Predictive GCE in the era of large surveys: challenges and opportunities

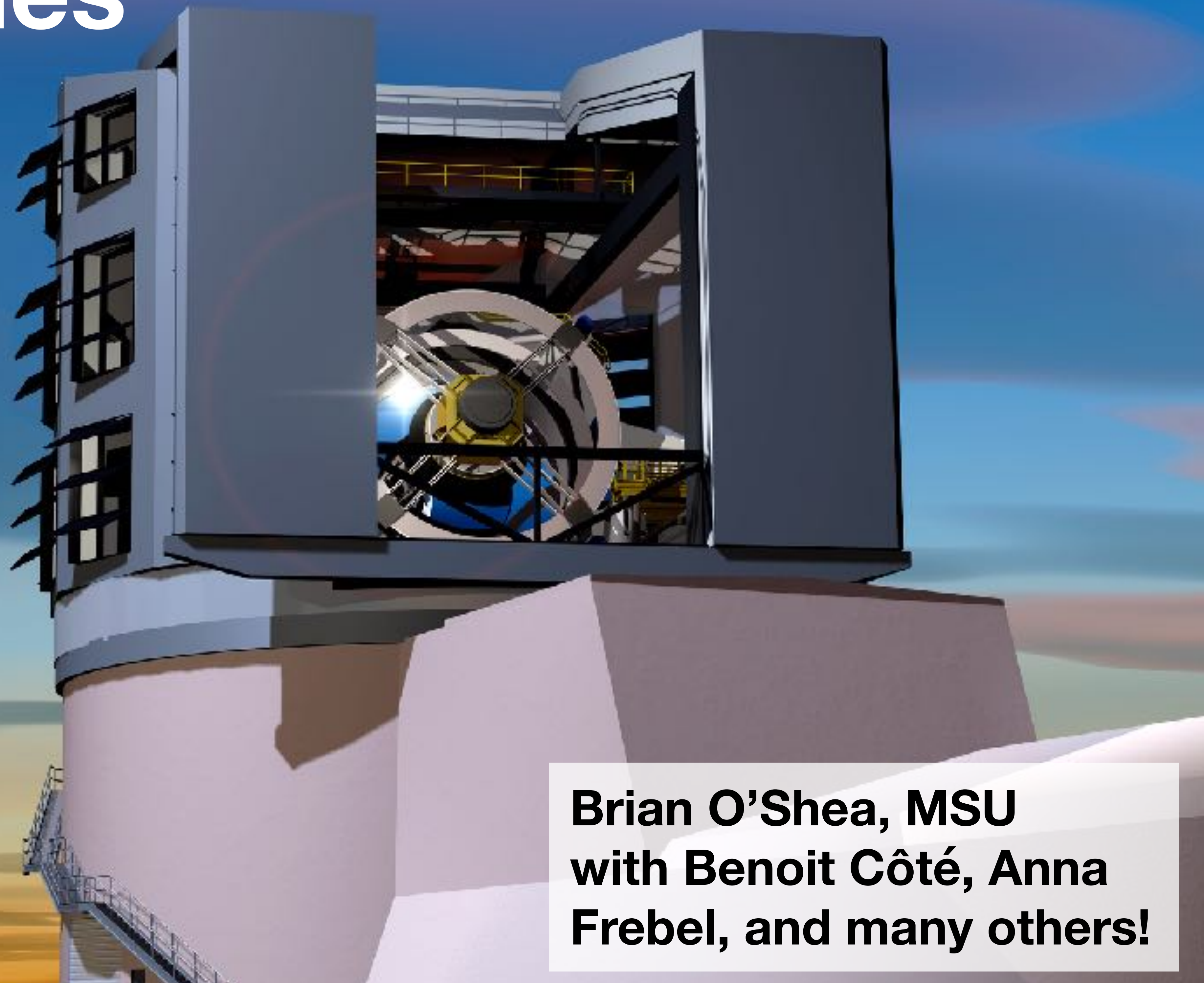


Image c/o LSST

Brian O'Shea, MSU
with Benoit Côté, Anna Frebel, and many others!

What ingredients are needed for GCE…

- in the era of many and diverse large, accurate, and precise astronomical surveys?
- that appropriately takes into account the impact of cosmological structure formation?
- to pose questions where we can be confident in the robustness of our answers?

A simple GCE model

Star formation rate $\dot{M}_\star(t) = \epsilon_\star \frac{M_{\rm gas}(t)}{\tau_\star},$

Galactic outflow $\dot{M}_{\rm out}(t) = \eta \dot{M}_\star(t),$

Galactic inflow $\dot{M}_{\rm in}(t) = \xi \dot{M}_{\rm out}(t),$

Metal production $\dot{M}_Z(t) = Y \dot{M}_*(t)$

(see, e.g., Côté et al. 2016 and many others)

A deeper dive into the ingredients

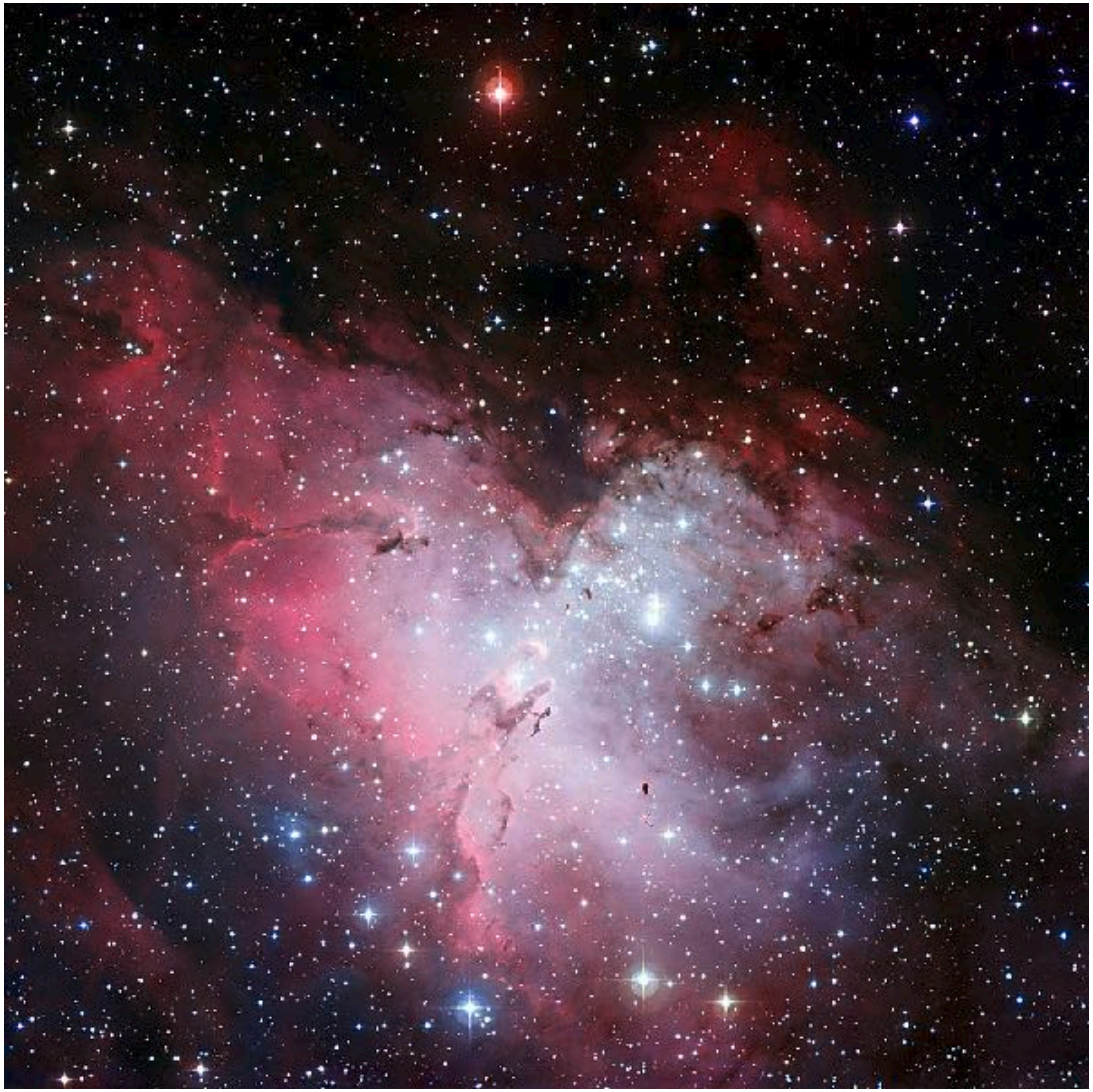
Nuclear physics

Uncertainties: reaction rates and cross sections

Image c/o Michigan State University

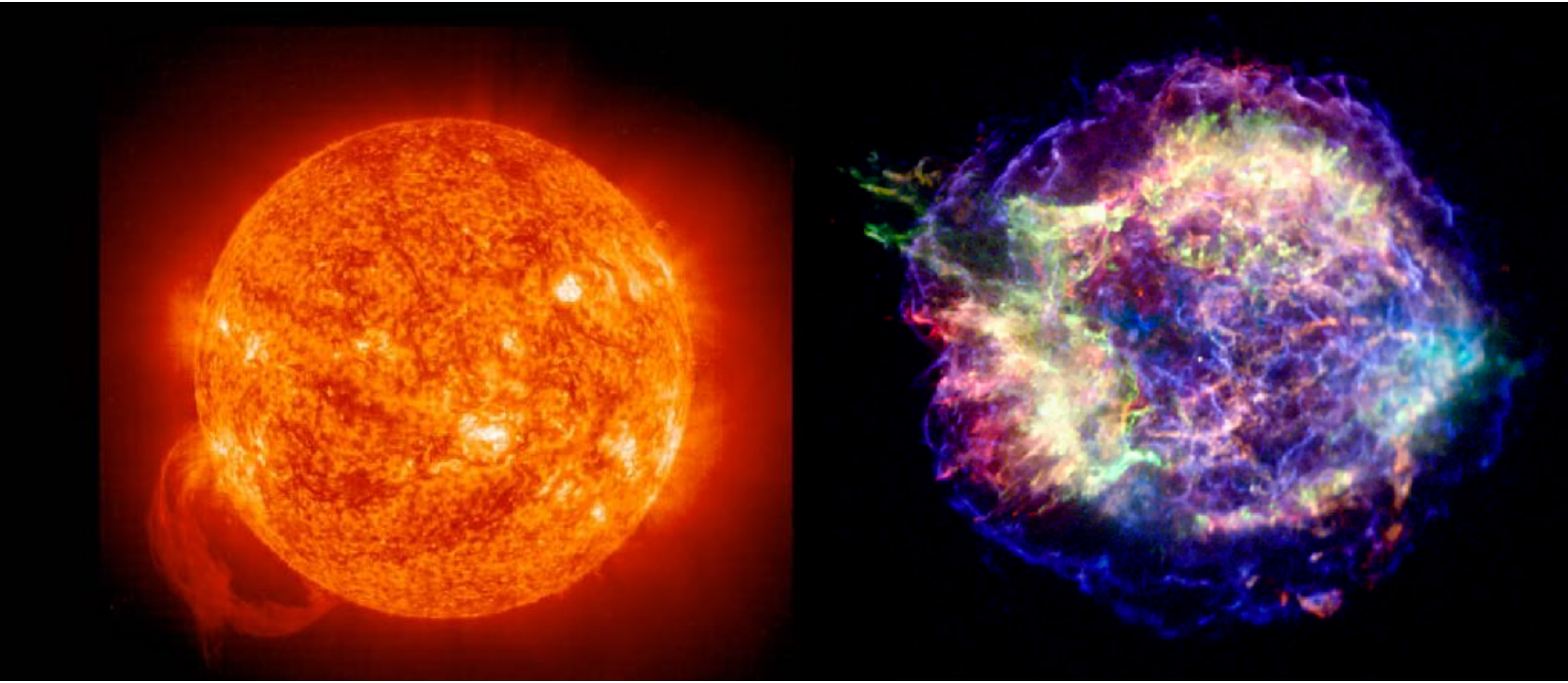
Star formation

Uncertainties: shape of IMF and its dependence on formation environment; stellar multiplicity; orbital properties



