Digging out DE properties (and more) from the LSS

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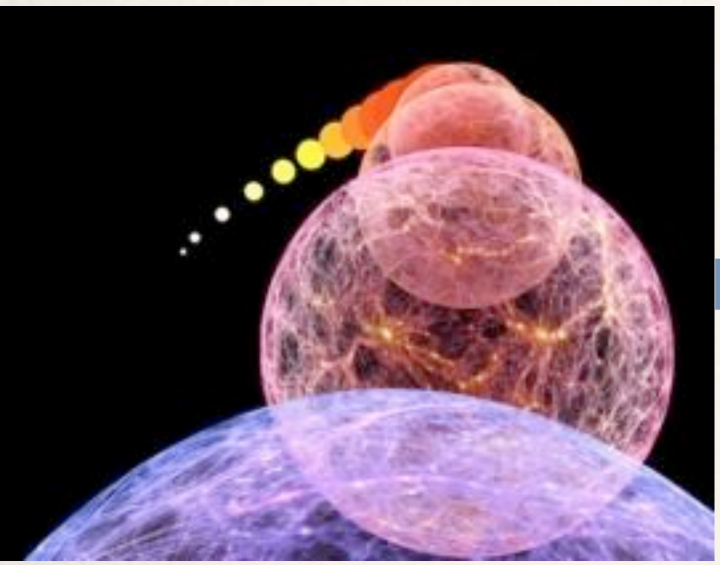
Vulcano, 20/5/2014

Outline

- Motivation
- Nonlinearities in LSS
- Perturbation theory and the need for resummations
- A consistent (and effective) resummation scheme
- Conclusions, Future work

