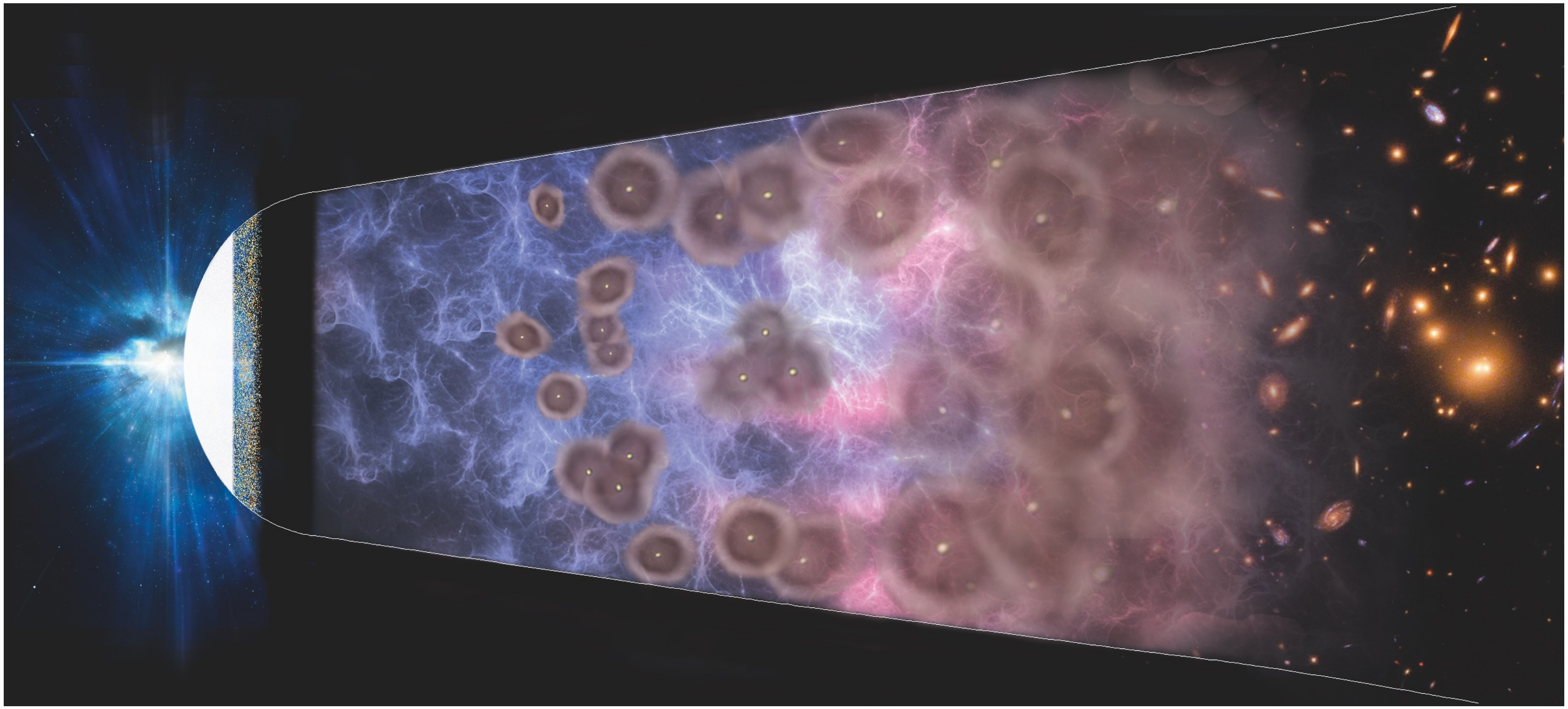
Early galaxy formation & its large-scale effects

Pratika Dayal



rijksuniversiteit groningen

DELPHi erc

NWO Netherlands Organisation for Scientific Research

Outstanding challenges

Linked to galaxy formation

- Minimum mass to which galaxies can form stars
- The star formation rates of early galaxies
- Escape of ionizing radiation
- Dust enrichment of early galaxies
- GW from the early Universe

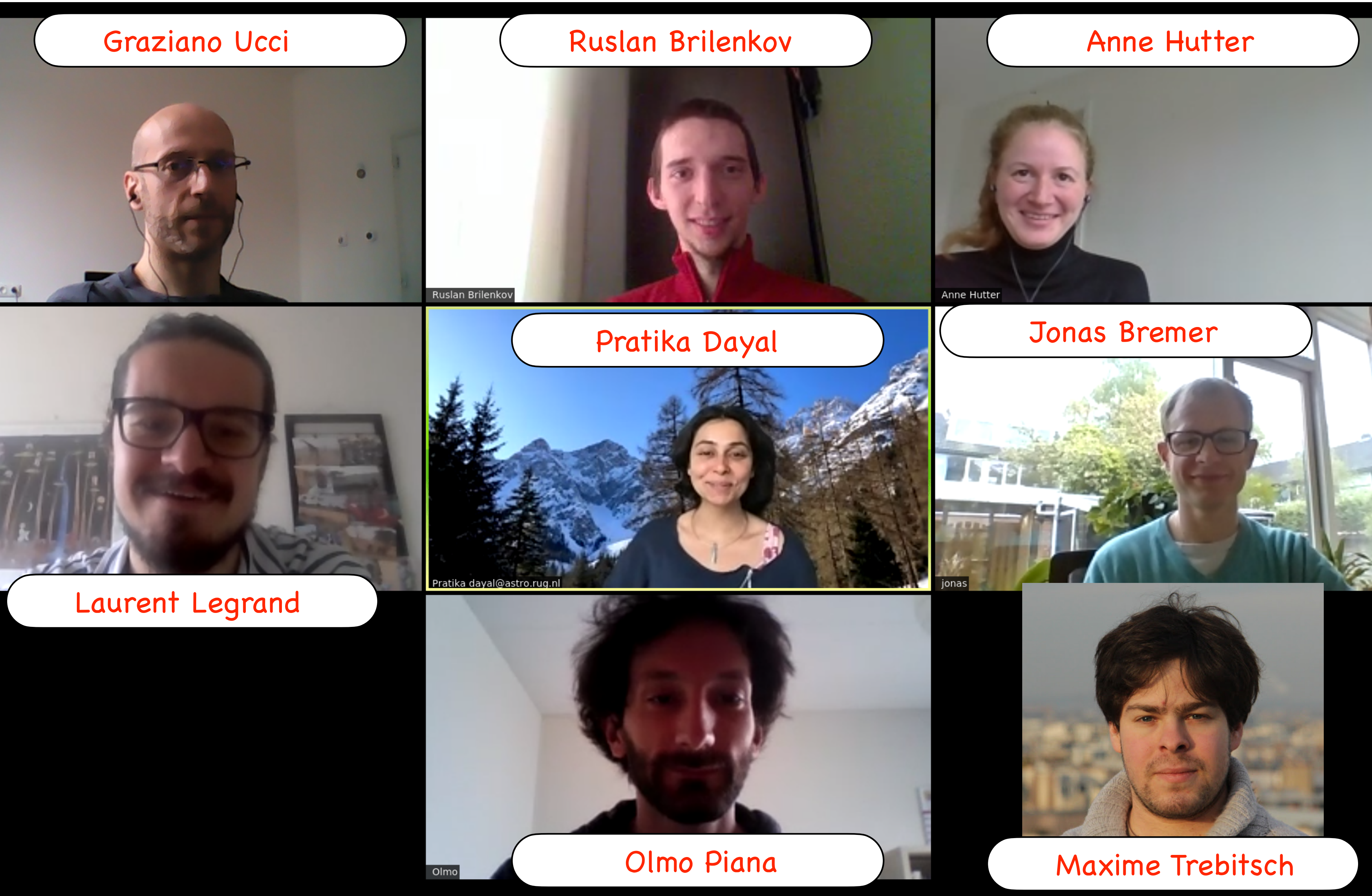
Linked to reionization

- External (UV) feedback impact
- Topology and history of reionization
- Key reionization sources (galaxies, BHs or..?)
- Using combination of galaxy and large scale data to constrain reionization in era of 21cm cosmology

Linked to cosmology

How can early galaxies be used to probe the cosmological model, specially in context of Dark Matter models

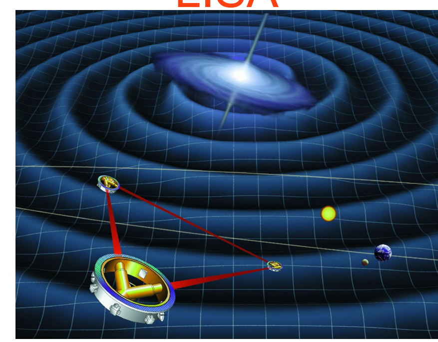
The team in Groningen



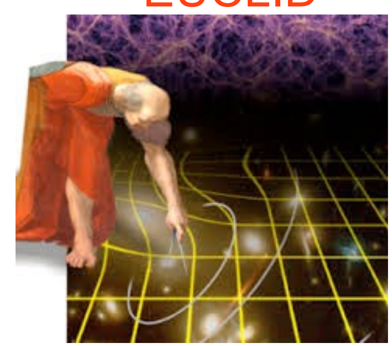
Key collaborators and collaborations

Rychard Bouwens: Leiden University, The Netherlands
Volker Bromm: University of Texas at Austin, USA
Marco Castellano: Observatory of Rome, Italy
Benedetta Ciardi: Max Planck Institute for Astrophysics, Germany
Tirthankar Choudhury: National Centre for Radio Astronomy, India
James Dunlop: Institute for Astronomy, U.K.
Andrea Ferrara: Scuola Normale Superiore, Italy
Stefan Gottloeber: Leibniz institute for Astrophysics, Germany
Hiroyuki Hirashita: ASIAA, Taiwan
Umberto Maio: Leibniz institute for Astrophysics, Germany
Antonella Maselli: University of Barcelona, Spain
Andrei Mesinger: Scuola Normale Superiore, Italy
Volker Mueller: Leibniz institute for Astrophysics, Germany
Noam Libeskind: Leibniz institute for Astrophysics, Germany
Fabio Pacucci: Harvard, USA
Laura Pentericci: Observatory of Rome, Italy
Elena Rossi: Leiden University, The Netherlands
Catherine Trott: ICRAR, Perth, Australia
Livia Vallini: Nordita, Stockholm, Sweden
Marta Volonteri: Observatory of Paris, France
Gustavo Yepes: Universita Autonoma di Madid, Spain…