Eagle Nebula (M16/NGC6611), image c/o ESO

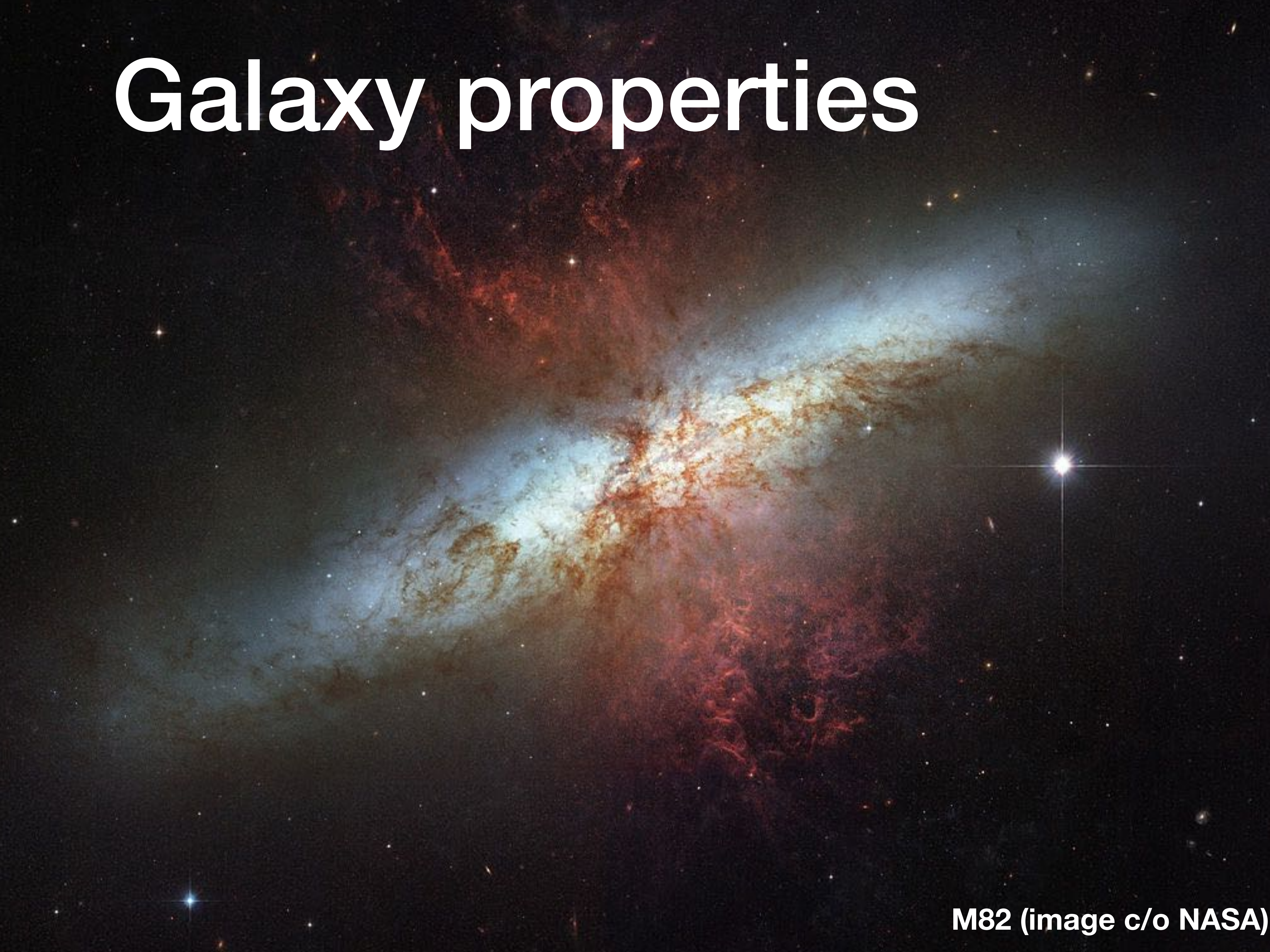
Stellar evolution



Uncertainties: mass range for Type II supernovae and remnants; Type Ia progenitor(s); compact object merger rates and properties

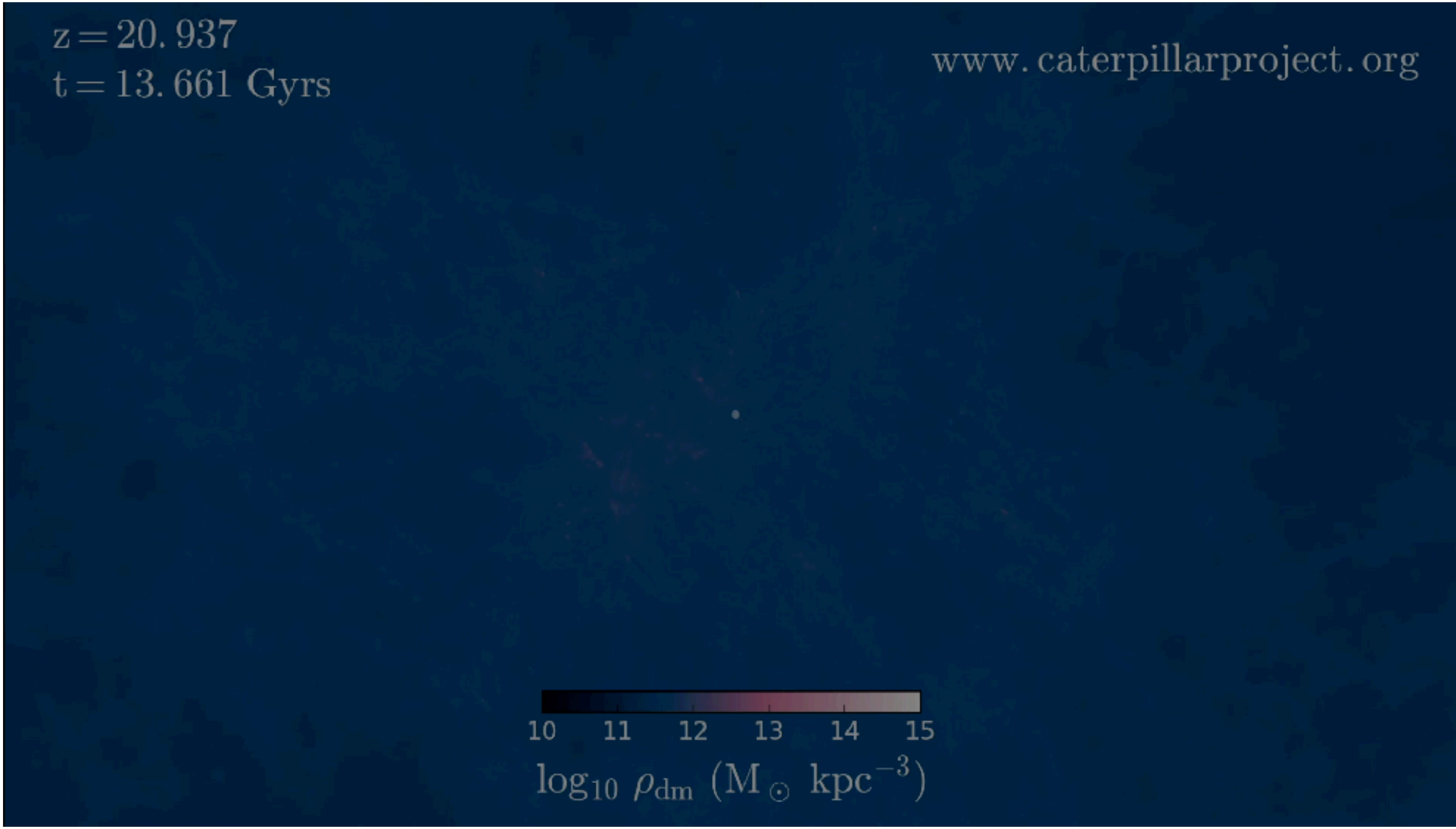
Images c/o NASA

Galaxy properties



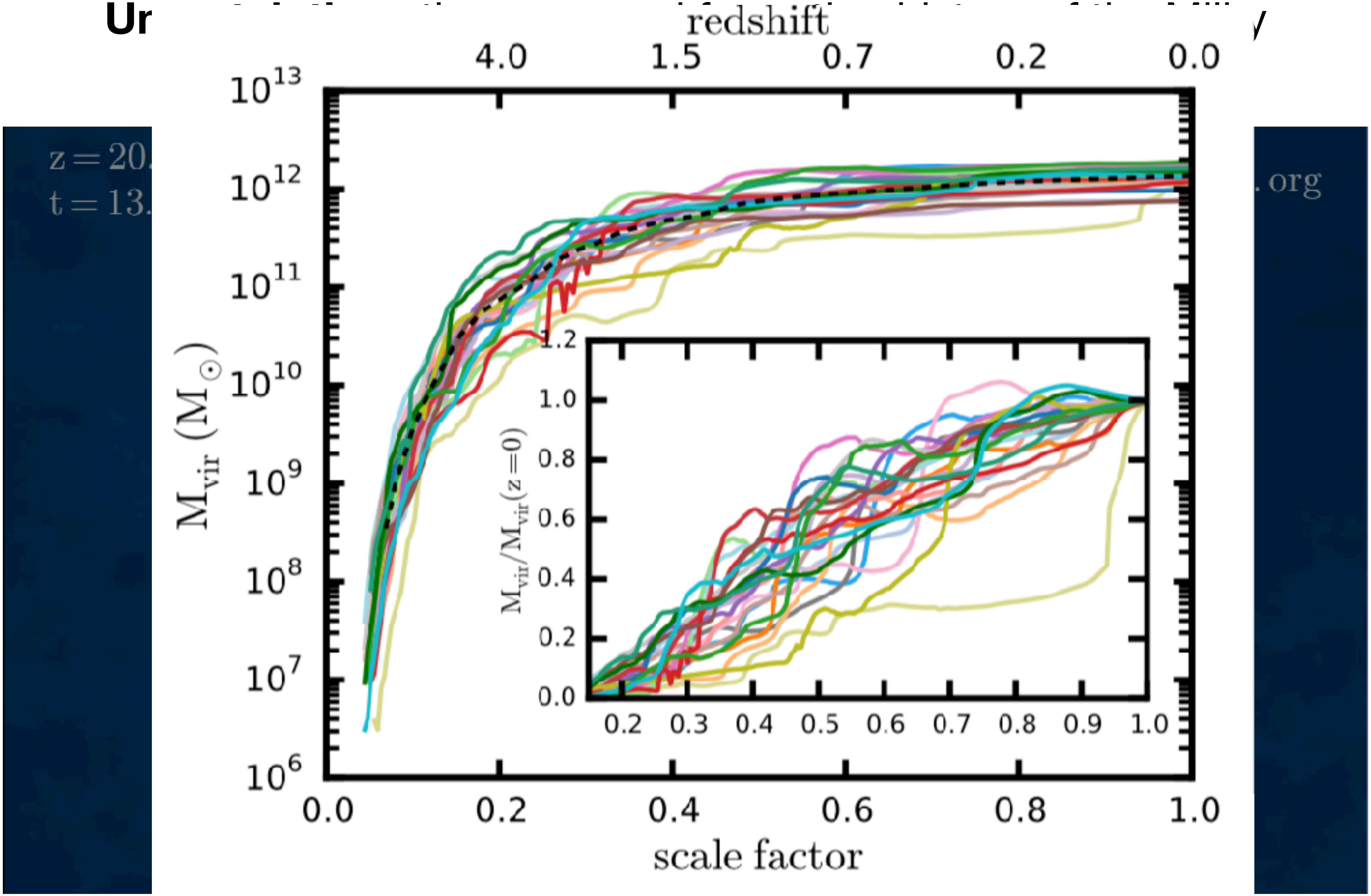
M82 (image c/o NASA)

Uncertainties: the mass and formation history of the Milky Way and its satellites



