Jet Propulsion Laboratory
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# 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

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

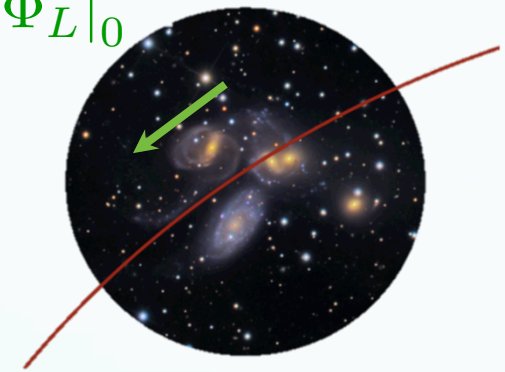
# Consistency relations

Assume Equivalence Principle

$\Phi_L = 0$

$\partial_i \Phi_L|_0$

$\Phi_L$



$\equiv$

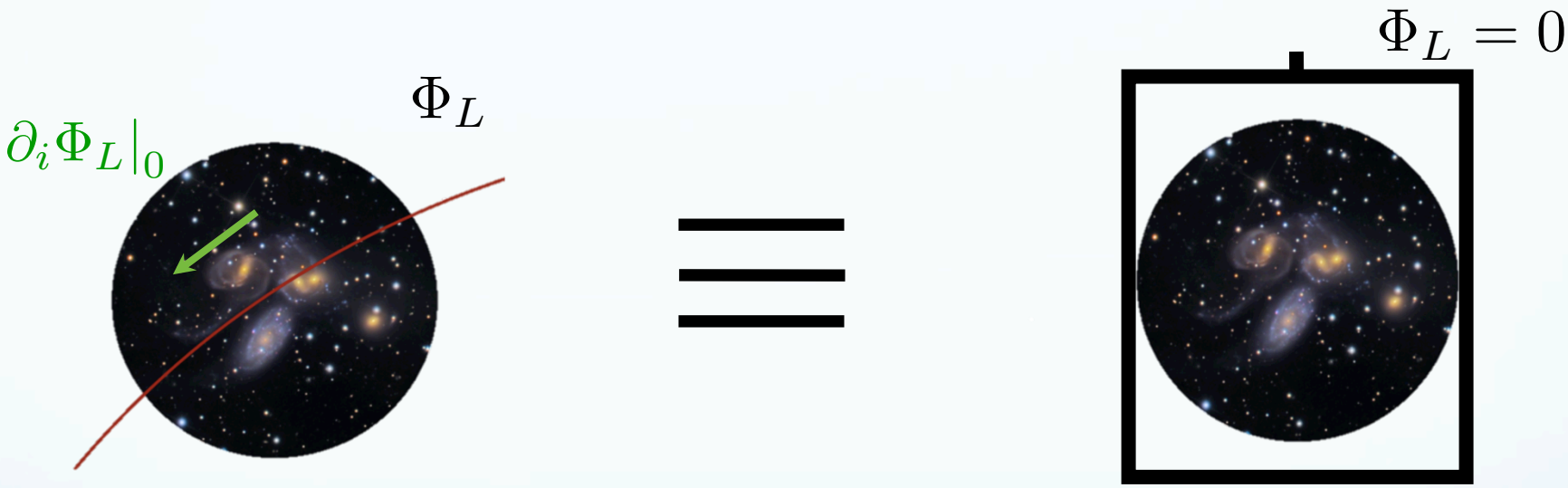
$$\vec{x} \to \vec{\tilde{x}} \equiv \vec{x} + \delta\vec{x}$$

