Modeling dwarf galaxies : a critical stepping stone towards understanding the Epoch of Reionization

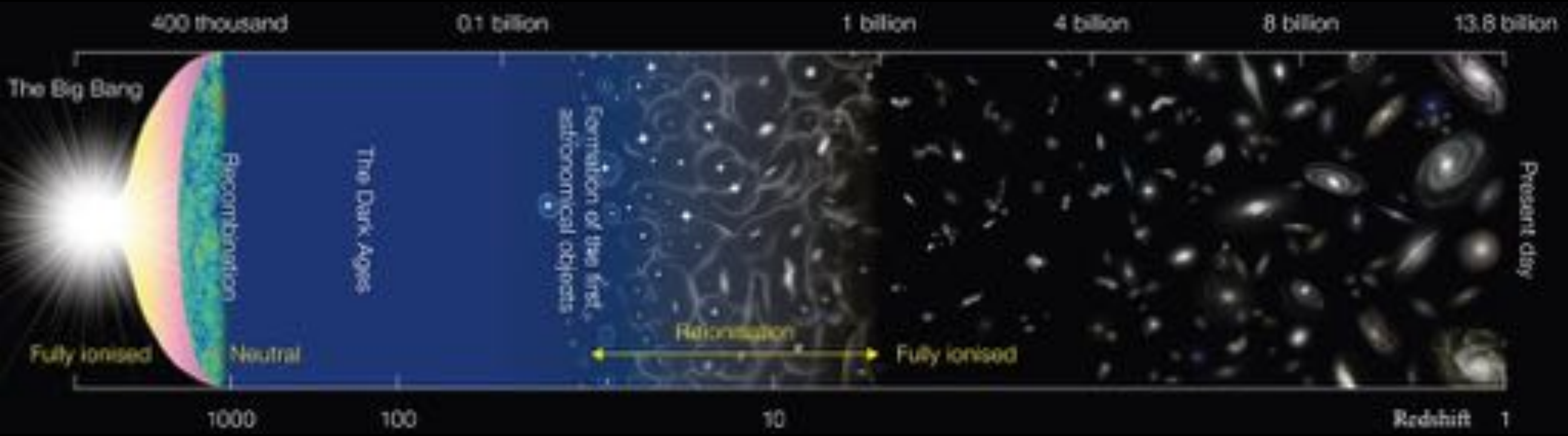
Yves Revaz

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EPFL - LABORATOIRE D'ASTROPHYSIQUE

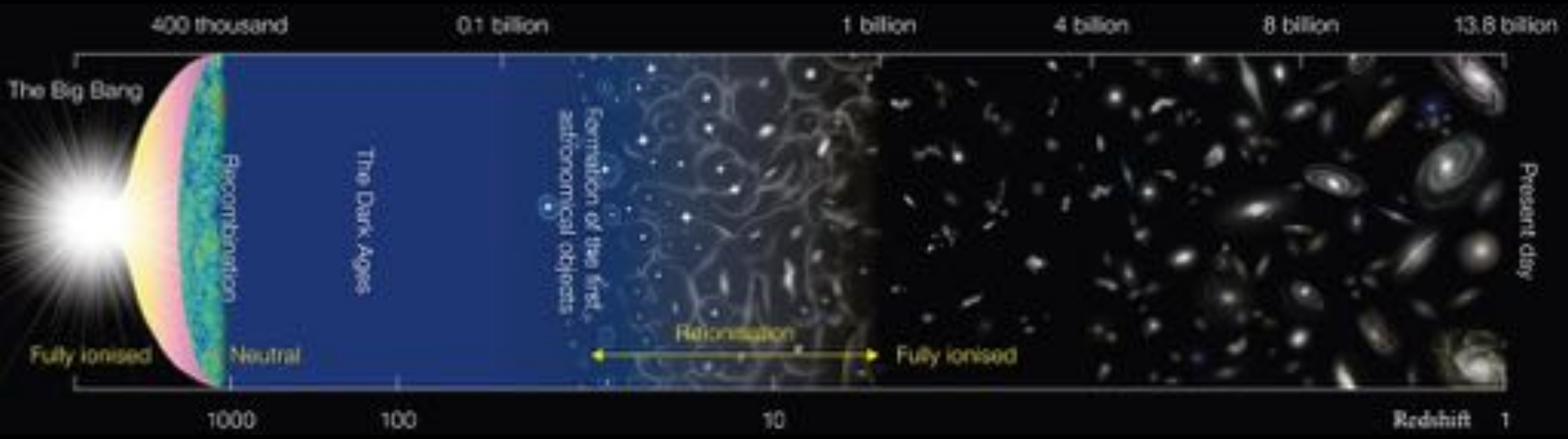
The Universe Timeline

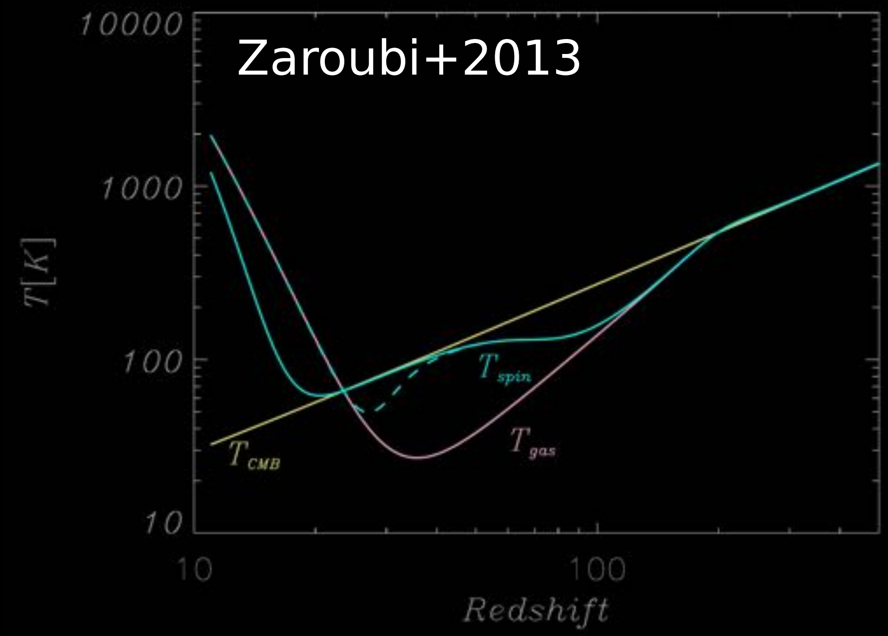
Credit:NAOJ



The Universe Timeline

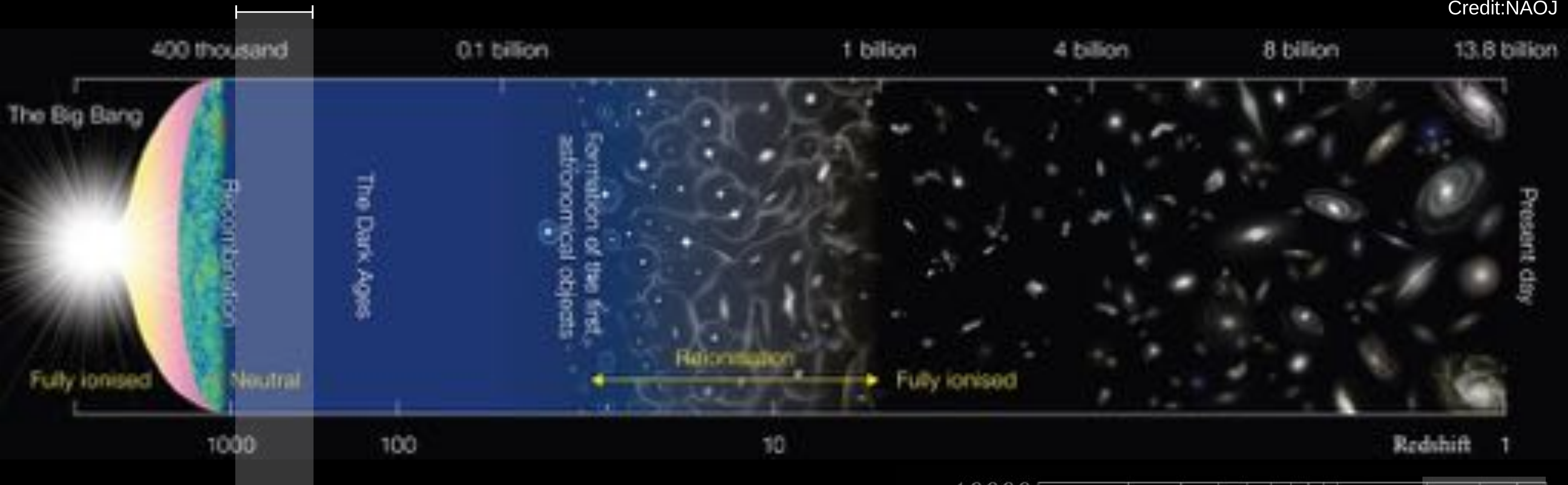
Credit:NAOJ

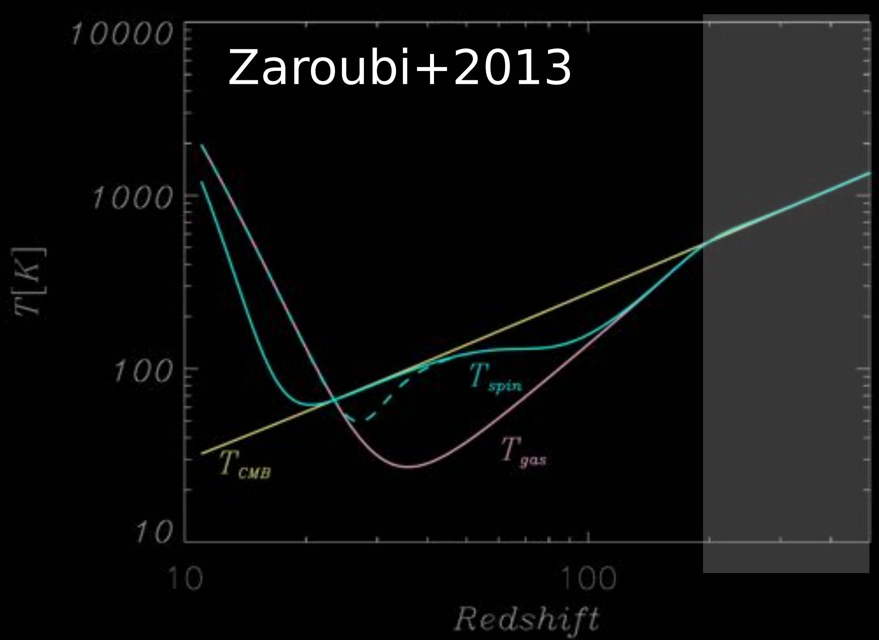




The Universe Timeline

Age of Ignorance
z ~1100-200





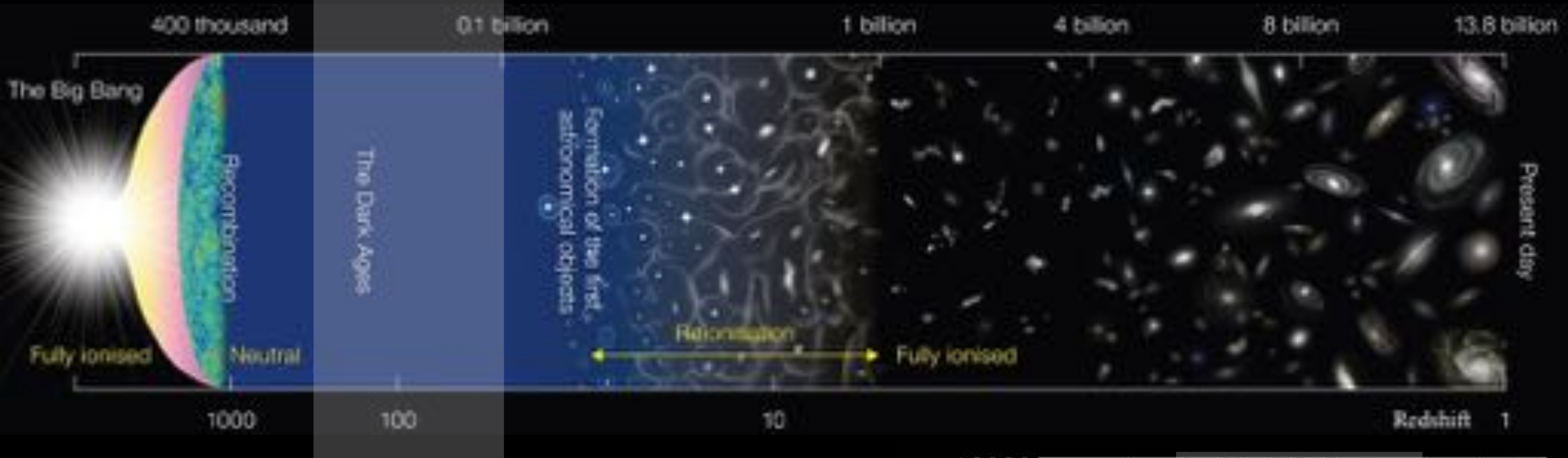
- The spin, CMB and gas temperature are all coupled.

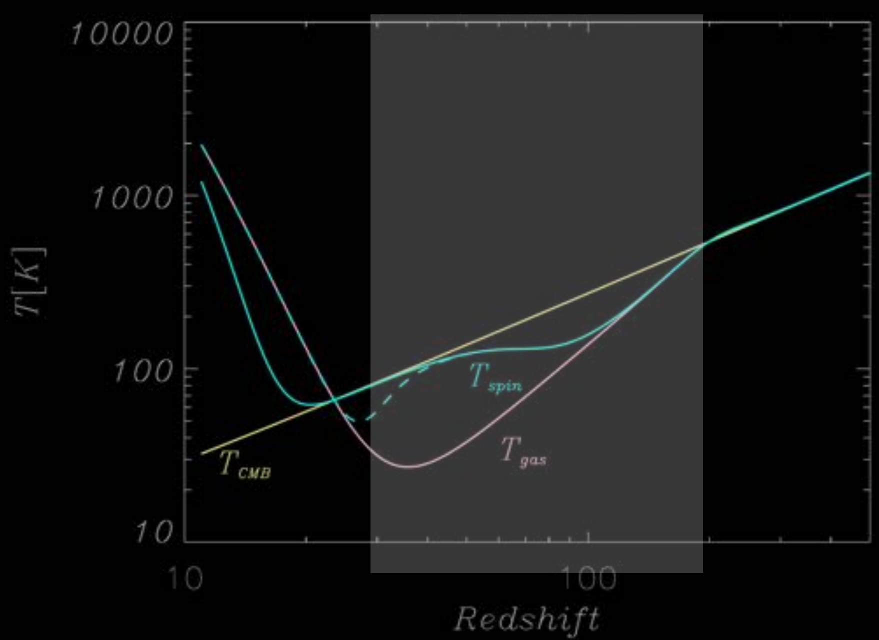
→ any 21cm HI signal is invisible aginst the CMB radiation.

The Universe Timeline

Dark Ages
z ~200-30

Credit:NAOJ





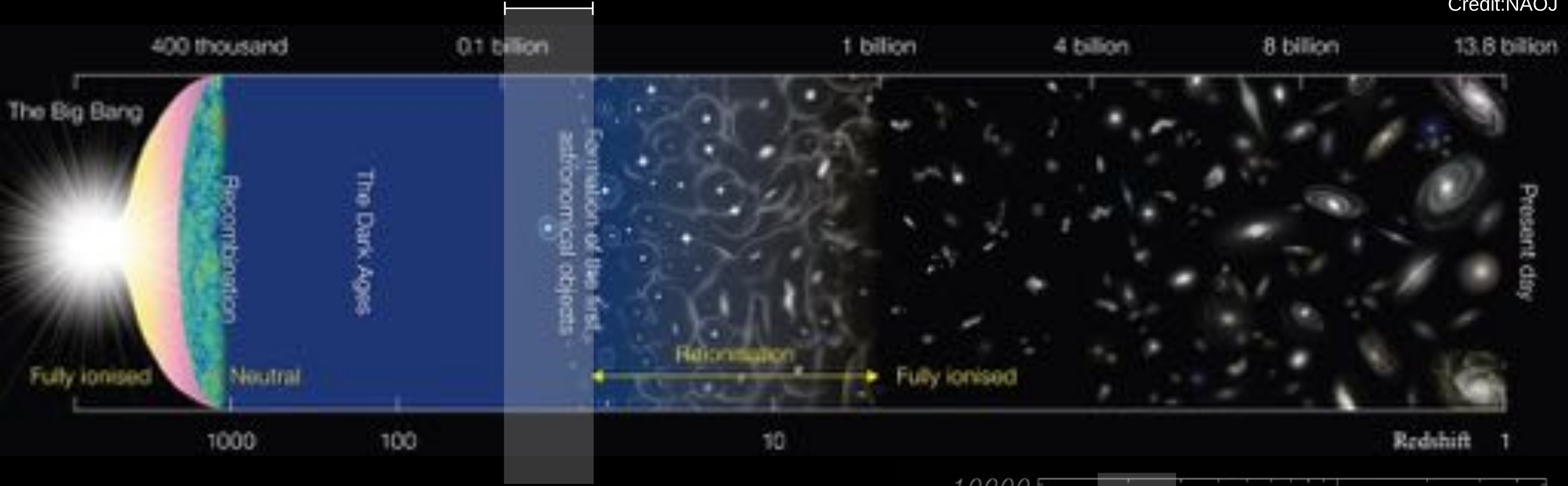
- The spin temperature couples with the colder than CMB gas temperature.

