Modeling the nonlinear growth of large scale structure with perturbation theories and N-body simulations: implications to on-going and future surveys

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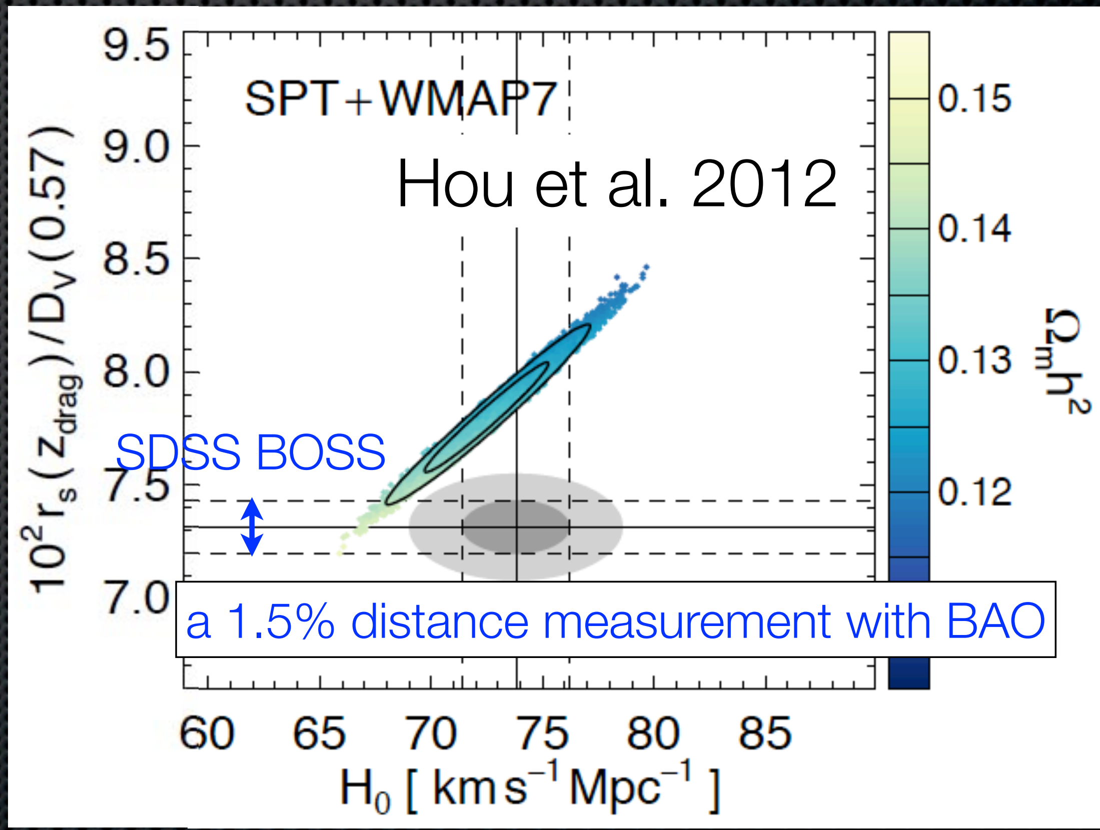
Outline

- Introduction
  - Needs for an accurate theoretical template for the galaxy clustering
  - Geometrical & dynamical test using anisotropy in the clustering
- Modeling the growth of cosmic density & velocity fields
  - Nonlinear gravitational evolution
  - Redshift-space distortions
- Connecting galaxies to the cosmic web
  - Modeling SDSS LRGs
  - Scale-dependent bias and primordial non-Gaussianities

Introduction

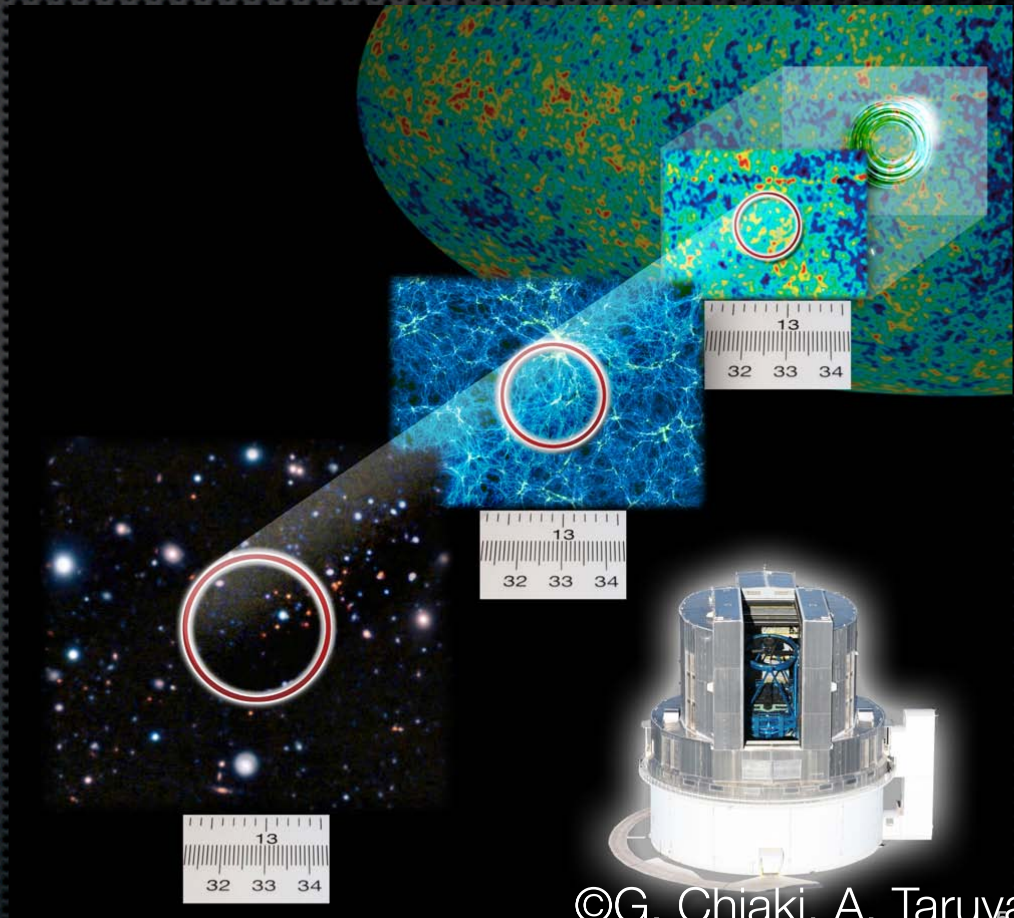
Observational cosmology: the current situation

- Crisis of ΛCDM cosmology?
  - New physics?
  - or just a systematic error in one (three?) experiment(s)?
- Next generation
  - Pinning down parameters
  - Extreme care is needed for systematics !!



Baryon Acoustic Oscillations: a geometrical test

- Sound wave in photon-baryon fluid
  - stoled at recombination
  - imprinted in nearby large-scale structure
- BAOs are standard ruler
  - probe of expansion history
  - powerful test for dark energy



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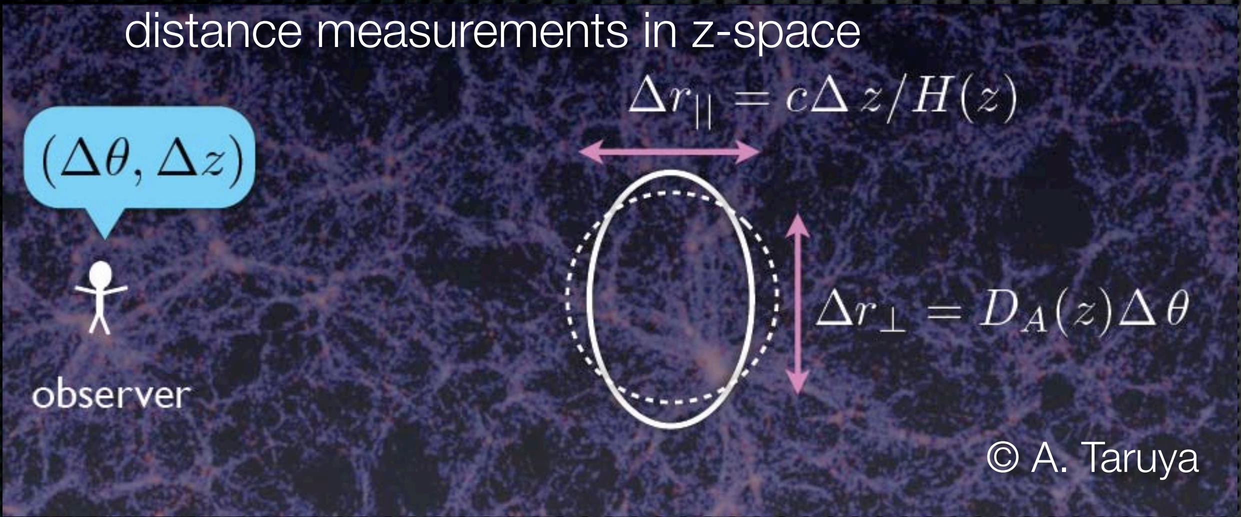
BAOs: how does it work?



- Alcock-Paczynski test

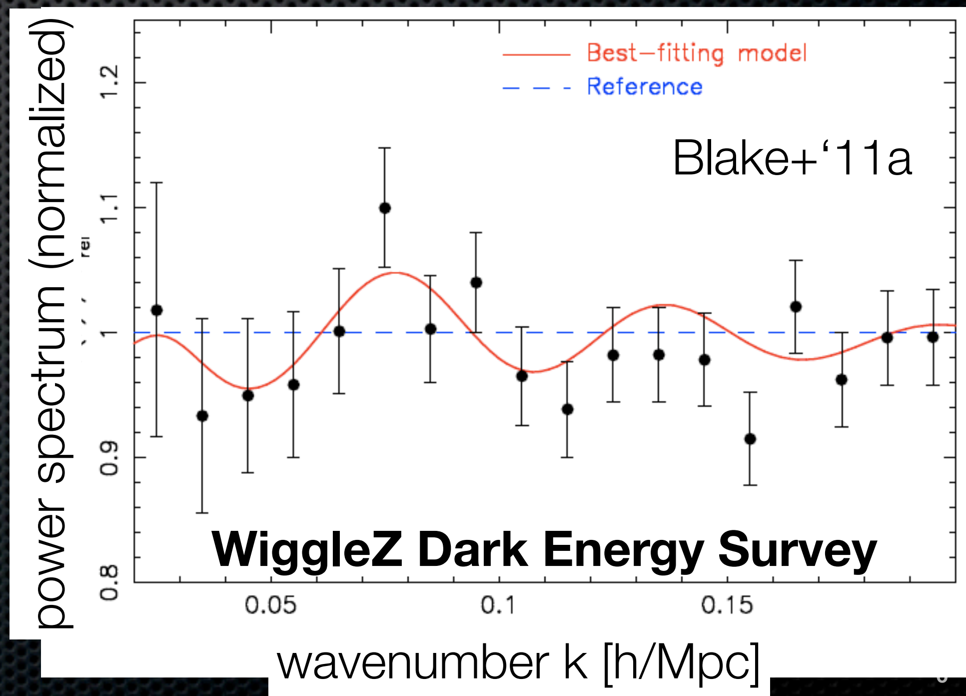
  Alcock & Paczinski '79, Matsubara & Suto '96, Ballinger+ '96

  - "cosmological distortion" because of a wrong cosmological assumption
  - constraints on ($D_A H$)

- BAOs mark a physical scale

  e.g., Peebles & Yu '70

  - constraints on D_V = (D_A^2/H)



Accelerated cosmic expansion

- Geometrical tests are not enough
  - DE/MG can mimic any expansion history
- Dynamical test?
  - growth rate of structure?
  - density field? Galaxy bias is a problem.
  - velocity field? Redshift-space distortions !

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

modified gravity

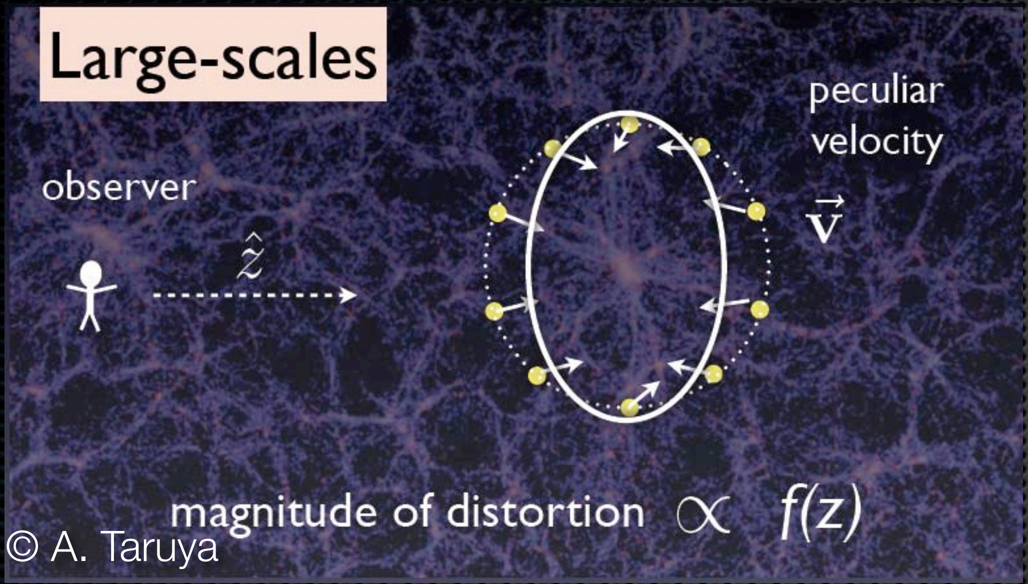
dark energy?

f(R), DGP, ...

- Geometrical (background) + Dynamical (perturbation) tests are essential !!

