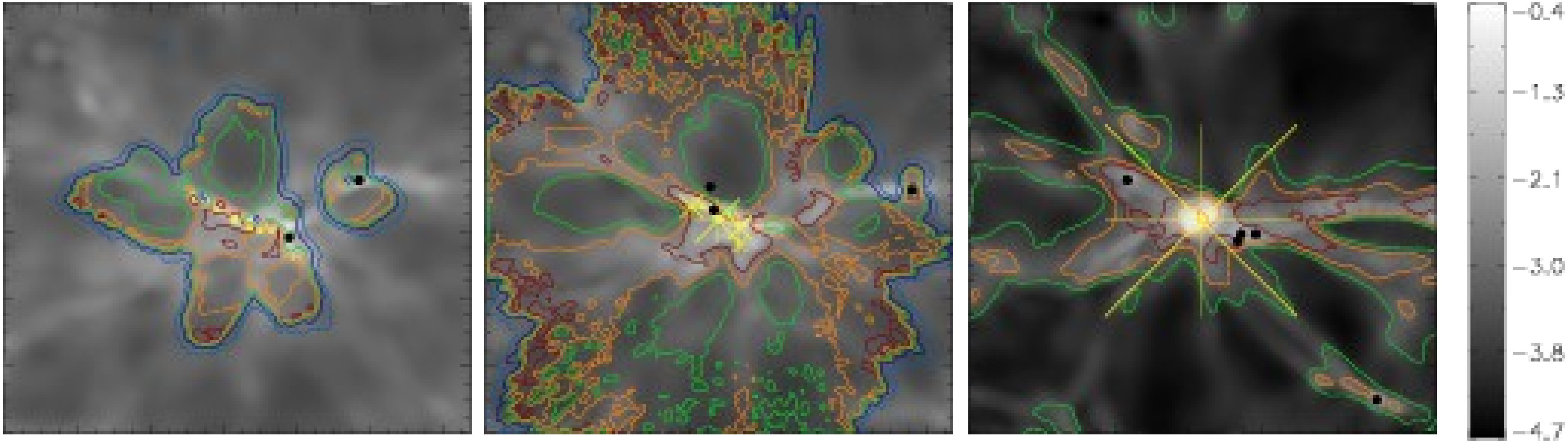


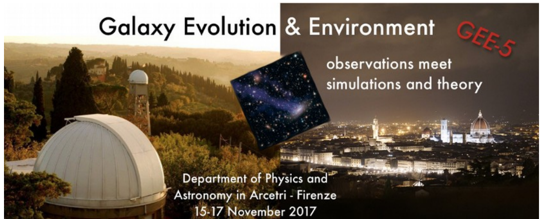
Star formation and Galaxy evolution as traced through cosmic env. and time

Luca Graziani

In collaboration with:

First@INAF, Italy: R. Schneider, M. Ginolfi, S. Marassi, R. Valiante, M. de Bennassuti
UniFI: S. Salvadori
MPA, Garching, Germany: B. Ciardi, M. Berge Eide, M. Glatzle.
UCL, London, UK: D. Kawata.

GEE5, November 15-17 2017, Firenze, Italy



Basic elements for Galaxy Formation (and evolution?)

The **diversity of galaxy populations: in Space and Time**

Morphology/Size:
spirals / ellipticals /dwarfs

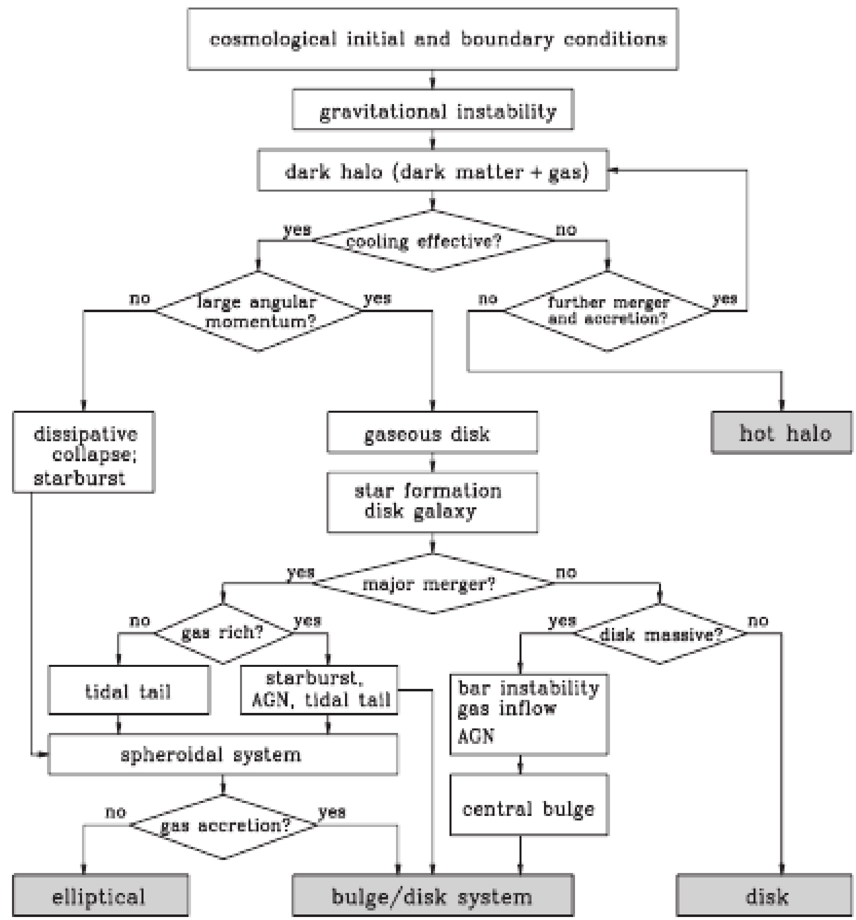
Luminosity and Stellar Mass:
L~ [10^{12} – 10^{3}] linked to M_* through stellar populations & RT

Mass of gas:
cold/hot phase → Models for Disk/Halo

Color:
Models for Stellar Populations
cold/diffuse ISM → RT through dust

Environment/Feedback:
Dynamics / RT / Chemistry

Nuclear Activity:
AGN Feedback



Galaxy Formation and Evolution (Mo et al.)

Large DM Sims + SAM Modeling of galaxy formation and evolution

Dark matter haloes + physically motivated prescriptions in **SAM**, calibrated at z=0

Large DM volumes necessary for galaxy surveys (mp_{XXL} = 8.456×10^{9} M_{sun}) → DM haloes hosting M_{*} >1.5×10^{10} M_{sun}
(De Lucia et al. 2006)

Large scale: from 100h^{-1} cMpc up to 3h^{-1} Gpc

SAM modeling:

Galaxy evolution follows DM evolution: mergers / accretion / dynamical interactions

Hot halo → gas cooling → cold disk formation
↔ Disk instabilities

Star formation in disks: quiescent / Merger and instability induced starbursts

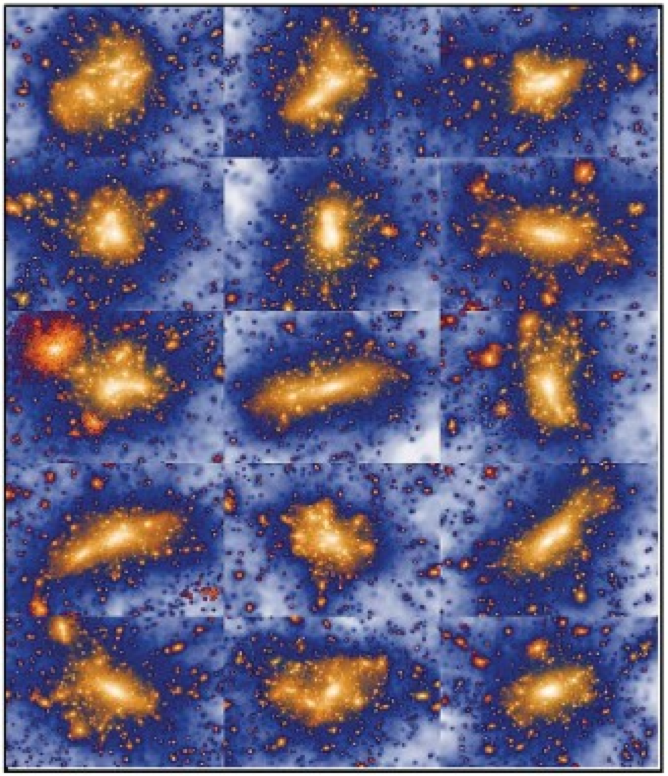
Supernova feedback and the production of metals

Supermassive black holes formation and feedback on star formation

Millenium II / Millenium / MXXL
(Springel 2005/Boylan-Kolchin 2009/ Angulo 2012)

Horizon Runs (Kim et al. 2011)

MultiDark-Galaxies (Knebe 2017)



Projected dark matter density for the 15 most massive MXXL Haloes
Each image is a region 6×3.7 h^{-1} Mpc wide
20 h^{-1} Mpc deep.

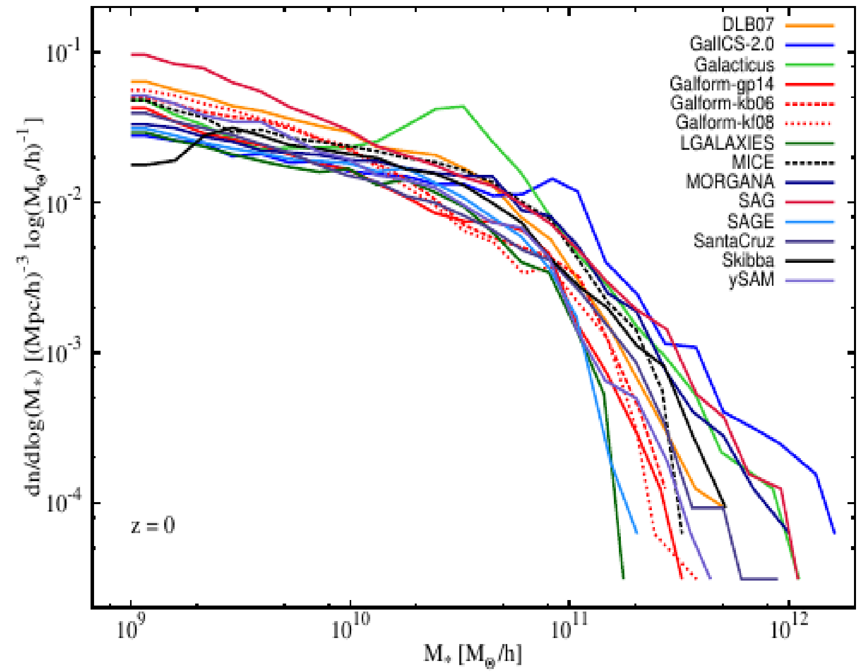
SAM Modeling of galaxy formation and evolution (nIFTy project)

