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

Irina Dvorkin

Institut d'Astrophysique de Paris

Sorbonne Université

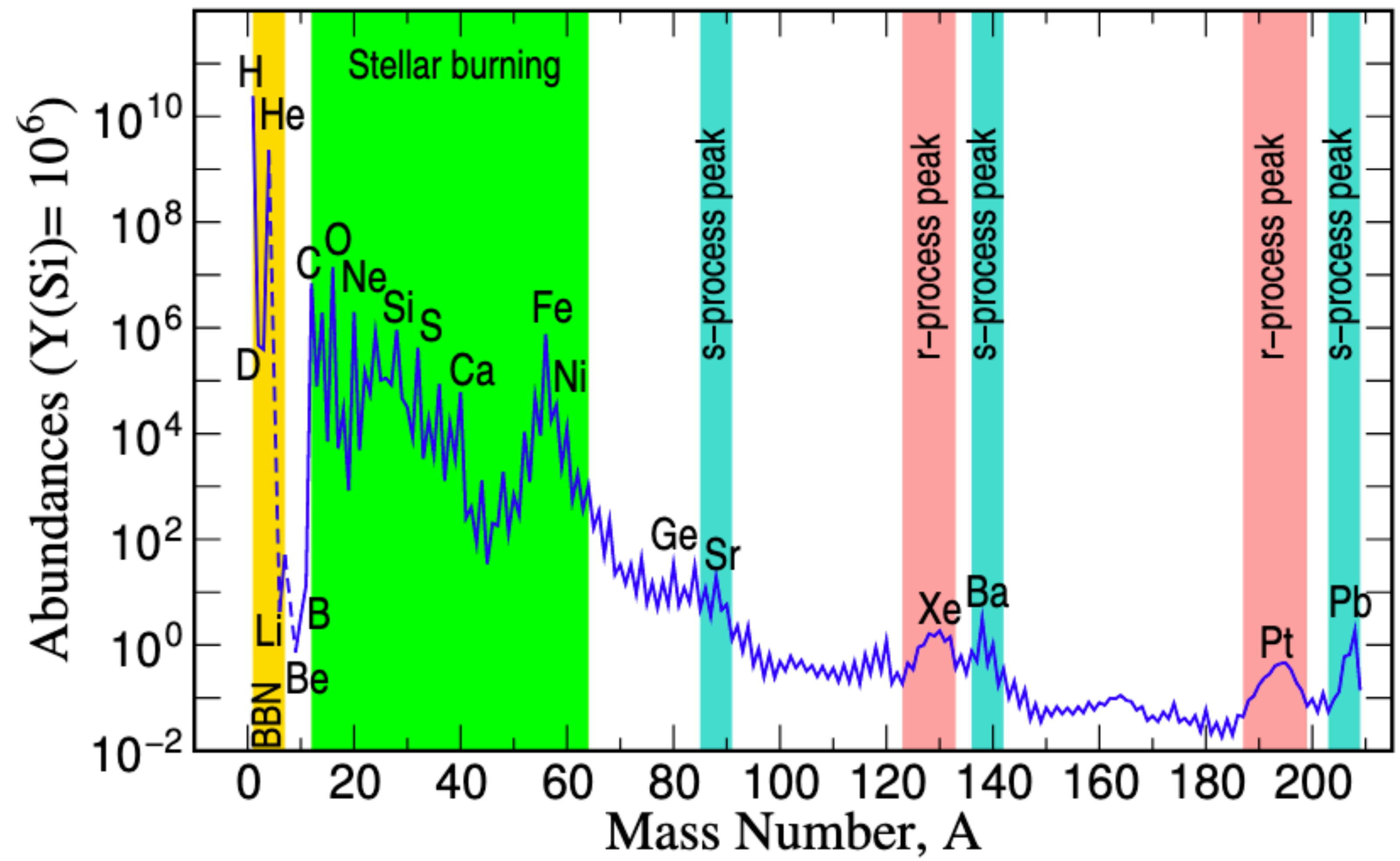
With: Frédéric Daigne, Elisabeth Vangioni, Joe Silk (IAP), Stéphane Goriely (Bruxelles), Paz Beniamini (Caltech)

King's College London virtual seminar, 25 November 2020

Introduction: r-process elements

- Elements above the iron peak are produced by neutron capture
- Slow process (s-process): timescale of 100s-1000s years, operates during stellar evolution
- Rapid process (r-process): timescale of seconds, requires high neutron densities

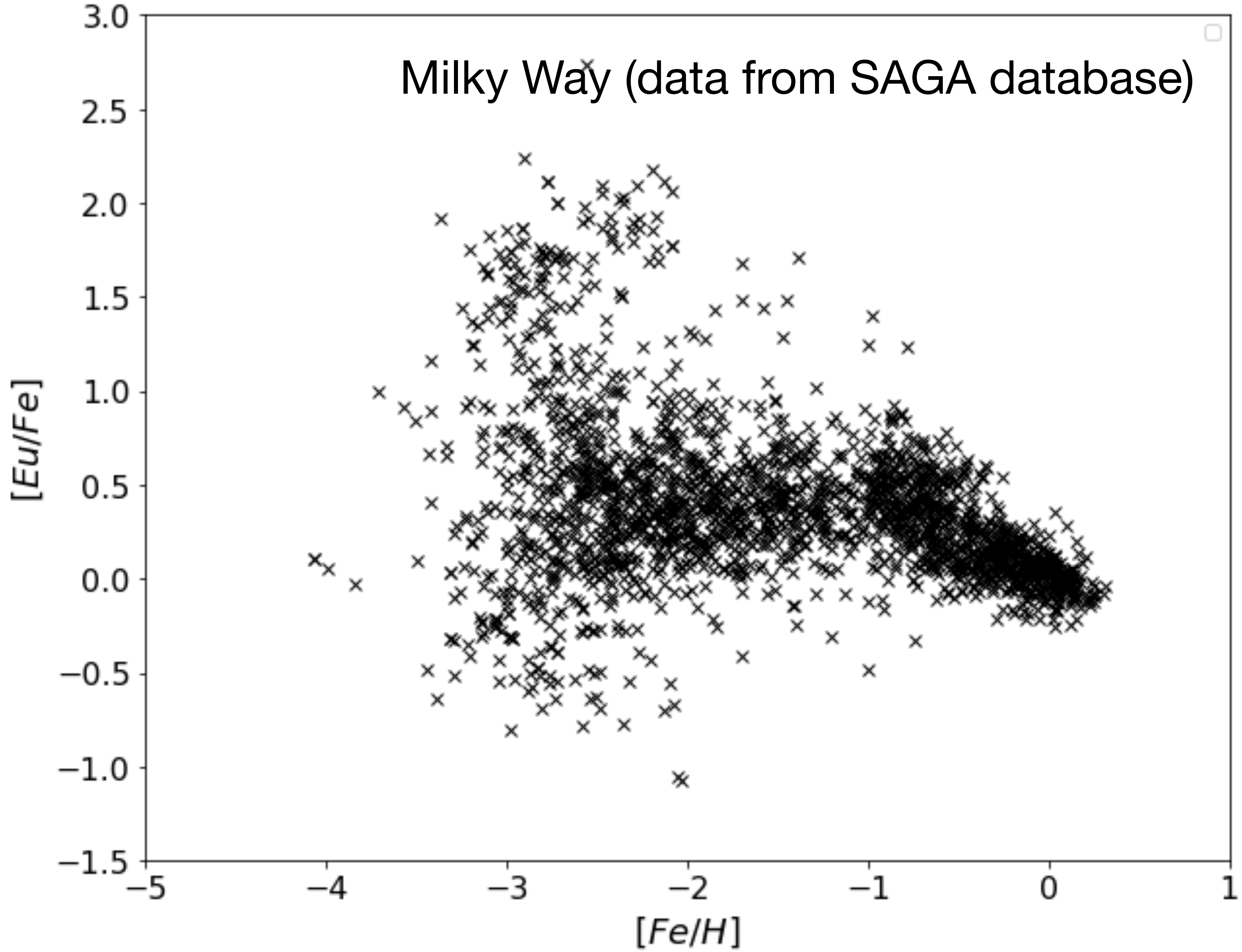
Cowan+2020



- Some elements form (almost) exclusively via r-process (Eu, Pt, U, …)
- Some unstable r-process elements (Th, U, Np, Pu, Cm, …)

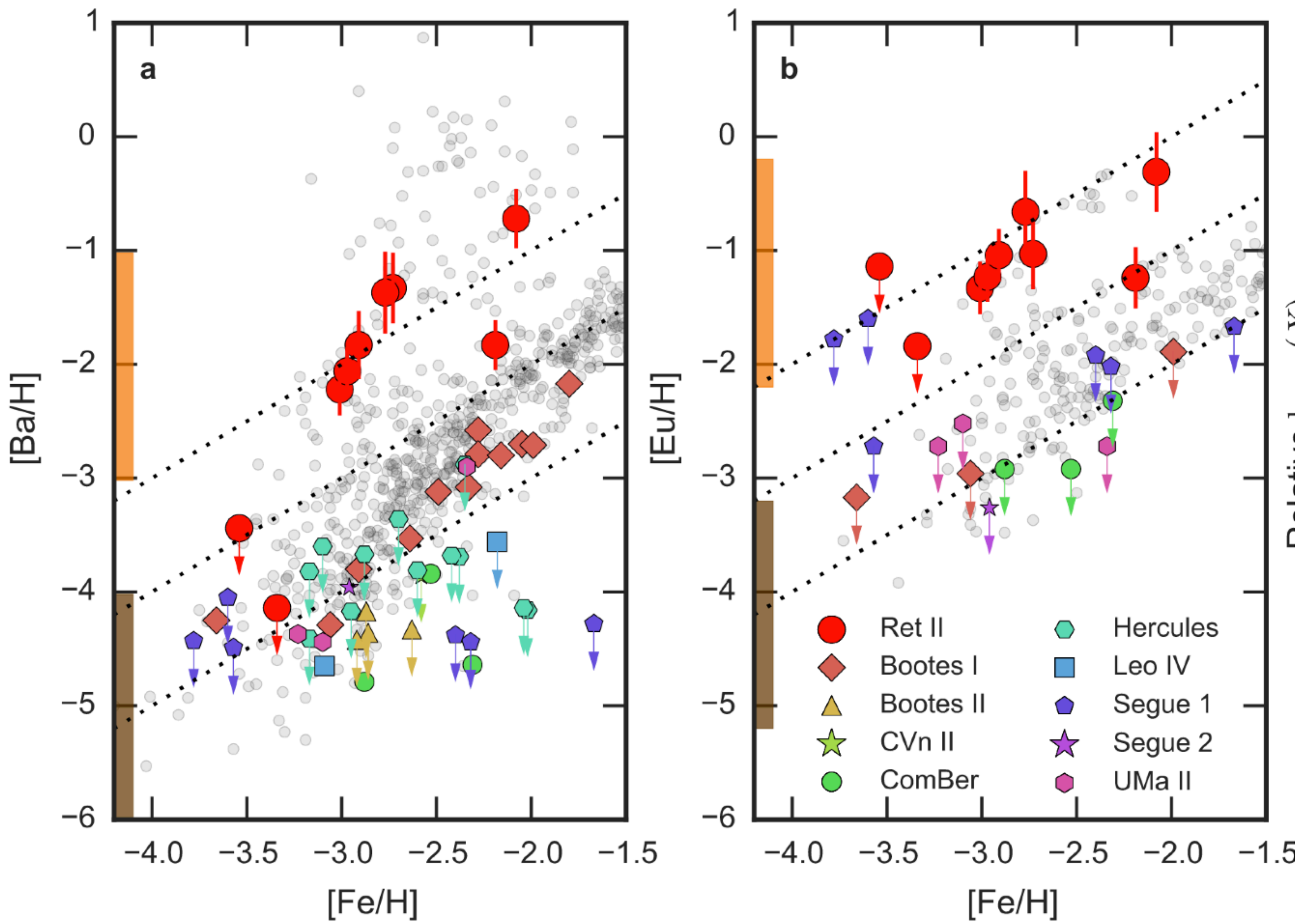
Observations of r-process elements

$$[\mathrm{X}/\mathrm{Y}] = \log_{10}(N_{\mathrm{X}}/N_{\mathrm{Y}}) - \log_{10}(N_{\mathrm{X}}/N_{\mathrm{Y}})_{\odot}$$



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

Ret II dwarf galaxy



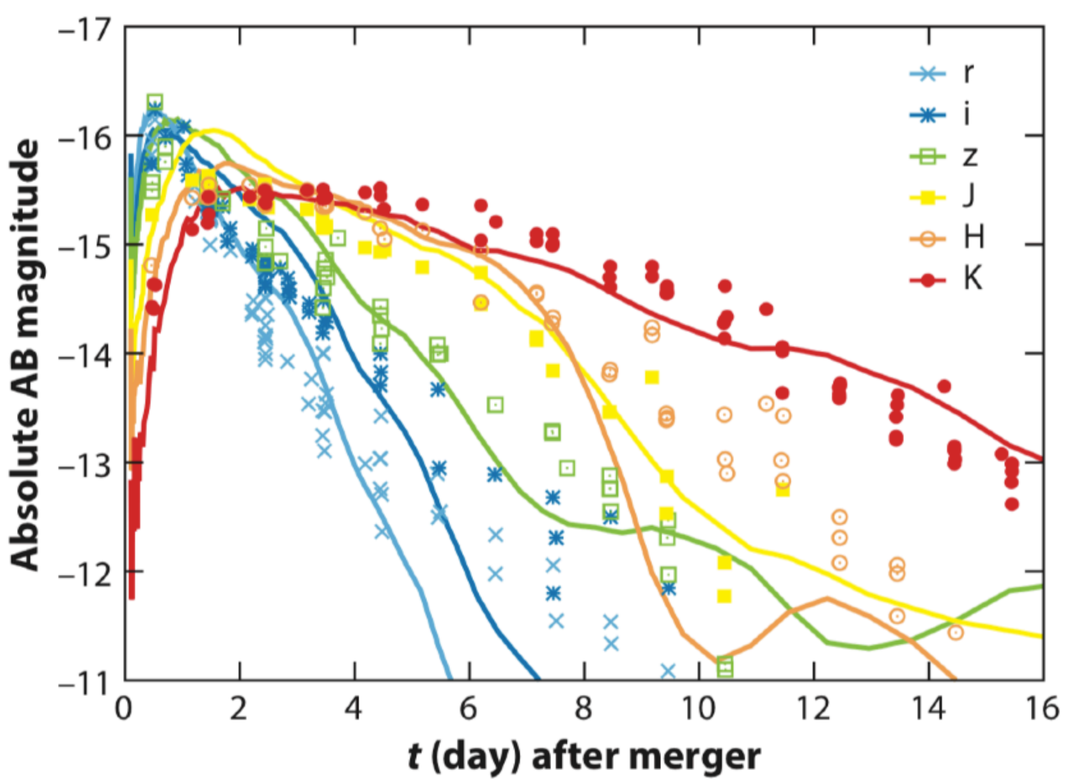
Ji+2016

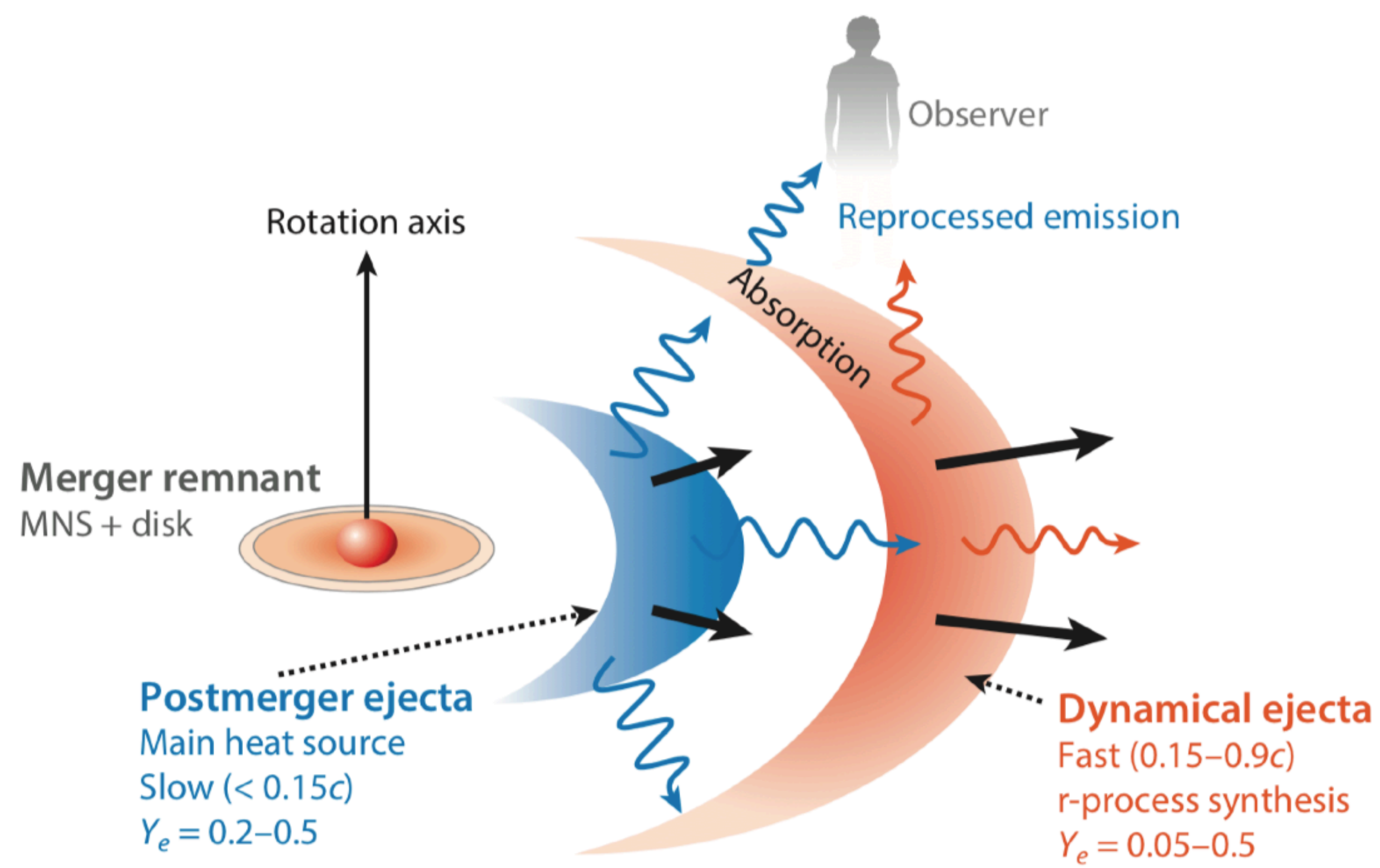
- Some low-metallicity stars have large Eu abundances —> **early enrichment**
- Large scatter in the [Eu/Fe]-[Fe/H] plane

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*

[Lattimer & Schramm 1974; Rosswog+1999; Goriely+2011; Just+2015; Beniamini+2016…]

