Lyman-α forest perturbative modeling and improved CMB constraining power

Jahmour Givans

BSM Double Feature

September 29, 2020

THE OHIO STATE UNIVERSITY

Based in part on . . .

PHYSICAL REVIEW D **102,** 023515 (2020)

Redshift-space streaming velocity effects on the Lyman-α forest baryon acoustic oscillation scale

Jahmour J. Givans[1,2,*] and Christopher M. Hirata[1,2,3]

[1]*Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, Ohio 43210, USA*
[2]*Department of Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, Ohio 43210, USA*
[3]*Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, Ohio 43210, USA*

(Received 6 March 2020; accepted 8 June 2020; published 8 July 2020)

The baryon acoustic oscillation (BAO) scale acts as a standard ruler for measuring cosmological distances and has therefore emerged as a leading probe of cosmic expansion history. However, any physical effect that alters the length of the ruler can lead to a bias in our determination of distance and expansion rate. One of these physical effects is the streaming velocity, the relative velocity between baryons and dark matter in the early Universe, which couples to the BAO scale due to their common origin in acoustic waves at recombination. In this work, we investigate the impact of streaming velocity on the BAO feature of the Lyman-α forest auto-power spectrum, one of the main tracers being used by the recently commissioned Dark Energy Spectroscopic Instrument (DESI). To do this, we develop a perturbative model for Lyman-α flux fluctuations which is complete to second order for a certain set of fields, and applicable to *any* redshift-space tracer of structure since it is based only on symmetry considerations. We find that there are 8 biasing coefficients through second order. We find streaming velocity-induced shifts in the BAO scale of 0.081%–0.149% (transverse direction) and 0.053%–0.058% (radial direction), depending on the model for the biasing coefficients used. These are smaller than, but not negligible compared to, the DESI Lyman-α BAO error budget, which is 0.46% on the overall scale. The sensitivity of these results to our choice of bias parameters underscores the need for future work to measure the higher-order biasing coefficients from simulations, especially for future experiments beyond DESI.

DOI: 10.1103/PhysRevD.102.023515

Breaking down the paper title

Over the next several slides, we'll address

- Redshift space
- Baryon acoustic oscillations (BAOs)
- Streaming velocity
- Lyman-α forest

Redshift space

- In real space, objects (like galaxies) are where they appear to be.
- In redshift space, an object’s position is distorted along our LOS
  - Caused by peculiar velocities
  - Convention is that line-of-sight lies along the z axis

