Radiation transport and Reionization

ENRICO GARALDI
Institute for Fundamental Physics of the Universe

RADIATION AFFECTS ALL SCALES IN THE UNIVERSE

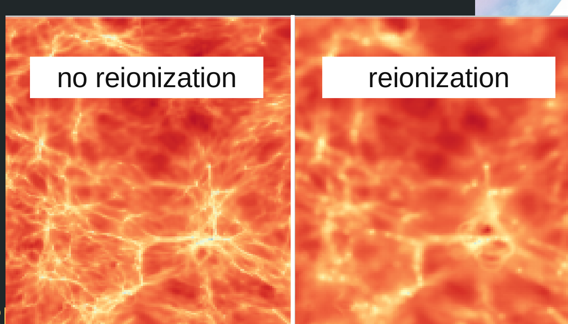
ISM

- HII regions
- gas cooling
- dust temperature
- …

→ see Harley Katz’s talk

IGM

- ionization state
- gas temperature
- density structure
- …



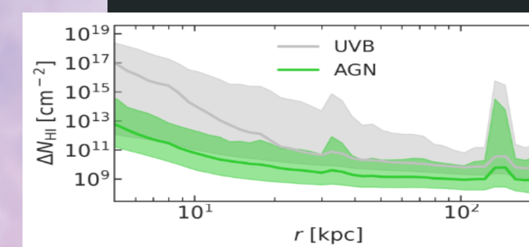
Katz et al. 2020

Tumlison et al. 2017

CGM

- density structure
- metal ions
- …

→ see Freeke van de Voort’s talk



Obreja et al. 2024

Part 1. Simulating radiation

THE RADIATION TRANSPORT EQUATION

Peebles 1971, Gnedin&Ostriker 1997,
Abel et al. 1999, Gnedin&Madau 2022

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\mathbf{n}}{a}\cdot\frac{\partial I_\nu}{\partial \mathbf{x}} - \underbrace{\frac{H(t)}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right)}_{\text{Cosmological redshift+dilution}} = \underbrace{-\kappa_\nu I_\nu}_{\text{Sinks}} + \underbrace{S_\nu}_{\text{Sources}}$$

Note:
- this equation is coupled to the energy and momentum equations
- we are ignoring scattering (usually a valid approx. outside stars and for non-resonant lines)

THE RADIATION TRANSPORT EQUATION

Peebles 1971, Gnedin&Ostriker 1997,
Abel et al. 1999, Gnedin&Madau 2022

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\mathbf{n}}{a}\cdot\frac{\partial I_\nu}{\partial \mathbf{x}} - \underbrace{\frac{H(t)}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right)}_{\text{Cosmological redshift+dilution}} = -\underbrace{\kappa_\nu I_\nu}_{\text{Sinks}} + \underbrace{S_\nu}_{\text{Sources}}$$

Challenge #1: 7 dimensions (vs. 4 for hydrodynamics)

Challenge #2: speed of light $\gg$ sound speed → need <u>much</u> shorter timesteps

→ One of the most demanding component of a simulation!

HOW TO DEAL WITH RADIATION?

accuracy* ↓ speed ↑

UV BACKGROUND

SEMI-NUMERICAL

DM+SAM+RT

HYDRO+decoupled/approximate RT

RADIATION-HYDRODYNAMICS

* very problem-dependent

HOW TO DEAL WITH RADIATION?

UV BACKGROUND

SEMI-NUMERICAL

DM+SAM+RT

HYDRO+decoupled/approximate RT

Typically used for IGM science only

RADIATION-HYDRODYNAMICS

accuracy* speed

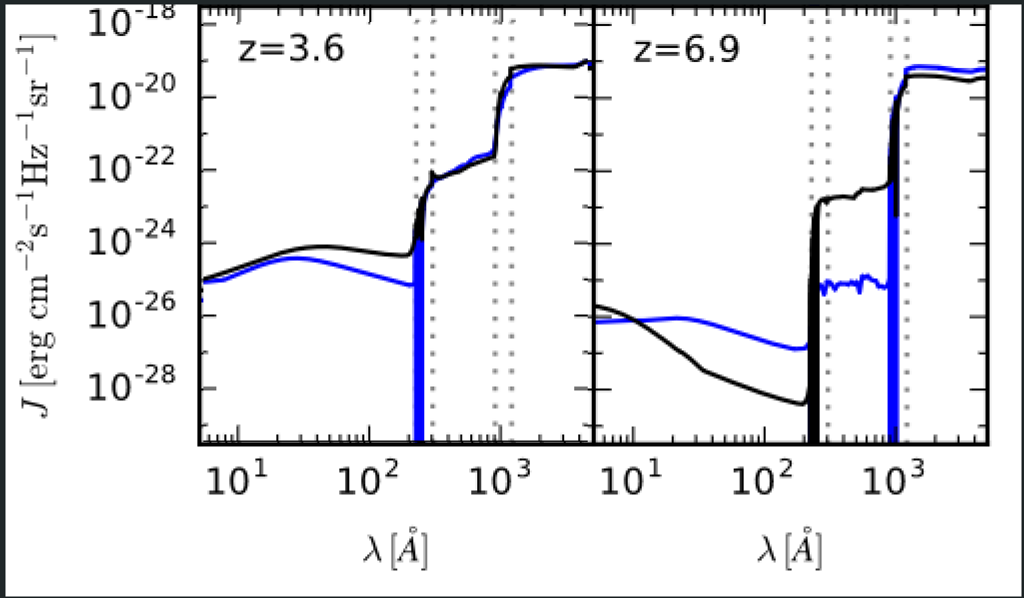
* very problem-dependent

HOW TO DEAL WITH RADIATION? UV BACKGROUND

Inject a spatially-uniform, time-evolving UVBG in each resolution element.

- Needs empirical corrections for self-shielded regions
- Does not capture reionization *topology*
- Essentially costless

Used by ~all large-volume simulations of the low-z Universe (IllustrisTNG, NewHorizon, FIREbox, SIMBA, SIMBA-EOR, EAGLE, MAGNETICUM, …) and by projects focused on galaxies only (FirstLight, FLARES, CHIPS, …)

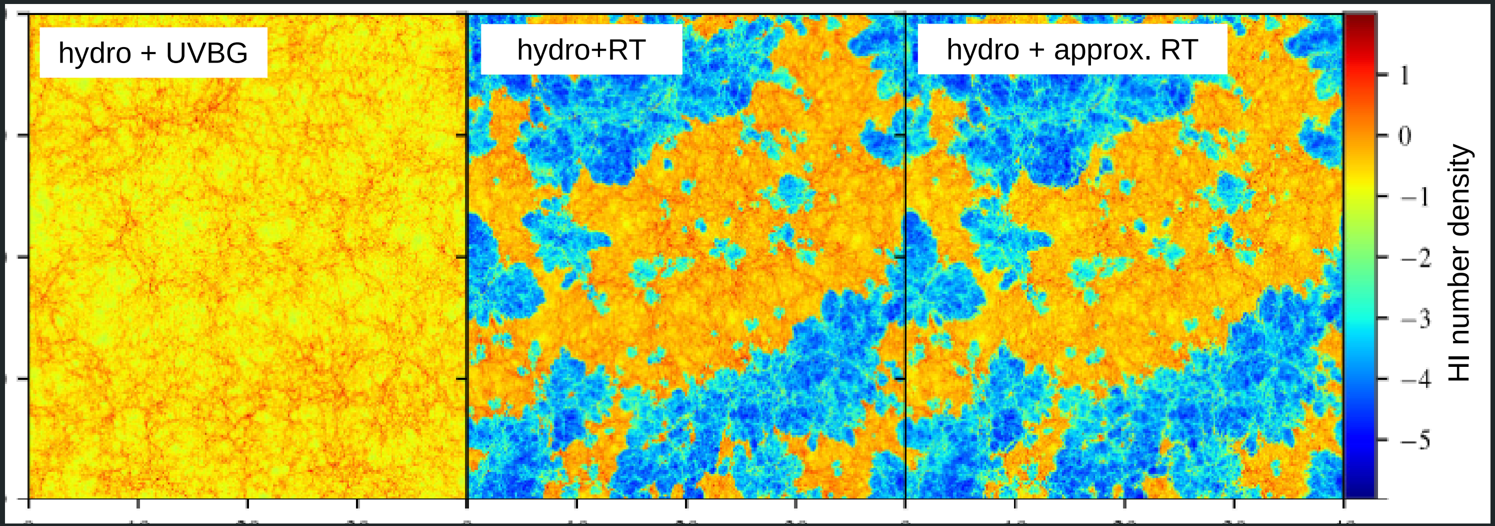


Puchwein et al. 2019

HOW TO DEAL WITH RADIATION? HYDRO + (APPROX.) RT

Run hydrodynamical simulations and include approximate RT effect on-the-fly.

- Works well on IGM scales, unclear on galaxy scales.
- Little extra cost over pure hydro.



Puchwein et al. 2022

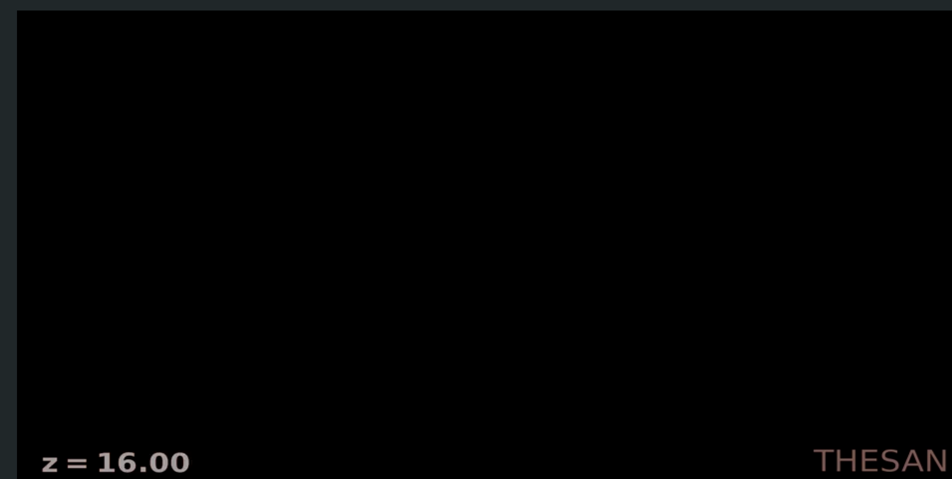
Only few examples so far: BlueTides (Huang et al. 2018), ASTRID (Bird et al. 2022), ASTRID-ES (Davies et al. 2023), PRIYA (Bird et al. 2023), Sherwood-Relics (Puchwein et al. 2022)

HOW TO DEAL WITH RADIATION? RADIATION-HYDRODYN.