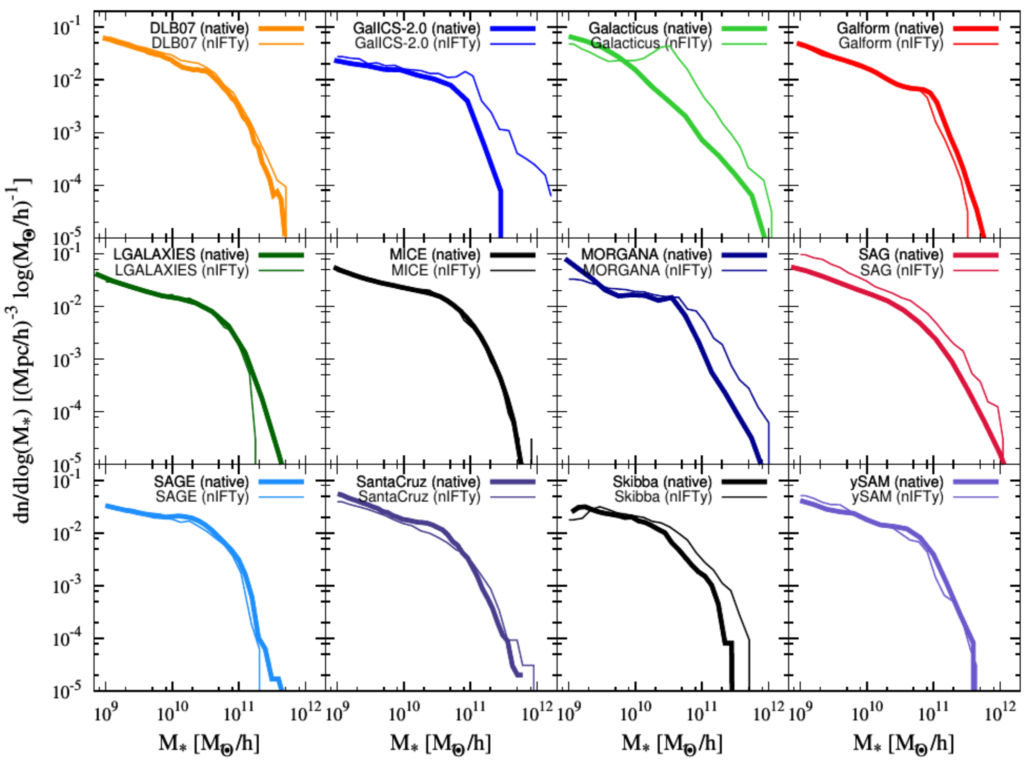
Key property: stellar mass function

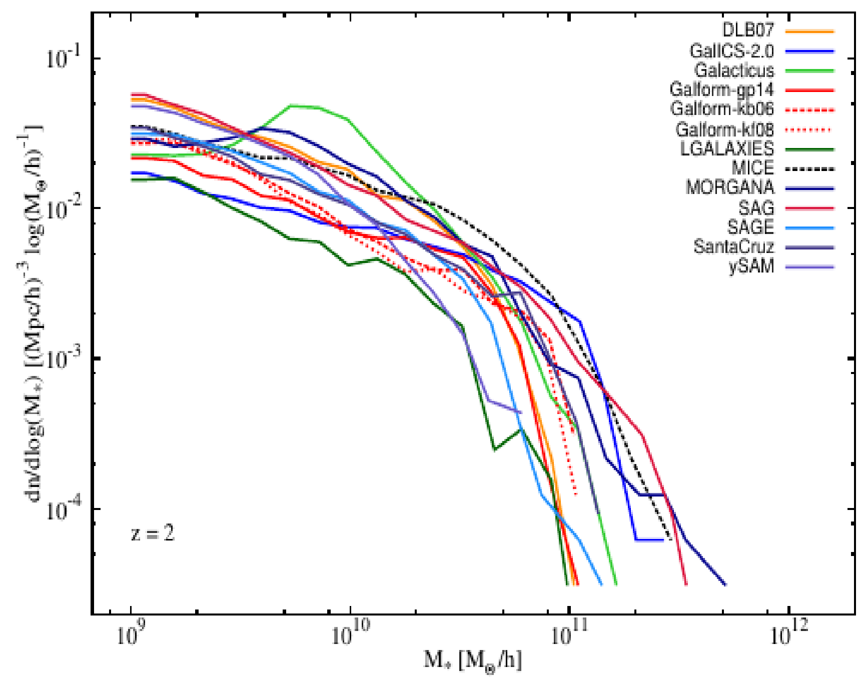
"Quite a range in both galaxy abundance and mass both at z = 0 (factor ~ 3) and larger at z = 2 → broad variation in the location of the peak in SFR"

Low sensitivity to halo mass defintion and IMF modeling

Models are sensitive to the specific DM model And require re-calibration







(Knebe et al. 2015, MNRAS)

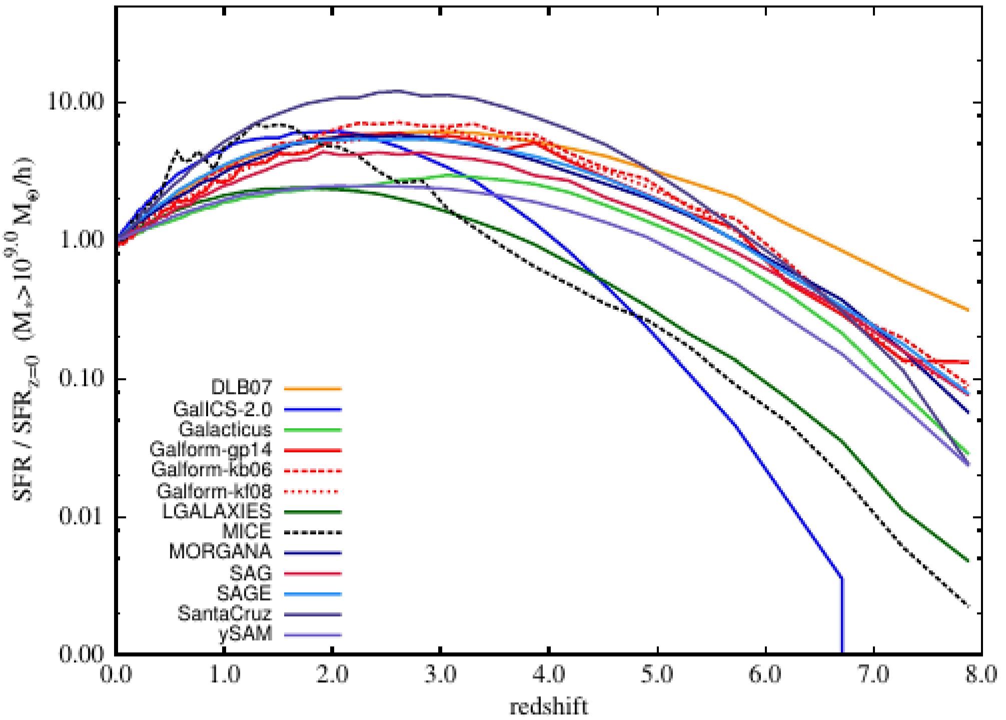
Large DM Sims +SAM Modeling of galaxy formation and evolution

Key property: SFR

The peak of star formation is z ~ 2 − 3 followed by a rapid decrease at late times (e.g.Madau & Dickinson 2014).

Differences in amplitude of an order of magnitude at redshift z > 6.

Great diversity in star formation rates across models irrespective of the stellar mass of the galaxy.



(Knebe et al. 2015, MNRAS)

All the curves normalized by SFR (z=0) to separate trends from absolute differences.

Parameter Tuning is by far the most decisive factor for the scatter (Henriques et al. 2009; Mutch et al. 2013).

Integrated properties can be statistically reproduced after tuning but other galaxy features require an **hydrodynamical approach**

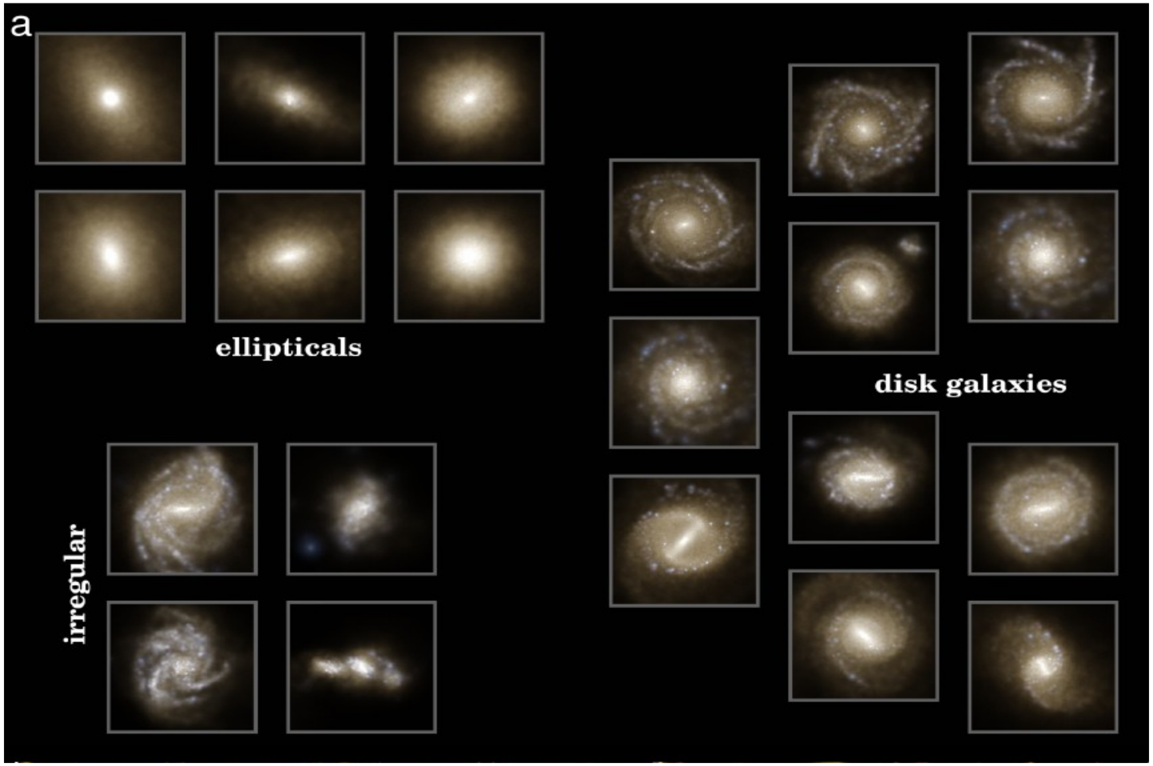
Large scale Hydrodynamical projects: the Illustris runs

