Transients and Chemical Pollution

Ministero dell'Università e della Ricerca

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Galactic chemical evolution models

(see Matteucci 2021 for a recent review)

- Stand-alone bundles or modules embedded in more complex, cosmological hydrodynamical simulations
- Describe how the chemical composition of the ISM evolves in different galaxies/galactic substructures due to several physical processes:

Transient rates and yields

$$\frac{d\Sigma_i(r,t)}{dt} = -\psi(r,t)X_i(r,t) + R_i(r,t) + \frac{d\Sigma_{i,inf}(r,t)}{dt} - \frac{d\Sigma_{i,out}(r,t)}{dt}$$

Star formation — Stellar feedback — Gas accretion — Galactic-scale outflow

From restless progenitor stars…

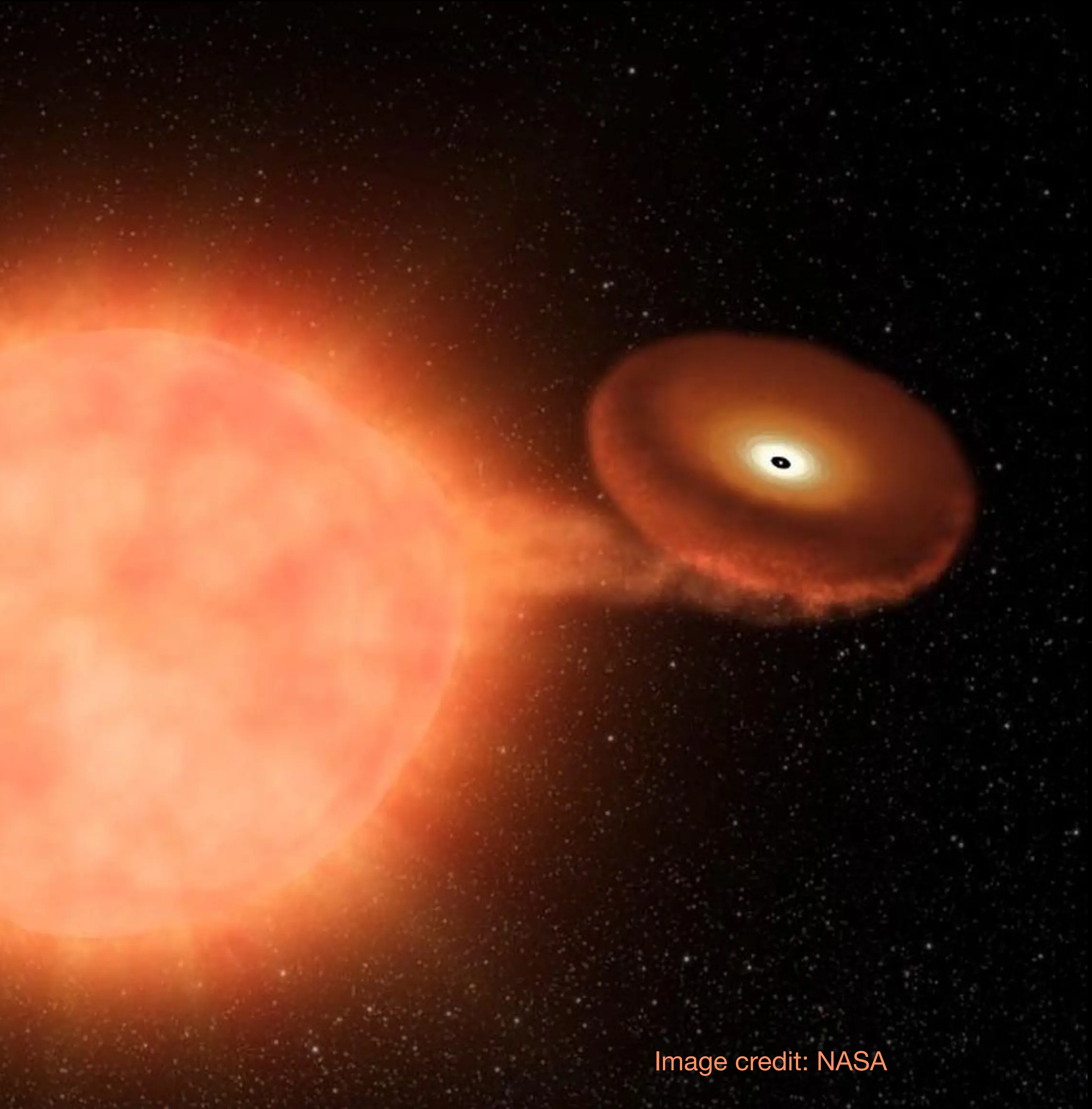


Image credit: NASA

Classical nova explosions occur in close binary systems where a CO or ONe WD accretes H-rich matter from a main-sequence or giant companion that overflows its Roche lobe. When the temperature of the deepest accreted layers exceeds $\sim 10^8$ K, a thermonuclear runaway is initiated (Gurevitch & Lebedinsky 1957)

The explosion does not disrupt the system and, after the ejection of the envelope, the process is re-initiated. On average, a nova experiences 10^4 outbursts during its lifespan (Bath & Shaviv 1978; Ford 1978)

Rare isotopes are produced in the outburst. ^{7}Li, ^{13}C, ^{15}N, and ^{17}O are discussed in this talk (Starrfield et al. 1972, 1978; Prialnik et al. 1978; Prialnik 1986; José & Hernanz 1998; Yaron et al. 2005; Starrfield et al. 2009; José et al. 2020; Starrfield et al. 2020)

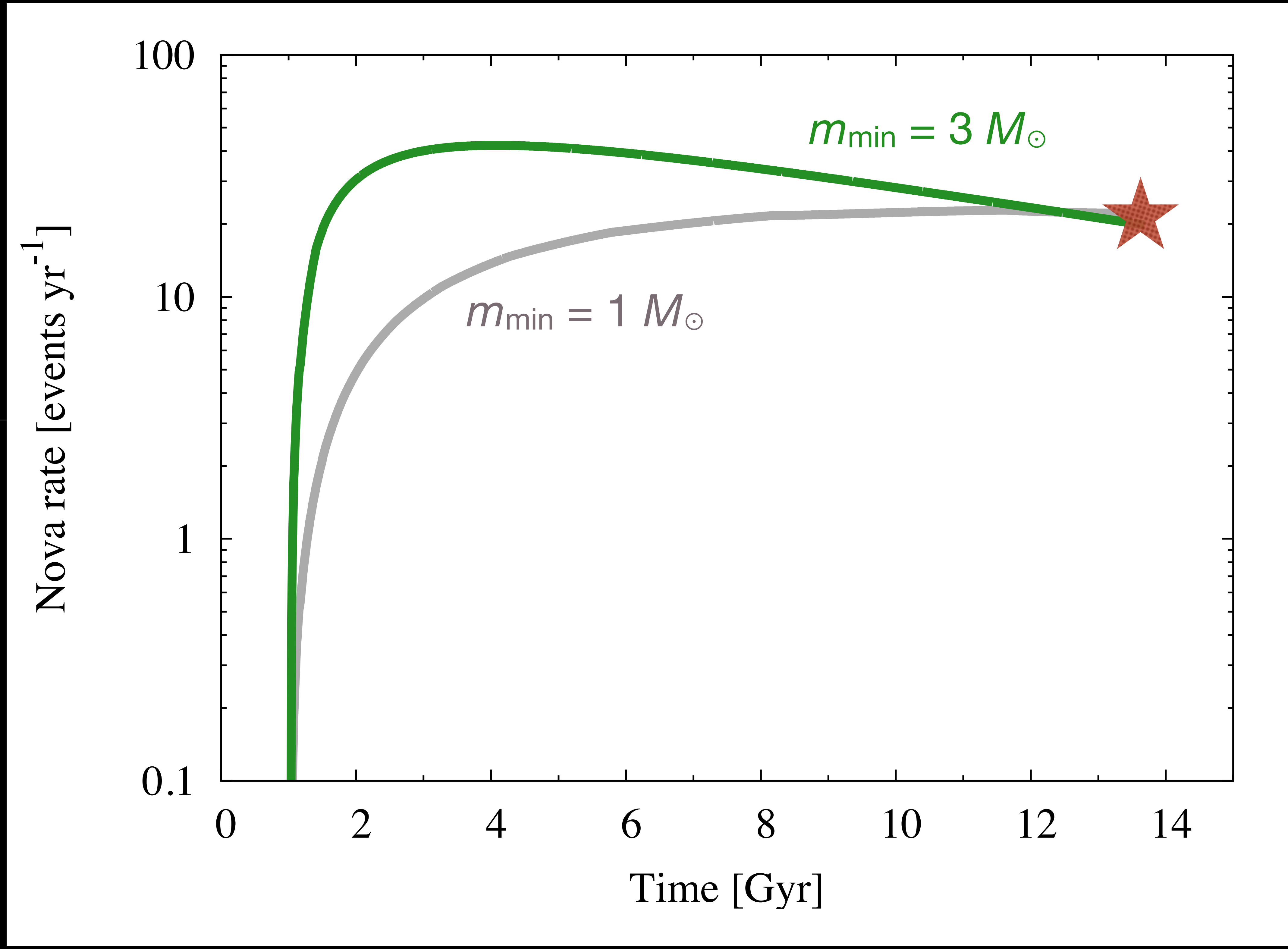
Long delay time: a star must die as a WD and the WD must cool enough to ensure a strong outburst (D'Antona & Matteucci 1991)

ISM enrichment on long timescales (Audouze et al. 1975; Vigroux et al. 1976; D'Antona & Matteucci 1991; Romano et al. 1999, 2001; Travaglio et al. 2001; Romano & Matteucci 2003; Romano et al. 2017, 2021; Cescutti & Molaro 2019; Kemp et al. 2022; Romano 2022)

Nova rate(s) in the Milky Way

$$R^{th}_{novae}(t) = \alpha\, n \int_{m_{WD}(t)}^{8} \psi(t - \tau_m - \Delta t)\, \phi(m)\, dm$$