Solve the fully-coupled R(M)HD equations

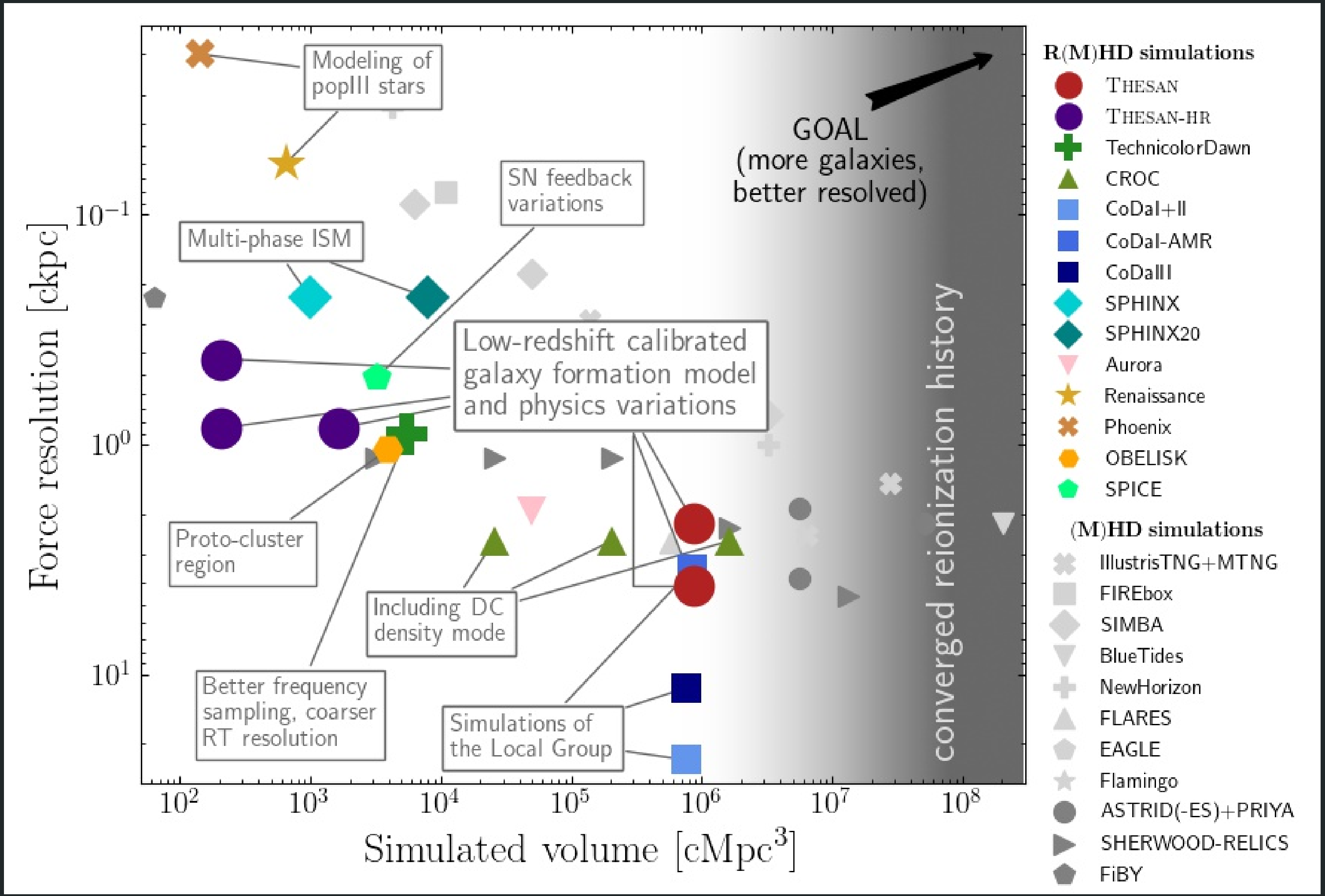
- Computationally very expensive → only few runs affordable
- The closest to the real Universe

Used by CROC (Gnedin 2014), Renaissance (Xu et al. 2016), CoDa I/II/III (Ocvirk et al. 2016, 2020, Lewis et al. 2022), AURORA (Pawlik et al. 2017), TechnicolorDawn (Finlator et al. 2018), SPHINX/SPHINX20 (Rosdahl et al. 2018,2022), Obelisk (Trebitsch et al. 2021,2023), Thesan (Kannan et al. 2022, Garaldi et al. 2022, Smith et al. 2022), SPICE (Bhagwat et al. 2023), …



Color: total gas density – opacity: HII fraction

THE RHD SIMULATIONS LANDSCAPE



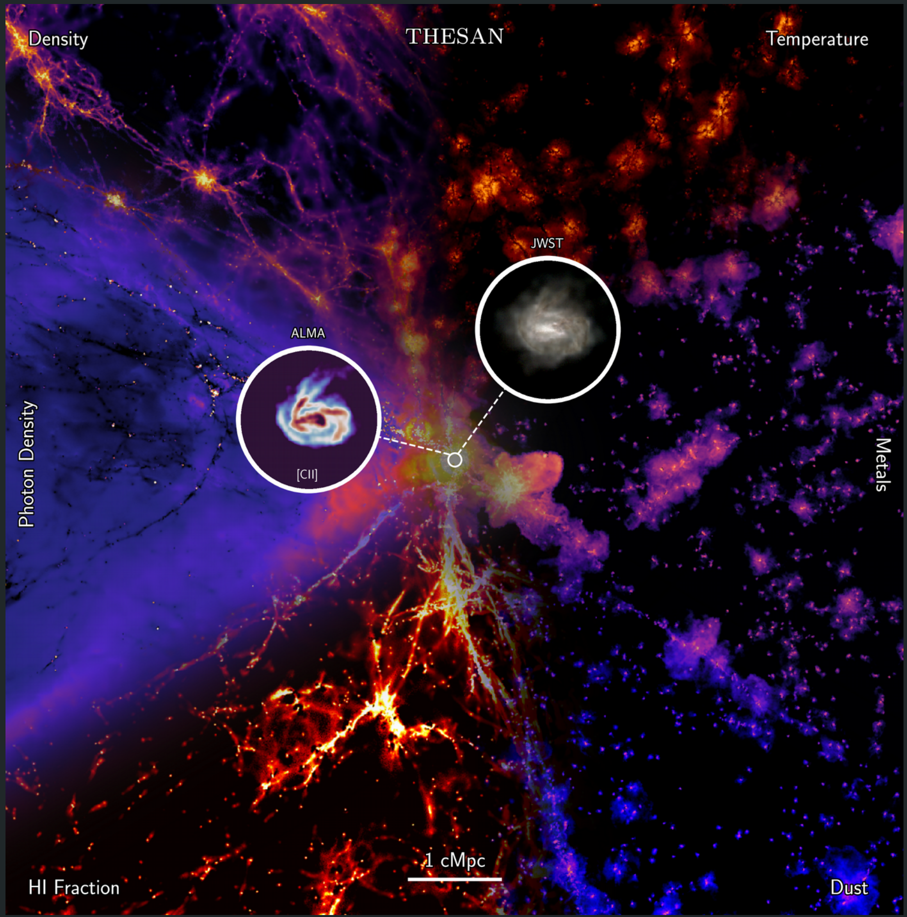
Garaldi et al. 2023b

→ volume for 21cm science

THESAN: GALAXY FORMATION MEETS REIONIZATION

Large cosmological RMHD simulations (AREPO code)

- Rich physics
  - Illustris-TNG galaxy formation model
  - radiation from stars, binaries and BH
  - cosmic dust
  - → A single free parameter at high-z
- Advanced numerics
  - variance-suppressed ICs
  - physical (f_{esc}, DM) and numerical variations
- Ongoing development:
  - zoom-in with accurate ISM, parent-box RT and improved dust model → see Ewald Puchwein's talk
- A unique tool to study the EoR-galaxy connection
- Now public (Garaldi et al. 2023b)



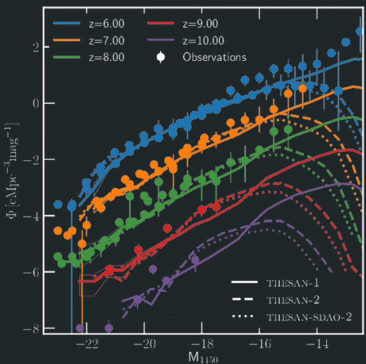
Garaldi et al., 2022, 2023b; Kannan, EG et al. 2022, Smith, EG, et al. 2022

THESAN: SUCCESSES AND FAILURES

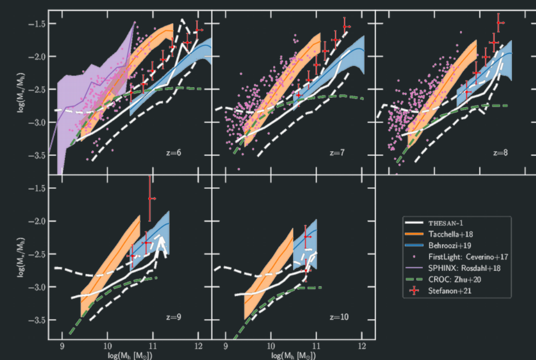
Garaldi et. al, 2022, 2023b; Kannan, EG et al., 2022; Shen,.. EG,.. 2023; Neyer,.. EG,.. 2023; Yeh,.. EG,..2022;

GALAXIES

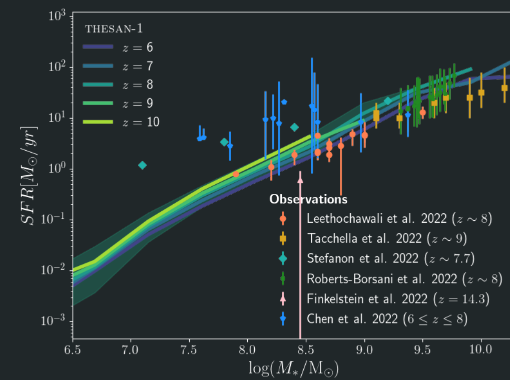
UV LUMINOSITY FUNCTION



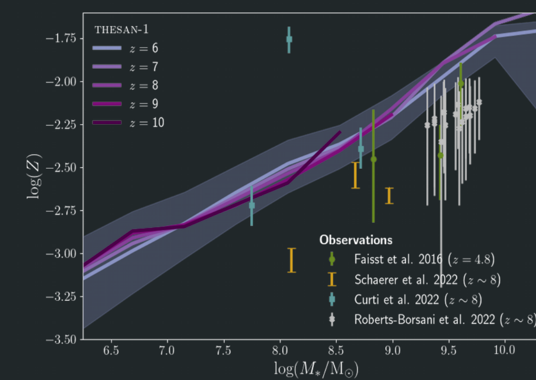
STELLAR-TO-HALO MASS RELATION



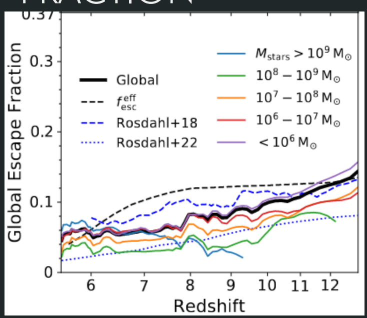
GALAXY MAIN SEQUENCE



(STELLAR) MASS – (GAS) METALLICITY RELATION

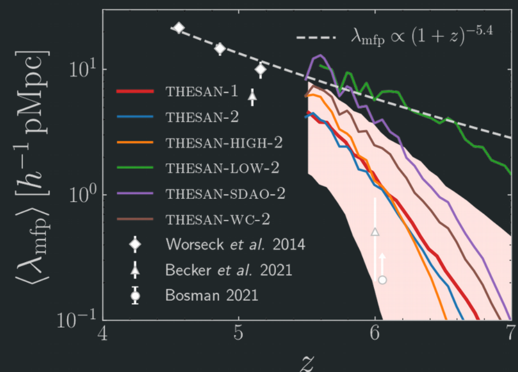


IONIZING ESCAPE FRACTION

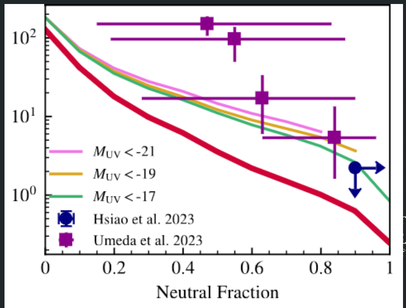


INTER-GALACTIC MEDIUM

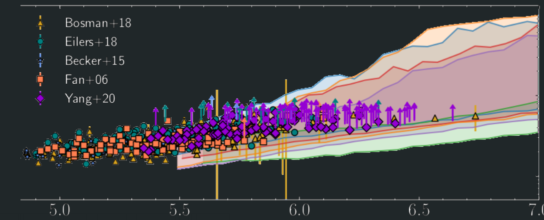
MEAN FREE PATH OF IONIZING PHOTONS



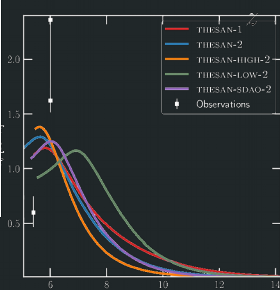
IONIZED BUBBLE SIZE



LYA OPTICAL DEPTH EVOLUTION



IGM MEAN TEMPERATURE



THE RADIATION TRANSPORT EQUATION

Peebles 1971, Gnedin&Ostriker 1997,
Abel et al. 1999, Gnedin&Madau 2022

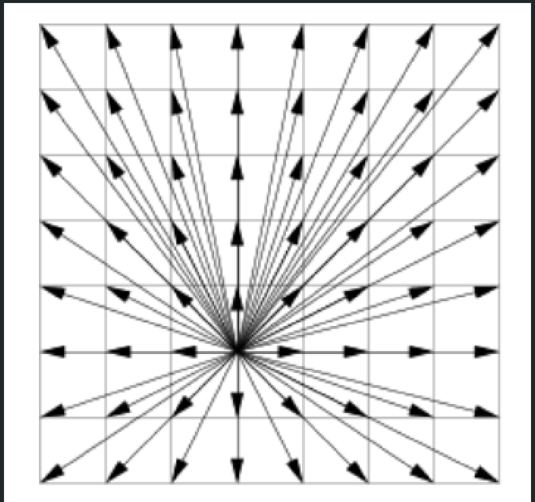
$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\mathbf{n}}{a}\cdot\frac{\partial I_\nu}{\partial \mathbf{x}} - \underbrace{\frac{H(t)}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right)}_{\text{Cosmological redshift+dilution}} = -\kappa_\nu I_\nu + S_\nu$$