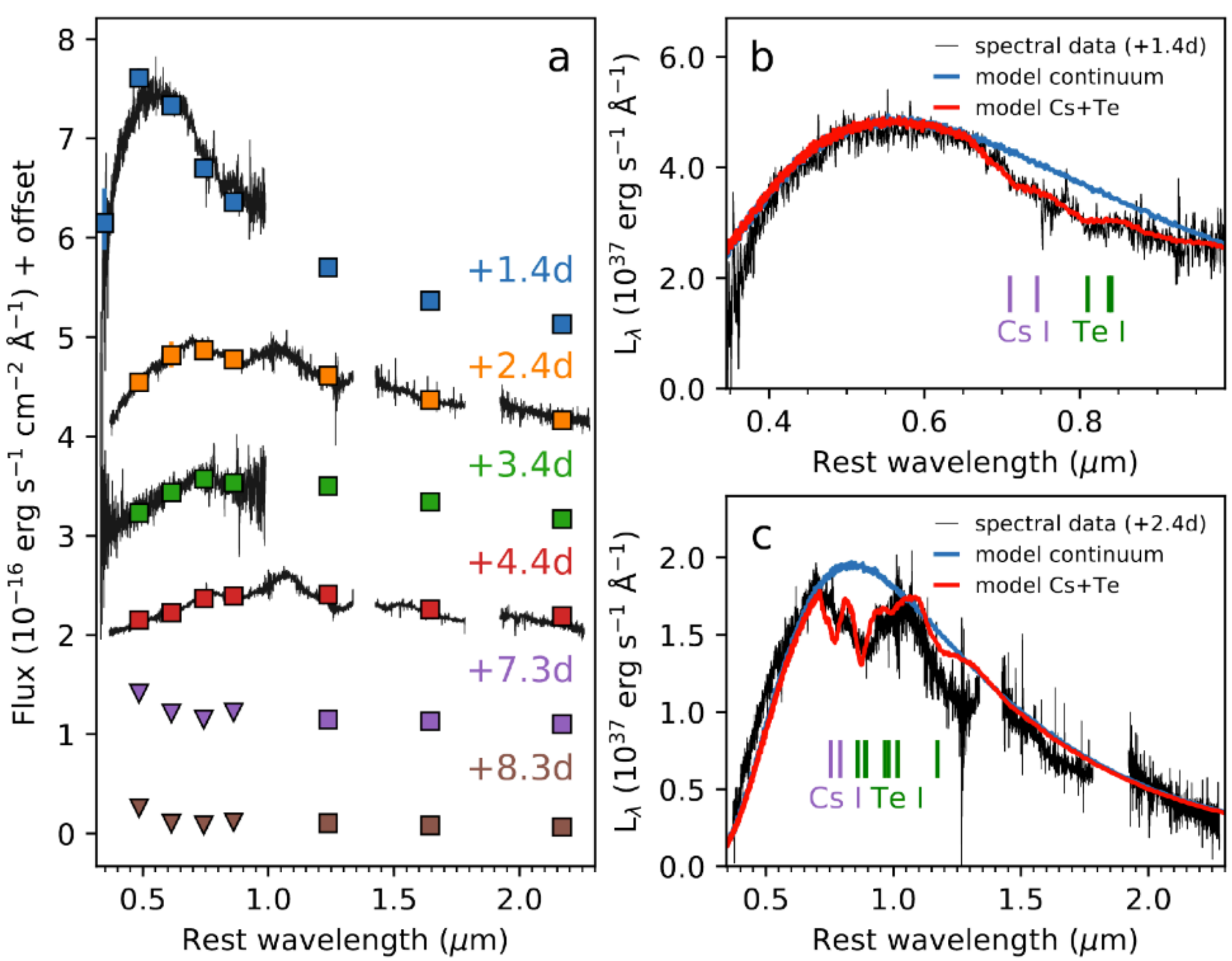


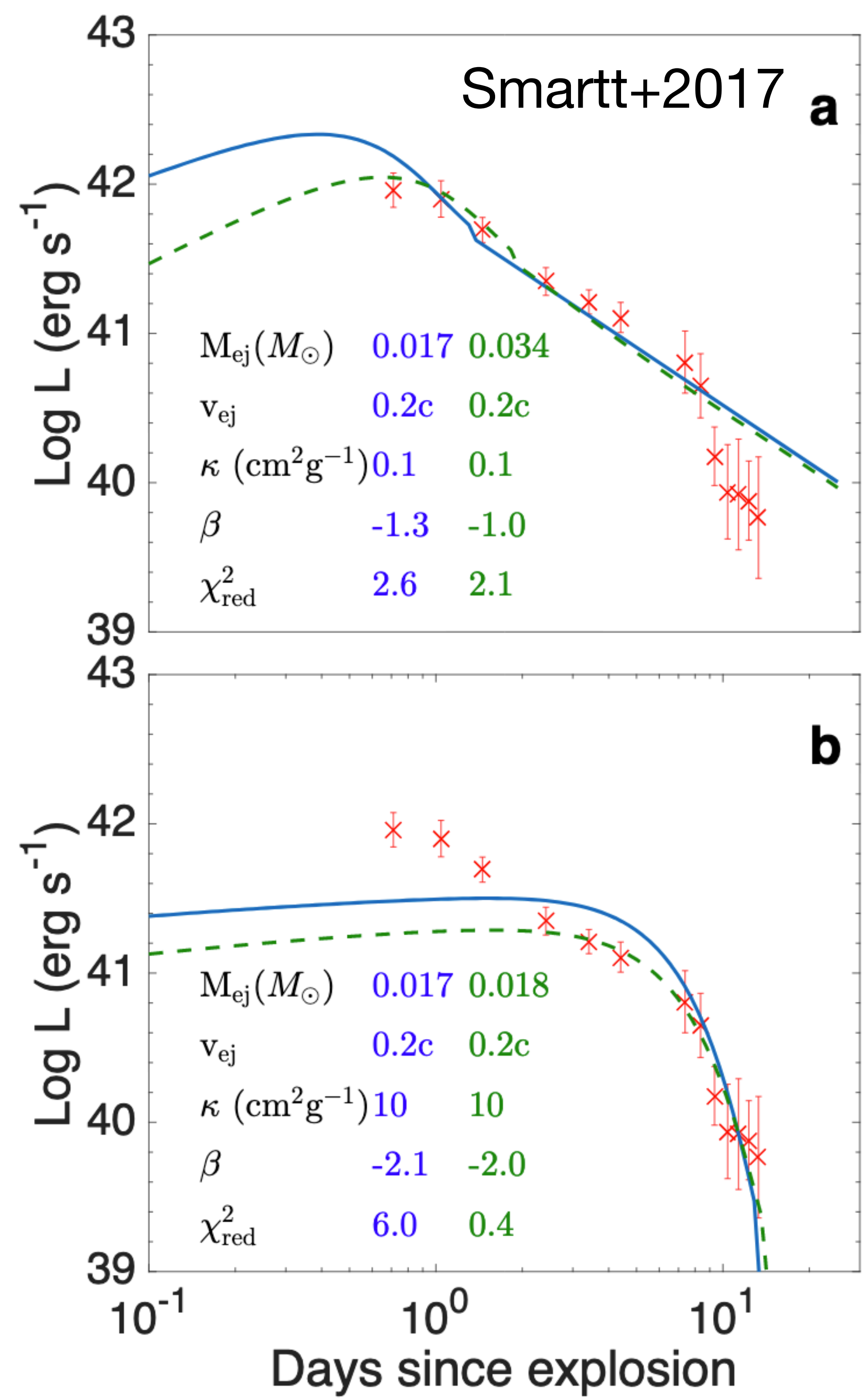


[Shibata & Hotokezaka 2020]

AT 2017gfo kilonova

- UV-optical-IR transient powered by the radioactive decay of r-process elements synthesized in the merger ejecta
- Opacity depends on the chemical composition of the ejecta (—> red/blue components of the light curve)

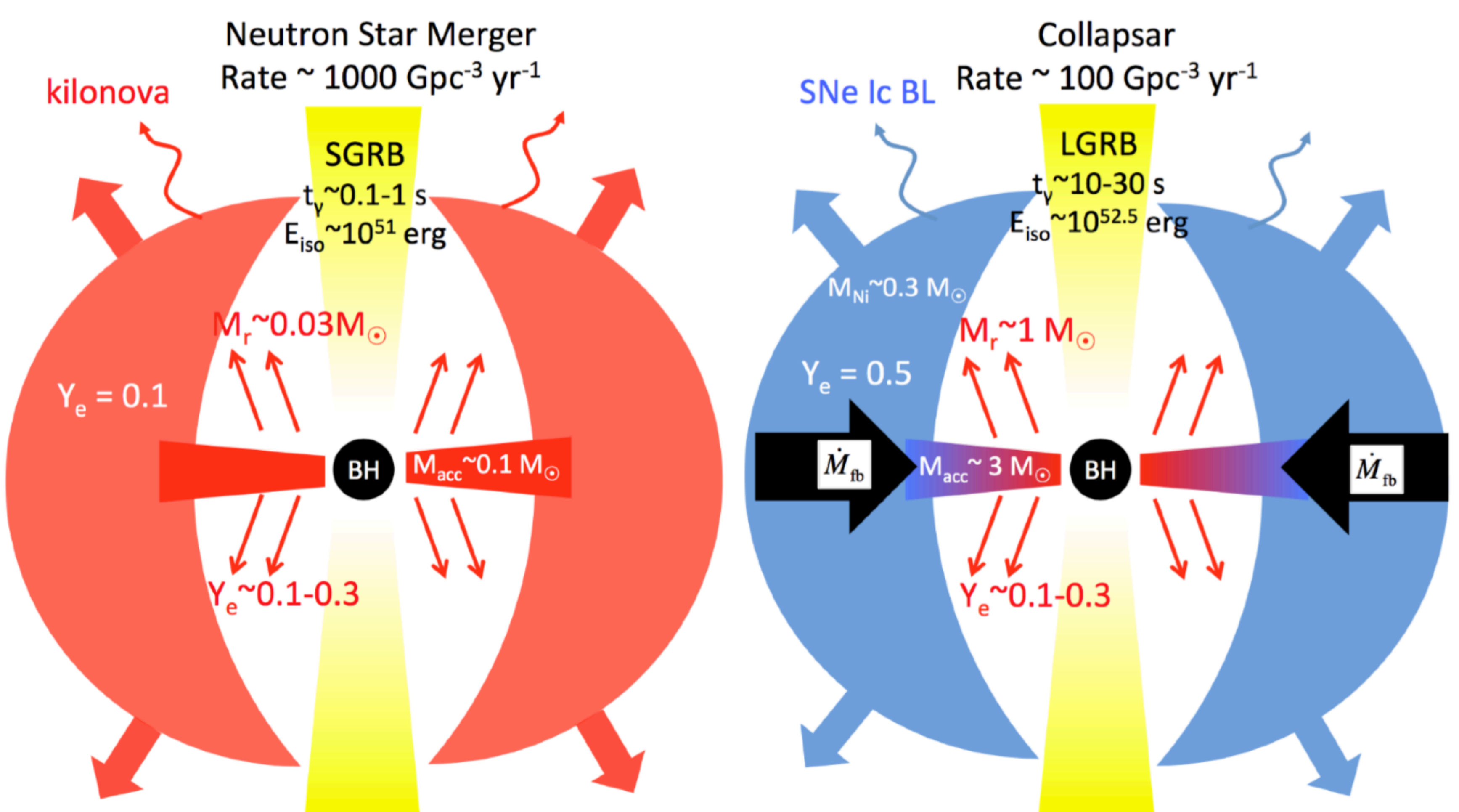


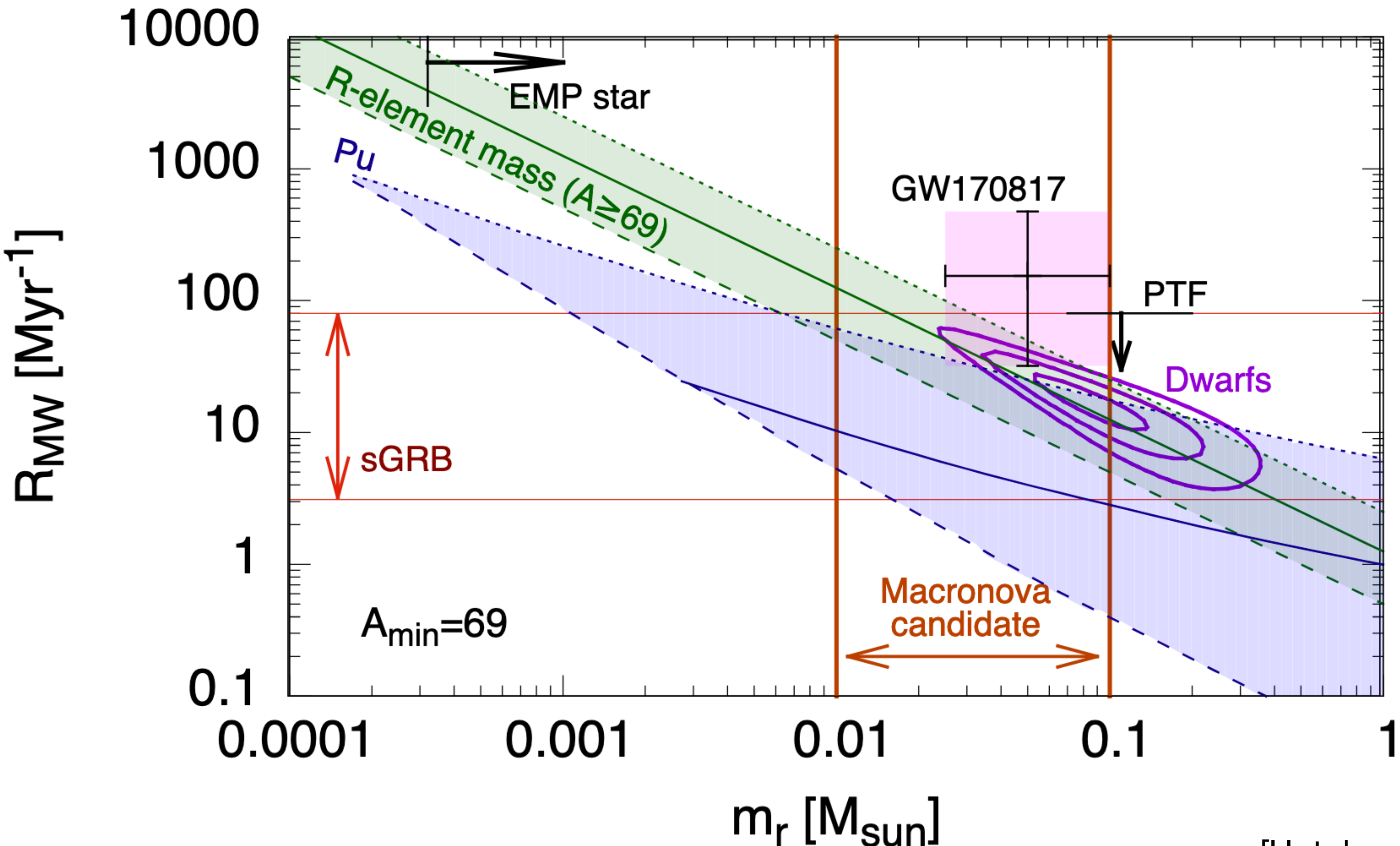


Core-collapse of massive stars

- 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

[Symbalisty+1985; Halevi & Mosta 2018; Siegel+2019…]

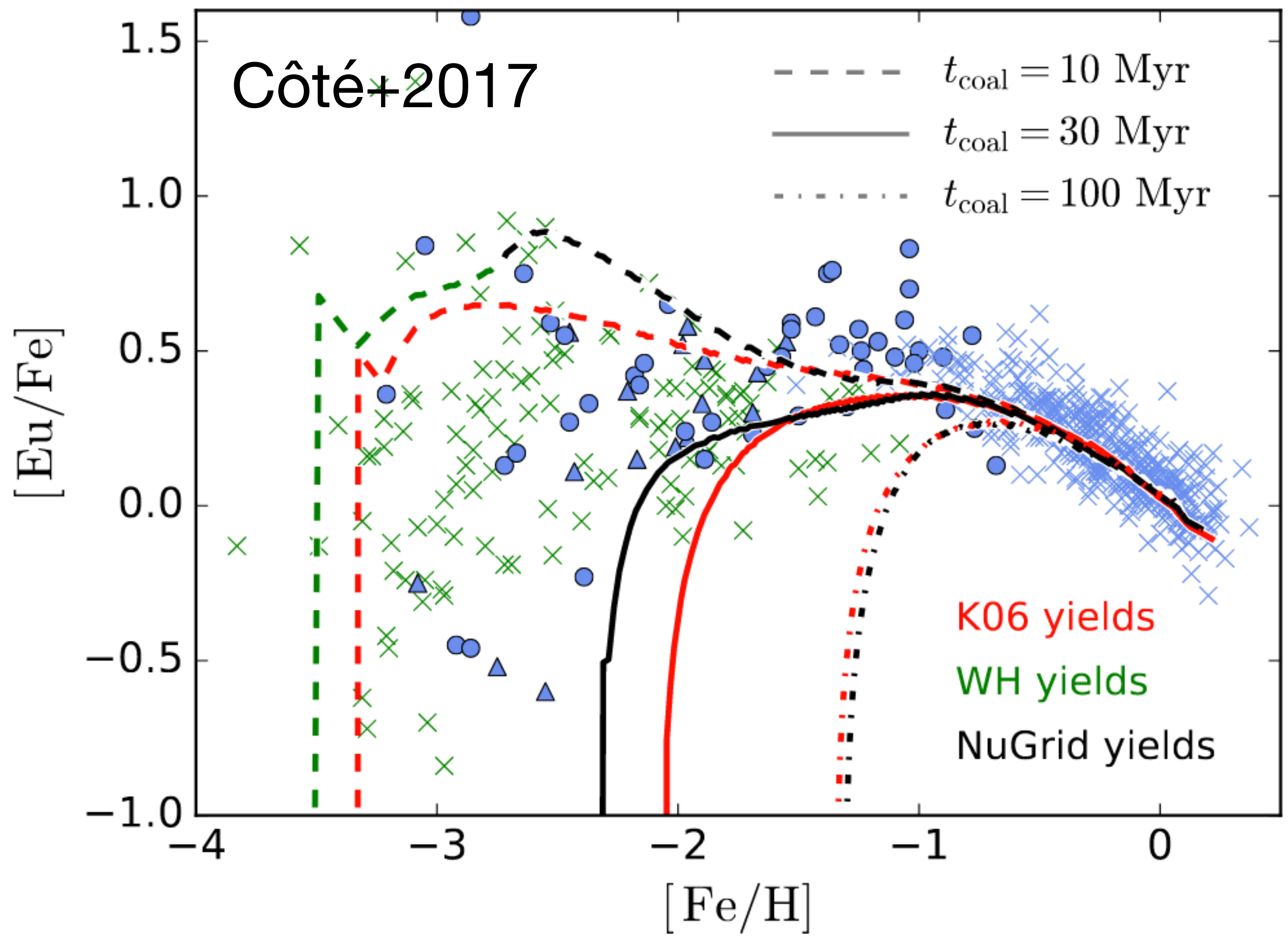


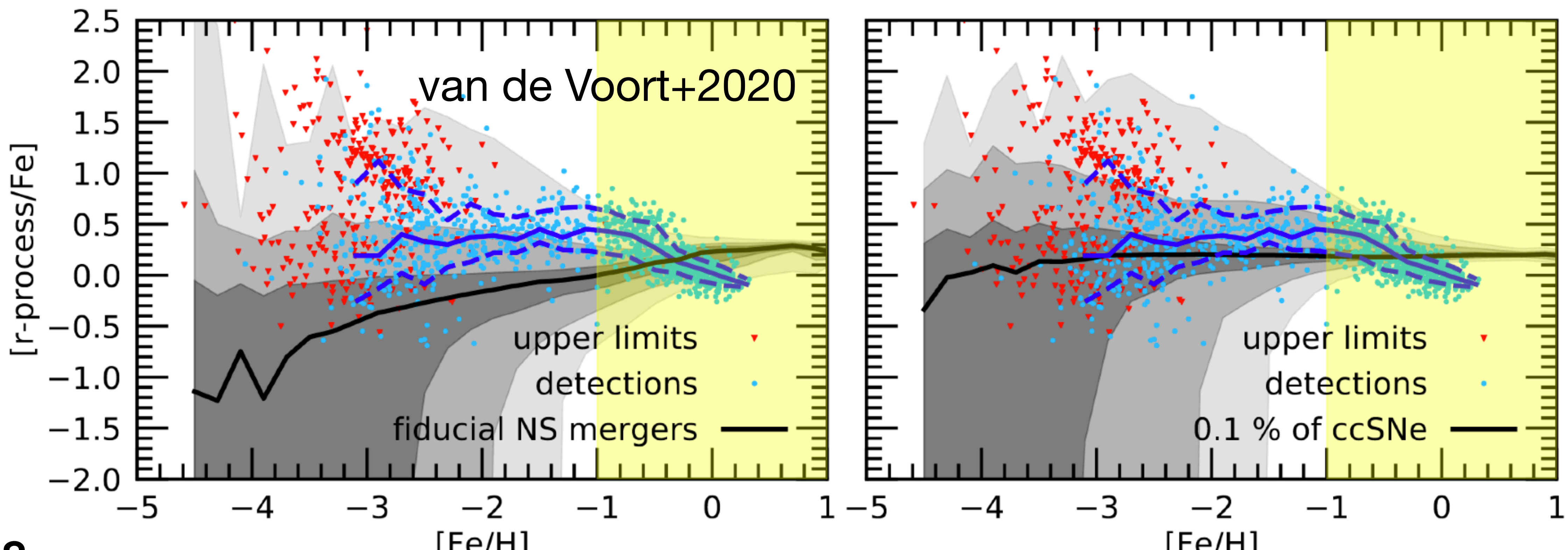


[Hotokezaka+2018]

Where did r-process elements form? (3)