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

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

# Consistency relations

Assume Equivalence Principle

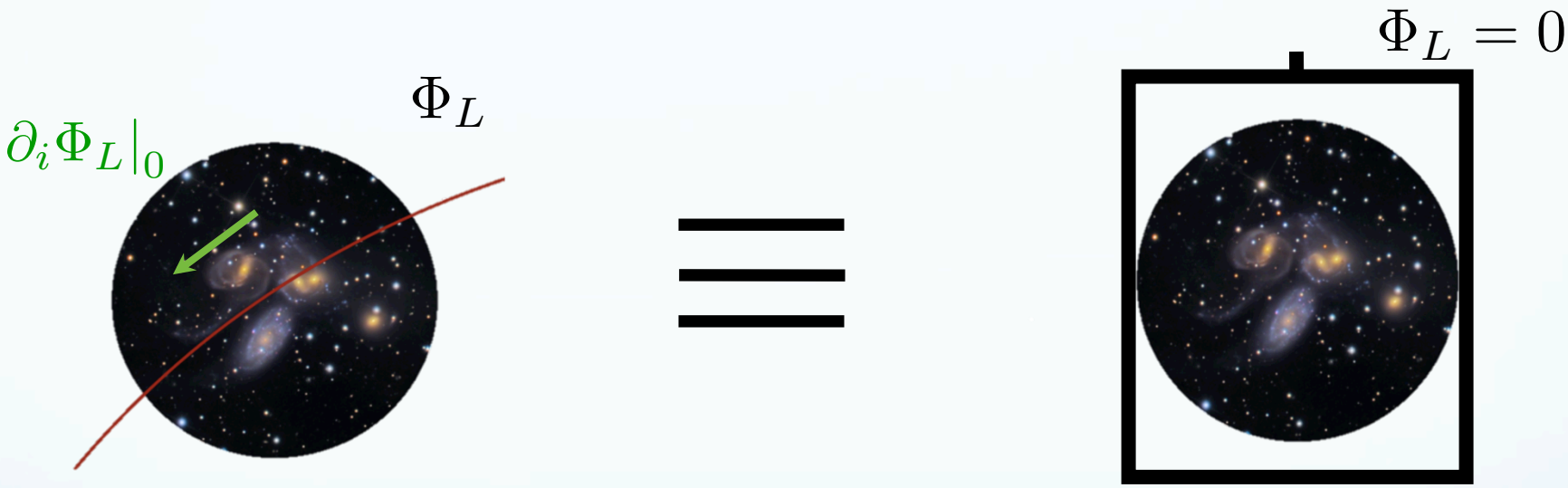



Assume Gaussianity
(no correlations long/short)

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

# Consistency relations

Assume Equivalence Principle




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*

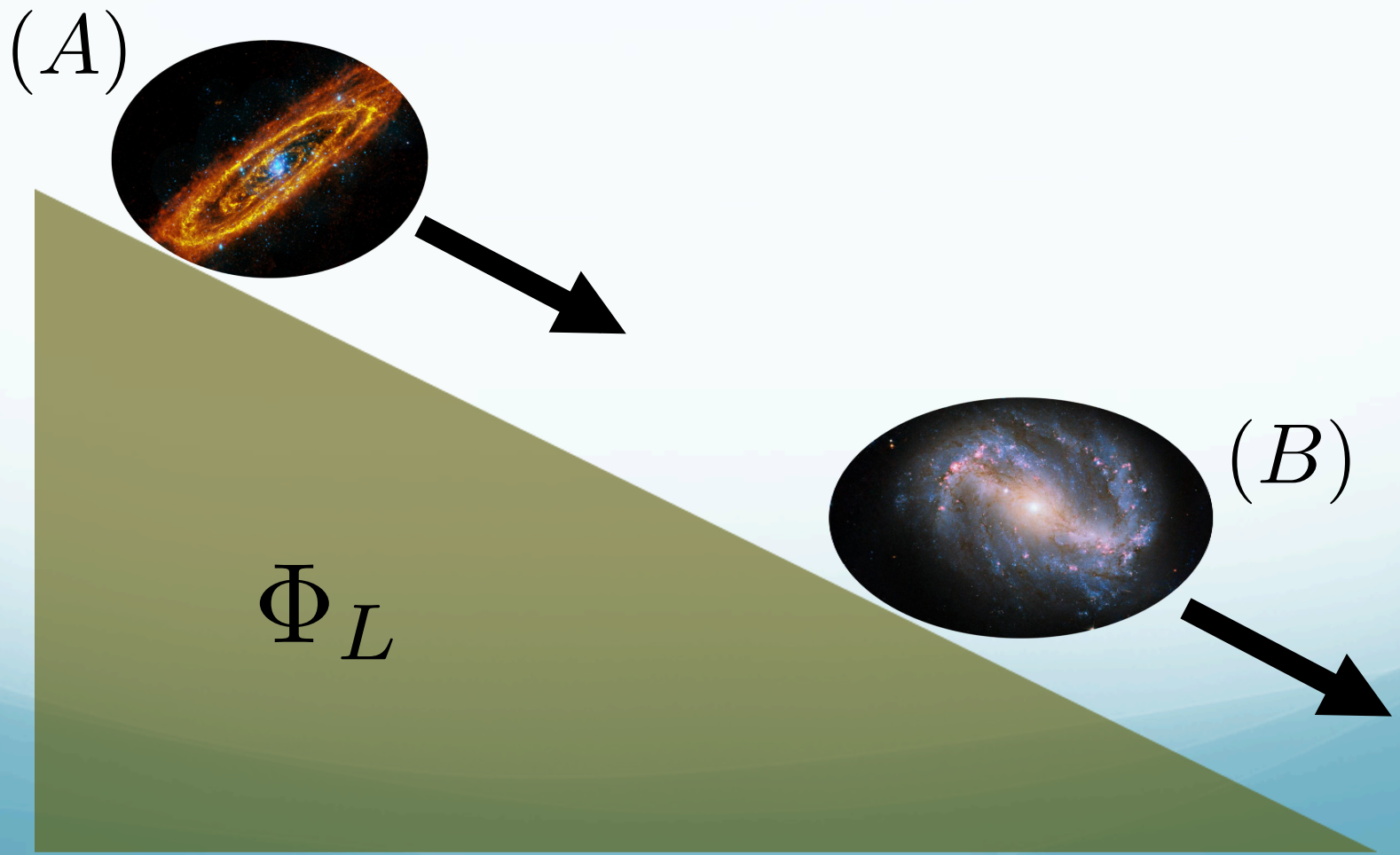
Redshift space — *with Creminelli, Simonović and Vernizzi, '13*

