Primordial non-Gaussianities and the LSS of the Universe

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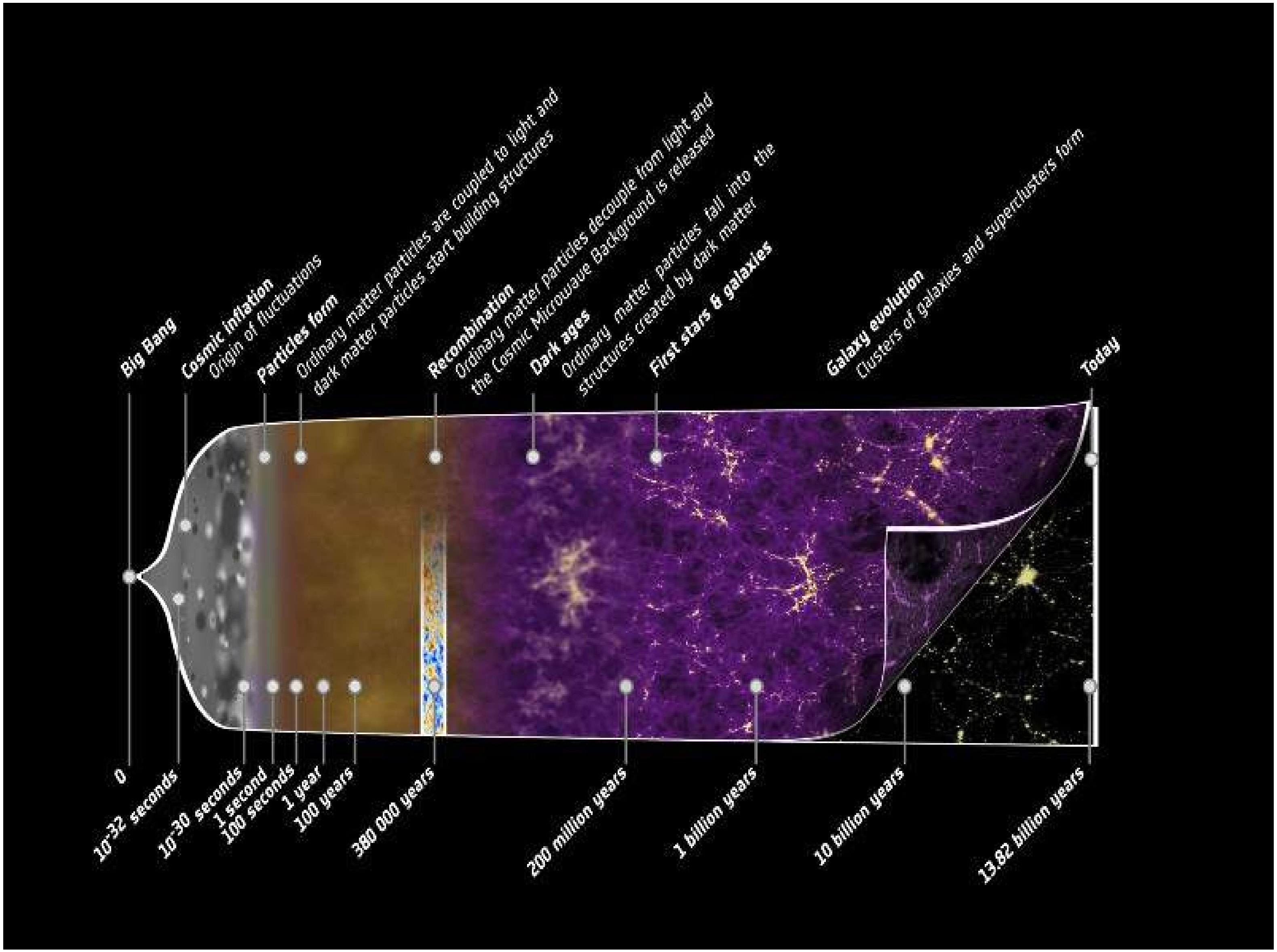
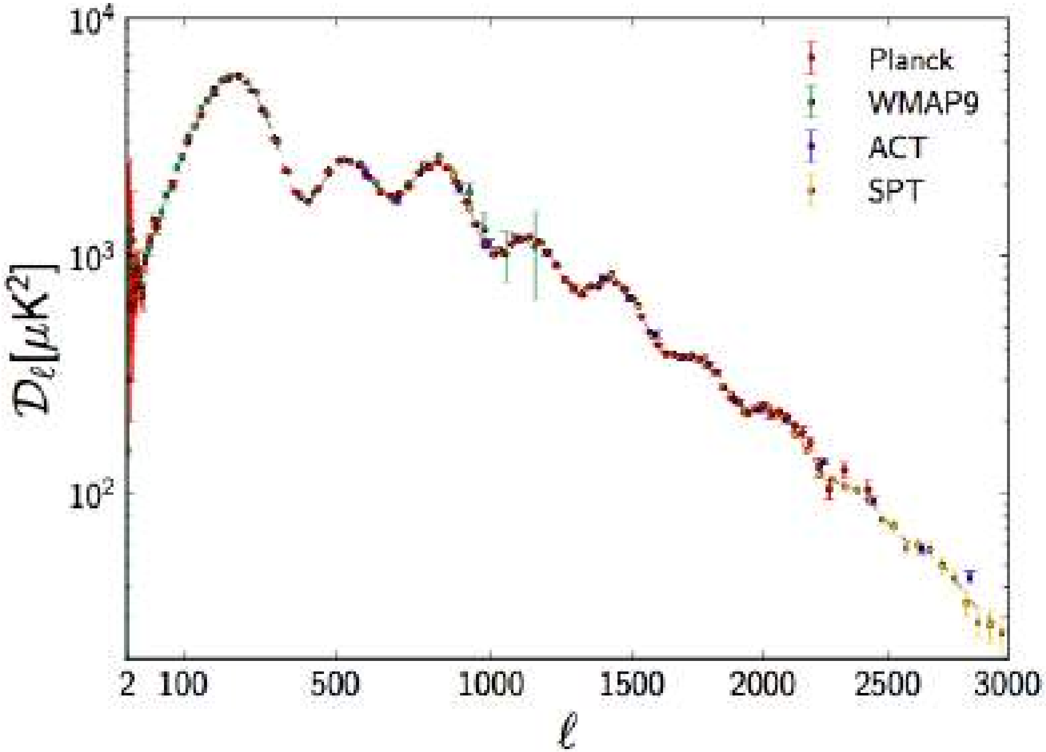
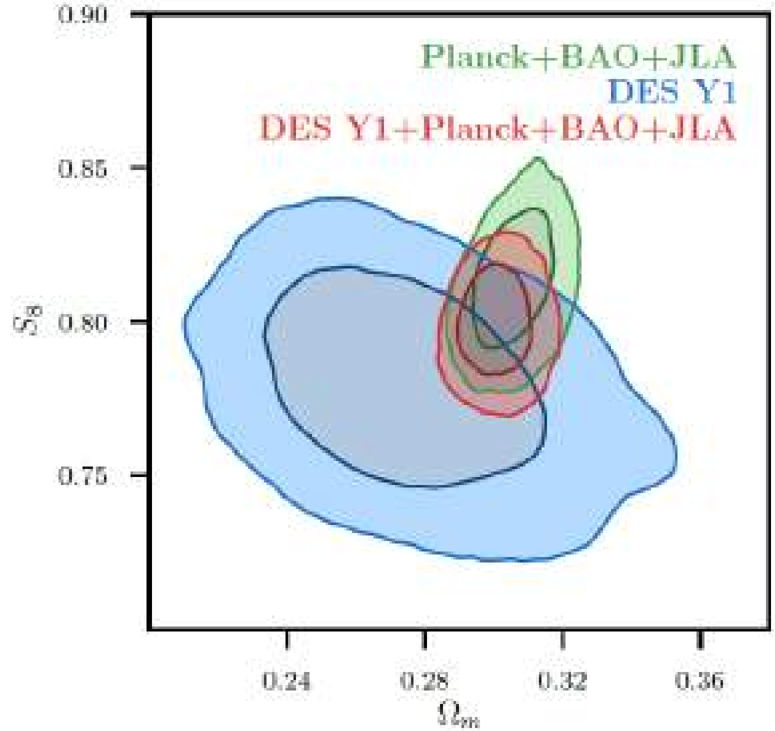
University of Geneva, 7/2/2020

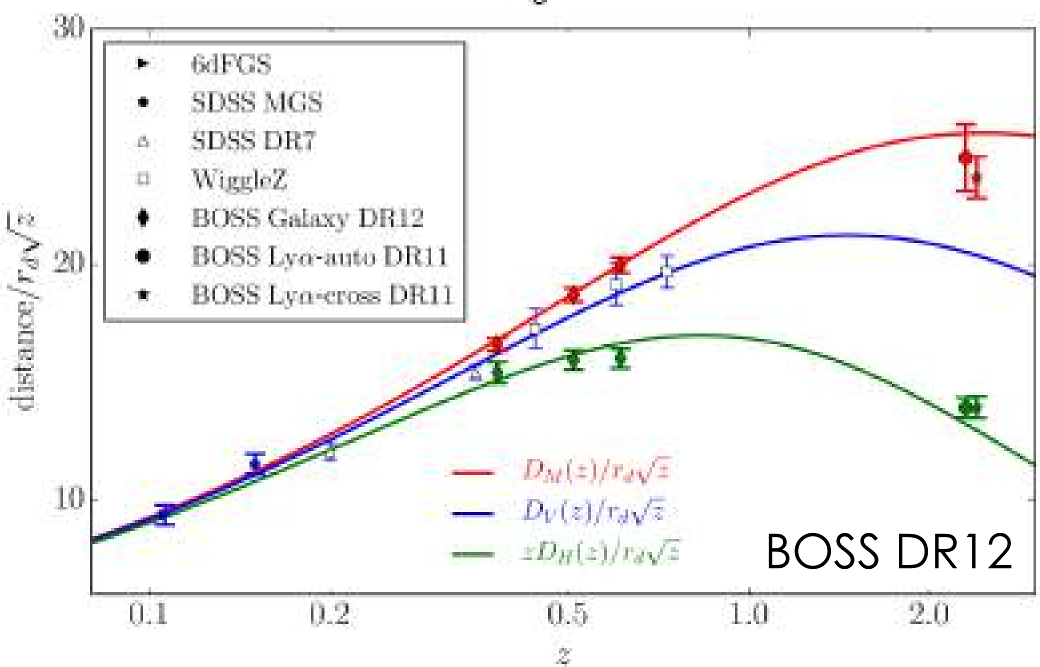
Mandatory slide : the long story short...

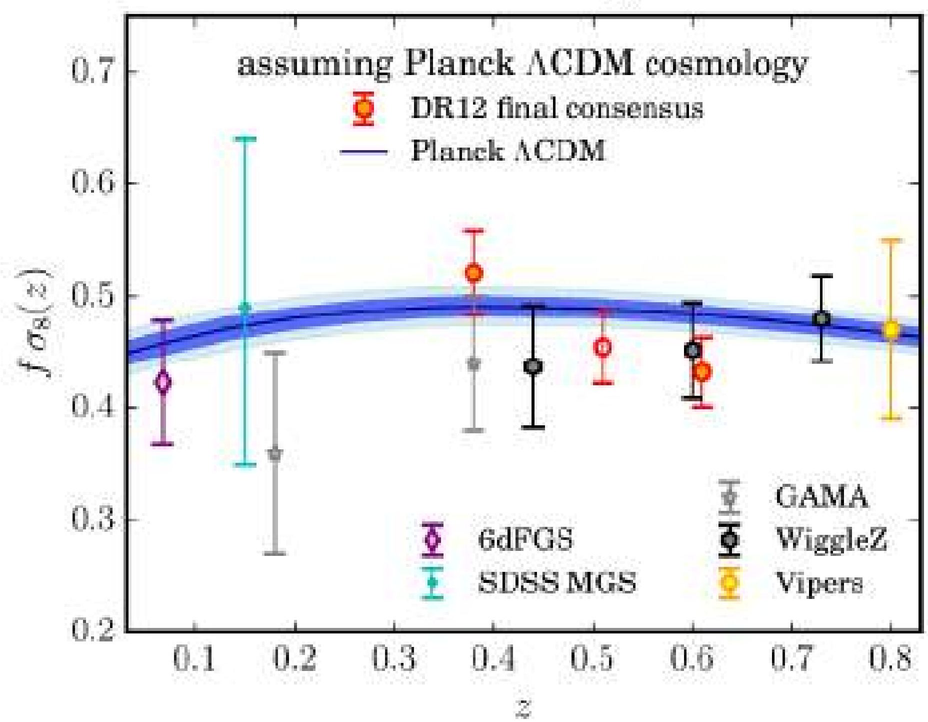


Observational status: a consistent picture

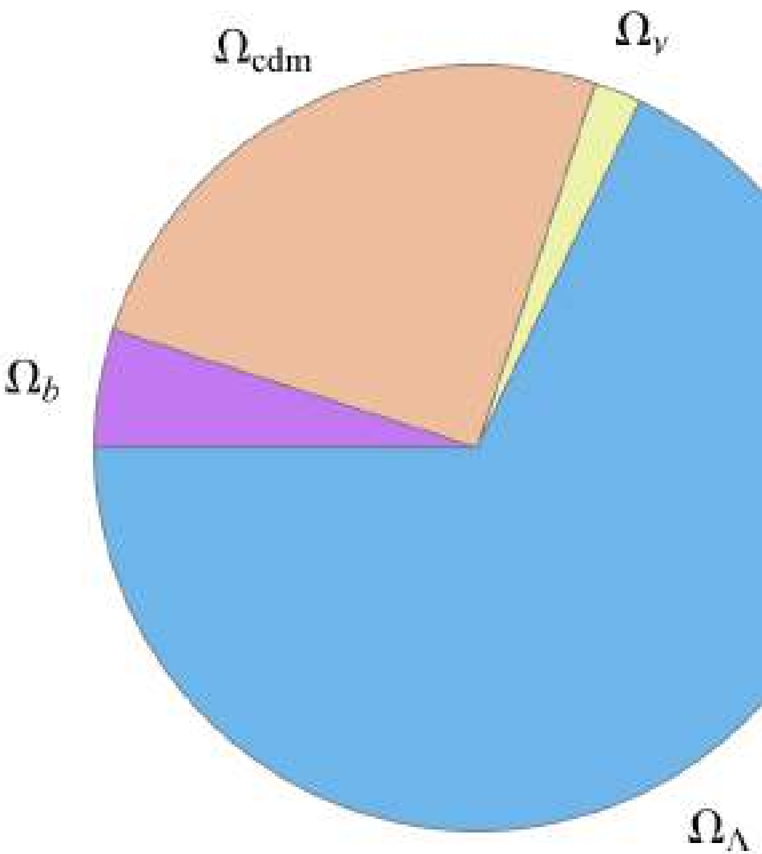








The pizza nobody asked for



+

~ Adiabatic
~ scale invariant
~ Gaussian initial conditions

Some pessimism...

Plenty of data: Future CMB missions + DES, DESI, LSST, Euclid, WFIRST, CHIME, HIRAX

Promise of dramatically improve error bars on cosmological parameters.

However...

Incremental improvement is not enough, not all parameters are born equal.
Precision cosmology means benchmarks to be achieved.

Examples are neutrino masses, inflationary parameters, N_eff, curvature, tensor modes...

Dark energy is the elephant in the room in this discussion.

This talk →

Primordial non-Gaussianities:

- Optimal signal weighting in eBOSS
- Zero bias tracers

Outline

- What are inflation and Primordial Non-Gaussianties

- Part I: optimal redshfit weights and eBOSS data analysis.

- Part II: zero bias tracers and cosmic variance cancellation.

Why we care

Inflation solves problems
and makes predictions :

- Large Scales causally connected in the past
- Observable Universe is (close to) flat

$$|\Omega_K| < 0.005$$

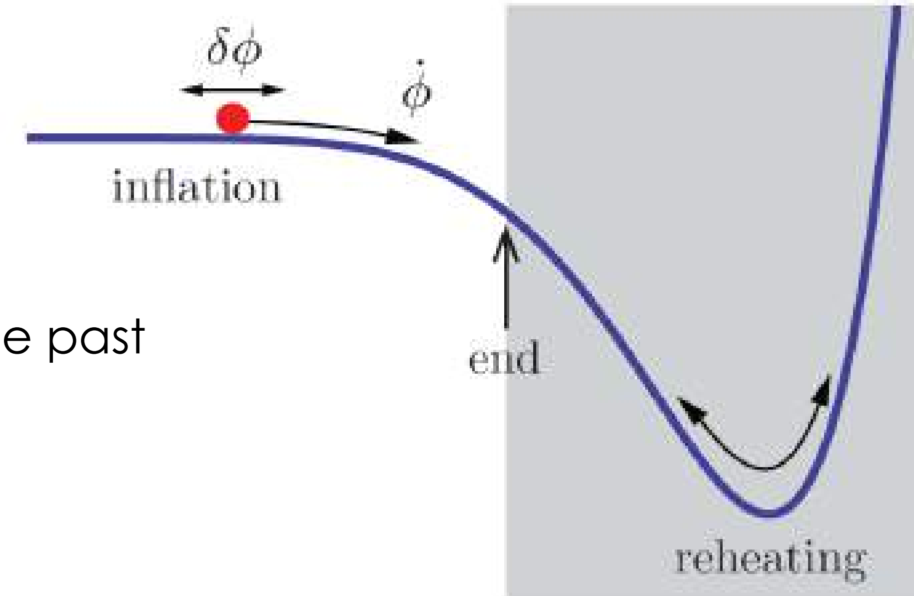
- Spectral index and runnings

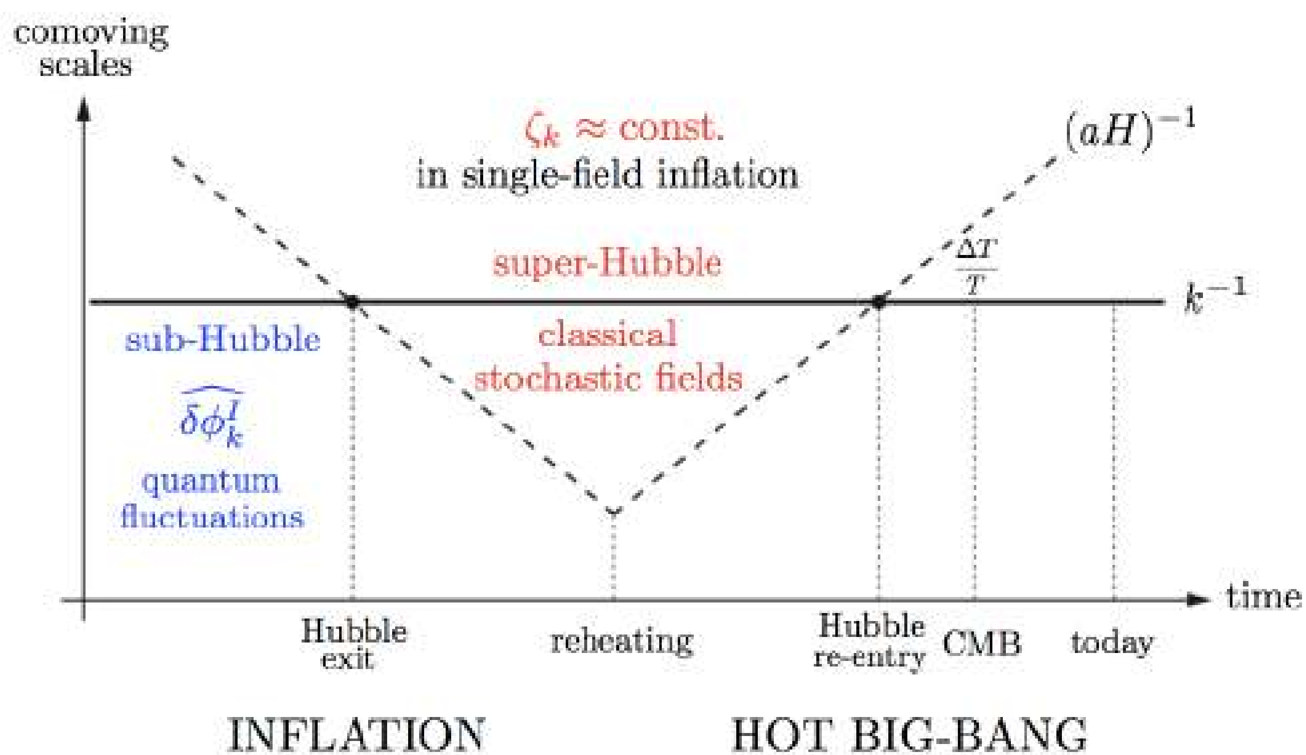
$$n_s = 0.9655 \pm 0.0062$$

- ~ Adiabiatic fluctuations

$$\alpha_{\rm iso} < 1\%$$

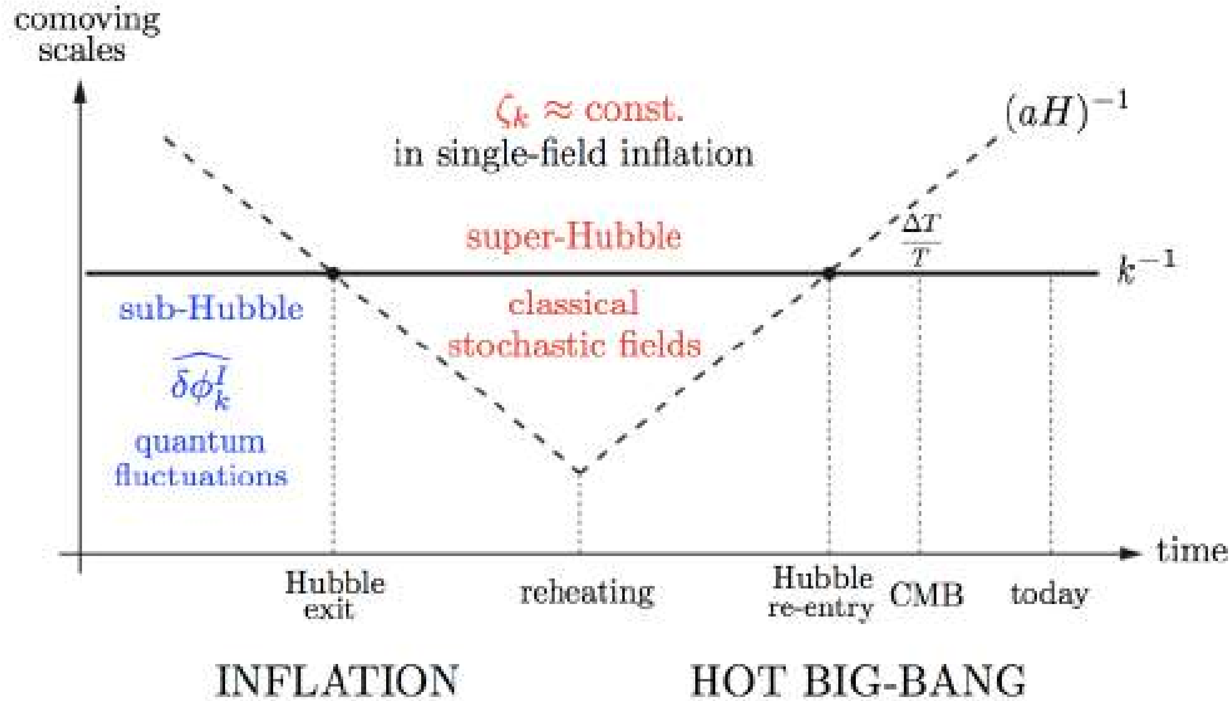
- ~ Gaussian fluctuations
- Tensor modes ? TBD





Credit : Baumann

The consistency relation

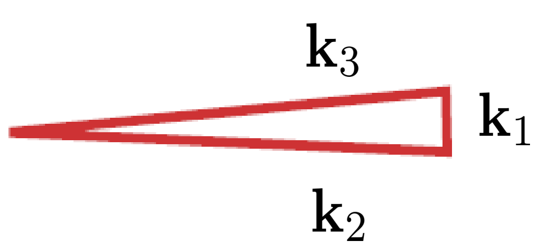


Higher point functions (PNG) as a probe of the dynamics of inflation.

$$\langle\, \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\,\rangle = (2\pi)^3\delta_D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\zeta(k_1,k_2,k_3)$$

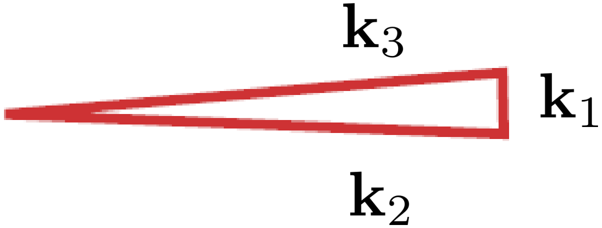
Local non Gaussianities are negligible in single field inflation.
A non perturbative result independent of the dynamics!