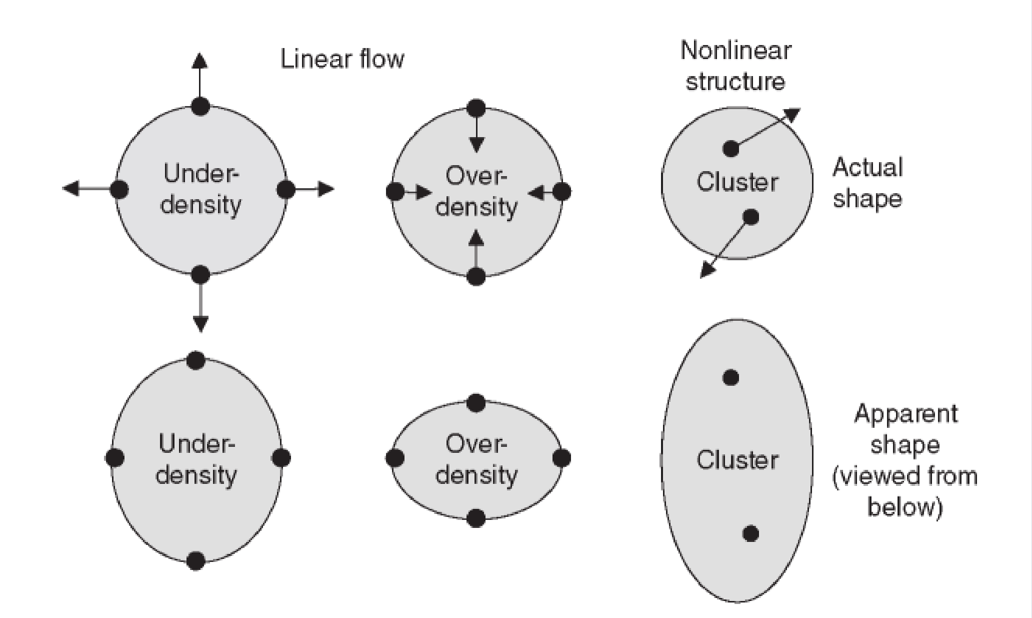


Image credit: Will Percival

BAOs

Primordial universe is a plasma of photons and baryons

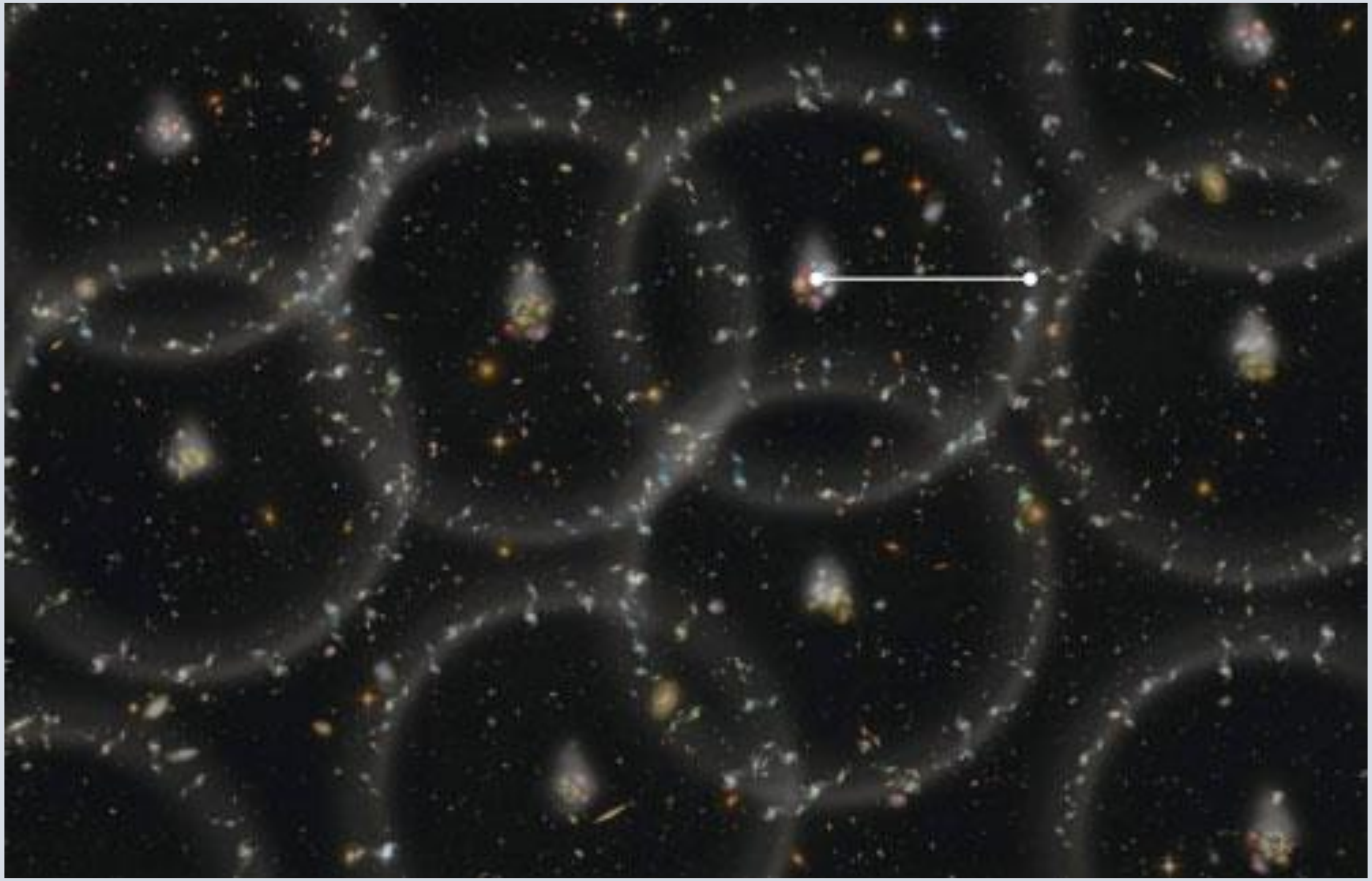
- Dark matter overdensities are seeded throughout

Tug-of-war between gravity and fluid pressure

Generates sound waves called BAOs

- Can travel a distance $r_d = 147$ comoving Mpc before decoupling
- Baryons left behind in spherical shell around overdensities

We get a standard ruler!



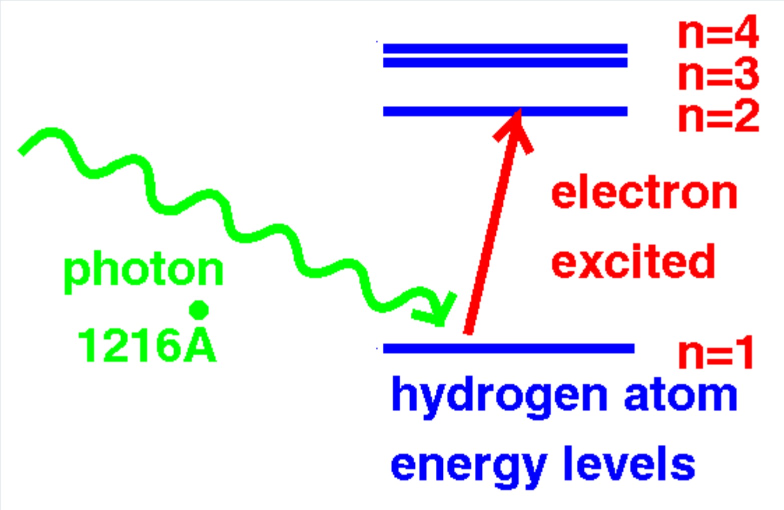
Credit: BOSS Collaboration

Streaming velocity

- Generated by the same physics that produced BAOs
- Baryons and dark matter have a supersonic relative velocity at decoupling
- More important than usual Jeans criteria for structure formation
  - Changes filtering mass of the intergalactic medium
- Will impact the BAO scale by some amount