Redshift-space distortions

Kaiser '87



$$s = r + \frac{v_{\rm LoS}(r)}{aH(z)}\hat{e}_{\rm LoS}$$

line-of-sight displacement due to peculiar velocity

position in real space

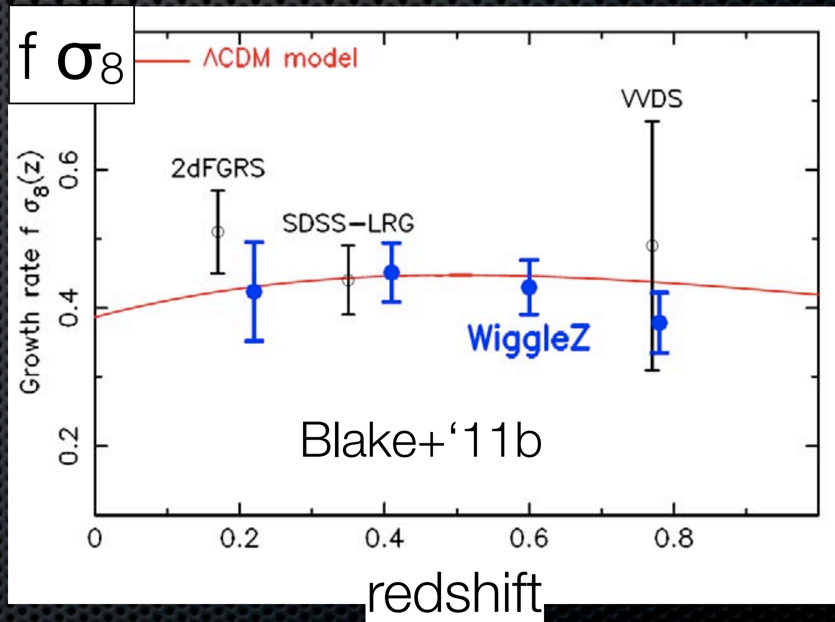
position in z-space

linear growth rate

Linder 05

$$f(z) \equiv \frac{d\ln D(z)}{d\ln a} \simeq [\Omega_{\rm m}(z)]^{\gamma}$$

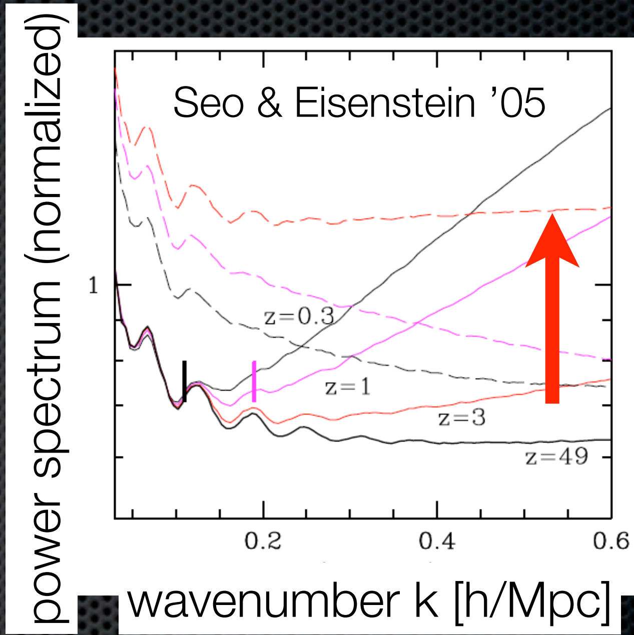
$$\gamma \simeq 0.55\,(\Lambda{\rm CDM}), \quad \simeq 0.68\,({\rm DGP})$$

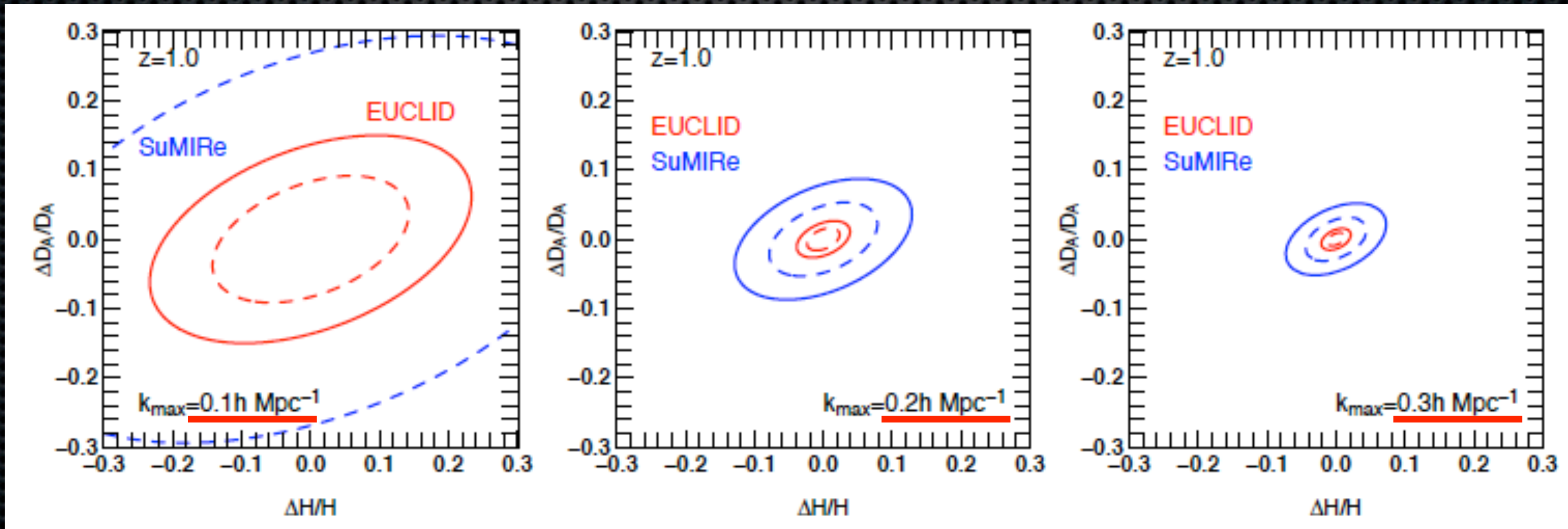


- Both AP & RSD test the anisotropic signal
- Accurate modeling in ***2D*** is the key !!

Theoretical challenge

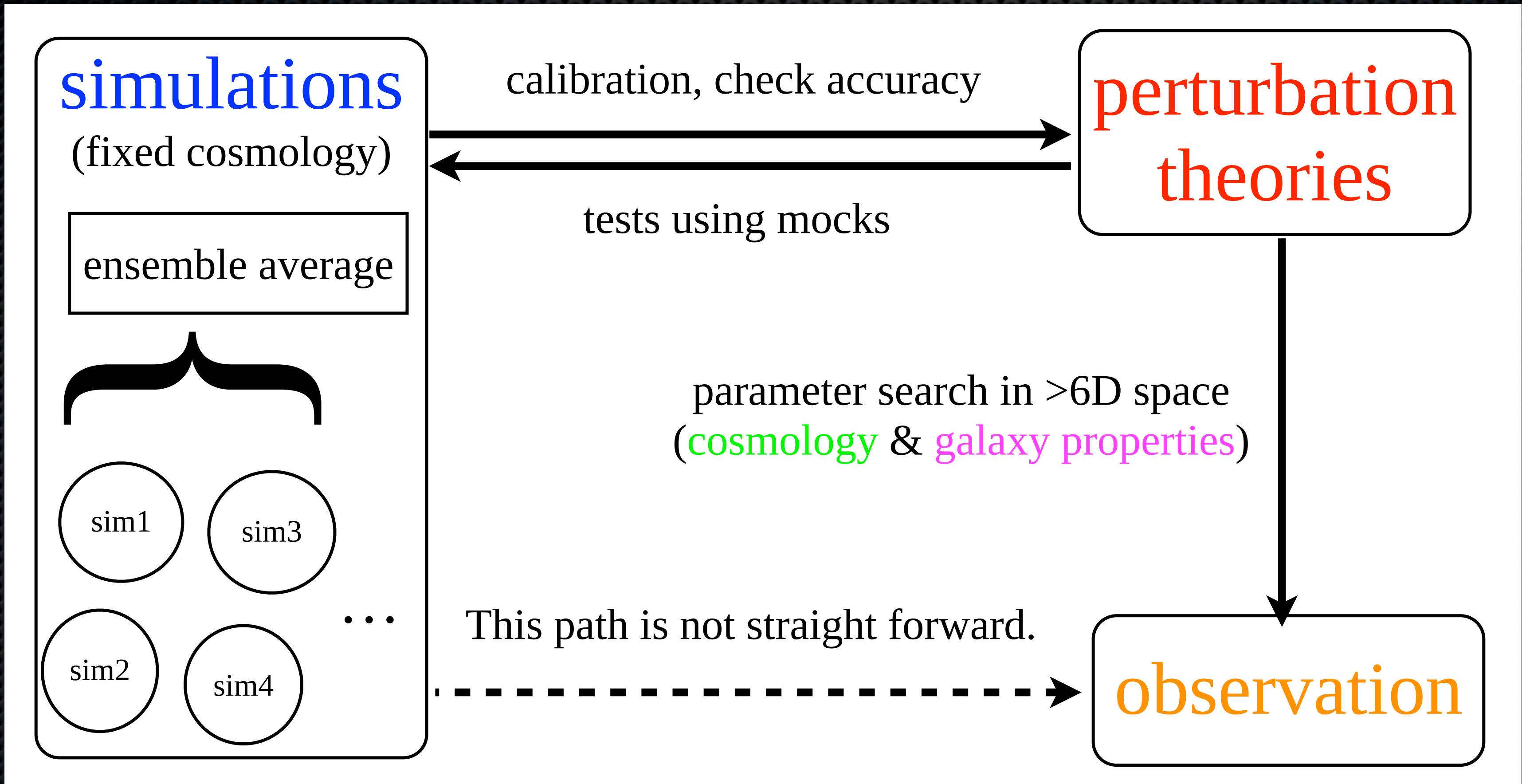
- How well do we understand *3 nonlinears*?
  - gravitational growth
  - redshift-space distortions
  - galaxy bias



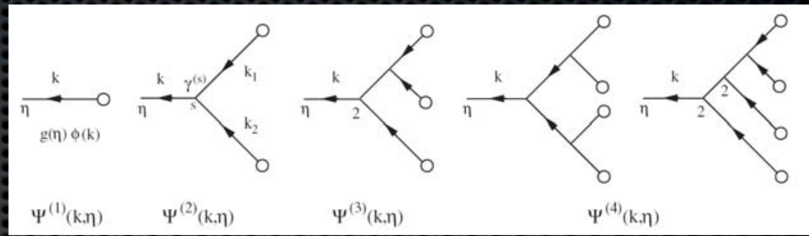


Modeling the growth of cosmic density & velocity fields

The strategy



based on Crocce&Scoccimarro06



Renormalized PT

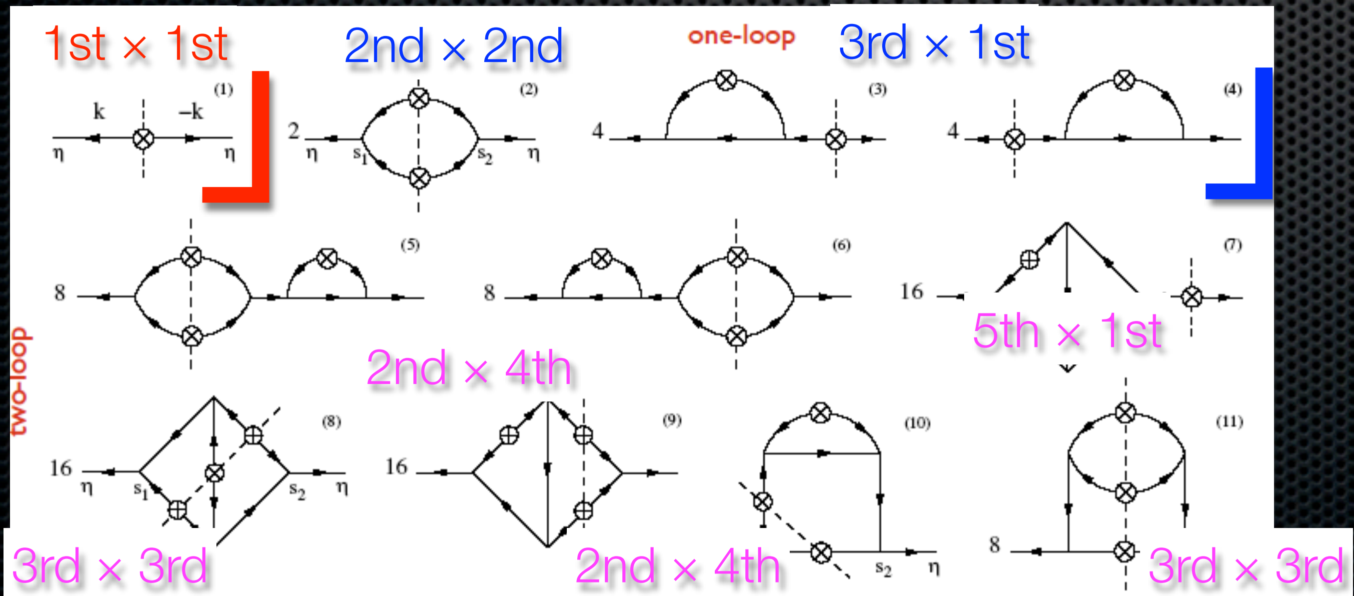
Crocce & Scoccimarr '06, Taruya & Hiramatsu '07, ...

- "Renormalize" higher-order terms back to lower-order

$$\delta = \delta^{(1)} + \delta^{(2)} + \delta^{(3)} + \delta^{(4)} + \dots$$

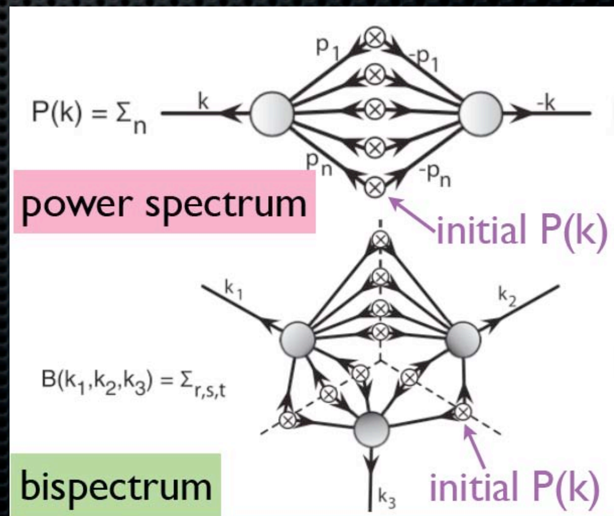
$$\theta = \theta^{(1)} + \theta^{(2)} + \theta^{(3)} + \theta^{(4)} + \dots$$

power spectrum $P = P^{(11)} + P^{(22)} + P^{(31)} + P^{(13)} + \dots$



ex. Gamma expansion

Bernardeau + '09

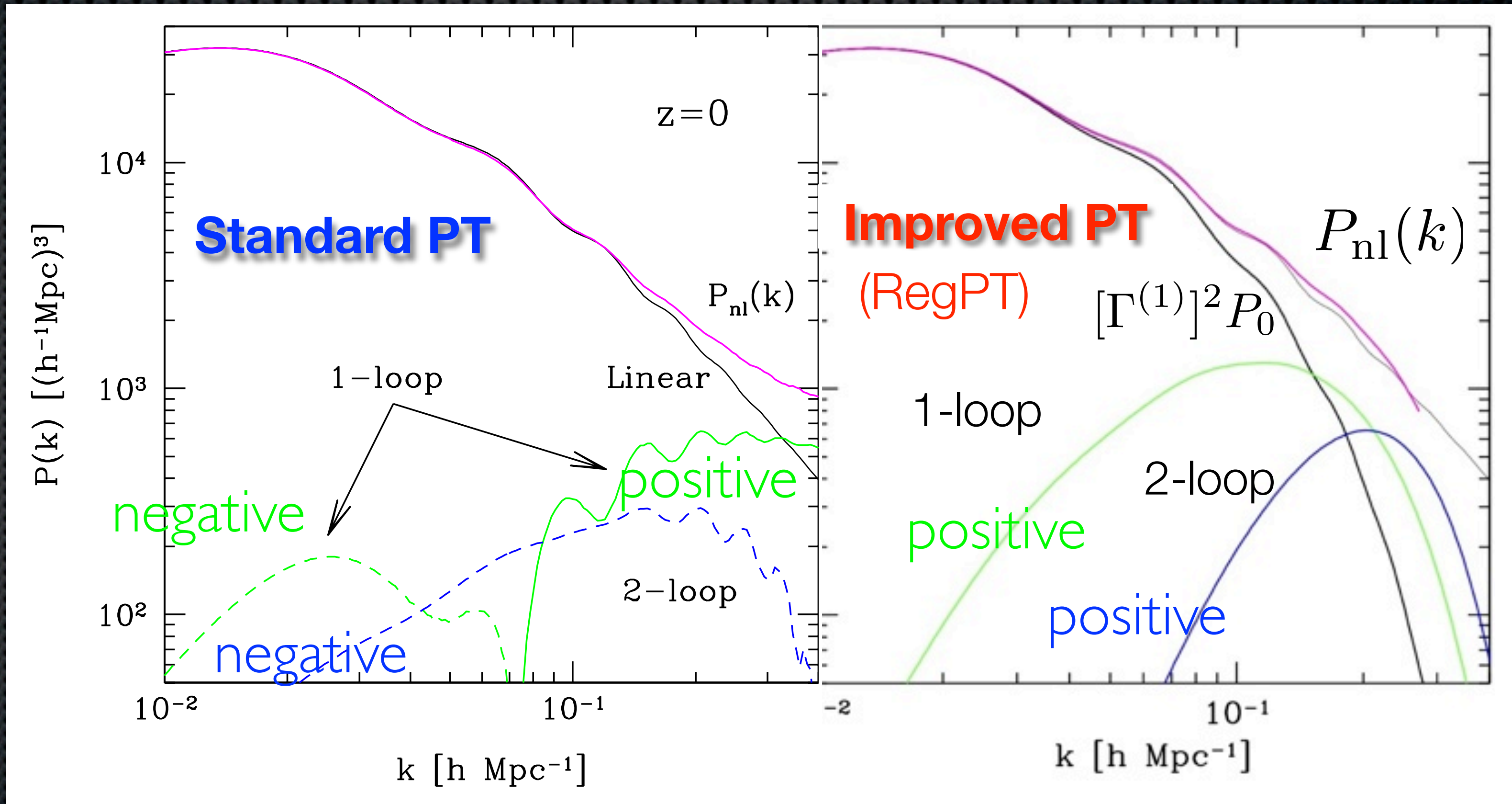


Convergence property

Taruya, Nishimichi et al. '12

- Better convergence
- All the terms are positive in RegPT

  ⇔ Alternating series in Standard PT
- Especially suitable for BAO modeling



Why Renormalized PTs work well?

