Consistency relations of the large scale structure

and how to break them

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Surveys for Cosmology

Many new surveys to come online: **LSST, WFIRST, EUCLID,…**

What's causing the accelerated expansion of the Universe ?

Cosmological constant?

Dark Energy?

Modifications of General Relativity?

And more

Equivalence Principle (EP)

→ Do all objects fall the same way?

Cornerstone of GR

Initial conditions

→ Is the distribution initially Gaussian?

Prediction of simplest inflation models

Simplest case and consistency relations

Breaking the Equivalence Principle

Non Gaussian initial conditions

Simplest case
and
consistency relations

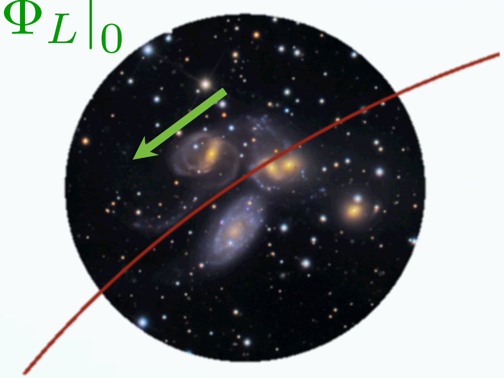
Consistency relations

Assume Equivalence Principle

$$\Phi_L(\eta, \vec{x}) = \Phi_L(\eta)|_0 + \partial_i \Phi_L(\eta)|_0 \, x^i + \boxed{\partial_i \partial_j \Phi_L(\eta)|_0 \, x^i x^j} + \ldots$$

Consistency relations

Assume Equivalence Principle



$$\equiv$$

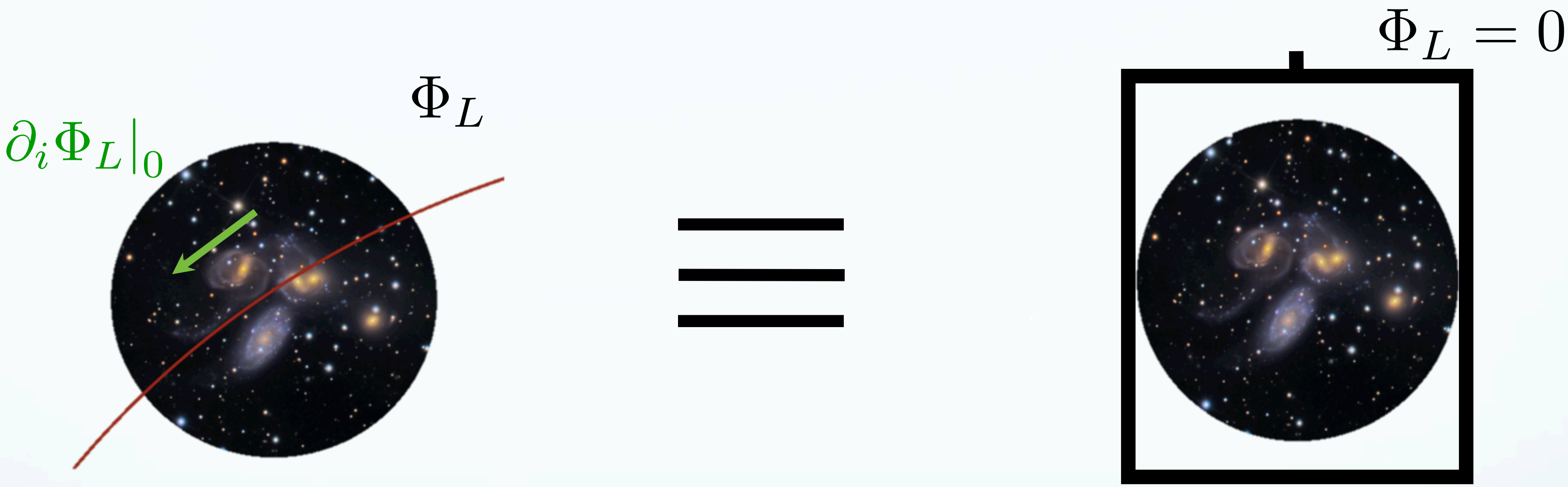
$$\vec{x} \to \tilde{\vec{x}} \equiv \vec{x} + \delta\vec{x}$$

$$\delta\vec{x}(\eta,\vec{p}) = -i\frac{\vec{p}}{p^2}\delta_L(\eta,\vec{p}) \propto \Phi_L(\eta,\vec{p})$$

$$\langle \delta^{(g)}(\eta_1,\vec{x}_1)\cdots\delta^{(g)}(\eta_n,\vec{x}_n)|\Phi_L\rangle = \langle \delta^{(g)}(\eta_1,\tilde{\vec{x}}_1)\cdots\delta^{(g)}(\eta_n,\tilde{\vec{x}}_n)\rangle$$

Consistency relations

Assume Equivalence Principle



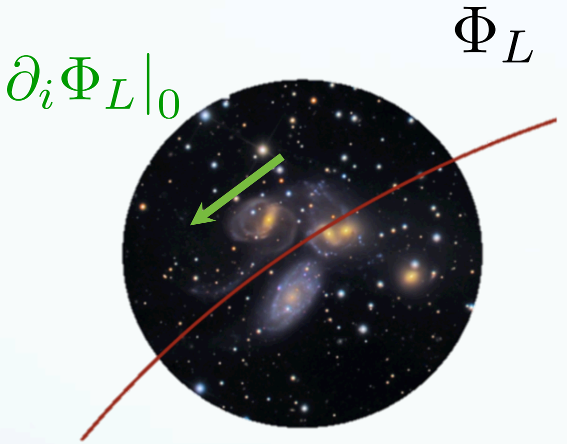
Assume Gaussianity

(no correlations long/short)

