Institute for Basic Science

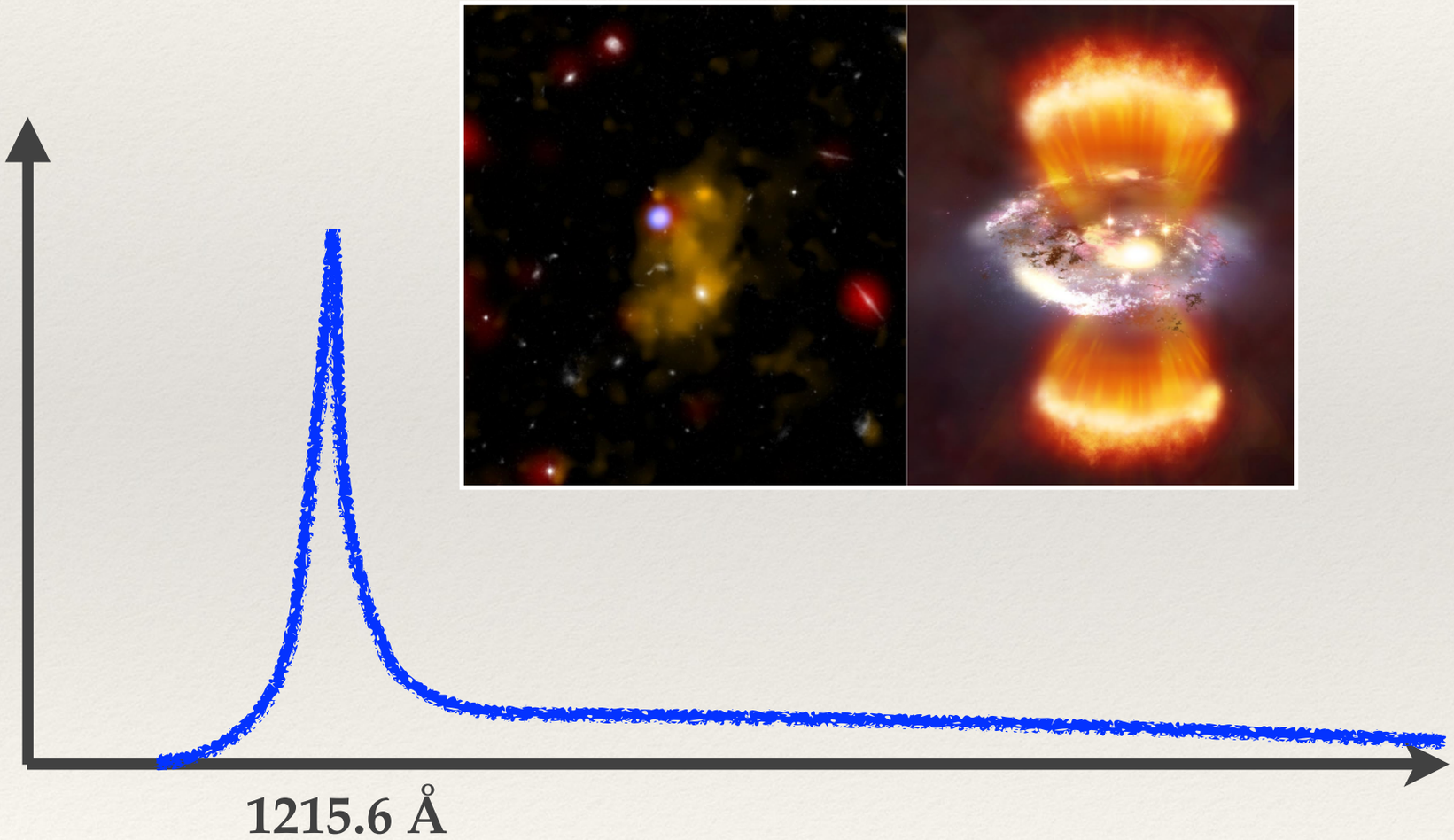
Double-peaked Lyα Emitters during Reionization

Hyunbae Park (IBS)
Aaron Smith (UT Dallas);
Intae Jung (CBNU);
Yajima Hidenobu (U of Tsukuba);
CoDa simulation team

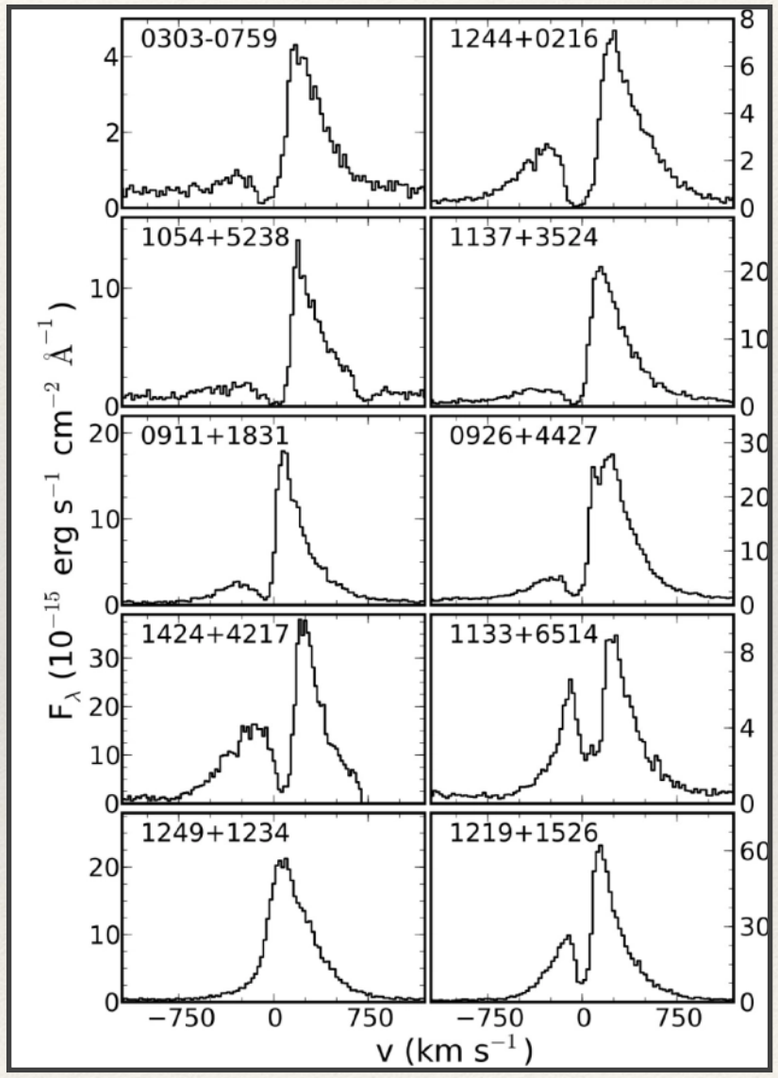
Park+ 2026: Double-Peaked Lyα Emission during Reionization Requires Nearby Voids and a Favorable Local Ionizing Background (to be submitted tonight)

Lyman Alpha Emitters (LAE)

Galaxies with strong Lyα emission



Low-z Lyα profiles

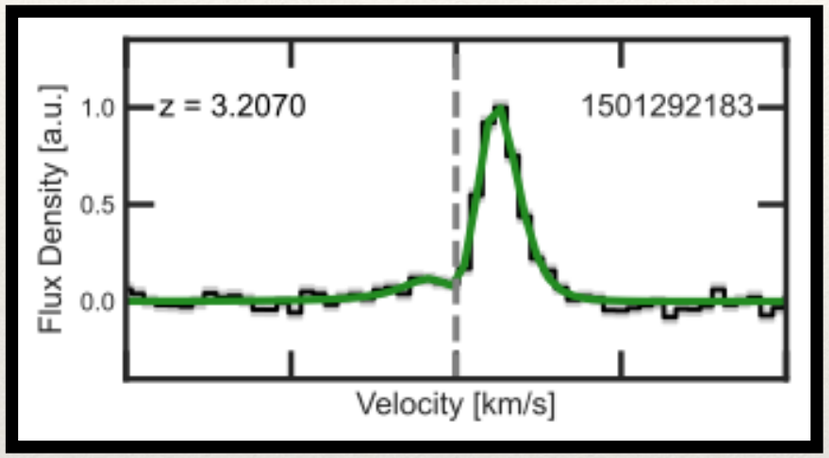


(Henry+ 2018)

