Inferring the position and size of individual HII regions using Lyman-alpha observations with JWST

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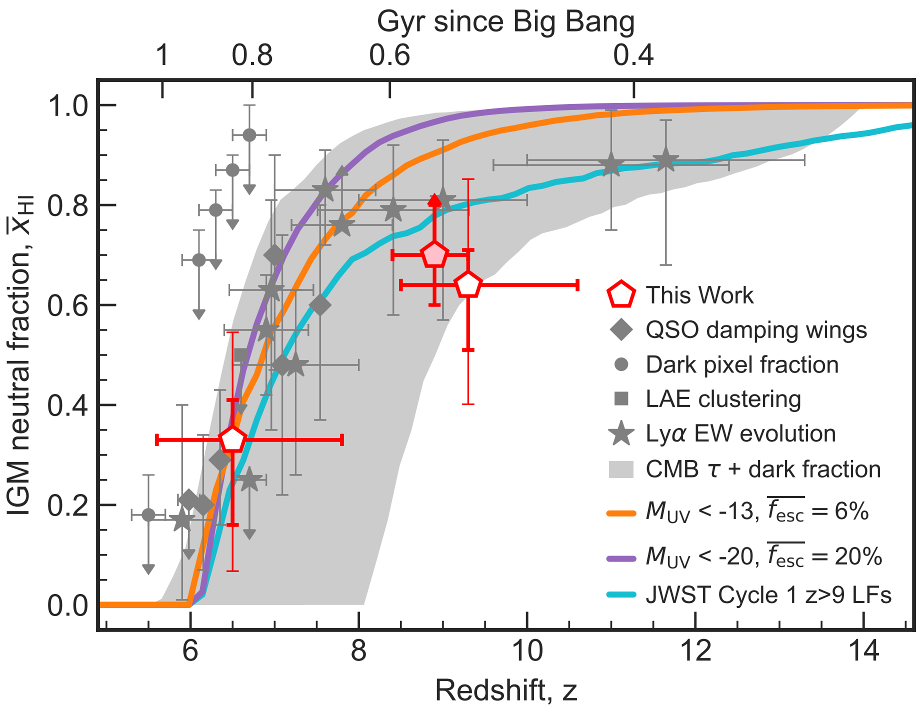
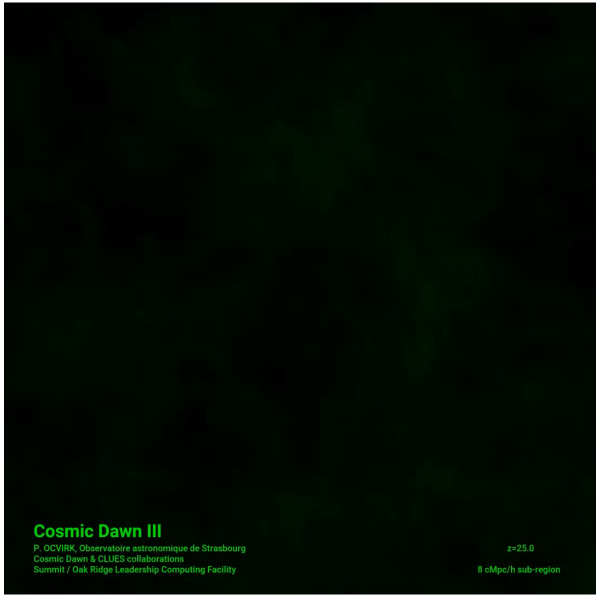
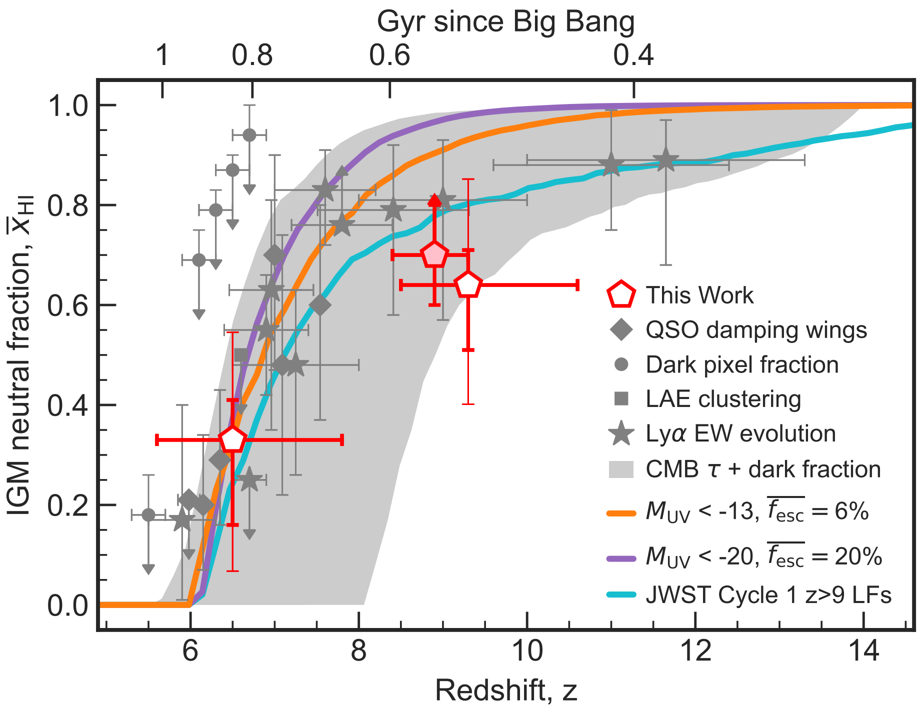
Importance of capturing morphology





Mason+25, Lewis+22, CoDa III, credit: P. Ocvirk

Importance of capturing morphology

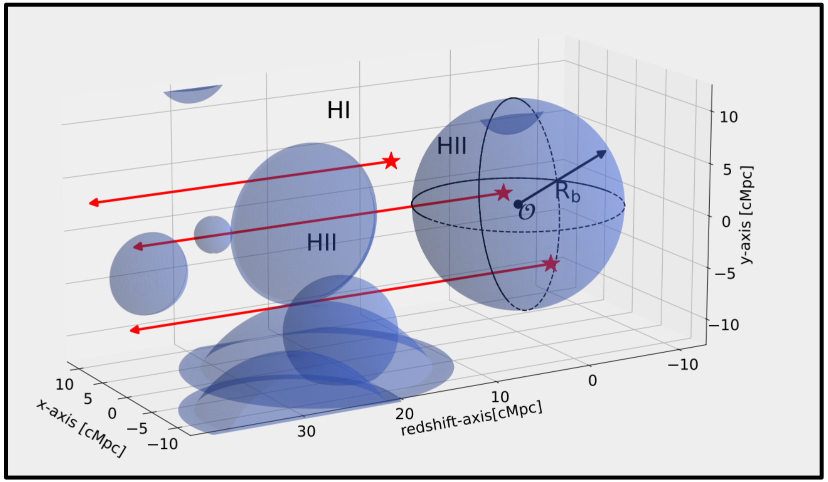


- Connect the sources of reionization to their impact on the IGM
- Answer what galaxies reionize the Universe

Mason+25, Lewis+22, CoDa III, credit: P. Ocvirk

Importance of capturing morphology

We can capture the ionization state around galaxies using the Lyman-α emission



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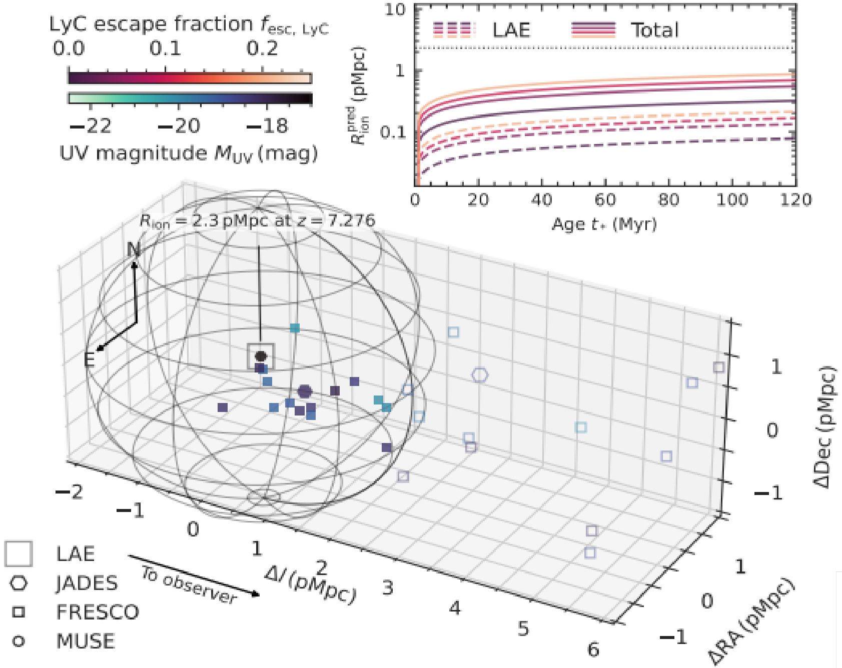
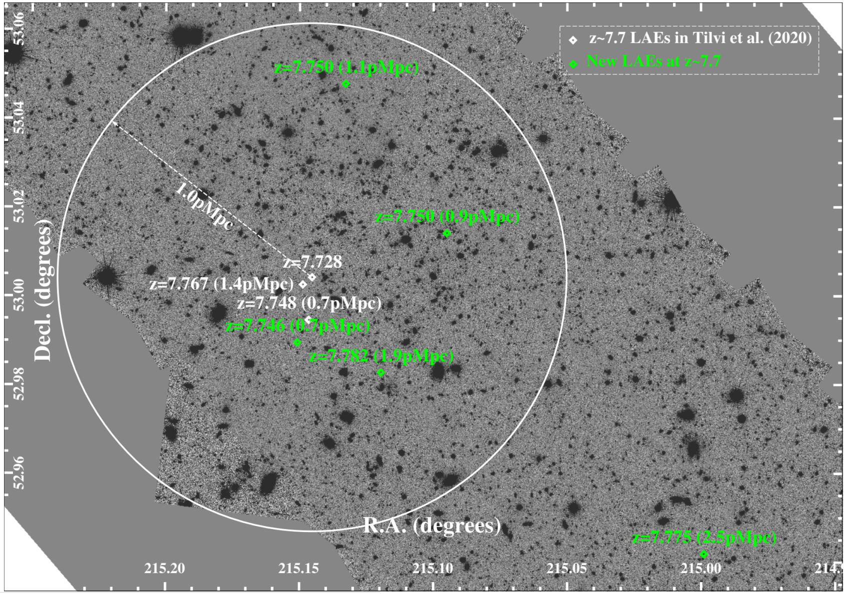
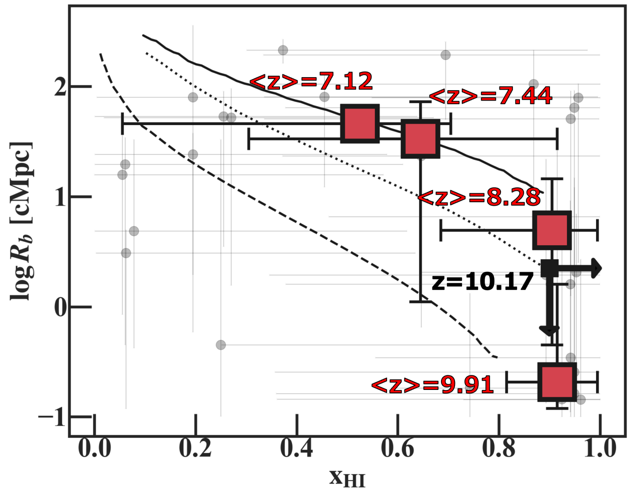
- Answer what galaxies reionize the Universe

Mason+25, Lewis+22, CoDa III, credit: P. Ocvirk







We can infer local HII regions **now** with JWST

See also:
Tilvi+20, Endsley & Stark 20, Jung+22, Hayes & Scarlata 23, Saxena+23, Witstok+24a, Tang+23, +24, Chen+24, Umeda+24, Napolitano+24

But…

Analysis of surrounding HII morphology is approximate:

- **Galaxies are treated individually.**

But…

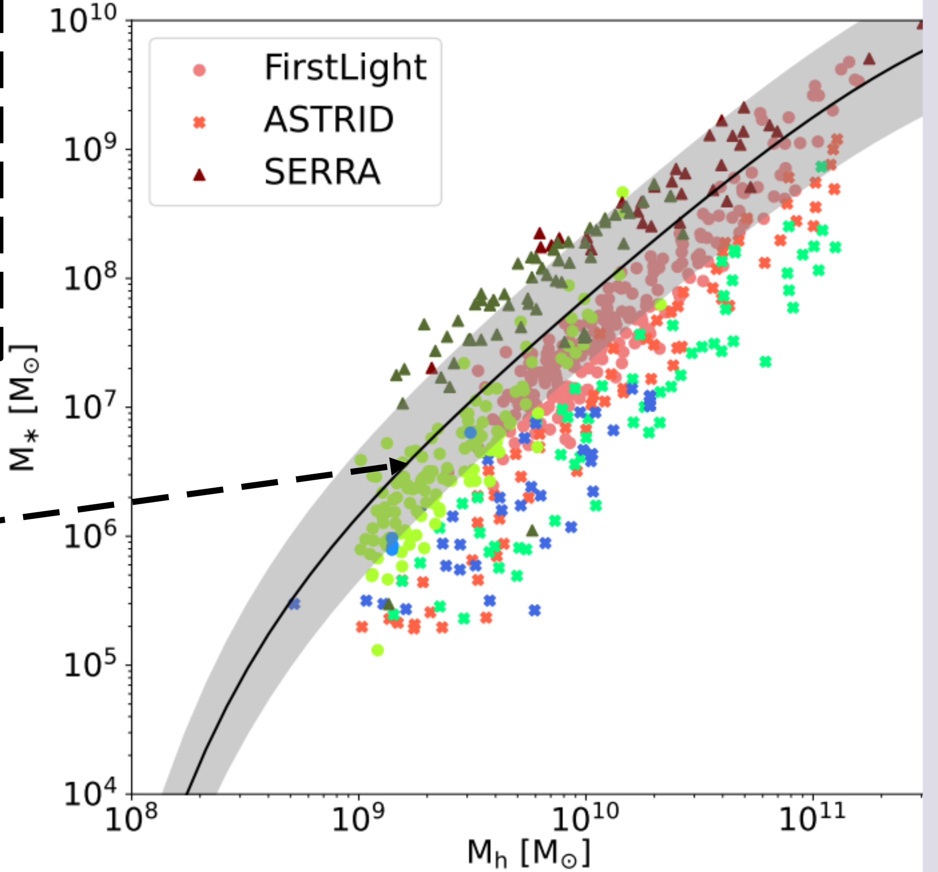
Analysis of surrounding HII morphology is approximate:

- **Galaxies are treated individually.**
- Many sources of stochasticity are ignored regarding galaxy properties

stochasticity at high redshifts

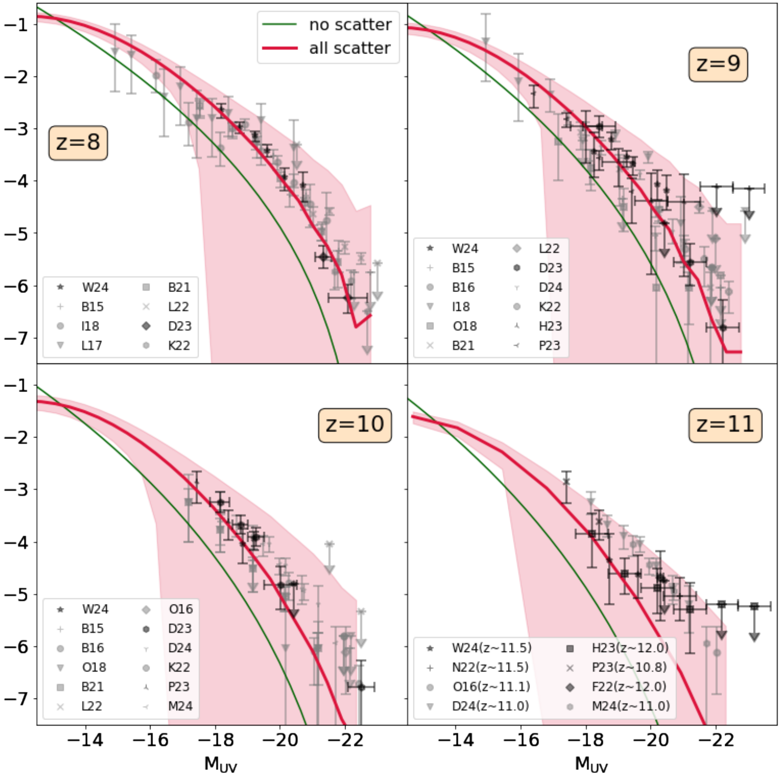
Scatter in the stellar-to-halo mass relation

We cannot ignore galaxy-to-galaxy scatter



IN+24, Ceverino+18, Lovell+21, Pallottini+22, Davies+23

Stochasticity is important



Galaxy-to-galaxy scatter is important in for global quantities during EoR (UV LF, EoR history …), **<u>but also locally on ionized bubble scales</u>**

Current estimates of stochasticity can predict JWST UV LF only up to z $\lesssim$ 12

IN+24, +in prep

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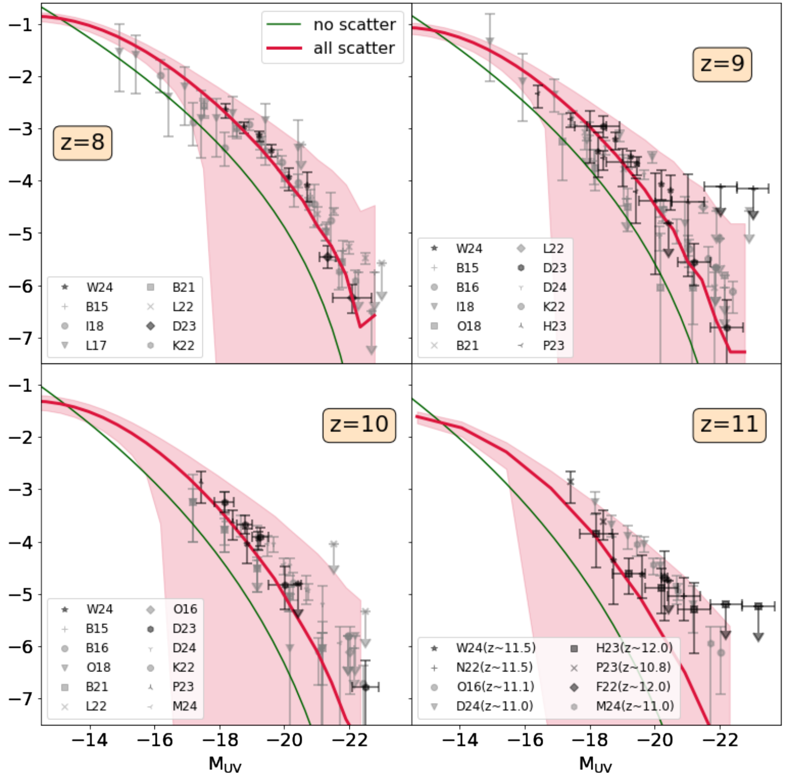

Current estimates of stochasticity can predict JWST UV LF only up to z ≲ 12

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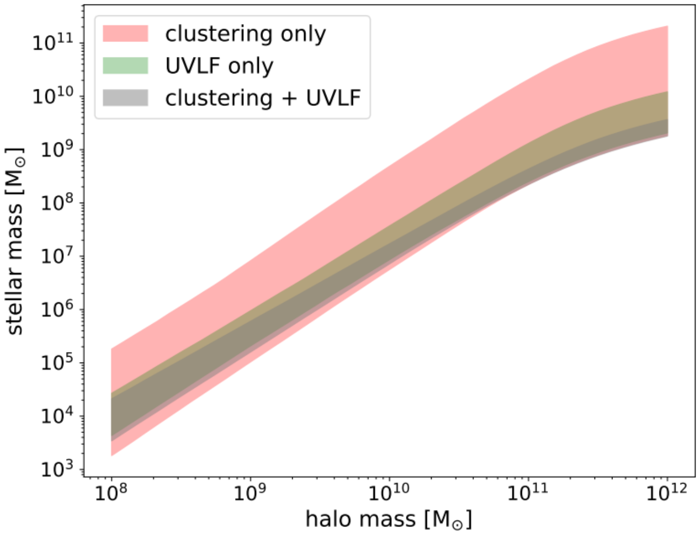
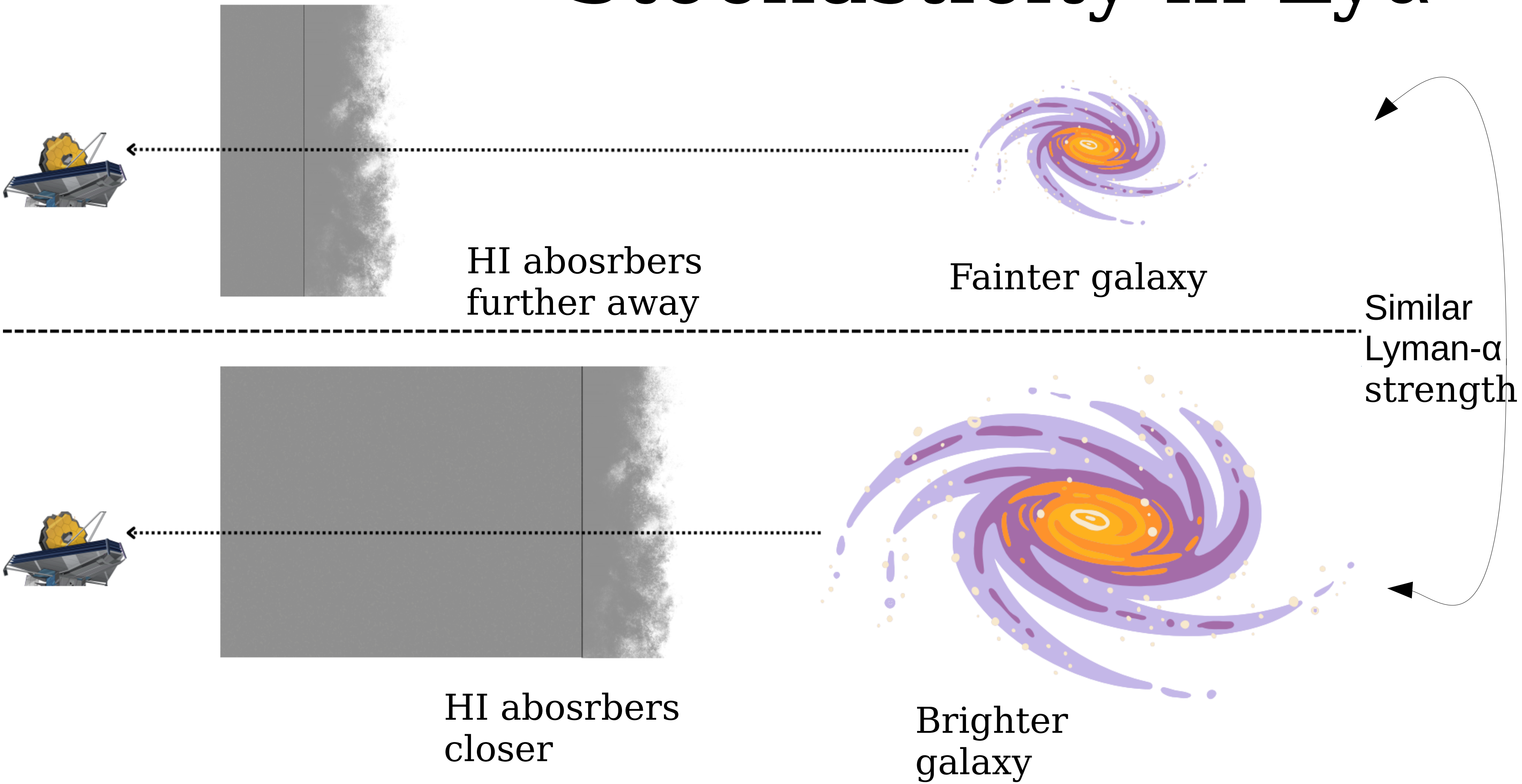
We can use UV LF and clustering to predict stochasticity

