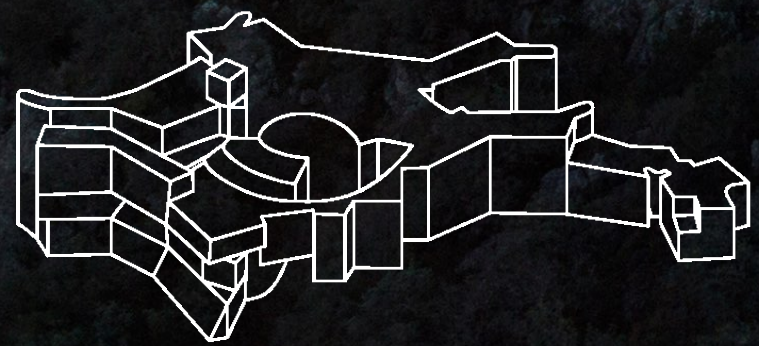


HETDEX - a Lyman- α Intensity Mapping Survey



MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

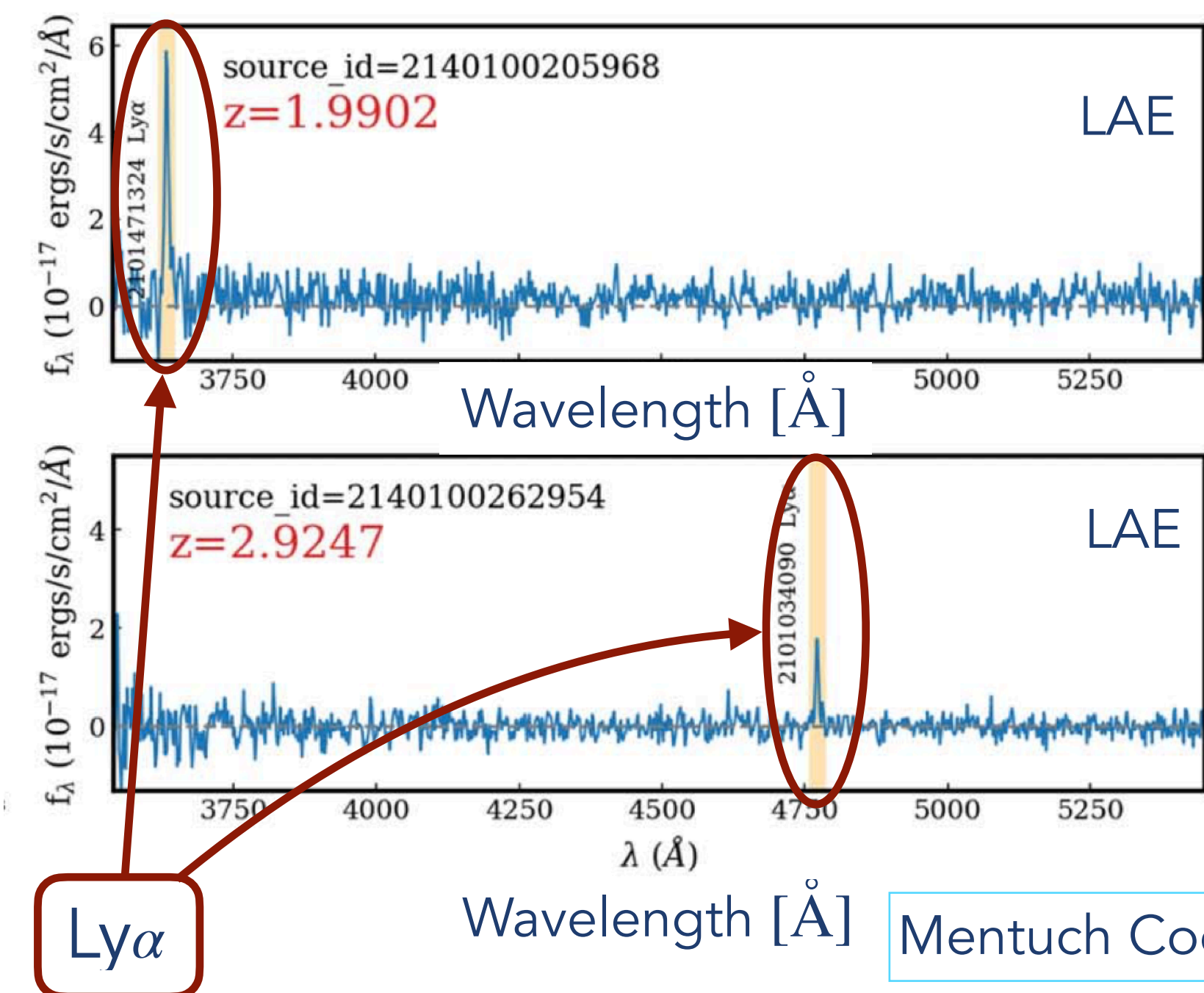
Maja Lujan Niemeyer

LINE INTENSITY MAPPING WORKSHOP 2.-6.06.2025

Image credit: USM

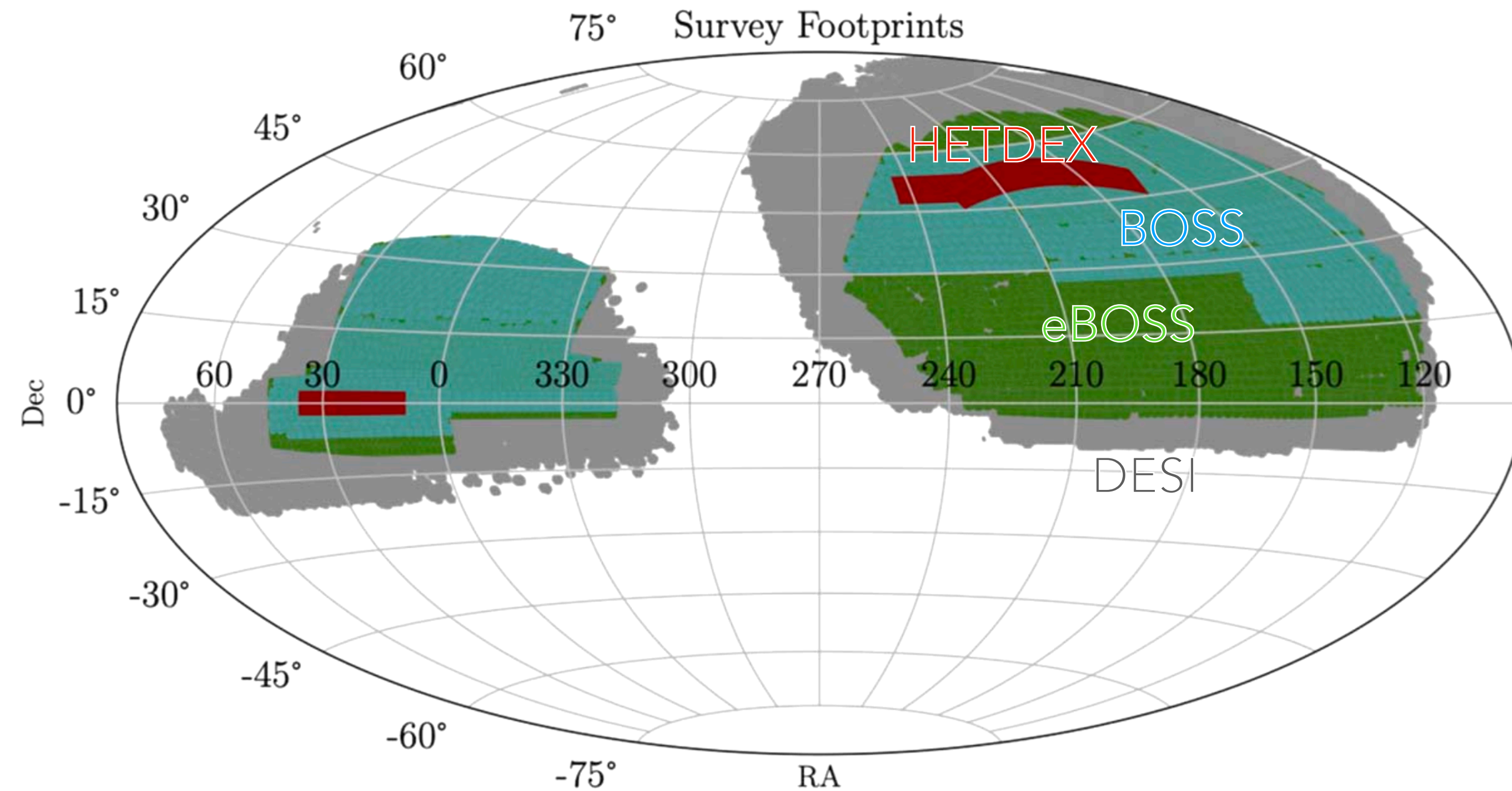
HOBBY-EBERLY TELESCOPE DARK ENERGY EXPERIMENT

- $\sim 10^6$ Ly α -emitting galaxies (LAEs) at $z \simeq 2 - 4$



HOBBY-EBERLY TELESCOPE DARK ENERGY EXPERIMENT

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- 10.9 Gpc^3 volume without target preselection
 $\leadsto$ "blind" IFU survey

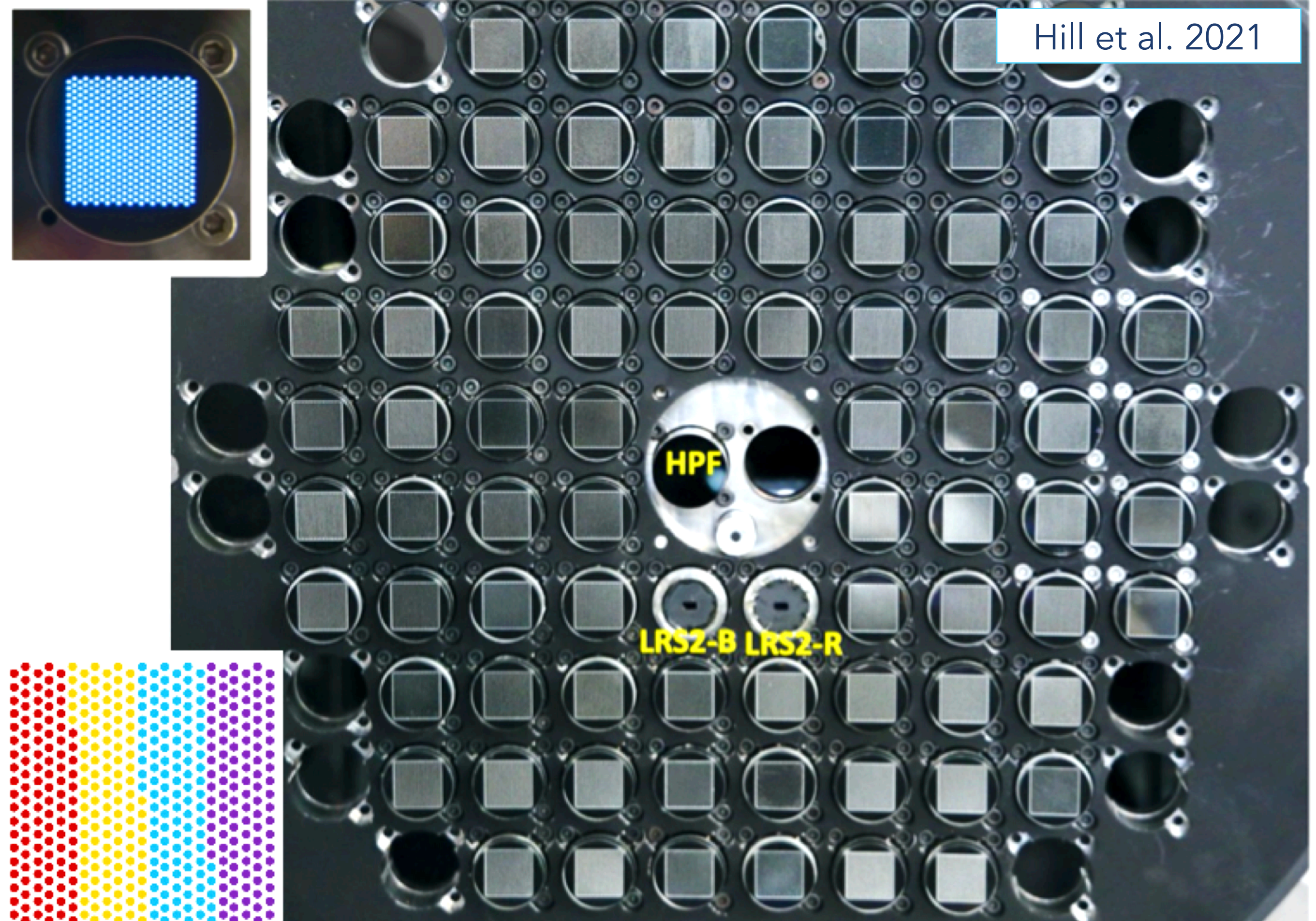


Gebhardt et al. 2021

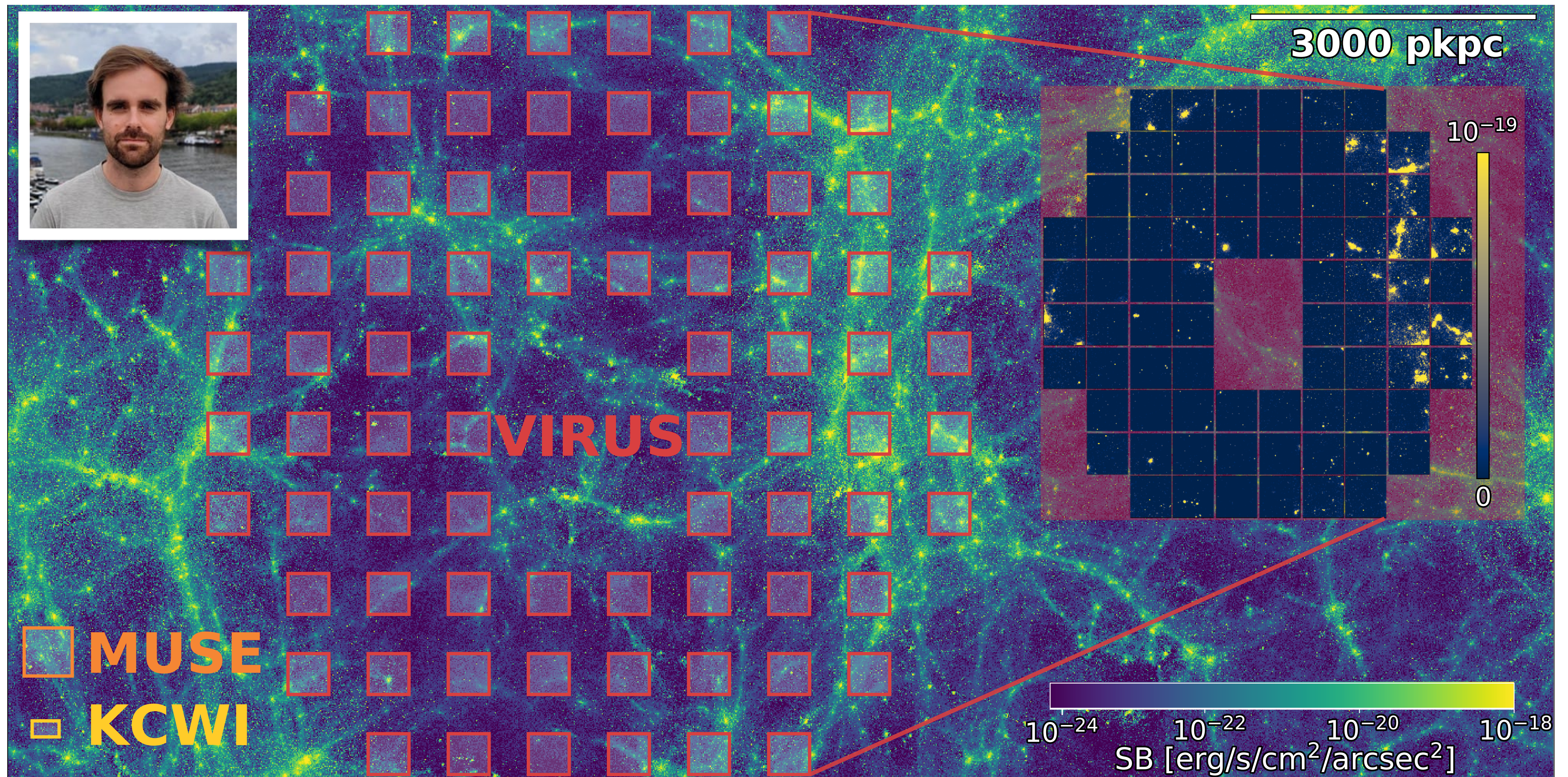
HOBBY-EBERLY TELESCOPE DARK ENERGY EXPERIMENT

- $\sim 10^6$ Ly α -emitting galaxies (LAEs) at $z \simeq 2 - 4$
 - 10.9 Gpc³ volume without target preselection
 $\leadsto$ "blind" IFU survey
 - On average 2.5 detected LAEs (above S/N threshold) per IFU in $> 10^6$ voxels.
- **Cross-correlation** of LAEs with intensity of remaining fibers retrieves Ly α photons from undetected galaxies.

