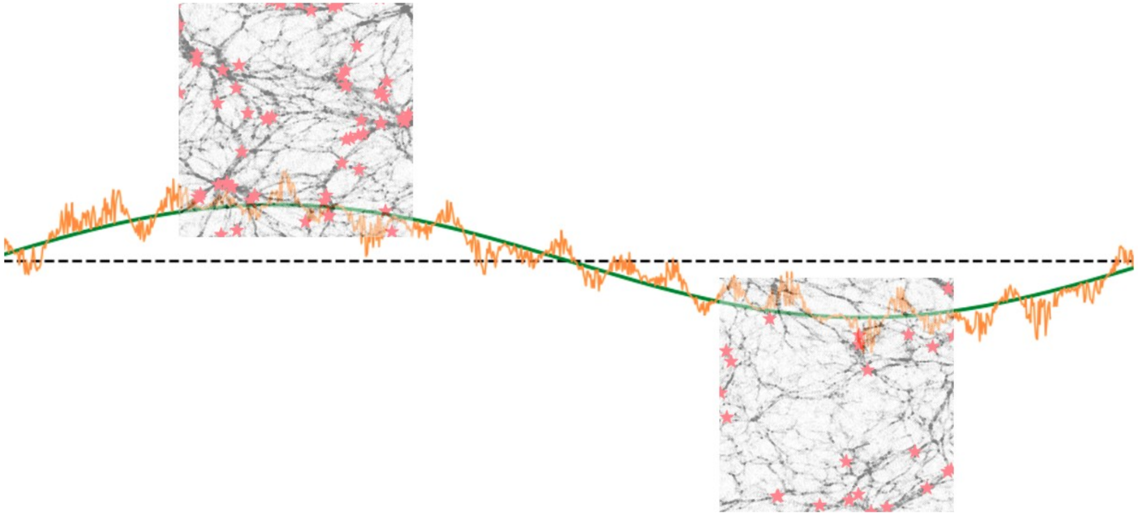
Connecting the visible Universe to the dark

Recent advances on galaxy bias predictions



Alex Barreira

ORIGINS Cluster
LMU - Munich

APEC Seminar – Kavli IPMU
March 2022

Standard cosmological model: ΛCDM

The ΛCDM model fits *almost* all of the data *almost* perfectly !

Λ

+

Particle Physics + GR + CDM

+

Inflation

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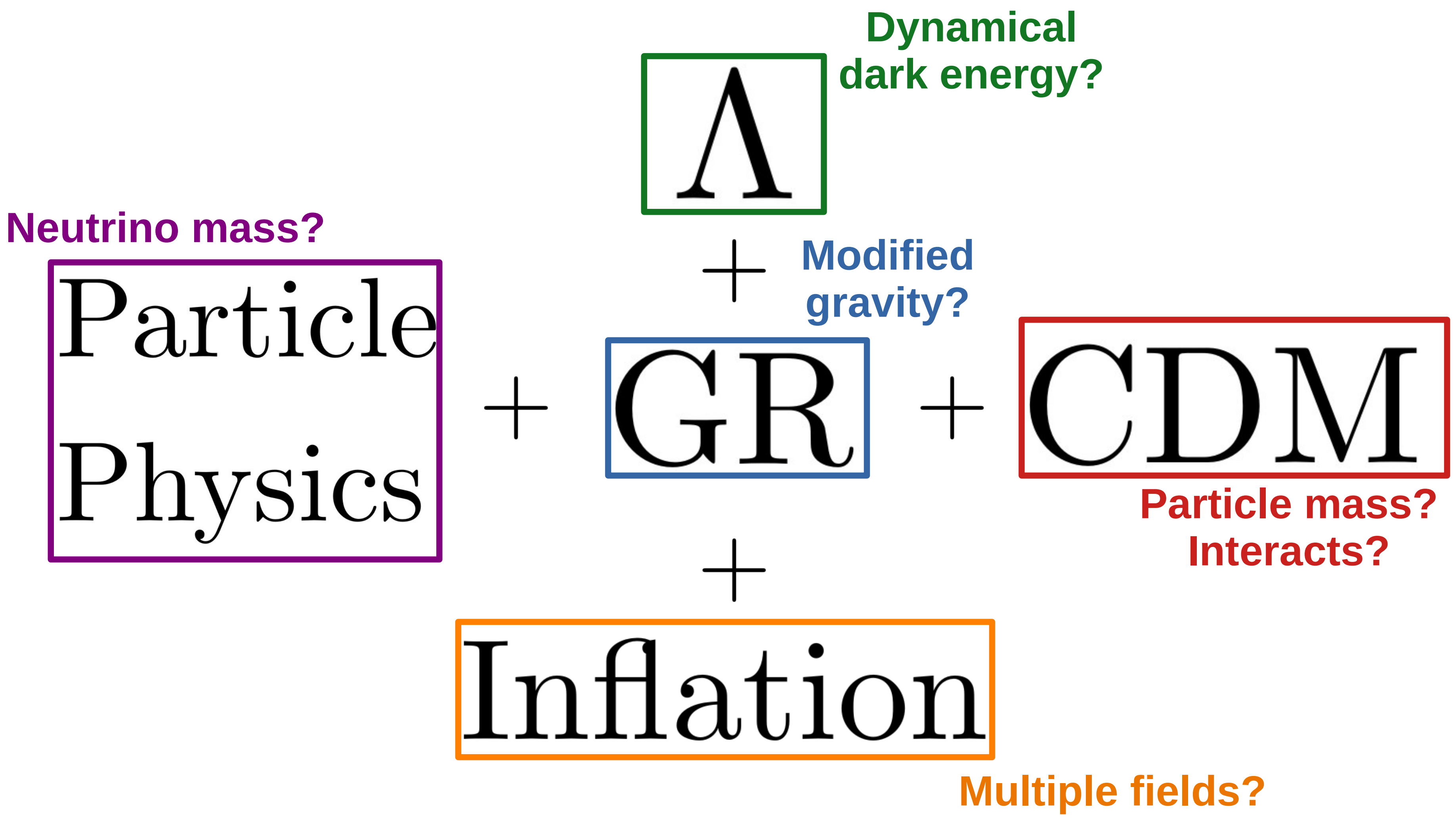
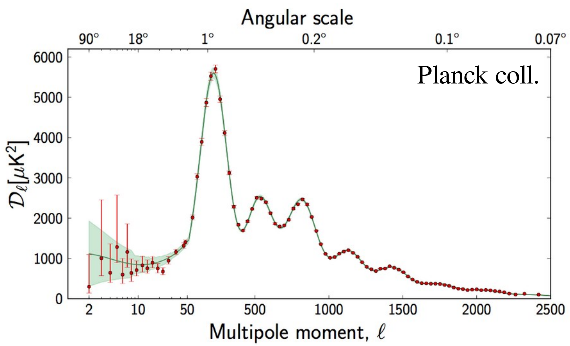
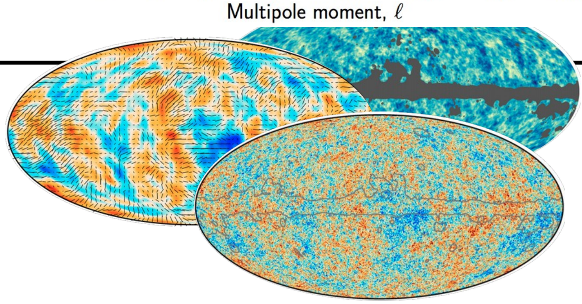


Lots of observational data

Cosmic Microwave Background

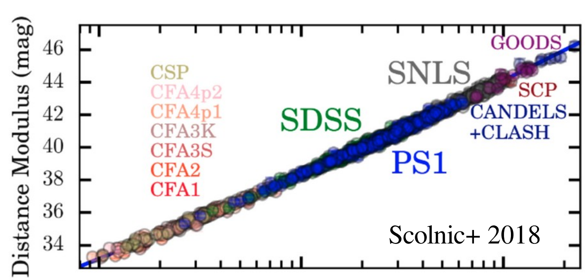
- Probably the most solid support for LCDM.
- Existing surveys: WMAP, Planck, ACT, SPT.
- Future surveys: Litebird, CORE, PIXIE, Simons Observatory.





Type Ia Supernovae

- First concrete evidence for the acceleration of the Universe.
- Important low-z anchor on the expansion rate.



Large-scale structure

- **Probably has the greatest potential for discoveries.**
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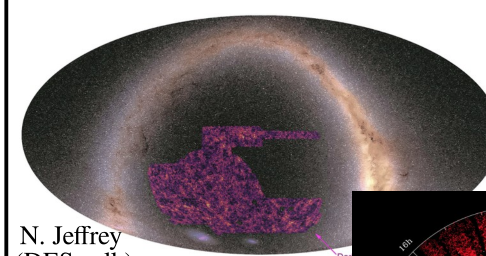
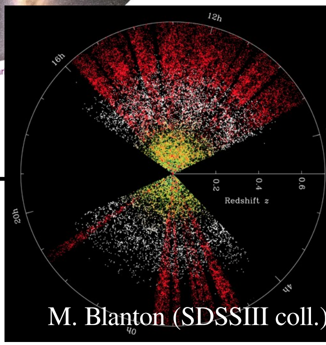


N. Jeffrey
(DES coll.)



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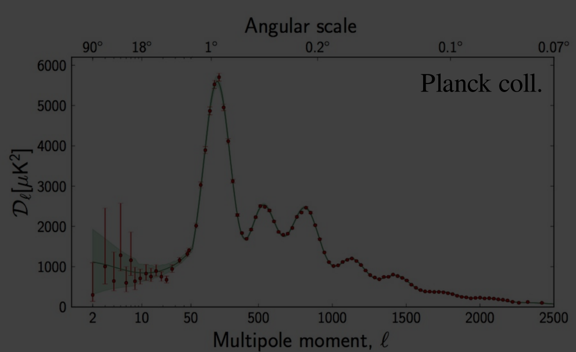

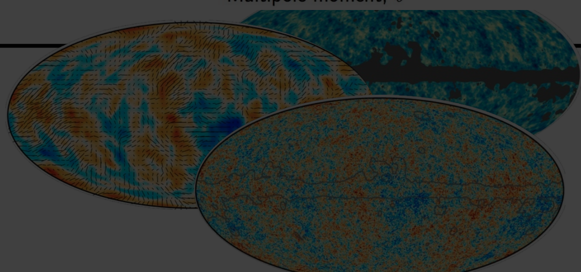

This talk !

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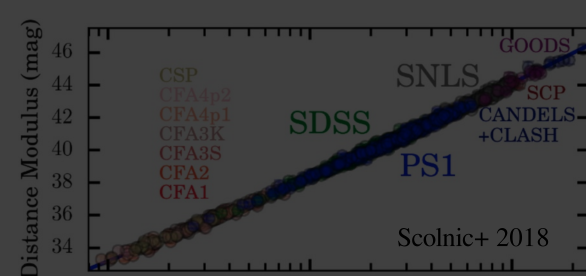

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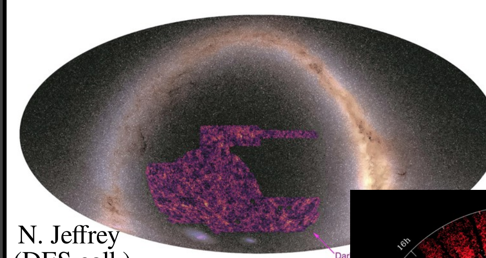

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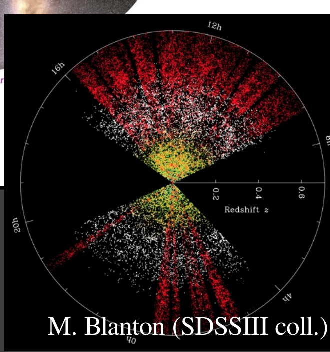
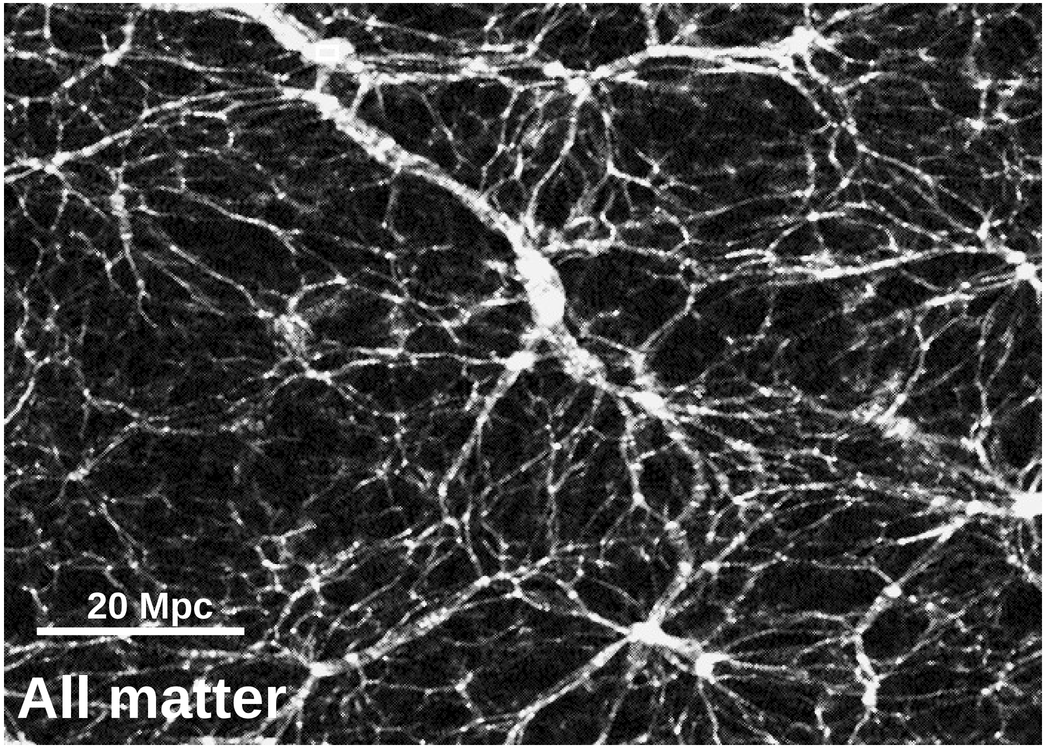


Large-scale structure and cosmology



Large-scale structure

- Forms under gravitational instability out of the primordial density fluctuations.
- Nonlinear, non-Gaussian field.
- Strong potential for discoveries on dark energy, dark matter, inflation, gravity, neutrinos.

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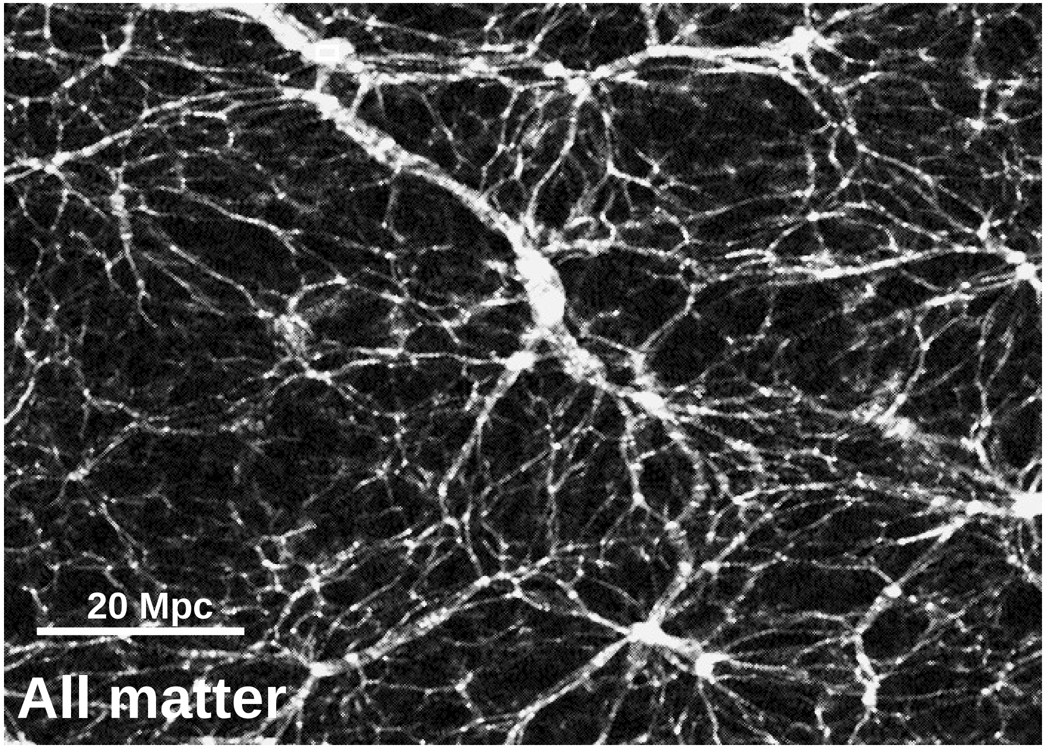

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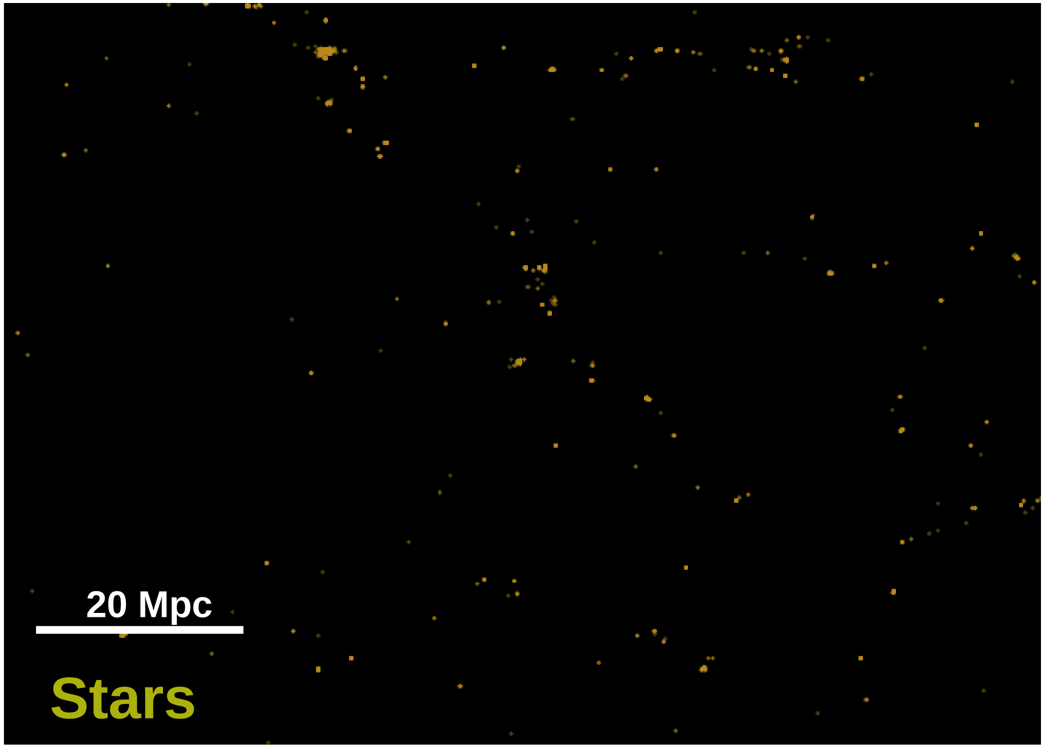
Outstanding modeling challenge: only ~15% of the total matter is visible!

Total matter = dark matter (~85%) + baryonic matter (gas, galaxies, clusters) (~15%)

Large-scale structure and cosmology



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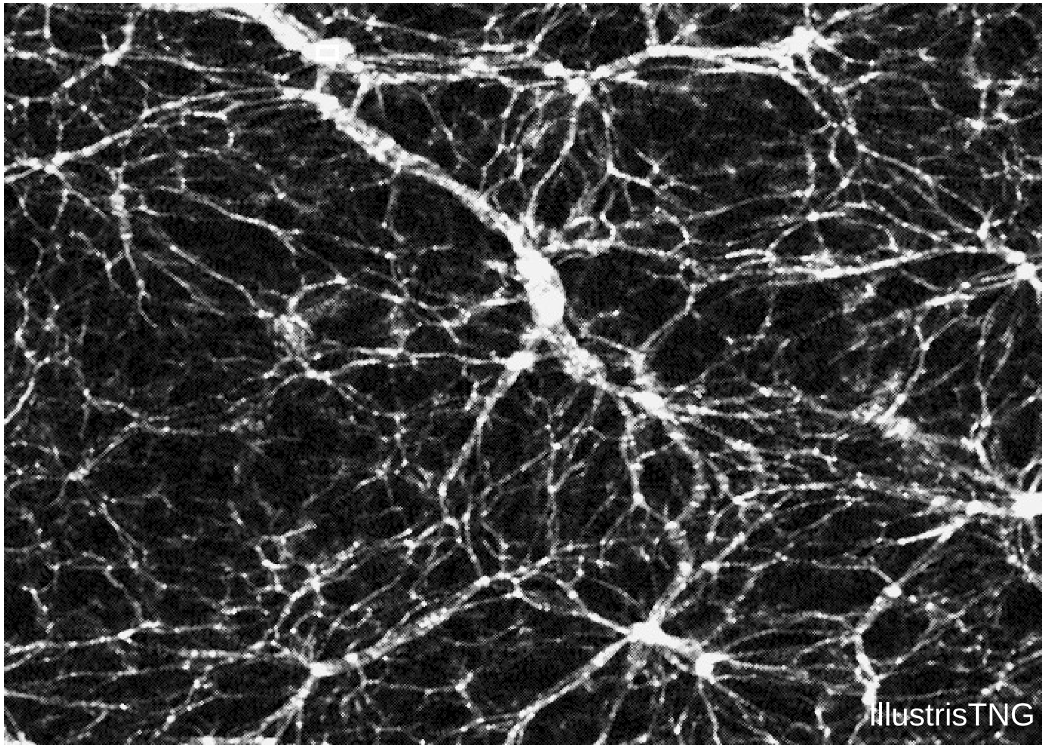
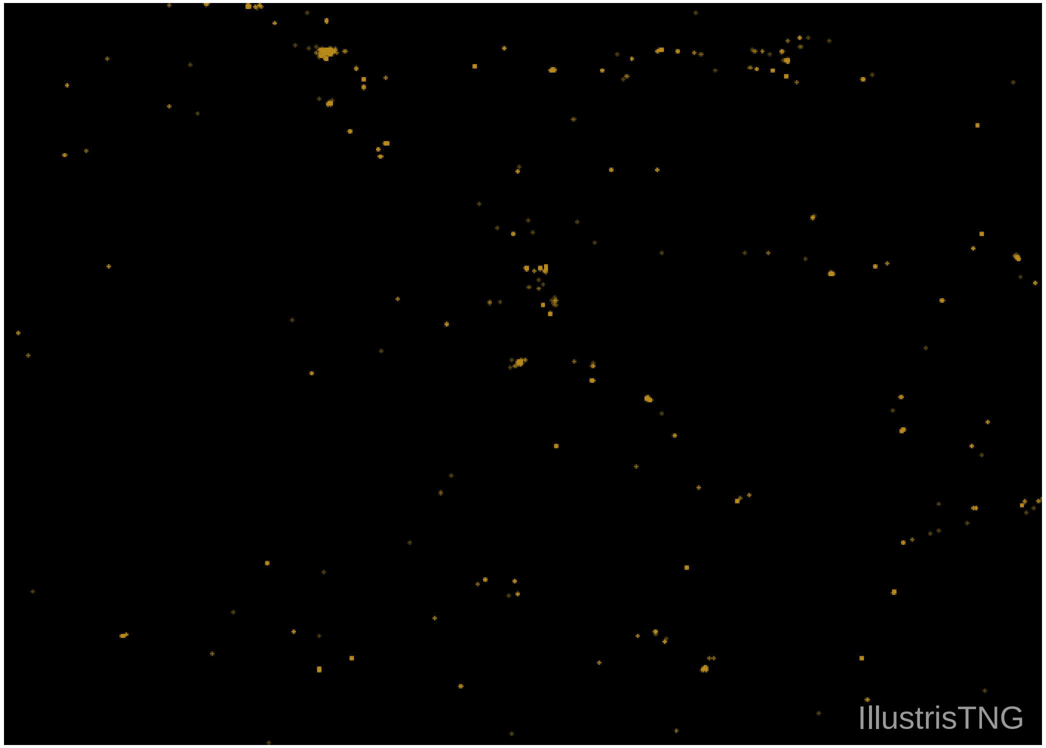
Exit light enter night

Large scale structure



Stars



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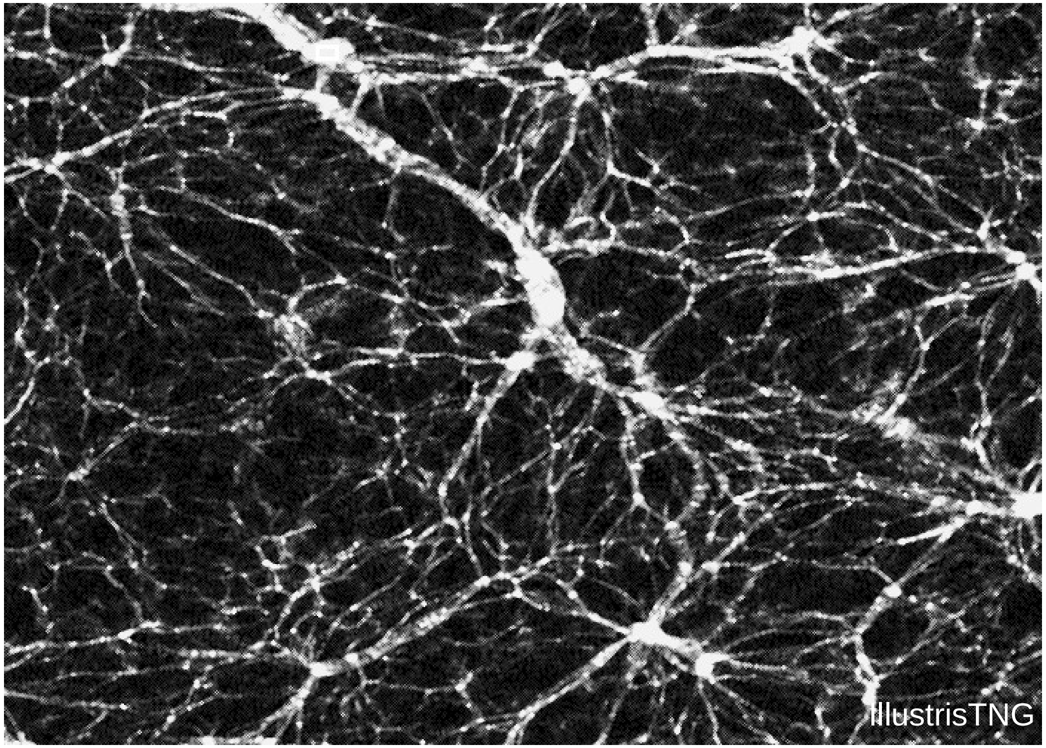
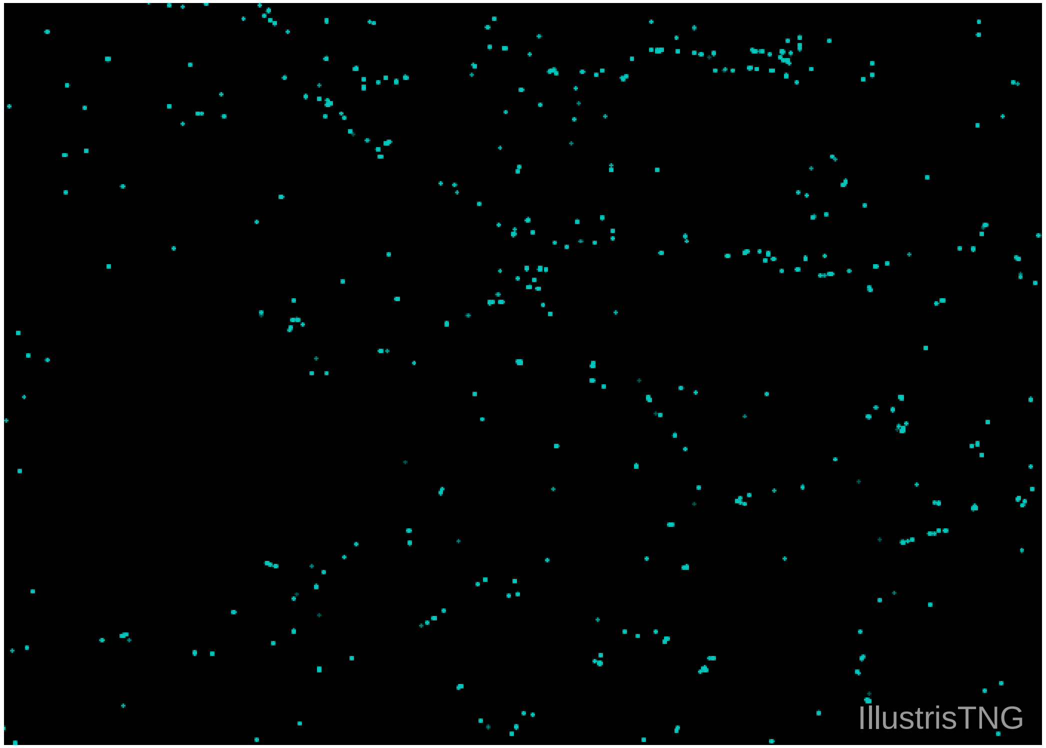


Neutral Hydrogen (21cm emission)



Exit light enter night

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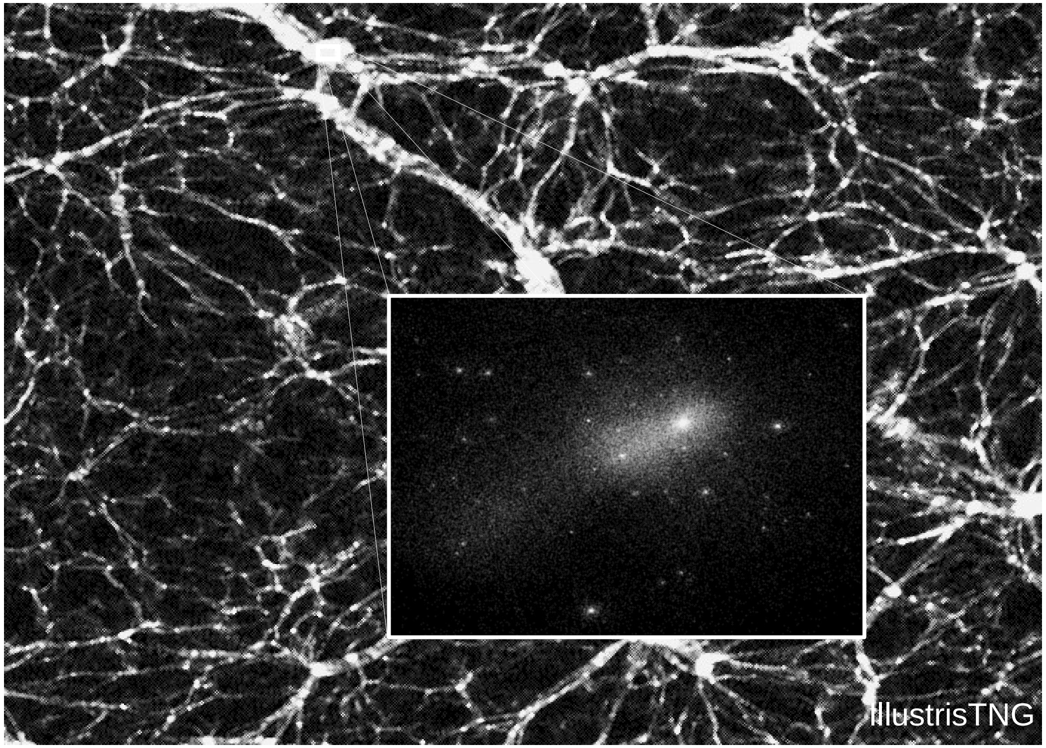

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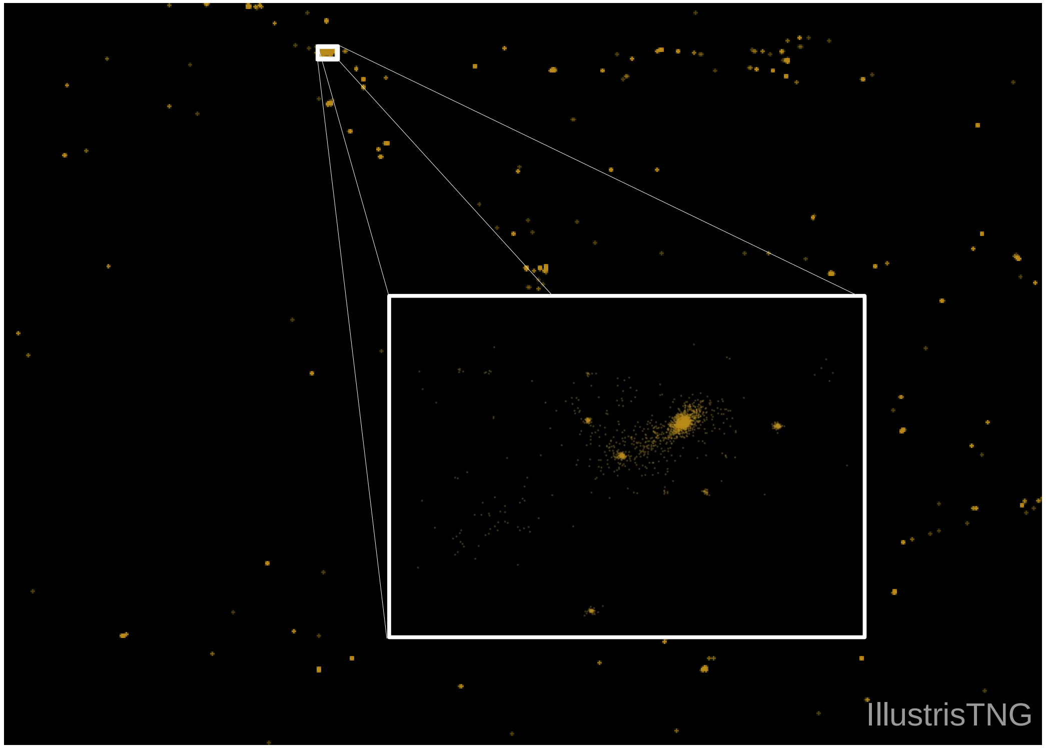

