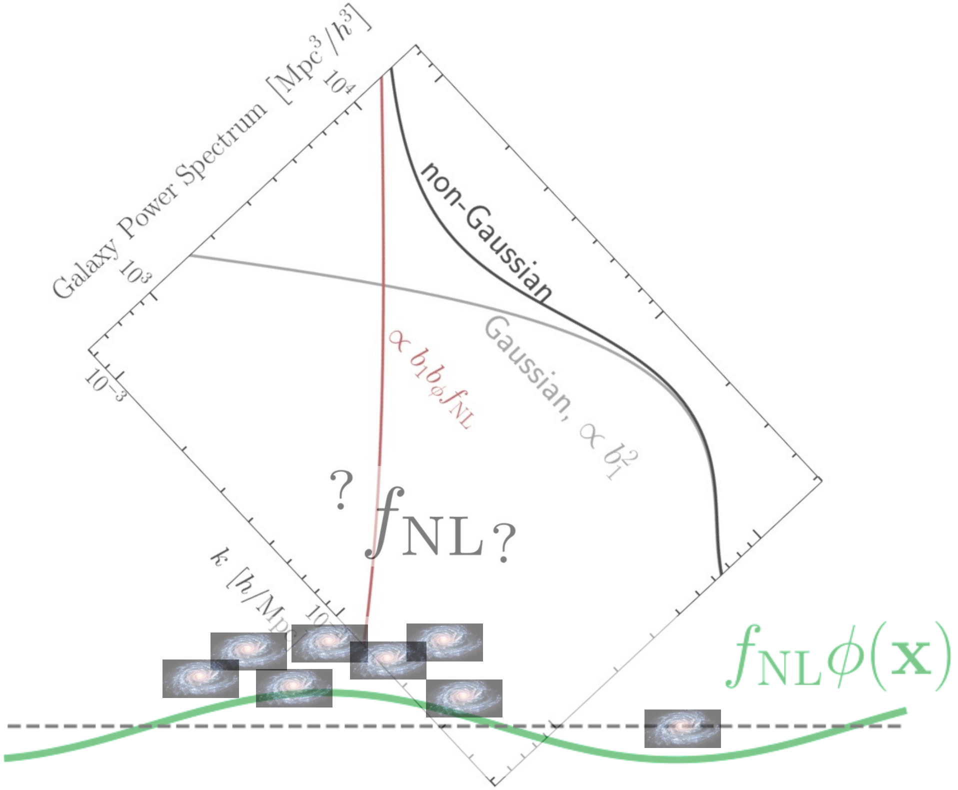
# Can we actually constrain $f_{NL}$ using the scale-dependent bias effect?


**Alex Barreira**

**ORIGINS Fellow**
**LMU - Munich**


**Based on:**
arXiv:2009.06622, arXiv:2107.06887, arXiv:2112.03253, arXiv:2205.05673, arXiv:2209.07251

**In collaboration with:**
Giovanni Cabass, Vincent Desjacques, Titouan Lazeyras, Dylan Nelson, Annalisa Pillepich, Fabian Schmidt


"Primordial non-Gaussianity and Beyond", Madrid 2022

# Can we actually constrain $f_{NL}$ using the scale-dependent bias effect?

**Yes,**

**but**

only if we **understand galaxy formation**
a lot better than we currently do!

# Galaxy bias and local-type PNG

**Local PNG leaves a distinct scale-dependent signature on the large-scale galaxy power spectrum.**

(Dalal+ 2007)

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Density contrast — Primordial potential

$$\delta_g(\boldsymbol{x}, z) \supset b_1(z)\delta_m(\boldsymbol{x}, z) + b_\phi(z) f_{\rm NL}\phi(\boldsymbol{x})$$

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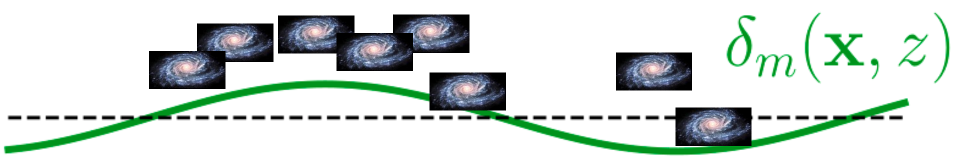
How many more galaxies form inside large-scale total mass perturbations?




How many more galaxies form inside large-scale primordial grav. potentials?


- **<u>The bias parameters are physical (not nuisance)</u>** parameters describing the galaxy-environment connection on large-scales (Desjacques, Jeong & Schmidt 2016).

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On large scales

$$\left[ b_1(z) + \frac{3\Omega_{m0}H_0^2 f_{\rm NL}}{2k^2} b_\phi(z) \right] \delta_m(\boldsymbol{x}, z)$$

k-dependent coefficient, **not bias.**

There are two bias parameters here.

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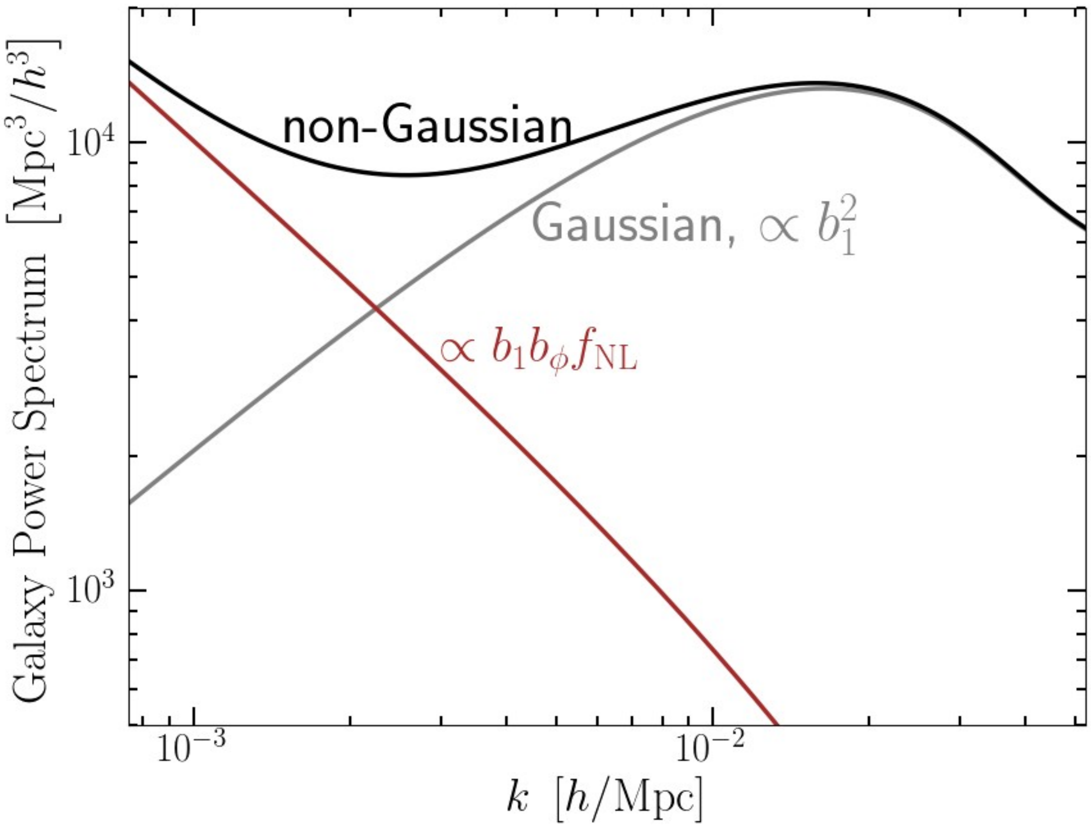


# Galaxy bias and local-type PNG

**Local PNG leaves a distinct scale-dependent signature on the large-scale galaxy power spectrum.**
(Dalal+ 2007)

**Cosmology**

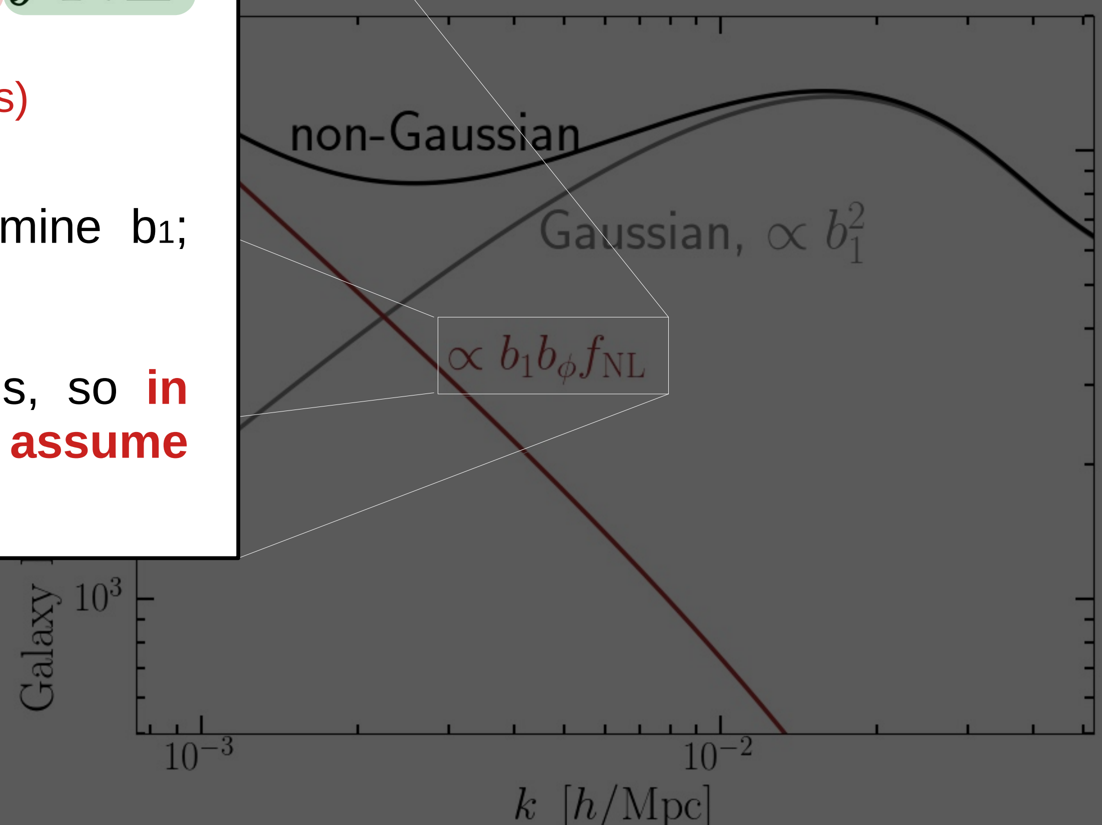
$$\text{Signature} \propto b_1 b_\phi f_{\rm NL}$$

**Galaxy formation**
(galaxy bias parameters)

- The data on small scales can determine $b_1$;
- A perfect degeneracy with $b_\phi$ remains, so **in order to constrain $f_{\rm NL}$ we need to assume something about galaxy formation.**