- (multi-point) propagators
  - *loss of initial memory*

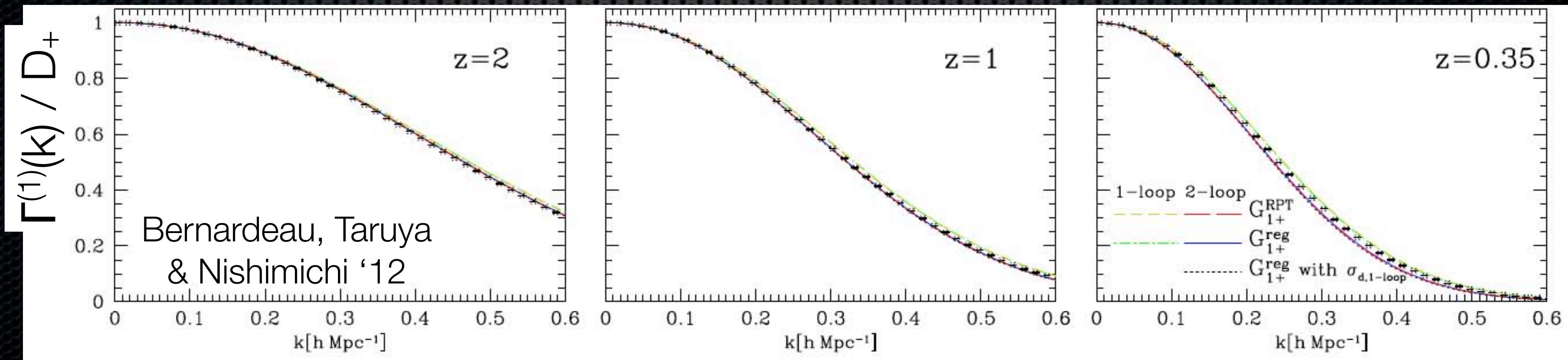
    Crocce & Scoccimarro '06
  - separate dynamics from initial condition
  - asymptotes are known

final state   initial state

$$\frac{1}{p!}\left\langle \frac{\delta^p \Psi_a(\mathbf{k},\eta)}{\delta\phi_{b_1}(\mathbf{k}_1)\dots\delta\phi_{b_p}(\mathbf{k}_p)} \right\rangle = \delta_{\rm D}(\mathbf{k}-\mathbf{k}_1-\dots-\mathbf{k}_p)\,\Gamma^{(p)}_{ab_1\dots b_p}(\mathbf{k}_1,\dots,\mathbf{k}_p;\eta)$$

$$P(k;\eta) = \left[\Gamma^{(1)}(k;\eta)\right]^2 P_0(k) + 2\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}\left[\Gamma^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q};\eta)\right]^2 P_0(q)P_0(|\boldsymbol{k}-\boldsymbol{q}|)$$
$$+\,6\int\frac{d^6\boldsymbol{p}d^3\boldsymbol{q}}{(2\pi)^6}\left[\Gamma^{(3)}(\boldsymbol{p},\boldsymbol{q},\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q};\eta)\right]^2 P_0(p)P_0(q)P_0(|\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q}|)$$

- **Directly testable by simulations**



Mapping to z-space

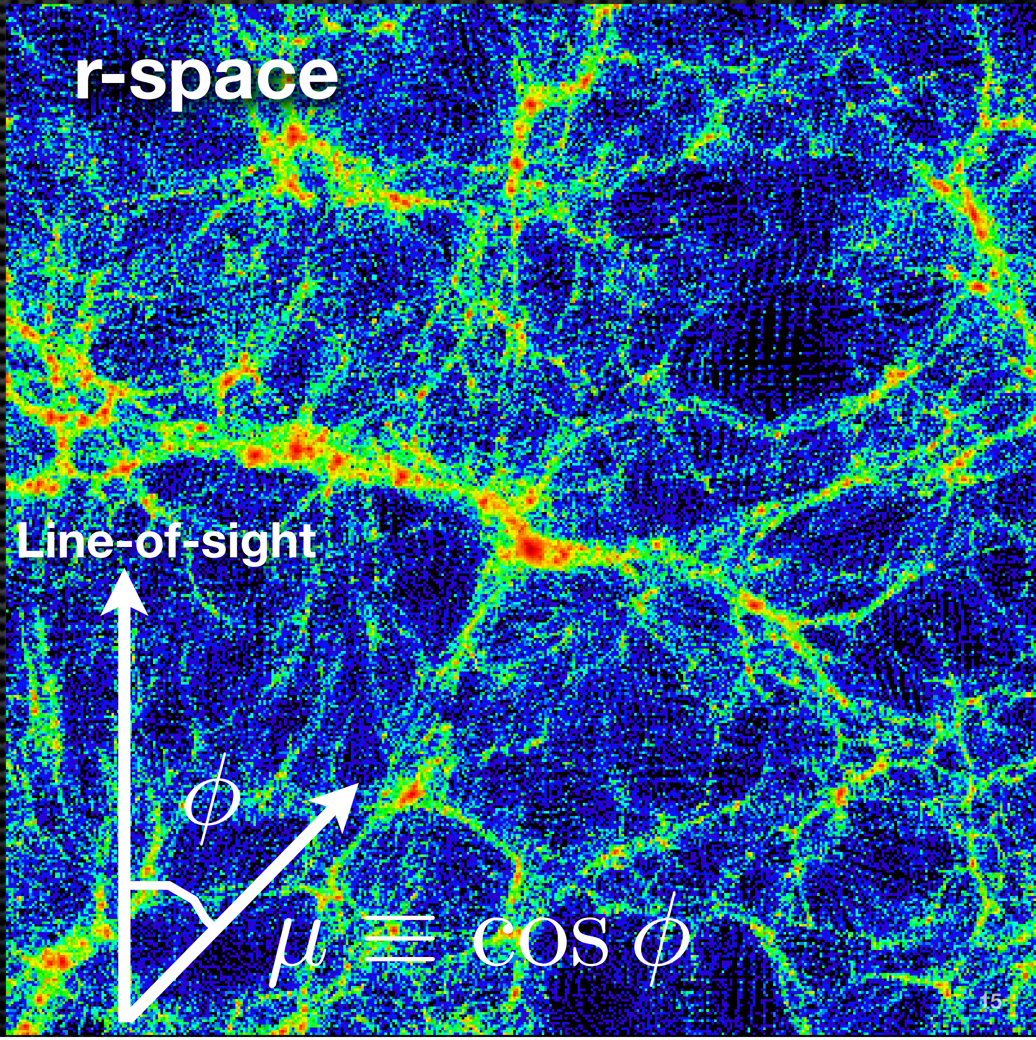
- Widely used model:

$$P(k,\mu) = D_{\rm f}(k\mu\, f\, \sigma_{\rm v}) \times \left[P_{\delta\delta}(k) + 2\, f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\right]$$

streaming model

Scoccimarro'04

- *2 ingredients*
  - (nonlinear) Kaiser effect
    - large scale coherent motion
  - Fingers-of-Gods effect
    - small scale virial motion



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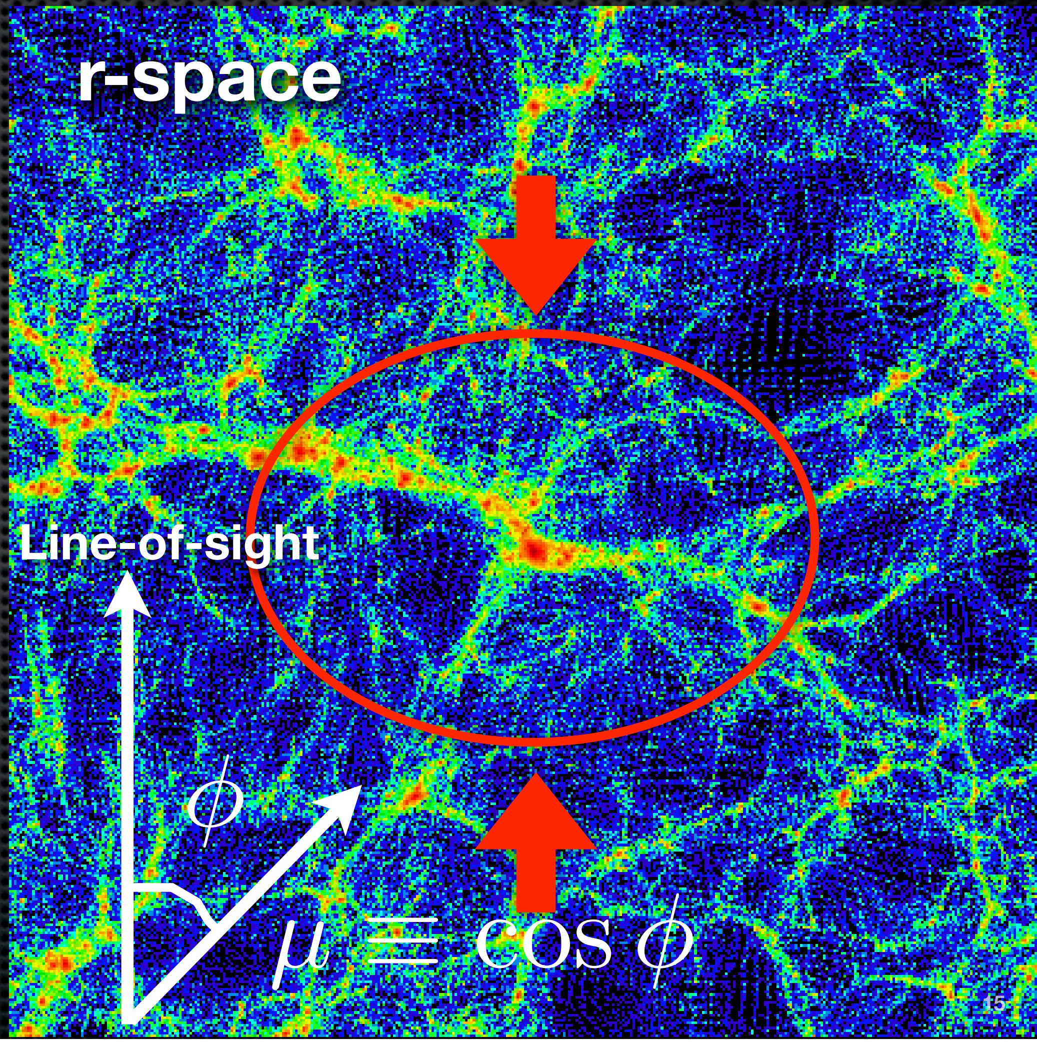

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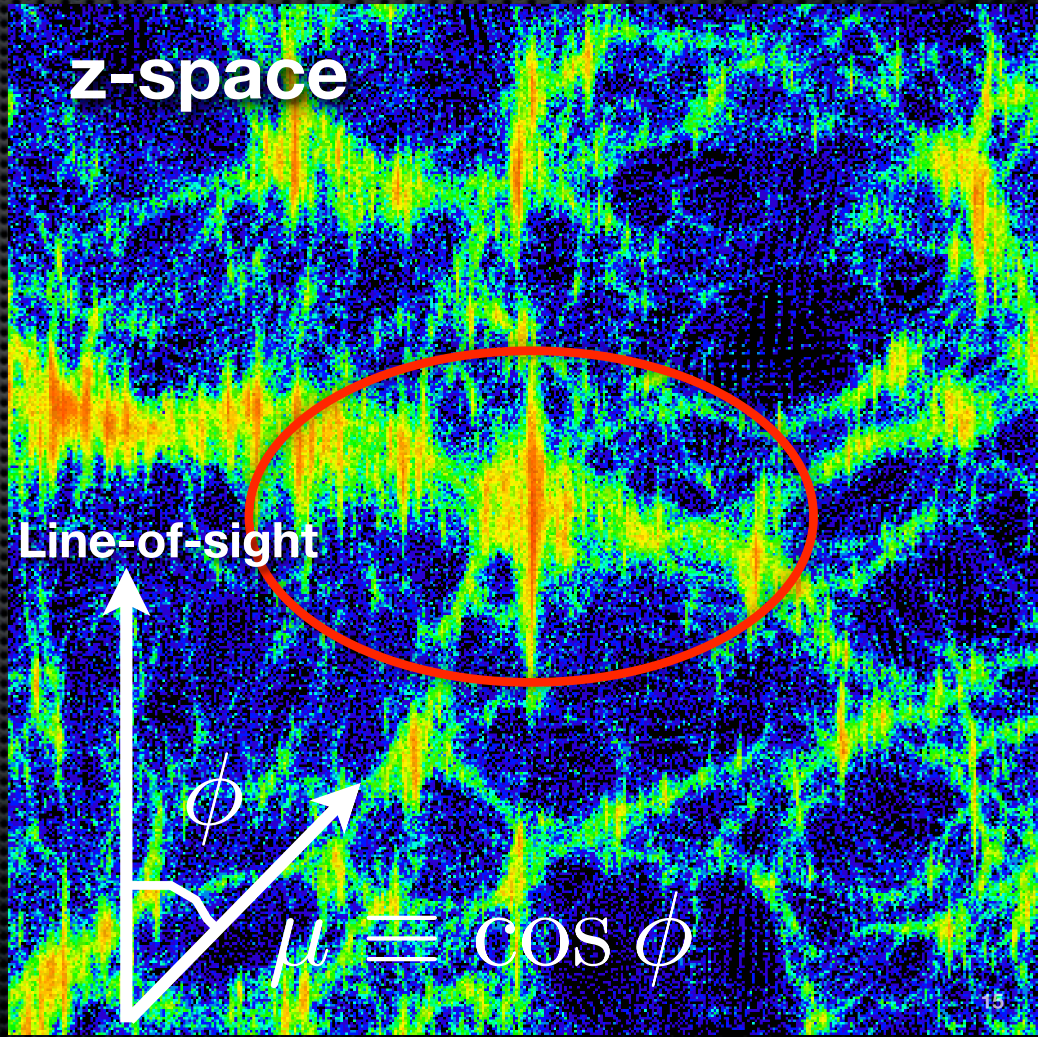

