Large Scale Structure ~~Theory~~ Phenomenology

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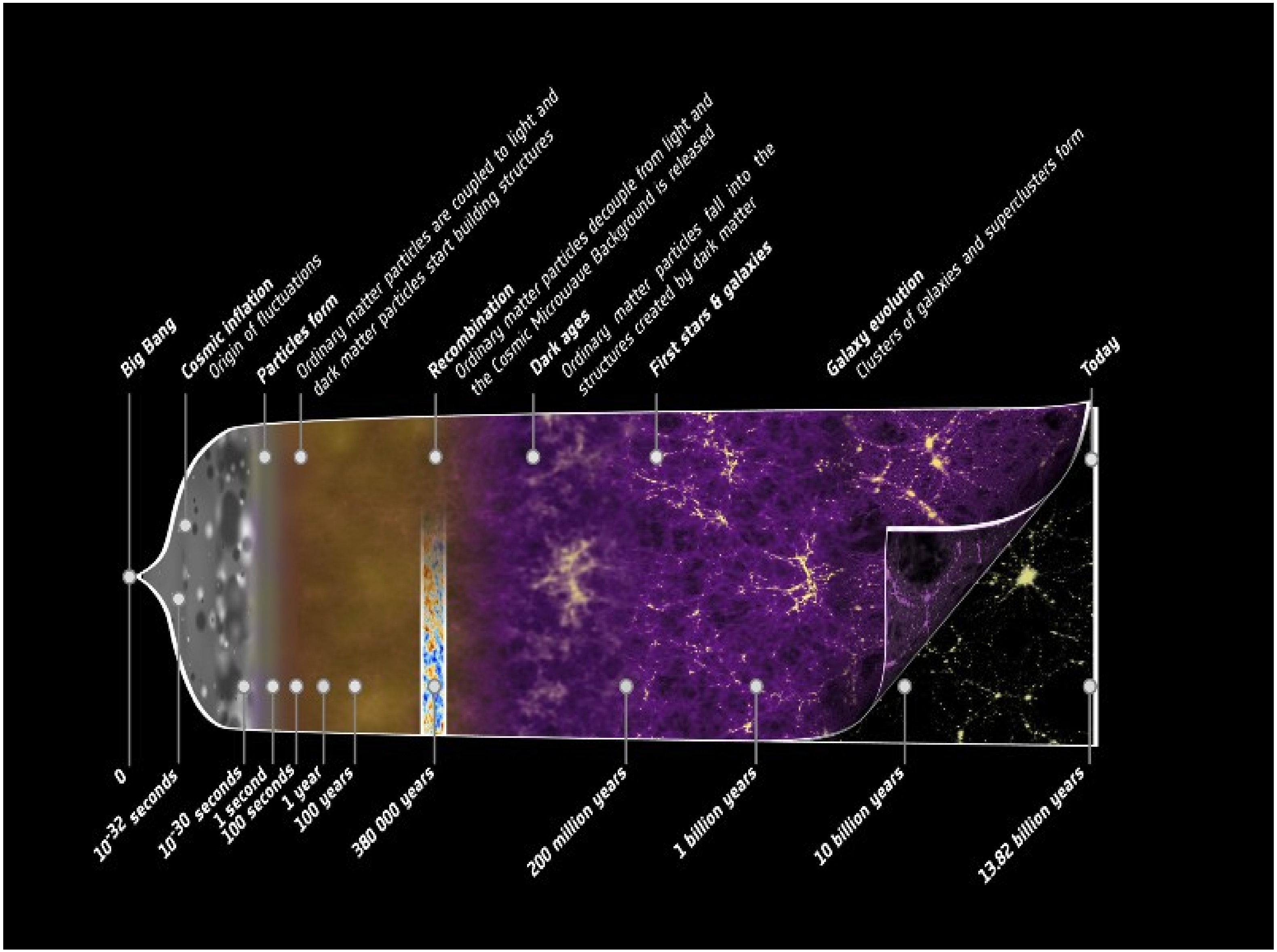
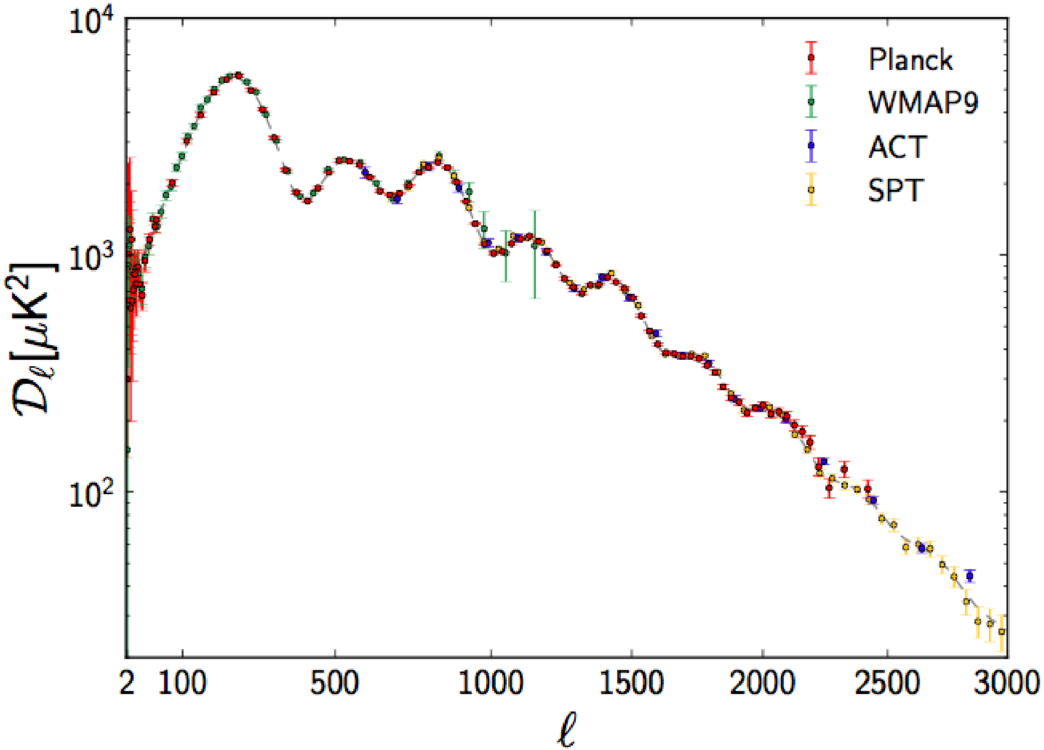
COSMO19, 09/06/2019

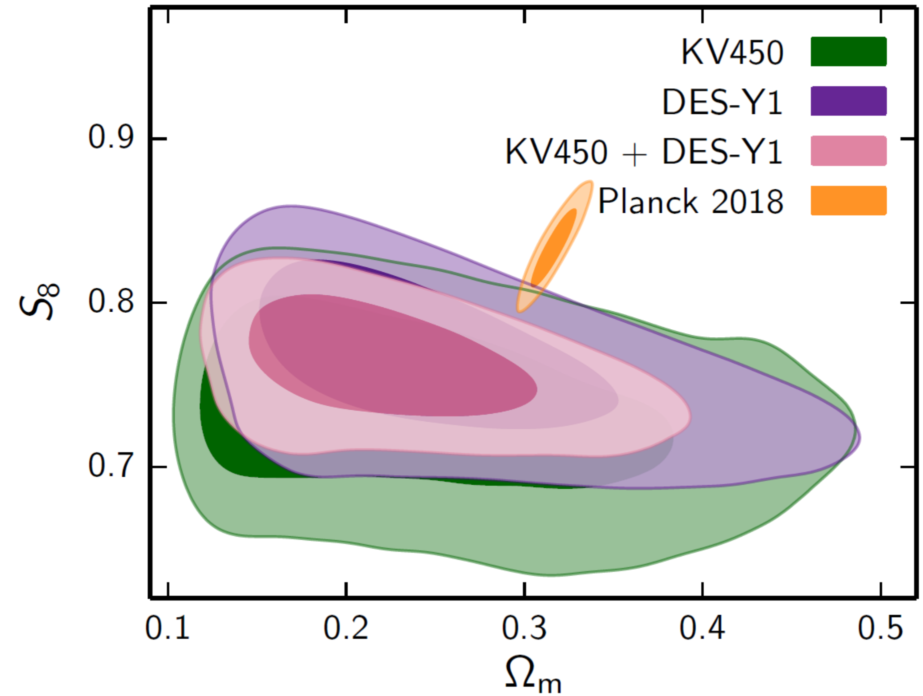
The long story short

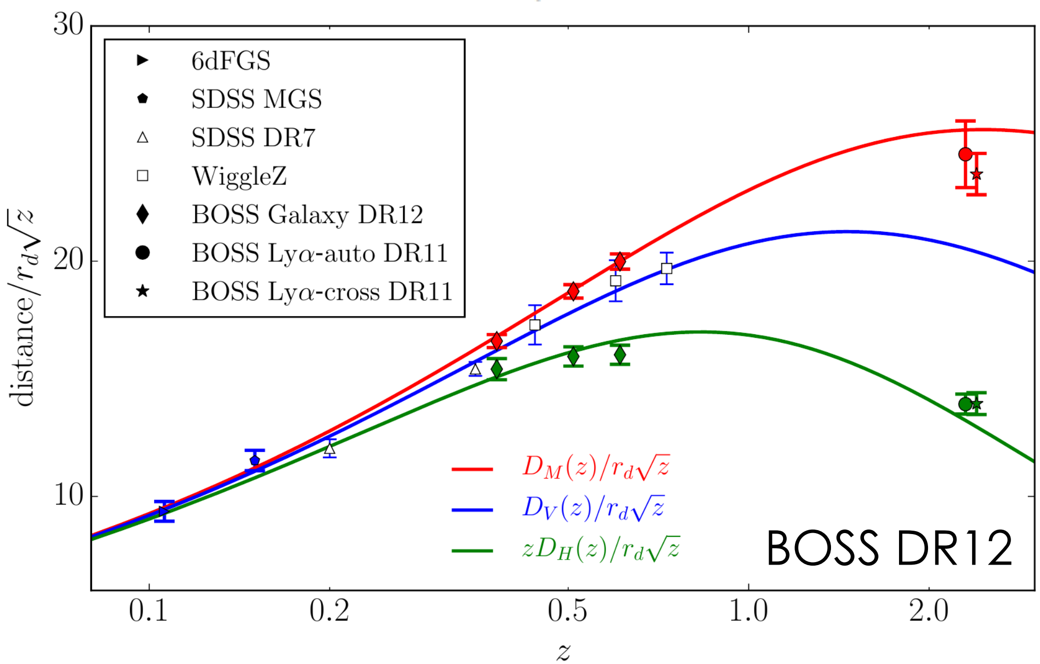


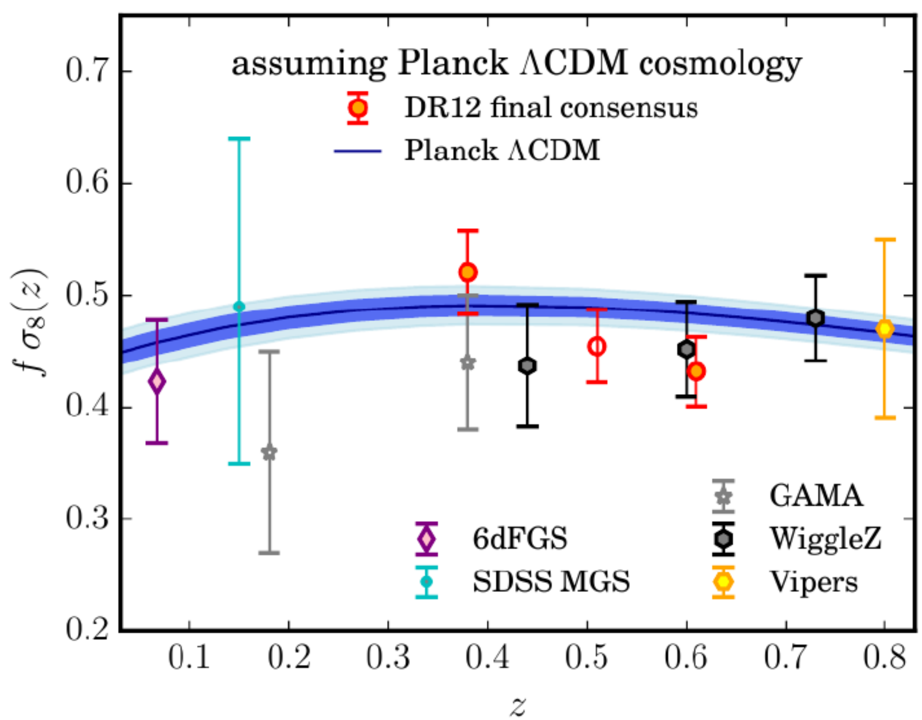
Credit:Nasa

Observational status

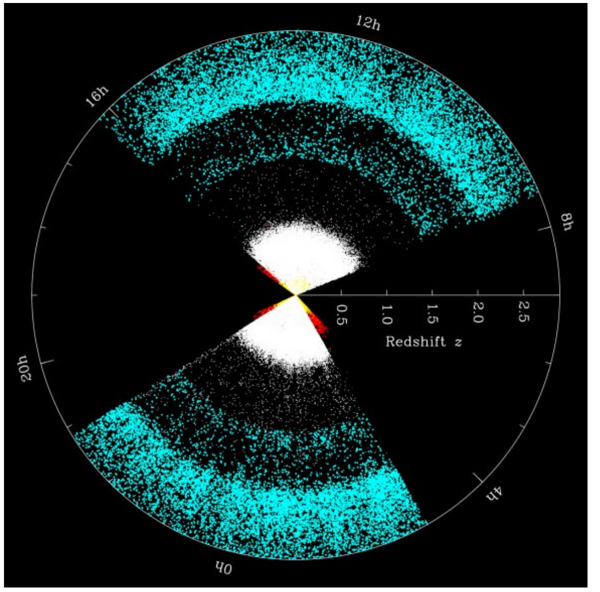








Why am I giving this talk?



LSS could be solved for exactly: Standard Model + GR

Non linearities and hierarchy of scales make exact solutions impossible:

Analytic approaches are almost the only game in town to extract cosmological parameters (% level or better accuracy)

Two main consequences:

1) Predictions are valid up to a certain scale and involve free parameters

- Understand the theory independently of improvements

2) Information not limited to 2-point statistics

- Crazy ideas are welcome!

Perturbation theory and its limits

$$\delta(\mathbf{k}) = \delta_1(\mathbf{k}) + \delta_2(\mathbf{k}) + \mathcal{O}(\delta_1^3)$$
$$= \delta_1(\mathbf{k}) + \int \mathrm{d}^3 q\, F_2(\mathbf{q}, \mathbf{k}-\mathbf{q})\delta_1(\mathbf{q})\delta_1(\mathbf{k}-\mathbf{q}) + \mathcal{O}(\delta_1^3)$$

$$\delta(\mathbf{x}) = \delta_1(\mathbf{x}) + \frac{17}{21}\delta_1^2(\mathbf{x}) - \nabla\delta_1(\mathbf{x})\Psi(\mathbf{x}) + \frac{2}{7}s_{ij}(\mathbf{x})s^{ij}(\mathbf{x}) + \mathcal{O}(\delta_1^3)$$

Cannot integrate over loop momenta to arbitrarily small scales.
Even if it converges, it converges to the wrong result.

EFT as a framework to parametrize small scale uncertainties.

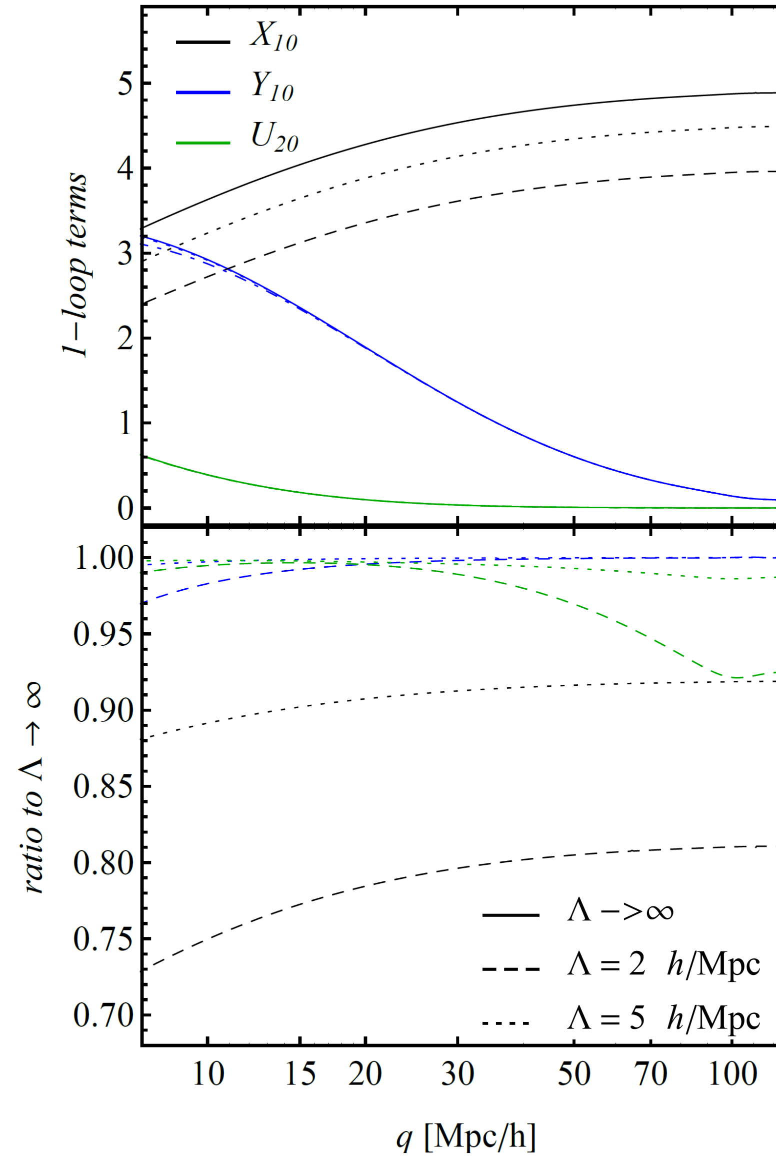
- Eulerian EFT Senatore Zaldarriaga, Baldauf, Carrasco, Foreman, Simonovic...
- Lagrangian EFT (LEFT) White, Vlah, Schmittfull, Porto, Senatore, Zaldarriaga...
- TSPT, Blas, Sibiryakov, Garny, Ivanov...
- GRPT Scoccimarro, Crocce
- Coarse-Grained PT, Pietroni, Peloso

UV Sensitivity

1loop correlation function of the relative displacement between two particles

$$\mathbf{\Psi}(\mathbf{q},t) = \mathbf{\Psi}^{(1)}(\mathbf{q},t) + \mathbf{\Psi}^{(2)}(\mathbf{q},t) + \mathbf{\Psi}^{(3)}(\mathbf{q},t)$$

$$1 \text{ loop} \sim \int^{\Lambda} \mathrm{d}^3 q W(\mathbf{q}, \mathbf{k}-\mathbf{q}) P(q) P(|k-q|)$$



