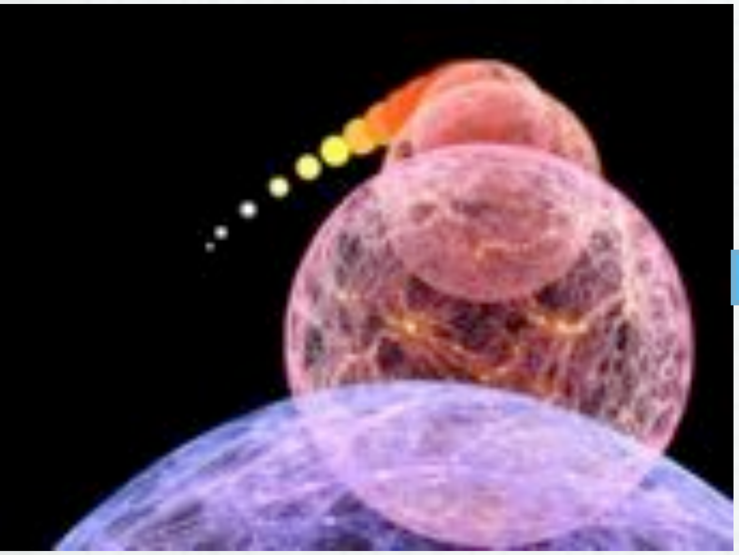
Understanding basic physics from the Large Scale Structure of the Universe

Massimo Pietroni - INFN Padova

LNGS, dec. 11, 2012

Understanding the LSS of the Universe

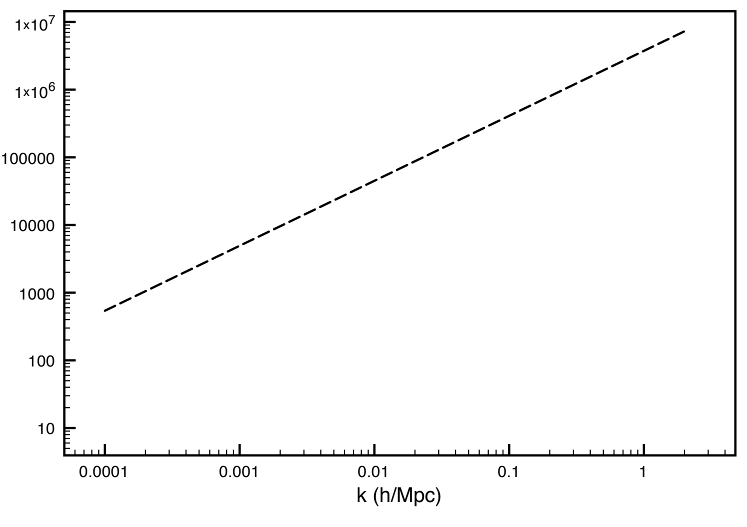
Inflation



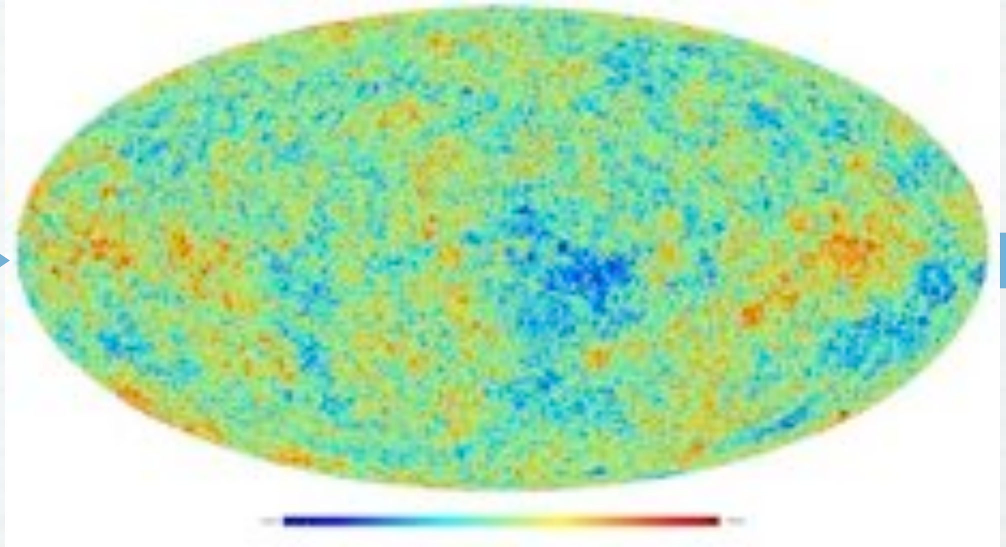
Linear, Gaussian

$$\left(\frac{\delta\rho}{\rho} \simeq 10^{-5}\right)$$

primordial density perturbations

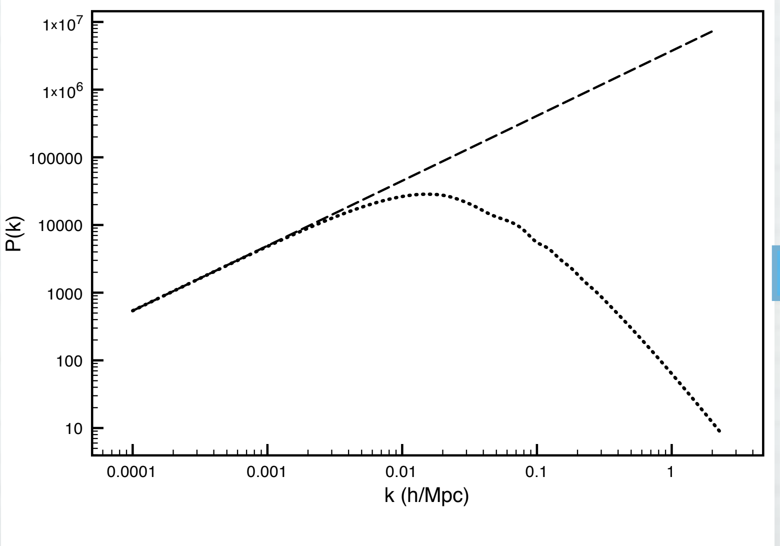


Decoupling

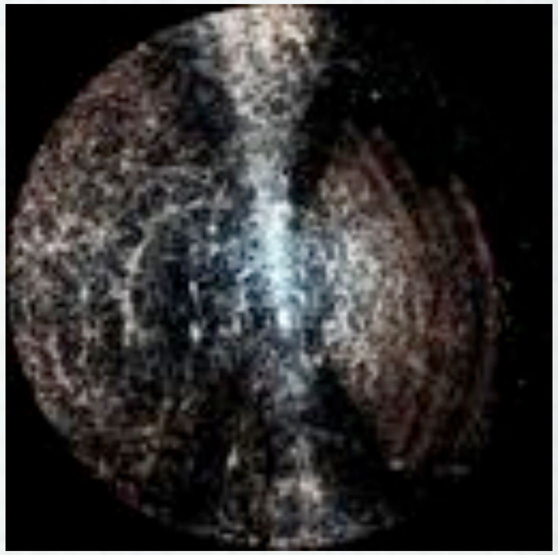


Linear, Gaussian

photon-baryon-DM-neutrino....fluid

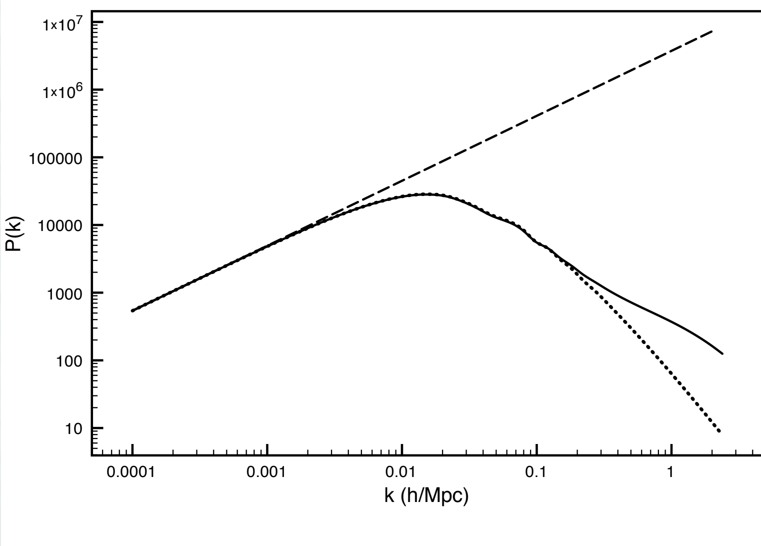


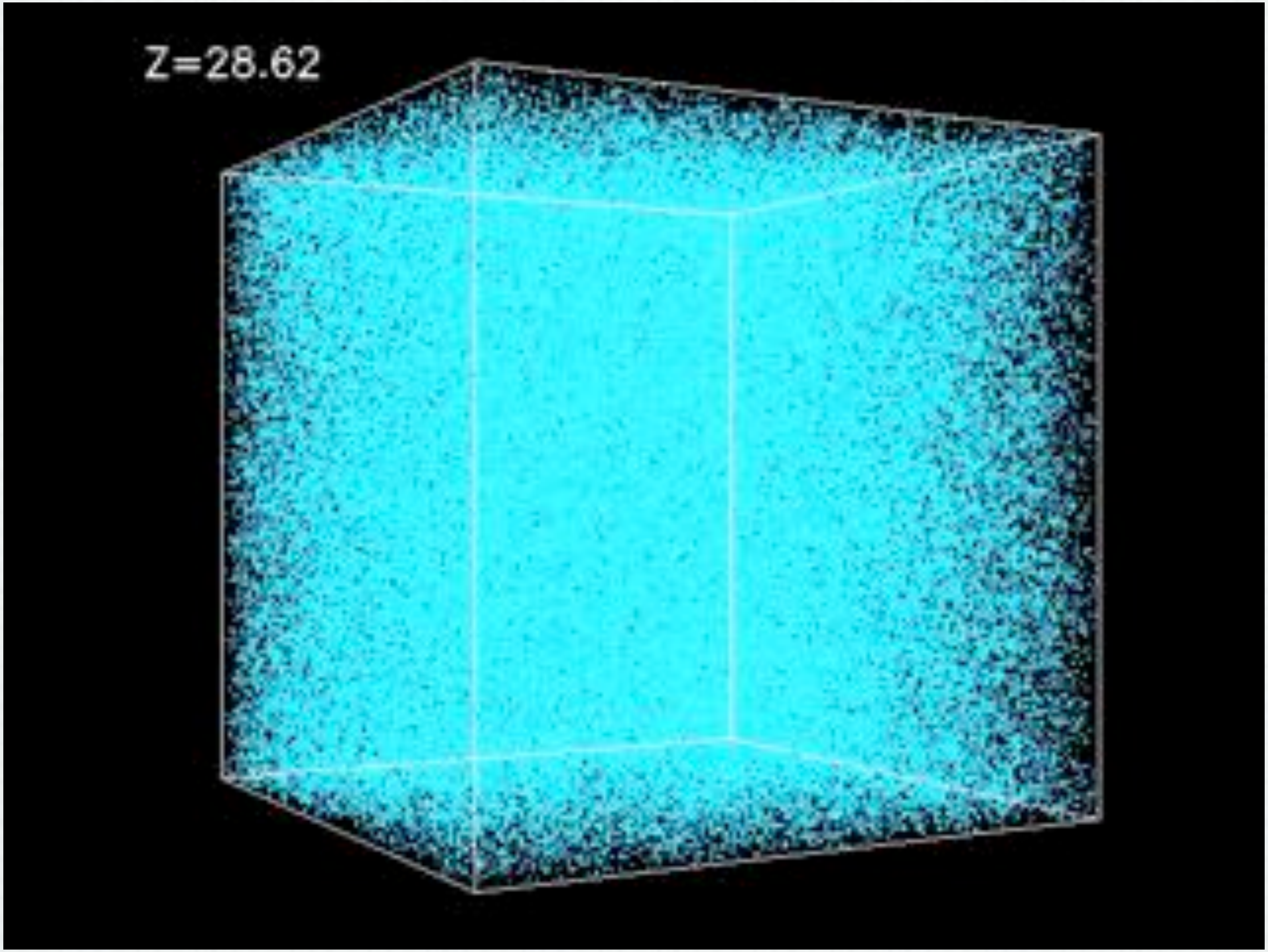
Today



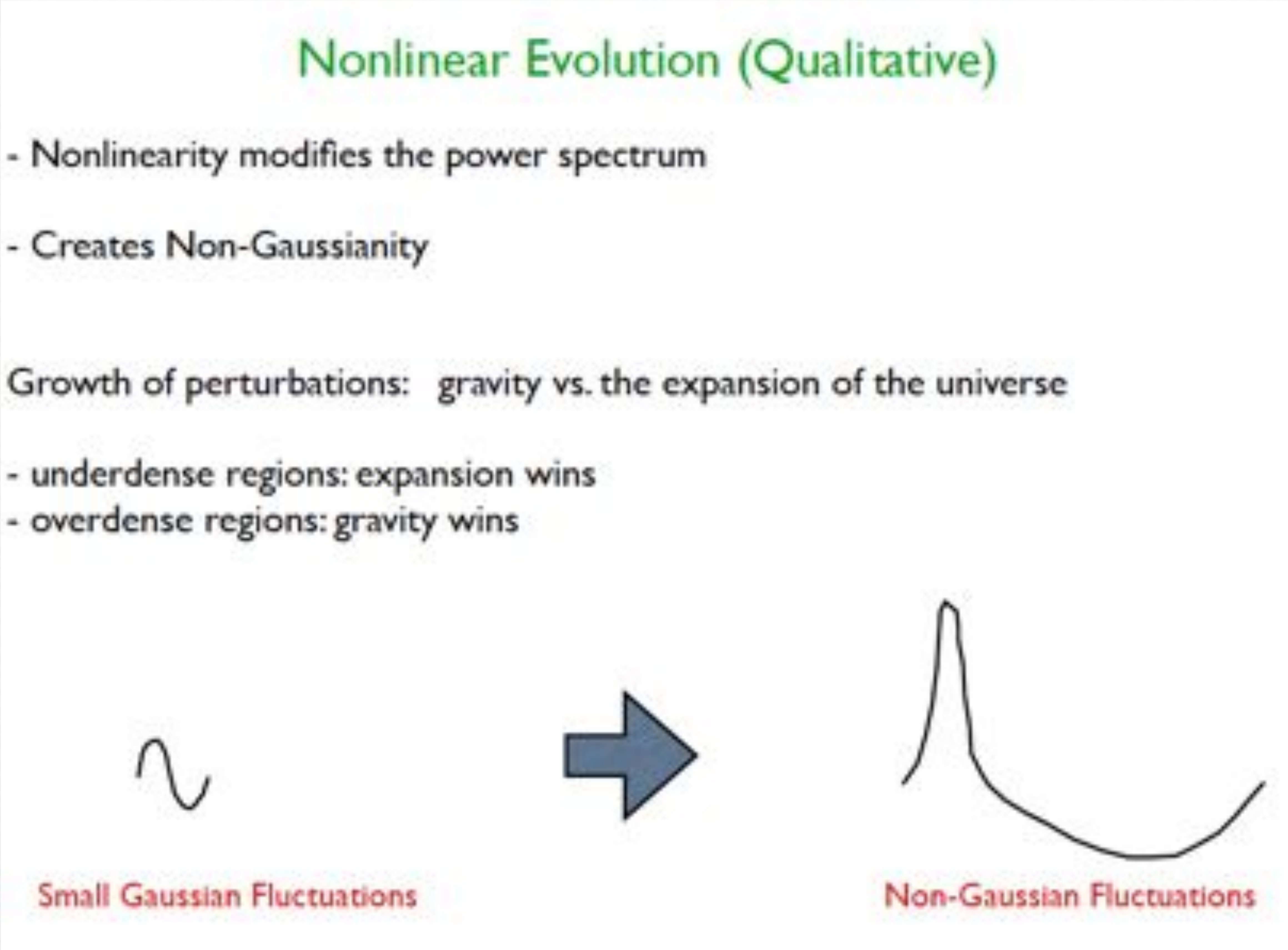
non-Linear, non-Gaussian

non-rel. matter





Movie by Kravtsov, Klypin
(National Center for Supercomputer applications)



Nonlinear Evolution (Qualitative)

- Nonlinearity modifies the power spectrum

- Creates Non-Gaussianity

Growth of perturbations: gravity vs. the expansion of the universe

- underdense regions: expansion wins
- overdense regions: gravity wins

Small Gaussian Fluctuations

Non-Gaussian Fluctuations

Movie by R. Scoccimarro

Why do we need to study the late (and non-linear) evolution?

- Dark Energy (Baryonic Acoustic Oscillations)
- Neutrino masses
- Primordial non-Gaussianity
- Weak gravitational lensing
- ...

The future of precision cosmology: non-linear scales

matter density

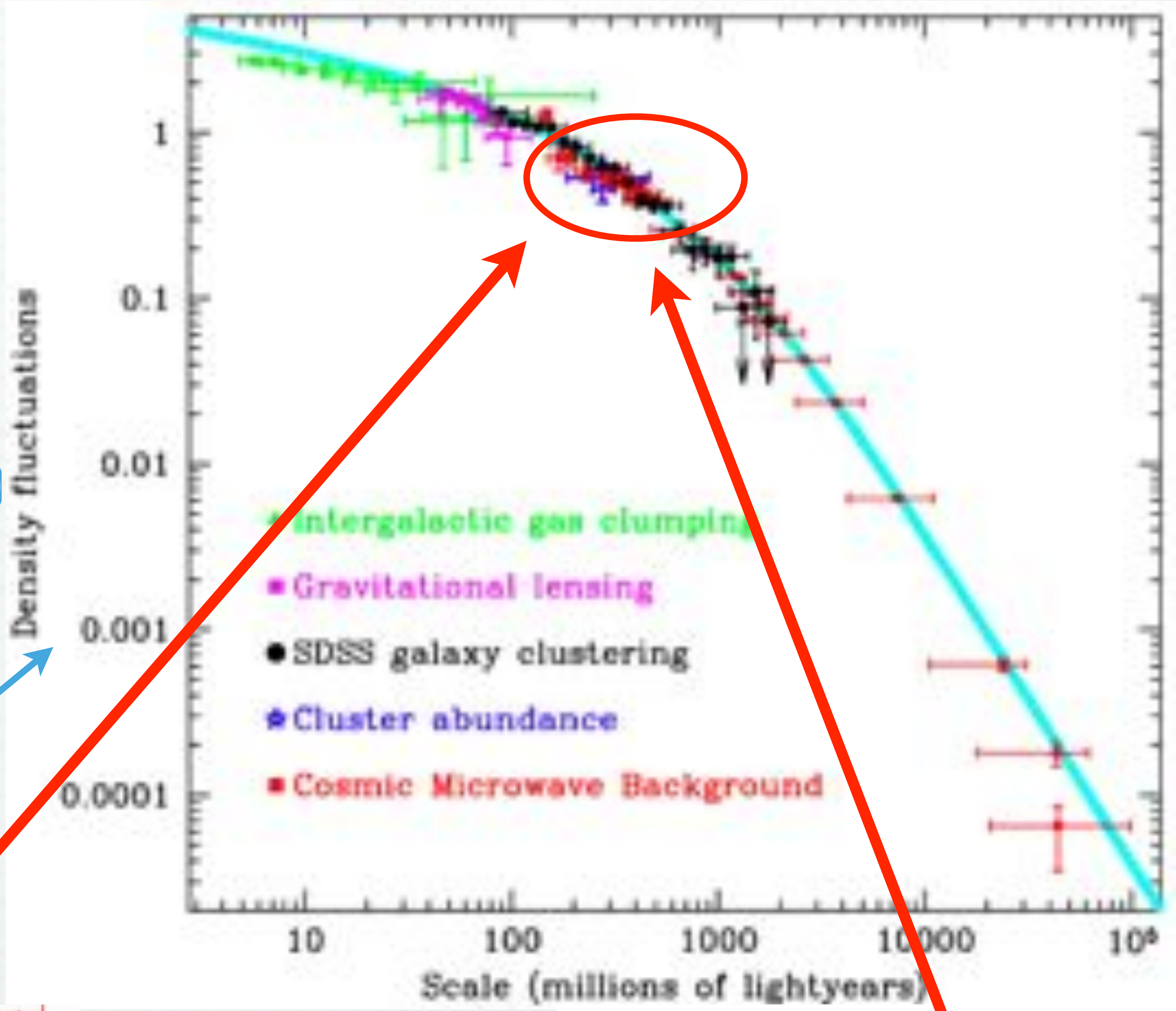
$$\rho(\mathbf{x},\,\tau) \equiv \bar{\rho}(\tau)[1 + \delta(\mathbf{x},\,\tau)]$$

power spectrum

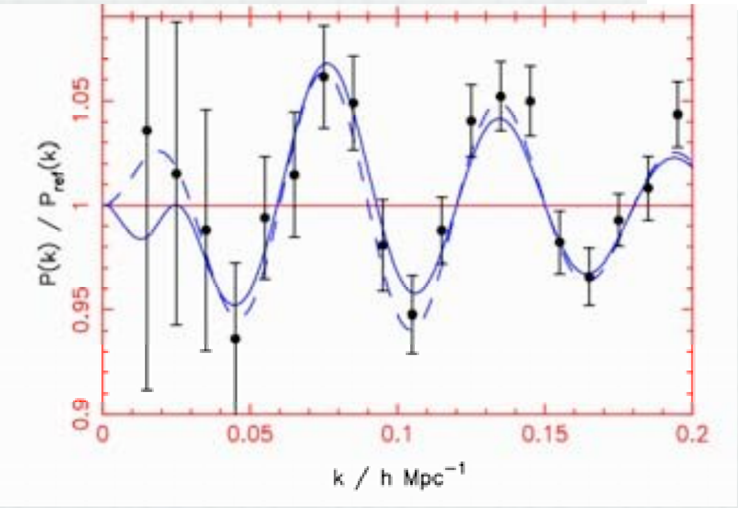
$$\langle\delta(\mathbf{k},\,\tau)\,\delta(\mathbf{k}',\,\tau)\rangle = P(k,\,\tau)\delta^{(3)}(\mathbf{k}+\mathbf{k}')$$