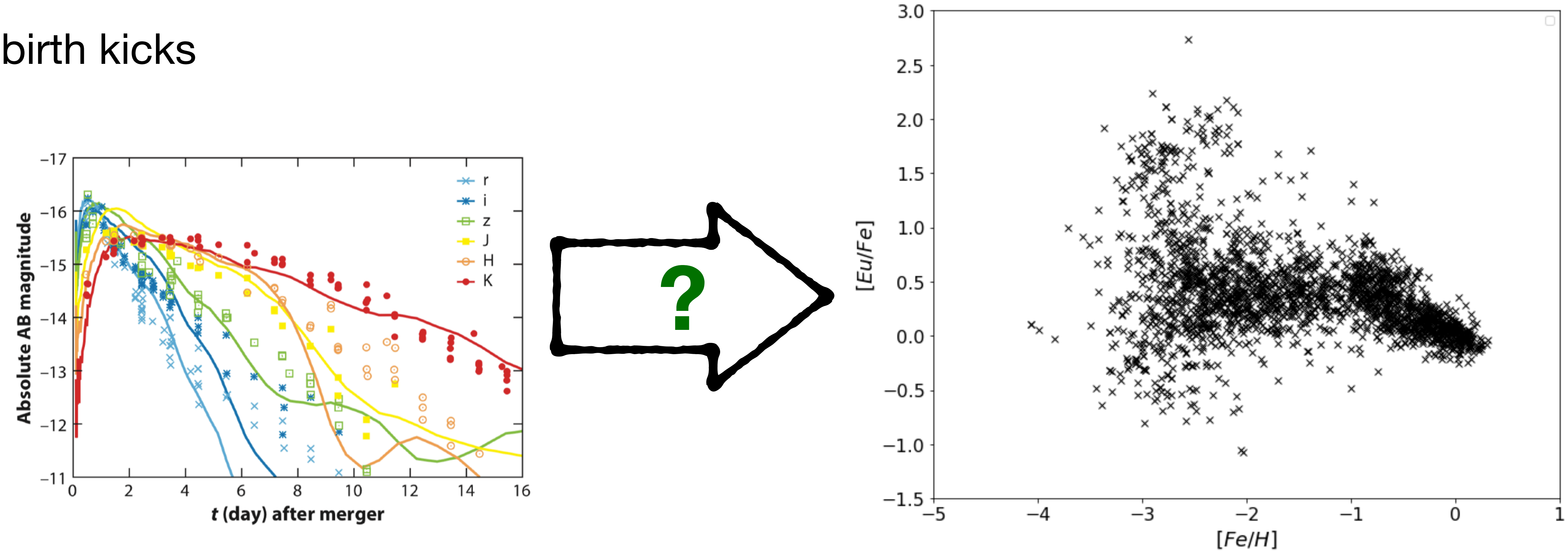
- Most models cannot reproduce the observed abundances with BNS mergers as unique source of r-process elements





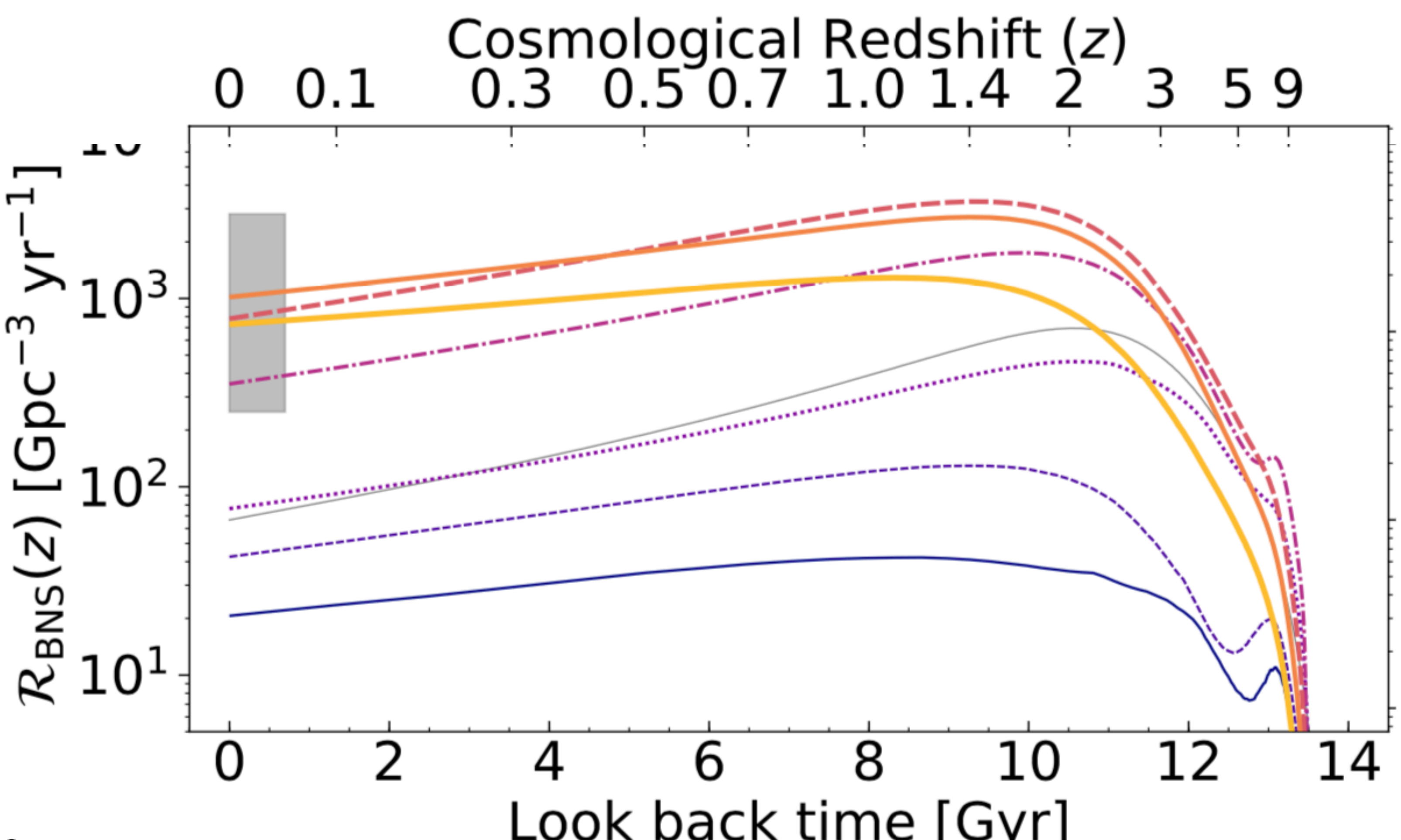
BNS mergers as r-process sources: key unknowns

- BNS merger rates and relation to host galaxy properties
  - Efficiency of forming binaries
  - Delay time distribution between binary formation and merger
- Yields of r-process elements
- Retainment fraction of metals in the galaxy (particularly dwarf galaxies)
- Mixing timescales of metals in the galaxy
- NS birth kicks



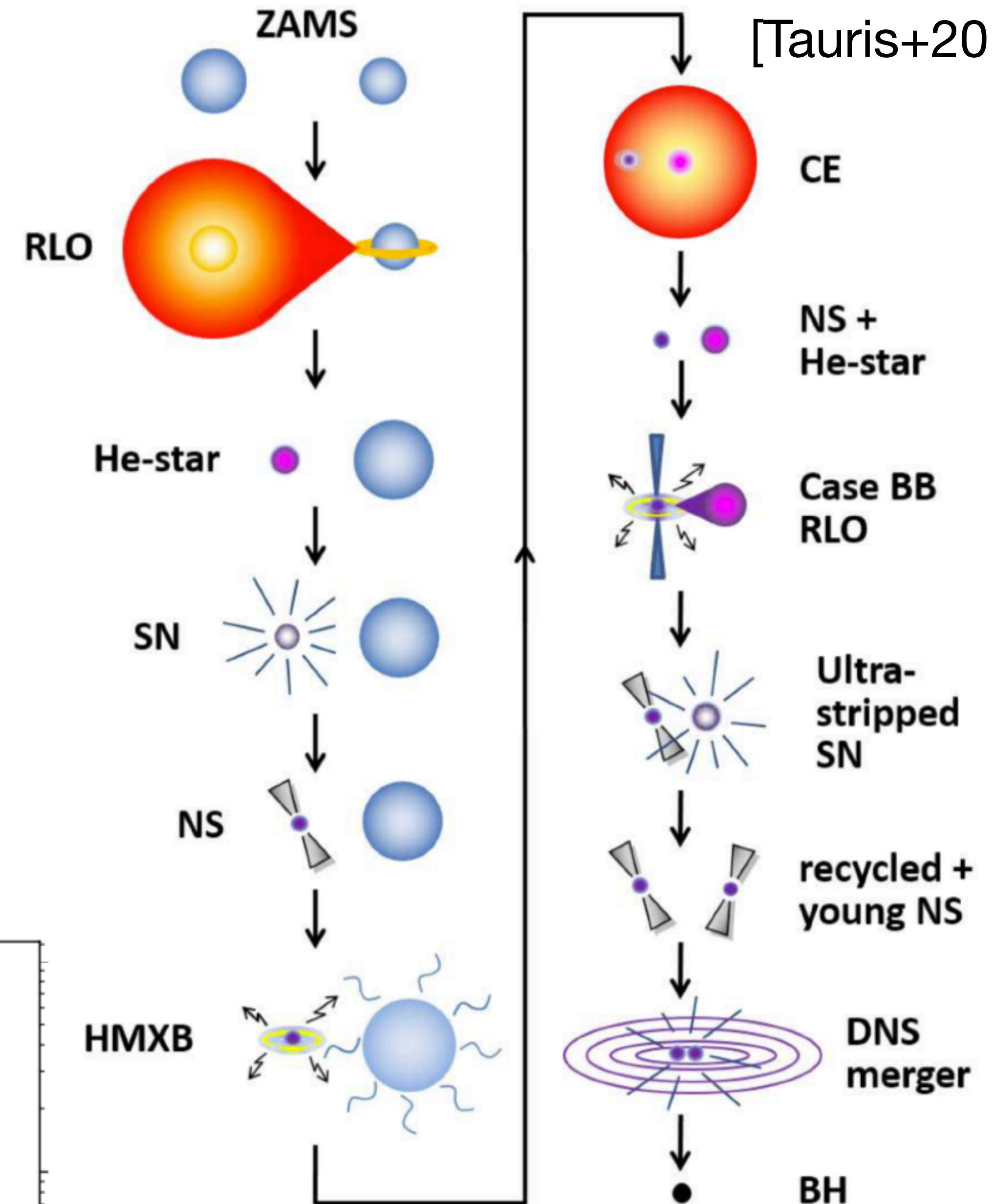
BNS formation and merger rates

- BNS form from massive stellar binaries
- Poorly known processes that strongly influence formation rates and delays to merger:
  - SN explosion mechanism
  - Common envelope phase
  - NS birth kicks
  - …



[Santoliquido+2020]

Common envelope efficiency

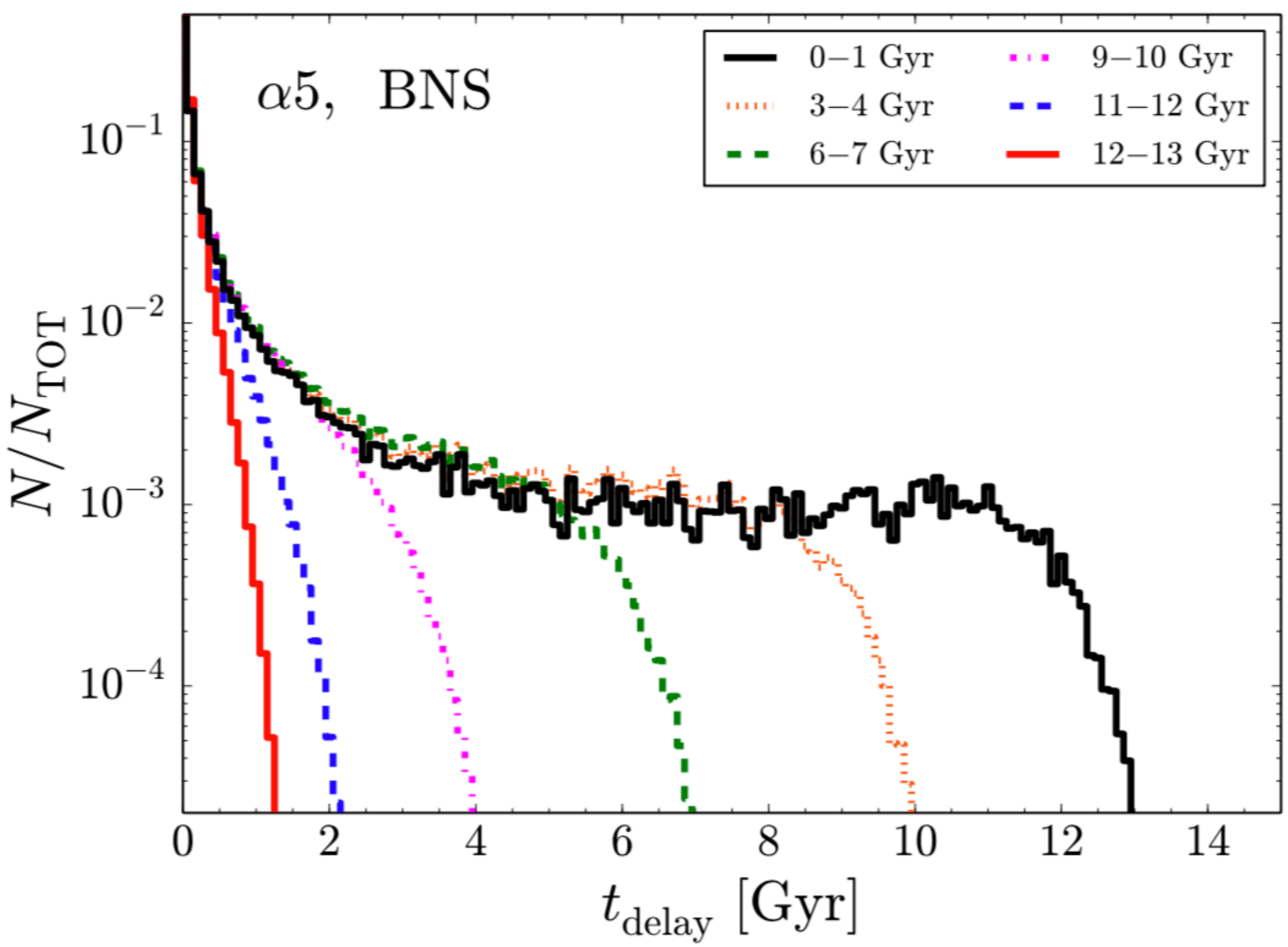


[Tauris+2017]

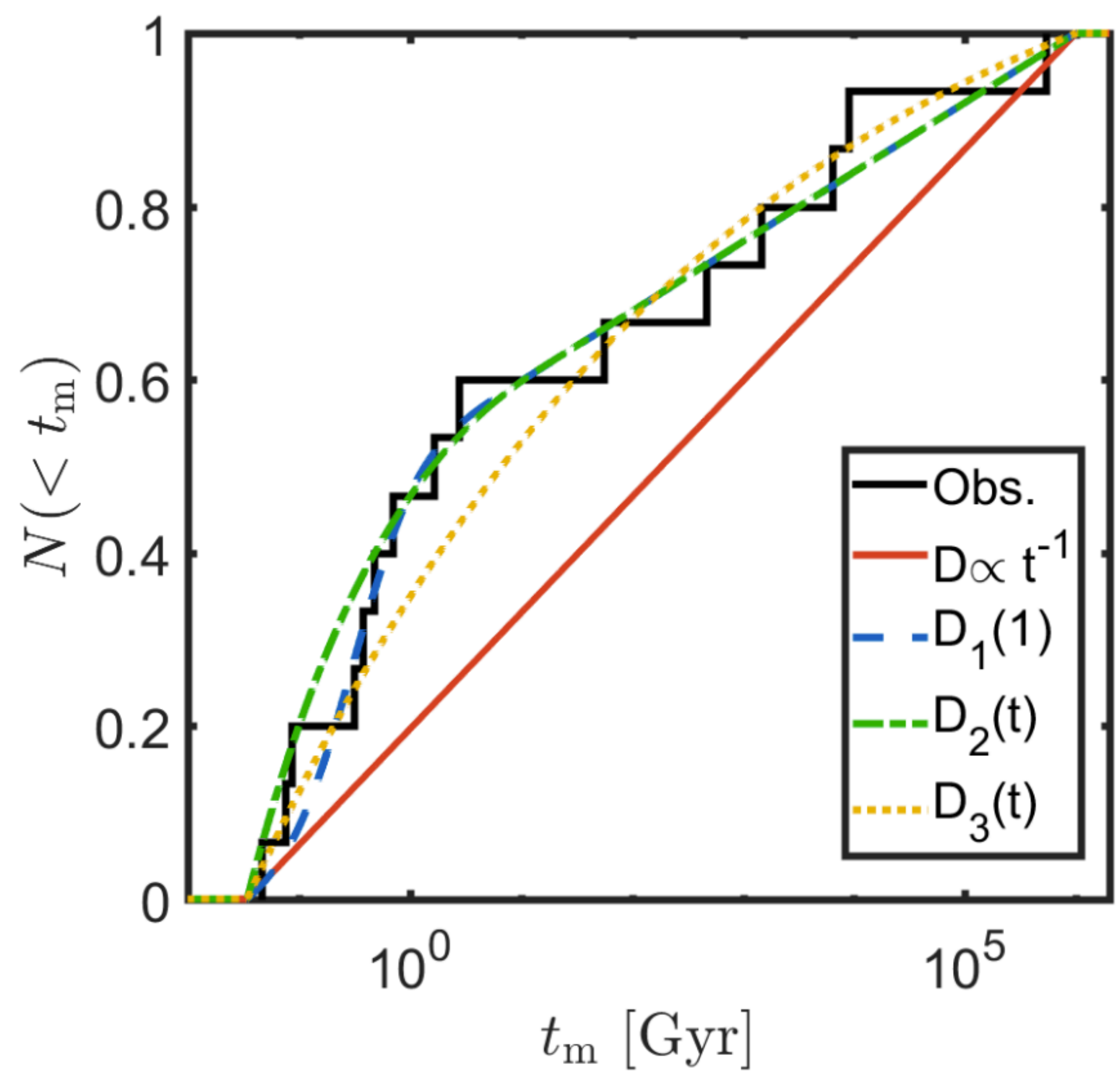
BNS mergers time delay distributions

- ✱ Population synthesis models prefer $P(t) \propto 1/t$ [Belczynski+2016, Mapelli+2019, ...]
- ✱ Separations of observed galactic binaries imply shorter delays [Beniamini+2016; Beniamini & Piran 2019]
- ✱ Time delay may depend on masses [Romero-Shaw+2020, Galaudage+2020]

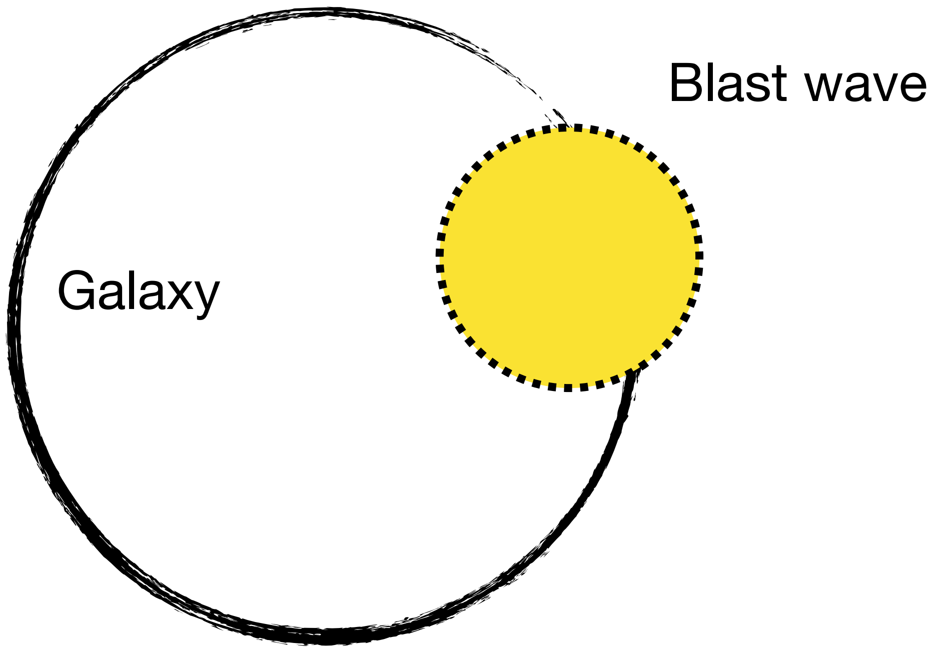
[Mapelli+2019]



[Beniamini&Piran 2019]



- Ultra-faint dwarf galaxies have low escape velocities
- If r-process elements are produced in energetic events, can they stay in the galaxy?