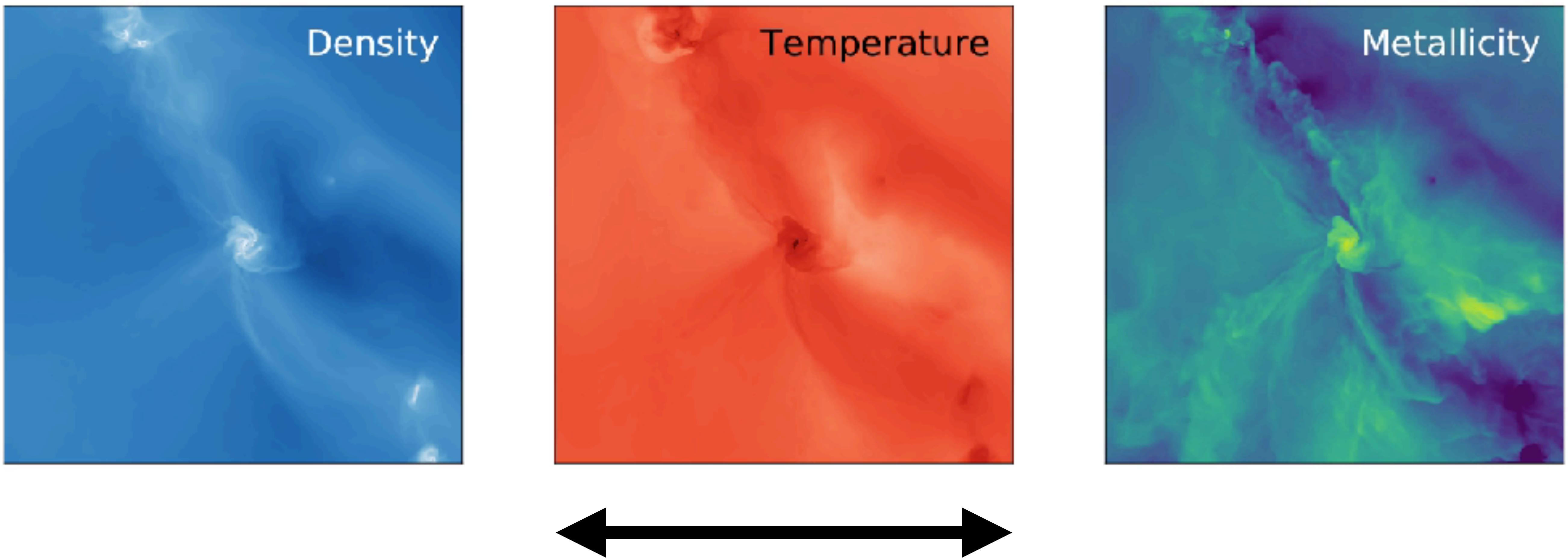
Movie c/o Brendan Griffen, MIT (Caterpillar Project: Griffen+ 2016, ApJ, 818:10; Griffen+ 2018, MNRAS, 2018, 474:443)

Ur … y



Movie c/o Brendan Griffen, MIT (Caterpillar Project: Griffen+ 2016, ApJ, <u>818</u>:10; Griffen+ 2018, MNRAS, 2018, <u>474</u>:443)

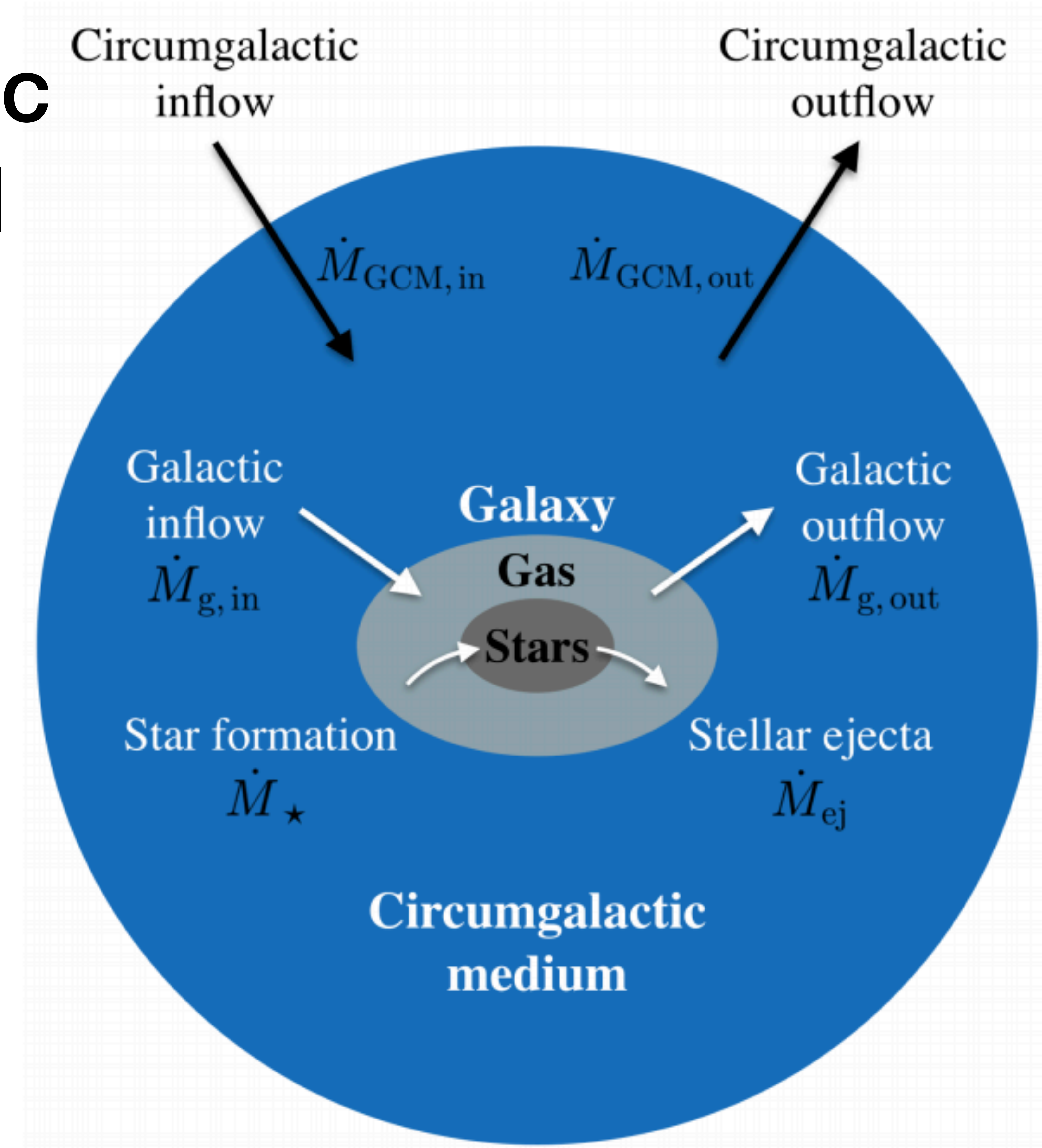
Uncertainties: the behavior of gas as it flows into and out of galaxies; mixing of metals into ISM, CGM, IGM



~150 kpc (0.3 R_{vir})

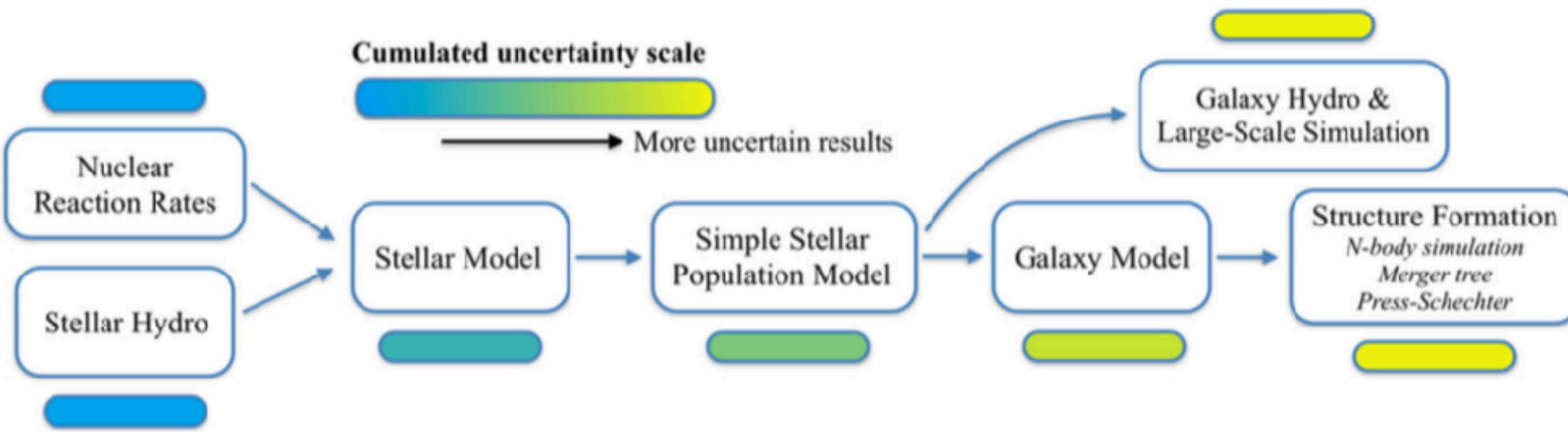
Movie: Corlies, Peeples, O'Shea, Tumlinson (2018)

A more realistic galaxy model



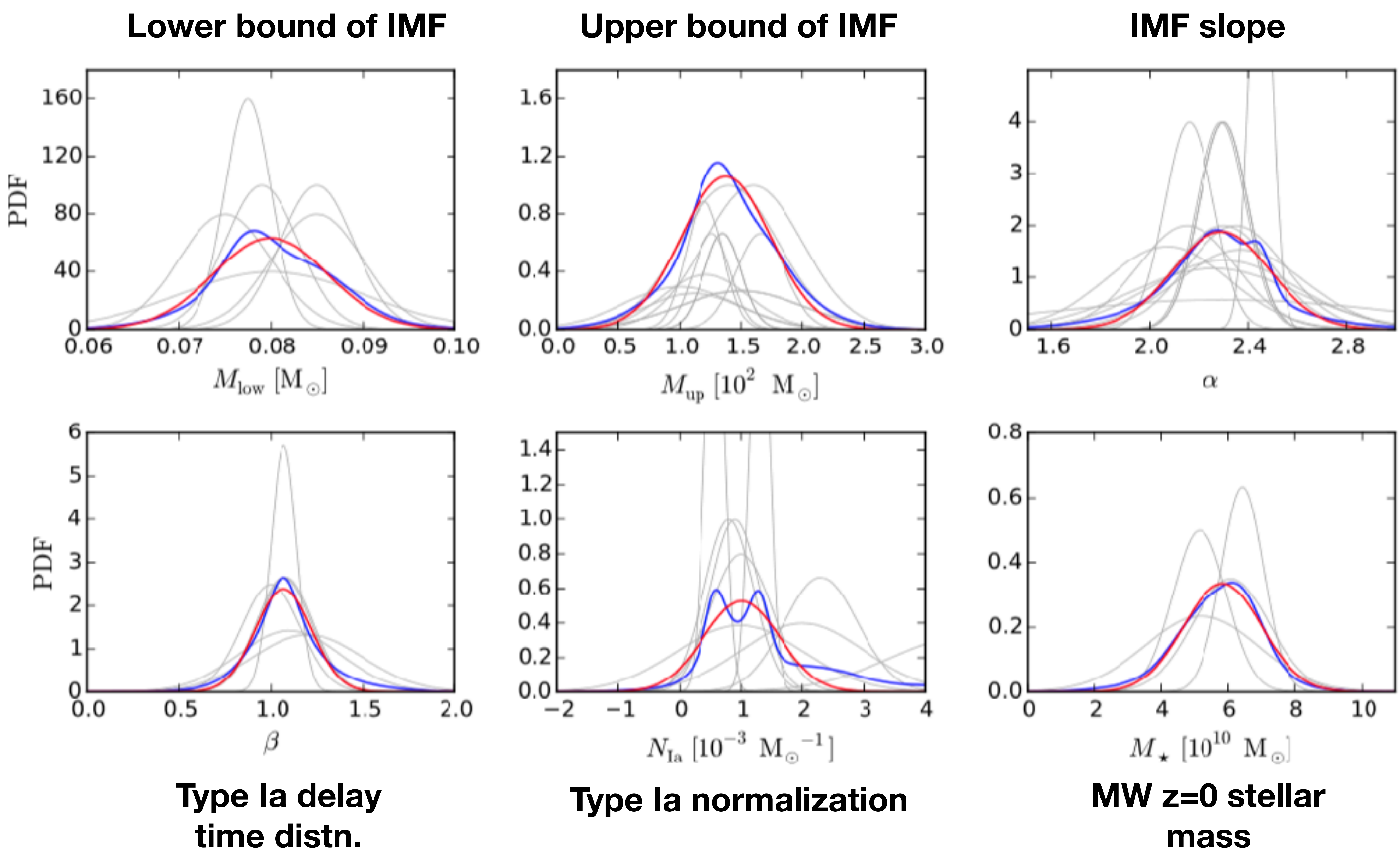
Côté et al. 2018 (ApJ, 859:67)