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

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

*Peloso & Pietroni '13*

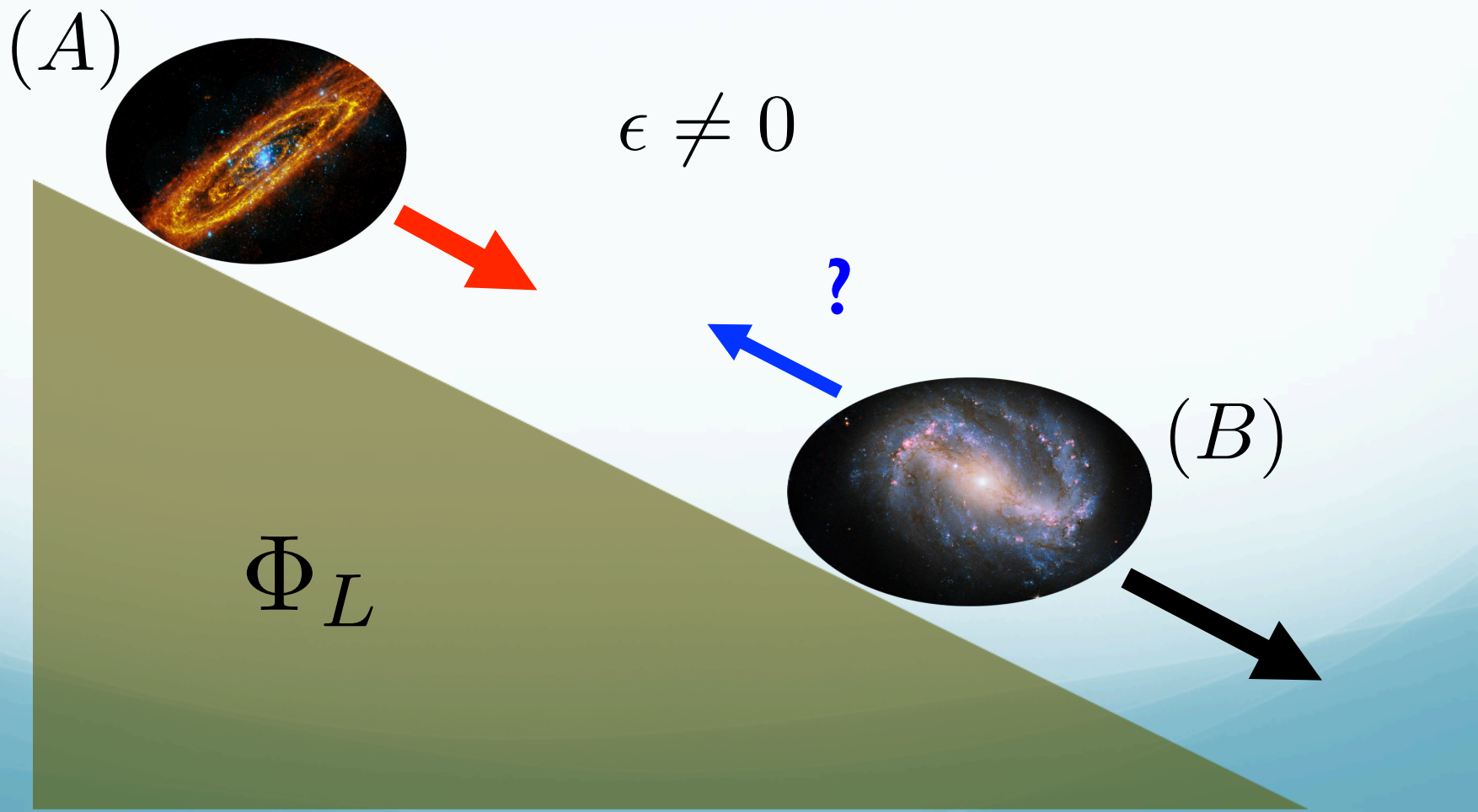
# Breaking the Equivalence Principle

# 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

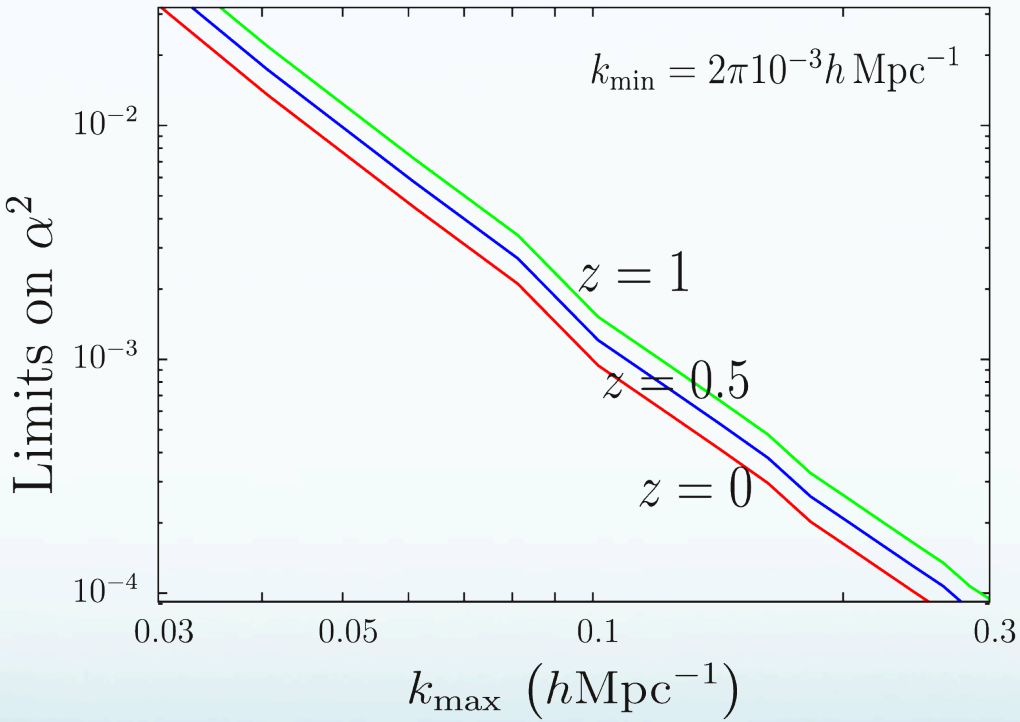
$$\langle \delta_{\vec{p}}(\eta) \delta^{(A)}_{\vec{k}_1}(\eta) \delta^{(B)}_{\vec{k}_2}(\eta) \rangle'_{p \to 0} = \left( \epsilon \frac{\vec{p} \cdot \vec{k}}{p^2} + \mathcal{O}[(k/p)^0] \right) P(\eta, p) P_{AB}(\eta, k)$$