`size' of the fluctuations at different scales/epochs:

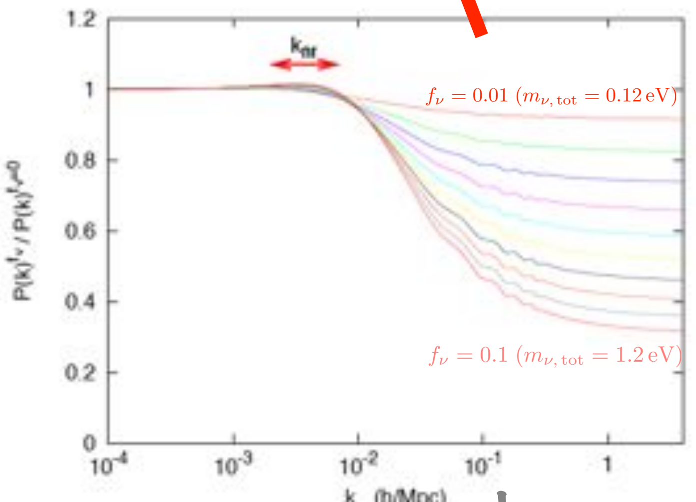
$$\Delta^2(k,\tau) = 4\pi k^3 P(k,\tau)$$

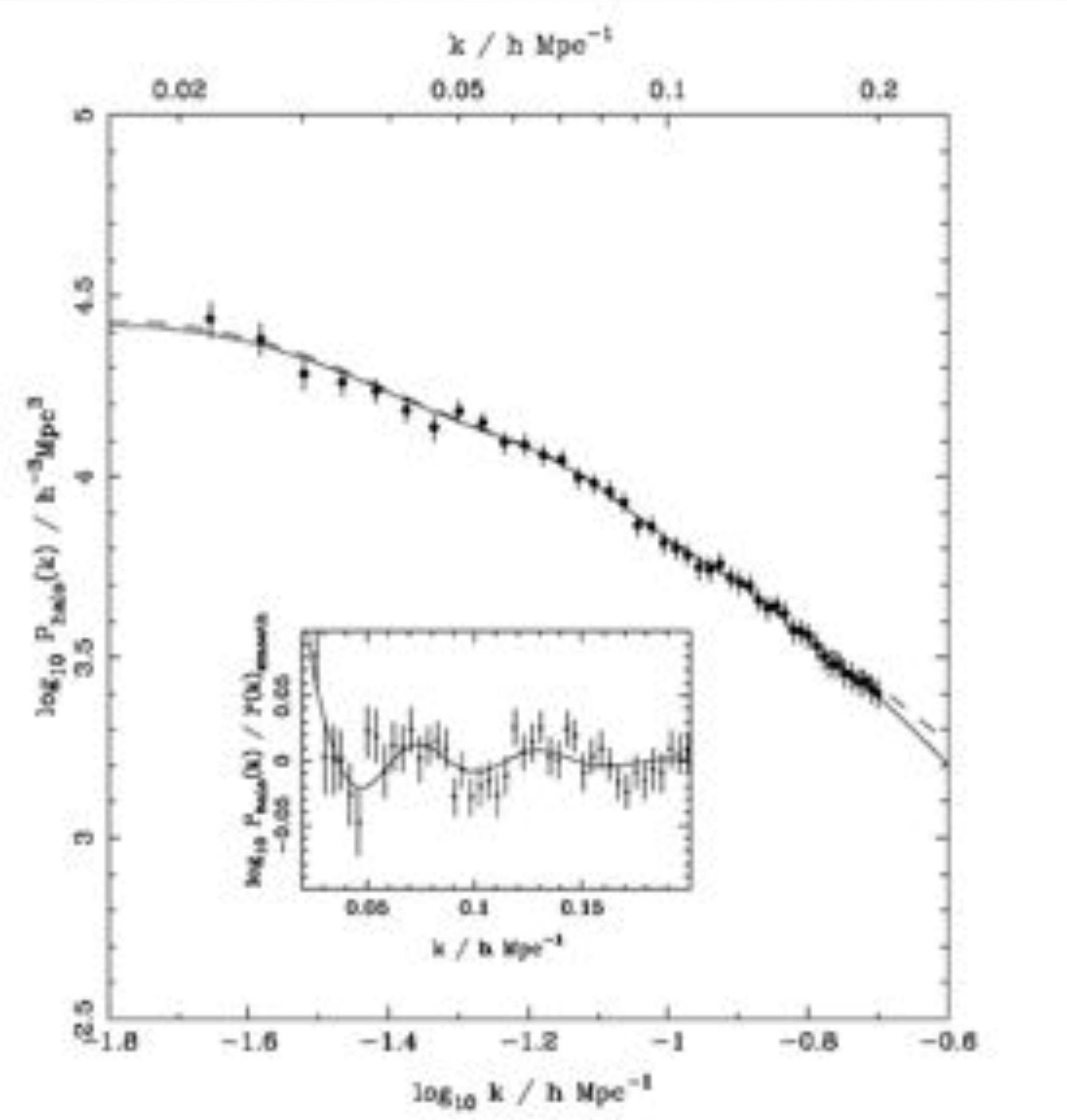


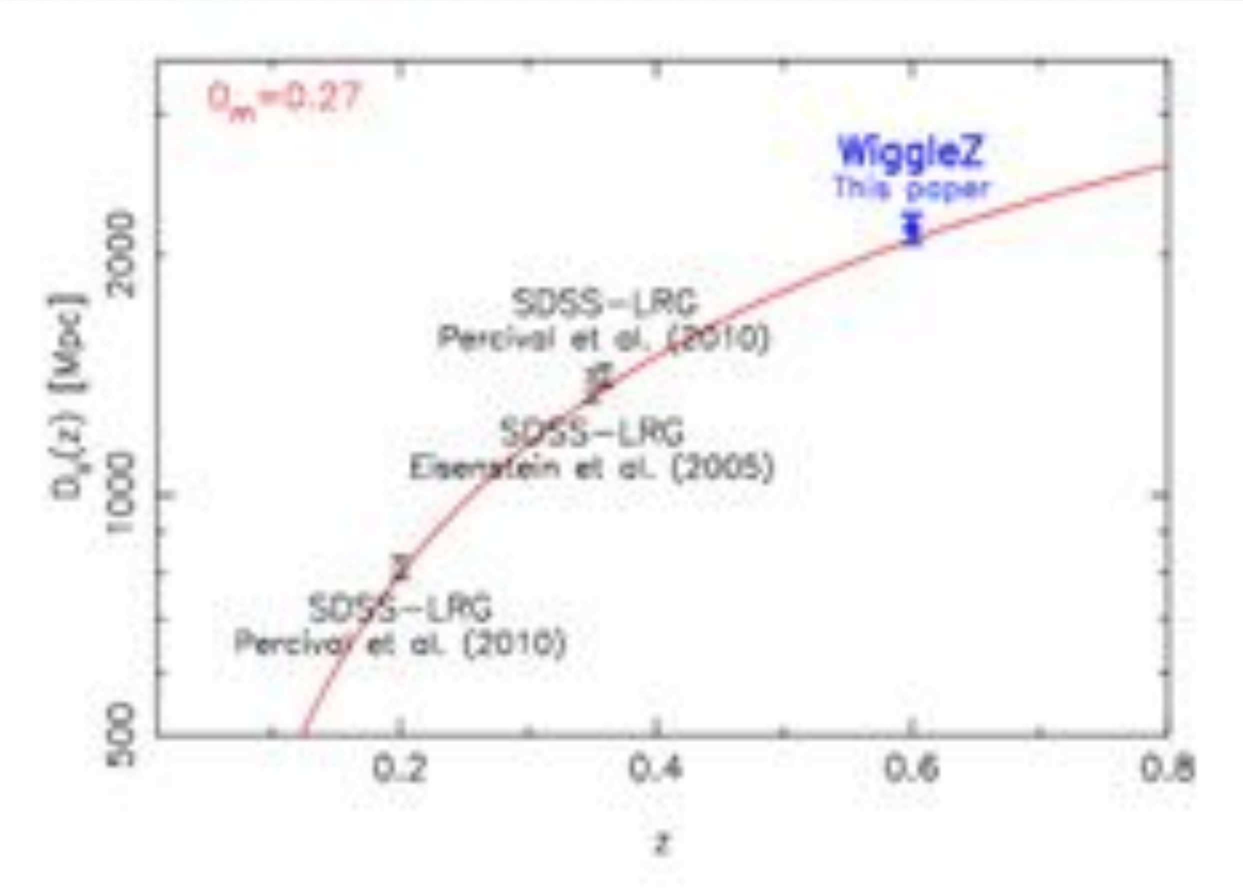
Baryonic Acoustic Oscillations (BAO)



Neutrino mass bounds





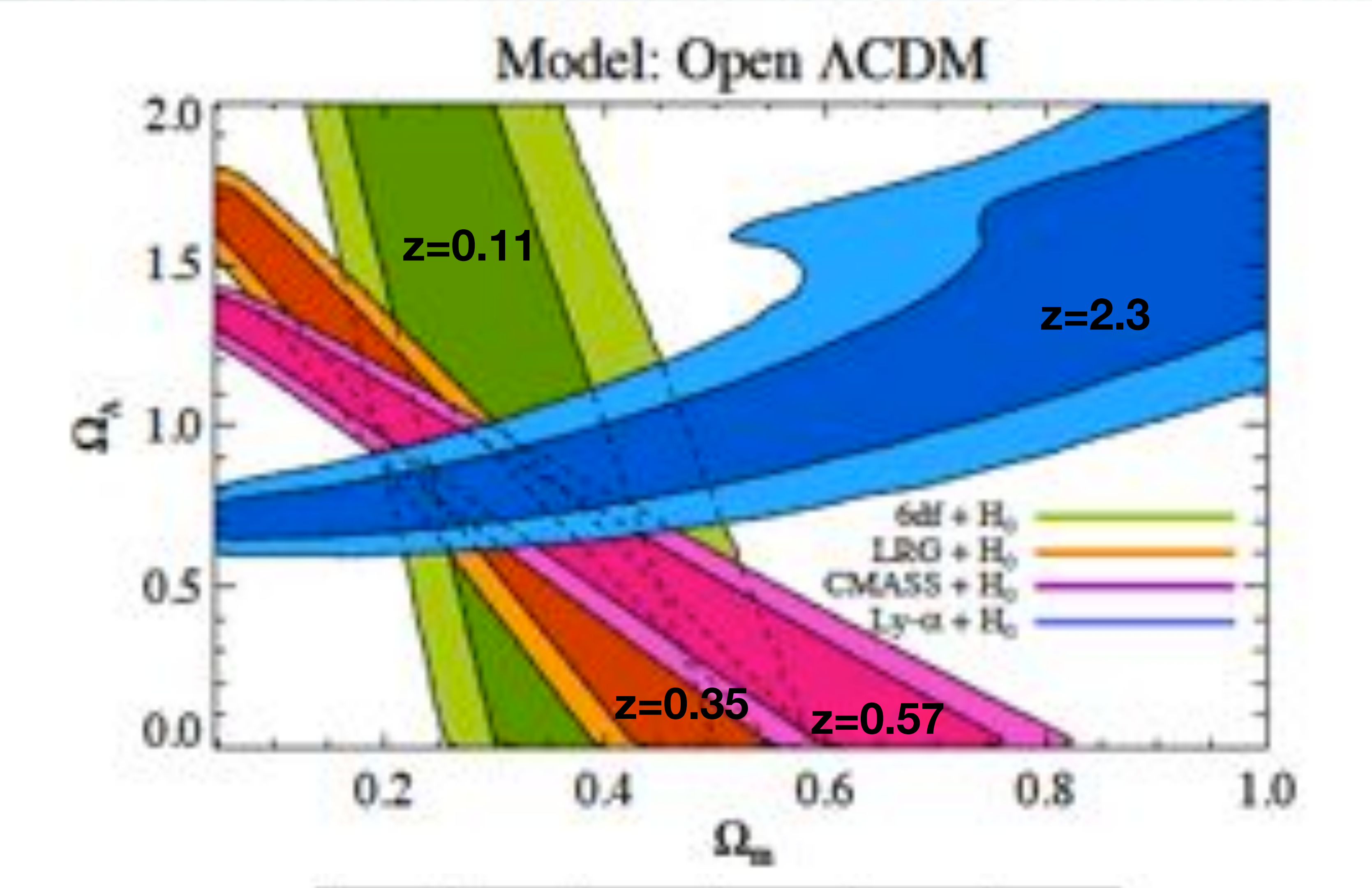


To be dramatically improved in the future: BOSS, EUCLID, ...

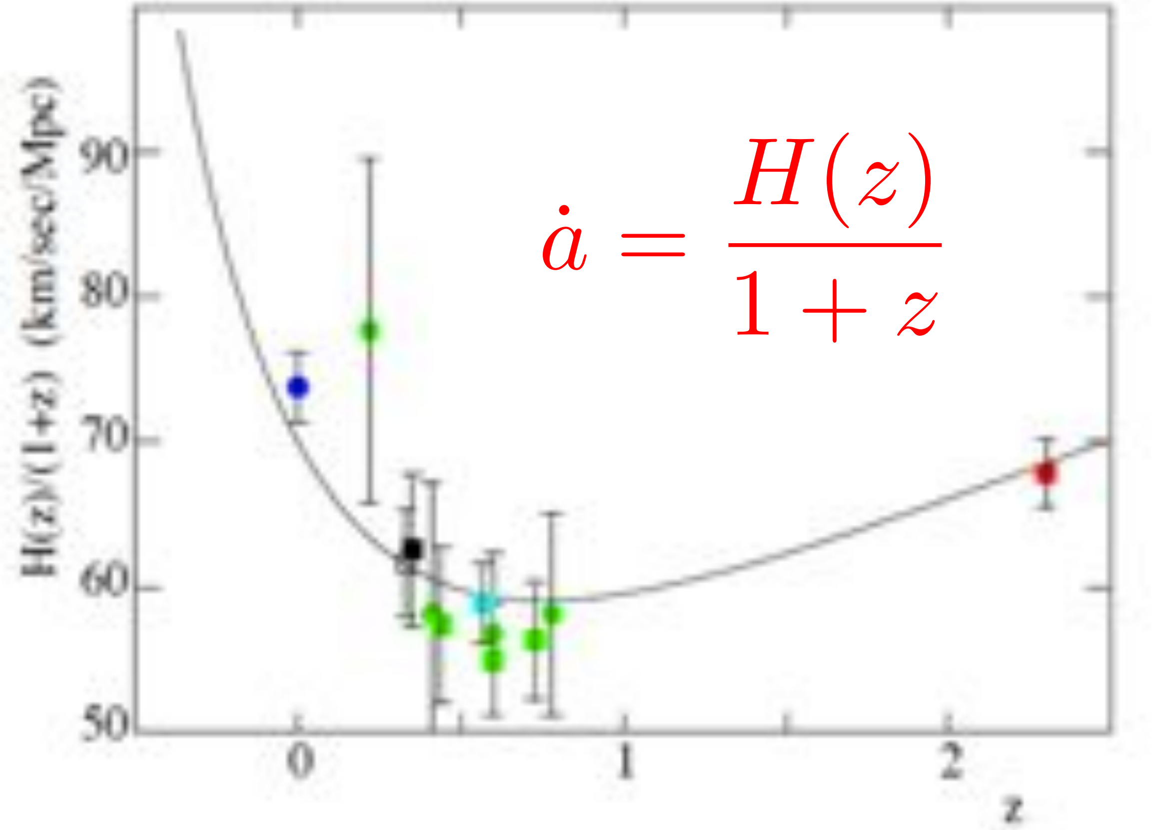
WiggleZ 1105.2862

New BOSS result: BAO in Lyα

1211.2616



Measurement of Dark Energy from LSS "alone" (+ Ho)!

