~~Cosmological Bounds on long range forces in the dark sector~~

Emanuele Castorina
University of Milan

~~w/ M. Archidiacono, D. Redigolo and E. Salvioni~~

BAM, 10/09/21

Infra-Red effects in galaxy clustering

(a.k.a. The galaxy power spectrum in General Relativity)

Emanuele Castorina
University of Milan

w/ Enea di Dio , 2106.08857

BAM, 10/09/21

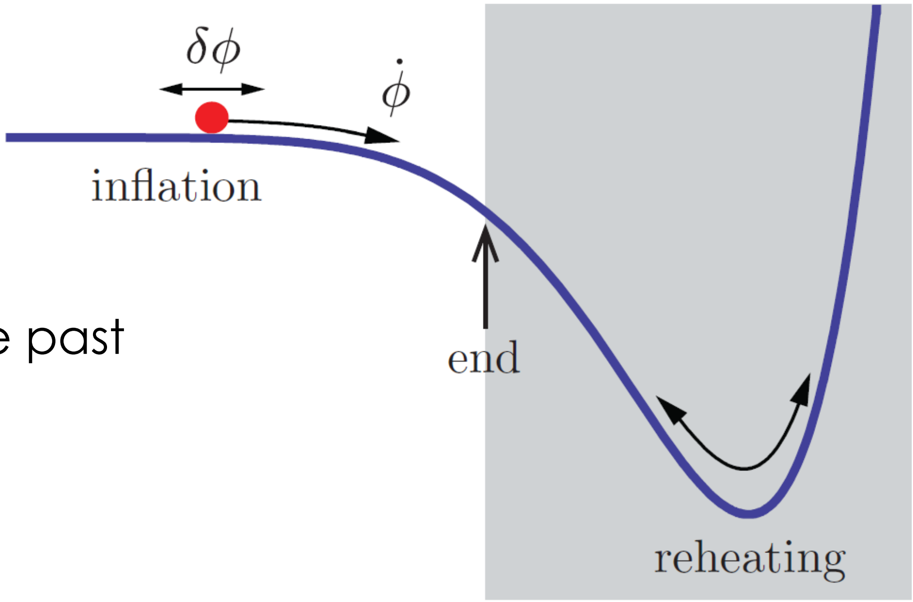
Outline

- Why we care about Primordial Non Gaussianities (PNG)

- Signatures of PNG in galaxy clustering

- The IR limit of the power spectrum

What we know about the ICs



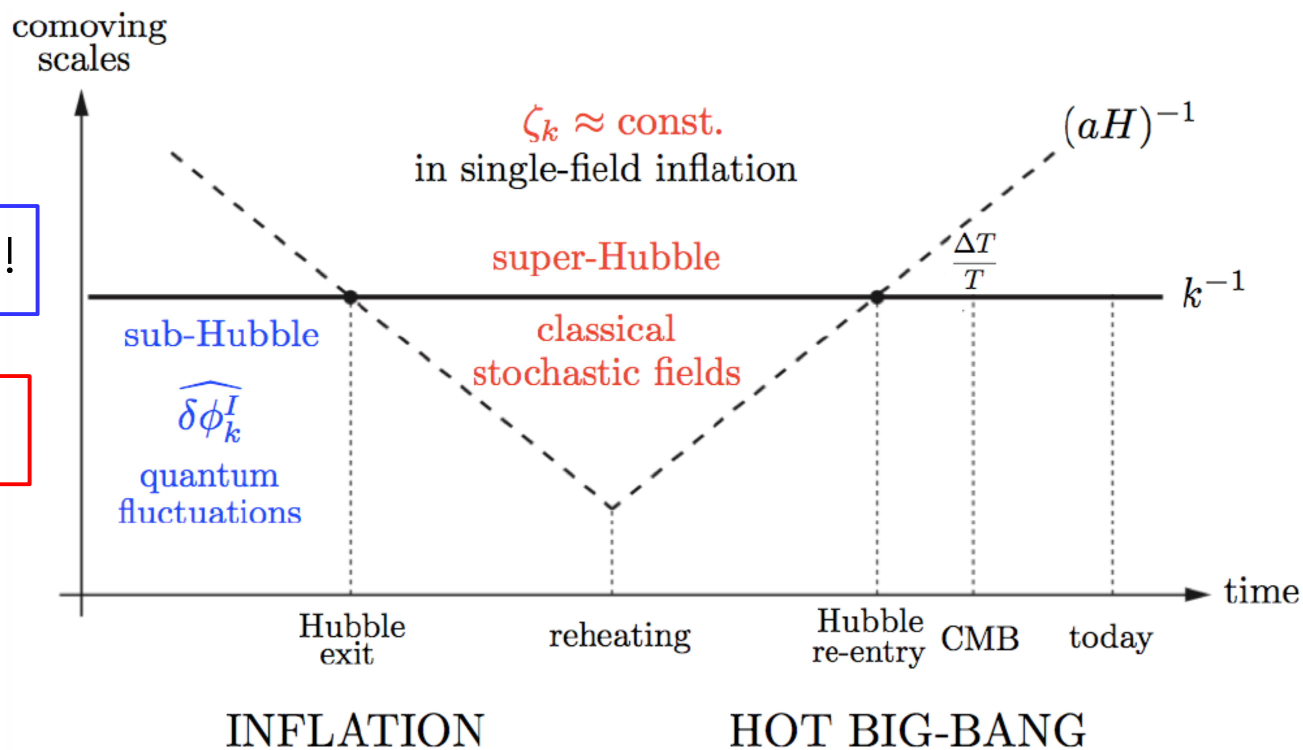
Inflation solves problems
and makes predictions :

- Large Scales causally connected in the past
- Observable Universe is (close to) flat
- Spectral index and runnings
- ~ Adiabiatic fluctuations

Two open questions :

1) Energy scale? Tensor modes !

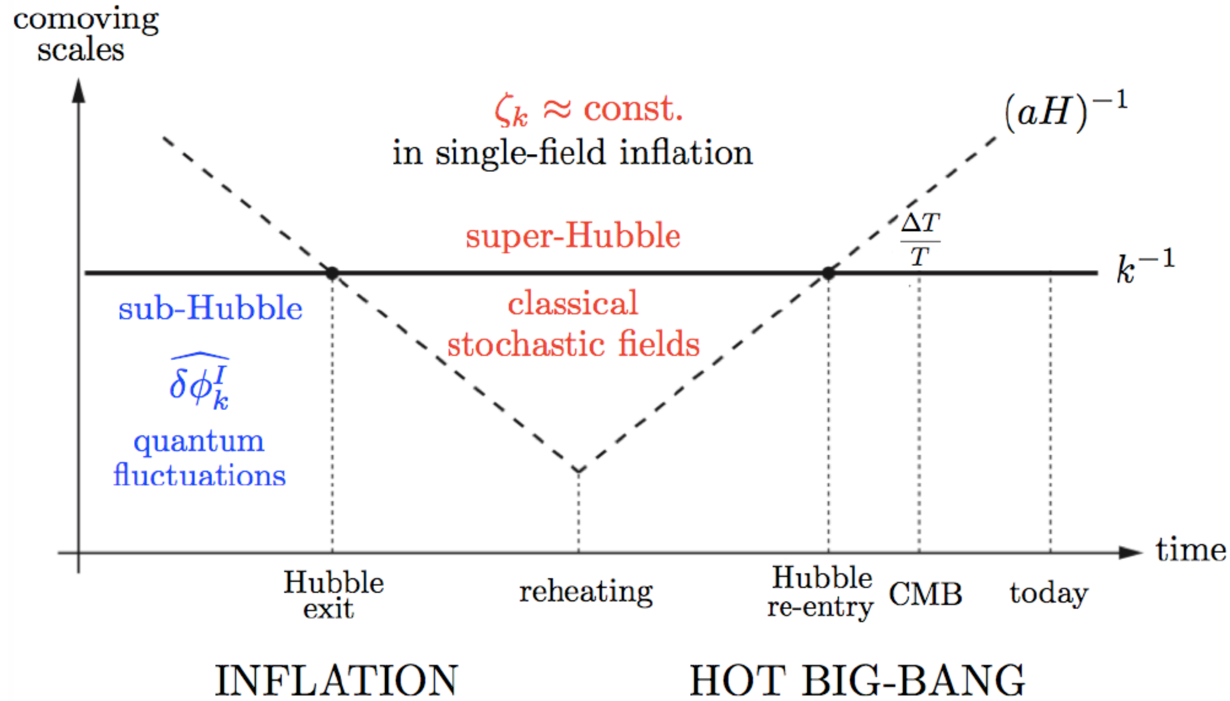
2) Dynamics ? PNG !



