RADIATION-HYDRODYNAMICAL MODELING OF THE GALAXY-IGM INTERPLAY DURING REIONIZATION

Enrico Garaldi

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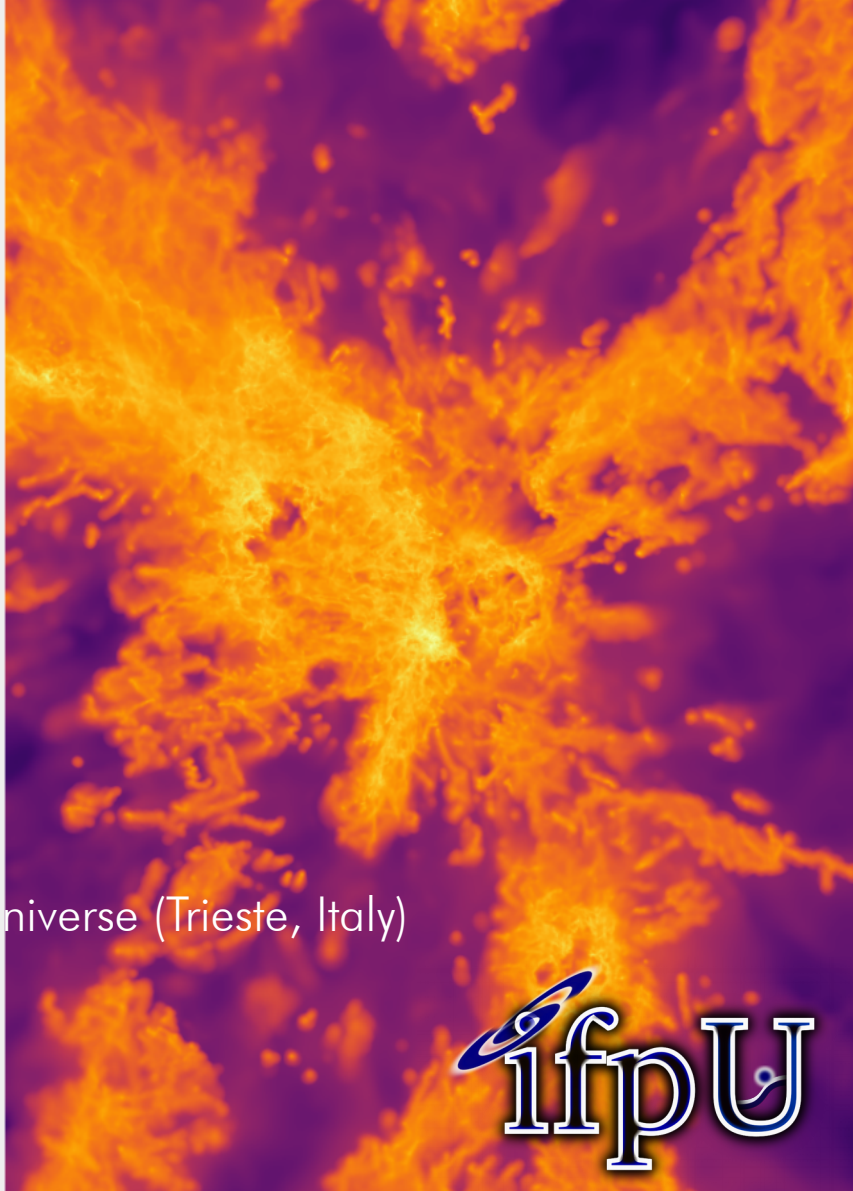
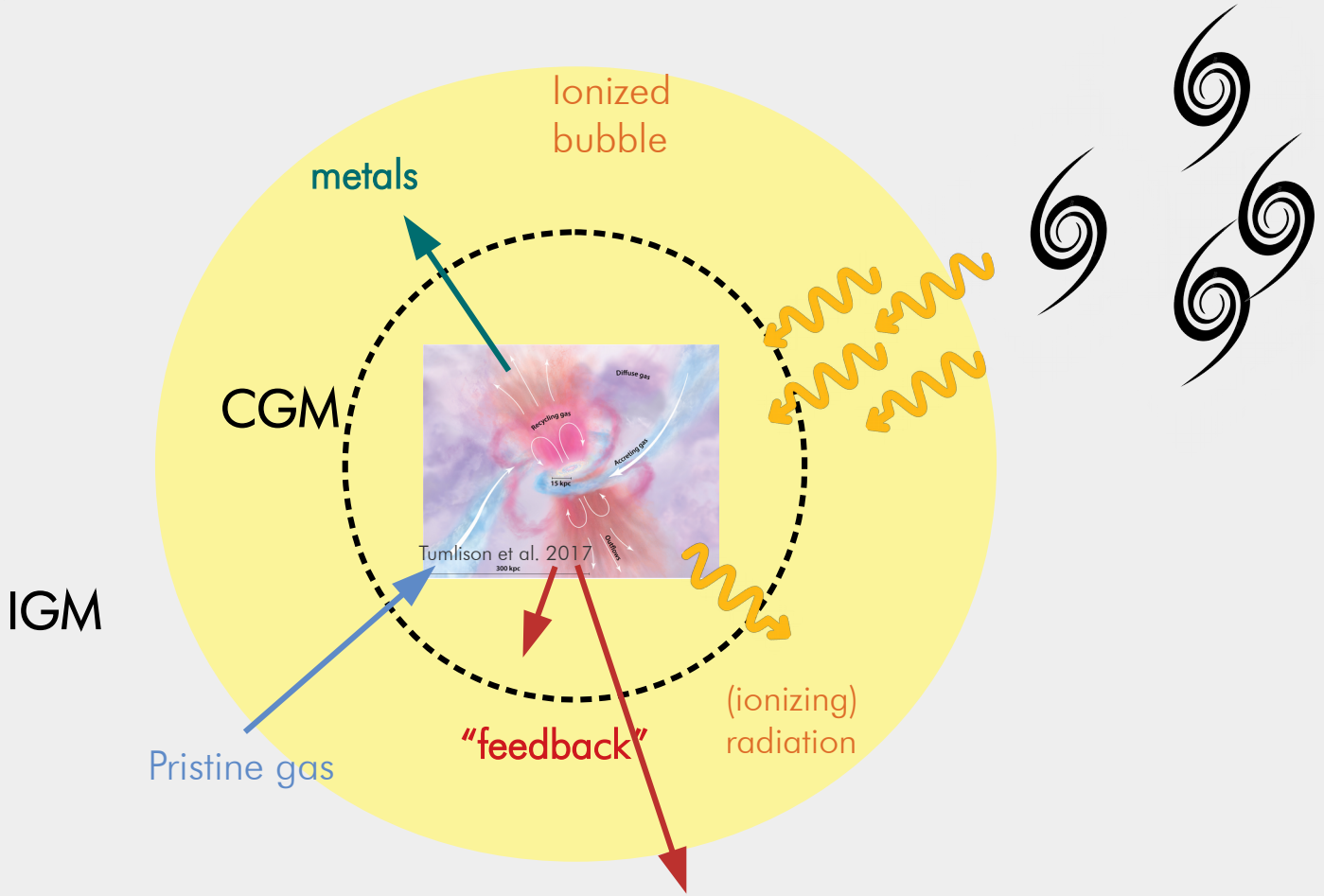
→ Assistant Prof. @ IPMU (Tokyo, from Jan. 2025)



THE COMPLEX INTERPLAY BETWEEN GALAXIES AND IGM DEMANDS ACCURATE SIMULATIONS



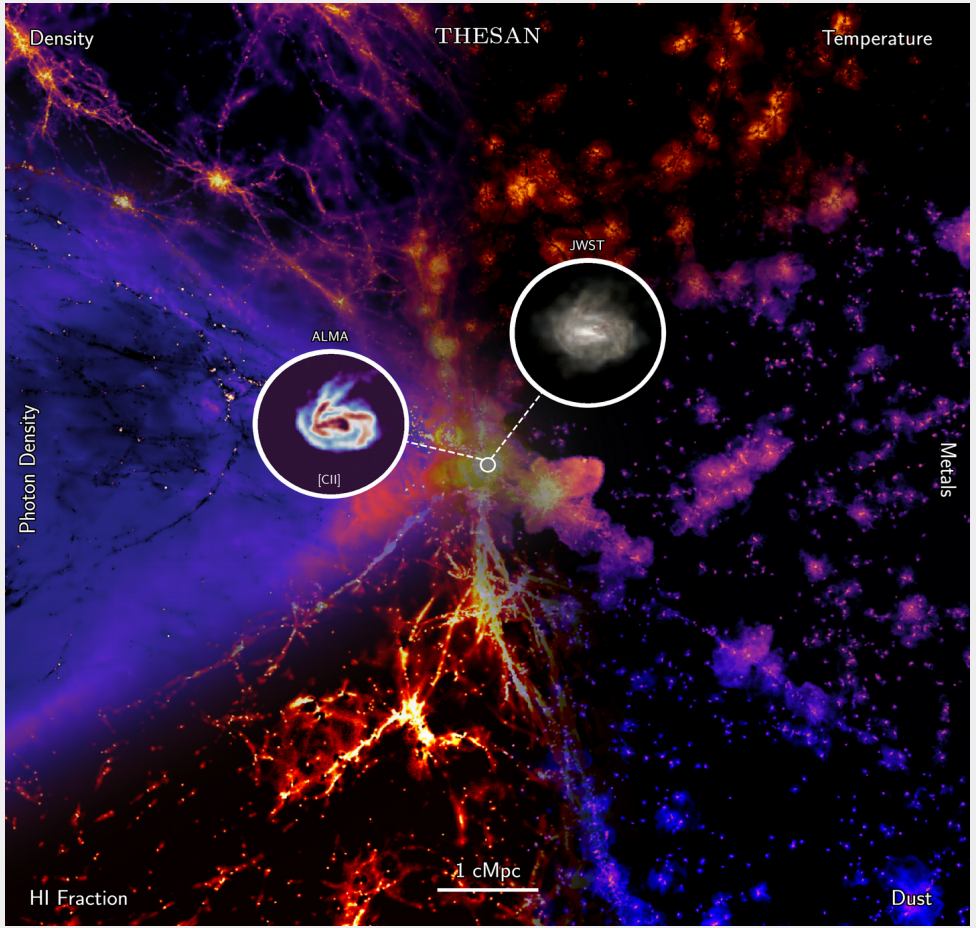
THESAN: REIONIZATION MEETS GALAXY FORMATION

Large cosmological RMHD simulations (AREPO code)

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

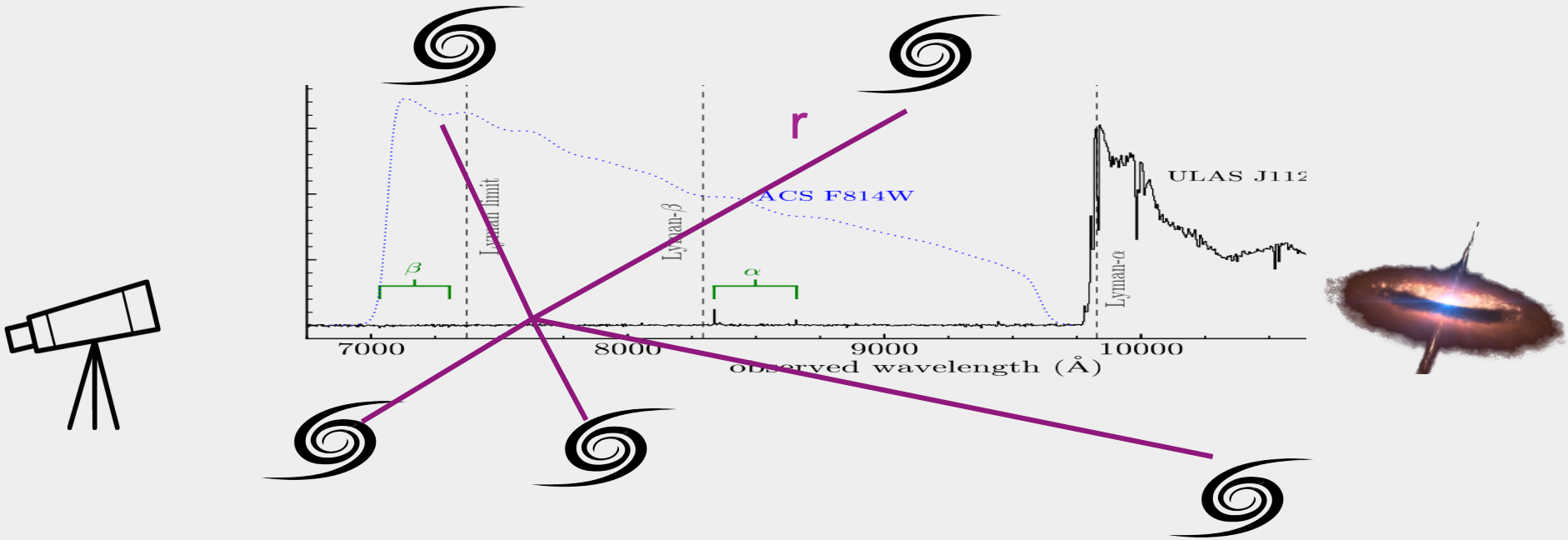
- **Rich physics**
  - Illustris-TNG galaxy formation model
  - radiation from stars, binaries and BH
  - cosmic dust, magnetic fields
  - variance-suppressed ICs