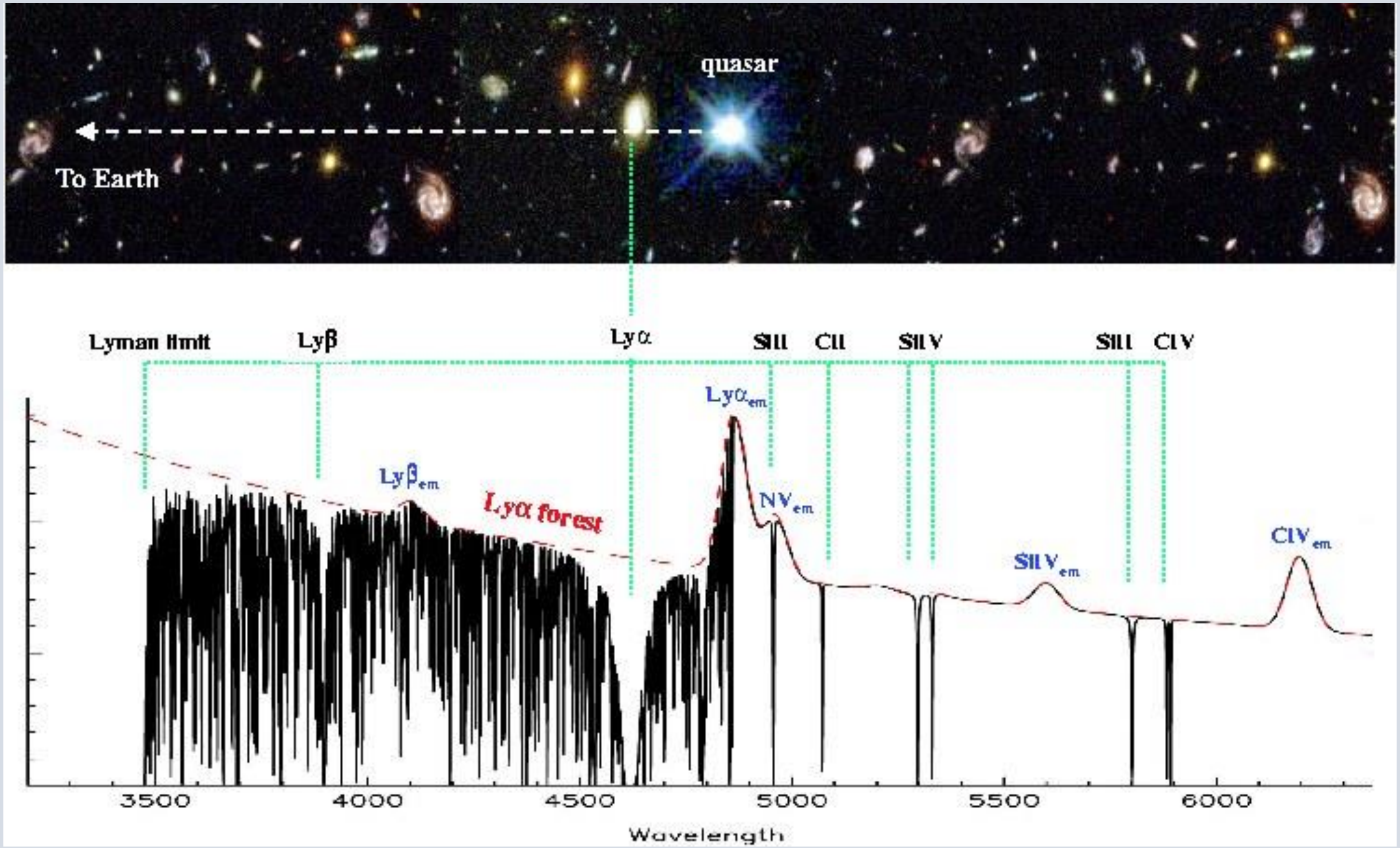
Lyman-α forest overview

- H I gas clouds spread throughout IGM
- Background quasar shines light, exciting Lyman-α transition
- Absorption in multiple H I clouds along LOS
- Creates a "forest" of absorption features in transmitted flux



Credit: M. White and L. Hernquist

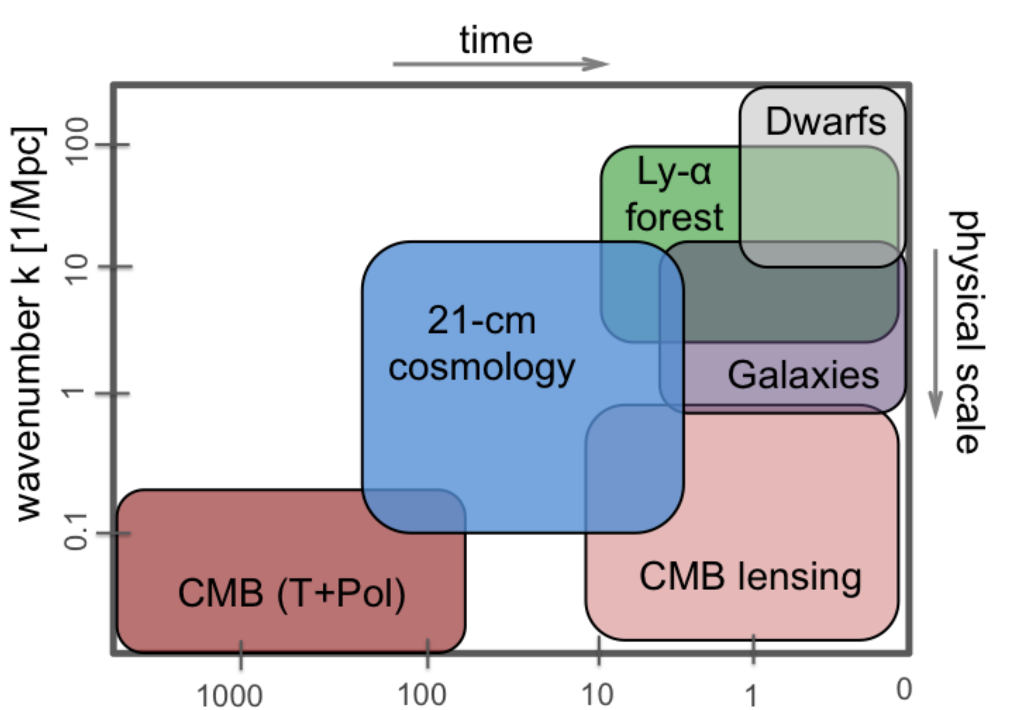
Visualizing the forest



Credit: John Webb

Why the Lyman-α forest?

