# Pinning Down Local Primordial Non-Gaussianity with Galaxy Bias

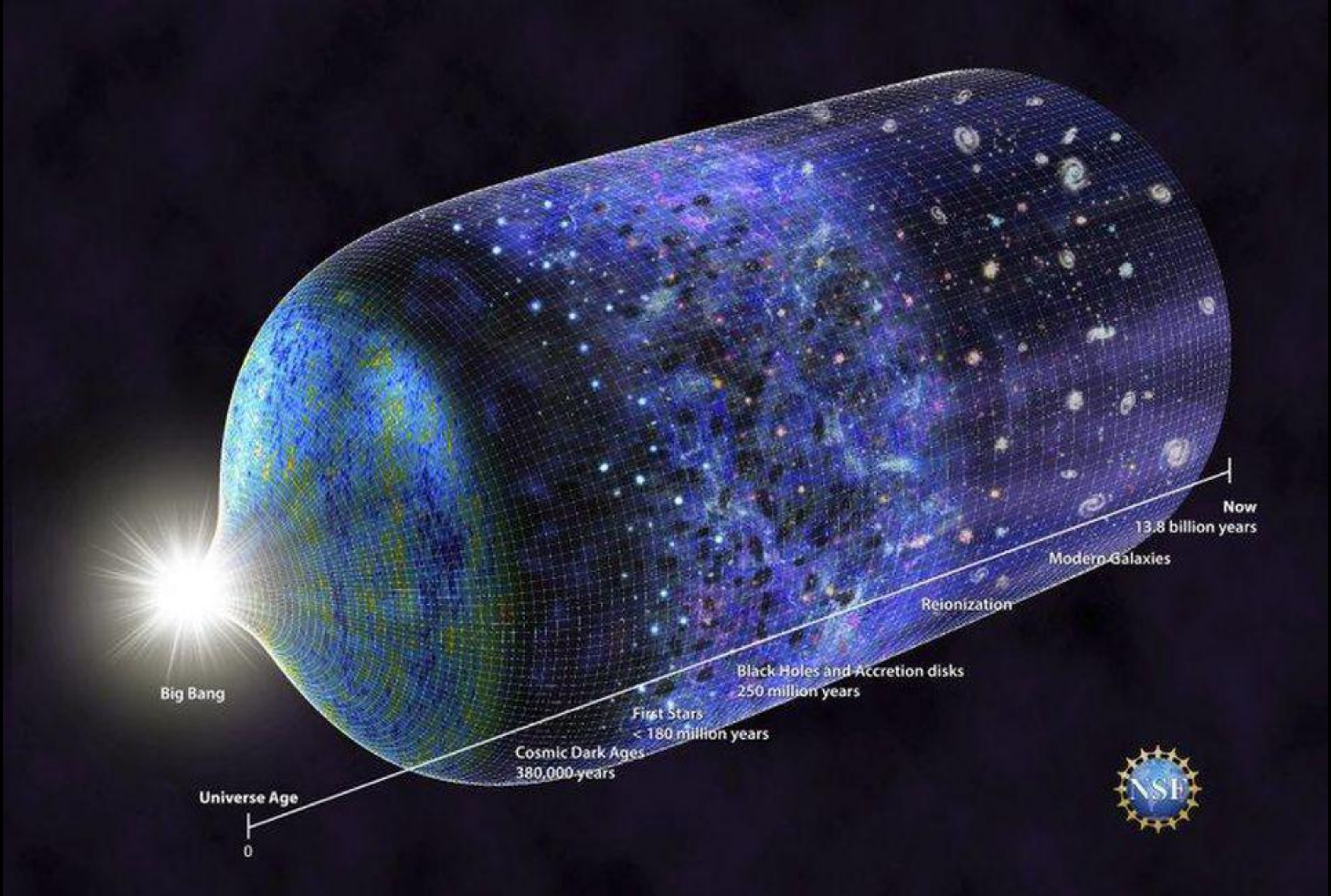
*BCCP Seminar*

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

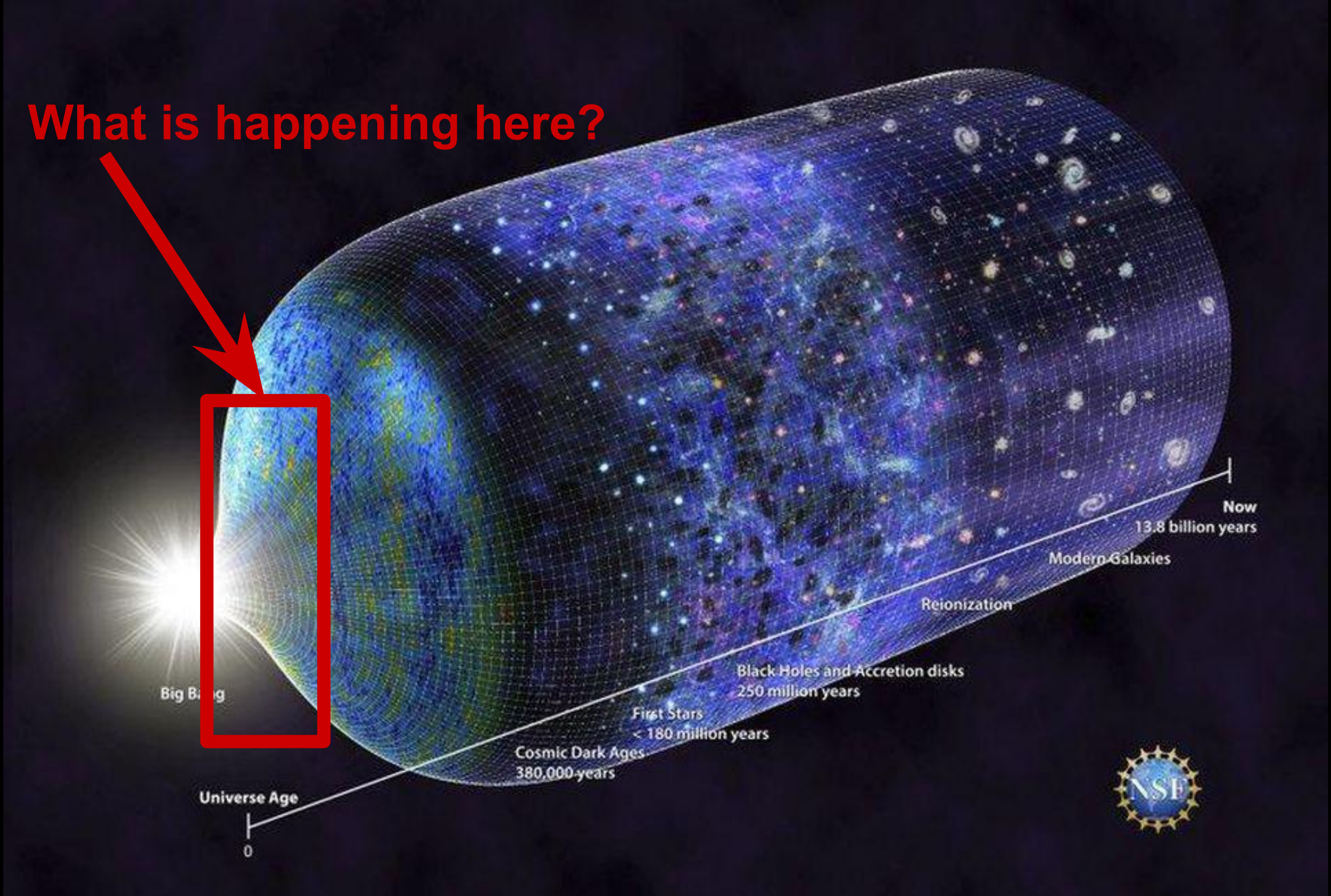
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Berkeley UNIVERSITY OF CALIFORNIA

U.S. DEPARTMENT OF ENERGY | Office of Science


Now
13.8 billion years
Modern Galaxies
Reionization
Black Holes and Accretion disks
250 million years
First Stars
< 180 million years
Cosmic Dark Ages
380,000 years
Big Bang
Universe Age
0
NSF

NSF


What is happening here?
Big Ba g
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0
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380,000 years
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Black Holes and Accretion disks
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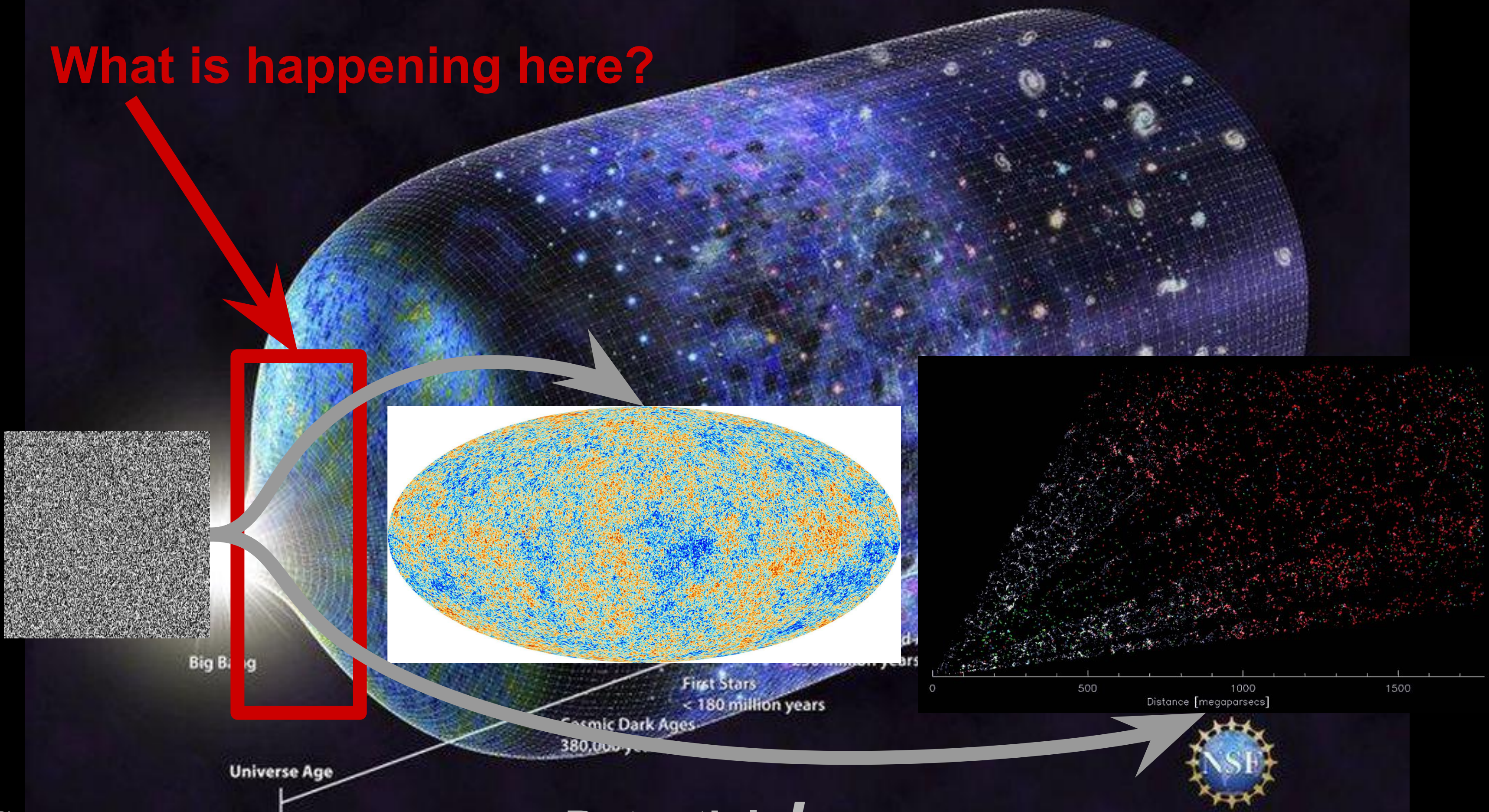
Now
13.8 billion years

