R-process Dust

Kenta Hotokezaka
(University of Tokyo)

Collaboration with Nanae Domoto and Dan Kasen

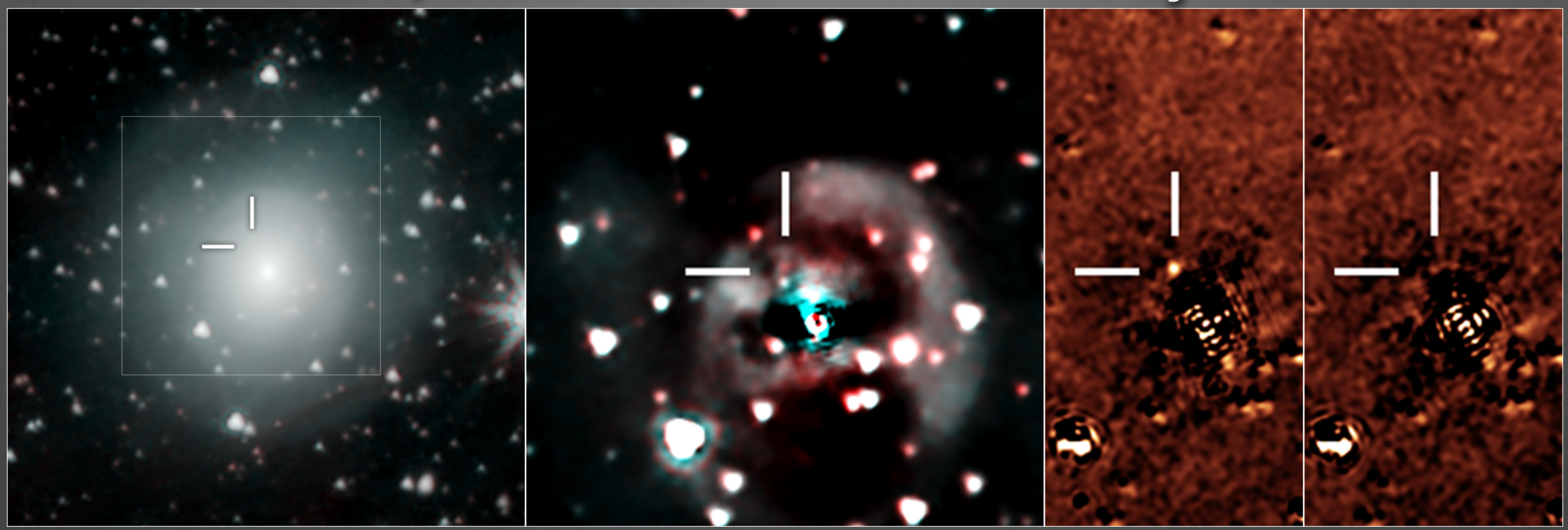
Outline

- Observational Clues
- R-process condensation: amounts and equilibrium
- Why the previous work concluded no dust formation in kilonovae?
- Kinetic approach for r-process dust formation
- Dust formation in kilonovae and implication

Spitzer Puzzle in AT2017gfo

Spitzer detection at 4.5 μm (non-detection at 3.6 μm)

Kasliwal+, Villar+18 Day 45



- The detection and limit => T ~ 500K if blackbody.
- Optically thick emission with 0.05c and 500K => L ~ 10^{39} erg/s.
- The β-decay luminosity is ~10^{39} erg/s.

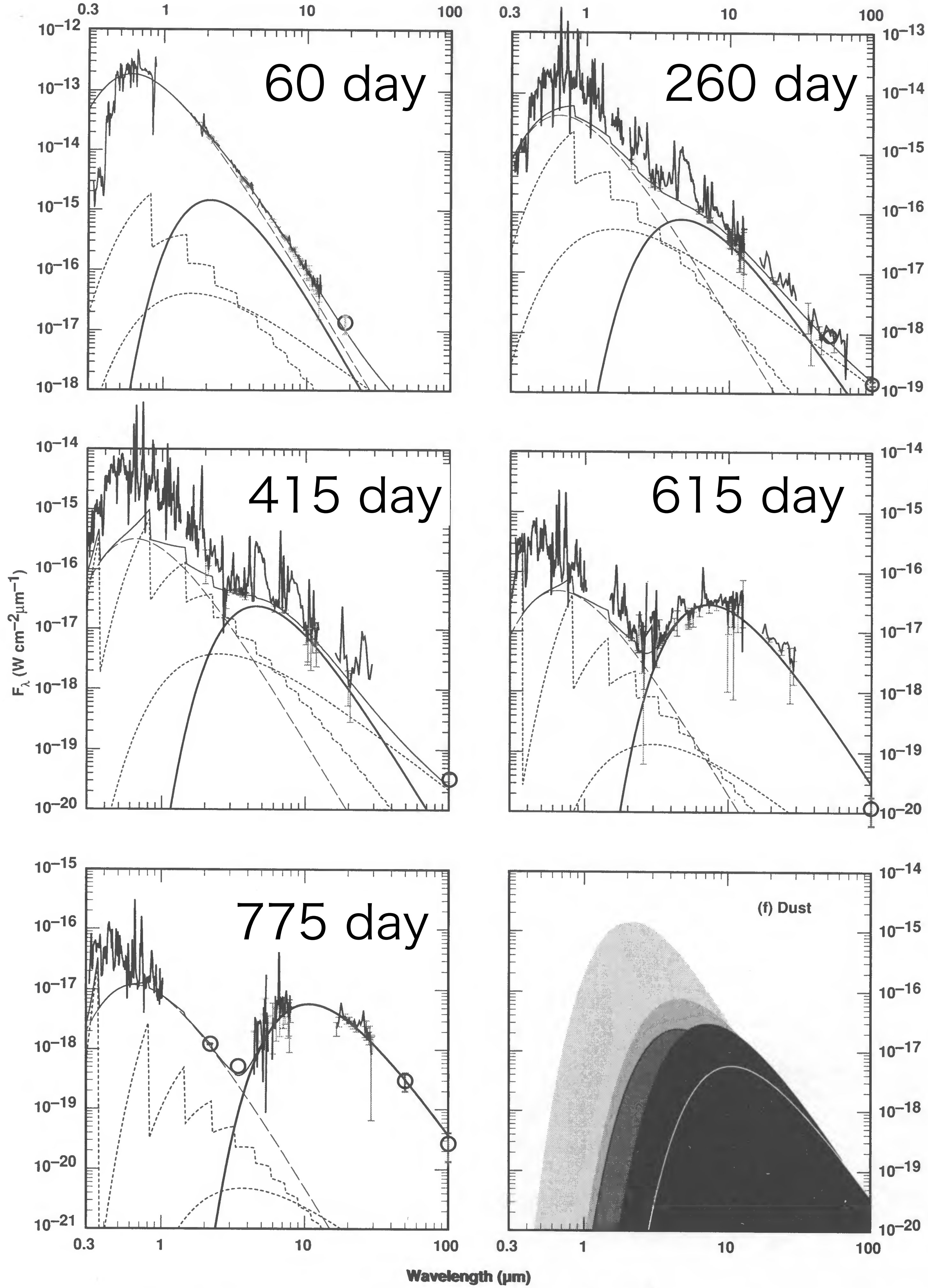
So, fully thermalized dust emission may be the solution:

$\tau_{dust} > 1 \Rightarrow M_{dust} \gtrsim 10^{-3} M_{sun}$ or ~ $0.03 M_{ej}$

But, do dust grains form in kilonova? (e.g., Takami+14, Gall et al., 2017)

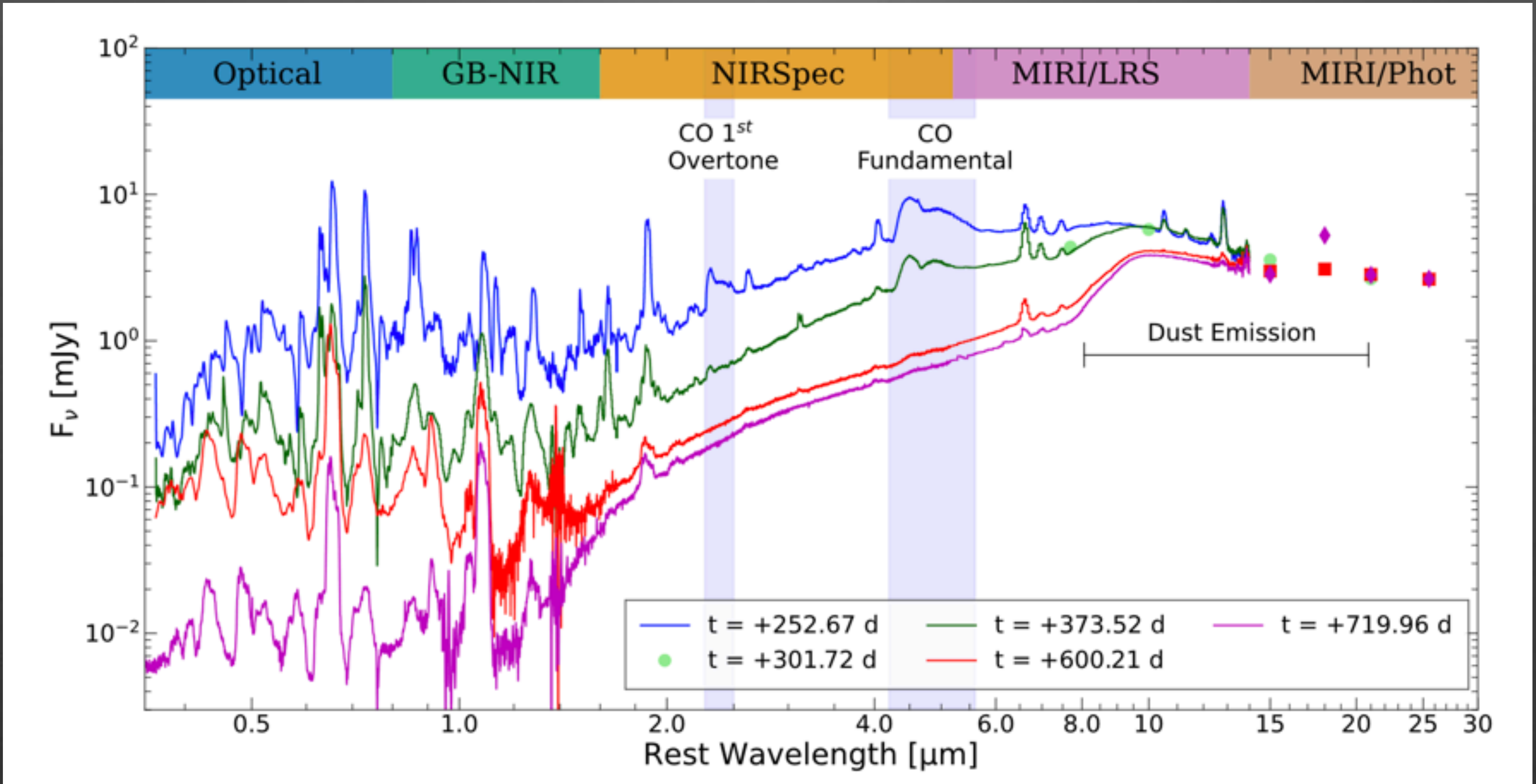
SN 1987A

(Wooden+1992)