Understanding the LSS of the Universe

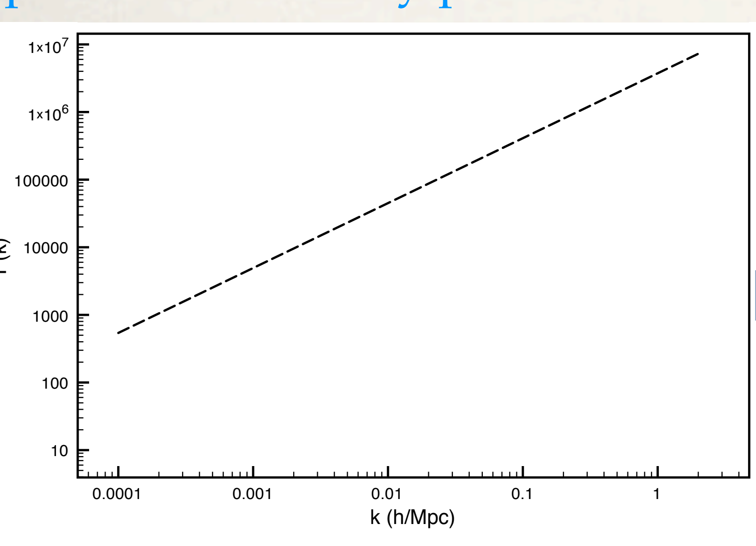
Inflation



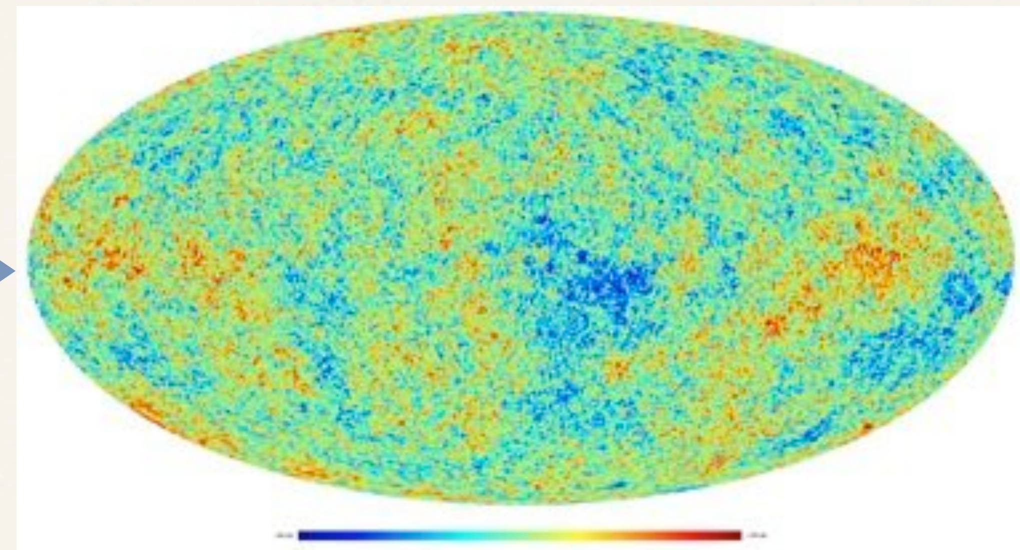
Linear, Gaussian

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

primordial density perturbations

