ASTRO 3D

GECO-16: Shedding new light on the first billion years of the Universe

THE UNIVERSITY OF MELBOURNE

Simulations of the EoR

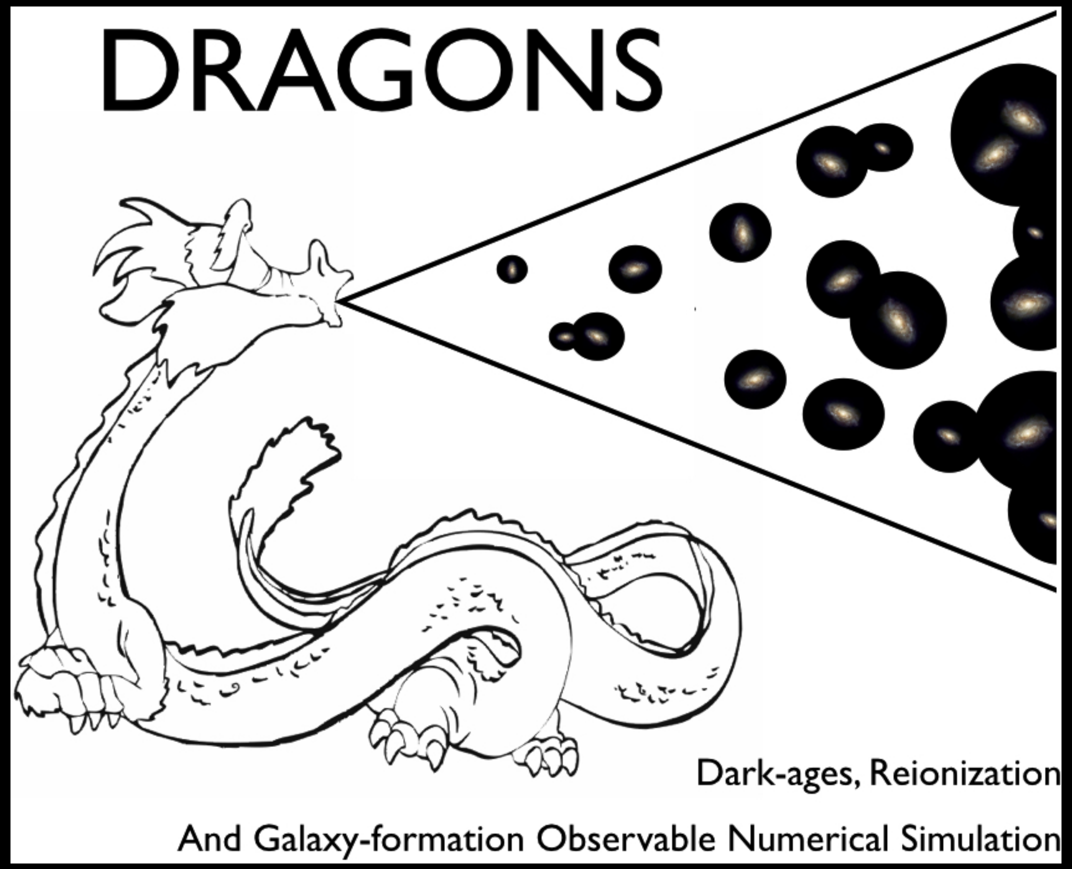
Fisher matrix forecasts on the astrophysics of galaxies during the EoR

BALU SREEDHAR

University of Melbourne, Australia
ARC Centre of Excellence for All Sky Astrophysics in 3D

Balu+, MNRAS, 520, 3368-3382 (2023)

Balu, Greig & Wyithe; arXiv:2305.05104



Prof Stuart Wyithe

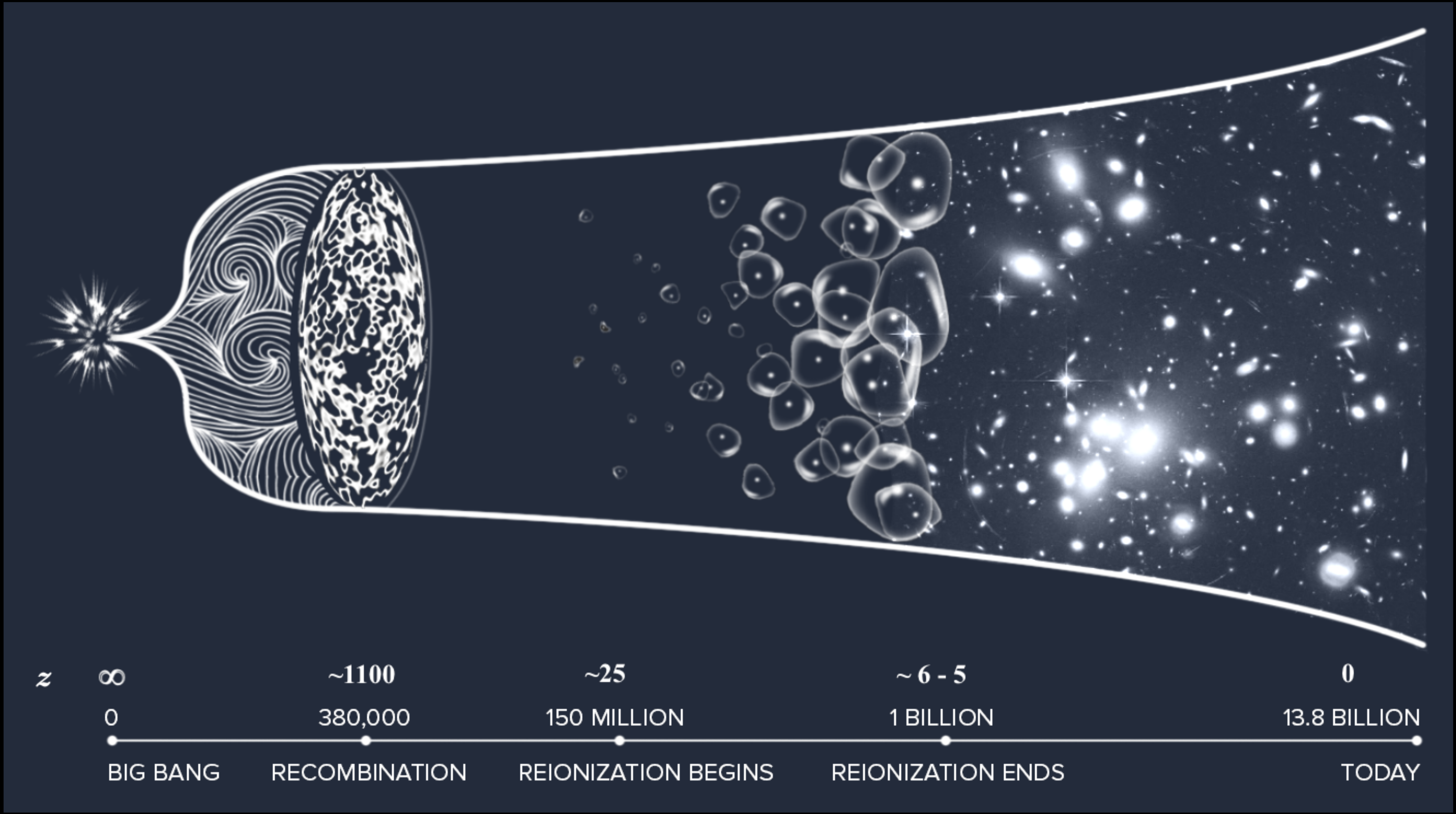
Dr. Bradley Greig

balu.sreedhar@student.unimelb.edu.au   s-balu.github.io   @balusrdhr

4th July 2023

What do we do?

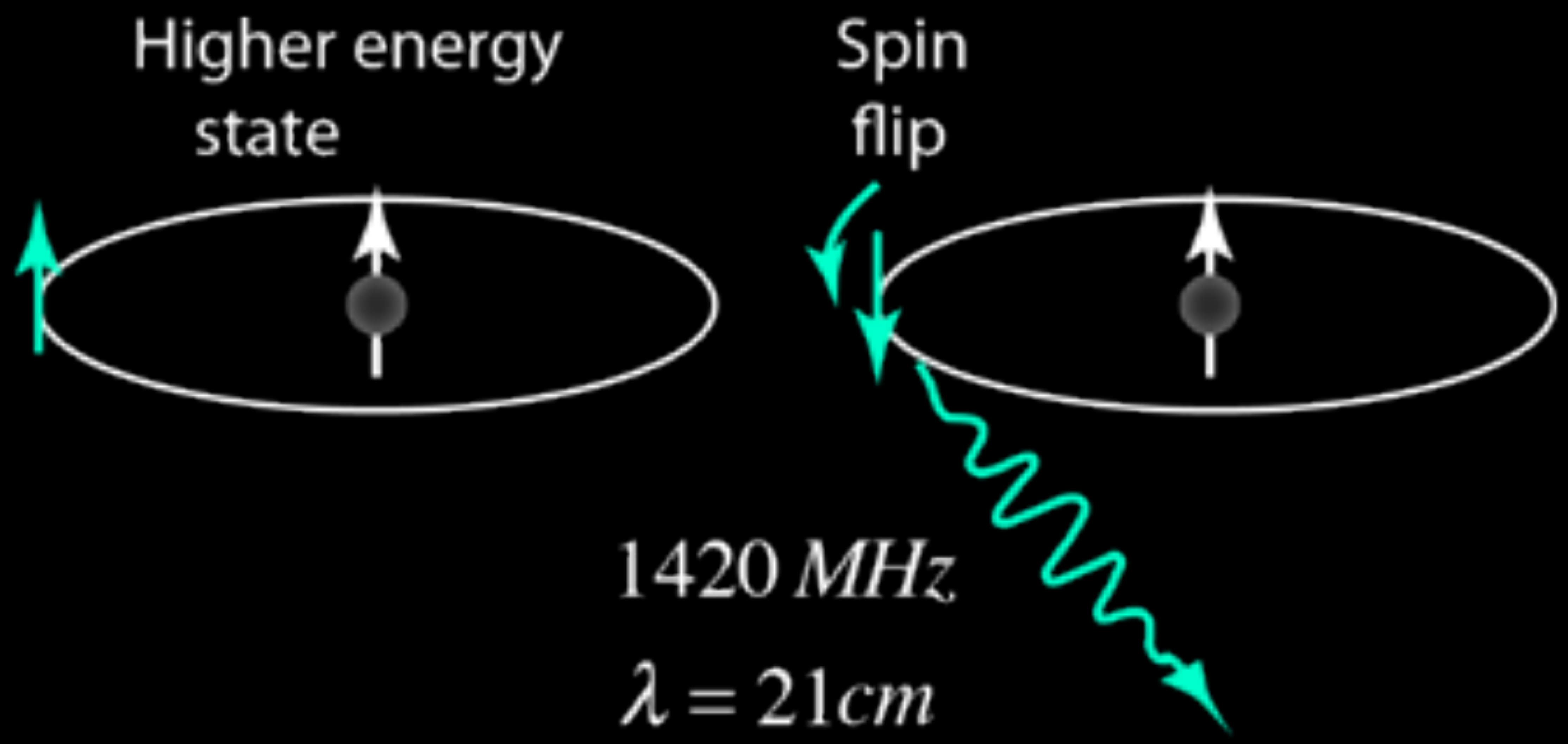
Epoch of Reionisation (EoR)



Credits: **Aman Chokshi**, University of Melbourne

What do we measure?

21-cm signal



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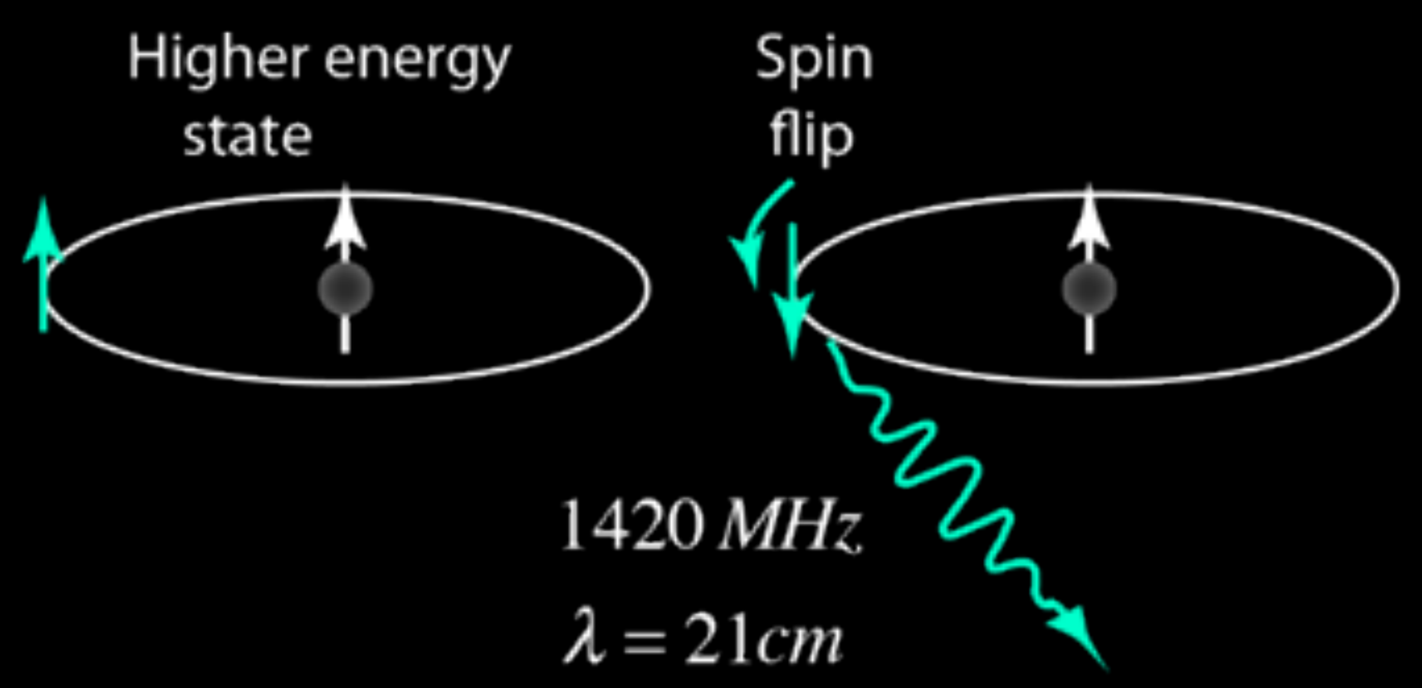

$$\delta T_b(\nu) = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau_{\nu 0}}\right)$$

$$\approx 27 x_{\rm HI}\left(1+\delta_{nl}\right)\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\text{mK}$$

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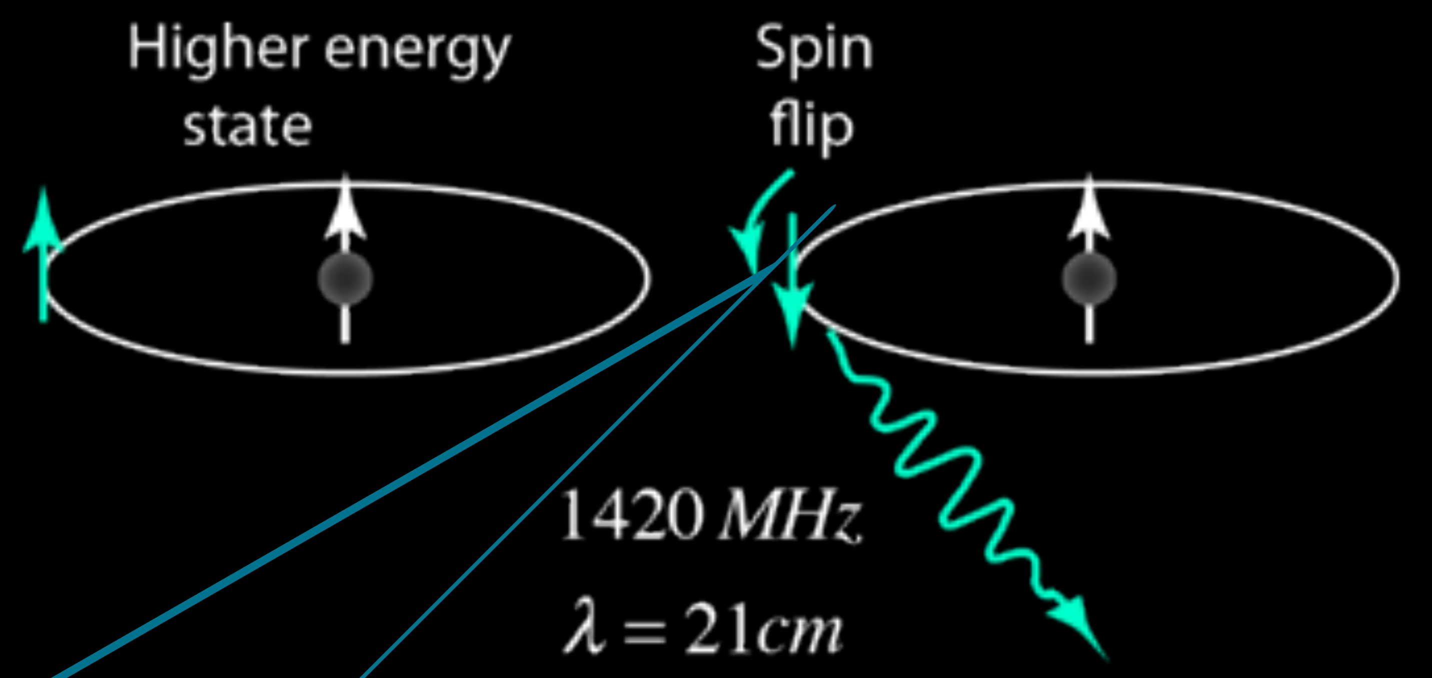

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Neutral fraction

Density contrast

LoS velocity gradient

Spin temperature

Cosmology

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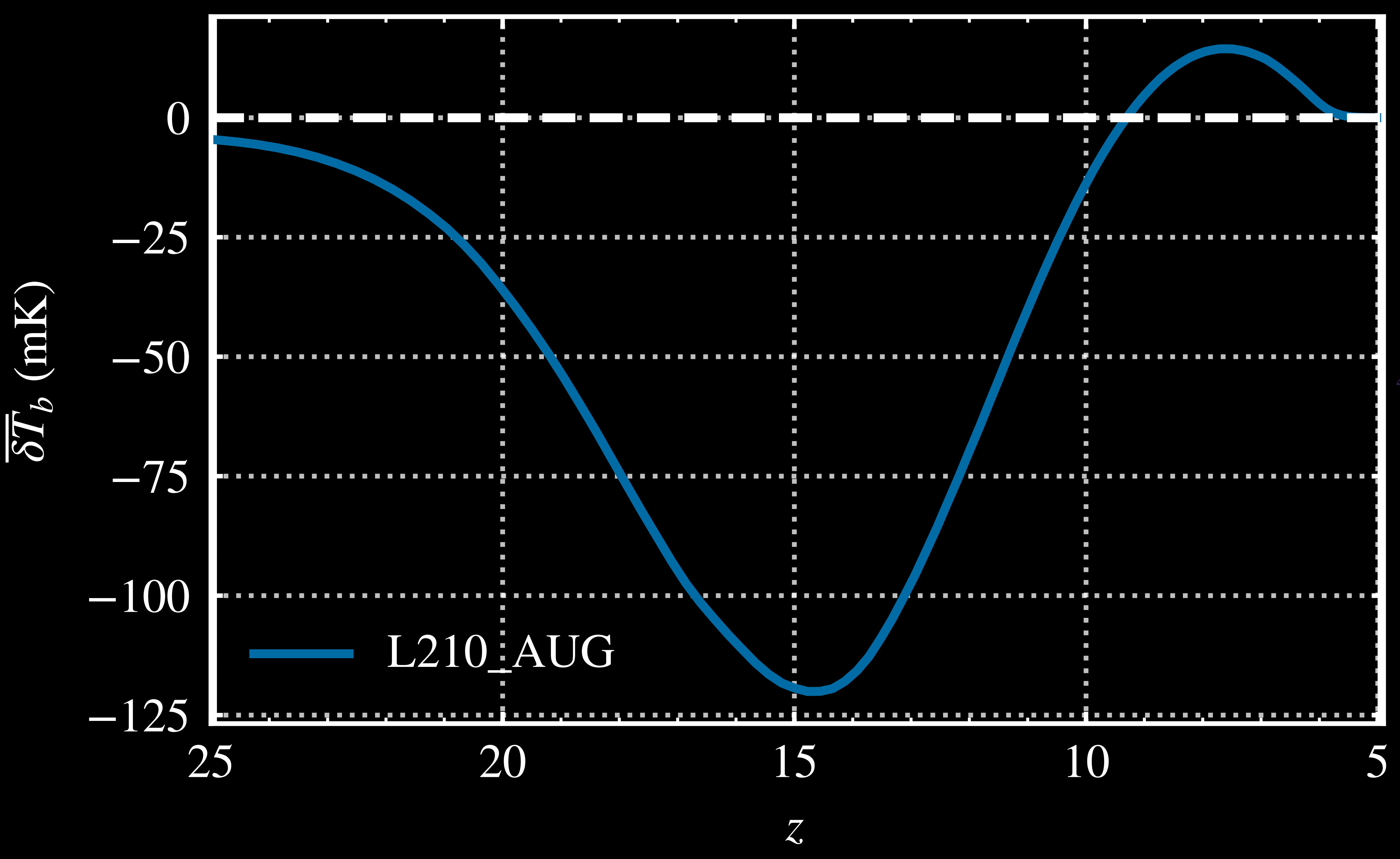
What do we actually measure?