- Robust tracer of structure at $2 < z < 6$
- Study reionization & thermal history of IGM
- Probe smaller physical scales
- Complement data from other probes



1903.05140

LSS perturbation theory basics

- Assume underlying matter field smooth, collisionless DM
  - Follows Poisson, continuity, and Euler equations
- At large scales, some fields can be treated as perturbations to others

These fields are perturbations	To these local fields
Density contrast	Cosmic density
Peculiar velocity	Particle velocity
Cosmological gravitational potential	Newtonian potential

- Linearize equations to solve for evolution of fields

PT and bias in Lyα forest

- Most (purely) PT models are based on linear theory

$$\delta_F = b_\delta \delta + b_\eta \eta$$

- My work introduced a complete 2nd order model
  - Applicable to any tracer in redshift space
  - Independently derived, but resembles EFT of LSS for galaxies

$$\delta_F(\boldsymbol{s}) = c_0 + c_1\delta + c_2 s_{zz} + c_3\delta^2 + c_4 s^2 + c_5\delta s_{zz} + c_6 t_{zz} + c_7 s_{zz}^2 + c_8\left(s_{xz}^2 + s_{yz}^2\right)$$

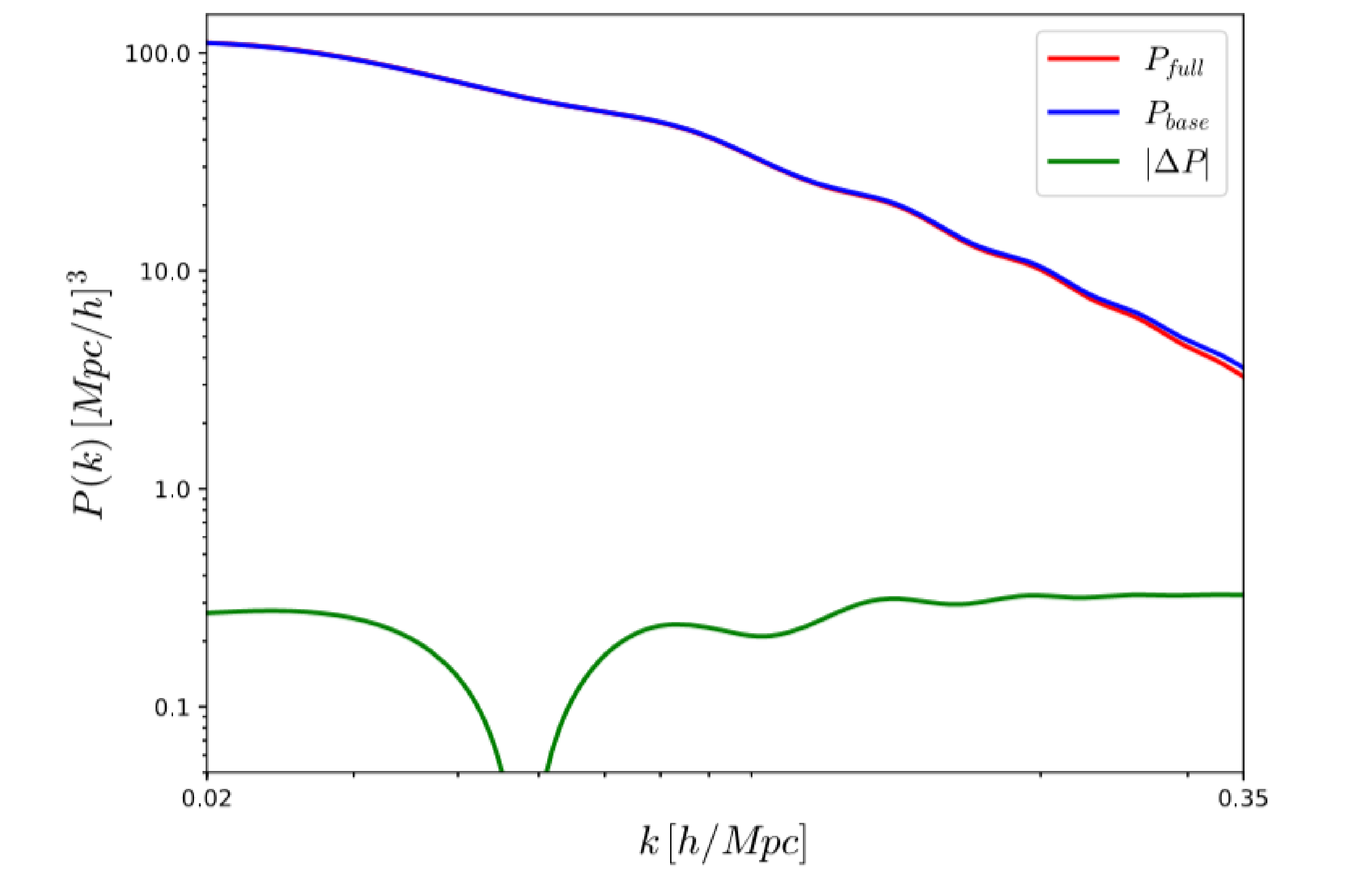
- Streaming velocity contributions added

$$b_v(v_s^2 - 1) + b_{1v}\delta(v_s^2 - 1) + b_{sv} s_{ij} v_{s,i} v_{s,j} + b_{vz}\left(v_{s,z}^2 - \frac{1}{3} v_s^2\right)$$

Getting bias coefficients and BAO scale shift

- A few of them come from simulations
- Others are derived from fluctuating Gunn-Peterson approximation
  - Formula for deriving optical depth in redshift space
  - Optical depth is related to flux, which is related to δ_F
- BAO scale parameter α is set by fitting a model to $P_F(k)$
  - Uses χ^2 minimization to calculate fitting coefficients
  - Compare α when $b_v = 0$ to α when b_v is the simulated value

