Hydrodynamical Biases in Chemical Enrichment by the First Supernovae

F.O.E.

Fifty-one Erg

2015

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Enriching the Early Universe

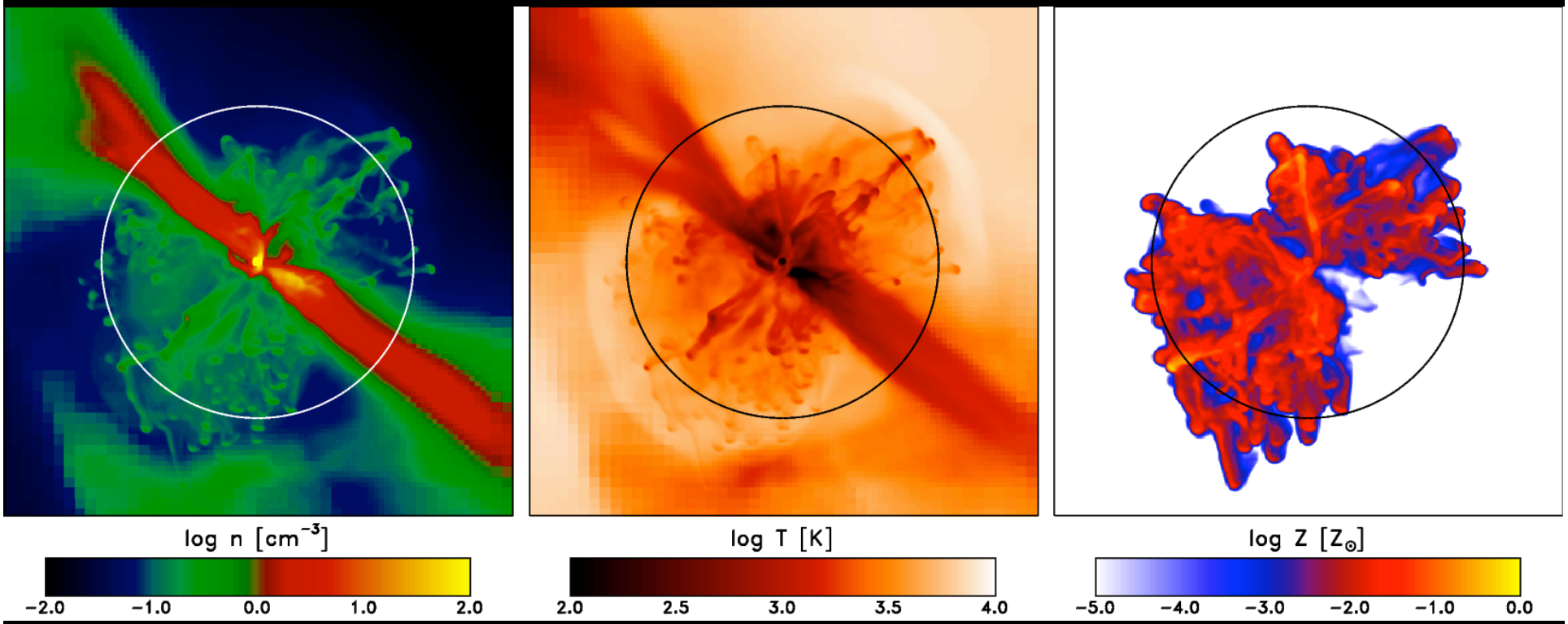
- How can the chemical abundances of ancient, metal-poor Pop II stars be linked with theorized yields of Pop III supernovae (stellar archaeology)?
- Does the hydrodynamics of ejecta dispersal and fallback homogenize the abundances?
- How long does it take before metal-enriched gas is able to cool and recollapse ("recovery time")?
- What fraction of ejecta end up in the IGM, ISM, and the next generation of stars?

Simulation Framework

- Cosmological simulations with dark matter and baryons
  - Simulate a Pop III star forming minihalo at high redshift
  - FLASH AMR hydro code embedded with N-body dark matter particle integration and multi-grid gravity solver
  - Non-equilibrium atomic and molecular chemistry leading to Pop III stars, and photoionization and cooling tables tabulated from CLOUDY after Pop III stars have been inserted
- Follow the transfer of ionizing radiation and expansion of gas due to photoheating in the aspherical H II region
- Insert supernovae in the kinetic-energy-dominated, free-expansion phase, and follow the gas and ejecta hydrodynamics for several tens of Myr

