Numerical Challenges for Galaxy Formation Simulations

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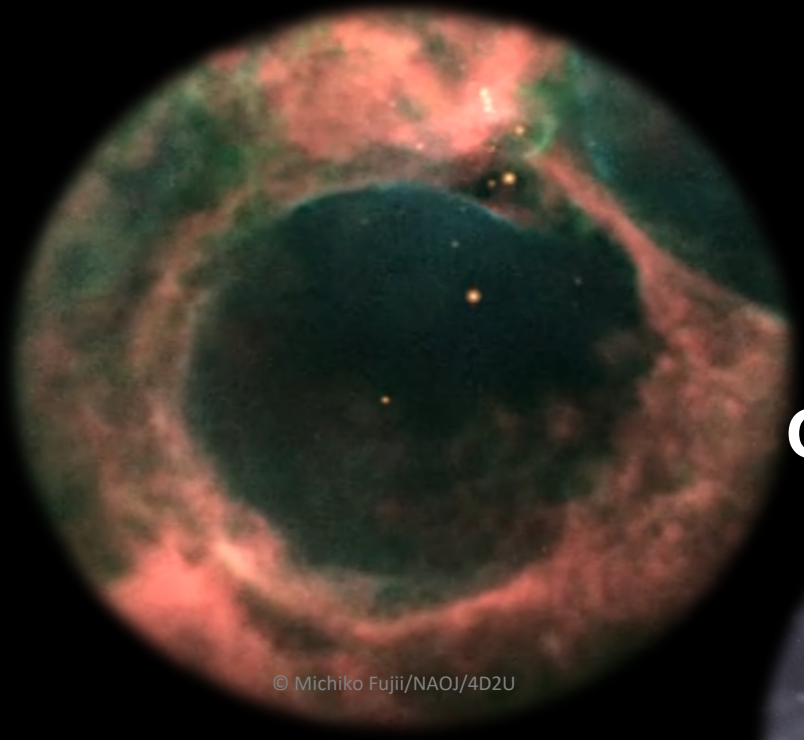
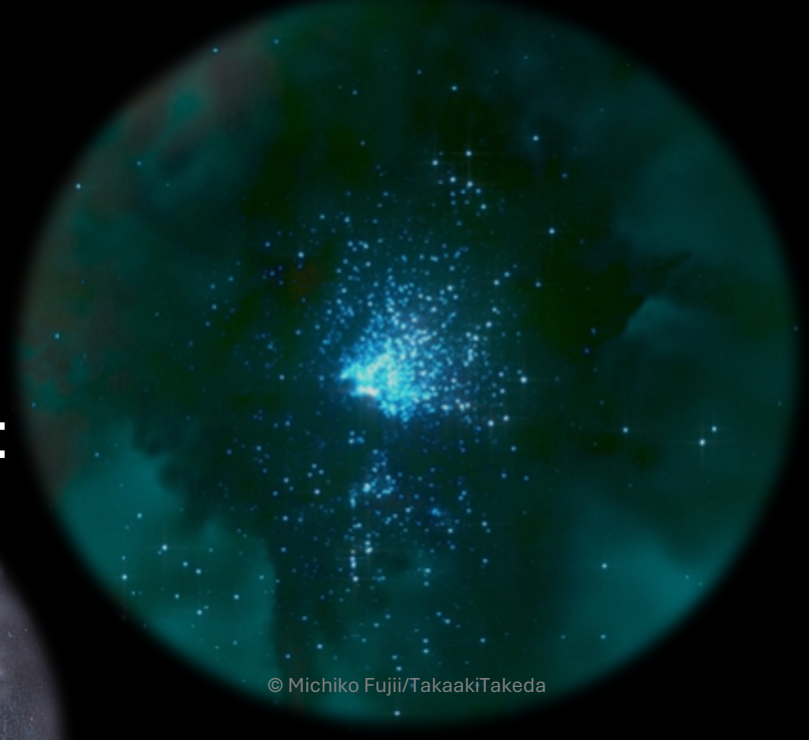
Numerical Challenges for Galaxy Formation Simulations

