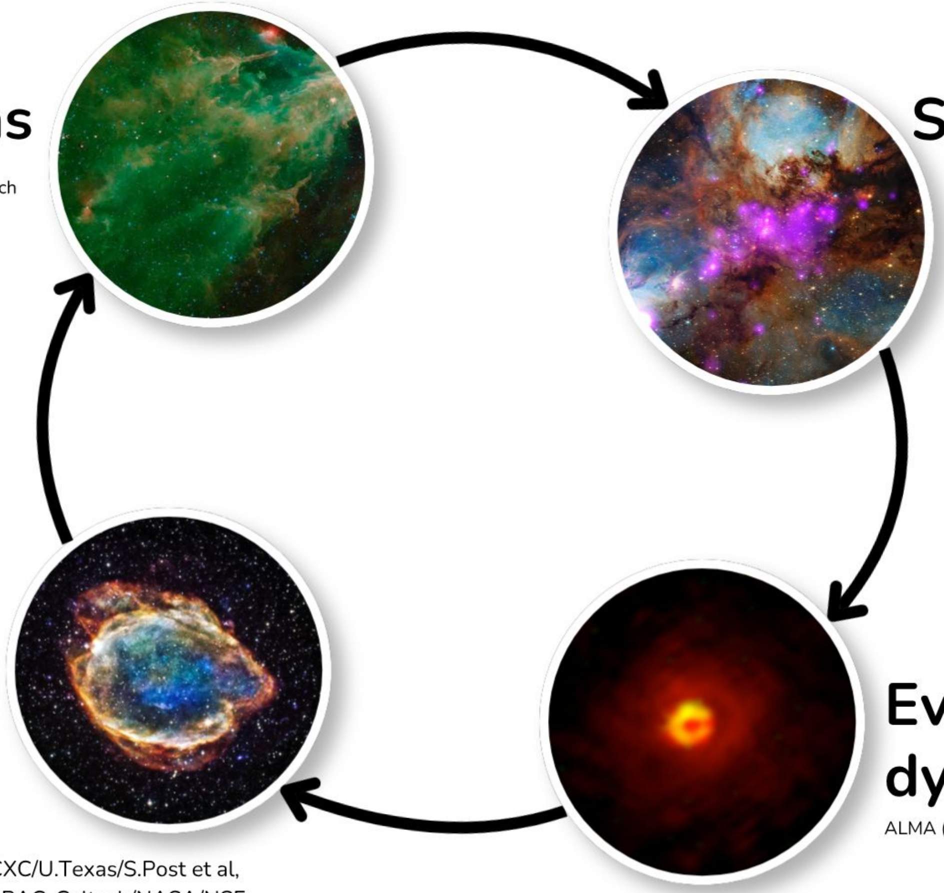
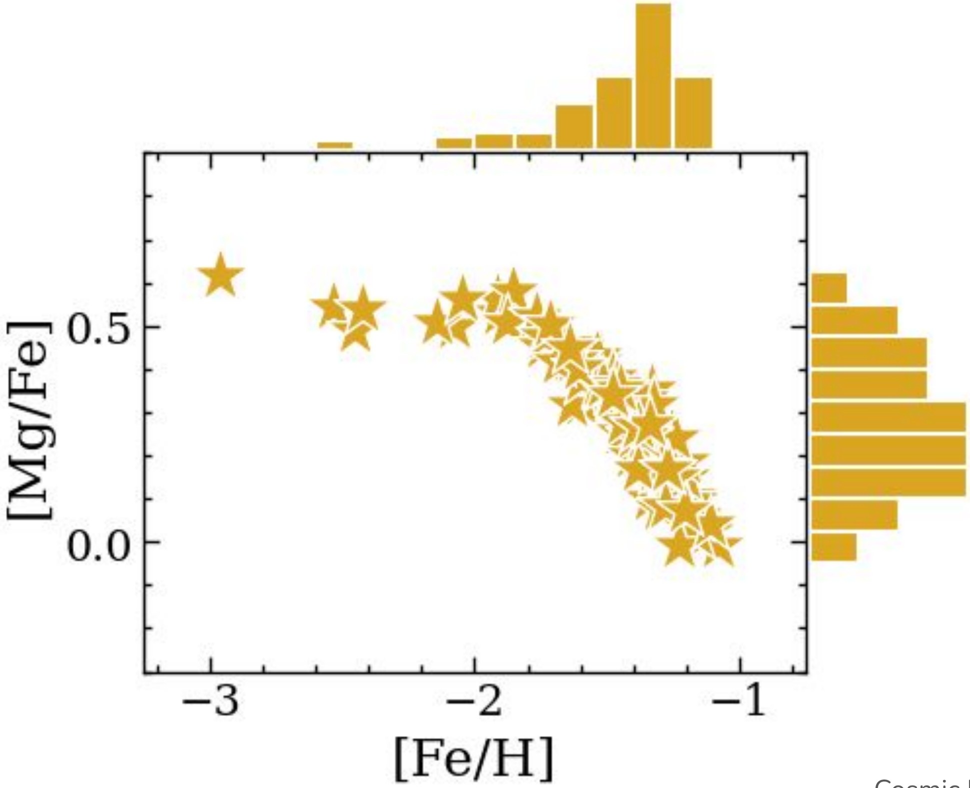
Data-Driven Bayesian Inference of Chemical Evolution in Dwarf Galaxies

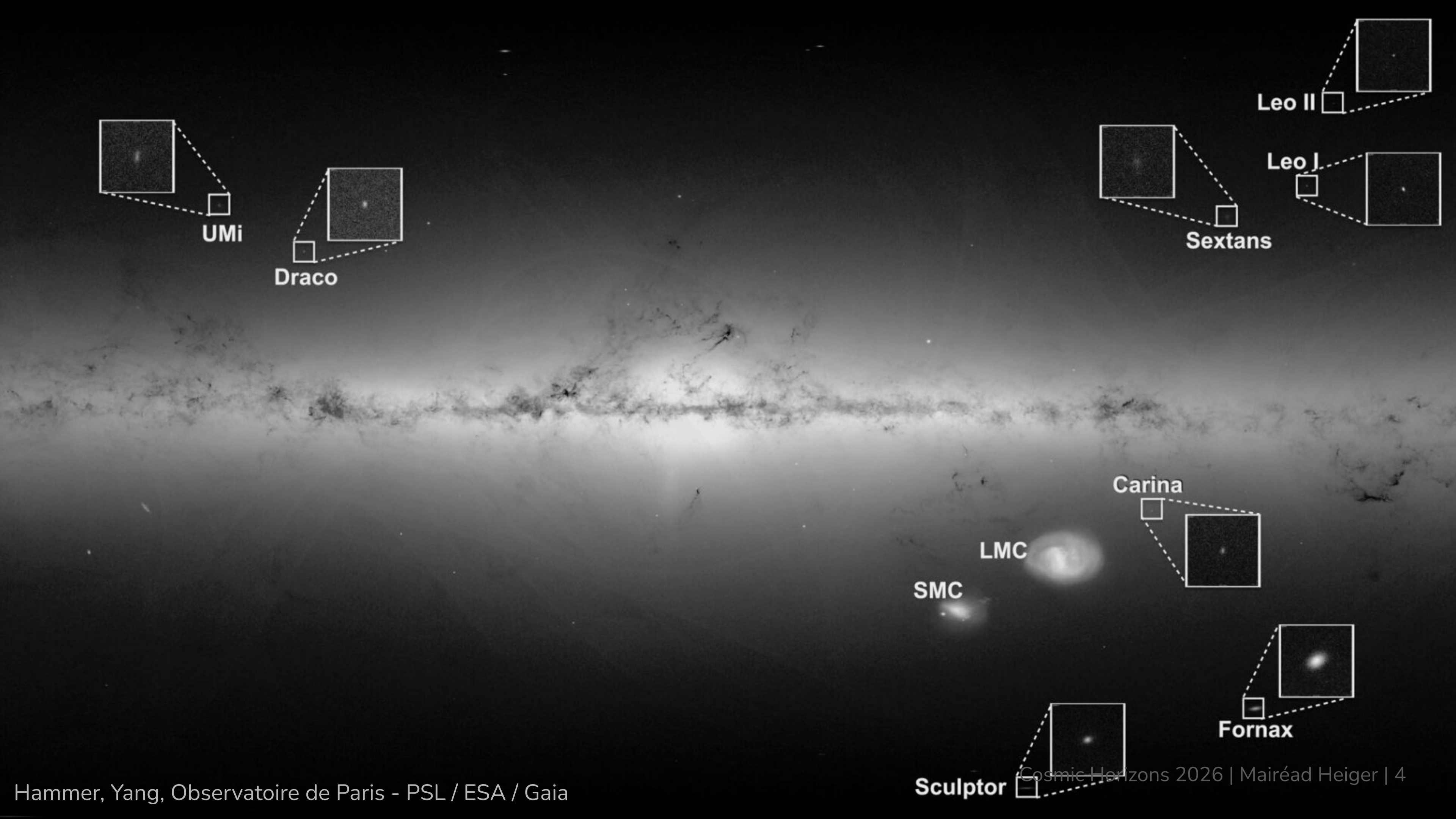
Mairéad Heiger
Alex Ji, Josh Speagle, Ting Li

UNIVERSITY OF TORONTO
DATA SCIENCES INSTITUTE


Gas
NASA/JPL-Caltech
Star formation
X-ray: NASA/SAO/CXC;
Infrared: NASA/ESA/CSA/STScI;
Image Processing: NASA/CXC/SAO/J. Major
Evolved and dying stars
ALMA (ESO/NAOJ/NRAO), Takigawa et al.
Ejecta
X-ray: NASA/CXC/U.Texas/S.Post et al,
Infrared: 2MASS/UMass/IPAC-Caltech/NASA/NSF

Chemical abundances are tightly coupled to the physics of galaxy formation and evolution





Hammer, Yang, Observatoire de Paris - PSL / ESA / Gaia

What underlying physics produced these observations?

Feedback

Supernova physics

Mergers

Star formation

Binary formation

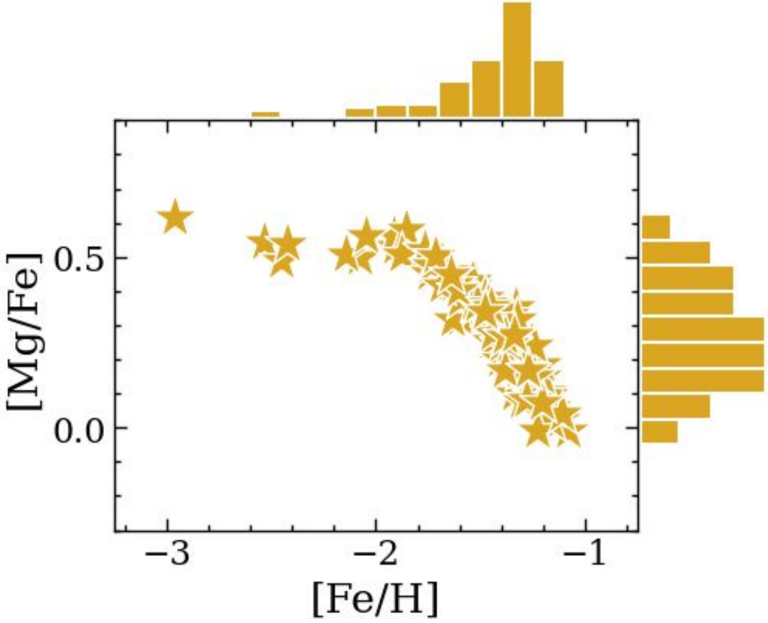
Stellar evolution

Mixing

Infall

Nucleosynthesis

???