Supernova in a Minihalo

8.5 Myr after a 10^{51} erg supernova with 40 $M_\odot$ of ejecta



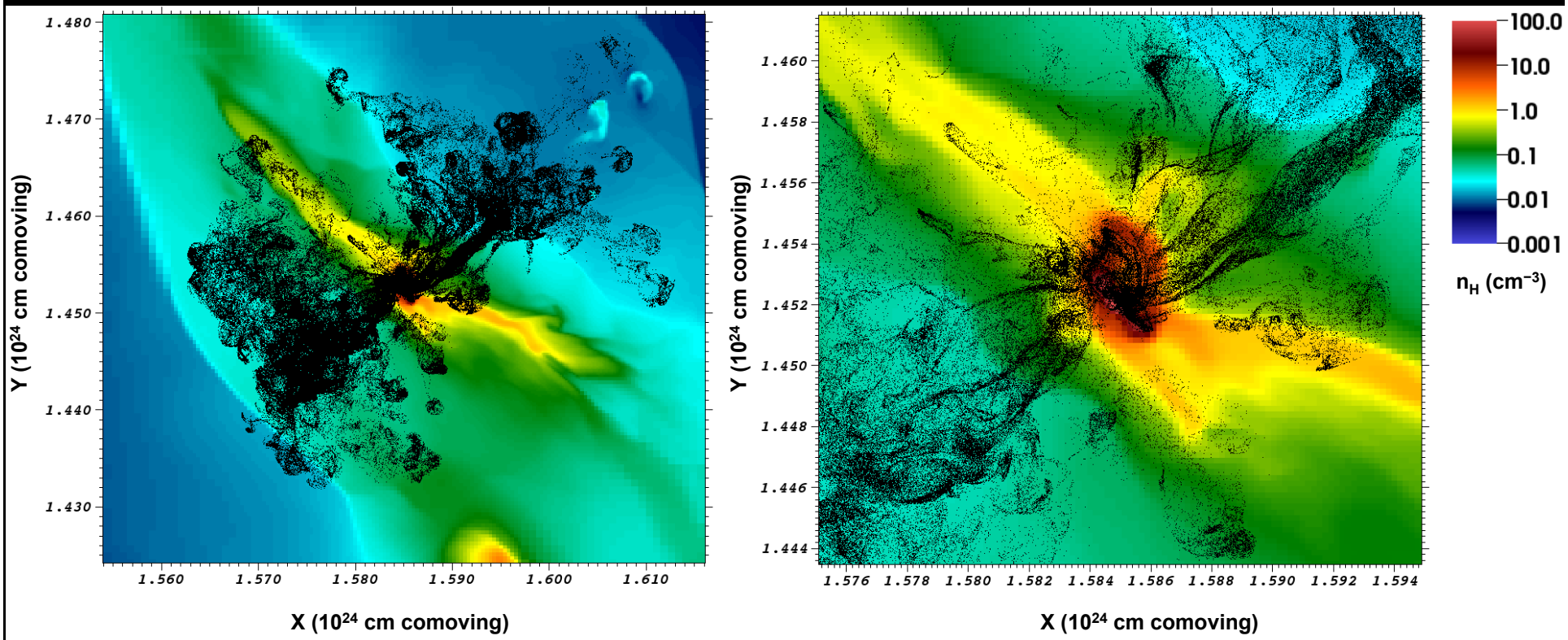
Circle encloses R_{vir} = 200 pc of a 10^6 $M_\odot$ minihalo