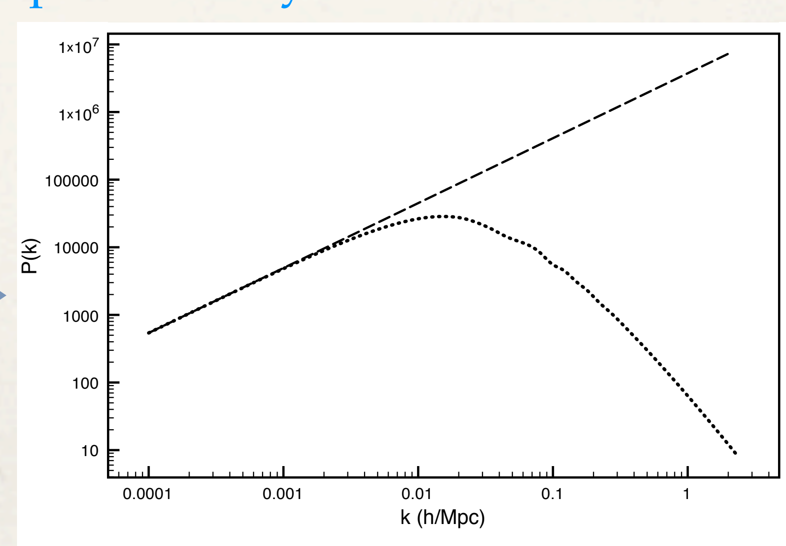


Decoupling

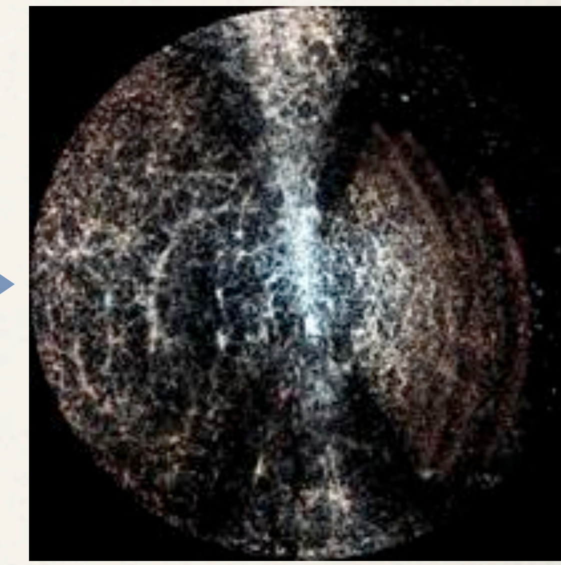


Linear, Gaussian

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

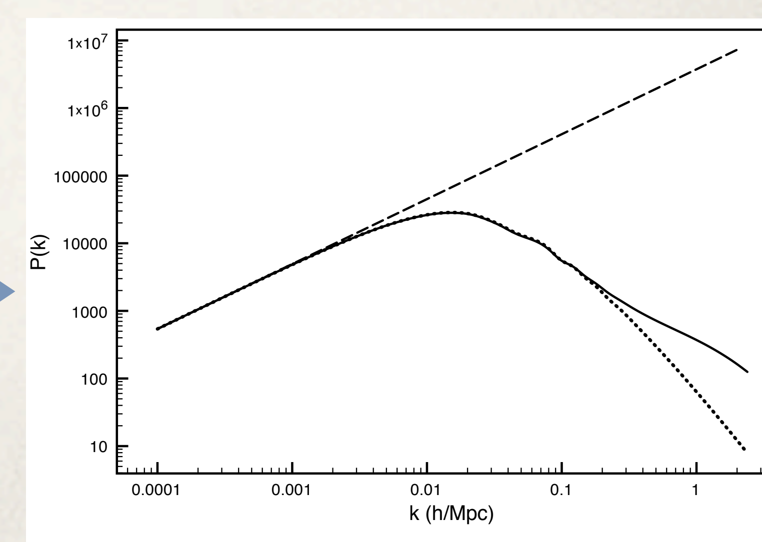


Today

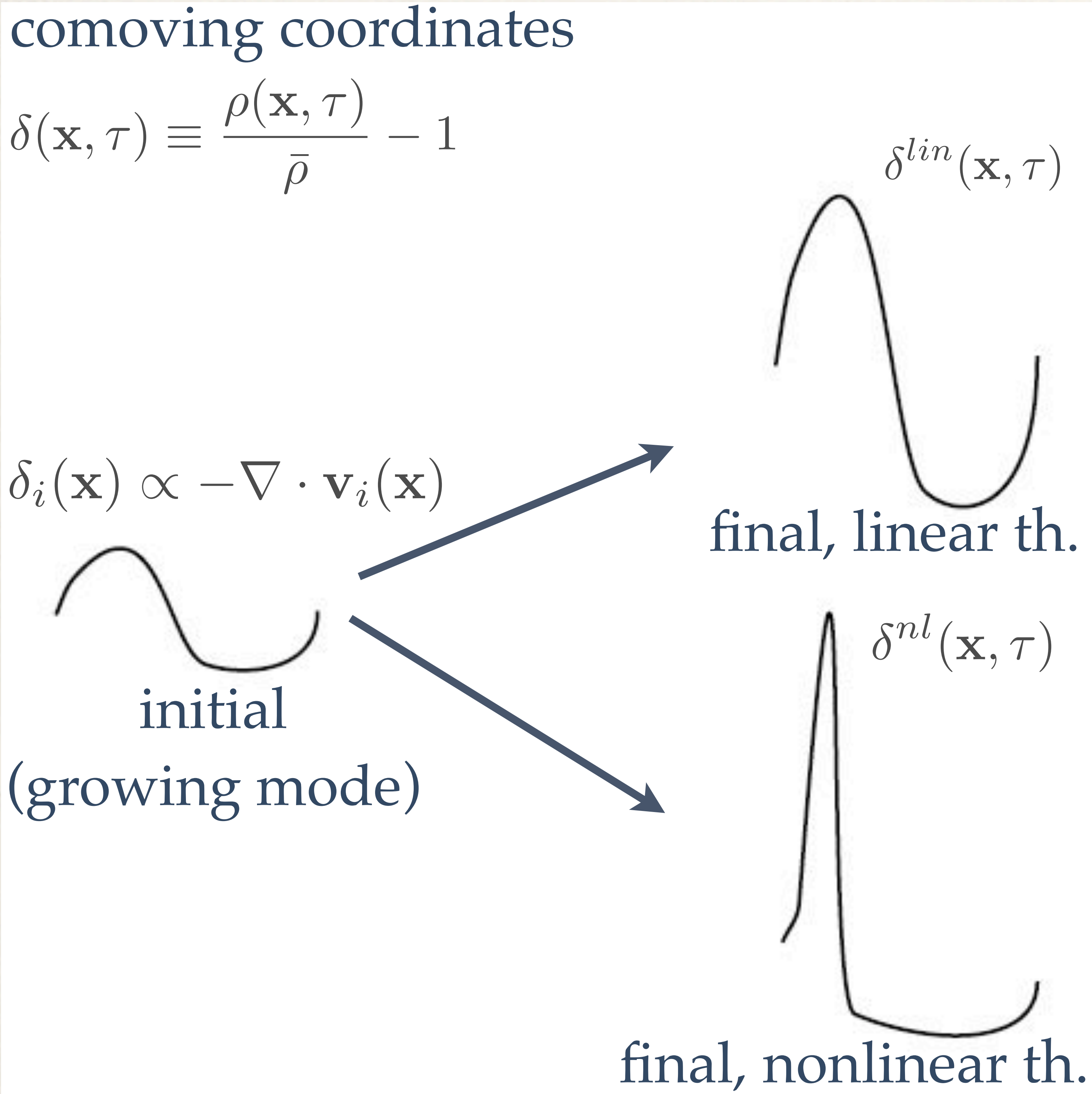