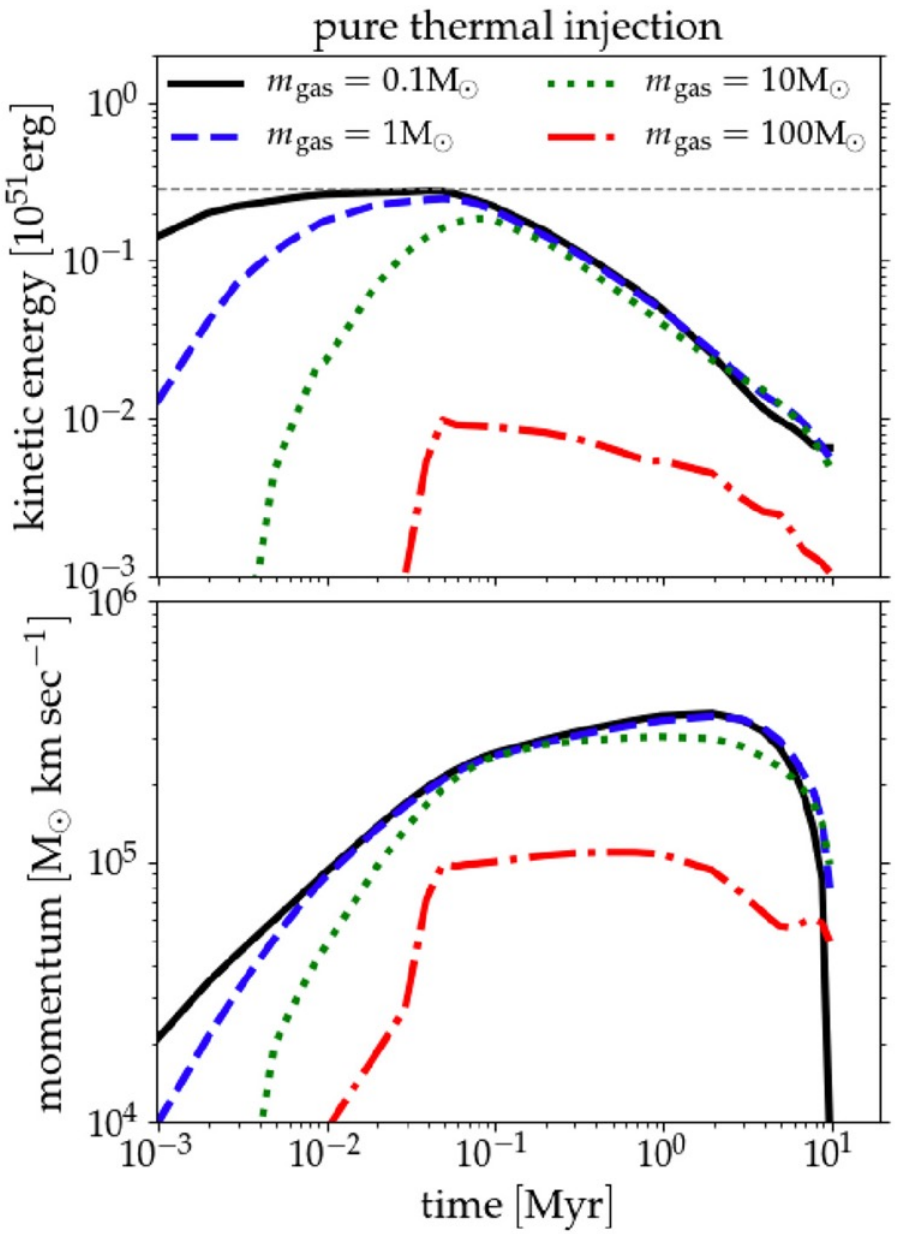
Feedback



Small-scale structures



Chemical enrichment

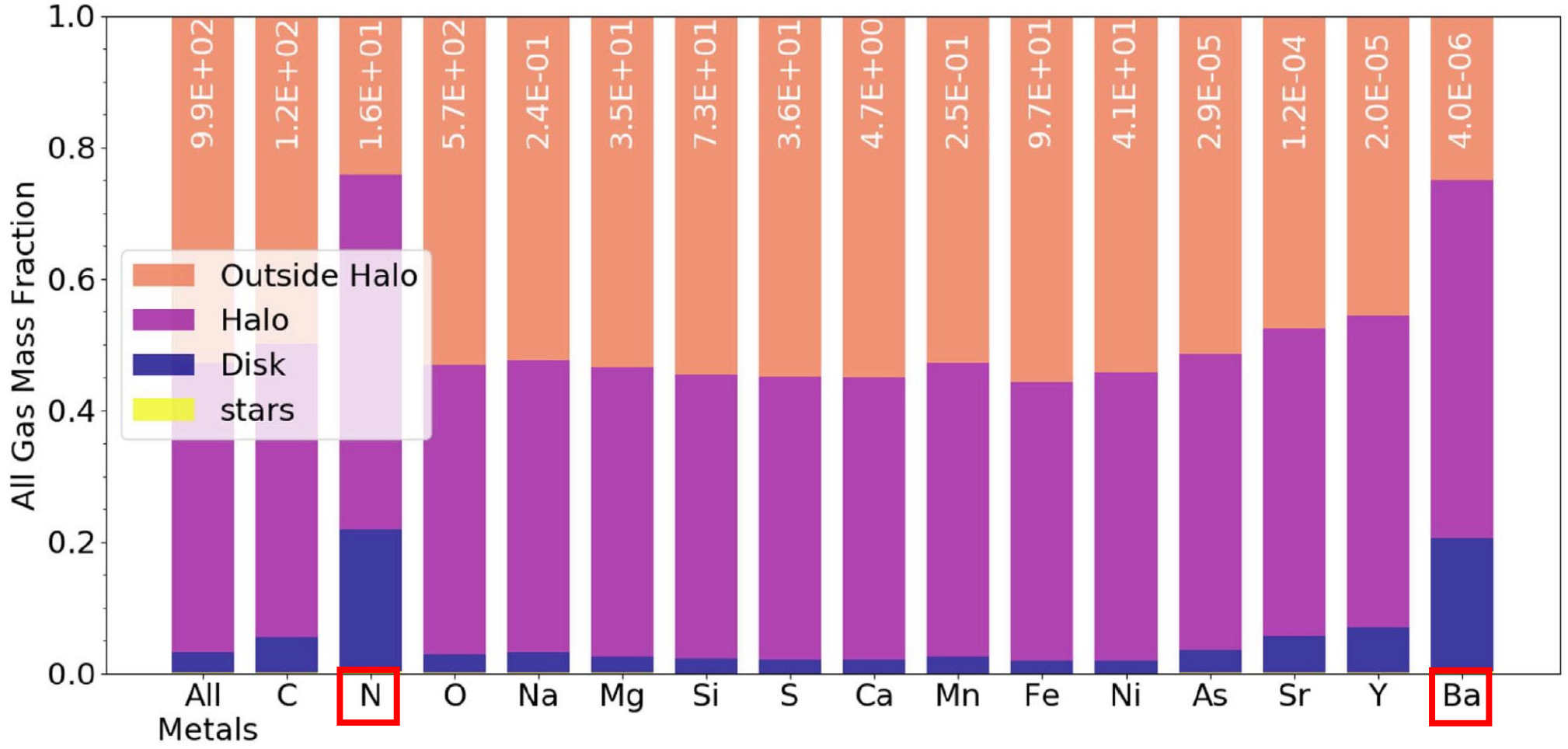


High-resolution simulations ($m_{gas} < 5\ M_{sun}$) are necessary to capture the galactic wind properties.

Hu (2019), MNRAS, 483, 3363

See Hu's talk

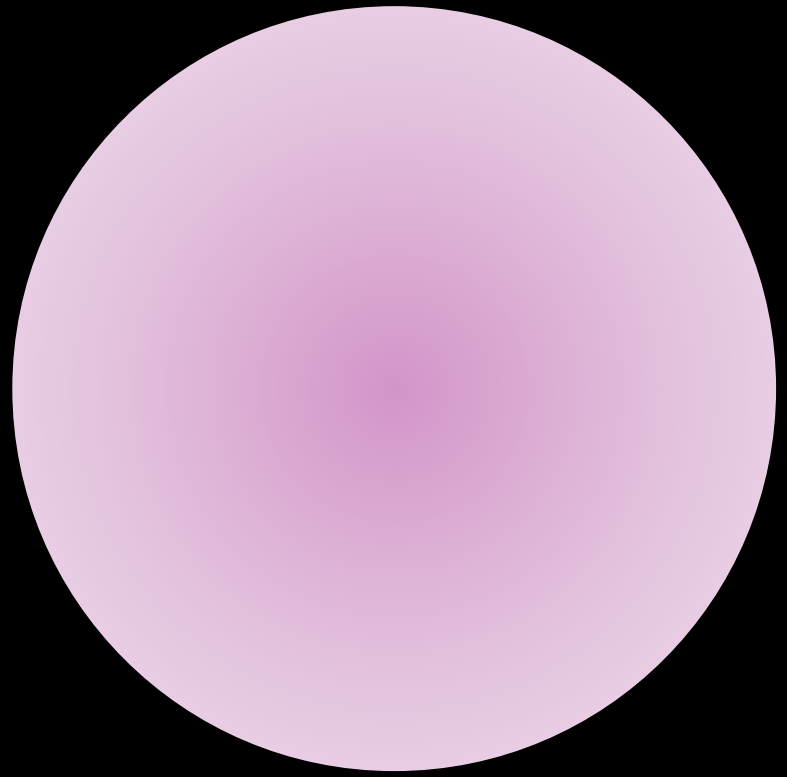
Elements ejected by AGB winds are retained in the halo.



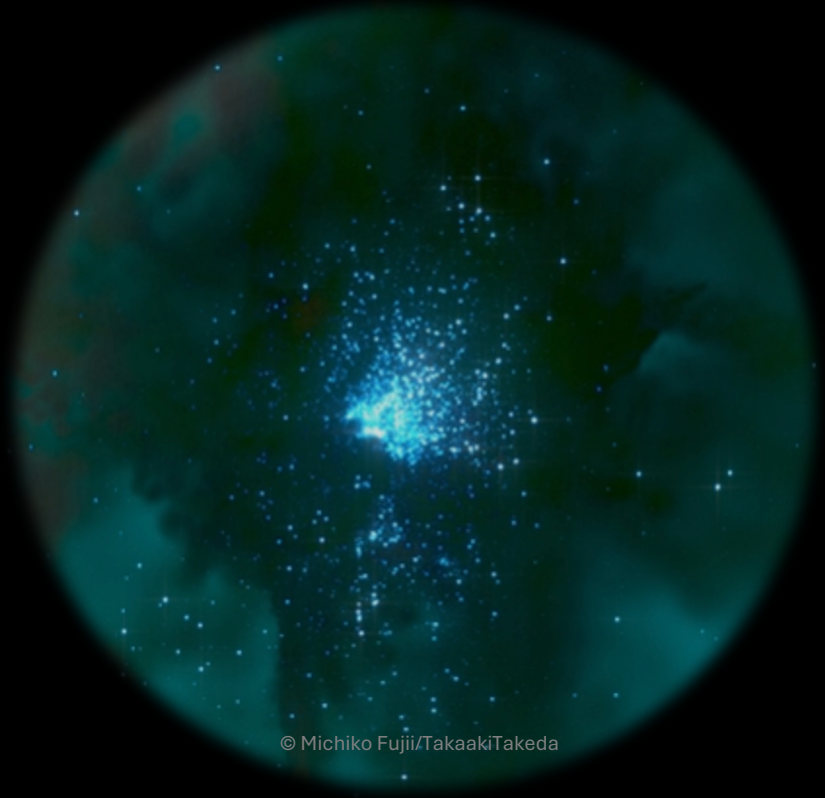
Emerick et al. (2018), ApJ, 869, 94

Star-by-star simulations

Simple stellar population



Individual stars



Star-by-star simulation projects

Feedback

LYRA (Gutcke et al. 2021)