Sinks Sources

SOLVING THE RT EQUATION: RAY TRACING

Idea: solve the RT eq. along "rays" cast from <u>all</u> sources to <u>all</u> resolution elements

- Accurate solution, but
- ...very expensive: $N_{rays} \sim \mathcal{O}(N_{sources} \times N_{res}^{2\text{-}3})$
- ...requires a lot of communication



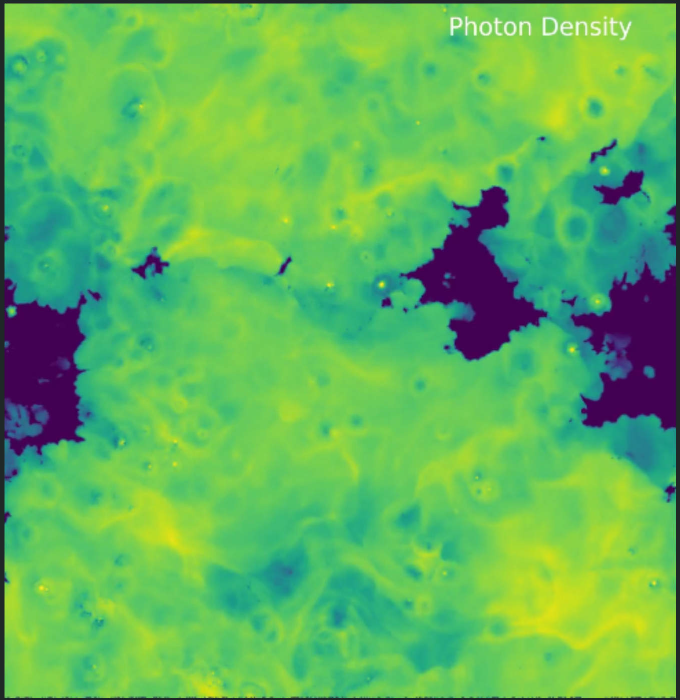
→ typically not feasible in large-volume simulations

but see Pawlik et al. 2017 (source grouping) and Hirling et al. 2023 (GPU implementation)

SOLVING THE RT EQUATION: MOMENTS METHODS

Idea: solve the first N moments of the RT equation (virtually always N=2)

- The RT equation becomes a set of conservation laws for a radiation fluid, with
- …little communication
- …same structure as hydro solver.
- But requires a closure relation (N eqs, N+1 unknowns)



SOLVING THE RT EQUATION: MOMENTS METHODS

Example for N=2:

Zeroth moment: $\int f(\mathbf{n})\, d\Omega$

First moment: $\int \mathbf{n}\, f(\mathbf{n})\, d\Omega$

Second moment: $\int \mathbf{n} \otimes \mathbf{n}\, f(\mathbf{n})\, d\Omega$

radiation variables

$$E_\nu = \frac{1}{c} \oint I_\nu \, d\Omega$$
$$\mathbf{f}_\nu = \oint \mathbf{n}\, I_\nu \, d\Omega$$
$$\mathbb{P}_\nu = \frac{1}{c} \oint \mathbf{n} \otimes \mathbf{n}\, I_\nu \, d\Omega$$

conservation laws

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{f}_\nu = -\kappa_\nu c E_\nu + S_\nu$$
$$\frac{\partial \mathbf{f}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\kappa_\nu c \mathbf{f}_\nu$$

$$\boxed{\text{Closure relation } \mathbb{P}_\nu = g(E_\nu, F_\nu) \equiv E_\nu\, \mathbb{D}_\nu}$$

($\mathbb{D}_\nu$ = Eddington tensor)

SOLVING THE RT EQUATION: MOMENTS METHODS

Example for N=2:

Zeroth moment: $\int f(\mathbf{n})\, d\Omega$

First moment: $\int \mathbf{n}\, f(\mathbf{n})\, d\Omega$

Second moment: $\int \mathbf{n} \otimes \mathbf{n}\, f(\mathbf{n})\, d\Omega$

radiation variables

$$E_\nu = \frac{1}{c} \oint I_\nu \, d\Omega$$
$$\mathbf{f}_\nu = \oint \mathbf{n}\, I_\nu \, d\Omega$$
$$\mathbb{P}_\nu = \frac{1}{c} \oint \mathbf{n} \otimes \mathbf{n}\, I_\nu \, d\Omega$$

conservation laws

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{f}_\nu = -\kappa_\nu c E_\nu + S_\nu$$
$$\frac{\partial \mathbf{f}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\kappa_\nu c \mathbf{f}_\nu$$

Closure relation $\mathbb{P}_\nu = g(E_\nu, F_\nu) \equiv E_\nu \, \mathbb{D}_\nu$

($\mathbb{D}_\nu$ = Eddington tensor)

Flux Limited Diffusion

- radiation flows in direction of least radiation
- accurate when the gas is optically thick.

SOLVING THE RT EQUATION: MOMENTS METHODS

Example for N=2:

Zeroth moment: $\int f(\mathbf{n})\, d\Omega$

First moment: $\int \mathbf{n}\, f(\mathbf{n})\, d\Omega$

Second moment: $\int \mathbf{n} \otimes \mathbf{n}\, f(\mathbf{n})\, d\Omega$

radiation variables

$$E_\nu = \frac{1}{c}\oint I_\nu \, d\Omega$$

$$\mathbf{f}_\nu = \oint \mathbf{n}\, I_\nu \, d\Omega$$

$$\mathbb{P}_\nu = \frac{1}{c}\oint \mathbf{n} \otimes \mathbf{n}\, I_\nu \, d\Omega$$

conservation laws

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{f}_\nu = -\kappa_\nu c E_\nu + S_\nu$$

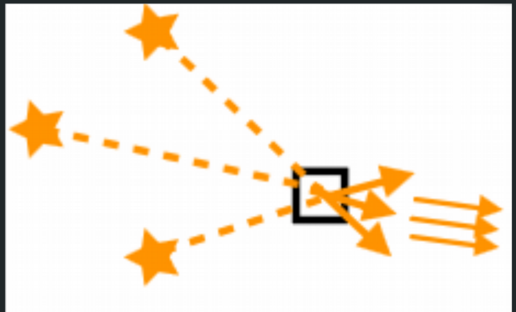
$$\frac{\partial \mathbf{f}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\kappa_\nu c \mathbf{f}_\nu$$

$$\boxed{\text{Closure relation } \mathbb{P}_\nu = g(E_\nu, F_\nu) \equiv E_\nu \mathbb{D}_\nu}$$

($\mathbb{D}_\nu$ = Eddington tensor)

Optically Thin Variable Eddington Tensor (OTVET)

- radiation flows as if all gas is optically thin → all sources matter for every cell
- computationally expensive



SOLVING THE RT EQUATION: MOMENTS METHODS

Example for N=2:

Zeroth moment: $\int f(\mathbf{n})\, d\Omega$

First moment: $\int \mathbf{n}\, f(\mathbf{n})\, d\Omega$

Second moment: $\int \mathbf{n} \otimes \mathbf{n}\, f(\mathbf{n})\, d\Omega$

radiation variables

$$E_\nu = \frac{1}{c} \oint I_\nu \, d\Omega$$
$$\mathbf{f}_\nu = \oint \mathbf{n}\, I_\nu \, d\Omega$$
$$\mathbb{P}_\nu = \frac{1}{c} \oint \mathbf{n} \otimes \mathbf{n}\, I_\nu \, d\Omega$$

conservation laws

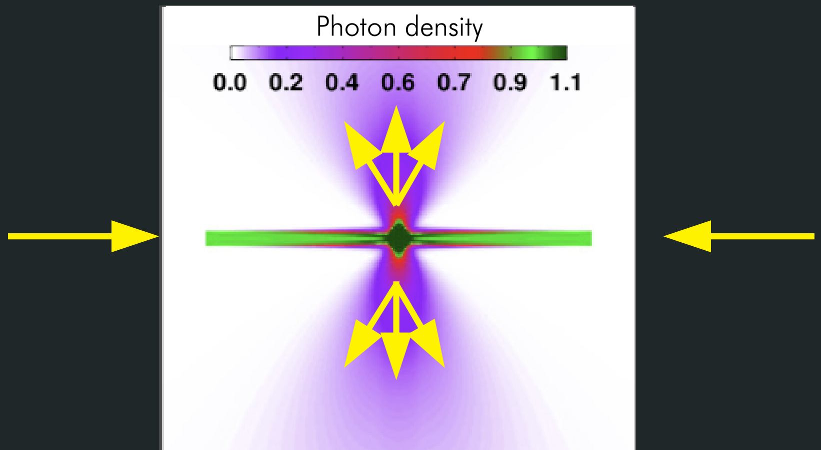
$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{f}_\nu = -\kappa_\nu c E_\nu + S_\nu$$
$$\frac{\partial \mathbf{f}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\kappa_\nu c \mathbf{f}_\nu$$

Closure relation $\mathbb{P}_\nu = g(E_\nu, F_\nu) \equiv E_\nu\, \mathbb{D}_\nu$

($\mathbb{D}_\nu =$ Eddington tensor)

M1 closure

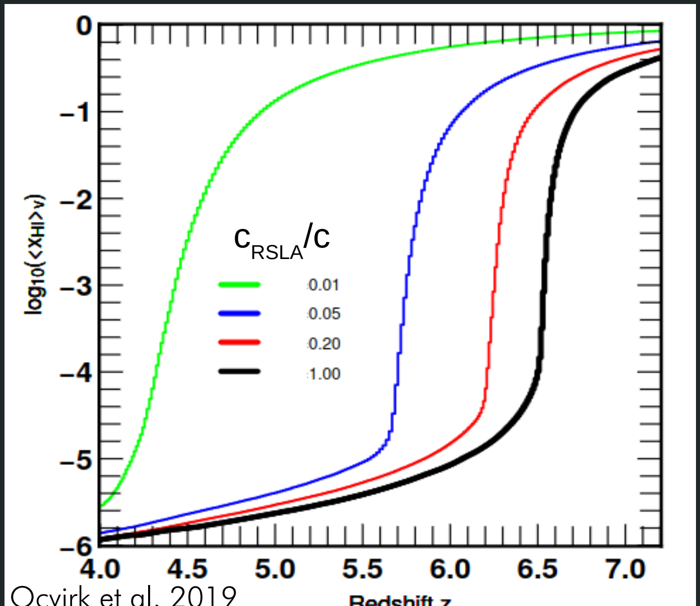
- fully-local expression for $\mathbb{P}_\nu$
- interpolation between pure diffusion and pure transport
- Independent of the number of sources
- most used because of efficiency
- has known artifacts (in corner cases)



SOLVING THE RT EQUATION: REDUCED SPEED OF LIGHT

Lower light speed to increase timesteps (dt~1/c).
- rationale: the relevant speed is <u>not</u> c, but the speed of ionization fronts

