Exploring Extreme Transients: Frontiers in the Early Universe and Time-Domain Astronomy

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

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in collaboration with

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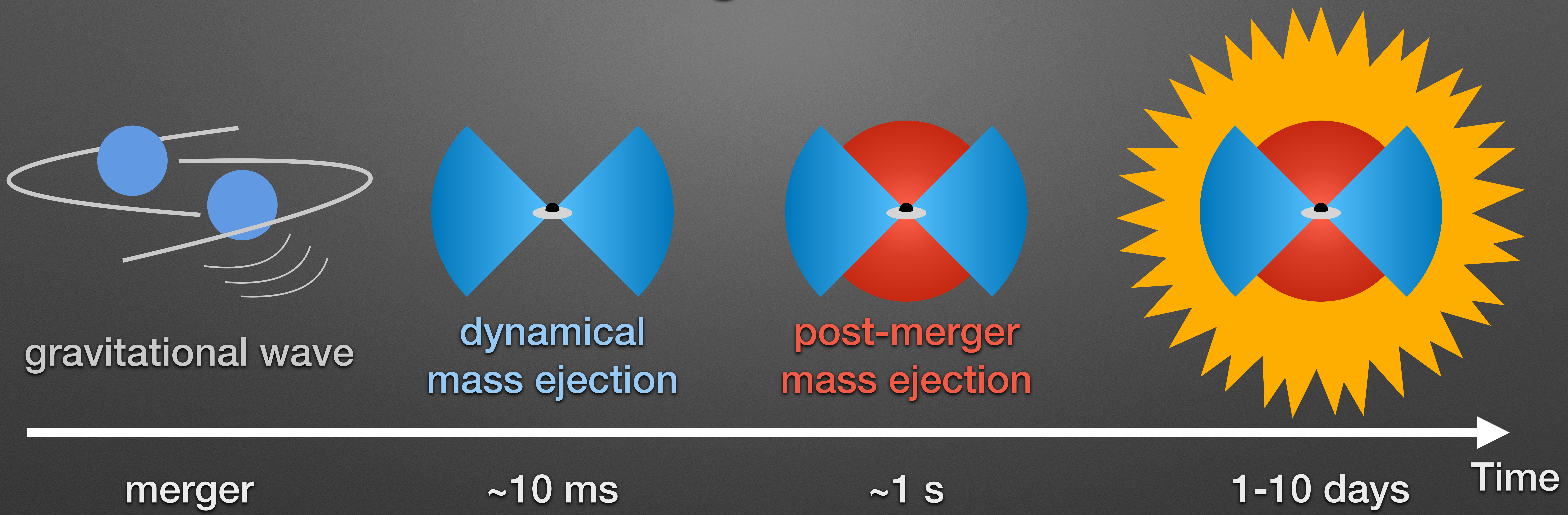
From neutron star merger to “kilonova”

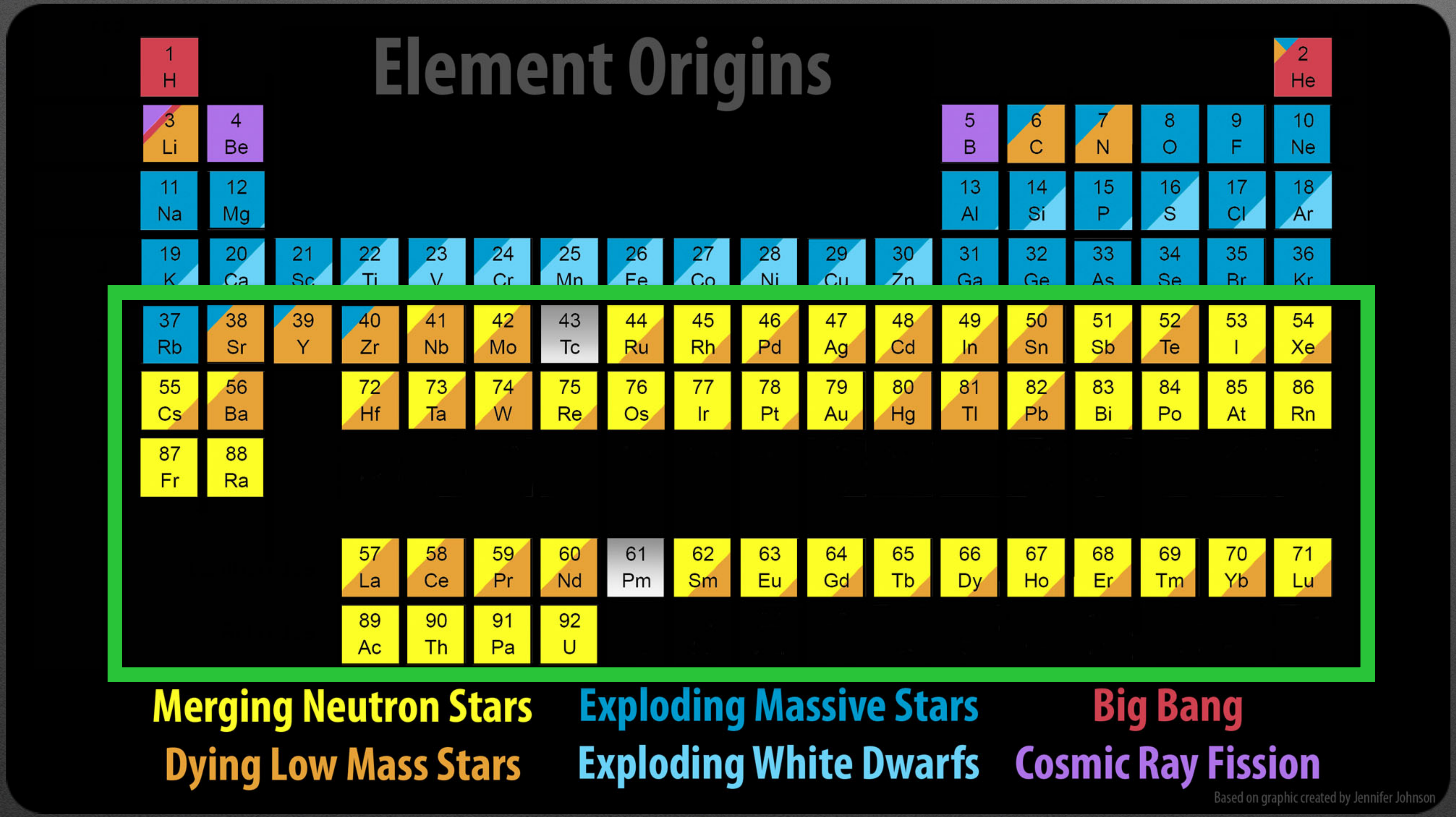


Kilonova:

- Thermal emission (looks like single-temperature blackbody in UV-Optical-NIR)
- Radioactively-powered by r-process elements

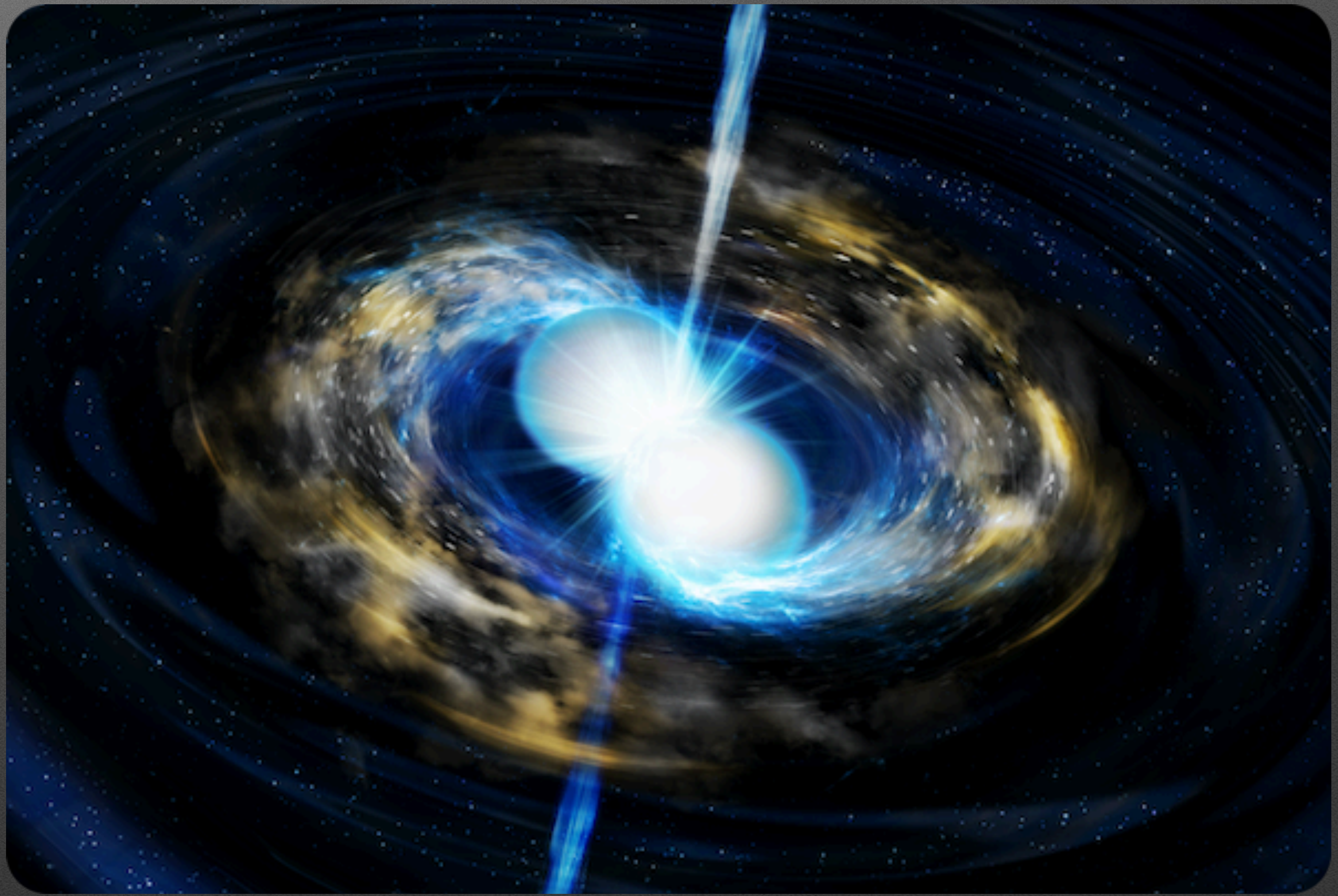
By decoding kilonova emission...

r-process nucleosynthesis



https://www.ligo.caltech.edu/WA/news/ligo20180817

mass ejection mechanism



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heavier elements than iron

P-Cygni feature around 1 μm

kilonova AT2017gfo
associated with GW170817

Sr II ?

