Field level bias modeling, time evolution, and local primordial non-Gaussianity

July 4 2024

Jamie Sullivan
(based on work w/ Stephen Chen, Uroš Seljak)

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BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Berkeley UNIVERSITY OF CALIFORNIA

U.S. DEPARTMENT OF ENERGY | Office of Science

Simplest Local Primordial Non-Gaussianity

Initial gravitational potential largely Gaussian

But primordial physics can add non-Gaussianity (PNG)

(Also Thomas', Xinyi's, Robin's, Karthik's talks)

E.g. multi-field inflation produces *local* PNG:

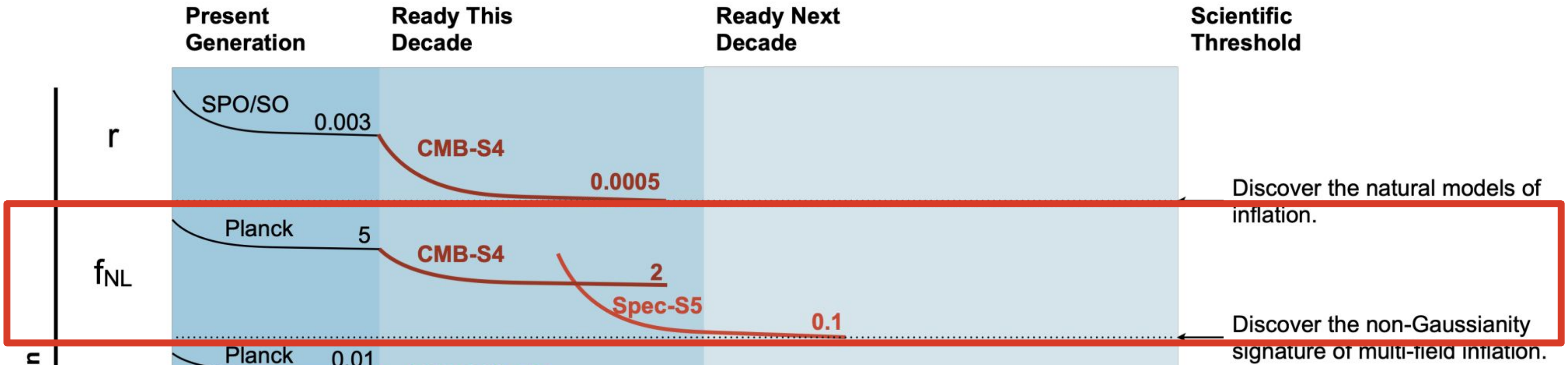
$$\boxed{\phi} = \phi_G + \boxed{f_{NL}^{\mathrm{loc}}} \left[\phi_G^2 - \langle \phi_G^2 \rangle\right]$$

Seed for structure

Counts multiple fields

Maldacena03, Acquaviva+03, Komatsu&Spergel01, many others

f_{NL} a Prime Target of Future Galaxy Surveys



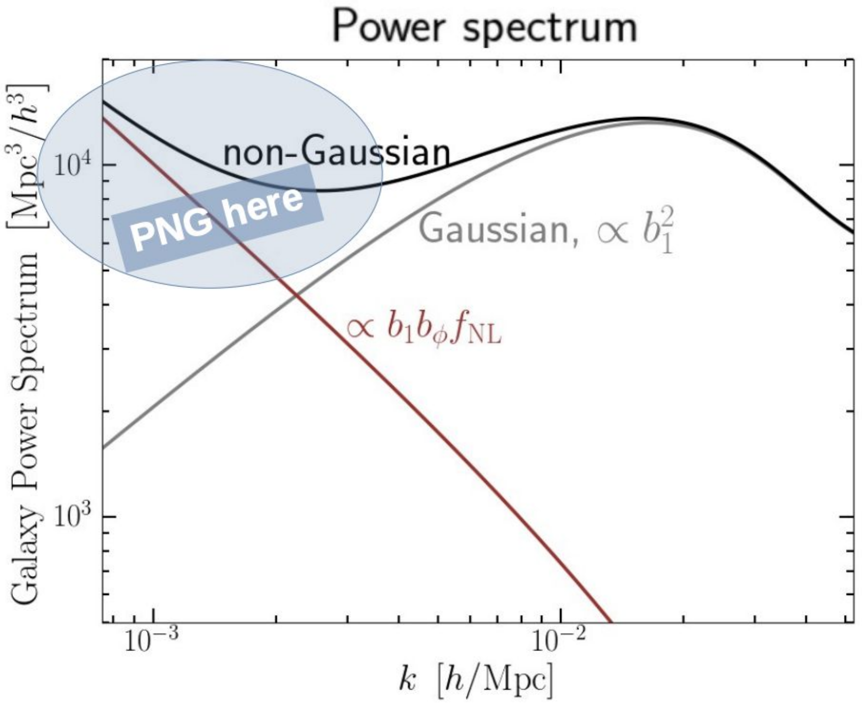
Spec-S5:

- DESI, Euclid, SPHEREx, PFS…
- Also SO x Rubin-LSST, CMB-S4

Chou+22 (Snowmass Cosmic Frontier)

Measuring LPNG in Galaxy Surveys

Measure power spectrum



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

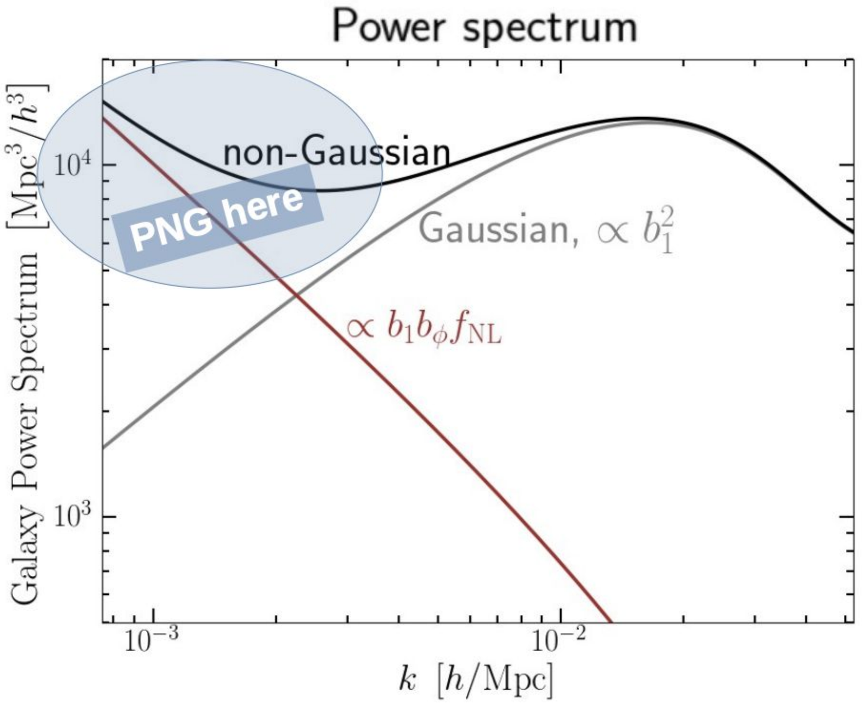
Measuring LPNG in Galaxy Surveys

Measure power spectrum

To model it need a galaxy bias model:

$$\boxed{\delta_g} = b\,\boxed{\delta} + \ldots$$

Galaxy overdensity **Matter overdensity**



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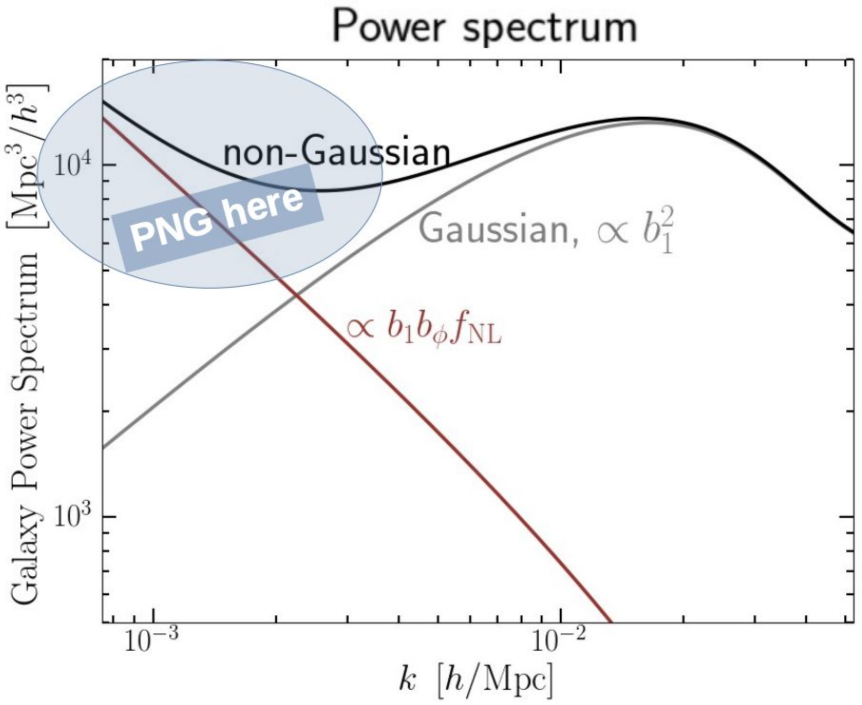
Galaxy overdensity

Matter overdensity



15 years ago, it was realized there is an **extra** bias signal

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

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

Constraining f_{NL}

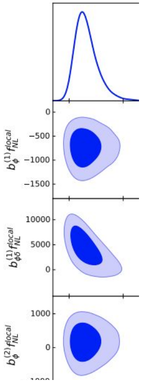
Option 1 - LPNG amplitude

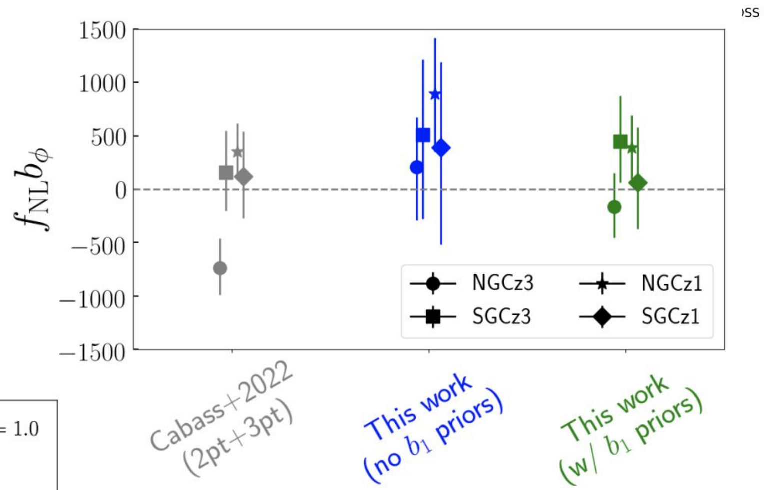
Assumption free!

