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Did binary neutron star mergers produce all the r-process elements in the Universe ?

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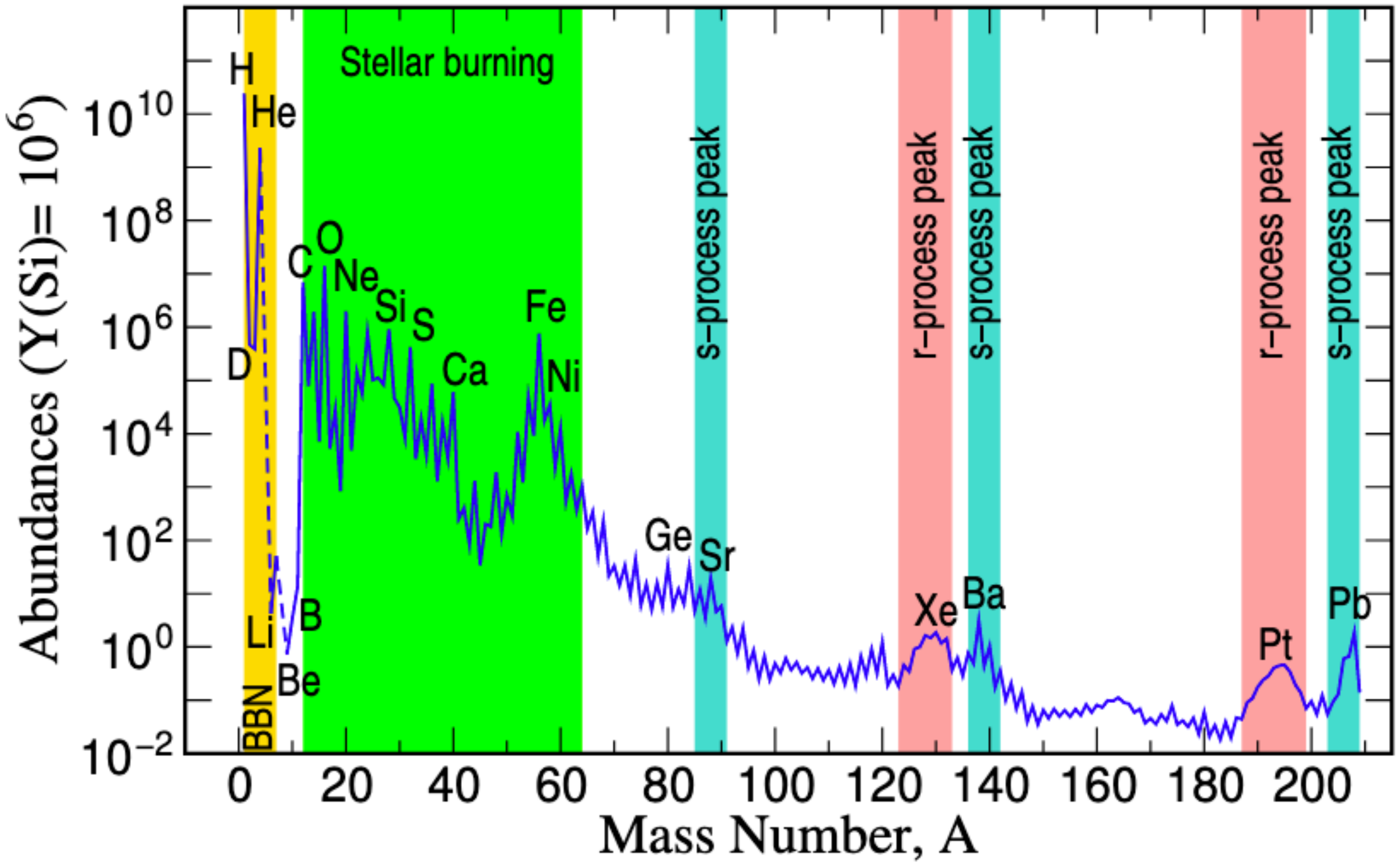
Introduction: r-process elements

- Elements above the iron peak are produced by neutron capture
- Slow process (**s-process**): timescale of 100s-1000s years
- Rapid process (**r-process**): timescale of seconds, requires high neutron densities
- Some elements form (almost) exclusively via r-process (Eu, Pt, U, …)

