FLAMINGO

Spilling Spectroscopic Survey Secrets with Perturbative Bias Phenomenology

2511.14677
2510.23597
2507.00284
2505.03626
2503.21736
2410.18039
2303.08901

BCCP Seminar
4/14/2026

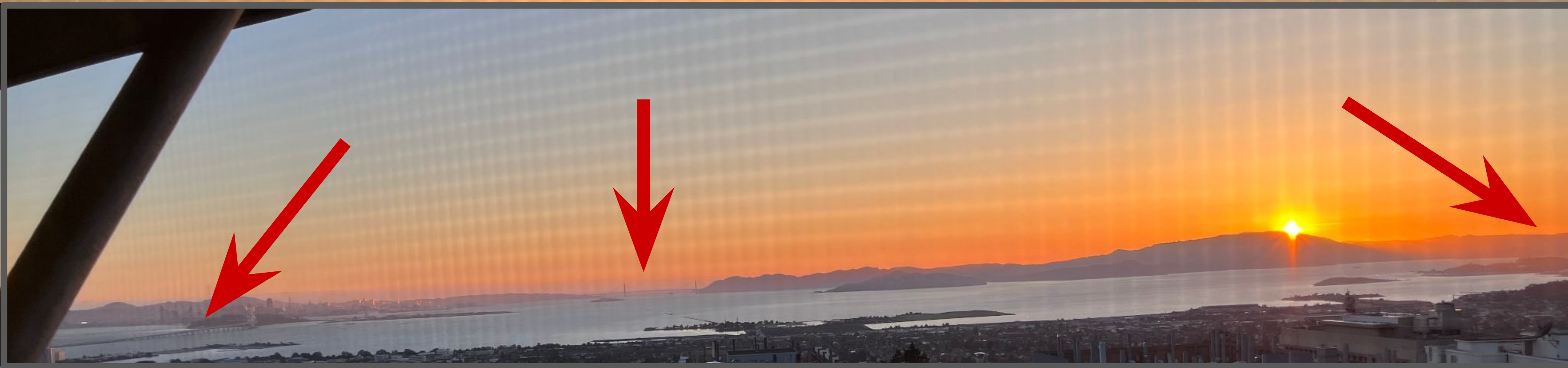
Jamie Sullivan - MIT

Misha Ivanov
Roger de Belsunce
Carol Cuesta-Lazaro
Uroš Seljak
Pat McDonald

The Brinson Foundation

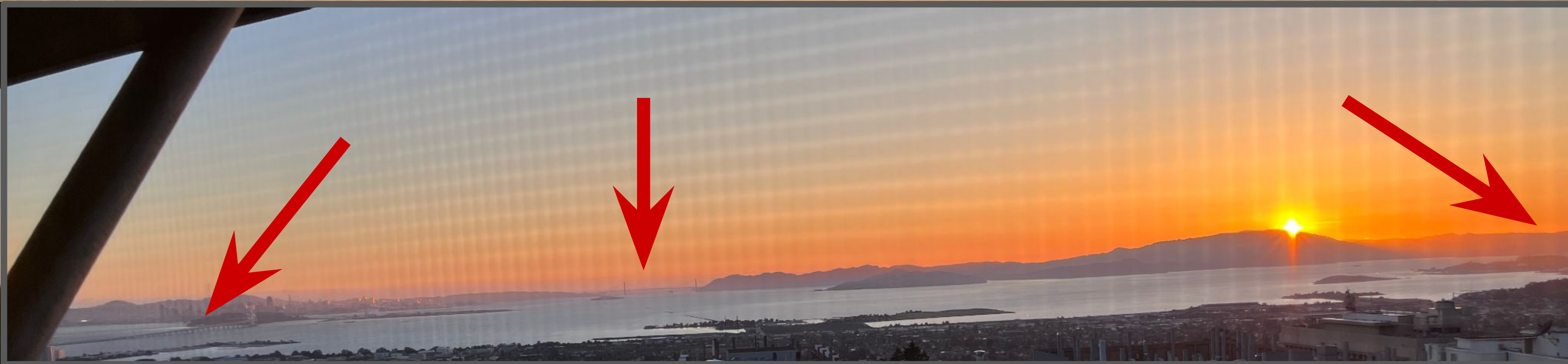
THE LEINWEBER INSTITUTES FOR THEORETICAL PHYSICS

Three-bridge view!



LSS age is dawning!

Three-bridge view!



LSS age is dawning!

Three-bridge view!

Large-scale structure

Fundamental physics from cosmological **perturbations**

Moments & correlators

probe distribution of fluctuations

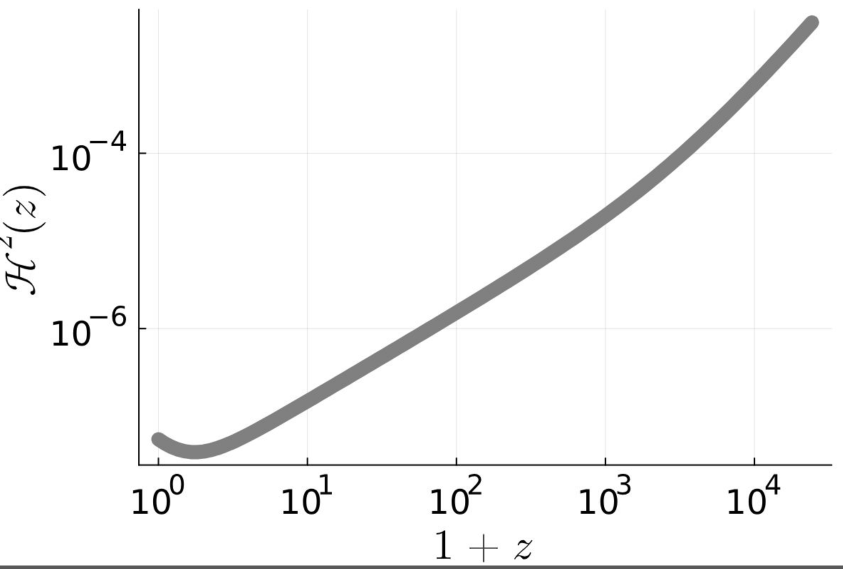
$$\langle\rho\rangle \qquad \delta \equiv \frac{\rho}{\langle\rho\rangle} - 1$$

$$\langle\delta^2\rangle, \langle\delta\delta\rangle \to P(k)$$

$$\langle\delta^3\rangle, \langle\delta\delta\delta\rangle \to B(k_1, k_2, k_3)$$

$$\vdots$$

$$H(z;\Omega_m, H_0, ...) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{de}(a;...)}$$



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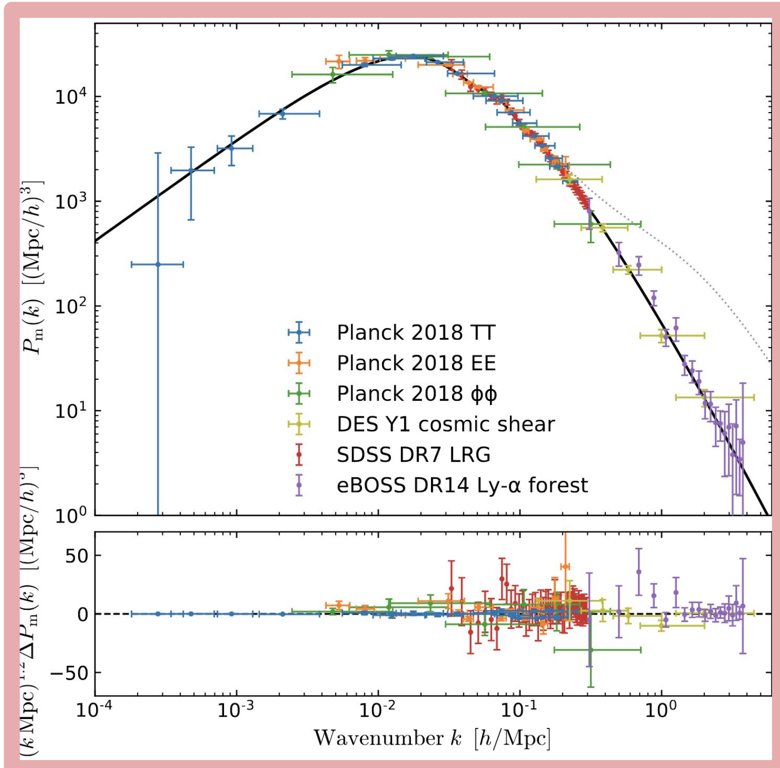

Planck18, M. Millea

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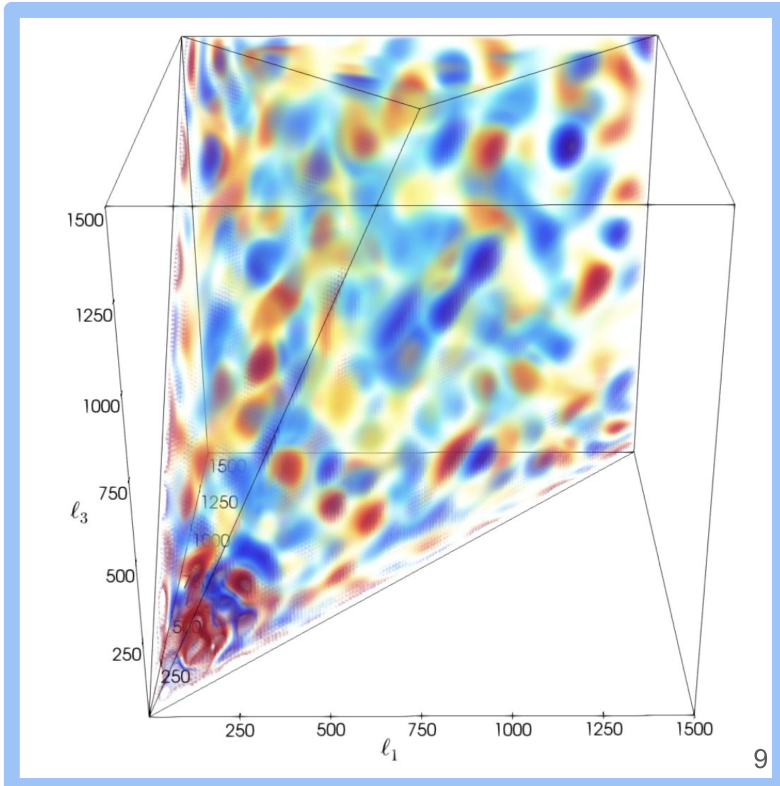
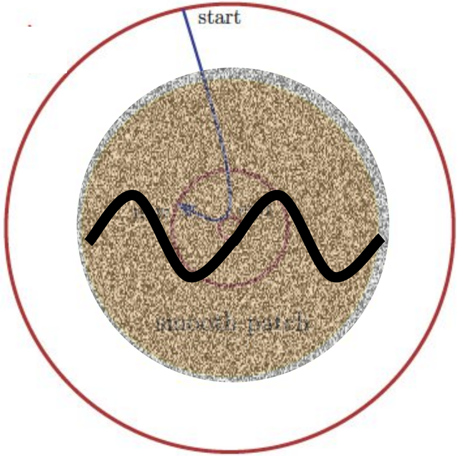


Planck18, M. Millea

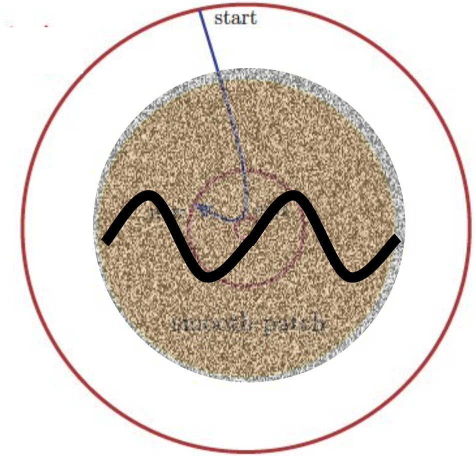
Modes into our eyeballs

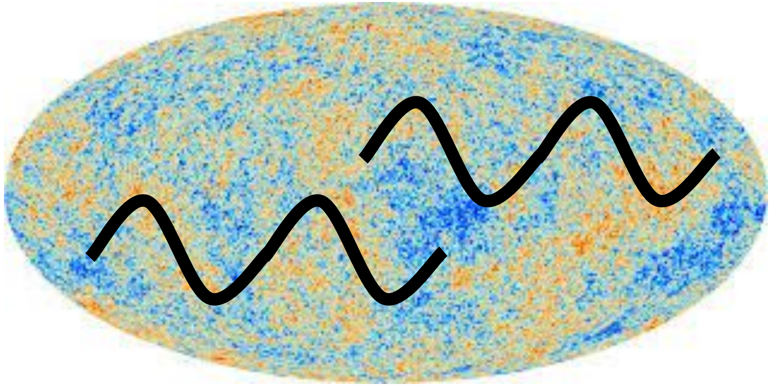


$$\delta(\mathbf{k})$$

ESA, DESI collaboration, Baumann (adapted)

Modes into our eyeballs





$\delta(\mathbf{k})$ $\qquad$ $L(k, z)\delta(\mathbf{k})$

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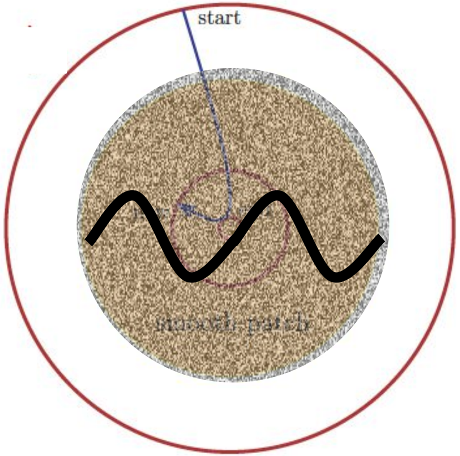
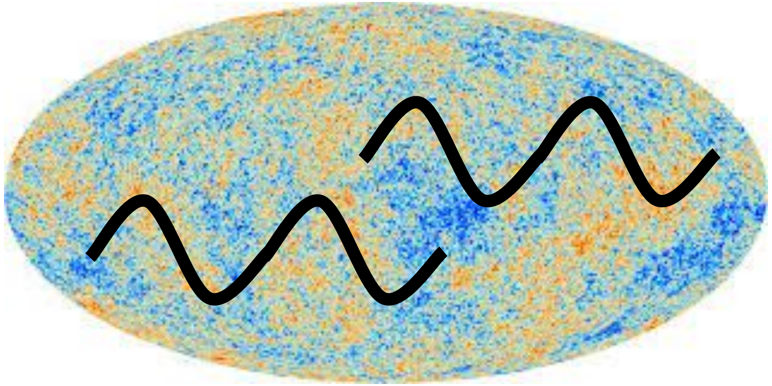
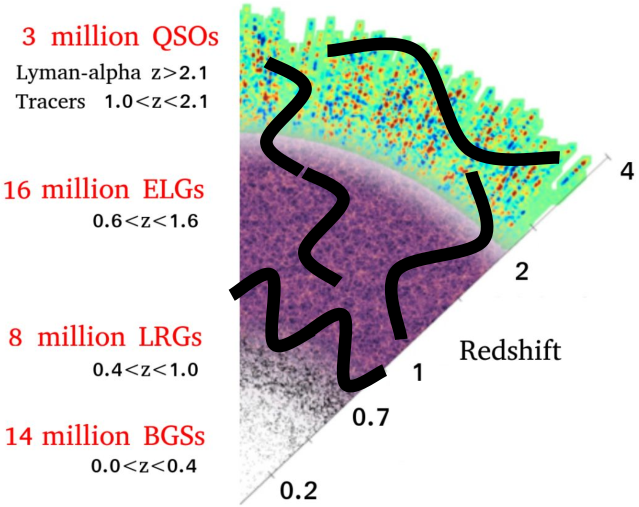


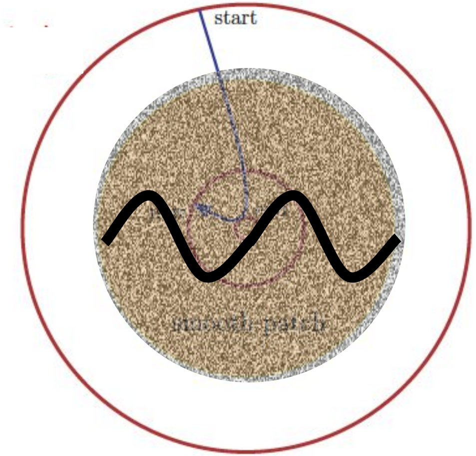


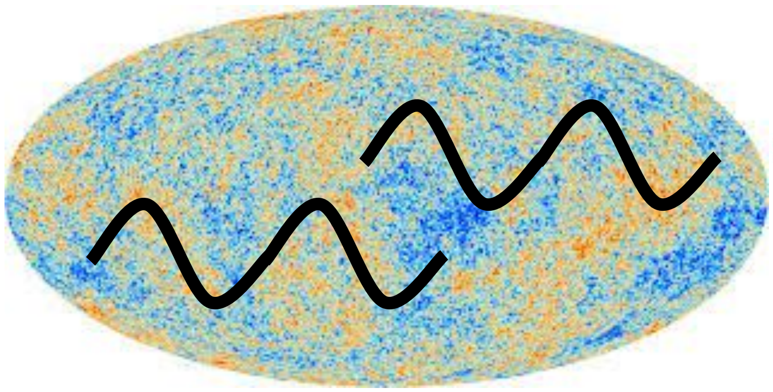


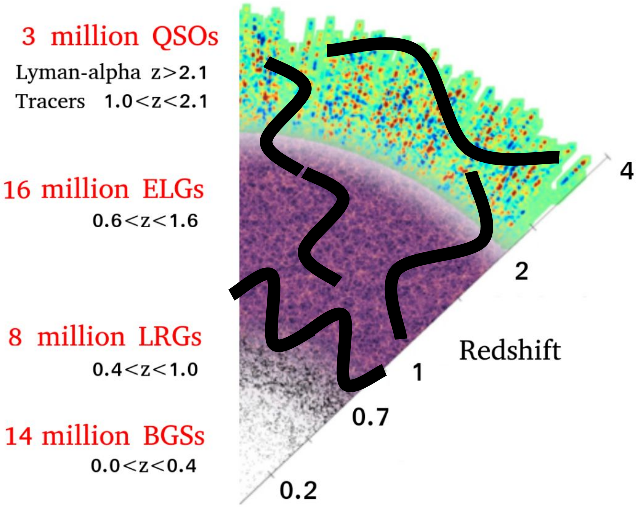
$$\delta(\mathbf{k}) \qquad L(k,z)\delta(\mathbf{k}) \qquad N[L(k,z)\delta(\mathbf{k})]$$

ESA, DESI collaboration, Baumann (adapted)

Modes into our eyeballs







Mode-modelling tradeoff*

$$\delta(\mathbf{k}) \qquad L(k,z)\delta(\mathbf{k}) \Longleftrightarrow N[L(k,z)\delta(\mathbf{k})]$$

ESA, DESI collaboration, Baumann (adapted)

Surveys spring forth!

Slew of galaxies

over next 10 years

Image source: C. Yeche, Besuner+25, Bacon+24, DESI collaboration, DES collaboration, NASA, LSST-Rubin

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>10^9 images

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~10^8 spectra

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Slew of galaxies

over next 10 years

>10^9 images

~10^8 spectra

> $10 billion*

Image source: C. Yeche, Besuner+25, Bacon+24, DESI collaboration, DES collaboration, NASA, LSST-Rubin

EFT and galaxy bias basis

Fluid dynamics model

Continuity:

$$\frac{\partial}{\partial\tau}\delta(\boldsymbol{x},\tau) + \boldsymbol{\nabla}\cdot\{[1+\delta(\boldsymbol{x},\tau)]\,\boldsymbol{v}(\boldsymbol{x},\tau)\} = 0$$

Momentum:

$$\frac{\partial}{\partial\tau}\boldsymbol{v}(\boldsymbol{x},\tau) + [\boldsymbol{v}(\boldsymbol{x},\tau)\cdot\boldsymbol{\nabla}]\,\boldsymbol{v}(\boldsymbol{x},\tau) + \mathcal{H}(\tau)\boldsymbol{v}(\boldsymbol{x},\tau) = -\boldsymbol{\nabla}\Phi(\boldsymbol{x},\tau)$$

Poisson:

$$\nabla^2\Phi(\boldsymbol{x},\tau) = \frac{3}{2}\mathcal{H}^2\Omega_m(\tau)\delta(\boldsymbol{x},\tau)$$

Desjacques+18

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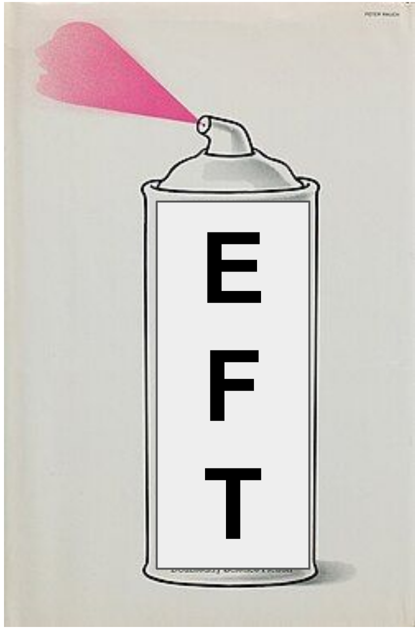
$$\nabla^2\Phi(\boldsymbol{x},\tau) = \frac{3}{2}\mathcal{H}^2\Omega_m(\tau)\delta(\boldsymbol{x},\tau)$$



Baumann, Senatore, Zaldarriaga, Carrasco, McDonald, Ivanov, Schmidt, Desjacques, many more...