Visible Integral-field Replicable Unit Spectrograph (VIRUS)

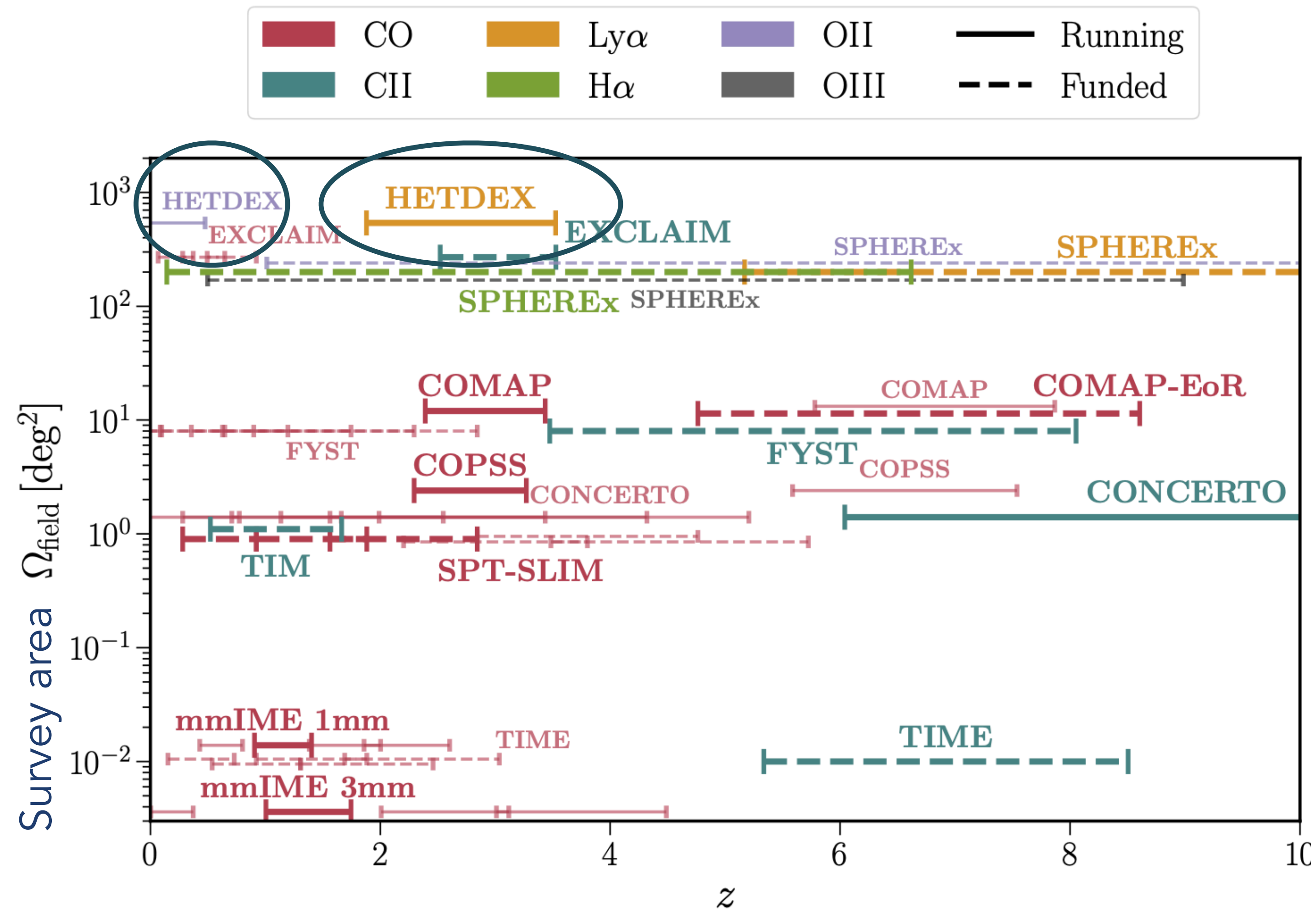


HOBBY-EBERLY TELESCOPE DARK ENERGY EXPERIMENT

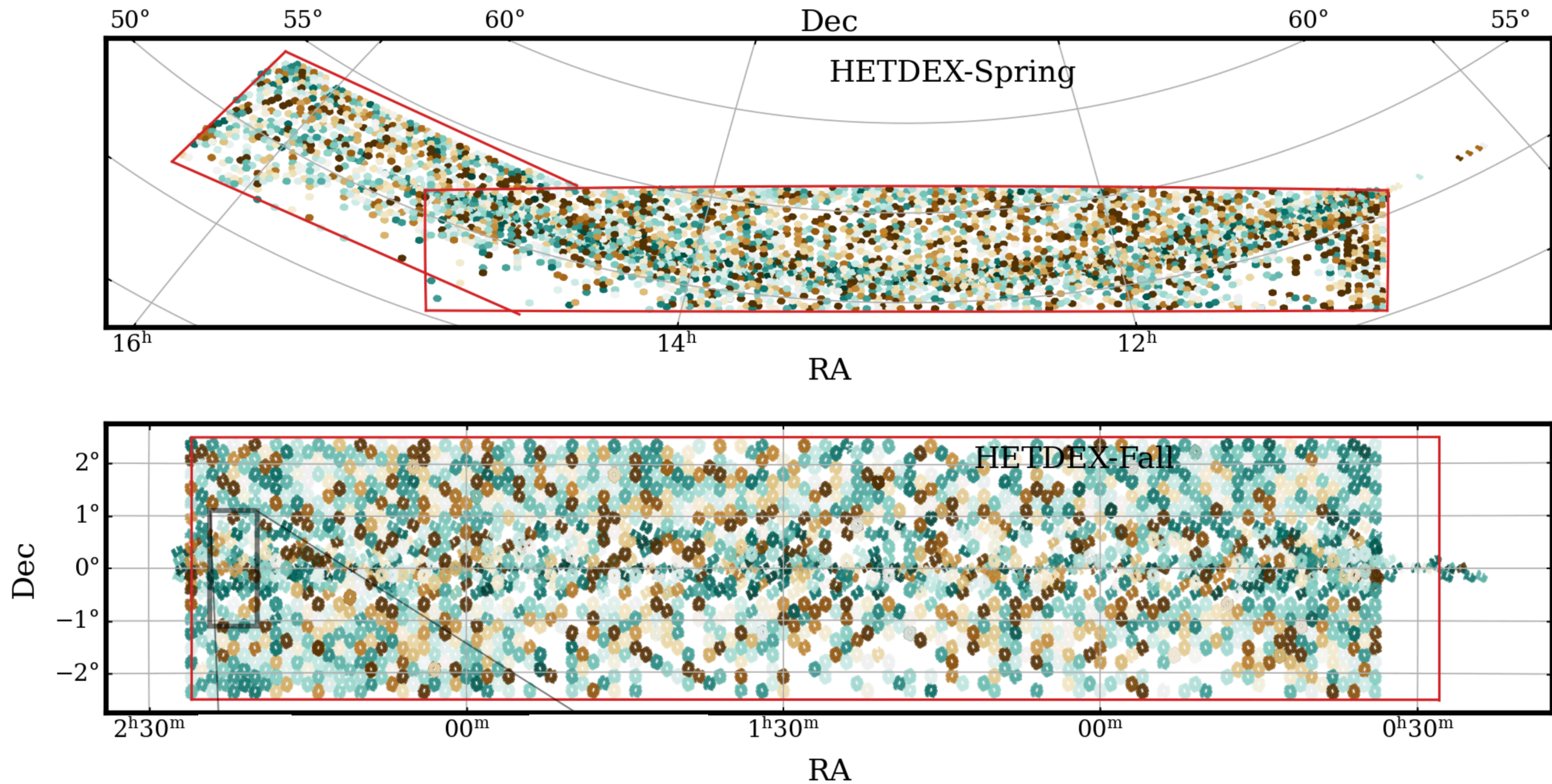


Credit: Chris Byrohl (Institute of Theoretical Astrophysics Heidelberg); simulation: Byrohl et al. 2021

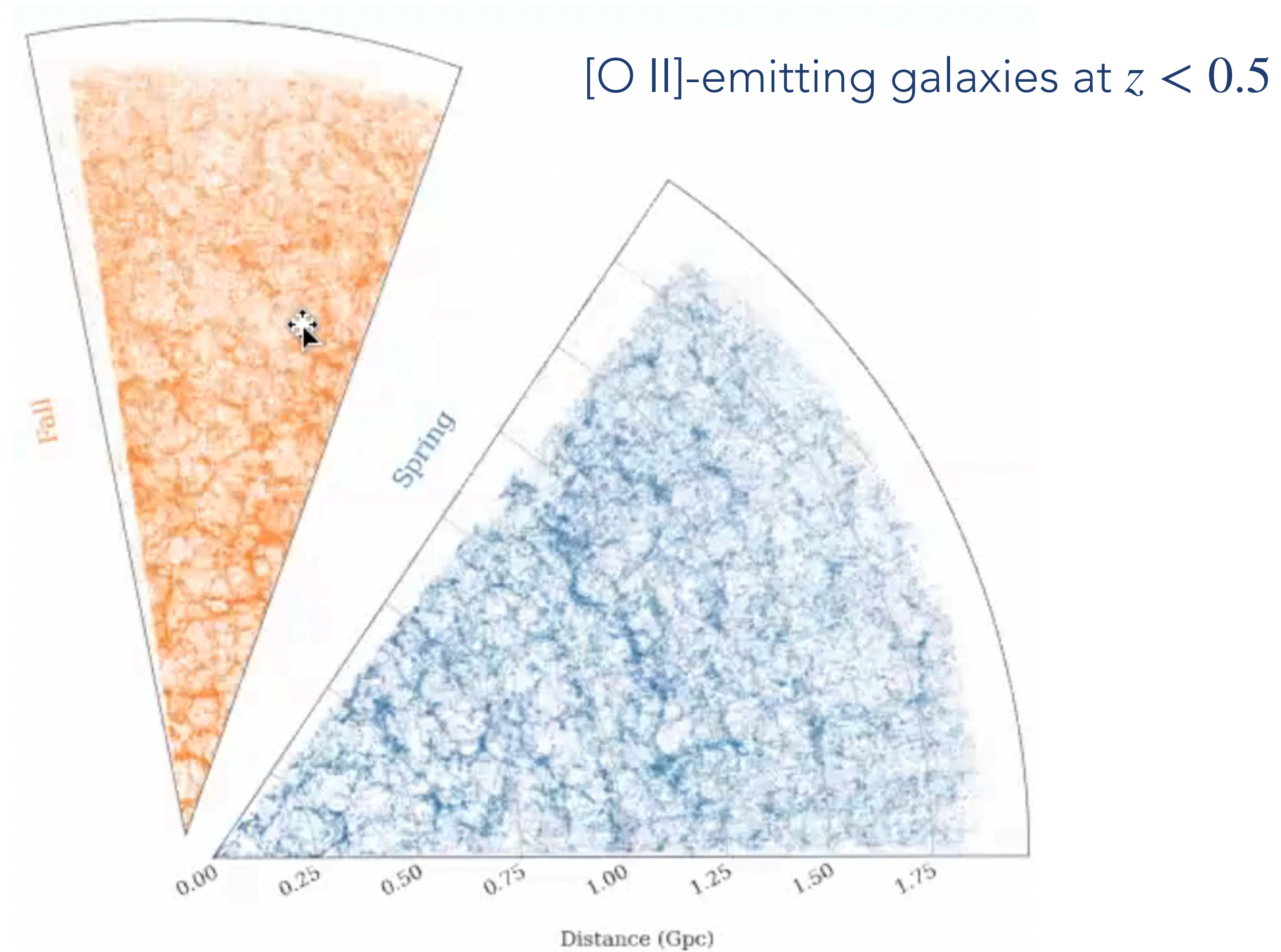
HETDEX - A LINE INTENSITY MAPPING SURVEY



HETDEX OBSERVATIONS ARE DONE!



HETDEX OBSERVATIONS ARE DONE!