Credit : Baumann

The consistency relation

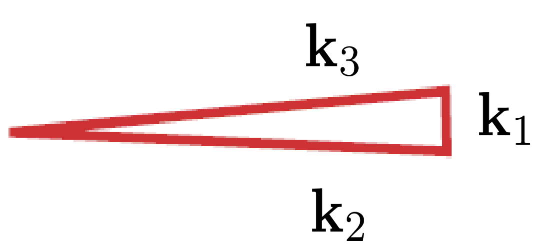
Higher point functions (PNG) as a probe of the dynamics of inflation.



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

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

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

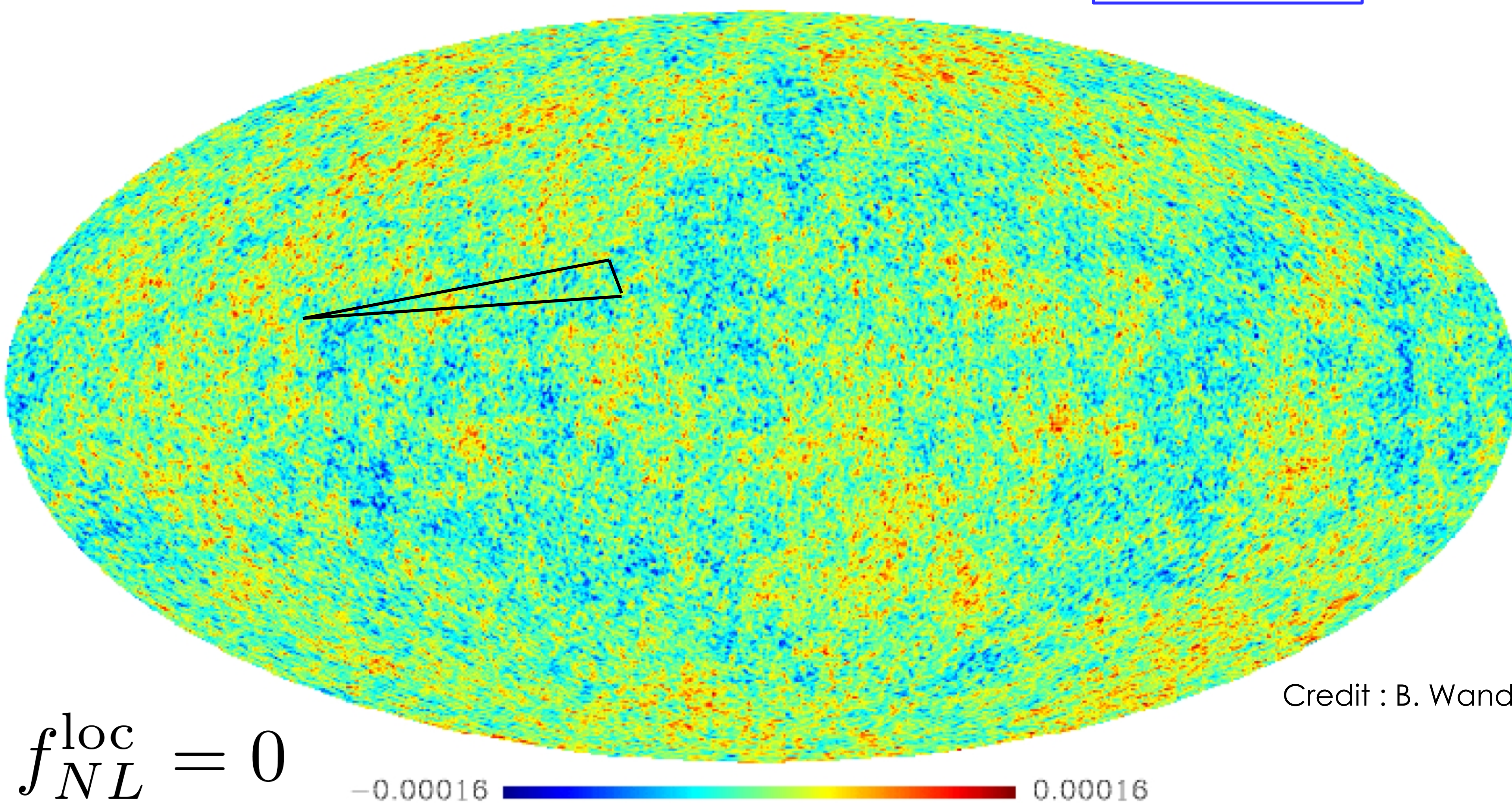


Maldacena
Creminelli&Zaldarriaga

Primordial Non-Gaussianities (PNG)

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

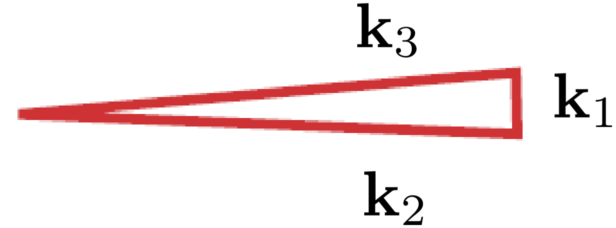
$$\boxed{\zeta = \zeta_g + \frac{3}{5} f_{NL}^{\mathrm{loc}} (\zeta_g^2 - \langle\, \zeta_g^2 \,\rangle)} \longrightarrow \boxed{\sigma_{f_{\mathrm{NL}}^{\mathrm{loc}}} \lesssim 1}$$



