Field level bias modeling, assembly bias, and primordial non-Gaussianity

Theoretical Modeling of Large-Scale Structure of the Universe
June 5 2024

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

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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)

(Oliver's talk)

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

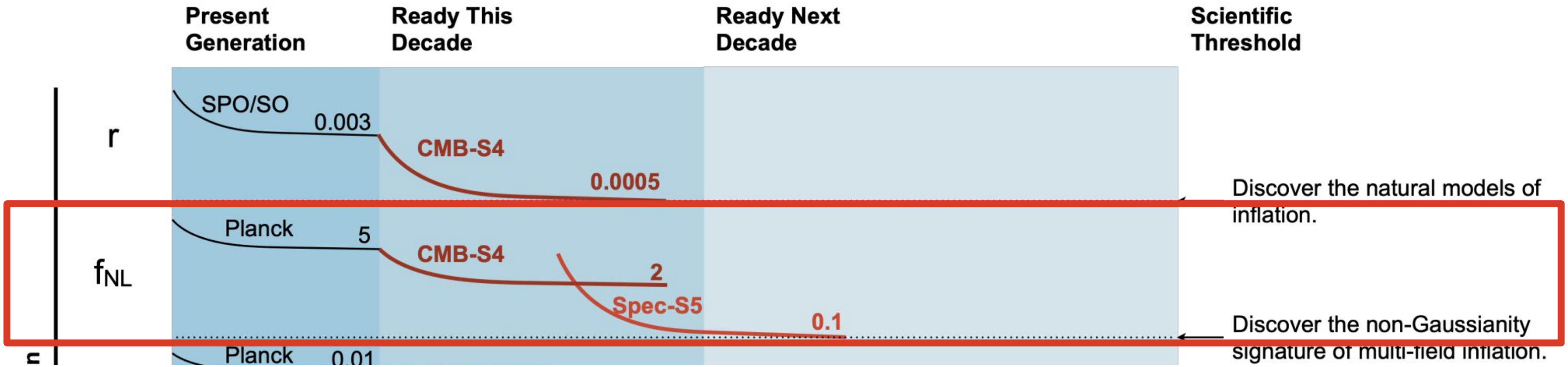
$$\phi = \phi_G + f_{NL}^{\rm loc} \left[\phi_G^2 - \langle \phi_G^2 \rangle\right]$$

Seed for structure (ϕ)

Counts multiple fields ($f_{NL}^{\rm loc}$)

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

f_{NL} a Prime Target of Future Galaxy Surveys



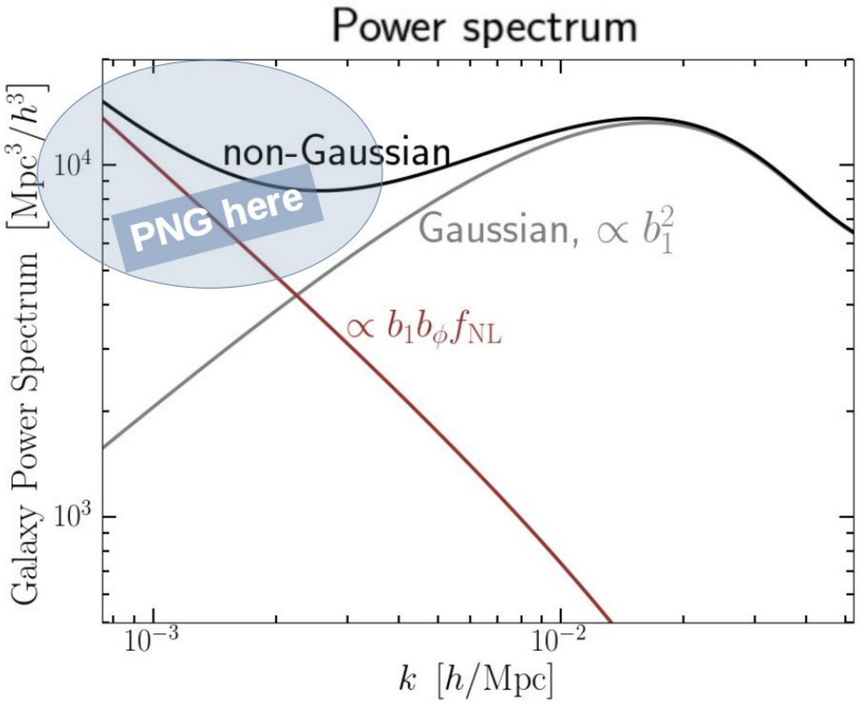
Spec-S5 (Martin's talk):

- 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

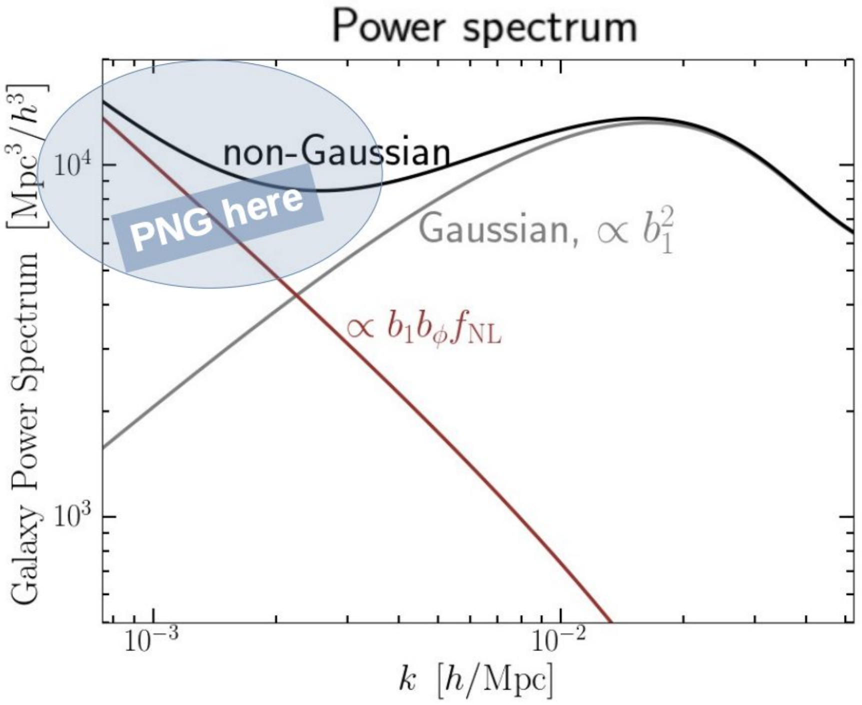
Measuring LPNG in Galaxy Surveys

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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Measuring LPNG in Galaxy Surveys

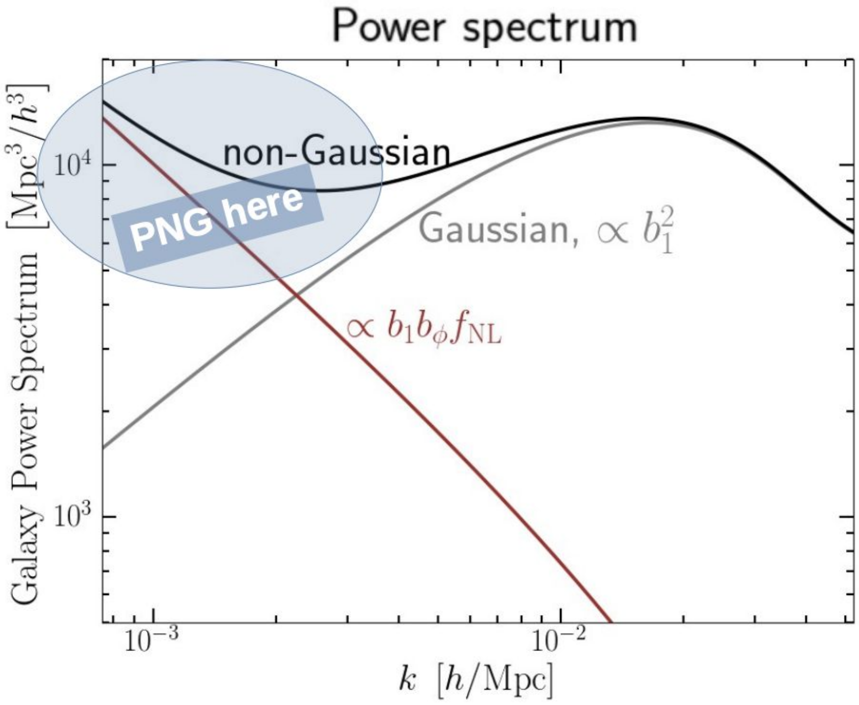
Measure power spectrum

To model it need a galaxy bias model:

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

Galaxy overdensity **Matter overdensity**

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



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

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

Constraining f_{NL}

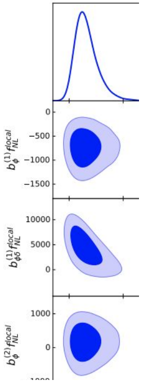
Option 1 - LPNG amplitude

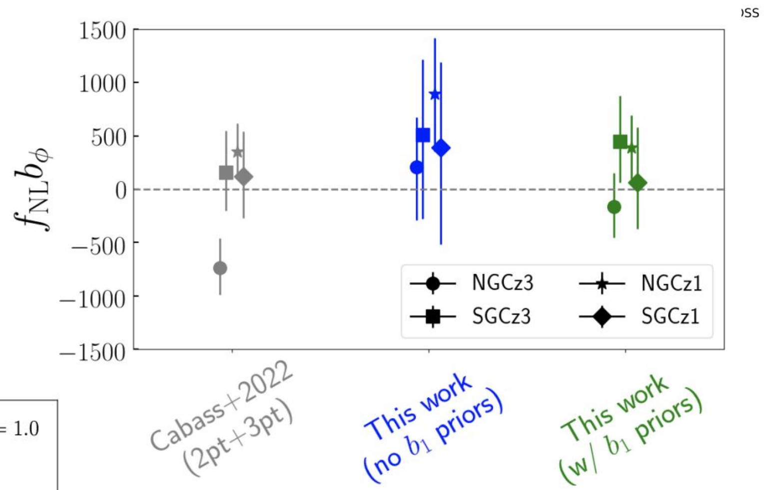
Assumption free!