Ritter+ 2012

Inhomogeneous Fallback

1100 pc

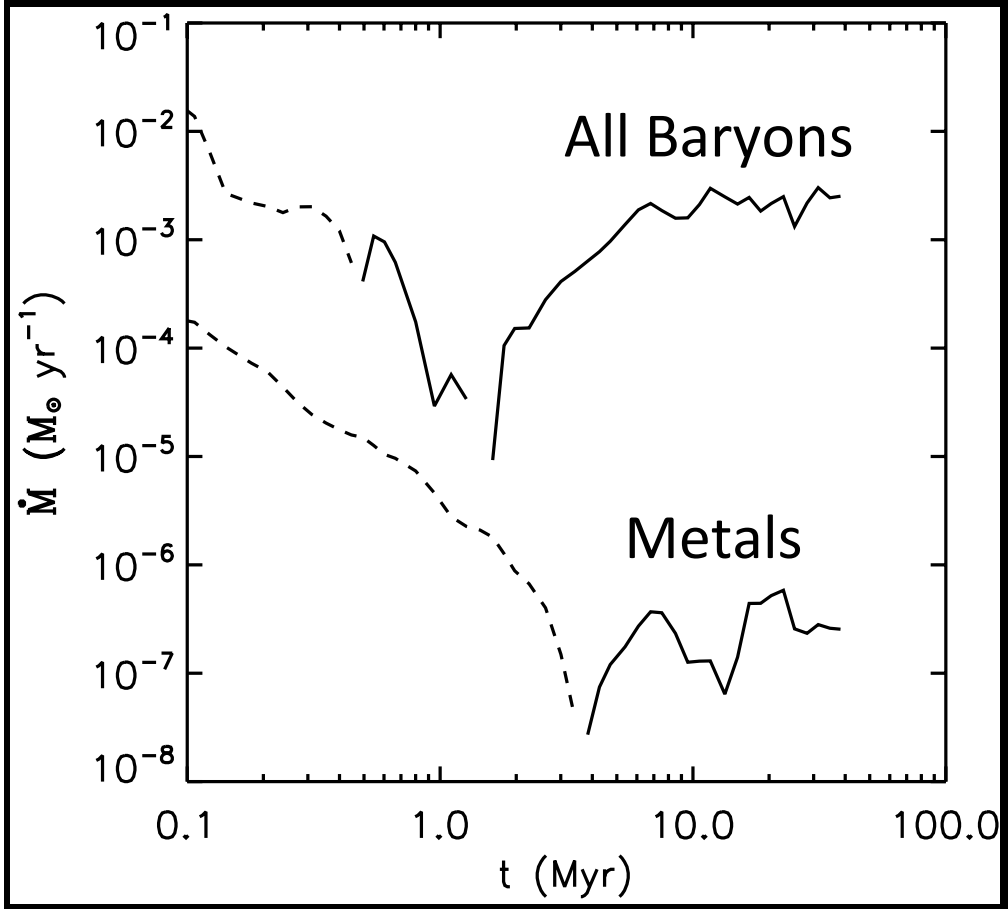
360 pc



40 Myr after SN, baryon density slice + ejecta particles in projection

Ritter+ 2012

Remnant Evolution

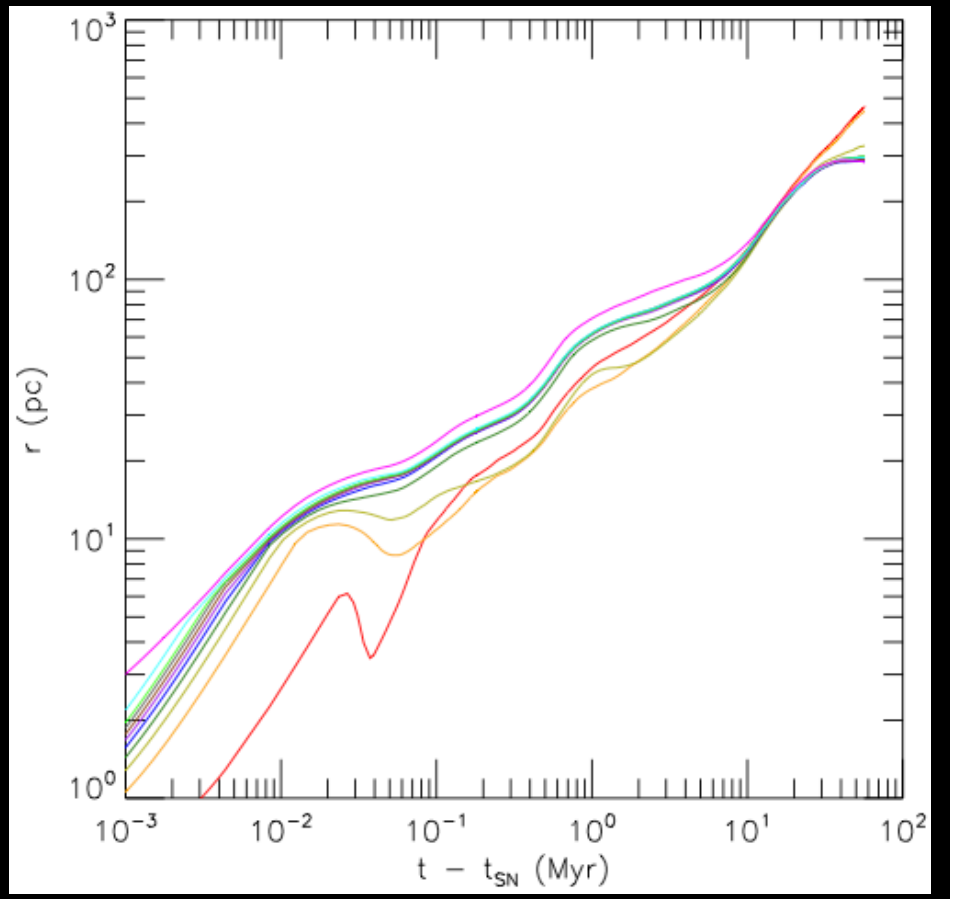


Ritter+ 2012

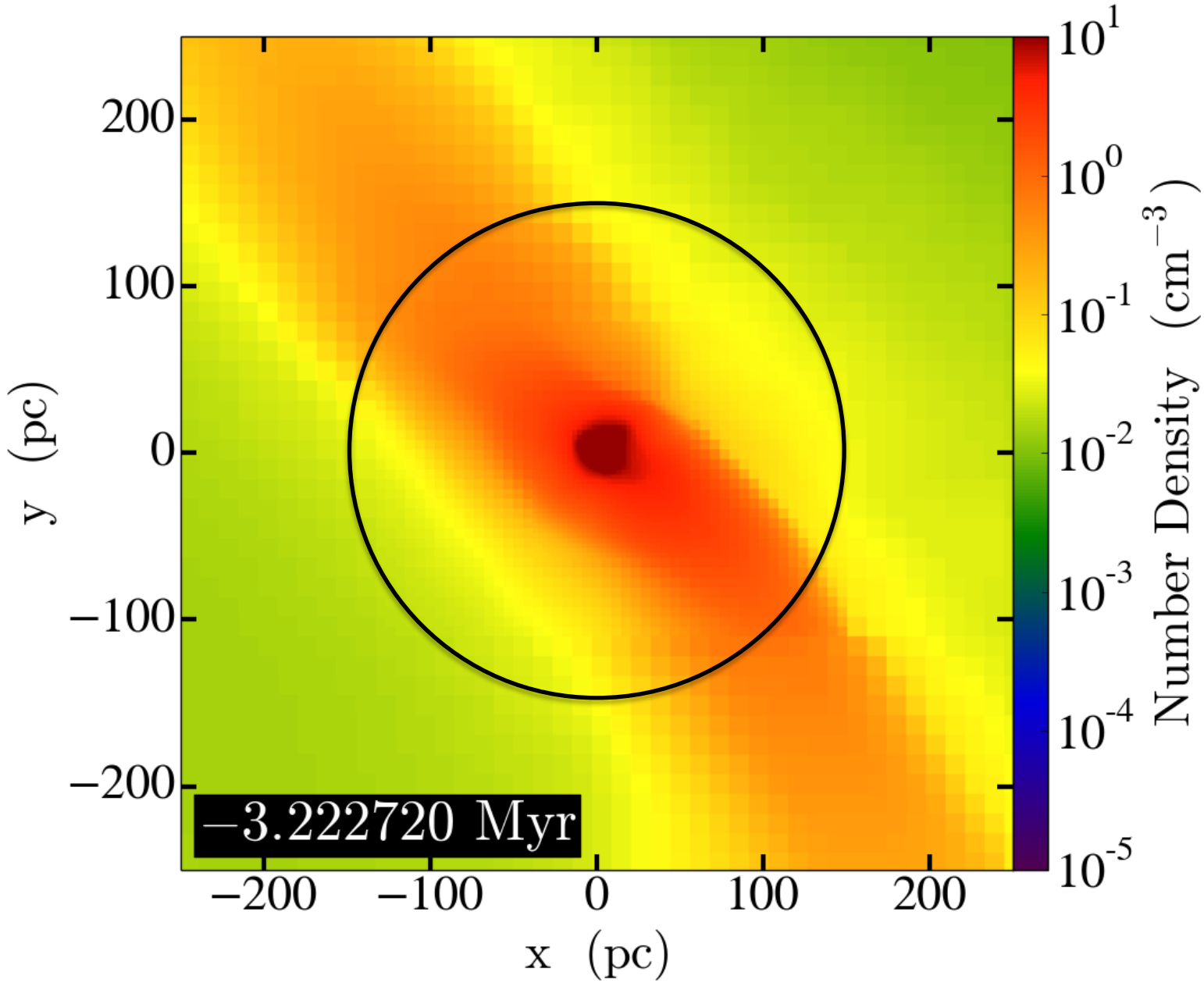
- Inflow of gas resumes after a few 100 kyr
- Metals begin to return after 4 Myr
- Total mass inflow rate ~ 2×10^{-3} $M_\odot$ yr^{-1}
- Average ISM metallicity ~ 10^{-2} $Z_\odot$
- Metals highly inhomogeneous in returning gas

Remnant Evolution

- Outer layers compress prior to reverse shock
- Inner layers remain at high entropy
- Supernova shell fragments recollapse