non-Linear,
non-Gaussian

non-relativistic matter



Linear versus Nonlinear



$$\dot{\delta} = -\nabla \cdot \mathbf{v}$$

scale-independent growth

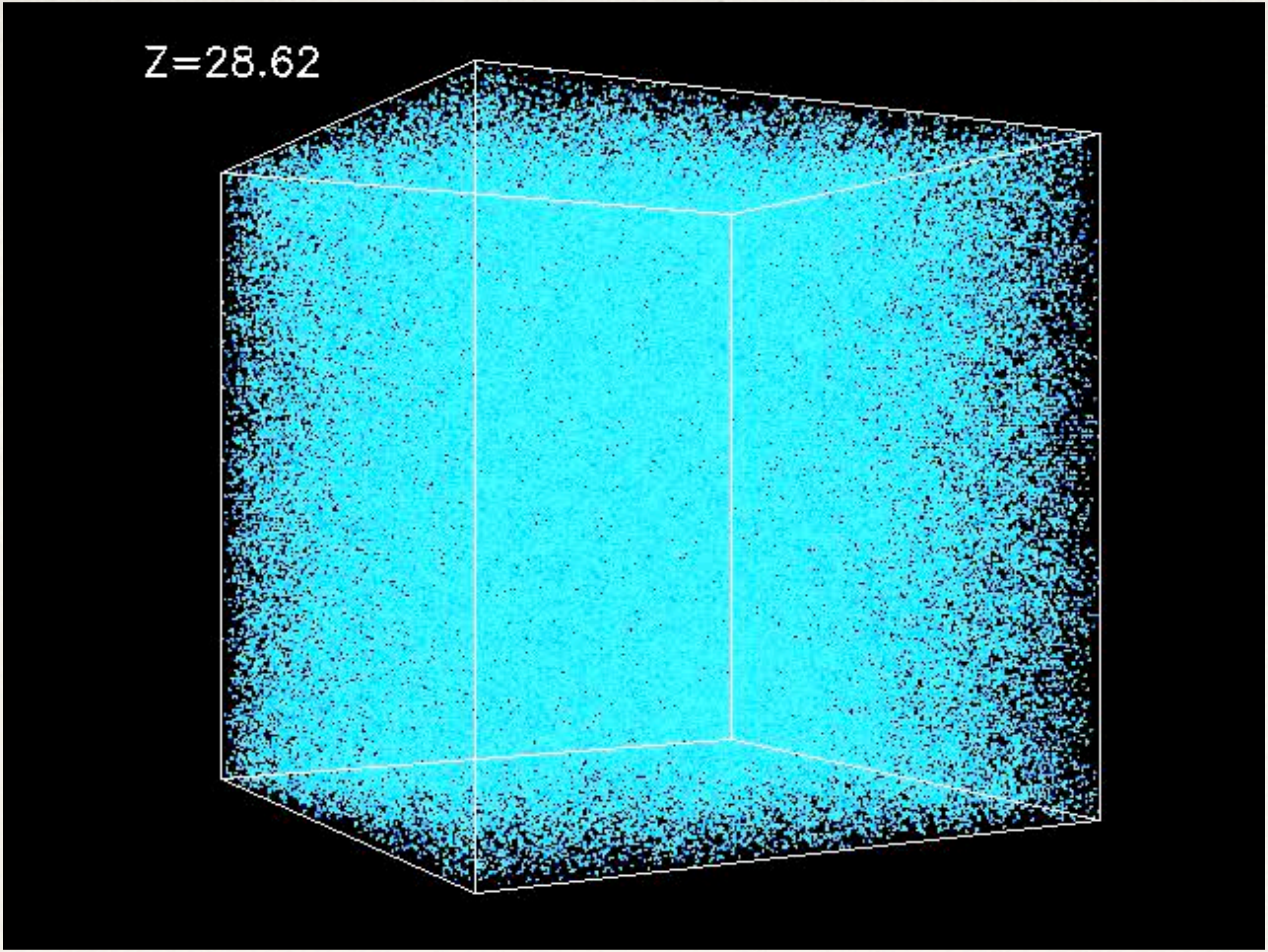
$$\delta^{lin}(\mathbf{x},\tau) = D(\tau)\delta_i(\mathbf{x})$$