Visualizing the shift



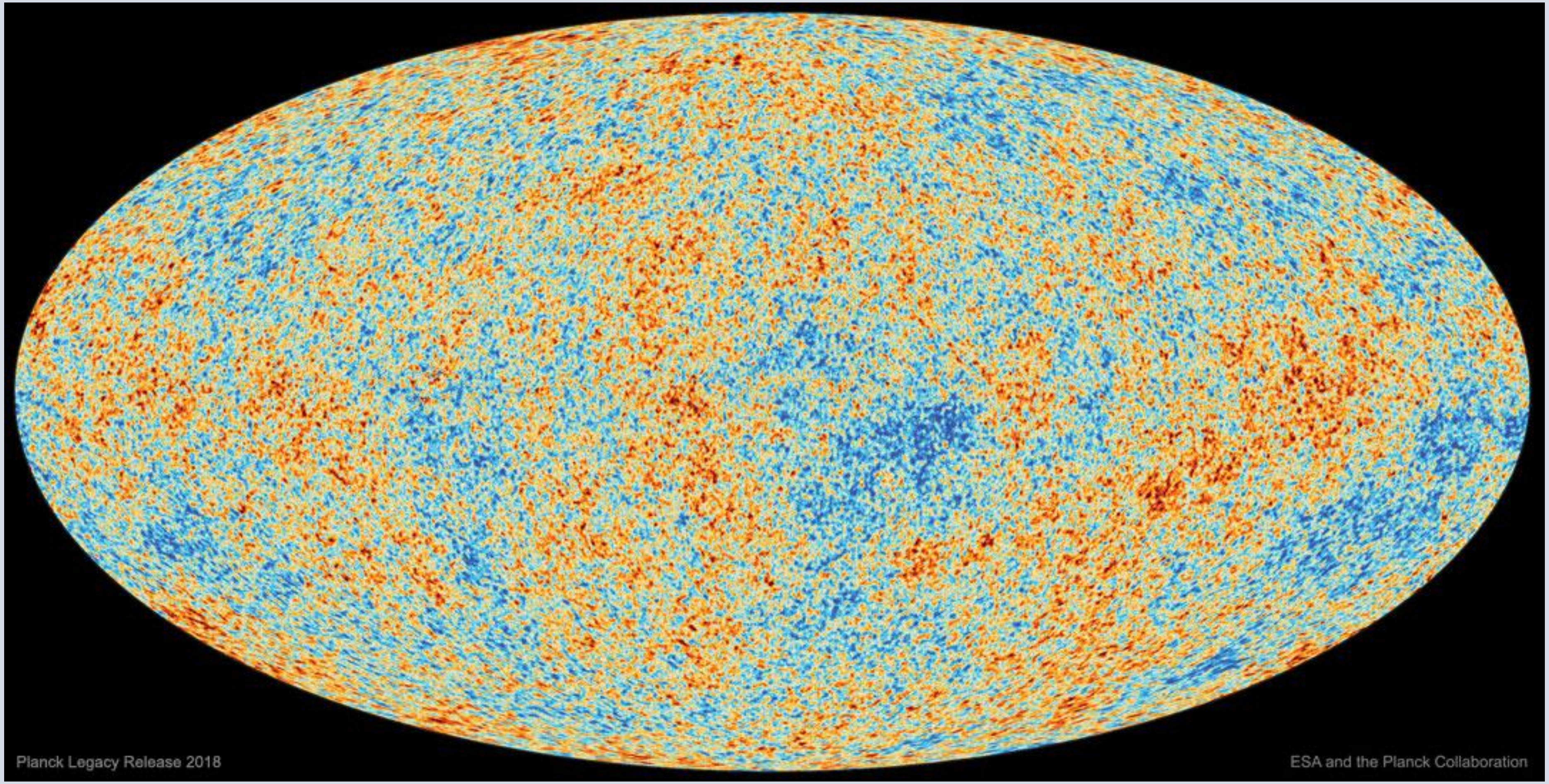
Paper results and takeaways

TABLE III. The BAO peak shift for three different μ values and three different choices of bias coefficients.

$\Delta\alpha$ in %	c_1, c_2, and c_3 from simulations, all others are zero	c_1 and c_2 from simulations, all others are zero	c_1 and c_2 from simulations, all others from FGPA
$\mu = 0$	0.081%	0.088%	0.149%
$\mu = 1/\sqrt{3}$	0.066%	0.070%	0.093%
$\mu = 1$	0.053%	0.054%	0.058%

- Results for peak shift depend strongly on bias parameters
- DESI precision for Lyman-α forest is 0.46%
  - Streaming velocity alone is important but relatively minor
- Go to higher order PT and get bias parameters

