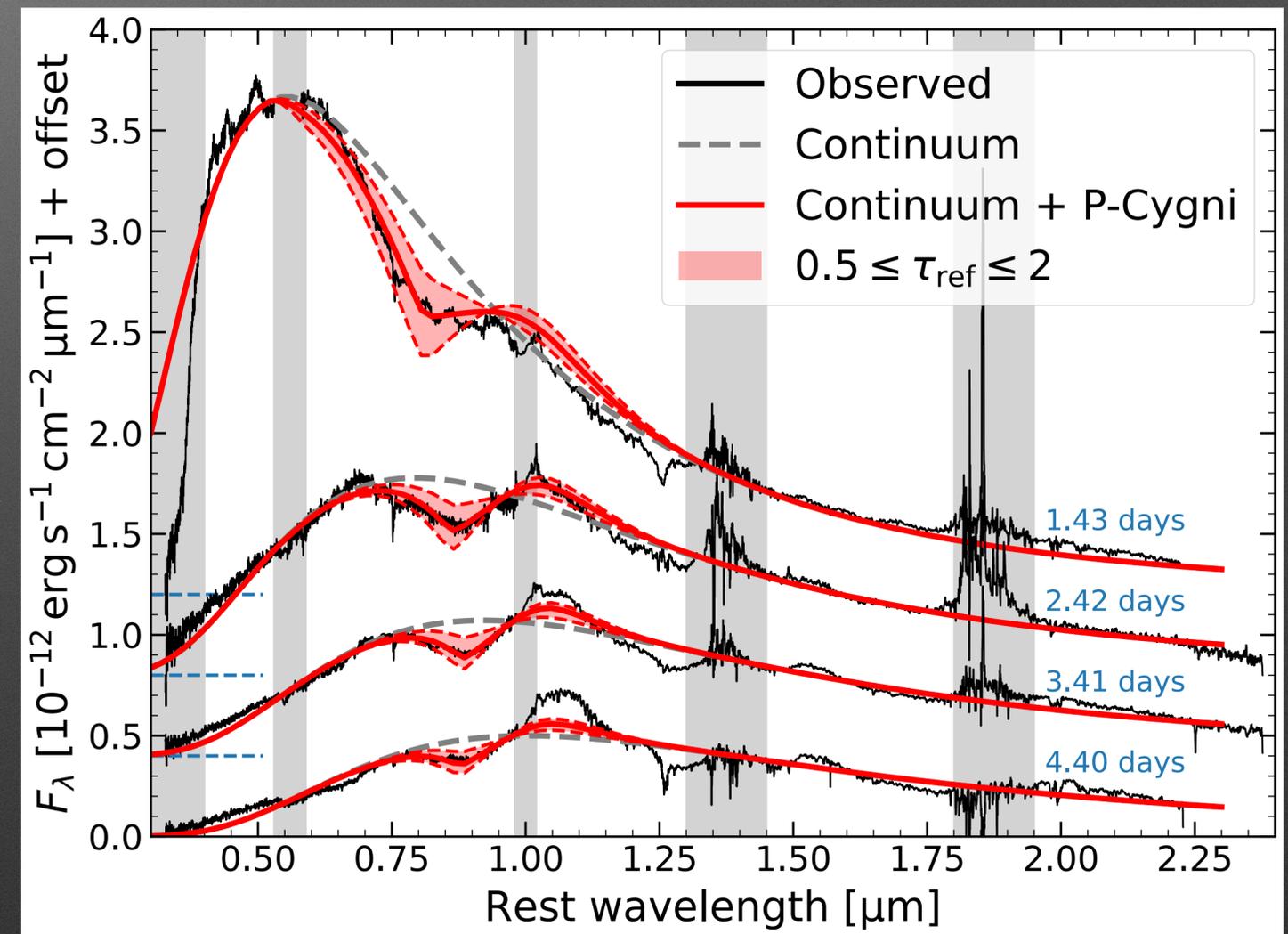
$$\text{Electron fraction : } Y_e = 1 - \frac{n_n}{n_n + n_p}$$

P-Cygni feature around 1 μm in the spectra of AT2017gfo



Zoom-in
at $\sim 1 \mu\text{m}$

VLT/X-shooter spectra of AT2017gfo



Pian+ 2017; Smartt+ 2017,
see also Sneppen+ 2024; Gillanders+ 2024

Sr II ?

Watson+ 2019;
Domoto+ 2021, 2022;
Gillanders+ 2022

VS

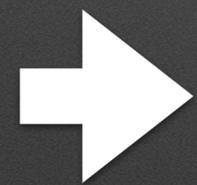
He I ?

Fernandez & Metzger 2013;
Perego+ 2022;
Tarumi+ 2023;
Sneppen+ 2024

Importance of non-LTE modeling

Sr abundance tension?

- Inferred Sr mass : $(1 - 5) \times 10^{-5} M_{\odot}$ e.g., Watson+ 2019
✳ assuming local thermodynamic equilibrium (LTE)
- Inferred total ejecta mass : $0.03 - 0.05 M_{\odot}$



Inferred Sr mass fraction :
 $\sim 10^{-3}$

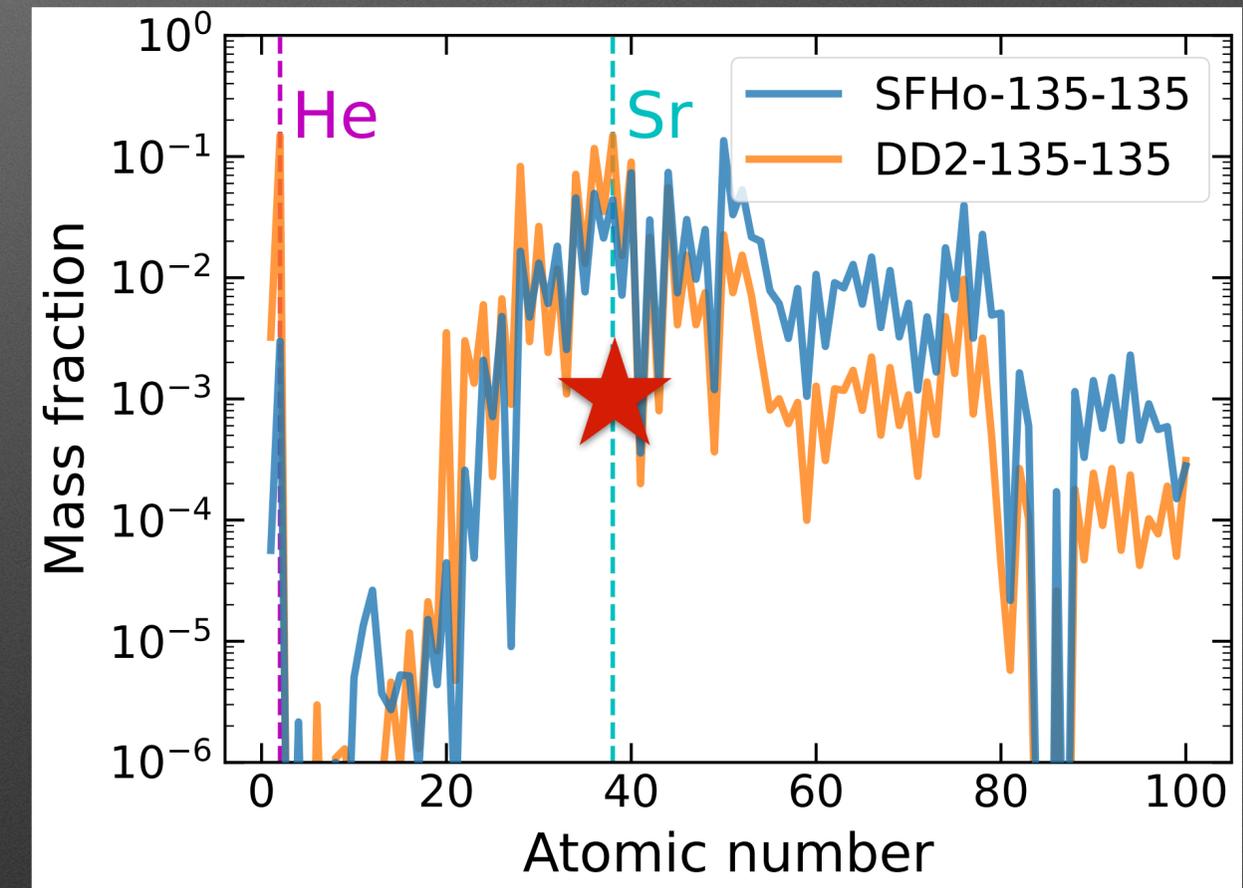


He production

- He is likely to be synthesized in kilonova ejecta. Fernandez & Metzger 2013
- Its abundance can be comparable to those of Sr