Cowan+2020

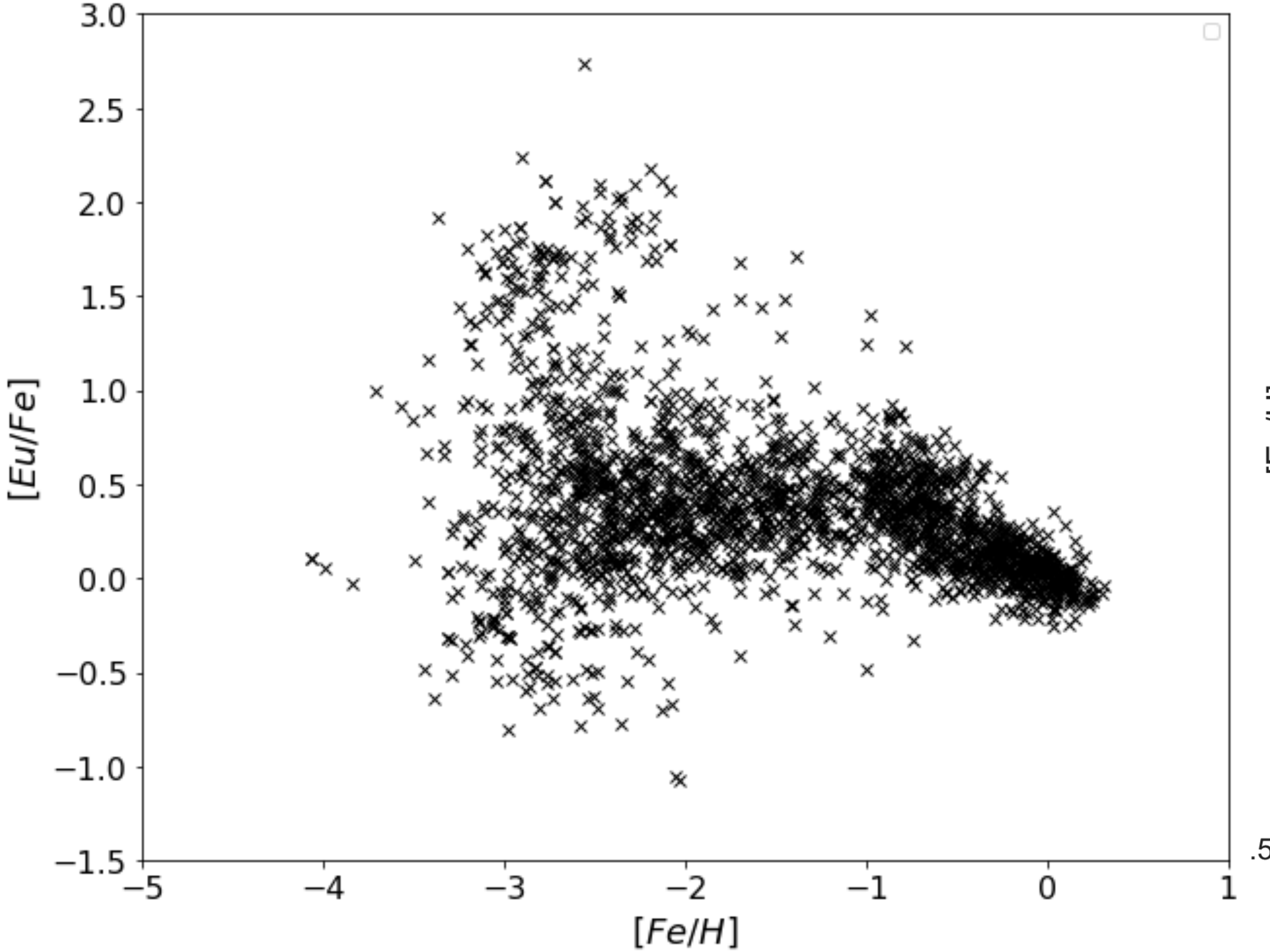


Pb

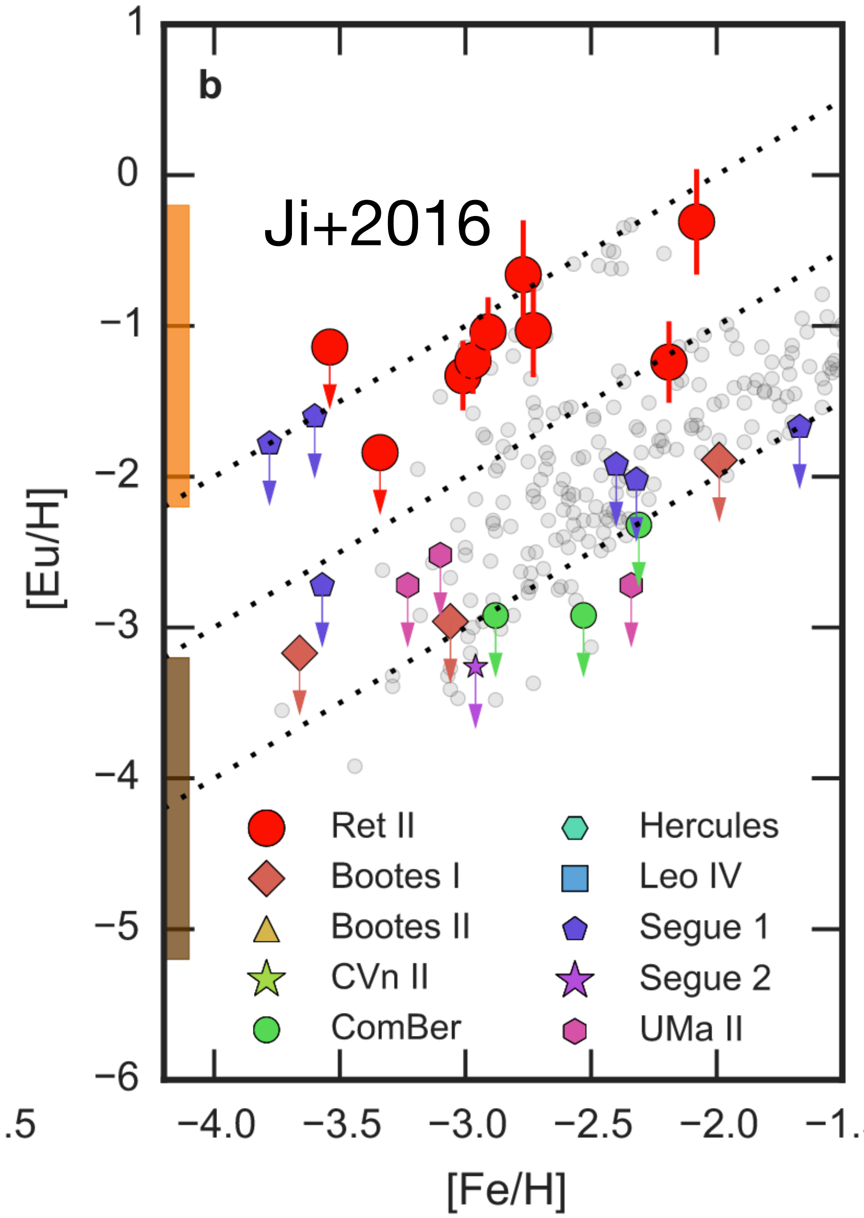
Pt

Observations of r-process elements

Milky Way (data from SAGA database)



Ret II dwarf galaxy

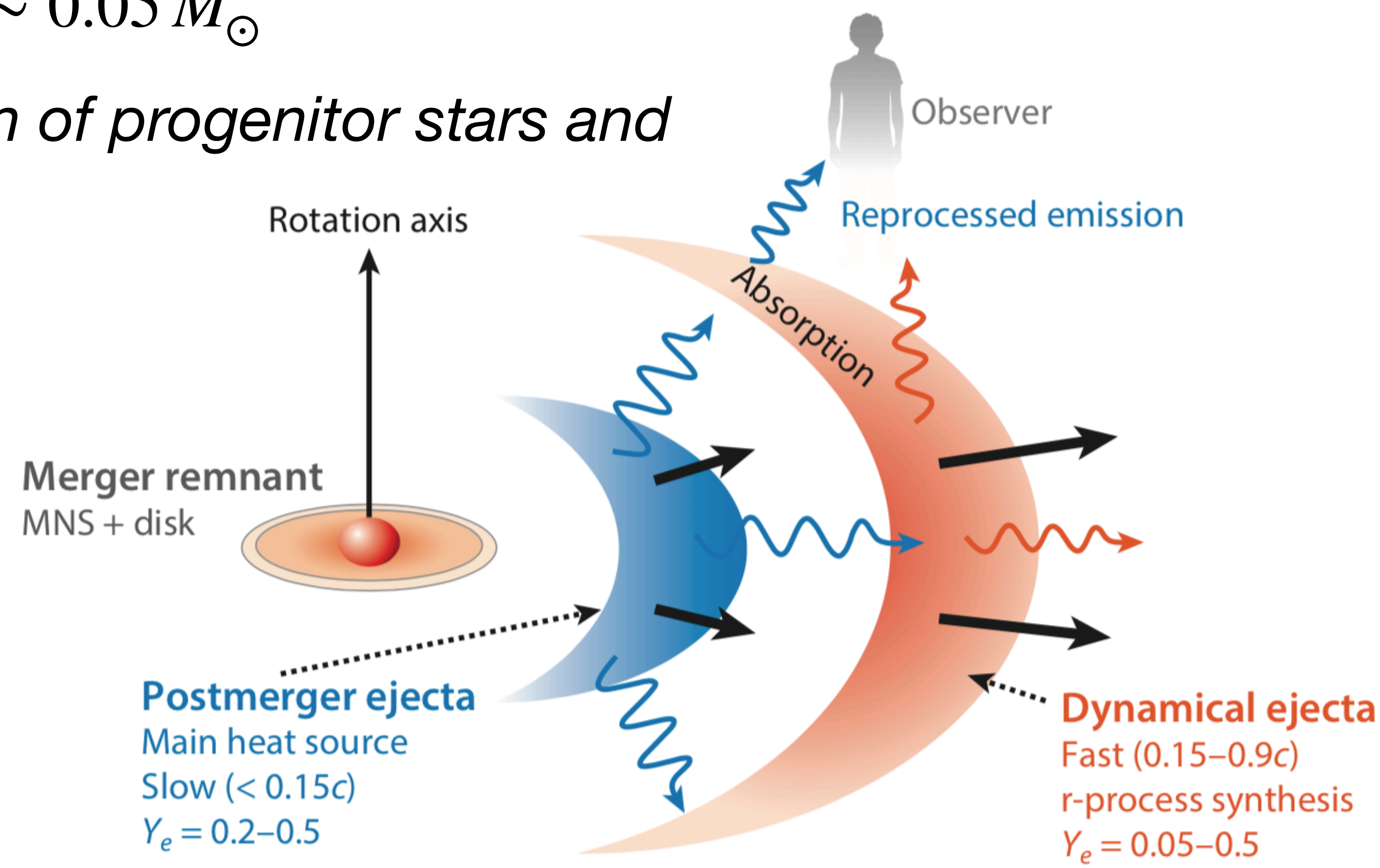


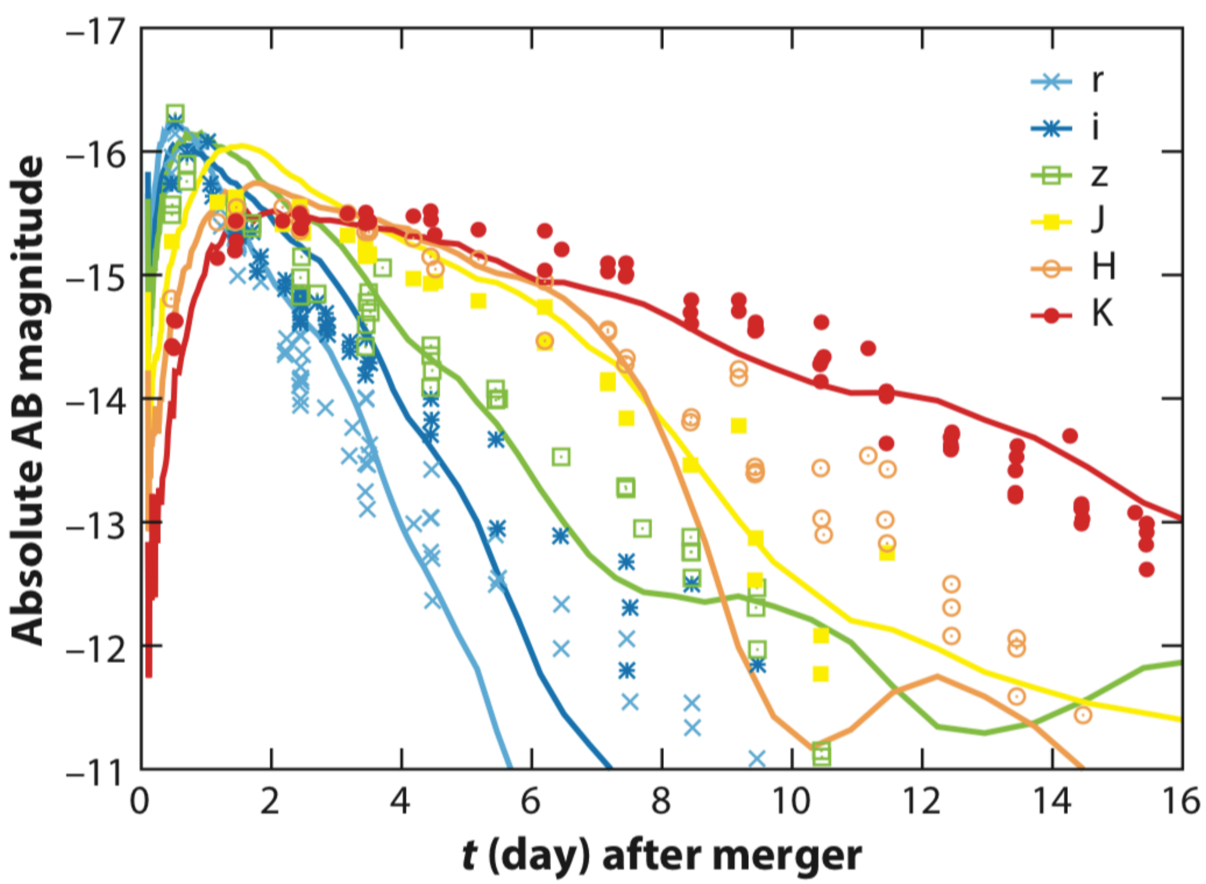
- Some low-metallicity stars have large Eu abundances —> early enrichment
- Large scatter in the [Eu/Fe]-[Fe/H] plane