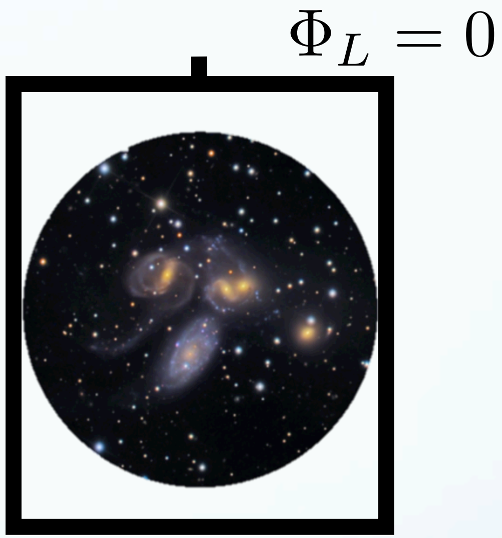
$$\langle \delta^{(g)}(\eta_1, \vec{x}_1) \cdots \delta^{(g)}(\eta_n, \vec{x}_n) | \Phi_L \rangle = \langle \delta^{(g)}(\eta_1, \vec{\tilde{x}}_1) \cdots \delta^{(g)}(\eta_n, \vec{\tilde{x}}_n) \rangle$$

Consistency relations

Assume Equivalence Principle



$$\equiv$$



Assume Gaussianity
(no correlations long/short)

$$\langle \delta_{\vec{p}}(\eta) \delta^{(g)}_{\vec{k}_1}(\eta_1) \cdots \delta^{(g)}_{\vec{k}_n}(\eta_n) \rangle'_{\vec{p}\to 0} = -P(p,\eta) \sum_a \frac{D(\eta_a)}{D(\eta)} \frac{\vec{k}_a \cdot \vec{p}}{p^2} \langle \delta^{(g)}_{\vec{k}_1}(\eta_1) \cdots \delta^{(g)}_{\vec{k}_n}(\eta_n) \rangle'$$

Riotto et al '13 Creminelli et al, '13

Consistency relations

$$\langle \delta_{\vec p}(\eta)\delta^{(g)}_{\vec k_1}(\eta_1)\cdots\delta^{(g)}_{\vec k_n}(\eta_n)\rangle'_{\vec p\to 0} = -P(p,\eta)\sum_a \frac{D(\eta_a)}{D(\eta)}\frac{\vec k_a\cdot\vec p}{p^2}\langle \delta^{(g)}_{\vec k_1}(\eta_1)\cdots\delta^{(g)}_{\vec k_n}(\eta_n)\rangle'$$

Linear

Non perturbative

$$\delta(\eta,\vec k) = D(\eta)\delta_0(\vec k)$$

- Extensions

Full relativistic treatment — *Creminelli et al, '13*

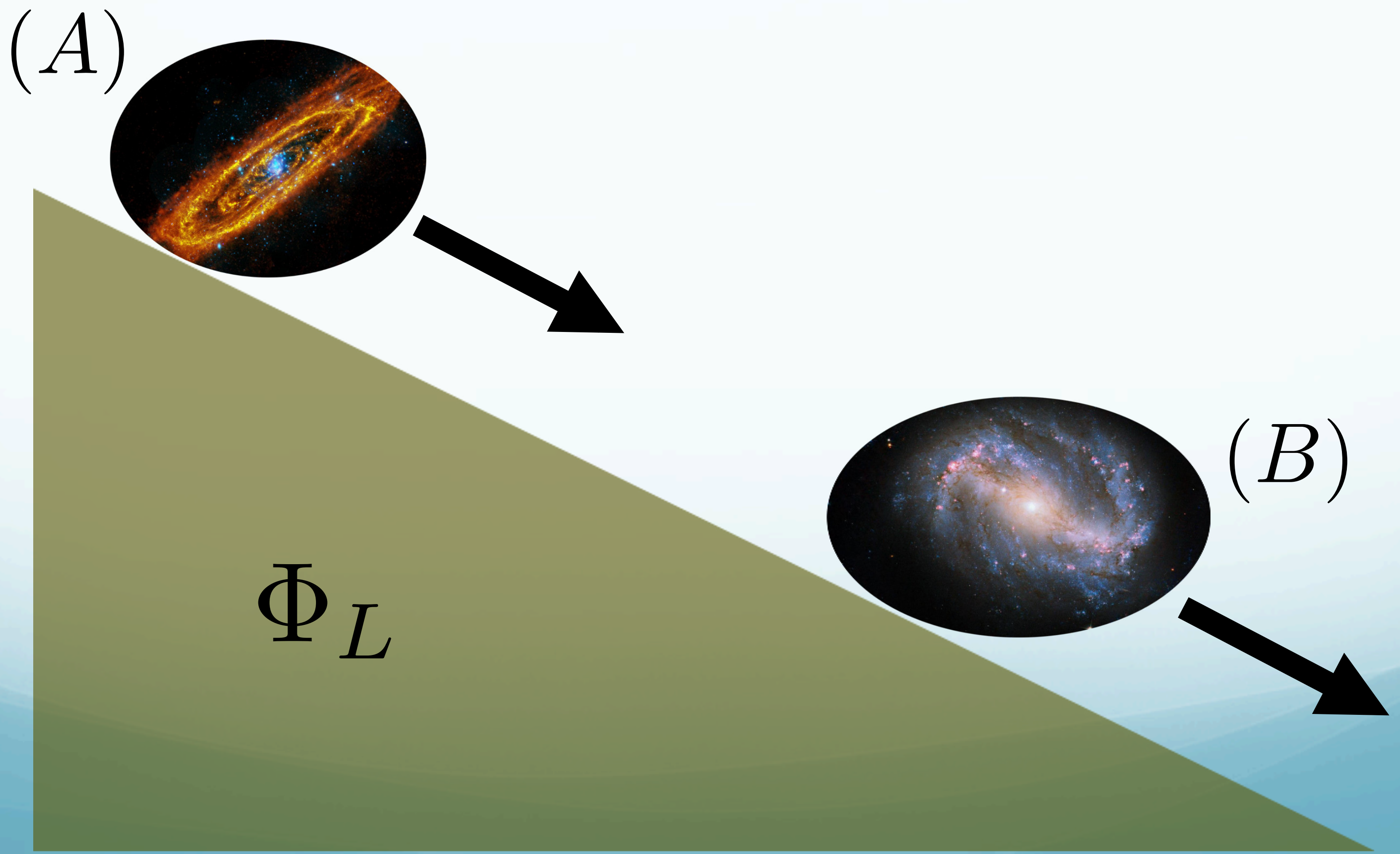
Redshift space — *with Creminelli, Simonović and Vernizzi, '13*