JWST view of core-collapse supernova

SN 2023ixf (Medler+2025)

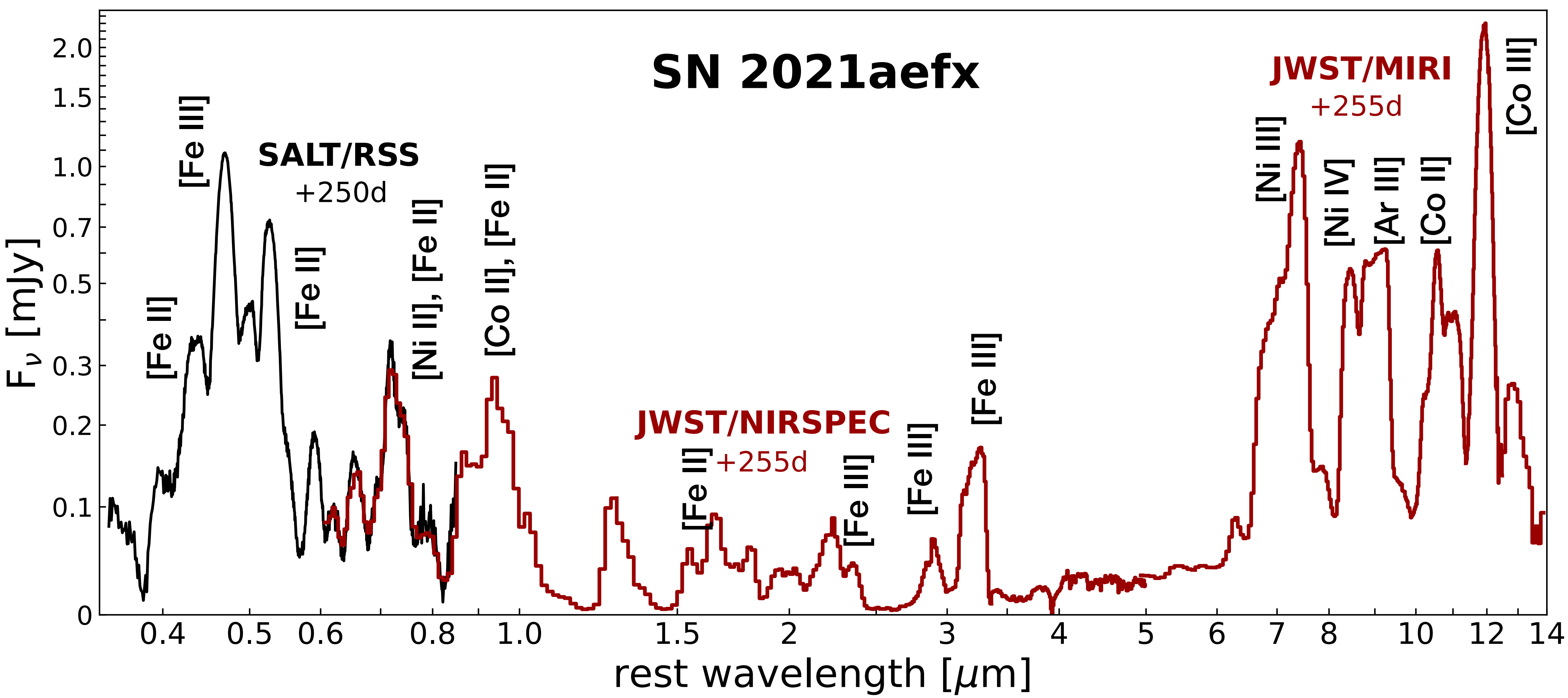


SN2023ixf clearly exhibits an IR excess by dust.

The dust emission dominates t >~ 400 day.

JWST view of supernova Ia

SN 2021aefx (Kwok+23, see also DerKacy+23)

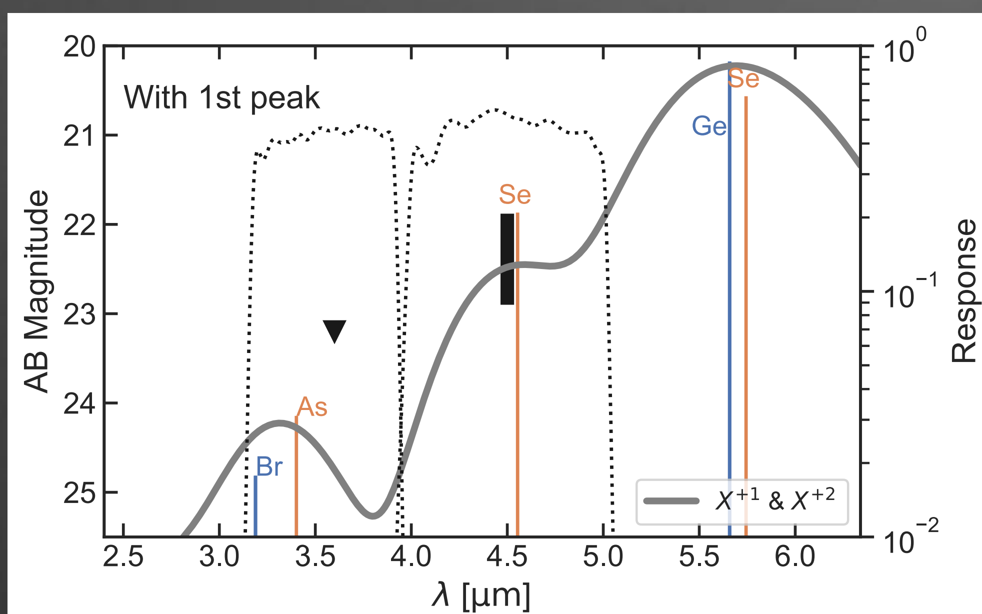


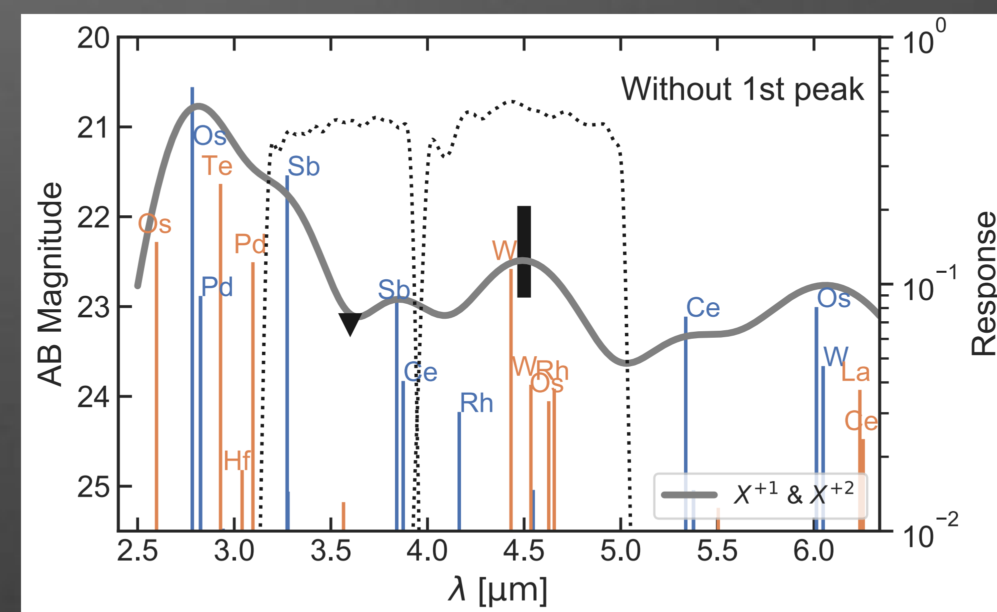
- Forbidden emission lines of metals (M1, E2 etc).
- Lines at >7μm are fine-structure lines (M1). Very prominent but less important for cooling.
- No clear dust emission in typical SNe Ia.

Early Consideration in AT2017gfo

Kilonova conditions are somewhat similar to SNe Ia

- **Less massive** ejecta with a large fraction of **radioactivity**. The velocity is **faster.** => Dust formation is qualitatively not favored and perhaps more difficult than SNe Ia (Takami+14).

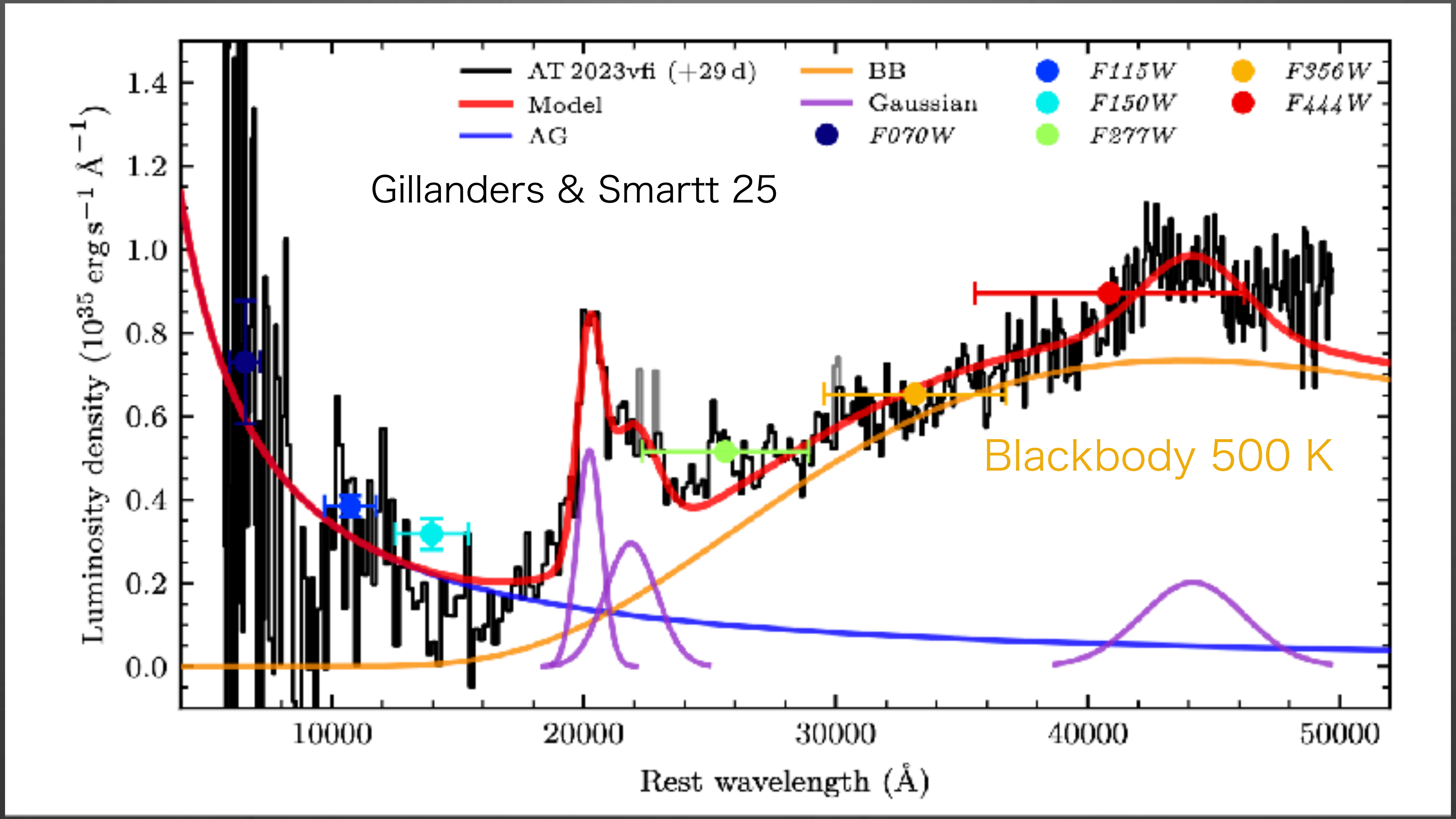




- Fine-structure lines of Fe group are at >10μm. Heavier elements have 1 - 10 μm. => It is not surprising that the nebular emission is strong at 5μm (KH+23).