$$\dot{\delta} = -\nabla \cdot [(1+\delta)\mathbf{v}]$$

mode-mode coupling

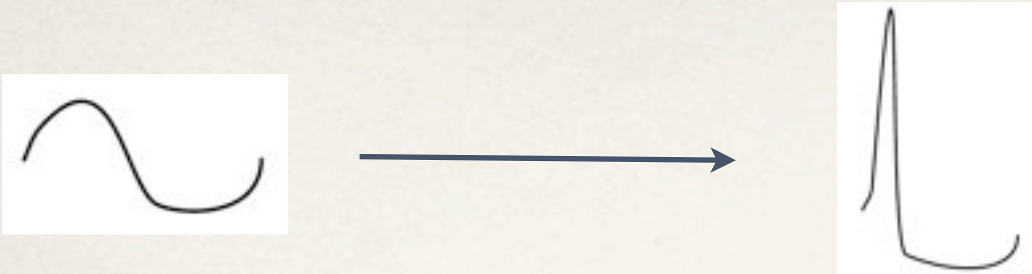
non gaussian

Overdense regions, gravity wins, underdense regions, expansion wins

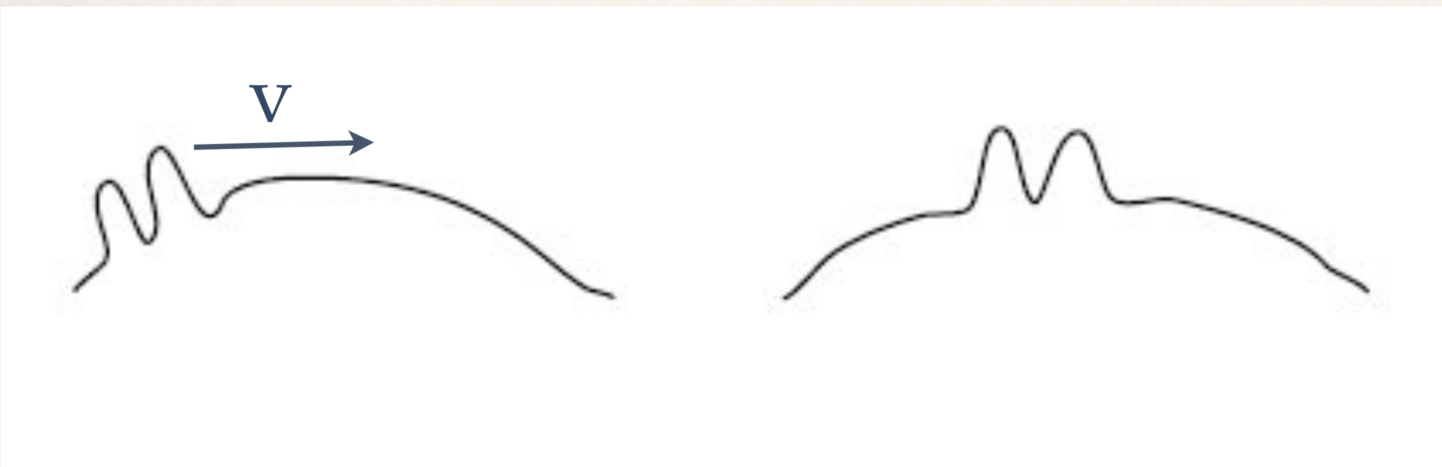


Movie by Kravtsov, Klypin
(National Center for Supercomputer applications)

