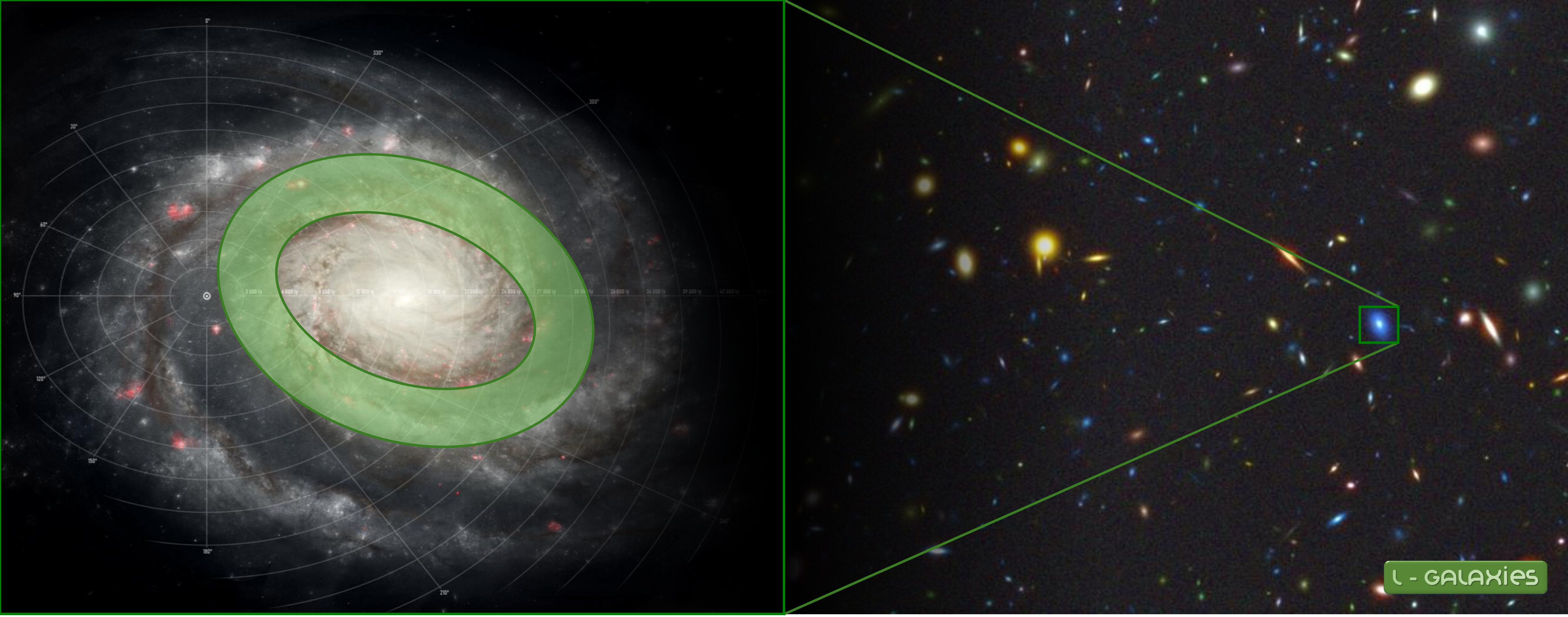


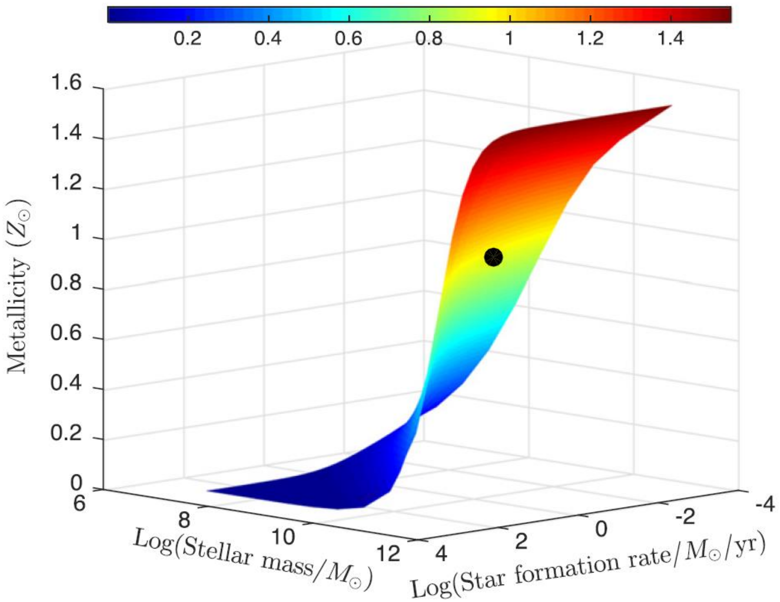
Modelling GHZs in cosmological galaxy evolution simulations

Rob Yates
University of Hertfordshire

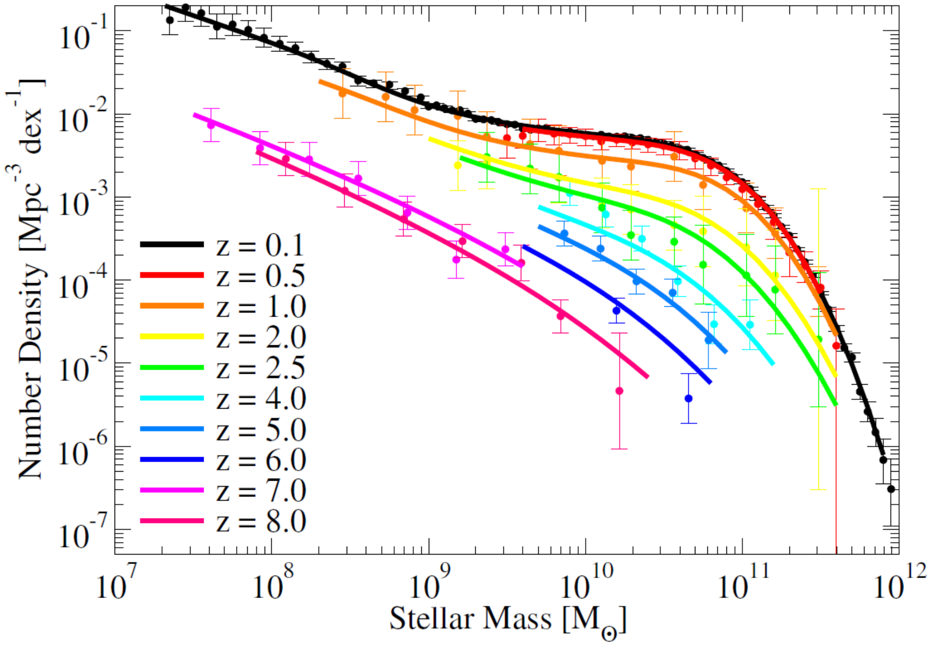
Molecules & Planets workshop:
Session 5: GCE: link with the GHZ

Cosmological simulation types

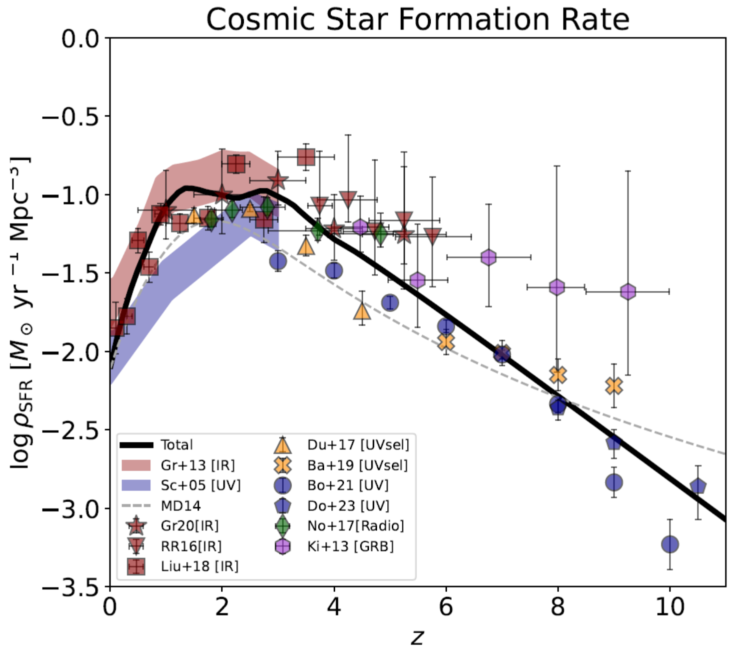
1) Empirical models



Dayal+15



Behroozi+13

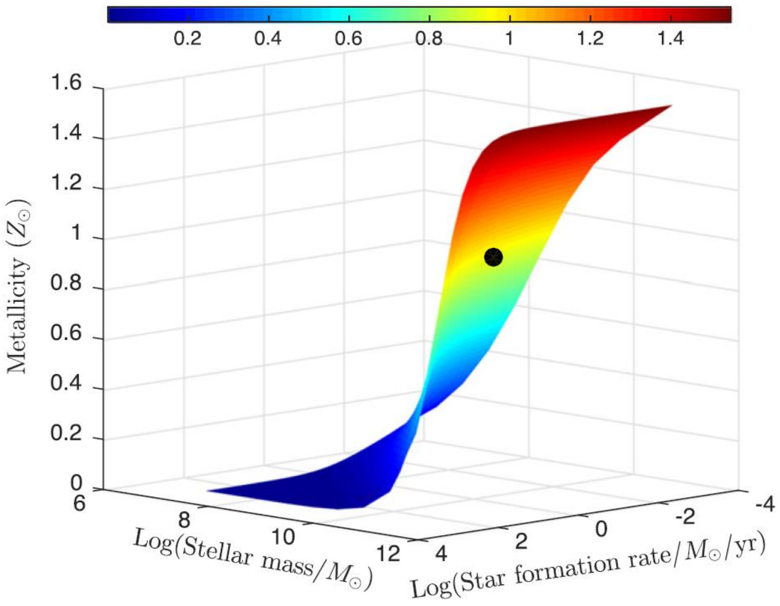


Lapi+24

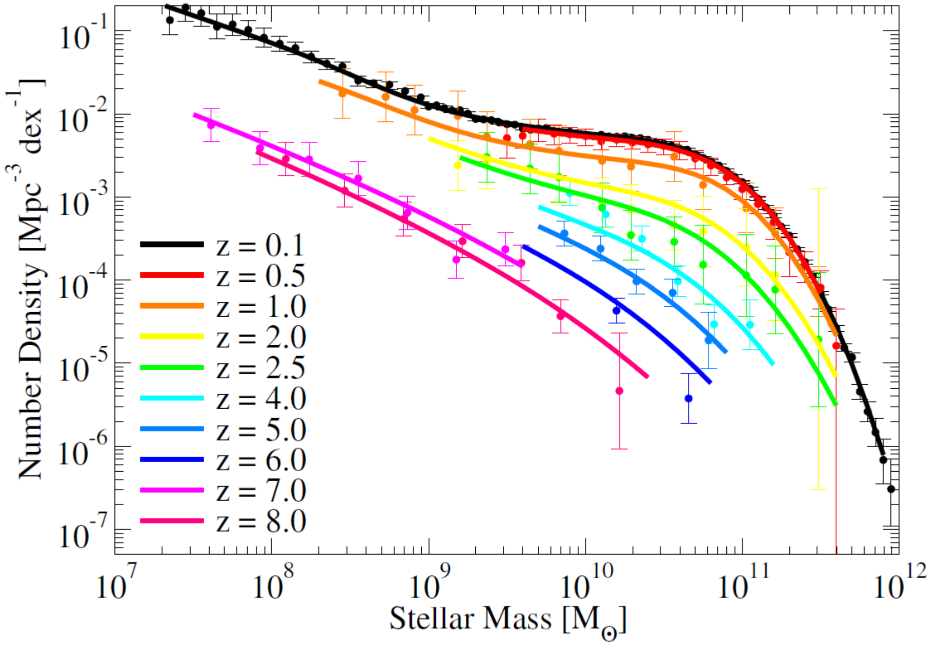
Use **empirical scaling relations** to infer galaxy evolution.
Varied star-formation histories (SFHs) **not considered**.

(GHZ studies: e.g. Dayal+15,16; Li & Zhang 15; Behroozi & Peeples 15; Gobat & Hong 16; Lapi+24)

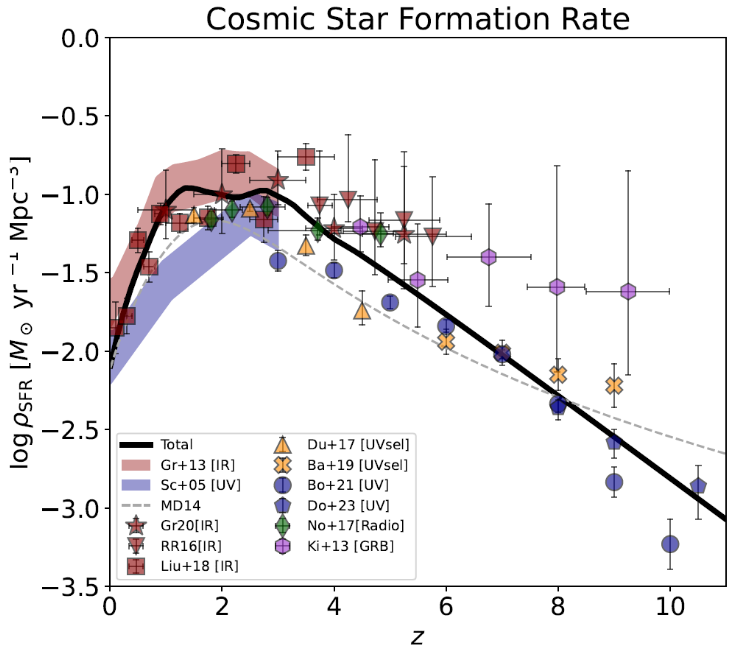
1) Empirical models



Dayal+15



Behroozi+13



Lapi+24

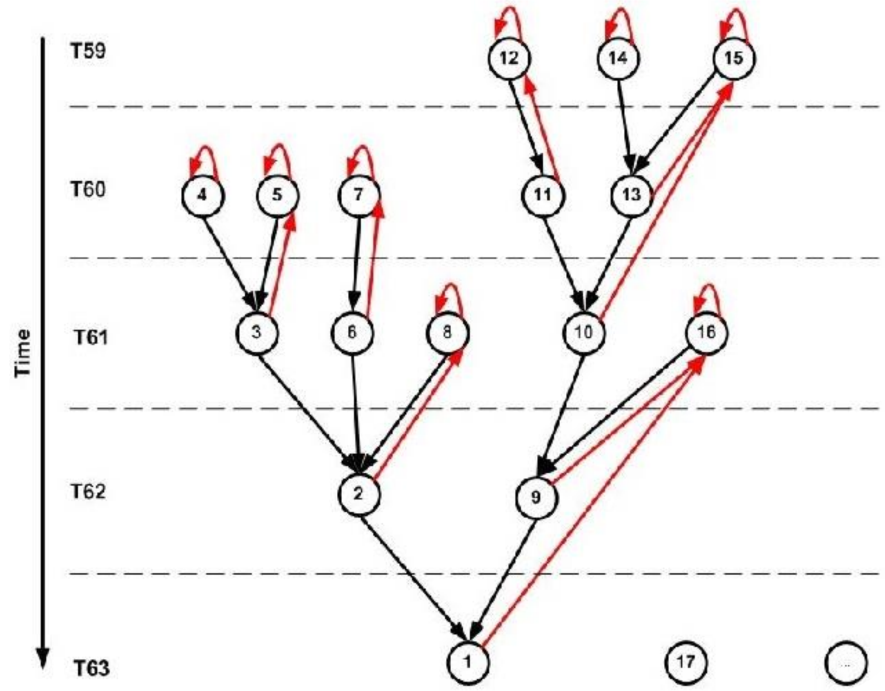
Use **empirical scaling relations** to infer galaxy evolution.
Varied star-formation histories (SFHs) **not considered**.