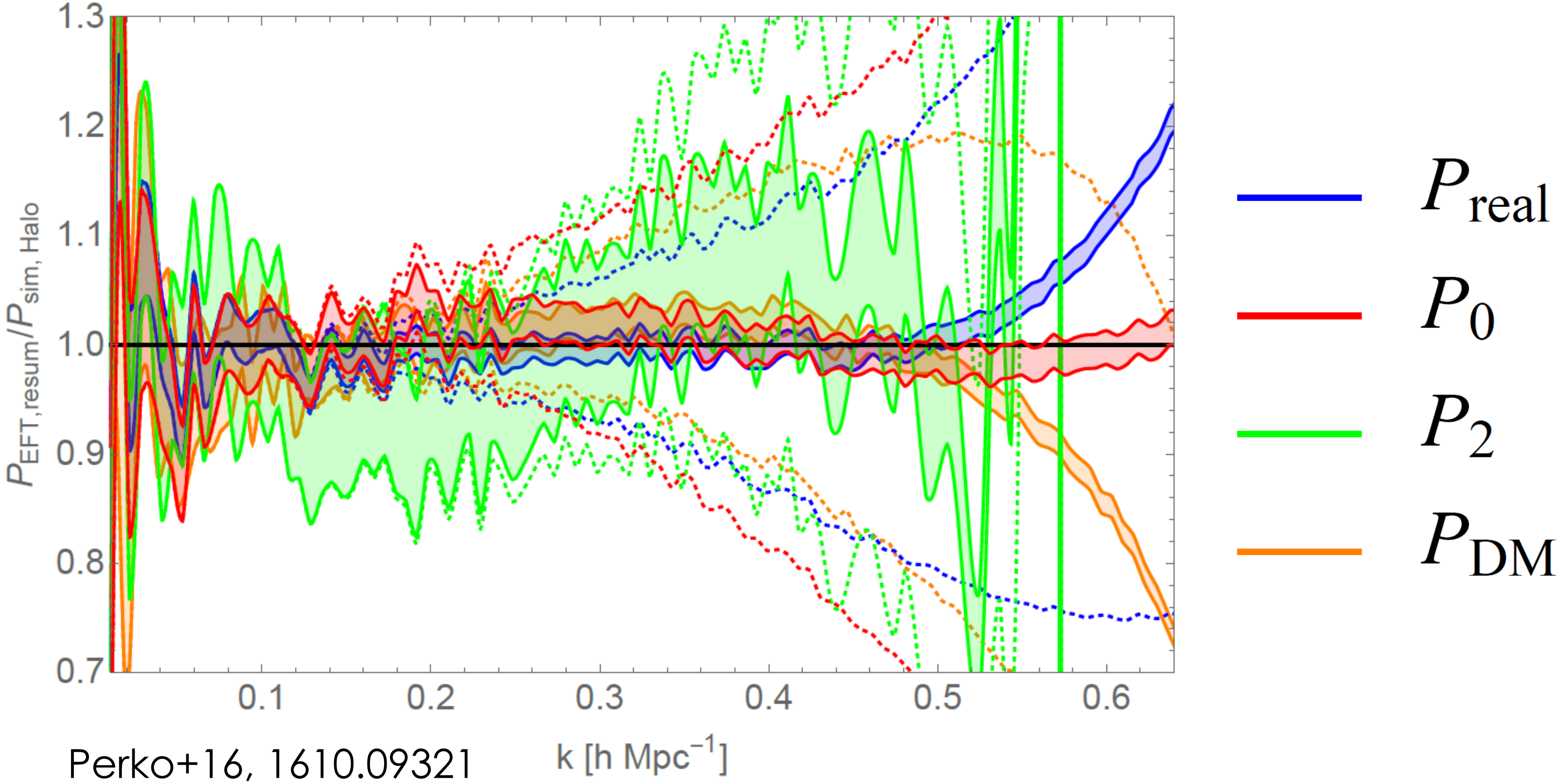
- Unphysical sensitivity of the result to small scales
- Free parameters are unavoidable

Galaxy bias is a similar problem

$$\delta_g(\mathbf{x}) = b_1(z)\delta(\mathbf{x}) + b_2(z)\delta^2(\mathbf{x}) + b_{s^2}(z)s^2(\mathbf{x})$$

Perturbation theory and its limits

$$P(k) = P_1(k) + P^{1-\text{loop}}(k) + c_s^2(z)\frac{k^2}{k_{NL}}P_1(k)$$



Perko+16, 1610.09321

Perturbation theory and its limits

Lots of insights over last 5+ years

✓ General galilean invariance (EP) of EOMs and consistency relations

✓ Resummation of long (IR) modes

✓ Extensions to neutrinos and MG (specific models)

✓ Better connection to what is actually measured (LC effects etc...)

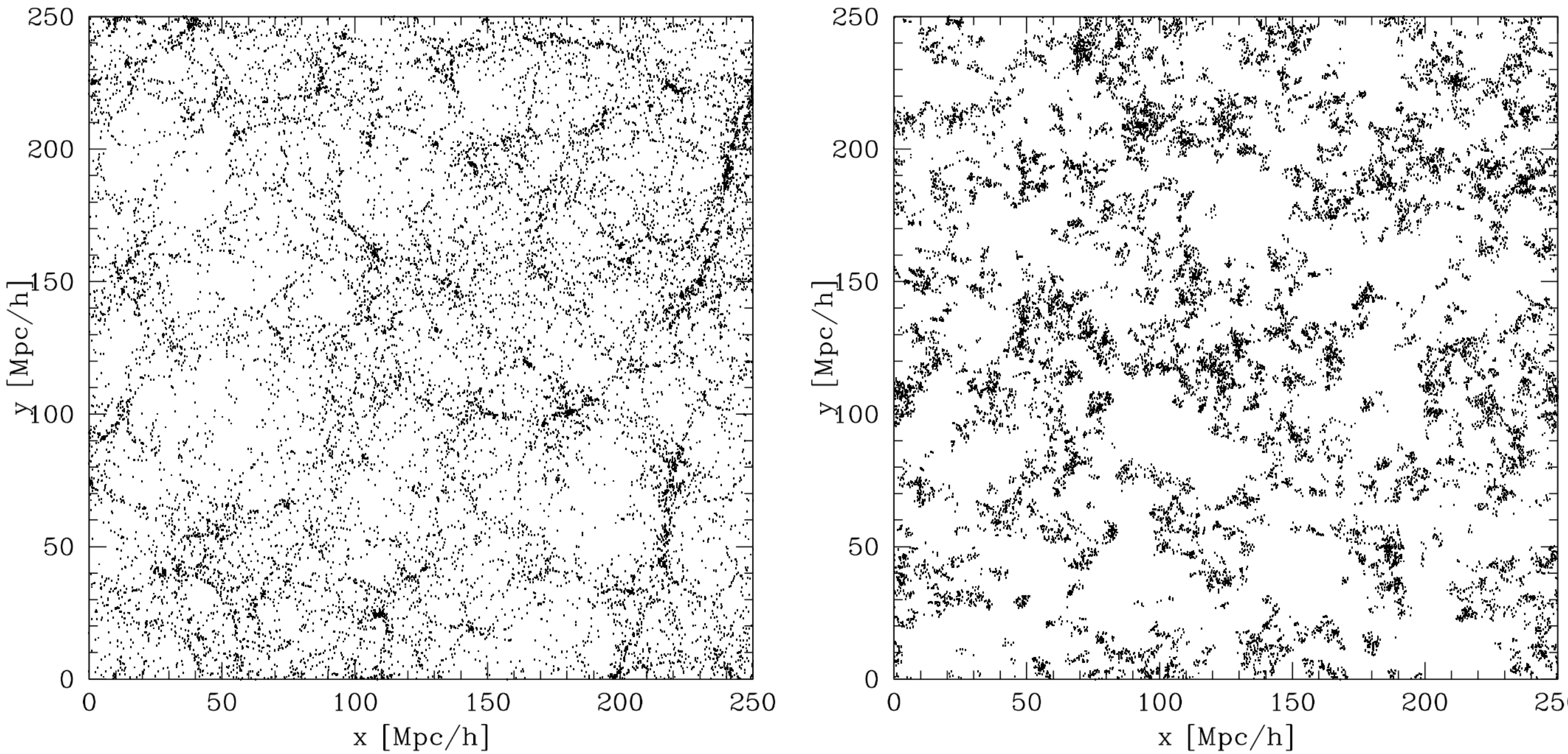
Incomplete wish list :

- 2loop P(k) and 1loop Bispectrum in redshift space

    - What exactly is the theory error?

- Why limiting to the signal? The Covariance is in principle calculable.
- Physical models for free parameters? Priors?
- Extensions to PNG, better understanding in EFTofDE
- More talking to observers!

Beyond P(k)



LSS and Levy flight could have the same P(k)

Crucial to go beyond P(k), be creative!

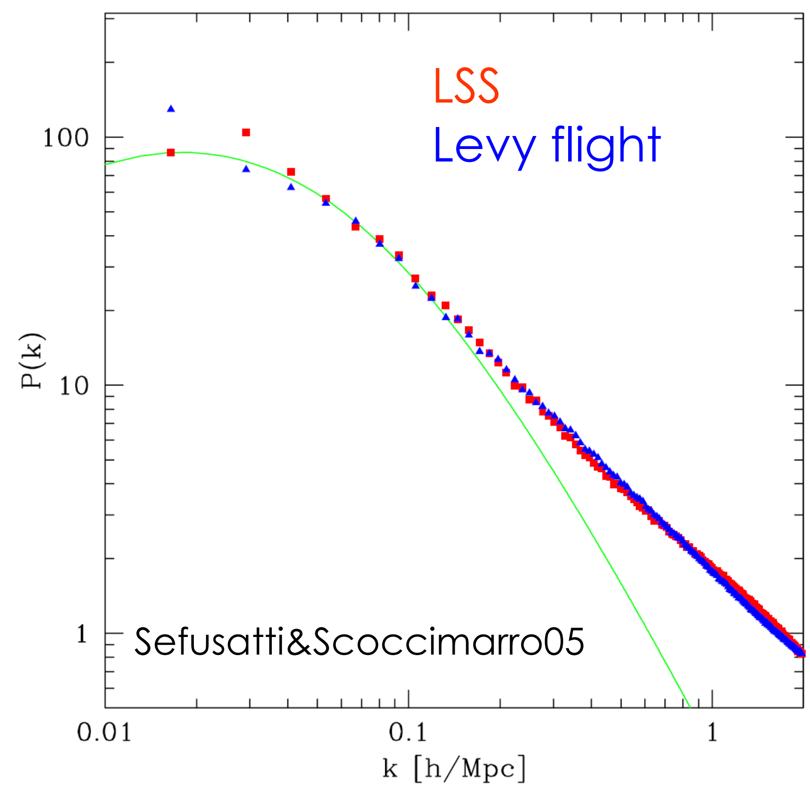
- Bispectrum and Trispectrum

    Up to 5x better constraints on neutrino masses

- Non linear transformations, peaks, voids, etc.

- Cosmology at the field level?

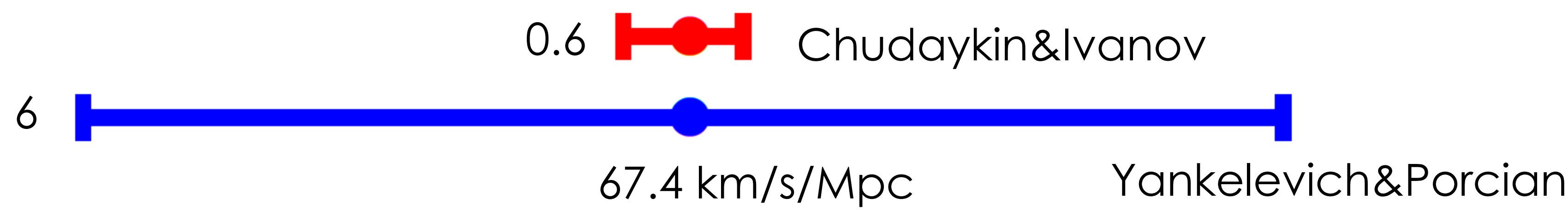
Same PT arguments apply here!

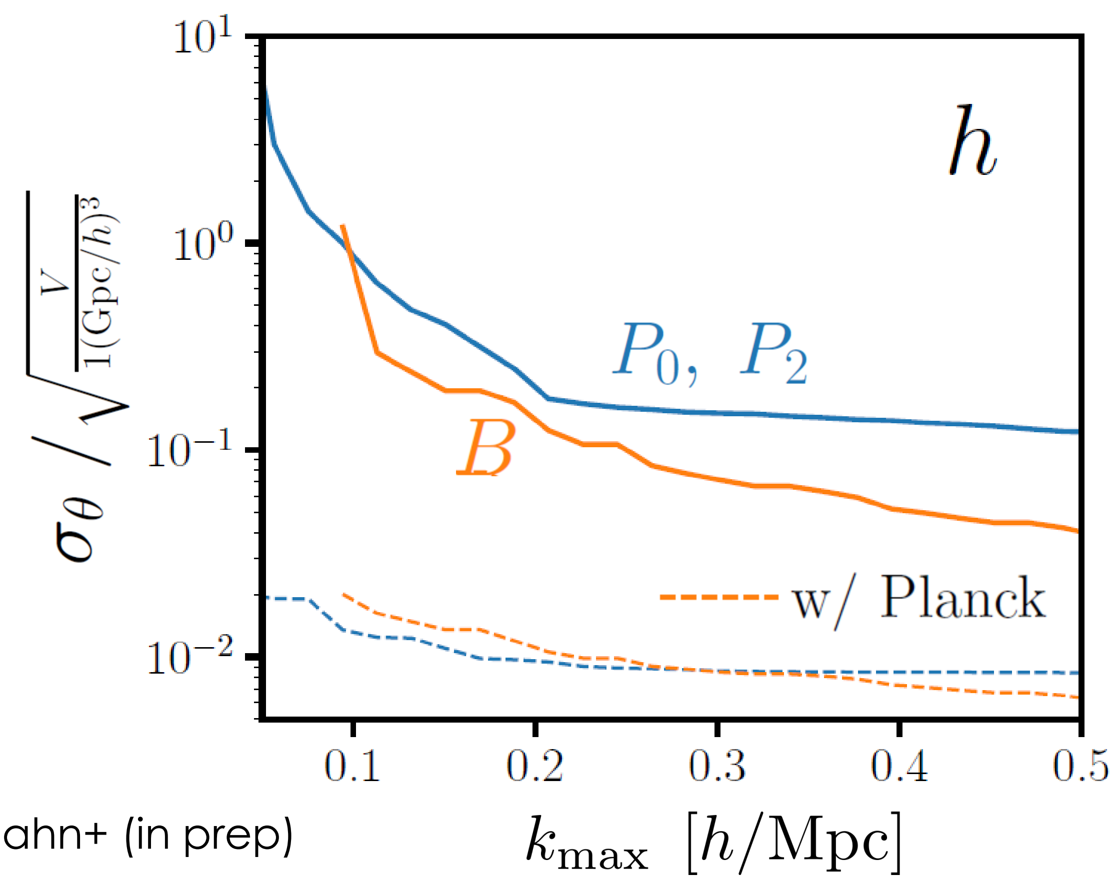


Mandatory slide, circa 2019: The Hubble (insert dramatic word)

Could LSS provide an independent low-z measurement of H0 (no need for r_s) ?

Using the Euclid Bispectrum





Gedanken experiment :

Raw information content in simulations

If achieved, crucial for solving H0 tension!

Hahn+ (in prep)

Outline

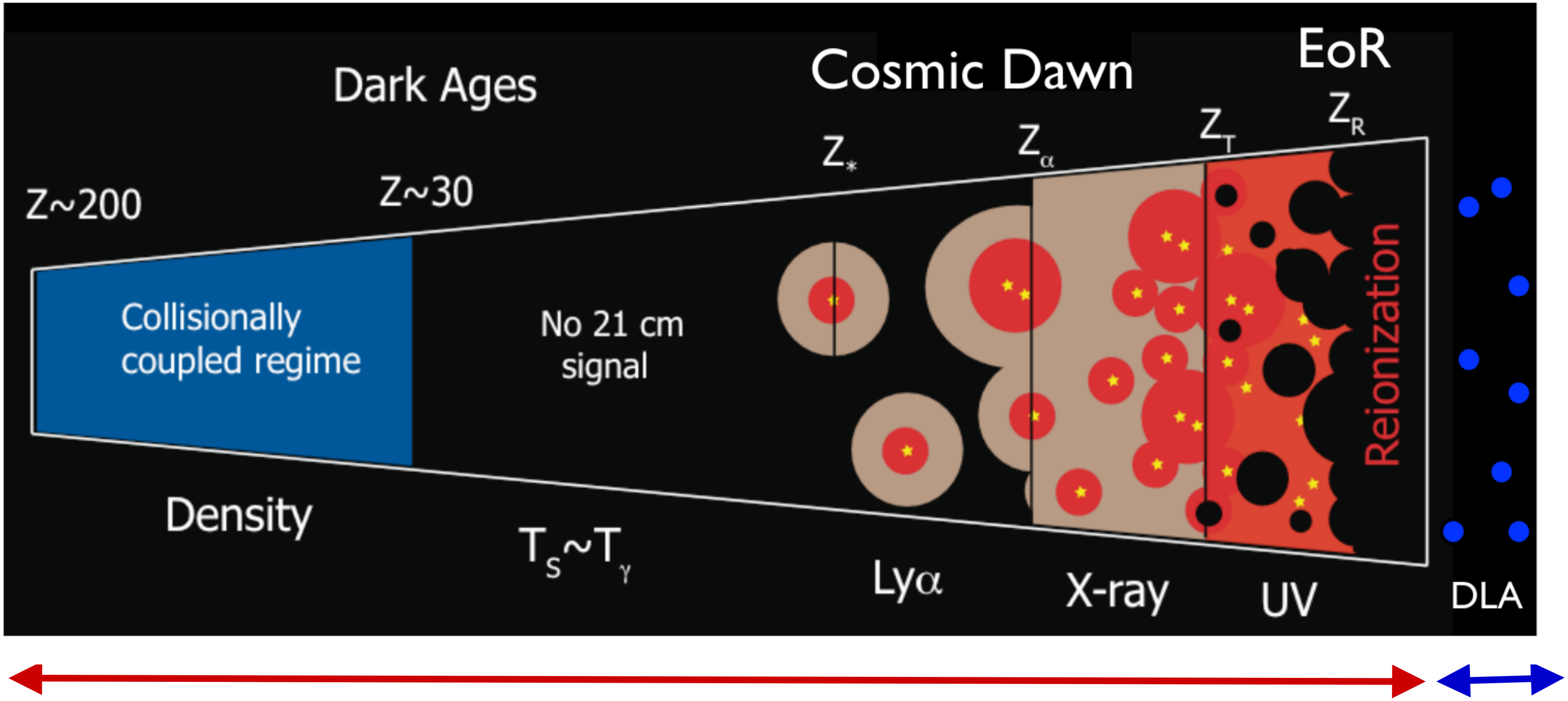
A few selected things that LSS theory can do for :

1) 21 cm

2) Weak Lensing

3) Galaxy surveys

The new kid on the block : 21 cm



Signal from Dark Ages, Cosmic Dawn and EoR are very intersting, Cosmology is degenarate with complicated astrophysics. Edges,LOFAR,HERA,SKA.