- Equal time correlators

$$\langle \delta_{\vec p}(\eta)\delta^{(g)}_{\vec k_1}(\eta)\cdots\delta^{(g)}_{\vec k_n}(\eta)\rangle_{p\to 0} = \mathcal{O}([k/p]^0)$$

Equal time correlators

$$\langle \delta_{\vec{p}}(\eta)\delta^{(A)}_{\vec{k}_1}(\eta)\delta^{(B)}_{\vec{k}_2}(\eta)\rangle = \mathcal{O}[(k/p)^0]$$



Breaking the assumptions

✧ Equivalence principle

$$\langle \delta_{\vec{p}}(\eta)\delta^{(A)}_{\vec{k}_1}(\eta)\delta^{(B)}_{\vec{k}_2}(\eta)\rangle'_{p\to 0} = \left(\epsilon\,\frac{\vec{p}\cdot\vec{k}}{p^2} + \mathcal{O}[(k/p)^0]\right) P(\eta,p)P_{AB}(\eta,k)$$

Model dependent

✧ Correlation short-long modes

➞ Local Non Gaussianity $\quad \Phi = \Phi_{\rm G} + f_{\rm NL}^{\rm Loc}(\Phi_{\rm G}^2 - \langle\Phi_{\rm G}\rangle^2)$

$$\langle \delta_{\vec{p}}(\eta)\delta_{\vec{k}_1}(\eta)\delta_{\vec{k}_2}(\eta)\rangle'_{p\to 0} = \left(\frac{6 f_{\rm NL}^{\rm Loc}\Omega_{\rm m,0}H_0^2}{p^2 T(p) D(\eta)} + \mathcal{O}[(k/p)^0]\right) P(\eta,p)P(\eta,k)$$