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Feedback
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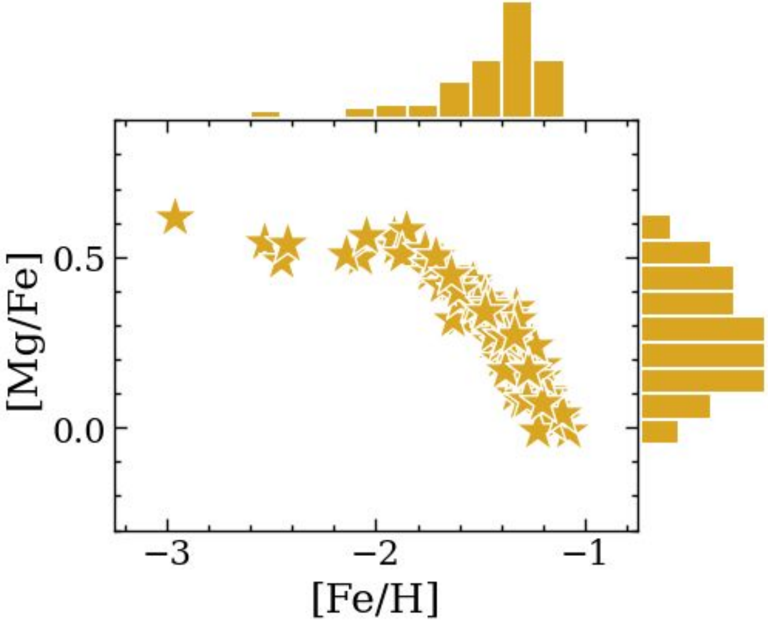
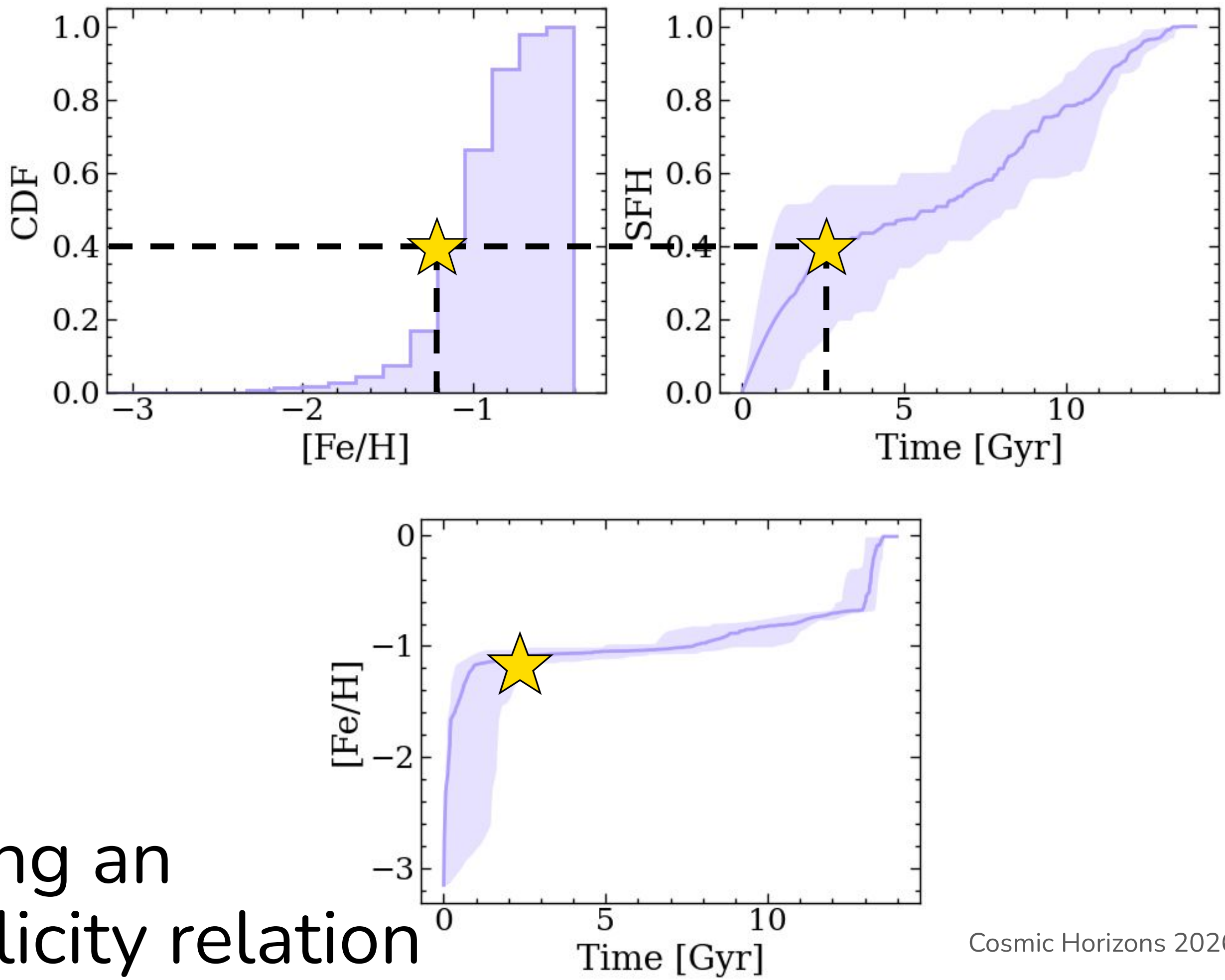
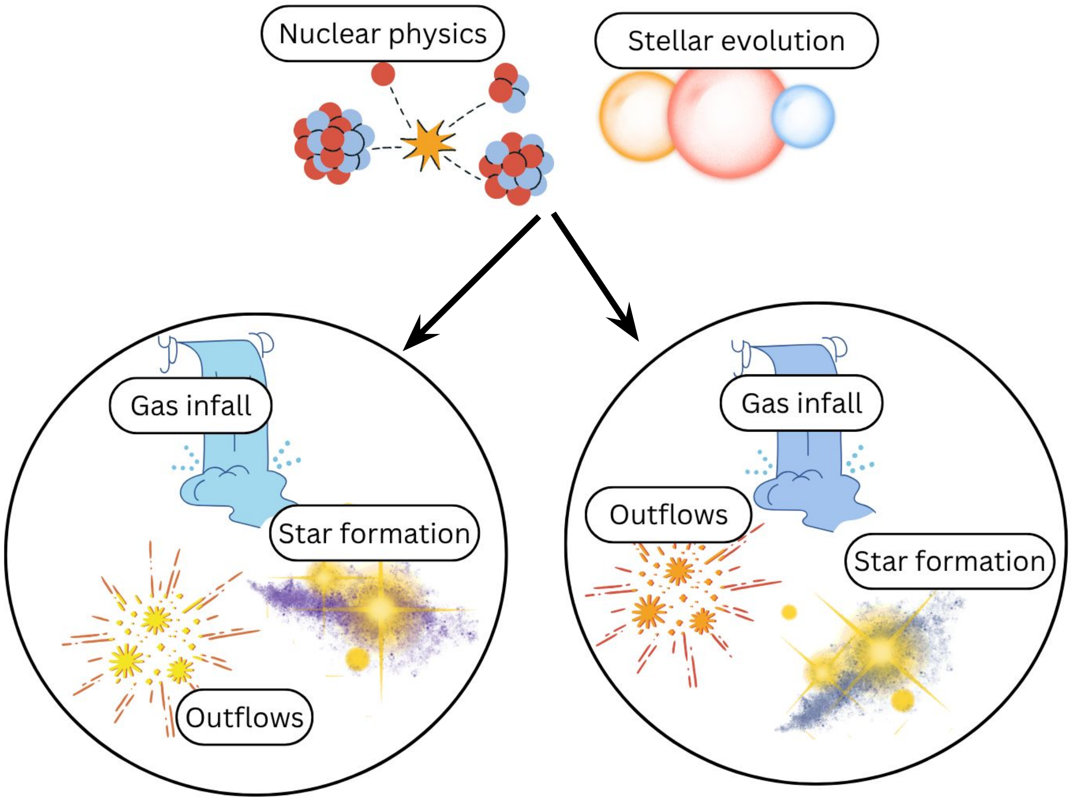
???

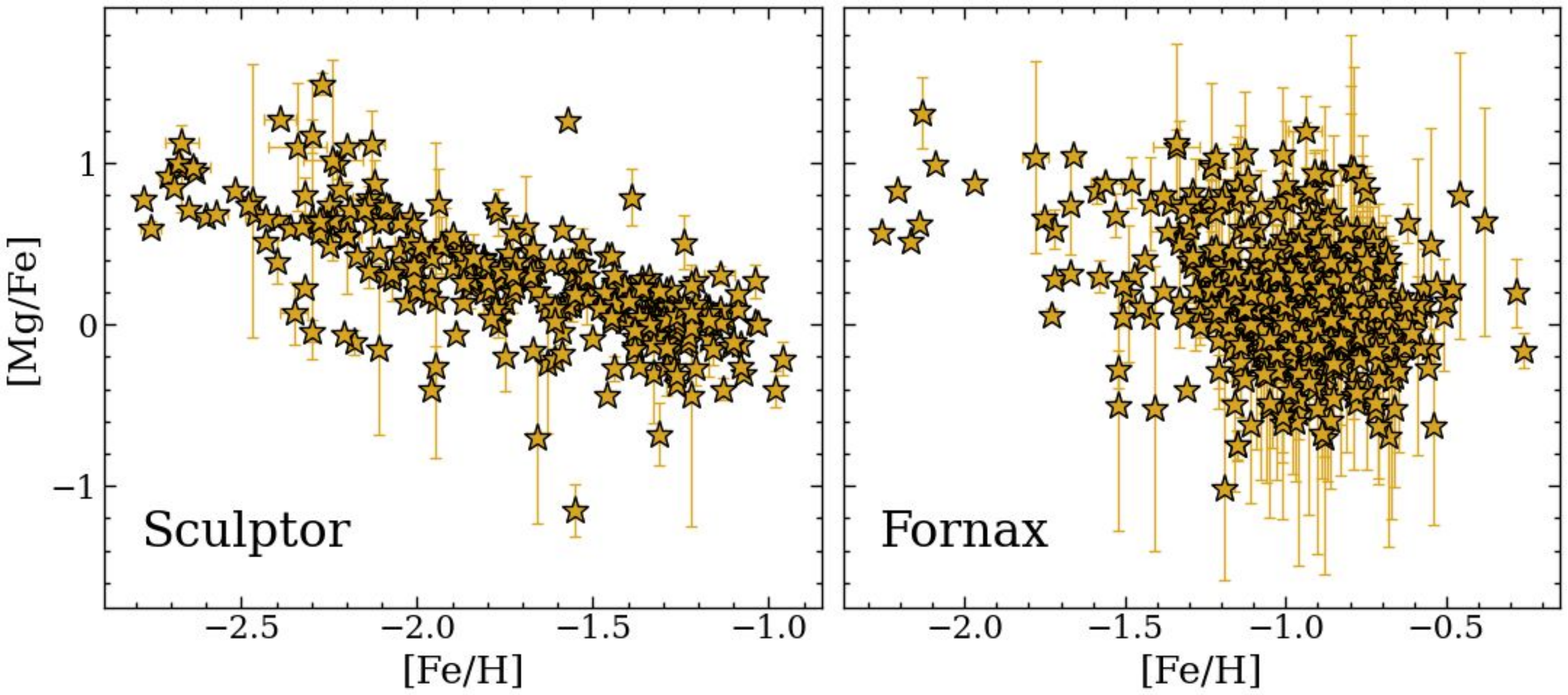




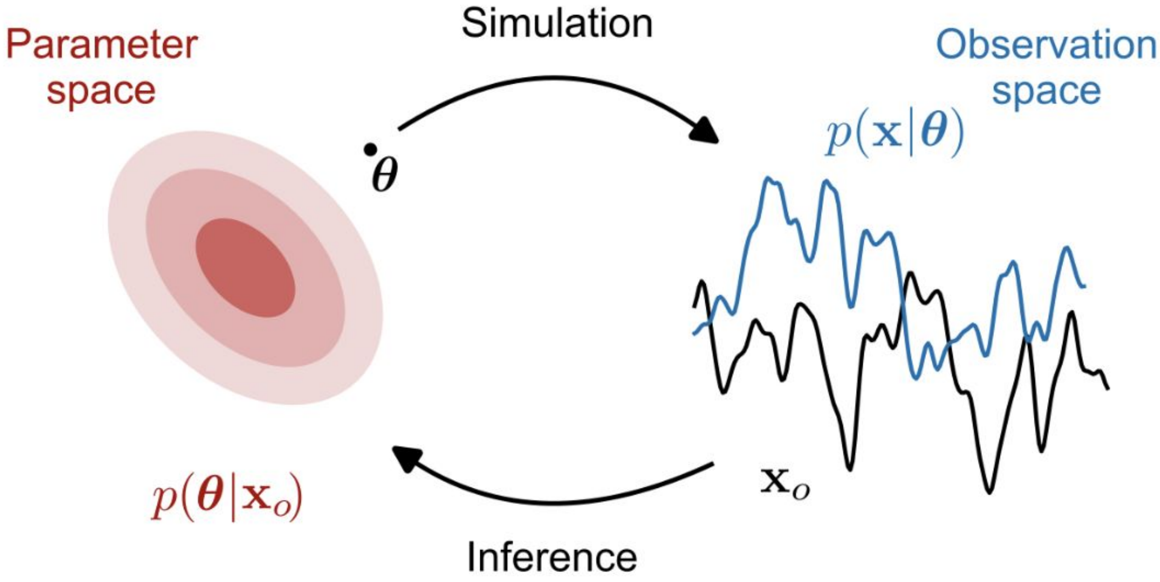
Constructing an age-metallicity relation