AT 2023vfi in GRB 230307A

JWST observation at 29 day (Levan+24)

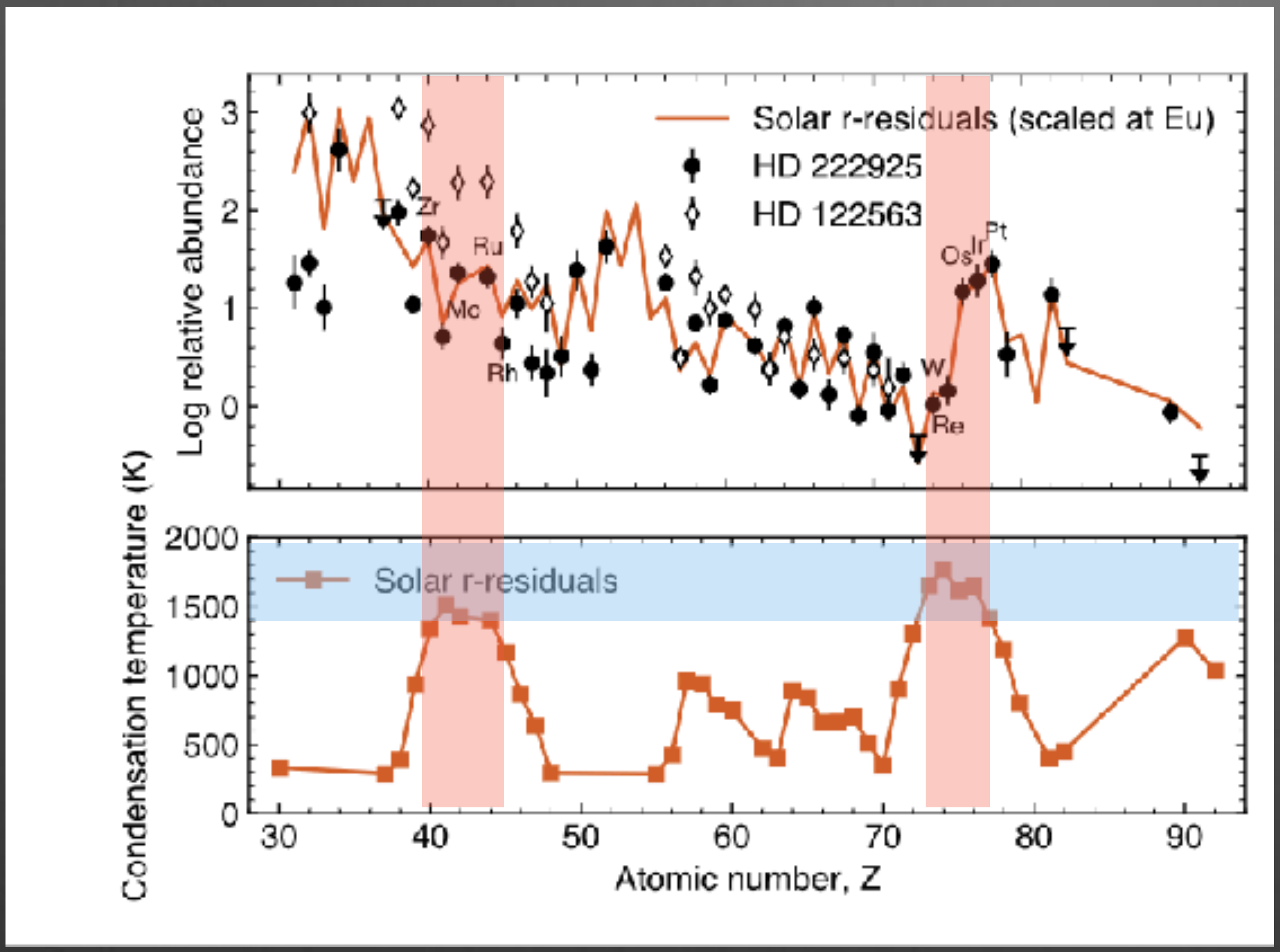


- Late-time IR emission is clearly continuum.
- It is unlikely that emission lines overlap and form a blackbody like shape.
- Something have large opacities around 5 μm (or at 500 K).
- Atoms have relatively low opacities. (Masaomi, Dan, Quentin, private communication)

Outline

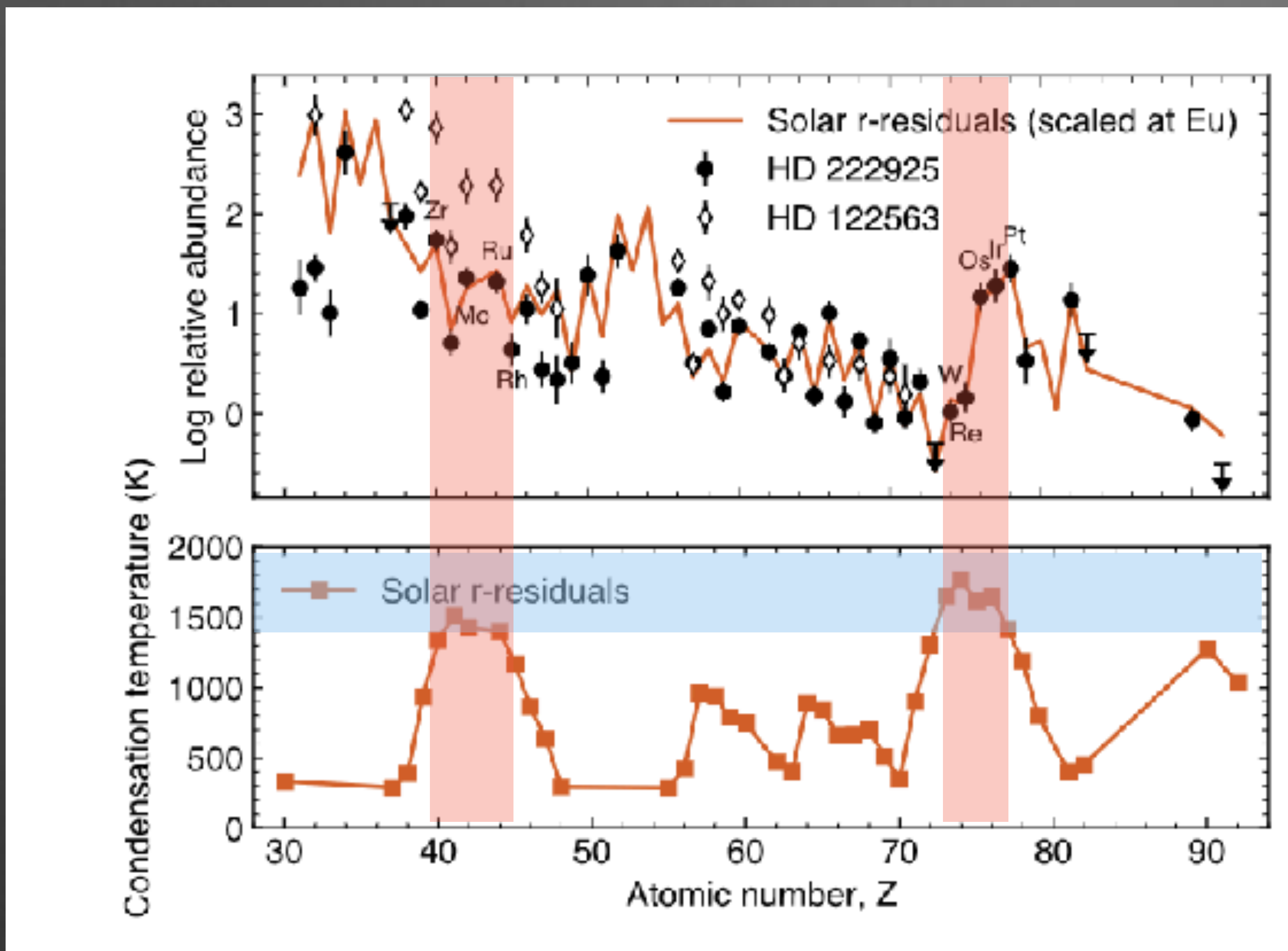
- Observational Clues
- R-process condensation: amounts and equilibrium
- Why the previous work concluded no dust formation in kilonovae?
- Kinetic approach for small grain formaion
- Dust formation in kilonovae and implication

Refractory elements in r-process



Refractory elements
1st: Zr, Mo, Ru
3rd: W, Os, Ir, Pt
They condense at < 1400K.
(if they are in equilibrium)