  → A single free parameter at high-z (f_{esc})
- **Numerical parameters:**
  - L_{box} = 95.5 cMpc
  - $m_{DM} = 3 \times 10^6\ M_{sun}$; $m_{gas} = 6 \times 10^5\ M_{sun}$
  - ϵ = 2.2 ckpc
  - z_{fin} = 5.5
- **Publicly available** at www.thesan-project.com



THE GALAXY – LYMANα CROSS-CORRELATION (GaLαCC)

Average normalised Lyman-alpha flux (T) as function of distance from galaxy (r)



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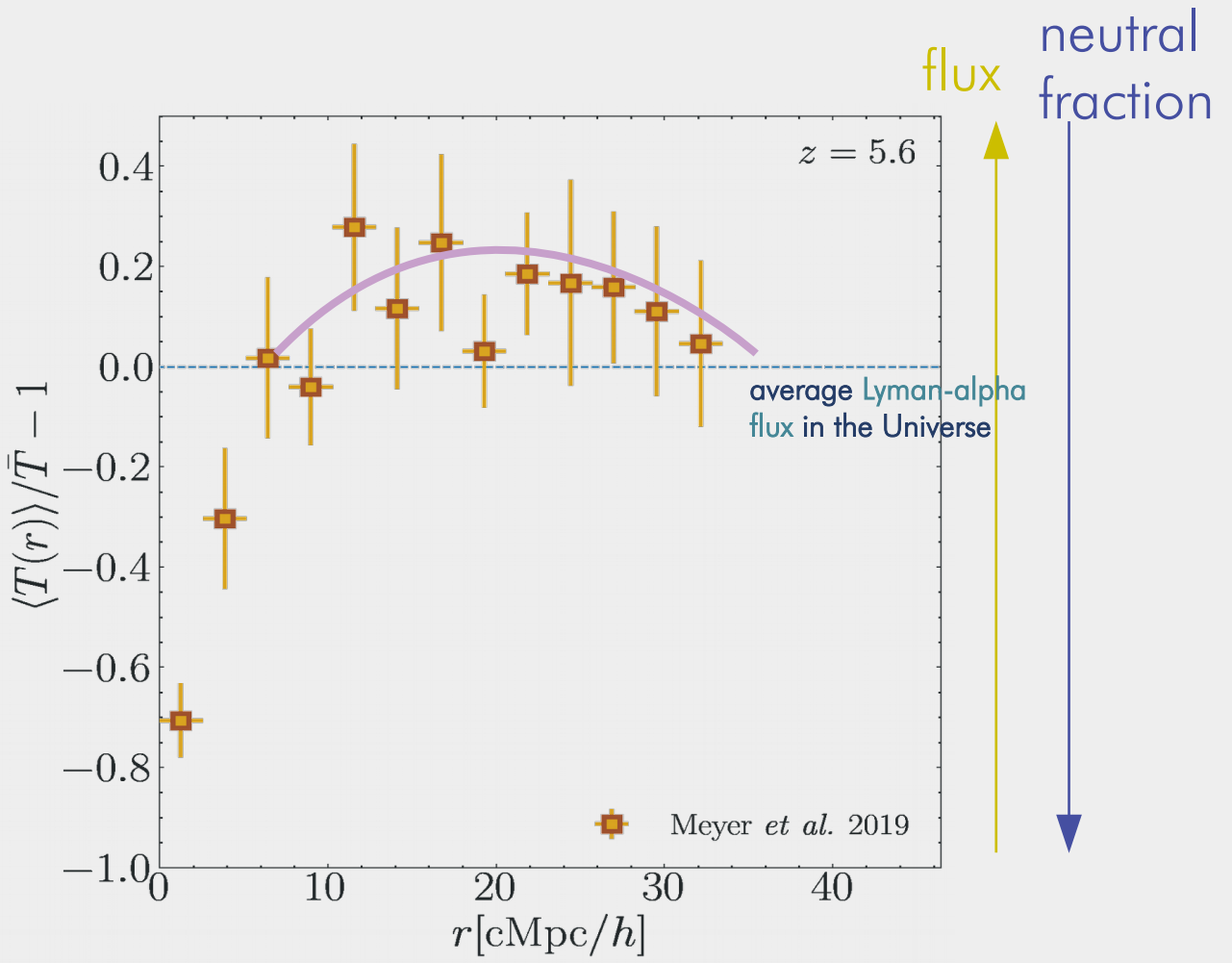

Garaldi et al., 2019

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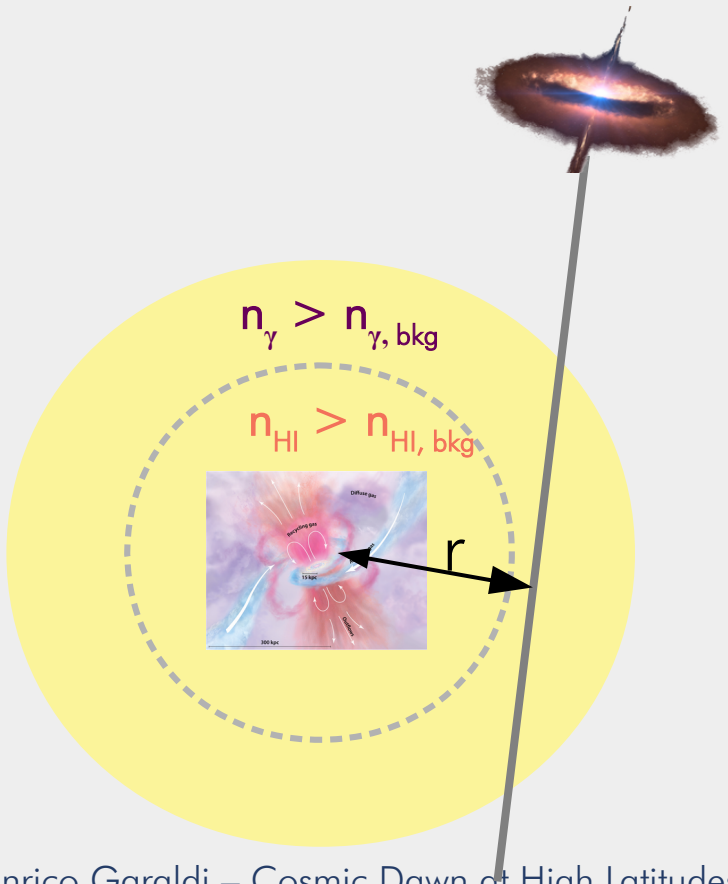

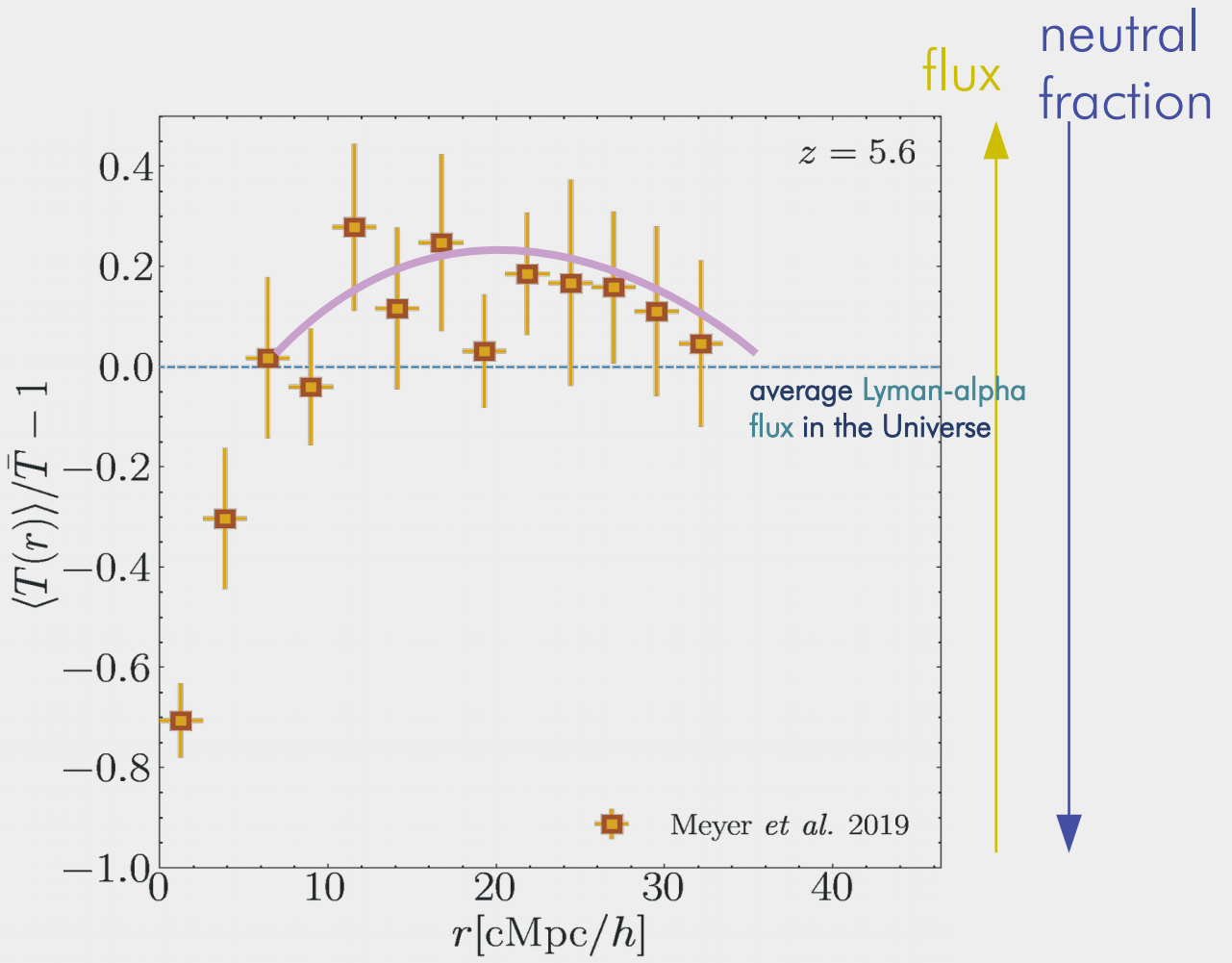

Garaldi et al., 2019

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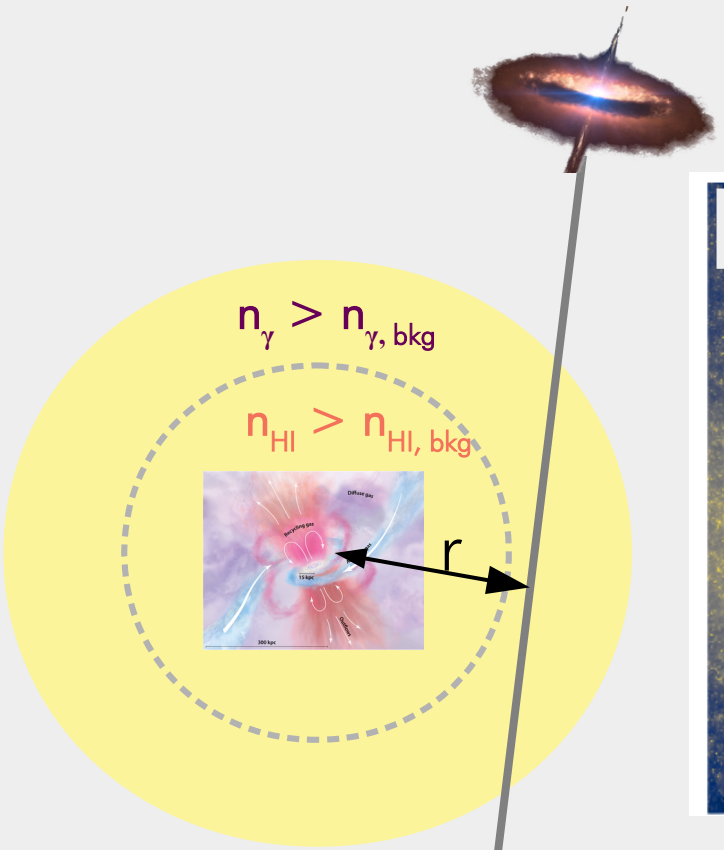
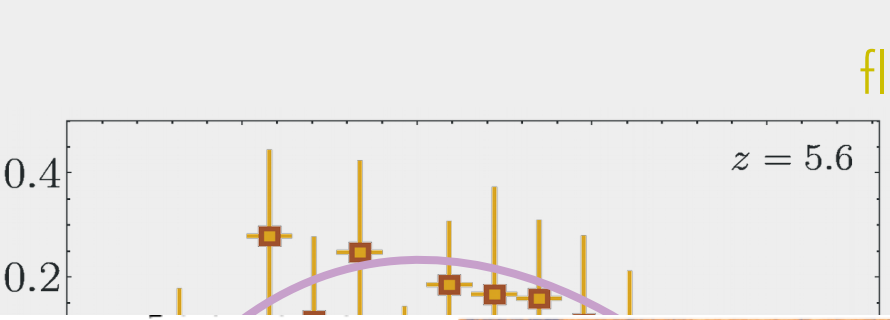
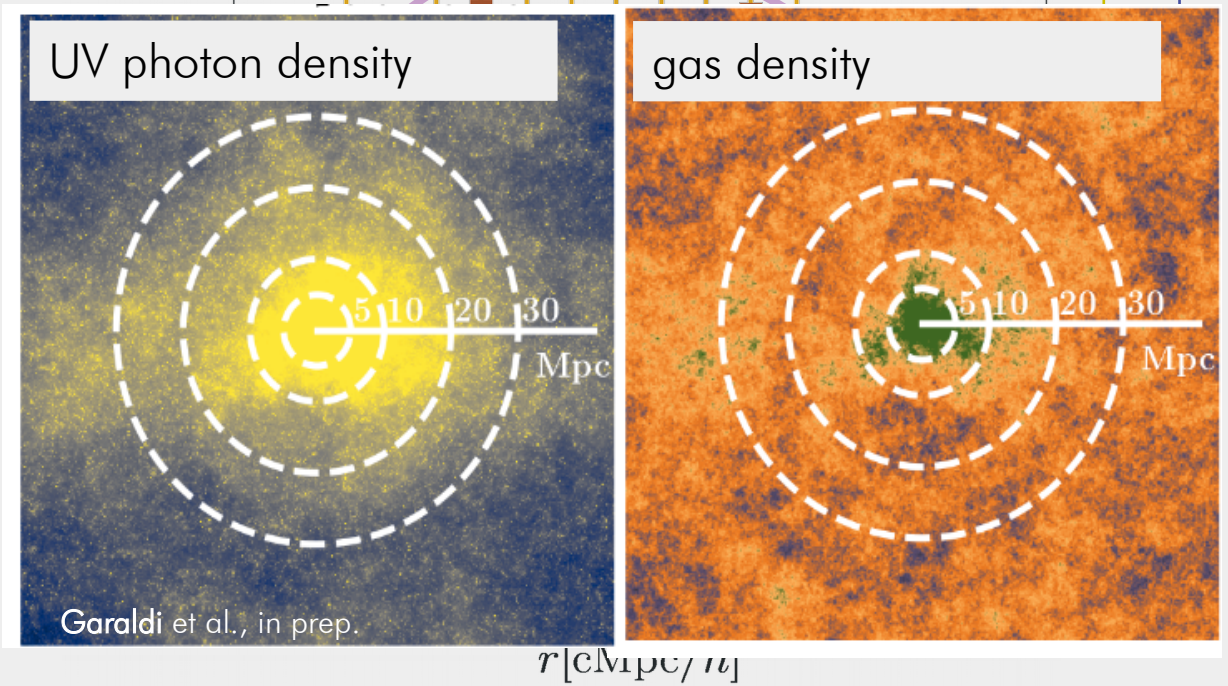