Mapping to z-space

- Widely used model:

$$P(k,\mu) = \underline{D_{\mathrm{f}}(k\mu\, f\, \sigma_{\mathrm{v}})} \quad \text{streaming model}$$
$$\times\ \underline{\left[P_{\delta\delta}(k) + 2\, f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\right]}$$

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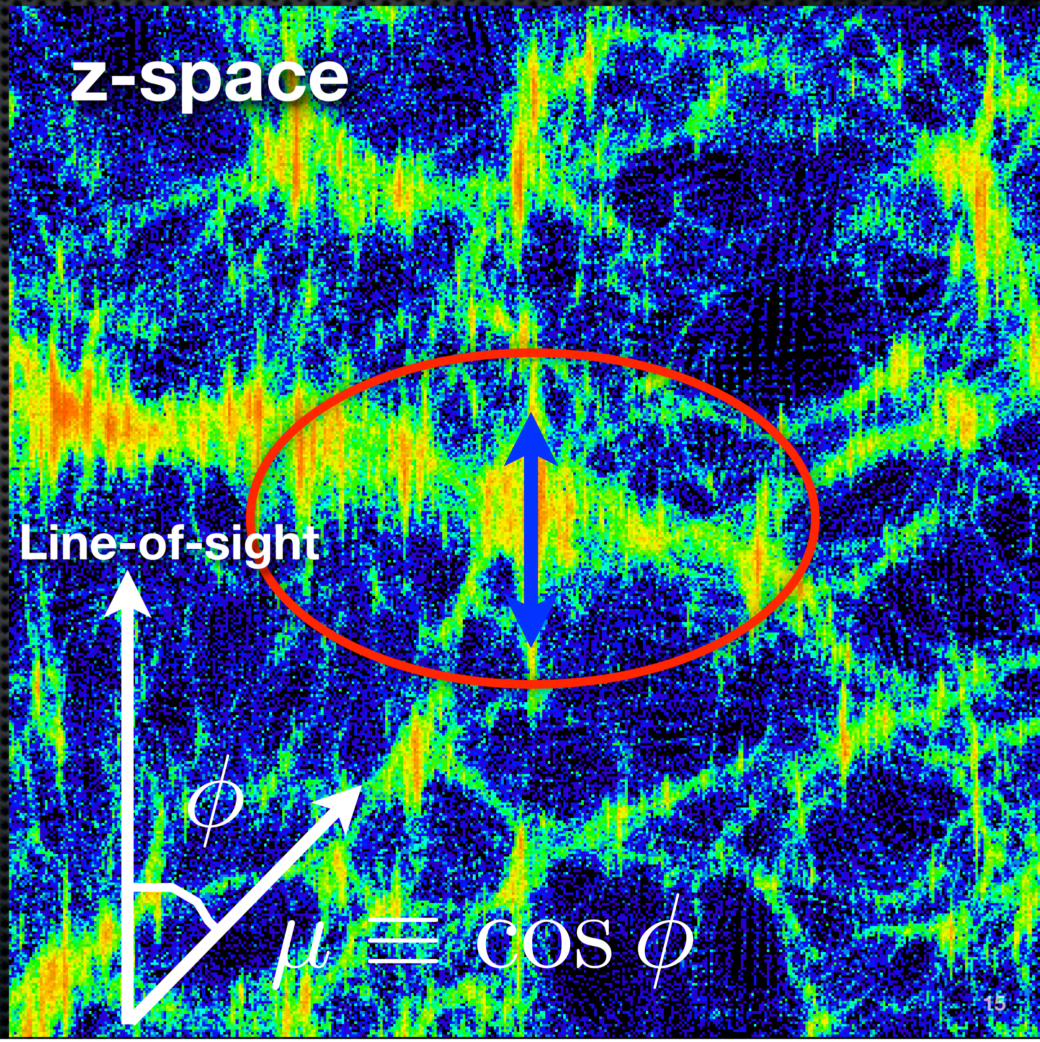


TNS model

Taruya, Nishimichi, Saito '10

- Streaming model fails
- Kaiser & FoG are not separable!
  - go back to exact expression
  - computed 2 correction terms

$$P(k,\mu) = D_{\rm f}(k\,\mu\,f\sigma_{\rm v}) \times \Big[P_{\delta\delta}(k) + 2\,f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)$$

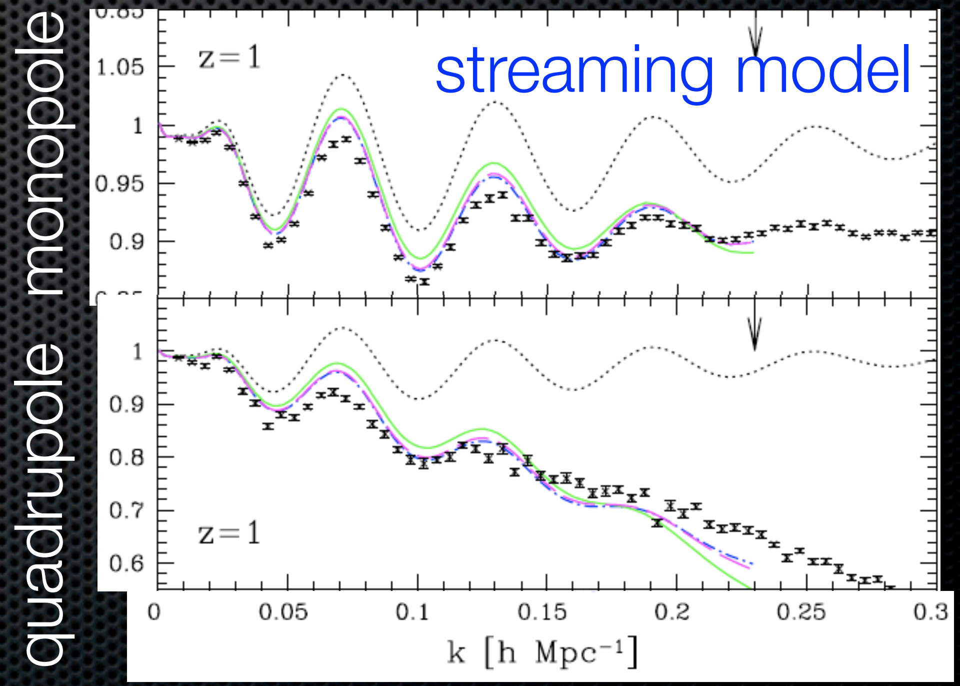
new terms! $+A(k,\mu;f) + B(k,\mu;f)\Big]$

A term ∝ cross-bispectrum of δ & θ

B term ∝ convolutions of $P_{\delta\theta}$ & $P_{\theta\theta}$

multipole moments

$$P(k,\mu) = \mathcal{L}_0(\mu)P_0(k) + \mathcal{L}_2(\mu)P_2(k) + \mathcal{L}_4(\mu)P_4(k) + \dots$$



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new terms!

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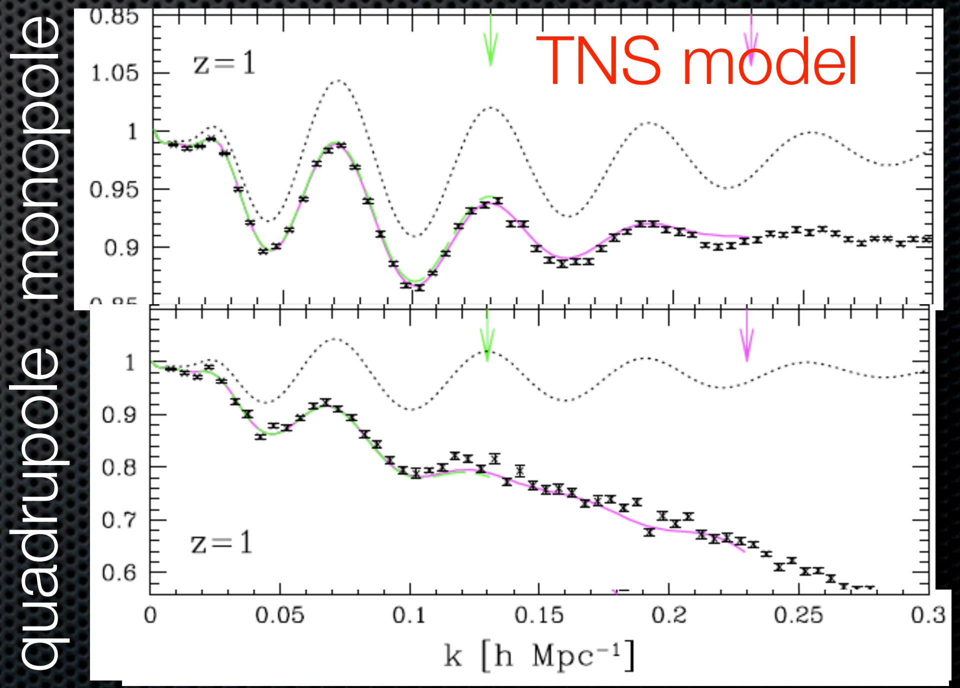


Limitation of PTs & non-pertubative corrections

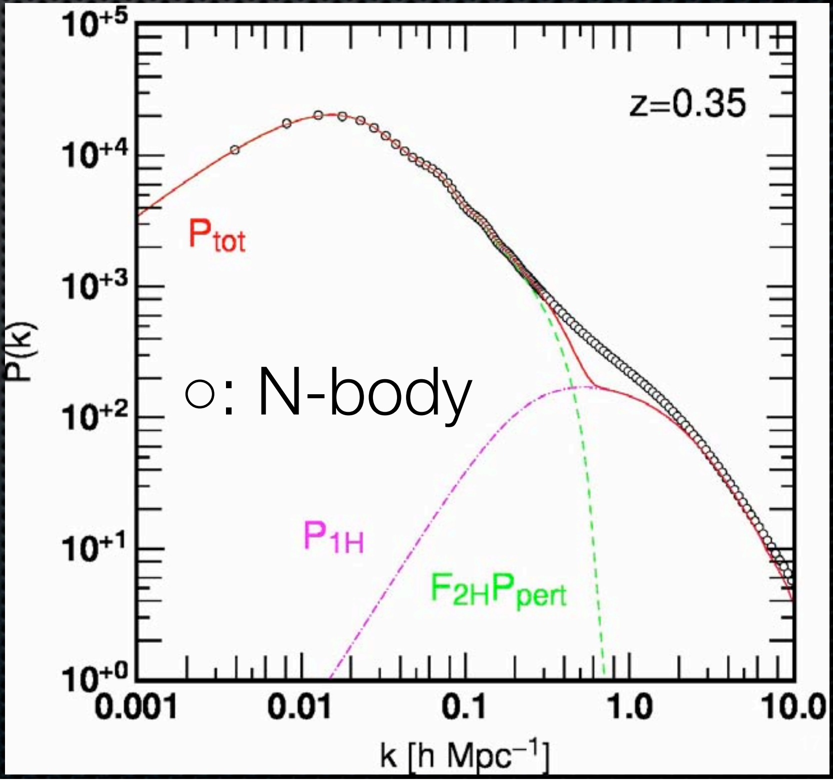
Valageas & Nishimichi 2011a, b

- single-stream flow is assumed in PTs
  - cannot follow the dynamics after shell crossing
- Combine PTs with halo model
  - halos are the place where shell cross takes place
  - a consistent formulation to avoid double counting

$$P_{\rm tot}(k) = F_{\rm 2H}(1/k) P_{\rm PT}(k) + [P_{\rm 1H}(k) - P_{\rm c.t.}(k)]$$

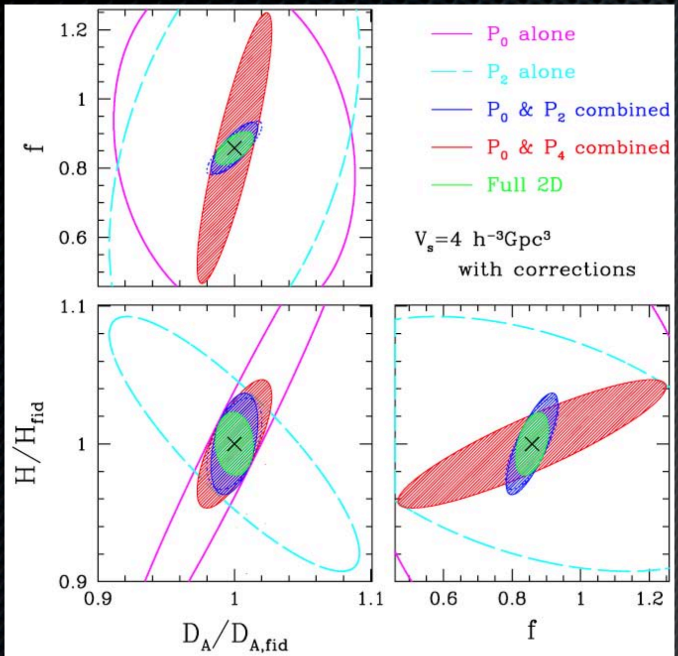
- A wide wavenumber range can be covered
  - Useful for weak lensing analyses

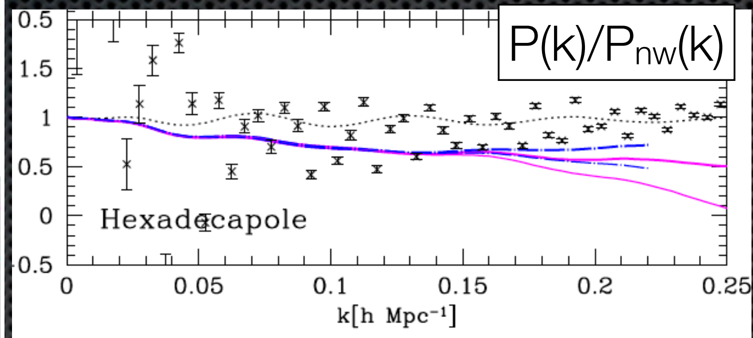
Valageas, Sato & Nishimichi 2012a, b



Combined theory in z-space

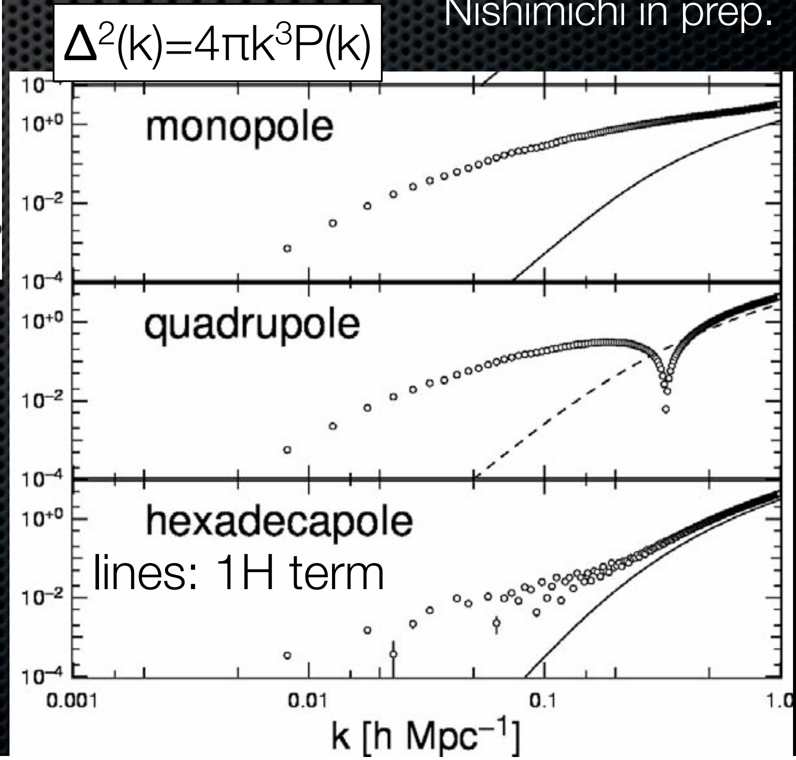
$$P(k,\mu) = \mathcal{L}_0(\mu)P_0(k) + \mathcal{L}_2(\mu)P_2(k) + \mathcal{L}_4(\mu)P_4(k) + \dots$$





Taruya, Nishimichi and Bernardeau '13

Nishimichi in prep.