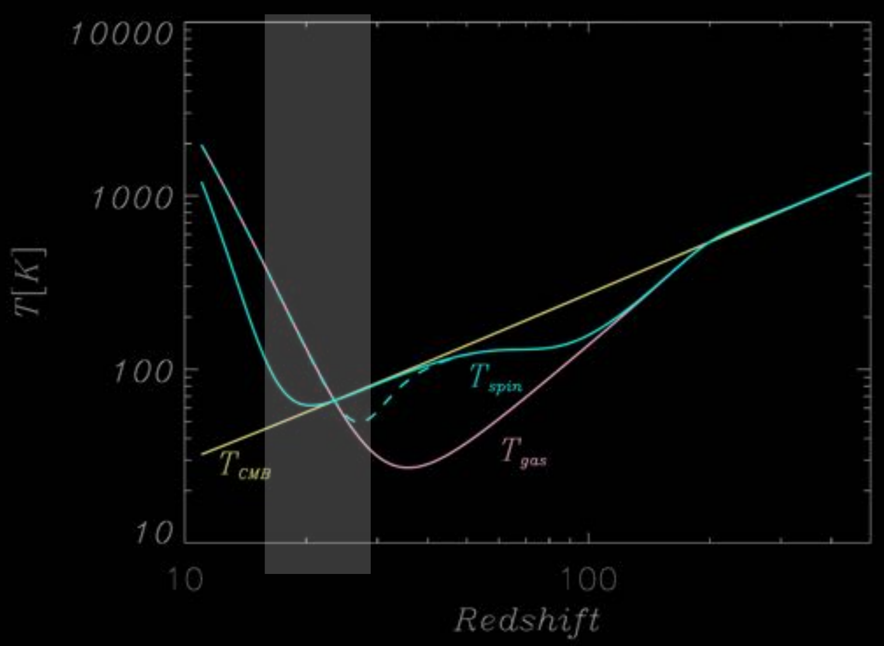
→ The 21cm HI signal could be detected in absorption against the CMB.

The Universe Timeline

Cosmic Dawn
z ~30-15

Credit:NAOJ

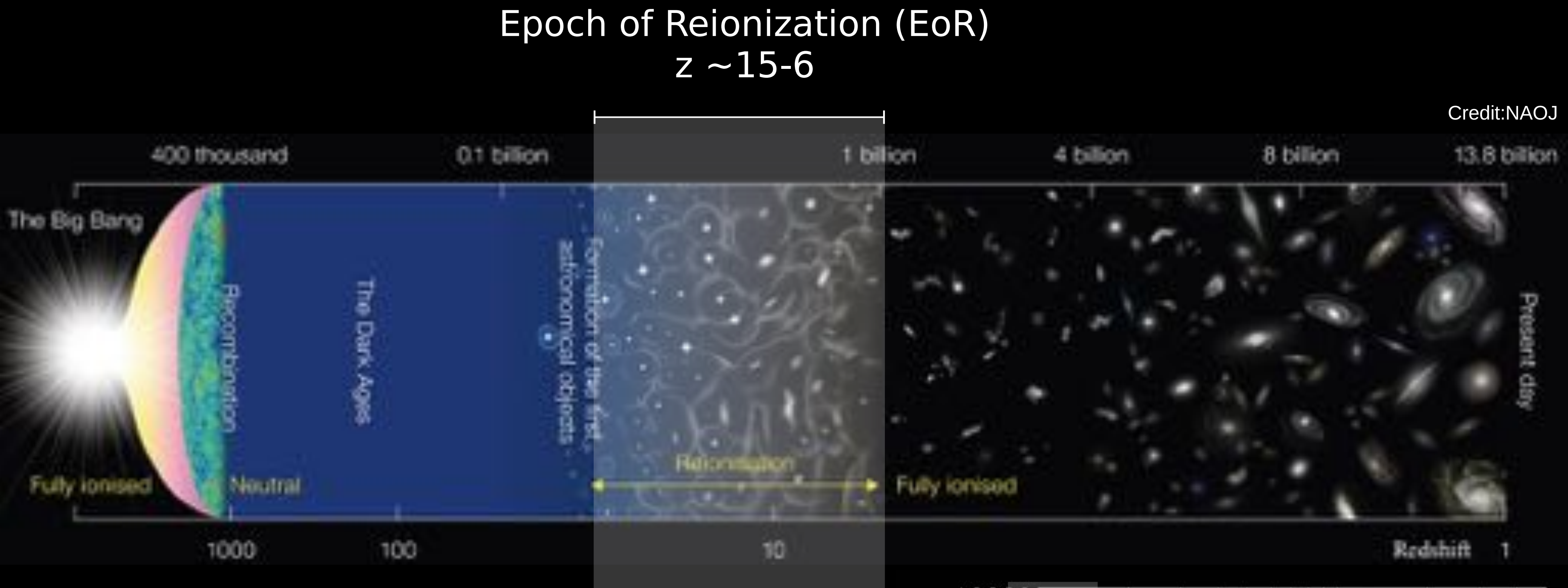


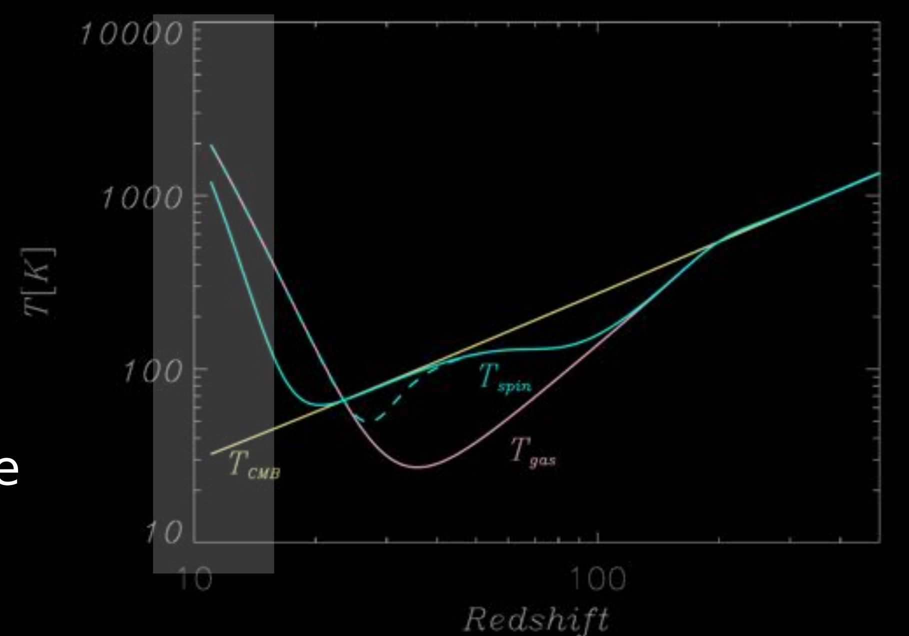


- Apparition of the first stars. The spin temperature couples with the gas heated by those first stars through Ly-α photons.

→ The 21cm HI signal can be detected in emission.

The Universe Timeline



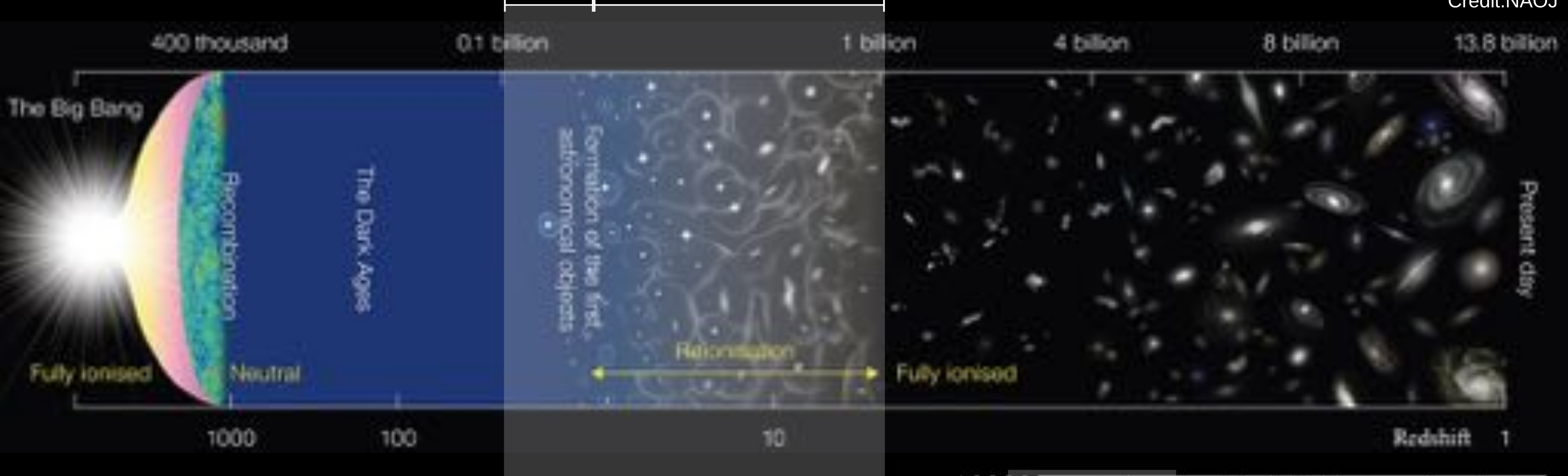


- Strong UV emission from the first stars and galaxies.

→ The hydrogen becomes ionized, leading to the apparition of bubbles around the first galaxies.

The Universe Timeline

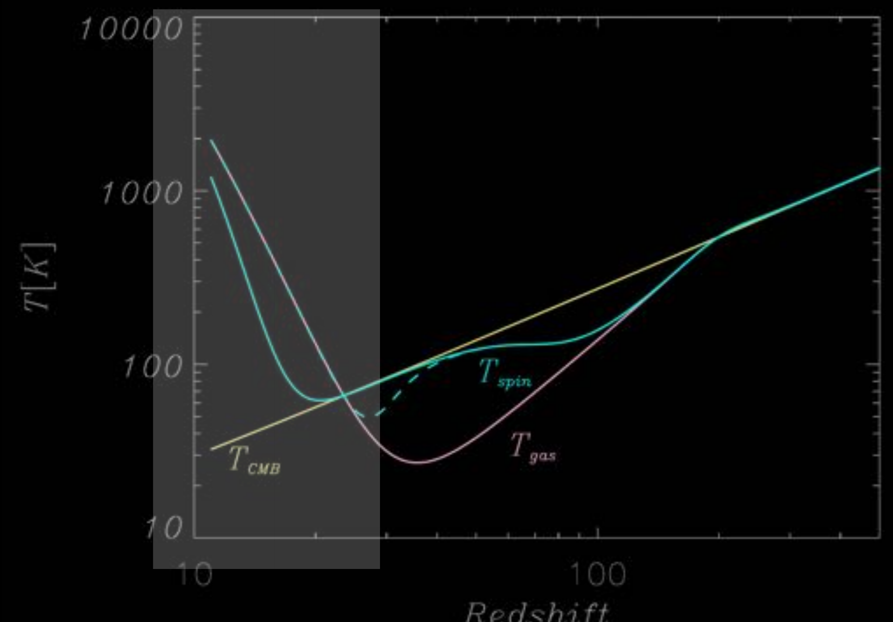
Cosmic Dawn Epoch of Reionization (EoR)
z ~30-15 z ~15-6



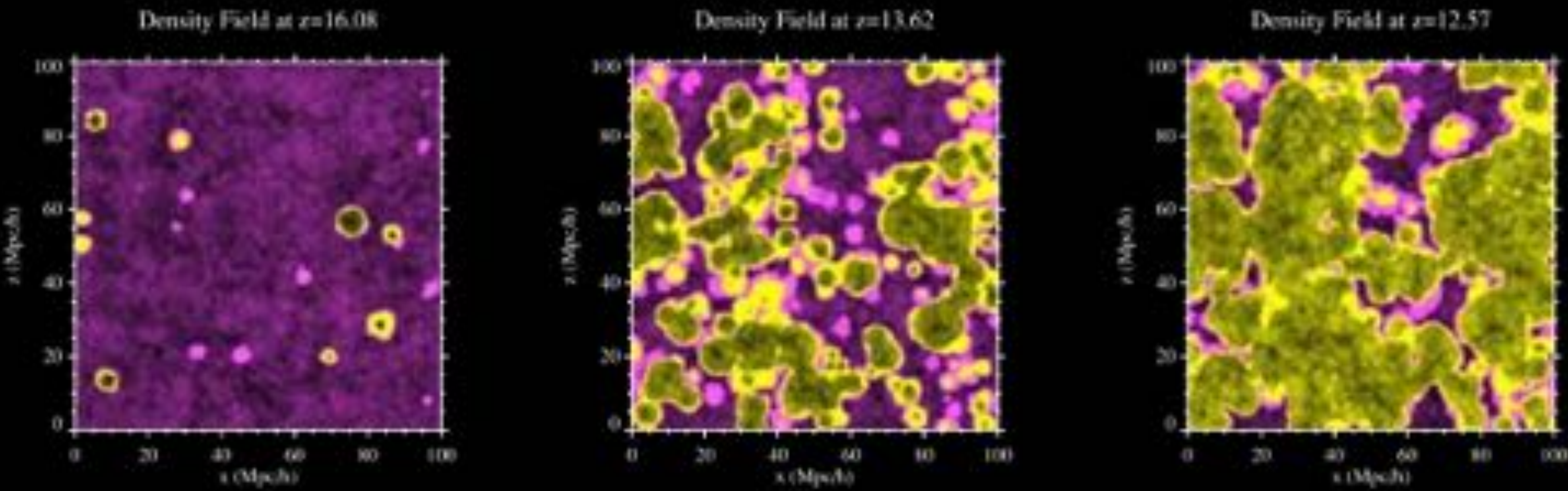
Low-Frequency Aperture Array (LFAA)

Frequences from 50 MHz (21cm at z=27)
to 350 MHz (21cm at z=3)