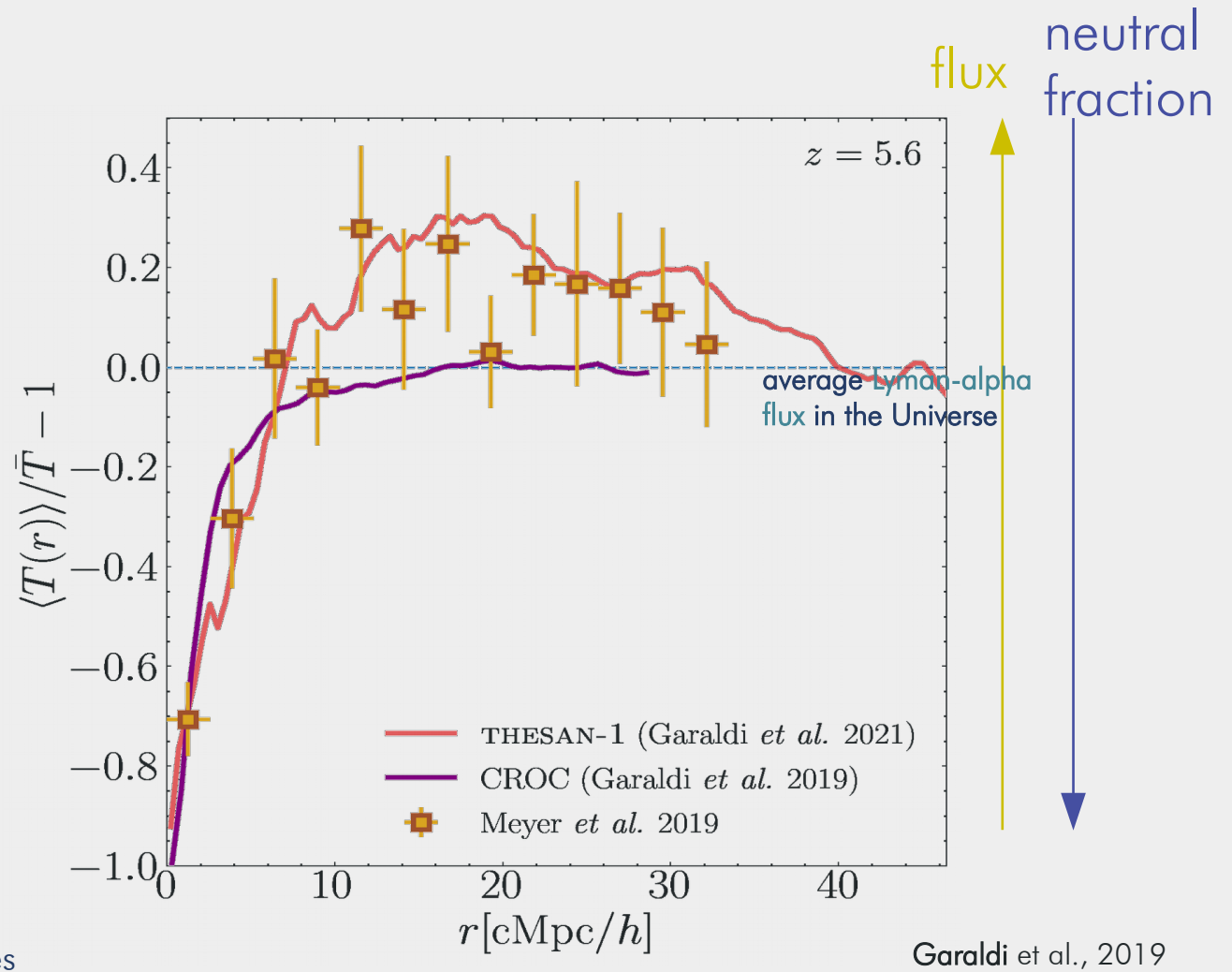


Garaldi et al., 2019

THE GaLαCC IS A HARD TEST FOR REIONIZATION MODELS

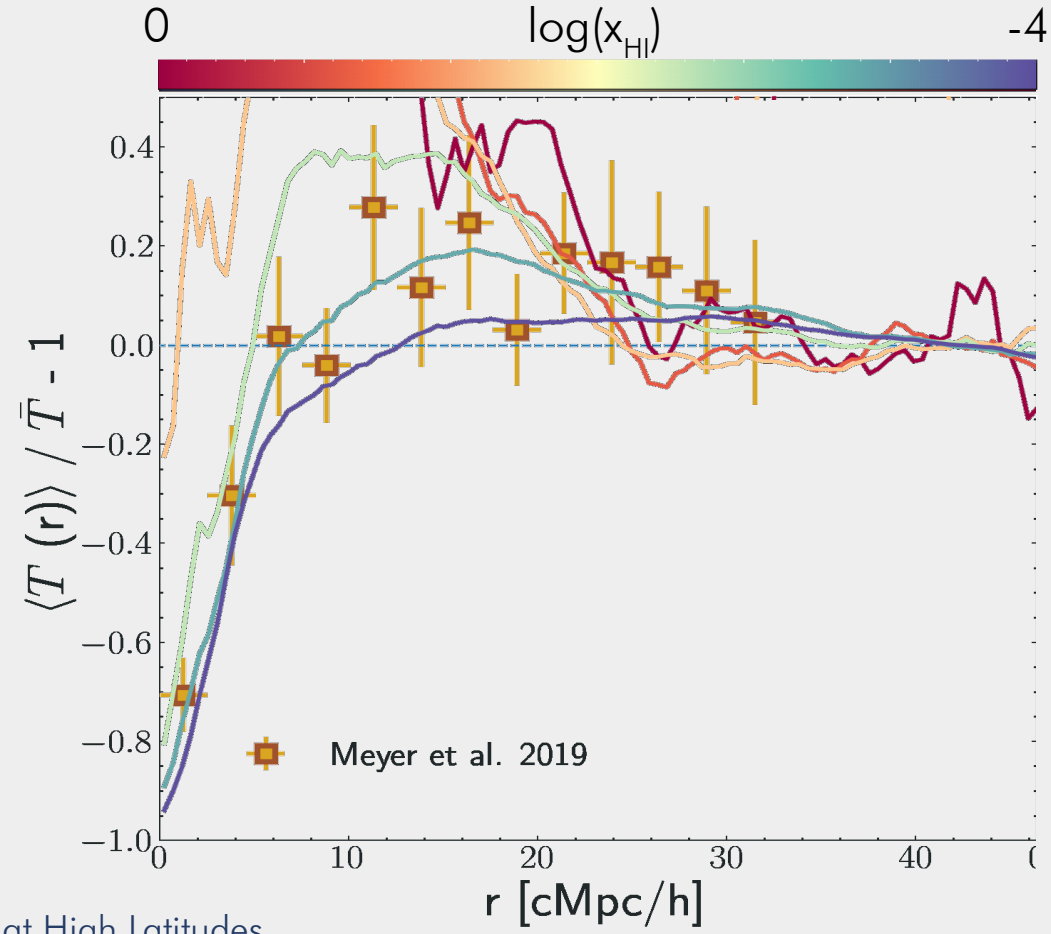
Both CROC and THESAN predict very well the IGM properties!

However, CROC places galaxies in the 'wrong' haloes (i.e. it breaks the stellar-to-halo mass relation, Zhu et al. 2020)