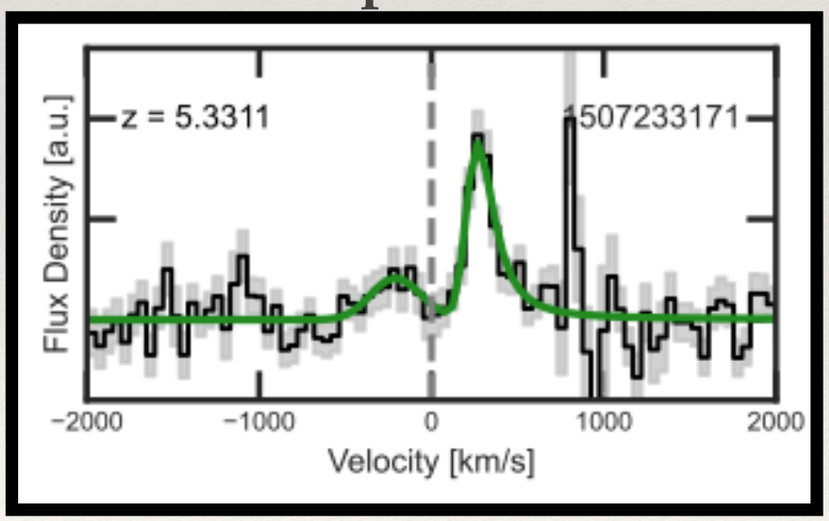
Two third of photons below 912 Å converted to Lyα photons.

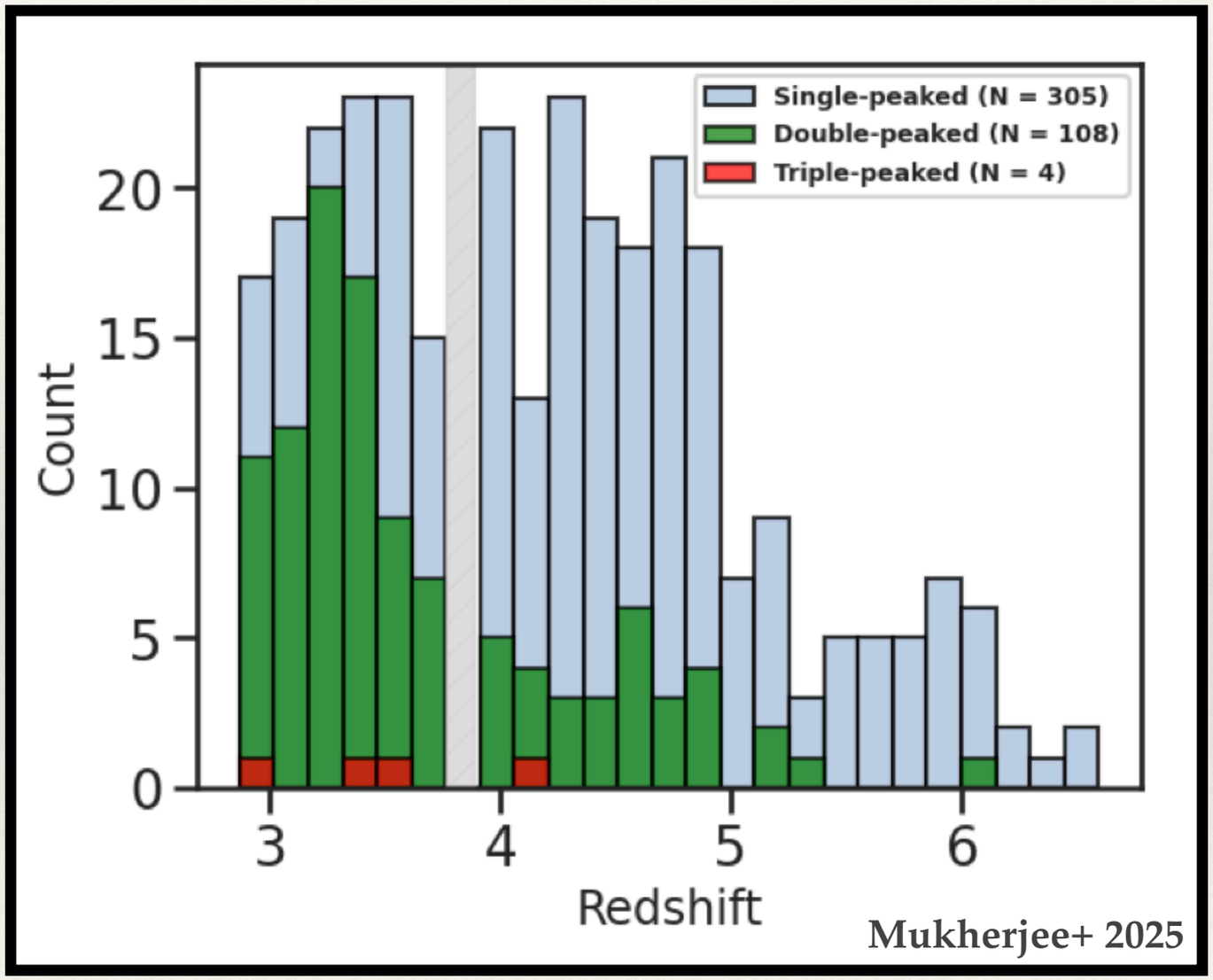
Double-Peaked LAEs at High z's

Single-peaked LAE



Double-peaked LAE

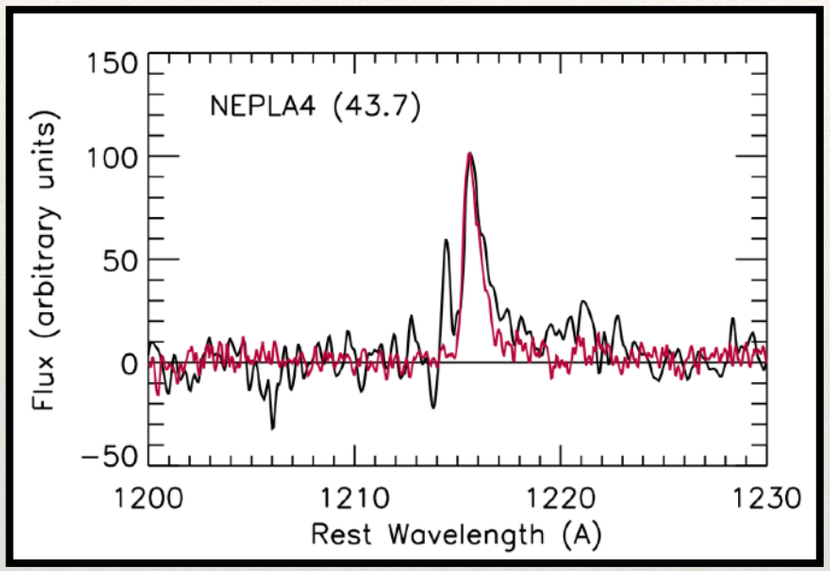




Diminishing number of double-peaked LAEs beyond $z \sim 5$.