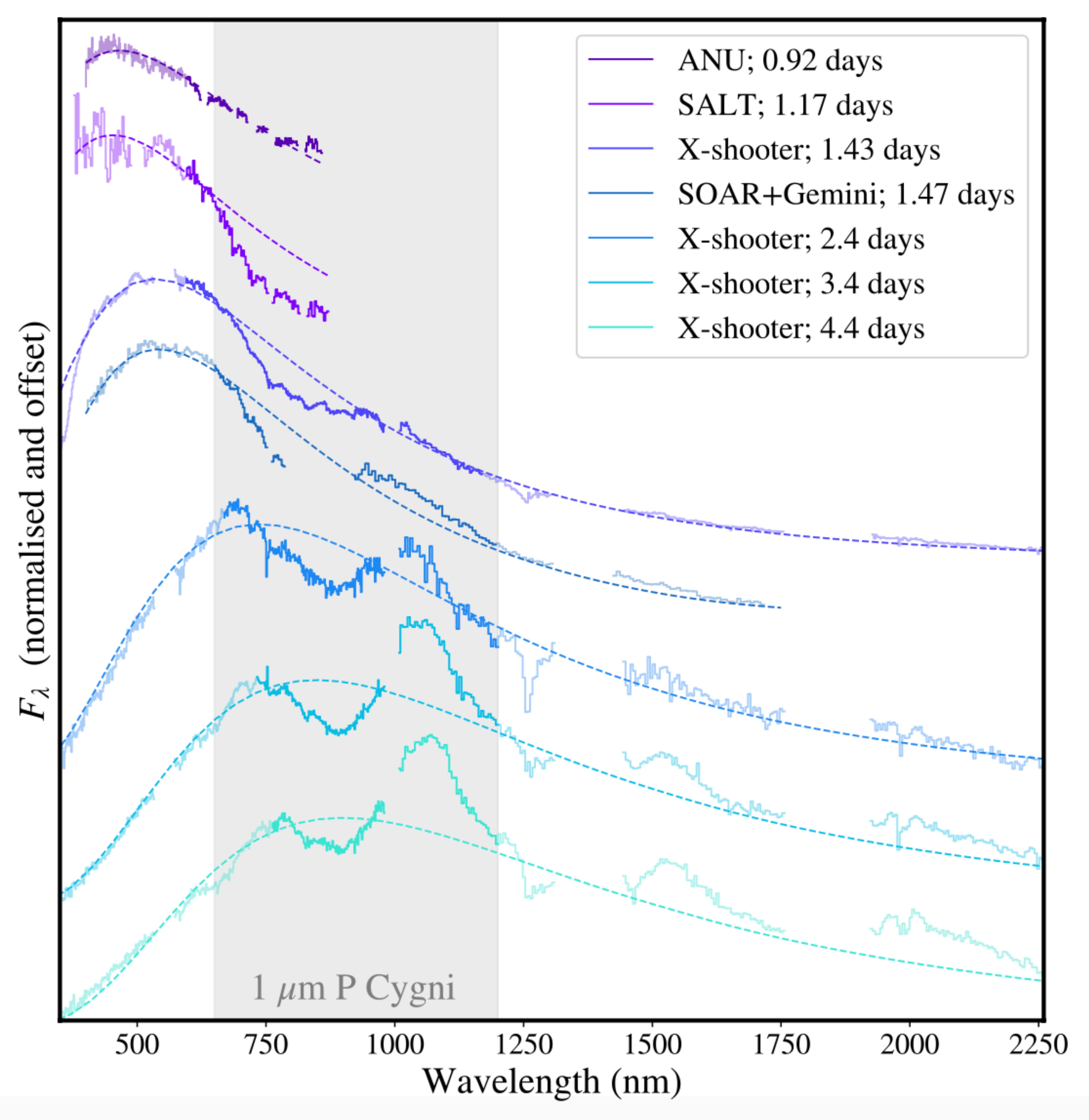
Watson+ 2019;
Domoto+ 2021, 2022;
Gillanders+ 2022

well investigated by LTE radiative transfer modeling
but ionization states may actually deviate from LTE
due to non-thermal electrons from beta decay

He I ?

Perego+ 2022;
Tarumi+ 2023;
Sneppen+ 2024

well known for supernova case
but non-LTE ionization modeling is required



Sneppen, Damgaard+ 2024

→ Non-LTE ionization modeling is needed for both elements

1. Non-LTE ionization modeling
2. Constraints from observation
3. Comparison with numerical simulation

Non-LTE ionization model

Helium

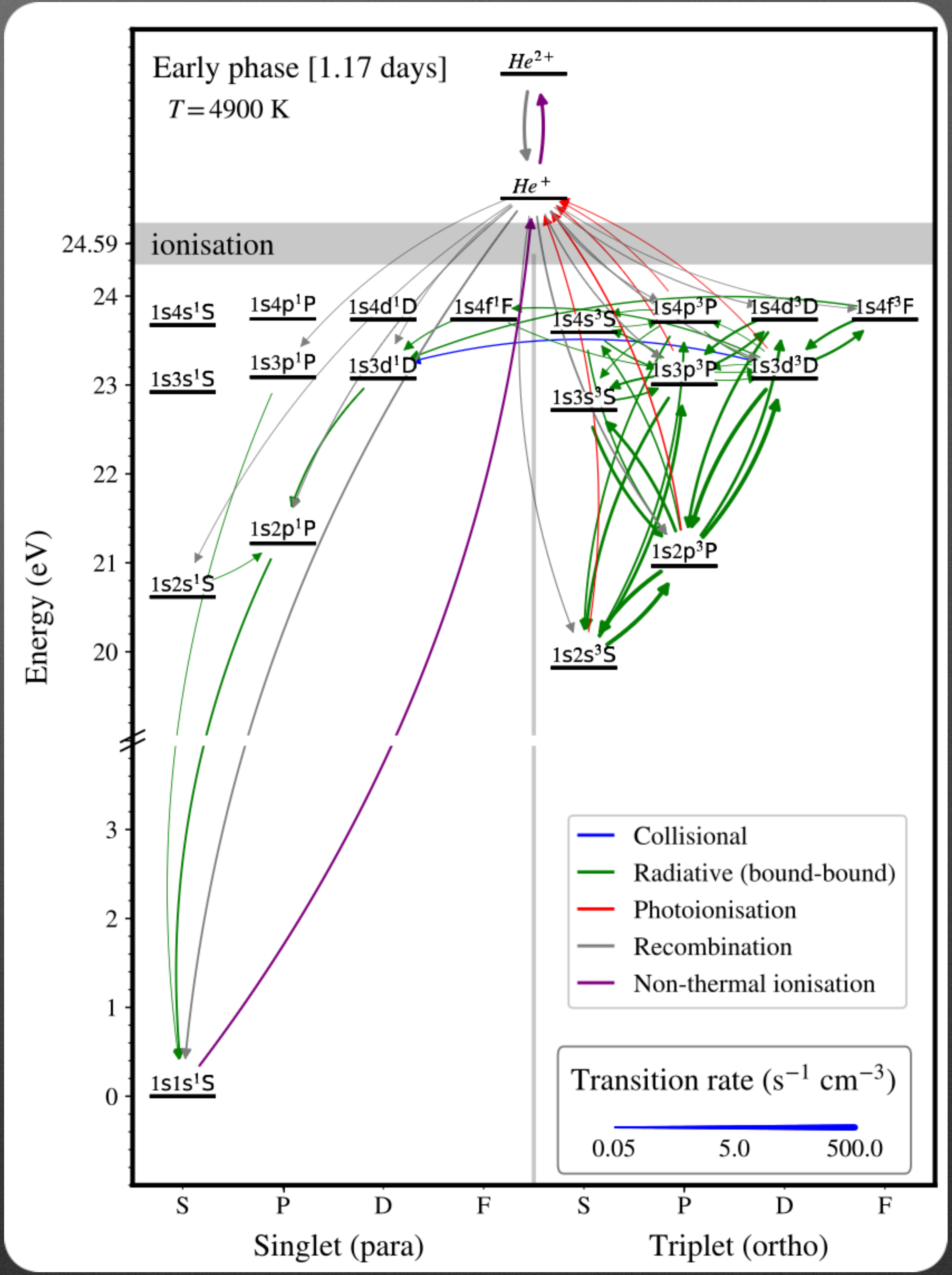
- 19 bound states for He I, ground state for He II and He III
- Consider both radiative and collisional processes
- Also consider non-thermal ionization

Strontium

- Consider up to 5th-ionized state (i.e. Sr VI)

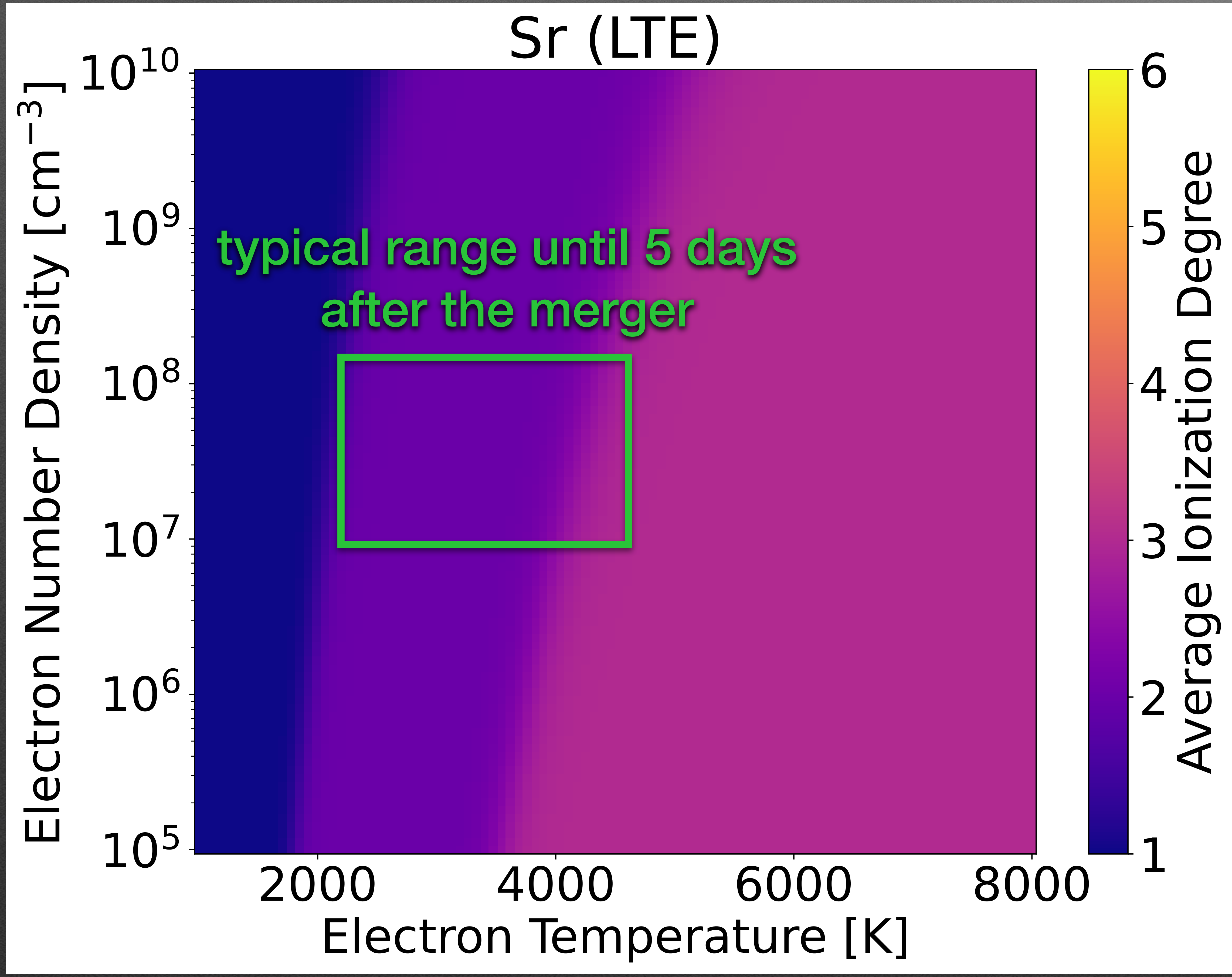
$$\frac{n_{i+1}}{n_i} = \left(\frac{n_{i+1}}{n_i}\right)^* + \frac{1}{n_e \alpha_i}\frac{\dot{q}}{w_i}$$