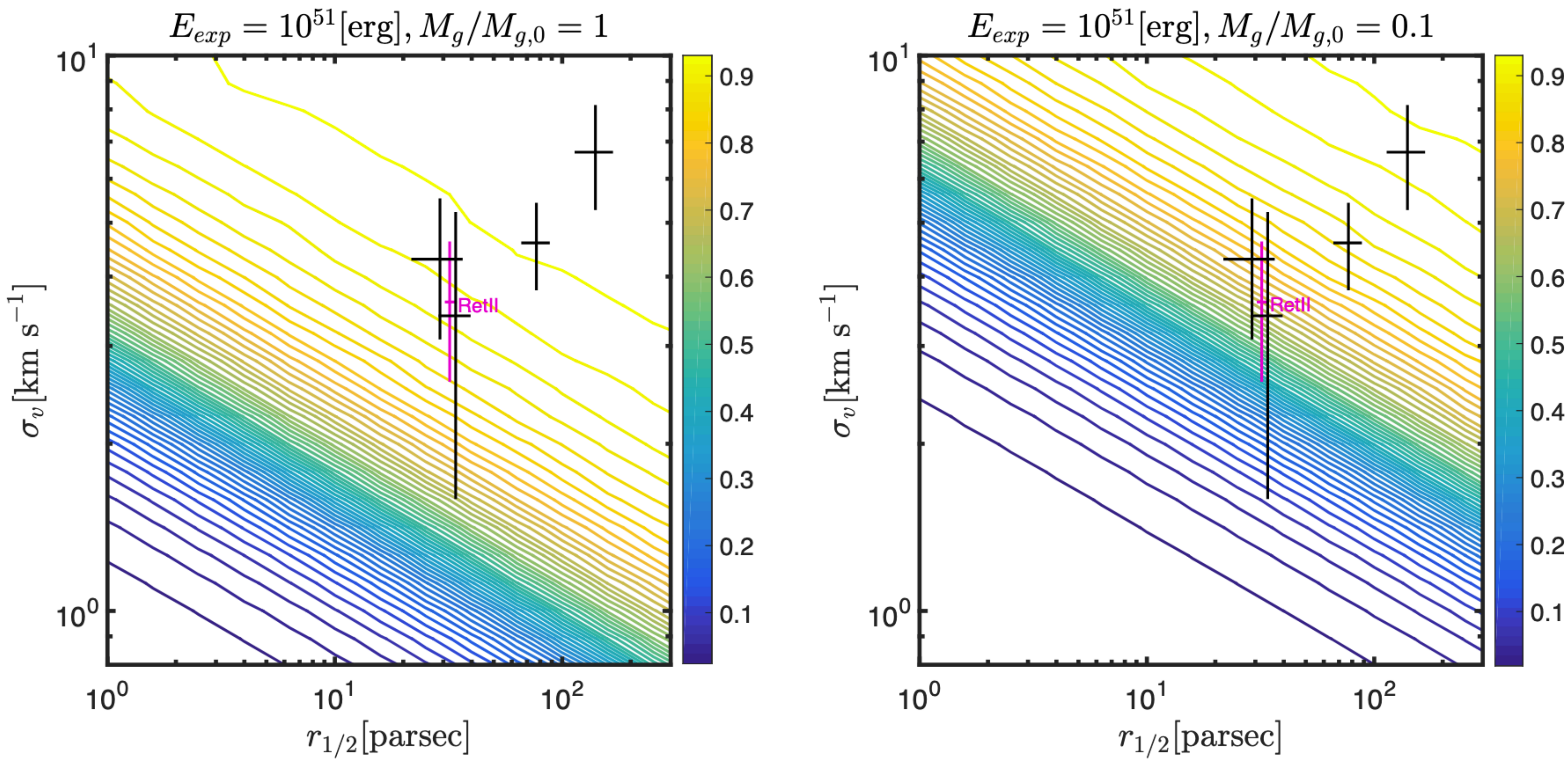


- Radius of blast wave depends on explosion energy, galaxy velocity dispersion and ambient density

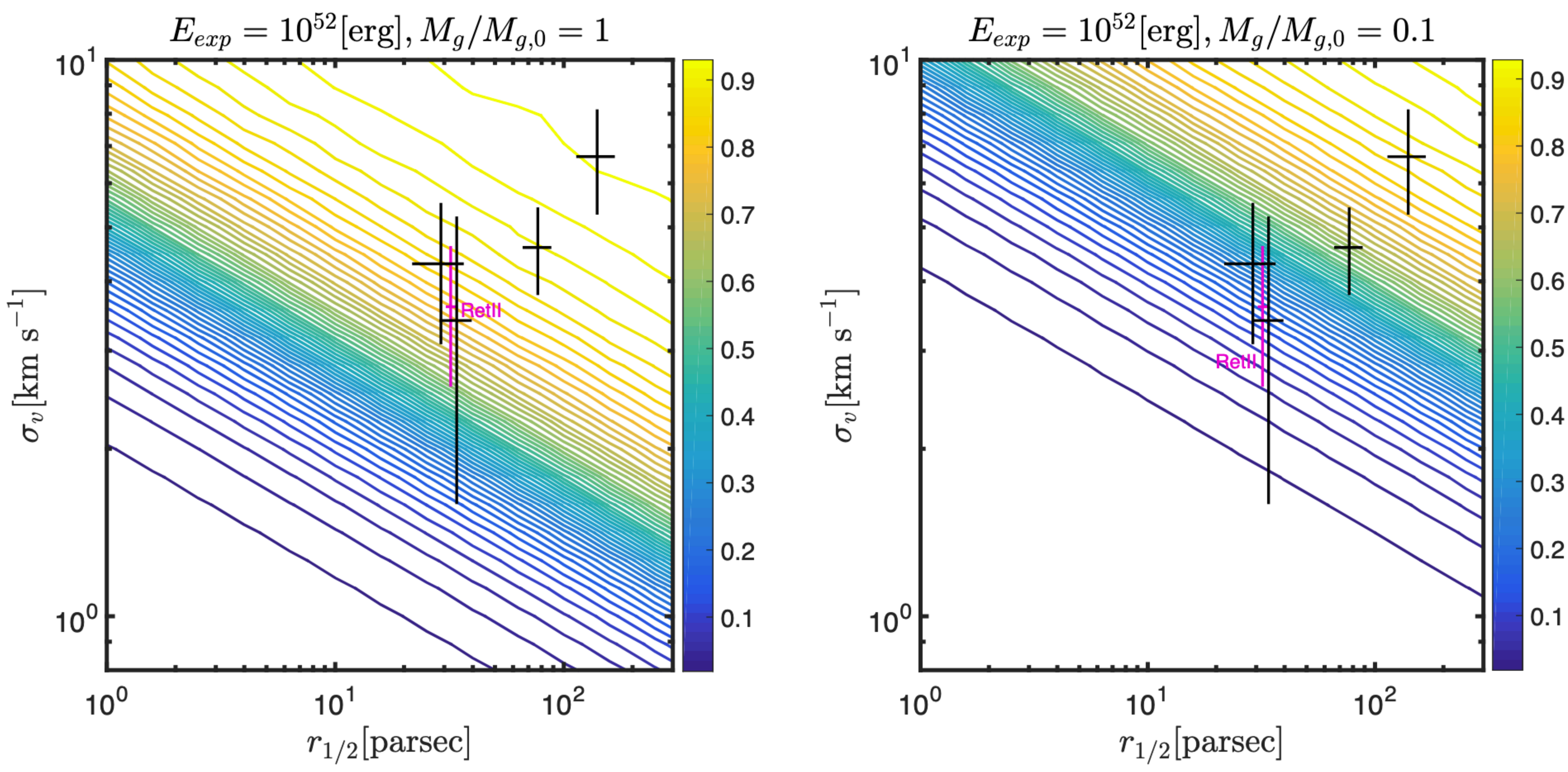
- Density profile in dwarf galaxies $$M_h(r) = \frac{5 r_{1/2} \sigma_v^2 (r/r_{1/2})^3}{G\left[1 + (r/r_{1/2})^2\right]}$$
- Unspecified heavy element formation process with explosion energy E_{exp}
- Potential well of the galaxy characterized by its velocity dispersion σ_v
- How much of the heavy elements produced in a dwarf galaxy can be retained?

[Beniamini, **ID**, Silk 2017]

[Beniamini, **ID**, Silk 2017]

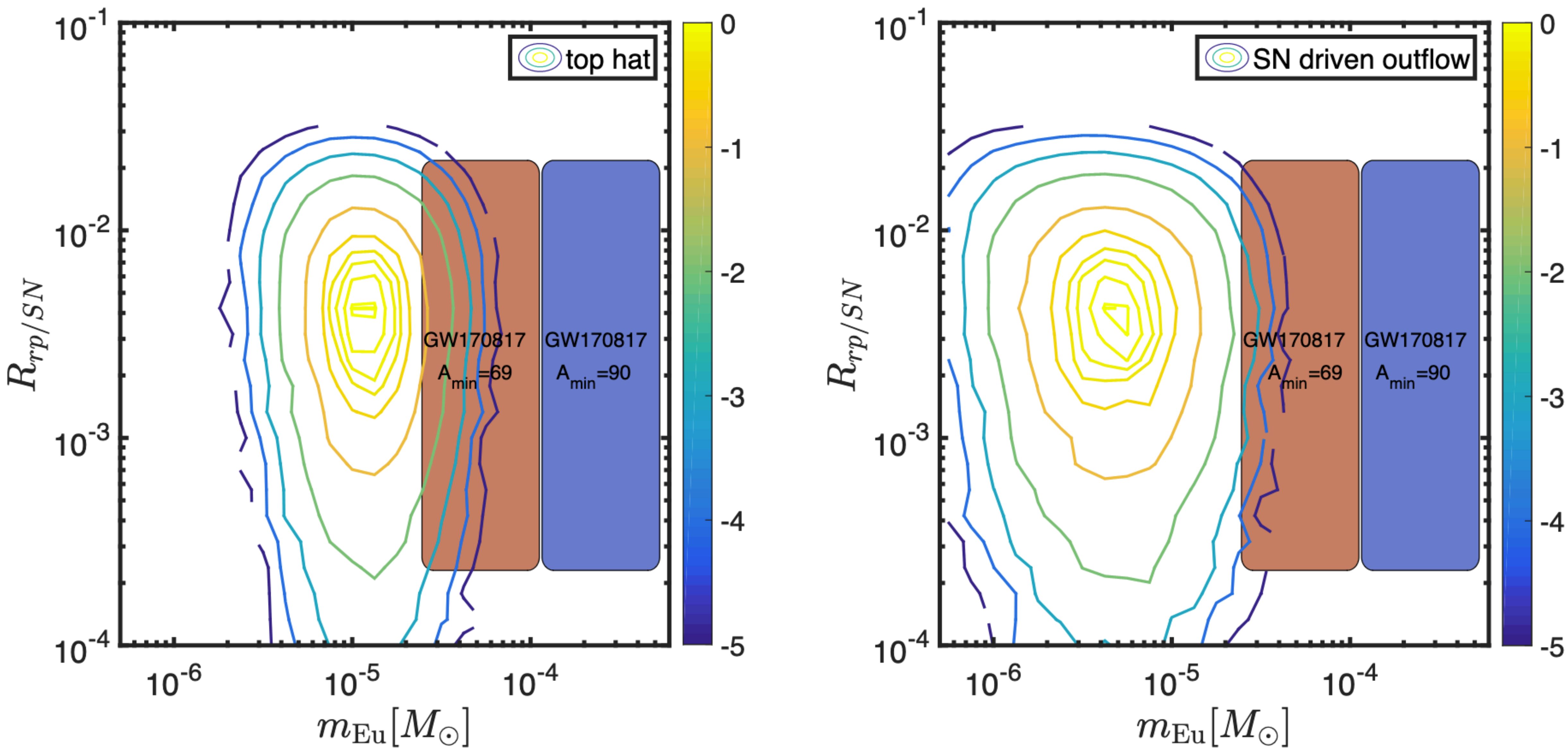


[Beniamini, **ID**, Silk 2017]



Beniamini, **ID**, Silk 2017

- For each dwarf galaxy from our sample, draw the number and times of events that produce heavy elements, estimate the number of stars formed with given Fe and Eu abundances, compare with observations
- Different gas loss models
- Events that produce r-process elements have to be very rare relative to CC SNe

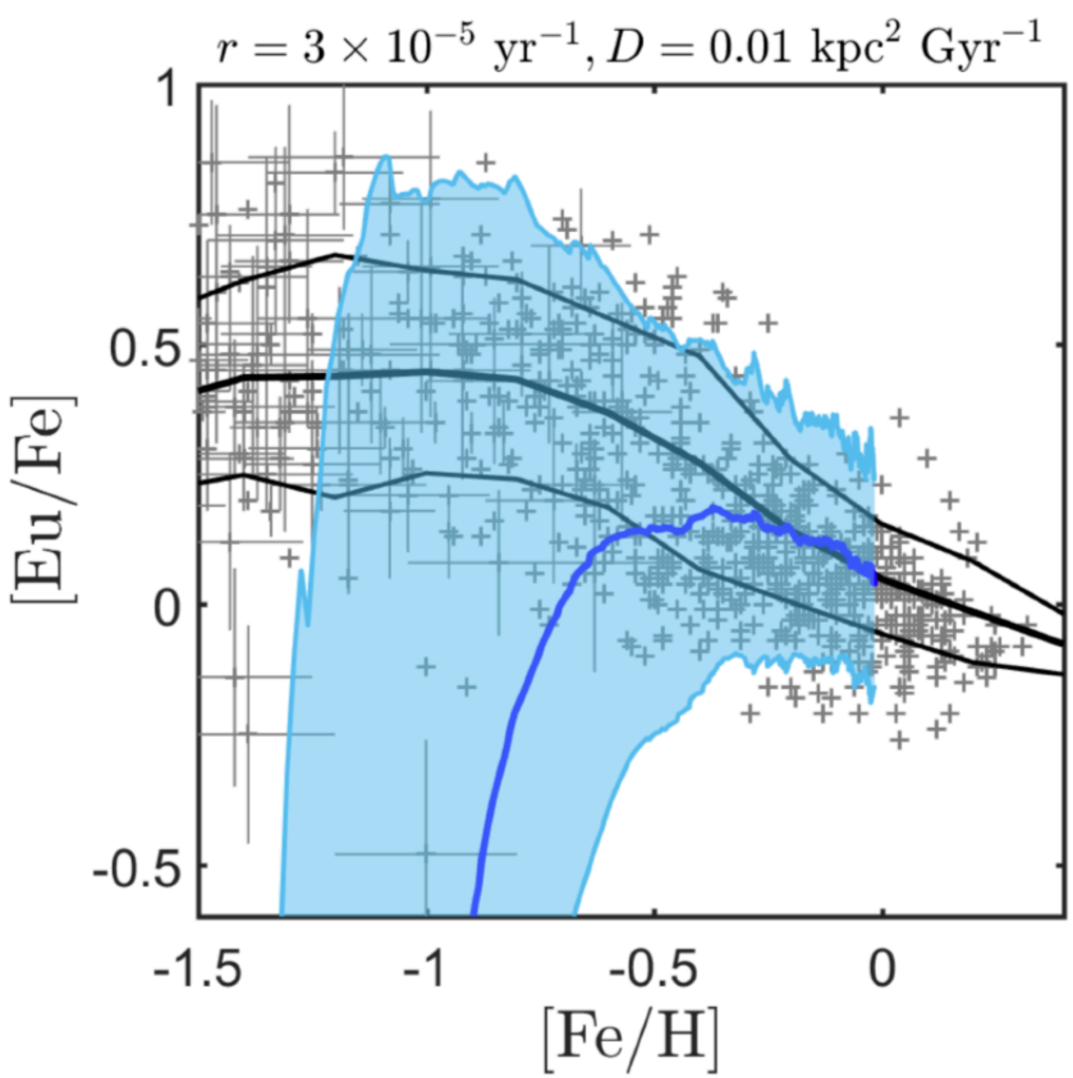


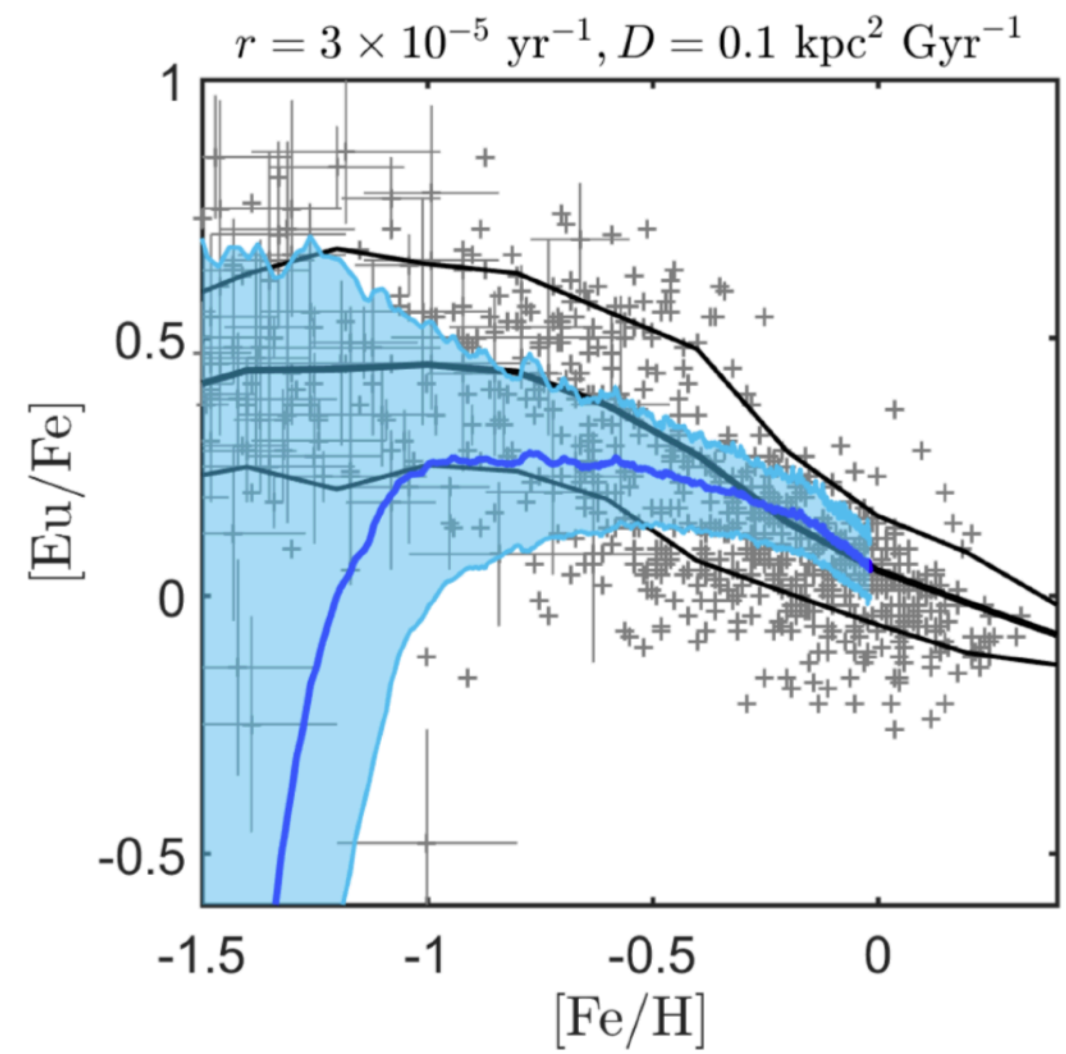
BNS mergers and mixing of r-process elements in the galaxy

* Turbulent mixing of r-process elements in the ISM

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

[Beniamini and Hotokezaka 2020]