Peloso & Pietroni '13

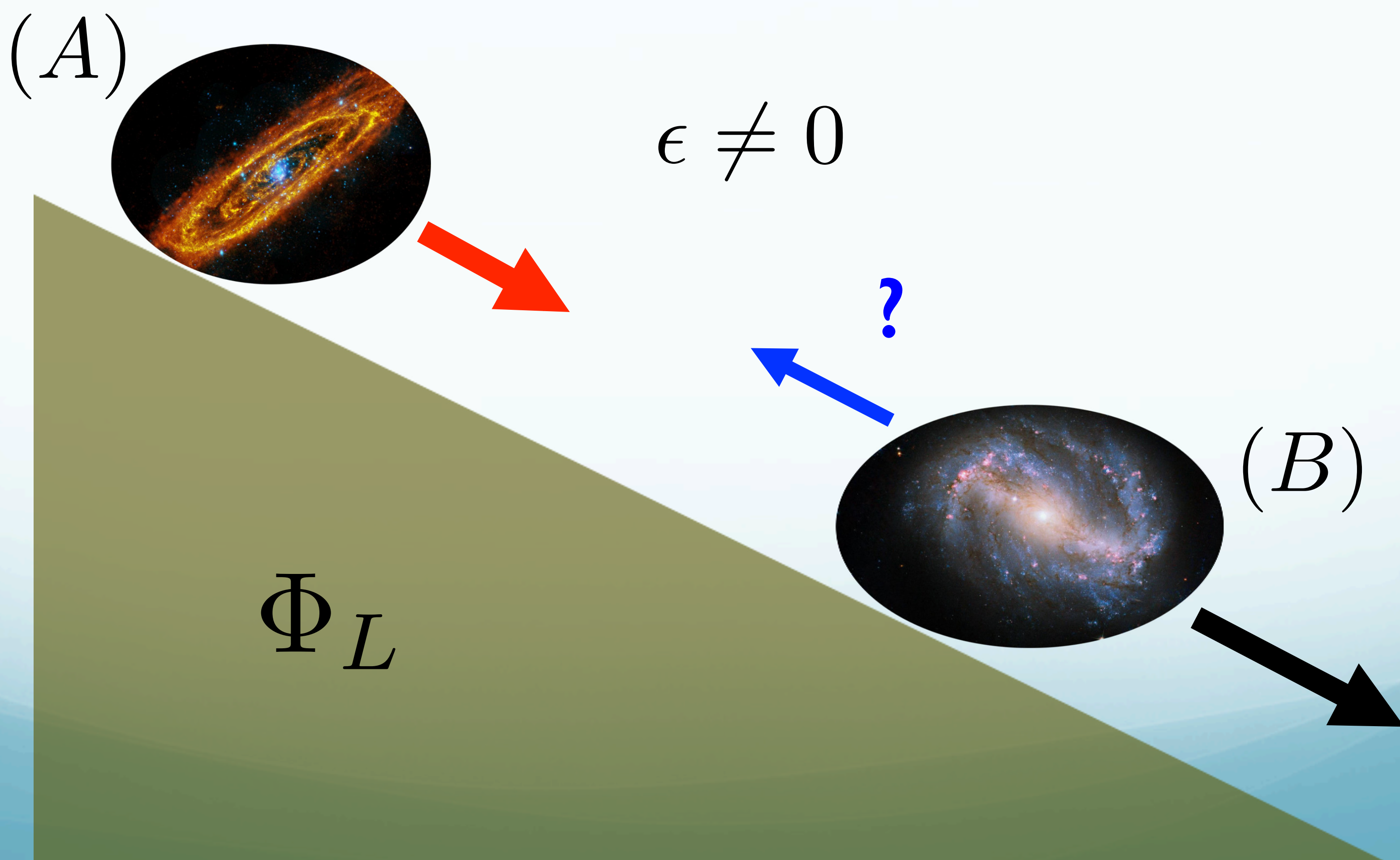
Breaking
the
Equivalence Principle

Motivations

- Test of gravity on unusual scales
- Extra coupling in the dark sector
- Difference screened/unscreened in modified gravity

The physical picture

$$\langle \delta_{\vec{p}}(\eta)\delta^{(A)}_{\vec{k}_1}(\eta)\delta^{(B)}_{\vec{k}_2}(\eta)\rangle'_{p\to 0} = \left(\epsilon\,\frac{\vec{p}\cdot\vec{k}}{p^2} + \mathcal{O}[(k/p)^0]\right) P(\eta,p)P_{AB}(\eta,k)$$



A toy model

with Creminelli, Hui, Simonović and Vernizzi, '13

Extra scalar field couples only to dark matter (B) but not baryons (A)

- ✧ Brans-Dicke type coupling: extra force $\alpha \nabla \varphi \quad \varphi \propto \alpha \Phi$

- ✧ Compute full bispectrum with SPT

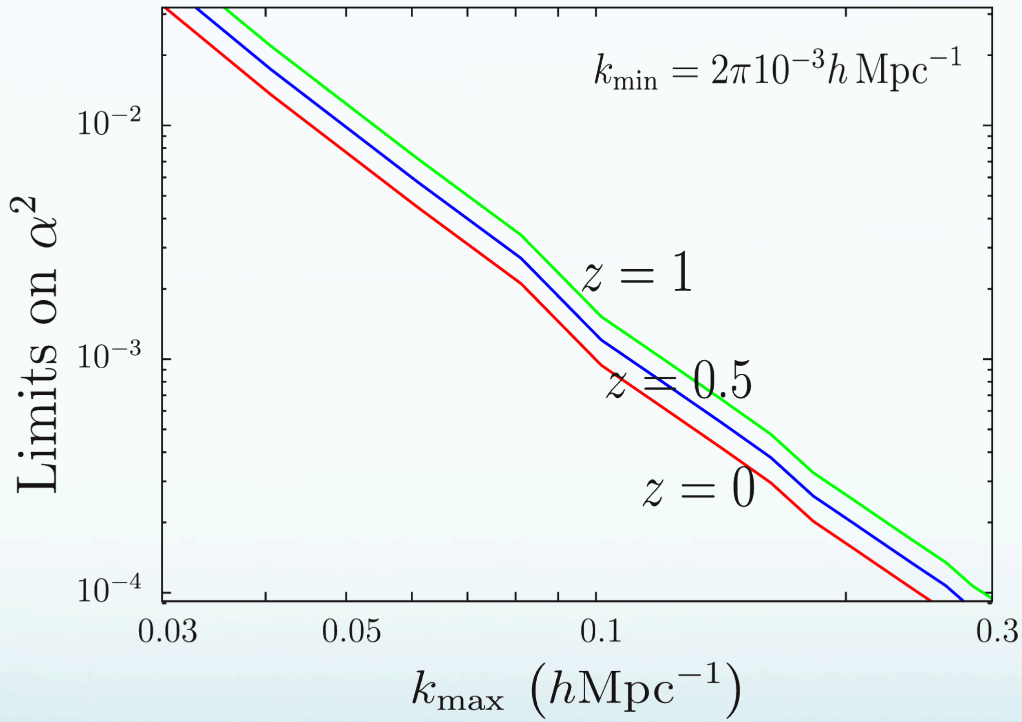
$$\langle \delta_{\vec{p}}(\eta) \delta^{(A)}_{\vec{k}_1}(\eta) \delta^{(B)}_{\vec{k}_2}(\eta) \rangle'_{p \to 0} = \left(\epsilon \frac{\vec{p} \cdot \vec{k}}{p^2} + \mathcal{O}[(k/p)^0] \right) P(\eta, p) P_{AB}(\eta, k)$$

$\epsilon \propto \alpha^2$

The results

$\epsilon \propto \alpha^2$

$$\langle \delta_{\vec{p}}(\eta)\delta^{(A)}_{\vec{k}_1}(\eta)\delta^{(B)}_{\vec{k}_2}(\eta)\rangle'_{p\to 0} = \left(\epsilon\,\frac{\vec{p}\cdot\vec{k}}{p^2} + \mathcal{O}[(k/p)^0]\right) P(\eta,p)P_{AB}(\eta,k)$$