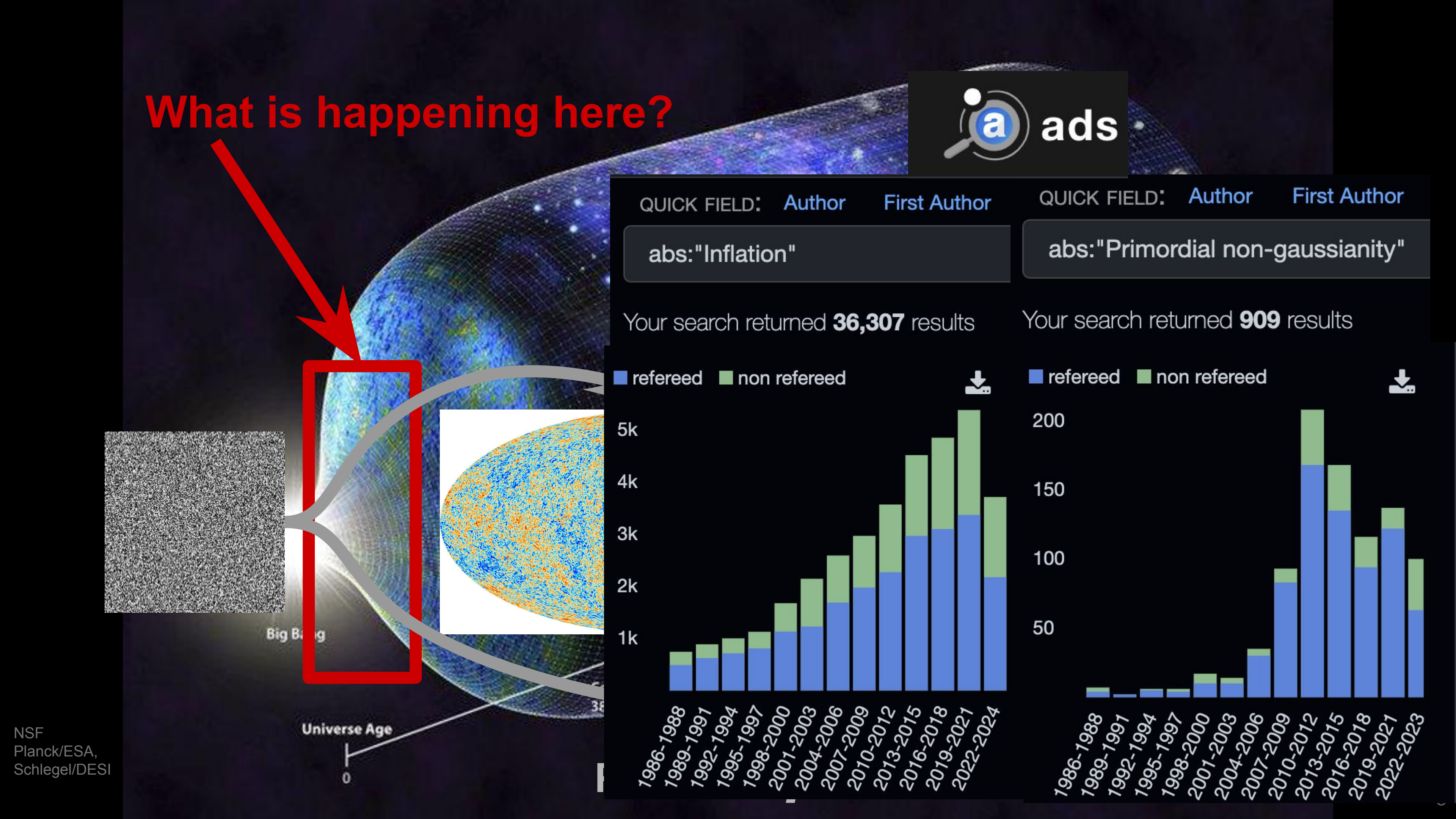
NSF

# What is happening here?




**Potential $\phi$**

NSF
Planck/ESA,
Schlegel/DESI


What is happening here?
ads
QUICK FIELD: Author First Author
abs:"Inflation"
Your search returned 36,307 results
refereed non refereed
5k
4k
3k
2k
1k
1986-1988 1989-1991 1992-1994 1995-1997 1998-2000 2001-2003 2004-2006 2007-2009 2010-2012 2013-2015 2016-2018 2019-2021 2022-2024
QUICK FIELD: Author First Author
abs:"Primordial non-gaussianity"
Your search returned 909 results
refereed non refereed
200
150
100
50
1986-1988 1989-1991 1992-1994 1995-1997 1998-2000 2001-2003 2004-2006 2007-2009 2010-2012 2013-2015 2016-2018 2019-2021 2022-2023
Universe Age
0
NSF
Planck/ESA,
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# Counting Inflationary Fields

Initial gravitational potential largely Gaussian

But primordial physics can add non-Gaussianity (PNG)

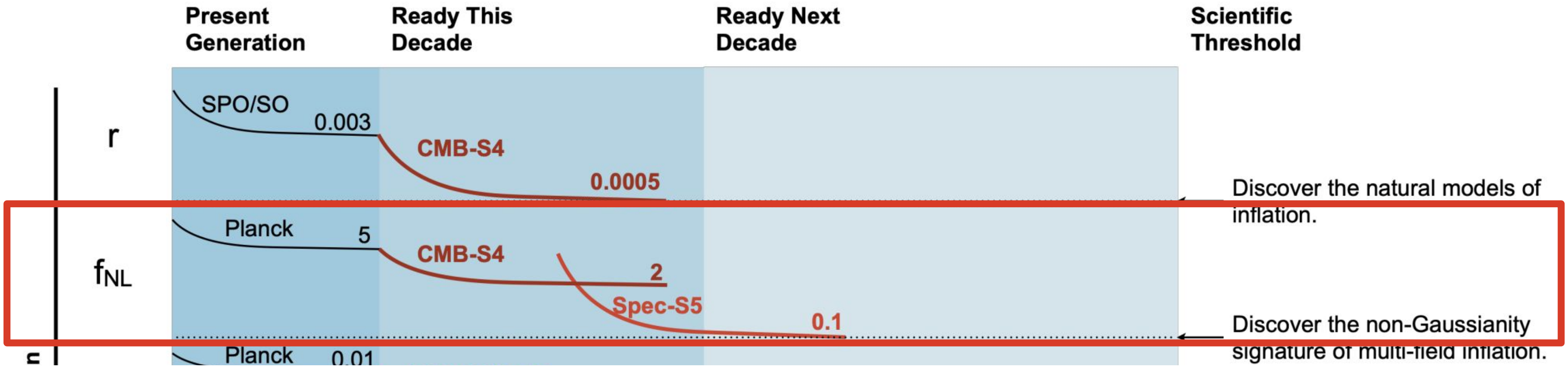
E.g. multi-field inflation produces *local* PNG:

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

**Seed for structure** **Counts (extra) fields**

Maldacena03, Acquaviva+03, Komatsu&Spergel01

# $f_{NL}$ a Prime Target of Future Galaxy Surveys



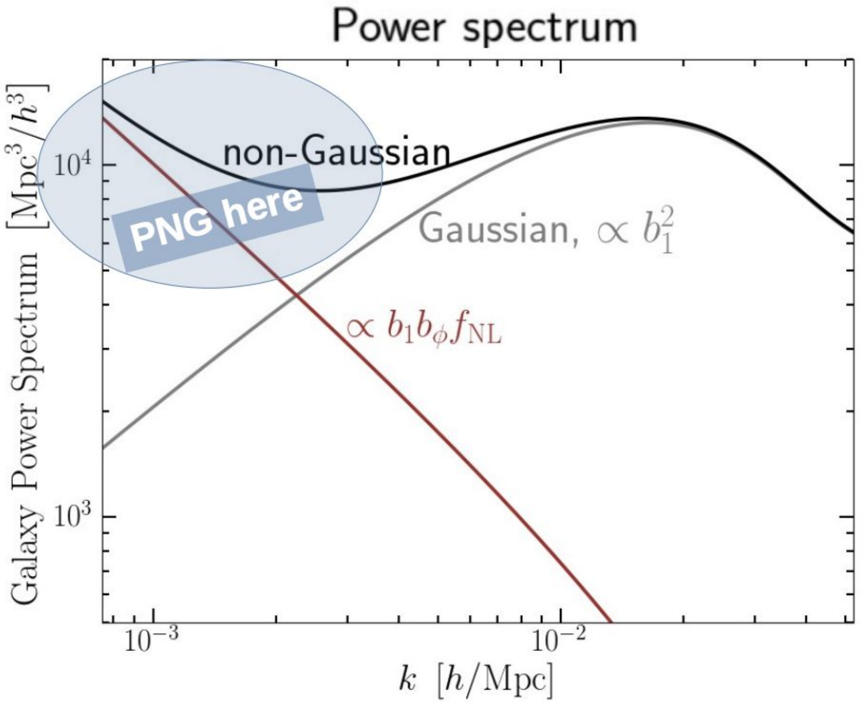

Not just Spec-S5 (MegaMapper):

- DESI, DESI-II(?), 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

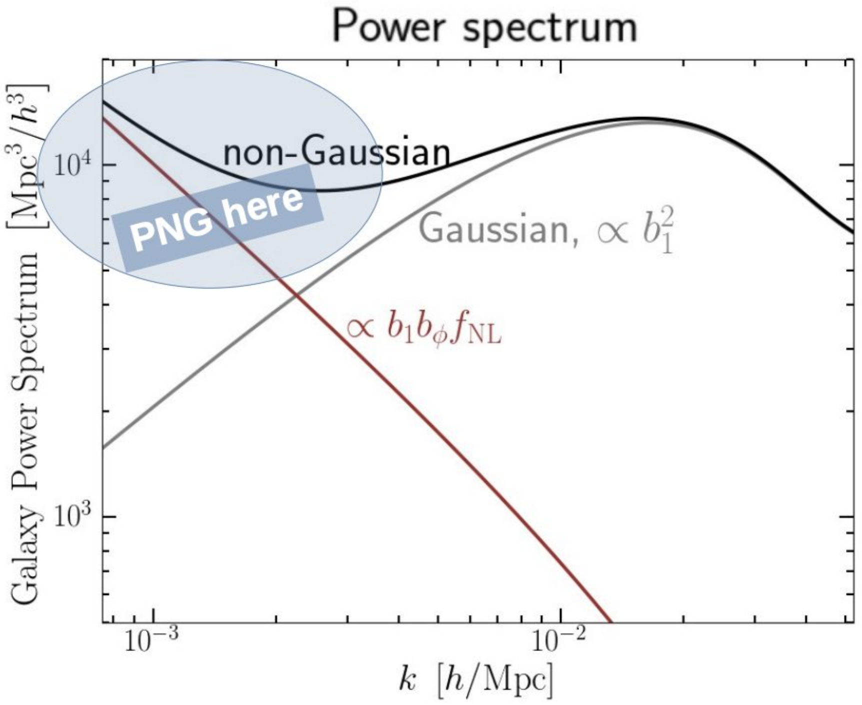
Measure power spectrum

To model it need a galaxy bias model:

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

**Galaxy overdensity**

**Matter overdensity**

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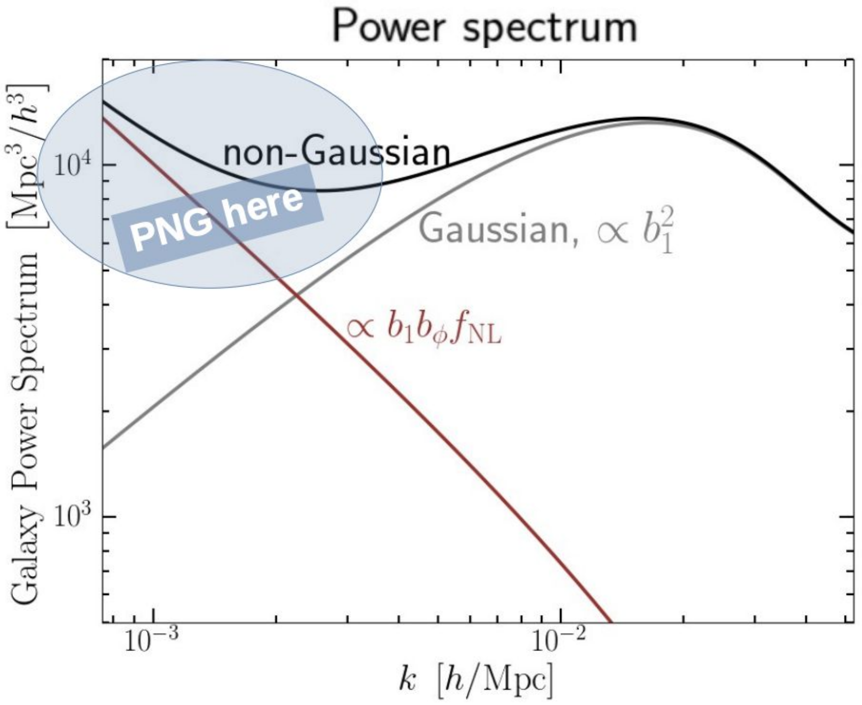
**Galaxy overdensity** **Matter overdensity**

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

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

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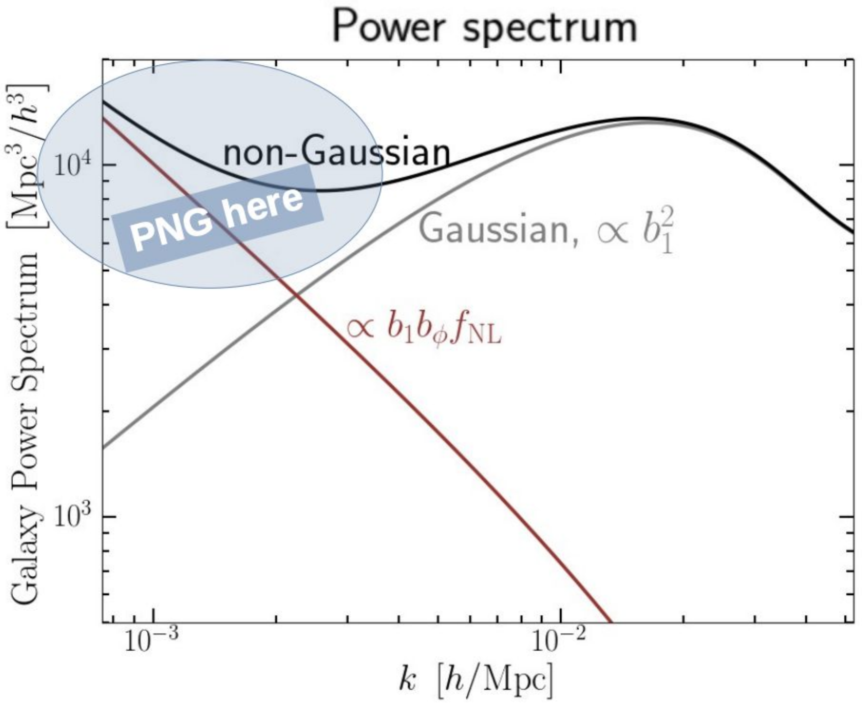