Refractory elements in r-process



Palme & Wlotzka 1976

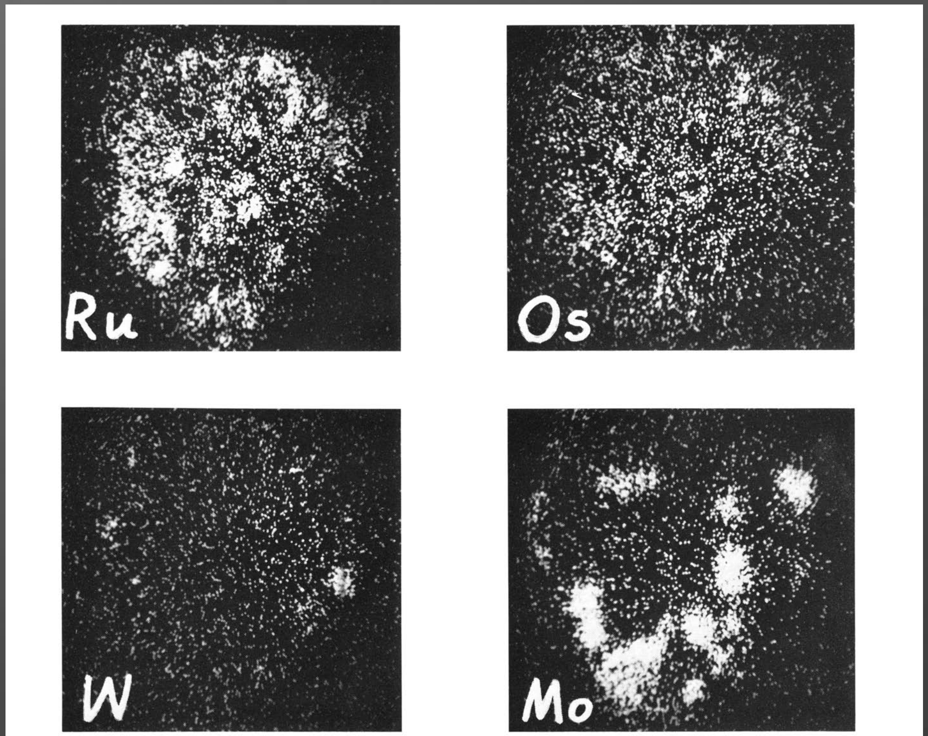
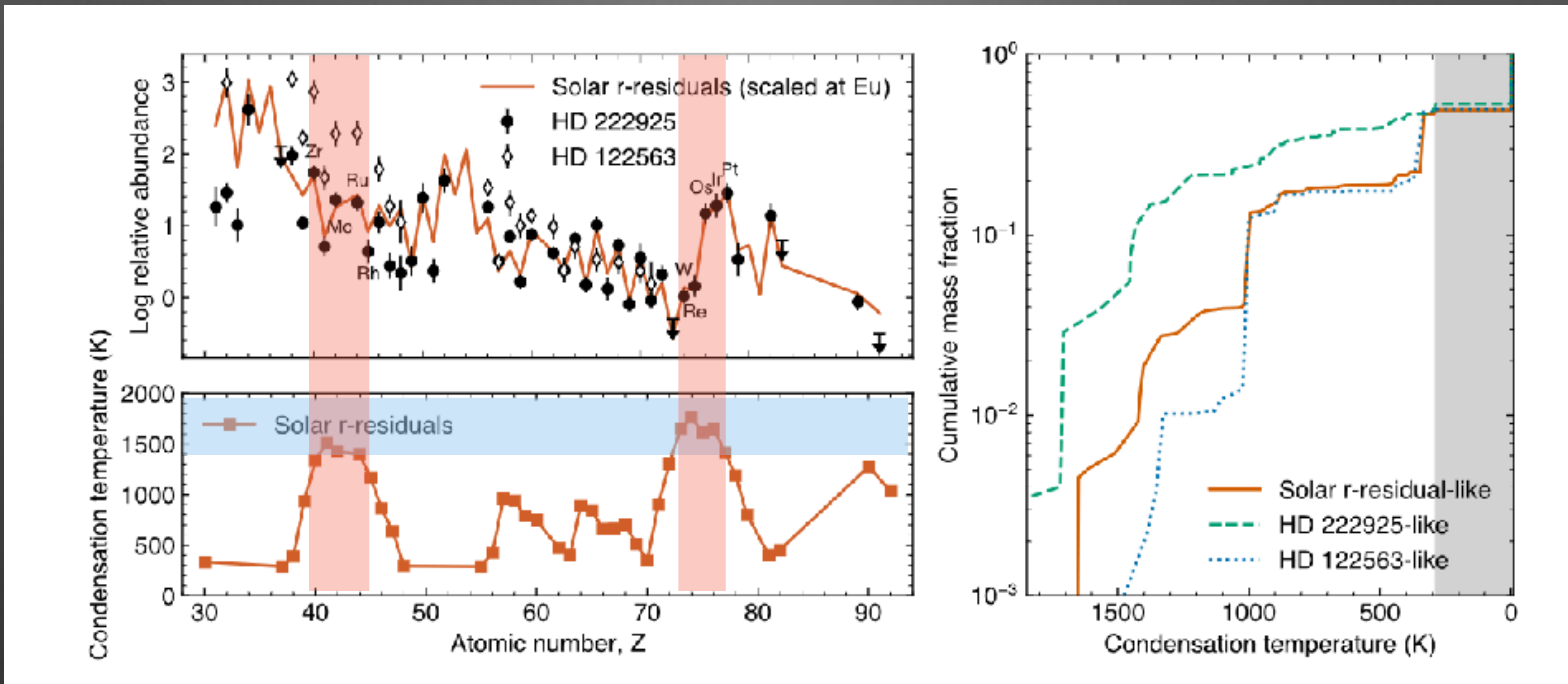


Fig. 3. X-ray scanning pictures of particle shown in Fig. 1.

In meteorites, they are sometimes seen in Pt-nugets, where they condense together.

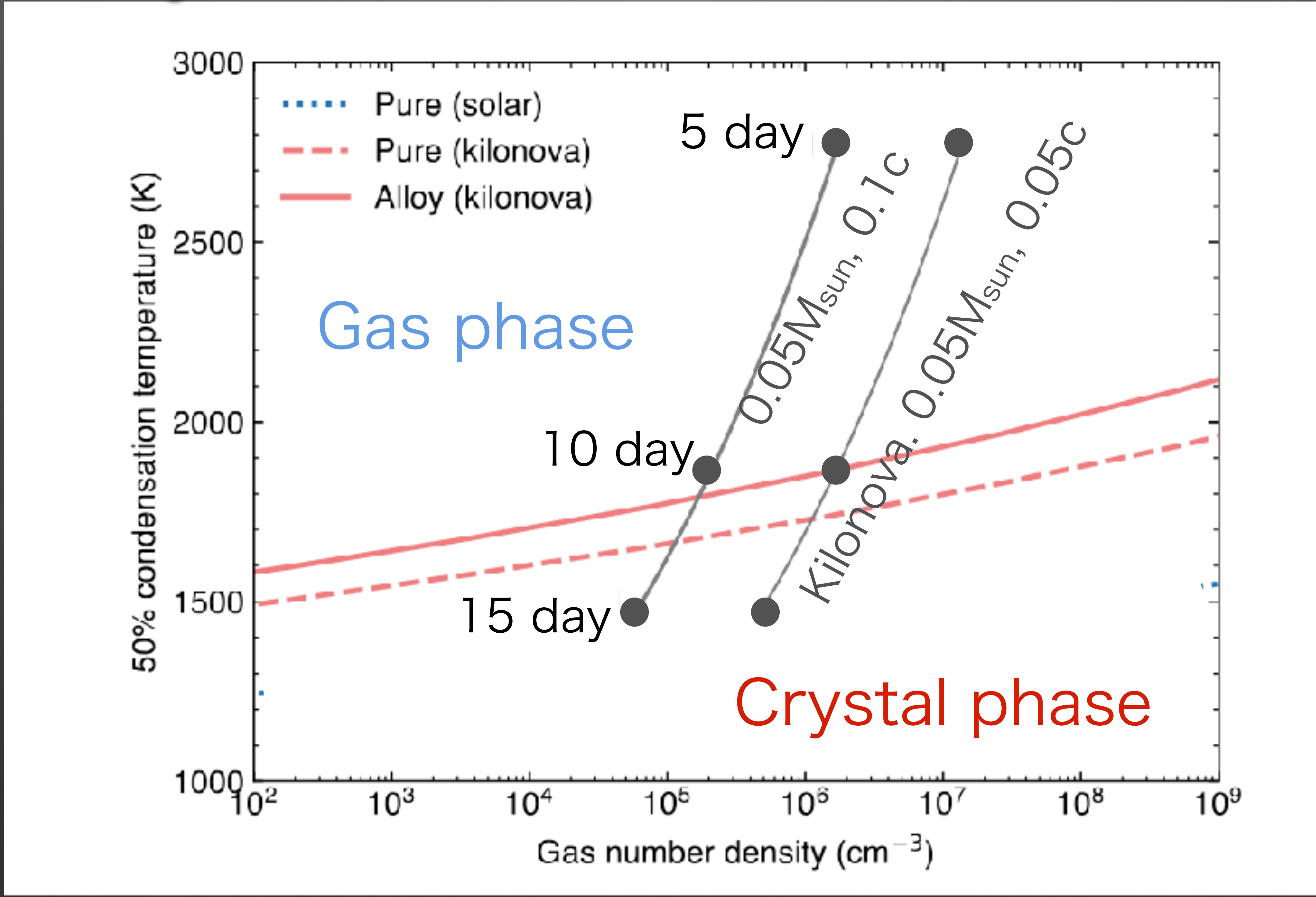
Refractory elements in r-process



- Mass fraction of refractory elements (Tc >~ 1400K) is ~ 0.01 - 0.1.
- This is roughly sufficient to make the ejecta optically thick at ~ 30 day.

Equilibrium

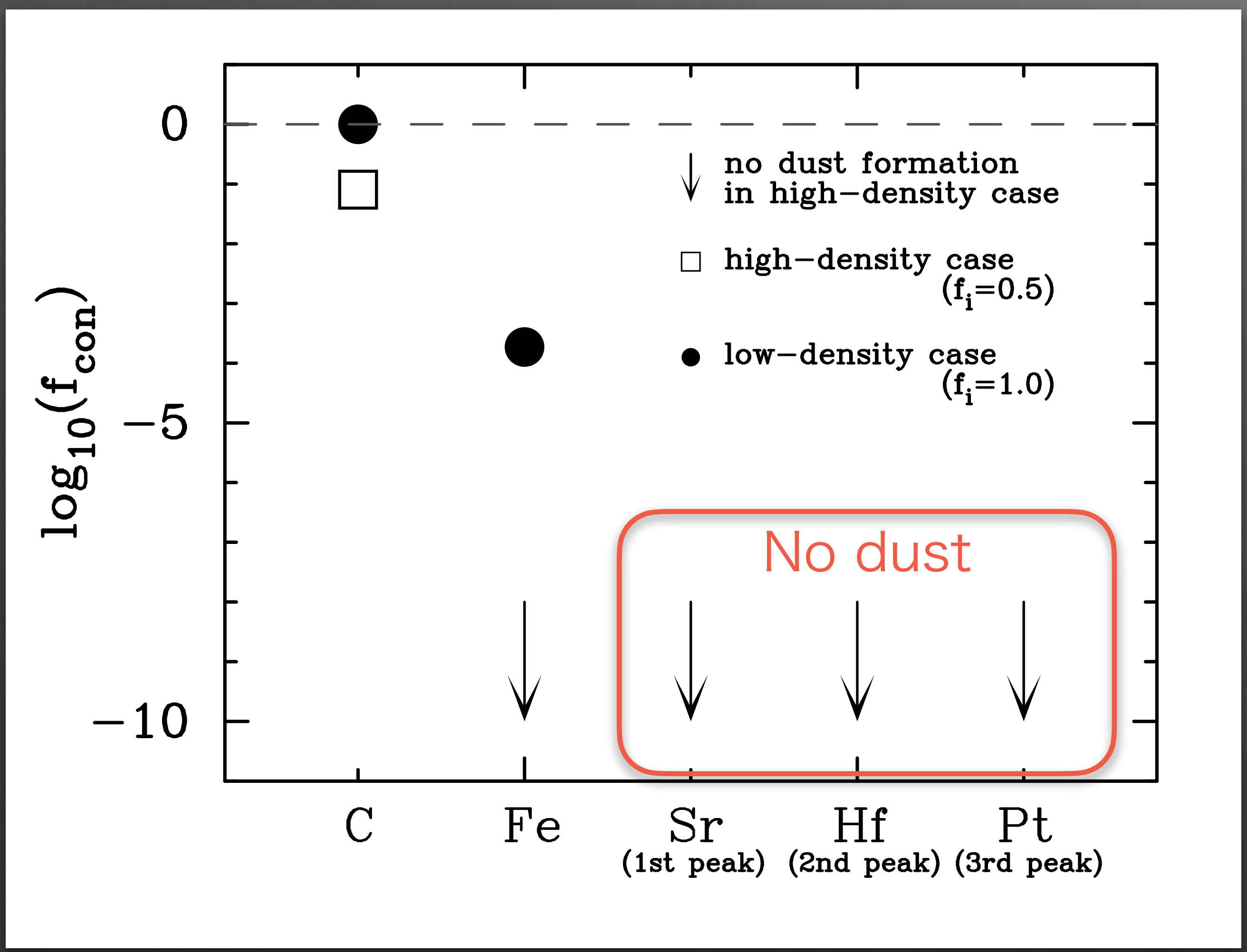
Refractory elements condensation (Domoto, KH, Kasen in prep)



Equilibrium state of refractory elements can be crystal.