LISA



EUCLID



Modelling reionization: evolution of volume filling fraction of ionized hydrogen

Fractional volume filled with ionized hydrogen

Growth of ionized regions due to ionizing photon output

Decrease in ionized region sizes due to recombination

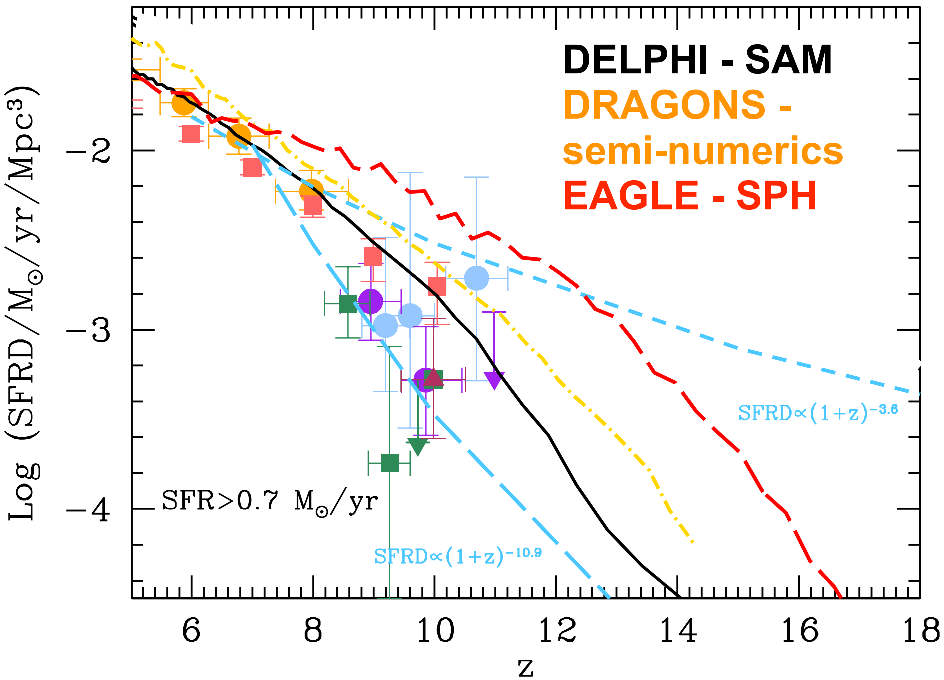
$$\frac{dQ_{II}}{dt} = \frac{dn_{int} f_{esc}}{dz} \frac{1}{n_H} - \frac{Q_{II}}{t_{rec}} \frac{dt}{dz}$$

$$t_{rec} = \frac{1}{\chi \, n_H \, (1+z)^3 \alpha_B \, C} \cdot$$

Measure of over-density as fn(space,time)

Dayal & Ferrara, 2018, Physics Reports, Volume 780, pg. 1-64

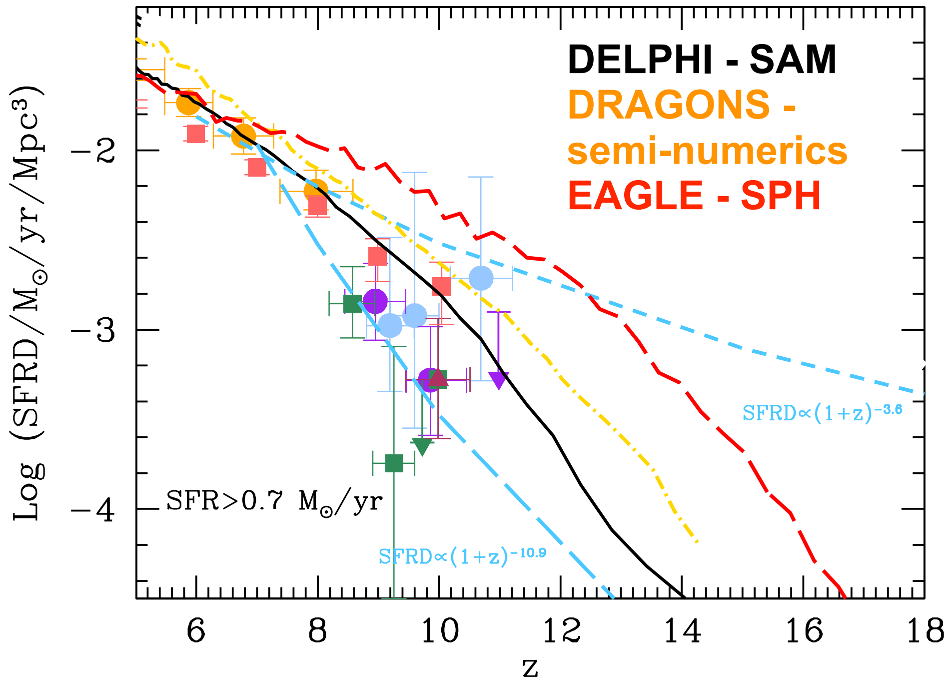
Modelling reionization: (some) basic problems



SFR density (used to model reionization) extremely uncertain at z>8.

Dayal & Ferrara, 2018, Physics Reports, Volume 780, pg. 1-64

Modelling reionization: (some) basic problems



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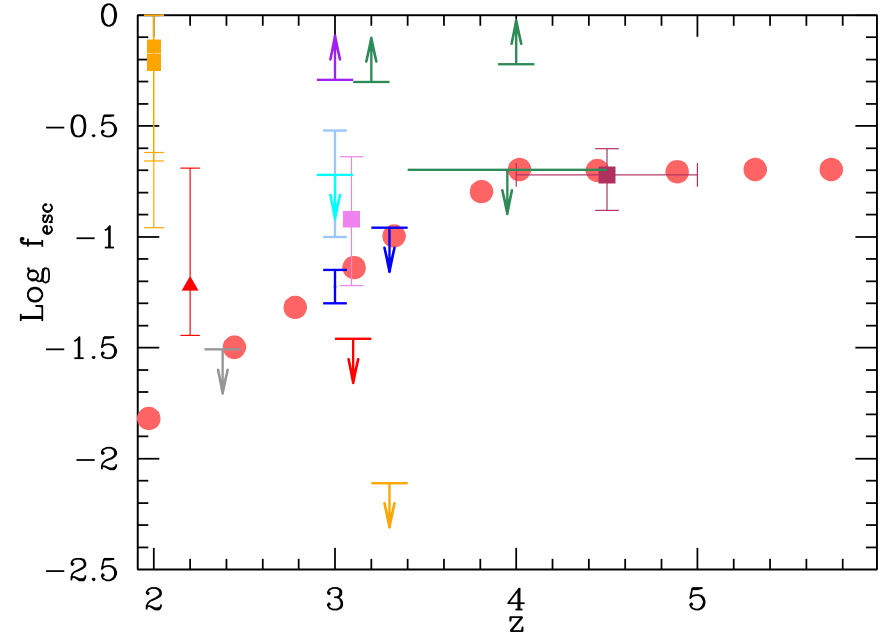
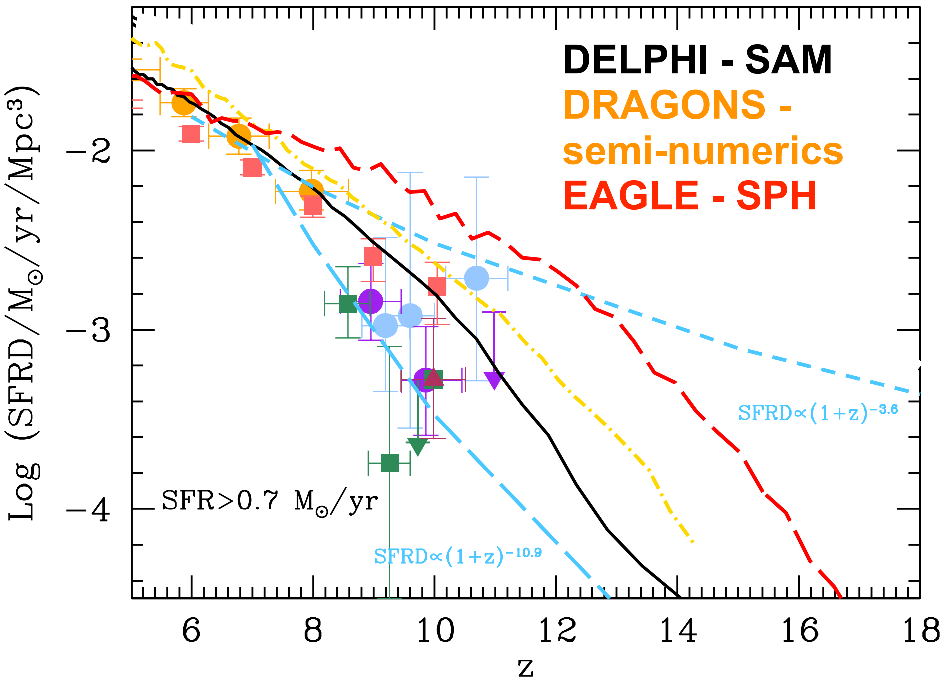


(Tentative) increase with z?