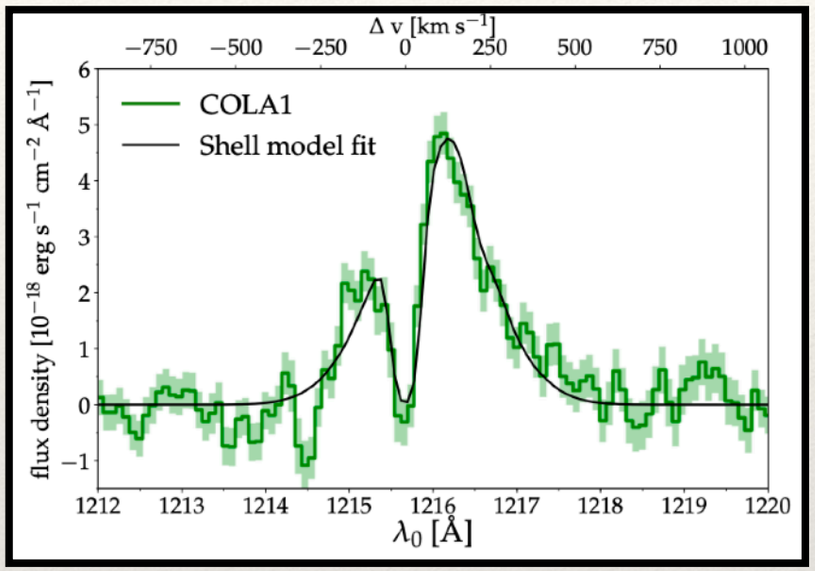
Doubled-Peaked LAEs at $z > 6$

$z = 6.6$



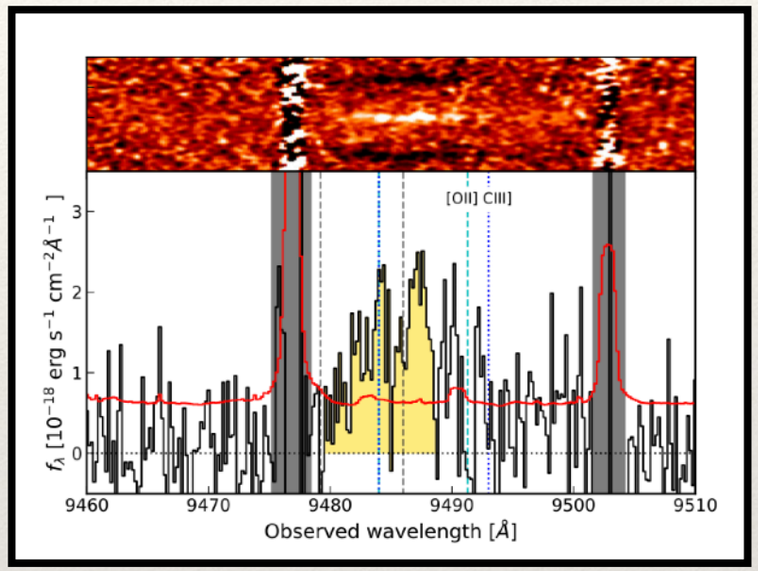
(Songaila+ 2018)

$z = 6.6$

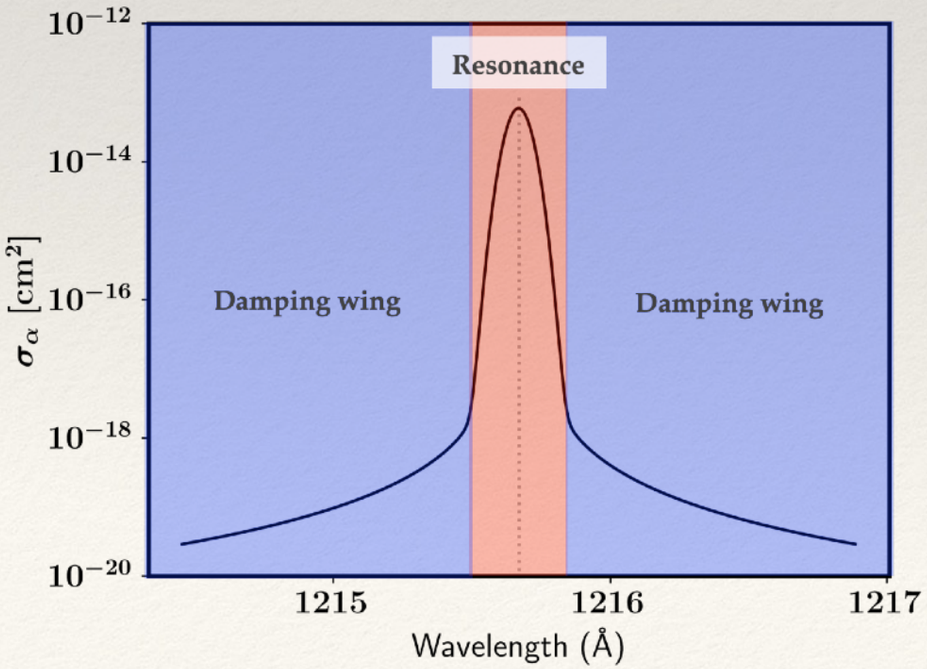


(Matthee+ 2018)

$z = 6.8$



(Meyers+ 2021)



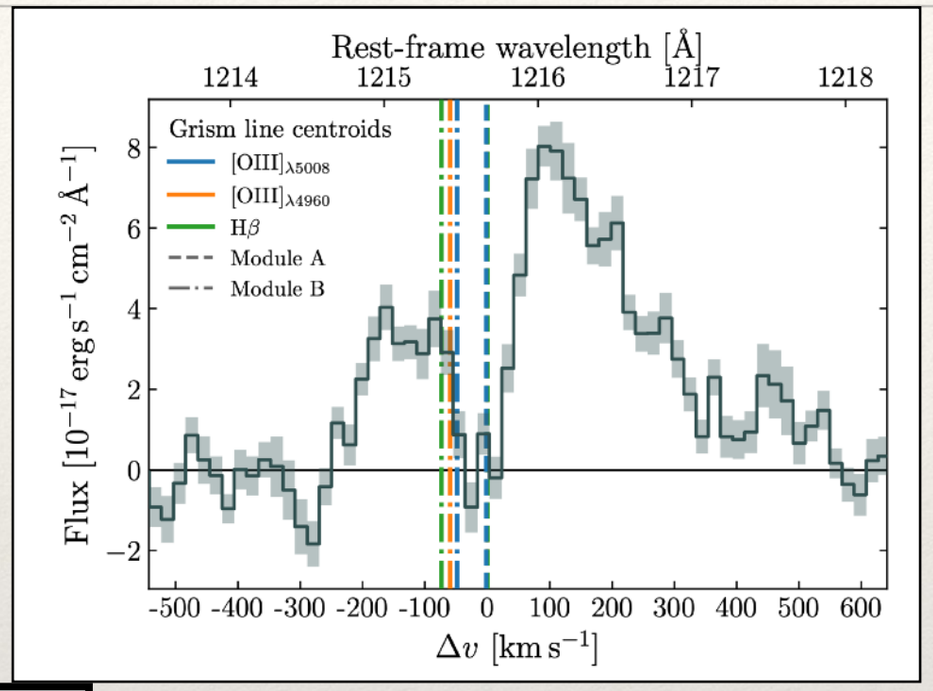
- $n_{\rm HI} \lesssim 10^{-10}$ cm^{-3} needed to avoid absorption at the resonance
- cosmic mean: $n_{\rm H} \sim 10^{-4}$ cm^{-3}

$\therefore x_{\rm HI} = n_{\rm HI}/n_{\rm H} < 10^{-6}$ required, but $x_{\rm HI} = 10^{(-4\ {\rm to}\ -5)}$ in HII regions.

Double-peaked LAEs not expected at $z > 6$!