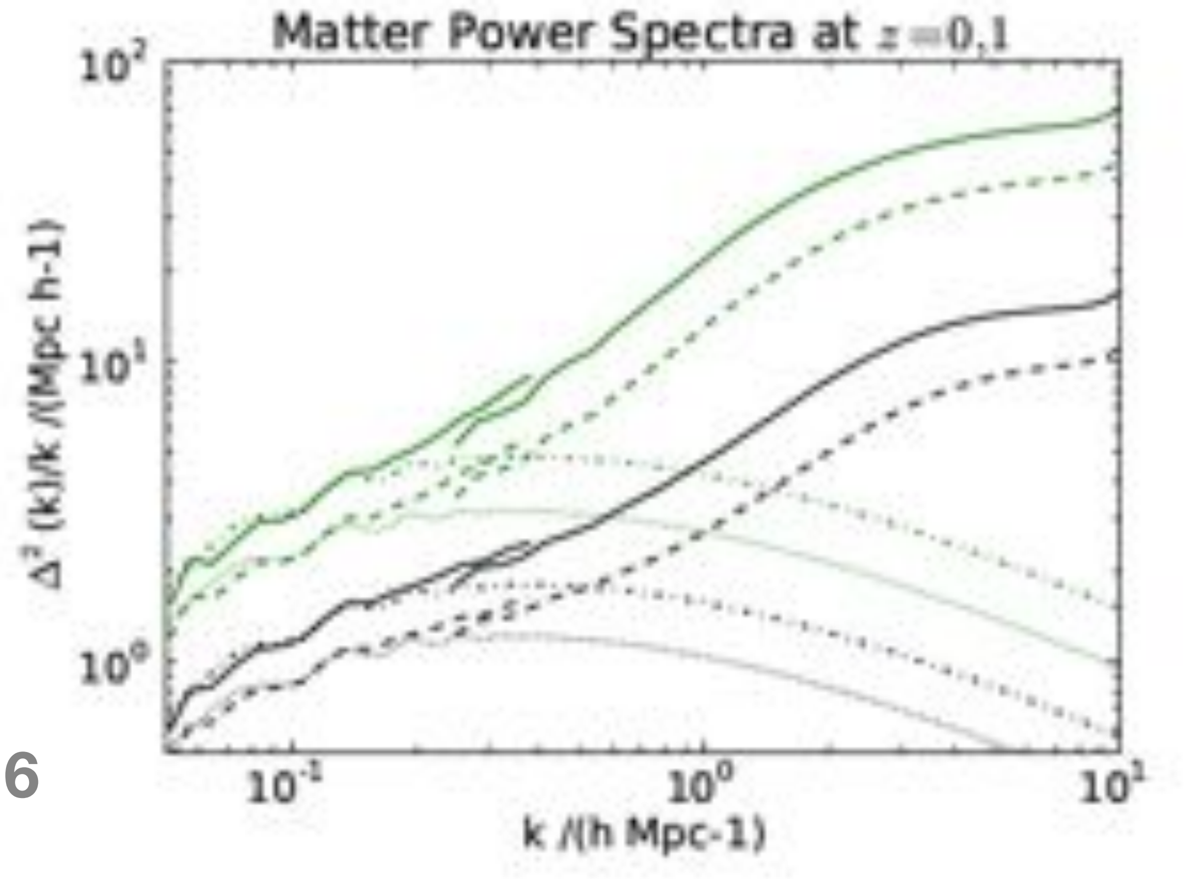


$$\dot{a} = \frac{H(z)}{1+z}$$

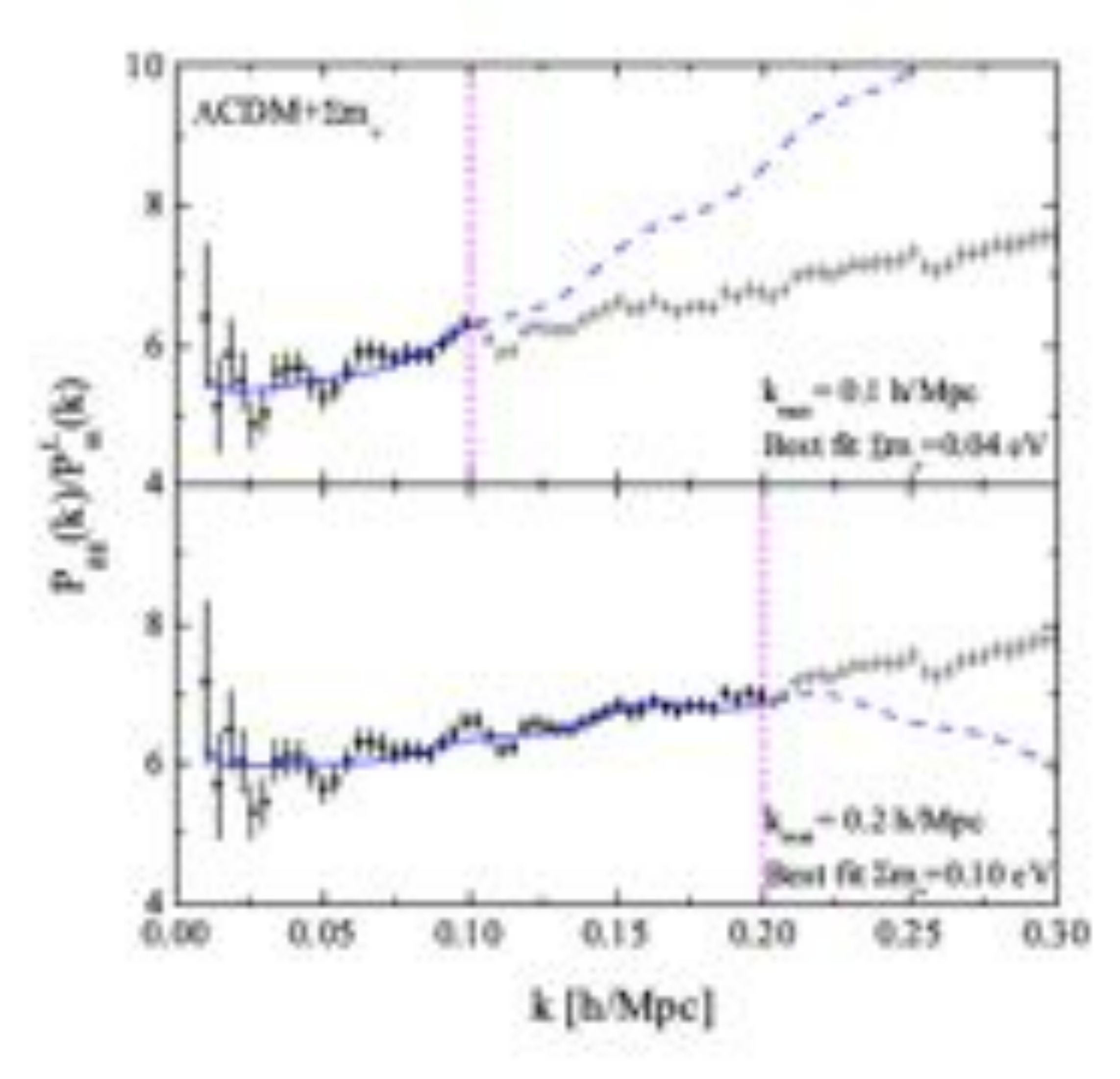
Deceleration to acceleration transition seen!!

Neutrino masses

nonlinearities crucial to increase the sensitivity!!



Bird et al 1109.4416



Zhao et al
1211.3741

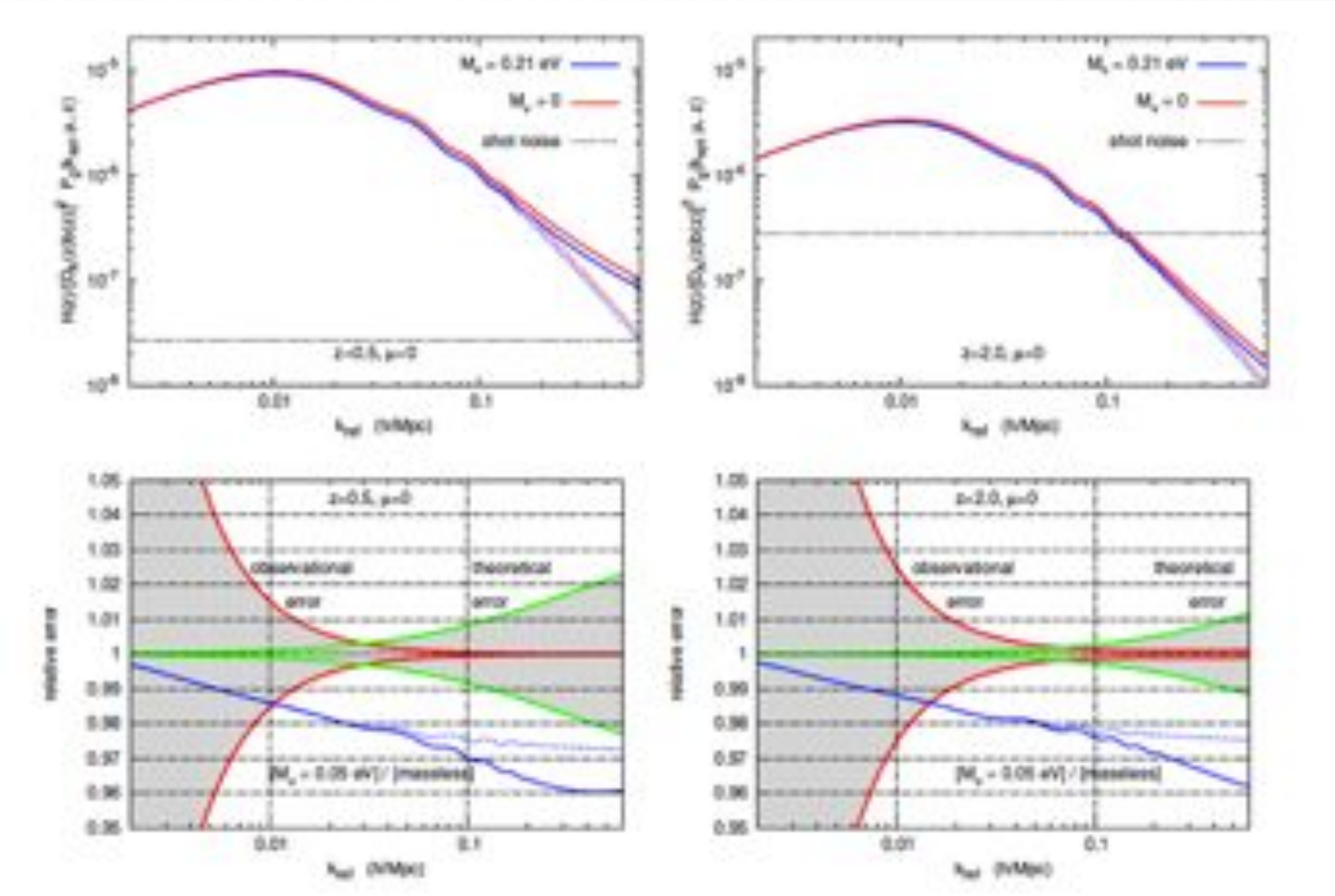
Now: LSS+CMB

$$M_\nu = \sum m_\nu < 0.3\,\mathrm{eV}$$

Planck+Euclid

$$\Delta M_\nu < 0.032\,\mathrm{eV}$$

Audren et al. 1210.2194



The LSS mantra

%

... and fast

→ scan over different cosmologies

not trivial even for Nbody

- Initial conditions, large volumes, mass resolution, time-stepping (Heitmann et al 2010)
- non-LCDM models: (massive neutrinos, coupled quintessence, f(R), primordial NG, clustering DE,...)
- not fast!

The Eulerian way

$$\frac{\partial\,\delta}{\partial\,\tau} + \nabla\cdot[(1+\delta)\mathbf{v}] = 0\,,$$

$$\frac{\partial\,\mathbf{v}}{\partial\,\tau} + \mathcal{H}\mathbf{v} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\phi$$

$$\nabla^2\phi = \frac{3}{2}\,\Omega_M\,\mathcal{H}^2\,\delta$$

subhorizon scales, newtonian gravity

Compact Perturbation Theory

Crocce, Scoccimarro '05

$$\frac{\partial\,\delta}{\partial\,\tau} + \nabla\cdot[(1+\delta)\mathbf{v}] = 0\,, \qquad \frac{\partial\,\mathbf{v}}{\partial\,\tau} + \mathcal{H}\mathbf{v} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\phi\,,$$

define $\left(\begin{array}{c}\varphi_1(\eta,\mathbf{k})\\ \varphi_2(\eta,\mathbf{k})\end{array}\right) \equiv e^{-\eta}\left(\begin{array}{c}\delta(\eta\,,\mathbf{k})\\ -\theta(\eta\,,\mathbf{k})/\mathcal{H}\end{array}\right)$ with $\eta = \log\dfrac{D^+(\tau)}{D^+(\tau_i)}$

$$\mathbf{\Omega} = \left(\begin{array}{cc}1 & -1\\ -3/2 & 3/2\end{array}\right)$$

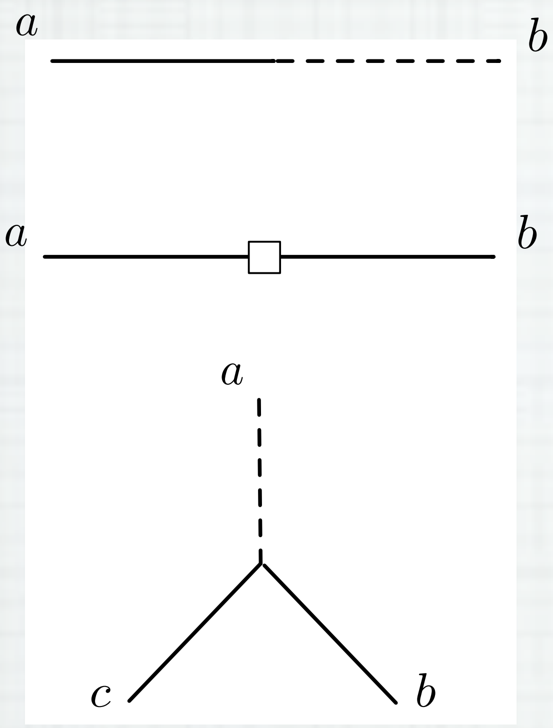
then we can write:

$$(\delta_{ab}\partial_\eta + \Omega_{ab})\,\varphi_b(\eta,\mathbf{k}) = e^\eta\gamma_{abc}(\mathbf{k},\,-\mathbf{k_1},\,-\mathbf{k_2})\,\varphi_b(\eta,\mathbf{k_1})\,\varphi_c(\eta,\mathbf{k_2})$$

linear

nonlinear

Perturbation Theory: Feynman Rules

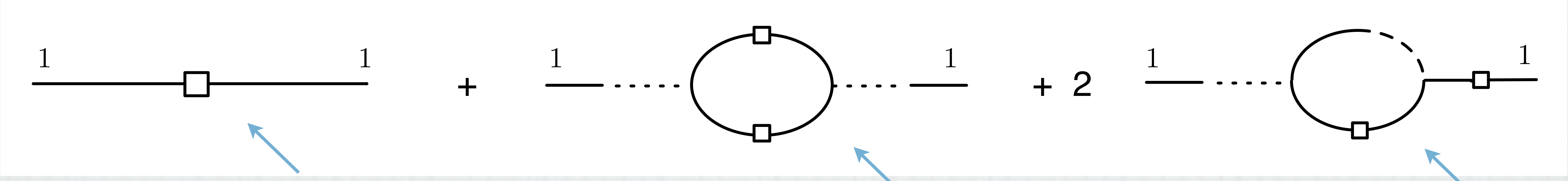


propagator (linear growth factor): $-i\, g_{ab}(\eta_a,\, \eta_b)$

power spectrum: $P^L_{ab}(\eta_a,\, \eta_b;\, \mathbf{k})$

interaction vertex: $-i\, e^{\eta}\, \gamma_{abc}(\mathbf{k_a},\, \mathbf{k_b},\, \mathbf{k_c})$

Example: 1-loop correction to the density power spectrum:



Linear Power spectrum

"P22"

"P13"

All known results in cosmological perturbation theory are expressible in terms of diagrams in which only a trilinear fundamental interaction appears

PT in the BAO range

1-loop propagator
@ large k:

$$G_{ab}(k;\eta_a,\,\eta_b) = g_{ab}(\eta_a,\,\eta_b)\left[1 - k^2\sigma^2\,\frac{(e^{\eta_a} - e^{\eta_b})^2}{2}\right] + O(k^4\sigma^4)$$

$(\sigma\, e^{\eta_a})^{-1} \simeq 0.15\,\mathrm{h\,Mpc}^{-1}$

in the BAO range!

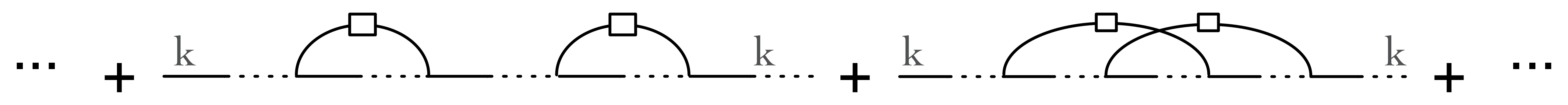
2-loop

$$\left(\sigma^2 \equiv \frac{1}{3}\int d^3q\,\frac{P^0(q)}{q^2}\right)$$

the PT series blows up in the BAO range

But it can be resummed!!

(Crocce-Scoccimarro '06)



$$G(k;\eta,\eta_{in})=\frac{\langle\delta(k,\eta)\delta(k,\eta_{in})\rangle}{\langle\delta(k,\eta_{in})\delta(k,\eta_{in})\rangle}\sim e^{-\frac{k^2\sigma^2}{2}e^{2\eta}}$$

physically, it represents the effect of multiple interactions of the k-mode with the surrounding modes: memory loss

`coherence momentum' $k_{ch}=(\sigma\, e^{\eta})^{-1}\simeq 0.15\,\mathrm{h\,Mpc}^{-1}$

↑ damping in the BAO range!

RPT: use G, and not g, as the linear propagator

(beware of Galileian invariance!! Peloso, MP, in progress)

Partial (!) list of contributors to the field

- “traditional” P.T.: see Bernardeau et al, Phys. Rep. 367, 1, (2002), and refs. therein; Jeong-Komatsu; Saito et al; Sefusatti;...
- resummation methods: Valageas; Crocce-Scoccimarro; McDonald; Matarrese-M.P.; Matsubara; M.P.; Taruya-Hiratamatsu; Bernardeau-Valageas; Bernardeau-Crocce-Scoccimarro; Tassev-Zaldarriaga,...

More General Cosmologies

$$\frac{\partial\,\delta}{\partial\,\tau} + \nabla\cdot[(1+\delta)\mathbf{v}] = 0\,,$$

deviation from geodesic
(e.g. DM-scalar field interaction)

$$\frac{\partial\,\mathbf{v}}{\partial\,\tau} + \mathcal{H}(1+A(\vec{x},\,\tau))\mathbf{v} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\phi\,,$$

$$\nabla^2\phi = 4\pi G\,(1+B(\vec{x},\,\tau))\,\rho\,a^2\,\delta$$

deviation from Poisson
(e.g. scale-dep. growth factor)

$$\Downarrow$$

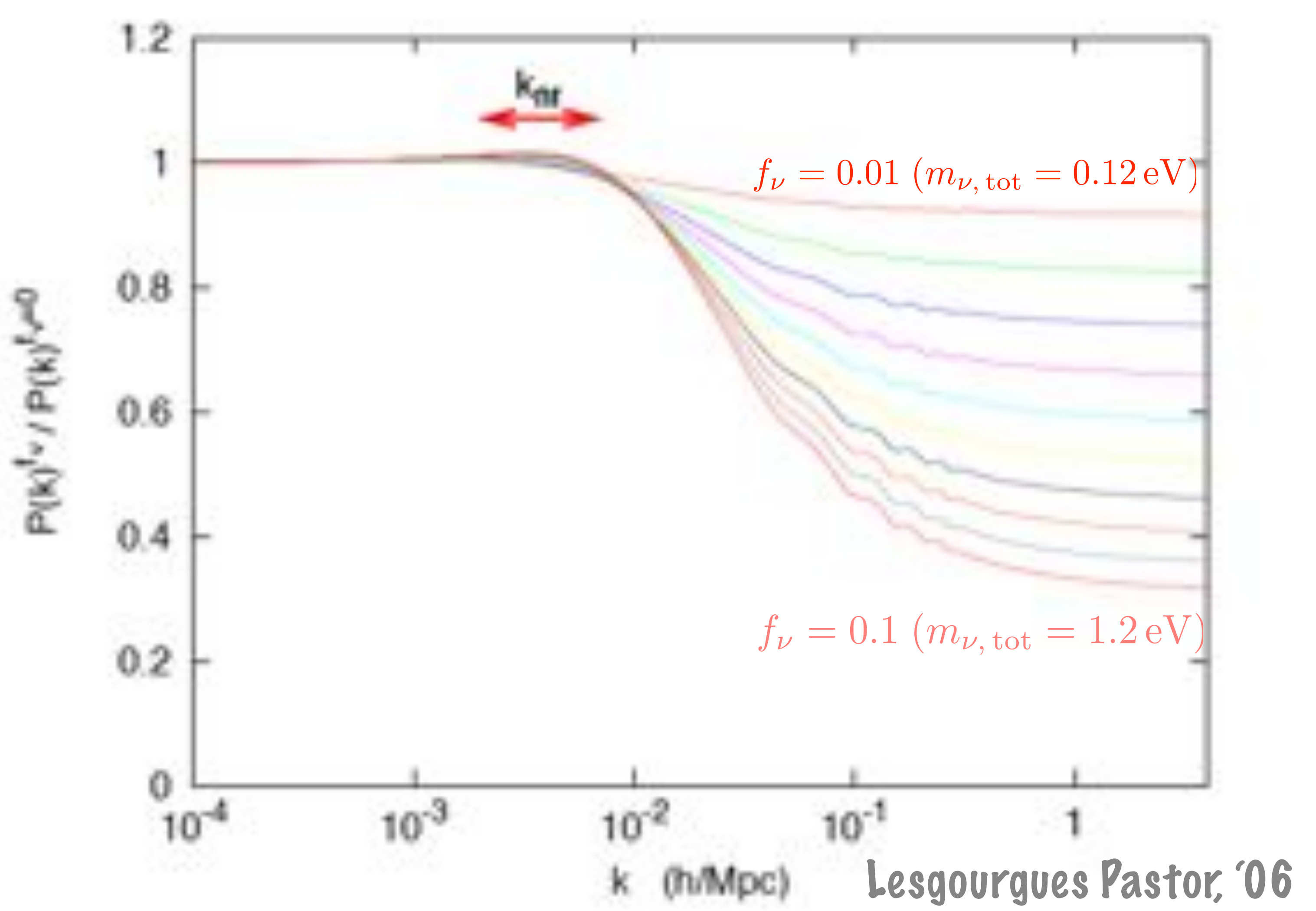
$$(\delta_{ab}\partial_\eta + \Omega_{ab}(\eta,\,\mathbf{k}))\,\varphi_b(\eta,\mathbf{k}) = e^\eta\gamma_{abc}(\mathbf{k},\,-\mathbf{k_1},\,-\mathbf{k_2})\,\varphi_b(\eta,\mathbf{k_1})\,\varphi_c(\eta,\mathbf{k_2})$$

$$(\eta = \log a)$$

$$\boldsymbol{\Omega}_{ab} = \begin{pmatrix} 1 & -1 \\ -\frac{3}{2}\Omega_M(1+B(\eta,\,\mathbf{k})) & 2+\frac{\mathcal{H}'}{\mathcal{H}}+A(\eta,\,\mathbf{k}) \end{pmatrix}$$