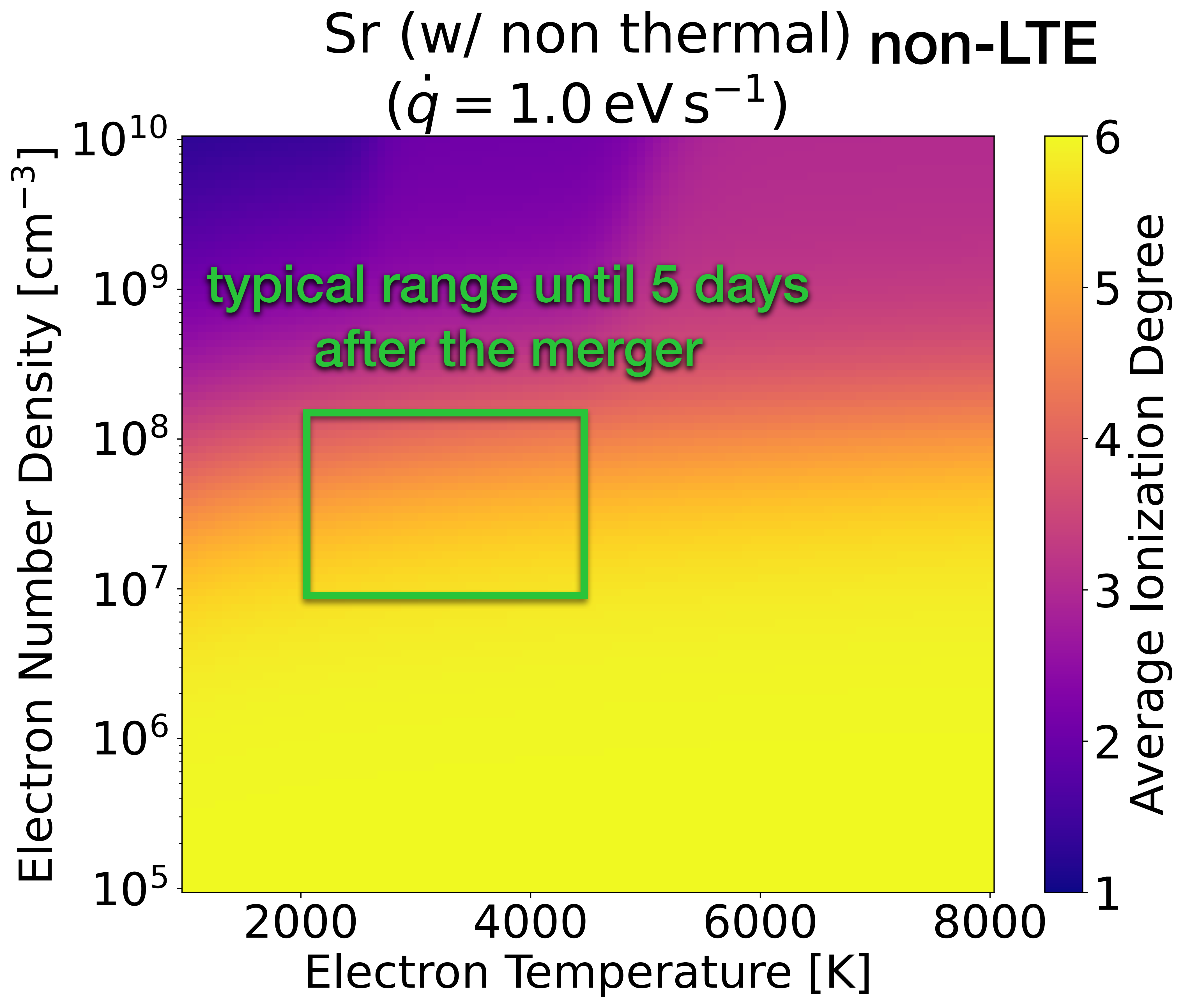
LTE population | non-thermal ionization correction



Sneppen, Damgaard+ 2024

Non-LTE effect for Strontium





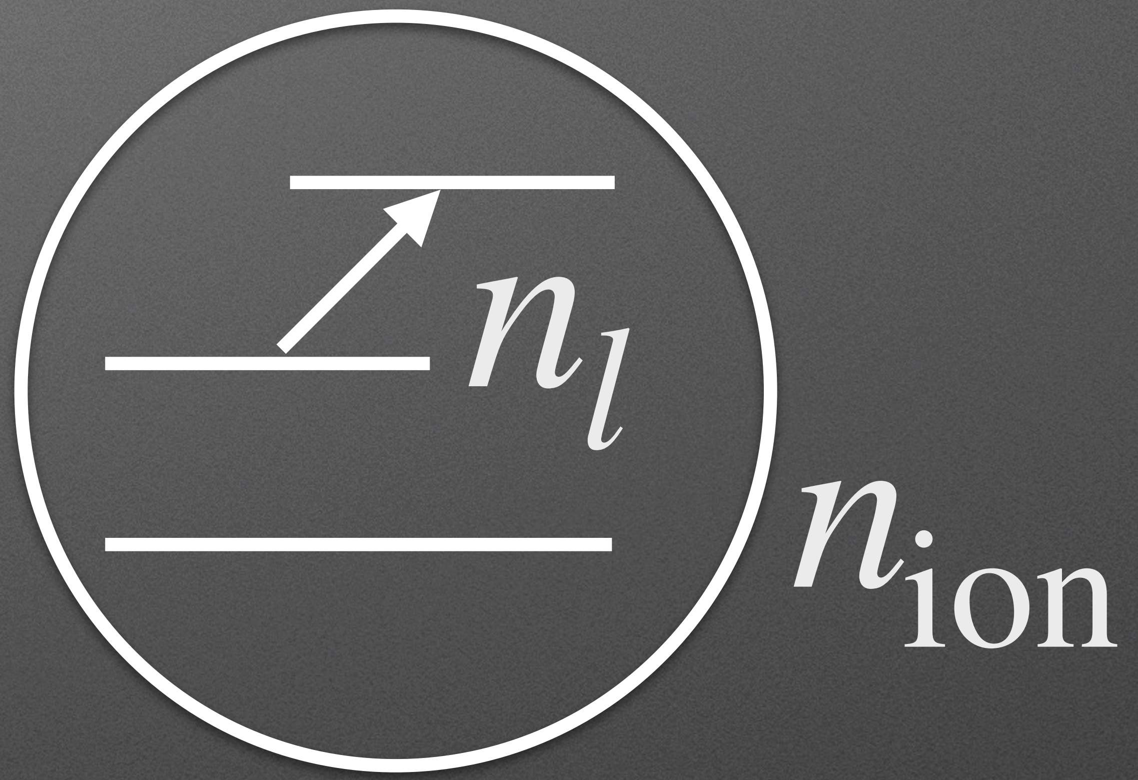
Sr II is dominant → over-ionized up to III-VI states

1. Non-LTE ionization modeling
2. Constraints from observation
3. Comparison with numerical simulation

Conversion to the element abundance

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

$$\tau_{\rm sob} = \frac{\pi e^2}{m_e c} \lambda_{\rm l} f_{\rm l} t n_{\rm l}$$



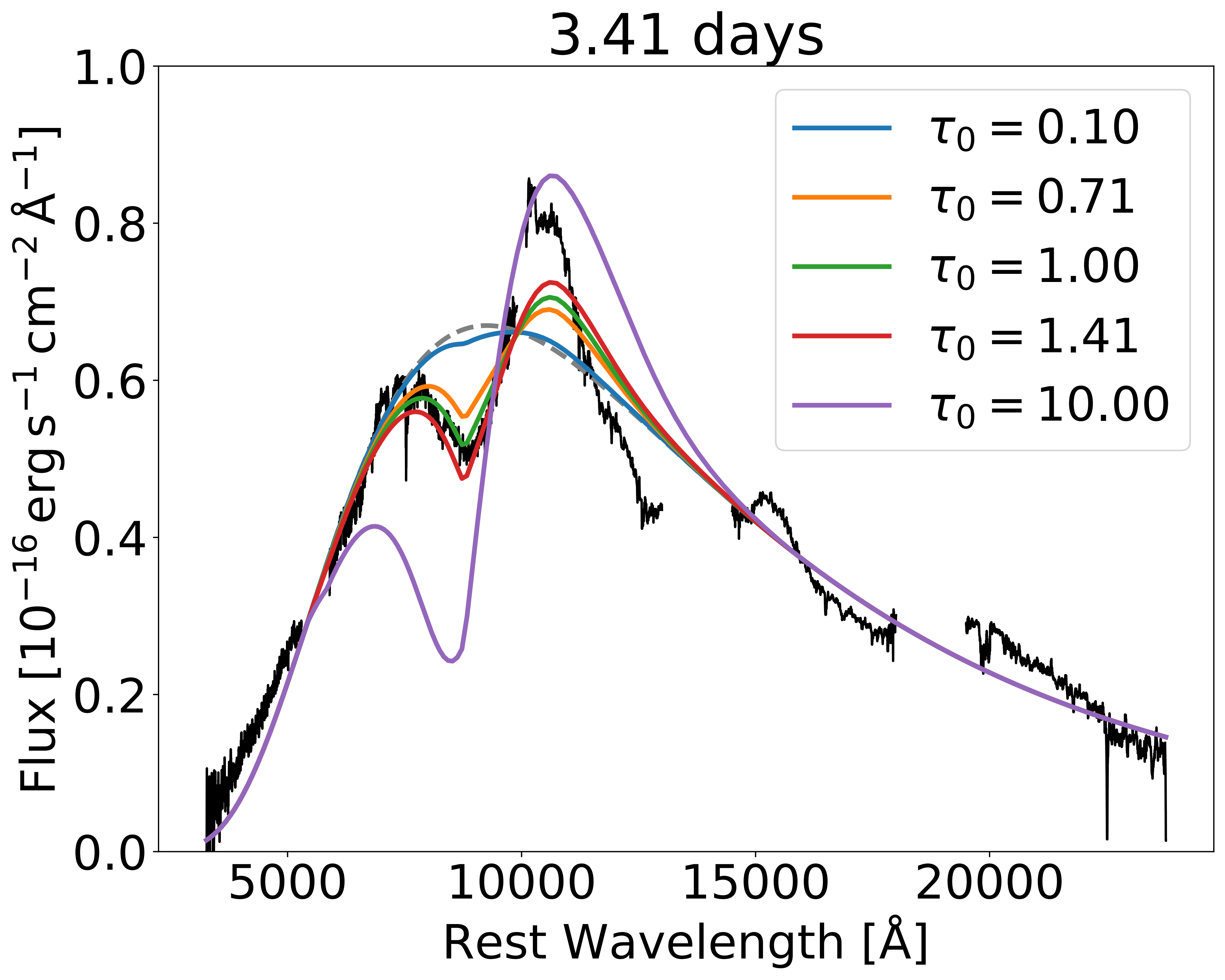
observed spectra → $\tau_{\rm sob}$ → $n_{\rm ion}$ → $n_{\rm total}$