$$\lim_{k_1\to 0} B_\zeta(k_1,k_2,k_3) = (n_s-1)P_\zeta(k_1)P_\zeta(k_3)$$



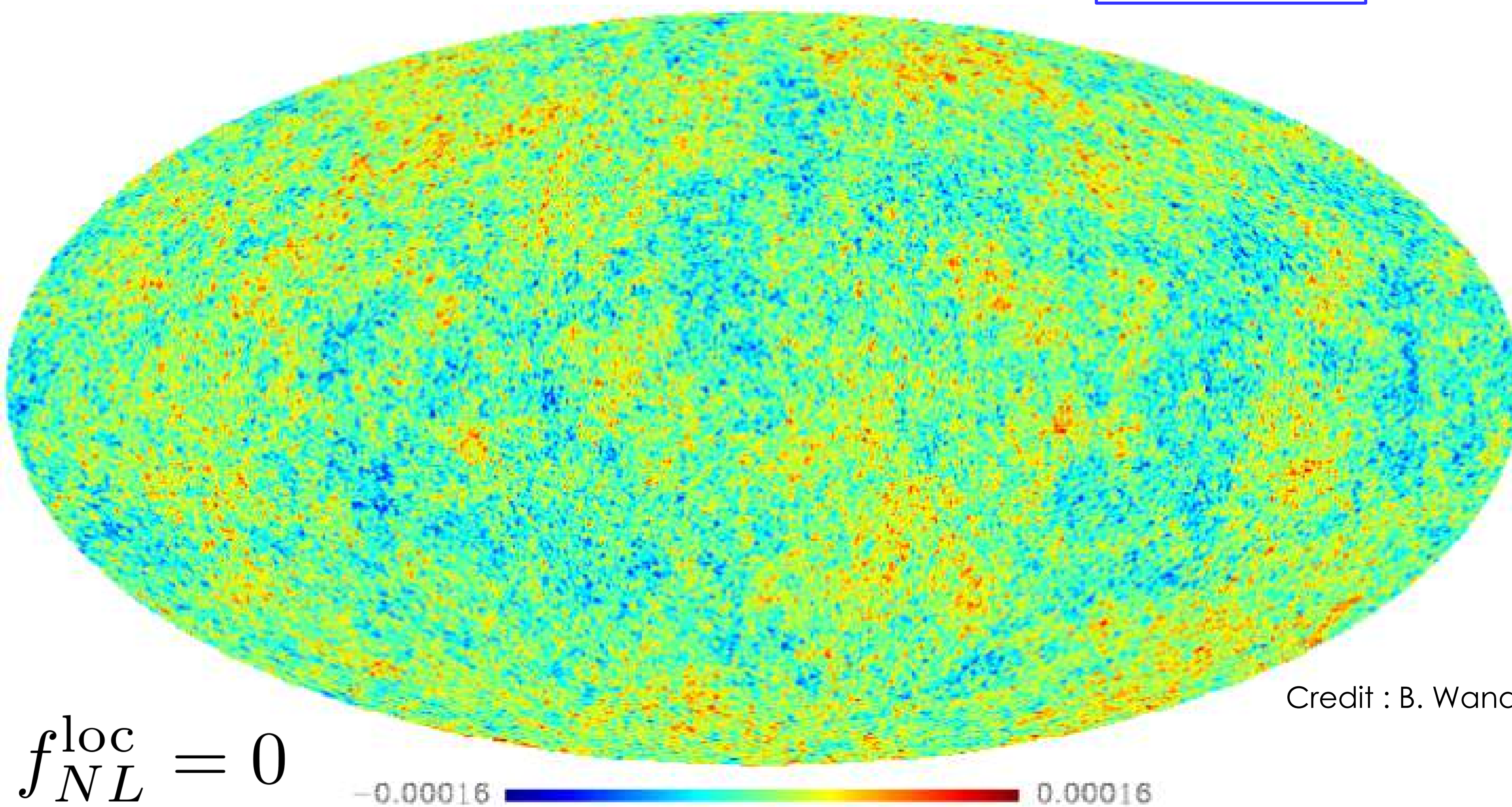
Maldacena
Creminelli&Zaldarriaga

Primordial Non-Gaussianities (PNG)



Detection of local PNG will rule out single field inflation.
Non detection of constrains multi-field models.

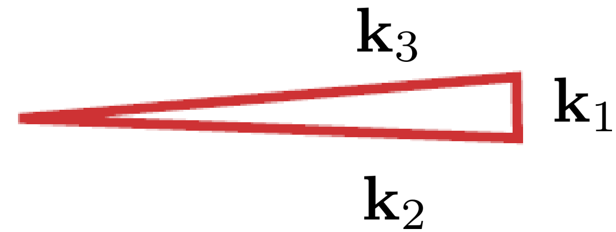
$$\boxed{\zeta = \zeta_g + \frac{3}{5} f_{NL}^{\rm loc}(\zeta_g^2 - \langle\, \zeta_g^2 \,\rangle)} \longrightarrow \boxed{\sigma_{f_{\rm NL}^{\rm loc}} \lesssim 1}$$



Credit : B. Wandelt

$$f_{NL}^{\rm loc} = 0$$

Primordial Non-Gaussianities (PNG)



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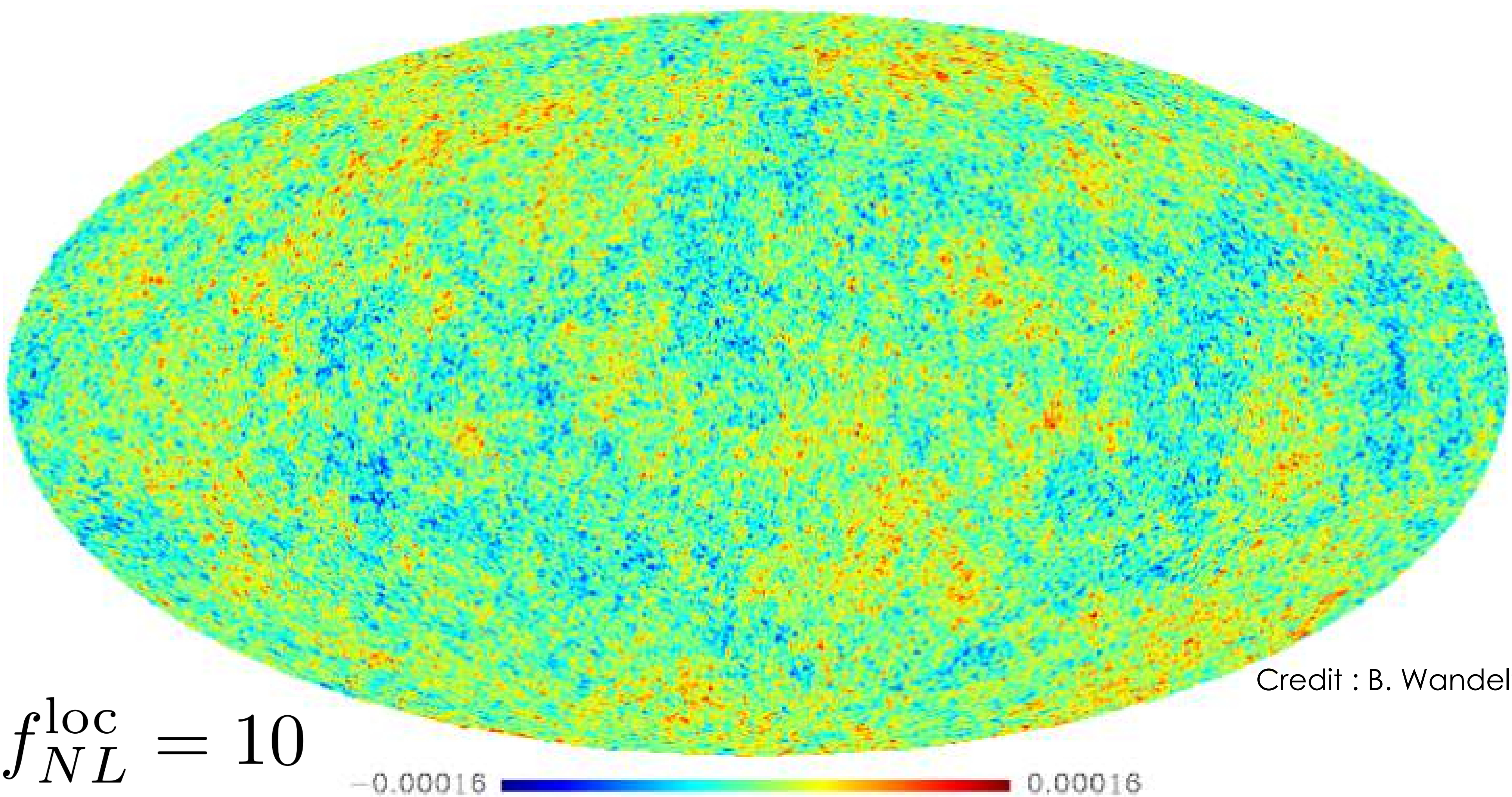
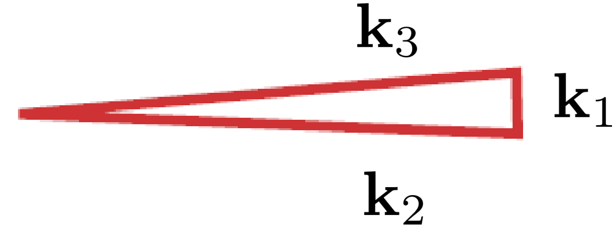


Credit : B. Wandelt

$$f_{NL}^{\mathrm{loc}} = 10$$

Primordial Non-Gaussianities (PNG)



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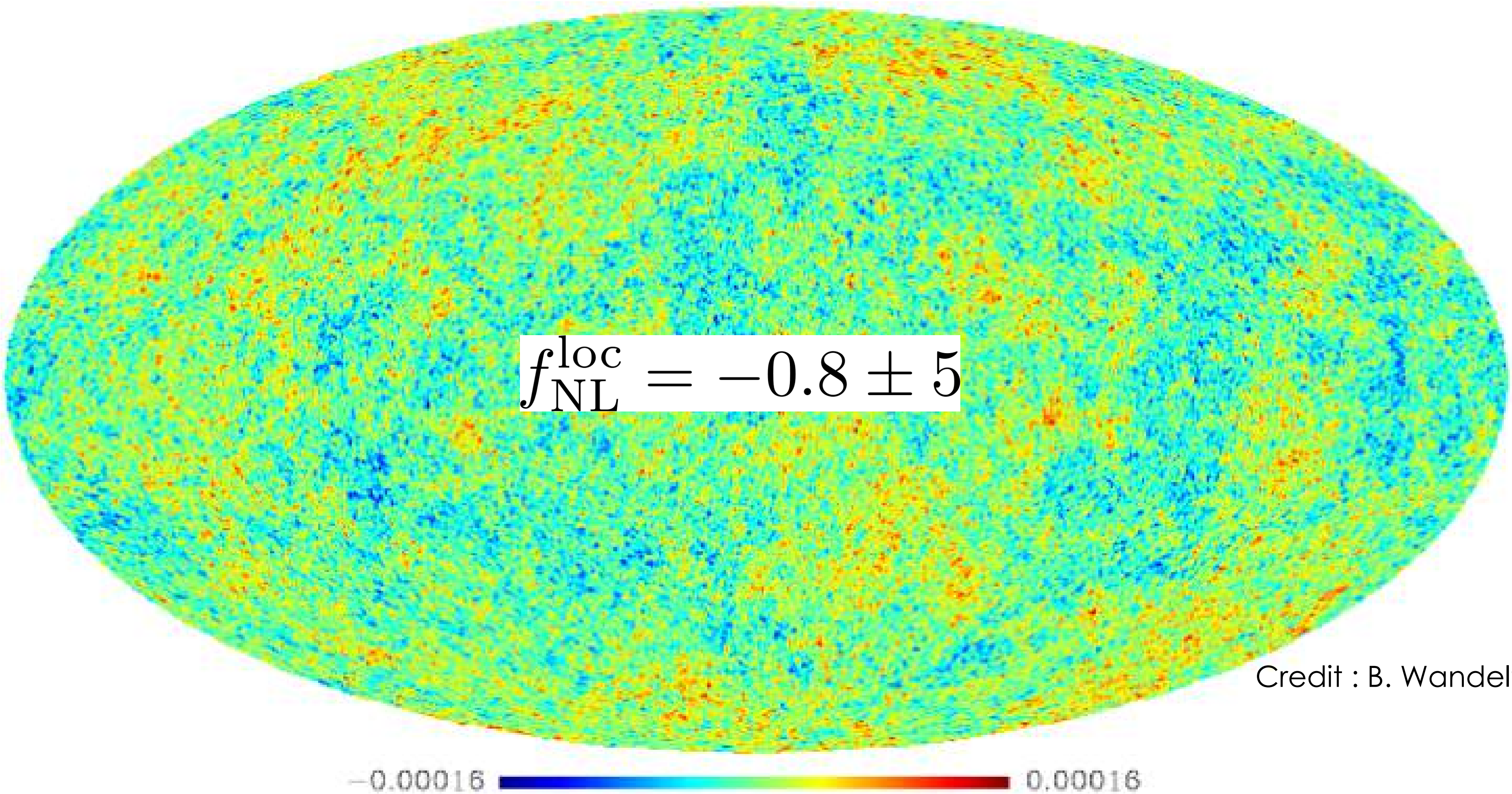


Credit : B. Wandelt

Primordial Non-Gaussianities (PNG)

After T_CMB, by far the most accurately determined parameter in cosmology

$$\zeta = \zeta_g + \frac{3}{5} f_{NL}^{\rm loc} (\zeta_g^2 - \langle\, \zeta_g^2 \,\rangle) \qquad \zeta_g \simeq 10^{-5} \qquad f_{\rm NL}^{\rm loc} = -0.8 \pm 5$$

It implies local PNG are measured with 0.05% precision.

Detection of local PNG will rule out single field inflation.
Non detection of fnl~1 constrains multi-field models.

If we get there, we are guaranteed to learn something. $\longrightarrow \sigma_{f_{\rm NL}^{\rm loc}} \lesssim 1$

Same argument applies to other shapes (parametrization).

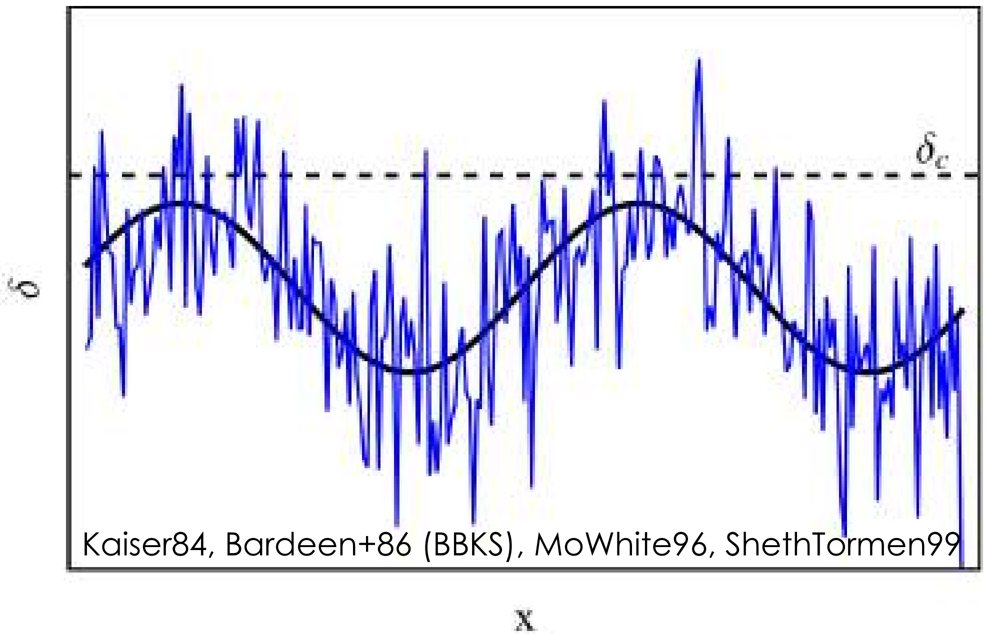
LSS is still far $\sigma_{f_{\rm NL}^{\rm loc}} \lesssim 25$ But could beat CMB in the near future. How ?

Constraining local PNG with the galaxy power spectrum

Galaxy bias

The relation between the galaxy field and the underlying dark matter field is very complicated, and it depends on all the variables relevant for galaxy formation

$$\delta_g(L) \equiv \frac{n_g(L|\delta, \nabla^2\delta, ...) - \bar{n}_g(L)}{\bar{n}_g(M)} = \mathcal{F}[\delta, \nabla^2\delta, ...; L]$$



Overdense regions host more galxies than the mean. Opposite for underdensities.

In a perfectly Gaussian Universe the Equivalence Principle and symmetries tells us that

$$\delta_g \simeq b_\phi \phi + b_{\nabla\phi}\, \mathbf{x} \cdot \nabla\phi + b_1 \delta_m + ...$$

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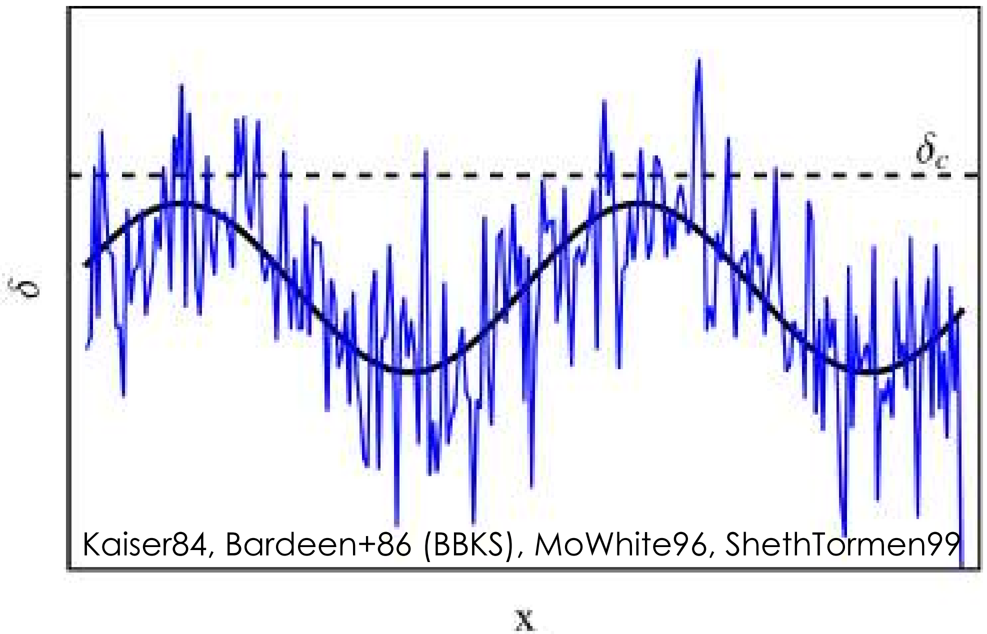

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$$\delta_g \simeq \cancel{b_\phi \phi} + \cancel{b_{\nabla\phi}\, \mathbf{x} \cdot \nabla\phi} + b_1 \delta_m + ...$$

$$P_{gg}(k) = b_1^2 P_m(k) + ...$$

$$P_{gm}(k) = b_1 P_m(k) + ...$$

Signatures of Primordial Non-Gaussianities

Luckily enough PNG show up in the galaxy power spectrum

A unique signature of PNG exists : Scale dependent bias. Dalal+08, Slosar+08

Split the Gaussian piece of the gravitational potential in long and short modes

$$\phi = \phi_l + \phi_s$$

$$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{NL}(\phi^2(\mathbf{x}) - \langle\, \phi^2(\mathbf{x})\,\rangle)$$
$$= \phi_l + f_{NL}\phi_l^2 + (1 + 2f_{NL}\phi_l)\phi_s + f_{NL}\phi_s^2 + \text{const.}$$

Density and potential are related by the Poisson equation

$$\Phi = \alpha(k)\delta(k)\ ,\ \alpha(k) = \frac{3H^2\Omega_m}{2k^2T(k)D(z)}$$

$\alpha(k) \propto k^{-2}$ At low-k

Scale dependent bias

The variance of the short scale density modes is affected by the large scales

$$\phi = \phi_l + \phi_s \qquad\qquad \left\langle\, \delta(\mathbf{x})^2 \,\right\rangle_{\rm short}^{1/2} = \sigma \longrightarrow \sigma(1 + 2 f_{NL}\phi_l)$$

Galaxy bias is the response to long-wavelength modes

$$b_1 = \frac{1}{\bar{n}_g}\frac{\partial n_g[\delta_l; \sigma^2(\phi_l)]}{\partial \delta_l} = \frac{1}{\bar{n}_g}\left[\frac{\partial n_g}{\partial \delta_l} + 2 f_{NL}\frac{\partial \phi_l}{\partial \delta_l}\frac{\partial n_g}{\partial \log \sigma}\right]$$

Using Poisson equation

$$b_1 = b + f_{NL} b_\phi \alpha(k) \xrightarrow{k \leq k_{\rm eq}} b + f_{NL} b_\phi k^{-2} \qquad\qquad b_\phi = \frac{\partial \log n_g}{\partial \log \sigma_8}$$

Information about PNG in the scale dependence of the bias on large scales.

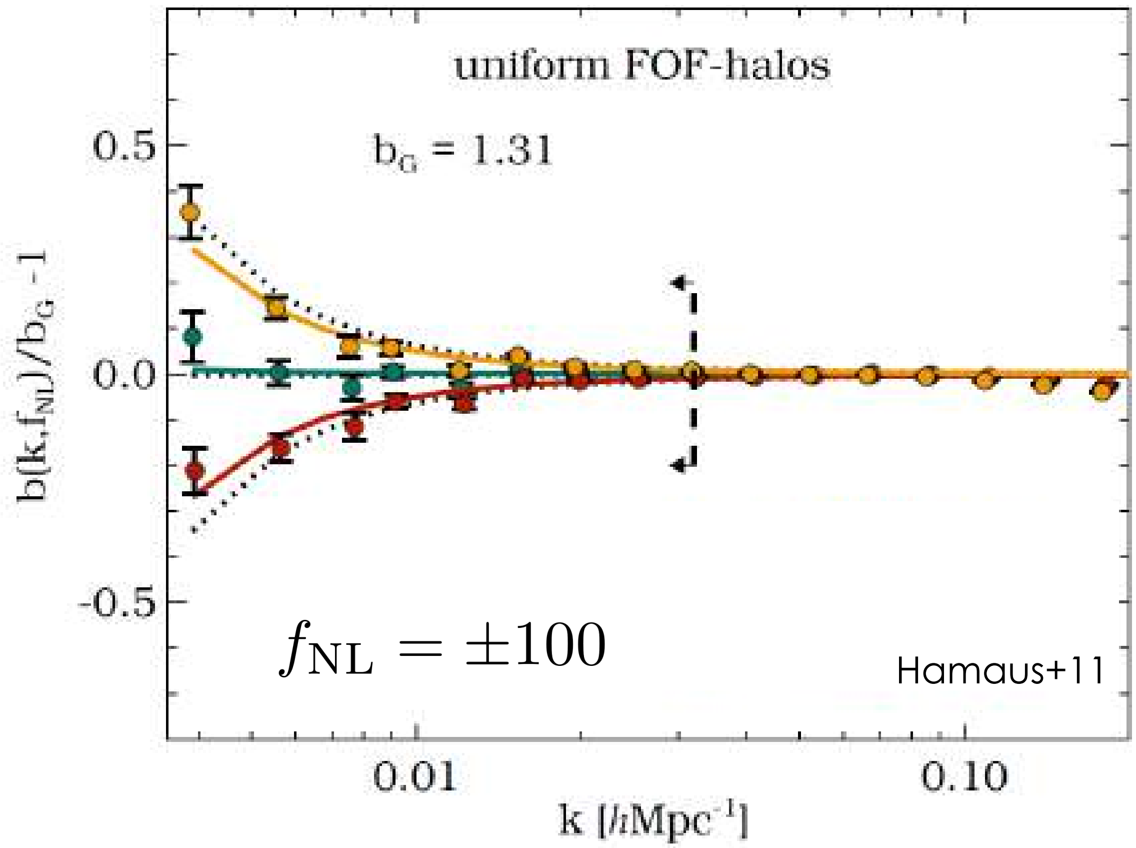
Dalal+08, Slosar+08

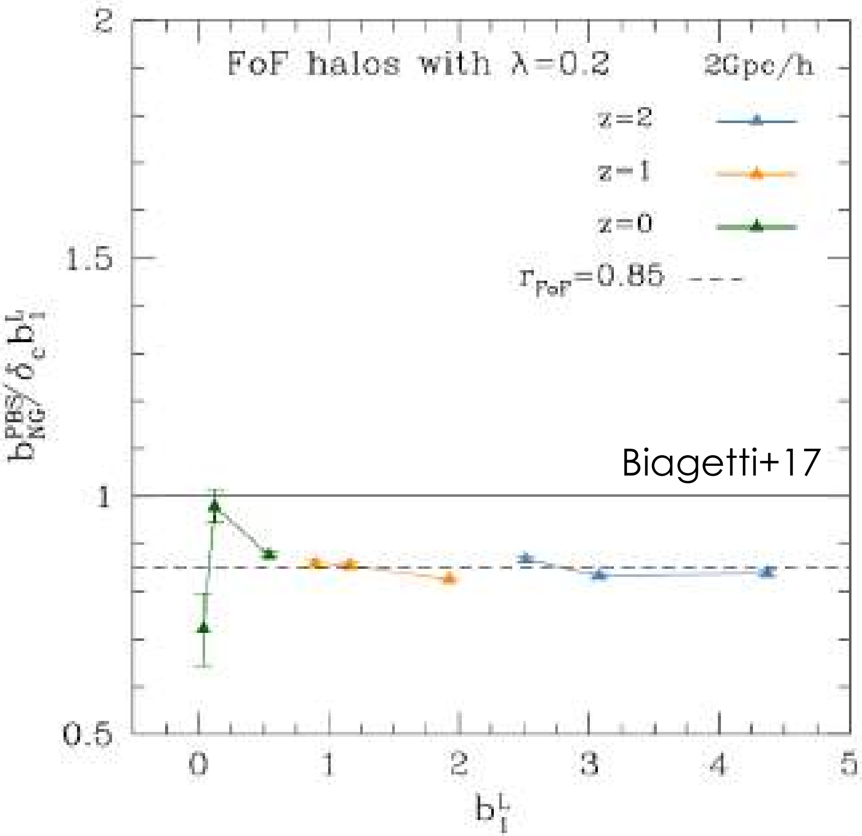
Scale dependent bias

How big is the signal?