Perego+ 2022
Sneppen+ 2024
Jacobi+ 2025

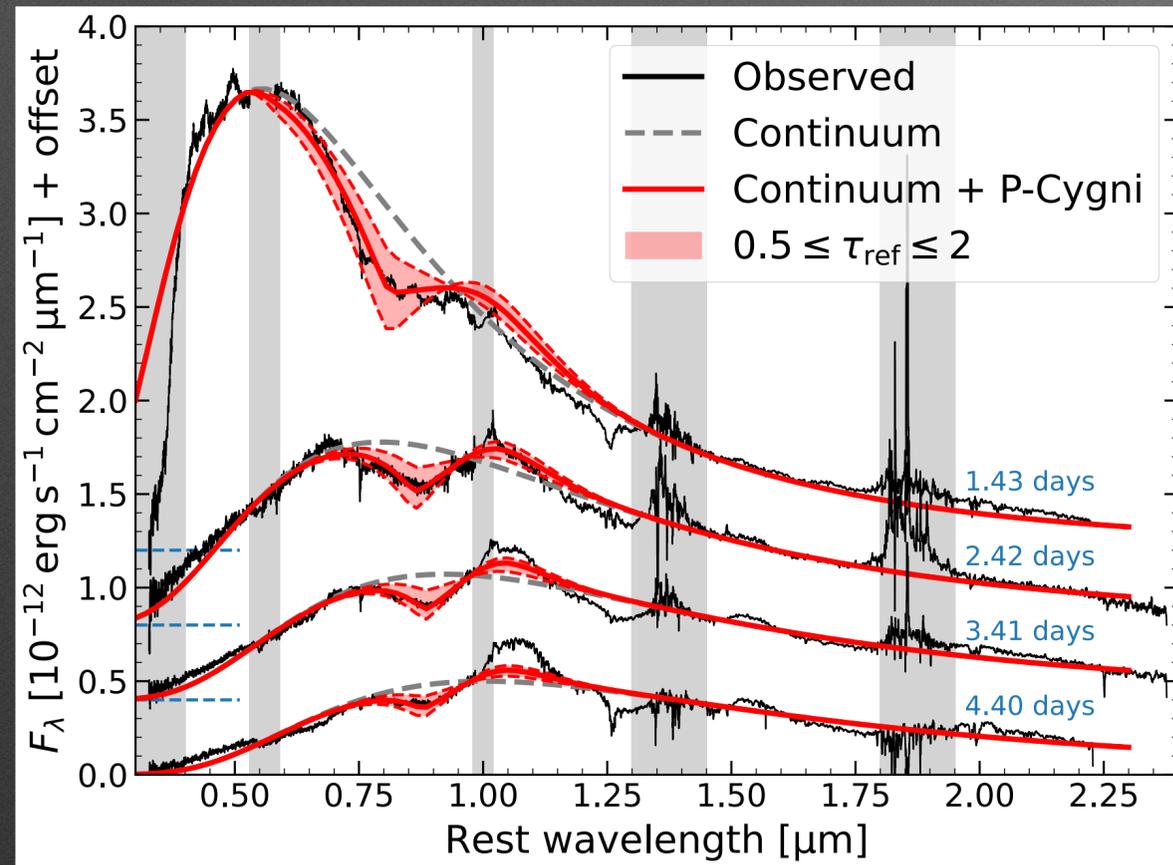
Abundance at 1 day after the merger



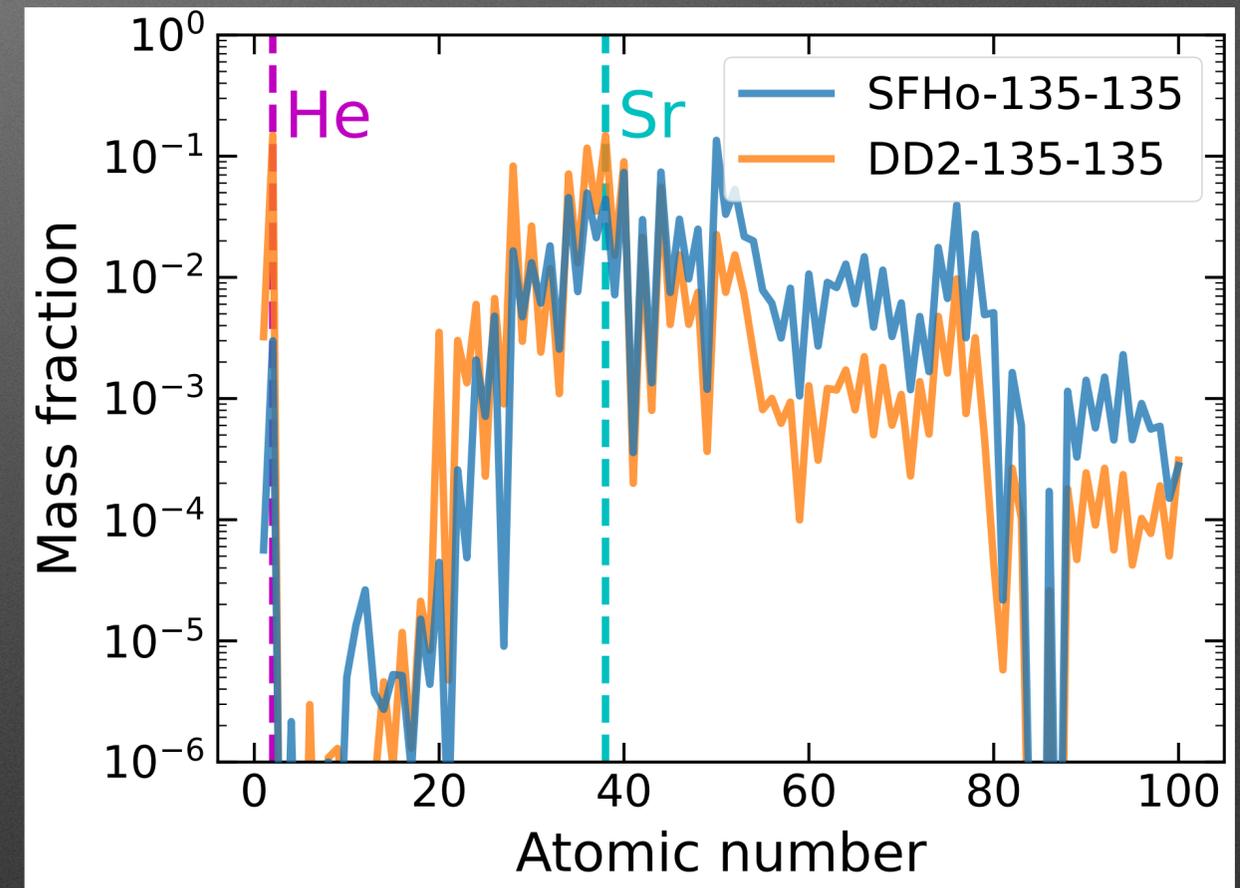
Kawaguchi+ 2022, 2023

This work

Observation



Simulation



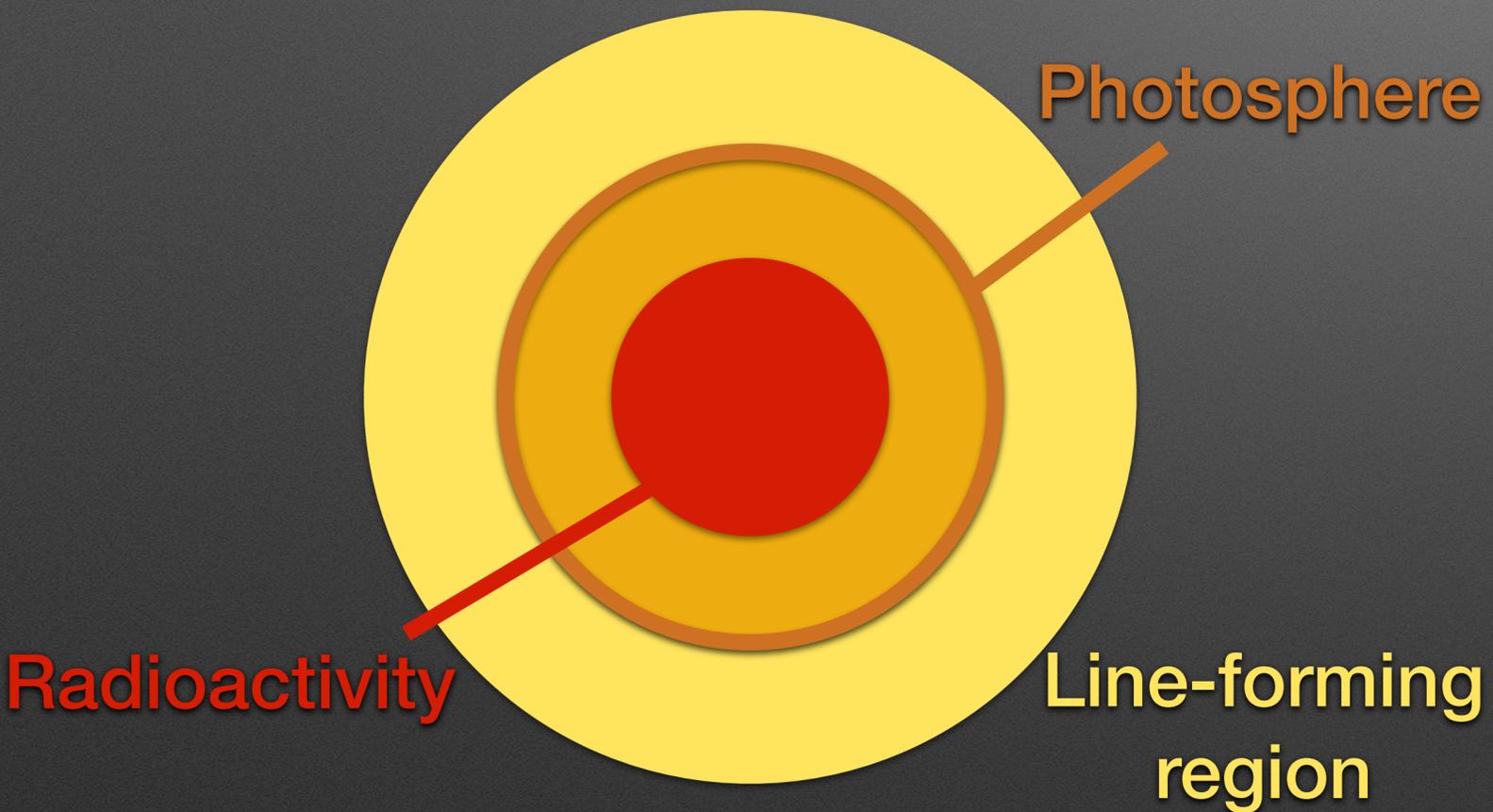
Detailed modeling
Better abundance estimate

- Nucleosynthesis conditions
- Mass-ejection mechanisms

1. **Non-LTE ionization modeling**
2. **Abundance constraints from observations**
3. **Comparison with numerical simulations**

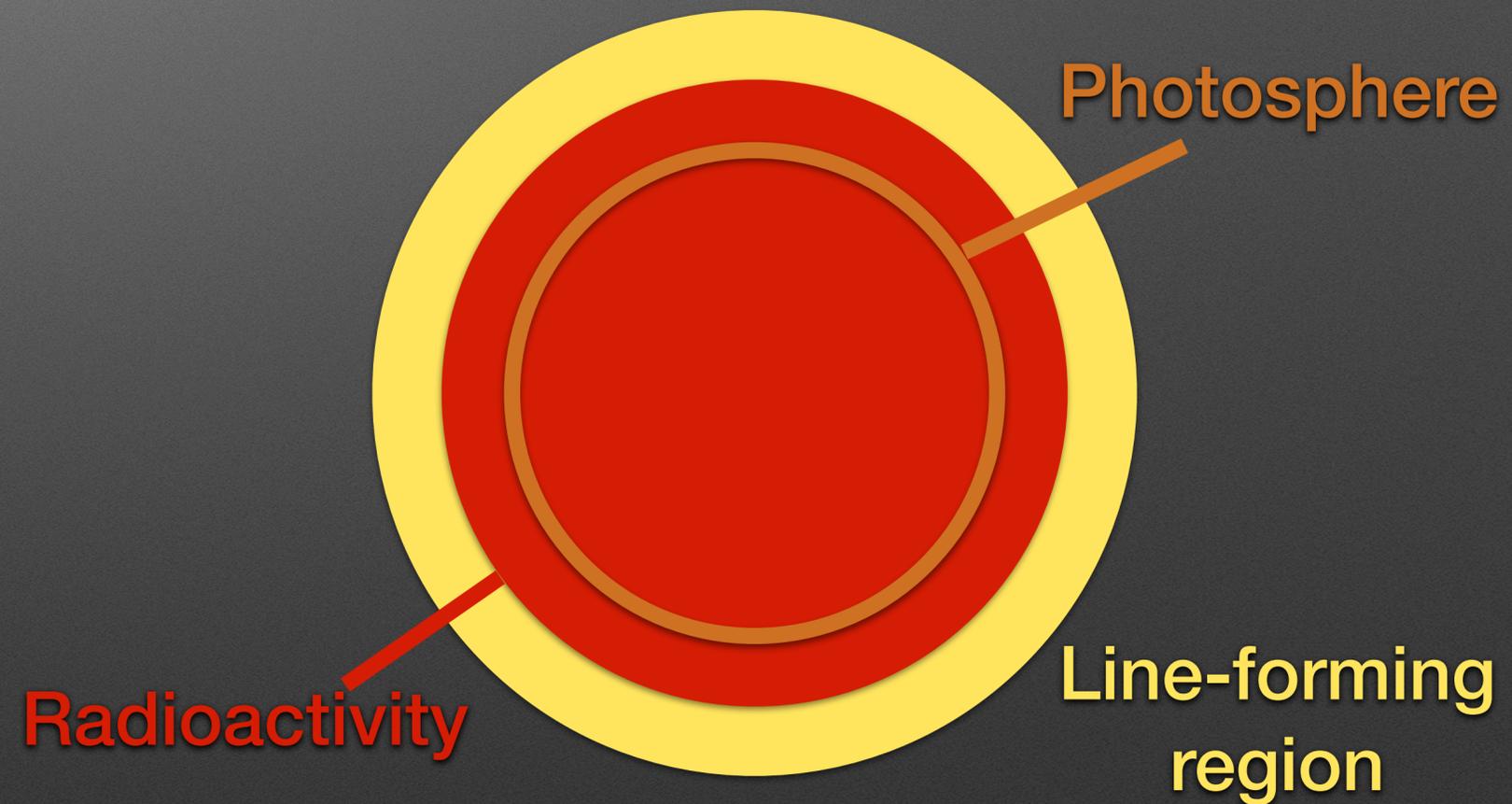
Radioactivity everywhere in kilonova ejecta

Supernova / Stellar atmosphere



LTE is basically valid

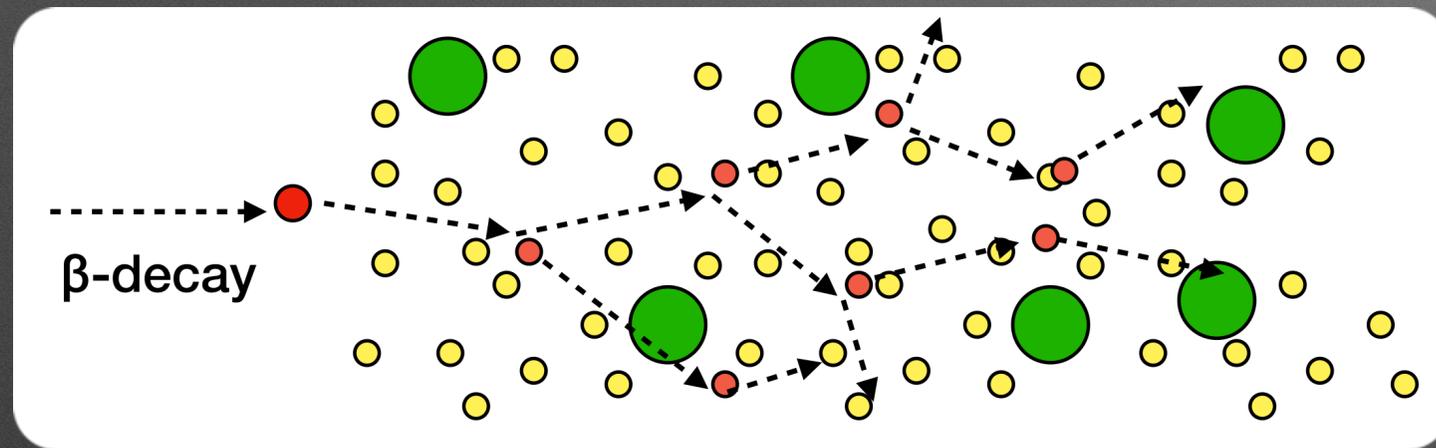
Kilonova



LTE may **not** be valid

Non-LTE = cloud chamber (霧箱)