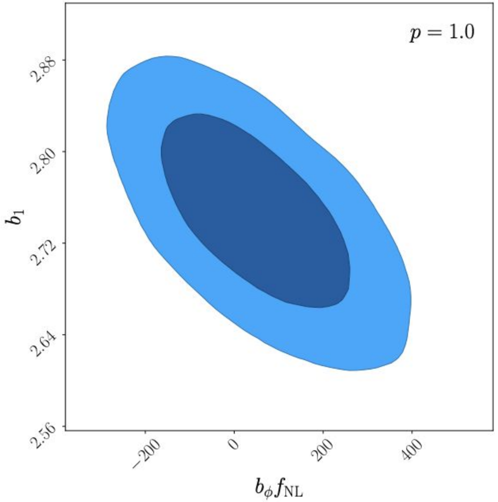
Option 2 - Constrain f_{NL}

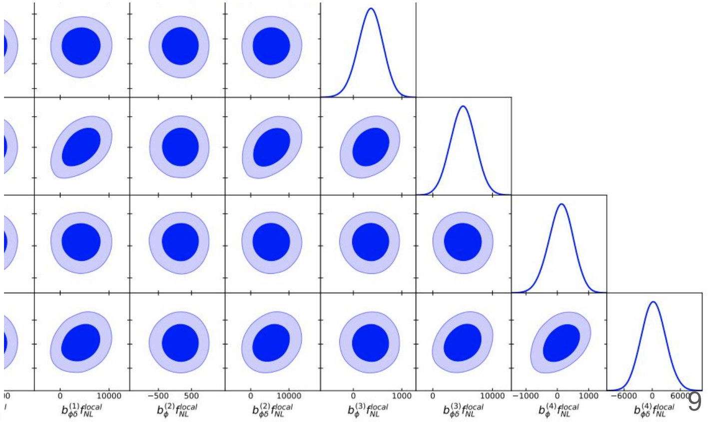
Requires knowing the value of b_ϕ

(Also plan surveys this way)









Cabass++22, Barreira 22, Castigiliari++23

Constraining f_{NL}

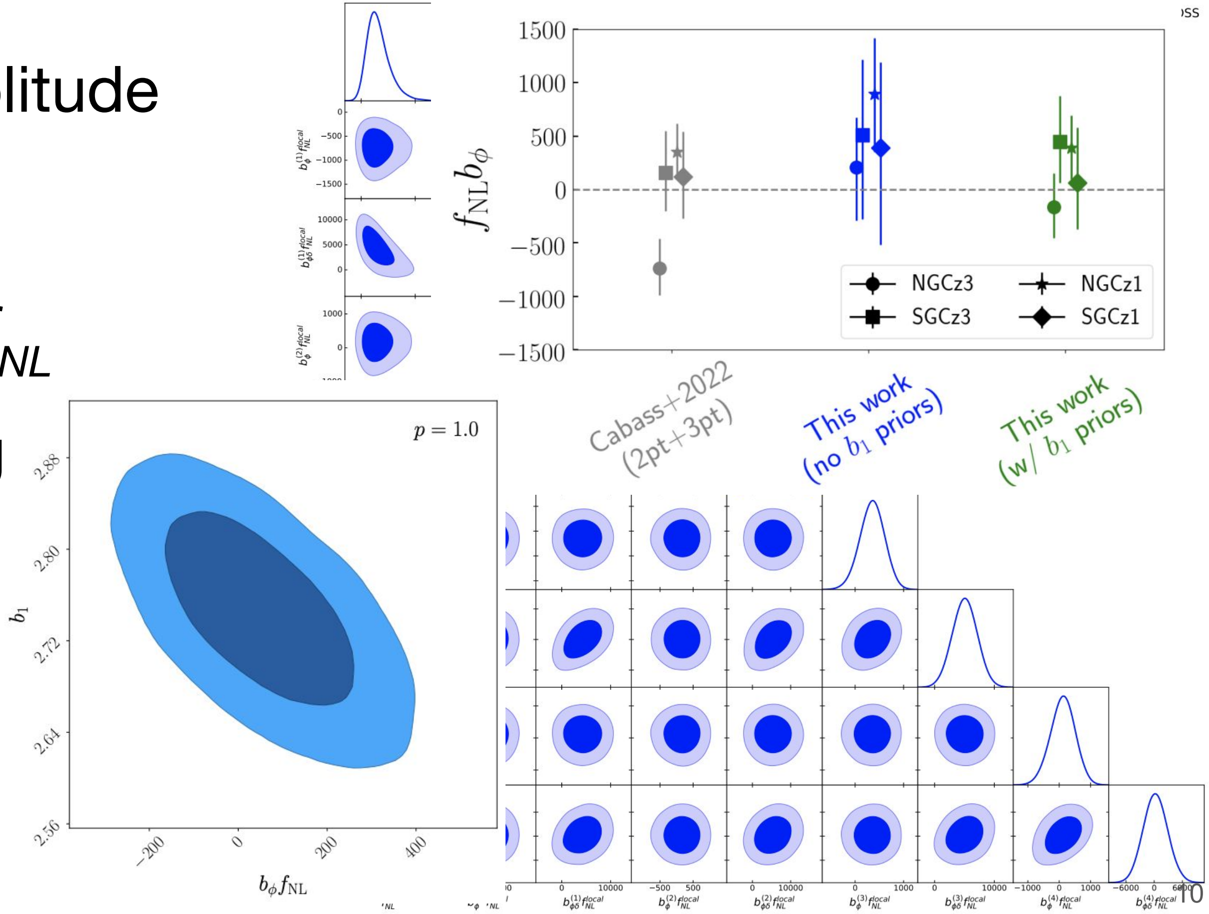
<u>Option 1</u> - LPNG amplitude

Assumption free!

<u>Option 2</u> - Constrain f_{NL}

Requires knowing **the value of b_ϕ**

Assume we are ambitious…



Cabass++22, Barreira 22, Castigiliari++23

Assuming a b_ϕ - Universal Mass Function

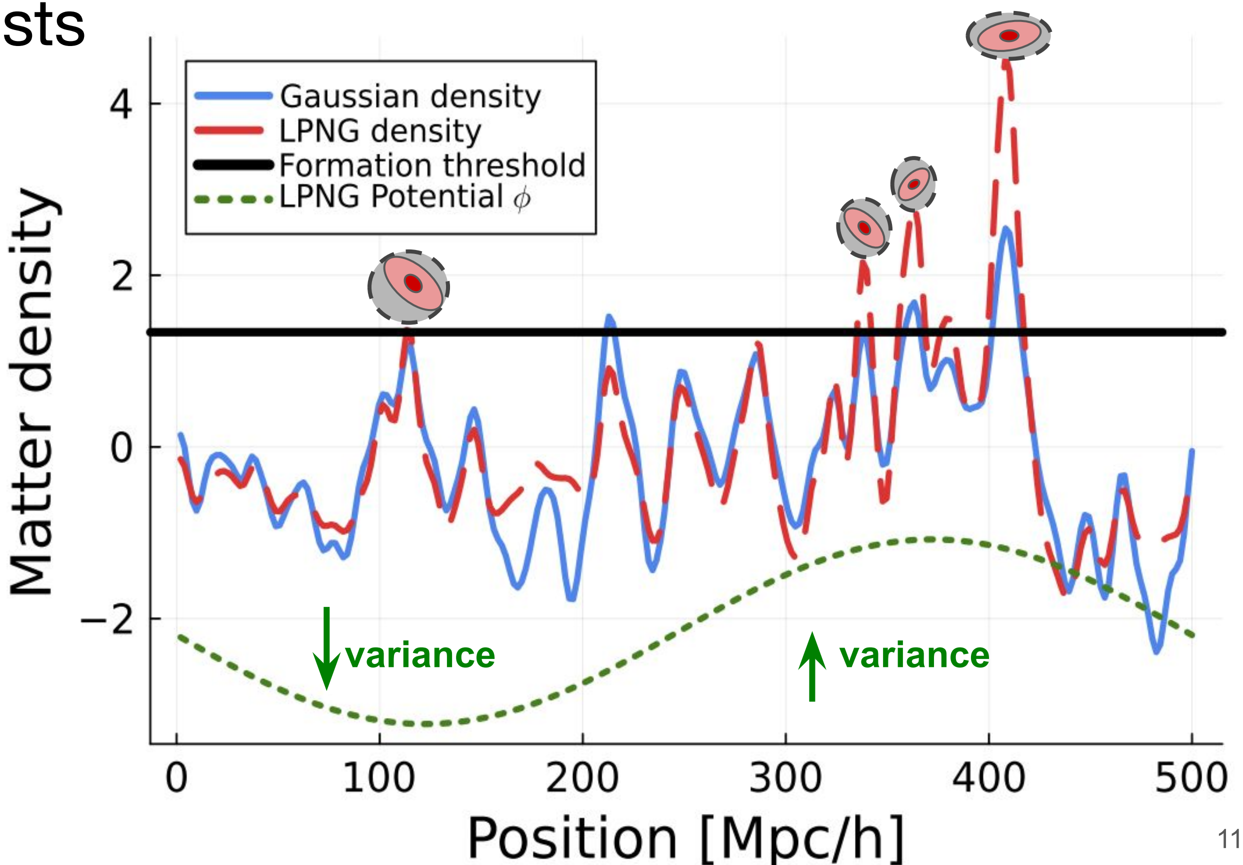
Cartoon: LPNG "boosts local variance"

Halos form after crossing threshold

Crossing affected by LPNG

Assume UMF form:

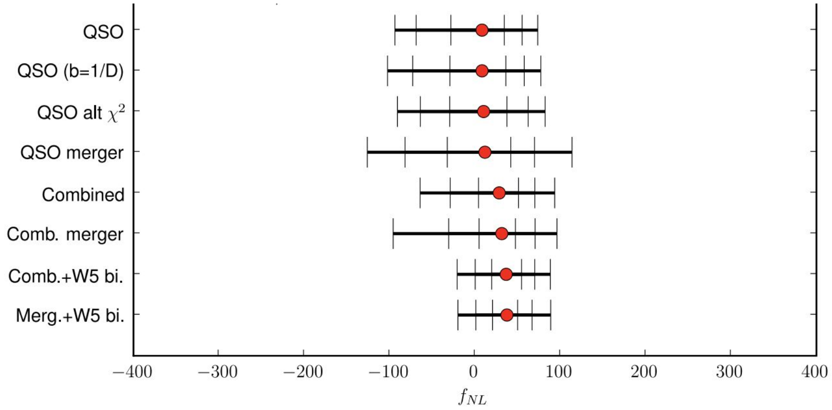
$$b_\phi(b,p) \propto b - p$$



Slosar+08, Desjacques+16

Galaxy survey f_{NL} - SDSS quasars

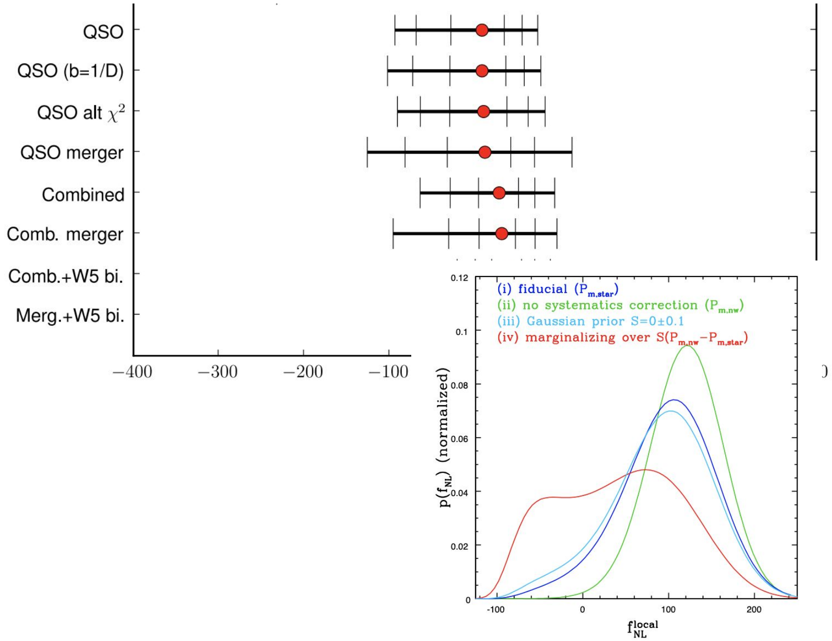
Slosar++08



Galaxy survey f_{NL} - SDSS quasars

Slosar++08

Ross++12

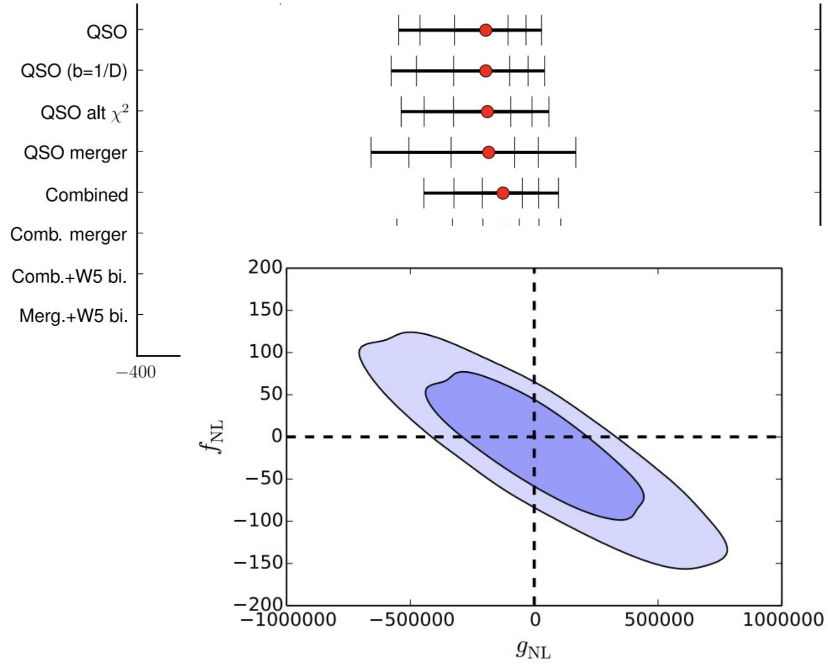


Galaxy survey f_{NL} - SDSS quasars

Slosar++08

Ross++12

Leistedt++14



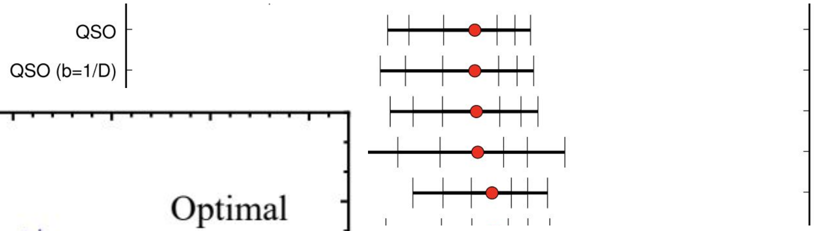
Galaxy survey f_{NL} - eBOSS quasars

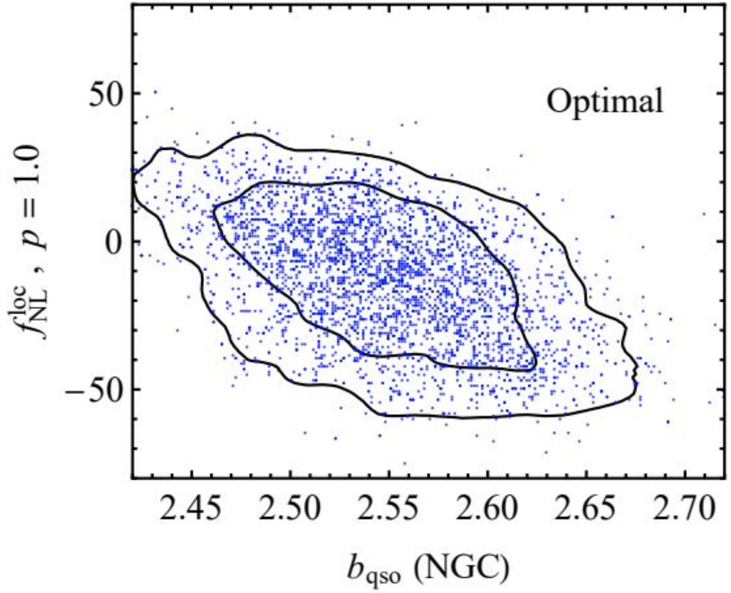
Slosar++08

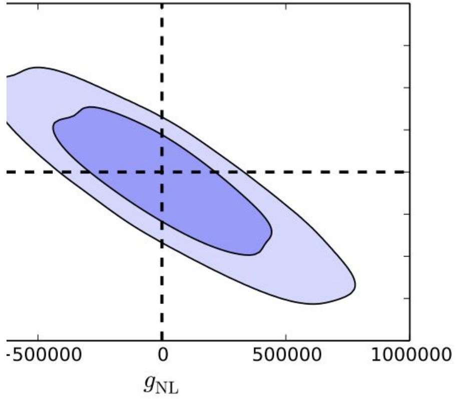
Ross++12

Leistedt++14

Castorina++19







Galaxy survey f_{NL} - eBOSS quasars

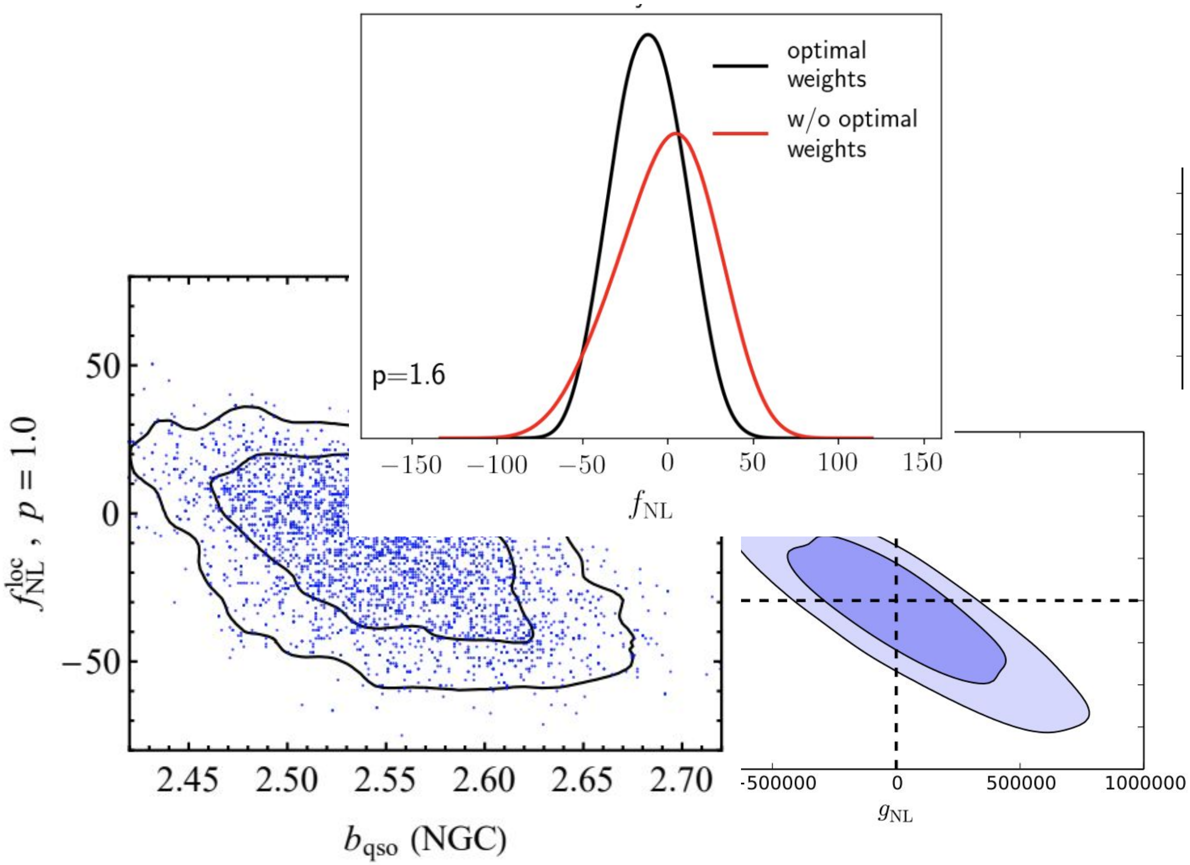
Slosar++08

Ross++12

Leistedt++14

Castorina++19

Mueller++21



Galaxy survey f_{NL} - BOSS LRGs

Slosar++08

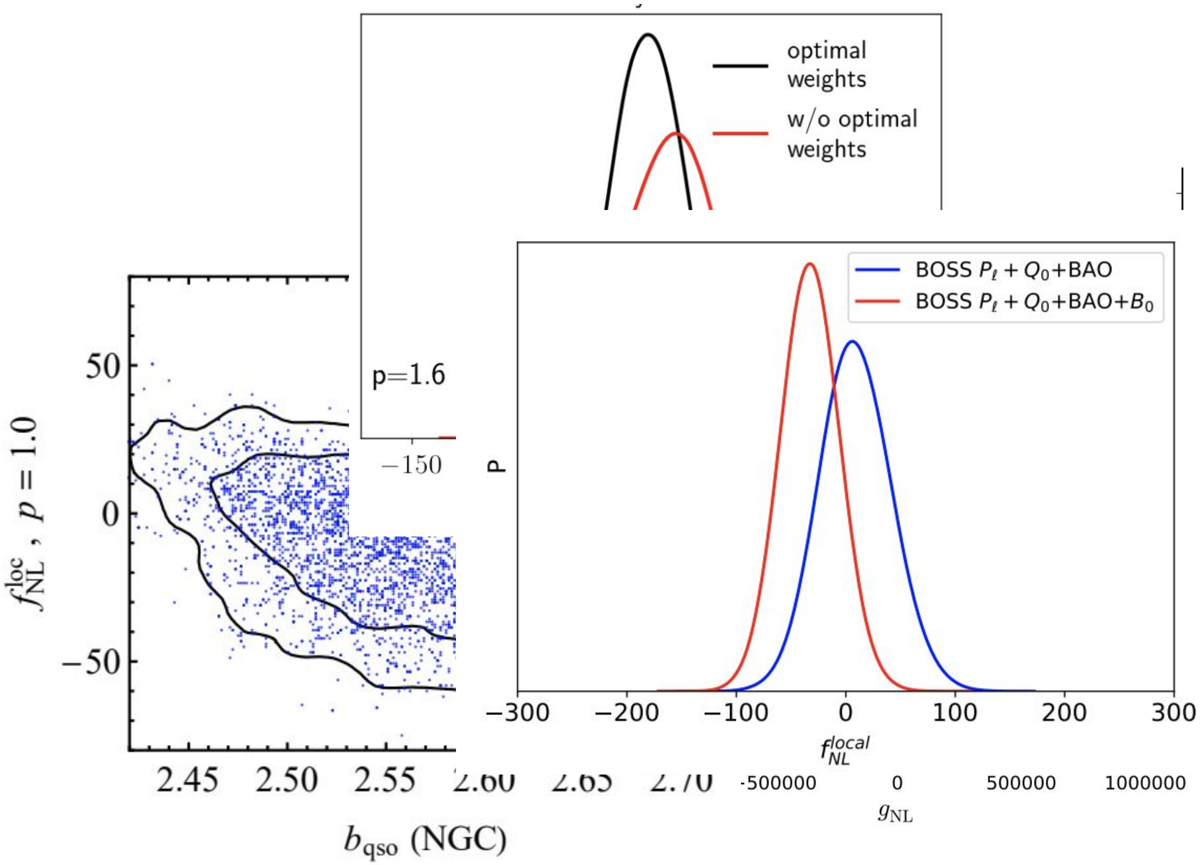
Ross++12

Leistedt++14

Castorina++19

Mueller++21

D'Amico++22



Galaxy survey f_{NL} - BOSS LRGs

Slosar++08

Ross++12

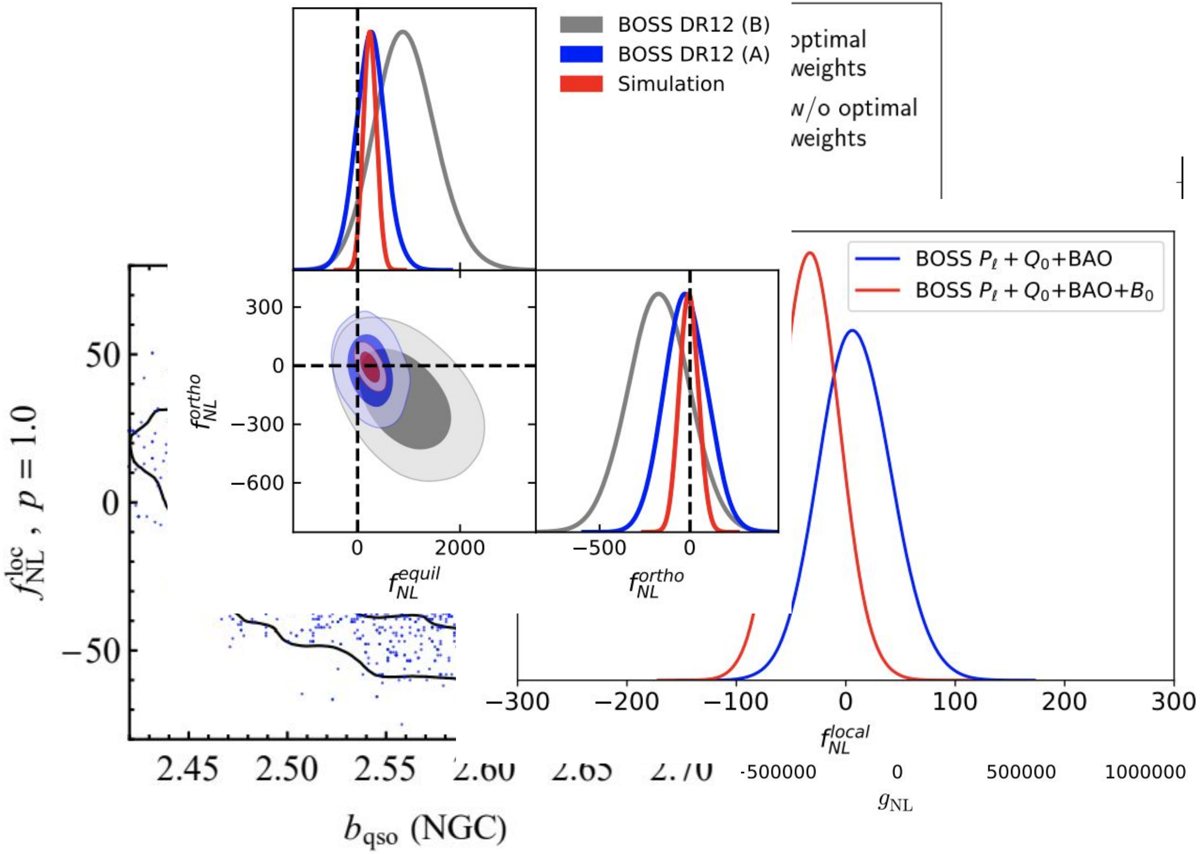
Leistedt++14

Castorina++19

Mueller++21

D'Amico++22

Cabass++22a



Galaxy survey f_{NL} - eBOSS/DESI

Slosar++08

Ross++12

Leistedt++14

Castorina++19

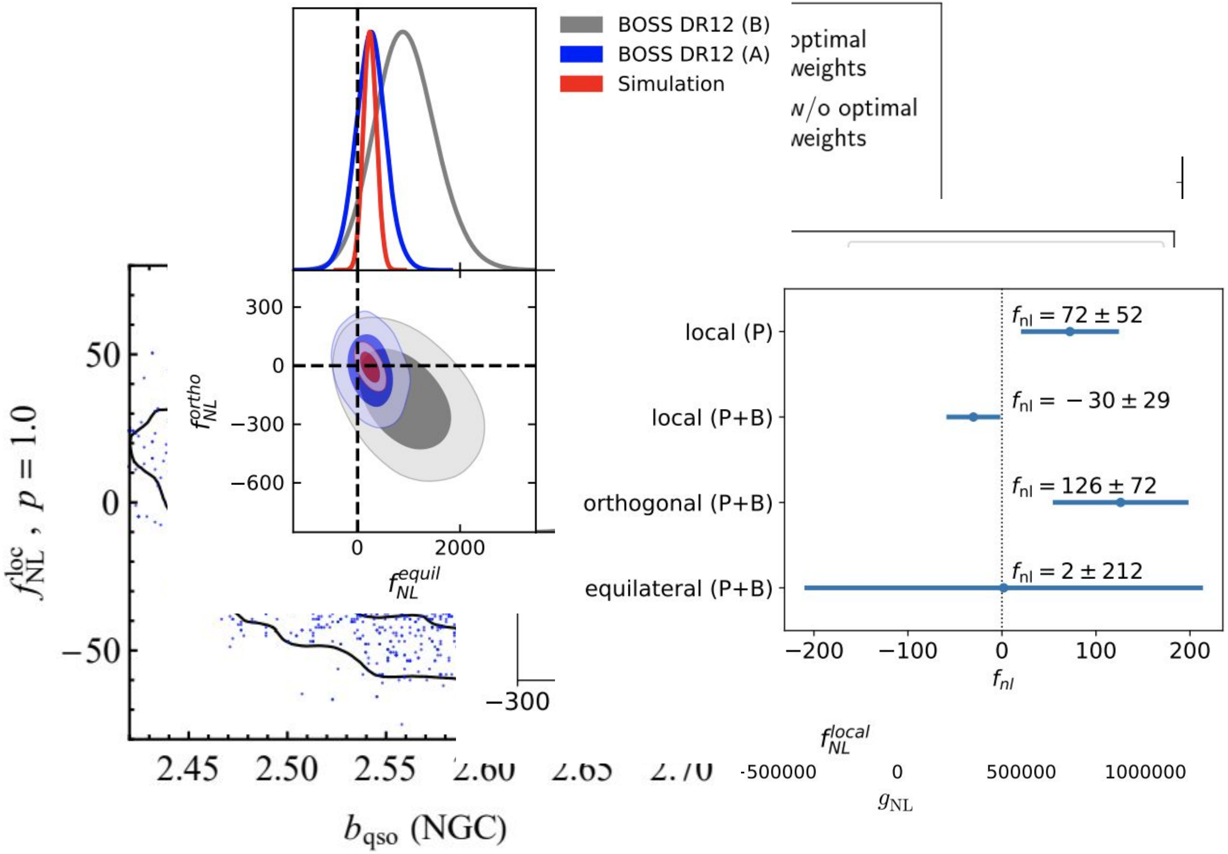
Mueller++21

D'Amico++22

Cabass++22a

Rezaie++23

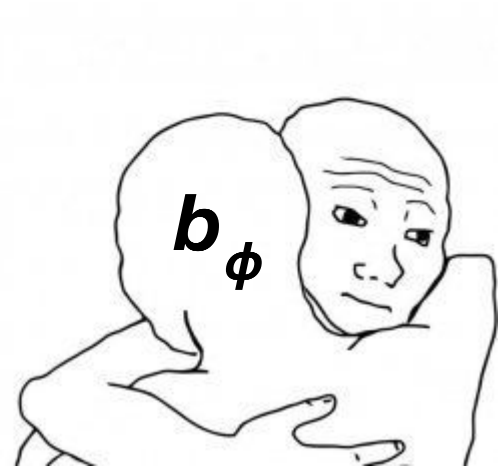
Cagliari++23



Embracing b_ϕ?

Two issues today:

1. Do we really need b_ϕ **in principle**?
   -> Test b_ϕ at field level
2. If yes, **how to decide** b_ϕ?
   -> Estimate from time-evolution