$$b_1 \to b + f_{NL} b_\phi k^{-2}$$

10% change if fnl~1 at k=10^-3 h/Mpc





For a universal, i.e self-similar, mass function, e.g. Sheth-Tormen

$$b_\phi = \frac{\partial \log n}{\partial \log \sigma_8} = \delta_c(b-1) = \delta_c b_L$$

Accurate to 10-20 %

Cosmic Variance

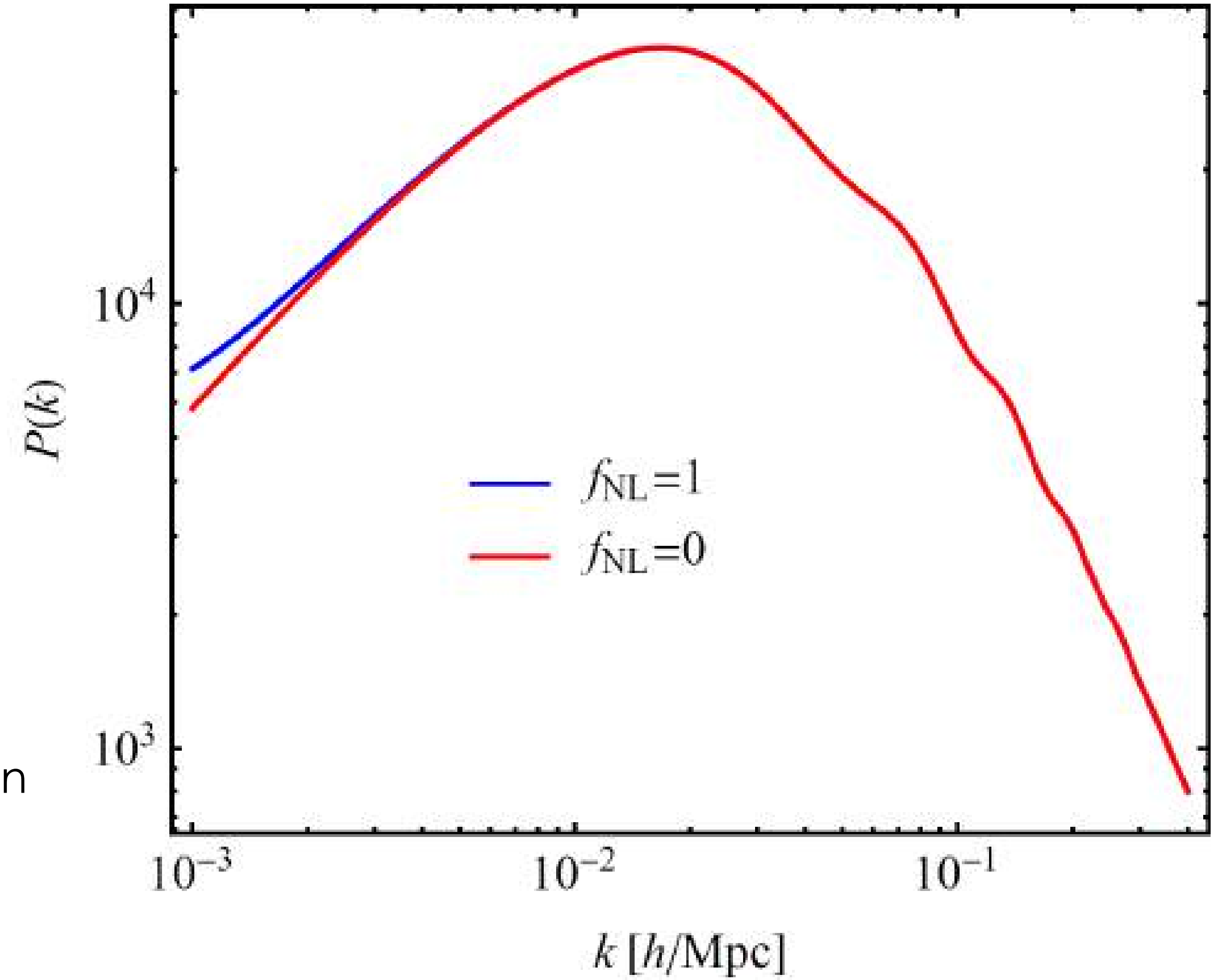
$$P_{gg}(k,\mu,z) = [b + f\mu^2 + f_{NL} b_\phi \alpha(k)]^2 P(k,z) + \frac{1}{\bar{n}(z)}$$

Error bars ~20 now,

~Comparable to Planck in the future (DESI,LSST)

Two main issues:

- Cosmic Variance is the dominant source of noise.
- Also, systematics at large scales are tough.
  E.g. Foregrounds, seeing, imaging sys., window function



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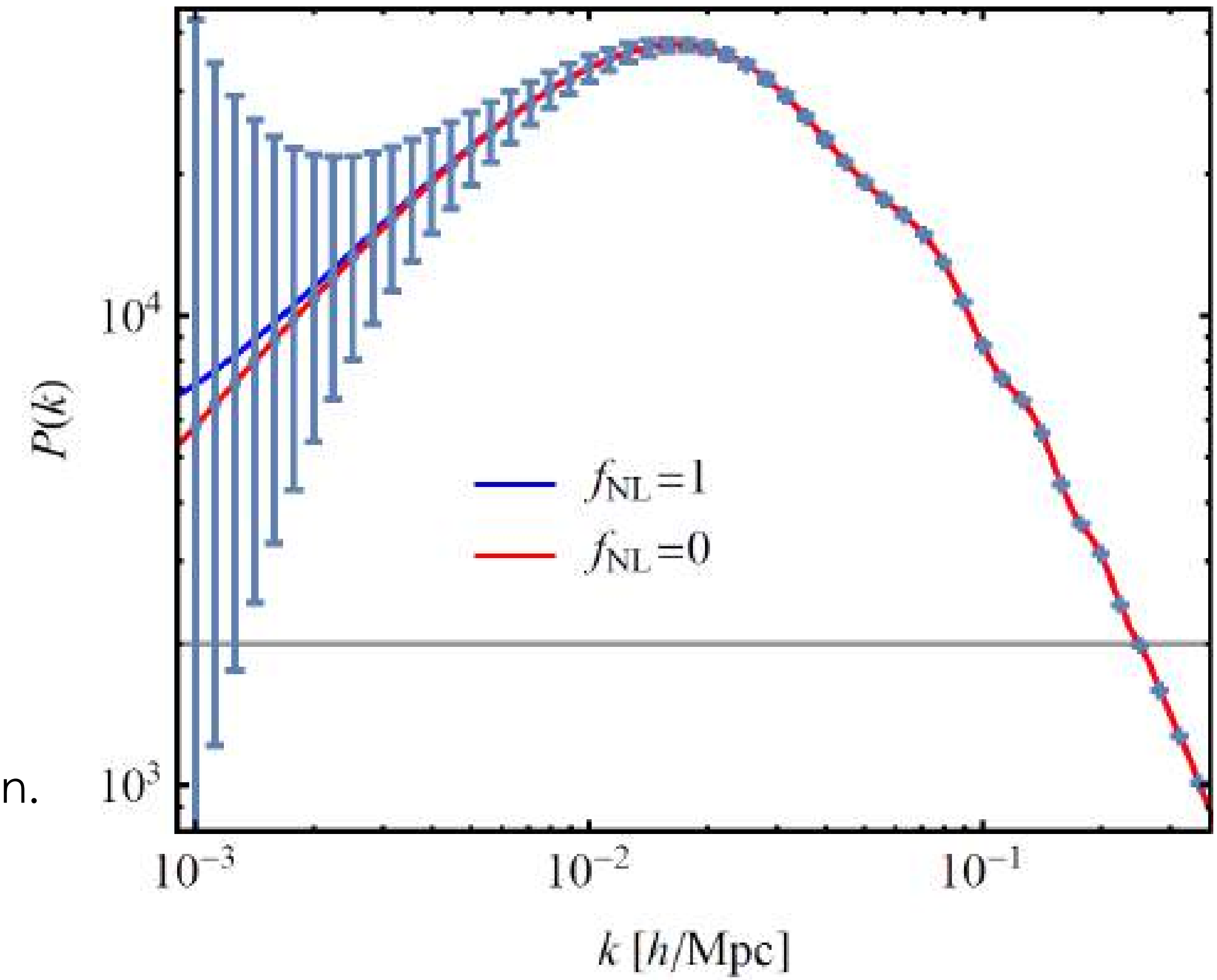
We need to do our best!



Part I
Optimal redshift weights
and
eBOSS DR14 analysis

w/ the eBOSS team

Reality vs Fisherland

Even for BAO, the real data analysis never yields the Fisher numbers...

- Unaccounted sys, modeling issues, etc…

Our analysis is never optimal

- We never do the right thing, i.e. full inverse noise weighting of the data.

  At high k, for Gaussian fields with ~uniform noise, FKP (standard method) is optimal for band-powers

  Tegmark+98

- We never do optimal signal weighing for cosmological parameters

  E.g. Optimal estimator for fNL in CMB is not just measuring the bispectrum.

  Creminelli+06

Zhu+14, pair weighing for BAO, Ruggeri+16 for RSD, Mueller+16 for fNL, eBOSS DR14

Can we do the same in LSS?

Reality vs Fisherland

We observe our past lightcone:

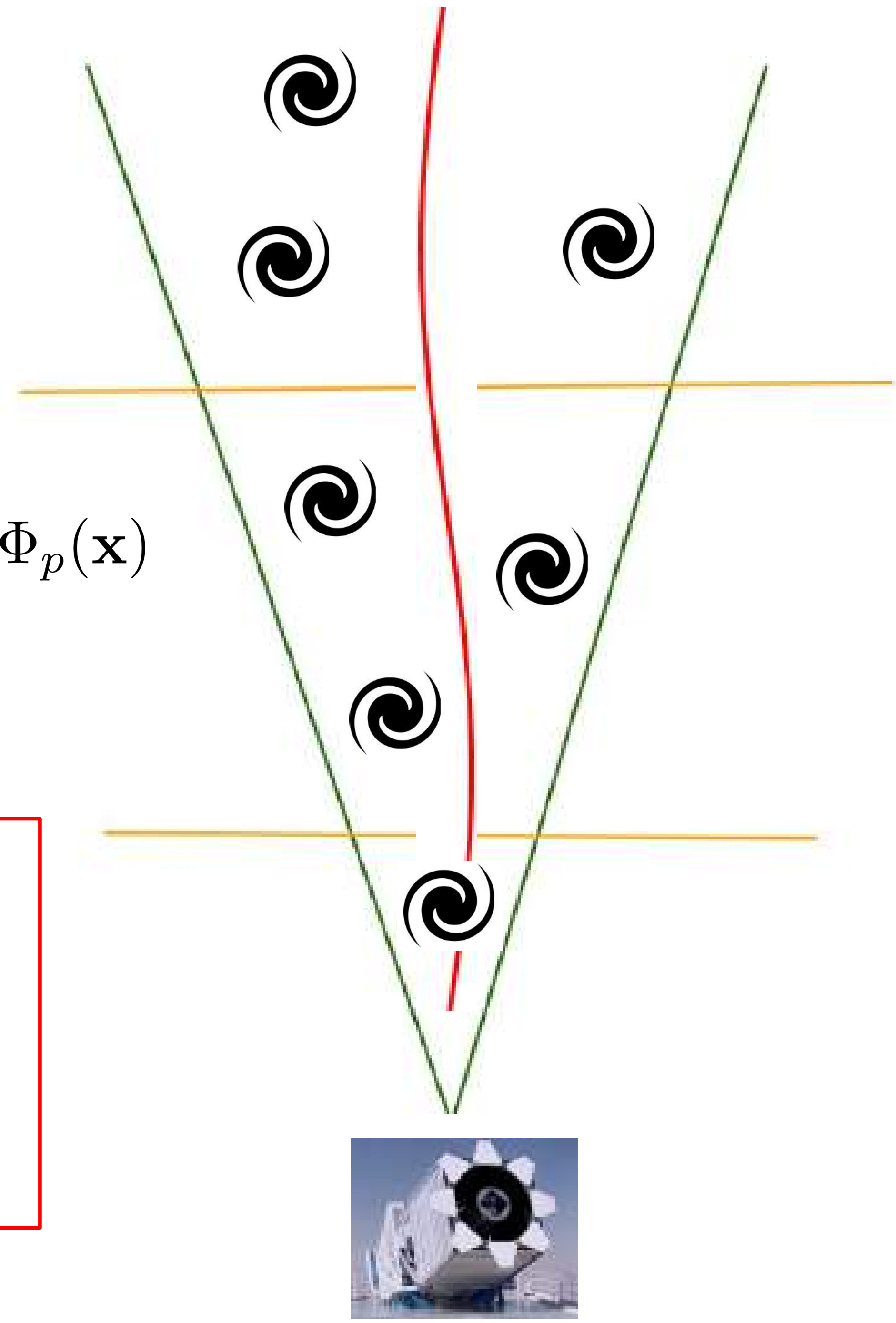
- The Gaussian part evolves with time;

  Smaller at high redshift.

- The PNG term does not,

$$\delta_g(\mathbf{x}, z) = b_1(z)\delta_m(\mathbf{x}, z) + f_{\rm NL} b_\phi(z)\Phi_p(\mathbf{x})$$

- More volume at high z.



Optimal signal extraction:

1) No redshift binning: loses large scale modes.

2) give more weight to high redshift objects.

Optimal Quadratic estimators

An optimal quadratic estimator is the answer. Given a set of galaxies positions

$$\hat{q}_{f_{\rm NL}} = \sum_{\mathbf{x}_1,\mathbf{x}_2} \frac{1}{2} \frac{\delta(\mathbf{x}_1)}{C_1} \frac{\partial C}{\partial f_{\rm NL}} \frac{\delta(\mathbf{x}_2)}{C_2} \qquad C = \langle \delta_g(\mathbf{x}_1, z_1)\delta_g(\mathbf{x}_2, z_2)\rangle + N$$

Inverse noise weighting of the pixels, and by the response to PNG.

$$\hat{q}_{f_{\rm NL}} \propto \int \frac{d\Omega_k}{4\pi} [\delta_0^{\tilde{w}}(-\mathbf{k}) \sum_{\ell=0,2} \delta_\ell^{w_\ell}(\mathbf{k})]$$

Estimator for multipoles of P(k)

$$\tilde{w}(z) = b_\phi(z) = b(z) - p\ , \ w_0(z) = D(z)(b(z) + f(z)/3)\ , \ w_2(z) = D(z)f(z)$$

Growth function

Growth rate

In the standard analysis w(z)=1.

Upweights high redshift objects, where fNL response is the largest.

Single vs pair weights

In our approach each galaxy has its own weight.

Previous approaches used pair weights. Pair weights are always an approximation, and not really well defined for large separation.

Cannot be used in Fourier Space.
Usually take take sqrt() and/or absolute value by hand.

$$w_{\mathrm{pair}}(z) \propto b(z) - p \rightarrow w_{\mathrm{single}} \propto \sqrt{|b(z) - p|}$$

Our optimal weights can be used in configuration space and Fourier space.
No extra work for cross-correlations.

Reality vs Fisherland

We used eBOSS DR14 data:

- 180k QSOs in 0.8<z<2.2

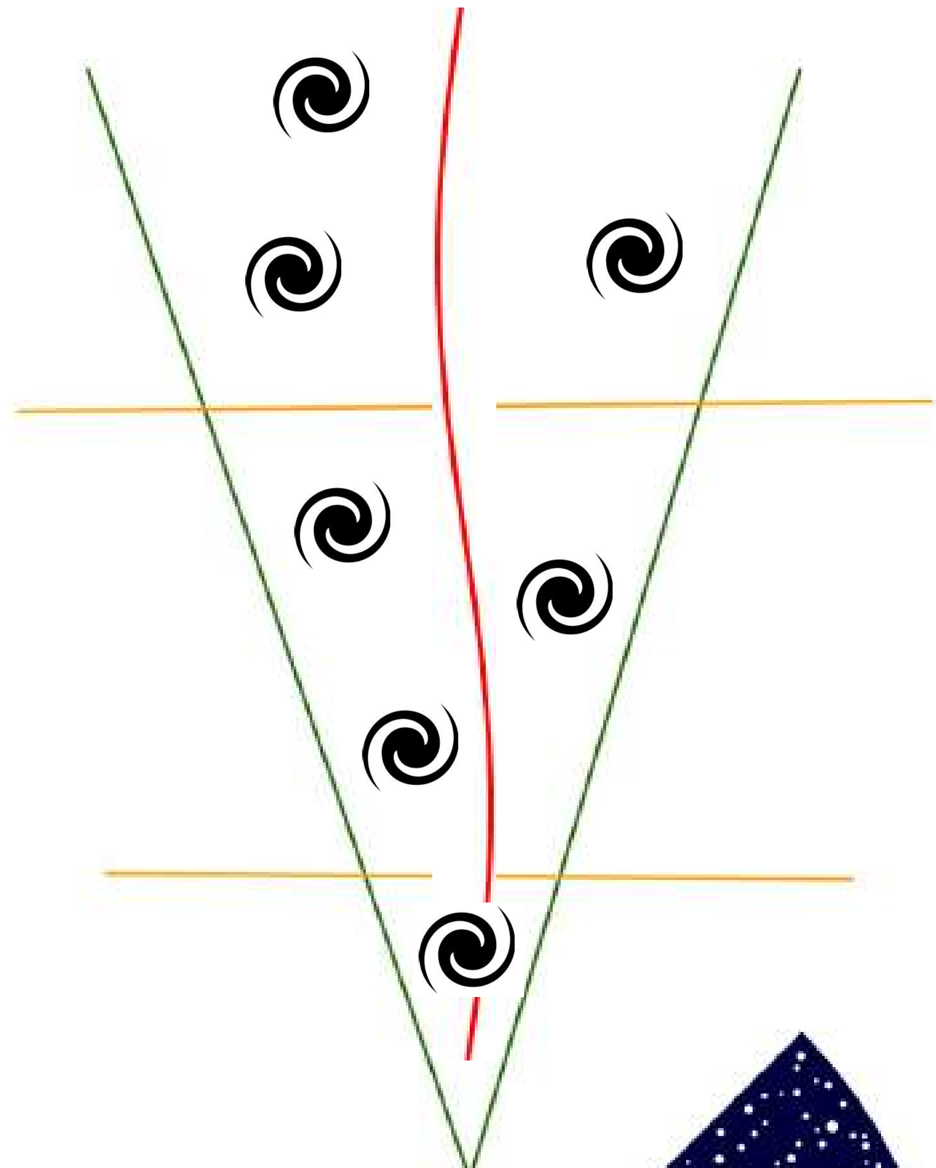
Lots of other QSOs at z<0.5 and z>2.2

- n(z)<10^-5 [Mpc/h]^-3

Noise dominated, nP<<1 at any scale

- 5% of the sky, V ~ 10 [Gpc/h]^3

- No significant contamination at low-k



Redshift binning destroys info along LOS,
1/3 of the modes relevant for fNL.

Full volume analysis + optimal weights.

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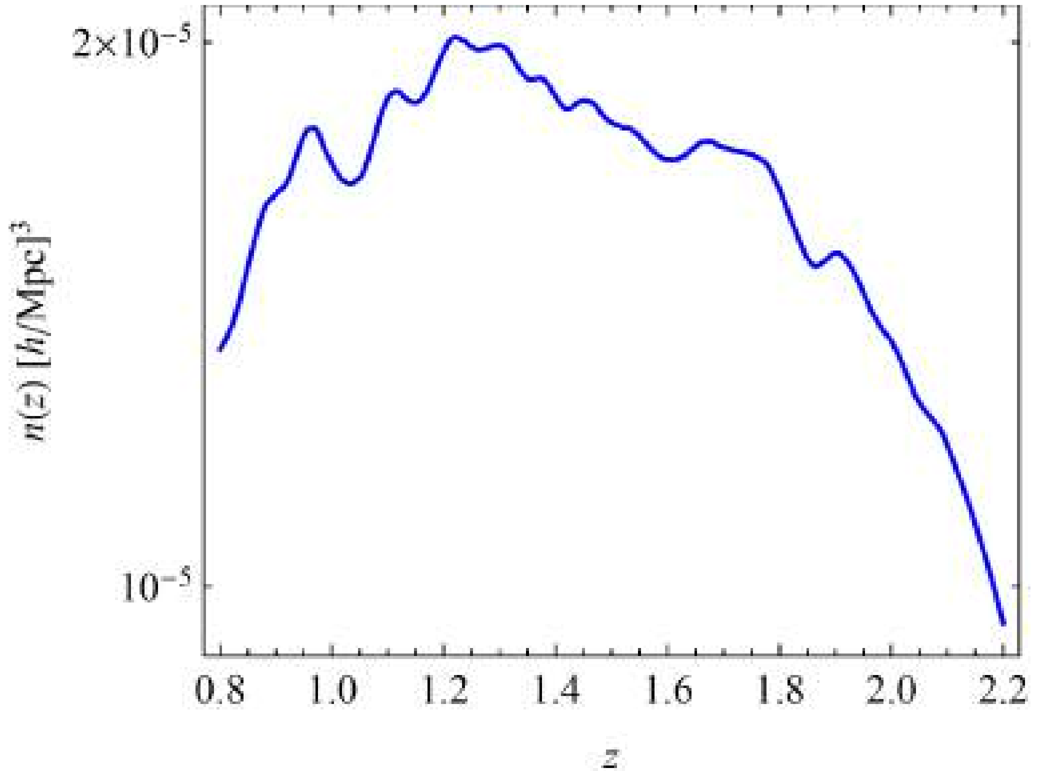
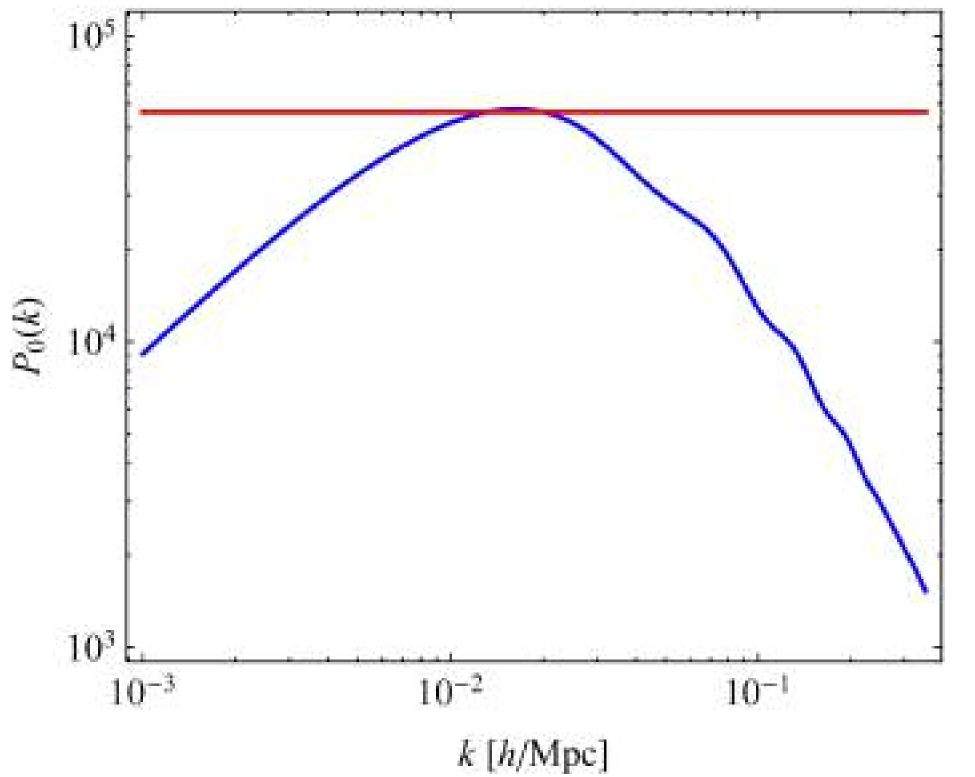
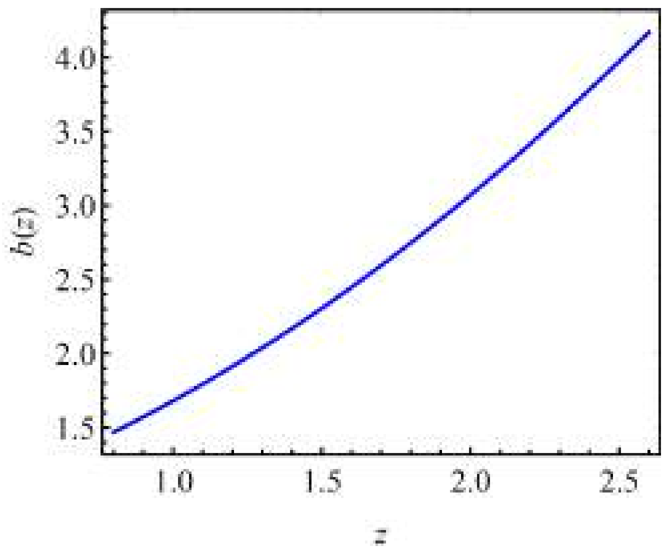
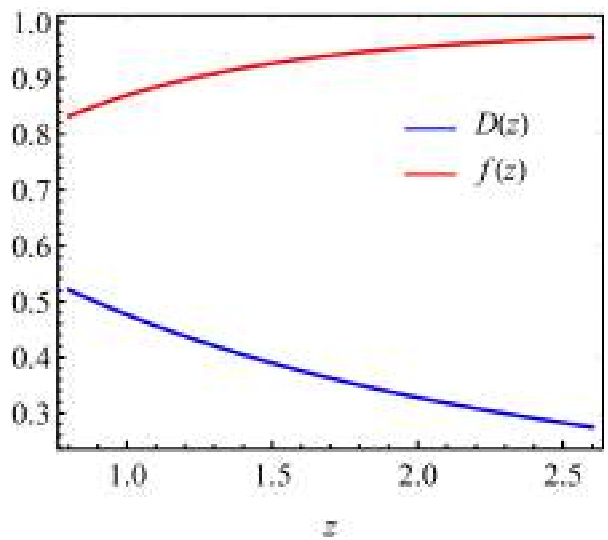