Works very well within galaxies ($c_{RSLA}\sim 10^{-3} – 10^{-4}$ c)
But has a strong impact on reionization history (Ocvirk et al. 2019, but see Gnedin et al. 2016)
- by artificially slowing down reionization fronts (Deparis et al. 2019)

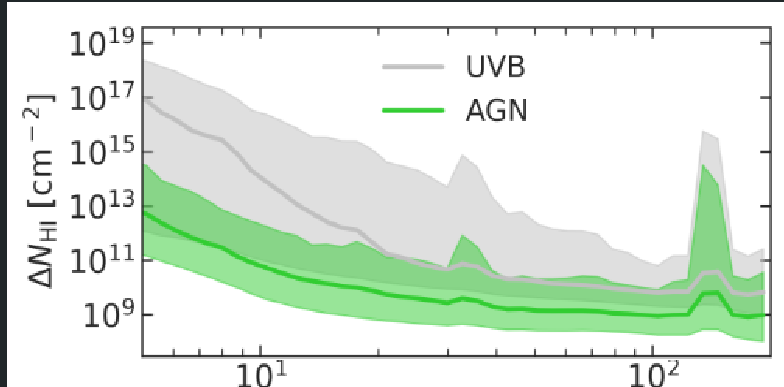


Ocvirk et al. 2019

See also: Variable speed of light (Katz et al. 2018)

IMPACT OF RADIATION ON GALAXIES

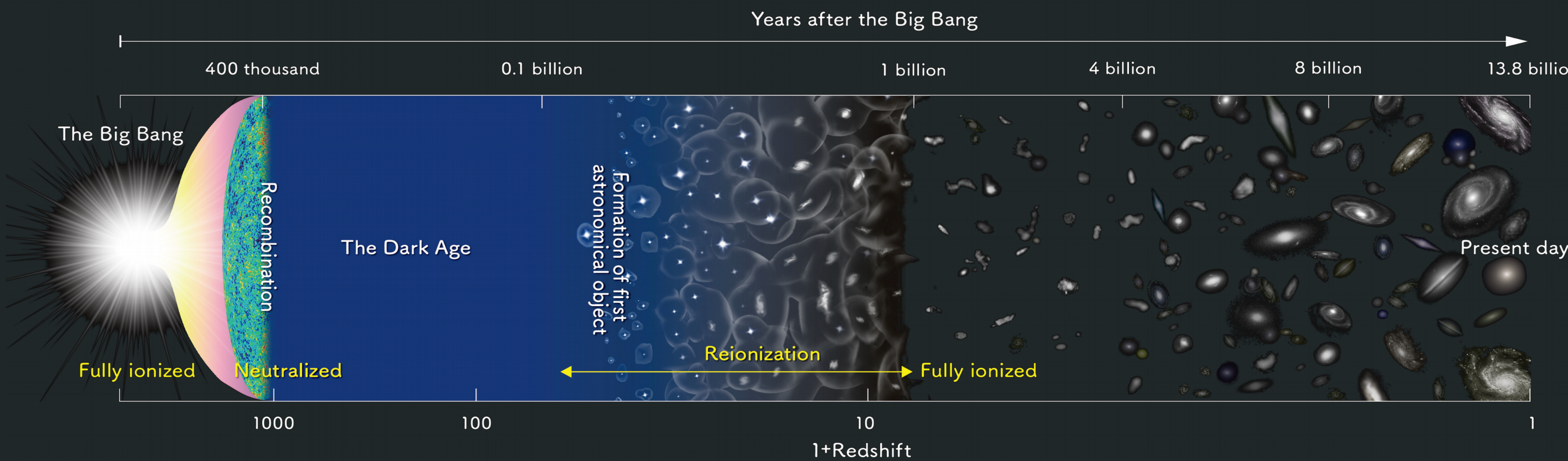
- mild effect on global galaxy properties (e.g. SFH, M_{star}, …)
  (e.g. Rosdahl et al. 2015, Kannan et al. 2019, Obreja et al. 2019)
- exception: dwarf galaxies!
  - Radiation reduces gas fraction by 40% in galaxies with $M_{star} \lesssim 10^{11}$ (Obreja et al. 2019)
- Impacts CGM conditions (Obreja et al. 2024, Schimek et al. 2024)
- "Puffs up" satellite galaxies, promoting their tidal destruction (Costa et al. 2019)