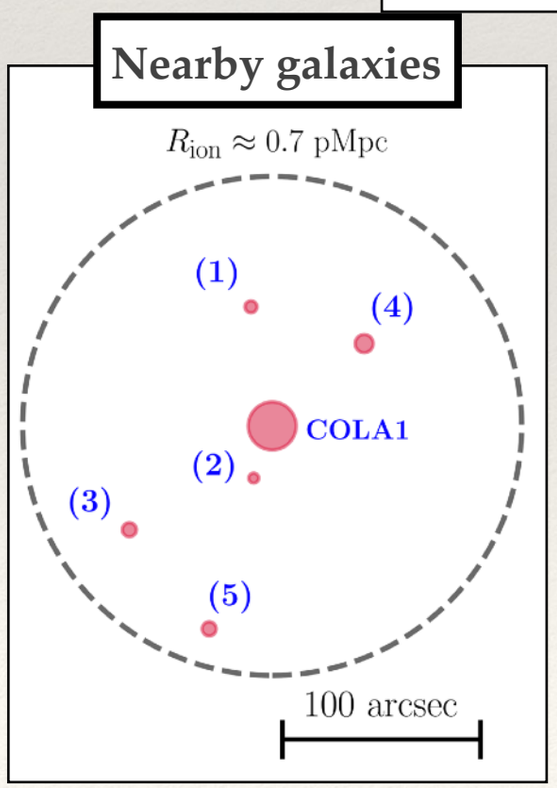
Details of COLA1

High S/N SED from VLT (Matthee+ 2018)



Precise systemic z from JWST (Torralba-Torregrosa+ 2024)

Nearby galaxies

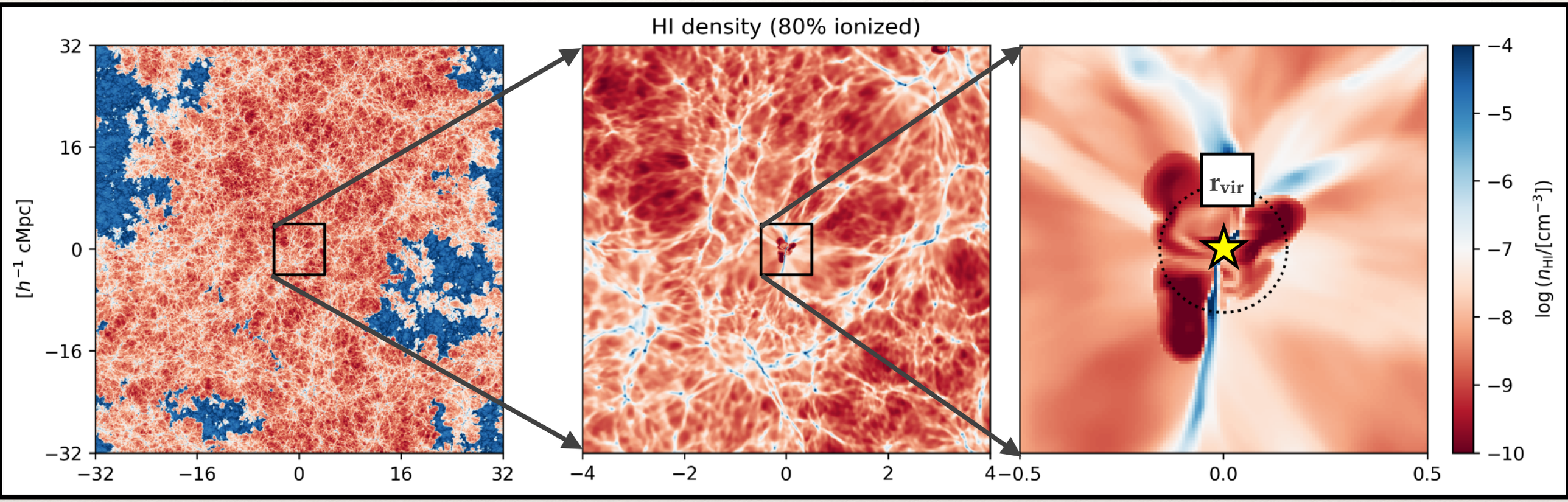


- **Powered by AGN? No.**
- **Other nearby bright galaxies? No.**
- **Recent Bursty SF? Maybe…**
- **Underdense region?**

Q: Do we see similar cases in the simulation? What can we learn from it?

Cosmic Dawn III Simulation

$z = 6$ snapshot (80 % ionized)



Code: RAMSES-CUDATON (tracks full speed of light; bubble growth)

Box & Resolution: 94 cMpc & 8192^3; l_{cell} ~ 10 kpc (good for IGM studies)

Subgrid models: Star formation, stellar radiation, supernova, SF suppression …

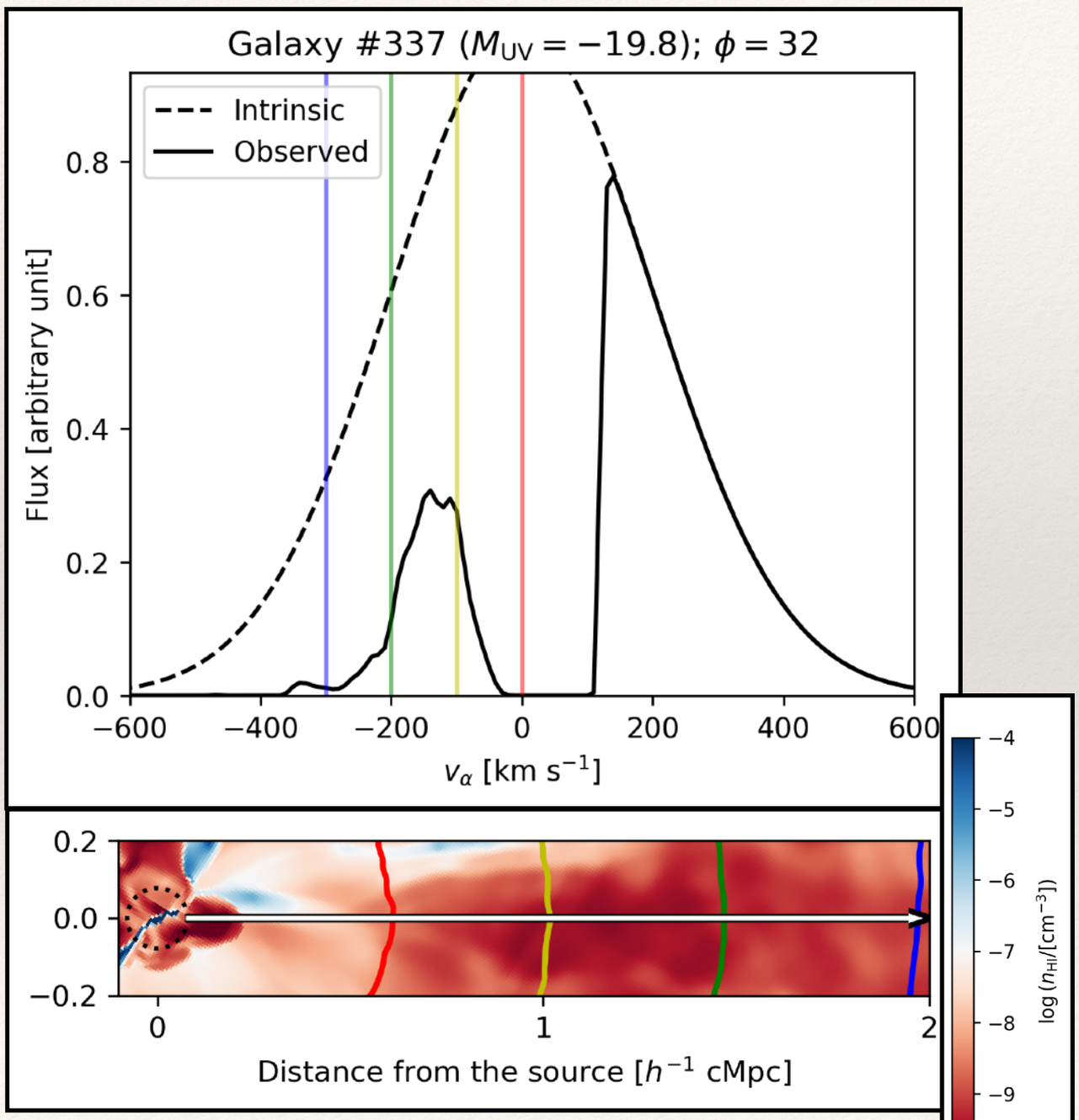
End of reionization: $z = 5.5$ (6.2 in CoDaII)