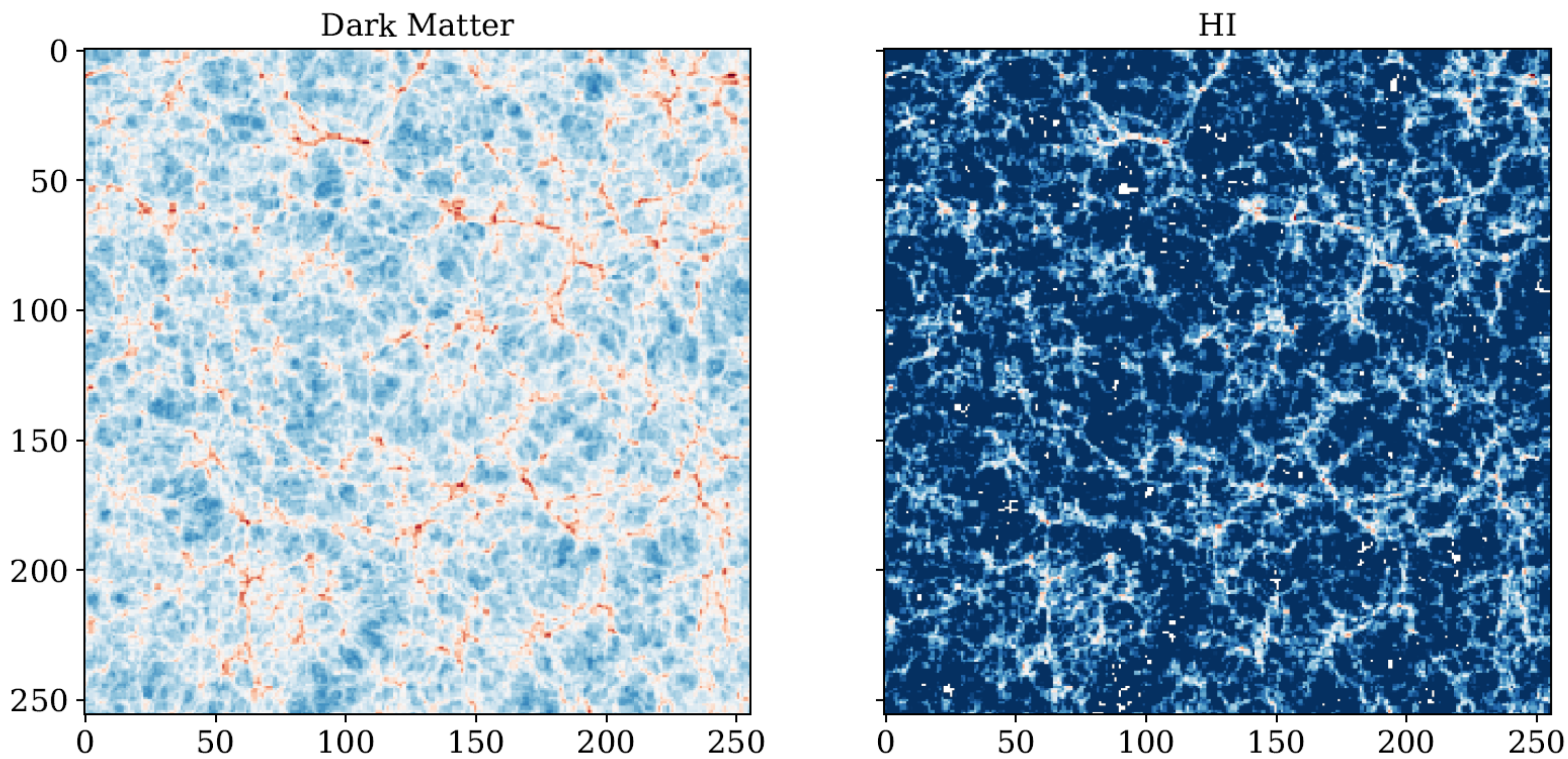
After EoR, the remaining fraction of neutral hydrogen lives in high density regions, Damped Lyman alpha systems (DLAs). It is shielded from ionizing photons. 21cm in GBT, CHIME, HIRAX, Tianlai, SKA

No photons left behind

Give up on observing individual galaxies.

Accurate redshifts: frequency resolution of the receivers.

Much like the CMB, but in 3D. Many more modes !



$$P_{21}(k,\mu;z) = \bar{T}_b^2(z)\left(P_{HI}(k,\mu;z) + \frac{1}{n_{eff}}\right) = \bar{T}_b^2(z)\left[(b_{HI} + f\mu^2)^2 P_m(k,z) + \frac{1}{n_{eff}}\right]$$

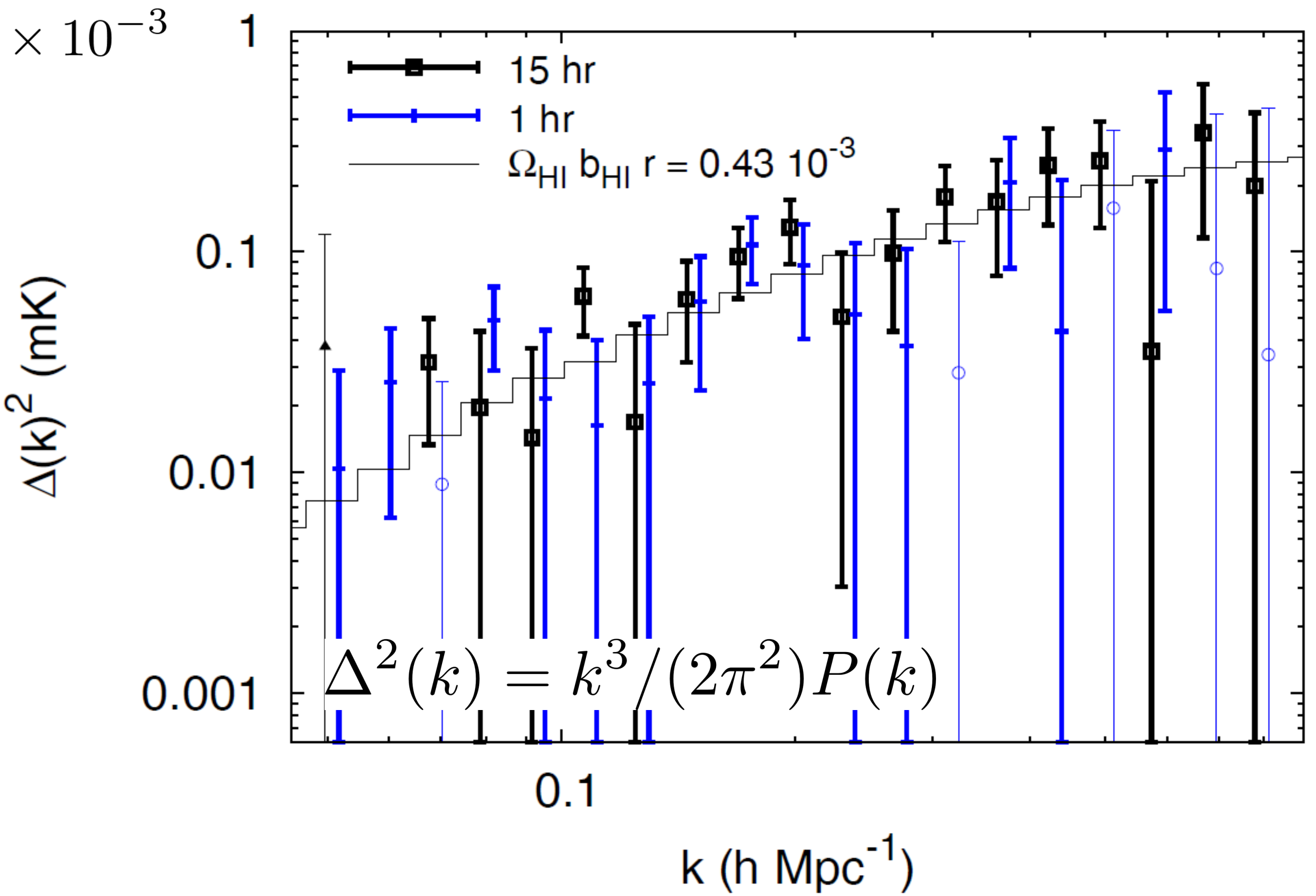
Observational status

We have several detections of 21cm P(k) at low-z in cross-correlation with galaxy surveys.

Chang08, Masui+13,Switzer+13

No detection of the 21cm P(k)

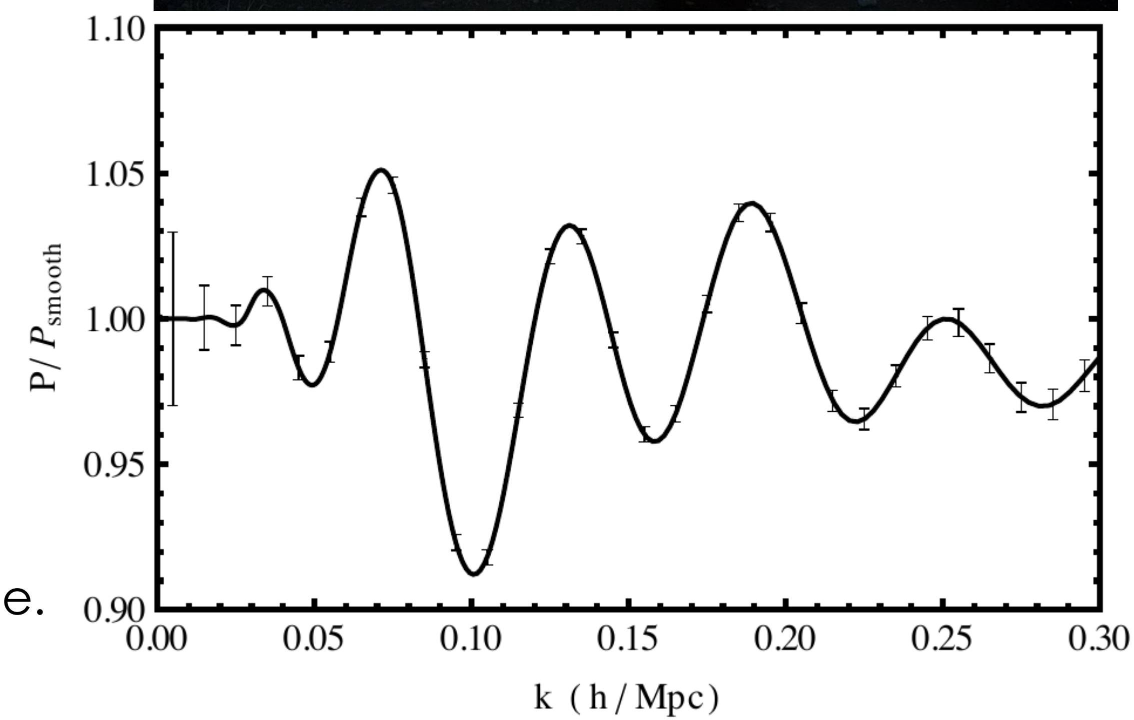
$$\Omega_{HI} b_{HI} = [0.62^{+0.23}_{-0.15}] \times 10^{-3}$$



Observational status

- GBT, 100 m single dish
- CHIME – Canadian experiment, taking data
  will detect BAO z=0.75-2
- HIRAX – South African experiment,
  1/2 funded and being prototyped
- FIRST: 500m single dish in China
- BINGO, proposed UK experiment
- Tianlai in China
- SKA and pathfinders

In the next 5 years,
demonstrate the promise of the technique.



Modeling the signal

What we measure is

$$P_{21}(k,\mu) = \bar{T}_b^2[P_{\rm HI}(k,\mu) + P_{\rm sn}] + P_{\rm th}$$

In the linear regime it's impossible to constrain the amplitude of the power spectrum

$$P_{21}(k,\mu) = \bar{T}_b^2[(b_{\rm HI}\sigma_8 + f\sigma_8\mu^2)^2 P_m(k)/\sigma^2_{8,\,\rm fid} + P_{\rm sn}] + P_{\rm th}$$

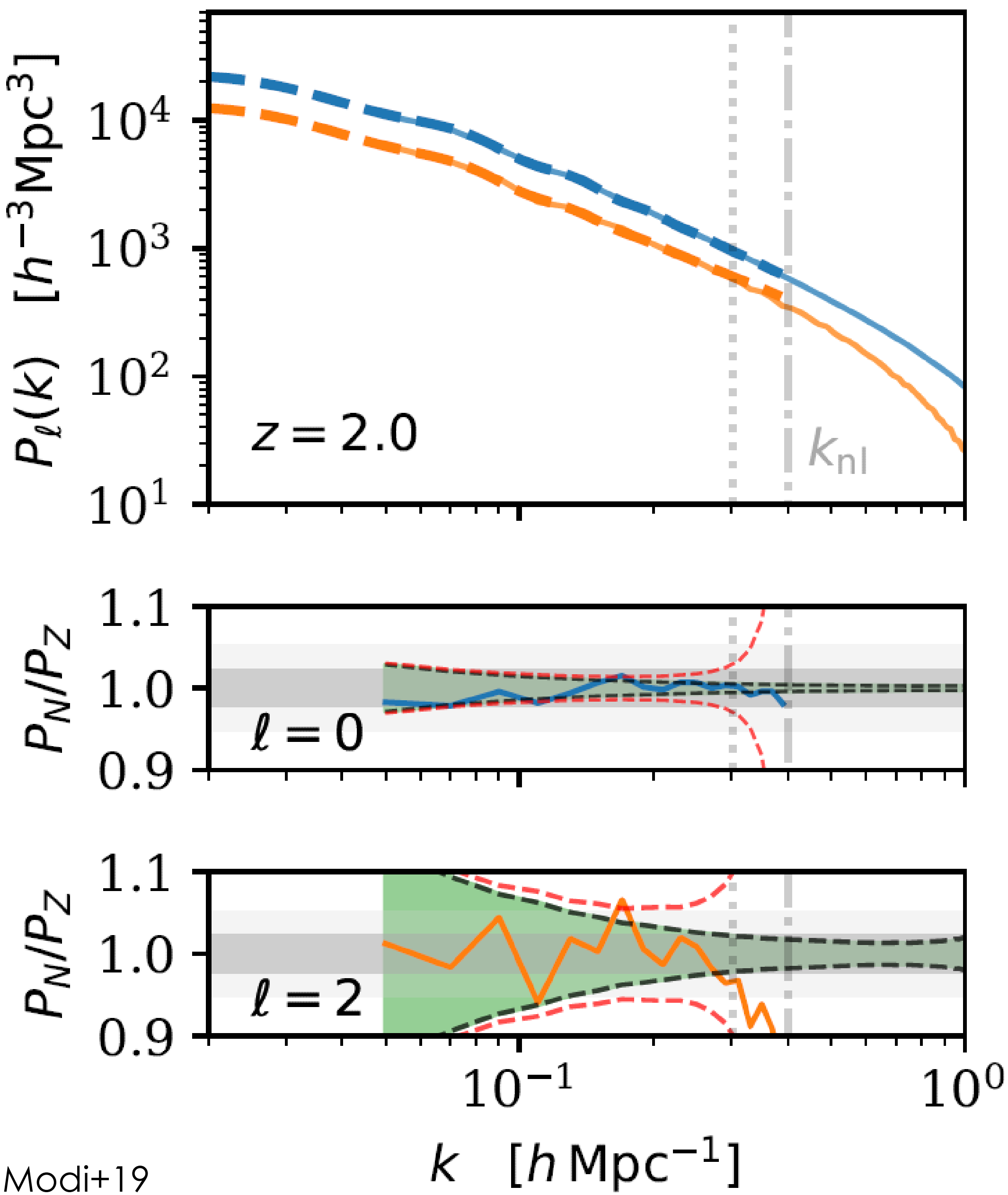
Three possible ways out :

- External prior on brightness temperature. Hard to get better than 5 % (Obuljen+17)
- Cross correlations with QSOs, LBGs, etc. (Chen+18)
- Use information in the mildly non linear regime.

Modeling the signal

$$P_{21}(k,\mu) = \bar{T}_b^2 P_{\rm HI}(k,\mu) = \bar{T}_b^2[\mathcal{O}(P_L(k)) + \mathcal{O}(P_L(k)^2) + ...]$$

$f\sigma_8,\ (f\sigma_8)^2$ $\qquad$ $(f\sigma_8)^{2-4}$

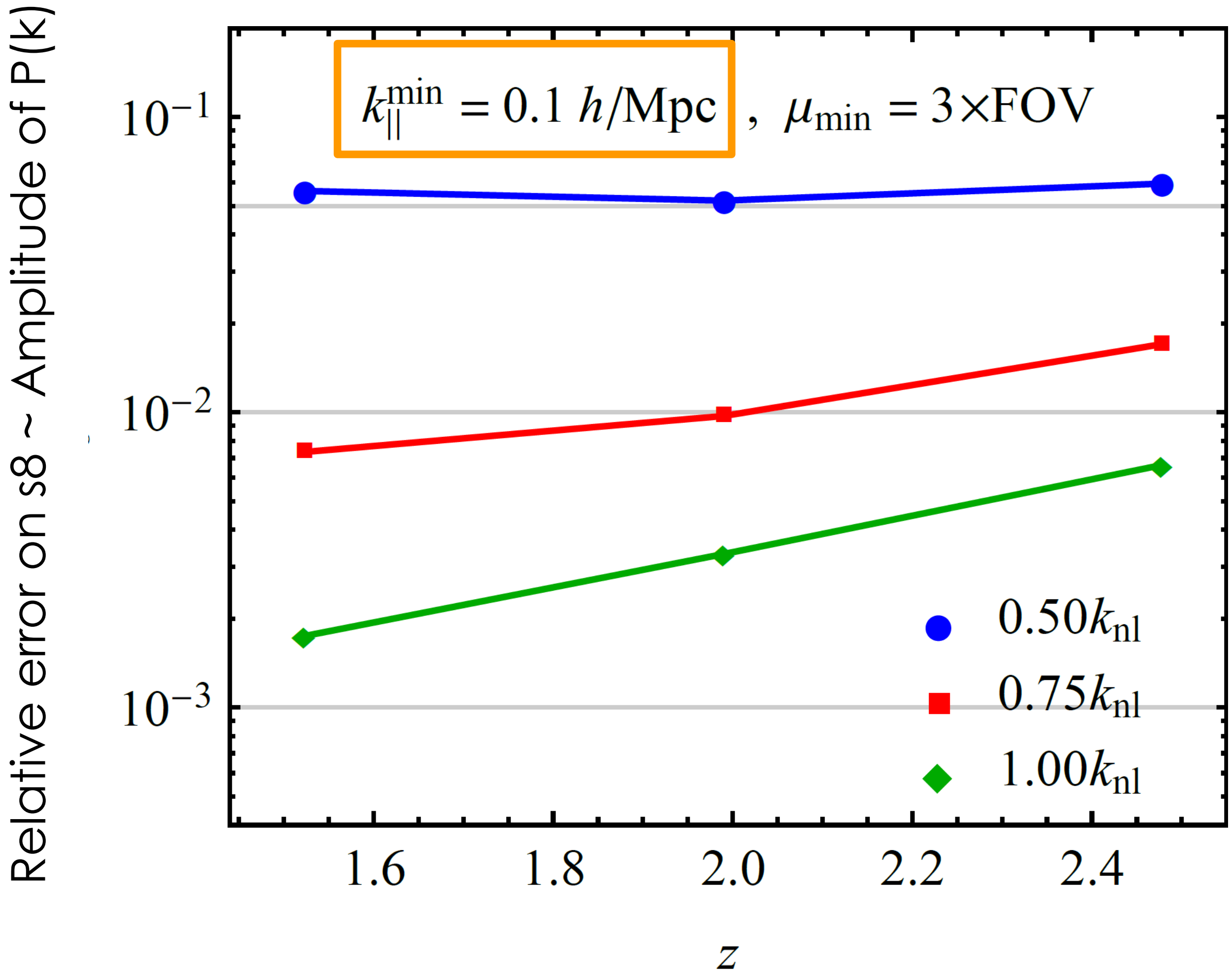


Modi+19

It turns out HI is the ideal tracer for PT: high-z, low mass halos, small satellite fraction

Quite a good fit to the simulations!