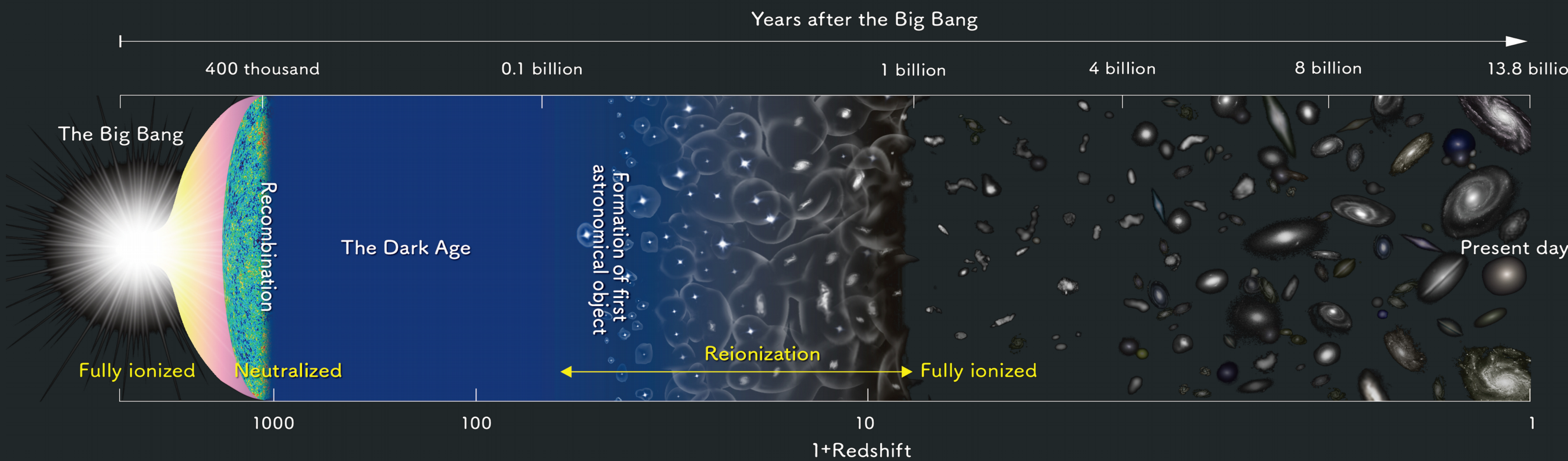
Obreja et al. 2024

Part 2. Cosmic reionization

RADIATION IS THE KEY INGREDIENT IN REIONIZATION



RADIATION IS THE KEY INGREDIENT IN REIONIZATION



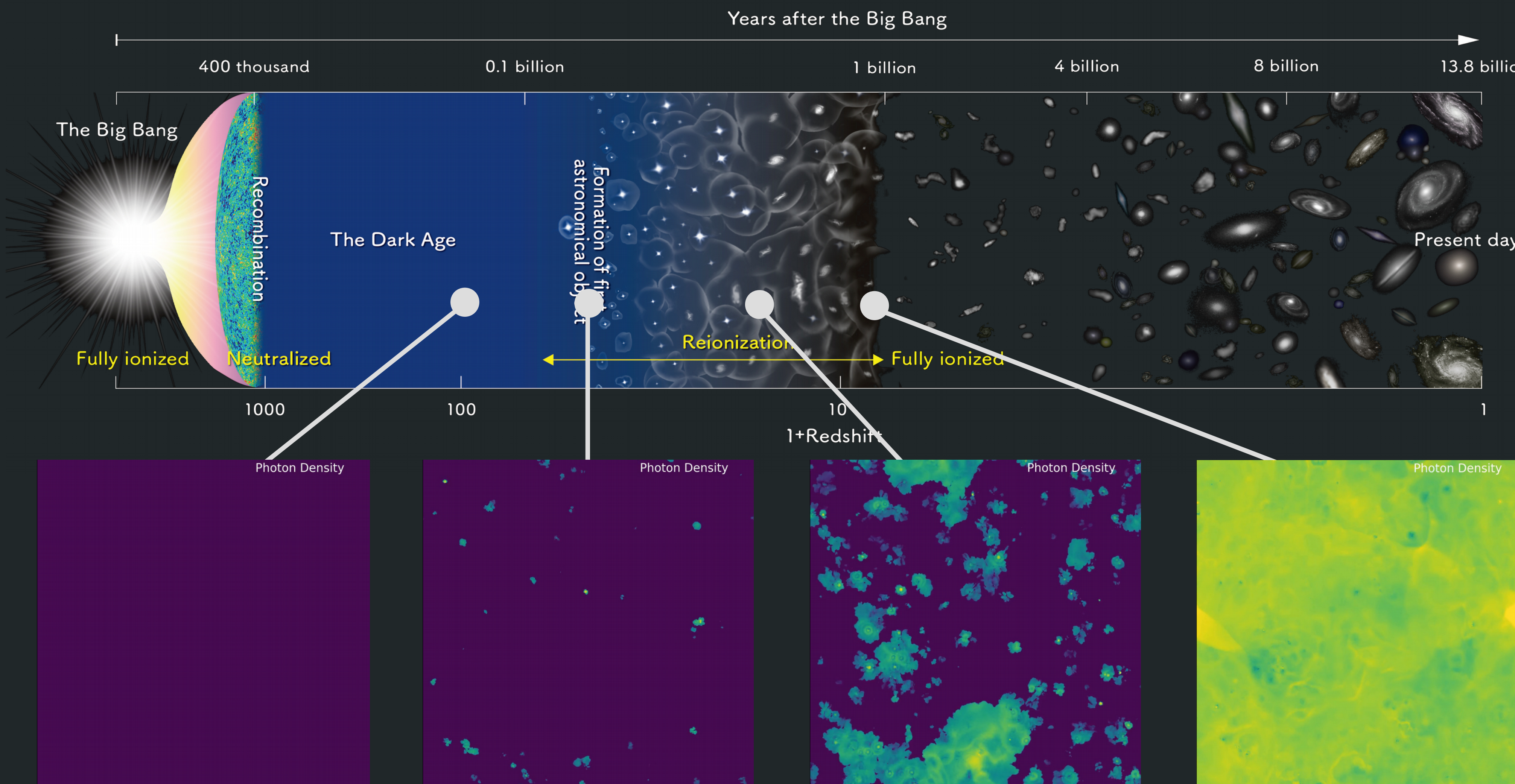
Hydrogen reionization

HI → HII
HeI → HeII

Helium reionization

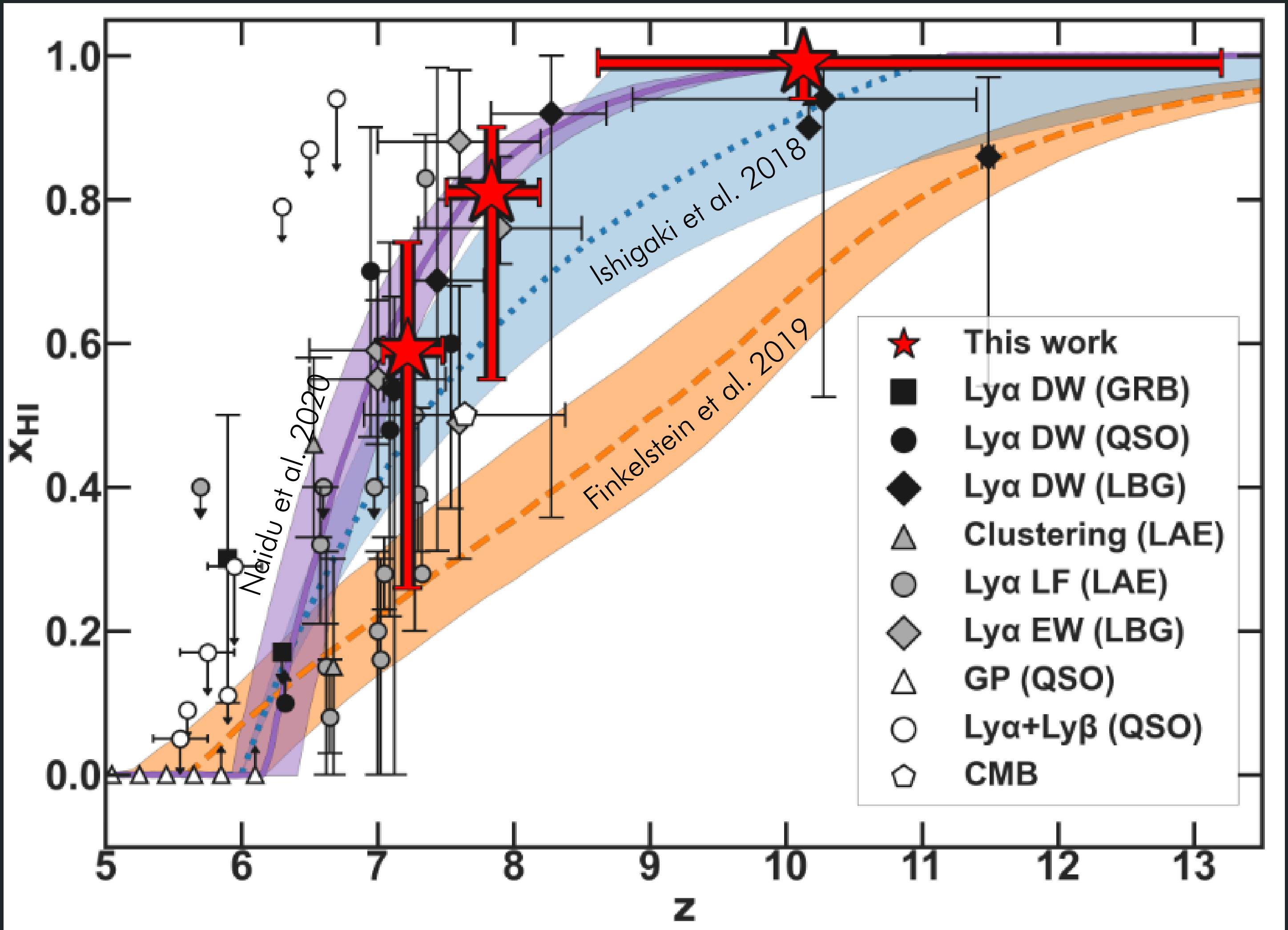
HeII → HeIII

RADIATION IS THE KEY INGREDIENT IN REIONIZATION



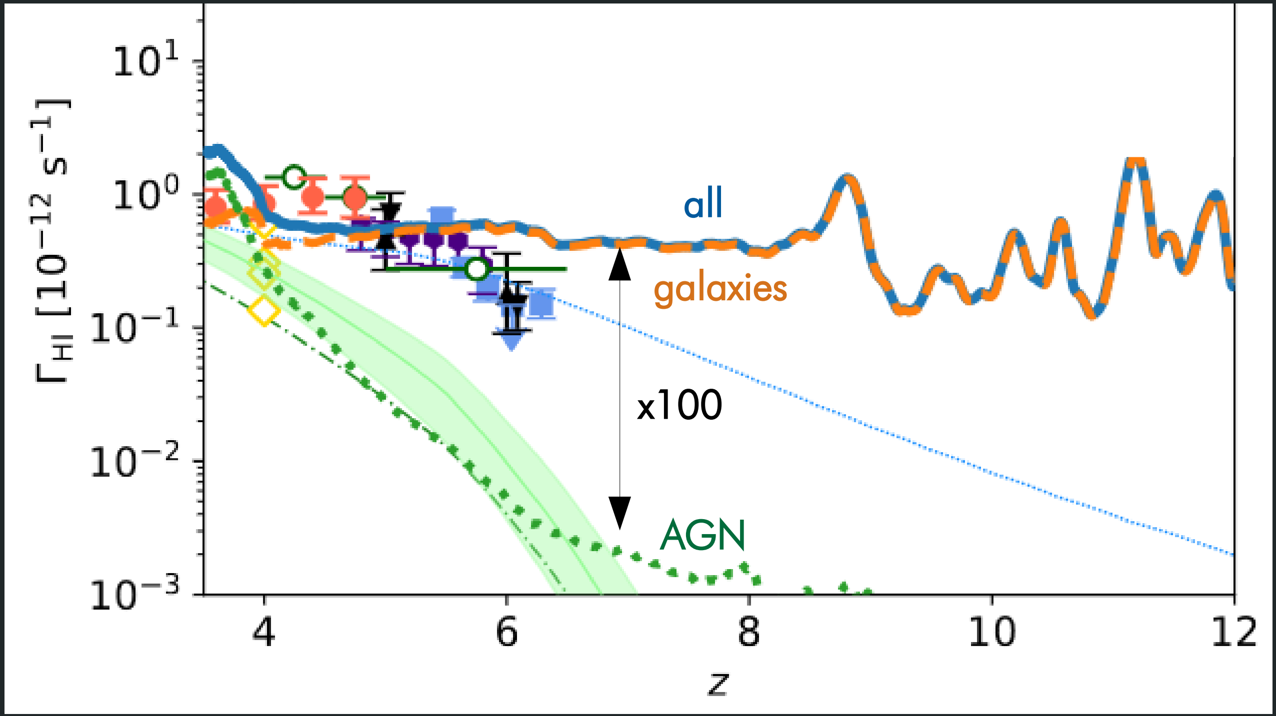
We NEED radiation transport to study cosmic reionization

WE ARE PINNING DOWN THE REIONIZATION HISTORY



Nakane et al. 2024

REIONIZATION IS DRIVEN BY GALAXIES



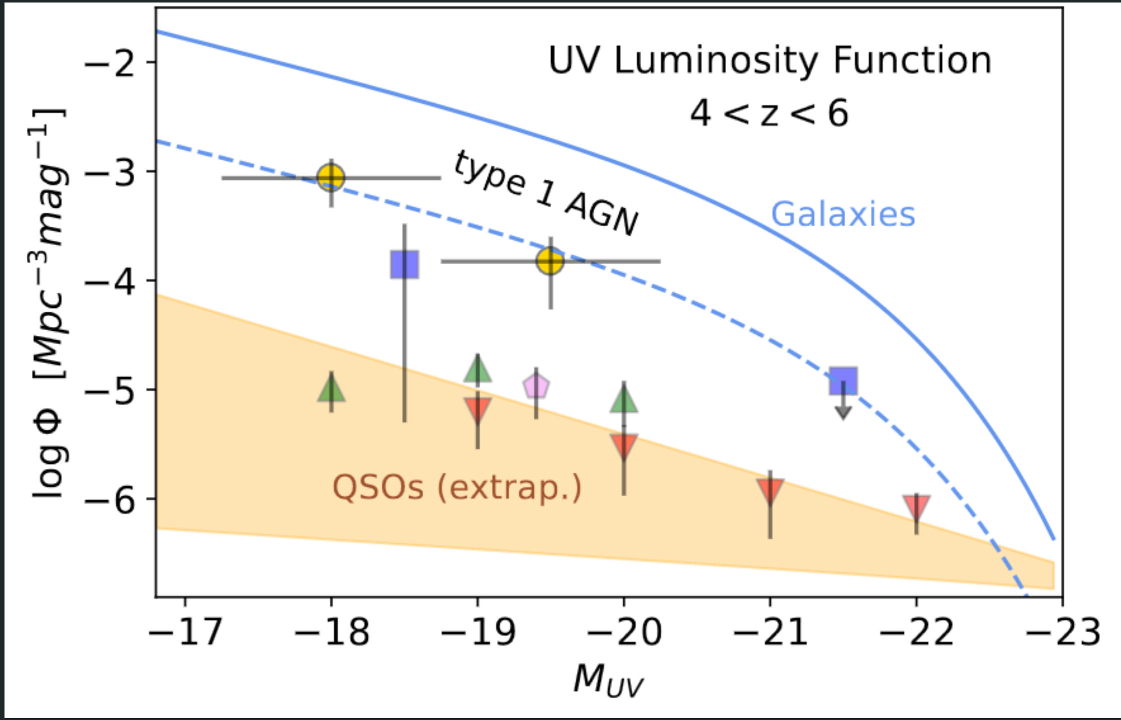
Trebitsch et al. 2021

Mainly by small, star-forming galaxies (e.g. Chardin et al. 2017, Trebitsch et al. 2021, Garaldi et al. 2019b)

- $\log(M_{star}) \sim 6 - 8$ (e.g. Rosdahl et al. 2022, Yeh et al. 2023, Kostyuk et al. 2022)
- but dominant mass evolves with redshift

HIGH-Z QUASARS CANNOT BE (TOO) RELEVANT

Large number of high-z AGNs seen by JWST. (e.g. Matsuoka et al. 2023; Greene et al. 2023; Harikane et al. 2023; Labbe et al. 2023; Kocevski et al. 2023; Matthee et al. 2023; Maiolino et al.2023; Kokorev et al. 2024)



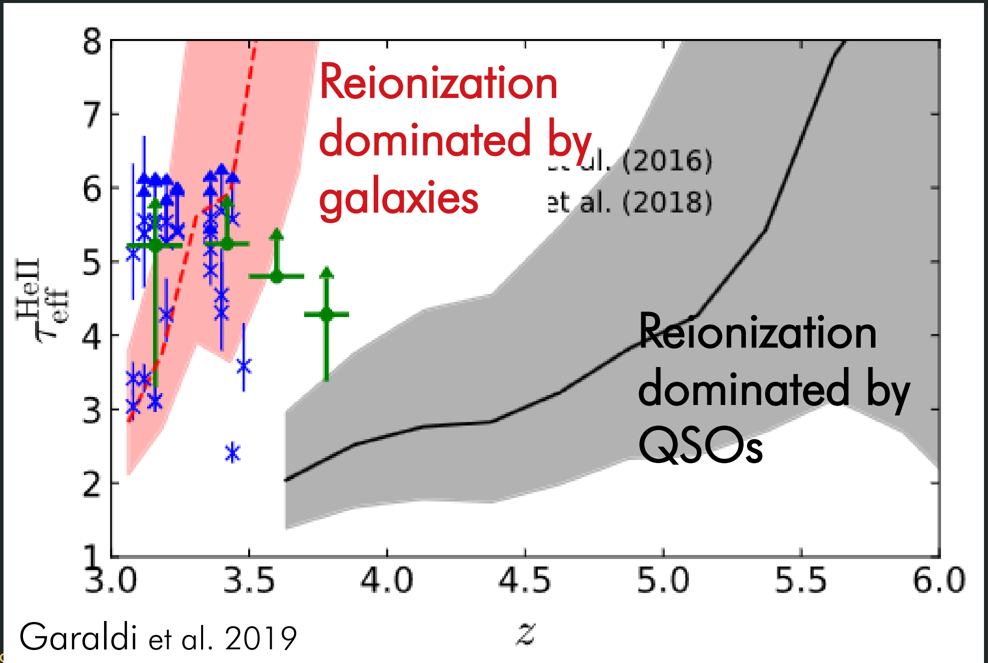
Maiolino et al. 2023

HIGH-Z QUASARS CANNOT BE (TOO) RELEVANT

Large number of high-z AGNs seen by JWST. (e.g. Matsuoka et al. 2023; Greene et al. 2023; Harikane et al. 2023; Labbe et al. 2023; Kocevski et al. 2023; Matthee et al. 2023; Maiolino et al.2023; Kokorev et al. 2024)

Their contribution to reionization cannot be large (Garaldi et al. 2019b)