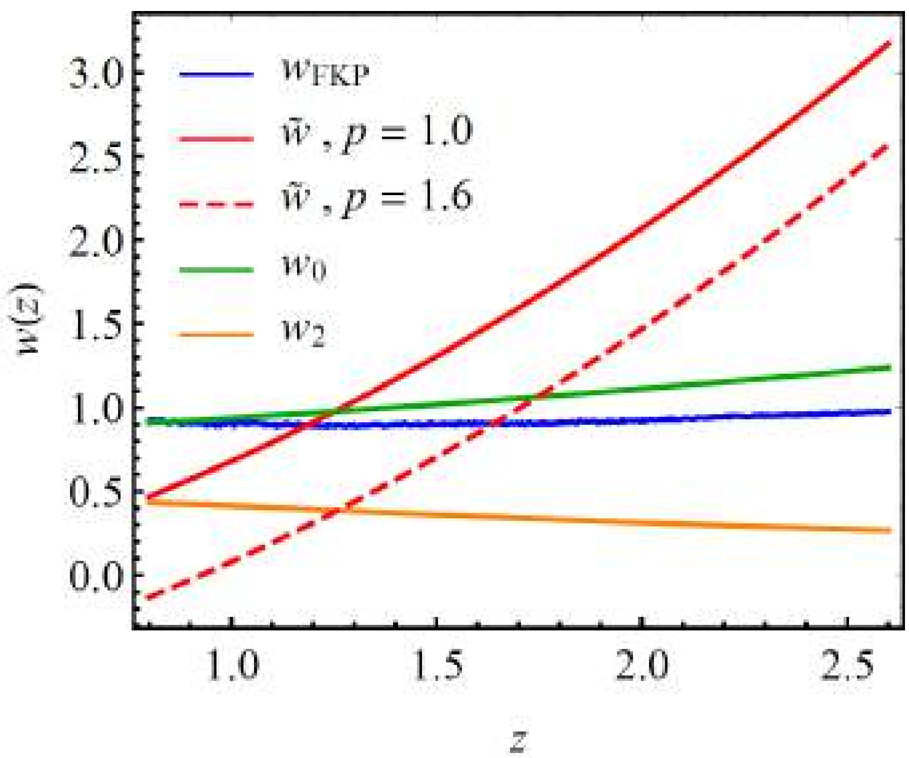


Weights

$$\tilde{w}(z) = b(z) - p \quad , \; w_0(z) = D(z)(b(z) + f(z)/3) \; , \; w_2(z) = D(z)f(z) \; .$$

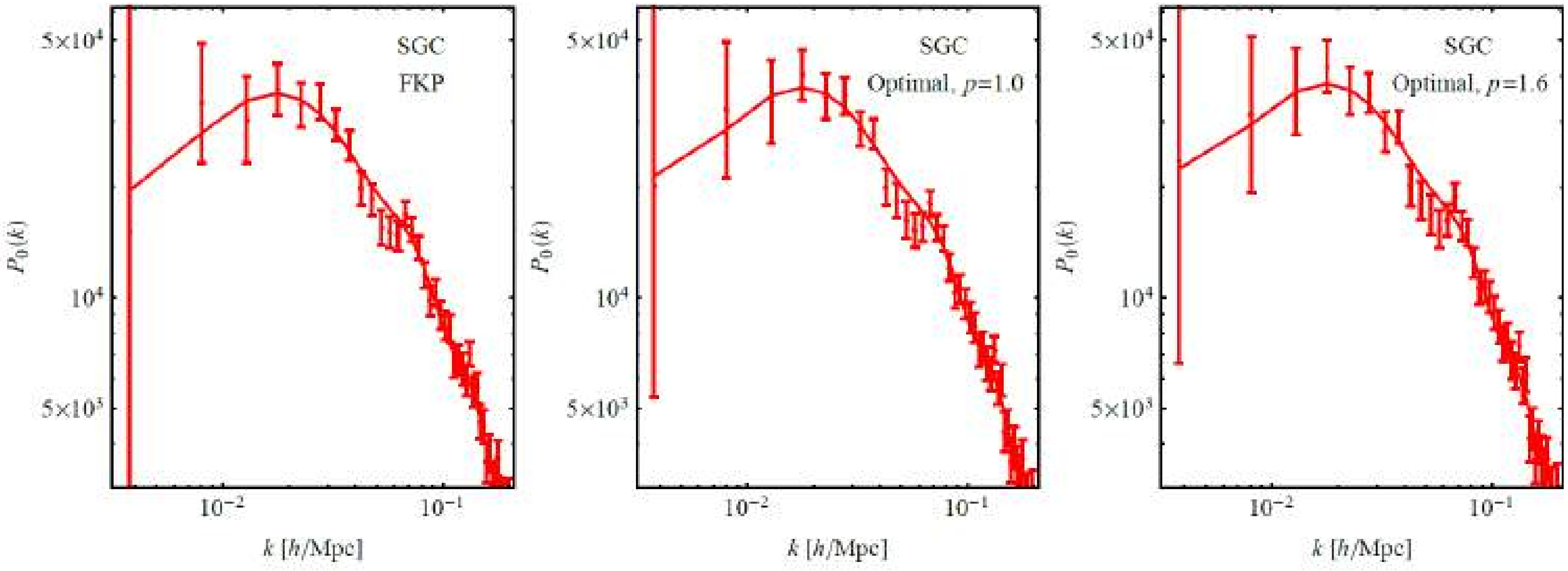






In the future it is desirable to have D(z)b(z) decreasing with redshift

The Data



Optimal weighting boils down to a change in the effective redshift of the sample.

High-z galaxies get more weight and ‘move’ the survey up in redshift

Dirty Laundry: We cannot use the quadrupole, unknown systematic at low-k.
Irrelevant for PNG assuming Planck Cosmology.

The Data

$$z_{\rm eff} = \frac{\int dz\ n(z)^2[\chi^2/H(z)]\ w(z)^2 z}{\int dz\ n(z)^2[\chi^2/H(z)]w(z)^2}$$

Standard (FKP)

$$z_{\rm eff} = 1.52$$

Optimal (p=1.0)

$$z_{\rm eff} = 1.64$$

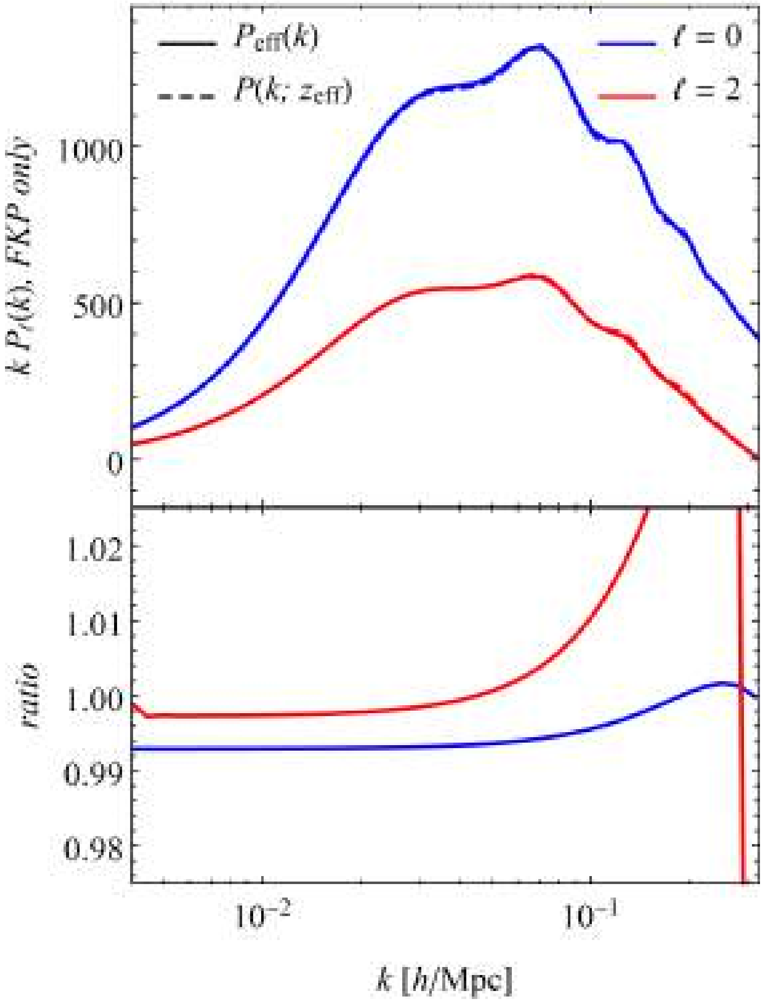
Optimal (p=1.6)

$$z_{\rm eff} = 1.74$$

Effective redshift

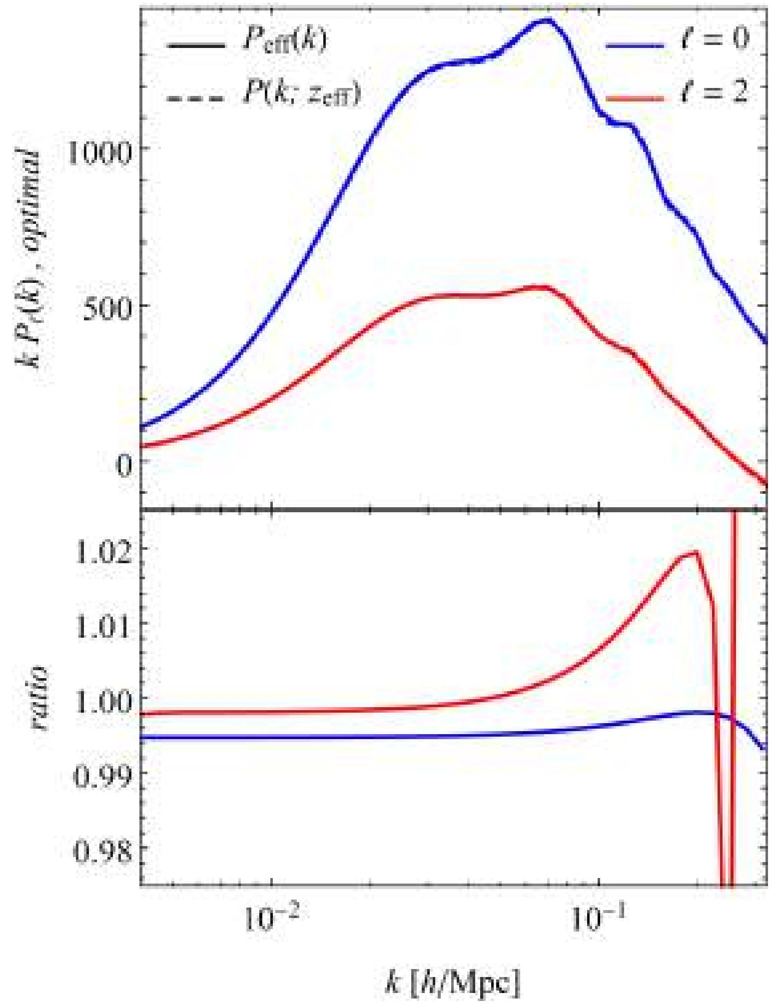
FKP weights:

$$z_{\rm eff}^{FKP} = 1.52$$



In the optimal case:

$$z_{\rm eff} = 1.64$$



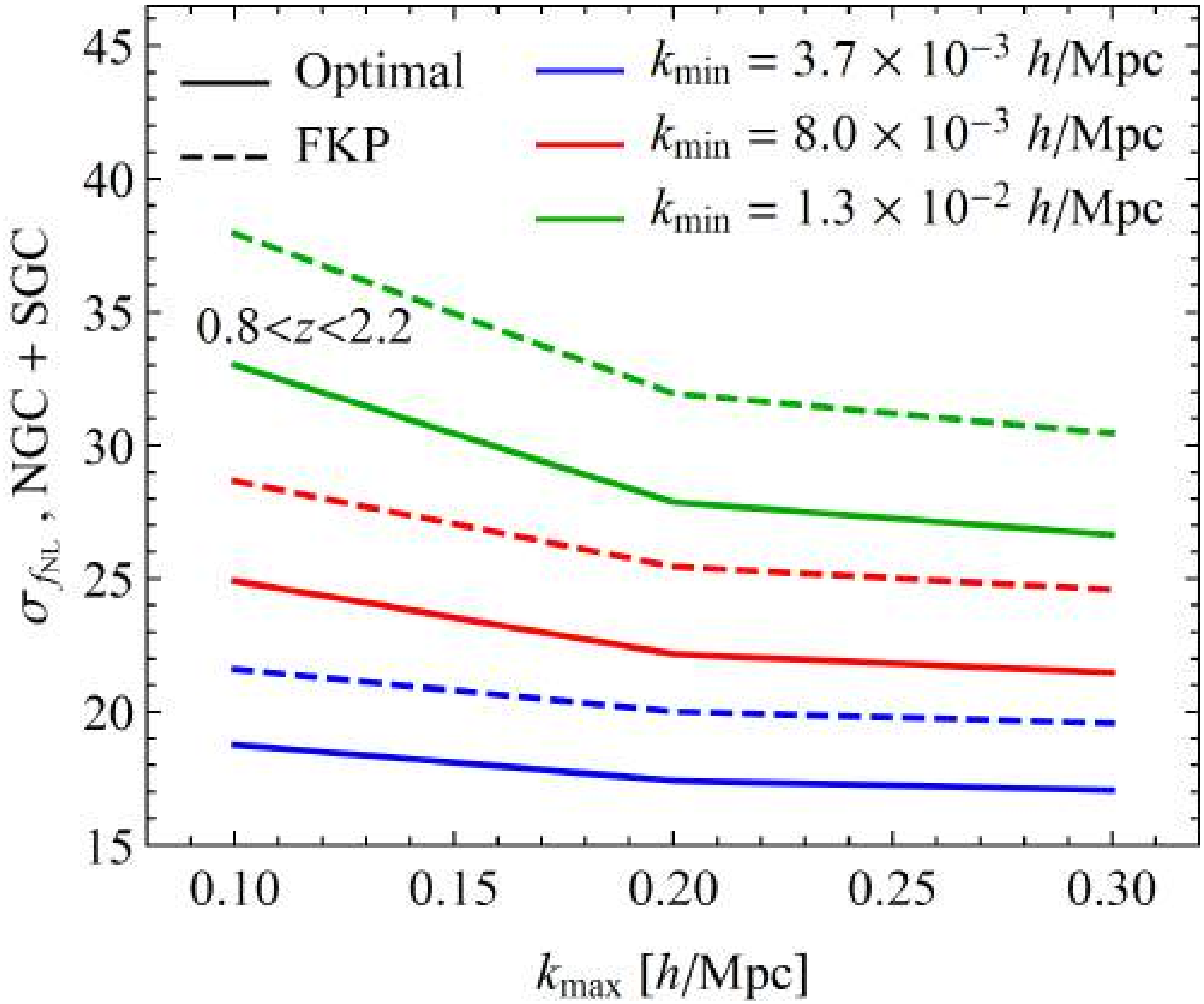
It remains true even including wide angles/GR effects.

Expected improvement over standard methods

$$P_{gg}(k,\mu,z) = [b(z) + f(z)\mu^2 + f_{NL}(b-p)\alpha(k,z)]^2 P(k,z) + \frac{1}{\bar{n}(z)}$$

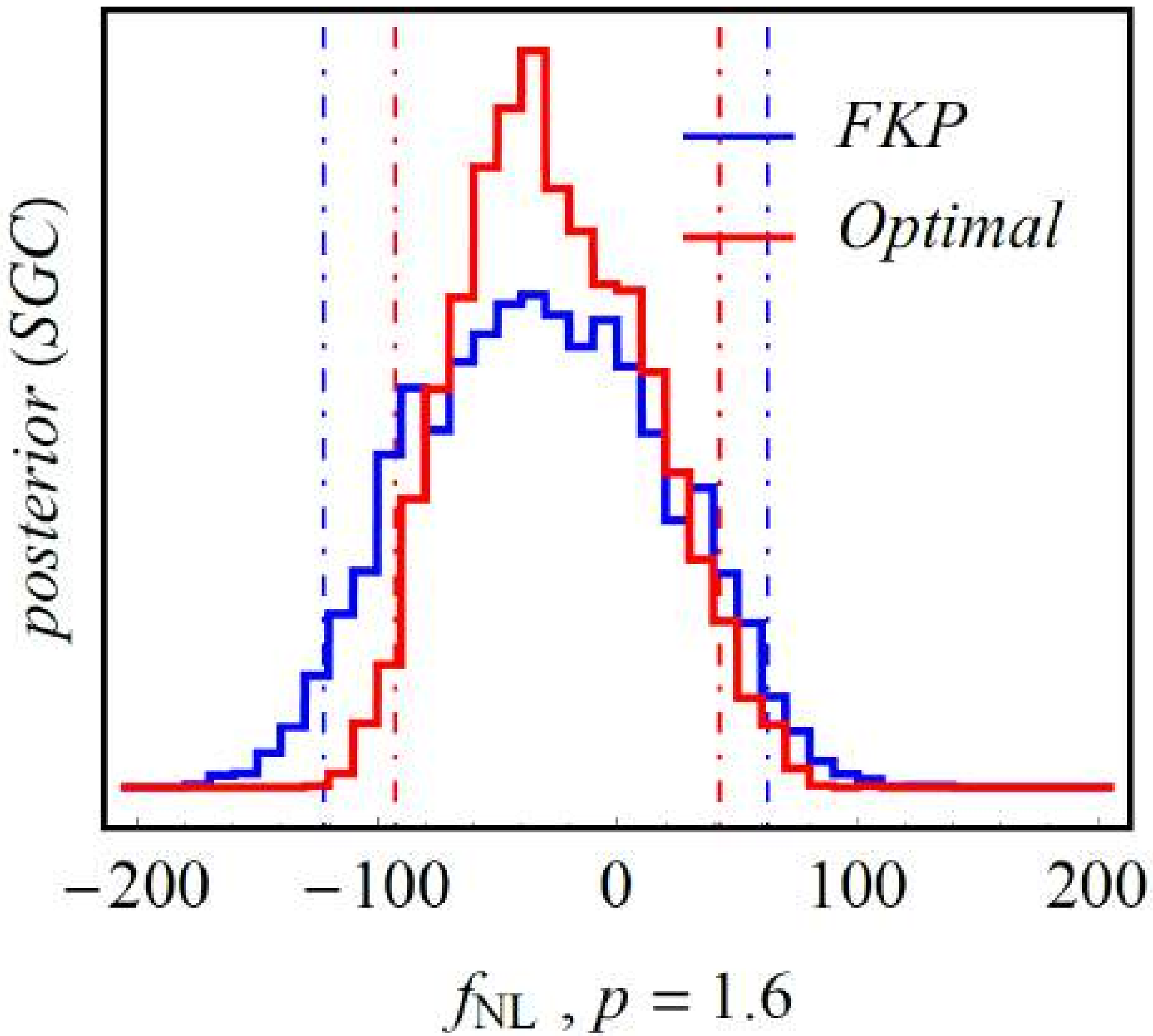
~20-25 % better error bars compared to the standard methods.

It means effectively ~40 % larger survey and ~40 % more QSOs.



eBOSS Quasars DR14 data in 0.8<z<2.2

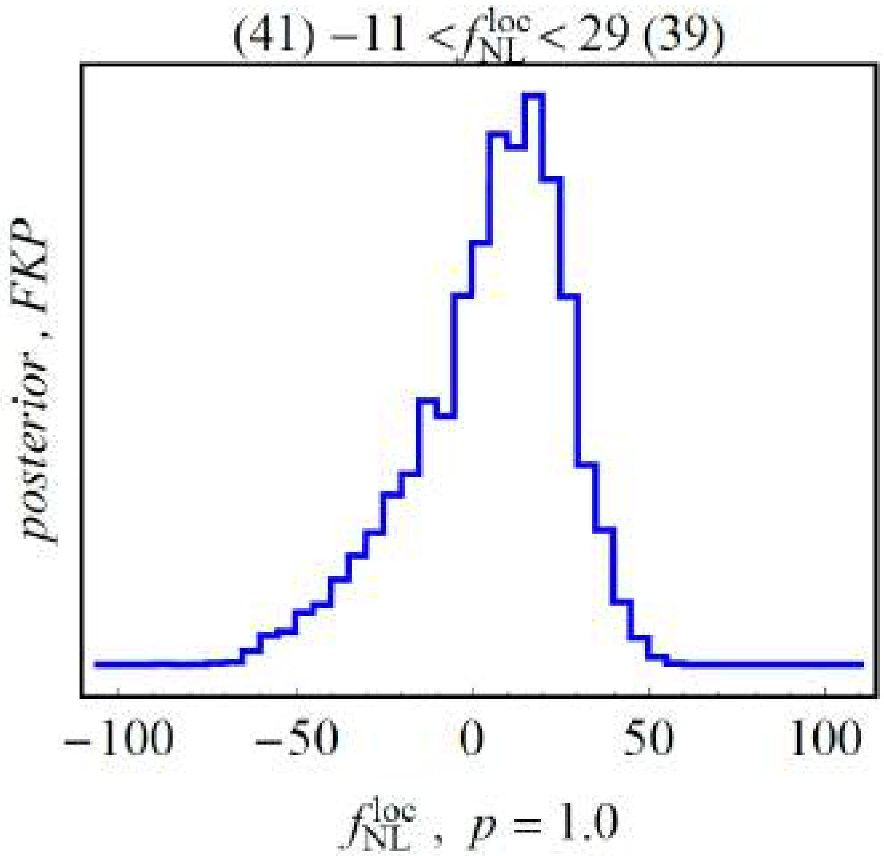
For lower PNG response, optimal weights help a lot.
More than 40 % improvement for p=1.6



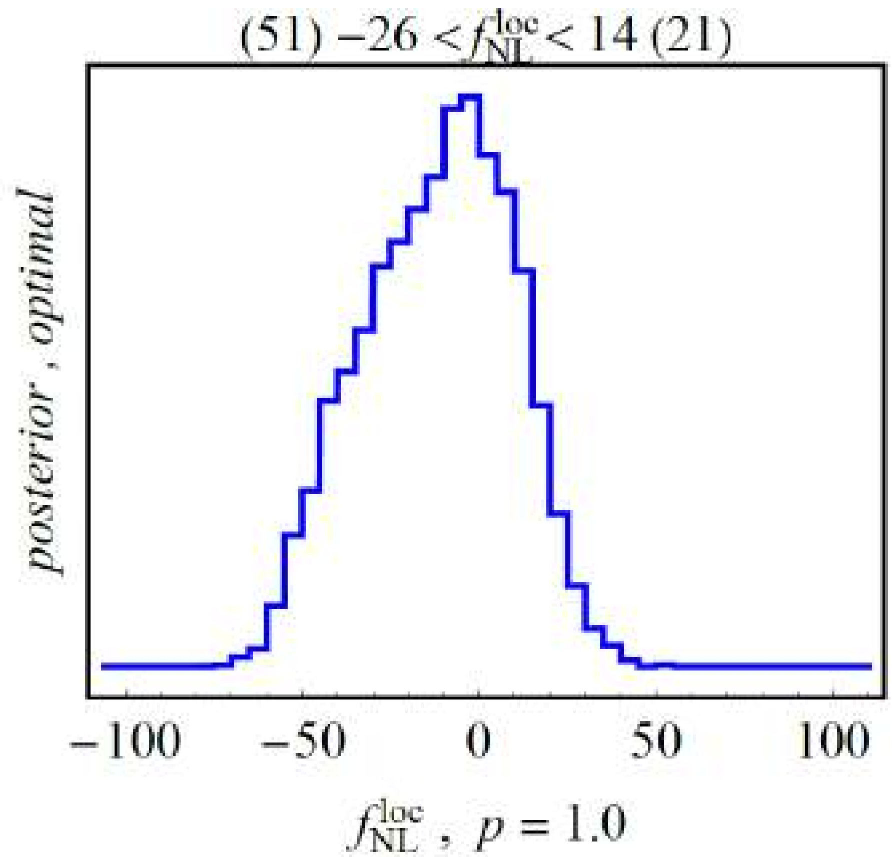
eBOSS Quasars DR14 data in 0.8<z<2.2

For the full dataset and p=1.0 we find 15% improvement, but do not reach Fisher value.