IN PREP

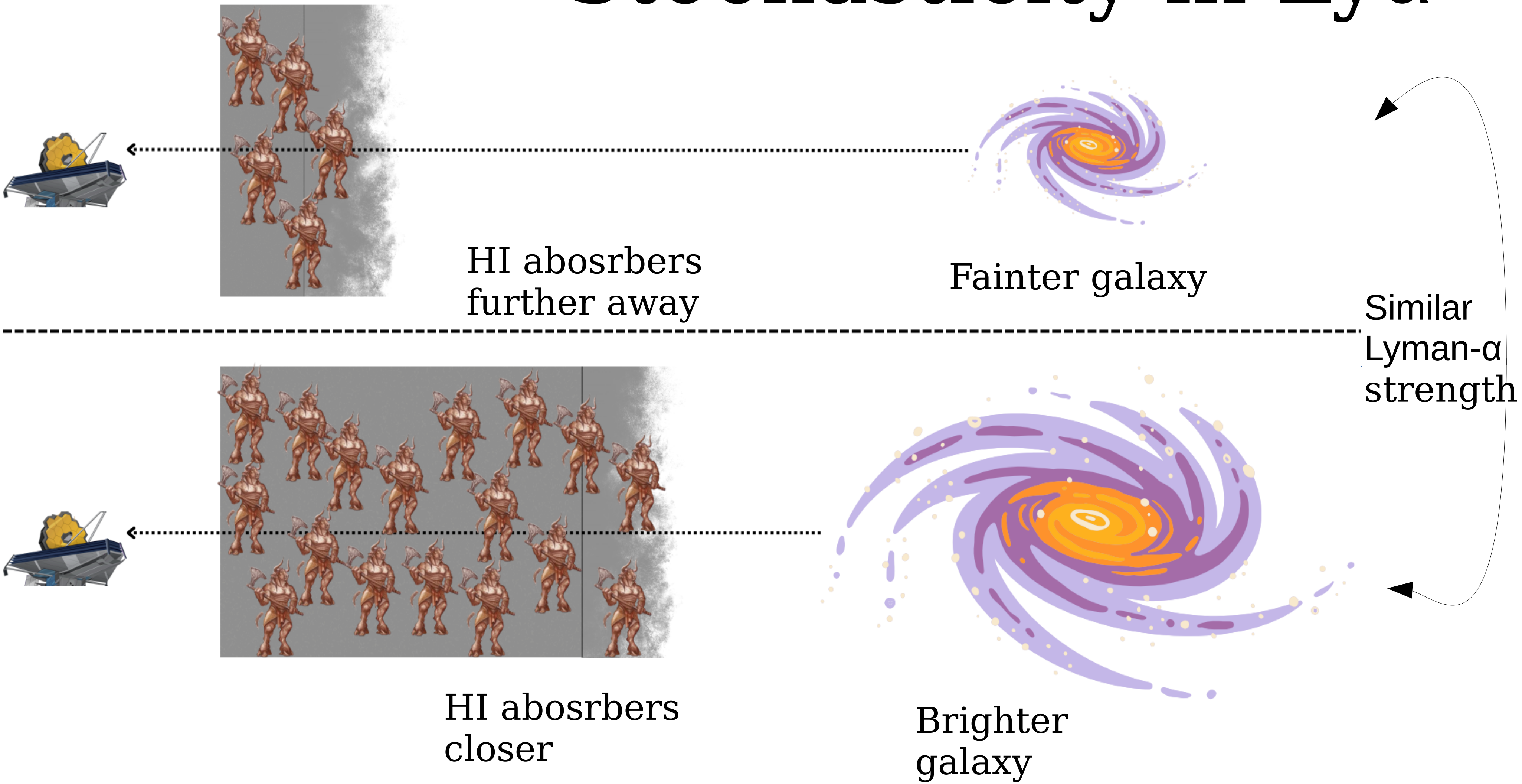


IN+24, +in prep

Stochasticity in Lyα



Stochasticity in Lyα



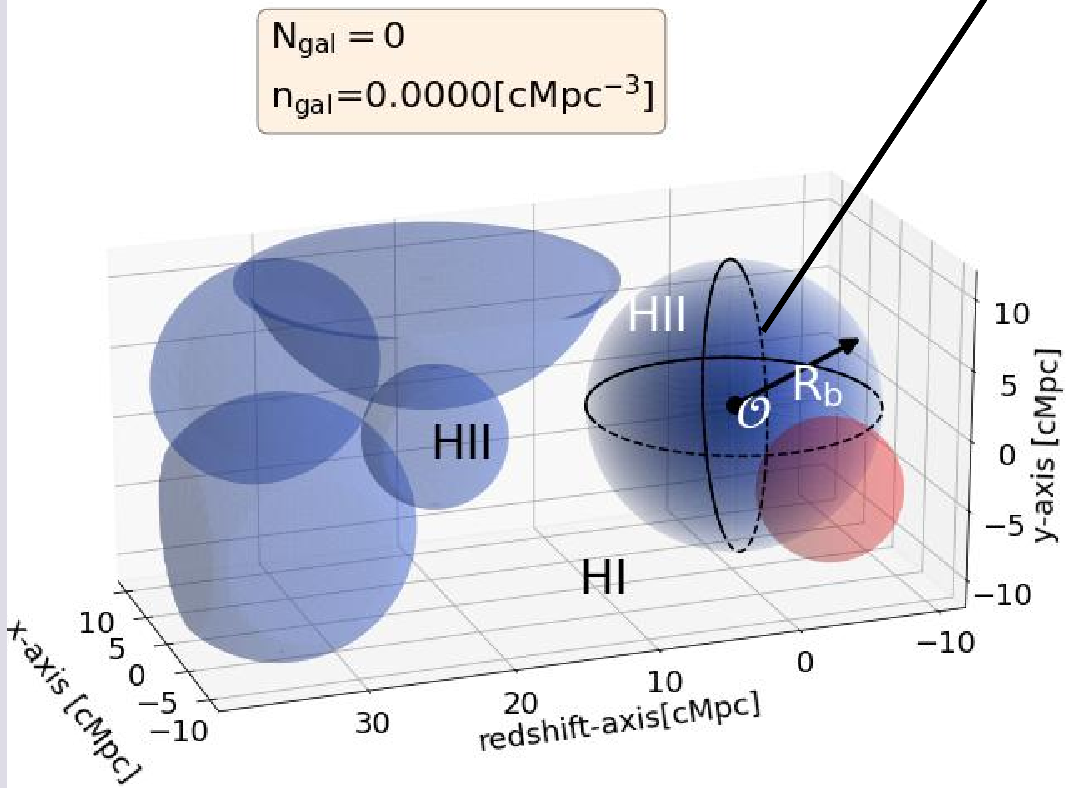
Inferring bubbles around galaxies

Forward-model sources of stochasticity:

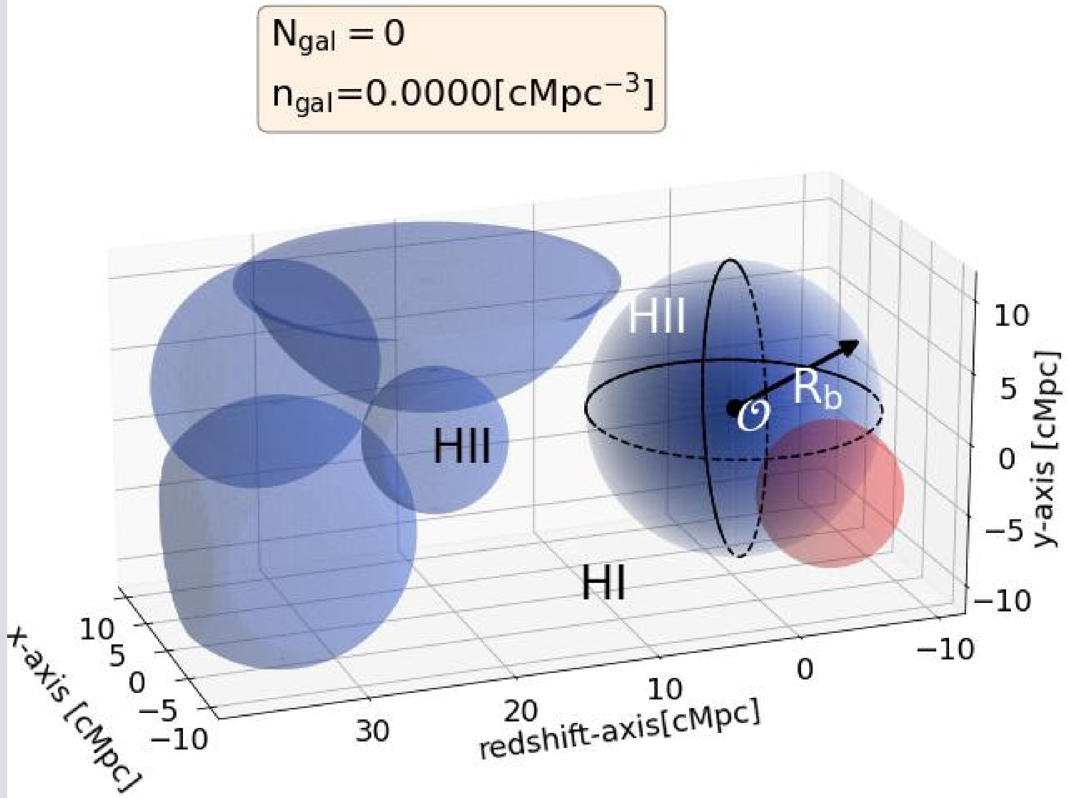
- global neutral fraction
- surrounding patchy EoR topology
- galaxy location
- Muv
- Lyα intrinsic flux (Δv, EW)
- NIRSpec noise

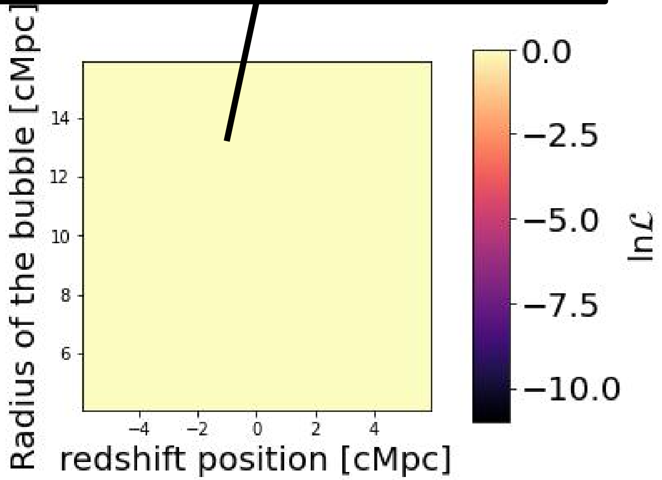
→ Self-consistent modeling for a number of galaxies