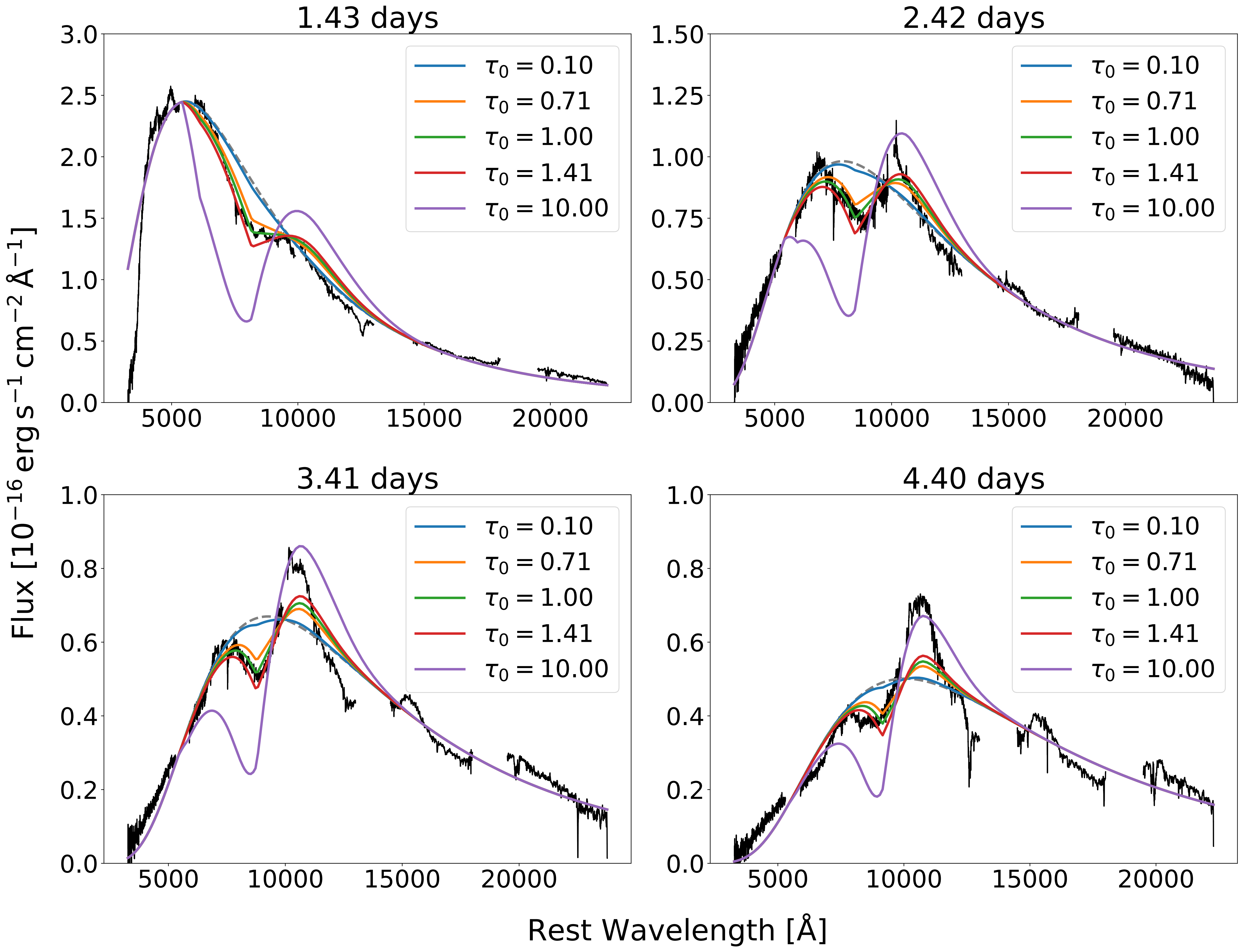
Depend on ionization model

Required conditions from observation

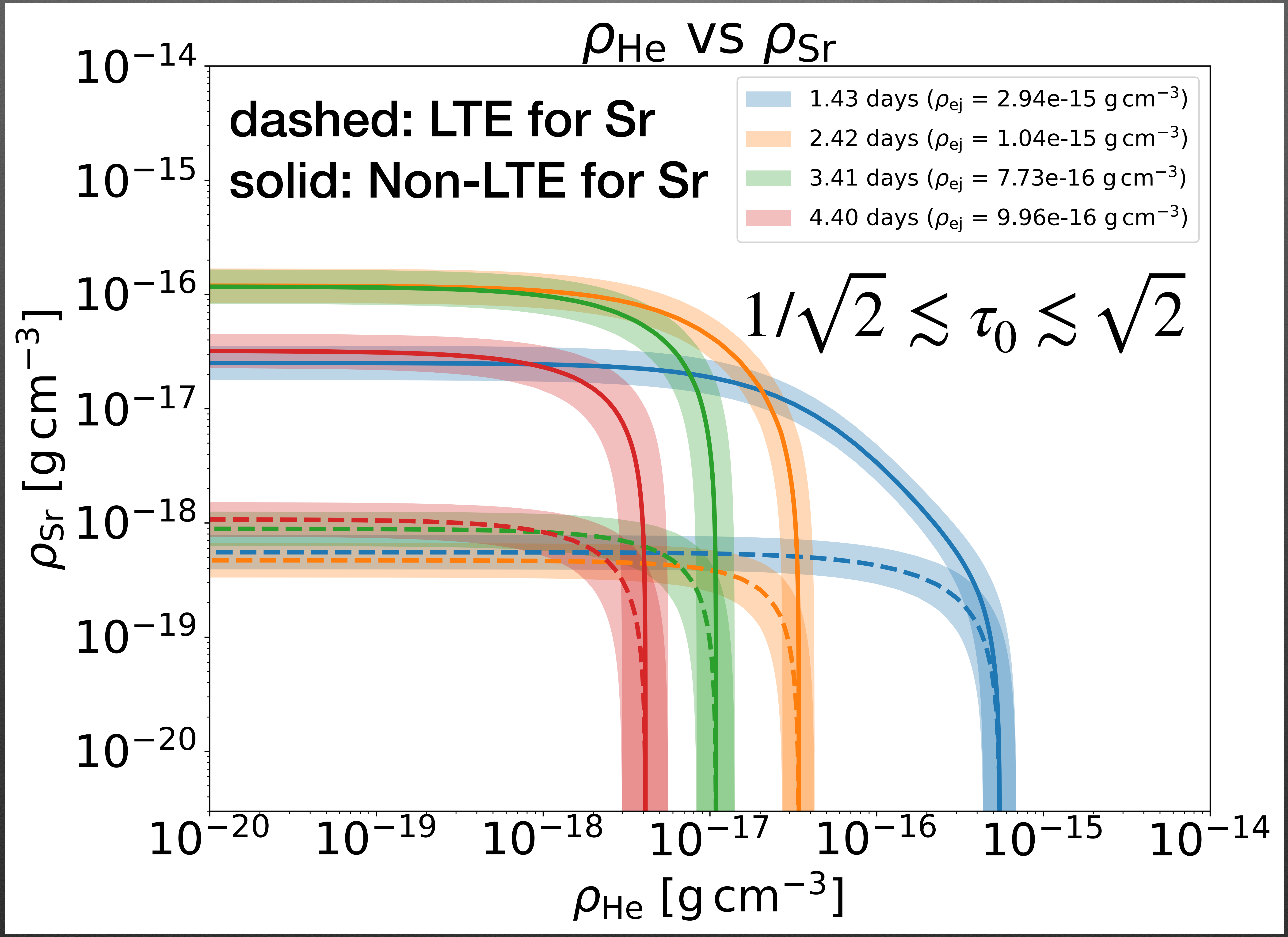
At all the epoch, $\tau_0 \sim 1$ is required