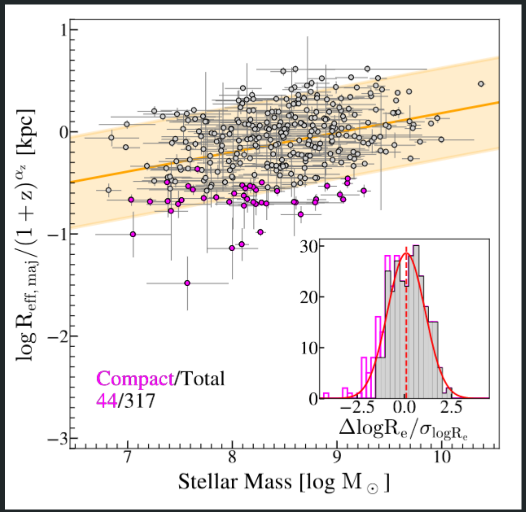
- QSOs ionize HeII along with HI
- but we observe HeII at z∼3 through its Ly-a forest



Garaldi et al. 2019

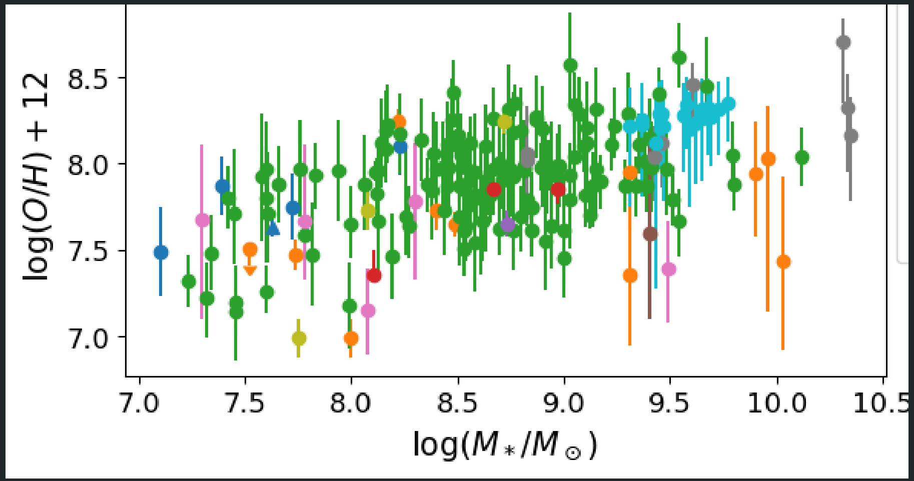
WE ARE NOW CHARACTERIZING THE FIRST GALAXIES

GALAXY SIZES



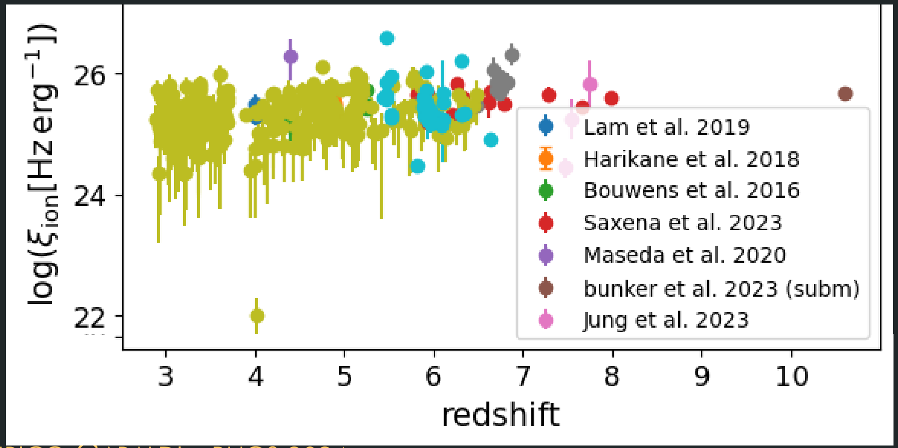
Morishita et al. 2023

MASS-METALLICITY RELATION



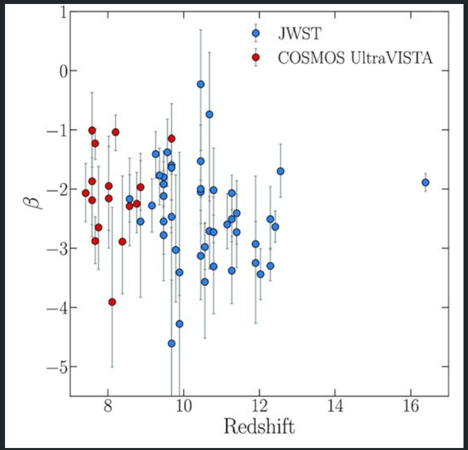
credits: CoReCon (Garaldi et al. 2023a)

IONIZING PHOTONS PRODUCTION EFFICIENCY



credits: CoReCon (Garaldi et al. 2023a)

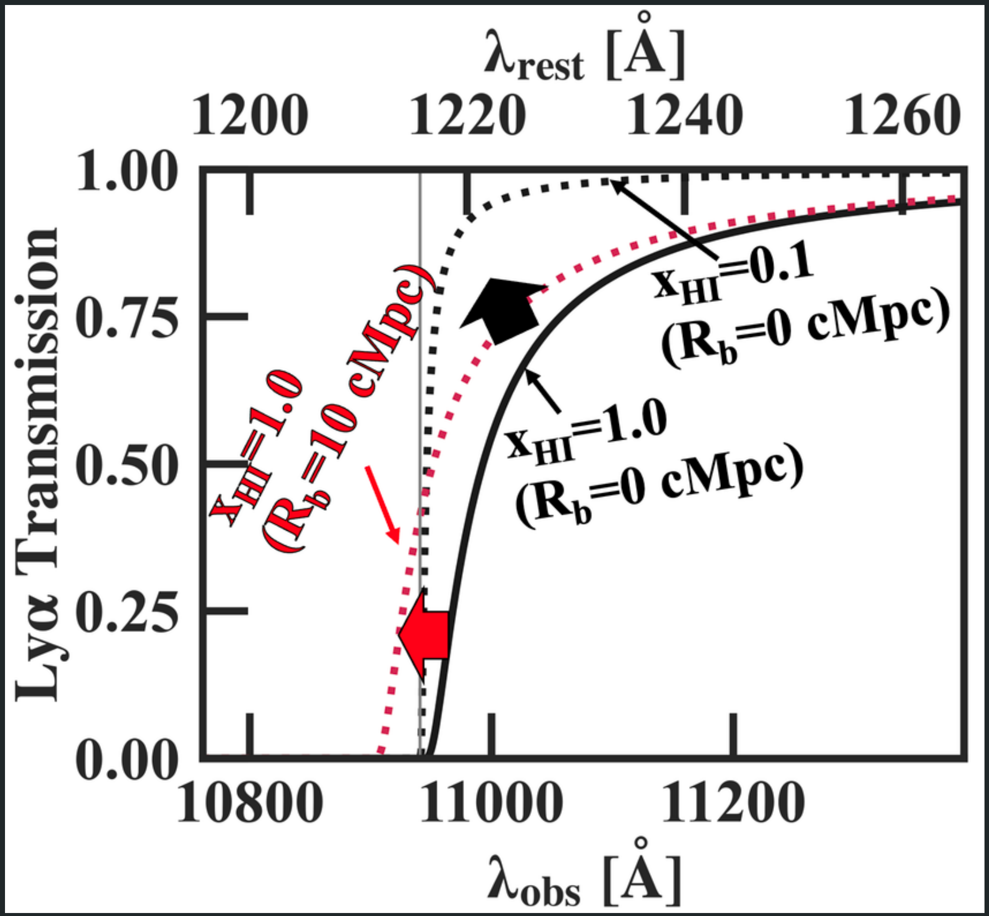
UV SLOPES



Cullen et al. 2023

→ see Jacob Shen's talk

DAMPING WING ABSORPTION REVEALS IONIZED BUBBLES



Umeda et al. 2023

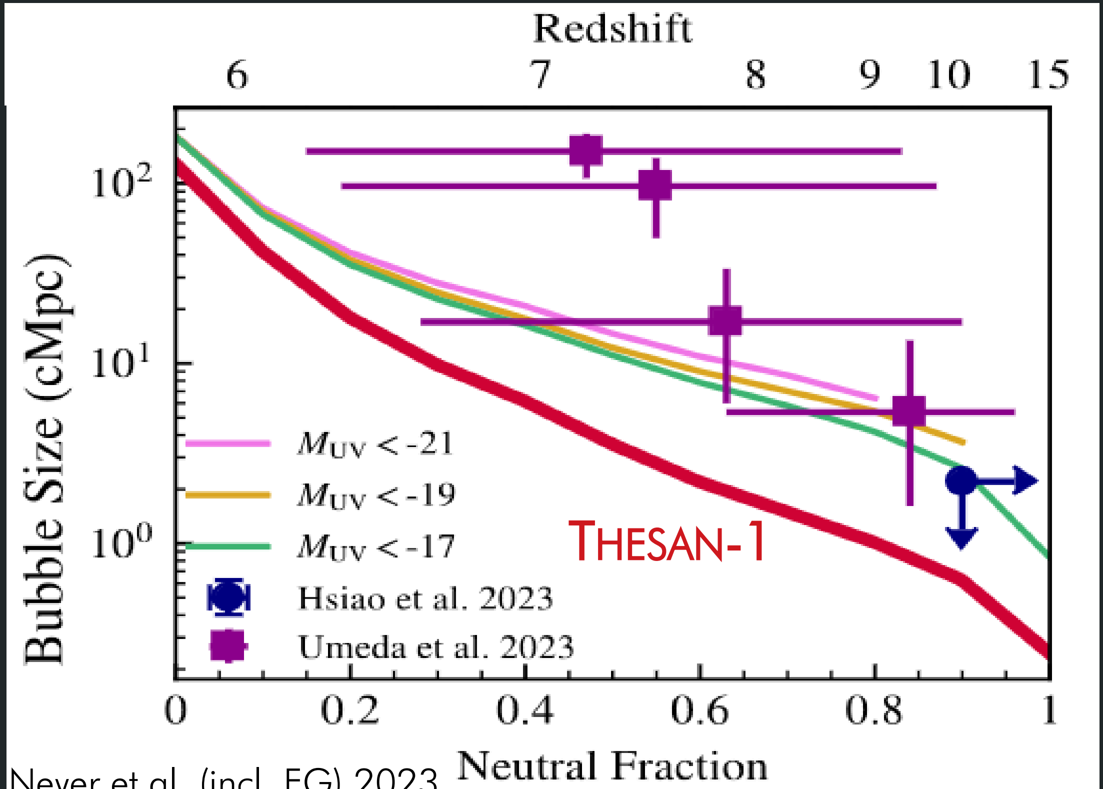
Ly-a transmission sensitive to ionization state and bubble size

(Mesinger & Furlanetto 2008)

DAMPING WING ABSORPTION REVEALS IONIZED BUBBLES

Observed bubble sizes seem larger than expected

e.g. Neyer et al. (incl. EG) 2023, Lu et al. 2024



Neyer et al. (incl. EG) 2023

REIONIZATION AND GALAXY FORMATION SHOULD TALK (MORE) TO EACH OTHER

Reionization affects structure formation

1. Photo-evaporation of halos below the atomic cooling limit ($M_{halo} \lesssim 10^8\ M_{sun}$ at $z=6$)
   - but many simulations show star formation in smaller objects! (Wise et al. 2014; Xu et al. 2016; Kimm et al. 2017, Rey et al. 2020, Gutcke et al. 2022)
2. Suppression of accretion flows onto galaxies
   - gas flow reduced by >90% (Katz et al. 2018)
3. "Puffing up" baryonic structures
   - imprint e.g. on the Ly-a forest PS (e.g. Montero-Camacho et al. 2019)