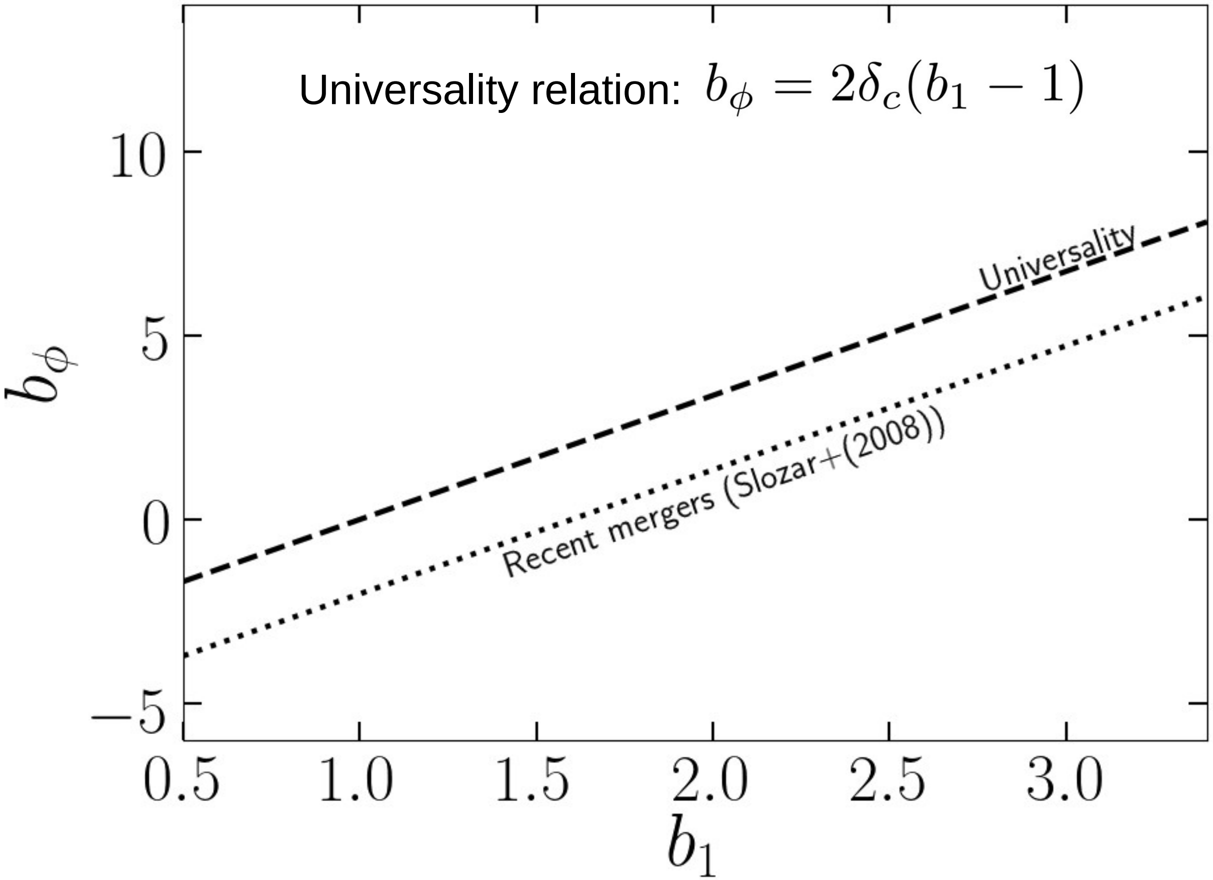
k-dependent coefficient, **not bias.**

There are two bias parameters here.



# What do current works do?

Most works assume a tight relation between the bias parameters $b_\phi$ and $b_1$.
(the idea is to fix $b_\phi$ in terms of $b_1$, which can be fit for on small scales)




However,

despite routinely used, these are very simplified relations and **have really no reason to hold for real tracers.**

So, how well do they perform actually?

# Predictions from Separate Universe simulations

- **The bias estimation**

$$b_1(z) = \lim_{k \to 0} \frac{P_{gm}(z)}{P_{mm}(z)}$$

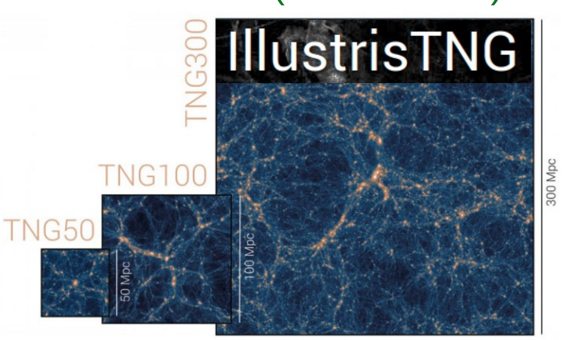
Using the fiducial simulation

$$b_\phi(z) = 4 \frac{\mathrm{d}\ln n_g(z)}{\mathrm{d}\ln \mathcal{A}_s}$$

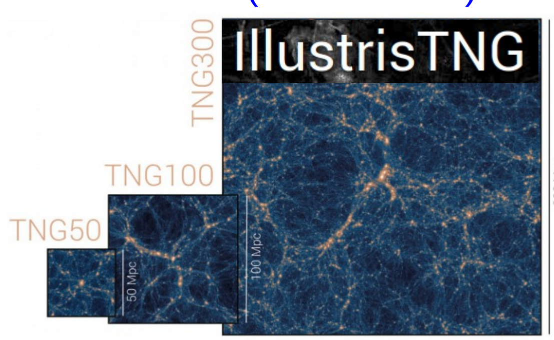
Finite differences using
separate universe simulations

- **The simulation set** (Barreira+2020)

**Separate Universe**
(5% lower As)




**Fiducial cosmology**
(Planck 2018)

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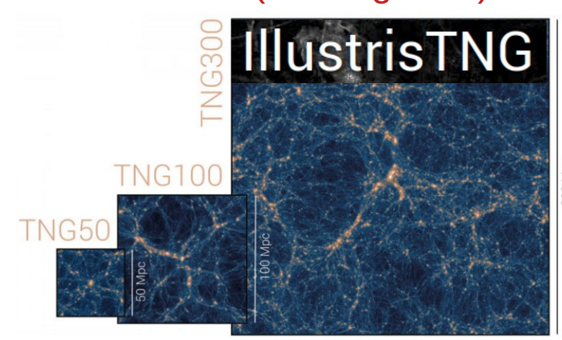


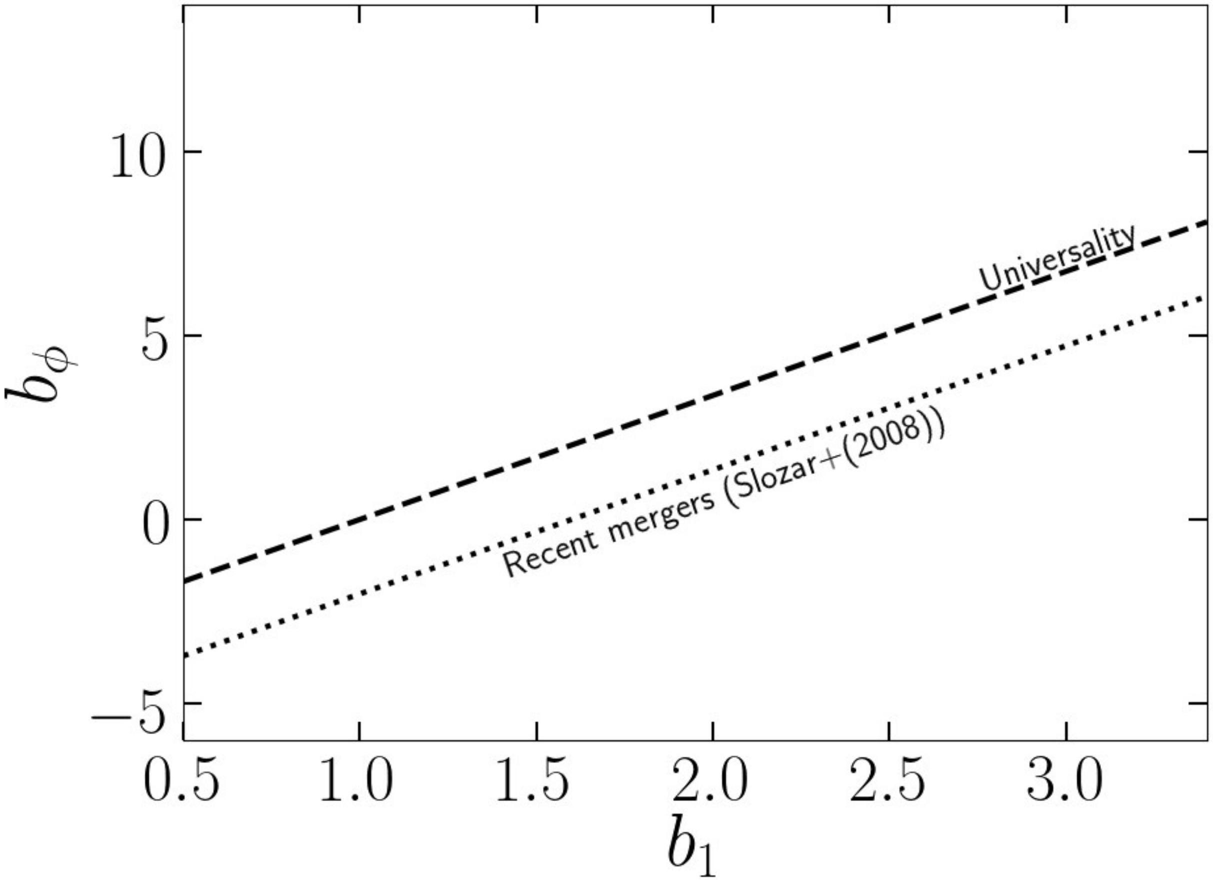

**Hydro (IllustrisTNG)**
L = 75 Mpc/h , Np = 2x1250^3
L = 205 Mpc/h, Np = 2x1250^3

**Gravity-only**
L = 560 Mpc/h, Np = 1250^3

# Much to learn still about the $b_\phi(b_1)$ relation

Relations assumed in the literature fail for a variety of tracers in simulations.

**Results from N-body simulations**




- Strong halo assembly bias signal.
  (Slozar+2008, Reid+2010, Lazeyras+2022
- Galaxies and HI in IllustrisTNG also not well described by simple relations.
  (Barreira+2020, Barreira 2021, Barreira 2022)
- Large theory uncertainty on $b_\phi(b_1)$:
  Impact of galaxy feedback model?
  Connection to real galaxy samples?

Barreira 2021, Barreira 2022, Lazeyras+ (2022)
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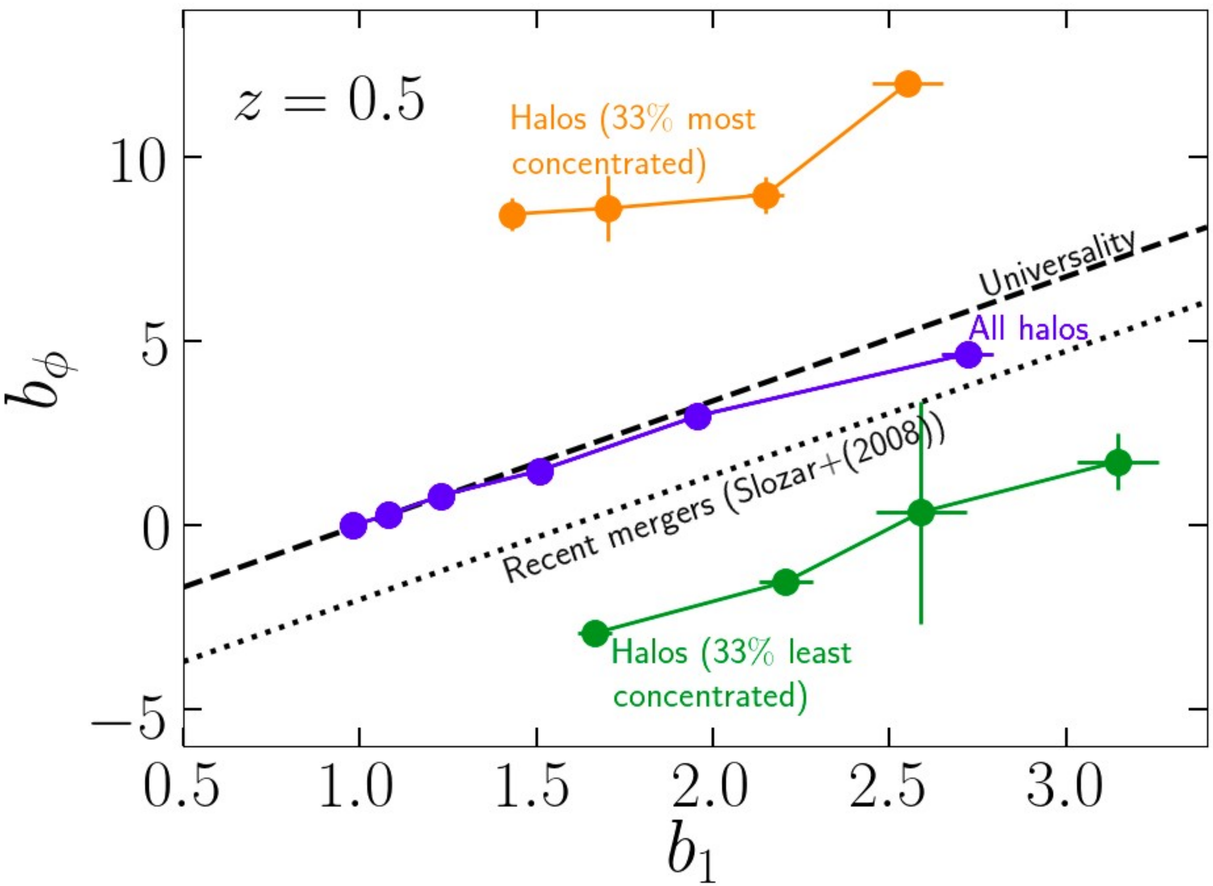