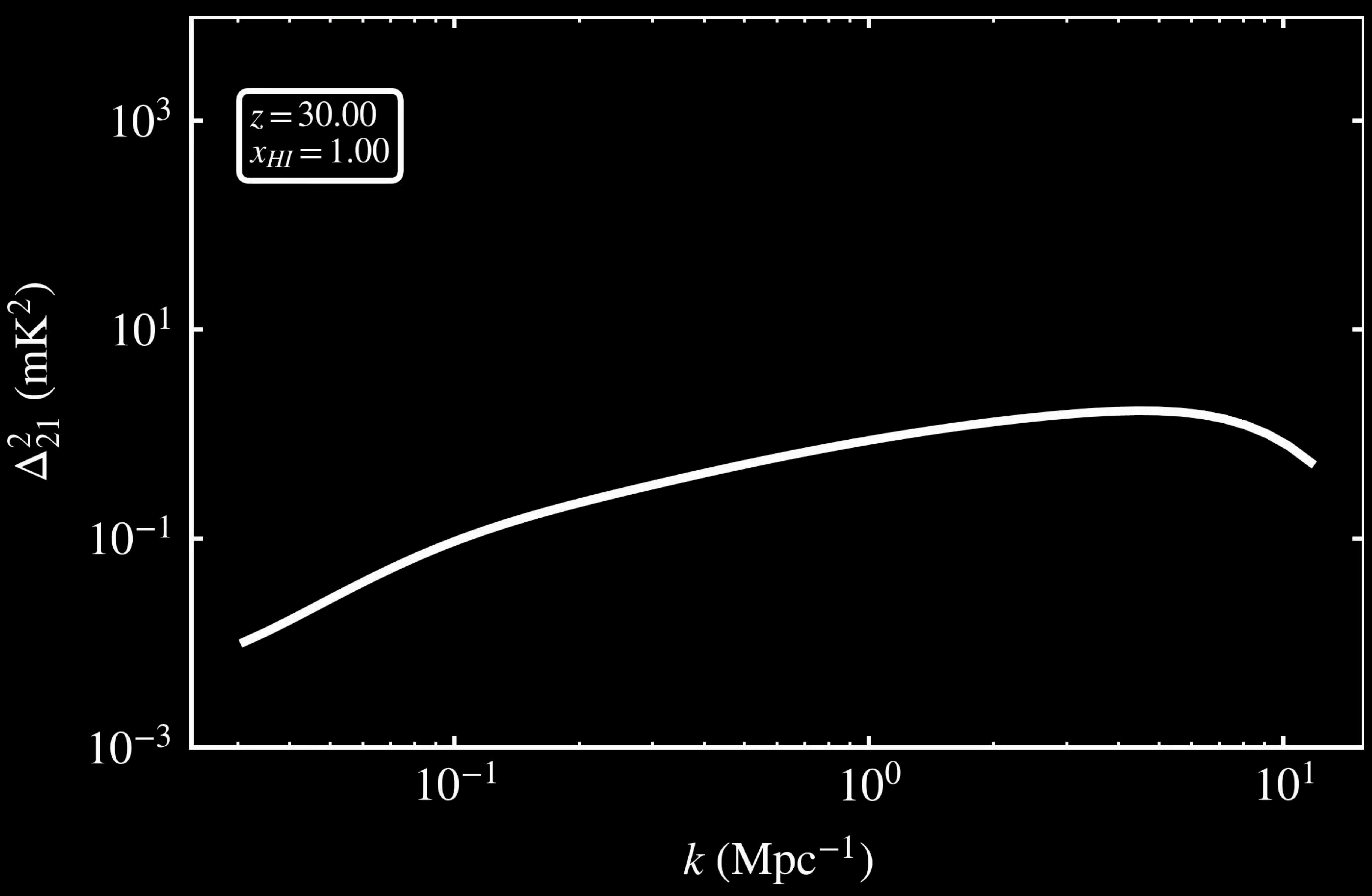
HI 21-cm statistics

21-cm Global/Sky-Averaged signal



e.g. **EDGES, SARAS, etc**

21-cm Power Spectra



e.g. **MWA, LOFAR, SKA, etc**

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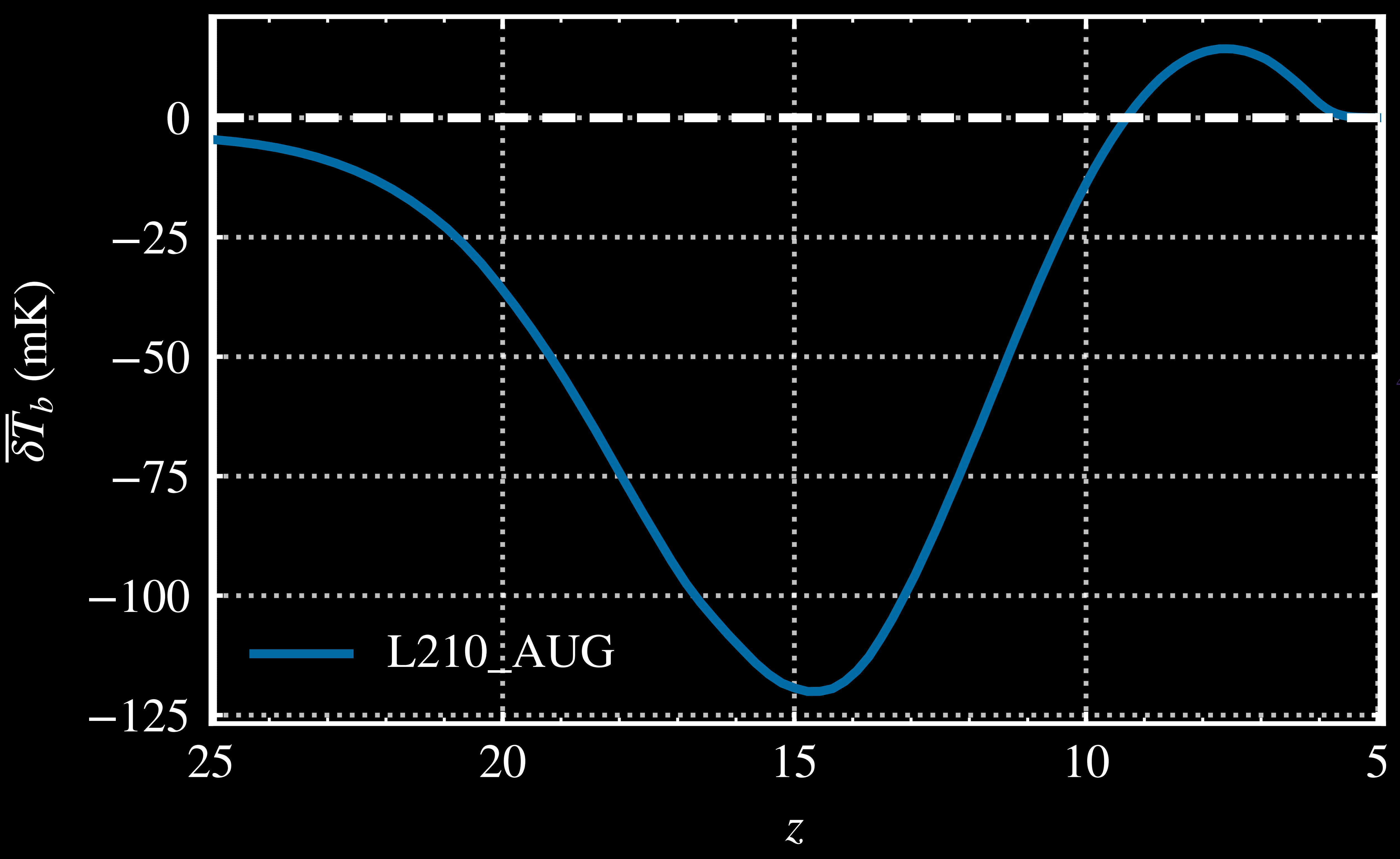

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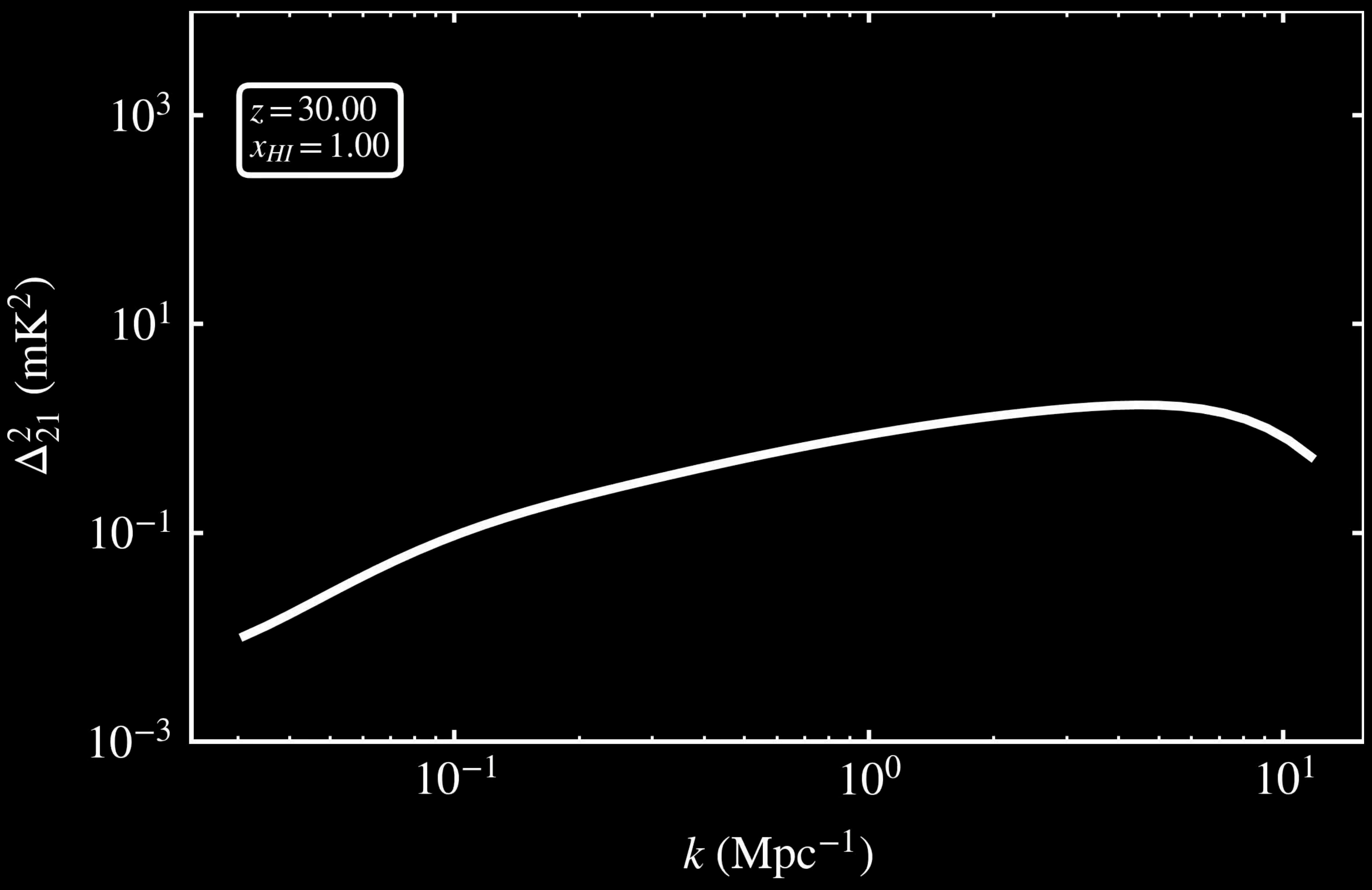

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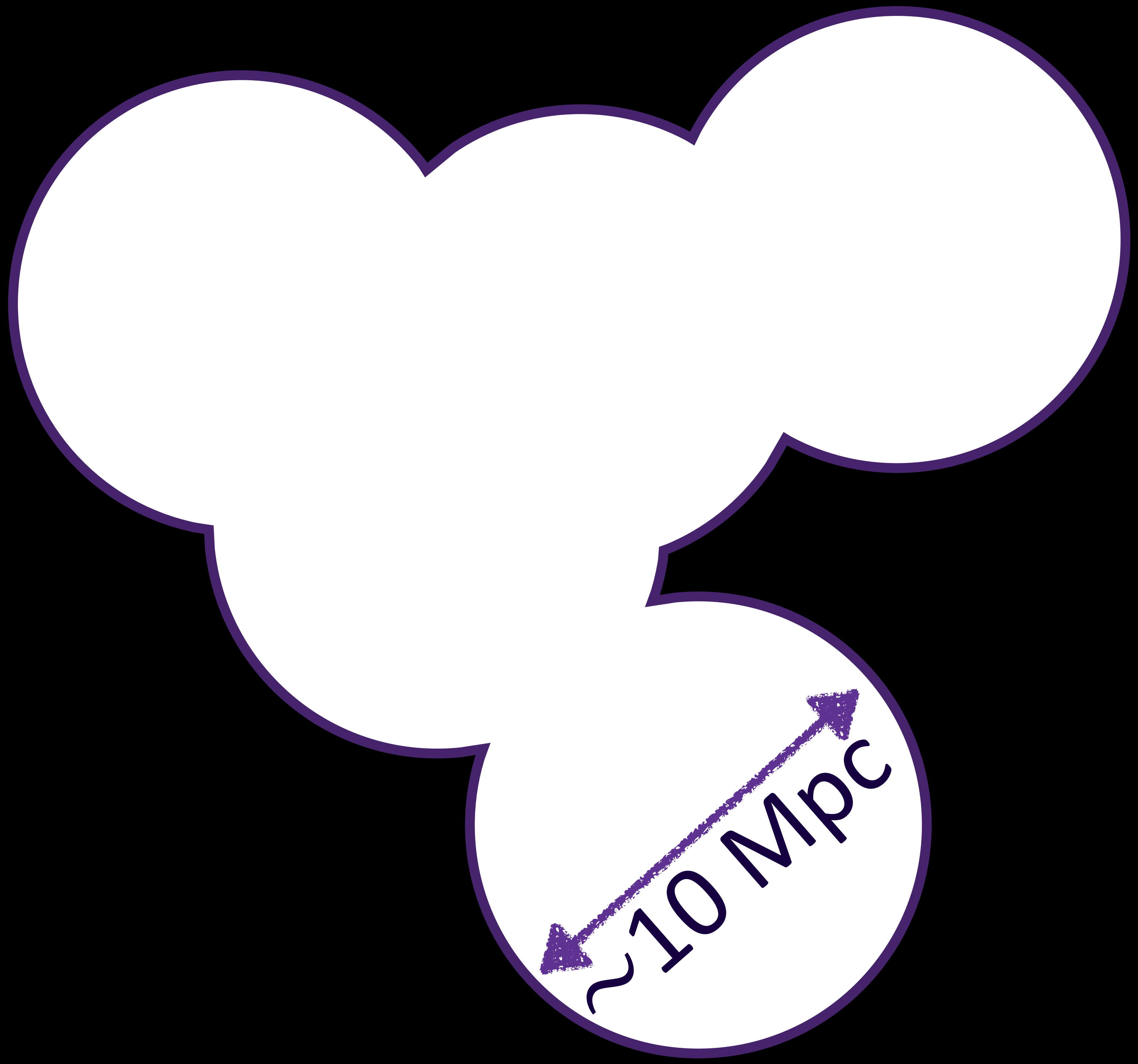
What do we do?

The Challenge...



Credits: **Simon Mutch**
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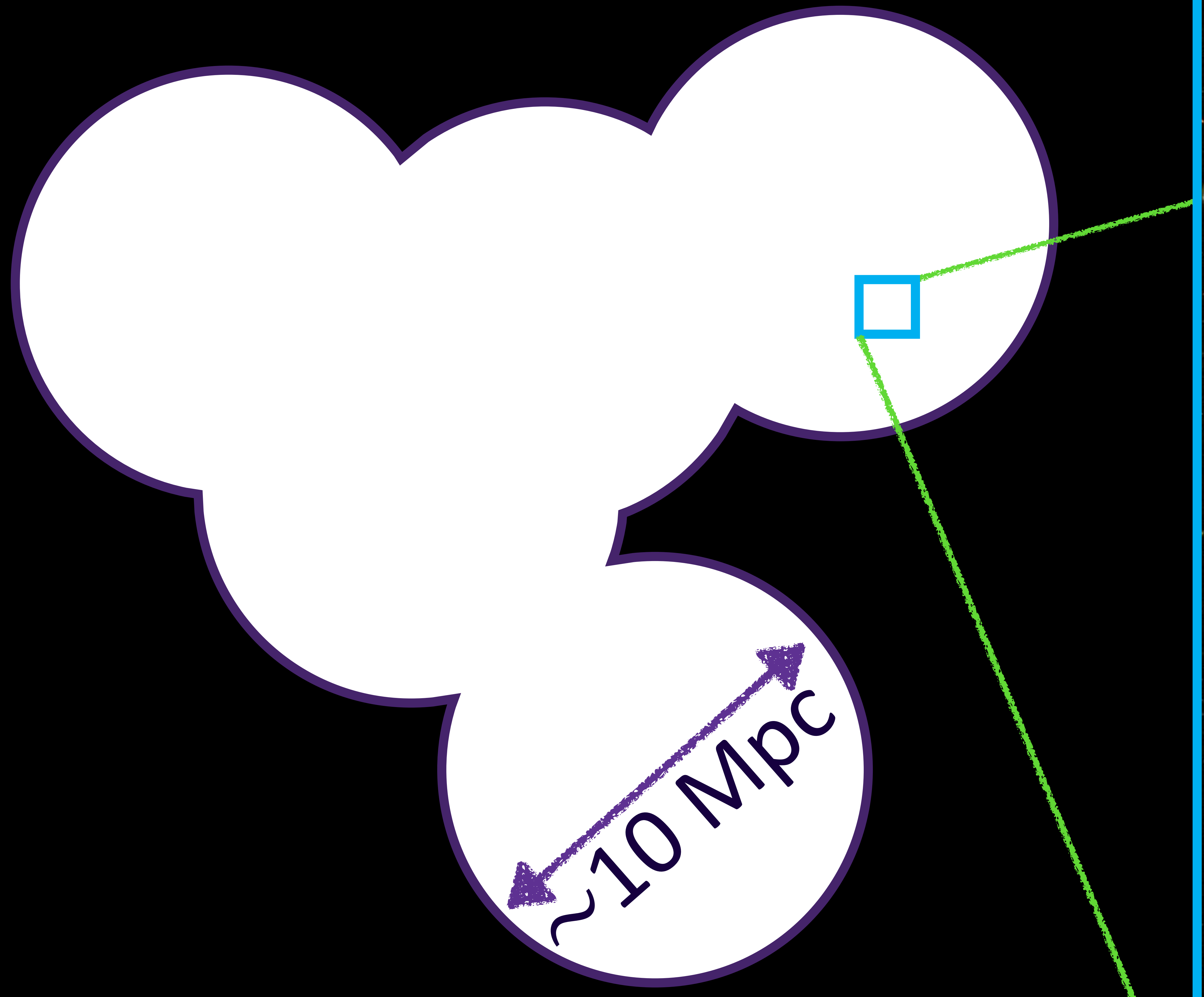

NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

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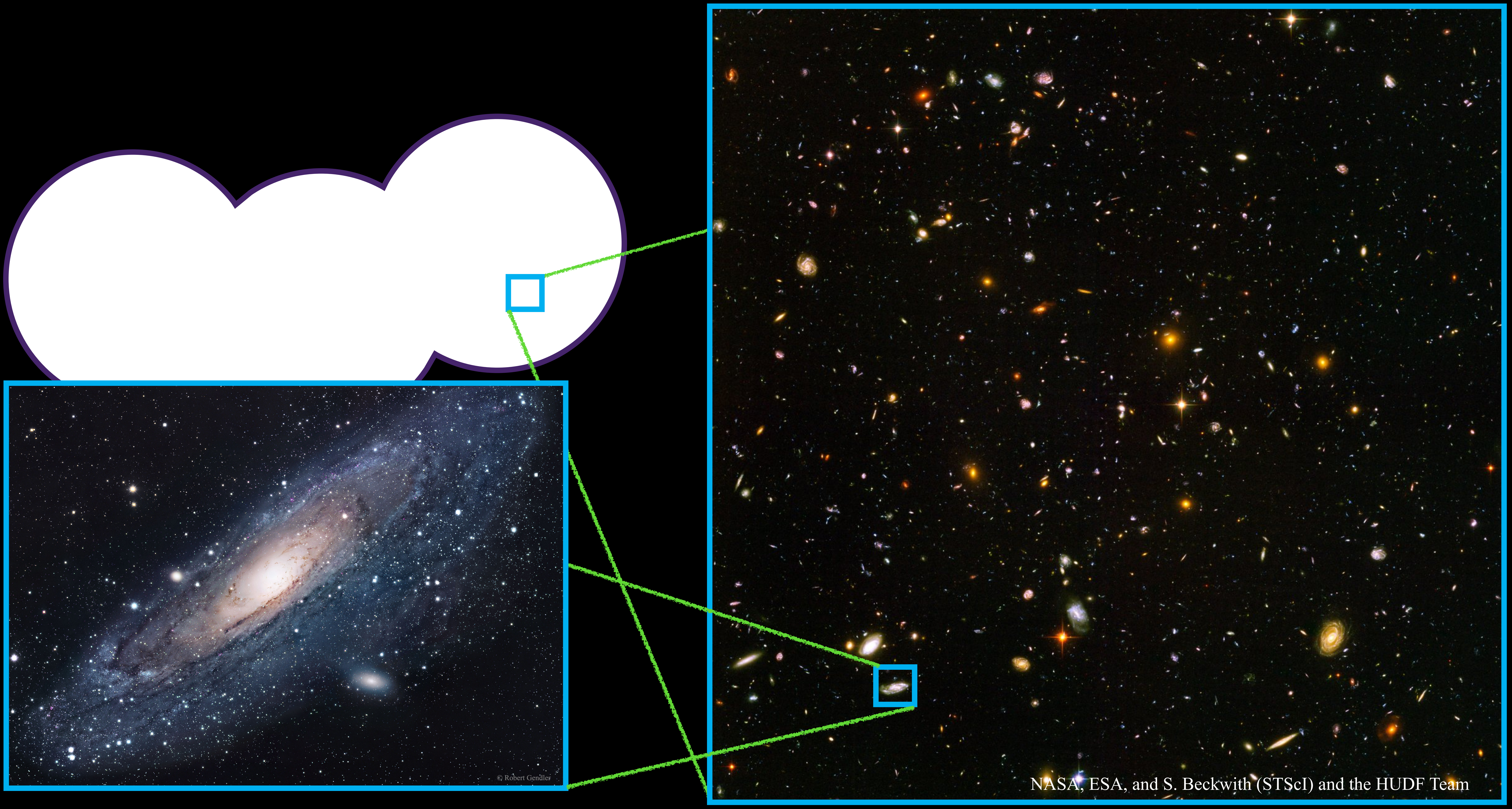