HIRAX performance

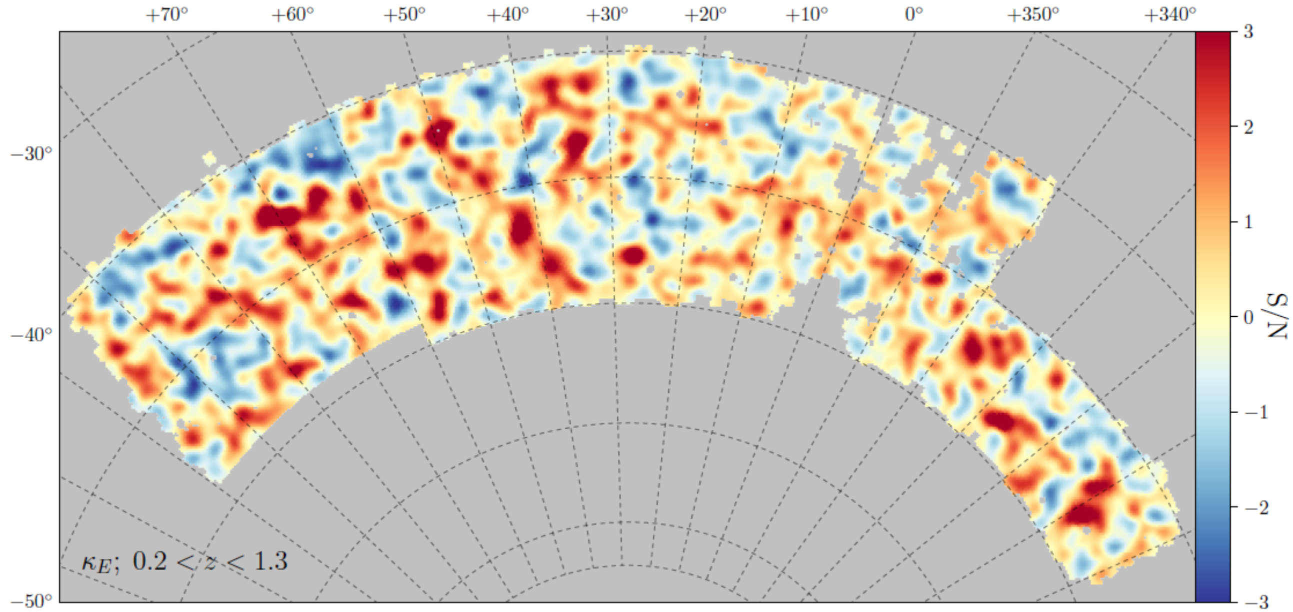


% measurement of growth of structure could be possible with 21cm.
Marginalized over bias parameters.

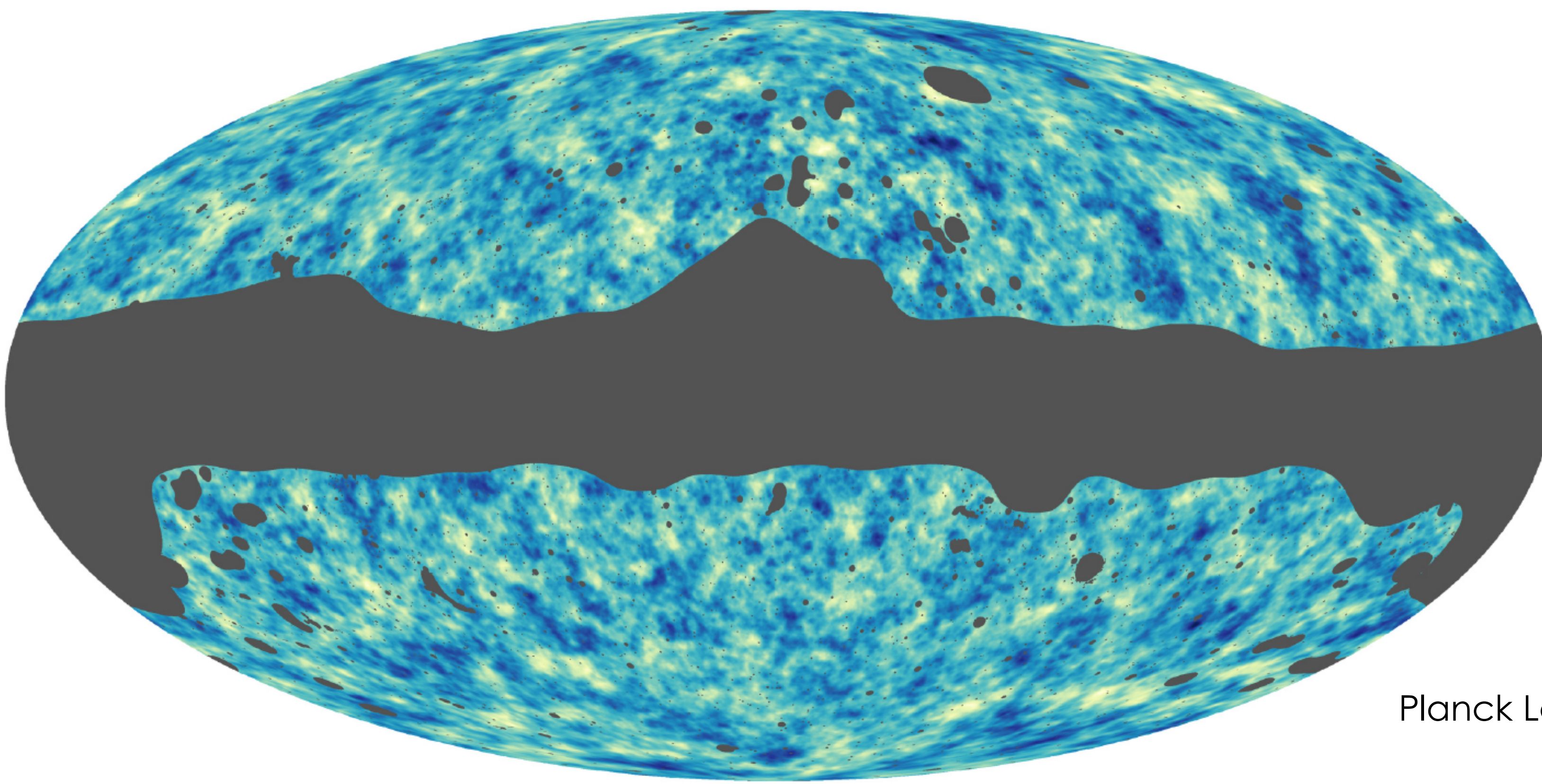
Hard with galaxy surveys at z>1.5.

Foregrounds can be overcome if we have a long enough lever arm.

Weak Lensing

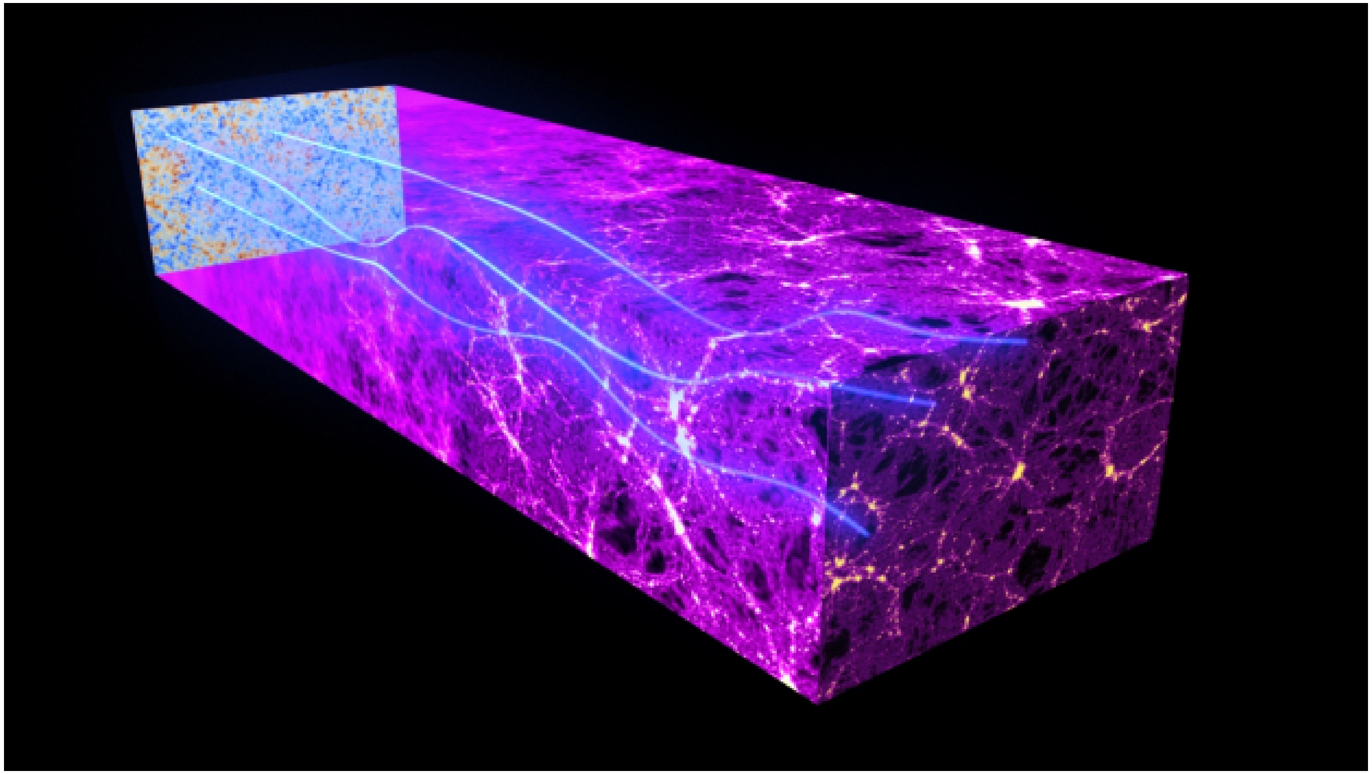


Chang+18

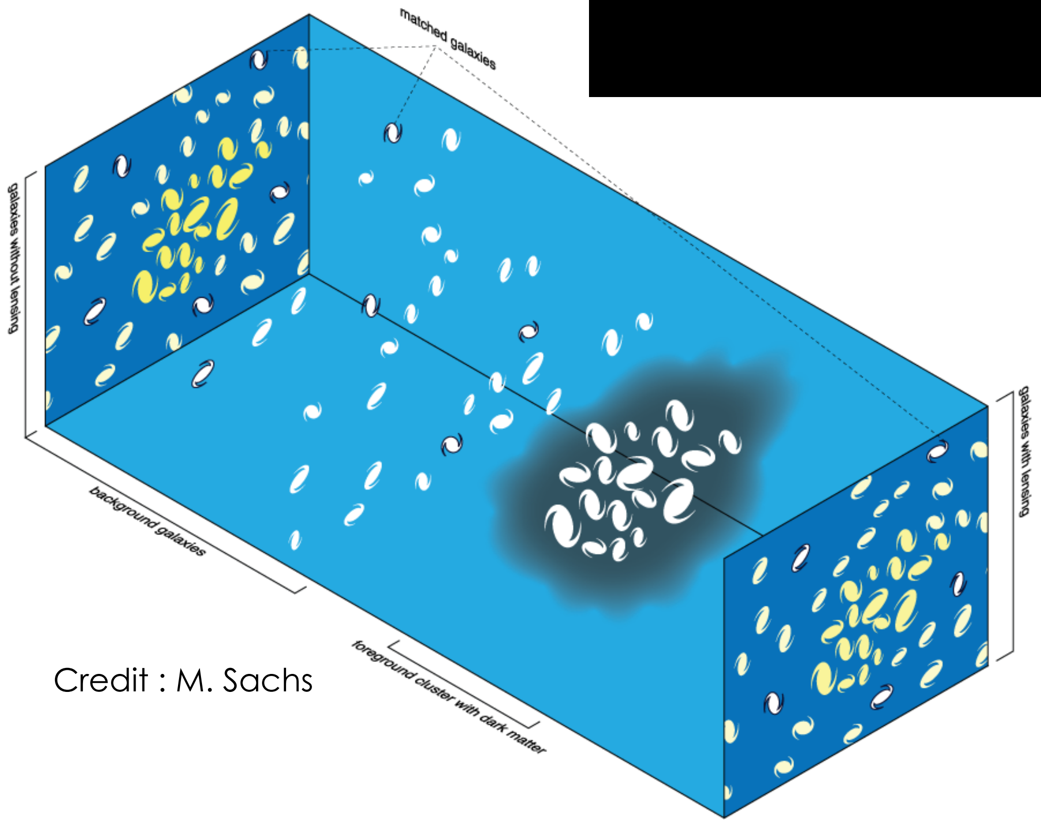


Planck Lensing

Weak Lensing

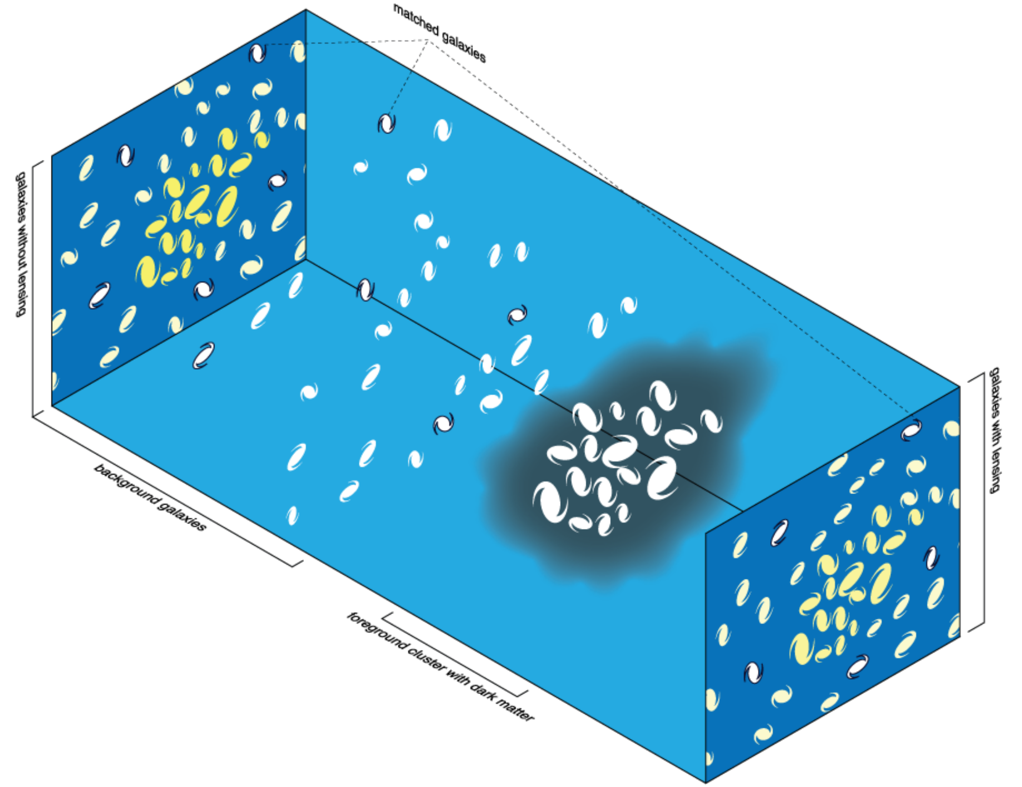


Credit : ESA

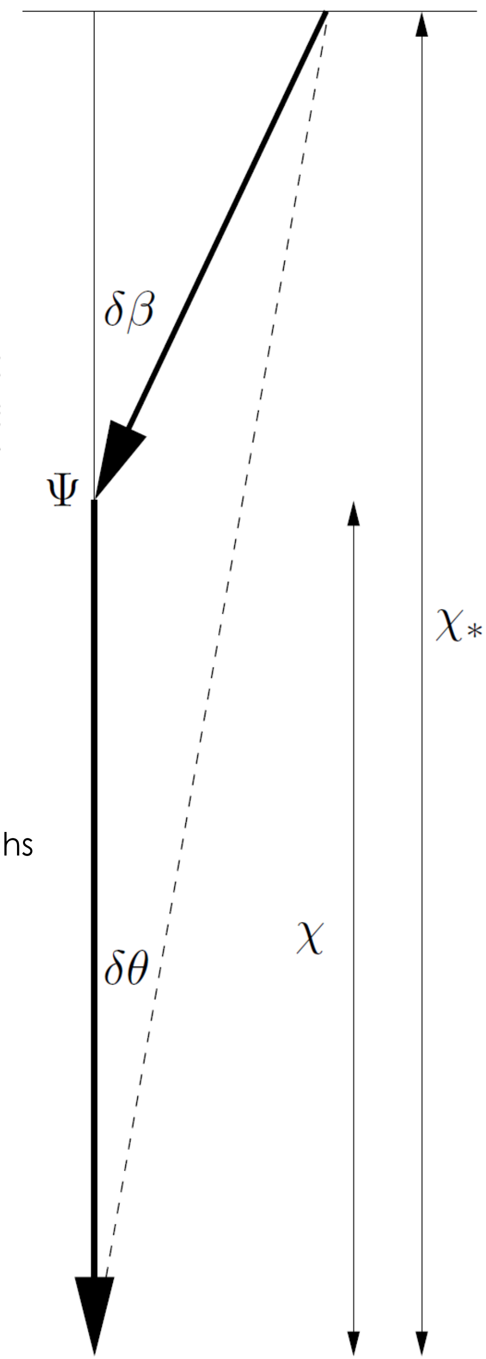


Credit : M. Sachs

Weak Lensing



Credit : M. Sachs



Credit : Lewis&Challinor06

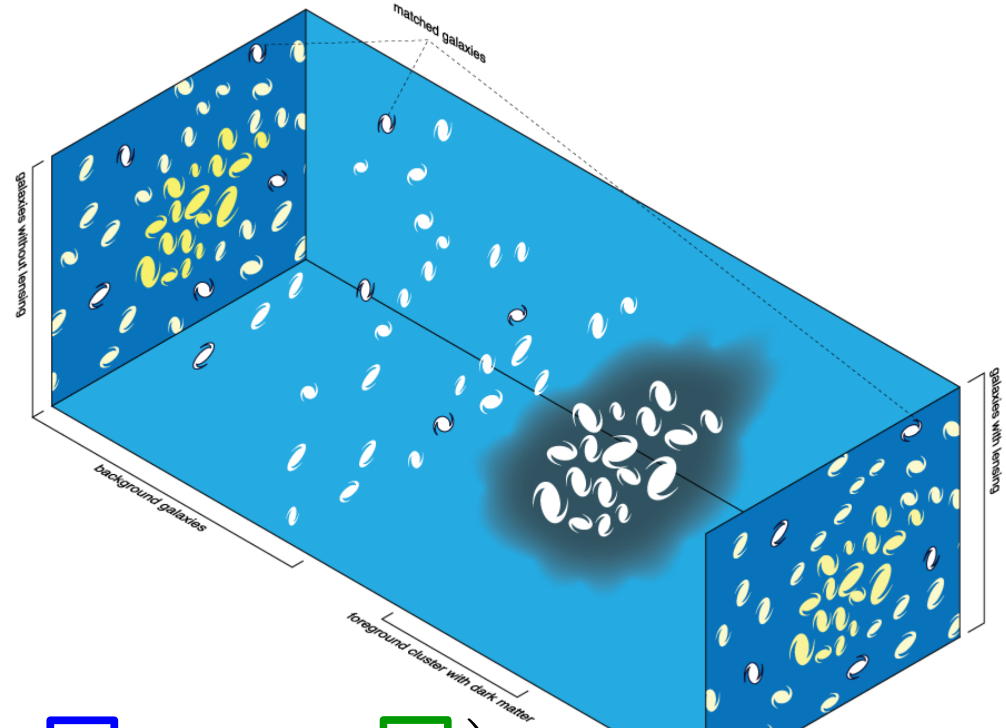
Lensing changes shape and positions

$$\mathbf{x}(\boldsymbol{\theta}, \chi_*) = \chi_* \boldsymbol{\theta} - 2 \int_0^{\chi_*} \mathrm{d}\chi' \, (\chi_* - \chi') \, \nabla_{\mathbf{x}} \Psi \left[\mathbf{x}(\boldsymbol{\theta}, \chi'), \chi'\right]$$