Takami+14 rules out the grain formation

Condensation fraction



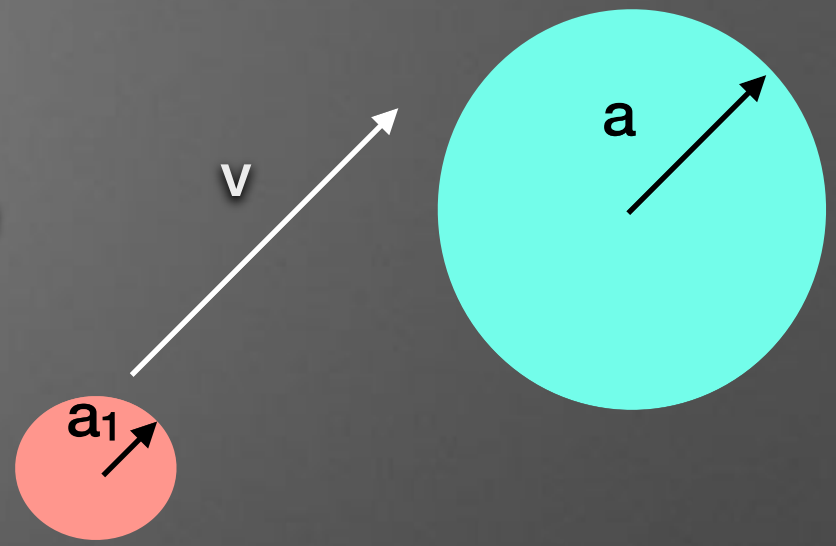
The issues:

1. Takami+14 considered only **low density ejecta**. So, atom-atom collision rarely occurs.
2. They use **classical nucleation theory**, which is not reliable for small cluster formation (Draine 1979).

Collision time

- The most important time scale is *collision time, t_{col}*

If $t_{col} > t$ at T ~ 1500K, dust formation is impossible



Number density of 1

$$t_{\rm col}^{-1}(a) = \pi a^2 v n_1$$

Relative velocity

$$v \approx \sqrt{\frac{2k_B T}{m_1}}$$

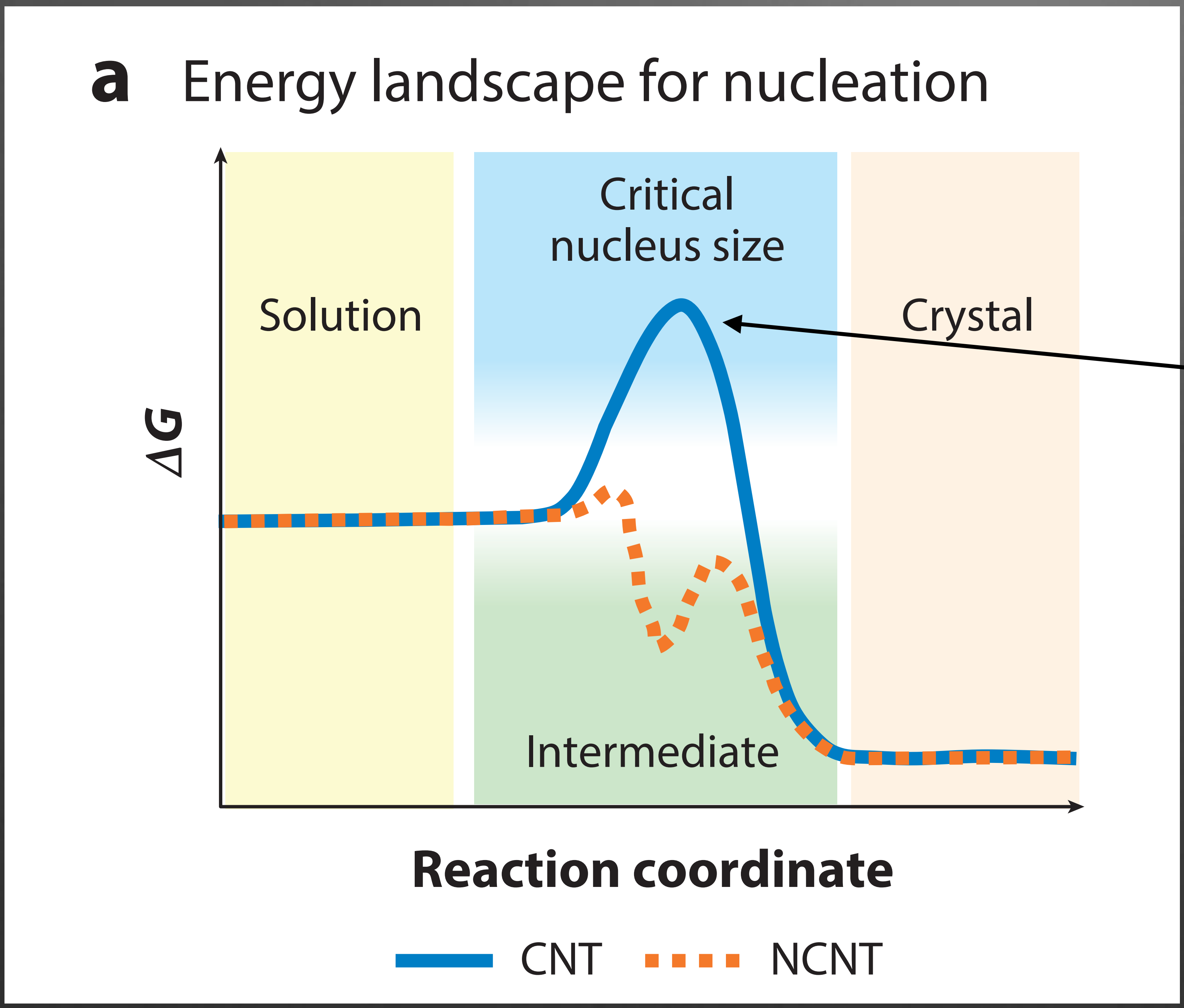
- For example, atomic collision:

$$t_{\rm col,atm} \approx 1\,{\rm day}\left(\frac{M_{\rm ej}}{0.05}\right)^{-1}\left(\frac{X_{\rm con}}{0.03}\right)^{-1}\left(\frac{v}{0.09c}\right)^{3}\left(\frac{t}{10\,{\rm day}}\right)^{3}$$

Takami+14 took M_{ej} ~ 0.01M_{sun} and v = 0.2c -> t_{col} >> t at T = 1500K.