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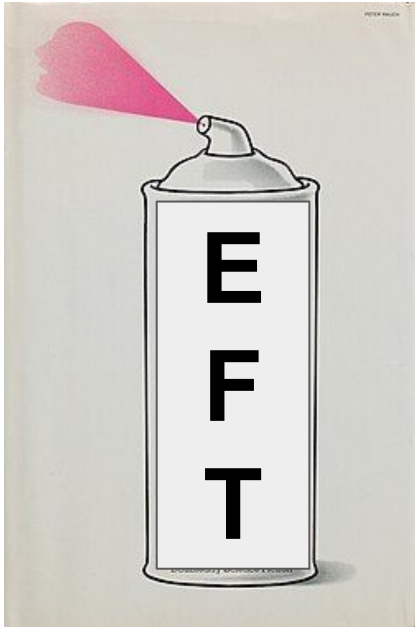
$$\frac{\partial}{\partial\tau}\boldsymbol{v}(\boldsymbol{x},\tau) + [\boldsymbol{v}(\boldsymbol{x},\tau)\cdot\boldsymbol{\nabla}]\,\boldsymbol{v}(\boldsymbol{x},\tau) + \mathcal{H}(\tau)\boldsymbol{v}(\boldsymbol{x},\tau) = -\boldsymbol{\nabla}\Phi(\boldsymbol{x},\tau)$$

$$\nabla^2\Phi(\boldsymbol{x},\tau) = \frac{3}{2}\mathcal{H}^2\Omega_m(\tau)\delta(\boldsymbol{x},\tau)$$

+ Galaxy formation

$$\delta_g = b_1[\delta] + b_{\nabla^2\delta}[\nabla^2\delta] + [\varepsilon] + \frac{1}{2}b_2\left[\delta^2\right] + b_{K^2}\left[(K_{ij})^2\right] + \left[\varepsilon_\delta\delta\right]$$



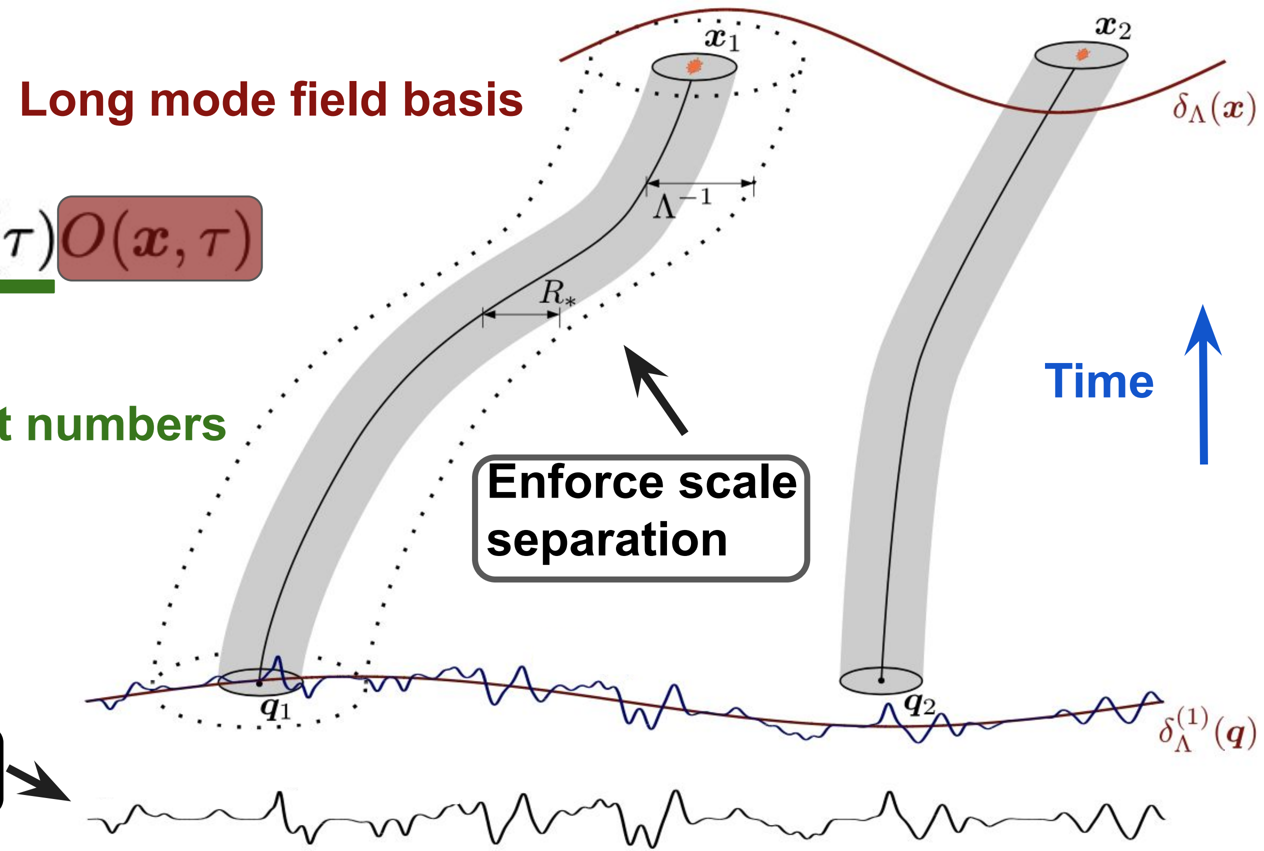
Baumann, Senatore, Zaldarriaga, Carrasco, McDonald, Ivanov, Schmidt, Desjacques, many more...

Long-mode linear regression

Long mode field basis

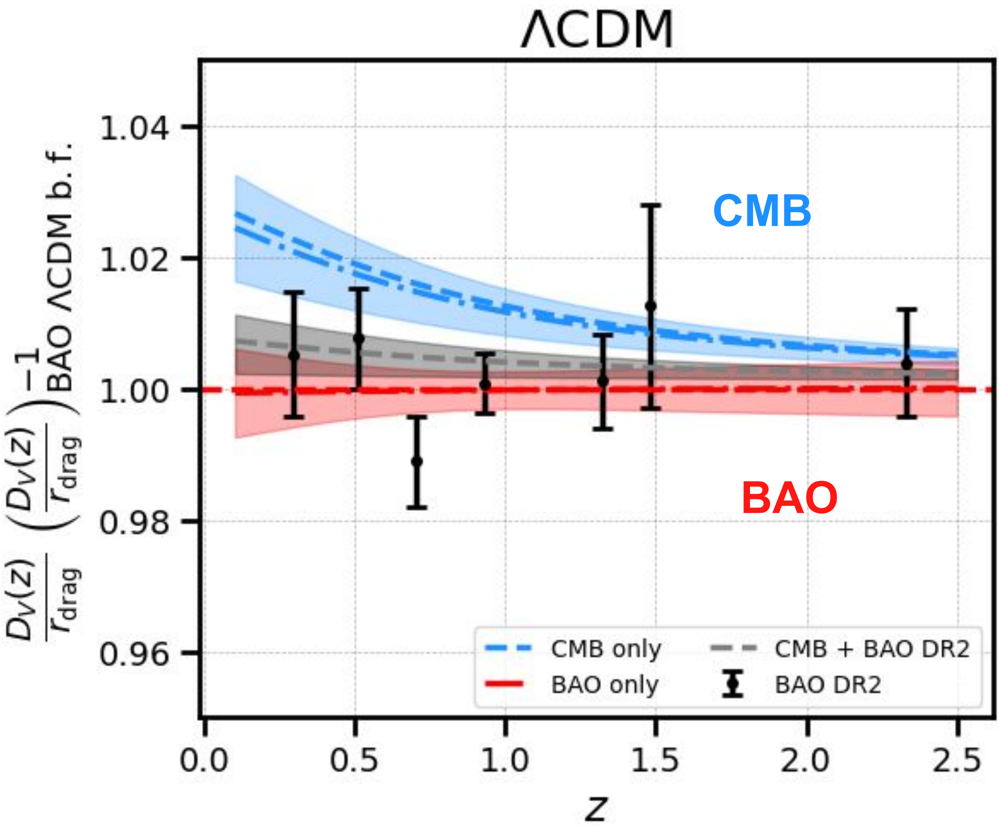
$$\delta_g(\boldsymbol{x},\tau) = \sum_O \underline{b_O(\tau)}\, O(\boldsymbol{x},\tau)$$

Small-scale-dependent numbers



Desjacques, Jeong, Schmidt 18

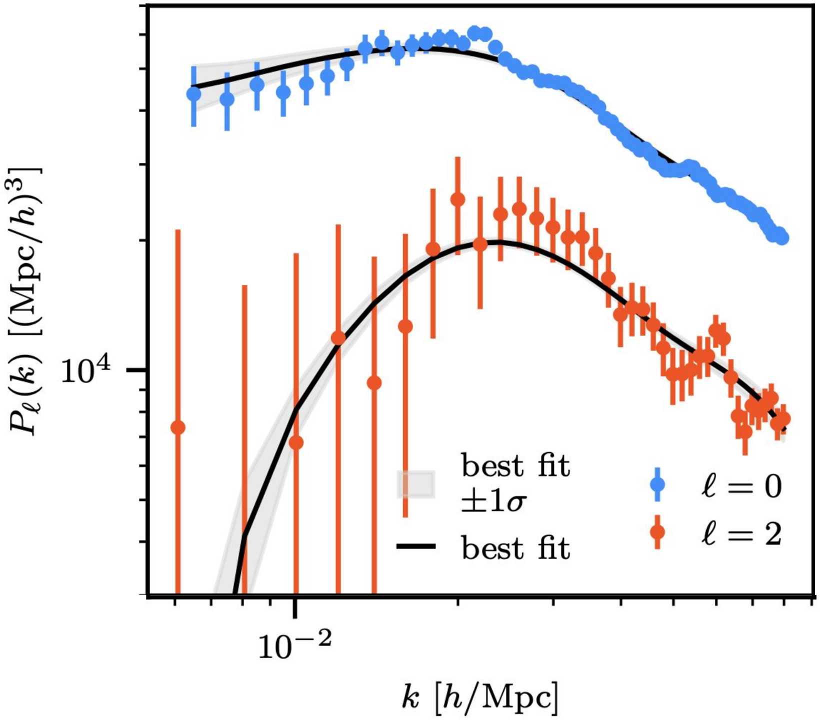
DESI: LCDM



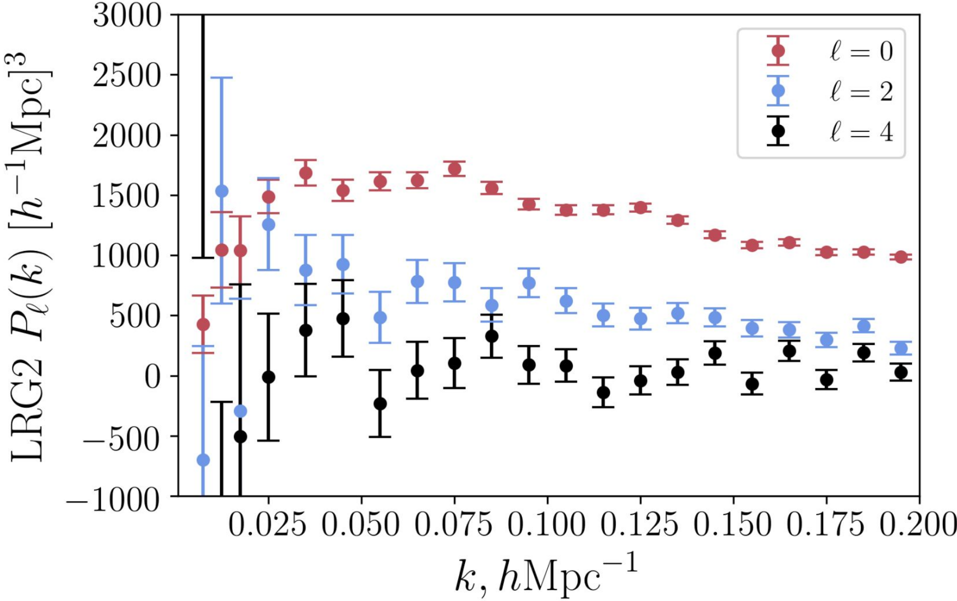
ΛCDM
CMB
BAO
1.04
1.02
1.00
0.98
0.96
0.0
0.5
1.0
1.5
2.0
2.5
z
$\frac{D_V(z)}{r_{\rm drag}} \left(\frac{D_V(z)}{r_{\rm drag}}\right)^{-1}_{\rm BAO\ \Lambda CDM\ b.f.}$
CMB only
BAO only
CMB + BAO DR2
BAO DR2

DESI: Primordial non-Gaussianity

$$f_{\rm NL}^{\rm loc} = -3.6^{+9.0}_{-9.1}$$

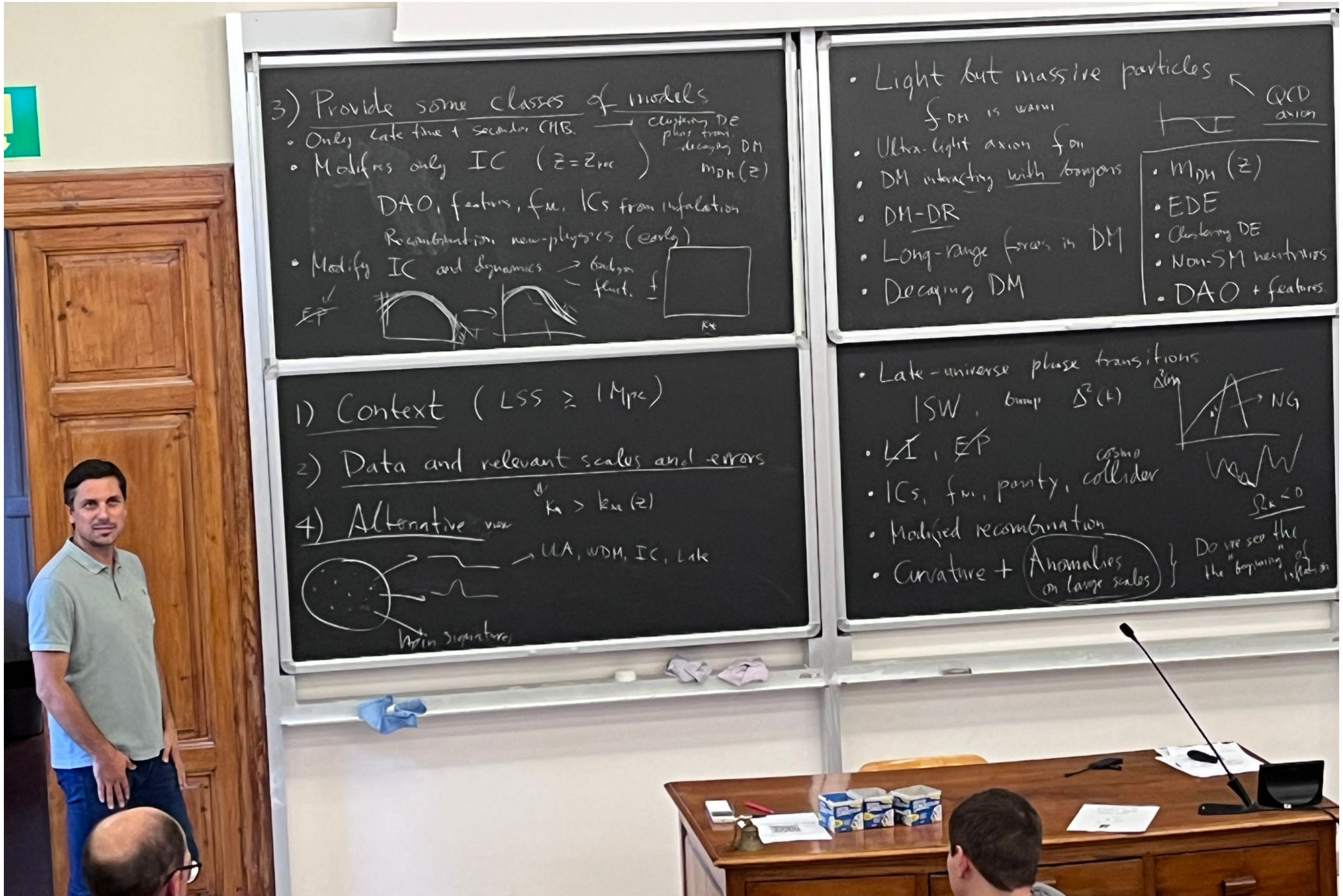


$$f_{\rm NL}^{\rm loc} = -0.1 \pm 7.4$$



Chassidon+24, Chuyadkin+25

Future physics from LSS



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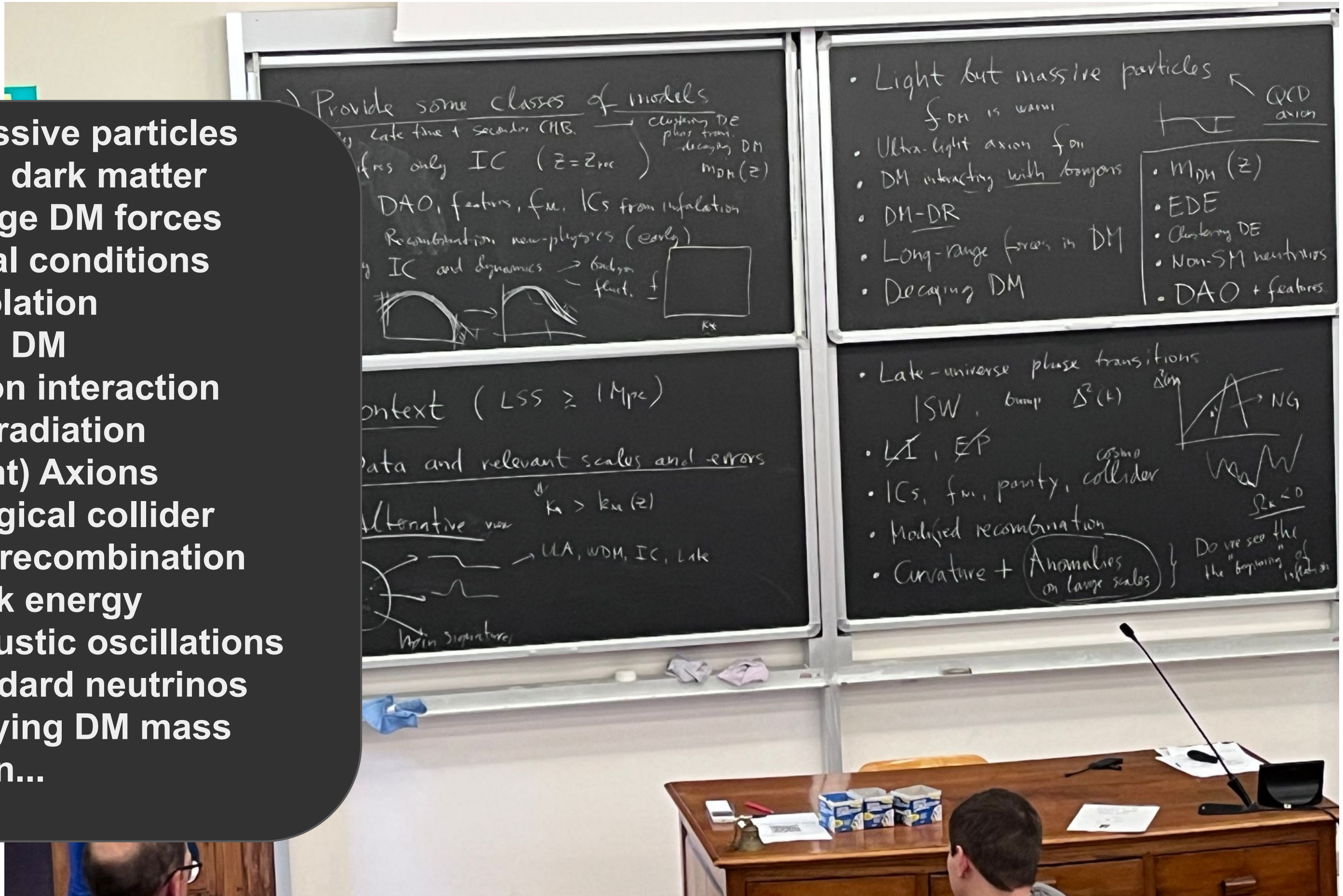
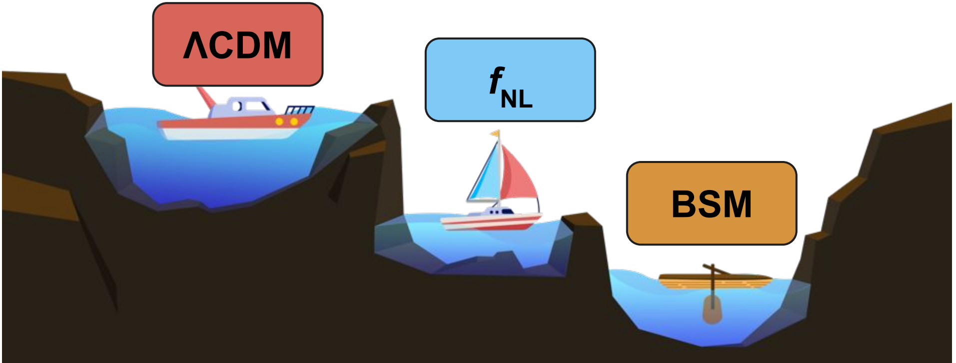
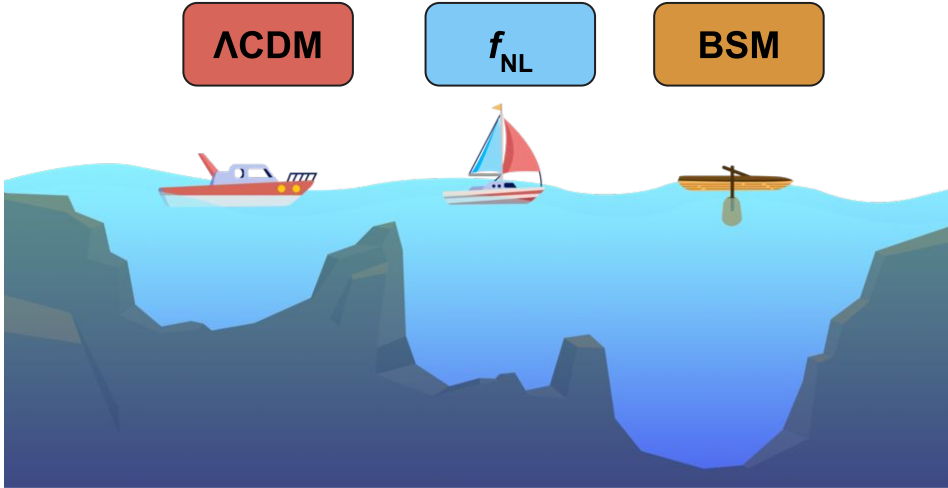


- Light massive particles
- Decaying dark matter
- Long-range DM forces
- New initial conditions
- Parity violation
- Decaying DM
- DM baryon interaction
- DM-dark radiation
- (ultra-light) Axions
- Cosmological collider
- Modified recombination
- Early dark energy
- Dark acoustic oscillations
- Non-standard neutrinos
- Time-varying DM mass
- And so on...