3D outputs: density, velocity, ionization fraction, temperature, and photoionization rate (Γ)

Galaxy catalog (938 galaxies with $M_{UV} < -19$)

(Ocvirk+ 2025)

Double-peaked Case from CoDaIII



Assuming gaussian intrinsic emission from viral radius

$$f_{\rm int}(v_\alpha) \propto \exp\left(-\frac{v_\alpha^2}{2\sigma^2}\right)$$ σ = 200 km/s

Lyα opacity along sightline

$$\tau(\nu_e) = \int_{r=r_{vir}}^{\infty} n_{\rm HI}\sigma_\alpha(\nu', T)dr$$

Observed profile

$$f_{\rm obs}(v_\alpha) = e^{-\tau_\alpha(v_\alpha)} f_{\rm int}(v_\alpha)$$

Double peak criteria

Significant blue side transmission : $F_{\rm blue,obs} > 0.1\ F_{\rm red,obs}$

Exclude highly attenuated ones : $F_{\rm red,obs} > 0.05\ F_{\rm red,int}$

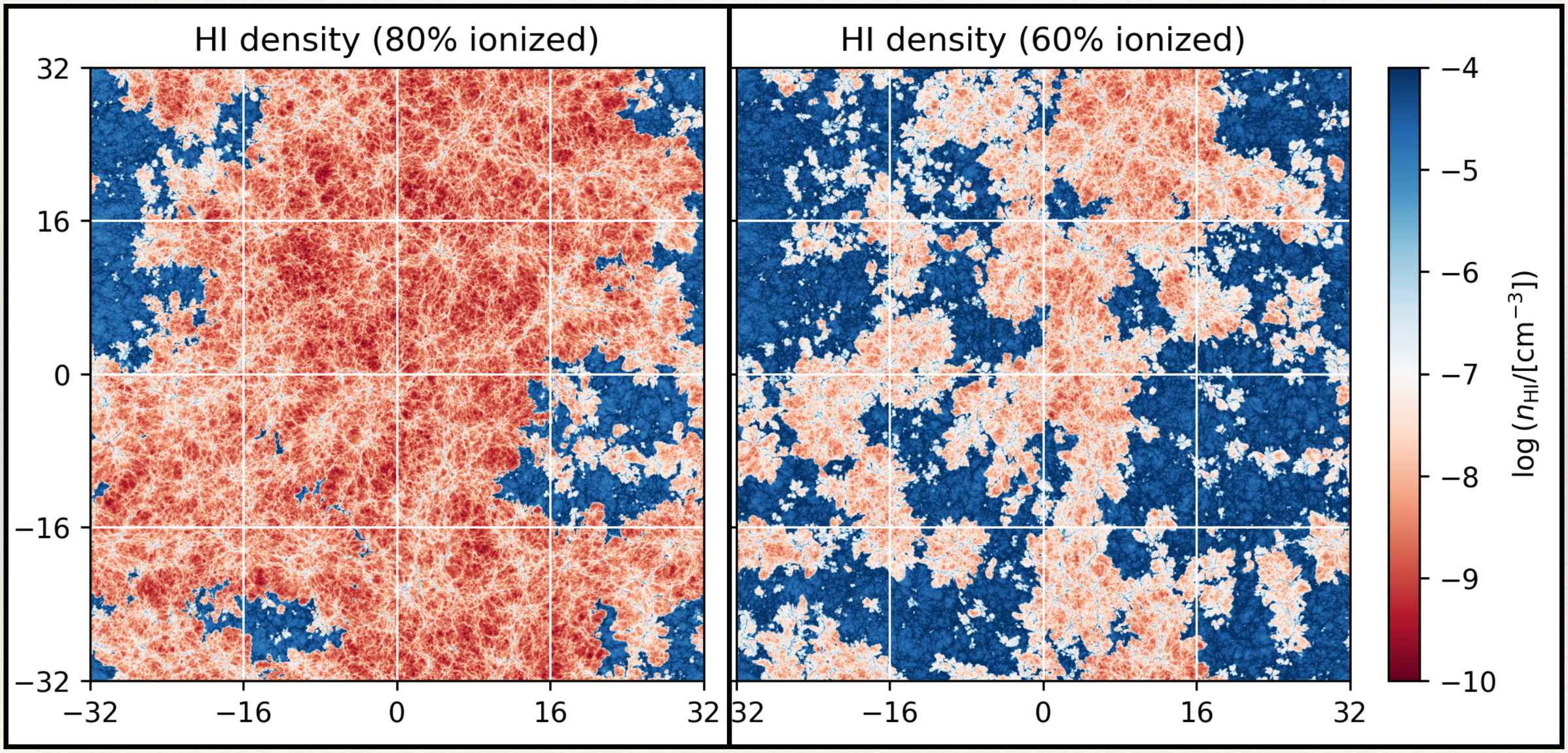
Dip in the middle : $\max_{0<v_\alpha<v_{\rm peak,red}} f_{\rm obs}(v_\alpha) < 0.5\, f_{\rm obs}(v_{\rm peak,red})$