Illustris/TNG Runs (Vogelsberger, 2014 / Springel 2017): Moving mesh → Arepo $0 < z < 20$

name	volume $[(\mathrm{Mpc})^3]$	DM particles / hydro cells / MC tracers	$\epsilon_{\mathrm{baryon}}/\epsilon_{\mathrm{DM}}$ [pc]	$m_{\mathrm{baryon}}/m_{\mathrm{DM}}$ $[10^5\,\mathrm{M}_\odot]$	$r_{\mathrm{cell}}^{\mathrm{min}}$ [pc]	$m_{\mathrm{cell}}^{\mathrm{min}}$ $[10^5\,\mathrm{M}_\odot]$
Illustris-1	106.5^3	$3 \times 1,820^3 \cong 18.1 \times 10^9$	$710/1,420$	$12.6/62.6$	48	0.15
Illustris-2	106.5^3	$3 \times 910^3 \cong 2.3 \times 10^9$	$1,420/2,840$	$100.7/501.0$	98	1.3
Illustris-3	106.5^3	$3 \times 455^3 \cong 0.3 \times 10^9$	$2,840/5,680$	$805.2/4008.2$	273	15.3

SUBGRID PHYSICS:

- Radiative (UVB+Cloudy)
- H-Reionization: UVB on instant.
- Stochastic star formation
- Cold phase not modeled consistently
- Feedback from SN Ia / II / AGB
- Feedback from star formation: Kinetic wind feedback
- Black holes and feedback from AGN → SF quencing by stochastic thermal feedback
- Magnetic field (TNG)
- Calibrated to reproduce mean stellar mass and halo mass from abundance matching



A variety of galaxy types in the Illustris ref. Run

Large scale Hydrodynamical projects: the EAGLE runs

EAGLE Run (Schaye 2015): SPH → Gadget-3

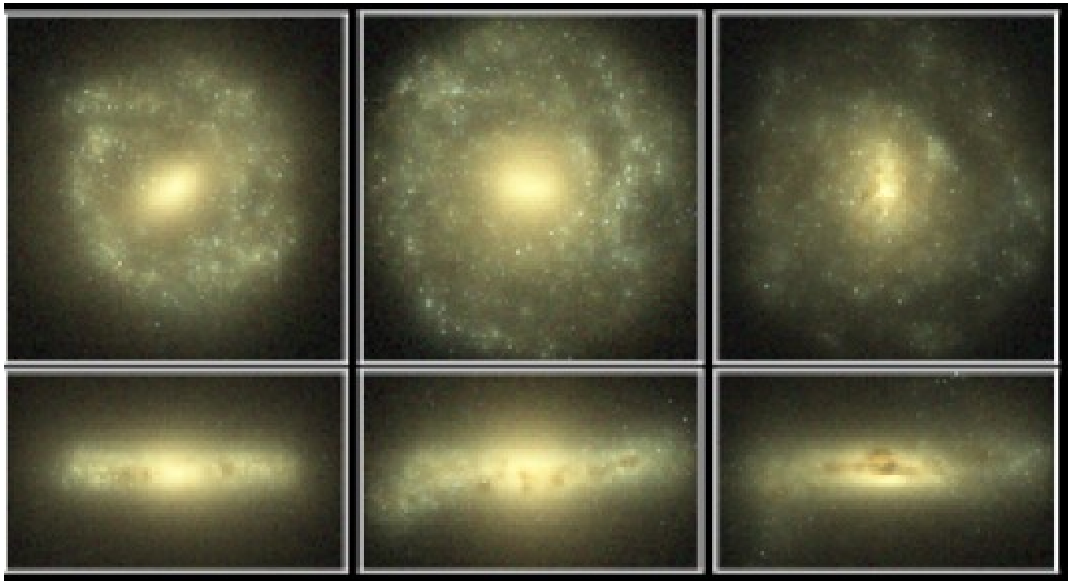
$0 < z < 20$

The resolution suffices to marginally resolve the Jeans scales in the warm ISM.

Name	L (cMpc)	N	m_g ($M_\odot$)	m_{dm} ($M_\odot$)	ϵ_{com} (comoving kpc)	ϵ_{prop} (pkpc)
L025N0376	25	376^3	1.81×10^6	9.70×10^6	2.66	0.70
L025N0752	25	752^3	2.26×10^5	1.21×10^6	1.33	0.35
L050N0752	50	752^3	1.81×10^6	9.70×10^6	2.66	0.70
L100N1504	100	1504^3	1.81×10^6	9.70×10^6	2.66	0.70

SUBGRID PHYSICS (OWL):

- Radiative cooling/Photoheating (UVB+Cloudy)
- H-Reionization: UVB on instant.
- Star formation: Z-dep threshold
- Cold phase not modeled consistently
- Stellar mass-loss and Type Ia supernovae
- Energy feedback from star formation: stochastic thermal feedback
- Black holes and feedback from AGN → SF quencing by stochastic thermal feedback
- Data calibrated at z~0 to match galaxy stellar mass function



Examples of galaxies simulated with the RT code SKIRT (Baes et al. 2011).

Other Large scale Hydrodynamical projects:

Blue Tides Simulation (SPH) (http://bluetides-project.org/) → largest hydrodynamic simulation
L = 400 Mpc/h down to z~8
(Croft, 2015)

Renaissance Simulations (AMR - ENZO) (http://galaxyportal.sdsc.edu/) → L=24.4h^{-1} cMpc,
down to z~6
Radiation Hydrodynamics + Metal enrichment
AMR Zoom-in → Stellar population transition/mini-halos
(Xu, 2016)

SPHINX simulations - the first billion years and reionisation (AMR-RAMSES): Cosmological radiation-hydrodynamical simulations of the first billion years of galaxy evolution in the Universe, capturing the interplay of hundreds of galaxies and resolving their inter-stellar medium down to scales of a few parsec. (Ongoing L~ 5-10 cMpc/h)

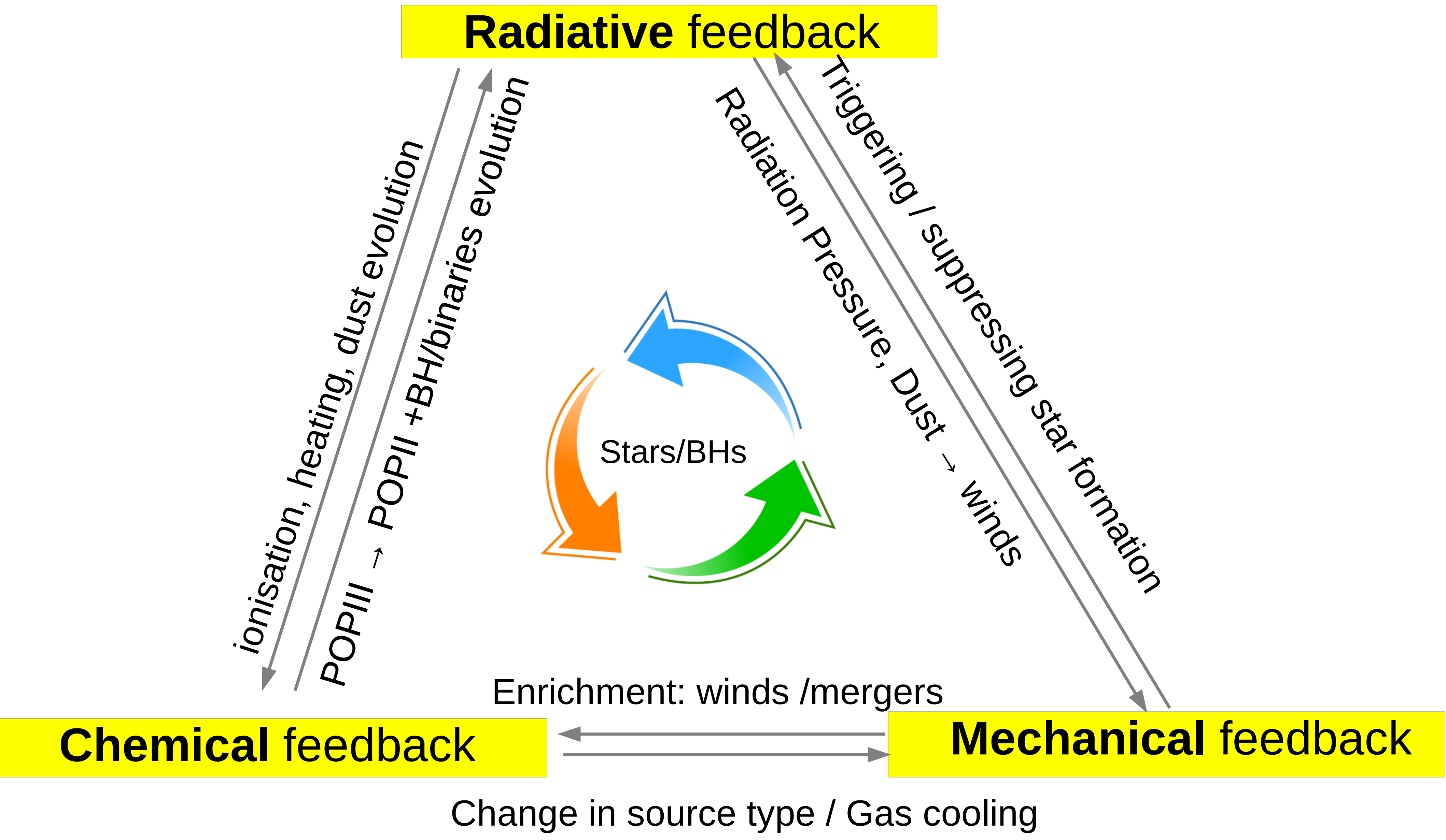
FIRE Project (GIZMO) (https://fire.northwestern.edu/about-fire/)

Combining spatial and temporal evolution with mass resolution in a flexible modeling remains difficult.

Accurate Feedback implementation remains the most challenging task.