Sluder, Ritter+ 2015


−3.222720 Myr
200
100
0
−100
−200
y (pc)
−200
−100
0
100
200
x (pc)
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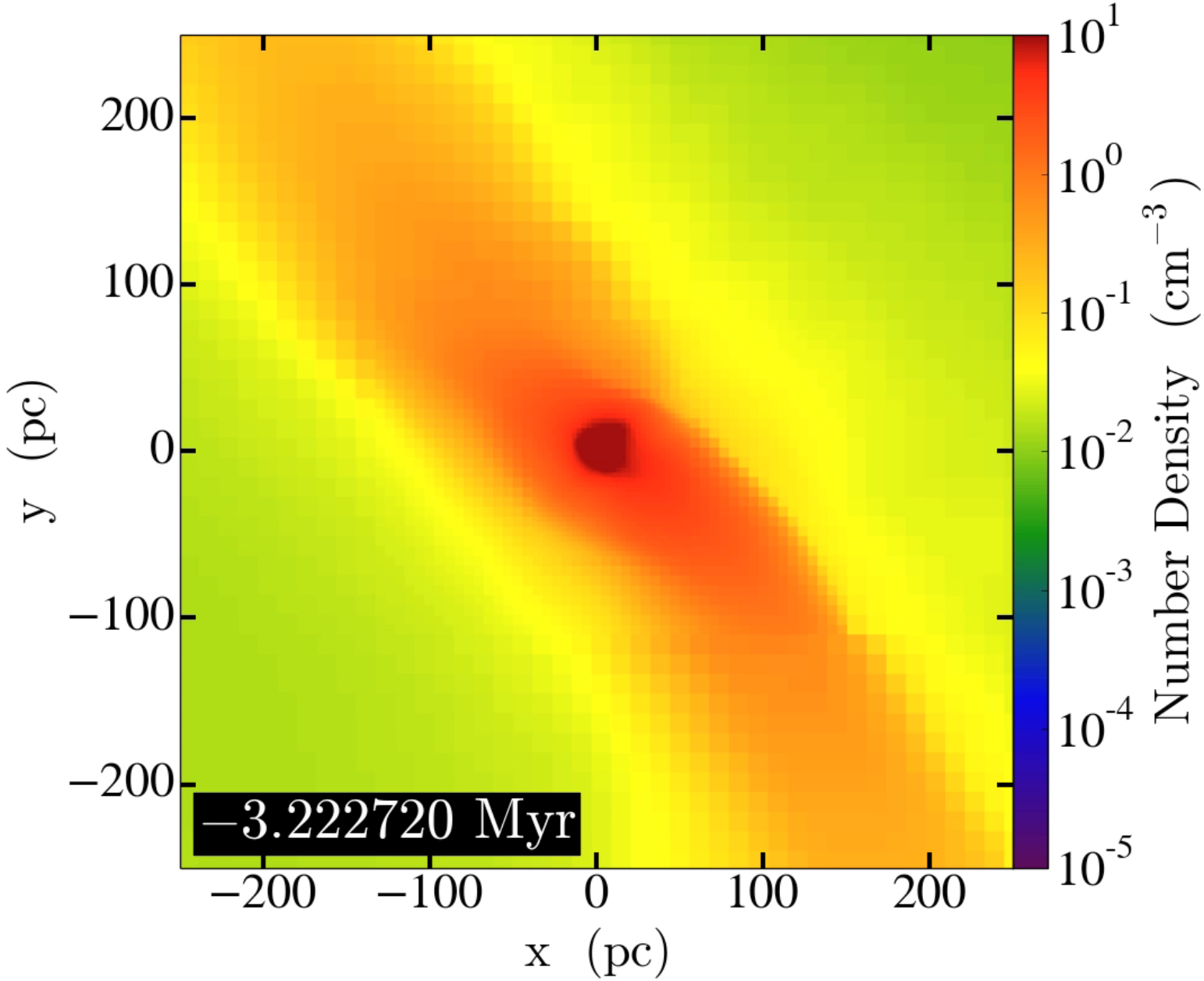