Bias lifts all model boats

New **bias phenomenology** for LSS fields and correlators





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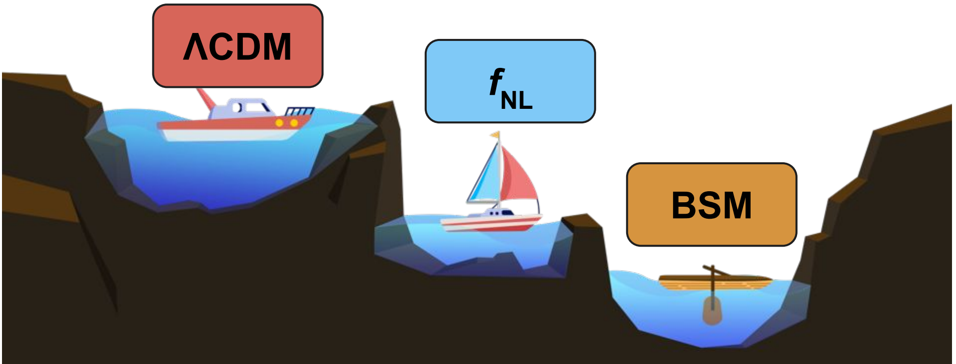
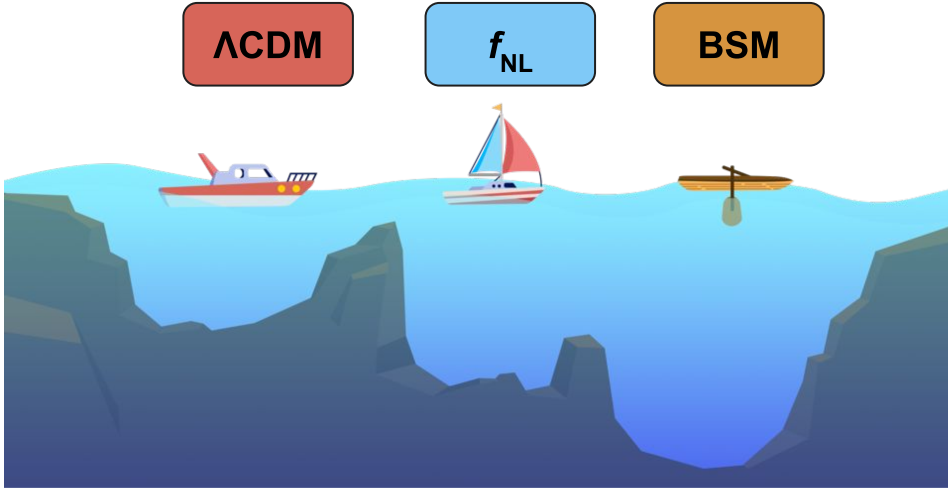
New **bias phenomenology** for LSS fields and correlators

1. How galaxies respond to primordial fluctuations
2. Intergalactic integrated bispectra
3. Tackling tracers of the thirties





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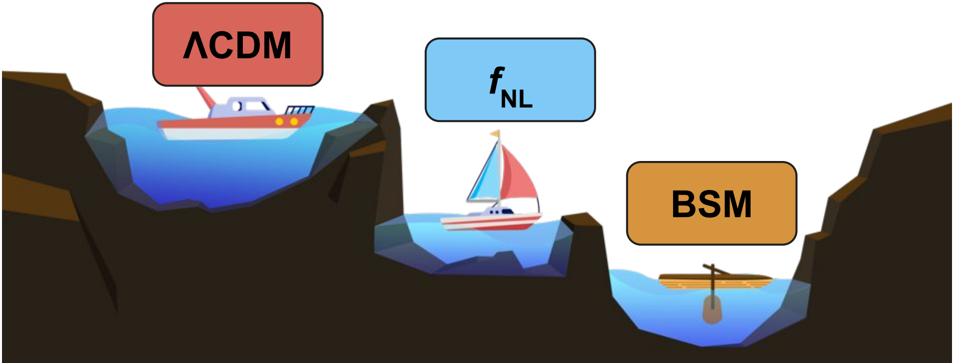
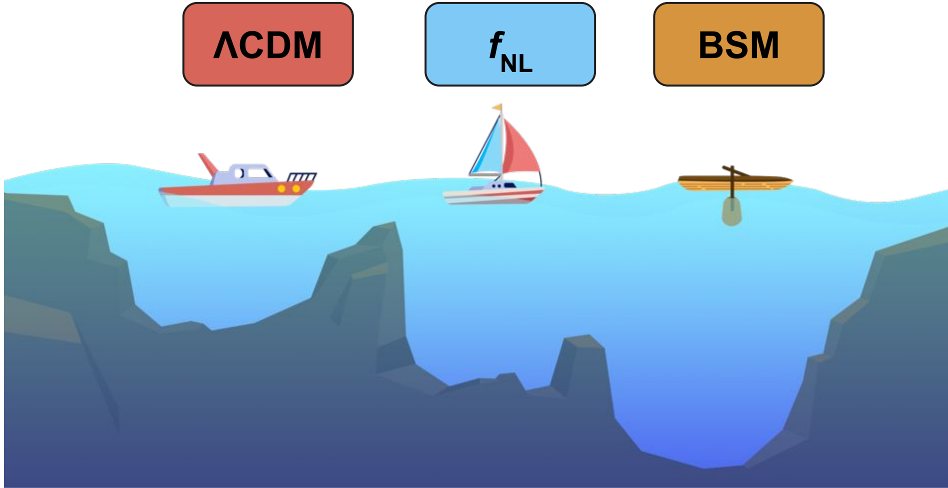




Primordial non-Gaussianity

Nonlinearity in early universe **modulates** statistics

Can search in late time field

$\propto f_{NL}$

$$\phi(\boldsymbol{k}) = \phi_G(\boldsymbol{k}) + \int_{\boldsymbol{k}_1}\int_{\boldsymbol{k}_2} K_{\rm NL}(\boldsymbol{k}_1, \boldsymbol{k}_2)\phi_G(\boldsymbol{k}_1)\phi_G(\boldsymbol{k}_2)(2\pi)^3\delta_D(\boldsymbol{k} - \boldsymbol{k}_{12})$$

Generates bispectrum (L.O.)

And something else...

Dala+08, Slosar+08, many more, inc. **JMS**+Chen24, **JMS**+23, **JMS**+Seljak25, Sharma,**JMS**+25

Galaxy power spectrum*

New bias parameter

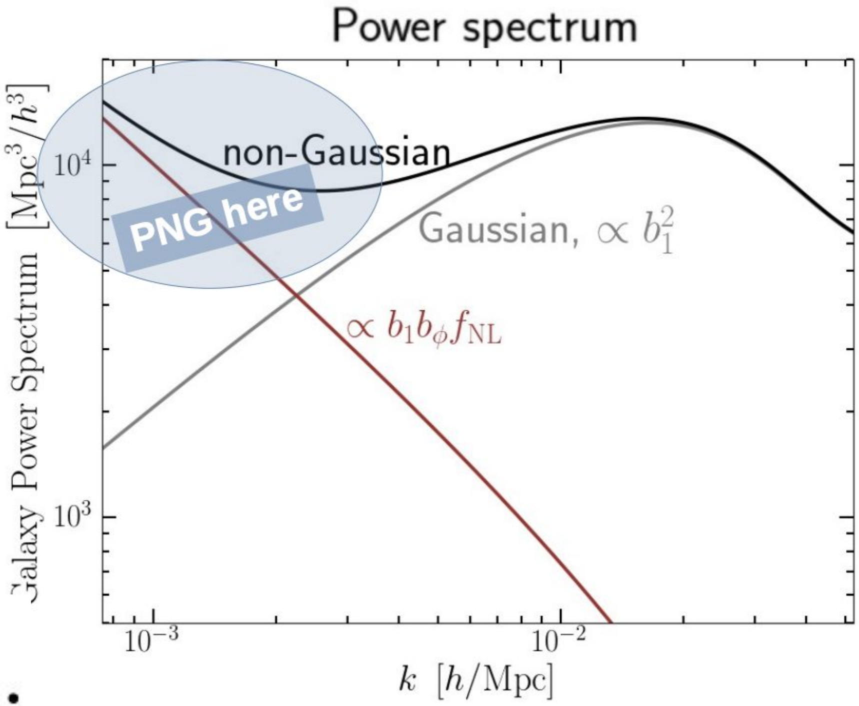
To model - simplest galaxy bias model:

$$\delta_g = b\,\delta + \ldots$$

Galaxy overdensity **Matter overdensity**

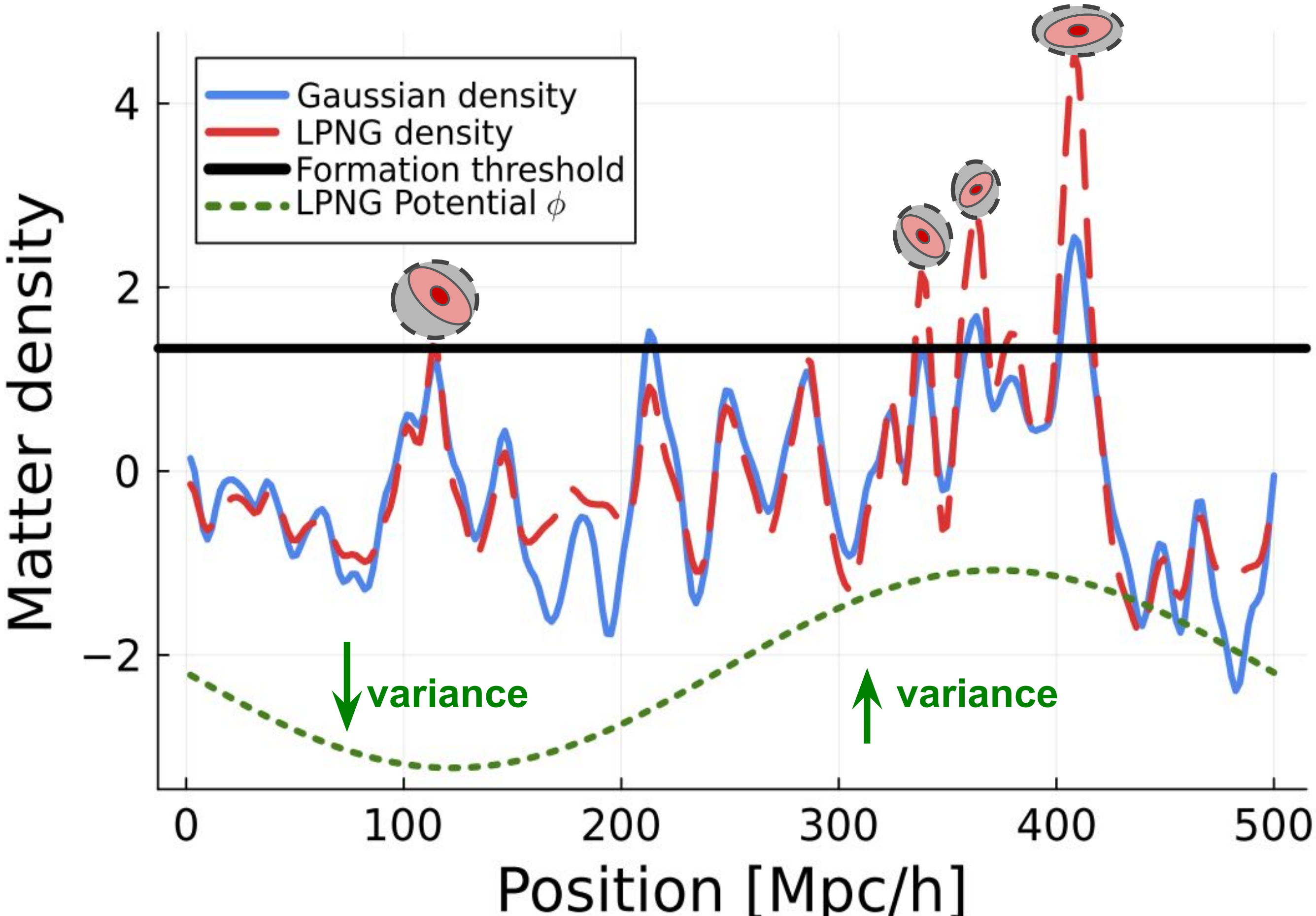
$$\delta_g = b\,\delta + b_\phi\, f_{\rm NL}^{\rm (loc)}\, \phi + \ldots$$

Shows up in **power spectrum**



Planck15, Dalal+08, Slosar+08, image from A. Barreira

Galaxies remember inflation



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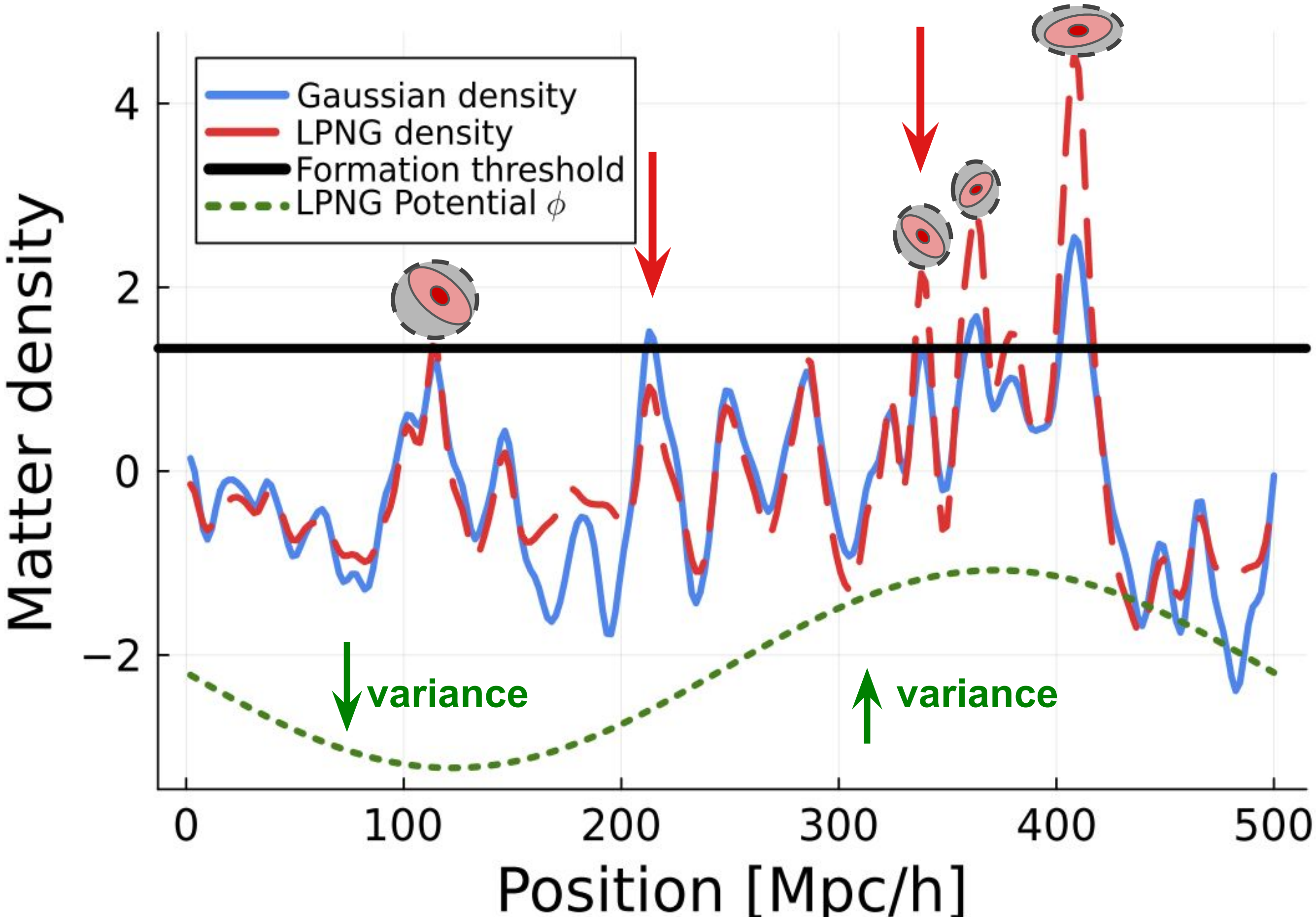