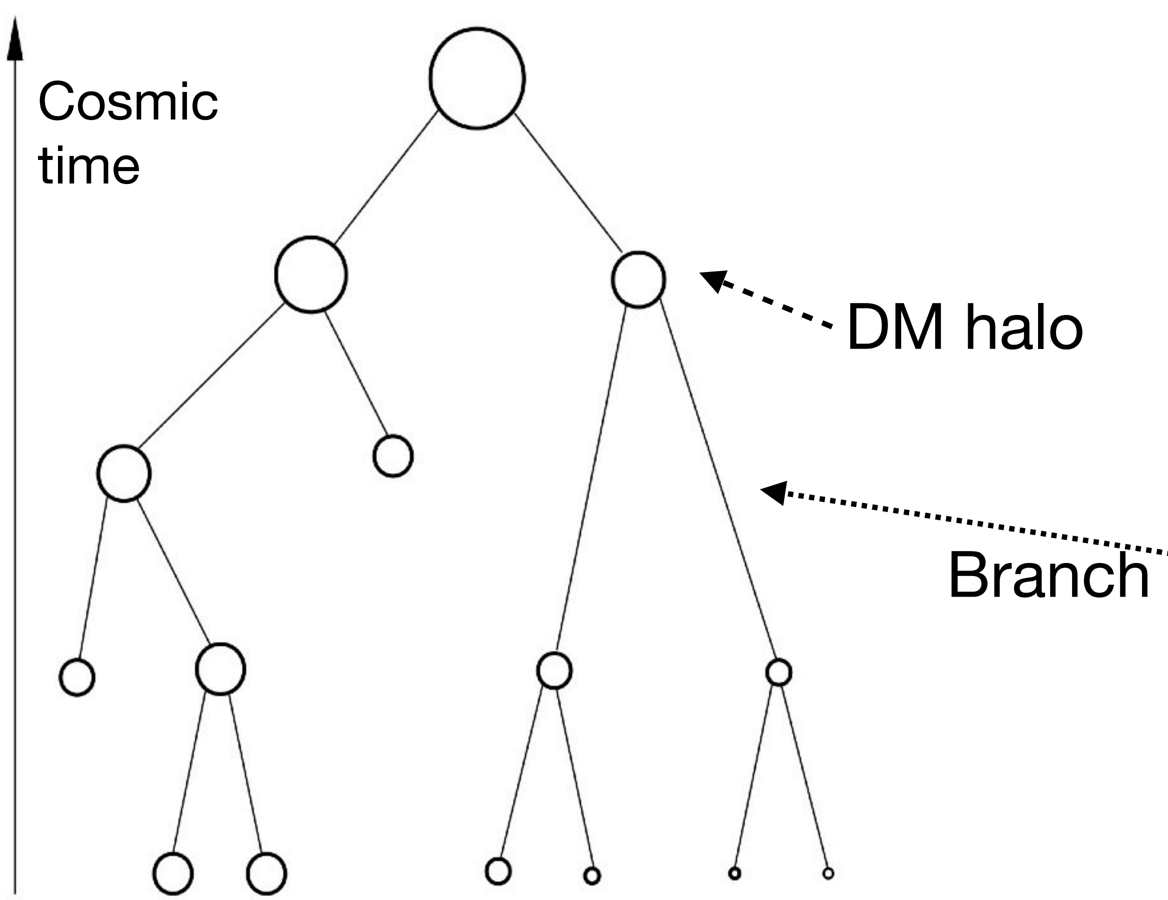


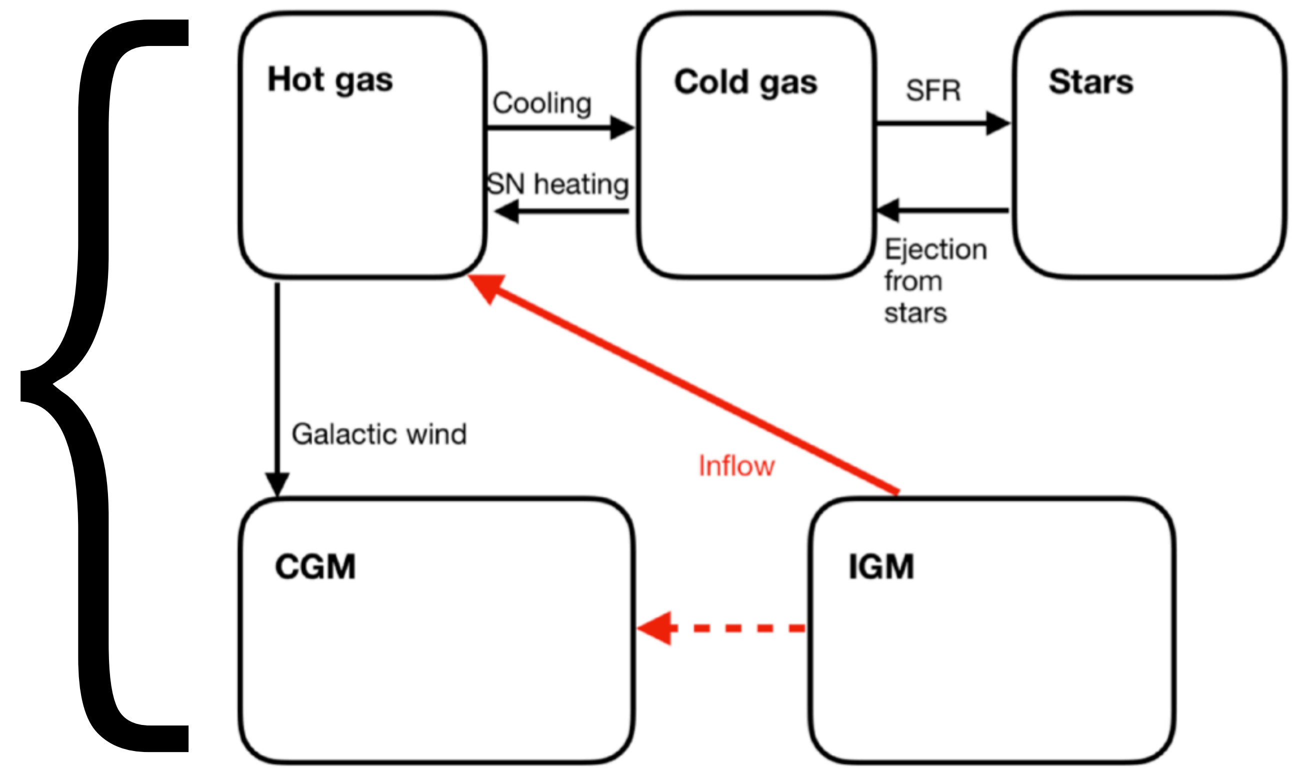


r-process in the Galaxy: chemical evolution model

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

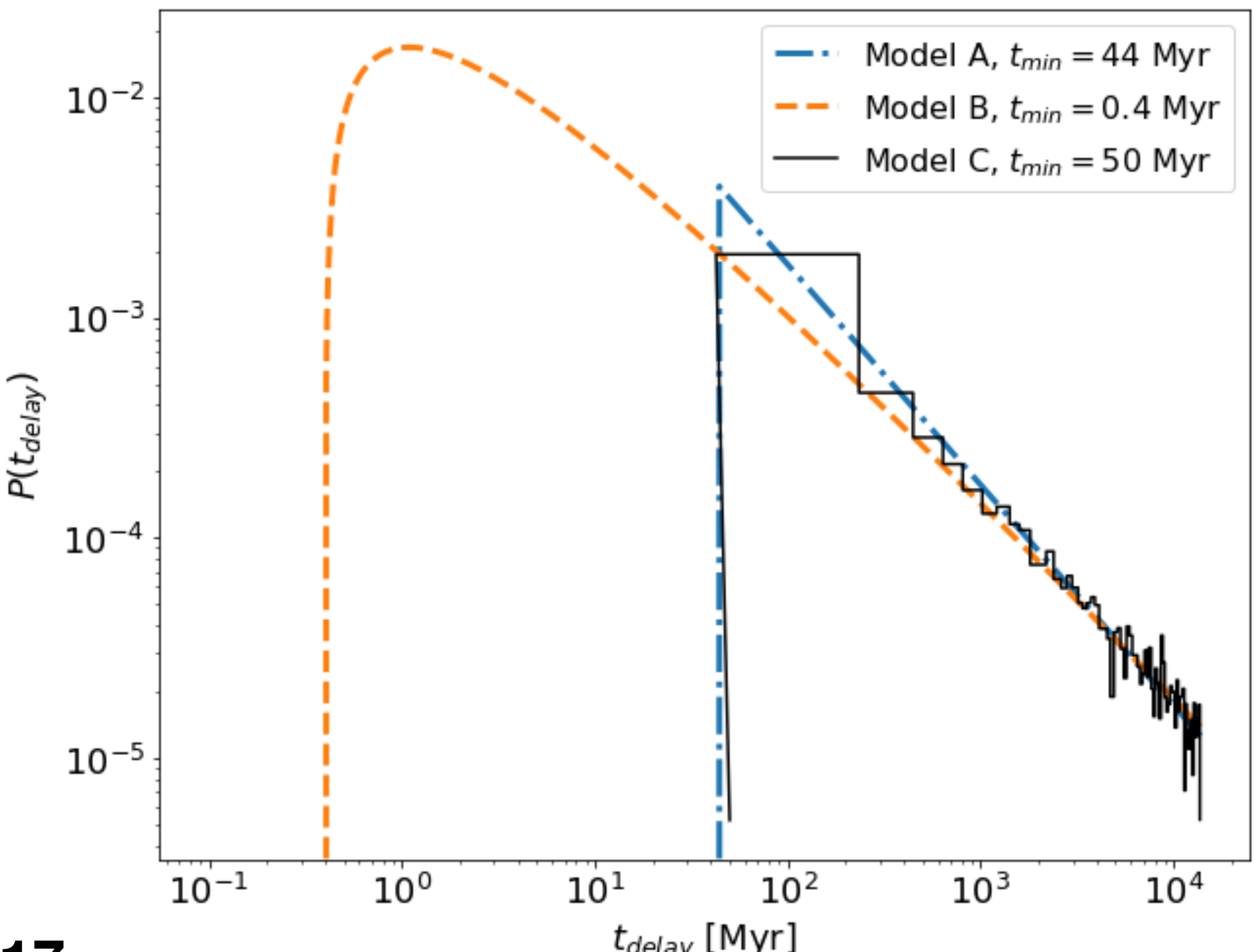




ID+2020

Formation and merger rates of BNS

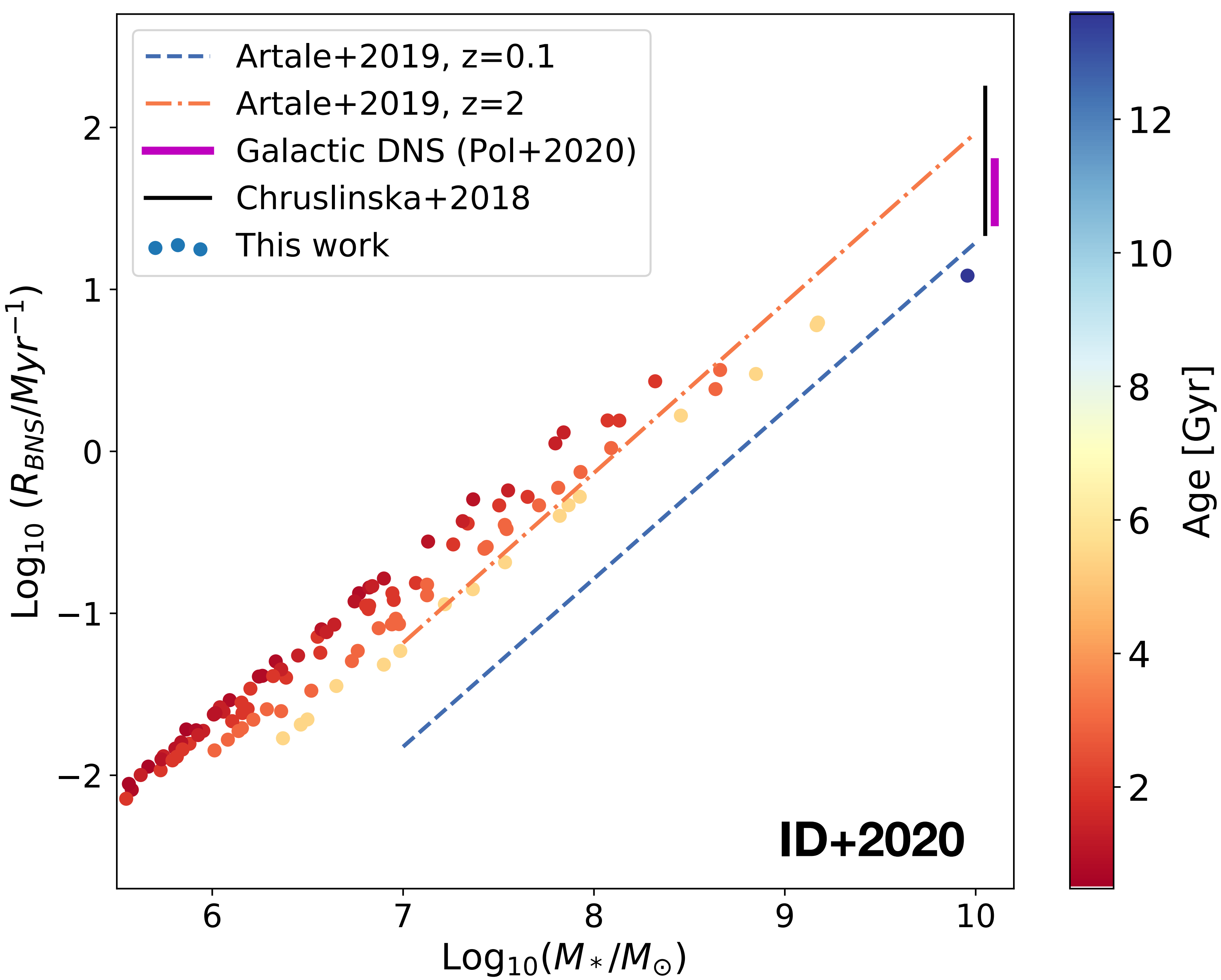
- NS form from massive stars (dependence on mass, metallicity [Fryer+2012])
- Efficiency parameter for binary formation
- r-process yield per event (degenerate with efficiency parameter)



- Distribution of time delays between formation and merger (with free parameters)
  - Model A: $P(t) \propto 1/t$
  - Model B: $P(t) \propto log(t/t_0)/t$
  - Model C: from [Chruslinska+2018]

ID+2020

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



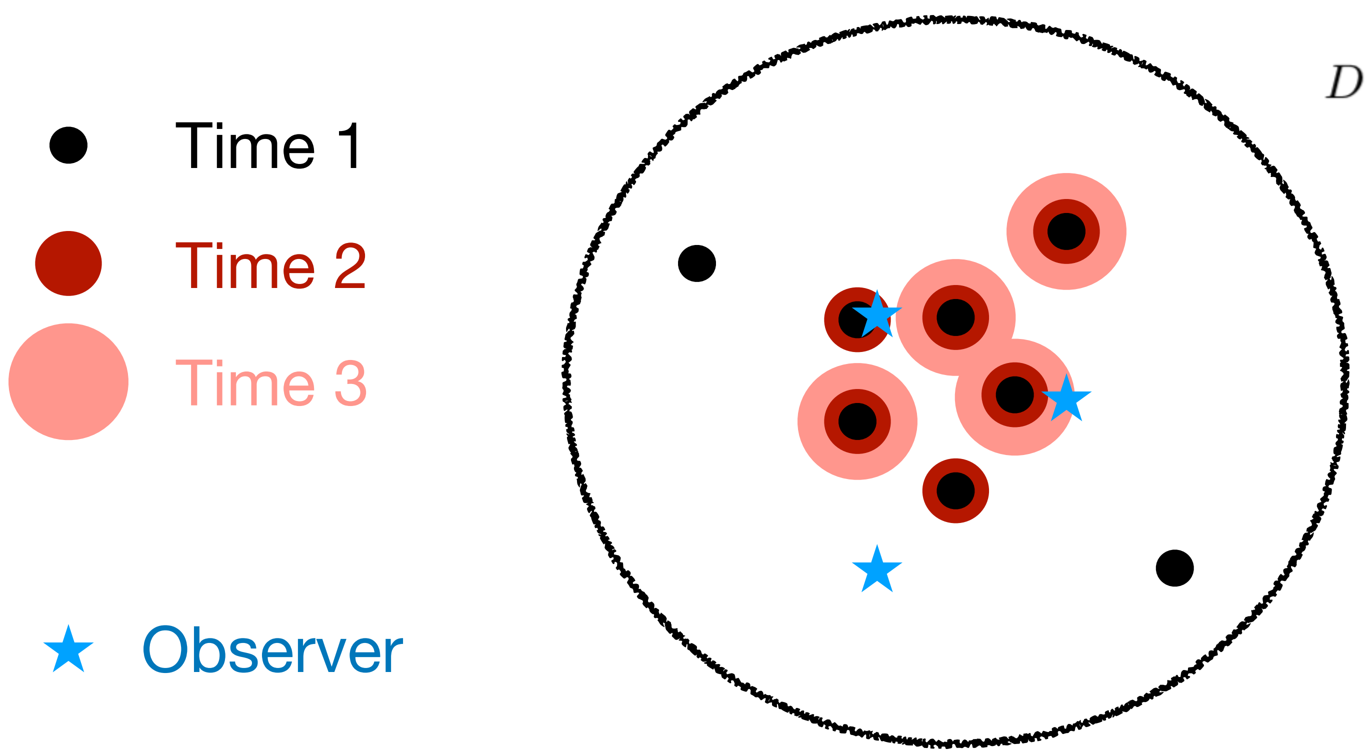
Galactic chemical evolution model: turbulent mixing

- 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]

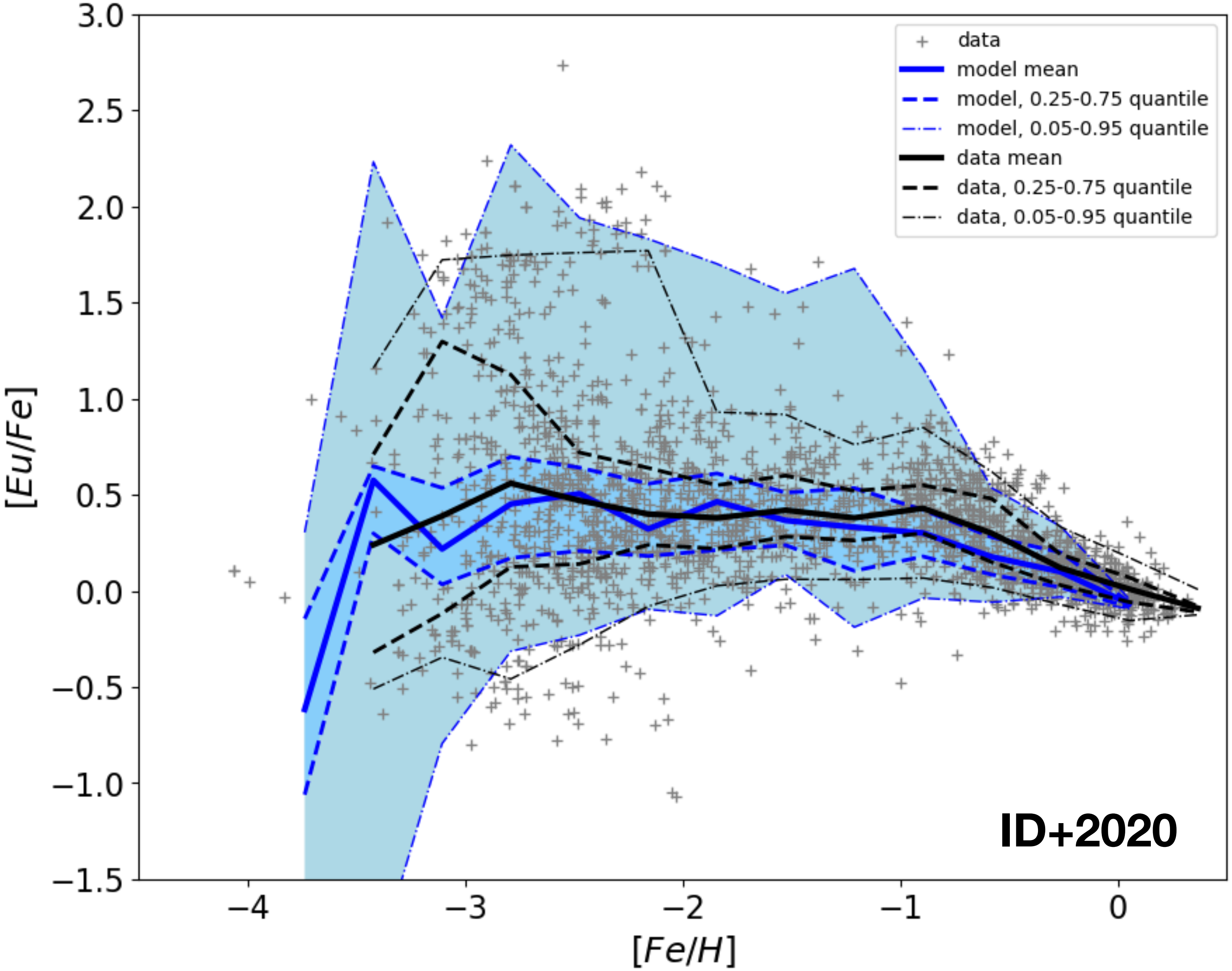
$$\rho_{Eu}(\vec{r}_{\rm obs}, t_{\rm obs}) = \sum_i \frac{m_{\rm rp}}{4\pi D(t_{\rm obs} - t_i)} \exp\left(\frac{|\vec{r}_{\rm obs} - r_i|^2}{4\pi D\Delta t}\right)$$