- Hexadecapole moment
  - does carry information !!
- more difficult to model by PTs
- more sensitive to 1H term

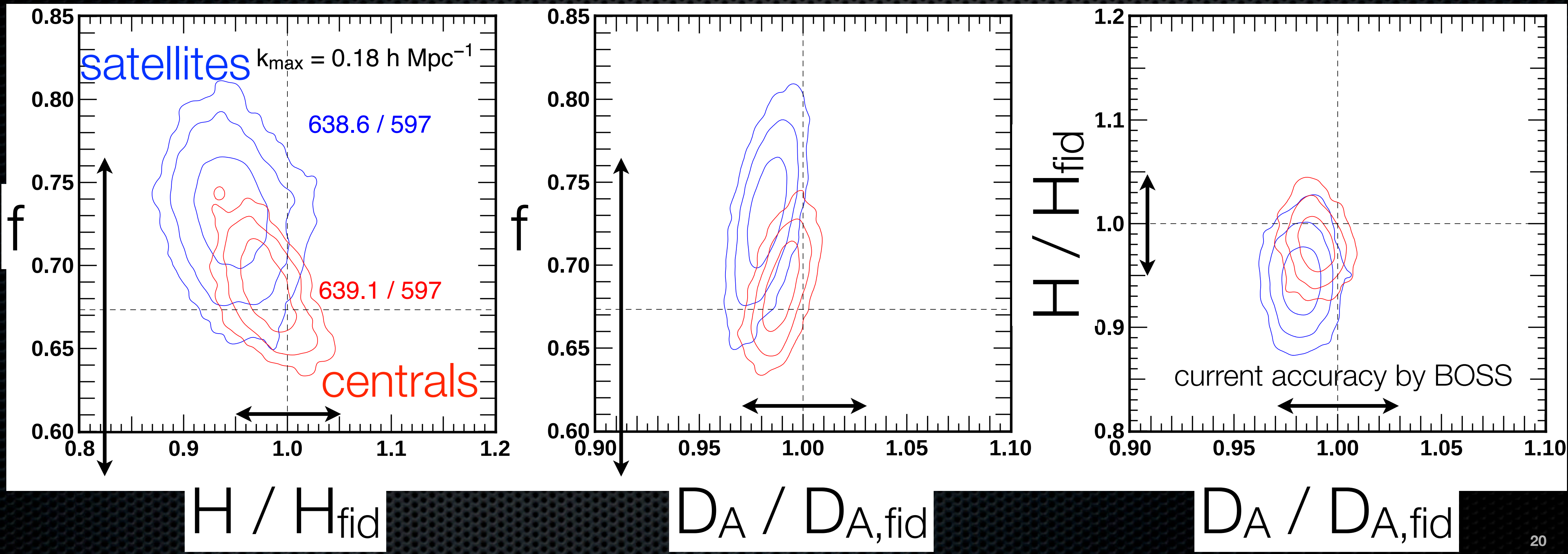
Connecting galaxies to the cosmic web

Tests with mocks (subhalos): a naive implementation of parametric bias

5 + 3 parameter fit

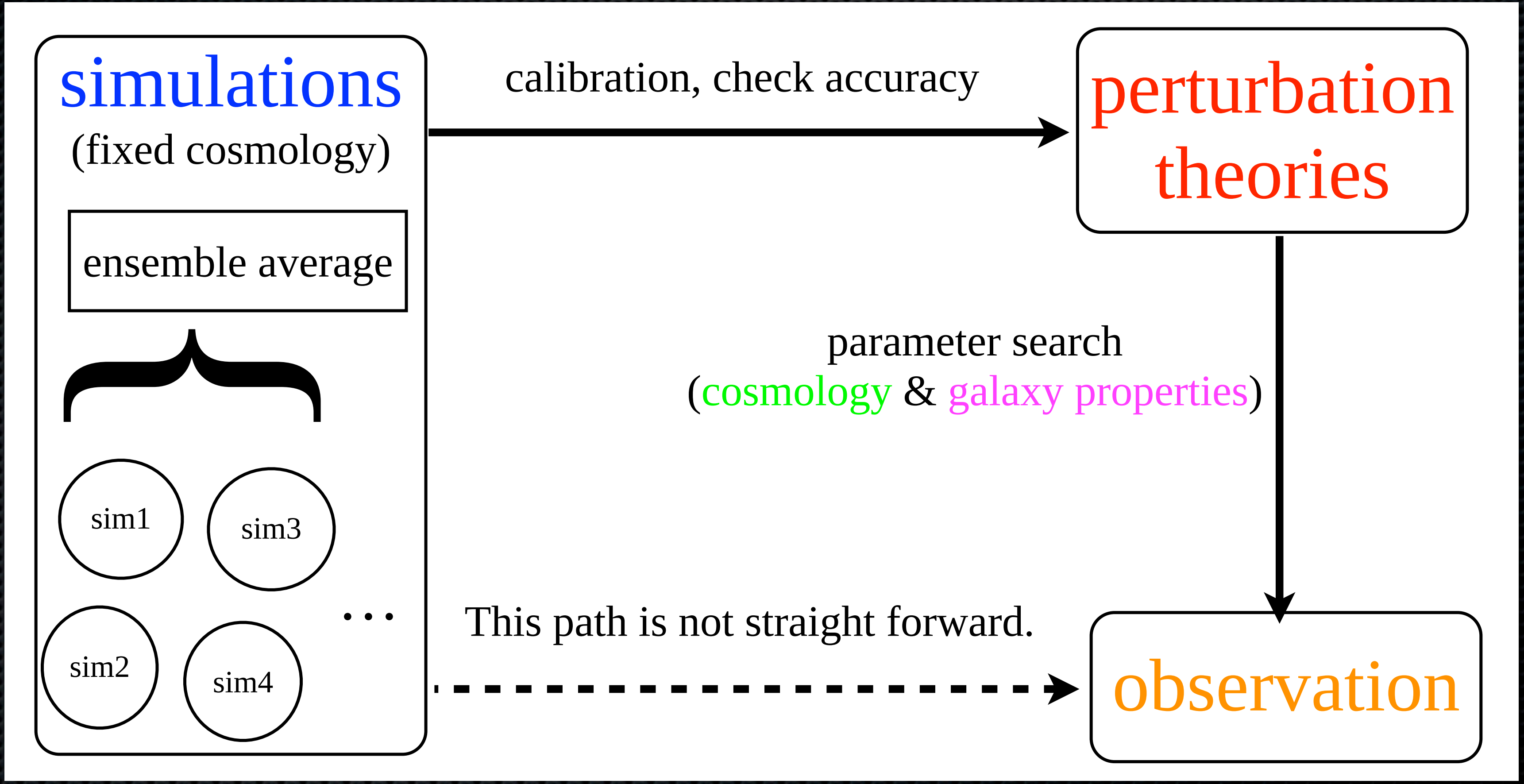
Can we recover the true cosmology?

$$b(k) = b\frac{1+Qk^2}{1+Ak} \qquad D_{\rm FoG}(x) = \left(1+\frac{x^2}{\alpha}\right)^{-\alpha} \qquad x = f\sigma_{\rm v}k\mu$$



Modeling Luminous Red Galaxies

Oka, Nishimichi et al. (in prep.)



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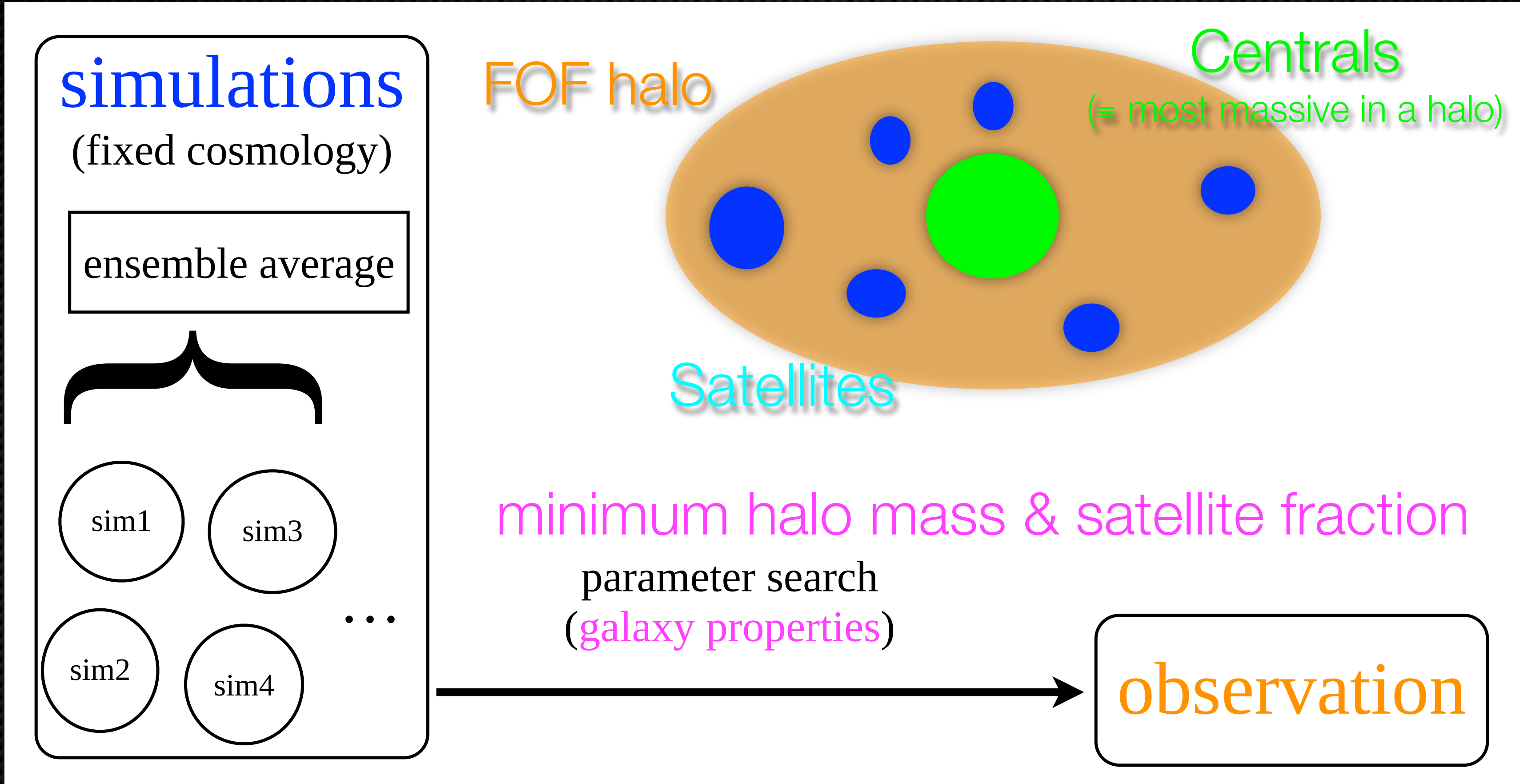


Halos vs. Subhalos

Oka, Nishimichi et al. (in prep.)

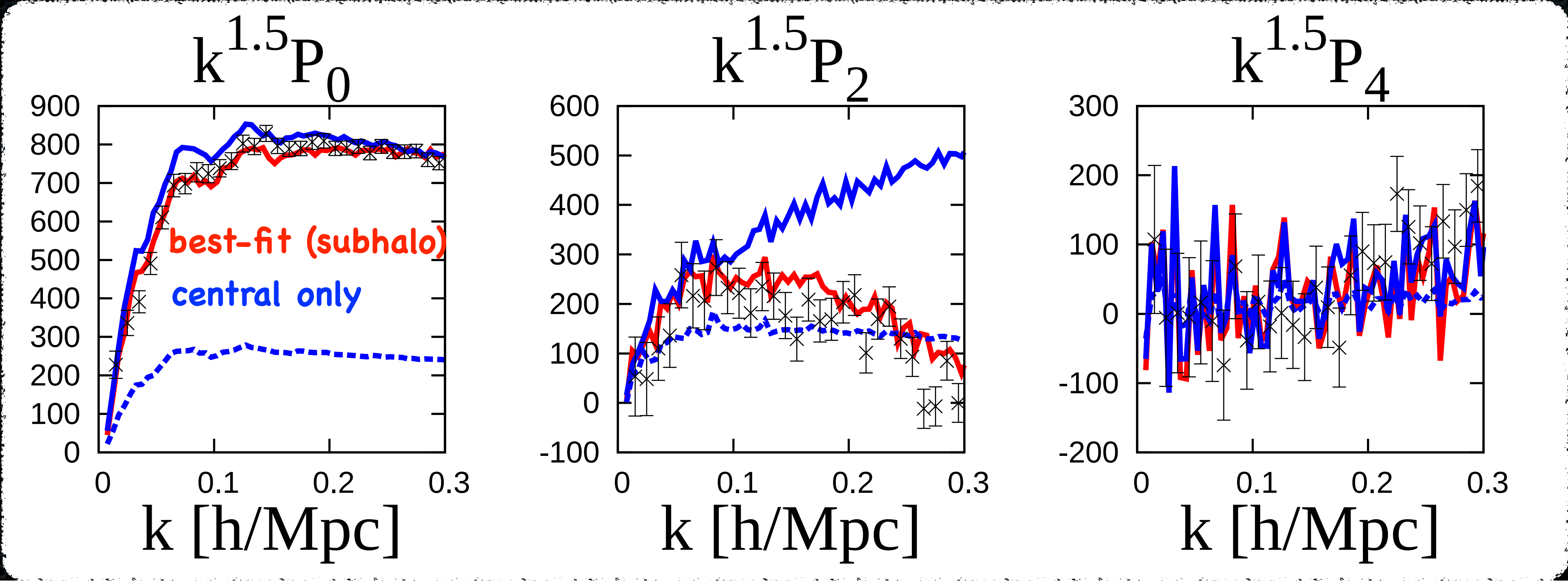
dashed: M_{min} = 1.77 [$10^{12} M_{sun}/h$], F_S = 0

solid: M_{min} = 28.3 [$10^{12} M_{sun}/h$], F_S = 0

solid: M_{min} = 12.6 [$10^{12} M_{sun}/h$], F_S = 0.25

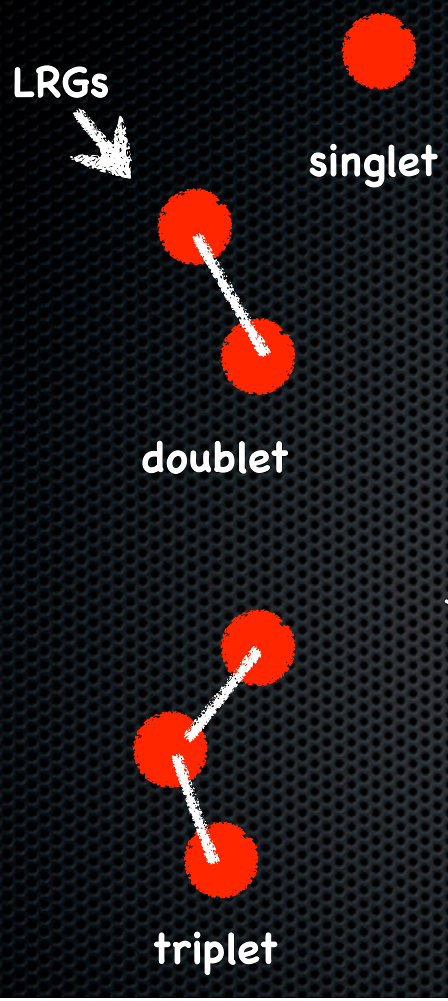
- We need satellites (20~30%) !
  - centrals cannot explain both P_0 & P_2 simultaneously

$$P(k,\mu) = \mathcal{L}_0(\mu)P_0(k) + \mathcal{L}_2(\mu)P_2(k) + \mathcal{L}_4(\mu)P_4(k) + \ldots$$