Ex: Scalar-Tensor: $\mathcal{A} = \alpha\,d\varphi/d\log a$ $\quad \mathcal{B} = 2\alpha^2$ $\quad \alpha^2 = 1/(2\omega+3)$

Massive Neutrinos and the Power Spectrum



Lesgourgues Pastor, '06

$$f_\nu = \frac{\Omega_\nu}{\Omega_m} = \frac{m_{\nu,\,\mathrm{tot}}}{94.1\,\Omega_m\,h^2\,\mathrm{eV}}$$

$$k_{nr} \simeq 0.018\,\Omega_m^{1/2}\left(\frac{m_\nu}{1\mathrm{eV}}\right)\,h\,\mathrm{Mpc}^{-1}$$

$$\frac{\Delta P}{P^{f_\nu=0}} \sim -8 f_\nu$$

The linear growth factor is scale dependent: $\delta_m(k \ll k_{nr}) \sim a\ ,\quad \delta_m(k \gg k_{nr}) \sim a^{1-3/5 f_\nu}$

Poisson equation for Cold DM + Neutrinos

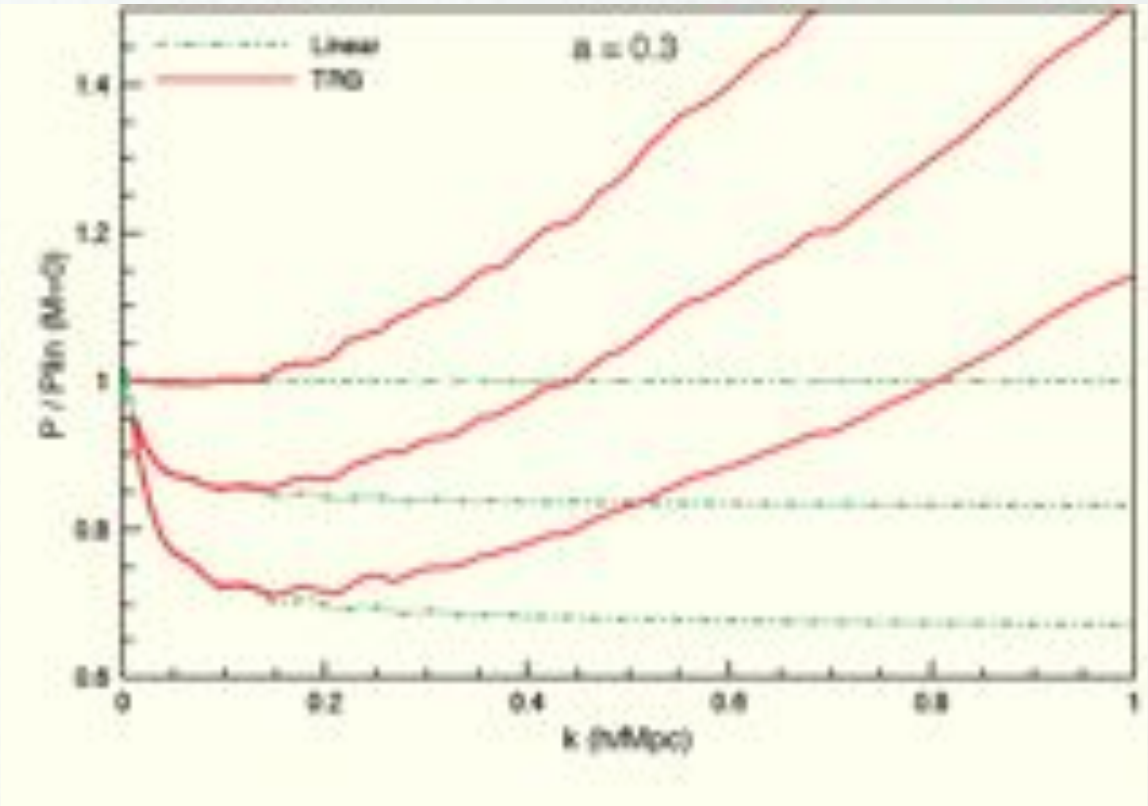
$$\nabla^2\phi = 4\pi G\, a^2\, (\rho_c\, \delta_c + \rho_\nu\, \delta_\nu) = 4\pi G\, a^2 \left(1 + \frac{\rho_\nu\, \delta_\nu}{\rho_c\, \delta_c}\right) \rho_c\, \delta_c$$

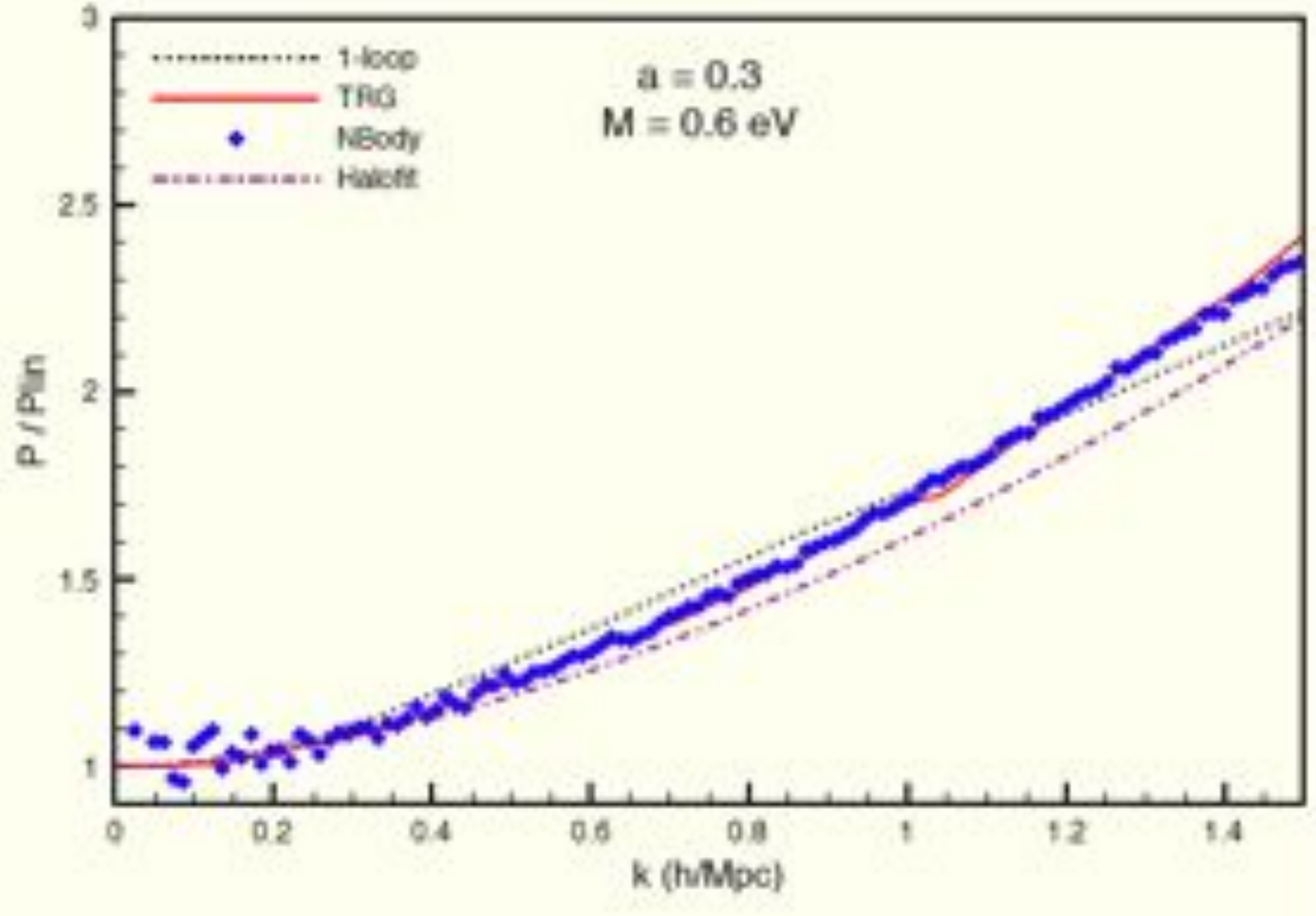
$$\mathcal{B}(k,\, \tau) \simeq \left.\frac{\rho_\nu\, \delta_\nu}{\rho_c\, \delta_c}\right|_{\text{linear th.}}$$

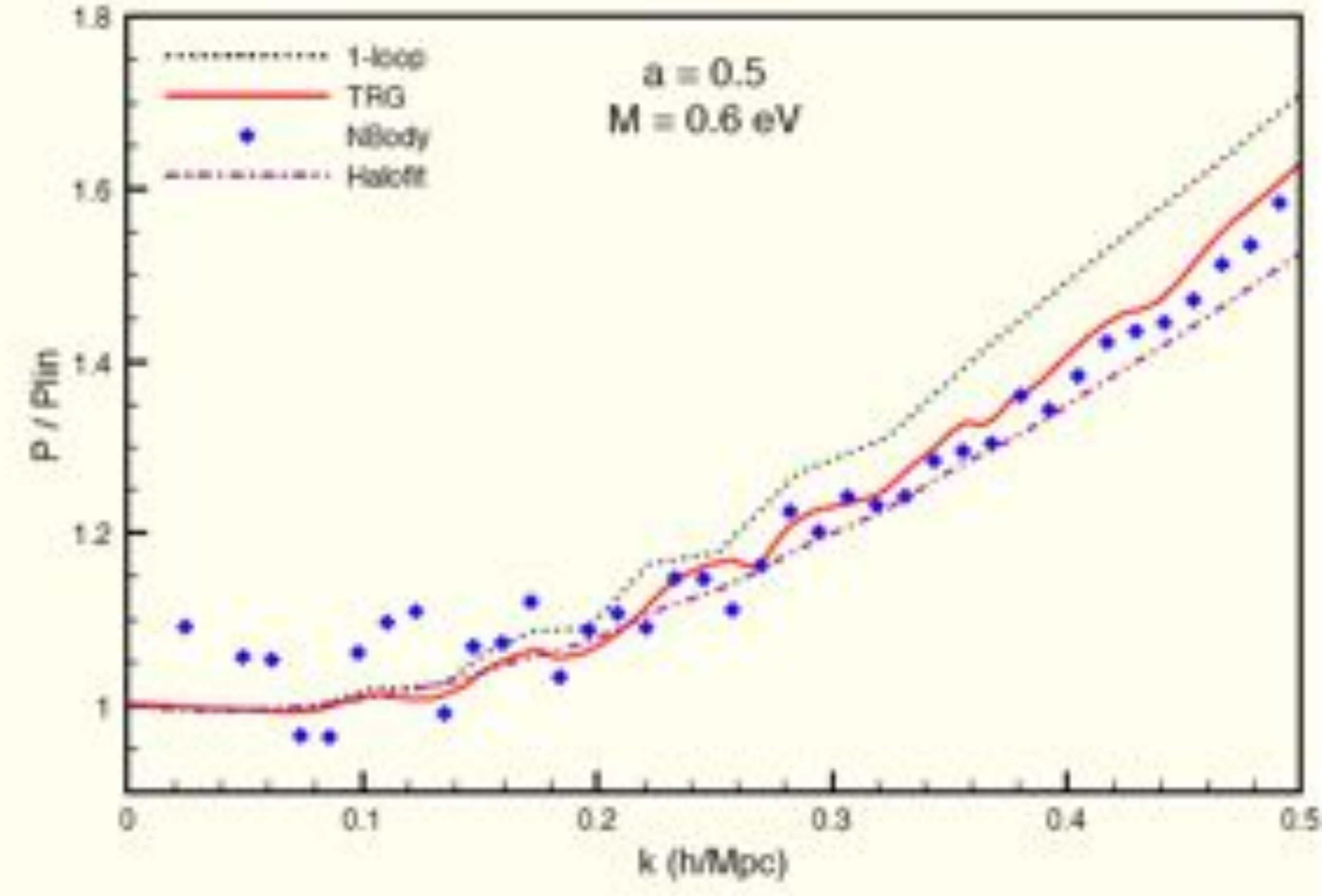
Non-Linear effects on νmass bounds: RG vs. 1-loop approximation

Lesgourgues, Matarrese, M.P., Riotto, '09

Cosmological Neutrino mass bounds should take non-linear effects into account!







Improving resummed PT methods: 2012 achievements

- PS established at % in the BAO range down to z=0
- fast implementations: from O(hrs) to O(mins) a P(k,z)
- scales smaller than BAO's

Exact time-evolution equations I: the propagator

Anselmi, Matarrese, MP
1011.4477

a) start from the exact expression

$$G_{ab}(k;\eta,\eta') = g_{ab}(\eta,\eta') + \int ds\, ds'\, g_{ac}(\eta,s)\Sigma_{cd}(k;s,s')G_{cb}(k;s',\eta')$$

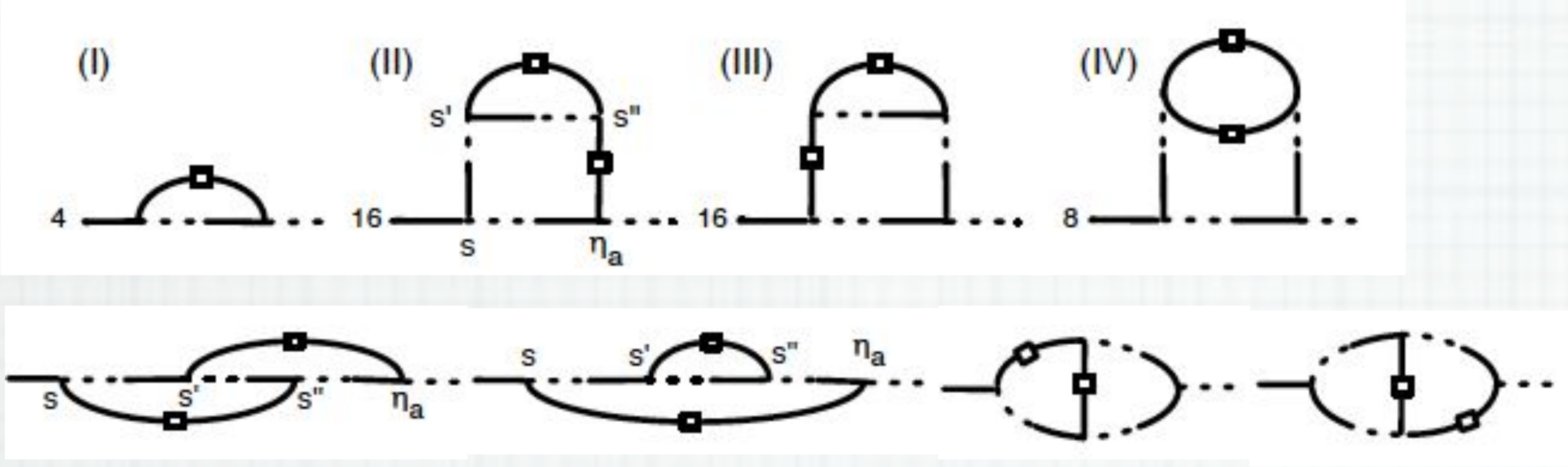
b) take the time derivative...

$$\partial_\eta G_{ab}(k;\,\eta,\eta') = \delta_{ab}\,\delta_D(\eta-\eta') - \Omega_{ac}\,G_{cb}(k;\,\eta,\eta') + \Delta G_{ab}(k;\,\eta,\eta')$$

$$\Delta G_{ab}(k;\,\eta,\eta') \equiv \int ds'\,\Sigma_{ad}(k;\,\eta,s')\,G_{db}(k;\,s',\eta')$$

c) compute Σ ...

$$\boxed{\Sigma_{ab}(k; s, s')}$$



+ higher loops...

small k: $\Sigma_{ab}(k; s, s') \simeq \Sigma_{ab}^{1-loop}(k; s, s') \longrightarrow \boxed{G_{ab} \to G_{ab}^{1-loop}}$

large k: $\int ds' \Sigma_{ad}(k; \eta, s') G_{db}(k; s', \eta') \simeq -k^2 \sigma^2 e^{\eta} (e^{\eta} - e^{\eta'}) G_{ab}(k; \eta, \eta')$

$$\boxed{G_{ab} \to \exp\left(-\frac{k^2\sigma^2(e^{\eta} - e^{\eta'})^2}{2}\right) g_{ab}}$$

1-loop evaluation of Σ gives the propagator at all loops!!

