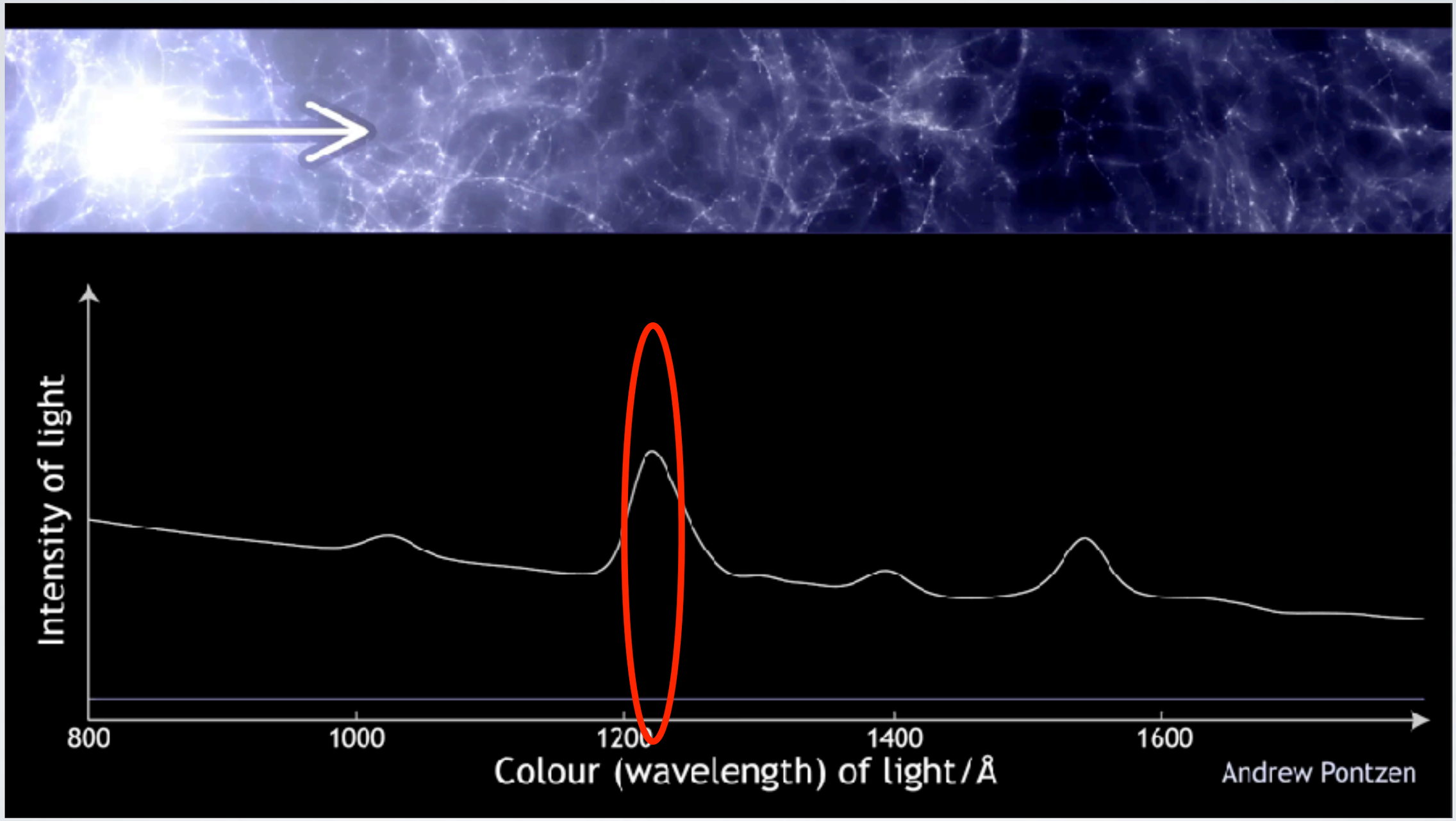
Lyman-alpha Forest in the Era of 10+m class Spectroscopic Surveys