Inferrence of the position and radius of the bubble

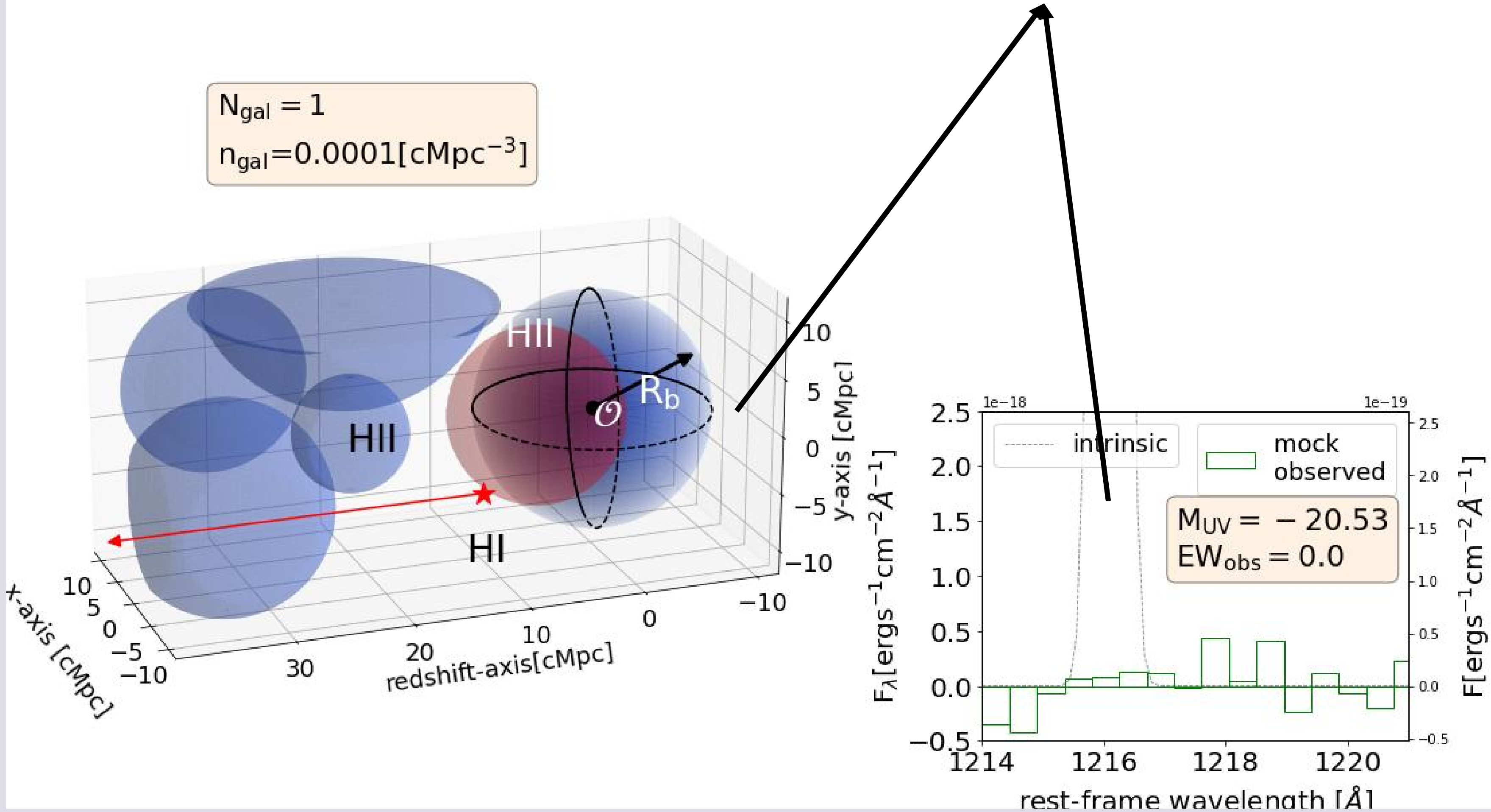


Situation with 0 galaxies observed

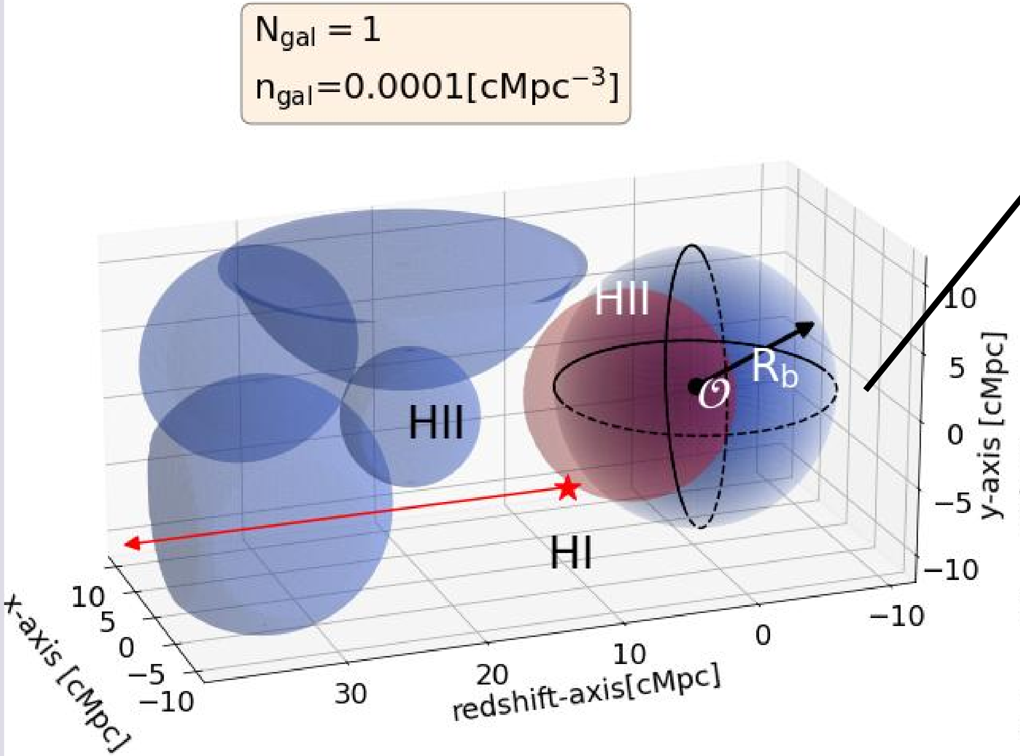


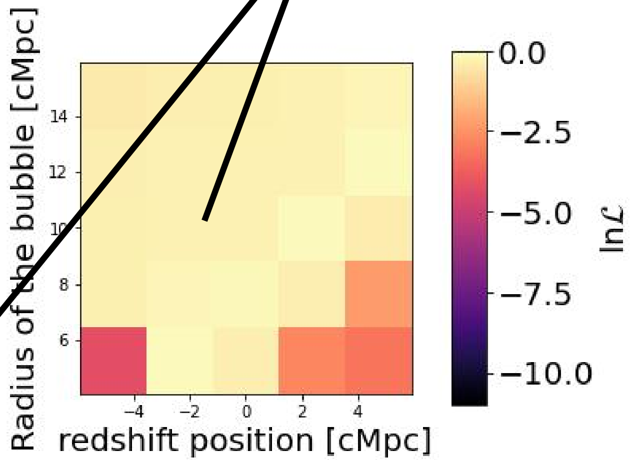


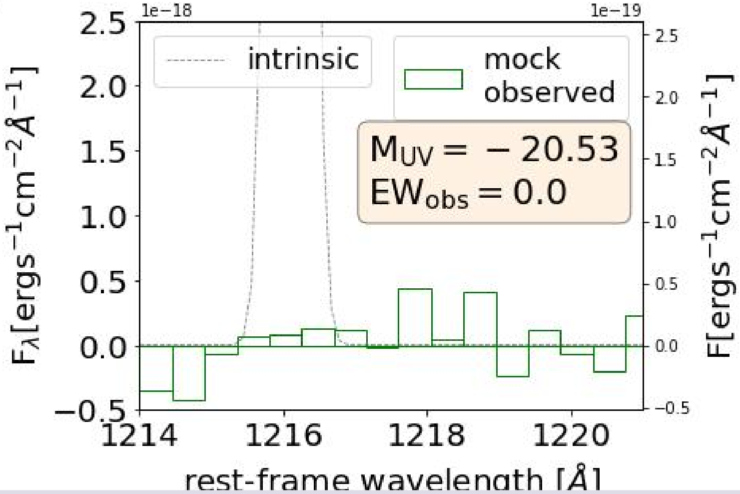
One galaxy observed (non-emitter!)

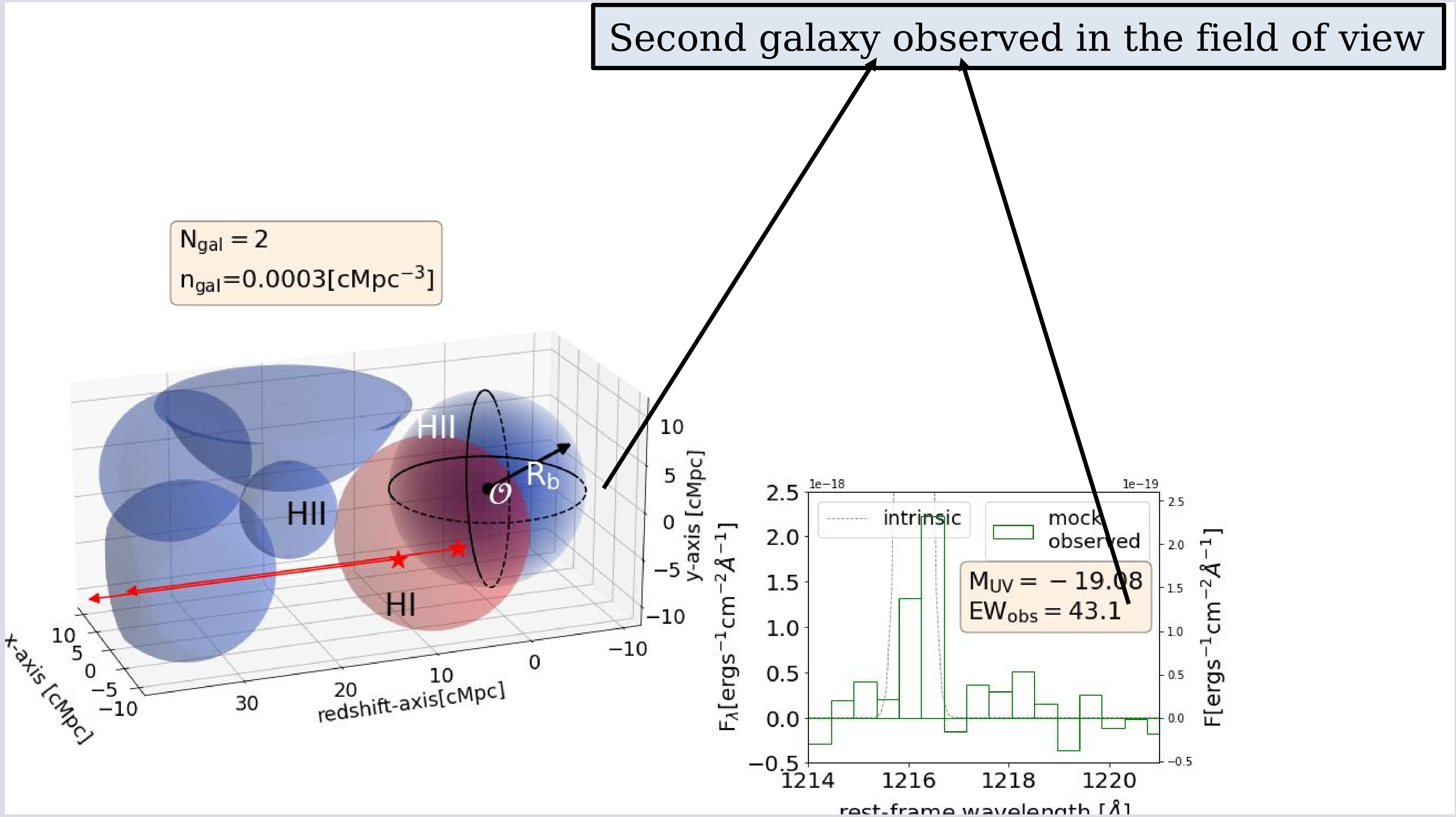


Very weak constraints



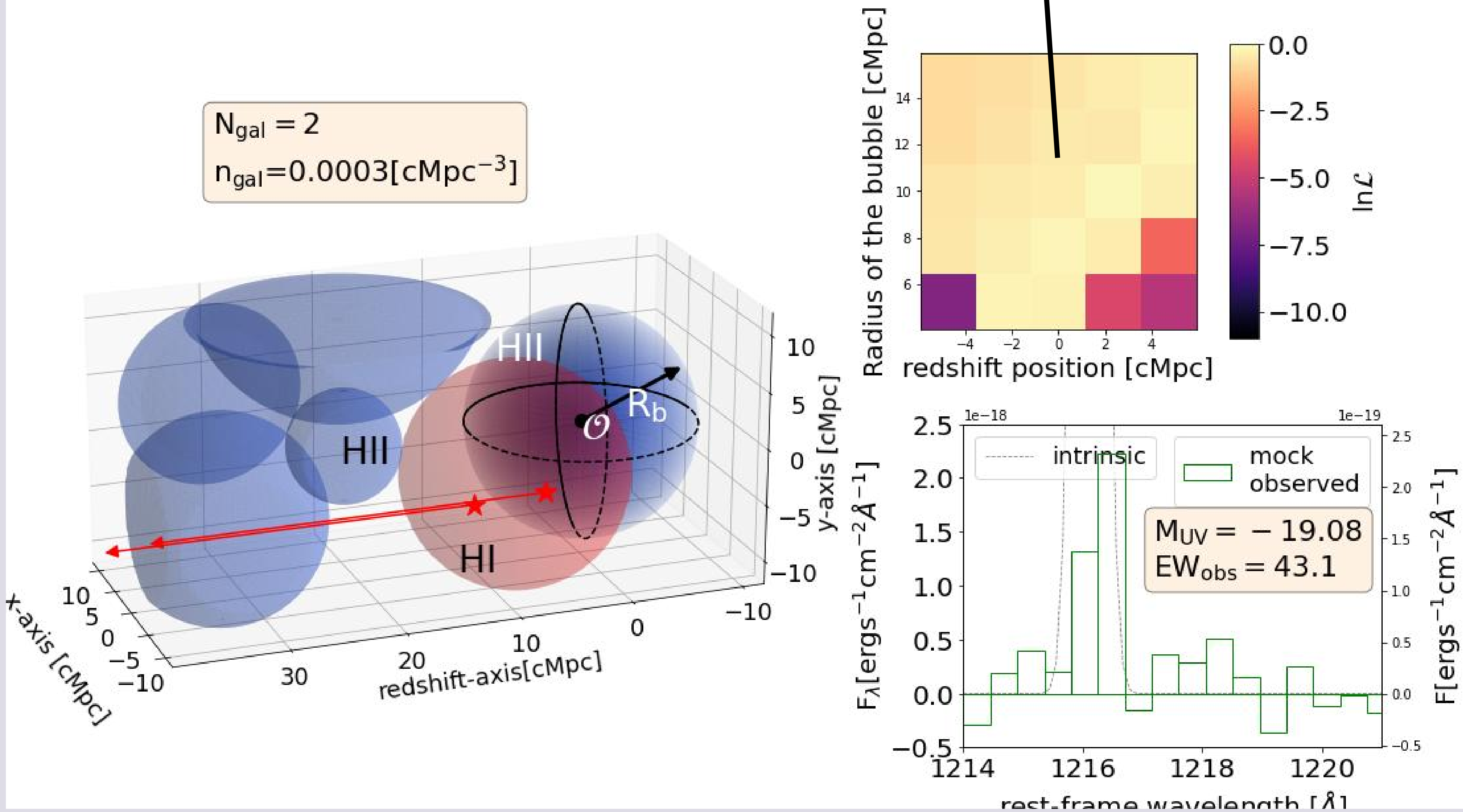






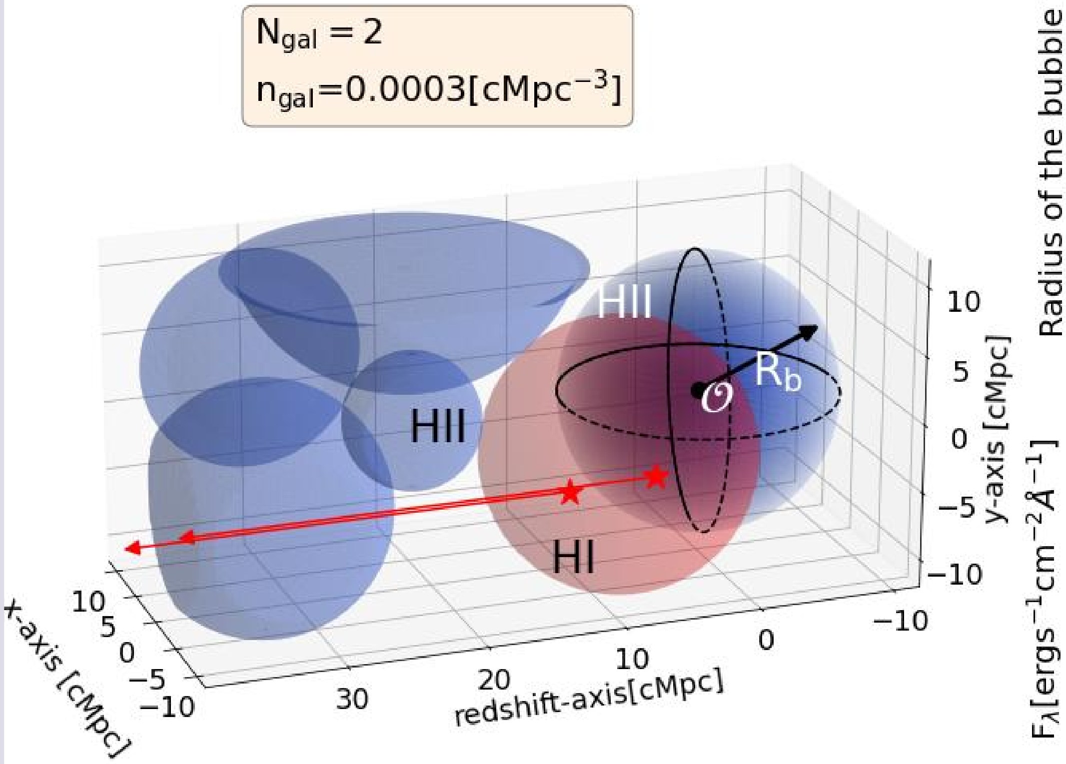
Second galaxy observed in the field of view
N_gal = 2
n_gal=0.0003[cMpc^-3]
HII
HII
HI
R_b
x-axis [cMpc]
redshift-axis[cMpc]
y-axis [cMpc]
intrinsic
mock observed
M_UV = − 19.08
EW_obs = 43.1
F_λ[ergs^-1cm^-2Å^-1]
F[ergs^-1cm^-2Å^-1]
1e−18
1e−19
rest-frame wavelength [Å]