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



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

- Model reproduces the observed abundances at low and high metallicities



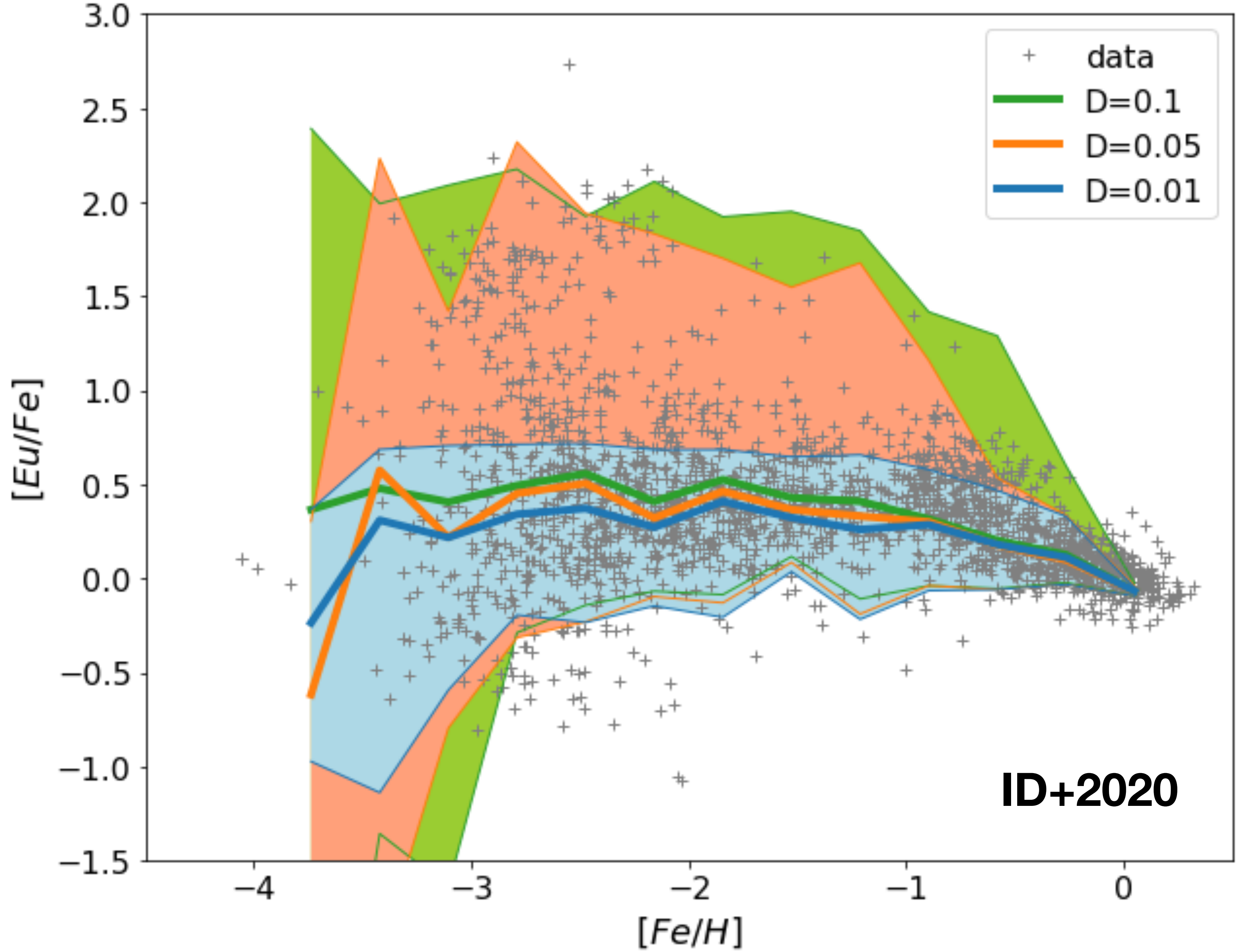
$$P(t) \propto t^{-1}$$

$$t_{min} = 10\ Myr$$

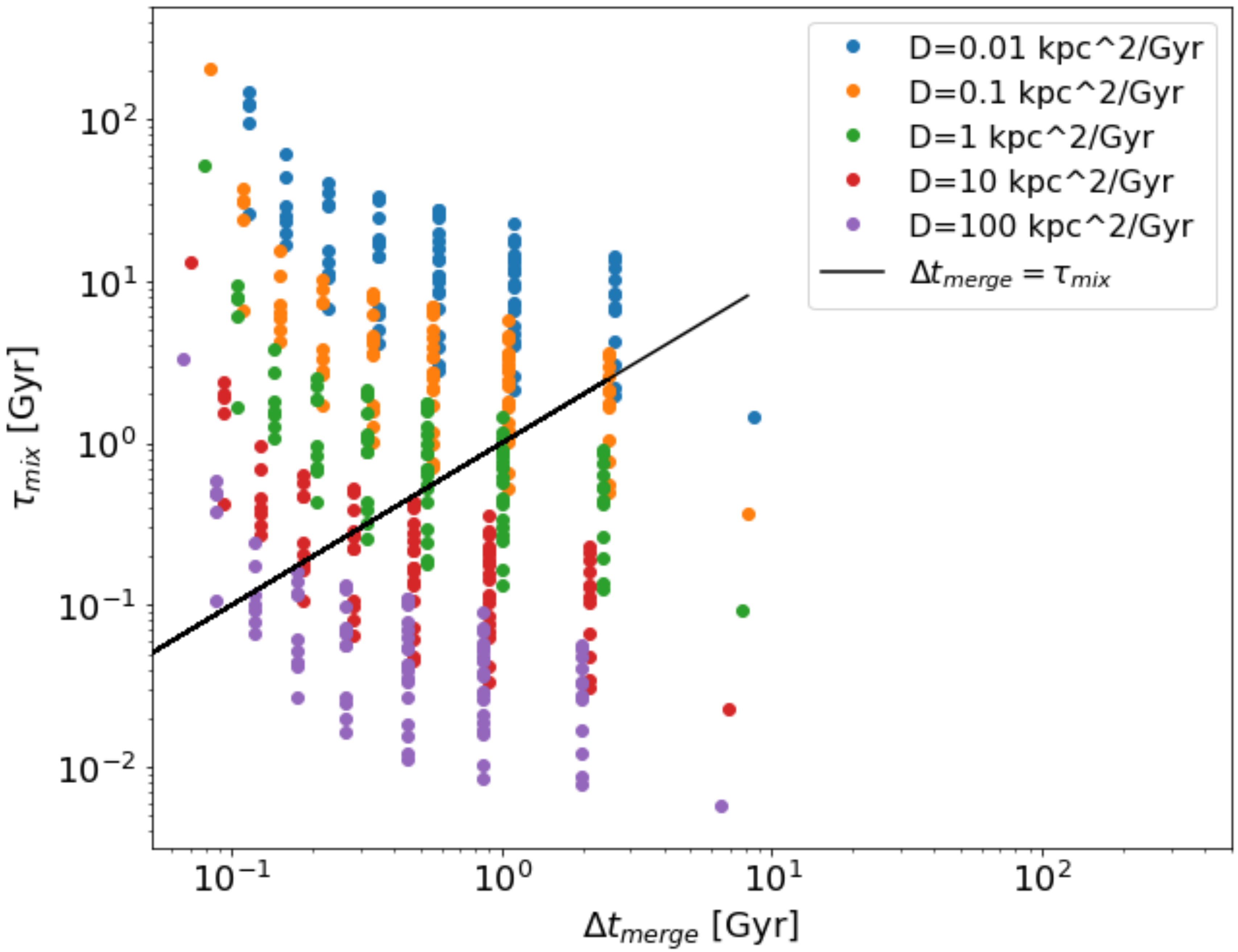
$$y_{Eu} = 2 \cdot 10^{-4}\ M_\odot$$

$$\alpha_{BNS} = 3 \cdot 10^{-3}$$

- Non-monotonic dependence of the scatter on the diffusion coefficient

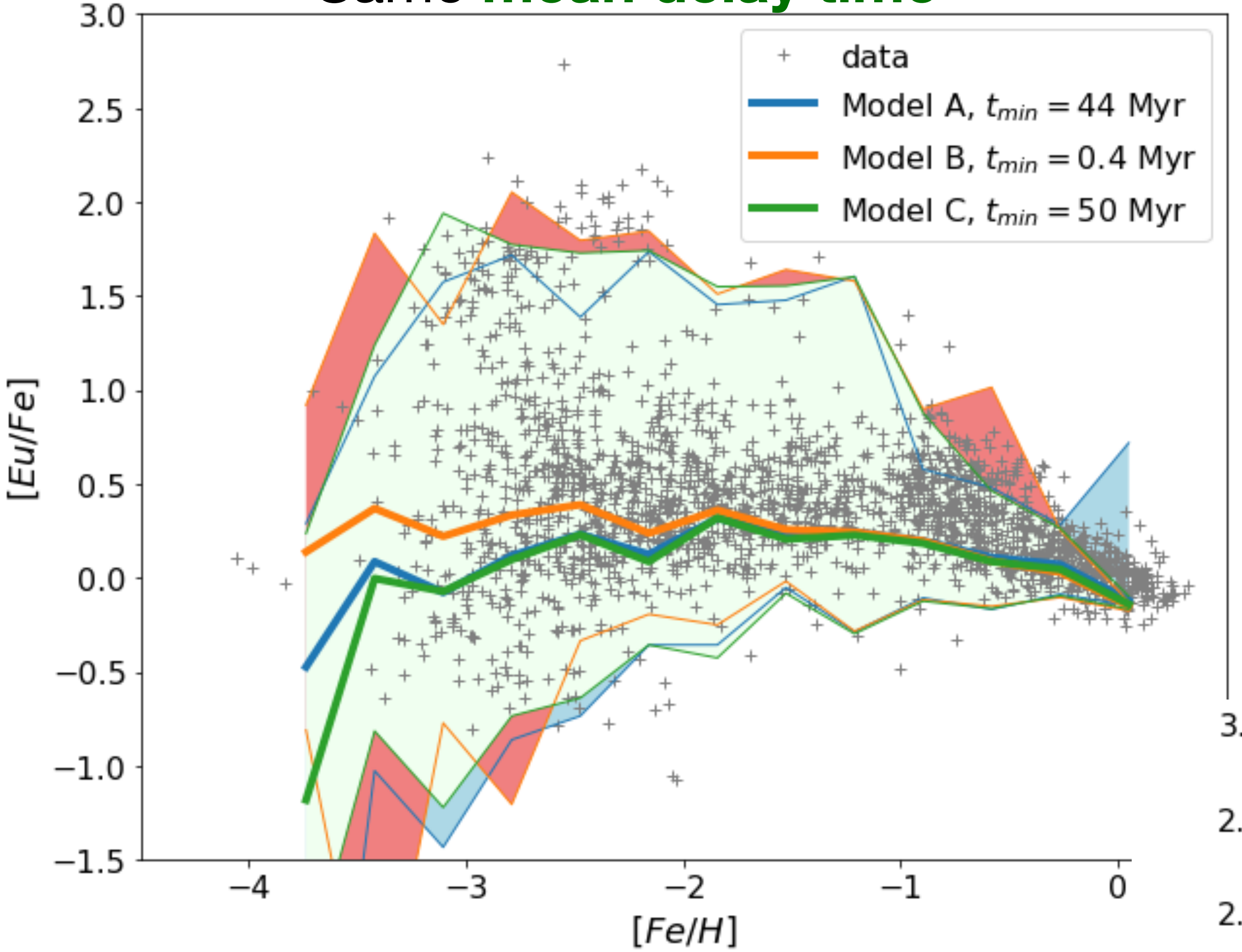


- Non-monotonic dependence of the scatter on the diffusion coefficient
- Different timescales: turbulent mixing and galaxy mergers



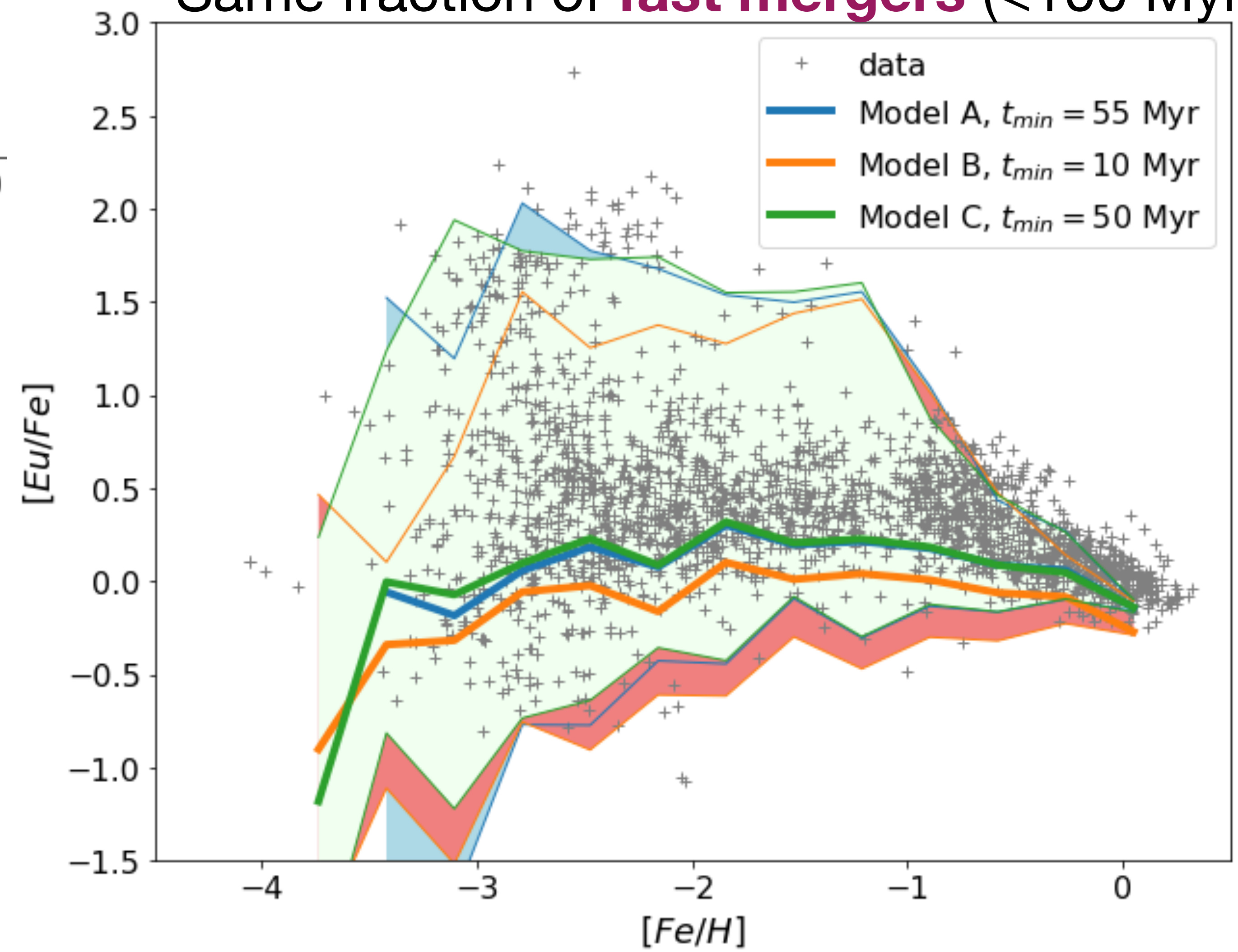
Results: r-process abundance in a Milky-Way-like galaxy

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)

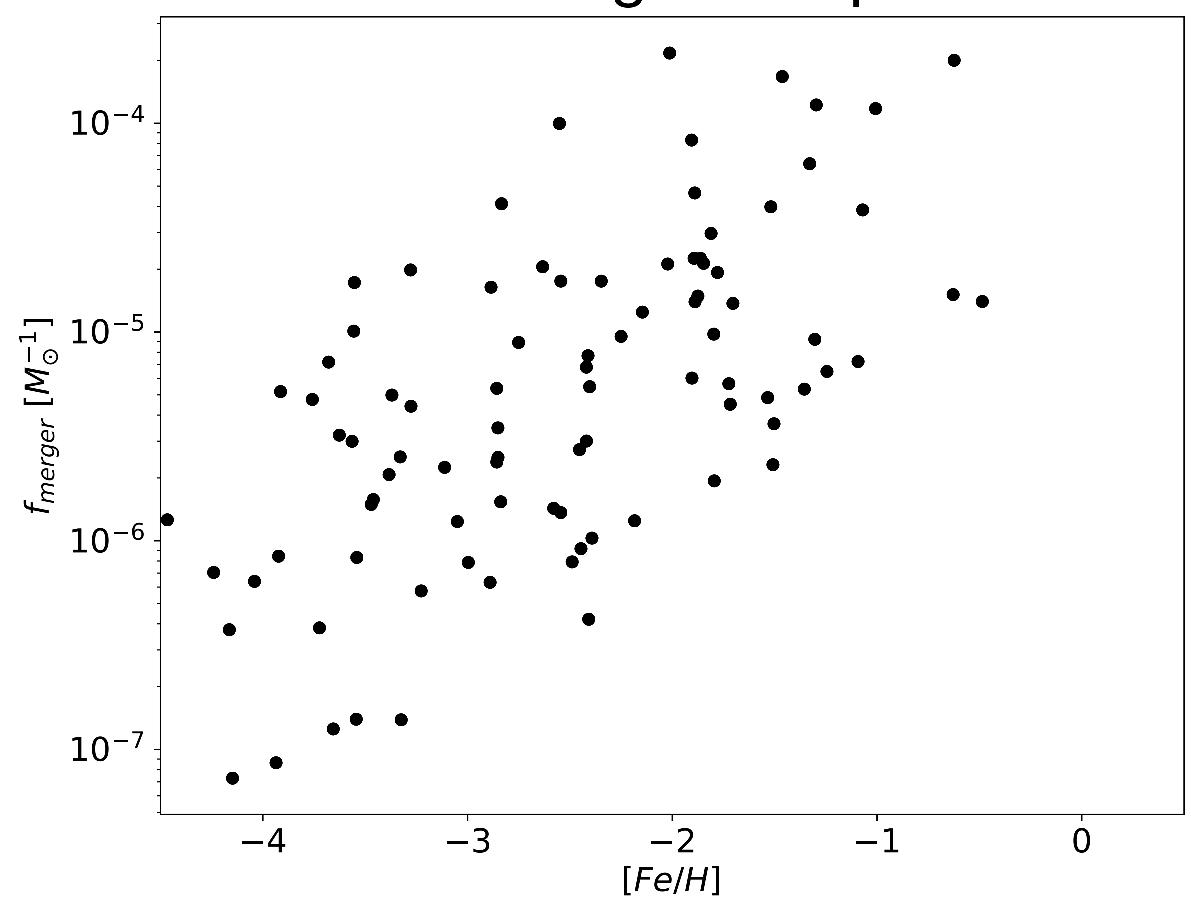


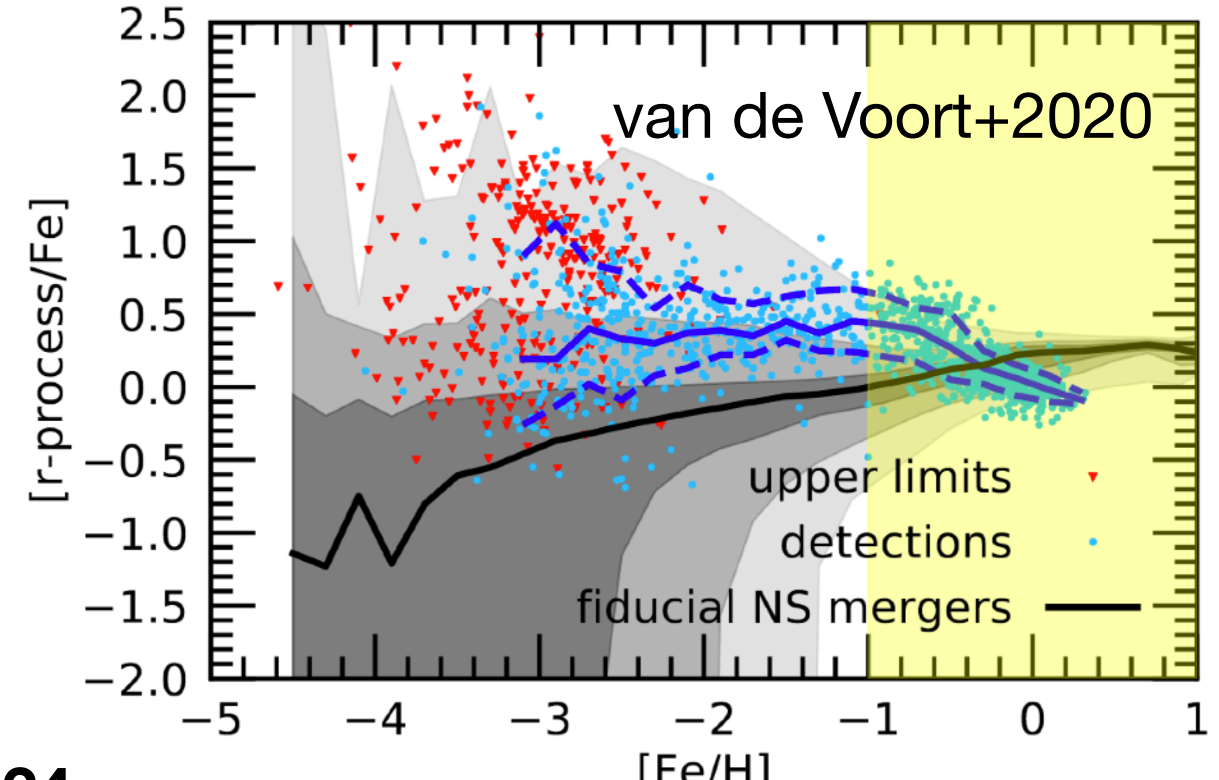
- The fraction of **fast mergers** determines the abundances at low metallicities
- The **mean delay time** determines the abundances at high metallicities