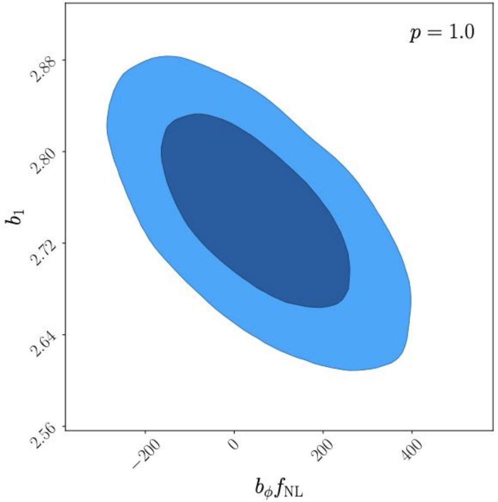
Option 2 - Constrain f_{NL}

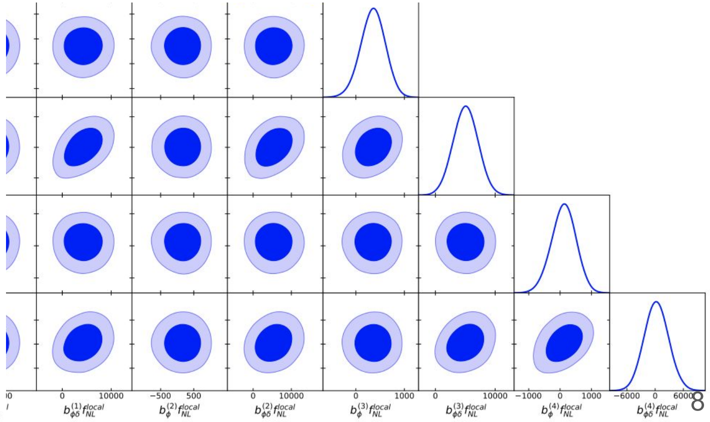
Requires knowing the value of b_ϕ

(Also plan surveys this way)









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

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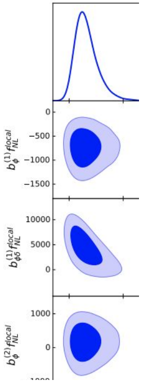
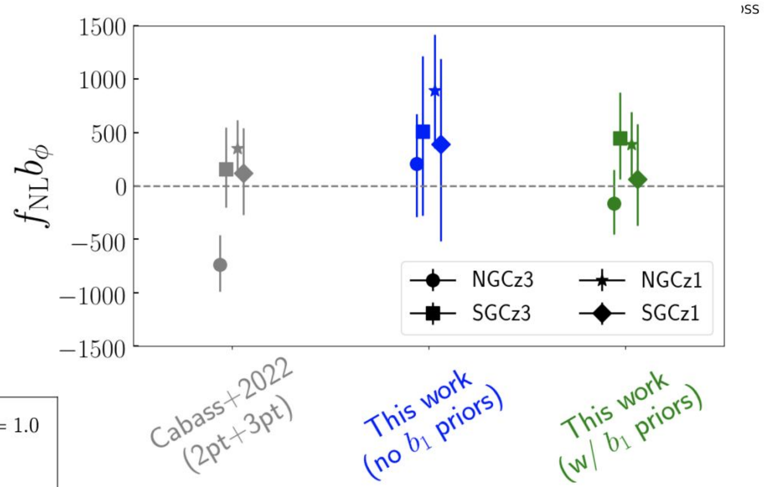
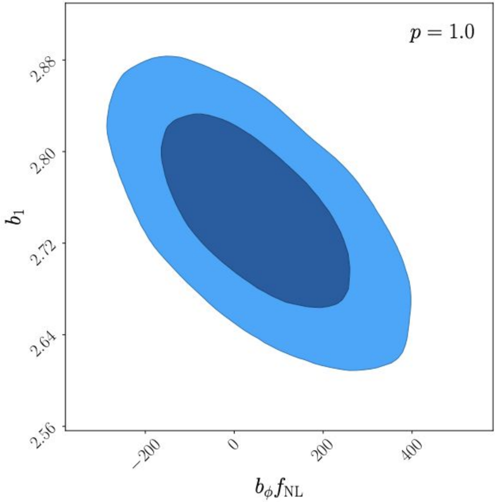
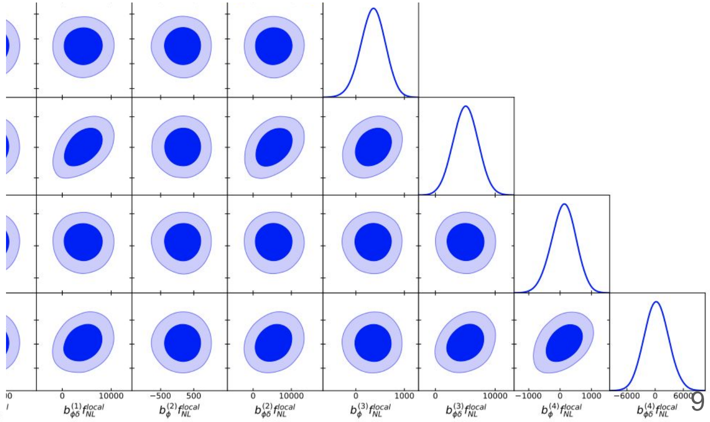
Requires knowing **the value of b_ϕ**

Assume we are ambitious…









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

Assuming a b_ϕ - Universal Mass Function

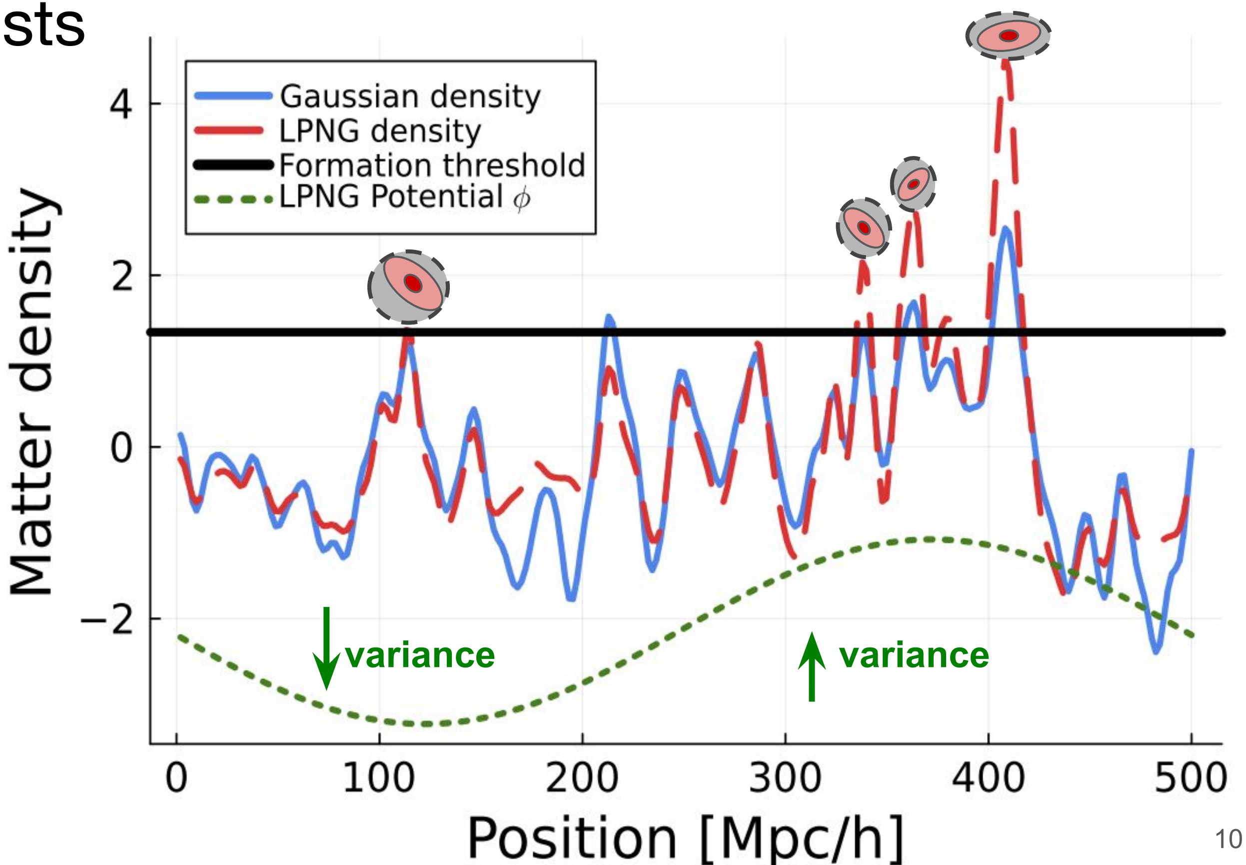
Cartoon: LPNG "boosts local variance"

Halos form after crossing threshold

Crossing affected by LPNG

Assume UMF form:

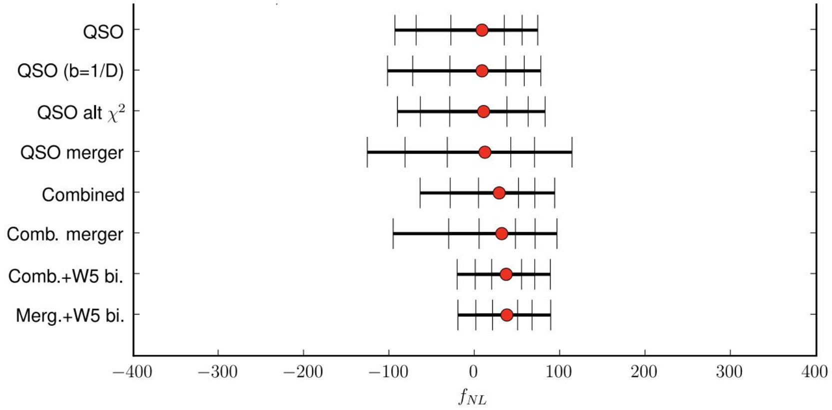
$$b_\phi(b,p) \propto b - p$$



Slosar+08, Desjacques+16

Galaxy survey f_{NL} - SDSS quasars

Slosar++08



Galaxy survey f_{NL} - SDSS quasars

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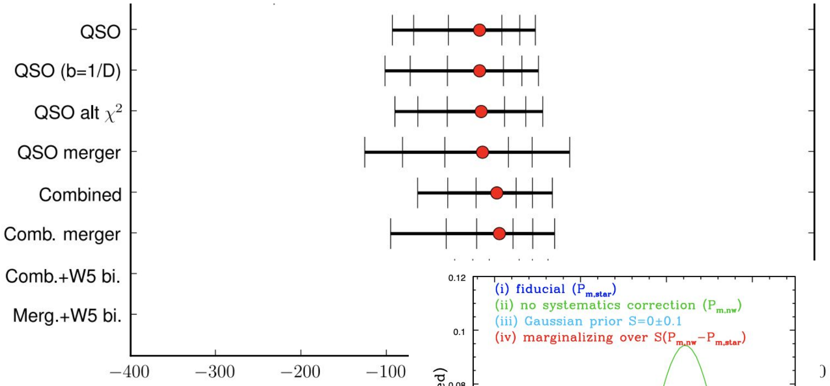
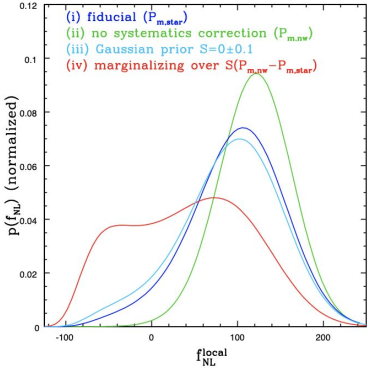
Ross++12