A multi-galaxy model to break degeneracies

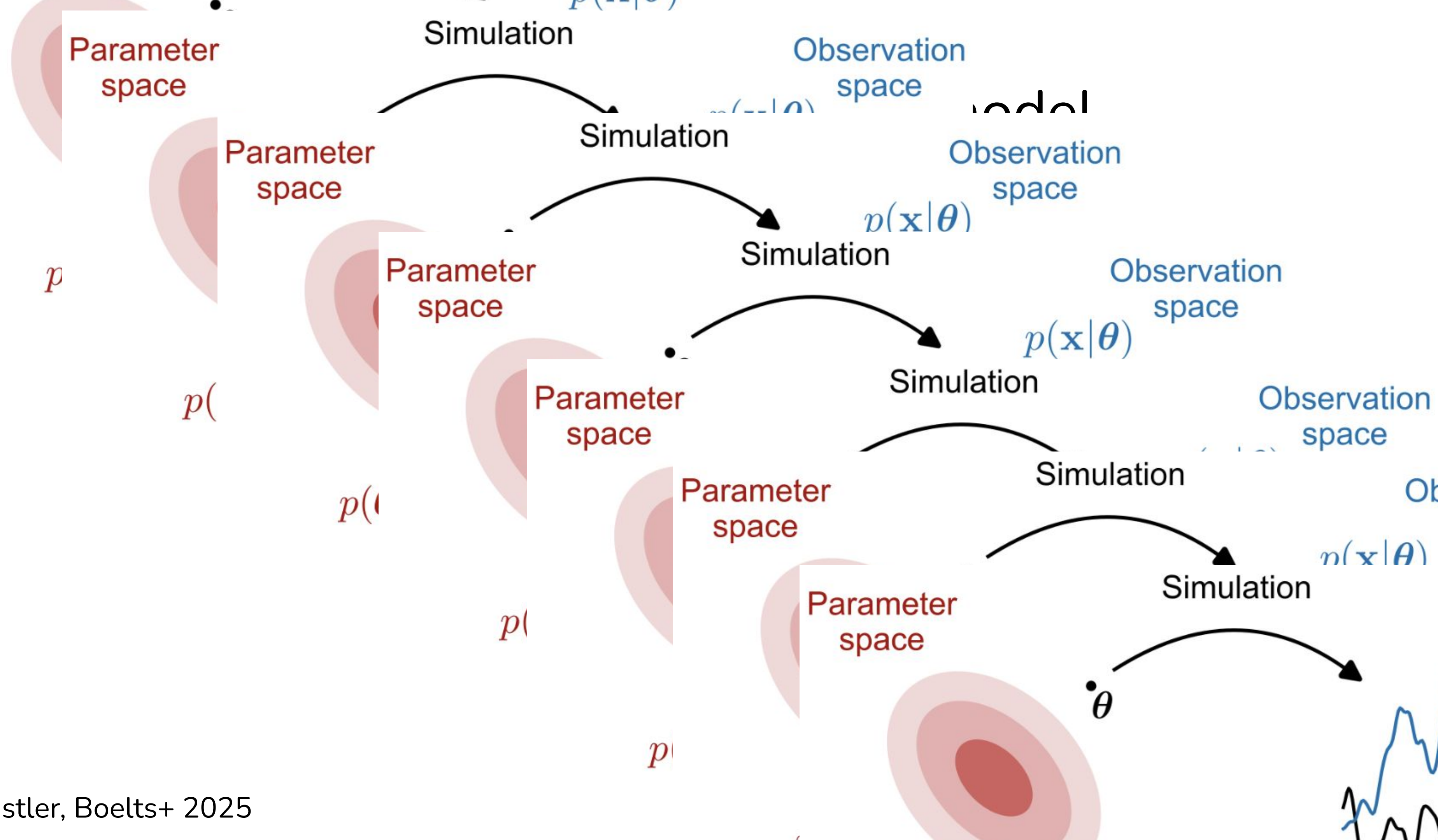



Sculptor
Fornax
[Mg/Fe]
[Fe/H]
[Fe/H]
1
0
−1
−2.5
−2.0
−1.5
−1.0
−2.0
−1.5
−1.0
−0.5