Feedback in galaxy formation

(Ciardi, Ferrara, 2005; Bromm, V. & Yoshida, N., 2010)



Feedback

(Ciardi, Ferrara, 2005; Bromm, V. & Yoshida, N., 2010)

- Is highly **non-linear** and **poorly constrained** by observations
- Nature/role of **radiation sources** not clear / **chemistry** not fully understood (e.g. grain growth) / **wind** models still unconstrained
- Requires multi-scale numerical simulations but a common framework is missing

Tools @ ERC FIRST:

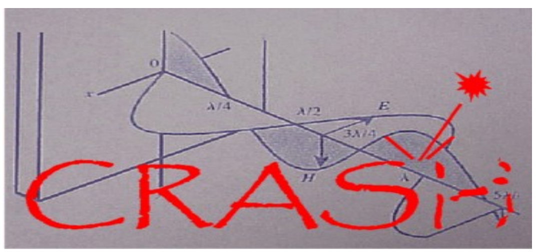
- Radiative → Chemical Feedback → **CRASH4**
- Star/galaxy formation → Mechanical Feedback → Chemical → **dustyGadget**
- Radiative + Chemical Feedback → Star formation → MW Reionisation → **GAMESH**

Feedback by first Stellar Populations: Radiative → Chemical

First Stars / First QSOs

↓

Radiative feedback



ionisation, heating, RT through dust

↓

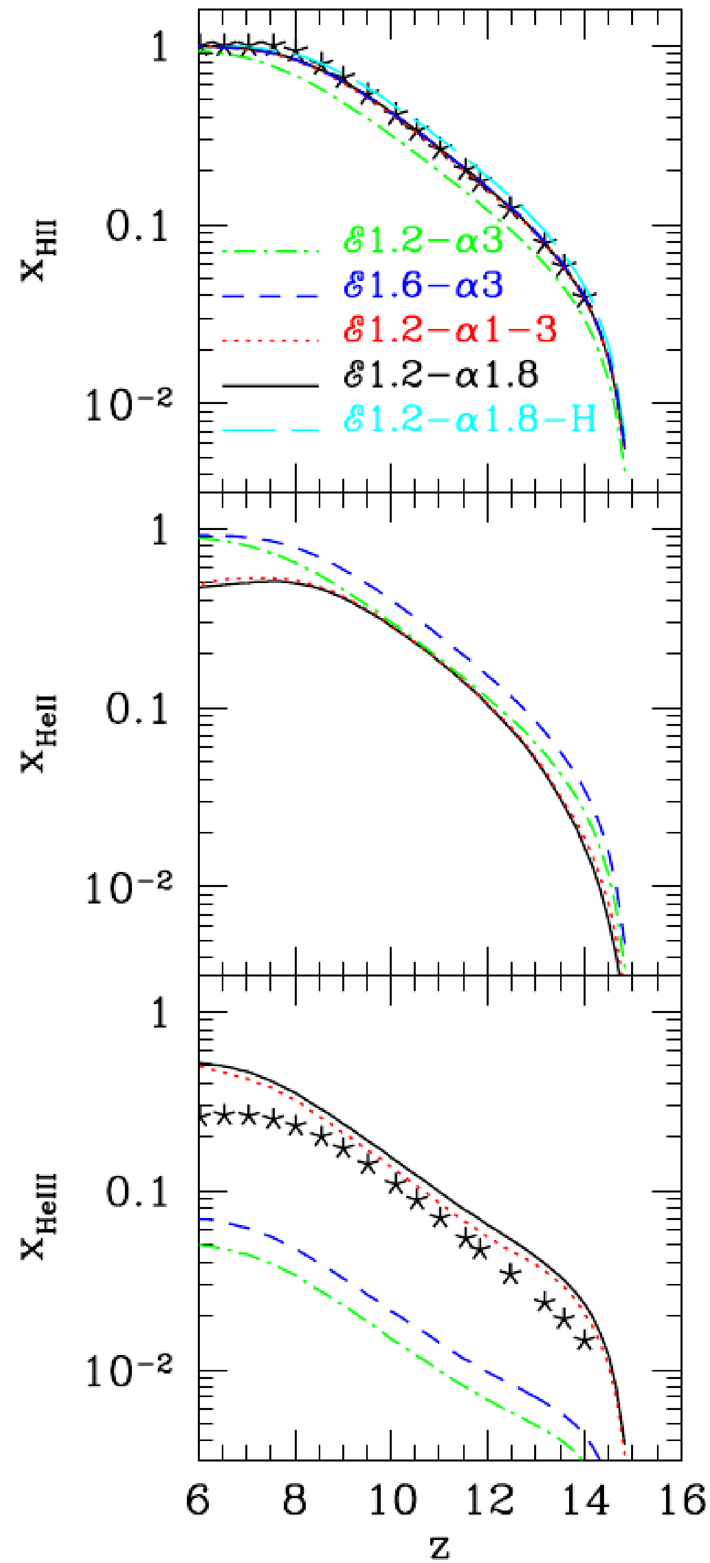
Chemical feedback

C.RA.S.H.

Monte Carlo 3D Radiative Transfer code

(H-ionising UV: 13.6 eV – 200 eV)

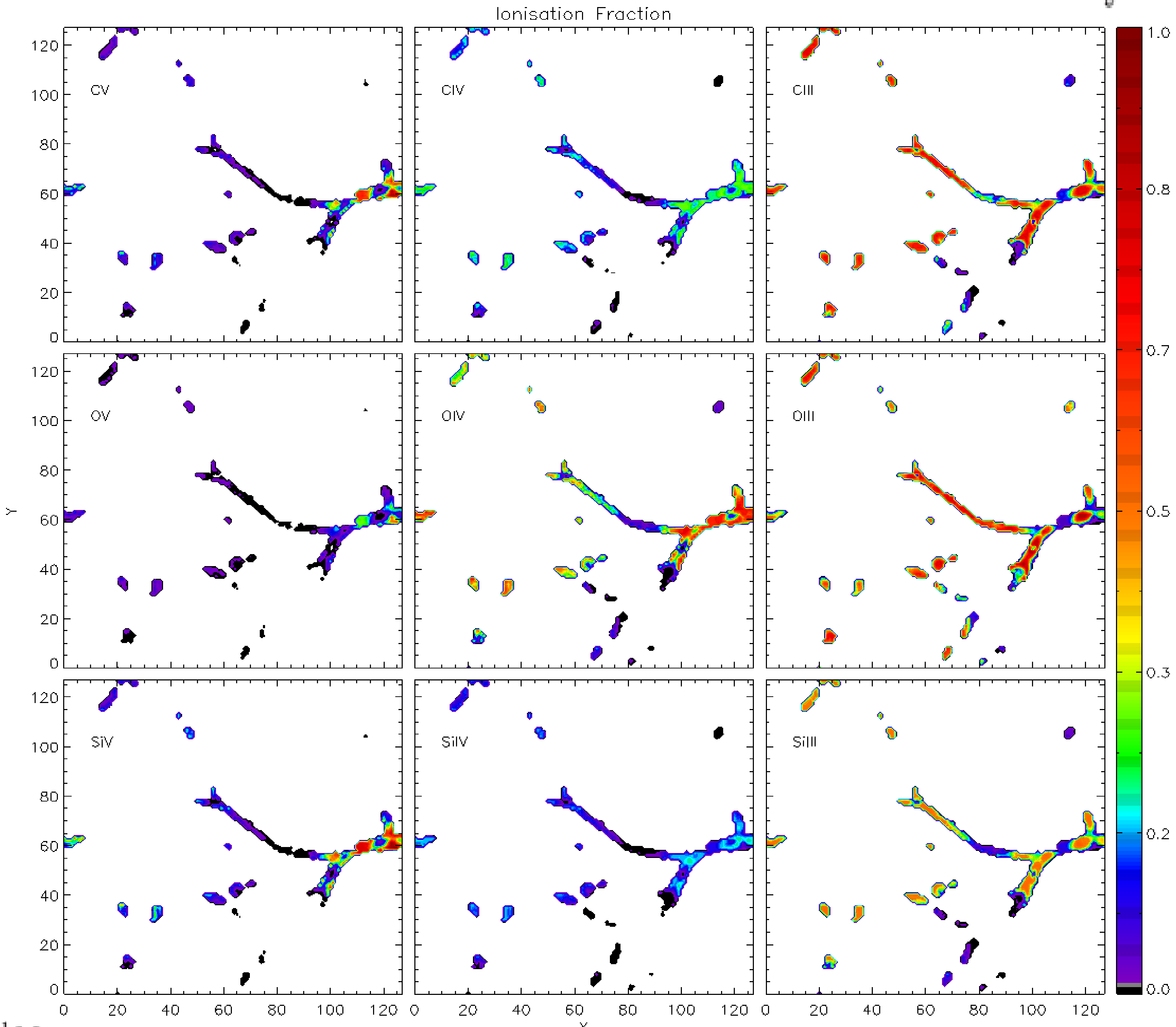
- Ionisation fractions of H, He, metals
- Gas temperature
- Radiation intensity / SED
- Ionisation and heating rates
- Reionisation history: x(z) ,T(z)



Ciardi, Bolton, Maselli & Graziani, MNRAS, 2012

Metal ions in cosmic web filaments

$Z_g = \Delta \times 0.0064 Z_{\odot}$



$L_b = 0.5\, h^{-1}$ Mpc

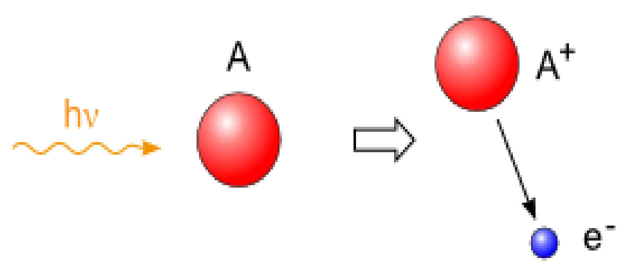
Graziani, Maselli, Ciardi MNRAS, 2013

CRASH4

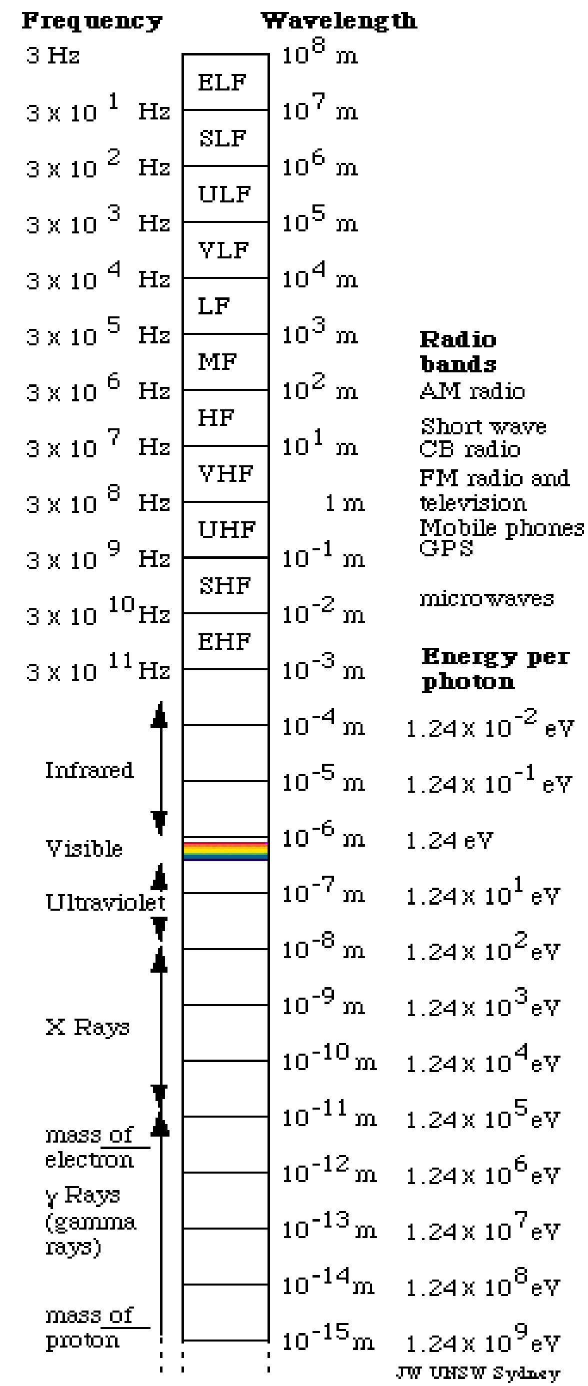
- **Multi-frequency band RT**:
  - → Extend up to soft x-rays: 10 KeV.
  - → Include Lyα RT coupled with continuum.
  - → LW band and molecules: H_2, CO.
  - → Dust → photon scattering **IS** relevant.