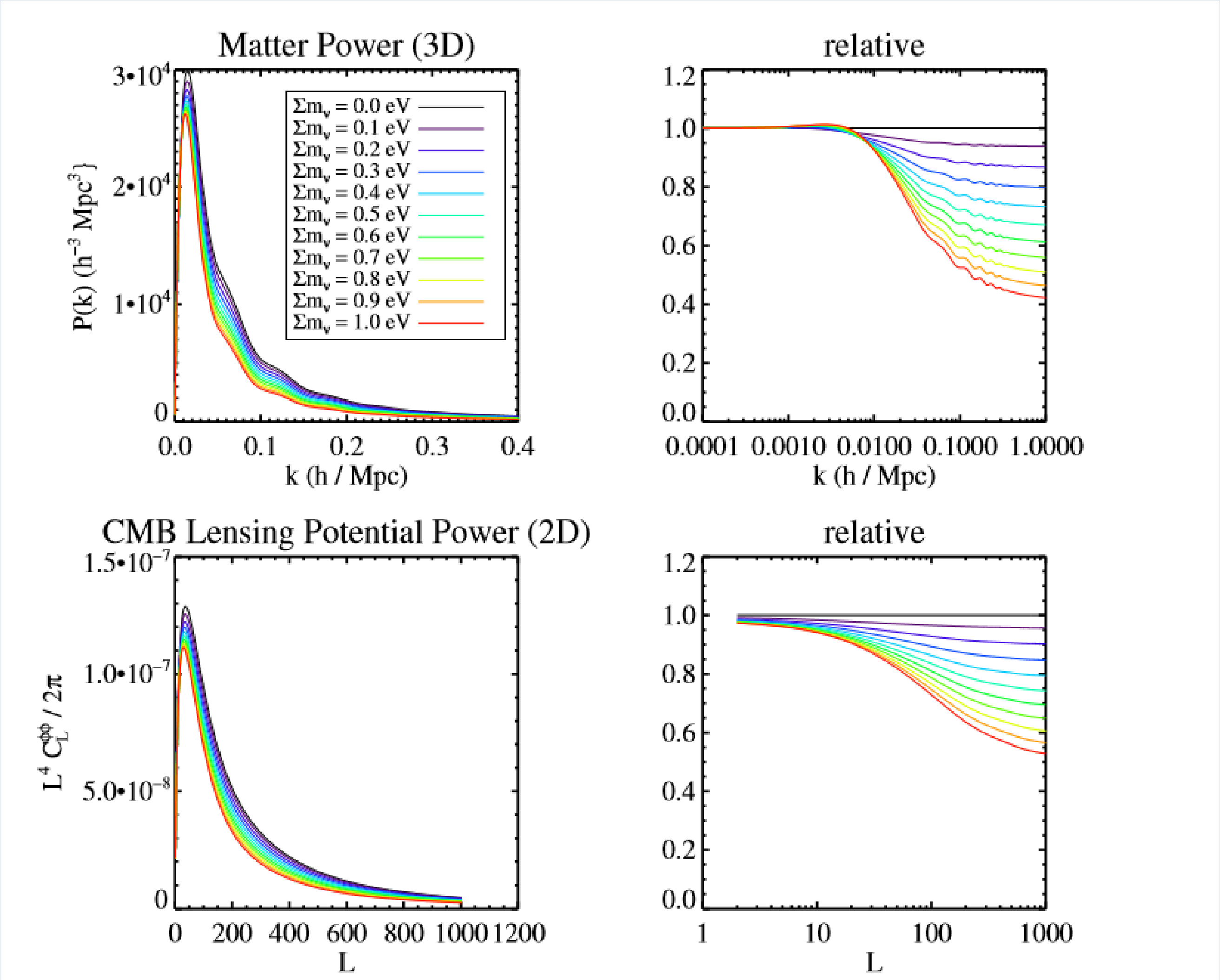
CMB Constraints



CMB application: neutrino masses (1/2)

- Expansion history changes as they become non-relativistic
  - Probes sensitive to history, like BAO, can measure the effect
- Neutrino masses suppress late-time amplitude of fluctuations
- Primary CMB spectrum and secondary CMB lensing spectrum

Suppression of power

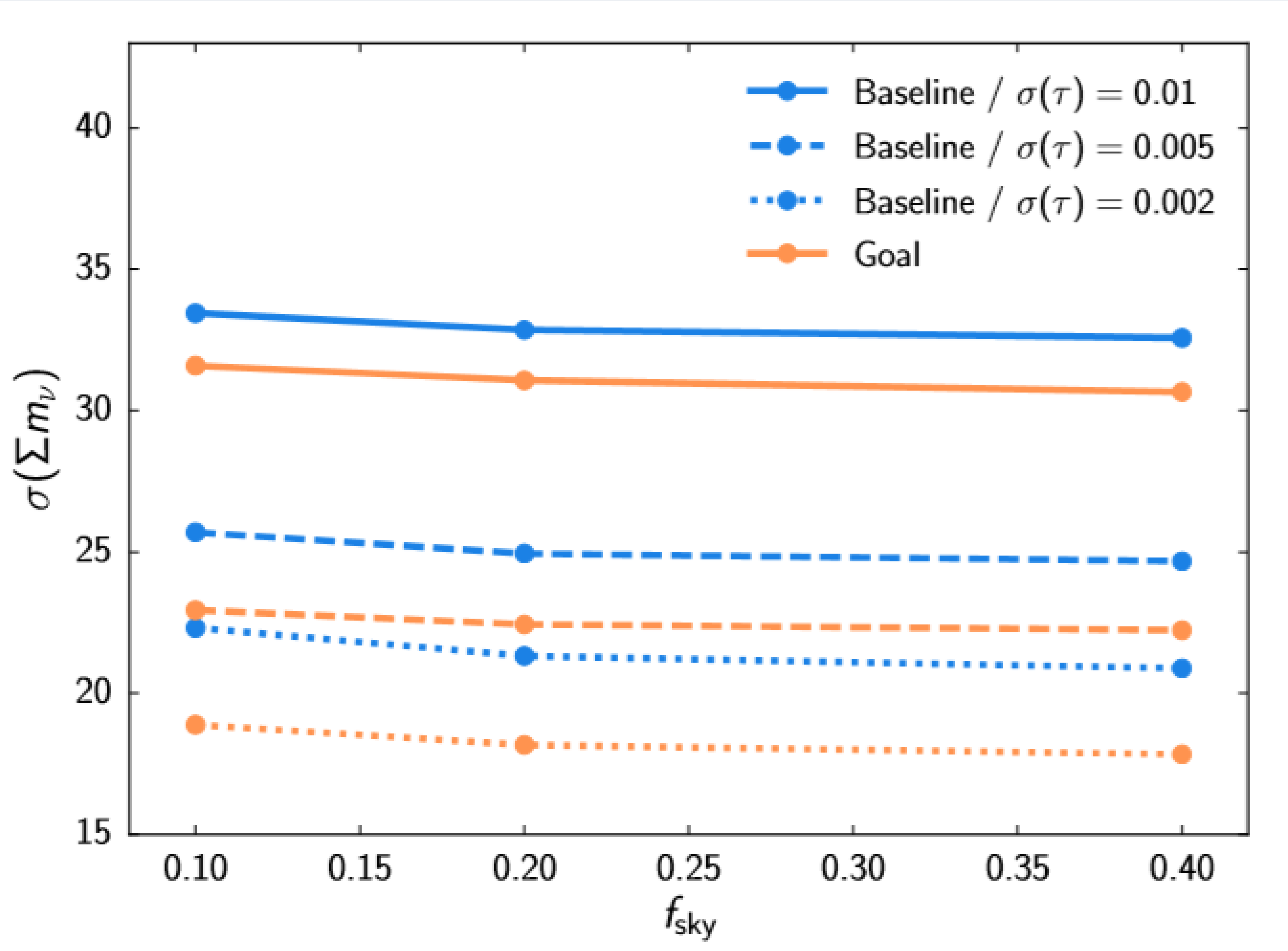


Abazajian et al. 2016 (CMB-S4 Science Book)

CMB application: neutrino masses (2/2)