Exact time-evolution equations II: the power spectrum

Anselmi, MP,
1205.2235

a) exact expression

$$P_{ab}(k;\eta,\eta') = G_{ac}(k;\eta,\eta_{in})G_{bd}(k;\eta',\eta_{in})P_{cd}(k;\eta_{in},\eta_{in}) + \int ds\, ds'\; G_{ac}(k;\eta,s)G_{bd}(k;\eta',s')\Phi_{cd}(k;s,s')$$

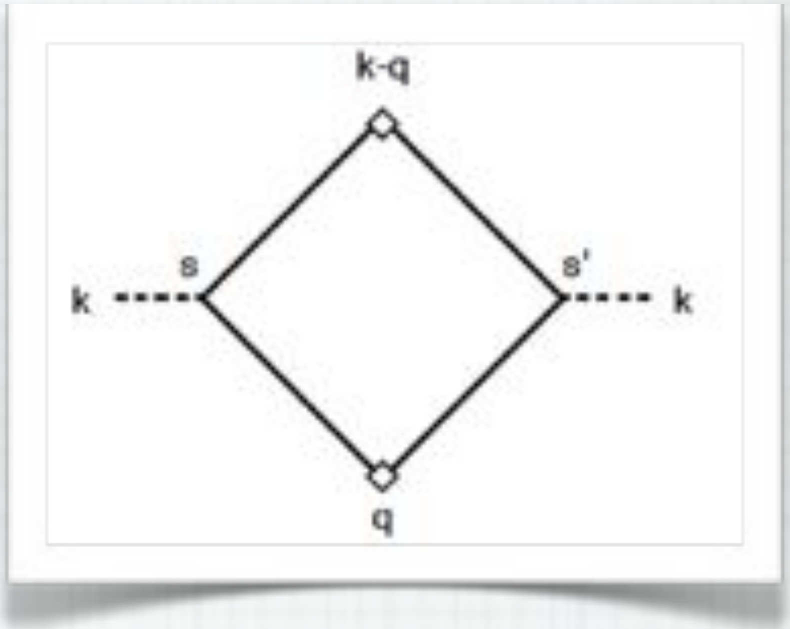
b) time derivative

$$\begin{aligned}\partial_\eta P_{ab}(k;\eta) = {} & -\Omega_{ac}\, P_{cb}(k;\eta) - \Omega_{bc}\, P_{ac}(k;\eta) \\ & + H_{\mathbf{a}}(k;\,\eta,\eta_{in})\, P_{\mathbf{ab}}(k;\eta) + H_{\mathbf{b}}(k;\,\eta,\eta_{in})\, P_{\mathbf{ab}}(k;\eta) \\ & + \int ds\, [\tilde\Phi_{ad}(k;\eta,s)\bar G_{bd}(k;\,\eta,s) + \bar G_{ad}(k;\,\eta,s)\tilde\Phi_{db}(k;s,\eta)]\end{aligned}$$

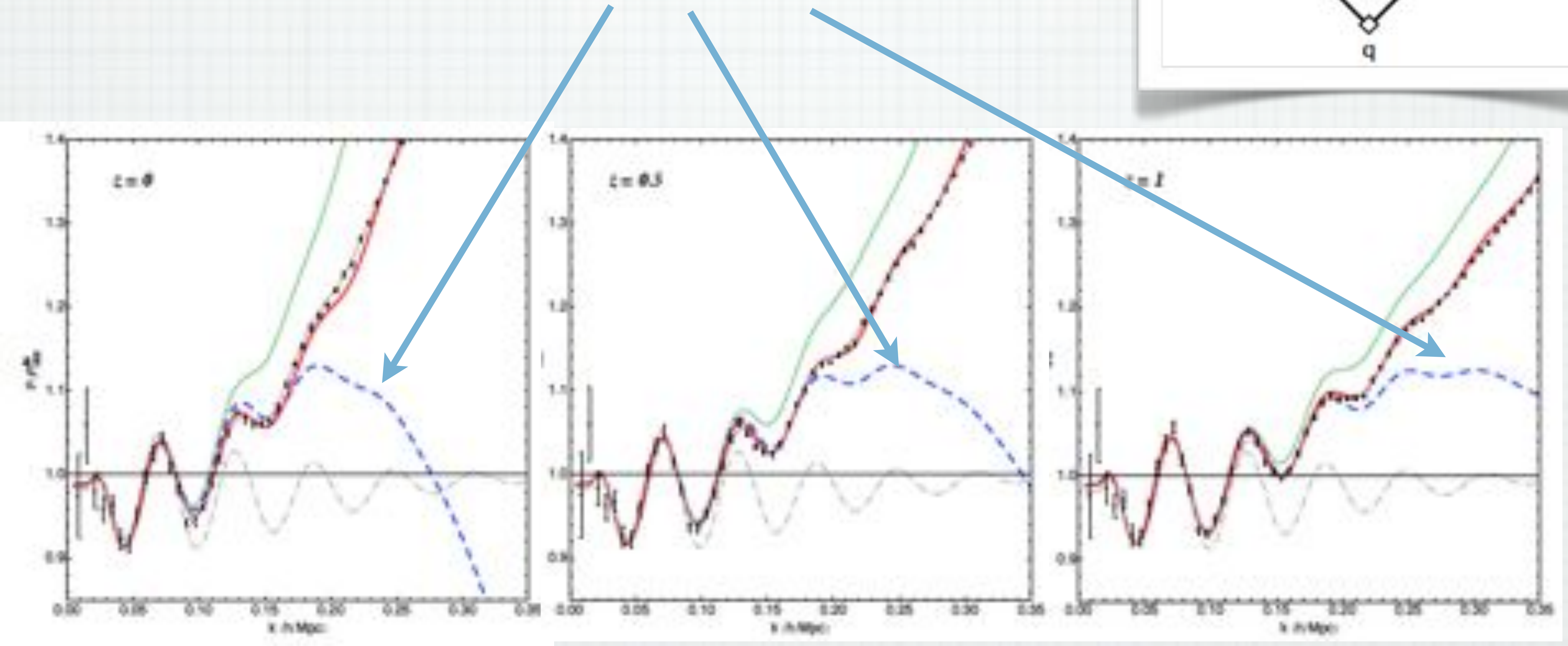
$$H_a(k;\,\eta,s) \equiv \int_s^\eta ds''\, \Sigma^{(1)}_{ae}(k;\,\eta\,,s'')\, u_e$$

Already computed for the propagator

$$\boxed{\Phi_{ab}(k;s,s')}$$



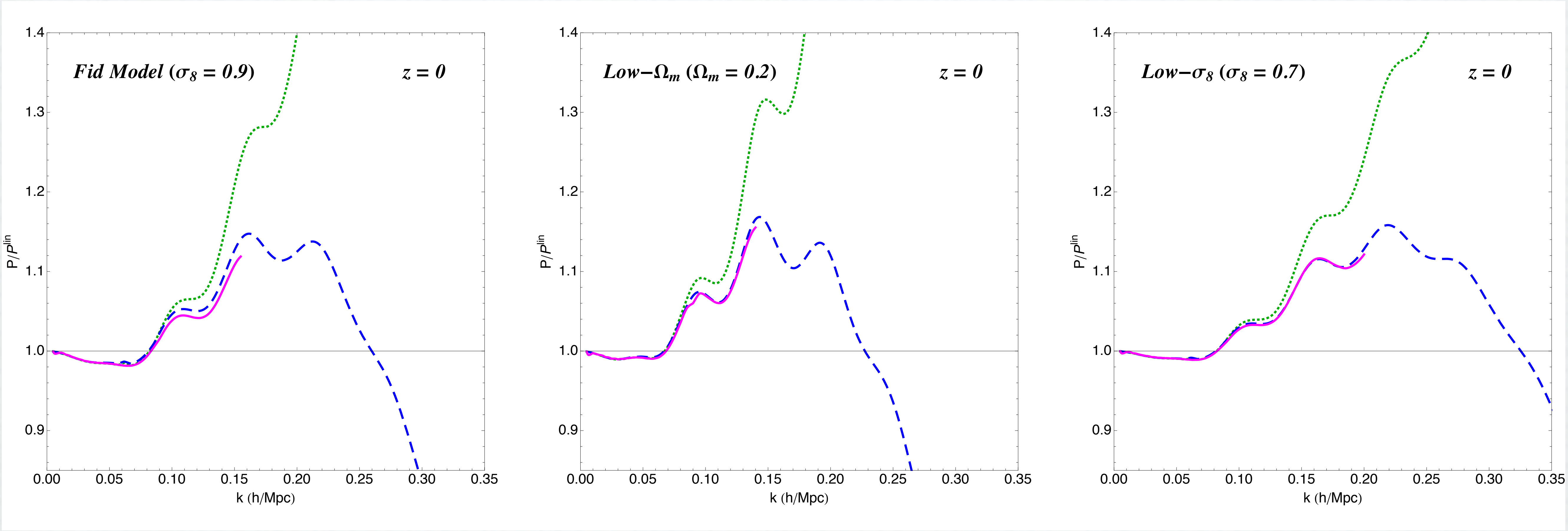
small k: $$\Phi_{ab}(k;s,s') \simeq \Phi_{ab}^{1-loop}(k;s,s')$$



1-loop evaluation of Σ and Phi reproduces the BAO's at the % level at all z

compare with PTbreeze

Crocce Scoccimarro Bernardeau 1207.1465



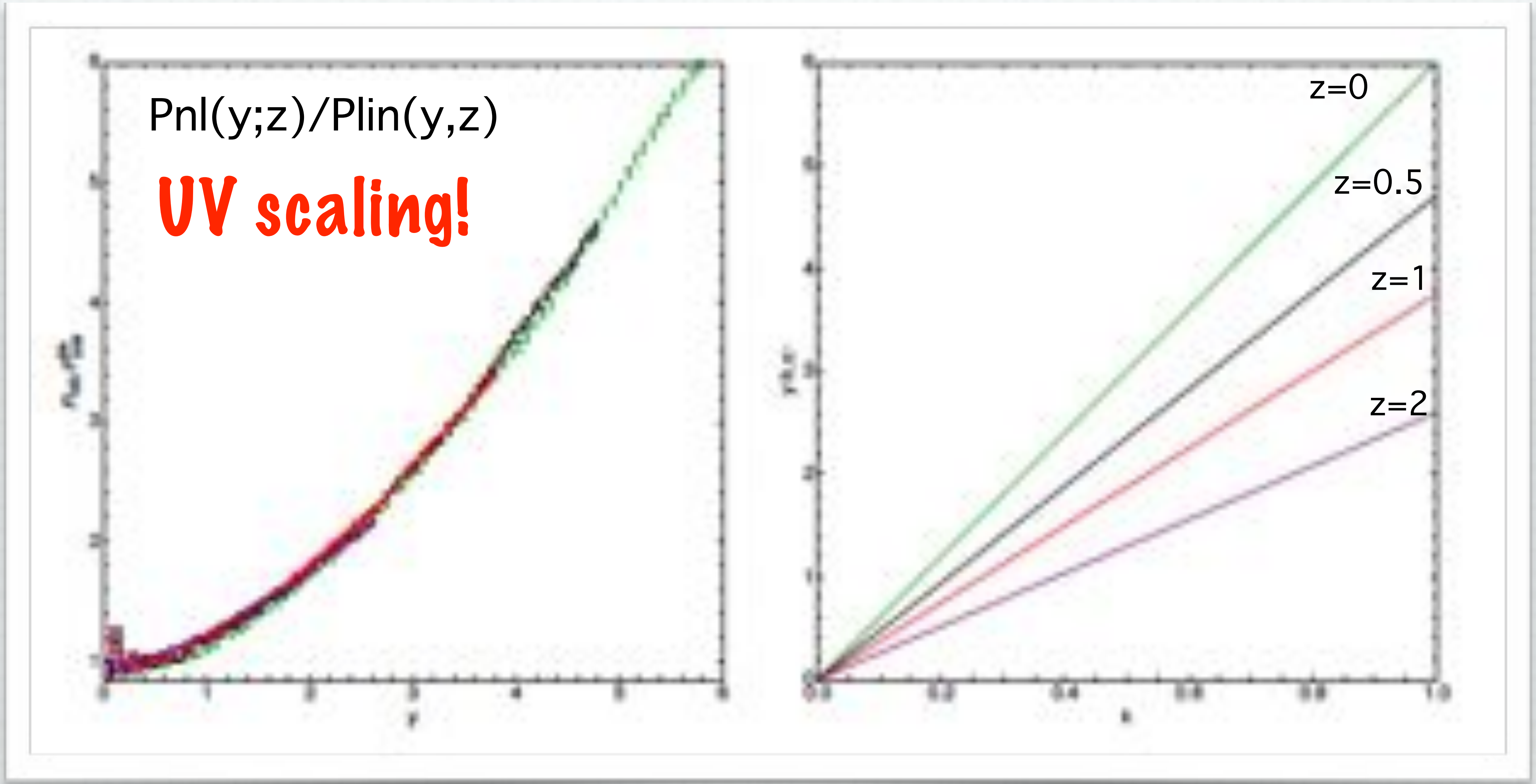
O(minutes) and O(%) accuracy in the BAO region achieved!

The large k regime for the PS

Anselmi, MP, 1205.2235

for the nonlinear propagator, the relevant variable in the large k regime is : $y \equiv k\,\sigma(e^{\eta} - e^{\eta_i})$

$$G(k;\eta,\eta_i) \sim \exp\left(-\frac{y^2}{2}\right)$$



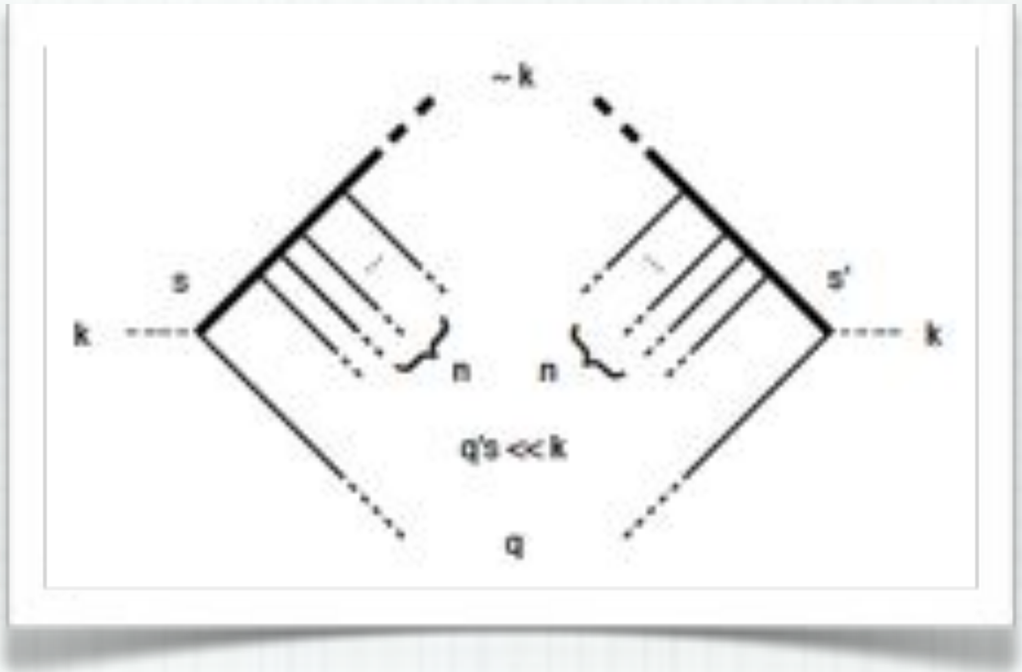
UV scaling!

The non-linear PS is y-dependent too. resummation possible !!

$\Phi_{ab}(k; s, s')$

large k

leading contributions to Phi:

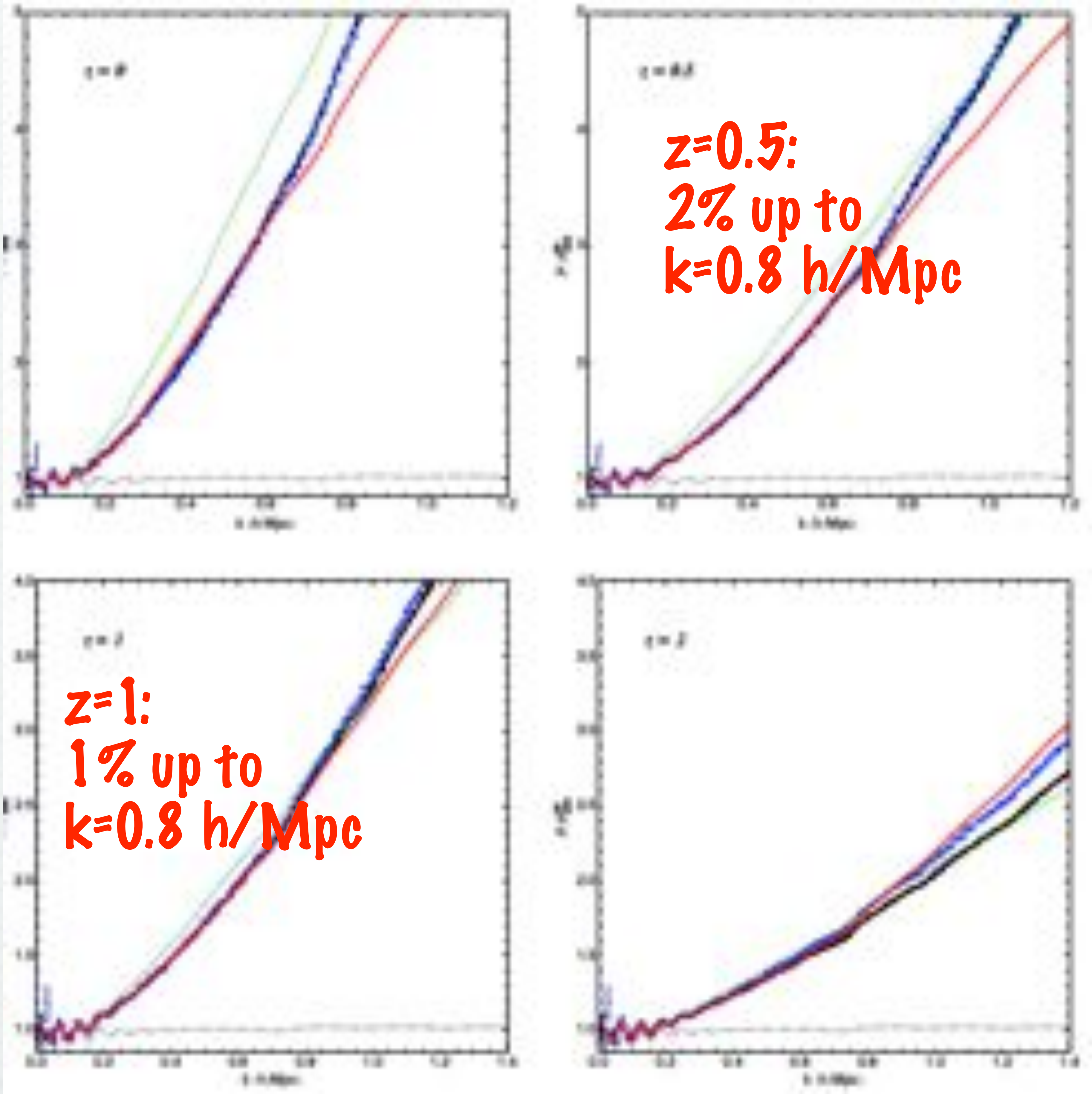


1 "hard" loop momentum, n-1 "soft" ones

$$\tilde{\Phi}_{ab}(k; s, s') \to e^{-\frac{k^2\sigma_v^2}{2}(e^s - e^{s'})^2} \left[\Phi^{(1)}_{ab}(k; s, s') + \left(k^2\sigma_v^2\, e^{s+s'}\right)^2 P(k) u_a u_b\right]$$

Can be obtained in eRPT: tree-level=UV limit

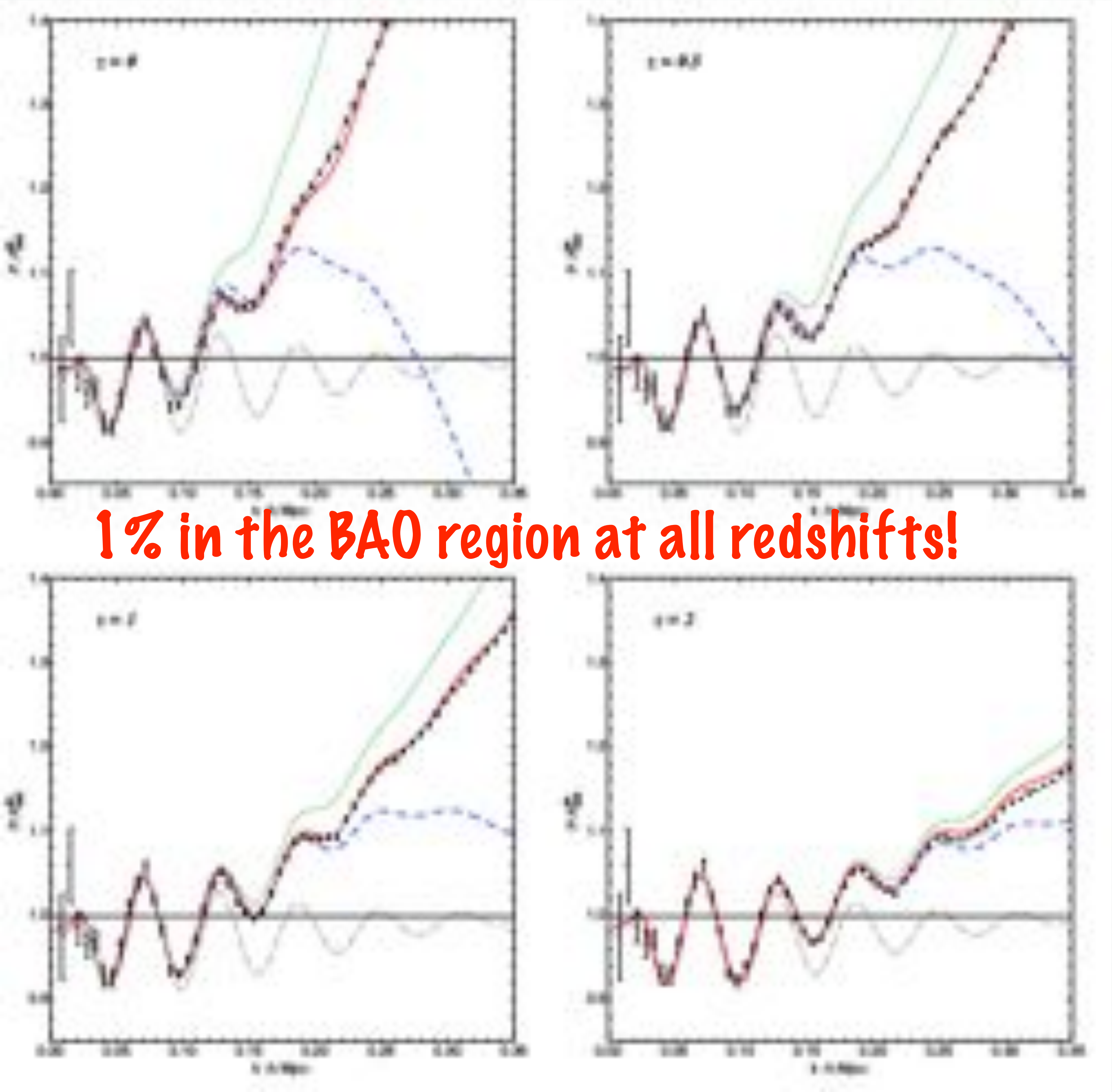
large k



z=0.5:
2% up to
k=0.8 h/Mpc

z=1:
1% up to
k=0.8 h/Mpc

BAO scales



1% in the BAO region at all redshifts!