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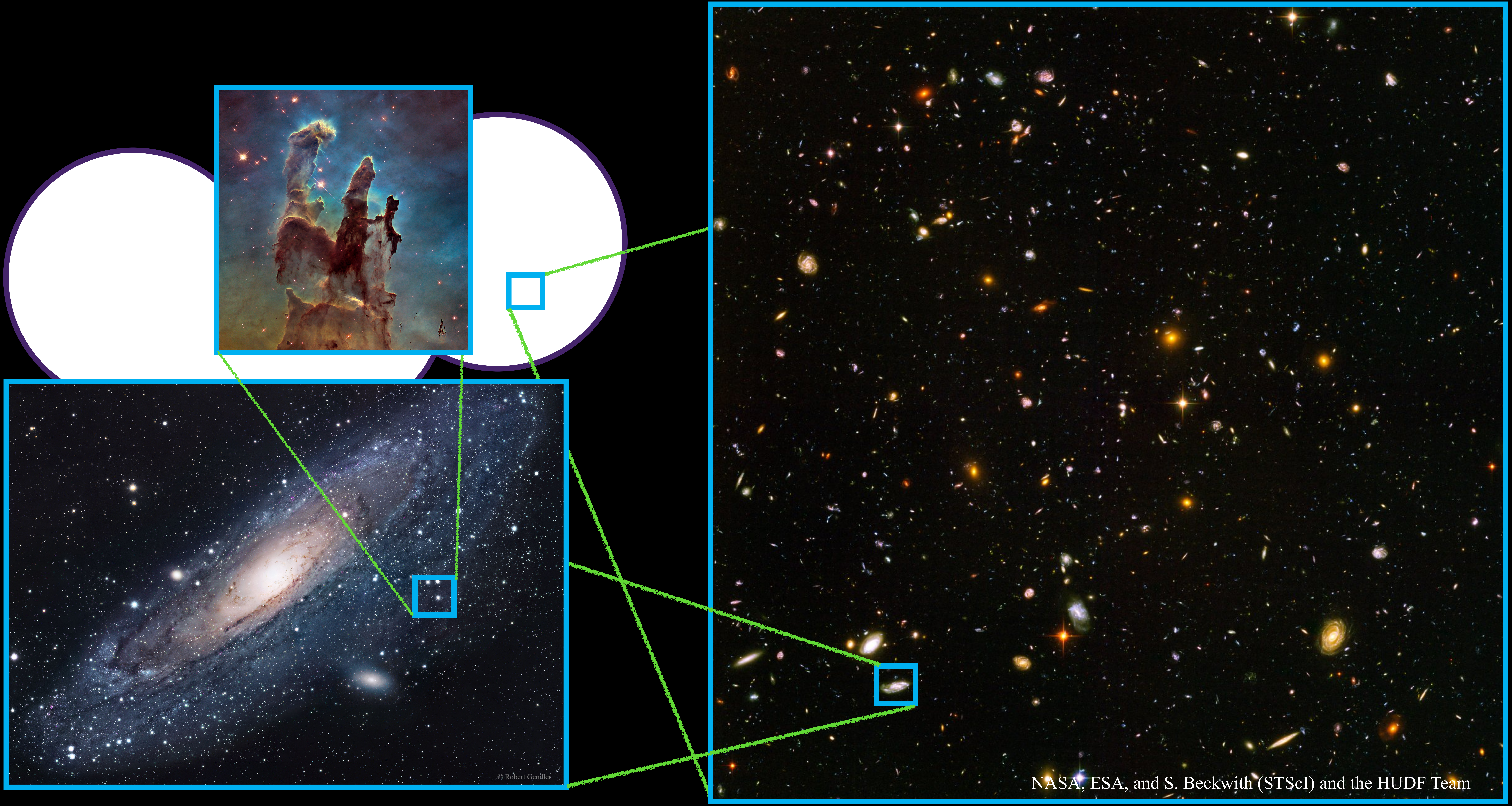

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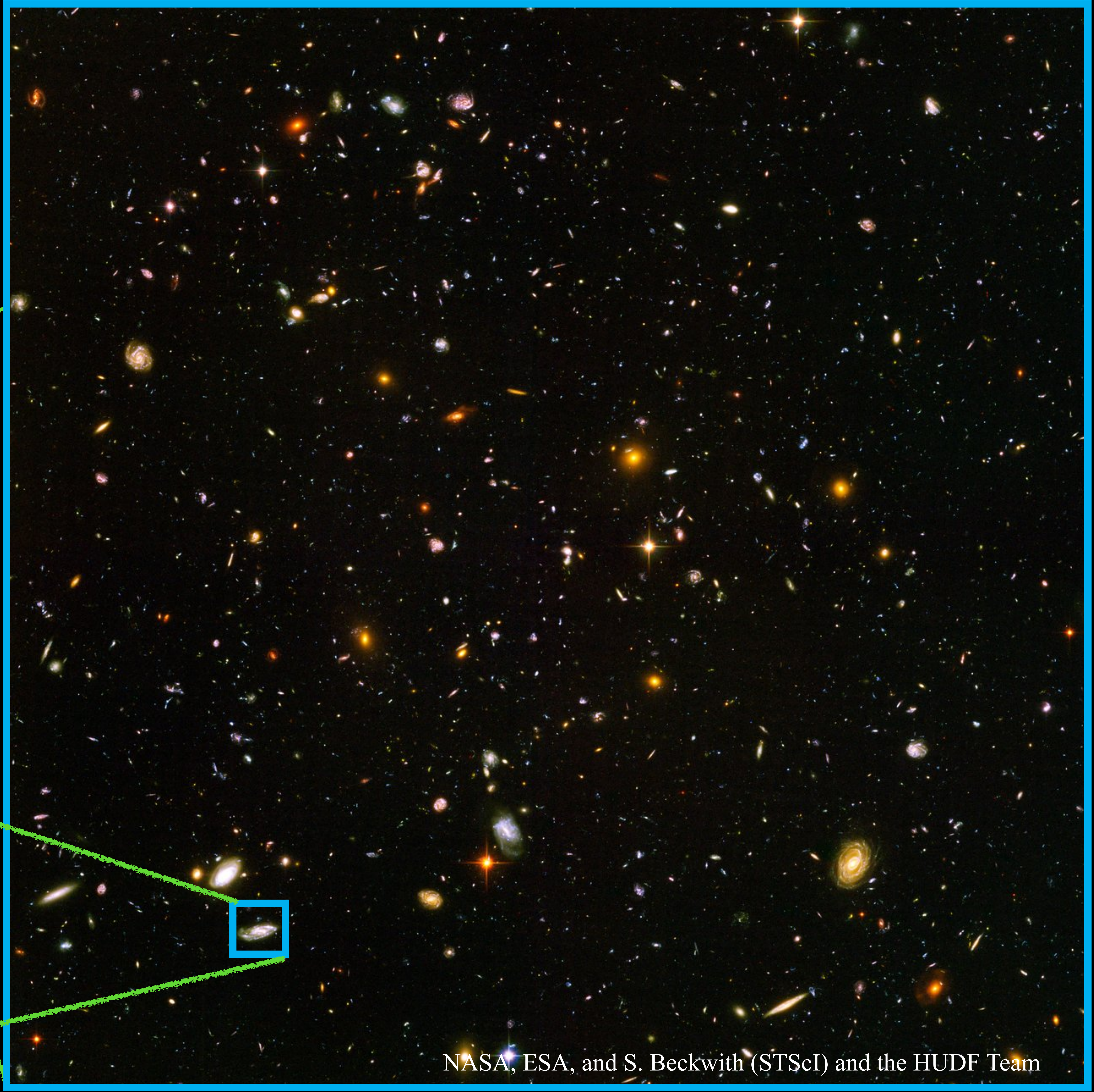
What do we do?

The Challenge...

NASA, ESA, J. Hester and A. Loll (Arizona State University)

NASA, ESA and the Hubble Heritage Team (STScI/AURA)

Robert Gendler



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What do we do?

Meraxes SAM

- SMF (z=0.6-8)
  [Mutch+ (2016), Qin+ (2017)]
- BH-$M_\star$ relation (z=0.6)
  [Qin+ (2017), Marshall+ (2019)]
- QSO UV LFs (z>1)
  [Qin+ (2017), Marshall+ (2020)]
- Ionizing emissivity (z>4)
  [Mutch+ (2016), Davies+ (2019)]
- Galaxy UV LF (z>5)
  [Liu+ (2016), Park+ (2017), Qiu+ (2019]
- Thompson scattering optical depth (z>6)
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- LBG correlation functions (z>4)
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- *Constraining UV escape fraction*
  [Mutch+ (2023)]
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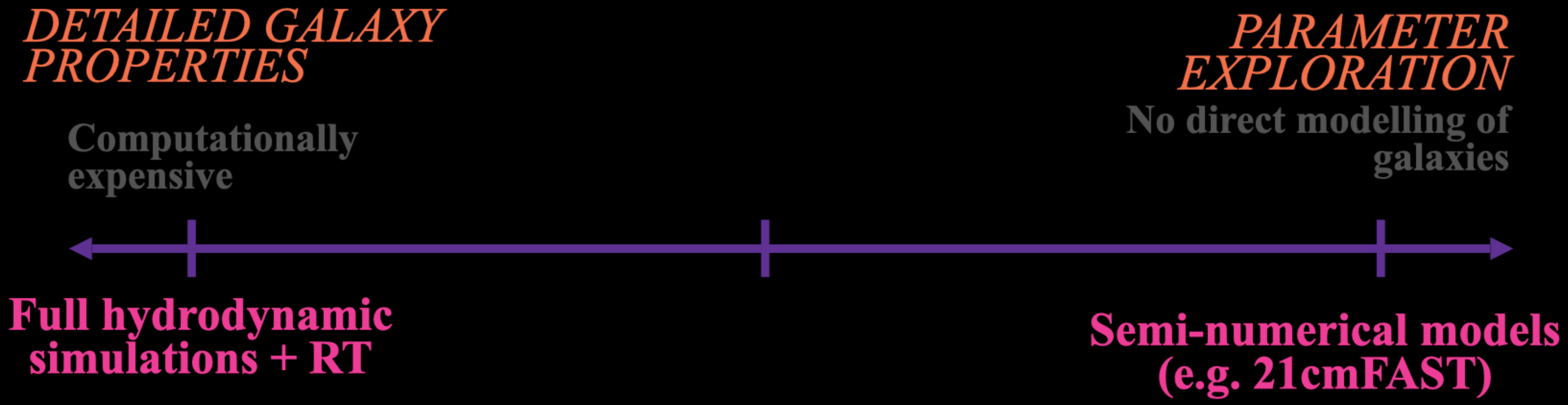
  [Qiu+2021]



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DETAILED GALAXY PROPERTIES

Computationally expensive

Full hydrodynamic simulations + RT

SIMPLE BUT DETAILED PRESCRIPTIONS

Galaxy population

Semi-analytic

MERAXES

PARAMETER EXPLORATION

No direct modelling of galaxies

Semi-numerical models (e.g. 21cmFAST)

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PARAMETER EXPLORATION

No direct modelling of galaxies

Semi-numerical models (e.g. 21cmFAST)

- Temporally and spatially coupled treatment of reionisation
- Radiative cooling, Star formation, Supernova feedback, AGN, etc
- Coupled with 21cmFAST for reionisation calculations

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What did we do?

- Need large volumes for EoR studies → Typical bubble sizes ~ 10 Mpc; ~ 100 Mpc typical X-ray mean free path
- Larger boxes → Lower resolution
- Higher resolution → more particles → computationally more expensive

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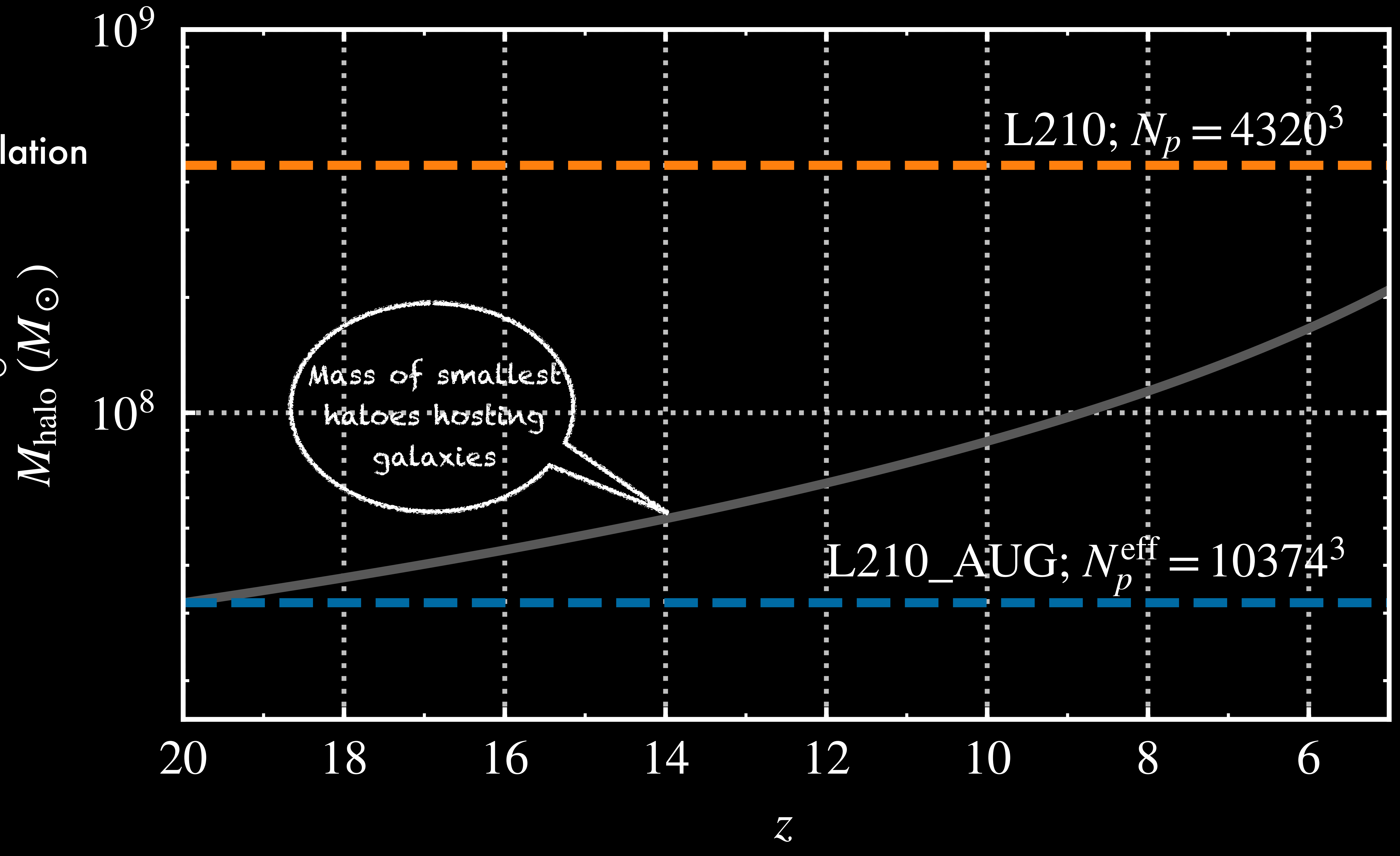
What did we do?

Augmentation: What & Why?

L210

- Pure DM N-body simulation
- 210 h^{-1} Mpc box
- $M_{res} \sim 2 \times 10^8 \, h^{-1} \, M_\odot$



L210_AUG

- Monte-Carlo Augmented N-body simulation
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- $M_{res} \sim 2 \times 10^7 \, h^{-1} \, M_\odot$

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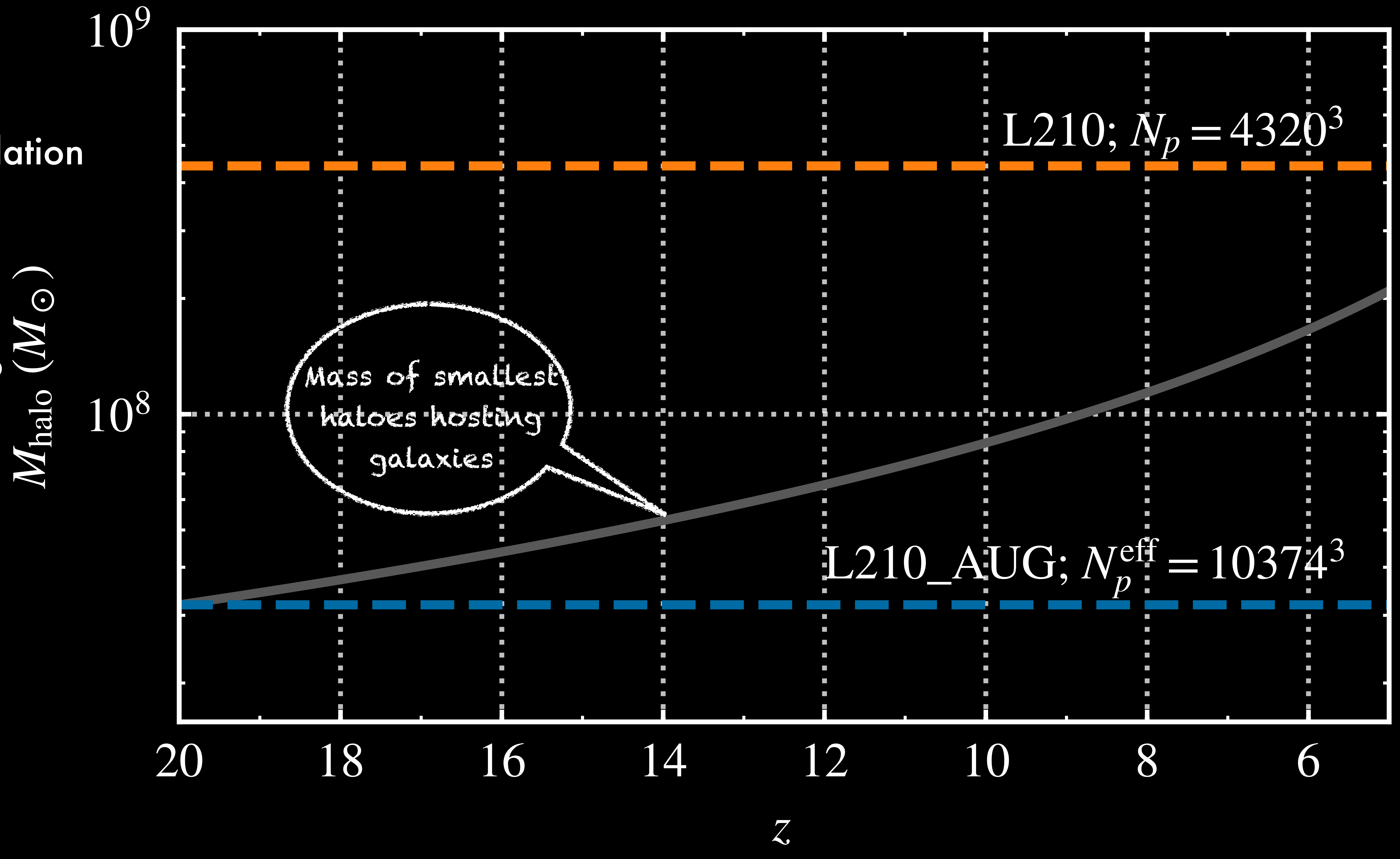