Applying a multi-galaxy model

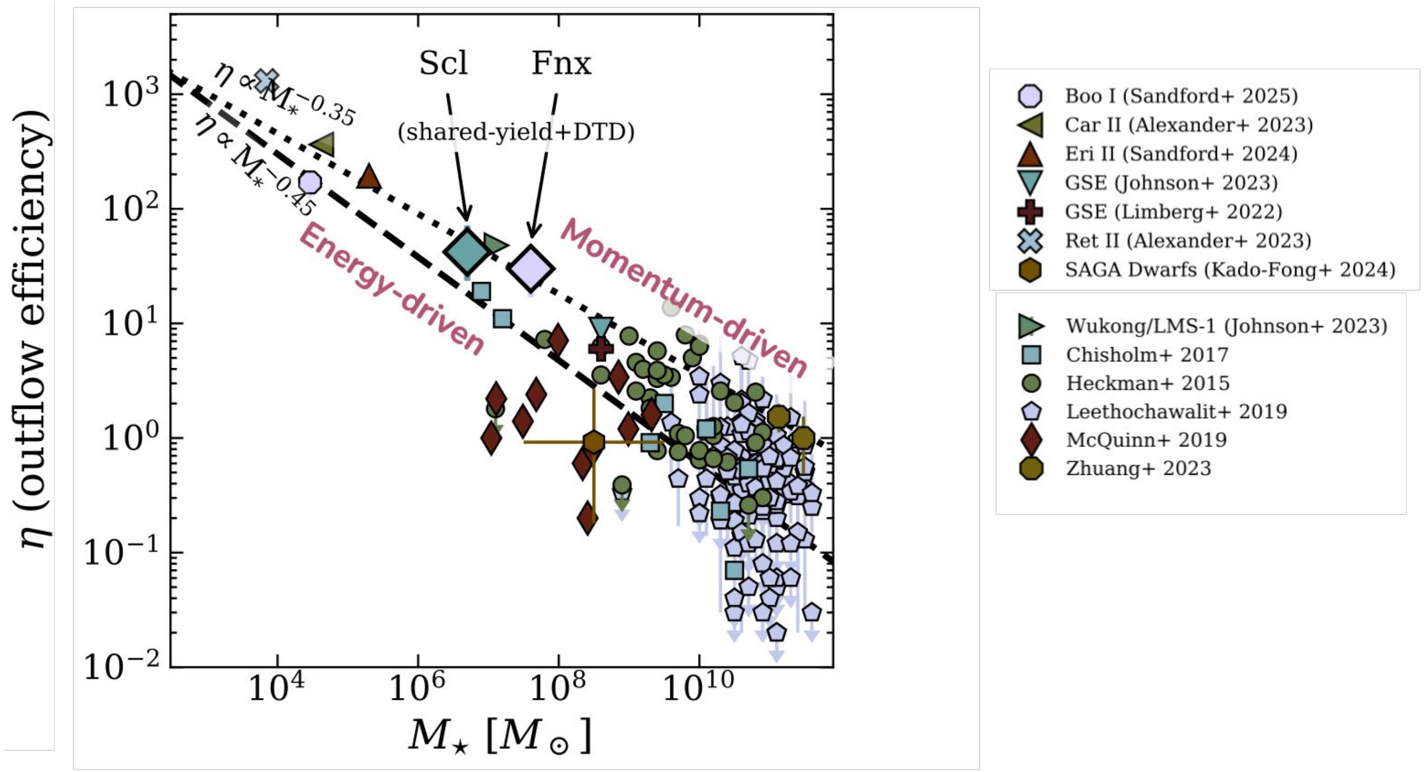


Deistler, Boelts+ 2025

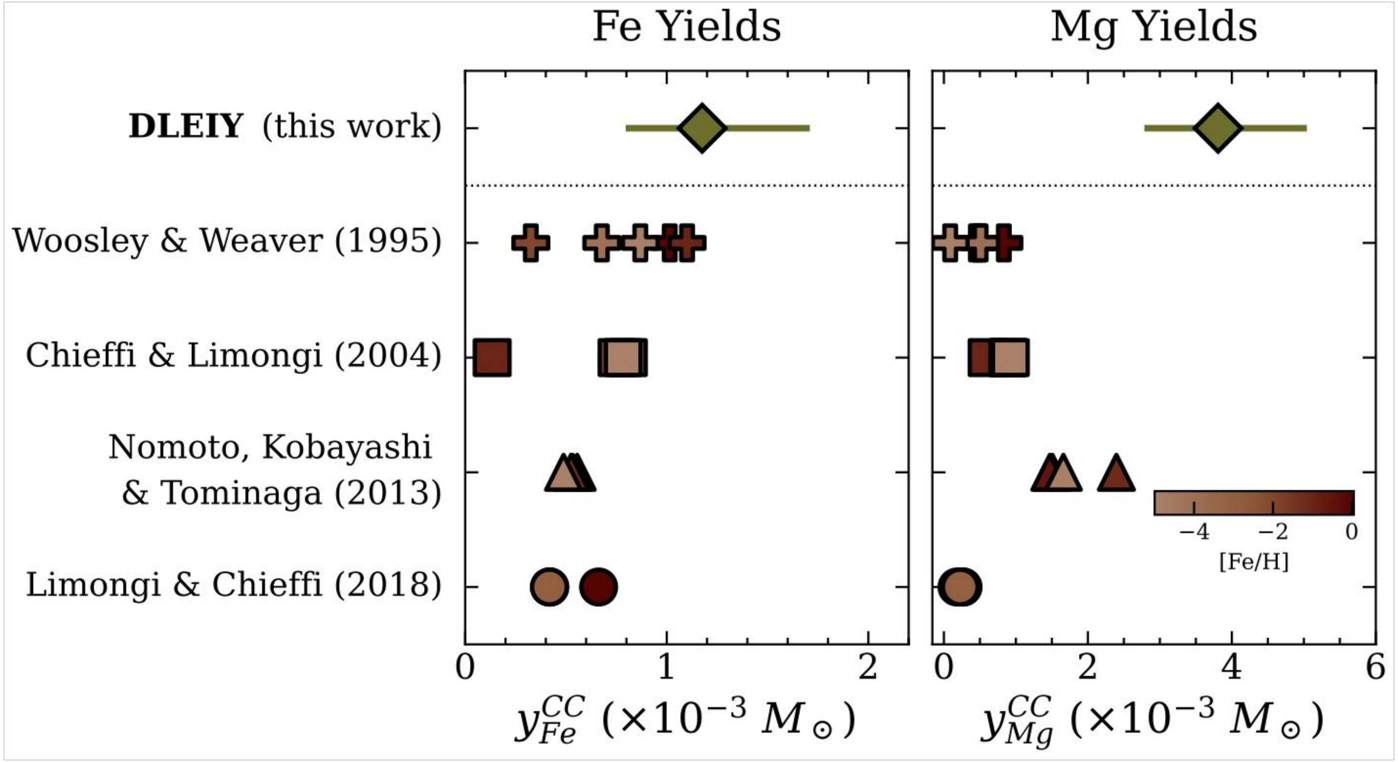


Deistler, Boelts+ 2025

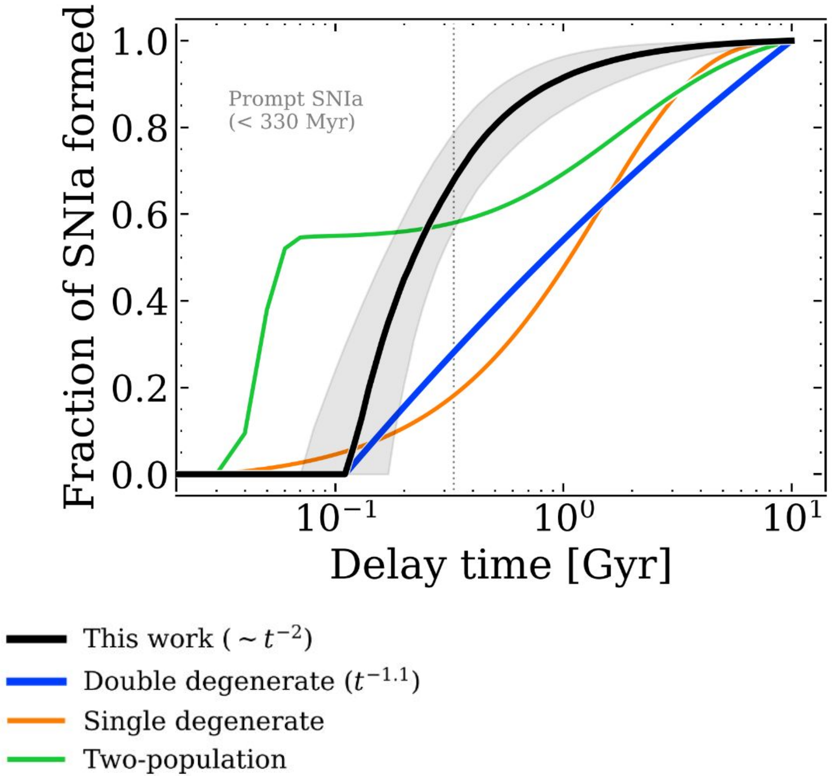
Galactic outflows – mass-loading factor

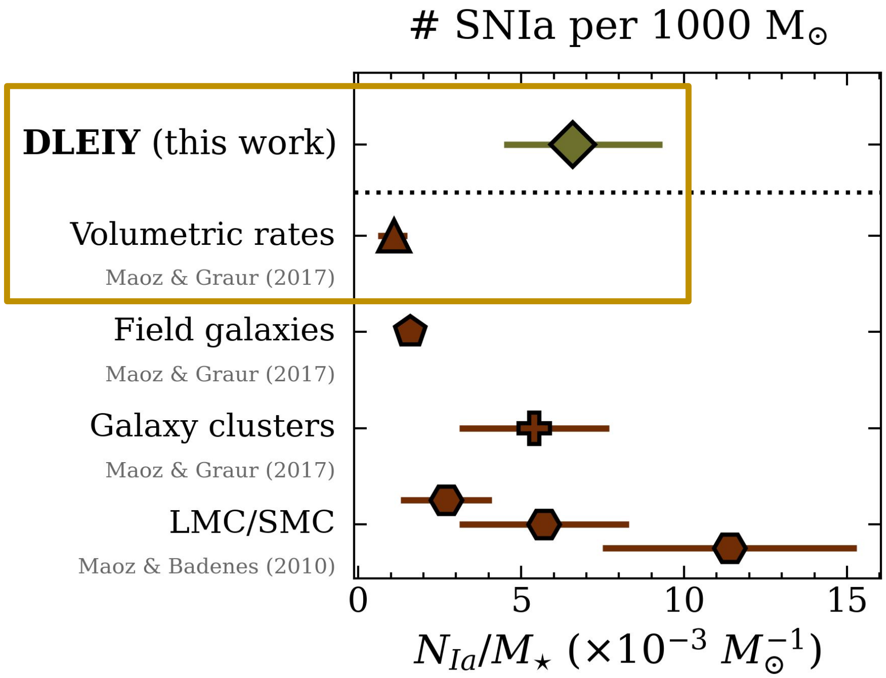


Empirical vs theoretical CCSN yields

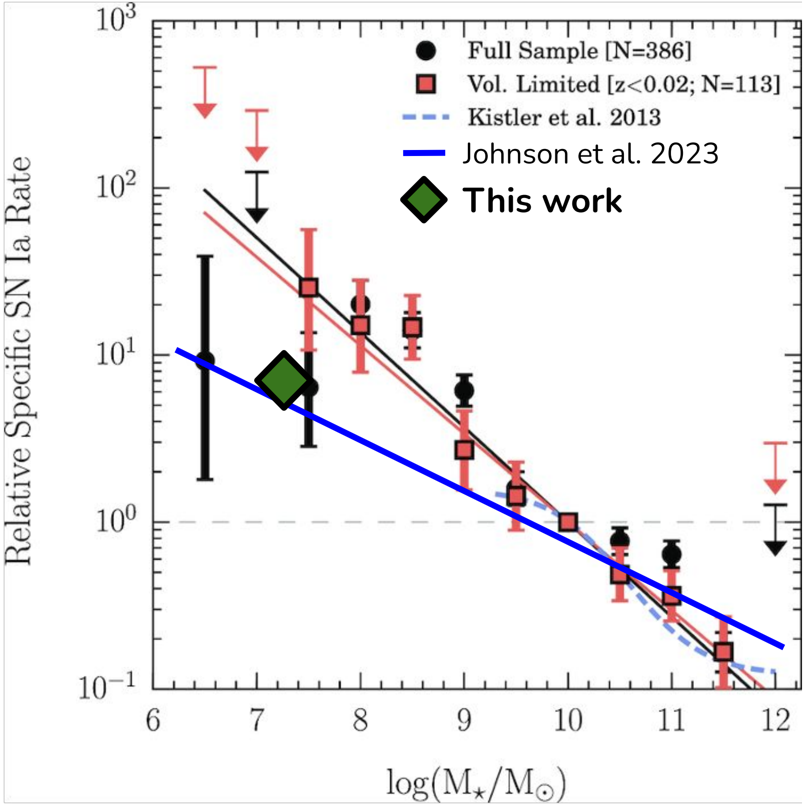


A large prompt population + a high specific rate





The specific rate is correlated with mass

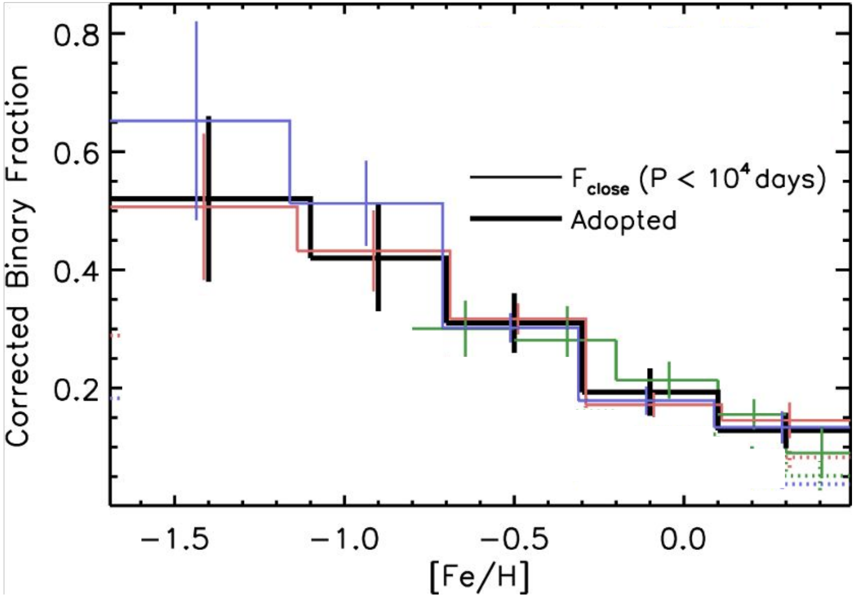


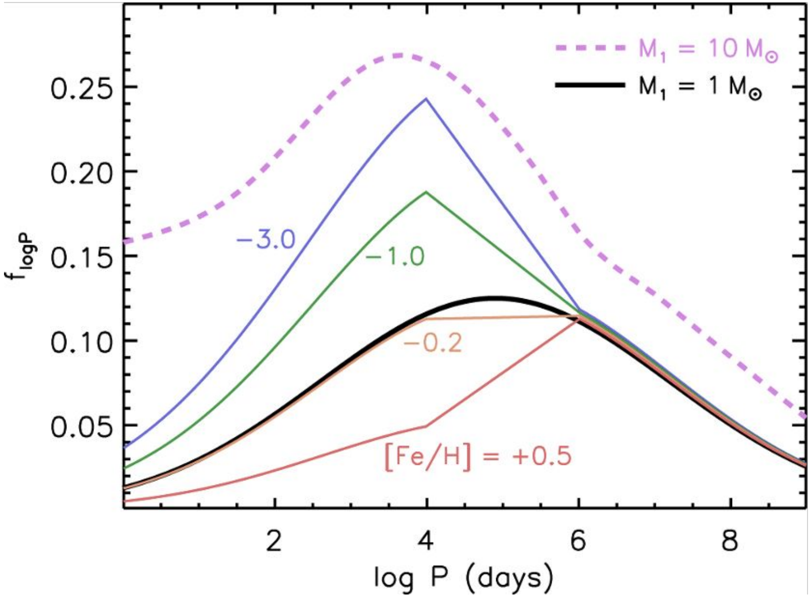
100x more SNIa per $M_\star$

10x more SNIa per $M_\star$

Brown+ 2019

Close binary fraction increases at low metallicities

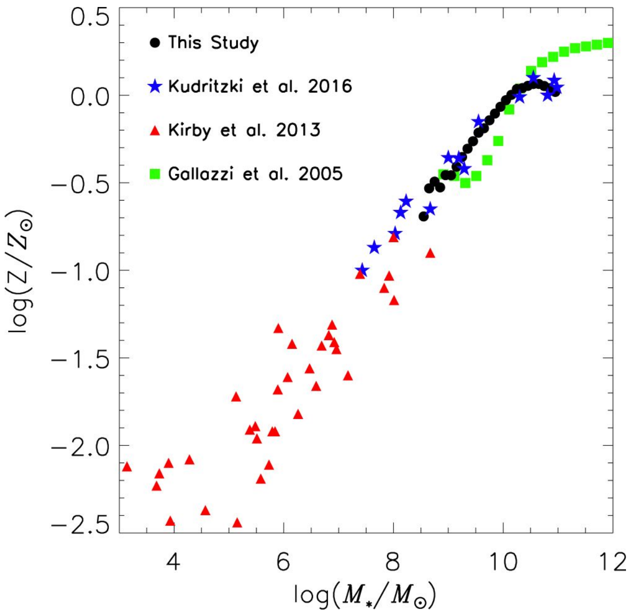




Moe+ 2019

Future work

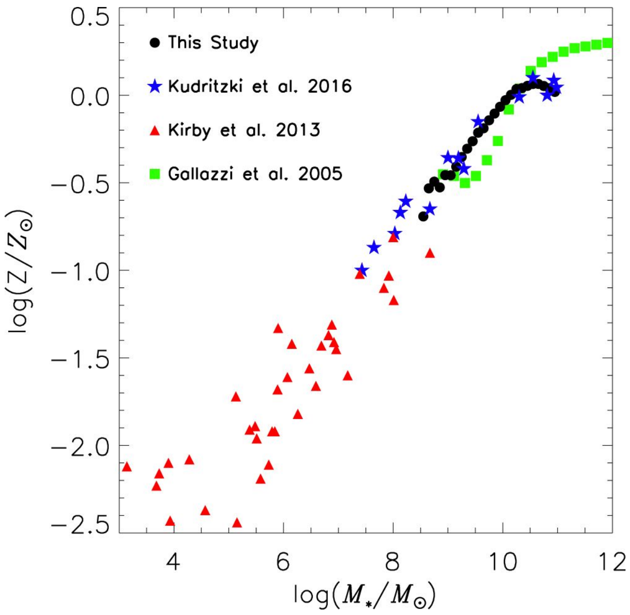
More galaxies



Zahid+ 2017