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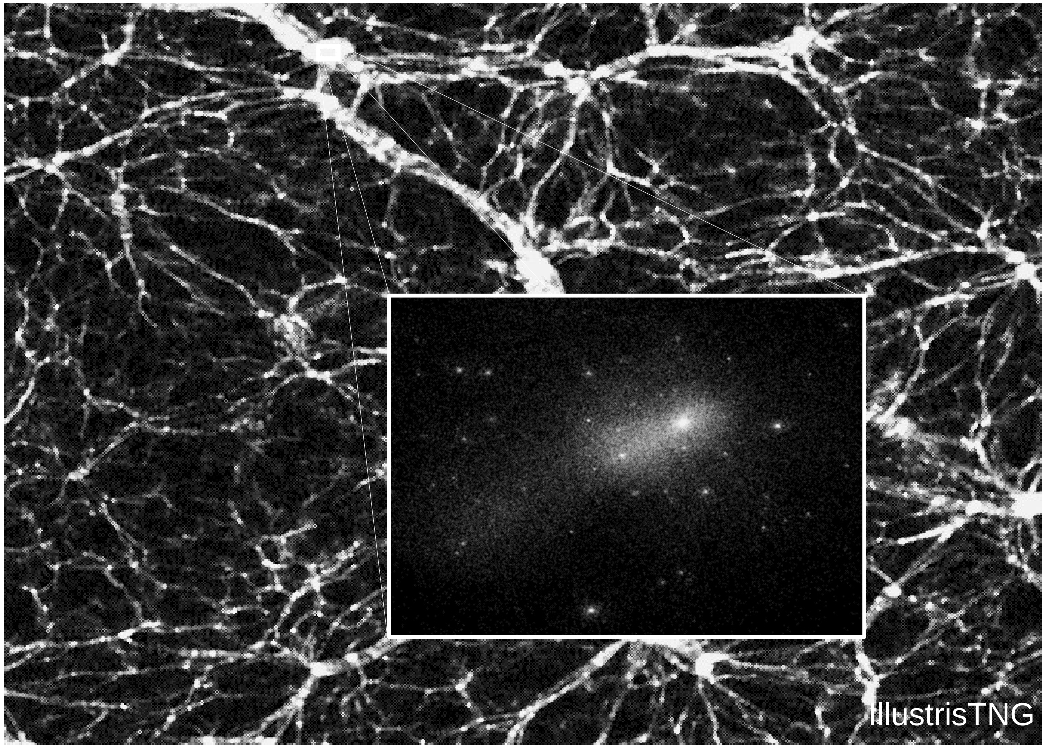

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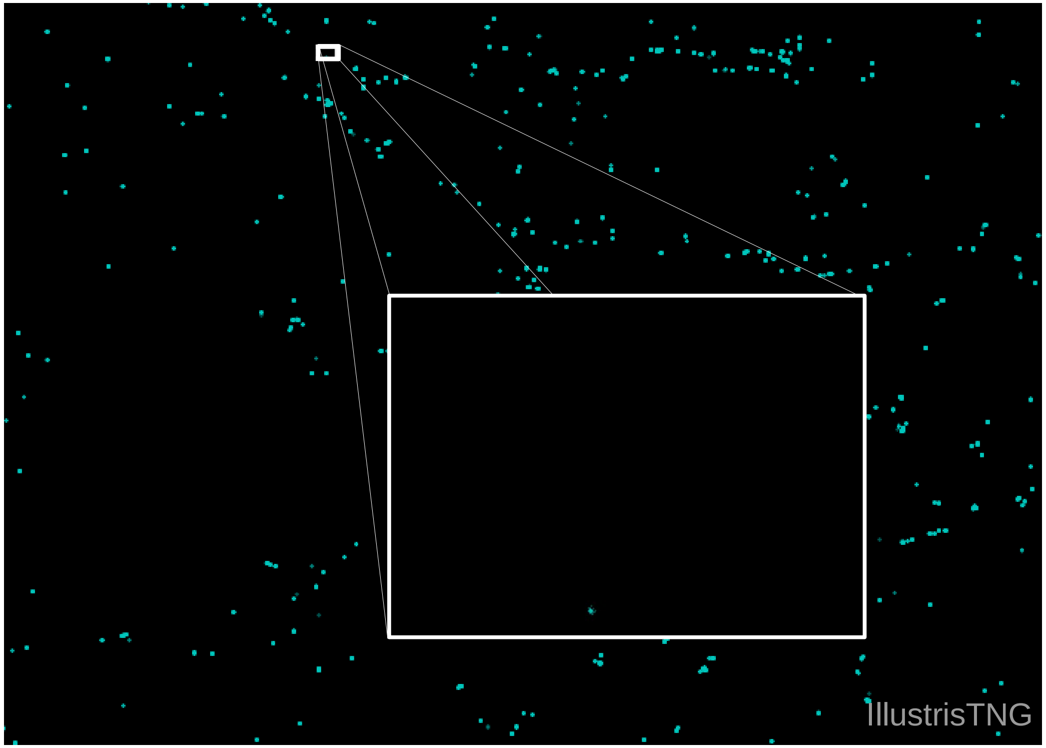

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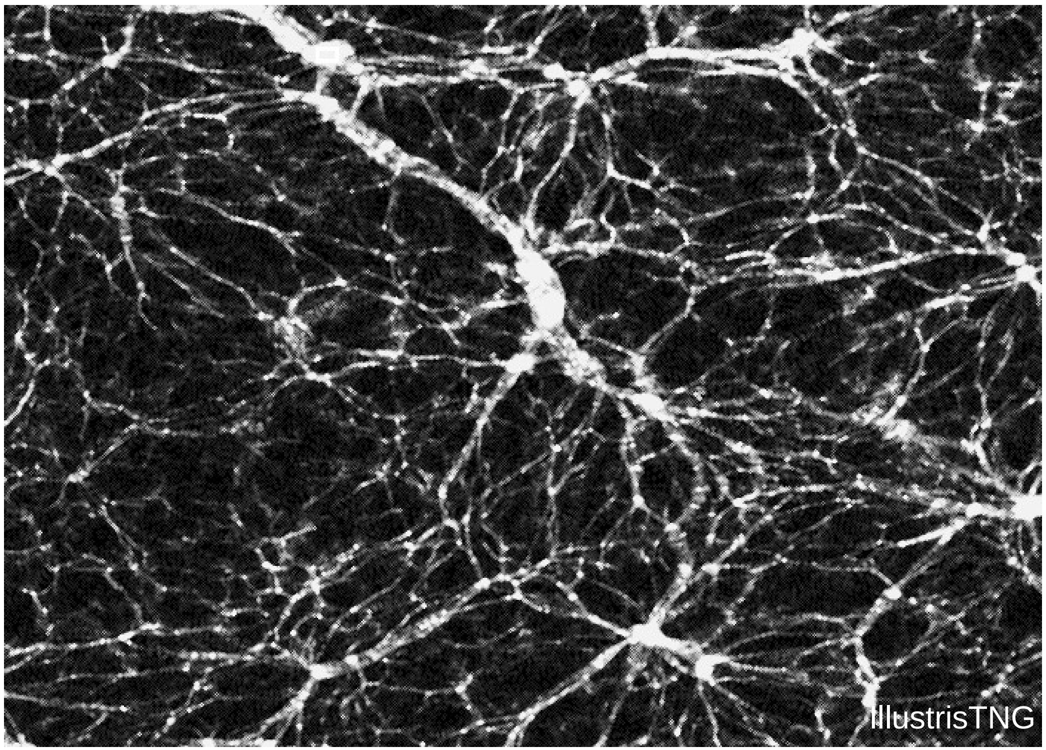
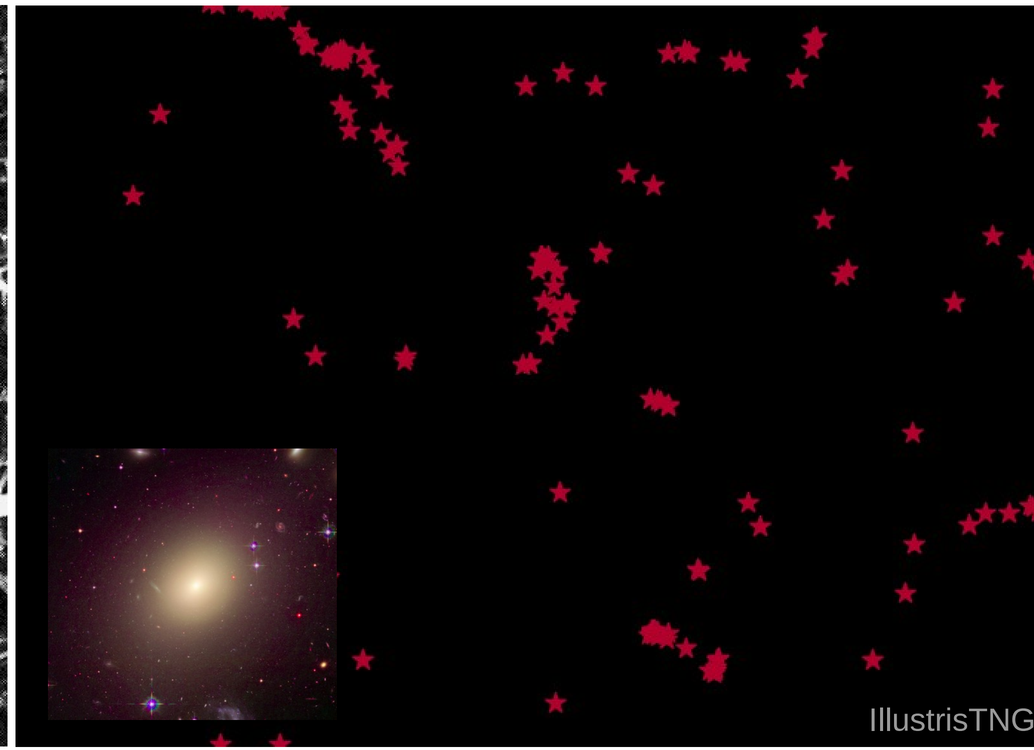


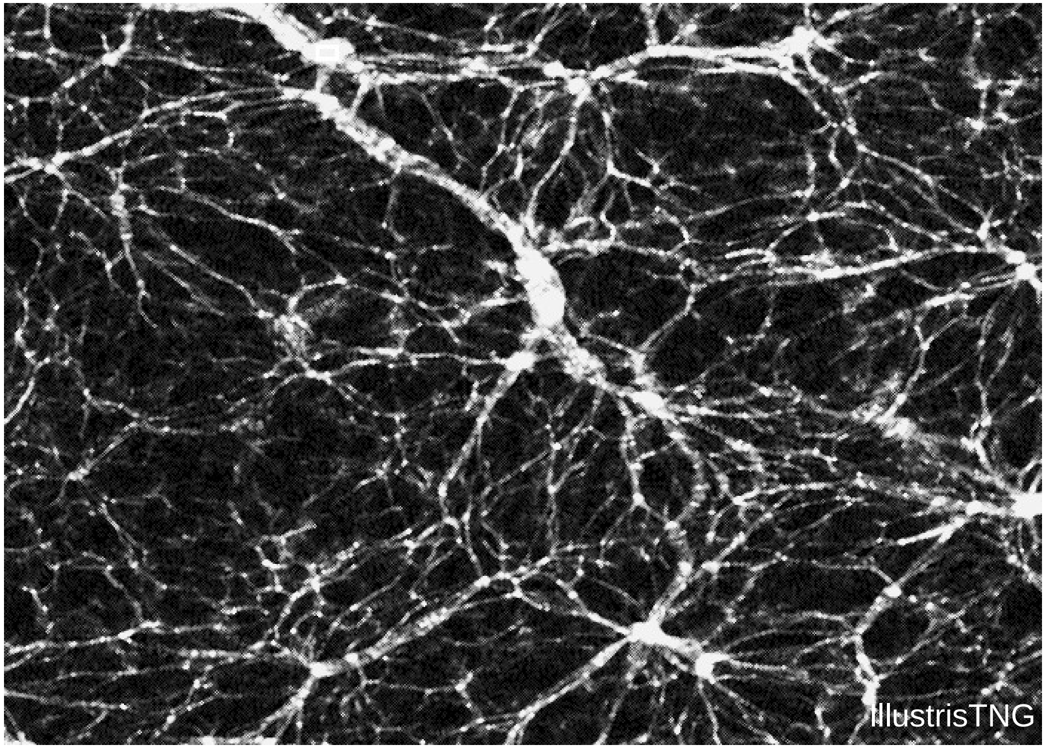
Quenched galaxies $\mathrm{sSFR} < 10^{-7}\mathrm{yr}^{-1}$



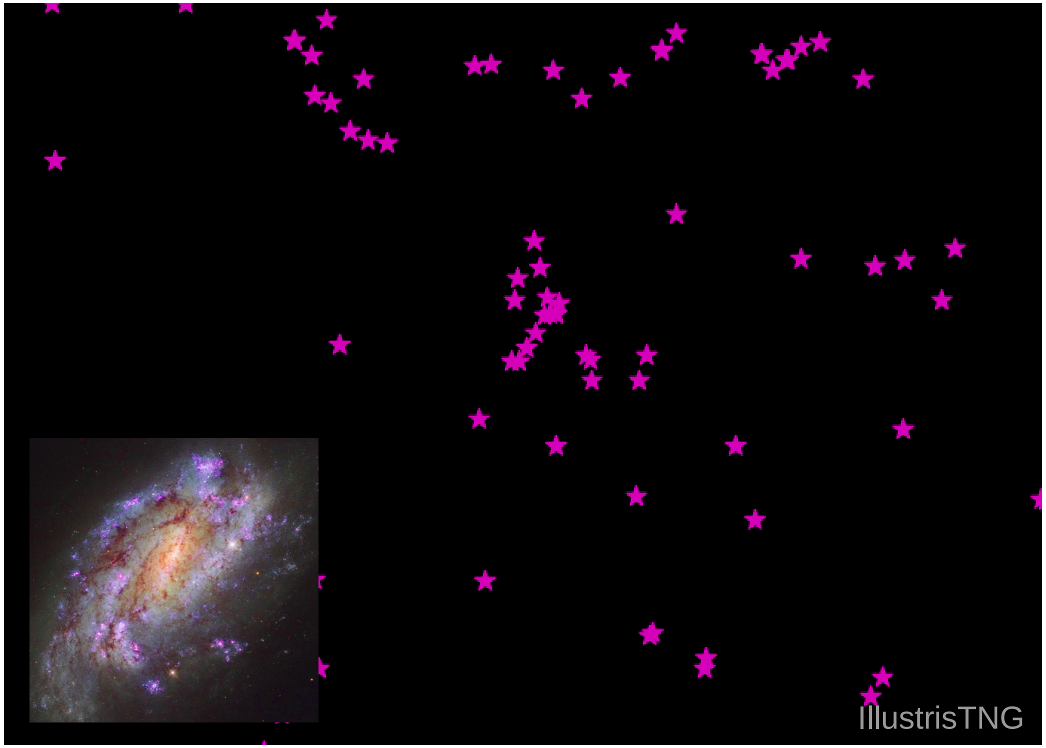
Definition: galaxy is any dark matter halo in the simulations that also contains stars.

Exit light enter night

Large scale structure



Star-forming gals. $\mathrm{sSFR} \geq 10^{-7}\mathrm{yr}^{-1}$



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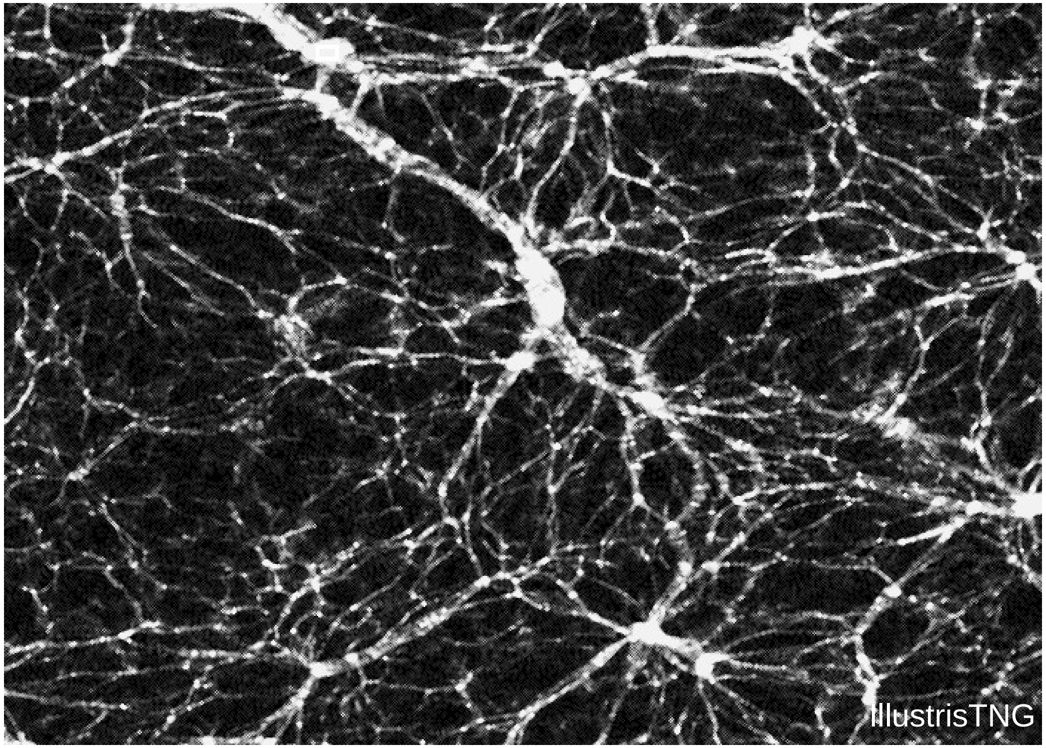
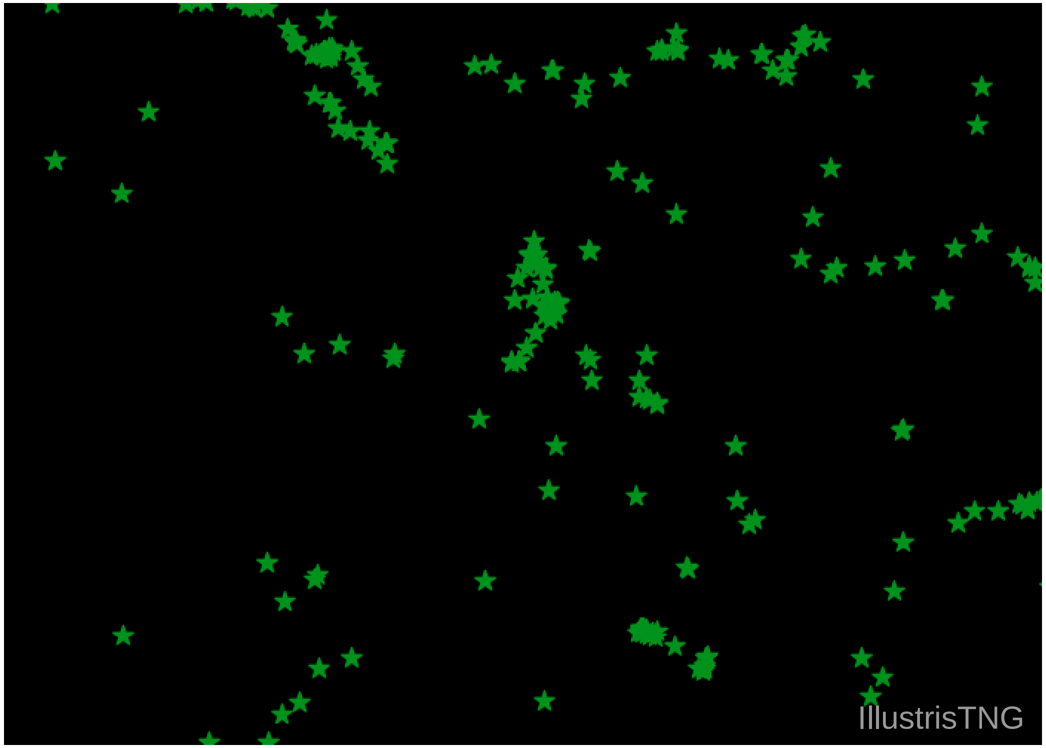


Low-mass galaxies $M_* \geq 10^9 M_\odot$



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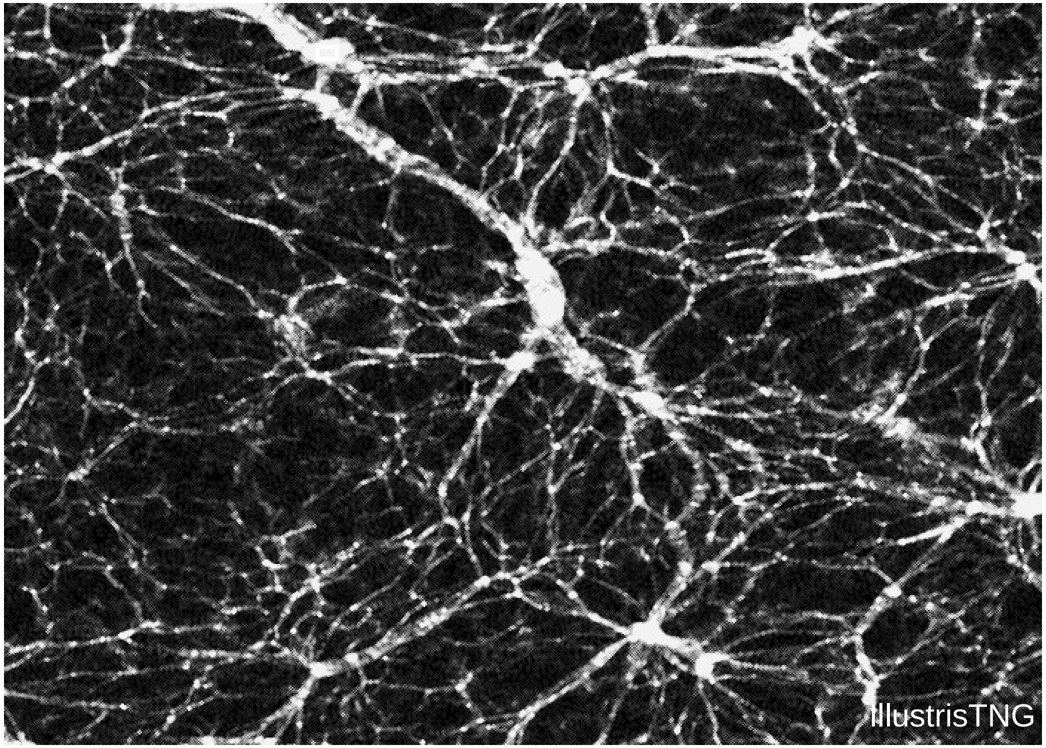
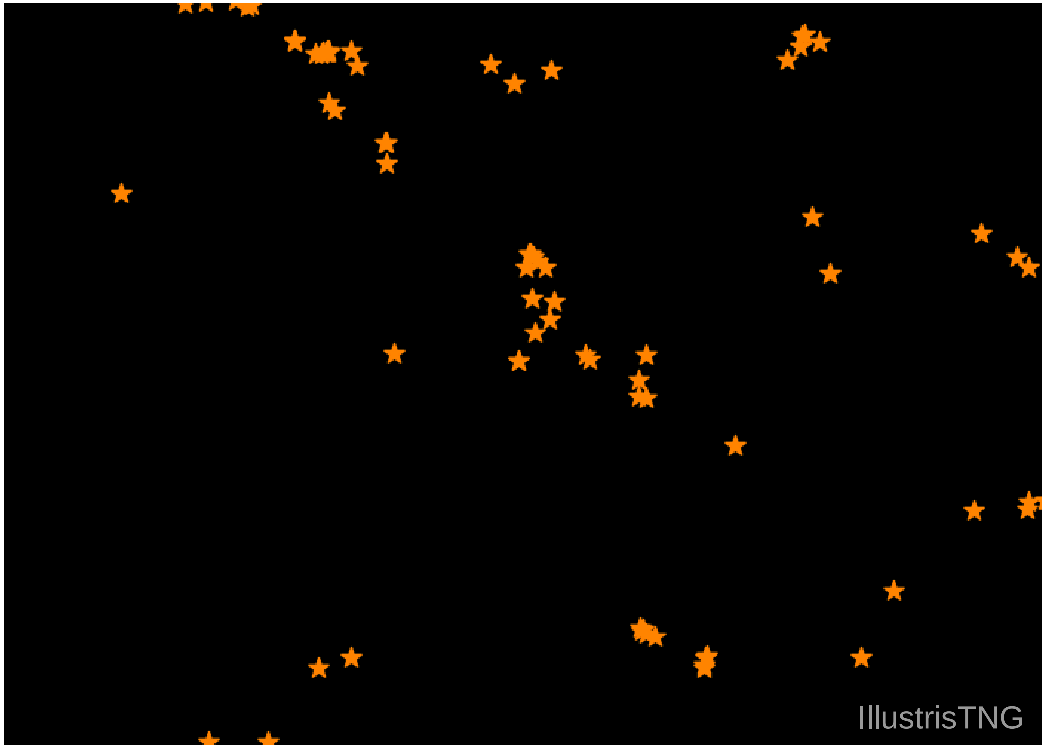


Mid-mass galaxies $M_* \geq 10^{10} M_\odot$



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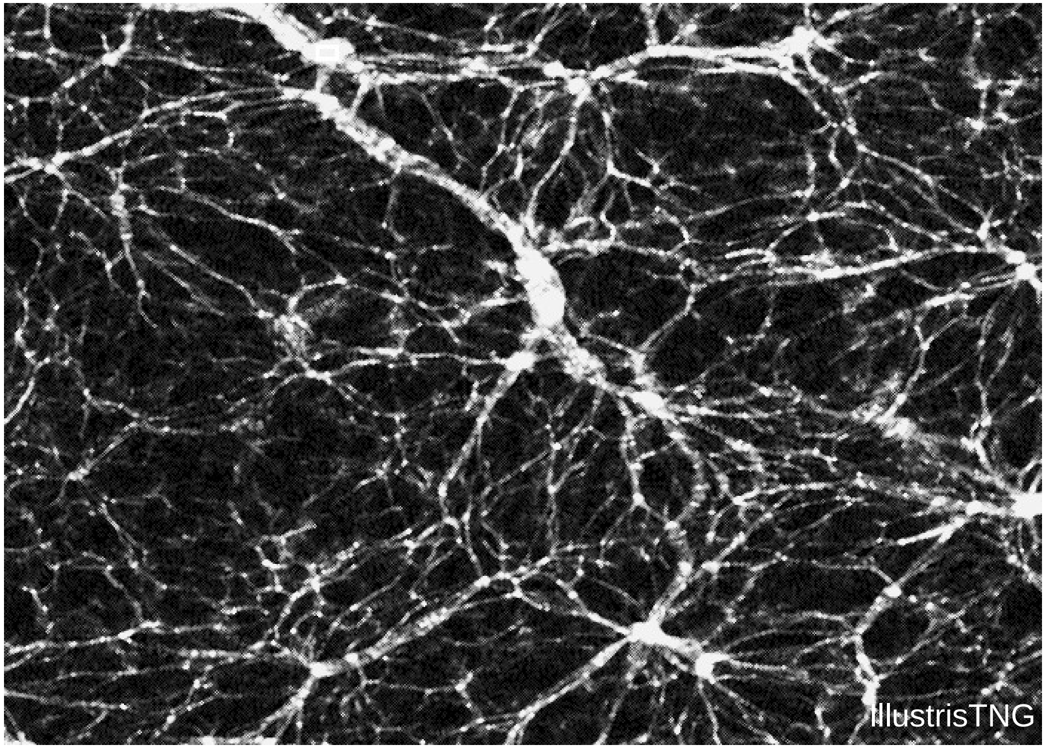
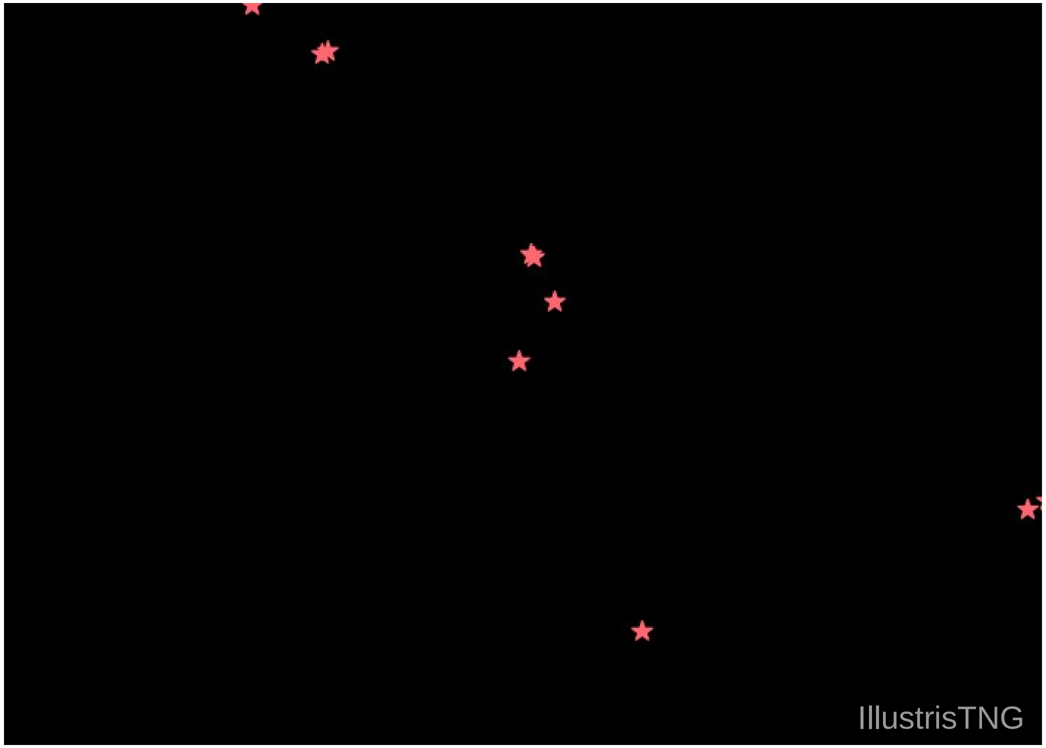


High-mass galaxies $M_* \geq 10^{11} M_\odot$



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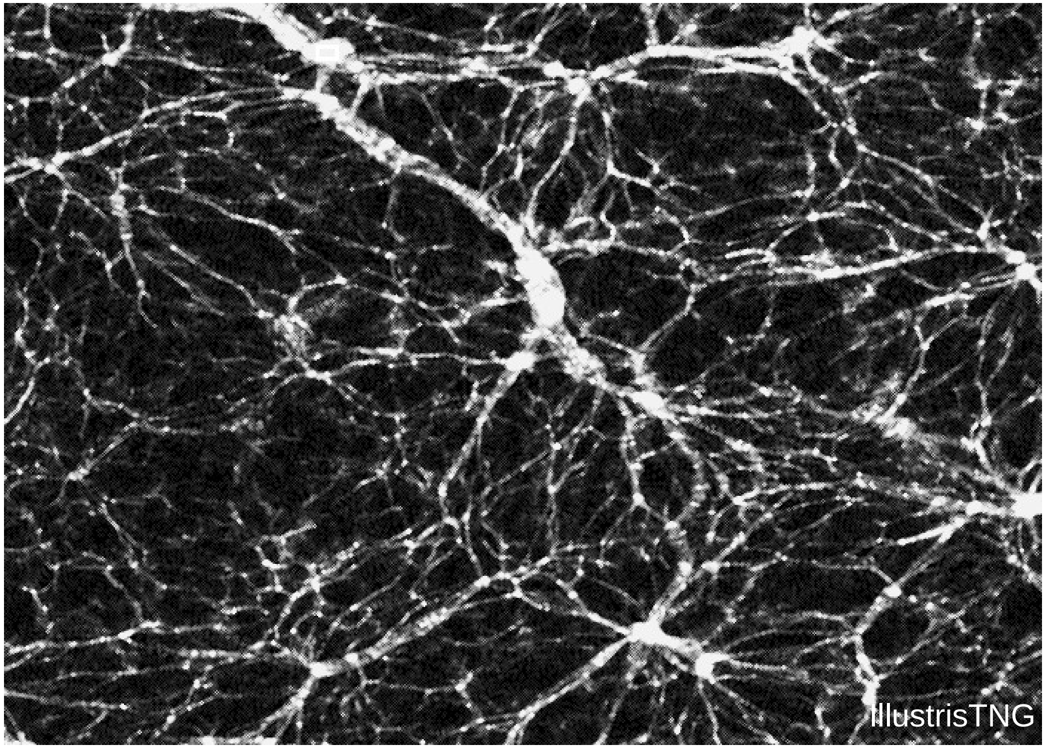
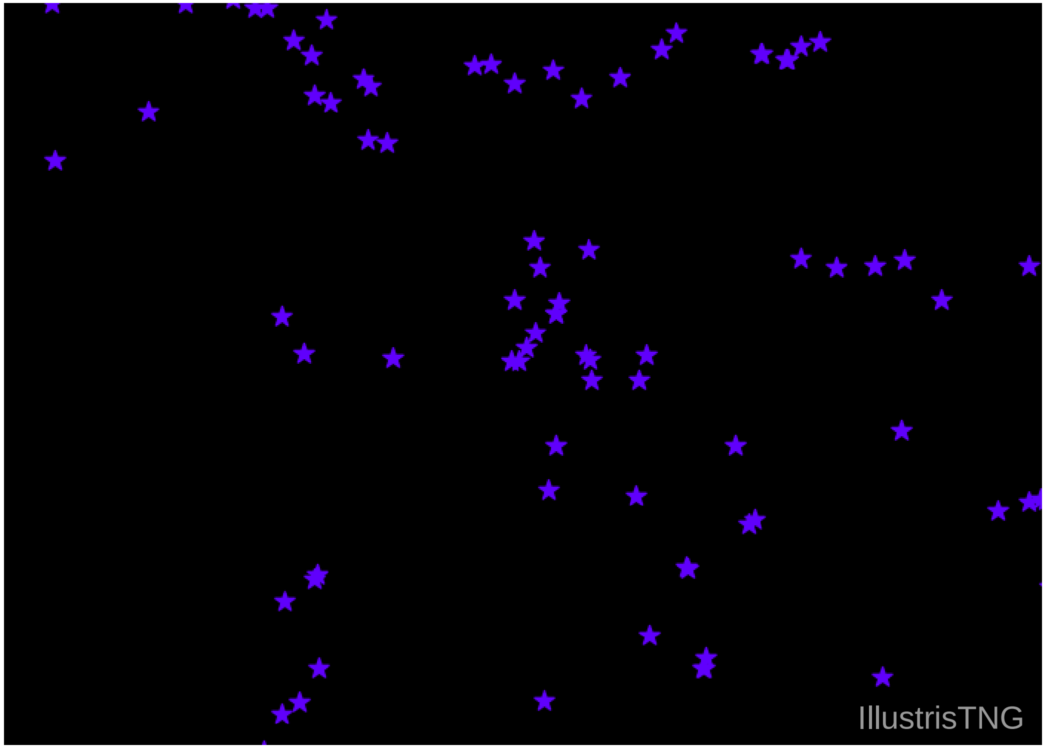