Multiplicity function

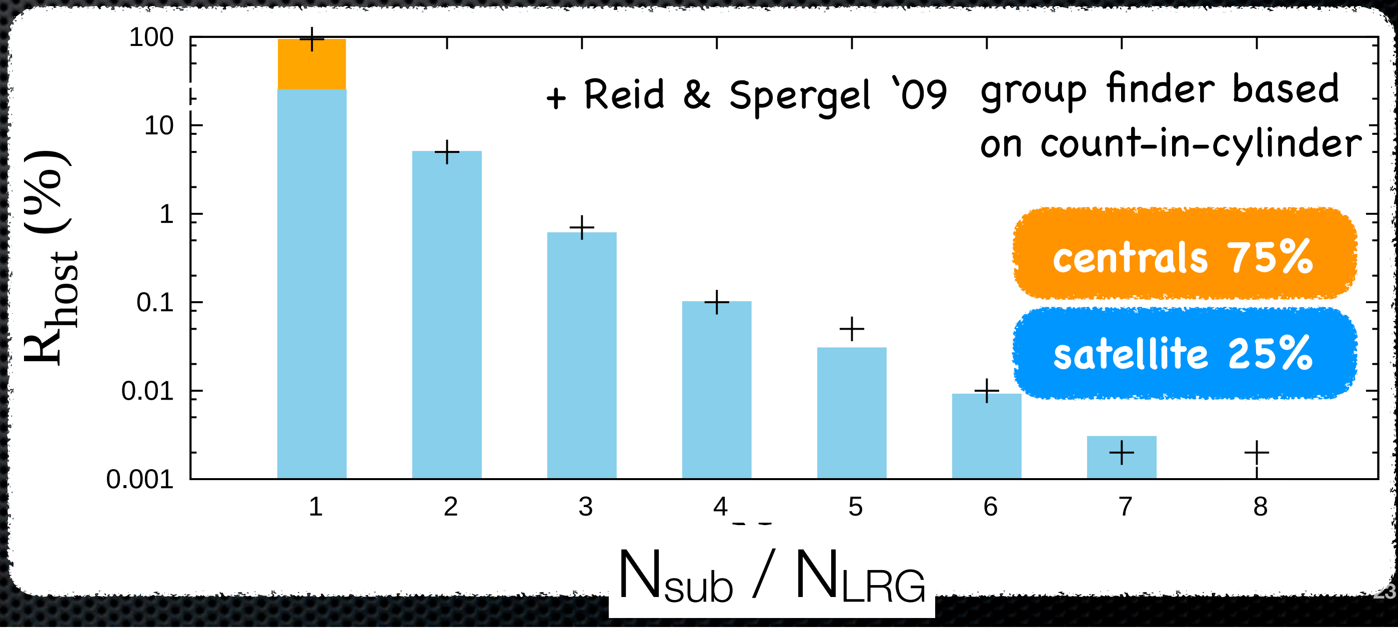
Oka, Nishimichi et al. (in prep.)



- best-fit model reproduces the multiplicity function pretty well
  - *a single LRG does not always mean a central galaxy !*

see also Hikage + '12,
who discuss the off-centering of LRGs
using correlation + weak lensing signals

fraction of host halos that have *N* subhalos/galaxies



Bias is not always bad!

Dalal+08
Slosar+08
Matarrese,Verde08
Afshordi,Tolley08
McDonald08
Taruya+09
Giannantonio,Porciani10
Desjacques,Jeong,Schmidt11a,b
and more ...

theory

Desjacques+09
Grossi+09
Pillepich+10
and more ...

simulation

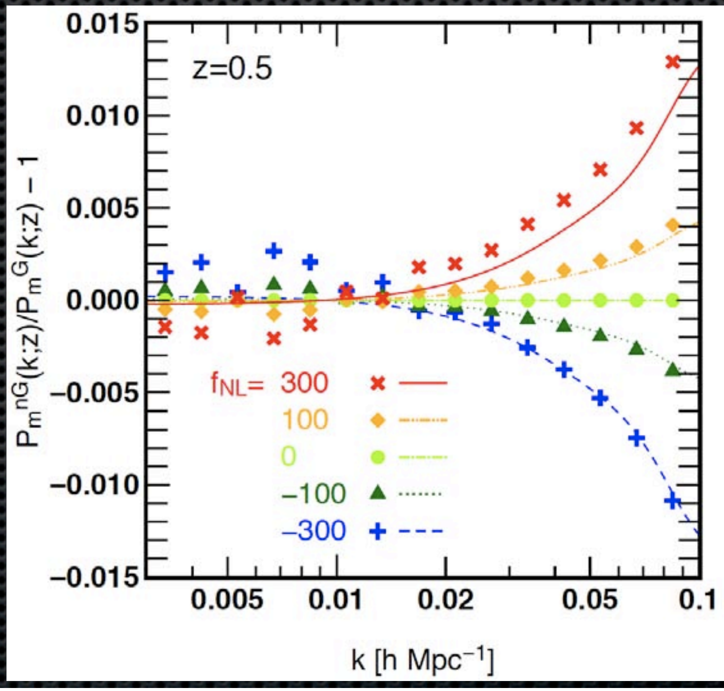
observation

Slosar+08

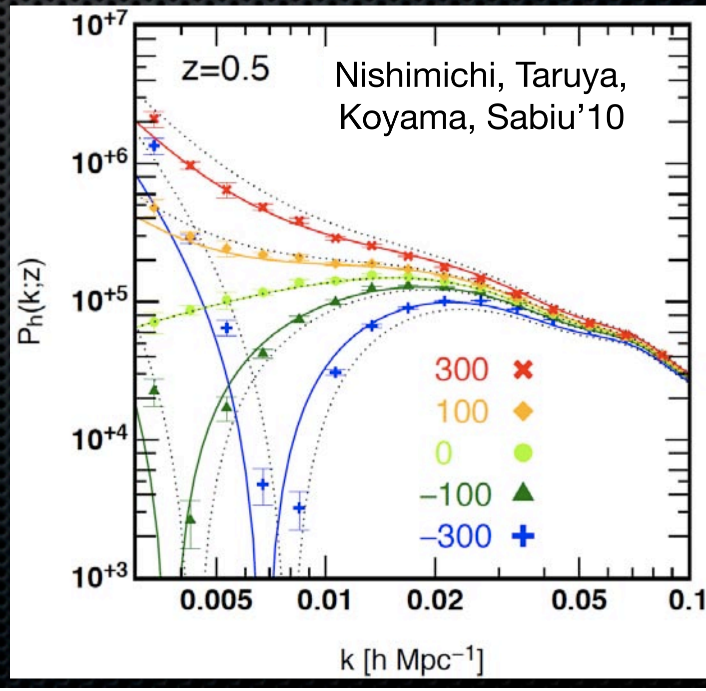
$-29 < f_{nl} < 69$ (QSOs+more)

- Scale-dependent bias has been a hot topic
  - a new window for primordial non-Gaussianities

matter power spec.



halo power spec.



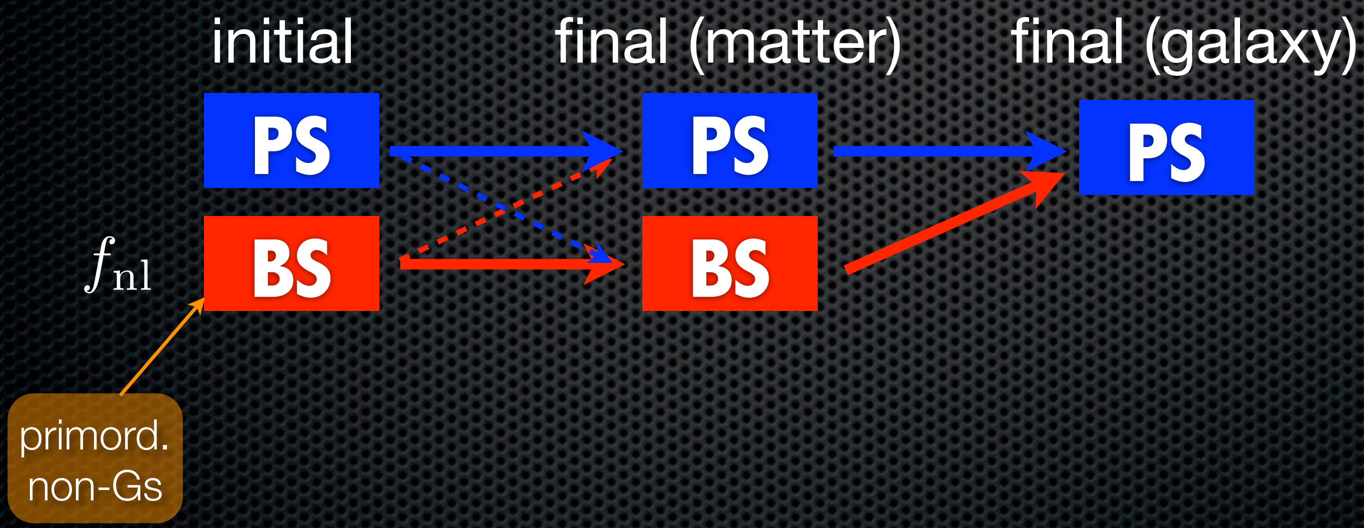
What we are looking at?

local-type non-G.

$$B_\zeta(k_1, k_2, k_3) = \frac{6}{5} f_{\rm nl}[P_\zeta(k_1)P_\zeta(k_2) + (2\,\text{perms.})]$$

ζ: curvature perturbation

$f_{\rm nl} = 37 \pm 20\,(68\%\text{CL})$ WMAP9 (Hinshaw+'13)



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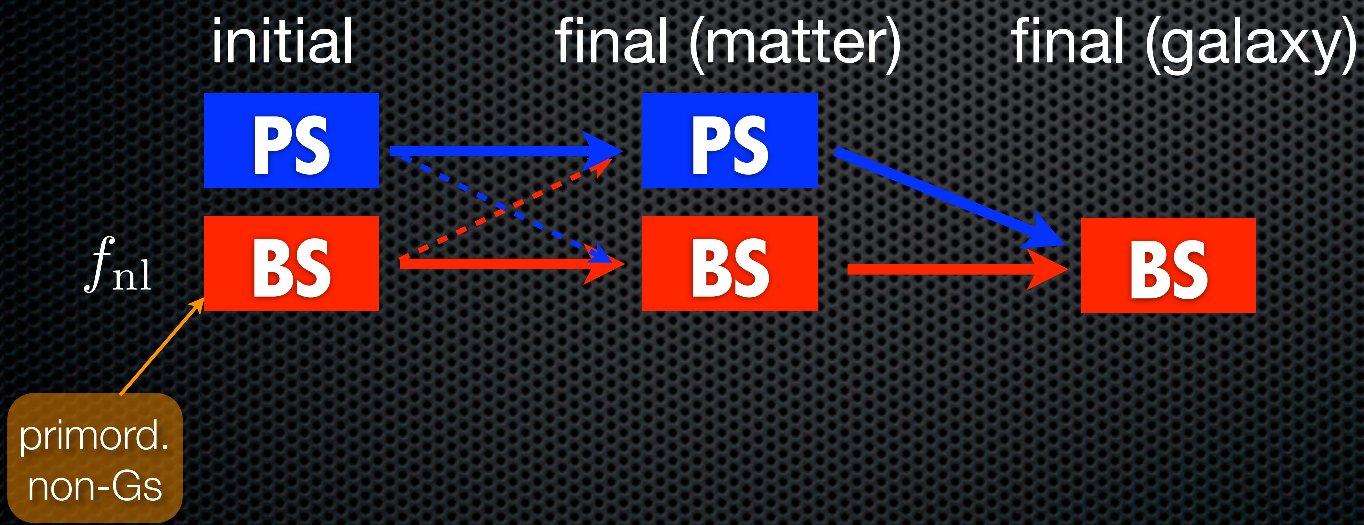


- What happens to the bispectrum of biased tracers?

What we are looking at?

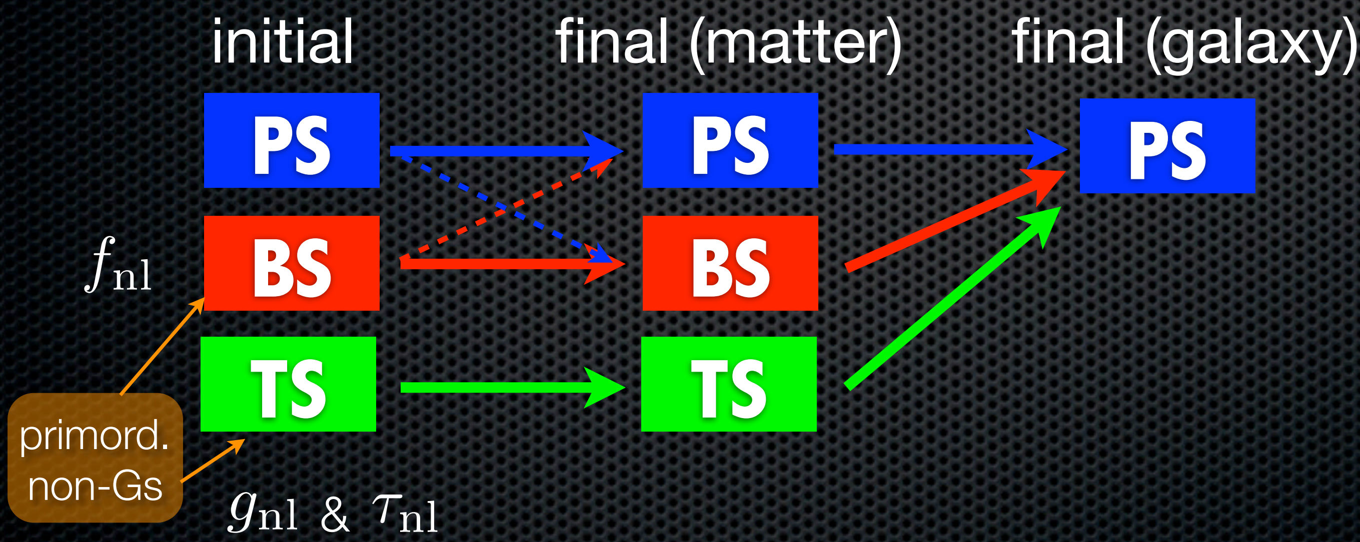
local-type non-G.

$$B_\zeta(k_1,k_2,k_3)=\frac{6}{5}f_{\rm nl}[P_\zeta(k_1)P_\zeta(k_2)+(2\,{\rm perms.})]$$