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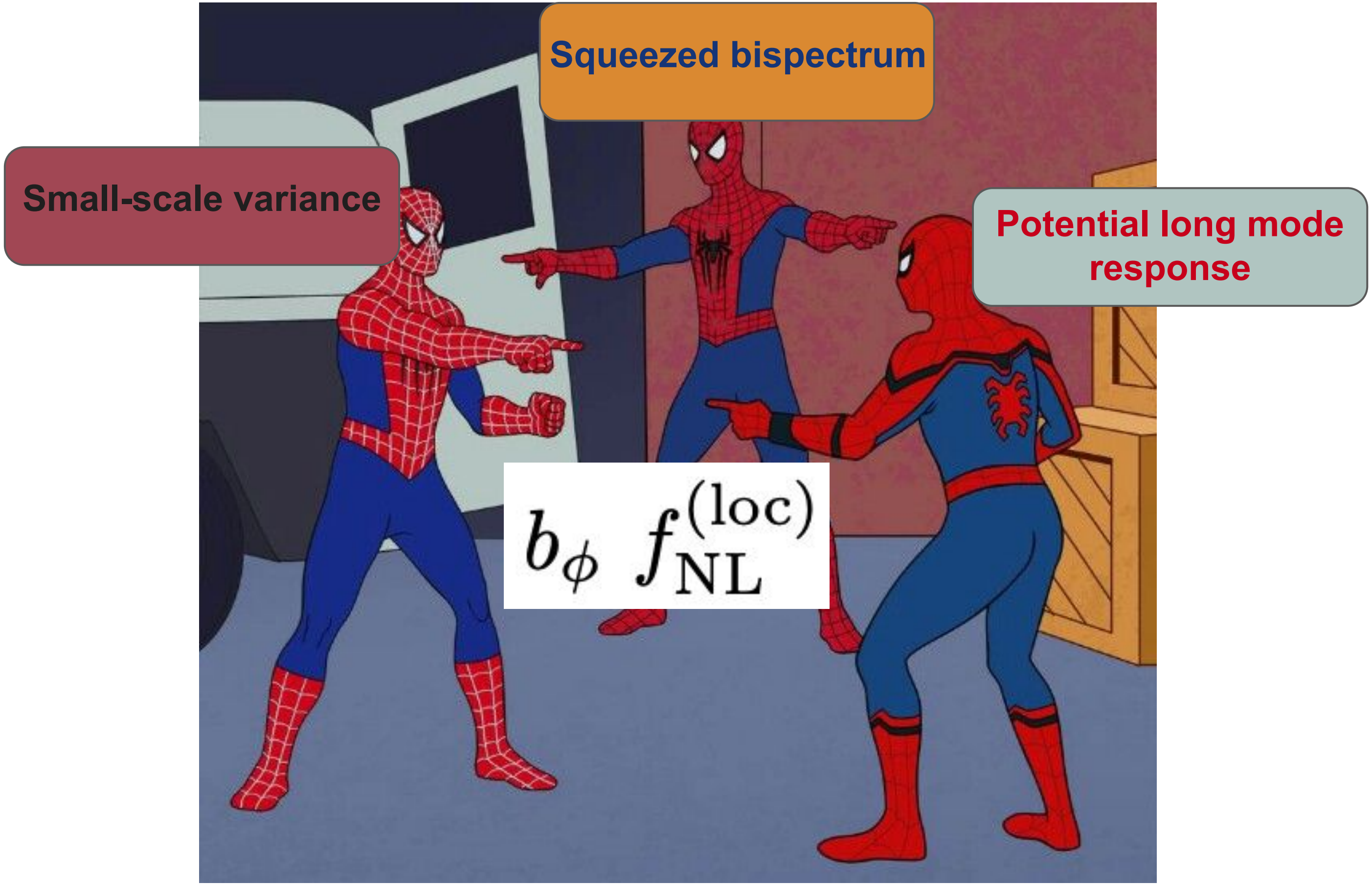
*** Degeneracy!**

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

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

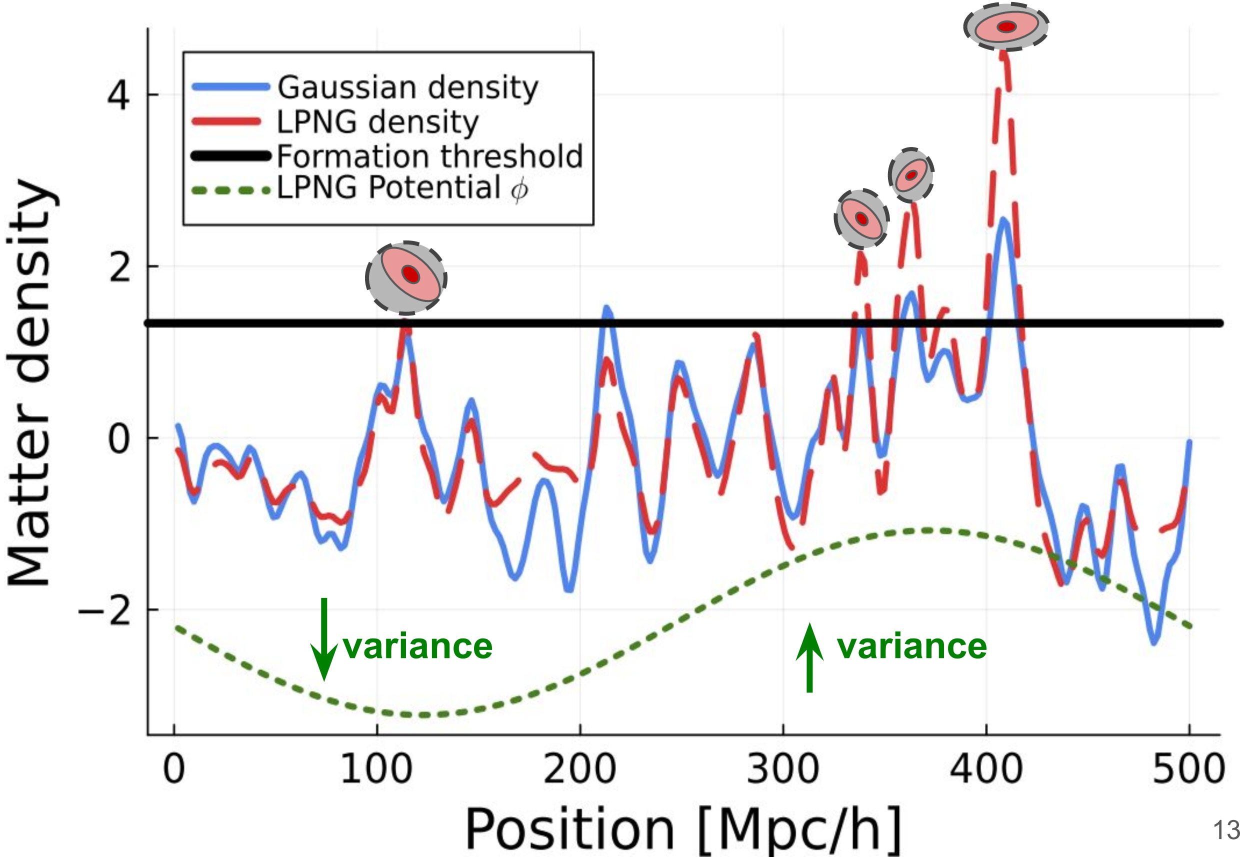
# Why extra bias? - Cartoon LPNG bias



# Why extra bias? - Cartoon LPNG bias

LPNG "boosts local variance"

Halos form after crossing threshold



# Why extra bias? - Cartoon LPNG bias

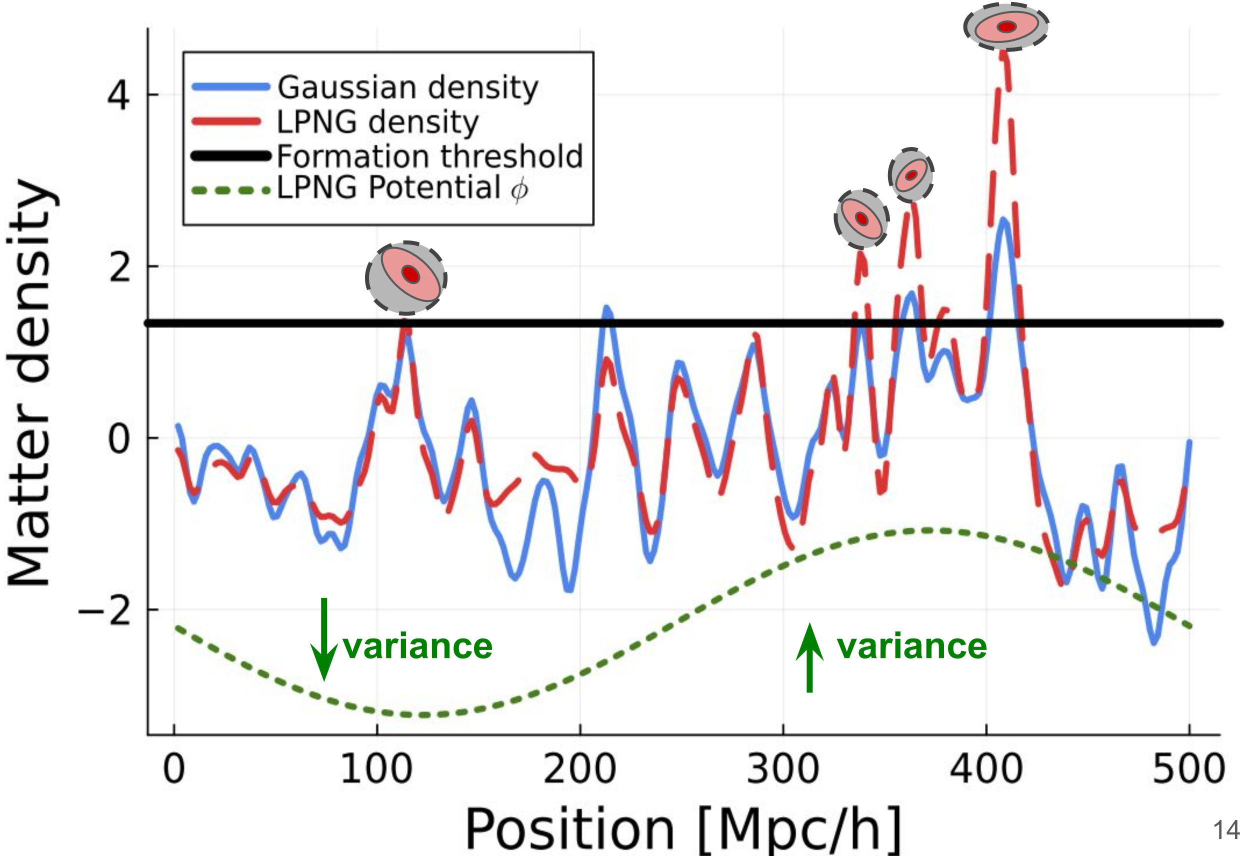
LPNG “boosts local variance”

Halos form after crossing threshold

Crossing affected by LPNG

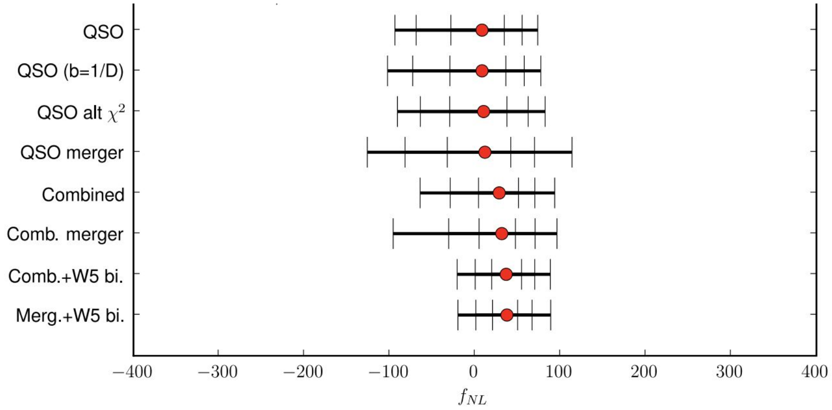
* **Assume** this form:

$$\boxed{b_\phi(b,p) \propto b - p}$$



# Galaxy survey $f_{NL}$ - SDSS quasars

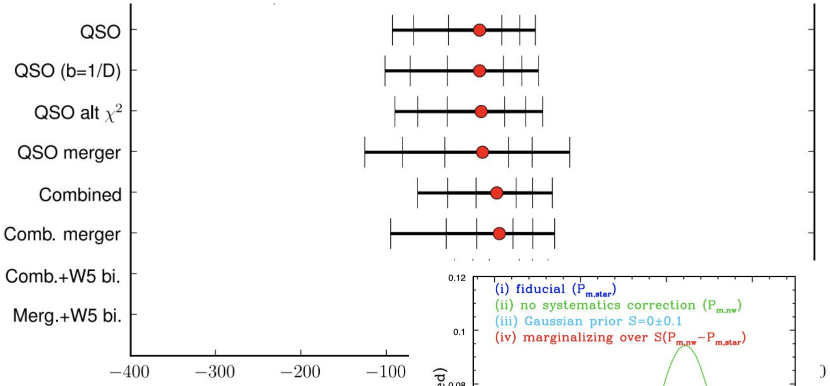
Slosar++08

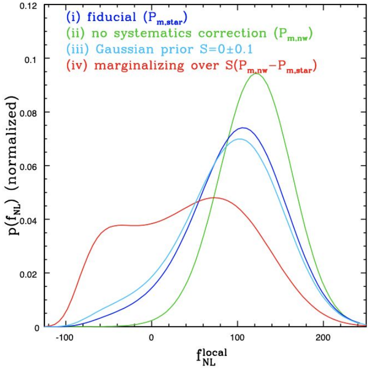


# Galaxy survey $f_{NL}$ - SDSS quasars

Slosar++08

Ross++12



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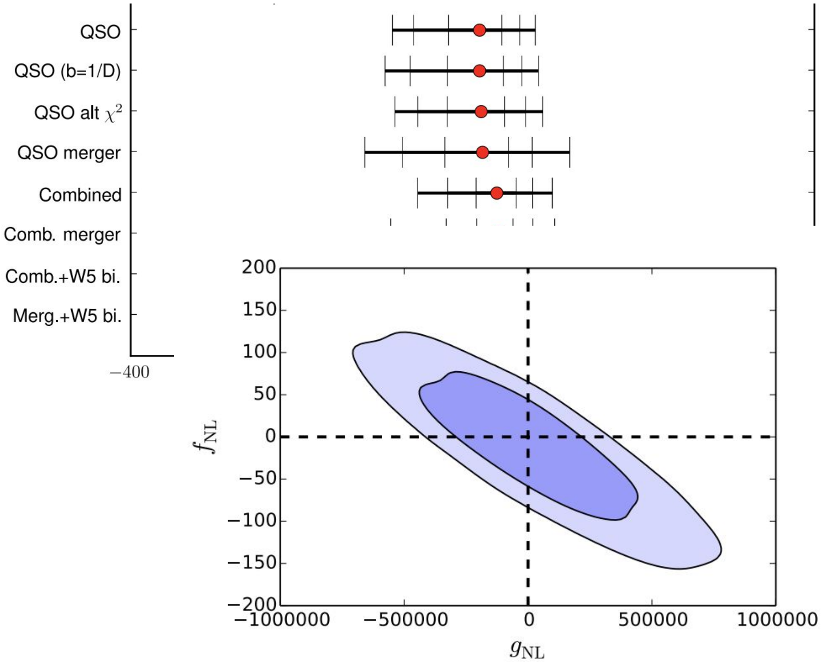
Leistedt++14