Propagation of uncertainty



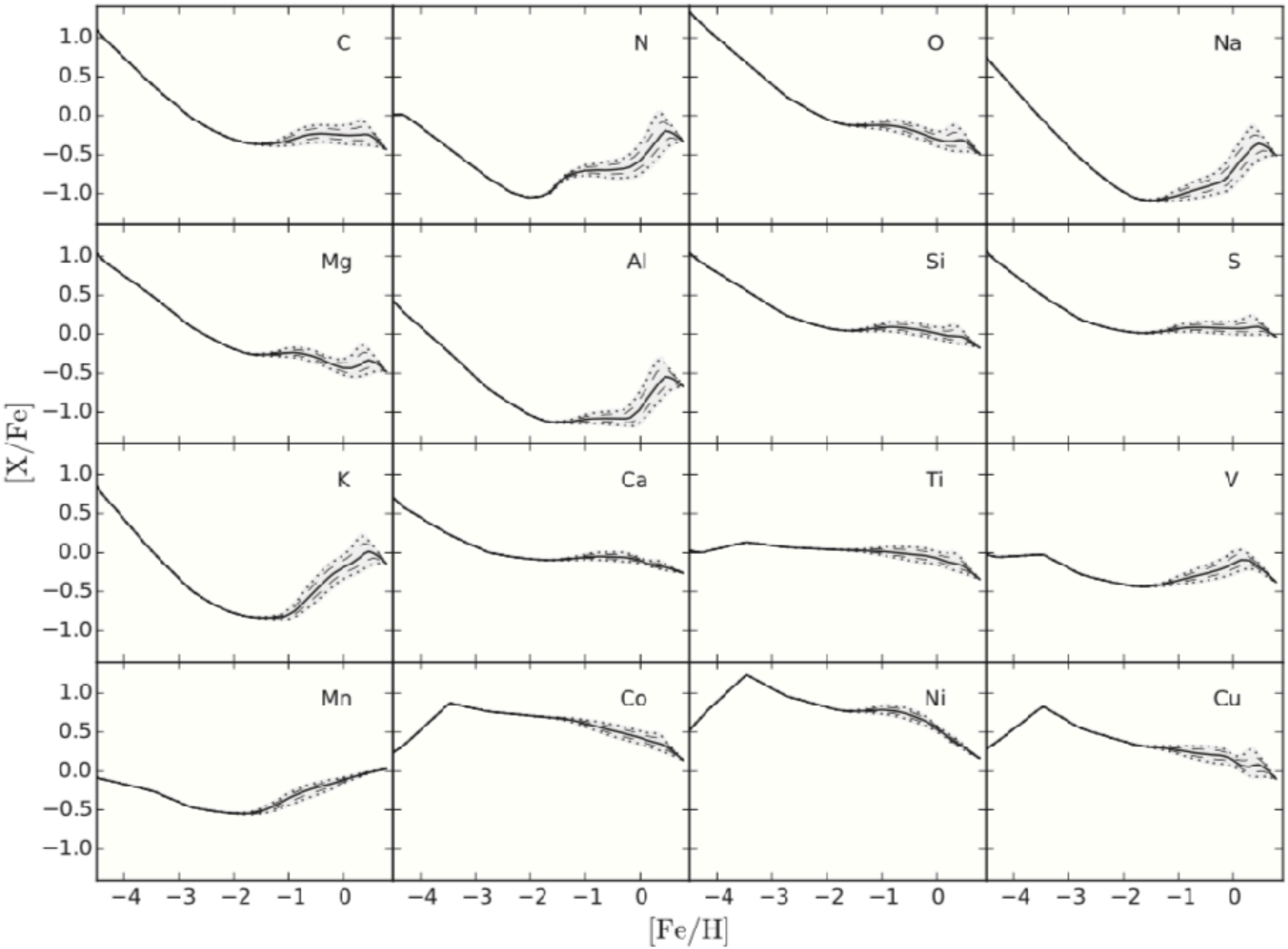
Côté et al. 2016 (ApJ, 824:82)

Uncertainty in a one-zone MW model

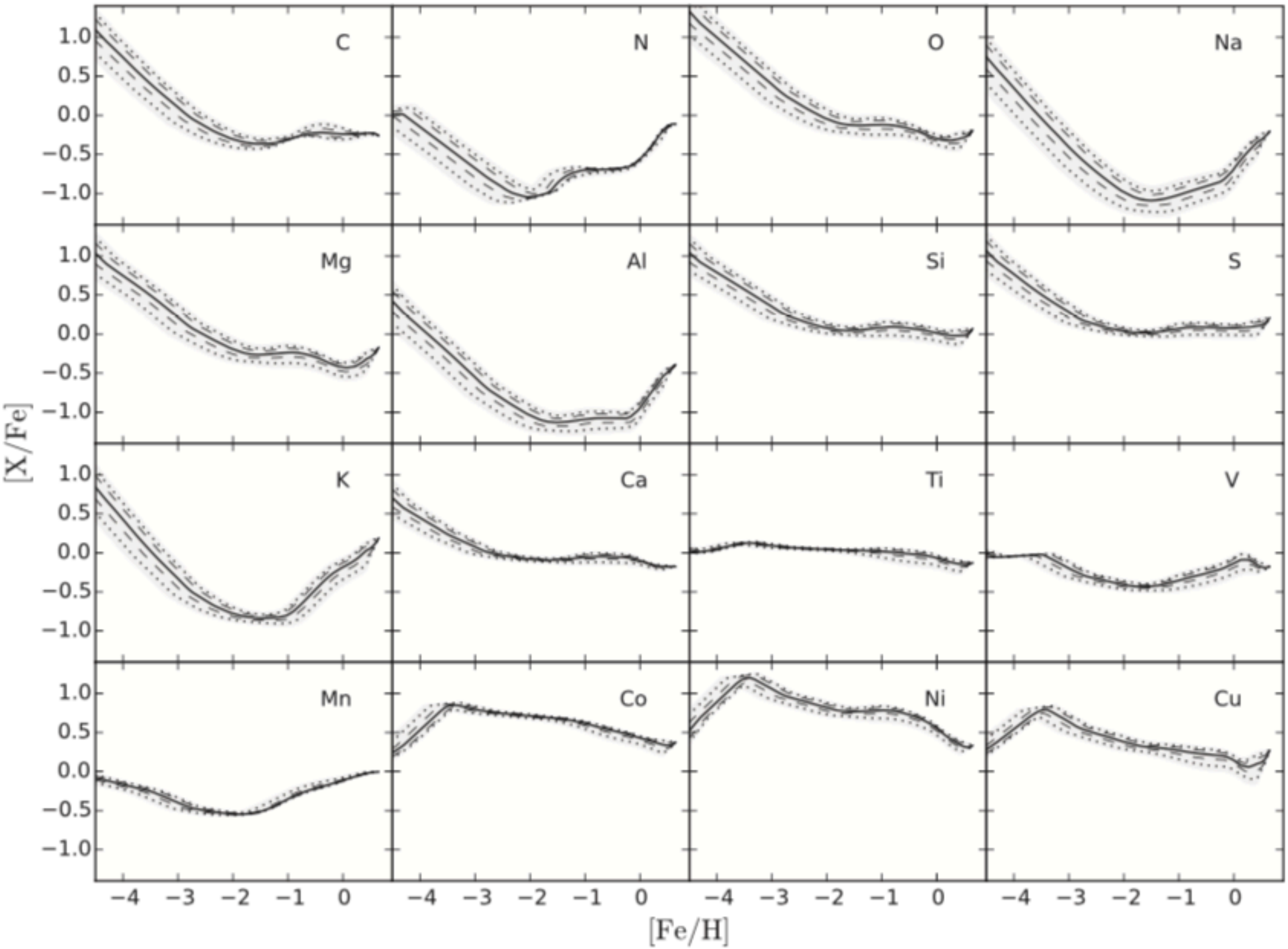


Côté et al. 2016 (ApJ, 824:82)