ζ: curvature perturbation

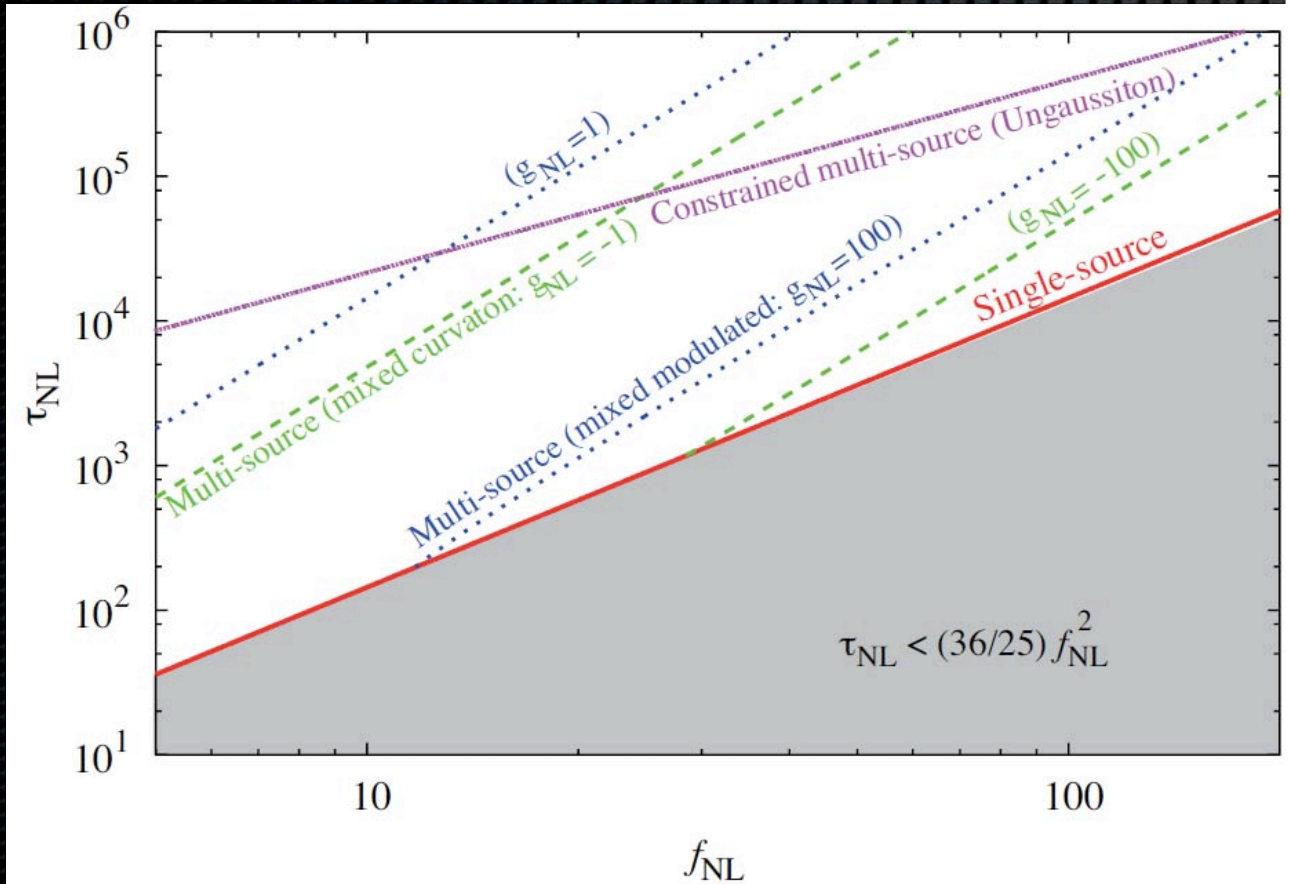
$f_{\rm nl}=37\pm 20\,(68\%{\rm CL})$ WMAP9 (Hinshaw+'13)

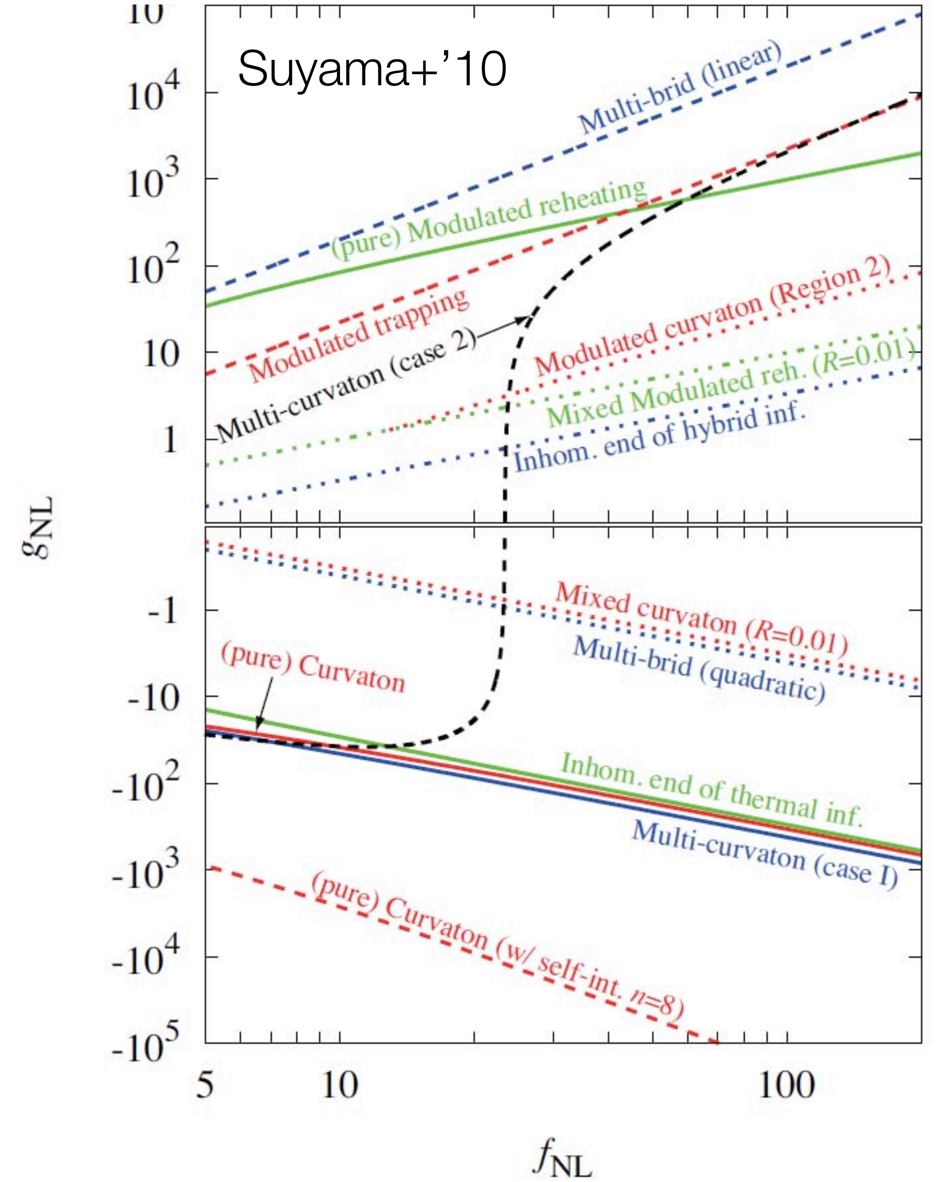
$$T_\zeta(k_1,k_2,k_3,k_4)=\tau_{\rm nl}[P_\zeta(k_{13})P_\zeta(k_3)P_\zeta(k_4)+(11\,{\rm perms.})]$$
$$+\frac{54}{25}g_{\rm nl}[P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3)+(3\,{\rm perms.})]$$



- What happens to the bispectrum of biased tracers?
- Can we measure the primordial trispectrum?

What we are looking at?