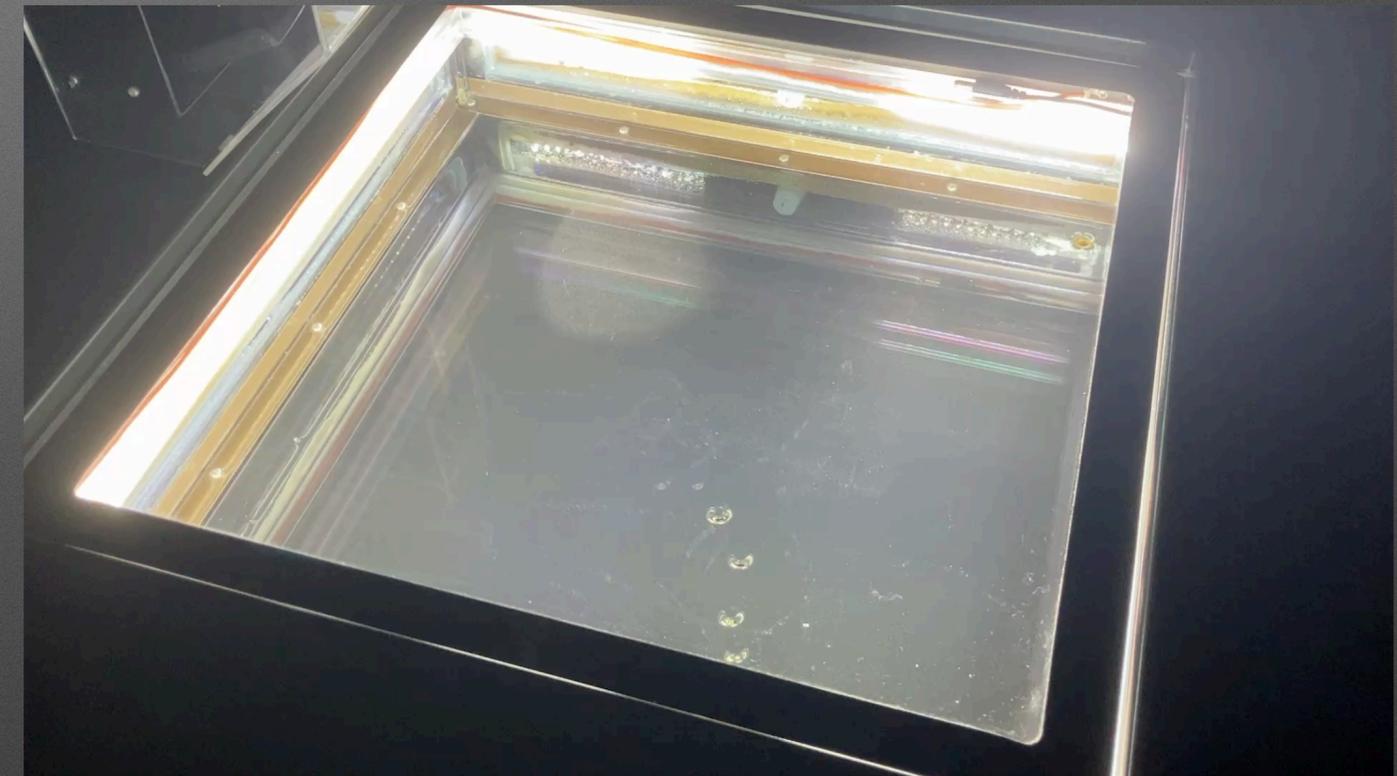
Schematic picture of “energy degradation”



“Non-thermal” ionization rate: $\Gamma_{\text{nt}} = \frac{D_{\text{ion}} \dot{q}}{I}$

- \dot{q} : Radioactive heating rate per ion
- I : Ionization potential
- D_{ion} : Energy fraction

The movie of cloud chamber (from Masaomi-san)



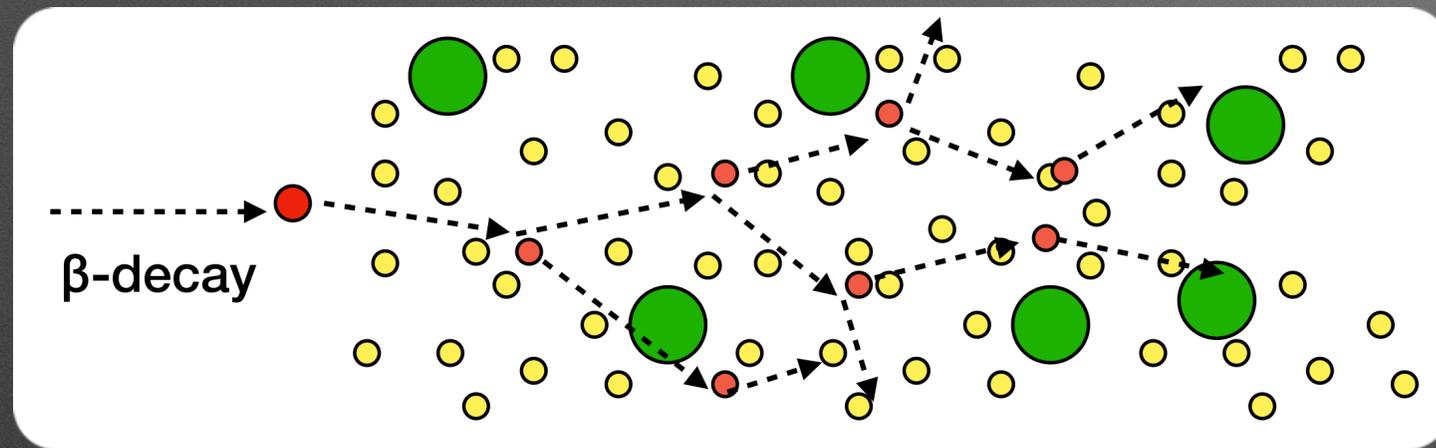
✧ For typical kilonova ejecta in early-phase,

$$\dot{q} \sim 1 \text{ eV s}^{-1} \text{ ion}^{-1} \left(\frac{\mu_{\text{ion}}}{100} \right) \left(\frac{\dot{Q}}{10^{10} \text{ erg s}^{-1} \text{ g}^{-1}} \right)$$

$$D_{\text{ion}} \sim 0.03$$

Non-LTE = cloud chamber (霧箱)

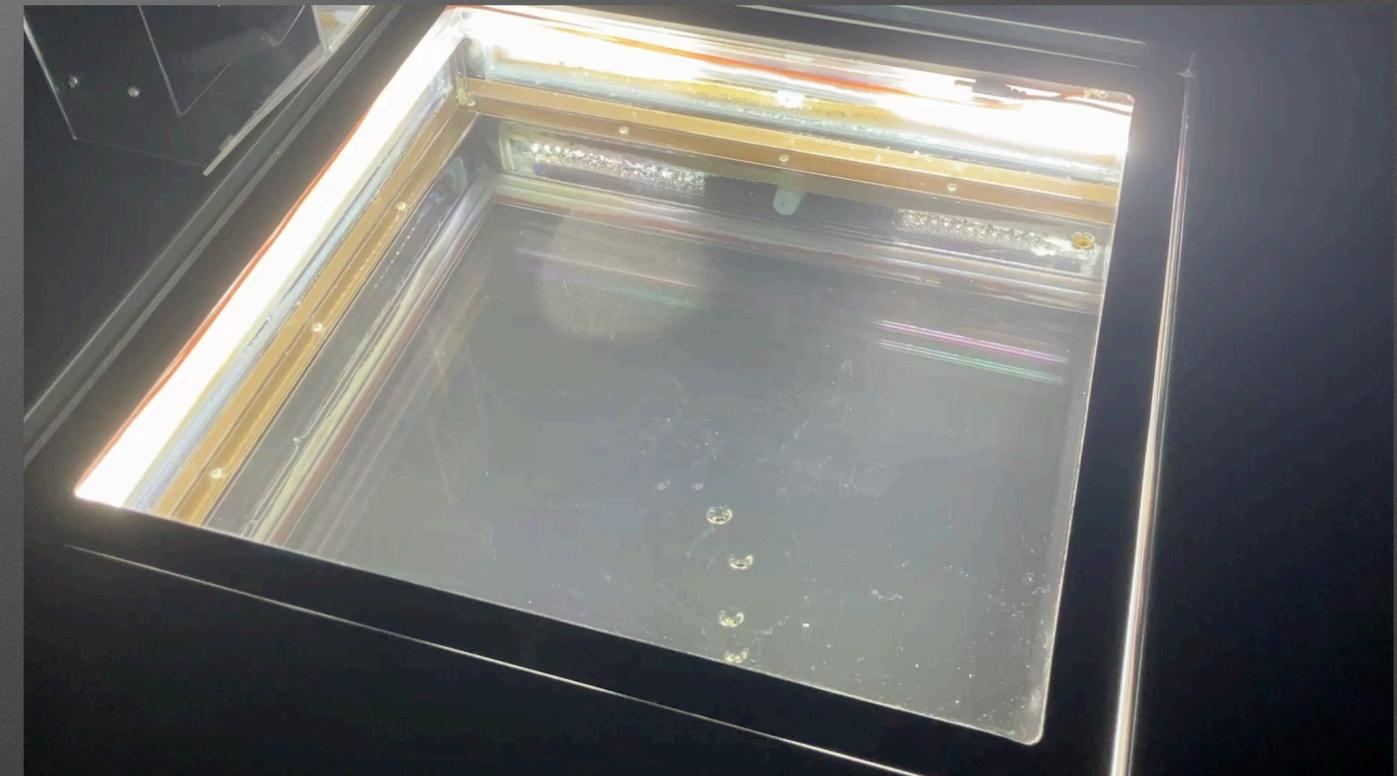
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Non-LTE ionization model for He

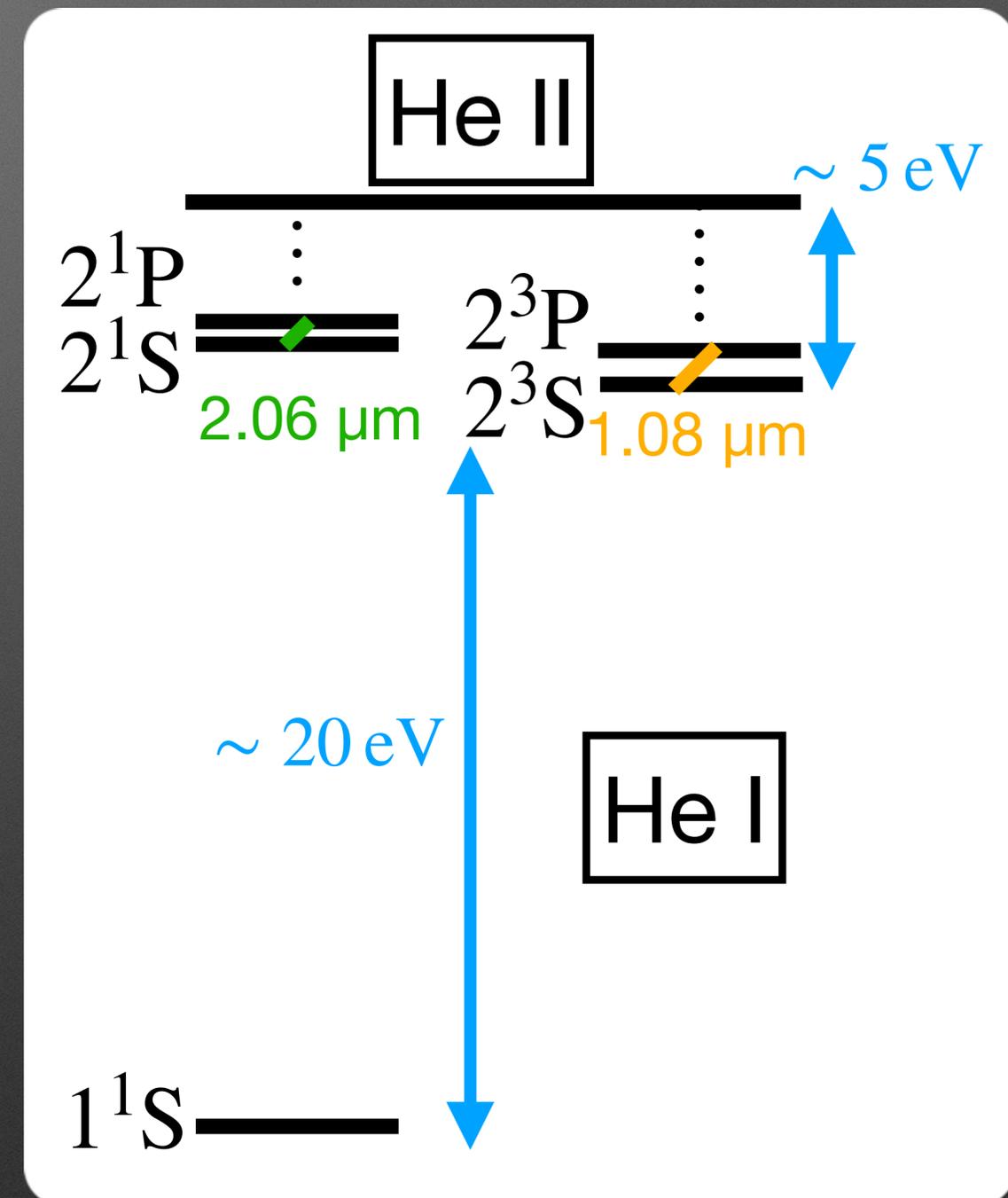
We perform “full” non-LTE calculation.