Modelling reionization: (some) basic problems



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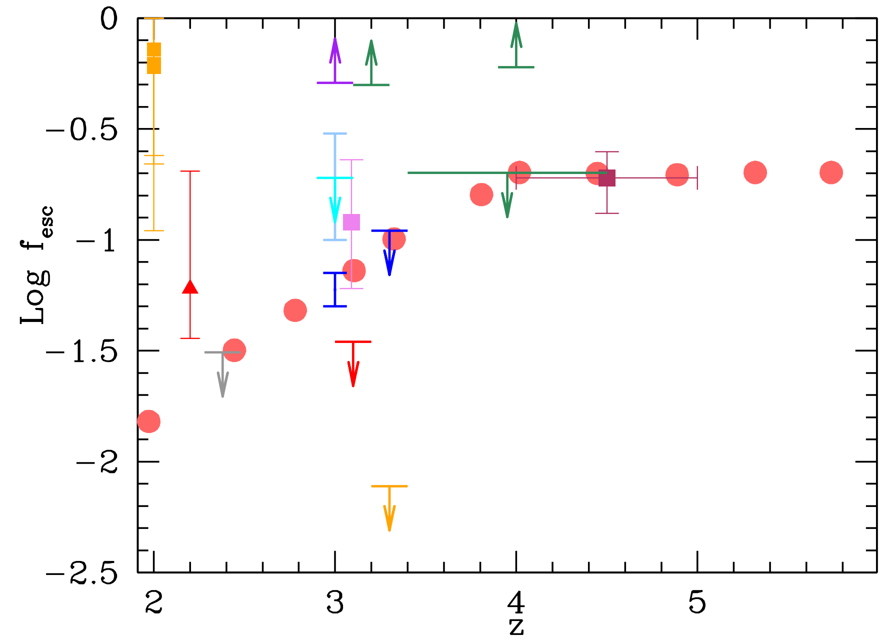
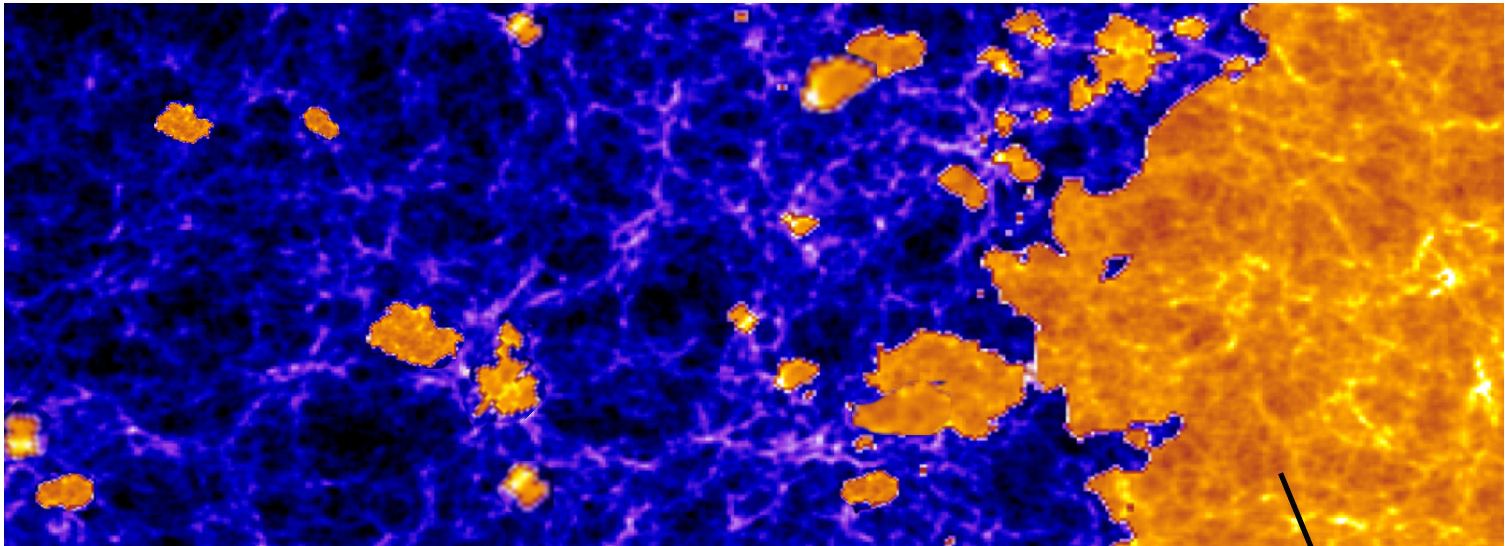


(Tentative) increase with z?

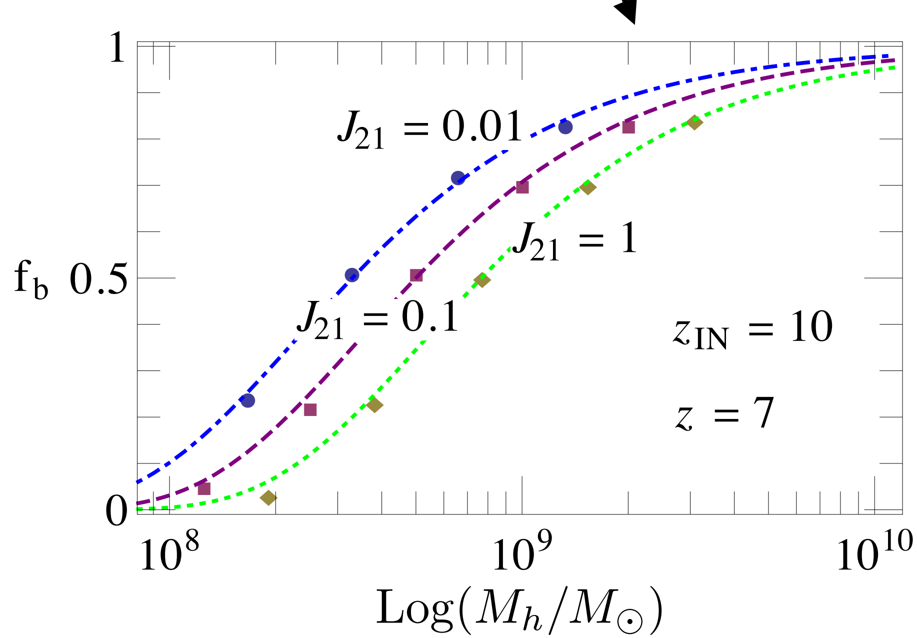
Key sources and topology (patchiness) of reionization fundamental open questions

A crucial problem: Reionization feedback on galaxy formation

Neutral hydrogen : T = T(CMB) **Ionized hydrogen : T ~ 20,000 K**



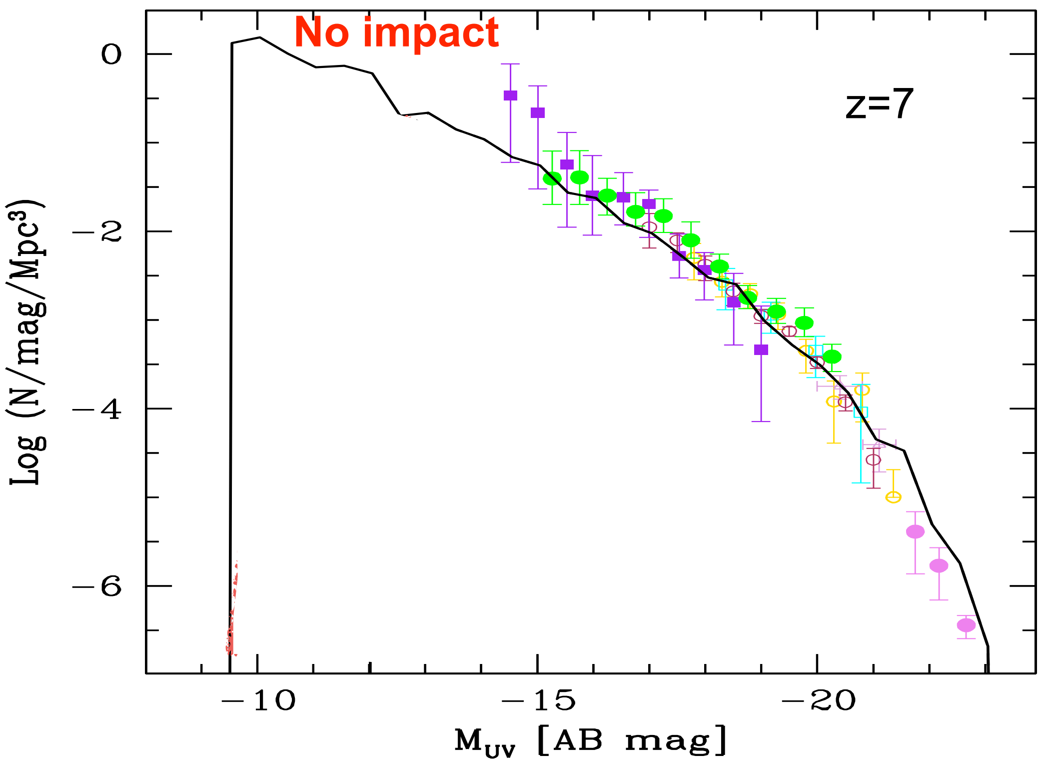
The UVB created during reionization can suppress the gas mass of low-mass galaxies. This suppression is a complex function of halo mass, strength of UVB, redshift of source and redshift at which the halo is irradiated by the UVB (Gnedin 2000; Sobacchi & Mesinger 2013)