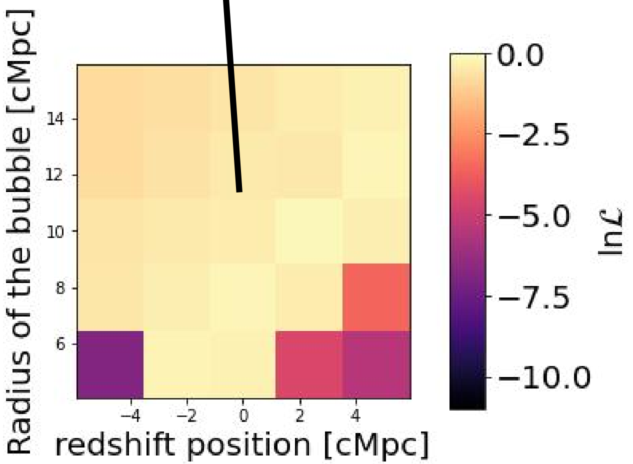
Additional constraints come by adding the second galaxy

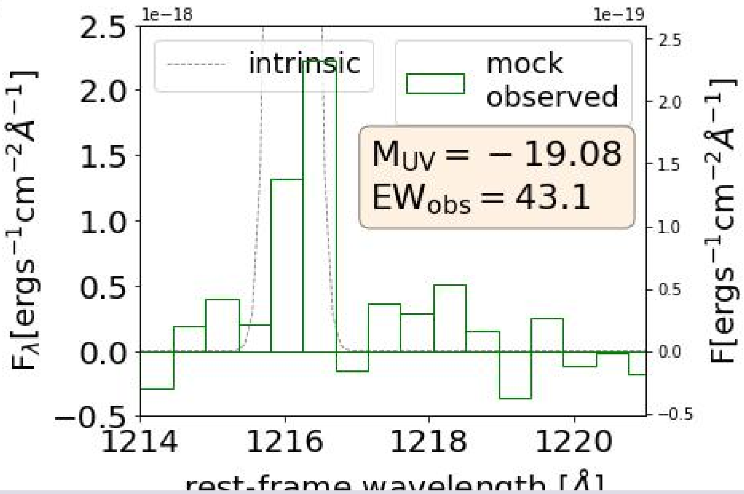


But two galaxies are not enough

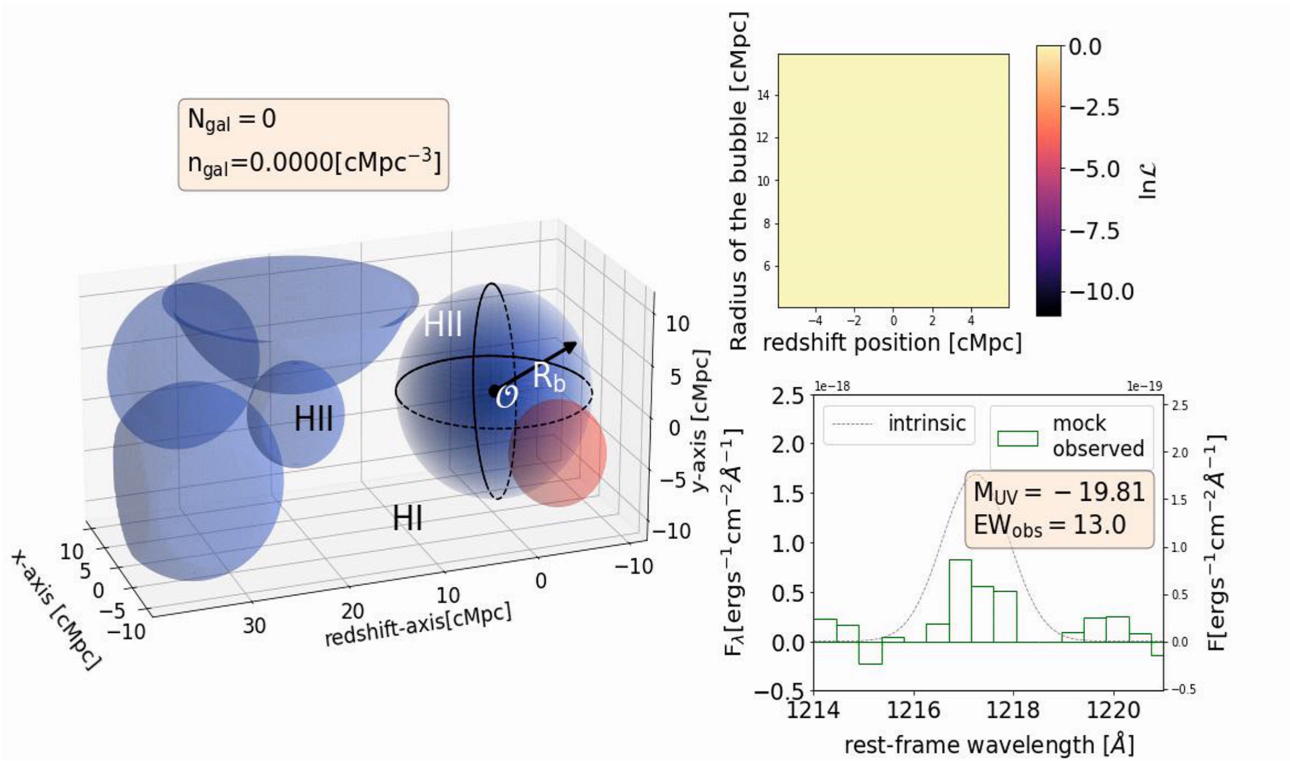
Additional constraints come by adding the second galaxy





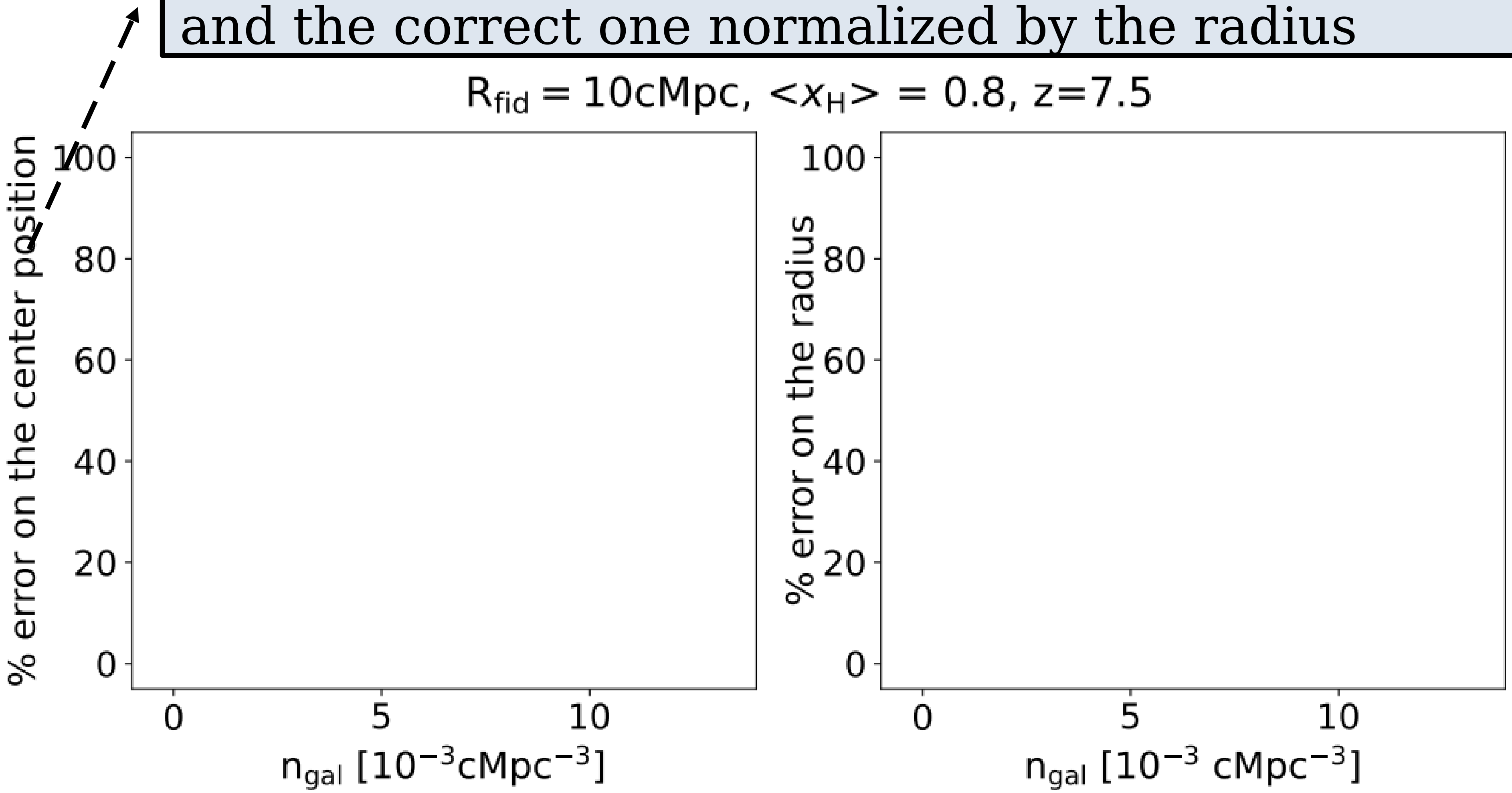


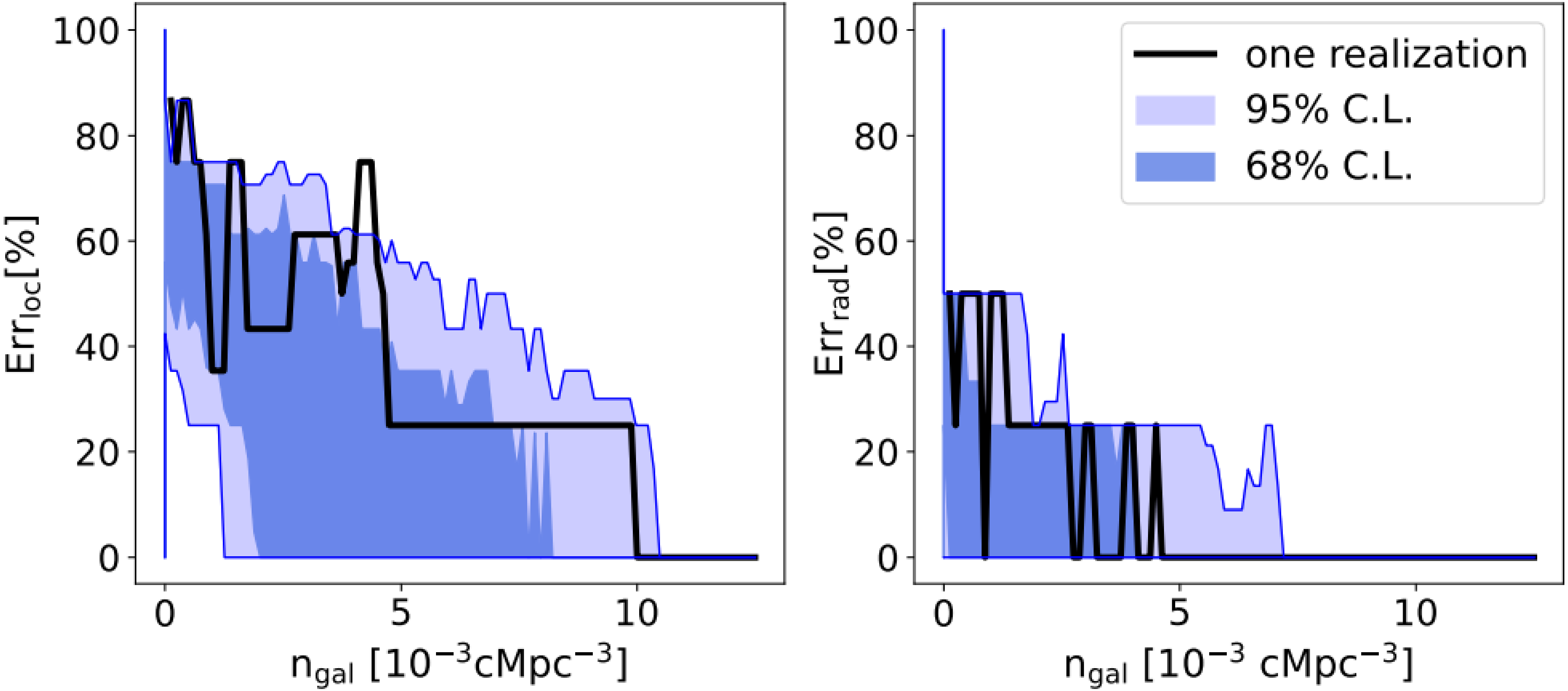
More galaxies -> better inference



How many galaxies we need to infer the bubble?