Highly efficient

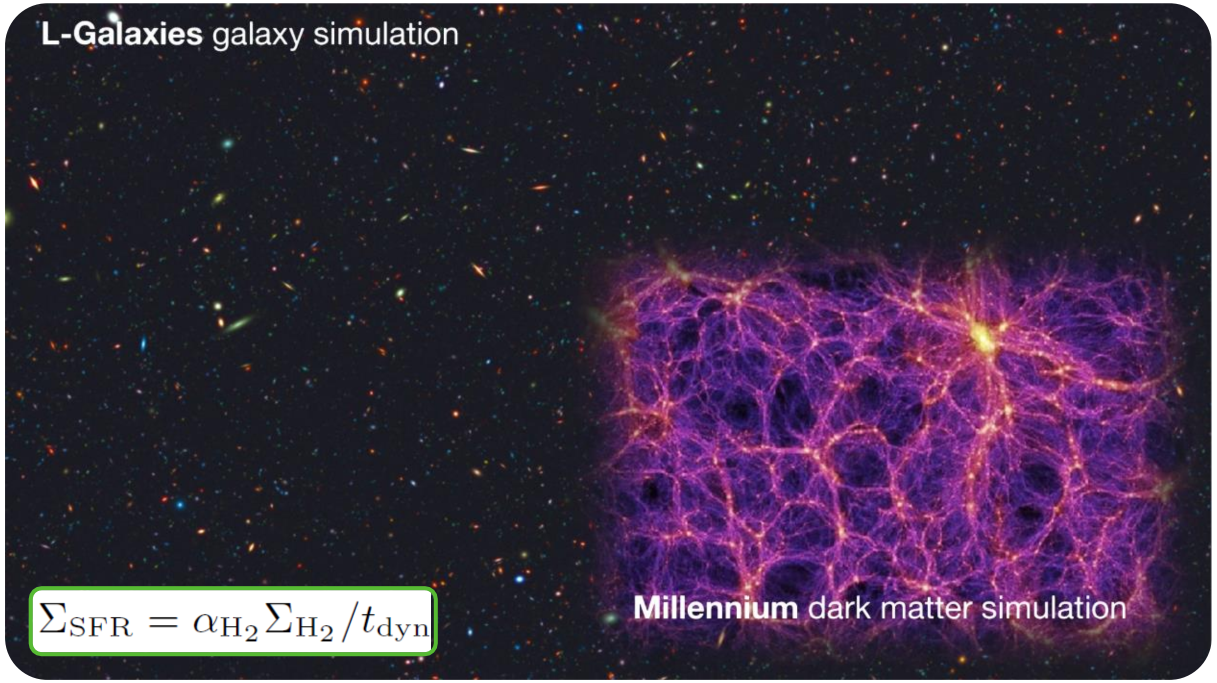
Average, galaxy-scale predictions

(GHZ studies: e.g. Dayal+15,16; Li & Zhang 15; Behroozi & Peeples 15; Gobat & Hong 16; Lapi+24)

2) Semi-analytic simulations



V. Springel

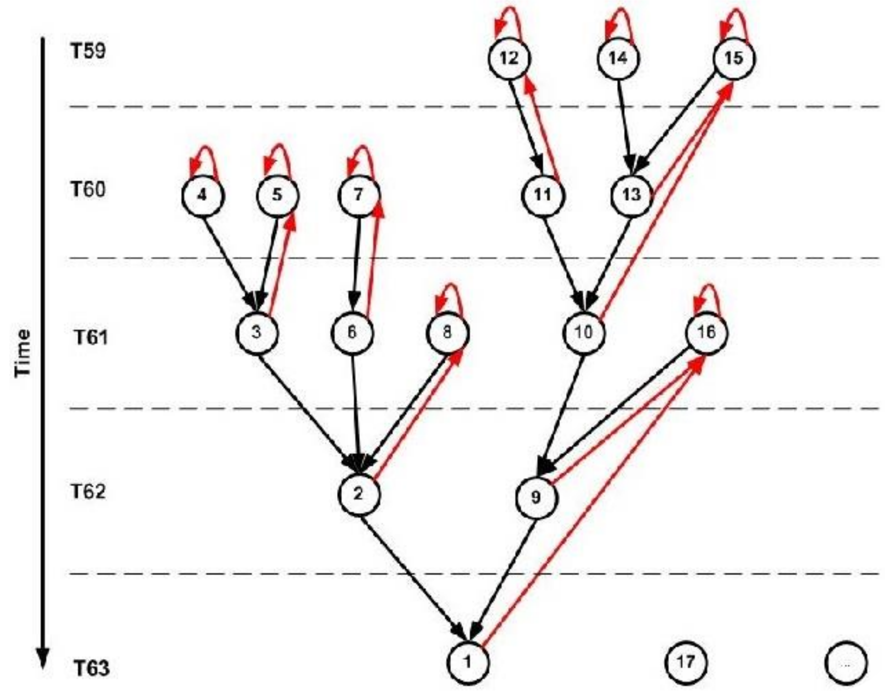


R. Yates

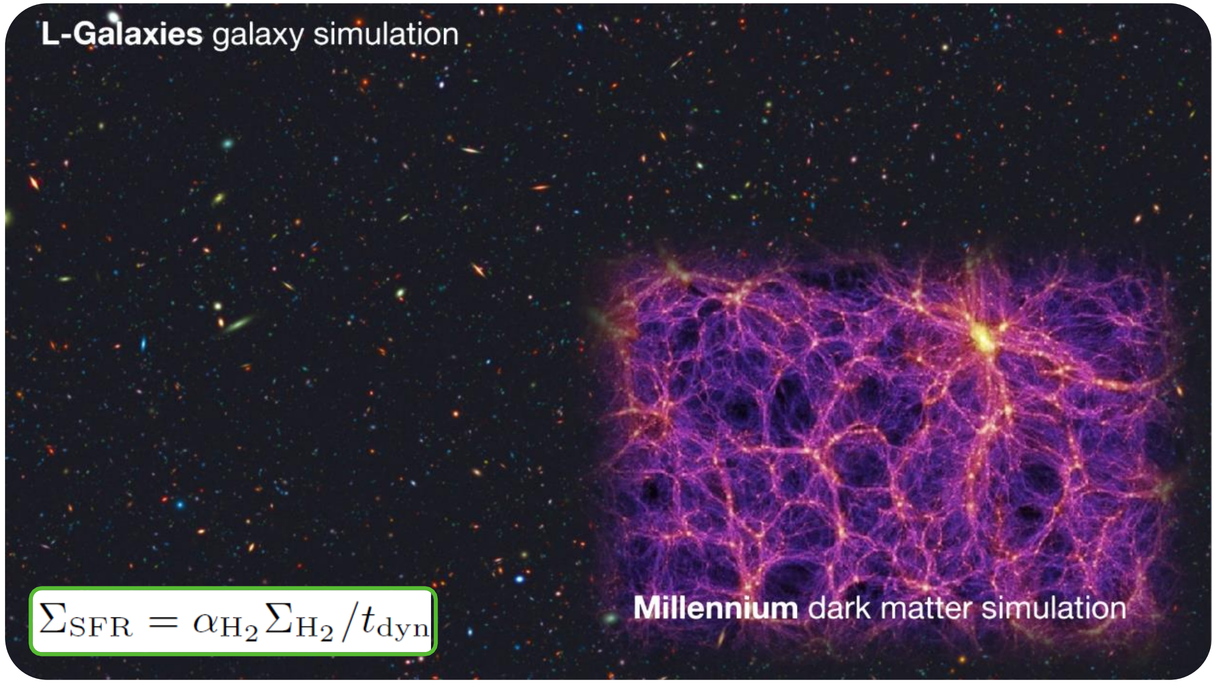
Consider diverse **cosmological context** via the underlying DM halo merger history.
Use analytic formulae to describe baryonic processes on **galaxy scales**.

(GHZ studies: e.g. Zackrisson+16; Stanway+18)

2) Semi-analytic simulations



V. Springel



R. Yates

Consider diverse **cosmological context** via the underlying DM halo merger history.
Use analytic formulae to describe baryonic processes on **galaxy scales**.

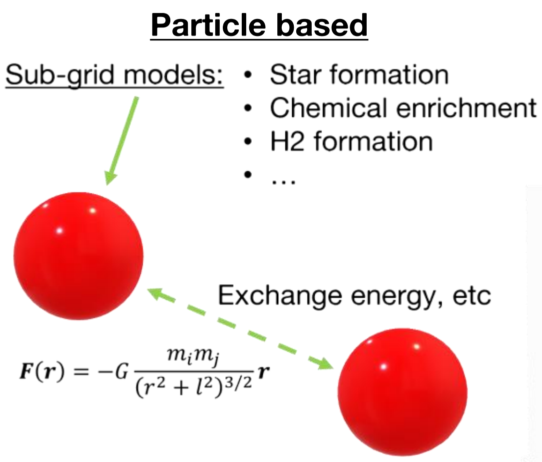
Efficient

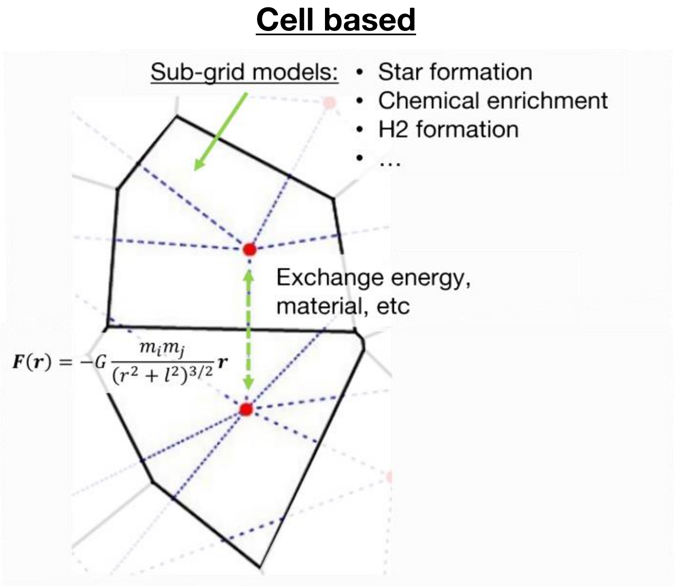
100s of CPU hrs per run

Individual, galaxy-scale predictions

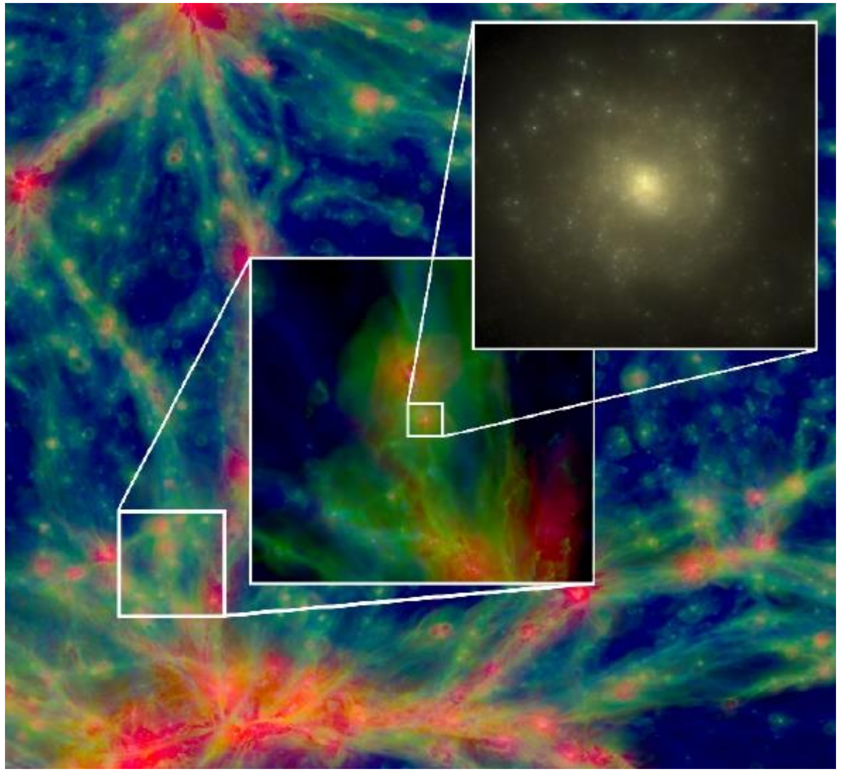
(GHZ studies: e.g. Zackrisson+16; Stanway+18)