(D'Antona & Matteucci 1991)



with the conditions

$$n \simeq 10^4, \quad m_{WD}(t) > m_{min}$$

and

$$m_{min}/M_\odot = [1, 3]$$

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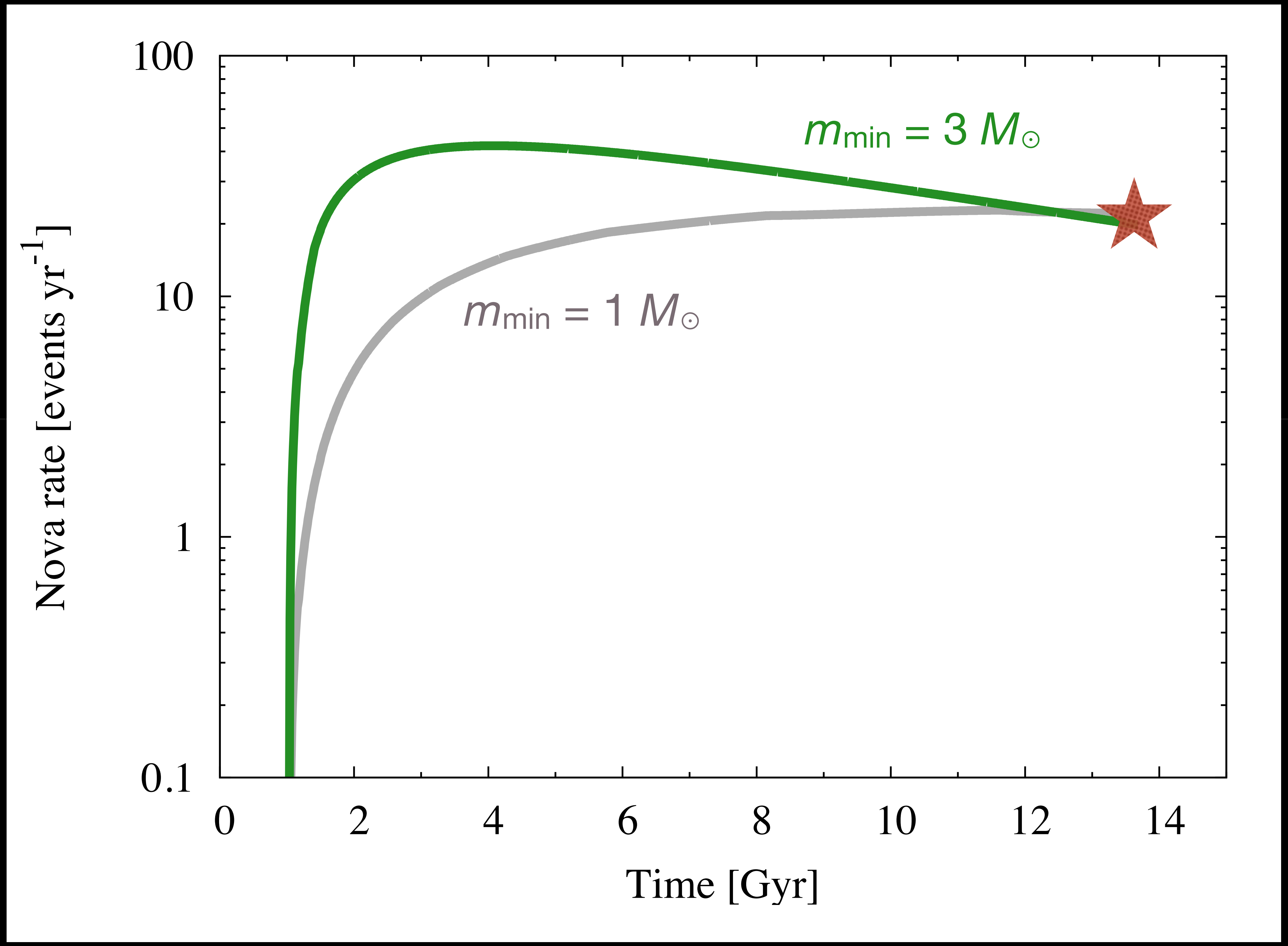


with the conditions

$$n \simeq 10^4, \quad m_{WD}(t) > m_{min}$$

and

$$m_{min}/M_\odot = [1, 3]$$

★ $$R^{obs}_{novae}(t_{now}) \leq 50\,\mathrm{yr}^{-1}$$

(Della Valle, Shafter & Starrfield 2023)

Novae as ^{7}Li factories - theory

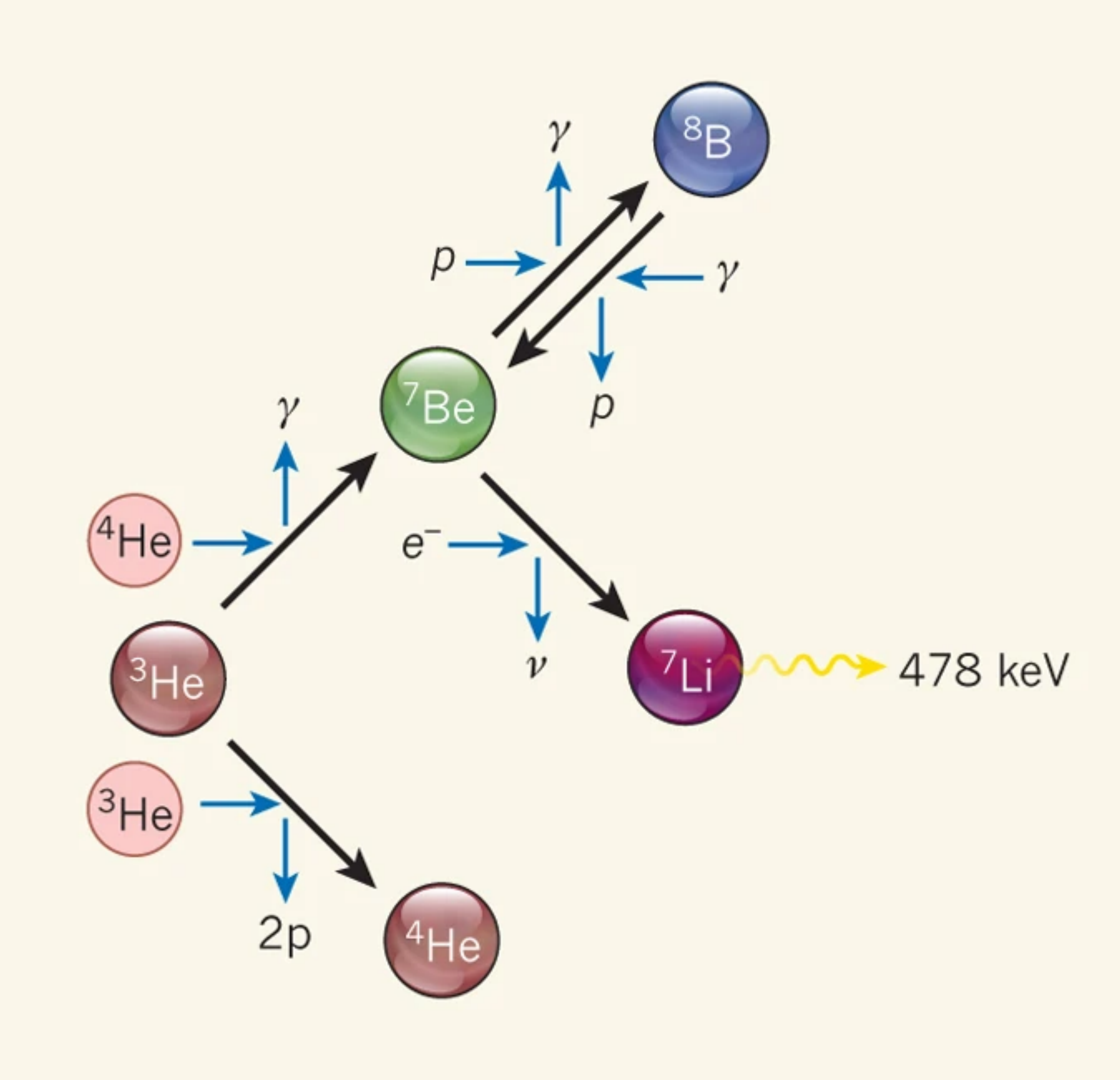
There exists a range of density-temperature conditions for which substantial ^{7}Li production can occur, which happens to overlap that characteristic of nova thermonuclear eruptions (Arnould & Norgaard 1975)

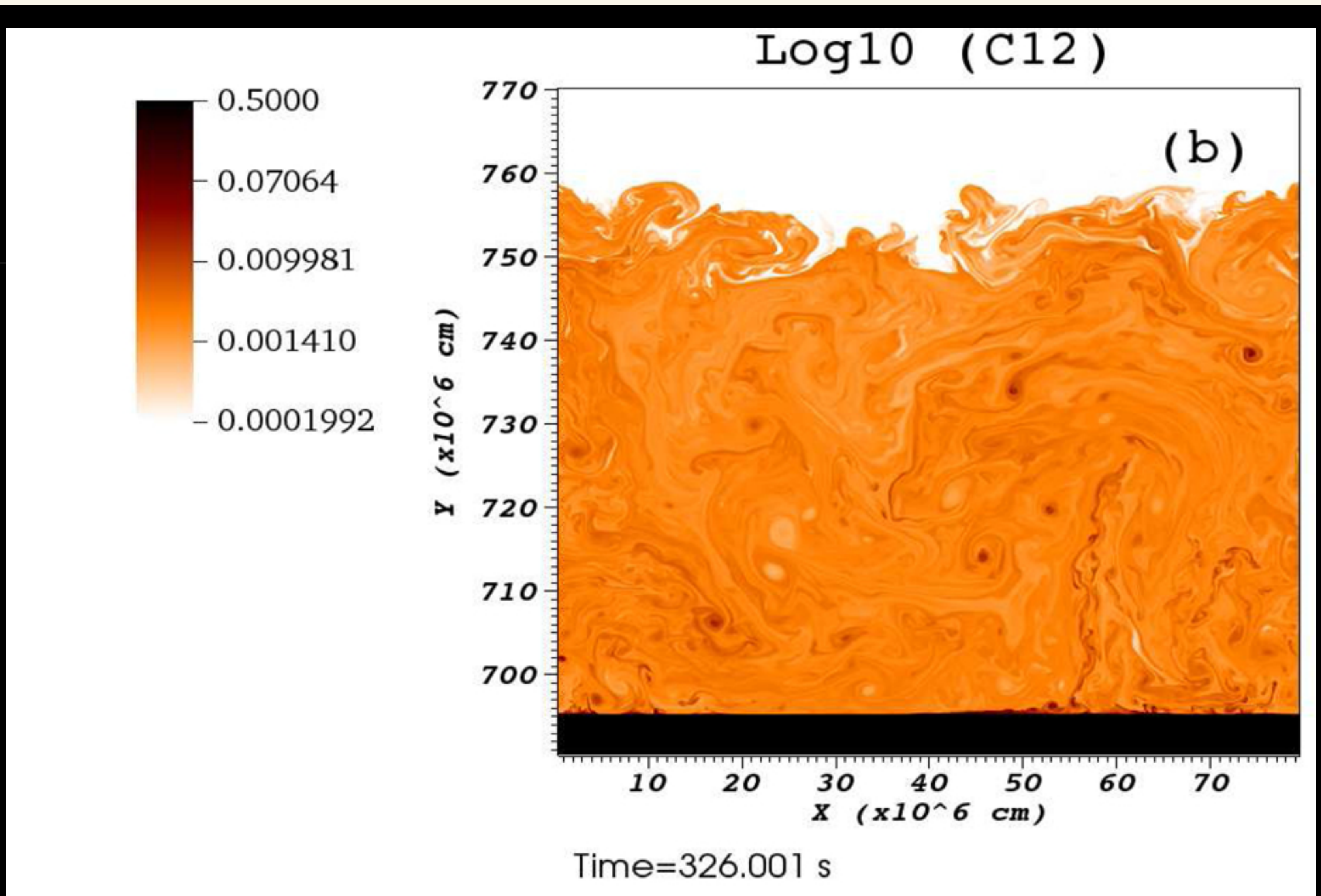
The pre-explosion ^{3}He concentration in the accreted envelope plays a key role in determining how much ^{7}Li is produced in the outburst (Starrfield et al. 1978)