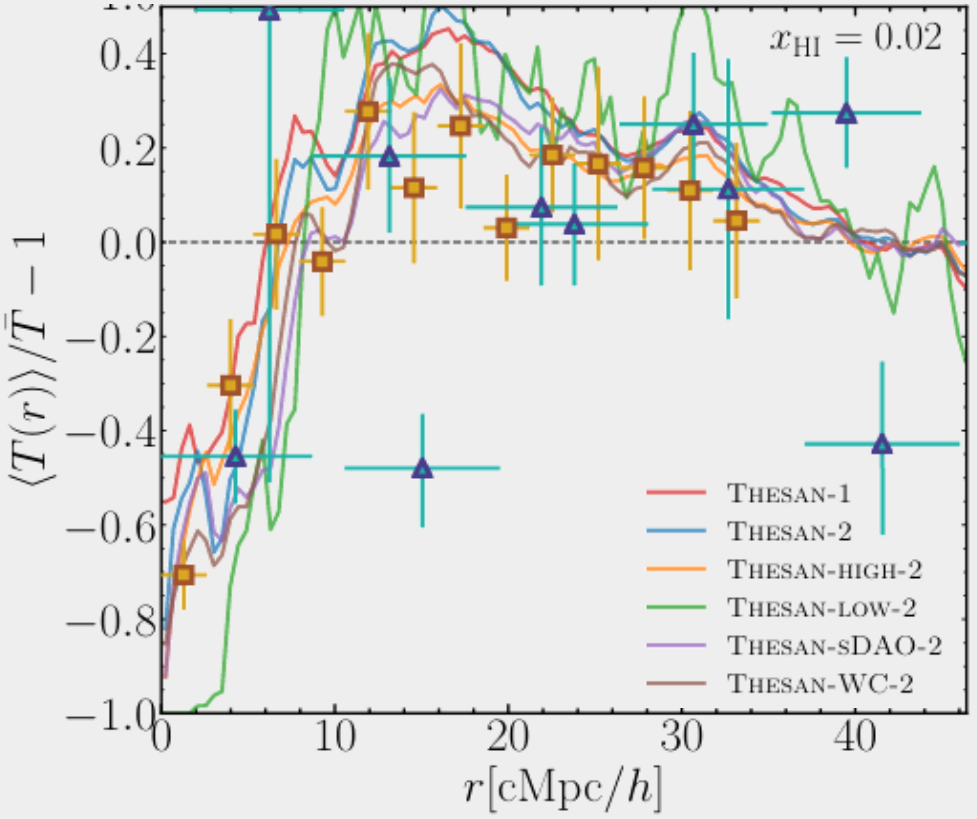
Garaldi et al., 2019

THE GaLαCC IS A POWERFUL TOOL TO CONSTRAIN REIONIZATION



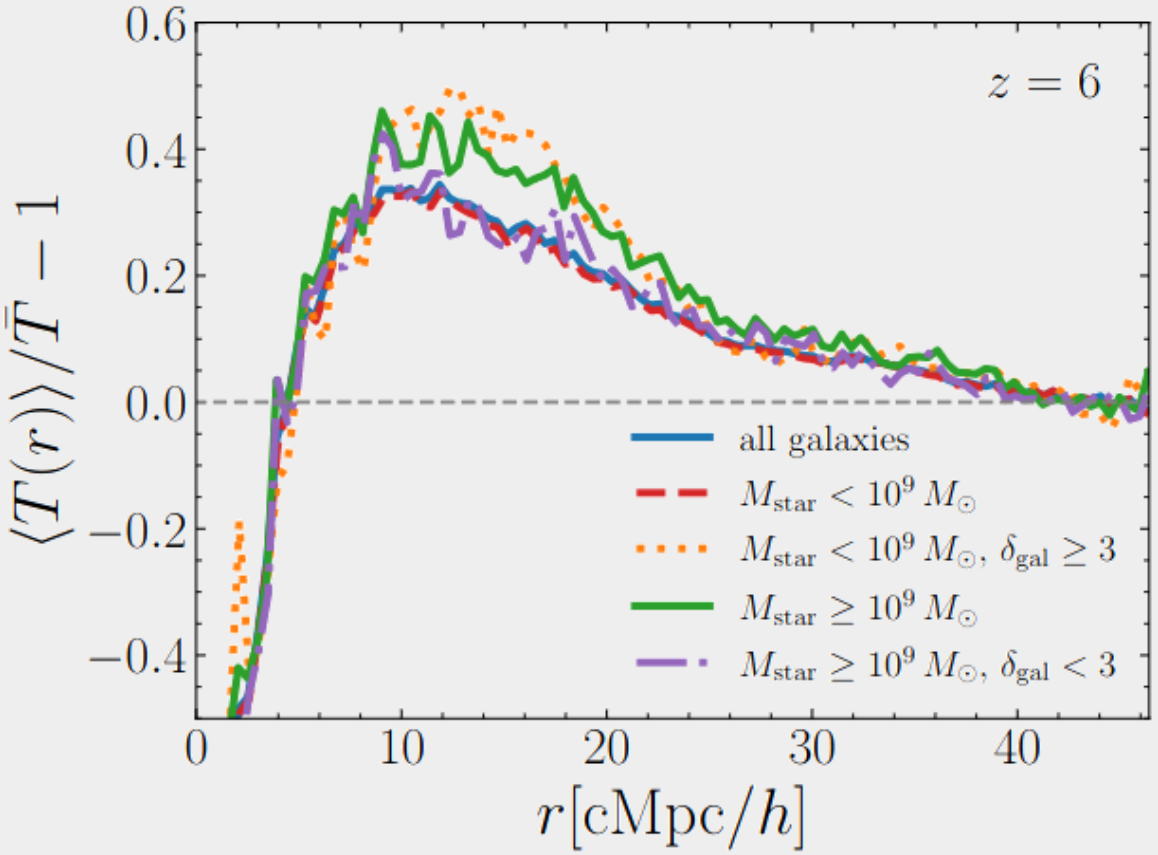
Garaldi et al., 2022

THE GaLαCC IS INSENSITIVE TO REIONIZATION SOURCES



Garaldi et al., 2022

THE GaLαCC IS A COLLECTIVE EFFECT OF GALAXIES LIVING IN THE LARGEST OVERDENSITIES



all galaxies, any overdensity

small galaxies, any overdensity

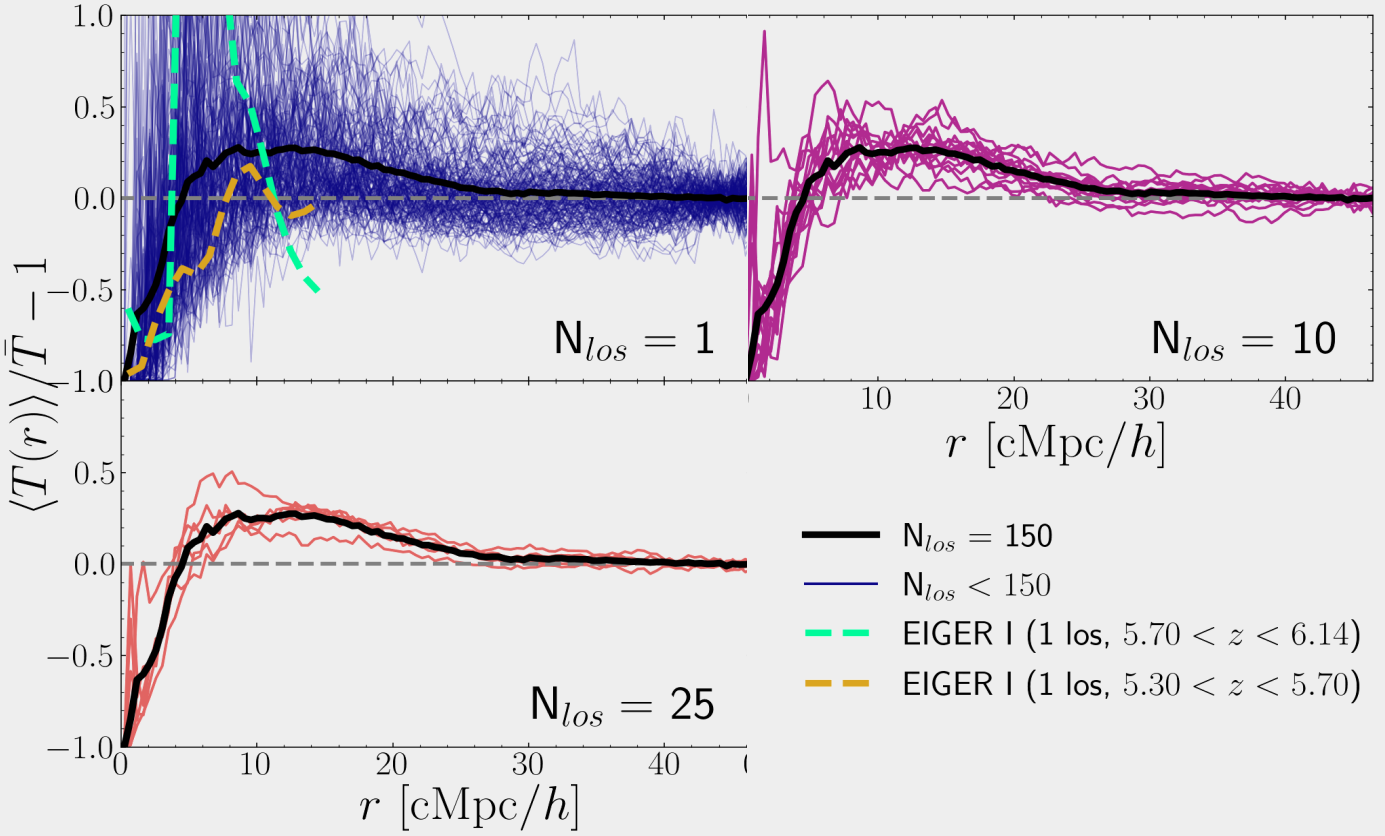
small galaxies, large overdensity

large galaxies, any overdensity

large galaxies, small overdensity

Garaldi et al., in prep.

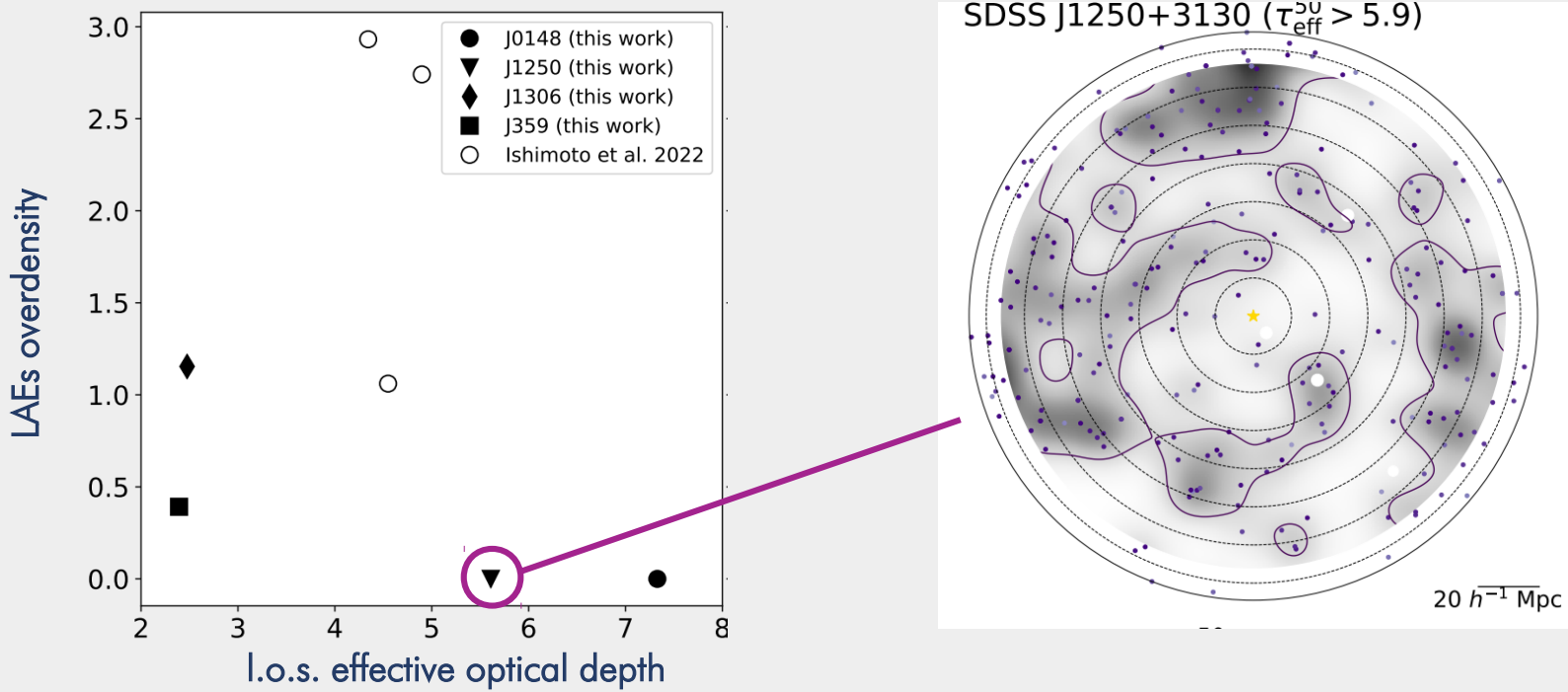
OBSERVATIONS ARE TOO SCARCE TO DELIVER QUANTITATIVE CONSTRAINT



Garaldi et al. in prep.

▸ At least 10-15 independent lines of sights required to make *qualitative* statements

THE GaLαCC HAS IMPLICATIONS FOR THE LOS OPTICAL DEPTH – GALAXY DENSITY RELATION



Christenson et al., 2023

(see also Becker+2018, Kashino+2020, Christenson+2021, Ishimoto+2022)

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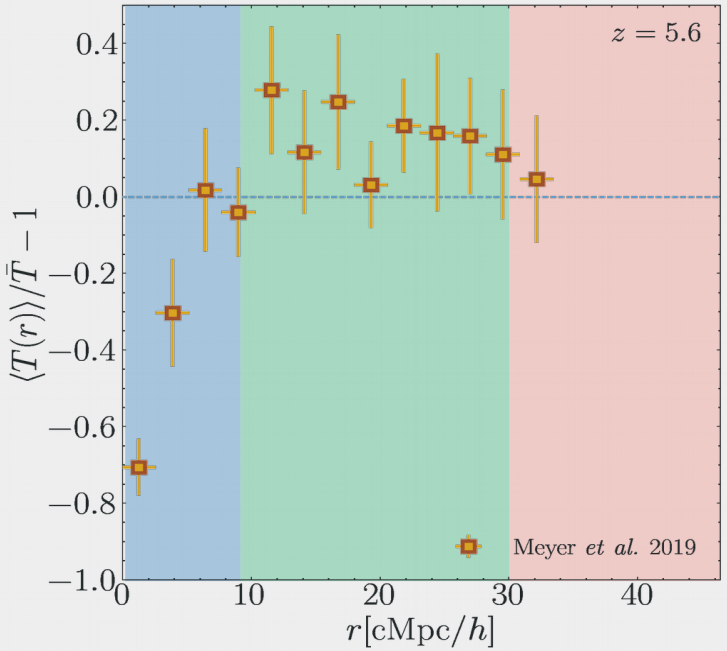