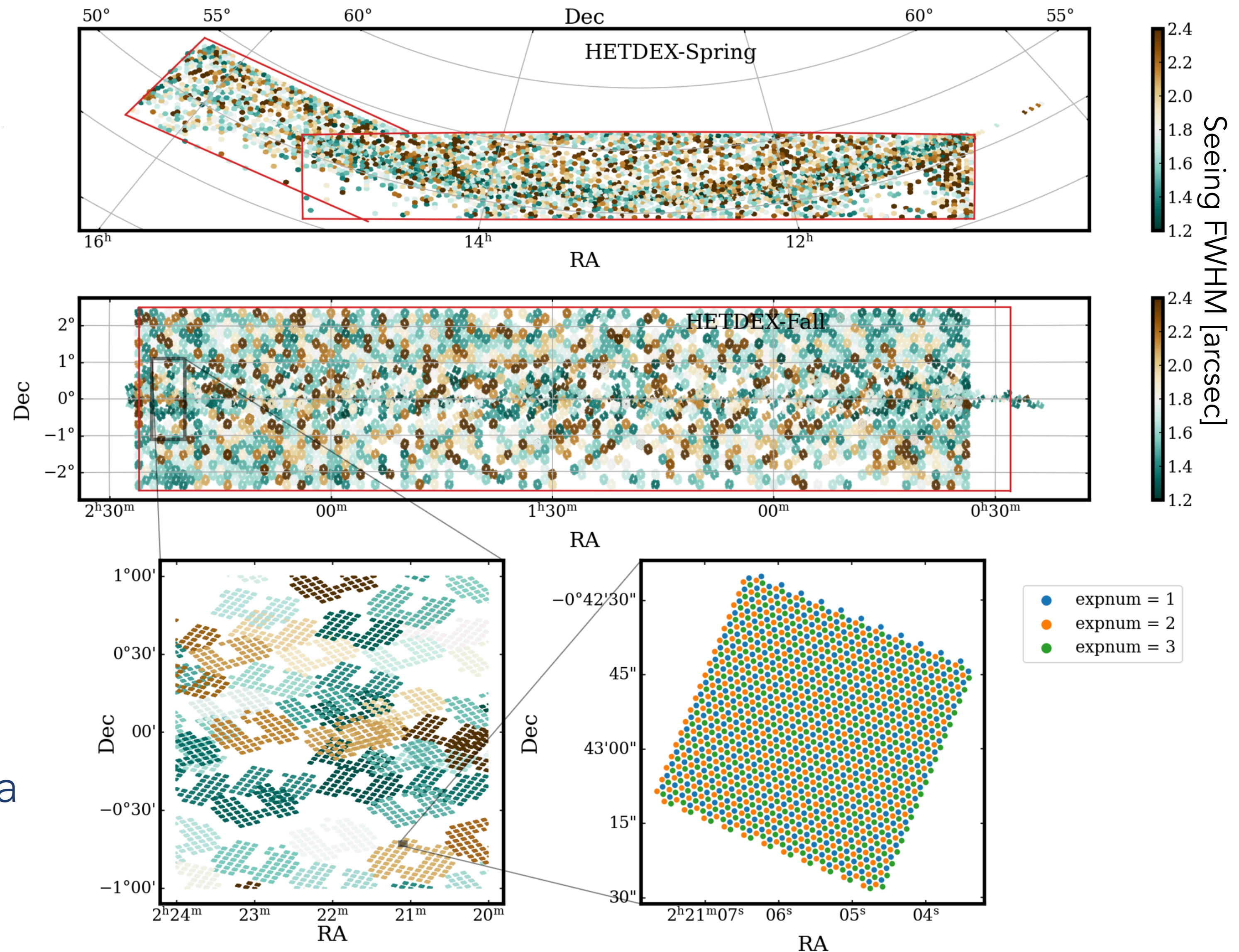


HETDEX - AVAILABLE DATA

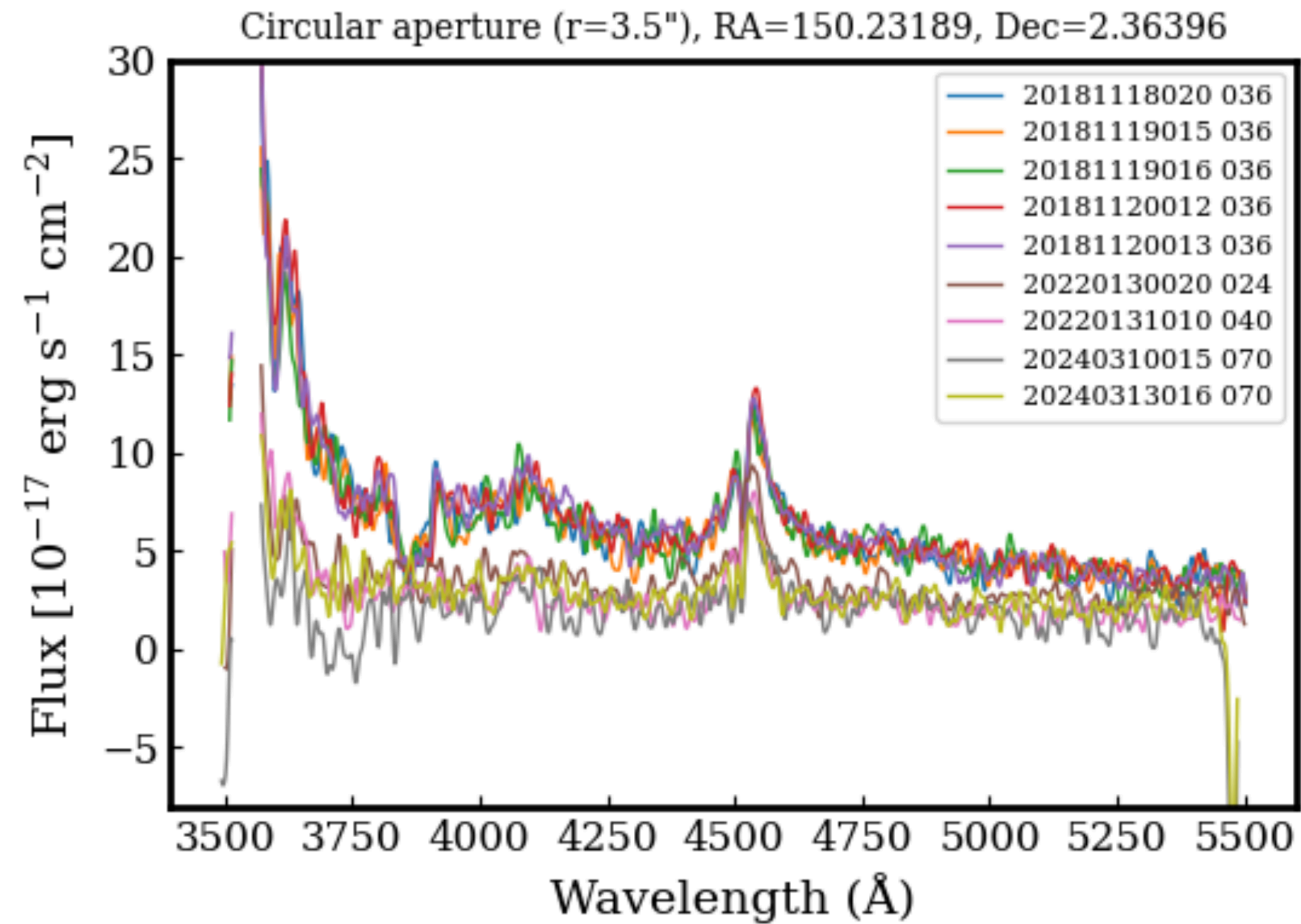
- hetdex.org/data-results/
- **HETDEX Source Catalog 1. Mentuch Cooper et al. 2023**. HETDEX Public Source Catalog 1: 220K Sources including over 50K Lyman Alpha Emitters from an Untargeted Wide-area Spectroscopic Survey
 - 51,863 LAEs at $1.88 < z < 3.52$
 - 123,891 [O II]-emitting galaxies at $z < 0.5$
 - 5274 $z < 0.5$ galaxies without emission lines
 - 4976 AGN
 - 37,916 stars
- **HETDEX AGN Catalog 1. Liu et. al 2022**. The Active Galactic Nuclei in the Hobby-Eberly Telescope Dark Energy Experiment Survey (HETDEX) I. Sample selection
 - 5322 AGN at $0.25 < z < 4.32$

HETDEX PUBLIC DATA RELEASE 2026

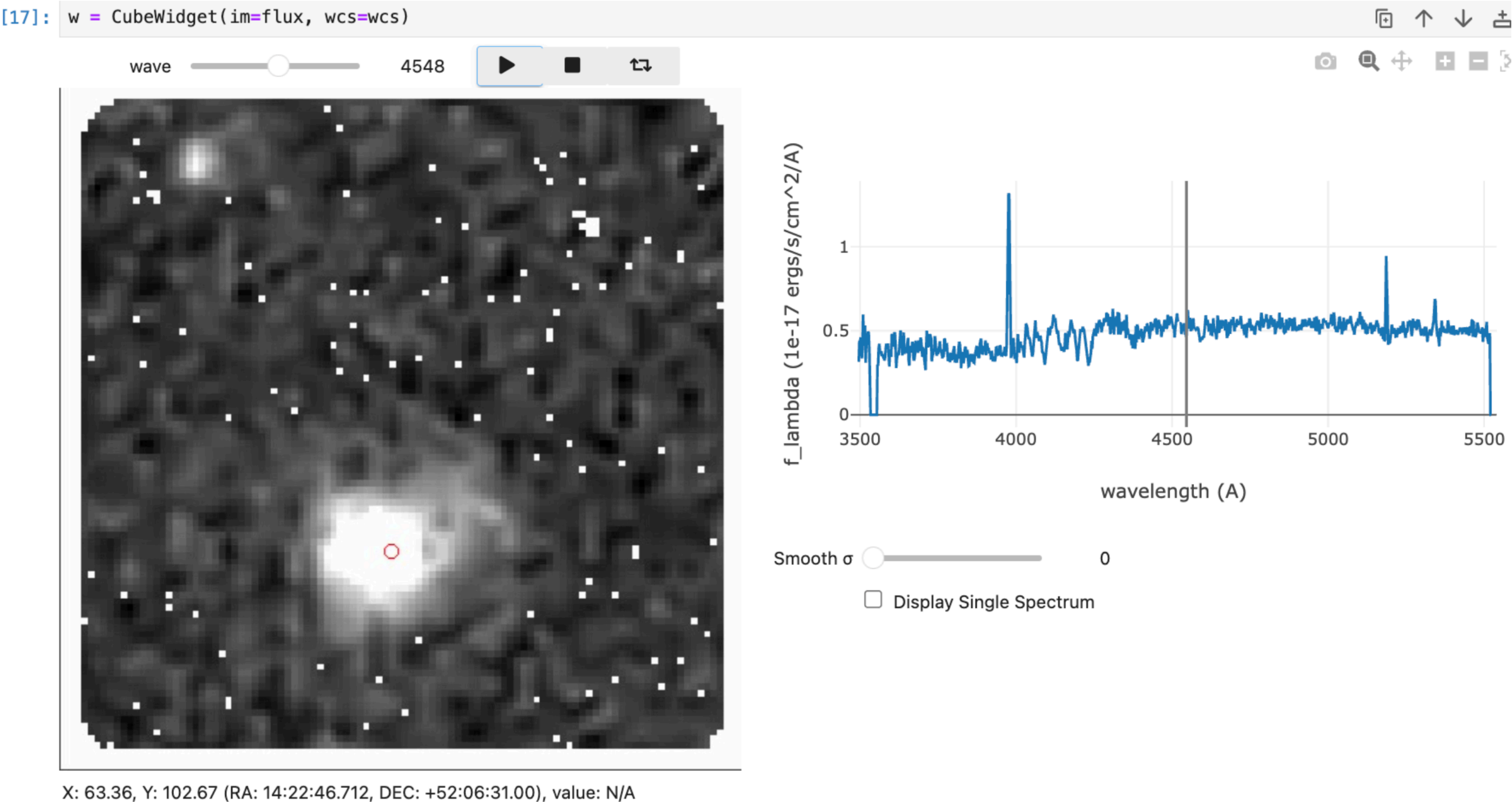
- new source catalog
- Flux data cubes
 - Spectral resolution: 1036 pixel with $2\text{\AA}$ per pixel
 - Spatial resolution: 104×104 pixel with $0.5''$ per pixel
- API to scan and work with the data