Standard



Optimal



Best constraints using LSS data. ~5x worse than CMB

Looking ahead, high redshift QSOs @ z>2.2 and final data release

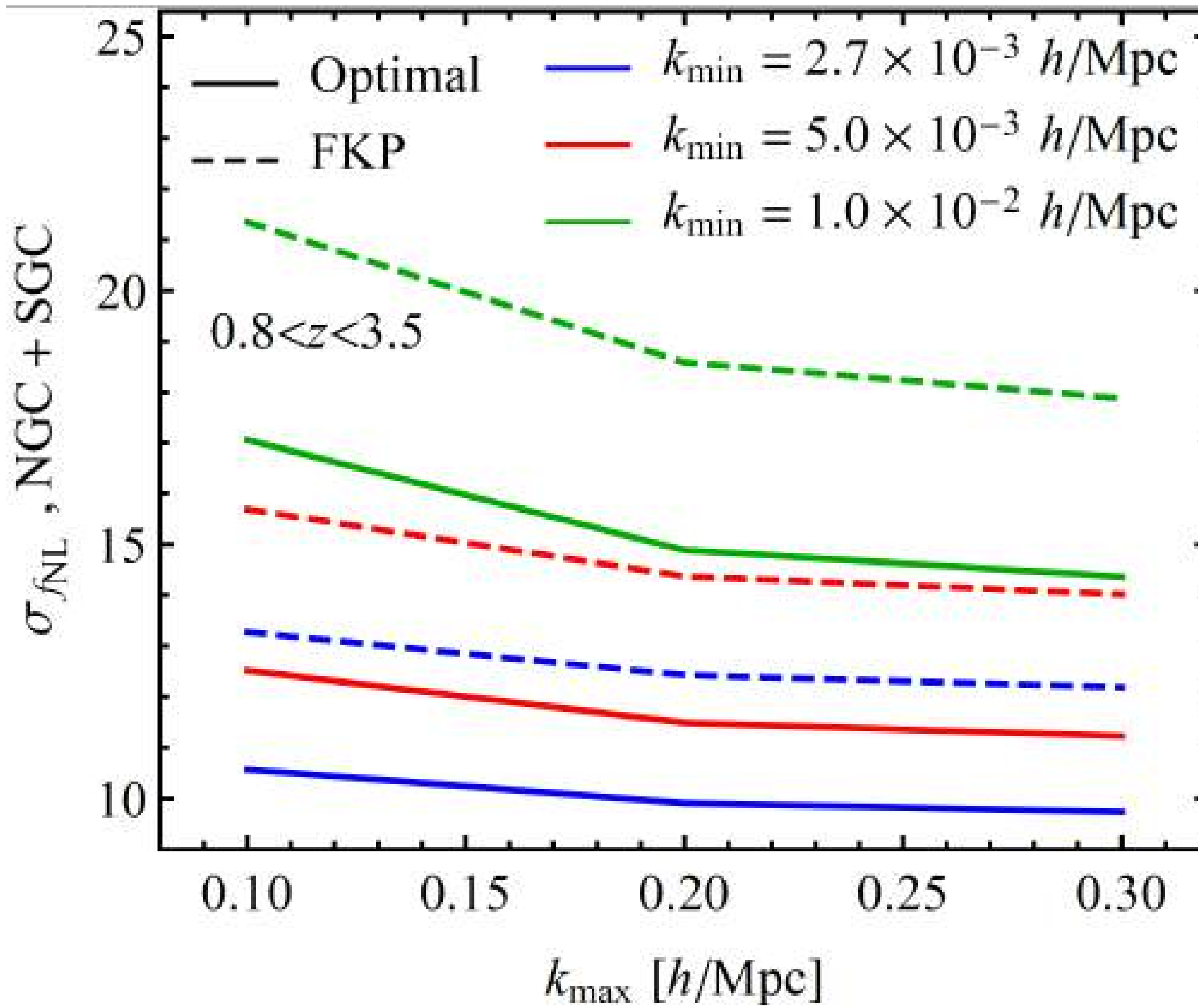
Including high-z QSOs can reduce a lot the error bar on PNG.

Still large gains of optimal analysis.

For DR14 footprint :

$$f_{\rm NL} \simeq 10$$

Final data (taken in 2019) release is ~3x more area



$f_{\rm NL} \simeq 3^{-1/2} 10 \simeq 5\text{-}6$ (Planck ~5)

Summary

Narrow road to improve over CMB on interesting cosmological parameters.

- Optimal methods will be needed to achieve theoretical benchmark

- With 5% of the sky and 200k QSOs we do better than 50% of the sky and 1M QSOs

    - Importance of spectroscopy

- Depending on the dataset, the OQE improves by 15-40%.

- We already have data to measure local PNG as good as CMB

    - 15% of the sky of noisy data comparable with Planck

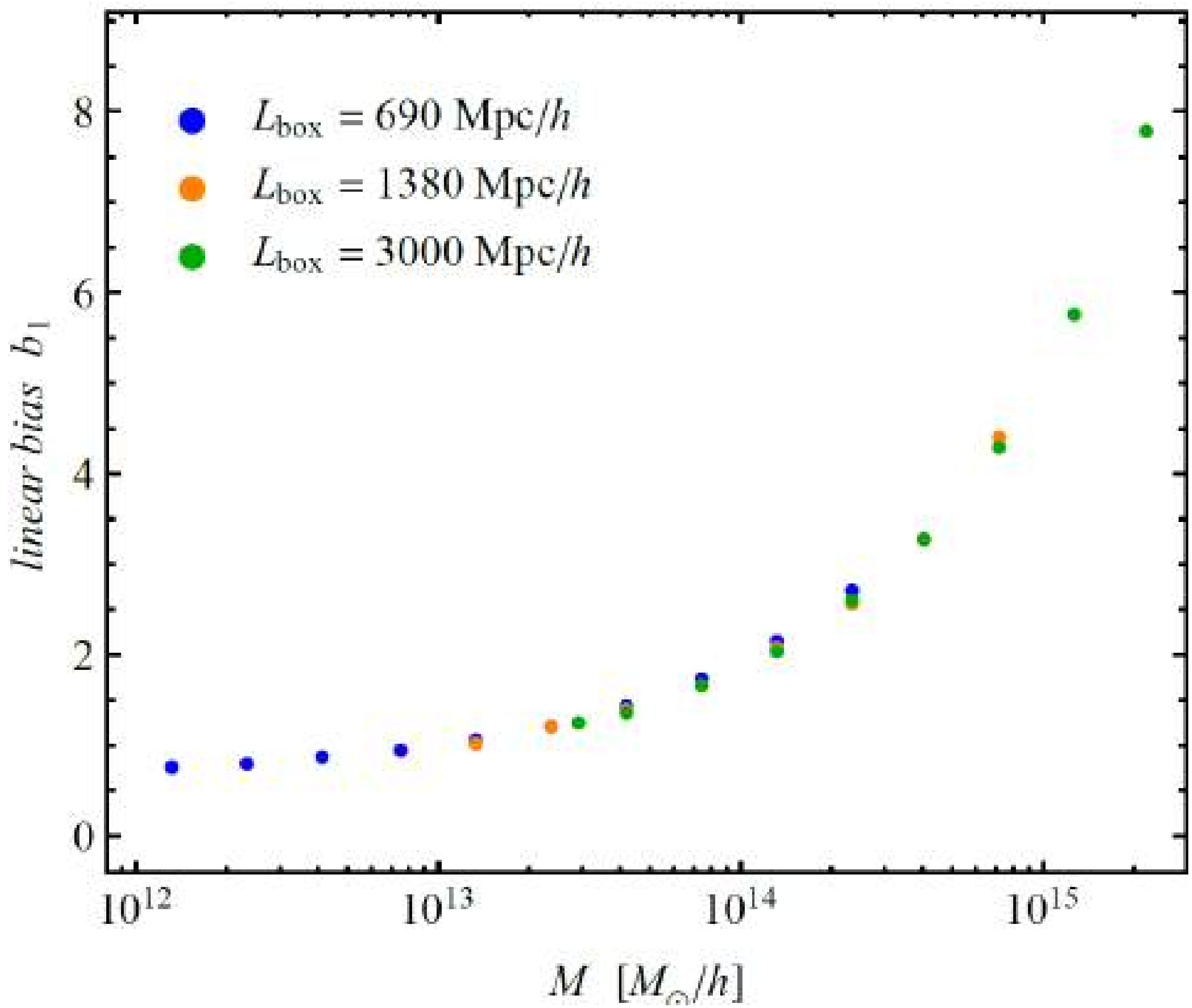
- Improvement much larger for Euclid (cosmic variance dominated)

Part II:
Primordial non-Gaussianities
and
zero bias tracers of the LSS

Why is b=0 interesting ?

$$P_{gg}(k) = b_1^2 P_m(k) + ... \longrightarrow 0$$

Linear bias at z=0



Linear bias is always larger than 0.6 for mass/luminosity selected samples.

Cosmic Variance

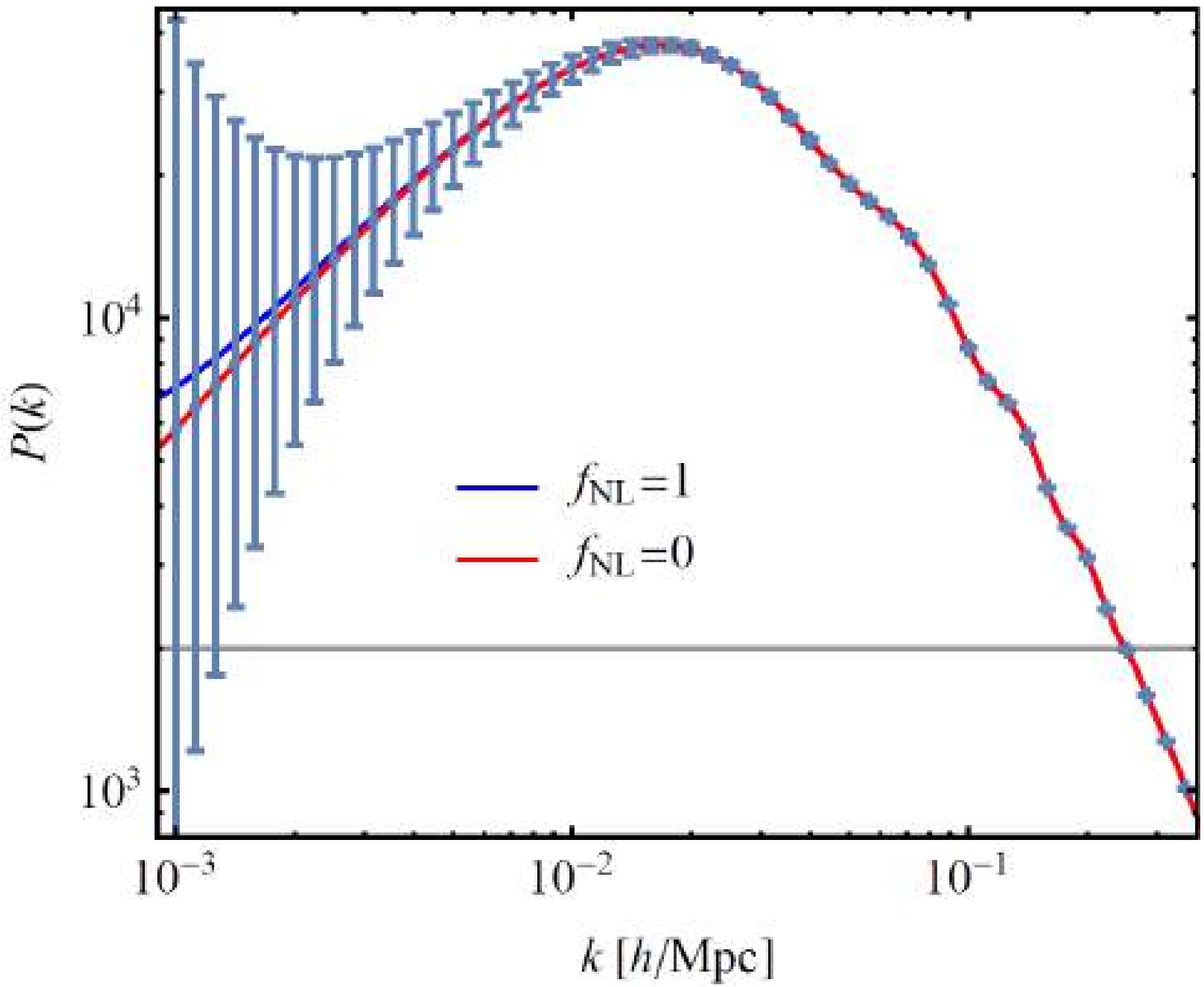
$$P_{gg}(k,\mu,z) = [b + f\mu^2 + f_{NL} b_\phi \alpha(k)]^2 P(k,z) + \frac{1}{\bar{n}(z)}$$

Error bars ~20 now,

~Comparable to Planck in the future (DESI,LSST)

How do we get to fnl~1 ?

Galaxy bispectrum?
Yet to see how well we can measure it



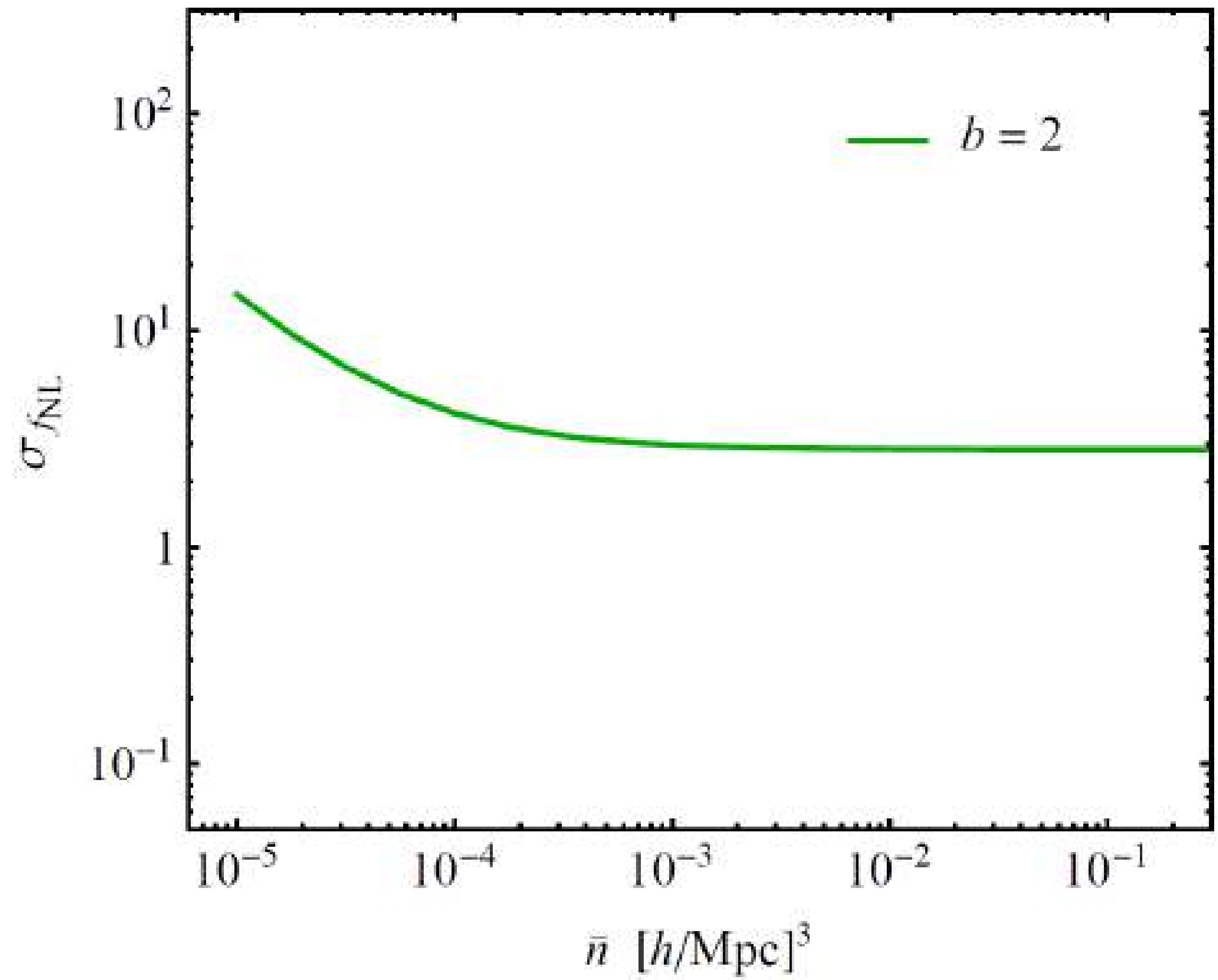
Cosmic Variance

$$P_{gg}(k,\mu,z) = [b + f\mu^2 + f_{NL} b_\phi \alpha(k)]^2 P(k,z) + \frac{1}{\bar{n}(z)}$$

Cosmic Variance limit:

No matter how many galaxies we see, the constraints do not improve for a single tracer.

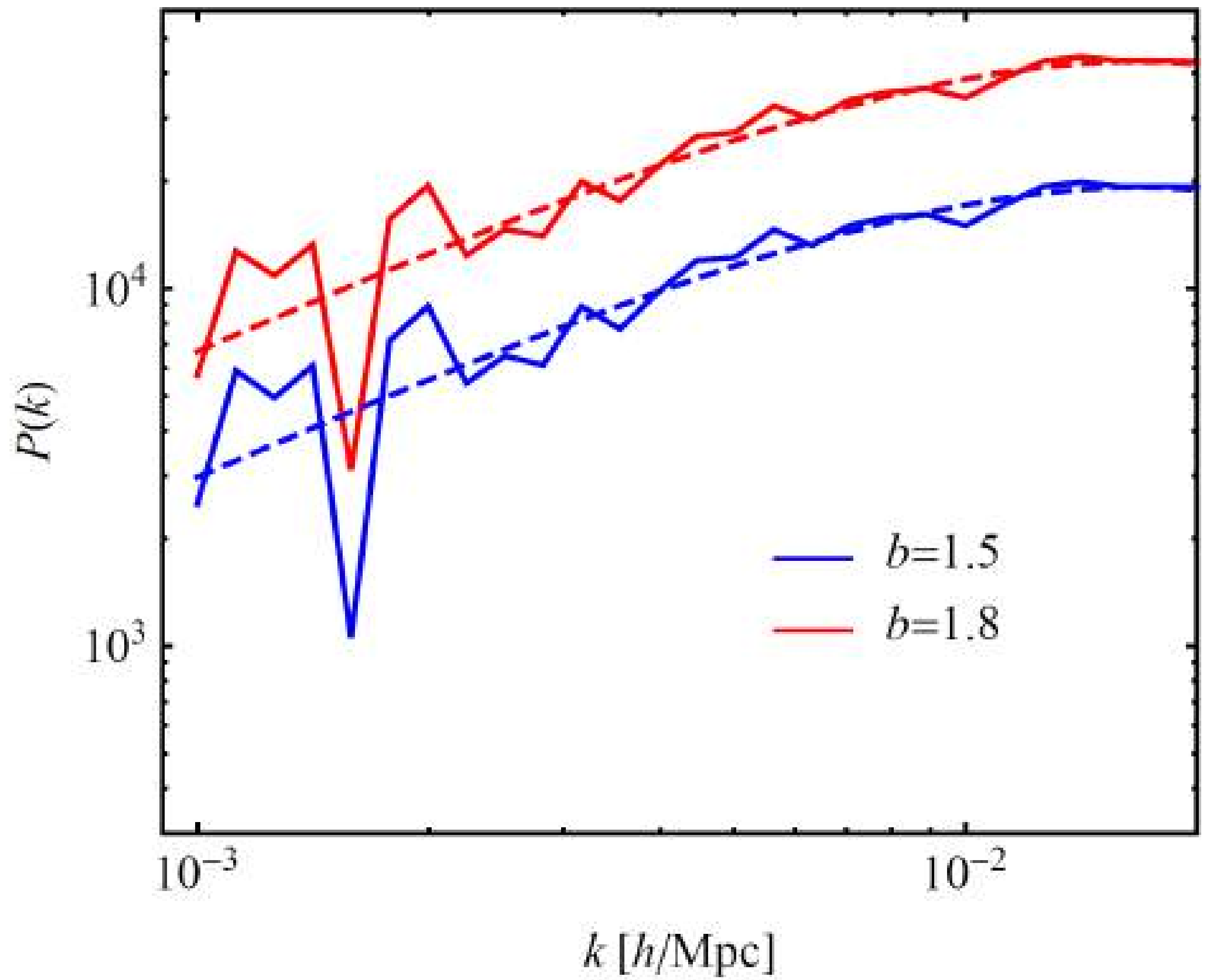
Any way out?