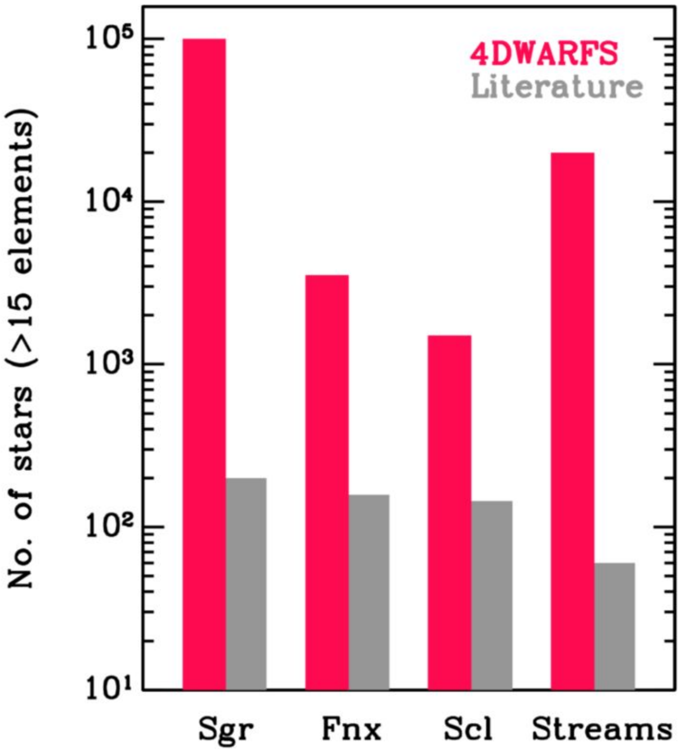
Future work

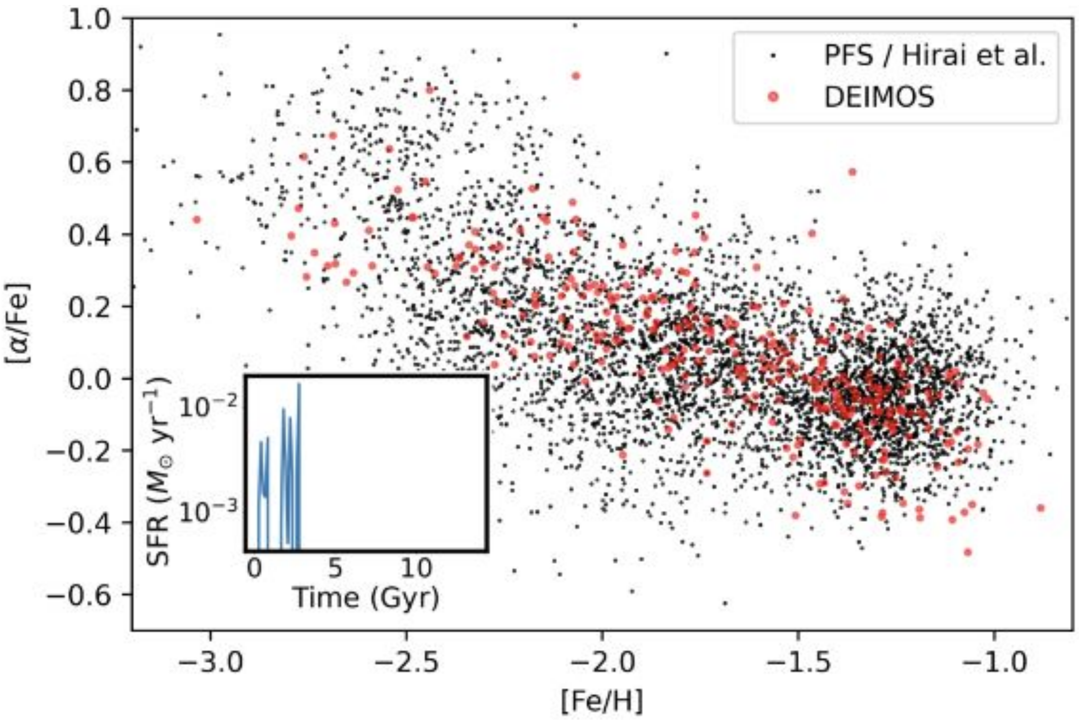
More galaxies



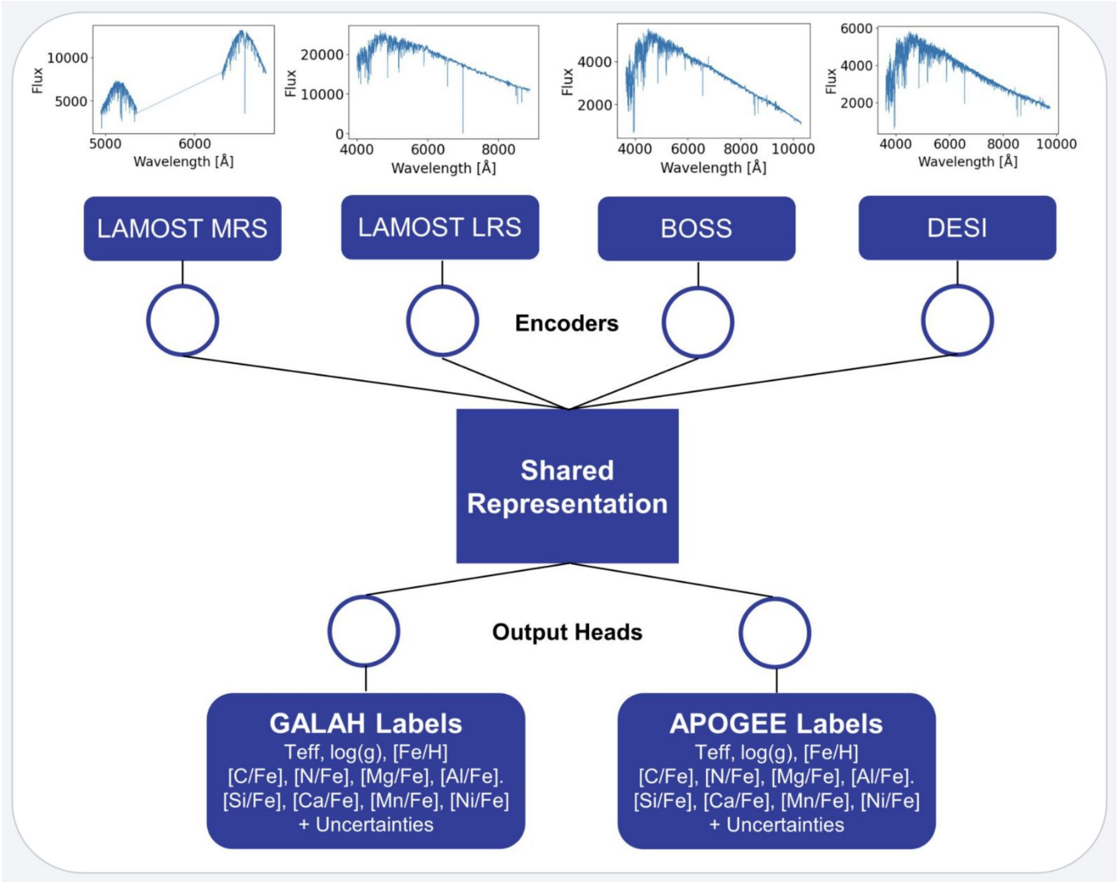
Zahid+ 2017

More elements





Skúladóttir+ 2020, Chiba+ 2026



Diego Martínez Vasquez

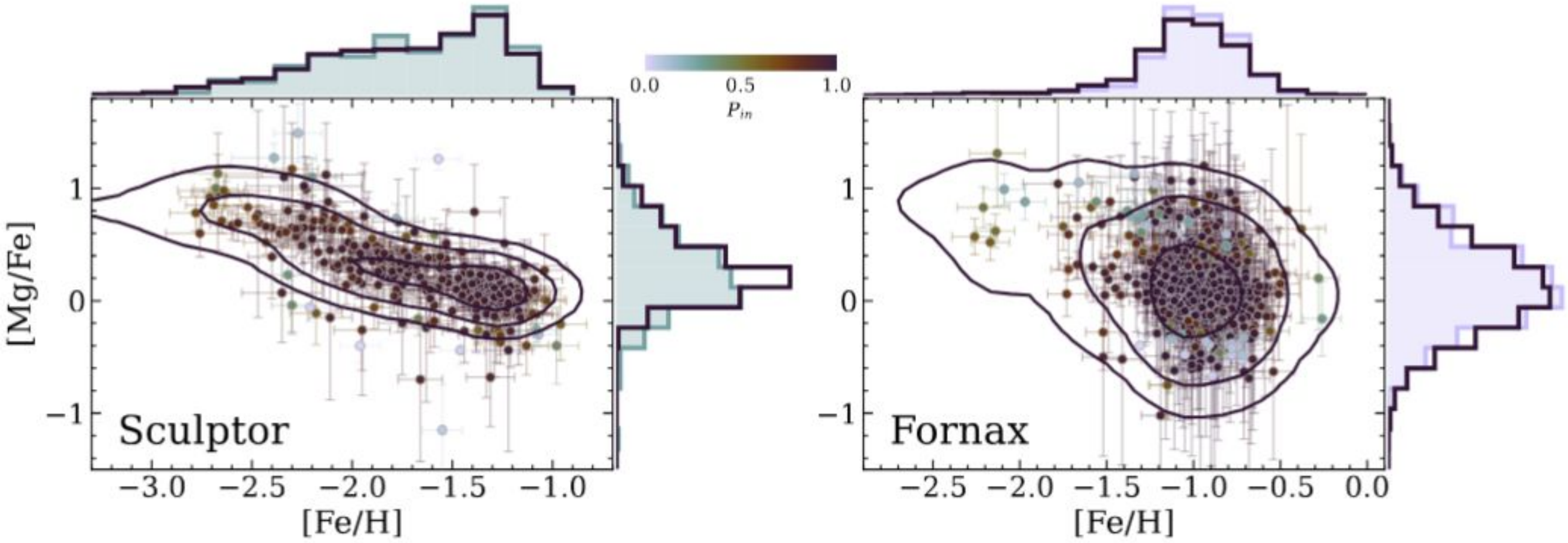
Isabelle Laing

+Biprateep Dey, Josh Speagle, Nathan Sandford, Ting Li, ...

Conclusions

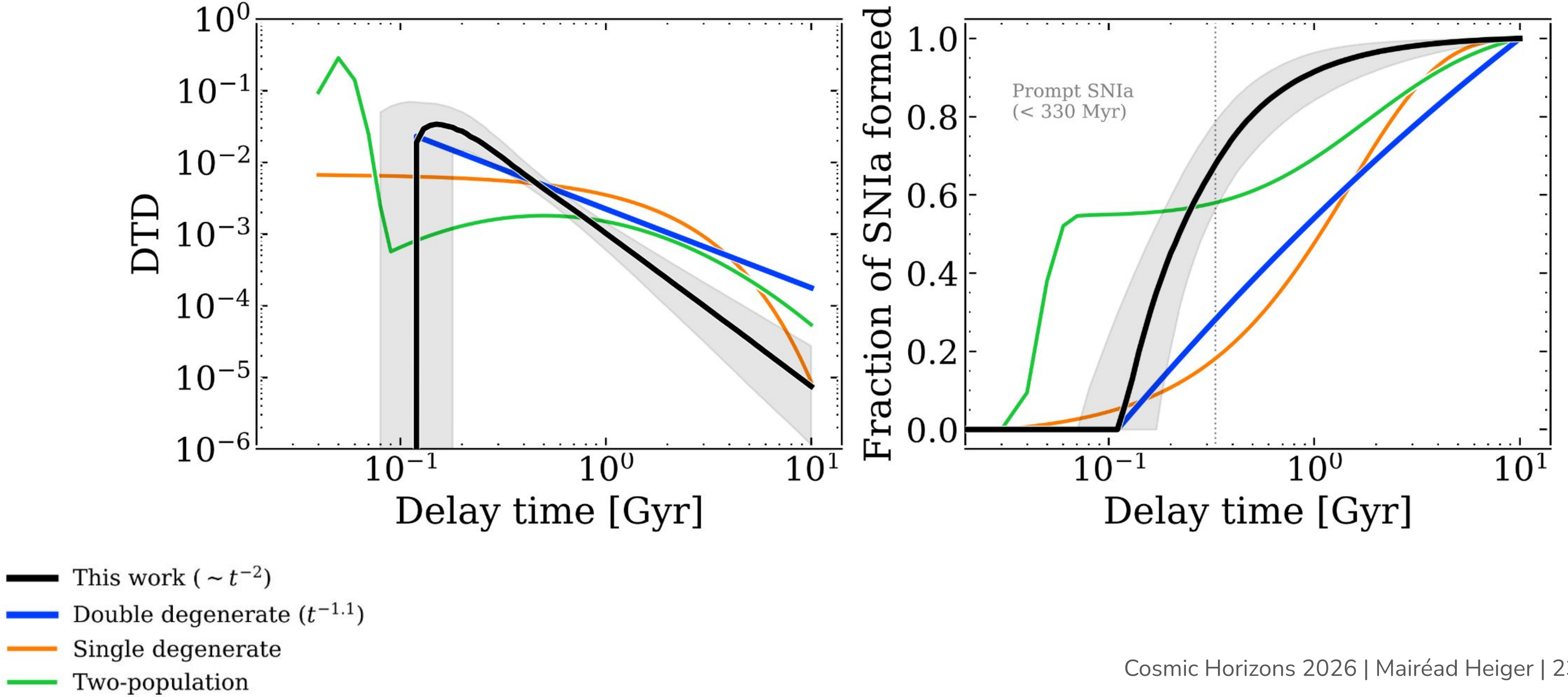
- A **joint model of multiple galaxies ➜** constraints on **environmental dependence** of processes in chemical enrichment
- Enhanced SNIa rate and fraction of prompt SNIa in Sculptor and Fornax suggests a **metallicity dependence**

arxiv:2602.22333

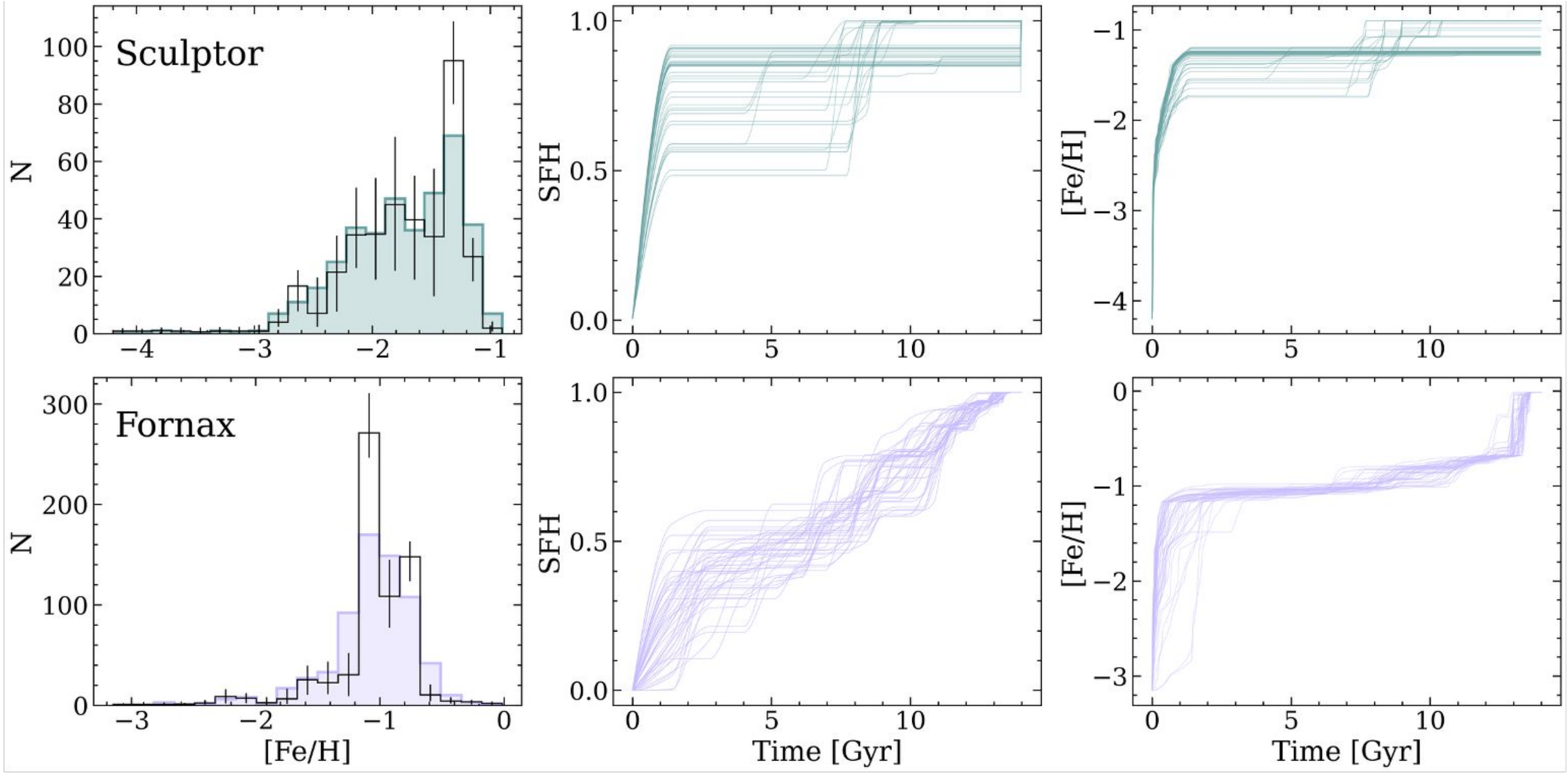


Sculptor
Fornax
[Mg/Fe]
[Fe/H]
[Fe/H]
P_{in}
0.0
0.5
1.0
1
0
−1
−3.0
−2.5
−2.0
−1.5
−1.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0