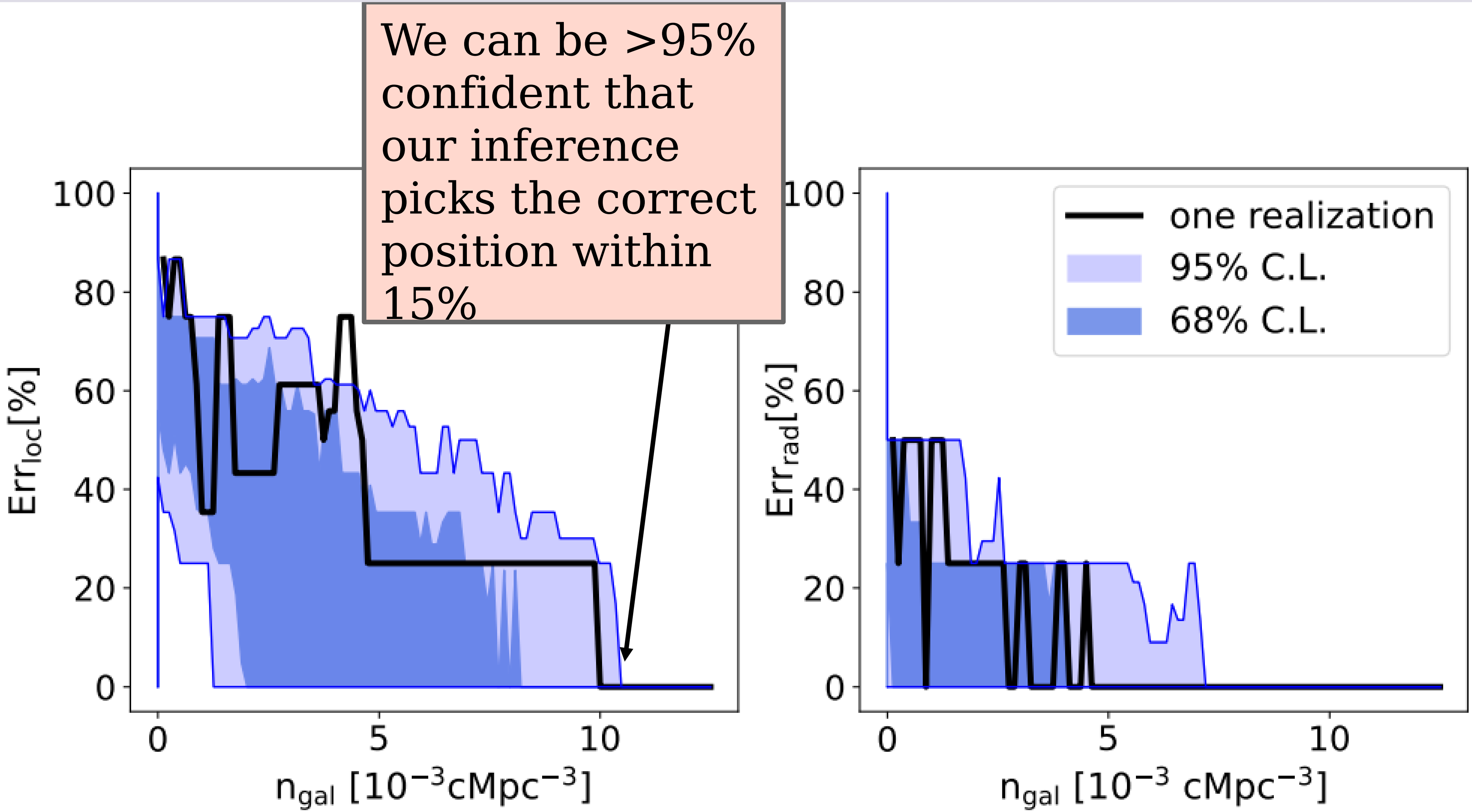
Distance between the inferred position of the bubble and the correct one normalized by the radius



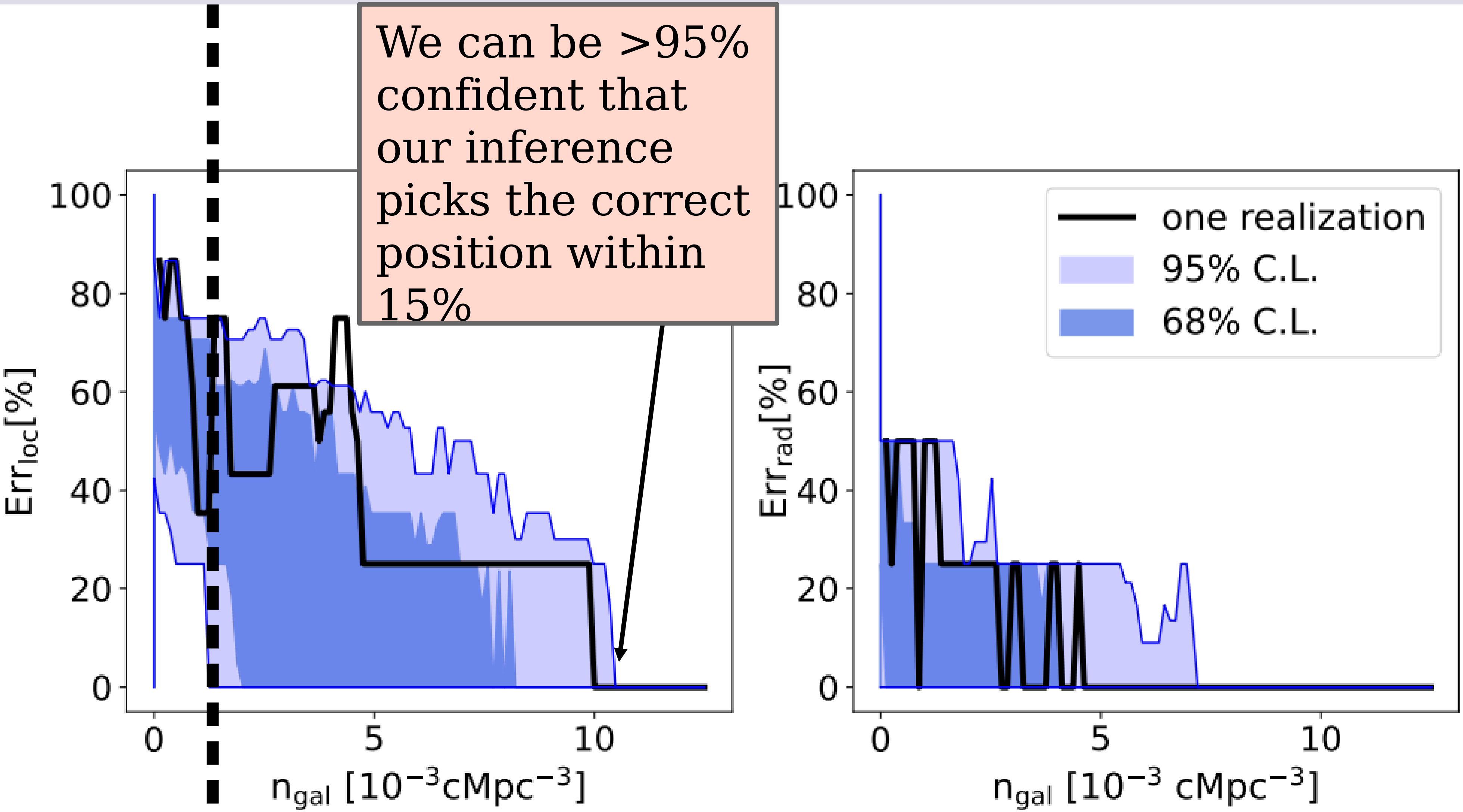


$Err_{loc}[\%]$
n_{gal} $[10^{-3}cMpc^{-3}]$
$Err_{rad}[\%]$
n_{gal} $[10^{-3}$ $cMpc^{-3}]$
one realization
95% C.L.
68% C.L.

IN+25


We can be >95% confident that our inference picks the correct position within 15%
one realization
95% C.L.
68% C.L.
$Err_{loc}[\%]$
$Err_{rad}[\%]$
n_{gal} [10^{-3}cMpc^{-3}]
n_{gal} [10^{-3} cMpc^{-3}]
0
20
40
60
80
100
0
5
10