→ direct imaging of the environment of the first stars and galaxies

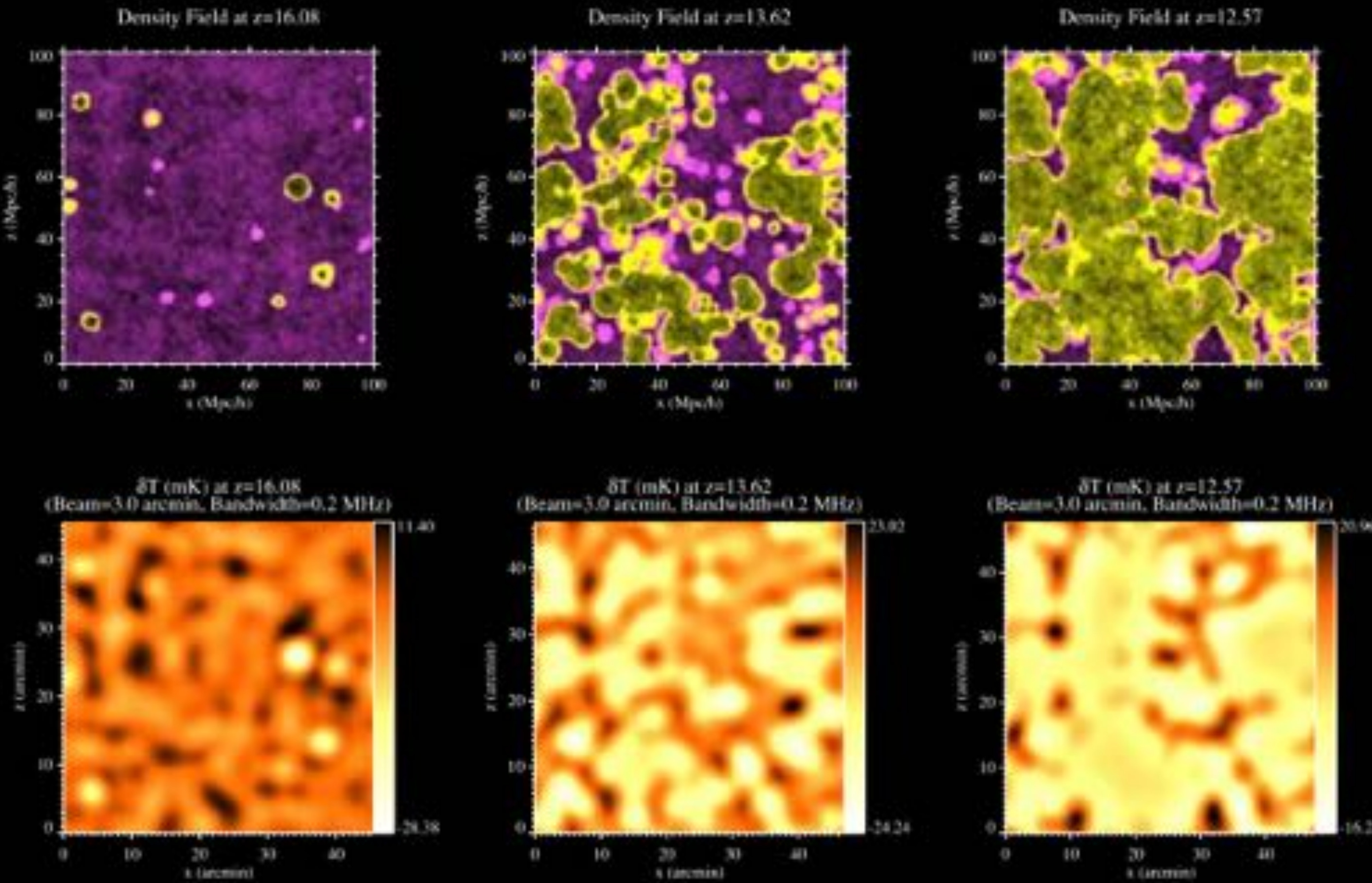


Direct imaging of neutral hydrogen



Mellema+2006

Direct imaging of neutral hydrogen

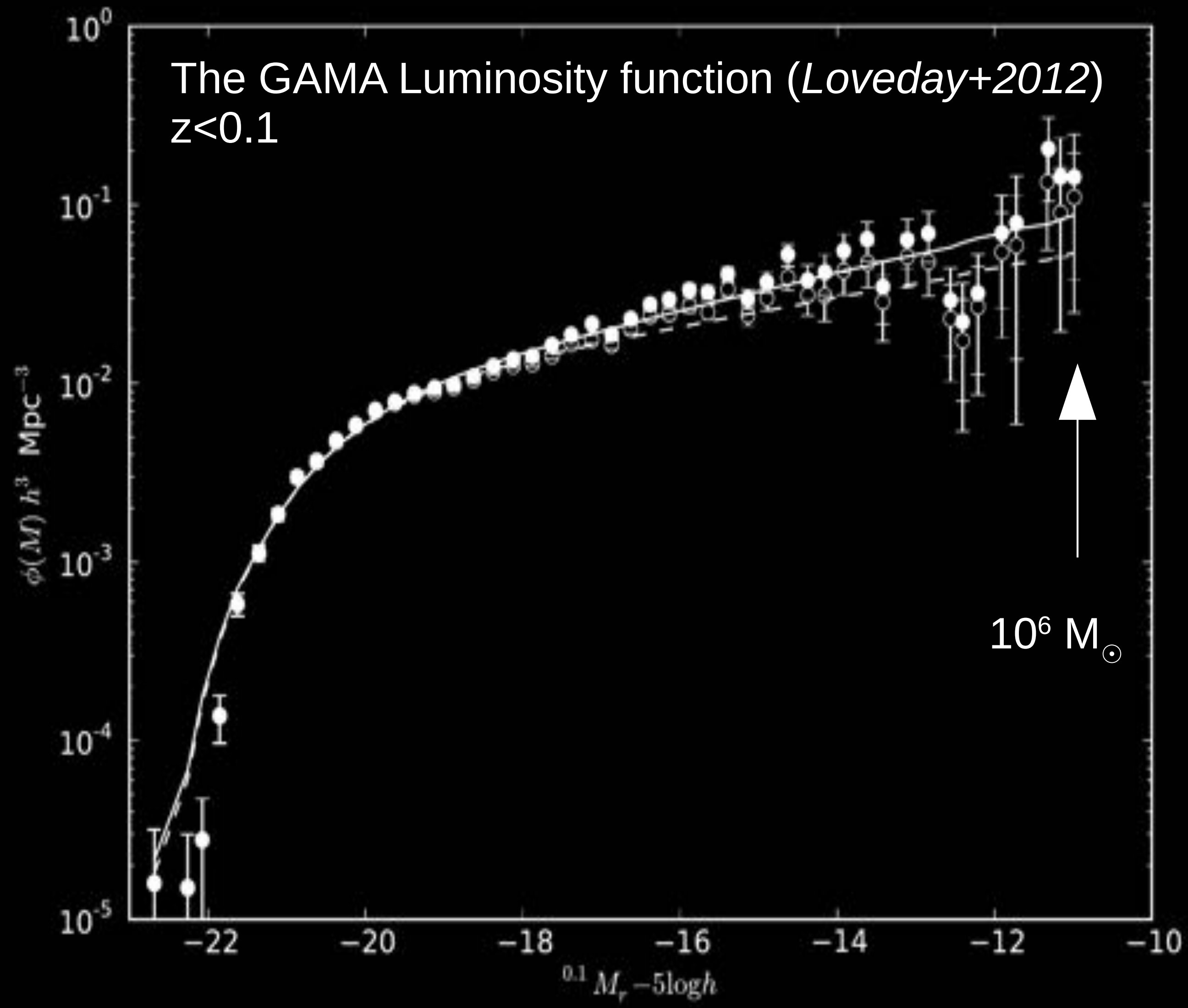


3-arcmin FWHM (SKA1-low) → spacial resolution of 10-30 kpc

Mellema+2006

The Role of Dwarf Galaxies during the EoR

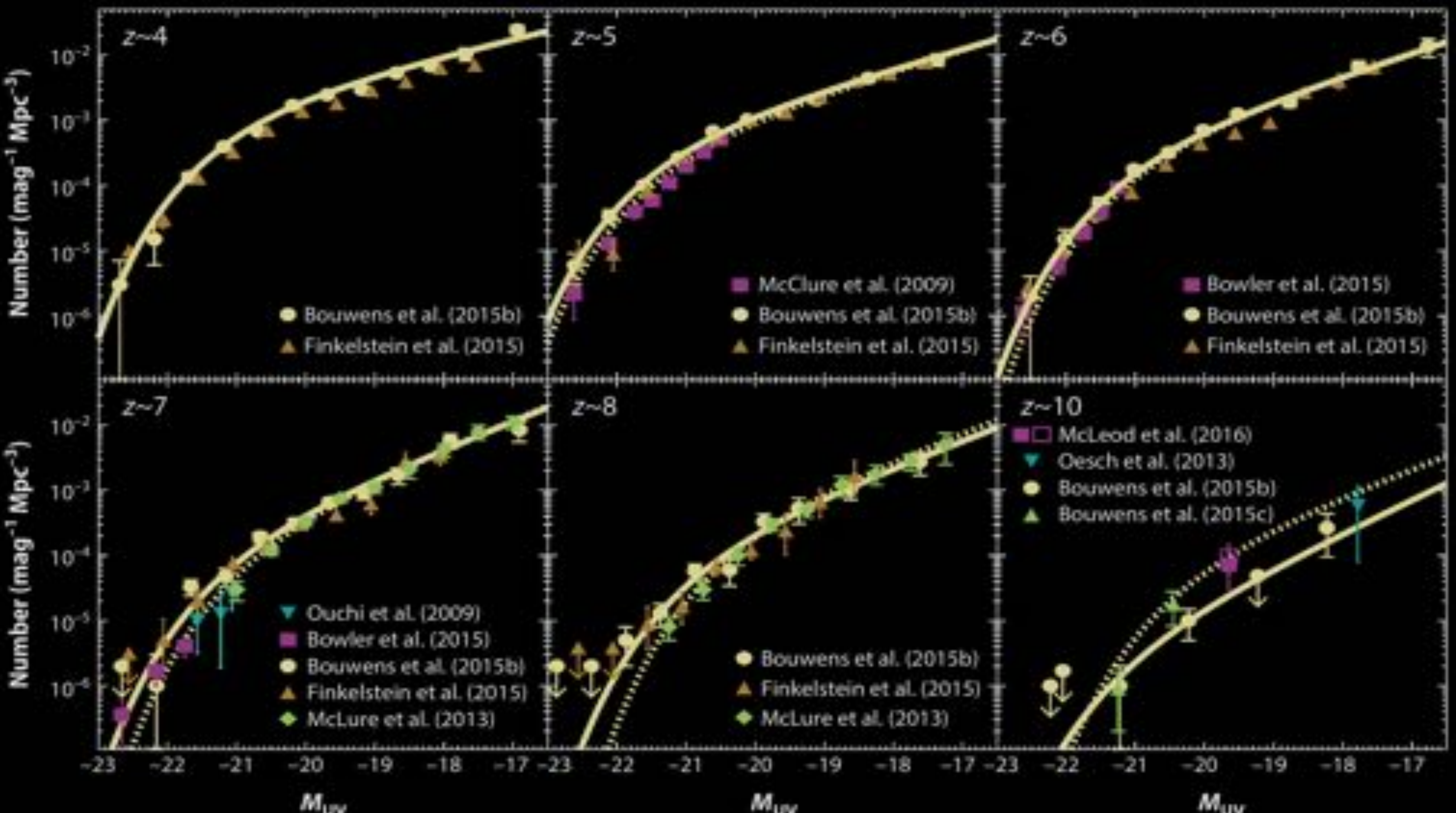
- Dwarf galaxies are the faintest galaxies, but the most abundant objects in the Universe



The Role of Dwarf Galaxies during the EoR

- They are also the most abundant galaxies at high redshift

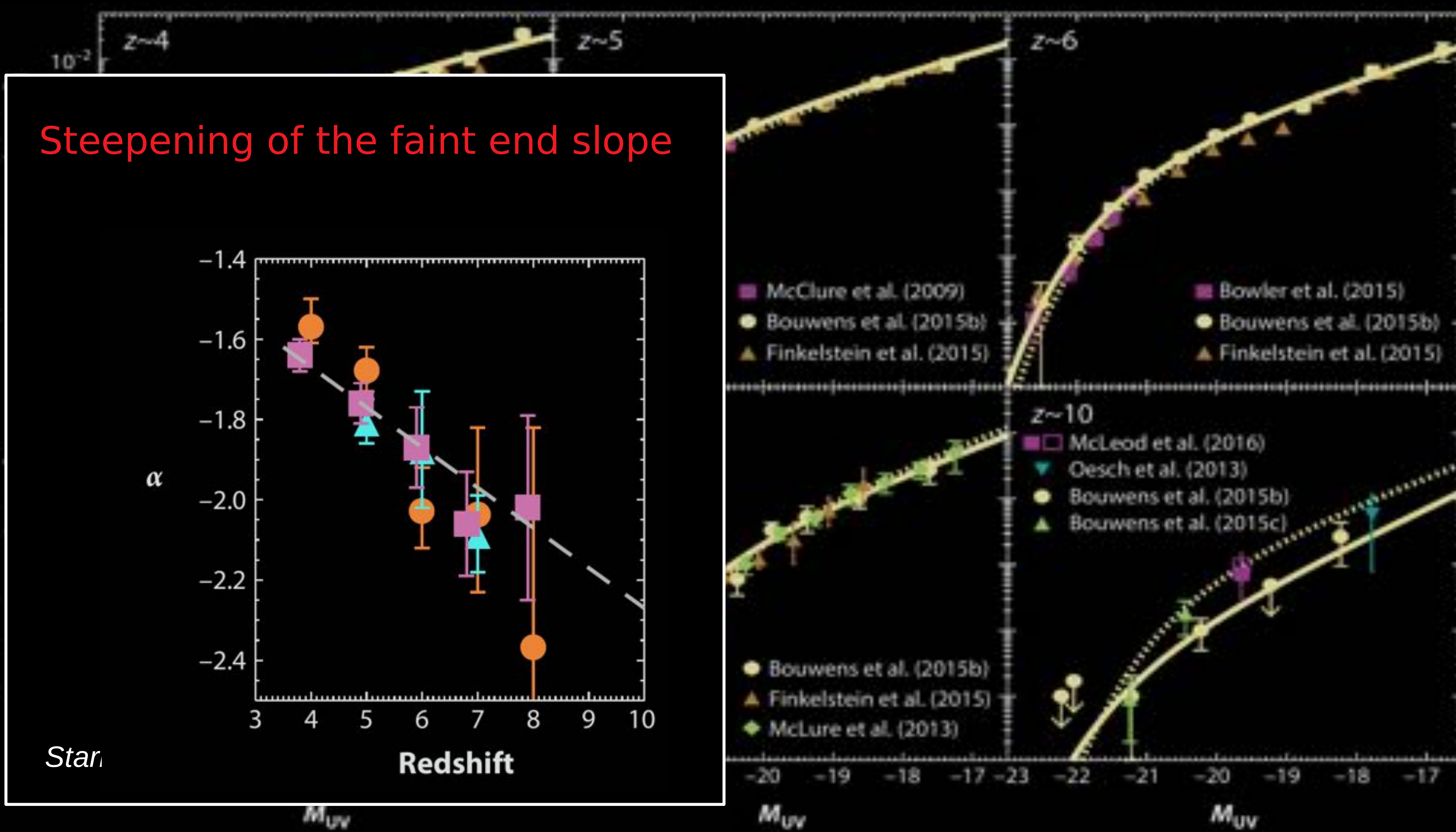
(see. Ouchi+2009,Oesch+2013,McClure+2009,2013,Bouwens+2015,Finkelstein+2015,Bowler+2015, Atek+2015)



The Role of Dwarf Galaxies during the EoR

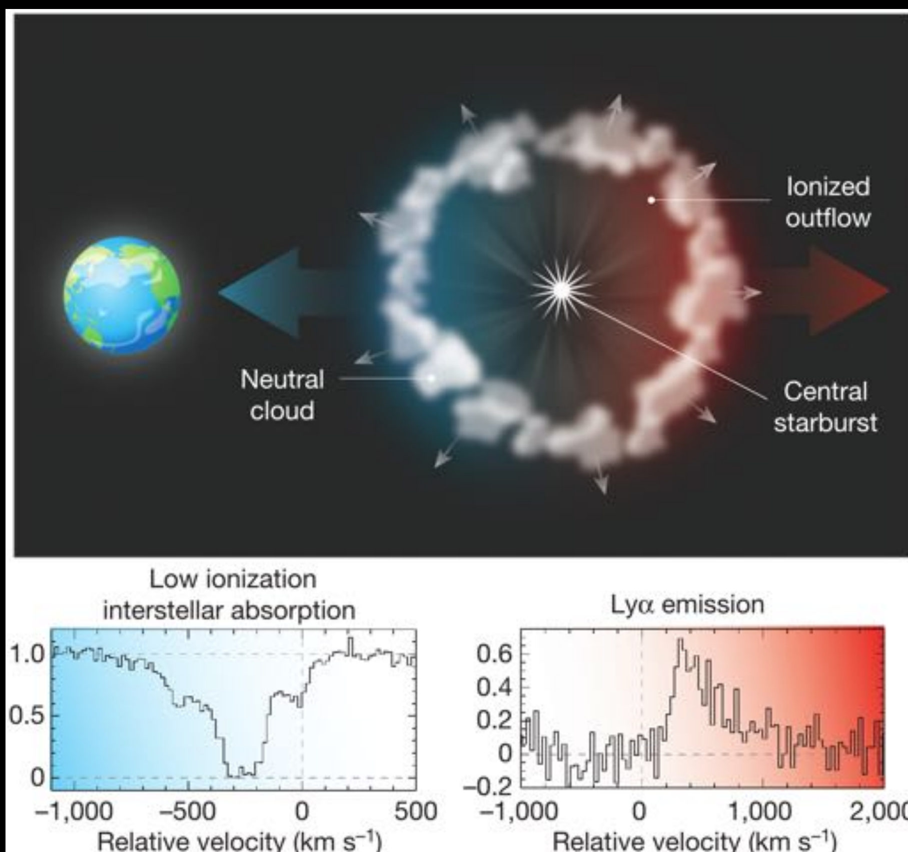
- They are also the most abundant galaxies at high redshift