[938 galaxies]×360 sightlines checked

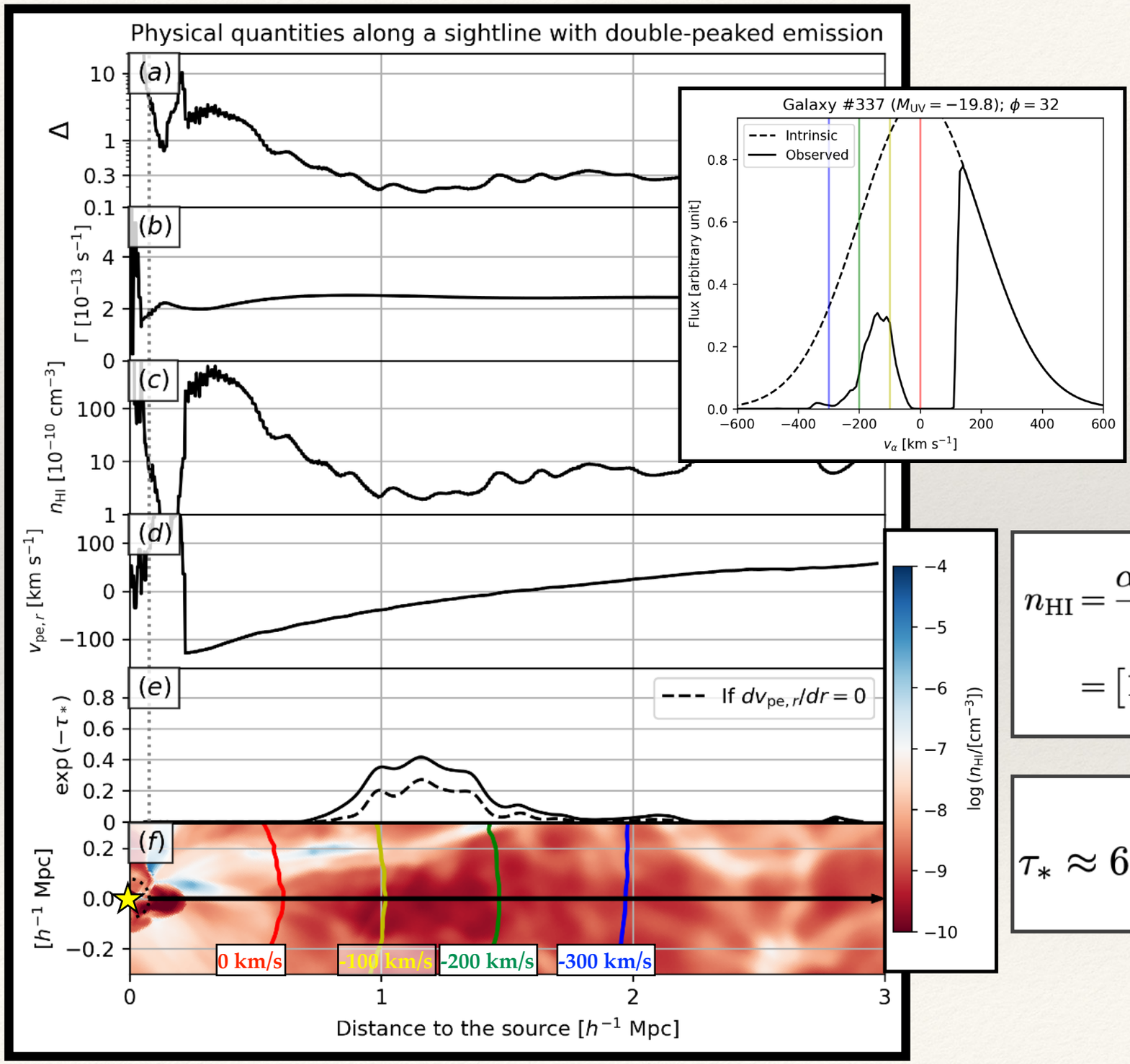
Results for $z = 6$ and 6.5

$z = 6$; $P_{\rm DP} = 0.3$ %

$z = 6.5$; $P_{\rm DP} = 0$ %



Physical Quantities Along the Sightline



- **Underdense void with $< 30\%$ of cosmic mean (Δ)**
- **Void size ~ 0.5 cMpc/h**
- **Located at ~ 1 cMpc/h**
- **Positive v gradient helps**

$$n_{\rm HI} = \frac{\alpha_{\rm B} n_{\rm HII}^2}{\Gamma} \approx \frac{\alpha_{\rm B} \bar{n}_{\rm H}^2}{\Gamma} \Delta^2$$
$$= \left[1.1 \times 10^{-8}\ {\rm cm}^{-3}\right] \left[\frac{10^{-13}\ {\rm s}^{-1}}{\Gamma}\right] T_4^{0.7} z_6^6 \Delta^2$$

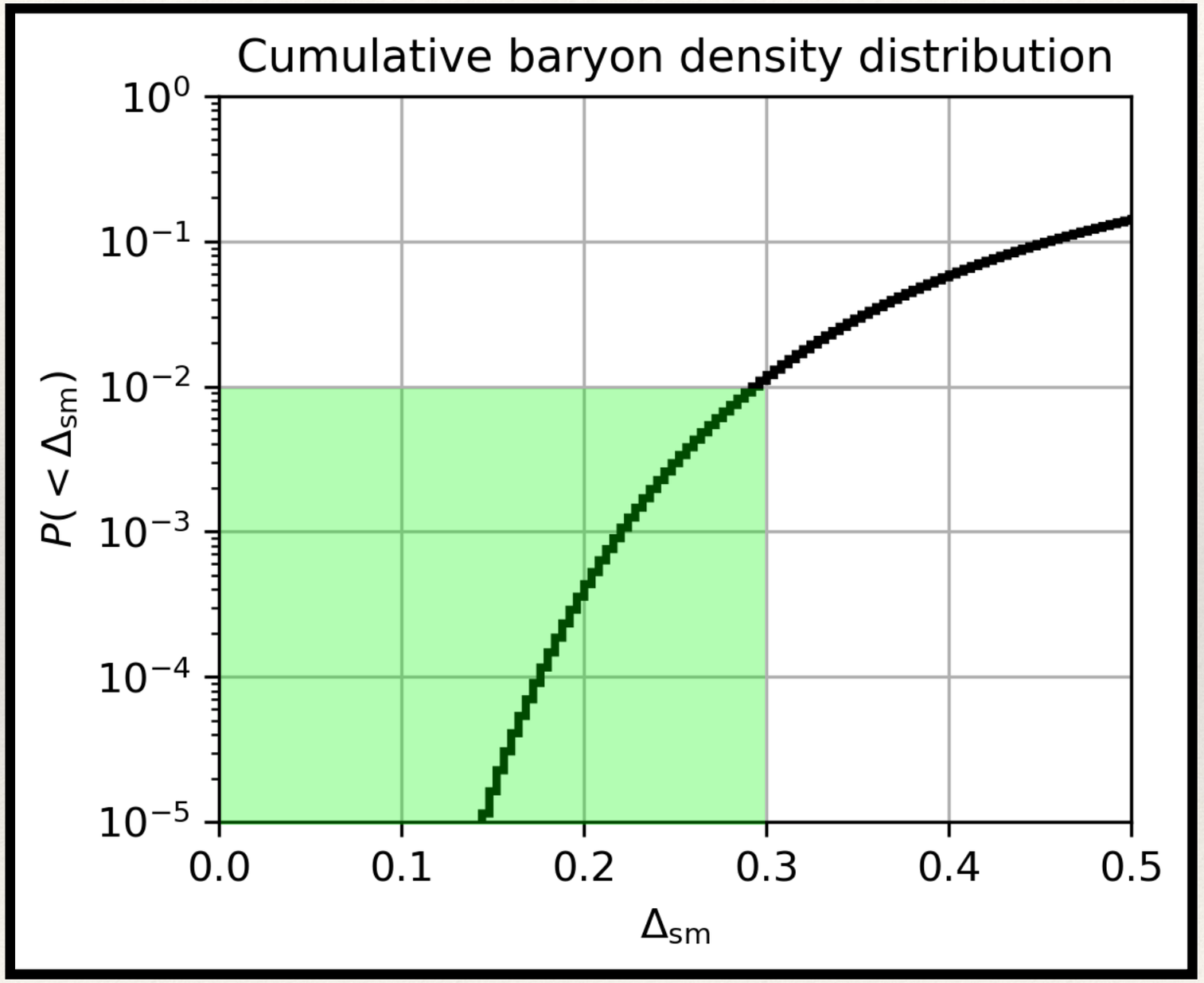
$T_4 \equiv T/[10^4\ {\rm K}]$

$z_6 \equiv [1+z]/7$

$$\tau_* \approx 65 \left[\frac{10^{-13}\ {\rm s}^{-1}}{\Gamma}\right] \left[\frac{T}{10^4\ {\rm K}}\right]^{0.7} z_6^{4.5} \Delta^2$$

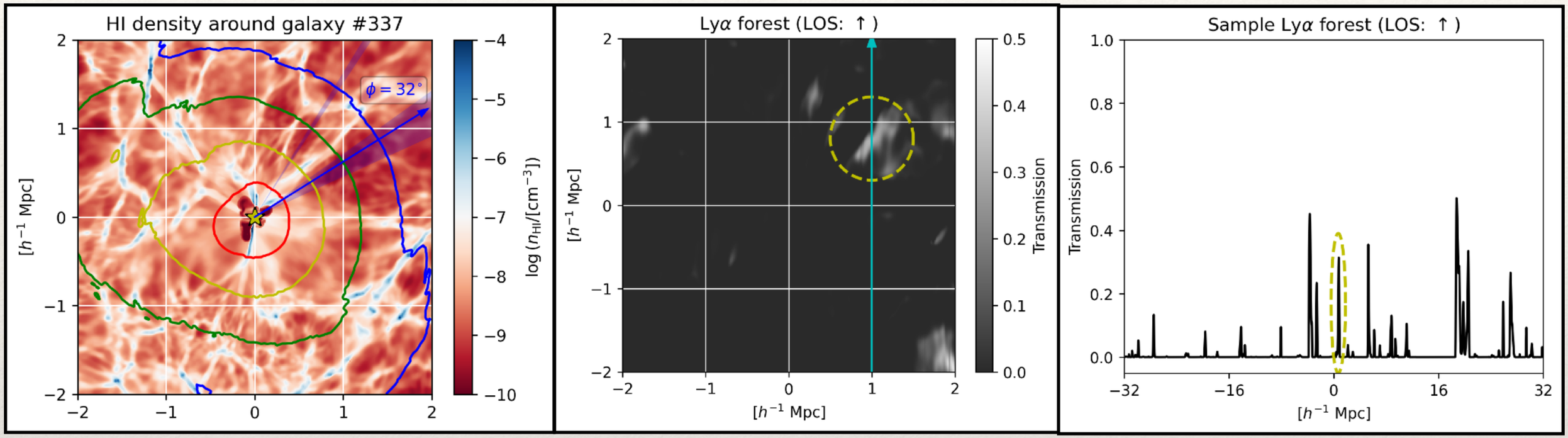
τ_* = (a few) for $\Delta = 0.3$

How rare are these voids?