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For details see

Y. Qiu et al., MNRAS, 500, 493–505 (2021)

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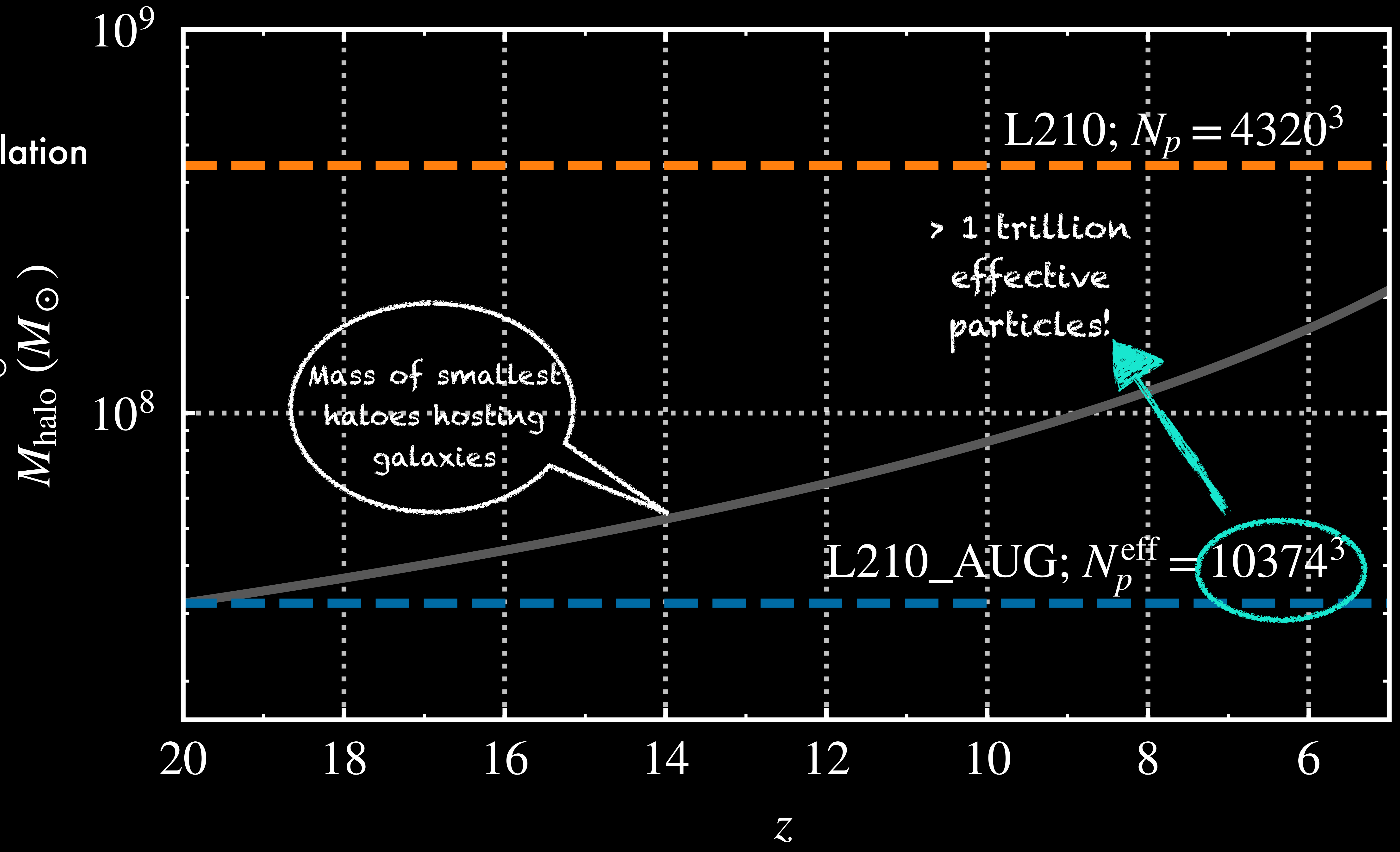

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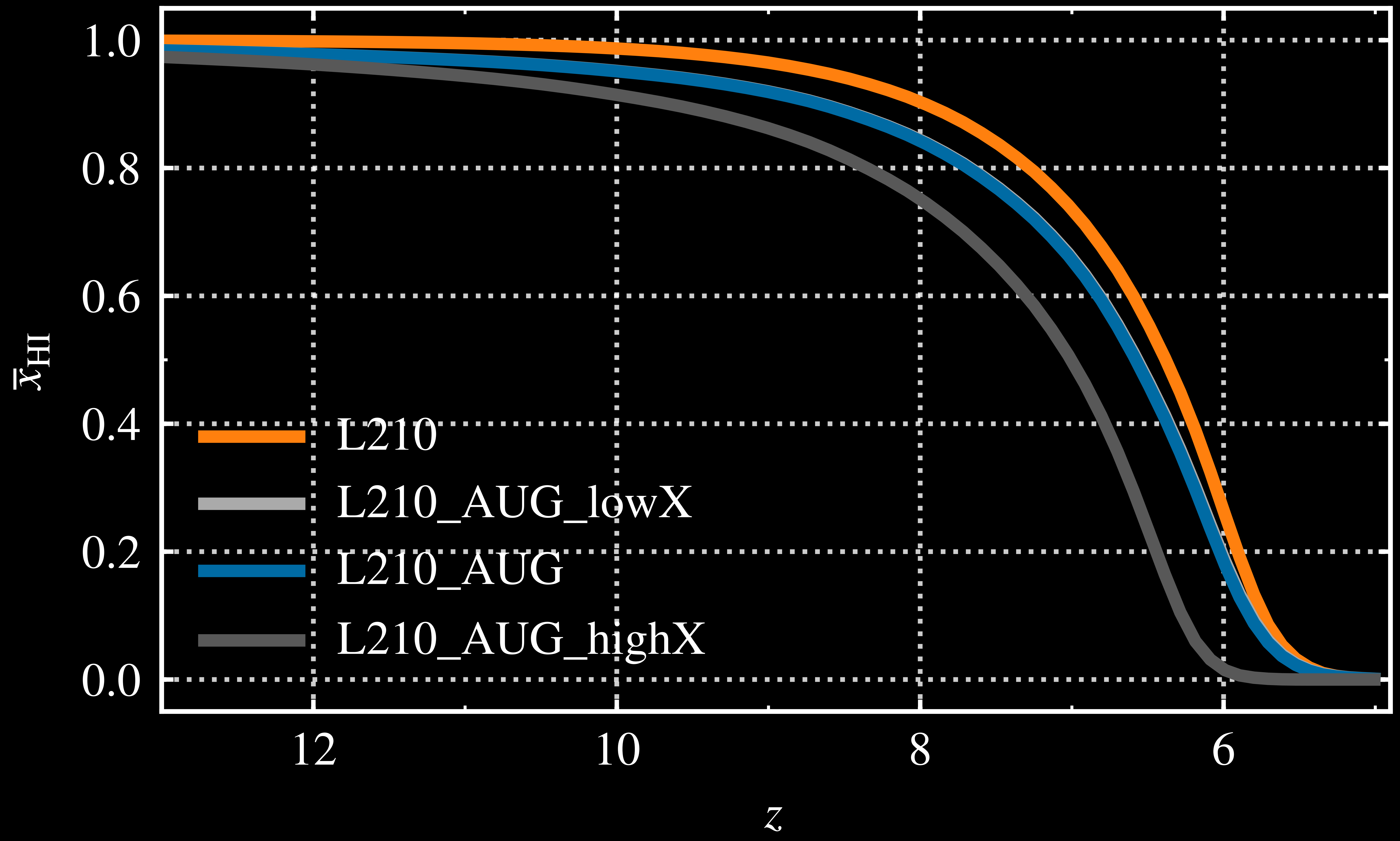
What did we do?

Reionisation histories



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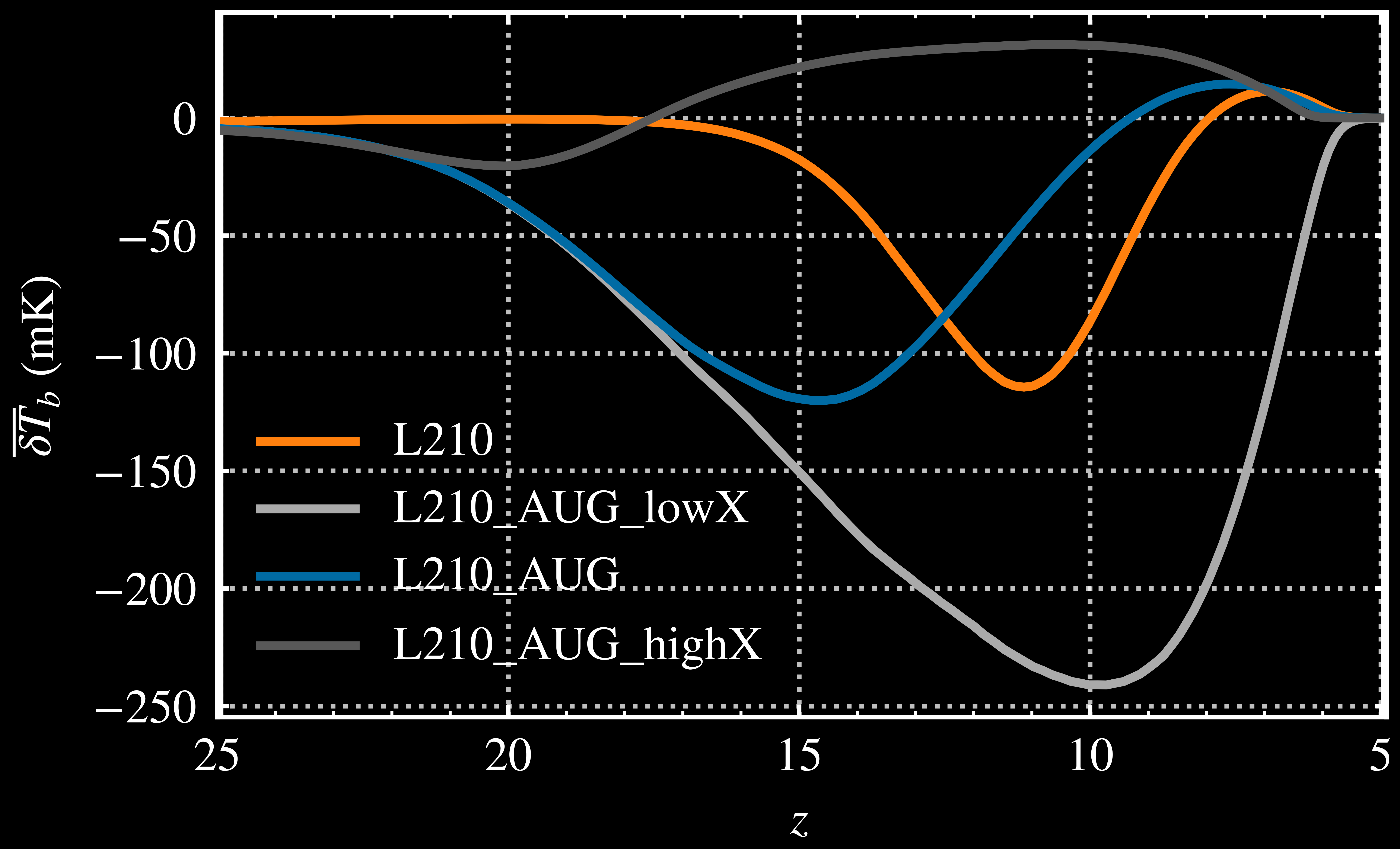

- L210 has less number of DM haloes w.r.t L210_AUG.
  - L210 has less photon sources w.r.t L210_AUG
- L210_AUG_highX(lowX) has more(less) amount of X-rays.
  - More heating in highX.

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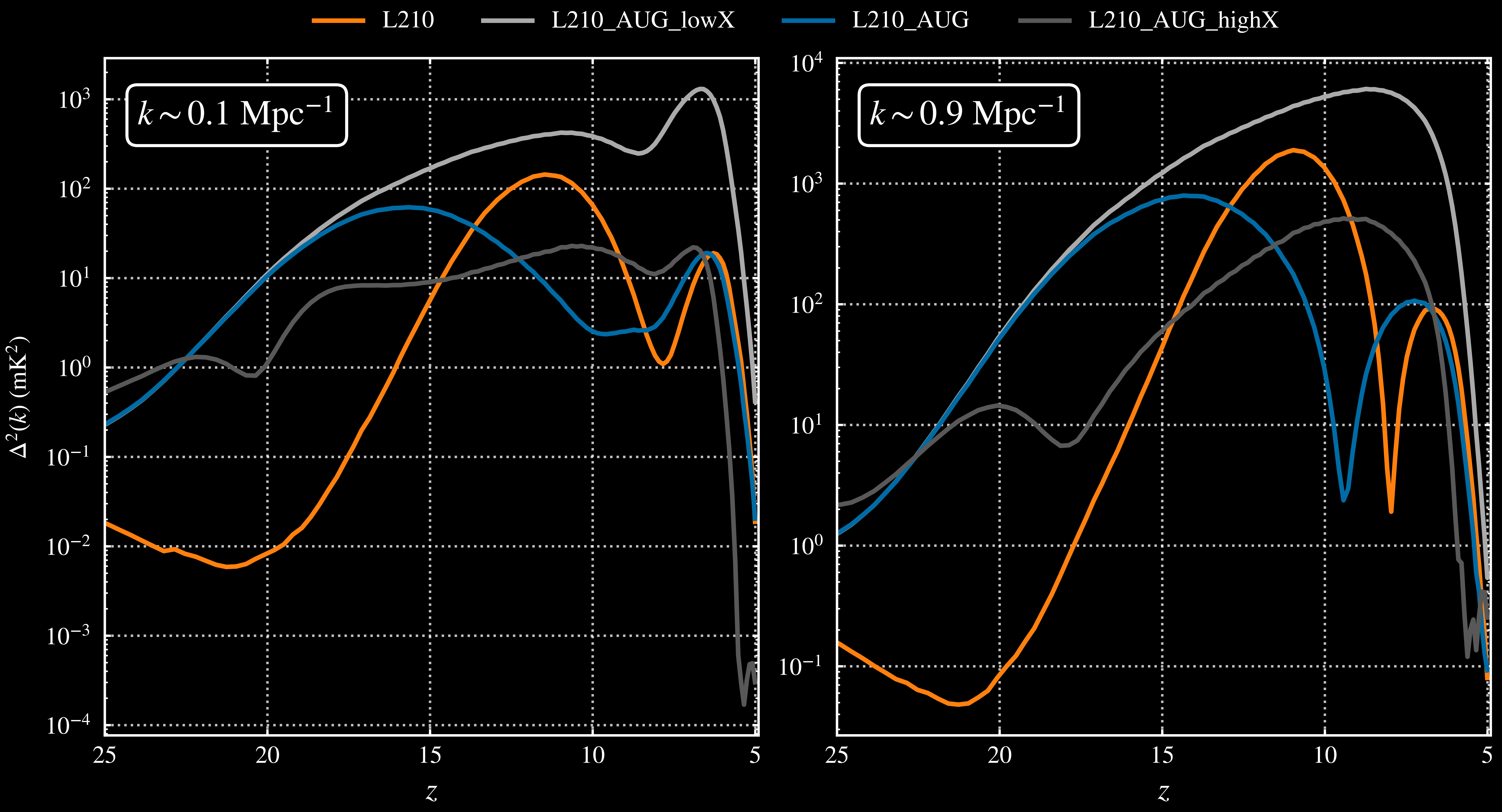
What did we do?

21-cm power spectrum



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What did we do?

What can we learn using the 21-cm PS from the EoR?

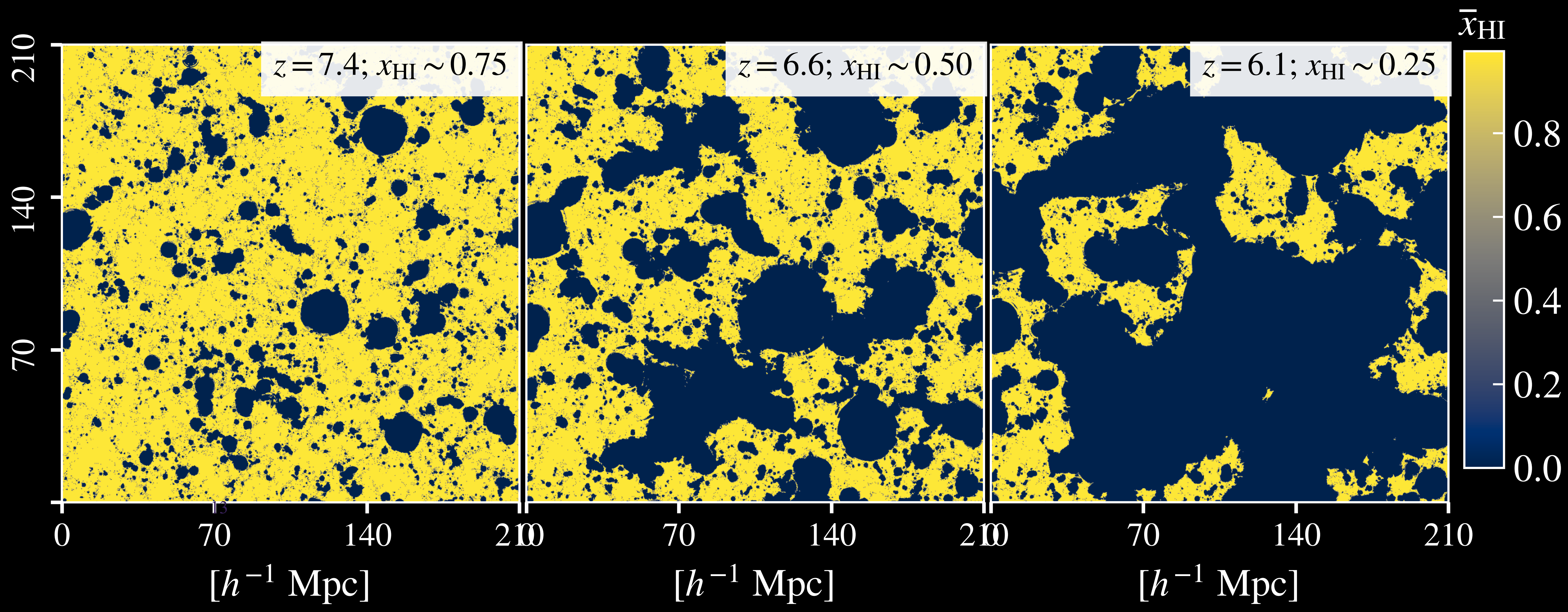
How do we do this?

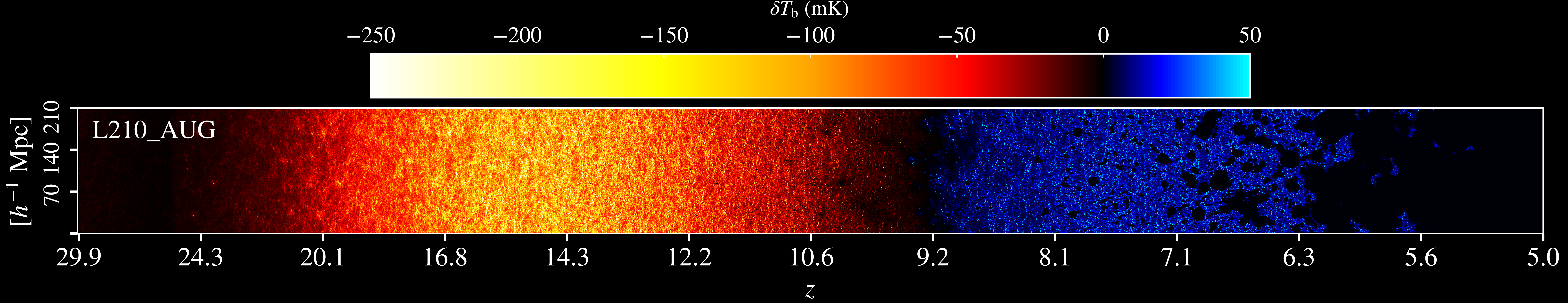
L210_AUG & Meraxes SAM

L210_AUG

- 210 h^{-1} Mpc box; $N_{eff} \sim 10^{12}$.
- Augmented GENESIS L210_N4320 *N*-body simulation.
- Statistically complete population of all atomically cooled galaxies down from $z \sim 20$.
- Calibrated w.r.t UV luminosity functions, CMB optical depth, IGM neutral fraction observations.

Ionisation morphology





"… first model of both reionisation and galaxy formation with low-mass galaxies and large enough to explore the impact of X-rays on the 21-cm signal."