Constraint from growth $\alpha^2 \lesssim 10^{-4}$

with Langlois, Mancarella and Vernizzi '15

→ More prone to degeneracies

Primordial Non-Gaussianity (PNG)

Why study non-Gaussianity?

$$\Phi = \Phi_{\mathrm{G}} + f_{\mathrm{NL}}^{\mathrm{Loc}}(\Phi_{\mathrm{G}}^2 - \langle\Phi_{\mathrm{G}}\rangle^2)$$

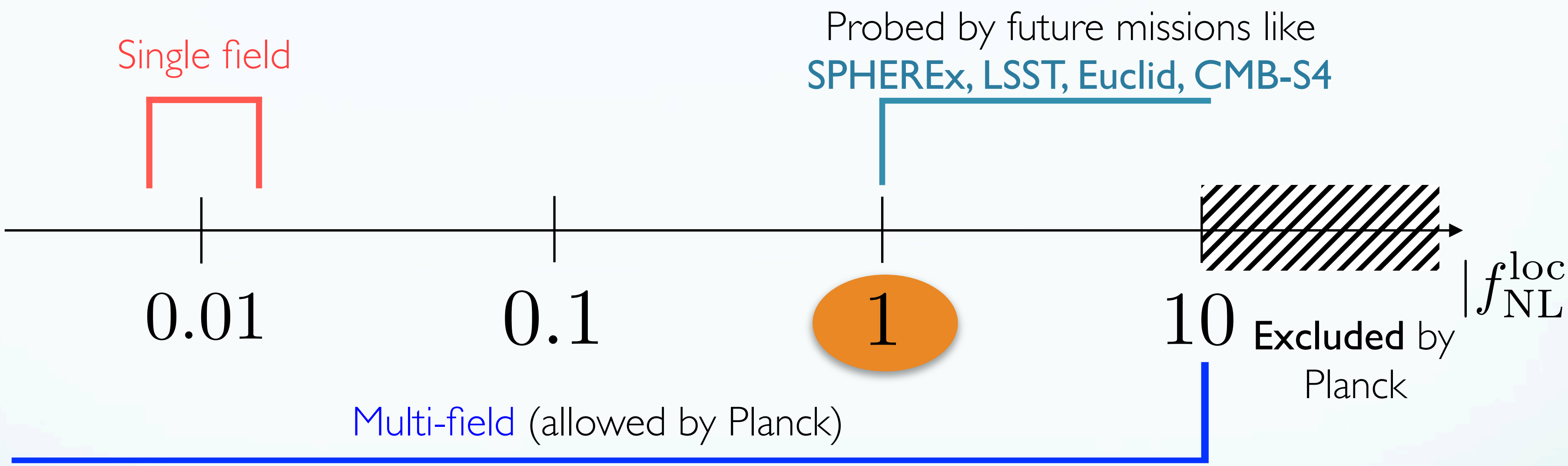
$\rightarrow$ $f_{\mathrm{NL}}^{\mathrm{loc}}$ $\longrightarrow$ $-\frac{5}{12}(n_s - 1)$ *Maldacena '02*

Single field inflation *Creminelli & Zaldarriaga '04*

$\longrightarrow$?

Multi-field inflation

Why study non-Gaussianity?