Credit : B. Wandelt

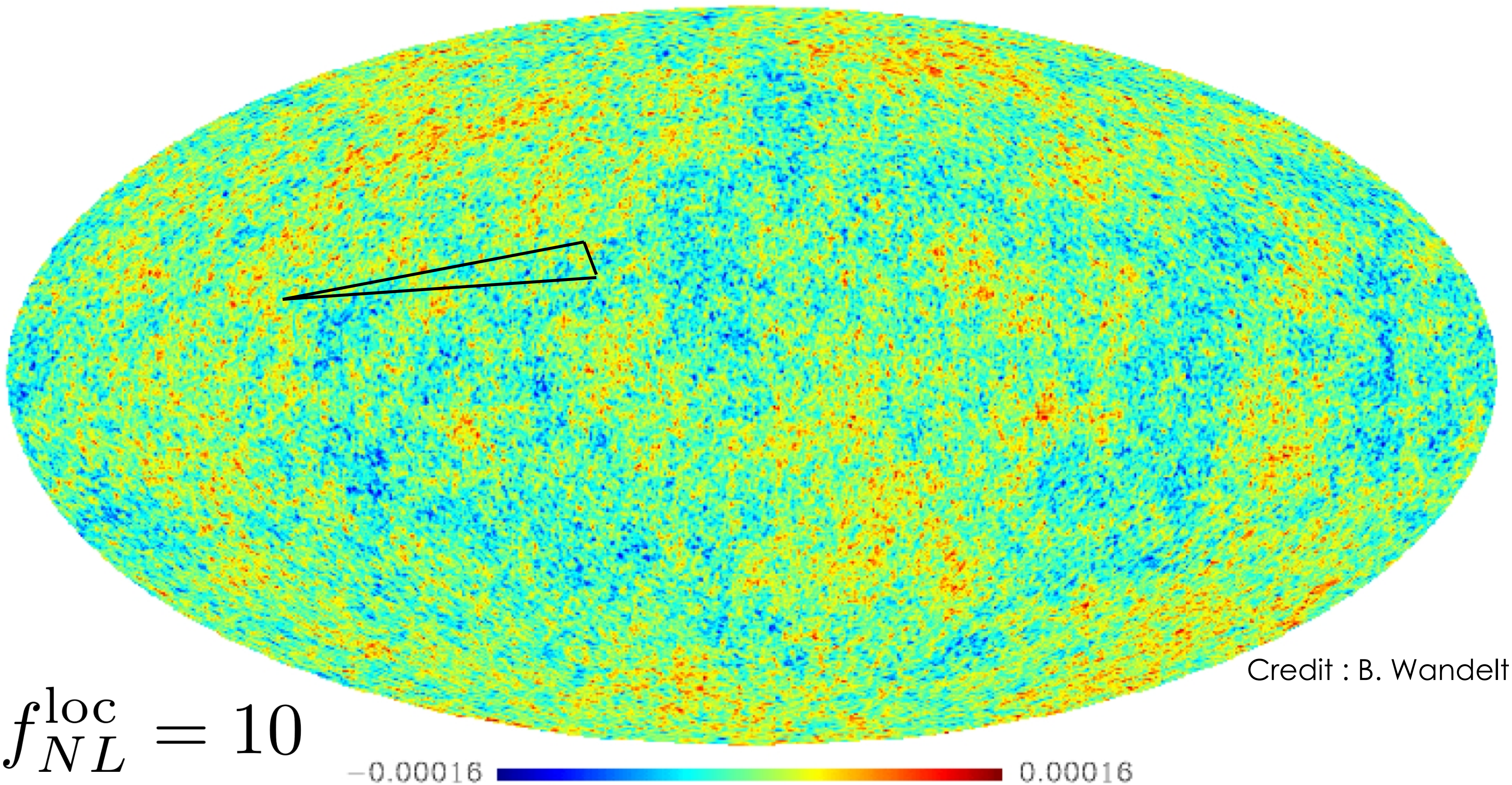
$$f_{NL}^{\mathrm{loc}} = 0$$

Primordial Non-Gaussianities (PNG)



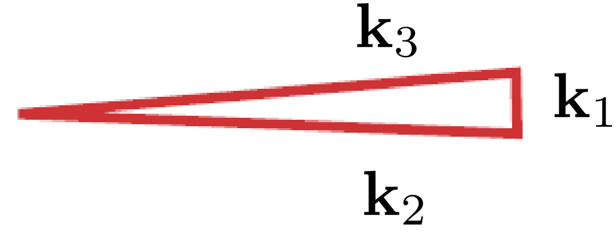
Detection of local PNG will rule out single field inflation.
Non detection, constrains multi-field models.

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



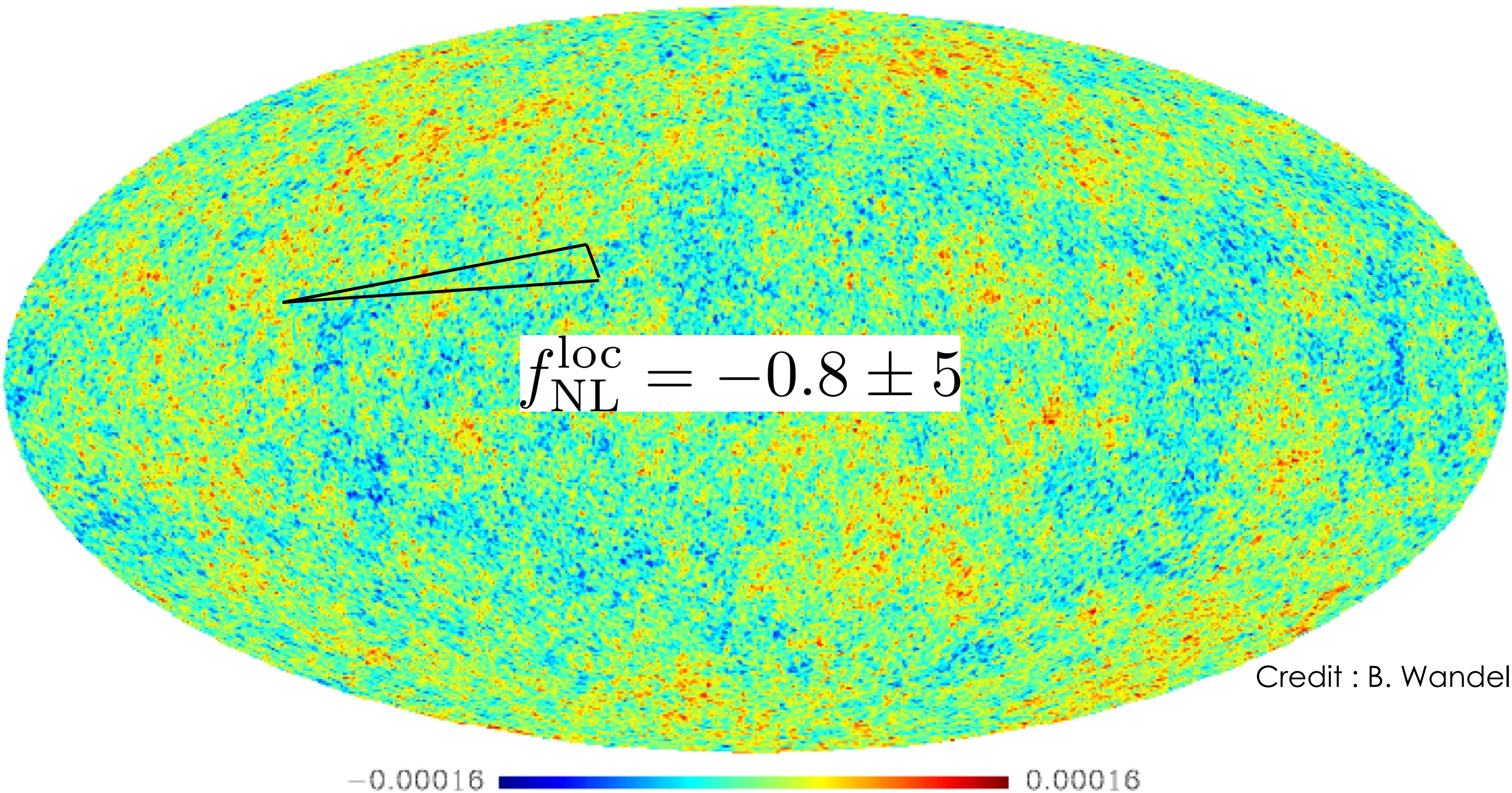
$$f_{NL}^{\rm loc} = 10$$

Primordial Non-Gaussianities (PNG)



Detection of local PNG will rule out single field inflation.
Non detection, 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

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. $\longrightarrow \quad \sigma_{f_{\rm NL}^{\rm loc}} \lesssim 1$