Galaxy survey f_{NL} - SDSS quasars

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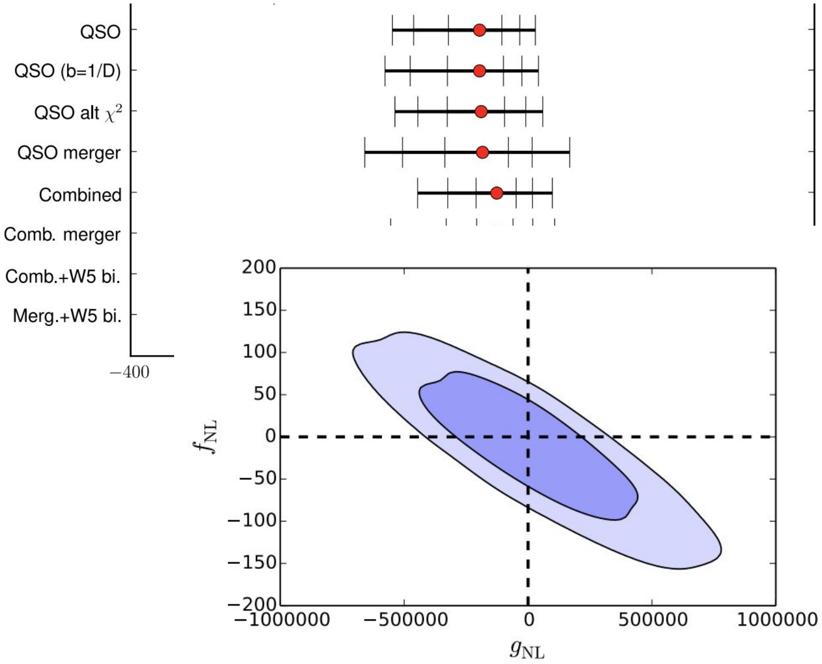
Leistedt++14



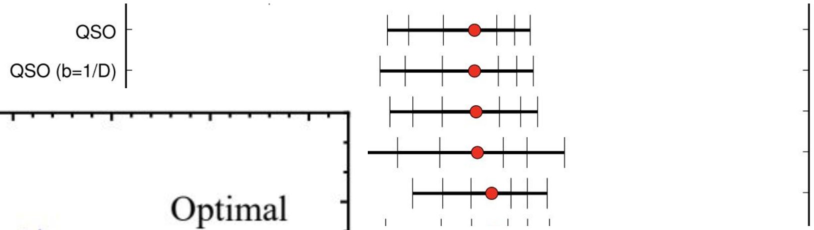
Galaxy survey f_{NL} - eBOSS quasars

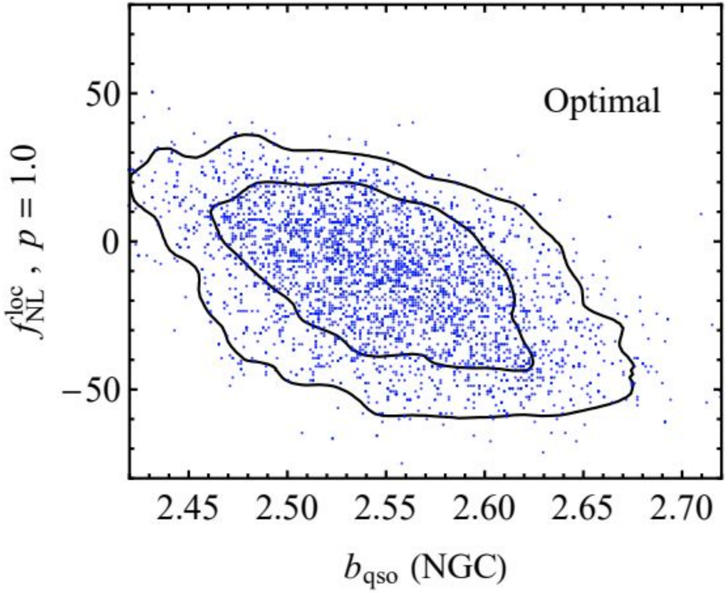
Slosar++08

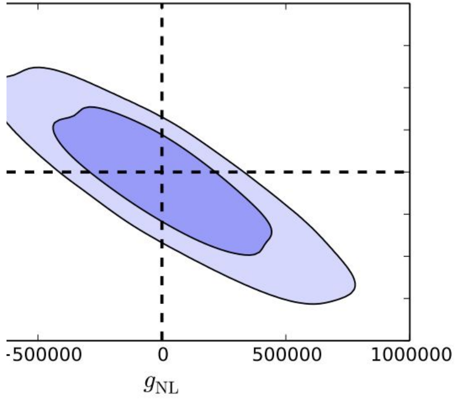
Ross++12

Leistedt++14

Castorina++19







Galaxy survey f_{NL} - eBOSS quasars

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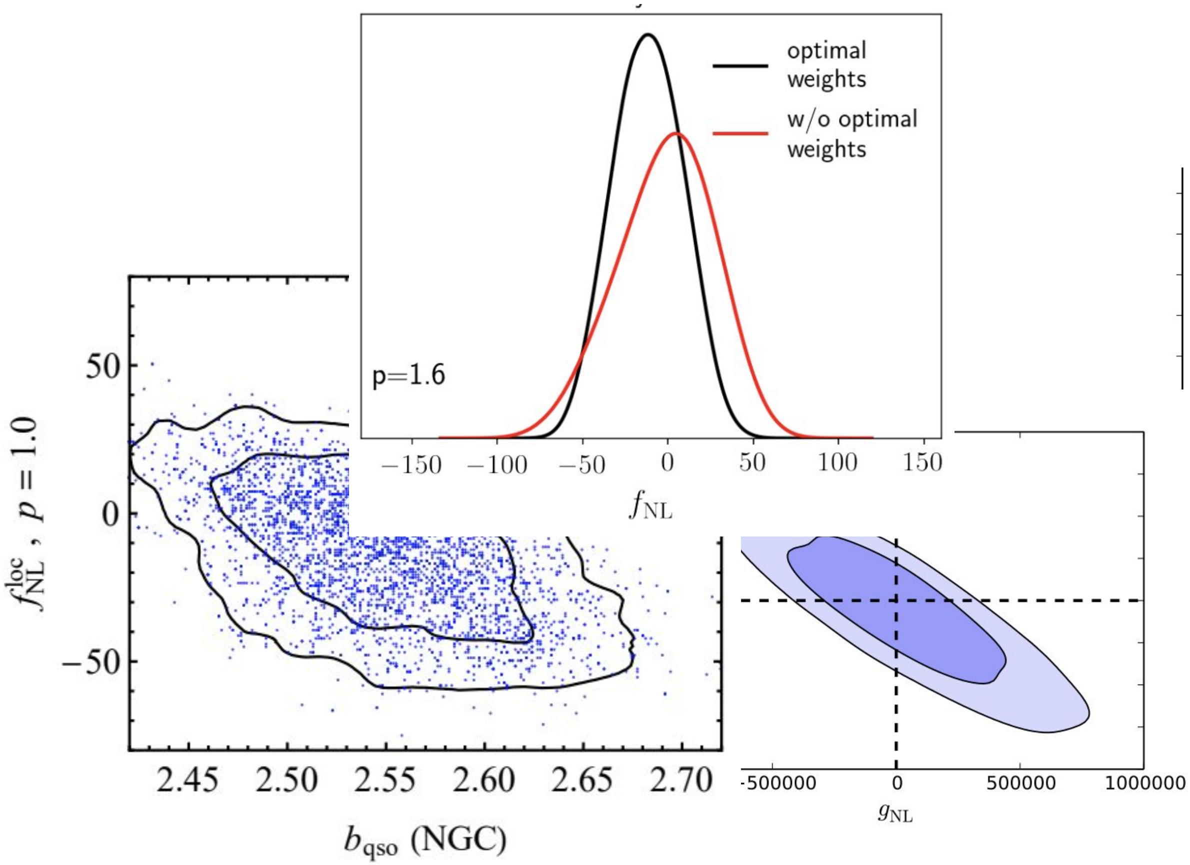
Ross++12