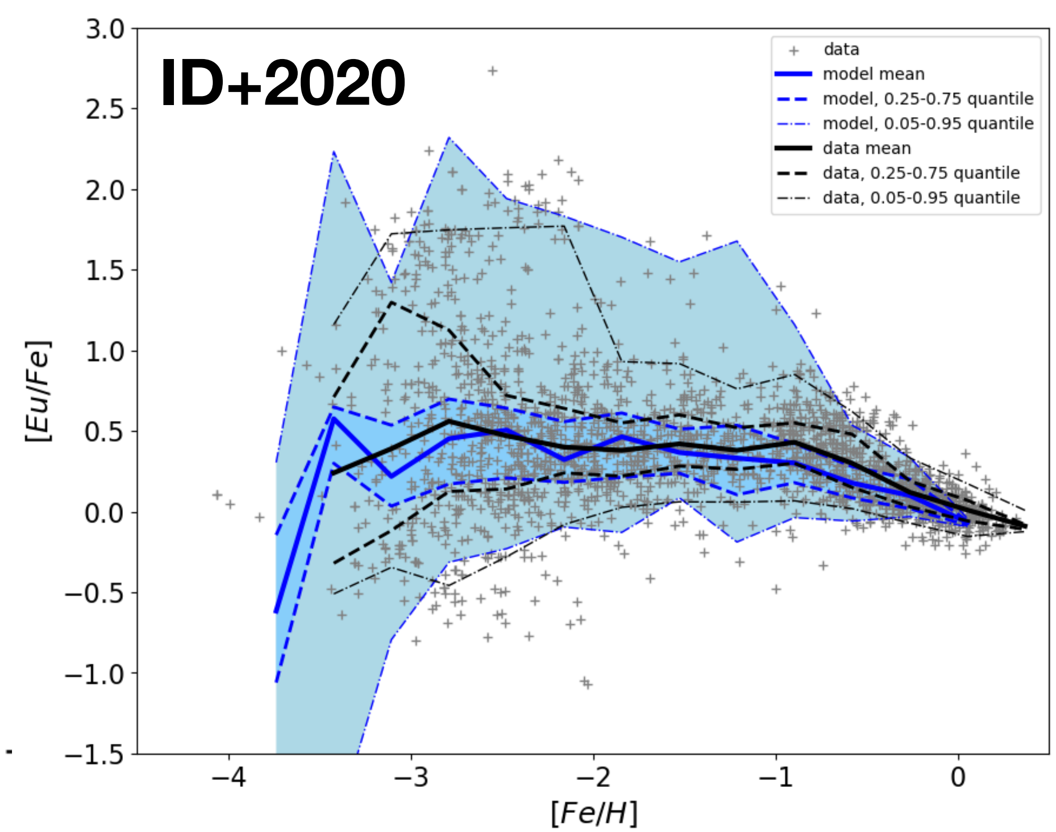
Why is there a difference with previous models?

- **NS formation efficiency**
- **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**

BNS merger rate per SFR



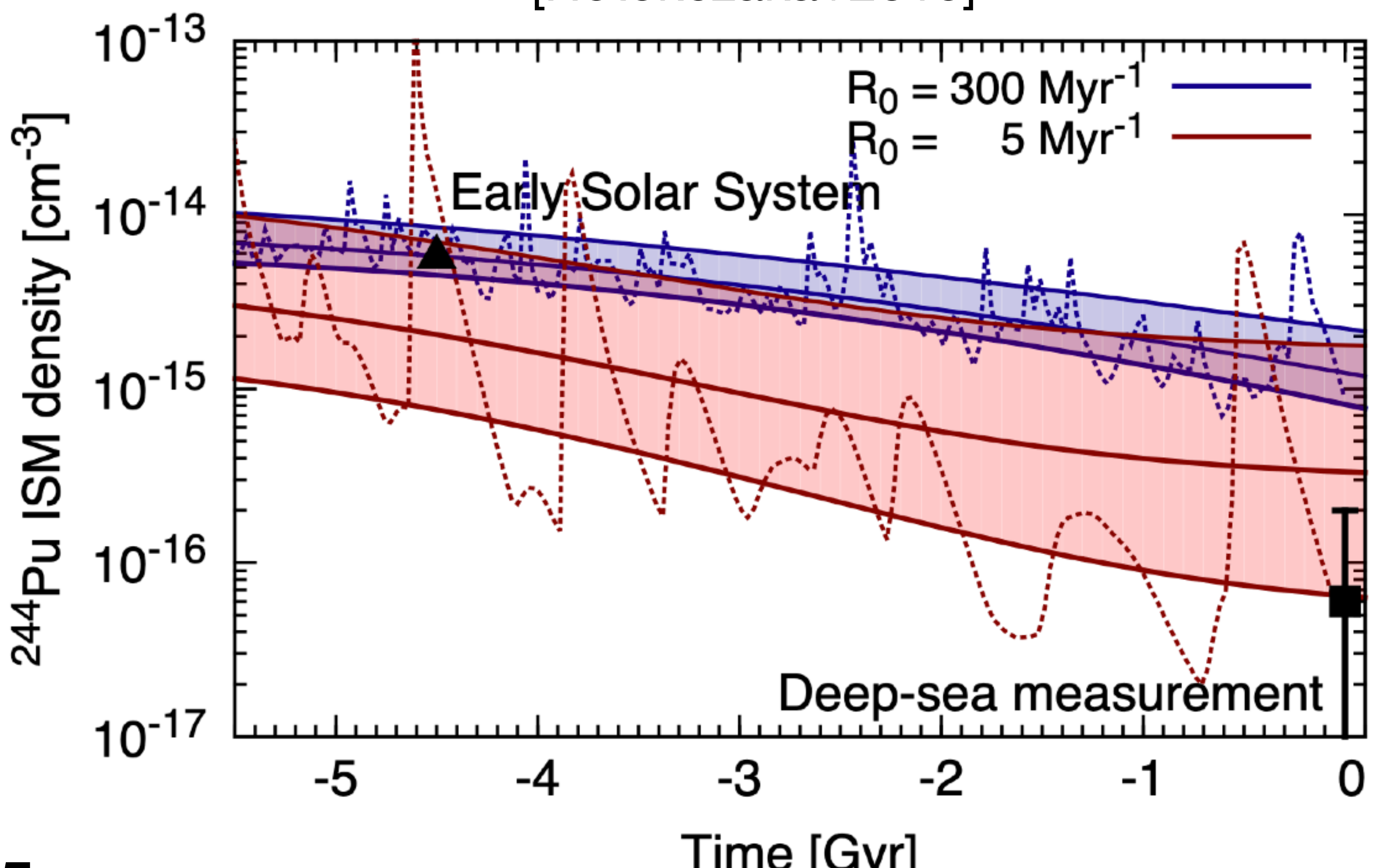




Can we use r-process abundances to study BNS merger in low-metallicity environments?

- **Need a better model for collapsar contribution**
- Need better BNS merger rate estimates
- Possible population of fast-merging BNS
- Radioactive r-process elements can give more clues (U, Pu, Cm, I…)

[Hotokezaka+2015]



- Pu half-life ~80 Myr
- Density estimates from geological samples

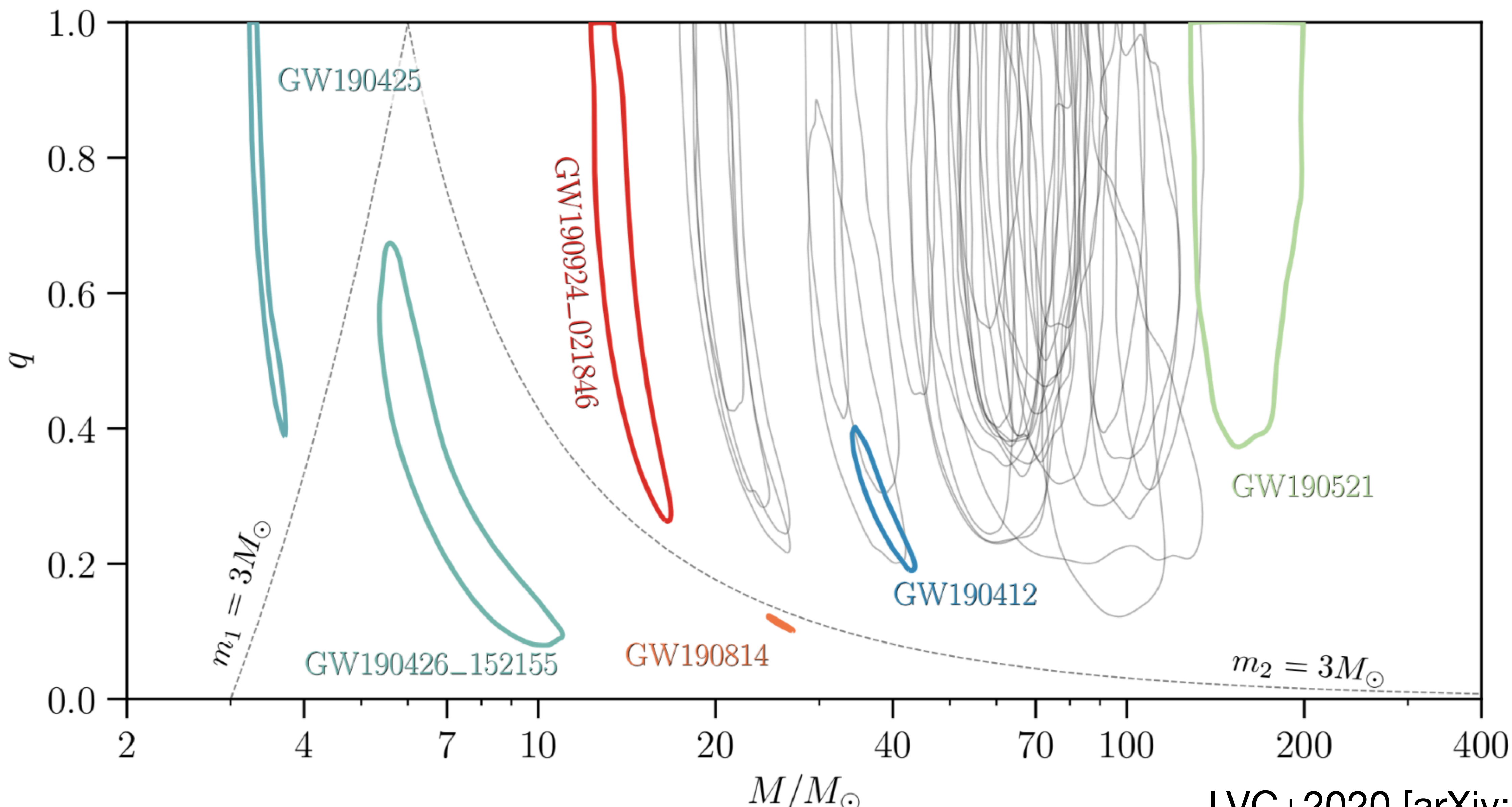
What GW tell us about compact binaries

GW sources published by LIGO/Virgo so far:

(with false alarm rate < 2/yr)

- ✱ 2 BNS
- ✱ 44 BBH
- ✱ 1 BHNS or BBH

- ✱ GW190521 : the heaviest BBH $M_{Tot} = 150 M_\odot$
- ✱ GW190814 : the most asymetric binary (q=0.1)
- ✱ GW190425 : very massive BNS $M_{Tot} = 3.4 M_\odot$

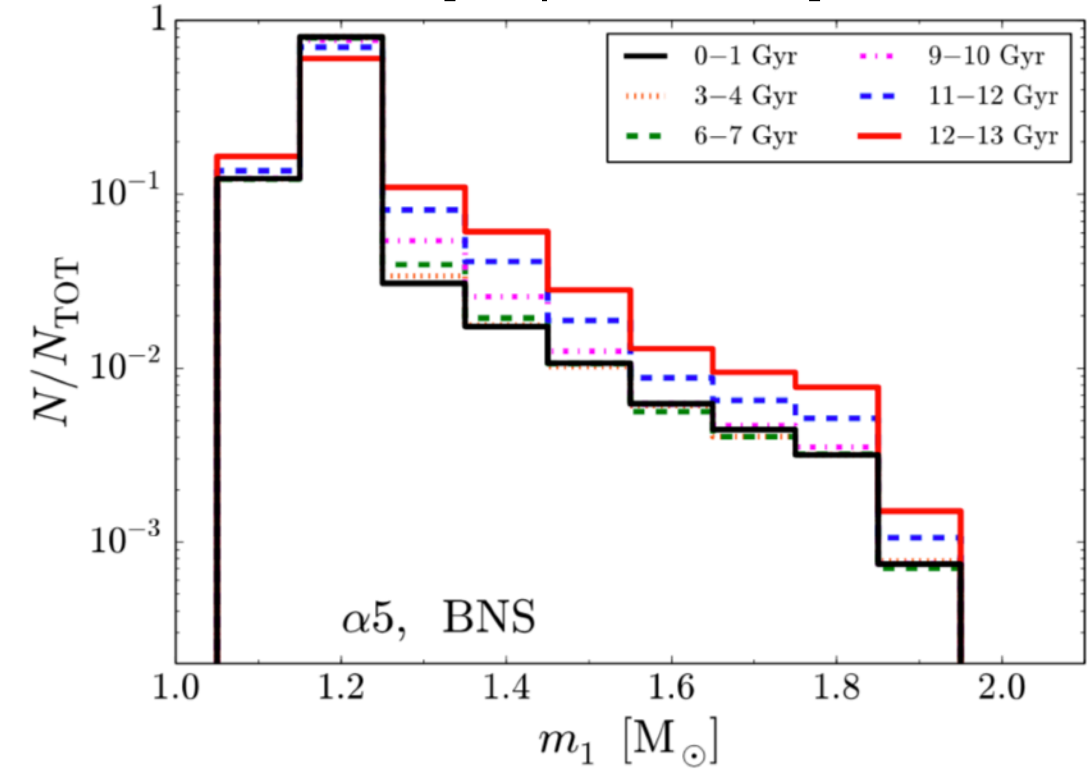


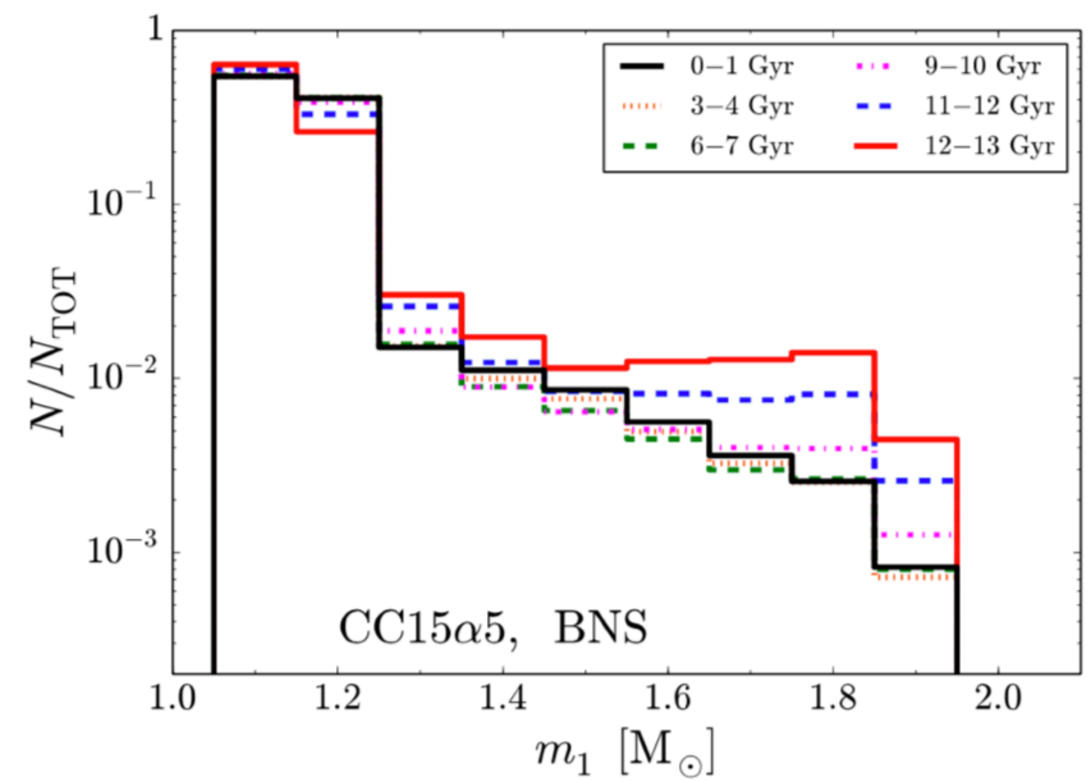
LVC+2020 [arXiv:2010.14527]

What GW tell us about compact binaries

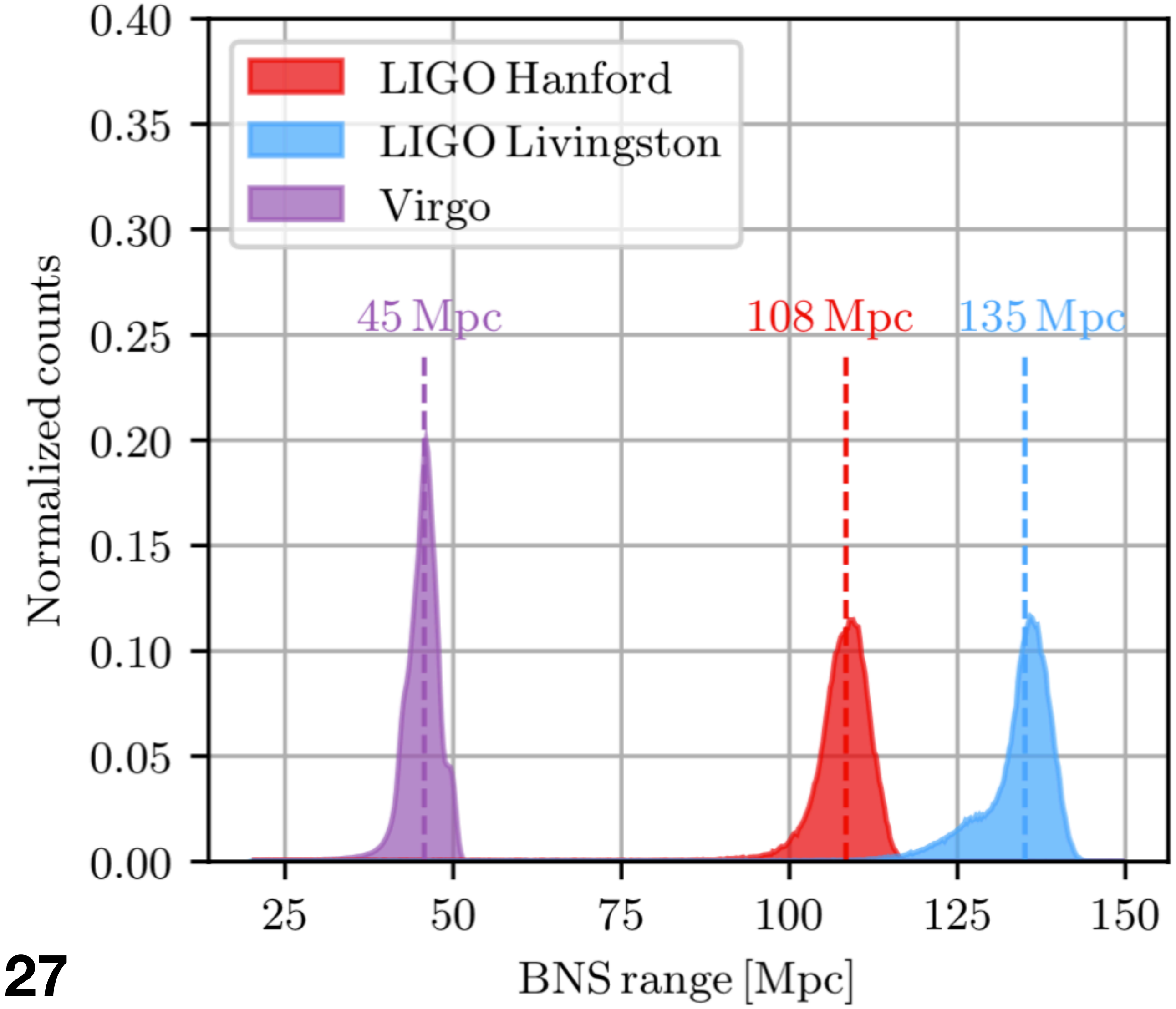
* Does the merger rate evolve with redshift?
* Does the formation channel depend on host galaxy properties?
* Is the observed population representative?