HETDEX PUBLIC DATA RELEASE 2026

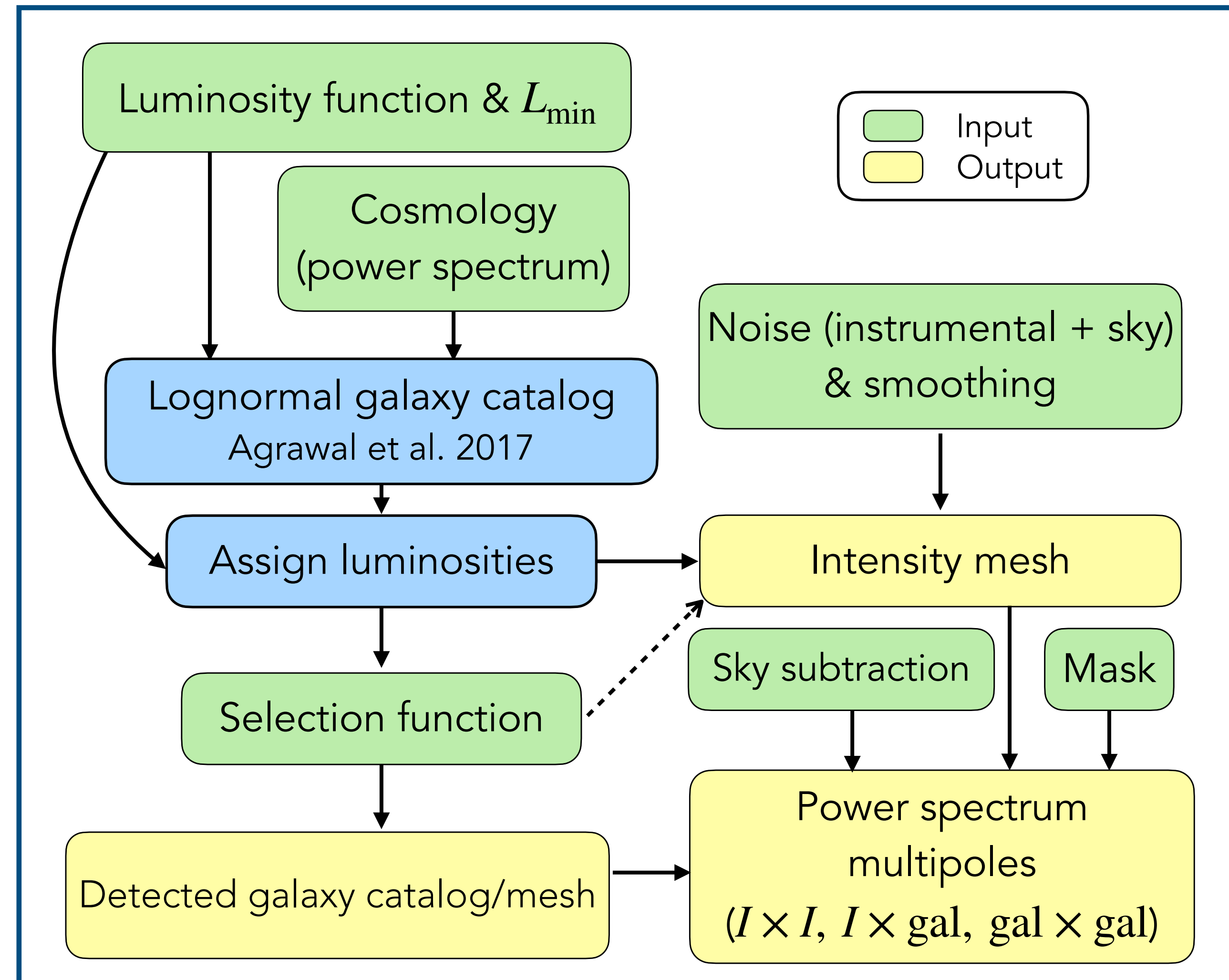


HETDEX PUBLIC DATA RELEASE 2026



LY α INTENSITY MAPPING AND RADIATIVE TRANSFER EFFECTS

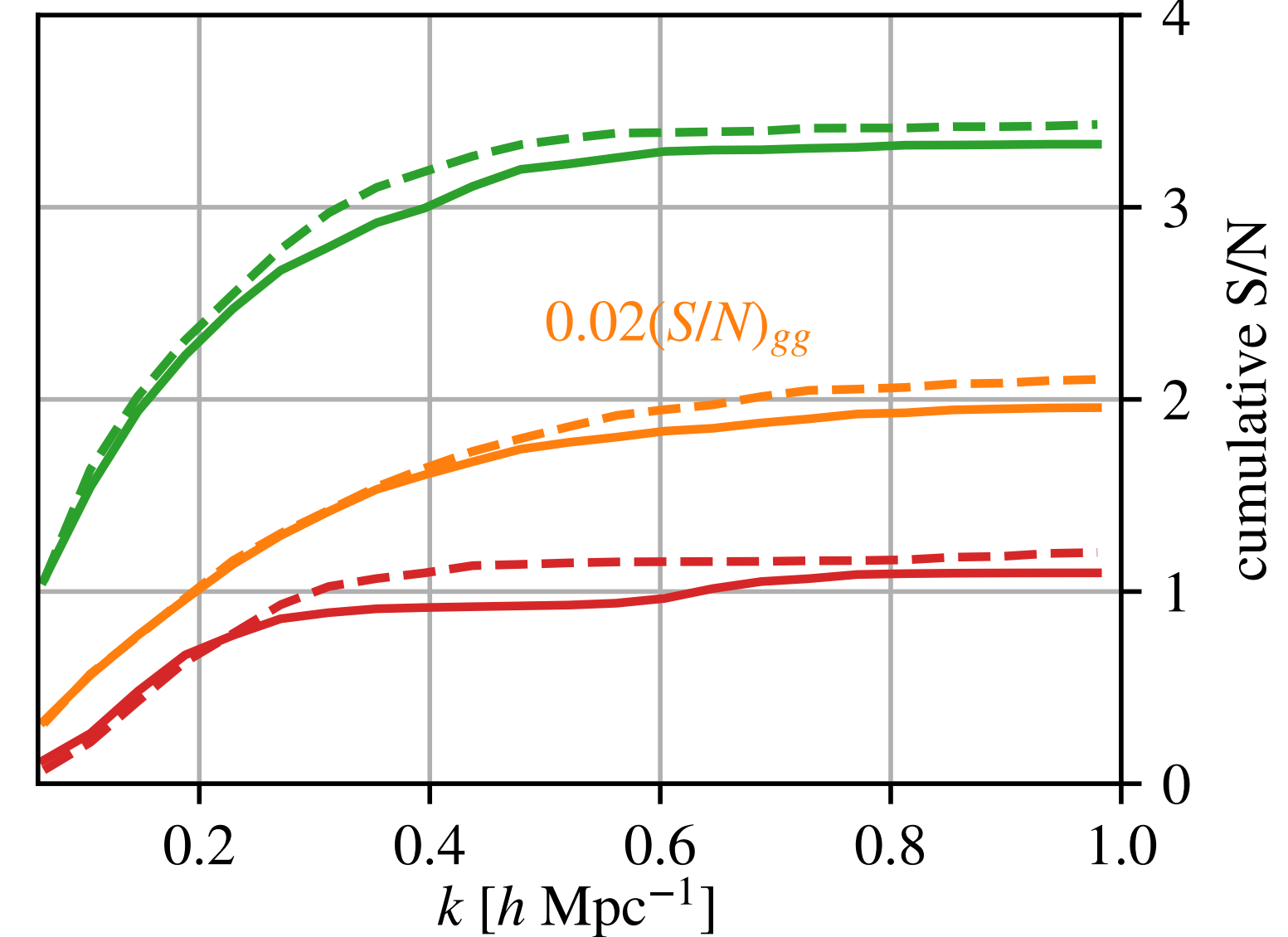
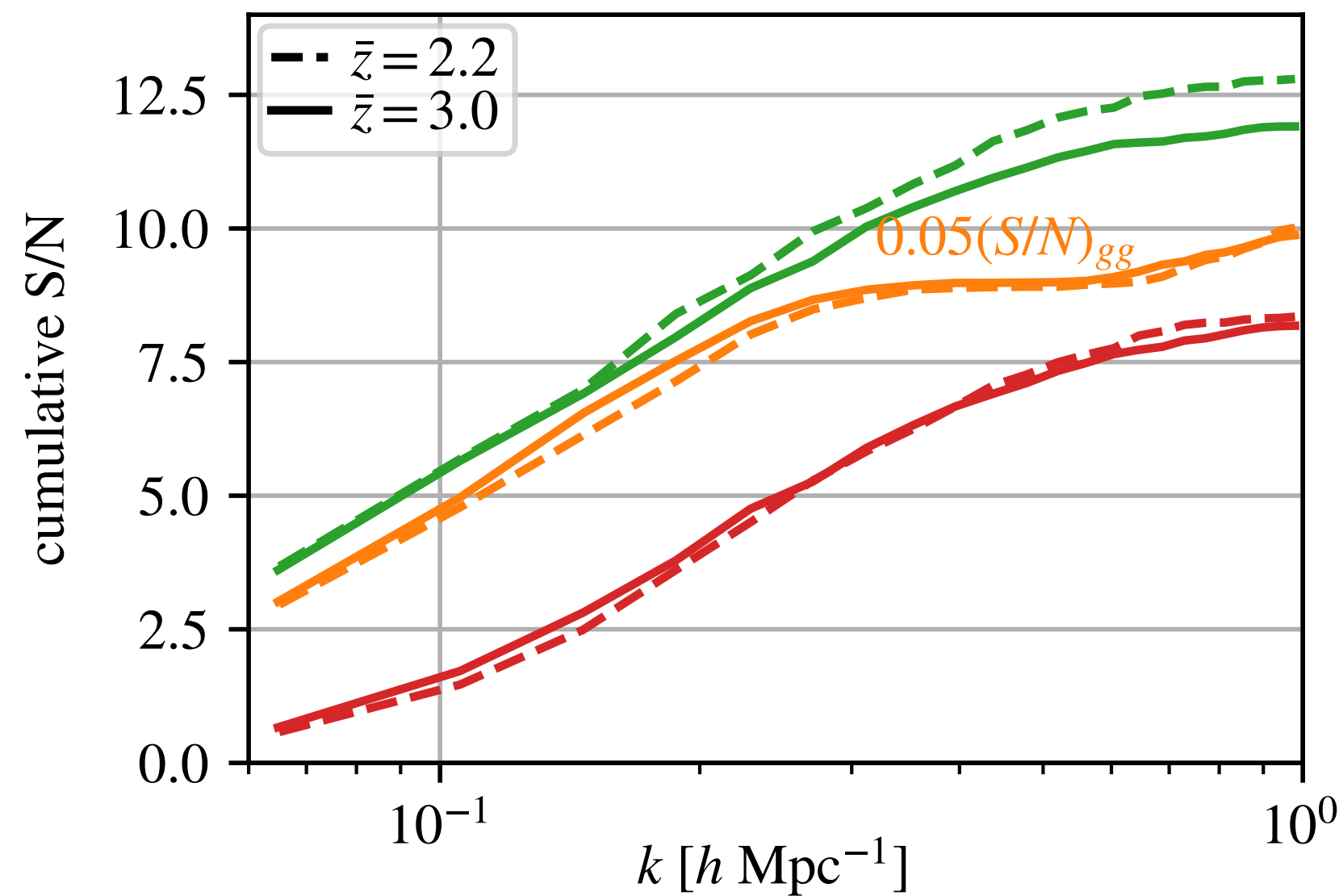
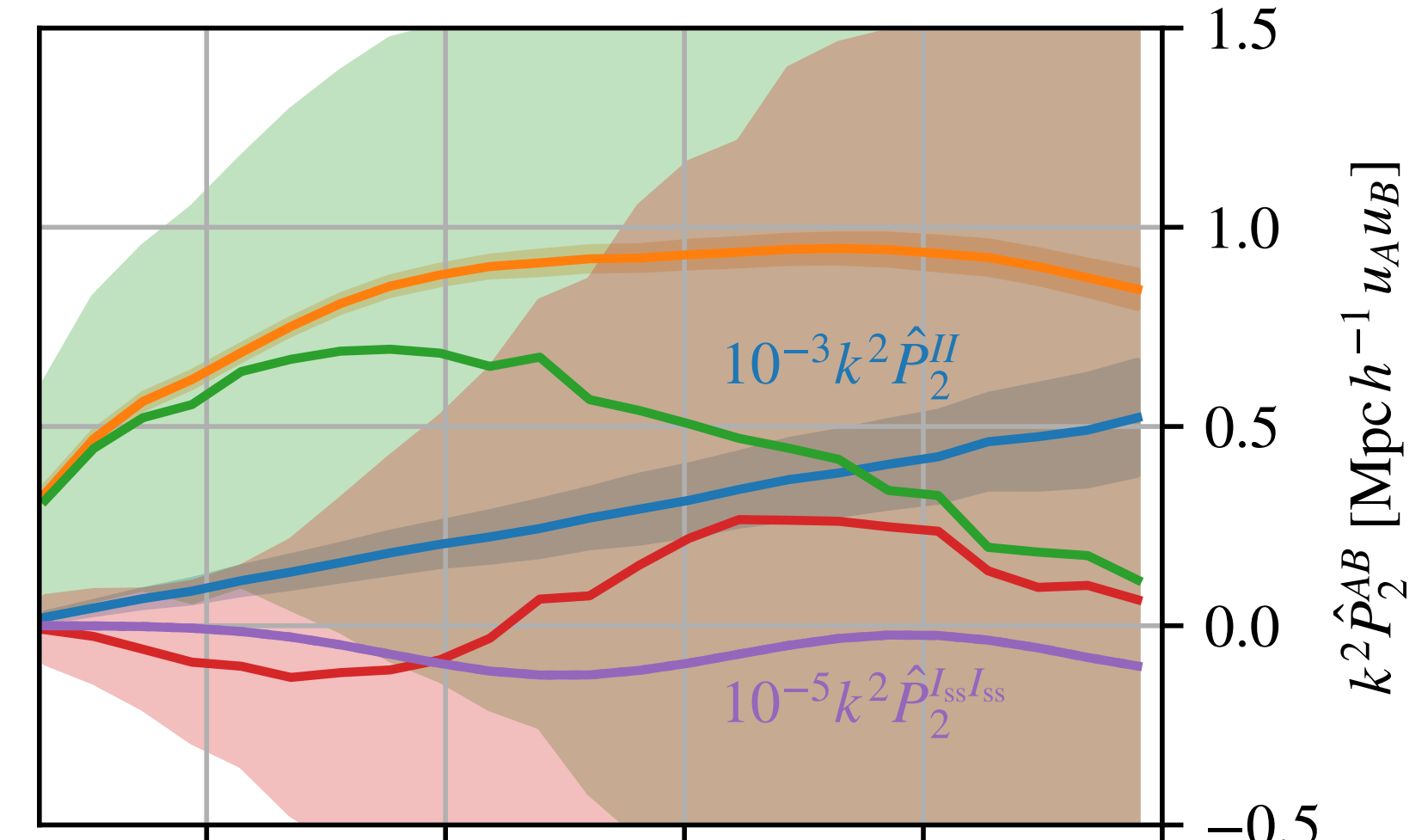
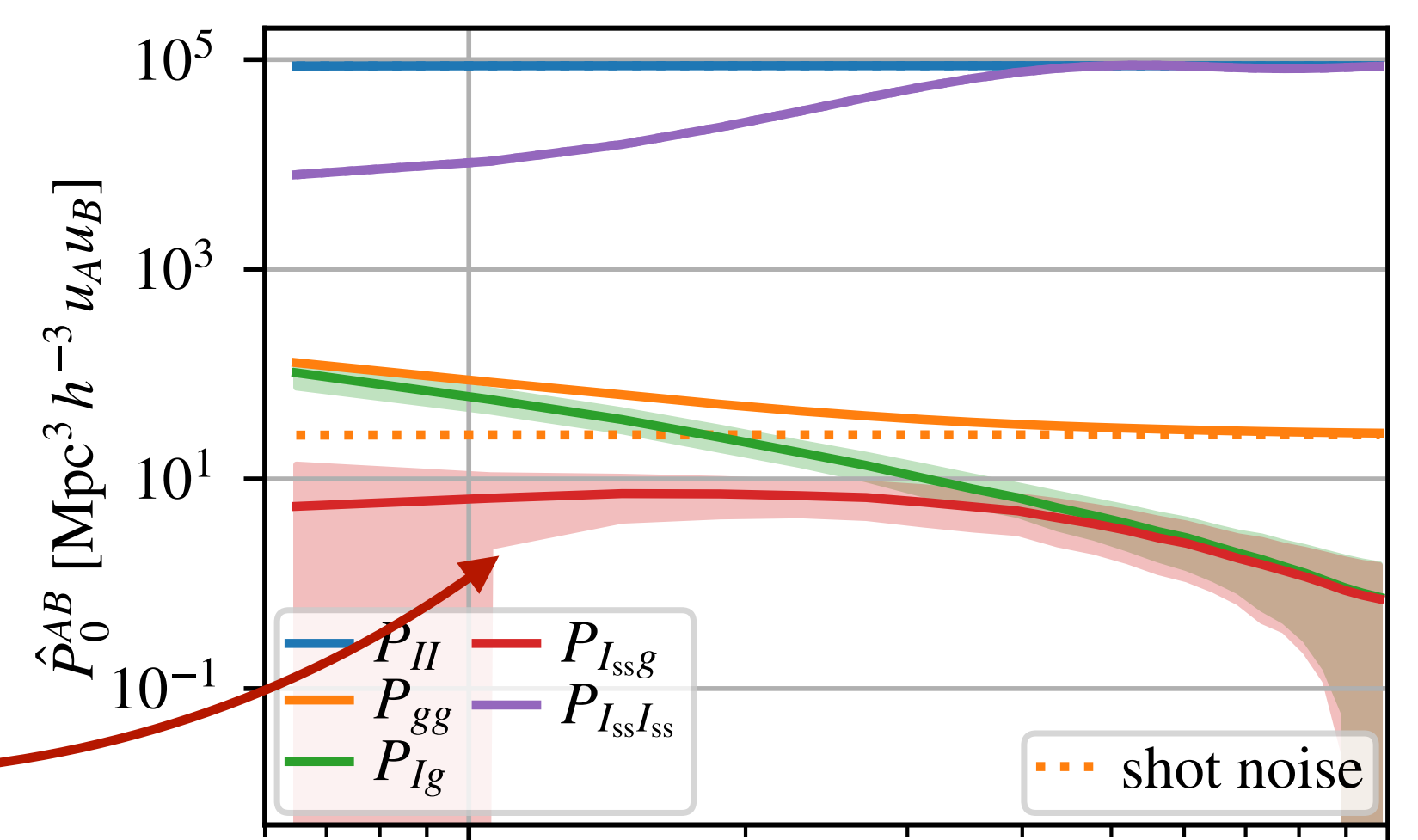
SIMPLE (INTENSITY MAP PRODUCER FOR LINE EMISSION)