3) Hydrodynamical simulations





R. Yates



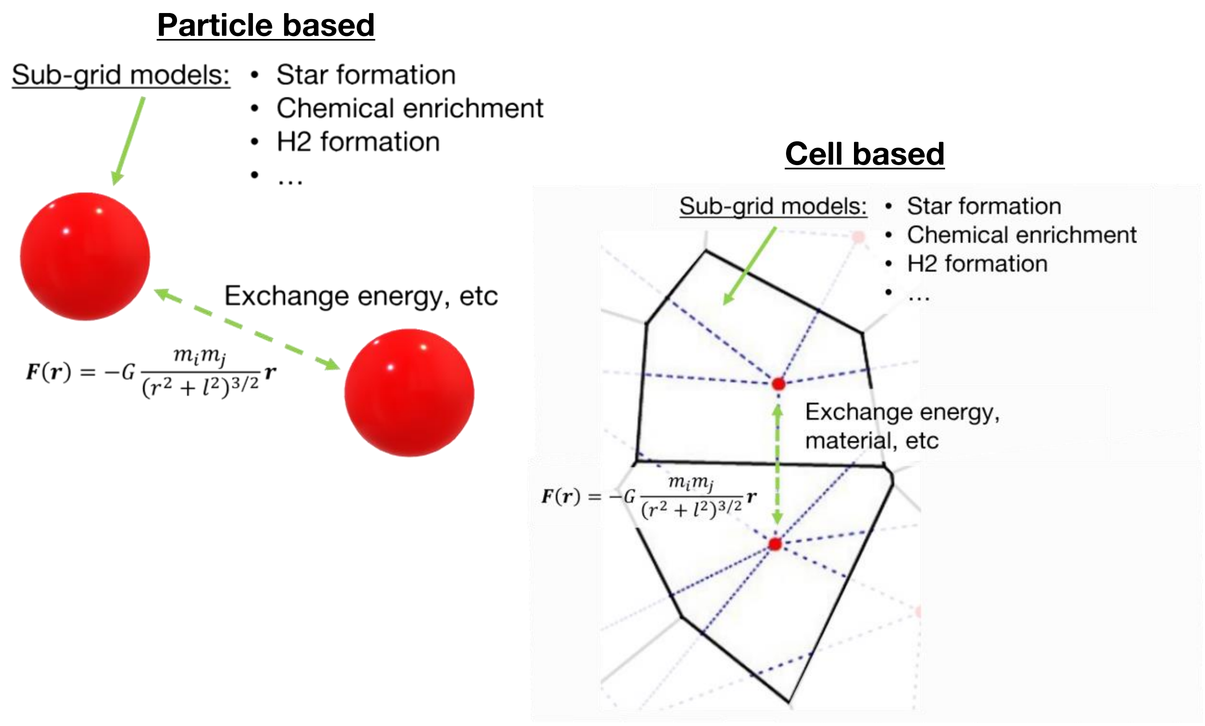
Schaye+15

Consider diverse **cosmological context** and model **small-scale** baryonic processes*.
Directly calculate the **morphological & hydrodynamical** evolution of galaxies.

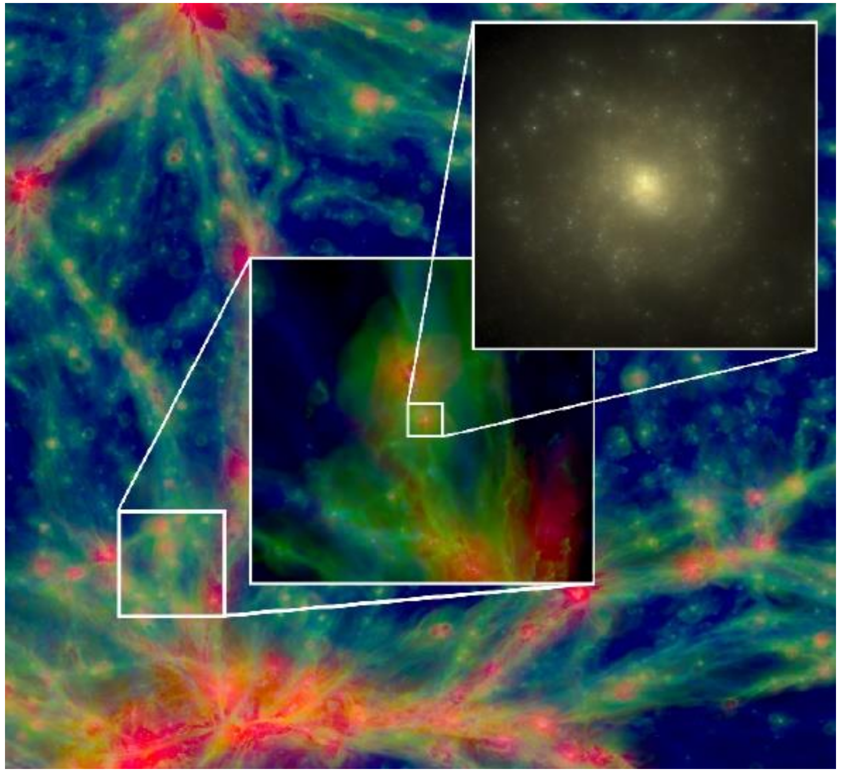
(GHZ studies: e.g. Forgan+17b; Boettner+24)

* Note: baryonic particles / softening lengths are $\mathcal{O}(10^4)$ M_{sun} / $\mathcal{O}(10^2)$ pc for relevant zoom-in simulations

3) Hydrodynamical simulations



R. Yates



Schaye+15

Consider diverse **cosmological context** and model **small-scale** baryonic processes*.
Directly calculate the **morphological & hydrodynamical** evolution of galaxies.

Inefficient

10s of millions of CPU hrs per run

Individual, sub-kpc-scale predictions

(GHZ studies: e.g. Forgan+17b; Boettner+24)

* Note: baryonic particles / softening lengths are $\mathcal{O}(10^4)$ M_{sun} / $\mathcal{O}(10^2)$ pc for relevant zoom-in simulations

Previous habitability studies

Assumptions about planet formation

1) Empirical approach:

Dayal+15:

$$N_{\rm HP} \propto \frac{M_*^2\, Z_{\rm g}^{\alpha}}{\psi}$$

number of habitable planets (HPs)
galaxy stellar mass
galaxy gas-phase metallicity
galaxy SFR (proxy for SN rate)

Dayal+16:

$$n_{\rm HP} \propto \frac{\rho_*\, Z_*^{\alpha}}{\rho_s}$$

number density of HPs
cosmic stellar mass density
galaxy stellar metallicity
cosmic sterilising radiation density

Behroozi & Peeples 16:

$$R_{\rm TP} = \frac{\bar{n}\,\psi}{\bar{m}_*} Z_{\rm g}^{\alpha}$$

rate of terrestrial planet (TP) formation
mean N_{TP} per star
mean star mass

TP = Terrestrial planet
≈ T_{earth}, R_{earth}, P_{earth}, etc

HP = Habitable planet
= TP that hasn't been sterilised or destroyed

Assumptions about planet formation

1) Empirical approach:

number of habitable planets (HPs)
galaxy stellar mass
galaxy gas-phase metallicity
galaxy SFR (proxy for SN rate)

Dayal+15: $$N_{\rm HP} \propto \frac{M_*^2 \, Z_{\rm g}^{\alpha}}{\psi}$$

number density of HPs
cosmic stellar mass density
galaxy stellar metallicity
cosmic sterilising radiation density

Dayal+16: $$n_{\rm HP} \propto \frac{\rho_* \, Z_*^{\alpha}}{\rho_s}$$

rate of terrestrial planet (TP) formation
mean $N_{\rm TP}$ per star
mean star mass

Behroozi & Peeples 16: $$R_{\rm TP} = \frac{\bar{n} \, \psi}{\bar{m}_*} Z_{\rm g}^{\alpha}$$

TP = Terrestrial planet

≈ $T_{\rm earth}$, $R_{\rm earth}$, $P_{\rm earth}$, etc

HP = Habitable planet

= TP that hasn't been sterilised or destroyed

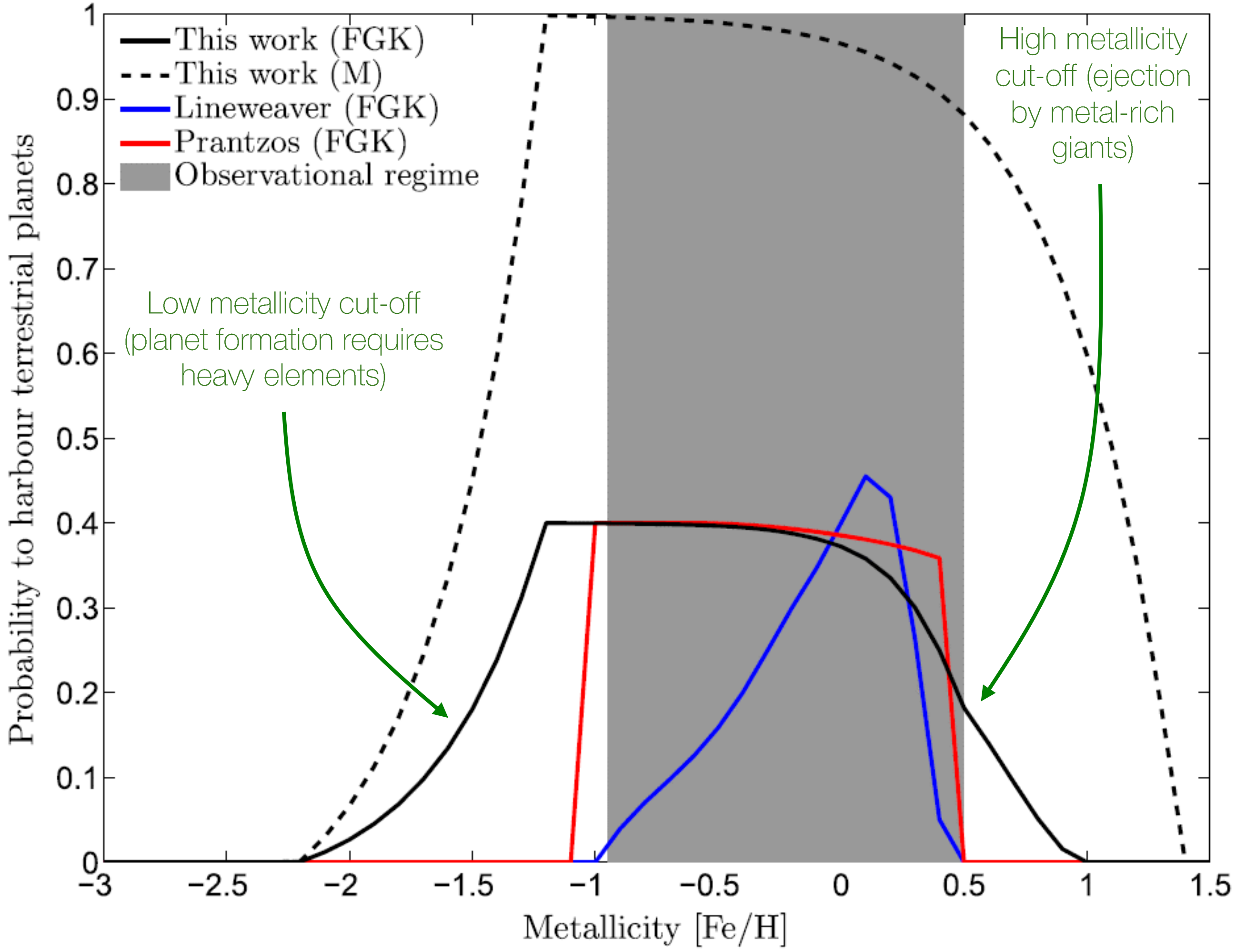
Metallicity dependence:

$$\alpha \sim 0 - 0.7$$

(see e.g. Prantzos 08; Buchhave+12; Wang & Fischer 15; Adams & Kane 16; Hobson+17)

Assumptions about planet formation

2) Semi-analytic & hydrodynamical approach:



Zackrisson+16

$$N_{\rm HP} = N_* P_{\rm TP}(1 - P_{\rm HJ})(1 - P_{\rm s})$$

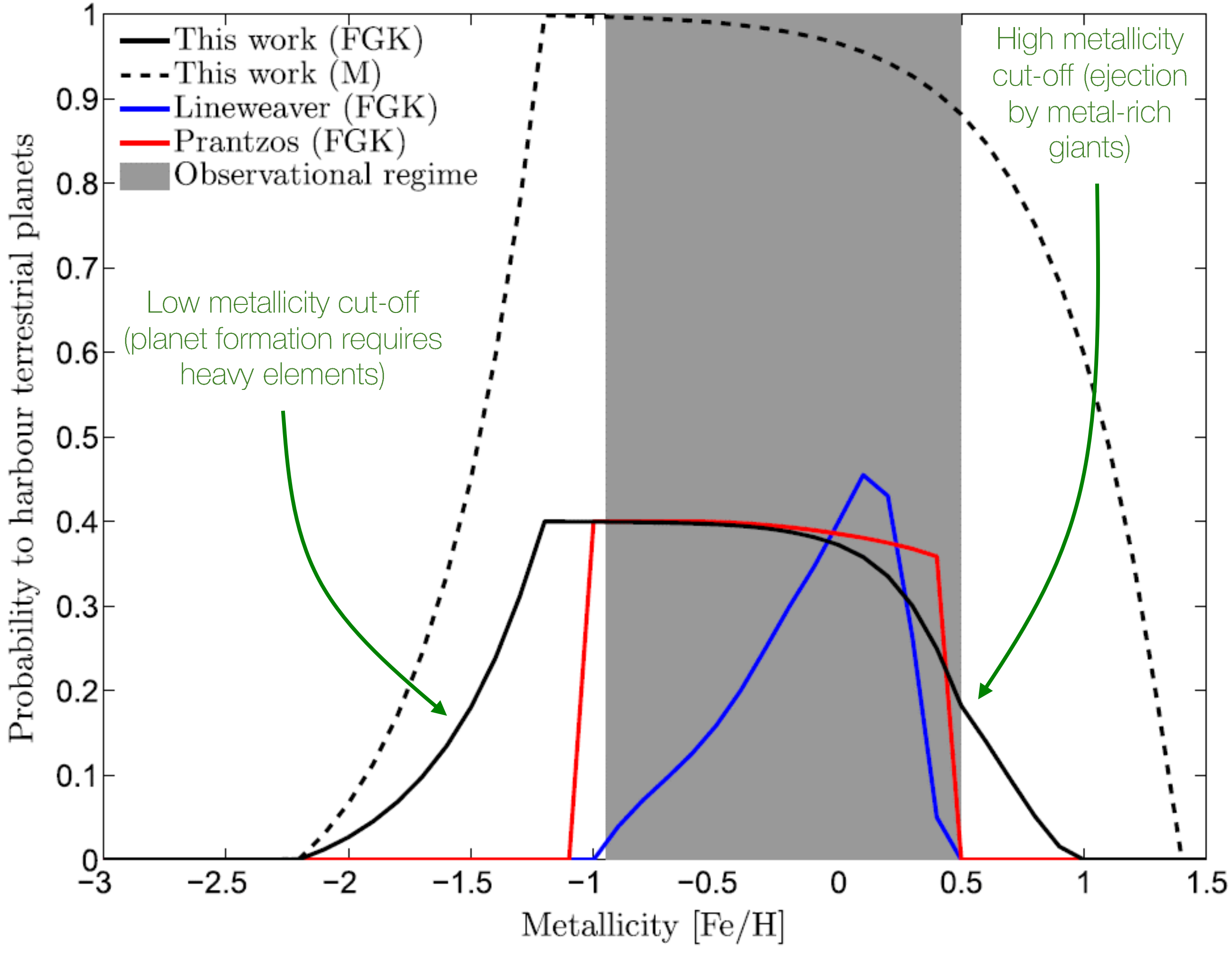
- $N_{\rm HP}$: Number of habitable planets
- N_*: Number of stars
- $P_{\rm TP}$: Probability of TP formation
- $P_{\rm HJ}$: Probability of destruction by hot Jupiters
- $P_{\rm s}$: Probability of sterilisation