- DESI BAO information helps break degeneracy of Σm_ν with Ω_m
    - Get BAO from galaxies, quasars, and Lyα forest
- SO (Goal) + DESI BAO + τ (LiteBIRD) : $\sigma(\Sigma m_\nu) = 17$ meV
    - Enable detection of $\Sigma m_\nu = 0.06$ eV at 3.5σ and $\Sigma m_\nu = 0.1$ eV at 5.9σ

Limits from Simons + DESI + τ

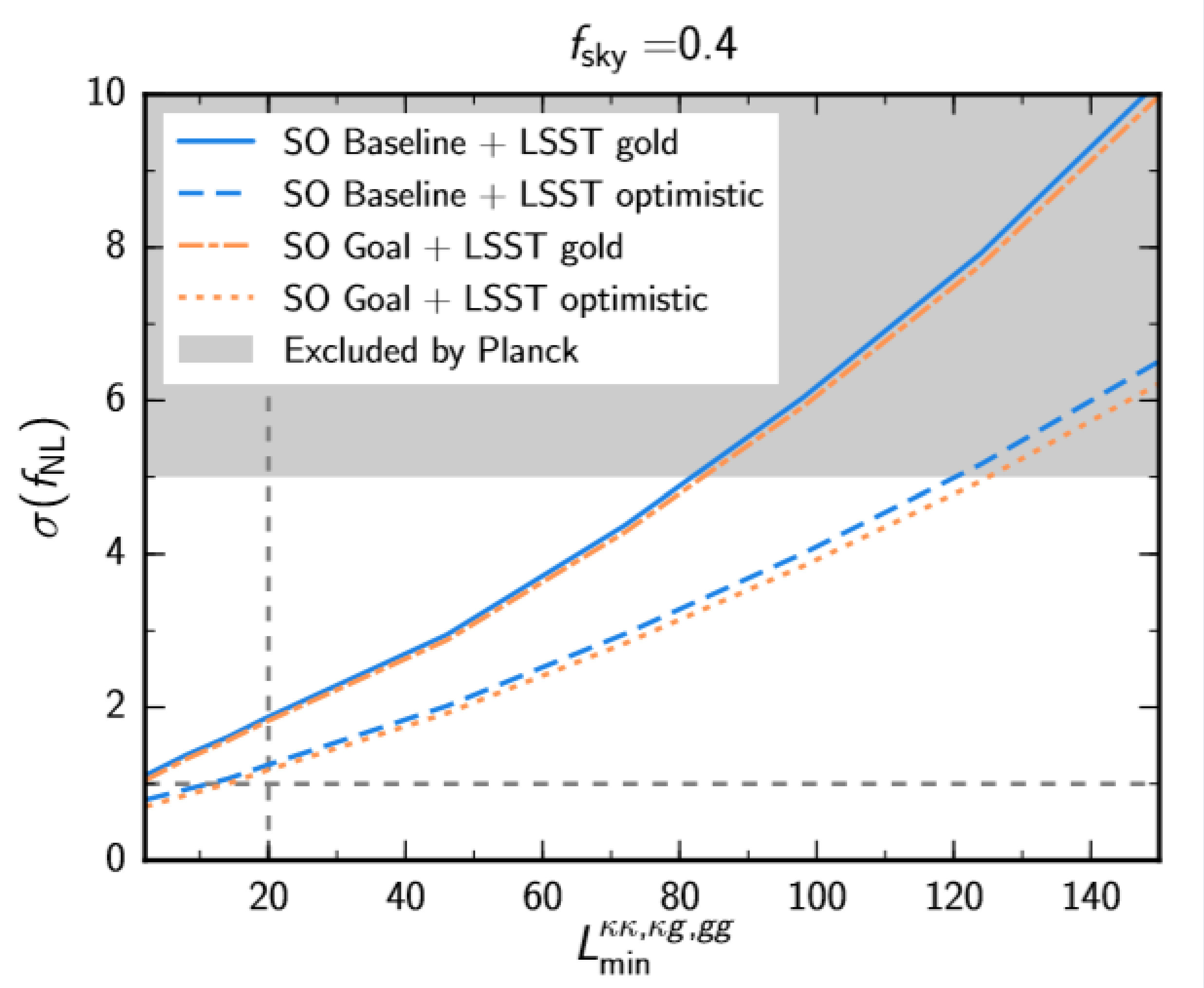


SO Collaboration, JCAP 02 (2019) 056

CMB application: primordial non-Gaussianity

- Local PNG parameterized by f_{NL}
  - Can place constraints on inflationary models
- Causes galaxies to exhibit scale-dependent bias $b(k) \propto f_{NL}/k^2$
- The same dependence is present in the Lyα forest
  - See U. Seljak, JCAP 03 (2012) 004 and S. Chongchitnan, JCAP 10 (2014) 034
- Could CMB + Lyα improve PNG constraints from CMB + galaxies?