Leistedt++14

Castorina++19

Mueller++21



Galaxy survey f_{NL} - BOSS LRGs

Slosar++08

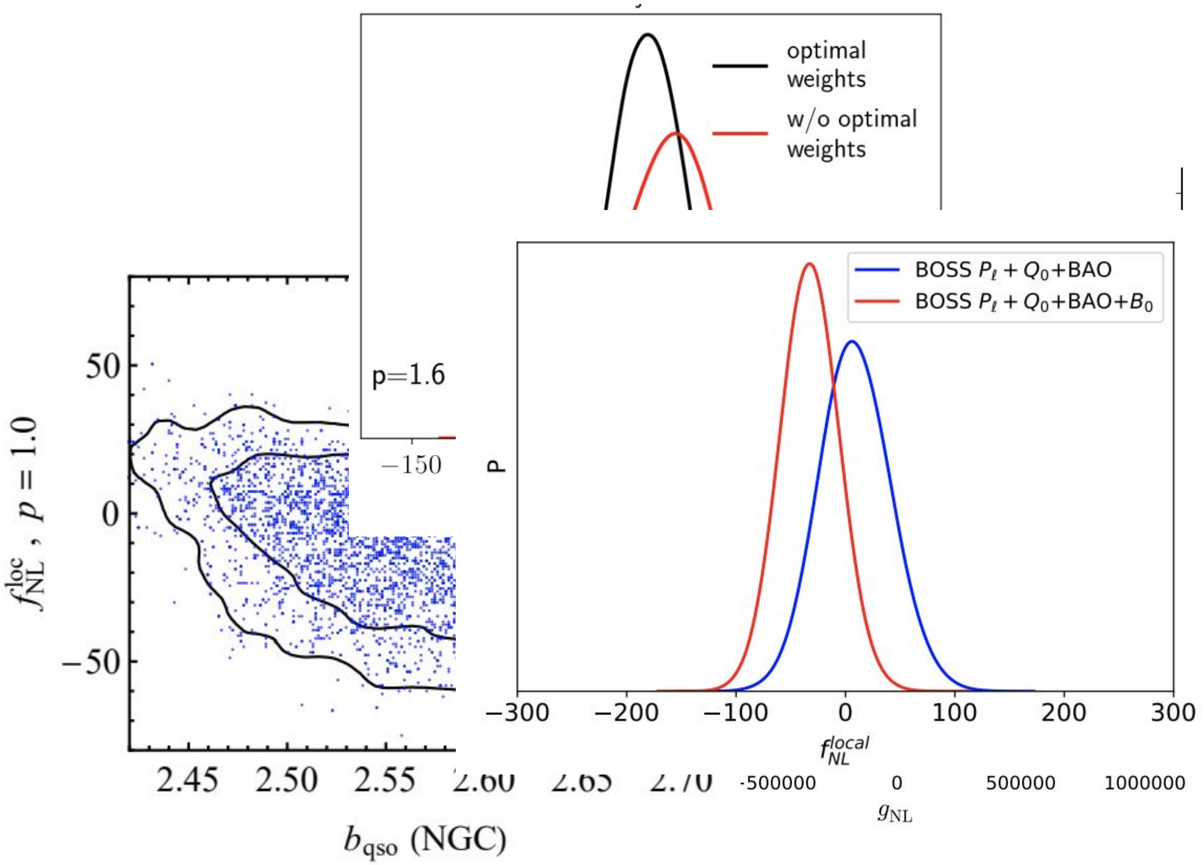
Ross++12

Leistedt++14

Castorina++19

Mueller++21

D'Amico++22



Galaxy survey f_{NL} - BOSS LRGs

Slosar++08

Ross++12

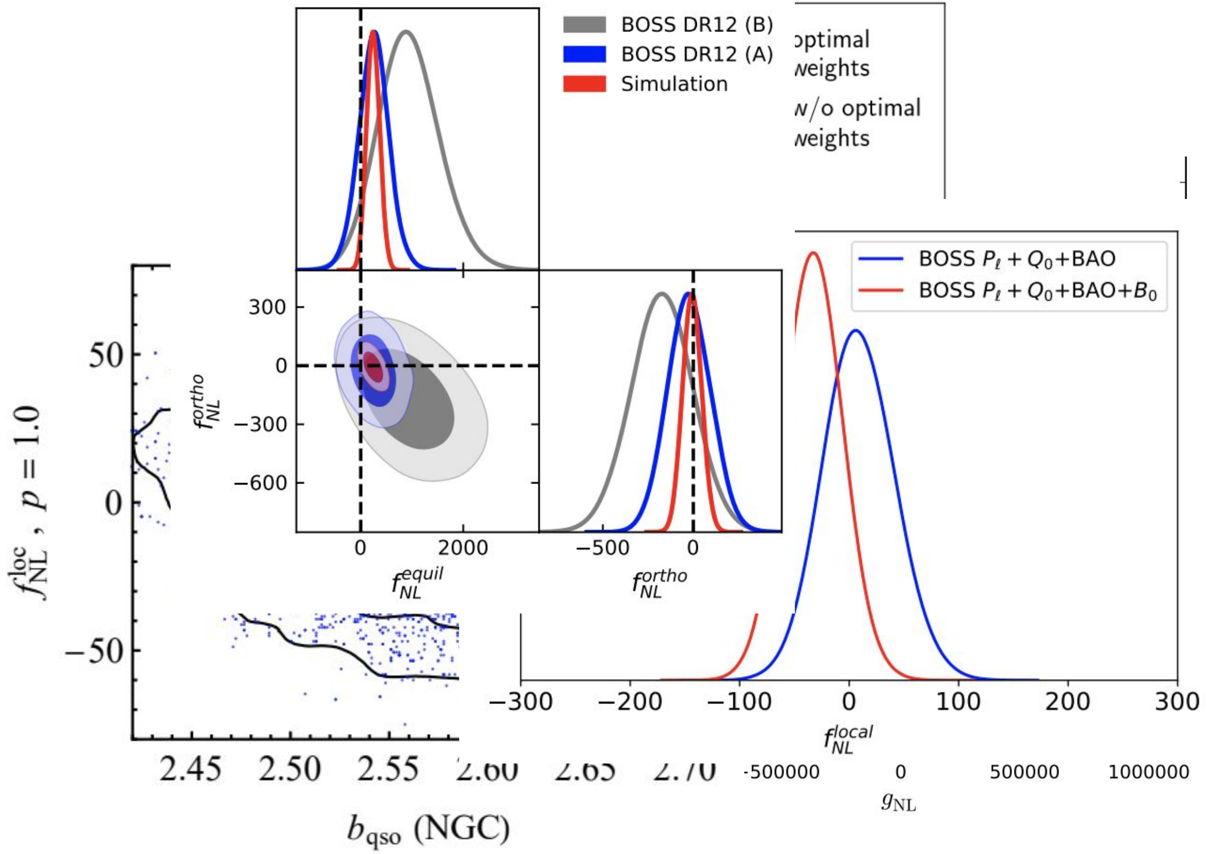
Leistedt++14

Castorina++19

Mueller++21

D'Amico++22

Cabass++22a



Galaxy survey f_{NL} - eBOSS/DESI

Slosar++08

Ross++12

Leistedt++14

Castorina++19

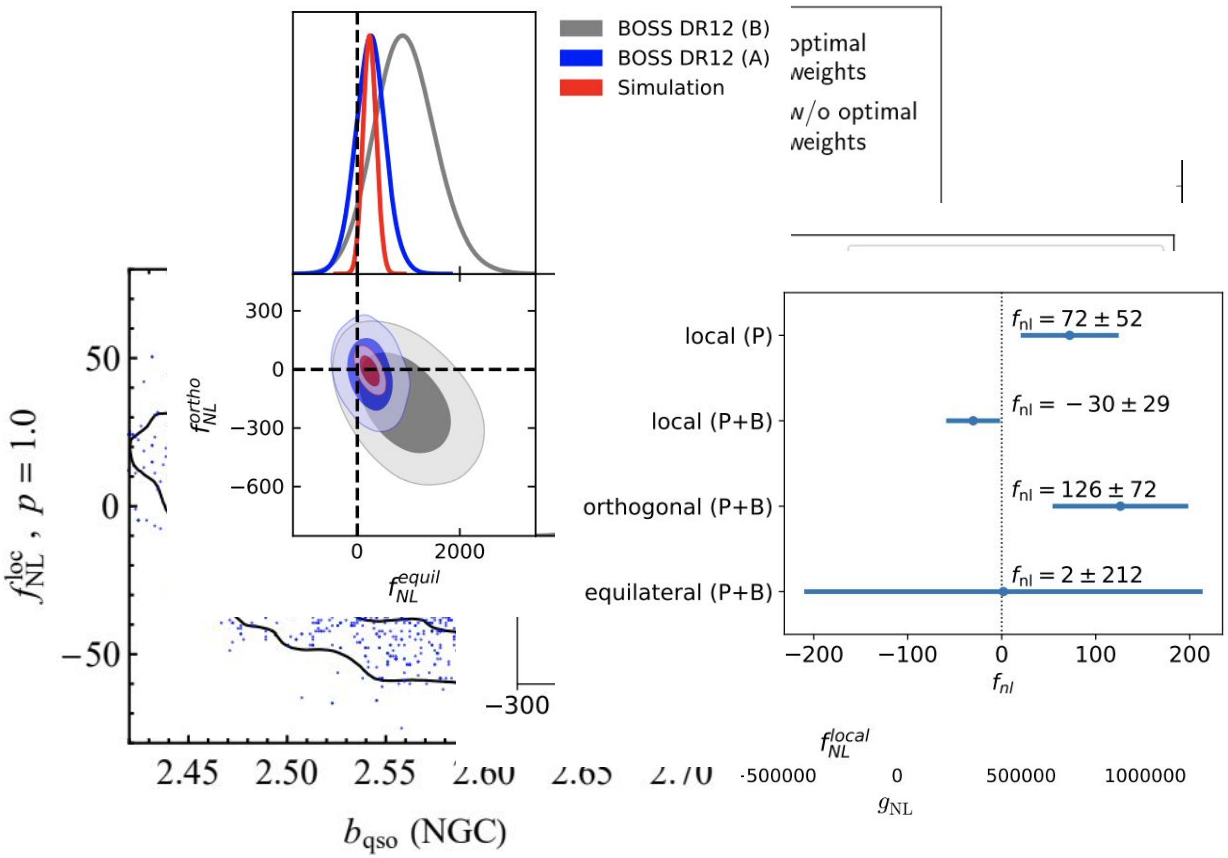
Mueller++21

D'Amico++22

Cabass++22a

Rezaie++23

Cagliari++23



Understanding b_ϕ

How worried should we be about standard assumption?

Can we break the degeneracy between b_ϕ and f_{NL}?