Cosmic Variance cancellation

In the limit of zero noise sample variance can be canceled

$$\frac{\delta_1}{\delta_2} = \frac{[b_1 + f_{\rm NL}(b_1 - 1)\alpha(k)]\delta_m + \epsilon_1}{[b_2 + f_{\rm NL}(b_2 - 1)\alpha(k)]\delta_m + \epsilon_2}$$



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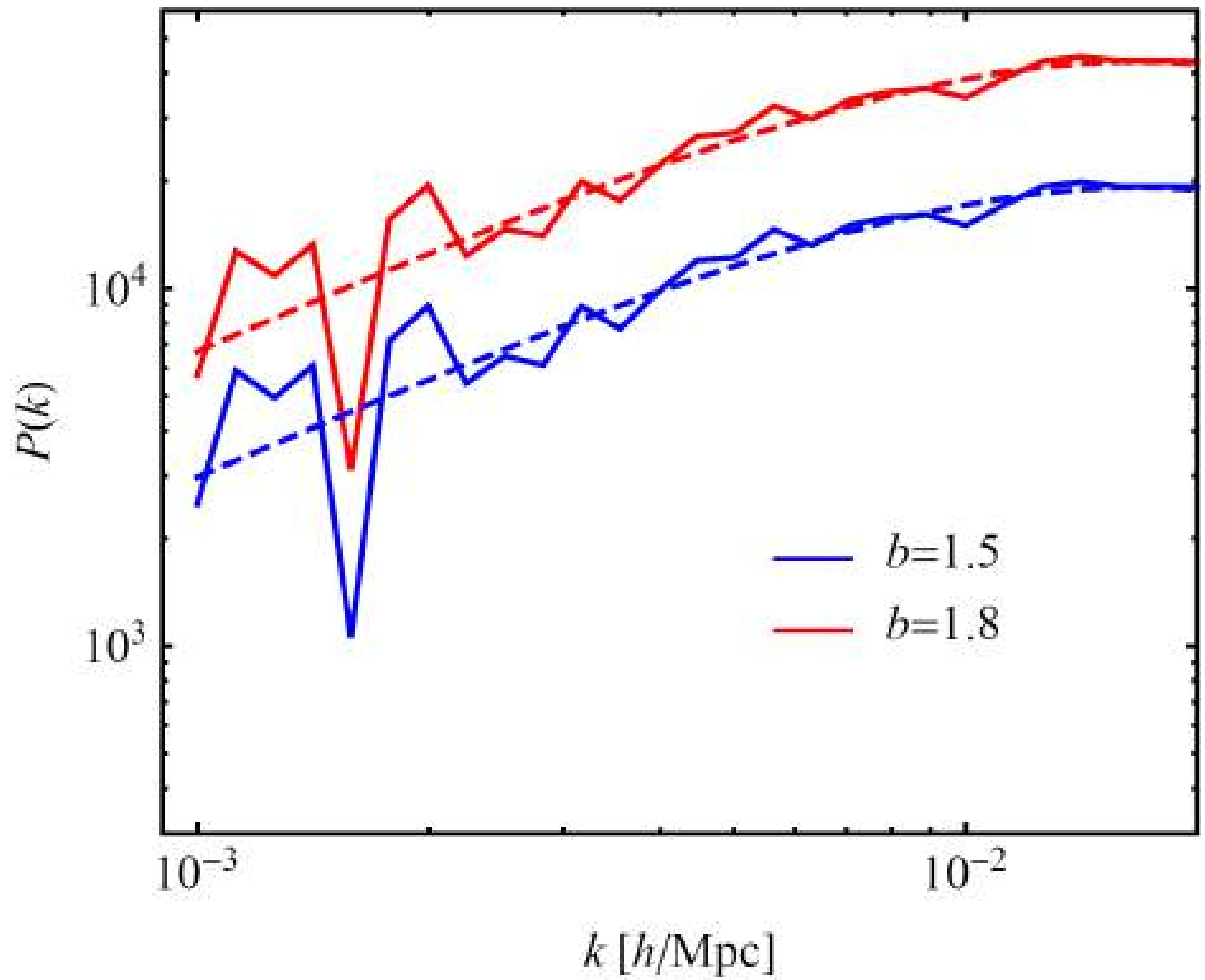

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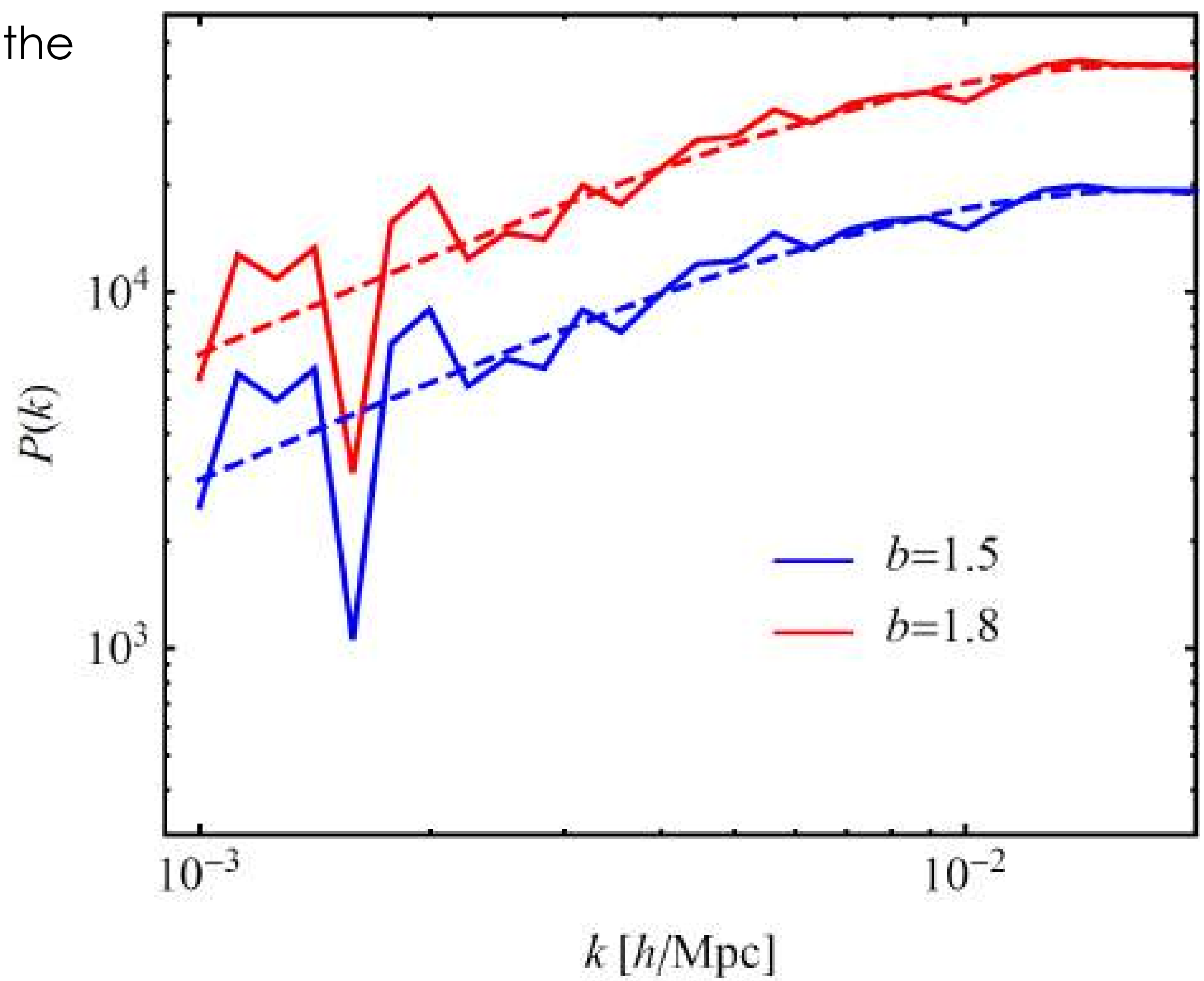
Use cross-correlations! Do not pay the price of CV twice.

Yields large improvements.

Very difficult on real data.
How to split?

CMB as the 2nd tracer.
Schmittfull&Seljak17

Still hard to achieve fnl~1



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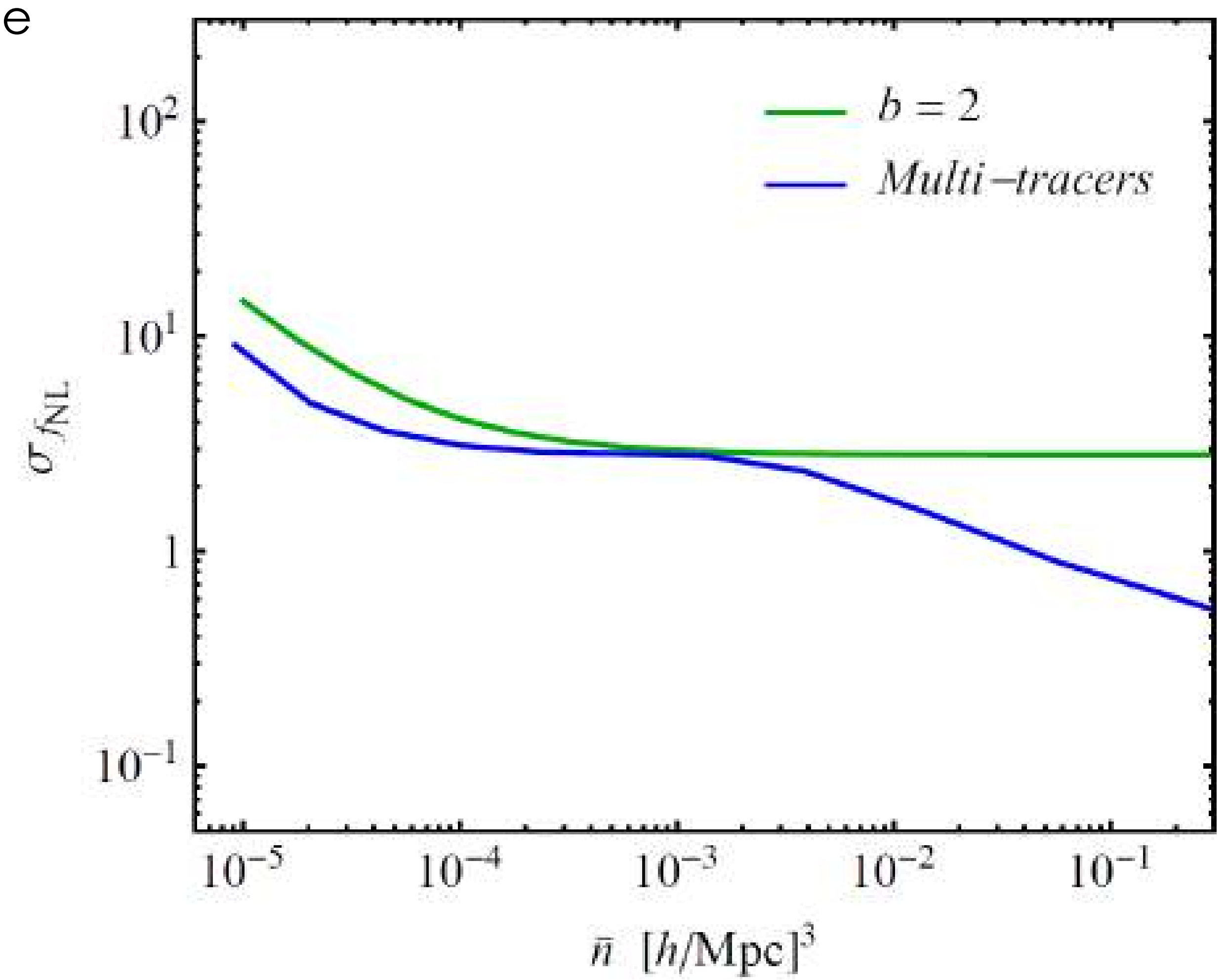

The real cosmic variance cancellation: zero bias tracers

On large scales we measure

$$\hat{P}_{gg}(k,\mu,z) = P_{gg}(k,\mu,z) + \frac{1}{\bar{n}(z)} = (b + f\mu^2)^2 P(k,z) + \frac{1}{\bar{n}(z)}$$

The error is proportional to the signal...

$$C_{ij} = \left\langle \hat{P}(k_i)\hat{P}(k_j) \right\rangle - \left\langle \hat{P}(k_i) \right\rangle \left\langle \hat{P}(k_j) \right\rangle$$

$$= \underbrace{\boxed{2\delta_{ij}\frac{(2\pi)^3}{V N_k}\left(P_{gg}(k_i) + \frac{1}{\bar{n}}\right)^2}}_{\sigma_P^2} + \frac{1}{V}\int \cancel{T}(\mathbf{k}_i, -\mathbf{k}_i, \mathbf{k}_j, -\mathbf{k}_j)$$

Error goes down with volume of the survey, ie more modes are available.

Diagonal piece, Cosmic Variance + shot-noise, is always much bigger than the Trispectrum, on large scales.

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$$\sigma_P^2 \longrightarrow \; = \boxed{2\delta_{ij}\frac{(2\pi)^3}{V N_k}\left(P_{\cancel{gg}}(k_i) + \frac{1}{\bar{n}}\right)^2} + \frac{1}{V}\int \cancel{T}(\mathbf{k}_i, -\mathbf{k}_i, \mathbf{k}_j, -\mathbf{k}_j)$$

Error goes down with volume of the survey, ie more modes are available.

Diagonal piece, Cosmic Variance + shot-noise, is always much bigger than the Trispectrum, on large scales.

The bottom line: $\boxed{\text{If bias is zero Cosmic Variance is zero ! Left with shot noise only.}}$

The real cosmic variance cancellation: zero bias tracers

Fisher information
$$\sigma_{f_{\rm NL}}^{-2} = F_{f_{\rm NL} f_{\rm NL}} \propto \frac{\overbrace{b^2(b-1)^2\alpha(k)^2P^2(k,z)}^{\text{Signal}}}{\Big(\underbrace{b^2P(k)}_{\text{CV}} + \underbrace{\frac{1}{\bar{n}}}_{\text{Noise}}\Big)^2}$$

Shot noise dominated regime

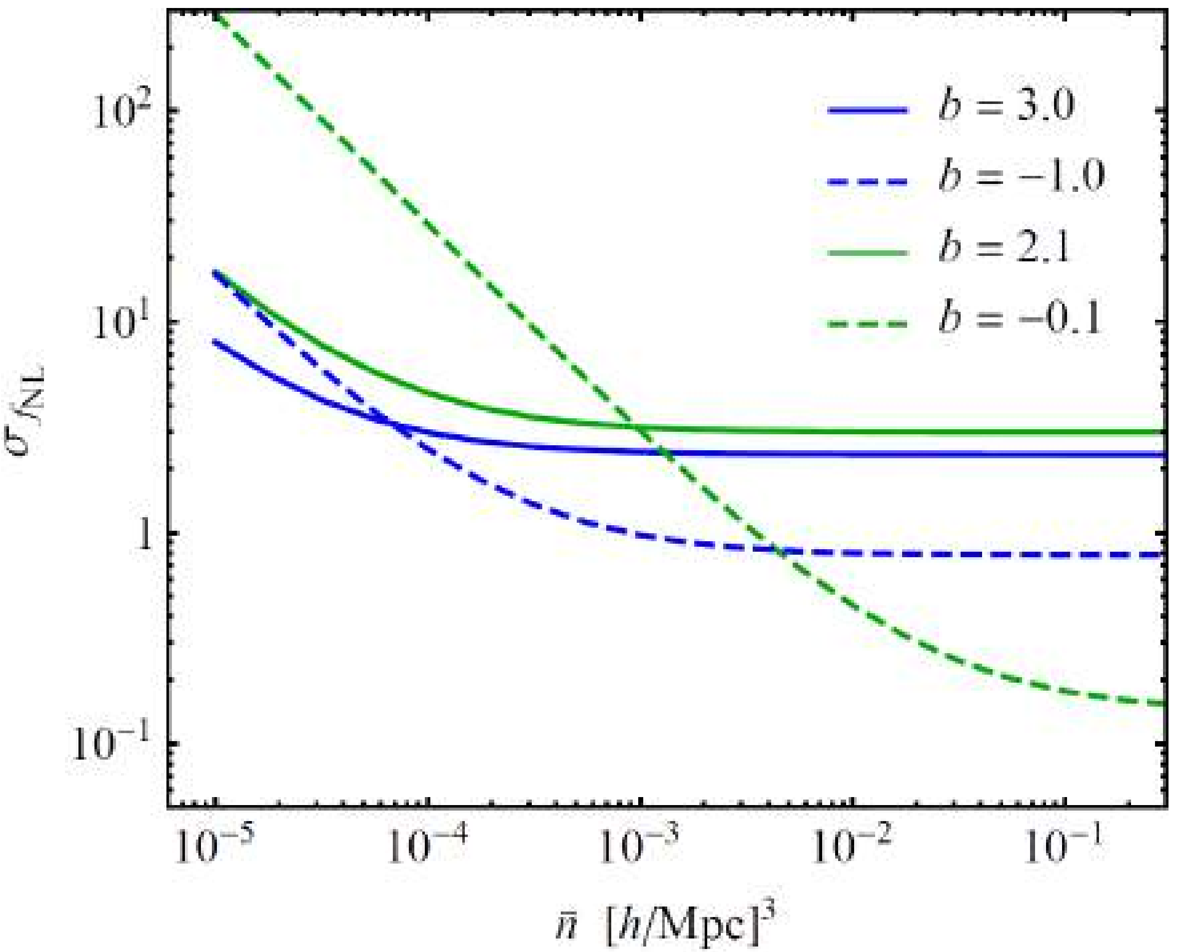
$$F_{f_{\rm NL} f_{\rm NL}} \longrightarrow \delta_c^2 b^2(b-1)^2\alpha(k)^2\bar{n}^2P^2(k,z)$$

CV dominated regime

$$F_{f_{\rm NL} f_{\rm NL}} \longrightarrow \frac{\delta_c^2(b-1)^2\alpha(k)^2}{b^2}$$

In principle zero bias could achieve infinite precision on fnl.

Halos/Galaxies never have zero bias
If selected by mass/luminosity.



A zero bias field

The goal :

We want to define a new tracer via a nonlinear transformation of the galaxy density field. The new tracer will have zero power on large scales.

Things to worry about :

Criterion can be applied to data

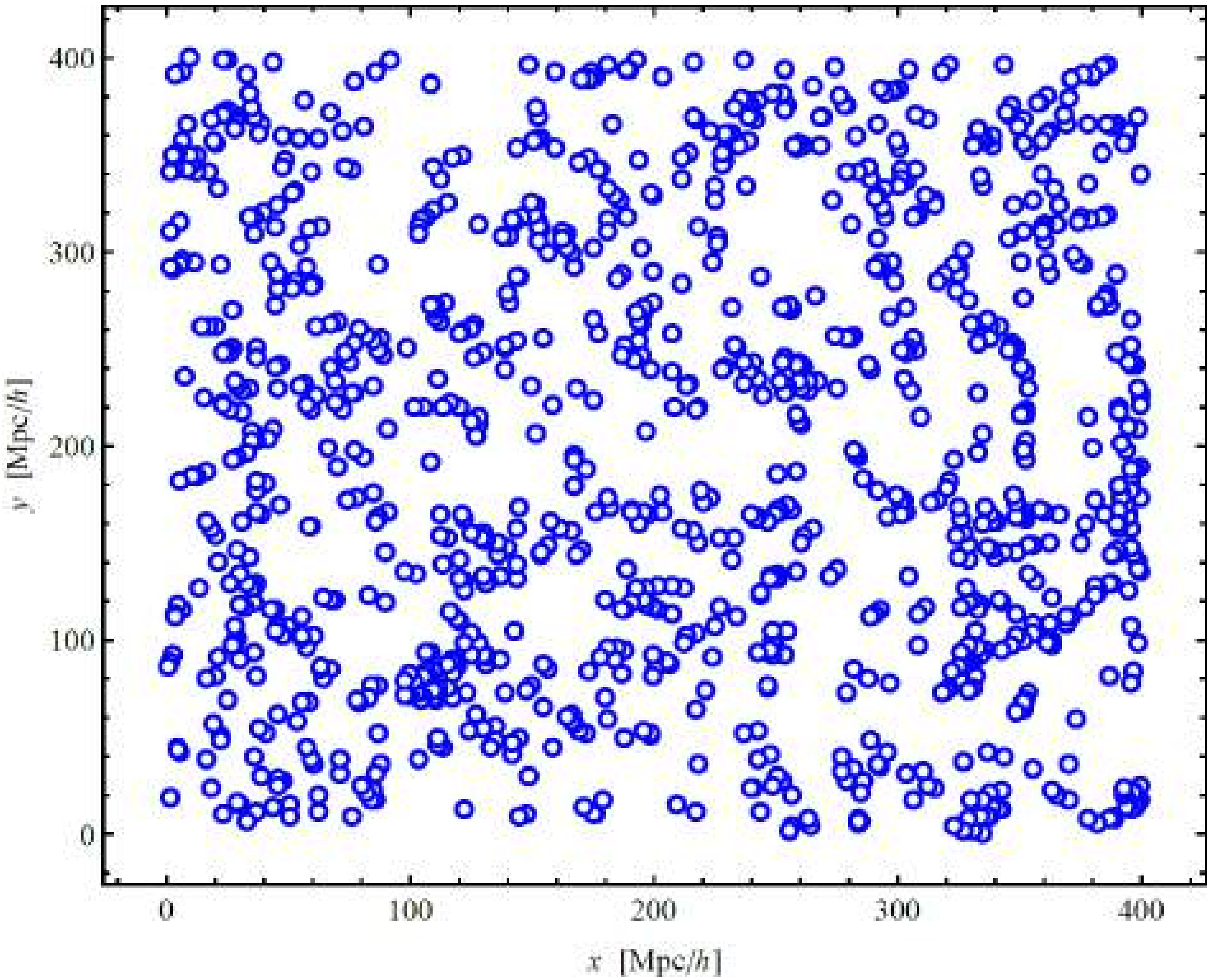
High number densities

Non-Poissonian shotnoise

Velocity bias

....

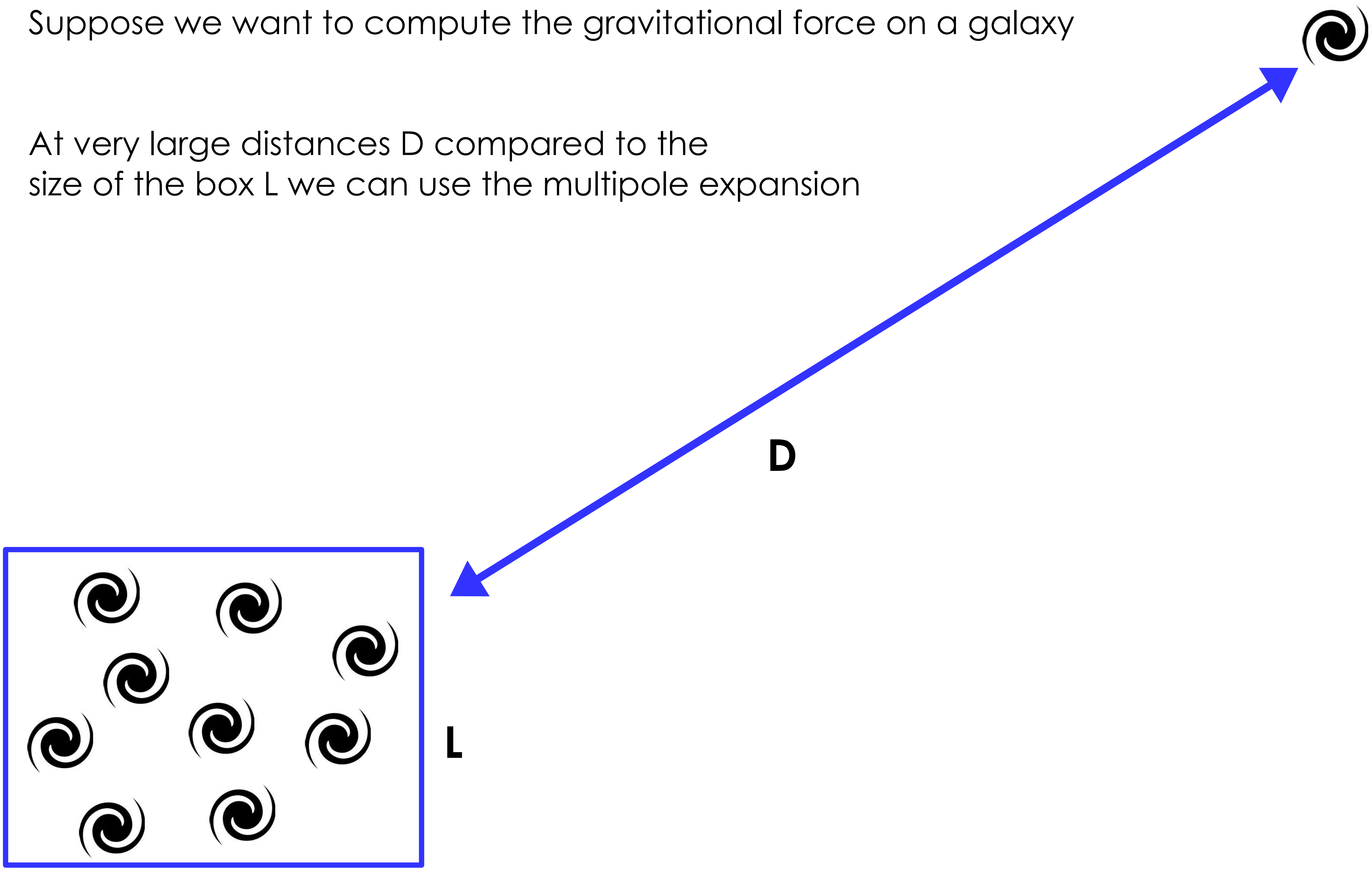
Voids? Too sparse



A zero bias field: Environment as a tracer

Suppose we want to compute the gravitational force on a galaxy

At very large distances D compared to the size of the box L we can use the multipole expansion



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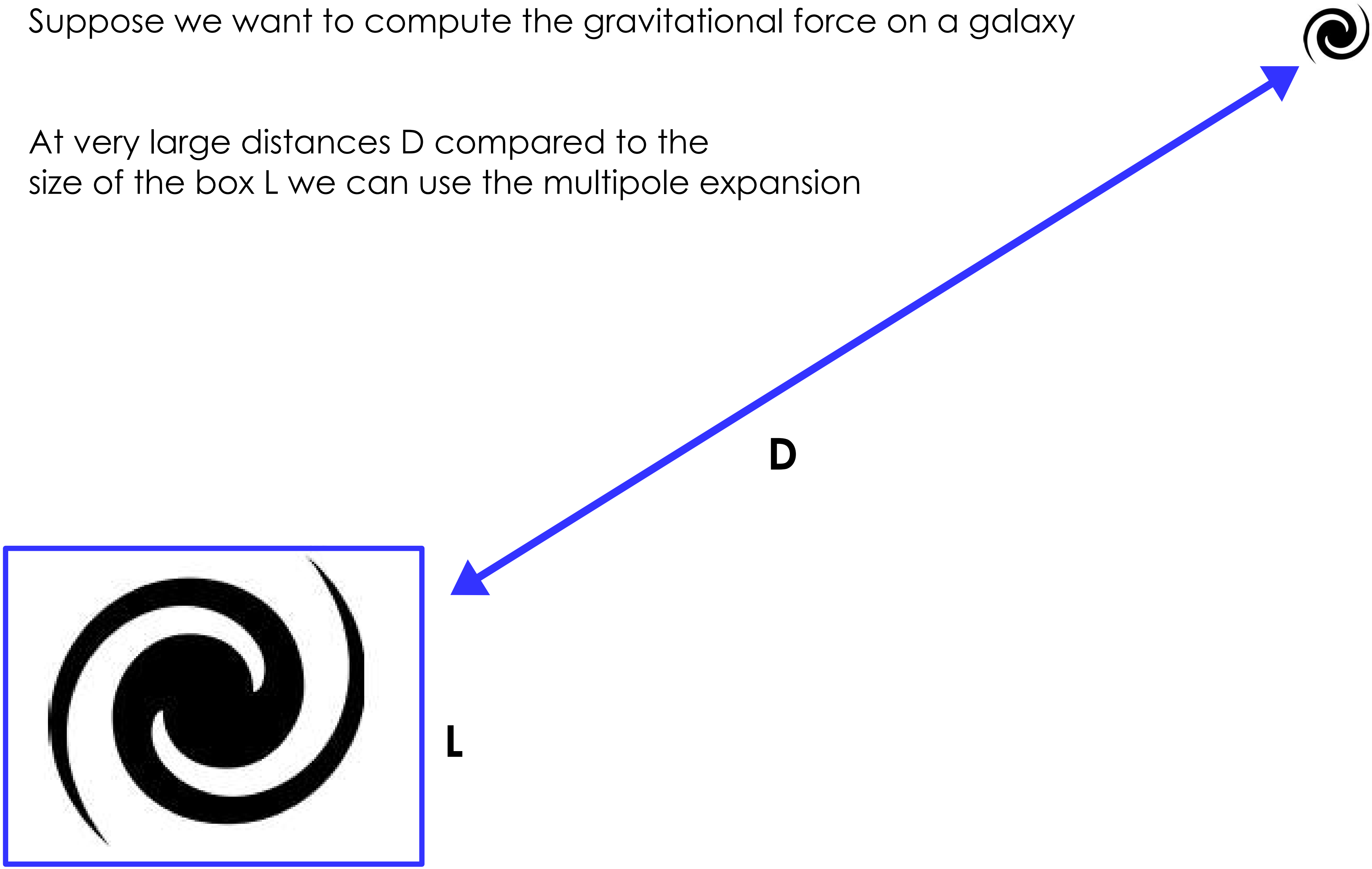