REGEL (Deng et al. 2024)

See Li’s talk

Small-scale structures

GRIFFIN (Lahén et al. 2020)

SIEGE (Calura et al. 2022)

EDGE-INFERNO

(Andersson et al. 2025)

SIRIUS (Hirai et al. 2021)

Aeos (Brauer et al. 2025)

Chemical enrichment

Michiko Fujii (Tokyo) | Takayuki Saitoh (Kobe) | Yutaka Hirai (Koeki)

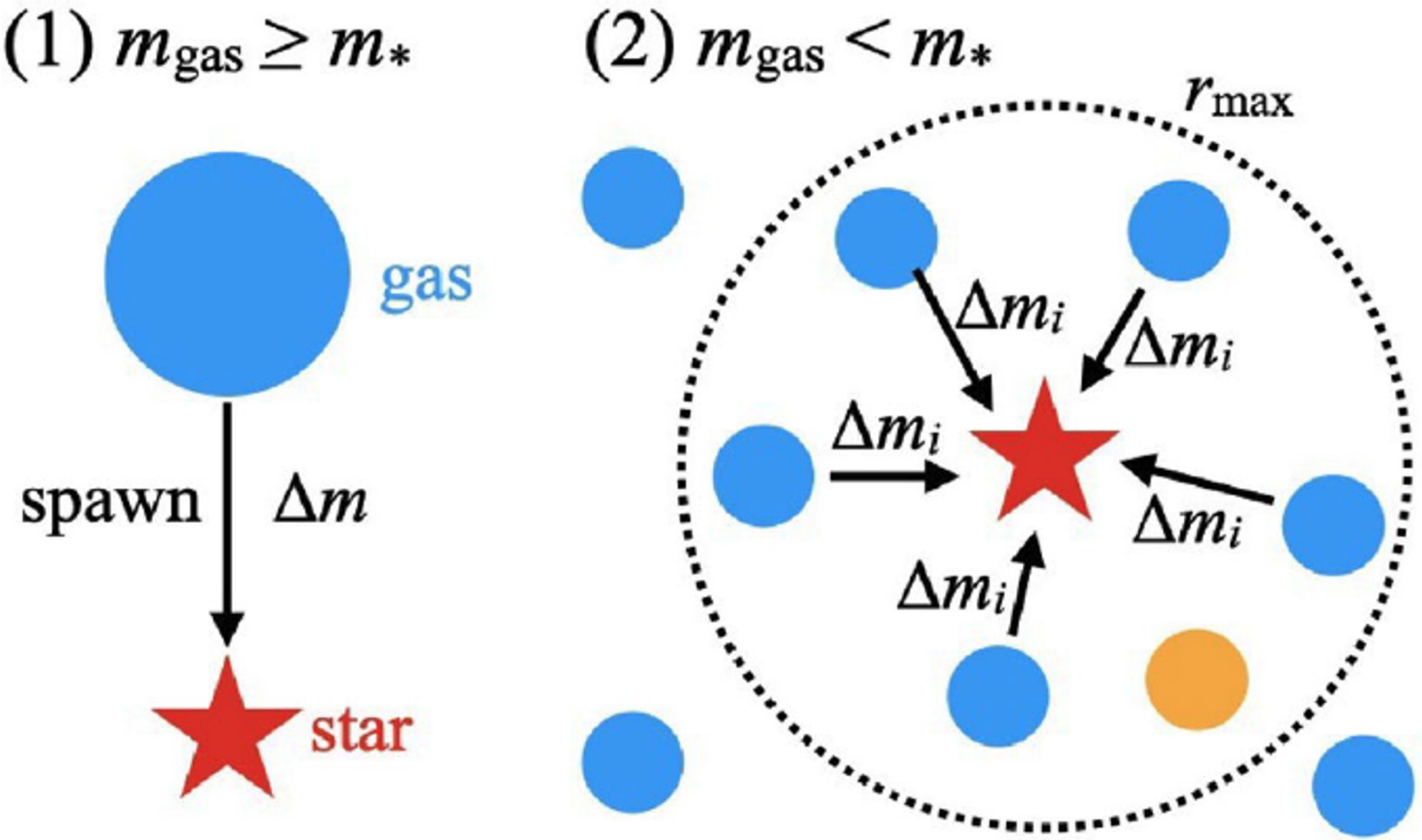
Simulations Resolving Individual Stars (SIRIUS) Project

Website:https://sites.google.com/g.ecc.u-tokyo.ac.jp/sirius-project/

Image Credit: Michiko Fujii/TakaakiTakeda

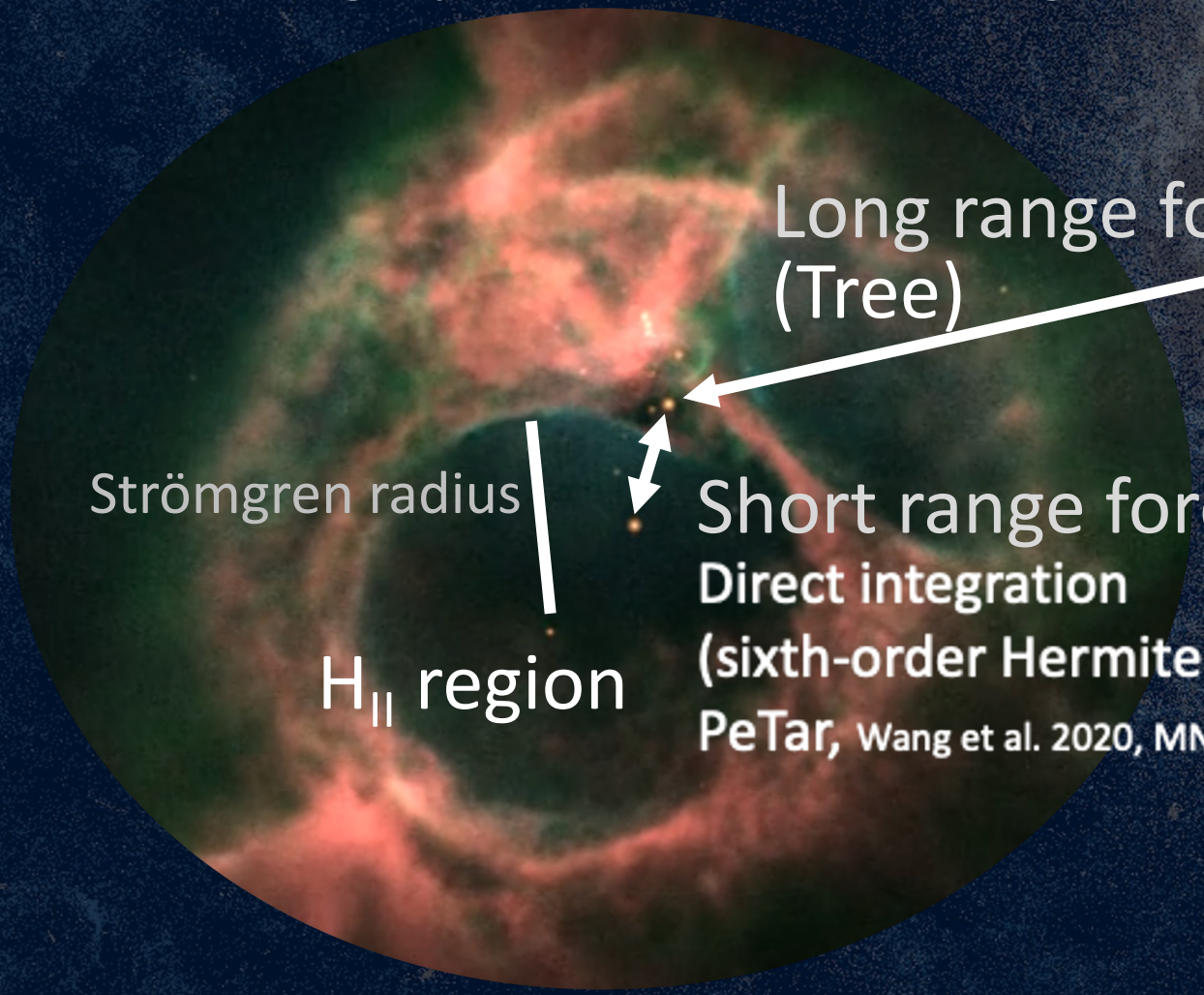
Star formation models in SIRIUS

Hirai et al. (2021), PASJ, 73, 1036



ASURA+BRIDGE code

Enables high-precision orbital integration for stars



Fujii, Saitoh, Wang, Hirai (2021), PASJ, 73, 1057
Fujii, Saitoh, Hirai, Wang (2021), PASJ, 84, 1074