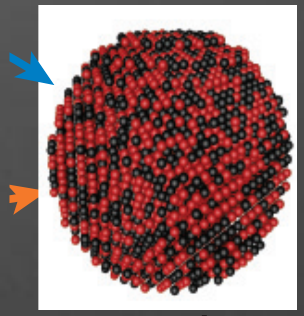
Nucleation Theory

Jun et al., 2022



Classical Nucleation

- Spherical shape with surface tension of ∞ size.
- Monomer capture and emission

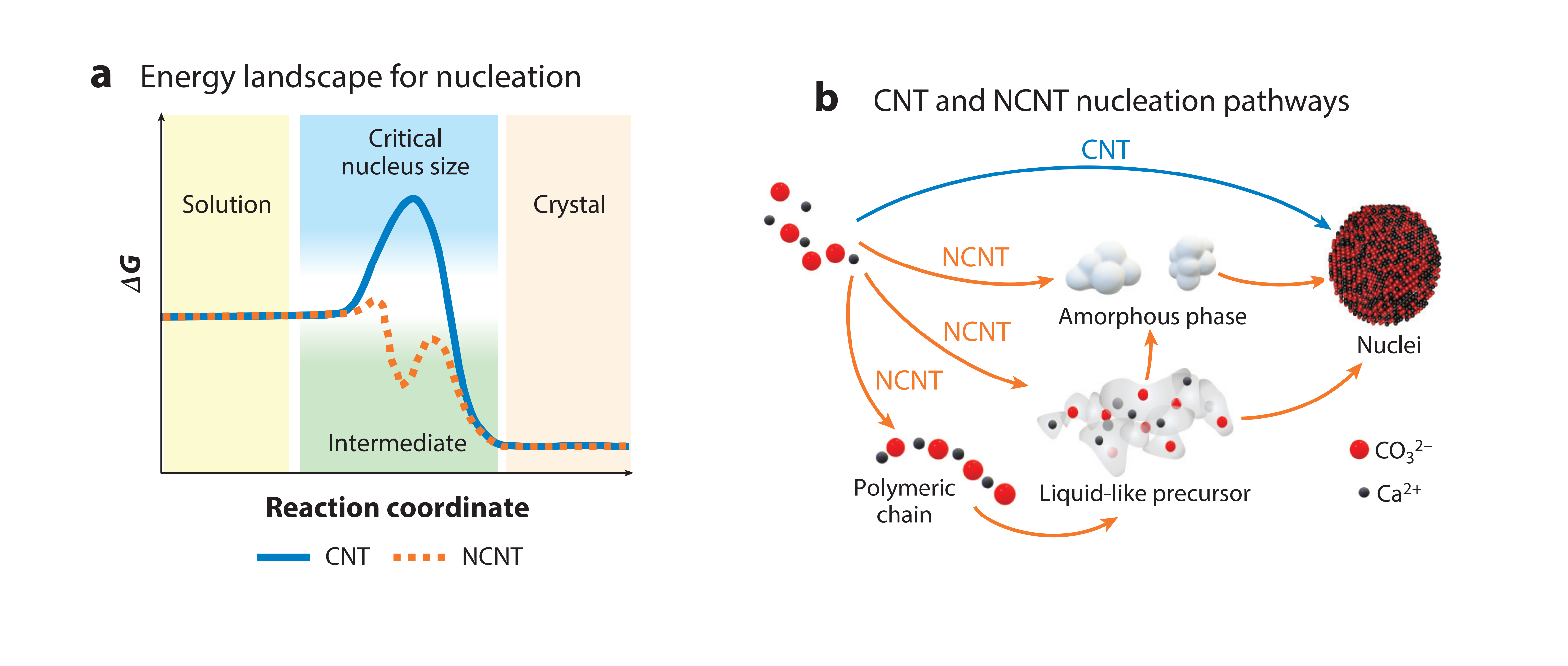


- Potential maximum appears, i.e., the surface energy vs volume energy

- Nucleation rate ~ $\exp(-\Delta G/kT)$

Nucleation Theory

Jun et al., 2022

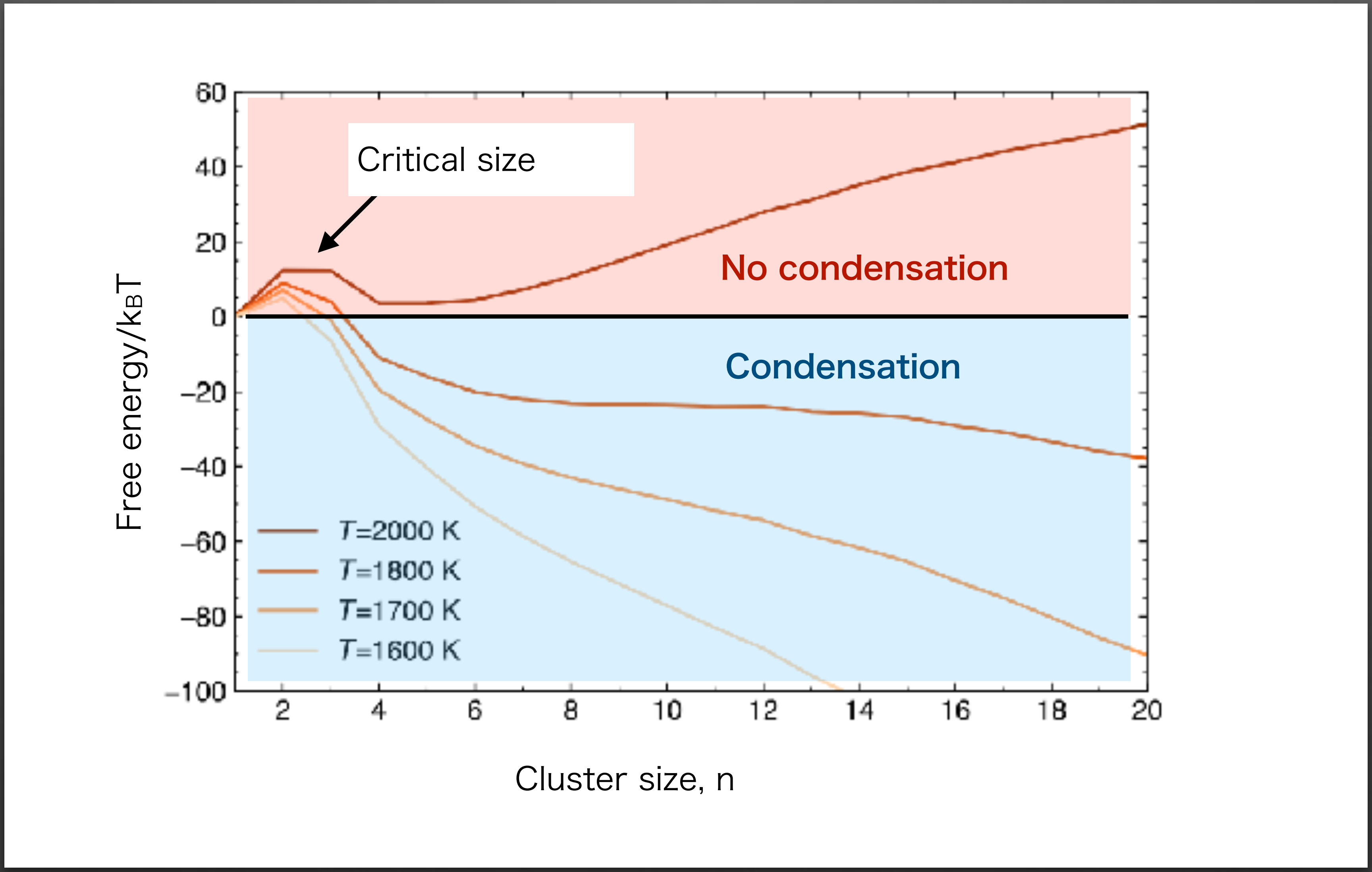


Non-classical paths may reduce the potential barrier and thus reduce the nucleation time.

Outline

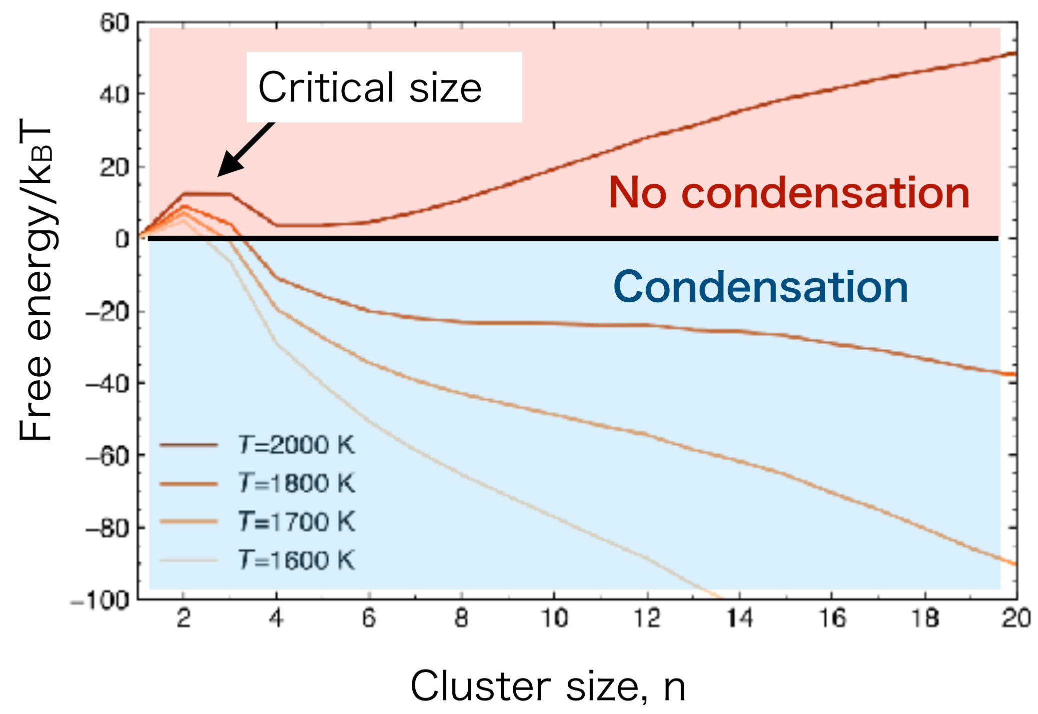
- Observational Clues
- R-process condensation: amounts and equilibrium.
- Why the previous work concluded no dust formation in kilonovae?
- Kinetic approach for r-process dust formation
- Dust formation in kilonovae and implication

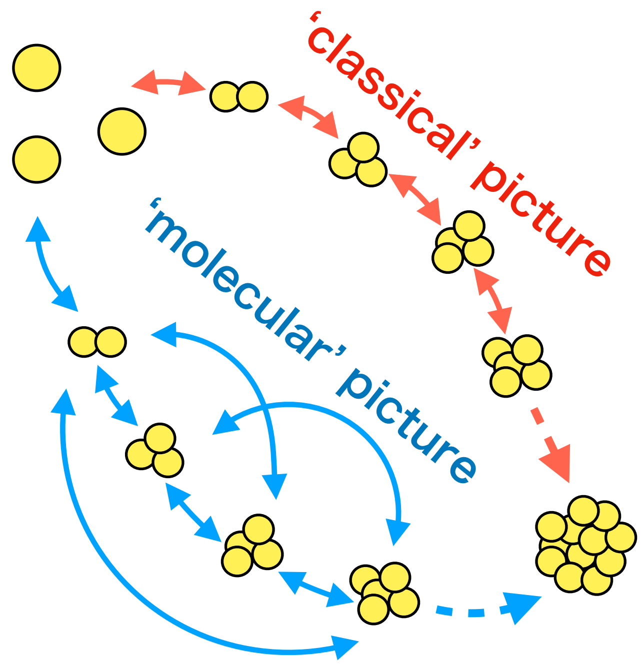
R-process cluster formation in kilonovae



Reaction rates are from Matsuka+19

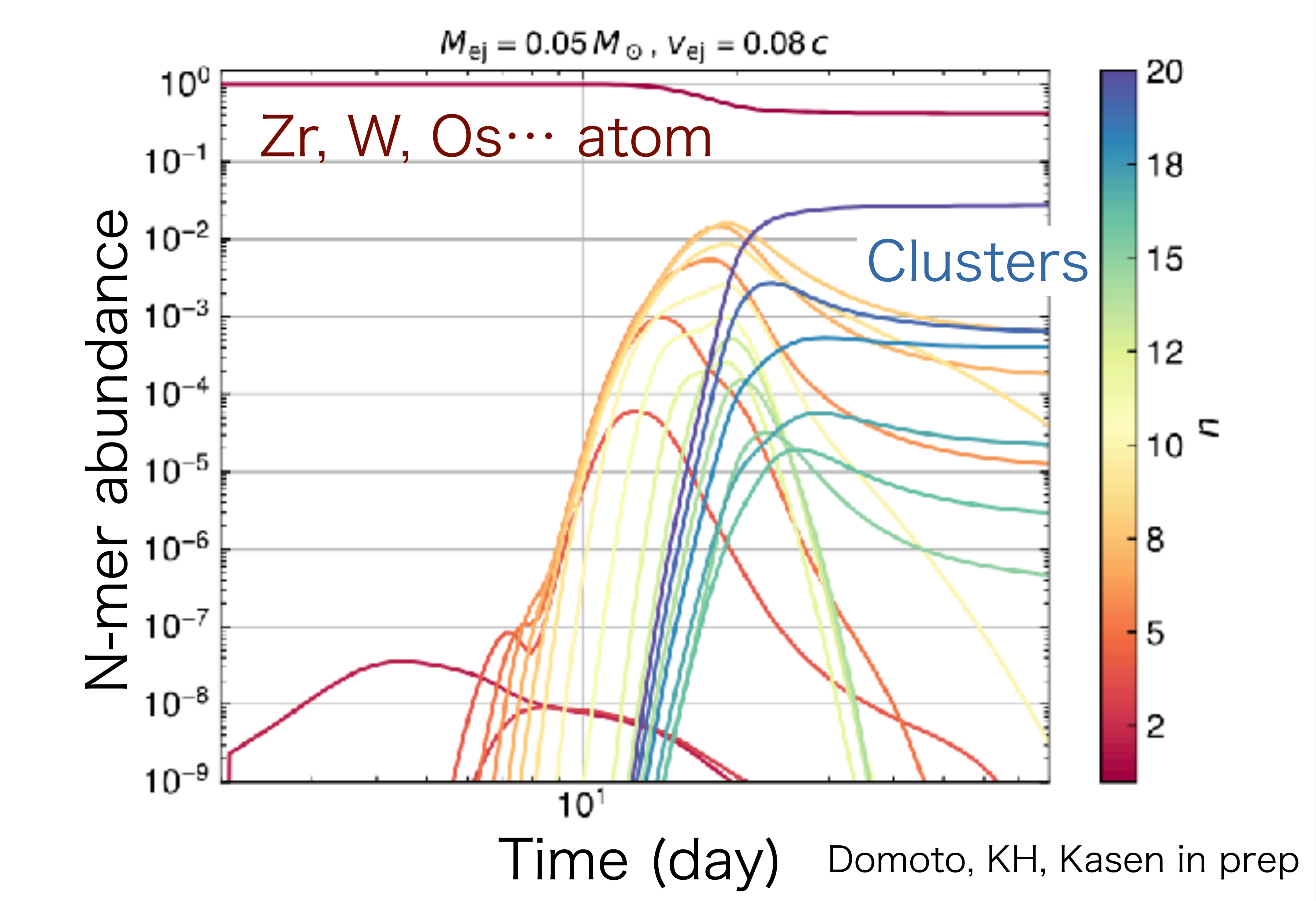
R-process cluster formation in kilonovae





Reaction rates are from Matsuka+19
Including cluster 'fission'.