Blue galaxies $(g - r) < 0.5$



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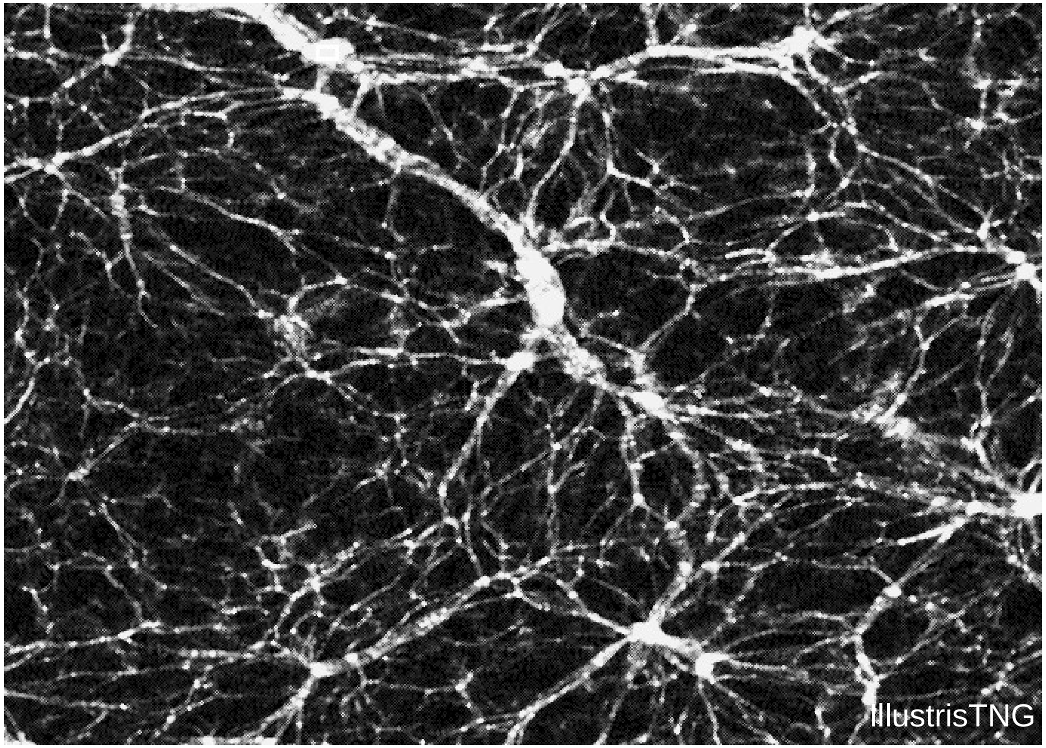
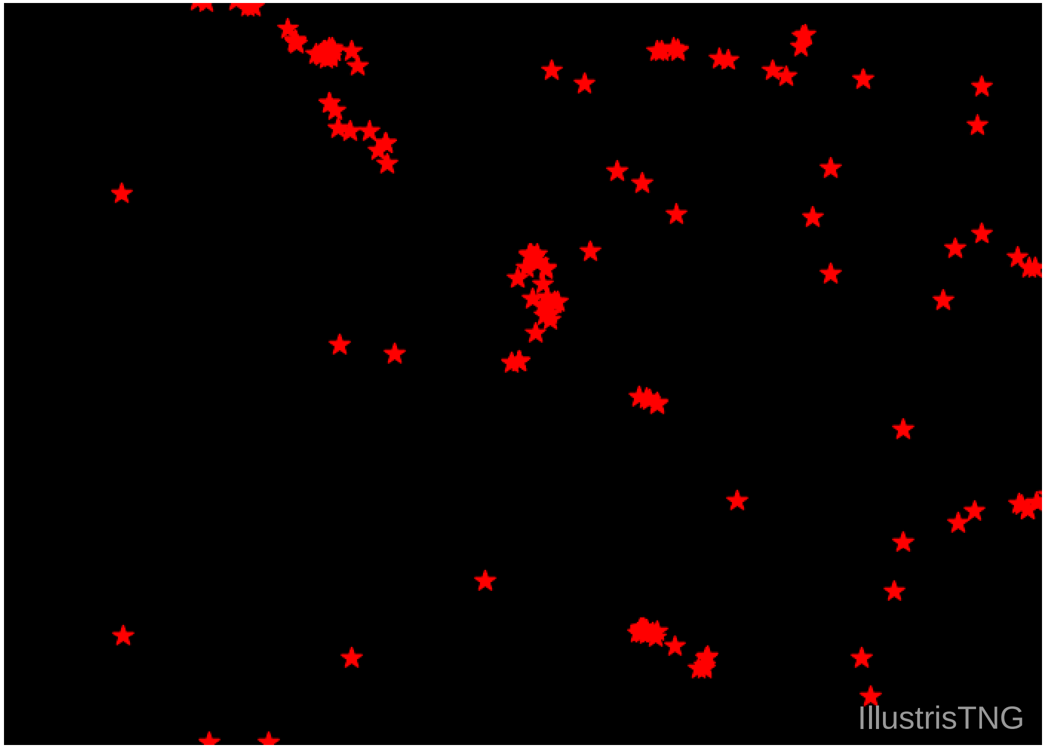


Red galaxies $(g - r) \geq 0.5$



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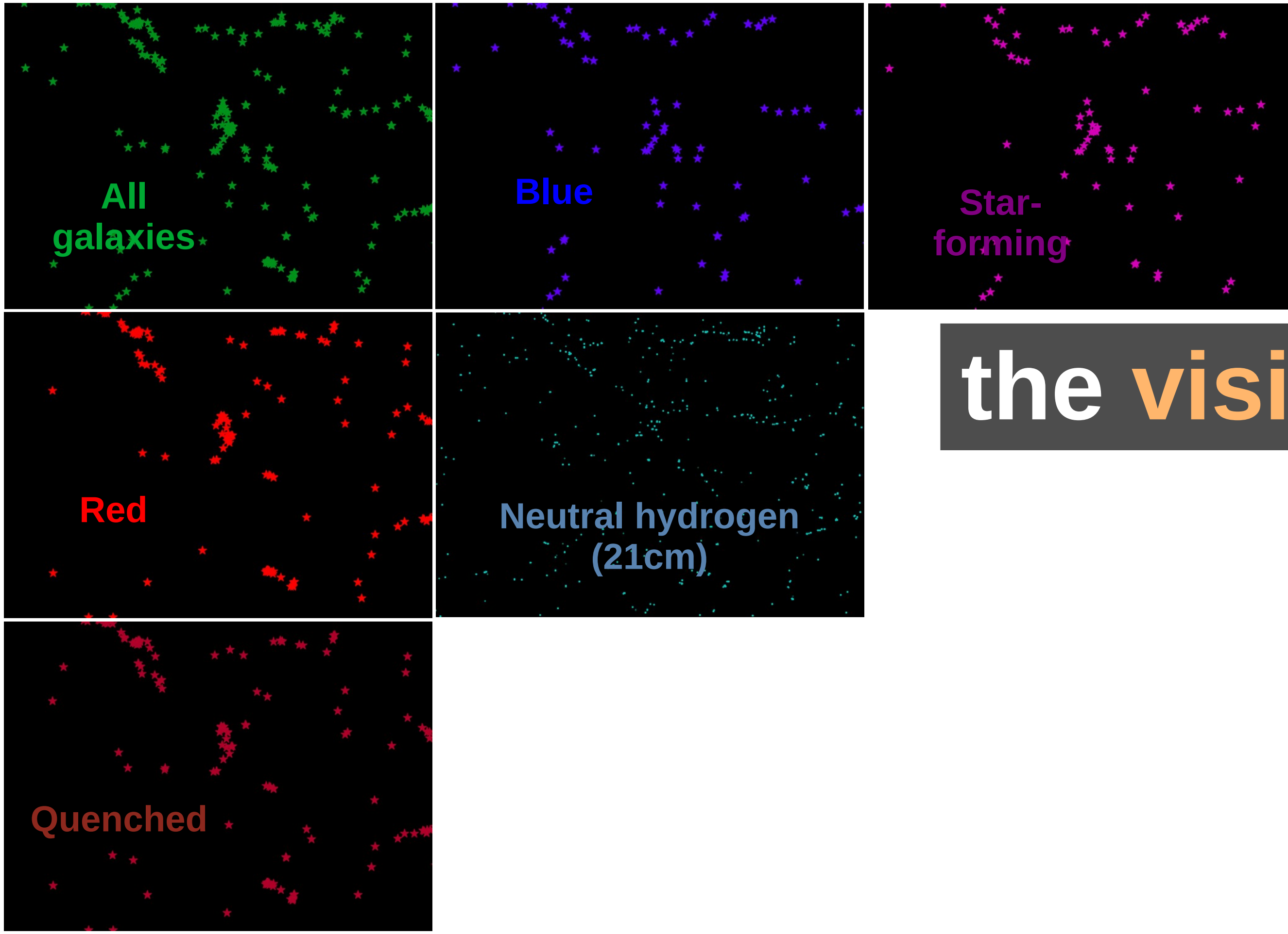
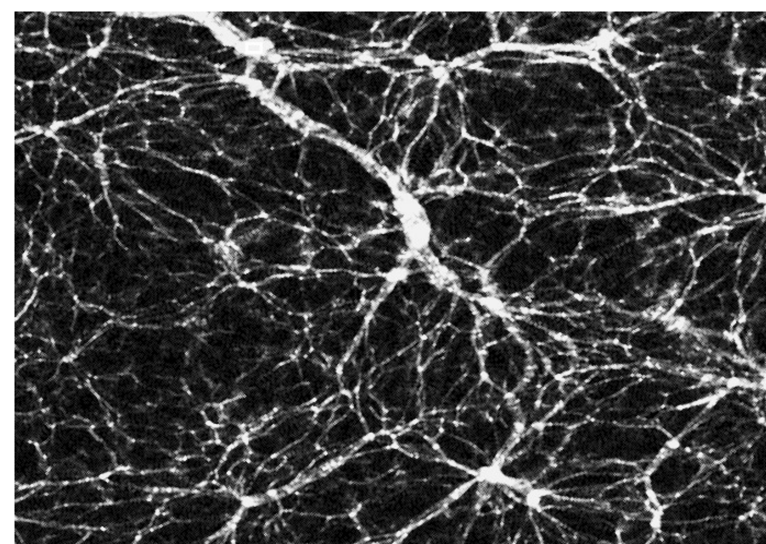
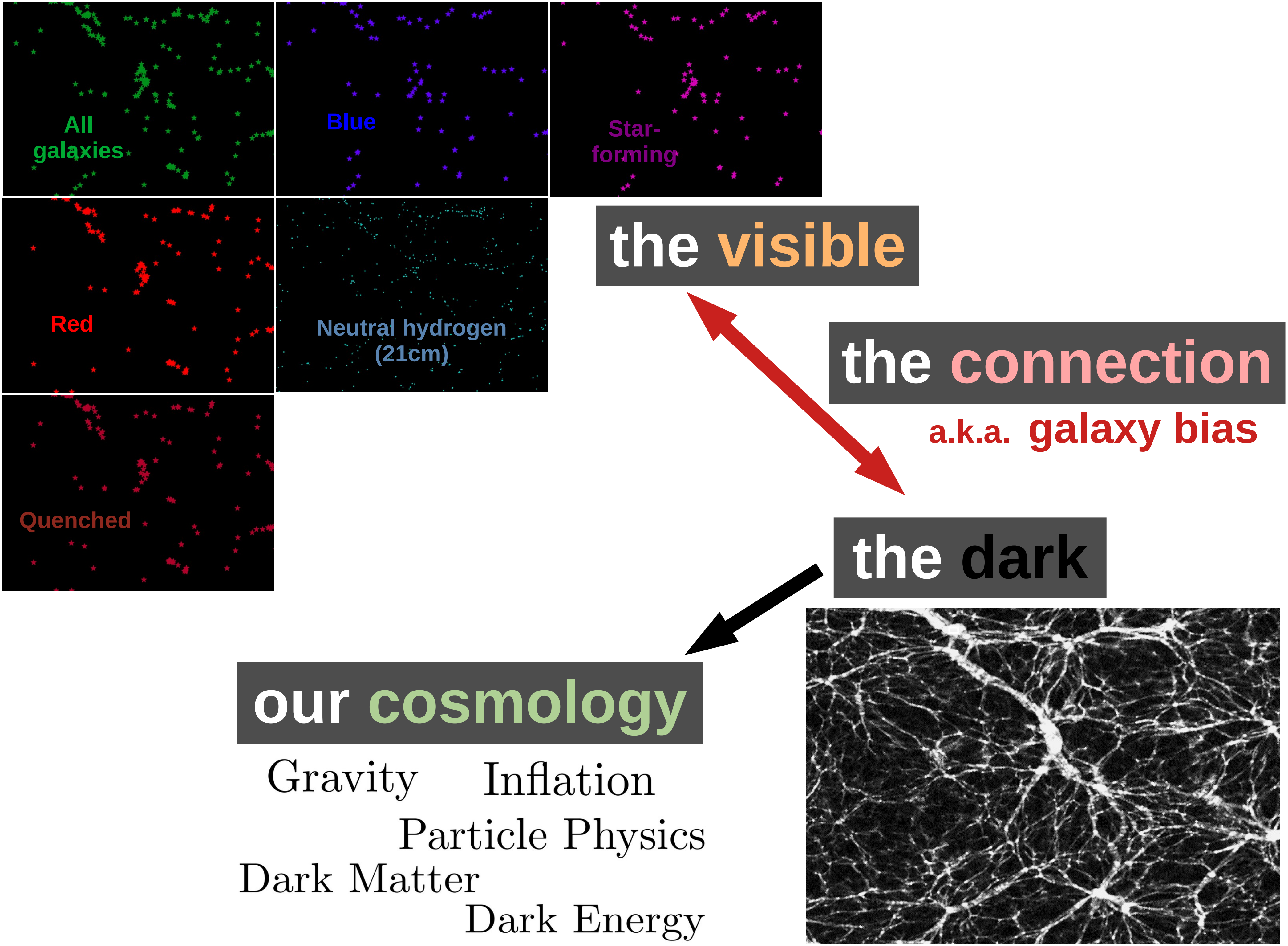


the visible

the dark




All galaxies
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a.k.a. galaxy bias
the dark
our cosmology
Gravity
Inflation
Particle Physics
Dark Matter
Dark Energy

Outline

- **What is galaxy bias?**

- **Recent results from galaxy formation simulations.**

- **Consequences for tests of inflation using galaxy data.**

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What is galaxy bias?

Desjacques, Jeong & Schmidt (2016)

How does galaxy formation depend on its **dark** environment ?

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How does galaxy formation depend on its **dark** environment ?

Local galaxy number density

Global galaxy number density

Large-scale perturbations (density, tidal, potential, etc.)

Stochasticity (shot-noise)

$$n_{\rm g}(\boldsymbol{x}, z) = \bar{n}_{\rm g}(z)\left[1 + \sum_{\mathcal{O}} b_{\mathcal{O}}(z)\mathcal{O}(\boldsymbol{x}, z)\right] + \epsilon(\boldsymbol{x}, z)$$

Bias parameters

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Local galaxy number density — $n_g(\boldsymbol{x}, z)$

Global galaxy number density — $\bar{n}_g(z)$

Large-scale perturbations (density, tidal, potential, etc.) — $\mathcal{O}(\boldsymbol{x}, z)$

Bias parameters — $b_{\mathcal{O}}(z)$

Stochasticity (shot-noise) — $\epsilon(\boldsymbol{x}, z)$

↓

The bias parameters are the **response** of galaxy formation to large-scale perturbations.

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Desjacques, Jeong & Schmidt (2016)

How does galaxy formation depend on its **dark** environment ?

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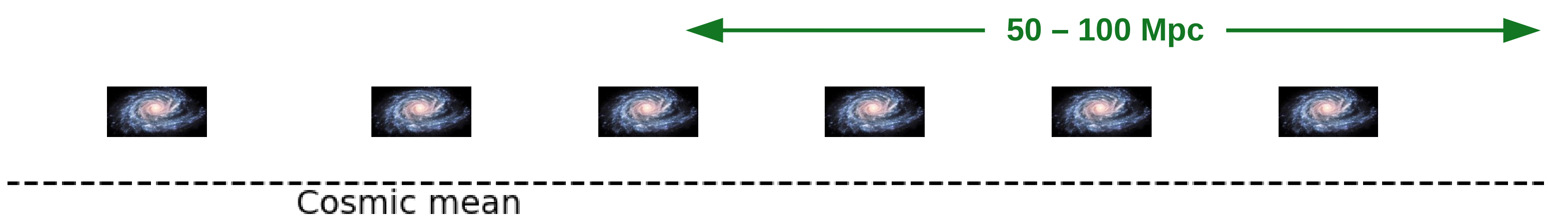

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Local galaxy number density — **Global galaxy number density** — **Stochasticity (shot-noise)**

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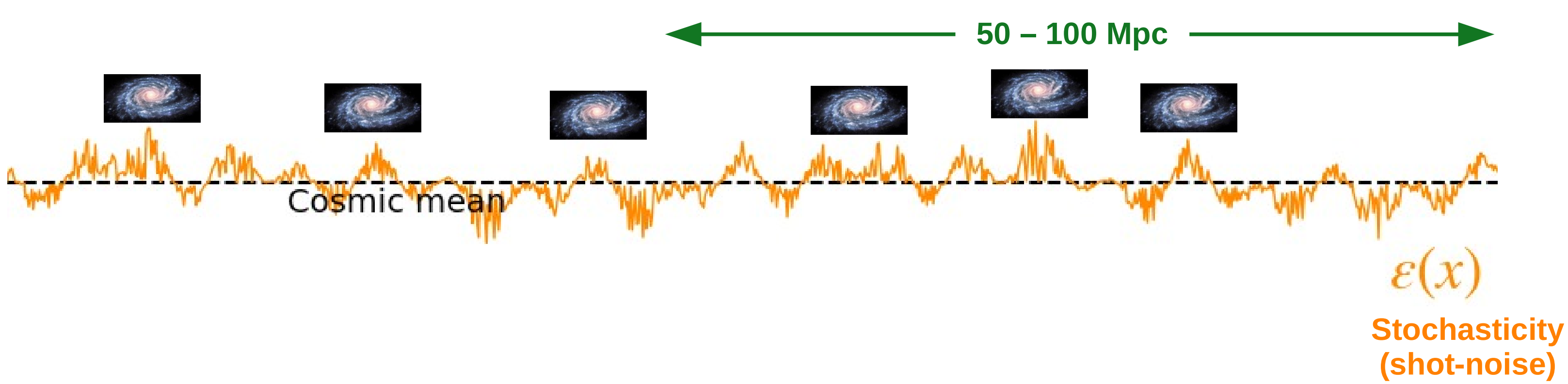

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- $n_g(\boldsymbol{x}, z)$: Local galaxy number density
- $\bar{n}_g(z)$: Global galaxy number density
- $\mathcal{O}(\boldsymbol{x}, z)$: Large-scale perturbations (density, tidal, potential, etc.)
- $b_{\mathcal{O}}(z)$: Bias parameters
- $\epsilon(\boldsymbol{x}, z)$: Stochasticity (shot-noise)

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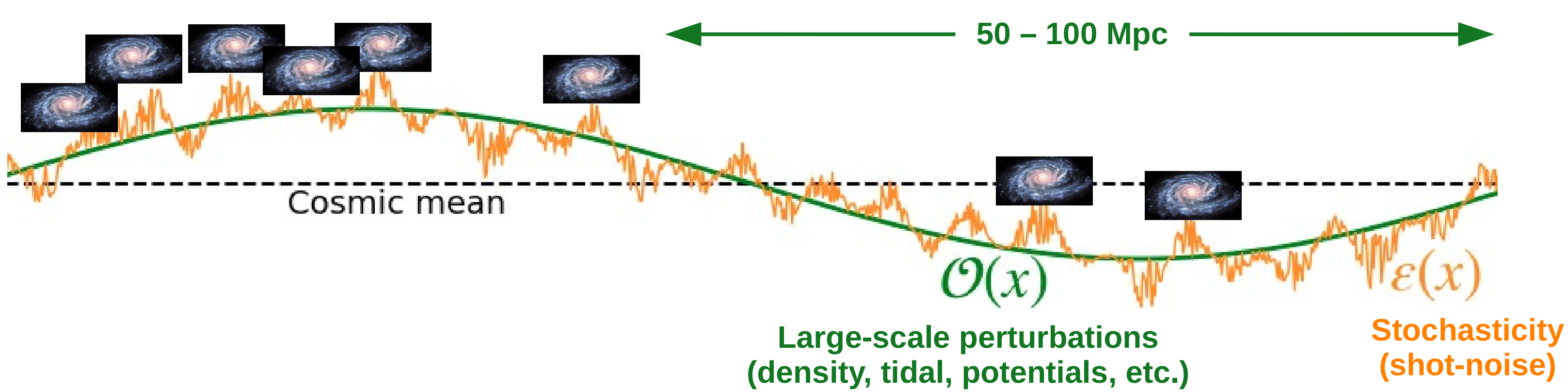

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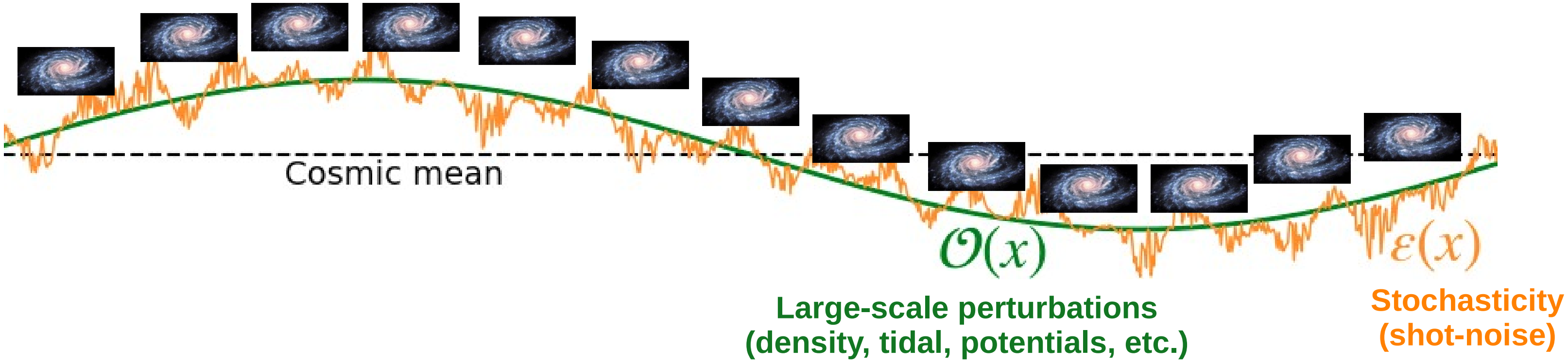
How does galaxy formation depend on its **dark** environment ?

$$b_{\mathcal{O}} = 0$$



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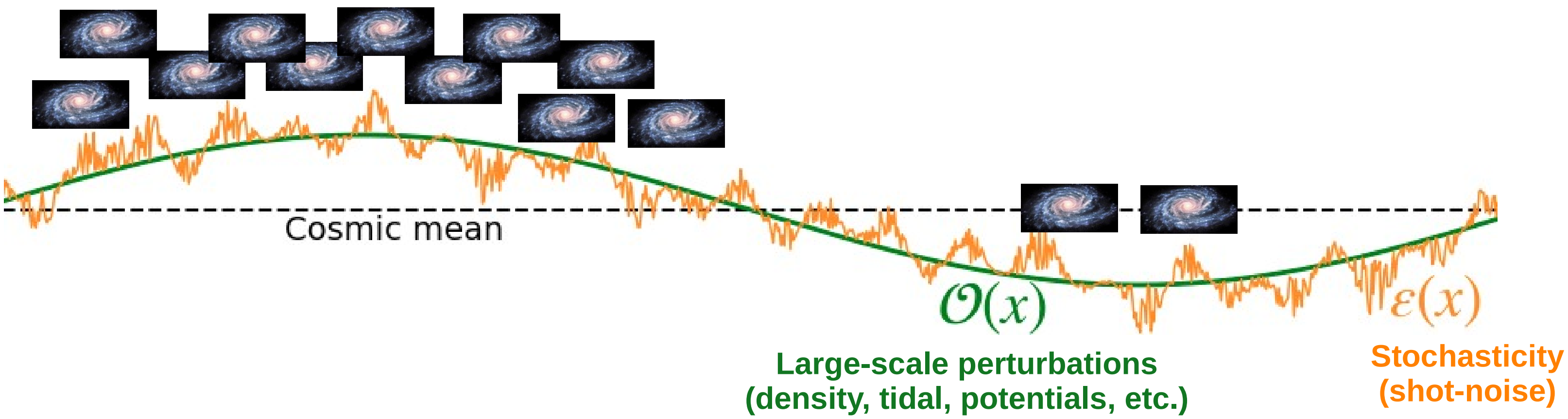
How does galaxy formation depend on its **dark** environment ?

$$b_{\mathcal{O}} > 0$$



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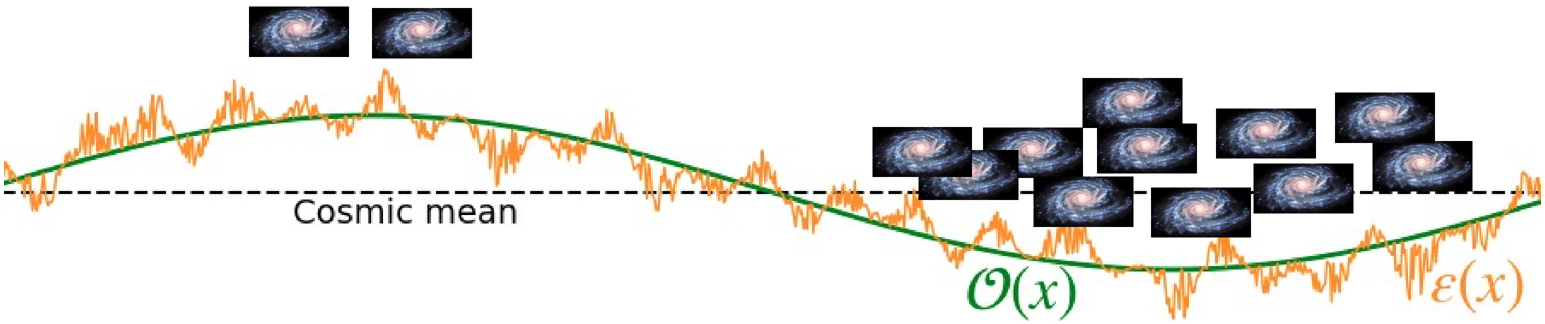

Large-scale perturbations (density, tidal, potentials, etc.)

Two reasons to study galaxy bias

Galaxy data = Cosmology x Galaxy bias

(dark energy, gravity, inflation, etc)

(galaxy-environment connection)

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Robust constraints on cosmology

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Insights on the galaxy-environment connection

A long history of **halo bias** studies

Density contrast

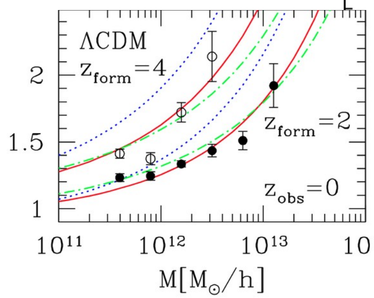
$$\delta_g(\boldsymbol{x}, z) \overset{\text{det.}}{=} b_1(z)\delta_m(\boldsymbol{x}, z) + b_\phi(z) f_{\rm NL}\phi(\boldsymbol{x})$$

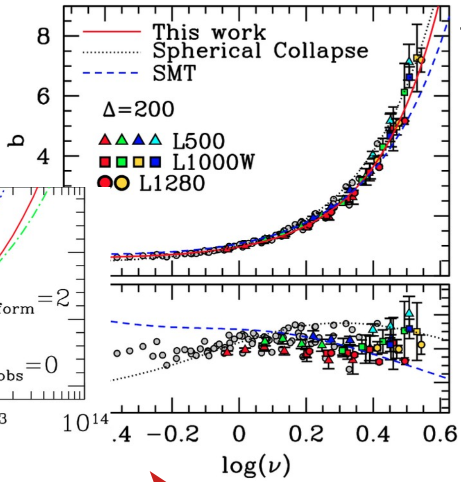
$$+ \quad \frac{b_2(z)}{2}\delta_m(\boldsymbol{x}, z)^2 + b_{K^2}(z)K_{ij}(\boldsymbol{x}, z)^2 + b_{\phi\delta}(z) f_{\rm NL}\phi(\boldsymbol{x})\delta_m(\boldsymbol{x}, z)$$

P.S. No such thing as scale-dependent bias: the bias parameters are only a function of z.

A long history of **halo bias** studies

Sheth&Tormen(1999)





Tinker+(2010)

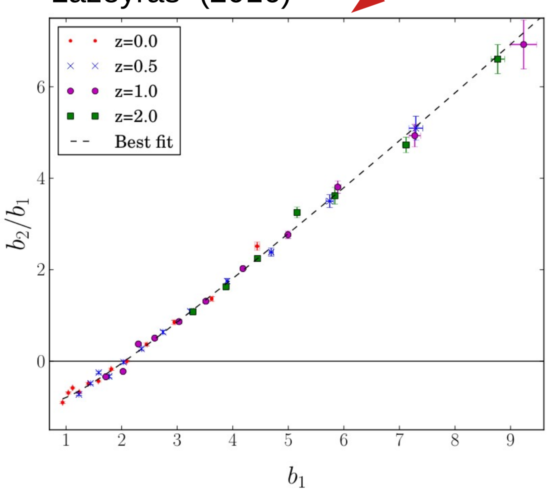
Density contrast

$$\delta_g(\boldsymbol{x}, z) \stackrel{\text{det.}}{=} b_1(z)\delta_m(\boldsymbol{x}, z) + b_\phi(z) f_{\rm NL}\phi(\boldsymbol{x})$$

Total mass density

$$+ \frac{b_2(z)}{2}\delta_m(\boldsymbol{x}, z)^2 + b_{K^2}(z) K_{ij}(\boldsymbol{x}, z)^2 + b_{\phi\delta}(z) f_{\rm NL}\phi(\boldsymbol{x})\delta_m(\boldsymbol{x}, z)$$

Lazeyras+(2016)



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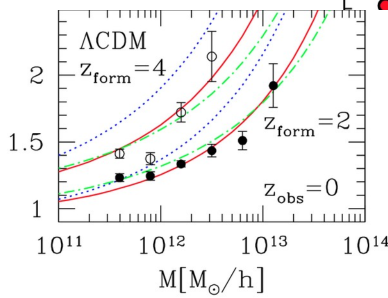
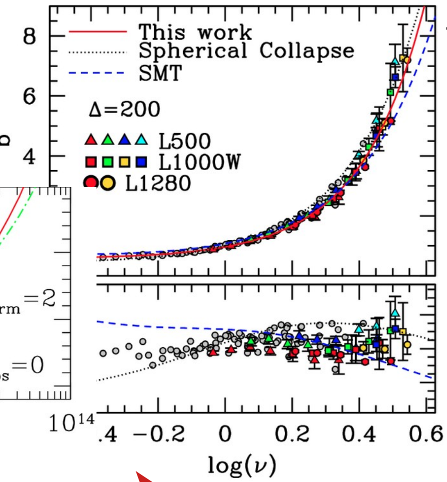


Tinker+(2010)



Density contrast

$$\delta_g(\boldsymbol{x},z) \overset{\rm det.}{=} b_1(z)\delta_m(\boldsymbol{x},z) + b_\phi(z) f_{\rm NL}\phi(\boldsymbol{x})$$

Total mass density

Tidal field

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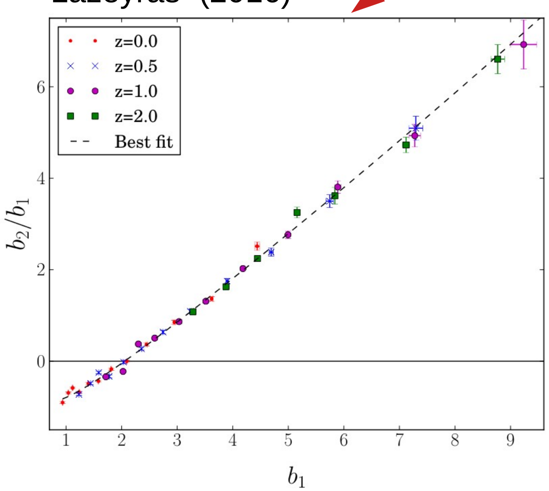
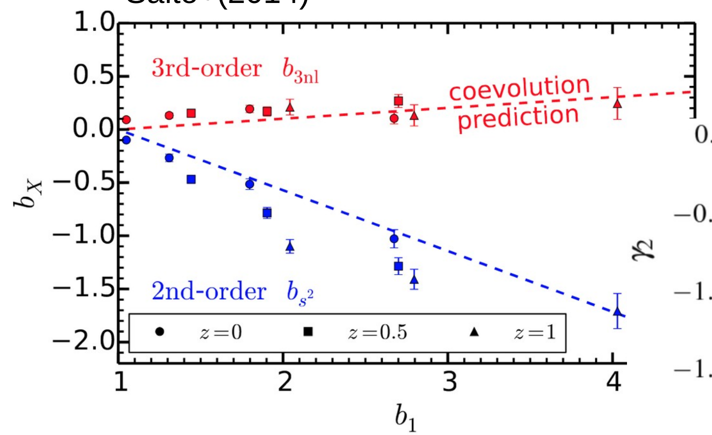


Saito+(2014)



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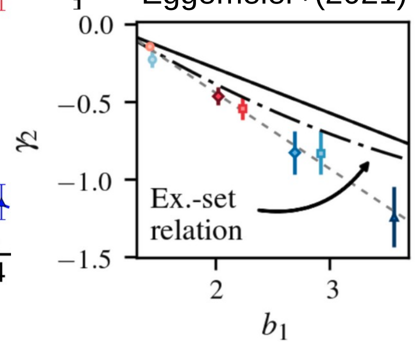
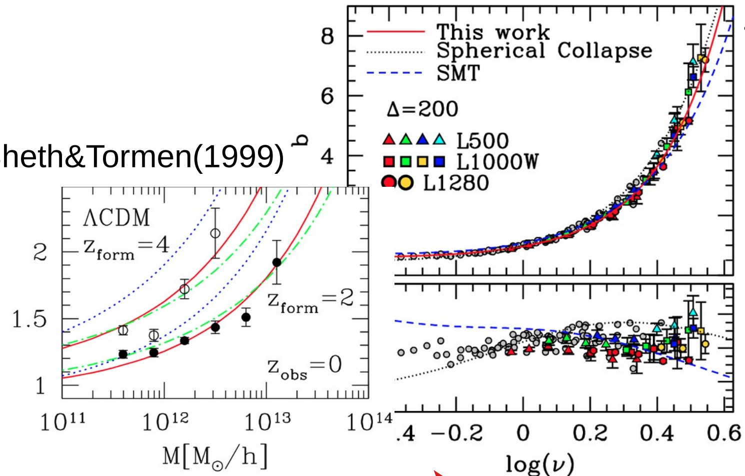


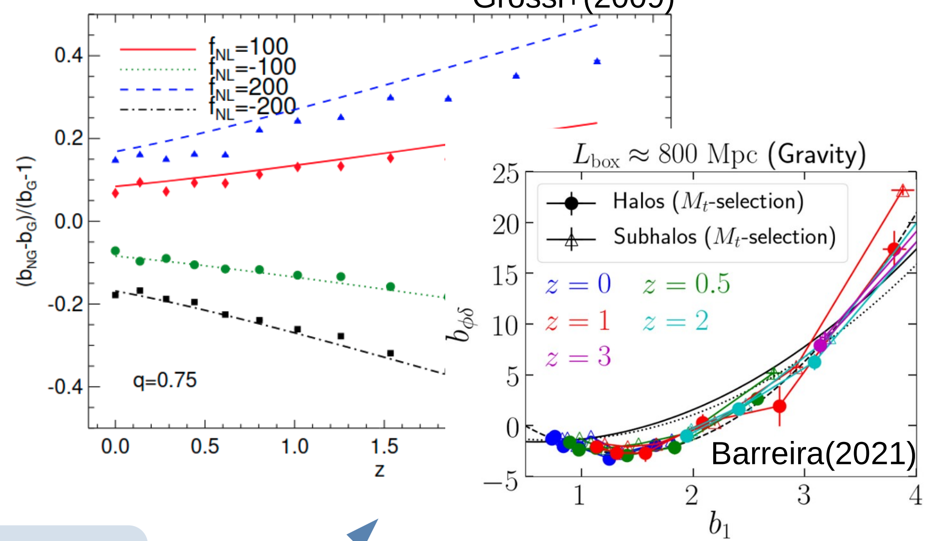
A long history of halo bias studies

Sheth&Tormen(1999)