τ_0: Sobolev optical depth on the photosphere



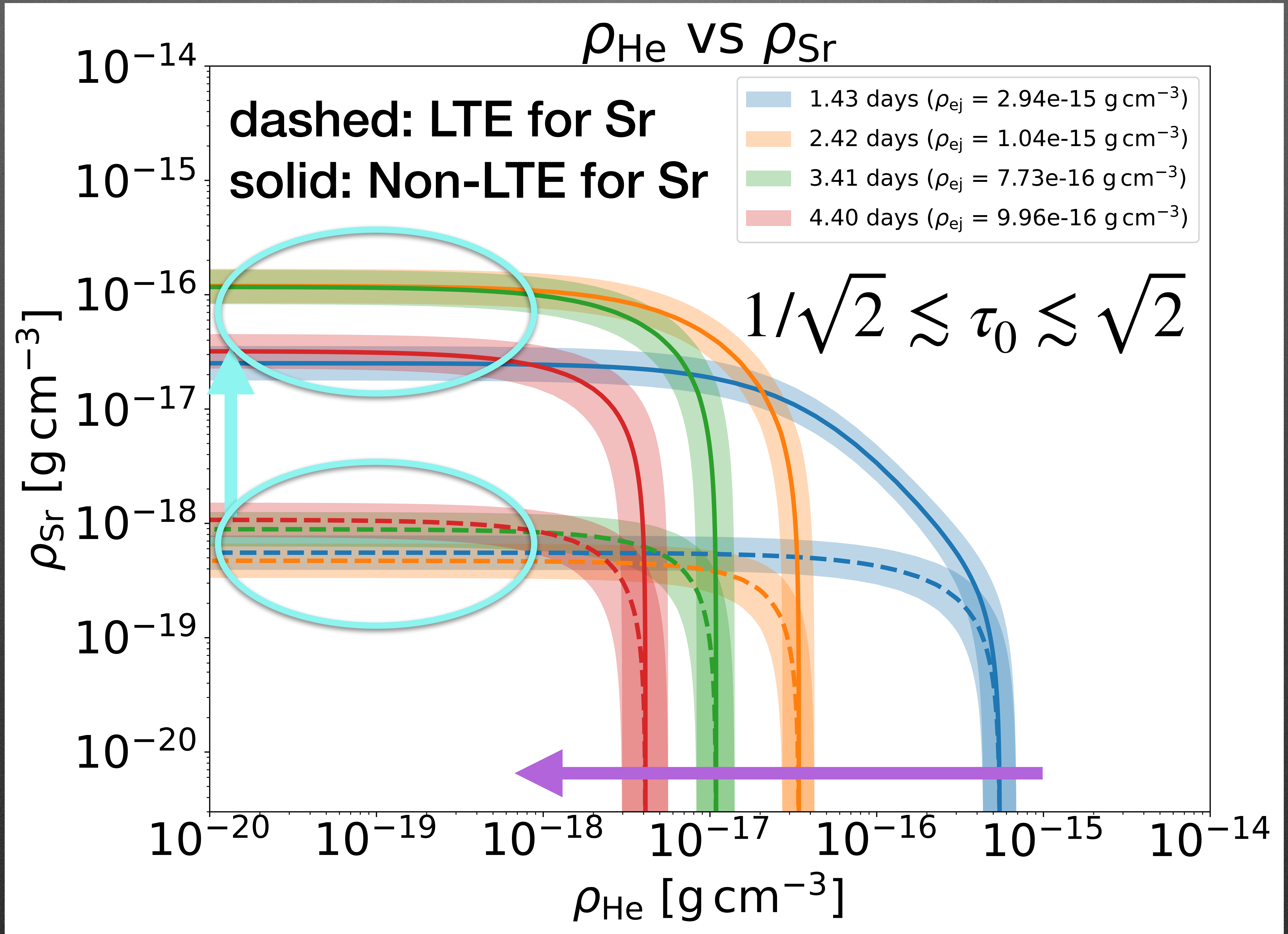


Constraints on the $\rho_{\mathrm{He}} - \rho_{\mathrm{Sr}}$ plane



Constraints on the $\rho_{\mathrm{He}} - \rho_{\mathrm{Sr}}$ plane

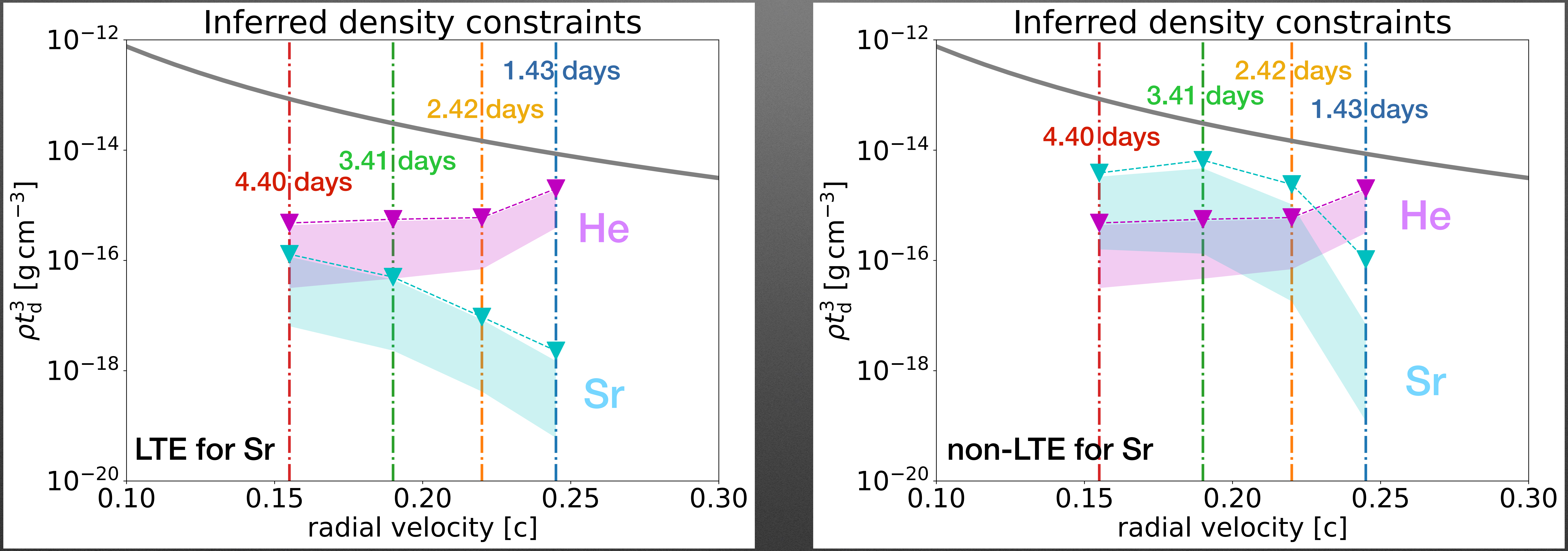
over-ionization by Non-LTE effect



photoionization effect

$\rho t_{\rm d}^3$: mass density at 1 day after merger

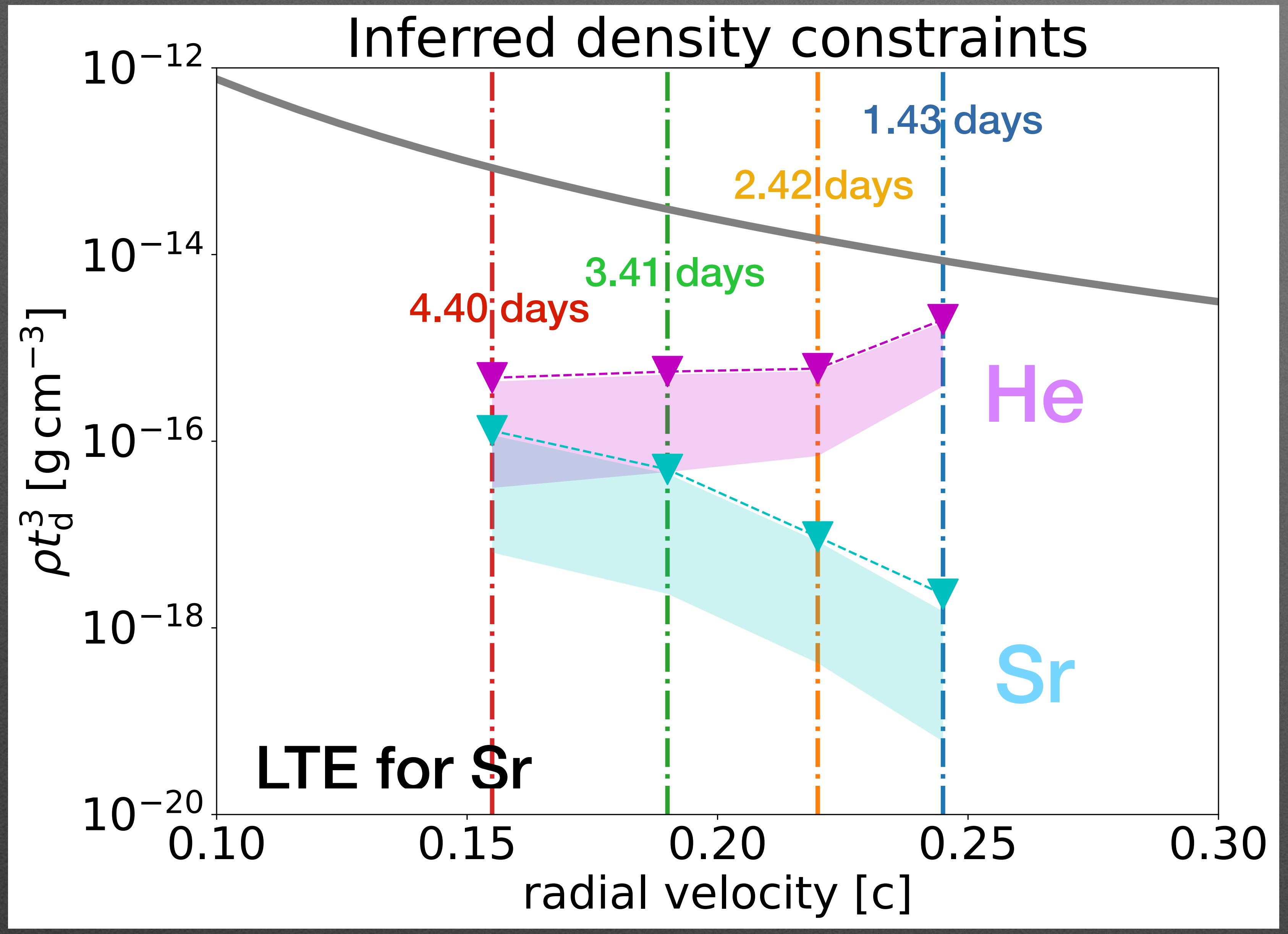
Constraints on the density profile

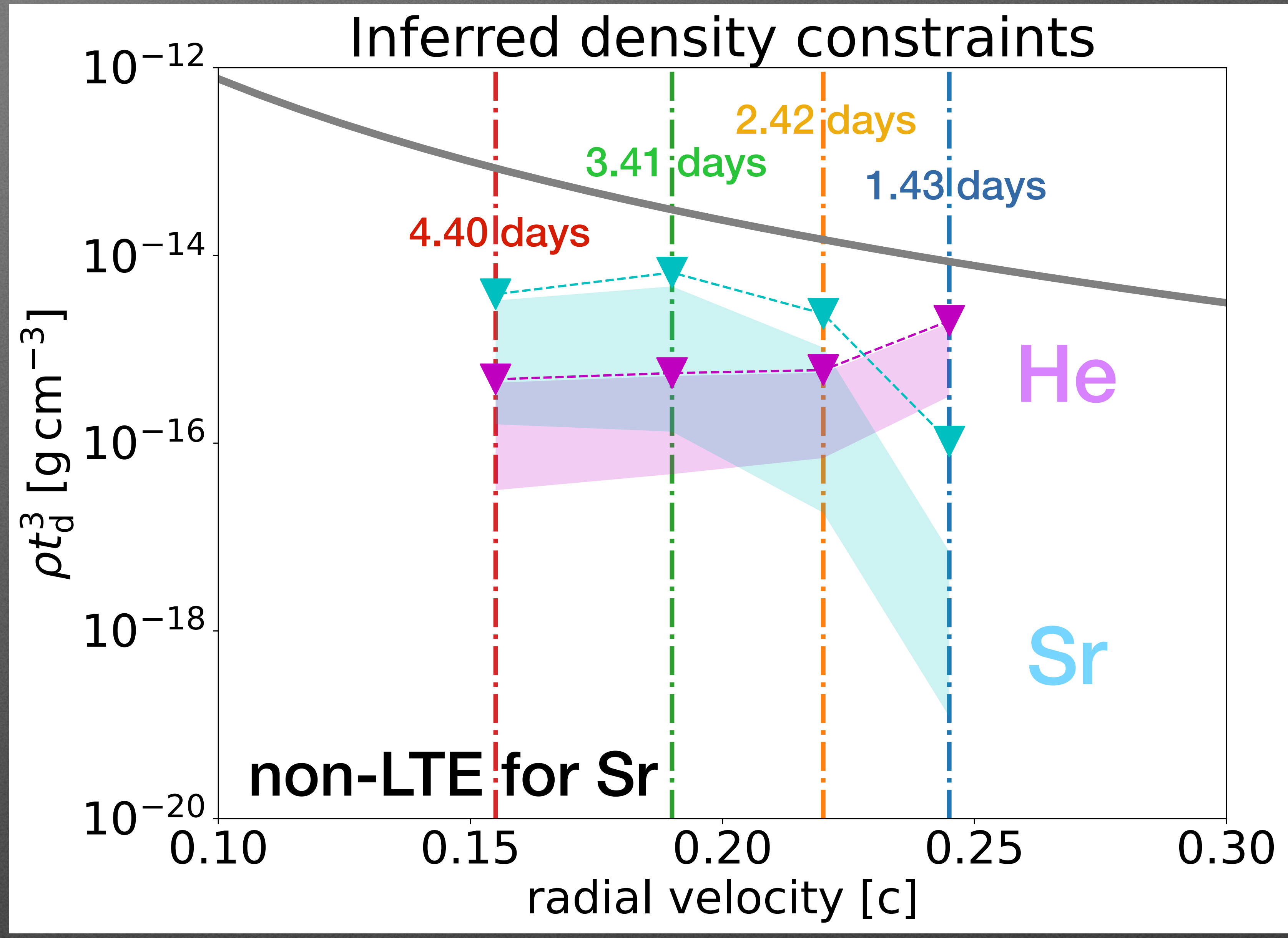


▼: upper limit

shaded region: 10-90% contribution to the line

Constraints on the density profile





integrate density

in $0.15c \lesssim v_r \lesssim 0.25c$

He mass

$$4 \times 10^{-5} \lesssim \frac{M_{\rm He}}{\rm M_\odot} \lesssim 3 \times 10^{-4}$$