Close galaxies increase optical depth

Nearby galaxies decrease optical depth

Distant galaxies do nothing to the optical depth

Garaldi et al., 2022

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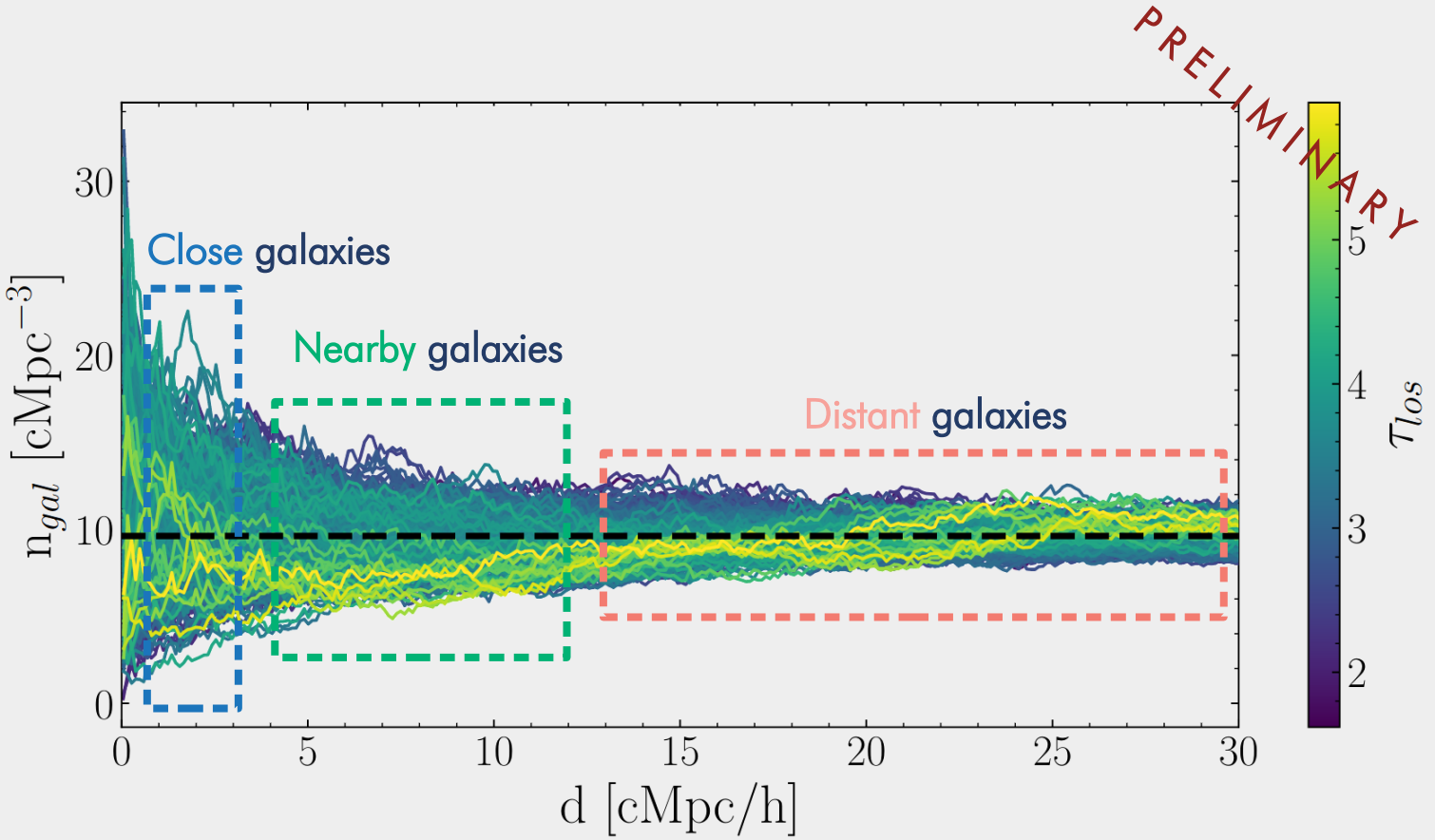
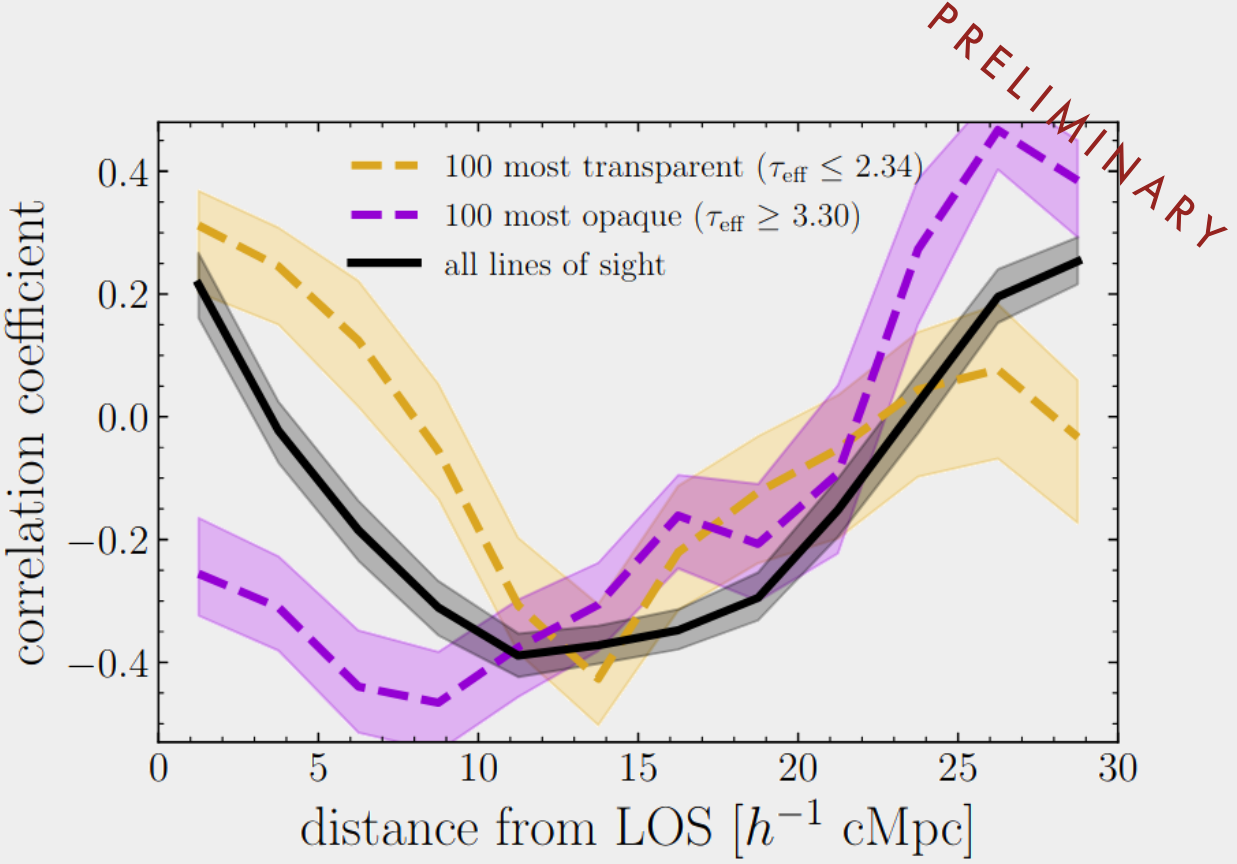


Garaldi et al., in prep.

THE GaLαCC HAS IMPLICATIONS FOR THE LOS OPTICAL DEPTH – GALAXY DENSITY RELATION

How relevant are galaxies at a given distance for the los optical depth?



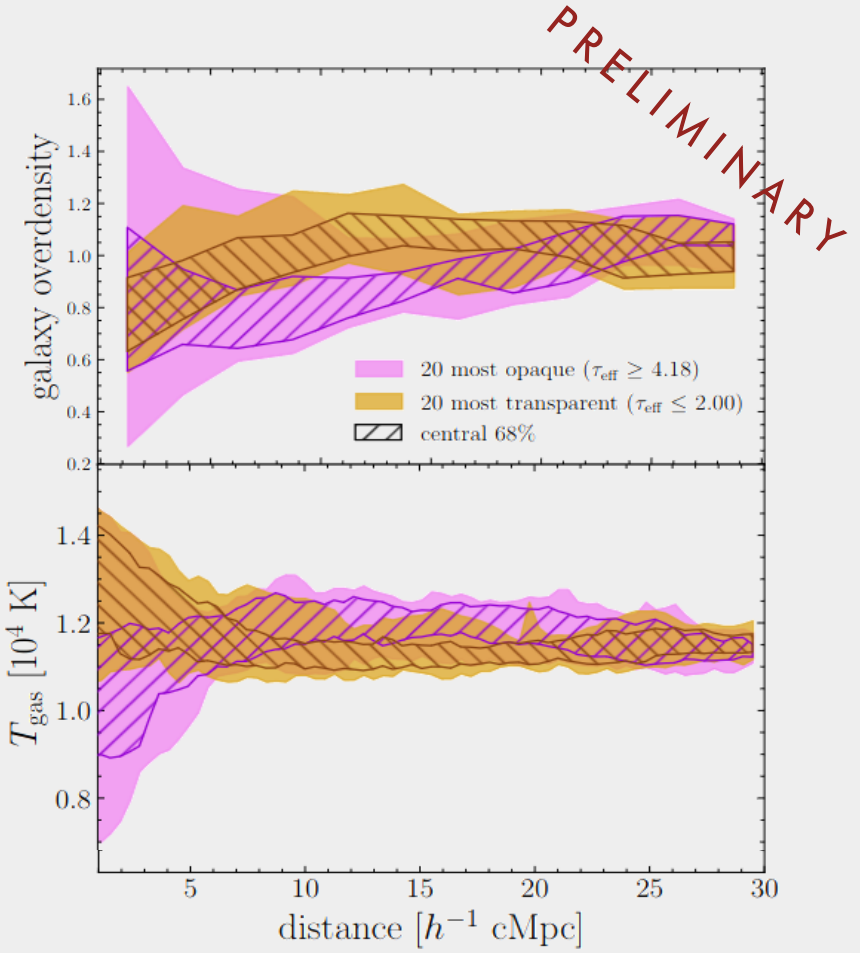
Garaldi et al., in prep.

THE GaLαCC HAS IMPLICATIONS FOR THE LOS OPTICAL DEPTH – GALAXY DENSITY RELATION

Opaque sightlines are colder and have less galaxies at intermediate distances.

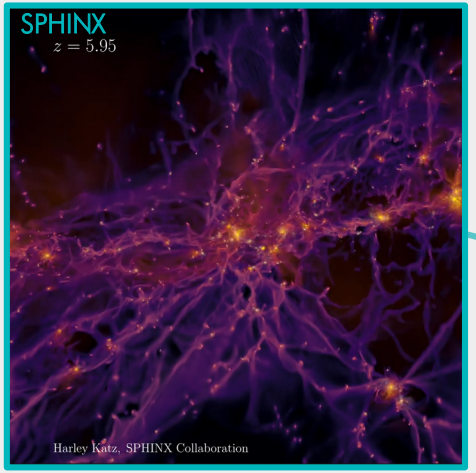
Transparent sightlines are hotter and have more galaxies at intermediate distances.

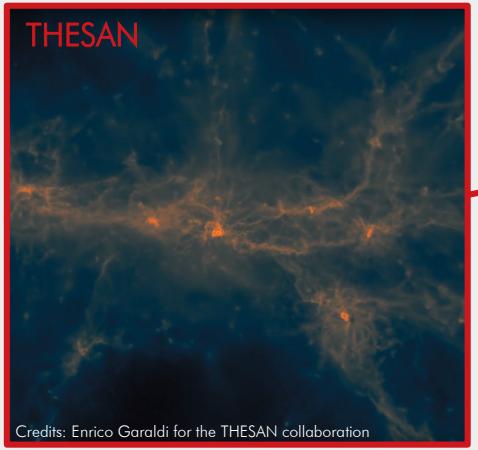
Nearby galaxies do not matter for l.o.s. opacity



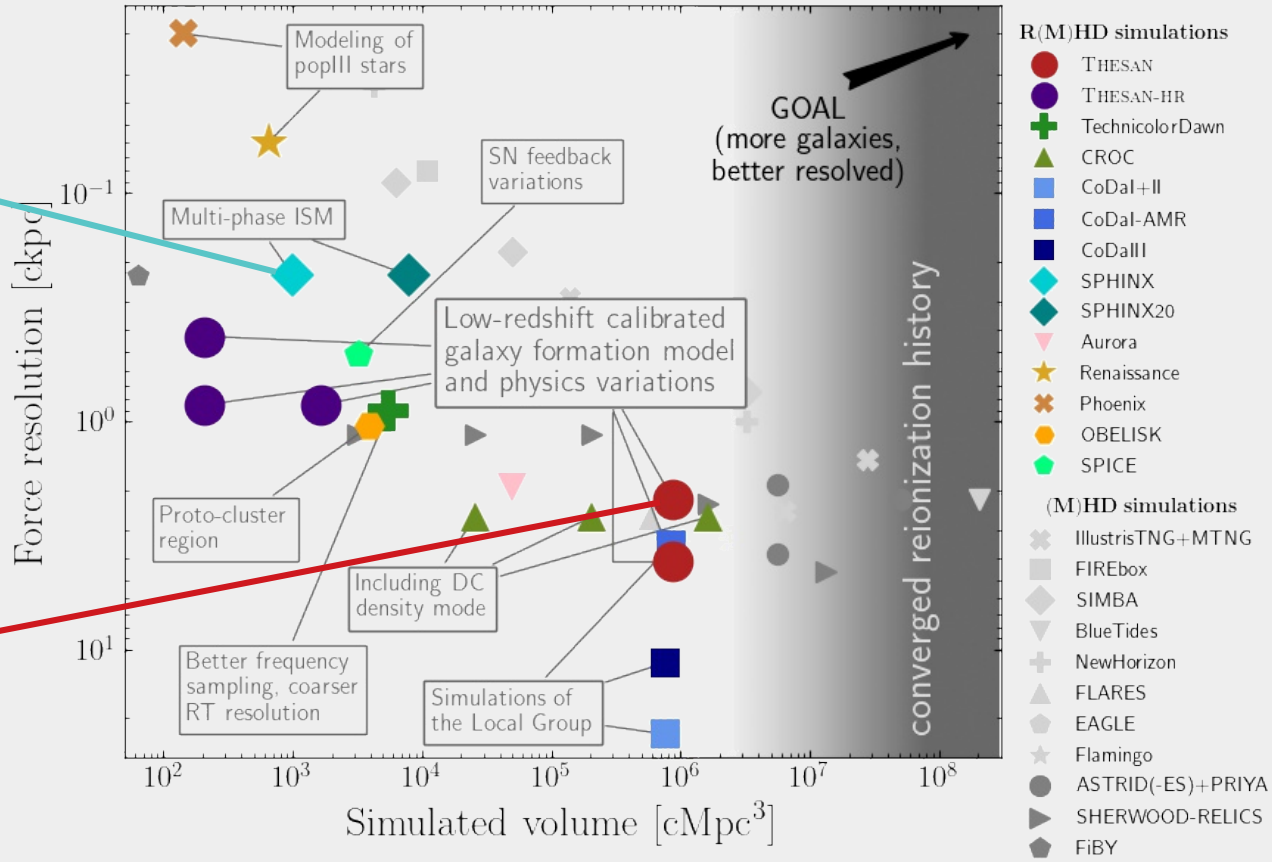
Garaldi et al., in prep.