"Cosmic Visions: Dark Energy" Workshop, LBNL
November 13, 2017

Khee-Gan ("K.-G,") Lee
Hubble Fellow, Lawrence Berkeley National Lab

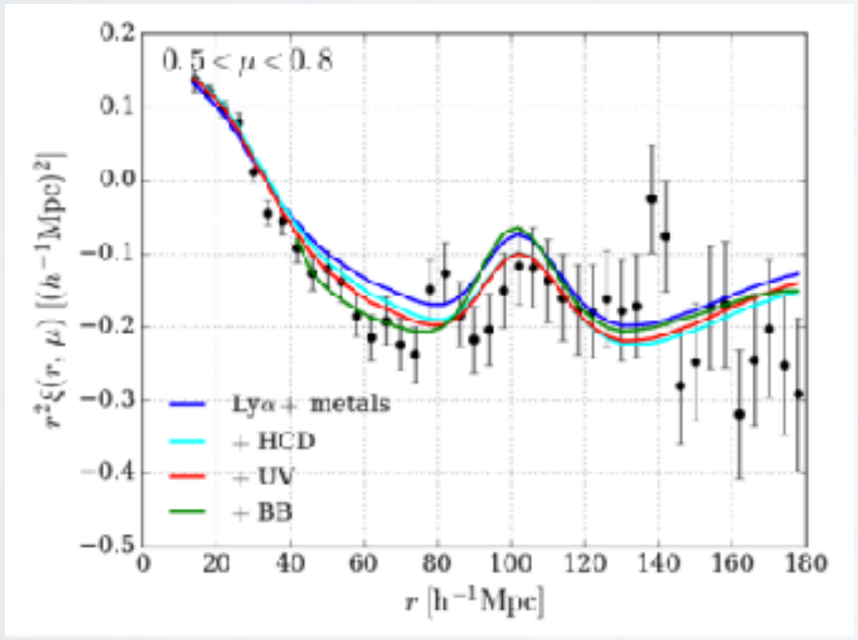
The Lyman-alpha Forest at z>2



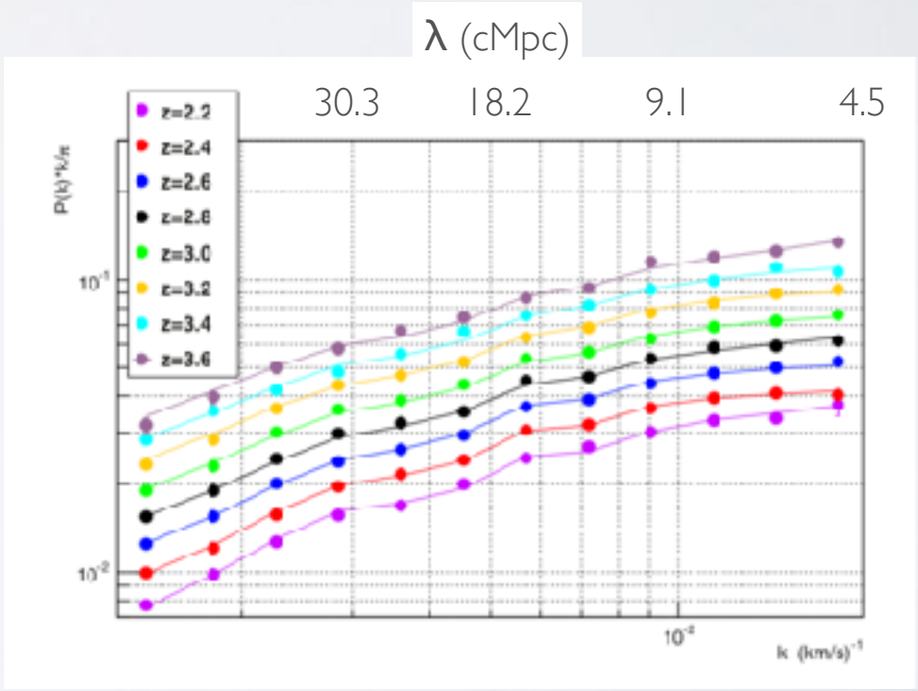
Restframe 1215.67Å absorption from neutral HI in intergalactic medium (https://youtu.be/HUo51YFHvls)

Lyα Forest Cosmology In BOSS

- Lyα forest provides a unique probe into cosmology at 2<z<4
- 2.5% BAO distance measurement at <z>~2.3 from 3D absorption correlations in BOSS (Bautista+2017). DESI will push this to <1%
- Small-scale power (r <20cMpc) is sensitive to, e.g. sum of neutrino masses: $\sum m_\nu$, amplitude of structure fluctuations, σ_8, slope and curvature of primordial matter power spectrum, n_s, $dn_s/d\ln k$. Measured only in 1D in BOSS due to sightline sparsity