- Secondary ionisation

$$E_\gamma - I_A = E_e$$

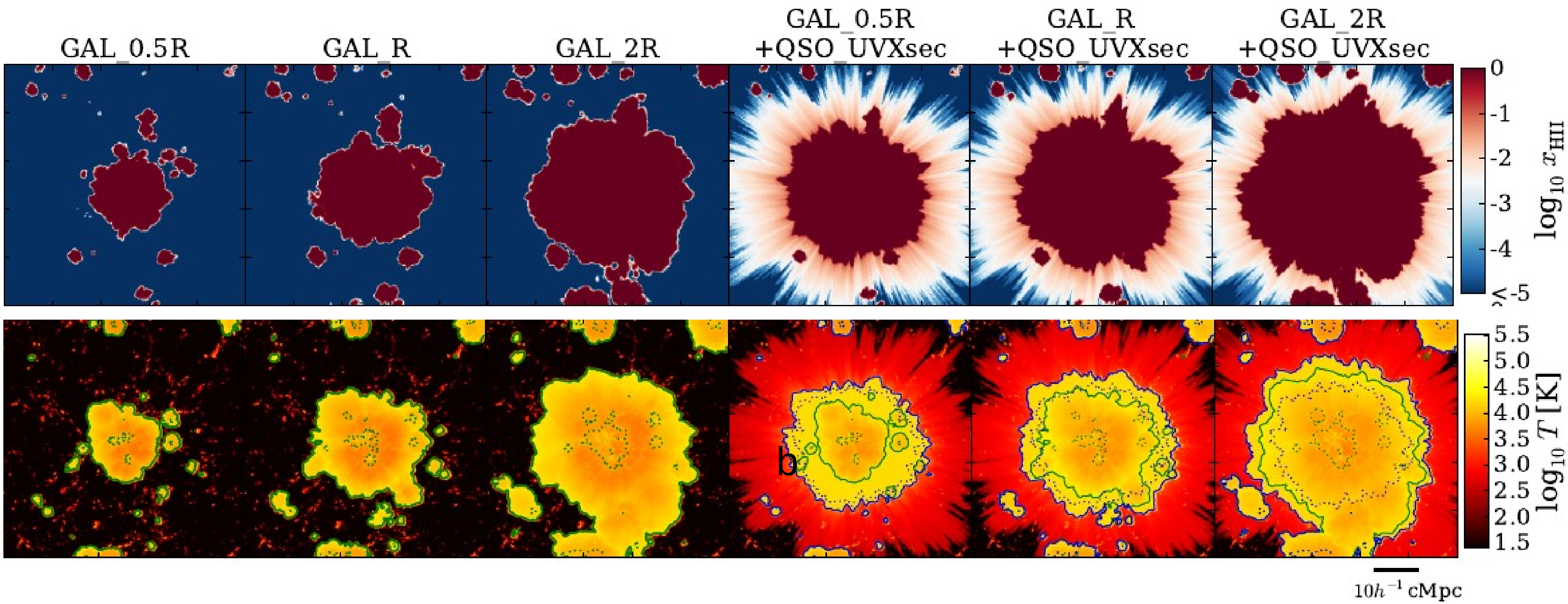


E_e > 30eV could collisionally **ionise/excite** the remaning neutral part.



Impact of Galaxies and QSOs-Small scale IGM

(Kakiichi, LG, et al.,2016, MNRAS, ArxiV: 1607.07744)



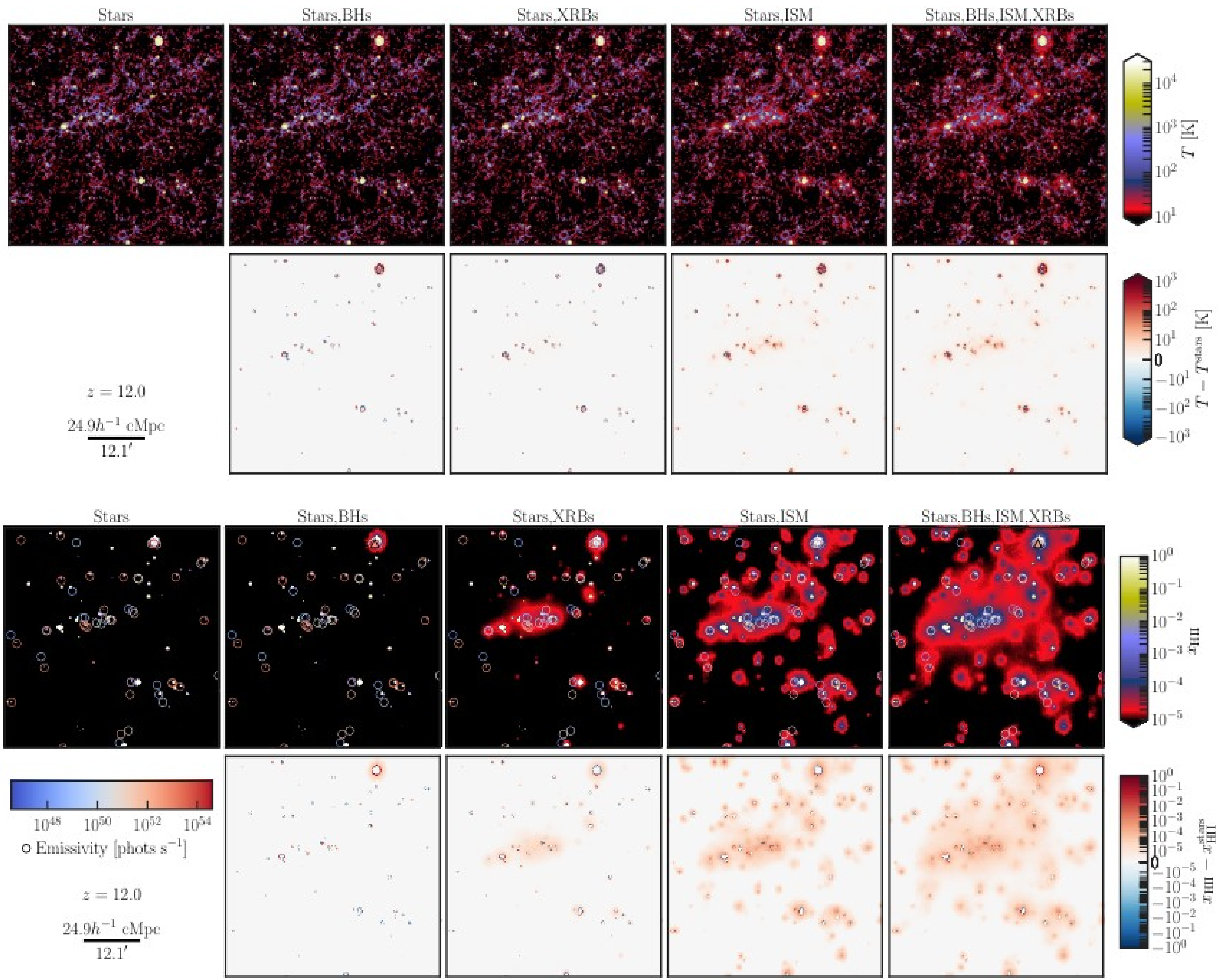
Effects of x-rays on HII regions of high-z QSOs on Global reionisation (z> 6).

→ How does the topology of ionised bubbles change?
→ What is the minimum scale to capture the statistics of bubble evolution?
→ Relative roles of stars/QSOs → Model stellar populations / QSO
→ IGM heating → Feedback on star formation in small galaxies
→ x-rays from binaries?? → Heating of the IGM at z > 10

(Iliev 2013, Madau 2017, Madau&Fragos 2016, Madau&Haardt 2015, Compostella 2014)

Epoch of Heating: effects of x-ray binaries

(M. Berge Eide, LG, et al., sub.)