Limits from Simons lensing + Rubin clustering



SO Collaboration, JCAP 02 (2019) 056

Conclusions

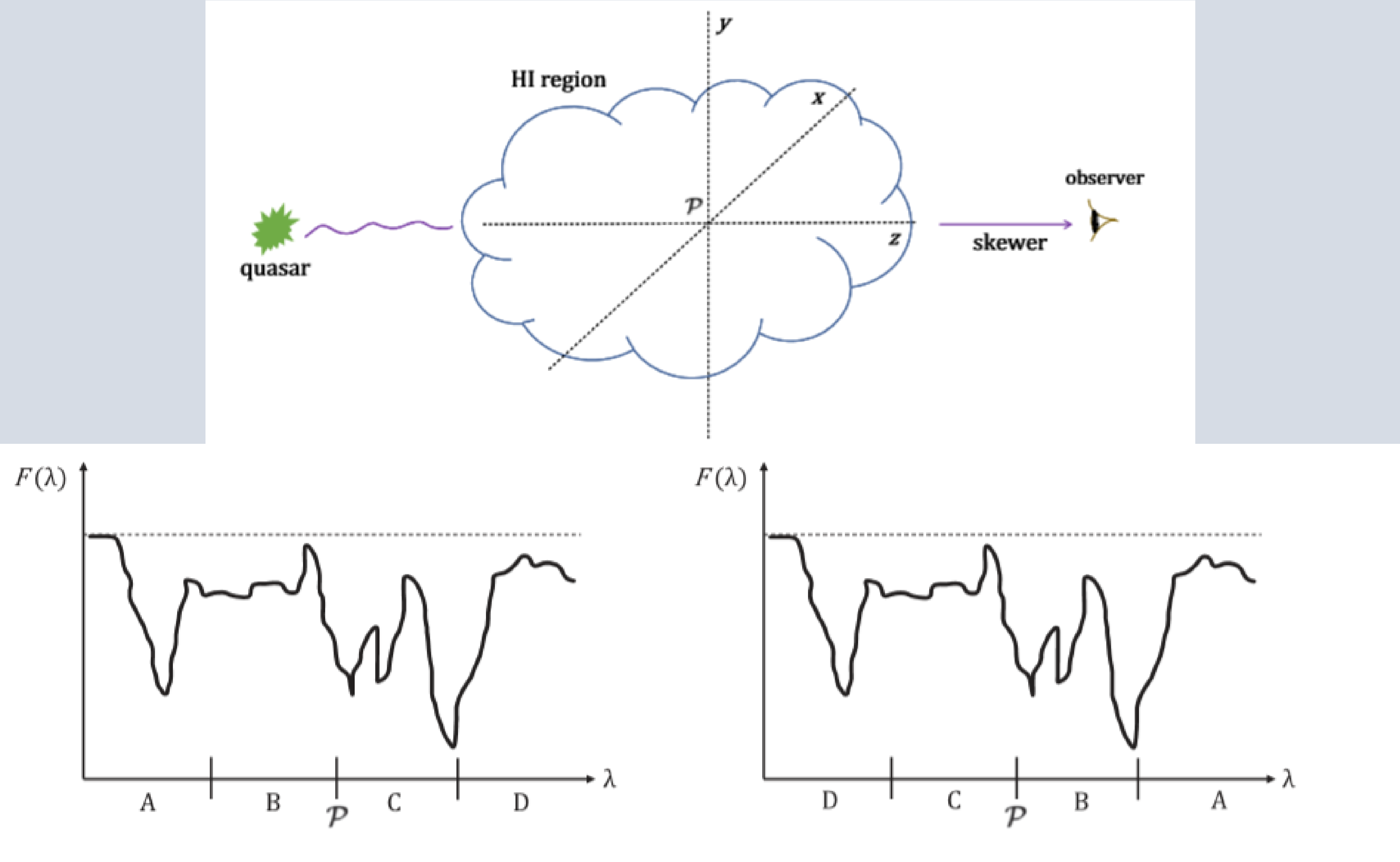
- Lyα forest is great for studying smaller scales at earlier times
- Perturbative modeling must improve to get accurate cosmology
  - In the future: complete 1-loop model and bias coefficients
- Complements CMB measurements including Σm_ν, PNG
- LSS + CMB data will help achieve unprecedented precision


KEEP
CALM
AND
CHECK
BACKUP SLIDES

Where did $\delta_F(s)$ come from?

- Get a physical picture of the situation
- Ask what symmetries are present (azimuthal symmetry)
- Consider all relevant fields
- Use group theory!
- Prove our expansion is the most general one possible for fields we consider

Physical picture



What group is this?

- System obeys group properties of $D_{\infty h}$
  - True if your region is over a very small redshift range
  - Same group that describes symmetry transformation of H_2 and CO_2
- Use a character table to get forms of contributions

$D_{\infty h}$	$\hat{E}$	$2\hat{C}_\infty^\varphi$	$\cdots$	$\infty\hat{\sigma}_v$	$\hat{i}$	$\hat{\sigma}_h$	$2\hat{S}_\infty^\varphi$	$\cdots$	$\infty\hat{C}_2$	linear functions & rotations	quadratic functions
Σ_g^+	$+1$	$+1$	$\cdots$	$+1$	$+1$	$+1$	$+1$	$\cdots$	$+1$	-	x^2+y^2, z^2
Σ_g^-	$+1$	$+1$	$\cdots$	-1	$+1$	$+1$	$+1$	$\cdots$	-1	R_z	-
Π_g	$+2$	$+2\cos\varphi$	$\cdots$	0	$+2$	-2	$-2\cos\varphi$	$\cdots$	0	(R_x, R_y)	(xz, yz)
Δ_g	$+2$	$+2\cos 2\varphi$	$\cdots$	0	$+2$	$+2$	$+2\cos 2\varphi$	$\cdots$	0	-	(x^2-y^2, xy)
Φ_g	$+2$	$+2\cos 3\varphi$	$\cdots$	0	$+2$	-2	$-2\cos 3\varphi$	$\cdots$	0	-	-
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	-	-
E_{ng}	$+2$	$+2\cos n\varphi$	$\cdots$	0	$+2$	$(-1)^n 2$	$(-1)^n 2\cos n\varphi$	$\cdots$	0	-	-
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	-	-
Σ_u^+	$+1$	$+1$	$\cdots$	$+1$	-1	-1	-1	$\cdots$	-1	z	-
Σ_u^-	$+1$	$+1$	$\cdots$	-1	-1	-1	-1	$\cdots$	$+1$	-	-
Π_u	$+2$	$+2\cos\varphi$	$\cdots$	0	-2	$+2$	$+2\cos\varphi$	$\cdots$	0	(x, y)	-
Δ_u	$+2$	$+2\cos 2\varphi$	$\cdots$	0	-2	-2	$-2\cos 2\varphi$	$\cdots$	0	-	-
Φ_u	$+2$	$+2\cos 3\varphi$	$\cdots$	0	-2	$+2$	$+2\cos 3\varphi$	$\cdots$	0	-	-
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	-	-
E_{nu}	$+2$	$+2\cos n\varphi$	$\cdots$	0	-2	$(-1)^{n+1} 2$	$(-1)^{n+1} 2\cos n\varphi$	$\cdots$	0	-	-
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	-	-