Sr mass (non-LTE)

$$2 \times 10^{-5} \lesssim \frac{M_{\rm Sr}}{\rm M_\odot} \lesssim 1 \times 10^{-3}$$

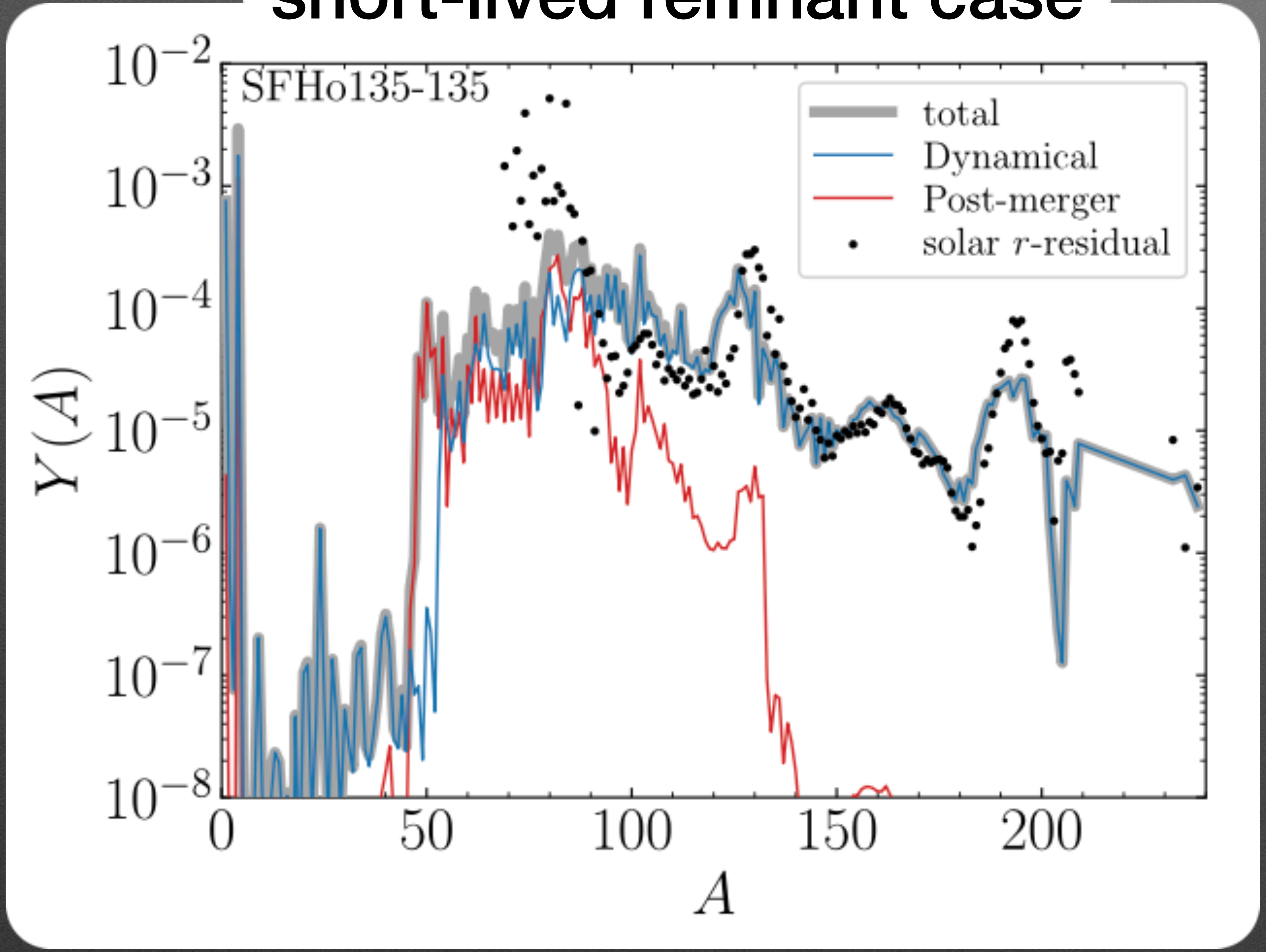
Sr mass (LTE)

$$6 \times 10^{-7} \lesssim \frac{M_{\rm Sr}}{\rm M_\odot} \lesssim 1 \times 10^{-5}$$

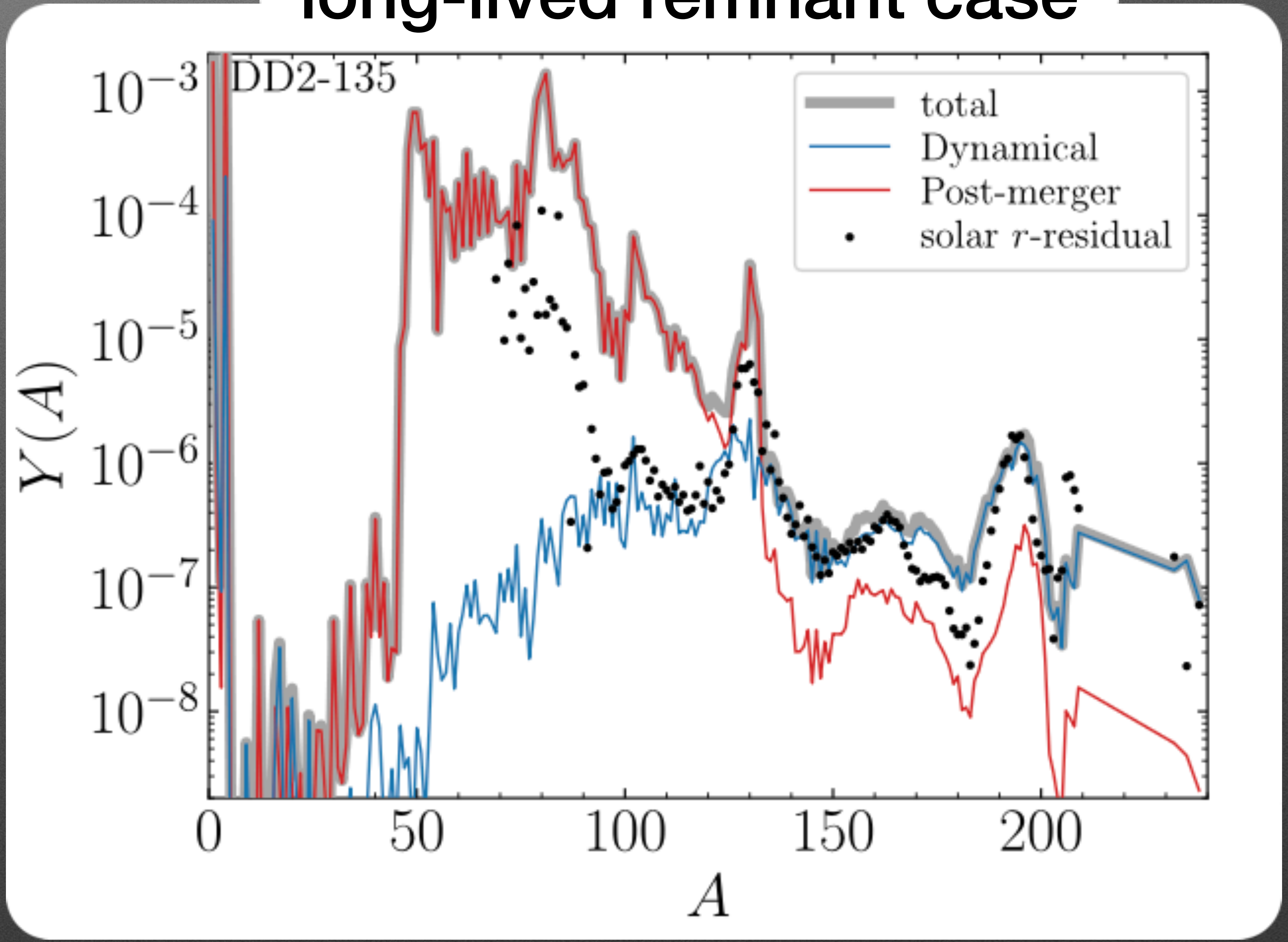
1. Non-LTE ionization modeling
2. Constraints from observation
3. Comparison with numerical simulation

Usually in numerical simulation papers…

short-lived remnant case



long-lived remnant case



Fujibayashi+ 2023

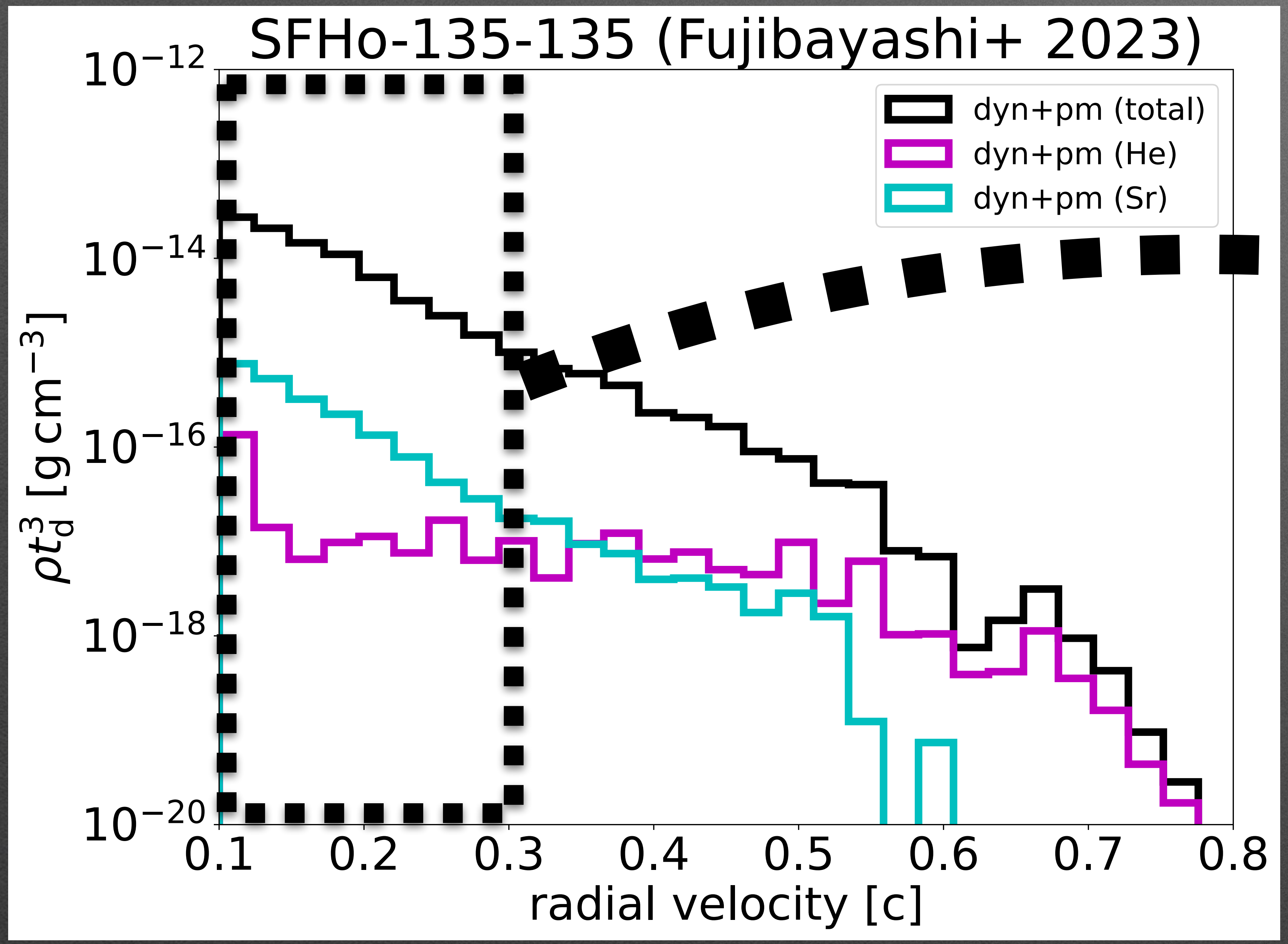
They usually show spatially integrated abundance