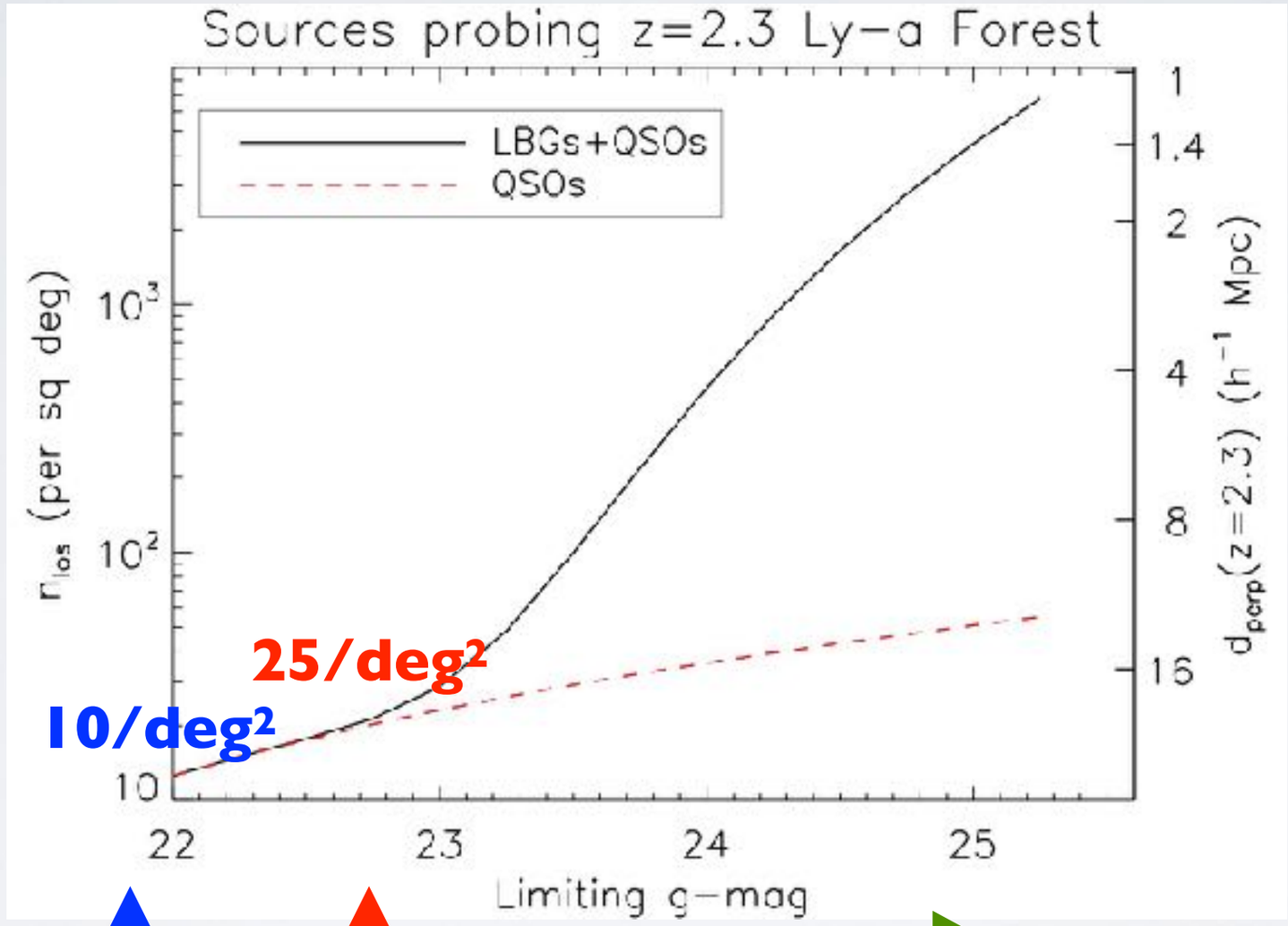


3D LyaF BAO, Bautista+2017



1D $P_F(k)$, Palanque-Delabrouille+2013

GOING BEYOND QUASARS FOR LY-ALPHA FOREST



# of Ly-a forest sightlines per sq deg

Average sightline separation

BOSS (2.5m)

DESI (4m)