Revision of ^{7}Li production in explosive hydrogen burning by including the ^{8}B(p, γ)^{9}C reaction rules out novae as ^{7}Li polluters at a Galactic scale (Boffin et al. 1993). However, such a conclusion comes from a parameterised, one-zone explosive nucleosynthesis model: need for hydrodynamic nova models

Hydrodynamic models that treat both the accretion and the explosion stages point again to large overproduction factors relative to the solar ^{7}Li abundance (Hernanz et al. 1996; José & Hernanz 1998)

Large variability of the yield depending on the choice of the model



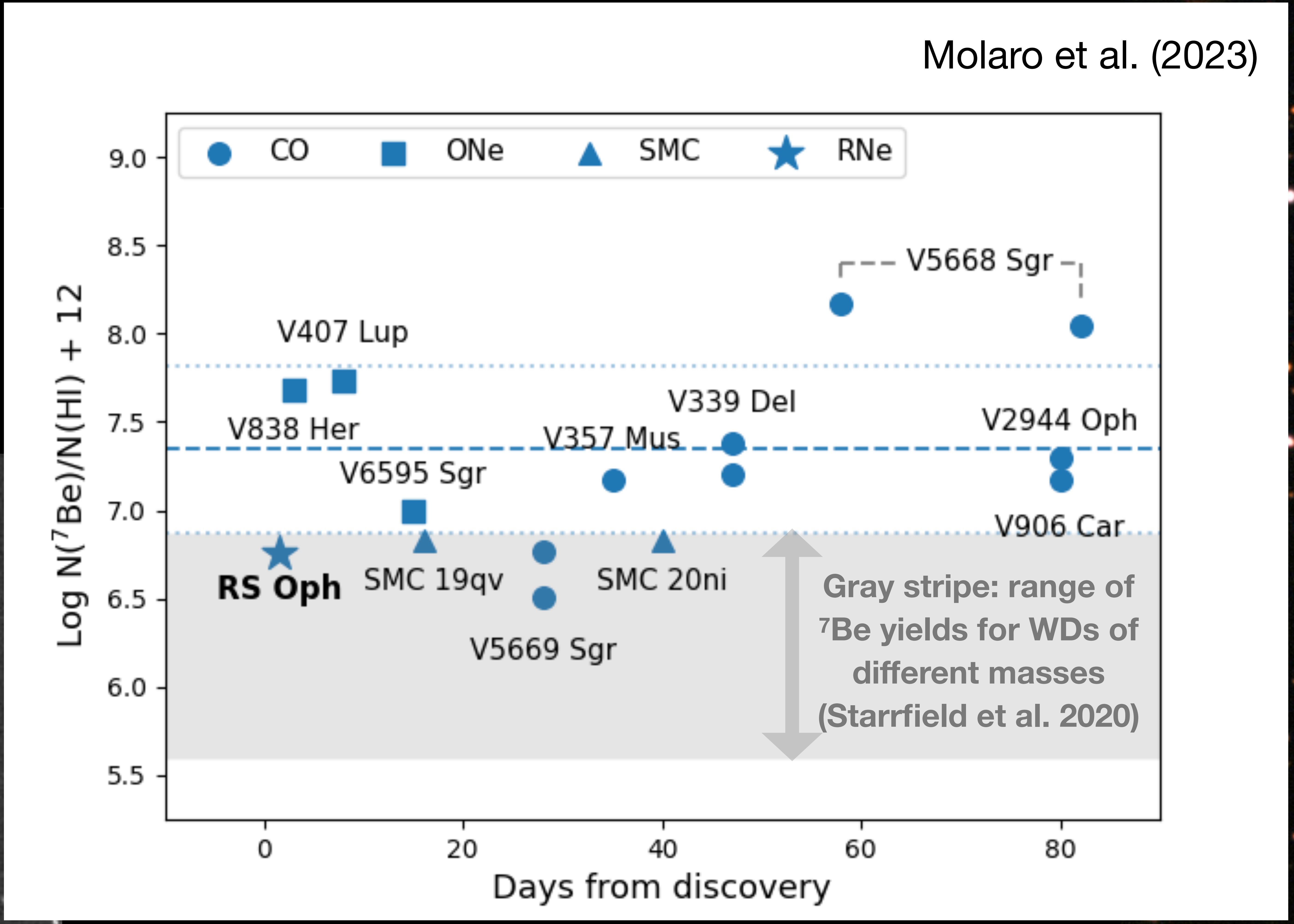


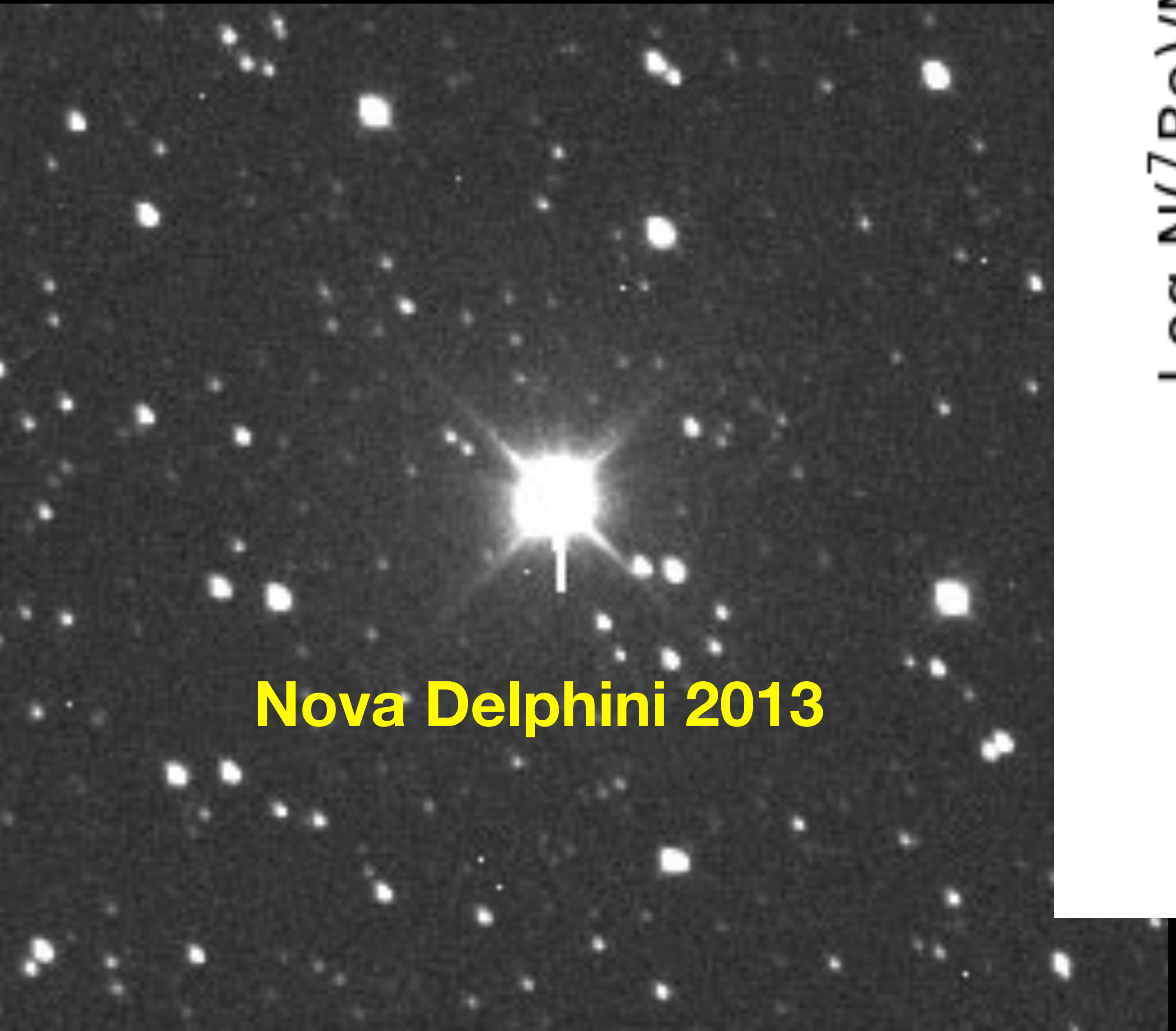
Casanova et al. (2018)

Novae as ^{7}Li factories - observations

First detections:

- Izzo, Della Valle et al. (2015)
- Tajitsu et al. (2015)