Balu+, MNRAS, 520, 3368-3382 (2023)

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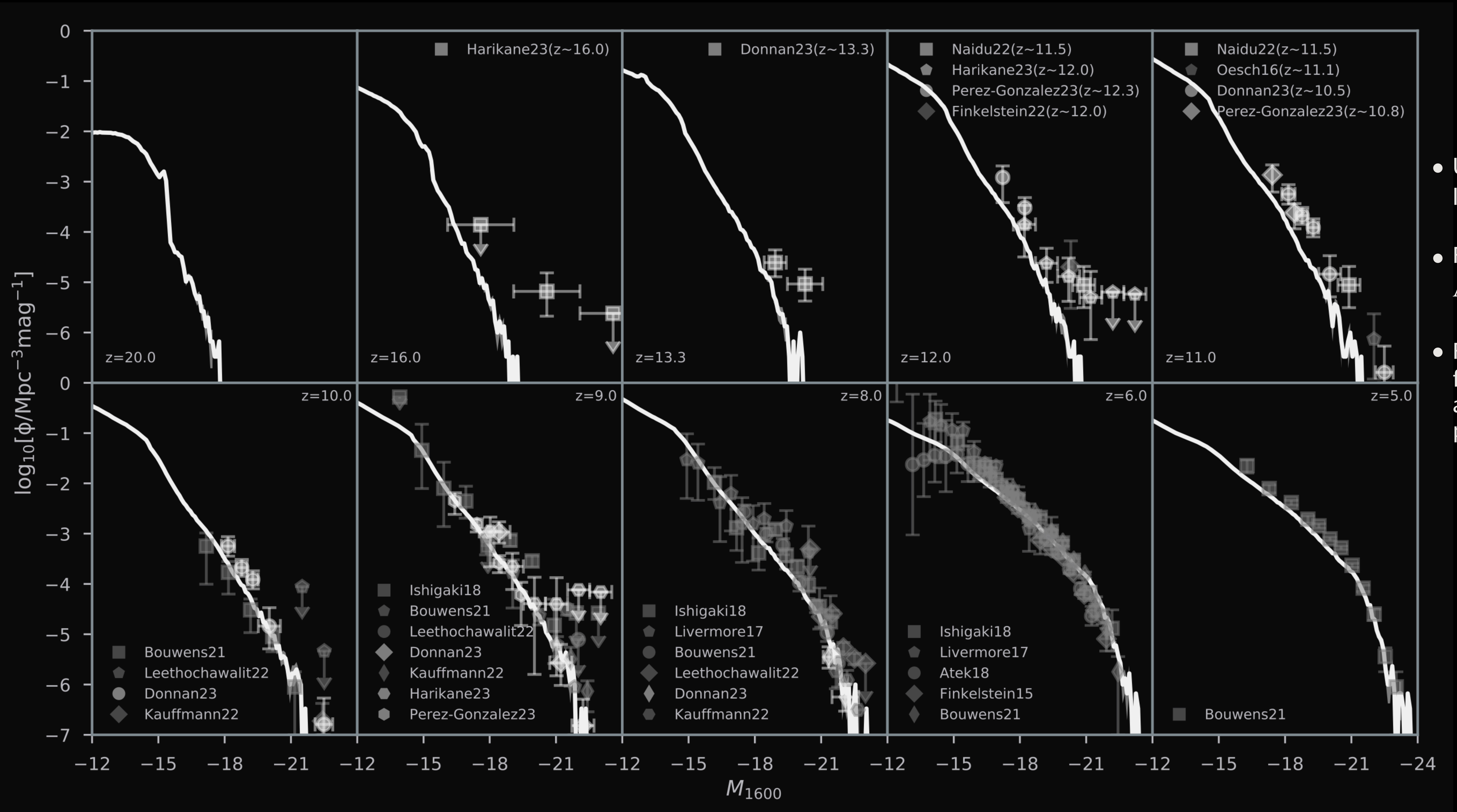
Something else we did…

$z \gtrsim 12$ JWST analogue galaxies

Implications of $z > \sim 12$ JWST galaxies for galaxy formation at high redshift

Yuxiang Qin, Sreedhar Balu, J. Stuart B. Wyithe

arXiv:2305.17959



- Using the forward-modelled JWST photometry, we looked for analogues for 8 of the $z \gtrsim 12$ galaxies.
- Faint galaxies ($M_{\mathrm{UV}} \gtrsim -19$) are consistent with ΛCDM; slight tension for massive $z \sim 12$ galaxies.
- For $z \gtrsim 16$ JWST galaxy candidates, boosted star-forming efficiencies and reduced feedback regulation are necessary relative to models of lower-redshift populations.

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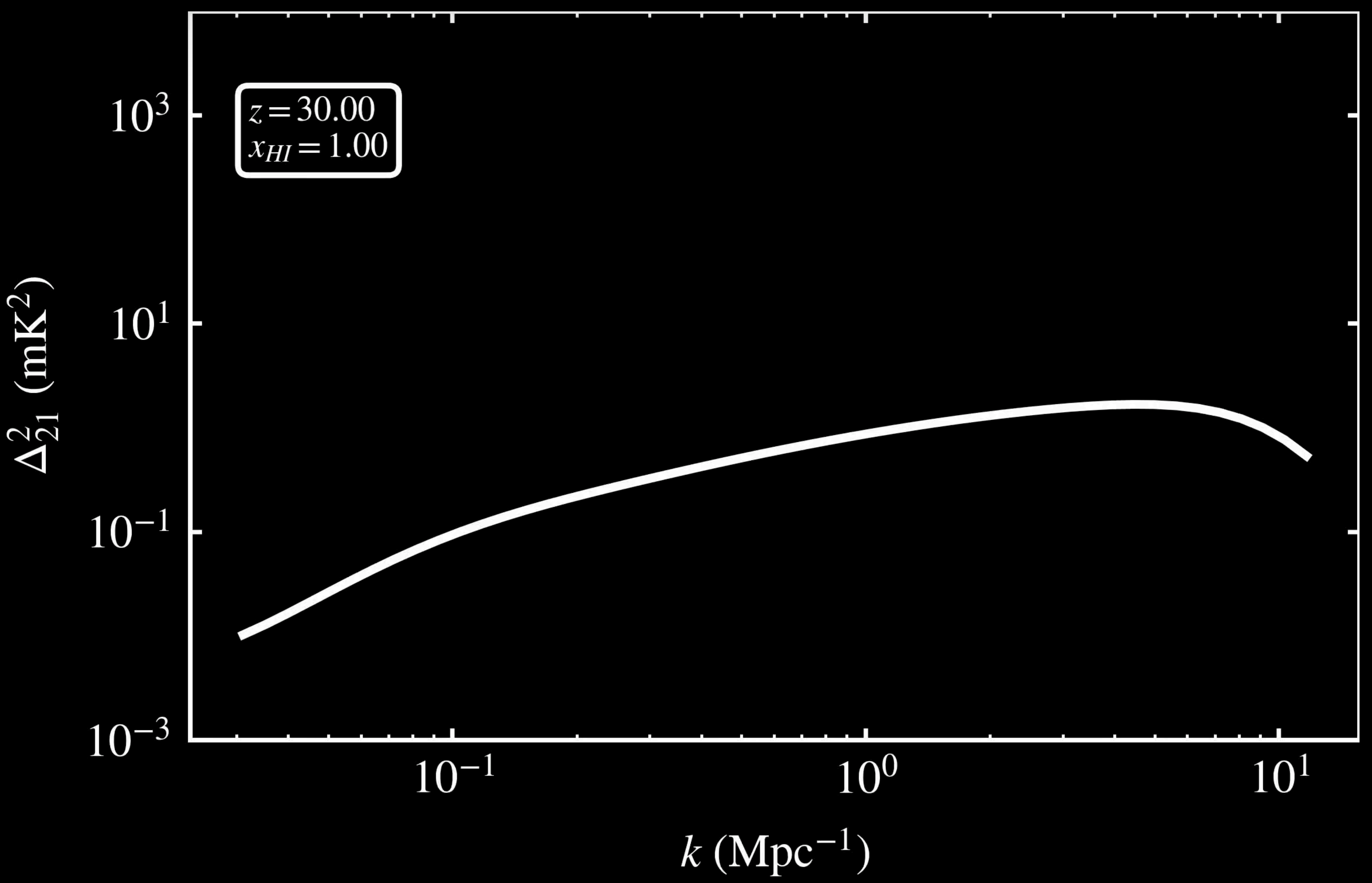
What did we do?

What can we learn using the 21-cm PS from the EoR?



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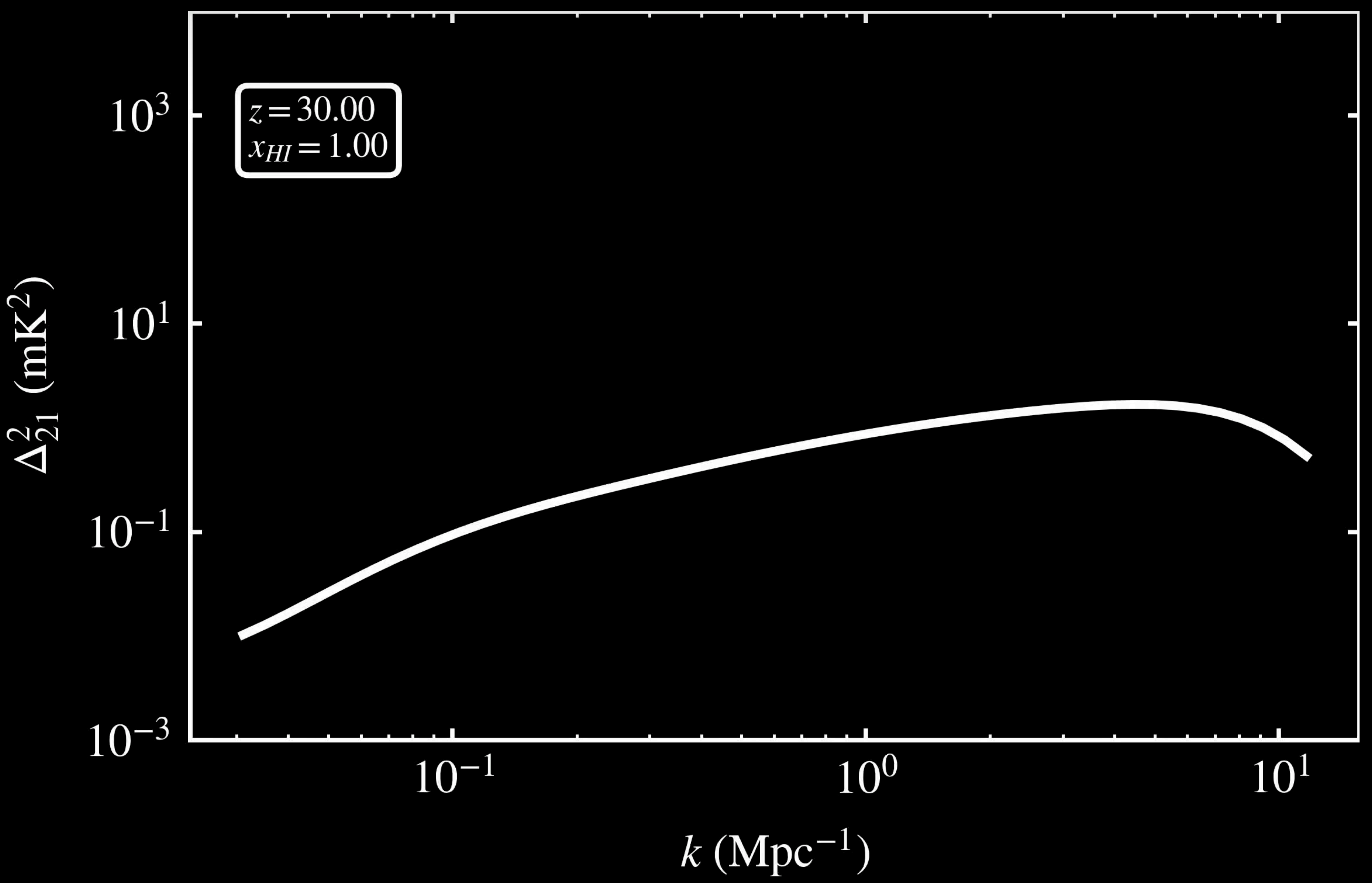

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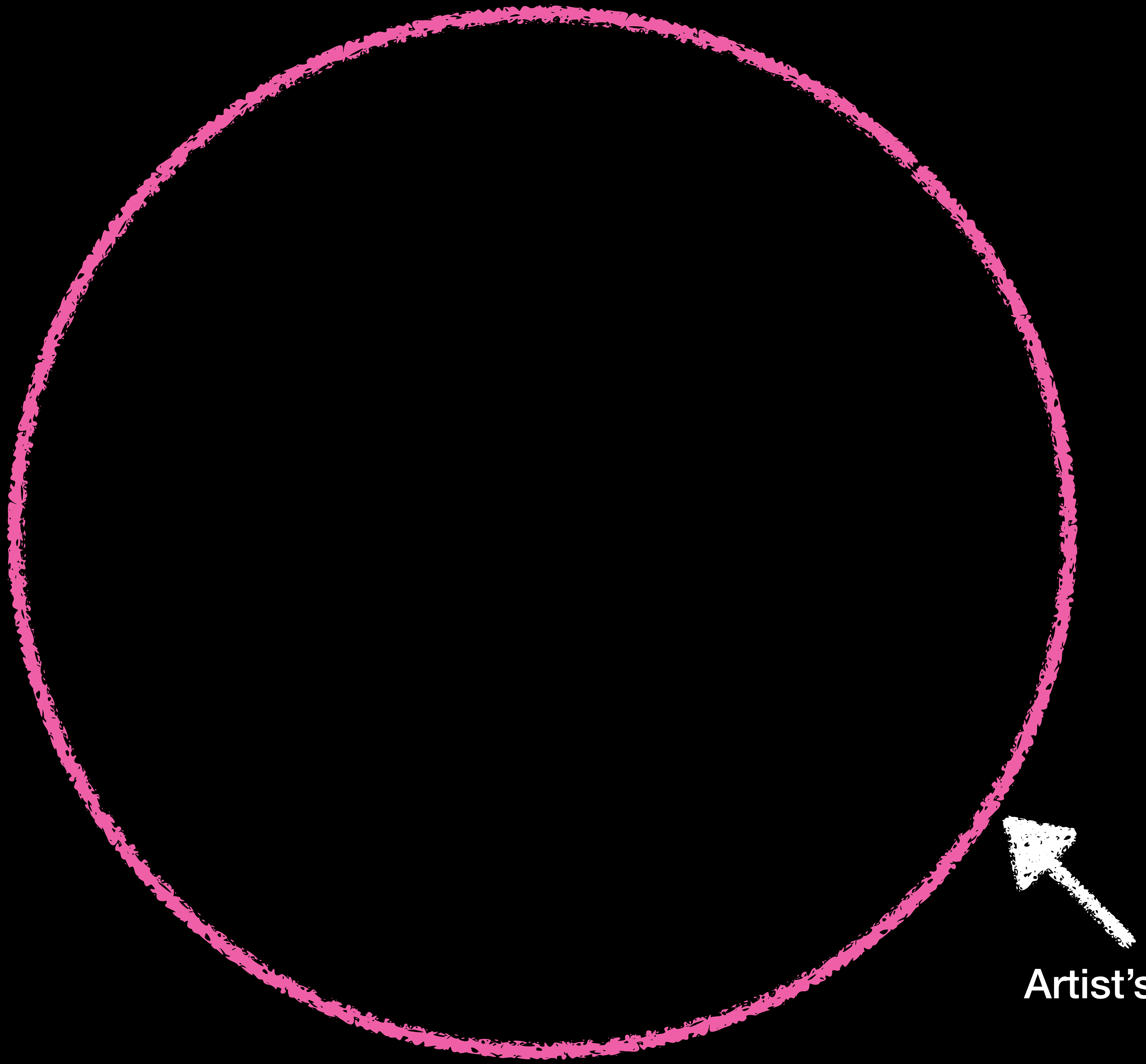
How do we do this?



Artist's impression of a DM halo

Mutch+, MNRAS, 462, 250–276 (2016)

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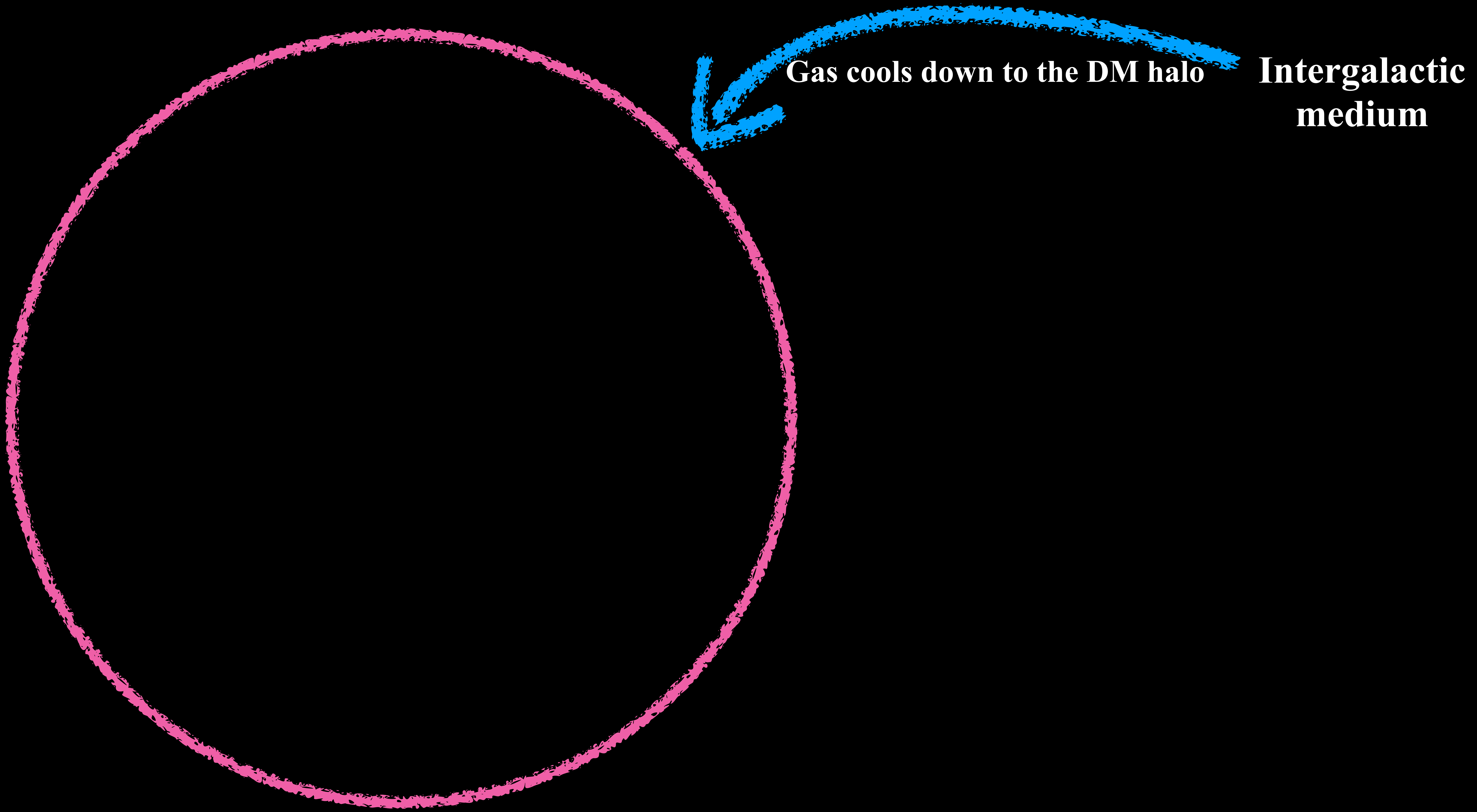
How do we do this?

Galaxy formation & evolution crash course



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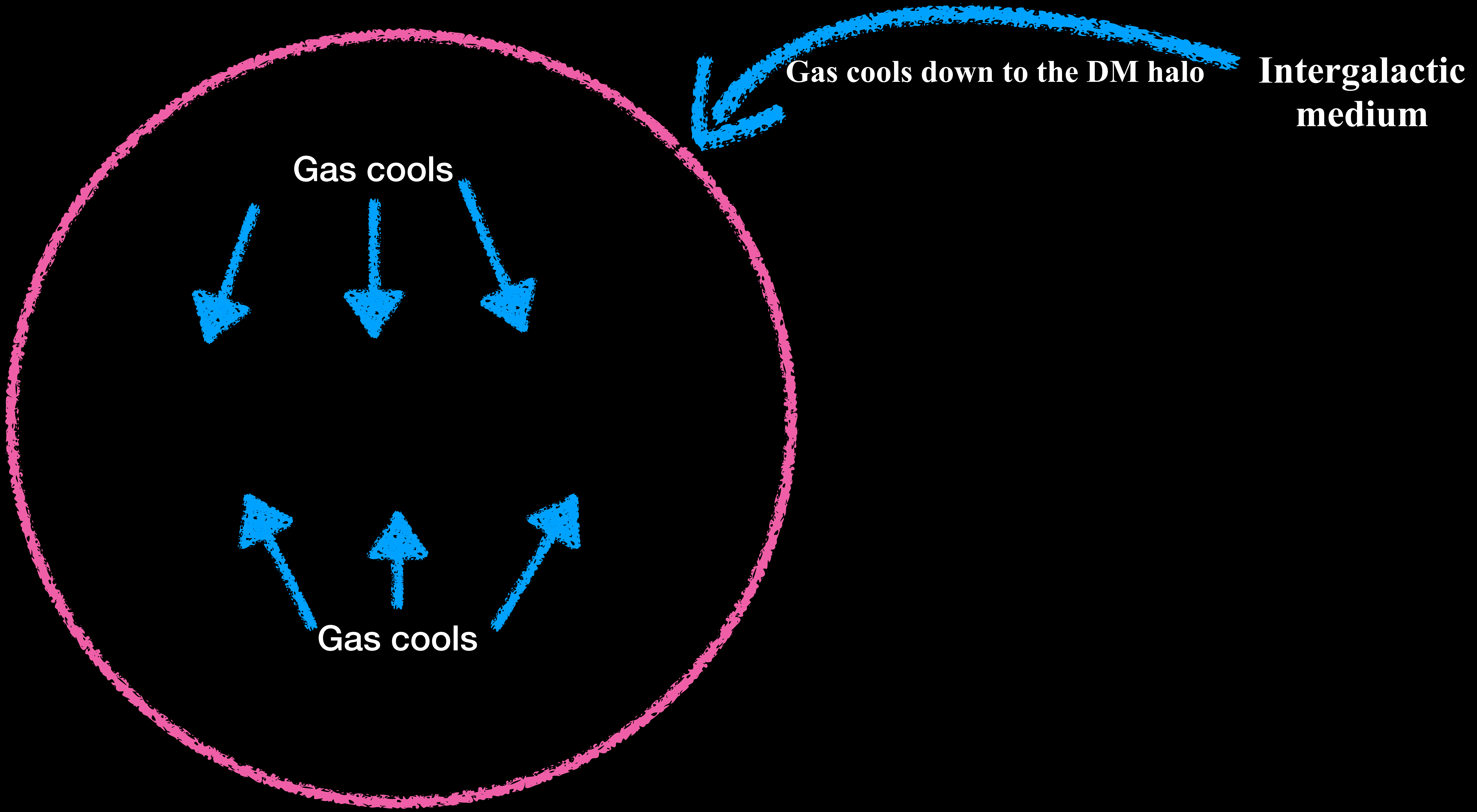