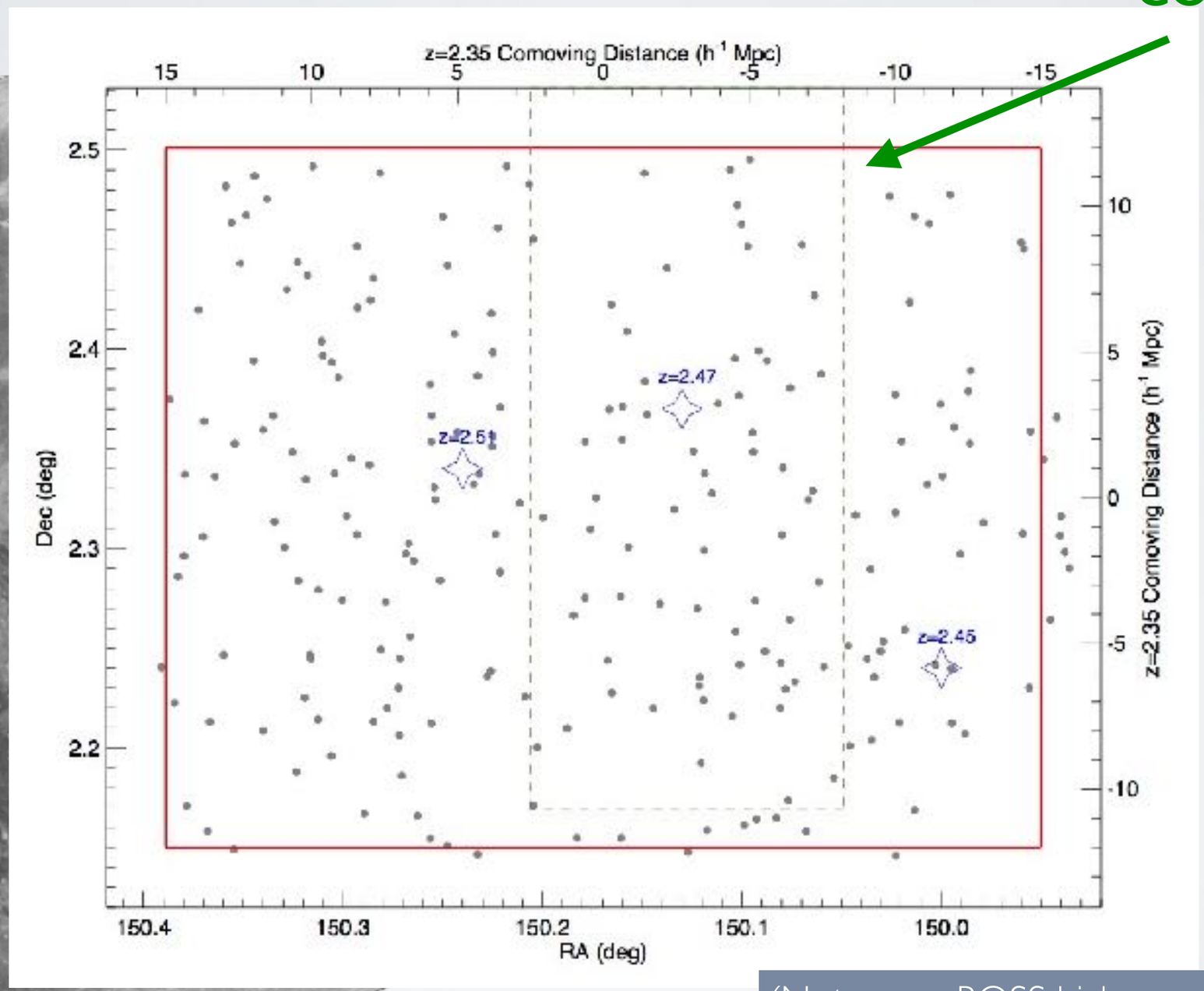
Huge jump in sightline availability with LBGs/star-forming galaxies!

COSMOS LYMAN-ALPHA MAPPING AND TOMOGRAPHY OBSERVATIONS (CLAMATO)

- Keck survey on COSMOS field (10hr, +02deg); **Lee+2017, arXiv:1710.02894**
- Aim to get spectra LBGs+QSOs at z~2-3, to sample 2.1<z<2.5 Ly-a forest with sightline separations of **~2.5h^{-1}Mpc**
- *First systematic use of galaxies as Lyα forest background sources!*
- 2-4hr integrations with 10.3m Keck-I telescope down to g<24.8
- ~60hrs on-sky observations so far
- Ongoing science analyses:
  - Cosmic voids at z~2.3
  - Protocluster characterization
  - Galaxy-absorption cross-correlation

Current Status: 240 sightlines over 27' × 21' area (0.16 deg^2), covering 2.05<z<2.55 with mean transverse separation $d_\perp$=2.5h^{-1}Mpc