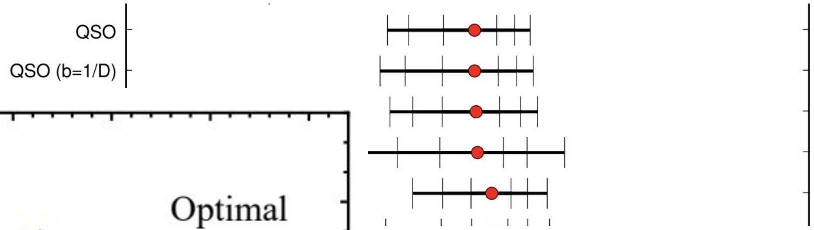
# Galaxy survey $f_{NL}$ - eBOSS quasars

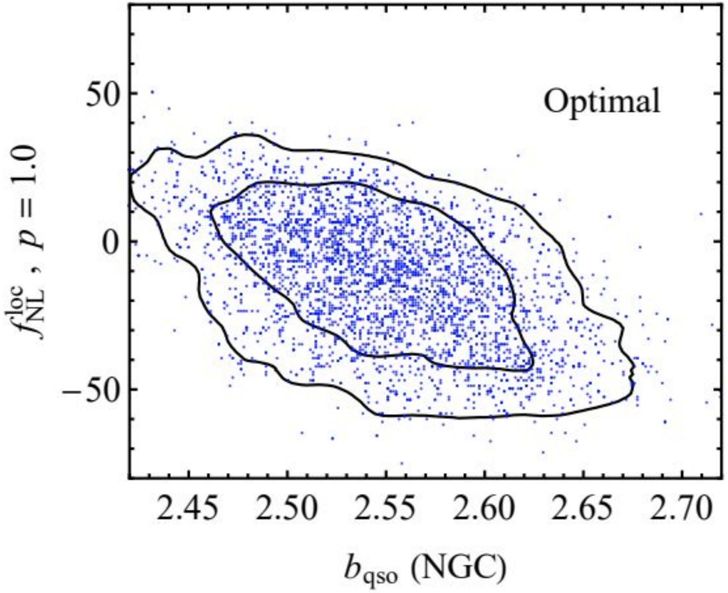
Slosar++08

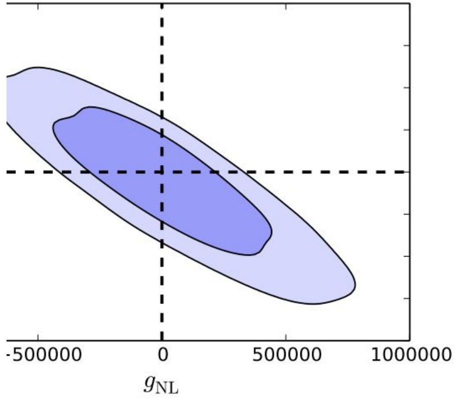
Ross++12

Leistedt++14

Castorina++19



# Galaxy survey $f_{NL}$ - eBOSS quasars

Slosar++08

Ross++12

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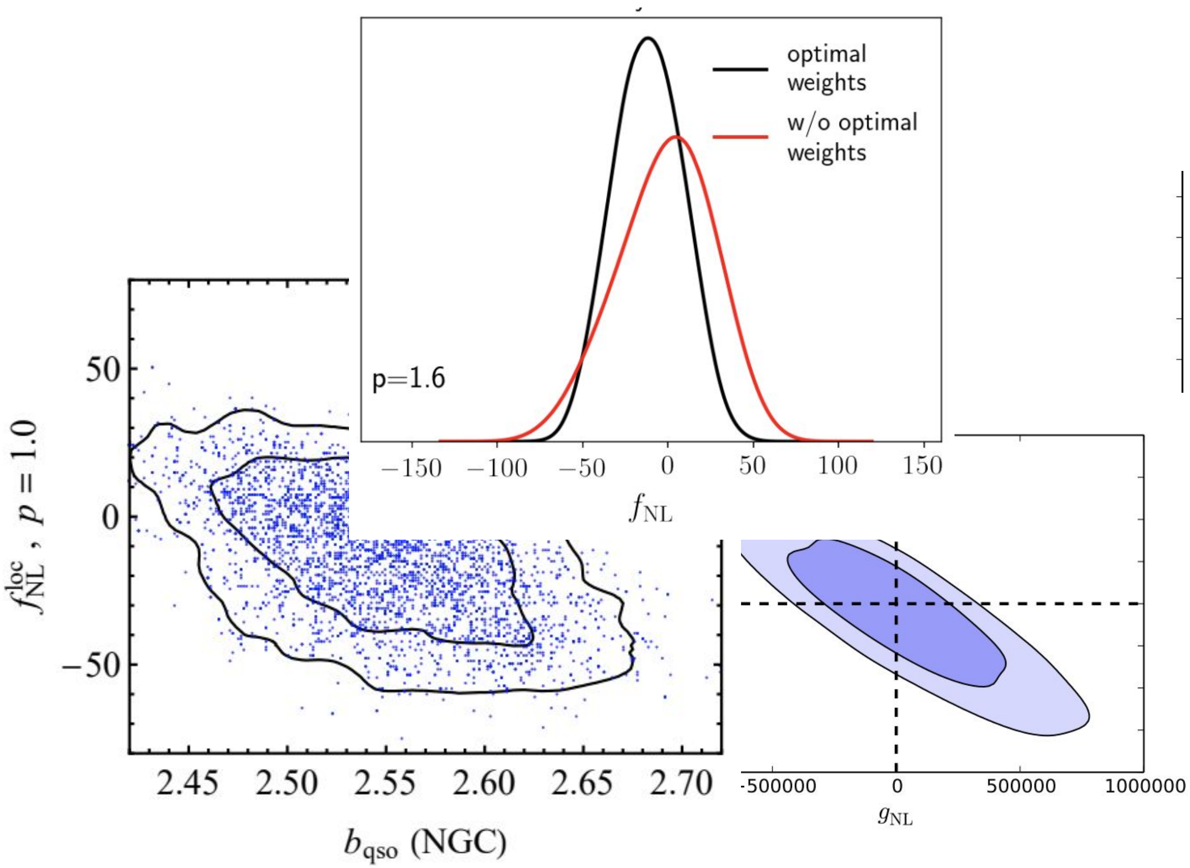
Castorina++19