Where did r-process elements form? (1)

Mergers of compact binaries (BNS and BHNS)

- Binary neutron star merger can produce a kilonova (GW170817)
- Rare events ~1% CCSN rate
- Mass in r-process elements per event : $\sim 0.05\, M_{\odot}$
- *Large time delays between the formation of progenitor stars and BNS mergers*



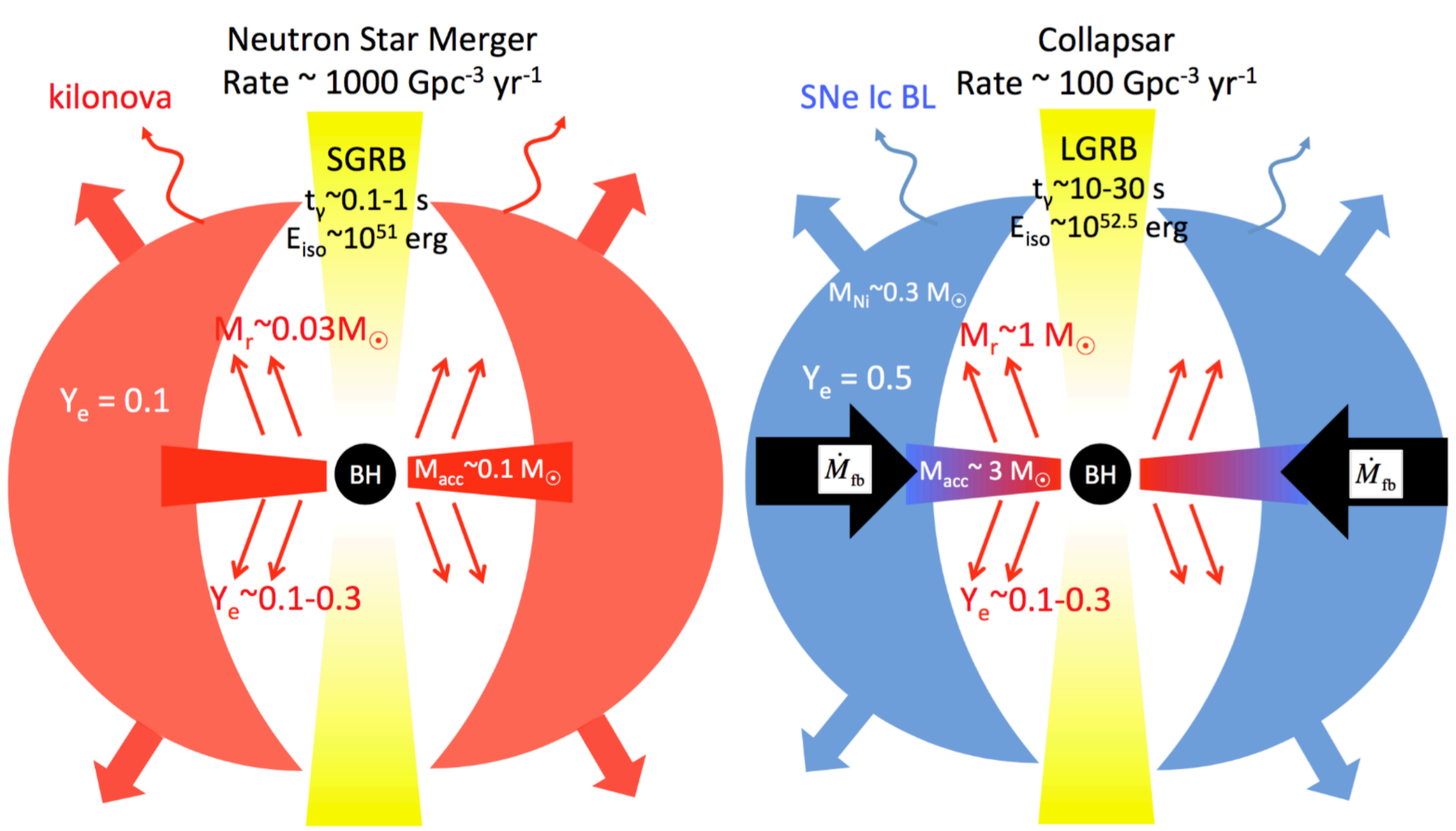


Shibata & Hotokezaka 2020

Where did r-process elements form? (2)

Core-collapse of massive stars

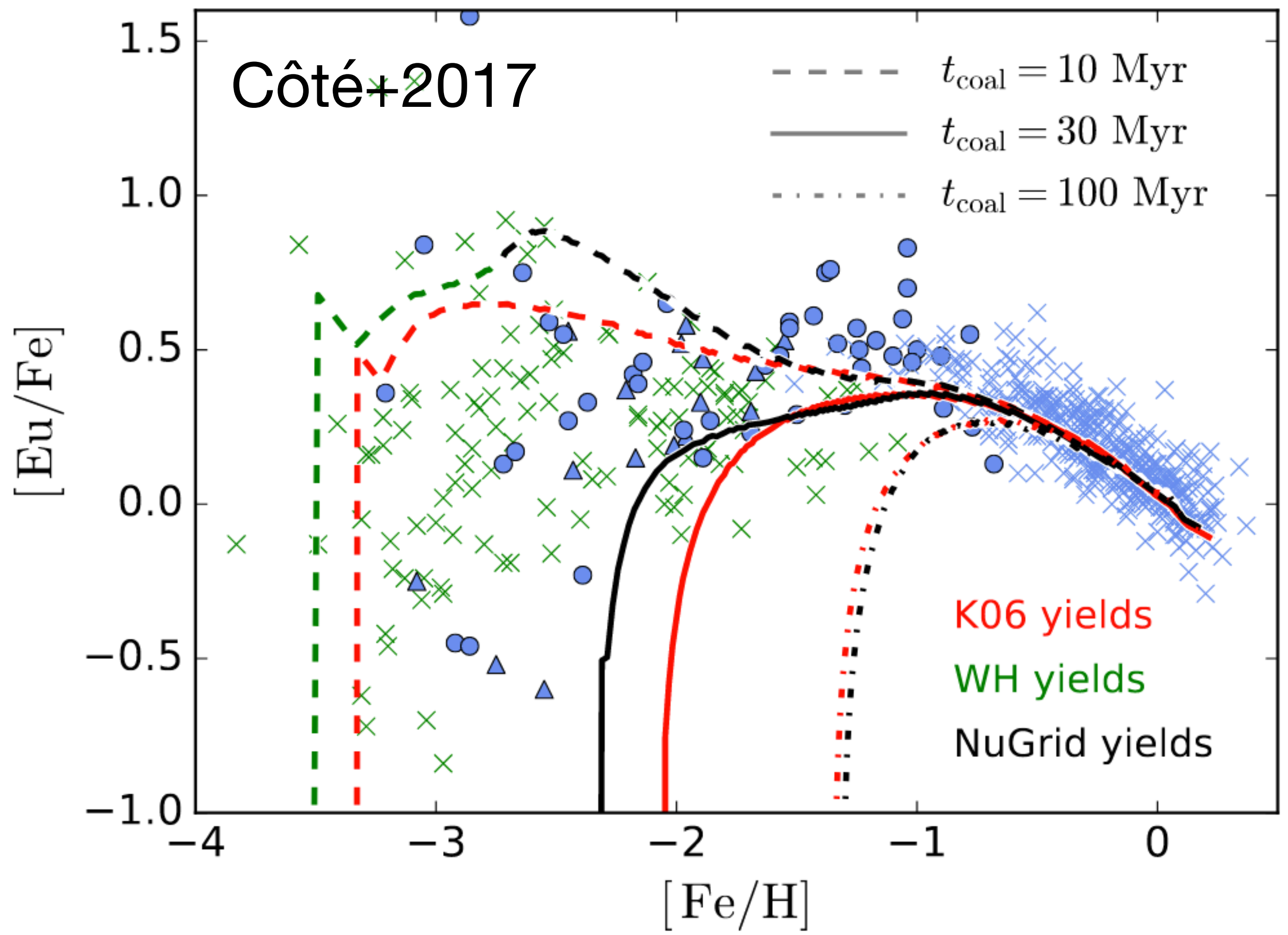
- Collapsars/magnetars
- Extremely rare events ~0.1% CCSN
- Mass in r-process elements per event : very large (up to $1\,M_\odot$ for collapsars!)
- Short time delays relative to the formation of progenitor stars