Attacking b_ϕ from **3 angles:**

1. Test b_ϕ in simulations at field level
2. *Data*-driven b_ϕ prior?
3. Can we *model* deviations from standard assumption? (Assembly bias, see also 2303.08901)

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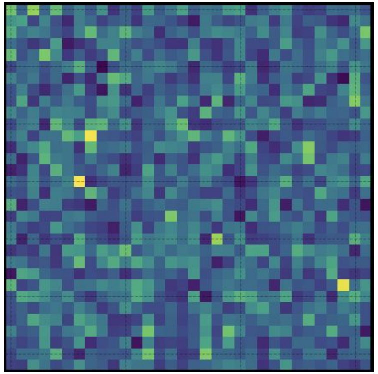
Field-level Bias Model

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

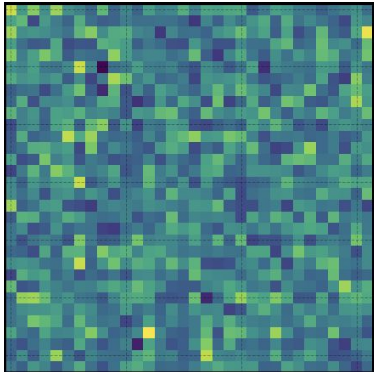
Field-level likelihood - simple regression - NL displacements

See Francisco’s, Matteo’s, Marcos’ talks. (+Juila’s and Kazu’s talks for PT flavor)

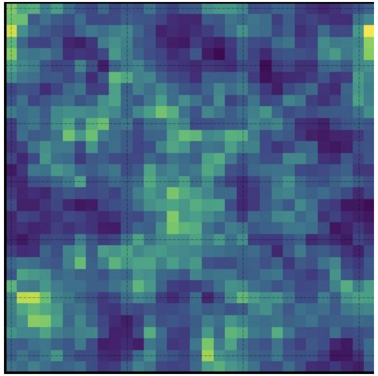
Halos **Matter** **Potential**



$= b_1$



$+ b_\phi f_{NL}$



Field-level Bias Model

At 2nd order in bias, 2 Local PNG terms

Neglect position-dependent variance

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

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

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

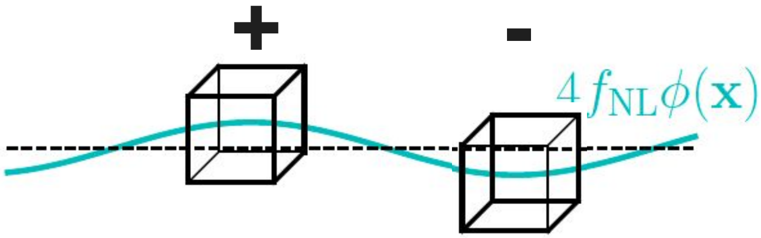
Separate Universe (response) b_ϕ

Separate Universe (->peak-background split)

Finite-difference 2 sims

Uses infinite-wavelength limit

Separate Universe $\mathcal{A}_s$



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

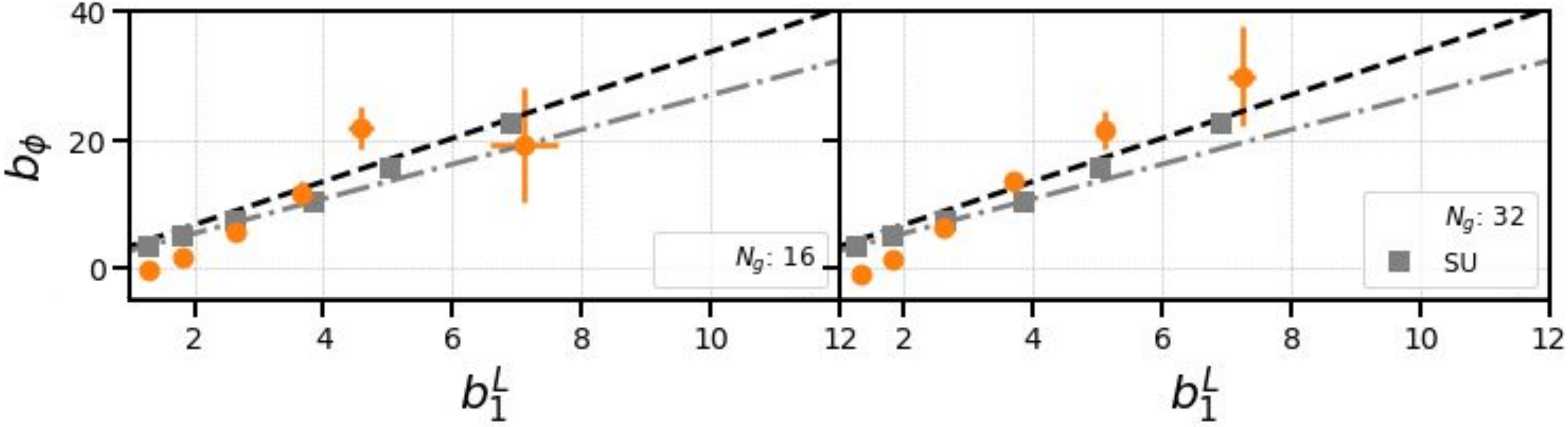
$$b_\phi(M,t) = 4 \mathrm{d}\ln n_g(M,t)/\mathrm{d}\delta\mathcal{A}_s$$

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

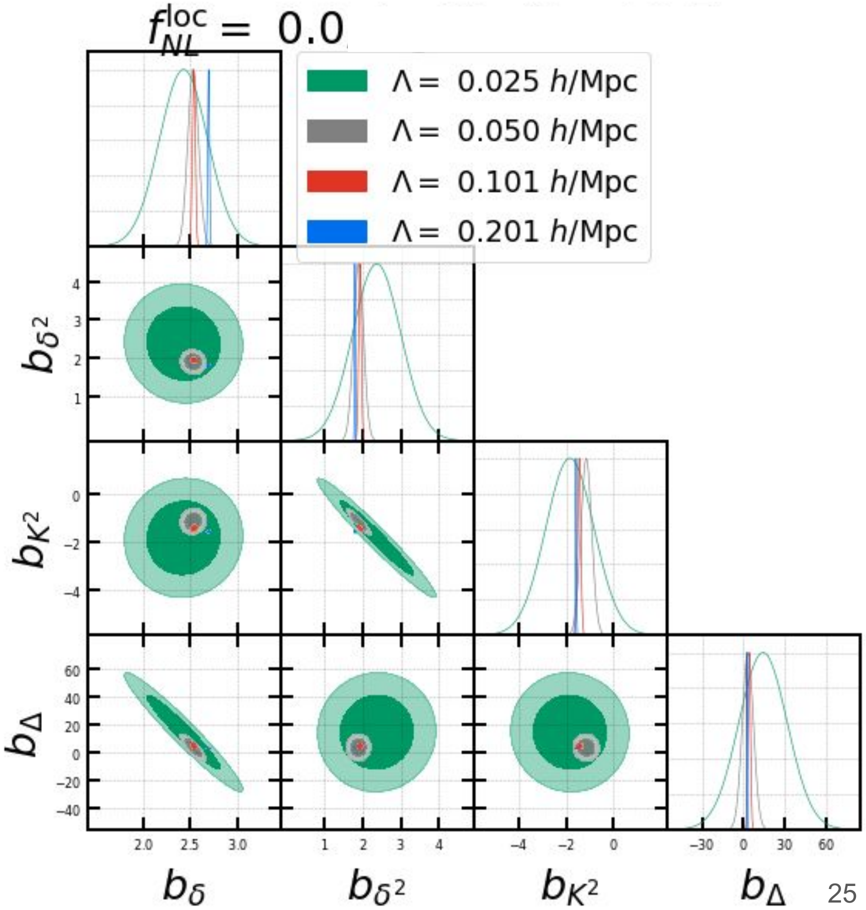
Somewhat resolution dependent…



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?