[Fe/H], M_*, IMF → Planet formation model → $N_{\rm HP}$

Emsenhuber+21; Boettner+24

Assumptions about planet formation

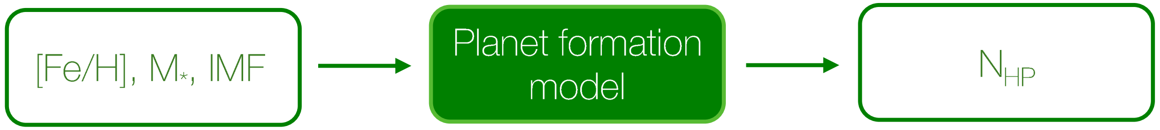
2) Semi-analytic & hydrodynamical approach:



Zackrisson+16

$$N_{\mathrm{HP}} = N_* P_{\mathrm{TP}}(1 - P_{\mathrm{HJ}})(1 - P_{\mathrm{s}})$$

Number of habitable planets; Number of stars; Probability of TP formation; Probability of destruction by hot Jupiters; Probability of sterilisation



Emsenhuber+21; Boettner+24

Q: Are these metallicity weightings missing TP formation at high redshift or large R_{GC}?

Results from previous studies

1a) HPs are mostly likely found in **massive elliptical galaxies** at low redshift

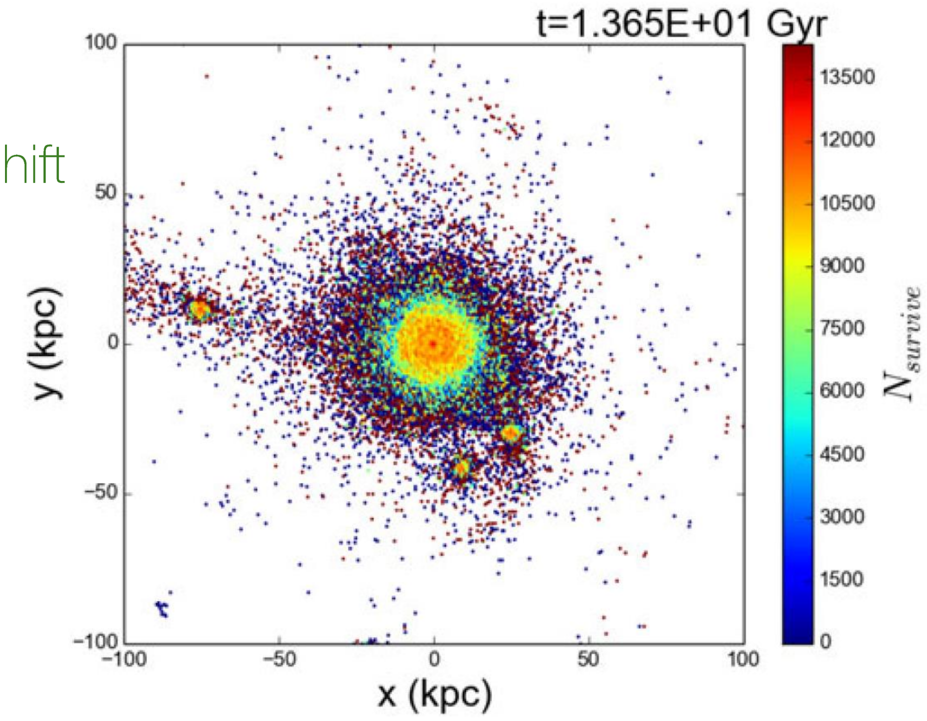
(e.g. Dayal+15,16; Gobat & Hong 16; Zackrisson+16)

Results from previous studies

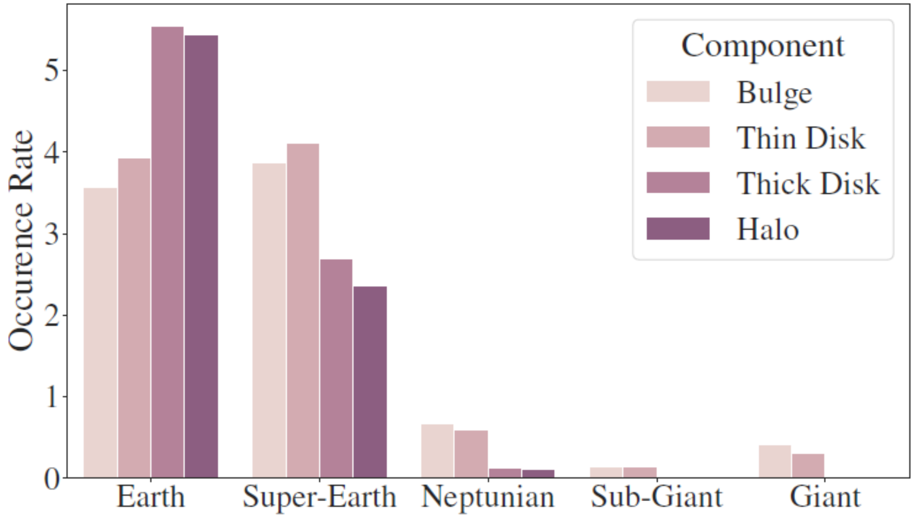
1a) HPs are mostly likely found in **massive elliptical galaxies** at low redshift
(e.g. Dayal+15,16; Gobat & Hong 16; Zackrisson+16)

But…

1b) **Dwarf galaxies, thick disc and halo** could also be cradles of life
(e.g. Forgan+17b; Boettner+24)



Forgan+17b



Boettner+24

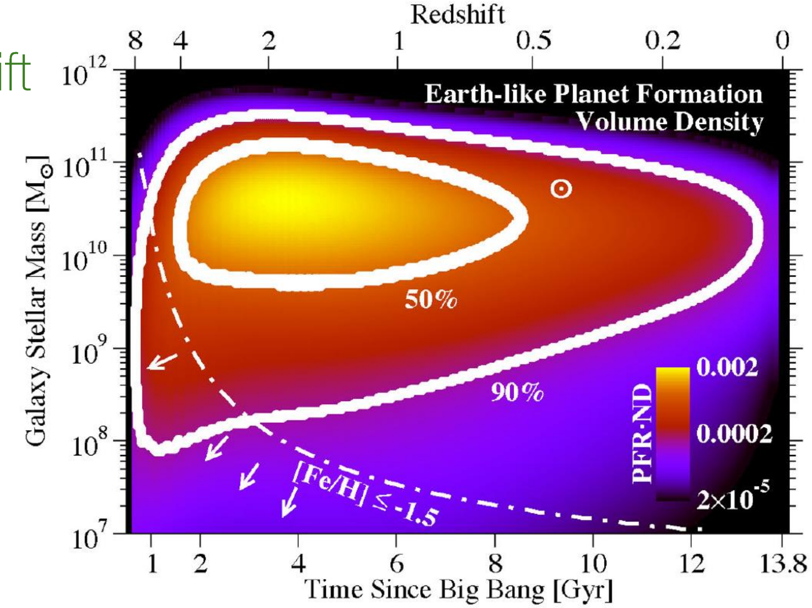
Results from previous studies

1a) HPs are mostly likely found in **massive elliptical galaxies** at low redshift
(e.g. Dayal+15,16; Gobat & Hong 16; Zackrisson+16)

But…

1b) **Dwarf galaxies, thick disc and halo** could also be cradles of life
(e.g. Forgan+17b; Boettner+24)

2a) P_{HP} is **not** significantly affected by the **chosen metallicity thresholds**
(e.g. Behroozi & Peeples; Stanway+18)



Behroozi & Peeples 16

Results from previous studies

1a) HPs are mostly likely found in **massive elliptical galaxies** at low redshift
(e.g. Dayal+15,16; Gobat & Hong 16; Zackrisson+16)

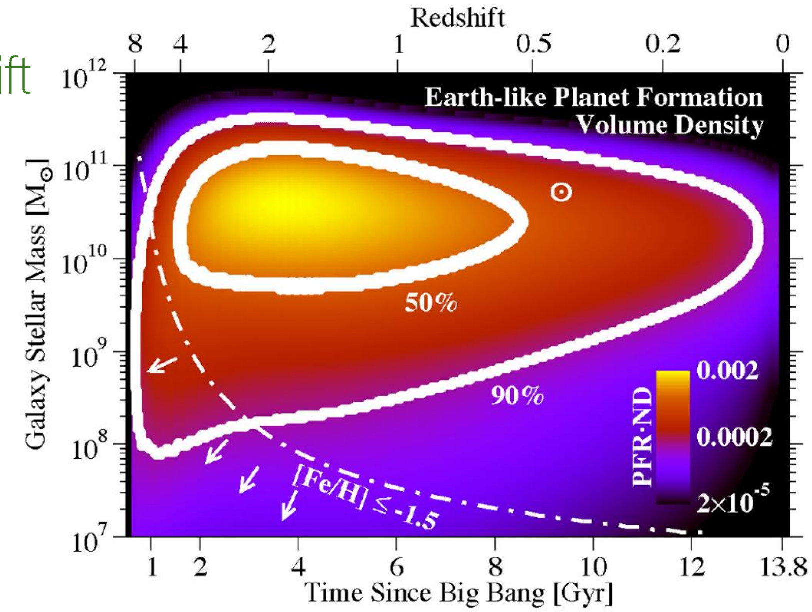
But…

1b) **Dwarf galaxies, thick disc and halo** could also be cradles of life
(e.g. Forgan+17b; Boettner+24)

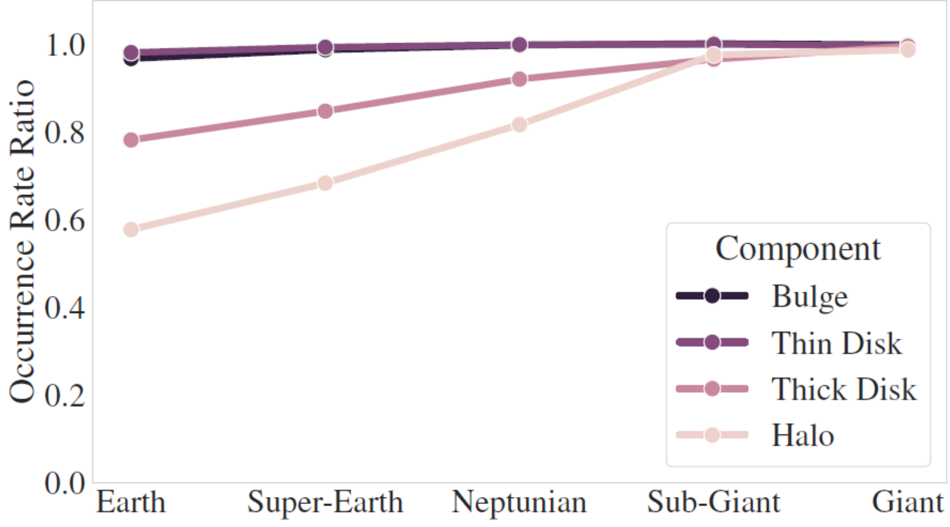
2a) P_{HP} is **not** significantly affected by the **chosen metallicity thresholds**
(e.g. Behroozi & Peeples; Stanway+18)

But…

2b) This neglects **planet formation at high redshift and large R_{GC}**
(e.g. Zackrisson+16; Boettner+24)



Behroozi & Peeples 16



Boettner+24

Results from previous studies

1a) HPs are mostly likely found in **massive elliptical galaxies** at low redshift
(e.g. Dayal+15,16; Gobat & Hong 16; Zackrisson+16)

But…

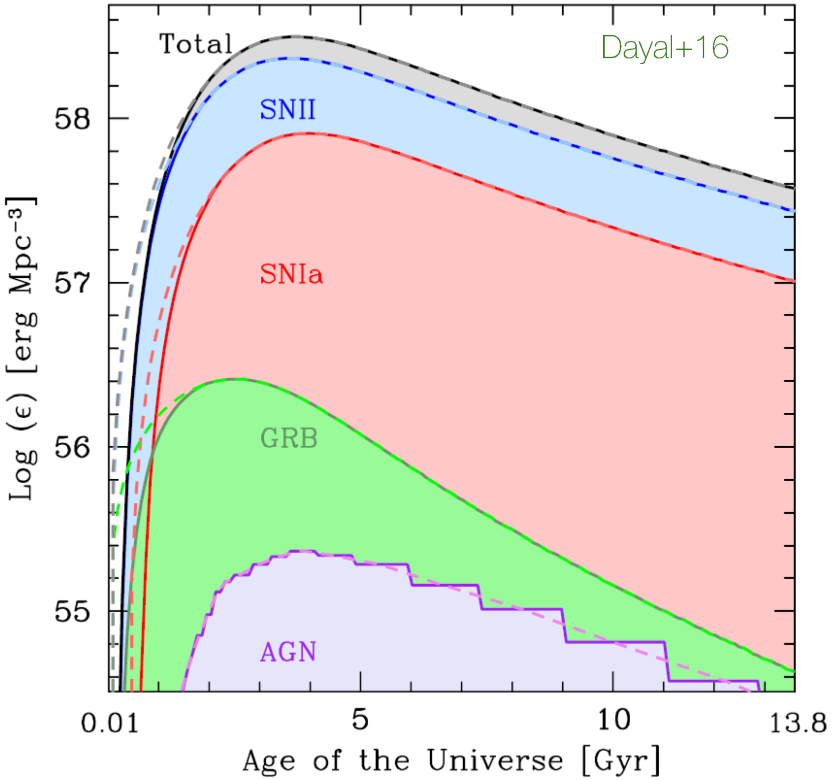
1b) **Dwarf galaxies, thick disc and halo** could also be cradles of life
(e.g. Forgan+17b; Boettner+24)