(Won’t really talk about assembly bias,
but see Sullivan+23, Barreira+Krause23, Fondi+23, Barreira…)

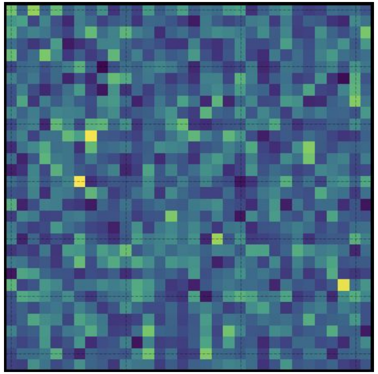
Field-level Bias Model

Idea: test of PNG bias at the field level (quadratic Lag model)

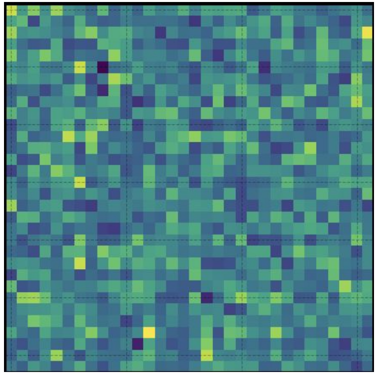
Field-level likelihood - simple regression - NL displacements

Schematically:

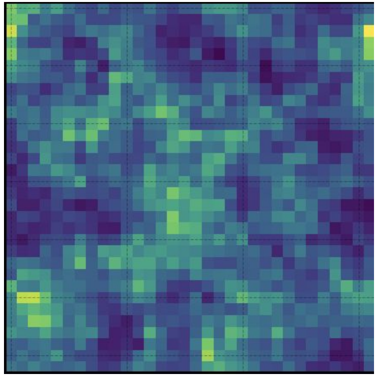
Halos **Matter** **Potential**



$= b_1$



$+ \; b_\phi f_{NL}$



Field-level Bias Model

At 2nd order in bias, 2 Local PNG terms

Neglect position-dependent variance

$$\mathcal{P}[\delta_t|\delta] = \prod_{\mathbf{x}} \left(2\pi\sigma_0^2\right)^{-\frac{1}{2}} \exp\left(-\frac{|\delta_t(\mathbf{x}) - \delta_{t,\mathrm{fwd}}(\mathbf{x},\delta)|^2}{2\sigma_0^2}\right)$$

$$\begin{aligned}\tilde{\delta}_{t,\mathrm{fwd}}(\mathbf{x},\delta) = \quad & \delta(\mathbf{x}) + b_\delta\ D(z)\ \delta^{\mathrm{adv}}(\mathbf{q}) \\ & + b_{\delta^2}\ D^2(z)\ \delta^{2,\mathrm{adv}}(\mathbf{q}) + b_{K^2}\ D^2(z)\ K_{ij}^{2,\mathrm{adv}}(\mathbf{q}) \\ & + c_{\nabla^2\delta}\ D(z)\ \left(\nabla^2\delta\right)^{\mathrm{adv}}(\mathbf{q}) \\ & + \epsilon_t(\mathbf{x}),\end{aligned}$$

$$\boxed{\begin{aligned}\delta_{t,\mathrm{fwd}}(\mathbf{x}) = \tilde{\delta}_{t,\mathrm{fwd}}(\mathbf{x},\delta) + b_\phi f_{NL}^{\mathrm{loc}} \phi^{\mathrm{adv}}(\mathbf{q}) \\ + b_{\phi\delta} f_{NL}^{\mathrm{loc}} \left[\phi\delta\right]^{\mathrm{adv}}(\mathbf{q})\end{aligned}}$$