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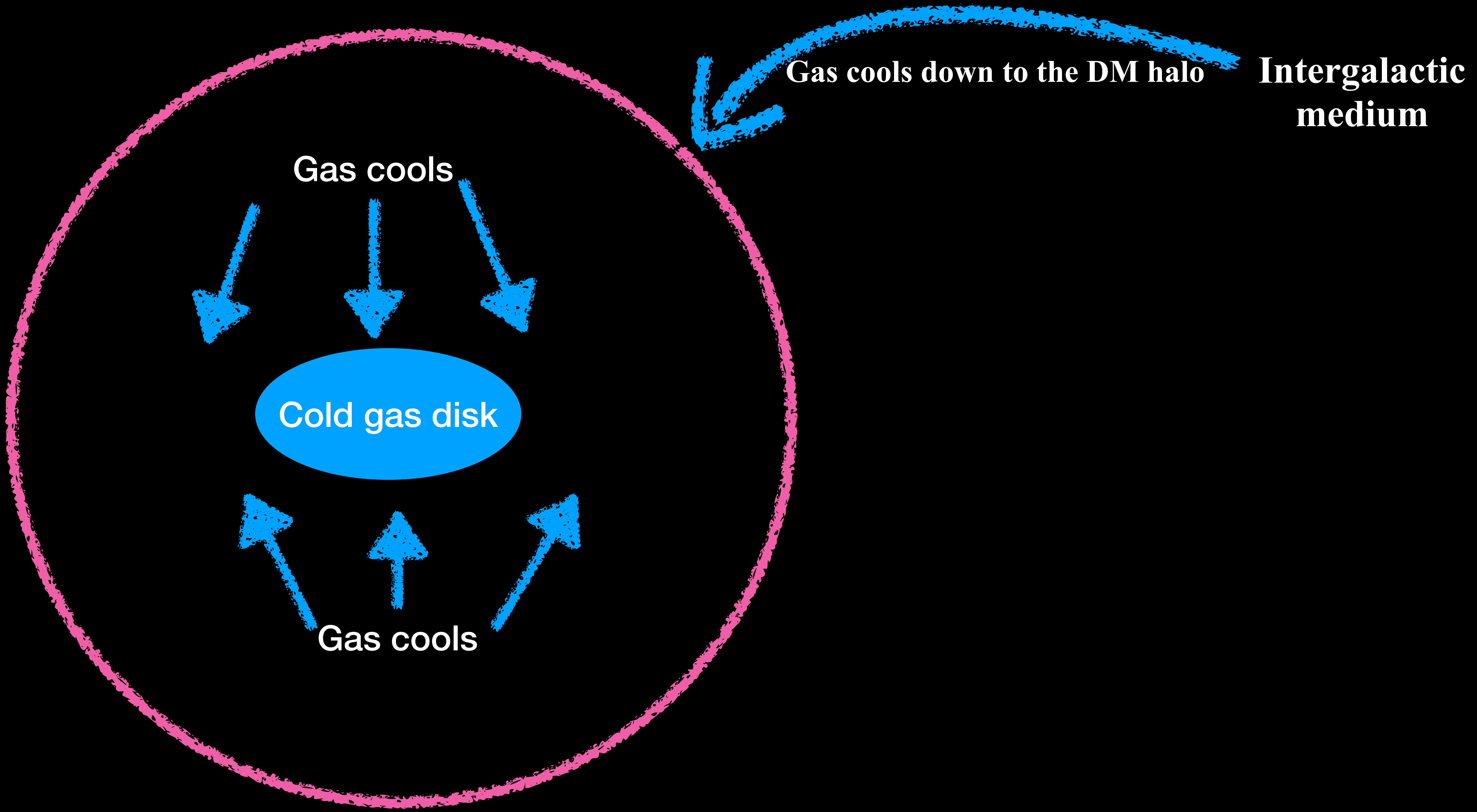

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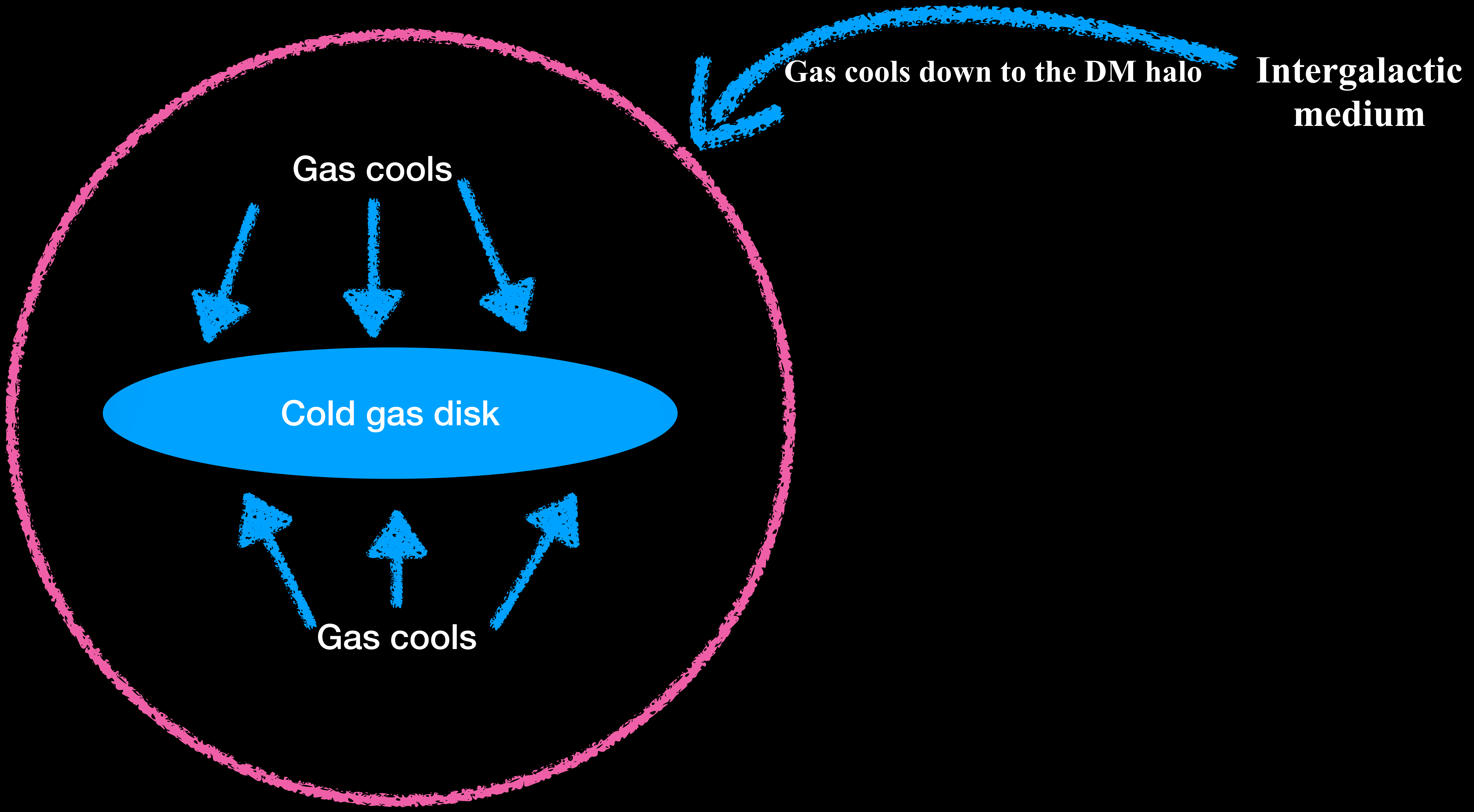

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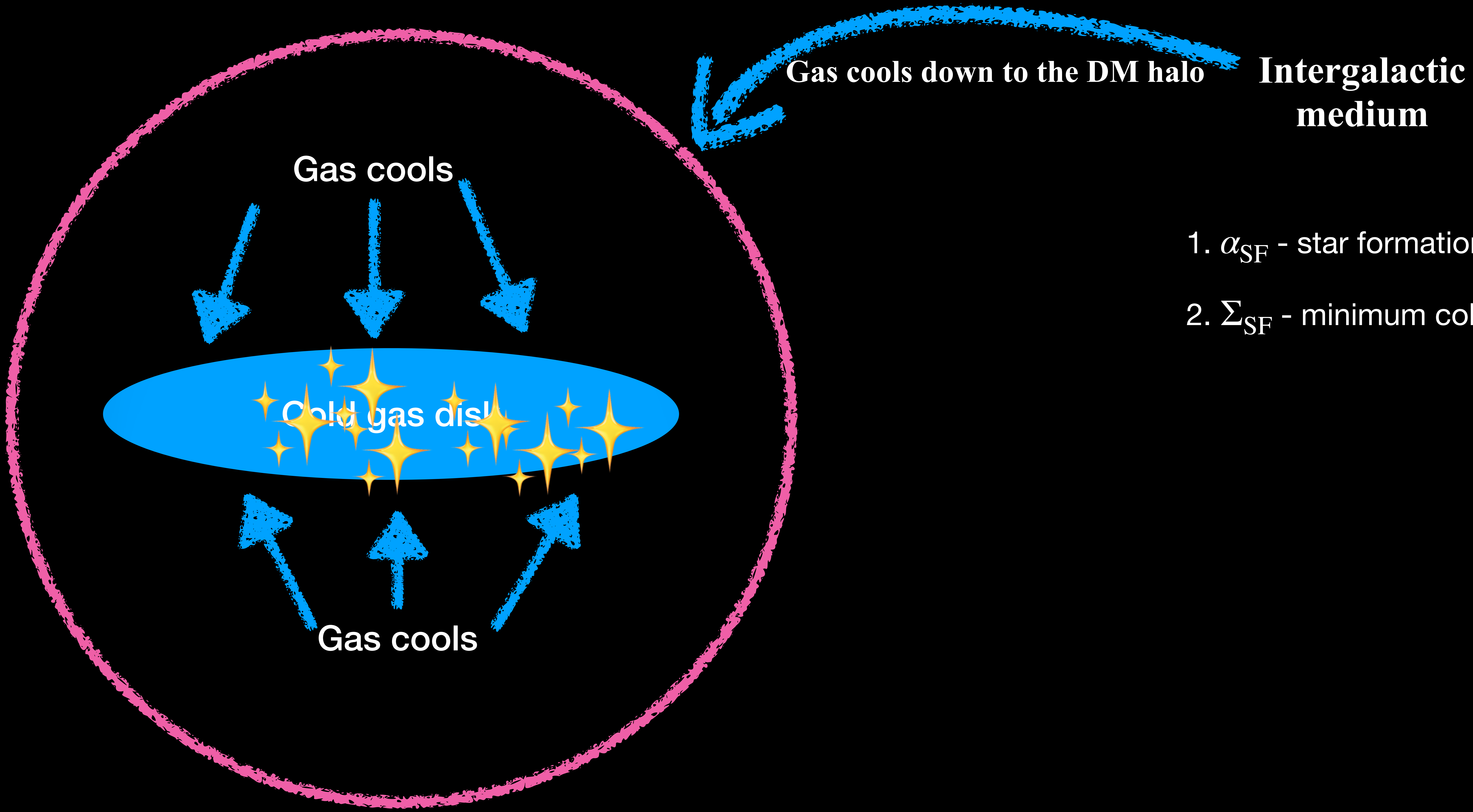

1. α_{SF} - star formation efficiency
2. Σ_{SF} - minimum cold gas needed for star formation to begin

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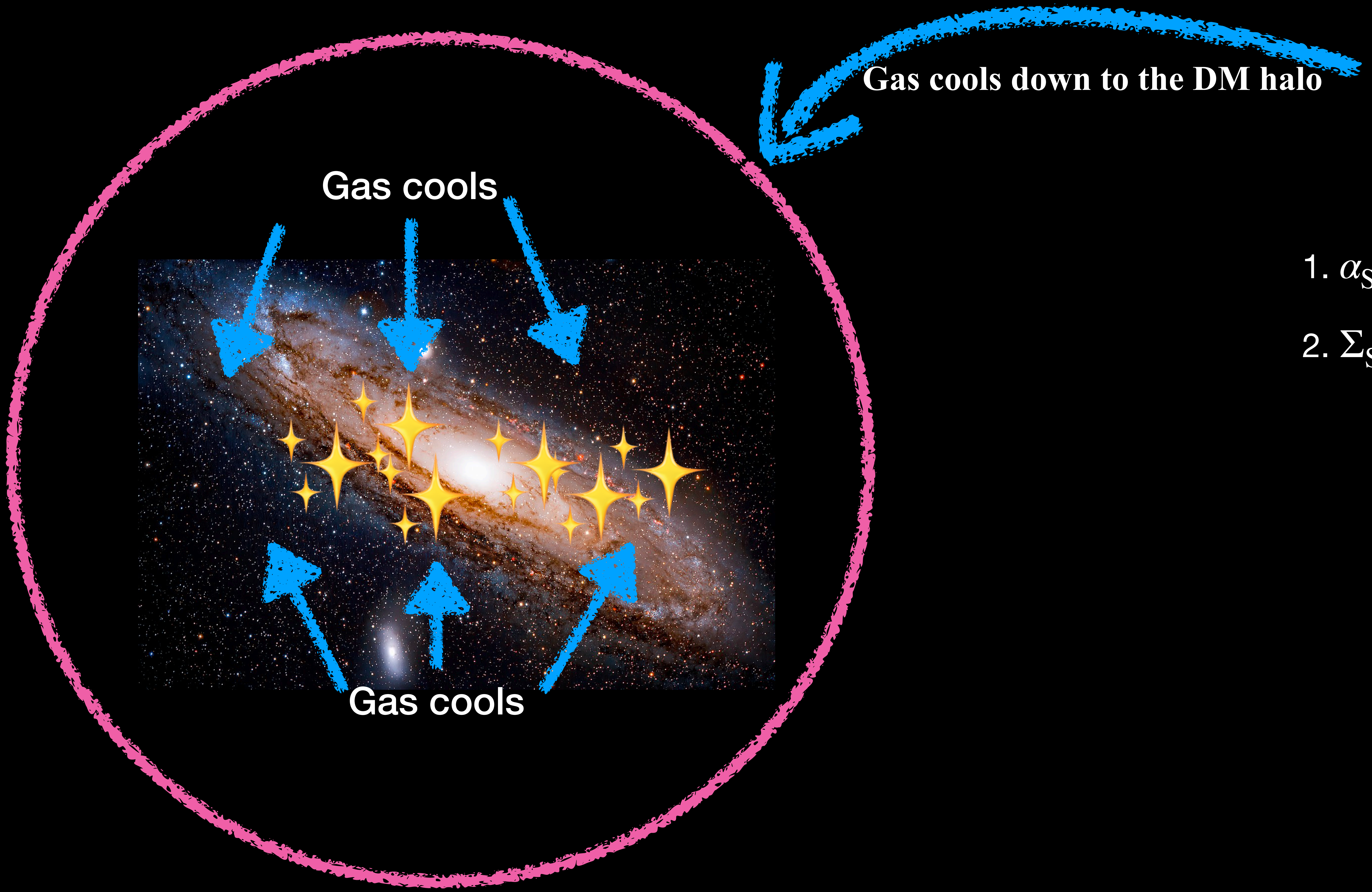

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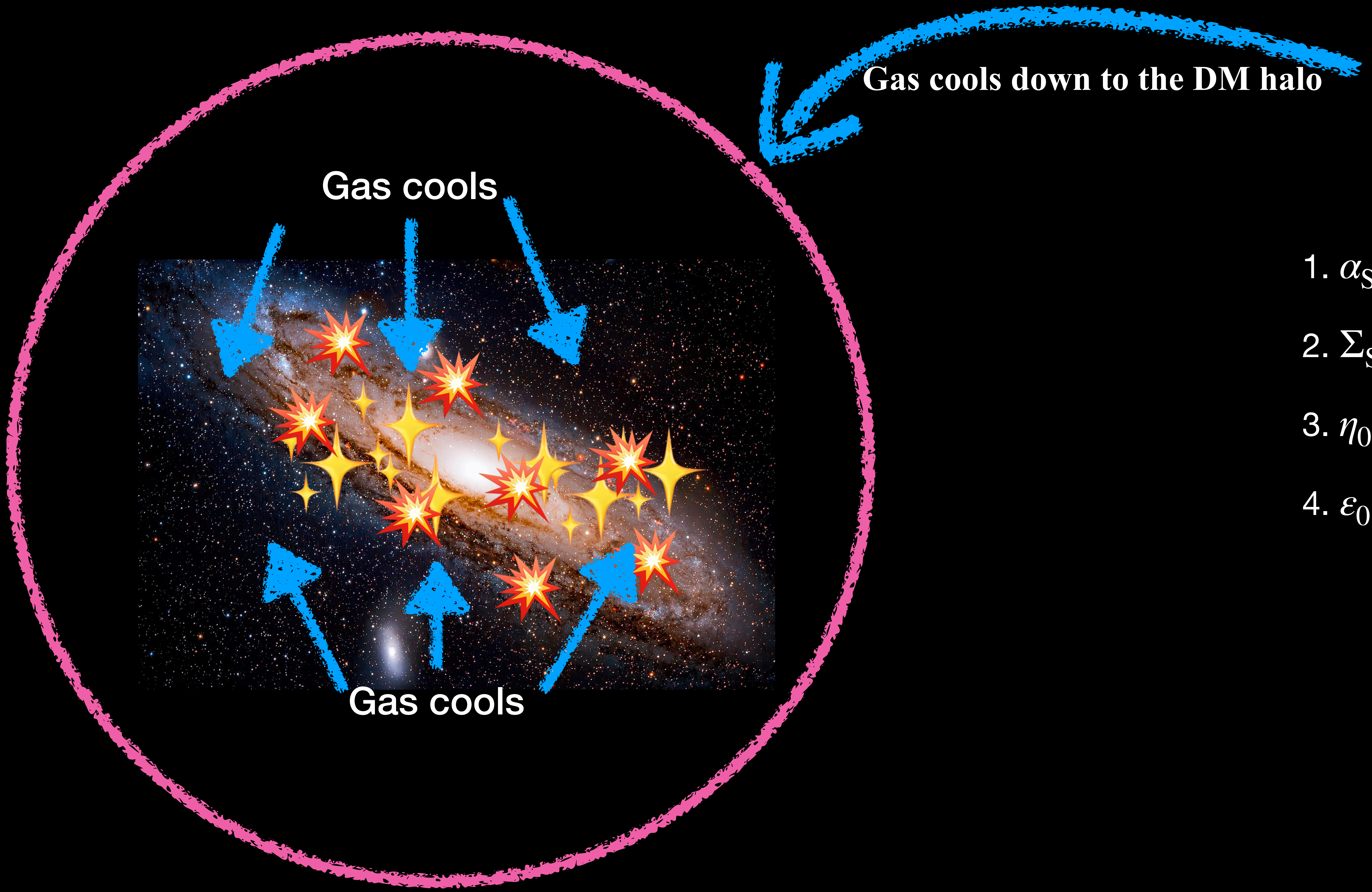

1. $\alpha_{\rm SF}$ - star formation efficiency
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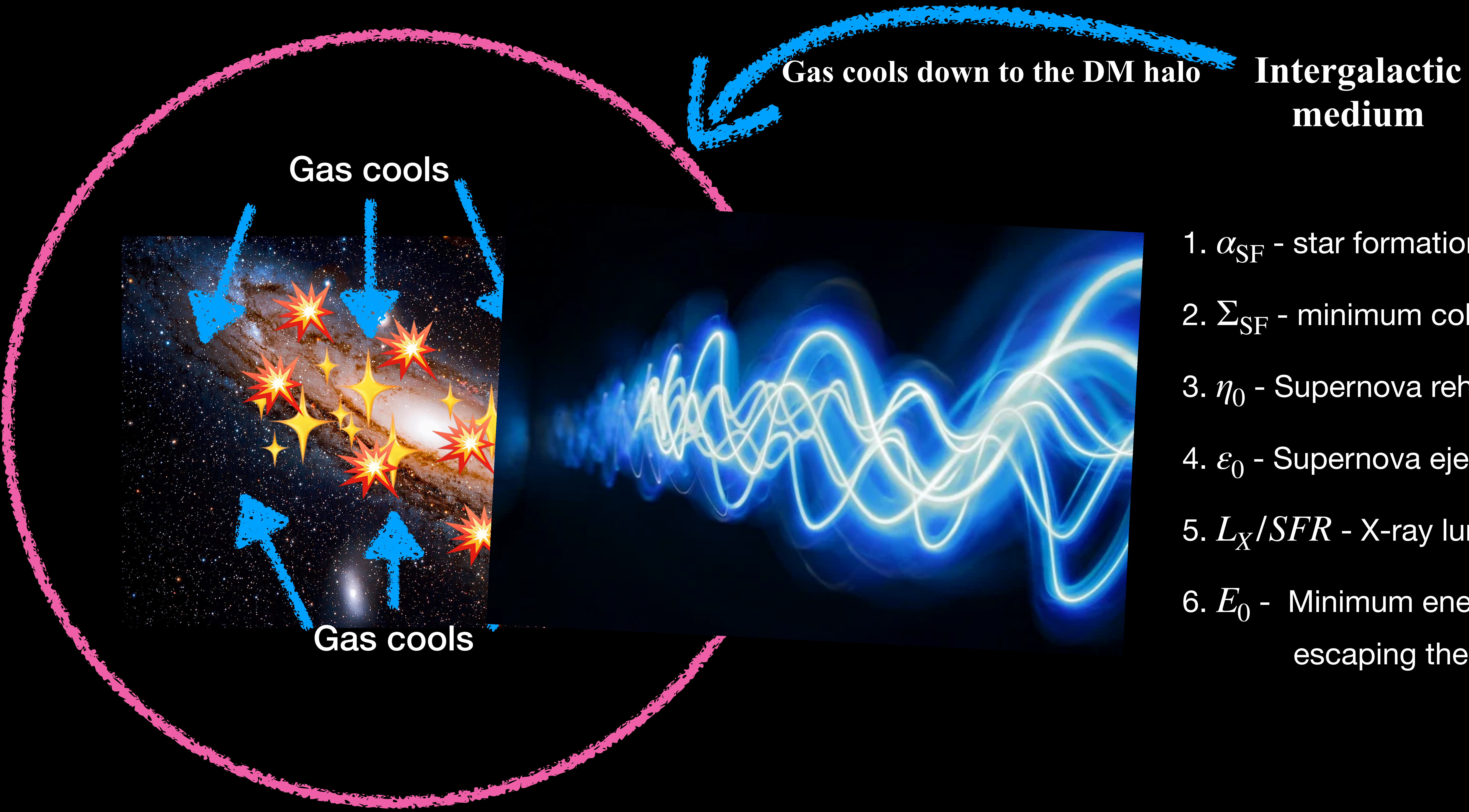