Impact of reionization on galaxy formation remains debated

No impact

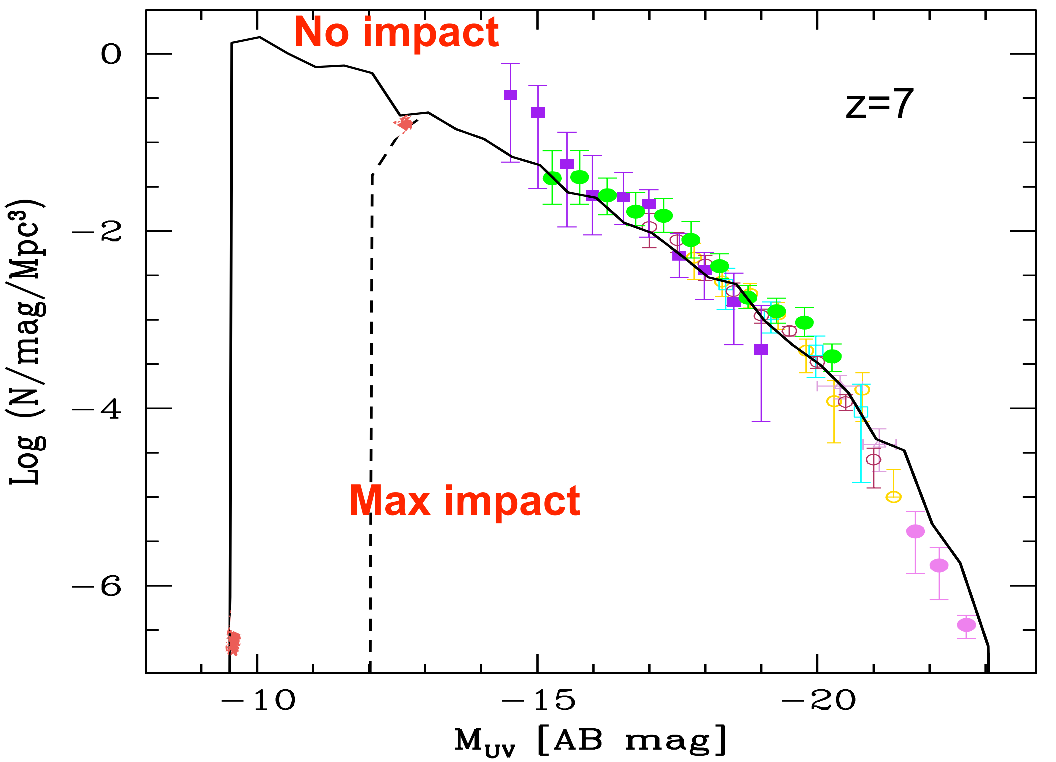
Gas too deep in potential well to be affected by UVB



Impact of reionization on galaxy formation remains debated

No impact
Gas too deep in potential well to be affected by UVB

Maximum impact
All galaxies below certain "critical" mass/velocity completely UVB suppressed.



Impact of reionization on galaxy formation remains debated

No impact

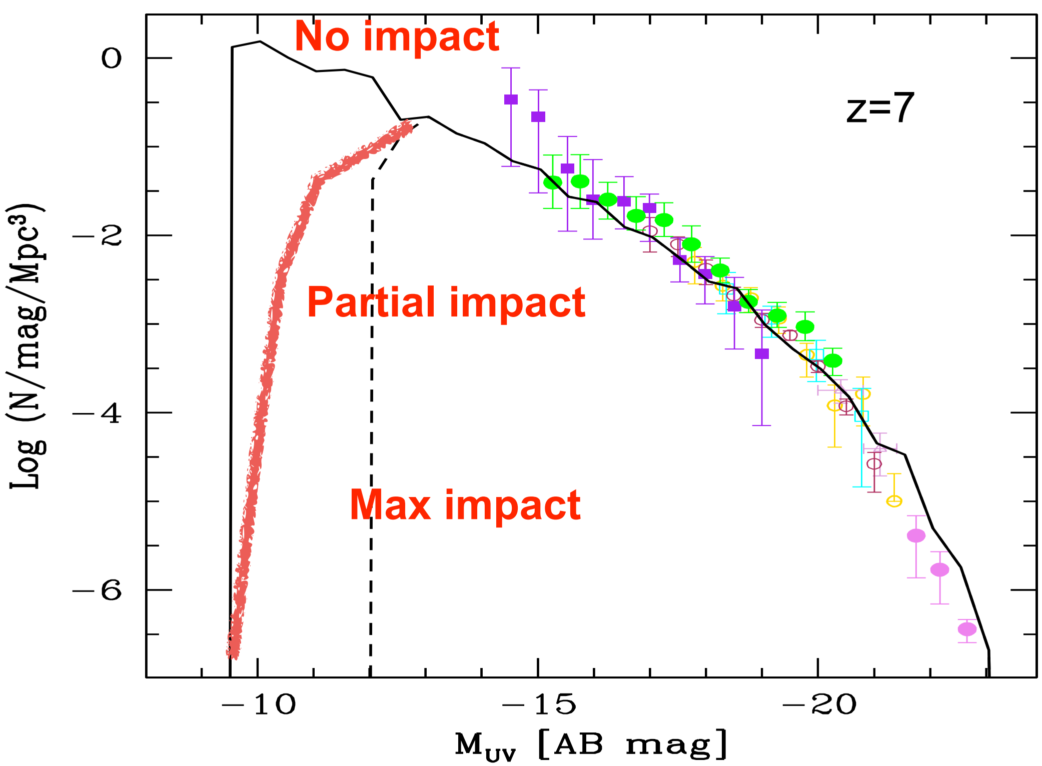
Gas too deep in potential well to be affected by UVB

Maximum impact

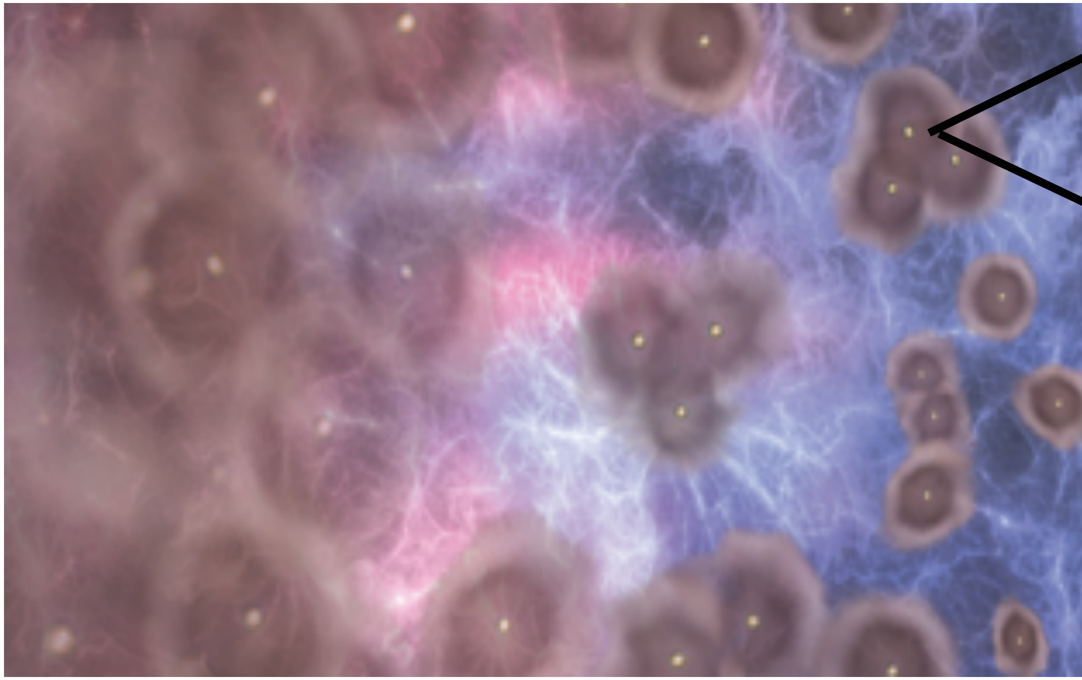
All galaxies below certain "critical" mass/velocity completely UVB suppressed.

Partial impact

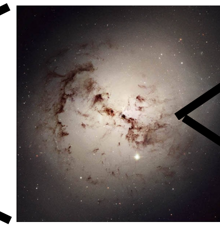
All galaxies below certain "critical" mass/velocity in ionized regions completely UVB suppressed.