Born approximation

$$\mathbf{x}(\boldsymbol{\theta}, \chi_*) = \chi_* \boldsymbol{\theta} - 2 \int_0^{\chi_*} \mathrm{d}\chi' \, (\chi_* - \chi') \, \nabla_{\mathbf{x}} \Psi \left[\boldsymbol{\theta}, \chi'\right]$$

Weak Lensing



Credit : M. Sachs

κ convergence

$\gamma_{1,2}$ distortions

ω rotation

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \begin{pmatrix} 1 - \boxed{\kappa} - \boxed{\gamma_1} & -\gamma_2 - \boxed{\omega} \\ -\gamma_2 + \omega & 1 - \kappa + \gamma_1 \end{pmatrix}$$

Lensing changes shape and positions

$$\mathbf{x}(\boldsymbol{\theta}, \chi_*) = \chi_* \boldsymbol{\theta} - 2 \int_0^{\chi_*} \mathrm{d}\chi' \, (\chi_* - \chi') \, \nabla_{\mathbf{x}} \Psi \left[\mathbf{x}(\boldsymbol{\theta}, \chi'), \chi' \right]$$

Born approximation

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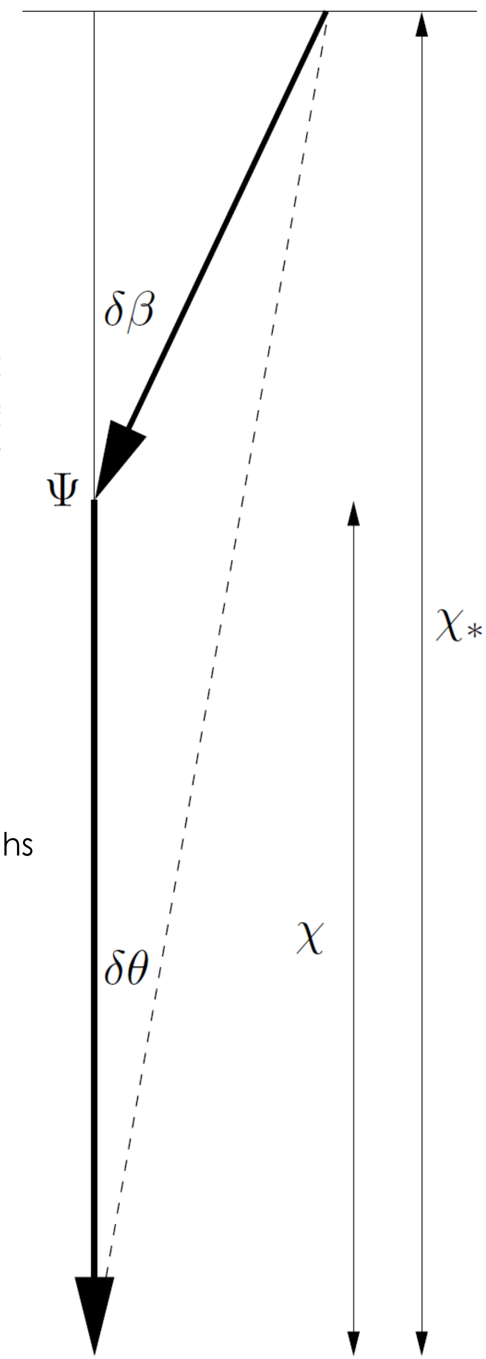
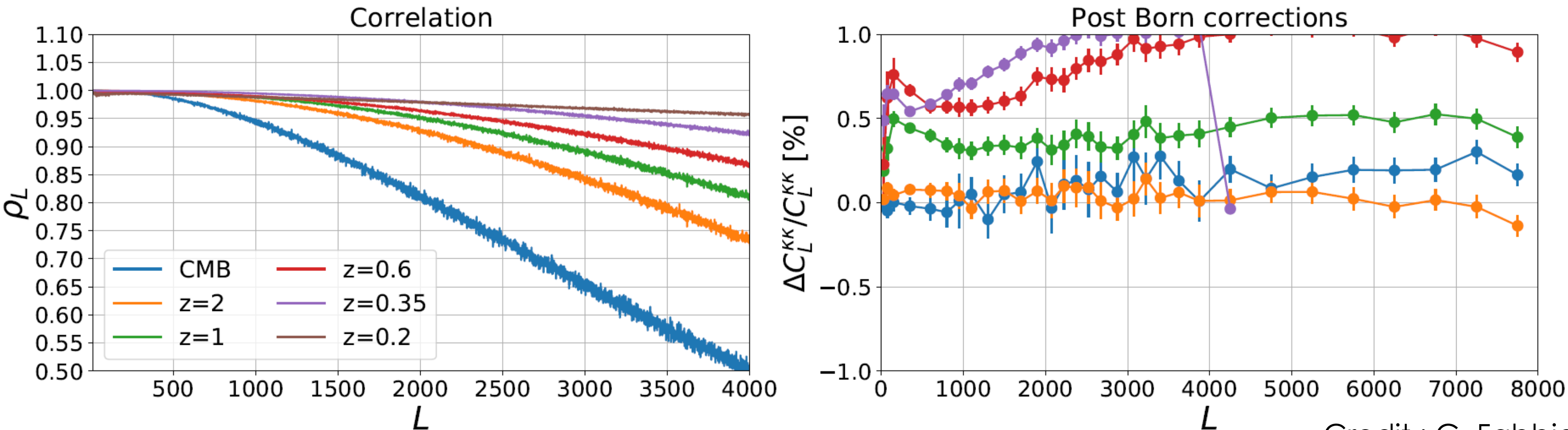


Credit : Lewis&Challinor06

Weak Lensing

How good is the Born approximation ?
Much better for the power spectrum than for the map itself



Credit : G. Fabbian

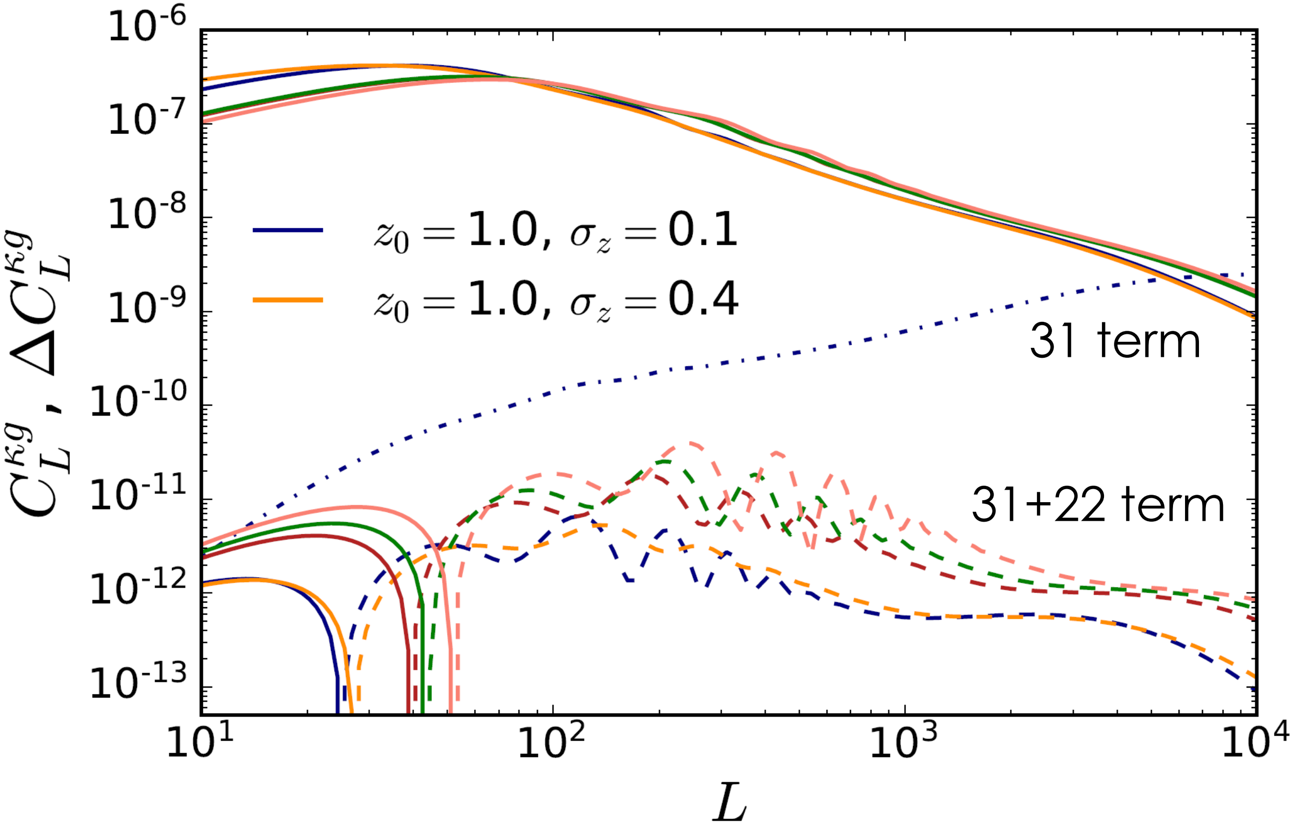
$$\kappa(\mathbf{L}) = \underbrace{\kappa^{(1)}(\mathbf{L})}_{\text{Born}} + \underbrace{\kappa^{(2)}(\mathbf{L})}_{\mathcal{O}(d^2)} + \underbrace{\kappa^{(3)}(\mathbf{L})}_{\mathcal{O}(d^3)} + \mathcal{O}\left(d^4\right)$$

$$\langle \kappa(\mathbf{L})\,\kappa(\mathbf{L}')\rangle = \underbrace{\langle \kappa^{(1)}(\mathbf{L})\kappa^{(1)}(\mathbf{L}')\rangle}_{\text{Born}} + \underbrace{\langle \kappa^{(2)}(\mathbf{L})\kappa^{(1)}(\mathbf{L}')\rangle}_{=0\ \text{(Limber/Gaussian)}} + \underbrace{\langle \kappa^{(1)}(\mathbf{L})\kappa^{(2)}(\mathbf{L}')\rangle}_{=0\ \text{(Limber/Gaussian)}}$$
$$+ \underbrace{\langle \kappa^{(1)}(\mathbf{L})\kappa^{(3)}(\mathbf{L}')\rangle + \langle \kappa^{(3)}(\mathbf{L})\kappa^{(1)}(\mathbf{L}')\rangle + \langle \kappa^{(2)}(\mathbf{L})\kappa^{(2)}(\mathbf{L}')\rangle}_{\approx 0} + \mathcal{O}\left(d^5\right)$$

Cooray&Hu01, Krause&Hirata09, Pratten&Lewis16

Weak Lensing

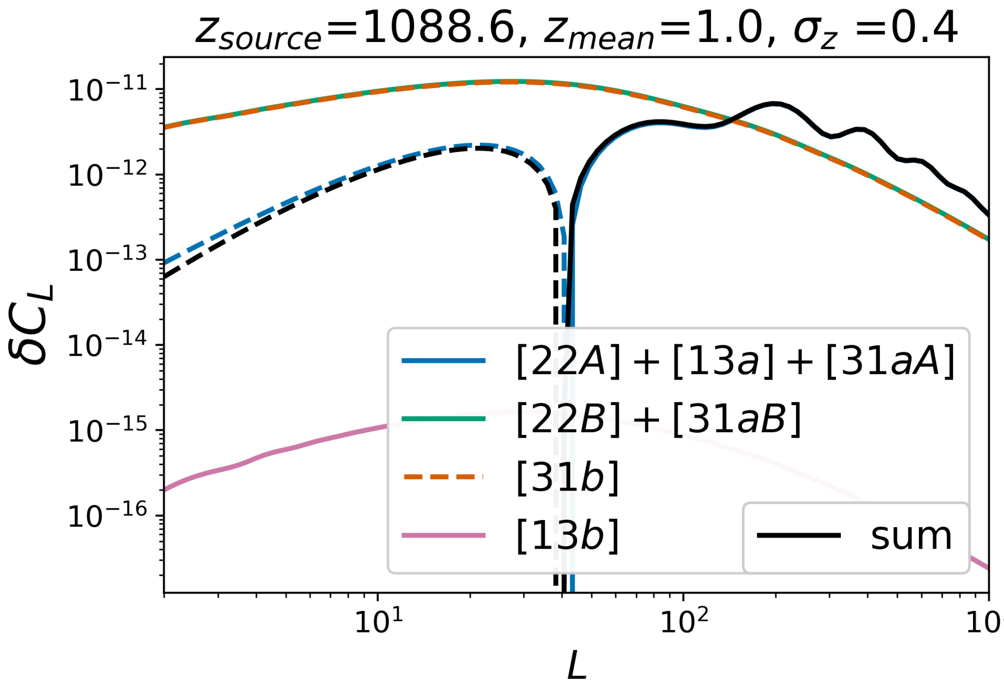
How good is the Born approximation ?
Understand it beyond Limber, and for <kg> and <gg>, possibly non perturbatively

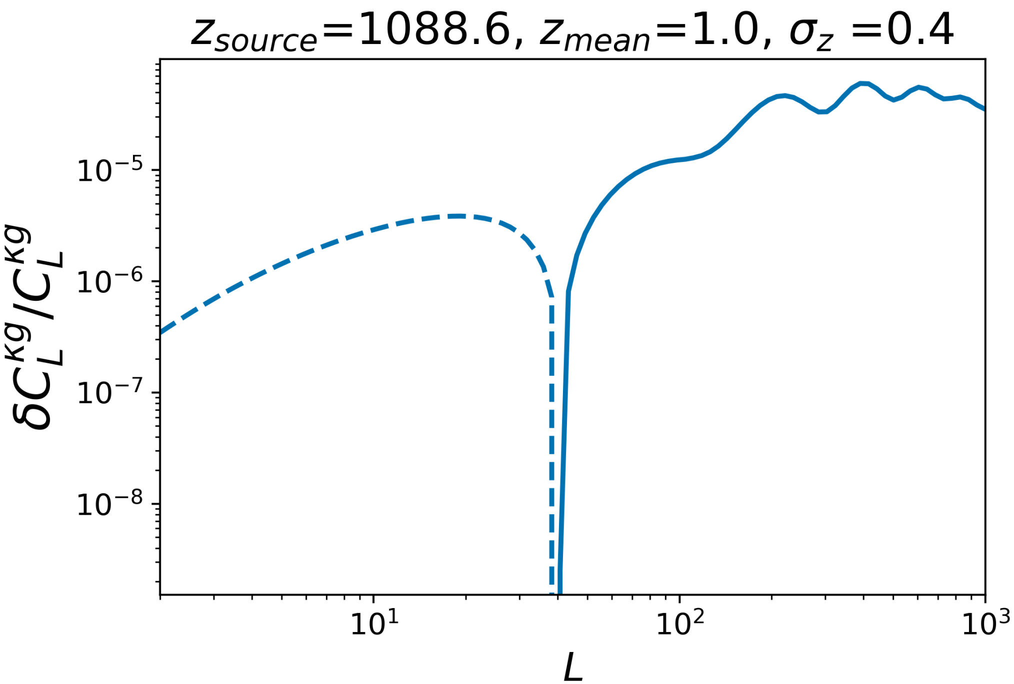


Corrections are dominated by modes with L'<L

<kg> and <gg> exhibit the same cancellations, provided position of galaxies is lensed

Weak Lensing





Beyond Limber terms are larger than Limber ones, but cancel between each other!

Only *lensed* positions are observable, ie derivative of deflection angles :

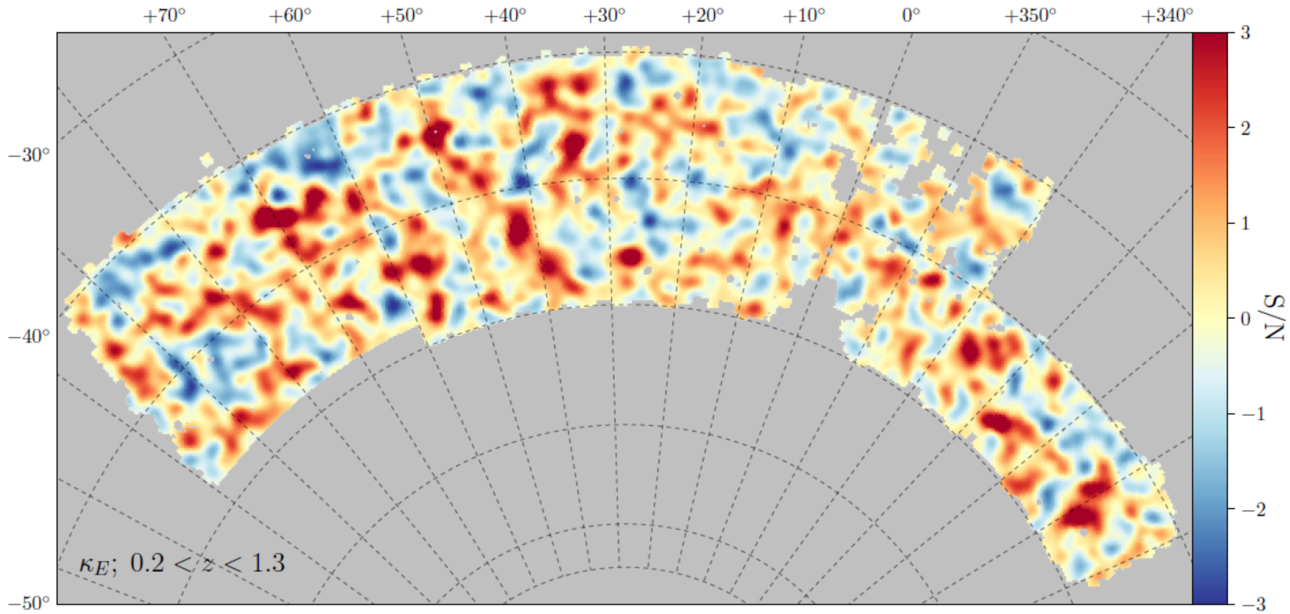
Equivalence principle/Consistency relations for LSS guarantees large shifts cancel

Peloso&Pietroni, Kehagias&Riotto,Creminelli+13

Weak Lensing

Overlapping lensing and galaxy fields allow us to probe both scalar dof of the metric