Mueller++21



# Galaxy survey $f_{NL}$ - BOSS LRGs

Slosar++08

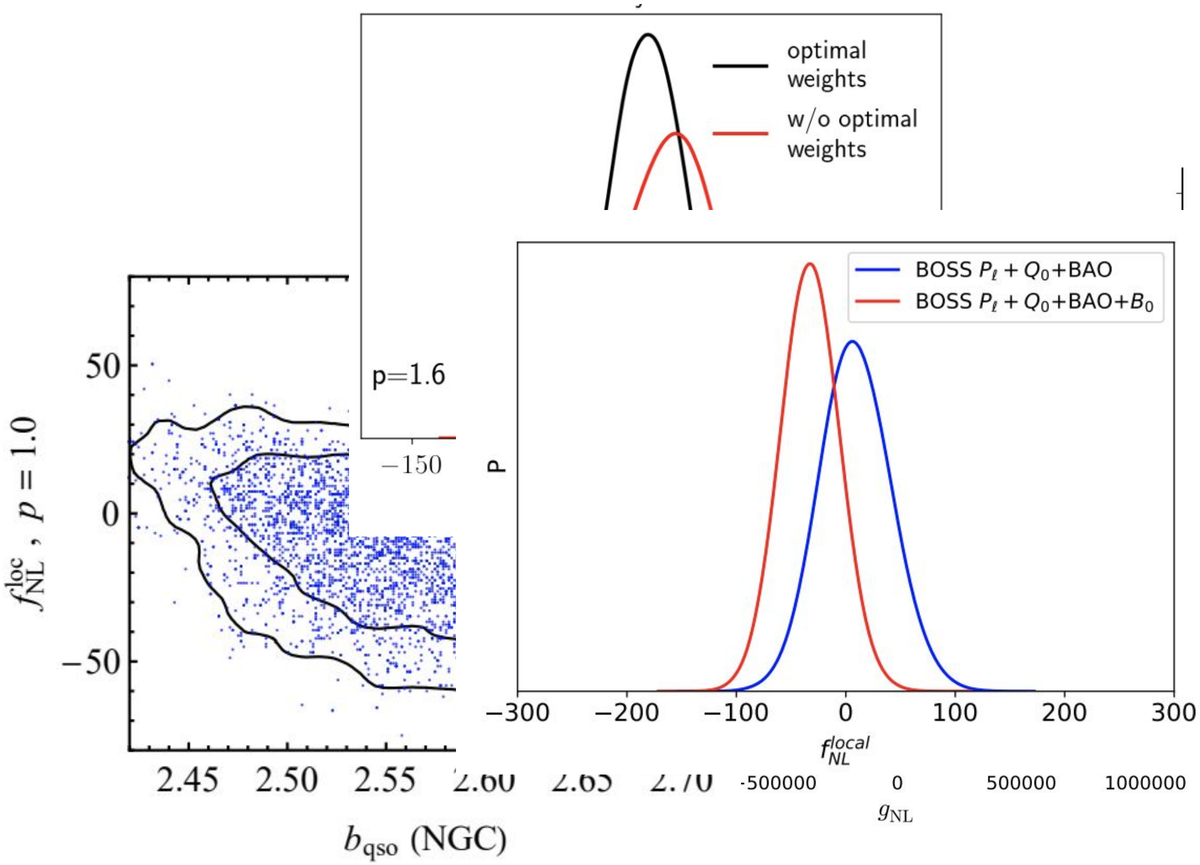
Ross++12

Leistedt++14

Castorina++19

Mueller++21

D'Amico++22



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Slosar++08

Ross++12

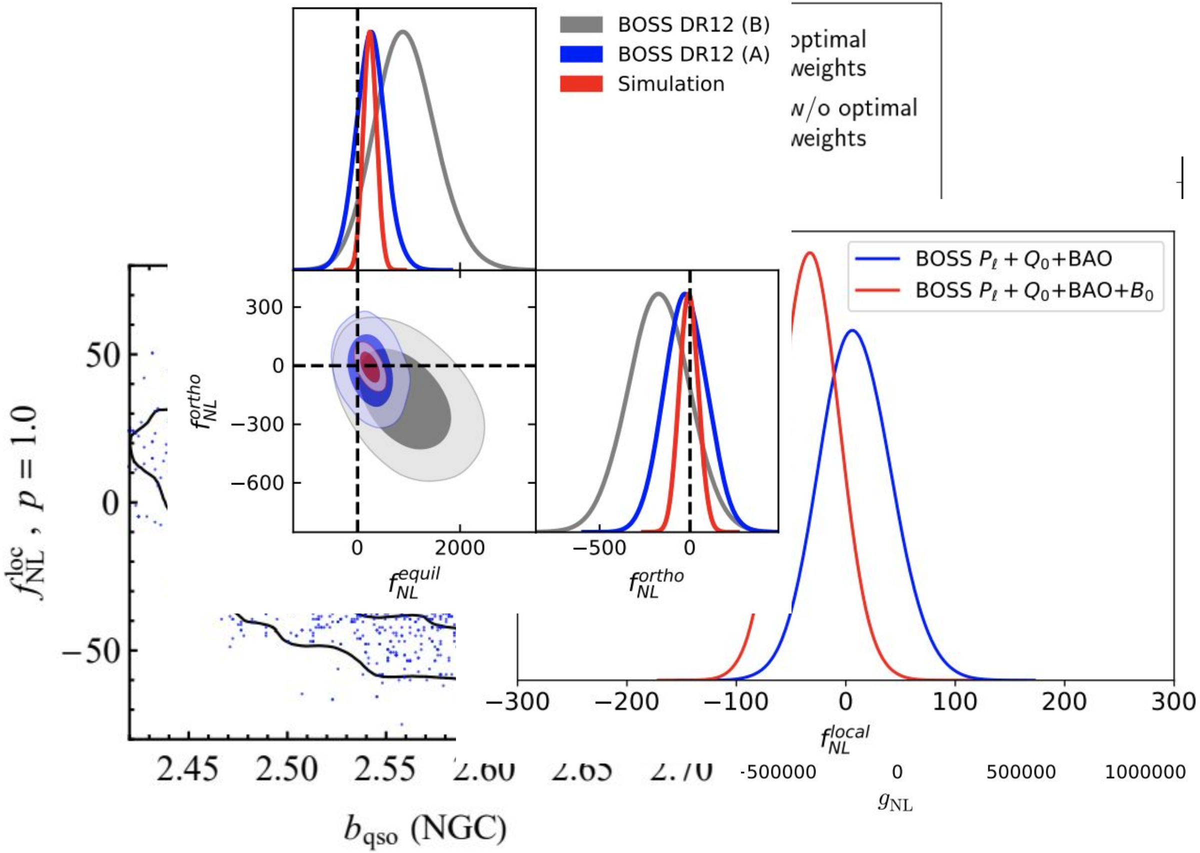
Leistedt++14

Castorina++19

Mueller++21

D'Amico++22

Cabass++22a



# Galaxy survey $f_{NL}$ - BOSS LRGs

Slosar++08

Ross++12

Leistedt++14

Castorina++19

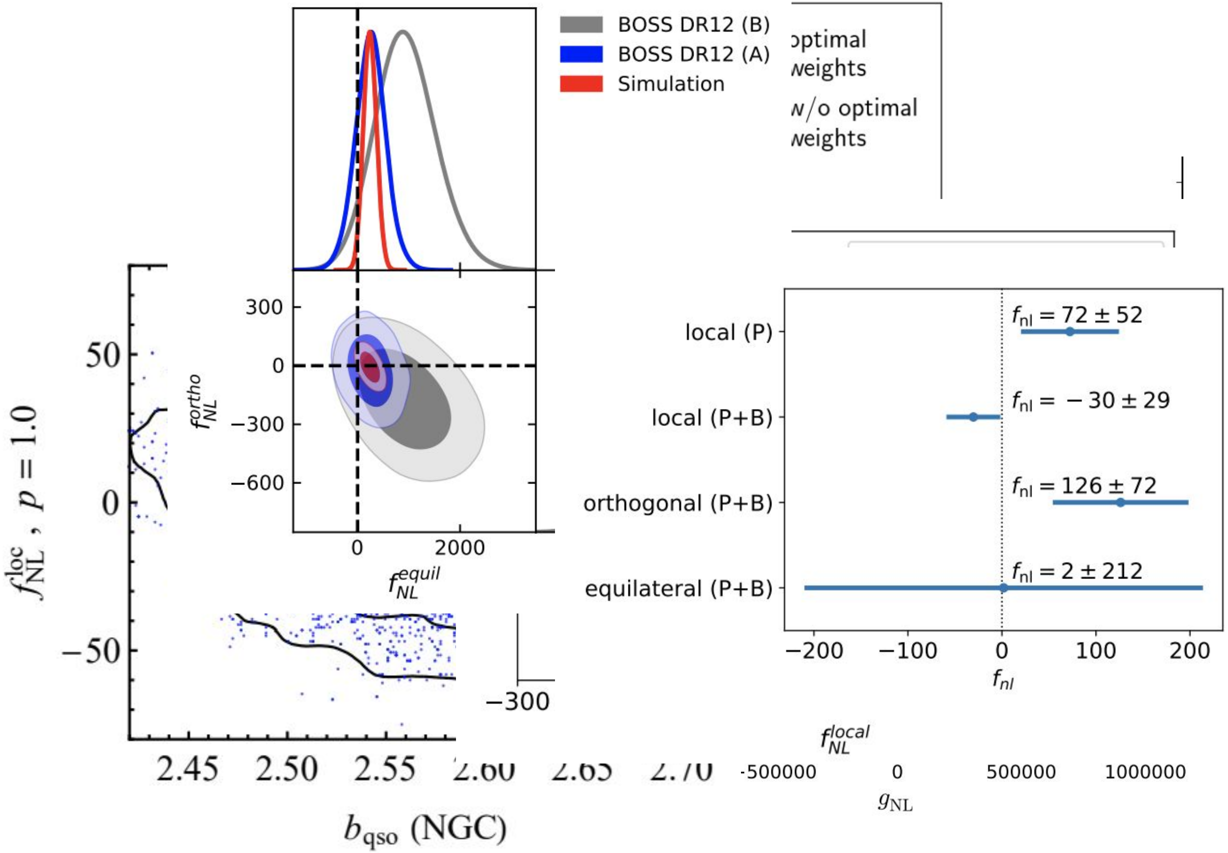
Mueller++21

D'Amico++22

Cabass++22a

Rezaie++23

All $\rightarrow \sigma(f_{NL}^{(loc)}) \gtrsim 20$



# The "*"'s return : Understanding $b_{\phi}$

How worried should we be about standard assumption?

Can we break the degeneracy between $b_{\phi}$ and $f_{NL}$?

Attacking $b_{\phi}$ from **3 angles:**

1. Test $b_{\phi}$ in simulations at field level -> surprises?
2. Can we *use* deviations from standard assumption?
3. A new way to estimate $b_{\phi}$ without $f_{NL}$?

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# How to measure $b_\phi$?

Annoying to do in power spectrum (2-loop, changing b1)

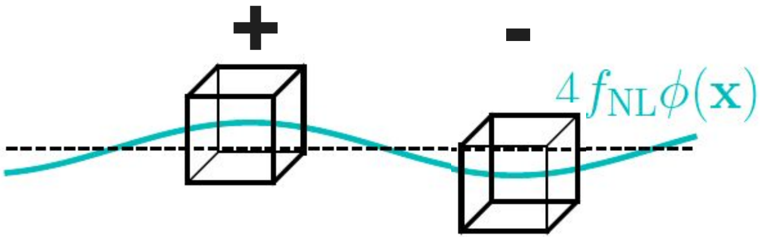
-> Separate Universe (related to Peak-background split)

Finite-difference 2 sims

Uses infinite-wavelength limit

Now standard

Separate Universe $\mathcal{A}_\mathrm{s}$




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

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

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

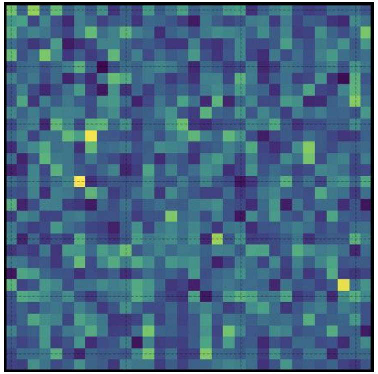
# 1. Field-level Bias Model

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

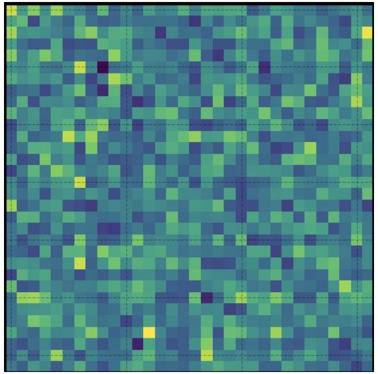
No sample variance - <u>no compression</u>

Field-level likelihood - vector of pixels - simple regression

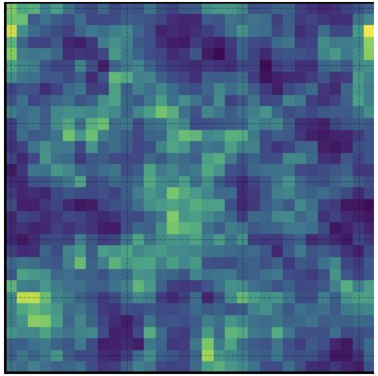
**Halos** **Matter** **Potential**



$= b_1$



$+ b_\phi f_{NL}$



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Field-level likelihood - vector of pixels - simple regression

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

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

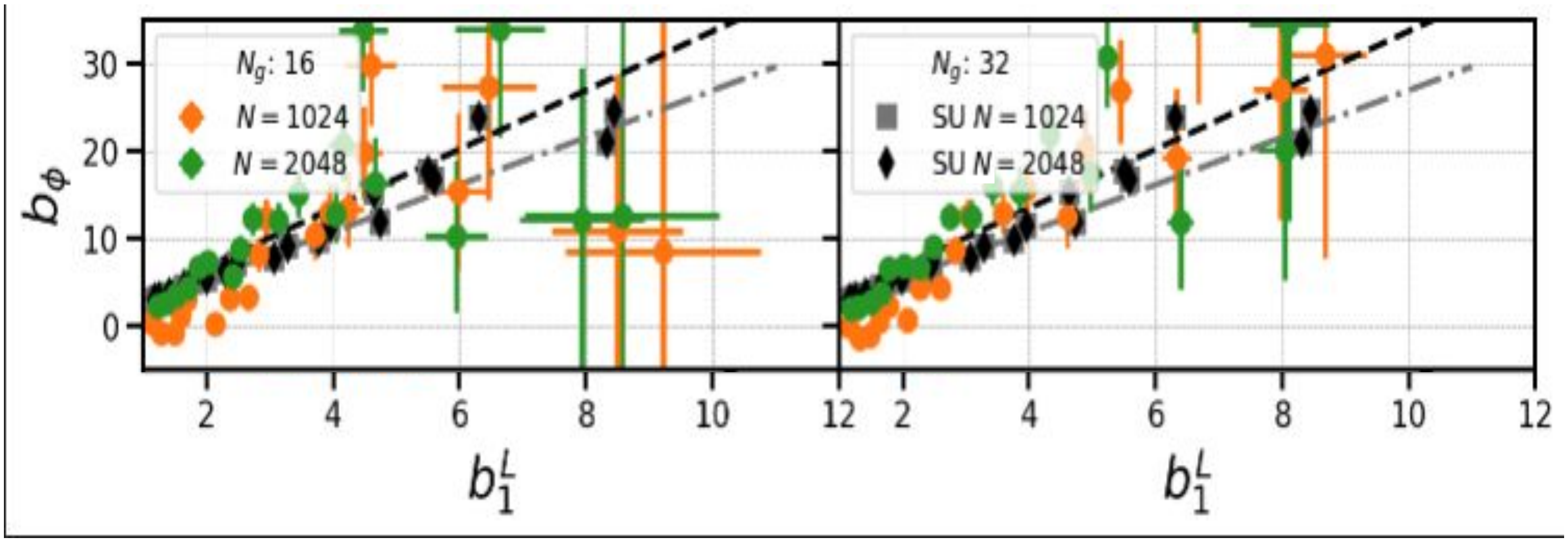
$$\mathcal{P}[\delta_t|\delta] = \prod_{\mathbf{x}} \left(2\pi\sigma_0^2\right)^{-\frac{1}{2}} \exp\left(-\frac{|\delta_t(\mathbf{x}) - \delta_{t,\mathrm{fwd}}(\mathbf{x},\delta)|^2}{2\sigma_0^2}\right)$$

# 1. Field-level Bias Model

Generally agree with UMF and SU on large scales

Somewhat resolution dependent…

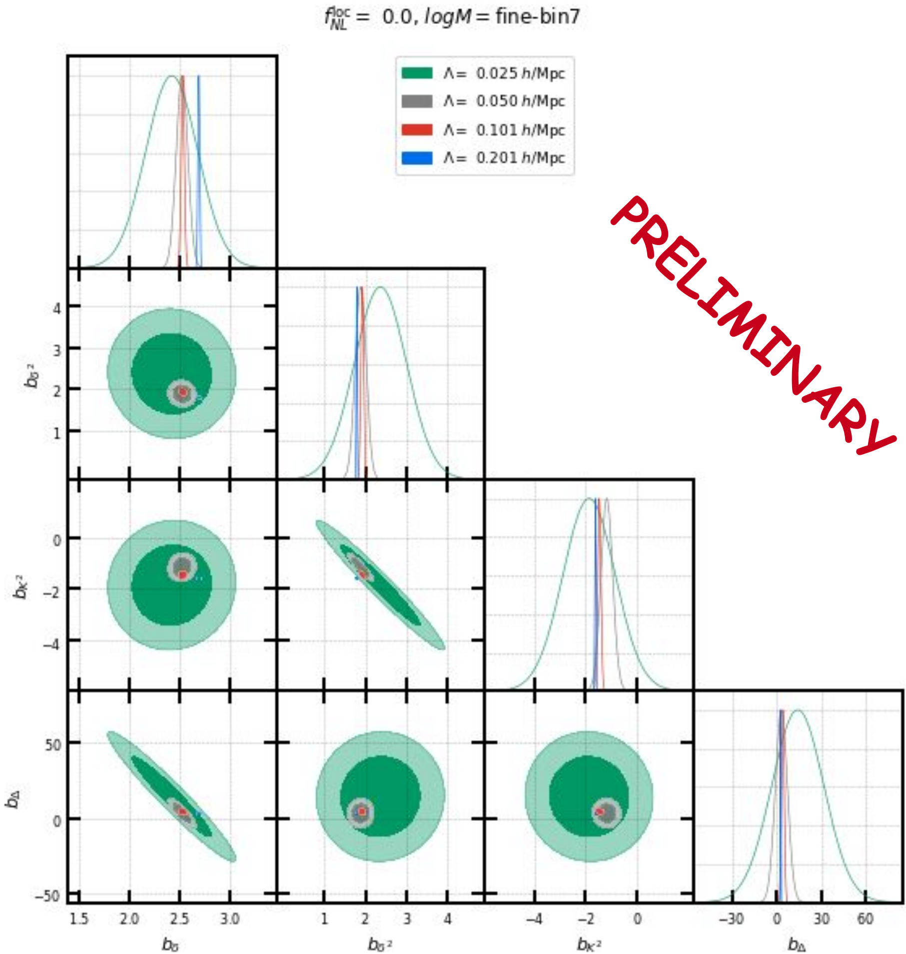
PRELIMINARY



# 1. Field-level Bias Model

How are we doing with the cutoff Λ?

Looks good for Gaussian up to red scale



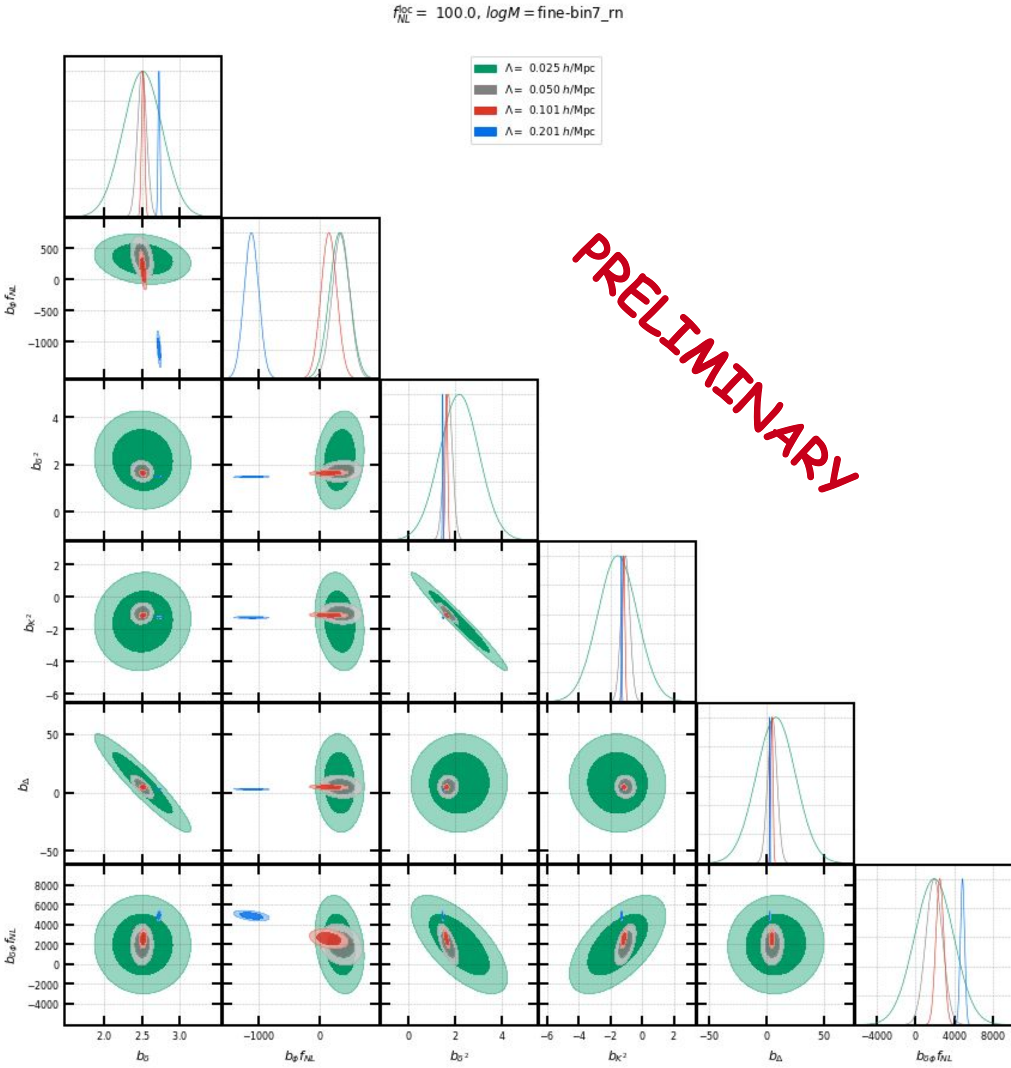
# 1. Field-lev

How are we doing with the cutoff Λ?