2a) P_{HP} is **not** significantly affected by the **chosen metallicity thresholds**
(e.g. Behroozi & Peeples; Stanway+18)

But…

2b) This neglects **planet formation at high redshift and large R_{GC}**
(e.g. Zackrisson+16; Boettner+24)

3a) **SNe-II** dominate planet sterilisation
(e.g. Dayal+16)



Results from previous studies

1a) HPs are mostly likely found in **massive elliptical galaxies** at low redshift
(e.g. Dayal+15,16; Gobat & Hong 16; Zackrisson+16)

But…

1b) **Dwarf galaxies, thick disc and halo** could also be cradles of life
(e.g. Forgan+17b; Boettner+24)

2a) P_{HP} is **not** significantly affected by the **chosen metallicity thresholds**
(e.g. Behroozi & Peeples; Stanway+18)

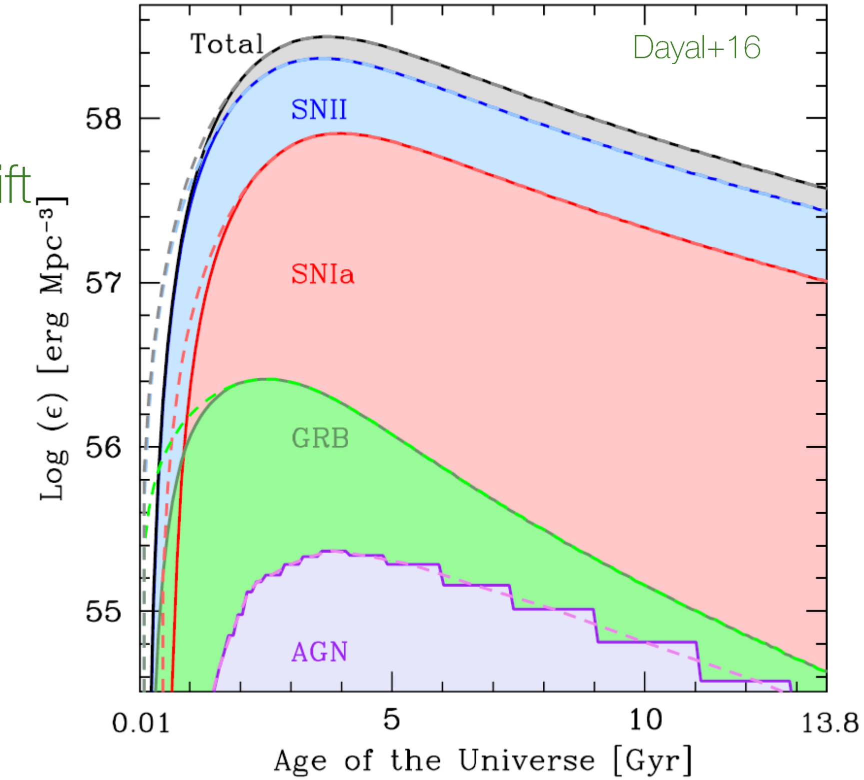
But…

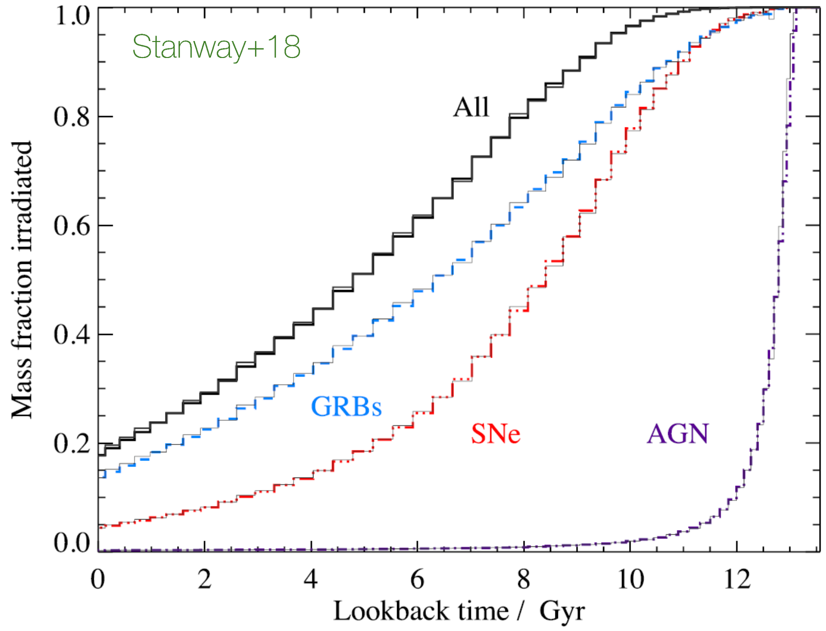
2b) This neglects **planet formation at high redshift and large R_{GC}**
(e.g. Zackrisson+16; Boettner+24)

3a) **SNe-II** dominate planet sterilisation
(e.g. Dayal+16)

But…

3b) **GRBs can dominate**, if they also occur in metal-rich environments
(e.g. Stanway+18)





Key limitations of previous studies

- **Only consider total metallicity:**
  This ignores the potential importance of individual chemical elements, dust-to-gas (DTG) ratio, and molecule formation

- **Instantaneous Recycling Approximation (IRA):**
  This under-estimates the delay time between star formation and enrichment of certain elements, especially iron

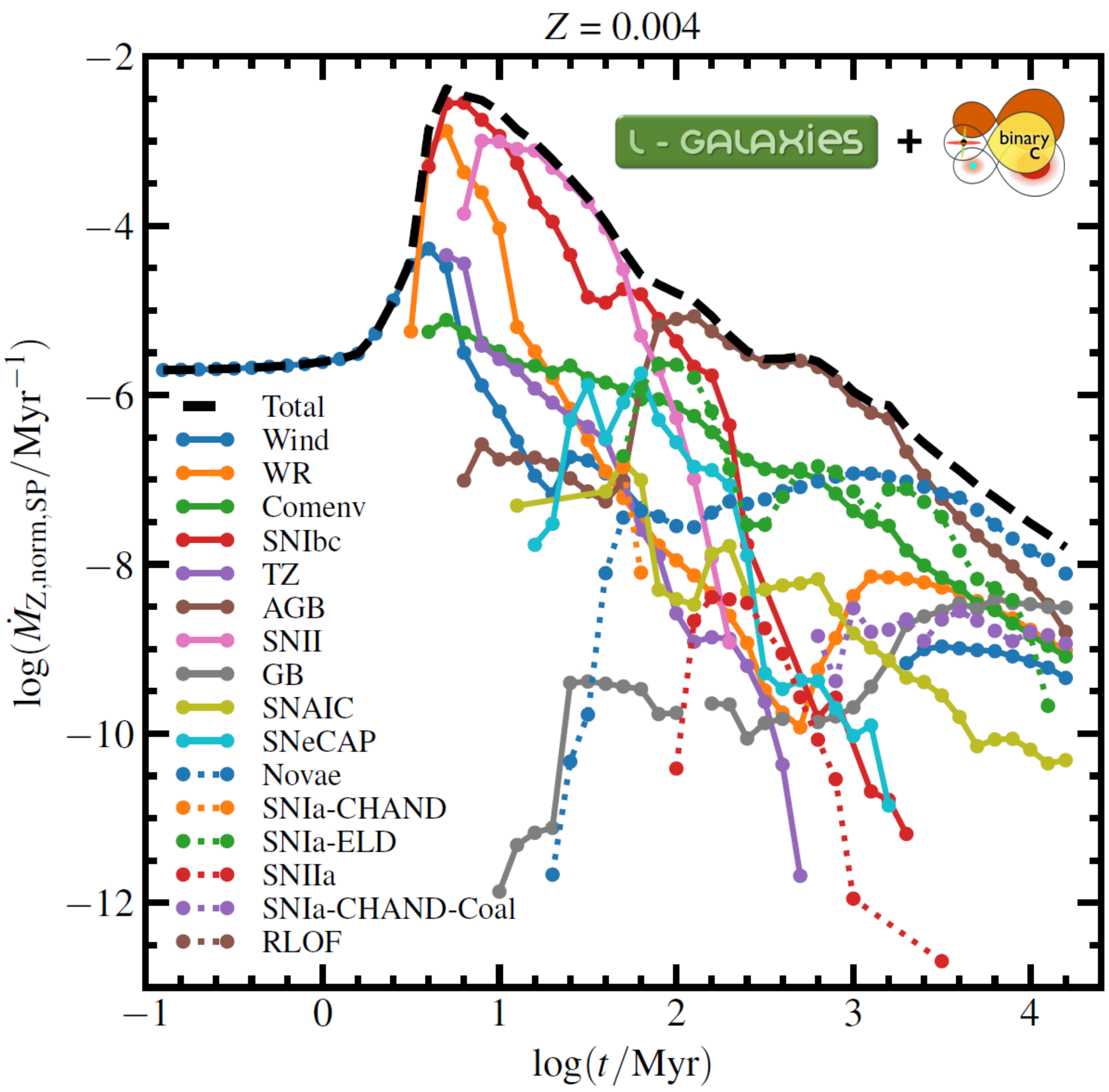
- **Scale vs. efficiency:**
  Empirical and semi-analytic simulations give galaxy-scale properties, whereas hydro sims are inefficient. This prohibits the study of resolved GHZs for large galaxy samples

The L-GALAXIES simulation

L-Galaxies

A cosmological-scale semi-analytic simulation

- Galaxy Chemical Evolution (GCE) model which includes **delayed enrichment** of **118 elements (487 isotopes)** from **various sources**, including binary stellar evolution



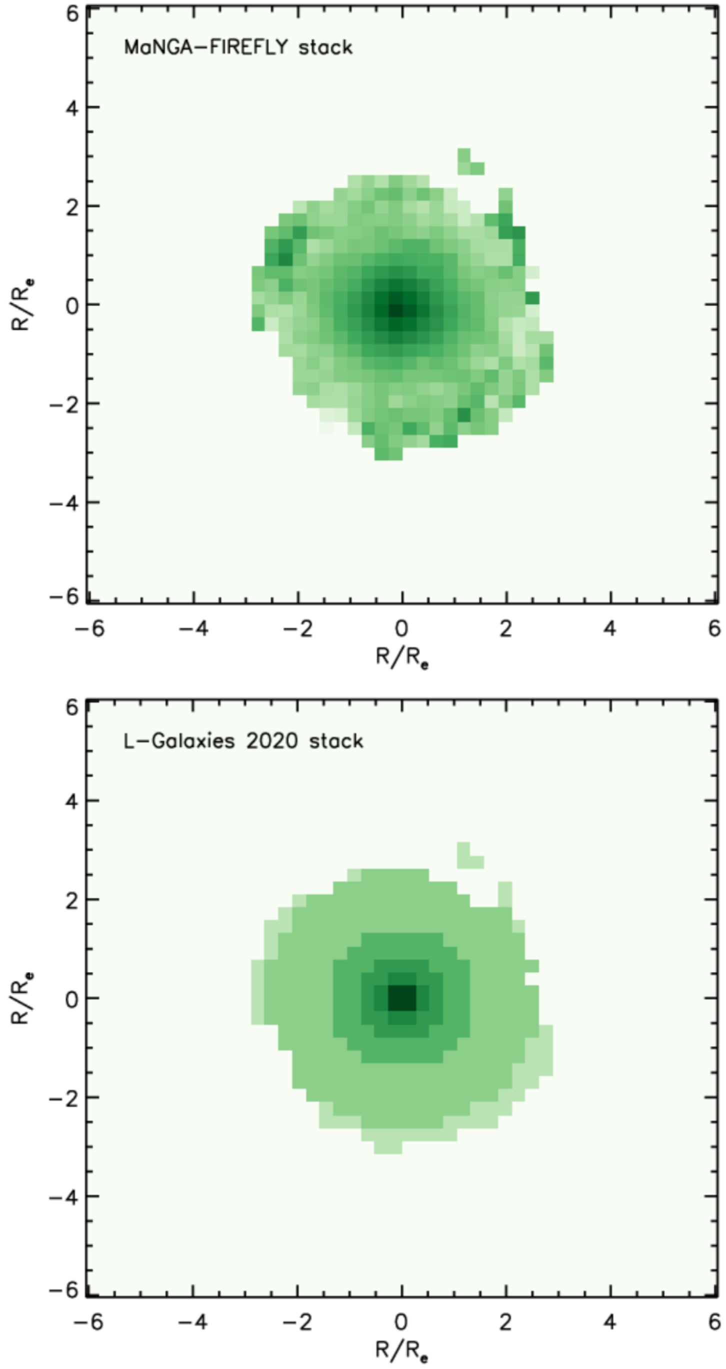
Yates+24

L-Galaxies

A cosmological-scale semi-analytic simulation

- Galaxy Chemical Evolution (GCE) model which includes **delayed enrichment** of **118 elements (487 isotopes)** from **various sources**, including binary stellar evolution

- **Radially resolved galaxy discs** (average of ~175 pc resolution within the inner ~1 kpc)