CFHTLens,KIDS, DES, HSC, LSST, Euclid ,WFIRST



Chang+18

$$\delta_g \sim \nabla^2 \Phi$$

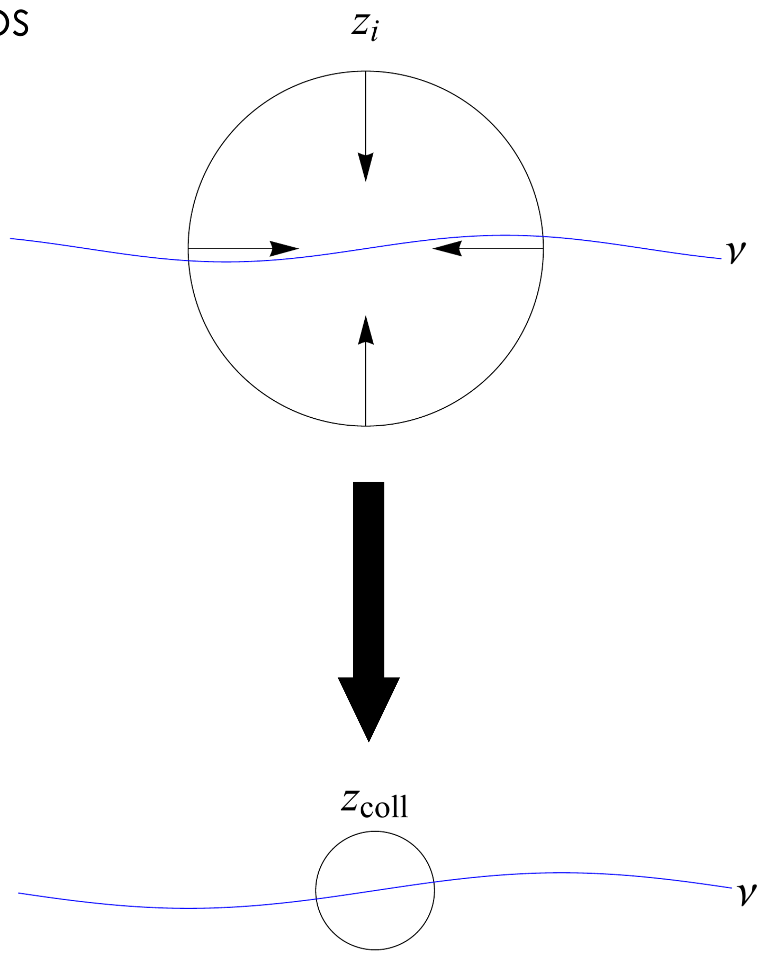
$$\kappa \sim \nabla^2 (\Phi + \Psi)$$

Useful probes of modified gravity

Weak Lensing

Neutrino masses/hierarchy could be measured by cosmological probes.
Limited by modeling at small scales, tau-degeneracy, etc...

$$\kappa \sim \delta_m$$ Including neutrinos



$$\delta_g \sim b\delta_{cb} + \mathcal{O}(f_\nu)$$

EC+13, LoVerde+14,Chang+18,Munoz&Dvorkin18, Fidler+18

Scale dependence alone is not a very powerful probe at the power spectrum level

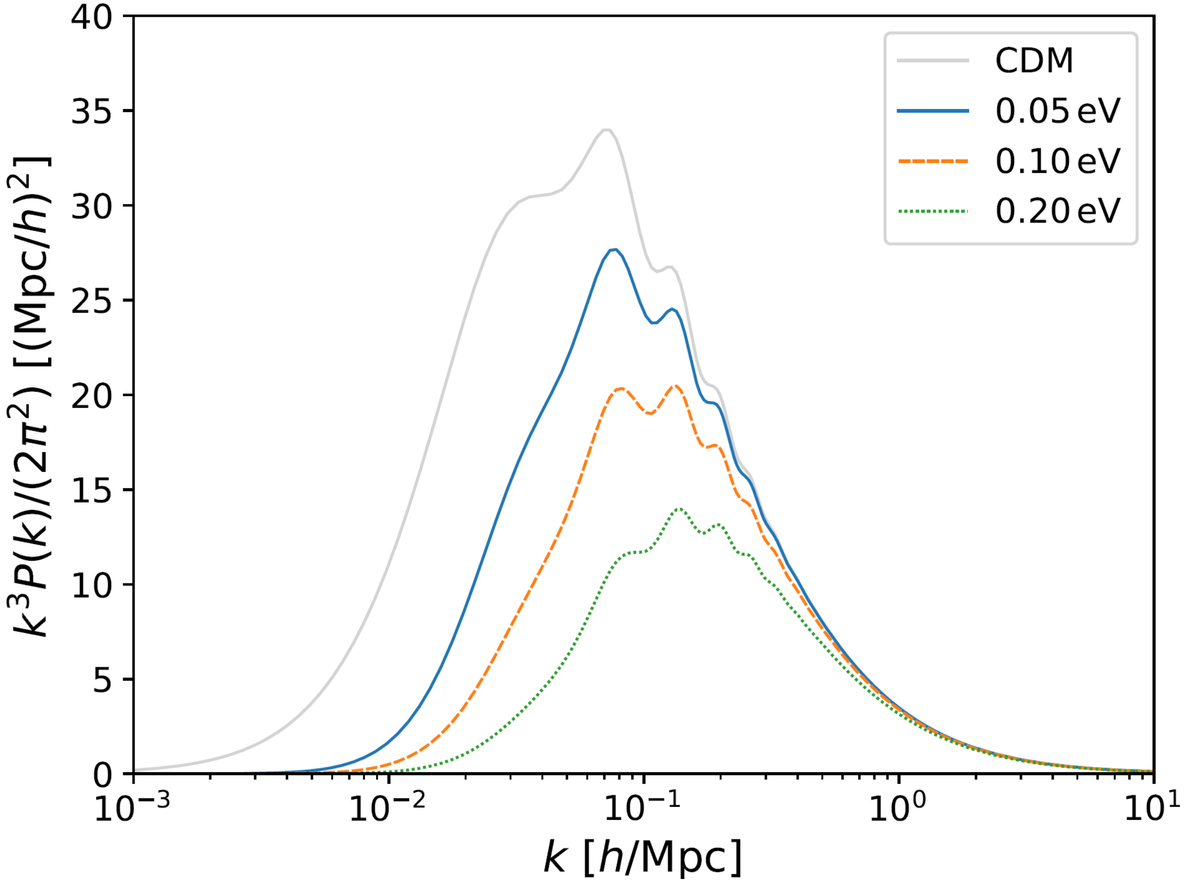
Schmittfull&Seljak18, Yu+19. See also Brinckmann+18

Weak Lensing

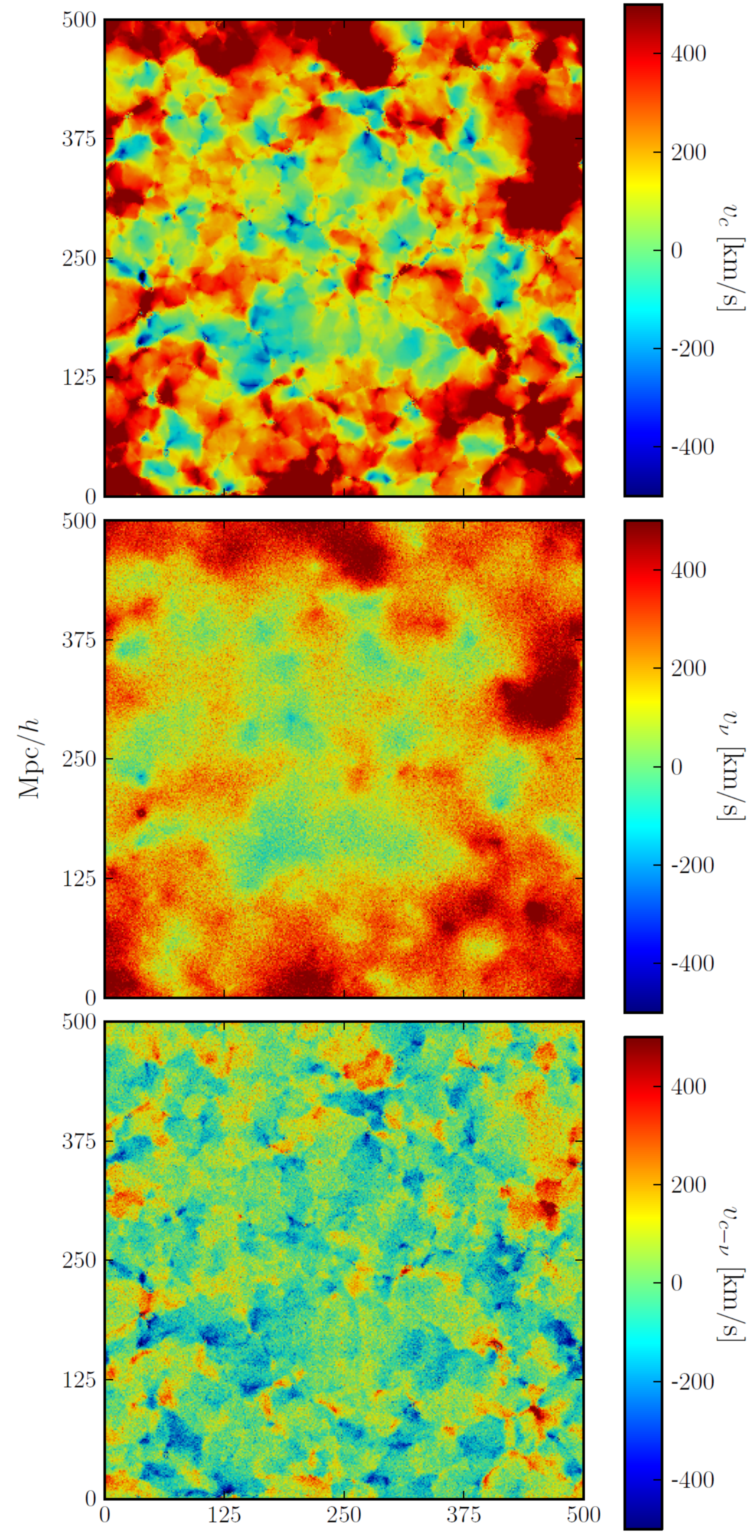
Relative velocities as a novel probe of neutrino masses.
Independent of tau, As, etc.
Hard to come up with observable signatures

Zhu+14,Inman+15,16,Yu+17,Okoli+16

$$\vec{\psi}_{\nu c}(\tau) = \int_0^\tau d\tau' \vec{v}_{\nu c}(\tau') = \vec{\nabla}\phi_{c\nu}$$



Inman+15



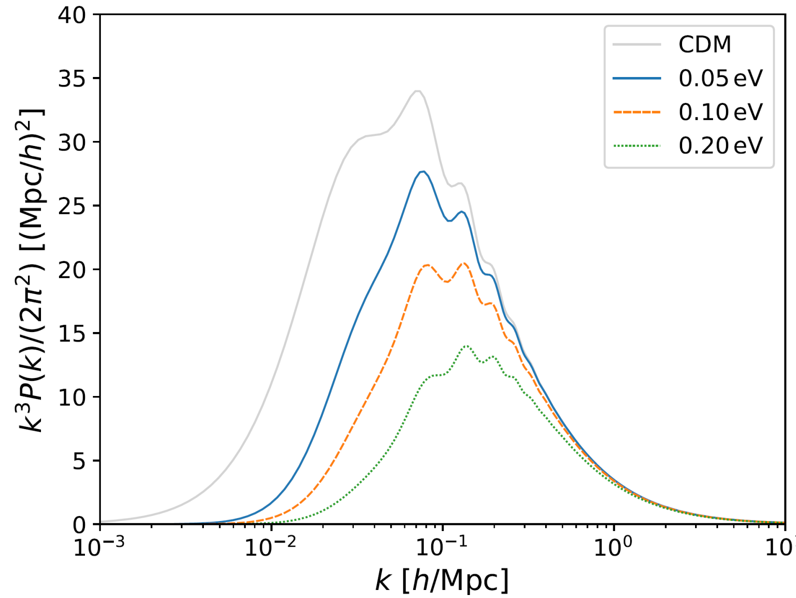
Weak Lensing

An OQE to measure the relative displacements

$$\vec{\psi}_{\nu c}(\tau) = \int_0^\tau d\tau' \vec{v}_{\nu c}(\tau') = \vec{\nabla}\phi_{c\nu}$$

$$\vec{x}_c = \vec{x}_\nu + \vec{\psi}_{c\nu}$$

$$\delta_c(\vec{x}_c) \sim \delta'_c(\vec{x}_c) + \vec{\psi}_{\nu c} \cdot \nabla \delta'_c(\vec{x}_c)$$



$$\boxed{\langle \delta_c(\vec{k})\delta_\nu(\vec{k}')\rangle_{\text{fixed } \phi_{c\nu}} = \vec{k}\cdot\vec{K} P_{\delta_c\delta'_\nu}(k)\phi_{c\nu}(\vec{K})}$$

The signal is parity odd, no Gaussian/non Gaussian biases like in CMB/21 cm.

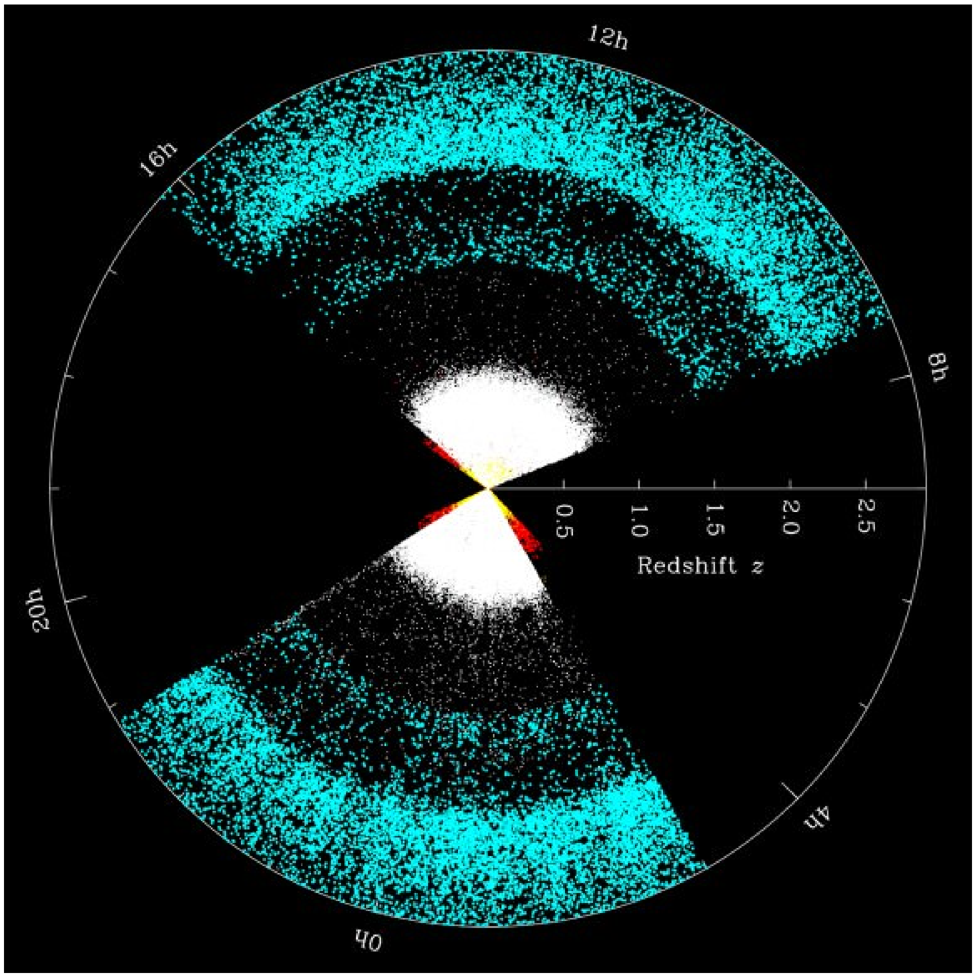
Hard to make it a 5sigma detection

~3sigma feasible, independent of other probes

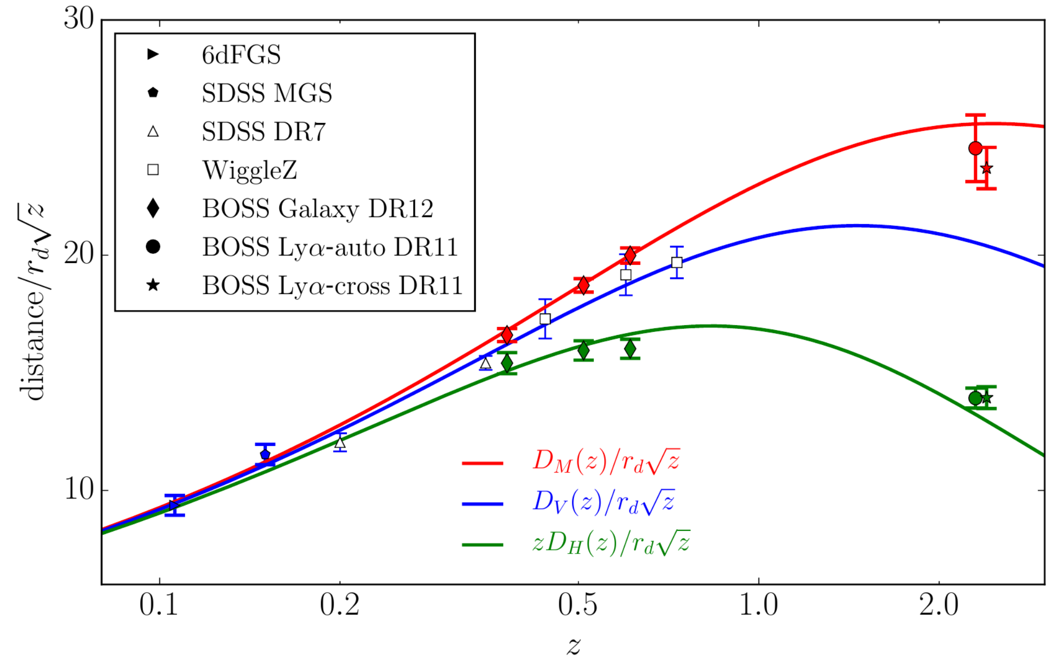
5sigma threshold

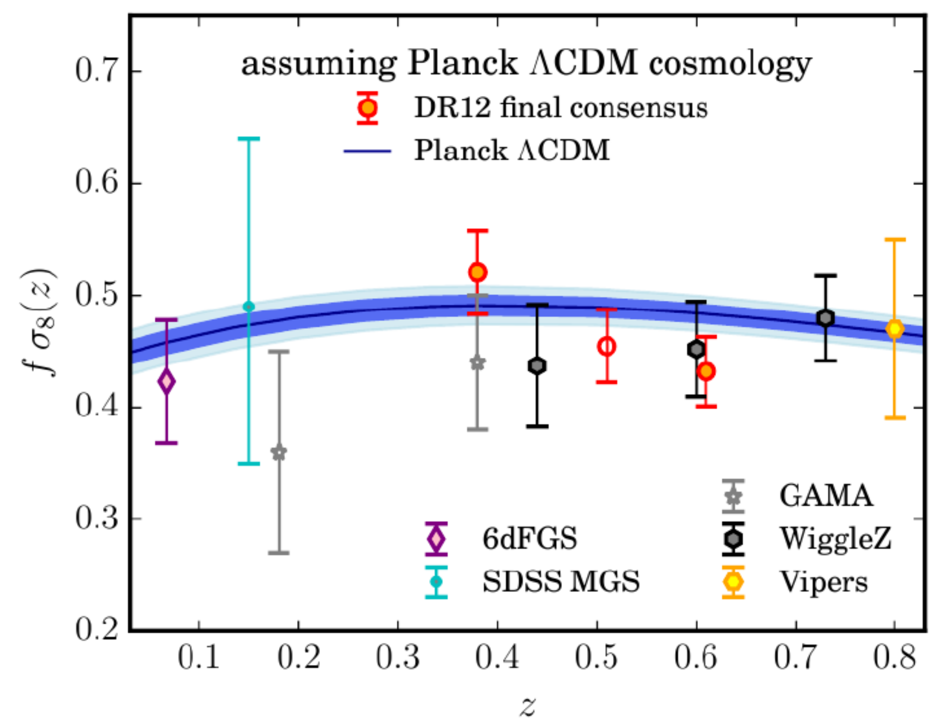
$\sum m_\nu$	$V/(P_{\epsilon_m} + 1/(b^2\bar{n}))$
$0.05\,eV$	3.6×10^8
$0.05\,eV\times 2$	9×10^7
$0.10\,eV\times 3$	1.5×10^6

Spectroscopic surveys



Credits : BOSS





Spectroscopic surveys

BAO and RSD mature techniques. Large improvements with DESI, Euclid, PFS, 4MOST…

Have access to the largest scales $\longrightarrow$ local Primordial non Gaussianities

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

$$\lim_{k_1 \to 0} B_\zeta(k_1, k_2, k_3) = \left[(n_s - 1) + \epsilon \mathcal{O}\left(\frac{k_2}{k_1}\right)^2 \right] P_\zeta(k_1) P_\zeta(k_3)$$

Maldacena
Creminelli&Zaldarriaga

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

$$\zeta = \zeta_g + \frac{3}{5} f_{NL}^{\rm loc} (\zeta_g^2 - \langle \zeta_g^2 \rangle) \qquad \zeta_g \simeq 10^{-5} \qquad f_{\rm NL}^{\rm loc} = -0.9 \pm 5.1$$

Planck18

Local PNG are measured with 0.05% precision.