Tinker+(2010)



Grossi+(2009)



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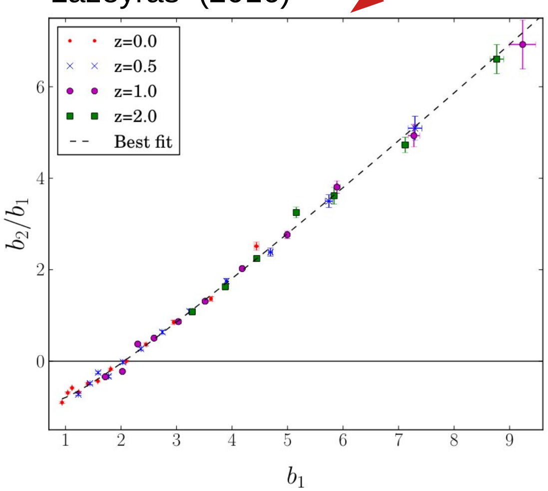

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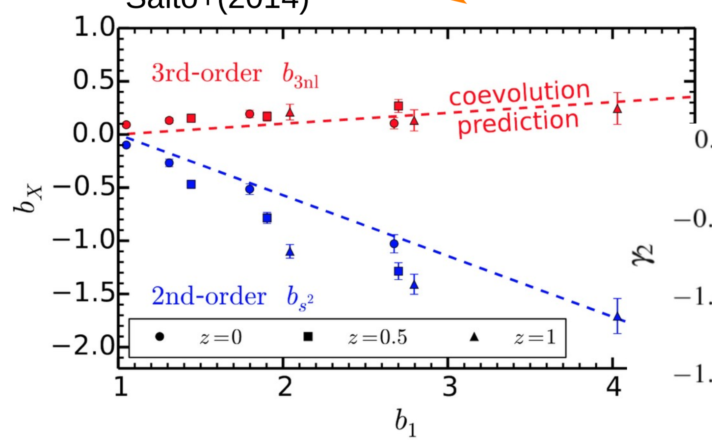

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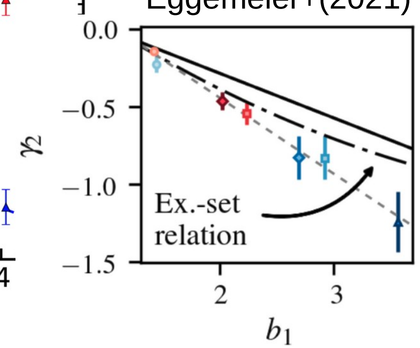

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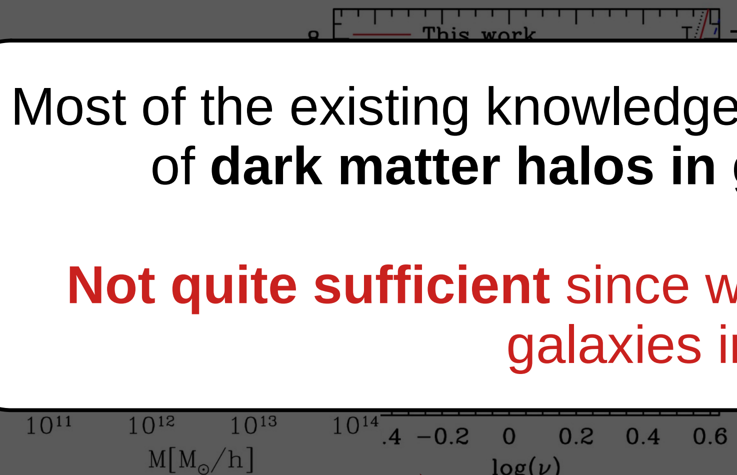

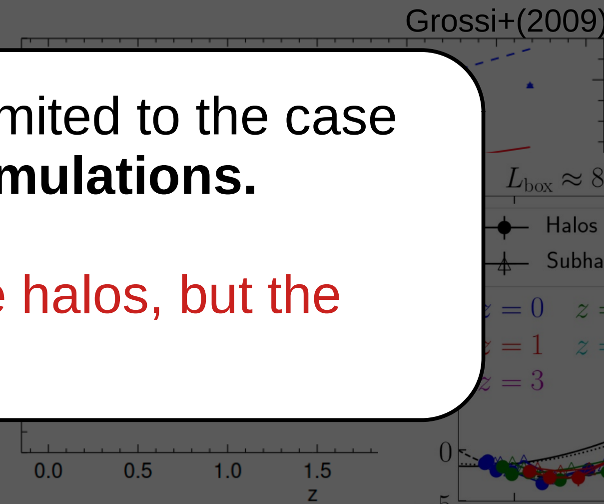

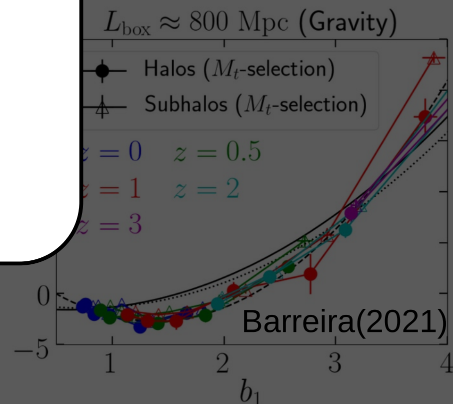

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Not quite sufficient since we don't observe halos, but the galaxies inside them.

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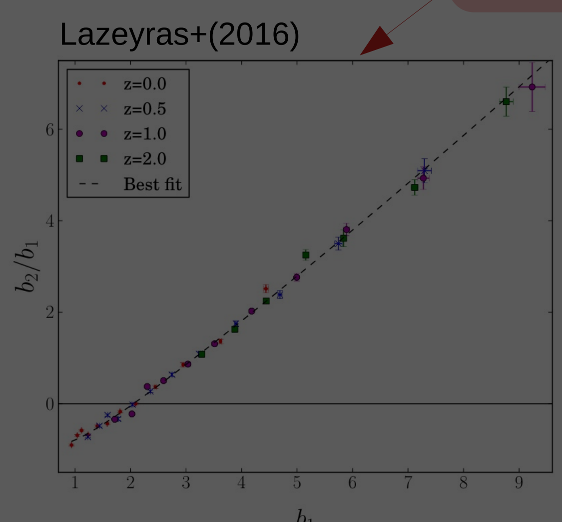

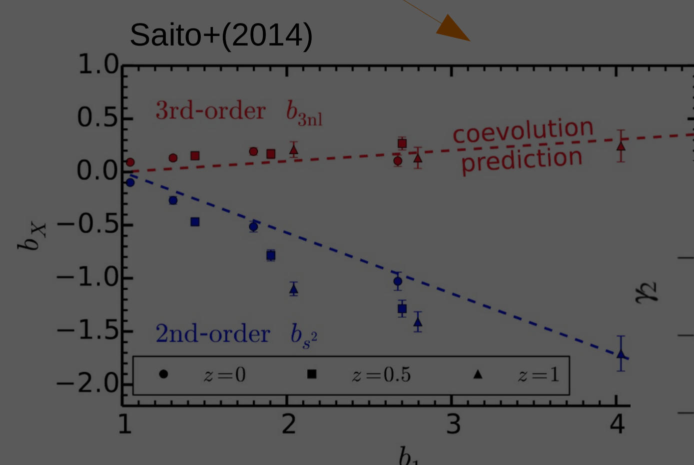

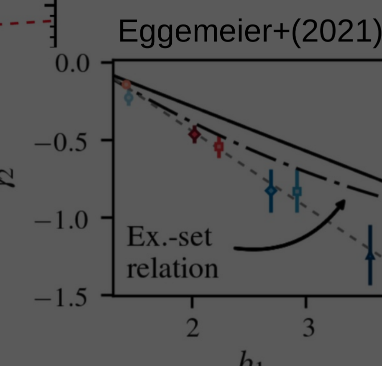

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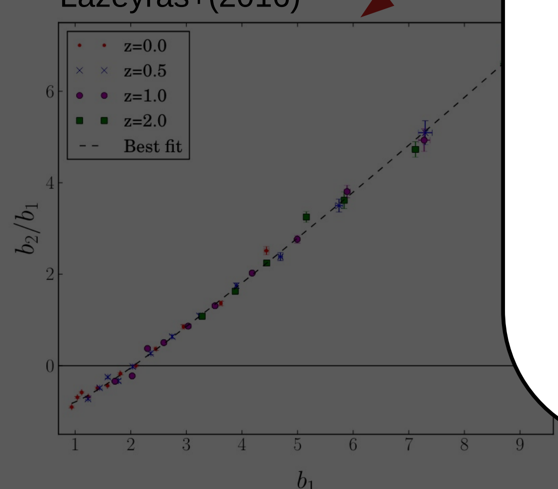

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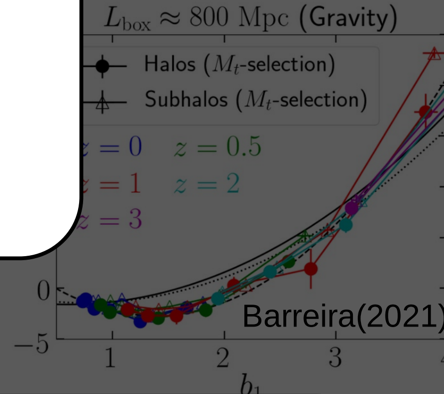
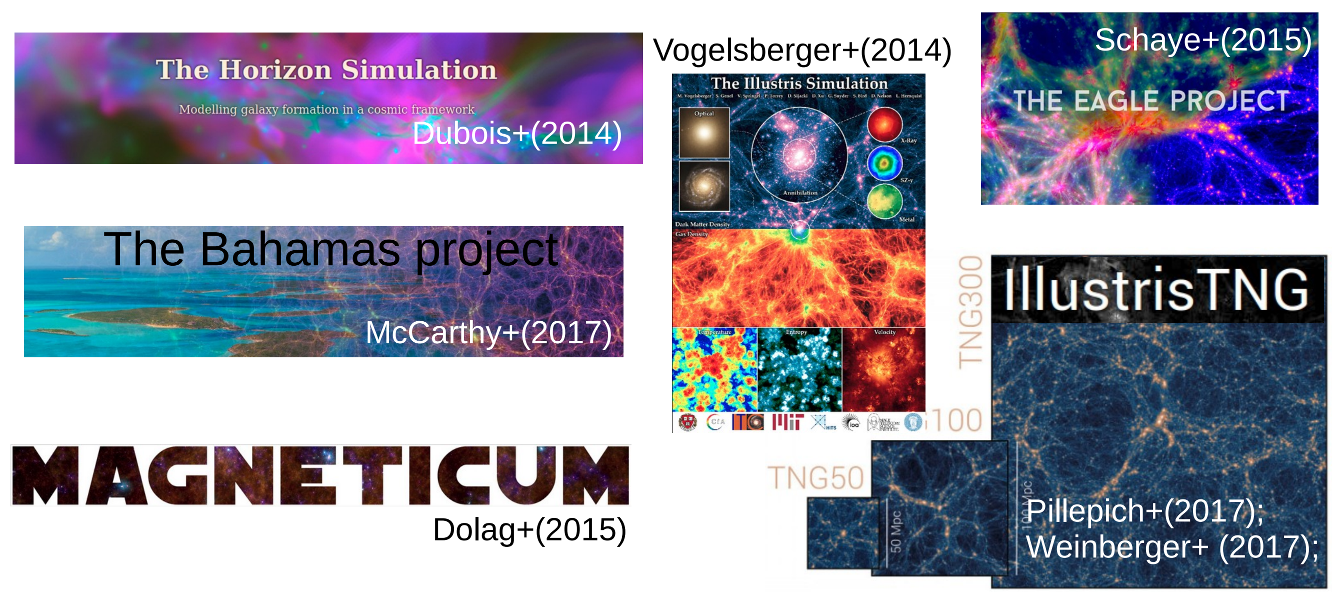


Galaxy bias studies made possible only recently as **galaxy formation simulations approach cosmological volumes.**



Outline

- **What is galaxy bias?**

- **Recent results from galaxy formation simulations.**

- **Consequences for tests of inflation using galaxy data.**

The IllustrisTNG galaxy formation model

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http://www.tng-project.org; Pillepich+(2017); Weinberger+ (2017);

- Gravity + hydrodynamical cosmological simulations of galaxy formation.
  (Lbox = 205Mpc/h, 75Mpc/h)

- Includes modeling of: gas cooling; star formation, stellar feedback, black hole growth & feedback.

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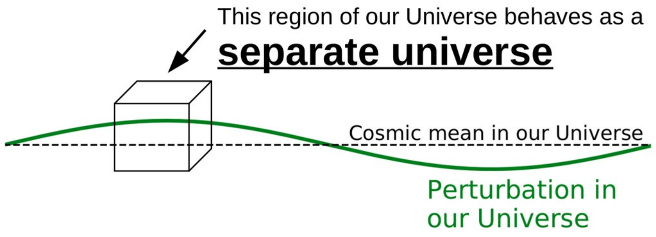
Separate Universe simulations



Sirko+(2005), Wagner+(2014), Li+(2014, 2016)
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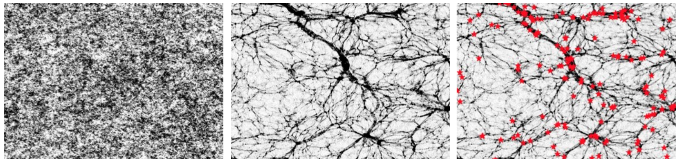

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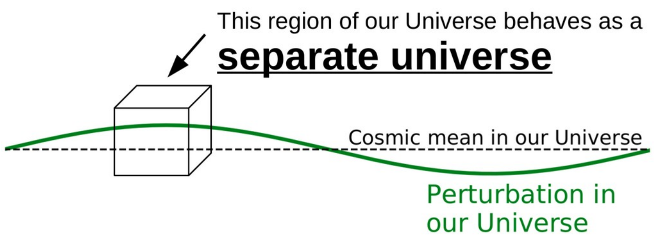

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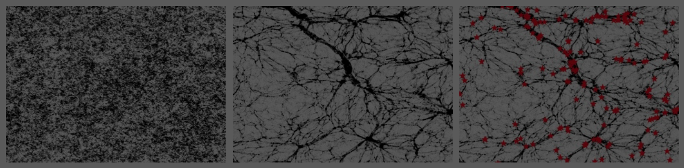

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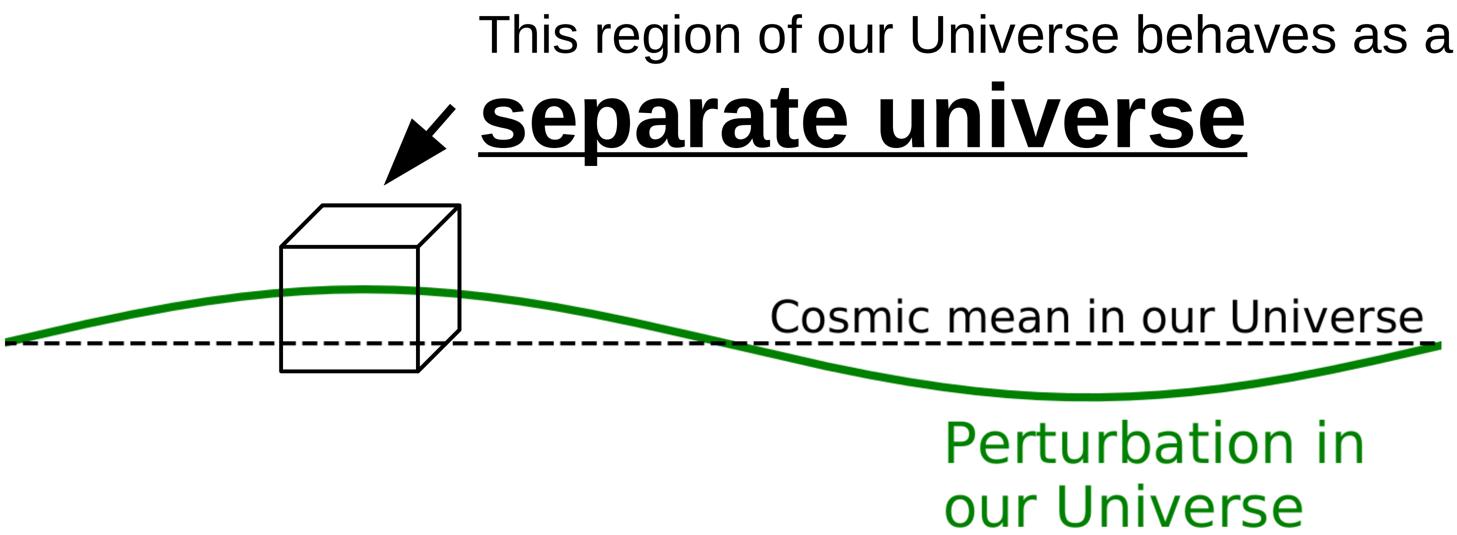
Separate Universe simulations

Local structure formation inside long-wavelength perturbations in a Fiducial cosmology is equivalent to global structure formation in a modified cosmology.



Significant advantage of this method:
simulation does not have to have a large volume to encompass large-scale perturbations!
(especially significant for hydrodynamical simulations, which are more expensive)

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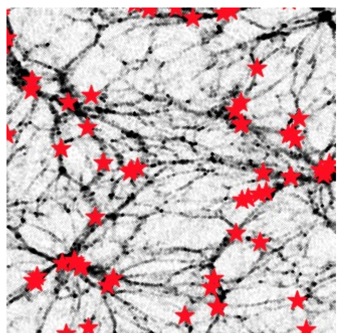
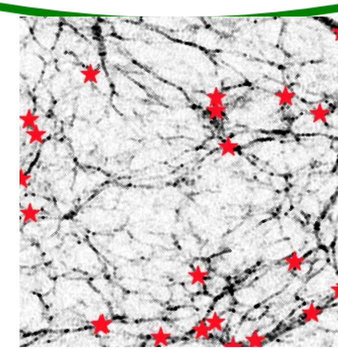
Simulation of one cosmology



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

VS.



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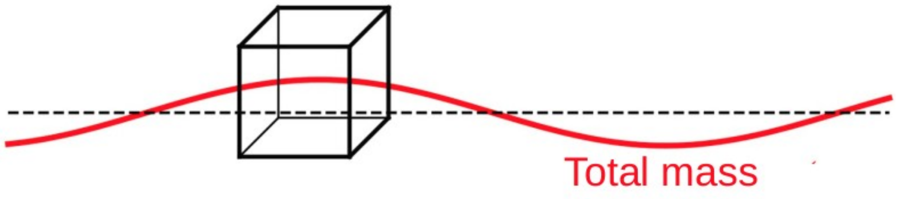
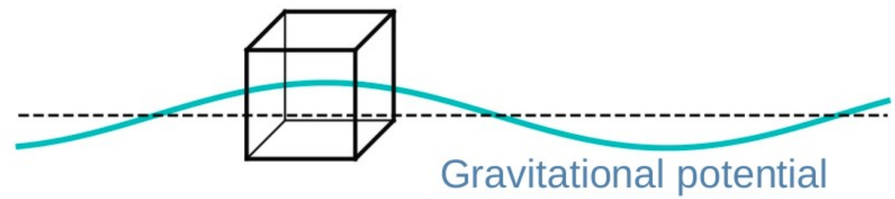


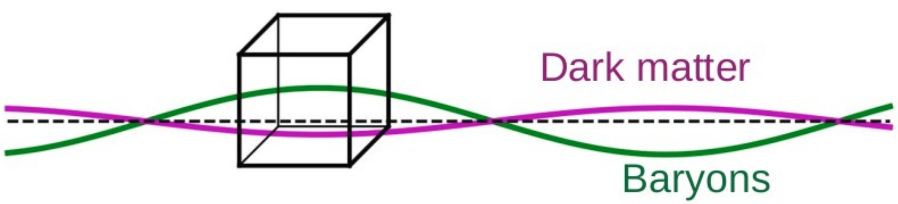
Separate Universe: modified cosmic matter density.

Sirko+(2005), Wagner+(2014), Li+(2014), Lazeyras+(2016)



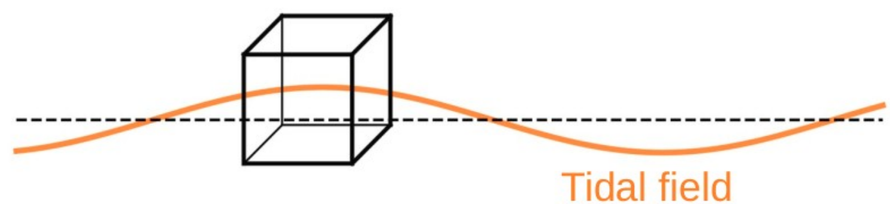
Separate Universe: modified amplitude of the primordial power spectrum.

Biagetti+(2016), Barreira+(2020), Barreira (2021)



Separate Universe: modified cosmic baryon and dark matter densities.

Barreira+(2020), Voivodic&Barreira (2021), Khoraminezhad+(2021)



Separate Universe: anisotropic spacetime (e.g. Bianchi cosmology).

Schmidt+(2018), Stuecker+(2020), Masaki+(2020), Akitsu+(2021)

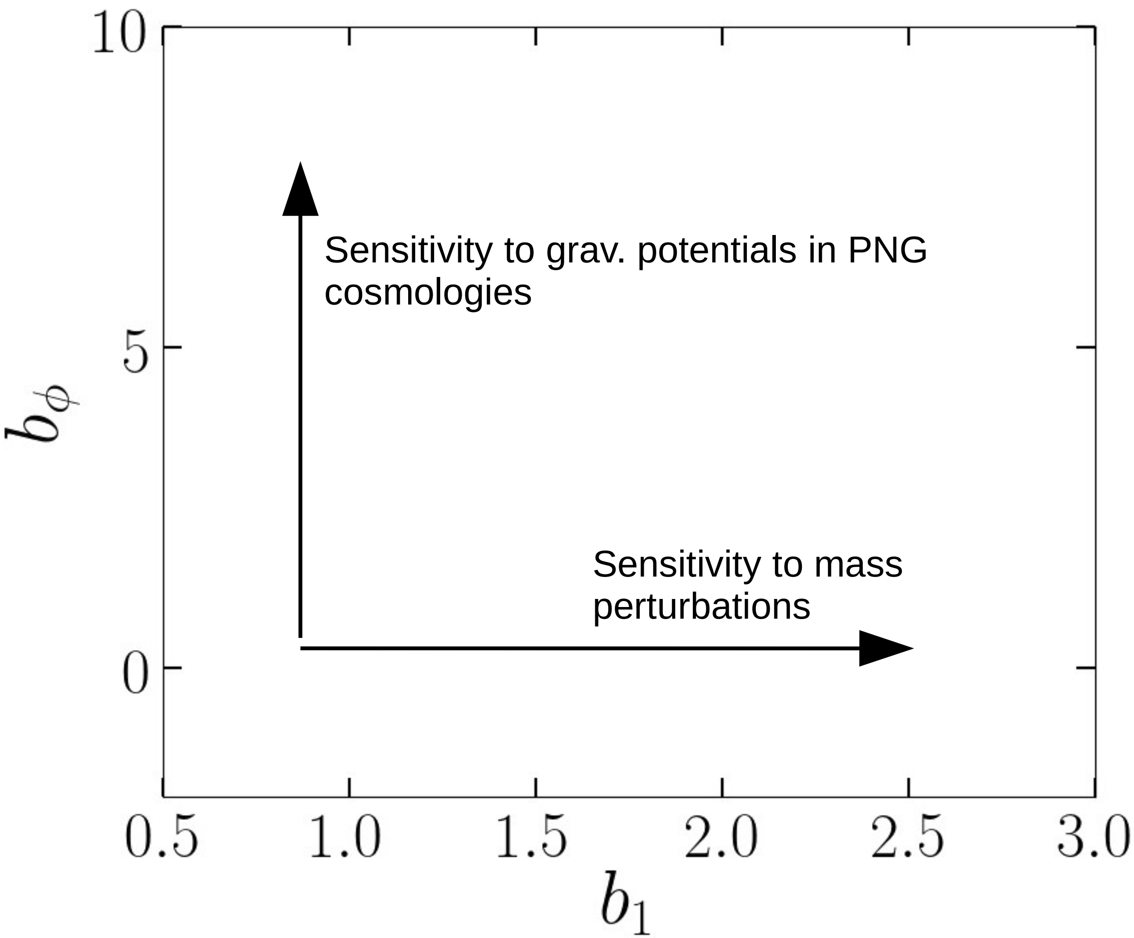
Results: PNG bias parameters

From separate universe simulations w/ IllustrisTNG

Barreira+(2020)
Barreira(2021)

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

Mass density **Gravitational potential**



Recall: the space of **bias parameters** organizes the tracers by their sensitivity to changes in **their environment.**

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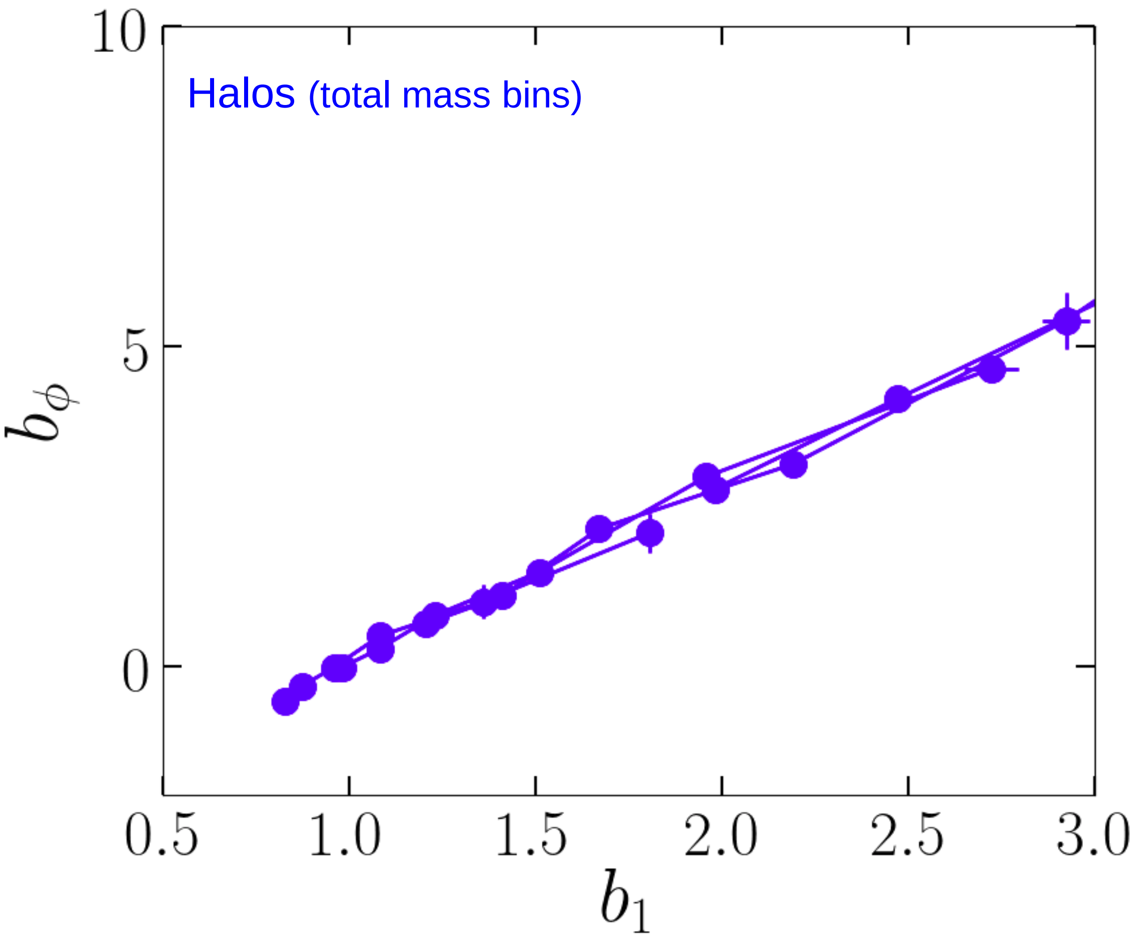

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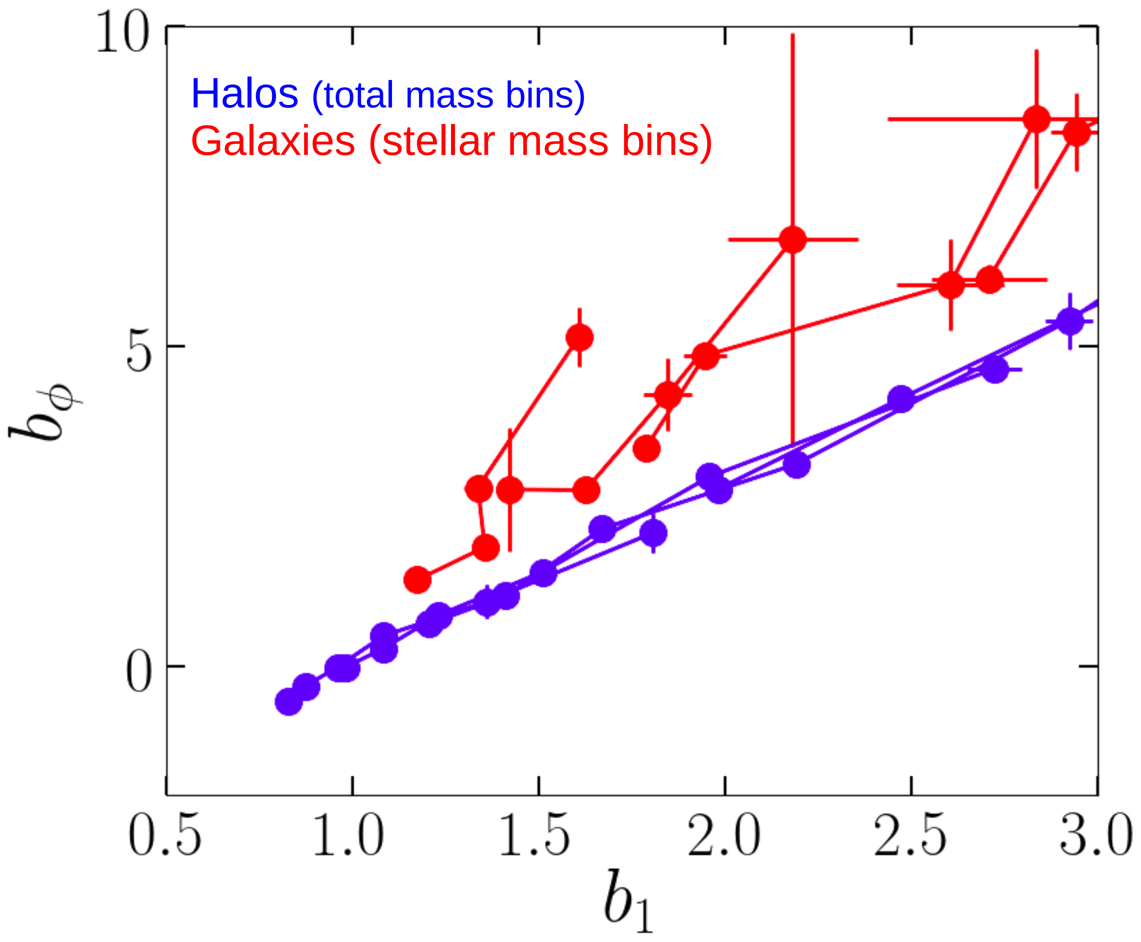

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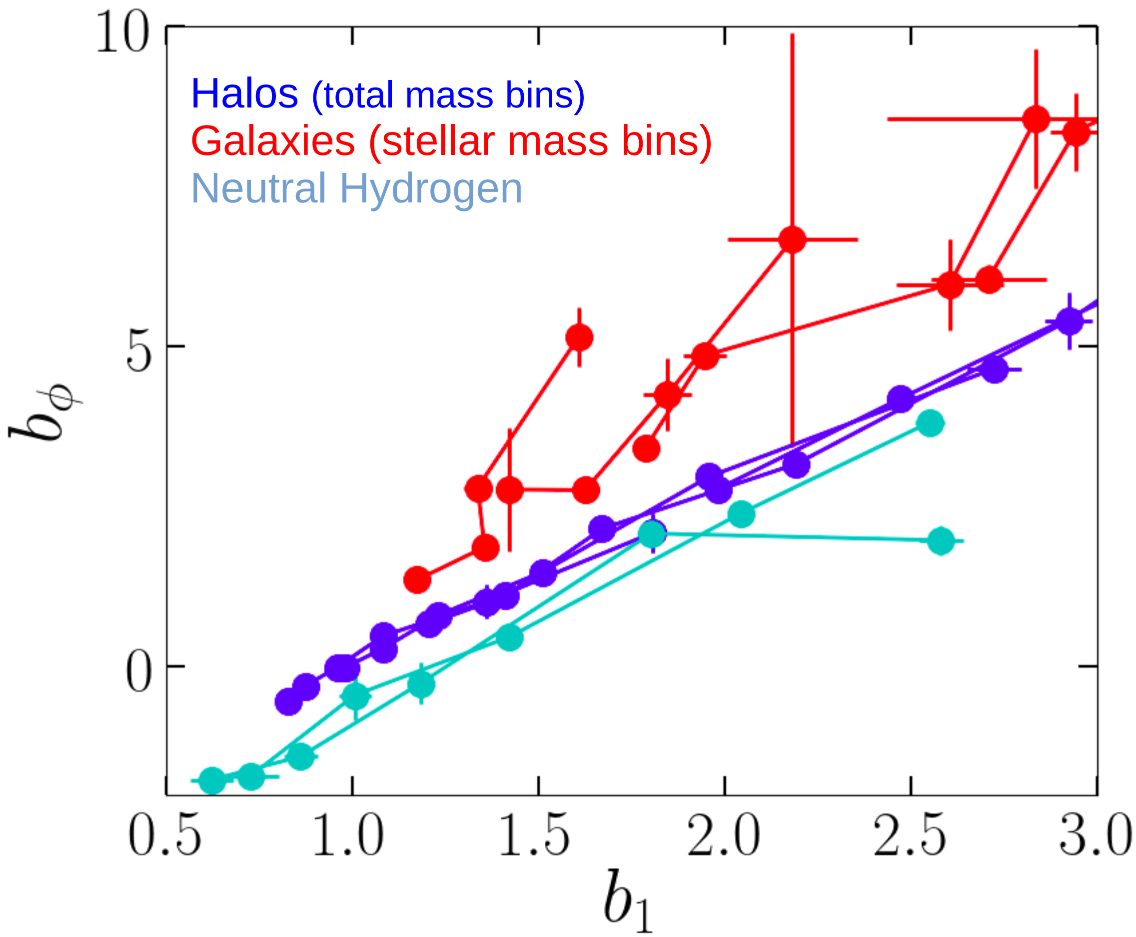