A large prompt population of SNIa



Applying a multi-galaxy model



$$P(D_i \mid \theta, A_k) \propto \sum_{j=1}^{J} w_j \; \mathcal{N}(D_i | T_j, C_i) =$$

$$\sum_{j=1}^{J} w_j \exp\left(-\frac{1}{2}(D_i - T_j) C_i^{-1} (D_i - T_j)^{\mathrm{T}}\right)$$

$$w_j \propto \dot{M}_{\star,j}$$

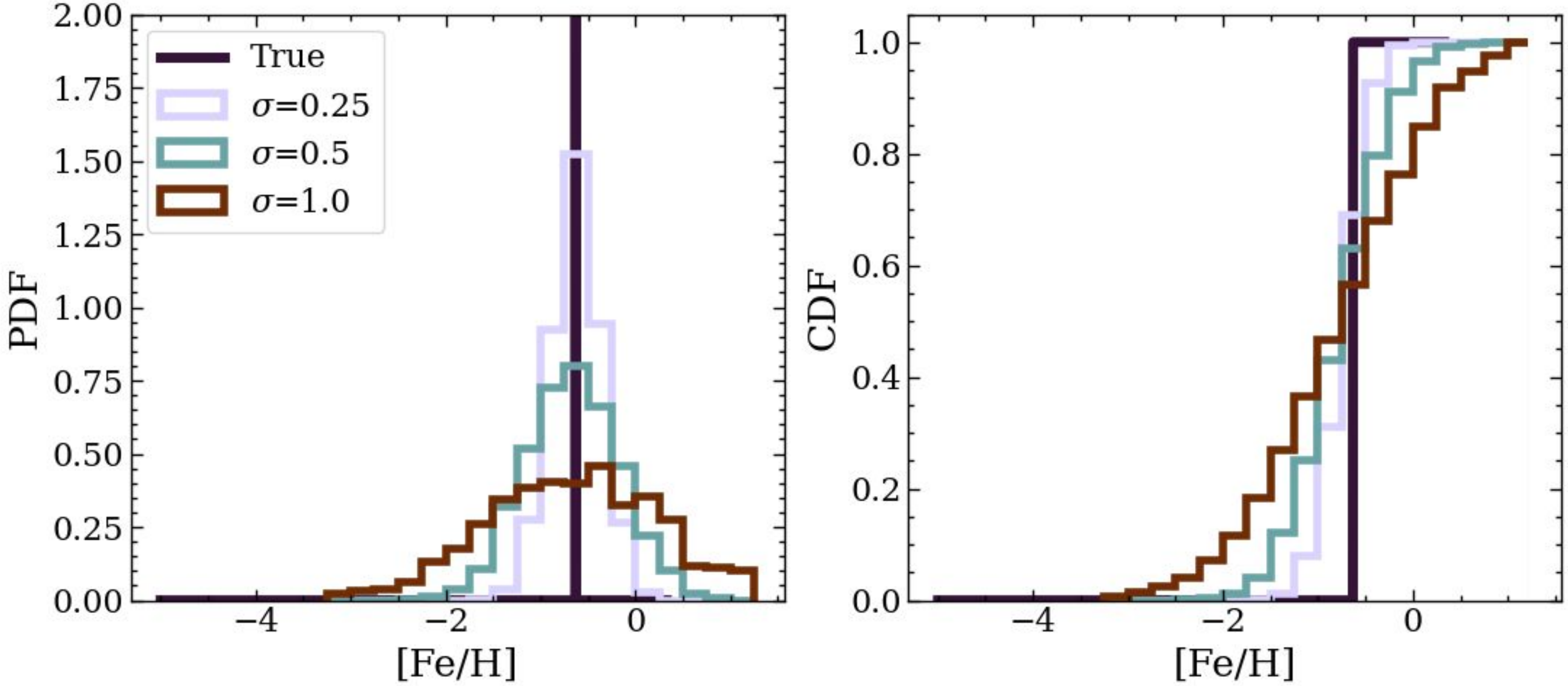
$$\log \mathcal{L}(D_i | \; \theta, \{A_k\}) \propto$$

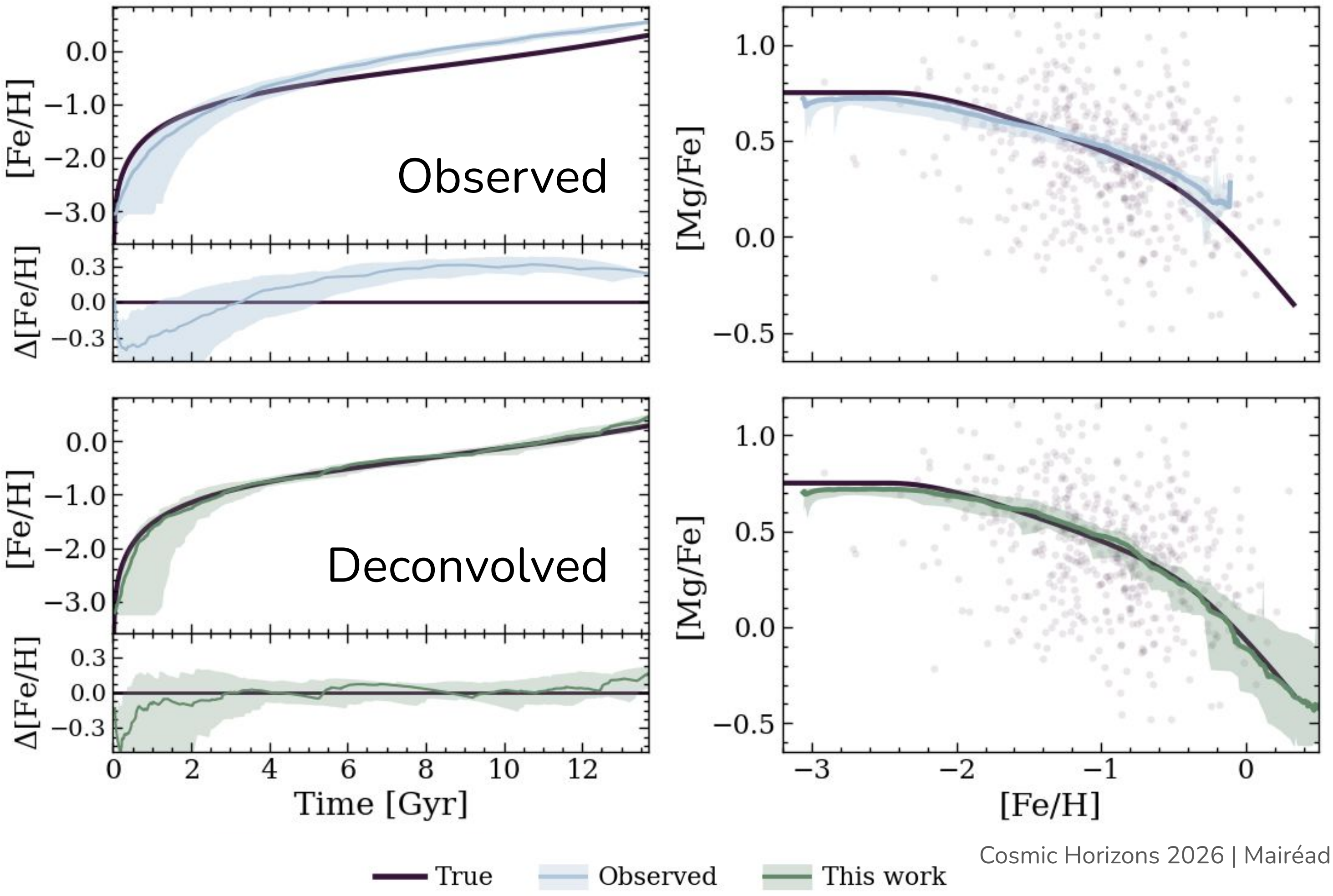
$$\log \sum_{k=1}^{K} (1-f) \times P_{\mathrm{in}}(D_i | \theta, A_k) + f \times P_{\mathrm{out}}$$

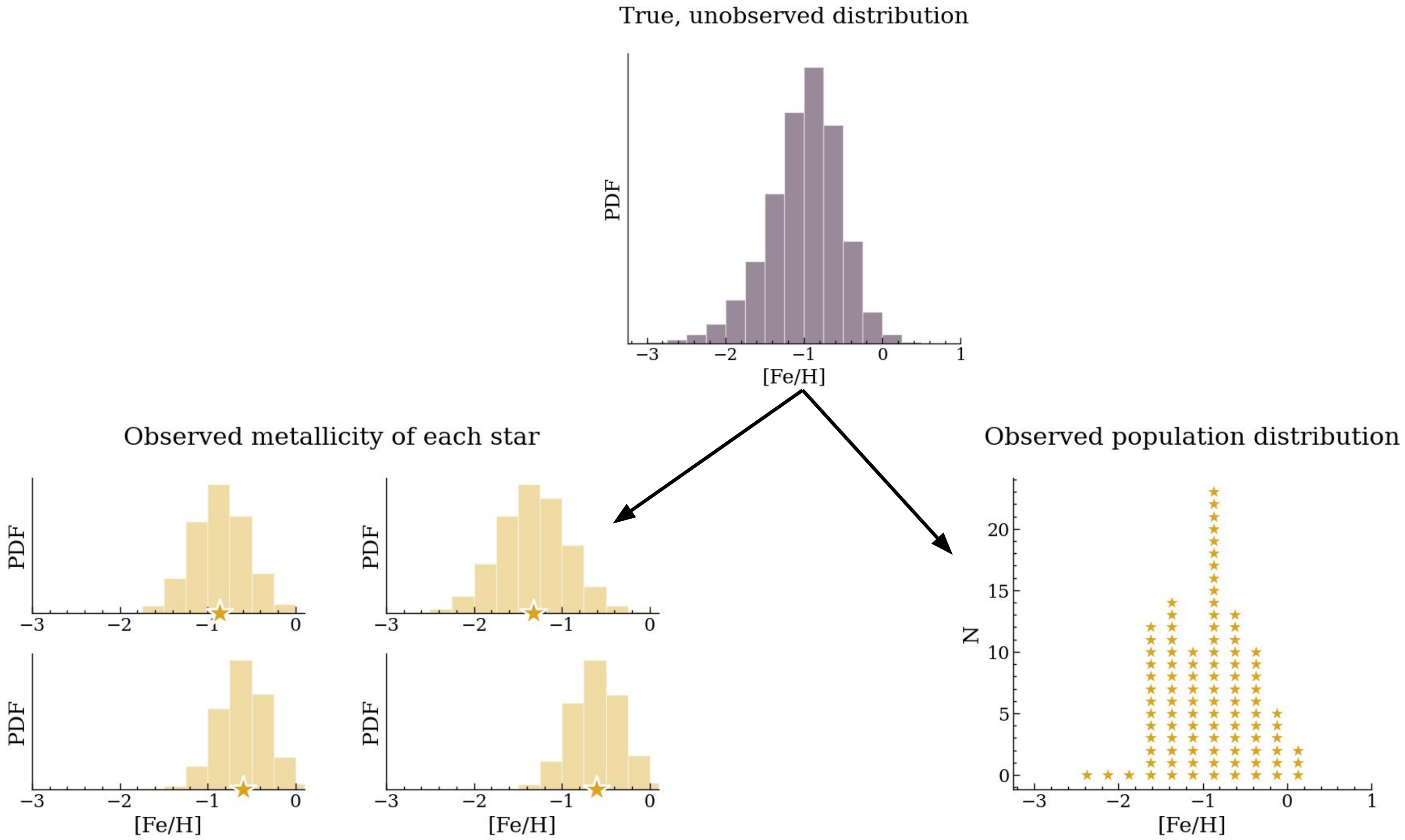
$$- \log K$$

Johnson+ 2023

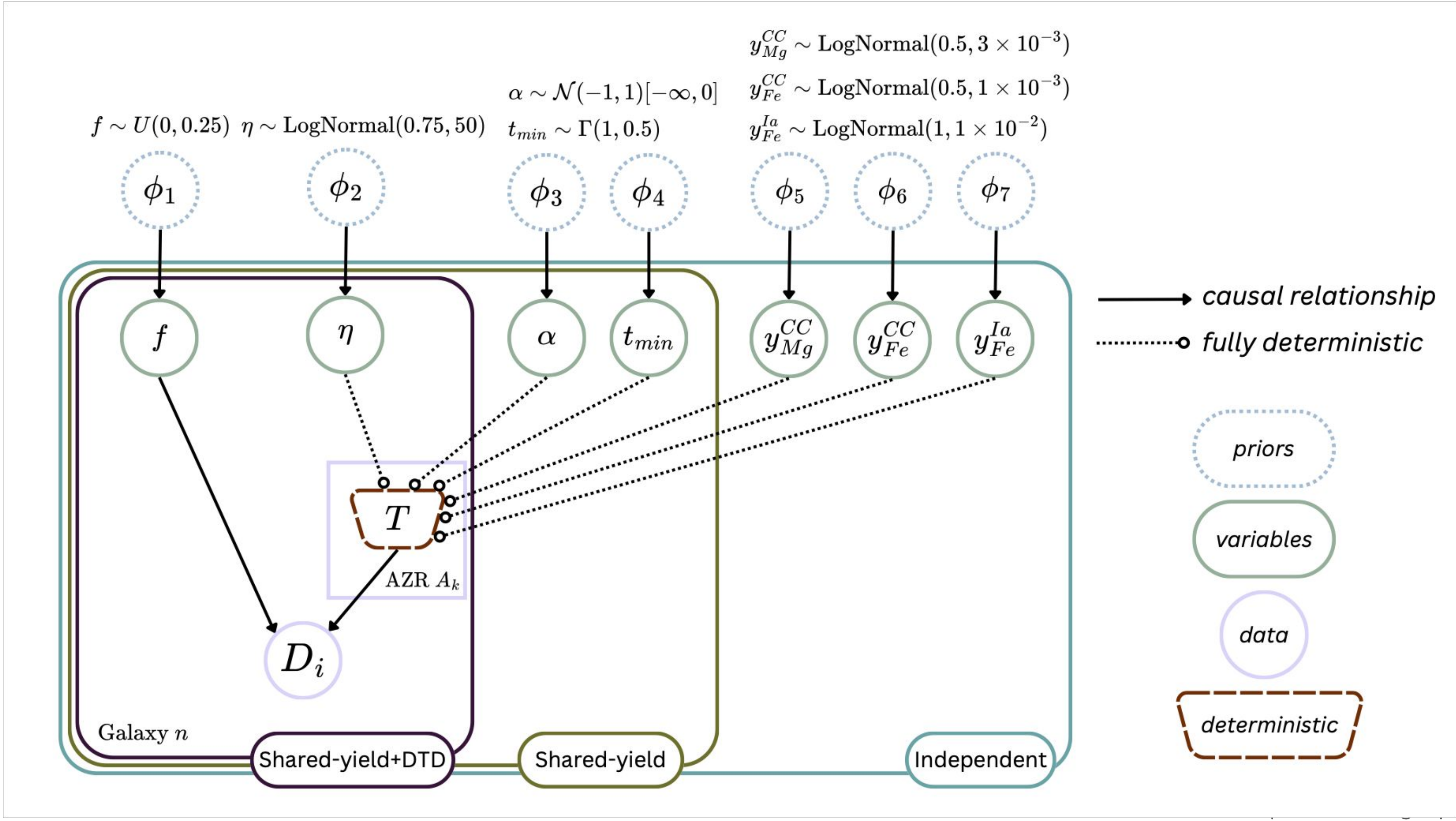
Measurement uncertainty → bias in the AZR!