HETDEX - LIM FORECAST

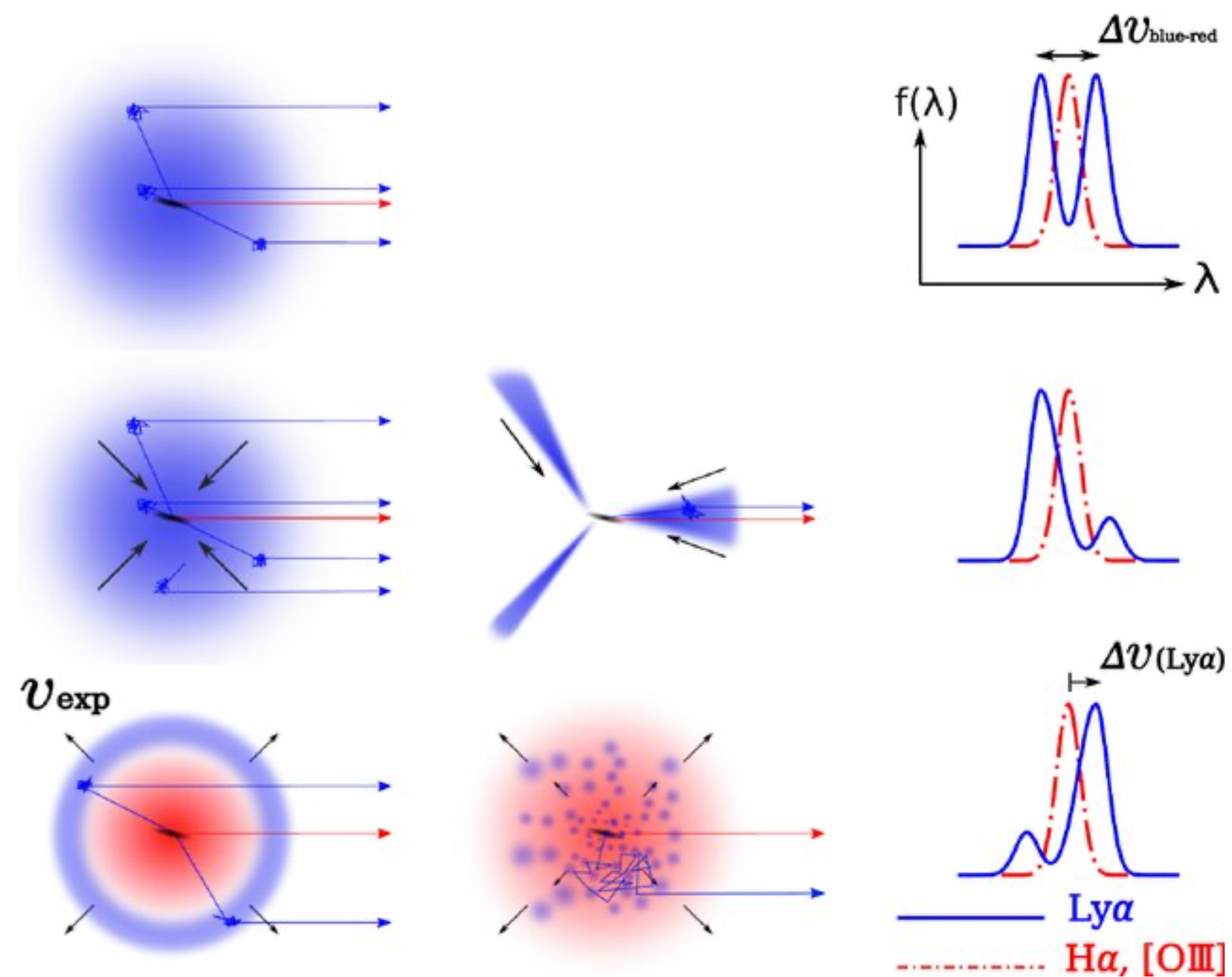
We will measure this: galaxies x sky-subtracted intensity

Removed shot noise from $P_{gg}(\mathbf{k})$ and intensity noise power from $P_{II}(\mathbf{k})$ and $P_{I_{ss}I_{ss}}(\mathbf{k})$



$\text{Ly}\alpha$ SCATTERING $\rightarrow$ PEAK SHIFT

FINGERS-OF-GOD-LIKE EFFECT



LY α SCATTERING $\rightarrow$ PEAK SHIFT

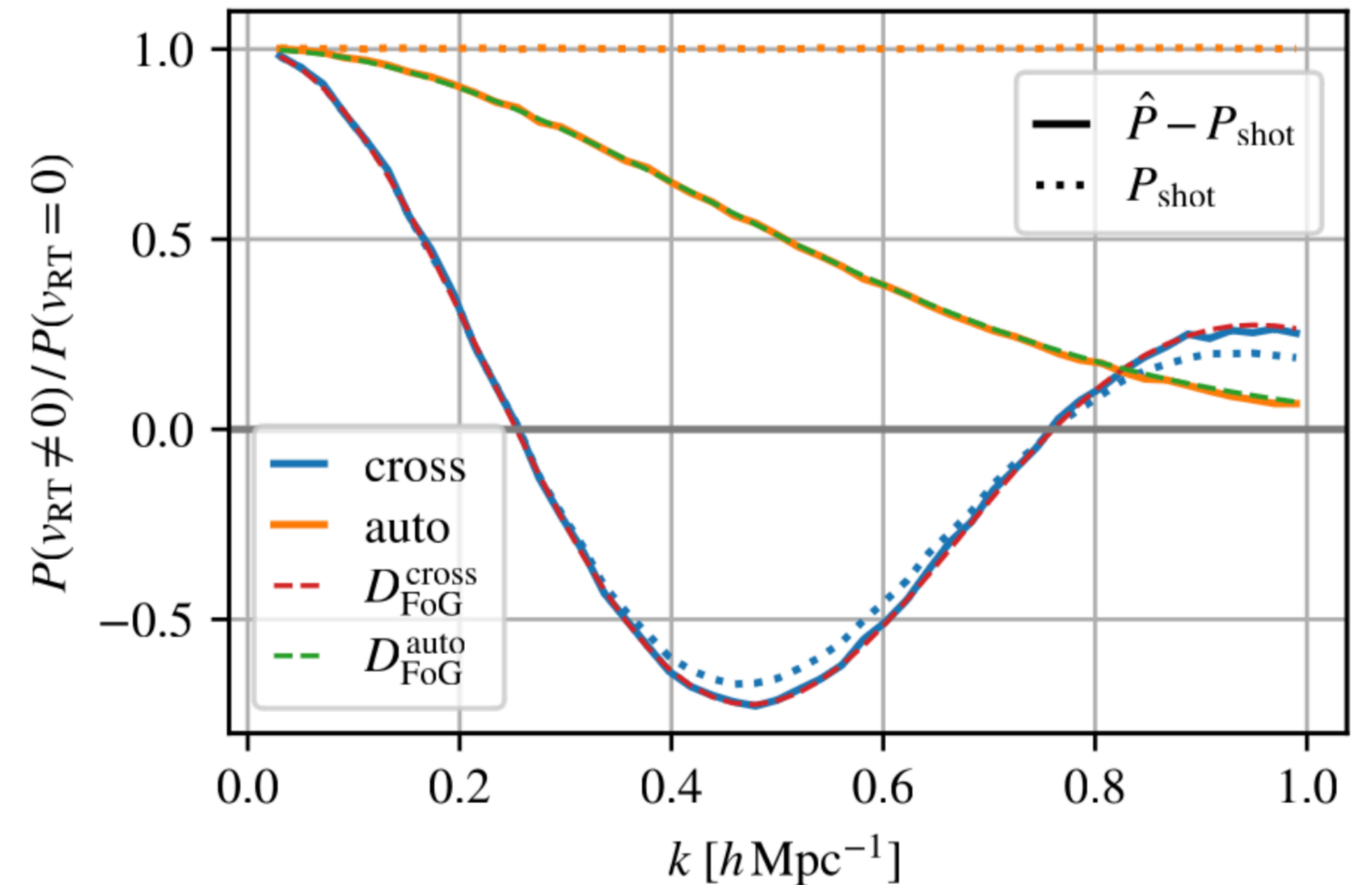
FINGERS-OF-GOD-LIKE EFFECT

Cross-power spectrum of Ly α tracer with non-Ly α tracer:

$$D_{\text{FoG}}^{\text{RT}} = \int du_{\parallel} P(u_{\parallel}) e^{ifk\mu u_{\parallel}} = e^{ifk\mu \bar{u}_x - \frac{1}{2}(f^2 k^2 \mu^2 \sigma_{u_x}^2)}$$

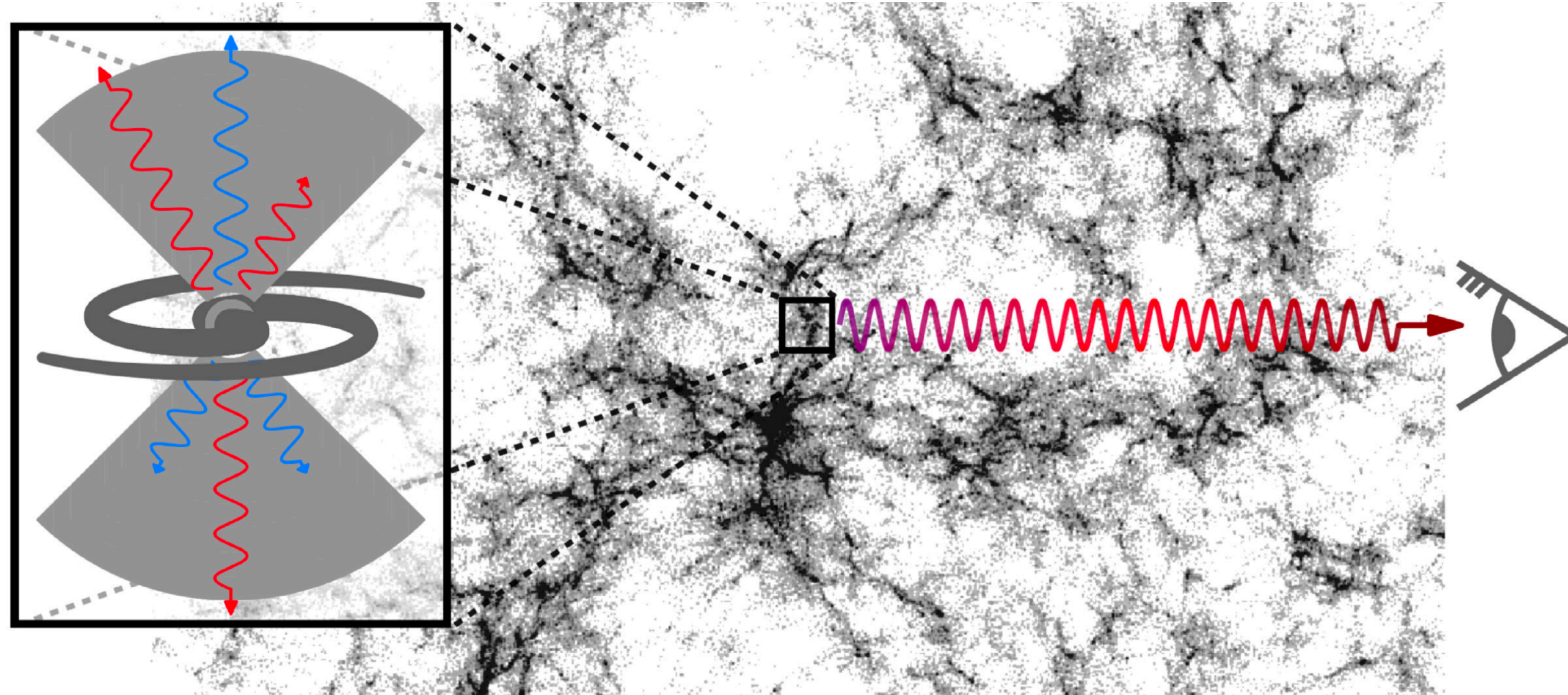
$\rightarrow$ Phase shift!

Gaussian PDF



LY α ABSORPTION DEPENDENT ON ENVIRONMENT

KAISER-LIKE EFFECT



$$\tau(\nu) \approx \frac{(c + v_z) n_{\text{H}}^2 \alpha_{\text{rec}}^A \sigma_{\text{Ly}\alpha}^{\text{tot}}}{\nu_{\text{Ly}\alpha} \Gamma \left| \frac{dv_z}{ds} + H(z) \right|}$$

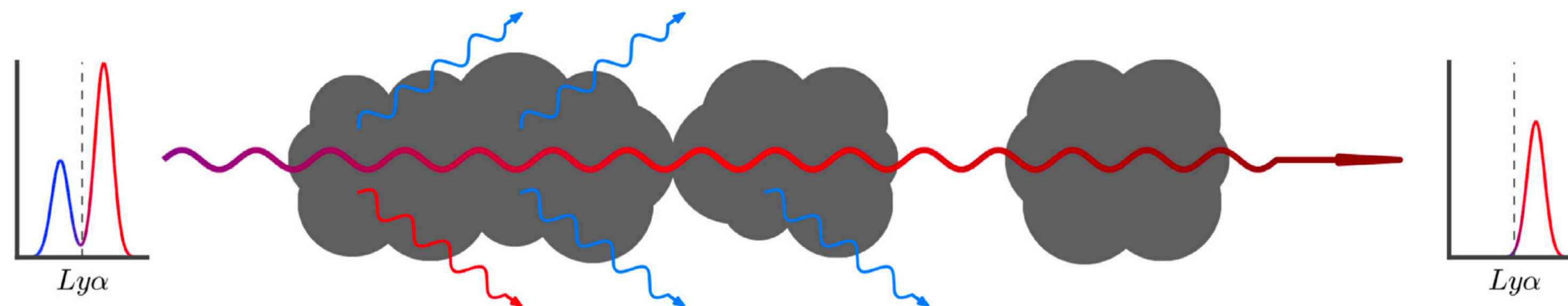
Optical depth depends on

- Neutral hydrogen density
- Velocity
- Velocity gradient of the environment.