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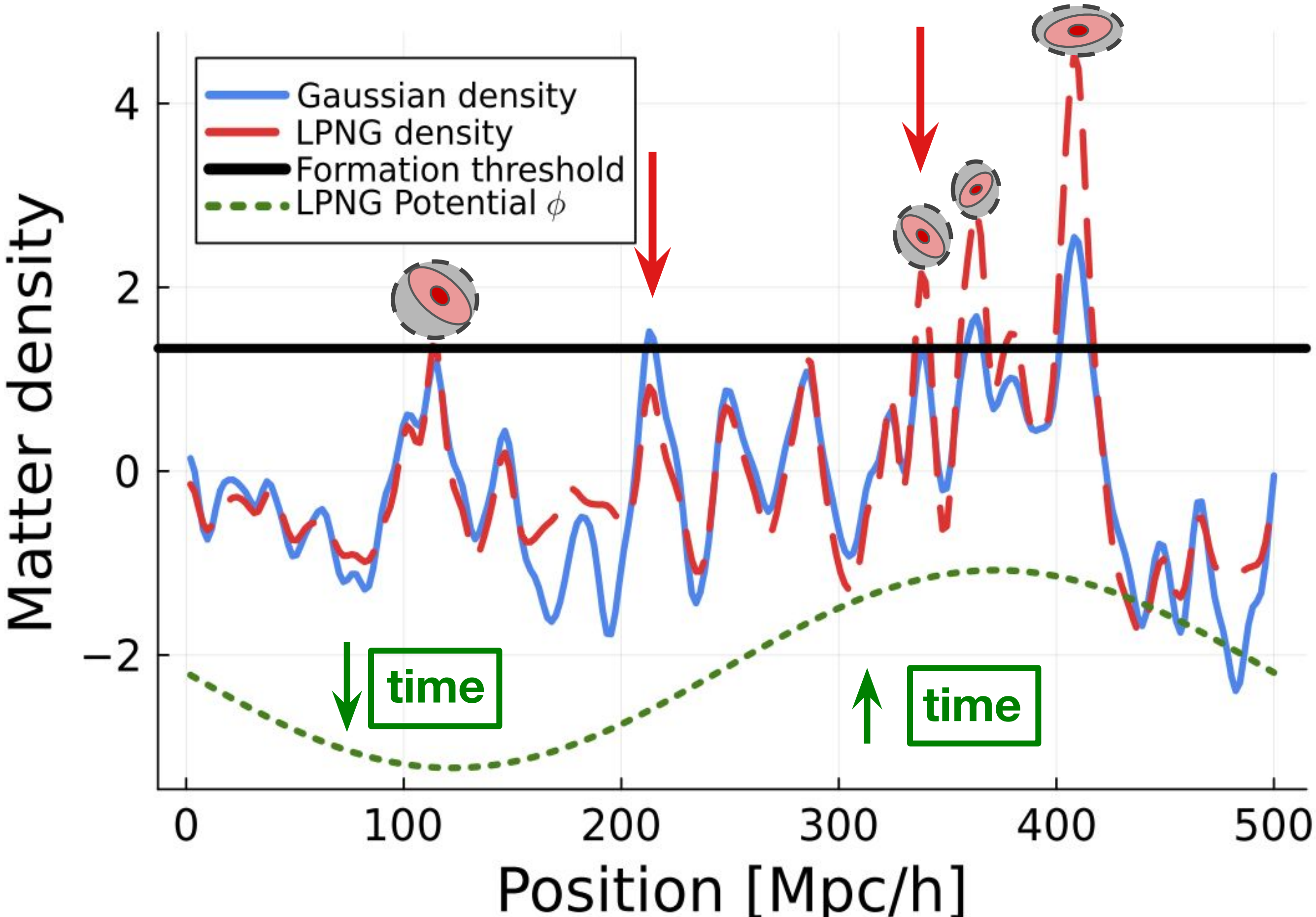
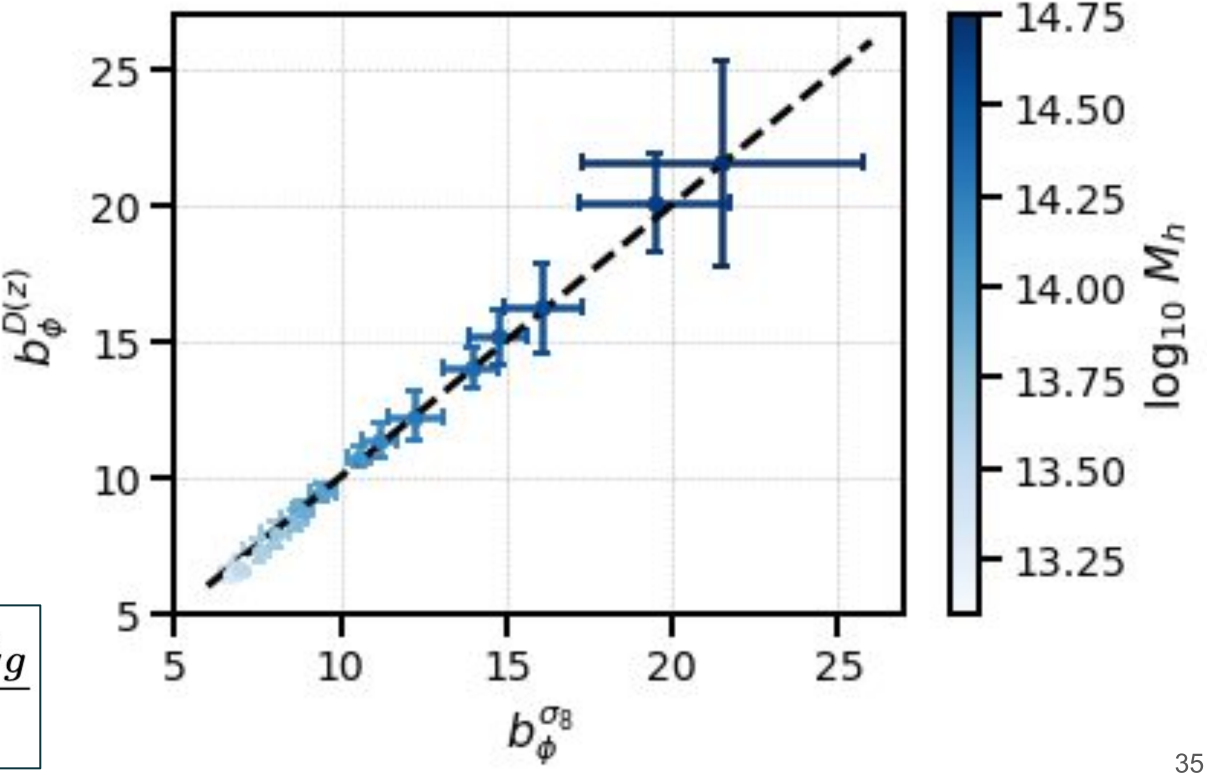


Bias from Time Evolution - Simulated Halos

N-body halos at $z = 1$

Evaluate bias via finite difference response to:
1. variance (σ_8)
2. growth

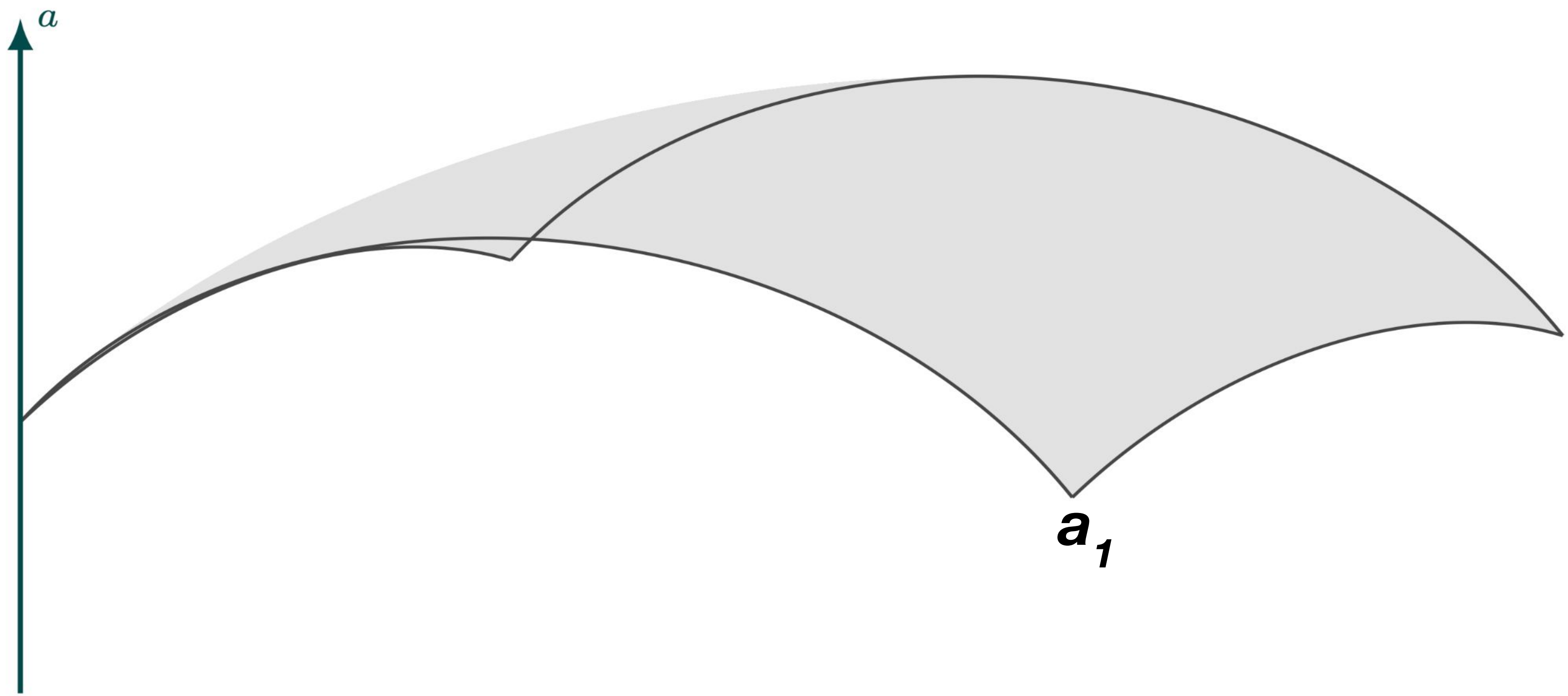
$$b_\phi^{X=\{\sigma_8, D(z)\}} = 2\frac{d\log n_g}{d\delta X}$$



Why does this work?

Absorb long mode into FLRW ~ **separate universe**

Time separate universe*



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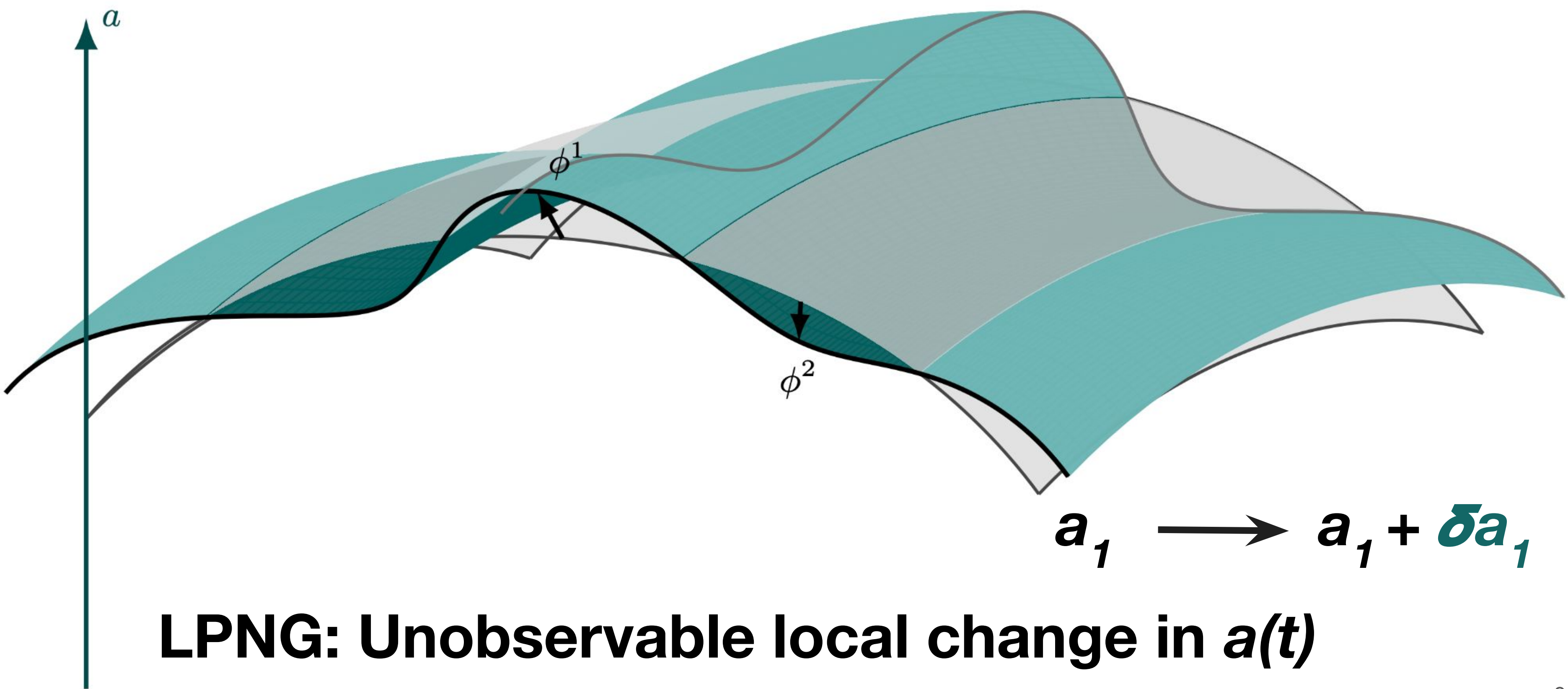
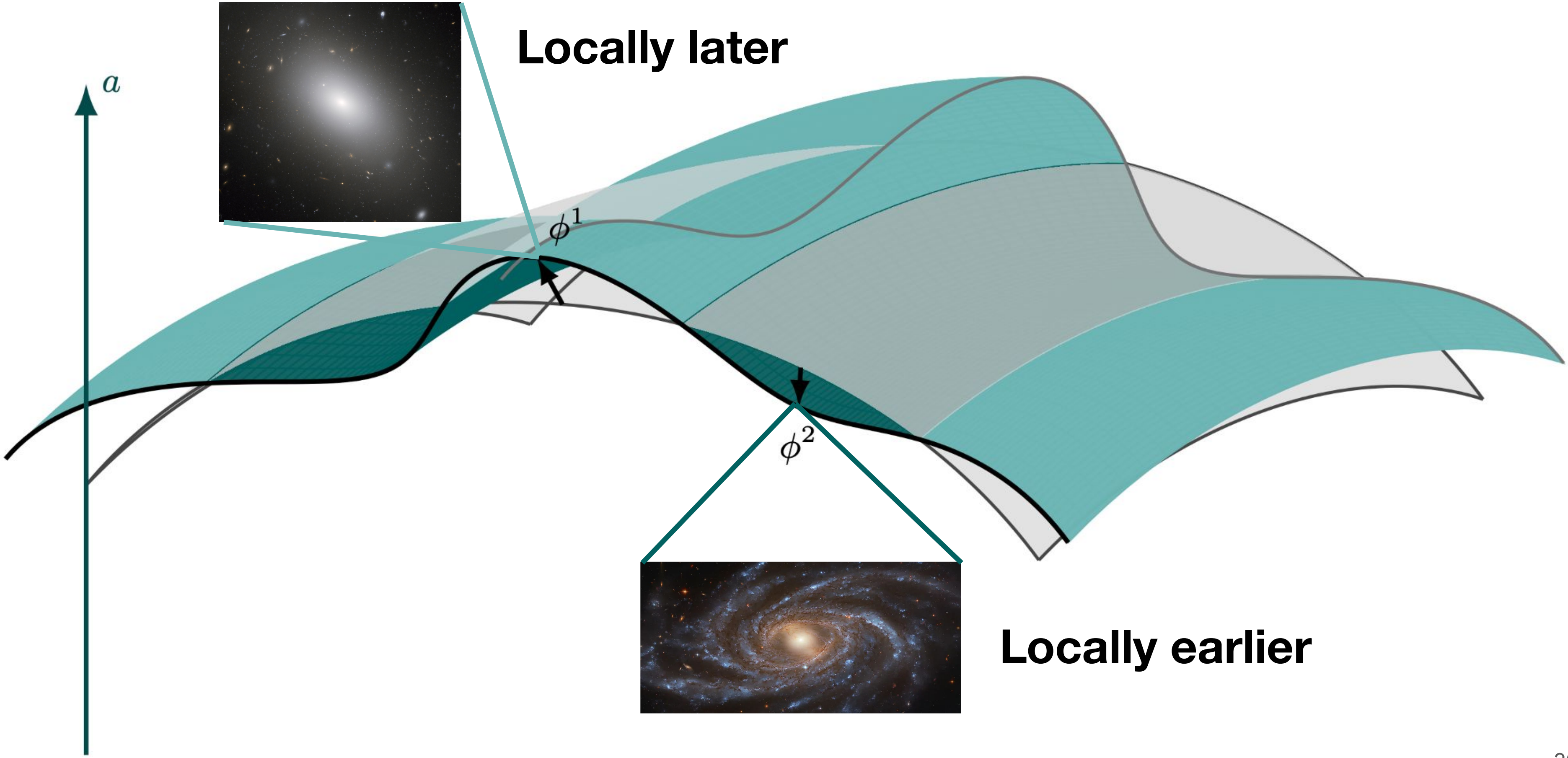


$a_1 \longrightarrow a_1 + \delta a_1$

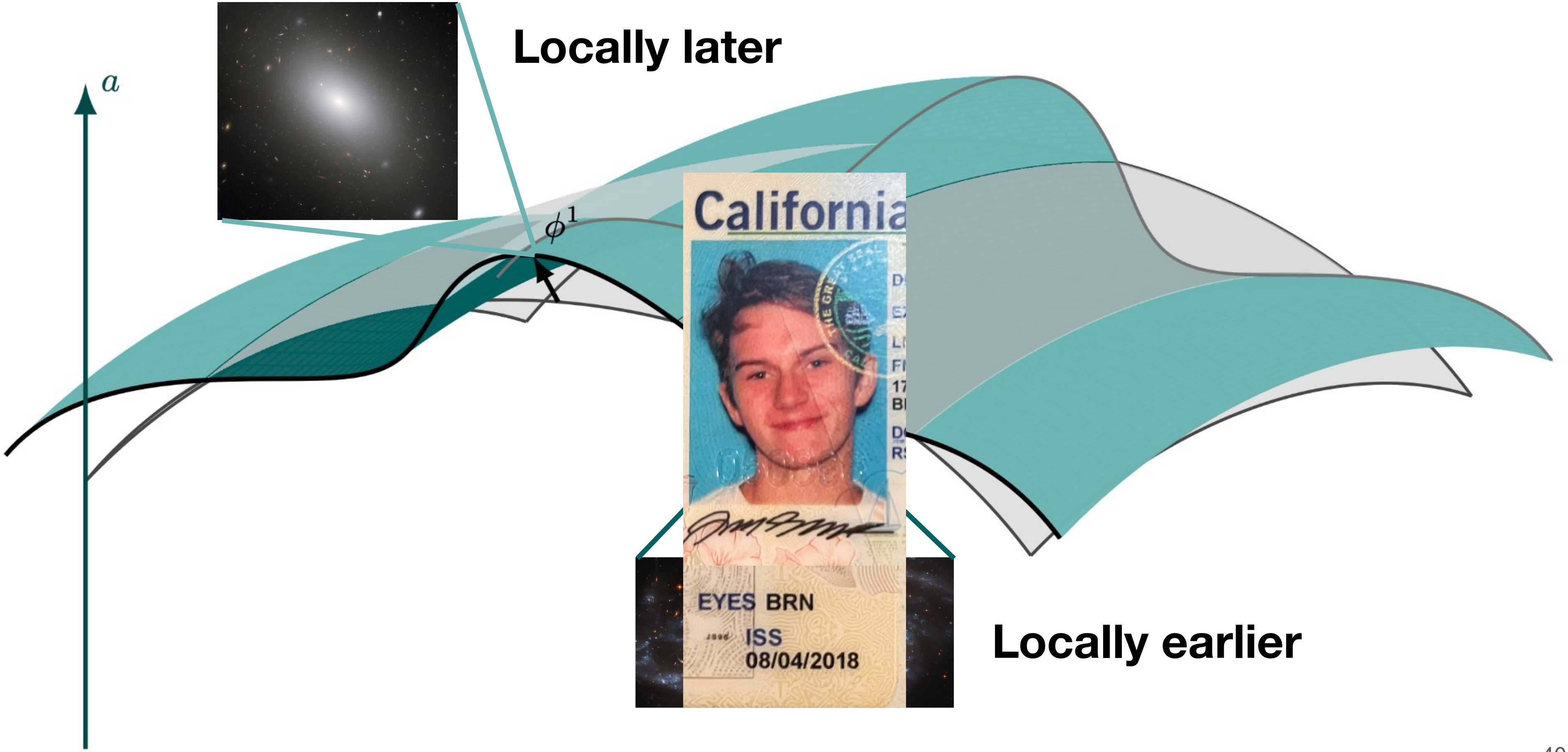
LPNG: Unobservable local change in *a(t)*

Time separate universe*



NASA

Time separate universe*



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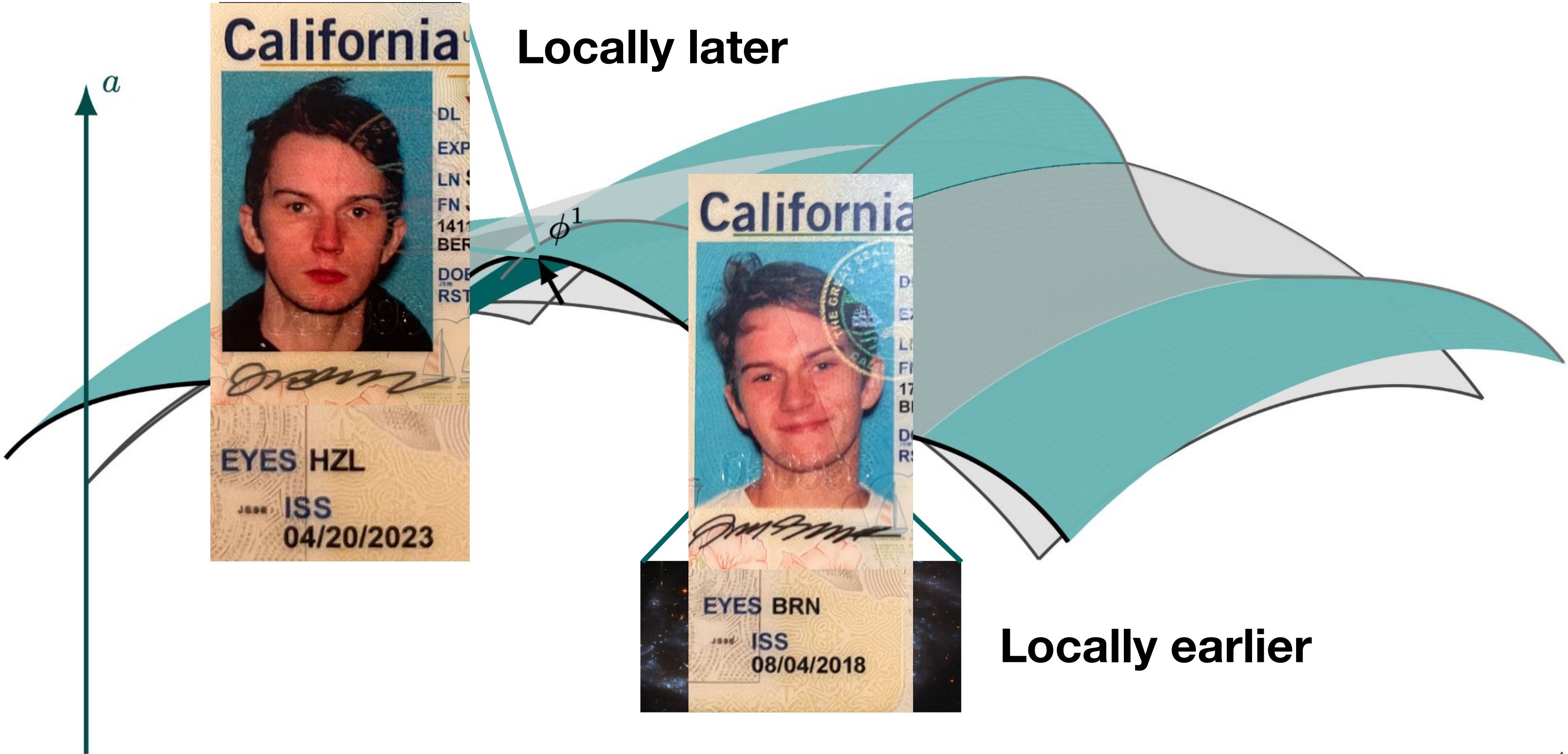

NASA

You can make this rigorous!