IN+25

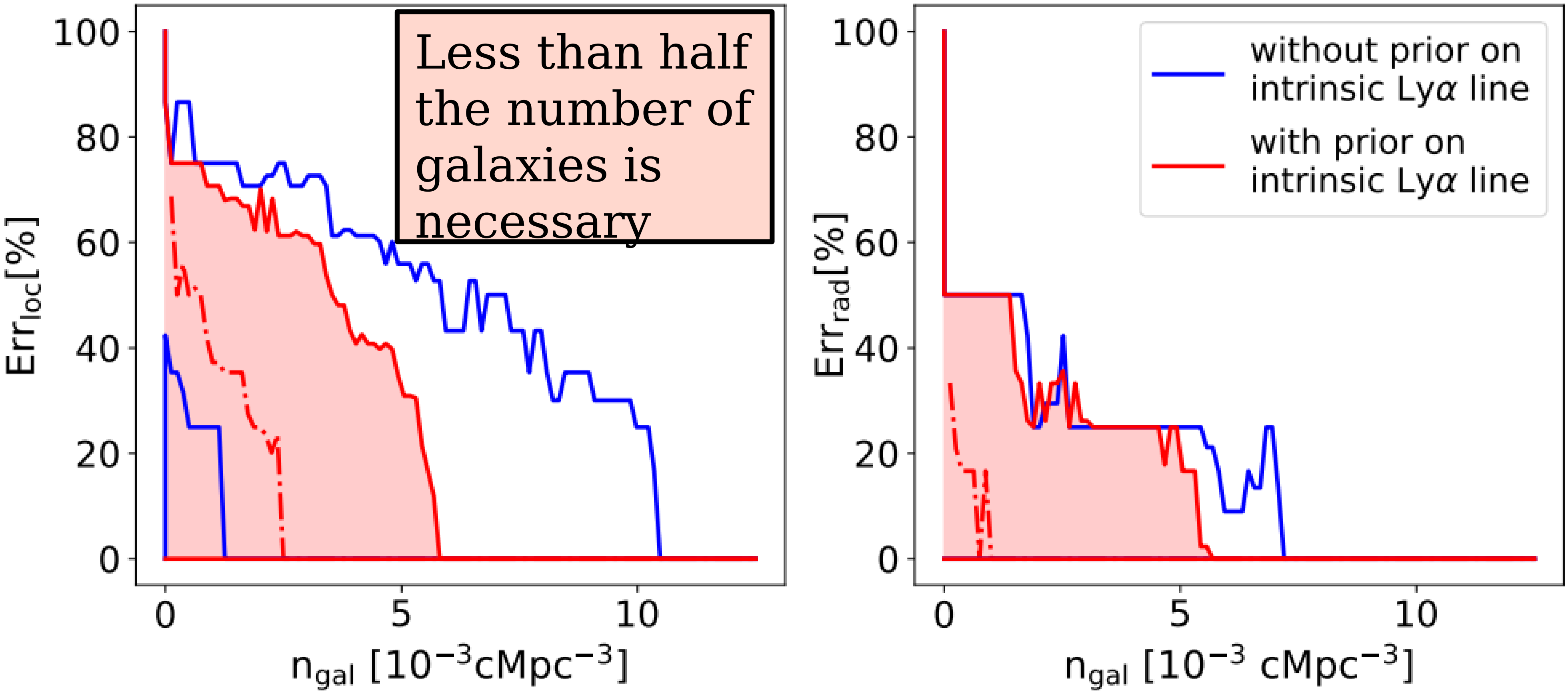


FRESCO observations of GOODS

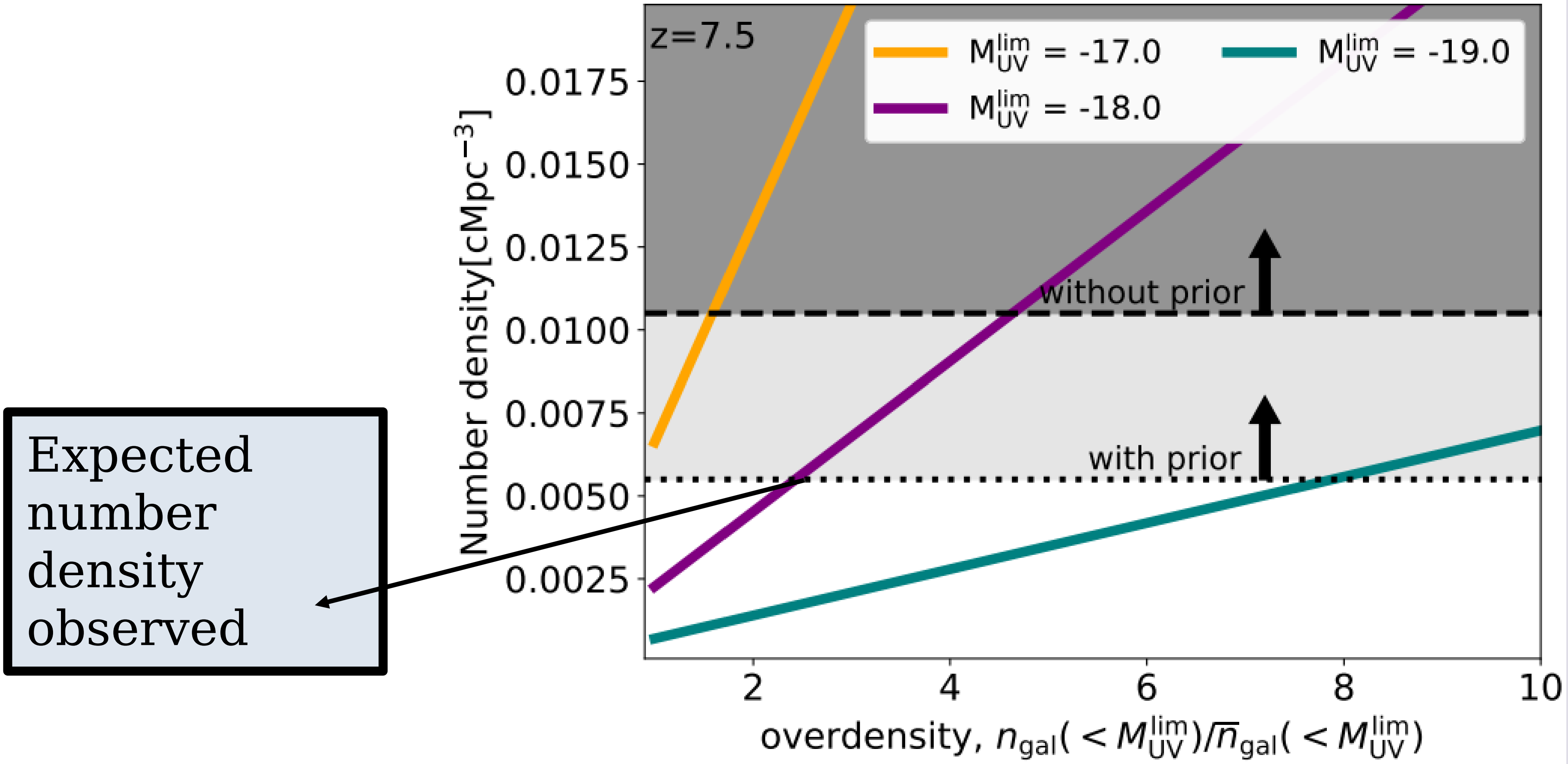
IN+25

That's not all -> we can put a prior on the intrinsic Lyman-alpha emission from other lines, like Hβ

R_b^{true} = 10cMpc, $<x_H>$ = 0.65, z=7.5



IN+25

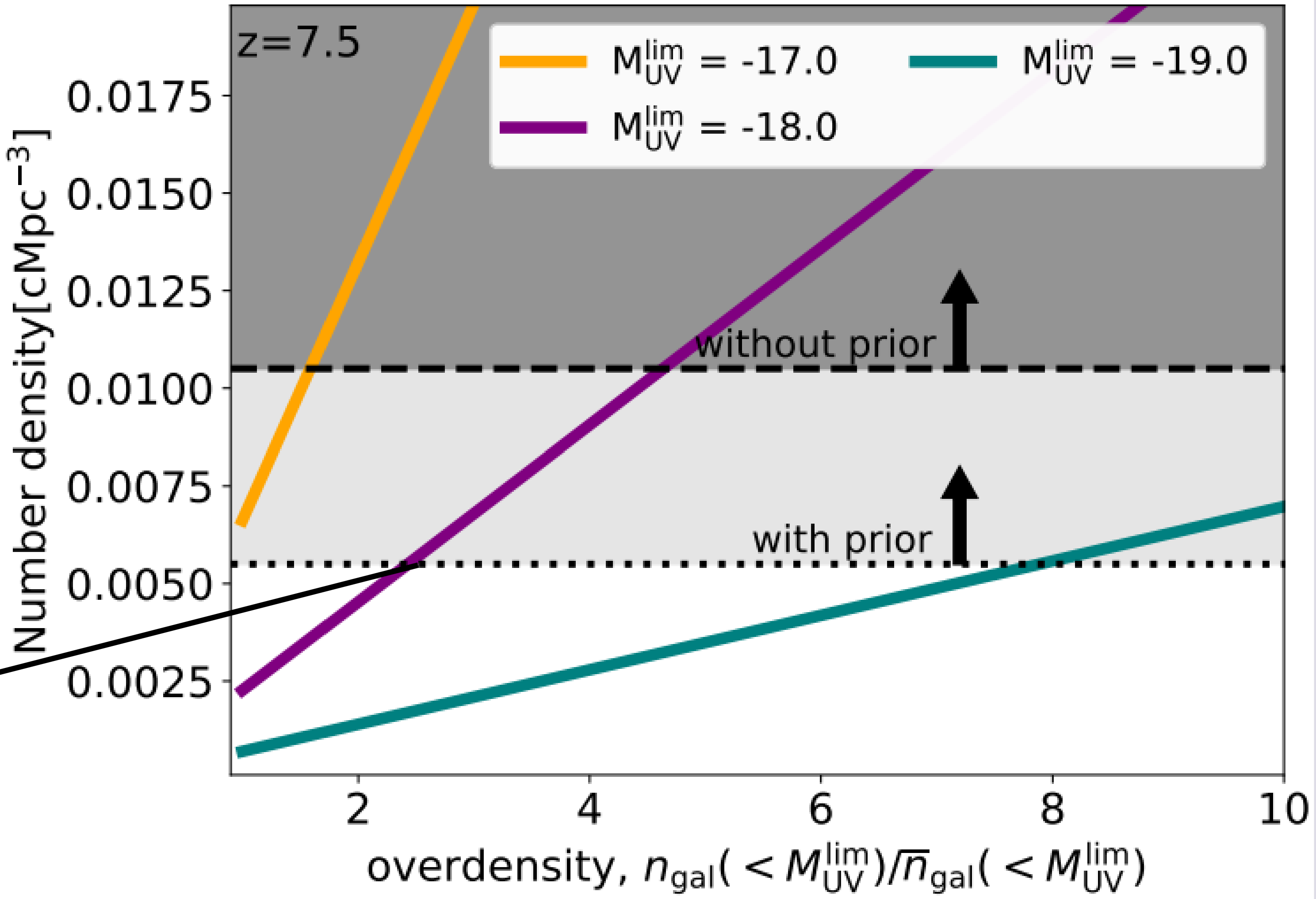


Expected number density observed
z=7.5
M_{UV}^{lim} = -17.0
M_{UV}^{lim} = -18.0
M_{UV}^{lim} = -19.0
without prior
with prior
0.0175
0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
Number density[cMpc^{-3}]
2
4
6
8
10
overdensity, $n_{gal}(<M_{UV}^{lim})/\overline{n}_{gal}(<M_{UV}^{lim})$

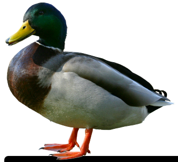
IN+25

A dedicated JWST NIRSpec survey can reach those numbers!

Expected number density observed



IN+25



Conclusions

- stochasticity is important for modeling of both large-scales EoR observables, and galaxy observations
- synergy of observations from many galaxies is necessary to correctly infer EoR properties

- With JWST we can statistically detect ionized bubbles in the first half of EoR and constrain stochasticity in galaxies

Bubble detection paper:

ArXiv: 2406.15237

Contact:
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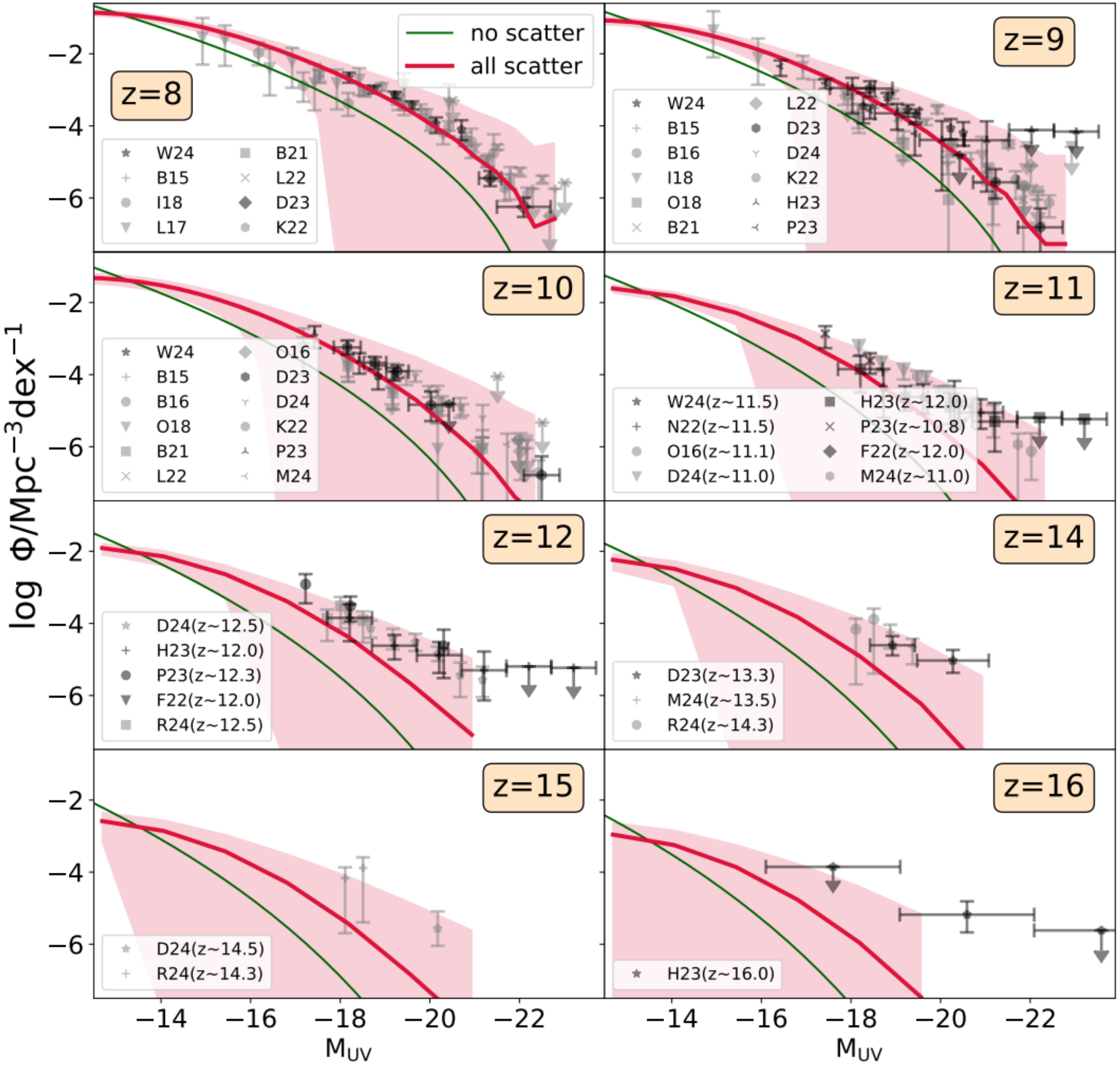
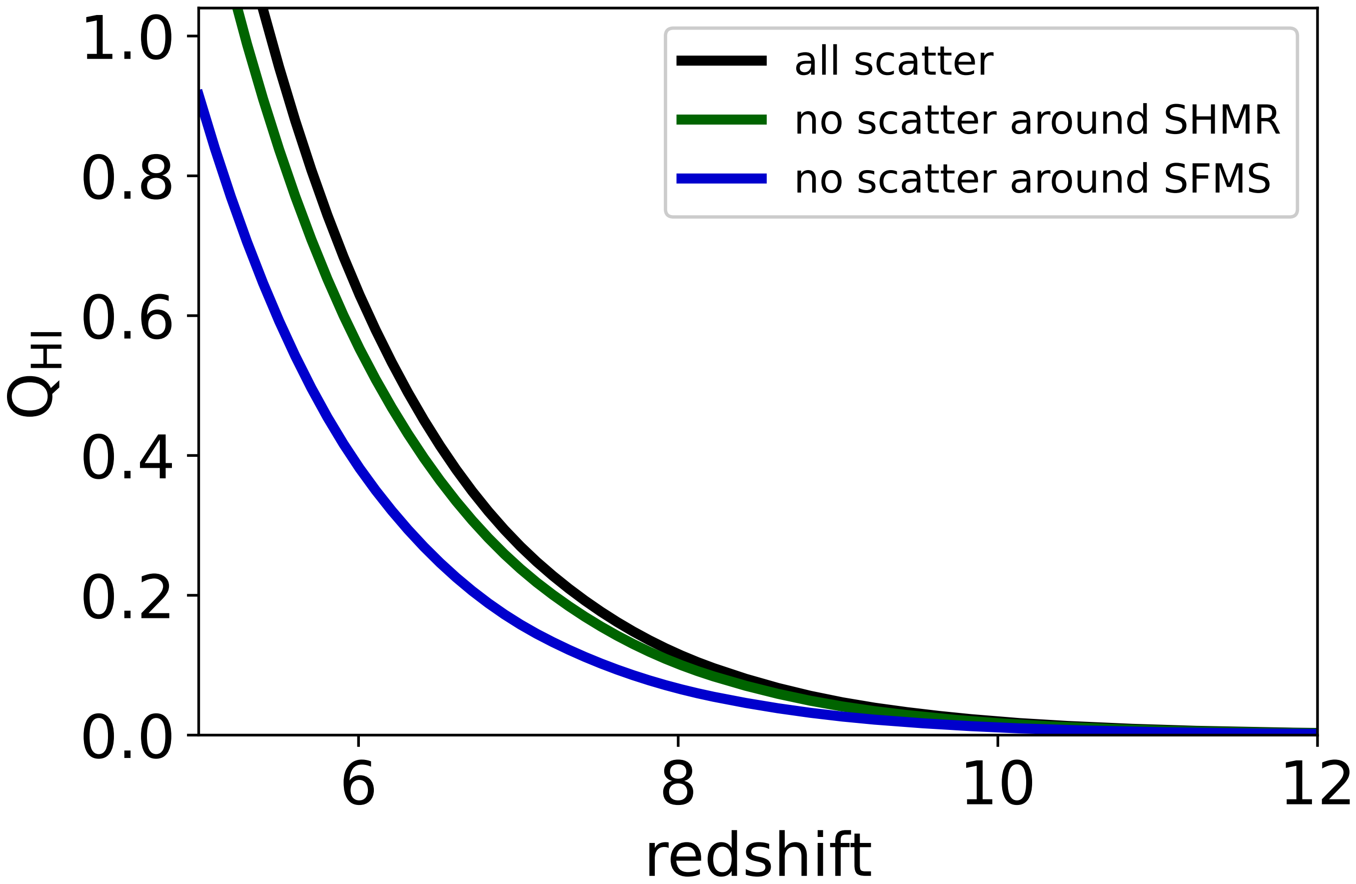
EXTRA SLIDES