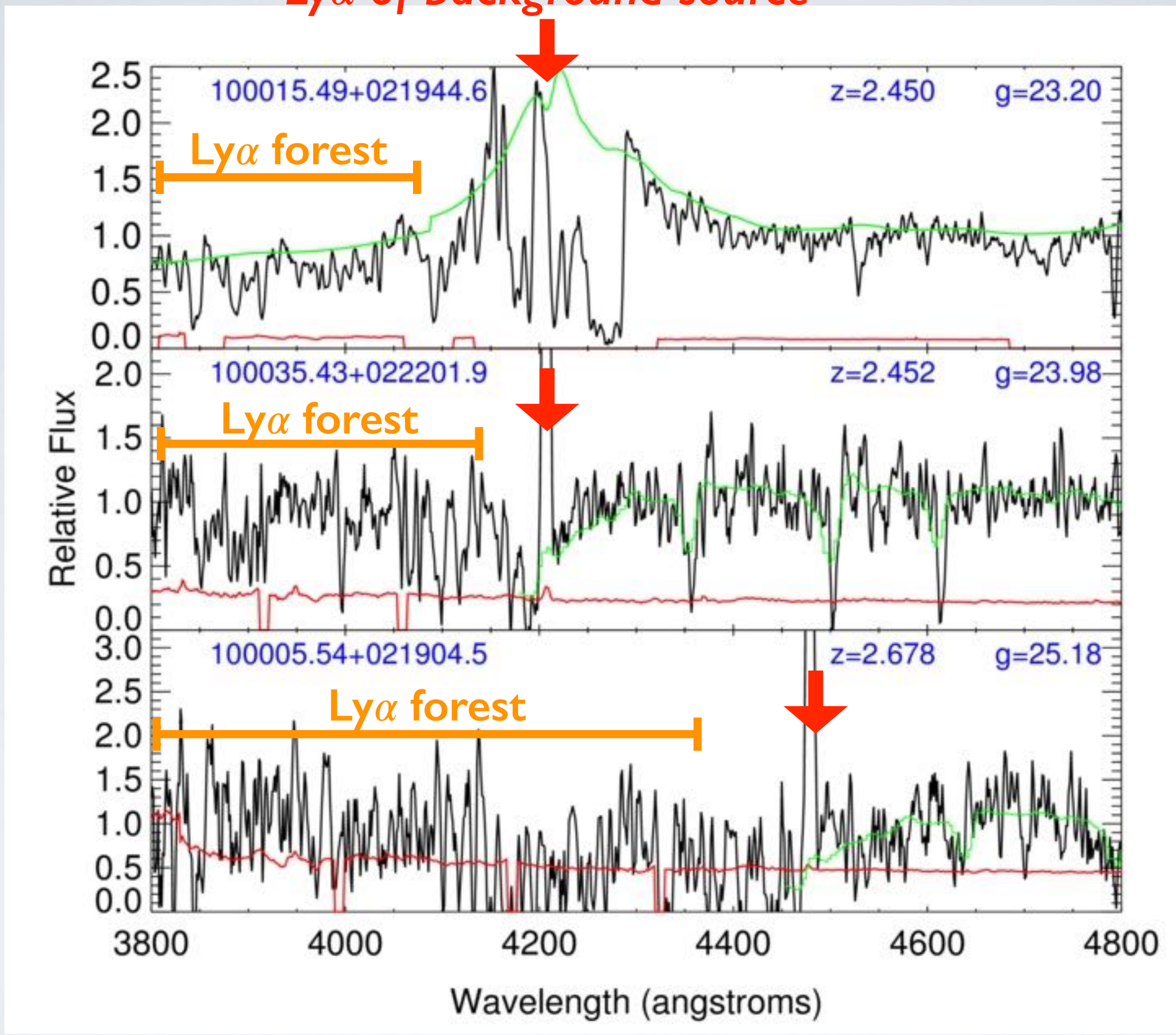
30 h^{-1}Mpc



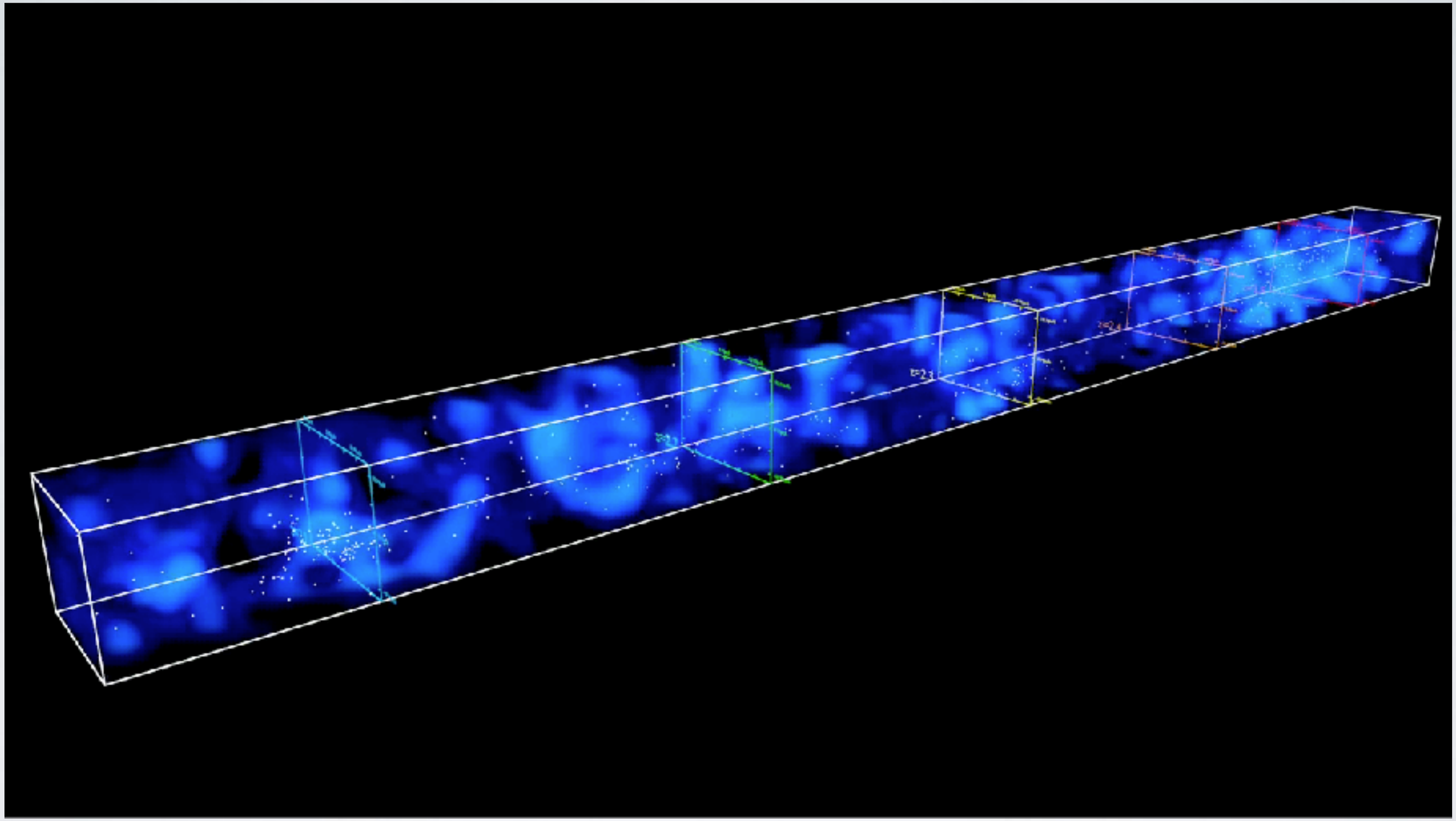
COSMOS/CANDELS Field

24 h^{-1}Mpc

(Note: zero BOSS high-z quasars within this footprint!)



Color scheme: **spectrum**, noise vector, spectral template