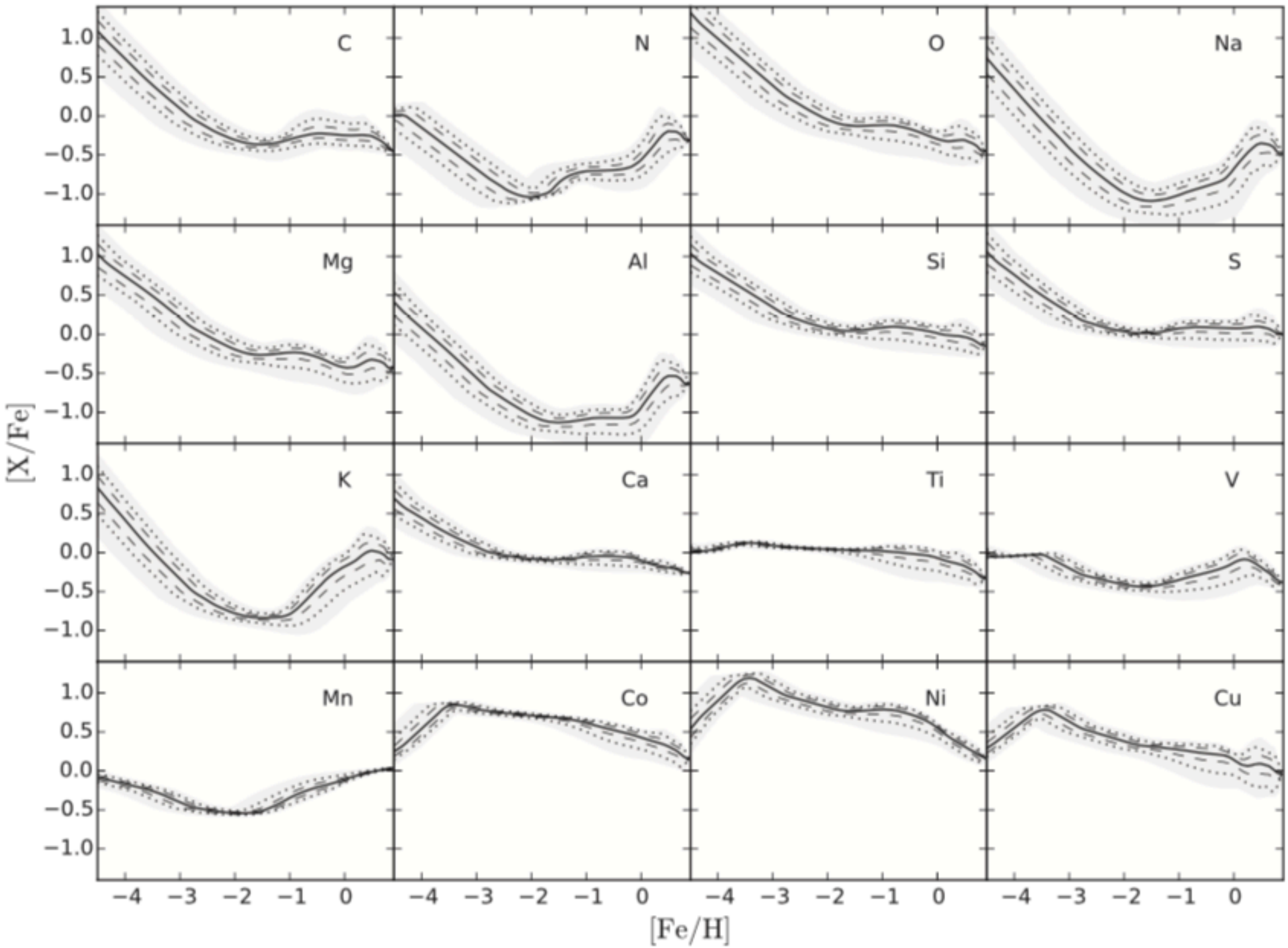
Varying N_{Ia} only



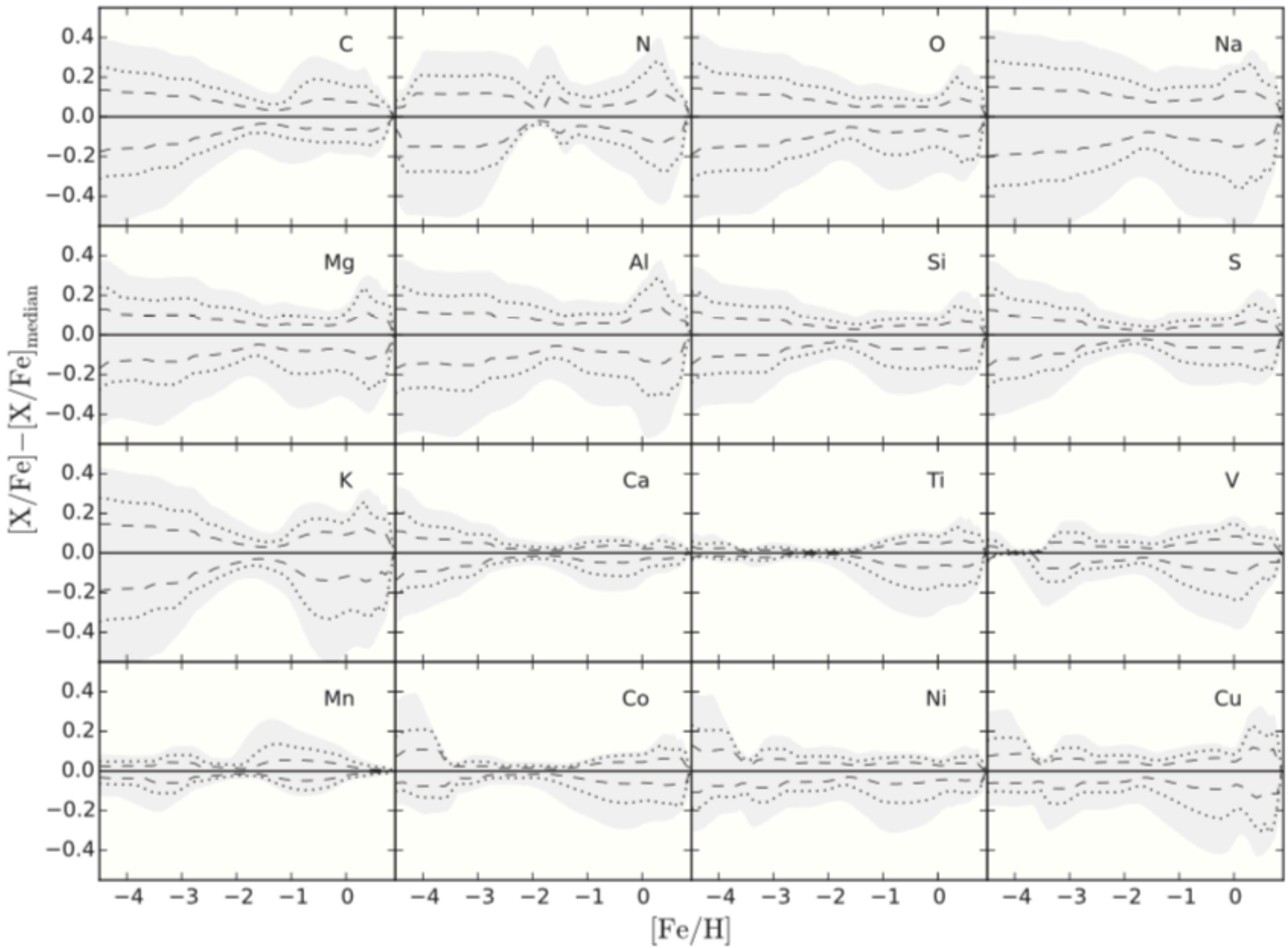
Varying α only



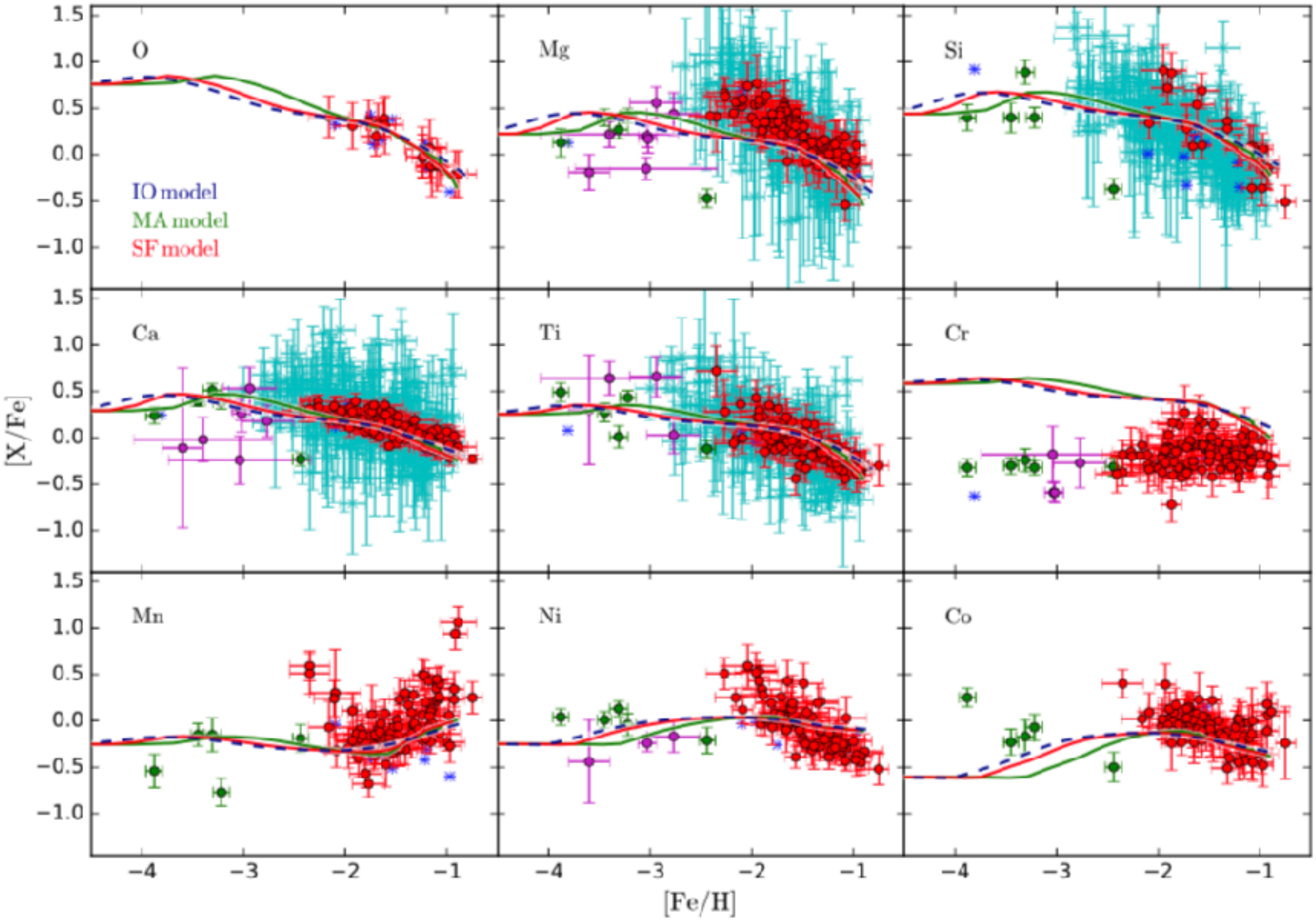
Varying everything simultaneously!



Varying everything simultaneously!

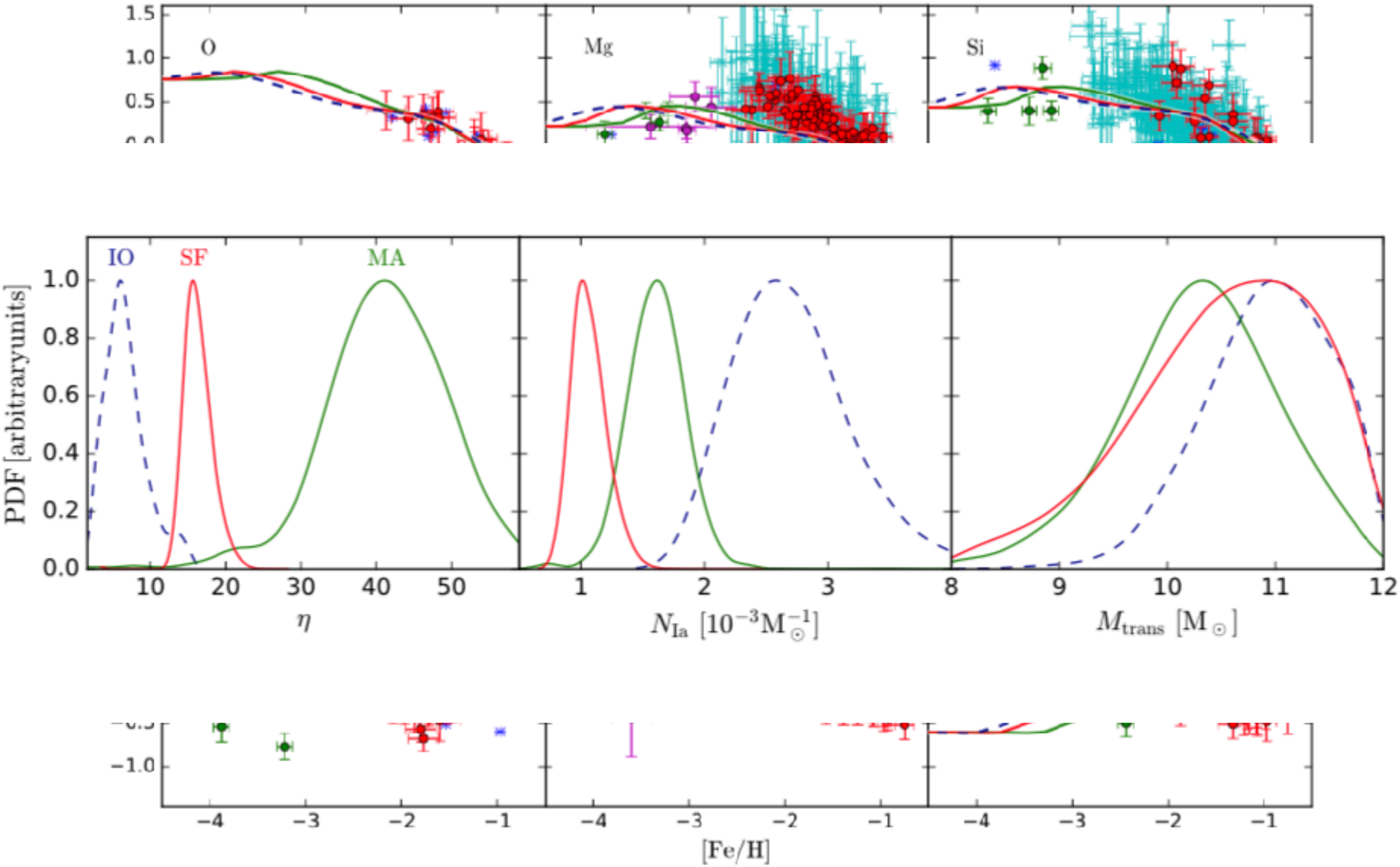


Uncertainties in galaxy model parameterizations



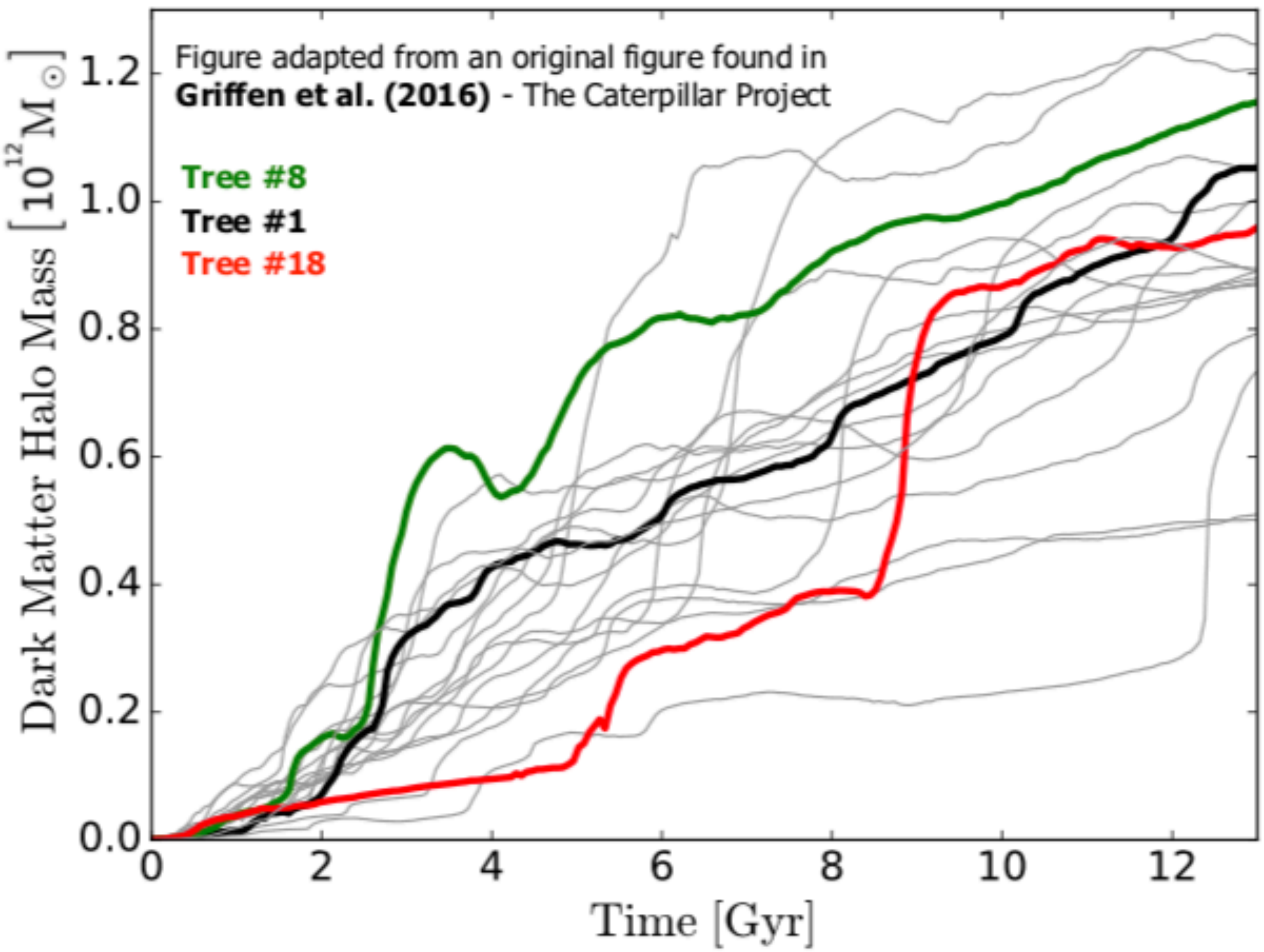
3 Inflow/outflow models fit to Sculptor; Côté et al. 2017 (ApJ, 835:128)