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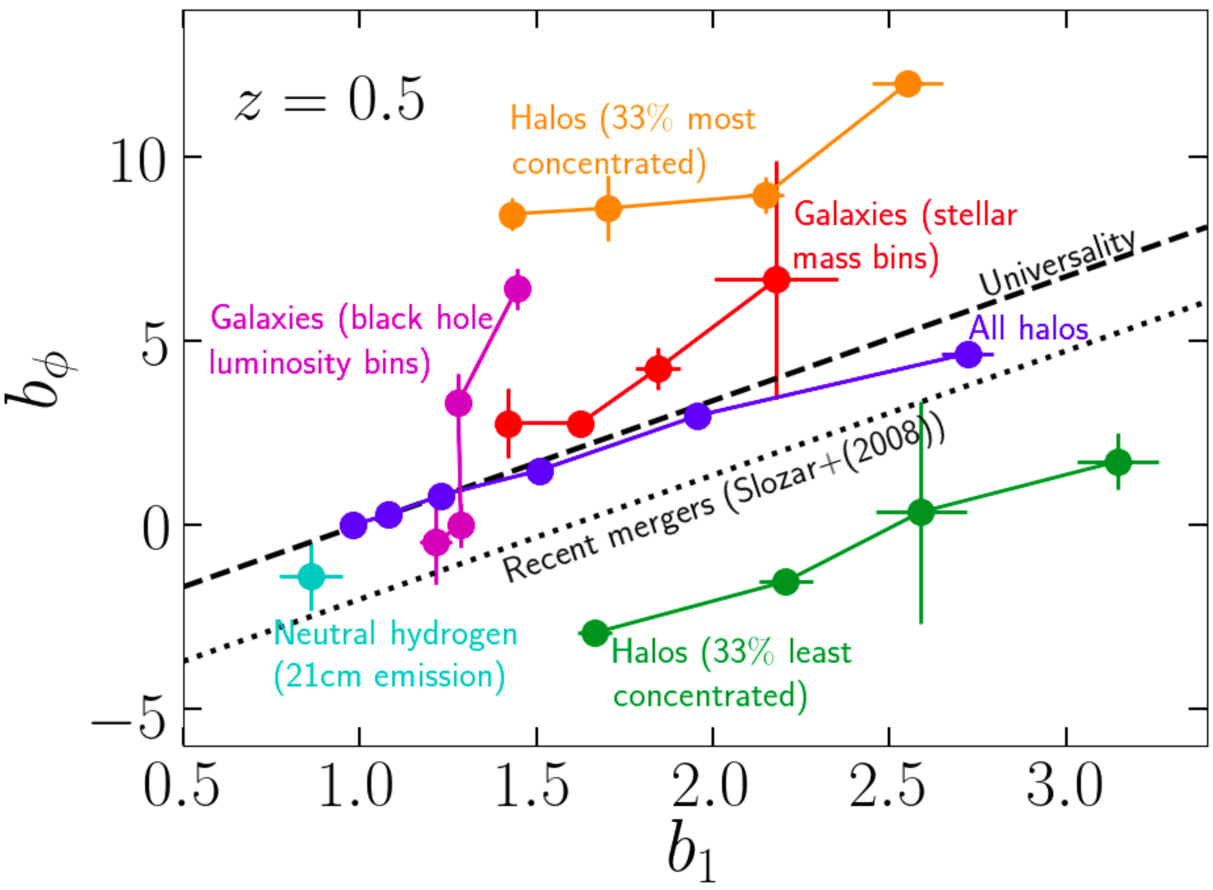


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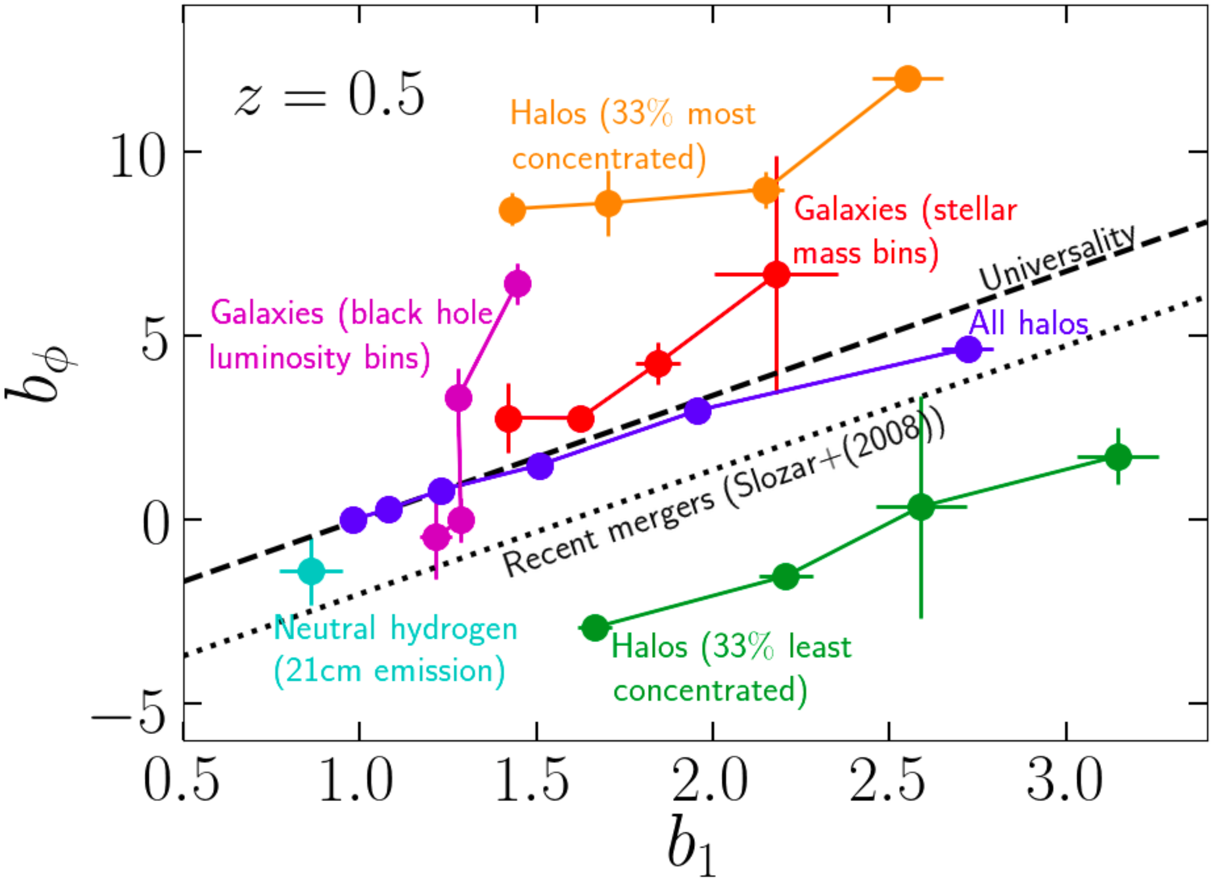


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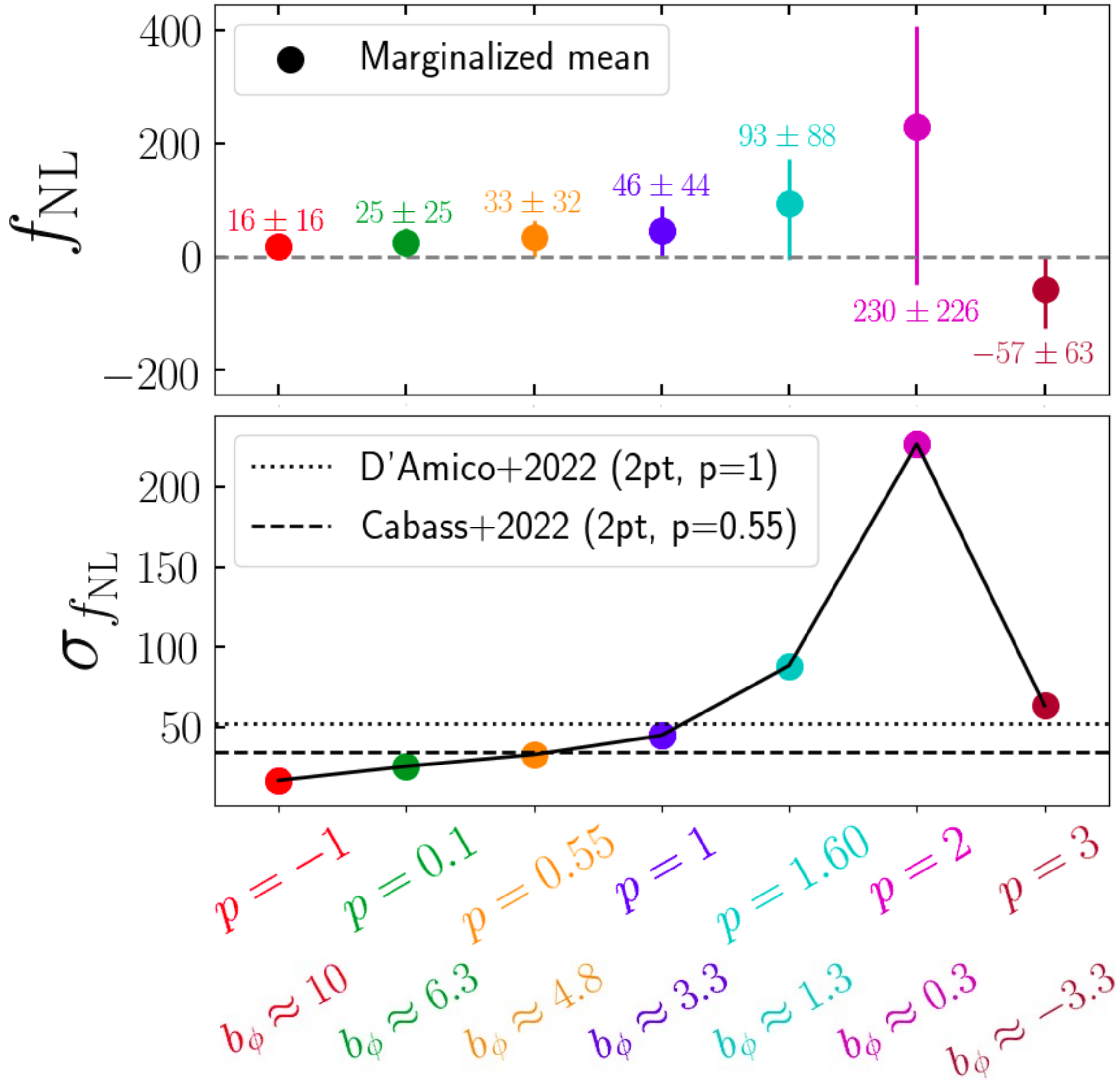
How does this uncertainty affect $f_{NL}$ constraints?

# Can we actually constrain fNL ?

**BOSS constraints for different bϕ(b1) relations**
(power spectrum only)




$$b_\phi = 2\delta_c(b_1 - p)$$

- Constraints are completely dominated by the assumed bϕ(b1) relation.
  This relation is unknown, and so we do not know which constraint is actually correct!
- Inferred precision on fNL can vary significantly on a range of O(1) values of bϕ.
  *Be careful with even O(1) uncertainty on bϕ.*
- Significance of detection is not affected, but it is still misleading to quote bounds on fNL.