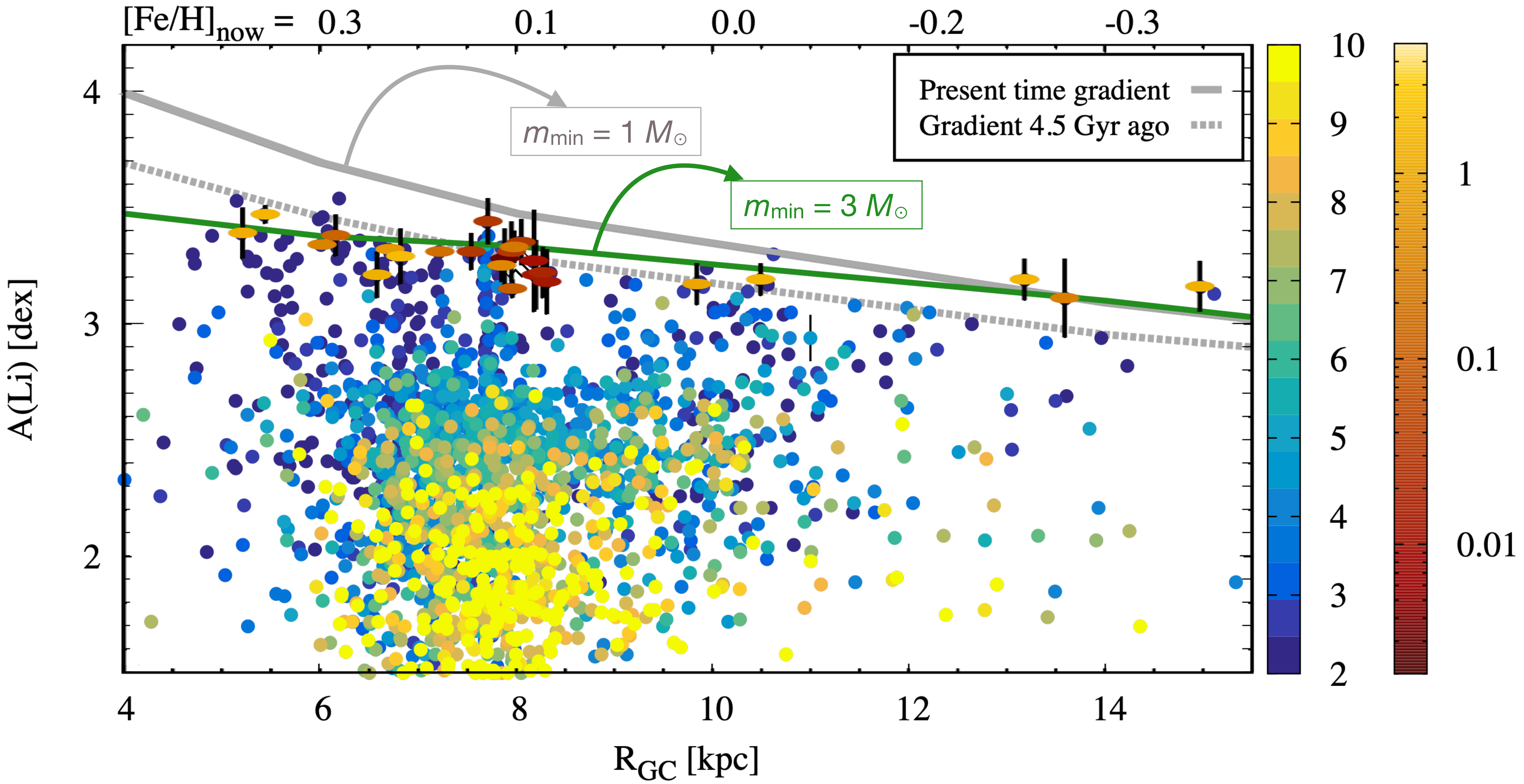
Nova Delphini 2013

Nova Centauri 2013 as seen in July 2015 by the New Technology Telescope at ESO's La Silla Observatory

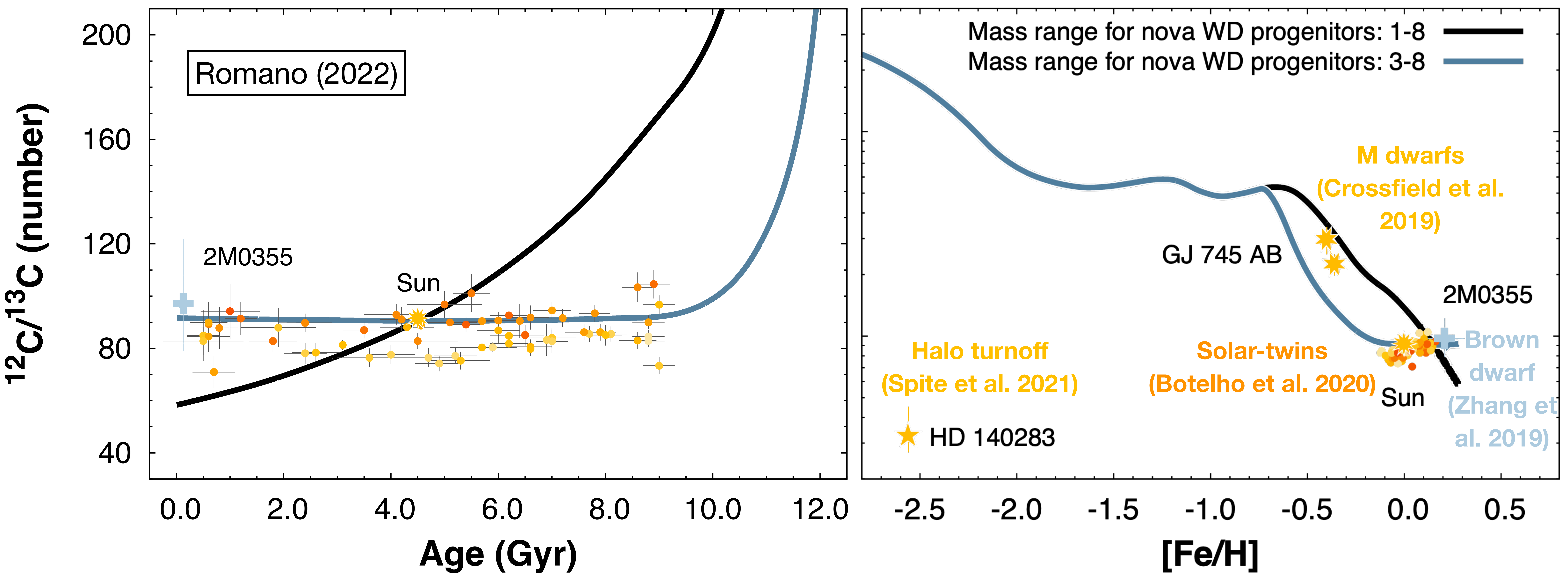
Novae as ^{7}Li factories - theory+observations

Data and models from Romano et al. (2021)

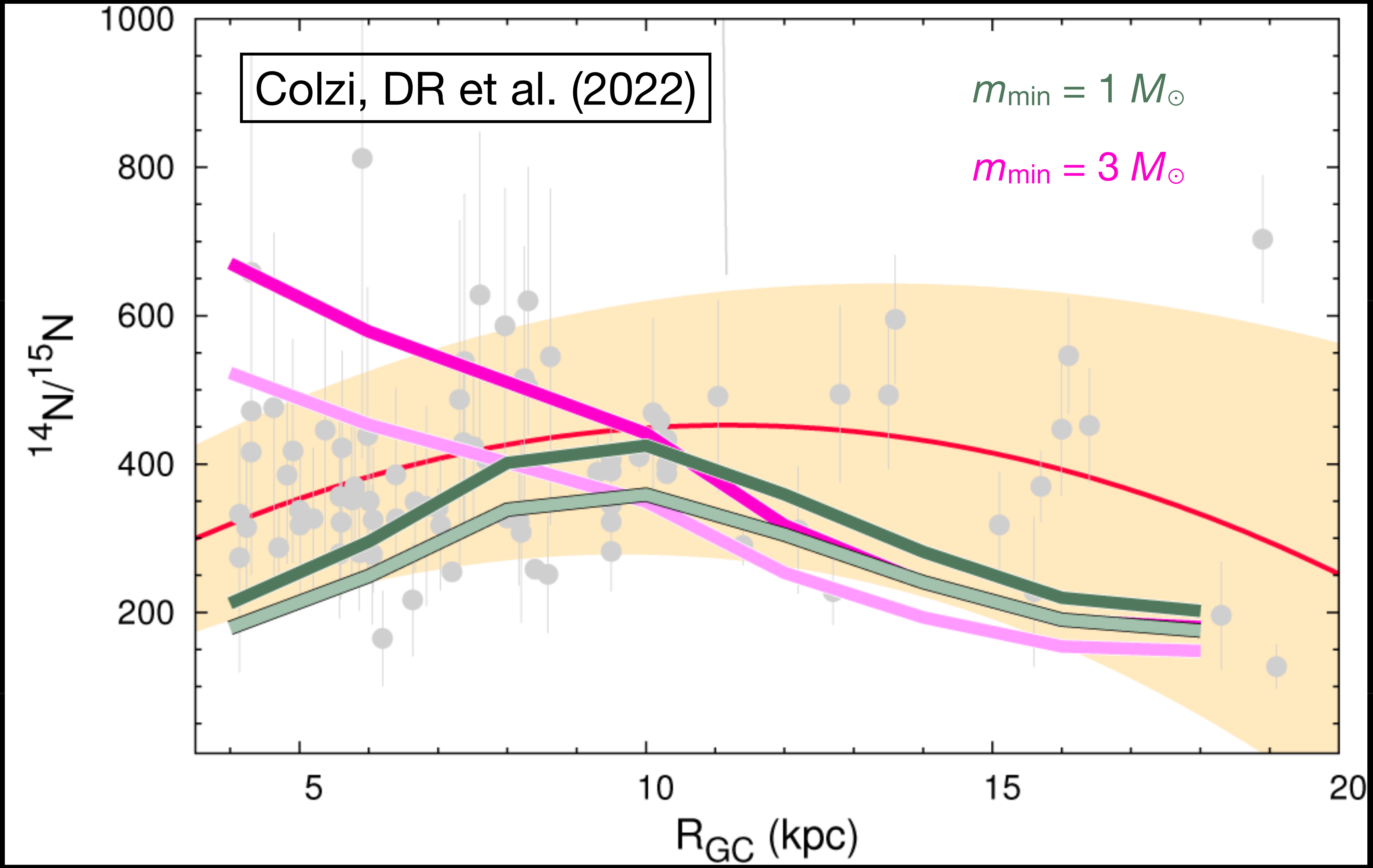
Field stars (circles) and open clusters (ellipses) are colour-coded according to their ages (in Gyr)