Rate equation

$$\sum_{j=1}^{21} \left(\Lambda_{kj} n_j - \Lambda_{jk} n_k \right) = 0 \quad (k = 1, 2, \dots, 21)$$

- 19 bound levels of He I
- respective ground levels of He II and He III

$$\Lambda = \underbrace{\mathbf{R}_{bb} + \mathbf{C}_{bb}}_{\substack{\text{radiative / collisional} \\ \text{bound-bound} \\ \text{transition}}} + \underbrace{\mathbf{R}_{bf/fb} + \mathbf{C}_{bf/fb}}_{\substack{\text{radiative / collisional} \\ \text{bound-free / free-bound} \\ \text{transition}}} + \underbrace{\Gamma_{nt}}_{\substack{\text{non-thermal} \\ \text{ionization}}}$$



Non-LTE ionization model for Sr

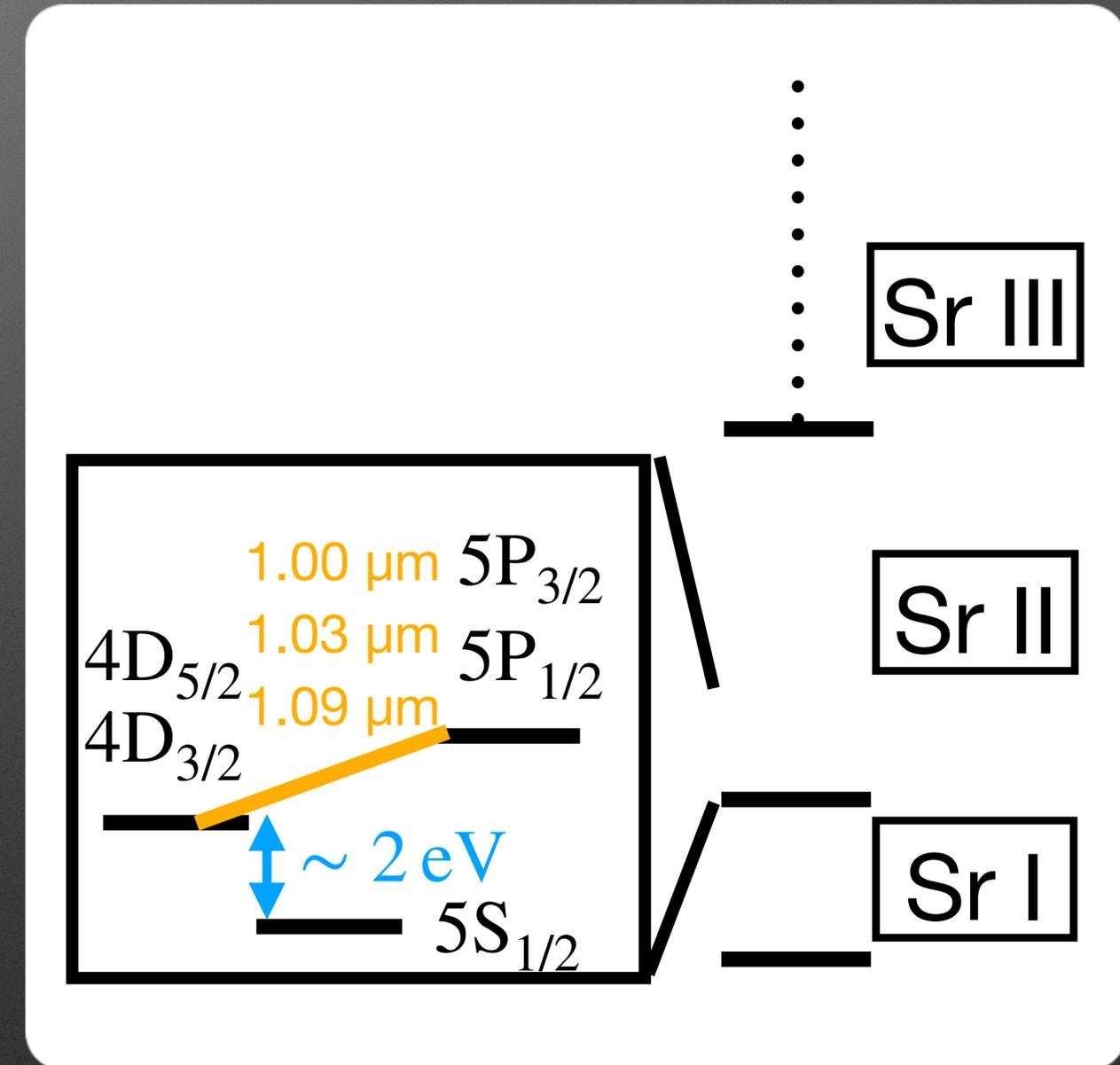
★ Due to the lack of the atomic data,
we cannot perform the “full” non-LTE calculation.

→ Approximate approach

Ionization :

$$\frac{n_{i+1}}{n_i} = \frac{R_{\text{ph}} + \Gamma_{\text{nt}}}{n_e \alpha_{i+1}} \approx \underbrace{W \left(\frac{n_{i+1}}{n_i} \right)^*}_{\text{thermal}} + \underbrace{\frac{1}{n_e \alpha_{i+1}} \frac{\dot{q}}{w_i}}_{\text{non-thermal}}$$

Excitation : Boltzmann distribution

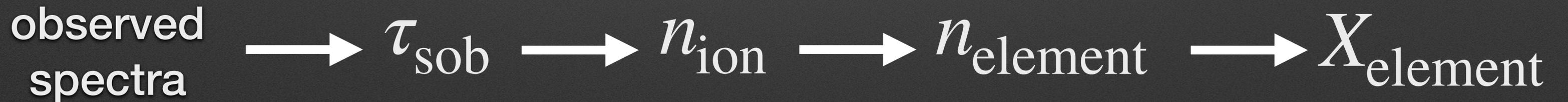
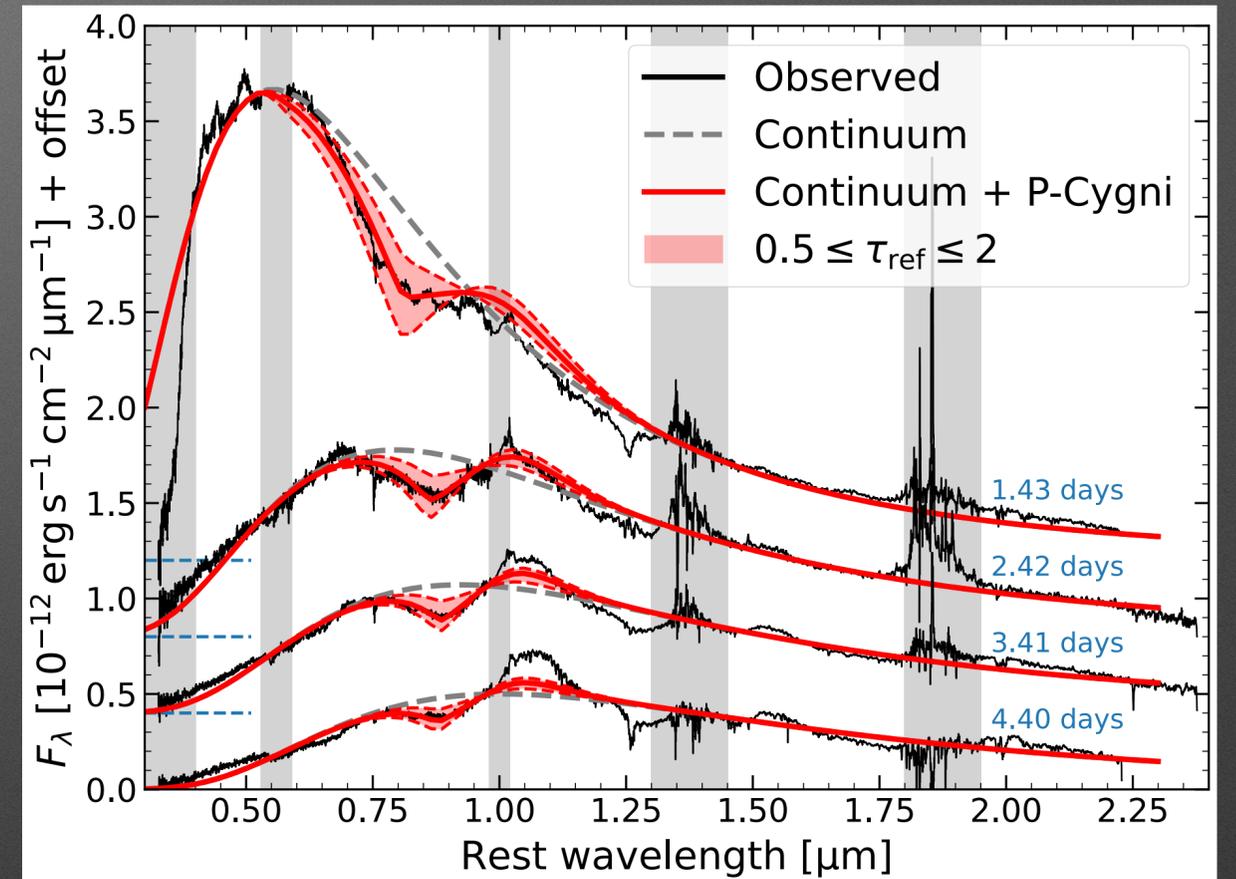
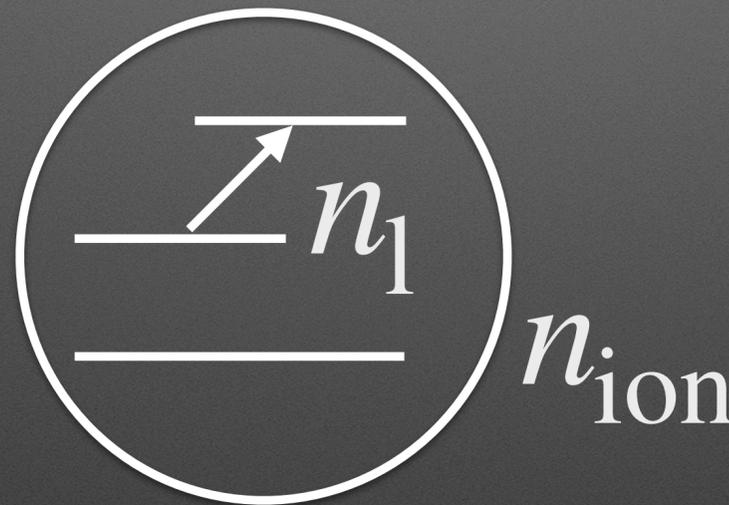


1. Non-LTE ionization modeling
2. Abundance constraints from observations
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Estimation of the element abundance

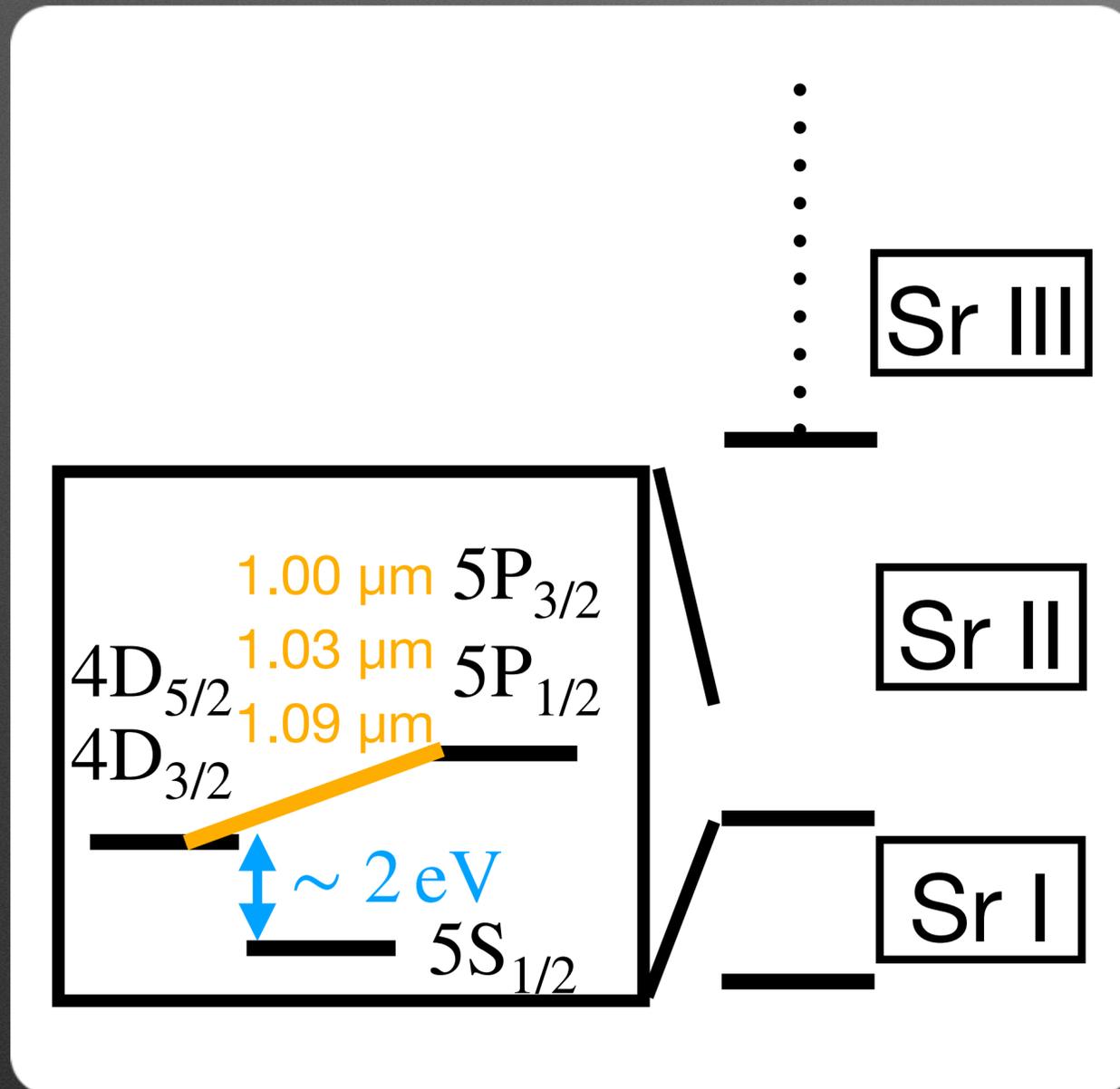
- Absorption line strength can be estimated by **Sobolev optical depth**:

$$\tau_{\text{sob}} = \frac{\pi e^2}{m_e c} \lambda_1 f_1 t n_1$$

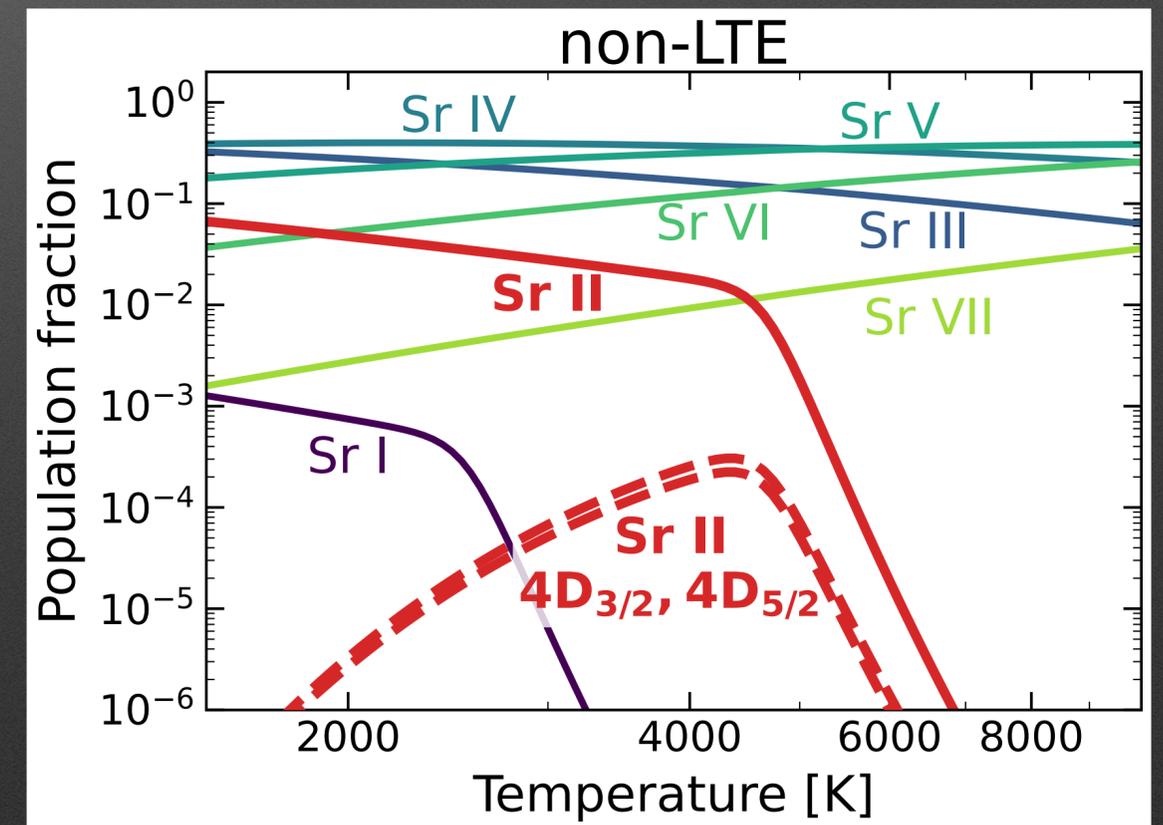
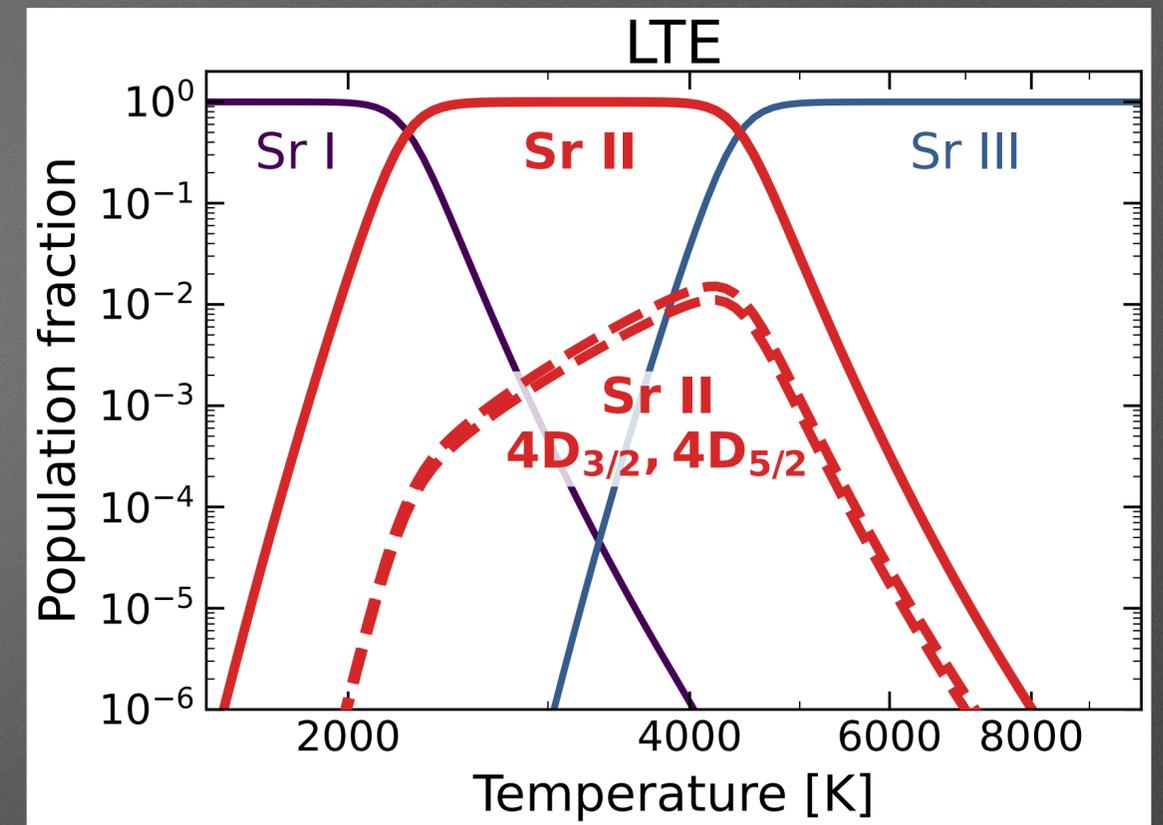


Depend on ionization model

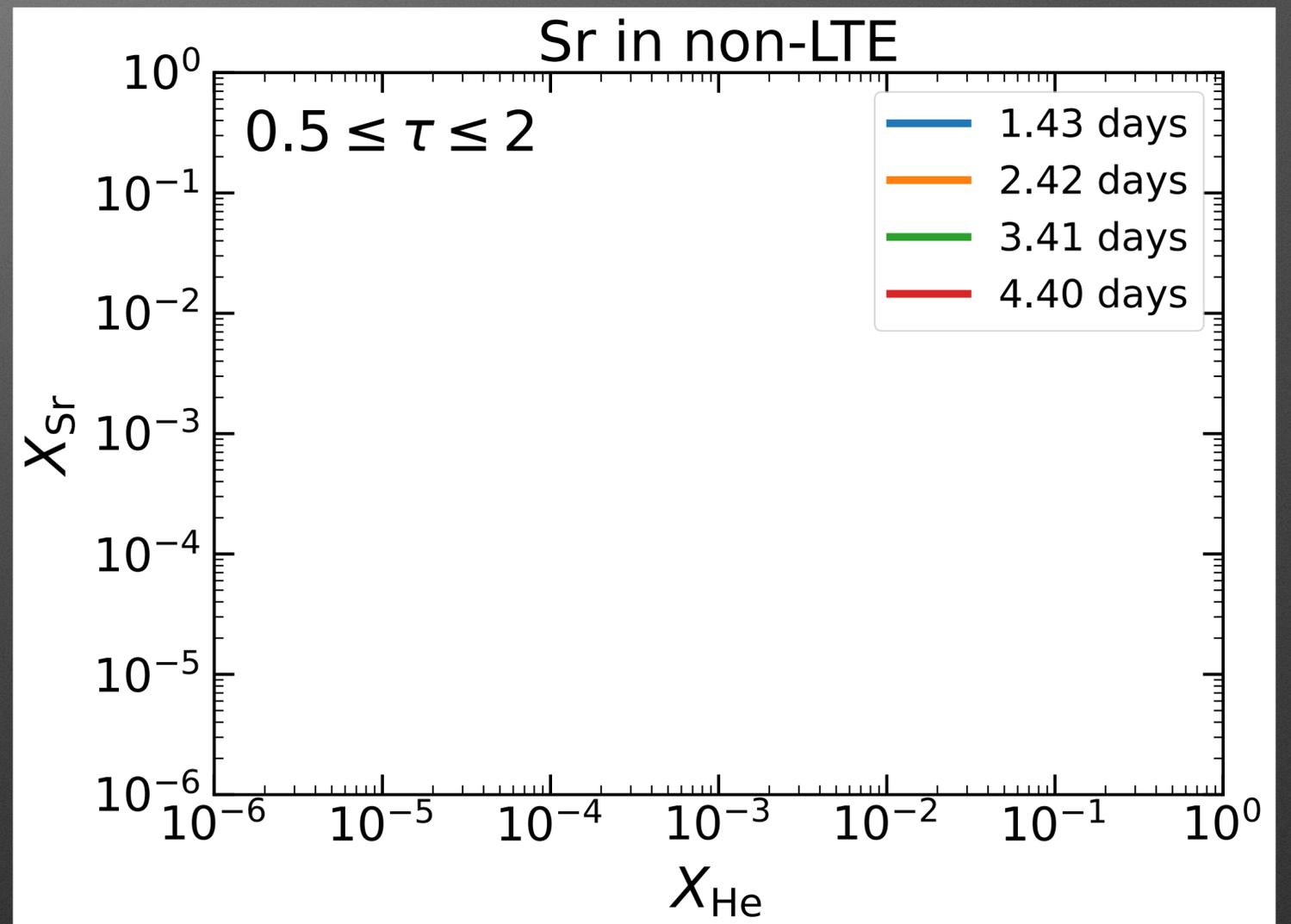
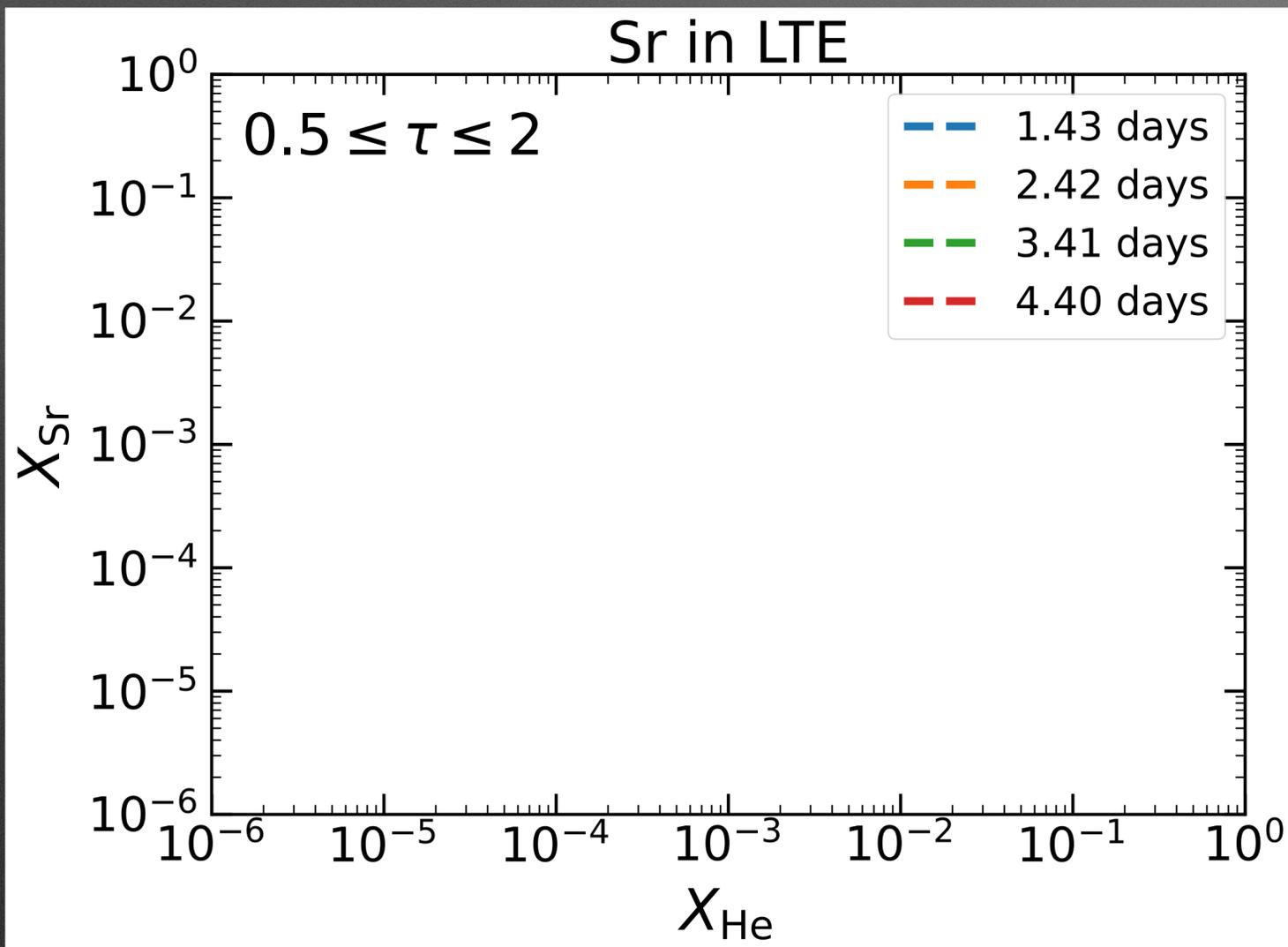
Sr: “over-ionization”