ASURA-BRIDGE Code

https://zenodo.org/records/11180637

Gravity: Tree (Banes & Hut 86)
+6th order Hermite
(Fujii+07; Fujii, YH+21a)

Hydrodynamics: Density independent smoothed particle hydrodynamics
(Saitoh & Makino 13)

Gas cooling (Ferland+13)

Star formation (YH+21)

Stellar feedback (Saitoh 17)

- H_{II} region (Fujii, YH+21b)
- Core-collapse supernovae (Nomoto+13)
- Type Ia supernovae (Seitenzahl+13)
- AGB stars (Cristallo+11; Karakas10)

Metal diffusion (YH & Saitoh 17)

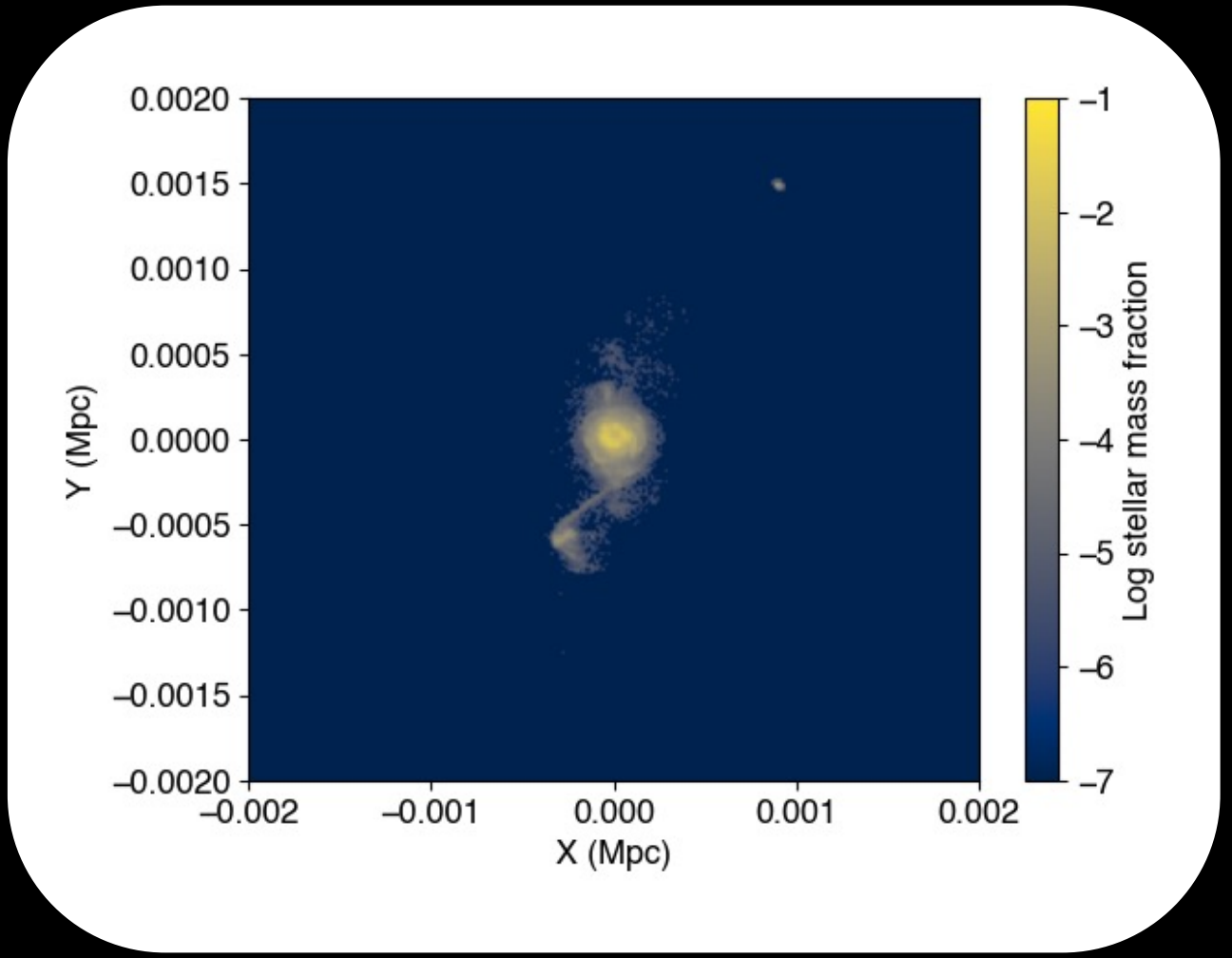
Image credit: Michiko Fujii, Takaaki Takeda

Cosmological zoom-in simulations in SIRIUS

Cosmological parameters:
Plank Collaboration (2020)