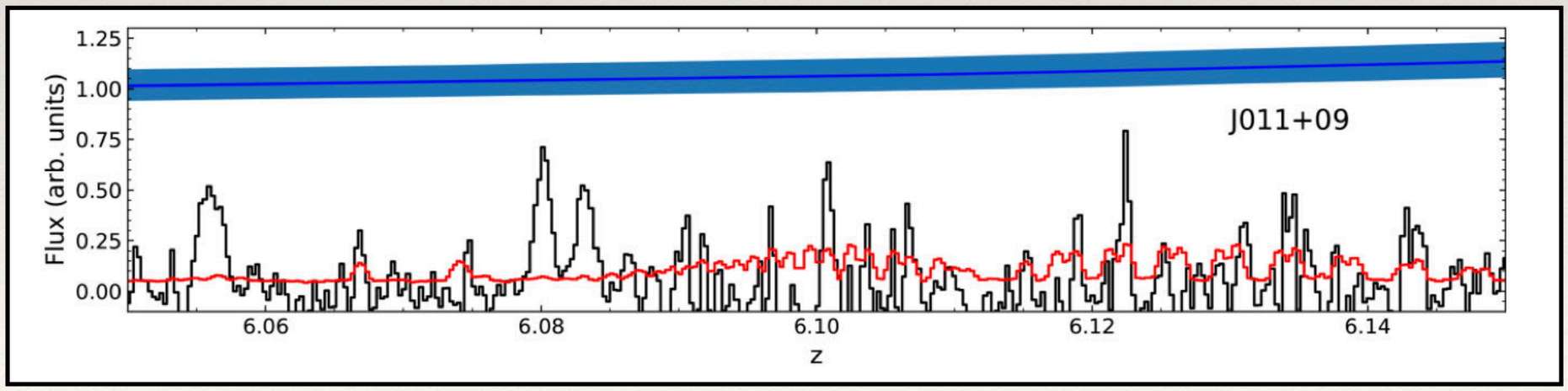


Tail of probability distribution (< 1%); Rare, but possible.

Connection to Lyα Forest



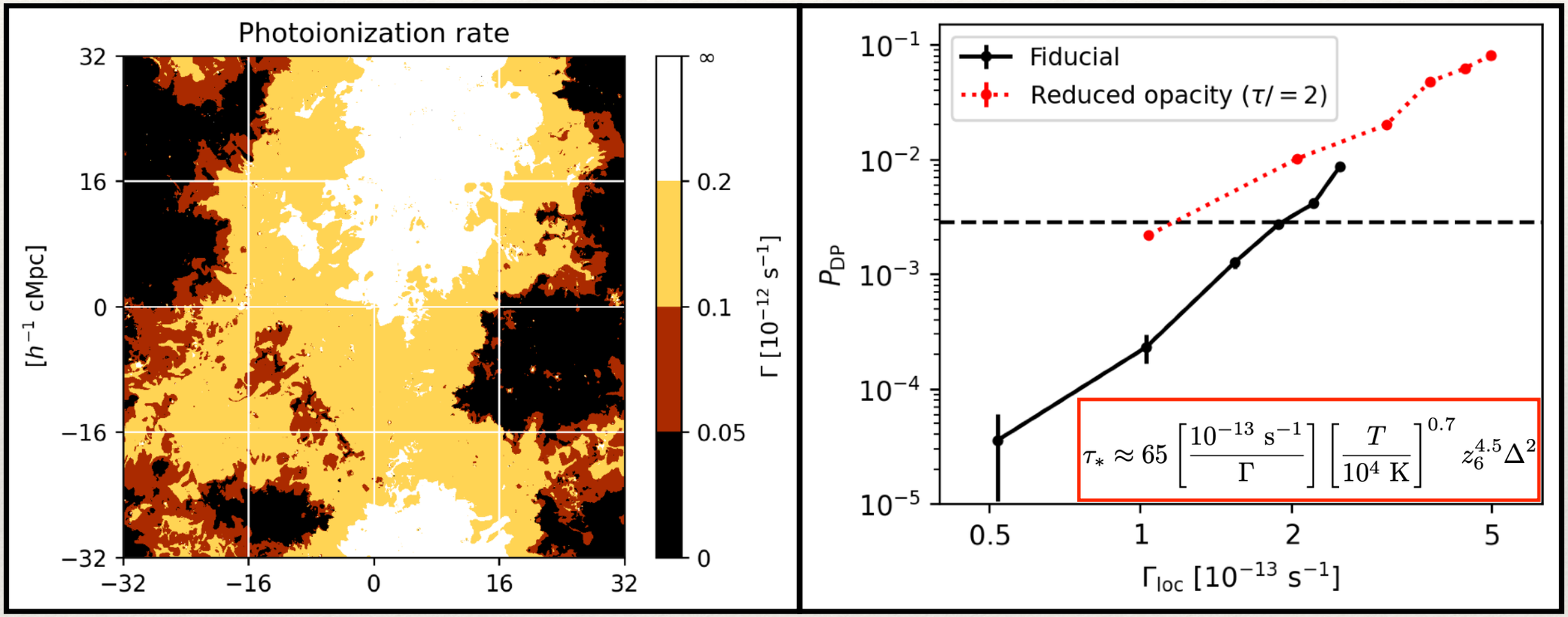
The same voids can also create transmission spike in the Lyα forest at z~6.



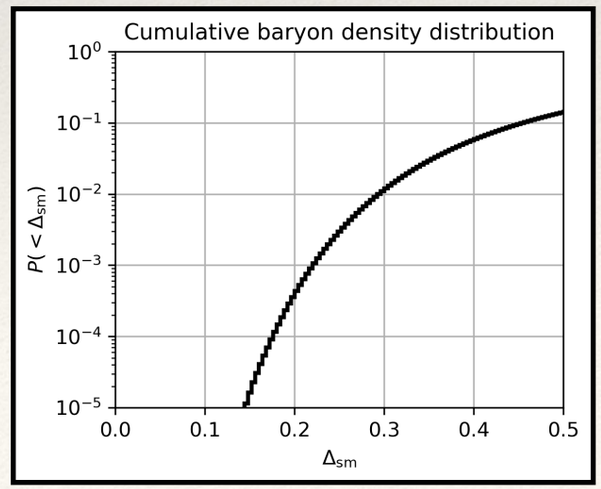
(Bosman+2022)

Spatial correlation but double-peaked emission and Lyα forest?