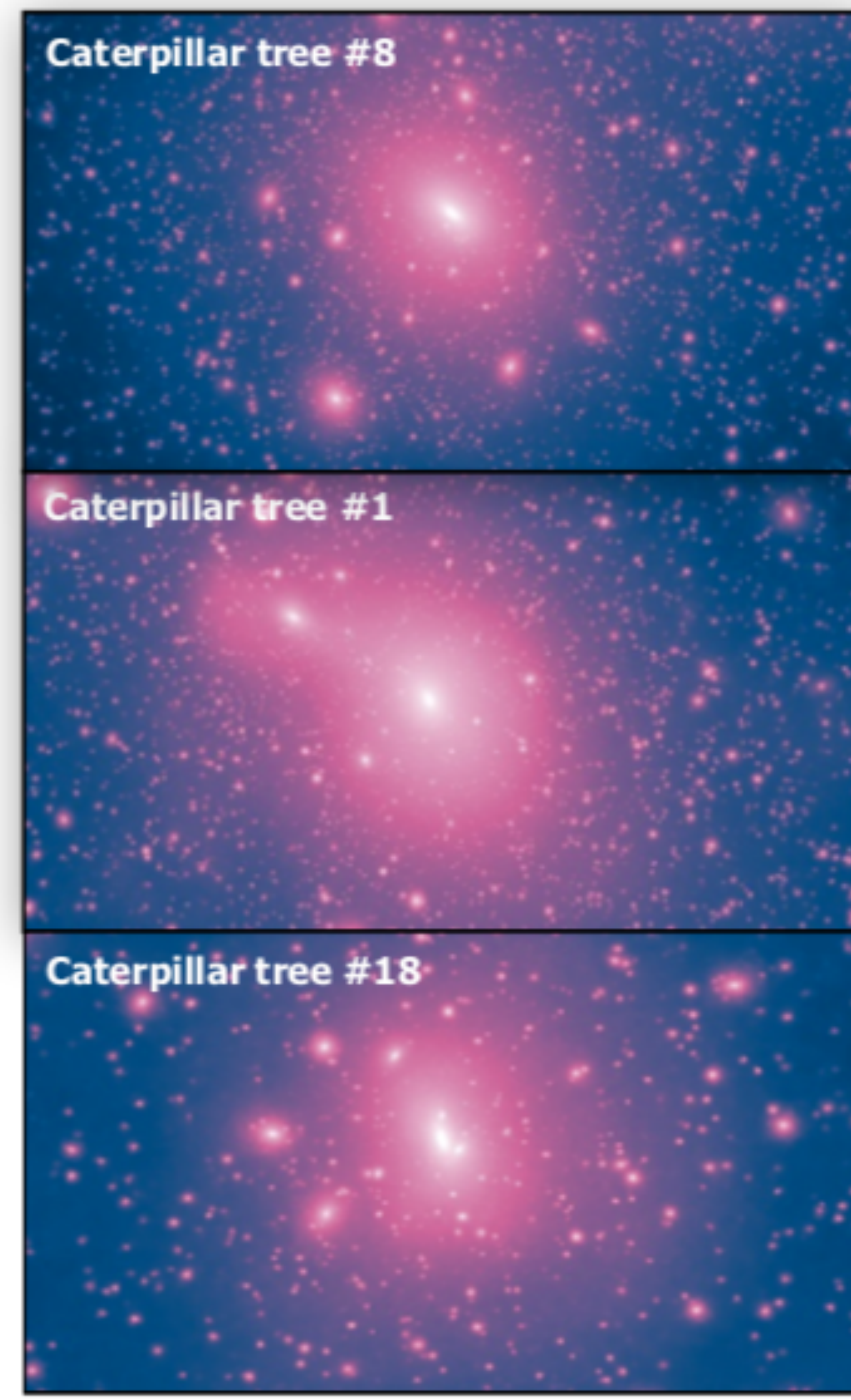
Uncertainties in galaxy model parameterizations



3 Inflow/outflow models fit to Sculptor; Côté et al. 2017 (ApJ, 835:128)

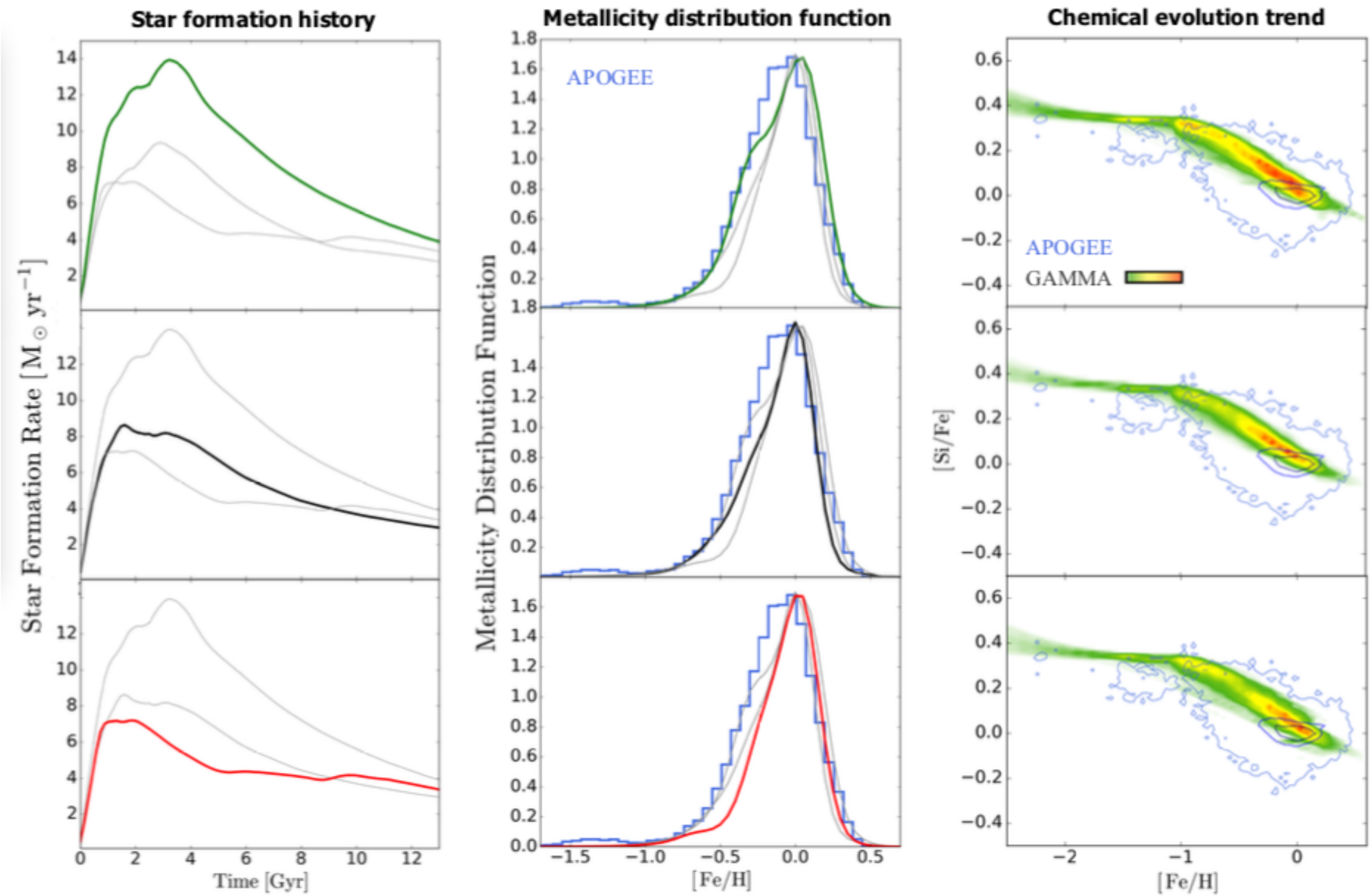
Uncertainty in MW formation history





Côté, O'Shea, Frebel, et al. 2018 (in prep.)