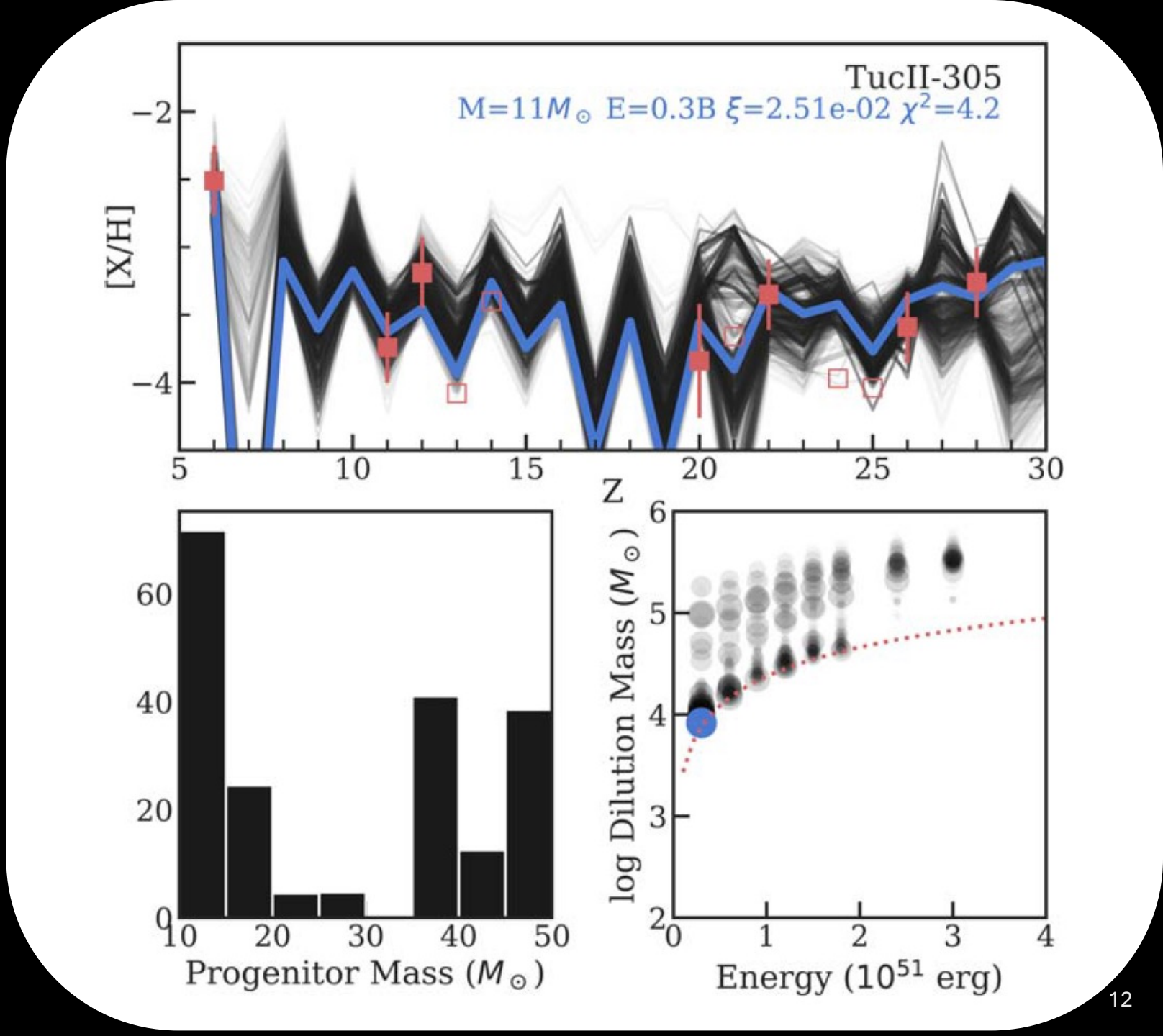
Gas particle mass:
18.9 M_{sun}

Gravitational softening length: **9.2 pc**



Hirai et al. (2025), ApJL, 980, L25

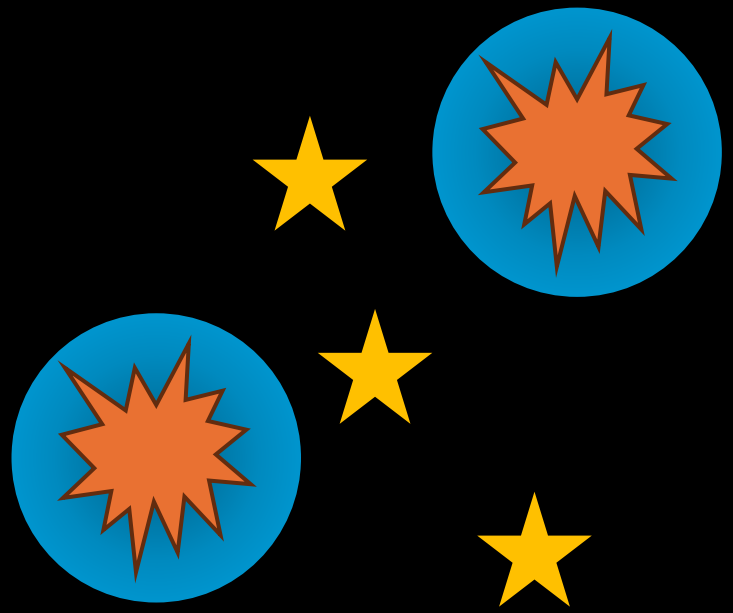
Abundance pattern indicates supernova yields