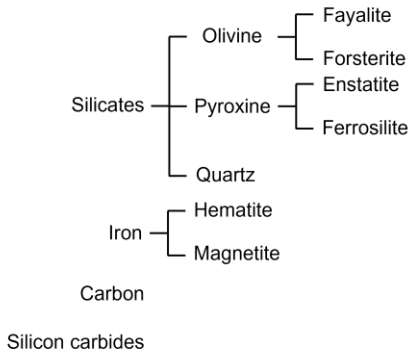


R. Yates

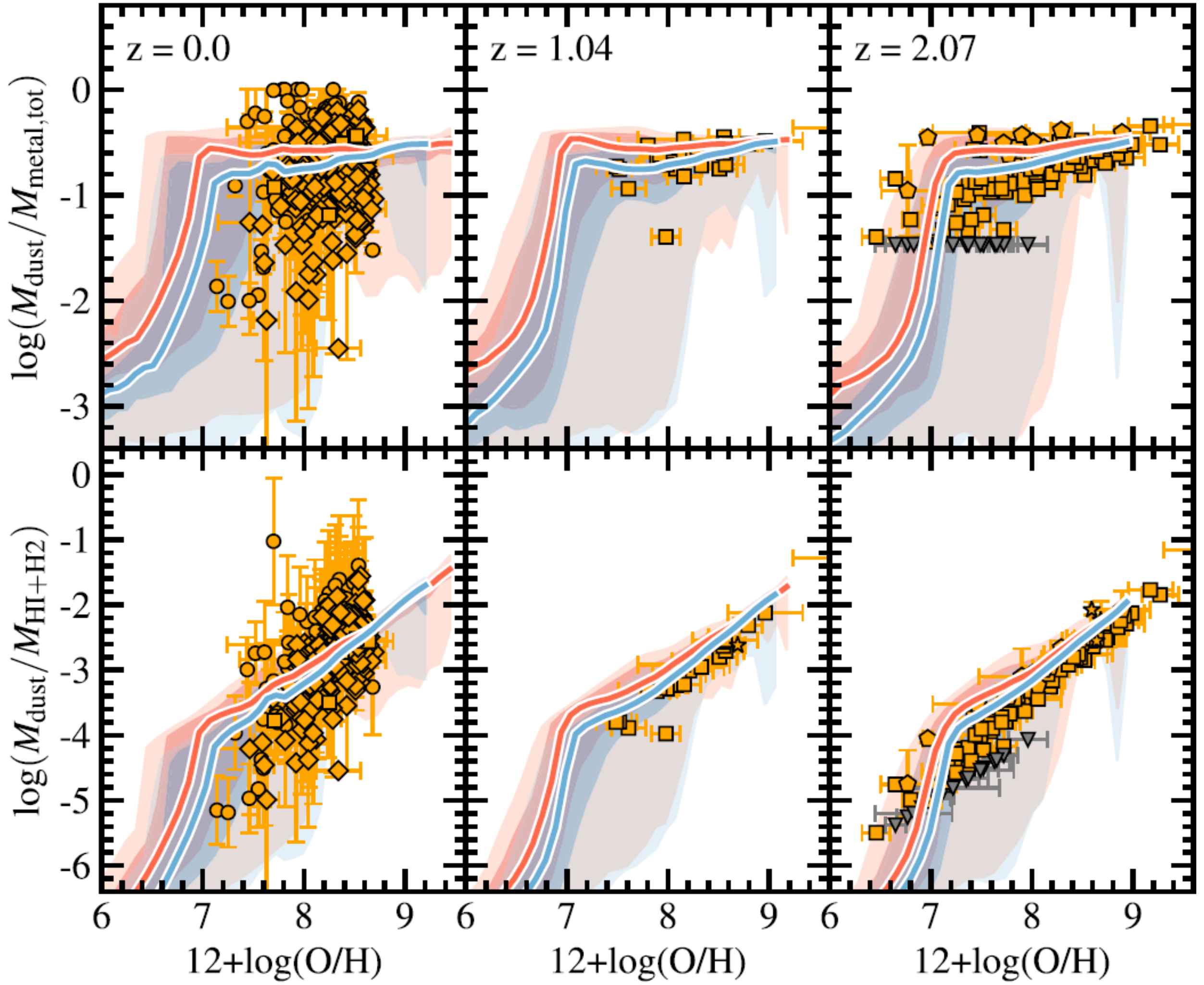
L-Galaxies

A cosmological-scale semi-analytic simulation

- Galaxy Chemical Evolution (GCE) model which includes **delayed enrichment** of **118 elements (487 isotopes)** from **various sources**, including binary stellar evolution
- **Radially resolved galaxy discs** (average of ~175 pc resolution within the inner ~1 kpc)
- **Dust production and destruction** is also modelled self-consistently, allowing for **variable DTG** & **DTM** ratios