The computational challenges: the scales required



Convergent reionization morphology
at scales ~ $(200h^{-1}\mathrm{Mpc})^3$



Galaxy sizes
~ 100 Kpc

MC sizes
~ 10-100 pc
(fesc)

- **Coupling galaxy formation with reionization requires modelling over 7 orders of magnitude in physical scales.**
- **Following reionization over the required convergence scales requires ~280 Mpc simulations with a mass resolution of about 10^6 solar masses.**
- **A self-consistent full coupling would require such hydro simulations to be fully coupled with RT.**

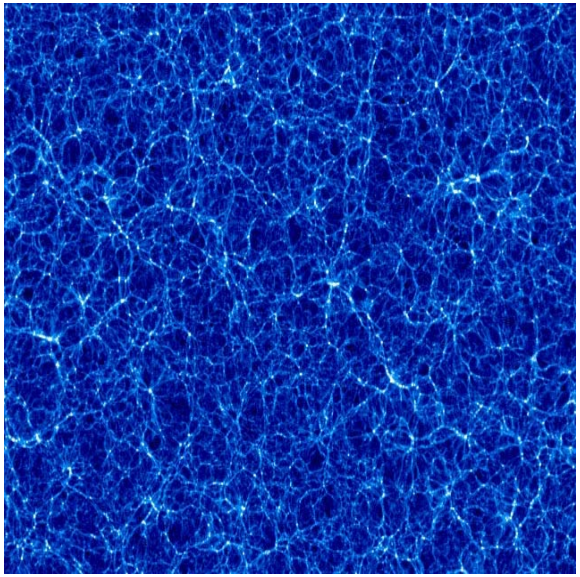
Enormous ongoing theoretical effort to model the EoR

No.	Main aim	Technique	box size [cMpc]	M_{DM} [$M_\odot$]	Key Physics	Code [reference]
				Small-scale models		
1	SF in GMC	Resimulated	1–10 R_{vir}	$\sim 10^2$–10^6	AIKO	FIRE [136]
2	SF, GF, EoR	AMR	1	1840	DIKO	[137]
3	GF, EoR	AMR+RT	4 h^{-1}	4×10^6	EO	EMMA [138]
4	UV fb	SPH+RT	5	2.5×10^5	EIO	[139]
5	UV fb, GF	SPH+RT	3-6 h^{-1}	0.18–1.4×10^6	GIKO	[140]
6	ISM,CGM	AMR	9.7 h^{-1} kpc	9.5×10^4	AIKL	[141]
7	UV fb, GF	SPH+RT	10 h^{-1}	4.3×10^7	GIO	[142]
8	GF, EoR	Eulerian+RT	20	4.8×10^5	EIKO	[143]
9	GF, EoR	AMR	40	3×10^4	diko	Renaissance [144,145]
10	GF, EoR	AMR+RT	20–40 h^{-1}	7×10^6	AIO	CROC [146]
				Intermediate-scale models		
1	GF, EoR	N-body+semi-numerical RT	100	3.9×10^6	DIKO	DRAGONS [147]
2	GF	SAM	–	$M_{min} = 10^8$	CIP	DELPHI [148]
3	EoR (LG)	Eulerian+RT	91	3.5×10^5	EIO	CoDA [149]
4	GF, EoR	SPH+ RT	12.5–100 h^{-1}	10^6–8×10^7	EIKO	Aurora [150]
5	f_{esc}	SPH	10–100 h^{-1}	6×10^6–9×10^8	GIKLM	[151]
6	GF	SPH	25–100 h^{-1}	1.2–9.7×10^6	FIJKM	EAGLE [133]
7	GF	Unstructured mesh	106	6.2×10^6	GIJK	Illustrus [152]
				Large-scale models		
1	EoR	N-body+RT	114–425 h^{-1}	0.55–5×10^7	HO	[134]
2	GF	SPH	400 h^{-1}	1.7×10^7	GIJKM	BlueTides [153]
3	GF	SAM	500 h^{-1}	1.3×10^9	BIJKP	GALFORM [154]
4	**GF+EoR**	**N-body+SAM_RT**	**160/h**	**9.2×10^6**	**CIKLO**	**Astraeus**

PD & Ferrara, 2018, Physics Reports,780, 1

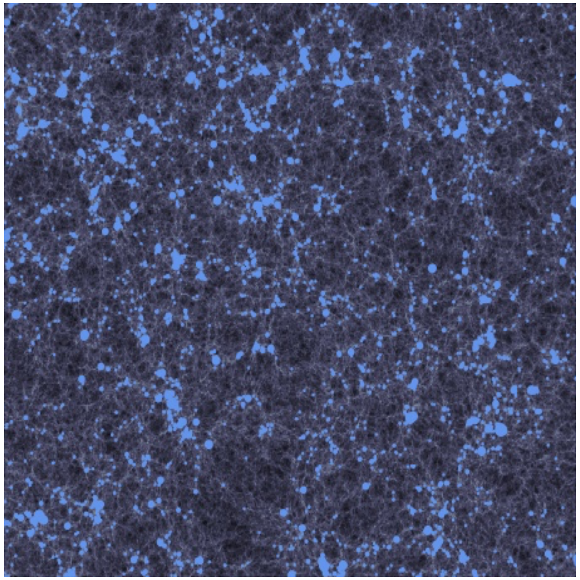
Astraeus framework: coupling galaxy formation and reionization

N-body simulation

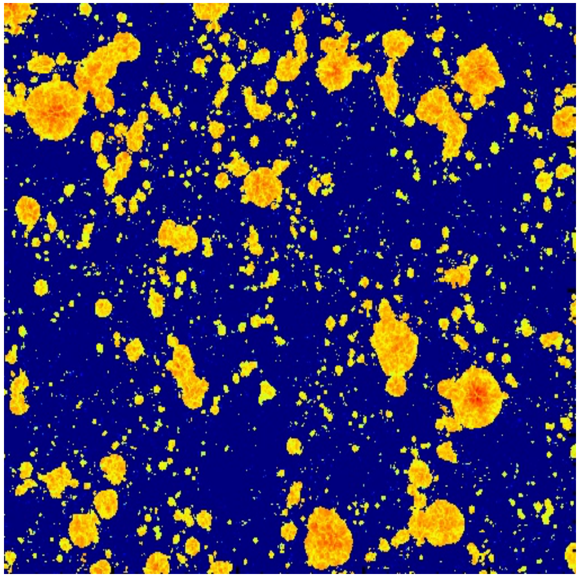


160 h^{-1} Mpc; 3840^3

Galaxy formation (DELPHI)



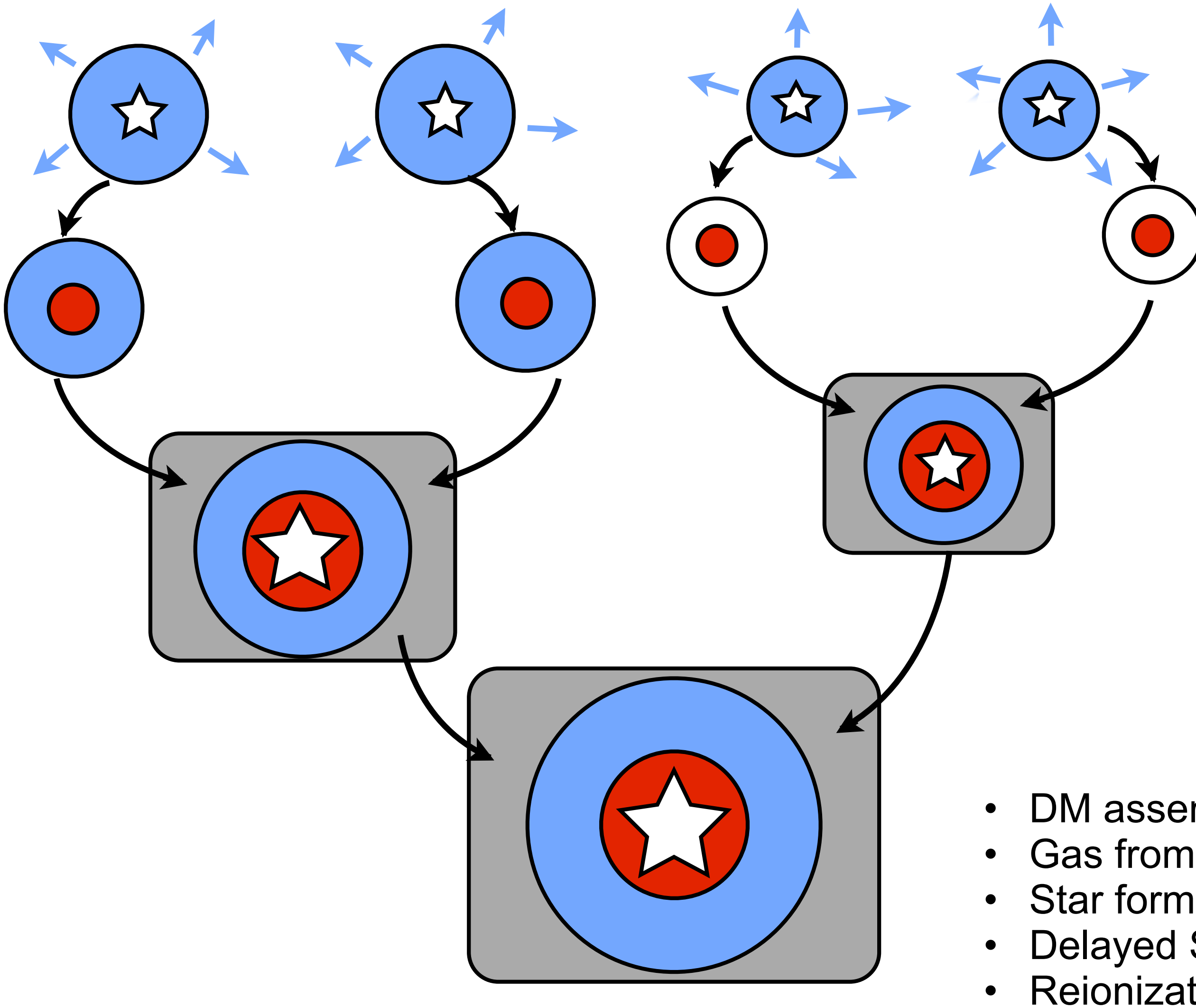
Reionization (CIFOG)



Astraeus: semi-numerical rAdiative tranSfer coupling of galaxy formaTion and Reionization in N-body dArk mattEr simUlationS

Astraeus I: Hutter, PD et al. (arXiv:2004.08401)
Astraeus II: Ucci, PD et al. (arXiv:2004.11096)
Astraeus IIII: Hutter, PD et al. (arXiv:2008.13215)

Key physics implemented in Delphi



- DM assembly from N-body simulation
- Gas from accretion & mergers
- Star formation based on halo potential
- Delayed SN feedback
- Reionization feedback

Exploring a wide range of reionization feedback models

Characteristic mass - halo mass at which half of baryons can be retained.