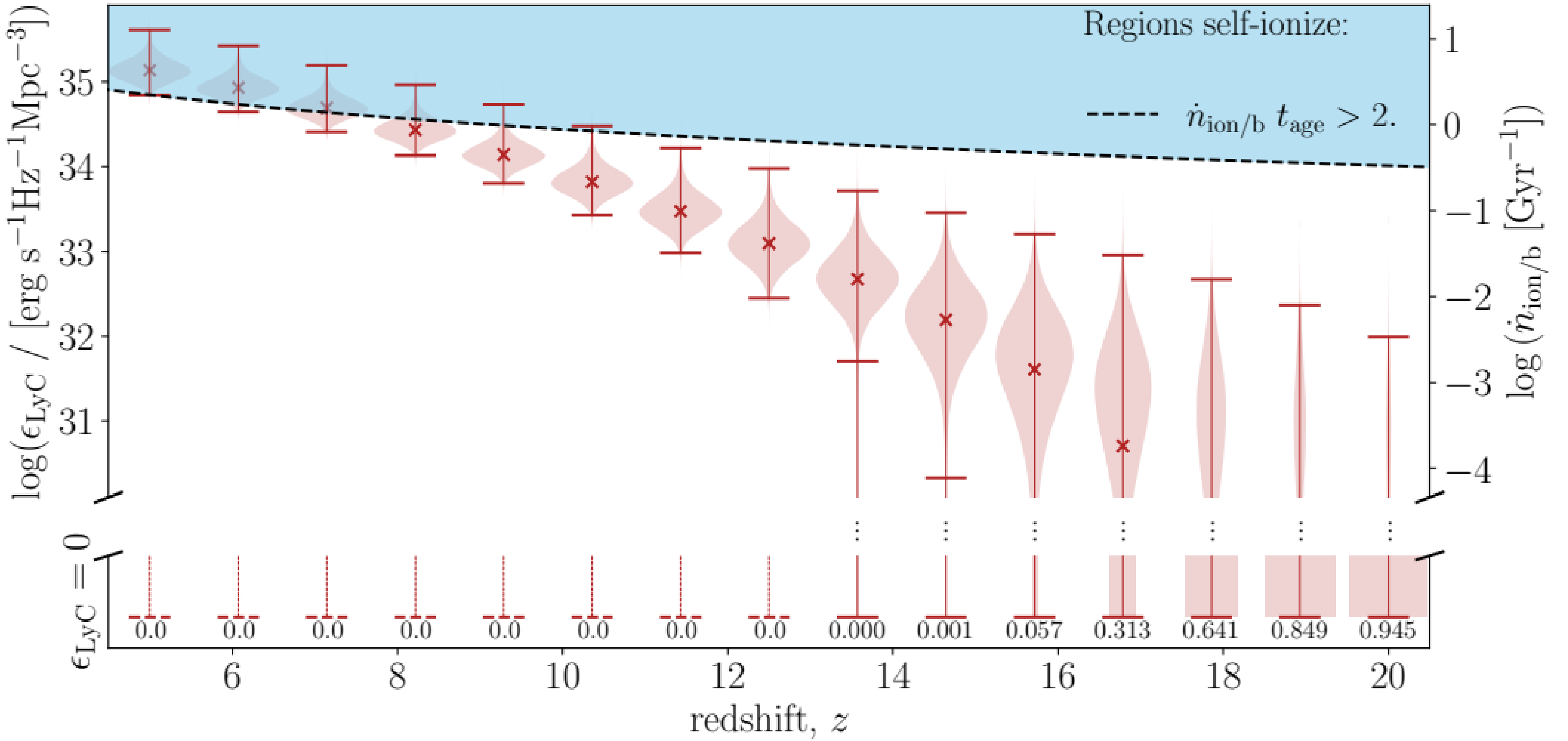


Full UVLF predictions

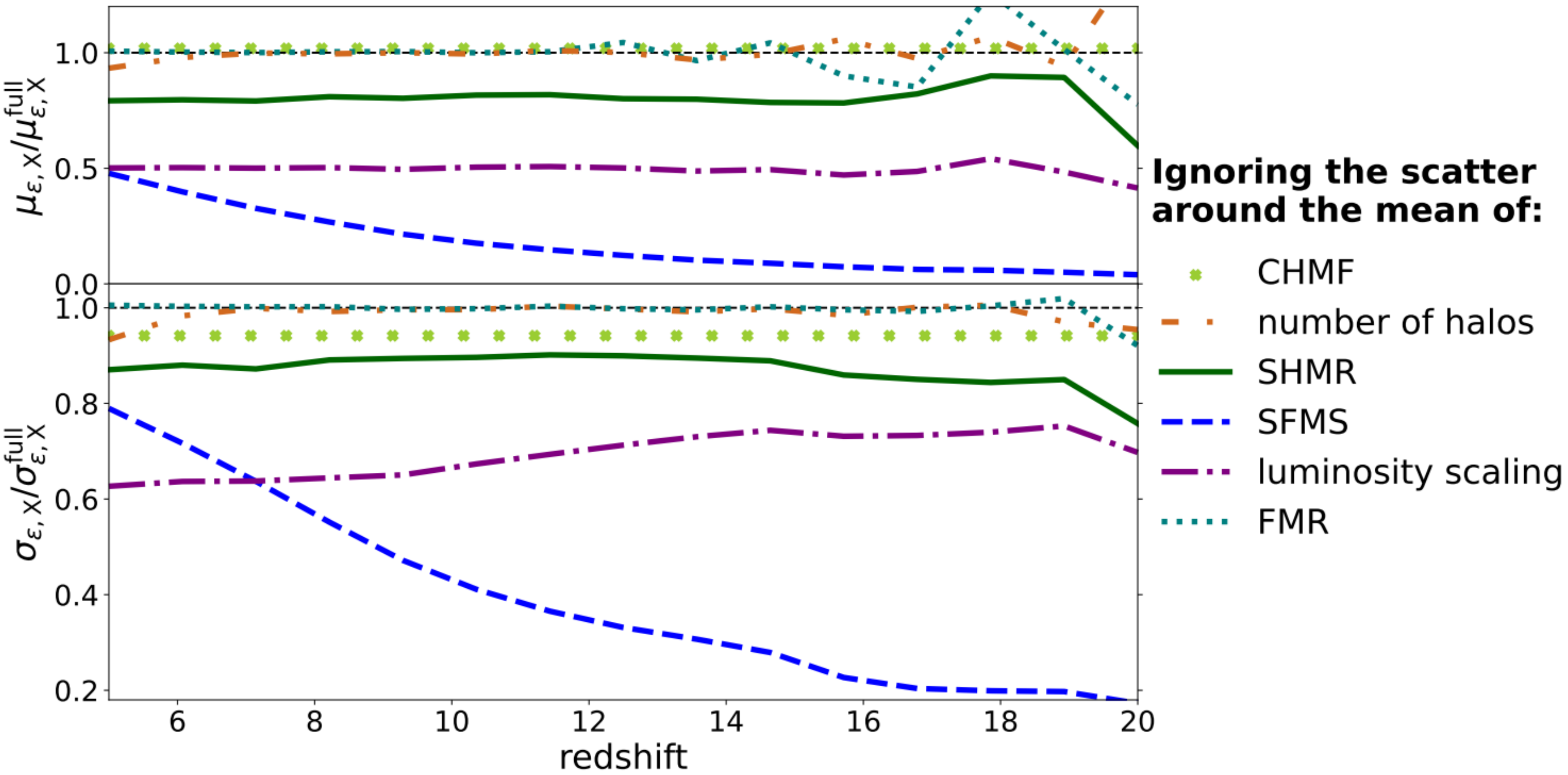
EoR history prediction



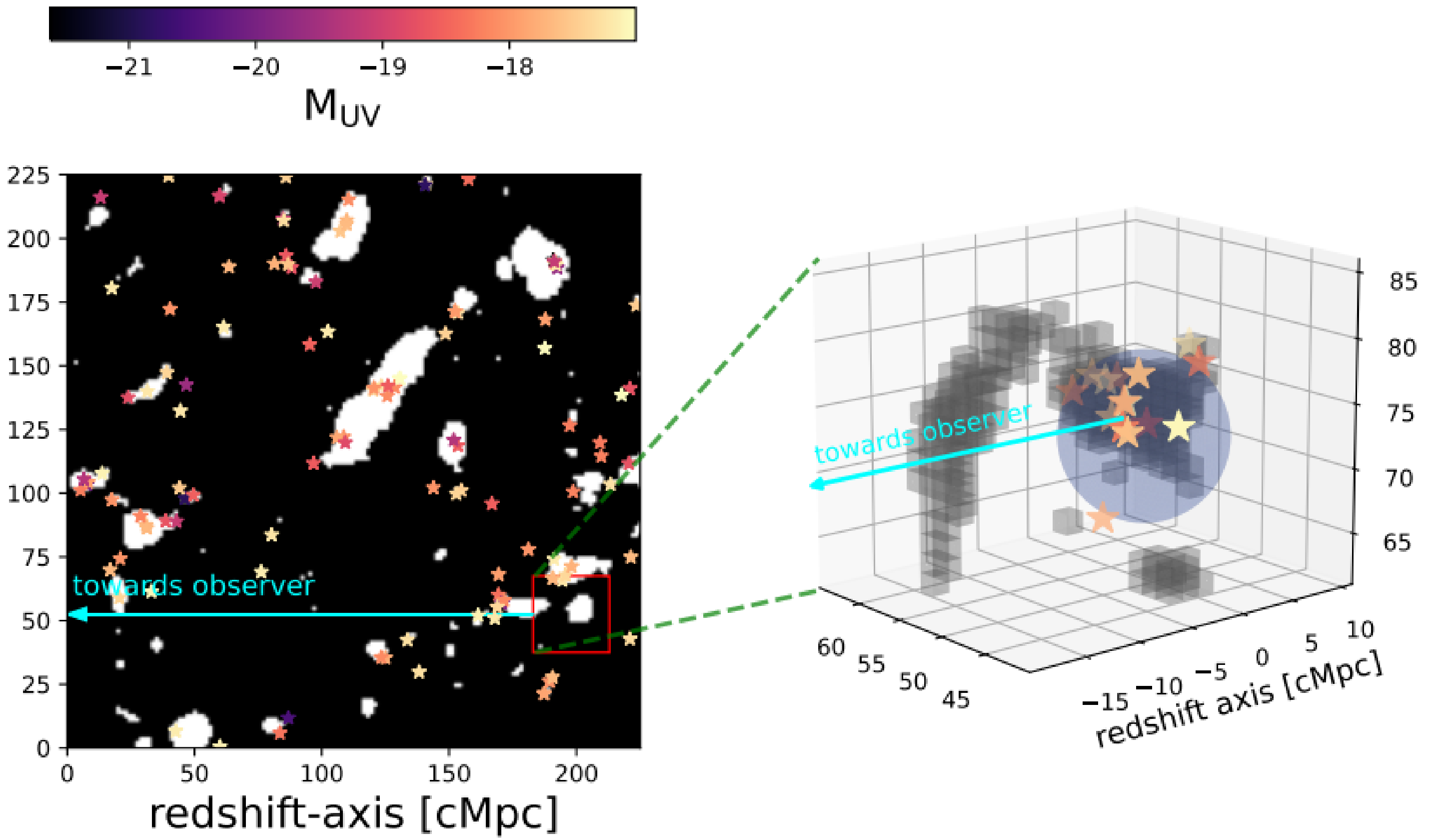
Ionizing emissivity stochastic prediction



X-ray emissivity stochasticity analysis



21cmFAST application



21cmFAST application