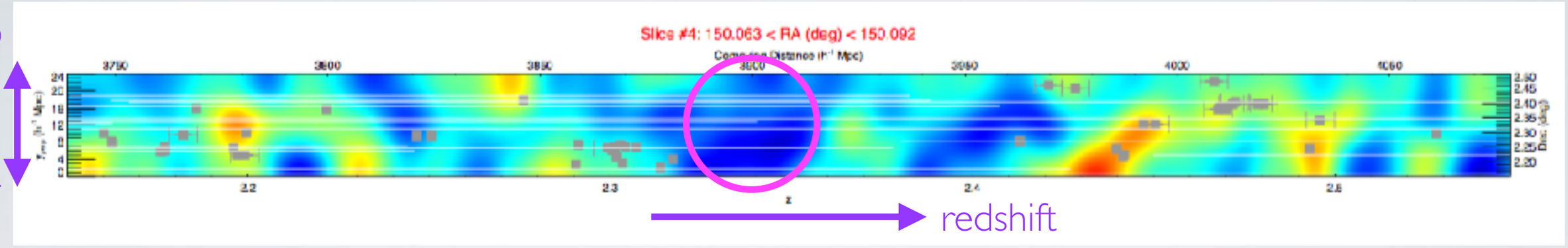


YouTube: *http://tinyurl.com/clamatovid-v2*

See also *http://tinyurl.com/clamato2017-x3d-v1*

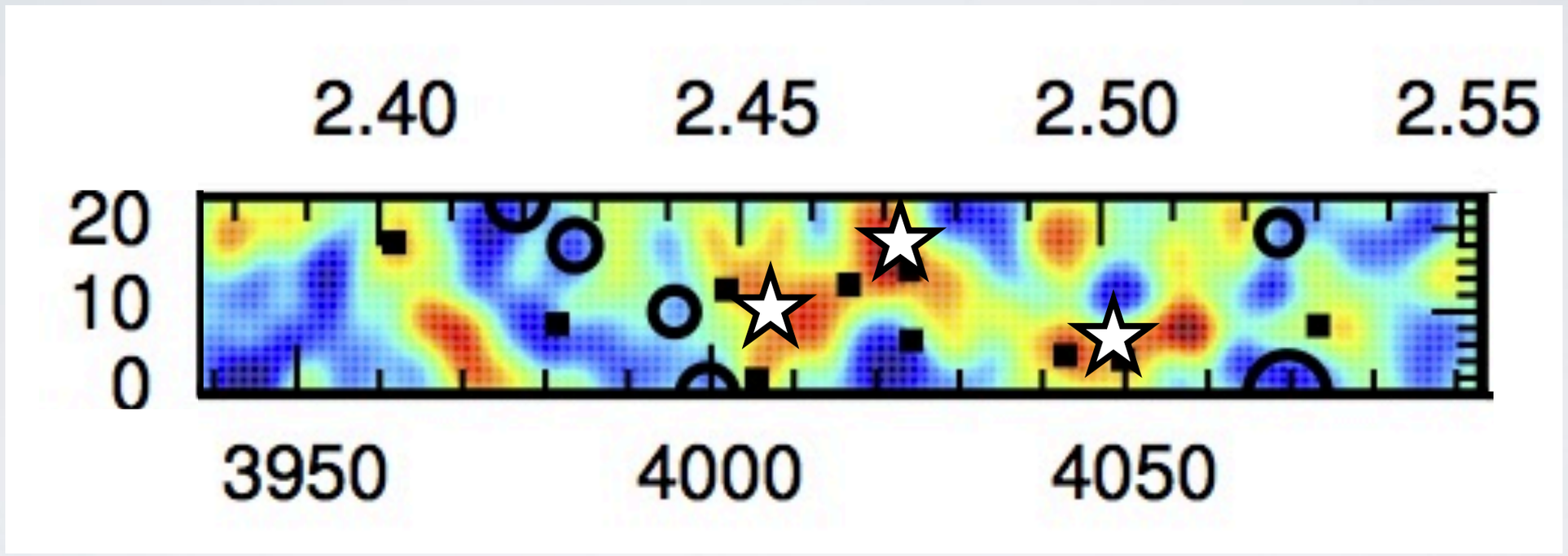
First Detection Of Cosmic Voids At High-z