Models explored:

- **minimum feedback** - only halos below a fixed virial temperature affected
  - gas affected after dynamical time

- **heating models** - characteristic mass depends on IGM temperature (10^4 - $4x10^4$ K)
  - gas affected after dynamical time
  - escape fraction constant/increases with decreasing mass

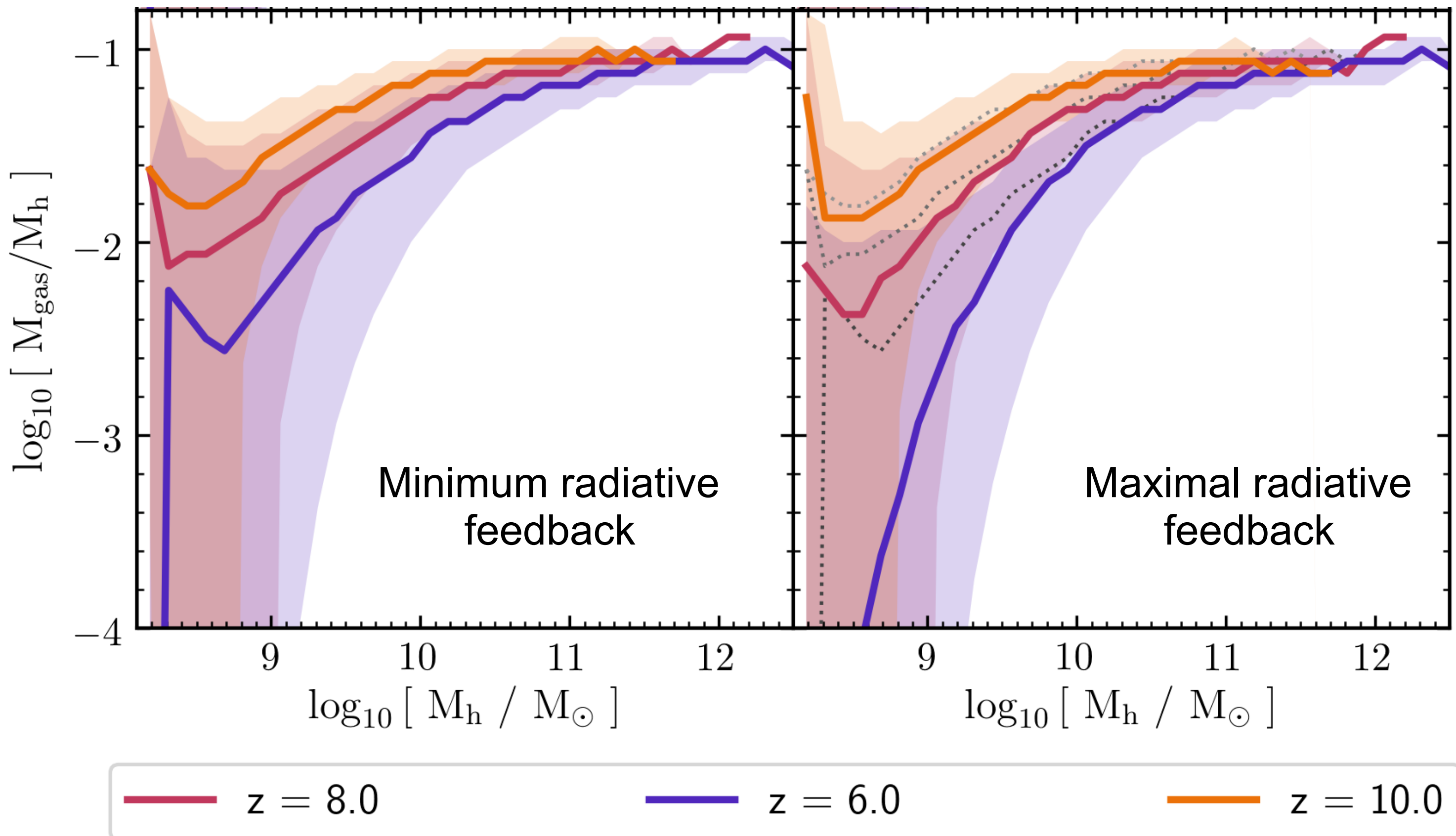
- **photoionization model** - characteristic mass depends on intensity of UV background
  - gas affected after dynamical time

- **Instantaneous model** - characteristic mass depends on IGM temperature ($4x10^4$ K)
  - gas affected instantaneously

- No impact of reionization feedback in "minimum" reionization feedback model
- For all other models, the earlier a galaxy is hit by the UV background, stronger is the impact of radiative feedback.
- Higher the IGM temperature, stronger is the impact of radiative feedback.

Astraeus I: Hutter, PD et al. (arXiv:2004.08401)

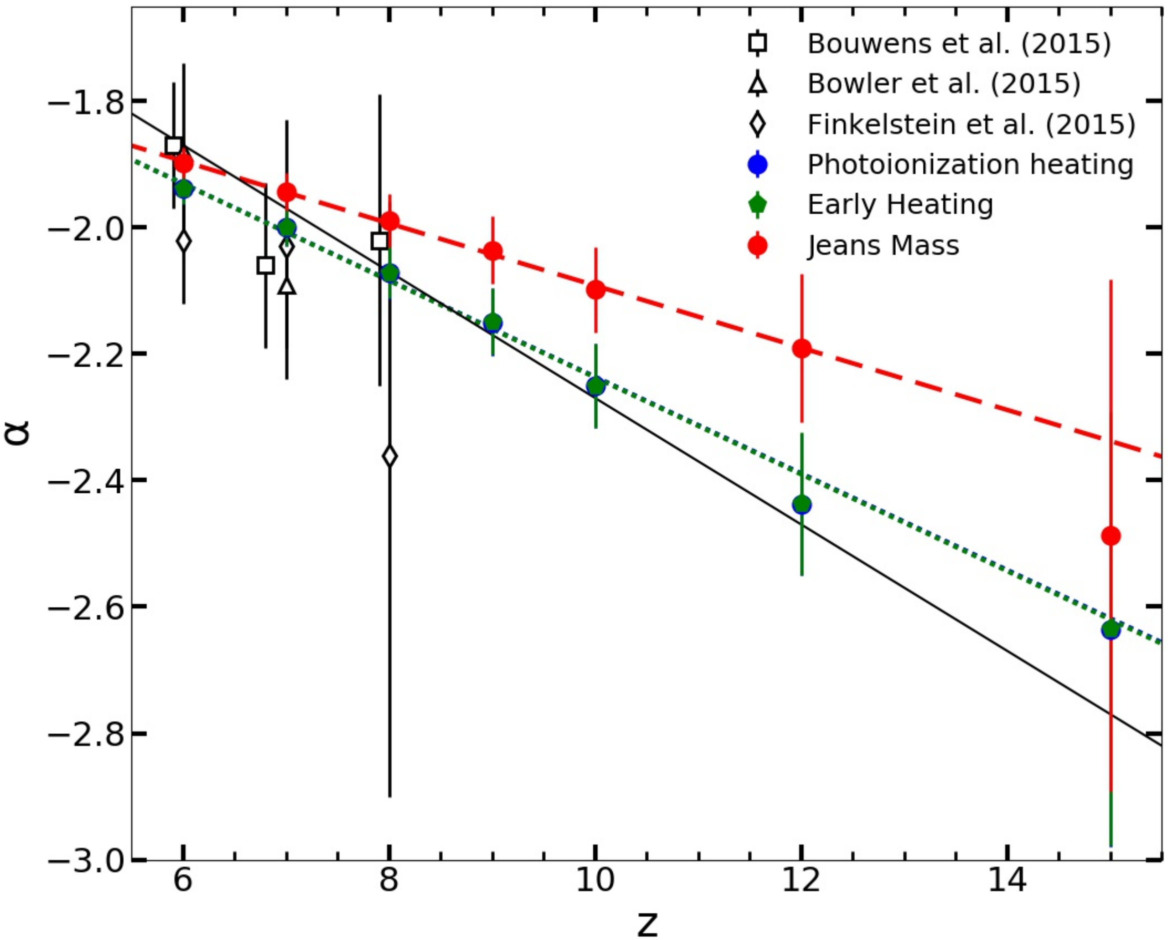
Impact of radiative feedback on gas fractions



- Gas fractions (and SFR) of low mass galaxies (<10^9 solar masses) most affected by radiative feedback.
- Effect of radiative feedback increases with decreasing redshift.