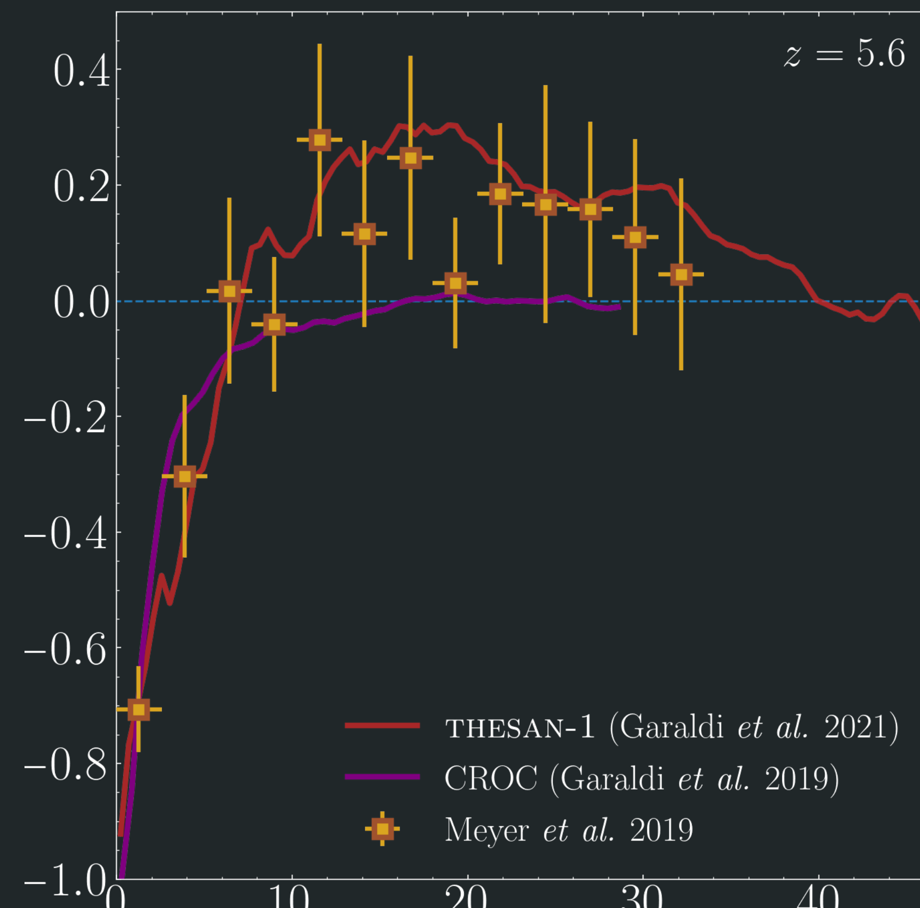
Galaxy formation affects reionization

mainly through the production and escape of ionizing photons (Trebitsch et al. 2017, Kimm et al. 2017, Rosdahl et al. 2018)

REIONIZATION AS A TEST OF GALAXY FORMATION MODELS

Example #1: IGM Ly-a modulated by galaxies (Garaldi et al. 2019, 2022, Kakiichi et al 2018, Meyer, 2019, 2020, Kashino 2023)

Difference in Ly-a flux over global average



Distance from galaxy

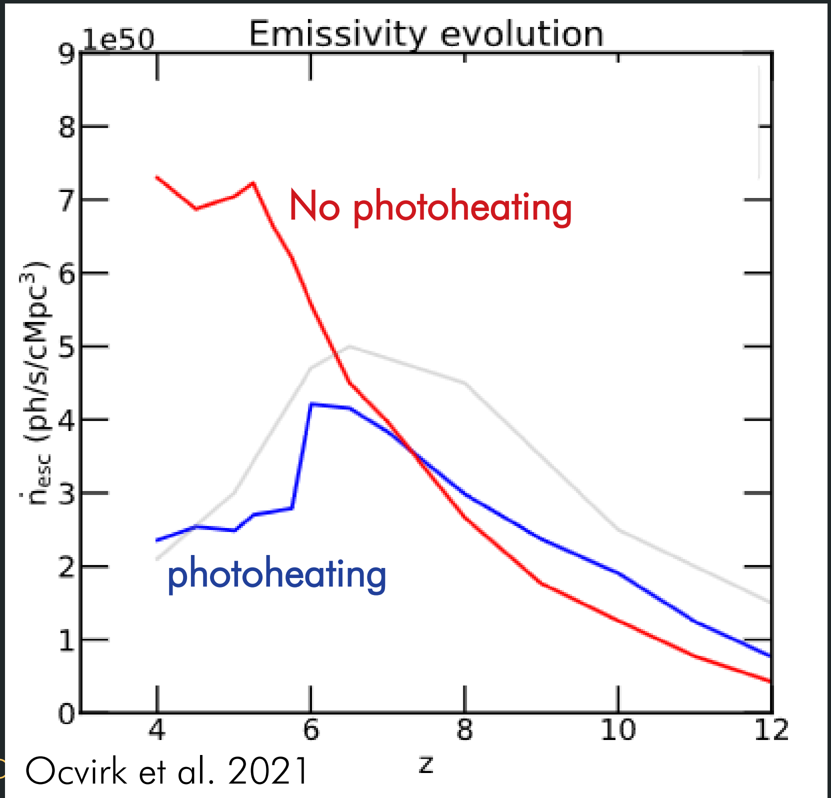
neutral fraction

Garaldi et al. 2022

REIONIZATION AS A TEST OF GALAXY FORMATION MODELS

Example #2: the mystery of global reionization feedback

Some simulations find a global suppression of SFR at the end of reionization (Kulkarni et al. 2019, Keating et al. 2020, Ocvirk et al. 2021), but other do not (Garaldi et al. 2022, SPHINX?)



Ocvirk et al. 2021

- consistent with photo-ionisation feedback
- …but synchronized over 10s Mpc within 100 Myr! → How?
- Reduced speed of light can hide this feature (Cain et al. 2023)

CHALLENGES FOR REIONIZATION SIMULATIONS

PHYSICS vs. NUMERICS

- What is the impact of numerical choices (RSLA, feedback, etc.) on the modeling of Reionization?
  → see talk by Aniket Bhagwat

MODEL TUNING

- How to ensure our models work also after the end of reionization?

SMALL VOLUMES

RHD simulations will be limited to $\mathcal{O}$(100 Mpc) for the foreseeable future, how do we extend their results to the Gpc scales needed? → see talk by Mladen Ivkovic

UNCERTAIN PHYSICS

- Unknown stellar Initial Mass Function, even more so at high-z → see Anne Hutter's talk
- Role of cosmic rays? might be important but are $\sim$never accounted for (Farcy et al. 2024)
- Relevance of PopIII stars? (virtually never modeled in galaxy simulations)
- ...

HOW TO DEAL WITH RADIATION? IGNORE IT

Inject heat from a spatially-uniform, time-evolving UVBG in each resolution element.

Needs empirical corrections for self-shielded regions
Does not capture reionization topology
Essentially costless

Used by:
- simulations of the post-reionization Universe (IllustrisTNG, EAGLE, NewHorizon, FIRE, SIMBA, FLAMINGO, ...)
- FirstLight (Ceverino et al. 2017)
- DUSTY-GADGET simulations (Graziani et al. 2019)
- FLARES (Lovell et al. 2021, Vijayan et al. 2021)
- CHIPS (Villasenor et al. 2021)

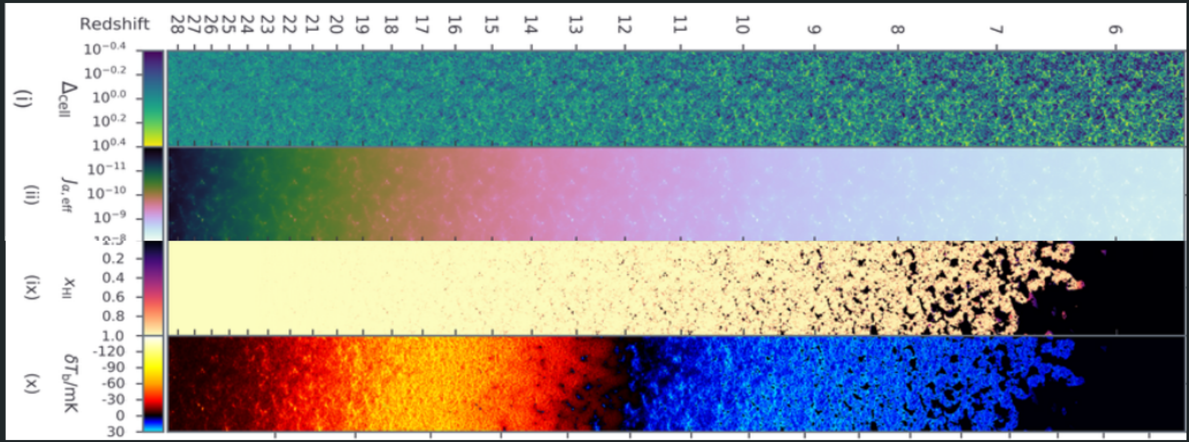
HOW TO DEAL WITH RADIATION? 2. SEMI-NUMERICAL

Infer the distribution of HII regions from the initial conditions using excursion set or abundance matching

Fails at scales ≲ Mpc
Issues at ionized bubbles overlap
Not always photons conserving
Galaxy/halo properties assigned
"by hand"

Very fast
Quickly explore parameter space
Easily simulate 100Mpc-Gpc box

Used by:
21cmFAST (Mesinger et al. 2011)
ARTIST (Molaro et al. 2019)
SCRIPT (Maity & Choudhury 2022)
AMBER (Trac et al. 2022)
BEORN (Schaeffer et al. 2023)



Credits: A. Mesinger

HOW TO DEAL WITH RADIATION? 3. DM + SAM + RT

Use DM density from N-body simulations + a semi-analytical model built for reionization-era galaxies + approximate RT

RT is approximate at best
baryon physics is approximate

Fast
Easily model $\mathcal{O}$(100 Mpc) volumes

Used by:
GRIZZLY (Ghara et al. 2015, 2018, *no SAM*)
DRAGONS (Poole et al. 2016, Angel et al. 2016, Mutch et al. 2016)
ASTRAEUS (Hutter et al. 2021)

HOW TO DEAL WITH RADIATION? HYDRO + (DE-COUPLED) RT

Run hydrodynamical simulations without RT, and include radiation by post-processing its outputs.

Missing gas response to photons
(Often) galaxy properties assigned independently of hydro sim.
Faster then full hydro-RT

Used by:
- C2-RAY simulations (e.g. Iliev et al. 2006b, Mellema et al. 2006, *H traces DM density*)
- ATON simulations (e.g. Chardin et al. 2017, Kulkarni et al. 2019, Keating et al. 2020)
- CRASH simulations (e.g. Eide et al. 2018,2020, Ma et al. 2022, Kostyuk et al. 2022)
- Cain et al. 2021, 2023
- ...