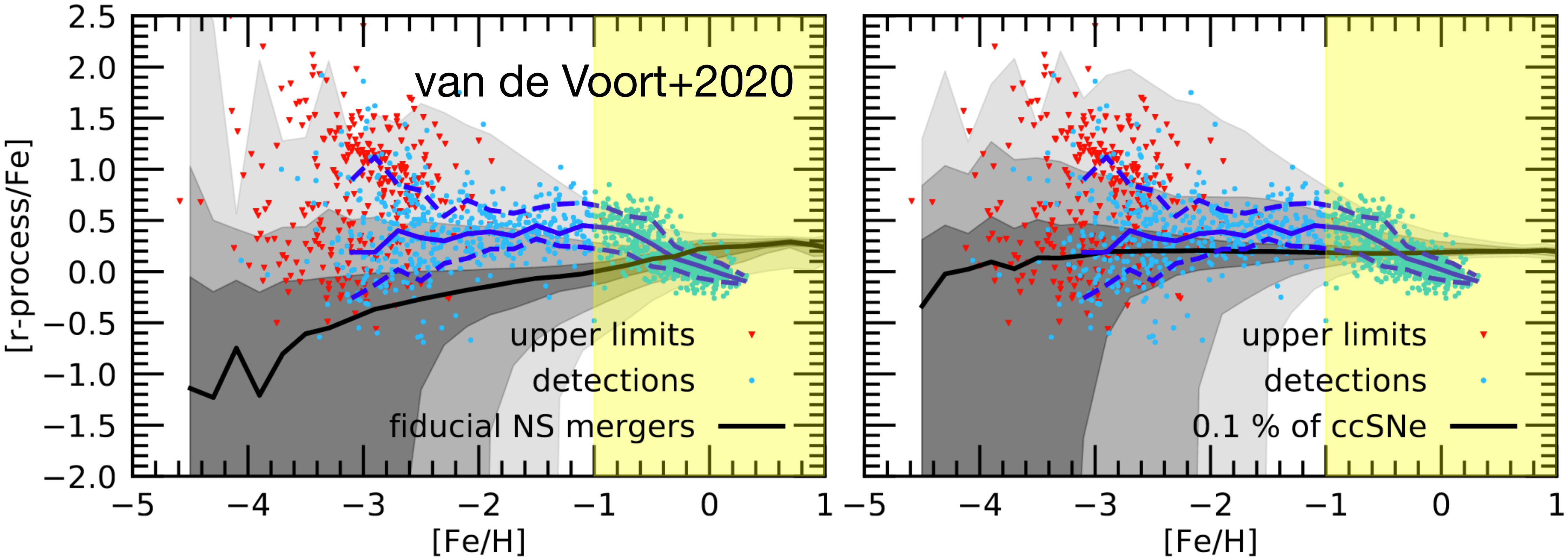


Siegel+2019

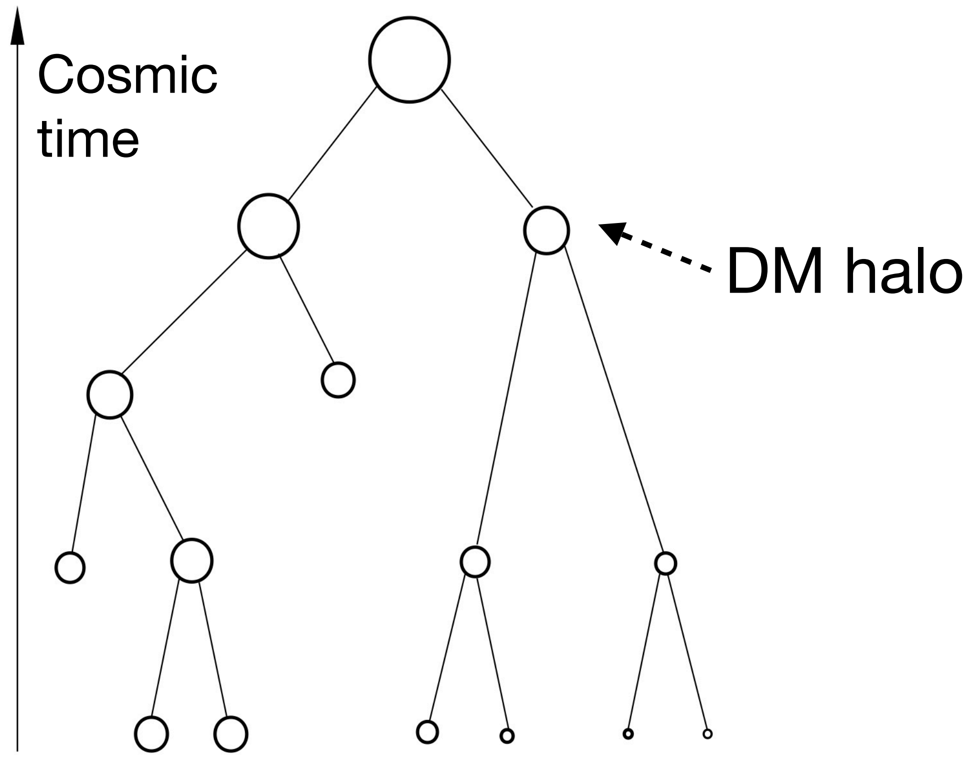
Where did r-process elements form? (3)

- Most models cannot reproduce the observed abundances with BNS mergers as unique source of r-process elements
- Large scatter at low metallicities difficult to explain





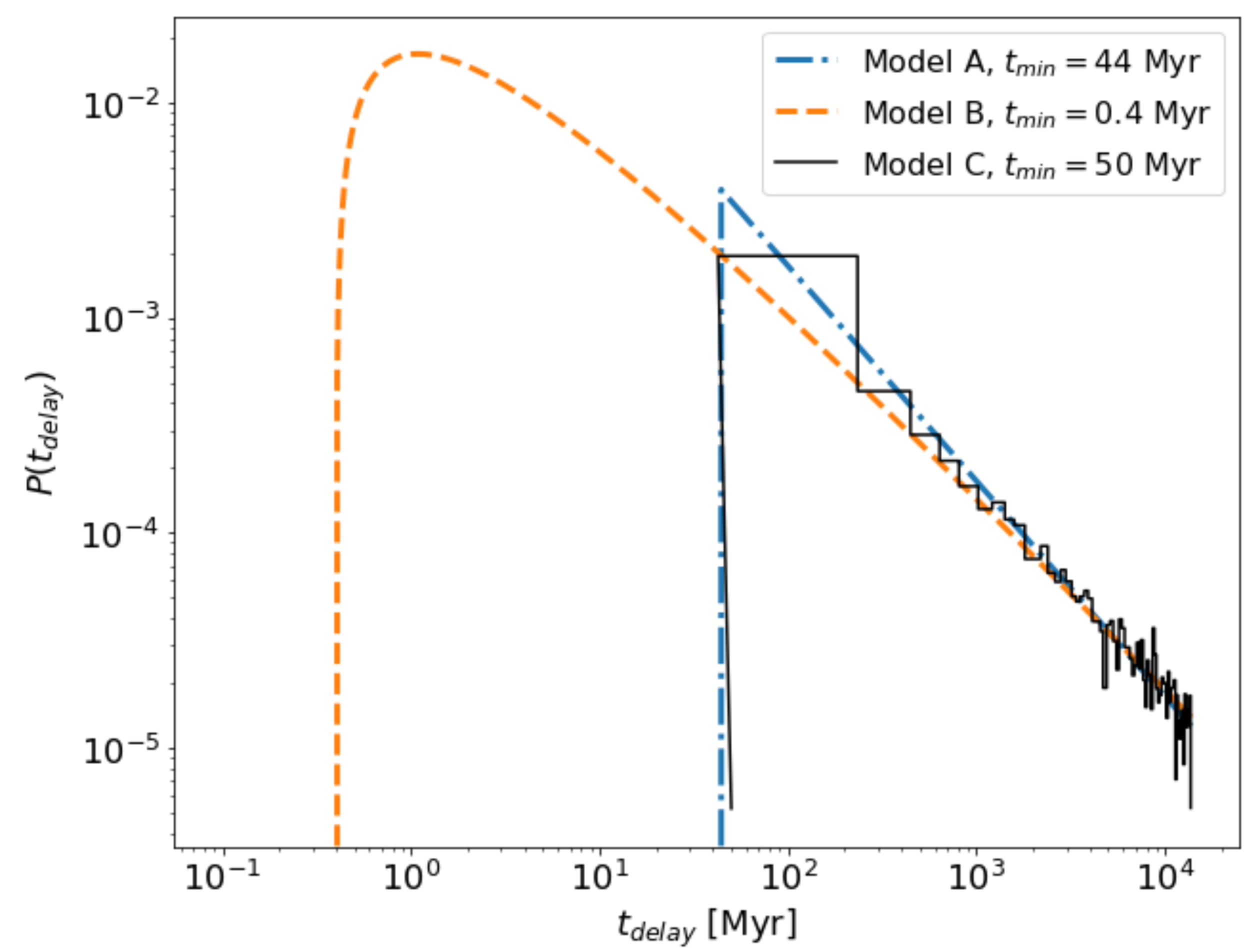
Semi-analytic model of a Milky-Way-like galaxy