Spectroscopic surveys

Future CMB mission : fNL~2-3

$$\boxed{\sigma_{f_{\rm NL}^{\rm loc}} \lesssim 1}$$

Future Galaxy Surveys : fNL~0.1-1

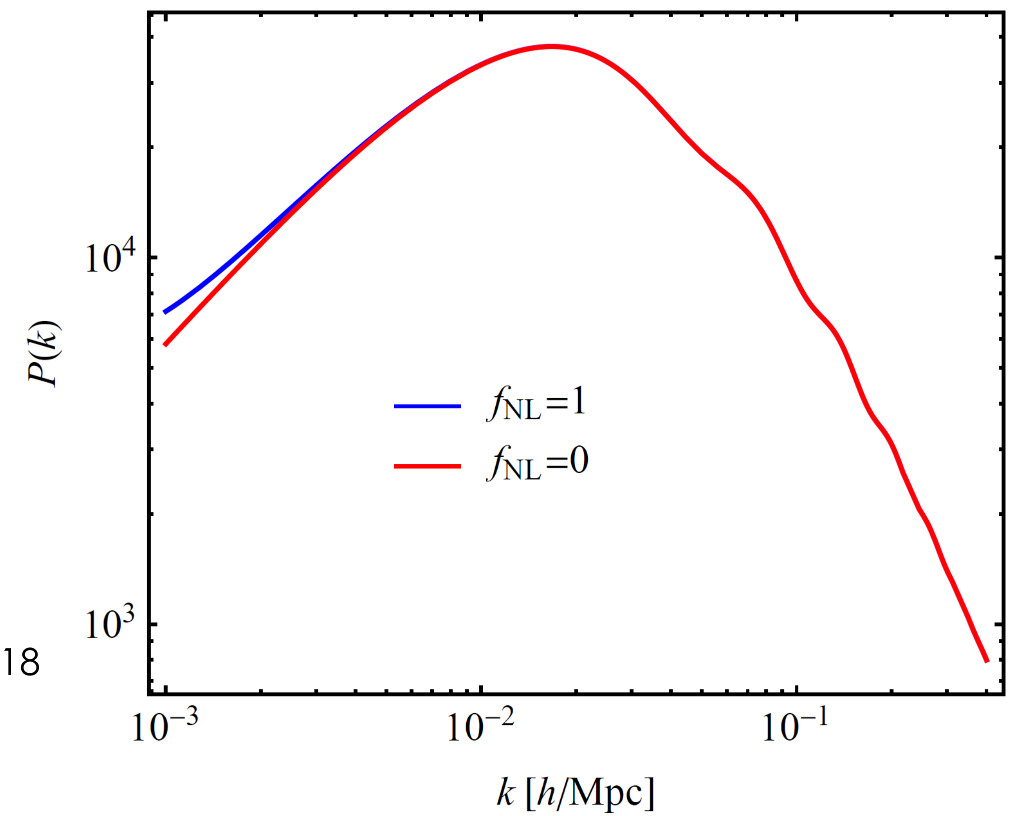
O(20) now

Signal in the galaxy power spectrum

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

Dalal+08

$$P_{gg}(k, \mu, z) = [b + f\mu^2 + f_{NL} b_{\Phi_p}\alpha(k)]^2 P_m(k, z)$$



Tiny signal!

Difficulties :

- Cosmic Variance (zero bias?)

- Foregrounds

Eventually dominated by Bispectrum

Sefusatti09, Baldauf+11,Jeong&Komatsu10, Karagiannis18

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 almost never do the full inverse noise weighting of the data. Tegmark+98

- In LSS, we never do optimal signal weighing for cosmological parameters

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

We need an idea of the z-evolution of the signal

↓

Trust your theory!

When the theory meets the data

We observe our past lightcone:

- The Gaussian part evolves with time;

  Smaller at high redshift.

- The PNG term does not,

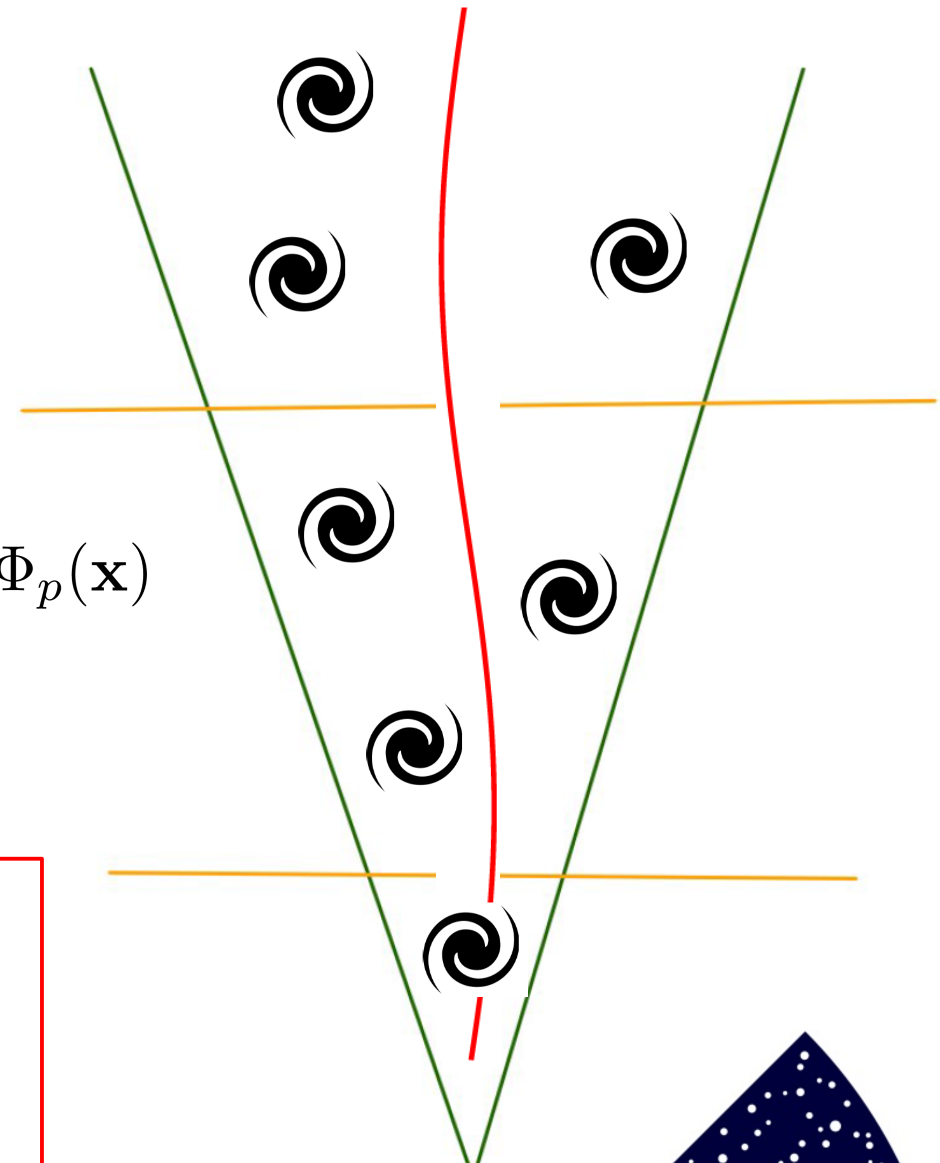
$$\delta_g(\mathbf{x}, z) = b_1(z)\delta_m(\mathbf{x}, z) + f_{\rm NL} b_{\Phi_p}(z)\Phi_p(\mathbf{x})$$

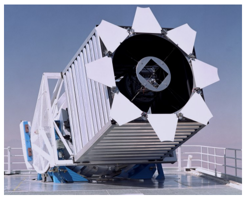
- More volume at high z.

Optimal signal extraction:

1) No redshift binning: loses large scale modes.

2) give more weight to high redshift objects.





eBOSS

eBOSS Quasars DR14 data in 0.8<z<2.2

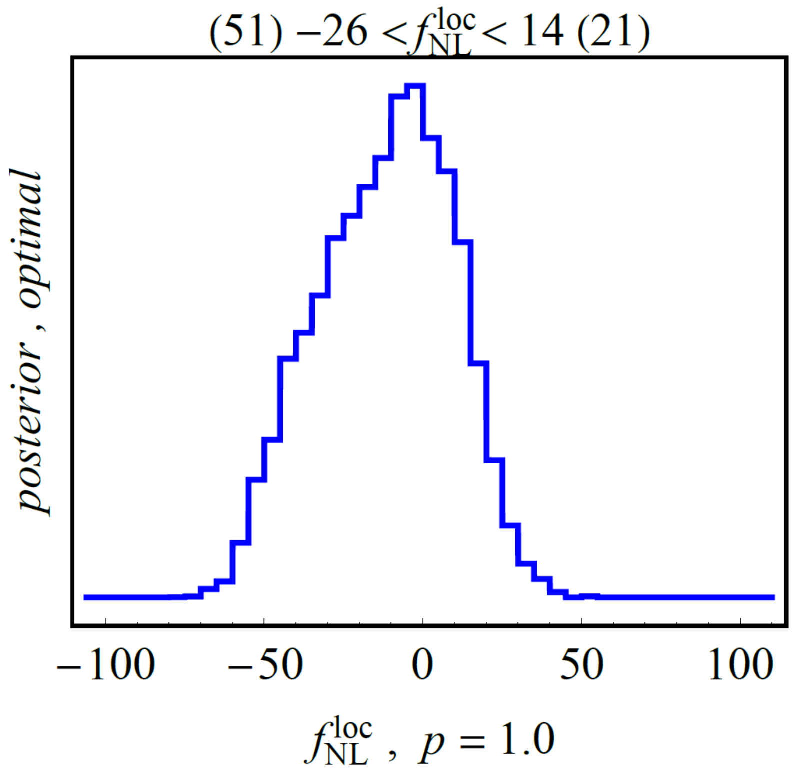
Analysis on 180k Quasars (QSOs) of SDSS-IV in 5 % of the sky. S/N per mode <<1.

$$w_{\rm G} \propto D(z) \quad w_{\rm NG} \propto b_{\Phi_p}(z)$$

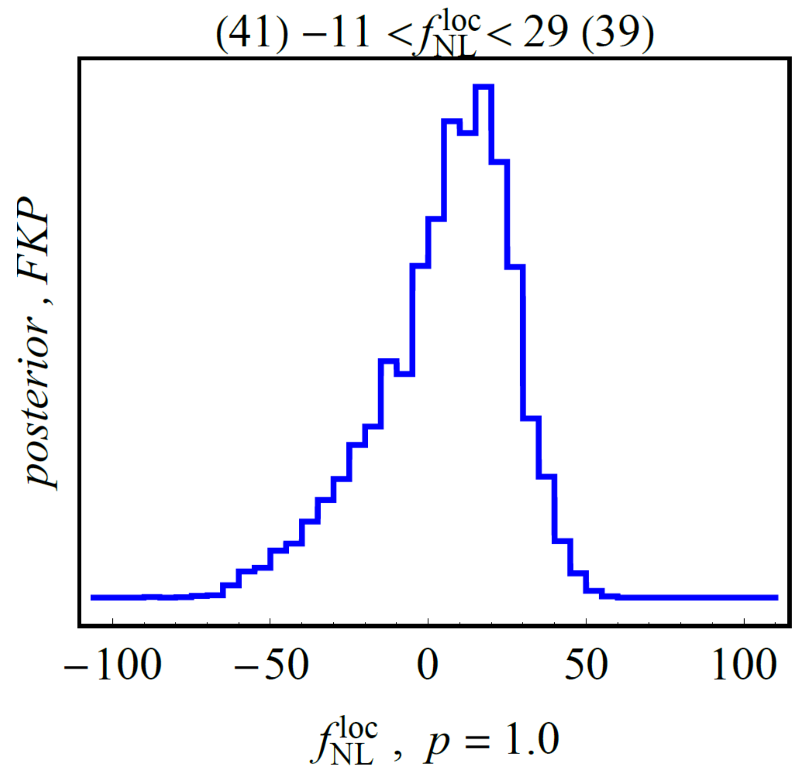
increases w/ time

decreases w/ time

Optimal



Standard



~15% improvement over standard methods. Corresponds to 1.3x bigger survey
Understanding the theory helps data analysis !

Tightest constraints using LSS data. Larger improvement in the future

Summary

LSS theory and experiments are alive and well!

Analytical calculations today are the only robust and unbiased way to extract cosmological parameters.

$\boxed{\text{Modeling has to improve to catch up with DESI/LSST/Euclid/21cm}}$

$\boxed{\text{How to make sure all information has been exploited?}}$

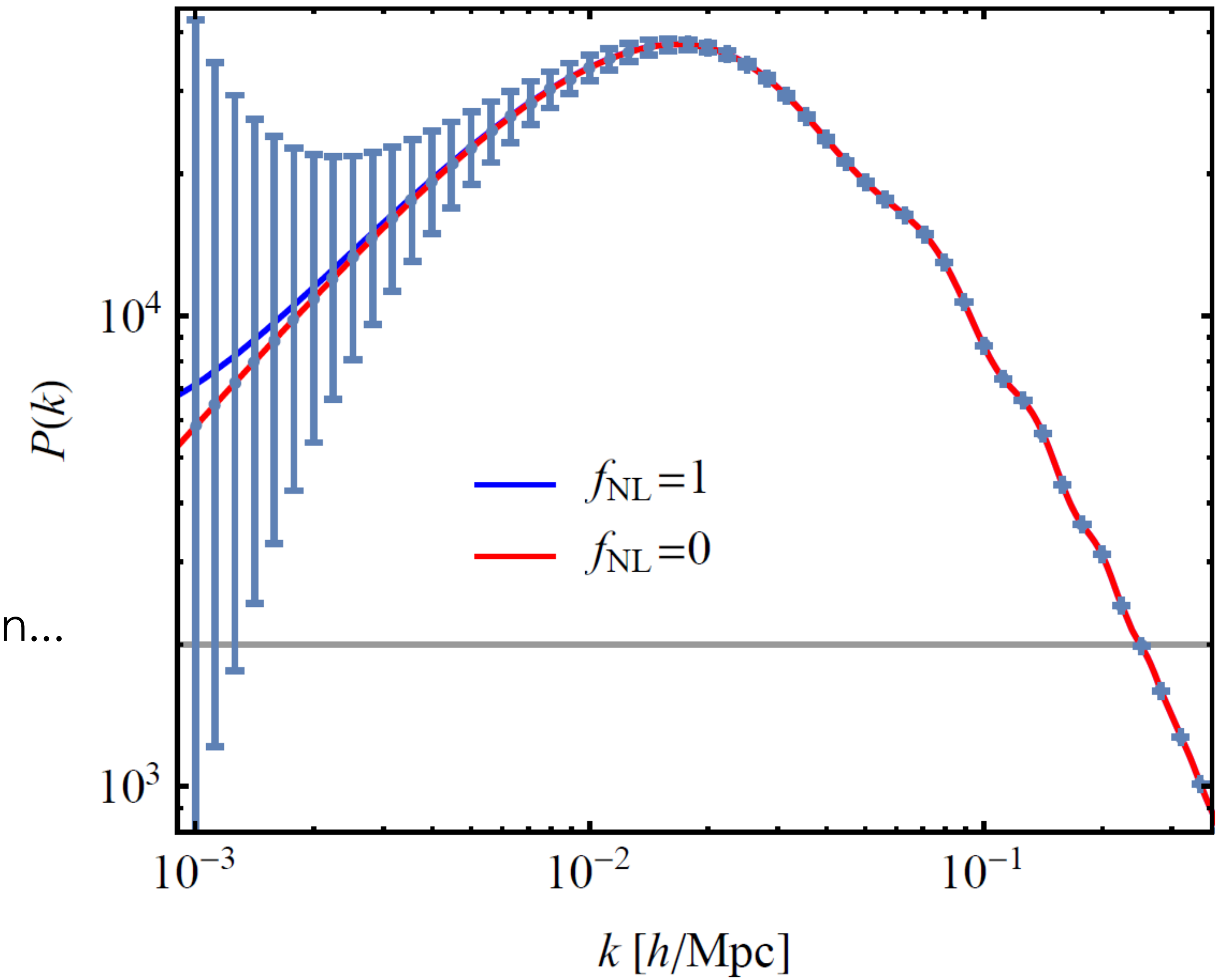
Thank you!

Cosmic Variance in PNG measurements

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

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…



The real cosmic variance cancellation: zero bias tracers

On large scales the fiducial, ie assuming PNG =0, power spectrum is

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

The error is proportional to the signal...