Krolewski, Lee, et al 2017, arXiv:1710.02612



- Currently most distant-known cosmic voids are at z~0.9 (VIPERS Survey, Hawken+2016)
- Clearly see coherent underdensities in the CLAMATO map at 2.05<z<2.55
- Search for voids in CLAMATO using simple "spherical underdensity" void finder (e.g. Stark, Font-Ribera, White, **Lee**, 2015): 339 voids with r>2Mpc/h and 48 with r>5Mpc/h
- Voids identified in the tomographic map are also devoid of galaxies with spec-z's in the same volume → 5.9σ underdense compared to random

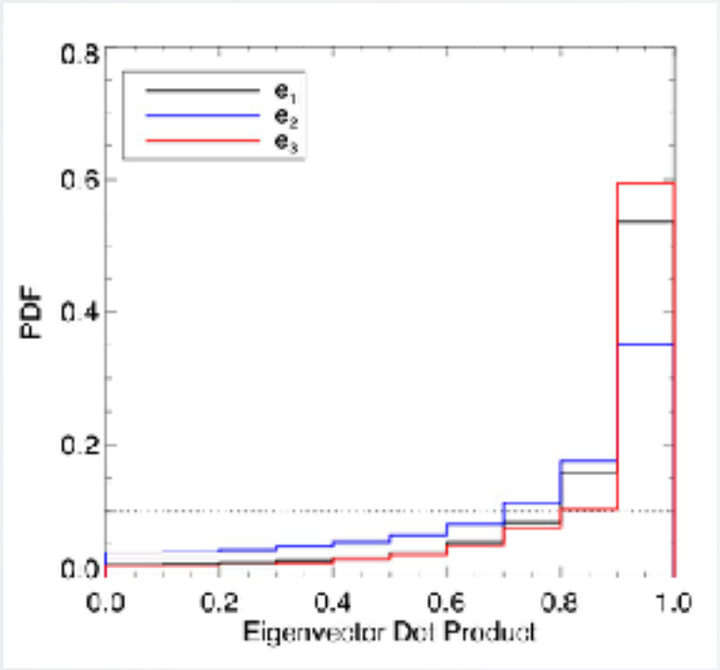
A forming supercluster at z=2.51?