Feedback along Galaxy formation:
Star formation ↔ Chemical+Radiative

Chemical feedback

GAMESH

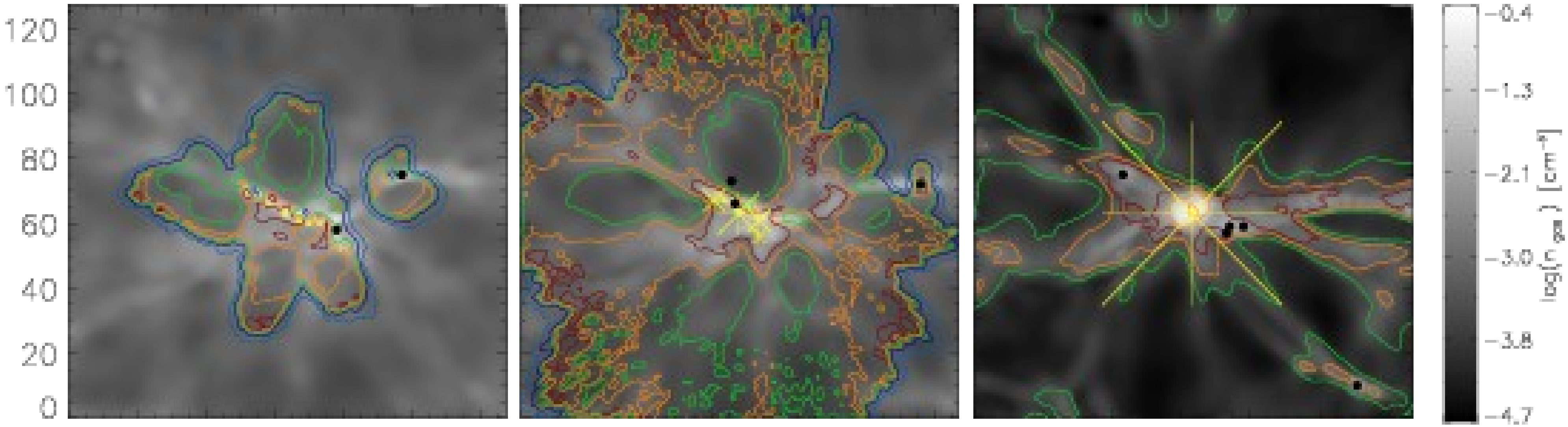
Atomic metals

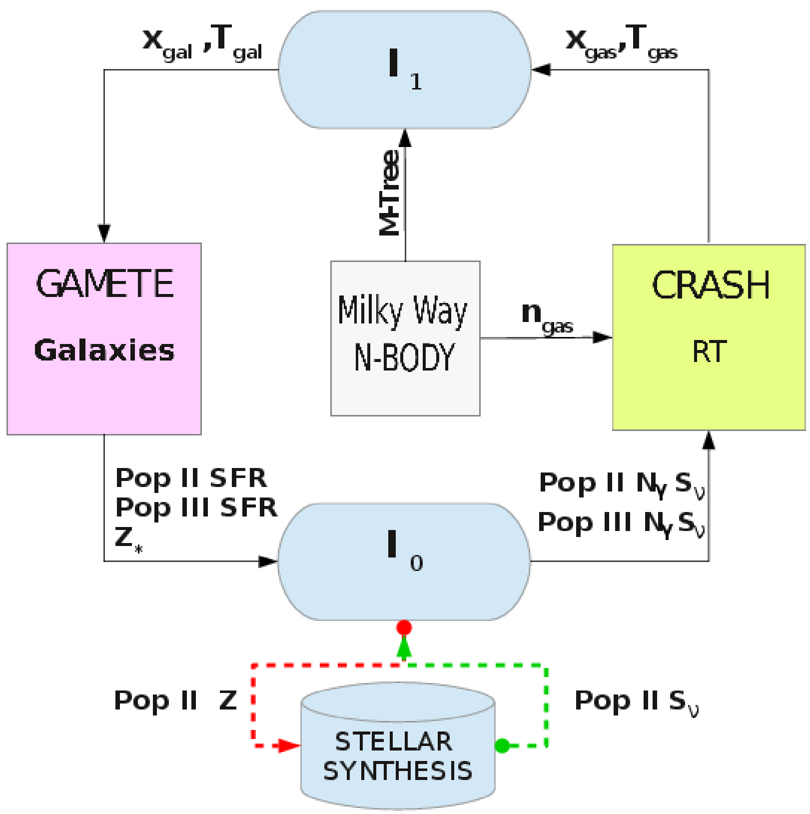
SF, Photo-heating feedback

Radiative Feedback

LG evolution: Dixon 2017, Ocvirk 2014, 2015, Sawala 2015, Salvadori 2007, 2010

GAMESH = GAMETE + CRASH + N-Body





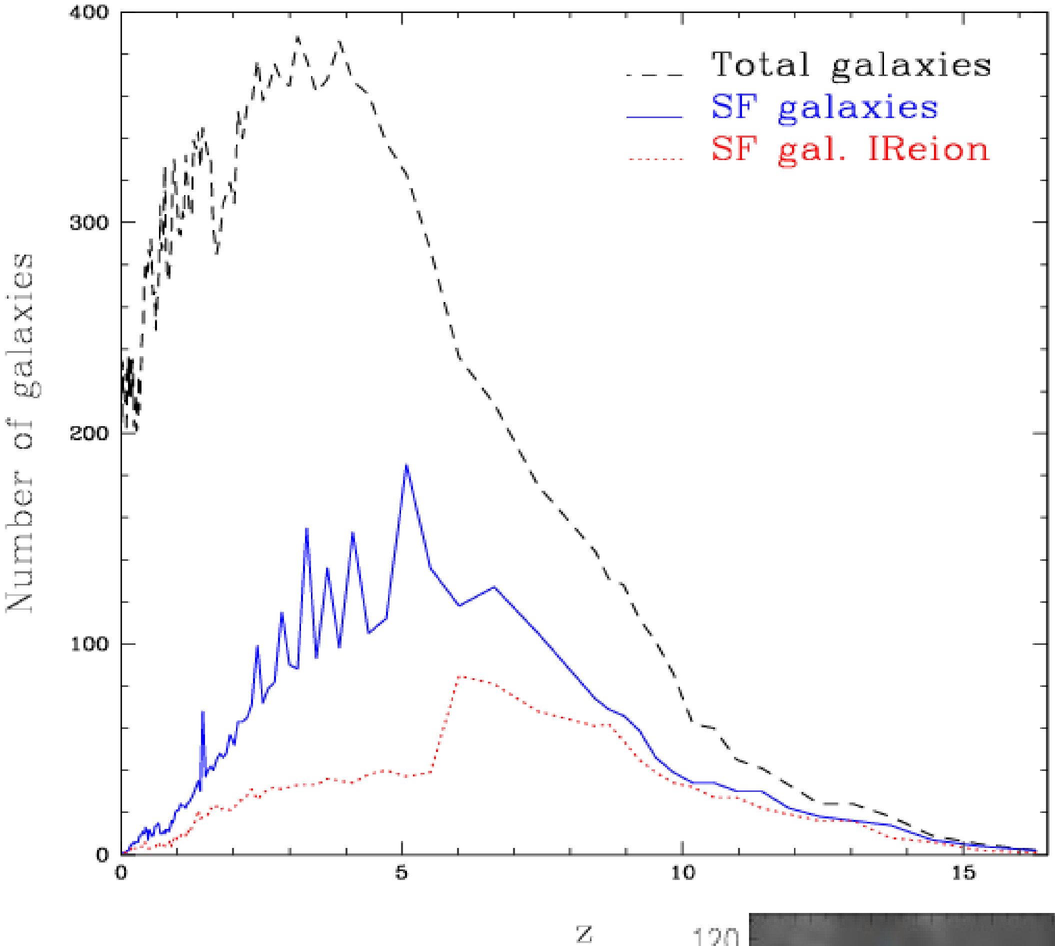
N-Body simulation: dynamical evolution of DM halos

GAMETE simulation: Star formation, metal production

CRASH simulation: RT, gas ionisation heating

Provides redshift evolution / mini halo resolution

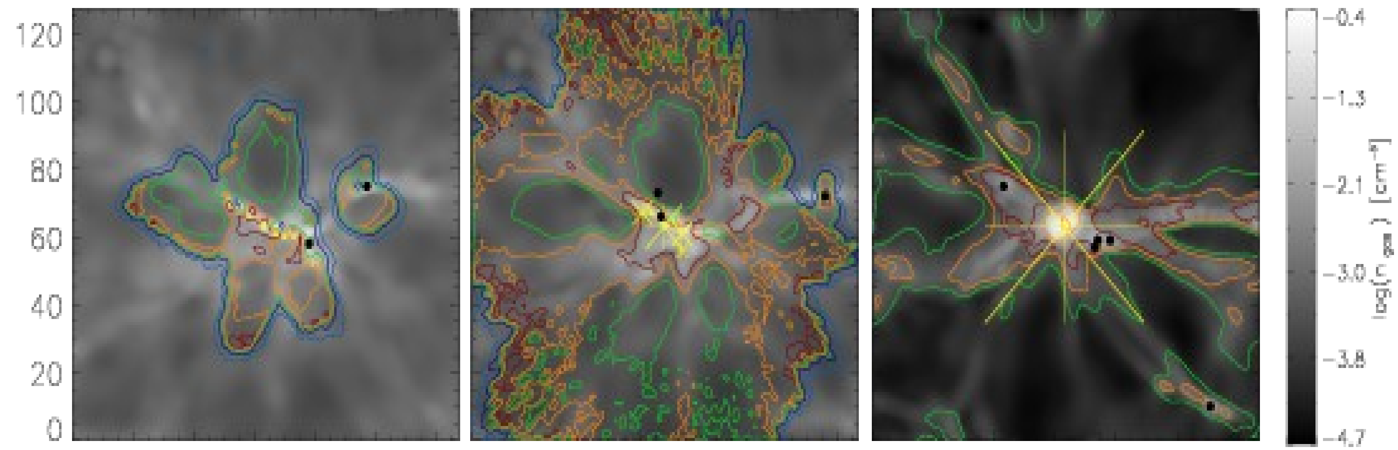
IGM reionisation changes the statistics of SF galaxies



Star formation statistics are very **sensitive to radiative environment.**

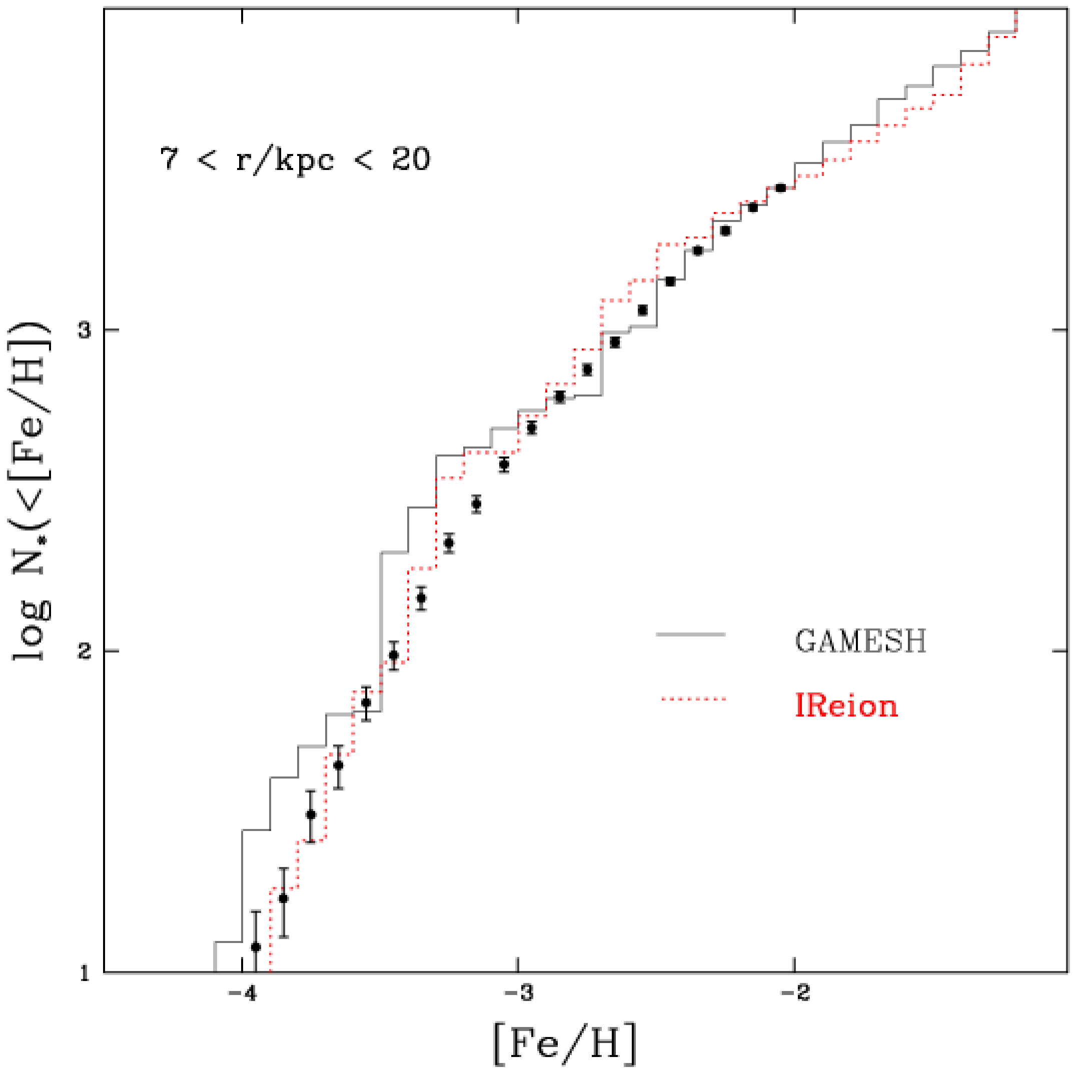
Reionisation is highly inhomogeneous

Galaxy environment changes in space and along the redshift evolution o the Local Group