Chiti et al. (2023), AJ, 165, 55

Mono-enriched

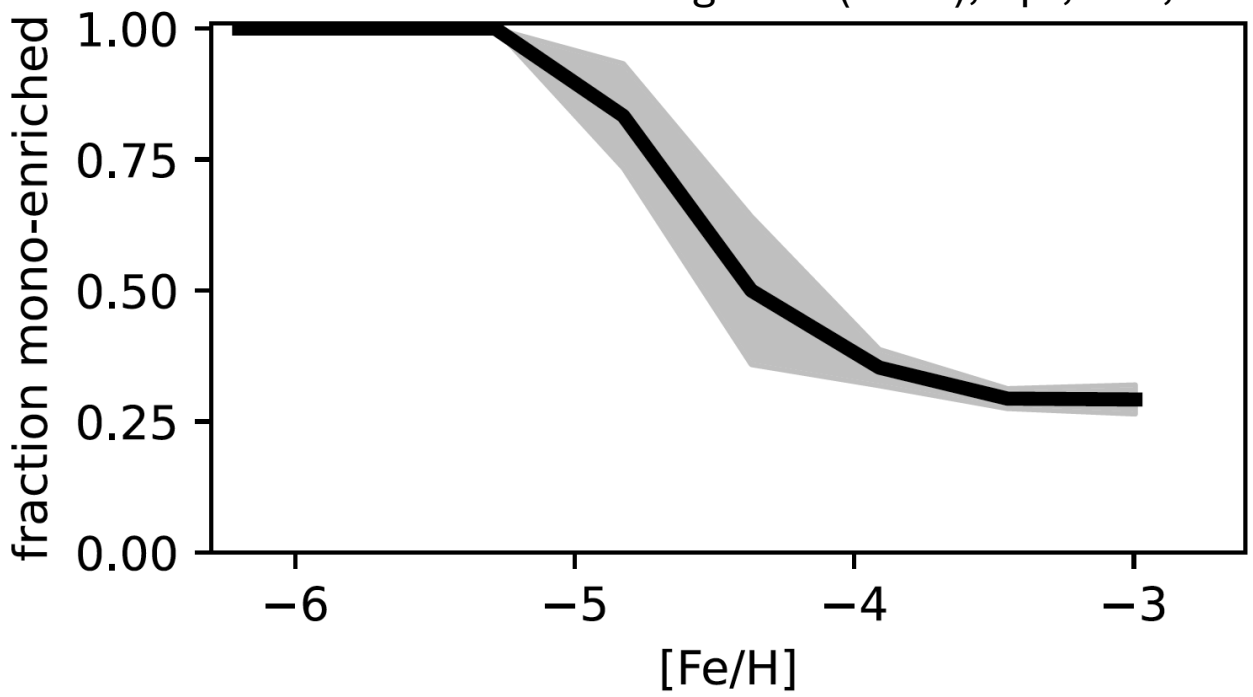
Multi-enriched

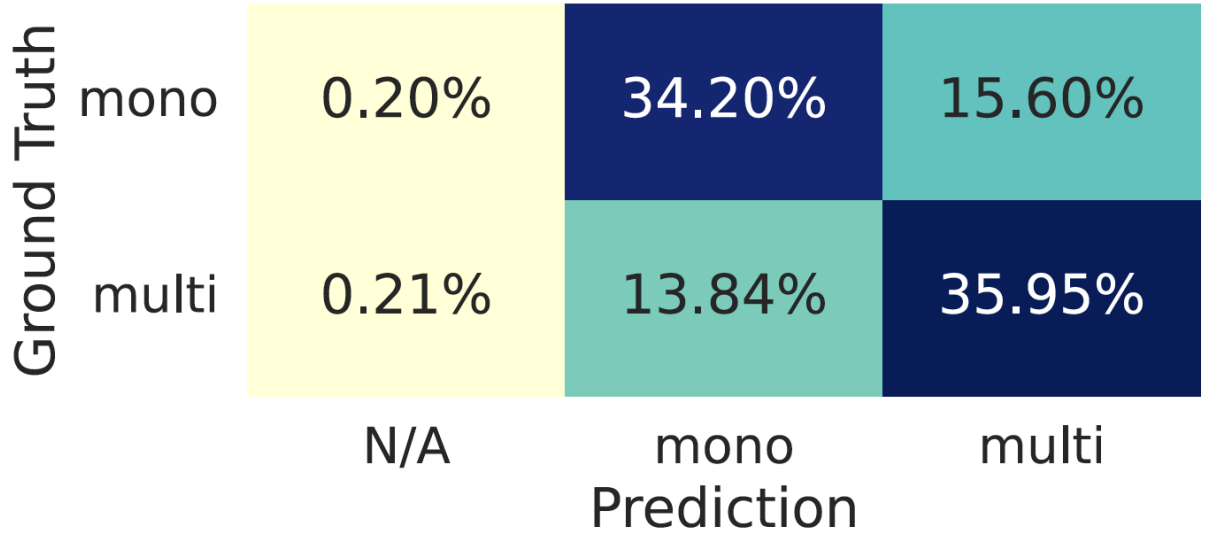


Machine learning predicts mono-enriched fraction

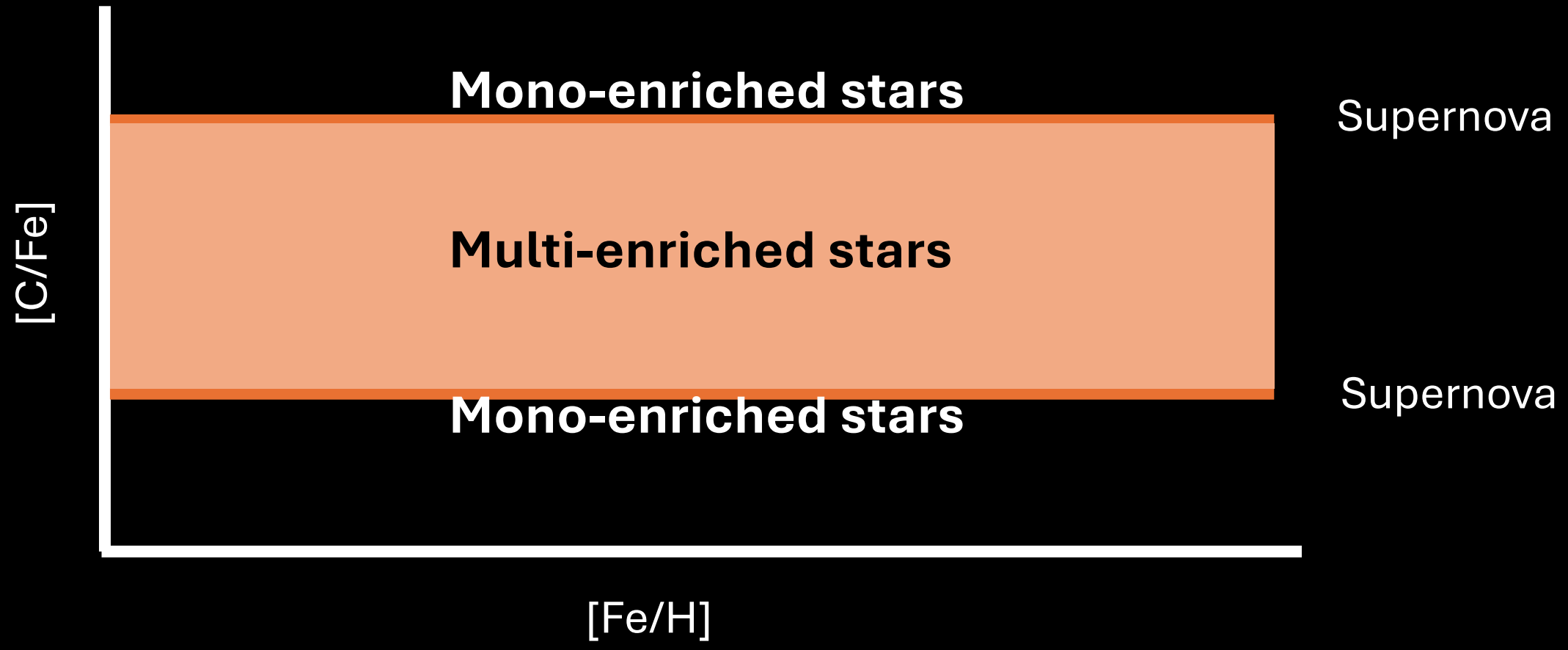
Simulations are necessary to derive the mono-enriched fraction

Hartwig et al. (2023), ApJ, 946, 20

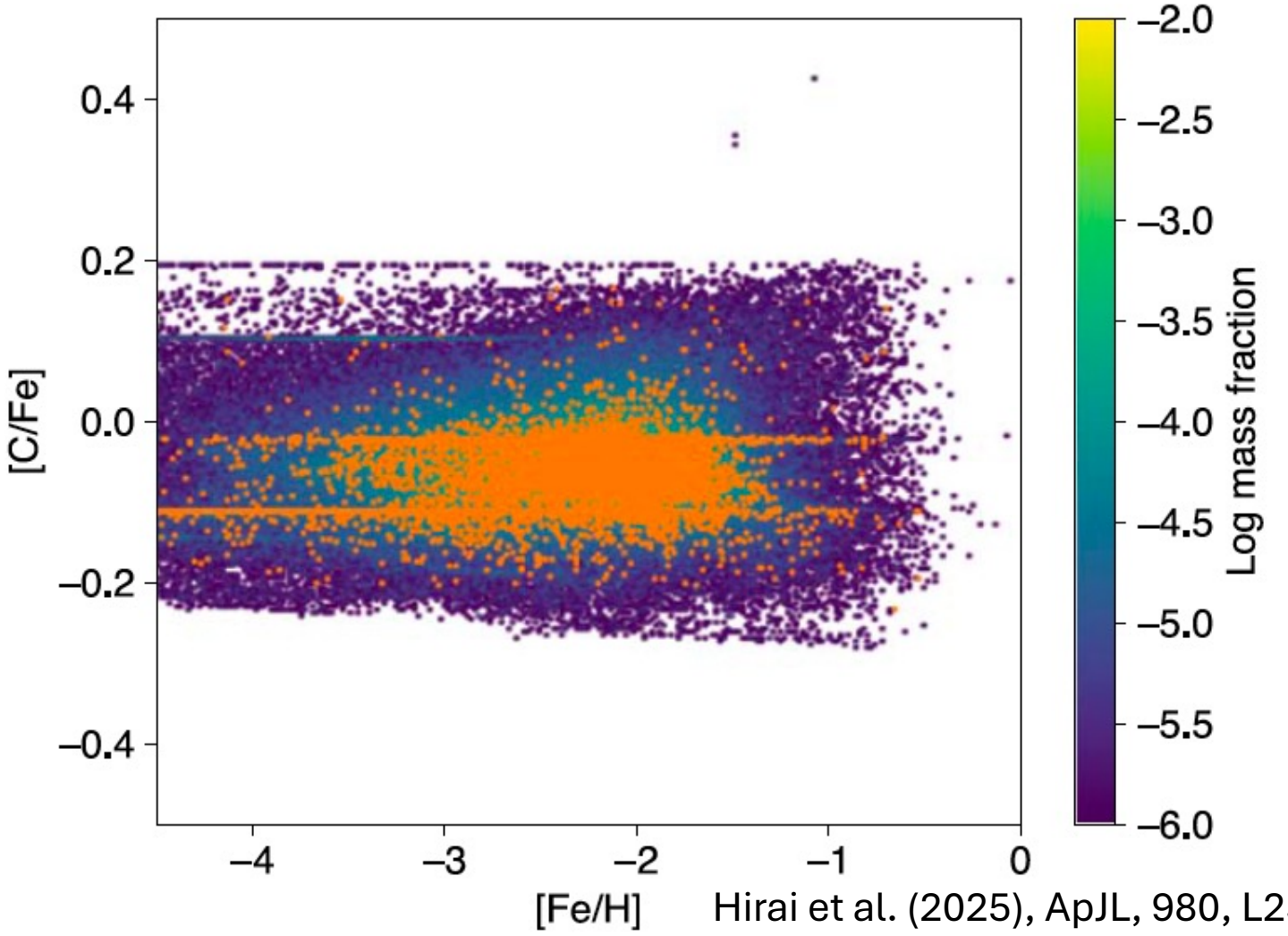




Simulated [C/Fe] vs. [Fe/H] can be used as an indicator to identify mono-enriched stars