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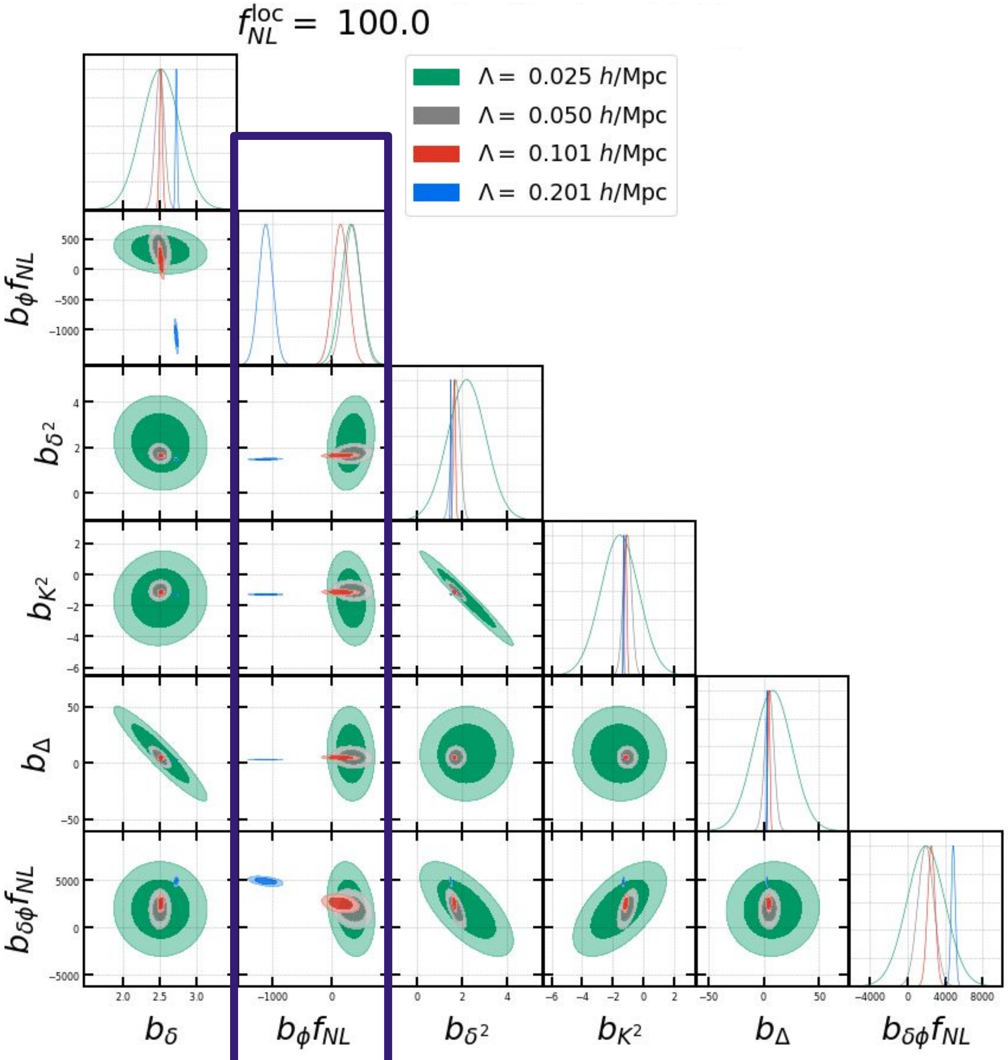
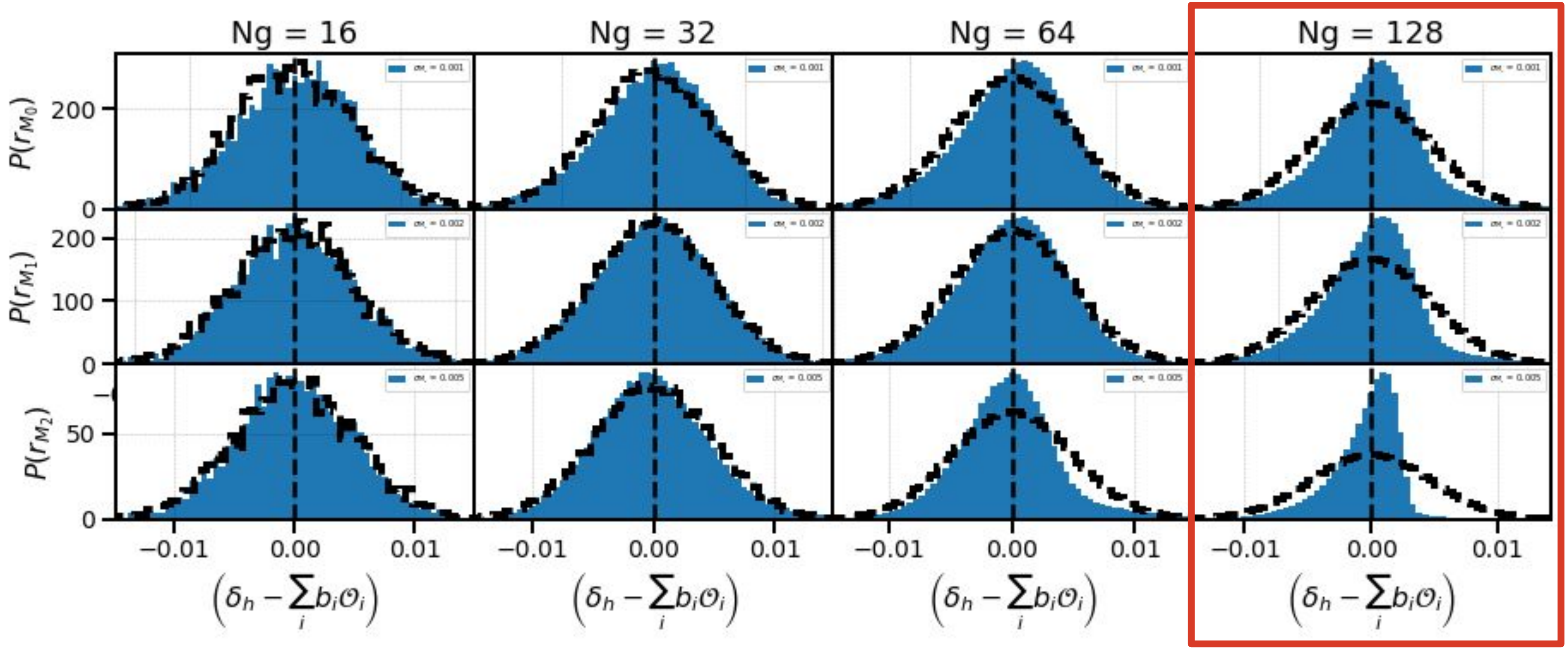
Adding PNG, much the same*

(*w/ renormalized operators)



Check with PDFs

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



Inferring Local PNG

Easy mode - fixed phases

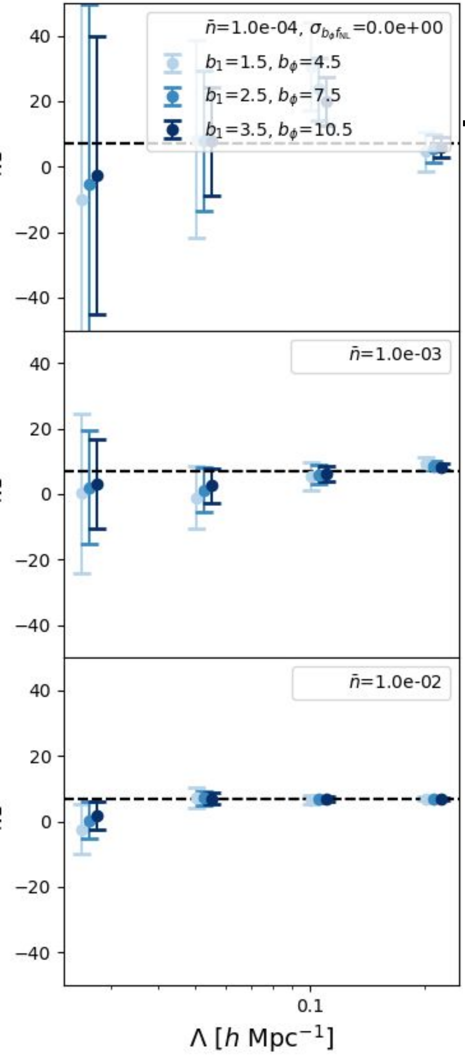
Inferring f_{NL}, marginalizing over from PT mocks?

Yes

Inferring f_{NL} from halos?

No…*

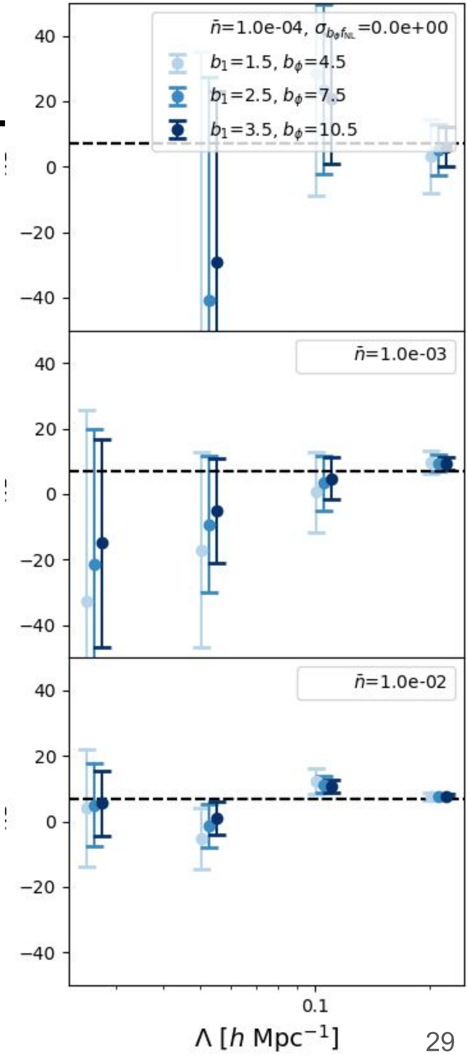
Inferring Local PNG



PT mock test

Bias-marginalized profile likelihood

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



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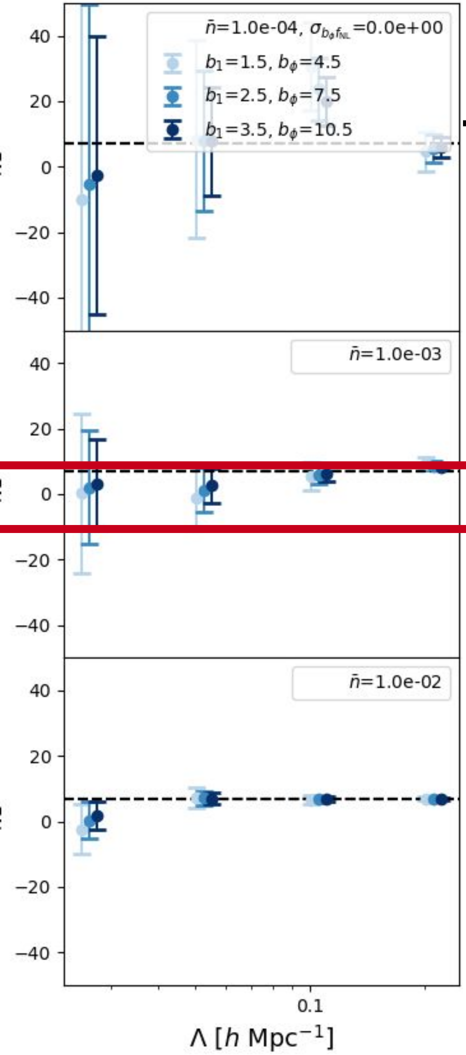

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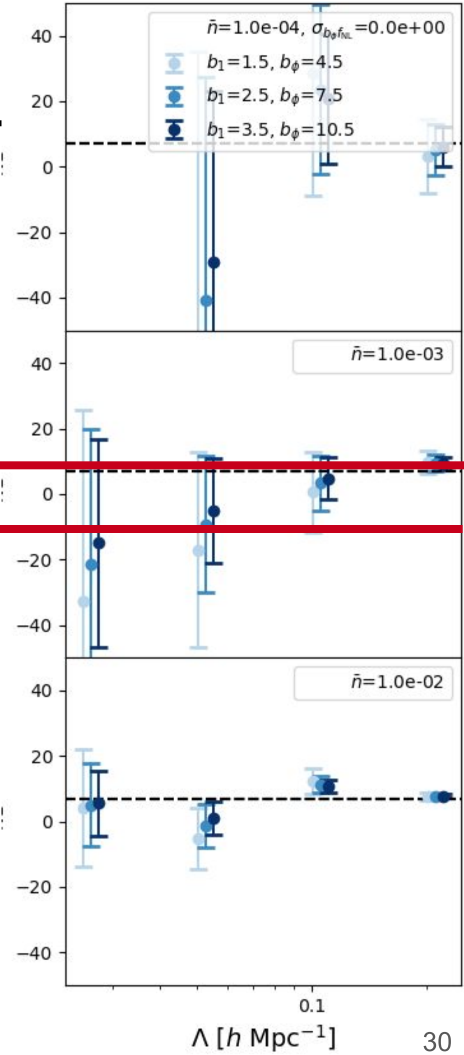
Linear