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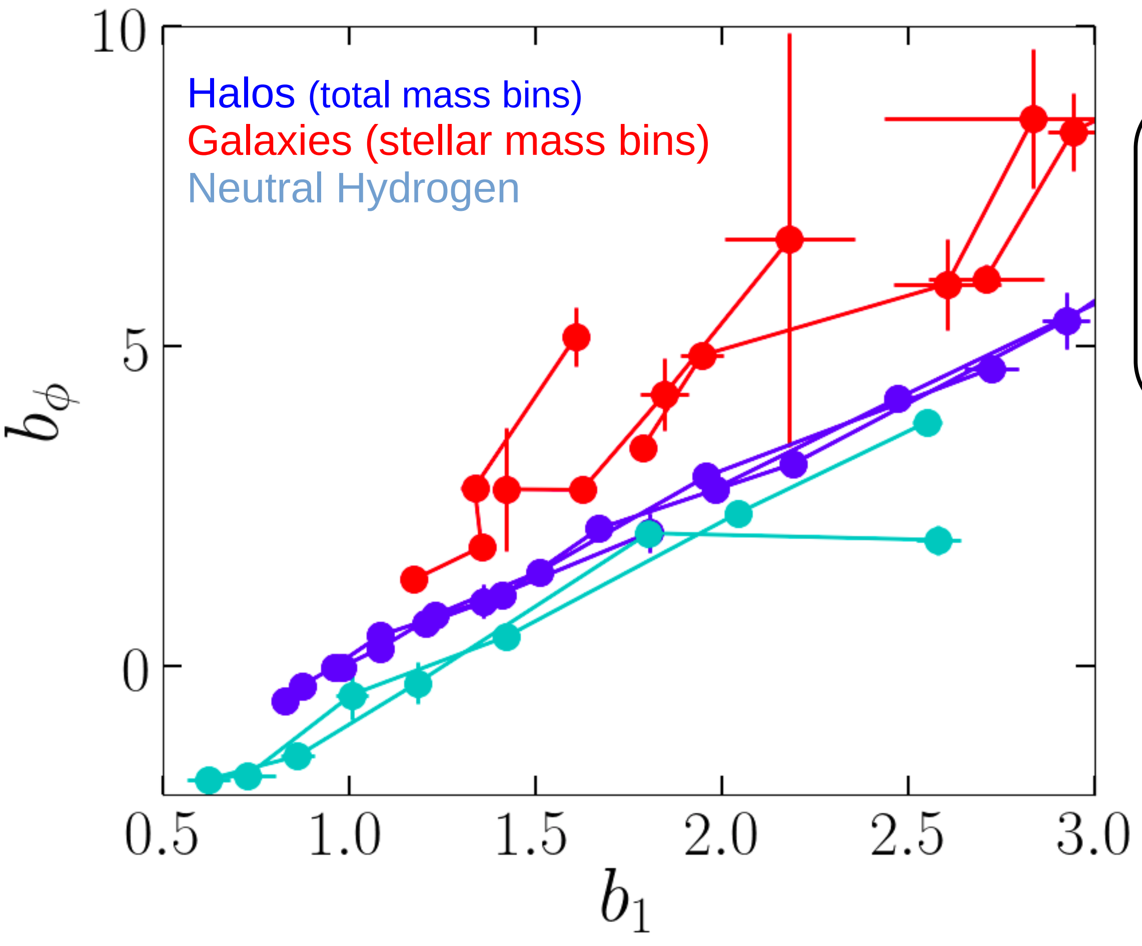

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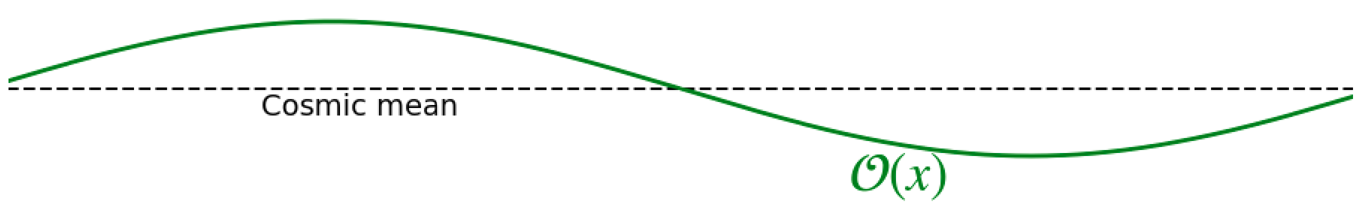

Voivodic & Barreira 2021

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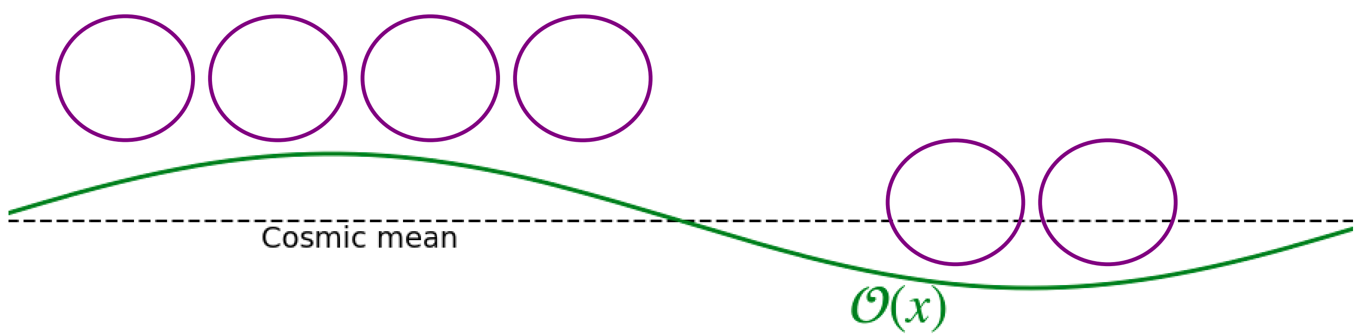

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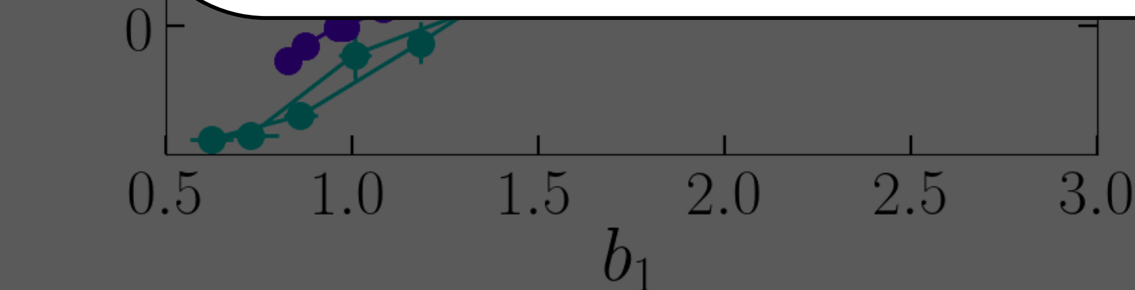

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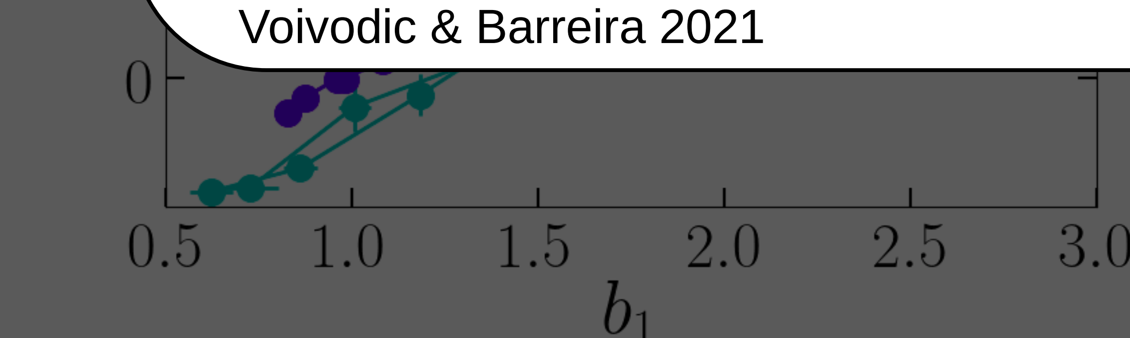

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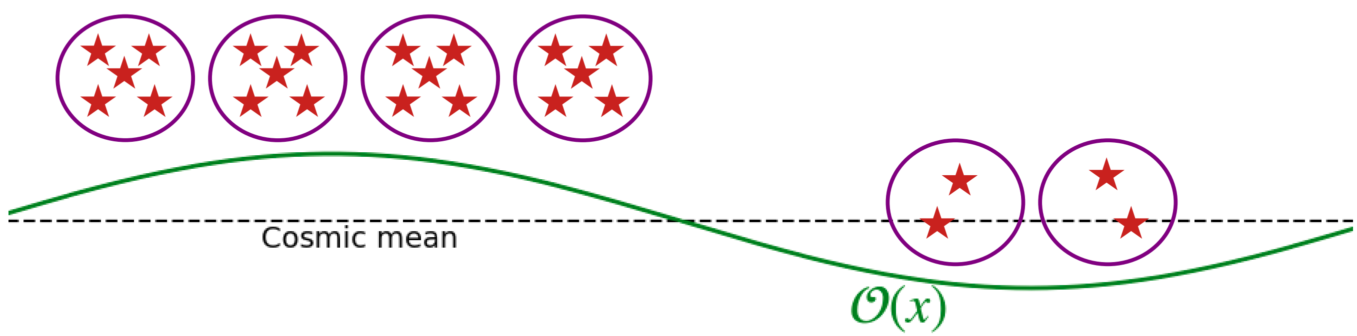
How many more halos exist inside the perturbations?

How many more galaxies each halo hosts inside the perturbations?



Voivodic & Barreira 2021

Halo occupation bias

Voivodic & Barreira 2021

Bias of the galaxies

$$b_g = \frac{1}{\bar{n}_g} \int \mathrm{d}M \, n_h(M) \, N_g(M) \, b_h(M)$$

Halo mass function | **Galaxy occupation distribution** | **Halo bias**

Halo occupation bias

Voivodic & Barreira 2021

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Halo mass function | Galaxy occupation distribution | Halo bias | Occupation bias

Bias of the neutral hydrogen

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Halo mass function | HI content | Halo bias | HI content bias

Halo occupation bias

Voivodic & Barreira 2021

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for grav. potentials in IllustrisTNG

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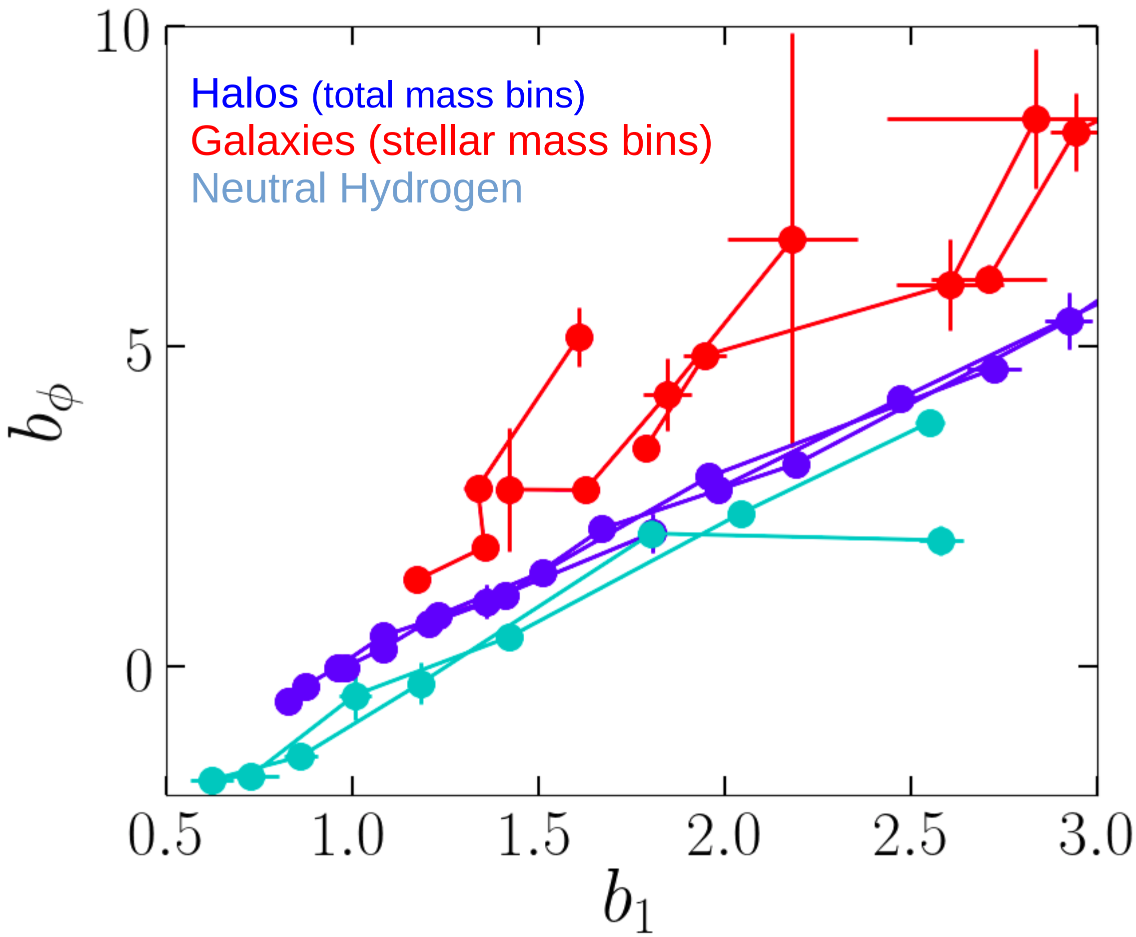

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Because inside $f_{\rm NL}\phi$ perturbations, the halos contain more galaxies and less neutral hydrogen.

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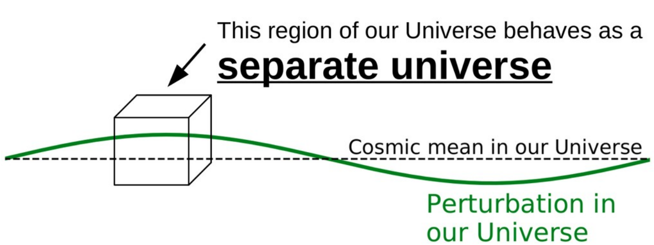

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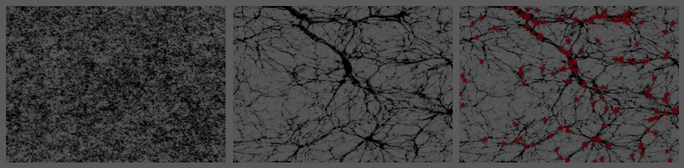


Jasche&Wandelt(2013), Wang+(2014), Seljak+(2018)
Schmidt+(2020), Schmittfull+(2021), Barreira+(2021)

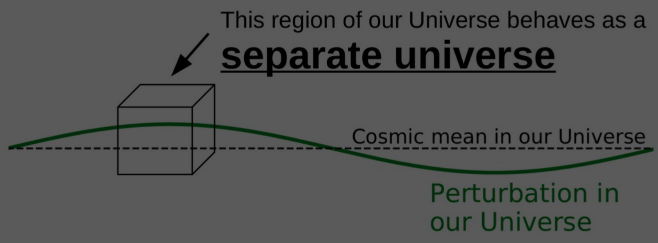
The IllustrisTNG galaxy formation model

http://www.tng-project.org; Pillepich+(2017); Weinberger+ (2017);

- Gravity + hydrodynamical cosmological simulations of galaxy formation. (Lbox = 205Mpc/h, 75Mpc/h)
- Includes modeling of: gas cooling; star formation, stellar feedback, black hole growth & feedback.
- Broadly matches a series of observations: cosmic star formation history, low-z stellar mass function, galaxy sizes, gas fractions in groups/clusters, color bimodality, etc.

Let us look at recent results obtained with two different numerical methods:

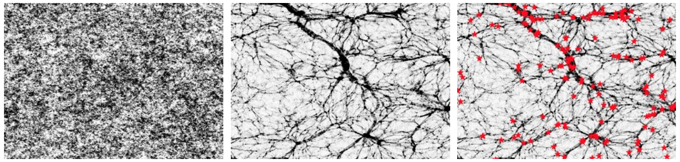
Separate Universe simulations



Sirko+(2005), Wagner+(2014), Li+(2014, 2016)
Schmidt+(2018), Barreira+(2019)

Galaxy forward models

$$\delta_g(\boldsymbol{x}, z) = \sum_{\mathcal{O}} b_{\mathcal{O}}(z)\mathcal{O}(\boldsymbol{x}, z)$$



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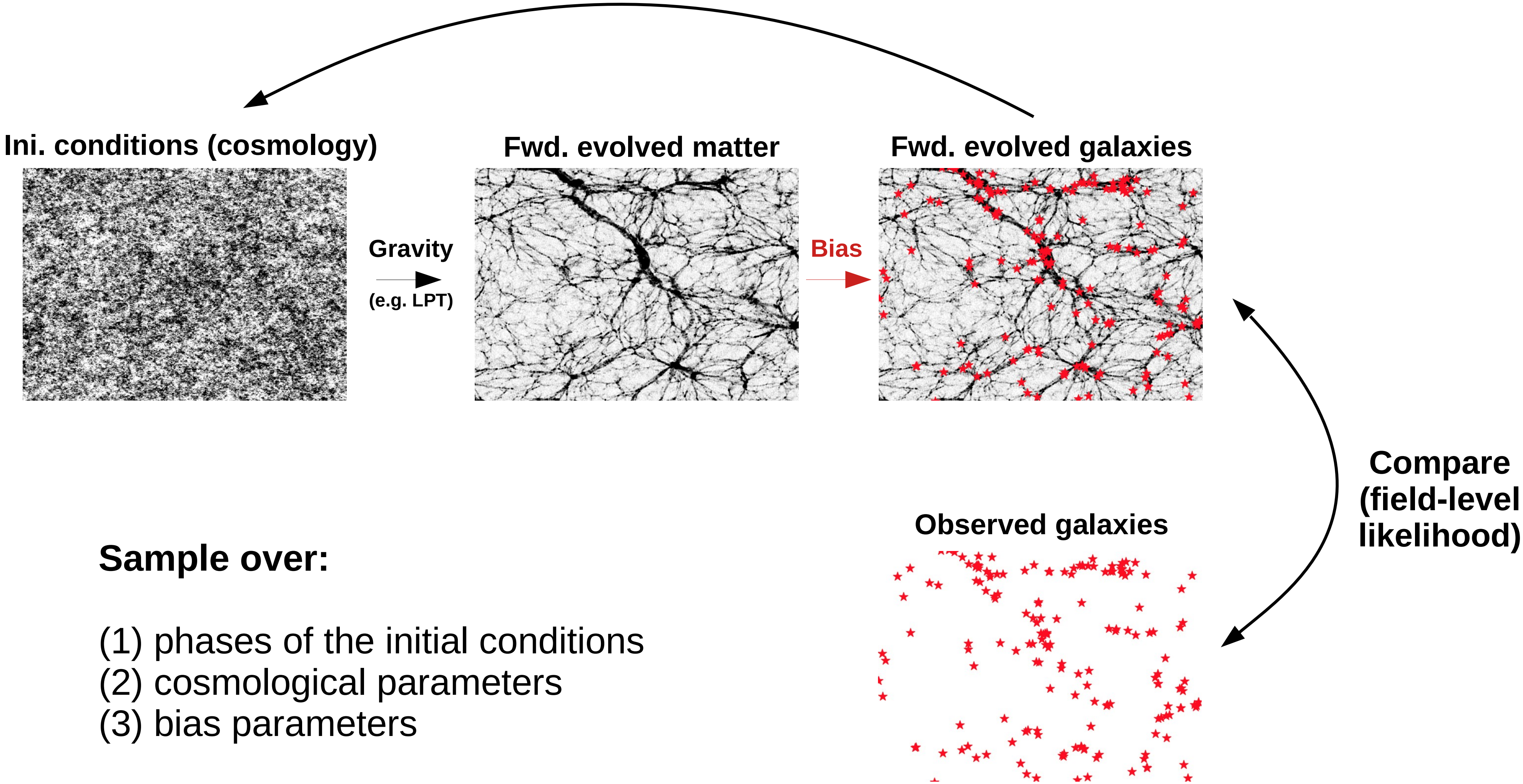
Galaxy **forward models**



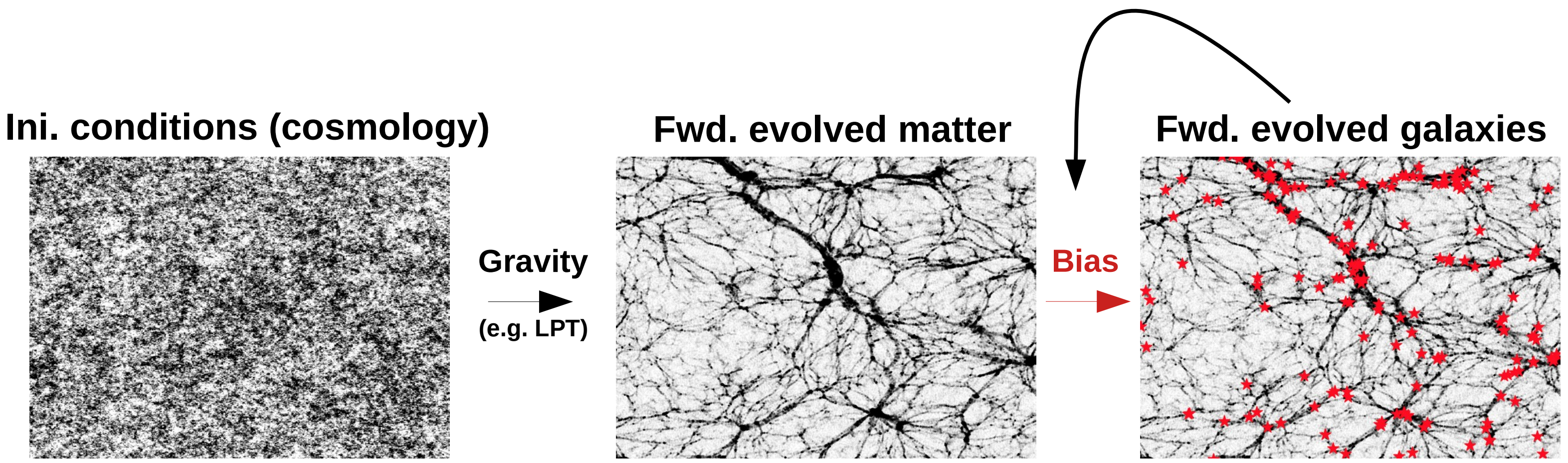
Sample over:

(1) phases of the initial conditions
(2) cosmological parameters
(3) bias parameters

Tractable disadvantage: numerically intensive

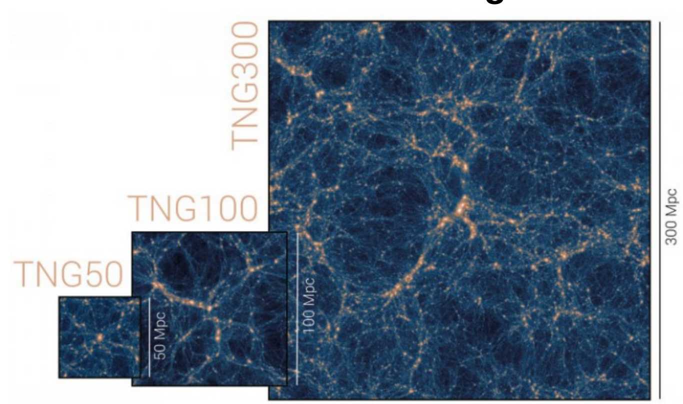
Significant advantage: inference is at the field-level (not a summary statistic), so it uses all available information. **Good signal-to-noise even from ~100Mpc boxes.**

Galaxy **forward models**



Compare (field-level likelihood)

Simulated galaxies



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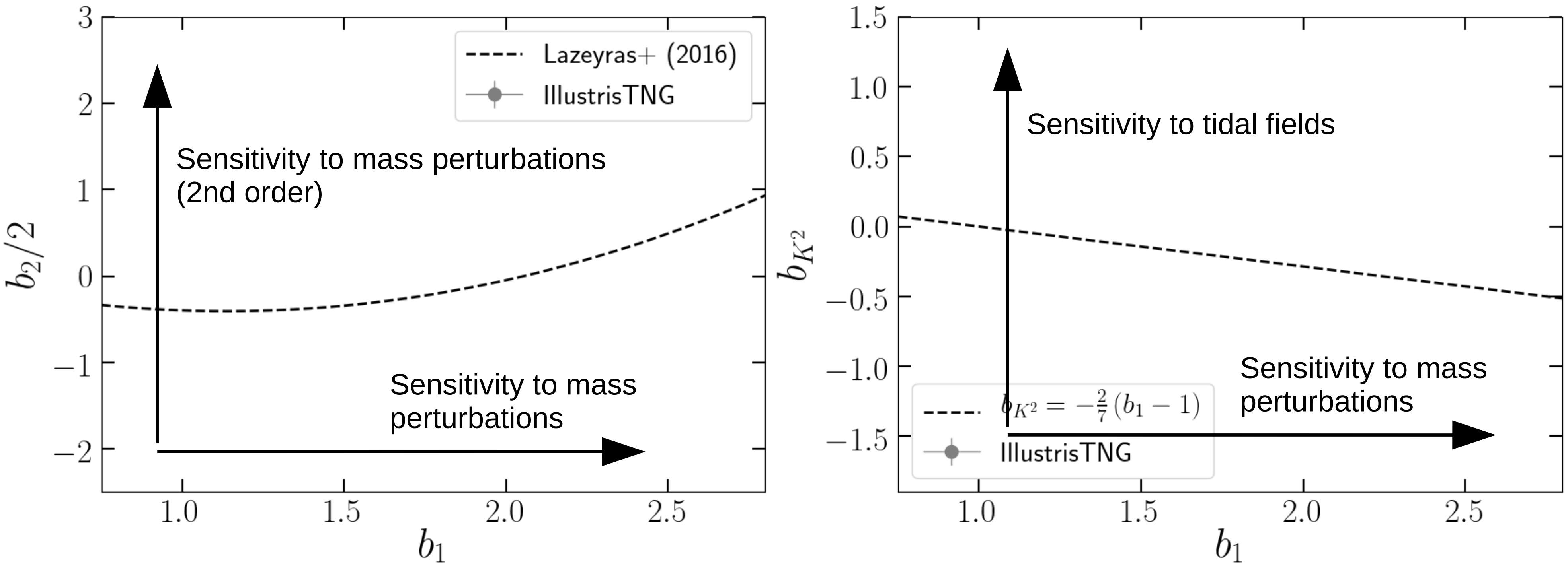
Results: quadratic bias parameters

From field-level foward models w/ IllustrisTNG

Barreira, Lazeyras & Schmidt (2021)
Lazeyras, Barreira & Schmidt (2021)

$$\delta_g(\boldsymbol{x}, z) \supset b_1(z)\delta_m(\boldsymbol{x}, z) + \frac{b_2(z)}{2}\delta_m(\boldsymbol{x}, z)^2 + b_{K^2}(z)K_{ij}(\boldsymbol{x}, z)^2$$

Mass density — **Mass density squared** — **Tidal field squared**



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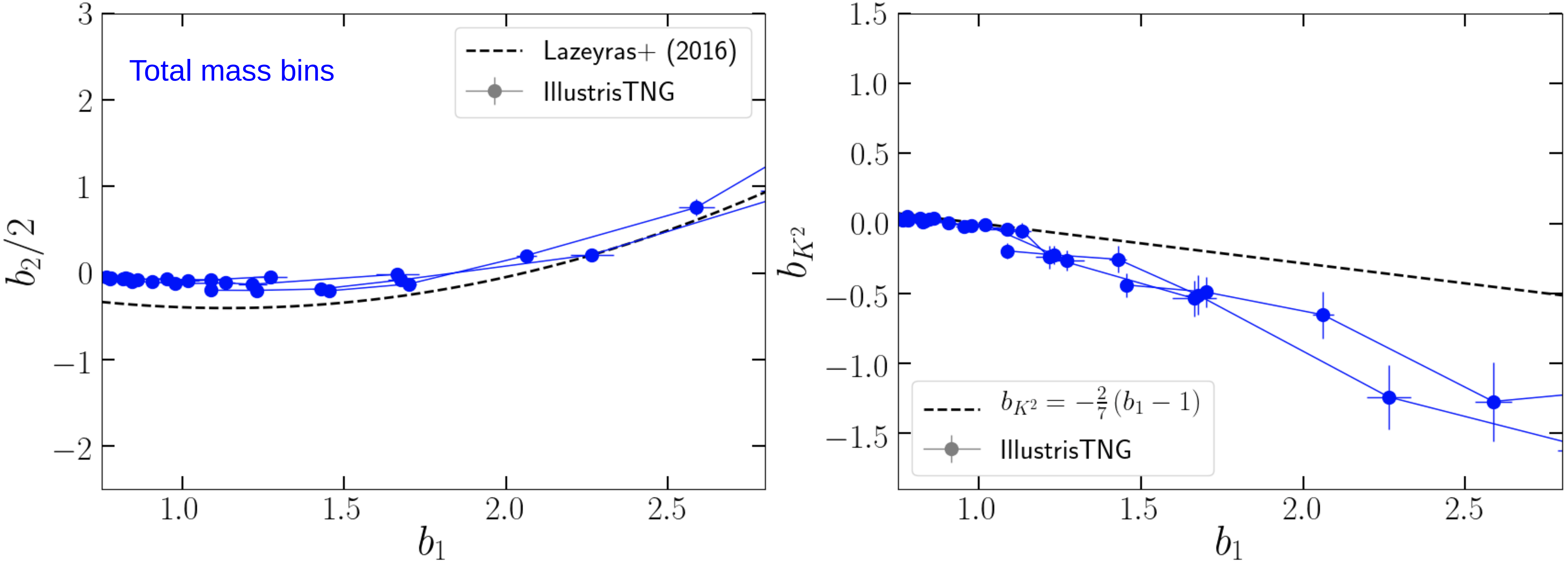

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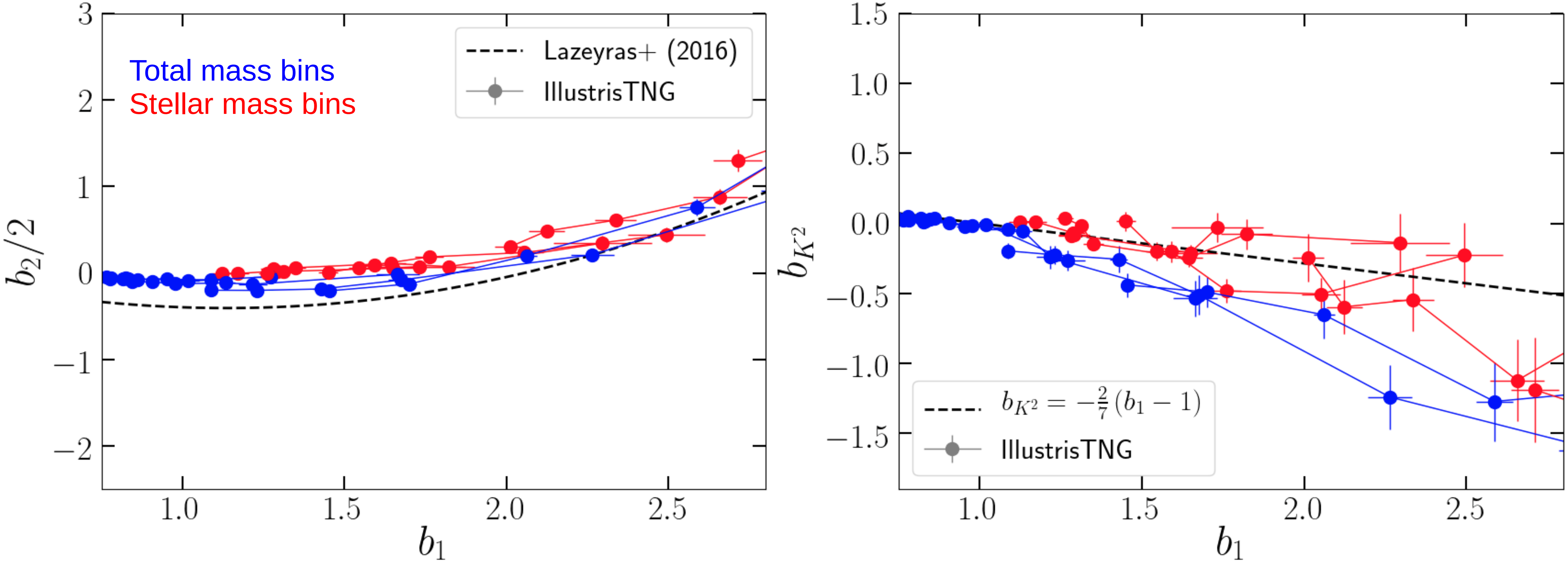

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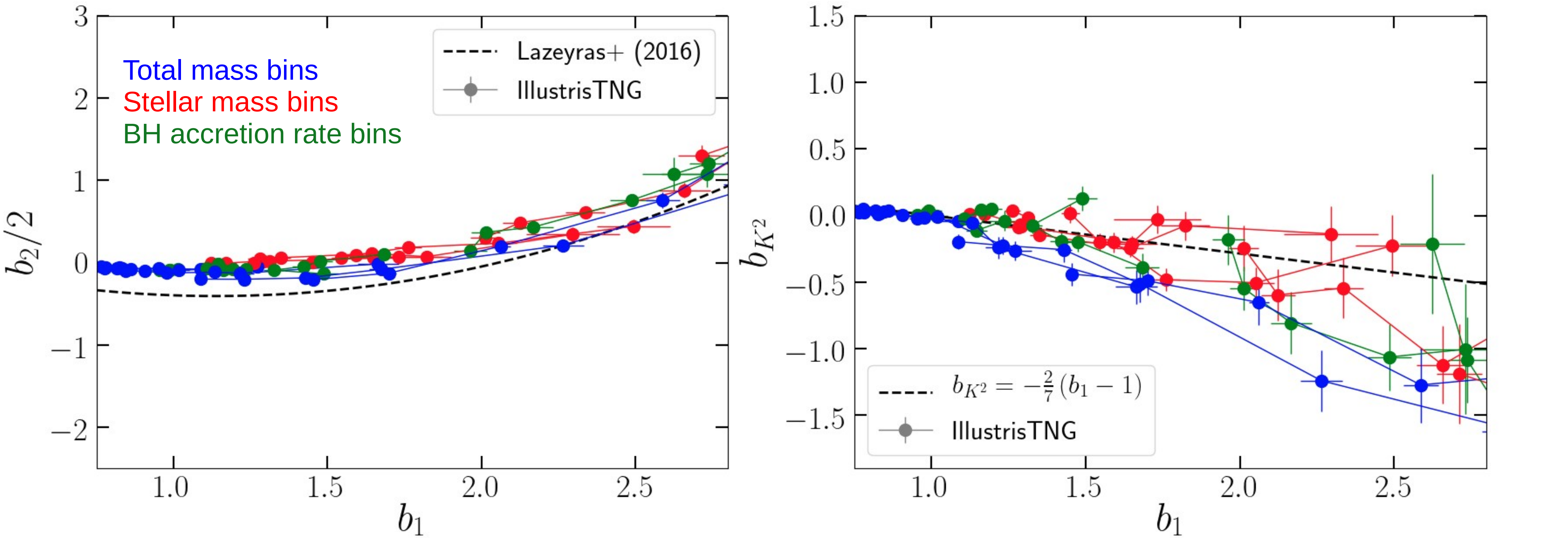