  For example:

  fNL = 0.1 ± 0.02 vs fNL = 20 ± 4

  are both 5σ, but have different implications.

  Should constrain fNLbϕ instead.

Barreira (2022)
2205.05673

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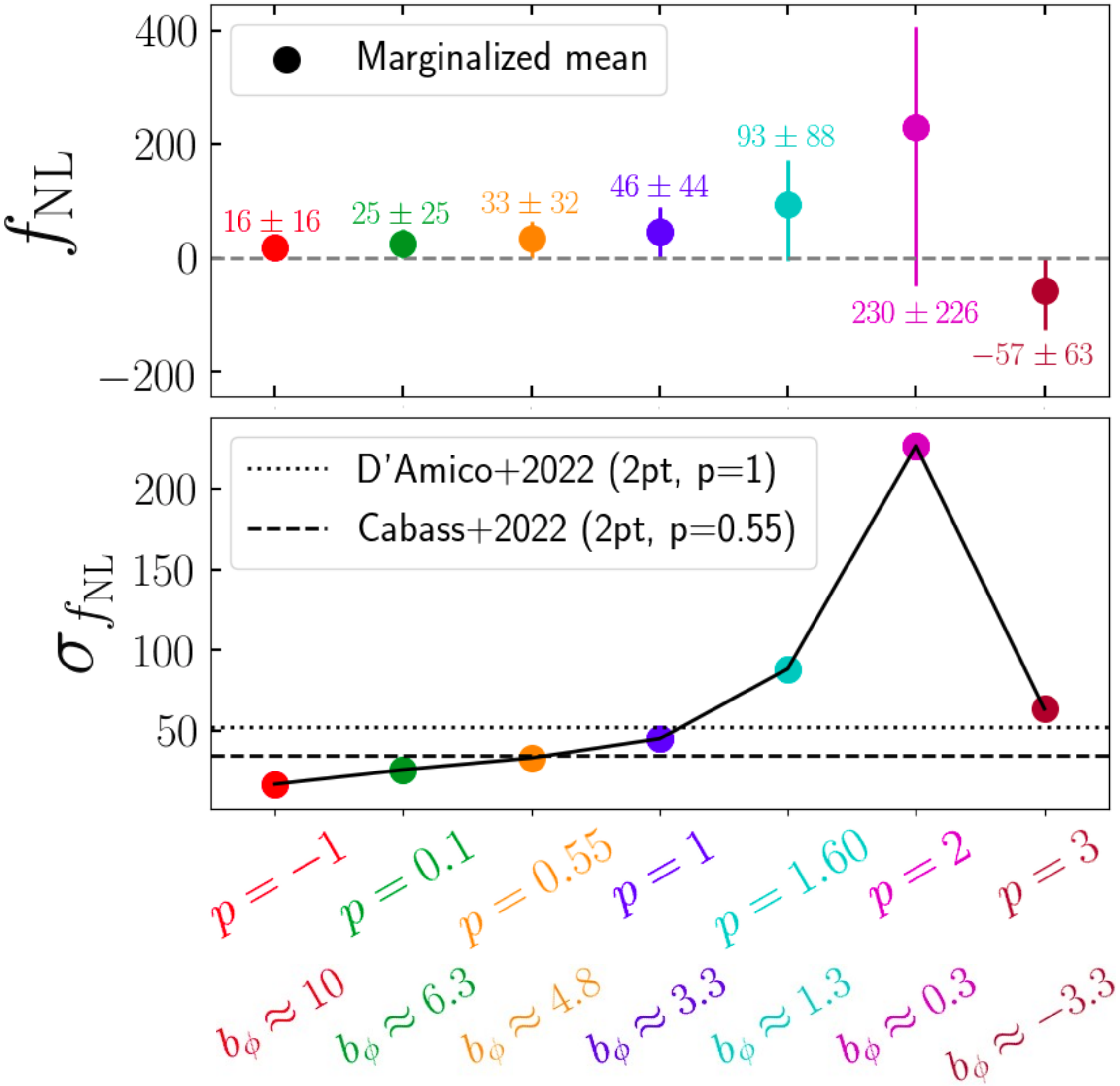


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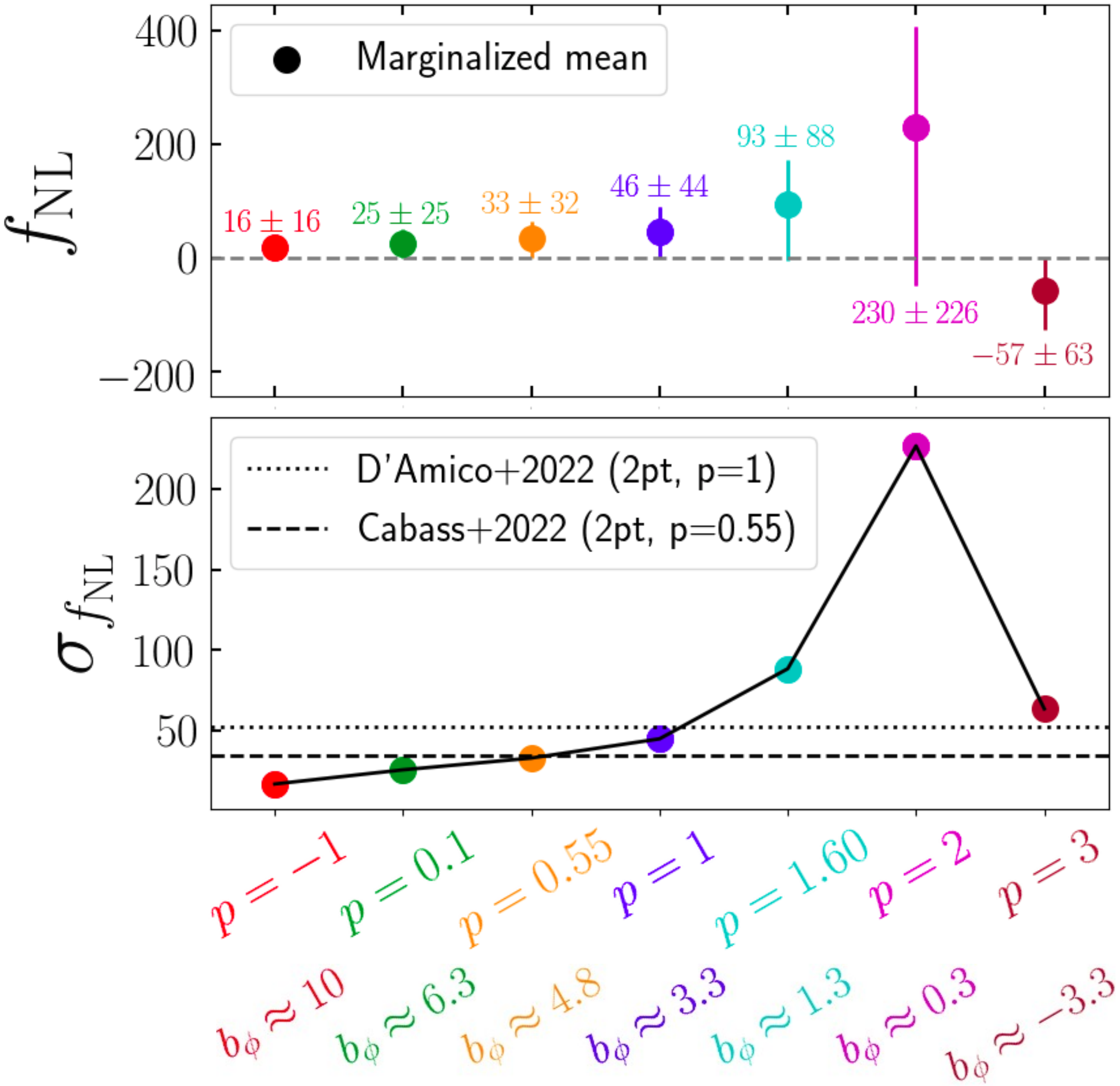


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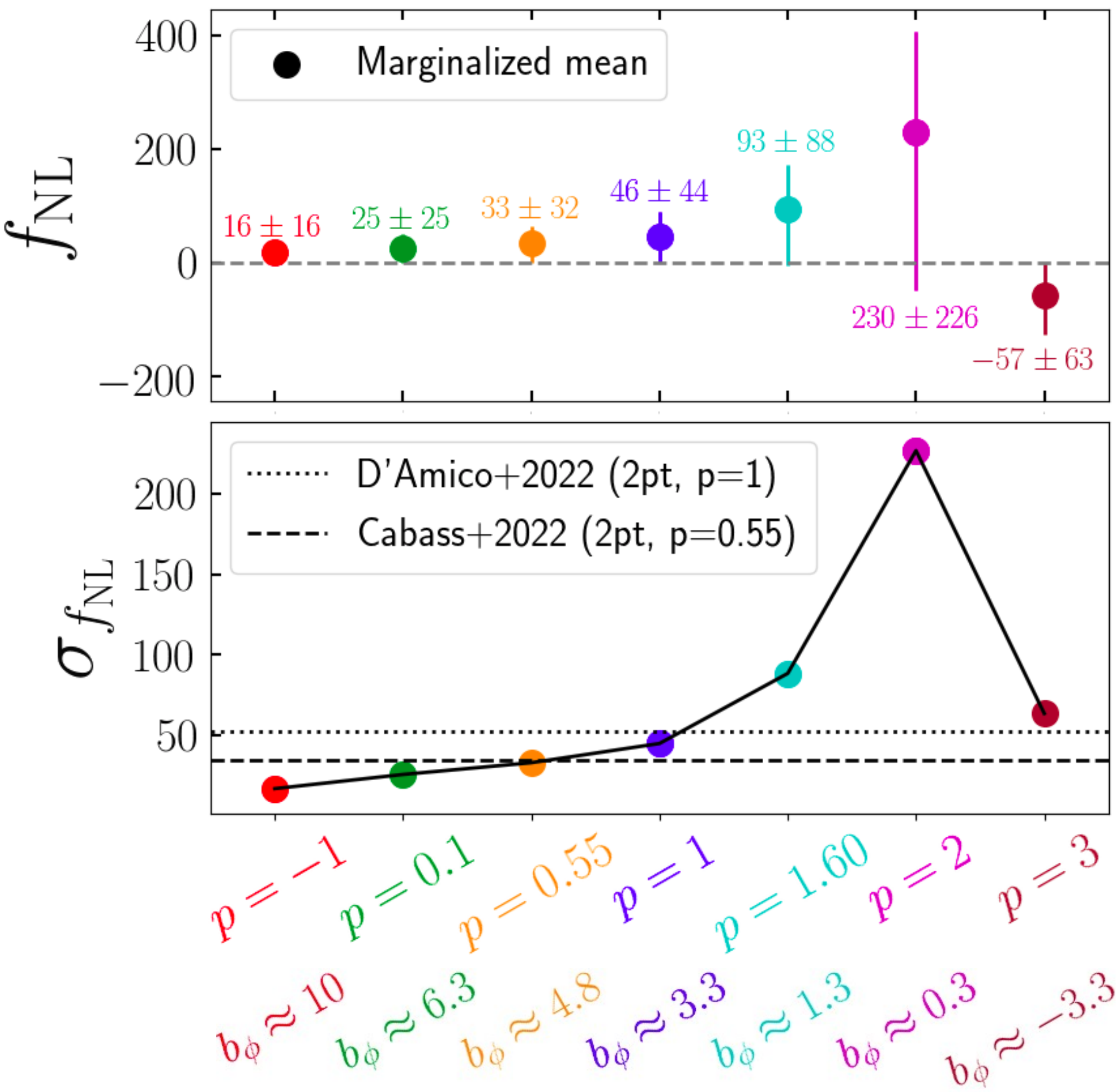