Astraeus I: Hutter, PD et al. (arXiv:2004.08401)

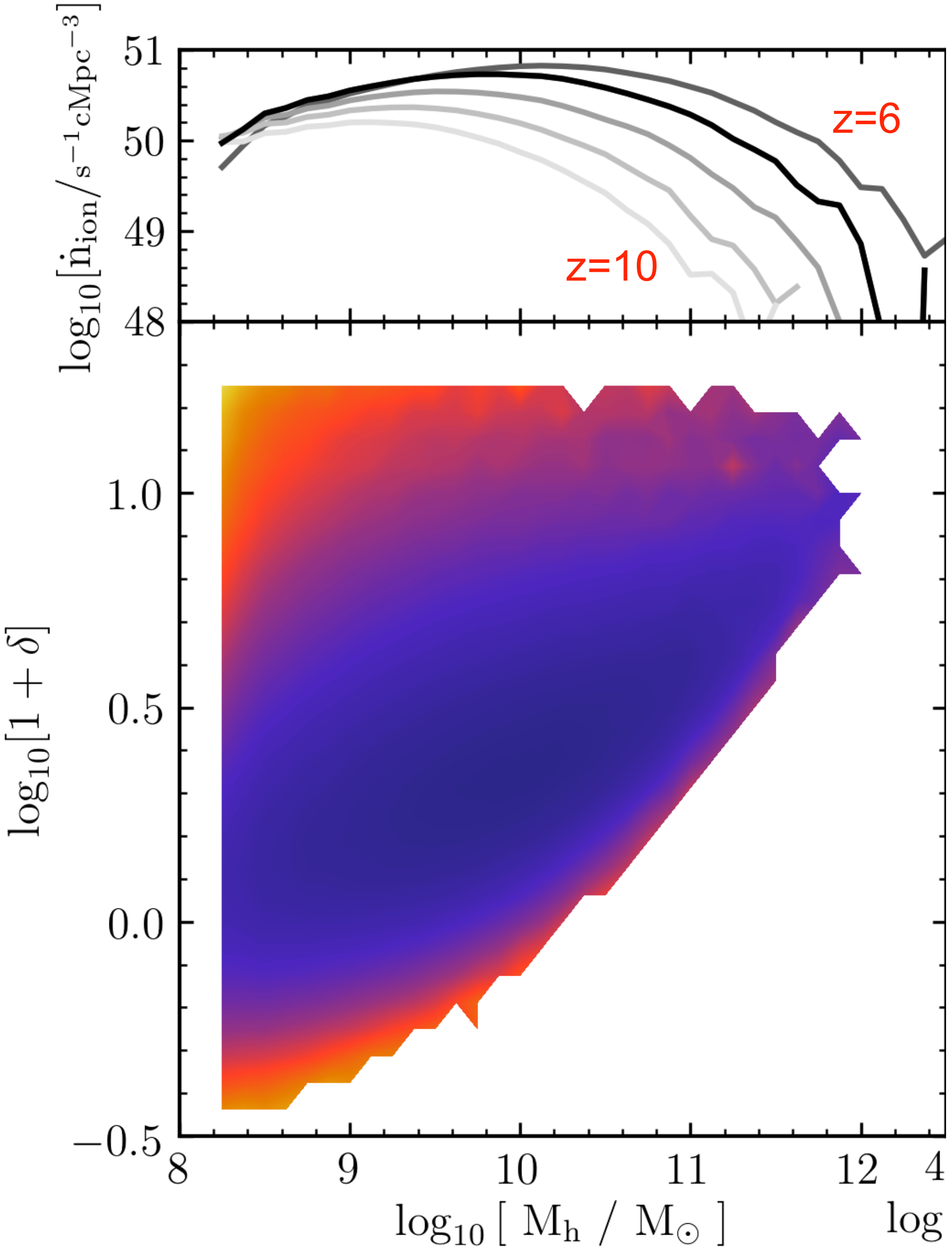
Faint end slope of the UV LF - hints on radiative feedback



- Faint-end slope shallows with decreasing z.
- Even accounting for cosmic variance, at z>9, JWST observations can distinguish between different radiative feedback models

Astraeus II: Ucci, PD et al. (arXiv:2004.11096)

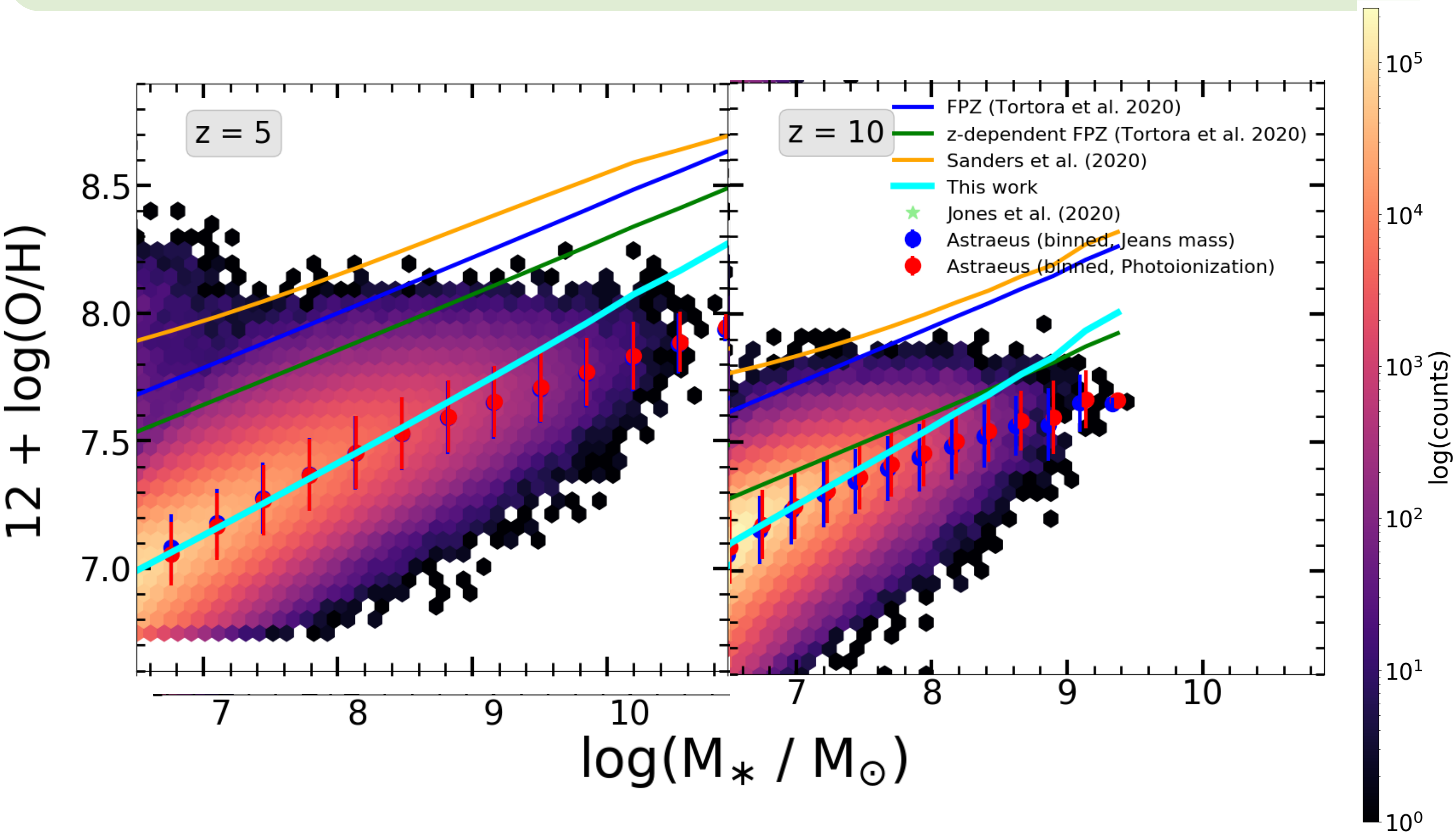
Where do most reionization photons come from?



- Most ionizing photons from intermediate halo mass (~10^{9-10}) galaxies in slightly over-dense regions.
- Majority of photons from galaxies whose halo mass corresponds to underlying density
- Stronger the impact of radiative feedback, lower is contribution of low-mass halos.

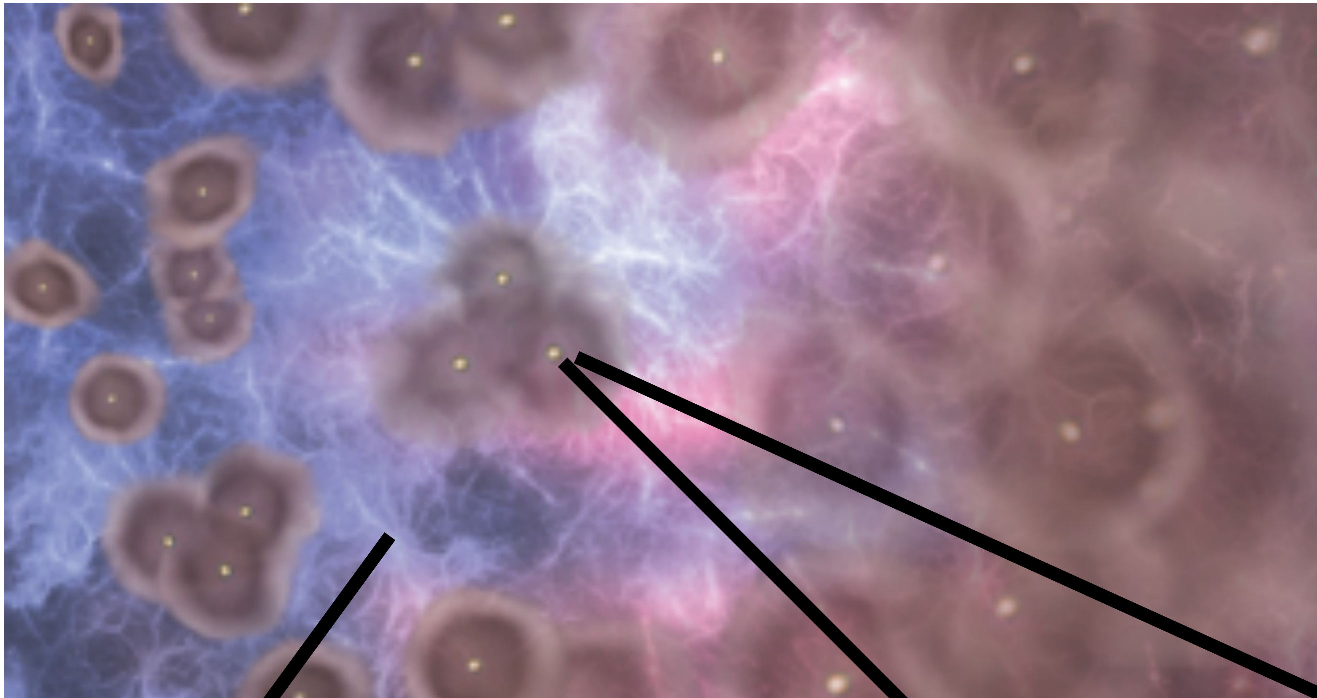
Astraeus IIII: Hutter, PD et al. 2021

Emergence of metallicity scaling relations



Mass-metallicity relation already in place at z~10 (Ucci et al., in prep, 2021)