RHD SIMULATIONS MUST CHOOSE BETWEEN RESOLVING GALAXIES AND COVERING LARGE VOLUMES





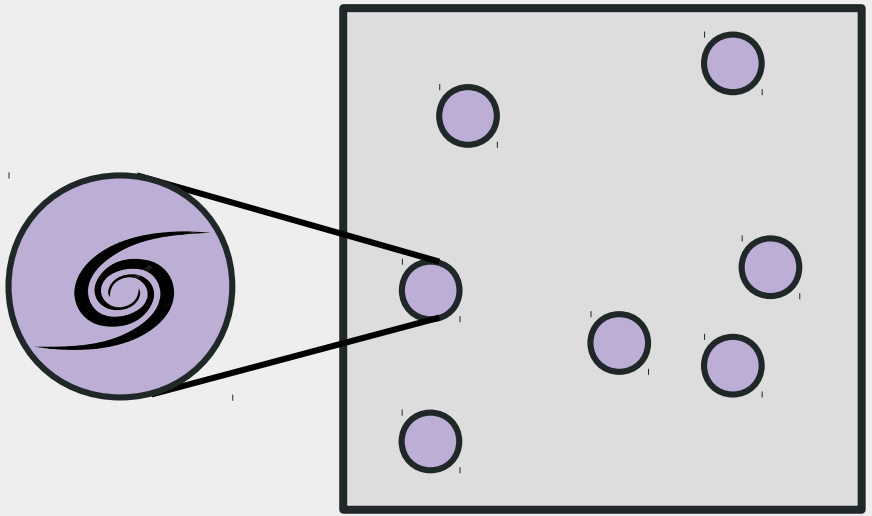
Simulated volume



Garaldi et al. 2023b

SIMULATING THE FULL DYNAMIC RANGE FROM IGM TO CGM TO ISM

Tiered approach: 1 large box + zoom-in simulations

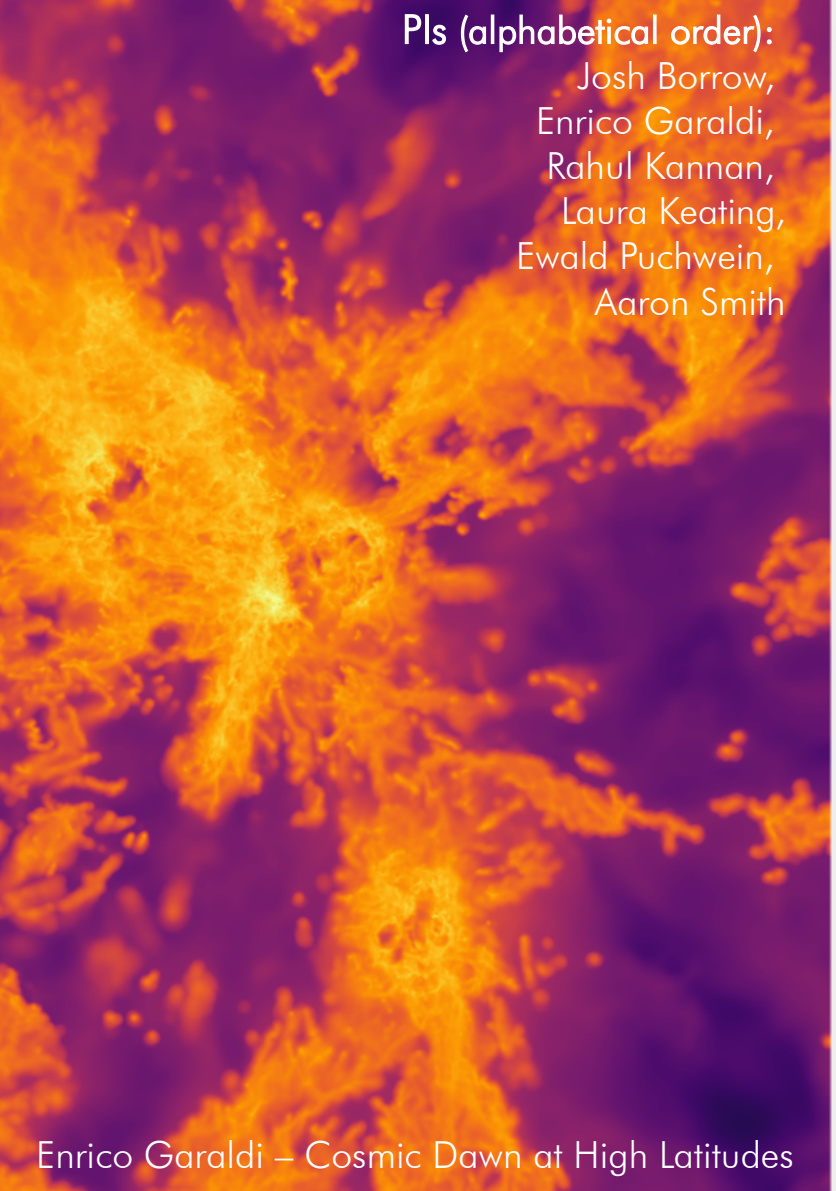


THESAN

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

THESANZOOM

(ongoing development)



PIs (alphabetical order):
Josh Borrow,
Enrico Garaldi,
Rahul Kannan,
Laura Keating,
Ewald Puchwein,
Aaron Smith

THESANZOOM: ISM AND CGM MEET REIONIZATION

Suite of zoom-in RMHD simulations of galaxies extracted from the THESAN box (ongoing).

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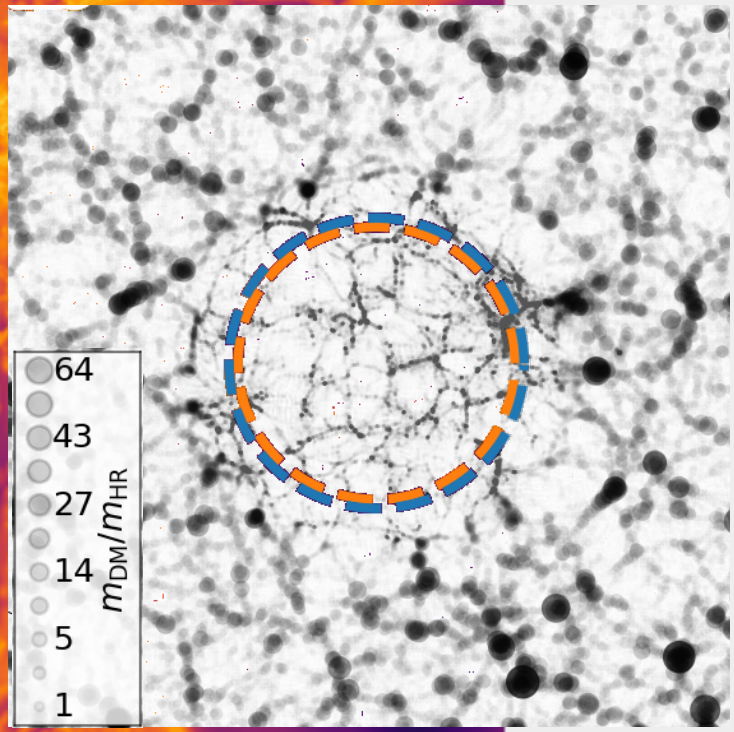

Problem with zoom-in: only gravity from environment

➞ but radiation travels >10s Mpc!

Garaldi et al., 2020

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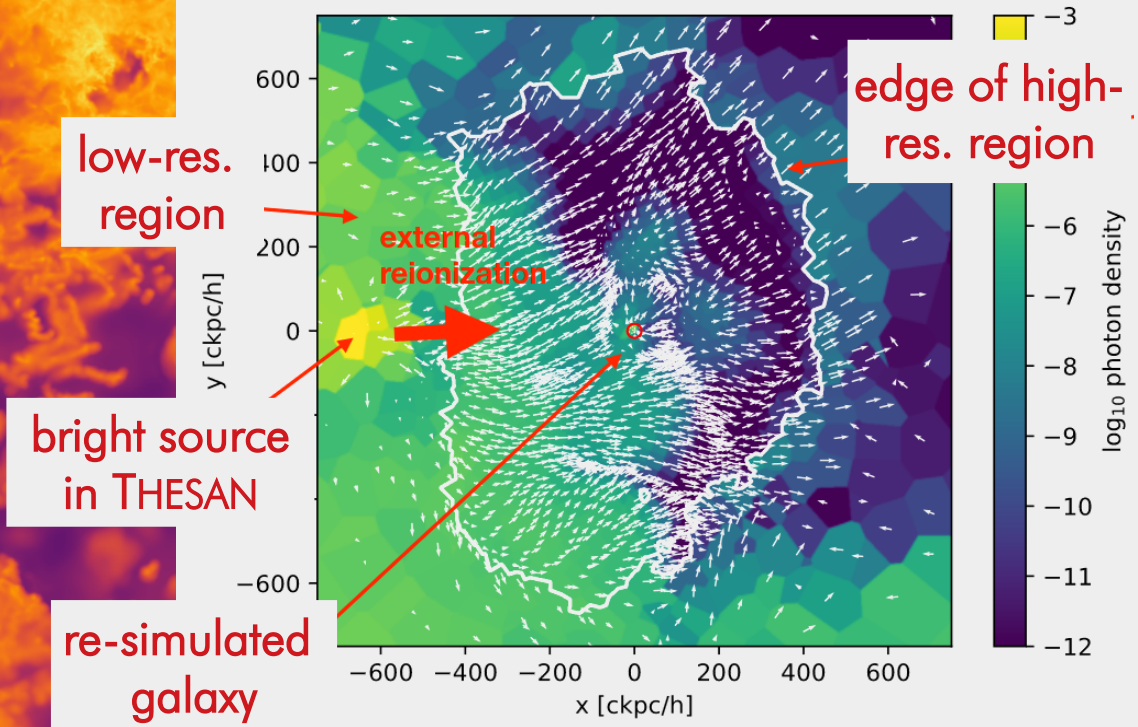

Problem with zoom-in: only gravity from environment

➞ but radiation travels >10s Mpc!

Our new solution: inject the time- and position-dependent radiation field from the parent simulations

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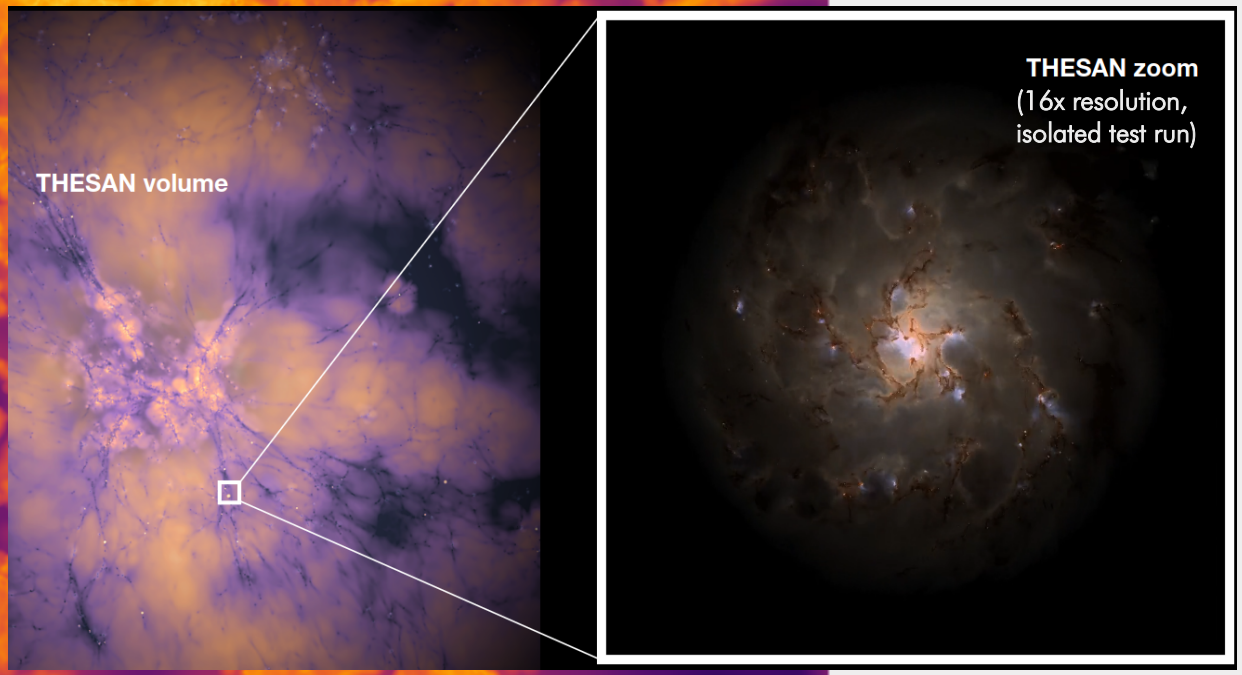