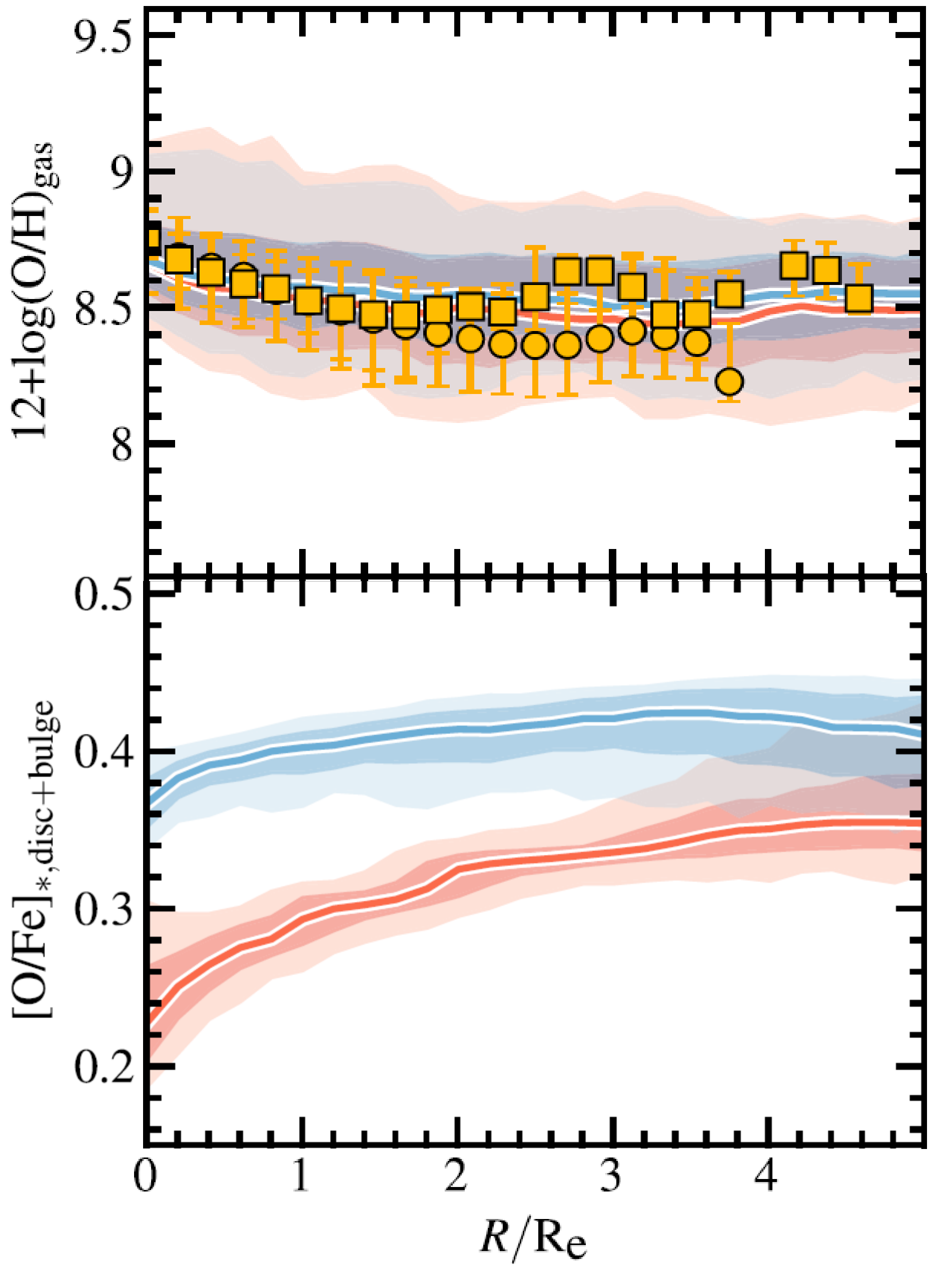
Yates+24



L-Galaxies: next gen GCE modelling

Metallicity → (radially resolved) → Chemical elements

Yates+13,24

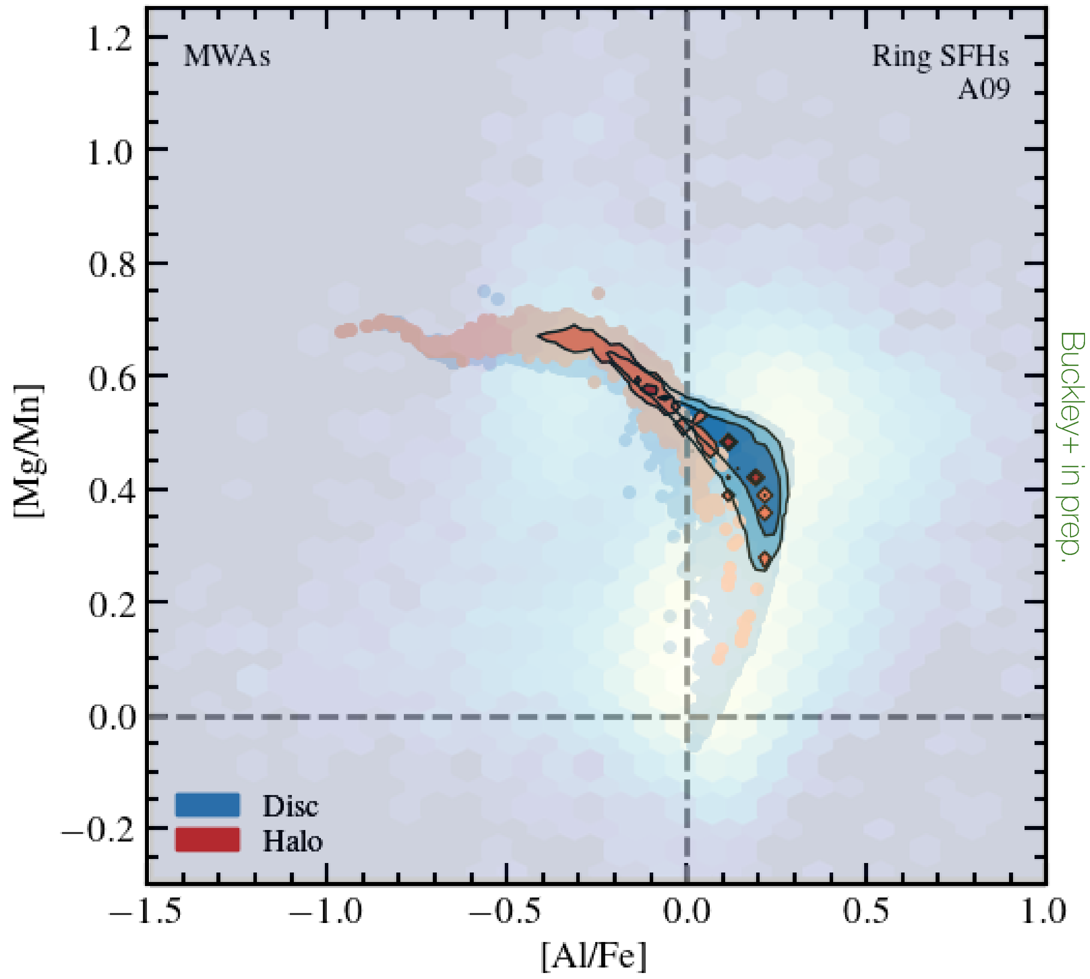


Yates+24

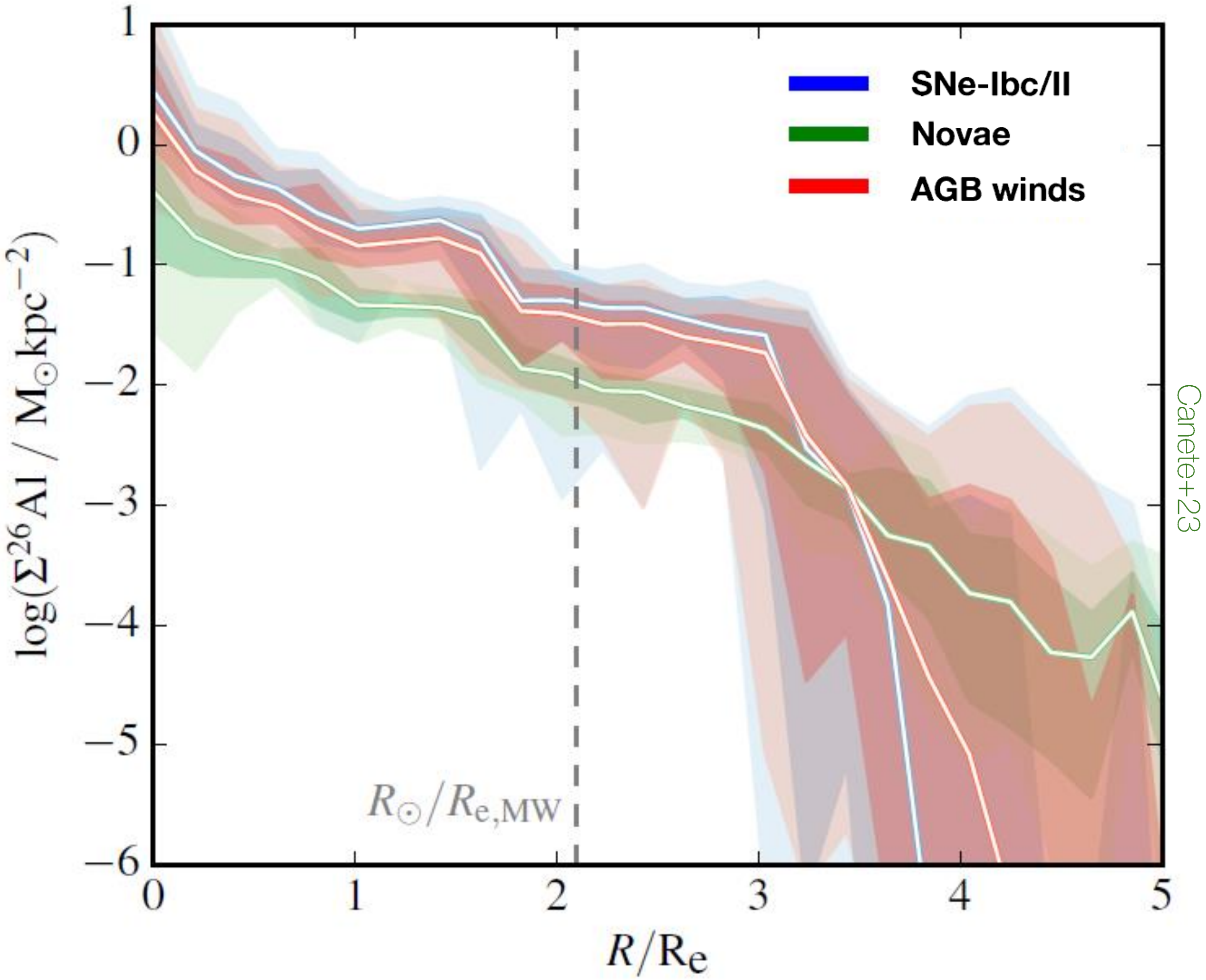
L-Galaxies: next gen GCE modelling

Metallicity → (radially resolved) → Chemical elements

Yates+13,24

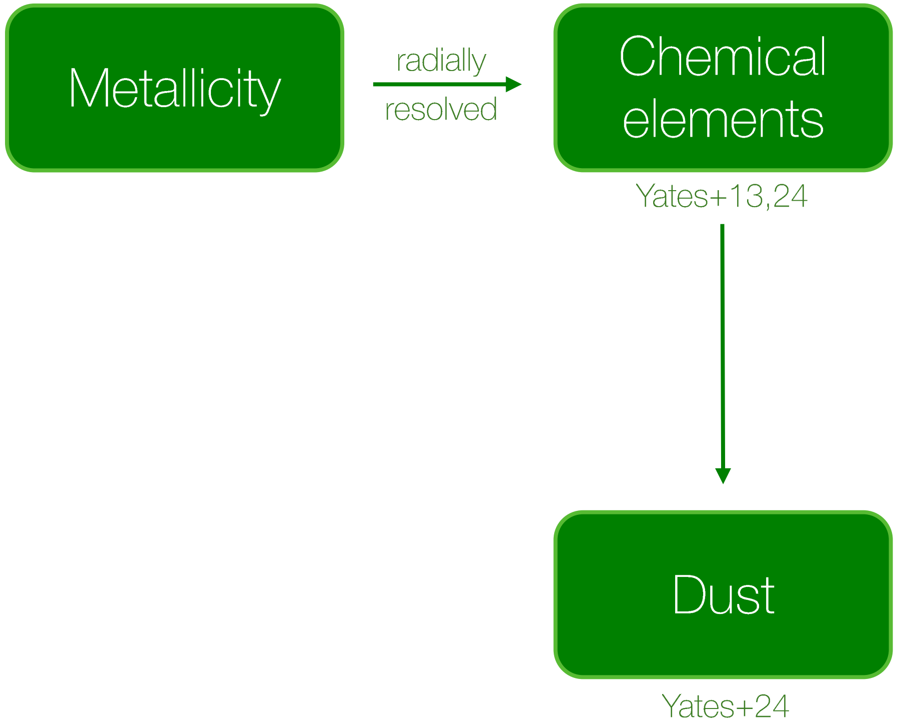


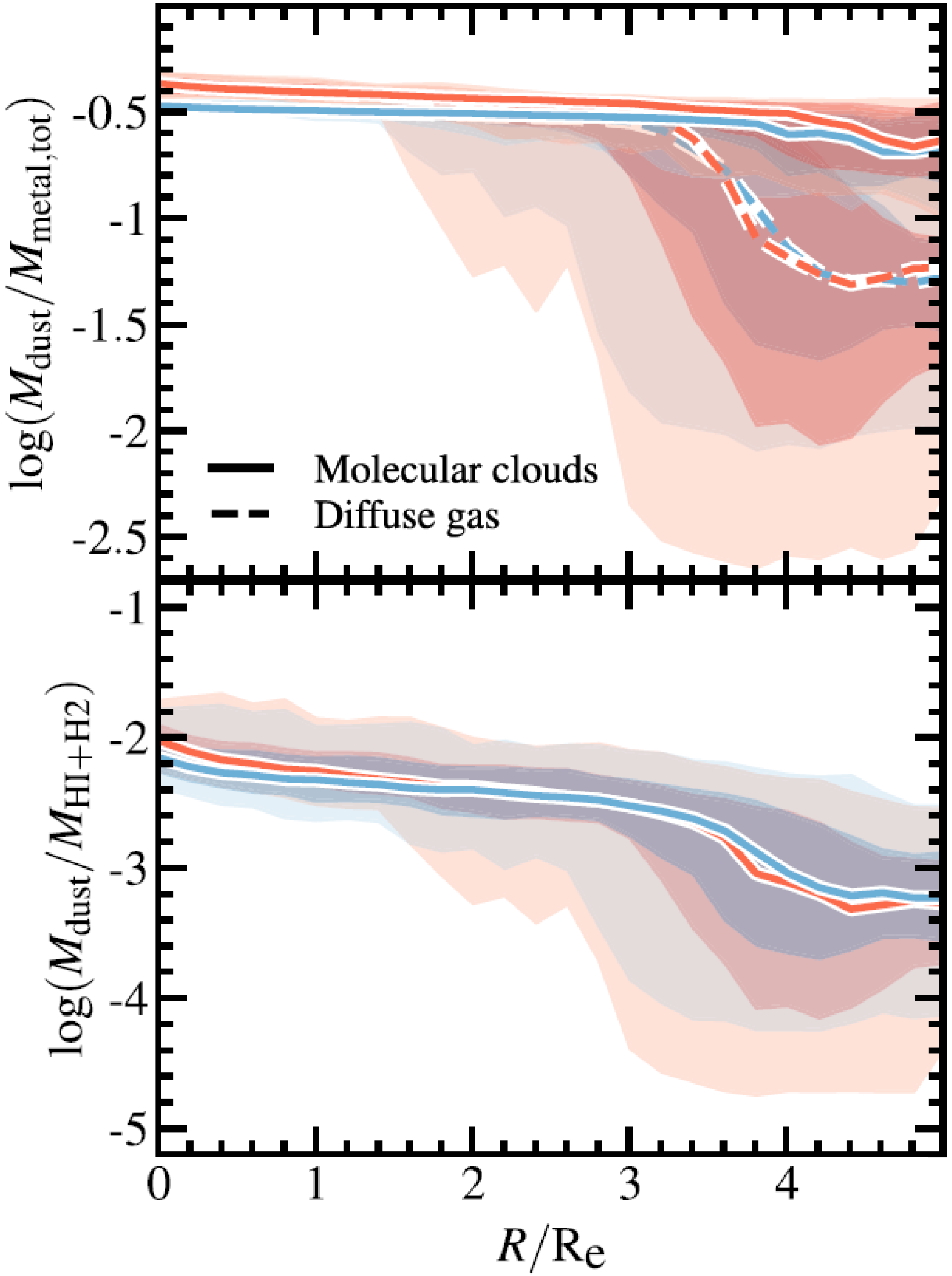
Buckley+ in prep.