$$\epsilon \propto \alpha^2$$

# 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?

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

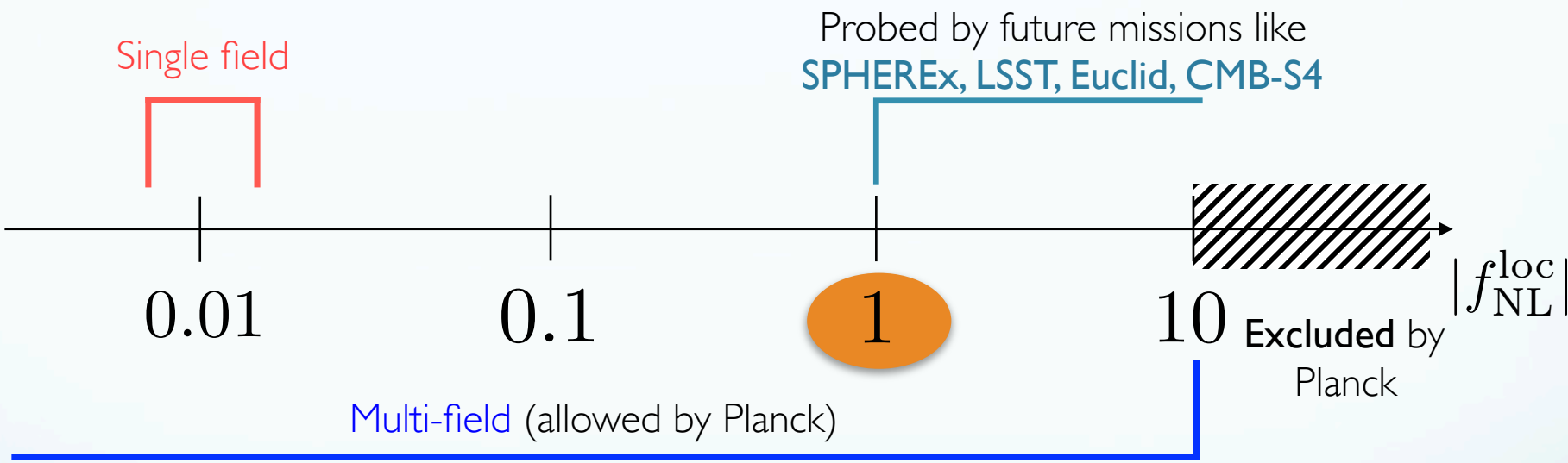
$\rightarrow$ $f_{\rm NL}^{\rm loc}$ $\rightarrow$ $-\frac{5}{12}(n_s - 1)$ *Maldacena '02*