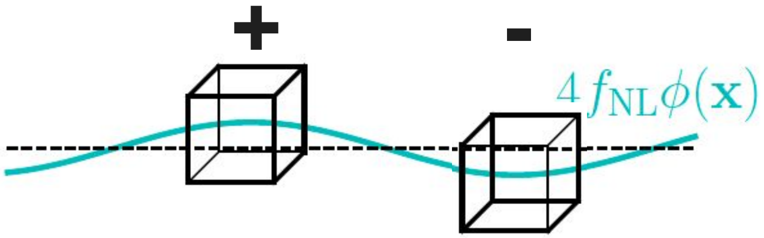
Separate Universe (response) b_ϕ

Separate Universe (->peak-background split)

Finite-difference 2 sims

Uses infinite-wavelength limit

Separate Universe $\mathcal{A}_s$



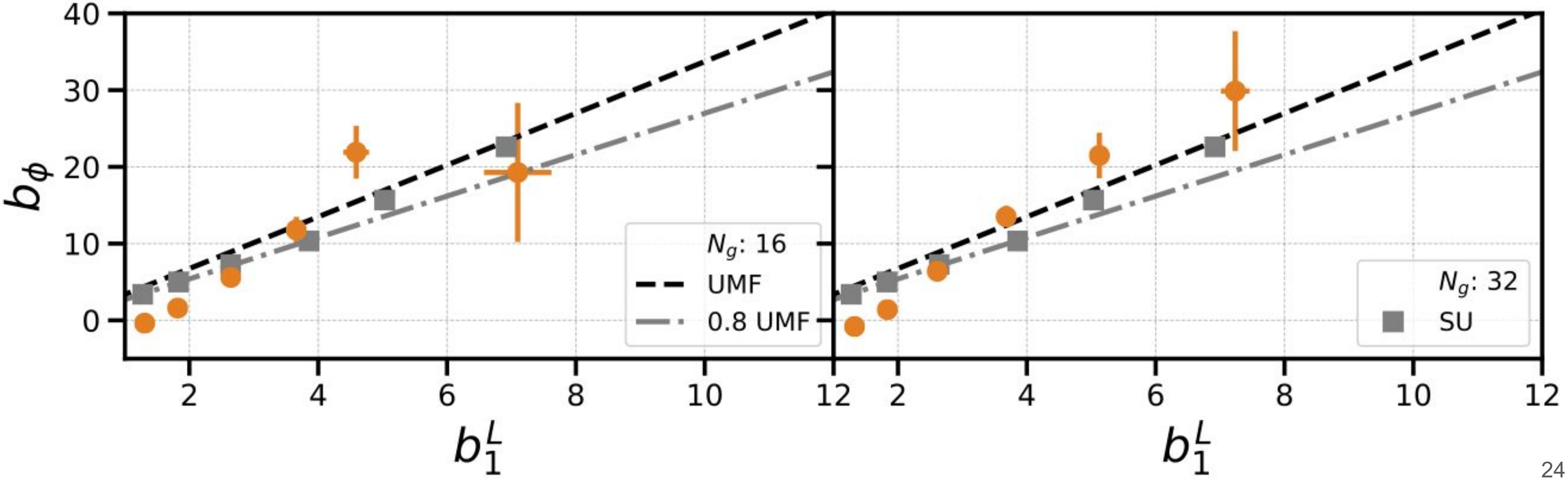
$$\mathcal{A}_s \;\rightarrow\; \mathcal{A}_s\left[1+\delta\mathcal{A}_s\right] \;,\; \delta\mathcal{A}_s = 4 f_{\rm NL}\phi_L$$

$$b_\phi(M,t) = 4\mathrm{d}\ln n_g(M,t)/\mathrm{d}\delta\mathcal{A}_s$$

Wagner+14, Baldauf+16, Afshordi+Tolley08, Desjacques+09, Biagetti+17, Barreira+20, and more

UMF Prediction

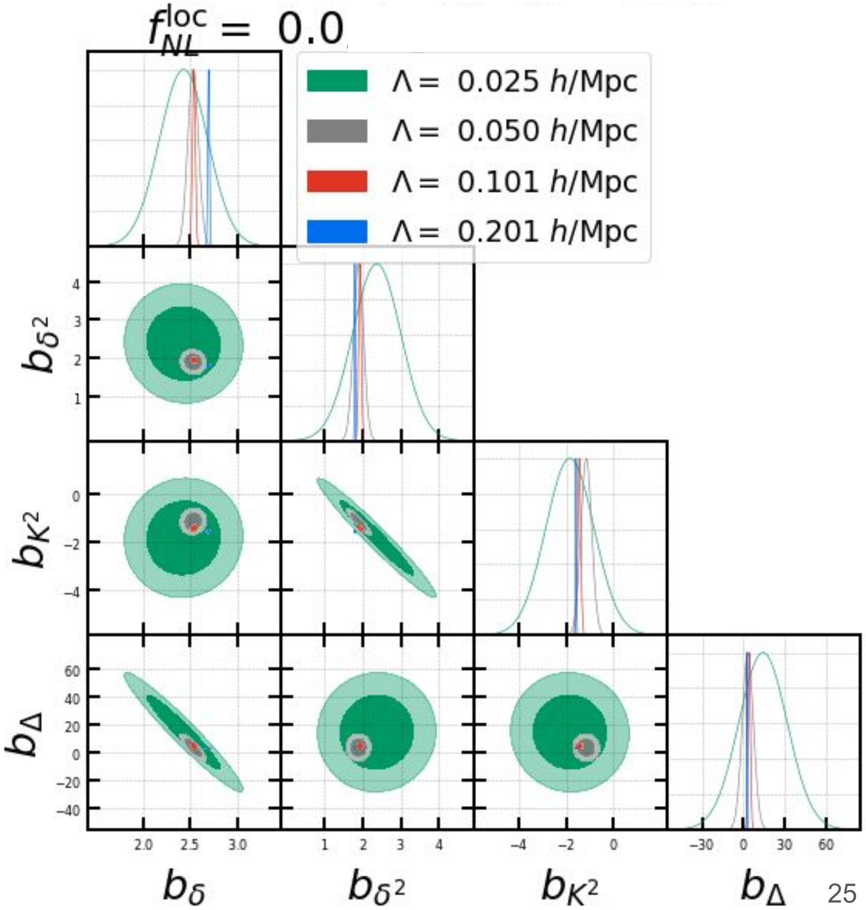
Roughly agree with UMF and SU on large scales



Quadratic Bias Parameters

How are we doing with the cutoff Λ?

Looks good for Gaussian up to red scale



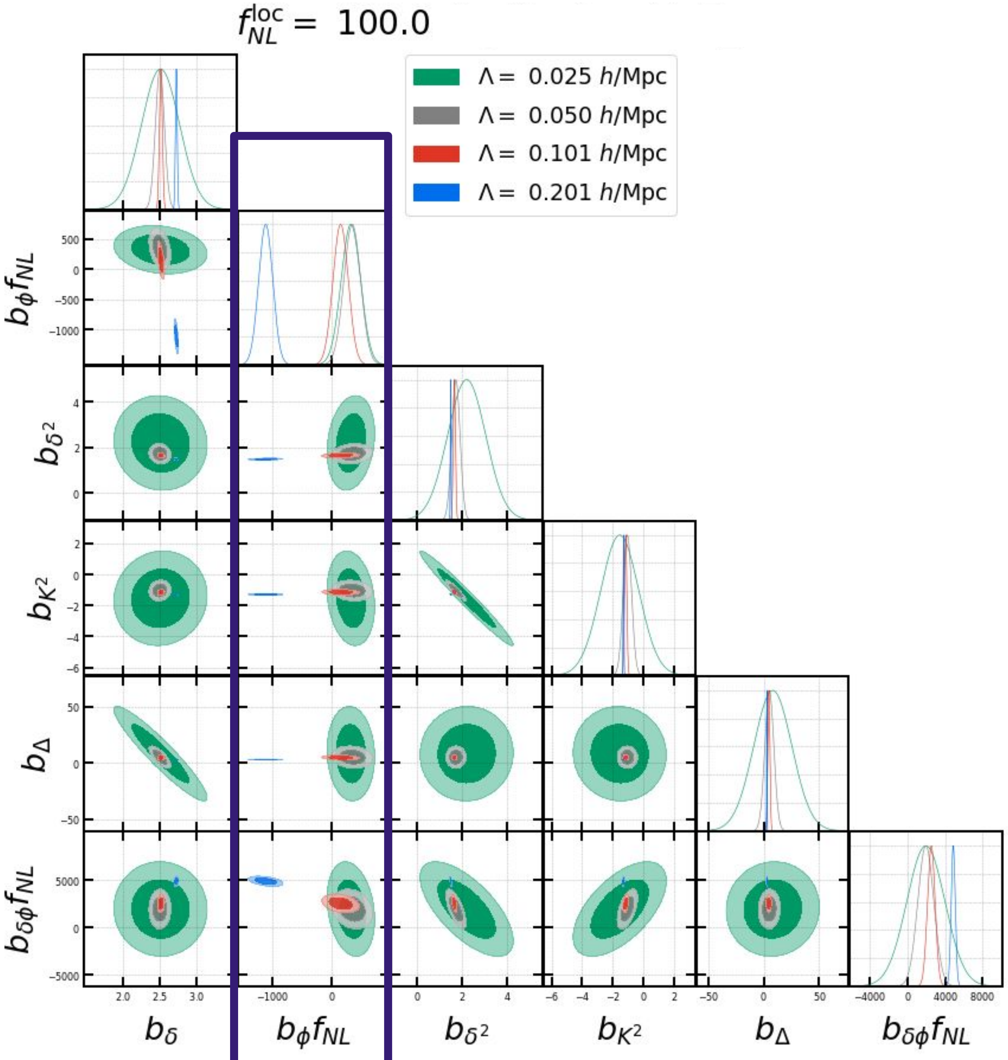
Quadratic I

How are we doing with the cutoff Λ?