Grain formation in kilonova

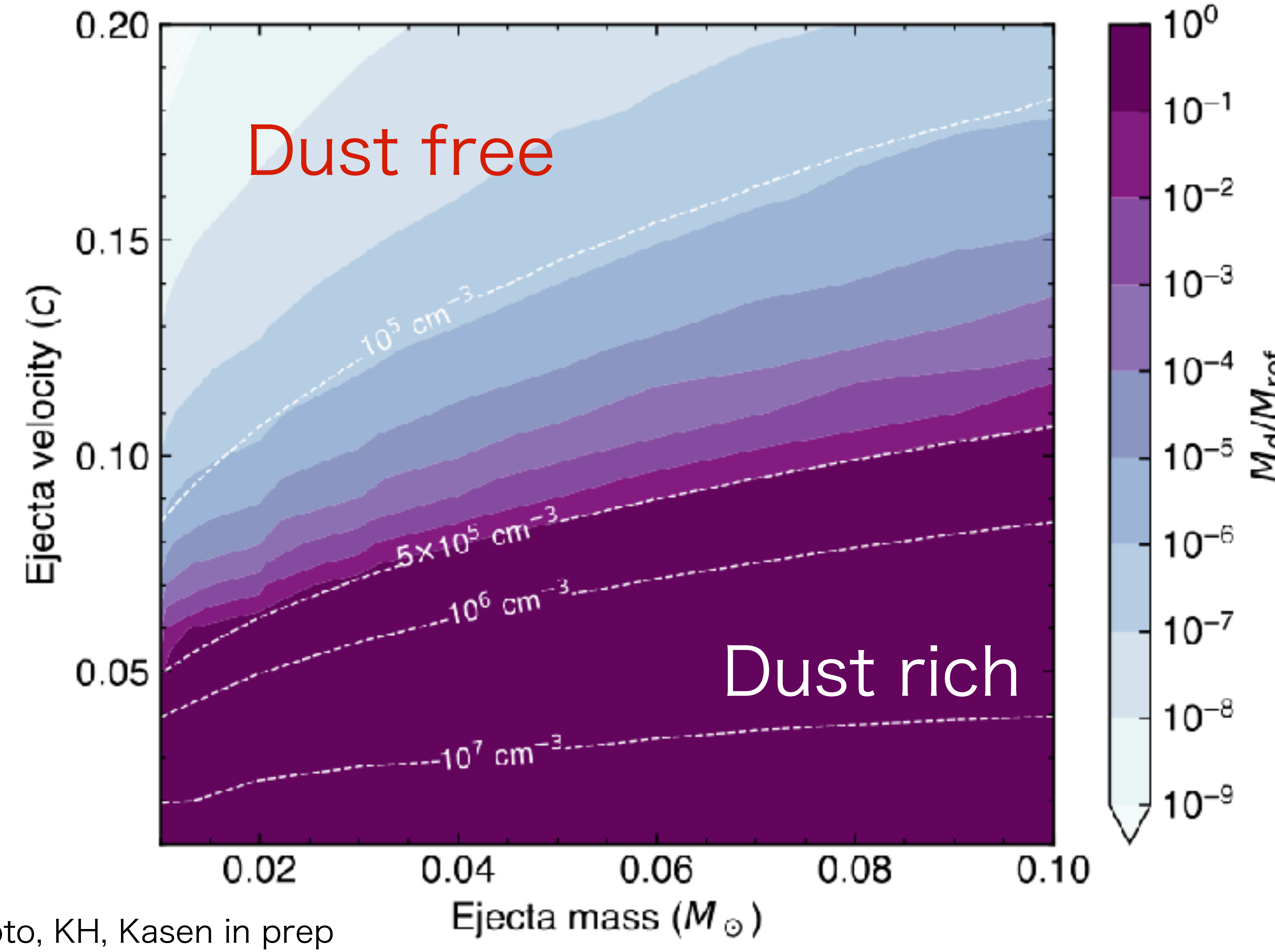


Zr, W, Os, Pt condense into grains at ~10 days.

They can produce the infrared continuum at later times.

Reaction rates of W are from Matsuka+19

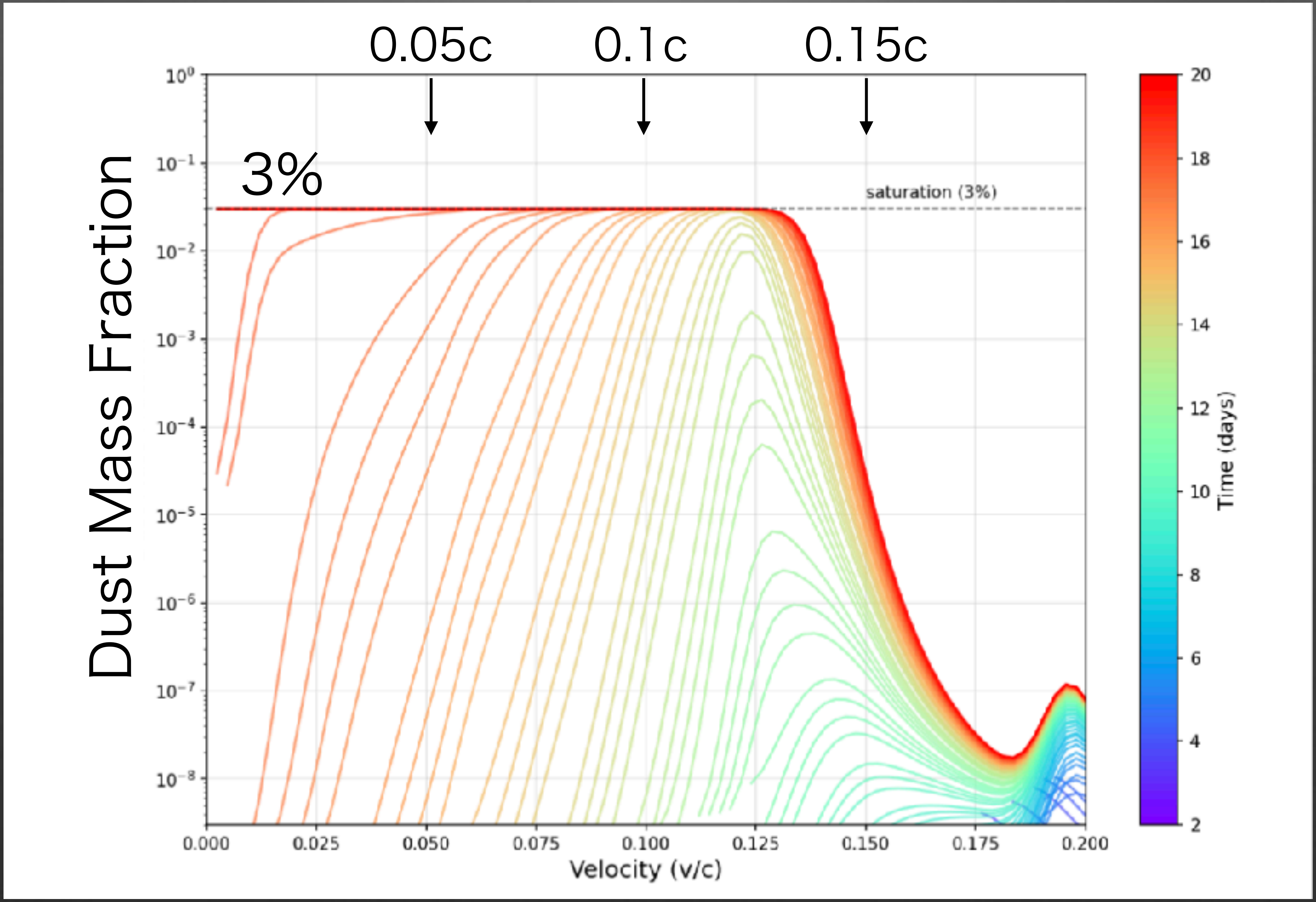
When grains may form?



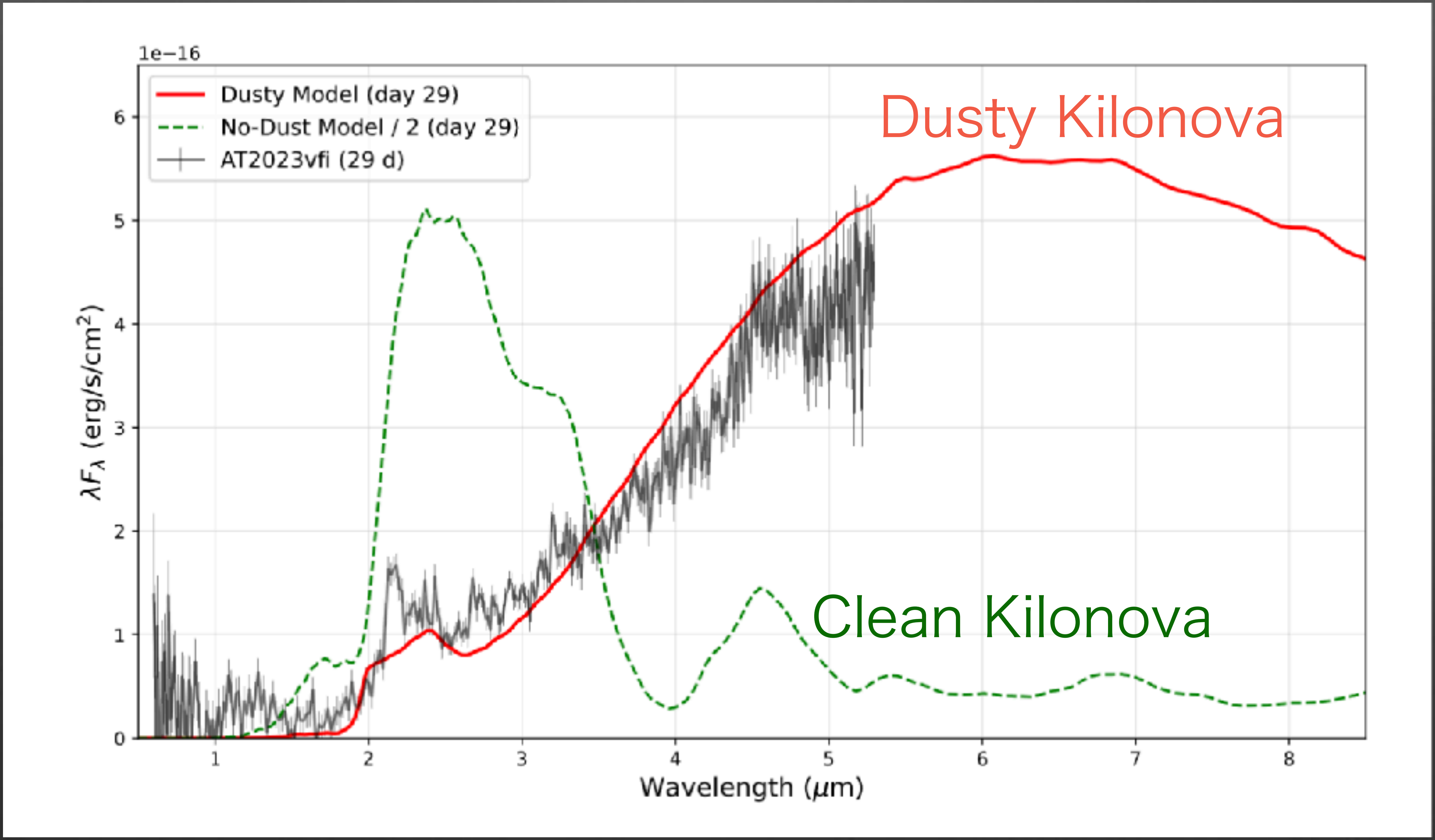
Domoto, KH, Kasen in prep

Very sensitive to velocity, i.e., density at T_{con}.