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

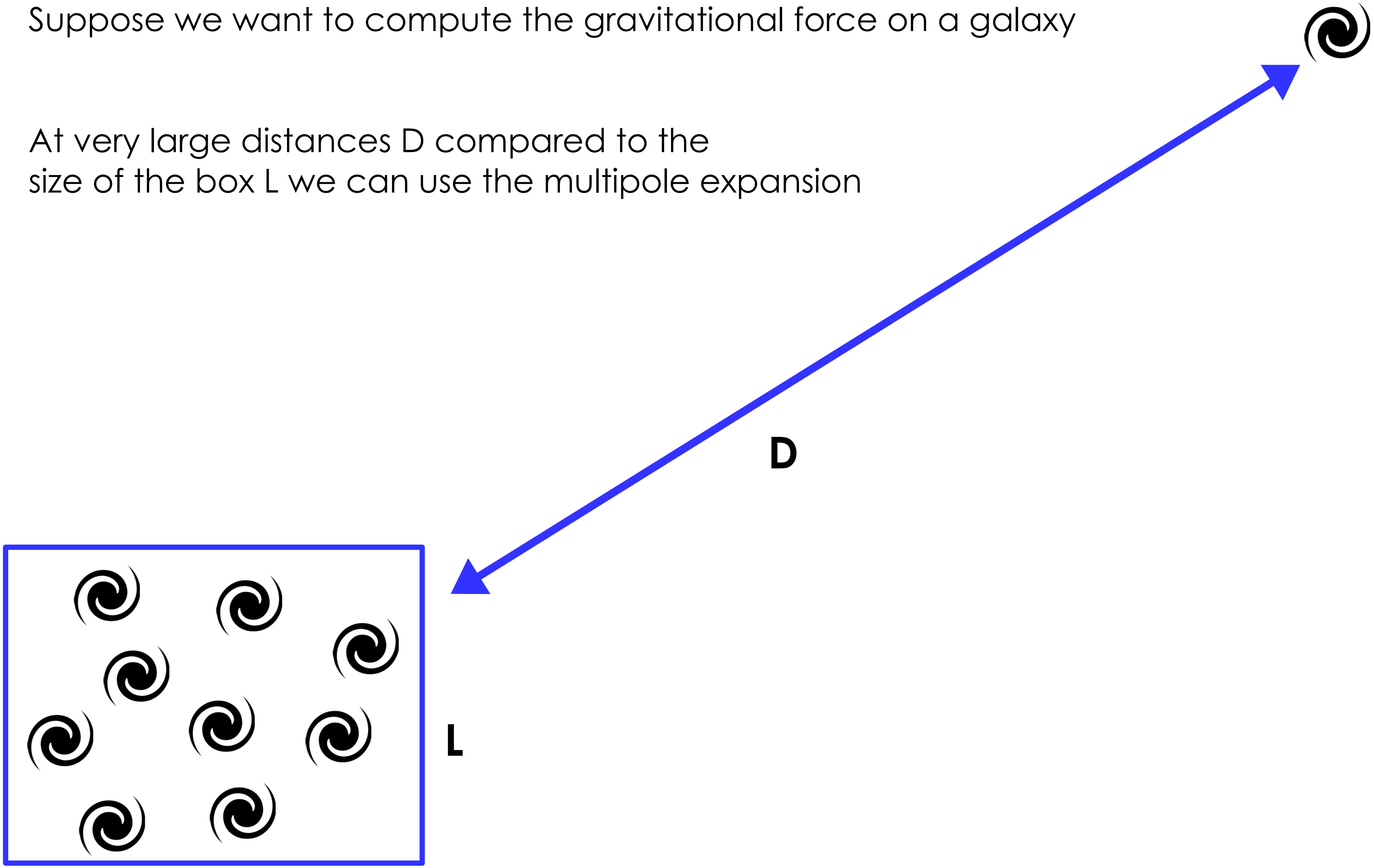
$$\sigma_P^2 \longrightarrow = \boxed{2\delta_{ij}\frac{(2\pi)^3}{N_k}\left(\cancel{P_{gg}}(k_i) + \frac{1}{\bar{n}}\right)^2} + \mathrm{Trisp}\cancel{\mathrm{e}}\mathrm{ctrum}$$

The bottom line: If bias is zero Cosmic Variance is zero ! Left with shot noise only.

A zero bias field

Suppose we want to compute the gravitational force on a galaxy

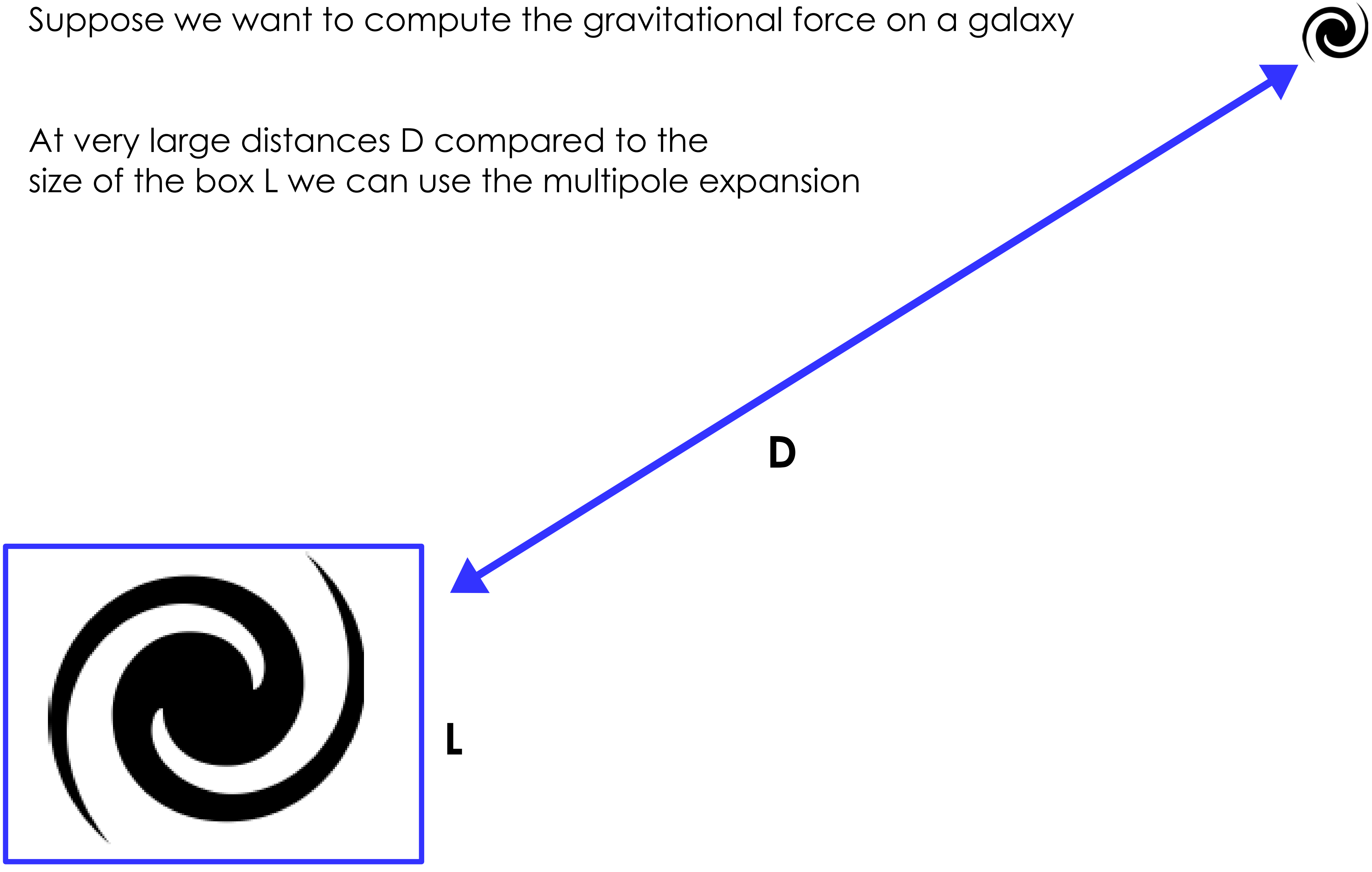
At very large distances D compared to the
size of the box L we can use the multipole expansion



A zero bias field

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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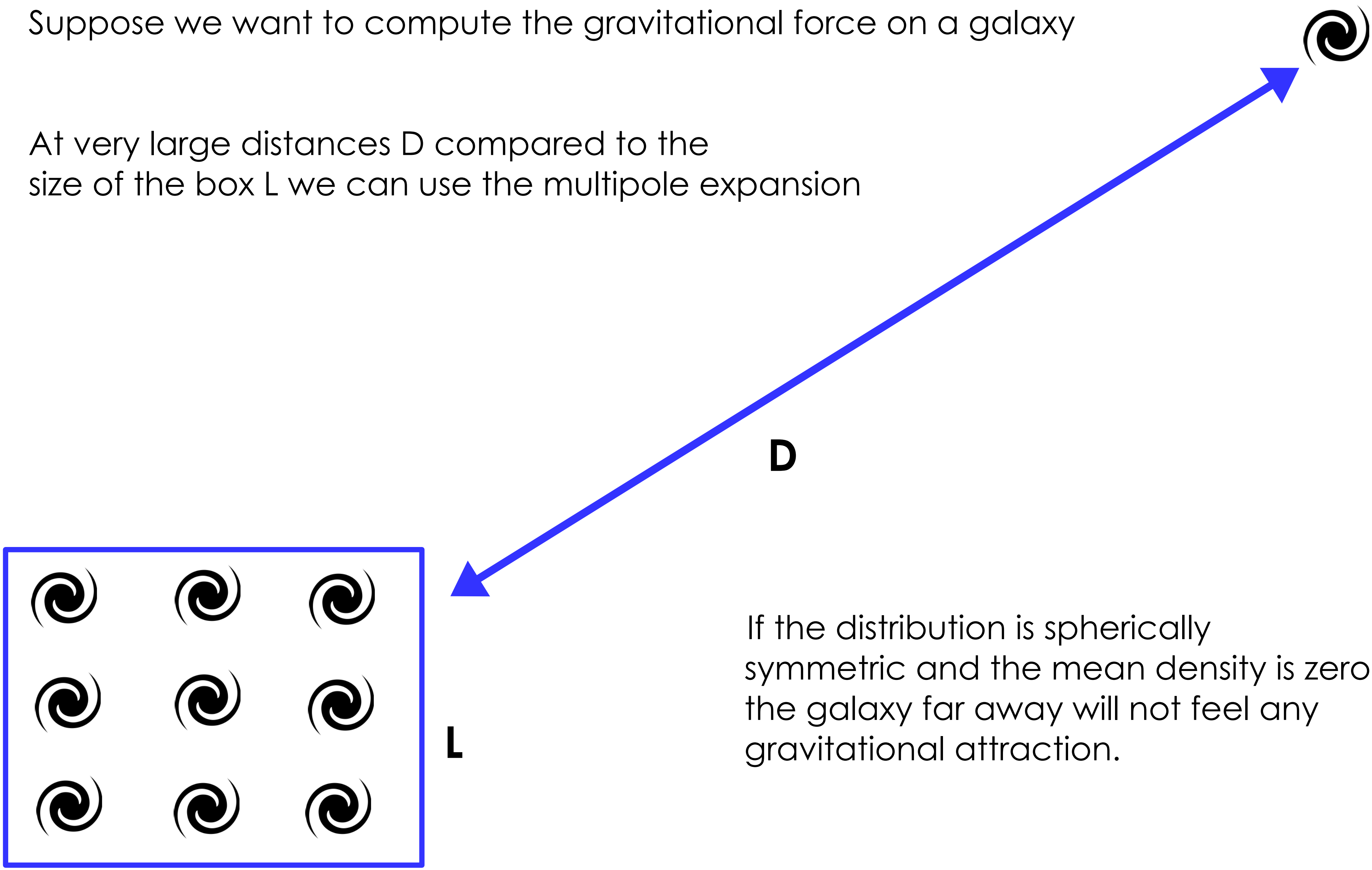
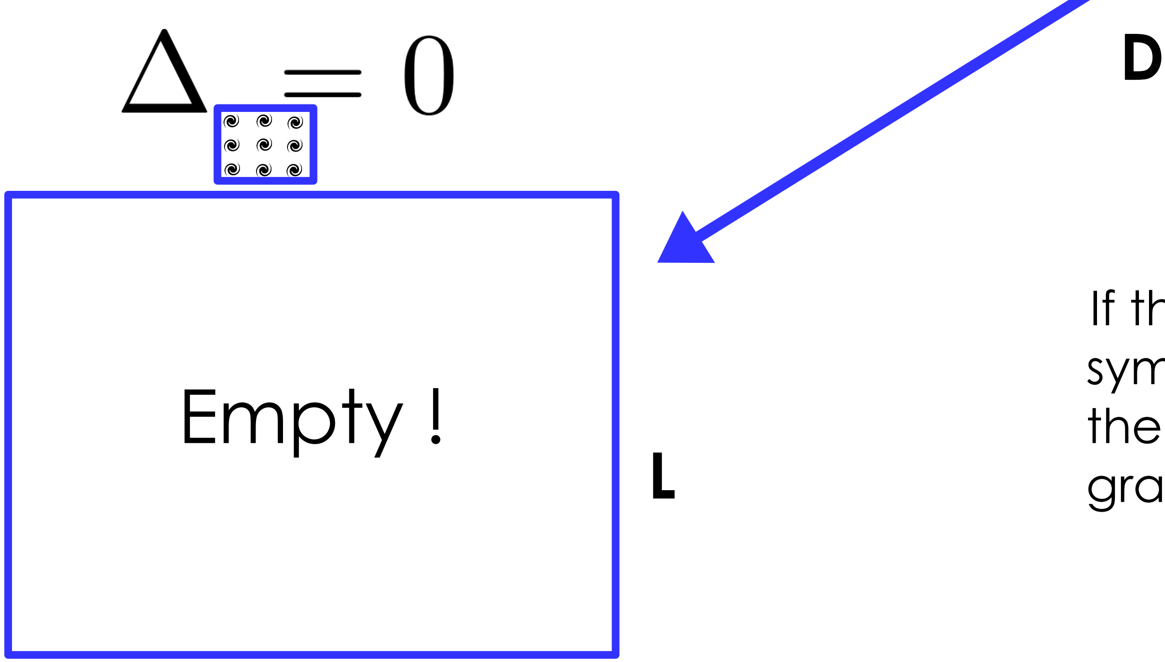


If the distribution is spherically symmetric and the mean density is zero the galaxy far away will not feel any gravitational attraction.

A zero bias field

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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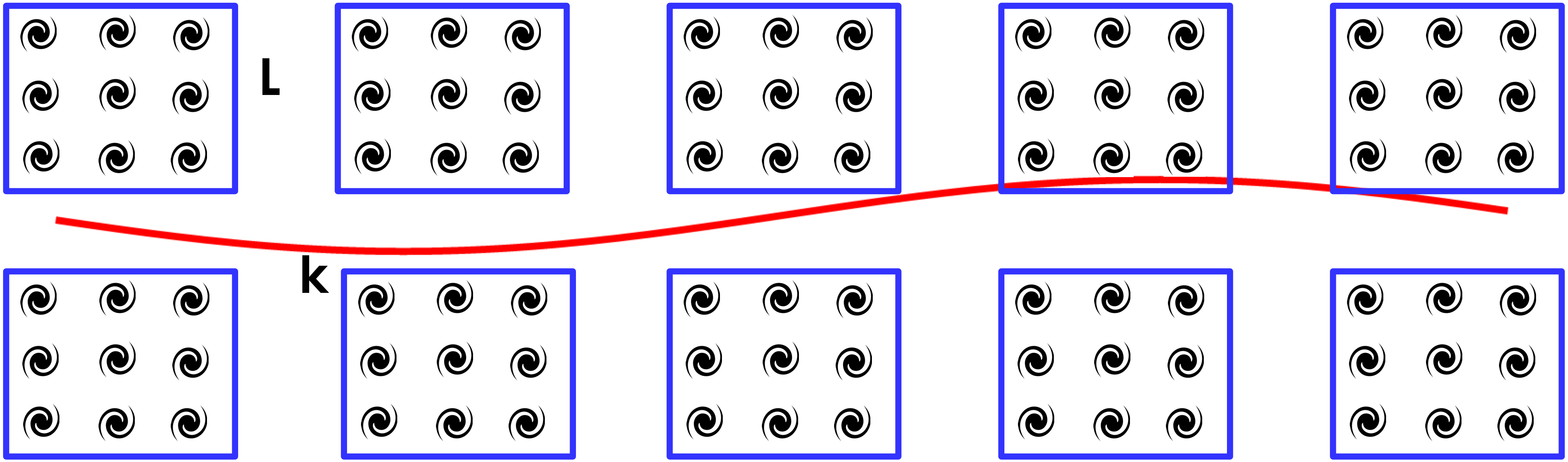
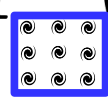
A zero bias field



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

Constraint on PNG

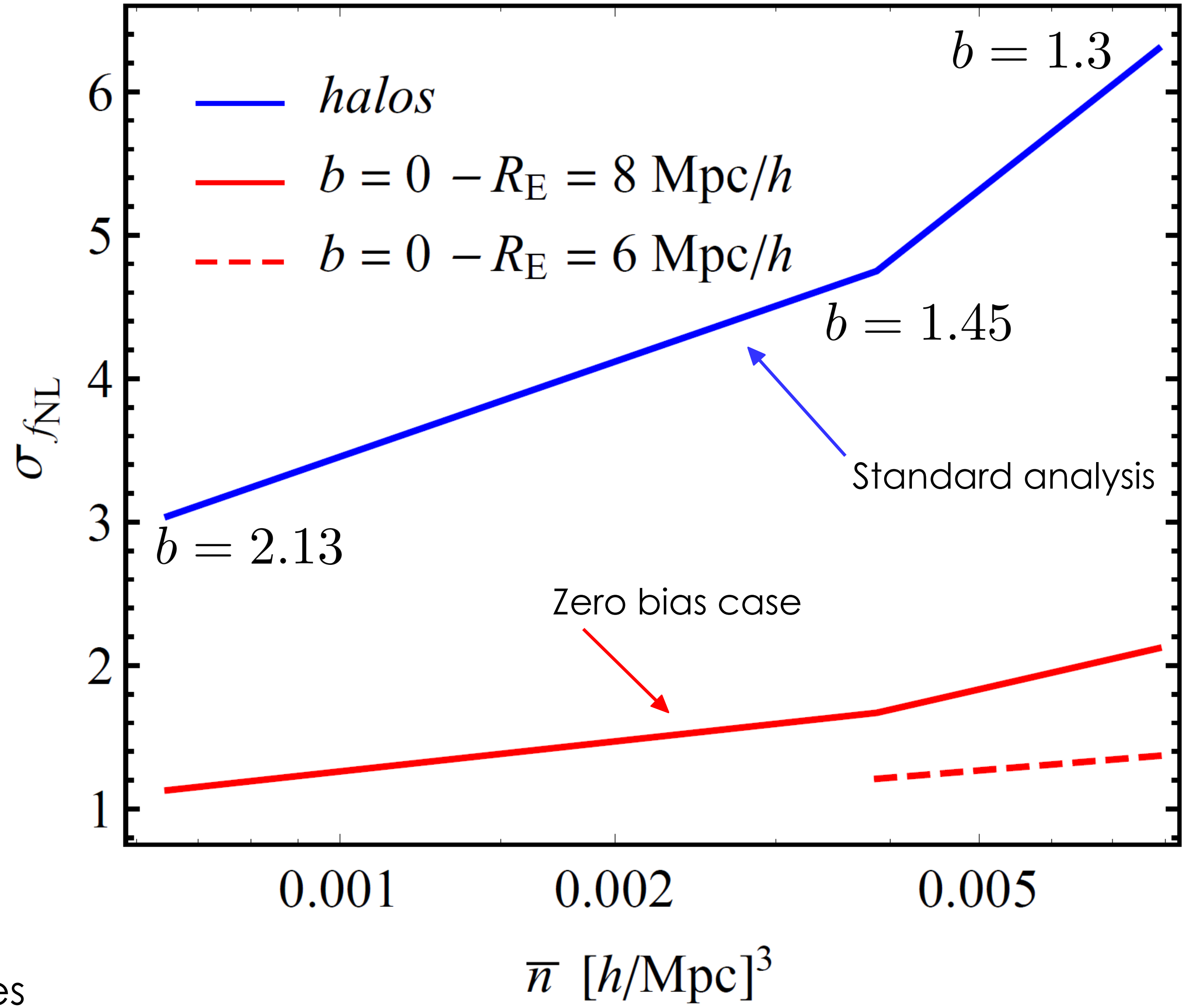
Setup:

- 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.



OQE

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

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

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

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

Multipoles of P(k) estimator

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

Growth function

Growth rate

In the standard analysis w(z)=1.

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

OQE

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

Use standard approach but include redsfhit weights