- Multi-phase ISM model
  - custom version of SMUGGLE (Marinacci+2019)
  - includes H_2, dust (incl. temperature), metal species, EUV-to-IR radiation
- Very high resolution
  - 3 levels: $m_{gas} \sim 10^4, 10^3, 10^2\ M_{sun}$
- $z_{fin} \sim 2$
  - can check for robustness of EoR analogs
- physics variations
  - CGM refinement
  - turbulence-based SFE
  - pre-SN stellar feedback

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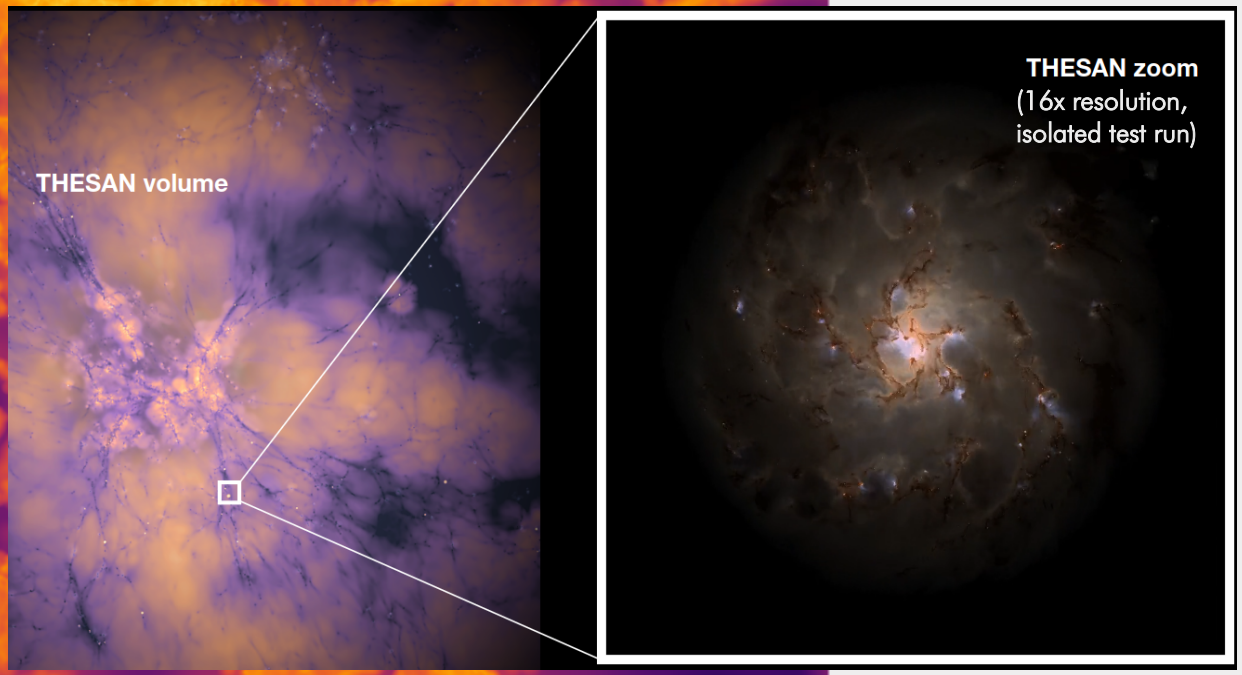
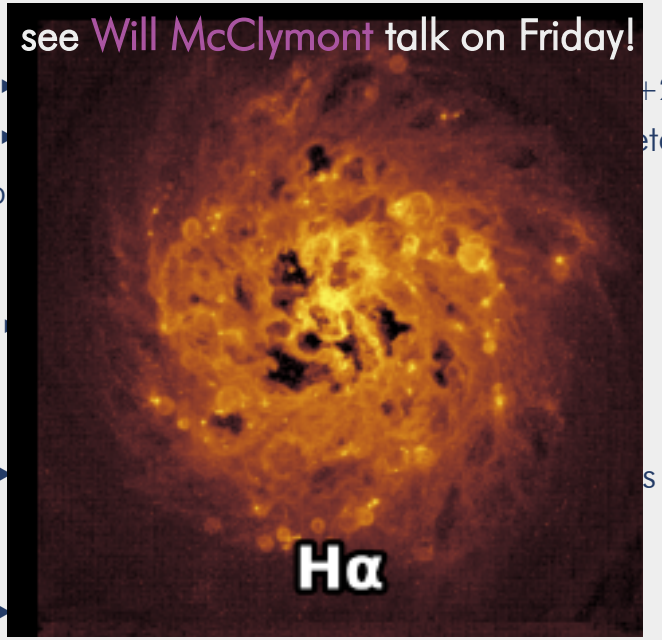


- see Will McClymont talk on Friday!
- +2019)
- etal
- sp
- s
- turbulence-based SFE
- pre-SN stellar feedback



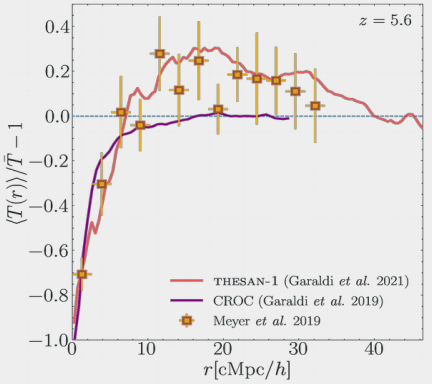
CONCLUSIONS.

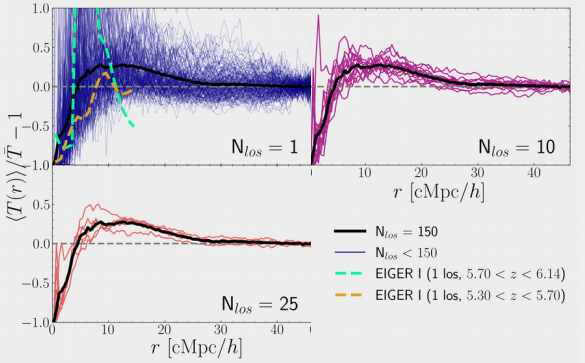
The galaxy – Lymanα cross-correlation…

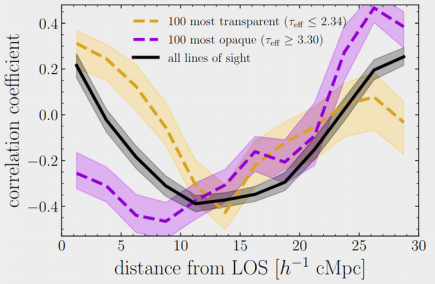
…is a powerful tool to test reionization+galaxy formation models and constrain the reionization history.

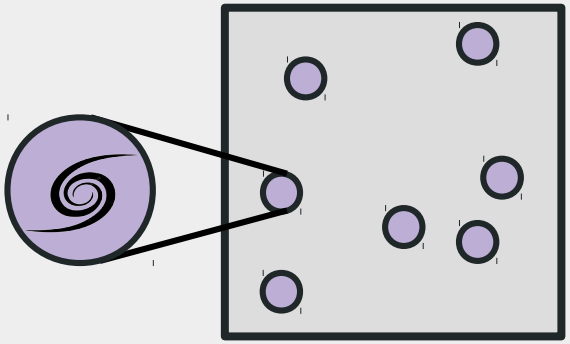
…requires a large number of sightlines. Surveys like EIGER and ASPIRE will deliver a first constrain.

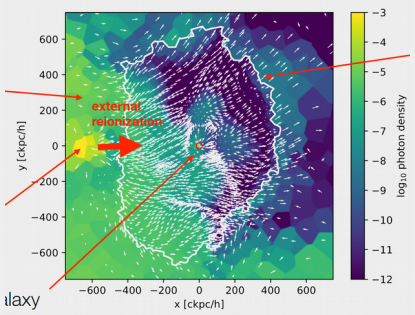
…delivers information on the optical depth – galaxy density relation.











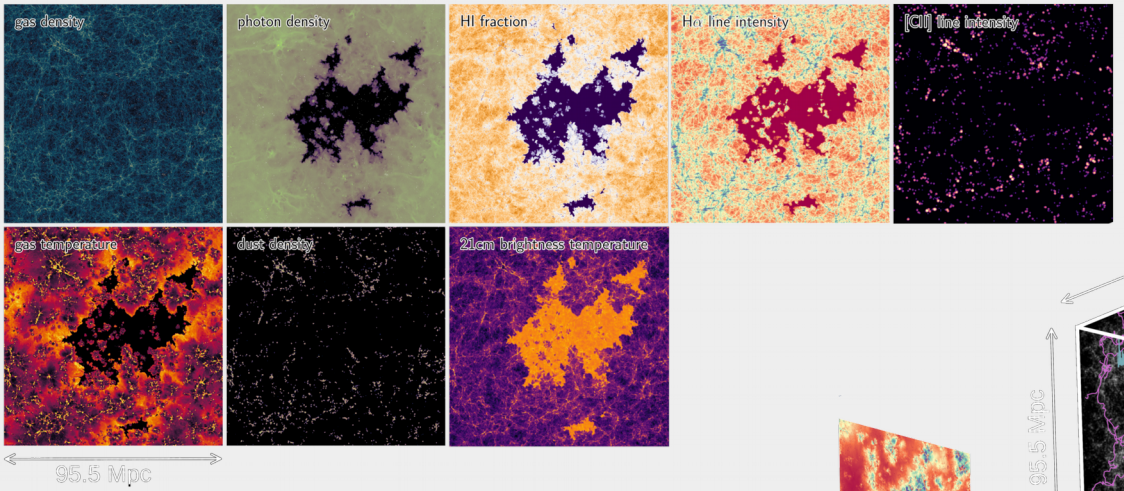
The ongoing THESANZOOM project will…

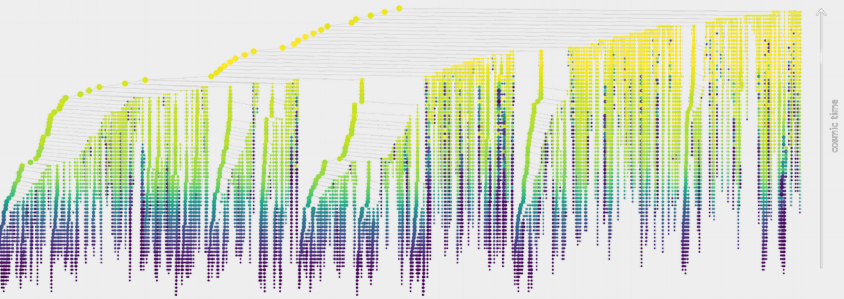
…bridge reionization and ISM scales in a self-consistent way.

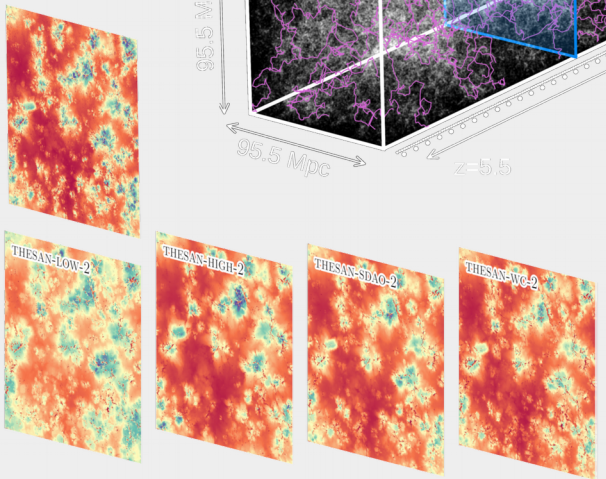
…allow detailed studies of the galaxy-IGM interplay from Cosmic Dawn to Cosmic Noon

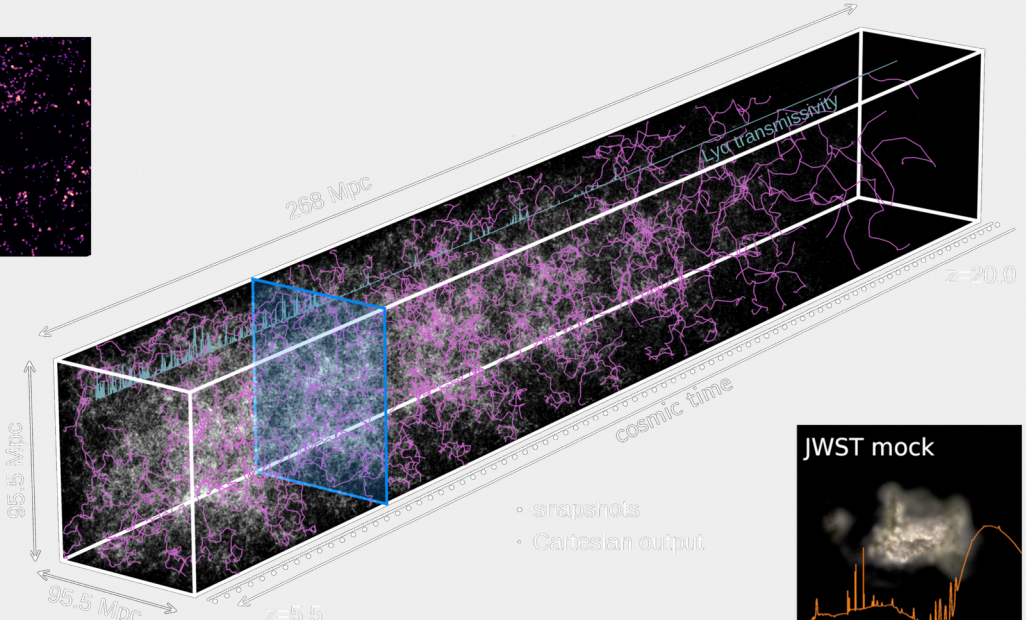
ADDITIONAL SLIDES

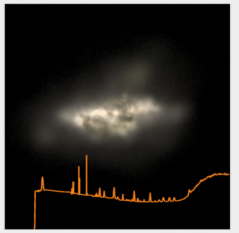
THESAN: REIONIZATION MEETS GALAXY FORMATION