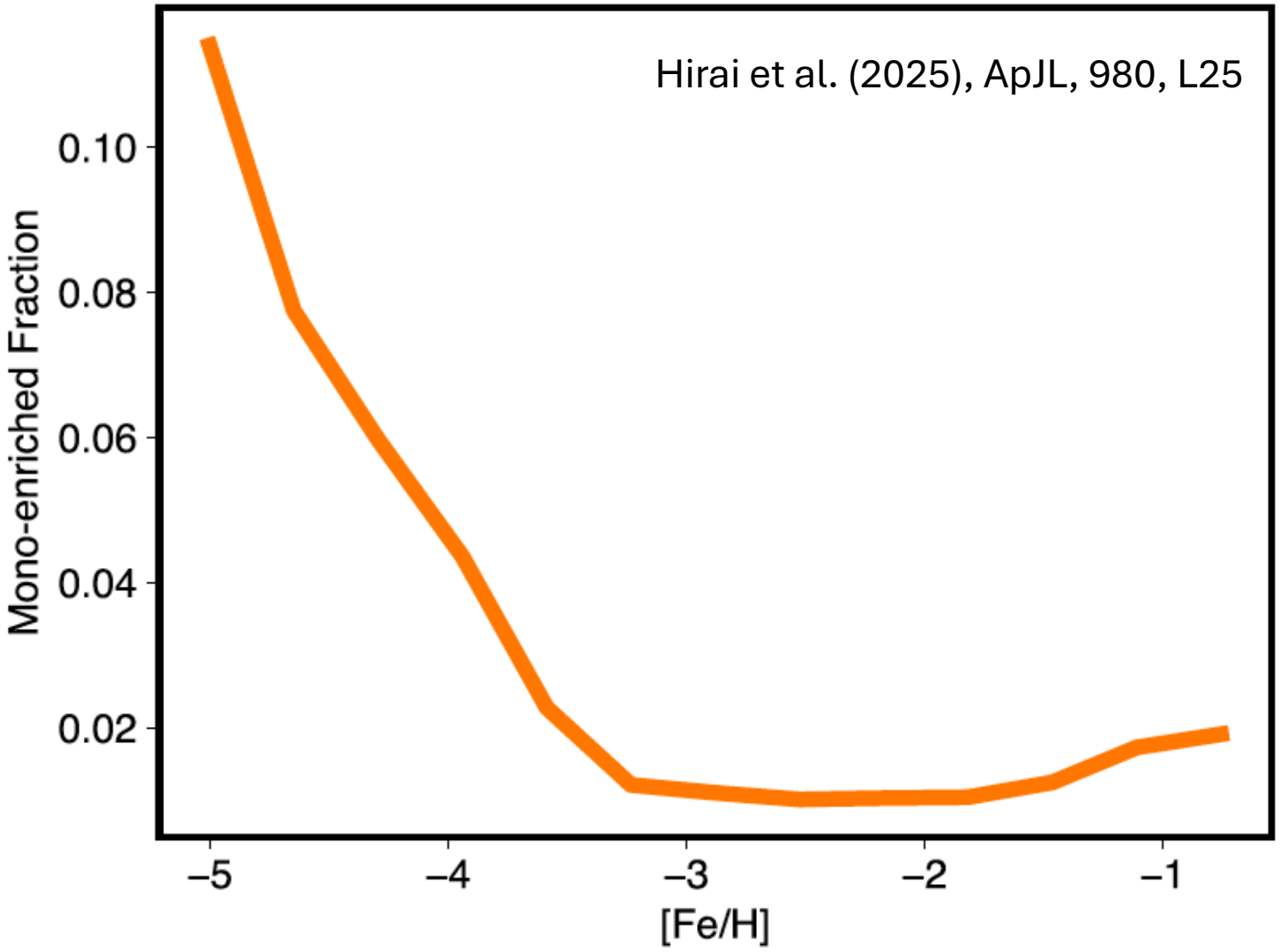


Mono-enriched star identified in simulated [C/Fe] vs. [Fe/H]