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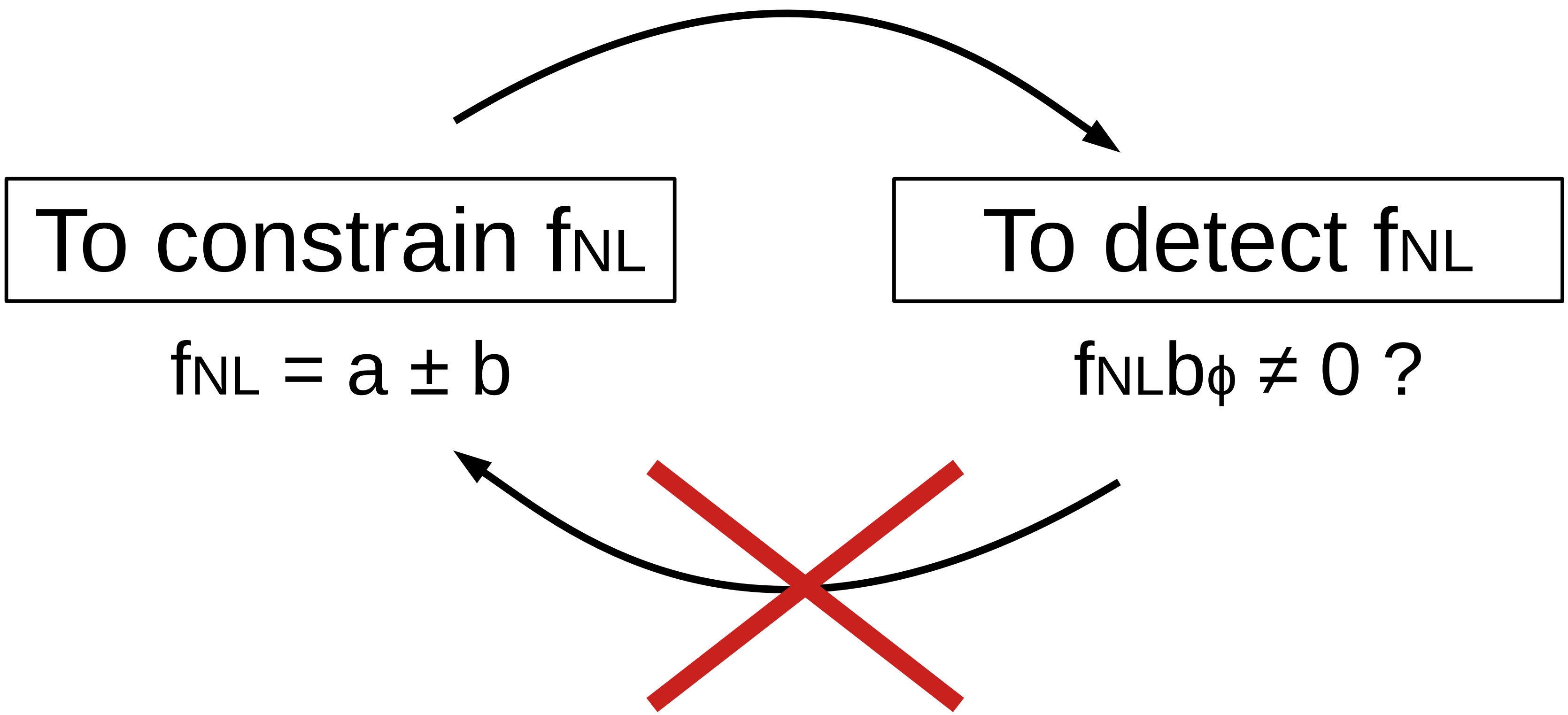
# Can we actually constrain $f_{NL}$ ?

**The CMB constrains $f_{NL}$ directly, and so can automatically detect it.**




**In LSS, the scale-dep. bias effect can detect, but cannot constrain $f_{NL}$.**

Should constrain $f_{NL}b_\phi$ instead.

Barreira (2022)
2205.05673

# What now?

**1)** Given our current poor knowledge on $b_\phi(b_1)$, we should start quoting bounds on $f_{NL} b_\phi$.

Detecting $f_{NL} b_\phi$ also rules out single-field inflation; we just won't know the $f_{NL}$ value.

**2)** Need to develop dedicated research programs for $b_\phi(b_1)$ in order to constrain $f_{NL}$.

**Challenges:** (i) galaxy formation physics and (ii) connection to observations.

**Opportunity:** theory priors on $b_\phi$ let us optimize galaxy selection strategies to detect local PNG.

**3)** Assessment of survey performance cannot leave out PNG bias considerations.

For example, plots like these are misleading as they assume the same bias relations for all surveys!

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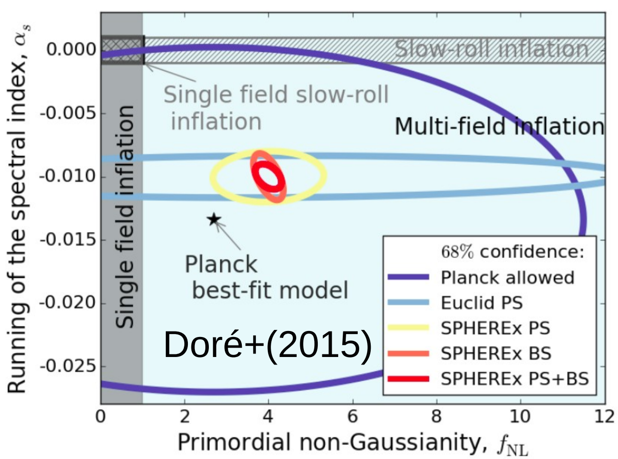
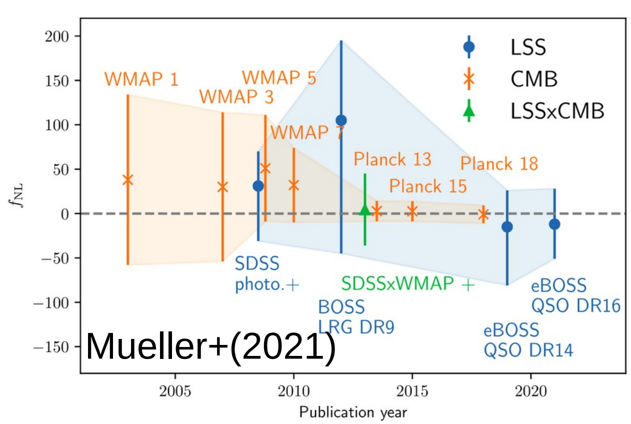
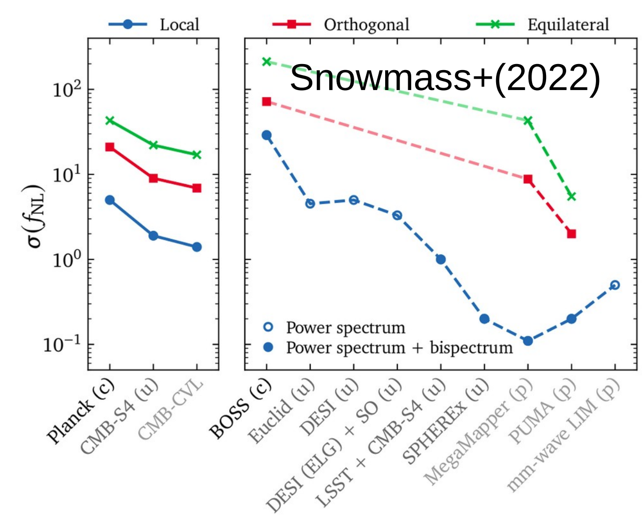


# Summary

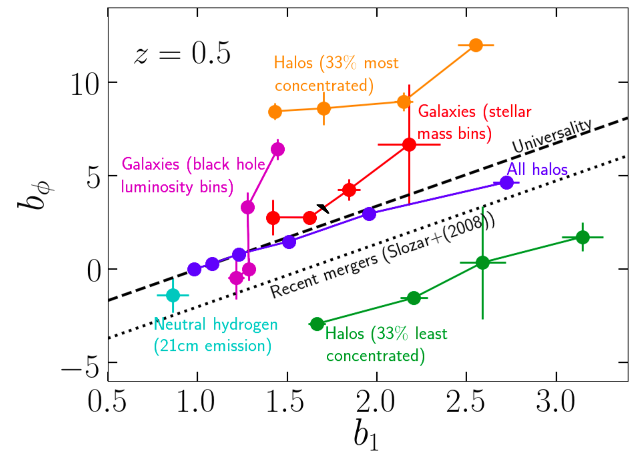
- **Can we actually constrain $f_{NL}$?**

  **Galaxy data does not primarily constrain $f_{NL}$**, but its product with uncertain bias parameters ($f_{NL} b_\phi$).

Cosmology

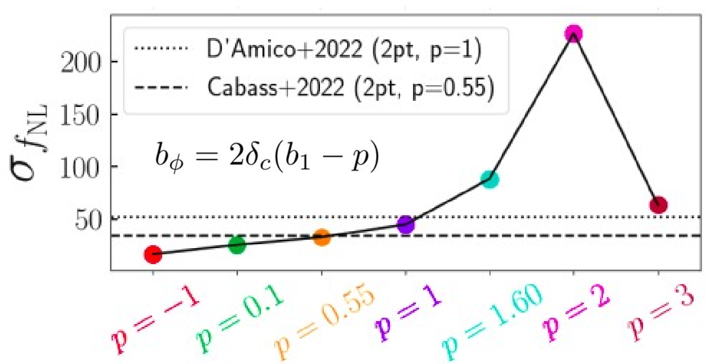
$$\text{Signature} \propto b_1 b_\phi f_{\rm NL}$$

**Galaxy formation**
(galaxy bias parameters)




- **Existing $f_{NL}$ constraints/forecasts are dominated by poor galaxy bias assumptions.**

  Current large theory uncertainty on $b_\phi(b_1)$, implies a serious systematic error on $f_{NL}$ bounds.




- **Need to revisit our approach to $f_{NL}$ constraints**

  Dedicated research programs to determine $b_\phi(b_1)$ for real galaxy samples.

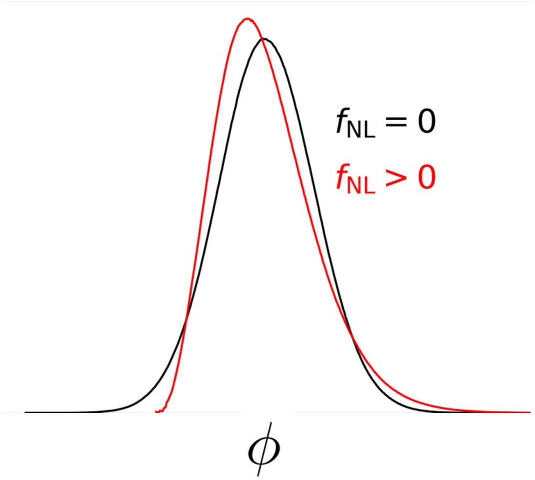
  Survey planning/performance needs to take PNG bias into account.
  What if our future surveys are targeting the wrong galaxies, i.e., with $b_\phi << 1$?

# Extra slides

# Local-type primordial non-Gaussianity (PNG)

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

Komatsu&Spergel(2001)




**Detecting fNL would be immensely profound: it rules out single-field inflation!**

The early universe was not as simple as it could have been!