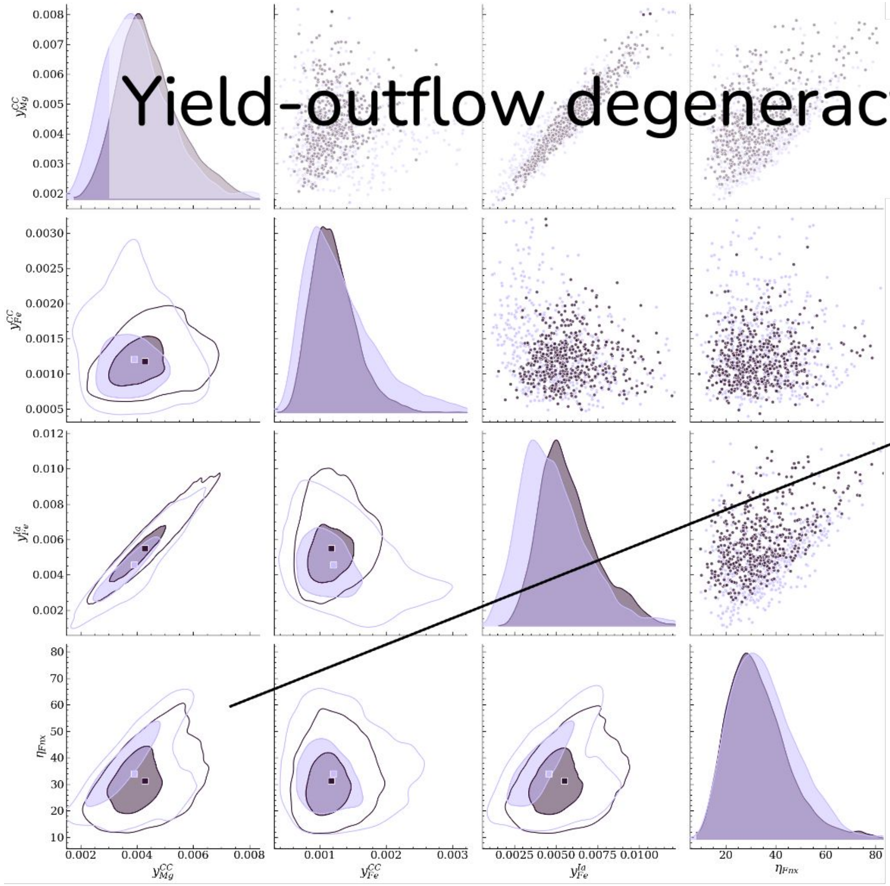

Observed
Deconvolved
[Fe/H]
Δ[Fe/H]
Time [Gyr]
[Mg/Fe]
[Fe/H]
True
Observed
This work

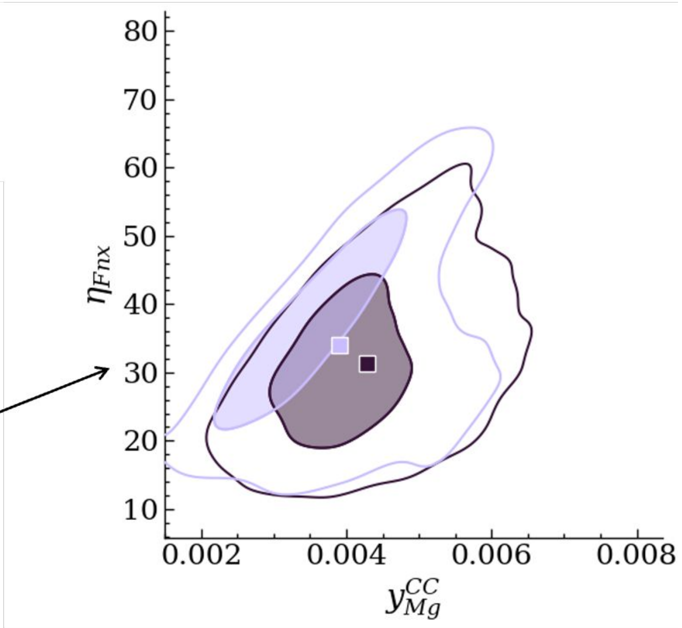


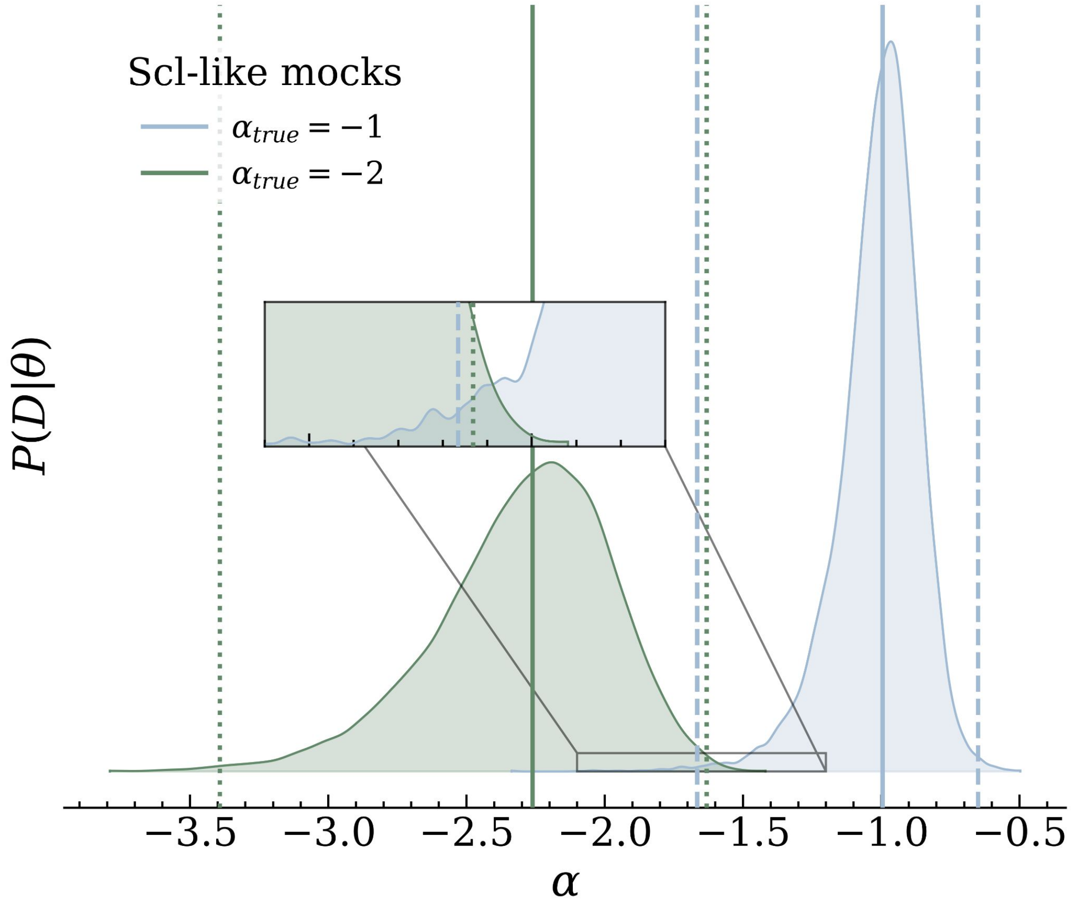
Leistedt & Hogg 2017


$y^{CC}_{Mg} \sim \mathrm{LogNormal}(0.5, 3 \times 10^{-3})$
$y^{CC}_{Fe} \sim \mathrm{LogNormal}(0.5, 1 \times 10^{-3})$
$\alpha \sim \mathcal{N}(-1, 1)[-\infty, 0]$
$f \sim U(0, 0.25)$
$\eta \sim \mathrm{LogNormal}(0.75, 50)$
$t_{min} \sim \Gamma(1, 0.5)$
$y^{Ia}_{Fe} \sim \mathrm{LogNormal}(1, 1 \times 10^{-2})$
ϕ_1
ϕ_2
ϕ_3
ϕ_4
ϕ_5
ϕ_6
ϕ_7
f
η
α
t_{min}
y^{CC}_{Mg}
y^{CC}_{Fe}
y^{Ia}_{Fe}
causal relationship
fully deterministic
priors
variables
data
deterministic
T
AZR A_k
D_i
Galaxy n
Shared-yield+DTD
Shared-yield
Independent