- Gas accretion, cooling, star formation inside each galaxy
- Elements produced in stars/ mergers are ejected into the interstellar matter

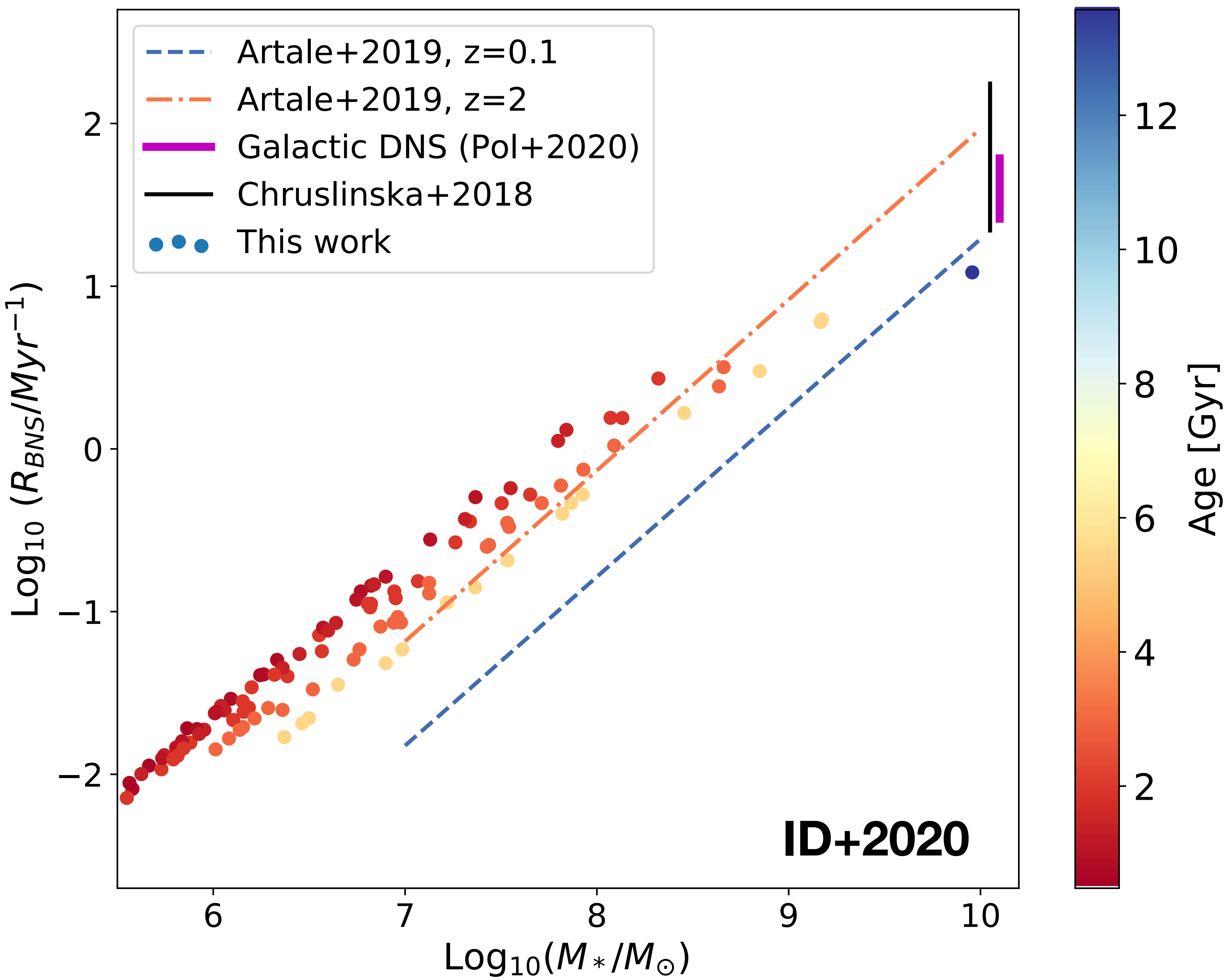
Formation and merger rates of BNS

- NS form from massive stars (some dependence on mass, metallicity)
- Efficiency parameter for binary formation
- Distribution of time delays between formation and merger: different phenomenological models



Galactic chemical evolution model: BNS merger rates

- Merger rate vs. redshift and stellar mass of the host galaxy: consistent with population synthesis models



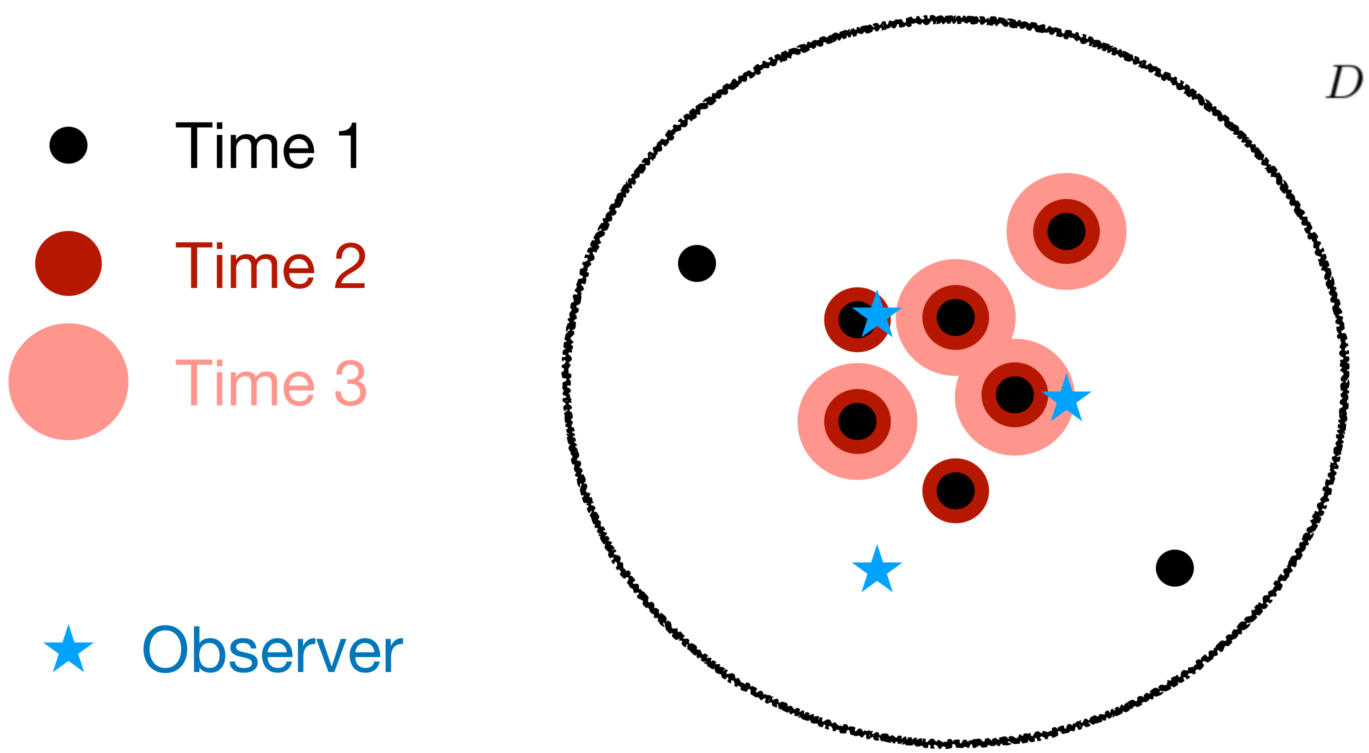
Galactic chemical evolution model: turbulent mixing

- BNS mergers occur at random locations inside the galaxy
- r-process elements diffuse in the interstellar matter
- An ‘observer' that is close to the BNS merger in time and space will ‘see' an enriched environment
- When galaxies merge everything is mixed together