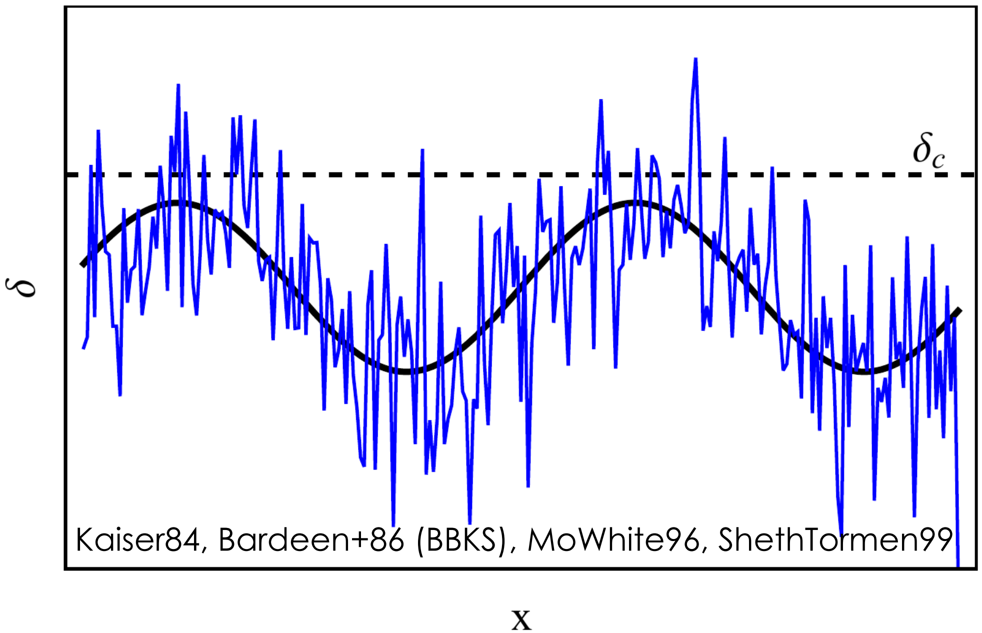
Same argument applies to other shapes (parametrization).

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

Galaxy bias

Proposition: I do not understand anything about galaxy formation ('UV' physics).
But I can do EFT!

$$\delta_g(L;x,z) \equiv \frac{n_g(L;x,z)-\bar{n}_g(L)}{\bar{n}_g(M)} = \sum_{\mathcal{O}} b_{\mathcal{O}}(L;z)\mathcal{O}(x,z)$$



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

Galaxy bias is defined as the response of the galaxy number density to the presence of long-wavelength modes

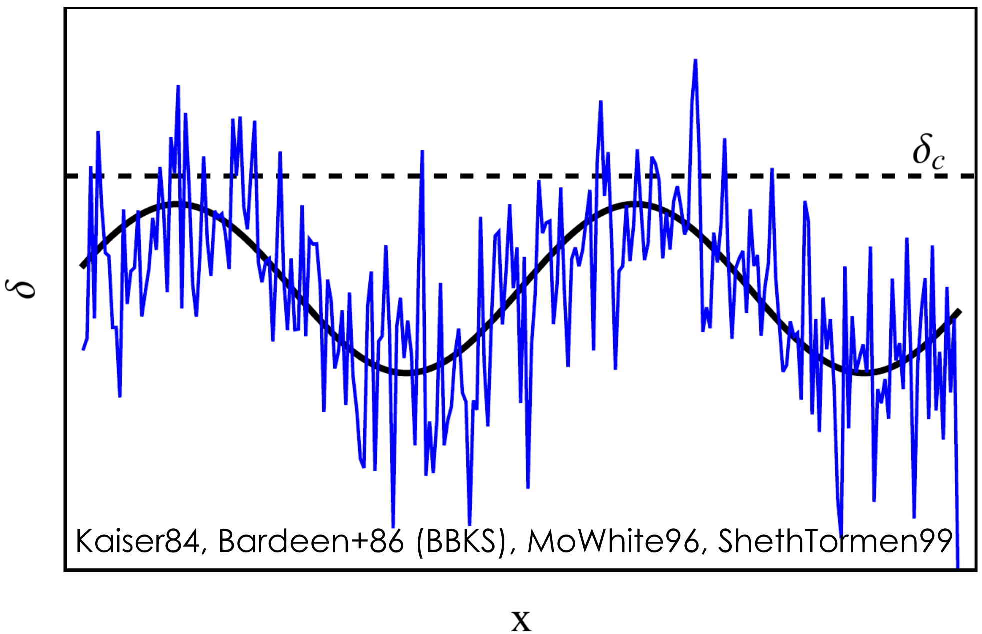
In a perfectly Gaussian Universe
the Equivalence Principle
and symmetries tells us that

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

Galaxy bias

Proposition: I do not understand anything about galaxy formation (‘UV’ physics).
But I can do EFT!

$$\delta_g(L;x,z) \equiv \frac{n_g(L;x,z) - \bar{n}_g(L)}{\bar{n}_g(M)} = \sum_{\mathcal{O}} b_{\mathcal{O}}(L;z)\mathcal{O}(x,z)$$



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

Galaxy bias is defined as the response of the galaxy number density to the presence of long-wavelength modes

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

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

Signatures of Primordial Non-Gaussianities

Luckily enough PNG show up in the galaxy power spectrum Dalal+08, Slosar+08

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

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

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

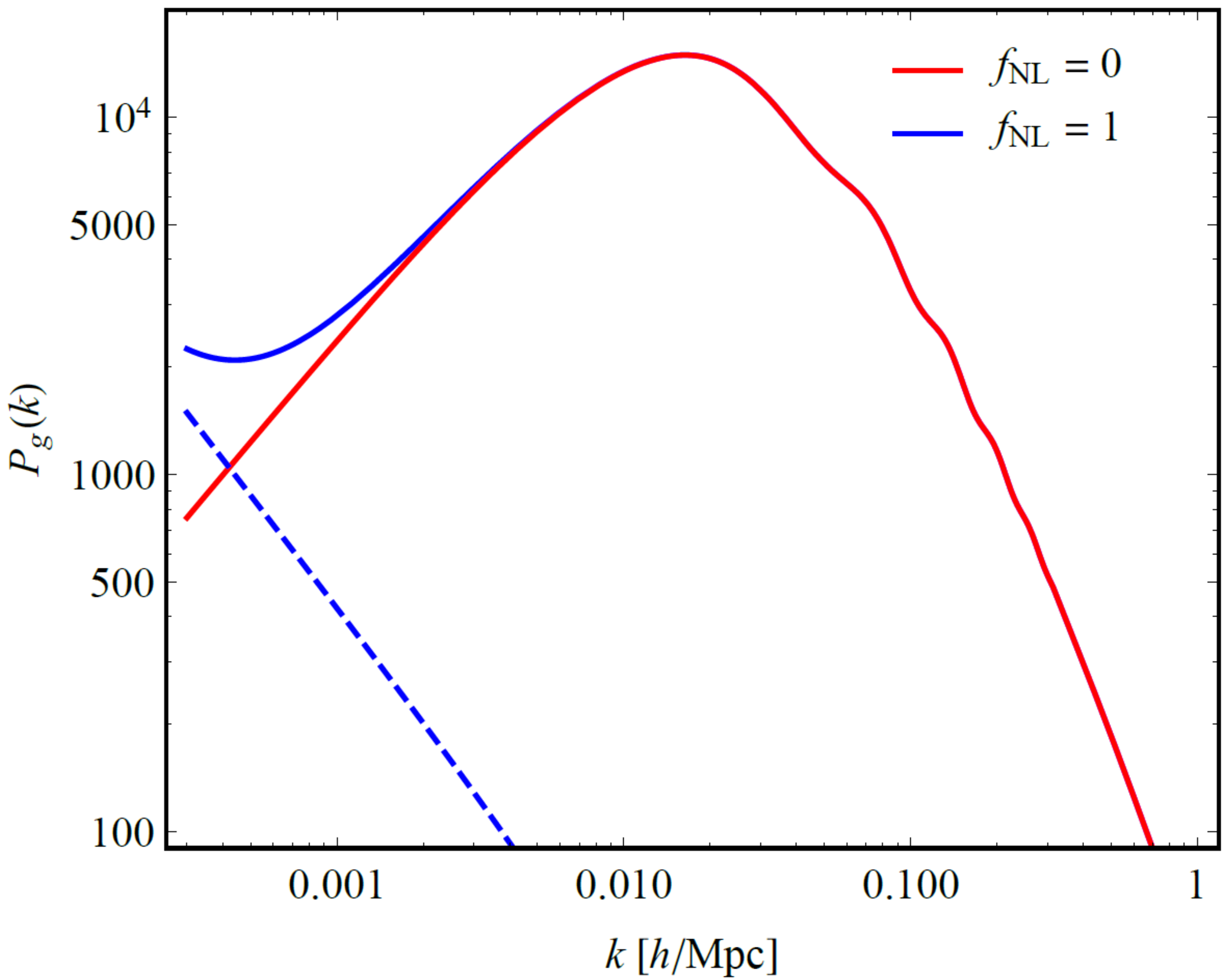
When I integrate out the short modes I have to introduce a term proportional to the gravitational potential