Novae as rare CNO isotopes factories



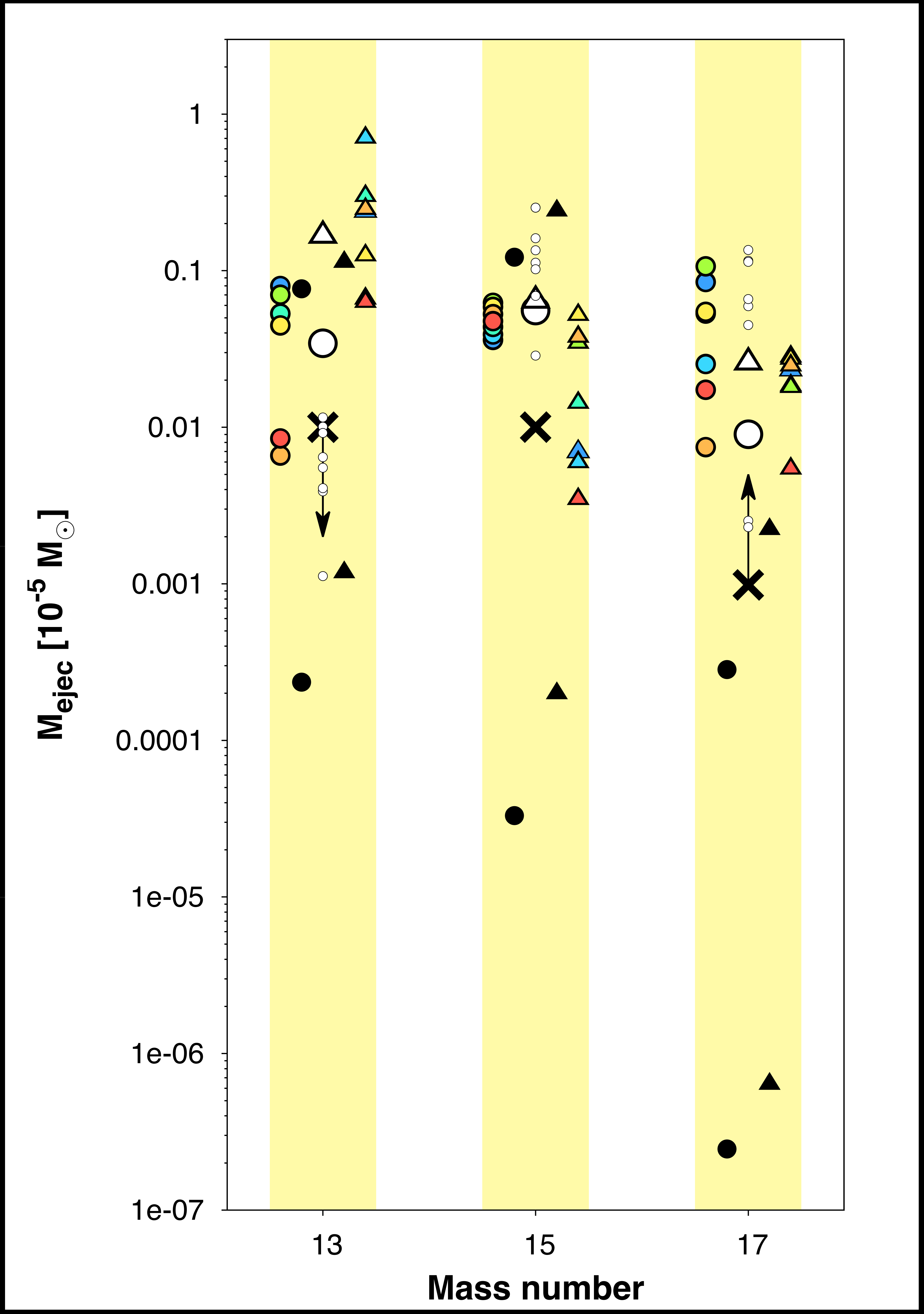
Novae as rare CNO isotopes factories



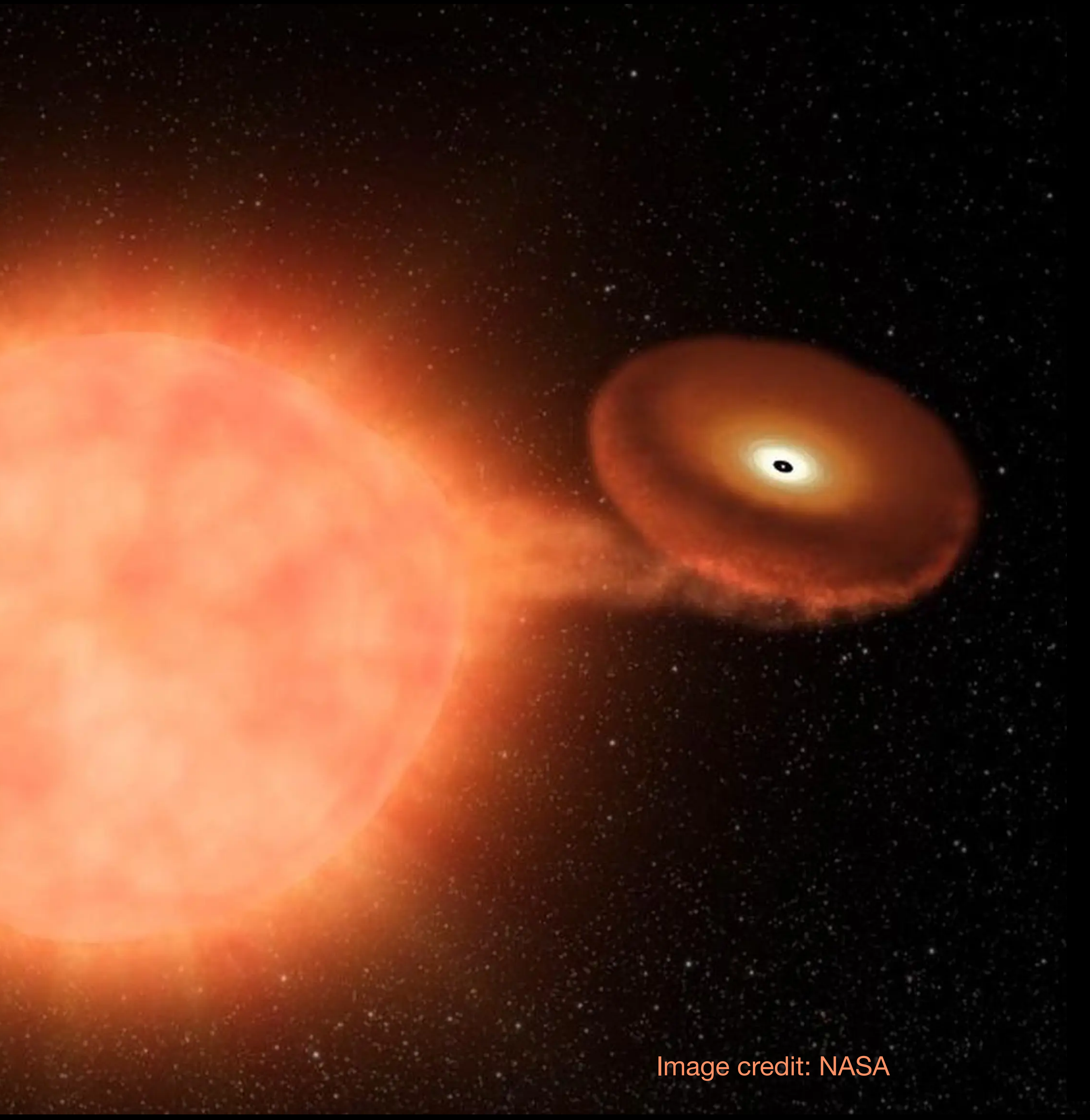
Gray circles: $^{14}N/^{15}N$ ratios from HCN and HNC isotopologue observations in Galactic star-forming regions performed with IRAM 30m in the context of the CHEMical complexity in star-forming regions of the OUTer Galaxy (CHEMOUT) project (Fontani et al. 2022) + homogeneous data for the inner MW disc (Colzi et al. 2018). The solid red line is the fit obtained using the whole sample, along with its 1σ uncertainty (orange shaded region)

Localised pollution? (or chemical fractionation?)

Yields of ^{13}C, ^{15}N, and ^{17}O from hydrodynamic models of nova outburst for CO (triangles) and ONe WDs (circles). Results from representative 1D models (José and Hernanz 1998, coloured symbols; Yaron et al. 2005, black symbols; Starrfield et al. 2009, small empty circles) are shown together with yields from simulations that switch from 1 to 3D, and viceversa (123–321 models, José et al. 2020, large empty symbols). In the latter suite of models, the metal enhancement of the envelope is not forced but naturally produced. The big X signs represent the average yields adopted in chemical evolution simulations (Romano et al. 2017)