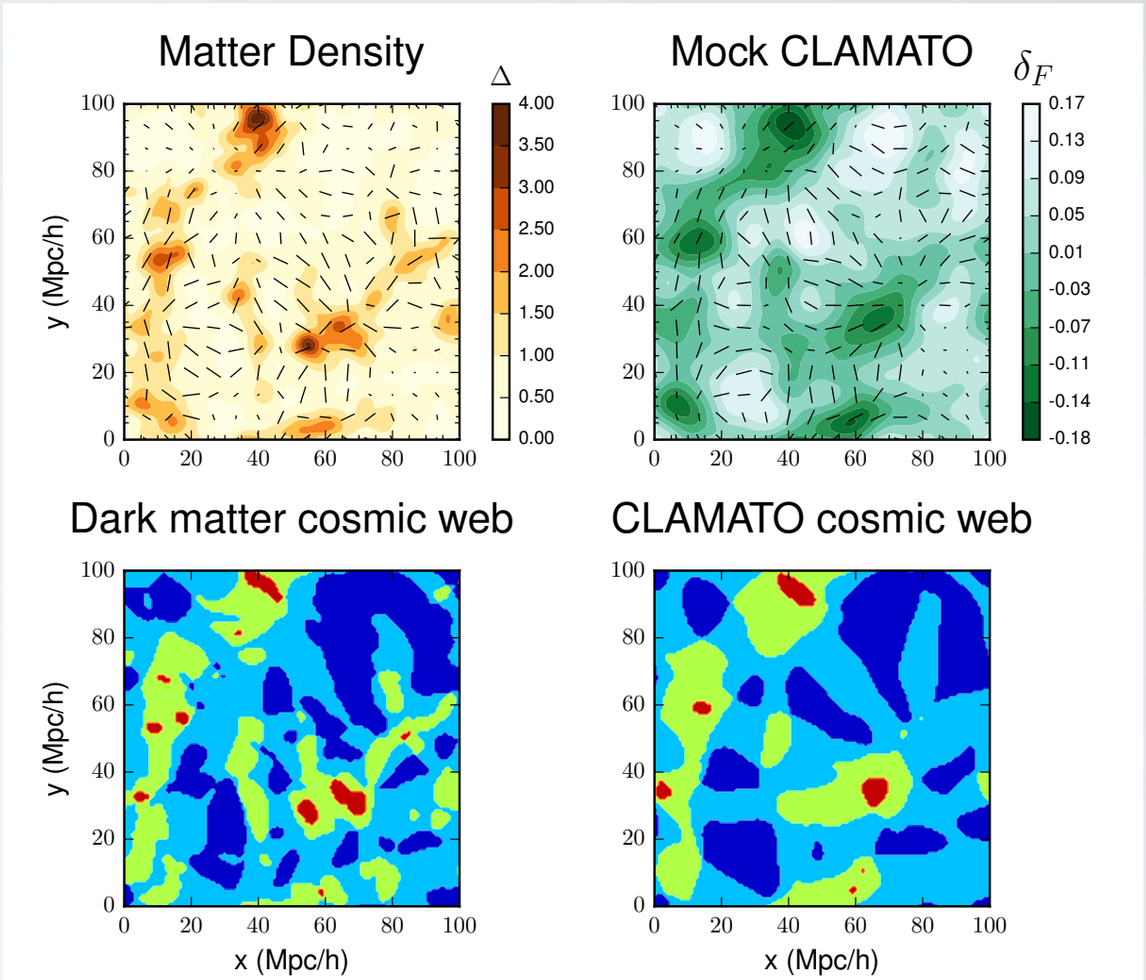


- The protoclusters at z=2.44, z=2.48 and z=2.51 are <100 cMpc from each other.
- CLAMATO is resolving real filamentary sub-structure at z~2.5!

Studying The High-z Cosmic Web With IGM Tomography

- **Lee** & White 2016, ApJ, 817,160
- Krolewski, **Lee**, Lukic & White 2017, ApJ, 837,31
- Zel'dovich-like approach: eigenvalue analysis of the gravitational tidal tensor $d^2\Phi/dx_i dx_j$
- tl;dr: IGM tomography can recover the eigenvectors of the cosmic web with sufficient fidelity to constrain intrinsic alignments from galaxies





Krolewski et al, 2017a

Mode-Counting in the Ly-alpha Forest

- CLAMATO at 2.0<z<2.6 yields effective comoving spatial resolution of 5Mpc/h → **k_{max} ~ 0.7h/Mpc**
- 1deg^2 over 2.0<z<2.6 covers 2×10^6 $h^{-3}Mpc^3$ → 16k modes/deg^2
- 10k deg^2 CLAMATO-like survey over 2<z<3 would yield 200+M modes, going to non-linear (c.f. ~10-15M modes in DESI and LSST)
- ~25M background galaxies at 2.3<z<3.5
  - Cross-correlation/multi-tracer techniques between b~2 galaxies + Lyα forest
  - 2x improvement in curvature measurements c.f. Pat McDonald) from galaxies alone

SSSI/BOA Survey Considerations

- S/N~1-2 per Å required at the faint limit (2-4hr integrations on $g<24.8$ with Keck)
- CLAMATO obtained N=1500/deg^2 projected sightlines at $2.0<z<2.5$ (d_perp=2.4Mpc/h)
  - ×2.5 to get coverage from $2.0<z<3.2$
  - ×1.5 for target selection overhead (assuming broadband color selection)

  → ***N=5000 per sq deg available for IGM tomography targets requiring 2-4hr integrations on 10m mirror*** (downscaling reduces sightline sampling by $\sqrt{N}$)
- 6.5m aperture will make this very slow (c.f. 12hr integrations on 15 deg^2 tomography survey with 8.2m Subaru PFS)
- On BOA with ~30-50k fibers per sq deg, can be integrated with galaxy survey using multi-pass strategy like DESI

Conclusions

- Lyα forest surveys with 10m-class facilities allow full 3D mapping of IGM down to non-linear scales (<5Mpc/h)
- Fully demonstrated on Keck over <1sq deg area. Upcoming Subaru-PFS survey (2020-2025) over 15 sq deg @ 2/3 the target density
- Instrumentation perspective:
    - Prefer large-aperture: 6.5m strongly disfavored
    - Blue sensitivity needed, so prefer shorter fiber runs → Cassegrain-mounted focal plane
- Theoretical work TBD (manpower limited…<10 people in entire business!):
    - Large number of linear+non-linear modes (~200M over 10k deg^2), but need cosmological forecasts
    - Systematics in Lyα forest: continuum fitting, inhomogeneous UV background
    - Hydro simulation grids currently needed for detailed analysis. Currently at O(100Mpc/h) — will Moore's Law catch up?