$$\delta_g \subset f_{\rm NL} b_\phi \Phi$$

Signatures of Primordial Non-Gaussianities

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

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

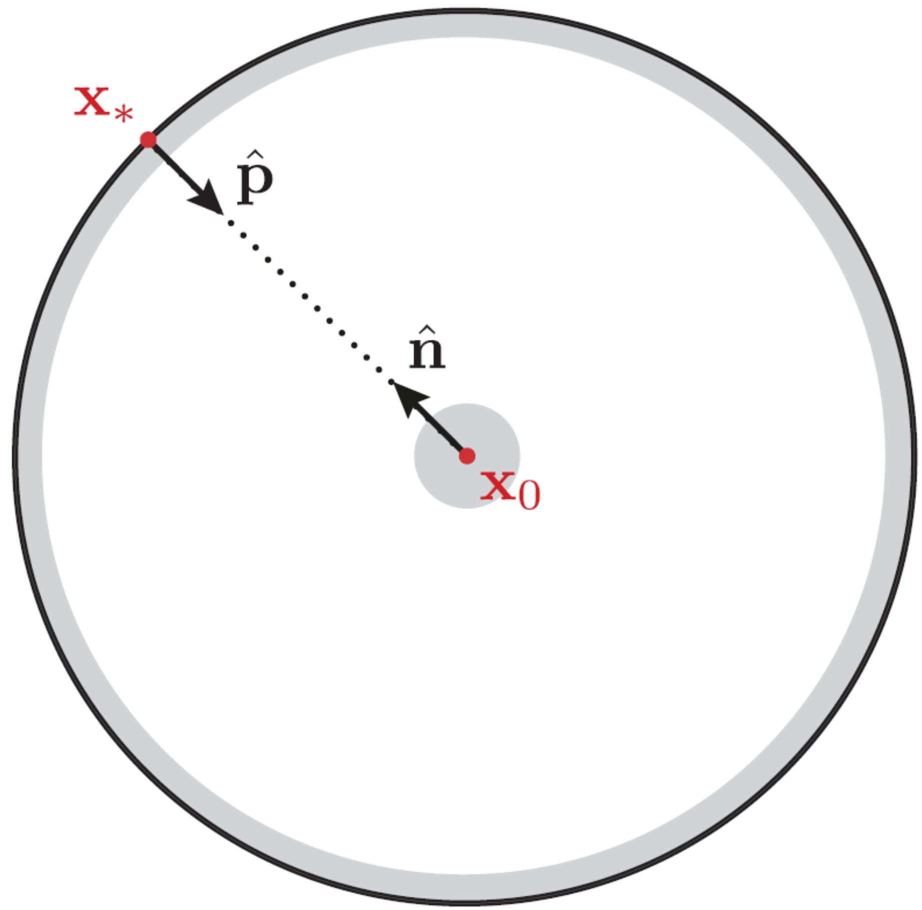


Do we understand large scales well enough for PNG~1 ?

PART II:

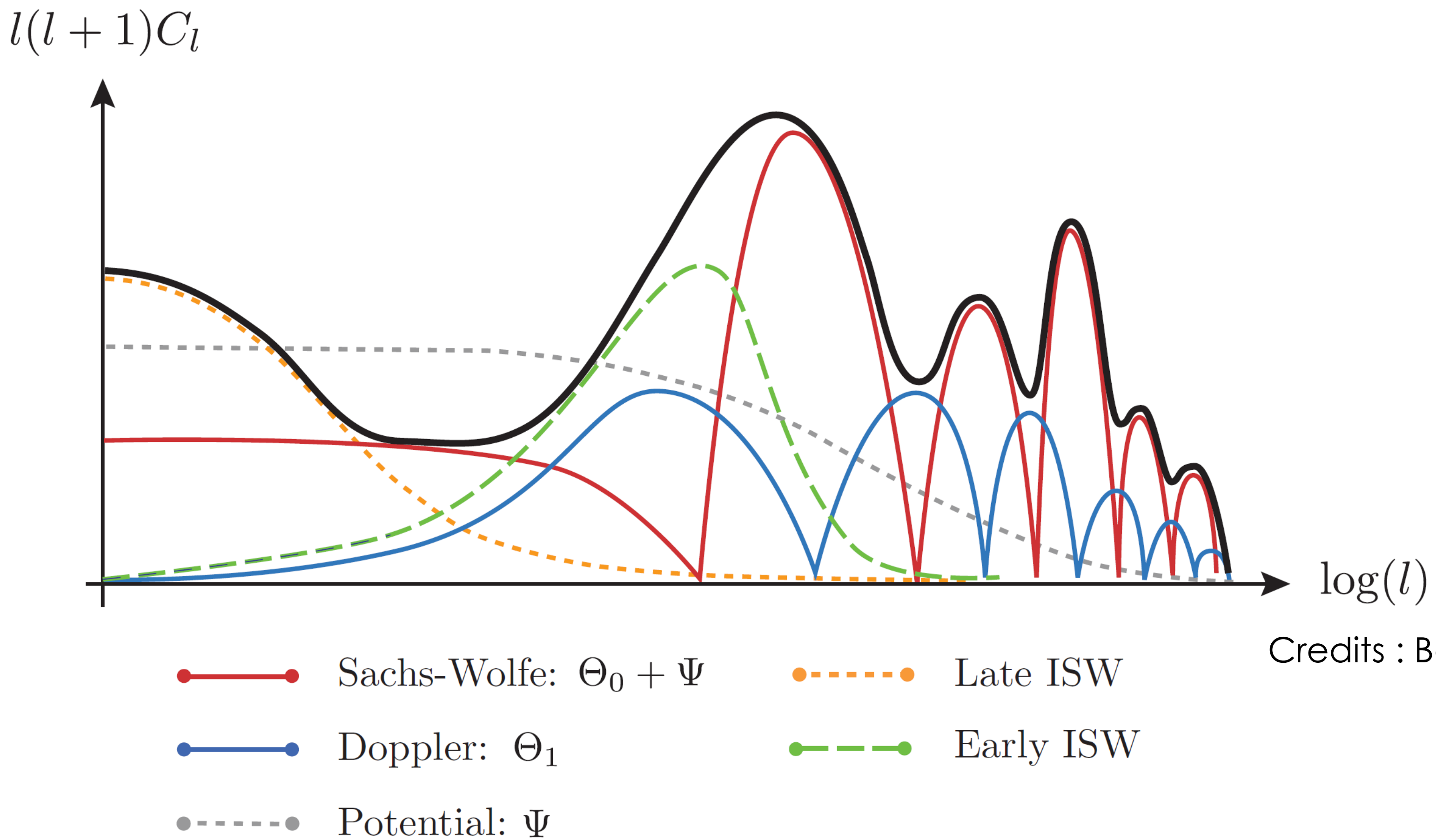
The large scale limit of the galaxy power spectrum