(see. Ouchi+2009,Oesch+2013,McClure+2009,2013,Bouwens+2015,Finkelstein+2015,Bowler+2015, Atek+2015)



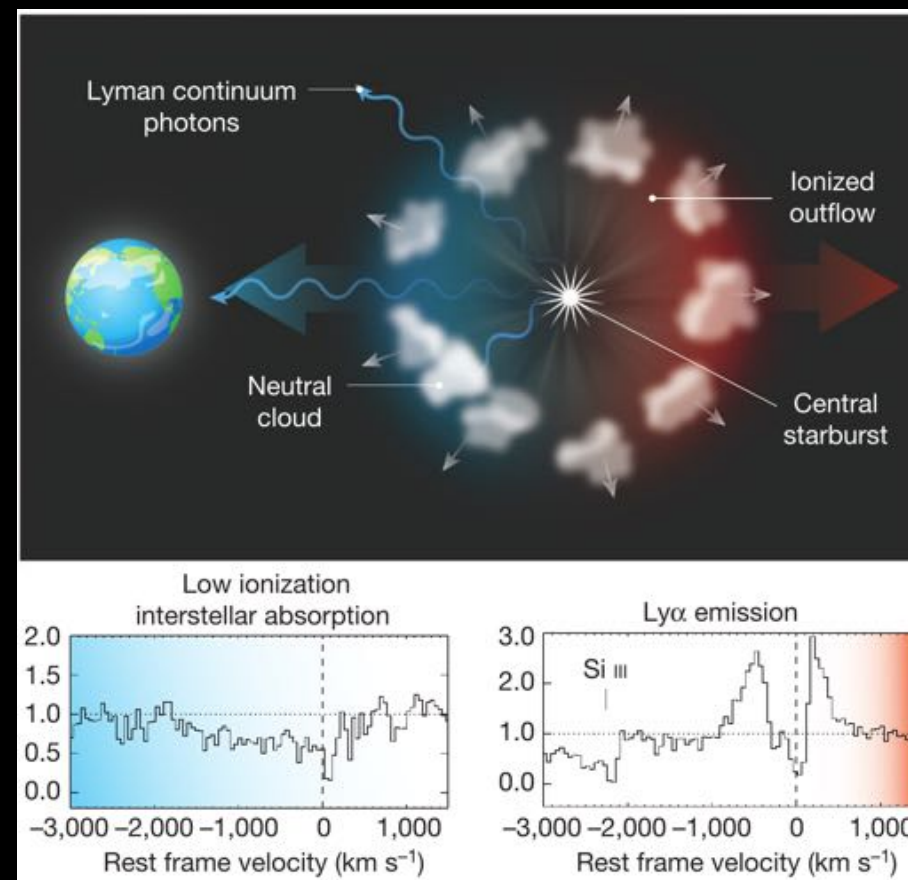
The ionizing escape fraction of Dwarf Galaxies

Nearly complete covering fraction of the neutral hydrogen



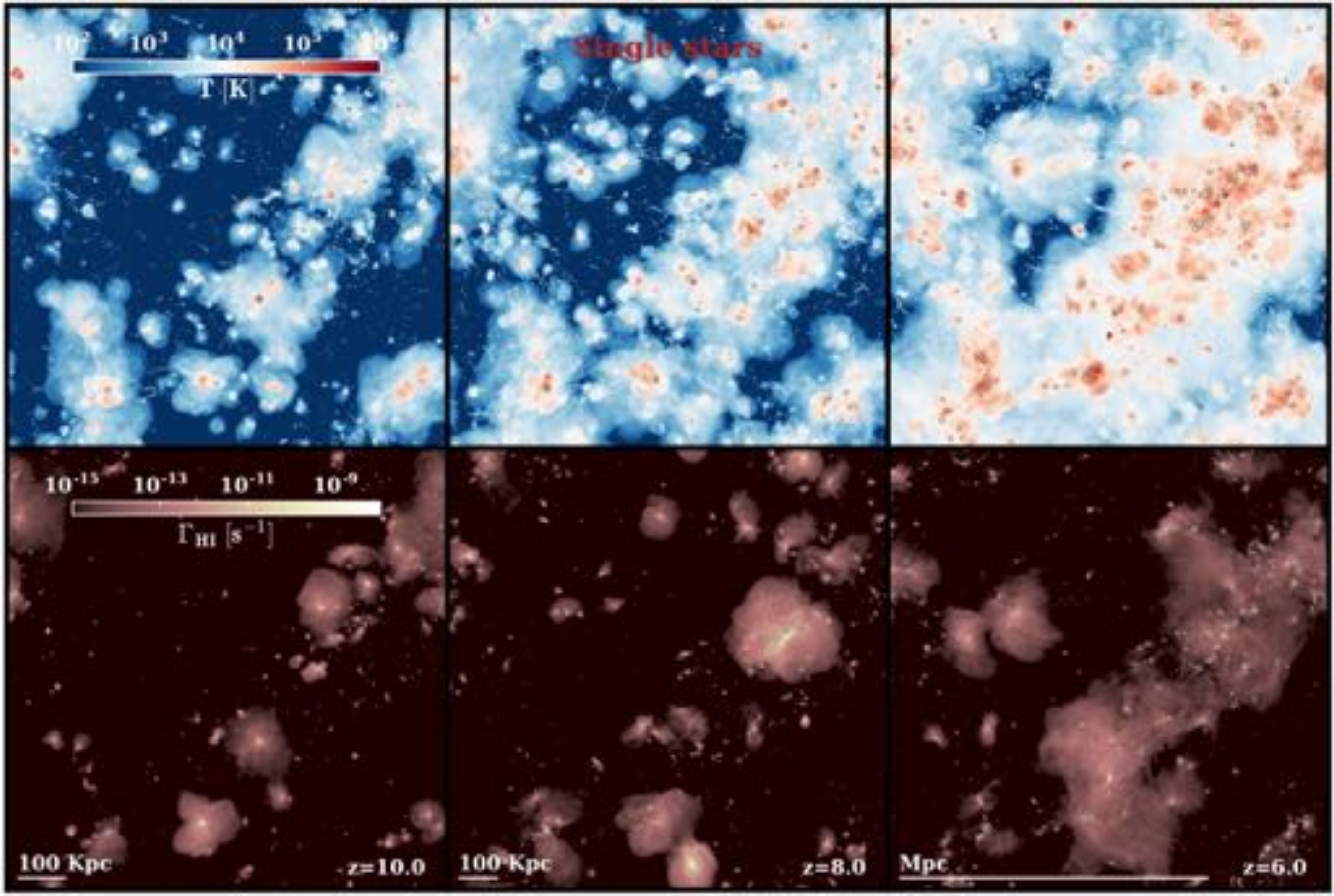
Absoprtion of ionizing Lyman continuum photons

Incomplete covering fraction of the neutral hydrogen

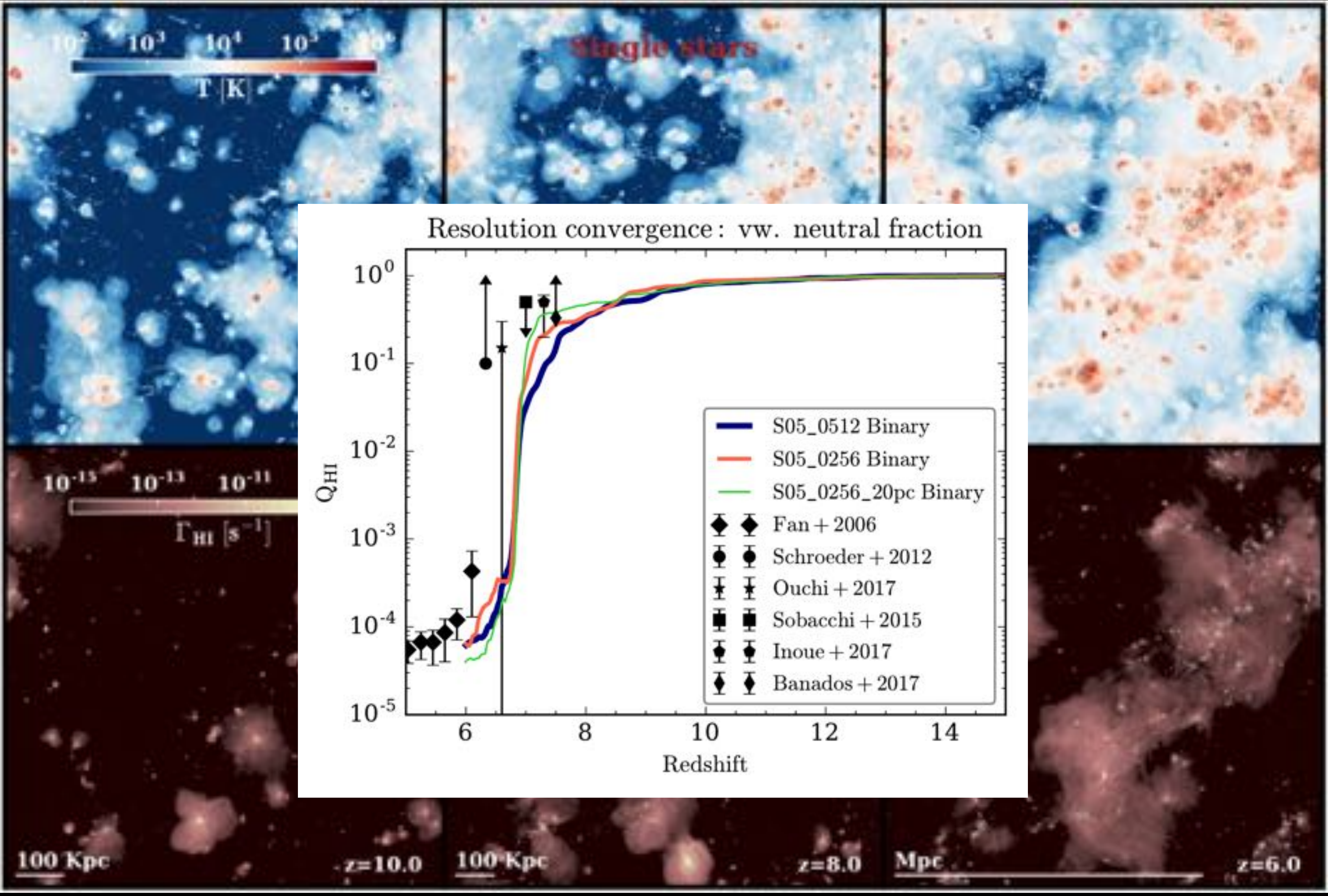


Important escape of ionizing Lyman continuum photons

Erb+2015



The SPHINX simulations *(Rosdahl+2018)*



The SPHINX simulations *(Rosdahl+2018)*

Our approach:

- Study dwarf galaxies through a full Hubble time and check if their properties reproduce in details observations.

→ This will give constraints on the feedback, escape fraction and impact of dwarf galaxies during the EoR.

Observational constraints: Plethora of high quality photometric and spectroscopic observations

- Line-of-sight velocities revealing the galaxy stellar dynamics
  (ex. Walker+09, Battaglia+08, Fabrizio+11,16)

- Deep colour magnitude diagrams allow to infer the galaxy star formation histories
  (ex: Dolphin+02, de Boer+12a,b, Weisz+2014a, de Boer+14; Weisz+14b; Santana+16, Kordopatis+16, Bettinelli+18)

- High resolution spectroscopy of individual stars allow to determine accurate stellar abundances providing strong constraints on the galaxy chemical evolution
  (ex: Shetrone+01,03, Koch+08; Aoki+09, Cohen+09, Frebel+10, Norris+10, Tafelmeyer+10, Letarte+10, Kirby+10, Venn+12; Lemasle+12; Starkenburg+13, Jablonka+15, Tsujimoto+15)

- Stellar population gradients, i.e., a variation of the population properties with galacto-centric distances, provide constraints on the interplay between dynamics and chemical evolution
  (ex: Harbeck+01, Tolstoy+04, Koch+06, Battaglia+06, Faria+07, Gullieuszik+09, Kirby+11, Battaglia+11, Vargas+14, Ho+15, Lardo+16, Spencer+17a, Suda+17, Okamoto+17)

GEAR : a chemo-dynamical code

Skeleton:

Gadget-2 (*Springel+05*)

- Gravity: Treecode (*Barnes+86*) + PM
- Hydro: SPH (*Lucy+77, Gingold+77*)

Improvements:

Revaz et al. 2016

- *SPH: pressure-entropy formulation* (*Hopkins 2013*)
- *Individual and adaptive time steps* (*Durier & Dalla Vecchia 12*)
- *Artificial viscosity* (*Monaghan+83, Rosswog+00*)

GEAR : a chemo-dynamical code

- **Baryonic physics:**

  Revaz+12, Revaz+16

- *Radiative cooling + UV heating*

  Grackle (*Smith+16*)
  - Primoridal cooling + metal lines
  - UV background heating (*Haardt & Madau+12*)

  Hydrogen self-shielding

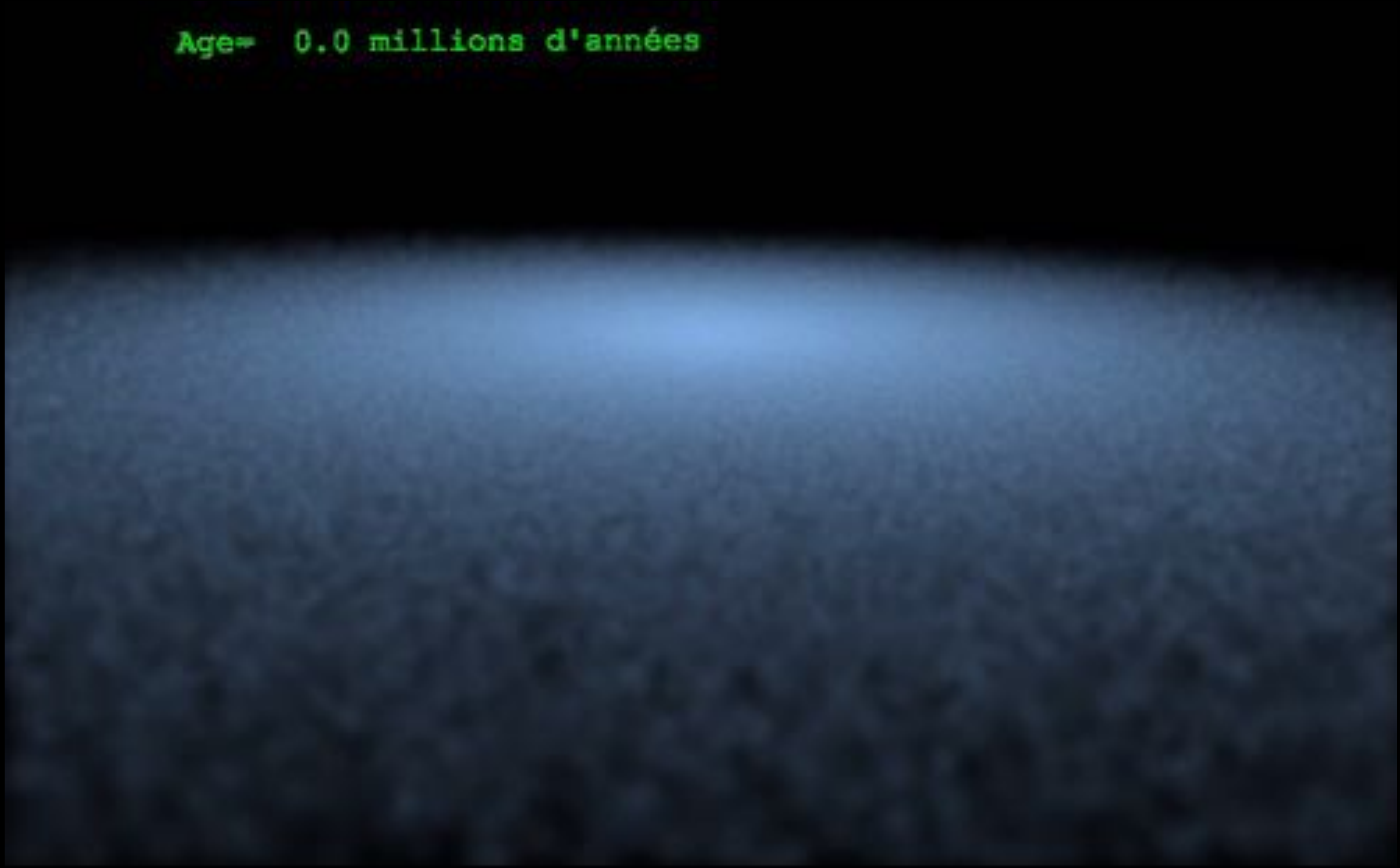
- *Star formation*

  Stochastic (*Katz+92,96*)
  Jeans based (*Revaz+18*)