10^{-3}
10^{-4}
10^{-5}
Number Density (cm^{-3})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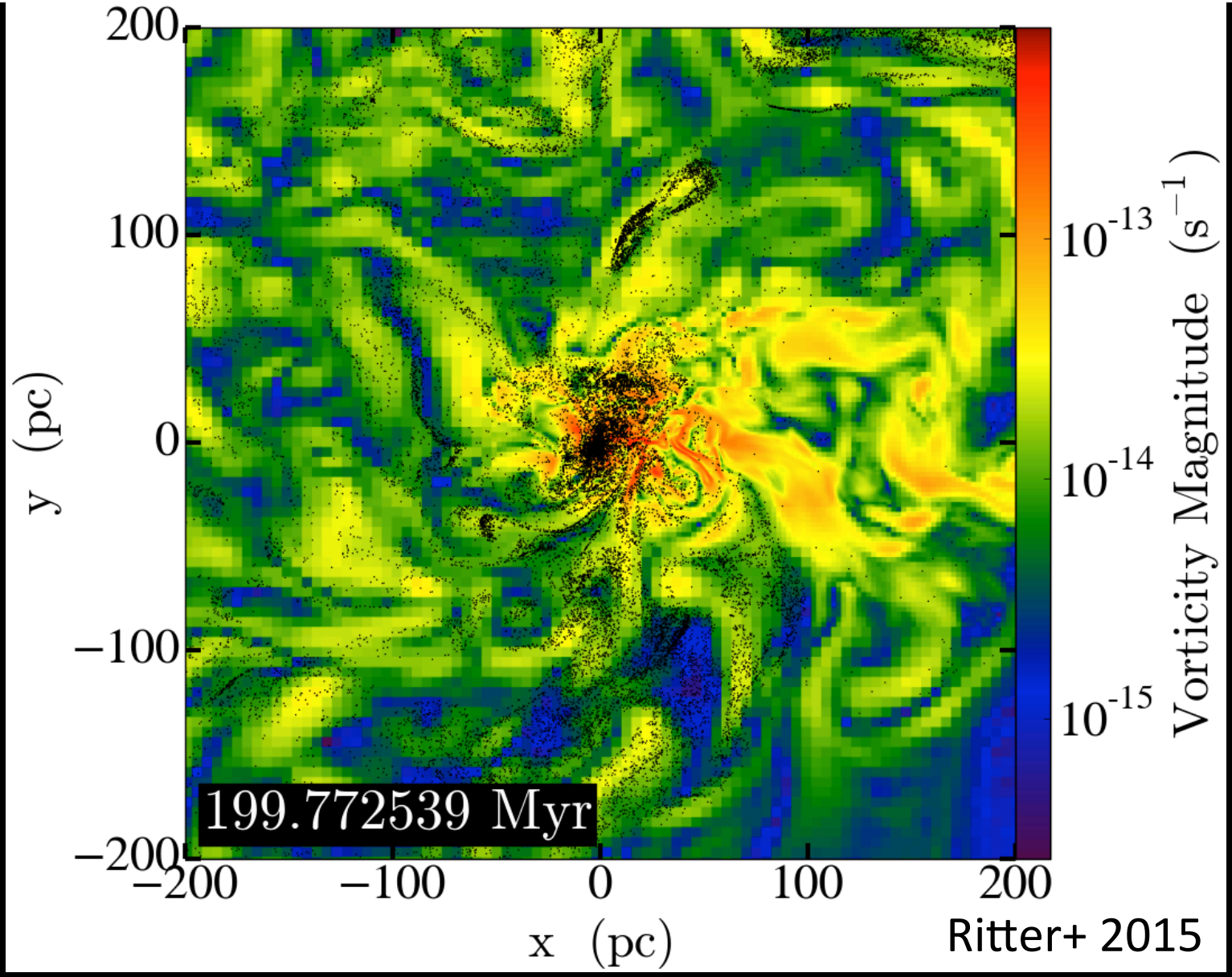
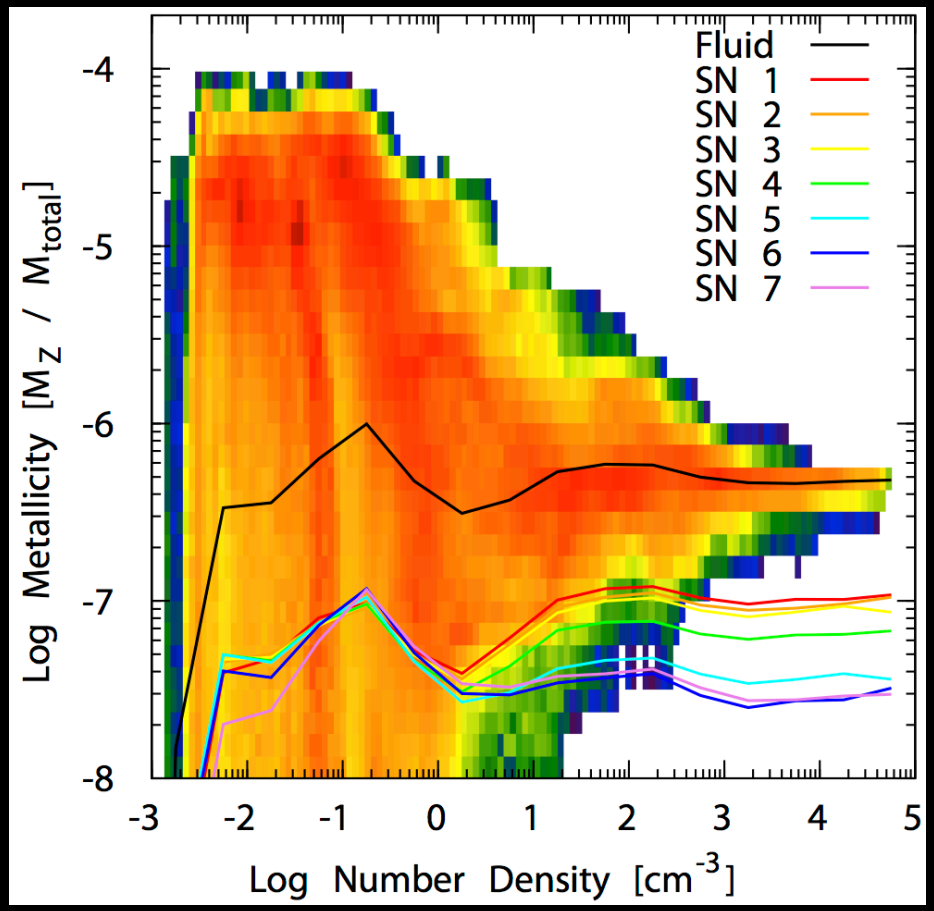