Absorb long mode into FLRW ~ **separate universe**

$$ds^2 = a^2(\tau)\left[-(1+2\psi)\,d\tau^2 + (1-2\phi)\,\delta_{ij}dx^i dx^j\right]$$

$$ds^2 = a_F^2(\tau_F)\left[-d\tau_F^2 + \frac{\delta_{ij}dx_F^i dx_F^j}{(1+K_F\tilde{r}_F^2)^2}\right]$$

$$a_F(\tau_F) = a(\tau)\left[1 + \frac{2}{3}\psi_{\rm ini} + \int_0^\tau d\tau'\left(-\phi' + \frac{1}{3}\partial_i V^i\right)\right]$$

$$H_F(\tau_F) = H\left[1 - \left(\psi + \frac{1}{\mathcal{H}}\phi'\right) + \frac{1}{3\mathcal{H}}\partial_i V^i\right]$$

$$K_F = \frac{2}{3}\left(\partial^2\phi - \mathcal{H}\partial_i V^i\right).$$

$$ds^2 = a_F^2(\tau_F)\left(-d\tau_F^2 + \delta_{ij}dx_F^i dx_F^j\right)$$

$$a_F(\tau_F) = a(\tau)\left(1 + \frac{2}{3}\psi_{\rm ini}\right)$$

consider long mode of **potential**

JMS+Seljak 25, Dai+16, Ginat+23

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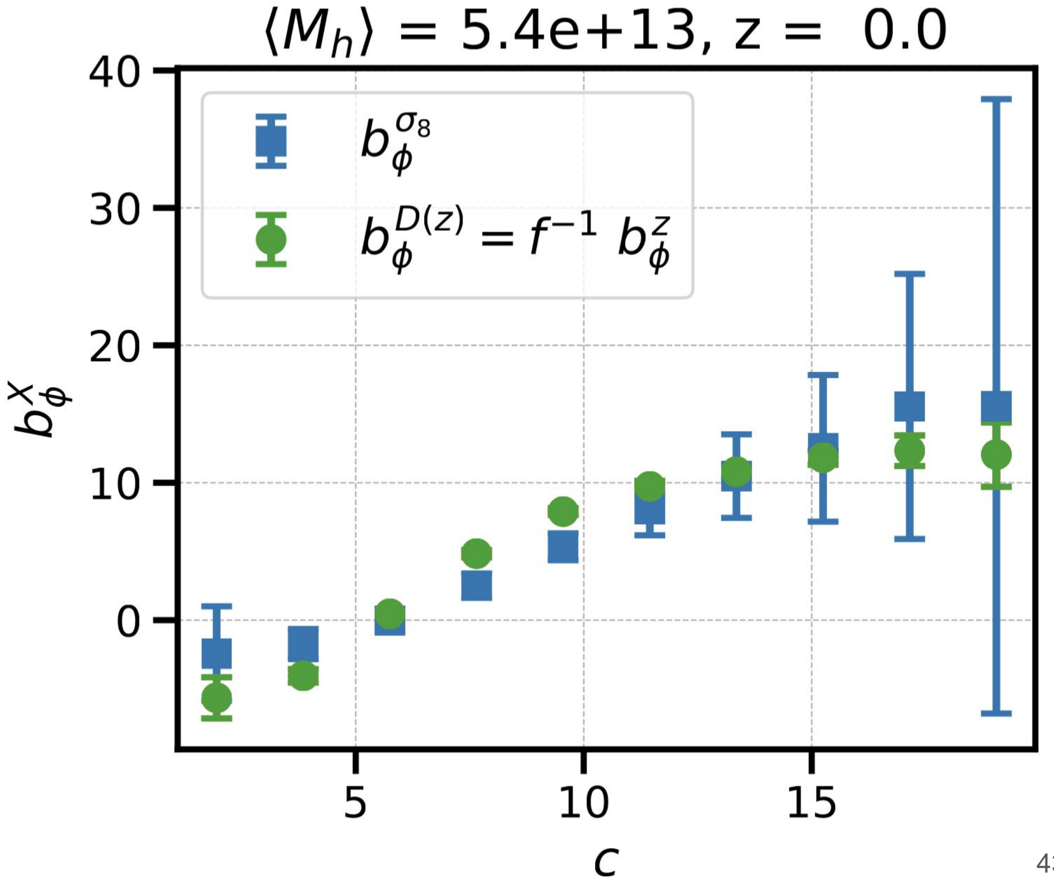
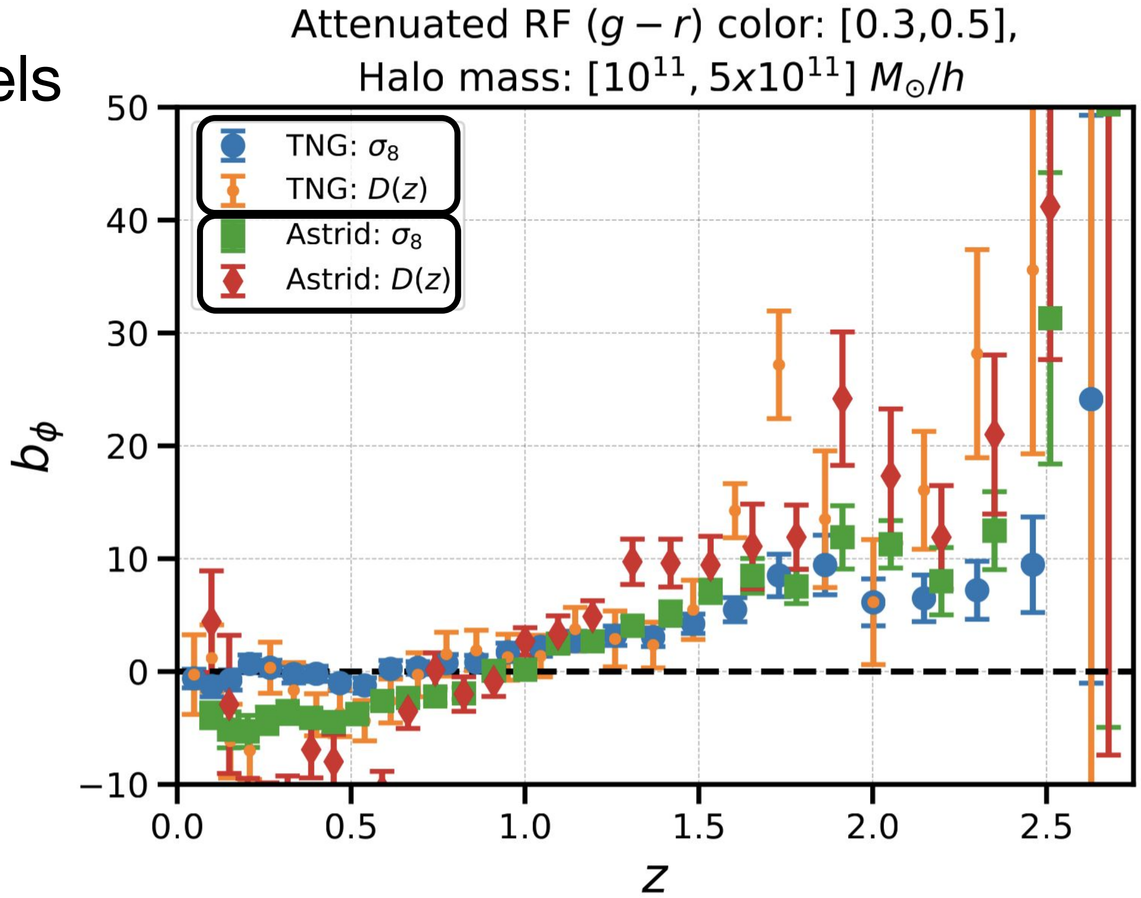


Hydrodynamical simulations

Multiple formation models (TNG, Astrid)

Relatively robust to (intrinsic) dust

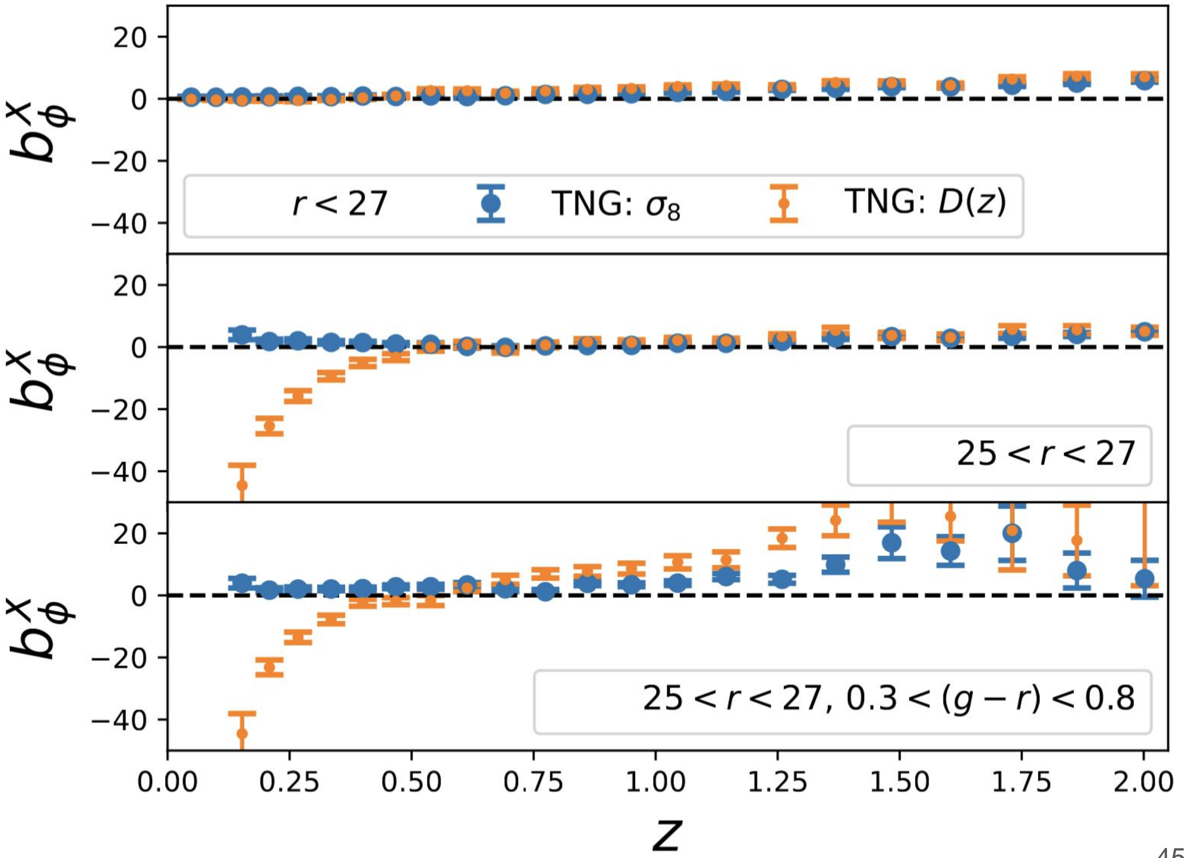
Time to go to the **data**?



Real life...

Selection function can have huge impact

Especially for **bright end** and **color**



Real life...

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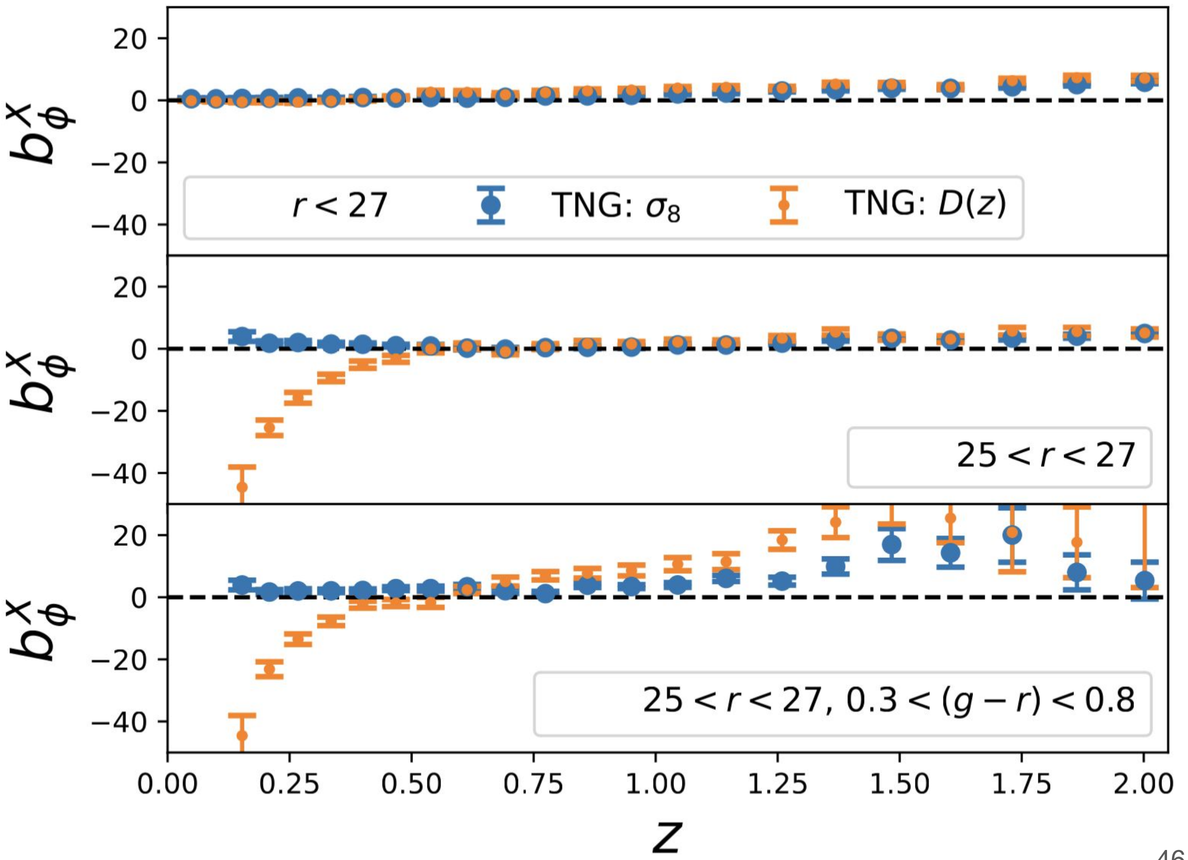
Treating this **now**!



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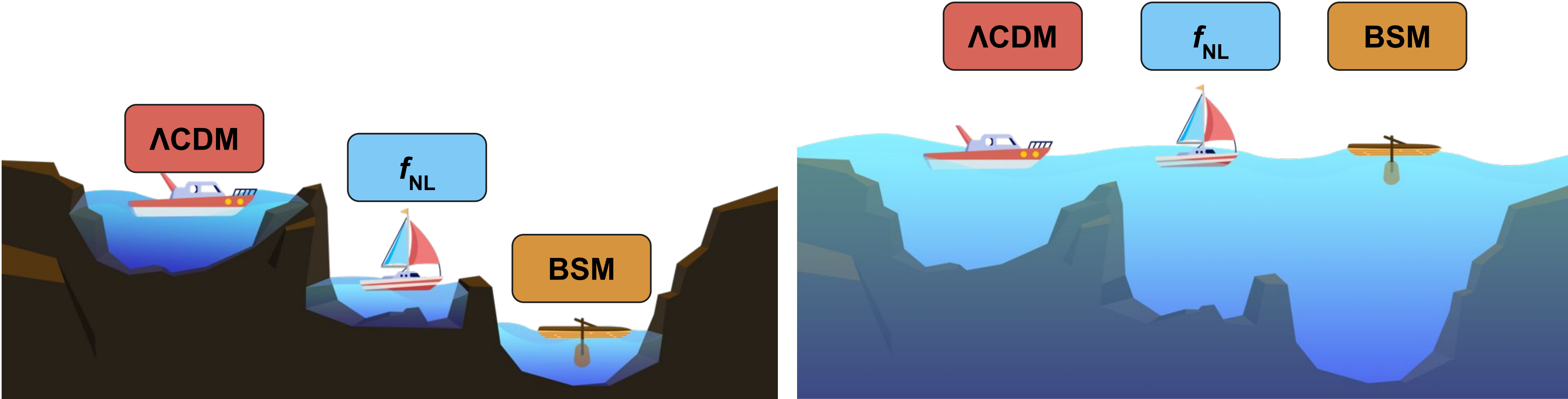
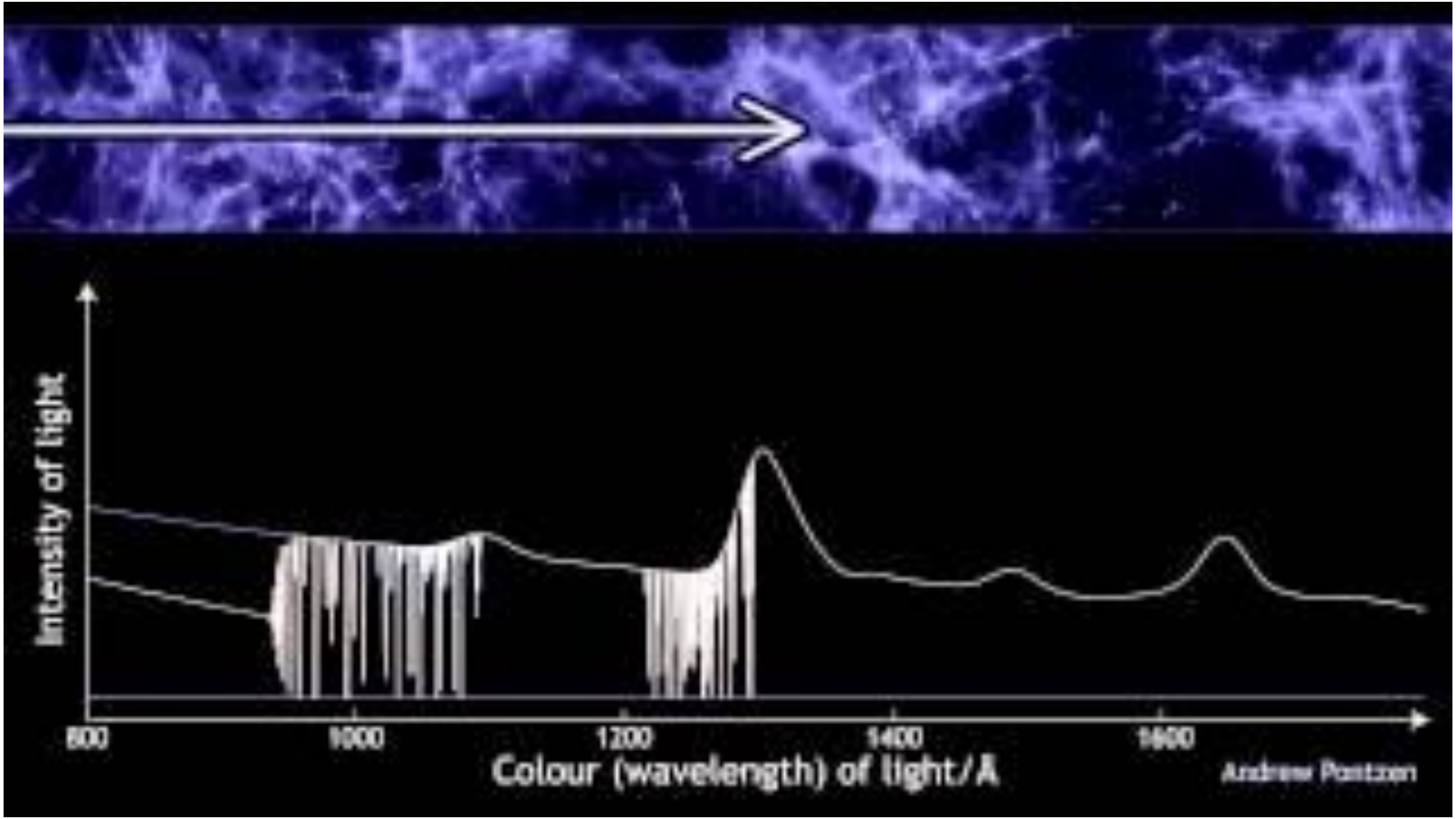