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2. Σ_{SF} - minimum cold gas needed for star formation to begin
3. η_0 - Supernova reheat efficiency
4. ε_0 - Supernova ejection efficiency
5. L_X/SFR - X-ray luminosity per SFR of the galaxy
6. E_0 - Minimum energy of the X-ray photon capable of escaping the galaxy

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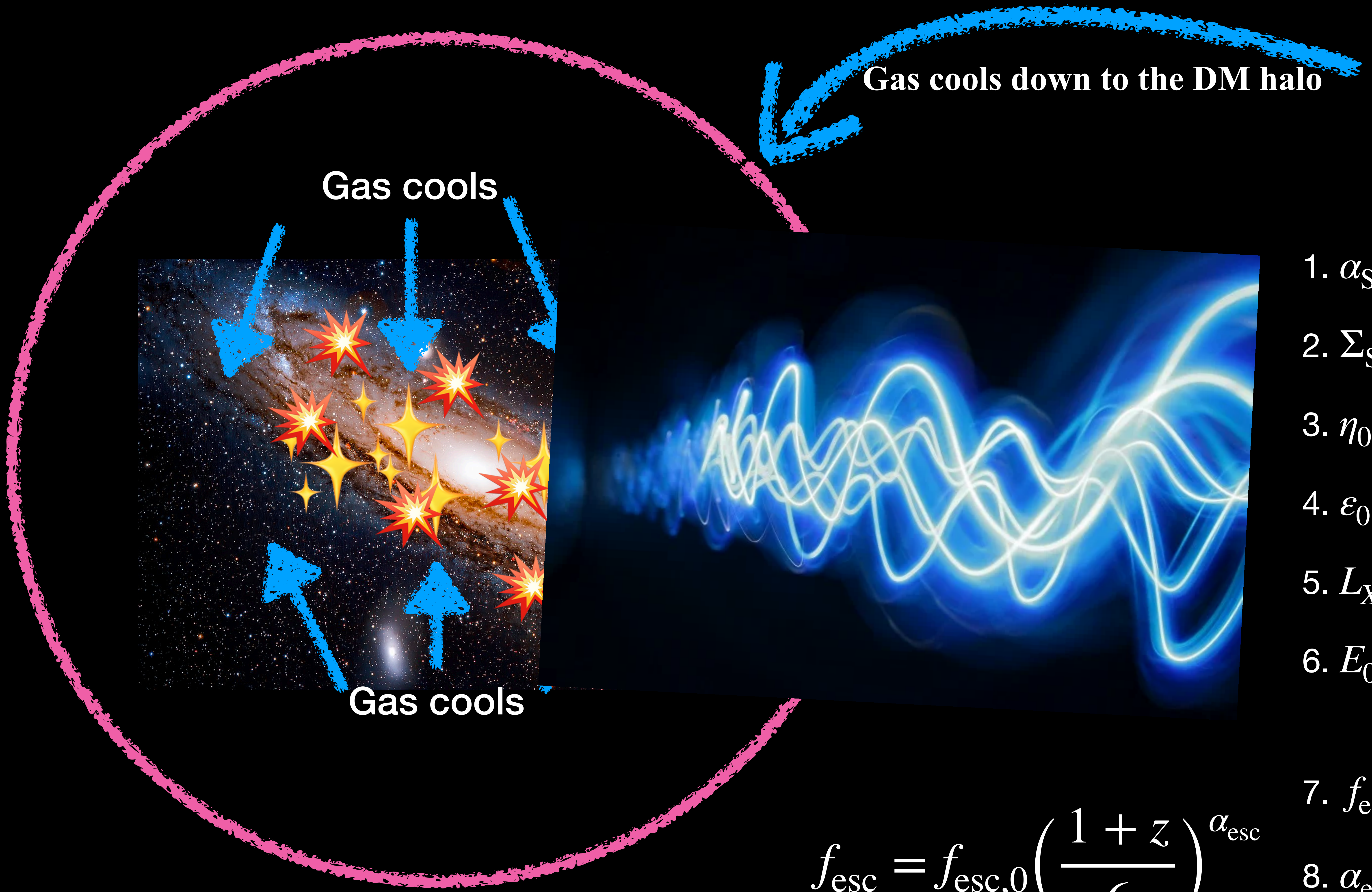
How do we do this?

Galaxy formation & evolution crash course



$$f_{\rm esc} = f_{\rm esc,0}\left(\frac{1+z}{6}\right)^{\alpha_{\rm esc}}$$

1. $\alpha_{\rm SF}$ - star formation efficiency
2. $\Sigma_{\rm SF}$ - minimum cold gas needed for star formation to begin
3. η_0 - Supernova reheat efficiency
4. ε_0 - Supernova ejection efficiency
5. L_X/SFR - X-ray luminosity per SFR of the galaxy
6. E_0 - Minimum energy of the X-ray photon capable of escaping the galaxy
7. $f_{\rm esc,0}$ - UV photons' escape fraction normalisation.
8. $\alpha_{\rm esc}$ - UV escape fraction power law dependence on redshift

Mutch+, MNRAS, 462, 250–276 (2016)

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What did we do?

What can we learn using the 21-cm PS from the EoR?

1. α_{SF} - star formation efficiency
2. Σ_{SF} - minimum cold gas needed for star formation to begin
3. η_0 - Supernova reheat efficiency
4. ε_0 - Supernova ejection efficiency
5. L_X/SFR - X-ray luminosity per SFR of the galaxy
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How did we do this?

Constraints using Fisher Matrix

$$\mathbf{F}_{ij} = \sum_{k,z} \frac{1}{\varepsilon^2(k,z)} \frac{\partial \Delta^2(k,z)}{\partial \theta_i} \frac{\partial \Delta^2(k,z)}{\partial \theta_j}$$

Pober+, **ApJ**, 782, (2014)

How did we do this?

Constraints using Fisher Matrix

$$\mathbf{F}_{ij} = \sum_{k,z} \frac{1}{\varepsilon^2(k,z)} \frac{\partial \Delta^2(k,z)}{\partial \theta_i} \frac{\partial \Delta^2(k,z)}{\partial \theta_j}$$

Error/noise on your data points

Derivative of your observations w.r.t parameters

Pober+, **ApJ**, 782, (2014)

How did we do this?

Constraints using Fisher Matrix

$$\mathbf{F}_{ij} = \sum_{k,z} \frac{1}{\varepsilon^2(k,z)} \frac{\partial \Delta^2(k,z)}{\partial \theta_i} \frac{\partial \Delta^2(k,z)}{\partial \theta_j}$$

Error/noise on your data points

Derivative of your observations w.r.t parameters

The Covariance matrix is the inverse of $\mathbf{F}_{ij}$ ***

$$\mathbf{C}_{ij} = \mathbf{F}_{ij}^{-1}$$

*** conditions apply: Gaussian likelihood.

Pober+, **ApJ**, 782, (2014)

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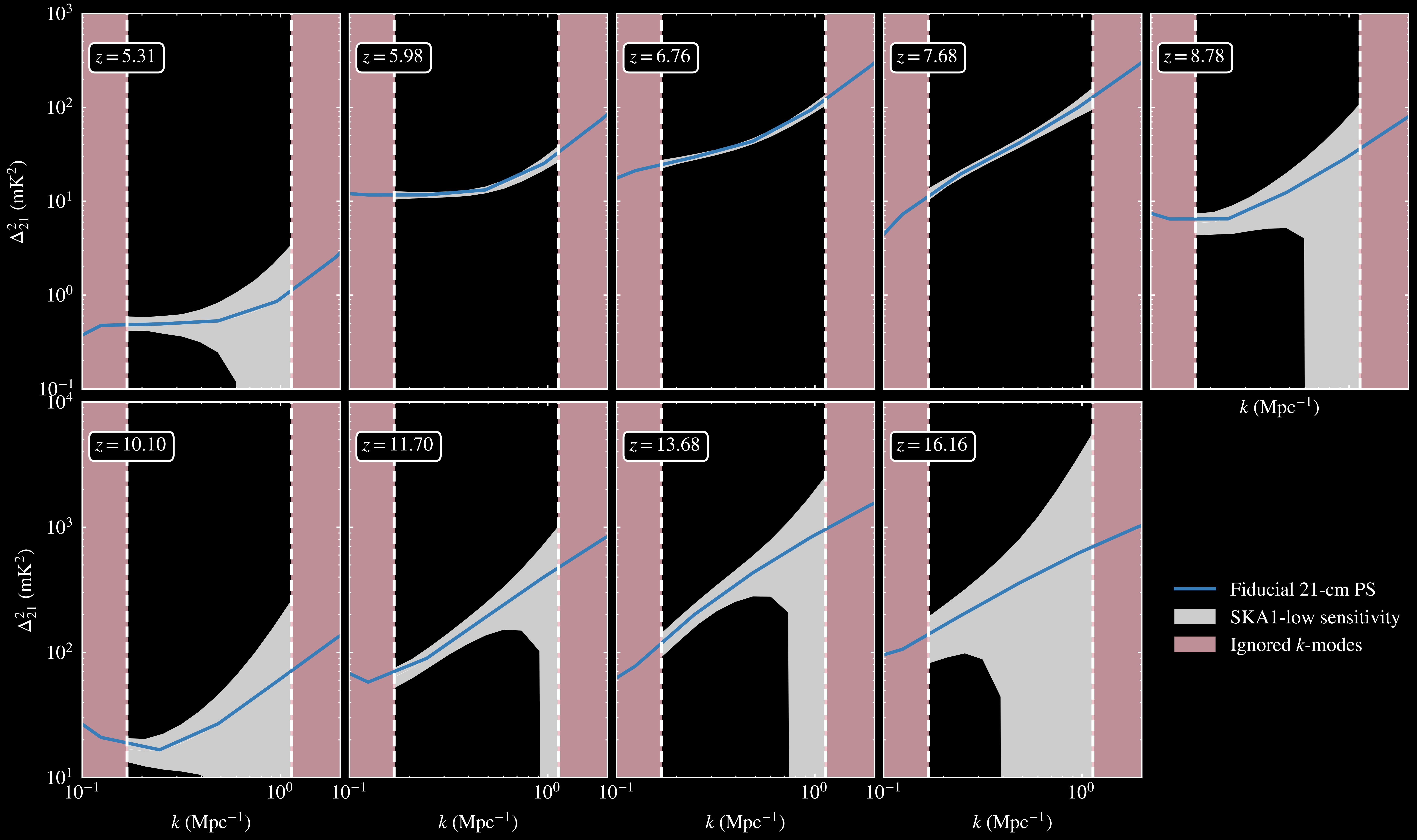
How did we do this?

SKA1-low sensitivity



- 11 redshifts between $z \in [5,24]$.
- 1,000 hours observation with SKA1-low.
- Moderate foreground scenario of 21cmSENSE

  (k-modes falling in EoR wedge not considered).

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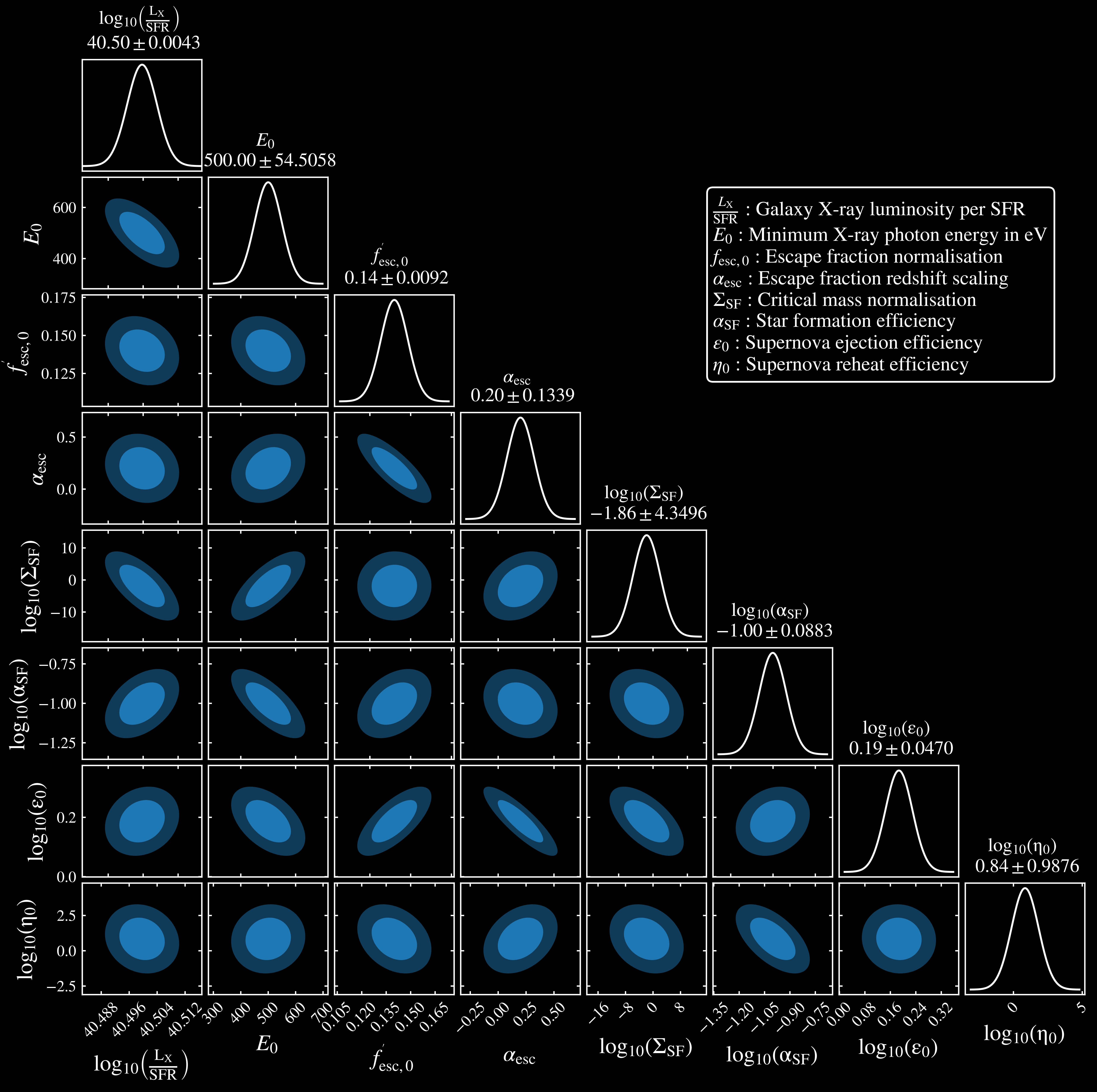
What did we do?

Fisher matrix constraints with 21-cm PS



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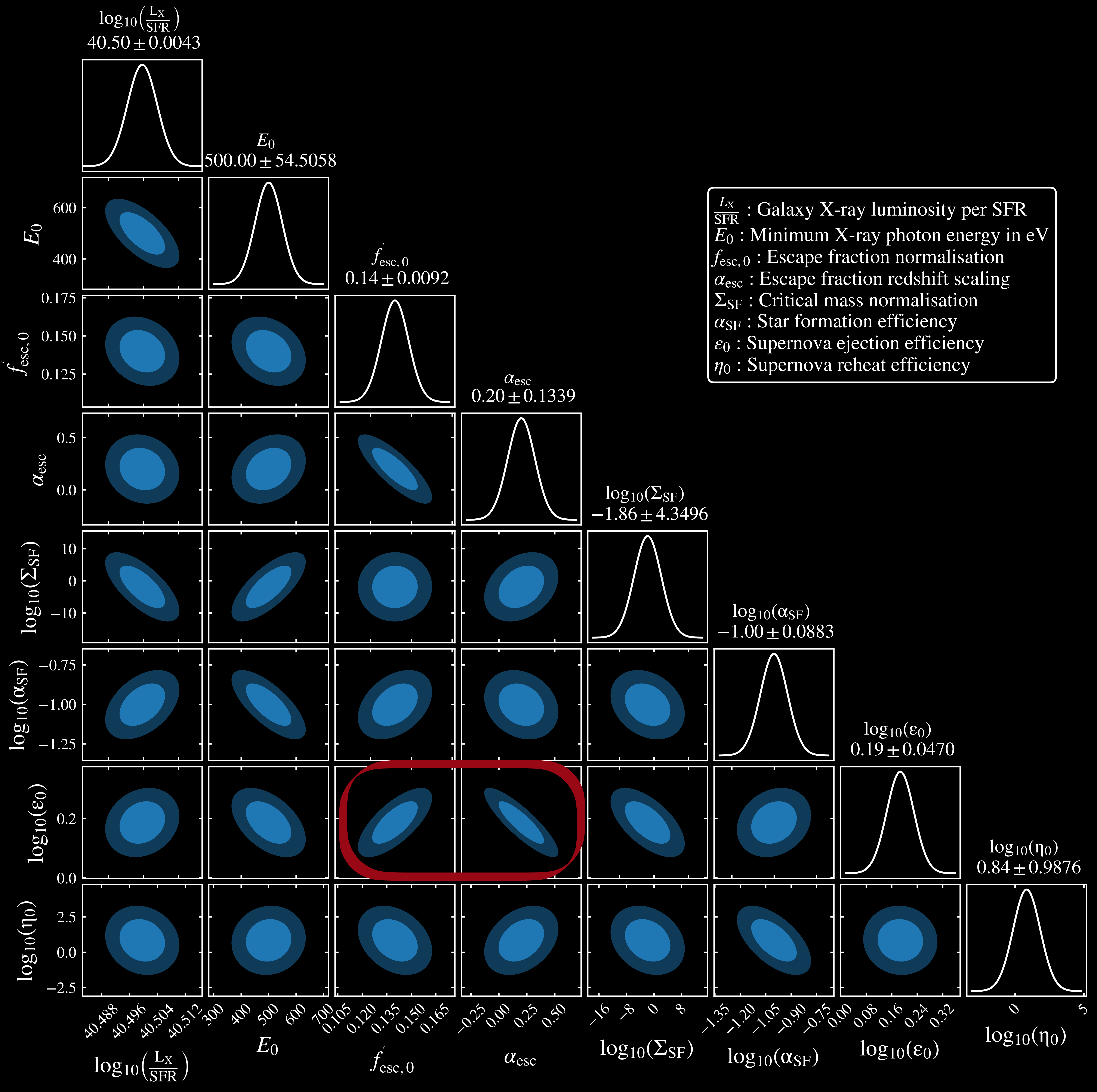
What did we do?