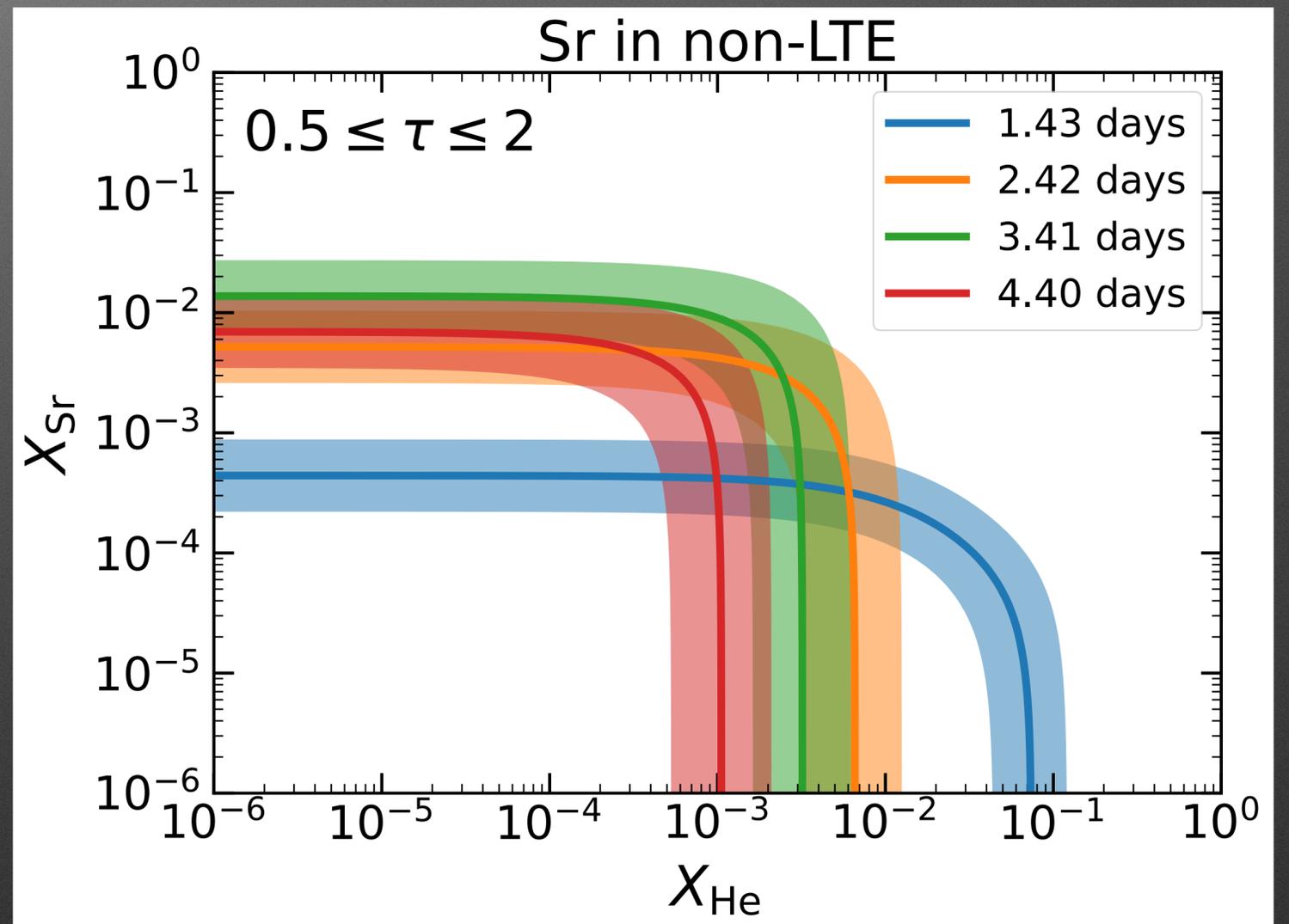
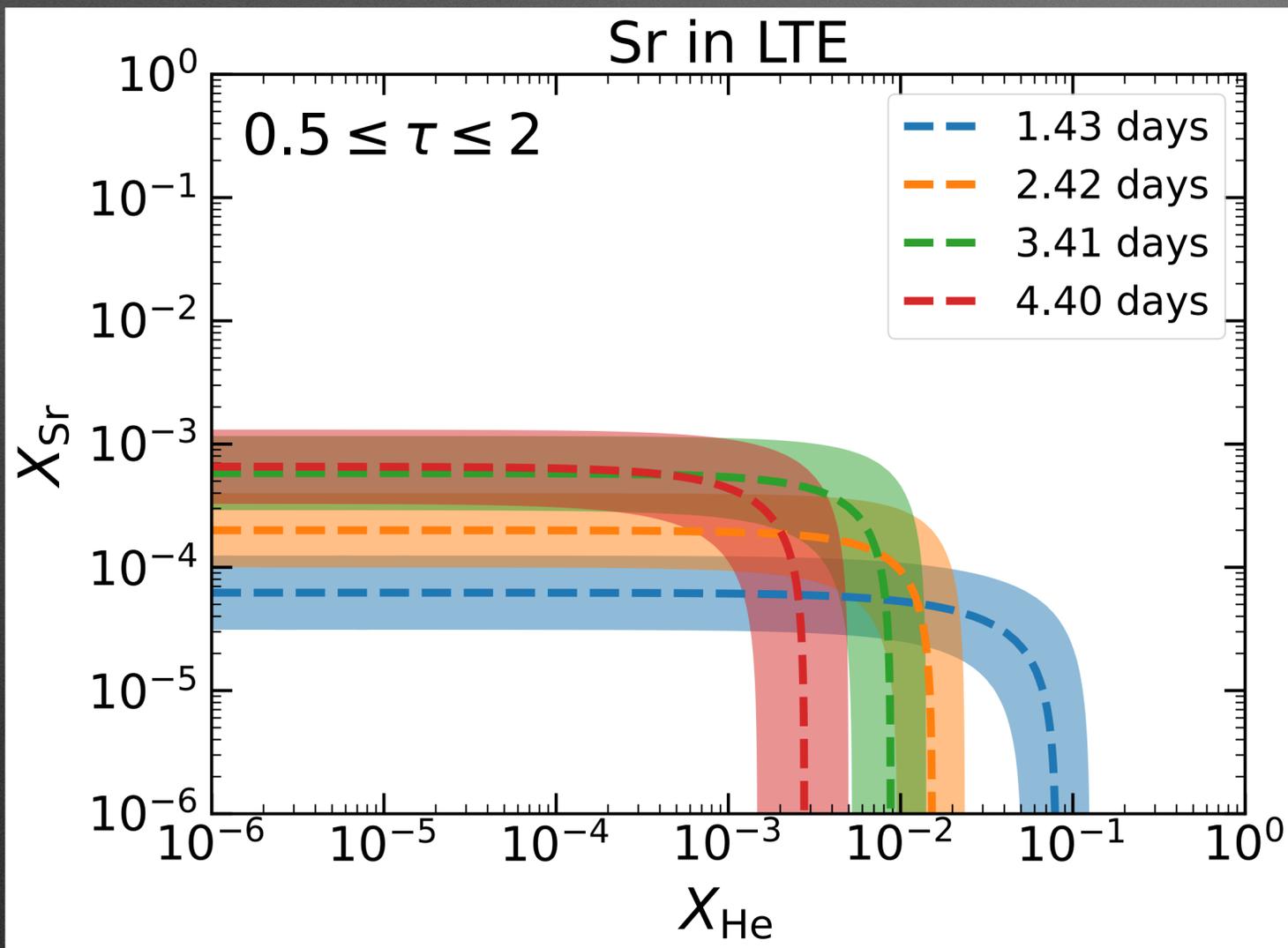
“over-ionization” by non-thermal electrons



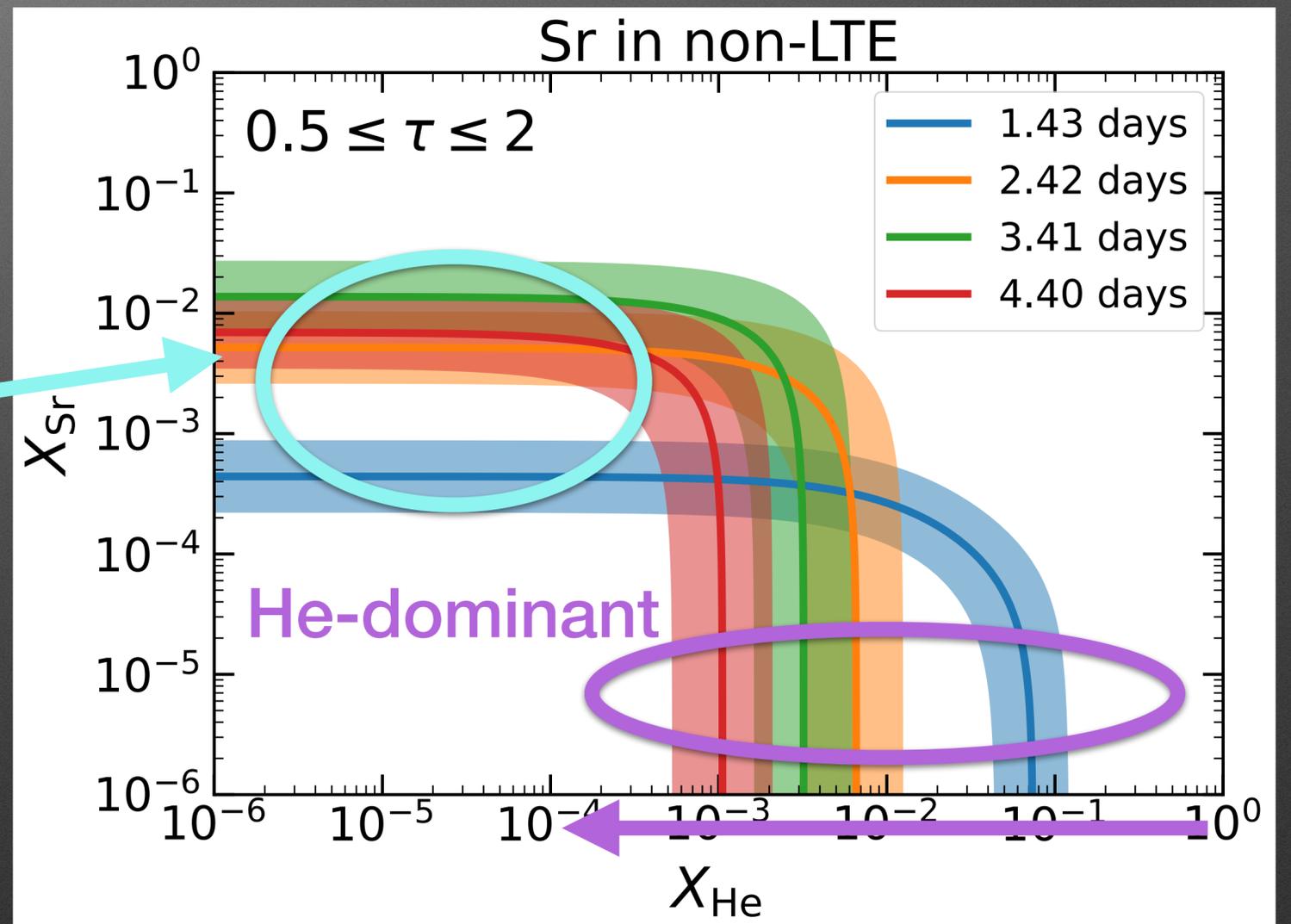
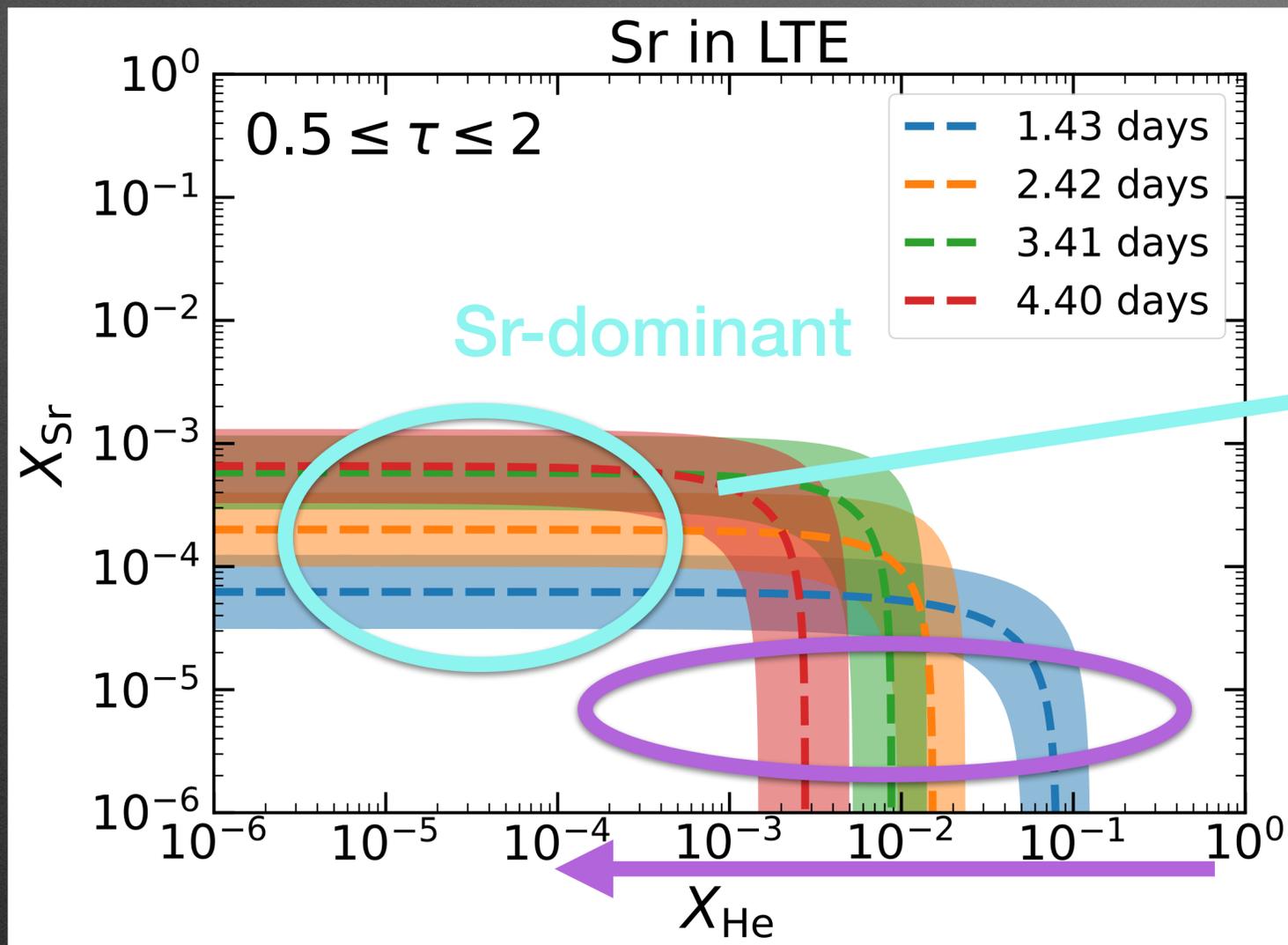
Constraints on the $X_{\text{He}} - X_{\text{Sr}}$ plane