Ejecta are sheet-like and highly inhomogeneous in the infalling gas. The vortical time scales $t_{vort} \sim |\nabla \times \mathbf{v}|^{-1}$ in the central turbulent core (10s of parsecs) are short enough to imply mixing down to microscopic scales.

Enrichment Bias



Ritter+ 2015

- Recollapse of metal-enriched gas after 200 Myr, when maximum density climbs up to n ~ 10^4 cm^{-3}
- Average metallicity of recollapsed gas is very low due to dilution with continued infall from the cosmic web
- Mixing of ejecta and dense primordial gas delayed at least until fallback
- The enrichment of metal-enriched star forming clouds is biased toward the earlier supernovae (material injected by later supernovae remains at high entropy)
- Infall-driven turbulence in the recollapsed gas has short vortical time scales, conducive to mixing
- Final dark matter-baryon ratio ~ 13
- Metal mass retained ~ 70%

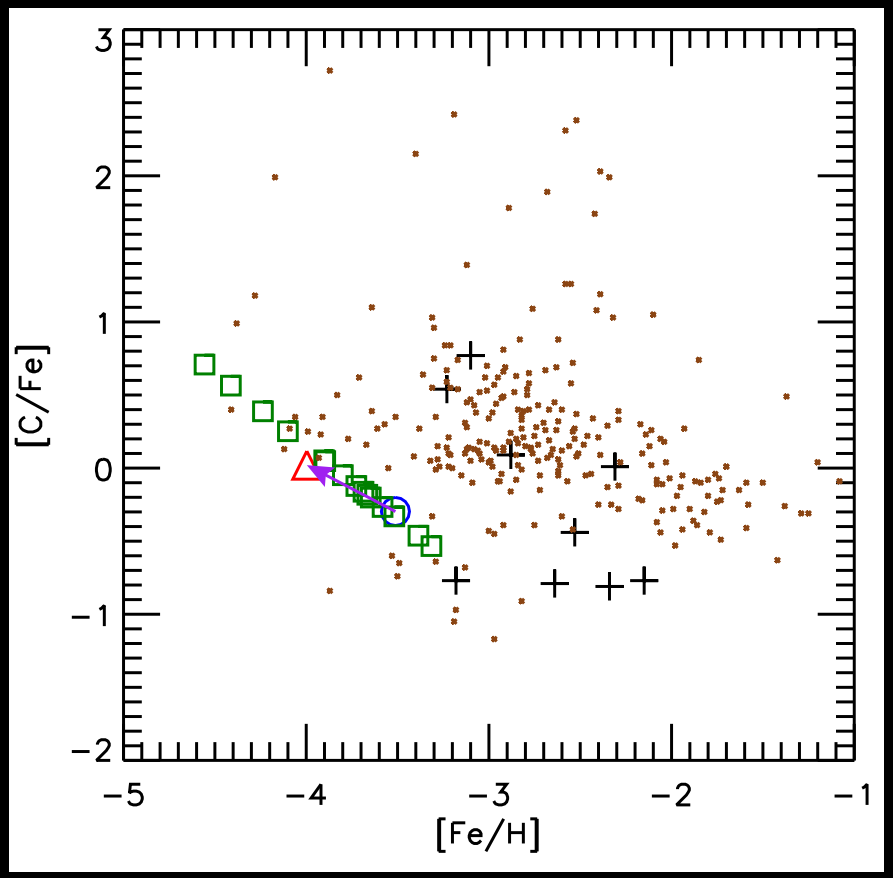
$\mathbf{Z} = \mathbf{H} \bullet \mathbf{Y}$

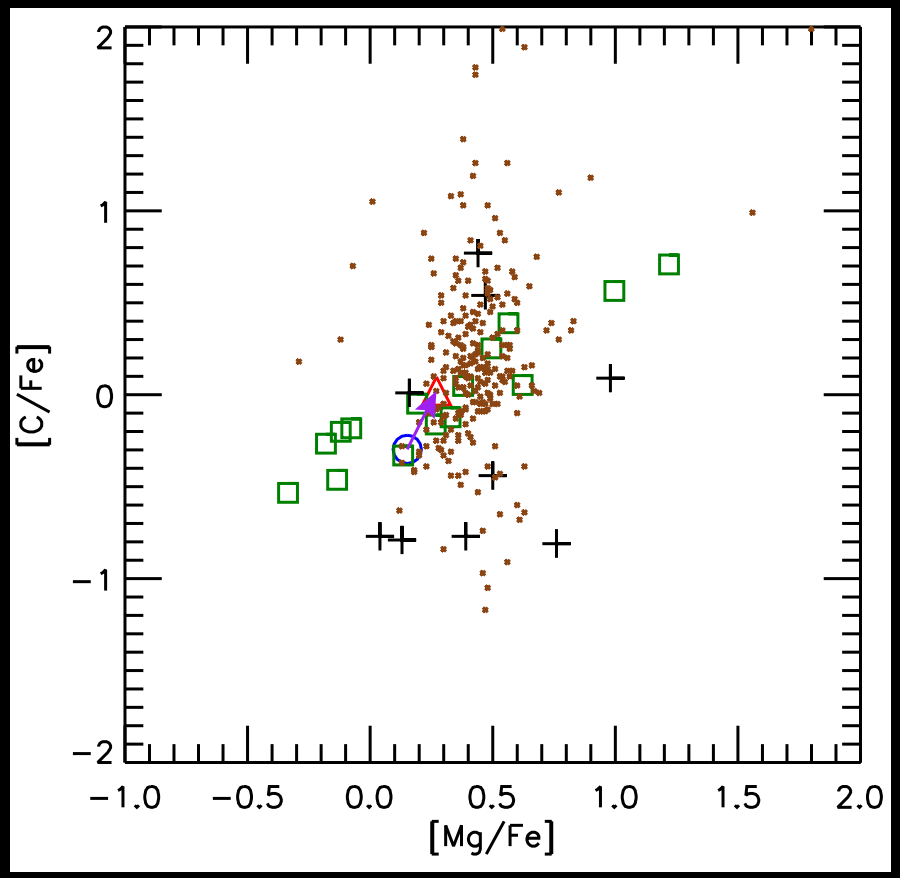
- **Y** = first-generation supernova chemical yields vector
  (mass, initial abundances, additional randomness?)