Anisotropic selection bias of LAEs

→ lower effective bias

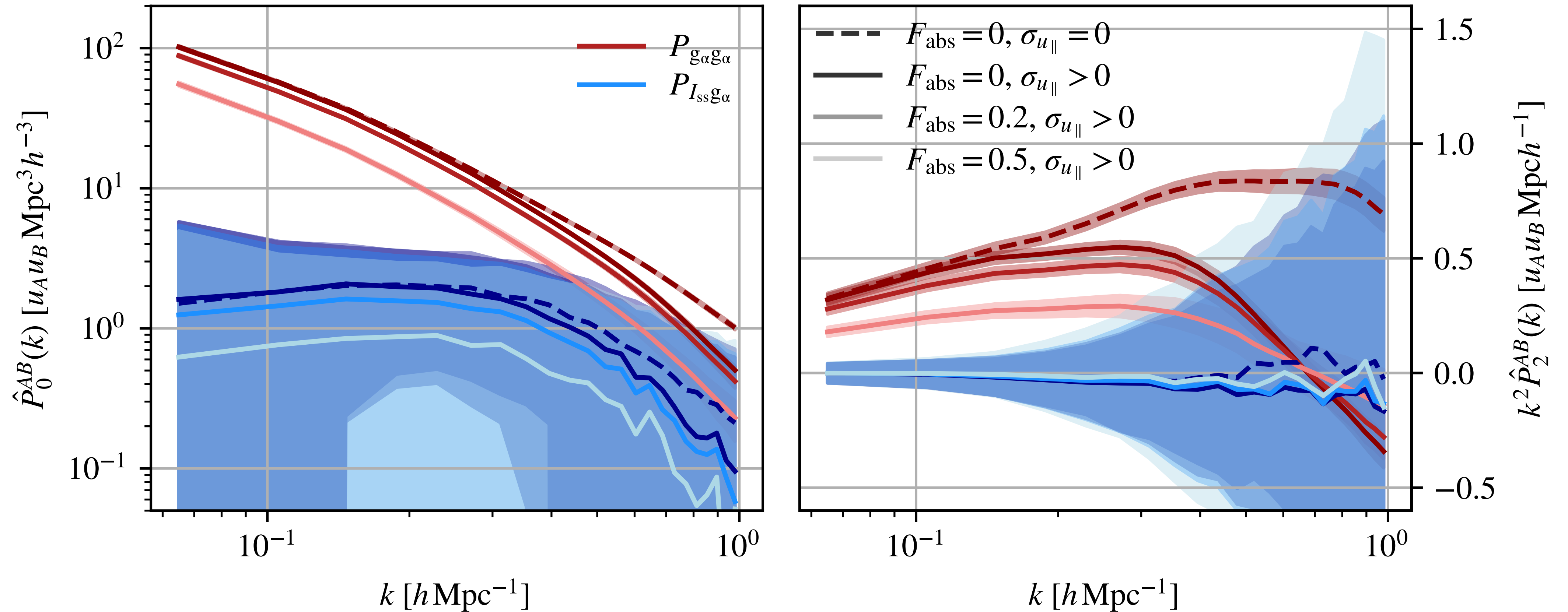
→ reduced or even inverted RSD



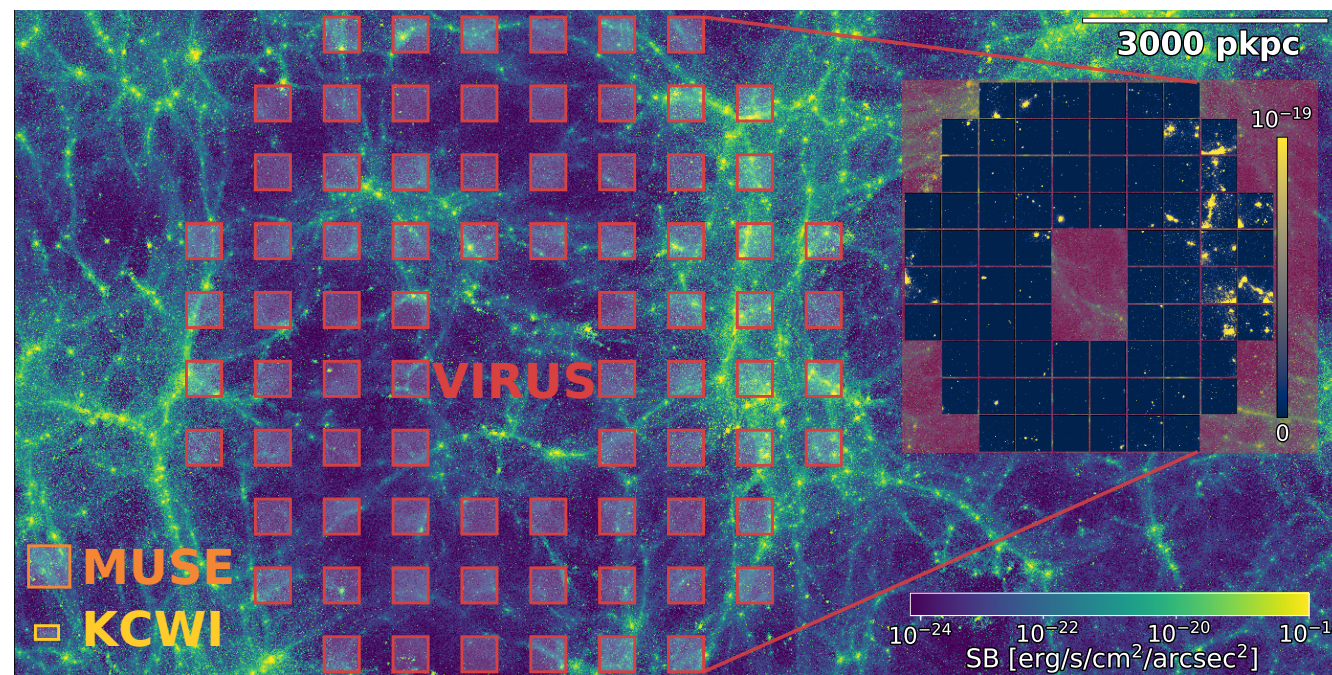
LY α ABSORPTION DEPENDENT ON ENVIRONMENT

KAISER-LIKE EFFECT

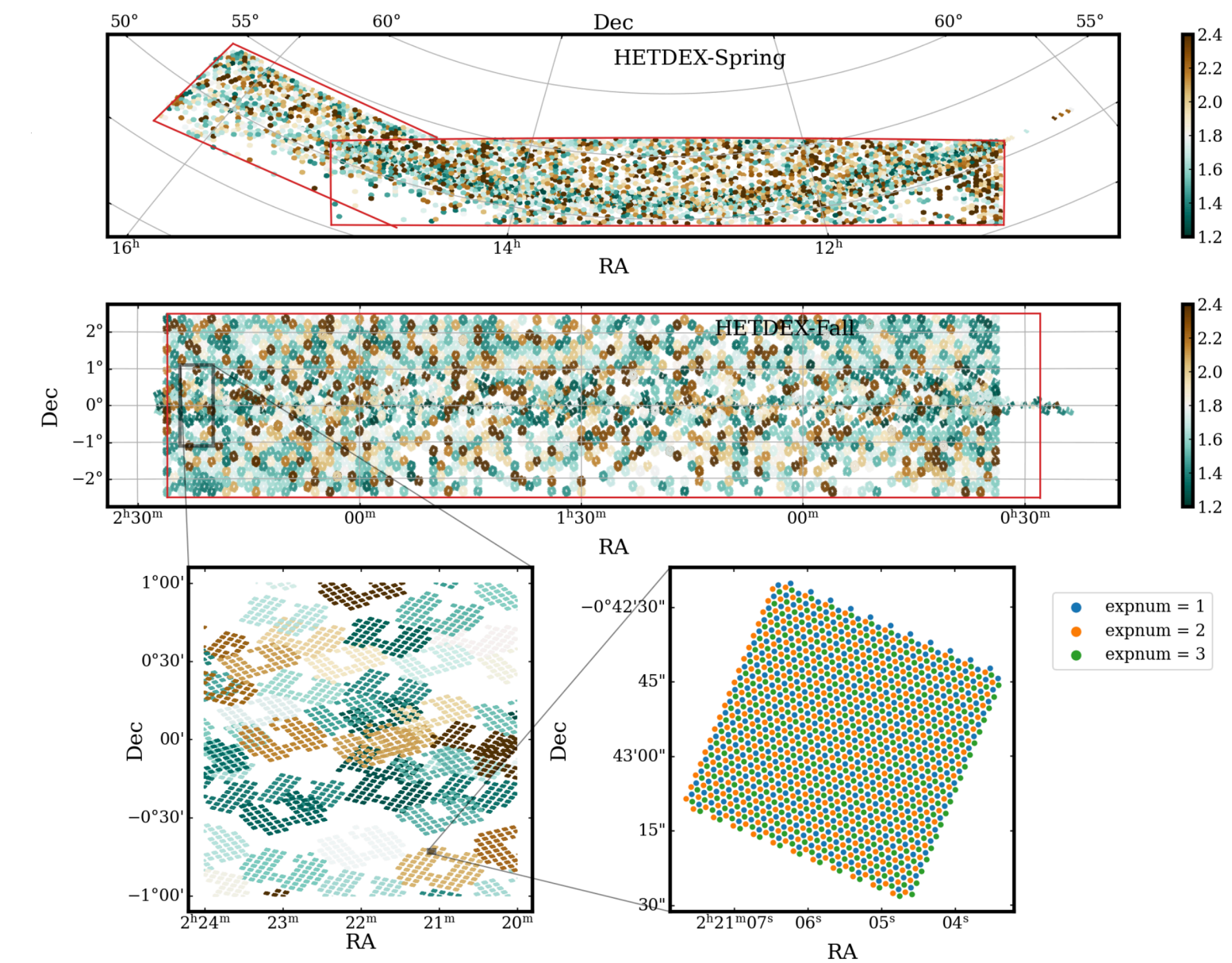
Suppression of the LAE-Ly α intensity cross-power spectrum $P_{g_\alpha \times I_\alpha}(k_\perp, k_\parallel)$



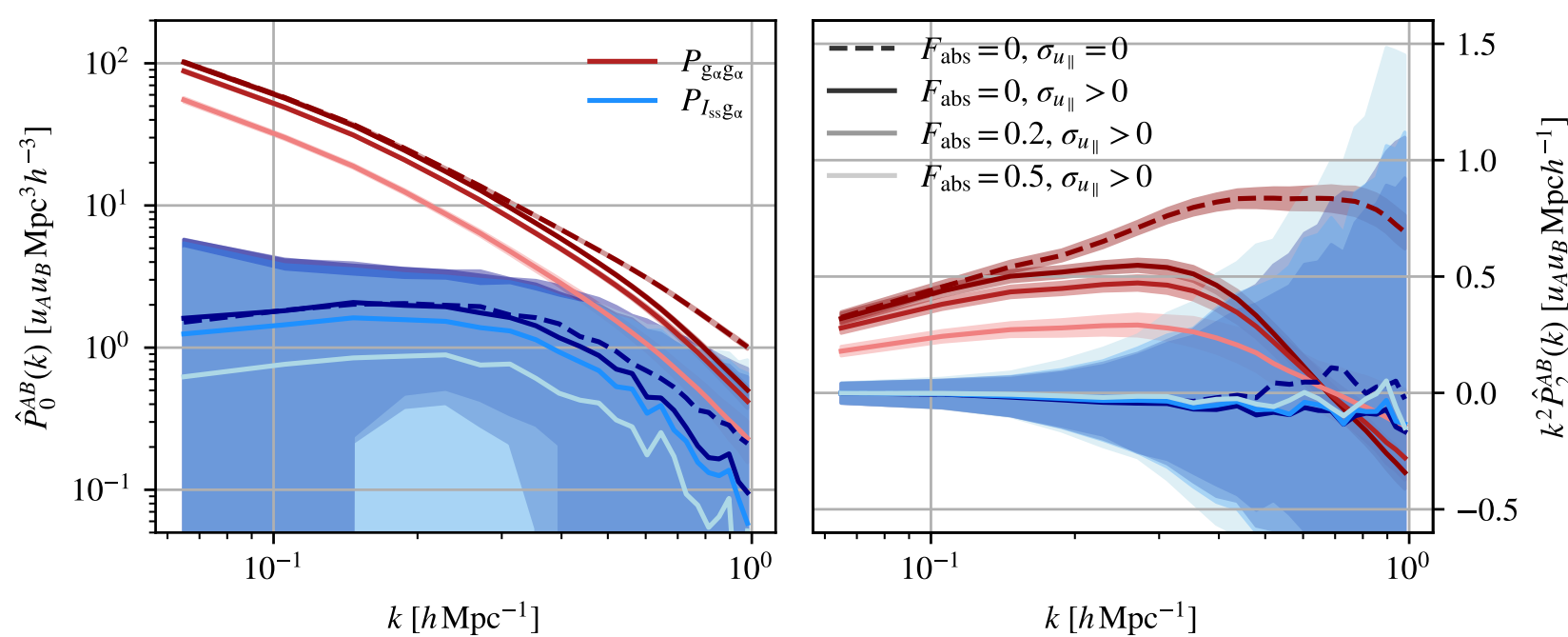
SUMMARY



HETDEX is an ideal LIM survey.



Public data release
in 2025!



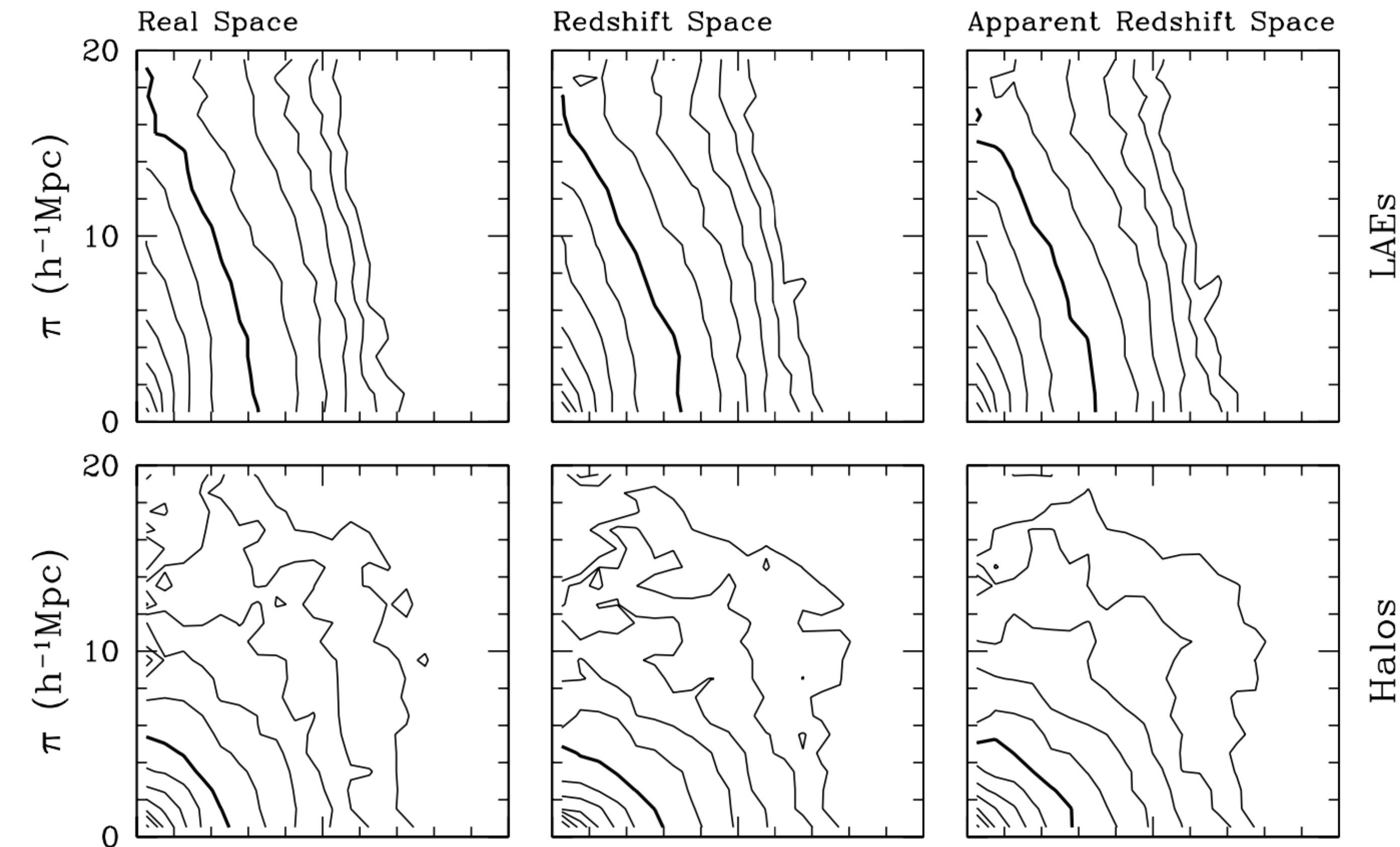
Radiative transfer effects
complicates the modeling.