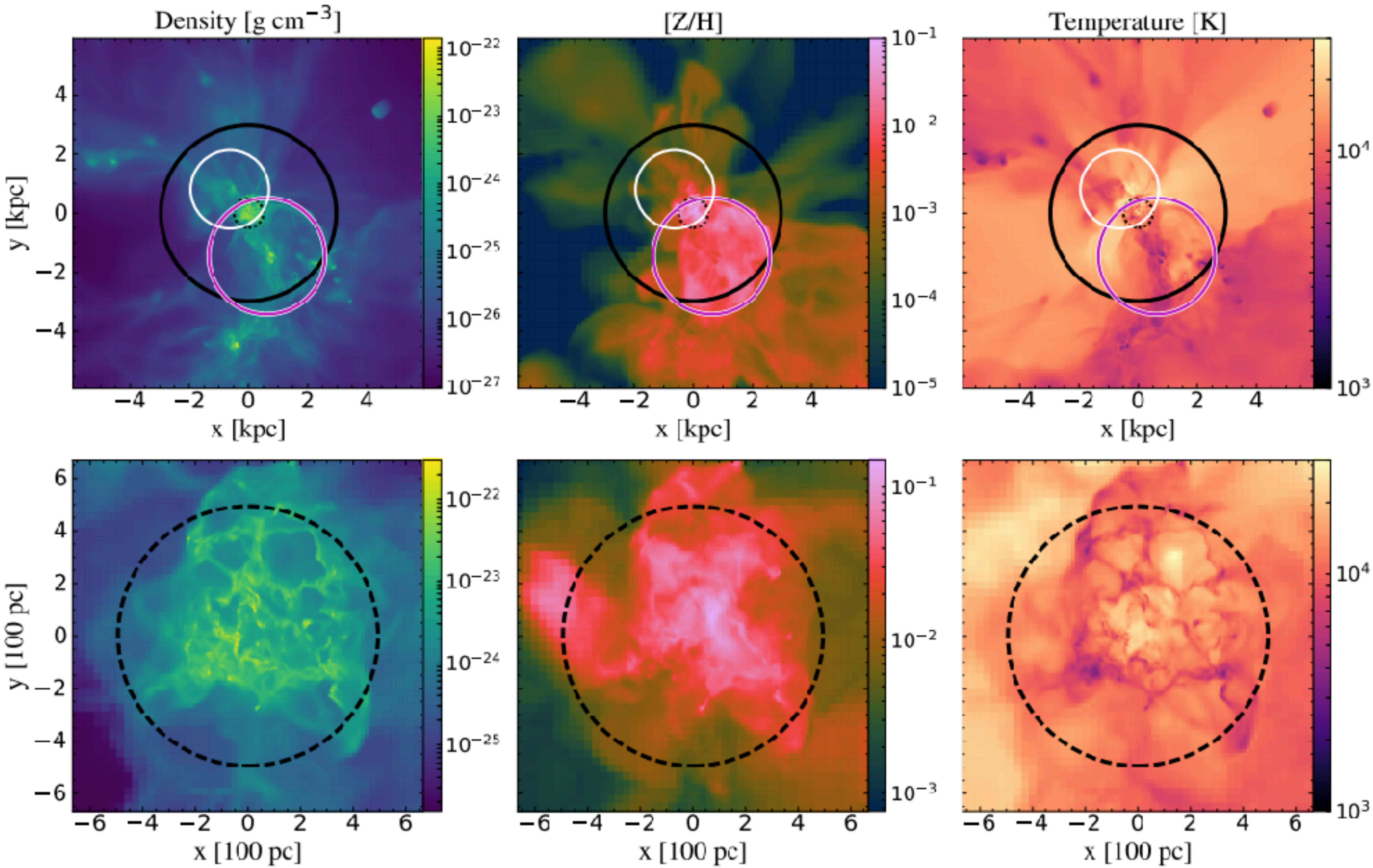
Uncertainty in MW formation history



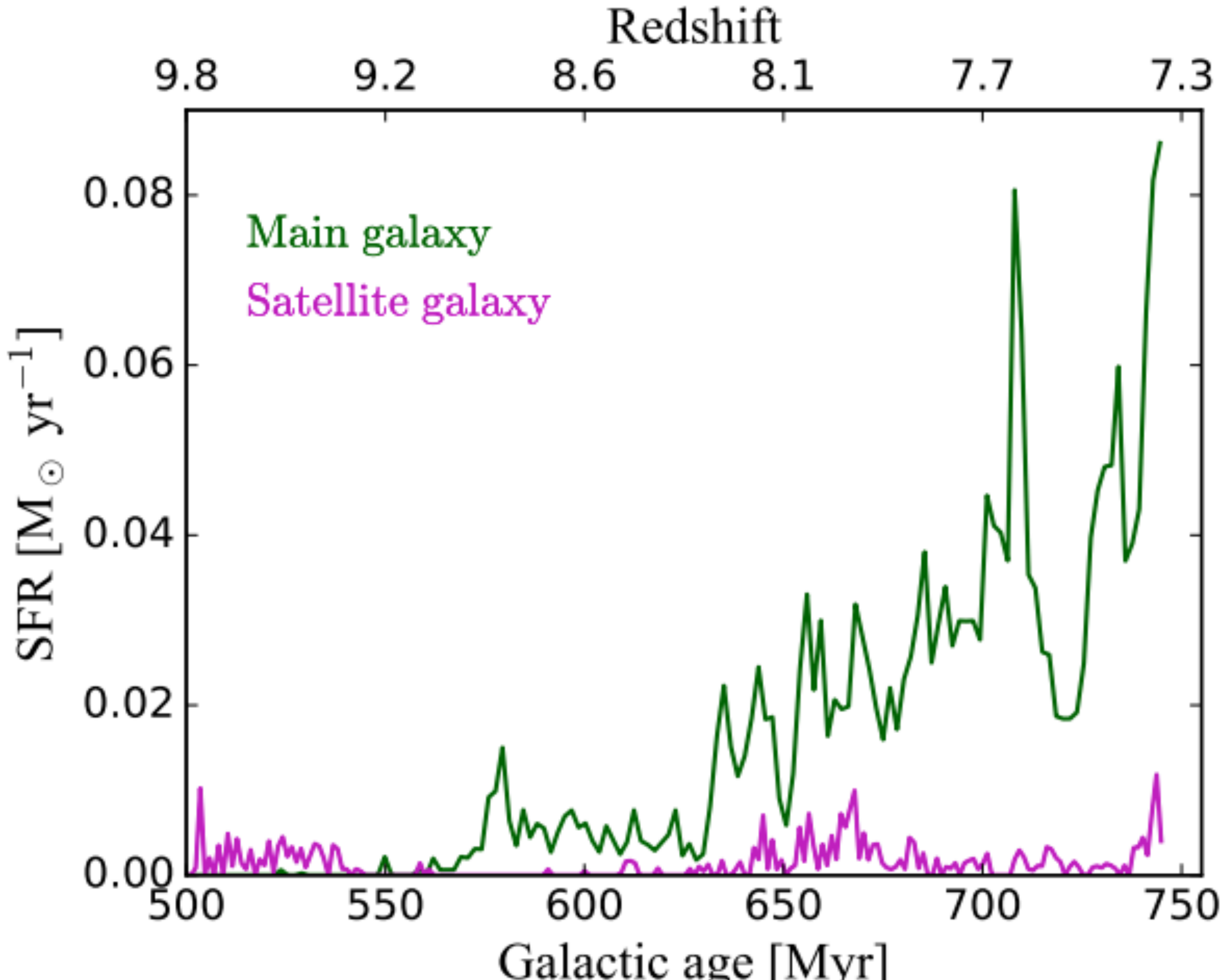
How do we deal with these uncertainties?

Use physics-rich galaxy formation simulations to calibrate models!

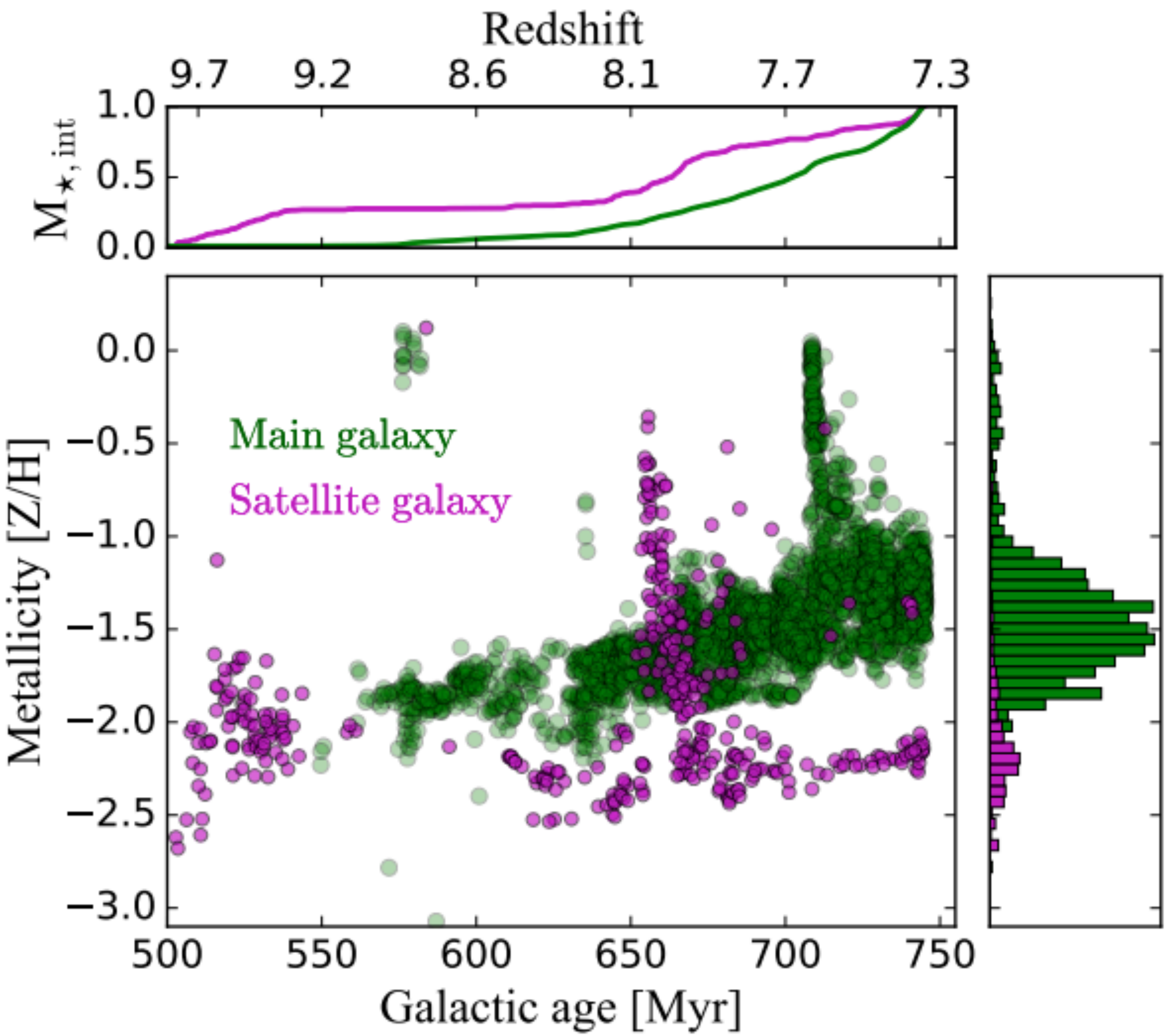
Côté et al. 2018 (ApJ, 859:67)



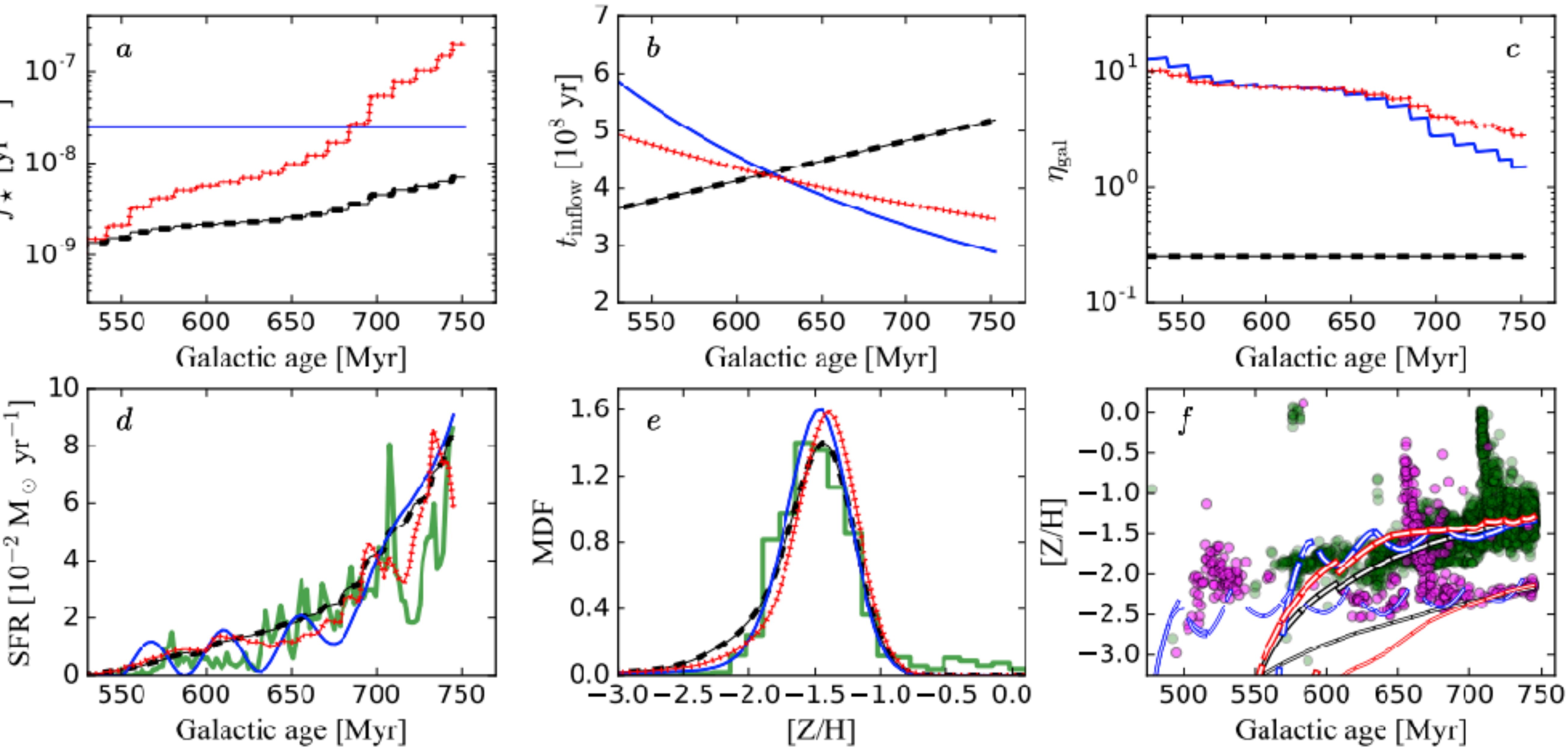
Density [g cm^{-3}]
[Z/H]
Temperature [K]
y [kpc]
x [kpc]
x [kpc]
x [kpc]
y [100 pc]
x [100 pc]
x [100 pc]
x [100 pc]



Redshift
9.8
9.2
8.6
8.1
7.7
7.3
Main galaxy
Satellite galaxy
SFR [M$_\odot$ yr^{-1}]
0.08
0.06
0.04
0.02
0.00
500
550
600
650
700
750
Galactic age [Myr]