Single field inflation *Creminelli & Zaldarriaga '04*

$\rightarrow$ **?**

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

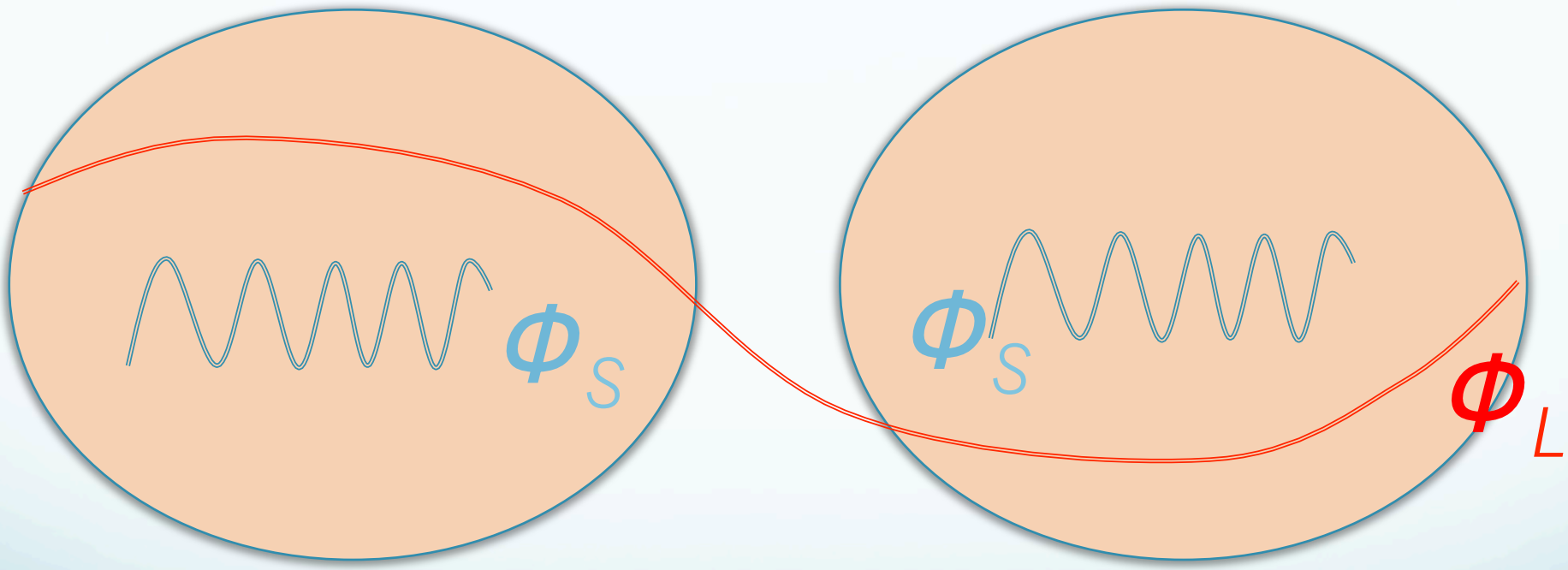
- CMB: Bispectrum

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

- Galaxy surveys: scale-dependent bias

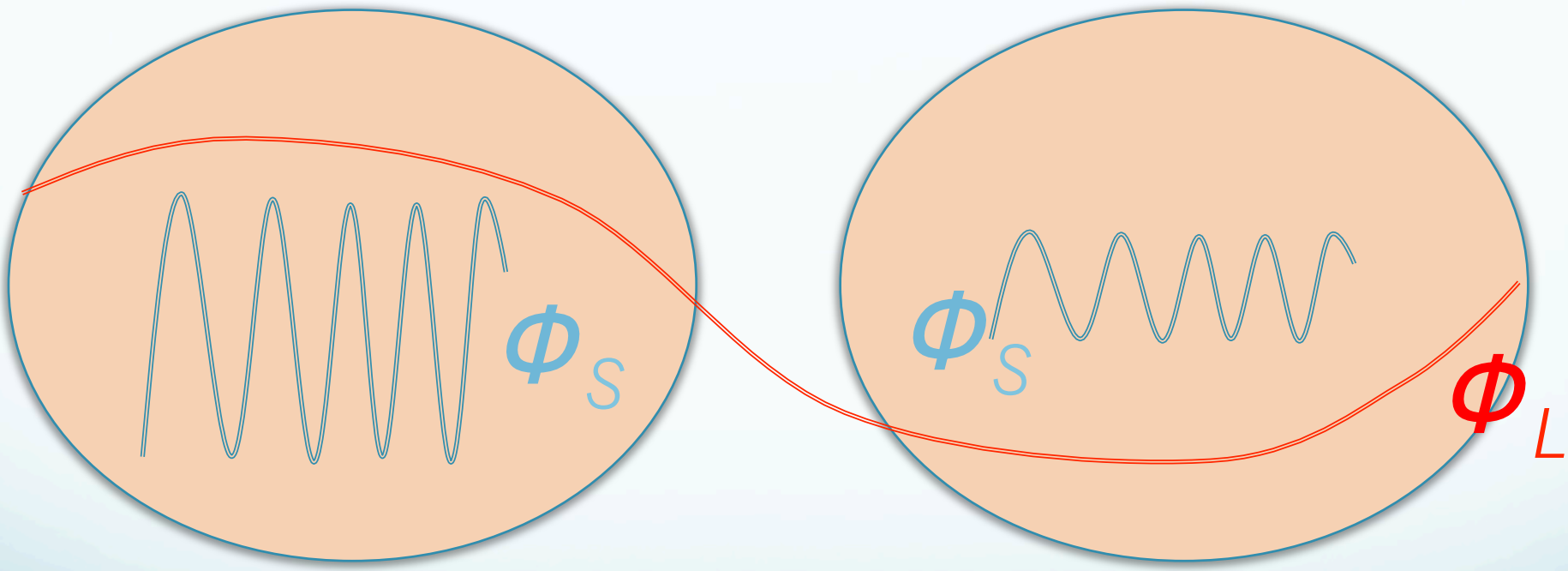