Looks good for Gaussian up to red scale

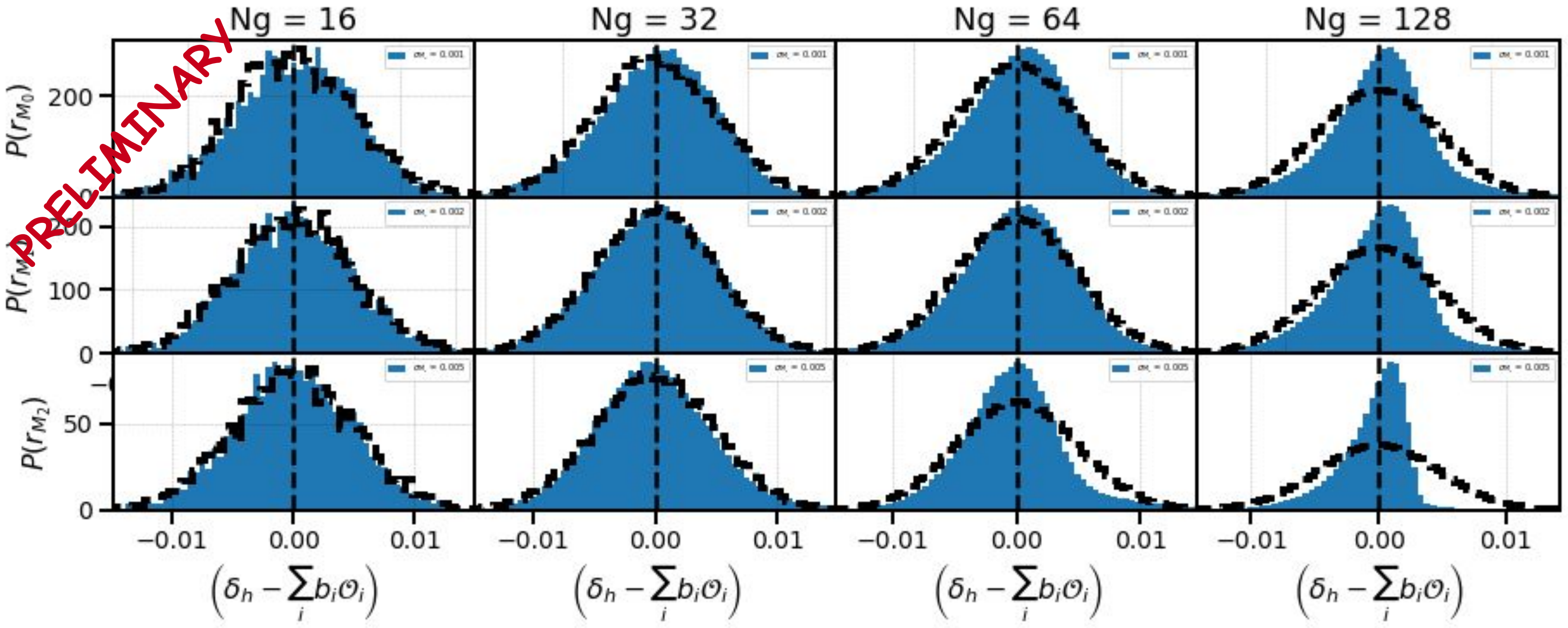
Adding PNG, much the same*

(*w/ renormalized operators)



# 1. Field-level Bias Model

Does this breakdown make sense? -> yes, bias model fails!



# 1. Field-level Bias Model

What's next?

- Quantify $f_{NL}$ information
- Cubic operators?
- Other types of PNG? (no SU)

No (real) surprises yet, reassuring!

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# 2. LPNG & Assembly Bias

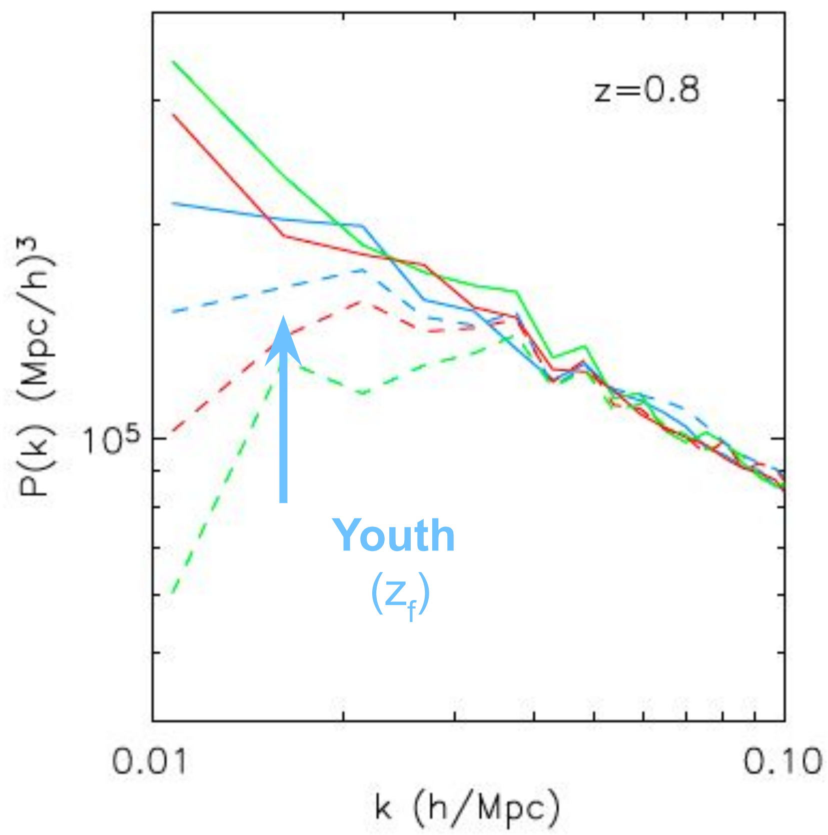
Halo assembly bias:

Slosar 08 -> “merger”

Reid 10 -> formation time

…

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



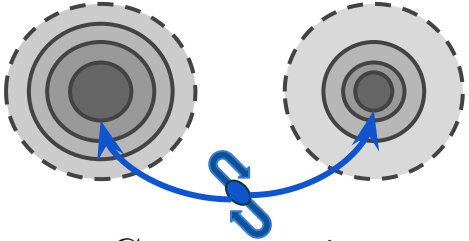
# 2. LPNG & Assembly Bias

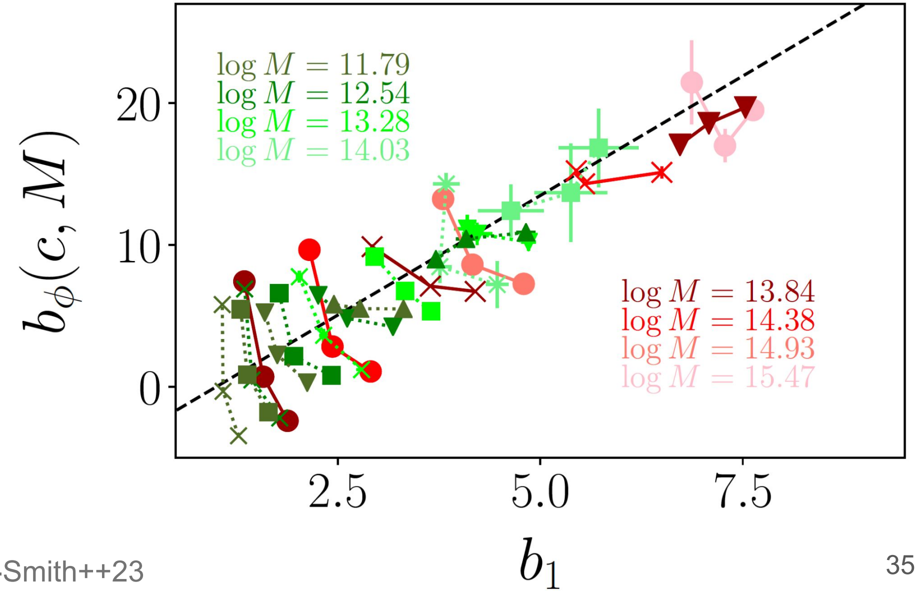
Halo concentration *c* has a large effect

Especially at low mass, enormous variation

Seems like a problem…

**Or is it?**




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

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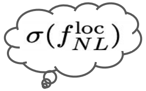


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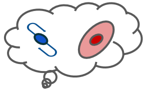
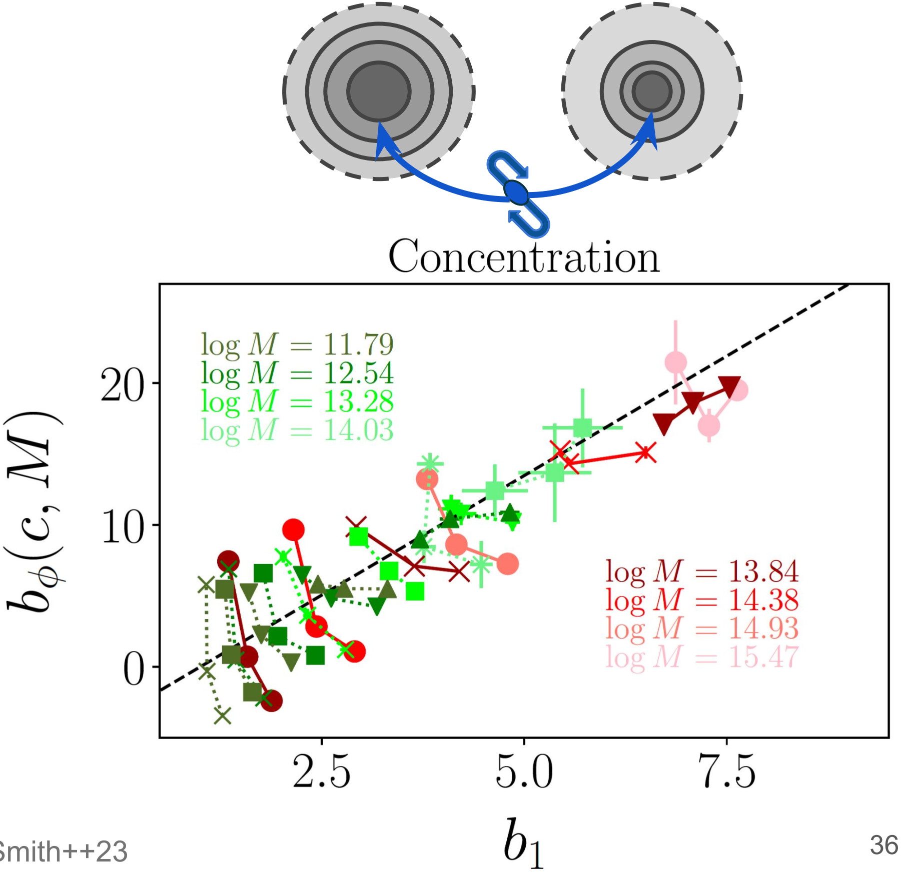