Looks good for Gaussian up to red scale

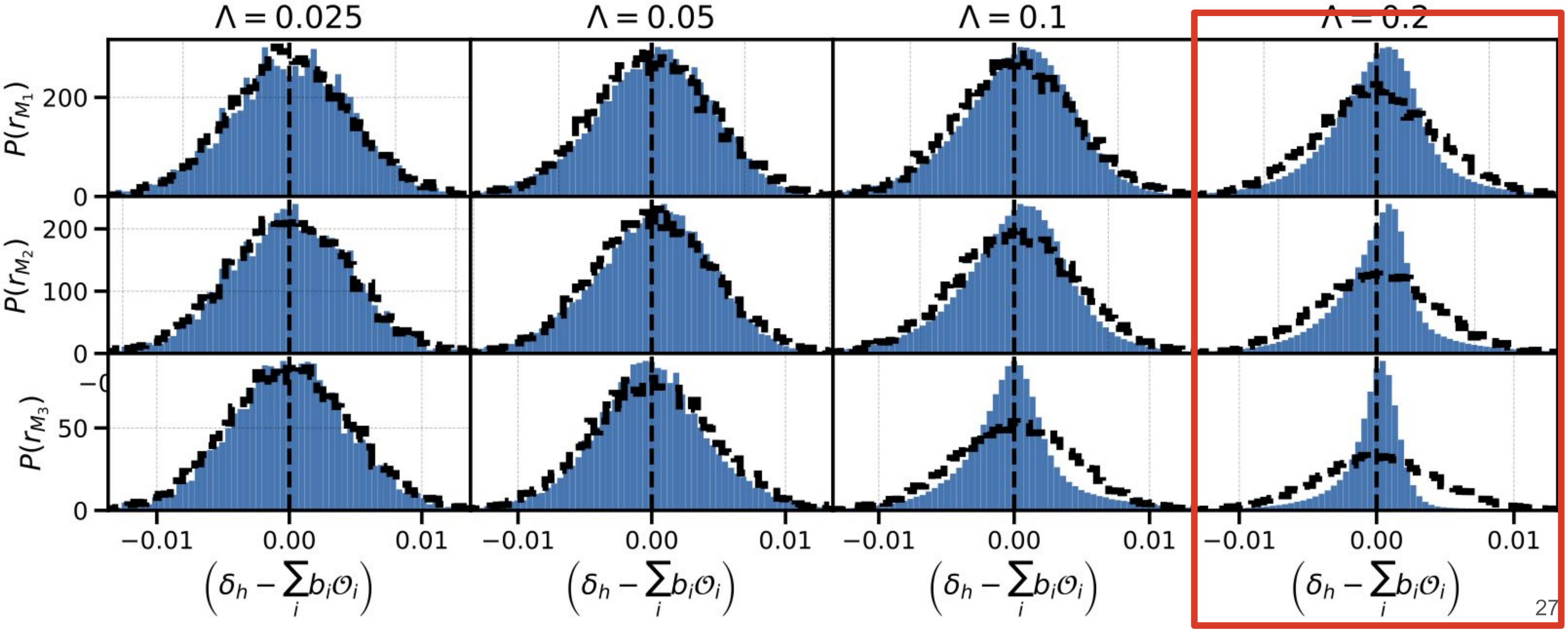
Adding PNG, much the same*

(*w/ renormalized operators)



Check with PDFs

Does this breakdown make sense? -> yes, small-scale failure



Inferring Local PNG

Easy mode - fixed ICs

Inferring f_{NL}, marginalizing over from PT mocks?

Yes

Inferring f_{NL} from halos?

No…*

Inferring Local PNG

PT mock test

Bias-marginalized profile likelihood

2-3x degradation on $\sigma(f_{NL})$ w/ quadratic bias

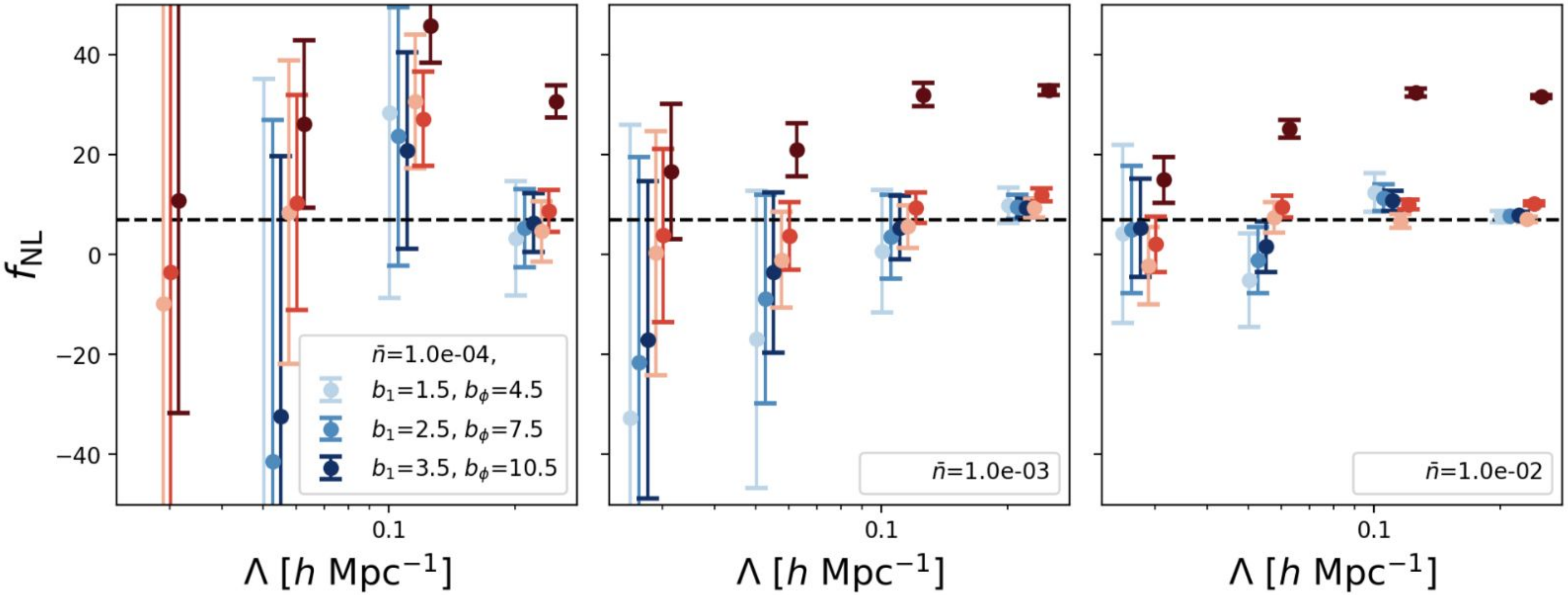
Also a bias

Linear

Quadratic

Even easy-mode pessimistic…

Inferring Local PNG



Even easy-mode pessimistic…

Final Thoughts

LPNG fits into the field-level bias model framework

Halo tests at z=1 indicate:

- Several sanity checks passed
- Challenges at 2nd order beyond 0.1 h/Mpc
- Need for density-dependent stoch.?

Linear model *not* suitable to infer f_{NL} on quasi-linear scales

-> Priors on $b_{\boldsymbol{\phi}}$ are *critical* for constraints

Bias from Time Evolution - Idea

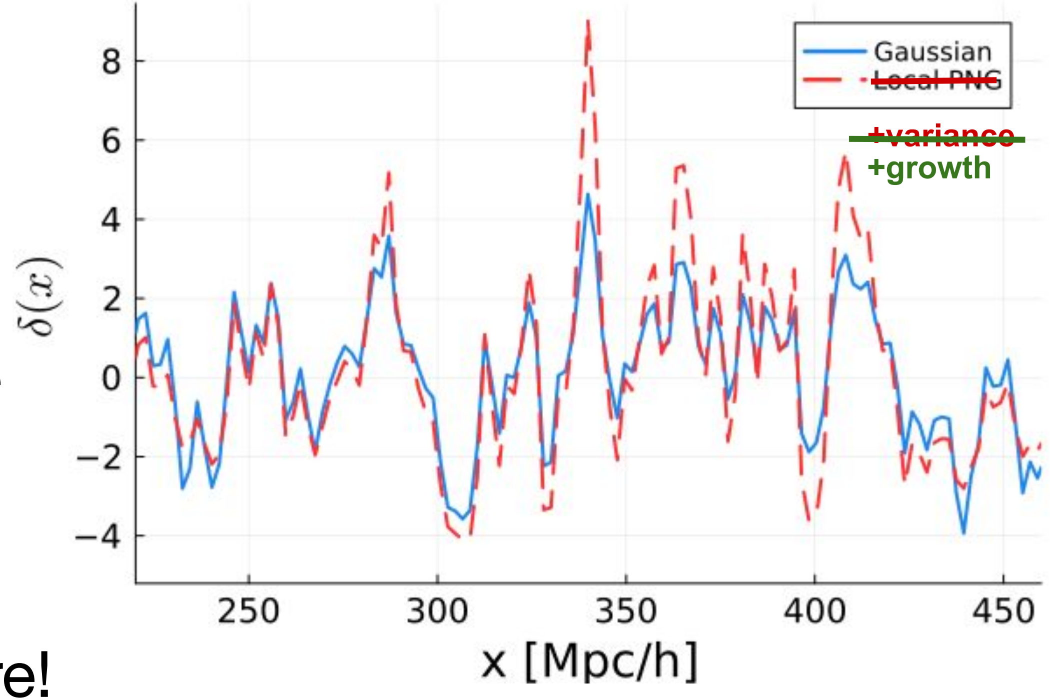
LPNG is “like” boosting
underlying variance

Bias from Time Evolution - Idea

LPNG is "like" boosting underlying variance

Can measure LPNG bias by running 2 simulations w/ diff variance

But boosting variance is ~equivalent to boosting growth of structure!



Slosar08, Marinucci23, others, Barreira20 (modified)

Bias from Time Evolution - UMF

Universality of mass function a decent first approximation

Peak-background split relates bias to peak height response

$$\sigma^2(M,z) = \frac{1}{2\pi^2}\int k^2 dk |W(R(M,z)k)|^2 D^2(z) P_L(k)$$

$$n(M) = n(M,\nu) = M^{-2}\nu f(\nu)\frac{\mathrm{d}\ln\nu}{\mathrm{d}\ln M} \qquad \nu = \delta_{\mathrm{c}}^2/\sigma^2(M)$$

Growth and change in variance perfectly degenerate via variance

Desjacques++16, Slosar++08, Jeong++11

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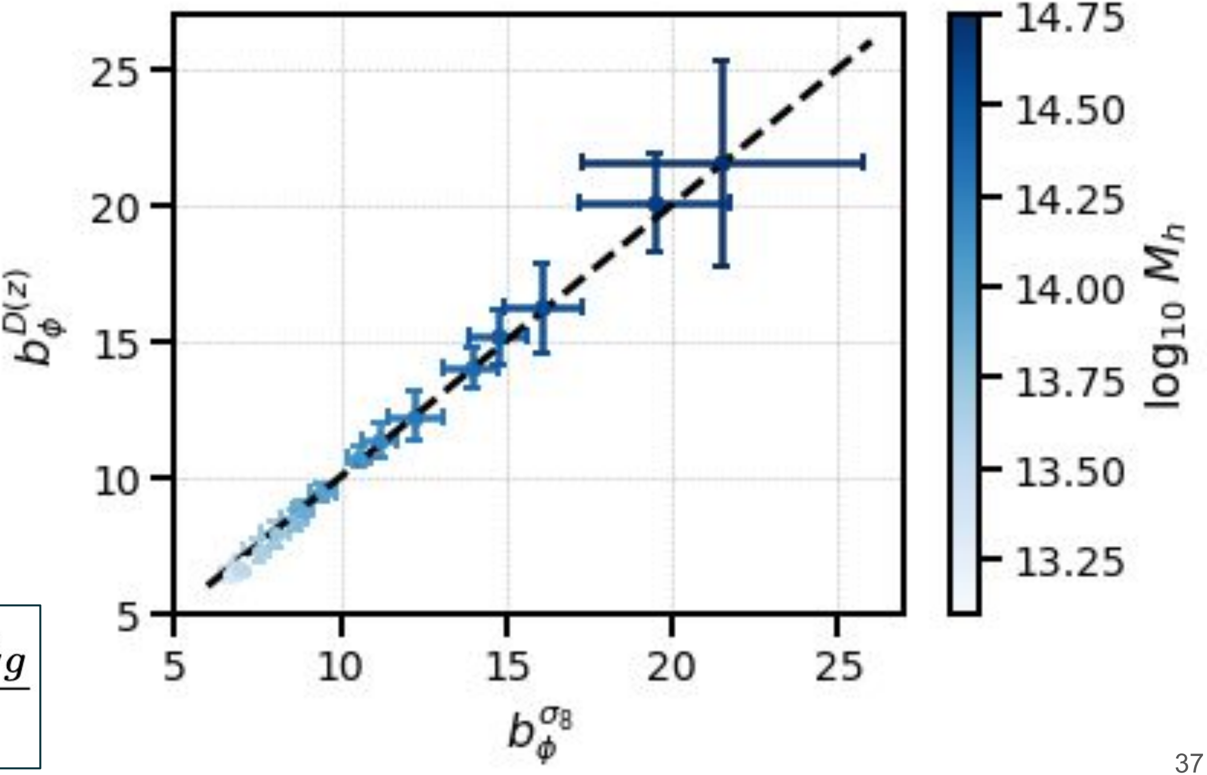
Growth and change in variance perfectly degenerate via variance