Practical Implementation

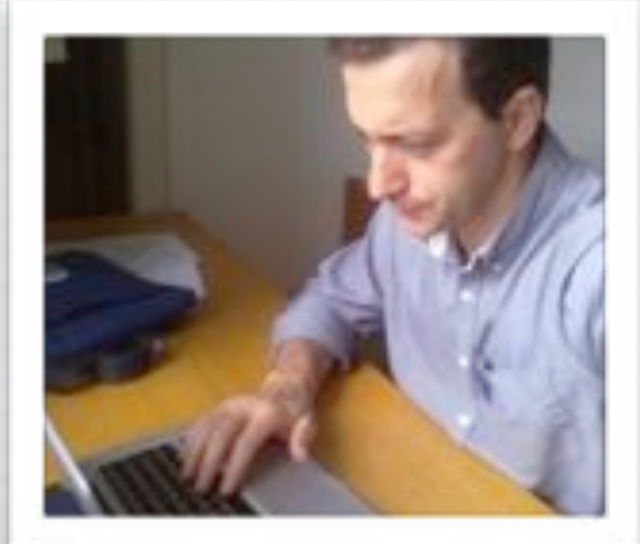
- linear PS at zin
- compute 5 momentum integrals:

$$H_1(k;\eta,-\infty) = -\,e^{2\eta}\frac{k^3\pi}{21}\int dr\left[19-24r^2+9r^4-\frac{9}{2r}(r^2-1)^3\log\left|\frac{1+r}{1-r}\right|\right]P^0(kr)$$

$$\Phi^{(1)}_{11}(k;\eta,\eta') = e^{\eta+\eta'}\frac{\pi}{4k}\int_0^\infty dq\int_{|k-q|}^{k+q}dp\frac{\left[k^2(p^2+q^2)-(p^2-q^2)^2\right]^2}{p^3q^3}P^0(q)P^0(p)$$

- integrate the evolution equation from zin to z: get Pdd, Pdt, Ptt
- public code available soon

O(1 min) for PS at all z



The intrinsic limit of (resummed) PT

The DM particle distribution function, $f(\mathbf{x},\mathbf{p},\tau)$, obeys the Vlasov equation:

$$\frac{\partial f}{\partial \tau} + \frac{\mathbf{p}}{am} \cdot \nabla f - am \nabla \phi \cdot \nabla_{\mathbf{p}} f = 0$$

with $p = am \frac{d\mathbf{x}}{d\tau}$ and $\nabla^2 \phi = \frac{3}{2} \Omega_M \, \mathcal{H}^2 \, \delta$ sub-horizon scales, Newtonian gravity

Taking moments,

$$\int d^3\mathbf{p} \, f(\mathbf{x},\mathbf{p},\tau) \equiv \rho(\mathbf{x},\tau) \equiv \bar{\rho} \, [1 + \delta(\mathbf{x},\tau)]$$

$$\int d^3\mathbf{p} \, \frac{p_i}{am} f(\mathbf{x},\mathbf{p},\tau) \equiv \rho(\mathbf{x},\tau) v_i(\mathbf{x},\tau)$$

$$\int d^3\mathbf{p} \, \frac{p_i \, p_j}{a^2 m^2} f(\mathbf{x},\mathbf{p},\tau) \equiv \rho(\mathbf{x},\tau) \, [v_i(\mathbf{x},\tau) v_j(\mathbf{x},\tau) + \sigma_{ij}(\mathbf{x},\tau)]$$

$$\dots$$

$$\frac{\partial n}{\partial \tau} + \frac{\partial}{\partial x^i}(n\, v^i) = 0$$

source term

$$\frac{\partial v^i}{\partial \tau} + \mathcal{H} v^i + v^k \frac{\partial}{\partial x^k} v^i + \frac{1}{n}\frac{\partial}{\partial x^k}(n\sigma^{ki}) = -\frac{\partial}{\partial x^i}\phi$$

$$\frac{\partial \sigma^{ij}}{\partial \tau} + 2\mathcal{H}\sigma^{ij} + v^k \frac{\partial}{\partial x^k}\sigma^{ij} + \sigma^{ik}\frac{\partial}{\partial x^k} v^j + \sigma^{jk}\frac{\partial}{\partial x^k} v^i + \frac{1}{n}\frac{\partial}{\partial x^k}(n\omega^{ijk}) = 0$$

$$\frac{\partial \omega^{ijk}}{\partial \tau} + \cdots = 0$$

$$\dots$$

$$\nabla^2\phi = \frac{3}{2}\,\Omega_M\,\mathcal{H}^2\,\delta$$

No sources for $\sigma^{ij},\ \omega^{ijk}, \dots, \vec{\nabla} \times \vec{v}, \dots$

$\sigma^{ij} = \omega^{ijk} = \cdots = \vec{\nabla} \times \vec{v} = 0$ is a fixed point

neglecting σ_{ij} and higher moments...

$$\frac{\partial n}{\partial \tau} + \frac{\partial}{\partial x^i}(n\, v^i) = 0$$

continuity

$$\frac{\partial \mathbf{v}}{\partial \tau} + \mathcal{H}\mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla\phi$$

Euler

$$\nabla^2\phi = \frac{3}{2}\Omega_M\, \mathcal{H}^2\, \delta$$

Poisson

$$[n = n_0(1+\delta)]$$

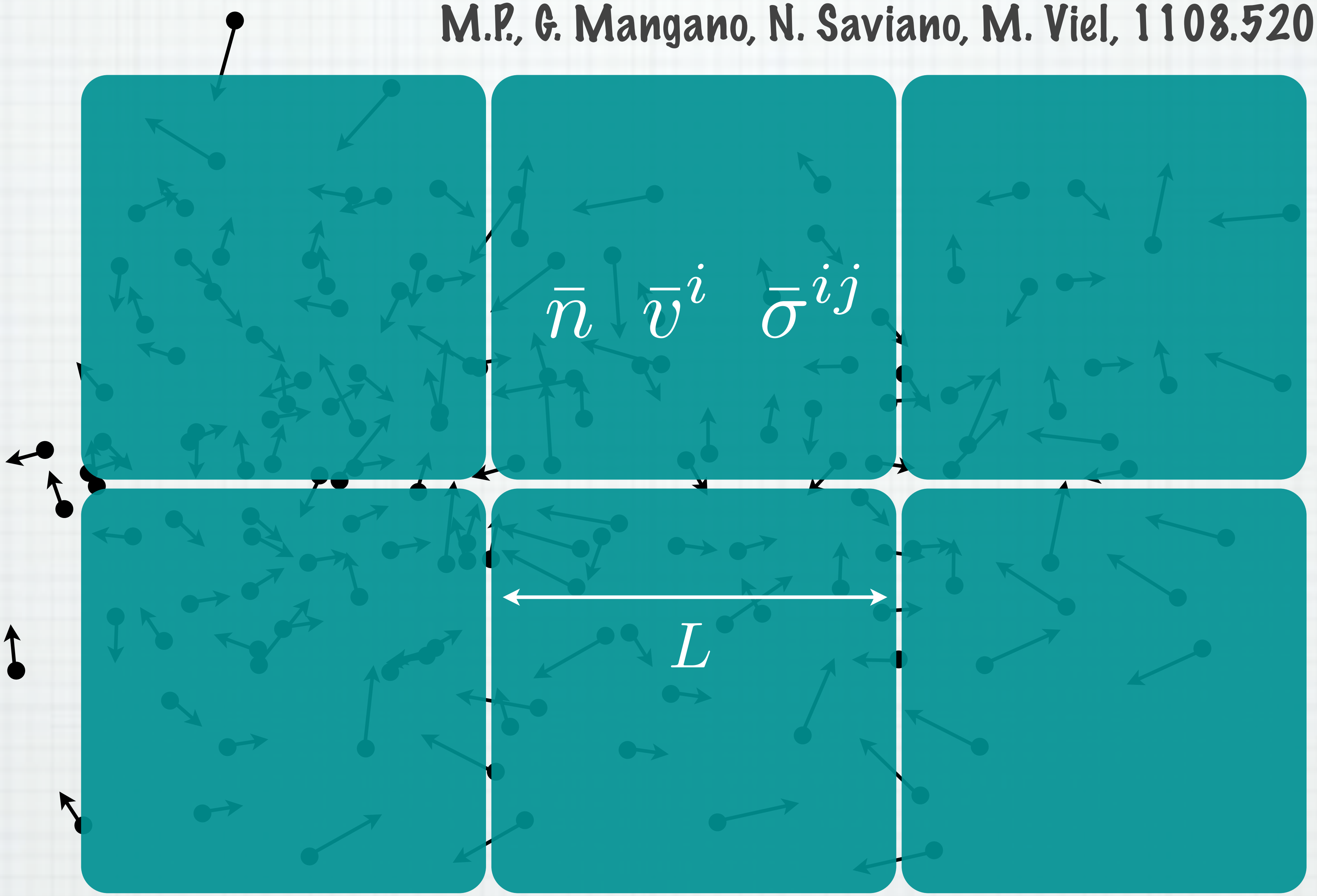
(RESUMMED) PT IS BASED ON THE "SINGLE STREAM APPROXIMATION"

$$\sigma_{ij} = 0 \leftrightarrow f(\vec{x}, \vec{p}, \tau) = g(\vec{x}, \tau)\delta_D(\vec{p} - am\vec{v}(\vec{x}, \tau))$$

self-consistent, but wrong!

Rederiving the fluid equations

Buchert, Dominguez, '05, Pueblas Scoccimarro, '09, Baumann et al. '10
M.P., G. Mangano, N. Saviano, M. Viel, 1108.5203



$$f_{mic}(x,p,\tau) = \sum_n \delta_D(x - x_n(\tau))\,\delta_D(p - p_n(\tau))$$

$$\bar{f}(x,p,\tau) = \frac{1}{V}\int d^3y\, W(y/L)\, f_{mic}(x+y,p,\tau)$$

Satisfies the "Vlasov eq."

Coarse-Grained Vlasov eq.

large scales

$$\left[\frac{\partial}{\partial\tau} + \frac{p^i}{ma}\frac{\partial}{\partial x^i} - am\nabla^i_x\bar{\phi}(\mathbf{x},\tau)\frac{\partial}{\partial p^i}\right]\bar{f}(\mathbf{x},\mathbf{p},\tau)$$

$$= \frac{am}{V}\int d^3y\,\mathcal{W}\left(\left|\frac{\mathbf{y}}{L}\right|\right)\nabla^i_{x+y}\delta\phi(\mathbf{x}+\mathbf{y},\tau)\,\frac{\partial}{\partial p^i}\delta f(\mathbf{x}+\mathbf{y},\mathbf{p},\tau)$$

short scales

$$\delta\phi = \phi - \bar{\phi}$$

$$\delta f = f_{mic} - \bar{f}$$

Vlasov in the L → 0 limit!

Short-distance sources

$q_\theta + q_w$

$$\frac{\partial}{\partial\tau}\bar{n}(\mathbf{x}) + \frac{\partial}{\partial x^i}\left(\bar{n}(\mathbf{x})\bar{v}^i(\mathbf{x})\right) = 0\,.$$

$$\frac{\partial}{\partial\tau}\bar{v}^i(\mathbf{x}) + \mathcal{H}\bar{v}^i(\mathbf{x}) + \bar{v}^k(\mathbf{x})\frac{\partial}{\partial x^k}\bar{v}^i(\mathbf{x}) + \frac{1}{\bar{n}(\mathbf{x})}\frac{\partial}{\partial x^k}(\bar{n}(\mathbf{x})\bar{\sigma}^{ki}(\mathbf{x}))$$
$$= -\nabla^i_x\bar{\phi}(\mathbf{x}) - \frac{1}{V}\int d^3y\,\mathcal{W}\left(\left|\frac{\mathbf{y}}{L}\right|\right)\frac{n(\mathbf{x}+\mathbf{y})}{\bar{n}(\mathbf{x})}\nabla^i_{x+y}\delta\phi(\mathbf{x}+\mathbf{y})\,,$$

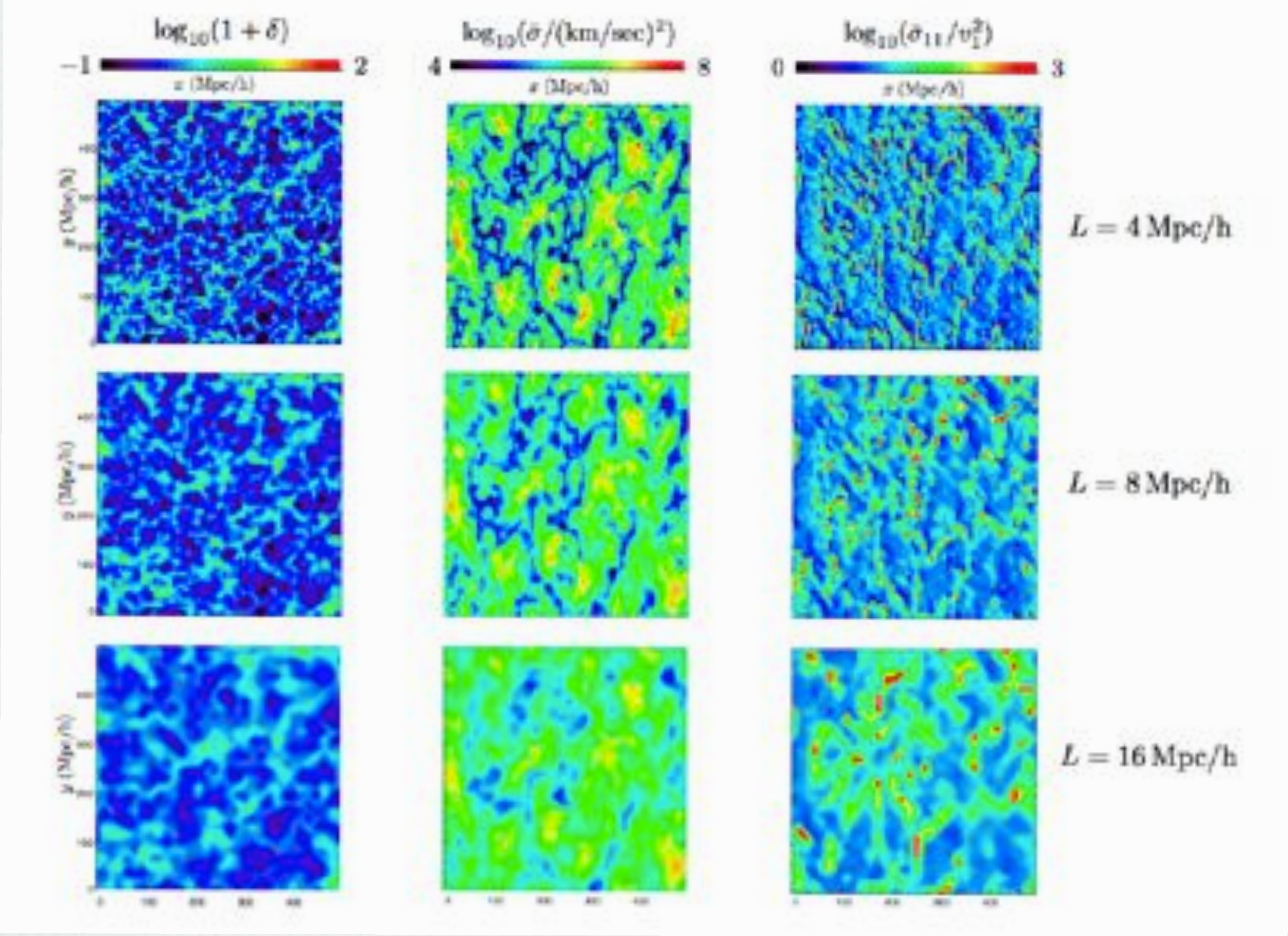
Short-distance sources

$$\frac{\partial}{\partial\tau}\bar{\sigma}^{ij} + 2\mathcal{H}\bar{\sigma}^{ij} + \bar{v}^k\frac{\partial}{\partial x^k}\bar{\sigma}^{ij} + \bar{\sigma}^{ik}\frac{\partial}{\partial x^k}\bar{v}^j + \bar{\sigma}^{jk}\frac{\partial}{\partial x^k}\bar{v}^i + \frac{1}{\bar{n}}\frac{\partial}{\partial x^k}\left(\bar{n}\,\bar{\varpi}^{ijk}\right)$$
$$= -\frac{1}{V}\int d^3y\;\mathcal{W}\left(\left|\frac{\mathbf{y}}{L}\right|\right)\frac{n(\mathbf{x}+\mathbf{y})}{\bar{n}(\mathbf{x})}$$
$$\times\left[\delta v^j(\mathbf{x}+\mathbf{y})\nabla^i_{x+y} + \delta v^i(\mathbf{x}+\mathbf{y})\nabla^j_{x+y}\right]\delta\phi(\mathbf{x}+\mathbf{y})\,.$$

$\bar{\sigma}^{ij}$ **and all higher-order moments are dynamically generated by coarse-graining!**

Coarse-Graining vs. Single-Stream

PT gets better ↓



SSA gets worse ↓

Well-behaved PT calls for dropping the single stream approximation

Compact form

$$\bar\varphi_a(\mathbf{k},\eta) = e^{-\eta}\begin{pmatrix} \bar\delta \\ -\frac{\bar\theta}{\mathcal{H}f} \\ \frac{k^2}{\mathcal{H}^2 f^2}\bar\sigma \\ \frac{k^2}{\mathcal{H}^2 f^2}\bar\Sigma \end{pmatrix}$$

$$\bar\sigma(\mathbf{k}) = \bar\sigma^{ii}(\mathbf{k})\,, \quad \bar\Sigma(\mathbf{k}) = \frac{k^i k^j}{k^2}\bar\sigma^{ij}(\mathbf{k})$$

$$(\delta_{ab}\partial_\eta + \Omega_{ab})\,\bar\varphi^b(\mathbf{k},\eta) =$$
$$e^\eta \int d^3q_1 d^3q_2 \delta_D(\mathbf{k}-\mathbf{q}_1-\mathbf{q}_2)\gamma_{abc}(k,q_1,q_2)\bar\varphi_b(\mathbf{q}_1,\eta)\bar\varphi_c(\mathbf{q}_2,\eta) - h_a(\mathbf{k},\eta)$$