$$\mathrm{Prob}(|f_{\rm NL}^{\rm Loc}| > 1) \gtrsim 50\%^{*}$$

with de Putter and Doré **arXiv:1612.05248**

$*$: 2-field models with spectator field

Measuring PNG from surveys

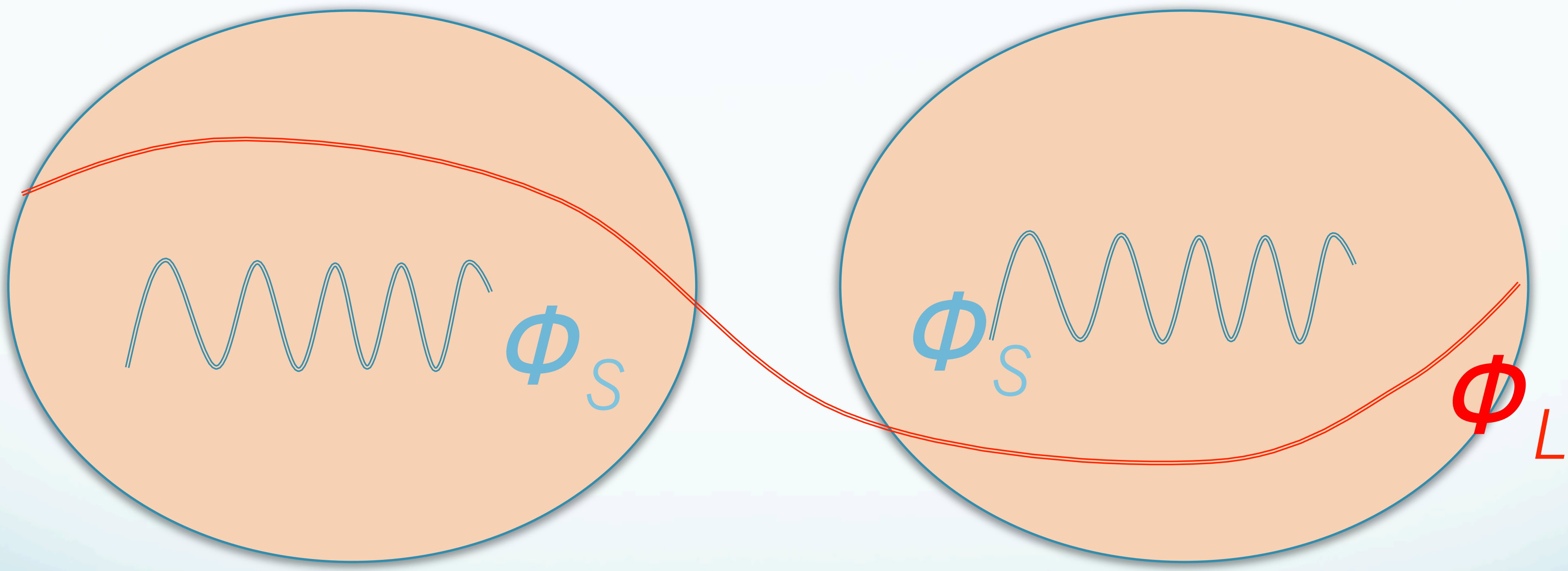
- CMB: Bispectrum

$$\sigma(f_{\rm NL}^{\rm Loc}) \sim 5$$

- Galaxy surveys: scale-dependent bias

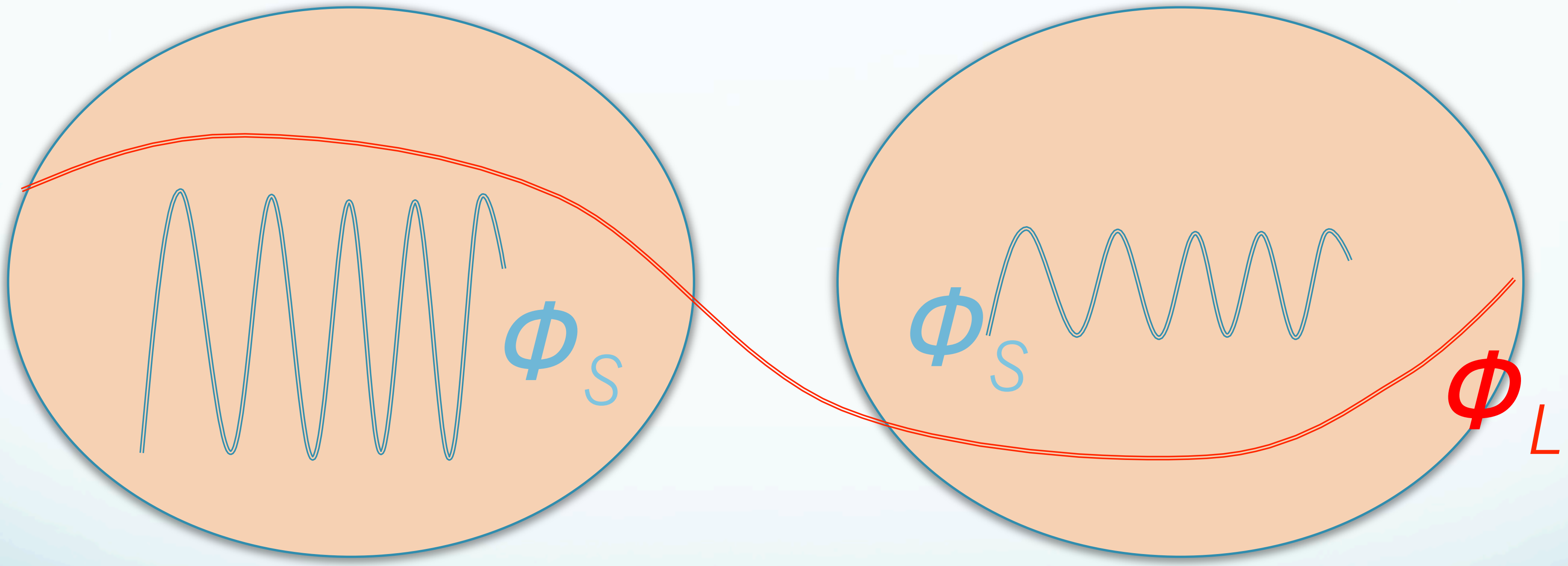
Scale-dependent bias

Single field inflation



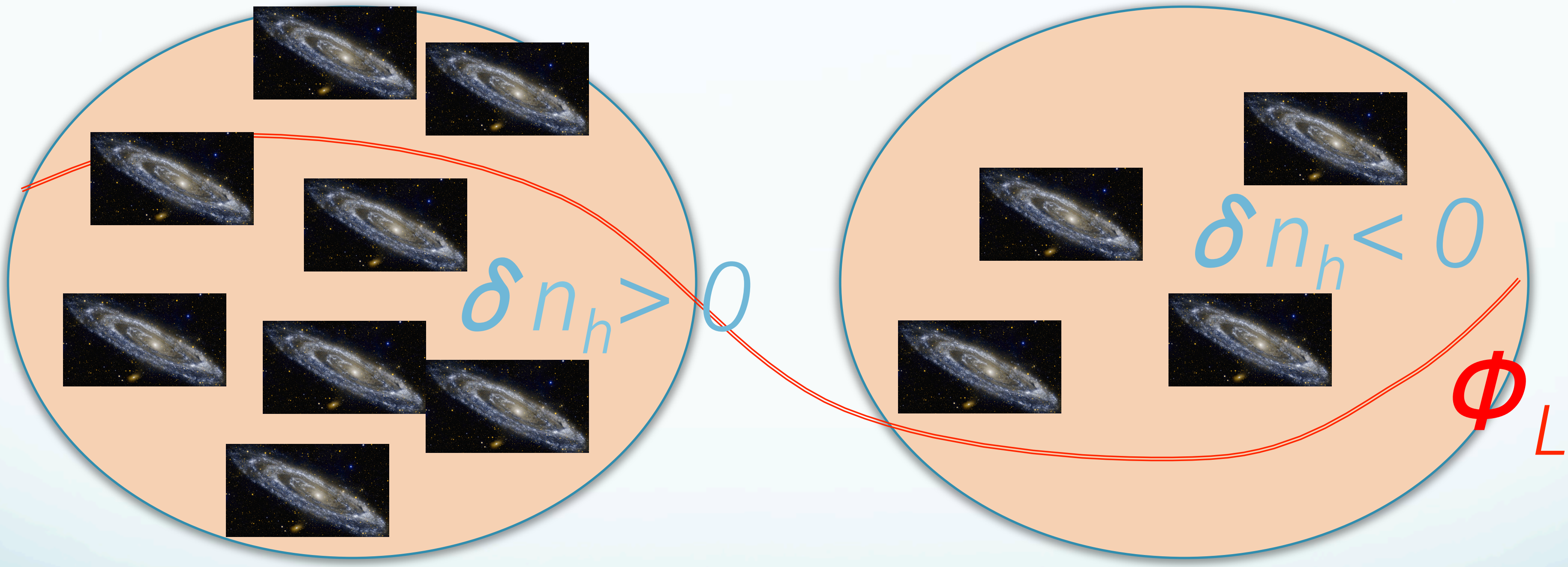
Scale-dependent bias

Multi-field inflation



Scale-dependent bias

Multi-field inflation



Scale-dependent bias

Scale-dependent bias

- Local PNG

$$\mathcal{M}(q) \equiv \frac{2q^2 T(q) D(z)}{3\Omega_m H_0^2}$$

$$b_{\rm NG}(q) = 2\, f_{\rm NL}^{\rm Loc}\,(b_\delta - 1)\,\delta_c\,\mathcal{M}^{-1}(q) \sim \frac{1}{q^2 T(q)}$$

- Equilateral PNG

Typical size of halos

$$b_{\rm NG}(q) = 6\, f_{\rm NL}^{\rm Eq}\,(b_\delta - 1)\,\delta_c\,(q\,R_*)^2\,\mathcal{M}^{-1}(q) \sim \frac{1}{T(q)}$$

Biasing and PNG

with de Putter, Green and Doré **arXiv:1612.06366**

- Generalized model of bias *McDonald & Roy '09, Assassi et al '15*

$$\delta_h = b_\delta \delta + b_{\mathrm{NG}}(q)\delta + F_{\mathrm{nonlocal}}[\nabla^2\delta] + F_{\mathrm{nonlinear}}[\delta]$$

$$\delta^2$$

$$\left[b_{q^2}(qR_*)^2 + b_{q^4}(qR_*)^4\right]\delta$$

Seen in simulations *Chan et al '12, Baldauf et al '12*

- Evolution or PNG?