**Idea -> Multi-tracer**

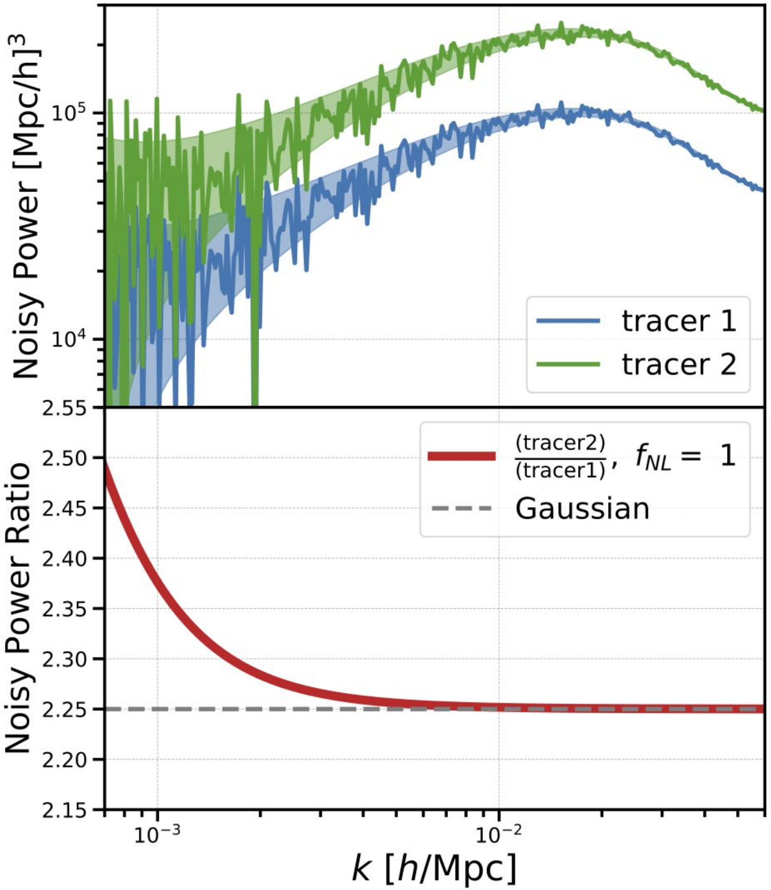



Slosar+08, Reid+10, Barreira+20, Lazeyras+22, Barreira&Krause23, Lucie-Smith++23

# Multi-tracer method

Two tracers share sample variance

Ratio effectively cancels it




Seljak09, McDonald+Seljak09, Schmittfull+Seljak18

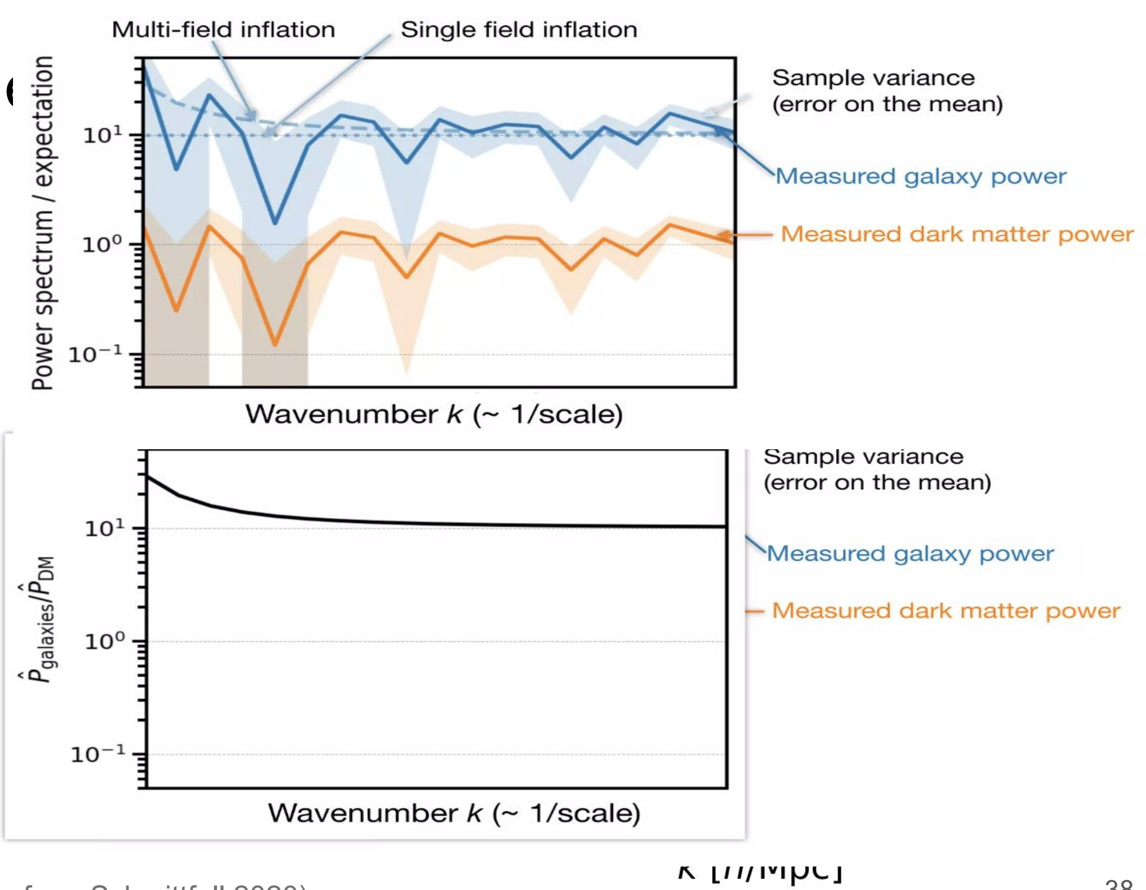
# Multi-tracer method

Two tracers share sampl

Ratio effectively cancels

Also CMB lensing

*(Perhaps the way forward for $f_{NL}$?)*




Seljak09, McDonald+Seljak09, Schmittfull+Seljak18 (image from Schmittfull 2020)

# Sub-sample Multi-tracer

**Idea**: Identify multi-tracer samples with sub-samples split by concentration (use ML)

*Big assumption about GHC! (Ignore the 🐘)

Error on $f_{NL}$ scales like:

$$\sigma(f_{\rm NL}^{(\rm loc)}) \propto \left(\frac{b_{\phi,1}}{b_1} - \frac{b_{\phi,2}}{b_2}\right)^{-1}$$

# Fisher forecast setup

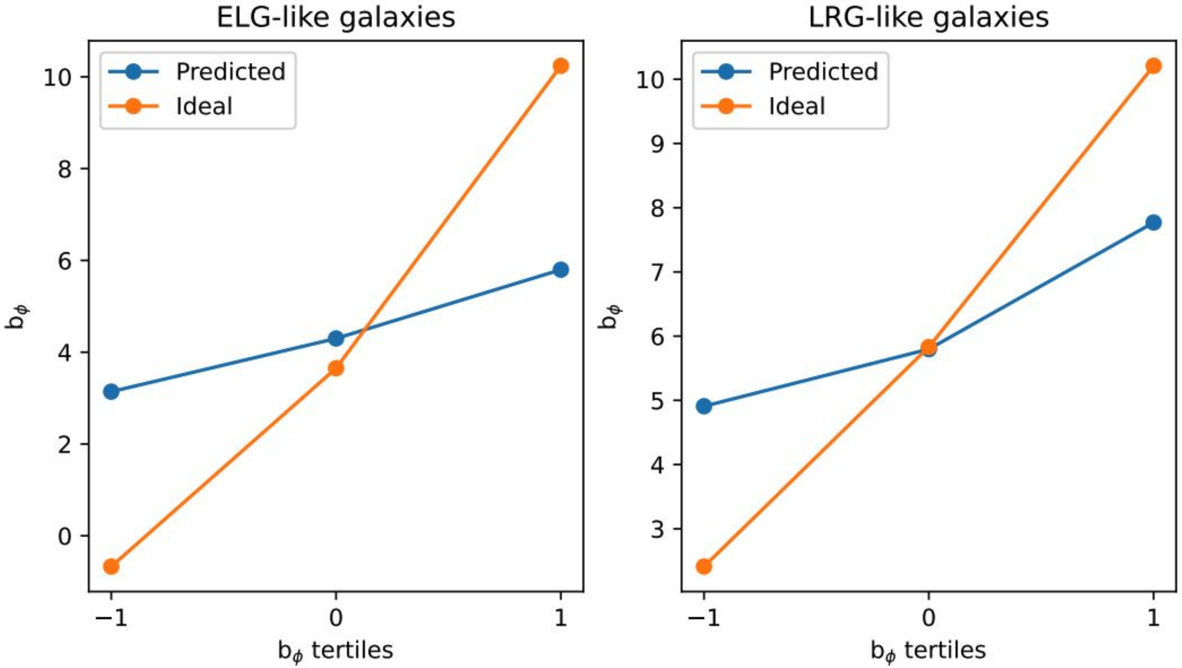
Fisher forecast - multiple simulated DESI-like galaxy samples

Emission Line Galaxies (ELGs) & Luminous Red Galaxies (LRGs)

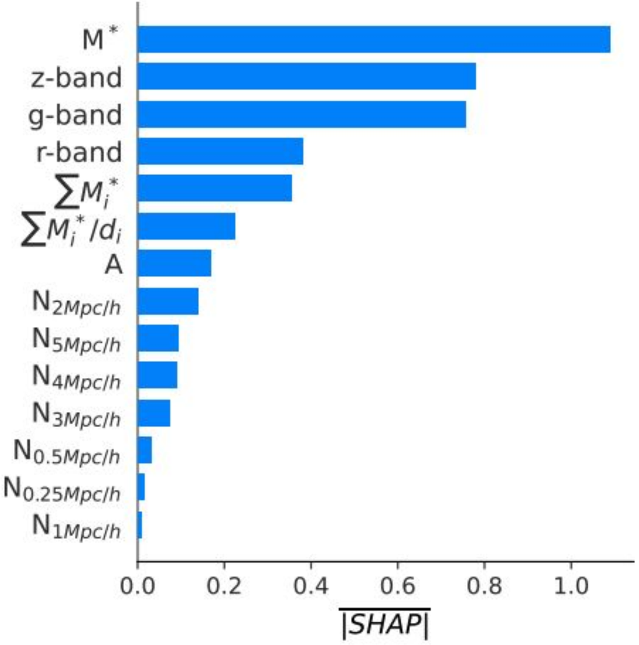
Require split $\boldsymbol{b_\phi}$ as input

IllustrisTNG

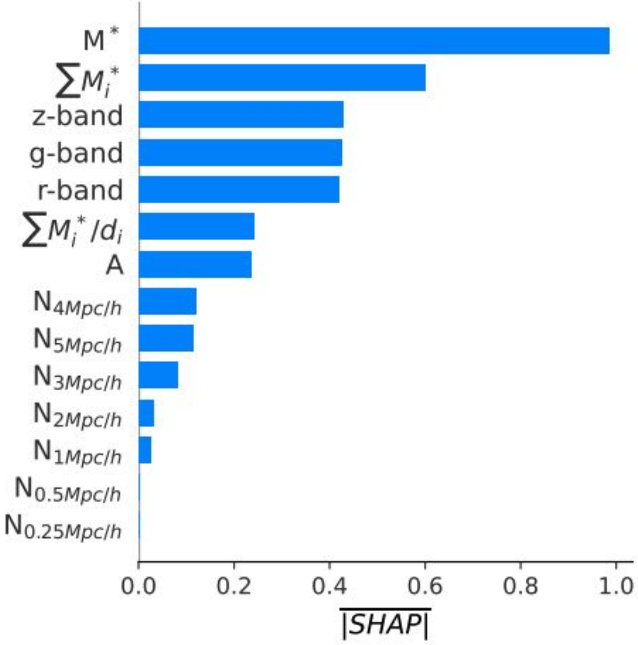
Work in redshift space



# Feature Importance

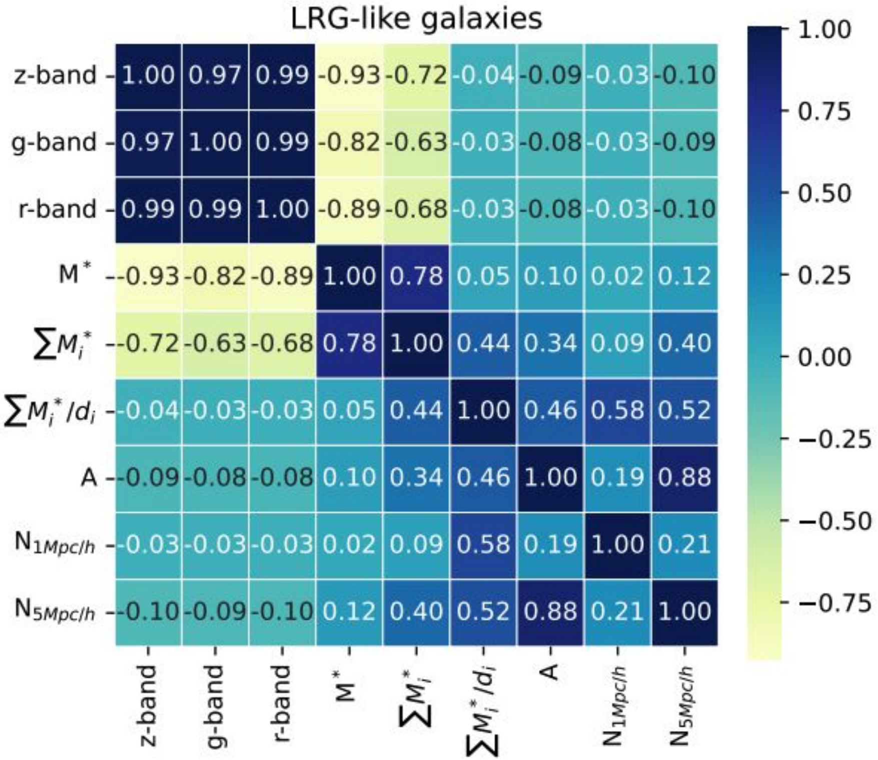


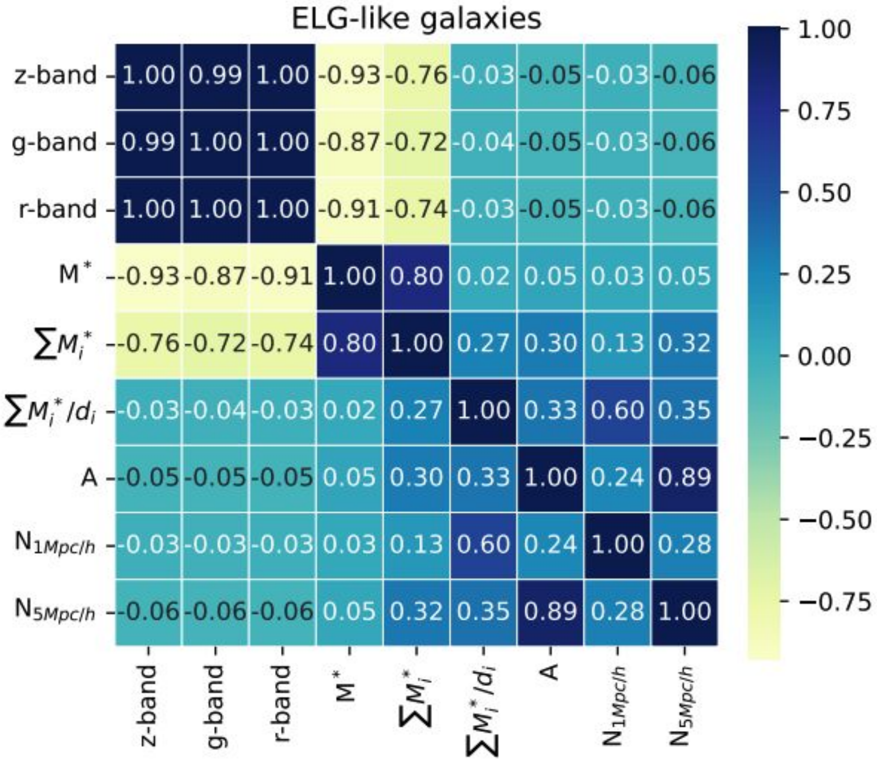

(a) ELG-like galaxies




(b) LRG-like galaxies

# Pearson Correlation



# Mock DESI Galaxies - Toward $\sigma(f_{NL})$~1 today!

Use multiple galaxy subsamples

Subsamples have different $b_\phi$

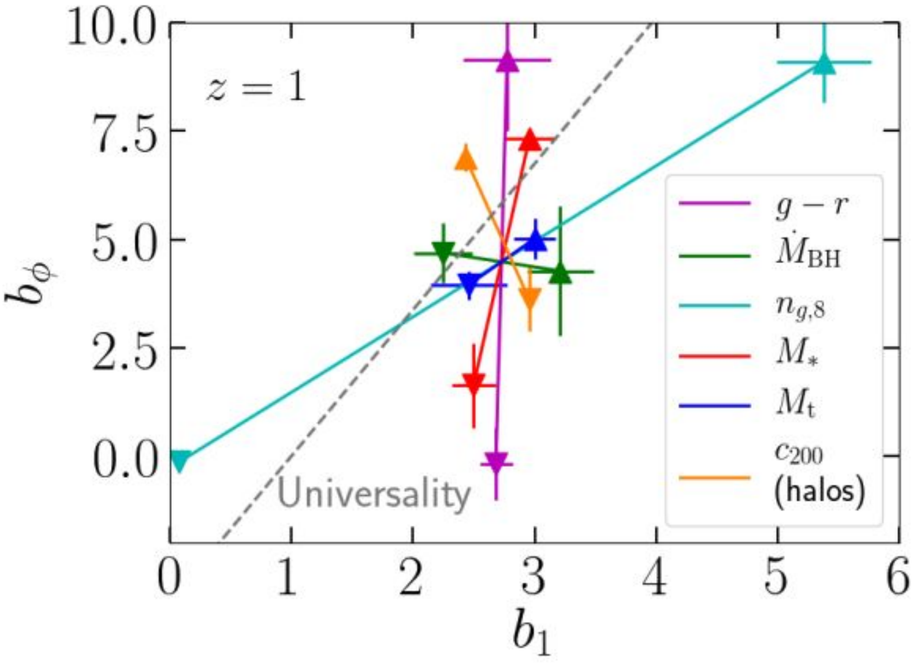
Large improvement over "naive" multitracer!