Constraints on the $X_{\text{He}} - X_{\text{Sr}}$ plane



Constraints on the $X_{\text{He}} - X_{\text{Sr}}$ plane



over-ionization
by non-LTE effect

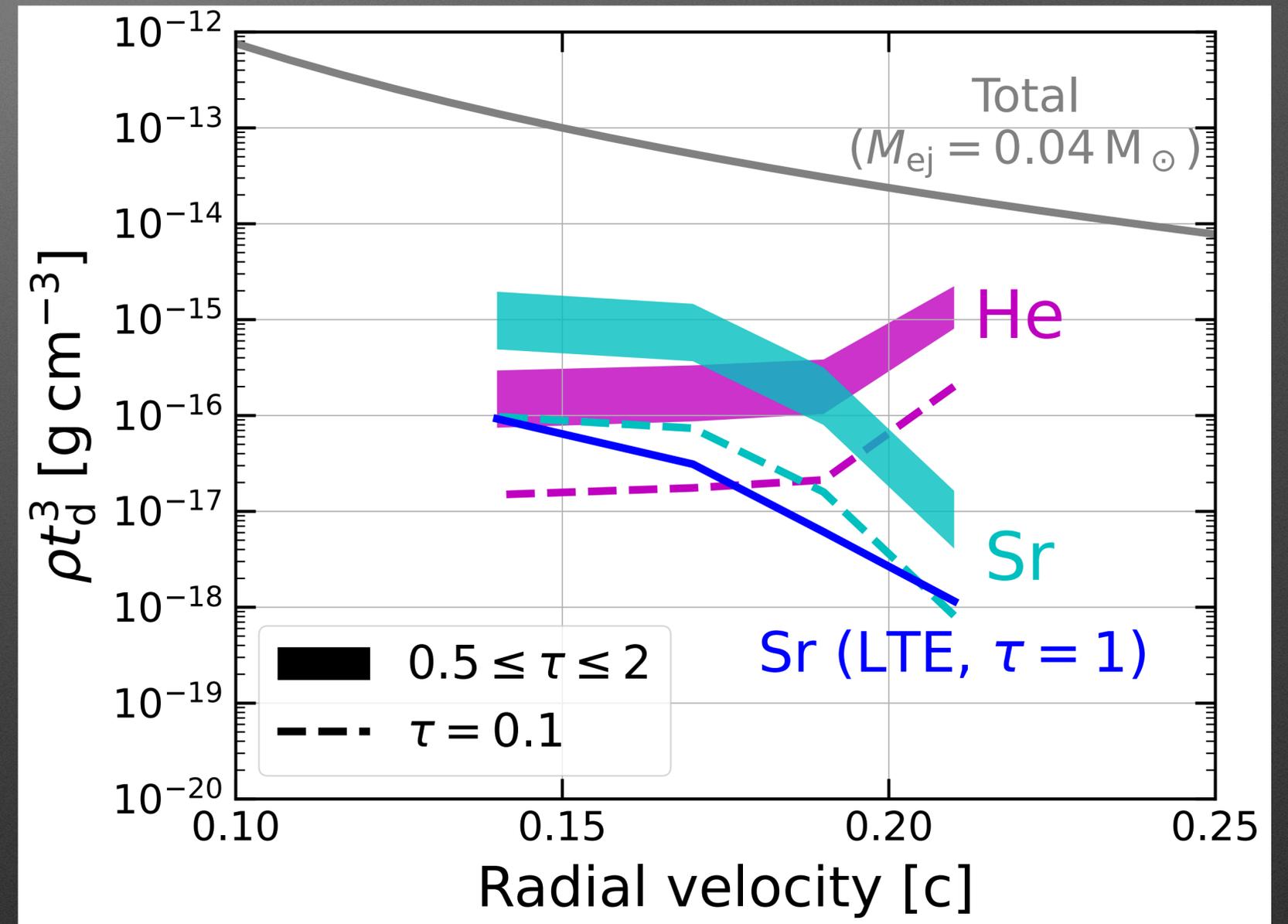
see Sneppen+24
see also Arya's poster
(last week)

temperature
decline

KC+ in prep

Constraints on the density profile

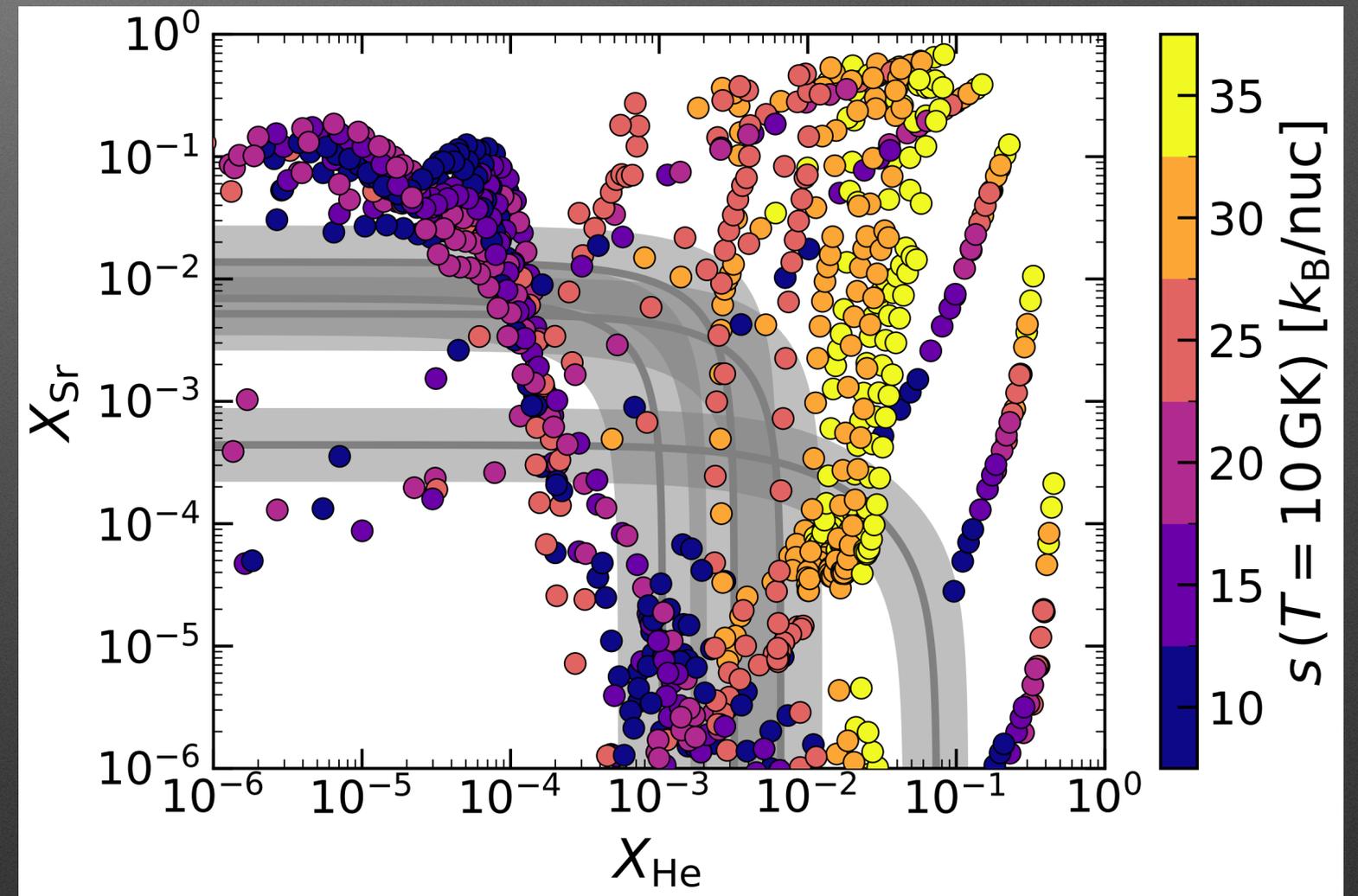
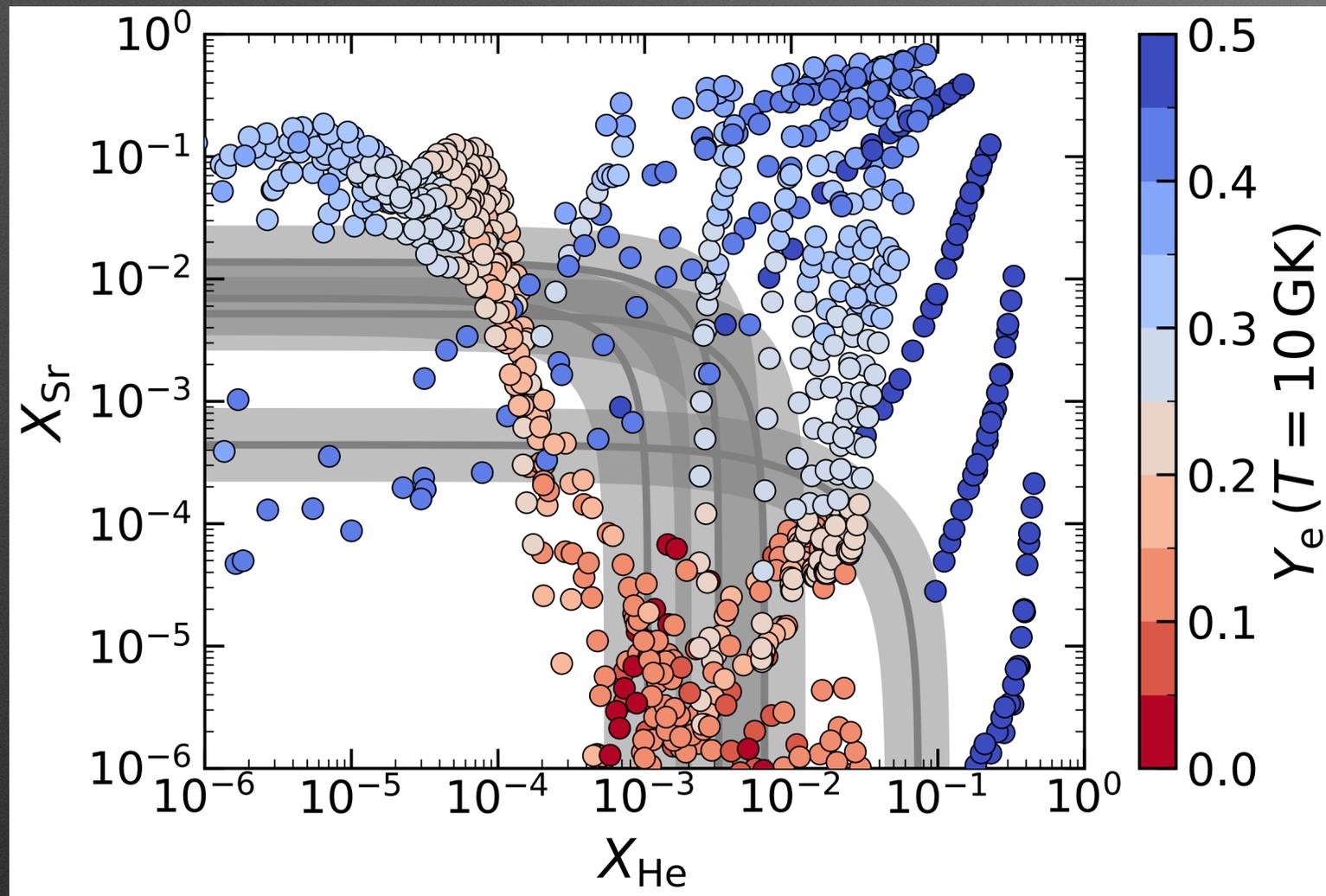
- The photosphere move inward in Lagrangian coordinates over time.
- We can perform “**Tomography**”.