Dusty Kilonova Transfer

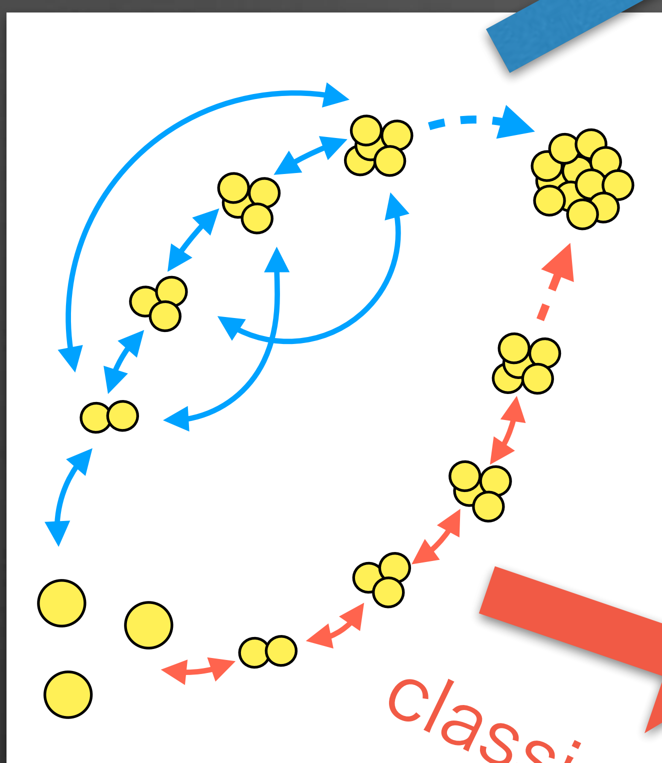


Dusty Kilonova

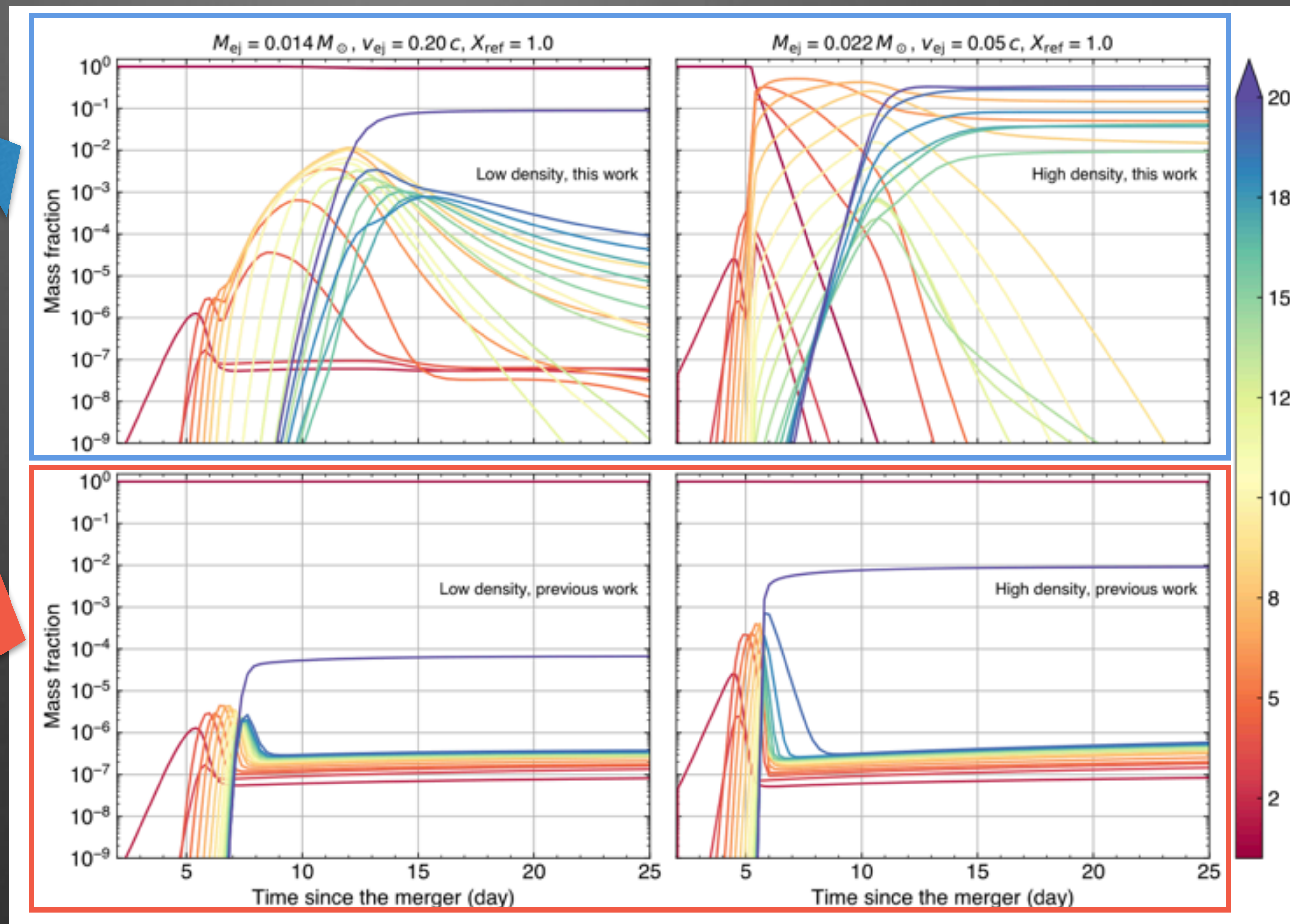


Classical and Non-Classical

Non-classical

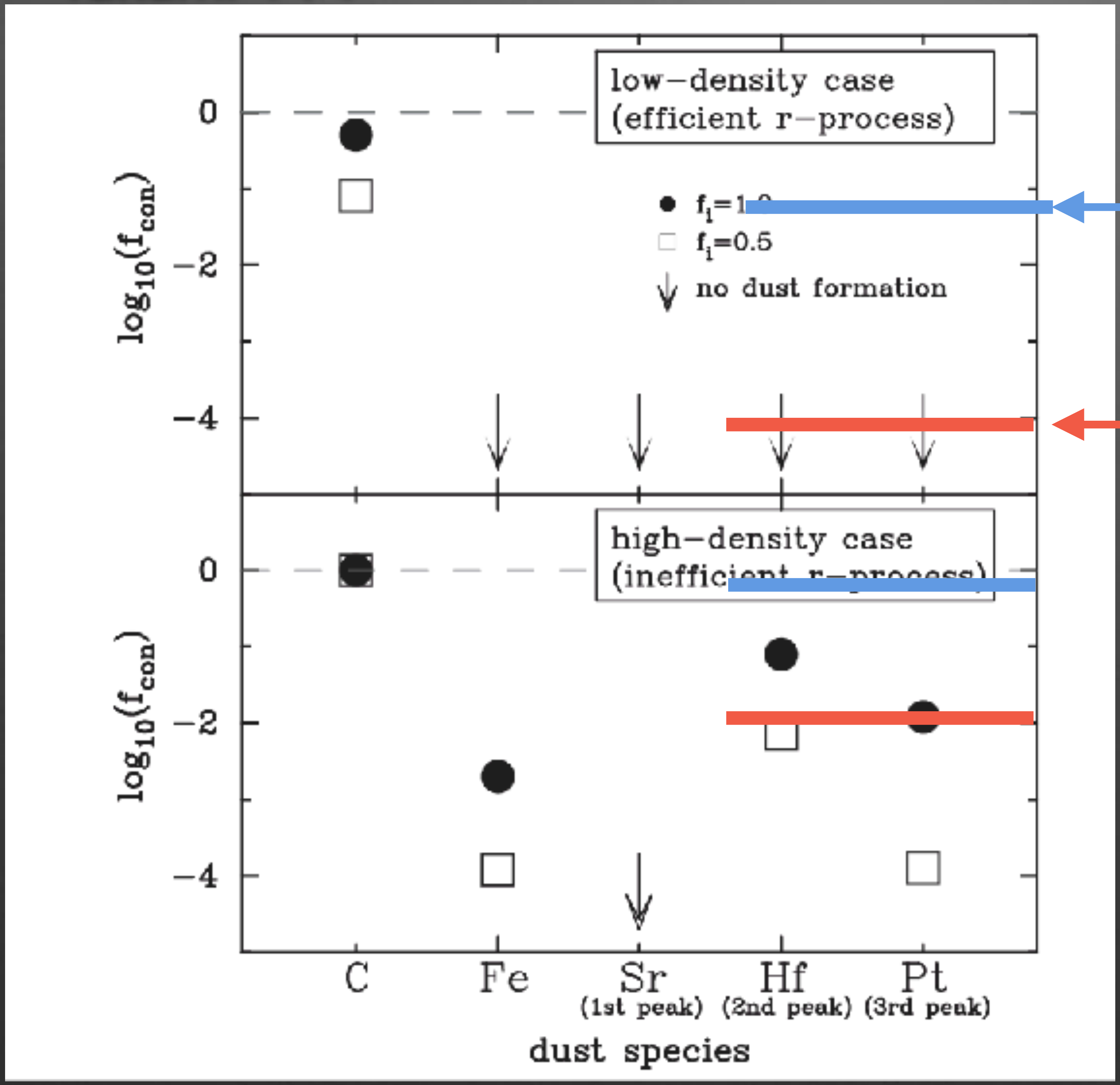


classical



Comparison with Classical Nucleation Theory

Takami +14



All possible routes included

Monomer-only

Our results are consistent with the CNT results if we turn off fission.

Summary

- $t \sim 30$ day, we see $L_\beta \sim 4\pi\sigma R^2 T_c^4$ with $T_c \sim 500$K.
- If dust, $\tau_{dust} \sim 1 \Rightarrow M_{dust} \sim 10^{-3} M_{sun}$
- The mass in refractory elements with the solar r-process is $M_{ref} \sim 10^{-3} M_{sun}$ in $M_r \sim 0.05 M_{sun}$
- Atomic collision time ~ 10 x dynamical time at T ~ 1500K, where refractory elements condense.
- Solving rate equations, we get $M_{dust} \sim 10^{-3} M_{sun}$
- If dust, we should be able to see transition from emission-line-dominated to dust-dominated KN in 10 - 30 days.
- KNe with low ejecta mass should be dust free.