From restless progenitor stars…



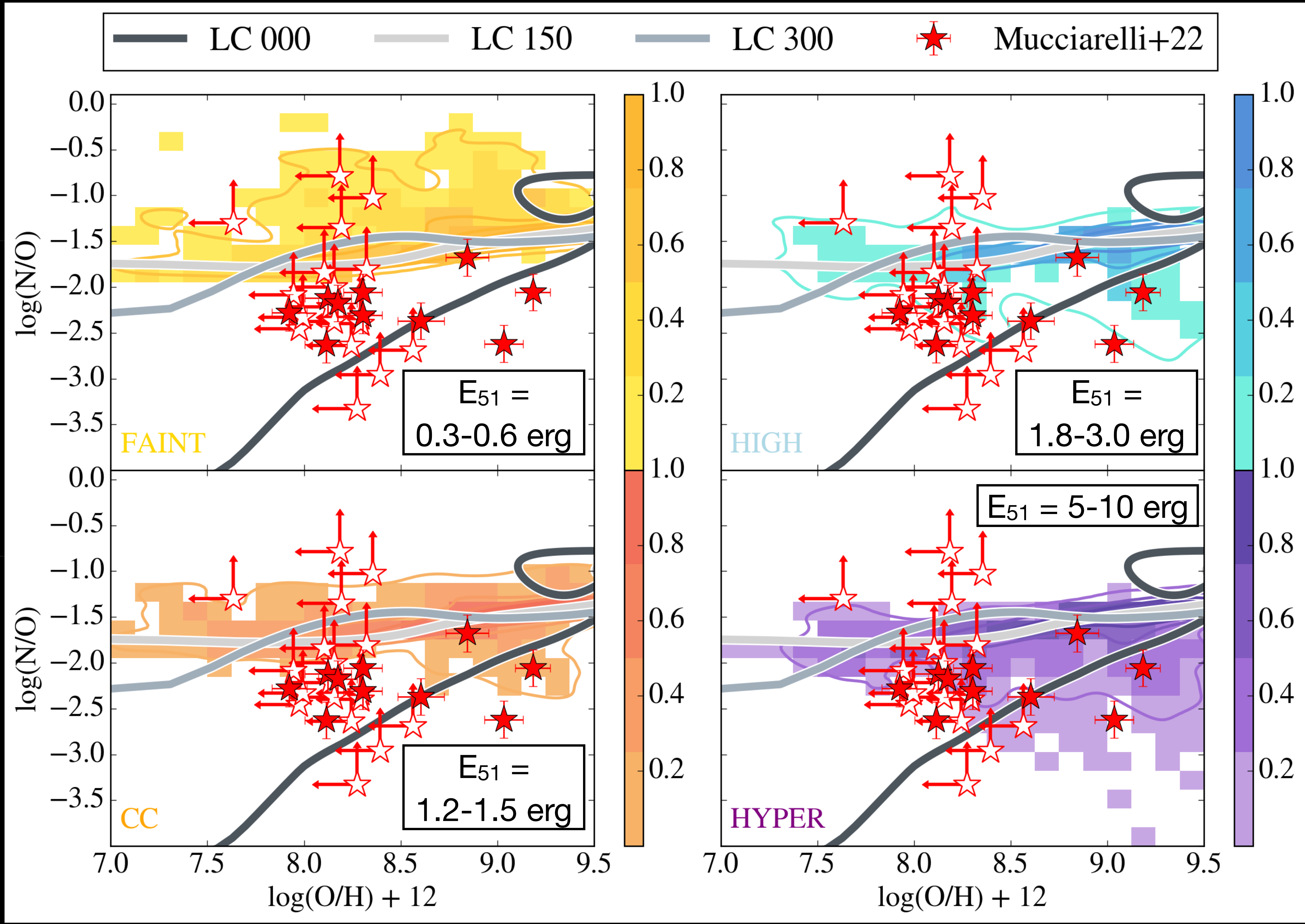
… to explosive multi-messenger signals

Pop III supernova pollution in the early MW

Inhomogeneous GCE model including Pop III stellar yields (no PISNe!) from Heger & Woosley (2010)

Different initial masses, levels of internal mixing, and explosion energies

(Data and models from Rossi, DR et al. 2024)



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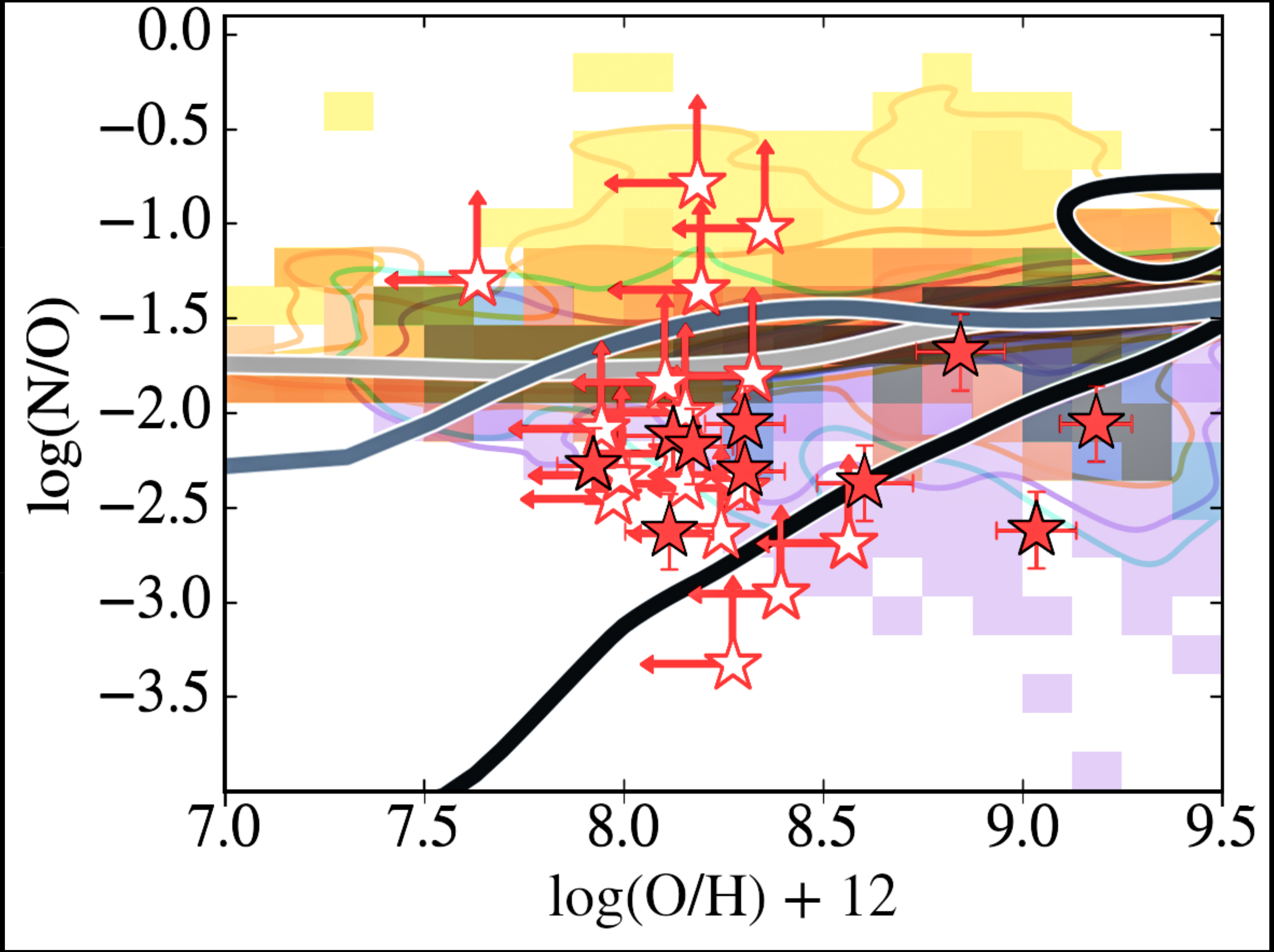


GN-z11: a compact starburst characterized by a top-heavy IMF?

(but see also Charbonnel et al. 2023; D'Antona et al. 2023; Kobayashi & Ferrara 2024; Nandal et al. 2024; Rizzuti et al. 2025 for alternative explanations)

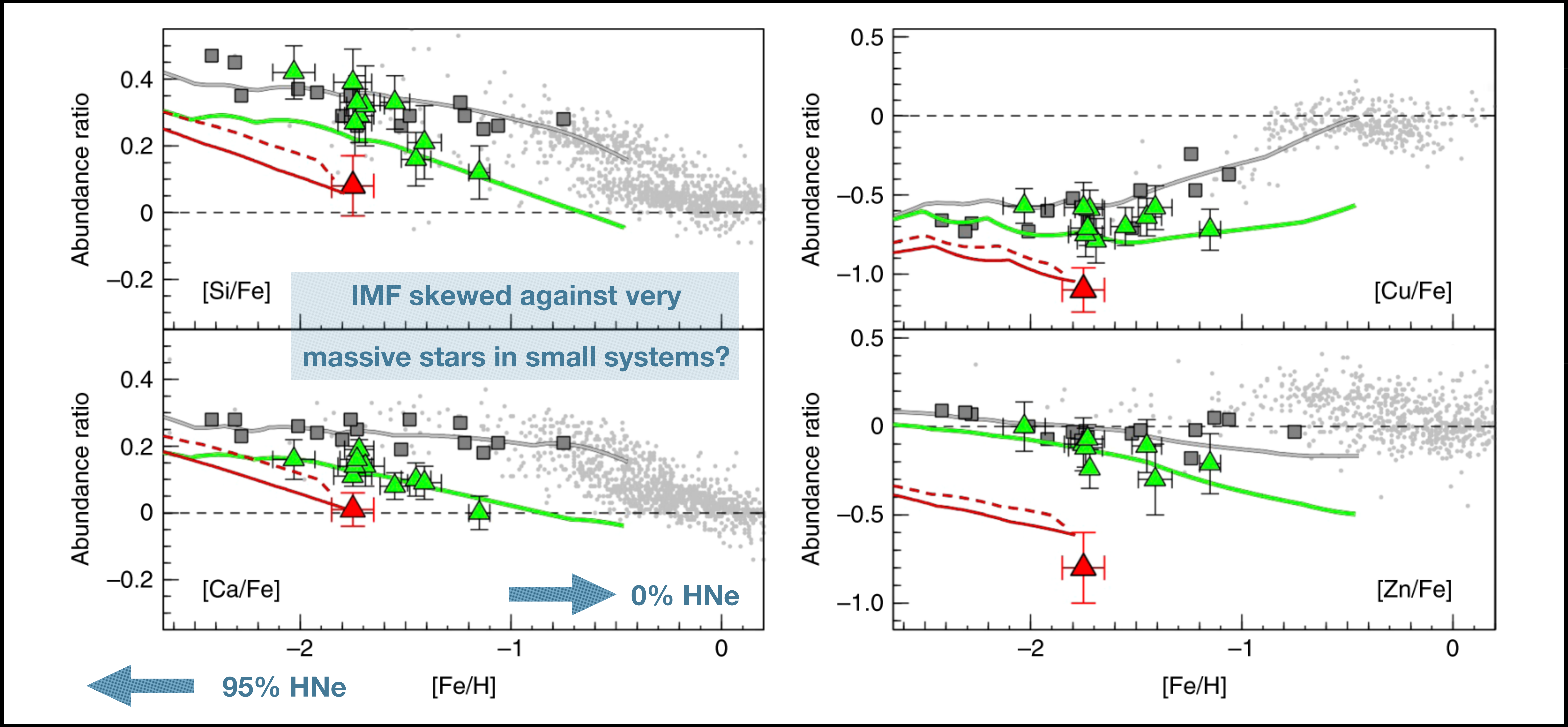
Rossi, DR et al. (2024)