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

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



Bias from Time Evolution - Non-Universality

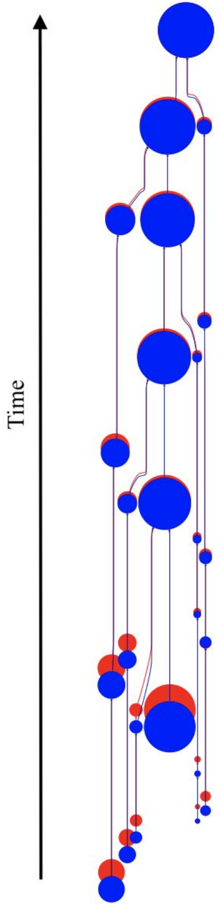
What about general tracers?

From SU, we argue adding LPNG *shifts time*

Any strongly time-dep. tracer property impacts b_ϕ

Halo conc., galaxy color, etc.

Seems to be true…



Pajer+13, Dai+15, Baldauf+11, Marinucci+23 (image)

Bias from Time Evolution - Hydro

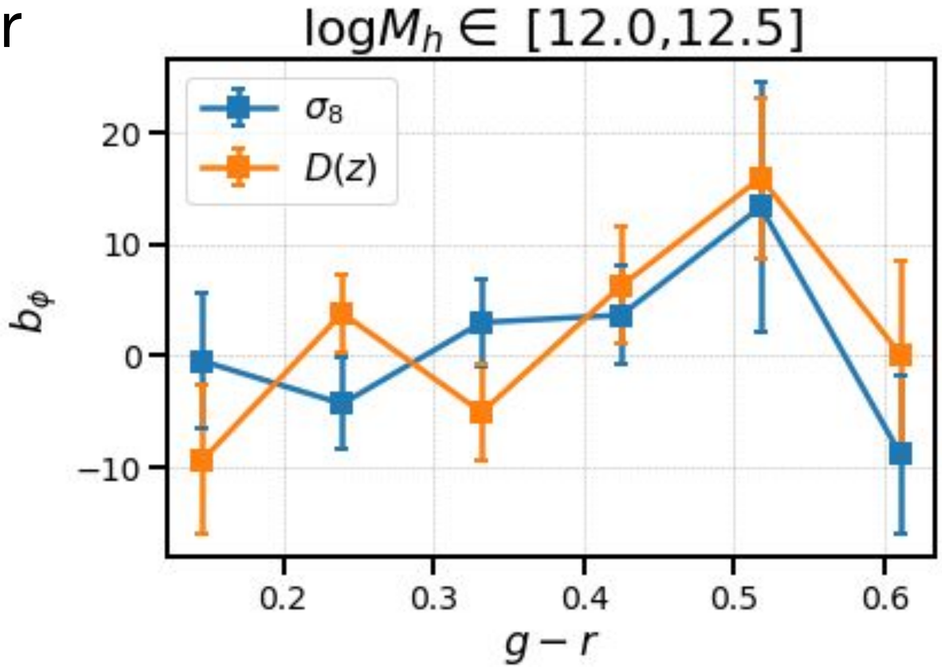
Can do the same w/ LPNG assembly bias - here w/ color

Holds roughly across mass

CAMELS hydro

Stay tuned for BOSS LRGs (<u>selection function</u>)

^Lessons from the past

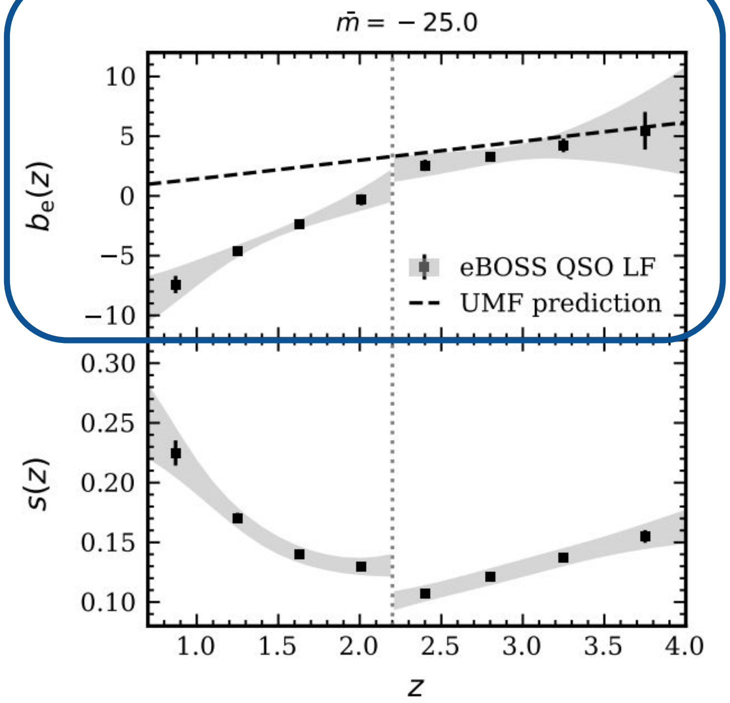


Bias from Time Evolution - Evolution Bias

Number density evolution in GR power

Past measurement in data

But color-dependent selection



$$\delta_n = \quad b\delta_m^{\rm syn} + \left[\frac{{\rm d}\ln(a^3\bar{n}_s)}{{\rm d}\eta} - 3\mathcal{H}\right]\frac{v}{k}$$