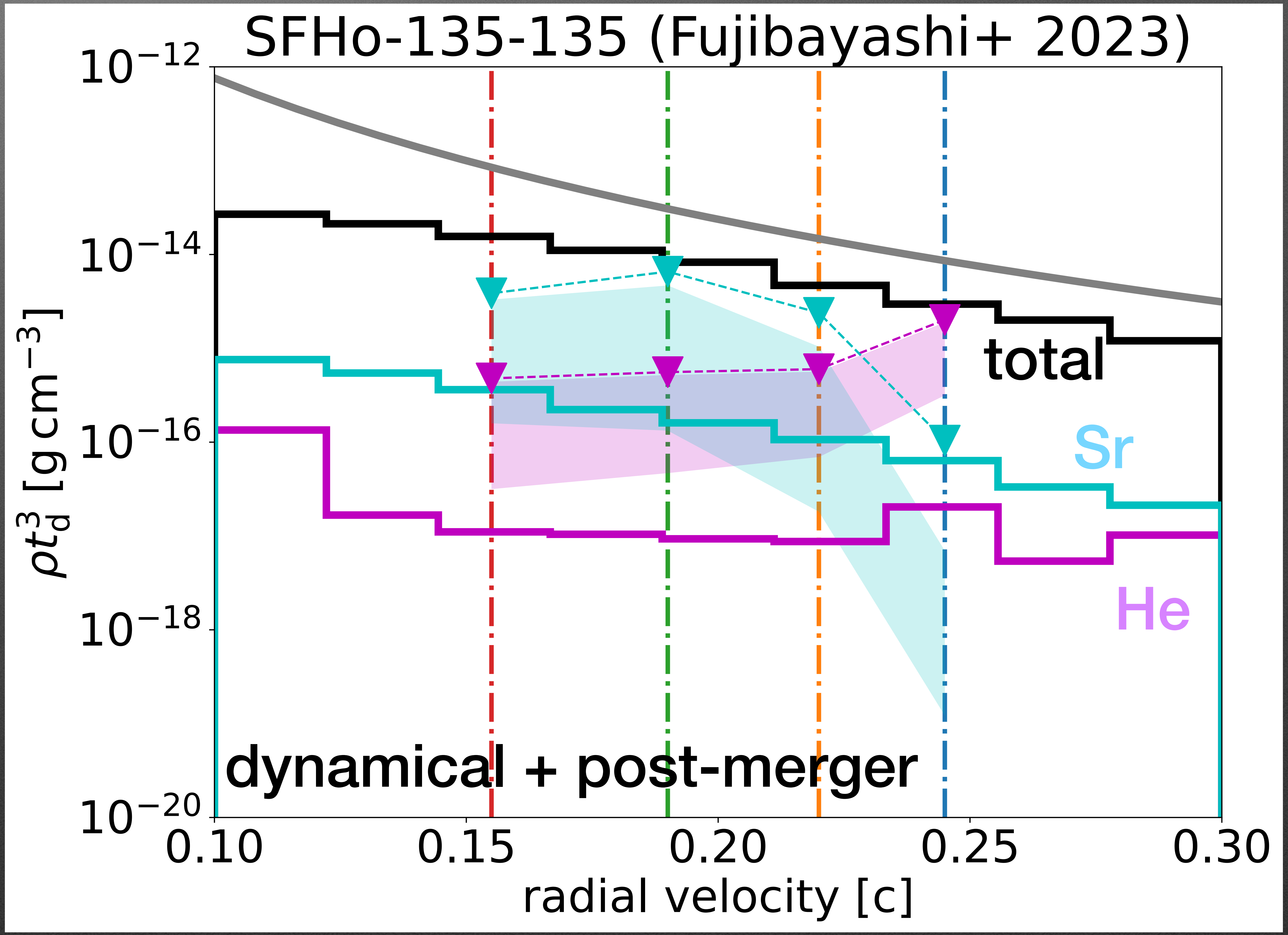
Now we can discuss spatially resolved abundance

▼: upper limit

shaded region: 10-90% contribution to the line

Short-lived remnant case





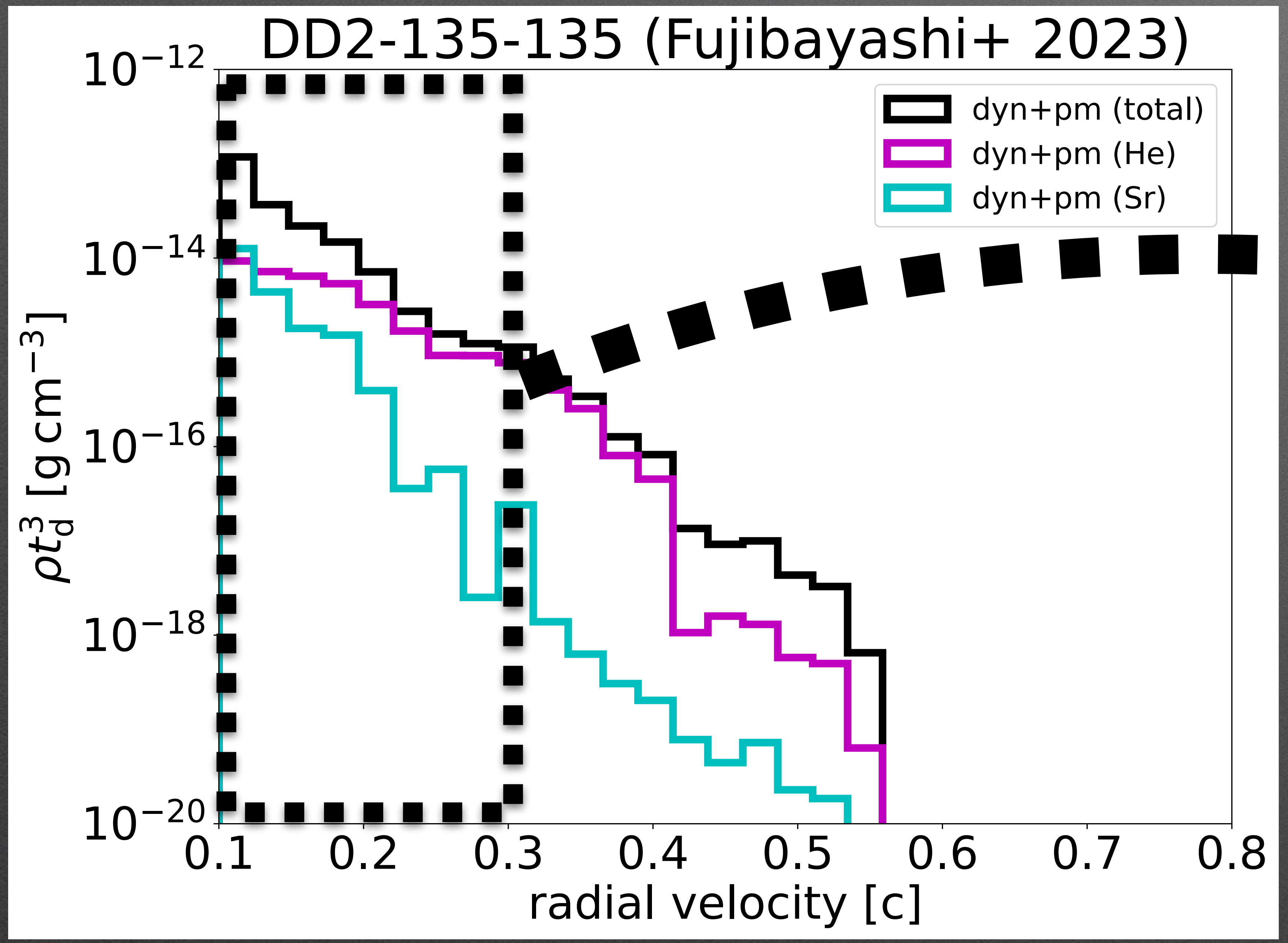
- Sr alone can roughly reproduce GW170817, but Sr density in the simulation is a bit low.
- When trying to match density, He contribution cannot be ignored.