z~12 z~9 z~6

Testable consequences: the MDF of the Milky Way at z=0



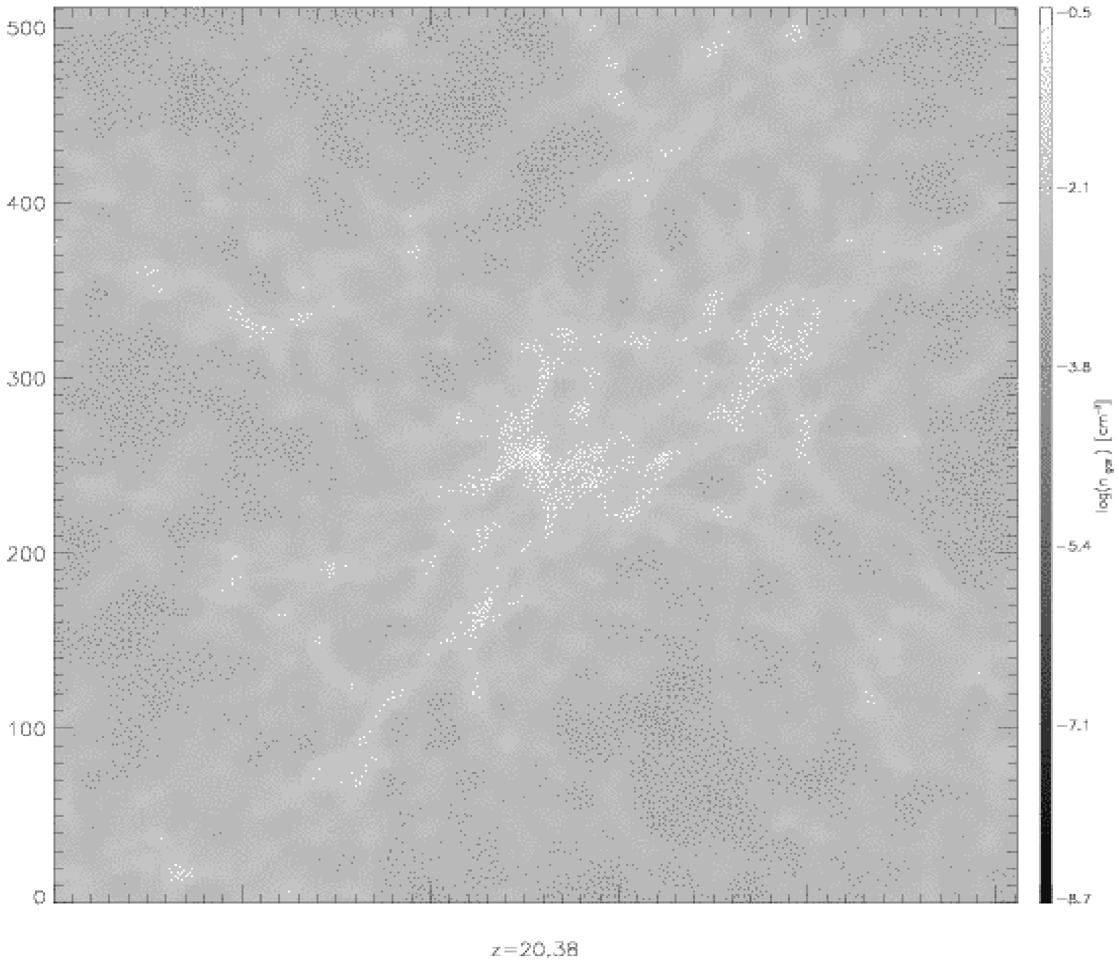
Low metallicity tail of the Milky Way MDF

Sensitive to reionisation.

Sensitive to metal enrichment.

IRA assumption should be removed → Stellar evolution plays a relevant role

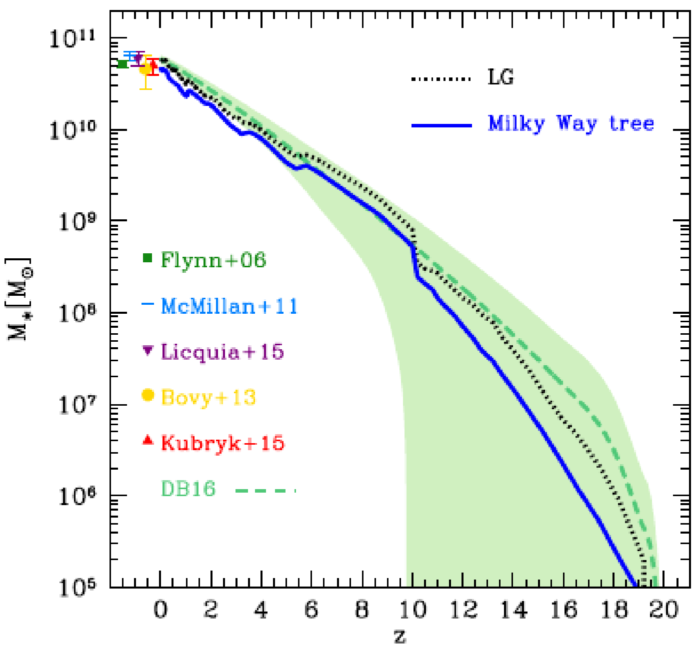
GAMESH → BARYONS in MW and MW progenitors

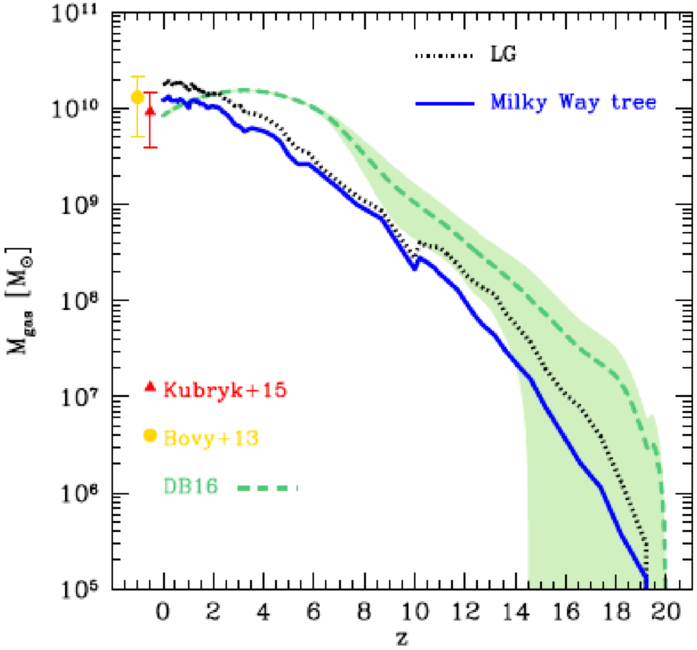


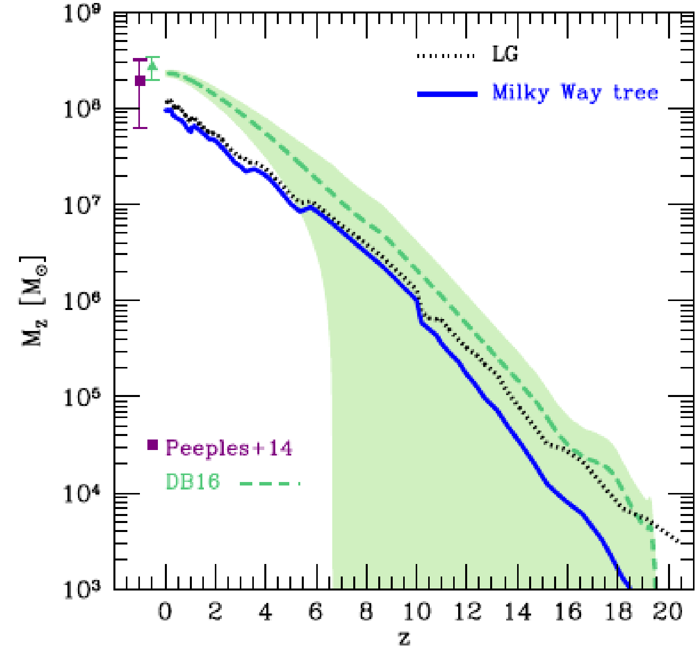
- Box side L: 8/4/1 cMpc
- M_p = 3.38 10^5 M_{sun}
- 0 < z < 20 → 155 snaps
- Grids: 513^3 cells
- 3 levels: 8 → coarse
  4 → fine (halo LG)
  1 → zoom-in
- Planck Cosmology
- FoF → max 13000 halos / 100 particles/halo
- Full particle based MergerTree ancestors/descendant
- Lya /mini-halos classified: T_{vir} = 2d4 K
- Central MW-like halo M=1.7d12M_{sun}
- Accretion history ← accretion from IGM

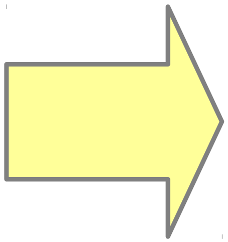
- MW-like halo fine in DM properties: M, T, V_c, c
- 4 cMpc, well resolved volume → LG
- Satellite statistics good!
- M31 position → wrong! Outside the LG!, M32, M33, LMC like halos present but in arbitrary positions