(Creminelli&Zaldarriaga 2004, Creminelli+ 2011, Tanaka&Urakawa 2011, Pajer+ 2013)

**Current tightest bound**

Planck collaboration (2018)

$$f_{\rm NL} = -0.9 \pm 5.1 \; (68\%)$$

**The latest from LSS**

Mueller+2021 (eBOSS QSO, 2pt)

$$f_{\rm NL} = -12 \pm 21 \; (1\sigma)$$

D'Amico+2022 (BOSS, 2pt+3pt)

$$f_{\rm NL} = -30 \pm 29 \; (1\sigma)$$

Cabass+2022 (BOSS, 2pt+3pt)

$$f_{\rm NL} = -33 \pm 28 \; (1\sigma)$$

**The milestone**

Expected from future LSS

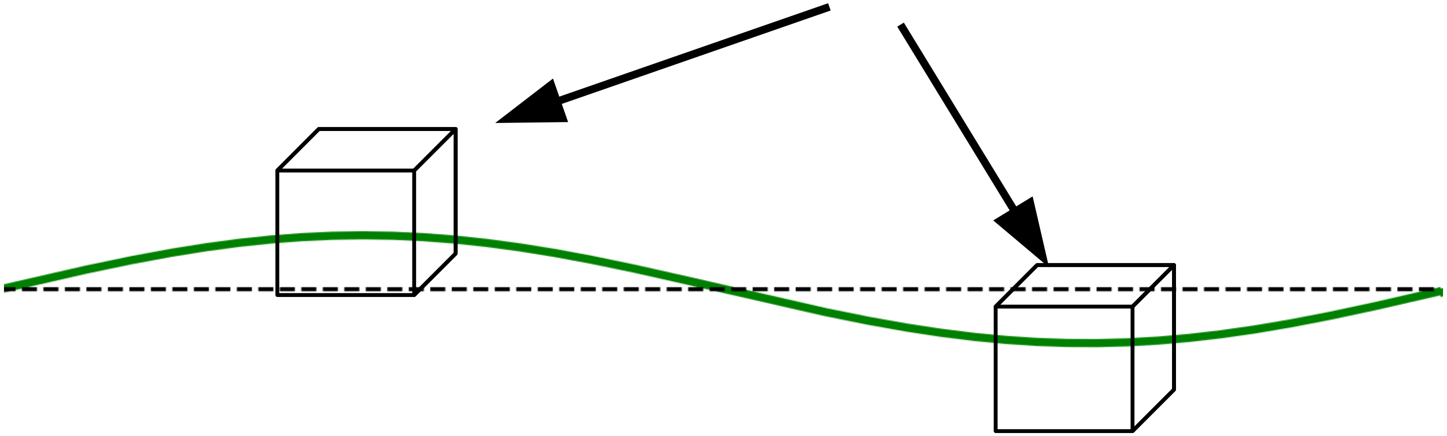
(SphereX, Euclid, Rubin, DESI, SKA)

$$\sigma_{f_{\rm NL}} \lesssim 1$$

# Predictions from Separate Universe simulations

**Separate Universe theorem:** local structure formation inside long-wavelength perturbations is equivalent to global structure formation in a modified cosmology.

These regions behave as
**separate universes**



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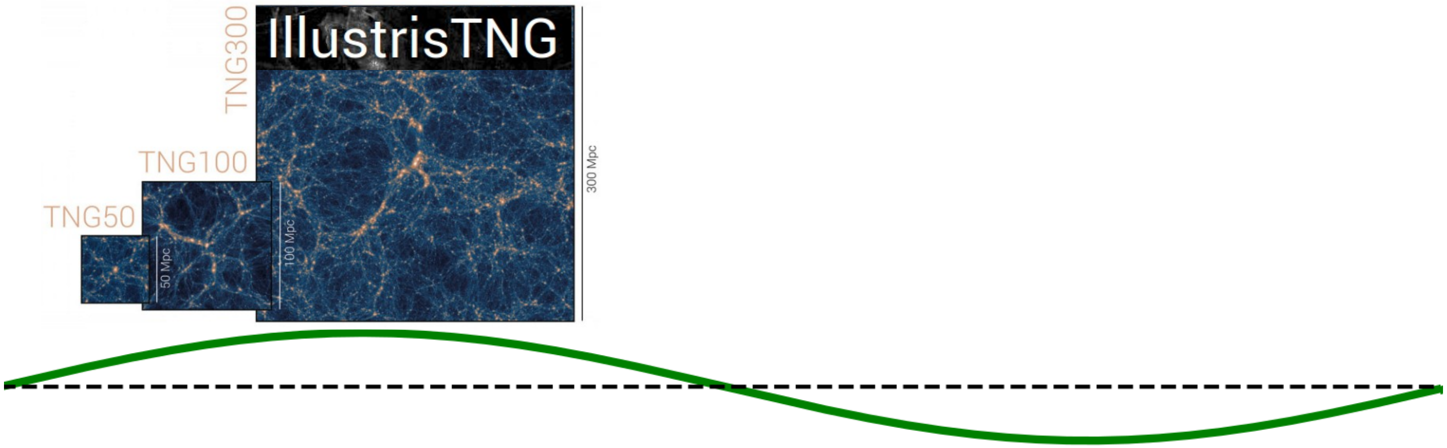

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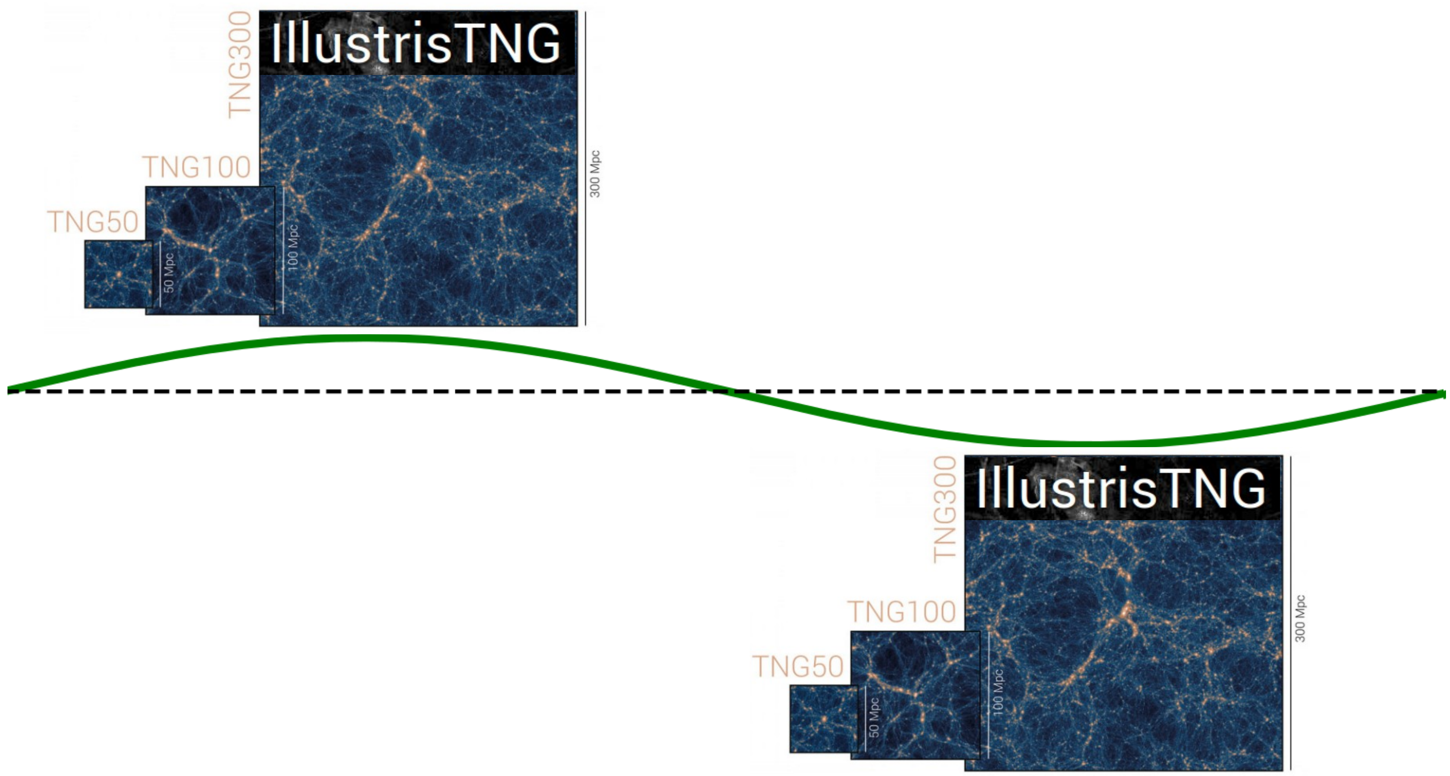



**Simulation of another cosmology (B)**

# Predictions from Separate Universe simulations

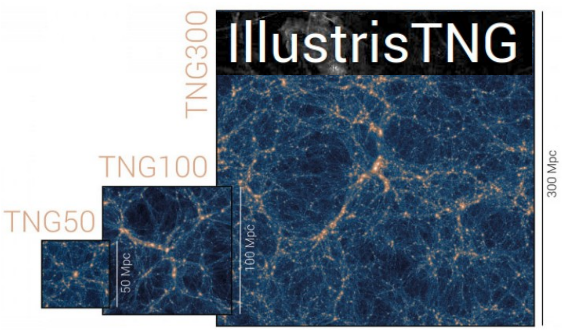
**Separate Universe theorem:** local structure formation inside long-wavelength perturbations is equivalent to global structure formation in a modified cosmology.

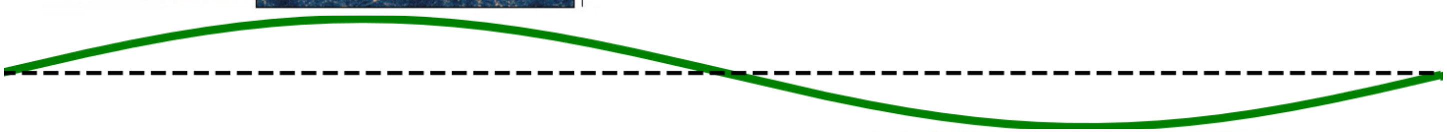
$$\text{bias} = \frac{1}{\mathrm{A}-\mathrm{B}}\left[\frac{n^{\mathrm{A}}}{n^{\mathrm{B}}} - 1\right]$$

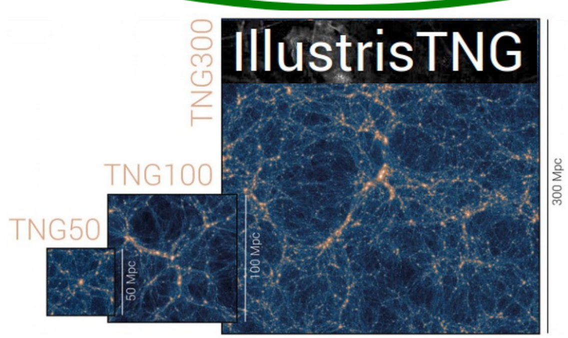
Bias as the **response** of the galaxy abundance to changes in the **cosmological parameters.**

**Big advantage for $b_\phi$ studies:** simulation does not have to be large volume to resolve the large-scale signature.

**Simulation of one cosmology (A)**






**Simulation of another cosmology (B)**

# A few FAQs

- **Can we marginalize over the $b_\phi$ parameter?**

  **No, this is ill defined.** The perfect degeneracy makes any prior invariably informative. In particular, wide priors introduce spurious projection effects.

  Barreira (2022), 2205.05673

- **Can multitracer or lensing cross-correlations help?**

  **Also no.** The additional information is unable to break this degeneracy.

- **Can the bispectrum help?**

  The galaxy bispectrum can probe $f_{NL}$ directly via the primordial signal, but marginalizing over the scale-dep. bias terms yields uncompetitive bounds.