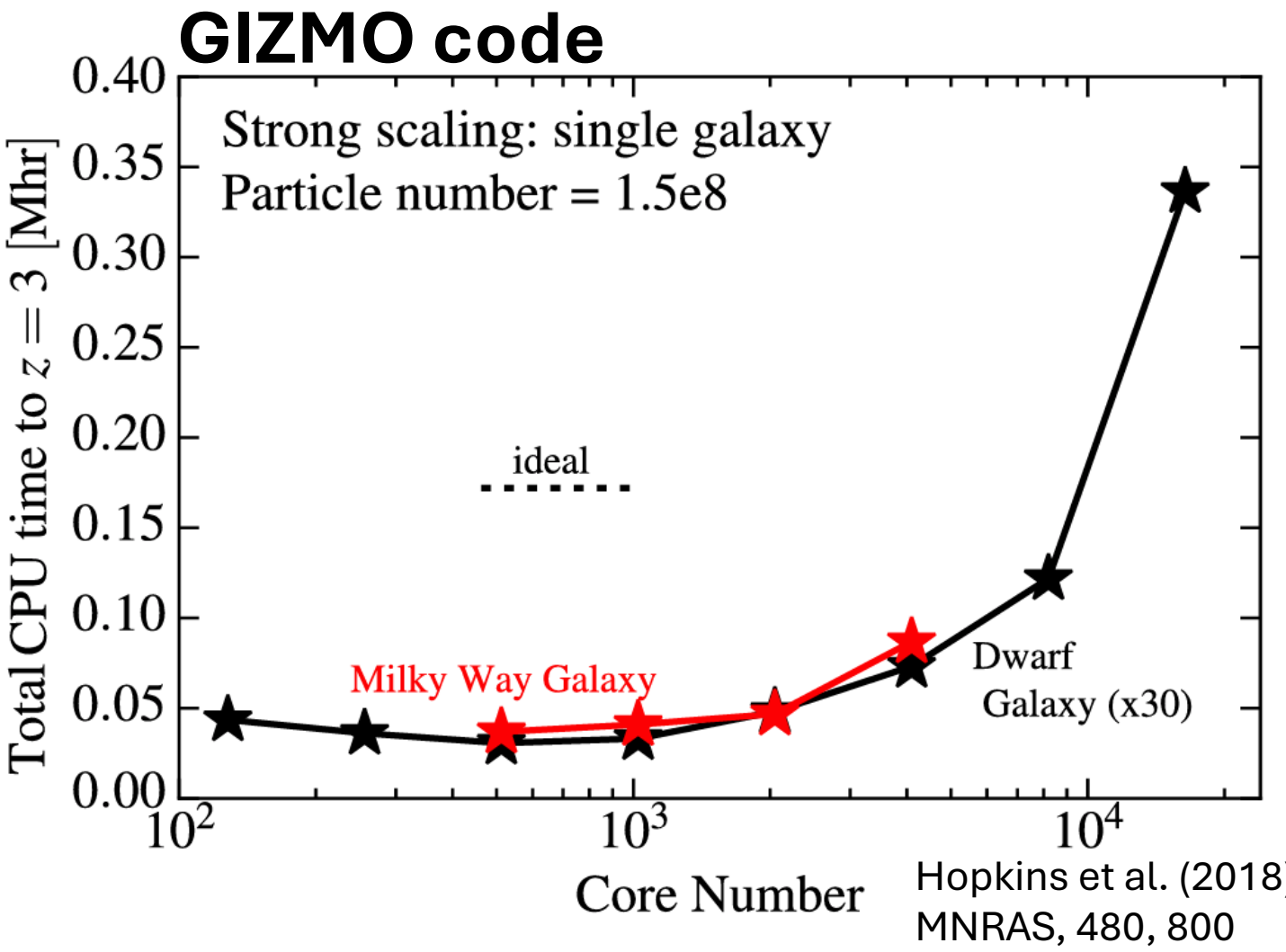
Hirai et al. (2025), ApJL, 980, L25

5% of stars with [Fe/H] < −3 in a simulated dwarf galaxy are mono-enriched



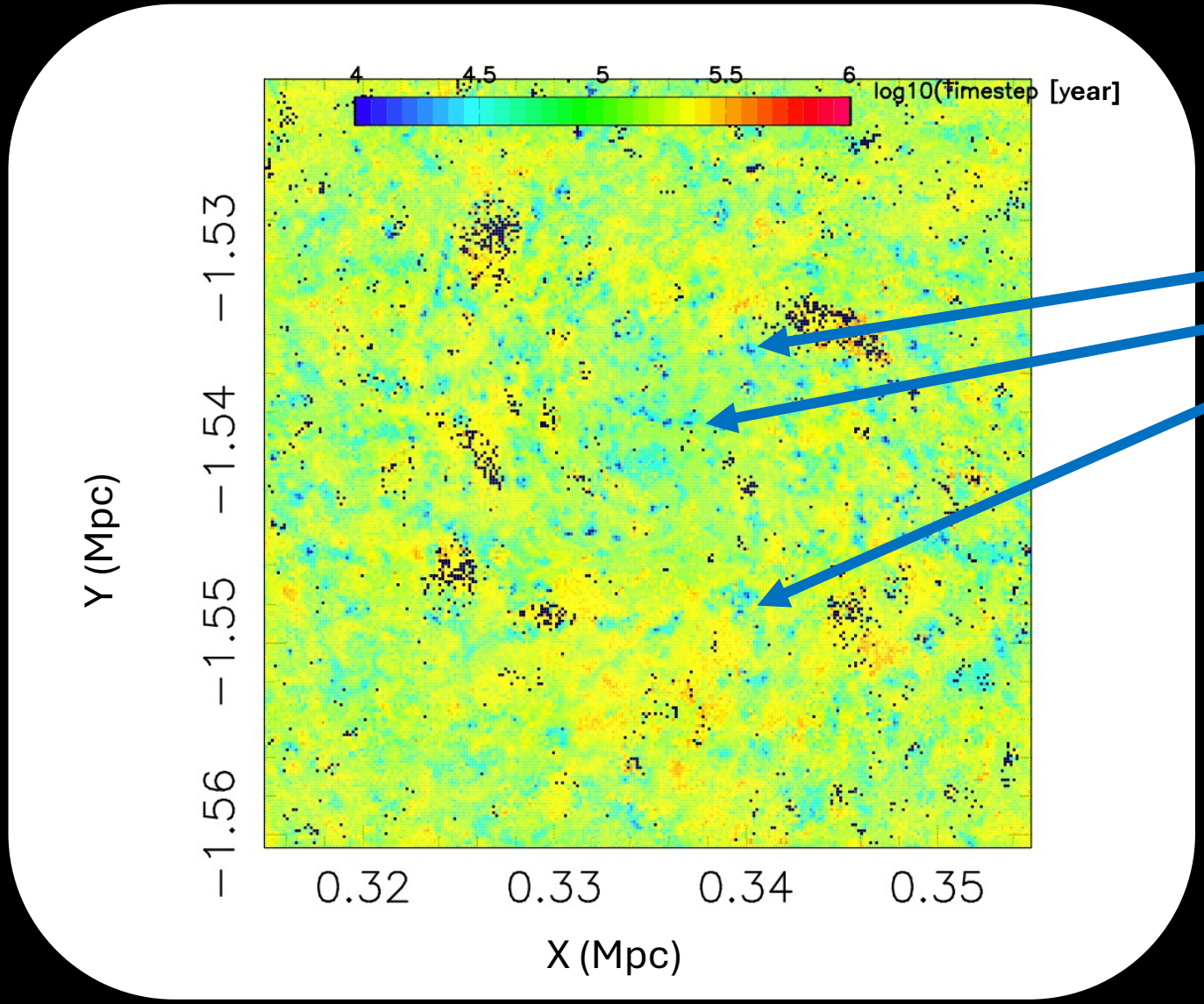
Star-by-star simulations for larger galaxies

Difficulty in scalability



Hopkins et al. (2018), MNRAS, 480, 800

Timestep distribution in a galaxy formation simulation



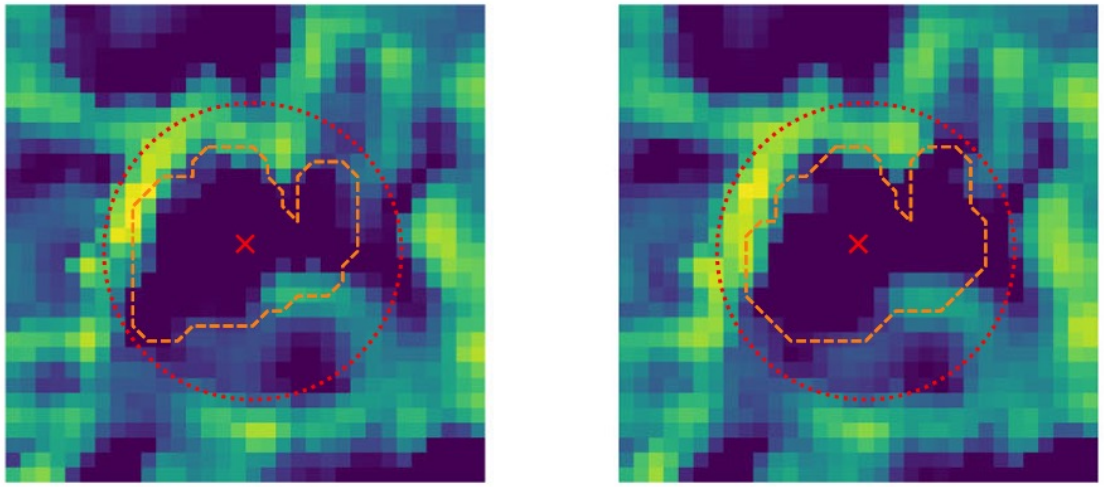
Regions around supernovae are integrated with short timesteps.

Simulation data taken from Hirai et al. (2022), MNRAS, 517, 4856

Introducing deep learning to accelerate the computation

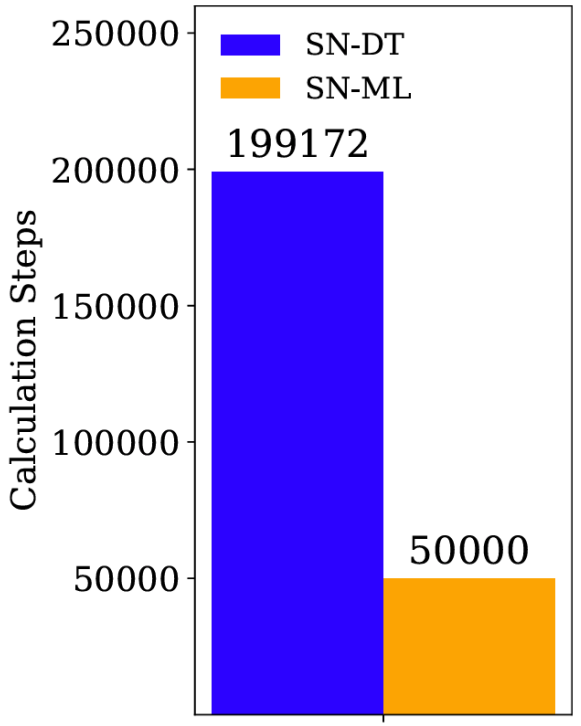
Keiya Hirashima
(RIKEN)

Supernova remnants



(b) SPH Sim. (t=0.1 Myr) (c) 3D-MIM (t=0.1 Myr)

Hirashima (incl. YH) et al. (2023), MNRAS, 526, 4054



Hirashima (incl. YH) et al. (2025), ApJ, 987, 86

Conclusions

- **Star-by-star simulations** are necessary to understand feedback, small-scale structures, and chemical enrichment of galaxies.
- **SIRIUS project** shows 5% of stars with [Fe/H] < −3 in a simulated dwarf galaxy are mono-enriched.
- **Deep learning** can be used to accelerate the computation of galaxy simulations.

SIRIUS project webpage:https://sites.google.com/g.ecc.u-tokyo.ac.jp/sirius-project/

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