An analogy: the CMB



$$\tilde{\Theta}(\hat{\mathbf{n}}) \equiv \Theta(\eta_0, \mathbf{x}_0, \hat{\mathbf{n}}) \approx \underbrace{(\Theta_0 + \Psi)_*}_{\uparrow\ \text{SW}} - \underbrace{(\hat{\mathbf{n}} \cdot \mathbf{v}_e)_*}_{\uparrow\ \text{Doppler}} + \underbrace{\int_{\eta_*}^{\eta_0} \mathrm{d}\eta' \, (\dot{\Psi} + \dot{\Phi})}_{\uparrow\ \text{ISW}}$$

An analogy: the CMB

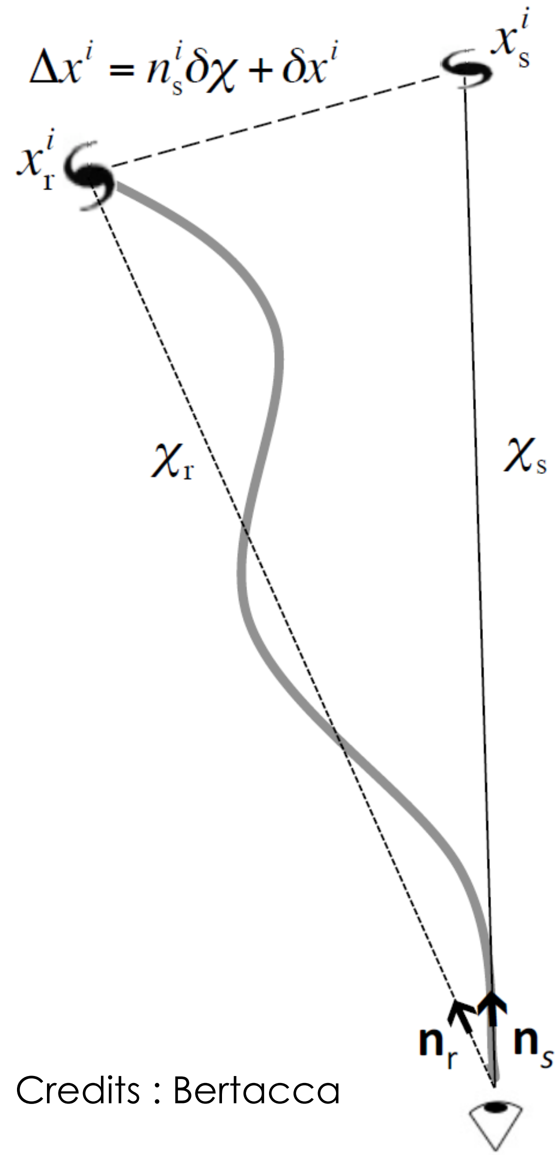


Credits : Baumann

$$\tilde{\Theta}(\hat{\mathbf{n}}) \equiv \Theta(\eta_0, \mathbf{x}_0, \hat{\mathbf{n}}) \approx \underset{\substack{\uparrow \\ \text{SW}}}{(\Theta_0 + \Psi)_*} - \underset{\substack{\uparrow \\ \text{Doppler}}}{(\hat{\mathbf{n}} \cdot \mathbf{v}_e)_*} + \int_{\eta_*}^{\eta_0} \underset{\substack{\uparrow \\ \text{ISW}}}{d\eta' \, (\dot{\Psi} + \dot{\Phi})}$$

Now for galaxies

$$\Delta_g = b_1\delta_g + \text{lensing} + \#\text{ of terms with }\Phi + \#\text{ of terms with }\int\dot{\Phi}$$
$$+\,\#\text{ of terms with }\nabla\Phi$$



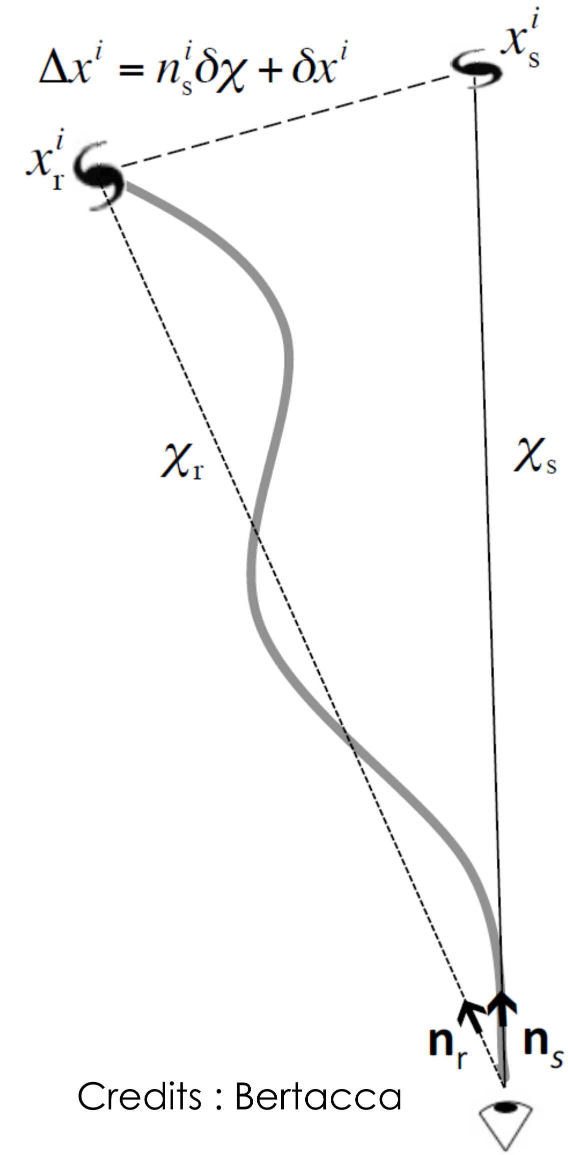
Credits : Bertacca

Now for galaxies

$$\Delta_g = \overbrace{\boxed{b_1 \delta_g + \text{lensing}}}^{\partial_i \partial_j \Phi} + \boxed{\# \text{ of terms with } \Phi + \# \text{ of terms with } \int \dot{\Phi}}$$

$$\boxed{+ \# \text{ of terms with } \nabla \Phi}$$

$$\frac{\mathcal{H}}{k} \partial_i \partial_j \Phi \qquad \left(\frac{\mathcal{H}}{k}\right)^2 \partial_i \partial_j \Phi$$



'Projection' effects proportional to the gravitational potential can be confused with local PNG.

How to compute the whole thing ?