Canete+23

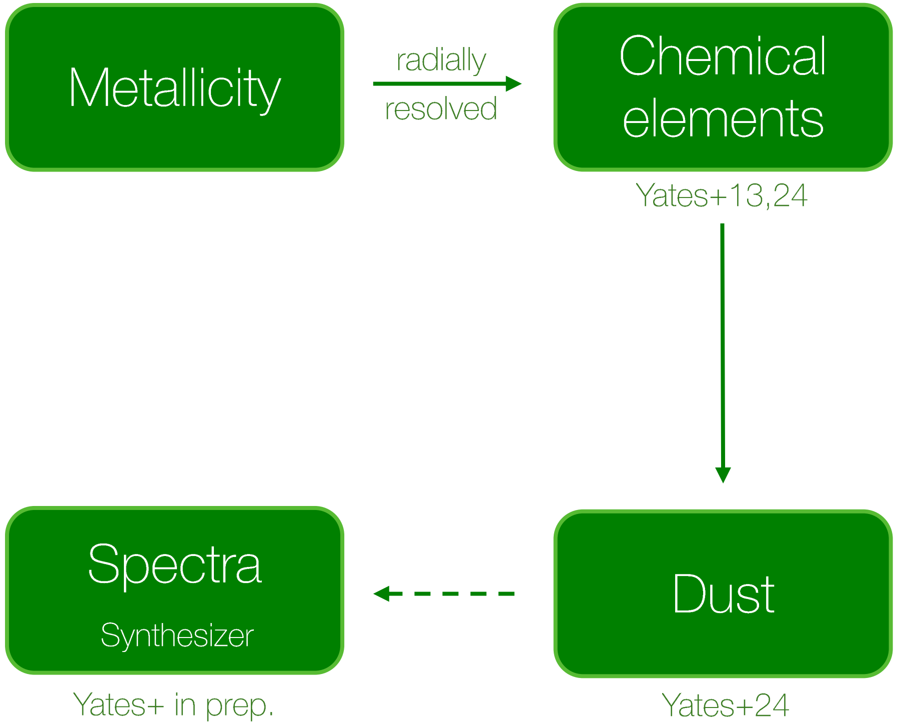
L-Galaxies: next gen GCE modelling

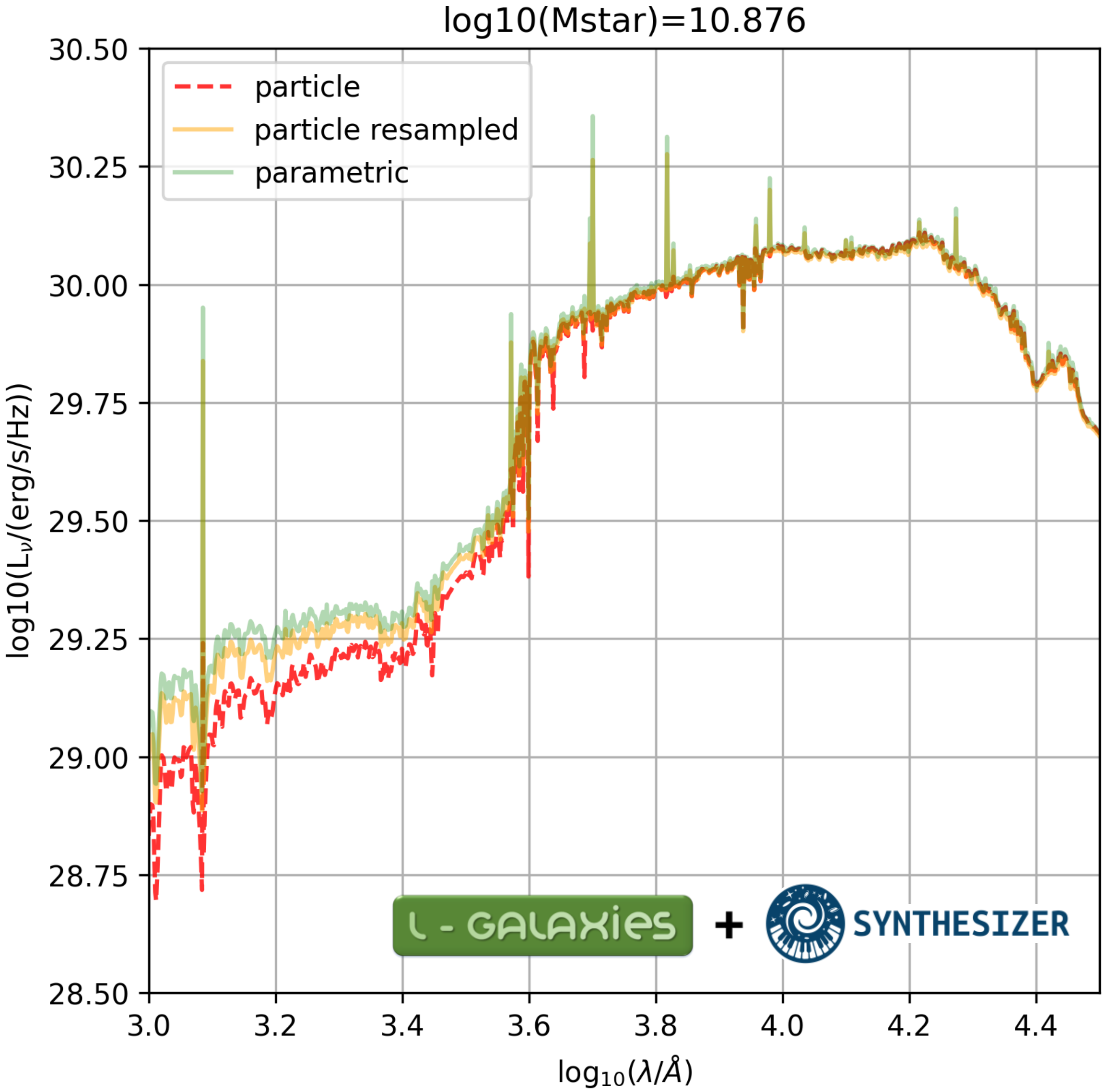




Yates+24

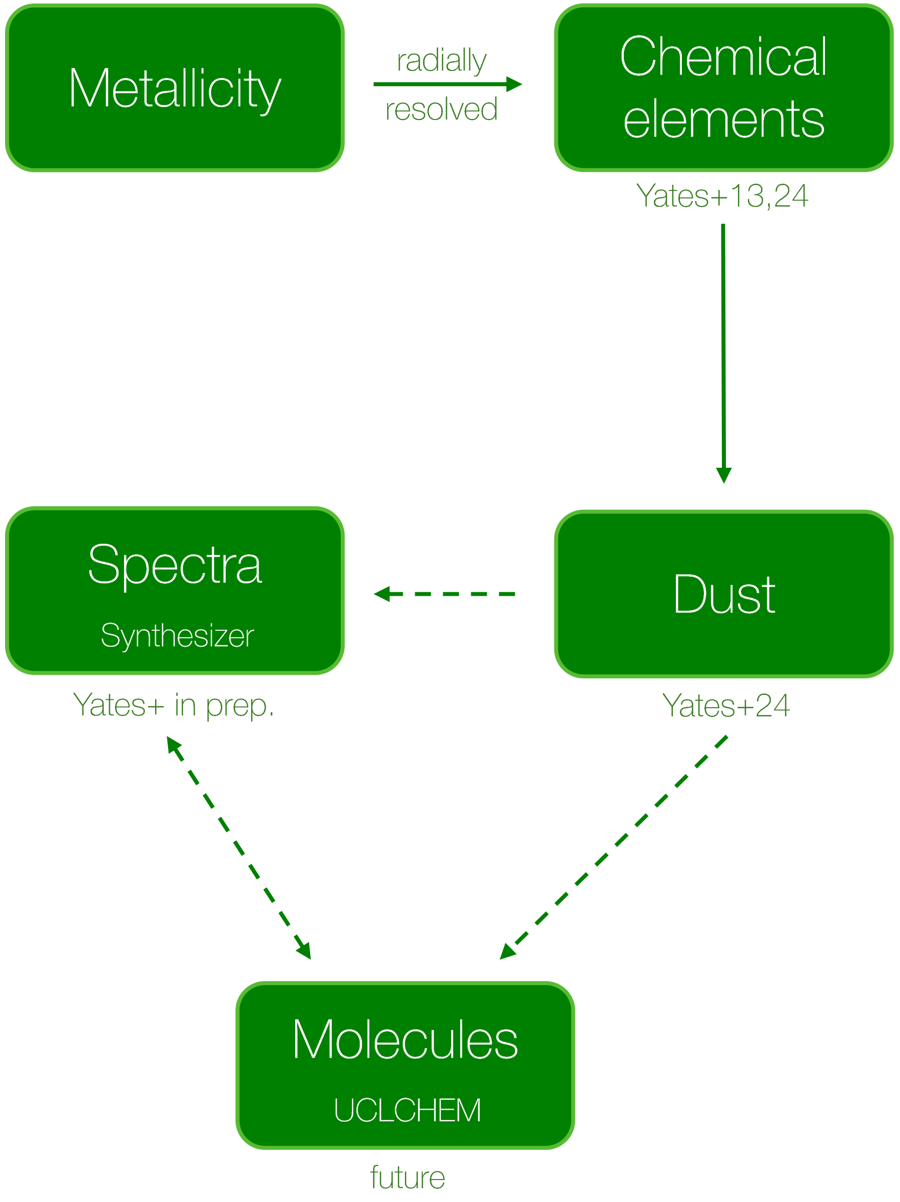
L-Galaxies: next gen GCE modelling

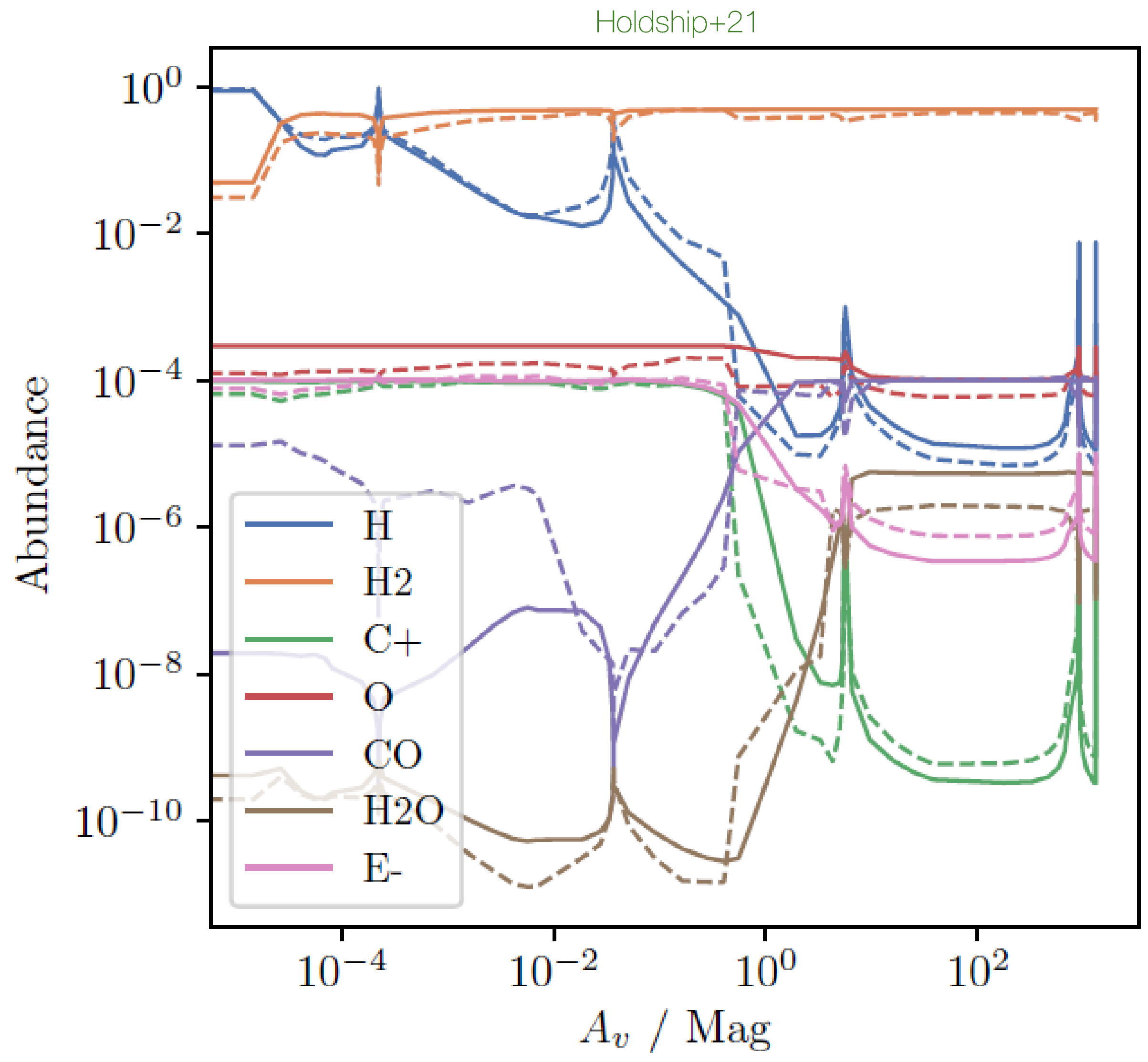




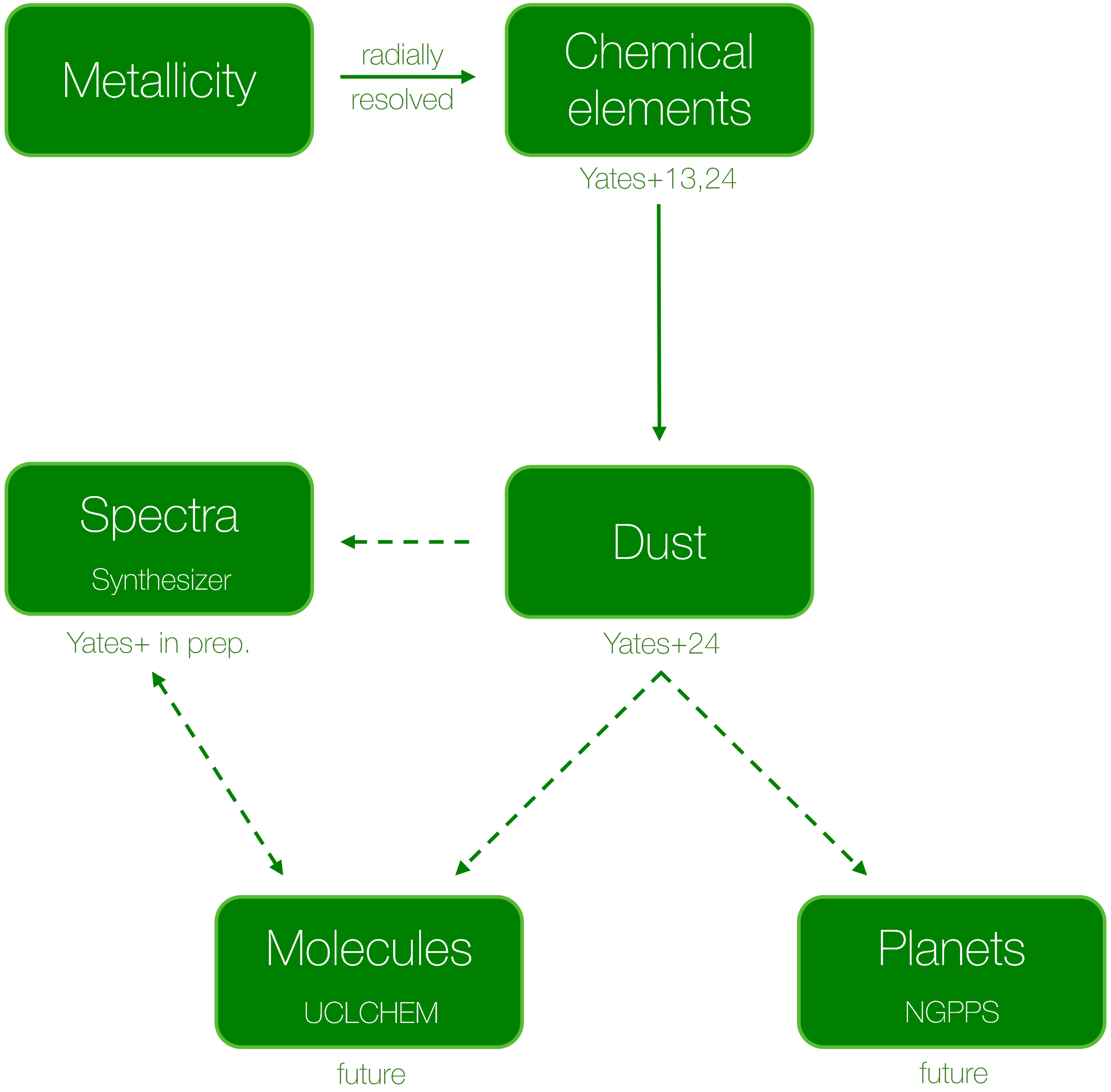
Yates+ in prep.

L-Galaxies: next gen GCE modelling

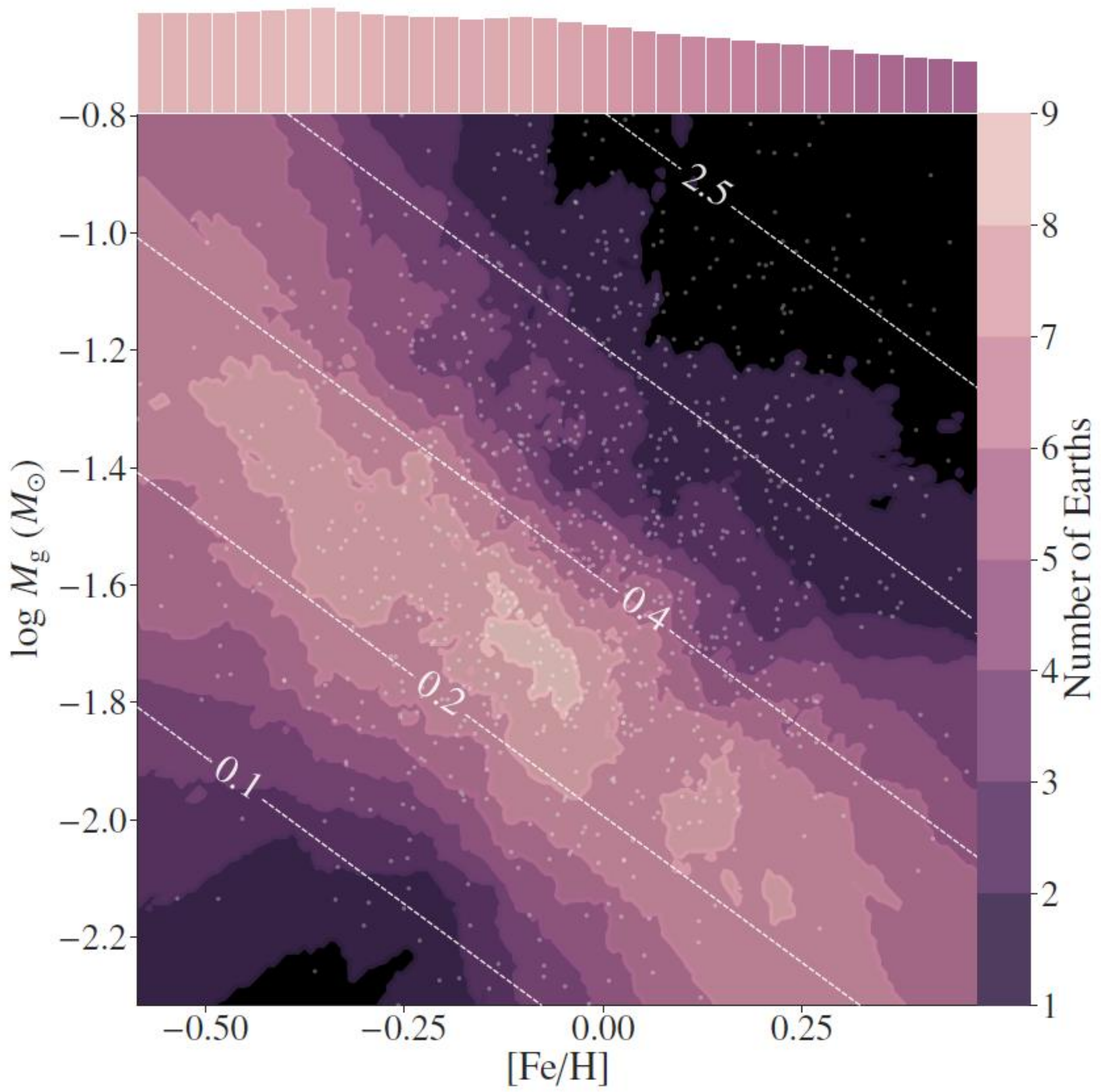




L-Galaxies: next gen GCE modelling



Boettner+24a,b



Summary

- Previous **empirical, semi-analytic, and hydrodynamical simulations** have revealed the **thick disc, stellar halo, and dwarf galaxies** as potential low-metallicity cradles of life, with further low-metallicity planet formation perhaps under-estimated

- However, these previous works assumed only (a) **total metallicities**, (b) **instantaneous enrichment**, and (c) **either low resolution or small sample sizes**

- L - GALAXIES is an efficient semi-analytic simulation which includes (a) **delayed enrichment** from **individual elements (and isotopes)**, (b) **radially resolved ISM**, and (c) **dust production & destruction**

- Next, we will add **synthetic spectra** and **molecule & planet formation emulators**, allowing us to predict GHZs within a wide range of galaxies (i.e. varied SFHs and metallicities) across all time and space