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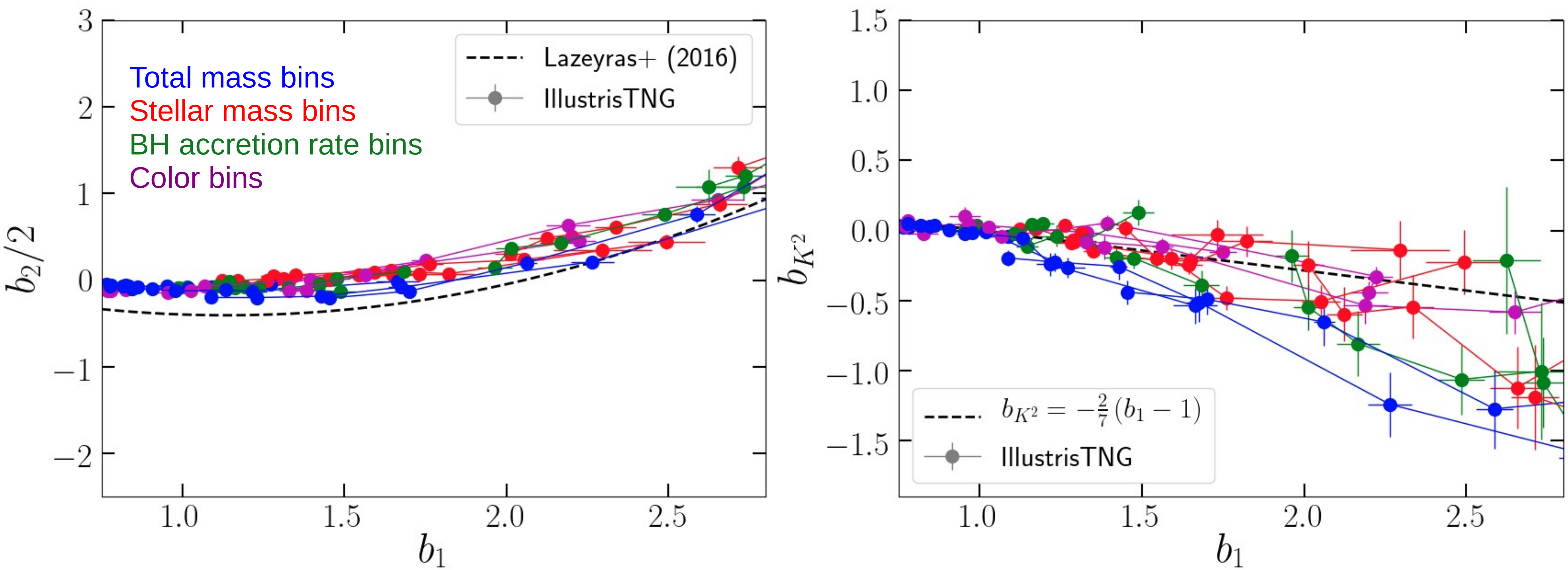

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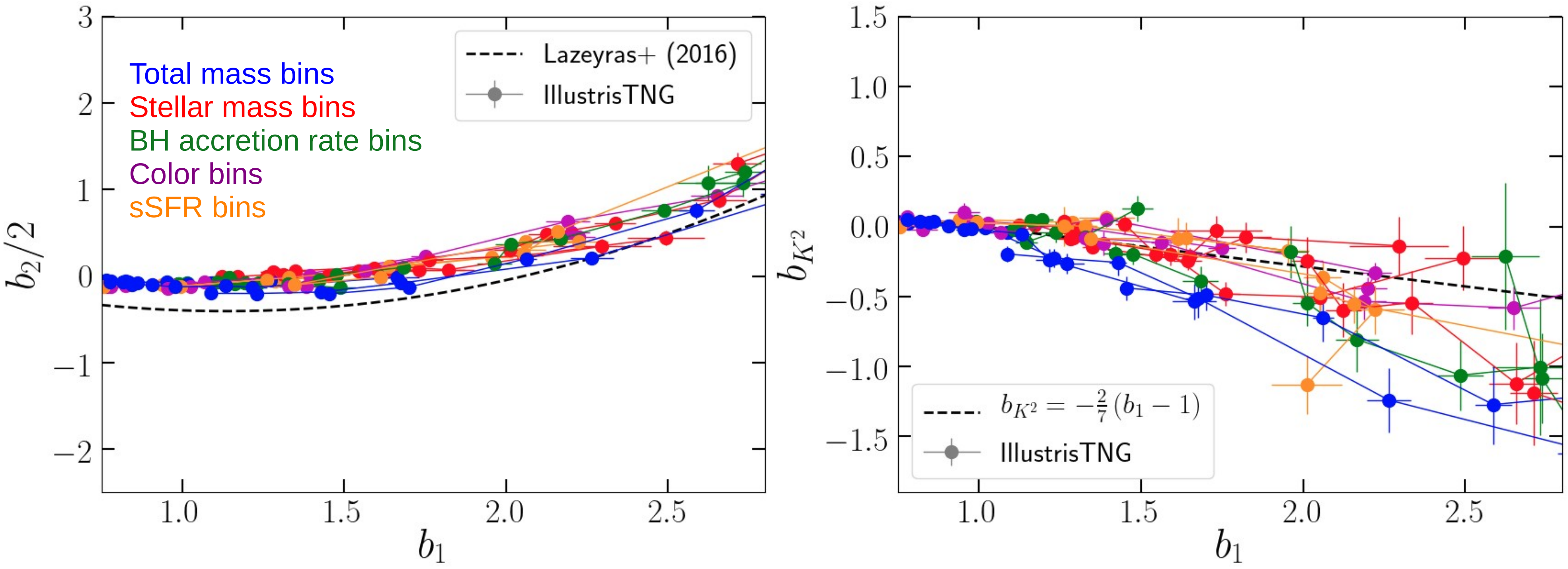

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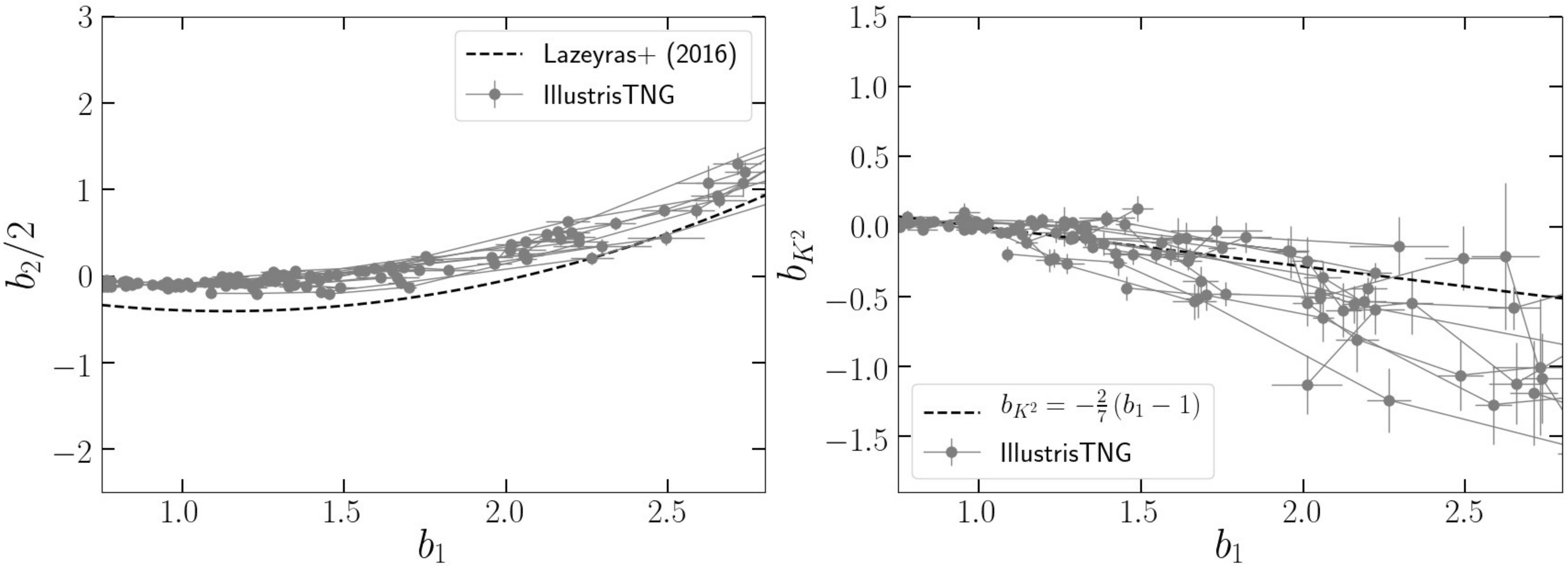

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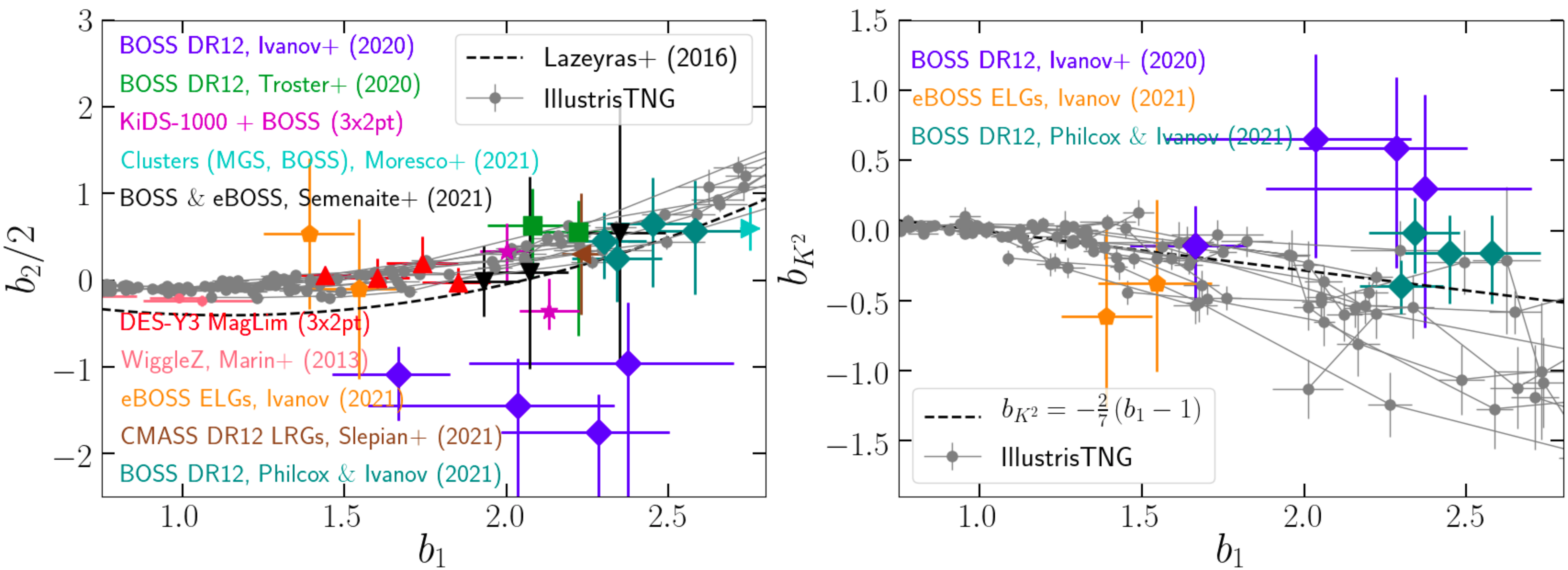


- Can we **improve cosmological constraints** by assuming priors on galaxy bias?
- Can we **test different galaxy formation models** via their bias predictions?

Galaxy data = Cosmology x Galaxy bias

(dark energy, gravity, inflation, etc) — (galaxy-environment connection)

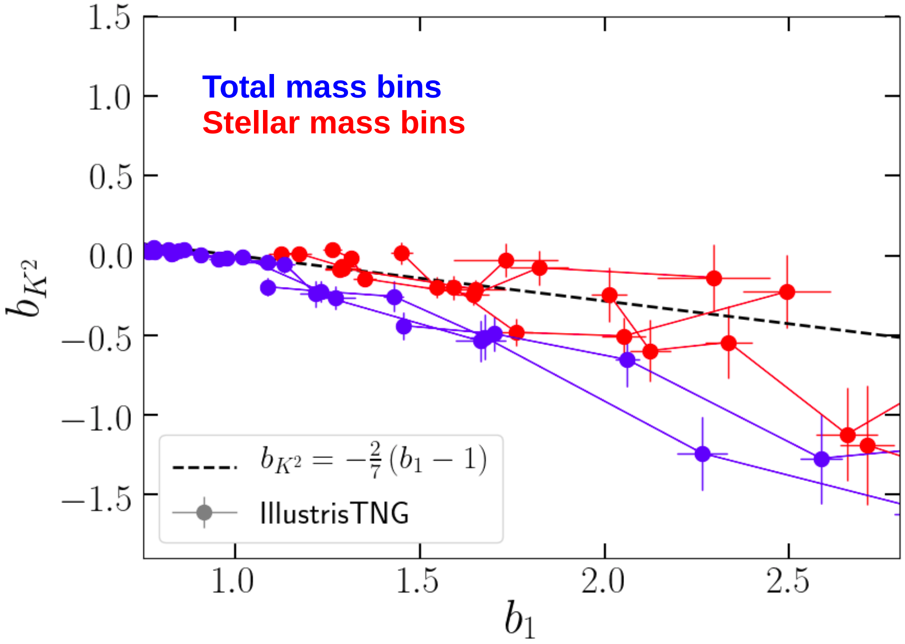
Results: connection to assembly bias

Barreira, Lazeyras & Schmidt (2021)
Lazeyras, Barreira & Schmidt (2021)

Halo abundance · Galaxy occupation · Halo bias · Occupation bias

$$b_g = \frac{1}{\bar{n}_g} \int \mathrm{d}M\, n_h(M, \ ) N_g(M, \ ) \Big(b_h(M, \ ) + R_{N_g}(M, \ ) \Big)$$

Galaxy tidal bias



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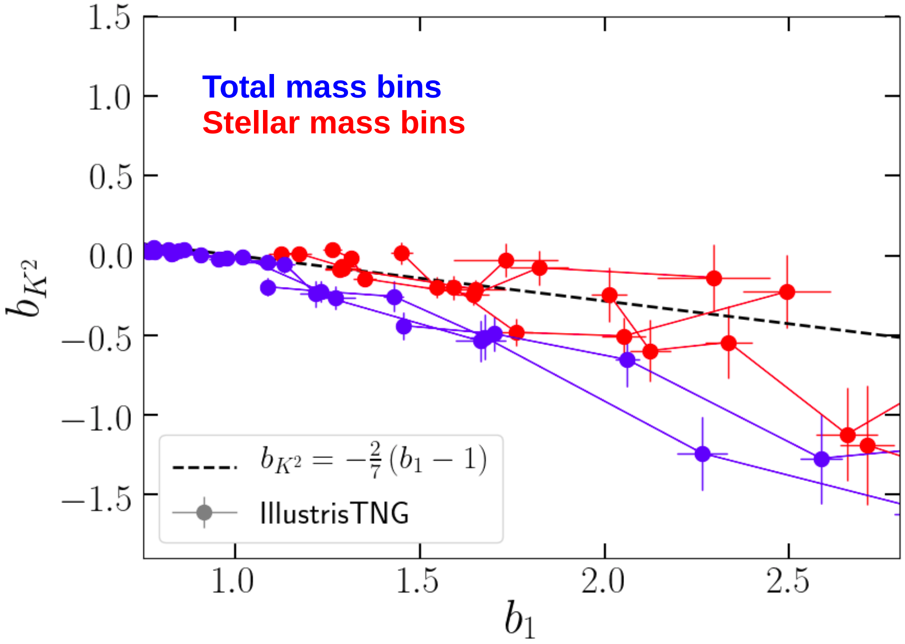

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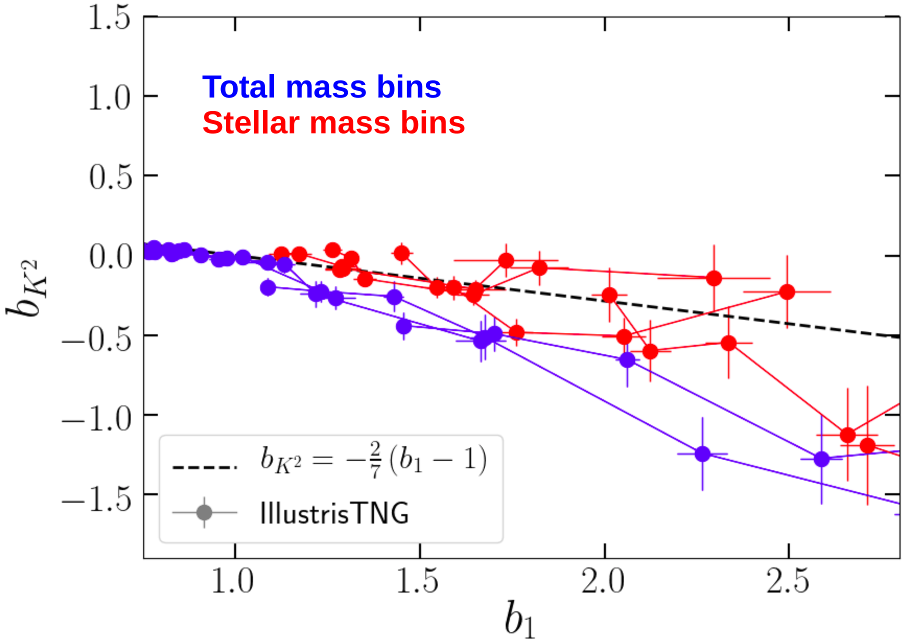
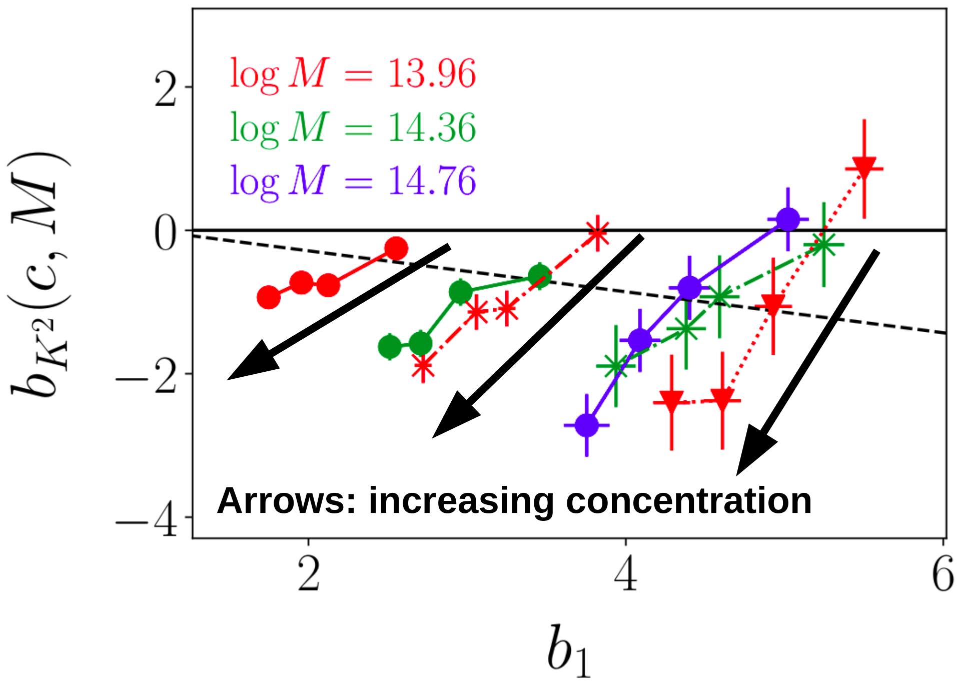


Halo assembly tidal bias



Imprints of halo assembly bias on the galaxy bias relations?

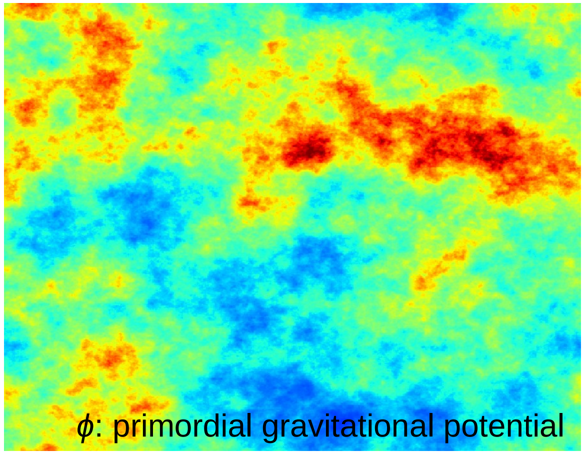
Outline

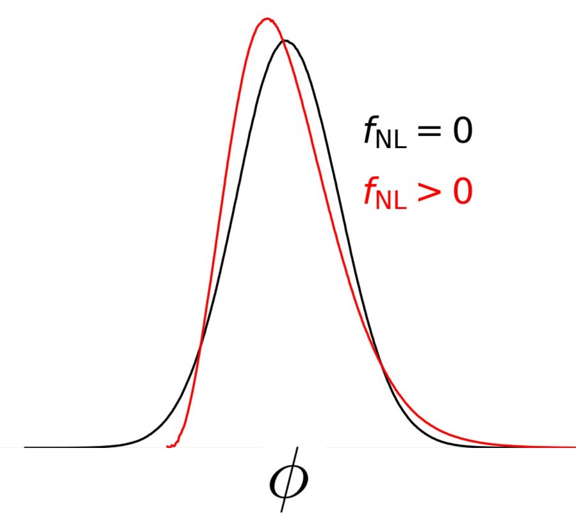
- **What is galaxy bias?**
- **Recent results from galaxy formation simulations.**
- **Consequences for tests of inflation using galaxy data.**

The search for local-type PNG, f_{NL}

Komatsu&Spergel(2001)

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





Detecting f_{NL} rules out the popular single-field inflation scenarios!

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

Current tightest bound (Planck 2018):

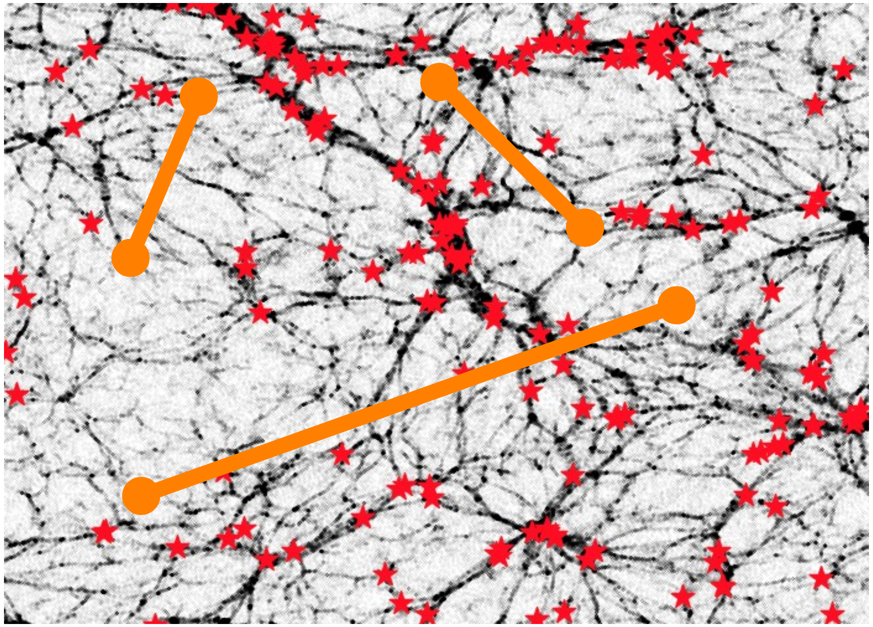
$$f_{\rm NL} = -0.9 \pm 5.1\ (68\%)$$

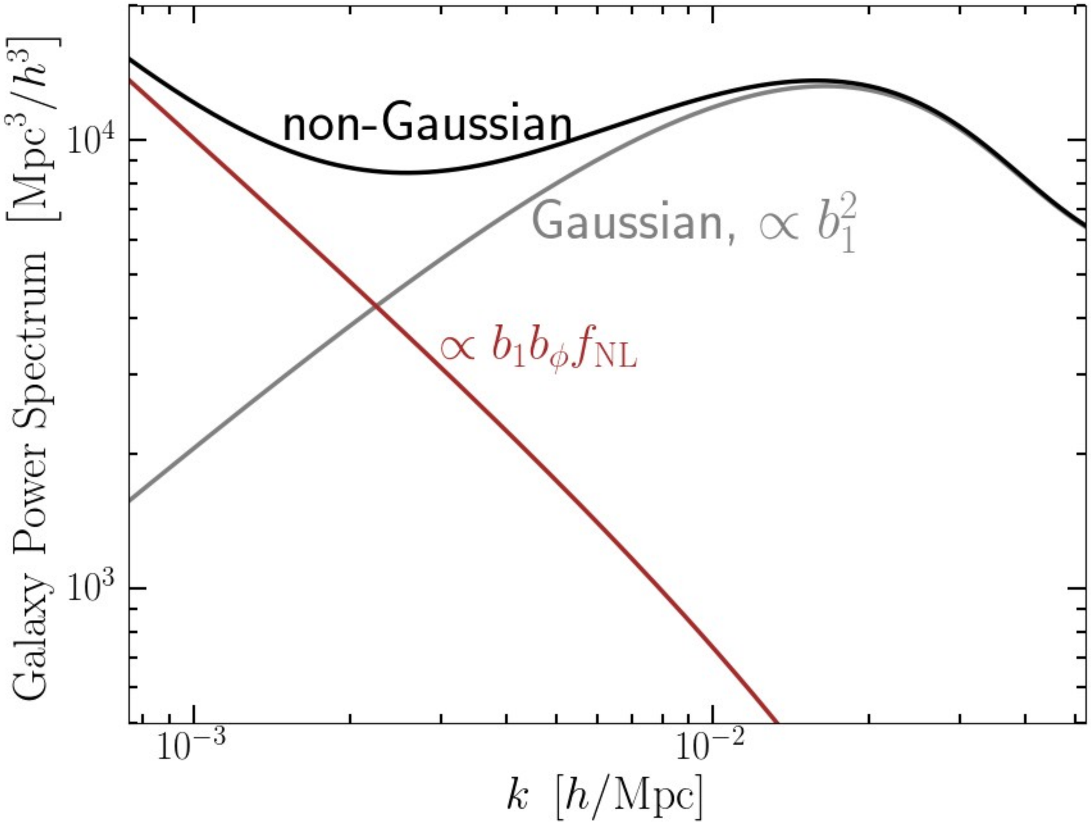
Future galaxy surveys aiming at:

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

The search for local-type PNG, f_{NL}

Local PNG leaves a distinct scale-dependent signature on the large-scale galaxy power spectrum (2pt function)
(Dalal+ 2008)





The search for local-type PNG, f_{NL}

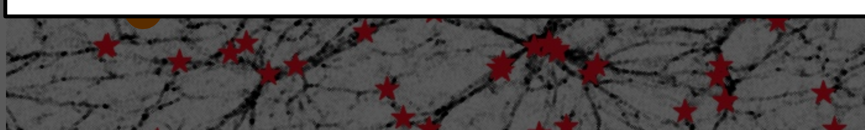
Local PNG leaves a distinct scale-dependent signature on the large-scale galaxy power spectrum (2pt function)

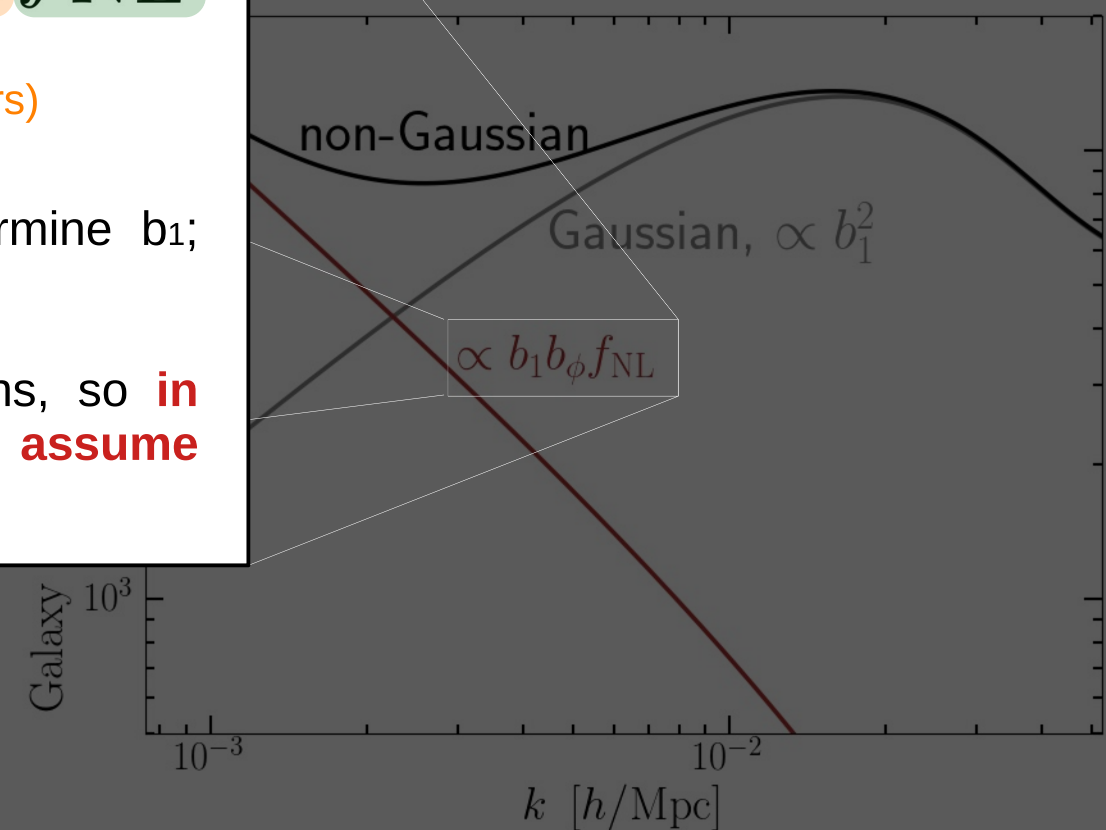
Cosmology

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

Galaxy formation
(galaxy bias parameters)

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

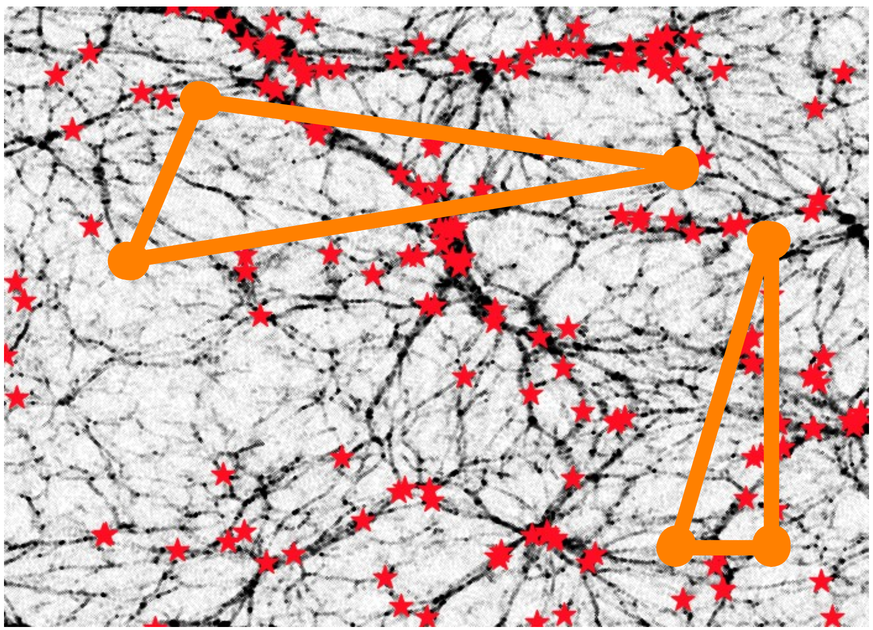


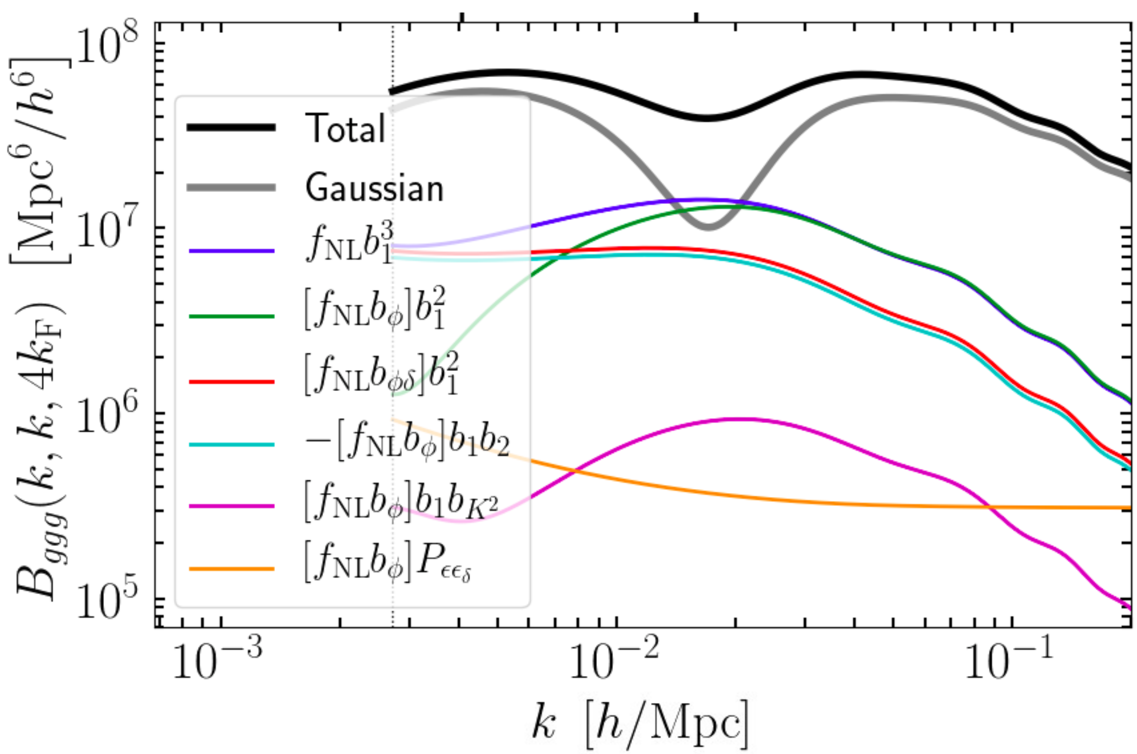


The search for local-type PNG, f_{NL}

Local PNG contributes also sizeably to the galaxy bispectrum (3pt function)

(Scoccimarro+(2003), Sefusatti&Komatsu(2007), Jeong&Komatsu(2011))





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Local PNG contributes also sizeably to the galaxy bispectrum (3pt function)

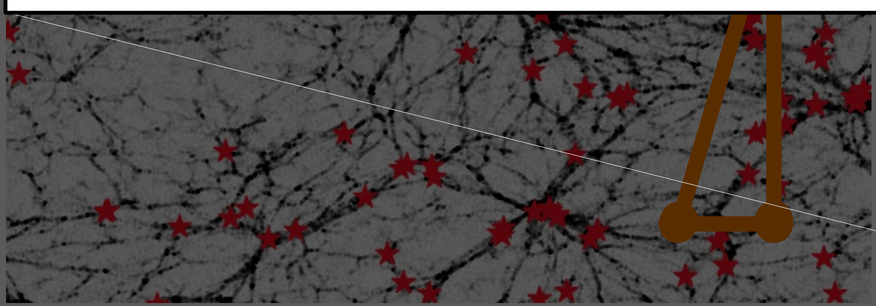
…atsu(2007), Jeong&Komatsu(2011))

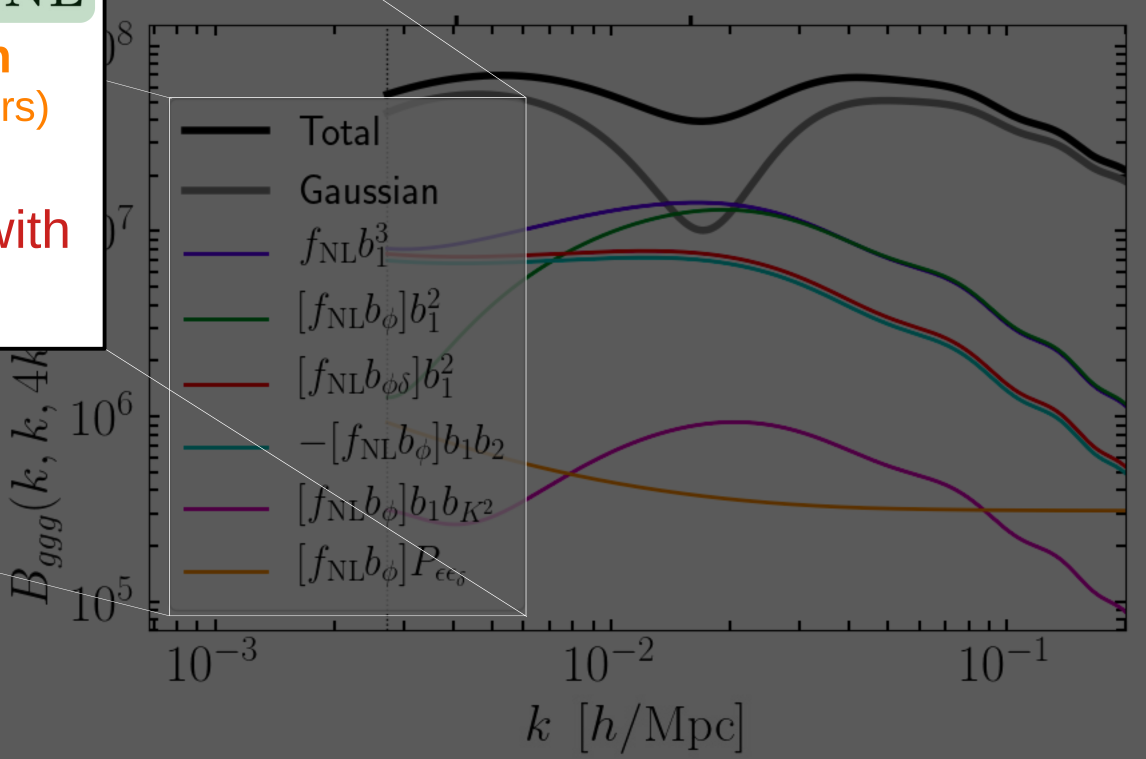
Cosmology

$$\text{Signatures} \propto b_\phi f_{NL}, b_{\phi\delta} f_{NL}$$

Galaxy formation
(galaxy bias parameters)

Galaxy bias is largely **degenerate** with f_{NL} in the bispectrum too.