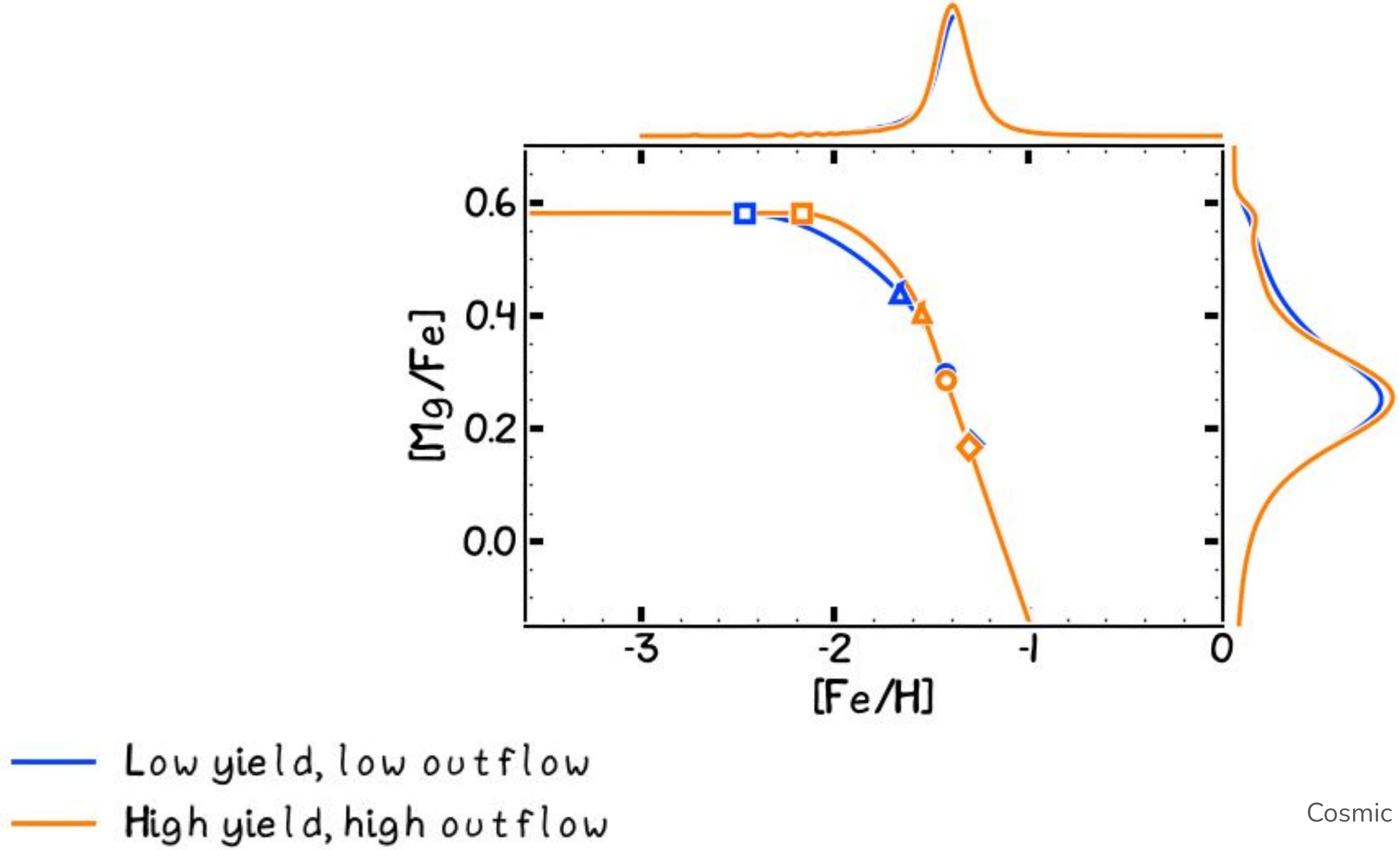
Yield-outflow degeneracy



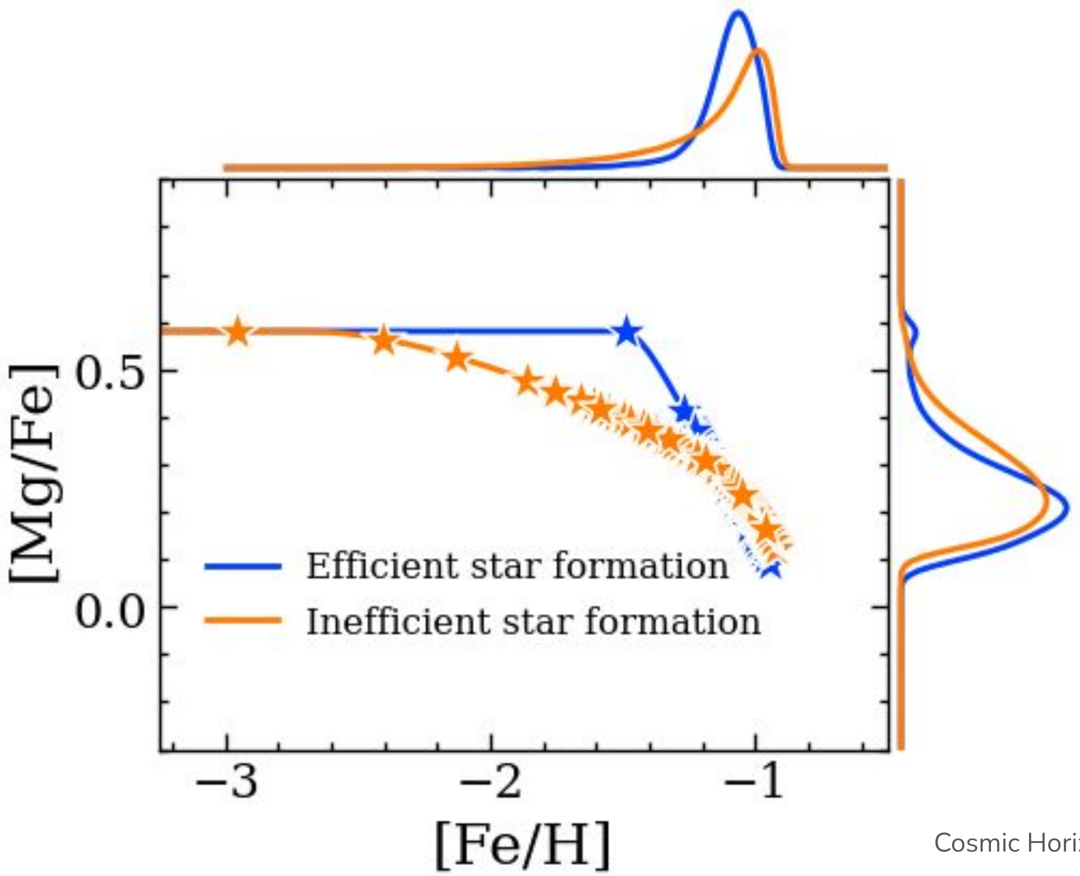



Scl-like mocks
$\alpha_{true} = -1$
$\alpha_{true} = -2$
$P(D|\theta)$
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
α

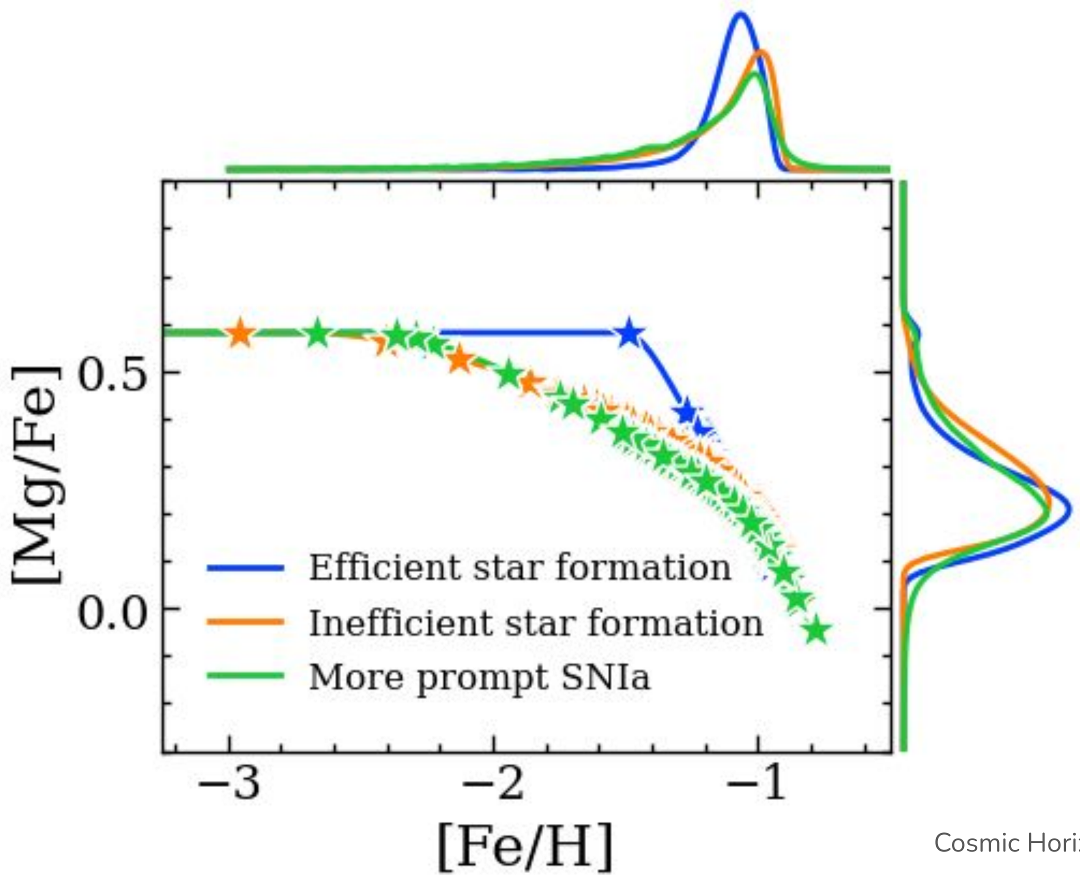
Yield/outflow degeneracy



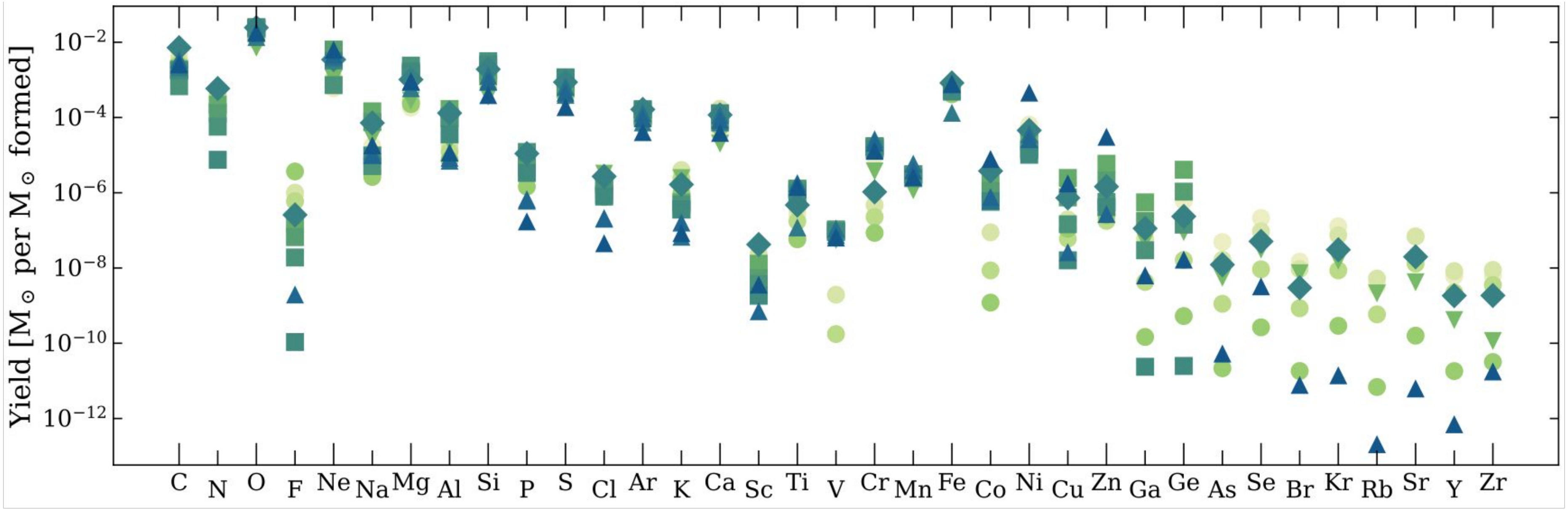
Chemical evolution is strongly degenerate



Chemical evolution is strongly degenerate

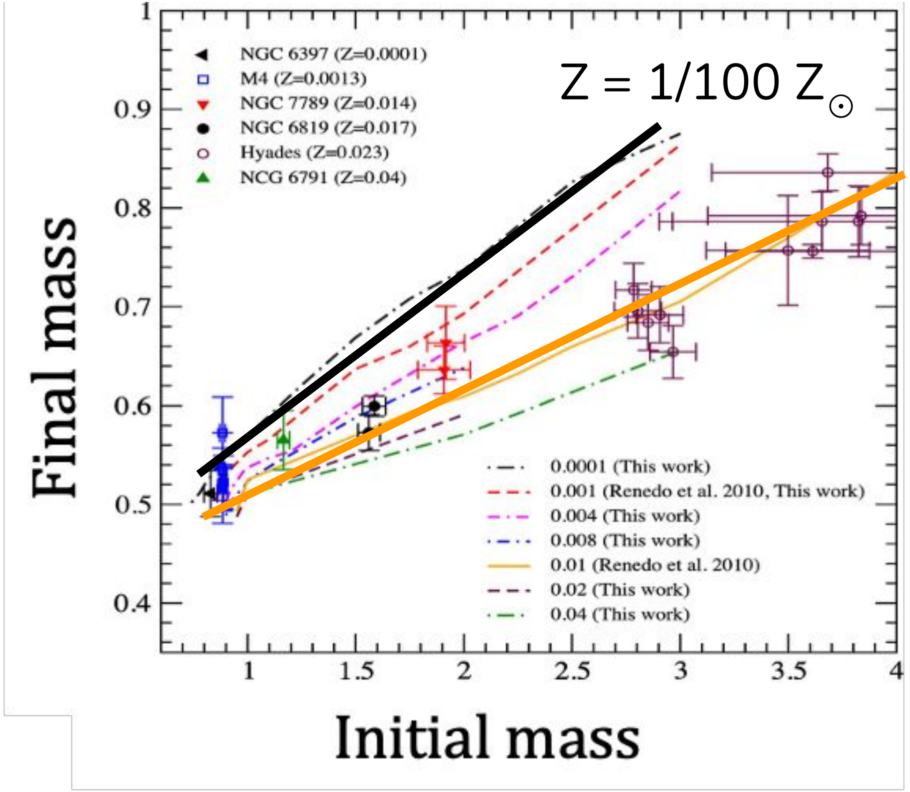


Theoretical yields are poorly constrained



Woosley & Weaver 1995, Chieffi & Limongi 2004, Nomoto+ 2013, Chieffi & Limongi 2013, Sukhbhold+ 2018, Limongi & Chieffi 2018

Metallicity affects stellar evolution



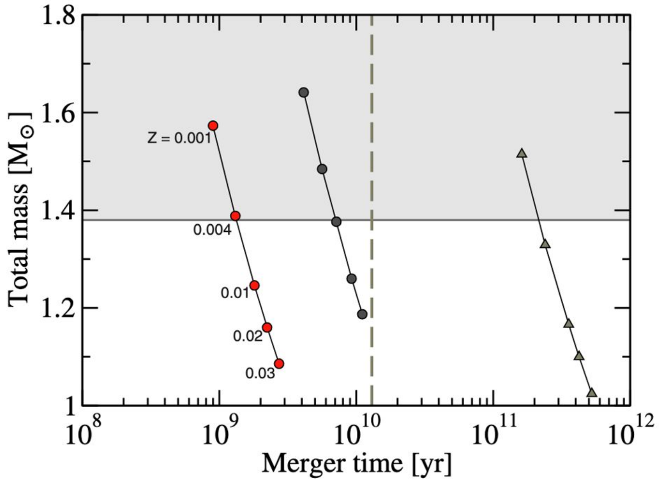


Figure 2. The total masses of known WD–WD systems along with their calculated merger times due to gravitational wave losses. Shown are the three systems from the collection in Nelemans et al. (2005) in which both WDs have masses exceeding 0.5 $M_\odot$: two with firm masses (circles) and one with only a lower limit on the mass of the secondary (triangles). Assuming these to have all resulted from stars with $Z \sim 0.02$, we show the "expected" total masses for a range of metallicities (as labeled) using the final masses derived in Umeda et al. (1999). The resulting merger times assume initial orbital separations as presently inferred for each.

Romero+ 2015, Kistler+ 2013