- *Self-consistent chemical evolution scheme*

  Single Stellar Population Scheme (SSP)
  - SNeIa (*Tsujimoto+95,Kobayashi+00*)
  - SNeII (*Iwamoto+99*) nucleosynthesis
  - SNe feedback + Thermal blast (*Stinson+08*)

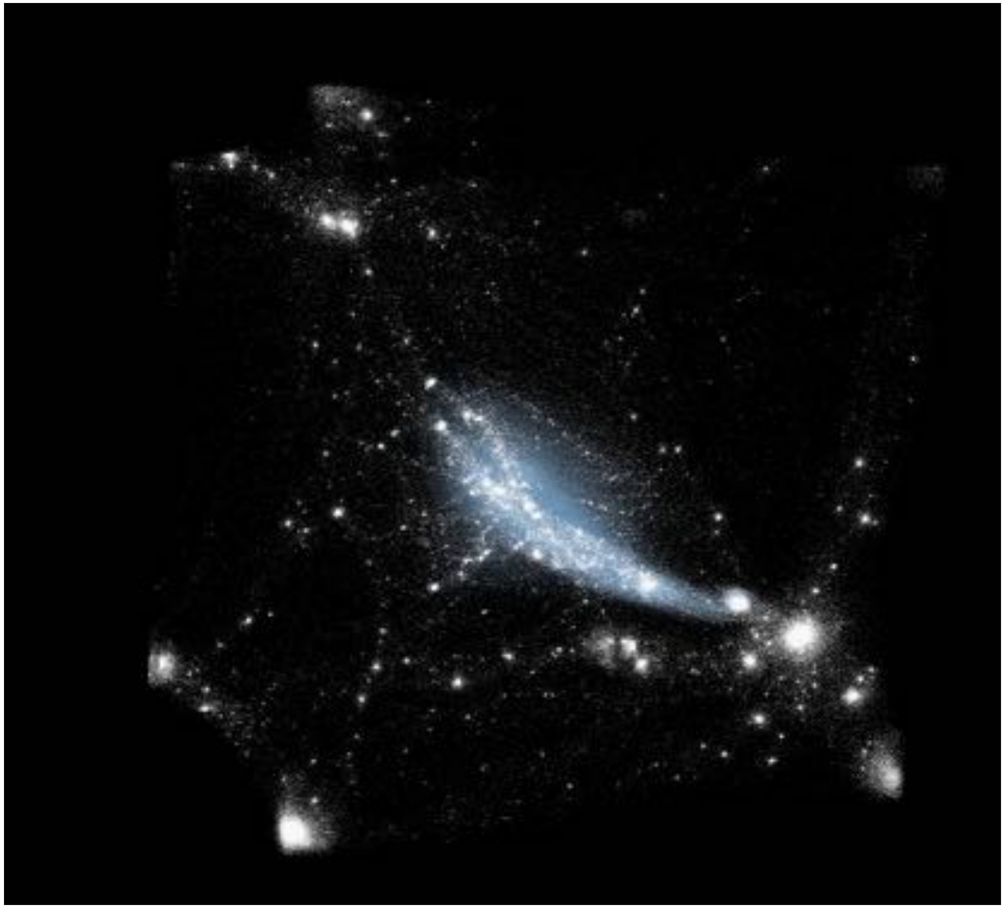
Milky Way model from the AGORA high-res. simulations comparison project

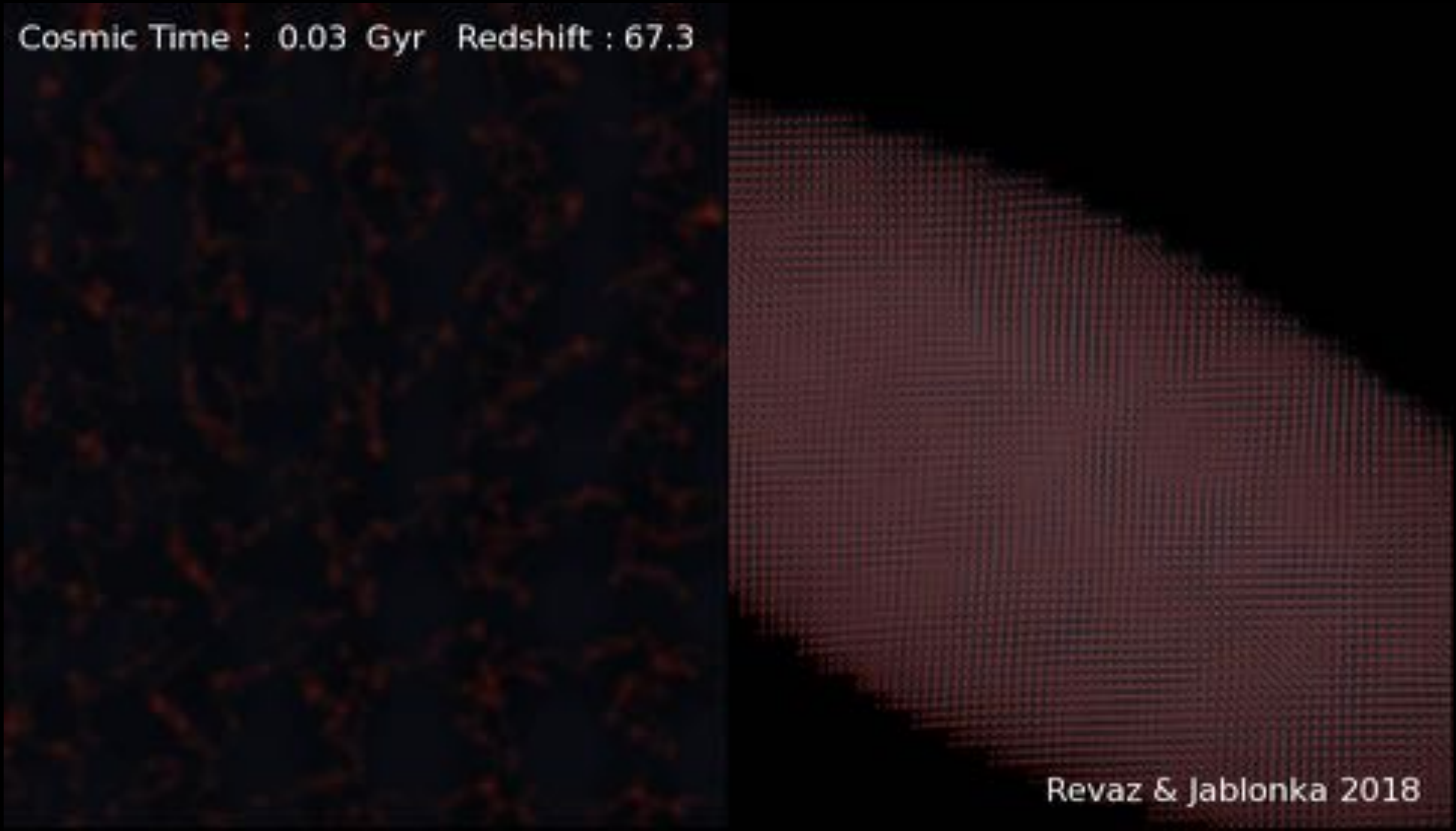


Zoom-in simulations of dwarf galaxies

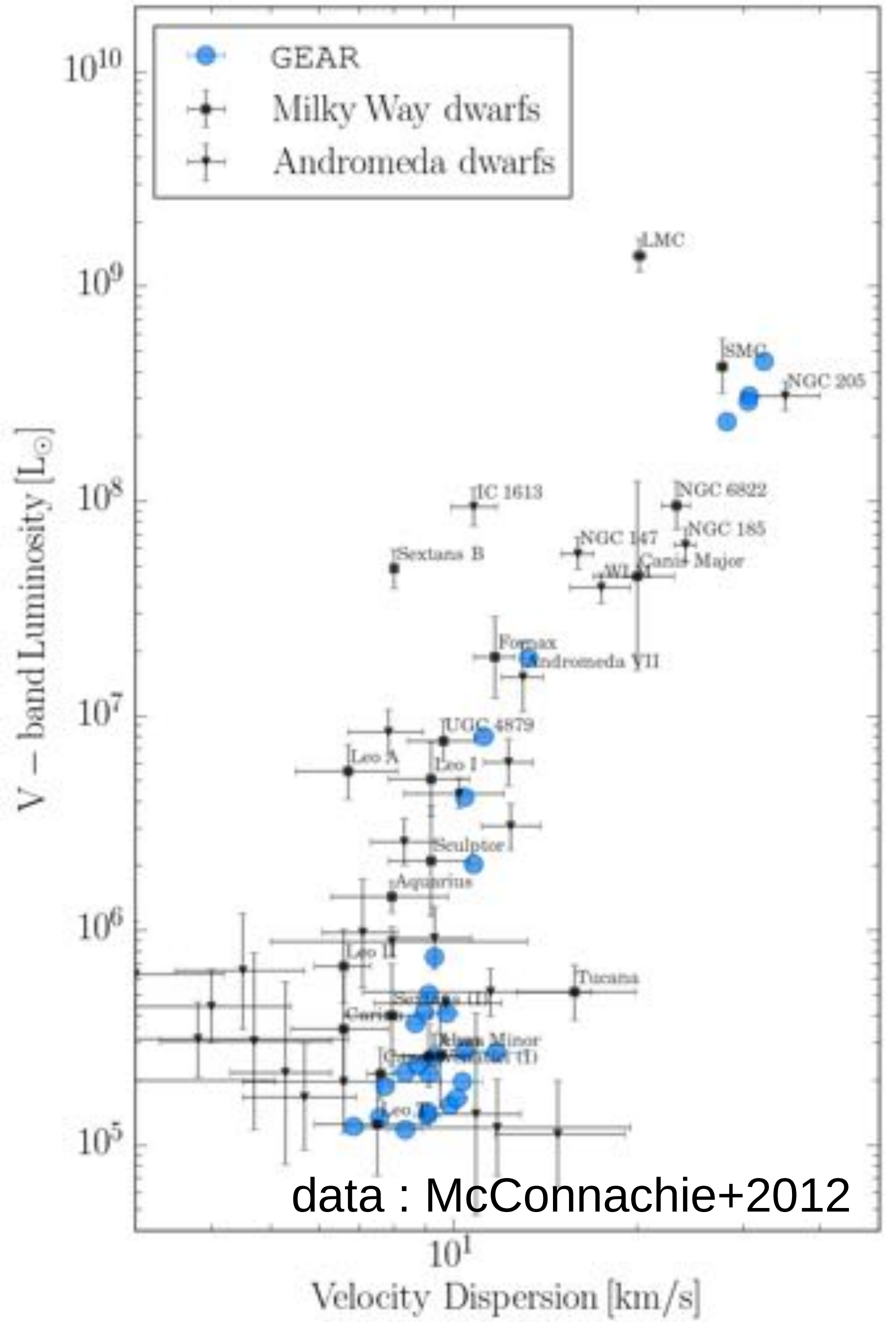
Revaz & Jablonka 2018

- Boxsize : $3.4\,\mathrm{Mpc/h}$
- Cosmological parameters from *Planck Collaboration et al. 2015*
- Stellar mass resolution : $1024\,\mathrm{M_\odot/h}$
- 66 Dwarf candidates
  - 27 with $10^5\,\mathrm{L_\odot} < \mathrm{L_V} < 10^9\,\mathrm{L_\odot}$
  - 39 with $L_\mathrm{V} < 10^5\,\mathrm{L_\odot}$