LY α ABSORPTION DEPENDENT ON ENVIRONMENT

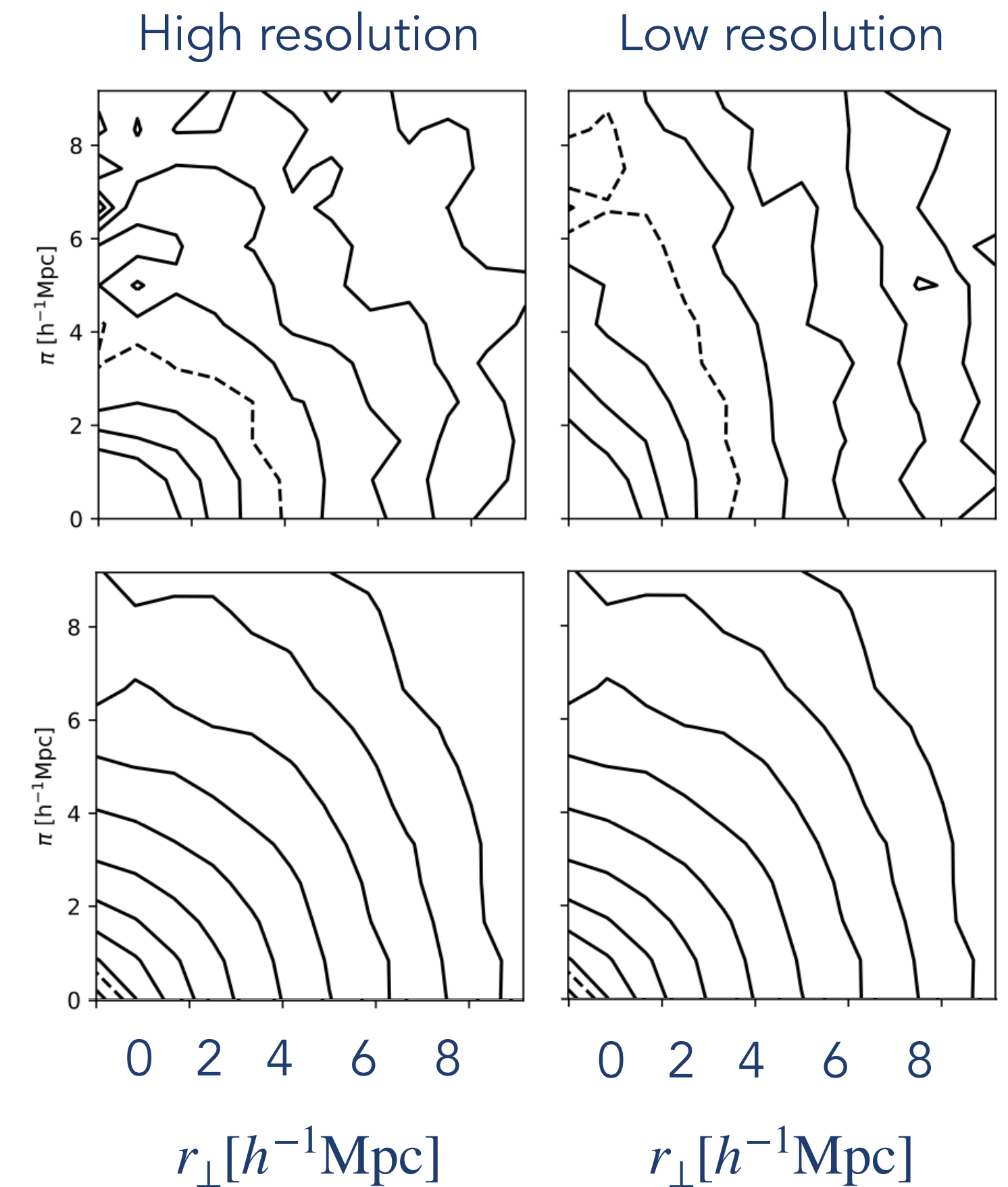
KAISER-LIKE EFFECT

Zheng et al. 2011

LAE correlation function



See also Wyithe & Dijkstra 2011, Behrens et al. 2018, Gurung-López et al. 2019, 2020

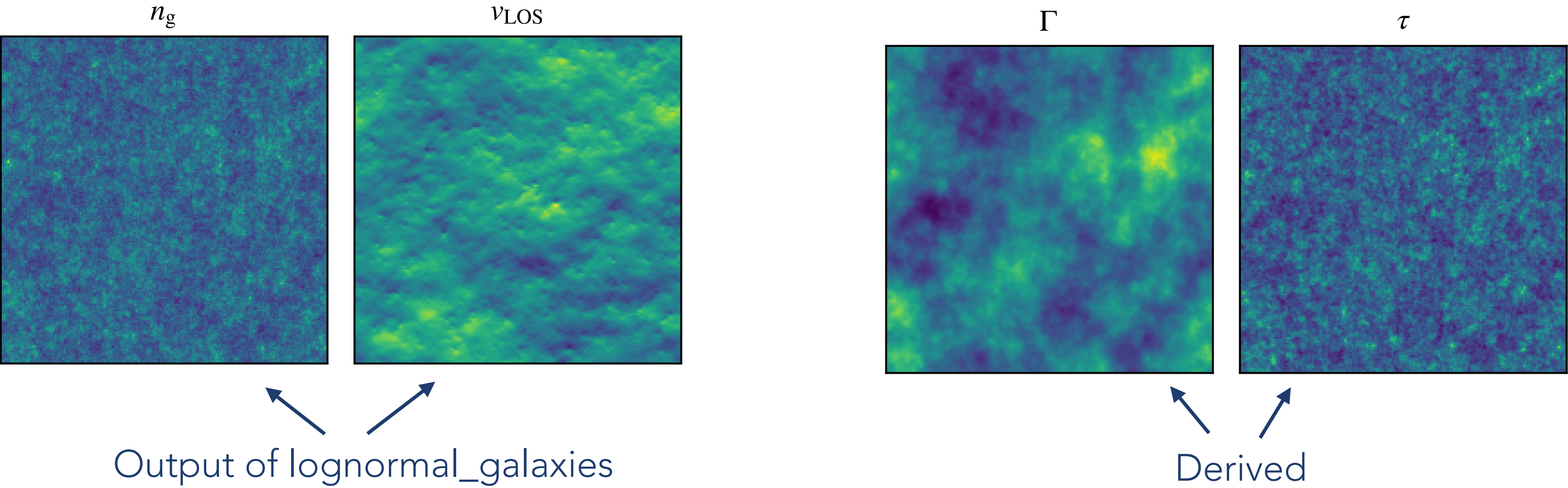


Behrens et al. 2018

LY α ABSORPTION DEPENDENT ON ENVIRONMENT

SIMPLE CODE

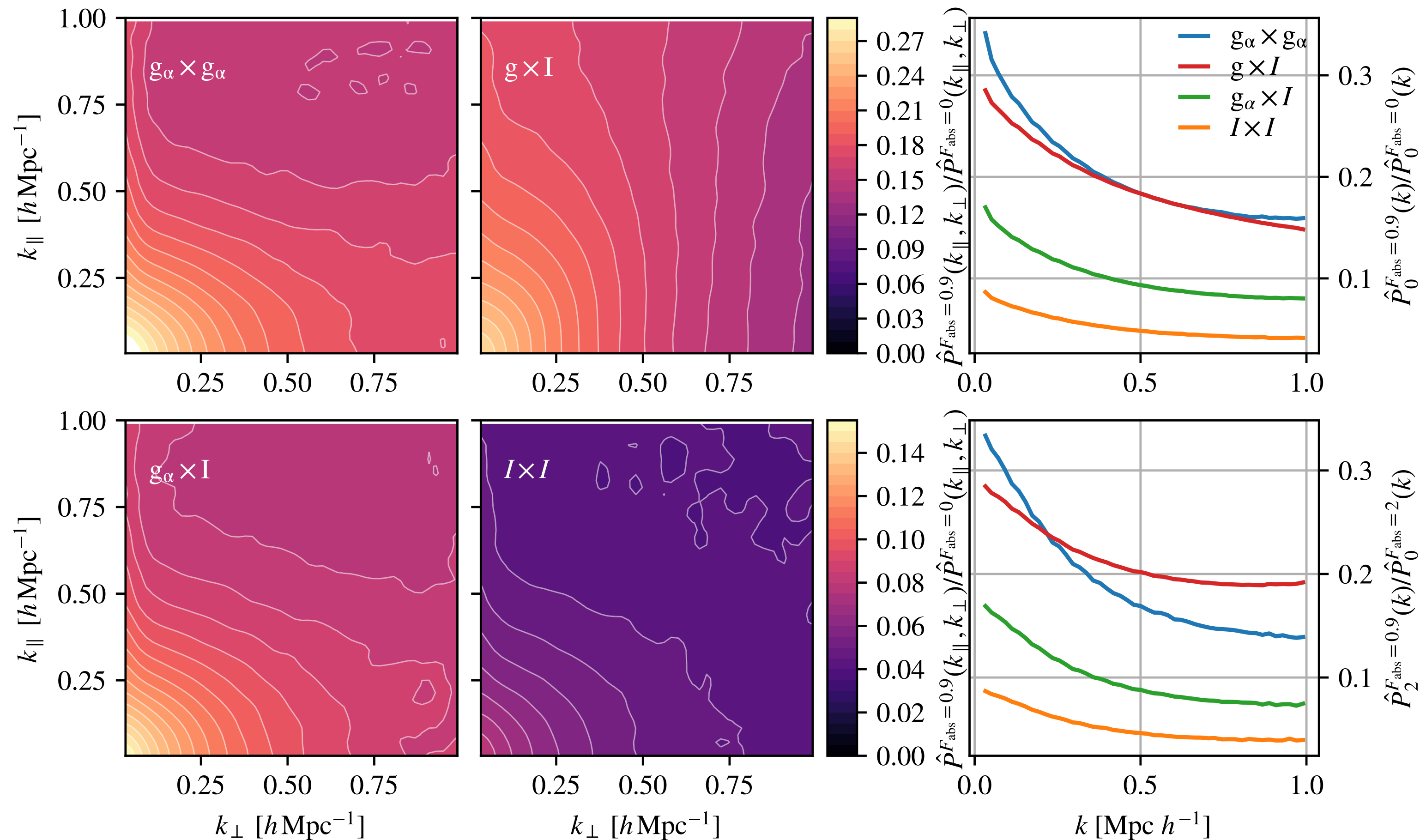
$$\tau(\nu) = \int_{r_{\text{vir}}}^{\infty} n_{\text{H}}(r) x_{\text{HI}}(r) \sigma_{\text{Ly}\alpha} \left(\nu \left[1 + \frac{v_z(r)}{c} \right] \right) \approx \frac{(c + v_z) n_{\text{H}}^2 \alpha_{\text{rec}}^{\text{A}} \sigma_{\text{Ly}\alpha}^{\text{tot}}}{\nu_{\text{Ly}\alpha} \Gamma \left| \frac{dv_z}{ds} + H(z) \right|}$$



LY α ABSORPTION DEPENDENT ON ENVIRONMENT

KAISER-LIKE EFFECT

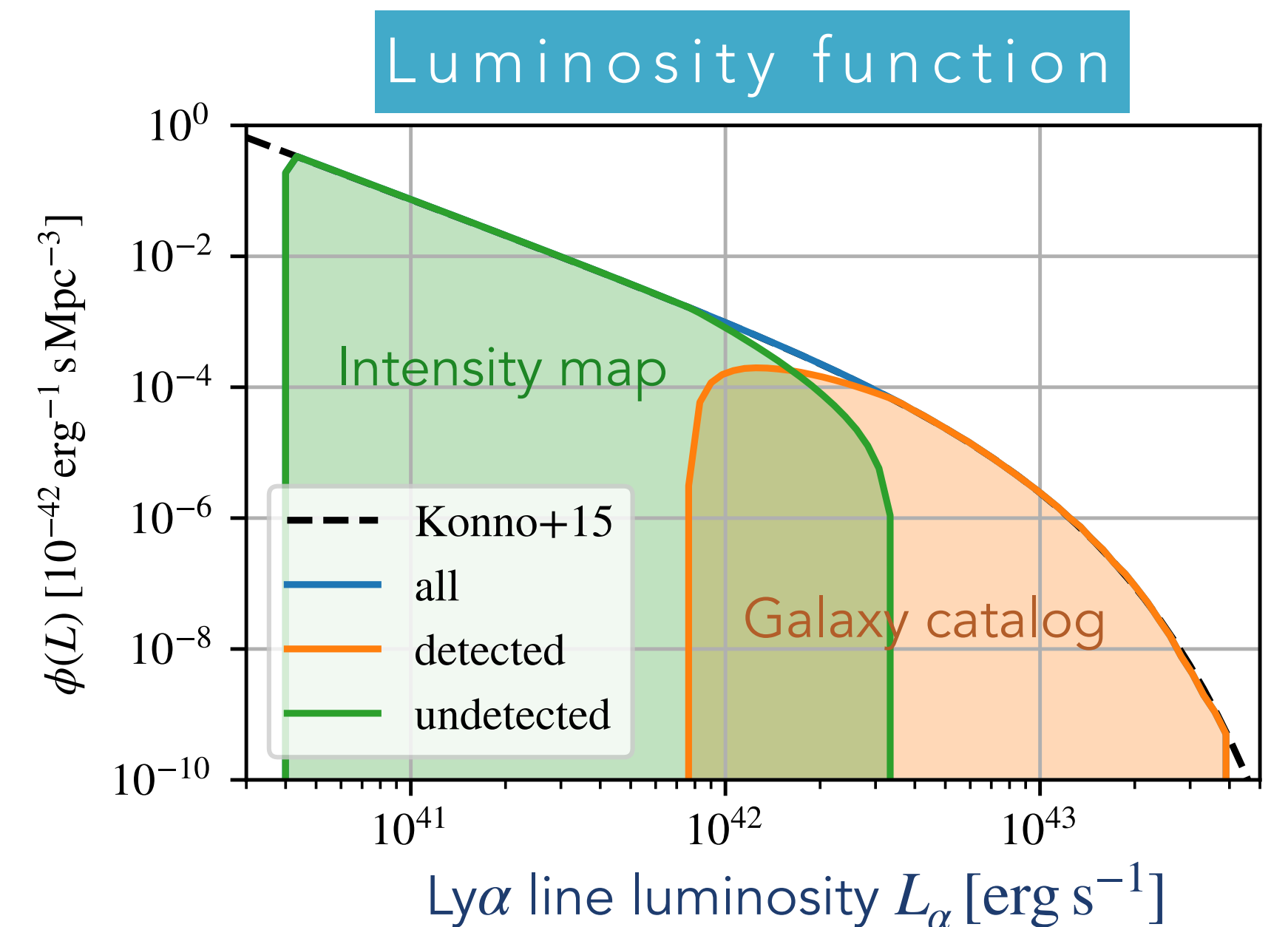
Suppression of the LAE-Ly α intensity cross-power spectrum $P_{g_\alpha \times I_\alpha}(k_\perp, k_\parallel)$