| ELG + LRG | $\sigma(f_{NL}^{\mathrm{loc}})$ |
|---|---|
| $p = 1$ | $\boxed{4.0}$ |
| (2) ($\overline{\mathrm{LRG}}$, $\overline{\mathrm{ELG}}$), ideal | 2.3 |
| (2) ($\overline{\mathrm{LRG}}$, $\overline{\mathrm{ELG}}$), pred | 2.3 |
| (2) (LRG+, ELG+), ideal | 1.4 |
| (2) (LRG+, ELG+), pred | 2.4 |
| (3) (LRG-, LRG+, ELG-), ideal | 0.8 |
| (3) (LRG-, LRG+, ELG-), pred | 2.0 |
| (3) (LRG-, ELG+, ELG-), ideal | 0.8 |
| (3) (LRG-, ELG+, ELG-), pred | 2.0 |
| (3) (LRG-, ELG+, else), ideal | 0.6 |
| (3) (LRG-, ELG+, else), pred | 1.5 |

# 2. LPNG & Assembly Bias

What next?

- Split by color (BK23) we're looking at it!
- *Why* the strong correlation w/ age/concentration?
- LRG / ELG mystery? (Marinucci+23)



# The “$*$”’s return : Understanding $b_\phi$

How worried should we be about standard assumption?

Can we break the degeneracy between $b_\phi$ and $f_{NL}$?

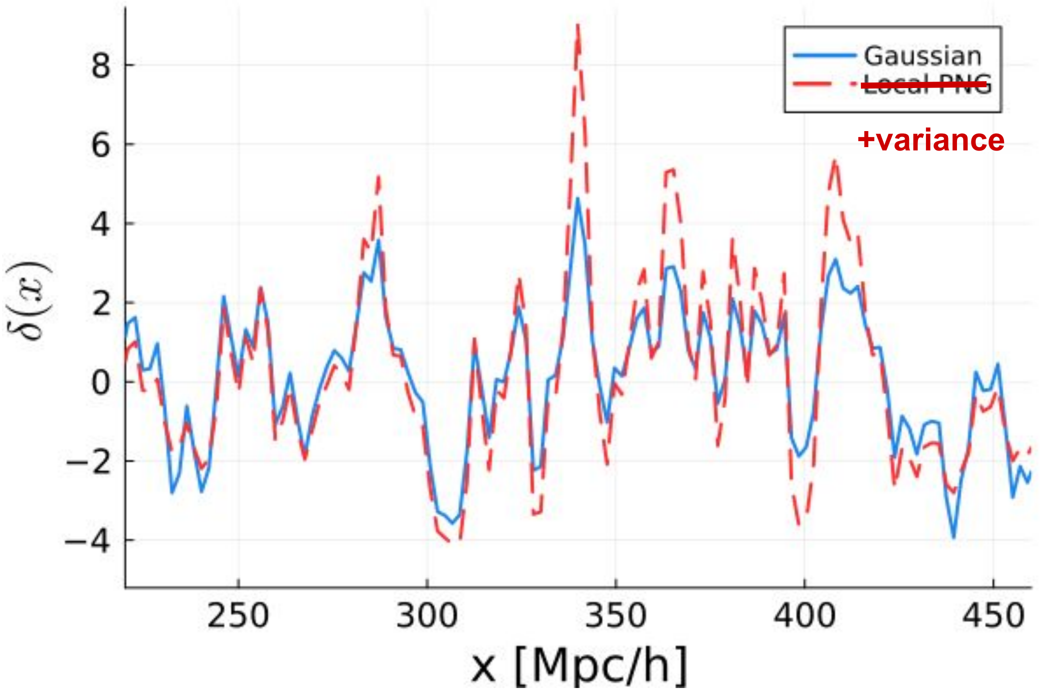
Attacking $b_\phi$ from **3 angles:**

1. Test $b_\phi$ in simulations at field level -> surprises?
2. Can we *use* deviations from standard assumption?
3. A new way to estimate $b_\phi$ without $f_{NL}$?

# 3. Growth is Variance - Idea

LPNG is "like" boosting underlying variance

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

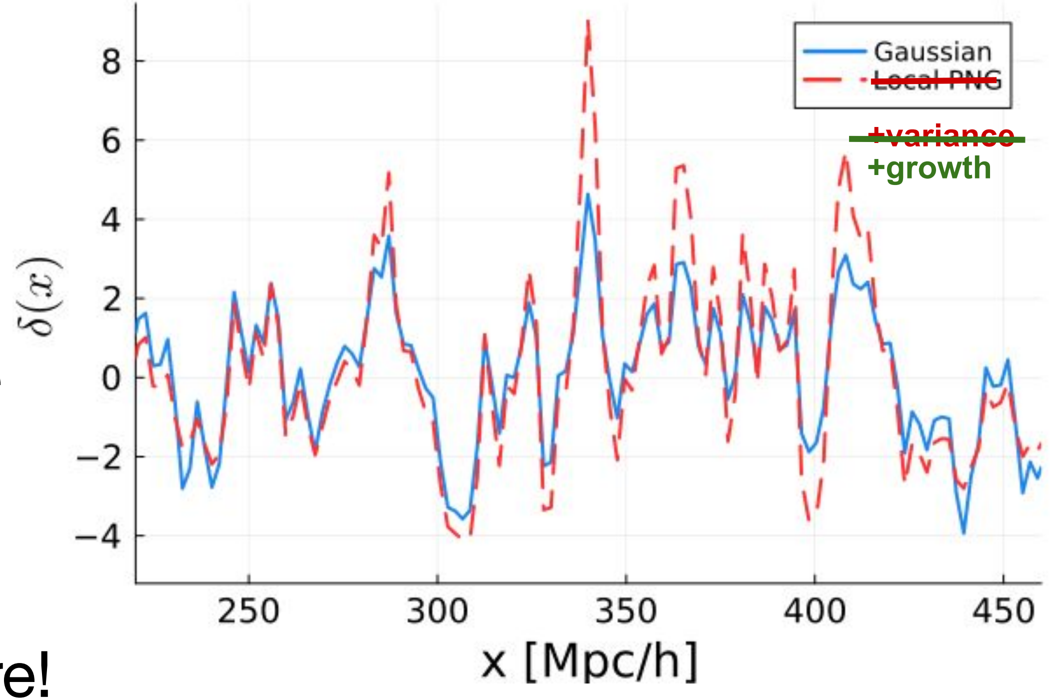


# 3. Growth is Variance - Idea

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!



# Separate universe with 1 universe? - PBS

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

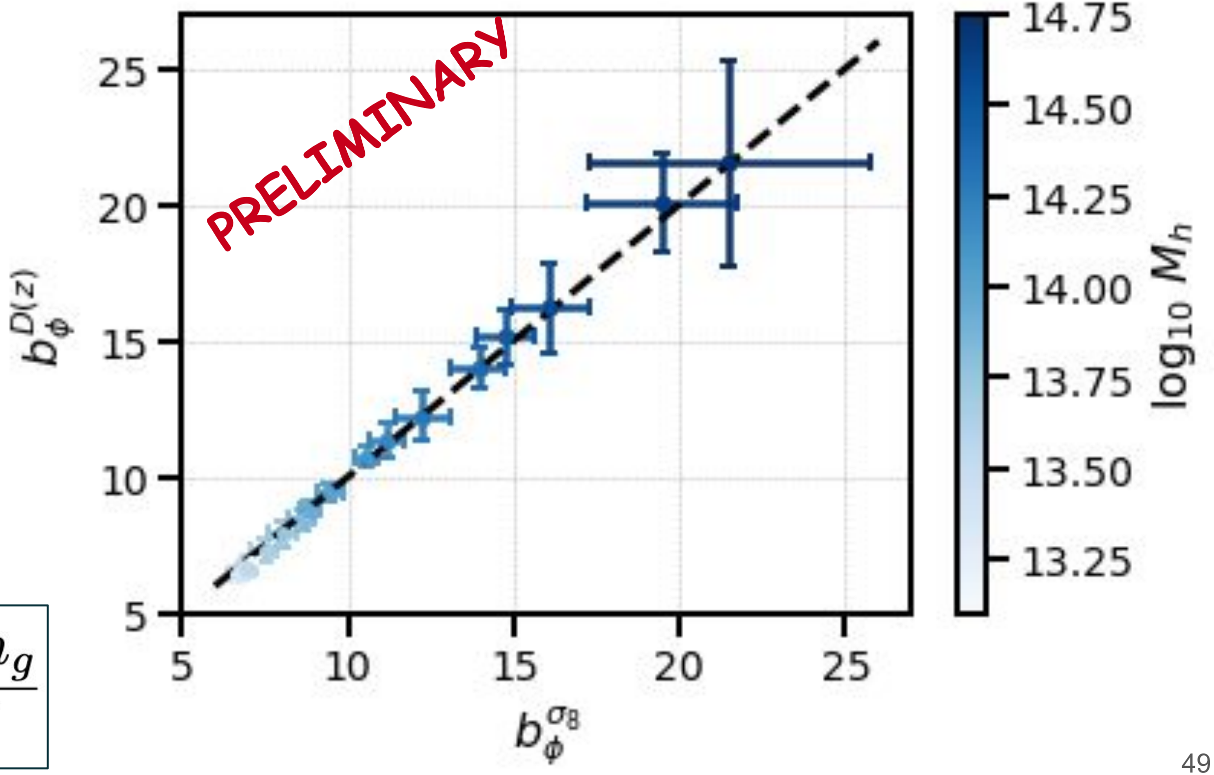
Desjacques++16, Slosar++08, Jeong++09

# 3. Growth is Variance - Simulated Halos

If you don't buy it:
N-body halos at $z = 1$

Evaluate bias via finite difference response to:
1. variance ($\sigma_8$)
2. growth

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



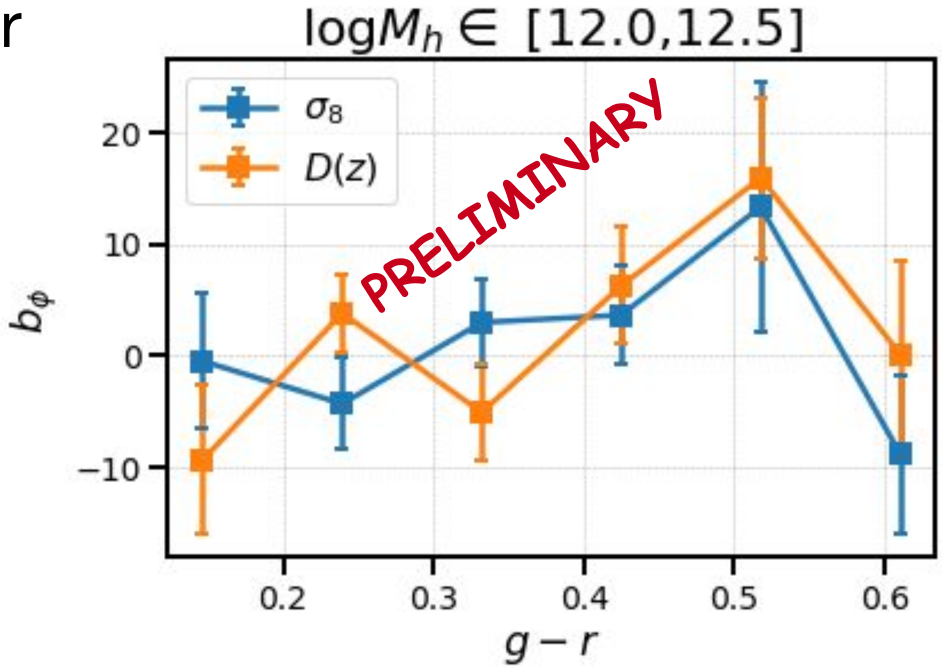
# 3. Growth is Variance - Hydro

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

Holds roughly across mass

Very preliminary, hydro sims out there are limited

Now looking at BOSS LRGs



# 3. Growth is Variance

Next:

- Do it with a real selection function
- Compare to GR evolution bias
- Pipe dream: **Plug this into multi tracer?** -> Ultimate analysis?

# Summary

LPNG a target for all upcoming spectroscopic surveys

Simulated picture shows standard assumption lacking

Want to improve theoretical understanding of $b_\phi$

Multi-tracer & assembly bias may provide a path forward

May be able to measure $b_\phi$ separately from $f_{NL}$

**Many interesting directions!**