(resummed) PT expansion in γ_{abc}

$$0 \le k \le k_{(R)PT} \simeq \frac{2\pi}{L}$$

cosmology up to mildly non linear scales

short-distance sources: measure from simulations

$$k > \frac{2\pi}{L}$$

cosmology-independent?

perturbative solution for the large scales

$$\bar{\varphi}_a^{(0)}(\mathbf{k},\eta) = g_{ab}(\eta)\bar{\varphi}_b^{in}(\mathbf{k}) - \int_0^\eta ds\, g_{ab}(\eta - s)\, h_b(\mathbf{k}, s)\,.$$

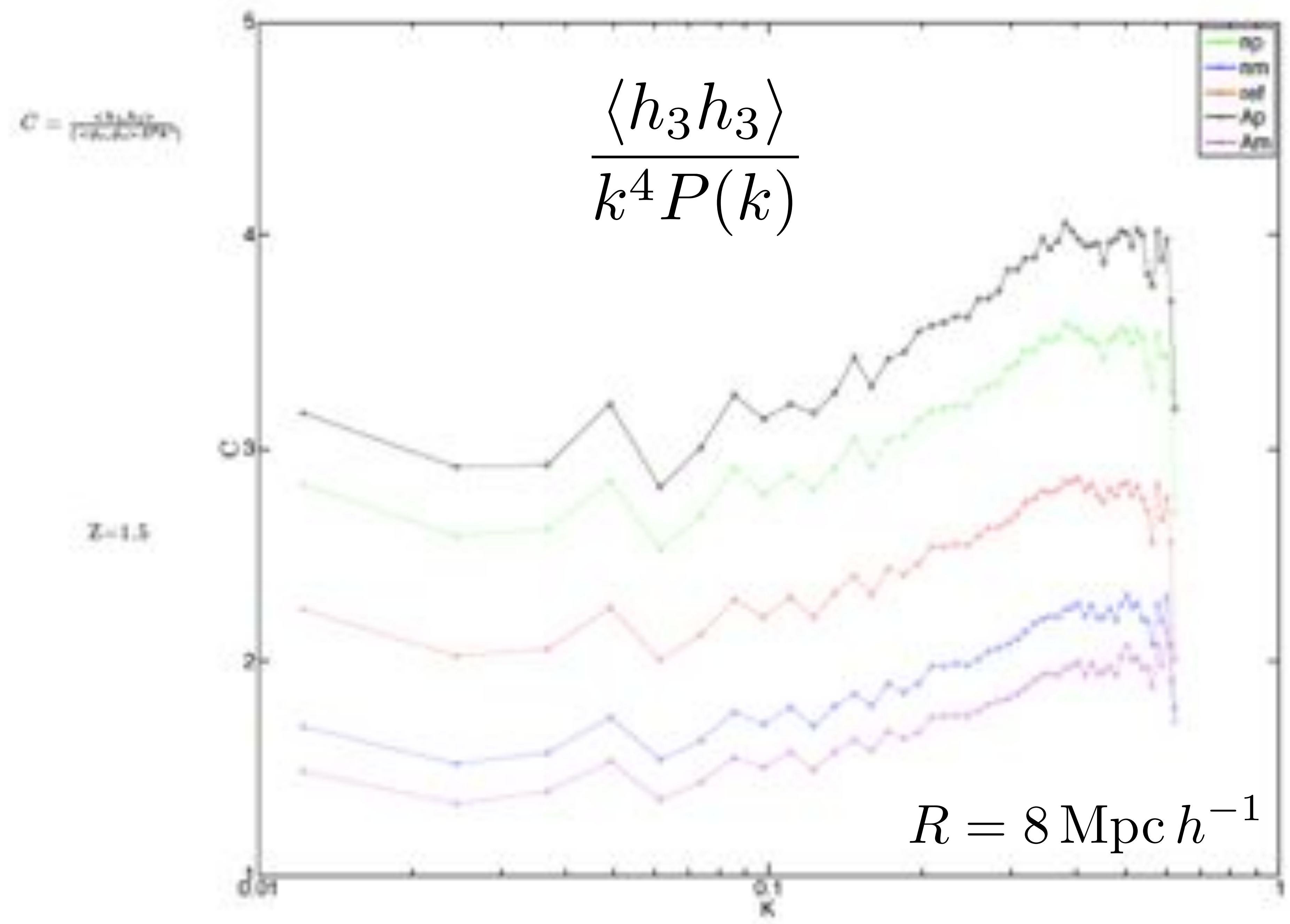
$$\bar{\varphi}_a^{(1)}(\mathbf{k},\eta) = \int_0^\eta ds\, g_{ab}(\eta - s)\, e^s\, \gamma_{bcd}(k, q_1, q_2)\bar{\varphi}_c^{(0)}(\mathbf{q}_1, s)\bar{\varphi}_d^{(0)}(\mathbf{q}_2, s)$$

$$\bar{\varphi}_a^{(2)}(\mathbf{k},\eta) = \int_0^\eta ds\, g_{ab}(\eta - s)\, e^s\, \gamma_{bcd}(k, q_1, q_2) \times \\ \left(\bar{\varphi}_c^{(1)}(\mathbf{q}_1, s)\bar{\varphi}_d^{(0)}(\mathbf{q}_2, s) + \bar{\varphi}_c^{(0)}(\mathbf{q}_1, s)\bar{\varphi}_d^{(1)}(\mathbf{q}_2, s)\right)\,,$$

$\bar{\varphi}_1^{(0)} - \bar{\varphi}_2^{(0)} = \mathcal{O}(h)$ **“linear” density and velocity “misalligned”**

need $\langle \varphi_{a_1}^{(0)} \cdots \varphi_{a_n}^{(0)} h_{b_1} \cdots h_{b_m} \rangle$ **correlators !**

Sources: cosmology dependence

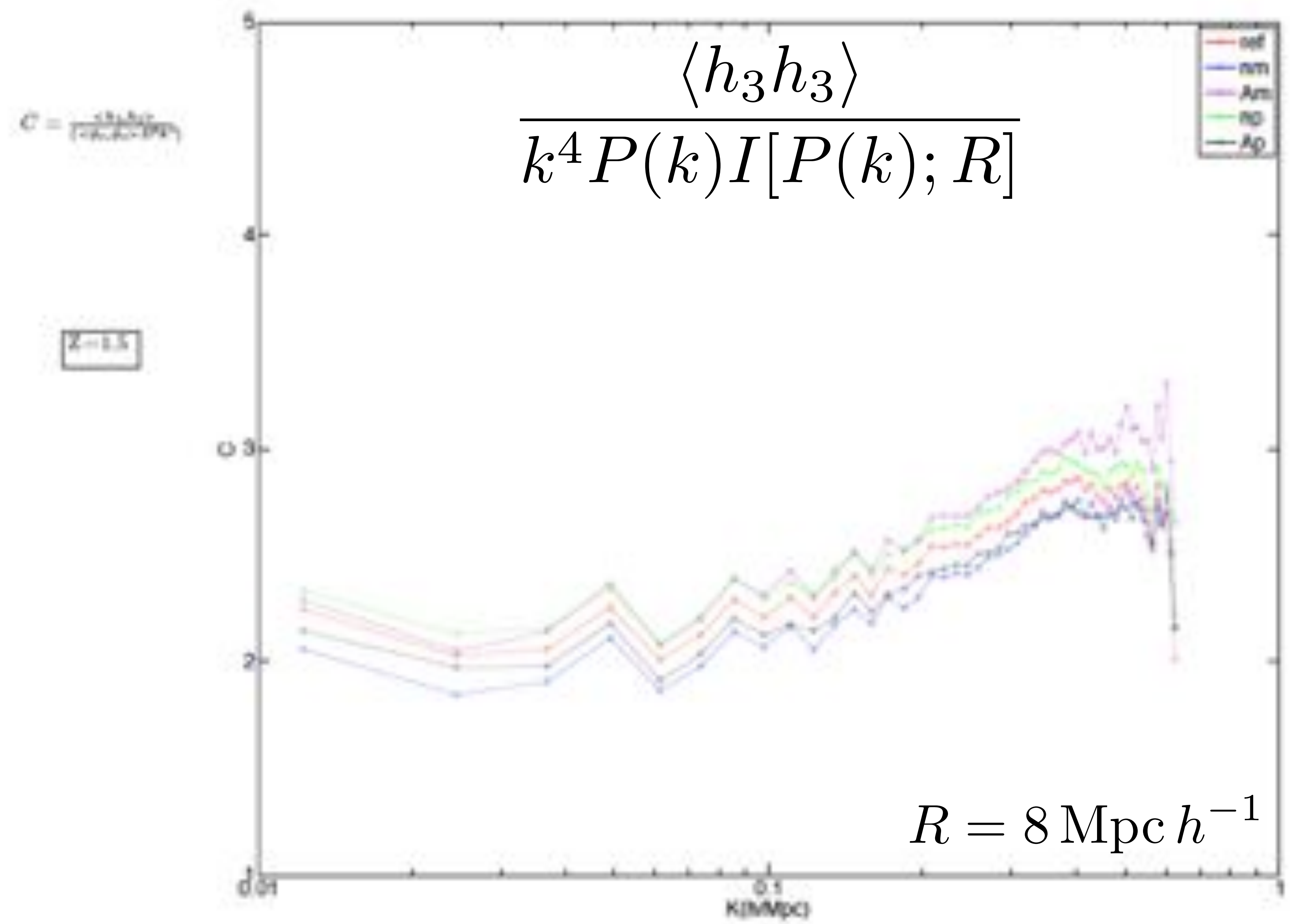


$$\frac{\langle h_3 h_3 \rangle}{k^4 P(k)}$$

$$R = 8\,\mathrm{Mpc}\,h^{-1}$$

$1.95 \cdot 10^{-9} < A_s < 3.0 \cdot 10^{-9}$ $0.932 < n_s < 1$

Sources: cosmology dependence



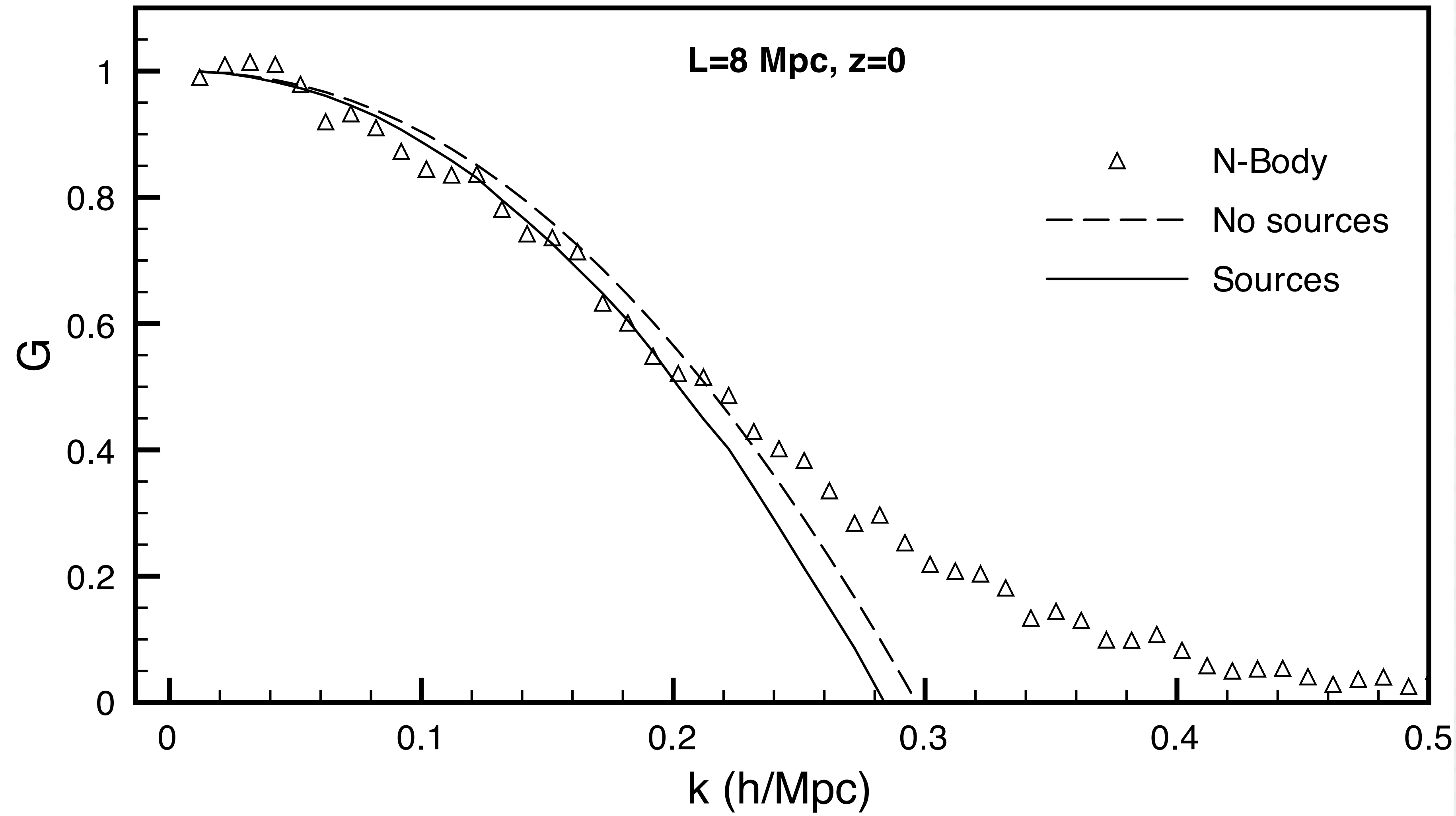
$$\frac{\langle h_3 h_3\rangle}{k^4 P(k) I[P(k); R]}$$

$R = 8\,\mathrm{Mpc}\,h^{-1}$

$1.95 \cdot 10^{-9} < A_s < 3.0 \cdot 10^{-9}$ $0.932 < n_s < 1$

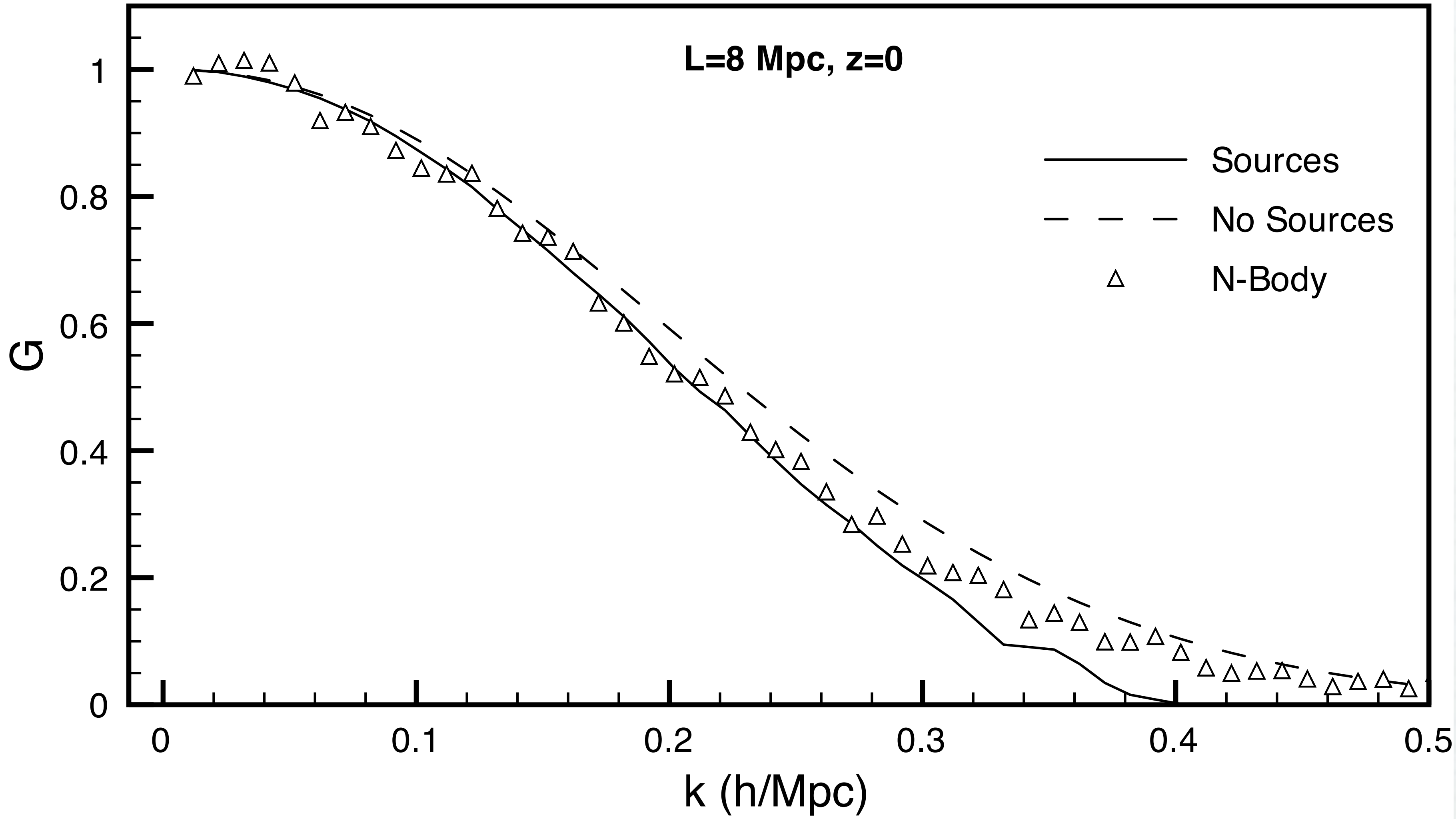
PT RECOVERS MOST OF THE COSMOLOGY DEPENDENCE !!

Propagator: 1-loop + sources



Mangano, Manzotti, MP, Saviano, Viel, in progress

Propagator: RPT+sources

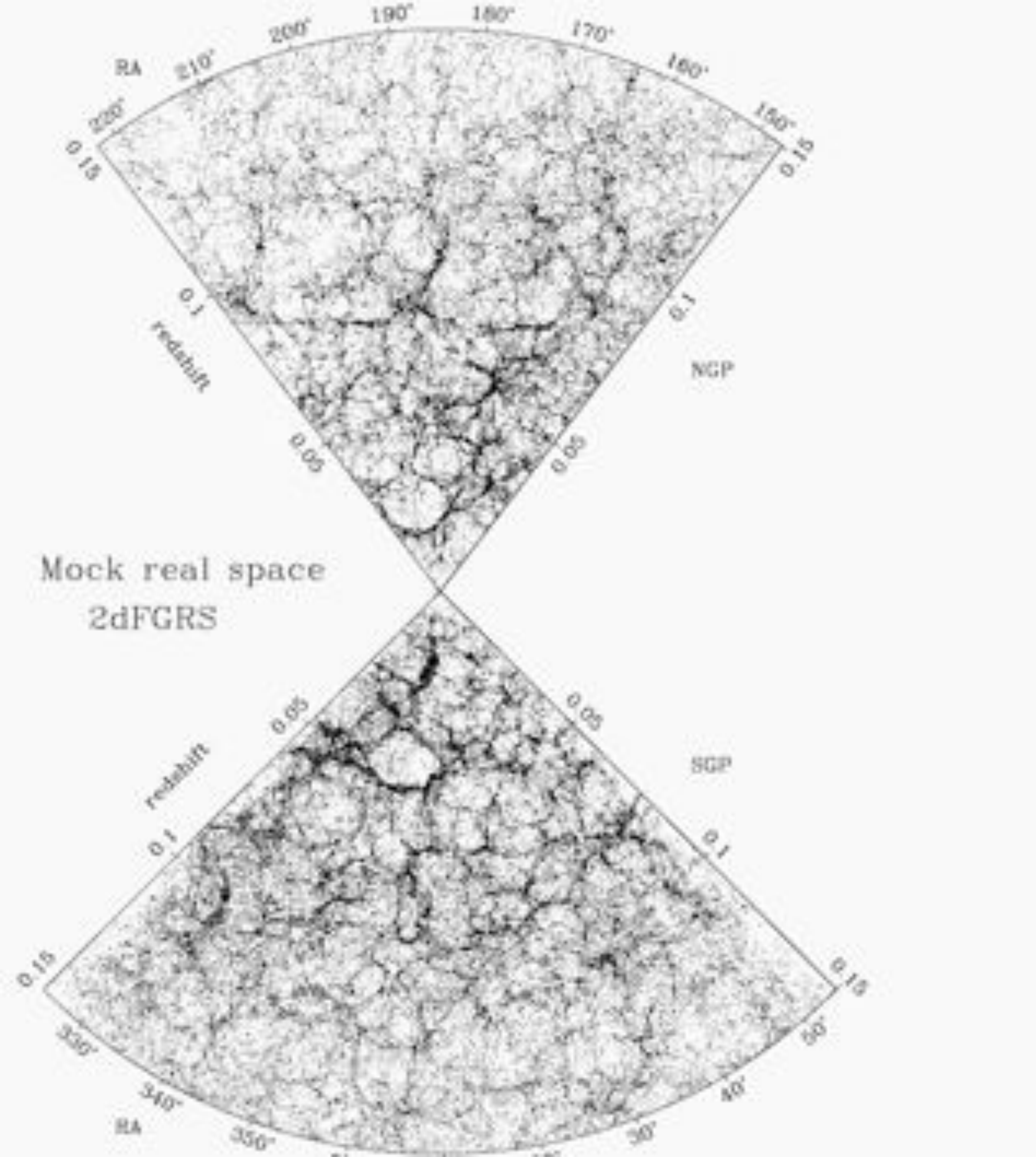


Mangano, Manzotti, MP, Saviano, Viel, in progress

PT RESUMMATIONS STILL NEEDED ON THE SMOOTH FIELDS!!