  Barreira (2020), 2009.06622
  Moradinezhad+ (2020), 2010.14523
  Barreira (2021), 2107.06887
  Cabass+ (2022), 2204.01781

# Ways to break the $b_\phi f_{NL}$ degeneracy? #1

- Multitracer analyses cannot break the degeneracy.

$$\langle \delta_g^A \delta_g^A \rangle = [b_1^A]^2 \langle \delta_m \delta_m \rangle + 2 b_1^A \left[ b_\phi^A f_{\rm NL} \right] \langle \delta_m \phi \rangle + \left[ b_\phi^A f_{\rm NL} \right]^2 \langle \phi \phi \rangle$$

$$\langle \delta_g^A \delta_g^B \rangle = b_1^A b_1^B \langle \delta_m \delta_m \rangle + \left( b_1^A \left[ b_\phi^B f_{\rm NL} \right] + b_1^B \left[ b_\phi^A f_{\rm NL} \right] \right) \langle \delta_m \phi \rangle + \left[ b_\phi^A f_{\rm NL} \right] \left[ b_\phi^A f_{\rm NL} \right] \langle \phi \phi \rangle$$

$$\langle \delta_g^B \delta_g^B \rangle = [b_1^B]^2 \langle \delta_m \delta_m \rangle + 2 b_1^B \left[ b_\phi^B f_{\rm NL} \right] \langle \delta_m \phi \rangle + \left[ b_\phi^B f_{\rm NL} \right]^2 \langle \phi \phi \rangle$$

- Every new sample brings with it an additional $b_\phi f_{NL}$ term

# Ways to break the $b_\phi f_{NL}$ degeneracy? #2

- Cross-correlation with lensing cannot break the degeneracy

$$\langle\delta_g\delta_g\rangle = b_1^2\langle\delta_m\delta_m\rangle + 2b_1\left[b_\phi f_{\rm NL}\right]\langle\delta_m\phi\rangle + \left[b_\phi f_{\rm NL}\right]^2\langle\phi\phi\rangle$$

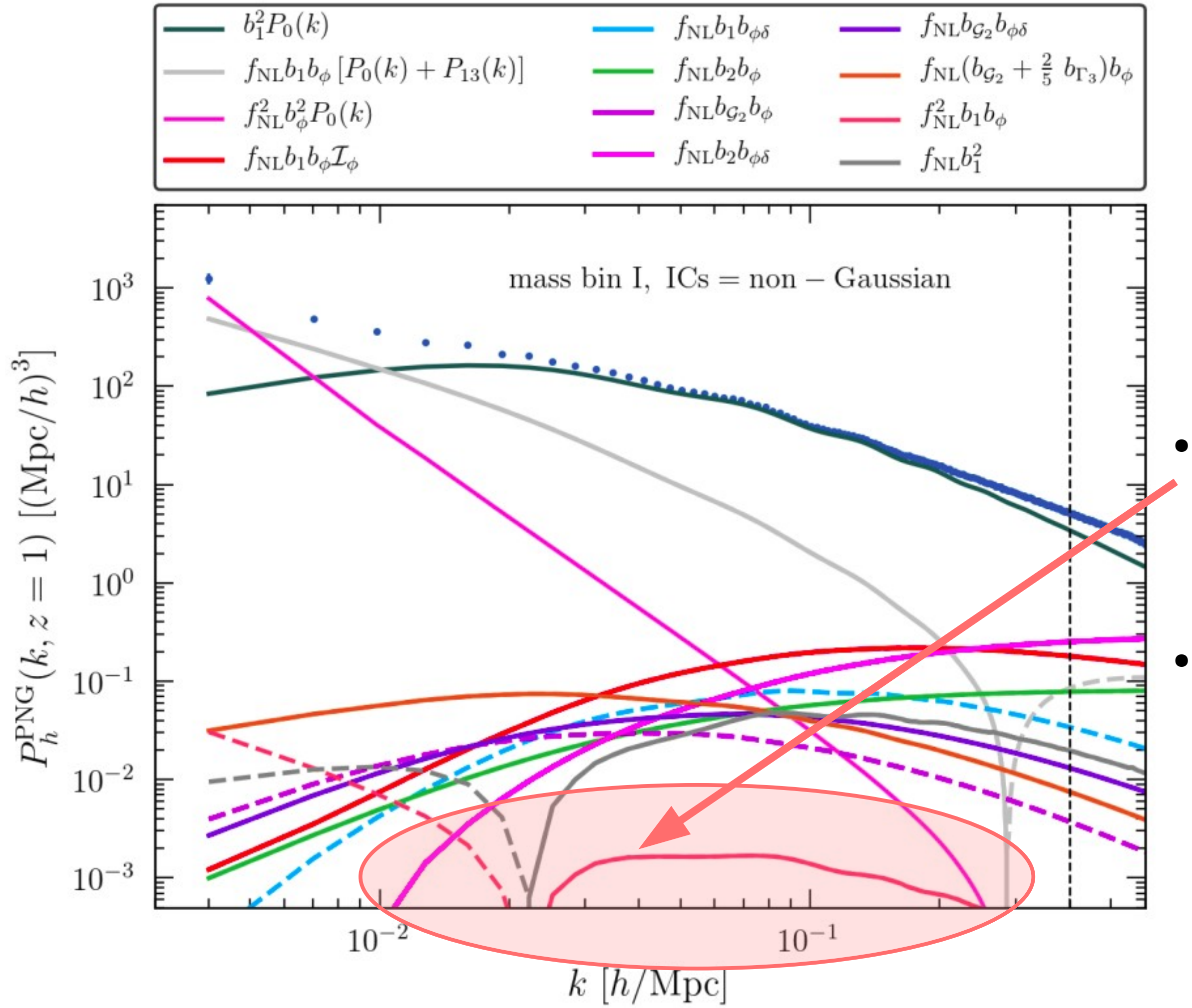
$$\langle\delta_g\delta_m\rangle = b_1\langle\delta_m\delta_m\rangle + b_1\left[b_\phi f_{\rm NL}\right]\langle\delta_m\phi\rangle$$

- Lensing does break degeneracies between $b_1$ and $\sigma_8$, but not between $b_\phi$ and $f_{NL}$.
- Lensing bispectrum is not a sensitive probe of $f_{NL}$.
(Jeong, Schmidt & Sefusatti 2011)

# Ways to break the $b_\phi f_{NL}$ degeneracy? #3

- The 1-loop power spectrum breaks the degeneracy, but only negligibly.

Moradinezhad Dizgah+2020



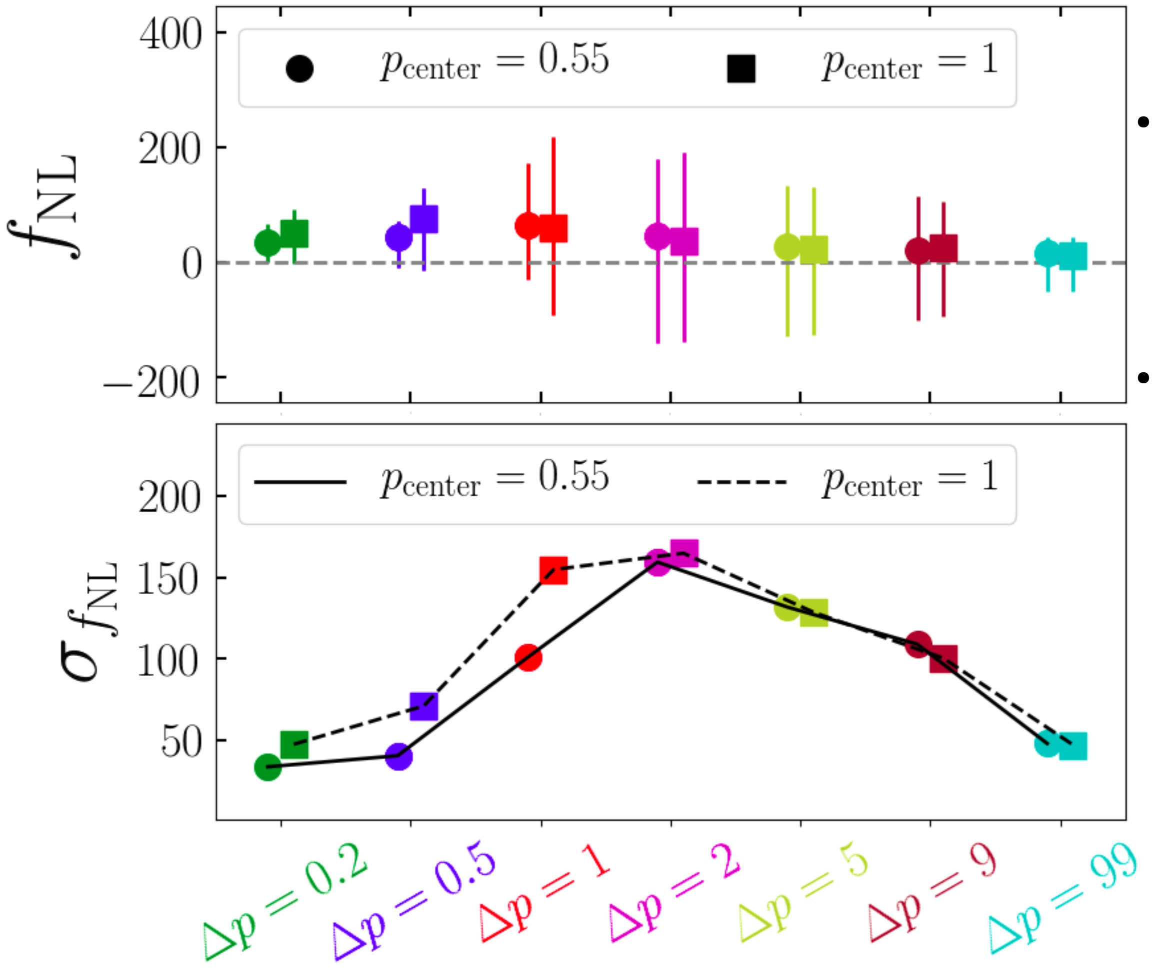

- Term ~ $b_\phi f_{NL}$^2 breaks the degeneracy, but is 4 orders of magnitude smaller.
- Only relevant if $f_{NL}$ ~ 1.0e4.

# Can we marginalize over the PNG bias ?

Marginalizing over the local PNG bias parameters is ill-defined.

**Impact of marginalizing over the $b_\phi(b_1)$ relation**
(power spectrum only)

$$b_\phi = 2\delta_c(b_1 - p)$$




- **Narrow priors** bias the result if they are centered at the wrong value.
- **Wide priors** bias the result due projection effects that drive the constraints to zero.

*Be careful with "loose" priors: they still dominate the constraints!*
*(cf. also* Moradinezhad+ (2020)*)*

Barreira (2022)
2205.05673

# Can the bispectrum help?

**Types of contributions to the galaxy bispectrum:**

**Leading-order PNG bias**

$$f_{\rm NL} b_\phi$$

$$\underbrace{\hphantom{f_{\rm NL} b_\phi}}$$

Contributes also to the power spectrum.

**Primordial bispectrum**

$$f_{\rm NL} b_1^3$$

**Higher-order PNG bias**

$$f_{\rm NL} b_{\phi\delta}$$

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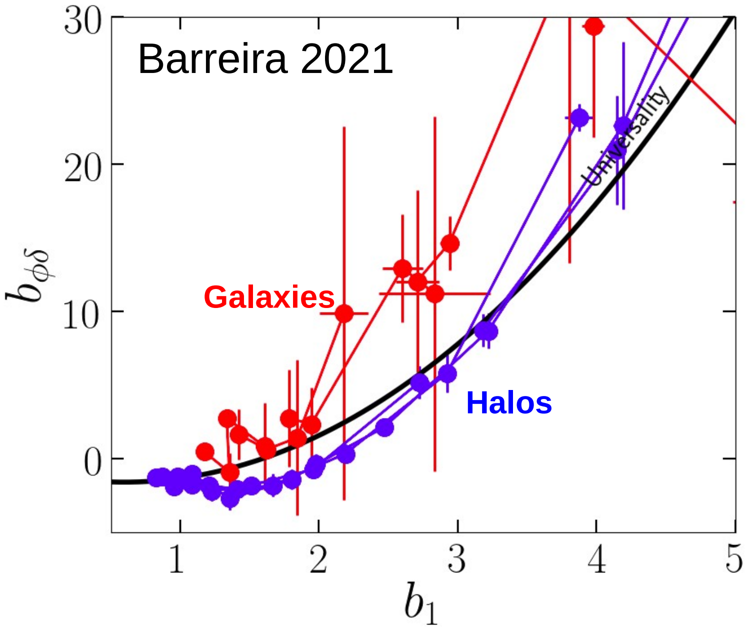
Large uncertainty also on higher-order PNG bias parameters



# Can the bispectrum help?

**Types of contributions to the galaxy bispectrum:**

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Contributes also to the power spectrum.