- **H** = explosion model and post-explosion hydrodynamics
  (highly stochastic random matrix)

- **Z** = second-generation stellar chemical abundances vector
  (observed star, element)

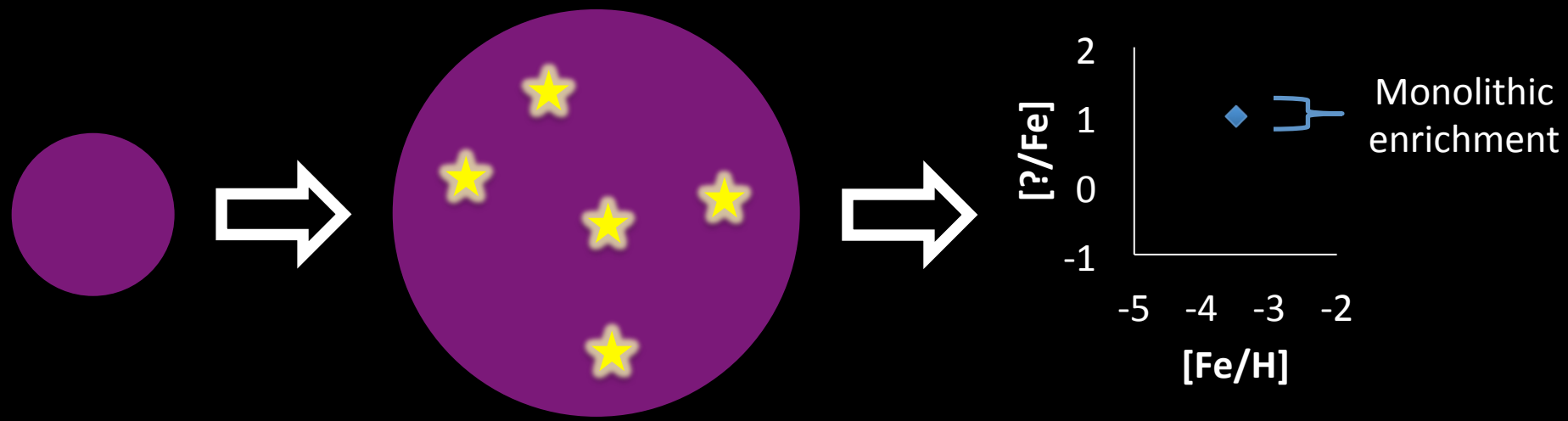
Modeling the Enrichment Bias



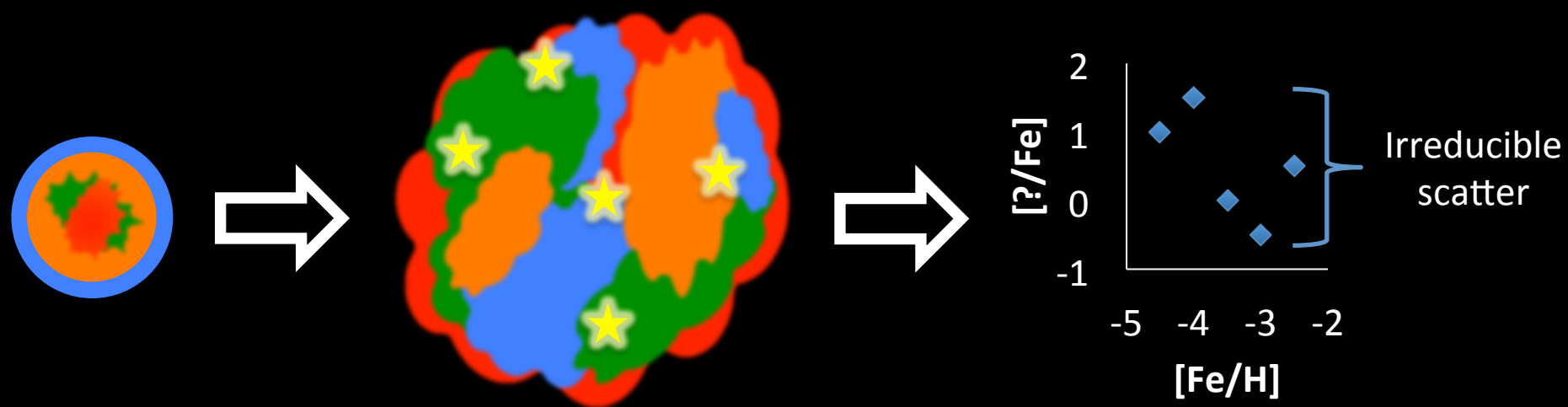


Sluder, Ritter+ 2015

Out with the old…



…in with the new!



Conclusions

- Measured abundances in ancient, metal-poor stars do not necessarily reflect the cumulative yields of their Pop III progenitor supernovae.
- Hydrodynamics-induced biases must be taken into account when attempting to reverse engineer the character of the contributing supernovae from chemical abundance measurements