RAY TRACING

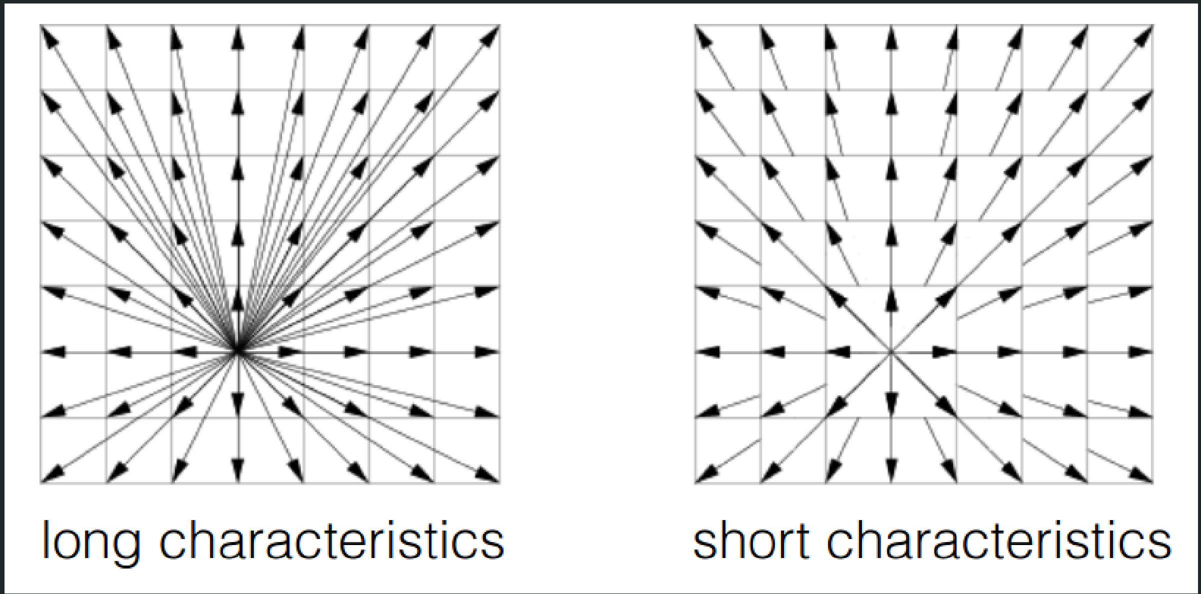
(a.k.a. method of characteristics)

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\mathbf{n}}{a}\cdot\frac{\partial I_\nu}{\partial \mathbf{x}} - \frac{H(t)}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right) = -\kappa_\nu I_\nu + S_\nu$$

Idea: solve the RT eq. along "rays" cast from all sources in the simulation to all resolution elements (long characteristic)

- Accurate solution, but very expensive: $N_{rays} \sim \mathcal{O}(N_{sources} \times N_{res}^{2\text{-}3})$ + a lot of communication → typically not feasible in large simulations

Short characteristics:
only propagate rays to next cell
→ easily parallelizeable
& reduced communication



SOLVING THE RT EQUATION: MONTE CARLO

Idea: random sample the radiation field through photon packets

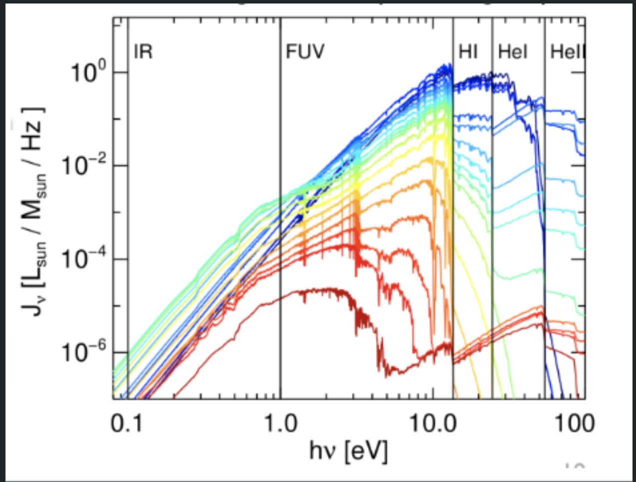
- Provides a very-accurate stochastic solution of the RT equation. But
- …has slow convergence ($\sqrt{N_{packets}}$)
- …requires heavy communication

→ typically applied in post-processing

SOLVING THE RT EQUATION: RADIATION SAMPLING

Radiation frequency has to be discretized into bins

Time and memory requirement scale with the number of bins,
→ typically only 3-5 used (notable exception: Finlator et al. 2018)



Problem: within a bin, the radiation spectrum is rigid but it should change with time due to differential absorption

DO WE NEED REALISTIC GALAXIES (FOR REIONIZATION)?

Reionization history ~ <u>total</u> number of photons injected into the IGM

- many simulation with simple galaxy physics do an excellent job

  (Kulkarni et al. 2017,2019,2020, Keating et al. 2020, Gnedin 2014, 2016, ...)

But ionizing escape fraction requires detailed ISM modeling

- energetic feedback clears channels for radiation escape (Trebitsch et al. 2017, Kimm et al. 2017; Rosdahl et al. 2018)

OUR ATTEMPT AT TACKLING (SOME) CHALLENGES: THESAN

Name	L_{box} [cMpc]	$N_{particles}$	m_{DM} [$M_\odot$]	m_{gas} [$M_\odot$]	ϵ [ckpc]	r_{cell}^{min} [pc]
THESAN-1	95.5	2×2100^3	3.12×10^6	5.82×10^5	2.2	10
THESAN-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	35
THESAN-WC-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	33
THESAN-HIGH-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	33
THESAN-LOW-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	32
THESAN-SDAO-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	33
THESAN-TNG-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	30
THESAN-NORT-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	35
THESAN-DARK-1	95.5	2100^3	3.70×10^6	-	2.2	-
THESAN-DARK-2	95.5	1050^3	2.96×10^7	-	4.1	-
THESAN-HR-RES8X	5.9	2×512^3	6.03×10^4	1.13×10^4	0.425	8
THESAN-HR	5.9	2×256^3	4.82×10^5	9.04×10^4	0.85	32
THESAN-HR-LARGE	11.8	2×512^3	4.82×10^5	9.04×10^4	0.85	15
THESAN-HR-SDAO	5.9	2×256^3	4.82×10^5	9.04×10^4	0.85	33
THESAN-HR-WDM	5.9	2×256^3	4.82×10^5	9.04×10^4	0.85	28
THESAN-HR-FDM	5.9	2×256^3	4.82×10^5	9.04×10^4	0.85	23

Exploring uncertain physics (photon escape, DM nature)

Exploring impact of radiation on large galaxies

Exploring impact of radiation on small galaxies

Exploring impact of DM nature on small galaxies

CHALLENGES FOR SIMULATIONS: NEW OBSERVATIONS

IGM EVOLUTION

- Robust measurements now available (e.g. Gaikward et al. 2021, 2023)
- rapid evolution of mean free path within $5<z<6$
- T_{IGM} has small tension with models at $3<z<4$

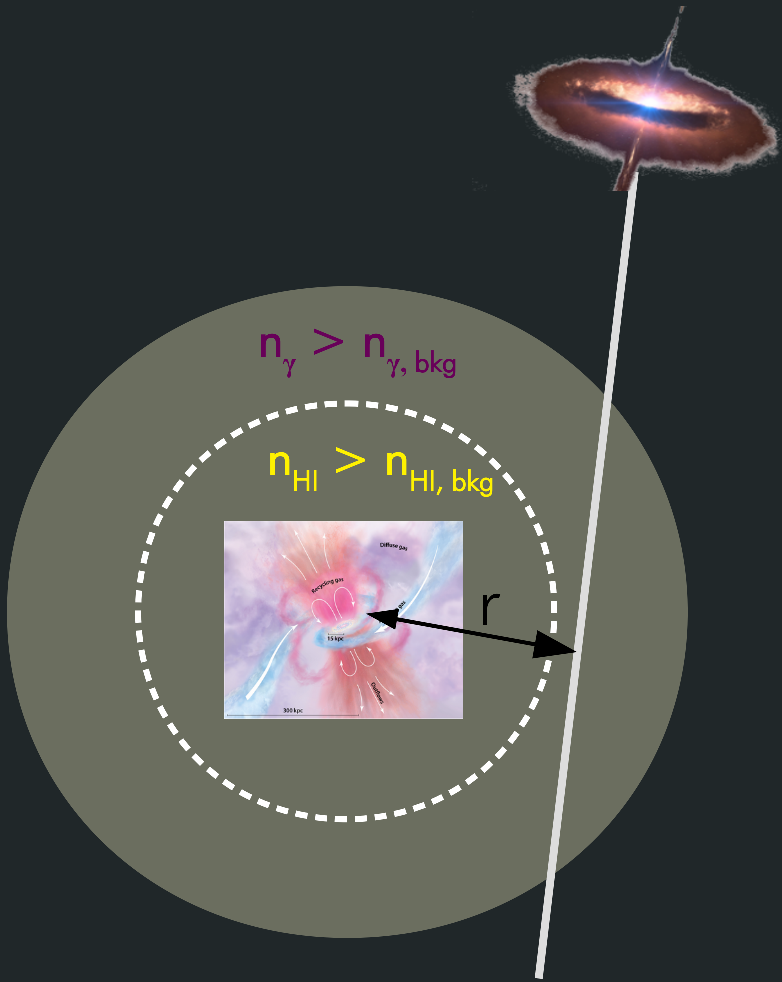
METAL ABSORBERS

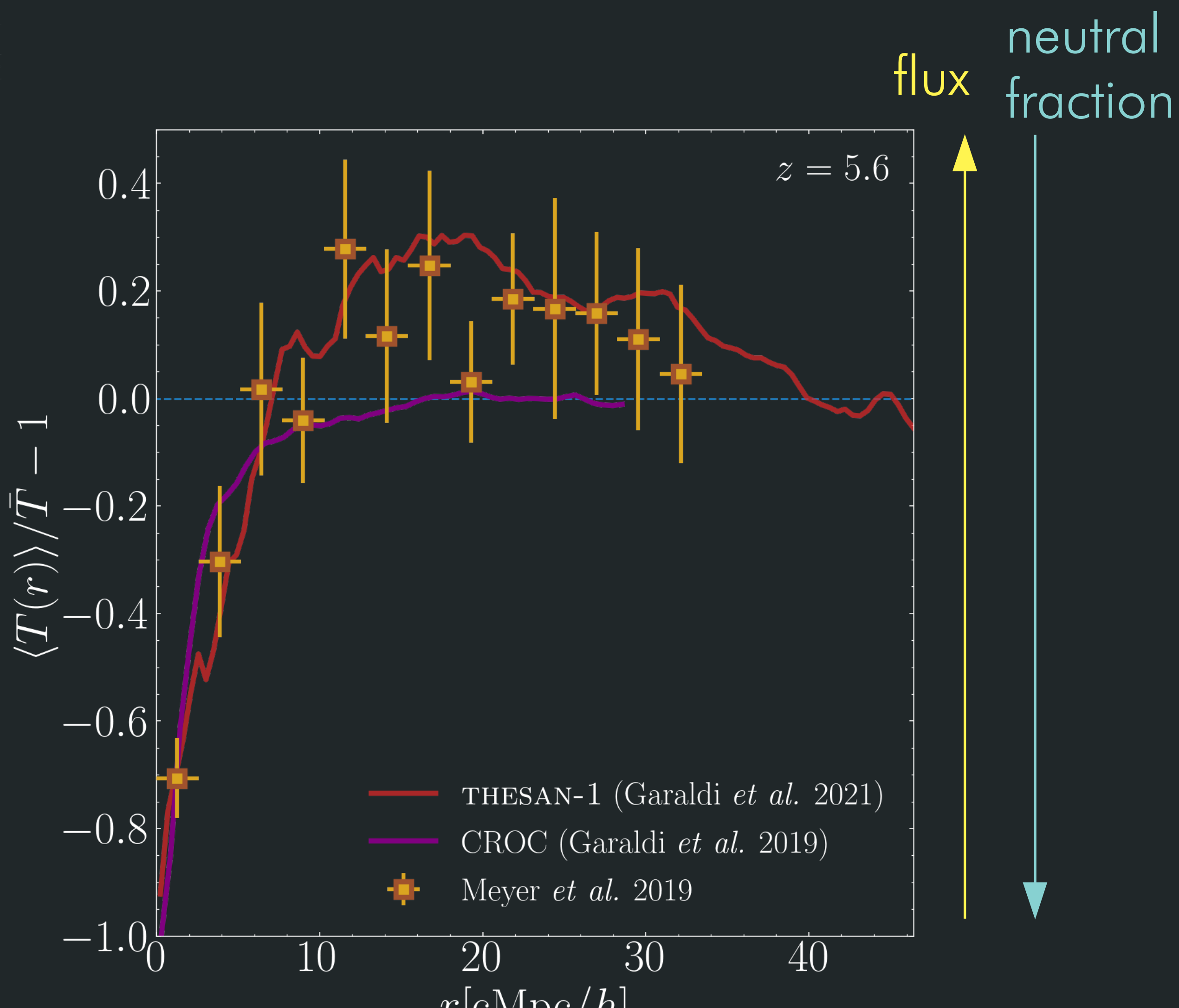
- catalogs now reach to $z\sim6$ (D'Odorico et al. 2013, Becker et al. 2019, Zou et al. 2021, Davies et al. 2023)
- can simulations reproduce these?

UNEXPECTED LAEs AT $z>8$

- Ly-a emitters found at $z=9$-10
- Requires large ionized bubbles → unlikely in our models (Lu et al. 2024)

REIONIZATION AS A TEST OF GALAXY FORMATION MODELS





Garaldi et al. 2022