Beniamini & Hotokezaka 2020

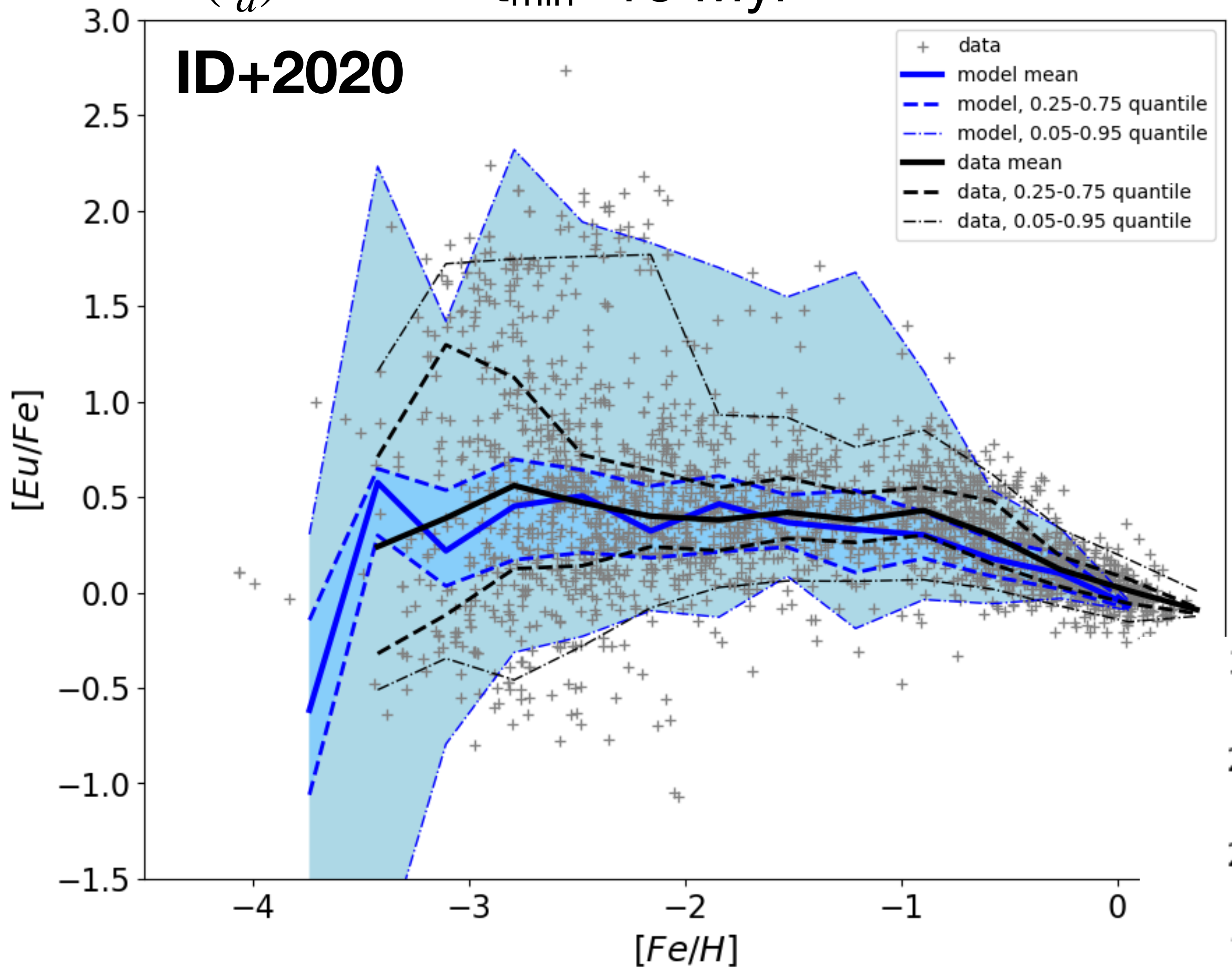
$$\rho_{Eu}(\vec{r}_{\rm obs}, t_{\rm obs}) = \sum_i \frac{m_{\rm rp}}{4\pi D(t_{\rm obs} - t_i)} \exp\left(\frac{|\vec{r}_{\rm obs} - r_i|^2}{4\pi D}\right)$$

$$D = \alpha c_s H = \alpha \left(\frac{c_s}{10 \rm km/s}\right)\left(\frac{H}{100 \ \rm pc}\right) \rm kpc^2 Gyr^{-1}$$



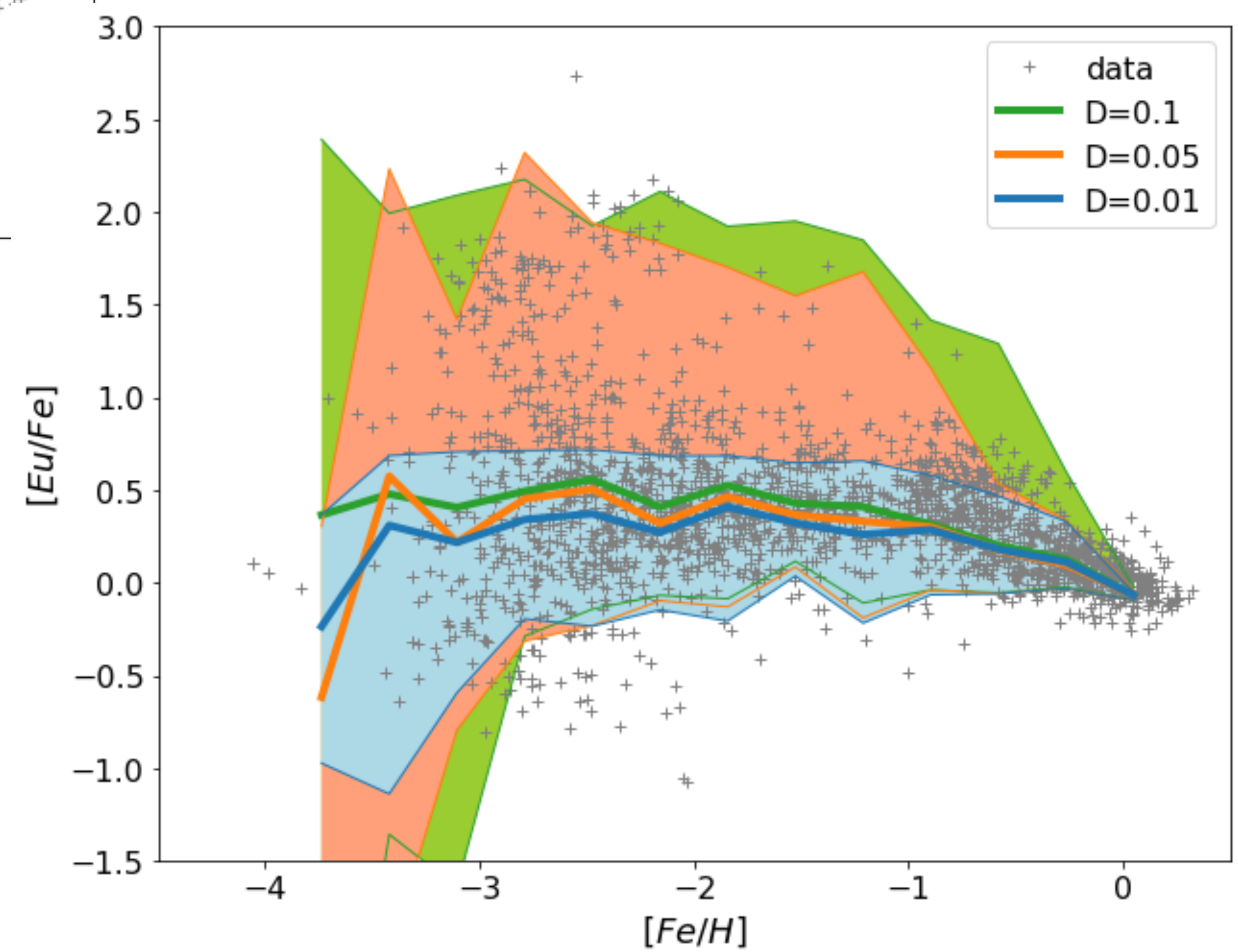
Results: r-process abundance in a Milky-Way-like galaxy