GAMESH → BARYONS in MW and MW progenitors

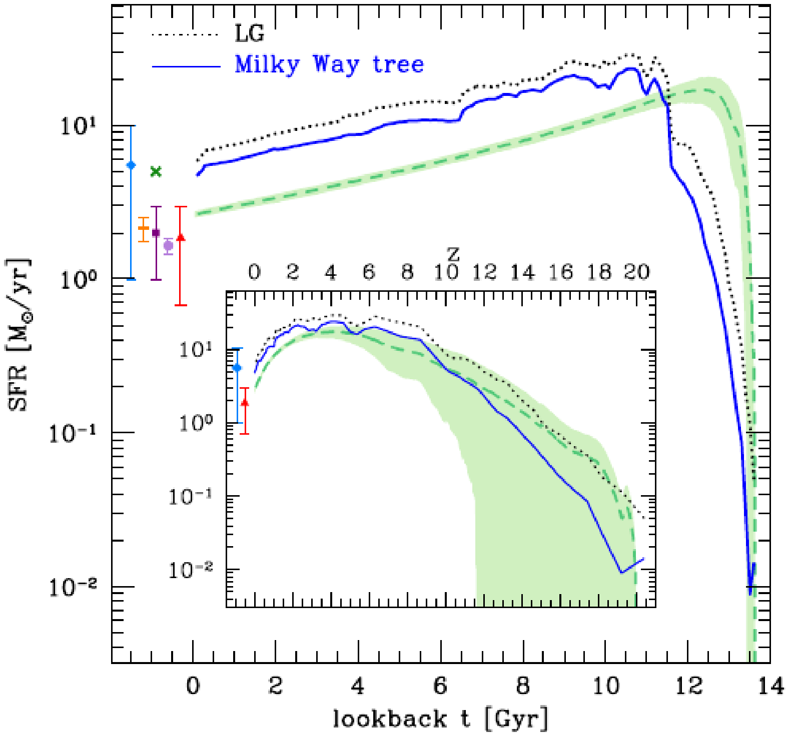






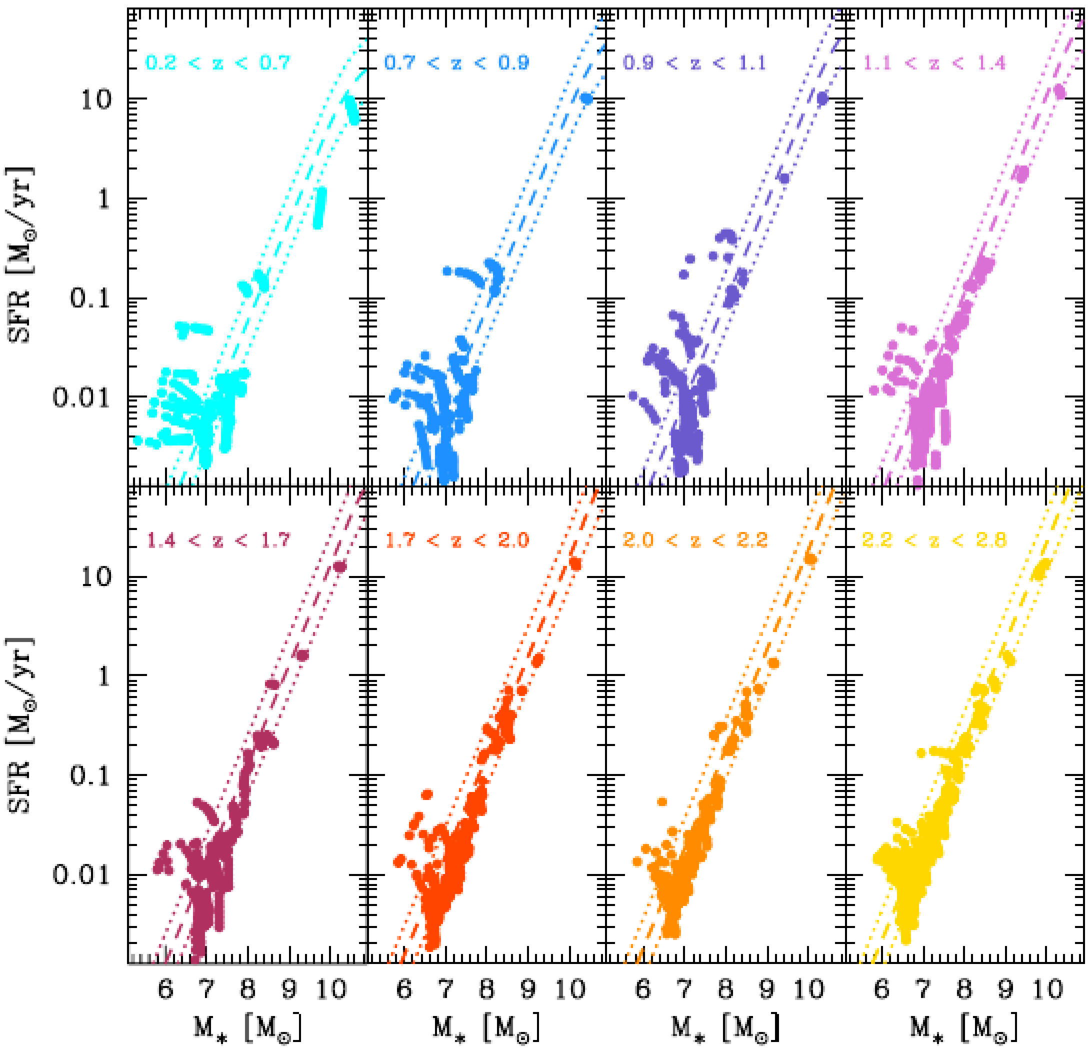


- MW-like halo fine in Baryonic props :
  M_{gas}, M_*, M_Z, SFR → OK
- SF efficiency 9%



Graziani, de Bennassuti, Schneider et al., MNRAS, 2017

GAMESH2 → BARYONS in MW and MW progenitors



Main Sequence → OK

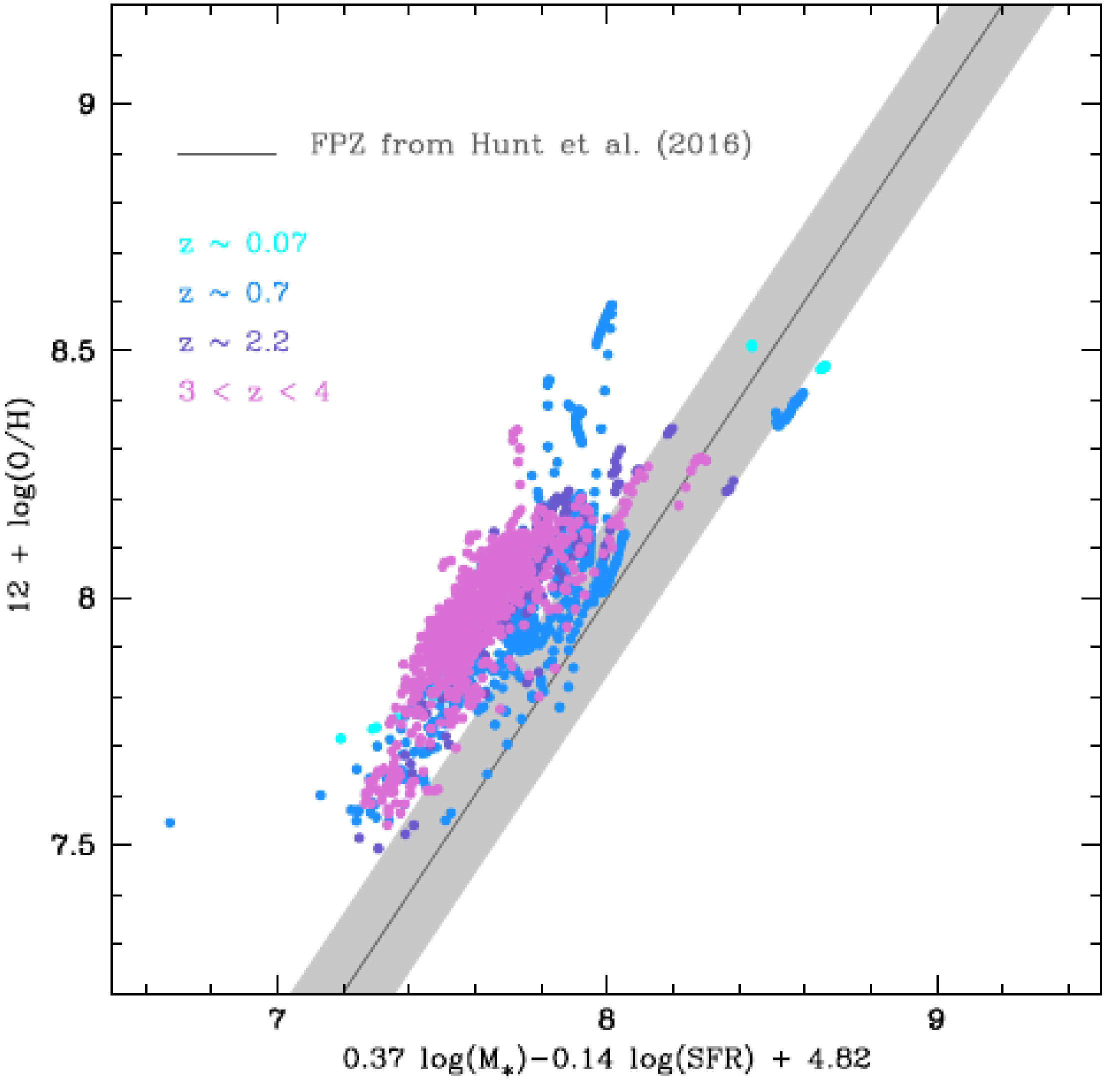
Along different z !

Small objects → dispersion

→ FEEDBACK!

Graziani, de Bennassuti, Schneider et al., MNRAS, 2017

GAMESH → BARYONS in MW and MW progenitors



Distribution of the MW progenitors relative to the fundamental plane of metallicity (Hunt et al. 2016a)

This scaling relation is believed to originate from the interplay between gas accretion, star formation and SN-driven outflows

The description of these physical processes obtained by GAMESH leads to results consistent with observations.

Graziani, de Bennassuti, Schneider et al., MNRAS, 2017

CONCLUSIONS: Feedback and star formation

- Radiative/Chemical feedback in Galaxy formation can be studied with multi-frequency RT codes:

  → Effects on successive star formation

  → Effects on IGM / ISM metal ions (Large scale env.).

  → Coupled with chemical feedback

  (GAMESH) can make predictions on:

  MDF / Chemical enrichment / SF history

- Chemical Feedback now accounts for dust production and evolution self-consistely incorporated into chemo-dynamical simulations of galaxy formation (dustyGadget)
- Coupling Chemistry + Hydro with RT → next step for consistent feedback from / to star formation!