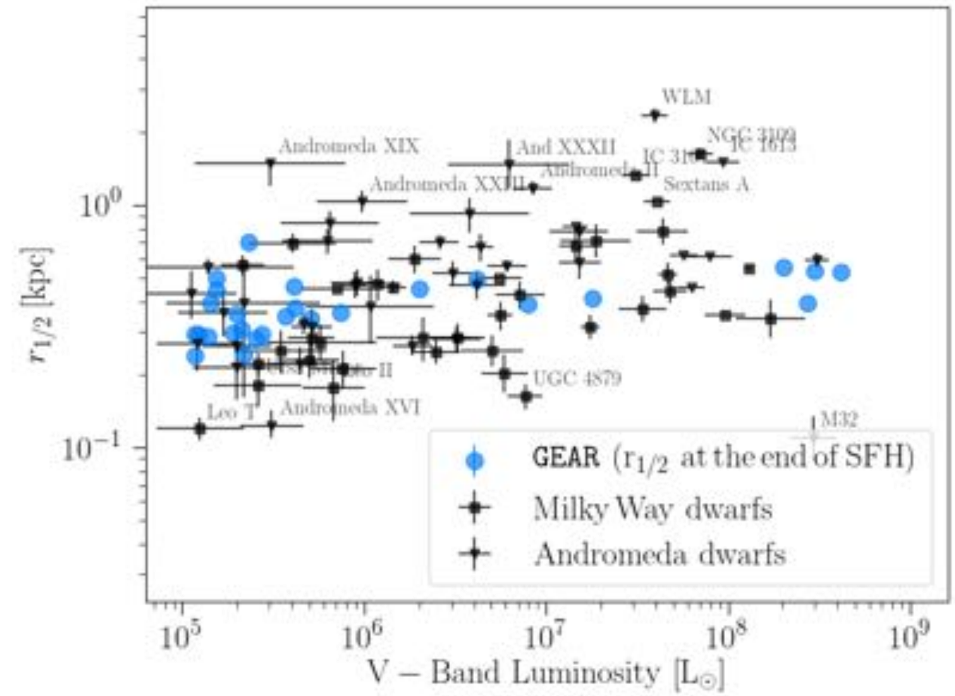


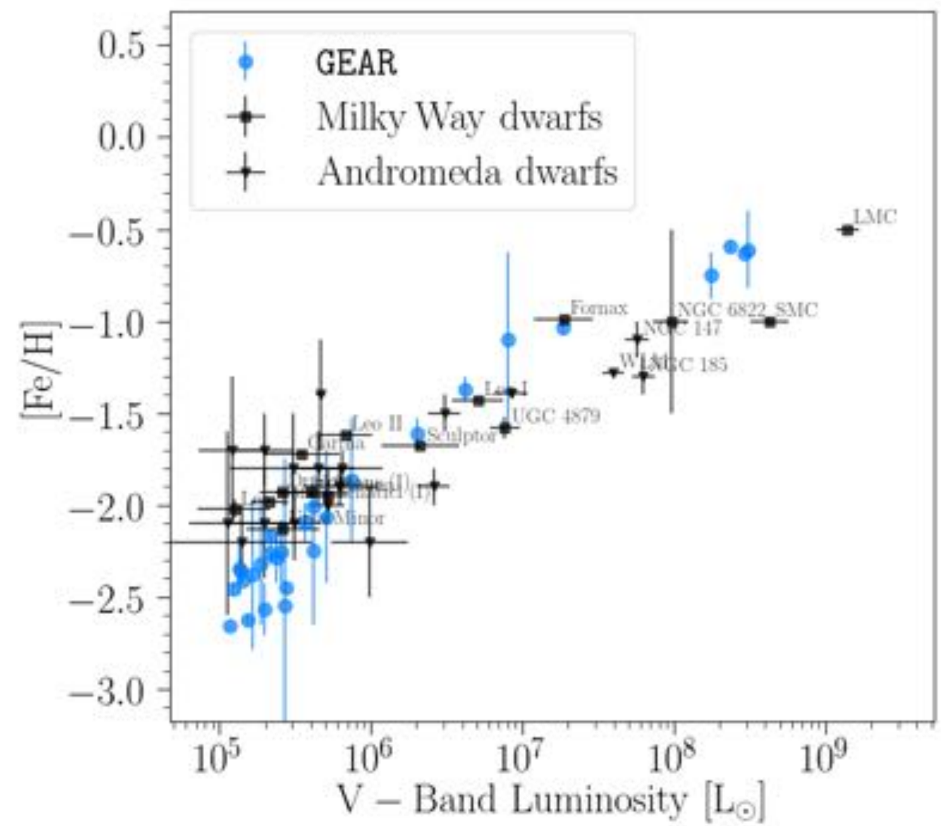

Cosmic Time : 0.03 Gyr Redshift : 67.3
Revaz & Jablonka 2018

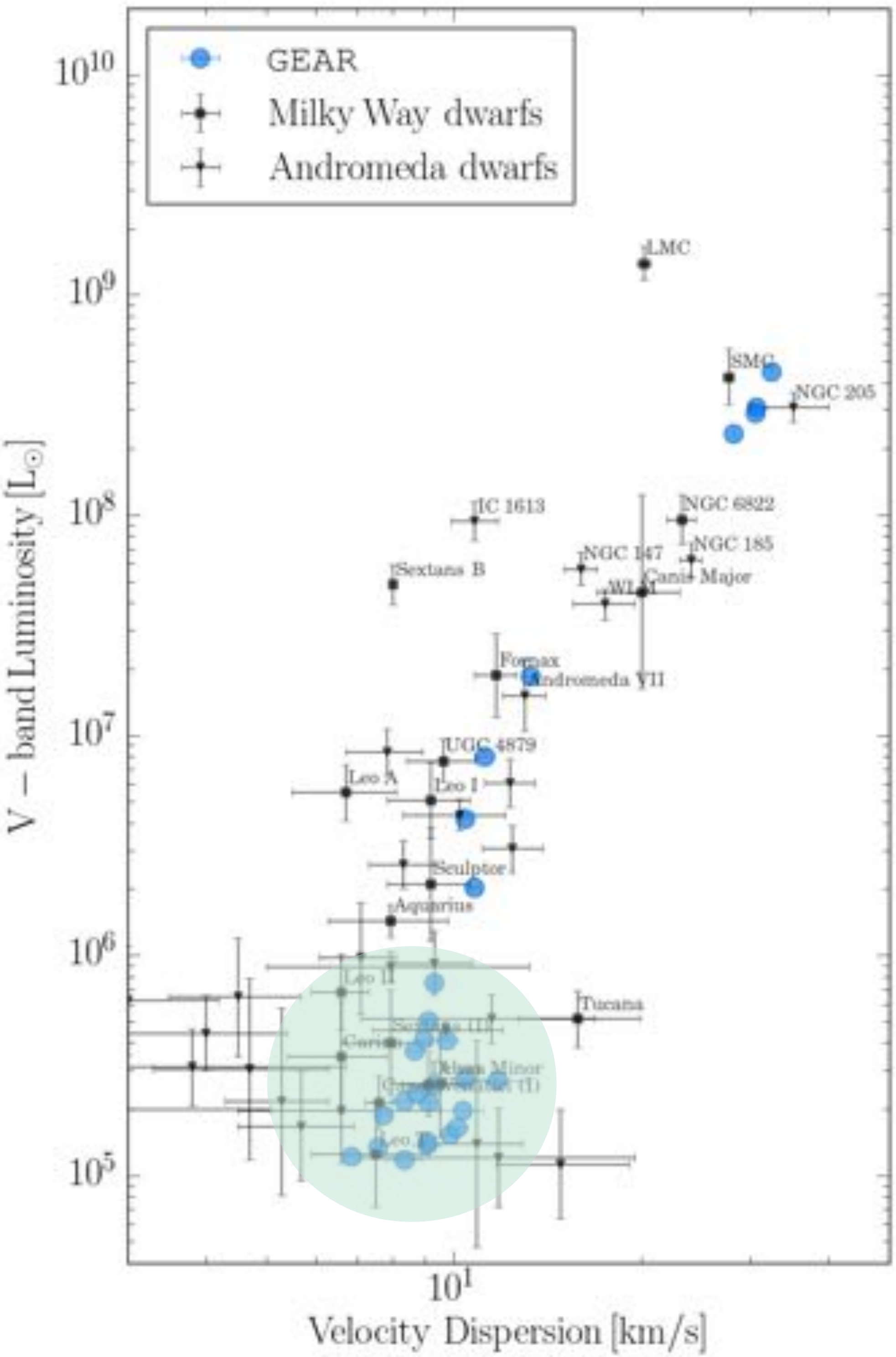
scaling relations

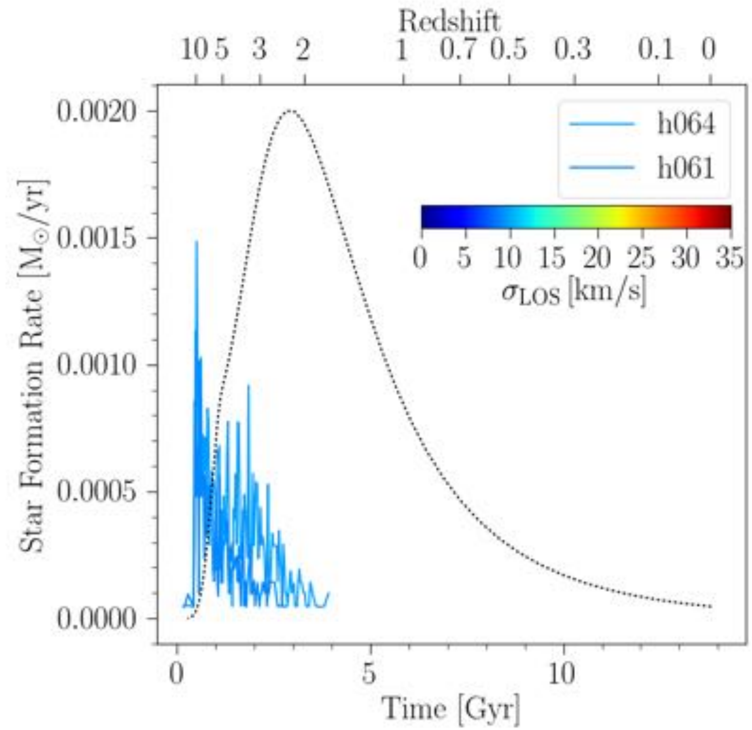


data : McConnachie+2012







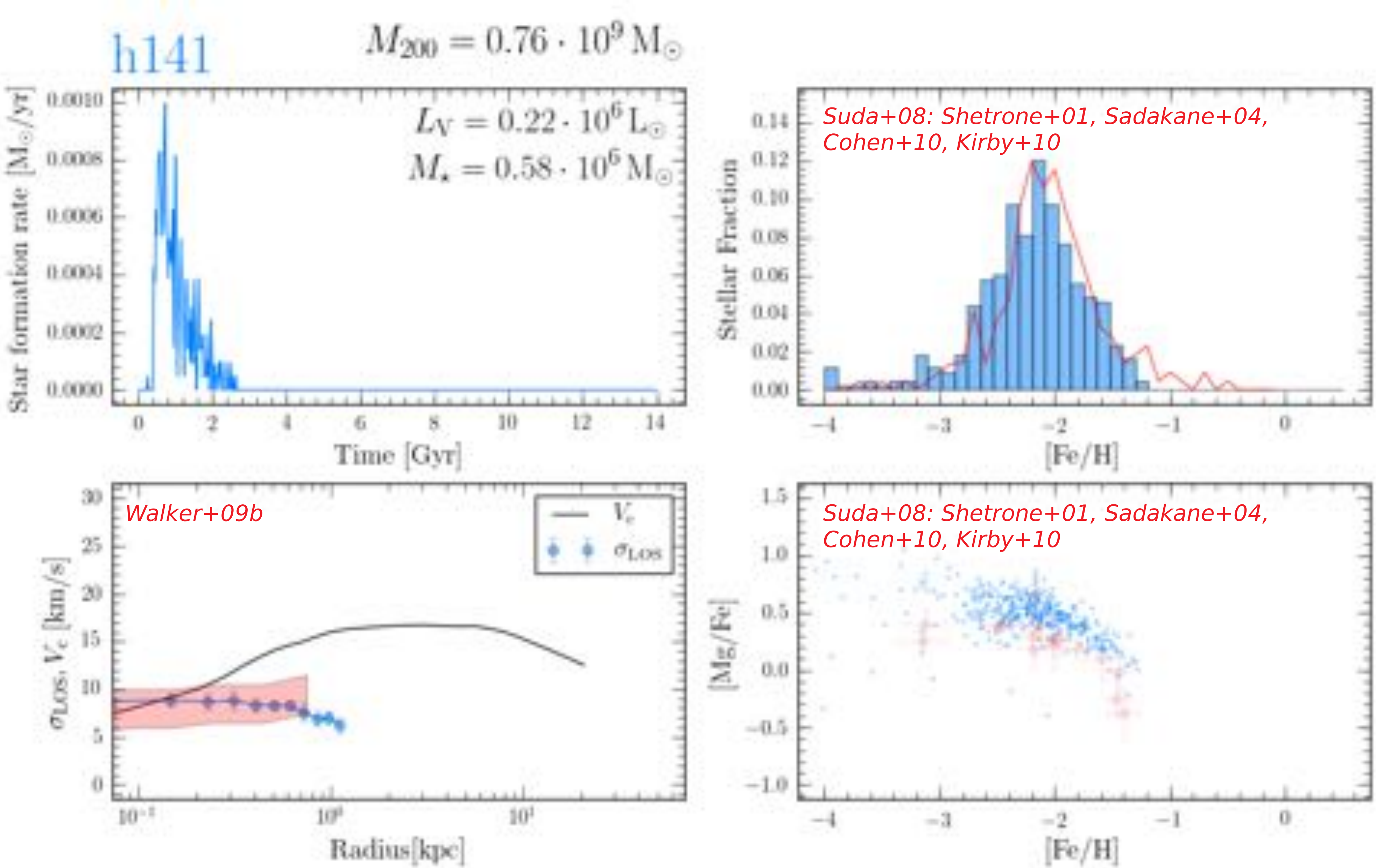


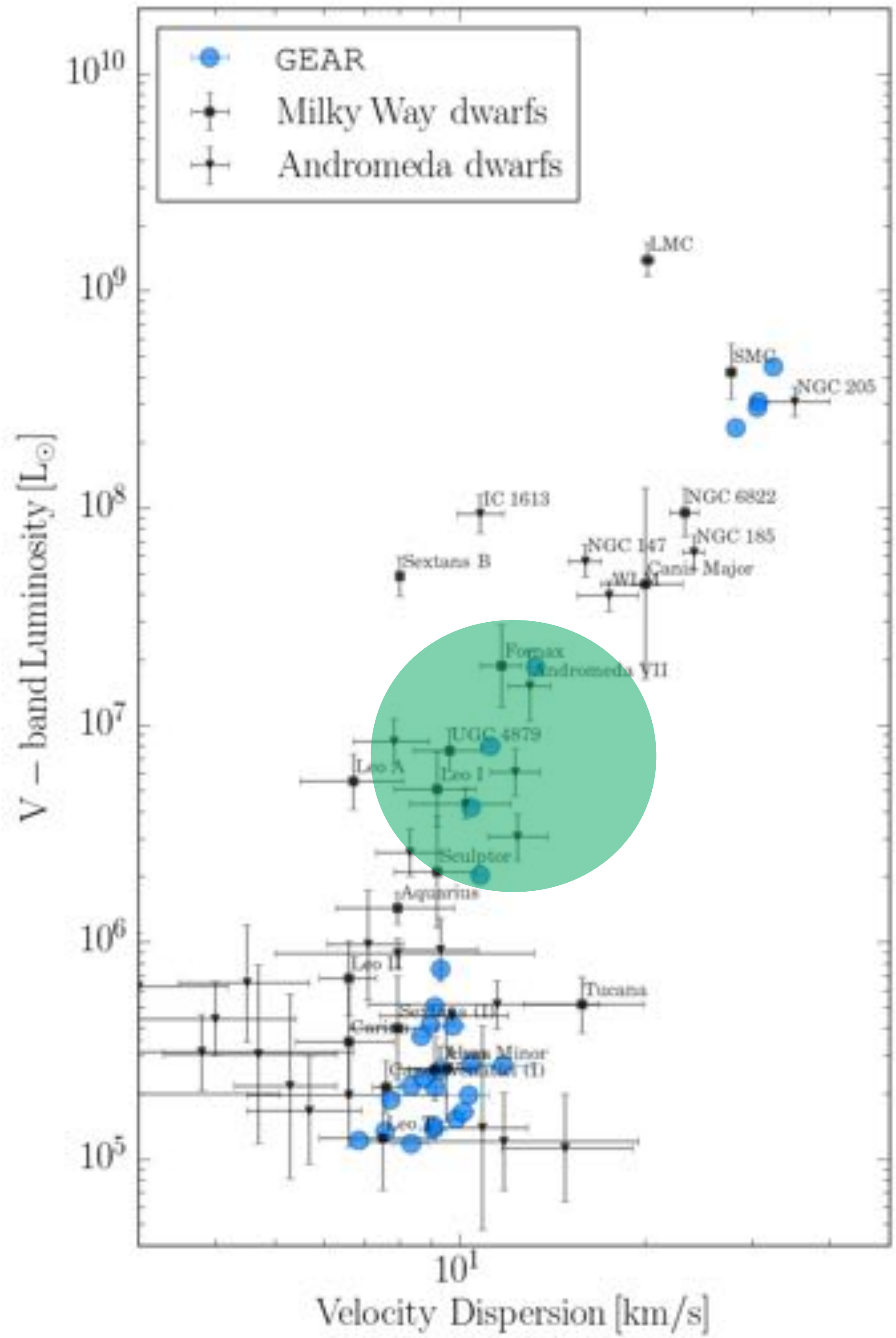
Quenched star formation histories

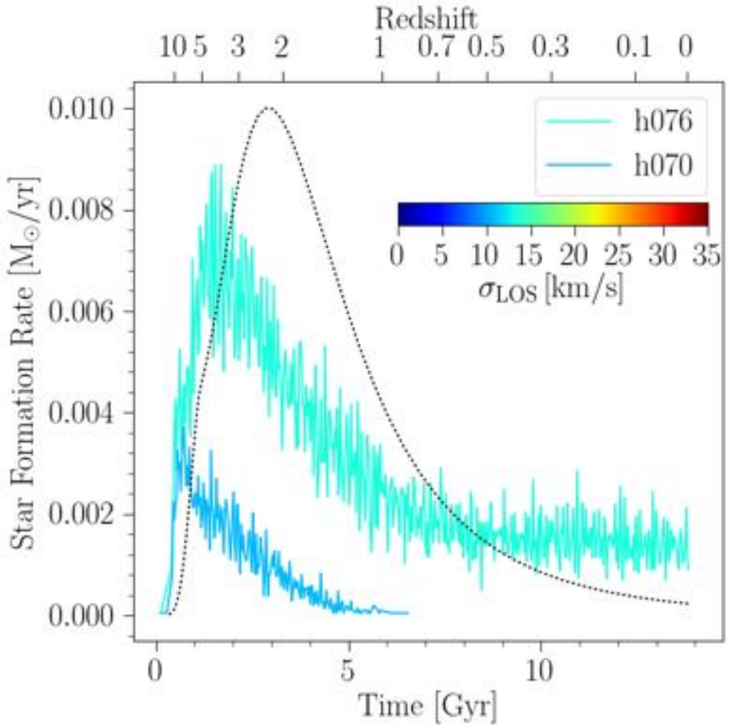
Ex:
- Ursa Minor
- Draco
- Sextans

quenched system

Ursa Minor model







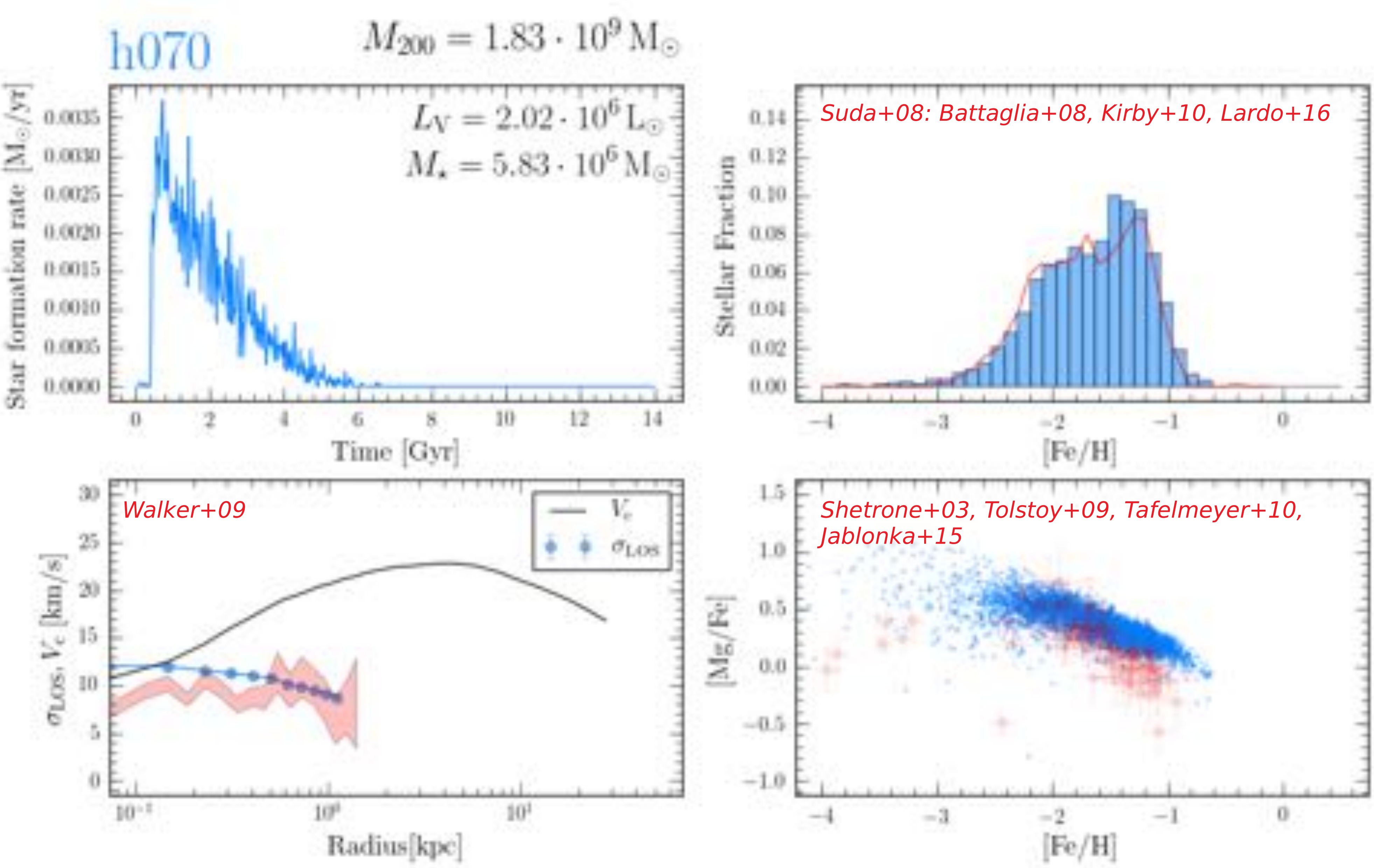
Extended star formation histories

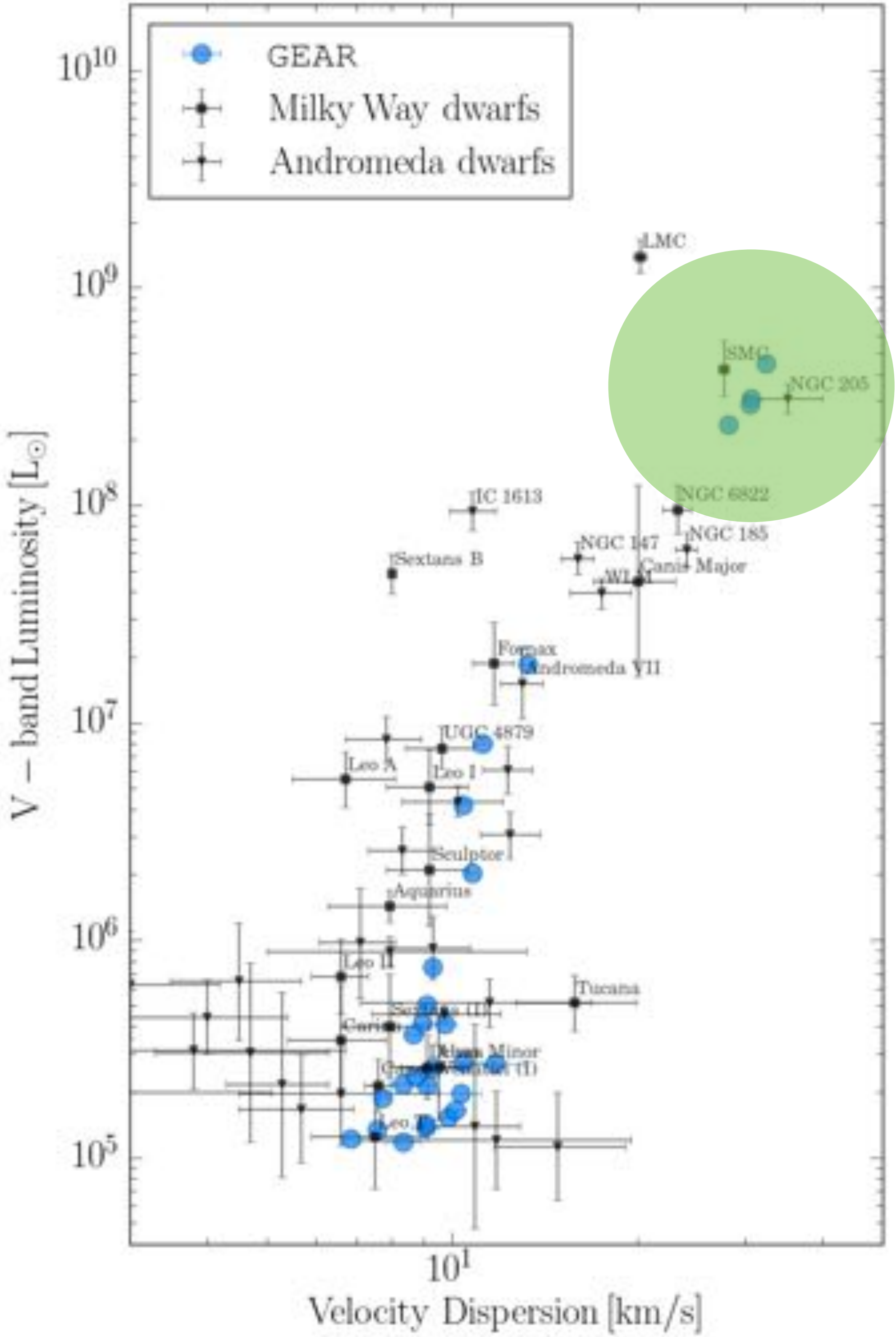
Ex: - Sculptor

- Andromeda II

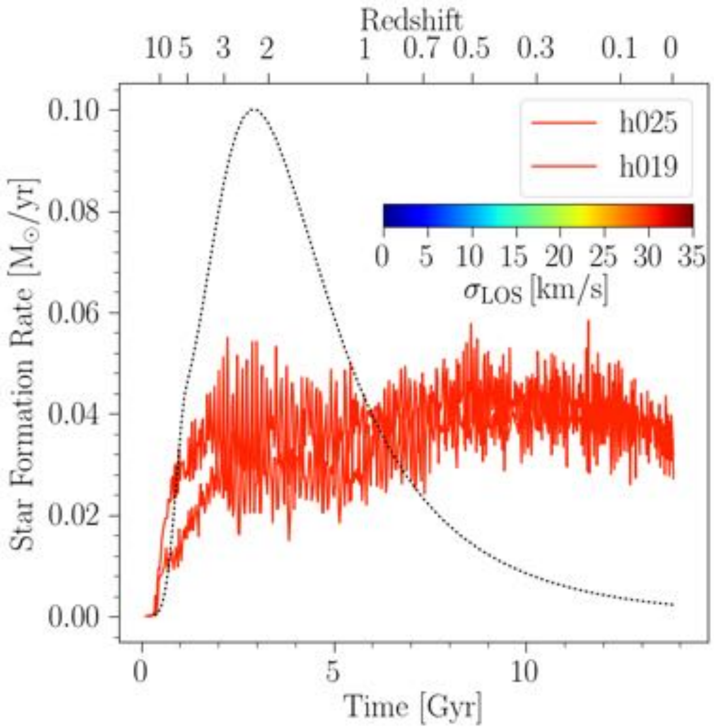
extended system

Sculptor model



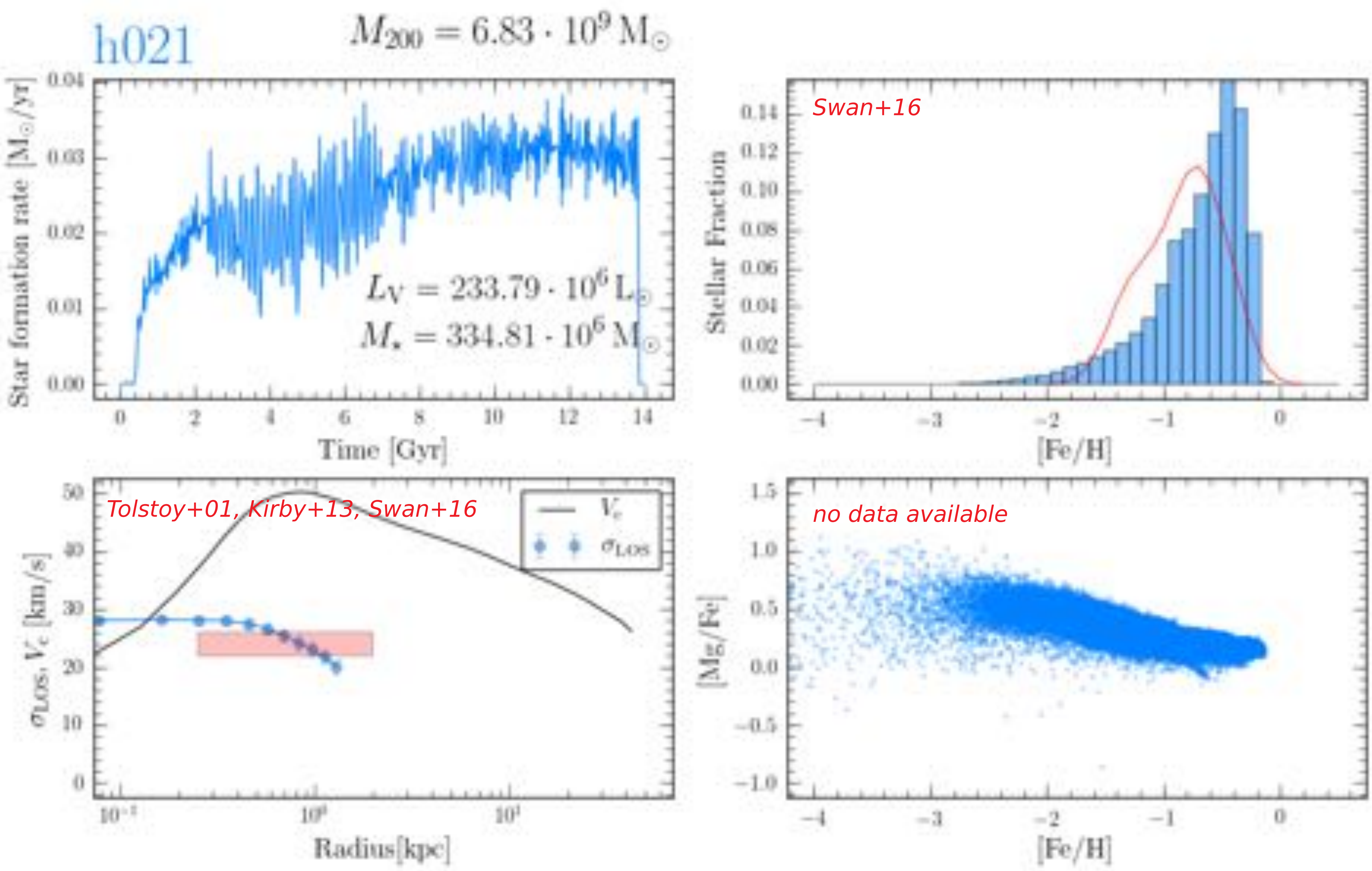


Sustainded star formation histories