$P(t_d) \propto t^{-1}$ t_{min}=10 Myr



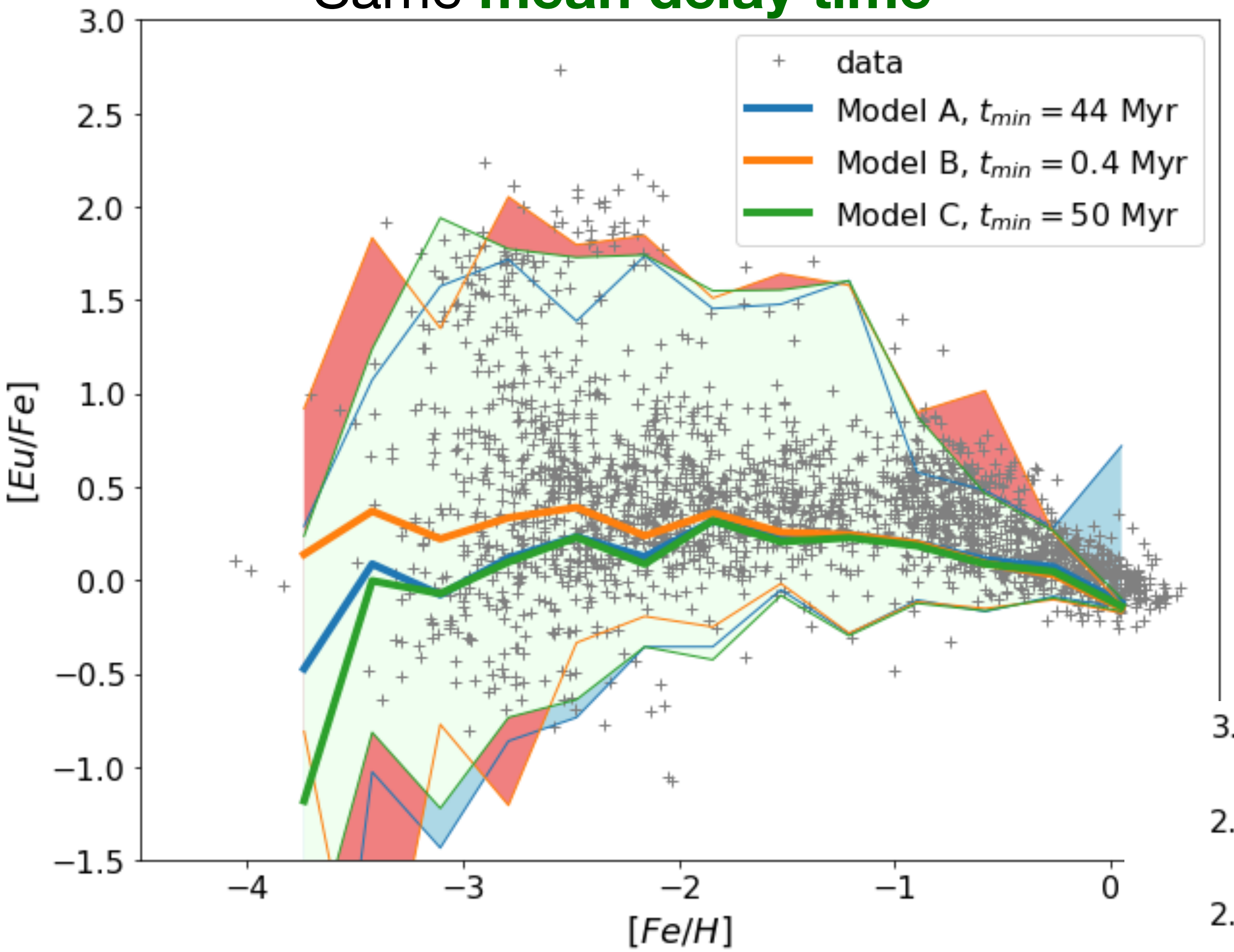
- Model reproduces the observed abundances at low and high metallicities

- The scatter is reproduced when turbulent mixing is included



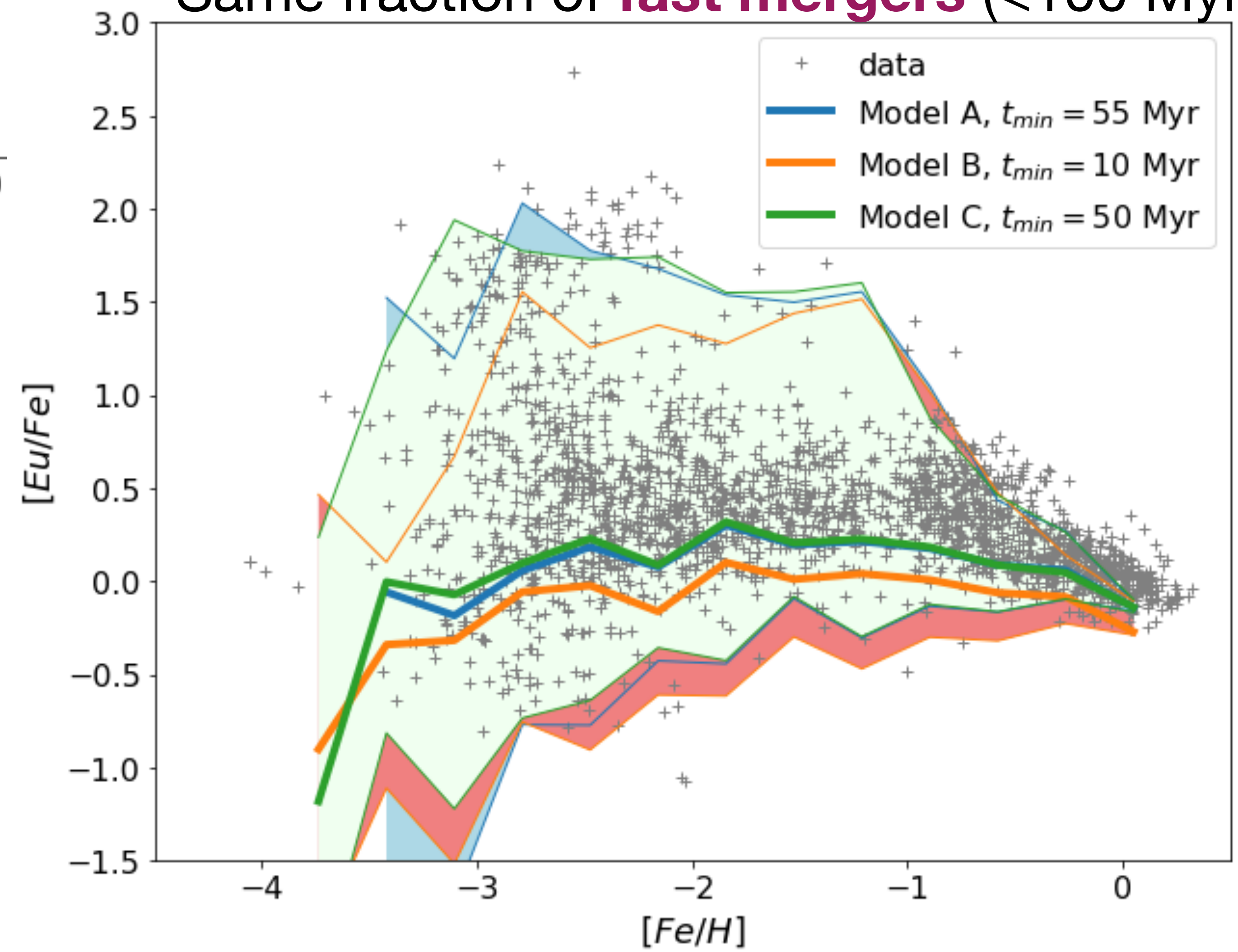
Results: r-process abundance in a Milky-Way-like galaxy

Same **mean delay time**



- Scatter in the abundances depends mainly on diffusion, not on the time delay distribution

Same fraction of **fast mergers** (<100 Myr)