Photons passing (through) gas*



The forest

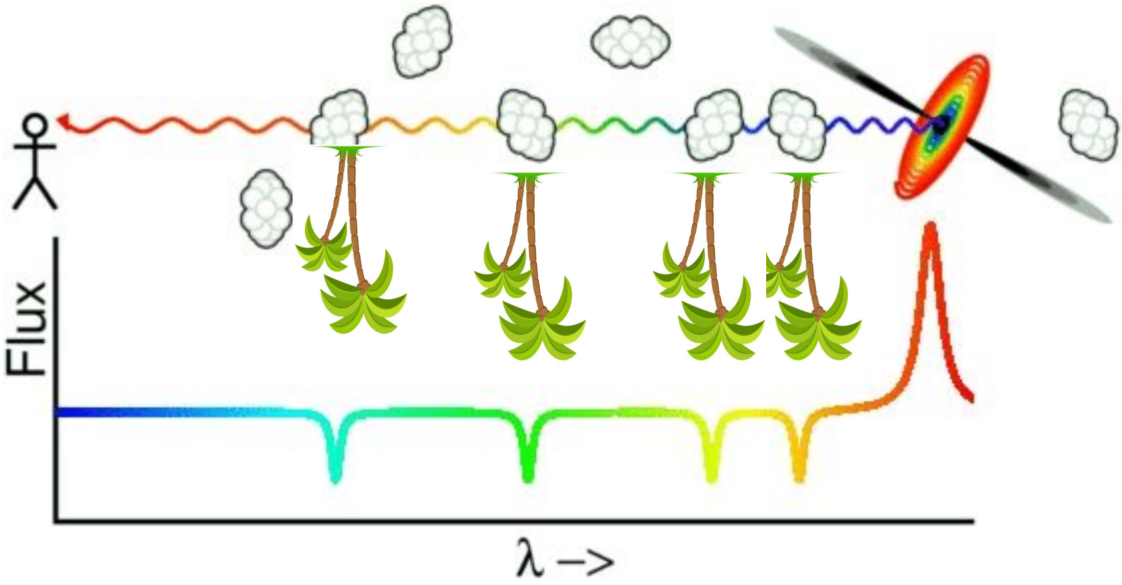
Background quasar flux

Absorbing HI clouds

Cloud redshifted

Lyman-α absorption

-> Spectra contain LSS tracers!



The forest

Background quasar flux

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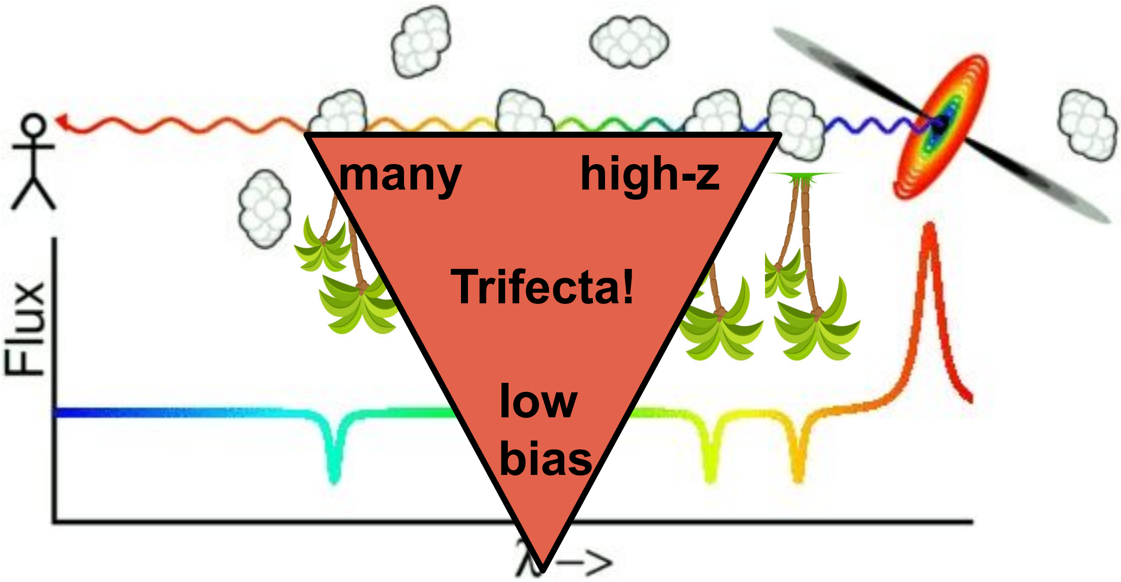


a unique high-z LSS opportunity*

E. Wright

From maps to lines to triangles

Two flux pixels can be correlated:

- In pairs for a <u>single</u> QSO
- Across multiple QSOs

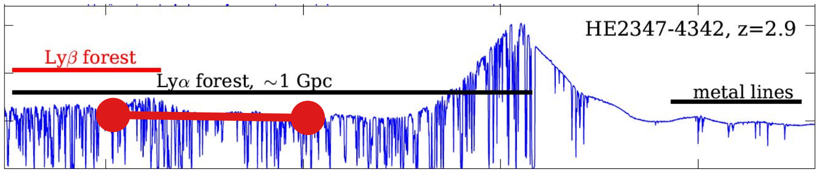
This is current SOTA

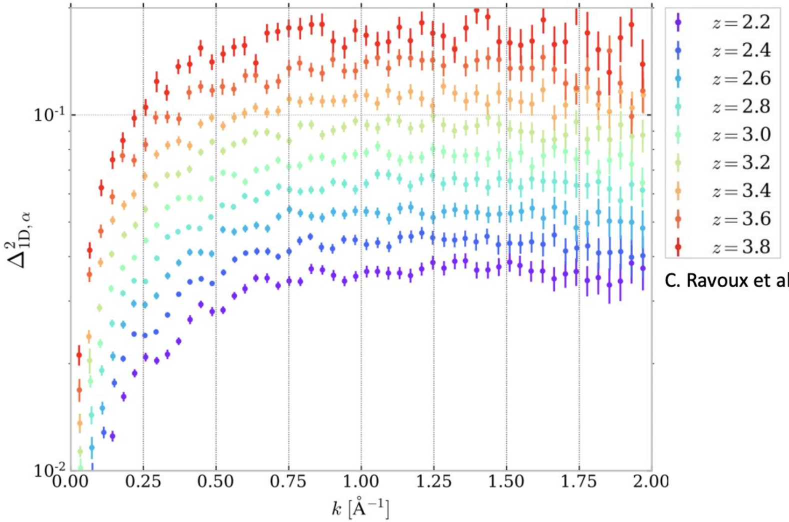
$$\langle \rho \rangle$$

$$\langle \delta^2 \rangle, \boxed{\langle \delta\delta \rangle \rightarrow P(k)}$$

$$\langle \delta^3 \rangle, \langle \delta\delta\delta \rangle \rightarrow B(k_1, k_2, k_3)$$

$$\vdots$$

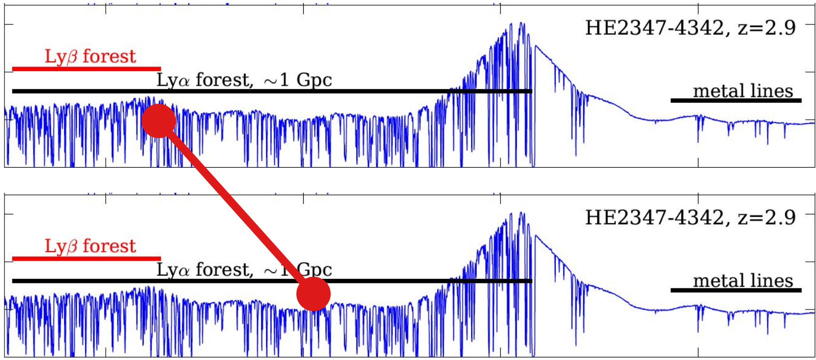




C. Ravoux et al 2023

de Belsunce+23, Abdul Karim+25, Ravoux+23, McQuinn+15, B. Keel

From maps to lines to triangles



Two flux pixels can be correlated:

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$\langle \delta^2 \rangle, \langle \delta\delta \rangle \to P(k)$

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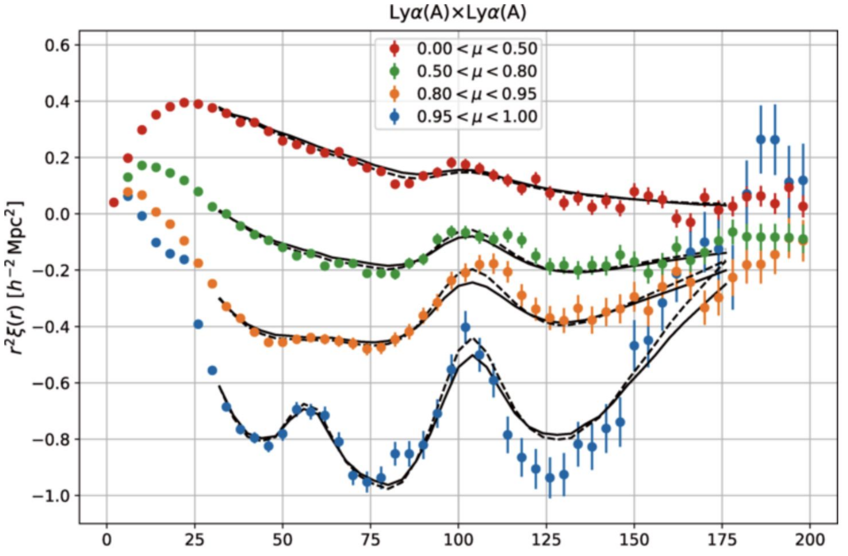
$\vdots$



de Belsunce+23, Abdul Karim+25, Ravoux+23, McQuinn+15, B. Keel

From maps to lines to triangles

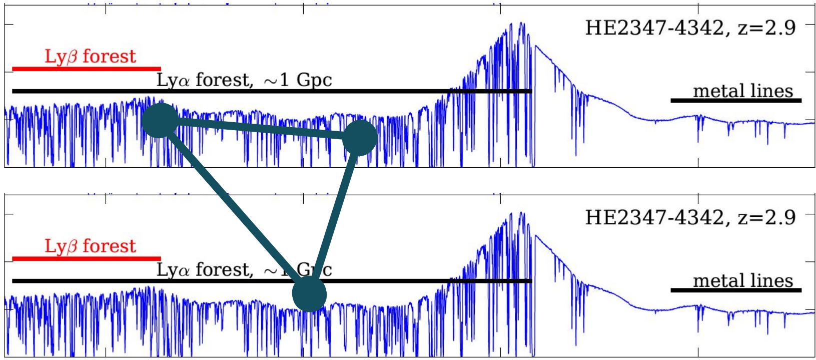
Two flux pixels can be correlated:

- **In pairs for a single QSO**
- **Across multiple QSOs**

This is current SOTA

Going to 3-pixel correlations:

- **quite challenging to measure**



$$\langle \rho \rangle$$

$$\langle \delta^2 \rangle, \langle \delta\delta \rangle \rightarrow P(k)$$

$$\langle \delta^3 \rangle, \langle \delta\delta\delta \rangle \rightarrow B(k_1, k_2, k_3)$$

$$\vdots$$

de Belsunce+23, Abdul Karim+25, Ravoux+23, McQuinn+15, B. Keel

Skew spectra - integrated bispectrum*

Quadratic cross-spectra:

$$\tilde{P}_{\mathcal{S}_i}(k) = \int \frac{\mathrm{d}\hat{\mathbf{k}}}{4\pi} \int_{\mathbf{q}} \mathcal{S}_n(\mathbf{q}, \mathbf{k}-\mathbf{q}) B(\mathbf{q}, \mathbf{k}-\mathbf{q}, -\mathbf{k})$$

How to model them?

- **Compute the bispectrum**
- **Identify structure of terms**

-> These become skew spectra kernels (*S_n*)

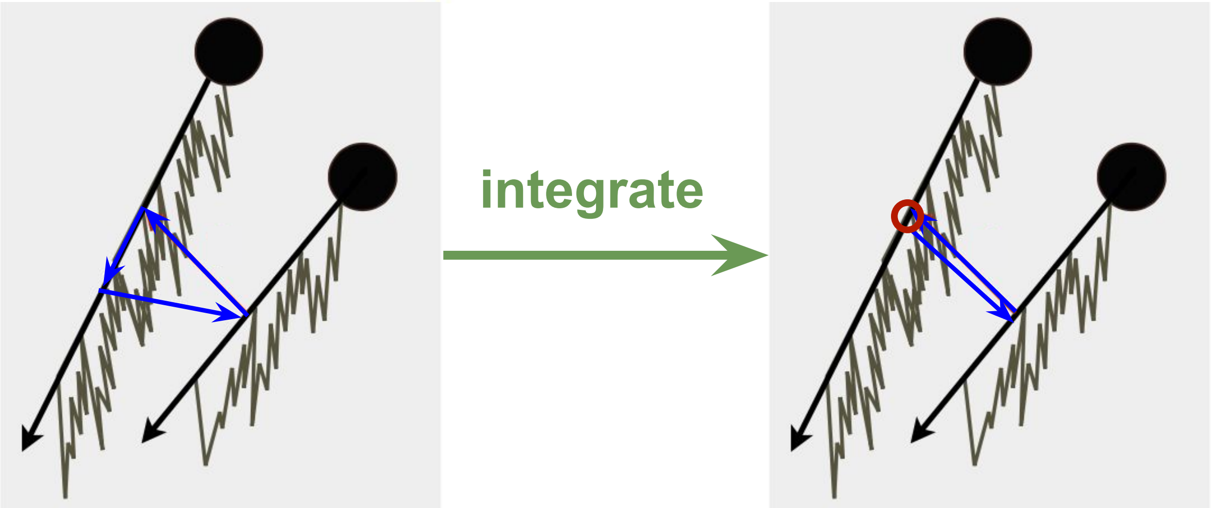
Schmittfull+14, Dizgah+19, Schmittfull+Dizgah20, Hou+22, Chen+24, Hou+24

Integrating away triangles and complexity

Compressed statistic: skew spectrum

Weight **Mode coupling**

$$\tilde{P}_{\mathcal{S}_i}(k) = \int \frac{\mathrm{d}\hat{\mathbf{k}}}{4\pi} \int_{\mathbf{q}} \underline{\mathcal{S}_n(\mathbf{q}, \mathbf{k}-\mathbf{q})}\, \boxed{B(\mathbf{q}, \mathbf{k}-\mathbf{q}, -\mathbf{k})}$$



Adapted from A. Font-Ribera

Lyman-α bias expansion

EFT det. bias of 3D tracer:

$$\delta_F = b_1\delta + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + b_{\Gamma_3}\Gamma_3$$

Ivanov24, Desjacques+18, Seljak12, Givans+Hirata20, Garny+21, Chen+21

Lyman-α bias expansion

EFT det. bias of RSD galaxies:

$$\delta_F = b_1\delta + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + b_{\Gamma_3}\Gamma_3$$
$$+ \quad \eta + \quad \eta\delta + \quad \eta^2$$

Usual RSD operators

Ivanov24, Desjacques+18, Seljak12, Givans+Hirata20, Garny+21, Chen+21

Lyman-α bias expansion

EFT bias expansion of SO(2)/azimuthal tracer:

$$\delta_F = b_1\delta + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + b_{\Gamma_3}\Gamma_3 + b_\eta \eta + b_{\delta\eta}\eta\delta + b_{\eta^2}\eta^2 + b_{(KK)_\parallel} K_{ij}K_{jl}\hat{z}^i\hat{z}^l + b_{\Pi^{[2]}_\parallel}\Pi^{[2]}_{ij}\hat{z}^i\hat{z}^j$$

Usual RSD operators get biases

Pick up "selection" operators

Ivanov24, Desjacques+18, Seljak12, Givans+Hirata20, Garny+21, Chen+21

Lyman-α bias expansion

EFT bias expansion of SO(2)/azimuthal tracer:

$$\delta_F = b_1\delta + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + b_{\Gamma_3}\Gamma_3$$
$$+ b_\eta\eta + b_{\delta\eta}\eta\delta + b_{\eta^2}\eta^2$$
$$+ b_{(KK)_\parallel}K_{ij}K_{jl}\hat{z}^i\hat{z}^l + b_{\Pi_\parallel^{[2]}}\Pi_{ij}^{[2]}\hat{z}^i\hat{z}^j$$

Usual RSD operators get biases

Pick up "selection" operators

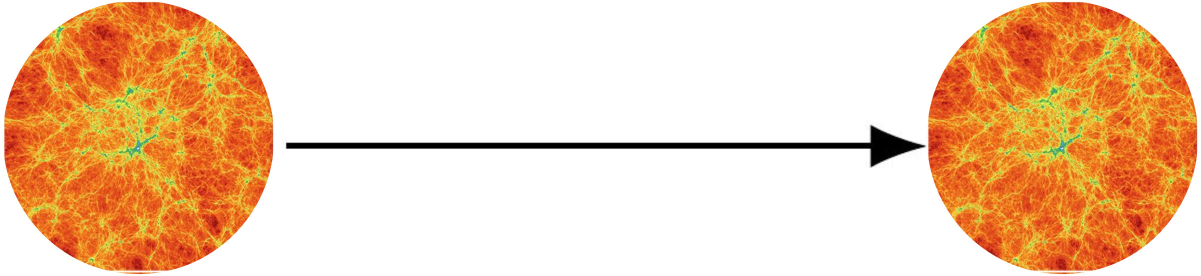
Why?