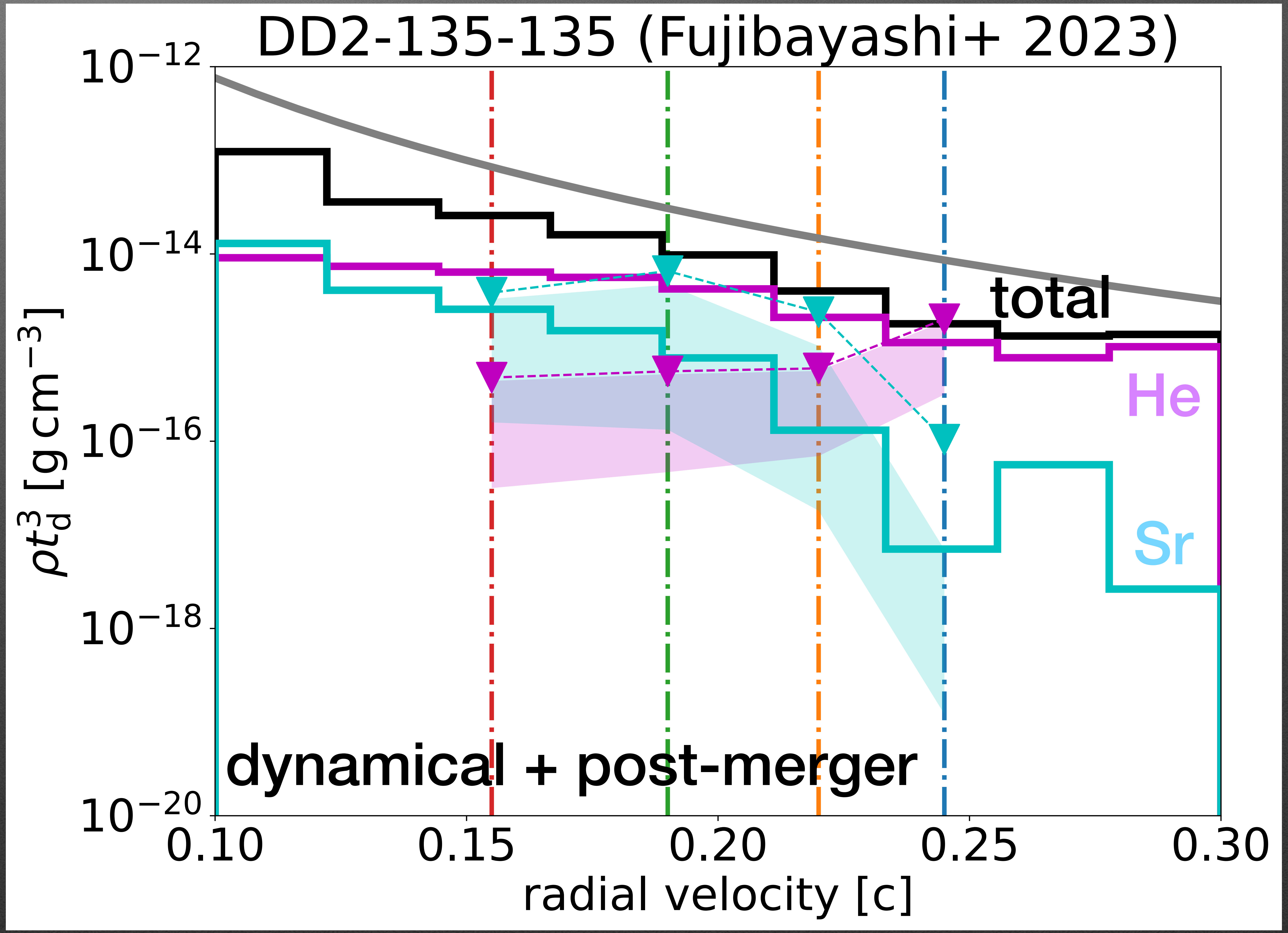
▼: upper limit

shaded region: 10-90% contribution to the line

Long-lived remnant case

dynamical + post-merger



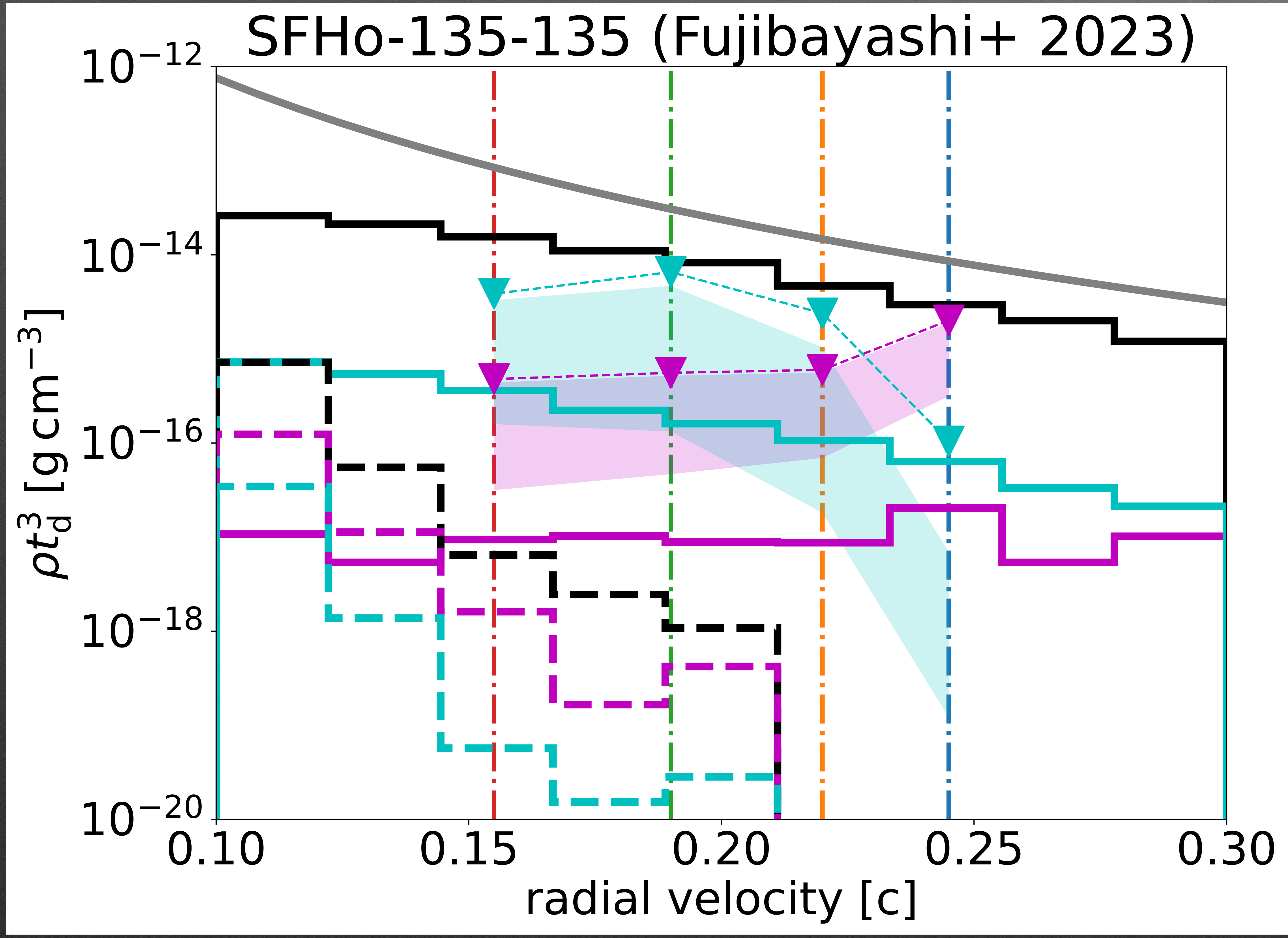


- Sr is OK but He is too much.

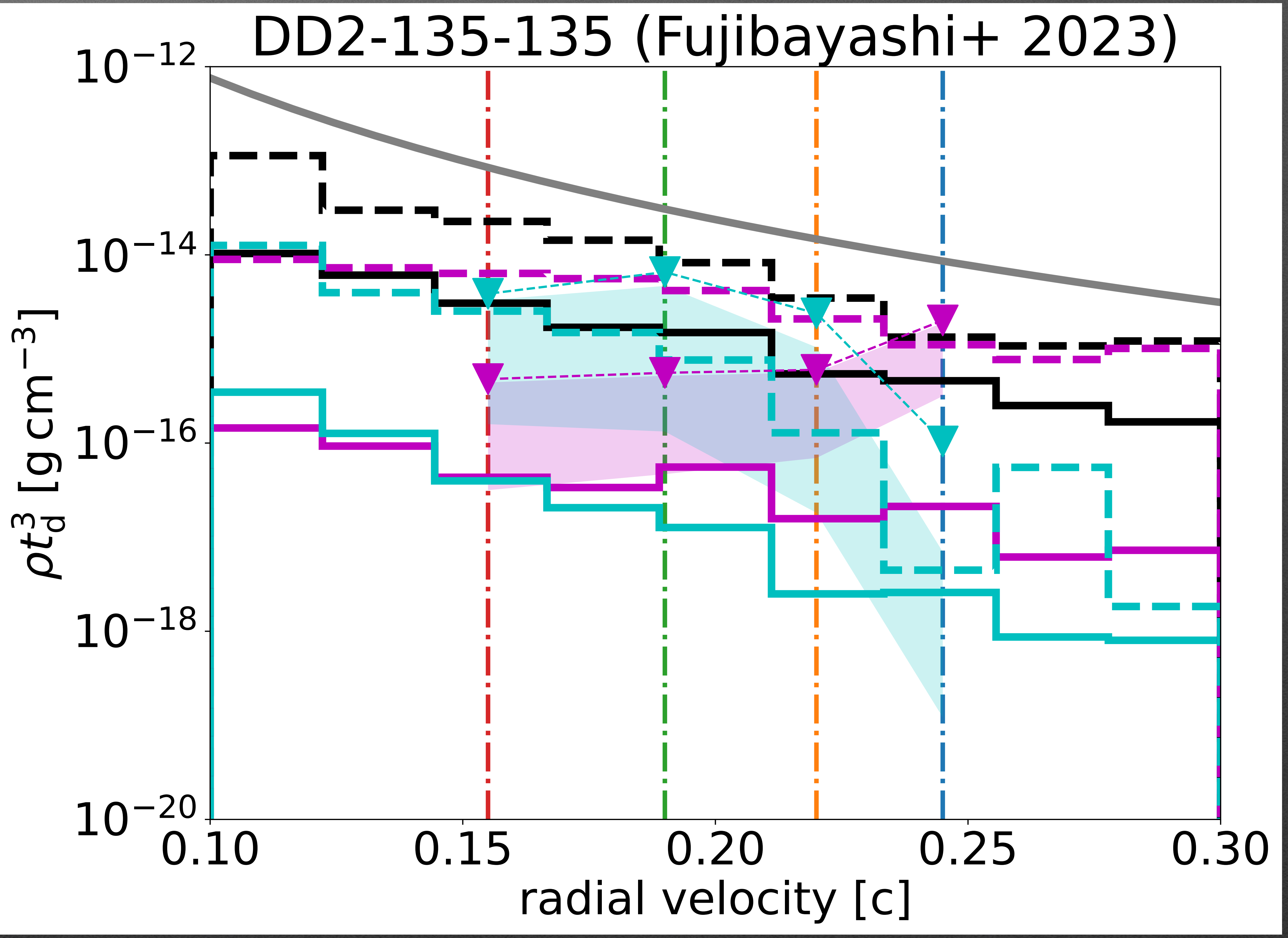
solid line: dynamical ejecta
dashed line: post-merger ejecta

Difference of mass ejection mechanism

short-lived remnant case



long-lived remnant case



dynamical ejecta is dominant ⟷ post-merger ejecta is dominant

Comparison with outer mass

mass in $0.15c \lesssim v_r \lesssim 0.25c$ (mass in $v_r \gtrsim 0.15c$)

in the solar mass		Short-lived remnant case	Long-lived remnant case
dynamical	total	2.86×10^{-3} (4.65×10^{-3})	4.70×10^{-4} (6.58×10^{-4})
	He	4.29×10^{-6} (4.59×10^{-5})	1.26×10^{-5} (2.20×10^{-5})
	Sr	6.15×10^{-5} (9.41×10^{-5})	4.29×10^{-6} (5.17×10^{-6})
post-merger	total	5.35×10^{-7} (5.35×10^{-7})	3.00×10^{-3} (3.85×10^{-3})
	He	1.18×10^{-7} (1.18×10^{-7})	1.33×10^{-3} (2.03×10^{-3})
	Sr	4.68×10^{-9} (4.68×10^{-9})	2.56×10^{-4} (2.71×10^{-4})

$$4 \times 10^{-5} \lesssim \frac{M_{\rm He}}{\rm M_\odot} \lesssim 3 \times 10^{-4}$$

$$2 \times 10^{-5} \lesssim \frac{M_{\rm Sr}}{\rm M_\odot} \lesssim 1 \times 10^{-3}$$

Sr for LTE: $6 \times 10^{-7} \lesssim \frac{M_{\rm Sr}}{\rm M_\odot} \lesssim 1 \times 10^{-5}$

(roughly) within inferred range

too much

More specifically, long-term hydrodynamical modeling is important.

Conclusion & Summary

- We construct Non-LTE ionization model for He and Sr in neutron star merger ejecta.
- Non-LTE ionization model is very important not only for He but Sr.
- Compared with numerical simulation results,
  short-lived case is roughly consistent with the inferred density profile in GW170817.