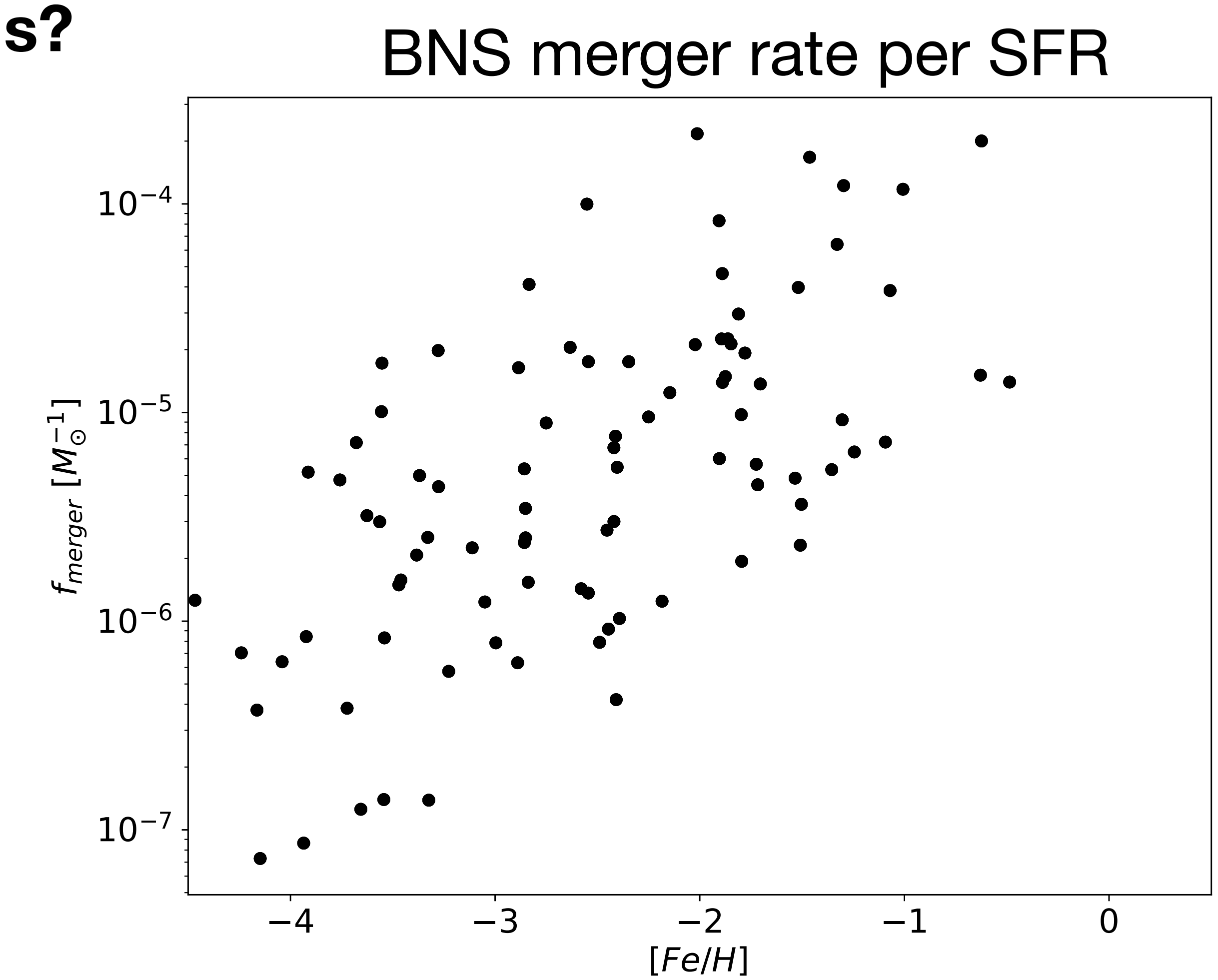


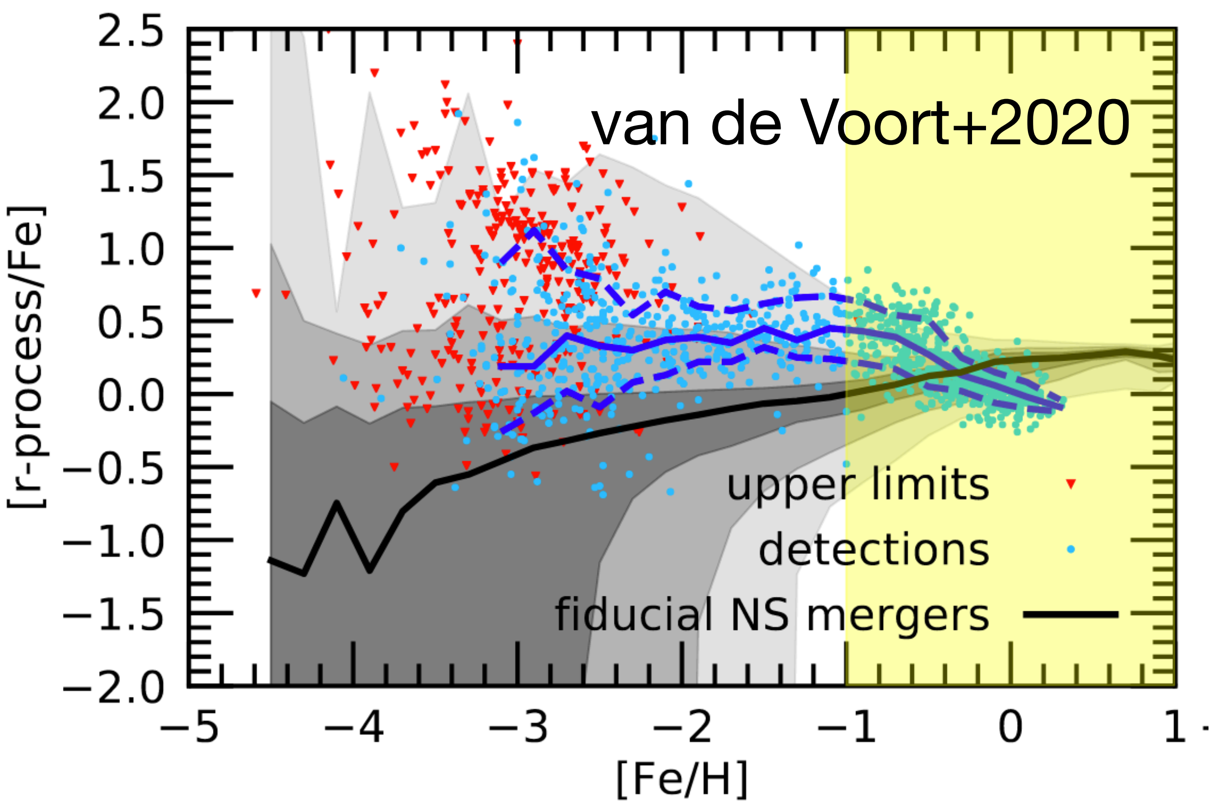
- The fraction of **fast mergers** determines the abundances at low metallicities
- The **mean delay time** determines the abundances at high metallicities

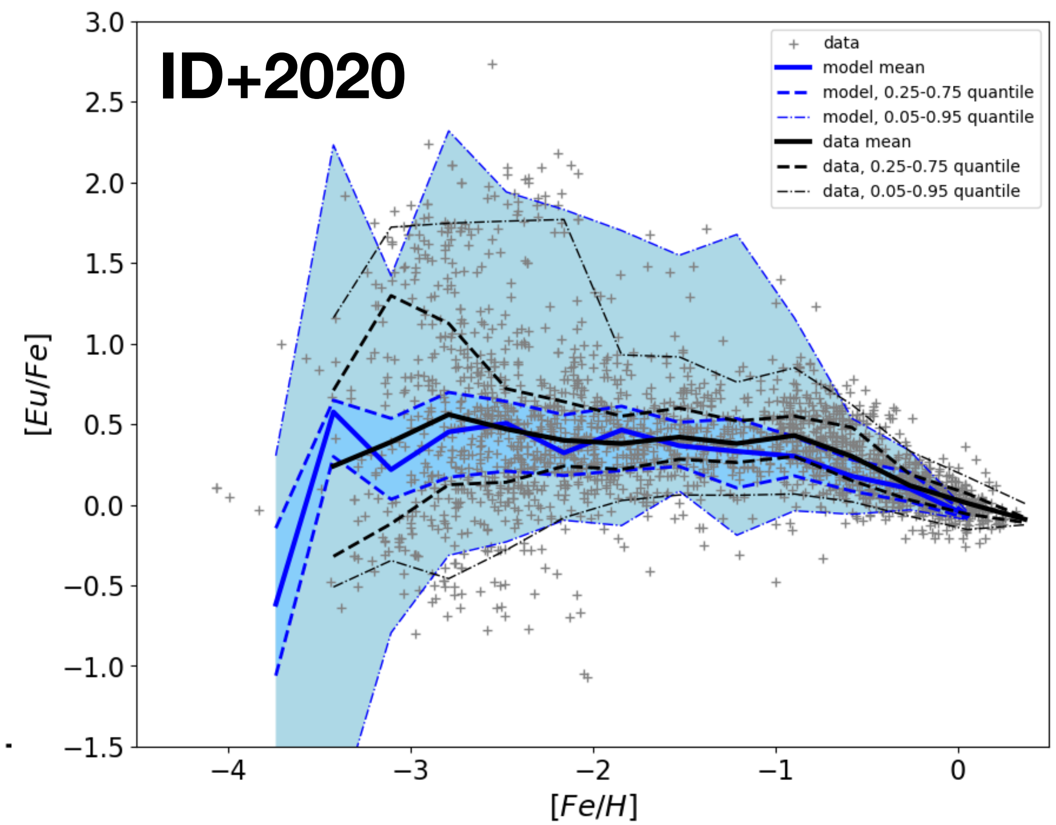
Results: r-process abundance in a Milky-Way-like galaxy

Why is there a difference with previous models?

- **NS formation efficiency** is metallicity-dependent
- **BNS merger rate** depends on galaxy stellar mass and redshift
- **Time delay** between formation and merger
- **Turbulent mixing** in the interstellar medium
- Differences in the **r-process yields**







Summary

Main conclusions

- BNS mergers can be a dominant r-process producing site
- The assembly history of a MW-like galaxy from small building blocks has only a weak impact on the scatter in the Eu abundances, which remains too small compared to observations
- The dispersion observed in the [Eu/Fe]-[Fe/H] plane can be explained by turbulent mixing of the freshly synthesized elements in the ISM

Did BNS mergers produce all the r-process elements in the Universe ?

- Maybe!
- More physical effects: kicks at NS birth, varying ejecta mass, …
- What is the role of NSBH mergers ?