The importance of being energetic

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-021-01493-y
Check for updates

A relic from a past merger event in the Large Magellanic Cloud

A. Mucciarelli[1,2] ✉, D. Massari[2,3], A. Minelli[1,2], D. Romano[2], M. Bellazzini[2], F. R. Ferraro[1,2], F. Matteucci[4,5,6] and L. Origlia[2]



Milky Way GCs

LMC GCs

LMC NGC 2005

NSM rate in the Milky Way

$$R^{th}_{NSM}(t) = \alpha_{NSM} \int_9^{30(50)} \psi(t - \tau_m - \Delta t_{NSM})\, \phi(m)\, dm$$

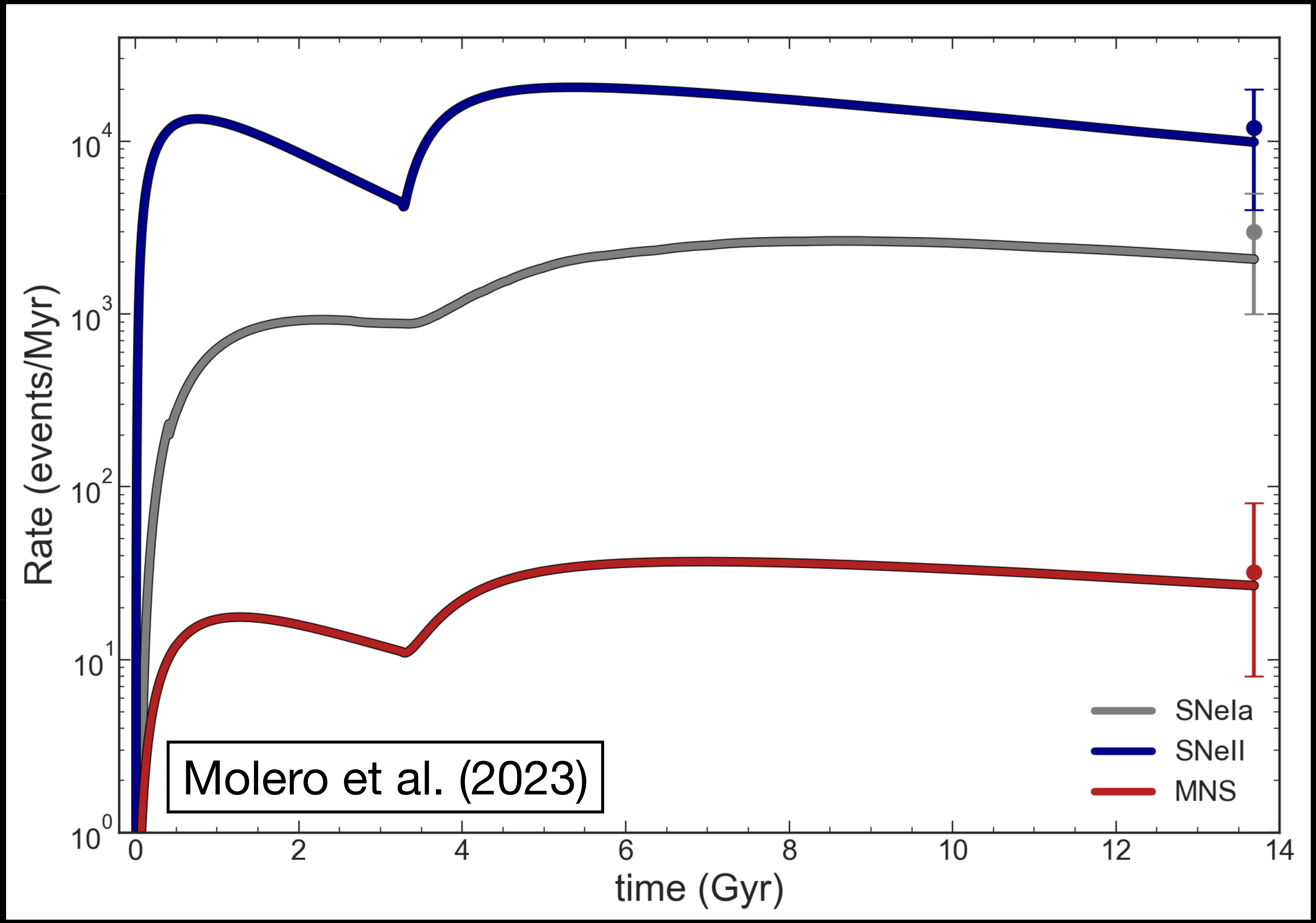
(Matteucci, DR et al. 2014)

$$R^{th}_{NSM}(t) = \int_{\tau_i}^{min(t, \tau_x)} \alpha_{NSM}(\tau)\, \psi(t - \tau) f_{NSM}(\tau) d\tau \int_9^{50} \phi(m)\, dm$$

(Simonetti, Matteucci, Greggio, Cescutti 2019;

Greggio, Simonetti, Matteucci 2021)

Observed SN rates:
Cappellaro, Evans & Turatto (1999)



Observed NSM rate:
Abbott et al. (2021)