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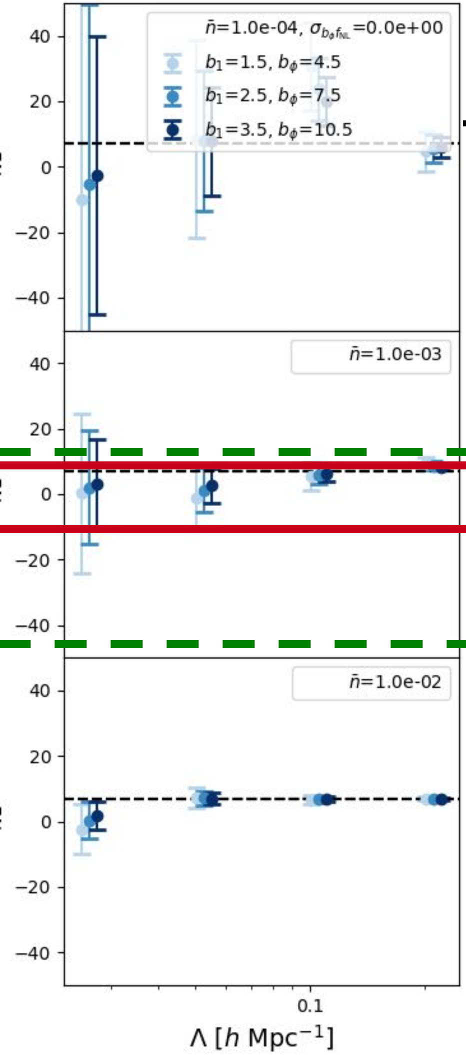

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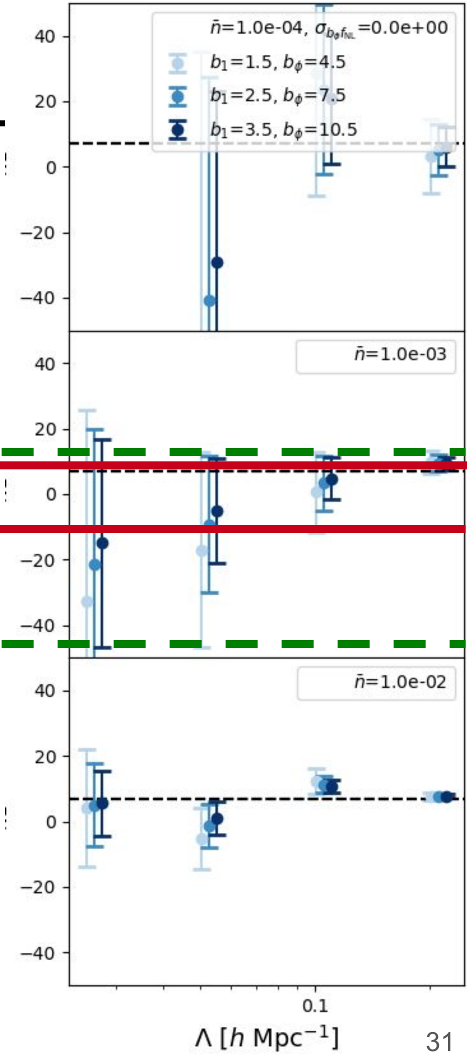
Quadratic



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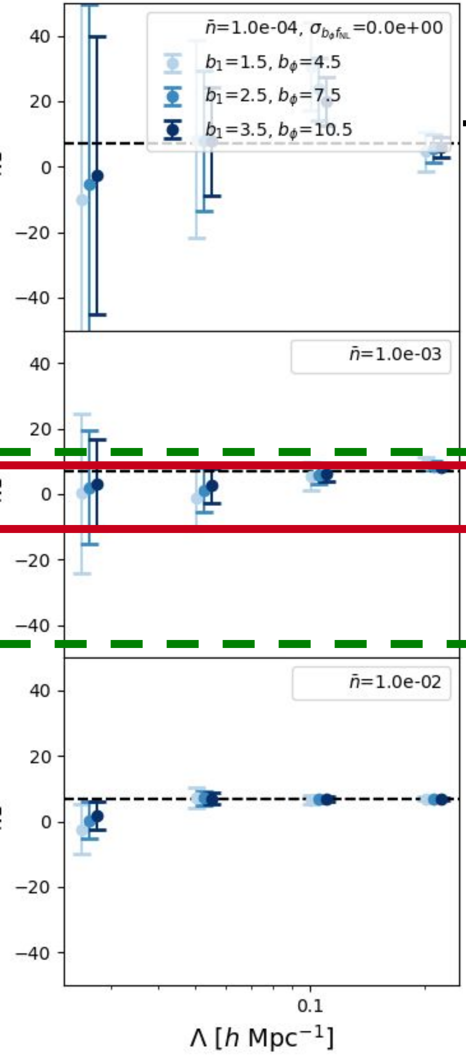

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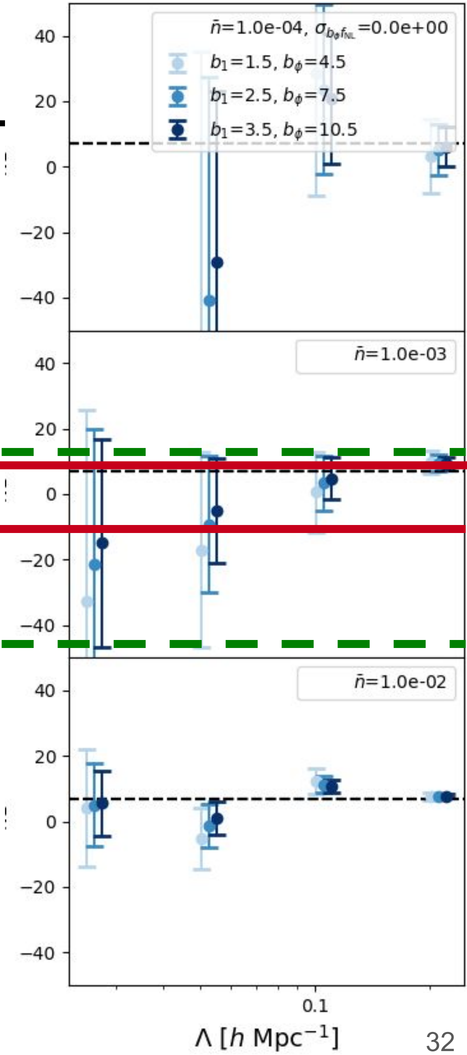
Even easy-mode pessimistic…



Bias from Time Evolution - Idea

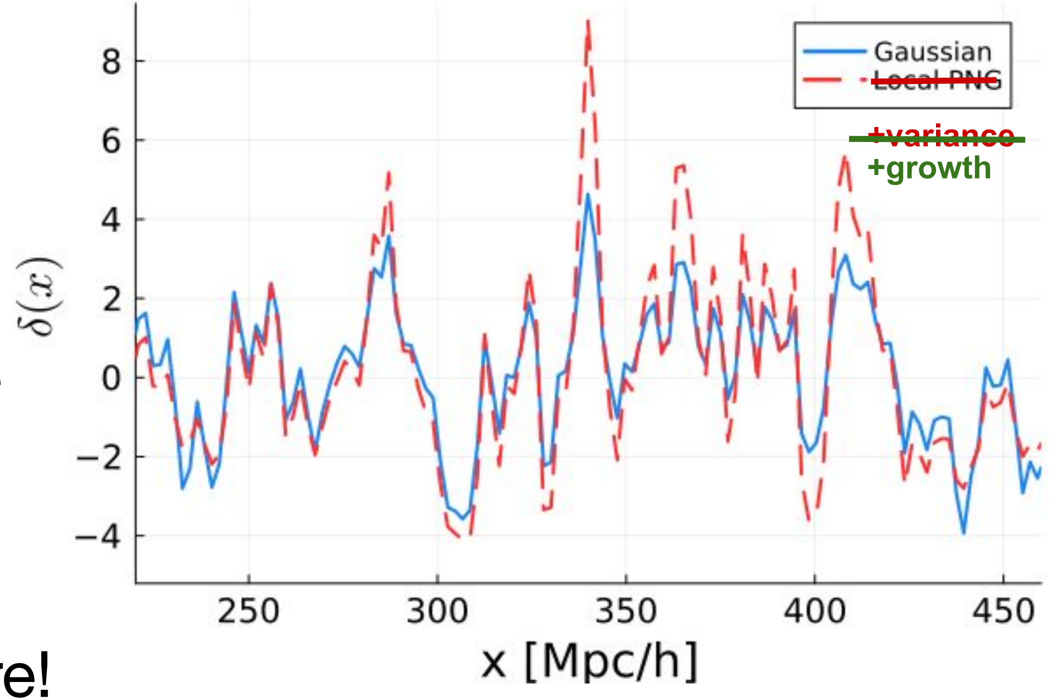
LPNG is "like" boosting
underlying variance

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)

Separate universe with 1 universe? - 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++12

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Growth and change in variance perfectly degenerate via variance