Fisher matrix constraints with 21-cm PS



- A lot of correlations between the model parameters
- UV escape fraction and supernova feedback

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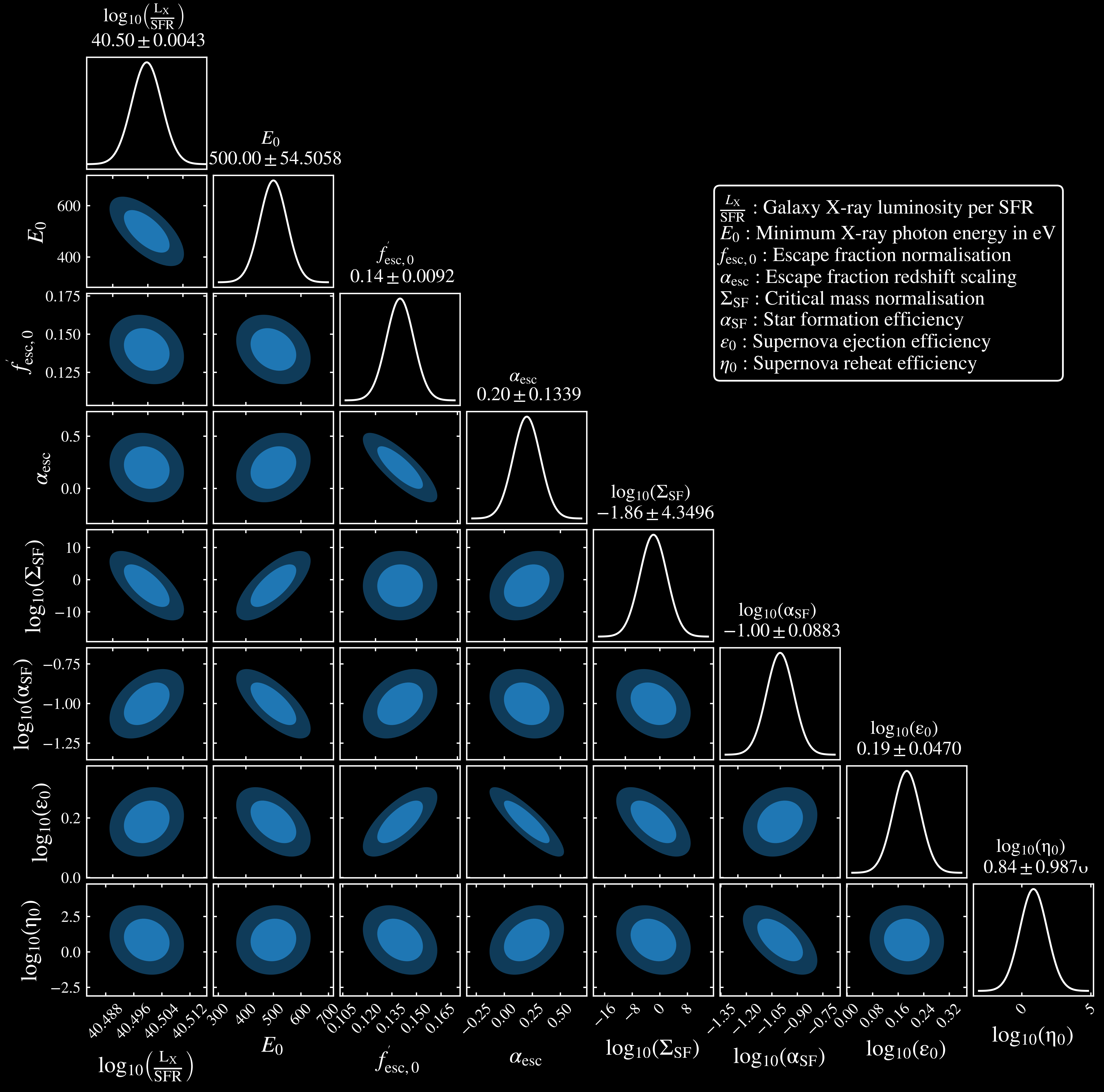
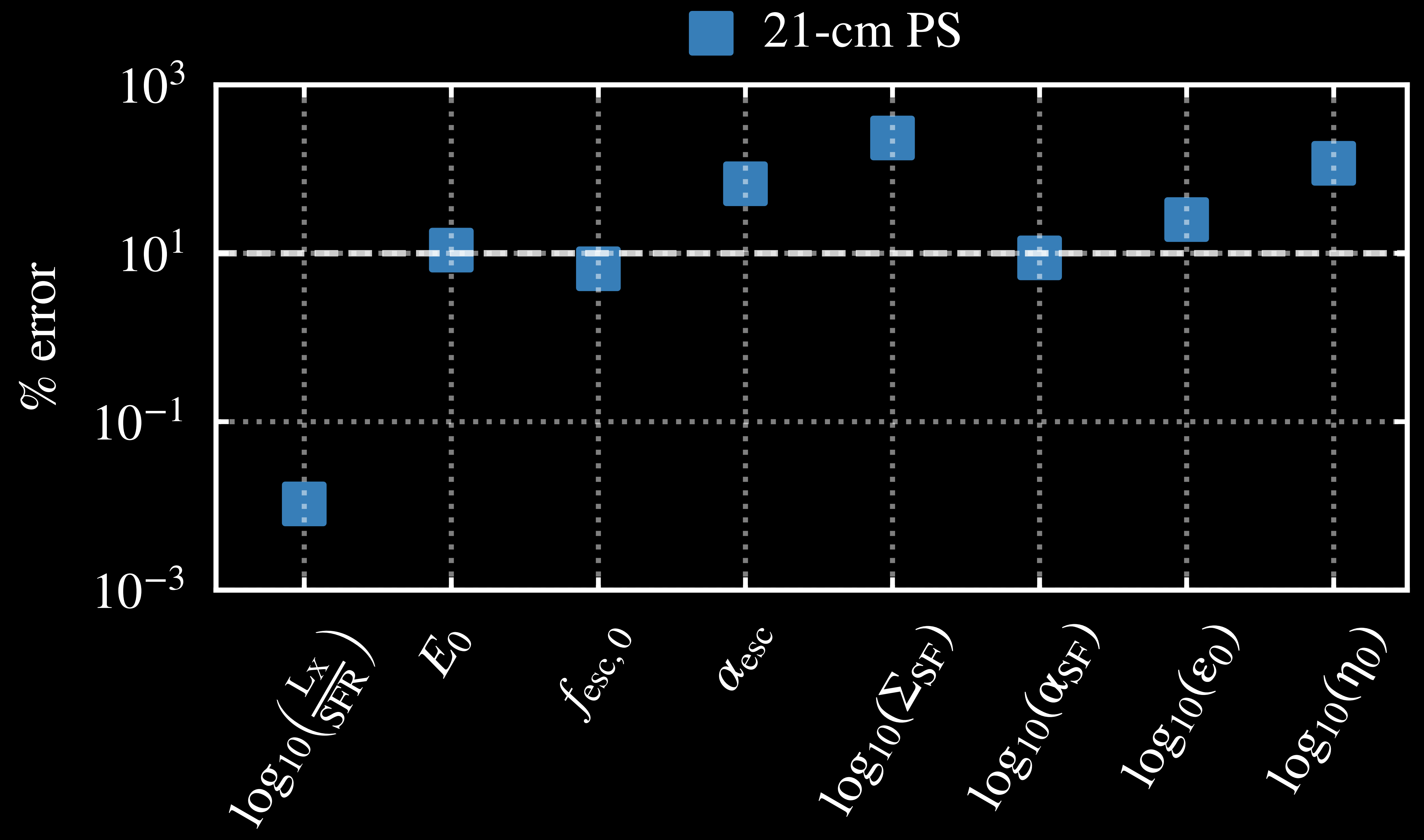
What did we do?

Fisher matrix constraints with 21-cm PS





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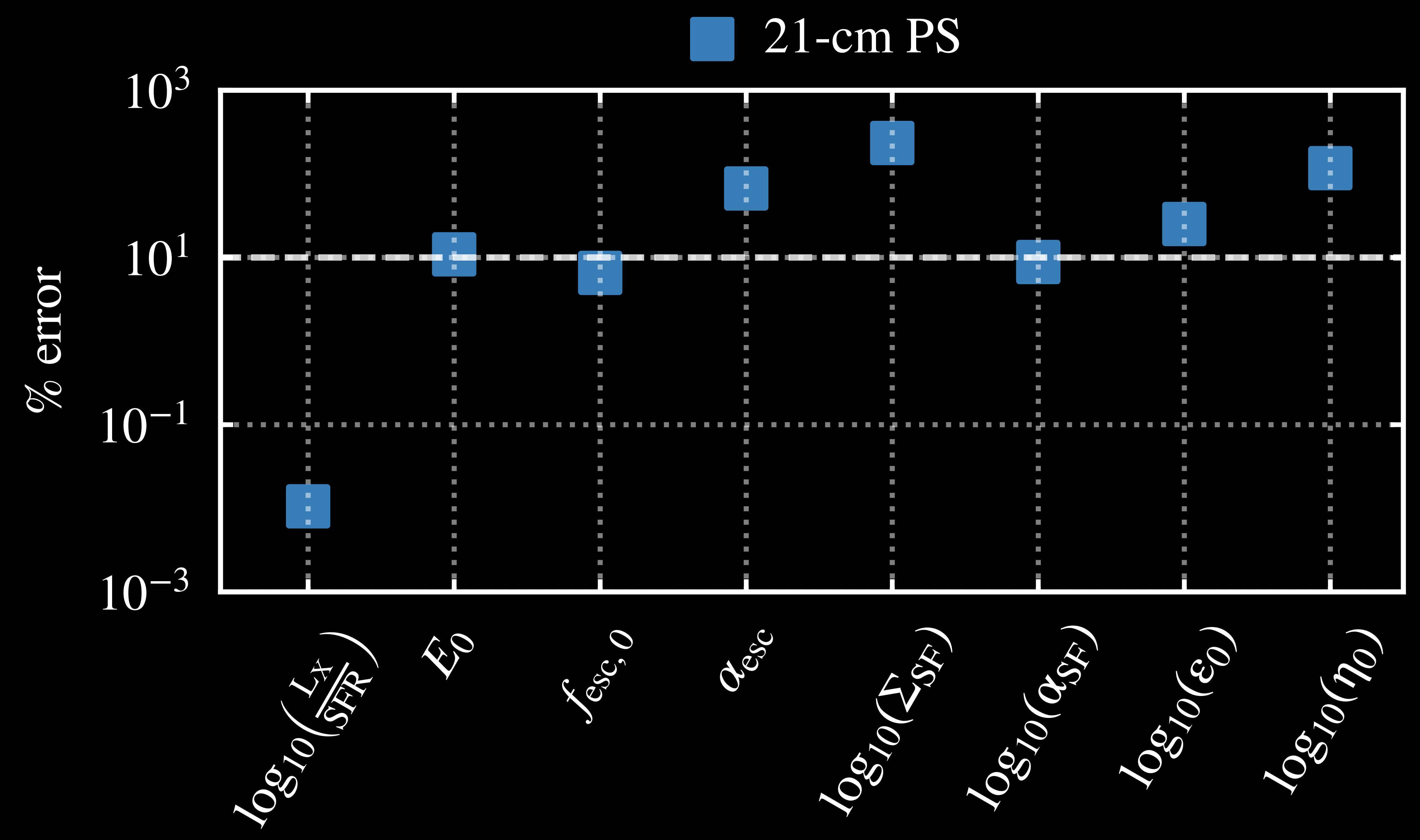
What did we do?

Fisher matrix constraints with 21-cm PS

- Tight constraints on the X-ray properties.
- Moderate constraints on the UV escape fraction and star formation efficiencies.
- Only weak constraints on Supernovae feedback properties.



$\frac{L_X}{SFR}$: Galaxy X-ray luminosity per SFR
E_0 : Minimum X-ray photon energy in eV
$f_{esc,0}$: Escape fraction normalisation
α_{esc} : Escape fraction redshift scaling
Σ_{SF} : Critical mass normalisation
α_{SF} : Star formation efficiency
ε_0 : Supernova ejection efficiency
η_0 : Supernova reheat efficiency

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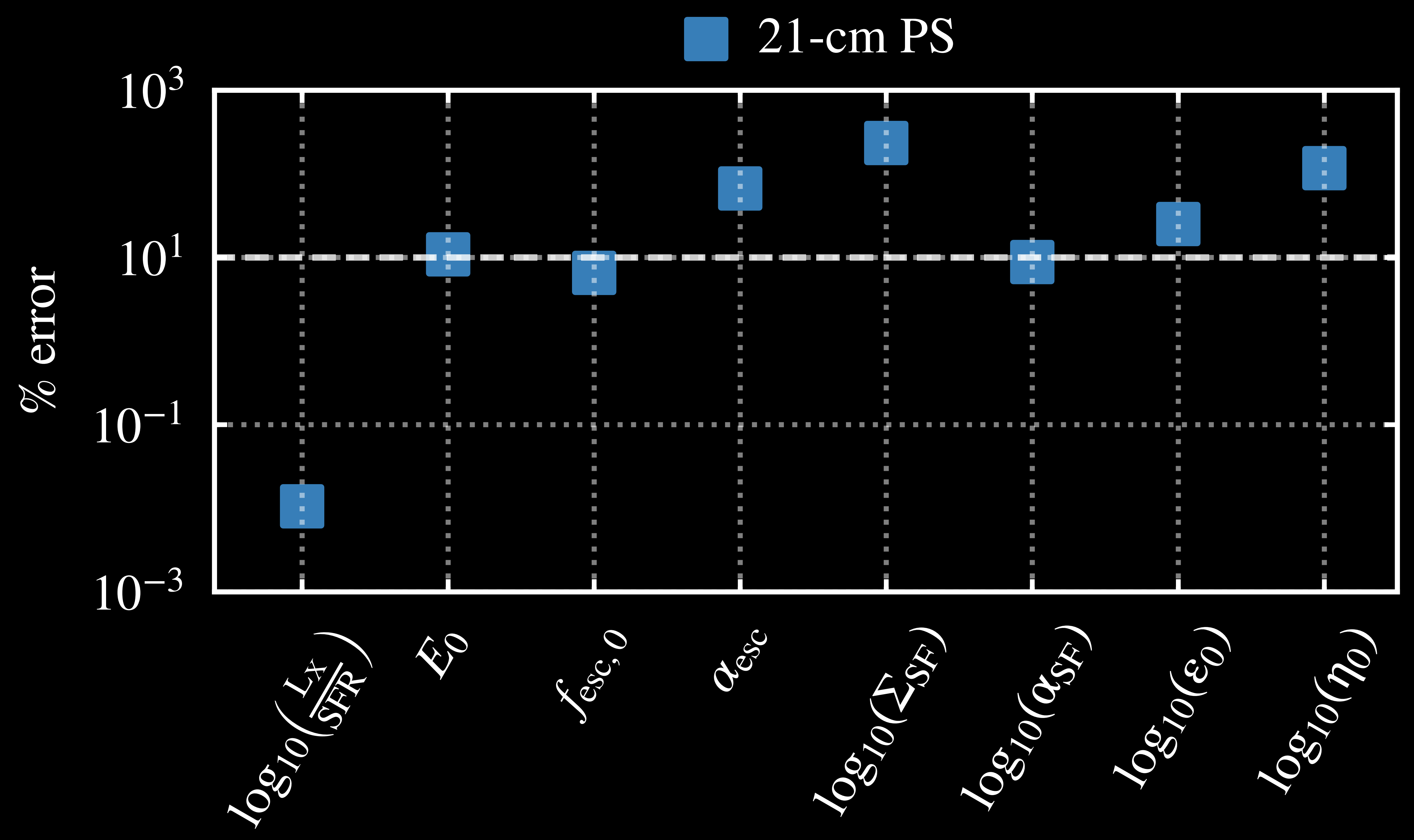
What did we do?

Fisher matrix constraints with 21-cm PS

- Tight constraints on the X-ray properties.
- Moderate constraints on the UV escape fraction and star formation efficiencies.
- Only weak constraints on Supernovae feedback properties.
- To improve constraints, we add in the UV LFs $z \in [5,10]$
- Vastly improves the constraints on star formation and supernova feedback.



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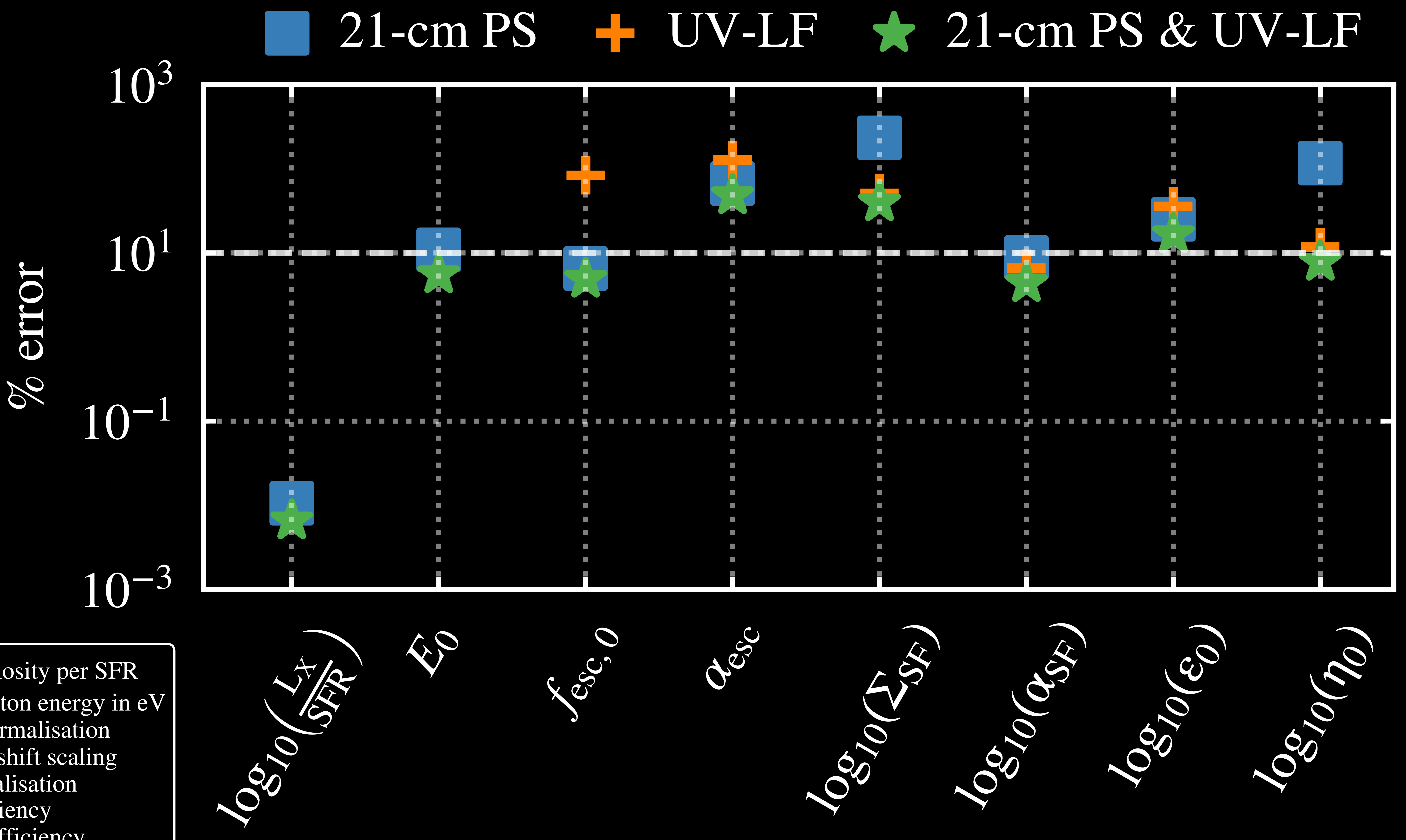
What did we do?

Fisher matrix constraints with 21-cm PS & UV LFs



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What did we do?

- X-ray properties of the galaxies in the early Universe tightly constrained by 21-cm PS.
- Synergy between different high-*z* observations.
  - Adding in the UV LFs improve constraints (star formation and supernova feedback).
- 10% constraints on most of the parameters.

$\frac{L_X}{SFR}$: Galaxy X-ray luminosity per SFR
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$f_{esc,0}$: Escape fraction normalisation
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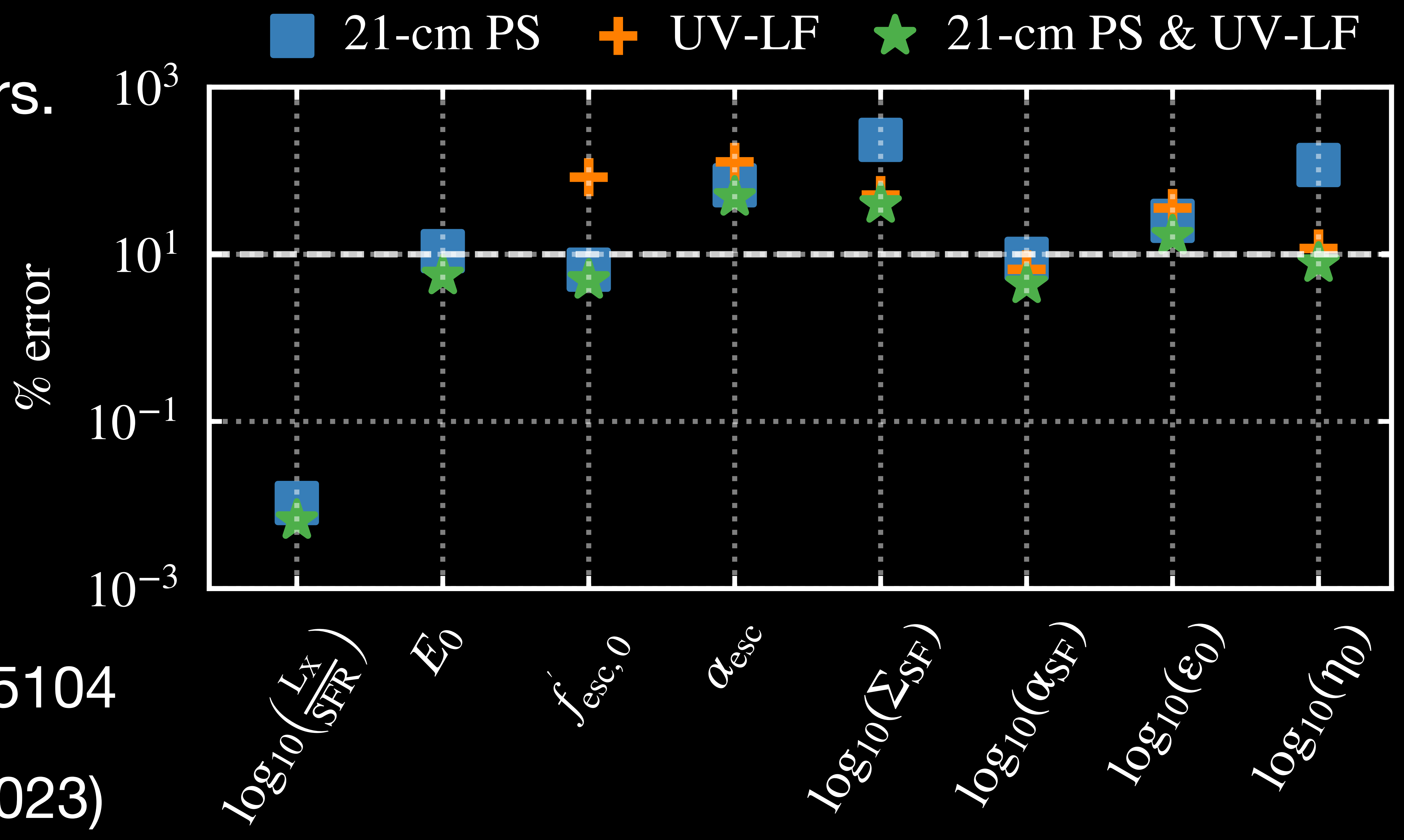

Balu, Greig & Wyithe; arXiv:2305.05104

Balu+, MNRAS, 520, 3368-3382 (2023)

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