# Scale-dependent bias

**Single field inflation**



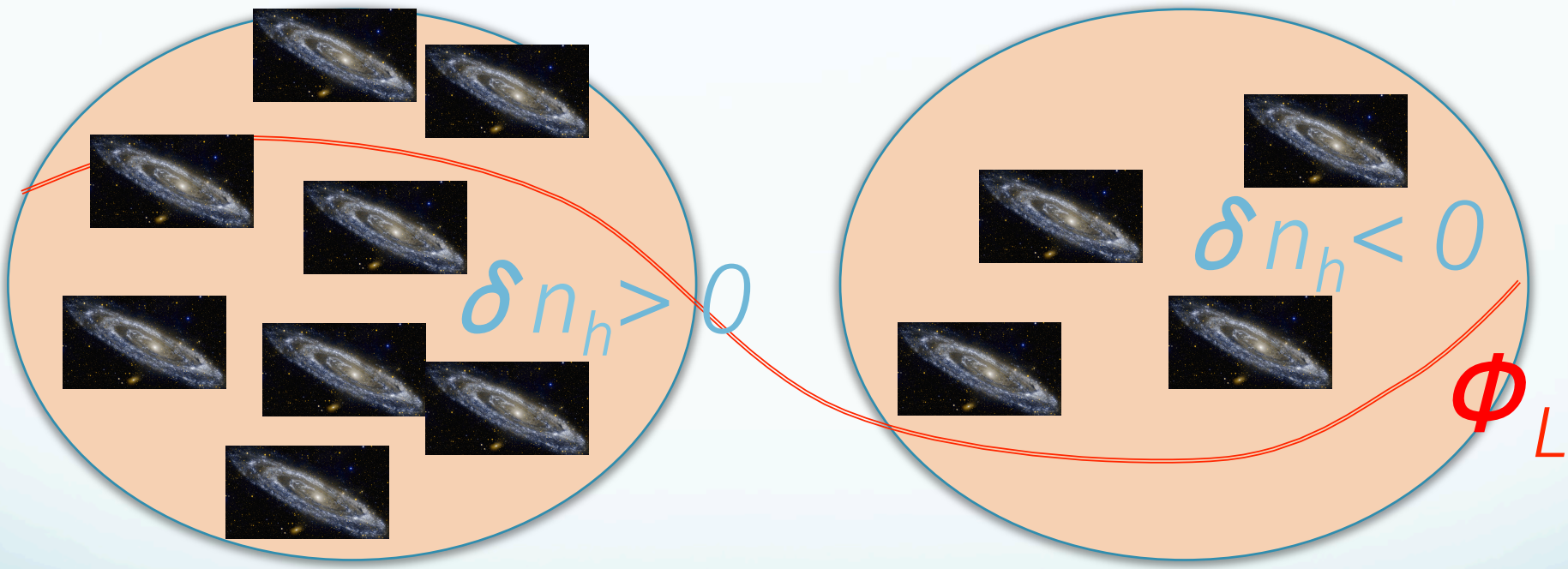
# Scale-dependent bias

**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*

$\delta^2$

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

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

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

✧ Evolution or PNG?