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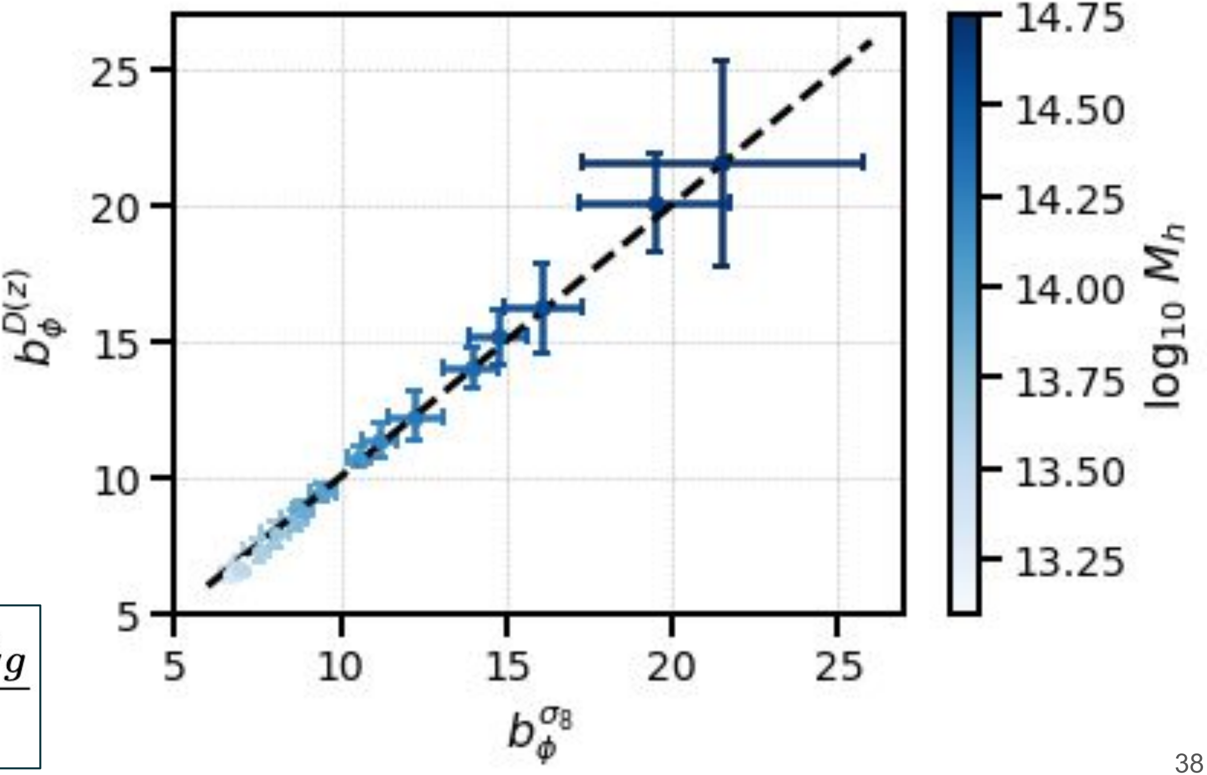
Bias from Time Evolution - Simulated Halos

N-body halos at $z = 1$

Evaluate bias via finite difference response to:

1. variance (σ_8)
2. growth

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



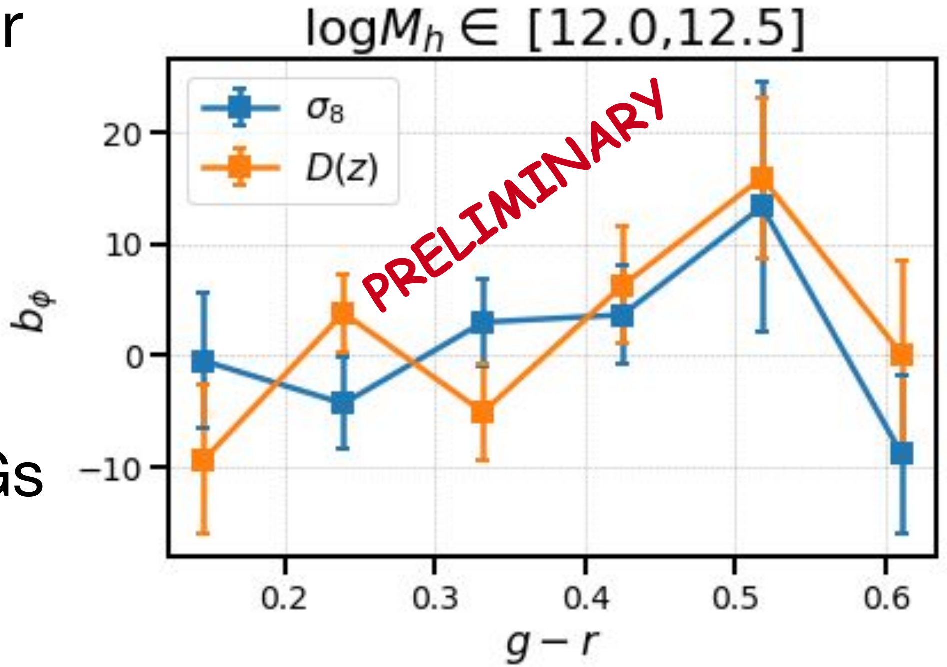
Bias from Time Evolution - Hydro

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

Holds roughly across mass

Hydro sims out there are limited

Now-> looking at BOSS LRGs (<u>selection function</u>)



LPNG & Assembly Bias

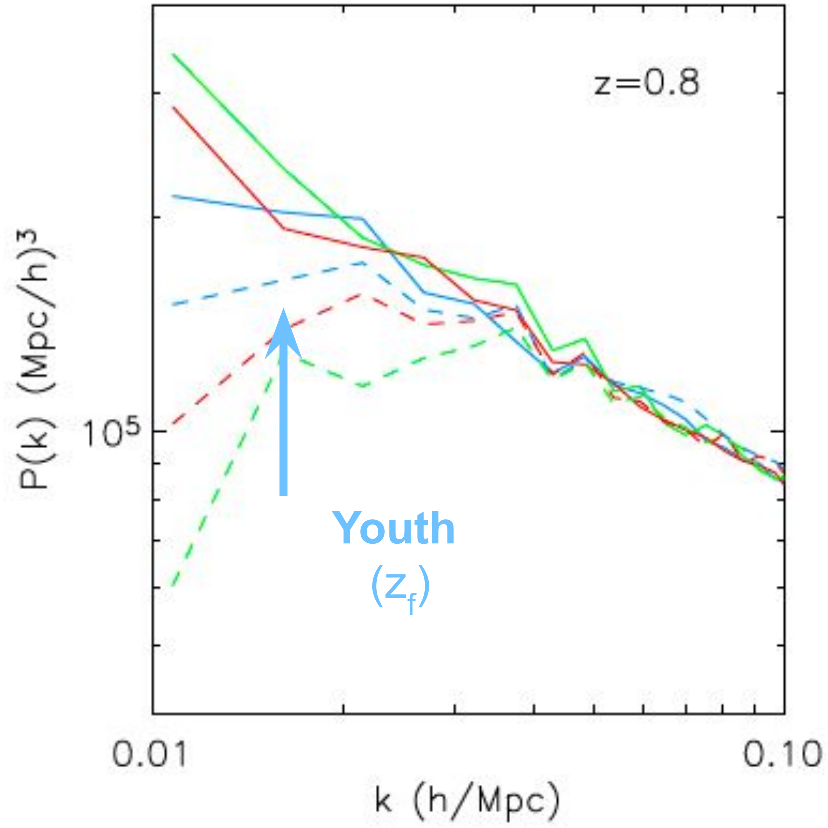
Halo assembly bias:

Slosar 08 -> “merger”

Reid 10 -> formation time

…

Lazeyras 22 -> concentration (also spin, axis ratio)

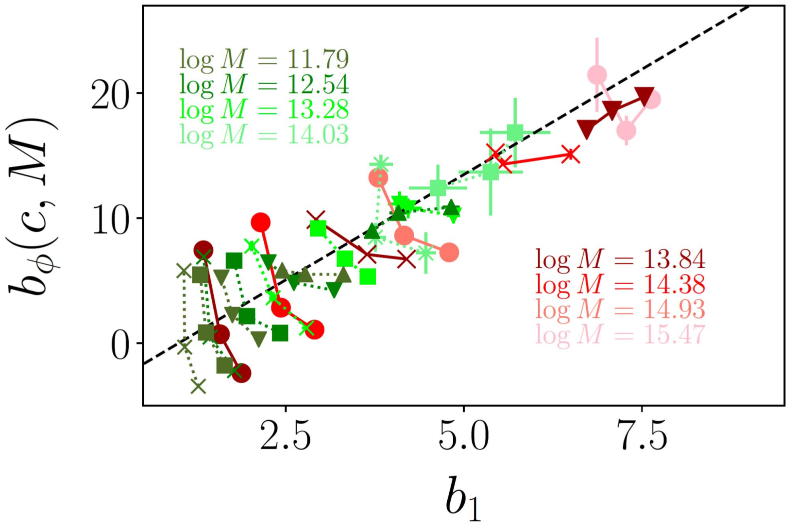


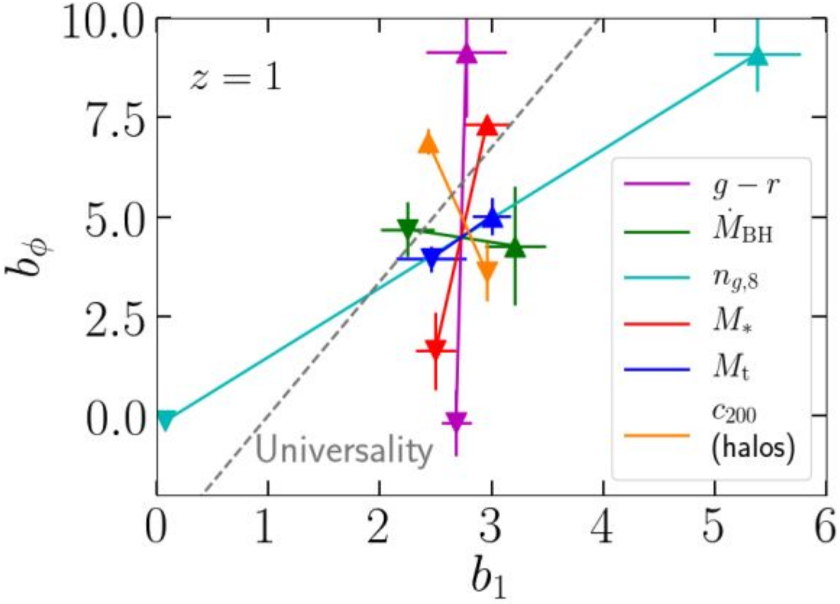
LPNG & Assembly Bias

Halo concentration *c* has a large effect (see 2303.08901)

Especially at low mass, enormous variation

Galaxy color is even stronger! **Why?!**





Slosar+08, Reid+10, Barreira+20, Lazeyras+22, Barreira&Krause23, Lucie-Smith++23, Marinucci+23

Final Thoughts

Unanswered questions:

- Information content of field-level vs *n*-point for PNG generally?
- What more to learn about b_ϕ assembly bias?
  - -> Physical understanding even for halos
- Is time-evolution bias applicable to other samples? (Working on LRGs now)
  - -> Deeper understanding of galaxy populations

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- Information content of field-level vs *n*-point for PNG generally?
- W

Lunch!

    -> Physical understanding even for halos

- Is time-evolution bias applicable to other samples? (Working on LRGs now)

    -> Deeper understanding of galaxy populations