[Mapelli+2019]

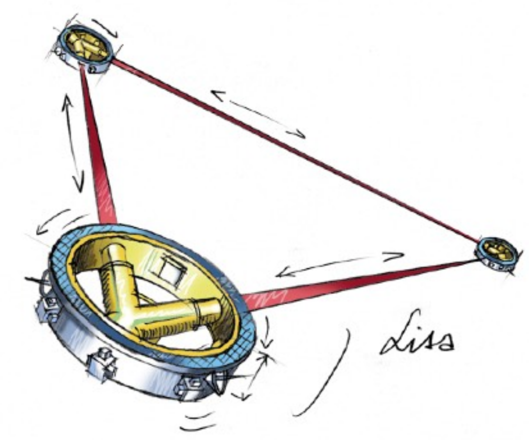




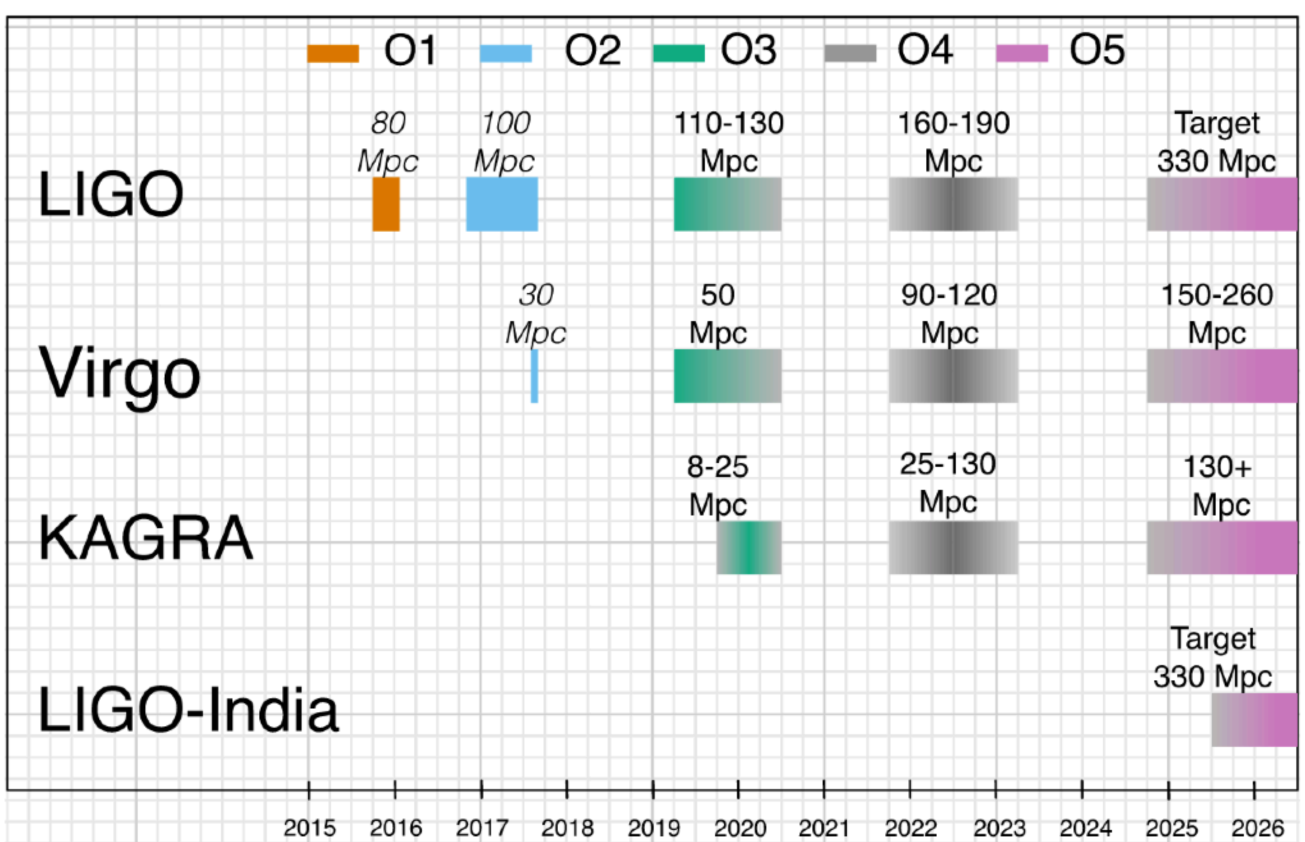
LVC+2020 [arXiv:2010.14527]



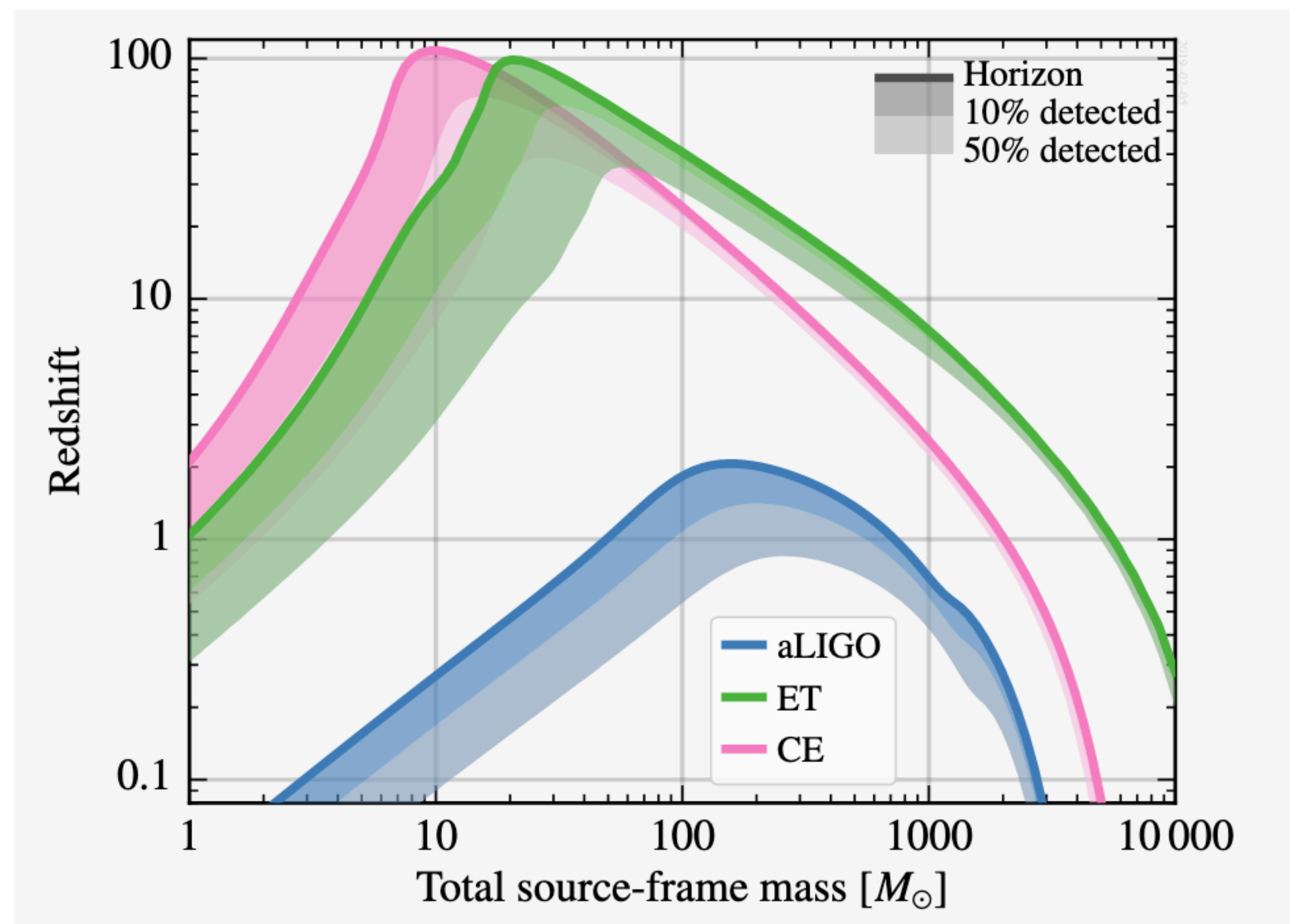
The future with GW



- New GW data —> better measurements of merger rates
- Upcoming LIGO/Virgo/Kagra runs
- 3G detectors (Einstein Telescope, Cosmic Explorer) will go even further…
- LISA will probe a different source population

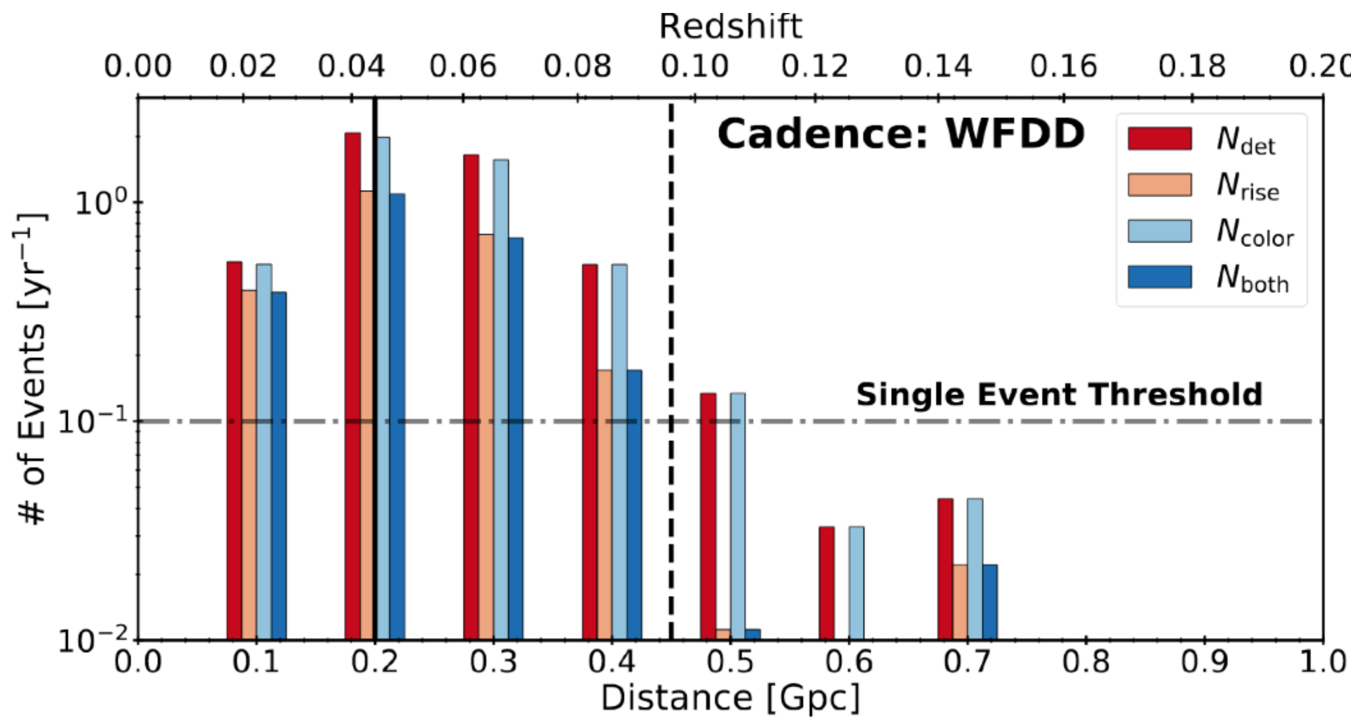


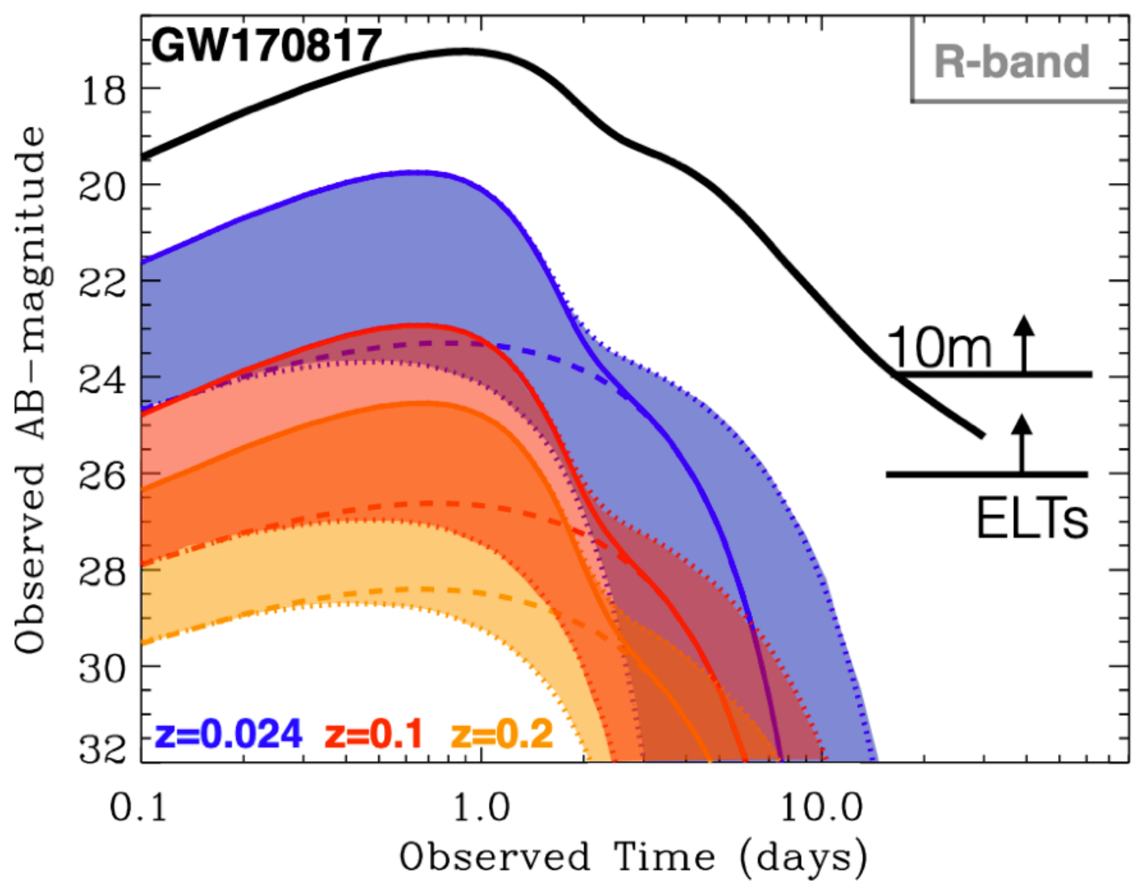
From GWIC-3G science case

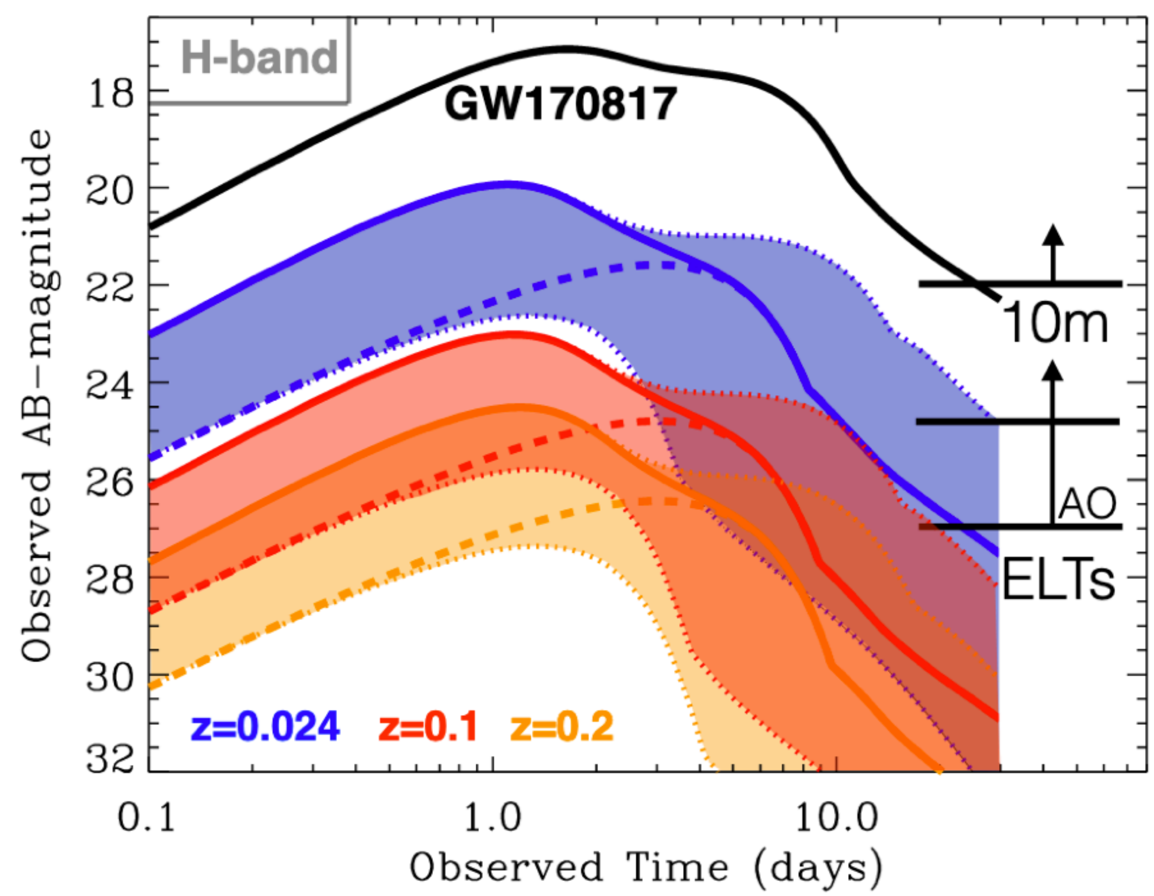


* EM observations of BNS mergers
    * Kilonovae (LSST, JWST, ELT, …)
    * Gamma-ray bursts (Fermi, Swift, SVOM, …)

Predictions for LSST [Cowperthwaite+19]







Optical [Chornock+2020, Astro2020 White Paper] IR

Thank you!