Ivanov24, Desjacques+18, Seljak12, Givans+Hirata20, Garny+21, Chen+21

The forest lives in *SO*(2)

Symmetries:

Translation



McDonald+Roy09, Givans+Hirata20; Illustris

The forest lives in *SO*(2)

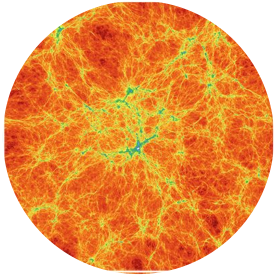
Symmetries:

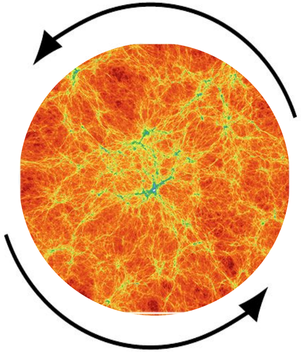
Translation

<u>In-sky</u> rotation

$\hat{z}$

$\otimes$





McDonald+Roy09, Givans+Hirata20; Illustris

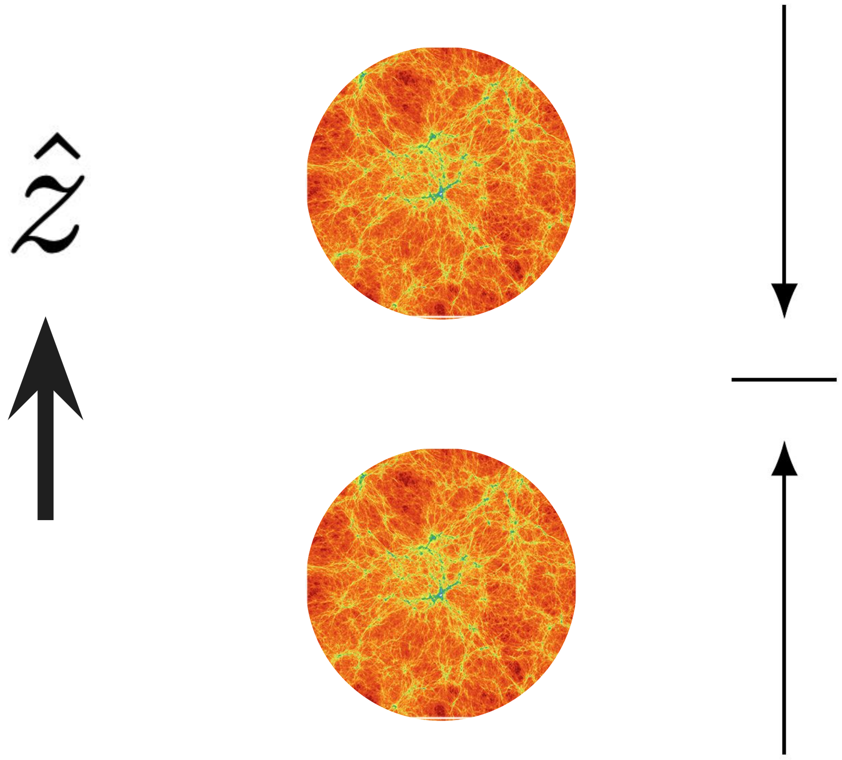
The forest lives in *SO*(2)

Symmetries:

Translation

<u>In-sky</u> rotation

Sightline symmetry



McDonald+Roy09, Givans+Hirata20; Illustris

The forest lives in *SO*(2)

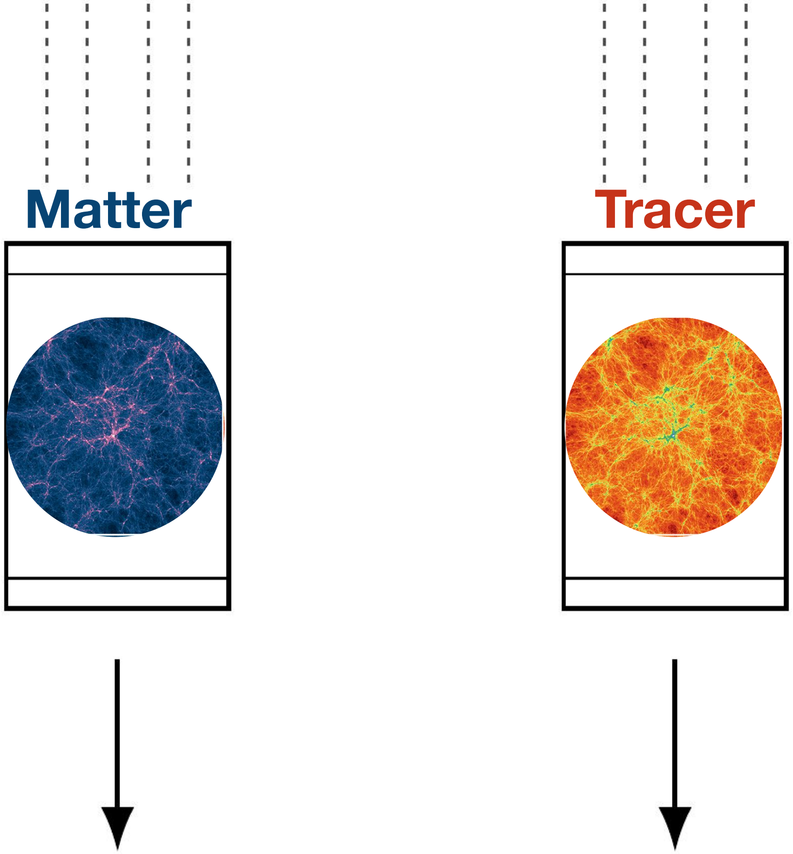
Symmetries:

Translation

<u>In-sky</u> rotation

Sightline symmetry

Equivalence principle



McDonald+Roy09, Givans+Hirata20; Illustris

Lyman-α bias expansion*

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$$\delta_F = b_1\delta + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + b_{\Gamma_3}\Gamma_3$$
$$+ b_\eta \eta + b_{\delta\eta}\eta\delta + b_{\eta^2}\eta^2$$
$$+ b_{(KK)_\parallel} K_{ij}K_{jl}\hat{z}^i\hat{z}^l + b_{\Pi^{[2]}_\parallel}\Pi^{[2]}_{ij}\hat{z}^i\hat{z}^j$$

Usual RSD operators get biases

Pick up "selection" operators

Ivanov24, Desjacques+18, Seljak12, Givans+Hirata20, Garny+21, Chen+21

New skew spectra - Lyman alpha

Now 26:

- Old

- Add bias

- New term

$$b_1^3 f^0 : \mathcal{S}_1 = F_2[\delta, \delta]$$
$$b_1^2 b_2 f^0 : \mathcal{S}_2 = \delta^2$$
$$b_1^2 b_{\mathcal{G}_2} f^0 : \mathcal{S}_3 = \mathcal{G}_2[\delta, \delta]$$
$$b_1^2 b_{(KK)_\parallel} f^0 : \mathcal{S}_4 = (KK)_\parallel[\delta, \delta]$$
$$b_1^2 b_{\Pi_\parallel^{[2]}} f^0 : \mathcal{S}_5 = \Pi_\parallel^{[2]}[\delta, \delta]$$
$$b_1^3 f^1 : \mathcal{S}_6 = \hat{z}^i \hat{z}^j \frac{\partial_i}{\nabla^2}\delta \frac{\partial_j}{\nabla^2}\delta$$
$$b_1^2 b_\eta f^1 : \mathcal{S}_7 = G_2^\parallel[\delta, \delta] + 2F_2[\delta^\parallel, \delta]$$
$$b_1 b_2 b_\eta f^1 : \mathcal{S}_8 = \delta^\parallel \delta$$
$$b_1 b_{\mathcal{G}_2} b_\eta f^1 : \mathcal{S}_9 = \mathcal{G}_2[\delta^\parallel, \delta]$$
$$b_1 b_\eta b_{(KK)_\parallel} f^1 : \mathcal{S}_{10} = (KK)_\parallel[\delta^\parallel, \delta]$$
$$b_1 b_\eta b_{\Pi_\parallel^{[2]}} f^1 : \mathcal{S}_{11} = \Pi_\parallel^{[2]}[\delta^\parallel, \delta]$$
$$b_1^2 b_{\delta\eta} f^1 : \mathcal{S}_{12} = \delta^\parallel \delta$$
$$b_1 (b_\eta)^2 f^2 : \mathcal{S}_{13} = 2G_2^\parallel[\delta^\parallel, \delta] + F_2[\delta^\parallel, \delta^\parallel]$$
$$b_2 (b_\eta)^2 f^2 : \mathcal{S}_{14} = \left(\delta^\parallel\right)^2$$
$$b_{\mathcal{G}_2} (b_\eta)^2 f^2 : \mathcal{S}_{15} = \mathcal{G}_2[\delta^\parallel, \delta^\parallel]$$
$$(b_\eta)^2 b_{(KK)_\parallel} f^2 : \mathcal{S}_{16} = (KK)_\parallel[\delta^\parallel, \delta^\parallel]$$
$$(b_\eta)^2 b_{\Pi_\parallel^{[2]}} f^2 : \mathcal{S}_{17} = \Pi_\parallel^{[2]}[\delta^\parallel, \delta^\parallel]$$
$$b_1 b_\eta b_{\delta\eta} f^2 : \mathcal{S}_{18} = \delta^{\parallel\parallel}\delta + 2\left(\delta^\parallel\right)^2$$
$$b_1^2 b_\eta f^2 : \mathcal{S}_{19} = \hat{z}^i \hat{z}^j \left[(\partial_i \delta)\left(\frac{\partial_j}{\nabla^2}\delta^\parallel\right) + 2\left(\partial_i \delta^\parallel\right)\left(\frac{\partial_j}{\nabla^2}\delta\right)\right]$$
$$b_1^2 b_{\eta^2} f^2 : \mathcal{S}_{20} = \left(\delta^\parallel\right)^2$$
$$b_1 (b_\eta)^2 f^3 : \mathcal{S}_{21} = \hat{z}^i \hat{z}^j \left[\left(\partial_i \delta^{\parallel\parallel}\right)\left(\frac{\partial_j}{\nabla^2}\delta\right) + 2\left(\partial_i \delta^\parallel\right)\left(\frac{\partial_j}{\nabla^2}\delta^\parallel\right)\right]$$
$$b_1 b_\eta b_{\eta^2} f^3 : \mathcal{S}_{22} = \delta^{\parallel\parallel}\delta^\parallel$$
$$(b_\eta)^2 b_{\delta\eta} f^3 : \mathcal{S}_{23} = \delta^{\parallel\parallel}\delta^\parallel$$
$$(b_\eta)^3 f^3 : \mathcal{S}_{24} = G_2^\parallel[\delta^\parallel, \delta^\parallel]$$
$$(b_\eta)^2 b_{\eta^2} f^4 : \mathcal{S}_{25} = \hat{z}^i \hat{z}^j \left(\partial_i \delta^{\parallel\parallel}\right)\left(\frac{\partial_j}{\nabla^2}\delta^\parallel\right)$$
$$(b_\eta)^3 f^4 : \mathcal{S}_{26} = \left(\delta^{\parallel\parallel}\right)^2.$$

New skew spectra - Lyman alpha

Now 26:

- Old

- Add bias

- New term

The good term

$$b_1^3 f^0 : \mathcal{S}_1 = F_2[\delta, \delta]$$

$$b_1^2 b_2 f^0 : \mathcal{S}_2 = \delta^2$$

$$b_1^2 b_{\mathcal{G}_2} f^0 : \mathcal{S}_3 = \mathcal{G}_2[\delta, \delta]$$

$$b_1^2 b_{(KK)_\parallel} f^0 : \mathcal{S}_4 = (KK)_\parallel[\delta, \delta]$$

$$b_1^2 b_{\Pi_\parallel^{[2]}} f^0 : \mathcal{S}_5 = \Pi_\parallel^{[2]}[\delta, \delta]$$

$$b_1^3 f^1 : \mathcal{S}_6 = \hat{z}^i \hat{z}^j \frac{\partial_i}{\nabla^2}\delta \frac{\partial_j}{\nabla^2}\delta$$

$$b_1^2 b_\eta f^1 : \mathcal{S}_7 = G_2^\parallel[\delta, \delta] + 2F_2[\delta^\parallel, \delta]$$

$$b_1 b_2 b_\eta f^1 : \mathcal{S}_8 = \delta^\parallel \delta$$

$$b_1 b_{\mathcal{G}_2} b_\eta f^1 : \mathcal{S}_9 = \mathcal{G}_2[\delta^\parallel, \delta]$$

$$b_1 b_\eta b_{(KK)_\parallel} f^1 : \mathcal{S}_{10} = (KK)_\parallel[\delta^\parallel, \delta]$$

$$b_1 b_\eta b_{\Pi_\parallel^{[2]}} f^1 : \mathcal{S}_{11} = \Pi_\parallel^{[2]}[\delta^\parallel, \delta]$$

$$b_1^2 b_{\delta\eta} f^1 : \mathcal{S}_{12} = \delta^\parallel \delta$$

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$$b_2 (b_\eta)^2 f^2 : \mathcal{S}_{14} = \left(\delta^\parallel\right)^2$$

$$= \mathcal{G}_2[\delta^\parallel, \delta^\parallel]$$

$$= (KK)_\parallel[\delta^\parallel, \delta^\parallel]$$

$$(b_\eta)^2 b_{\Pi_\parallel^{[2]}} f^2 : \mathcal{S}_{17} = \Pi_\parallel^{[2]}[\delta^\parallel, \delta^\parallel]$$

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$$b_1^2 b_{\eta^2} f^2 : \mathcal{S}_{20} = \left(\delta^\parallel\right)^2$$

$$b_1 (b_\eta)^2 f^3 : \mathcal{S}_{21} = \hat{z}^i \hat{z}^j \left[\left(\partial_i \delta^{\parallel\parallel}\right)\left(\frac{\partial_j}{\nabla^2}\delta\right) + 2\left(\partial_i \delta^\parallel\right)\left(\frac{\partial_j}{\nabla^2}\delta^\parallel\right)\right]$$

$$b_1 b_\eta b_{\eta^2} f^3 : \mathcal{S}_{22} = \delta^{\parallel\parallel}\delta^\parallel$$

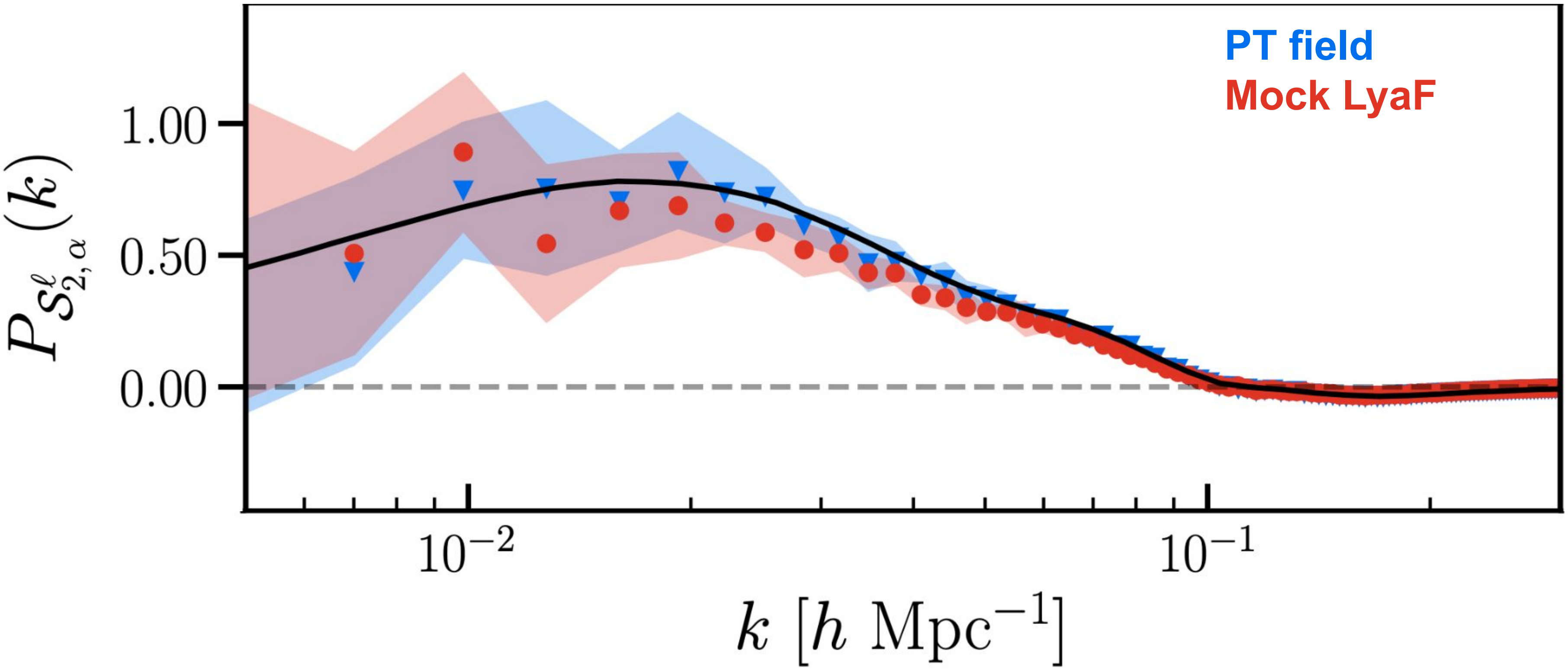
$$(b_\eta)^2 b_{\delta\eta} f^3 : \mathcal{S}_{23} = \delta^{\parallel\parallel}\delta^\parallel$$

$$(b_\eta)^3 f^3 : \mathcal{S}_{24} = G_2^\parallel[\delta^\parallel, \delta^\parallel]$$

$$(b_\eta)^2 b_{\eta^2} f^4 : \mathcal{S}_{25} = \hat{z}^i \hat{z}^j \left(\partial_i \delta^{\parallel\parallel}\right)\left(\frac{\partial_j}{\nabla^2}\delta^\parallel\right)$$

$$(b_\eta)^3 f^4 : \mathcal{S}_{26} = \left(\delta^{\parallel\parallel}\right)^2.$$

Agreement with simulations (1/26)



Ready for data!

Intergalactic integrated bispectra

Galaxies are locked up in halos

Probing gas outside of halos complementary

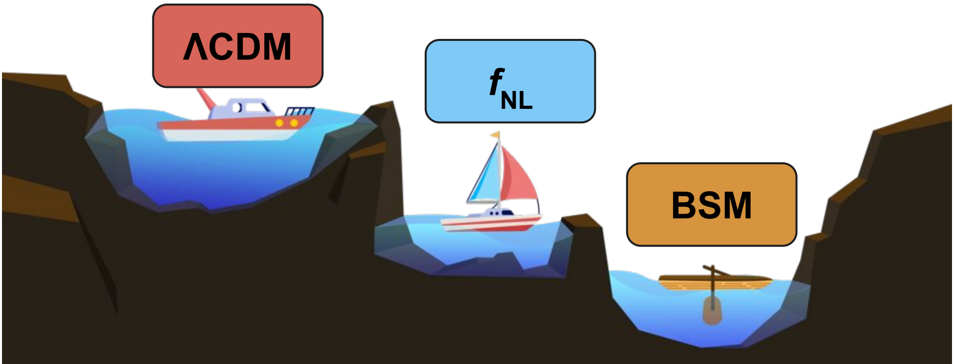
Developed EFT compressed Lya bispectrum

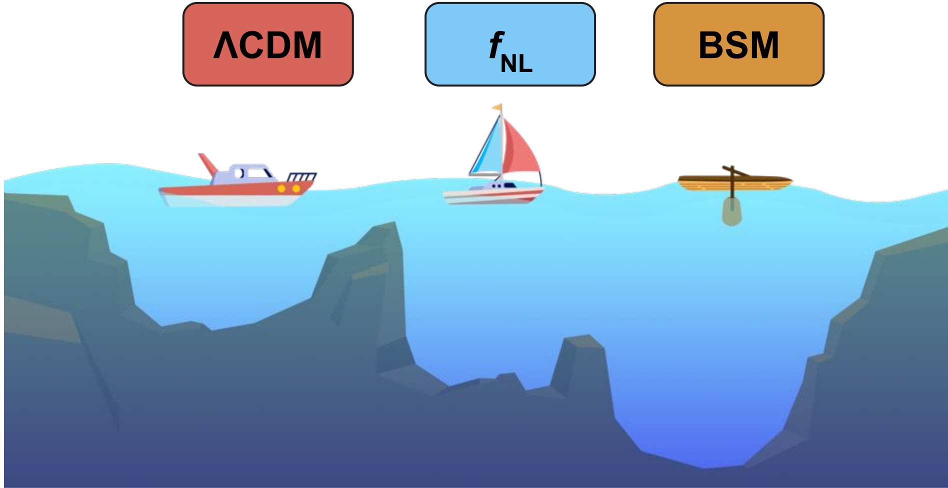
Working toward a data analysis program!