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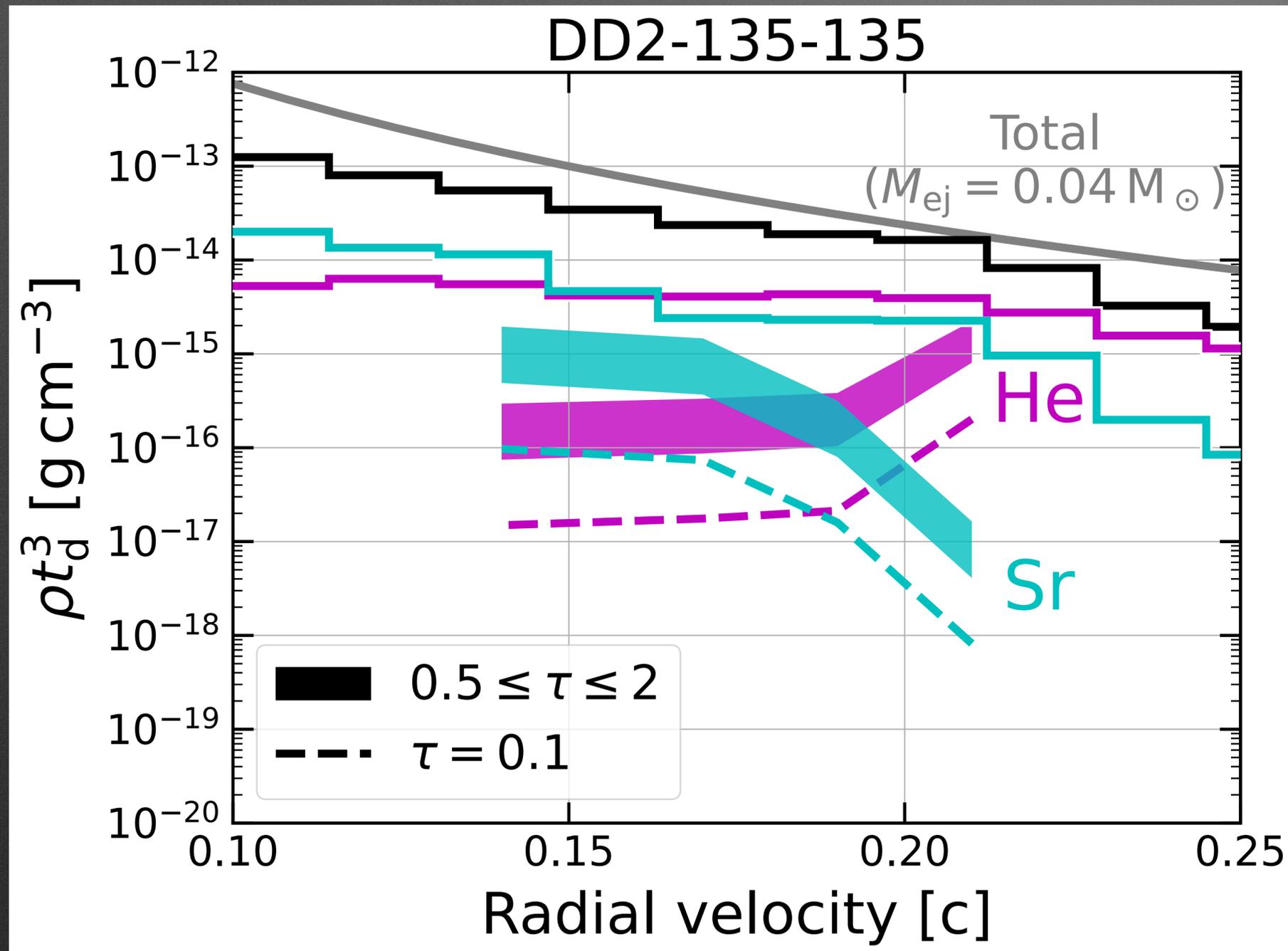
Nucleosynthesis conditions

Wanajo+ 2018

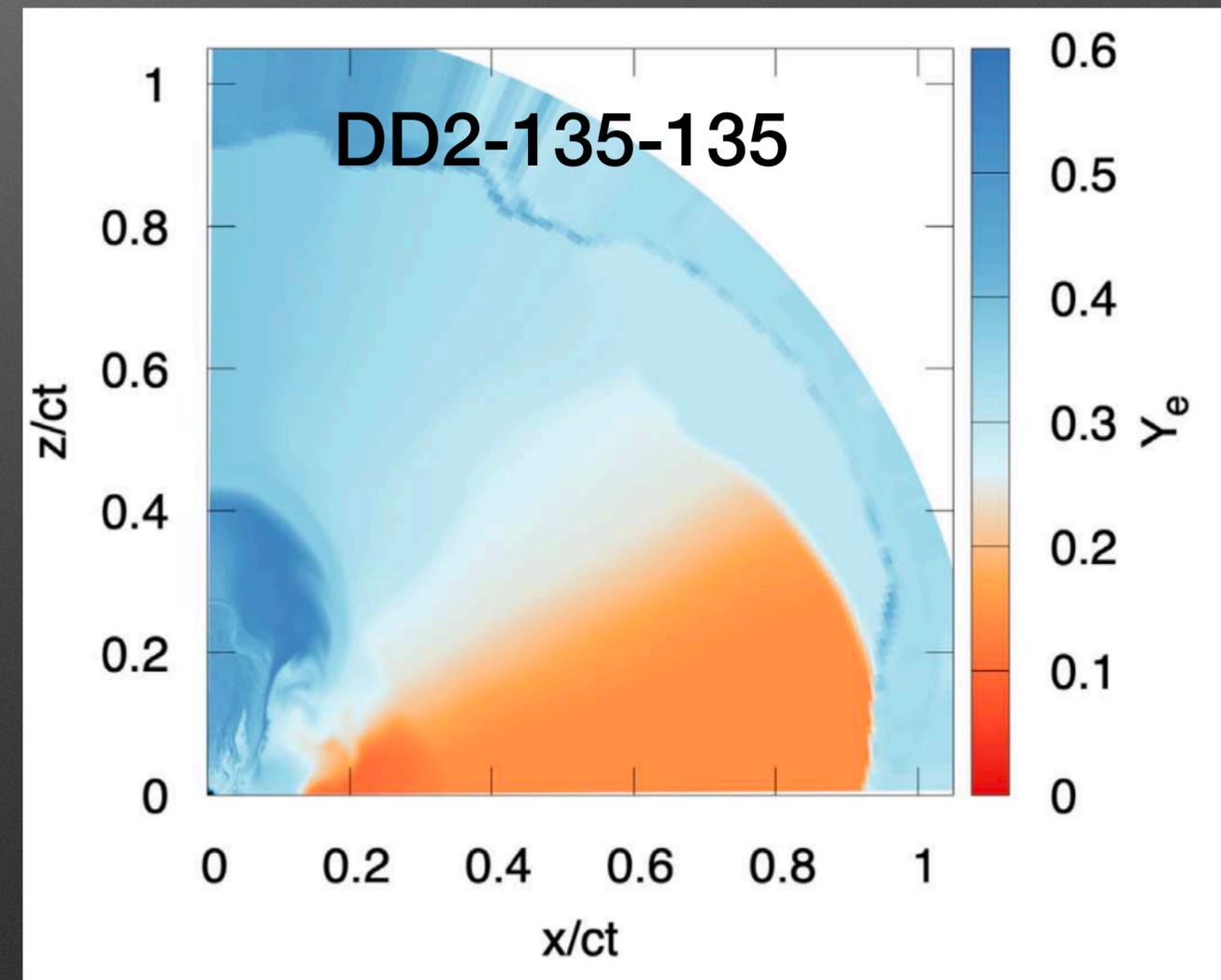


Relatively low Y_e ($\lesssim 0.3$) and low entropy ($\lesssim 30 k_{\text{B}} \text{ nuc}^{-1}$)

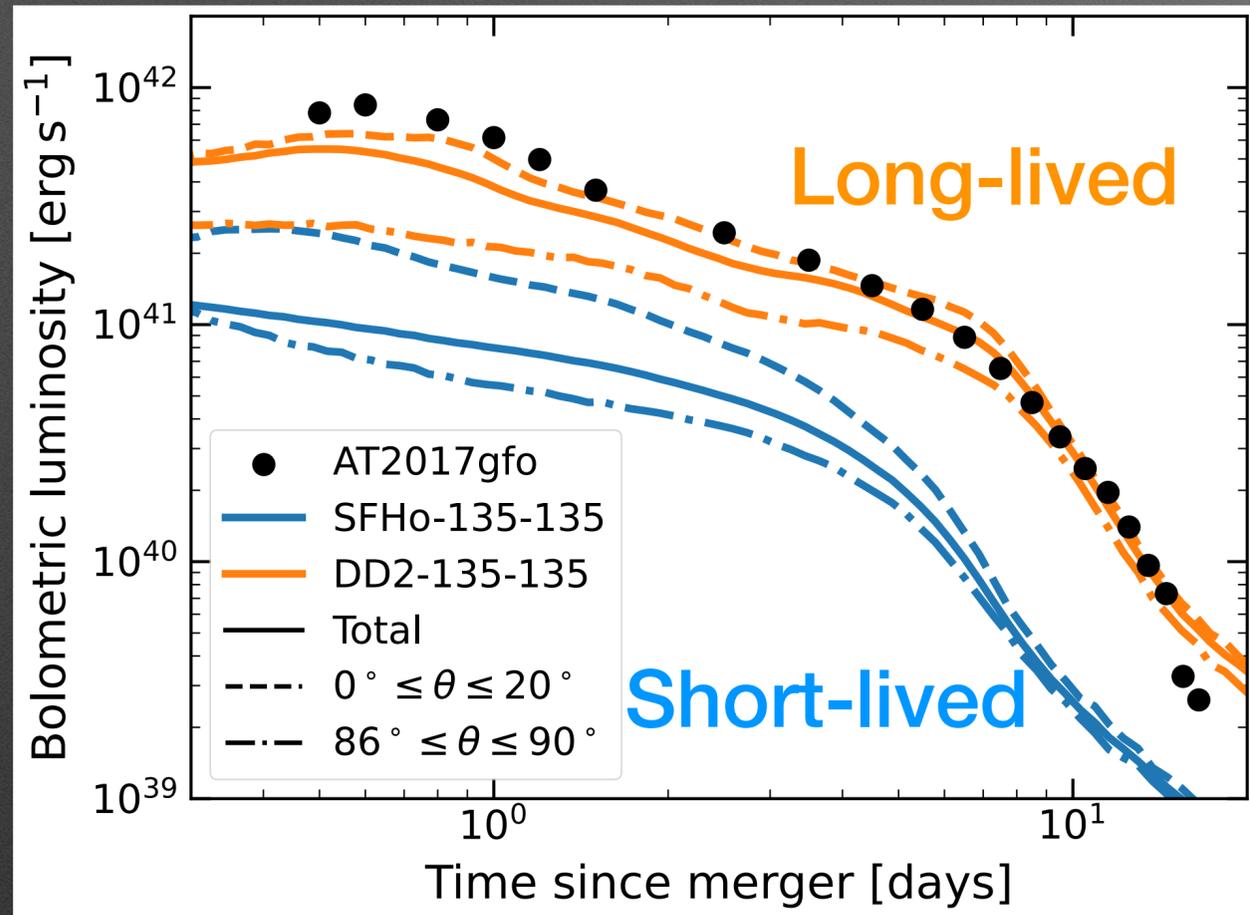
Comparison with merger simulation



Long-lived remnant case
→ Post-merger ejecta is dominated



Combined constraints: light curve and spectra



	Light curve (e.g., Kawaguchi+)	Spectra (This work)
Short-lived	too faint ($\sim 0.01 M_\odot$)	—
Long-lived	good ($\sim 0.065 M_\odot$)	too much He and Sr

In GW170817, a sufficient post-merger mass ejection with **low Y_e ($\lesssim 0.3$)** and **low entropy ($\lesssim 30 k_B \text{ nuc}^{-1}$)** ?

Summary

- Non-LTE ionization model for He and Sr in neutron star merger ejecta
 - Important not only for He but Sr
- Sr: Non-LTE modeling **reduces the Sr abundance tension** (increasing required amount)
- Our constraints for GW170817 is consistent with a sufficient post-merger mass ejection **with small Y_e ($\lesssim 0.3$) and low entropy ($\lesssim 30 k_B \text{ nuc}^{-1}$)**
→ closer to the solar abundance ratio?