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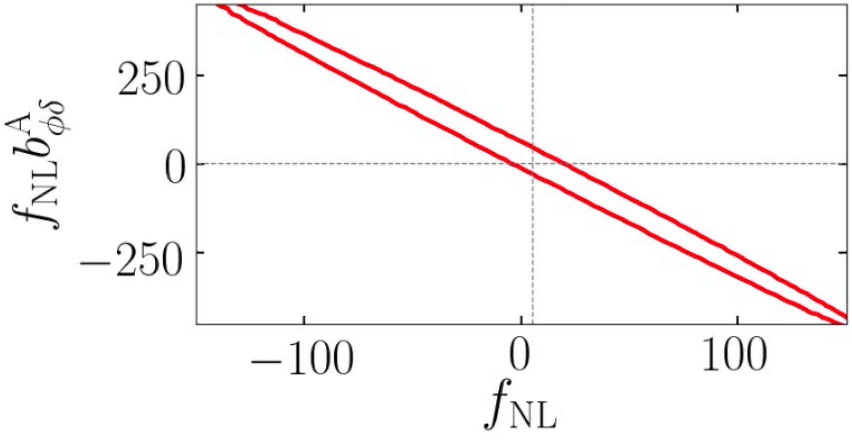
$$f_{\rm NL} b_1^3$$

**Higher-order PNG bias**

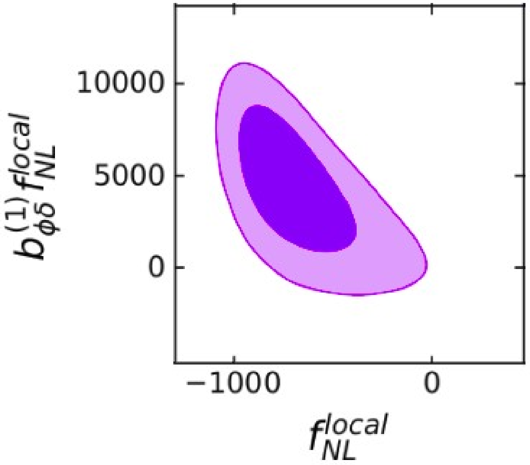
$$f_{\rm NL} b_{\phi\delta}$$

Have similar scale-dependence in the galaxy bispectrum, i.e. **the higher-order PNG bias washes the primordial signal.**

Real-space, idealized survey (Barreira 2021)

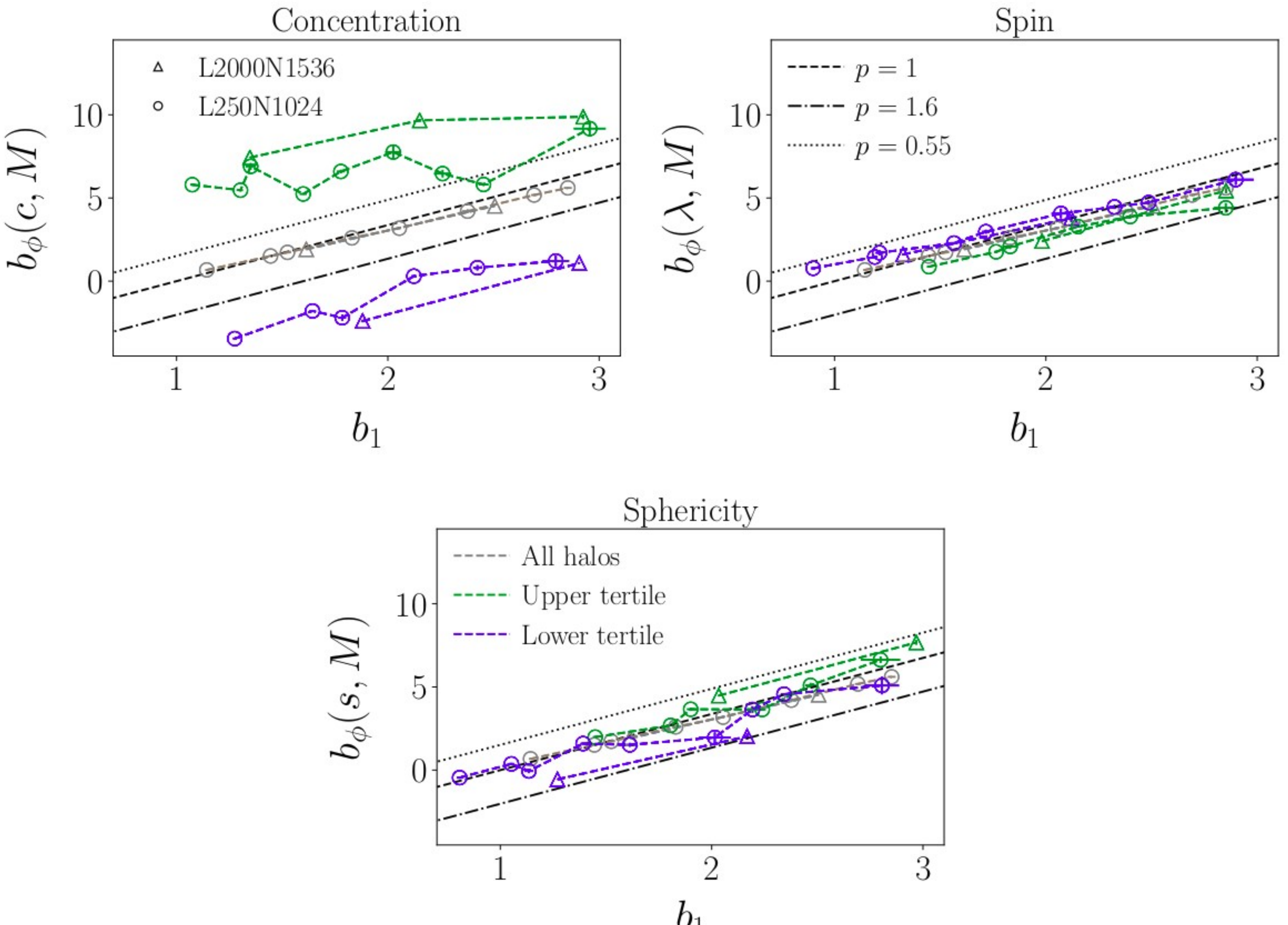



Redshift space, BOSS (Cabass+ 2022)



# Assembly bias in the local PNG halo bias

- Halo concentration impacts the $b_\phi(b_1)$ relation very significantly.
- Halo spin and sphericity have a much milder impact on the $b_\phi(b_1)$ relation.

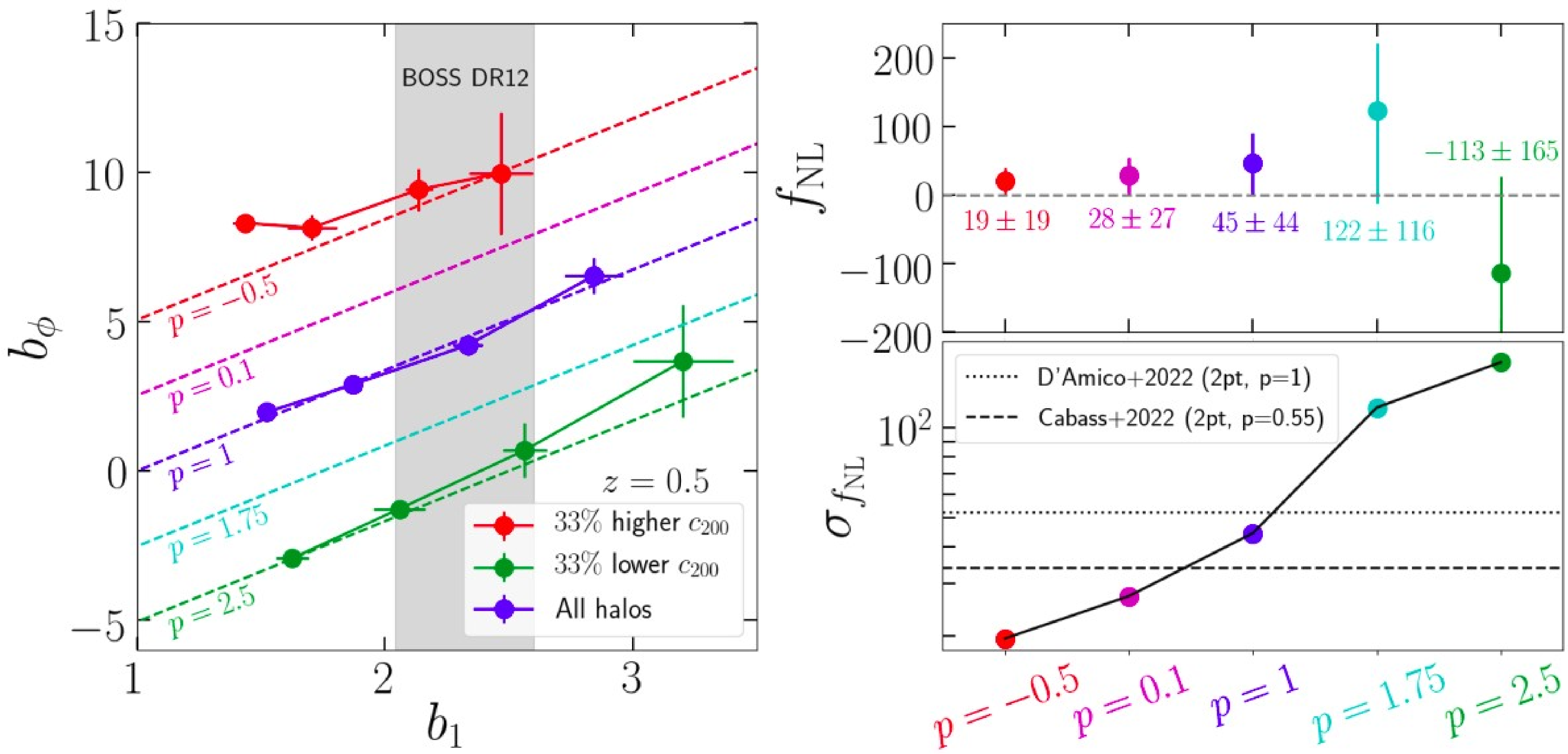



Lazeyras, Barreira, Schmidt, Desjacques (2022)

# Assembly bias in the local PNG halo bias

- The constraints on $f_{NL}$ depend strongly on the concentration of the halos that are assumed to host these galaxies.

- A good knowledge of (at least) the host halo concentration distributions of galaxies is necessary in order to robustly constrain $f_{NL}$.




Lazeyras, Barreira, Schmidt, Desjacques (2022)

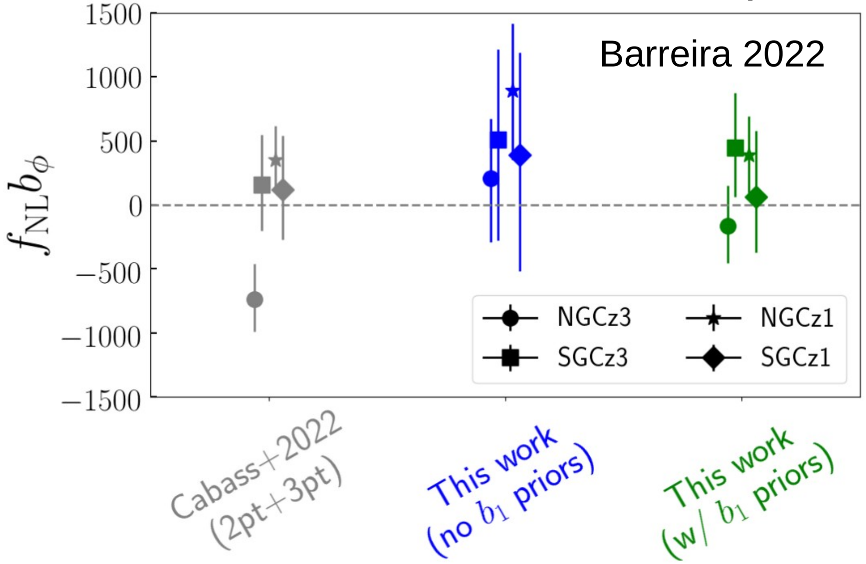
# Significance of detection analyses

Independently of the PNG galaxy bias relations,
**we can only constrain the product $f_{NL} b_\phi$.**

## Pros:

- Can still be used to detect local PNG, and thus rule out single-field inflation!
- Independent of assumptions about galaxy bias;

**BOSS constraints on $f_{NL} b_\phi$**




## Cons:

- The value and error bar on $f_{NL}$ cannot be known.
  *"When do we stop looking for $f_{NL}$?"*
- Cannot compare/combine constraints with the CMB;
- The bispectrum becomes less useful.

Barreira (2020), 2009.06622
Barreira (2021), 2107.06887

Barreira (2022)
2205.05673