Eu enrichment in the Milky Way

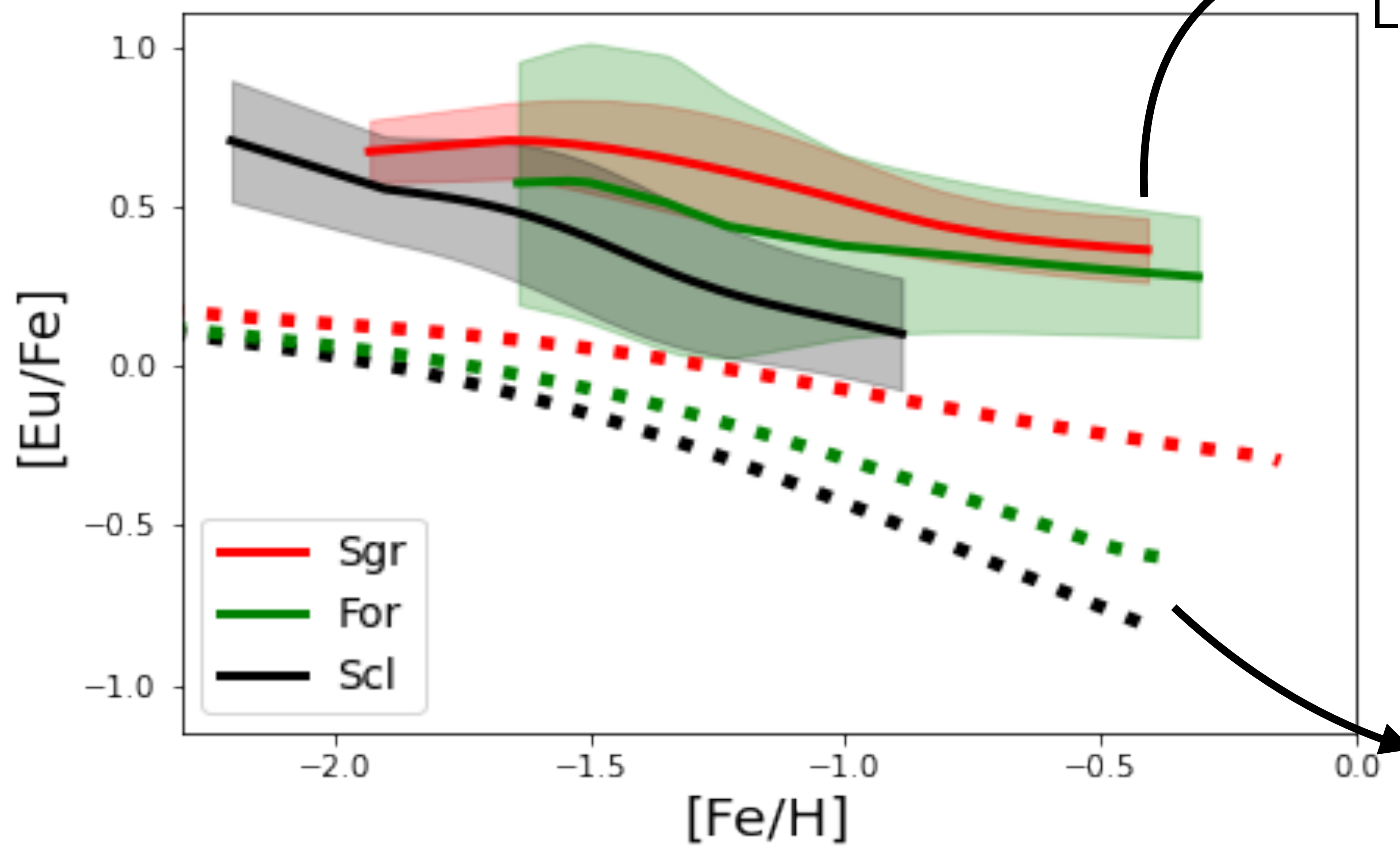
Slide courtesy: Marco Palla

r-process outside the MW

Palla+ (incl. DR) submitted

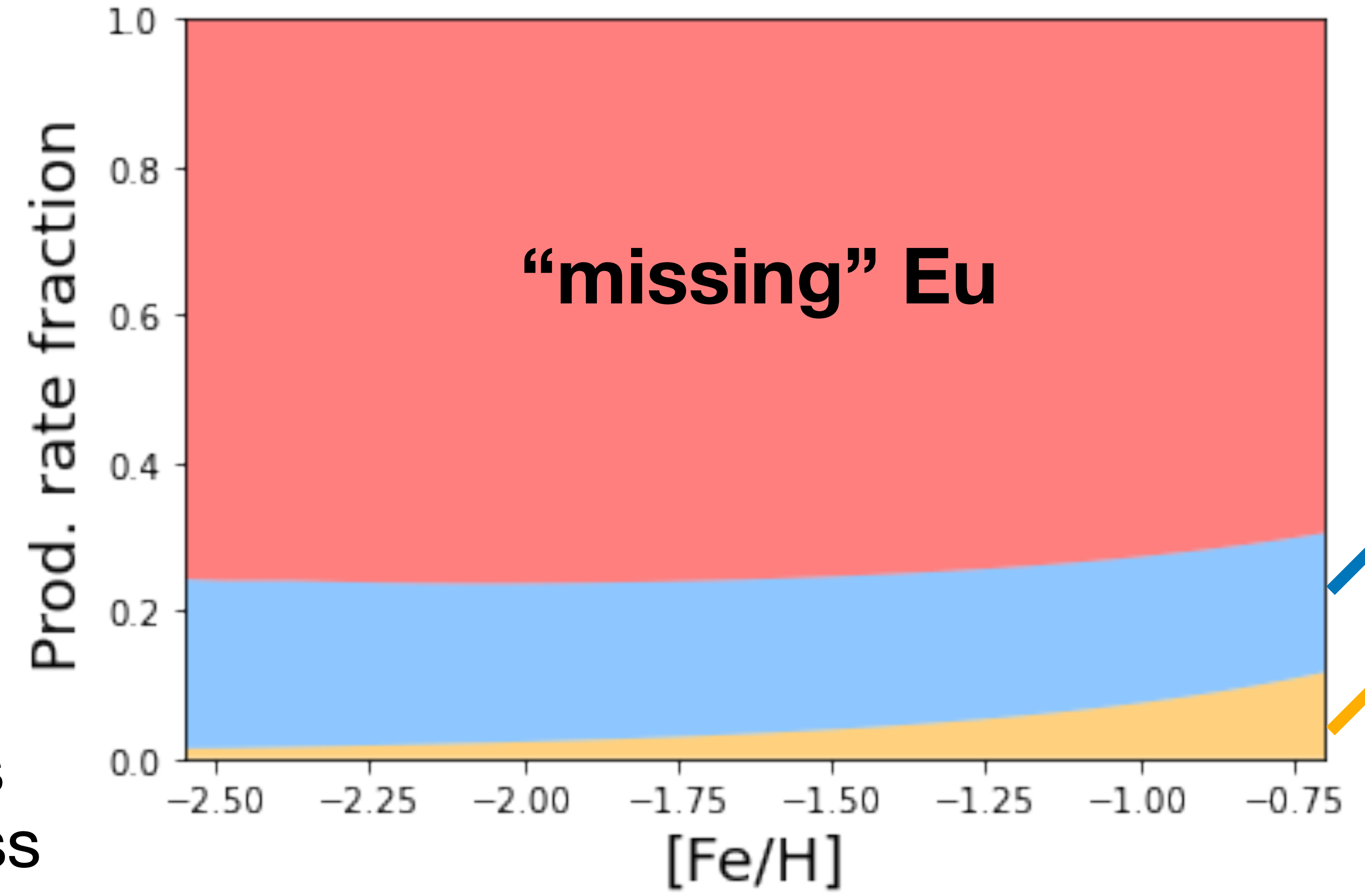
Local group dwarfs

Abundance trends (Hill+19, Reichert+20, Liberatori+25)



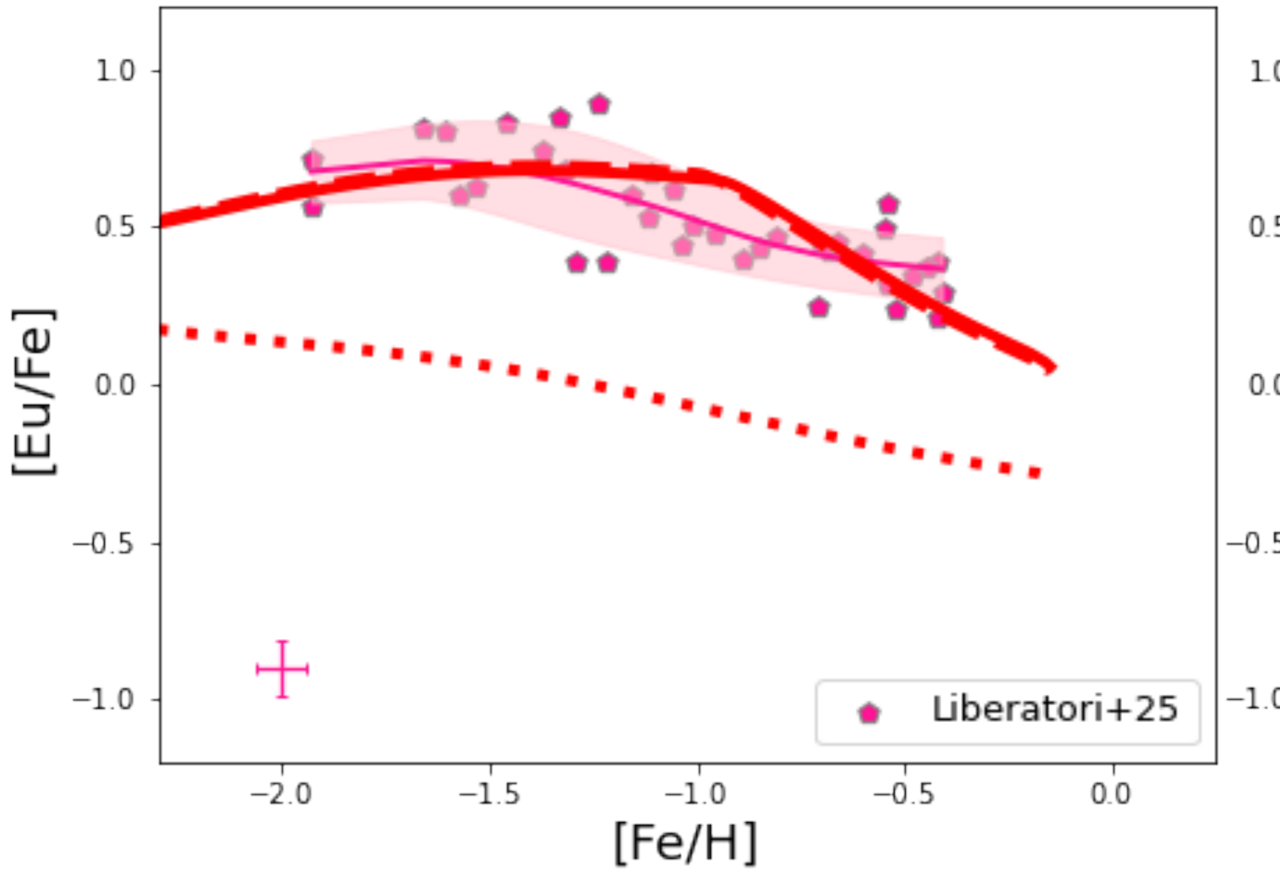
GCE models predictions with “standard" r-process prescriptions

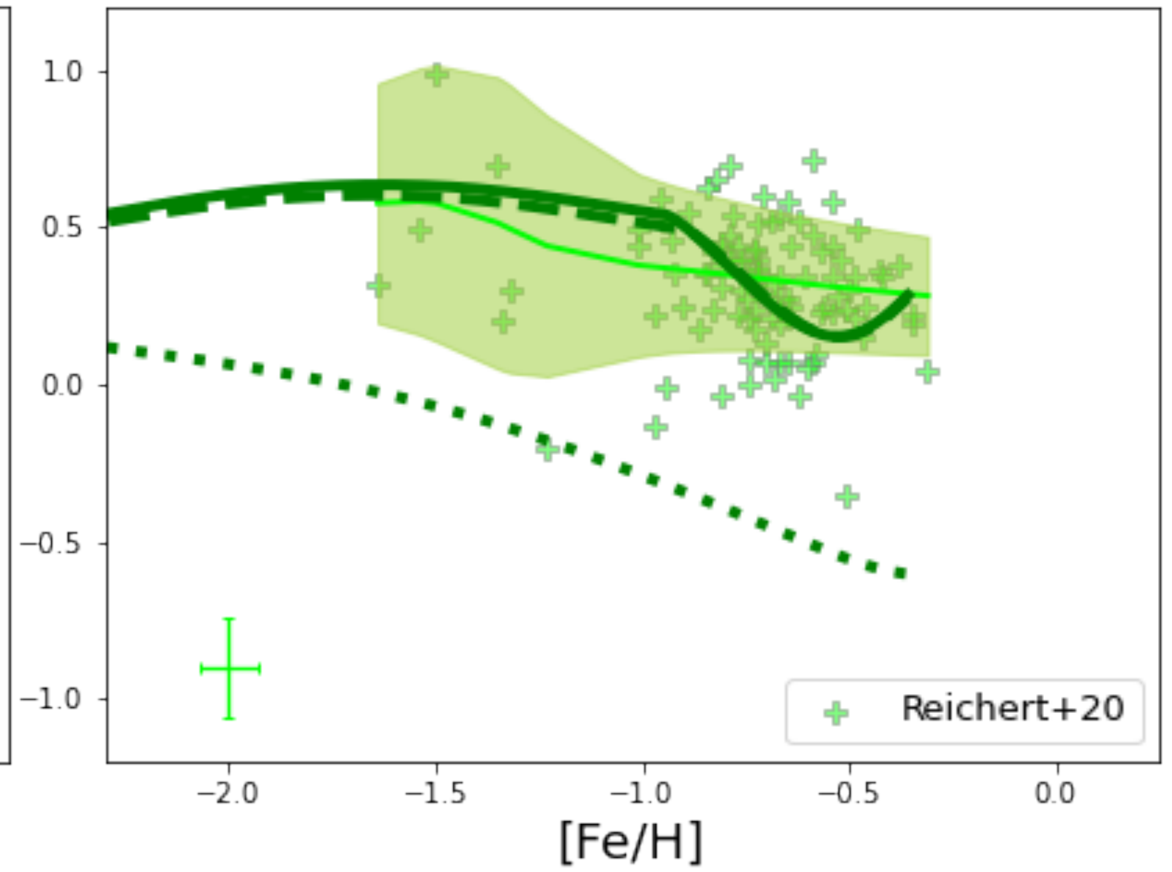
~3/4 of Eu content missing to match observations !



MRD-SNe/ collapsars

CBMs





Increased r-process production rate by CBMs at low metallicity

($Z \lesssim 2 \times 10^{-3} \simeq 0.15\ Z_\odot$)

(still consistent with MW abundance pattern)

Congratulazioni Laura, Enrico, Massimo e Massimo!