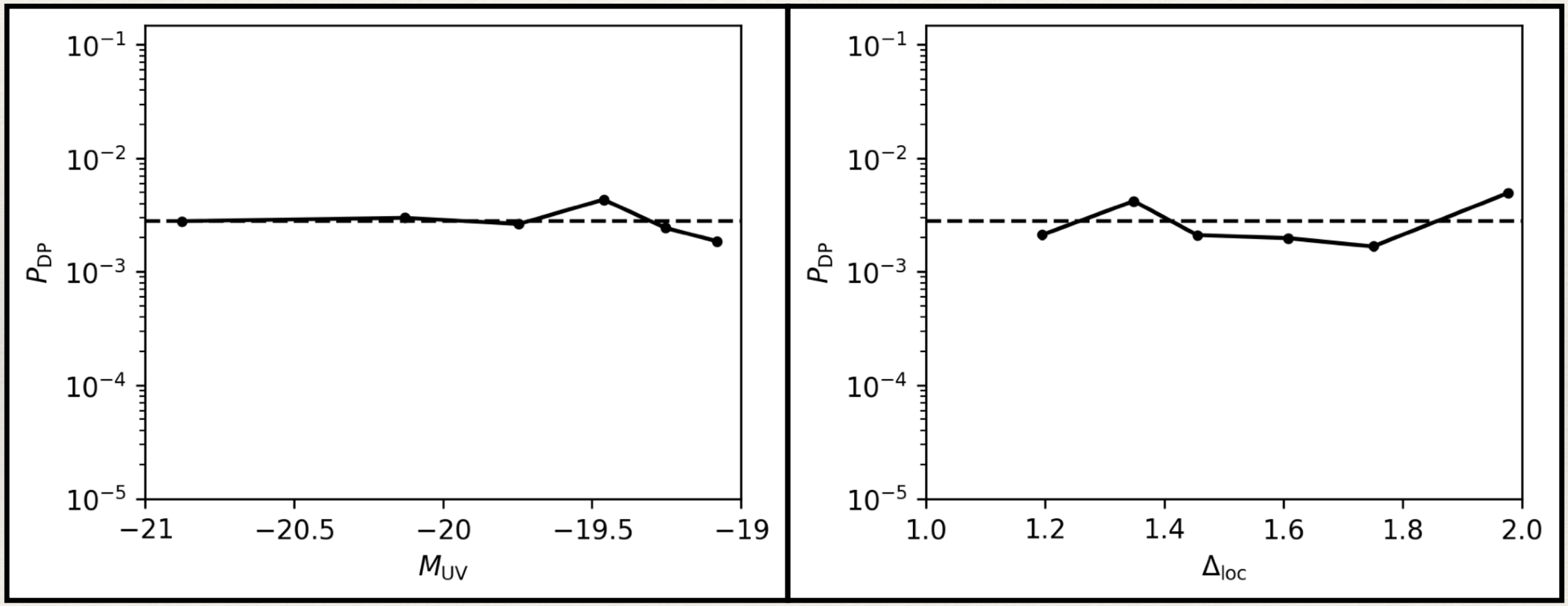
Strong Γ Dependence



10^4 times increase P_{DP} for 10 times increase Γ



M_{UV} & Local Density Dependence

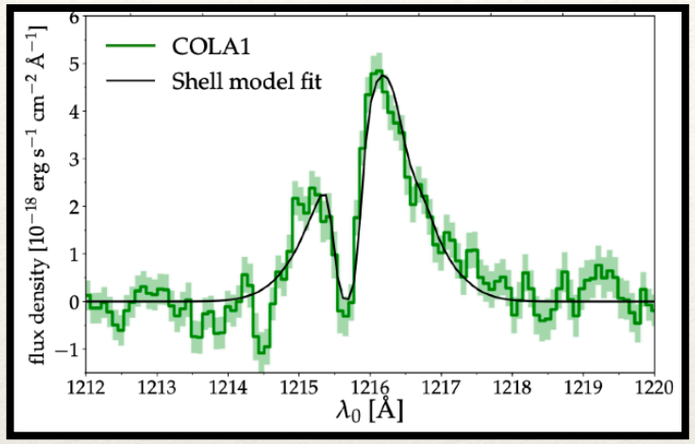


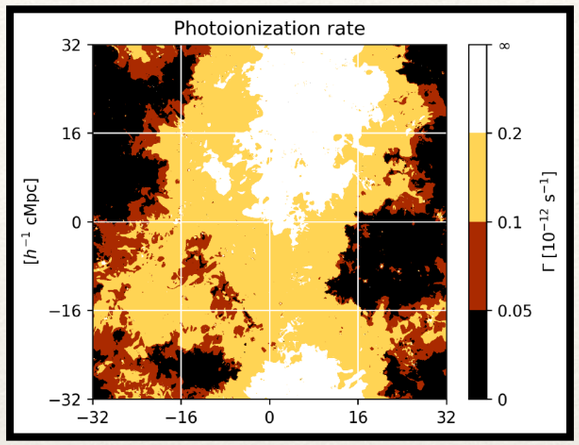
No significant dependence
Consistent with the COLA1 case

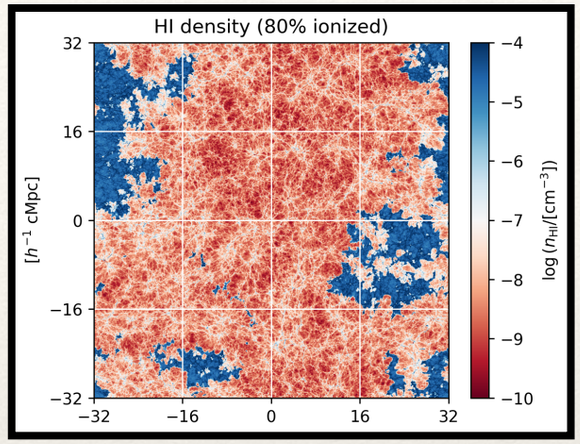
Summary

- 0.3% sightlines with double peaks for $z = 6$ (80% ionized)
  0% for $z = 6.5$ (60% ionized)
- Double-peaked emission are associated with a void at a right distance.
- Spatial correlation with Lyα transmission spikes expected
- Strong Γ dependence -> probe of ionizing background
- No significant M_{UV} or Δ dependence

Discussion

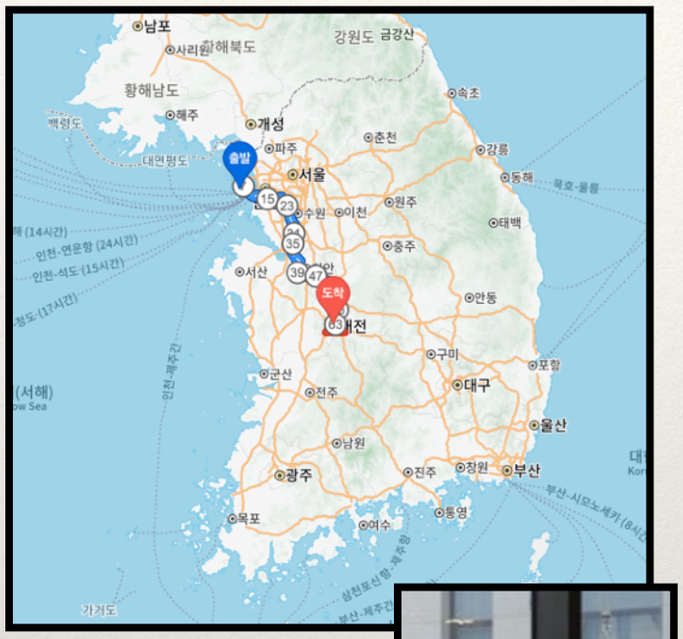






- New probe of ionizing background & reionization history
- More observations to come from JWST, ELT, GMT, & TMT
- Reionization earlier than in CoDaIII? (~80 % at $z = 6.5$?)
- Different reionization geometry?
  (Fewer large HII regions vs numerous small HII regions)
- Limited volume of CoDa simulation?
  (missing >30 Mpc HII regions?)

IBS CTPU-CGA



Daejeon, Korea

Cosmology research group of ~20 people

Looking into topic that will survive next 100 years!

Planning to hire 1 - 2 computational cosmologists later this year!