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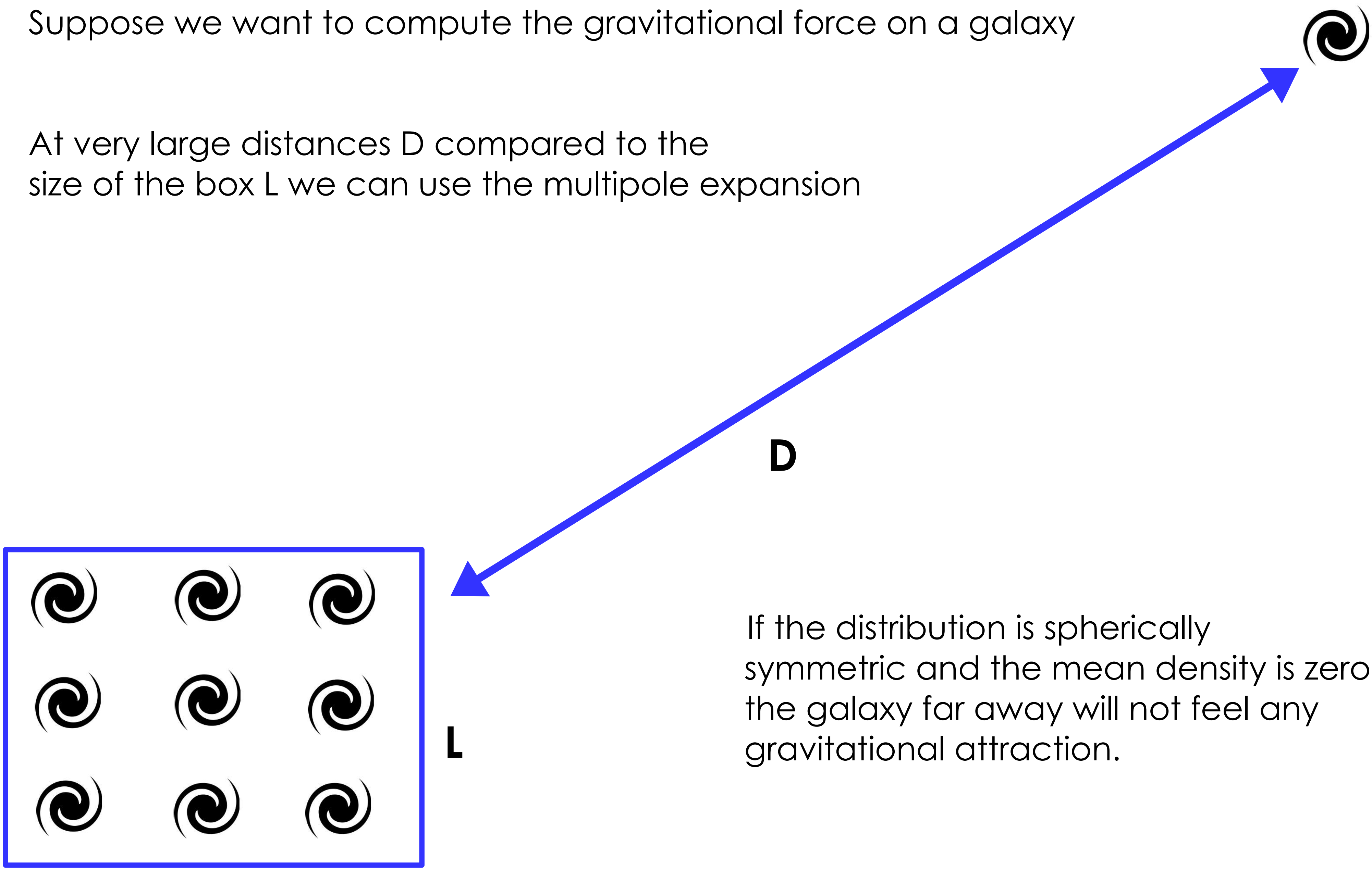

If the distribution is spherically symmetric and the mean density is zero the galaxy far away will not feel any gravitational attraction.

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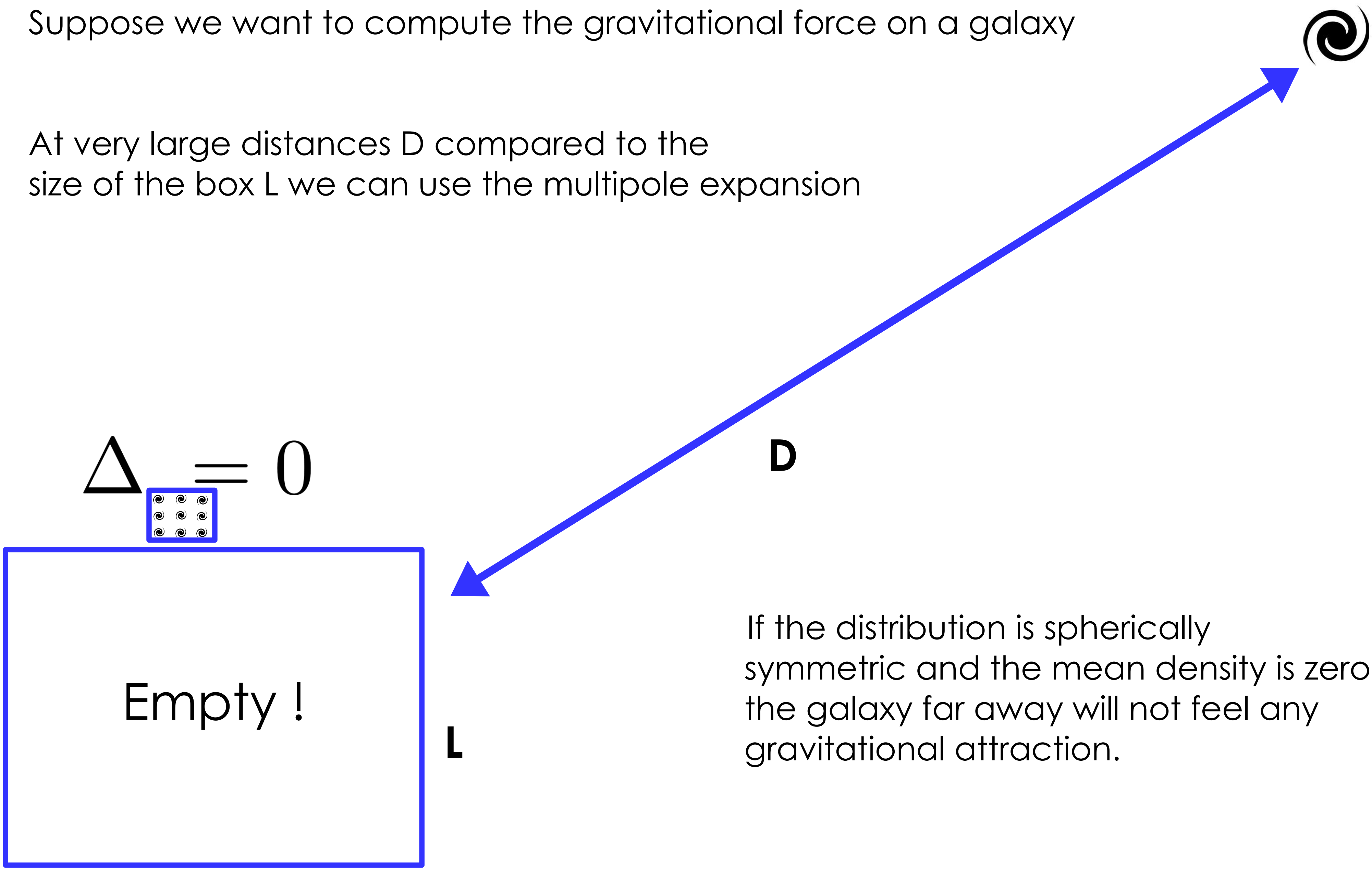

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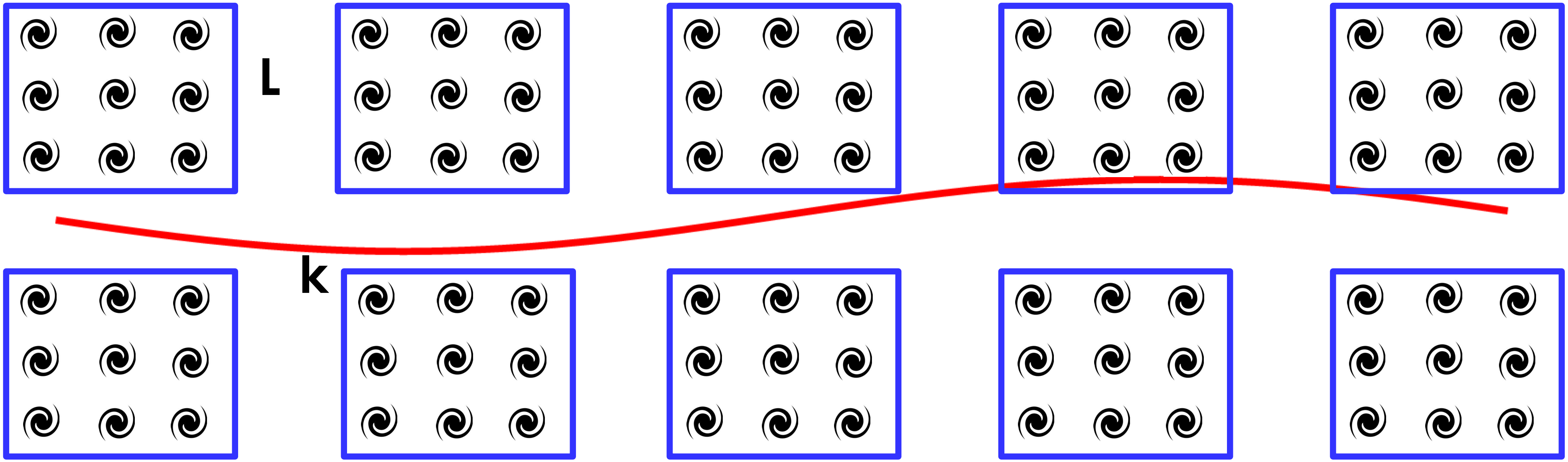
A zero bias field: Environment as a tracer



On scales much larger than L the power is zero

$$P(k \ll 1/L) \simeq 0$$

Complete understanding of this effect in Excusions Sets/Peaks theory

A zero bias field : Simple Peaks theory calculation

It happens that in our Universe the shape of the P(k) is such that $\sigma^2(R) \propto R^{-(n+3)}$

$$b = \sum_i \frac{\mathcal{O}(1)}{\sigma^2(R_i)}$$

Halo/galaxy scale

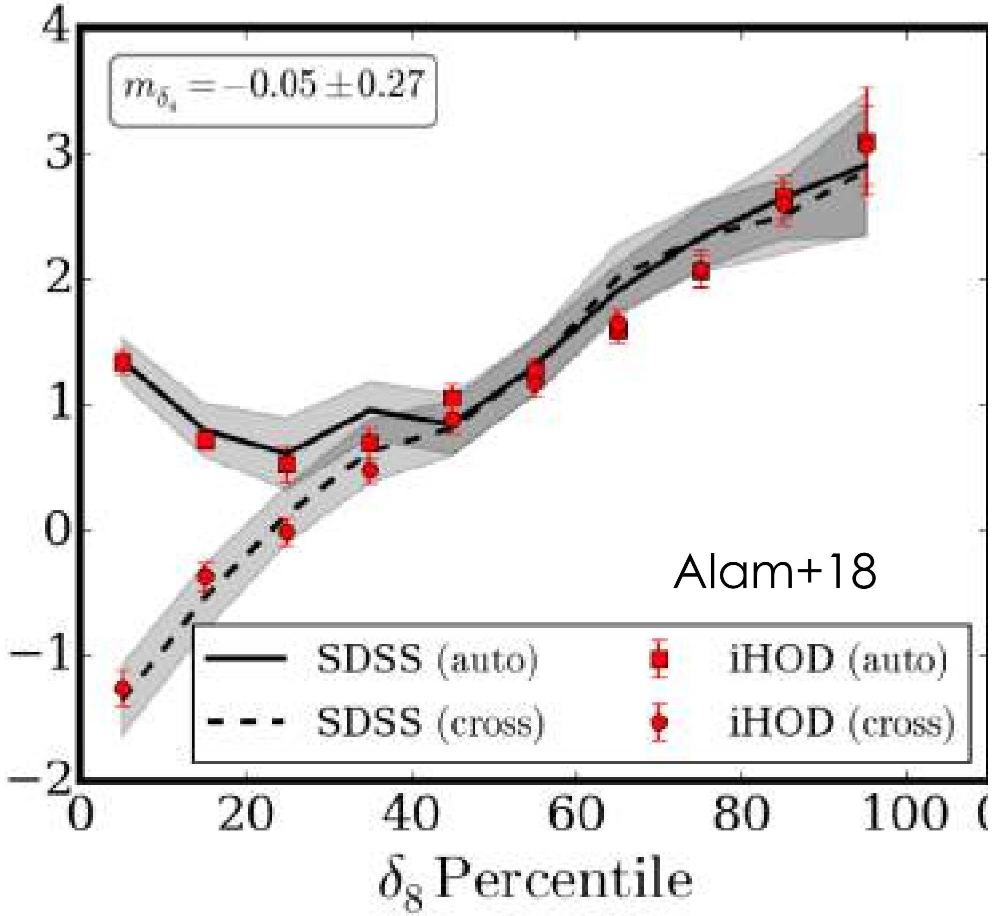
$$R_{pk} \ll R_E \simeq L \longrightarrow \sigma^2(R_{pk}) \gg \sigma^2(R_E)$$

The constraint on the largest scale will dominate over the others

$$b \simeq \frac{\Delta}{\sigma_E^2}$$

In real data, Alam et al. and Paranjape et al. 2018

Galaxy Bias



Density at 8 Mpc/h

Tracers with zero bias have been found in Sloan main sample (in redshift space).
~25 % of all the galaxies

Simulations

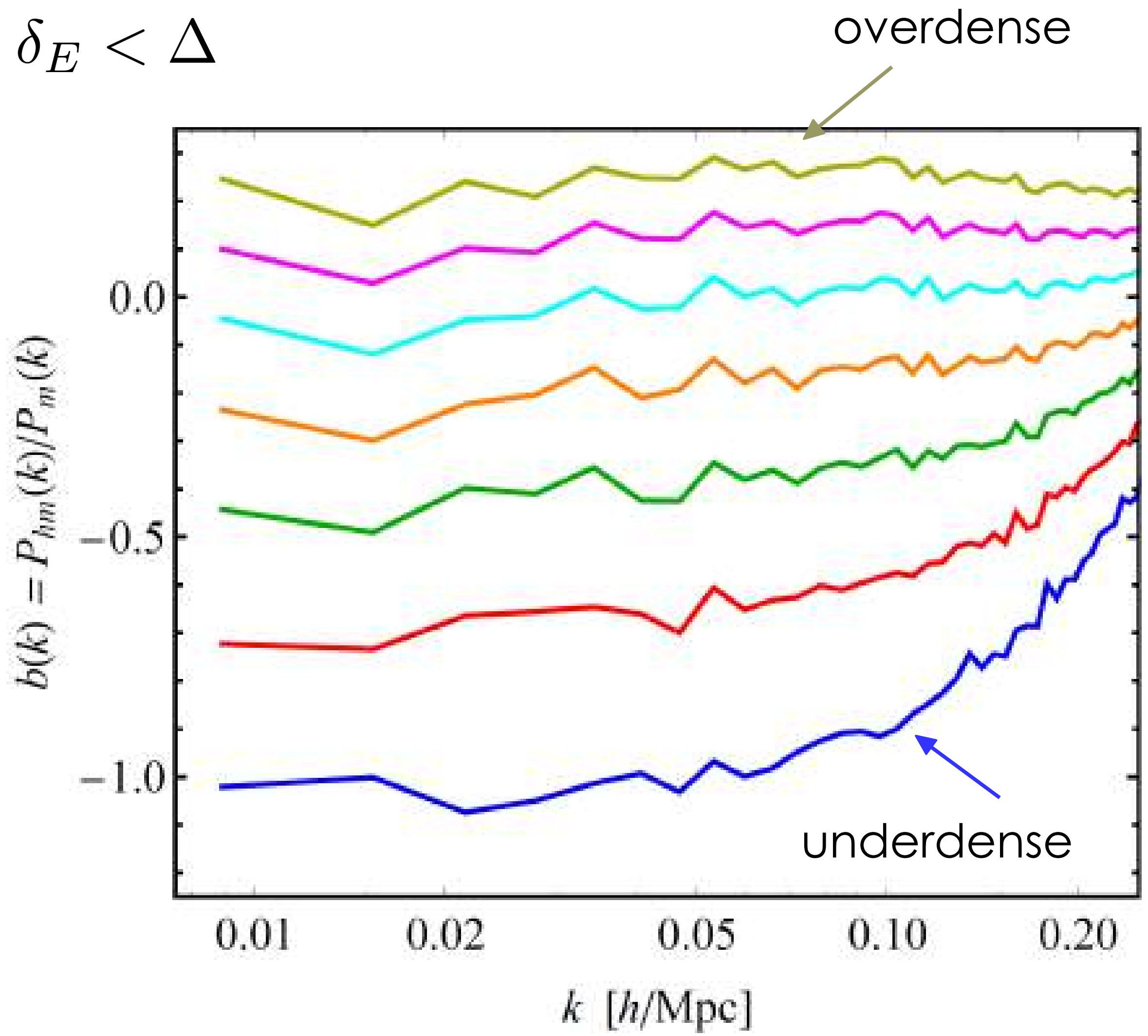
1) Fix environmental threshold Δ @ 8 Mpc/h.

2a) Select all the halos in regions with $\delta_E \geq \Delta$

This is the *high bias* sample.

2b) Select all the halos in regions with $\delta_E < \Delta$

This is the *low bias* sample.



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This is the *high bias* sample.

2b) Select all the halos in regions with $\delta_E < \Delta$

This is the *low bias* sample.

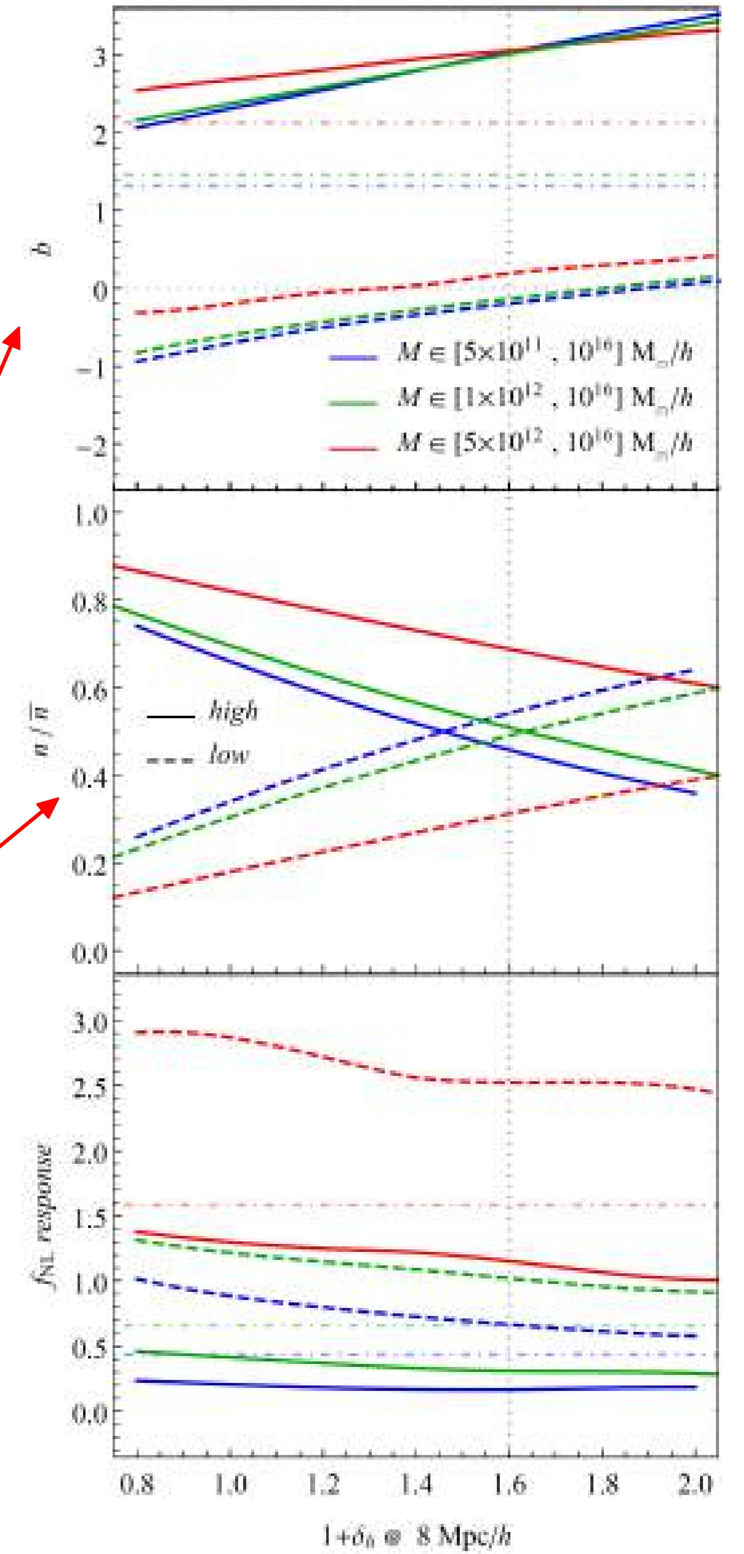
3) Measure the bias of the high and low sample

4) Measure the fraction of objects in the two samples

Run additional simulations with different σ_8
to measure fNL response

$$b_\phi = \frac{\partial \log n}{\partial \log \sigma_8}$$

5) Measure scale dependent bias



Forecast on PNG

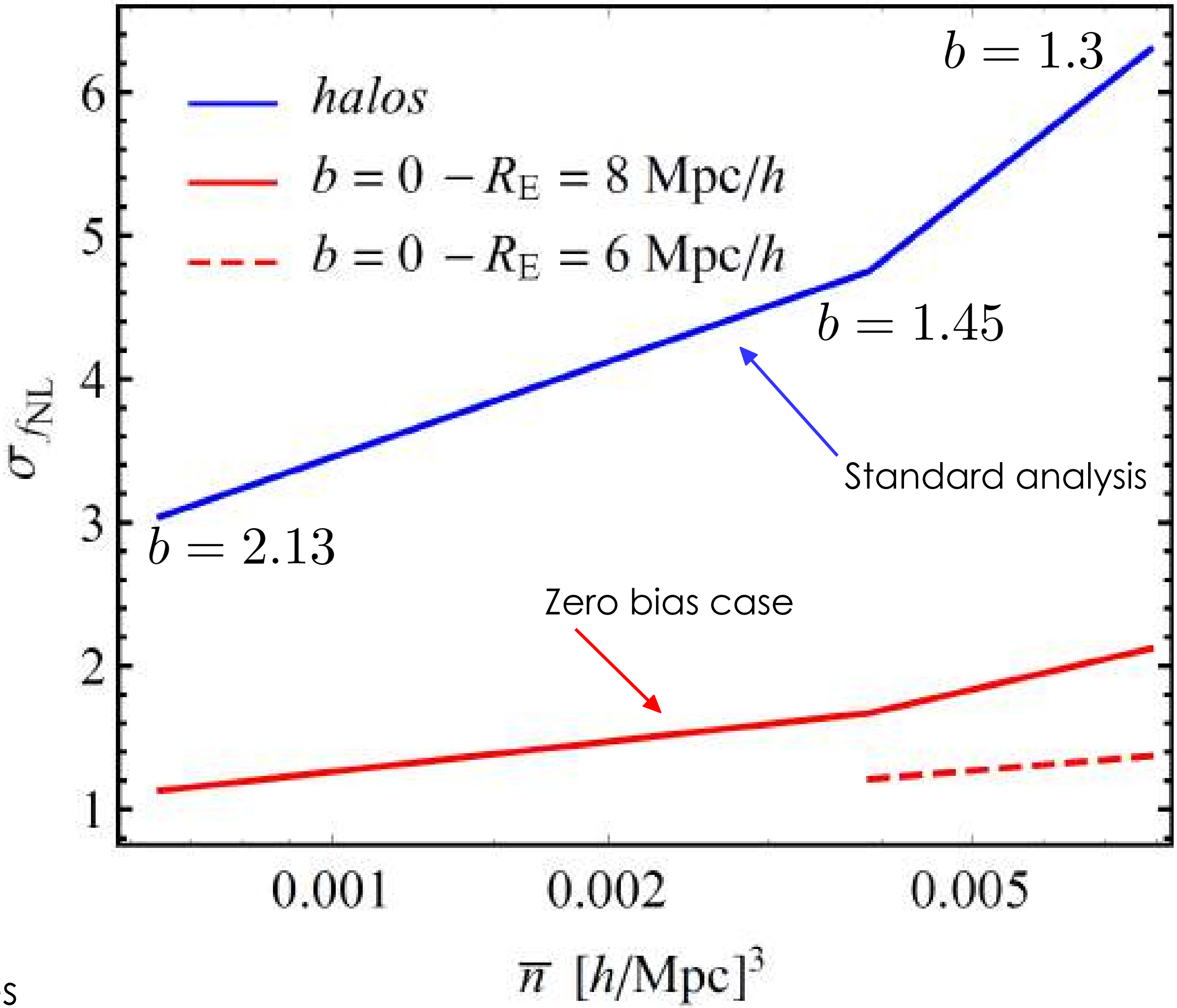
Setup:

- z=1.
- V = 50 (Gpc/h)^3.
- Marginalized over other parameters.