Ex: - NGC 6822

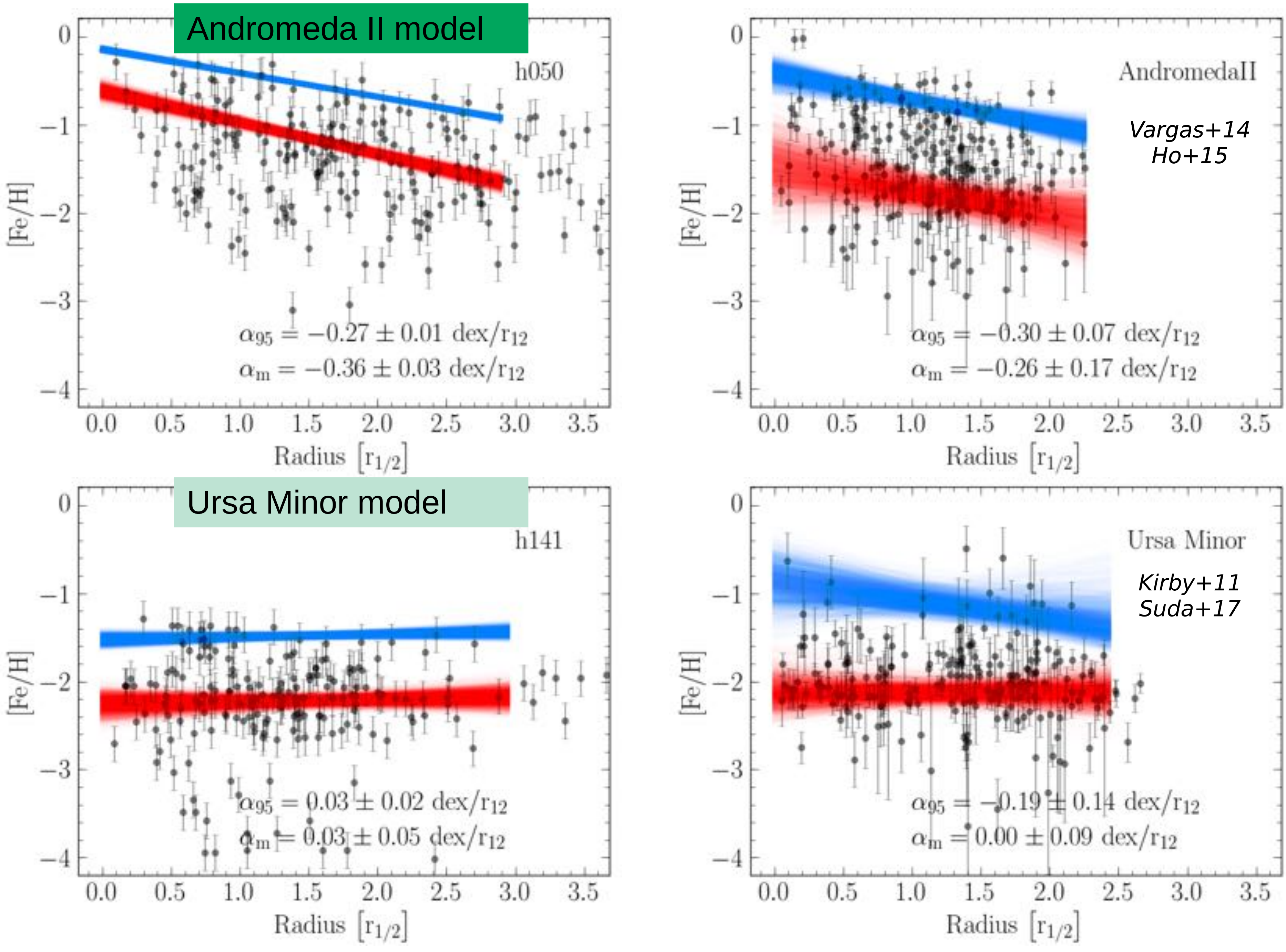


extended system

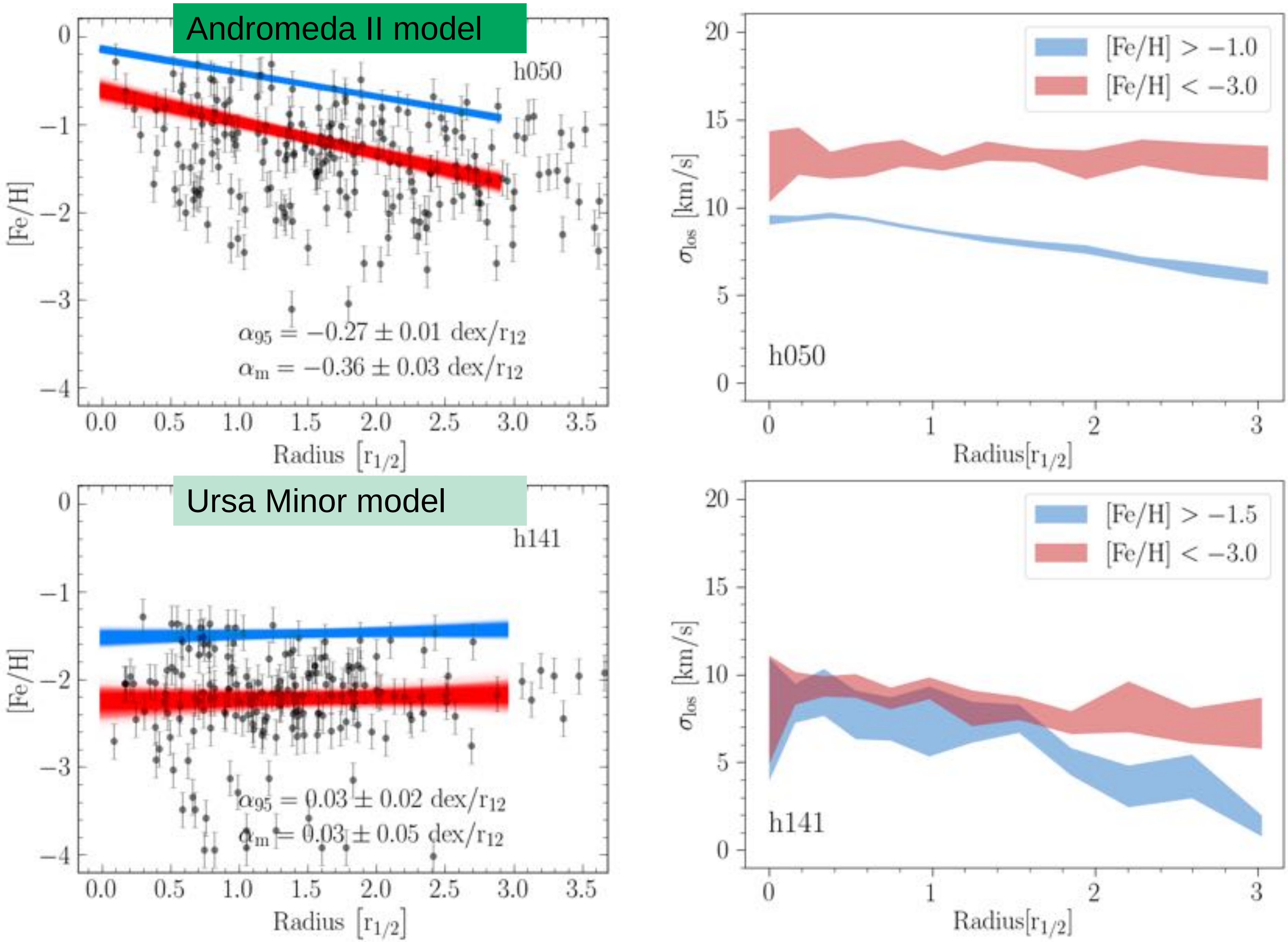
NGC 6822 model



Metallicity gradients

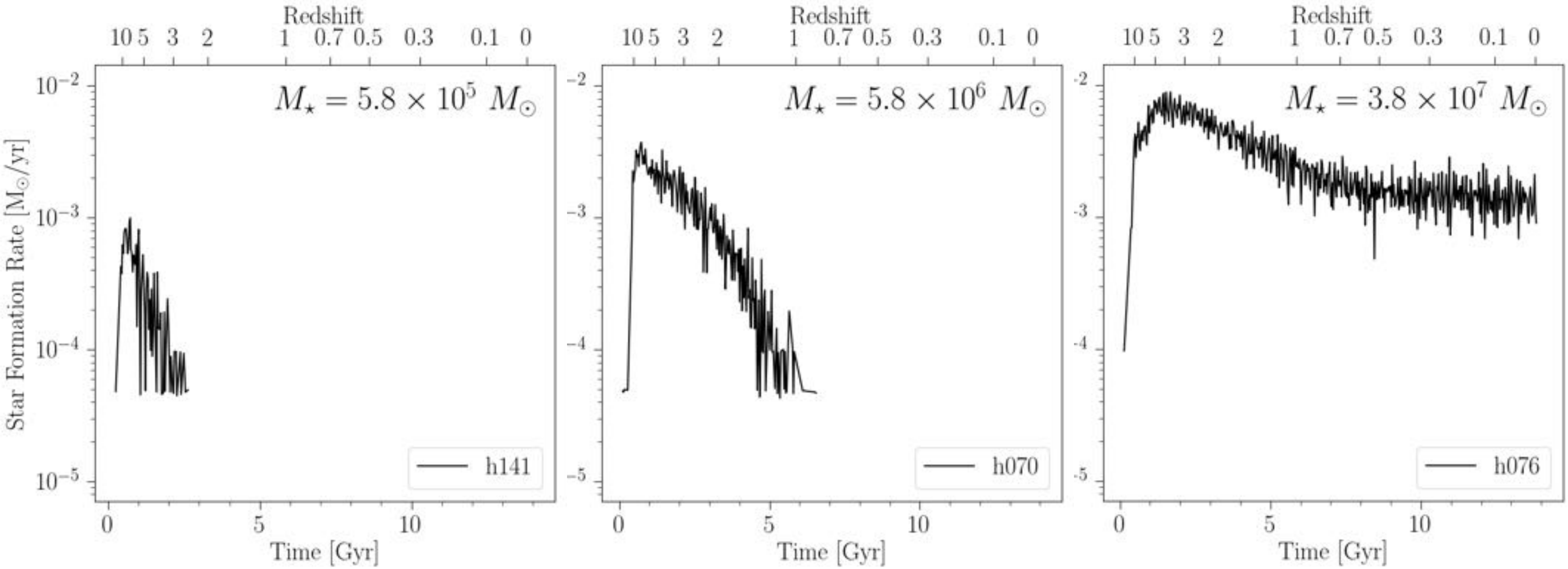


Kinematically distinct stellar populations



Burstiness of the star formation histories : impact on the Hydrogen morphology

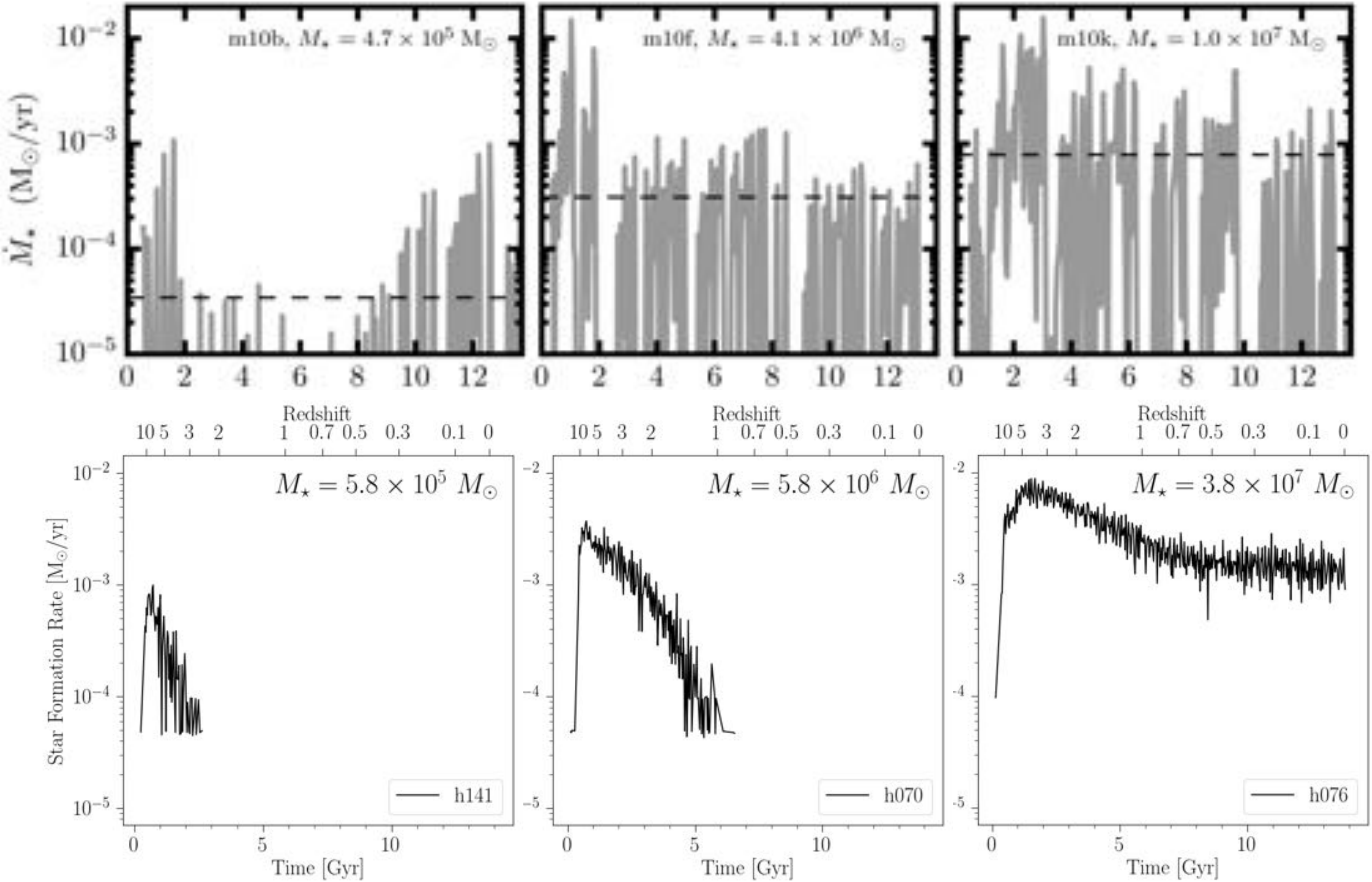
Revaz+2018




a=0.359 t=3.653 Gyr

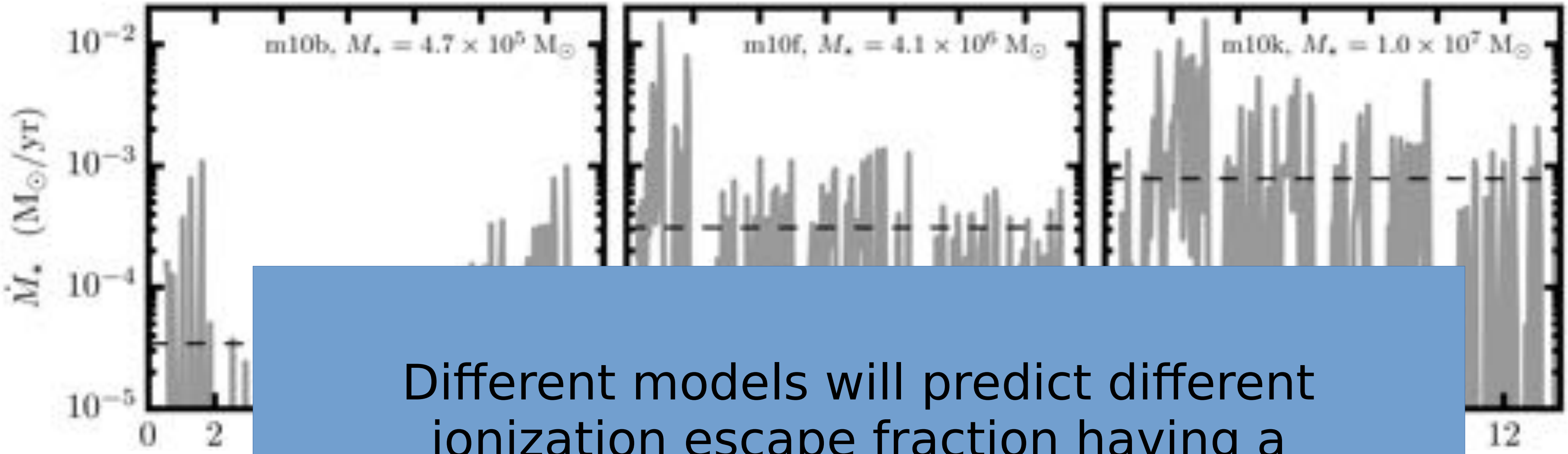
Burstiness of the star formation histories : impact on the Hydrogen morphology

FIRE simulations: *Fitts+2017*

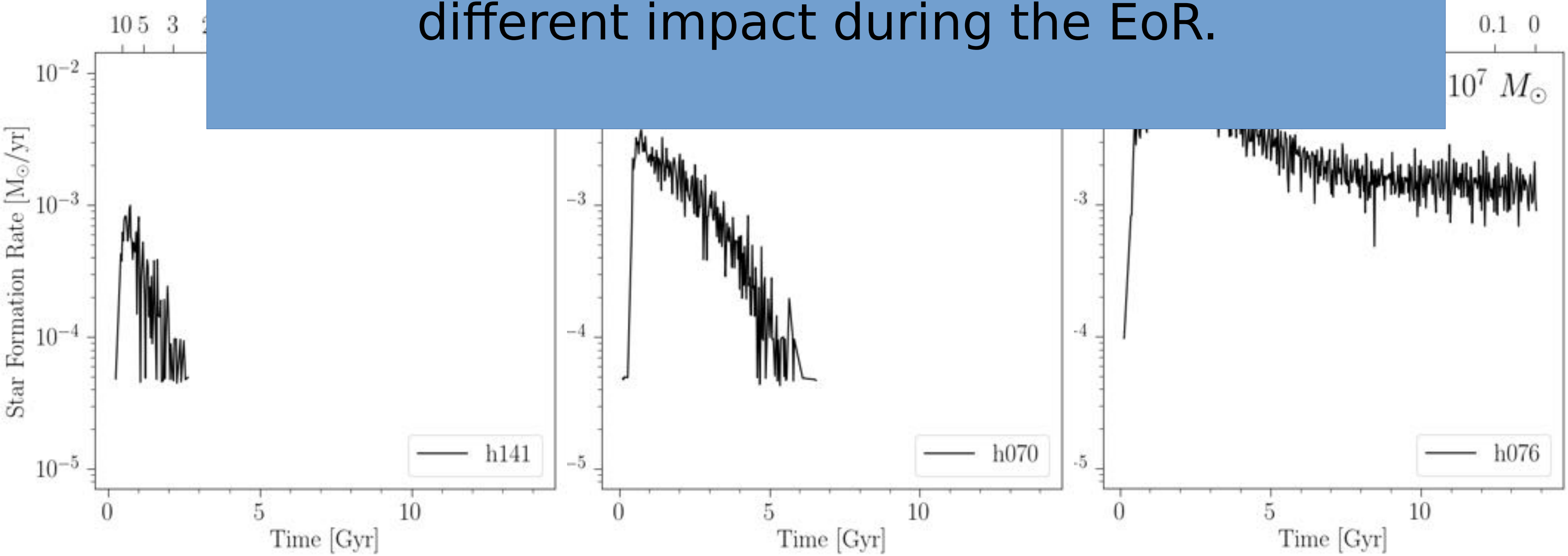


Burstiness of the star formation histories : impact on the Hydrogen morphology

FIRE simulations: *Fitts+2017*



Different models will predict different ionization escape fraction having a different impact during the EoR.



Conclusions

- It is essential to study dwarf galaxies in order to interpret the upcoming SKA observations of the EoR.

- An accurate comparison with local group observations is needed to calibrate cosmological numerical simulations and predict dwarf properties during the EoR.

- GEAR cosmological simulations of dwarf galaxies reproduce:

  - scaling relations
  - metallicity distribution functions, alpha-abundances ratios
  - line of sight velocity profiles
  - metallicity gradients
  - kinematically distinct stellar populations

Next steps:

- Include the effects of POP III stars

- Predict the escape fraction of ionizing photons using indirect probes like Ly-α radiation (*Verhamme+2015,2017*)

- Include a self-consitent treatment of the photons radiative transfer

The End