Credits : Bertacca

Infra-Red divergences

Many of the other GR terms are either IR divergent or IR sensitive

$$\langle\, \Delta(\mathbf{s})_1)\Delta(\mathbf{s}_2)\,\rangle \supset \langle\, \Phi(\mathbf{s}_1)\Phi(\mathbf{s}_2)\,\rangle \sim \int \frac{\mathrm{d}q}{2\pi^2} q^{-2} P_m(q) j_0(q|\mathbf{s}_2 - \mathbf{s}_1|)$$

The divergence comes from the variance (contact term), q –> 0.

$$\xi^{\rm div}(s, s_1, \mu) \equiv \sum_{\mathcal{O}\mathcal{O}'} \xi^{\rm div}_{\mathcal{O}\mathcal{O}'}(s, s_1, \mu)$$

finite

$$\xi^{\rm div}\,(s, s_1, \mu) = \sum_{\mathcal{O}\mathcal{O}'} \xi^{\rm div}_{\mathcal{O}\mathcal{O}'}(s, s_1, \mu) = \boxed{\sum_{\mathcal{O}\mathcal{O}'} \tilde{\xi}^{\rm div}_{\mathcal{O}\mathcal{O}'}} + \sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\rm div}_{\mathcal{O}\mathcal{O}'}$$

Infra-Red divergences

Many of the other GR terms are either IR divergent or IR sensitive

$$\langle\, \Delta(\mathbf{s})_1)\Delta(\mathbf{s}_2)\,\rangle \supset \langle\, \Phi(\mathbf{s}_1)\Phi(\mathbf{s}_2)\,\rangle \sim \int \frac{\mathrm{d}q}{2\pi^2} q^{-2} P_m(q) j_0(q|\mathbf{s}_2 - \mathbf{s}_1|)$$

The divergence comes from the variance (contact term), q –> 0.

It turns out all IR divegences cancel among themselves in the sum

$$\xi^{\mathrm{div}}(s, s_1, \mu) \equiv \sum_{\mathcal{O}\mathcal{O}'} \xi^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'}(s, s_1, \mu)$$

finite

$$\xi^{\mathrm{div}}\,(s, s_1, \mu) = \sum_{\mathcal{O}\mathcal{O}'} \xi^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'}(s, s_1, \mu) = \boxed{\sum_{\mathcal{O}\mathcal{O}'} \tilde{\xi}^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'}} + \sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'}$$

$$\boxed{\sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'} = 0}$$

All terms are important, including ones at obsever positions

Infra-Red divergences

finite

$$\xi^{\mathrm{div}}(s, s_1, \mu) = \sum_{\mathcal{O}\mathcal{O}'} \xi^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'}(s, s_1, \mu) = \boxed{\sum_{\mathcal{O}\mathcal{O}'} \tilde{\xi}^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'}} + \sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'}$$

$$\boxed{\sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\mathrm{div}}_{\mathcal{O}\mathcal{O}'} = 0}$$

Cancellations like this one happen all the time. Can't be by chance !

- In QFT, Weinberg soft theorems, IR-div in QED etc...

- In Cosmology, very large or infinite terms cancel exactly in:

    - Loops in SPT, e.g. P22+P13 at 1-loop, 2-loop is divergent

    - Post-Born correction to lensing/shear observables

    - Now, GR/projection corrections to clustering

Infra-Red divergences

finite

$$\xi^{\rm div}(s,s_1,\mu)=\sum_{\mathcal{O}\mathcal{O}'}\xi^{\rm div}_{\mathcal{O}\mathcal{O}'}(s,s_1,\mu)=\boxed{\sum_{\mathcal{O}\mathcal{O}'}\tilde{\xi}^{\rm div}_{\mathcal{O}\mathcal{O}'}}+\sum_{\mathcal{O}\mathcal{O}'}(\sigma^2)^{\rm div}_{\mathcal{O}\mathcal{O}'}$$

$$\boxed{\sum_{\mathcal{O}\mathcal{O}'}(\sigma^2)^{\rm div}_{\mathcal{O}\mathcal{O}'}=0}$$

Cancellations like this one happen all the time. Can't be by chance !

- In QFT, Weinberg soft theorems, IR-div in QED etc...

- In Cosmology, very large or infinite terms cancel exactly in:

    - Loops in SPT, e.g. P22+P13 at 1-loop, 2-loop is divergent

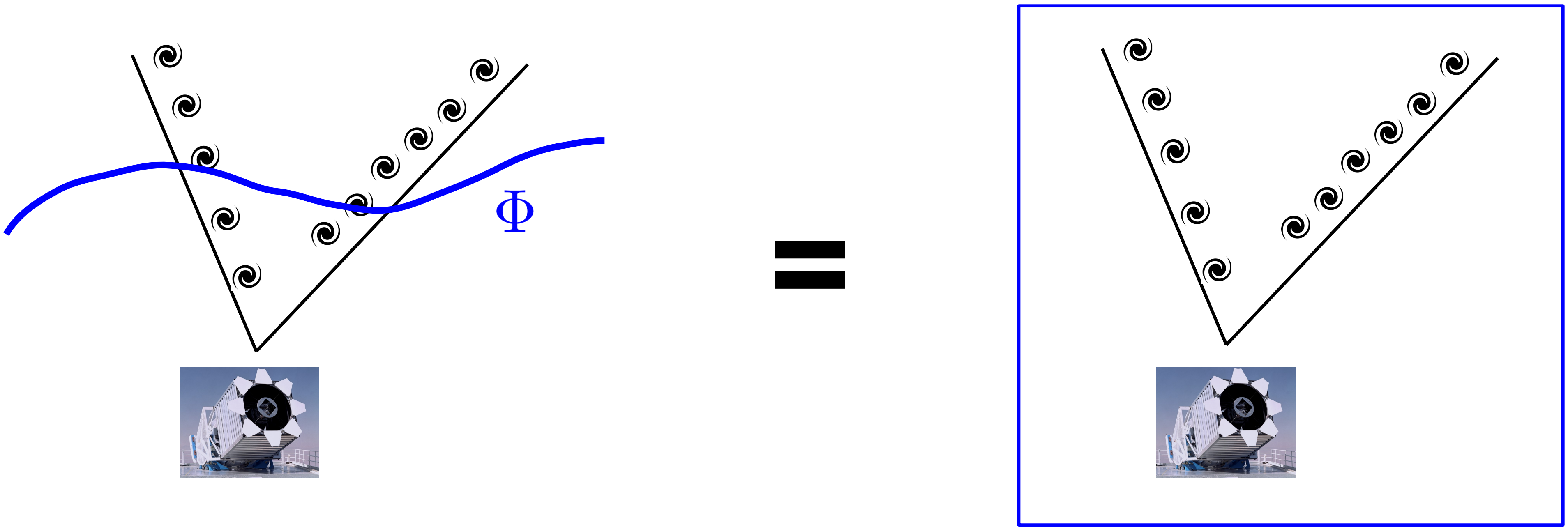
    - Post-Born correction to lensing/shear observables

    - Now, GR/projection corrections to clustering

Weinberg adiabatic mode, consistency relations

Adiabatic modes in cosmology

This is nothing else than the mathematical formulation of the elevator argument

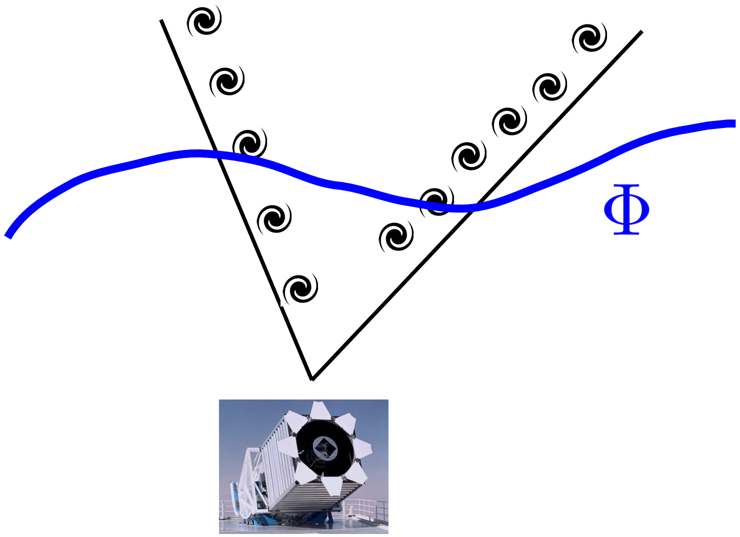


Residual diff-invariance allows under certain conditions
to absorb long-wavelength gravitational potential
in a change of coordinates