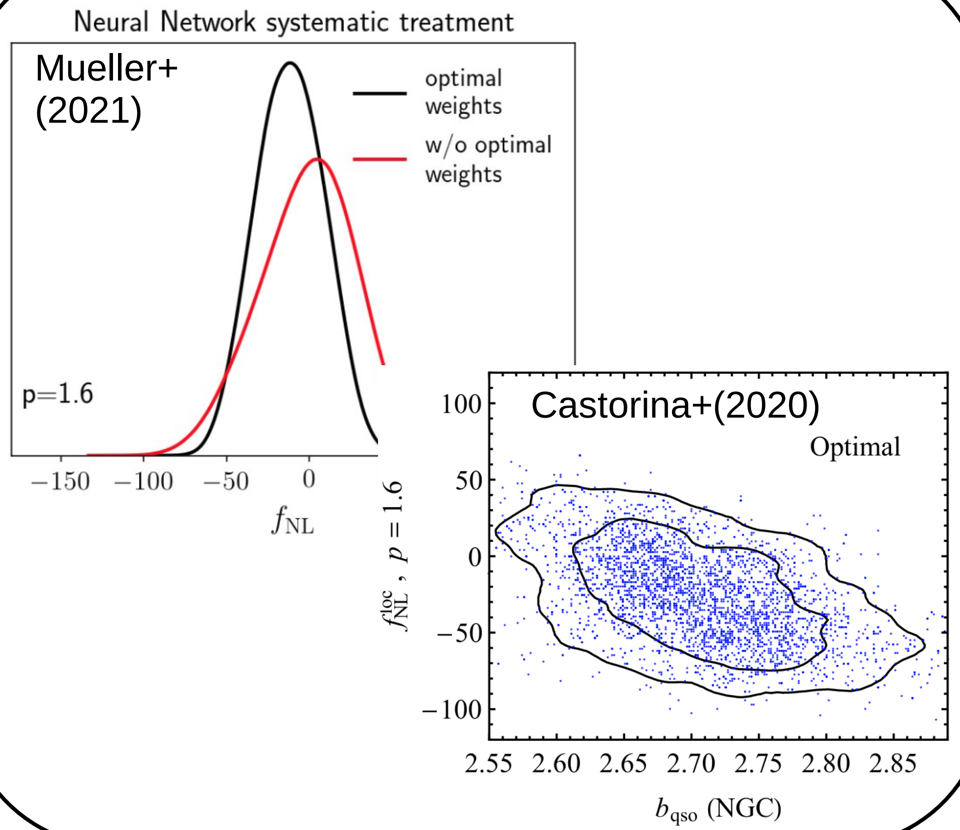




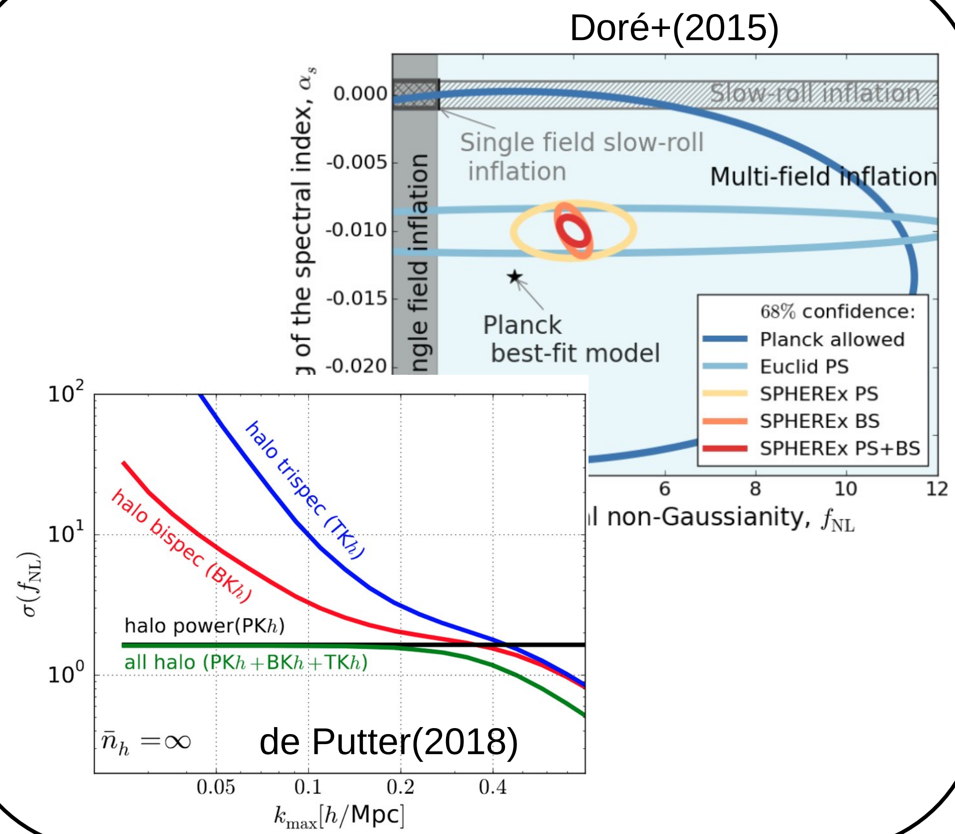
The search for local-type PNG, f_{NL}

How did all past works constrain/forecast f_{NL} then?

Many real data constraints



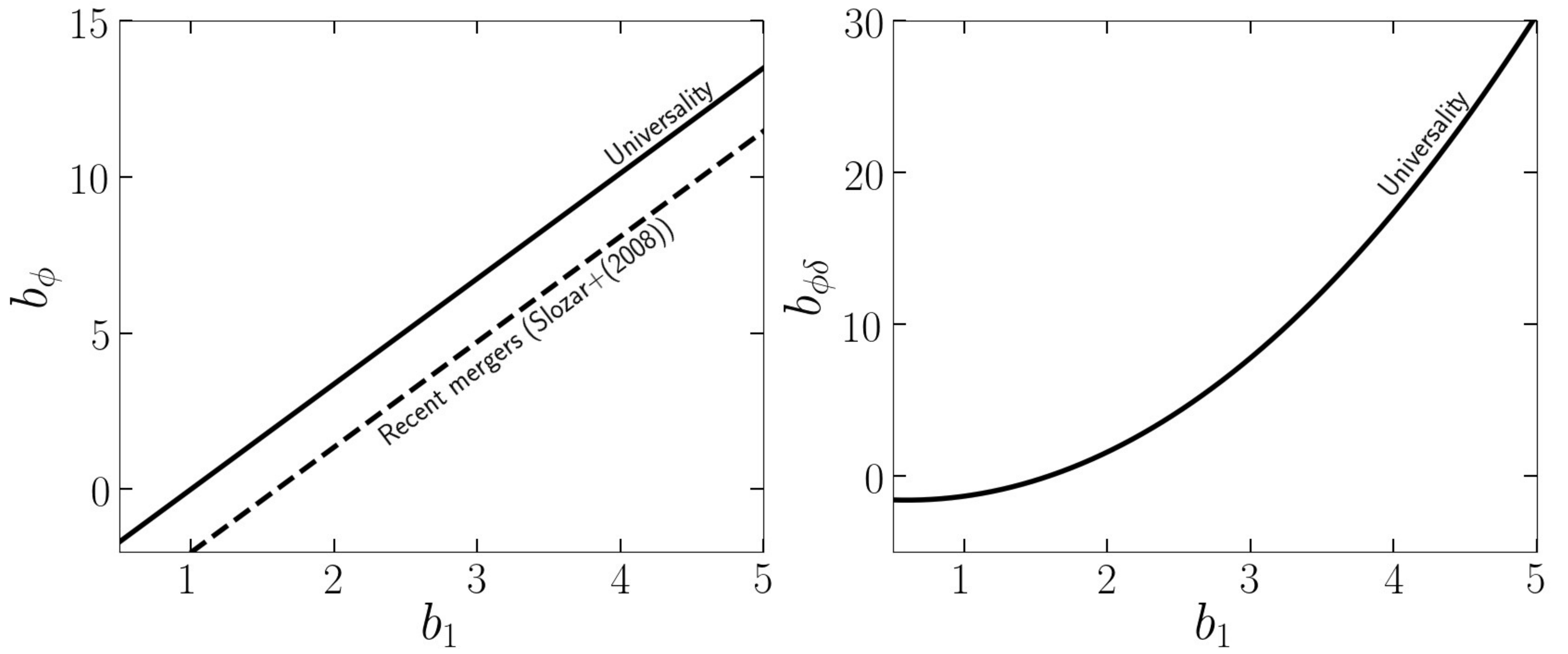
Many more future data forecasts



The PNG bias relations

The universality relations

(fix b_ϕ and $b_{\phi\delta}$ in terms of b_1, which can be fitted for)



Despite being routinely used, there is no reason for these relations to hold for real galaxies/tracers, **and they do not!**

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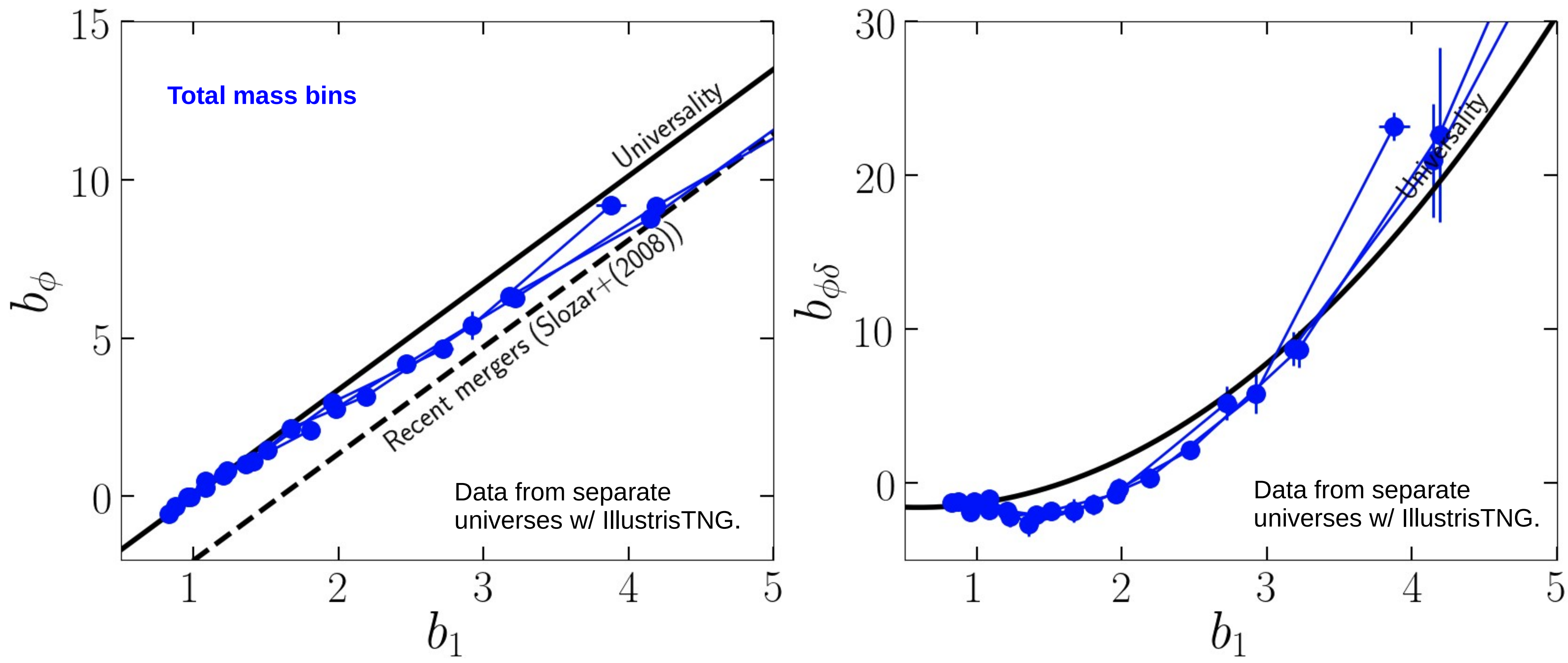

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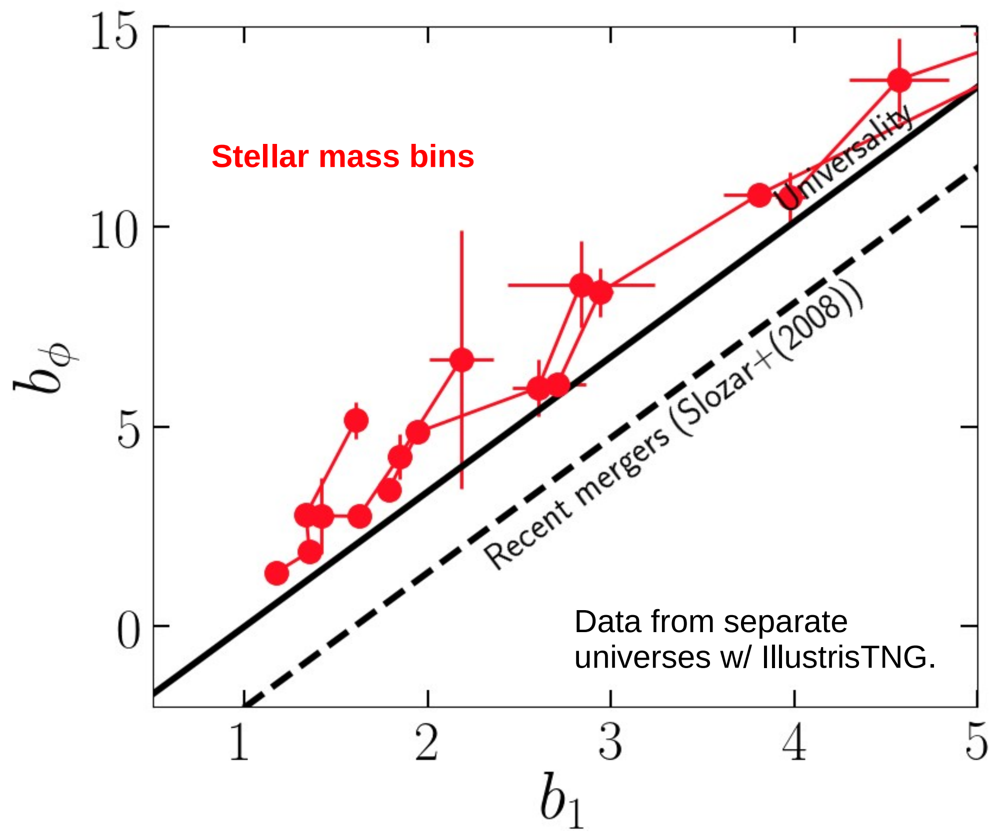

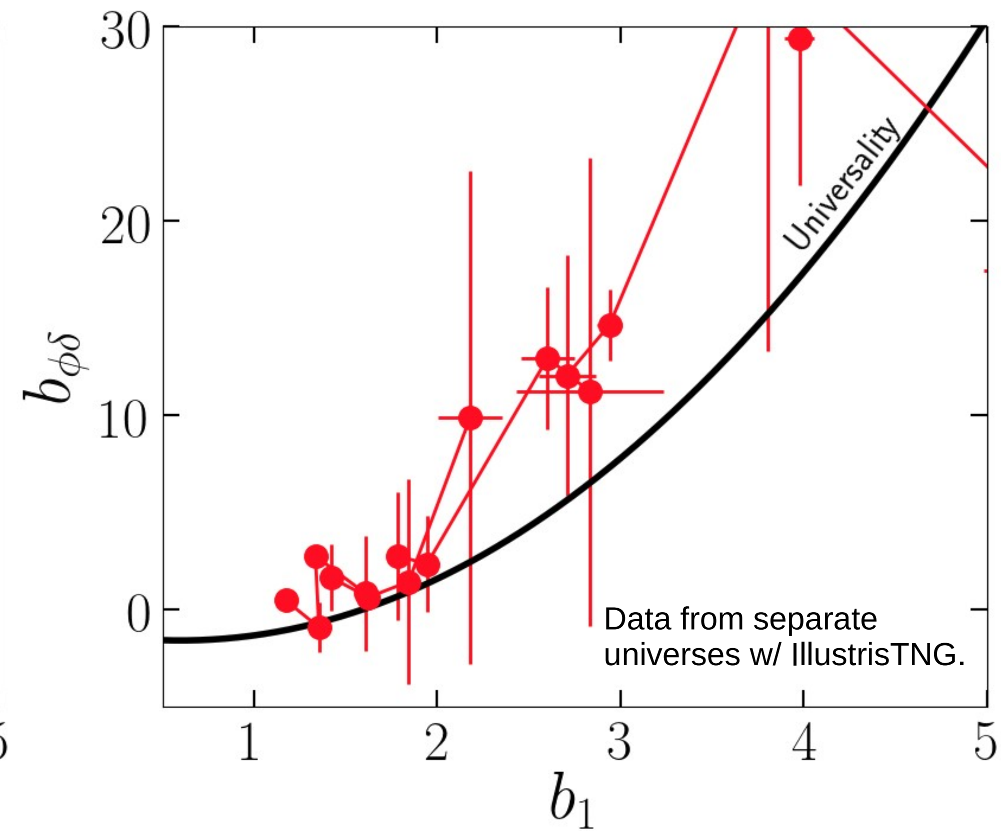

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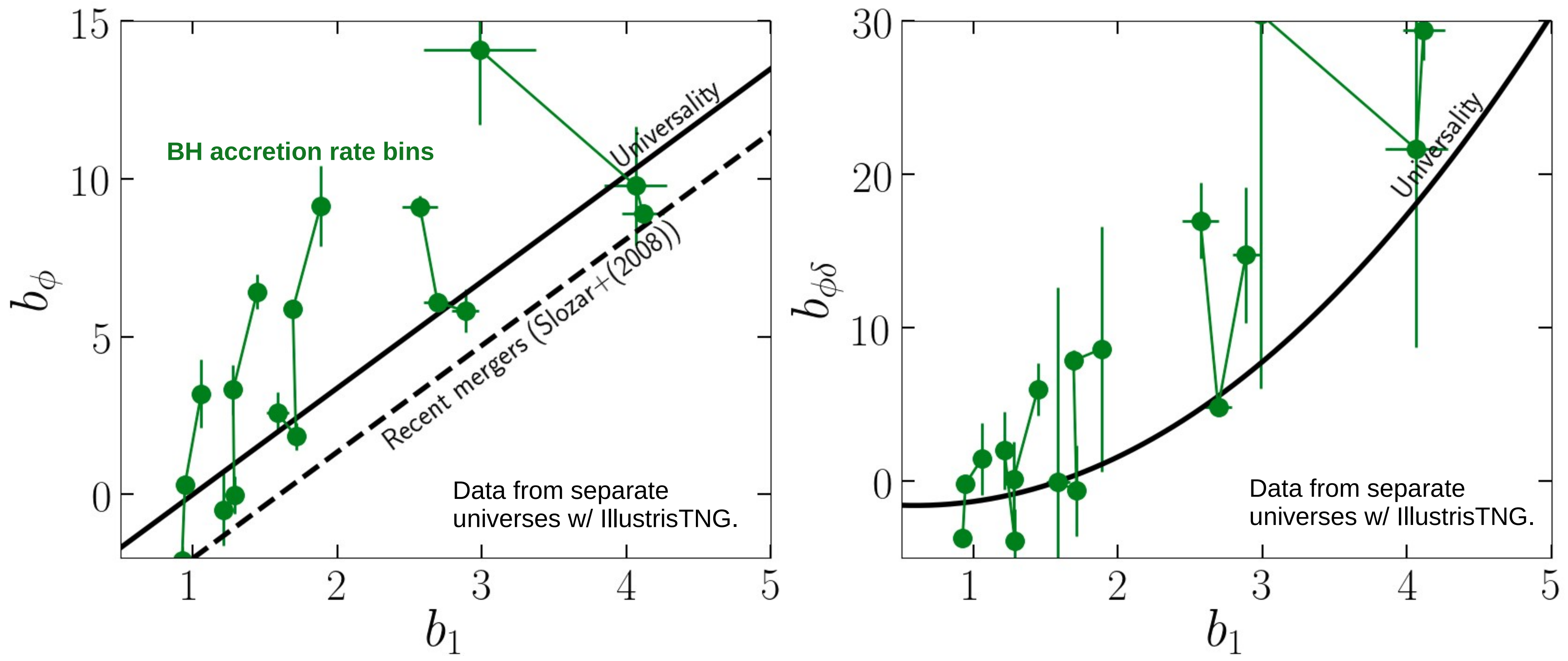

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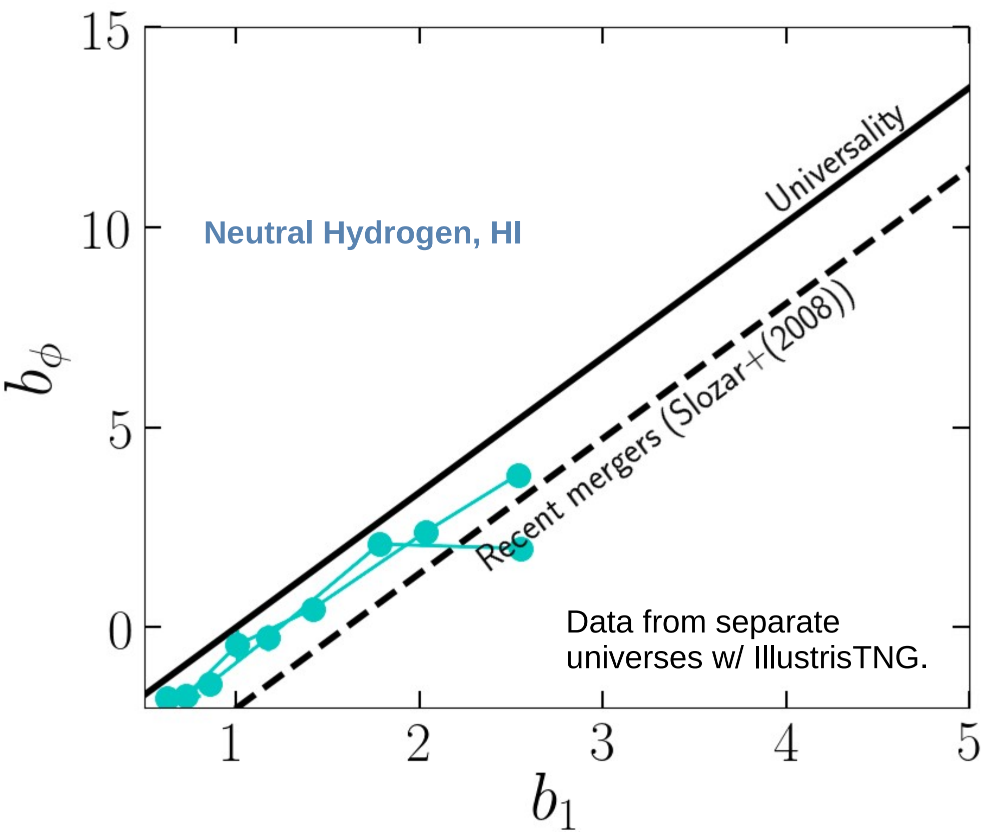

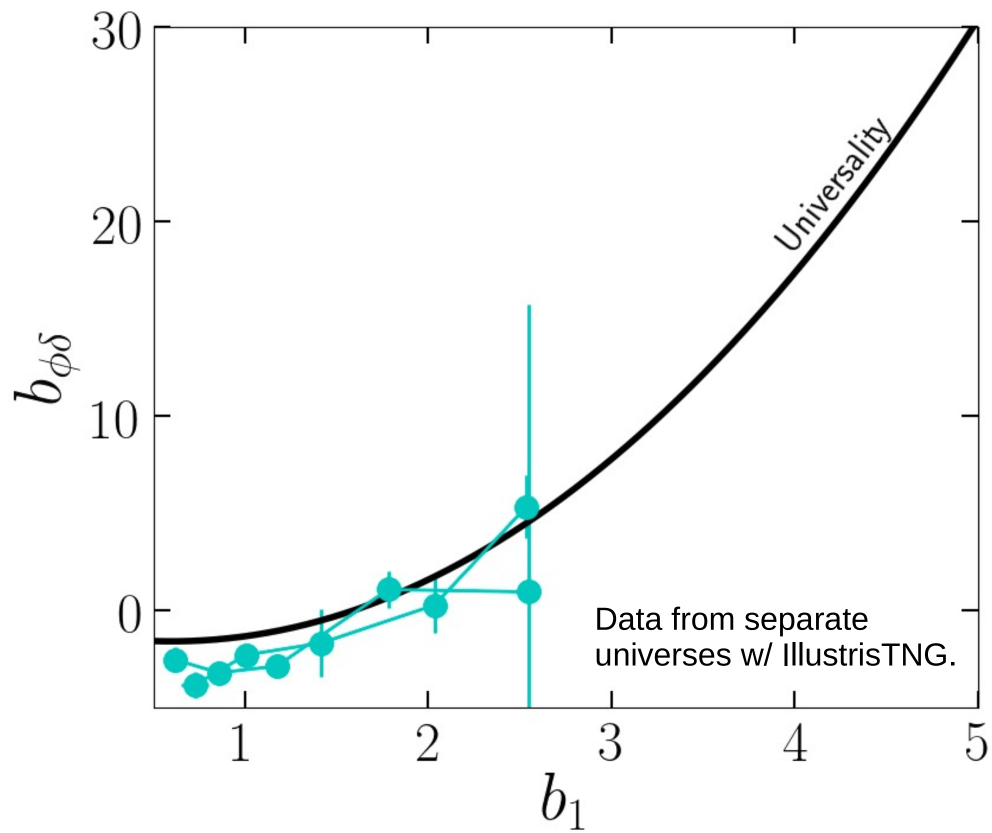

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The PNG bias relations

The universality relations

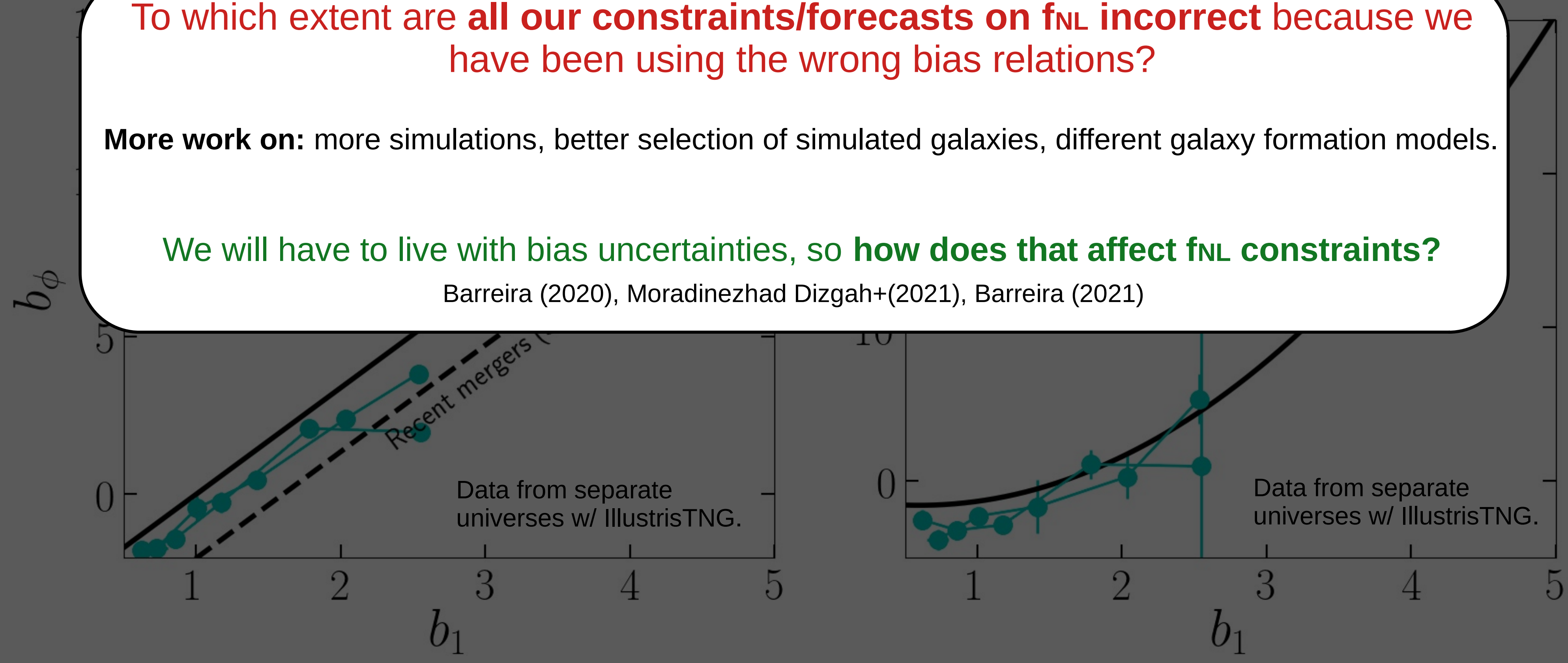
(fix b_ϕ and $b_{\phi\delta}$ in terms of b_1, which can be fitted for)

To which extent are **all our constraints/forecasts on f_{NL} incorrect** because we have been using the wrong bias relations?

More work on: more simulations, better selection of simulated galaxies, different galaxy formation models.

We will have to live with bias uncertainties, so **how does that affect f_{NL} constraints?**

Barreira (2020), Moradinezhad Dizgah+(2021), Barreira (2021)



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The impact of bias uncertainties

Barreira 2021

Simulated likelihood analysis for an idealized fictitious survey.