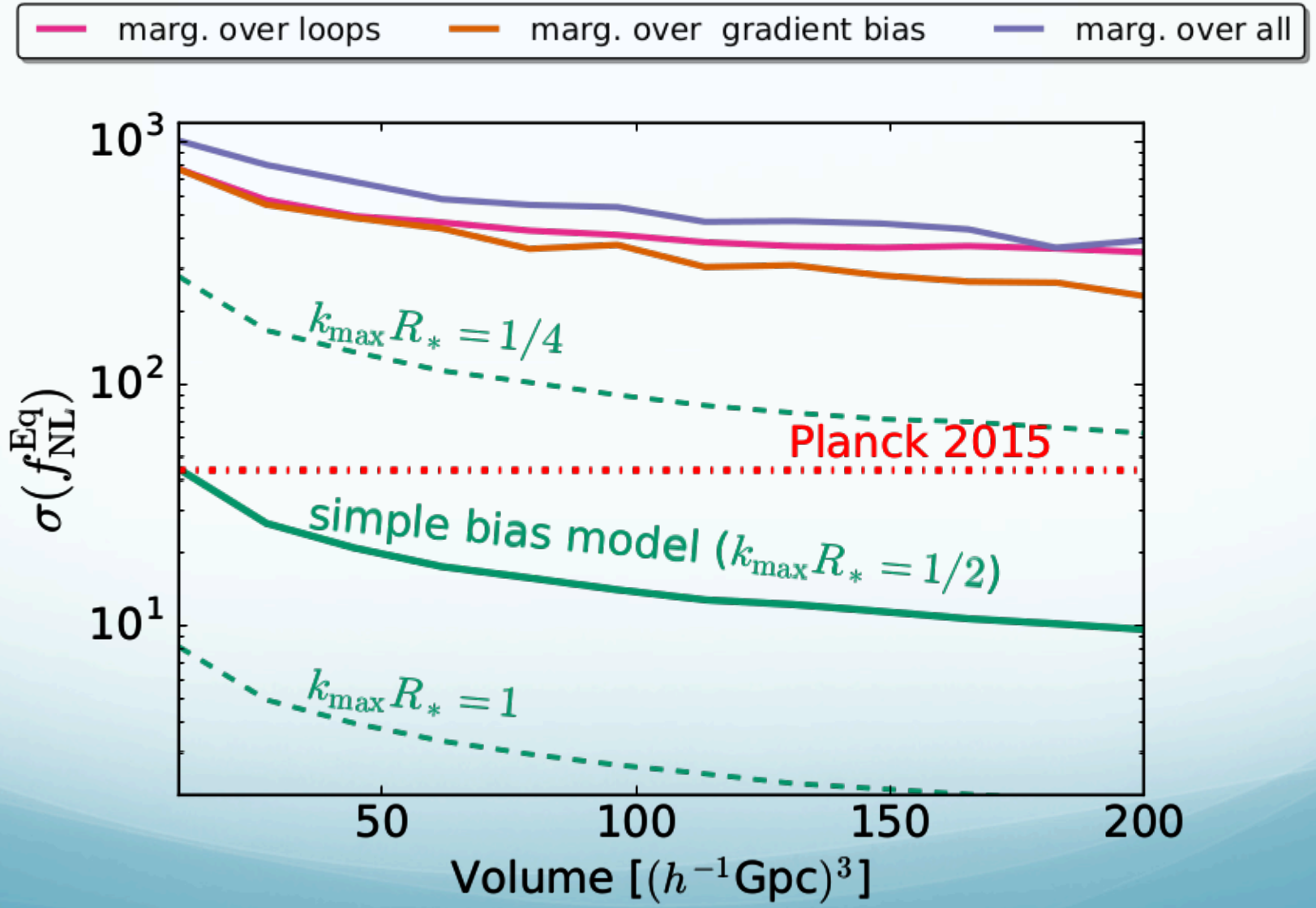
$$T(q) \sim 1 + T_1 q^2 + T_2 q^4$$

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

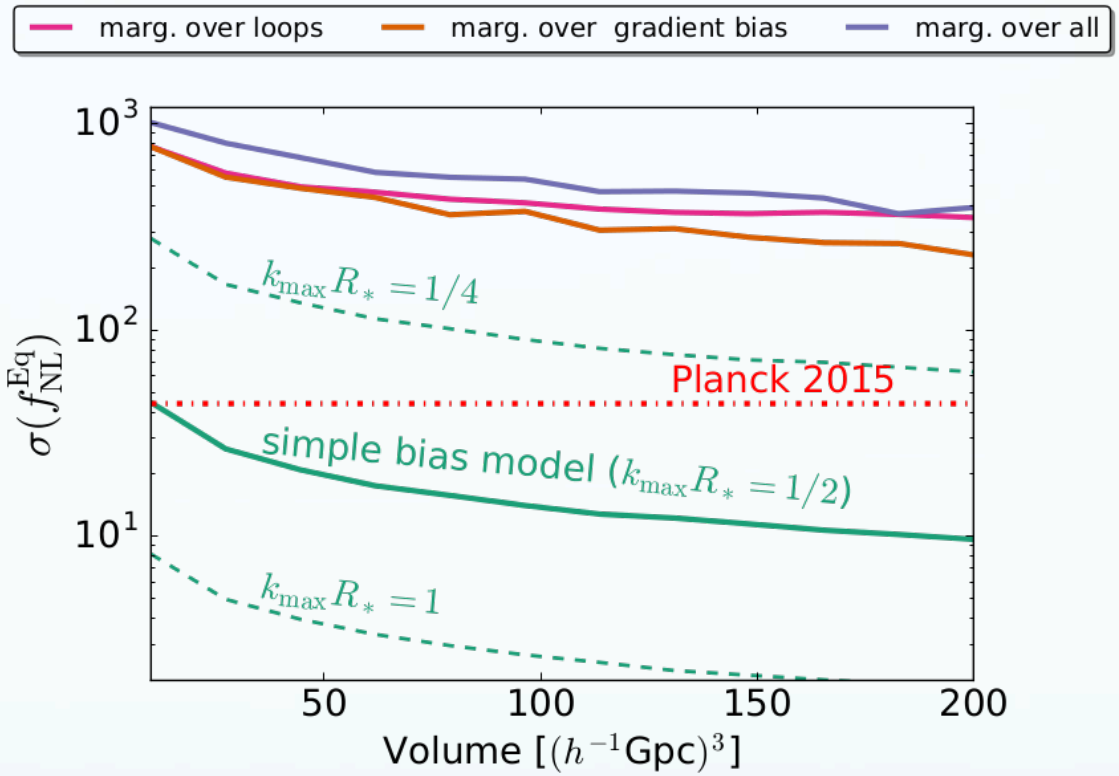
$$b_{\rm NG}^{\rm Eq} \sim c + c_1 q^2 + \cdots \quad ?$$

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

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