SIMPLE EXAMPLE SETUP - HETDEX

BASIC SETTINGS

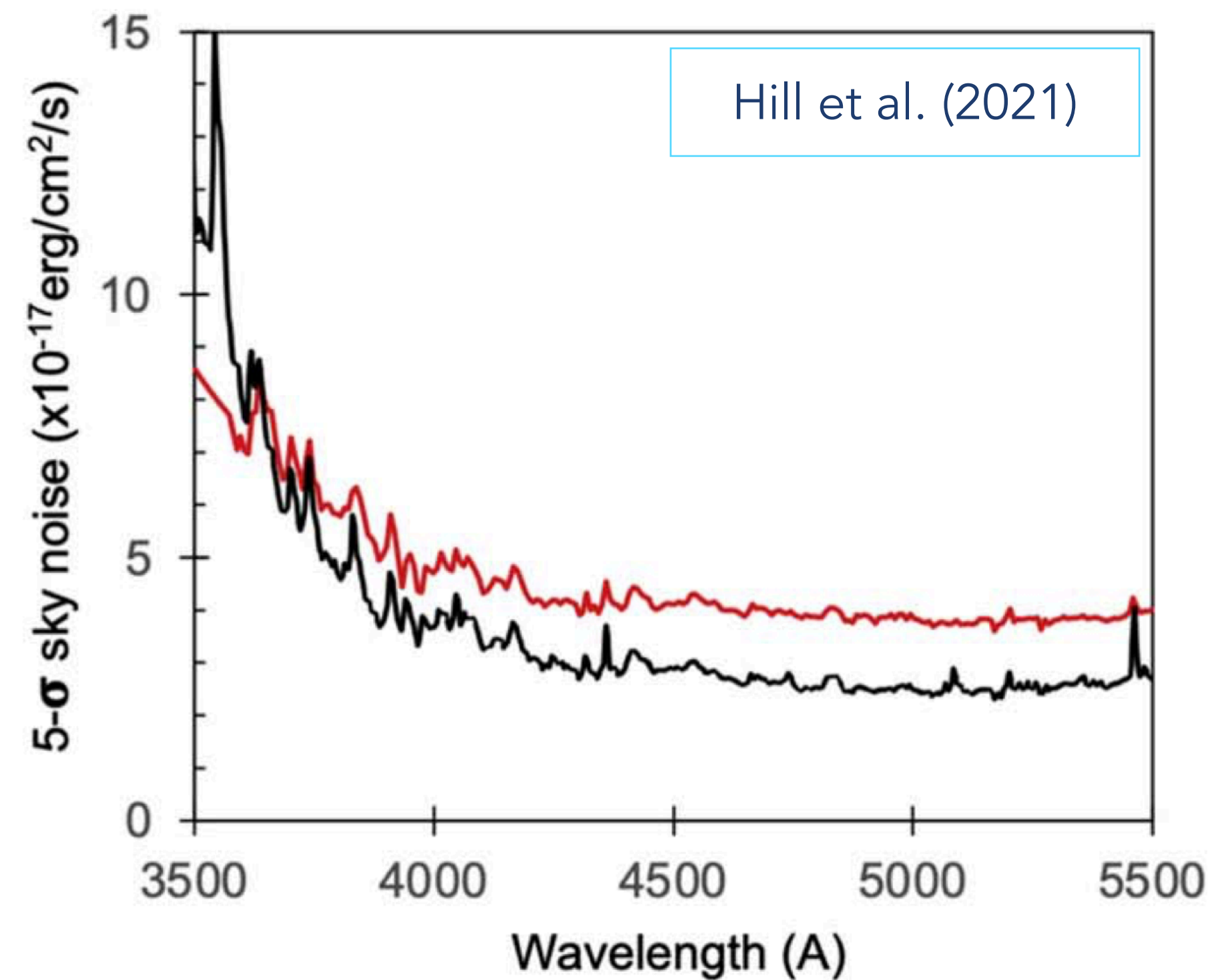
- Flat Λ CDM cosmology with $H_0 = 67.66 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{b,0}h^2 = 0.022$, $\Omega_{m,0}h^2 = 0.142$, $\ln(10^{10}A_s) = 3.094$, and $n_s = 0.9645$.
- Bias $b = 1.5$.
- $\text{Ly}\alpha$ rest-frame wavelength $1215.67 \text{ \AA}$.
- Luminosity function of Konno et al. (2016) for $z = 2.2$.
- Minimum luminosity $L_{\min} = 4 \times 10^{40} \text{ erg s}^{-1}$.
- Galaxy catalog: **detected** galaxies.
Intensity map: **undetected** galaxies
- Two redshift parts: $z \in [1.88, 2.57]$ and $z \in [2.57, 3.52]$.
- Box size: $622 (624) h^{-1} \text{ Mpc}$.
- Voxel size: $2 h^{-1} \text{ Mpc}$.
- 7 (9) mocks with different masks to obtain full HETDEX volume.
- Smoothing along the LOS $\sigma_\lambda = 2.38 \text{ \AA} \sim 1.76 (1.27) h^{-1} \text{ Mpc}$.



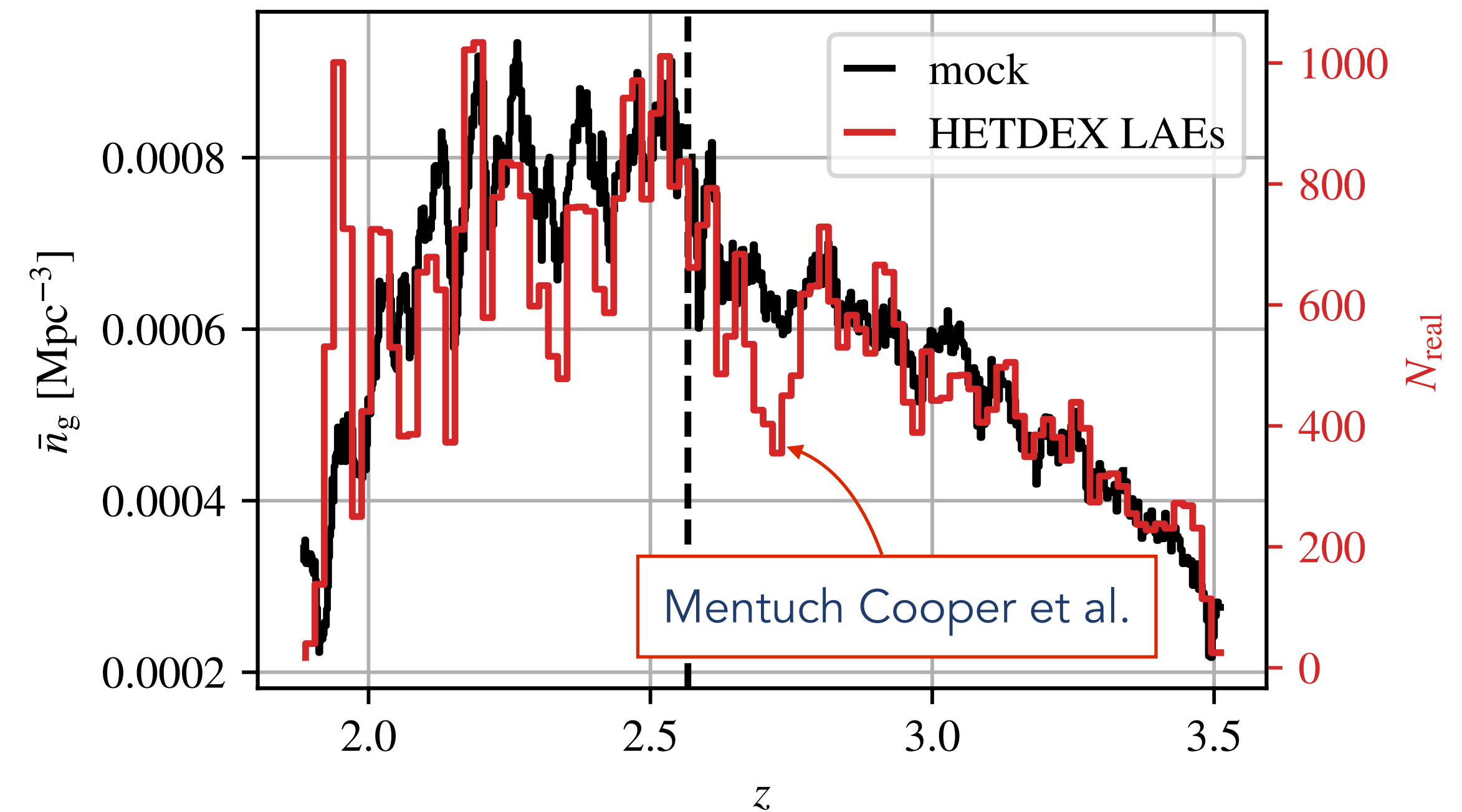
SIMPLE EXAMPLE SETUP - HETDEX

HETDEX-LIKE SELECTION FUNCTION AND NOISE

Measured sky noise in HETDEX (black line)



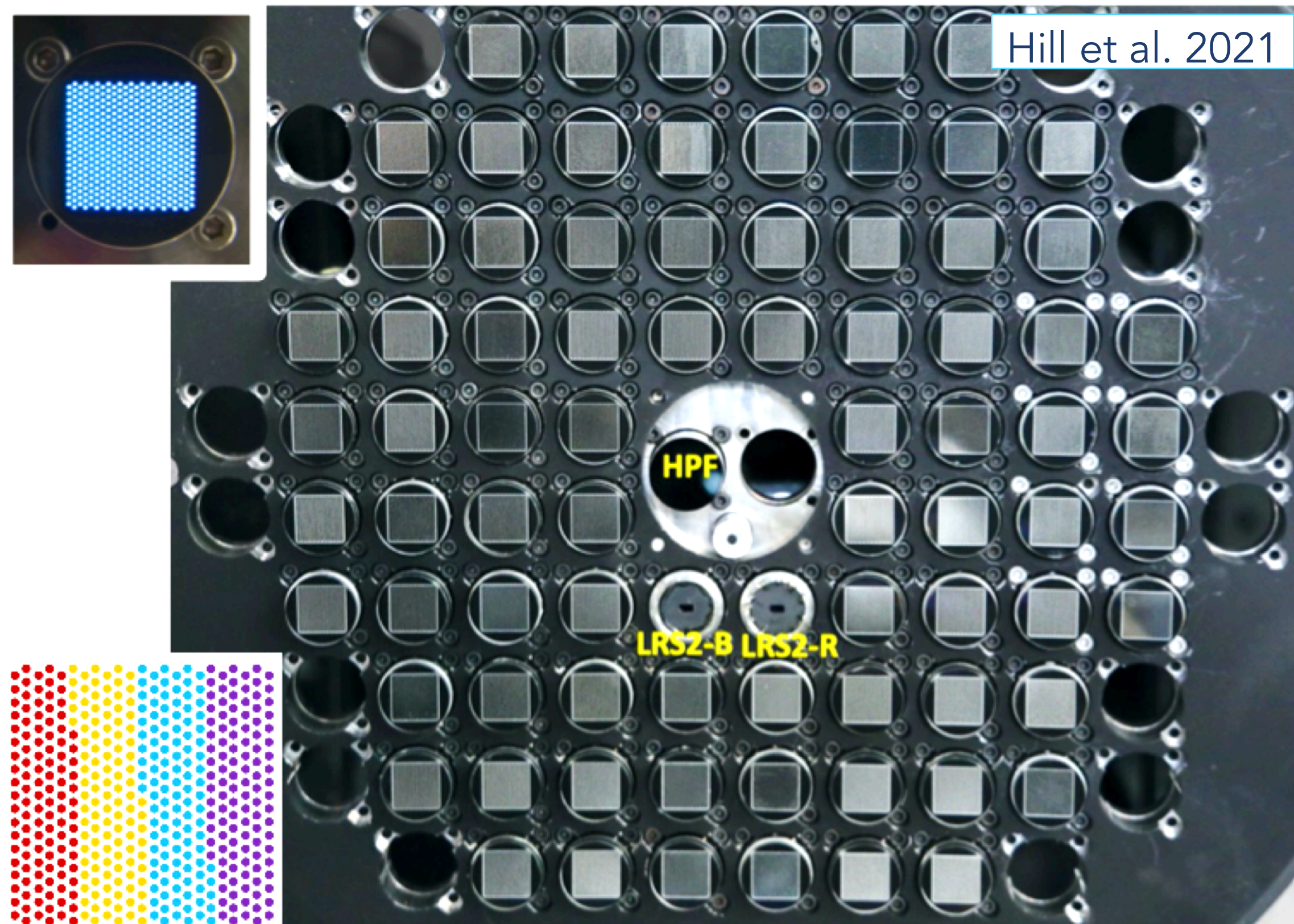
Reproduced shape of $n_g(z)$



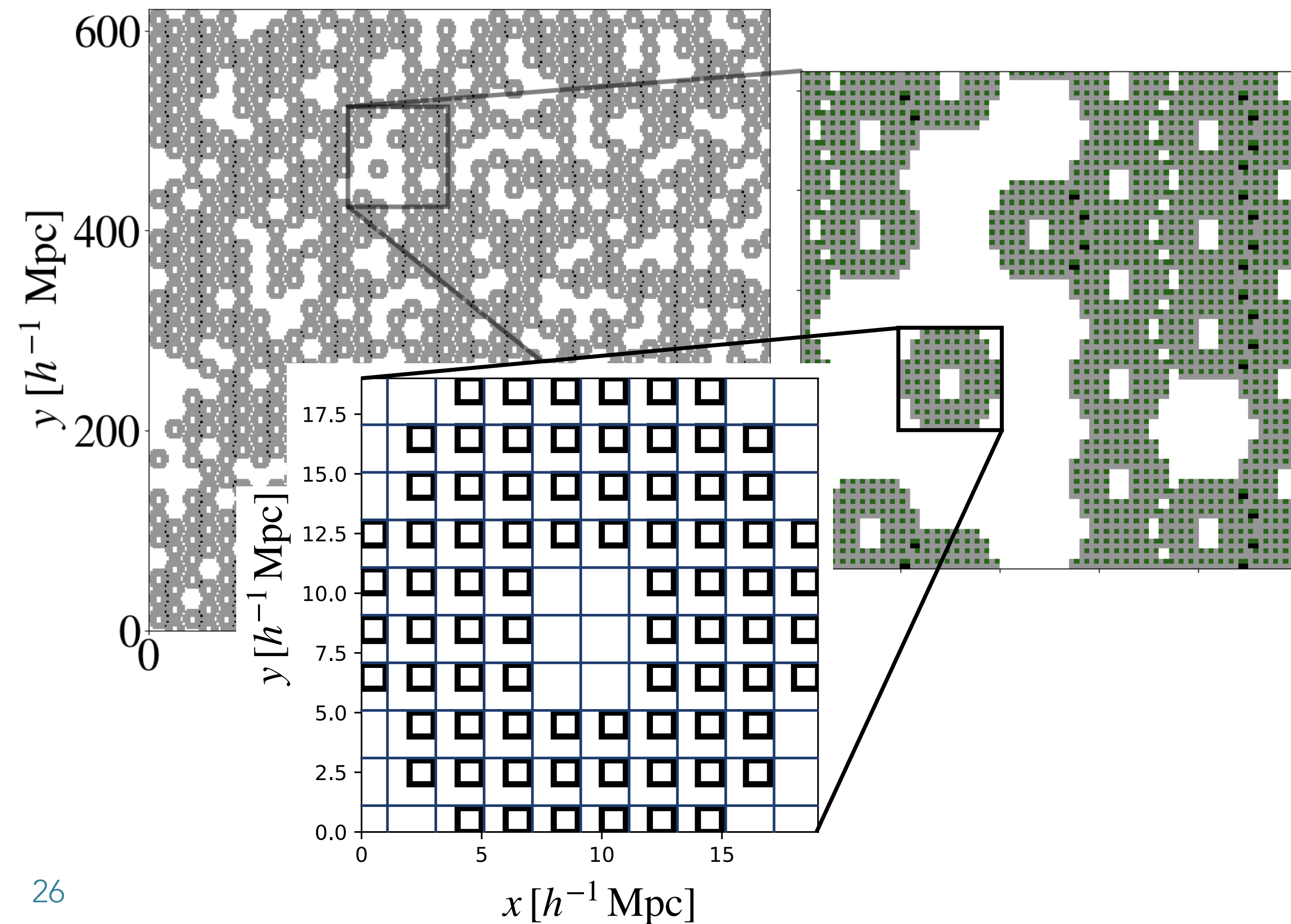
SIMPLE EXAMPLE SETUP - HETDEX

HETDEX-LIKE MASK

VIRUS layout



Example mask used for the mocks



HETDEX “LIM” PAPERS

- “Surface Brightness Profile of Lyman- α Halos out to 320 kpc in HETDEX” – M. Lujan Niemeyer, E. Komatsu, C. Byrohl et al.; [ApJ 929 90](#); [arXiv:2203.04826](#)
- “Ly α Halos around [O III]-selected Galaxies in HETDEX” – M. Lujan Niemeyer, W. P. Bowman, R. Ciardullo et al.; [ApJL 934 L26](#); [arXiv:2207.11098](#)
- “HETDEX Public Source Catalog 1—Stacking 50,000 Lyman Alpha Emitters” – D. Davis, K. Gebhardt, E. Mentuch Cooper et al.; [ApJ 954 209](#); [arXiv:2307.03096](#)
- “Absorption Troughs of Lyman Alpha Emitters in HETDEX” – L. H. Weiss, D. Davis, K. Gebhardt et al.; [ApJ 962 102](#); [arXiv:2401.02490](#)
- “Using Ly α Absorption to Measure the Intensity and Variability of $z \sim 2.4$ Ultraviolet Background Light” – L. H. Weiss, K. Gebhardt, D. Davis et al.; [ApJ 983 72](#); [arXiv:2504.13253](#)
- Several papers in preparation (Ly α blobs, Ly α profiles around LAEs and AGN, Ly α absorption halos, **cross-P(k) of LAEs with Ly α intensity**)

SKY SPECTRUM