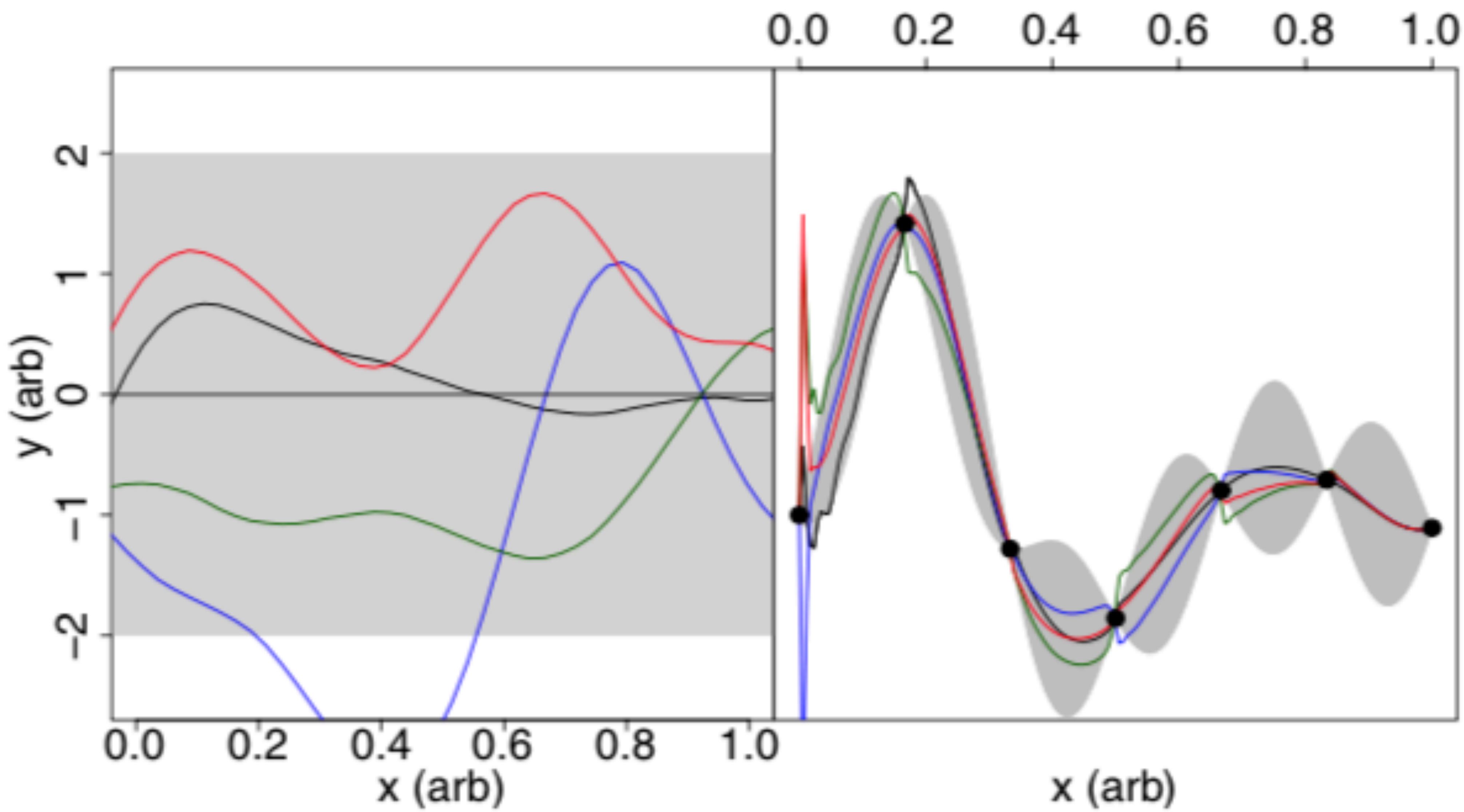
Redshift
9.7
9.2
8.6
8.1
7.7
7.3
1.0
0.5
0.0
M⋆, int
Main galaxy
Satellite galaxy
Metallicity [Z/H]
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
500
550
600
650
700
750
Galactic age [Myr]



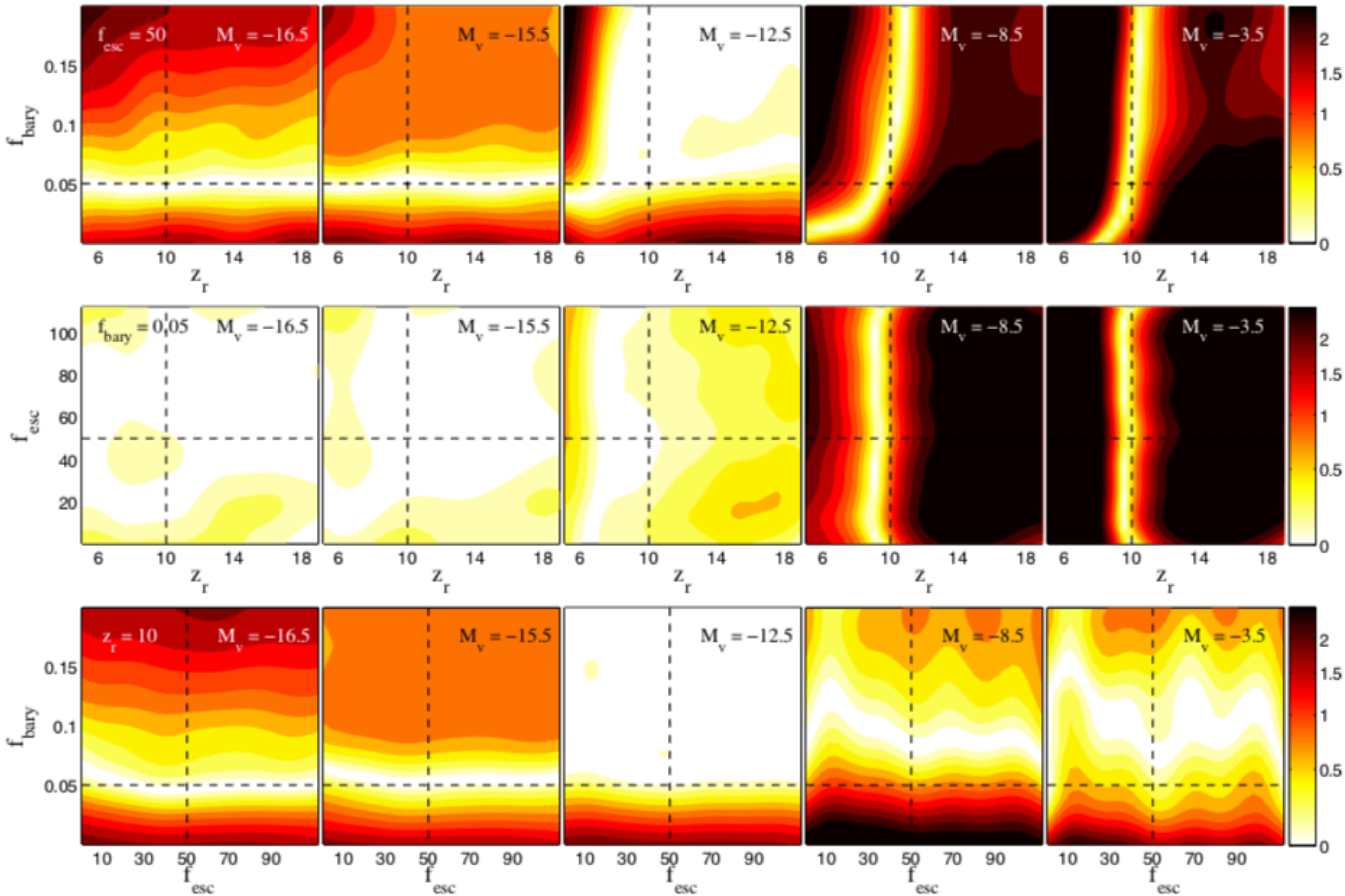
a
$f_\star$ [yr^{-1}]
Galactic age [Myr]
b
$t_{\rm inflow}$ [10^3 yr]
Galactic age [Myr]
c
$\eta_{\rm gal}$
Galactic age [Myr]
d
SFR [10^{-2} M$_\odot$ yr^{-1}]
Galactic age [Myr]
e
MDF
[Z/H]
f
[Z/H]
Galactic age [Myr]

Comparing to observations

Gaussian process emulators

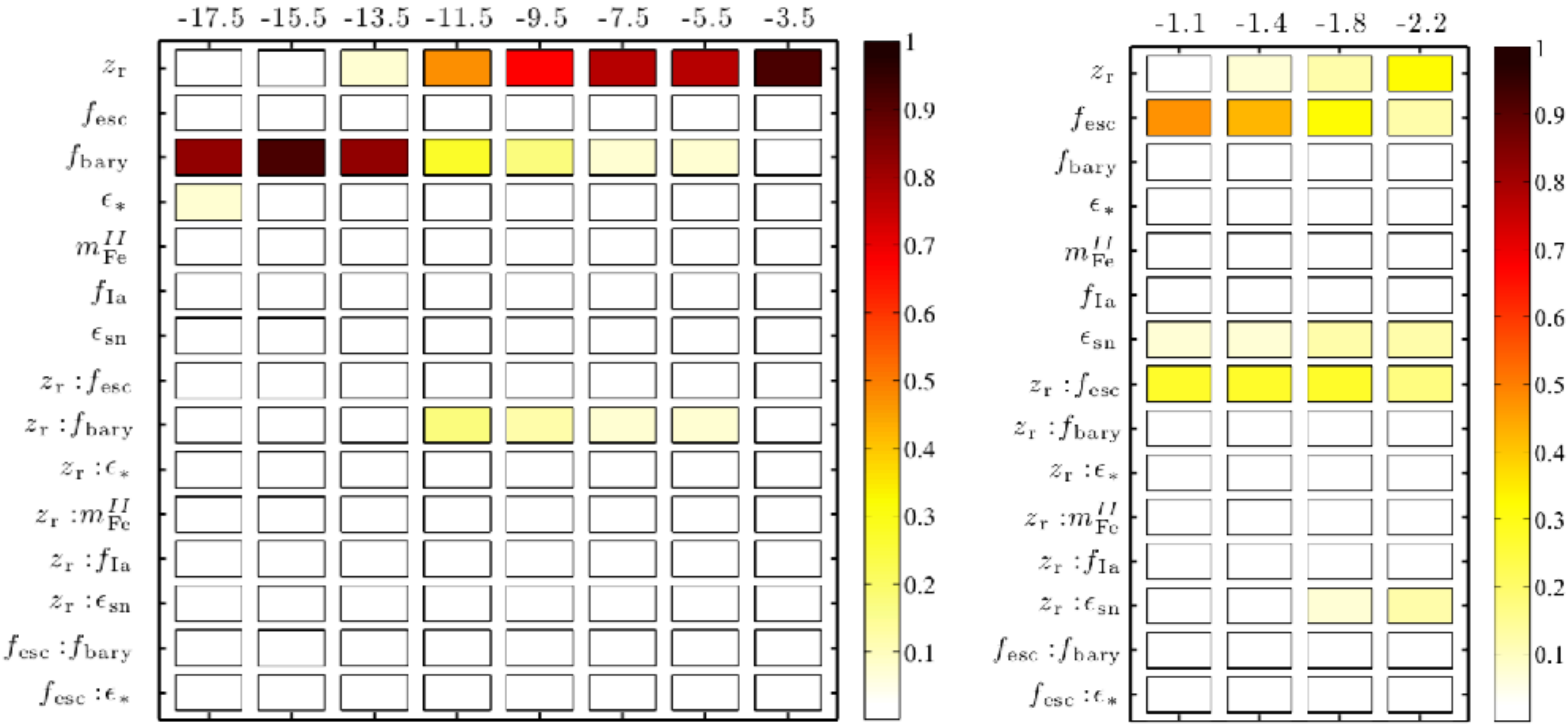


Gómez et al. 2012 (ApJ, 760:112)



Gómez et al. 2012 (ApJ, 760:112)

Parameter sensitivity analysis



Gómez et al. 2014 (ApJ, 787:20)

Overall goal: robust, quantitative predictions* from models compared to observed chemical abundances in stars, using r-process enrichment at low metallicity as an example application!

***with estimates of true uncertainty from models and observations**

Where do things stand?

- **Existing theoretical tools**: SYGMA, OMEGA+, GAMMA, Gaussian Process emulator, MCMC.
- **Existing observational databases**: JINABase, Stellab
- **Theory needs**: metal mixing model, disk model, dark matter particle tagging.
- **Observational needs**: additional datasets!

Expect entire pipeline by this time next year!

To summarize:

1. Making quantitative, believable predictions taking advantage of modern observational surveys requires a sophisticated GCE framework

2. Hydrodynamic simulations can inform GCE models in a variety of useful ways (and make prettier pictures)

3. The future of the JINA-CEE GCE pipeline is bright!