Redshift-space distorsions

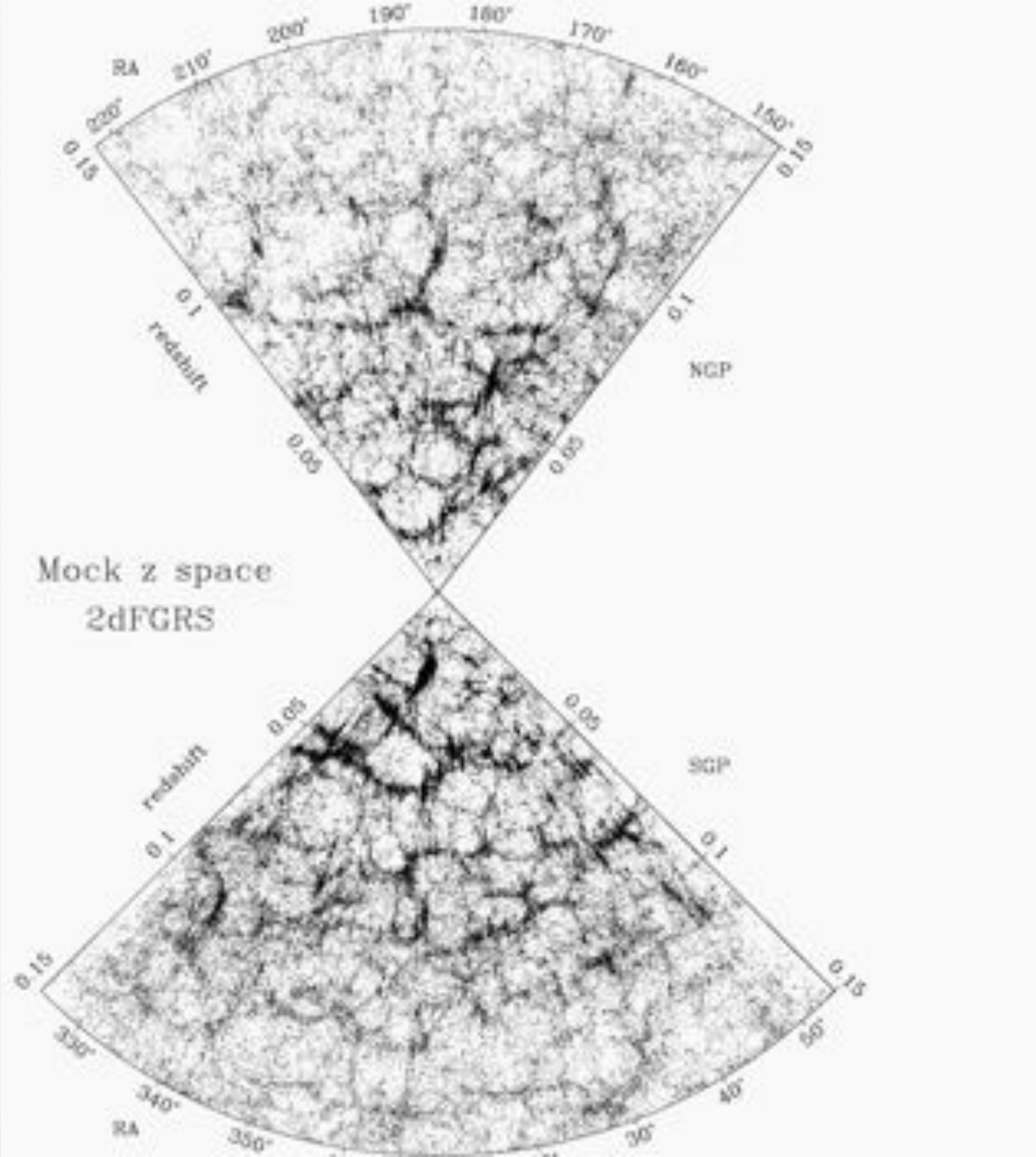
real-space


RA
220°
210°
200°
190°
180°
170°
160°
150°
0.15
0.15
0.1
redshift
0.1
NGP
0.05
0.05
Mock real space
2dFGRS
0.05
0.05
redshift
SGP
0.1
0.1
0.15
0.15
330°
340°
RA
350°
30°
40°
50°

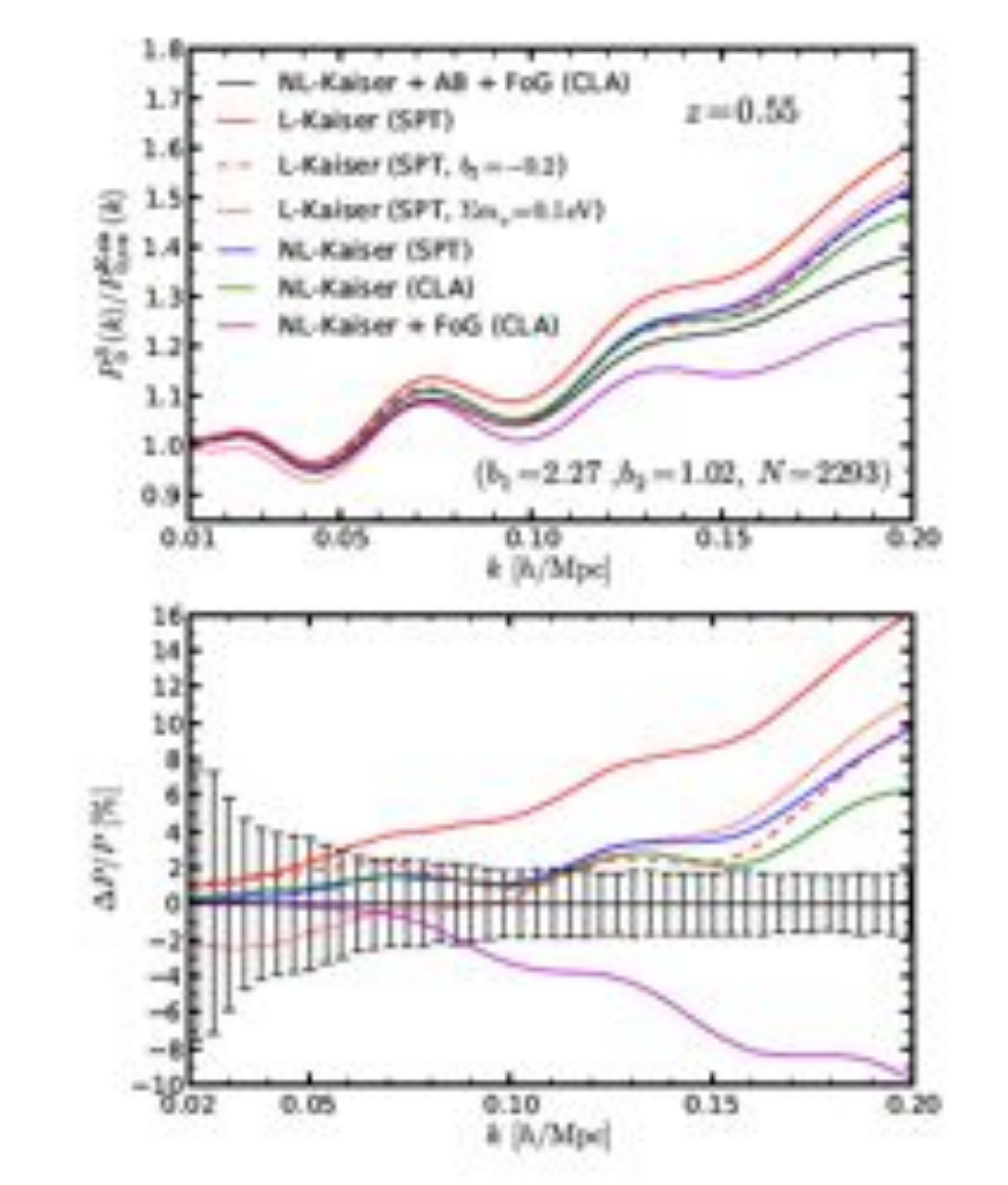
redshift-space

large scale:
Kayser

small scale:
FoG



RSD modeling



Zhao et al
1211.3741

IR-UV mixing in redshift space

microscopic level:

$$\vec{x}_n \to \vec{s}_n = \vec{x}_n + \frac{p_n^z}{a\mathcal{H}m}\hat{z}$$

(plane parallel approx.)

$$\delta_D(\vec{k}) + \delta_s(\vec{k}) = \int \frac{d^3\vec{x}}{(2\pi)^3} e^{i\vec{k}\cdot\vec{x}} \left[1 + \delta(\vec{x})\right] \exp\left[ik_z v_z(\vec{x})/\mathcal{H}\right]$$

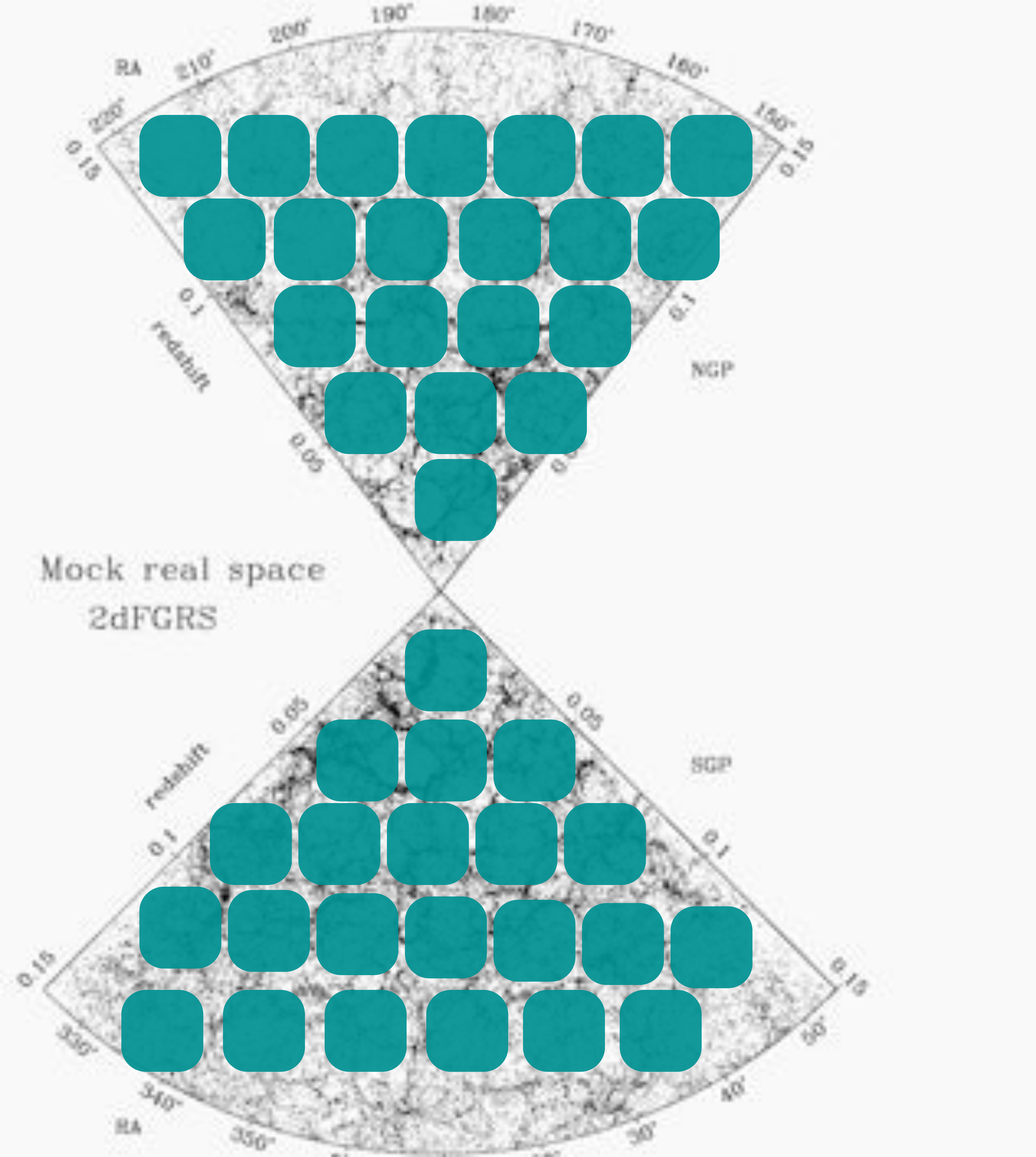
see Scoccimarro '04,

$\langle \delta_s(\vec{x})\, \delta_s(\vec{y}) \rangle$ gets contributions from terms like $\langle \delta(\vec{x})\, \delta(\vec{y}) v_z^2(\vec{y}) \rangle \sim \langle \delta(\vec{x})\, \delta(\vec{y}) \rangle \langle v_z^2 \rangle$

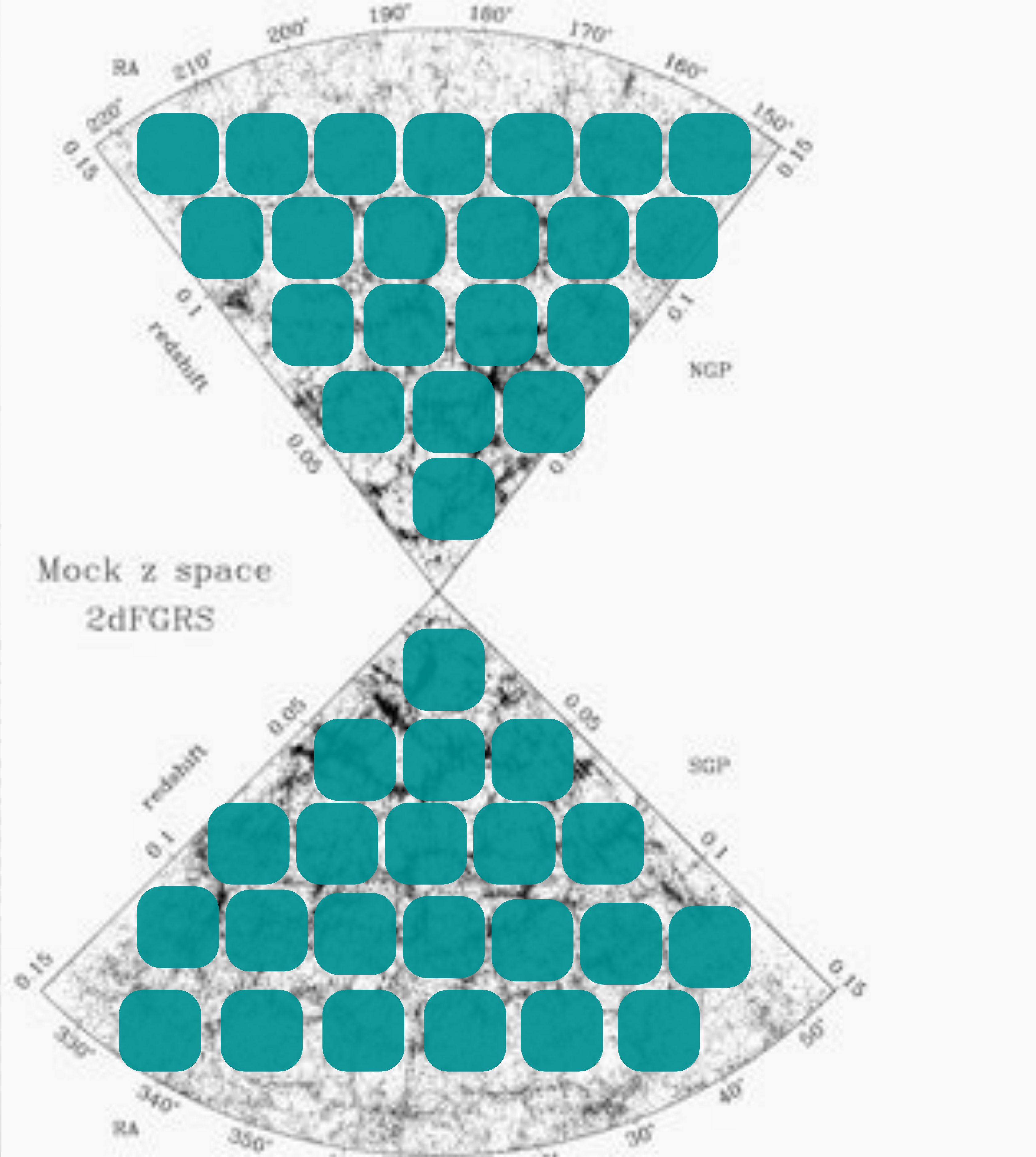
Large scales feel short ones!!

Problems for PT even at very large scales:
Desjacques, Baldauf, McDonald, Okumura, Seljak, Vlah, '11-'12

real-space


RA
220°
210°
200°
190°
180°
170°
160°
150°
0.15
0.15
0.1
0.1
redshift
0.05
NGP
Mock real space
2dFGRS
0.05
0.05
redshift
SGP
0.1
0.1
0.15
0.15
330°
340°
RA
350°
30°
40°
50°

redshift-space



Integrate out the FoG!

Coarse-grained redshift space

smoothed fields:

$$\delta_D(\vec{k}) + \bar{\delta}_s(\vec{k}) =$$

$$\int \frac{d^3\vec{x}}{(2\pi)^3} e^{i\vec{k}\cdot\vec{x}} \left[1 + \bar{\delta}(\vec{x})\right] \exp\left[ik_z \bar{v}_z(\vec{x})/\mathcal{H} - \bar{\sigma}_{zz}(\vec{x})k_z^2/(2\mathcal{H}^2) + \cdots\right]$$

better behavior of the expanded exponential

$$\bar{\delta}(\vec{k}) \neq -\frac{\bar{\theta}}{f\mathcal{H}}$$

"tree-level" corrections to Kayser's formula

$$e^{-\bar{\sigma}_{zz}(\vec{x})k_z^2/(2\mathcal{H}^2)}$$

FoG resummation!

Summary

- Future surveys demand a lot of effort on non-linear effects: real space, redshift space, bias;
- Improved PT methods OK for BAOs and beyond (up to O(1 h/Mpc));
- Agreement between independent approaches;
- Good: speed, flexibility;
- Common limit: the single stream approximation;
- PT and N-body are complementary tools: let's exploit it! Coarse-grained PT