Bias lifts all model boats

New **bias phenomenology** for LSS fields and correlators

1. How galaxies respond to primordial fluctuations
2. Intergalactic integrated bispectra
3. **Tackling tracers of the thirties**





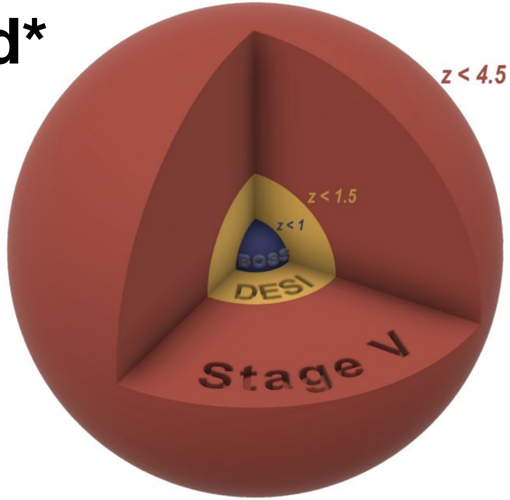
2030s spectroscopy*

Future of LSS is at $\boldsymbol{z > 2}$

DESI-II, Spec-S5 (US), WST (EU), MUST (CN)

↑: large $\boldsymbol{k}_{\mathbf{NL}}$, probe new volume

↓: tyranny of D_{L}, **galaxies not well understood***

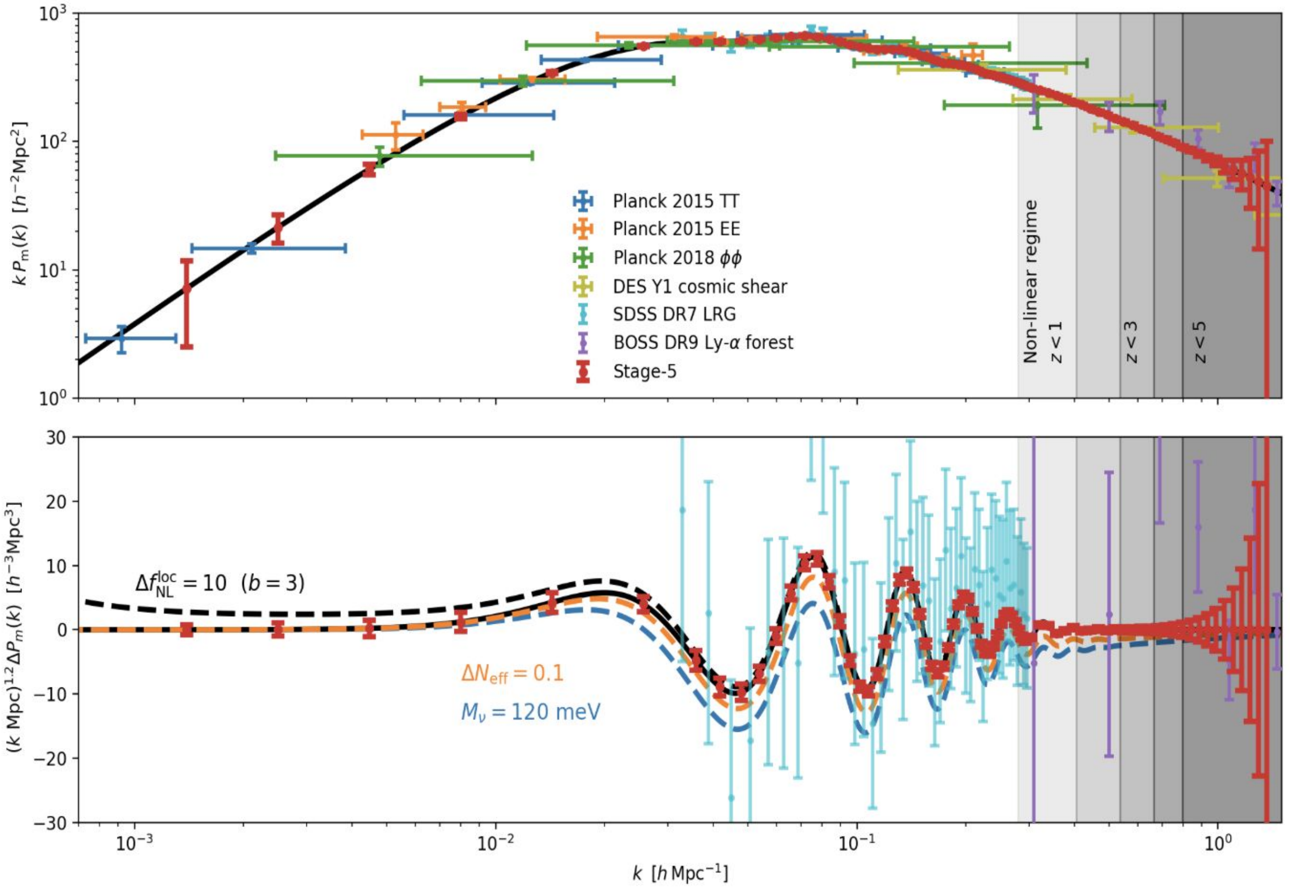


C. Yeche, Besuner+25, Bacon+24, Zhao+24

Exciting errorbars

Standard extensions today

ΛCDM of 2030s



Besuner+25

High-z galaxies are different

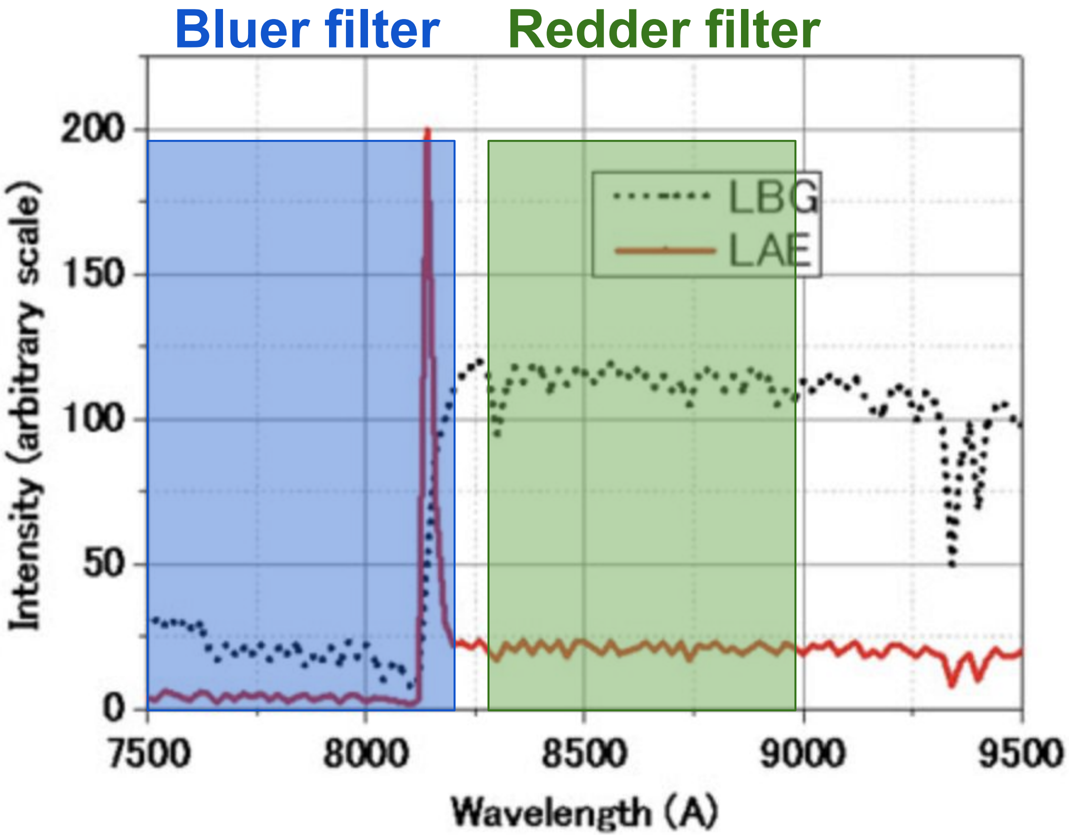
Lyman-alpha emitter **(LAE)**

Lyman-break galaxy **(LBG)**

Observational definition

Physically opaque

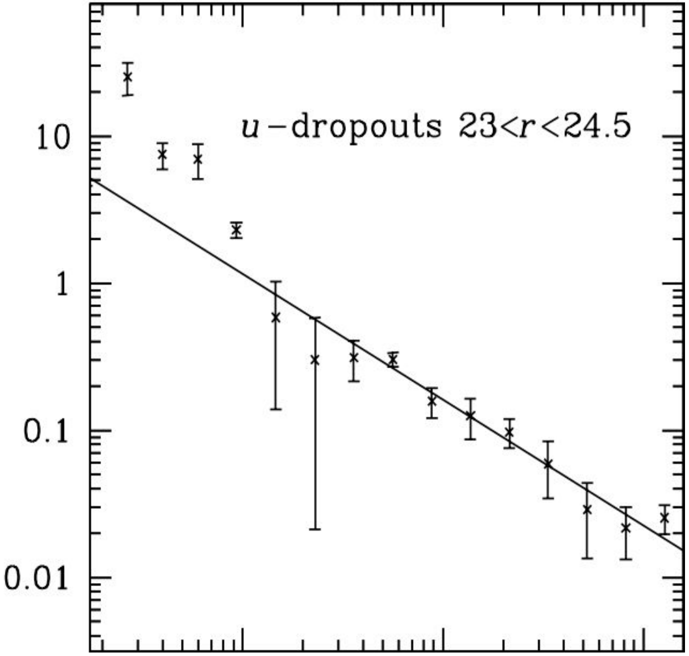
A new k_{max}?



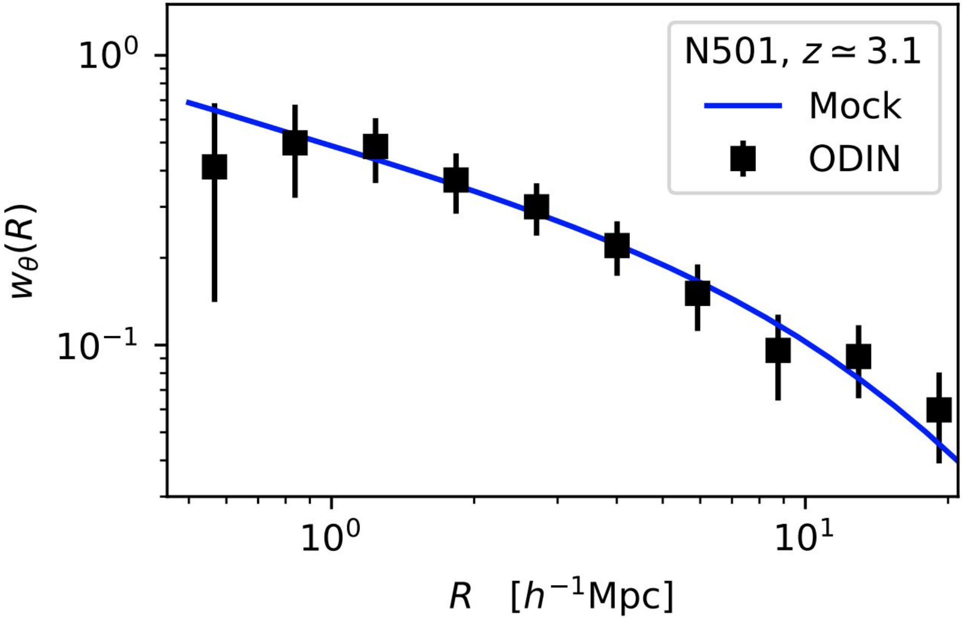
J. Dunlop (adapted)

High-z non-linear clustering?

LBGs - higher mass



LAEs - lower mass



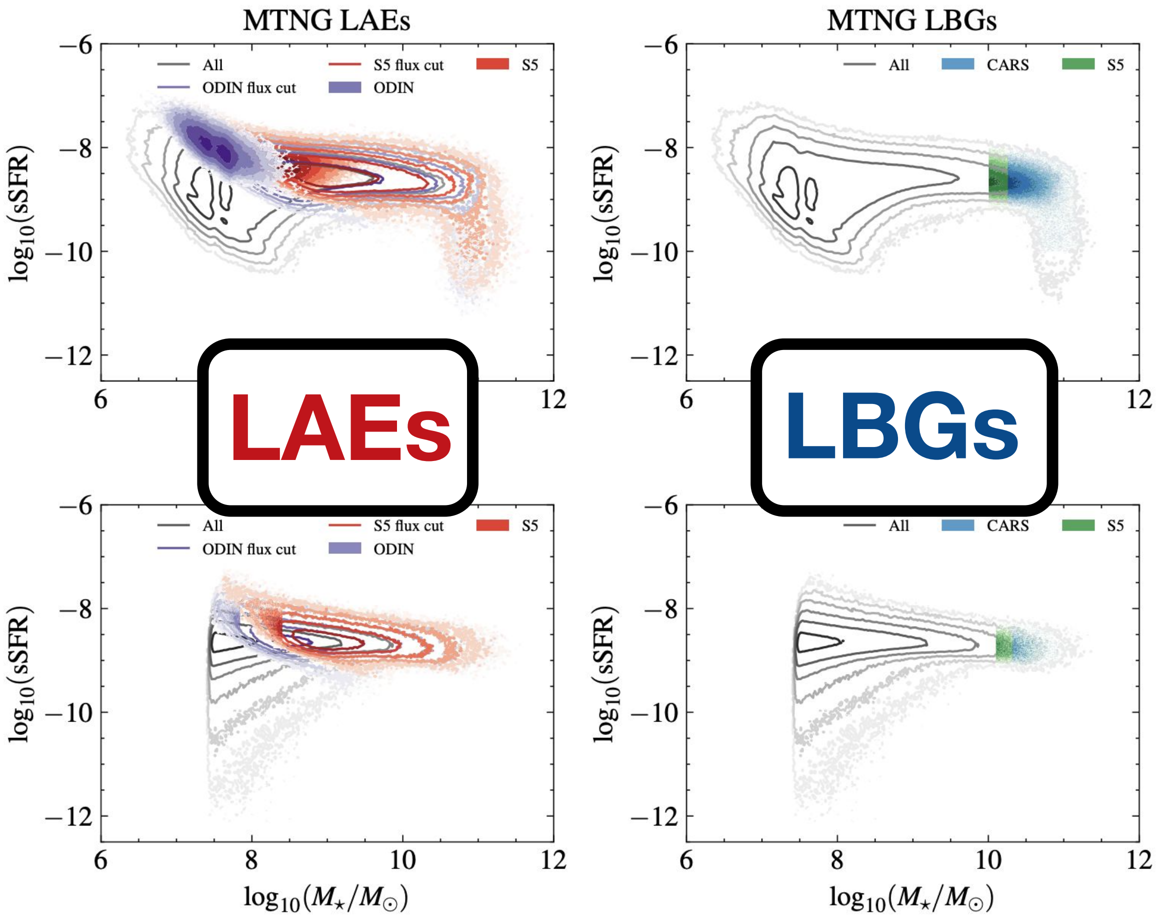
Besuner+24, Hildebrandt+09, Schlegel+22, White+24

Simulation Selection

No realistic colors or spectra

Do best possible w/ hydro properties

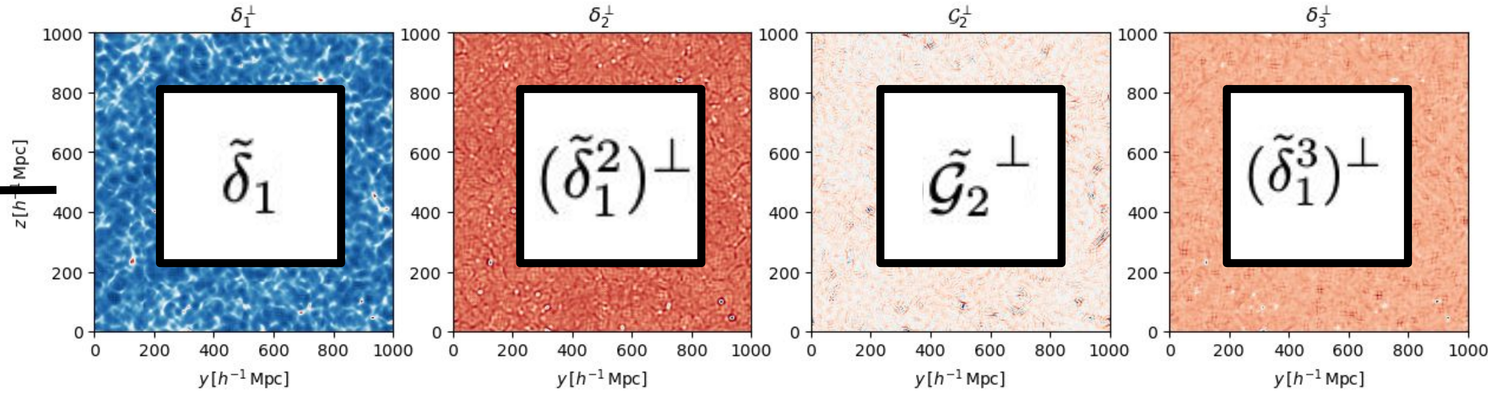
Stellar mass
Star formation rate
Metallicity



Field-level machinery

EFT expansion

$$\delta^{\mathrm{EFT}}(\boldsymbol{k}, \hat{\boldsymbol{z}})$$



Redshift space, look at **scale dependence** in**:**

$$P_{\mathrm{err}}(k, \mu) = \langle |\delta^{\mathrm{EFT}}(\boldsymbol{k}, \hat{\boldsymbol{z}}) - \delta_g^{\mathrm{truth}}(\boldsymbol{k}, \hat{\boldsymbol{z}})|^2 \rangle'$$

Schmittful+18,+20, Abidi+Baldauf+16, Ivanov+24a,b,c, **JMS**+Chen24, Modi+19, Tucci+24, Schmidt25, Akitsu+25

k_{max}

LAEs:

$k_{max} \gtrsim$ **0.3** [h/Mpc]

LBGs:

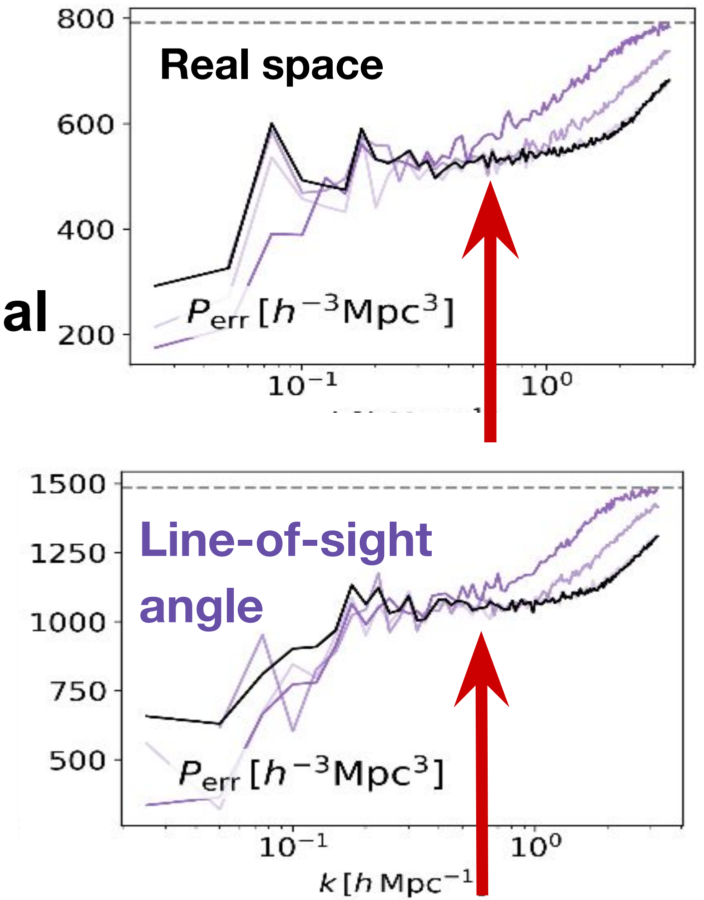
$k_{max} \gtrsim$ **0.2** [h/Mpc]

Set by **velocities**!

LAE

Residual field power

LBG



JMS+25

Tackling tracers of the thirties

EFT k_{max}-reach similar/better than current surveys

Simulation/selection-dependent in detail

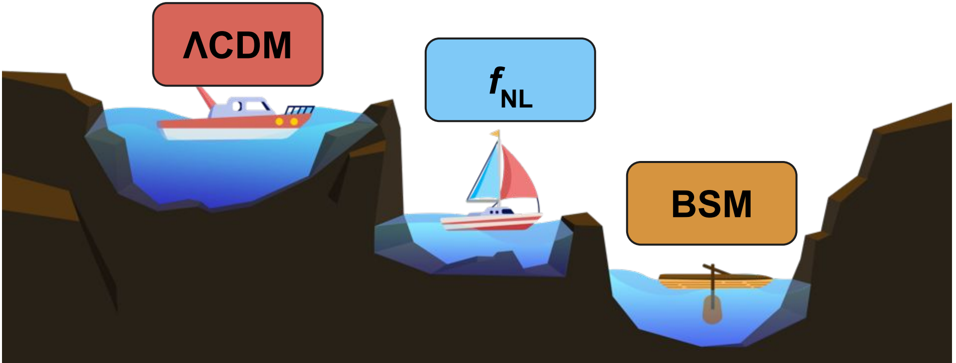
Path toward simulation-based priors

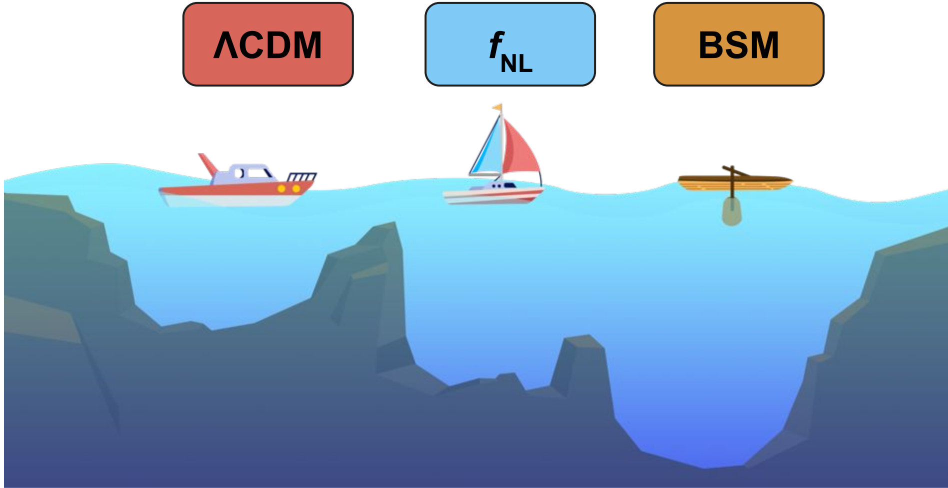
The future is bright!

Bias lifts all model boats

New **bias phenomenology** for LSS fields and correlators

1. How galaxies respond to primordial fluctuations
2. Intergalactic integrated bispectra
3. **Tackling tracers of the thirties**





Remembrances

Symmetry-based bias - engine of LSS age!

Developing bias phenomenology bears fruit:

- **Data-driven PNG bias estimates**
- **Extend to new data (LyaF SS)**
- **Preparing for future surveys (LAEs/LBGs)**