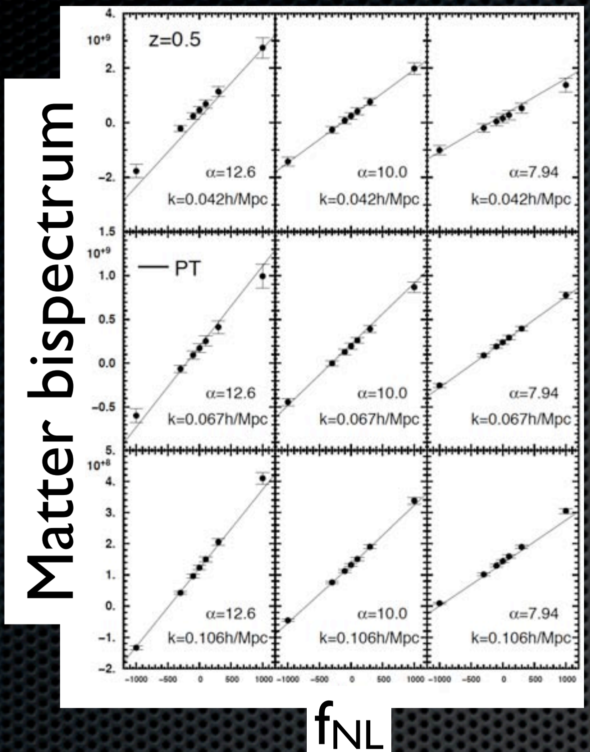


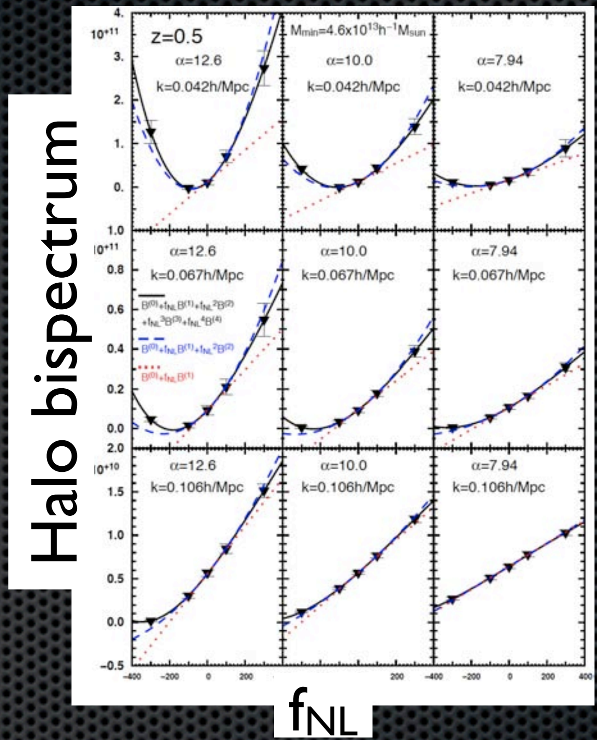


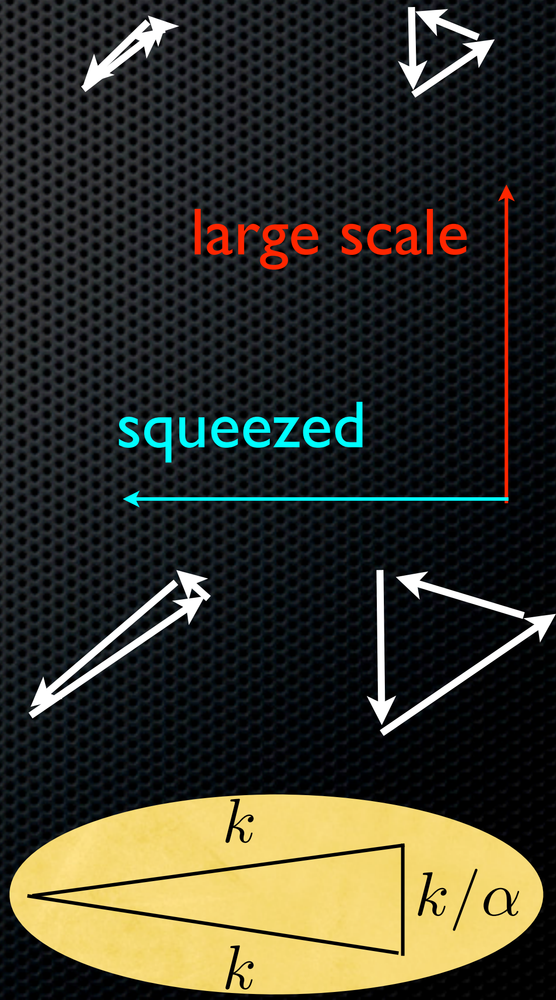
non-Gs $g_{\rm nl}$ & $\tau_{\rm nl}$

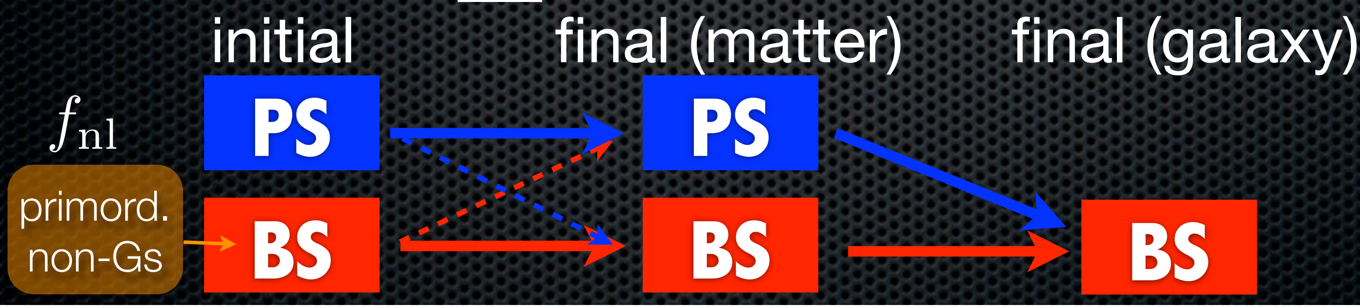
Bispectrum

Nishimichi, Taruya, Koyama & Sabiu '10







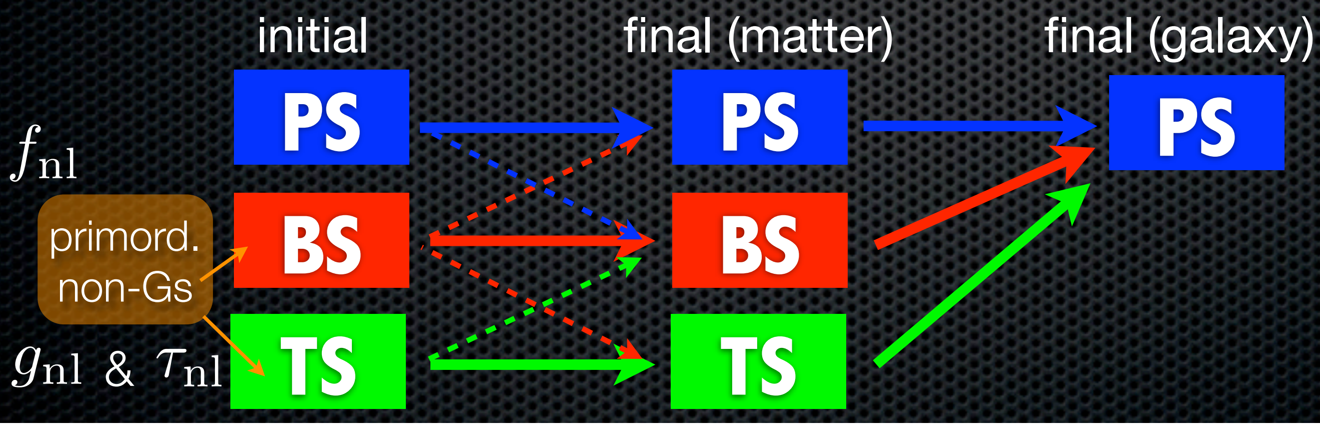


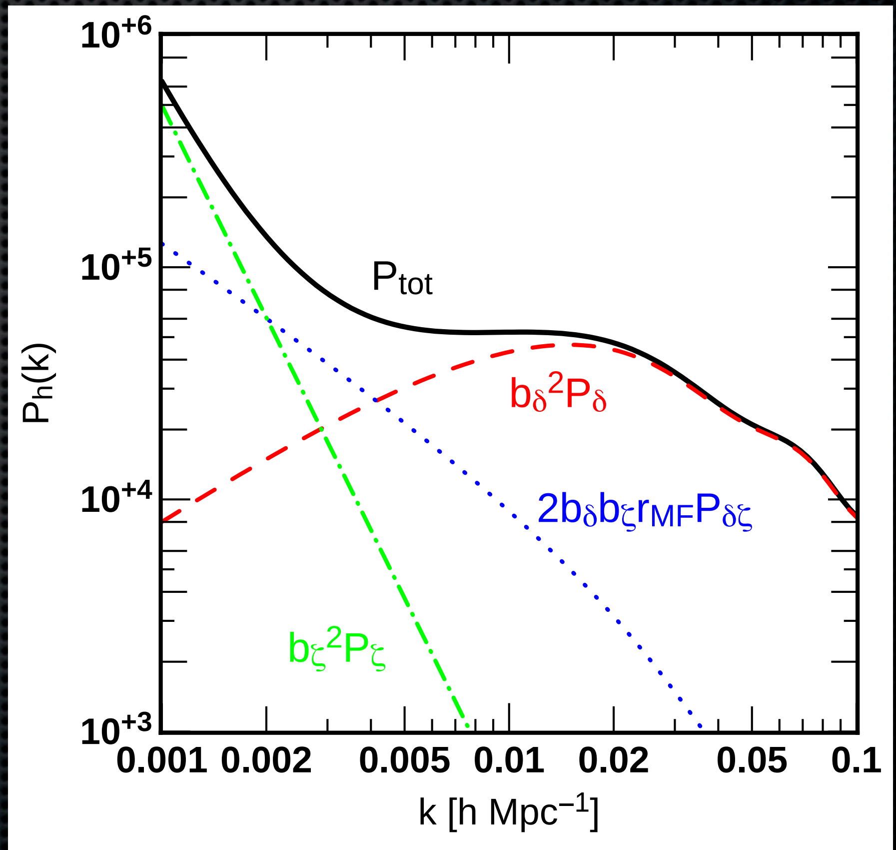
General local-type non-G

Nishimichi '12

- Curvature perturbation is expressed as
  - a Taylor series of multiple Gaussian fields
  - includes higher-order coupling at any order
- The resultant halo P(k) is very generic !

$$P_{\rm h}(k) = b_\delta^2 P_\delta(k) + 2r_{\rm MF} b_\delta b_\zeta P_{\delta\zeta}(k) + b_\zeta^2 P_\zeta(k)$$





New tests f_{nl} vs τ_{nl}

Nishimichi '12

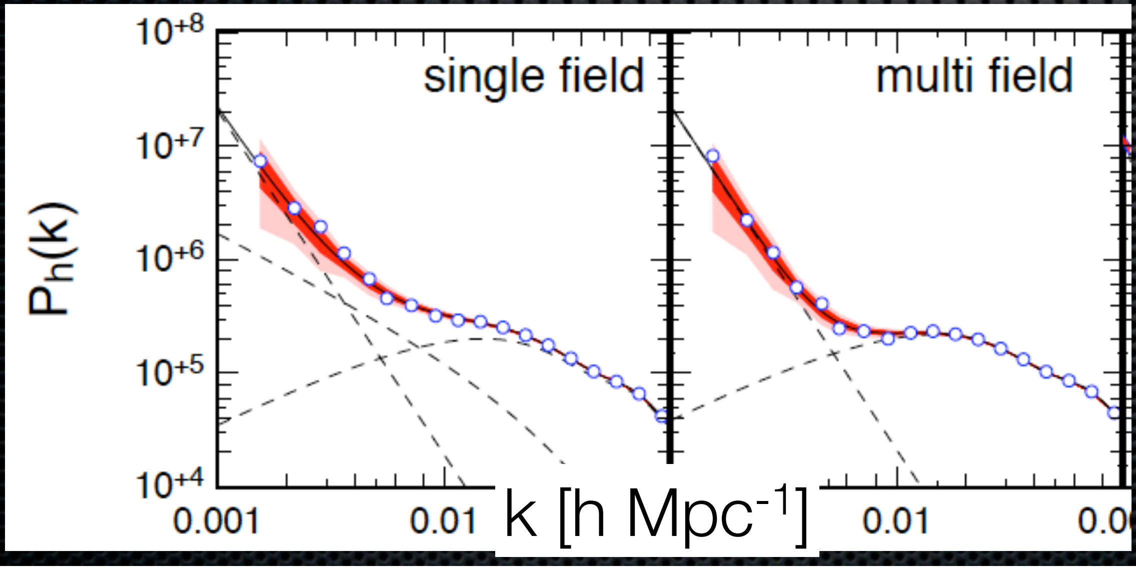
- Suyama-Yamaguchi inequality

$$\tau_{\rm nl} \geq \frac{36}{25} f_{\rm nl}^2$$

>: multiple sources

=: single source

  - Robust. Just a Cauchy-Schwarz inequality.



- Generalized SY inequality can be tested using P(k) of biased tracers!

$$|r_{\rm MF}| \leq 1$$

  - shape of P(k) tells us about that

left: $f_{nl} = 100$, $\tau_{nl} = (36/25)f_{nl}^2$
→ $r_{MF} = 1$

right: $f_{nl} = 0$, $\tau_{nl} = (36/25)f_{nl}^2$
→ $r_{MF} = 0$

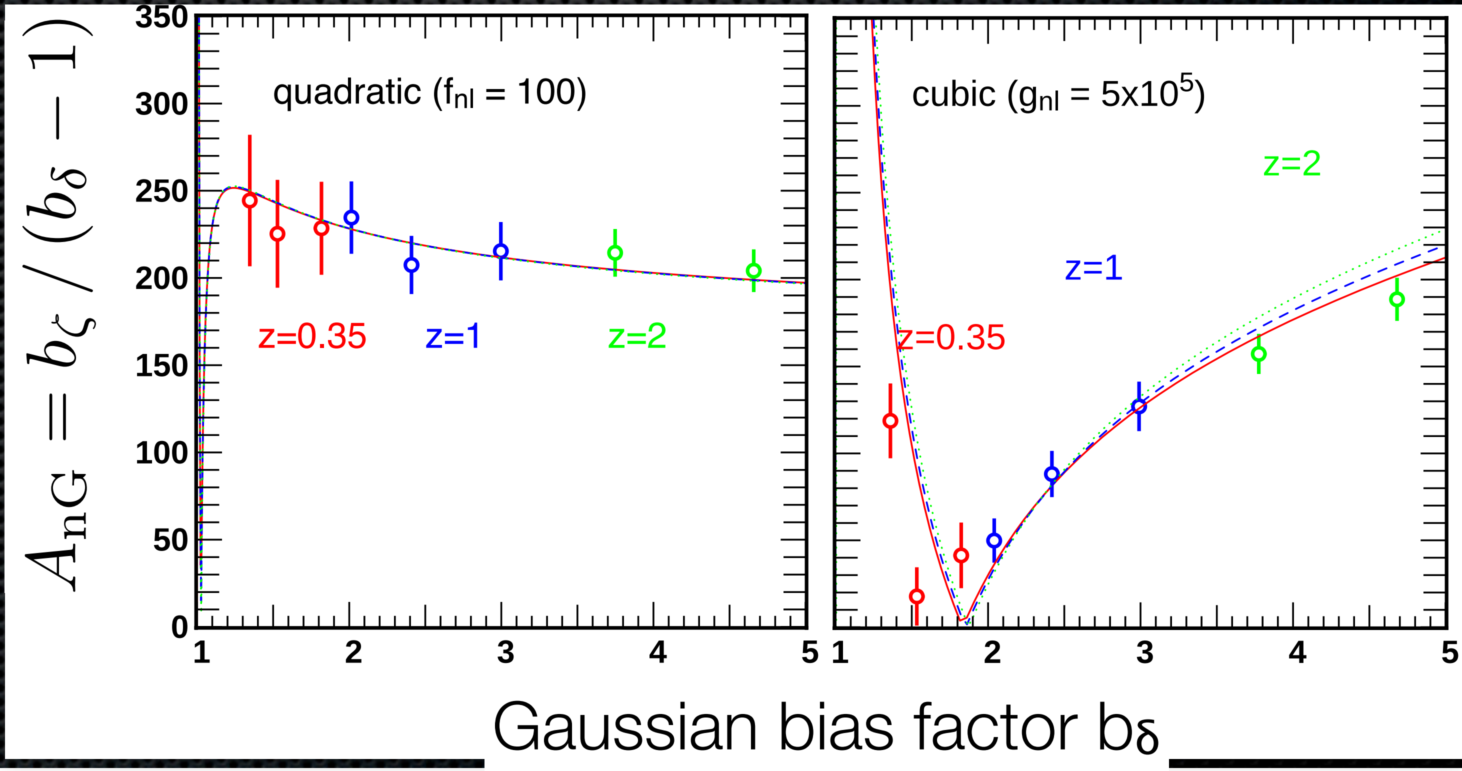
$$P_{\rm h}(k) = b_\delta^2 P_\delta(k) + 2r_{\rm MF} b_\delta b_\zeta P_{\delta\zeta}(k) + b_\zeta^2 P_\zeta(k)$$

New tests f_{nl} vs g_{nl}

Nishimichi '12

$$P_h(k) = b_\delta^2 P_\delta(k) + 2 r_{MF} b_\delta b_\zeta P_{\delta\zeta}(k) + b_\zeta^2 P_\zeta(k)$$

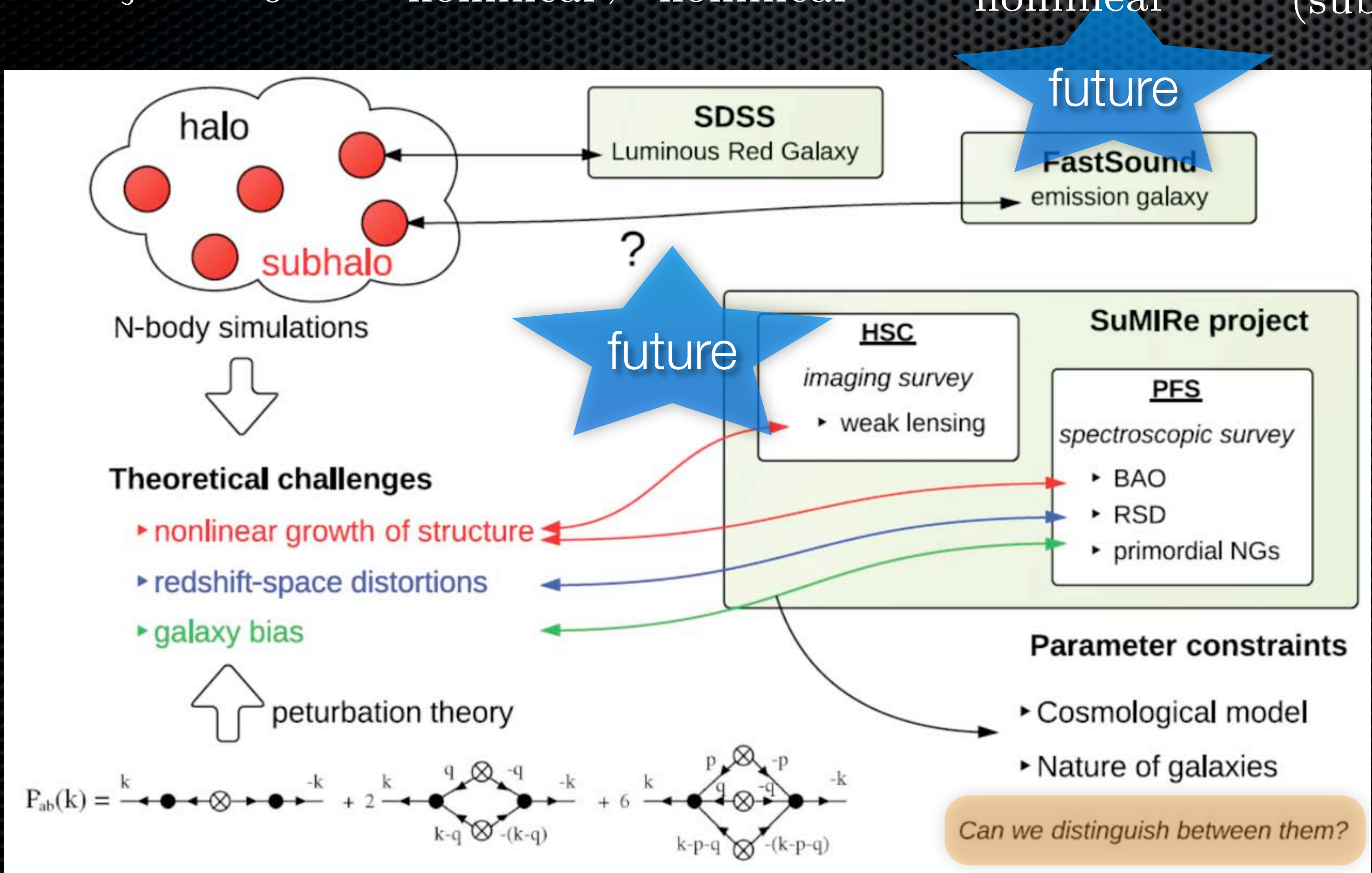
- Approximate Consistency relation btwn Gaussian and non-Gaussian bias factors in case of f_{nl}
  - Multiple tracers
  - different redshifts



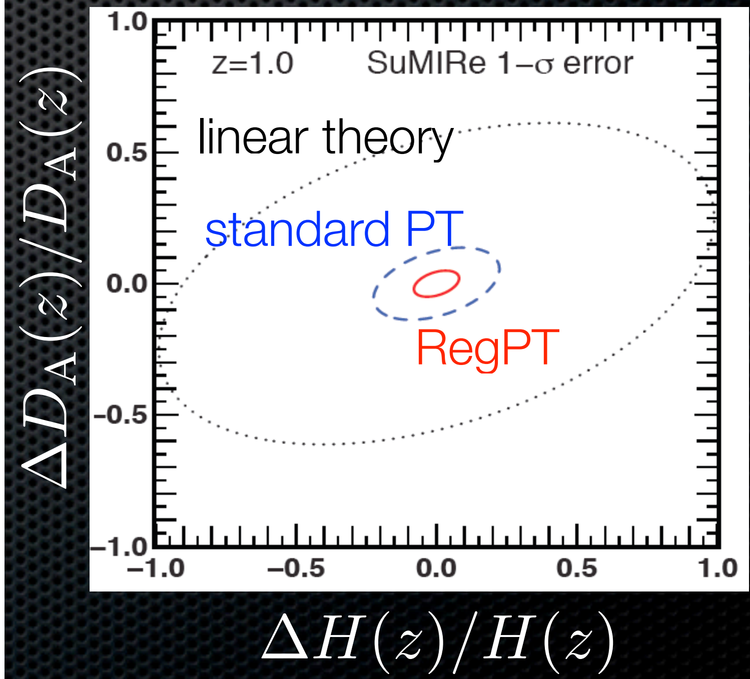
Summary

I am here !!

$$\zeta \rightarrow \delta_0 \rightarrow \delta_{\rm nonlinear}, \theta_{\rm nonlinear} \rightarrow \delta^{\rm z\,space}_{\rm nonlinear} \rightarrow \delta^{\rm z\,space}_{\rm (sub)halo} \overset{?}{\rightarrow} \delta^{\rm z\,space}_{\rm galaxy}$$



current status



※ when bias is controlled