Using a combination of 21cm and galaxy data to constrain the EoR



SKA EoR Synergy group

Euclid EoR group

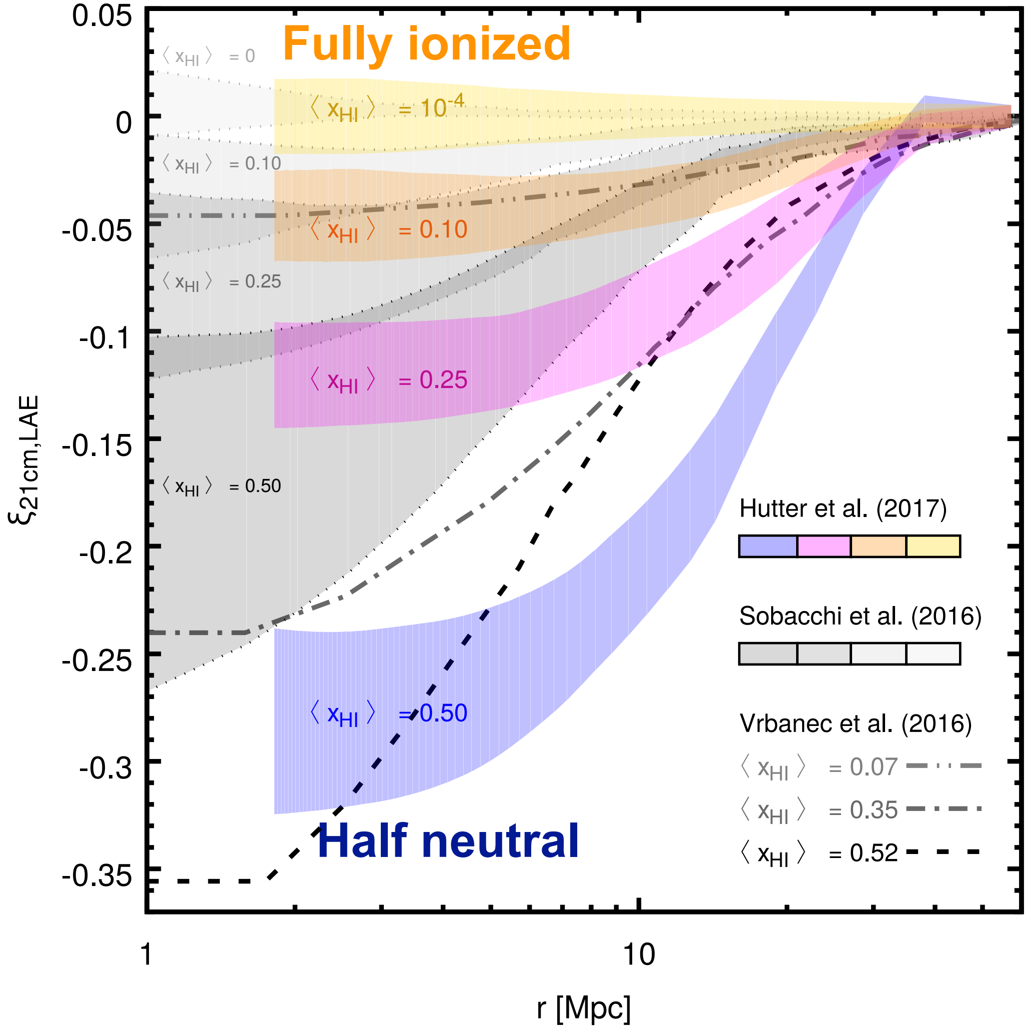
21cm emission from neutral hydrogen

Galaxy populations
HST, VLT, Subaru,
JWST, E-ELT, EUCLID

SMBH hosts
LISA

Cross-correlating 21cm data with (spectroscopically confirmed) galaxy data will yield information on reionization state & topology

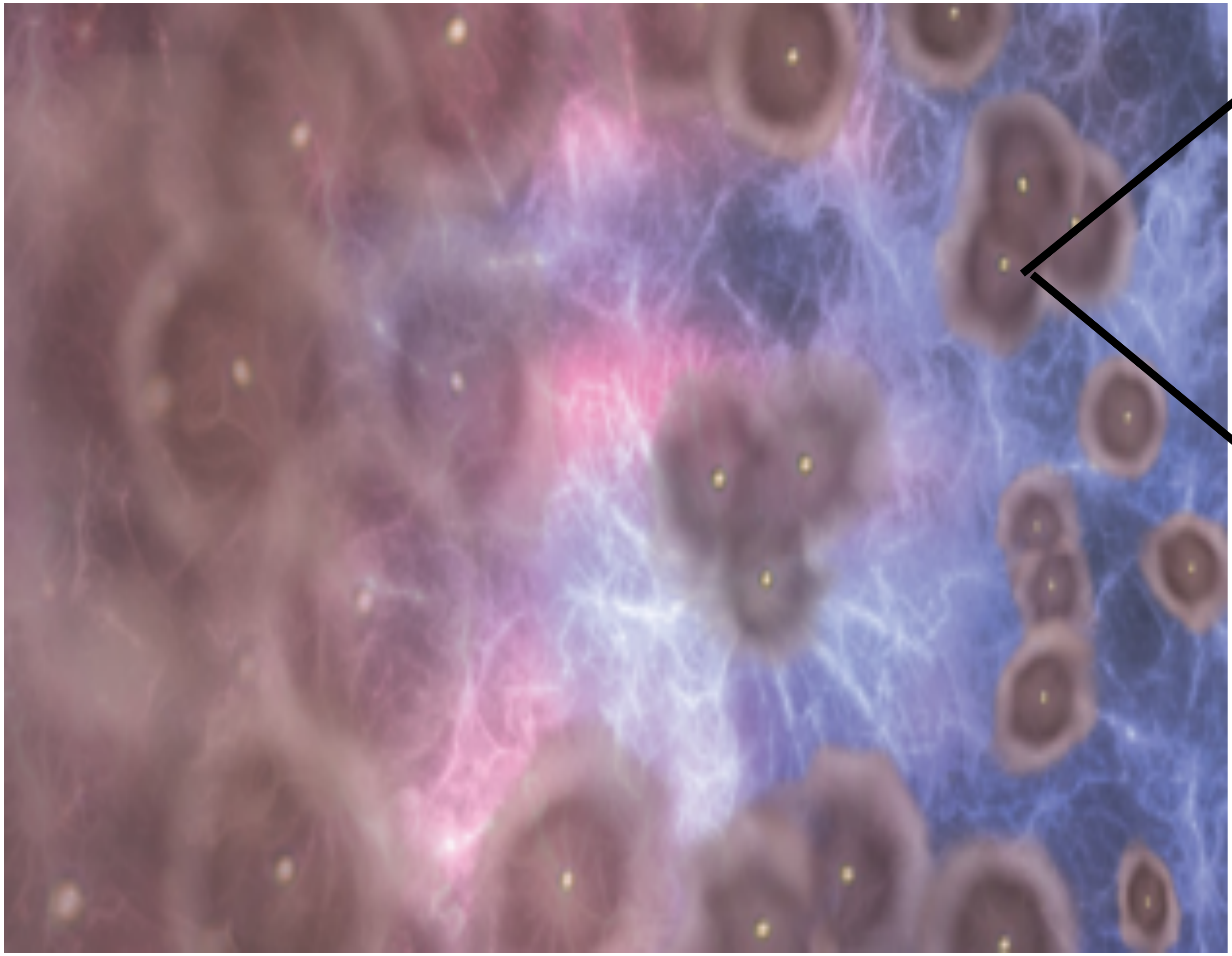
The 21cm-LAE cross-correlation: pilot results

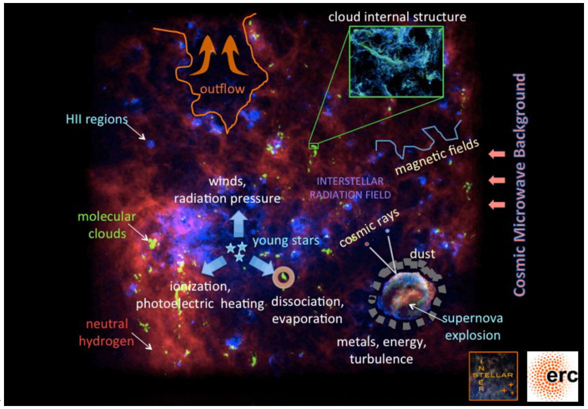


Combining 21cm and LAE data should allow us to differentiate between an IGM that is xx% ionized to one that is completely neutral

Hutter, Dayal et al. 2017

Synergising forthcoming facilities





ISM (dust/ionization): ALMA, JWST

IGM: SKA, Lofar2

Properties of early galaxy populations: JWST, Euclid, WFIRST, E-ELT, Athena, LISA

The emerging picture..

- Modelling reionization still open problem due to key physical uncertainties for both galaxies and IGM (z-evolution of cosmic SFRD, fesc, C).

- A key computational challenge arises due to the mass and physical scales required to model the galaxy formation-reionization interplay.

- Due to these issues, sources and topology of reionization remain outstanding problems in astrophysics.

- We are now moving towards an era of needing extremely large and resolved simulations that can simultaneously shed light on ISM physics and large-scale impact of early galaxies.