$$b_e \equiv \frac{d\ln(a^3\overline{\mathrm{n}}_g)}{d\ln a}$$

Challinor+Lewis11, Jeong++11, Baldauf+11, Yoo++10, DJS16, Wang++20

Bias from Time Evolution - Simulated Selection

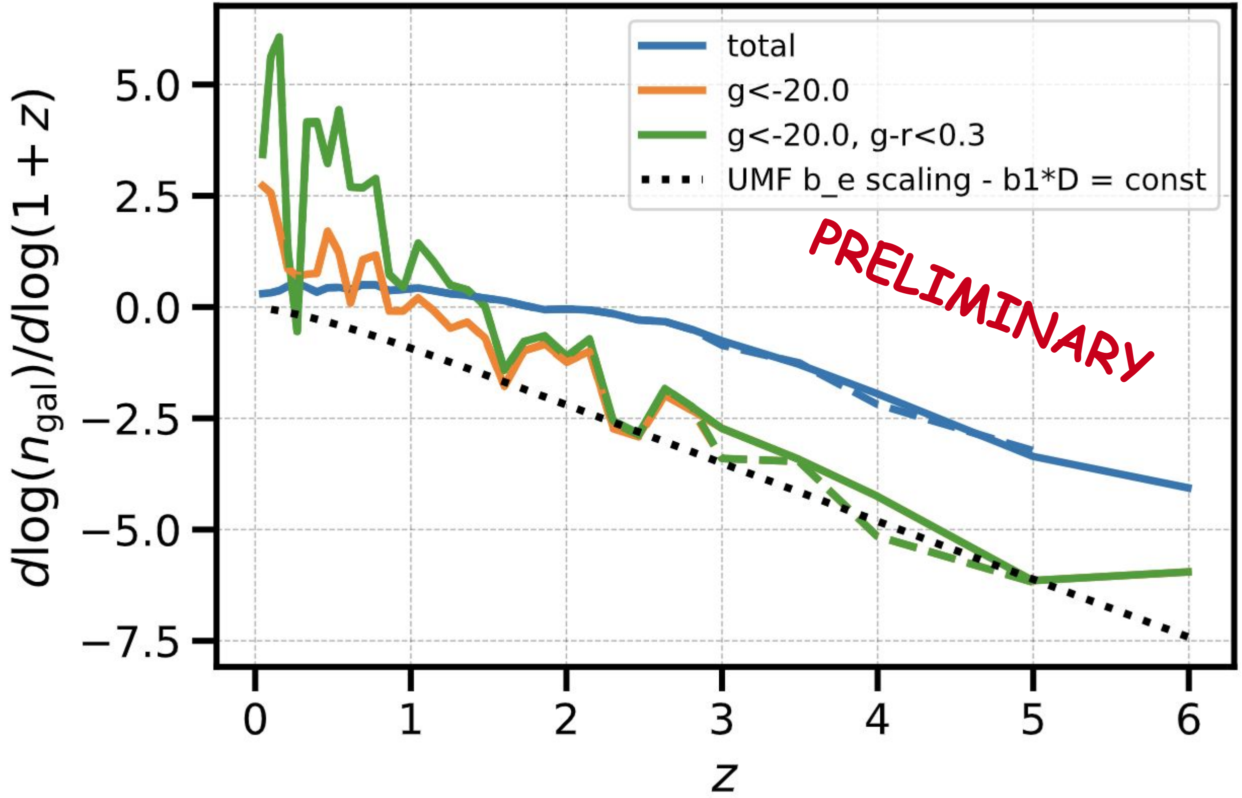
Number

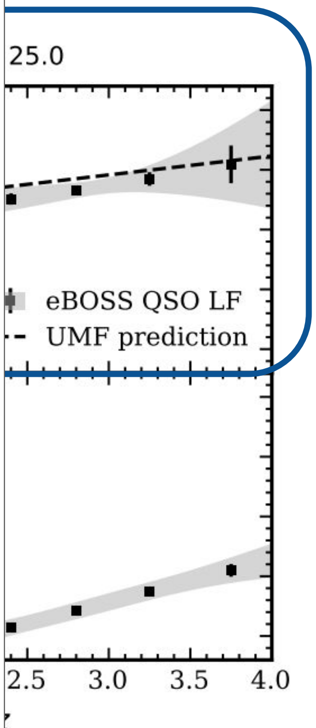
Past mea

But colo

$\delta_n = \; b\delta_m^{\rm syn} +$

b





Bias from Time Evolution - Final Thoughts

Priors on b_ϕ are *critical* for constraints

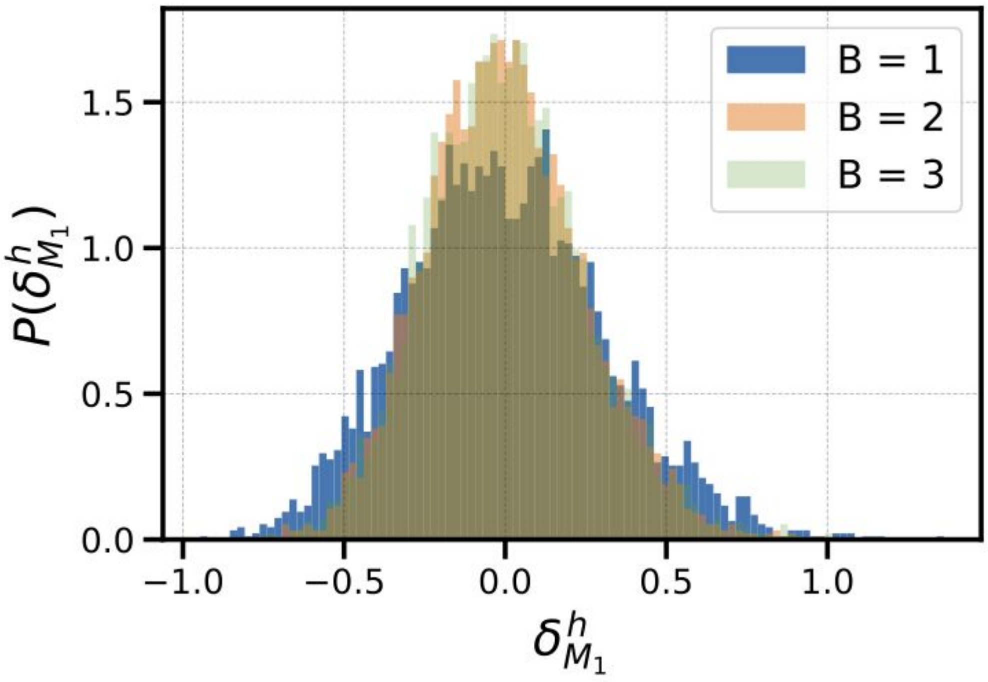
Time evolution a potential path forward

Color-dependent, magnitude-limited selections

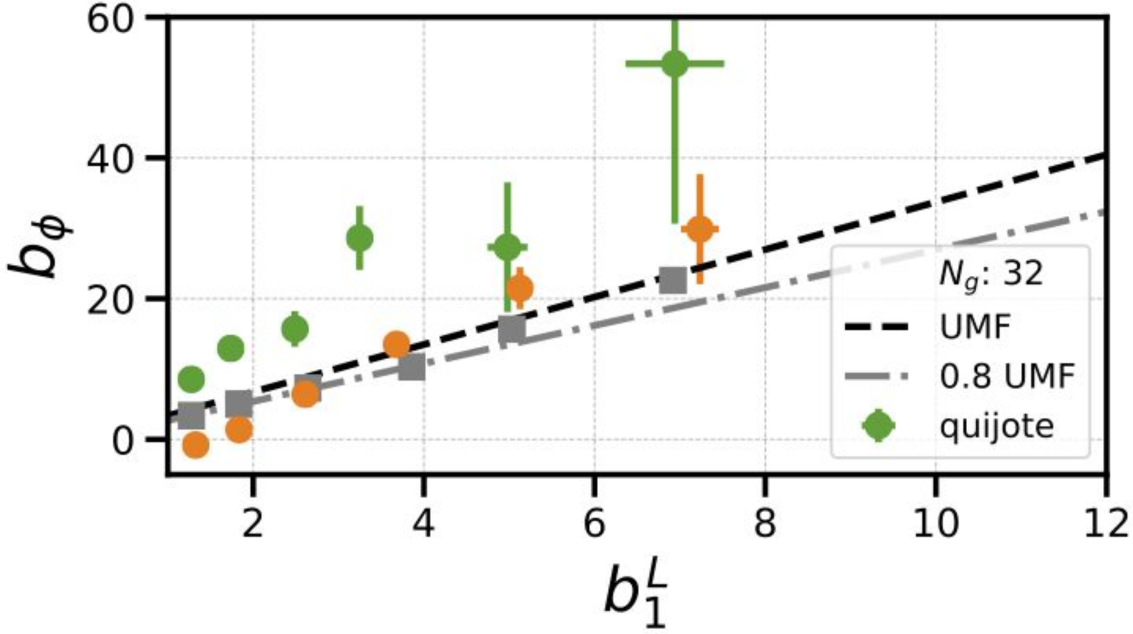
Joint inference with power spectrum dipole/octopole?

Extra

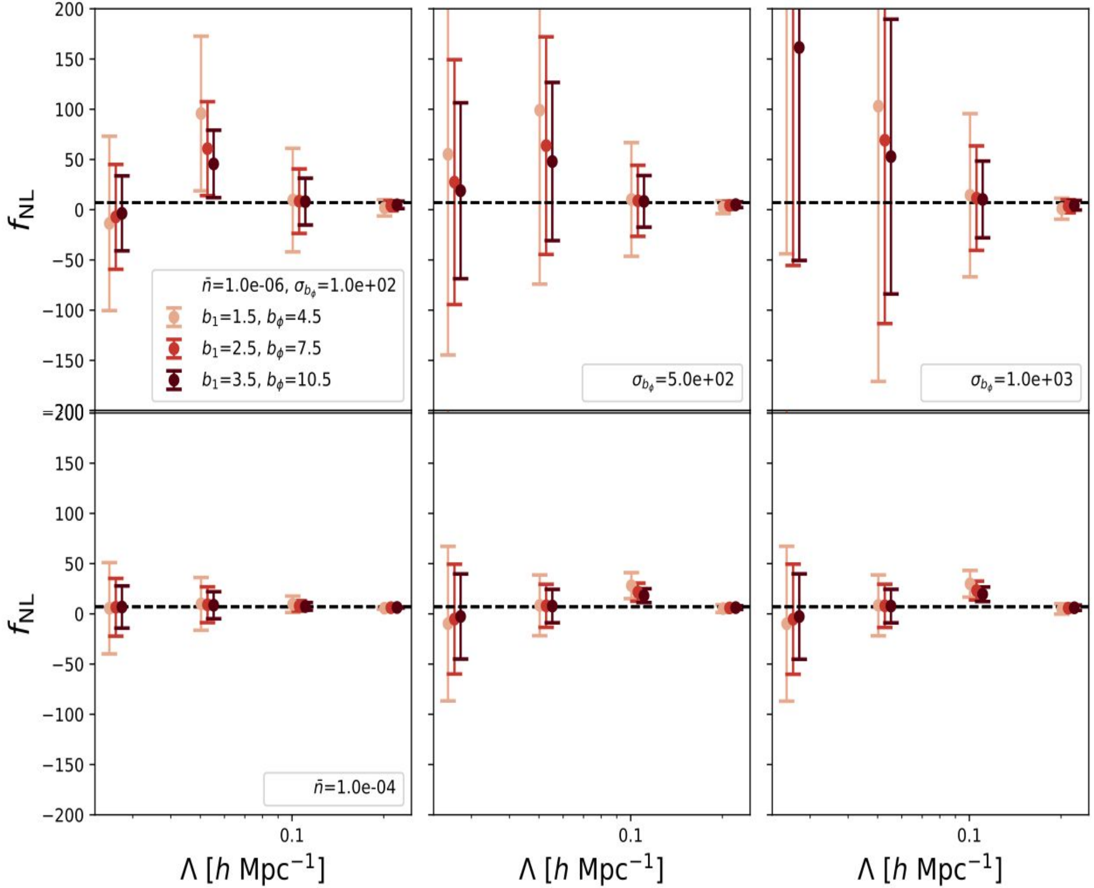
Force resolution - FastPM



Force resolution - Quijote

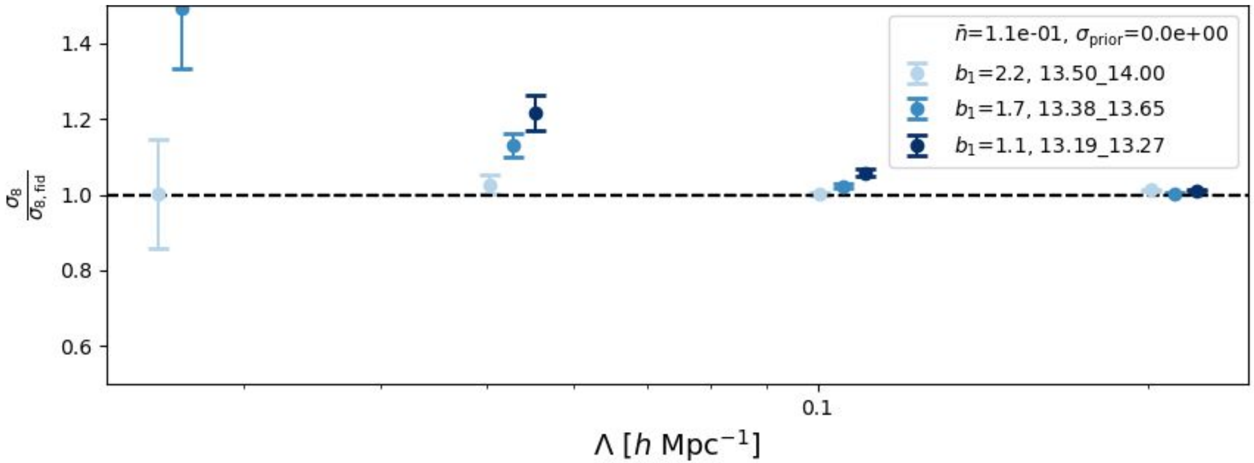


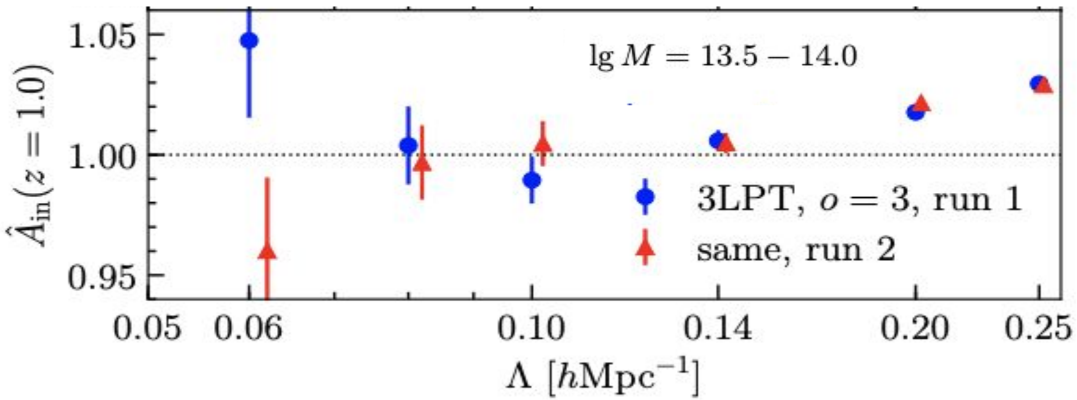
Priors



$\bar{n}$=1.0e-06, σ_{b_ϕ}=1.0e+02
b_1=1.5, b_ϕ=4.5
b_1=2.5, b_ϕ=7.5
b_1=3.5, b_ϕ=10.5
σ_{b_ϕ}=5.0e+02
σ_{b_ϕ}=1.0e+03
$\bar{n}$=1.0e-04
$f_{\rm NL}$
Λ [h Mpc^{-1}]
0.1
200
150
100
50
0
−50
−100
−150
−200

σ_8 Halos





Schmidt20