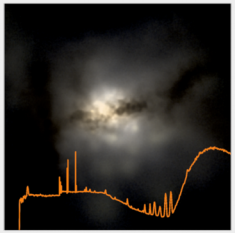






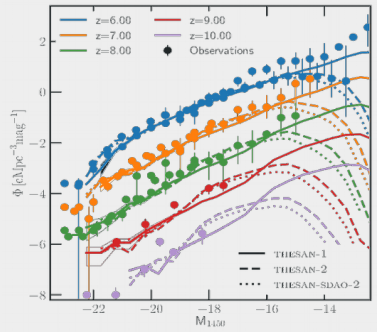




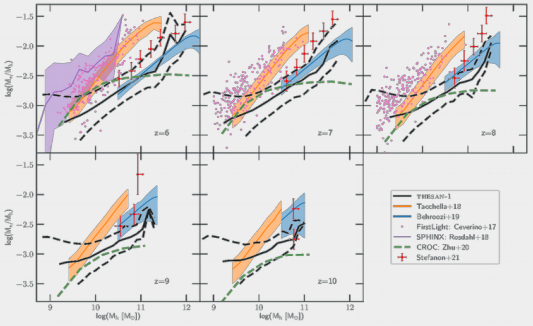


THESAN: REIONIZATION MEETS GALAXY FORMATION

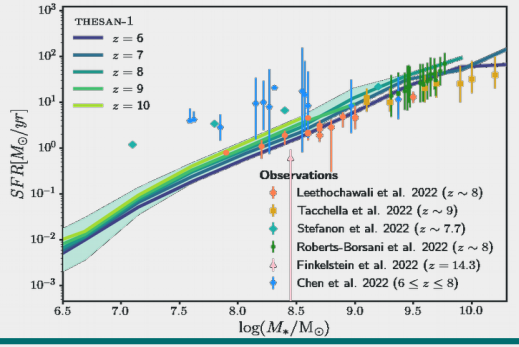
UV LUMINOSITY FUNCTION



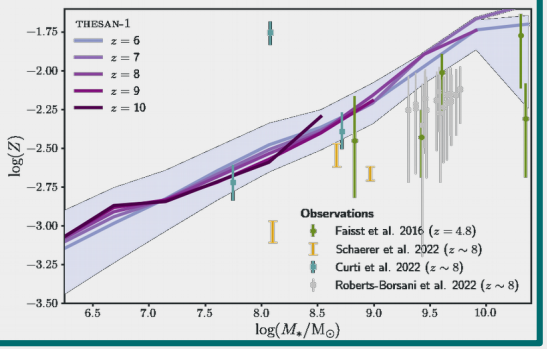
STELLAR-TO-HALO MASS RELATION



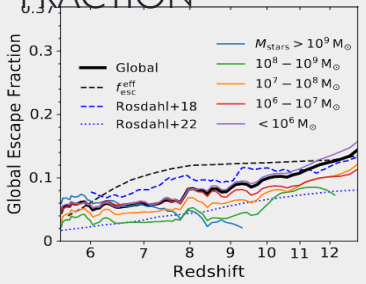
GALAXY MAIN SEQUENCE



(STELLAR) MASS – (GAS) METALLICITY RELATION



IONIZING ESCAPE FRACTION

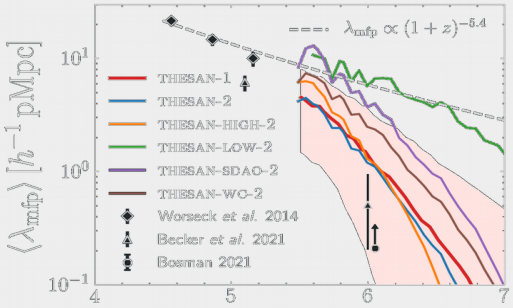


GALAXIES

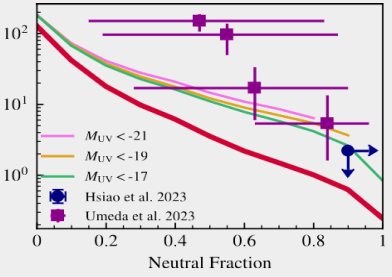
EG et. Al, 2022, 2023; Kannan, EG et al., 2022; Shen,.. EG,.. 2023; Neyer,.. EG,.. 2023; Yeh,.. EG,.. 2022;

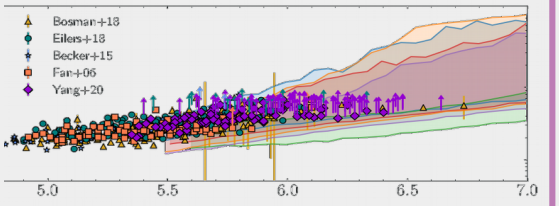
INTER-GALACTIC MEDIUM

MEAN FREE PATH OF IONIZING PHOTONS

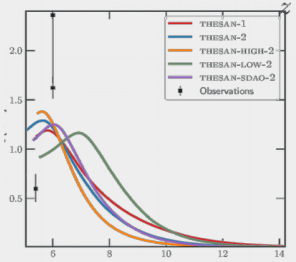


IONIZED BUBBLE SIZE





LYA OPTICAL DEPTH EVOLUTION

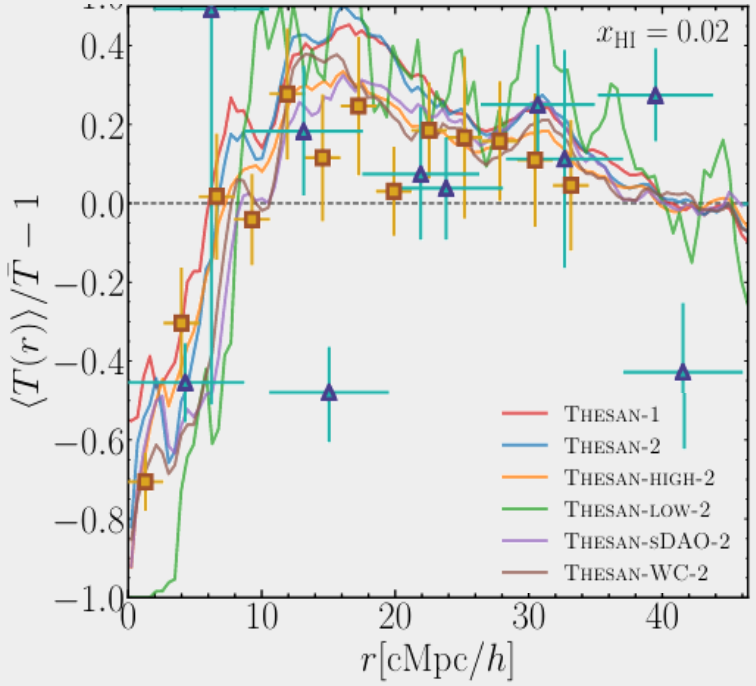


IGM MEAN TEMPERATURE

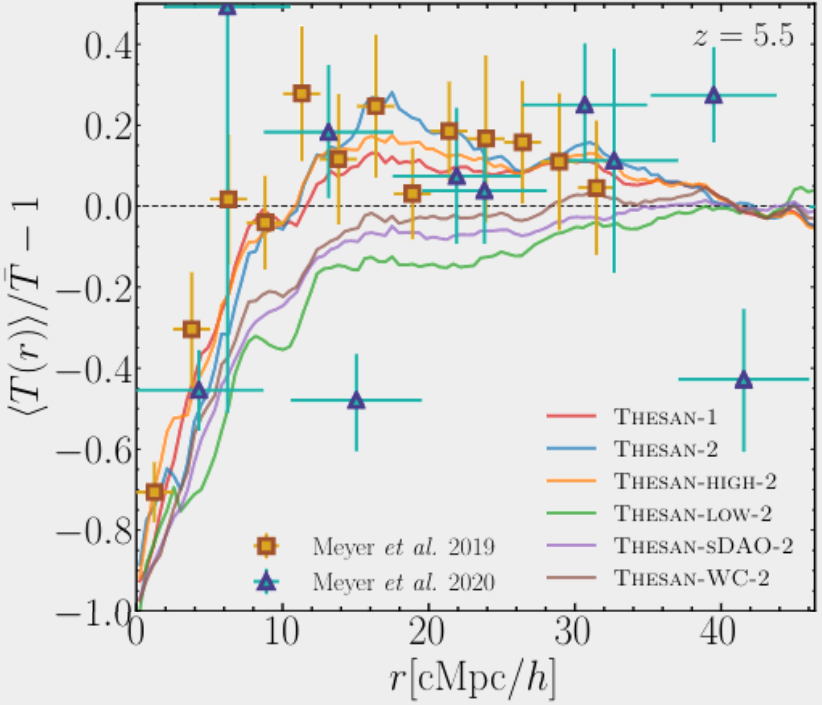
THE GaLαCC IS INSENSITIVE TO REIONIZATION SOURCES

ONCE THE REIONIZATION HISTORY IS ACCOUNTED FOR

different redshift, same x_{HI}

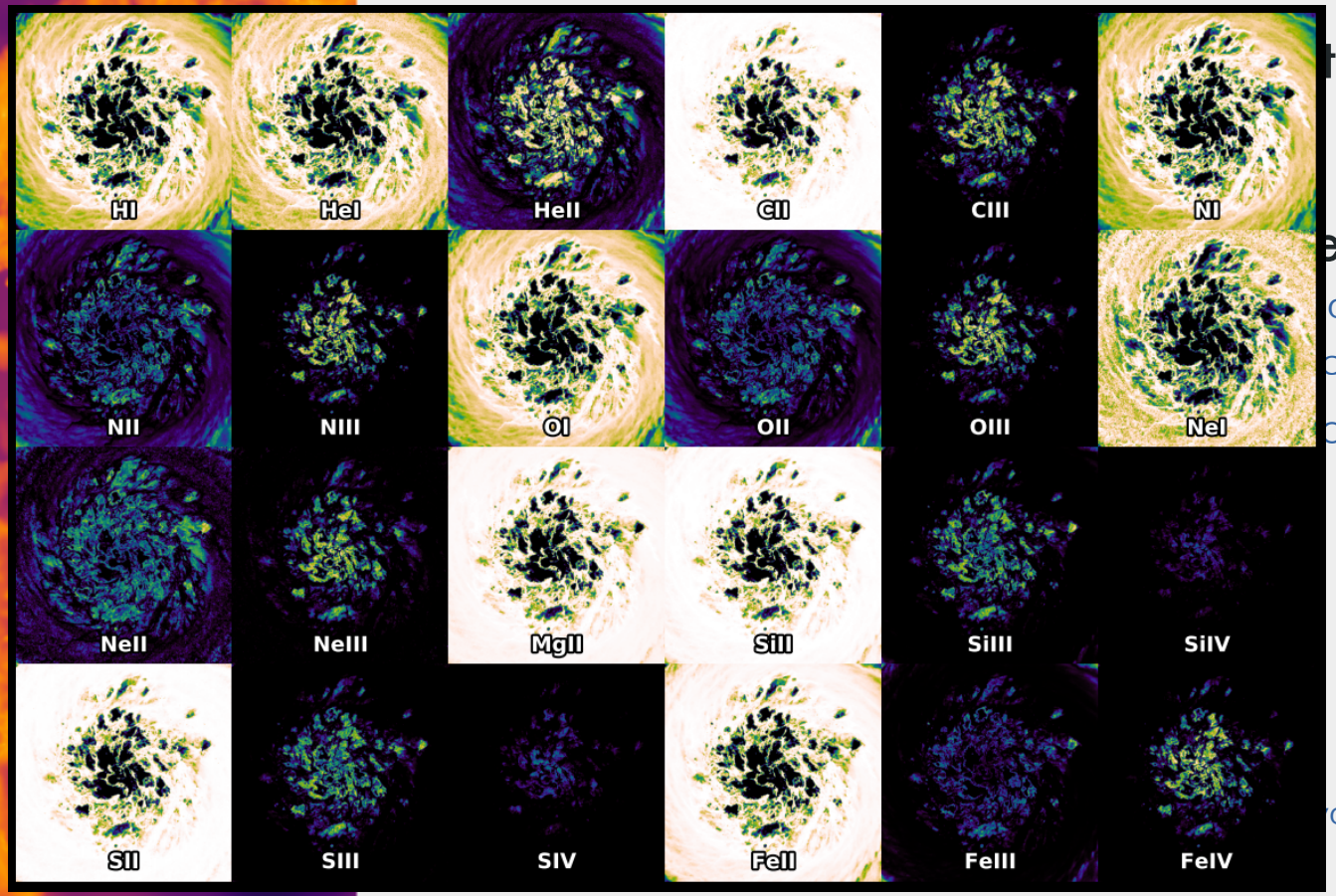


same redshift, different x_{HI}



Garaldi et al., 2022

THESANZOOM: ISM AND CGM MEET REIONIZATION



ted from

el

arinacci+2019

cl. temperature),

o-IR radiation

10^3, 10^2 M_{sun}

an de Voort)

- pre-SN stellar feedback