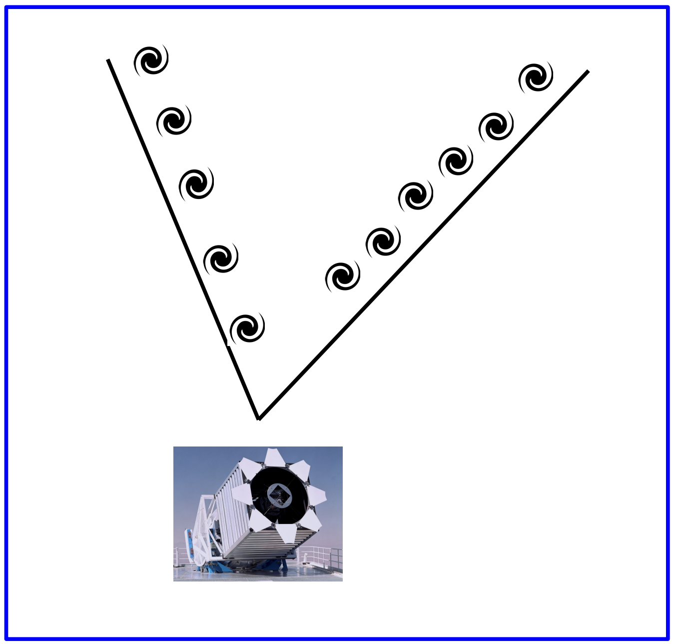
Weinberg04, Kheagias&Riotto13, Peloso&Pietroni13, Creminelli+13

Adiabatic modes in cosmology

This is nothing else than the mathematical formulation of the elevator argument



=



$$\sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\text{div}}_{\mathcal{O}\mathcal{O}'} = 0 \quad \longleftrightarrow \quad \Phi\left(k,\tau\right) + \frac{\mathcal{H}\left(\tau\right)}{k} v\left(k,\tau\right) = \text{constant} \quad \text{for} \quad k \to 0$$

Adiabatic modes in cosmology

This is nothing else than the mathematical formulation of the elevator argument

$$\sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\rm div}_{\mathcal{O}\mathcal{O}'} = 0 \longleftrightarrow \Phi\left(k,\tau\right) + \frac{\mathcal{H}\left(\tau\right)}{k} v\left(k,\tau\right) = \text{constant} \quad \text{for} \quad k \to 0$$

This is equivalent to the conservation of the comoving curvature perturbations outside the horizon.

This is the case for :

- Adiabatic initial conditions

- Absence of large scale anisotropic stresses

- Absence of local PNG

- GR is the only long range force

They all need to be valid for the cancellation. Same for Maldacena's CC.

Adiabatic modes in cosmology

This is nothing else than the mathematical formulation of the elevator argument

$$\sum_{\mathcal{O}\mathcal{O}'} (\sigma^2)^{\rm div}_{\mathcal{O}\mathcal{O}'} = 0 \quad \longleftrightarrow \quad \Phi\left(k,\tau\right) + \frac{\mathcal{H}\left(\tau\right)}{k} v\left(k,\tau\right) = \text{constant} \quad \text{for} \quad k \to 0$$

This is equivalent to the conservation of the comoving curvature perturbations outside the horizon.

This is the case for :

- Adiabatic initial conditions
- Absence of large scale anisotropic stresses
- Absence of local PNG
- GR is the only long range force

They all need to be valid for the cancellation.

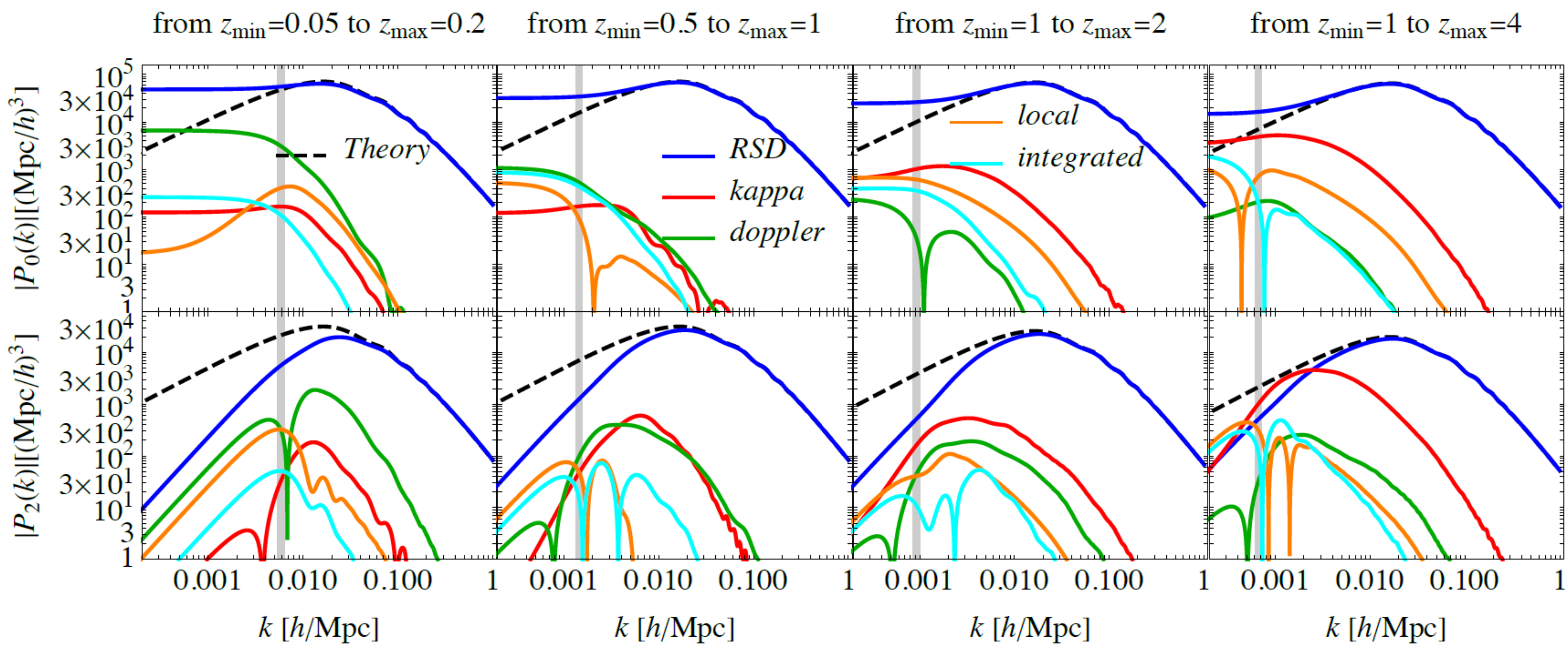
Aficionados' box

All other IR sensitivities are removed

We disagree with Grimm+20, their P(k) is not the observed one

Away from k→0, still go as k^-4

The galaxy power spectrum in General Relativity



Doppler dominates at low-z, lensing at high-z. All the rest is negligible.

Window function much more important than projection effects.

Summary

We can compute the full GR power spectrum including all GR effects, arbitrary window functions, and other observational effects.

- We now understand why flat-sky limit works

- Figured out the IR safe expressions for the observables. Relation to adiabatic modes and LSS consistency relations.

- Projection effects are not very important, few % at most.

What about local PNG ? Are they affected by GR terms ?

- Quantitative statements await computation of the covariance in GR

Thank you !