Forecast setup
(not survey specific)

- **Model:** tree-level power spectrum and bispectrum; No RSD, relativistic effects or obs. systematics.
- **Data:** Multitracer power spectrum, and bispectrum (noiseless realization of the model at the fiducial);
- **Covariance:** Gaussian + partial non-Gaussian;
- **Galaxies:** 2 stellar mass selected samples;
- **Volume, redshift, fiducial, k_{max}:**
  - V = 100 Gpc^3/h^3;
  - z = 1
  - f_{NL} = 5;
  - k_{max} = 0.2 h/Mpc
- **Cosmology:** fixed, except f_{NL} and A_s;
- **Shot-noise:** leading-order (4 parameters);

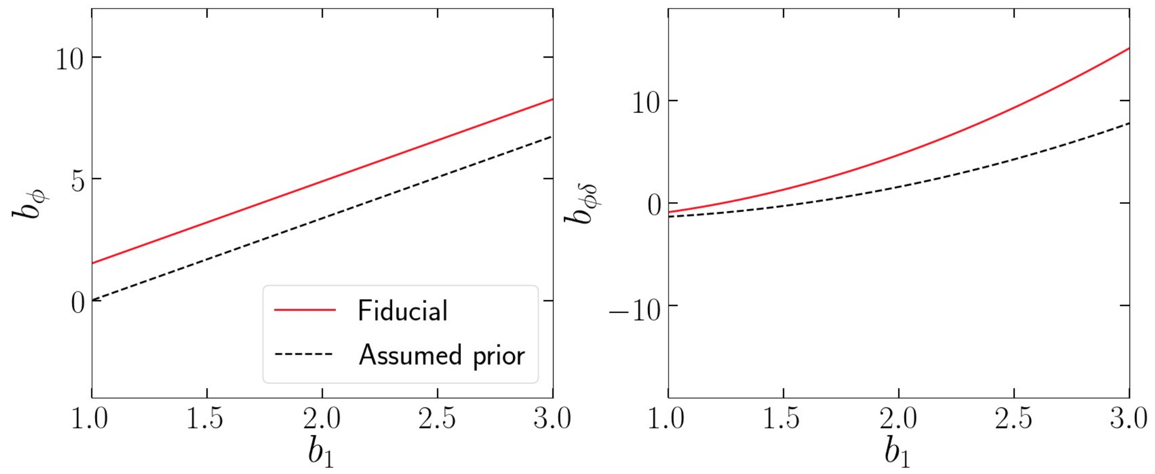
Priors on PNG bias parameters

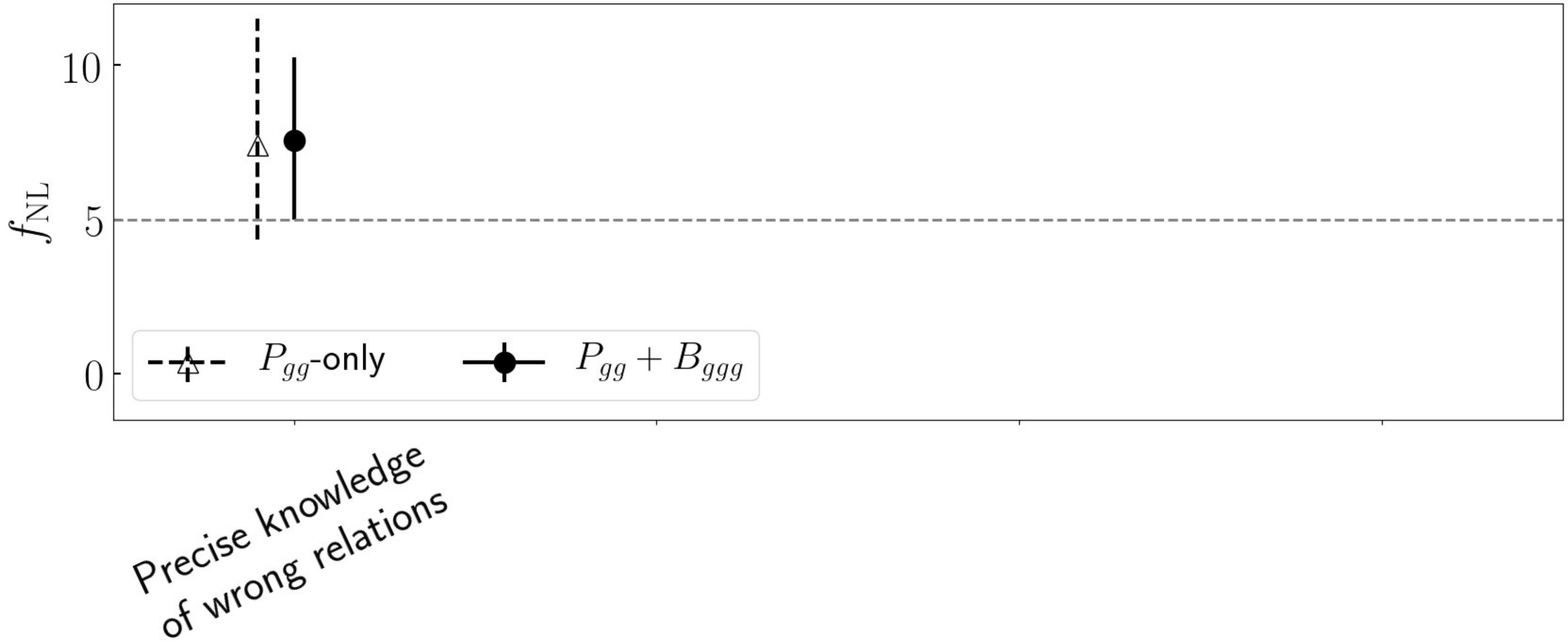
Barreira 2021

Prior centered on the wrong relation

Zero uncertainty

<u>Aproach 1:</u>
marginalize over Gaussian priors on the bias parameter relations





Priors on PNG bias parameters

Barreira 2021

Prior centered on the wrong relation

Uncertainty of $\Delta b_\phi = 1$, $\Delta b_{\phi\delta} = 5$

Aproach 1:
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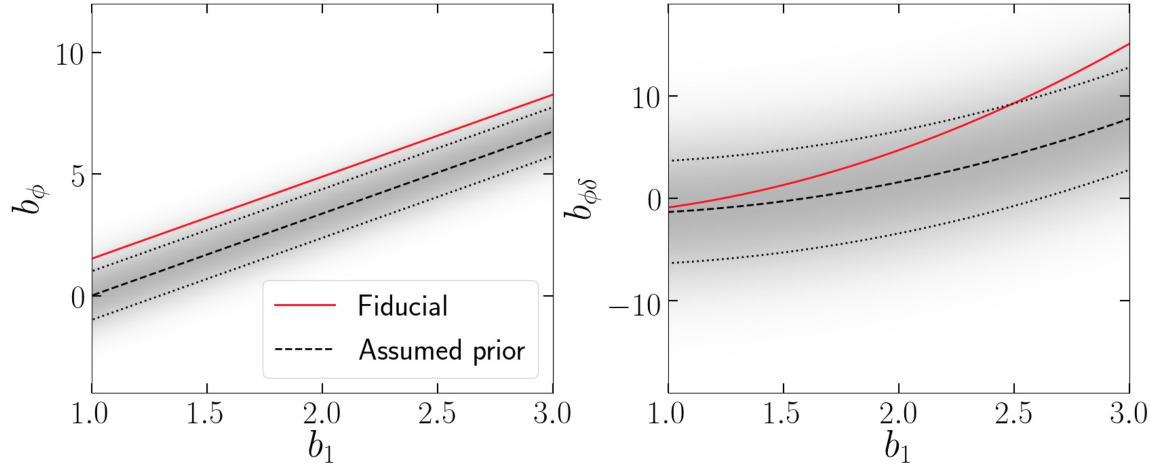
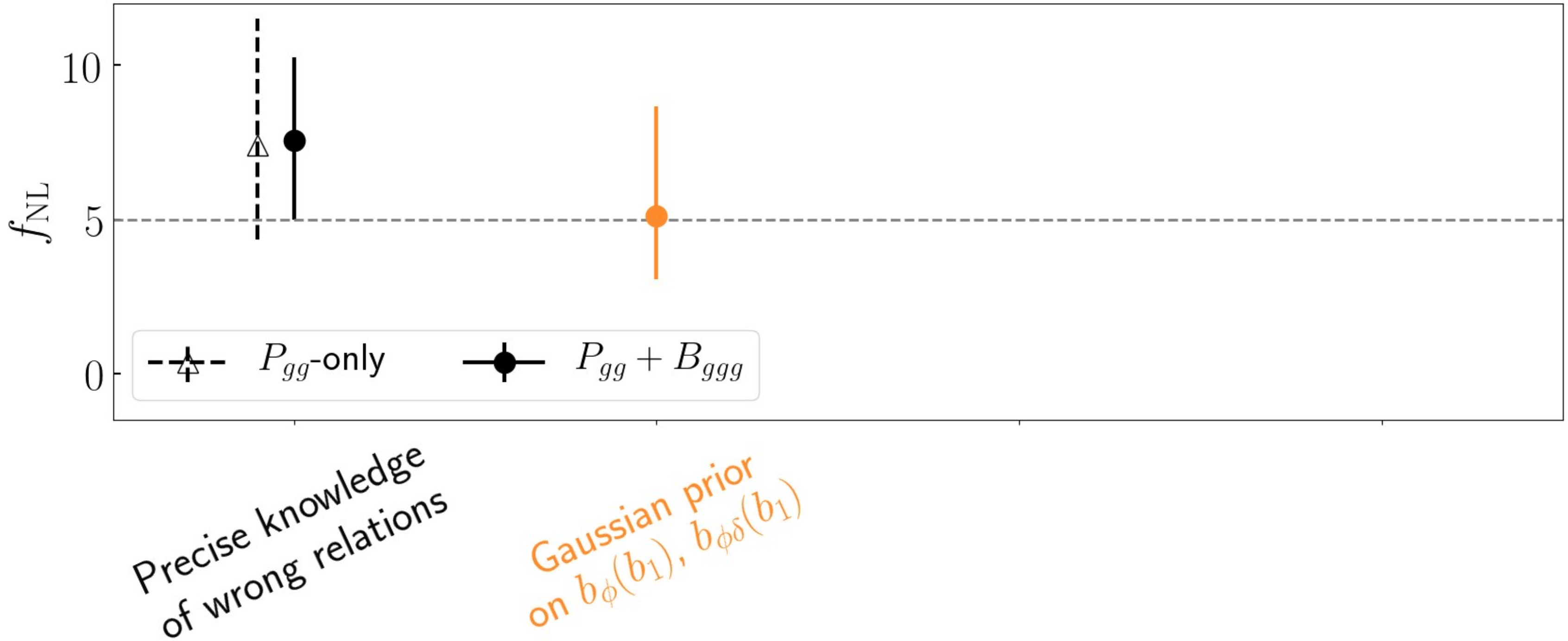




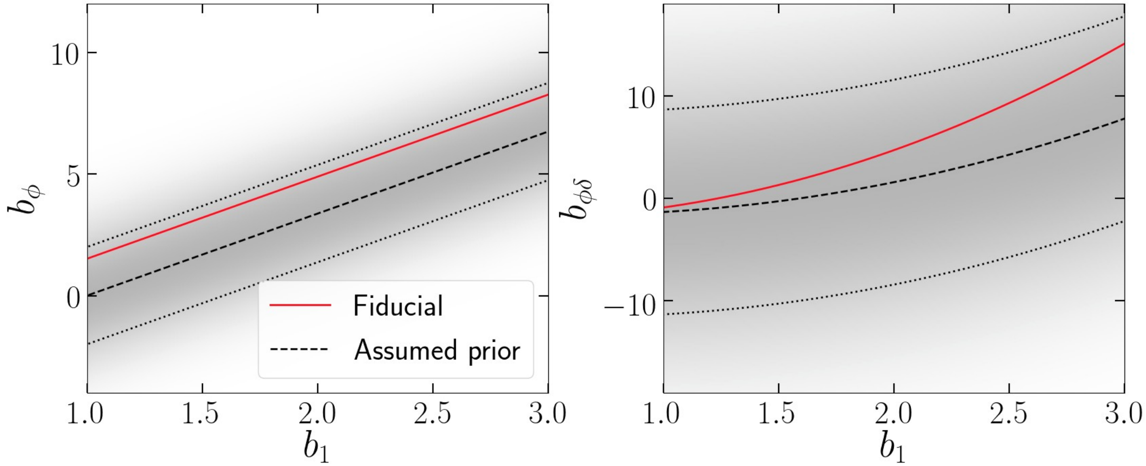
Priors on PNG bias parameters

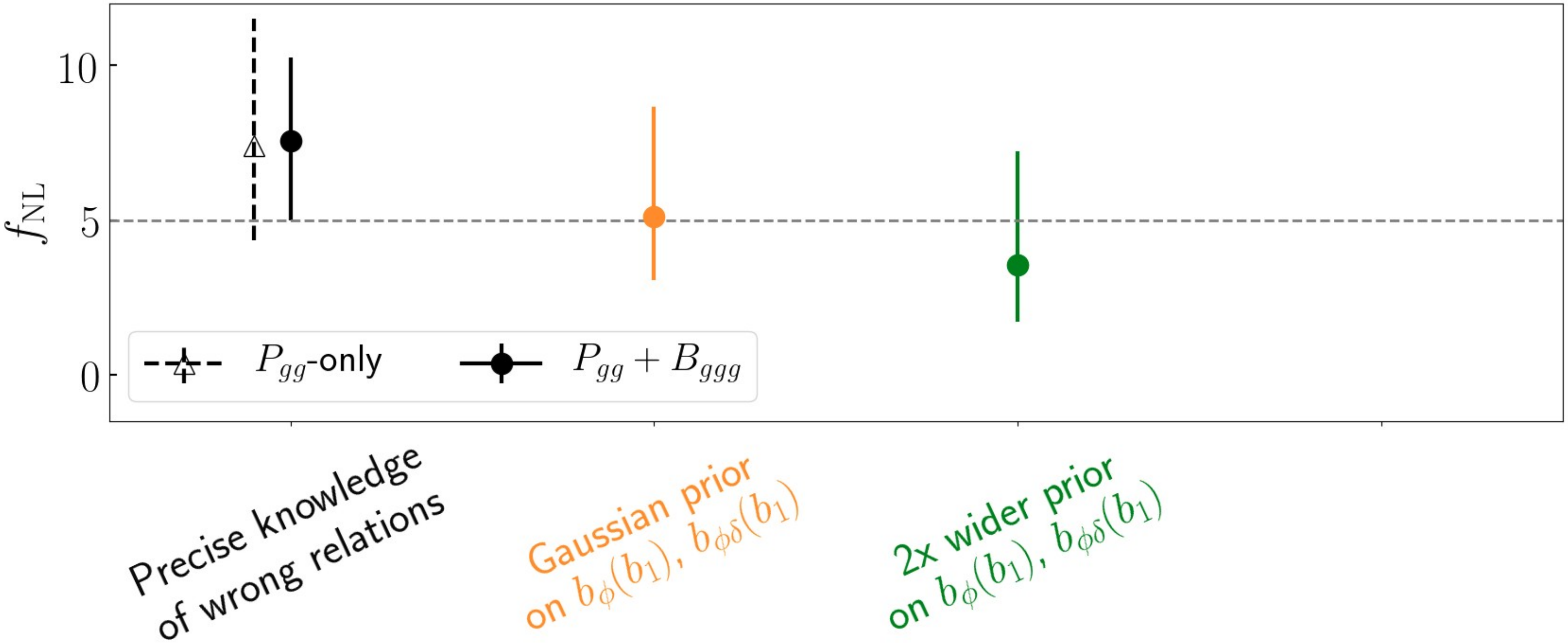
Barreira 2021

Aproach 1:
marginalize over Gaussian priors on the bias parameter relations

Prior centered on the wrong relation

Uncertainty of $\Delta b_\phi = 2$, $\Delta b_{\phi\delta} = 10$





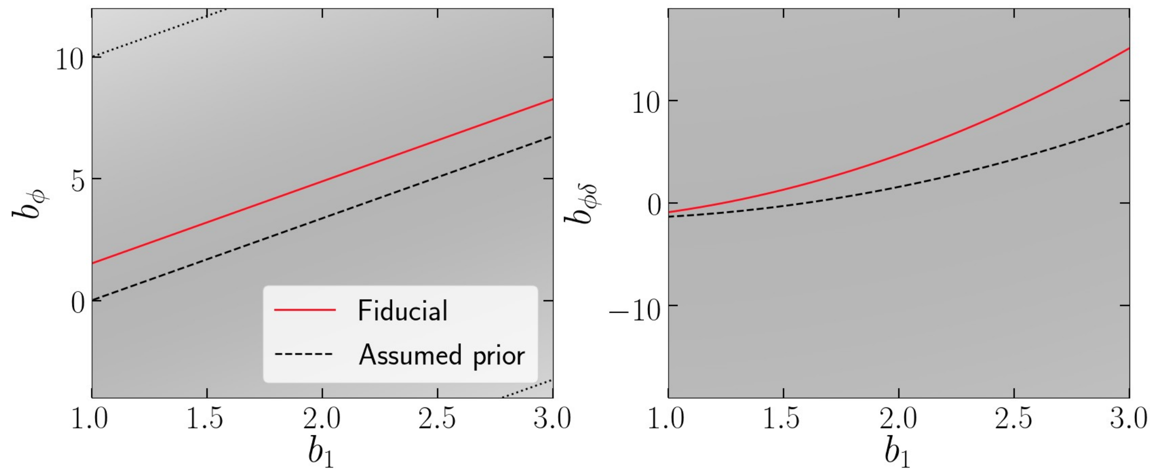
Priors on PNG bias parameters

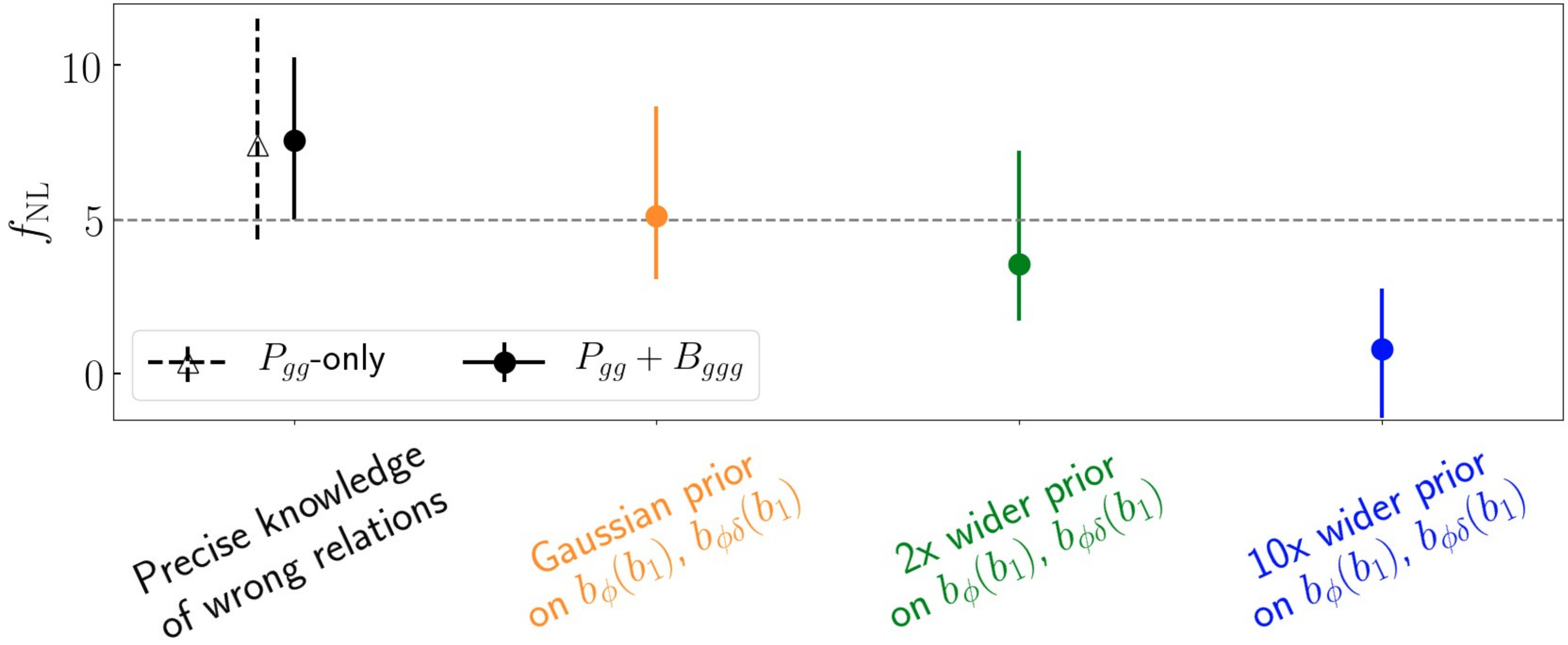
Barreira 2021

Aproach 1:
marginalize over Gaussian priors on the bias parameter relations

Prior centered on the wrong relation

Uncertainty of $\Delta b_\phi = 10$, $\Delta b_{\phi\delta} = 50$



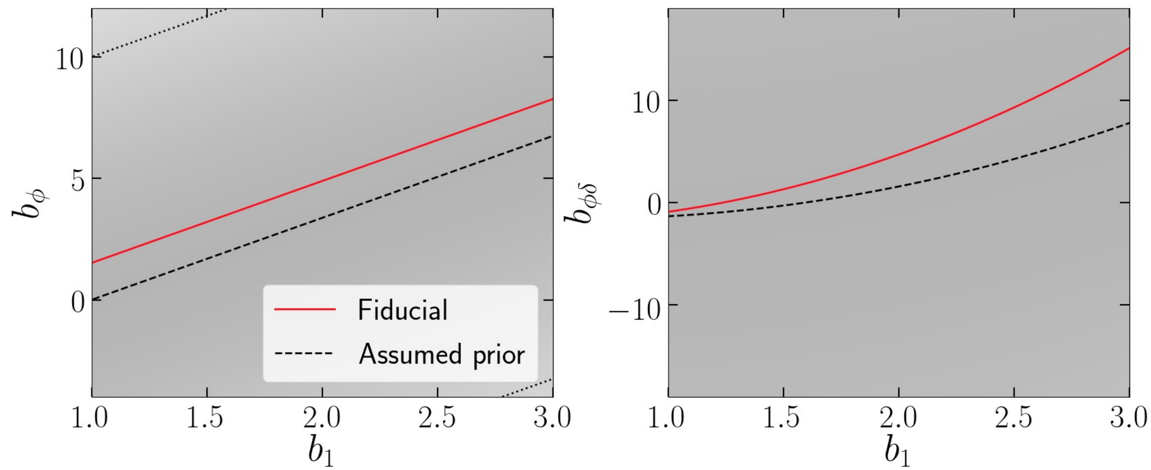


Priors on PNG bias parameters

Barreira 2021

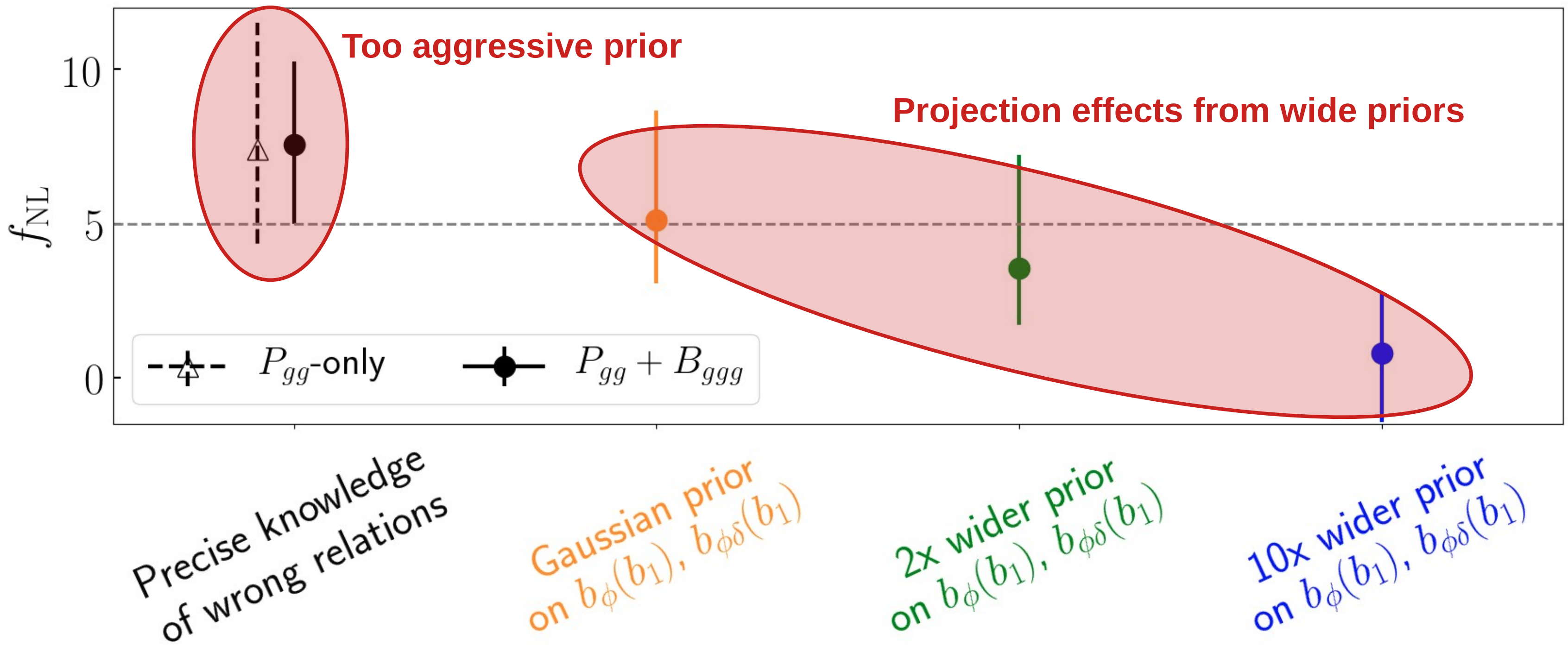
Prior centered on the wrong relation

Uncertainty of Δb_ϕ = 10 , $\Delta b_{\phi\delta}$ = 50



<u>Aproach 1:</u>
marginalize over Gaussian priors on the bias parameter relations

Wide priors are not conservative!
We really need accurate and precise priors from simulations to constrain f_{NL}.



The impact of bias uncertainties

Barreira 2021

Aproach 2: fits for the products of $f_{NL}b_{\phi}$ and $f_{NL}b_{\phi\delta}$.

The advantage

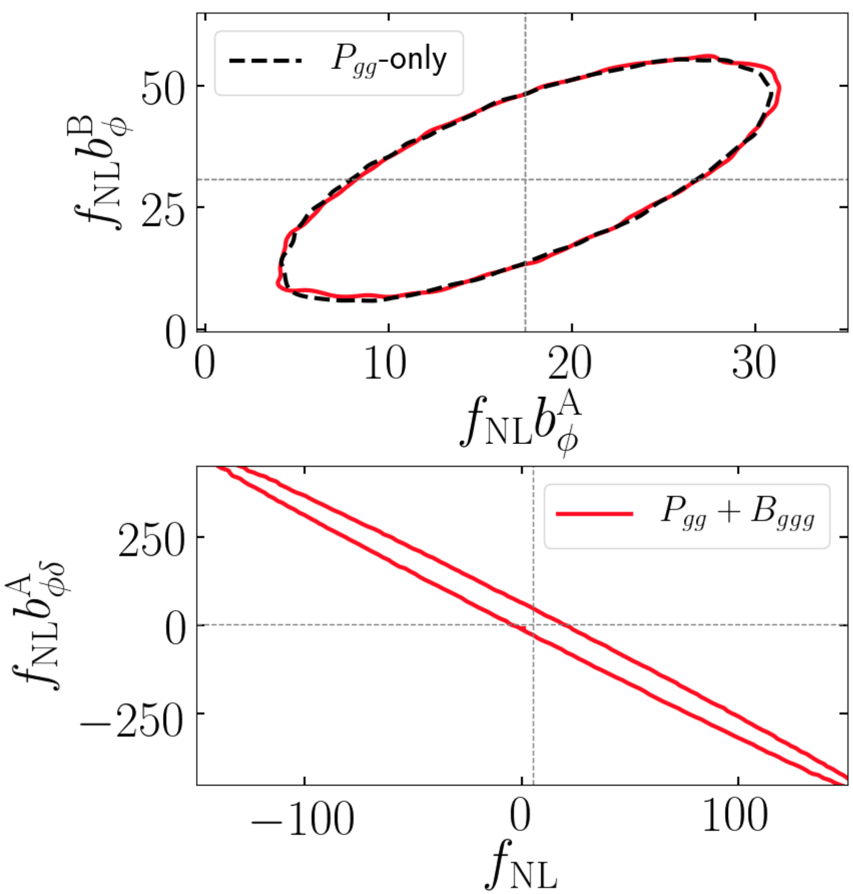
Bypasses any assumptions on PNG bias, while still allowing to distinguish f_{NL} from zero

(we just won't know the exact value).

The impact of bias uncertainties

Barreira 2021

Aproach 2: fits for the products of $f_{NL}b_{\phi}$ and $f_{NL}b_{\phi\delta}$.



The advantage

Bypasses any assumptions on PNG bias, while still allowing to distinguish f_{NL} from zero

(we just won't know the exact value).

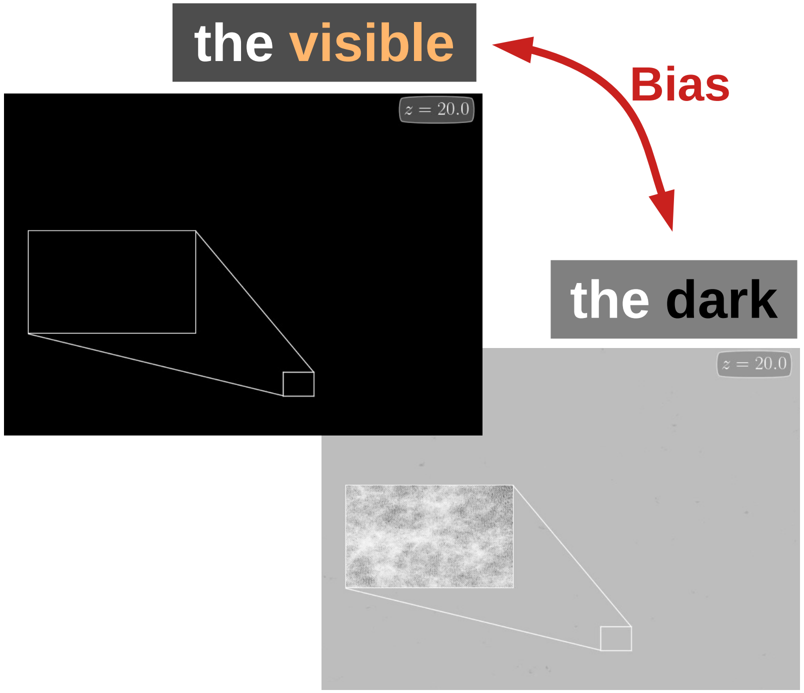
The disadvantage

The bispectrum does not improve the constraints

(new parameter degeneracies arise).

The recommendation

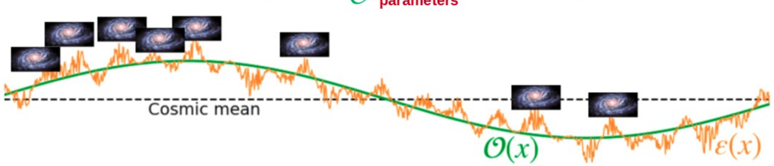
At least power spectrum analyses should adopt this **bias-assumption-free approach.**



Local galaxy number density · Global galaxy number density · Large-scale perturbations (density, tidal, potential, etc.) · Stochasticity (shot-noise)

$$n_g(\boldsymbol{x}, z) = \bar{n}_g(z)\left[1 + \sum_{\mathcal{O}} b_{\mathcal{O}}(z)\mathcal{O}(\boldsymbol{x}, z)\right] + \epsilon(\boldsymbol{x}, z)$$

Bias parameters



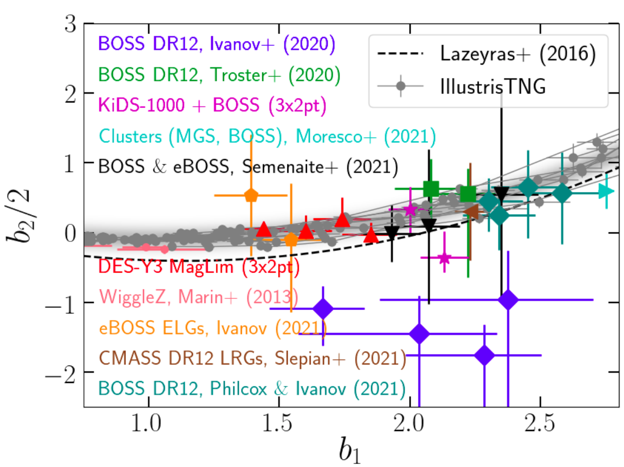
Summary

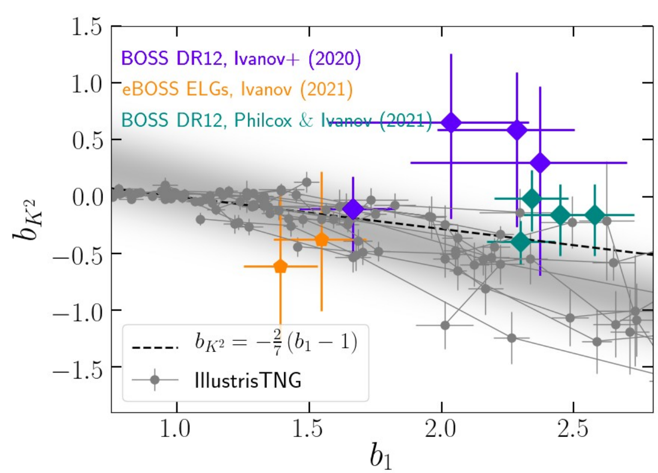
- **Galaxy bias** is the relation between the visible and the dark Universe: it is crucial to infer cosmology from galaxy data.

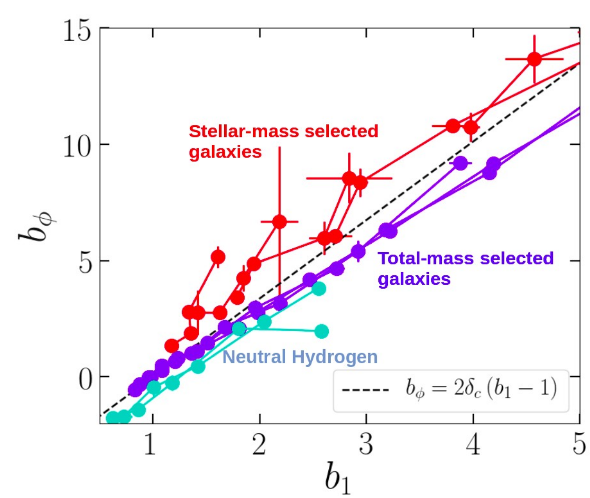
  It leads also to new insights about the galaxy-environment connection **(eg. halo occupation responses, assembly bias).**

- **Separate universe simulations and field-level forward models** are powerful tools to advance our understanding of galaxy bias and the differences to halo bias.

- **Need to revisit local PNG contraints using galaxy data**, which make unjustified assumptions about galaxy bias!







Extra slides

HOD bias derivation

Origin of the HOD bias:

$$
\begin{aligned}
b_{g,\mathcal{O}} &= \frac{\partial \ln n_g}{\partial \mathcal{O}} \\
&= \frac{1}{\bar{n}_g} \frac{\partial}{\partial \mathcal{O}} \int \mathrm{d}M n_h(M) N_g(M) \\
&= \frac{1}{\bar{n}_g} \int \mathrm{d}M n_h(M) N_g(M) \left[\frac{\partial \ln n_h(M)}{\partial \mathcal{O}} + \frac{\partial \ln N_g(M)}{\partial \mathcal{O}} \right] \\
&= \frac{1}{\bar{n}_g} \int \mathrm{d}M n_h(M) N_g(M) \left[b_{h,\mathcal{O}}(M) + R_{N_g,\mathcal{O}}(M) \right]
\end{aligned}
$$

Halo bias expansion:

$$n_h(\boldsymbol{x}, z) = \bar{n}_h(z) \left[1 + b_h(z) \mathcal{O}(\boldsymbol{x}, z) \right]$$

HOD bias expansion:

$$N_g(\boldsymbol{x}, M, z) = \bar{N}_g(M, z) \left[1 + R_{N_g}(M, z) \mathcal{O}(\boldsymbol{x}, z) \right]$$