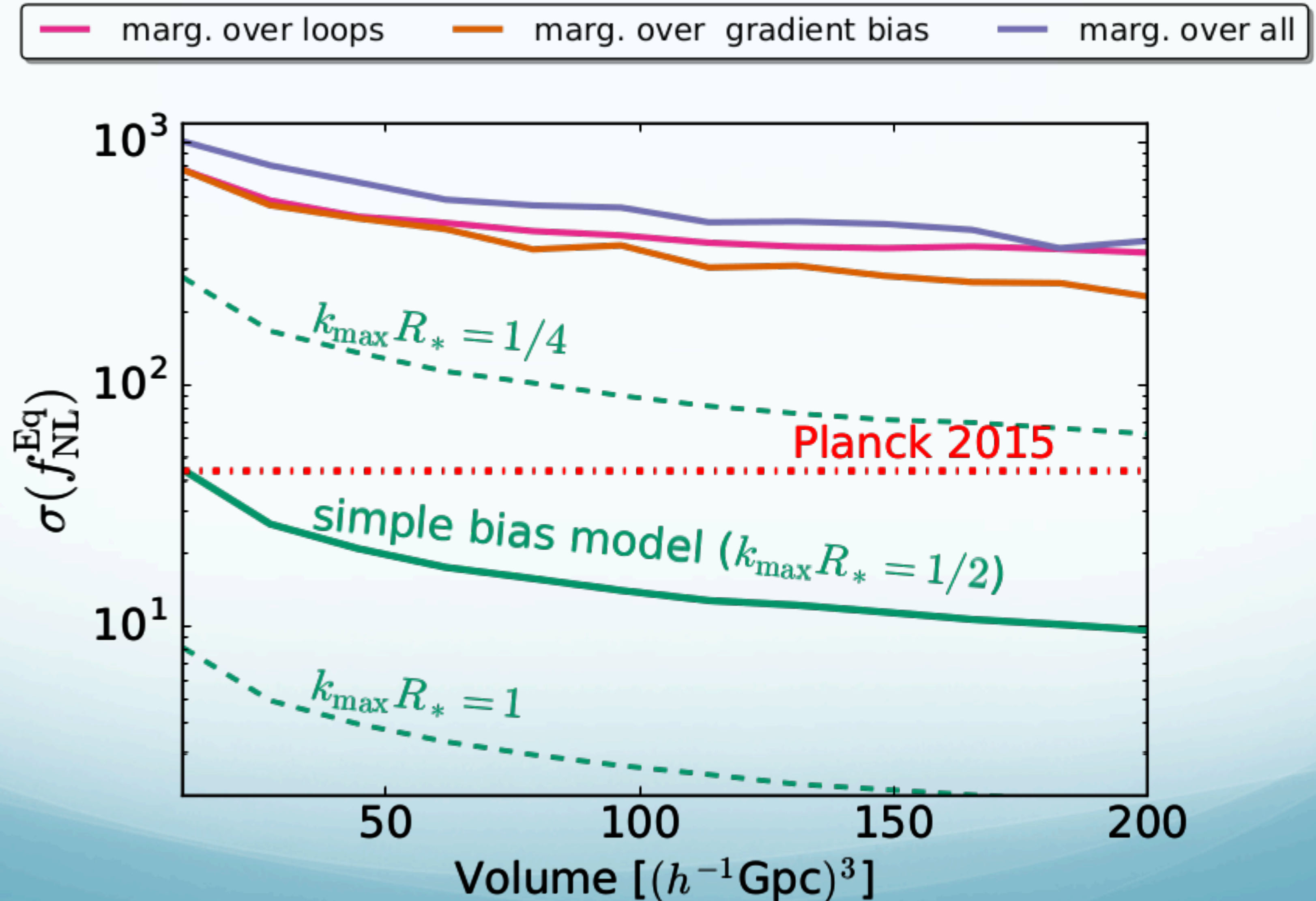
$$T(q) \sim 1 + T_1 q^2 + T_2 q^4$$

$b_{\mathrm{NG}}^{\mathrm{Loc}} \sim q^{-2}$ ✓

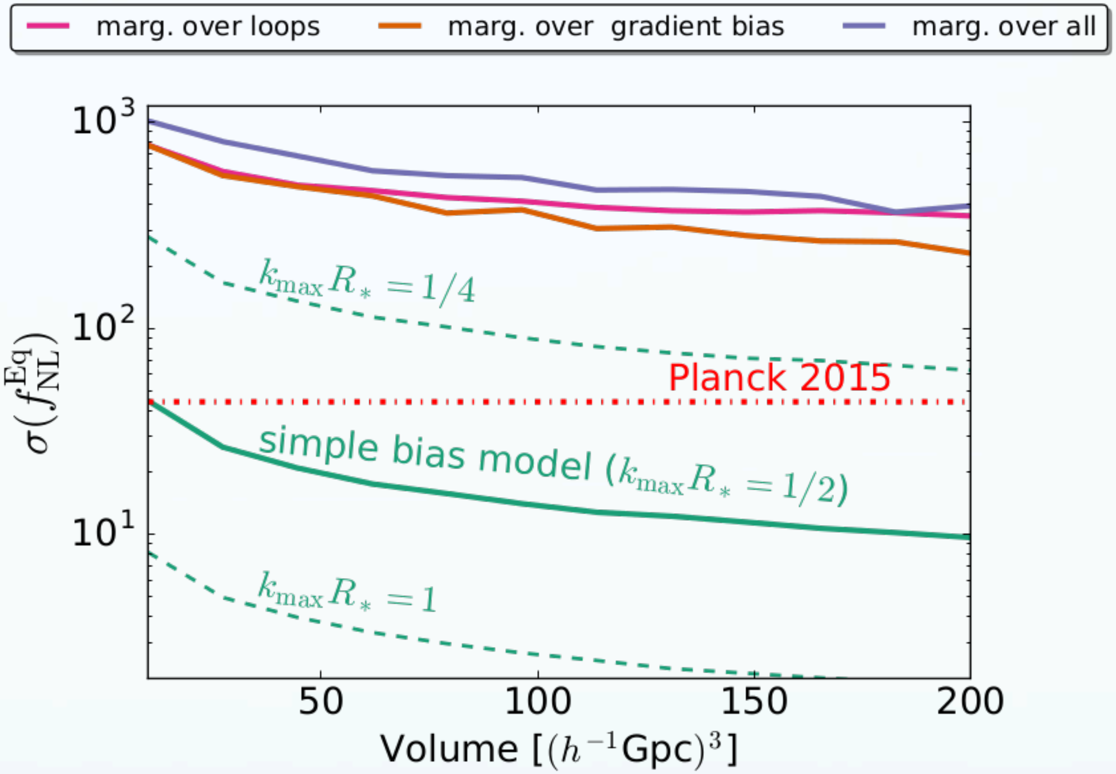
$b_{\mathrm{NG}}^{\mathrm{Eq}} \sim c + c_1 q^2 + \cdots$ **?**

Consistency relation ***not*** broken

Equilateral PNG and bias



Equilateral PNG and bias



What is helping us

$$F_{\rm nonlocal}[\nabla^2\delta] \quad \longrightarrow \quad R_*^{-1} > k_{\rm max}$$

$$T(q) \quad \longrightarrow \quad k_{\rm eq} \sim 10^{-2} h/{\rm Mpc} < k_{\rm max} \sim 10^{-1} h/{\rm Mpc}$$

Conclusions

Consistency relations are robust consequences of $\Lambda\mathrm{CDM}$

Not satisfied if Equivalence principle is broken $\longrightarrow$ $\sigma(\epsilon) \sim 10^{-3}$

Broken in multi-field inflation, with $f_{\mathrm{NL}}^{\mathrm{Loc}} \sim 1$ for spectator fields

Unbroken for equilateral PNG $\longrightarrow$ degenerate with evolution

Bispectrum more appropriate for PNG beyond local