For standard tracers there is no improvement for high densities, limited by CV. Low bias is worse.

In our approach 3x smaller error-bars.

Gain at high number densities limited by the noise in the zero bias tracers.



Summary II

- At fixed number of galaxies try to minimize Cosmic Variance to reduce error bars.

- Environment offers a simple way to select any sample we want.

    - Detected in data.

    - Understood within Peaks/Excursion Sets Theory.

- Primordial non-Gaussianities benefit a lot from zero bias tracers.

    - 3X improvement over standard analysis.

- PNG analysis in BOSS data to happen in 2020

Conclusions

- (Non-)Detection of PNG is in the reach of next gen. galaxy surveys

  - New ideas and methods will be required

- Optimal statistical techniques can bring us closer to the Fisher matrix.

  - 20% improvement in eBOSS, larger in Euclid/DESI.
  - Need to extend it to the Bispectrum.

- Primordial non-Gaussianities benefit a lot from zero bias tracers.

  - 3X improvement over standard analysis.
  - Check it in realistic Euclid mocks

Thank you!

Effective redshift

Can we approximate the full result

$$P_{A,eff}(k) = (2A+1)\int \frac{d\Omega_k}{4\pi}\,\mathrm{d}^3 s_1\,\mathrm{d}^3 s_2\, e^{i\mathbf{k}(\mathbf{s}_2-\mathbf{s}_1)}\delta(\mathbf{s}_1)\delta(\mathbf{s}_2)W(\mathbf{s}_1)W(\mathbf{s}_2)\mathcal{L}_A(\hat{k}\cdot\hat{s}_1) \tag{4.16}$$

$$= (-i)^A(2A+1)\sum_{\ell,L}\begin{pmatrix}\ell & L & A\\ 0 & 0 & 0\end{pmatrix}^2\int \mathrm{d}s\, s^2 j_A(ks)\int \mathrm{d}s_1\, s_1^2\,\xi_\ell(s;s_1(z))Q_L(s;s_1(z)) \tag{4.17}$$

With

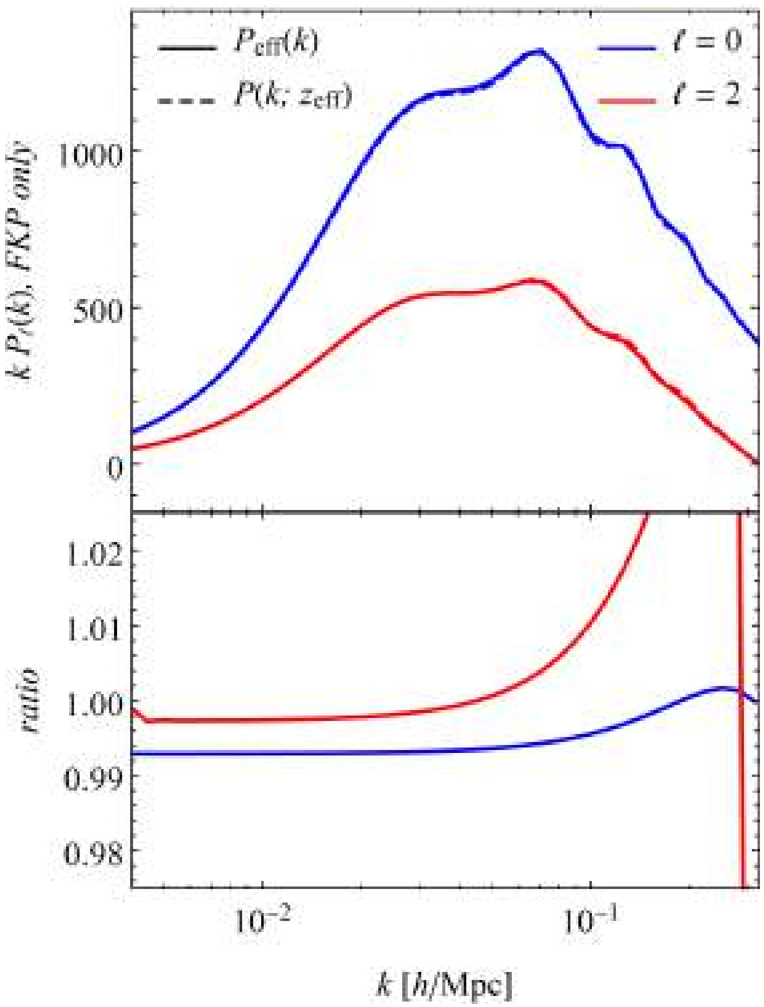
$$P_A(k;z_{\rm eff}) = (-i)^A(2A+1)\sum_{\ell,L}\begin{pmatrix}\ell & L & A\\ 0 & 0 & 0\end{pmatrix}^2\int \mathrm{d}s\, s^2 j_A(ks)\xi_\ell(s;z_{\rm eff})Q_L(s)$$

Pretty accurate in linear and non linear theory.

Effective redshift

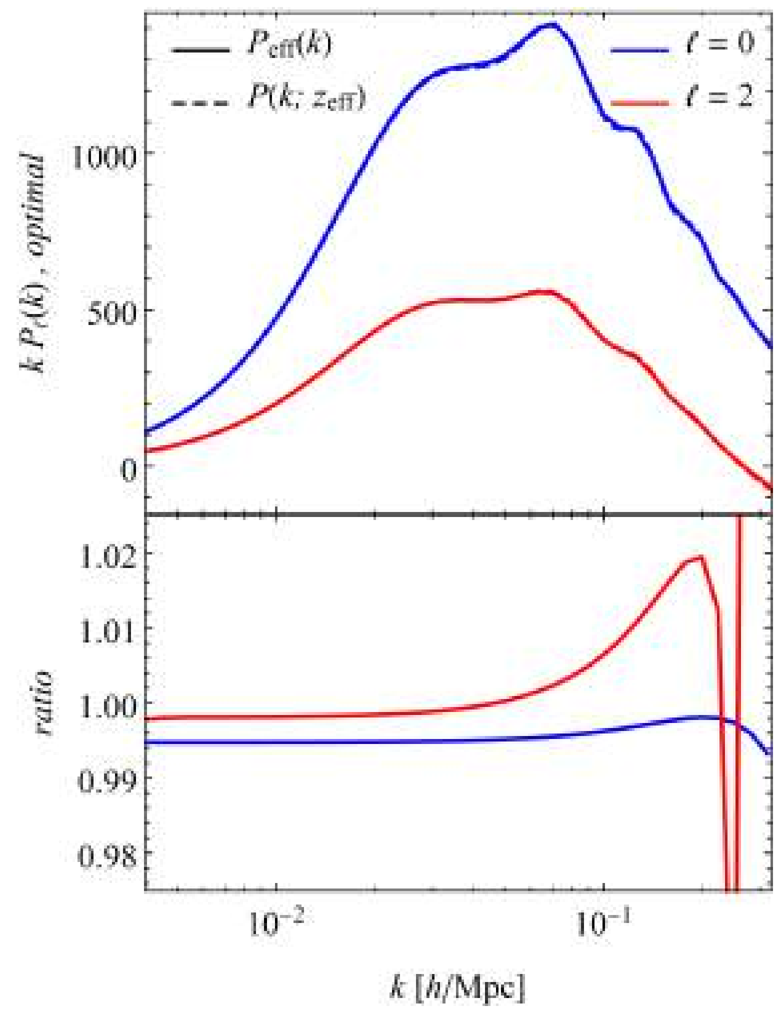
FKP weights:

$$z_{\rm eff}^{FKP} = 1.52$$



In the optimal case:

$$z_{\rm eff} = 1.64$$



It remains true even including wide angles/GR effects.

What is bias? What is a halo?

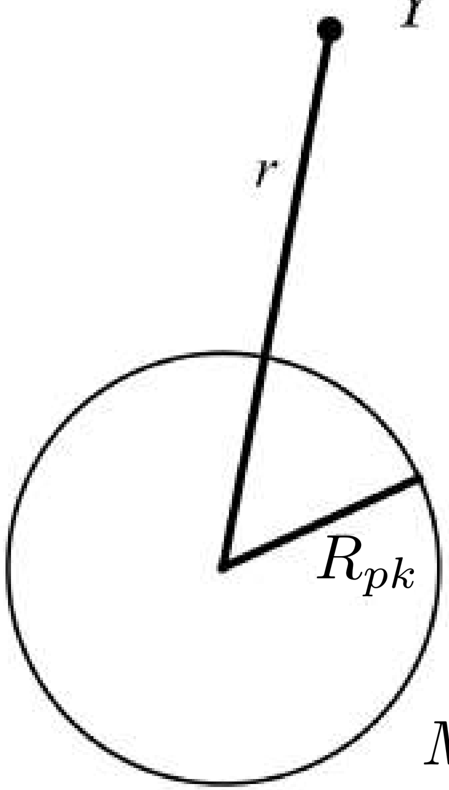
Bias means halos sample fields around them differently than the dark matter does.

What is a halo ? A # of constraints, i.e. a non-linear transformation of the matter field

$$\mathcal{C}_{pk} = \{\delta_{pk} > \delta_c \, , \, \nabla \delta_{pk} = 0, \nabla^2 \delta_{pk} < 0\}$$

We define bias as the ratio between the halo-matter cross correlation and the matter auto-power spectrum

$$Y = \delta \, , \, \nabla^2 \delta \, , \, s_{ij}$$



$$M = \frac{4\pi}{3} \rho R_{pk}^3$$

$$b \equiv \frac{\langle \, \delta_m | \text{halo at } R_{pk} \, \rangle}{\langle \, \delta_m \delta_m \, \rangle}$$

Halo bias depends only on the constraints, not on what fields is used in the cross-correlation.

$$b = 1 + \frac{\nu_c^2 - 1}{\delta_c} \, , \; \nu_c = \frac{\delta_c}{\sigma(R_{pk})}$$

A zero bias field : Excursions Sets Peaks calculation

Constraints can be more general than sitting on a halo,

$$b \equiv \frac{\langle\, \delta_m | \mathcal{C}_{pk},\, \delta_E = \Delta \,\mathrm{at}\, R_E \,\rangle}{\langle\, \delta_m \delta_m \,\rangle} \qquad \mathcal{C}_{pk} = \{\delta_{pk} > \delta_c\,,\, \nabla\delta_{pk} = 0, \nabla^2\delta_{pk} < 0\}$$

Two steps calculation : first compute the conditional mean and then integrate over the constraints. The halo scale and the environmental scale are correlated.

For a Guassian random field this is linear in the conditioned variables

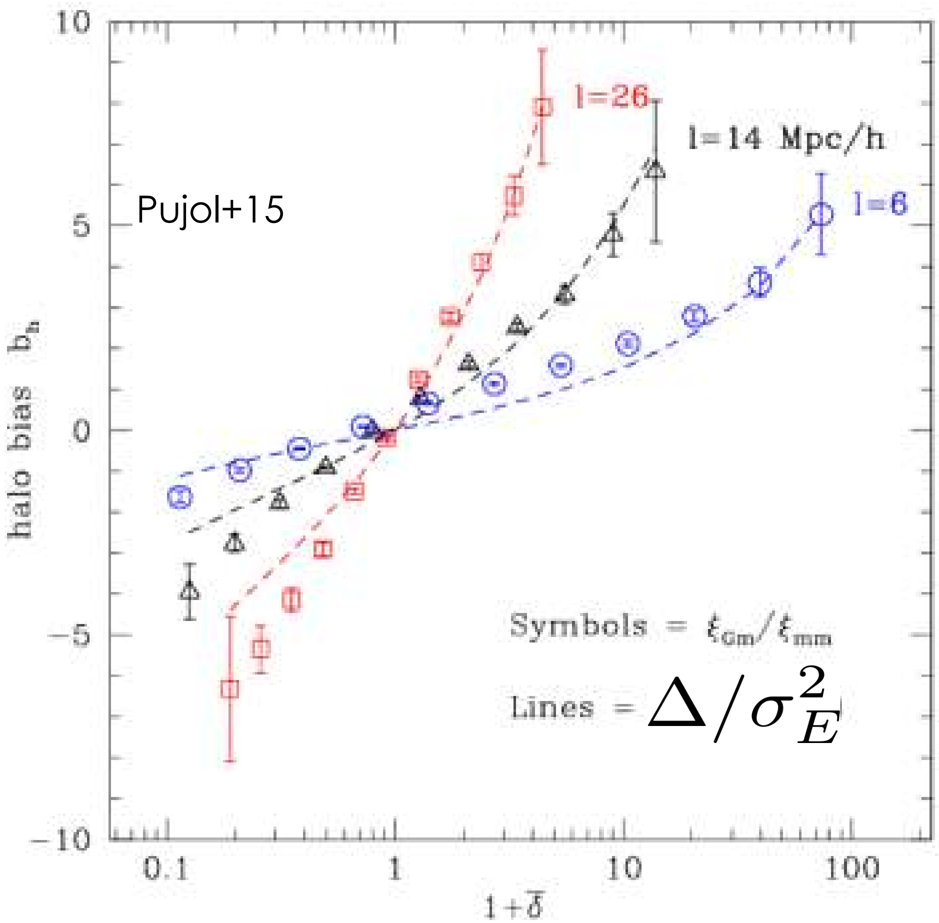
$$\nu_{pk} \equiv \frac{\delta_{pk}}{\sigma(R_{pk})}\,,\; x_{pk} \equiv -\frac{\nabla^2\delta_{pk}}{\langle\,(\nabla^2\delta_{pk})^2\,\rangle}\,,\; \nu_E \equiv \frac{\delta_E}{\sigma(R_E)}$$

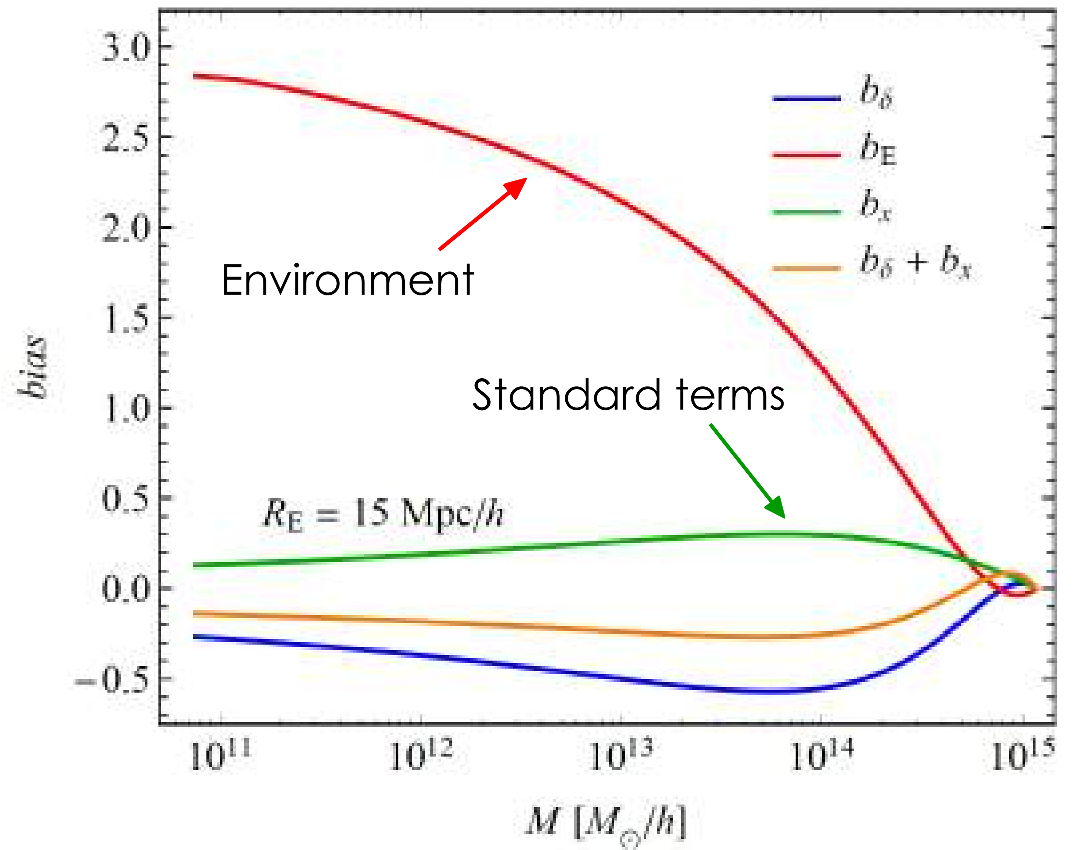
$$b = \frac{\langle\, \delta_m | \{\nu_{pk},\, x_{pk},\, \nu_E\, | \mathcal{C}\}\,\rangle}{\langle\, \delta_m \delta_m \,\rangle} = b_\delta \,\langle\, \nu_{pk} | \mathcal{C} \,\rangle + b_x \,\langle\, x_{pk} | \mathcal{C} \,\rangle + b_E \,\langle\, \nu_E | \mathcal{C} \,\rangle$$

E.g. in spherical collapse $\langle\, \nu_{pk} | \mathcal{C} \,\rangle = \dfrac{\delta_c}{\sigma(R_{pk})}$

Zero bias fields

The environmental term is much bigger than the others.
Environment is the strongest constraint.





If environment is so dominant then to a approximation

$$b \simeq \frac{\Delta}{\sigma_E^2}$$

Bias does not depend on mass anymore or Luminosity.

Zero bias fields

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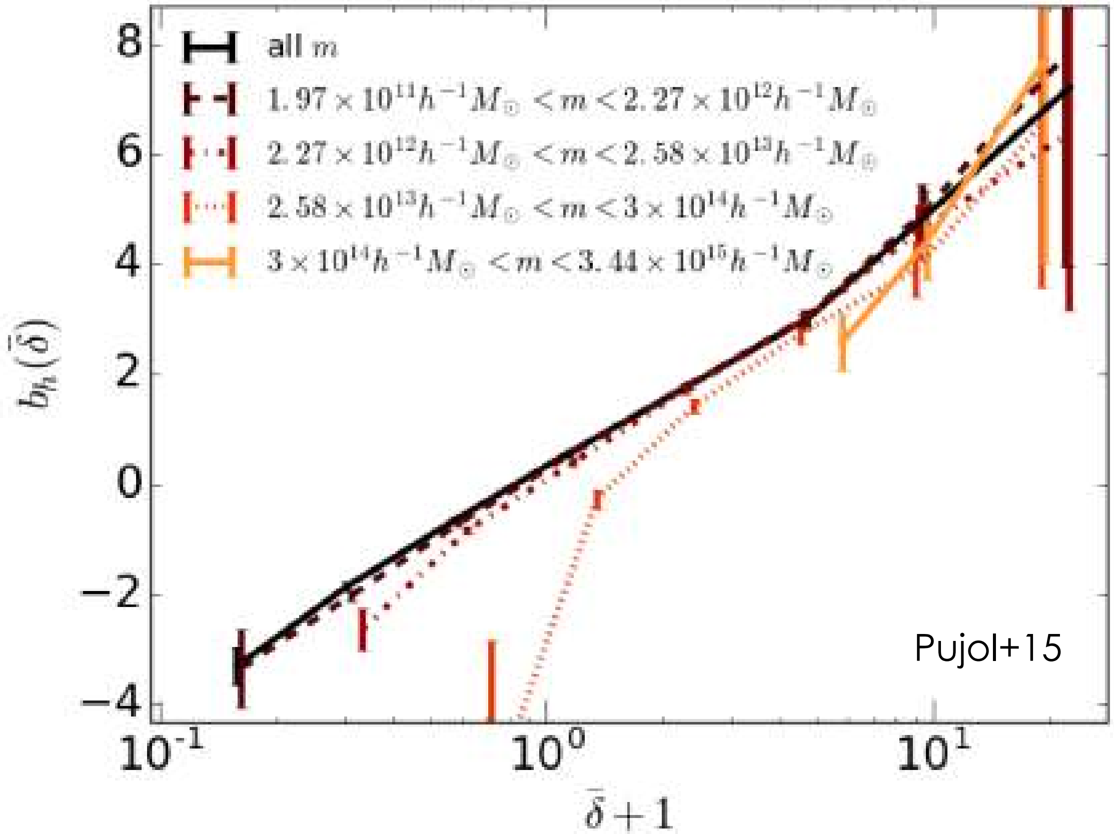

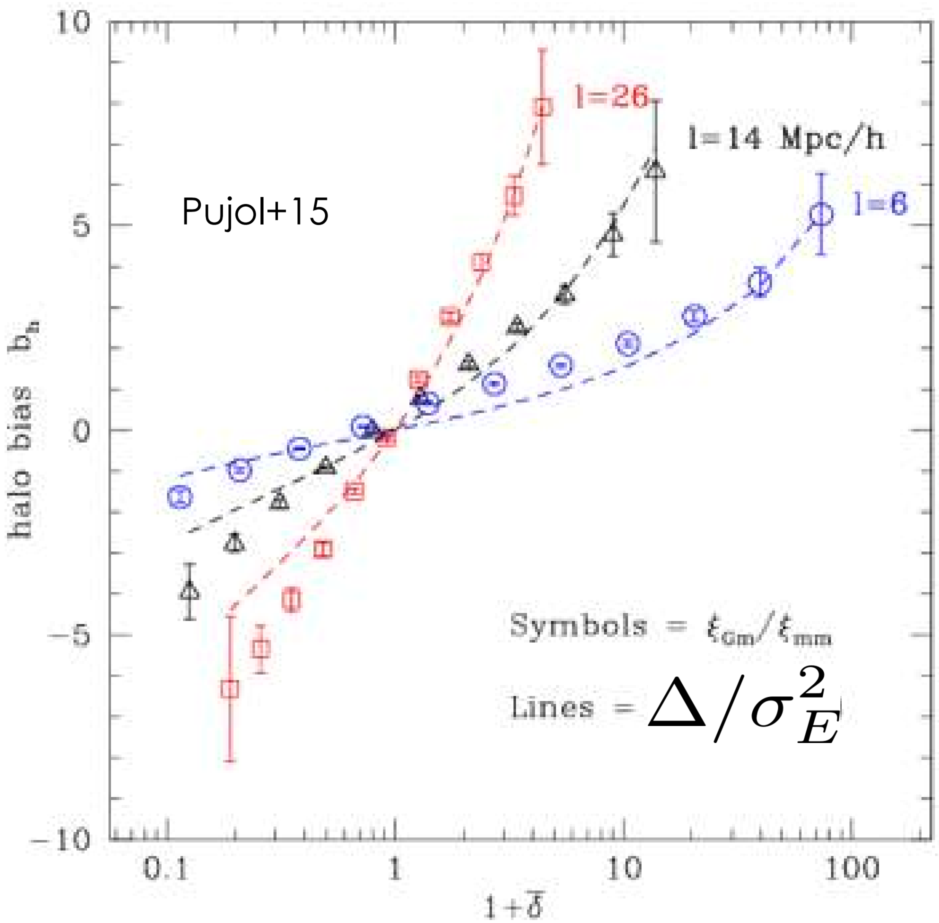

Halos in homogeneous environments have zero bias

$$b \simeq \frac{\Delta}{\sigma_E^2} \longrightarrow \boxed{b \simeq 0 \text{ IF } \Delta \simeq 0}$$

Stochasticity

Shot noise is a constant only if halos and galaxies are a Poisson process.

$$\mathcal{S}(k) \equiv P_{hh}(k) - \frac{P_{hm}(k)^2}{P_{mm}(k)} \xrightarrow{k\to 0} \frac{1}{\bar{n}}$$

Environment selection introduces large exclusion effects.

We find evidence for non-Poissonian shotnoise.

Larger for the near field.

More noise at larger environmental scale.