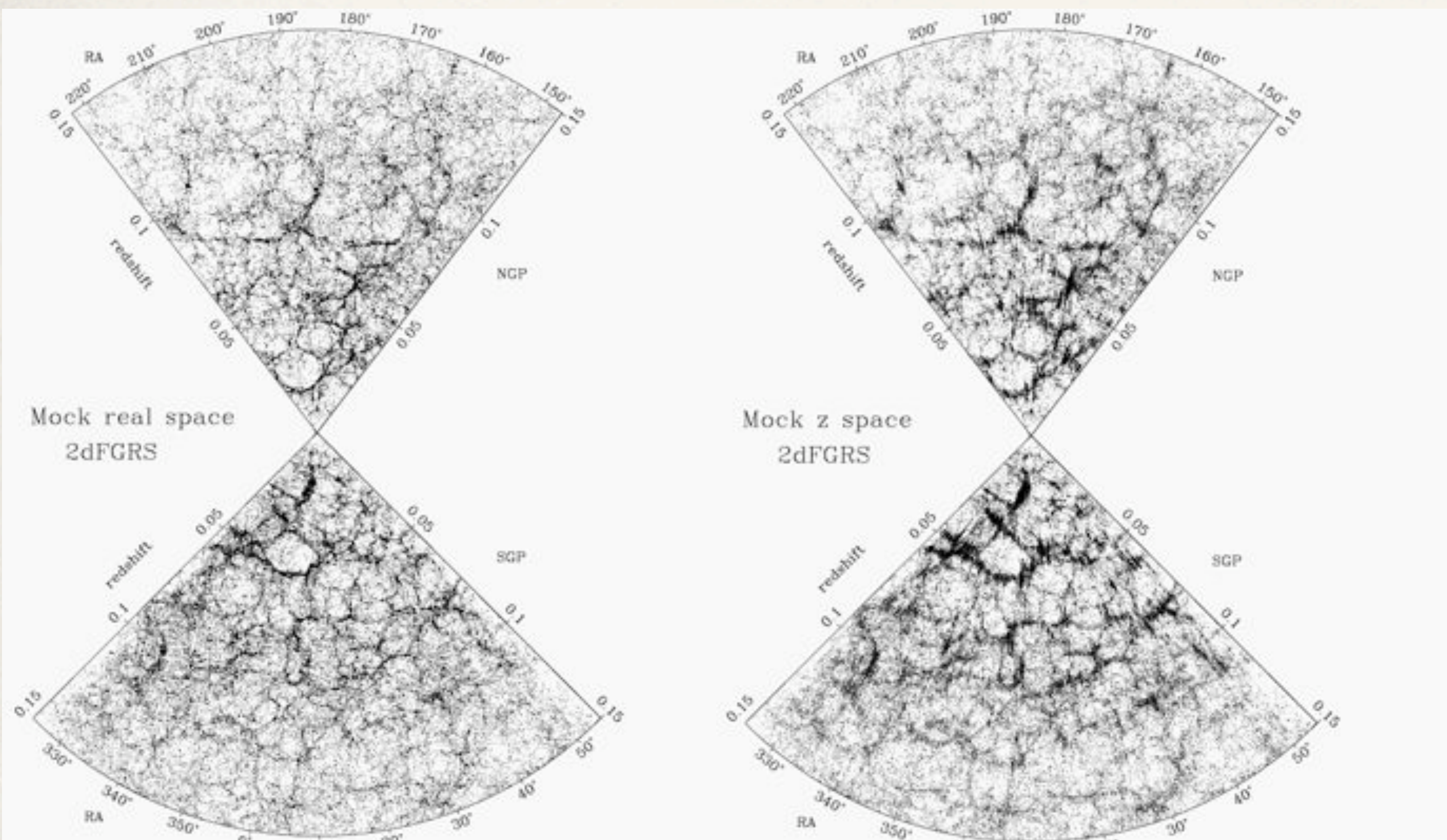
Life is Nonlinear (I)



Mode-mode coupling



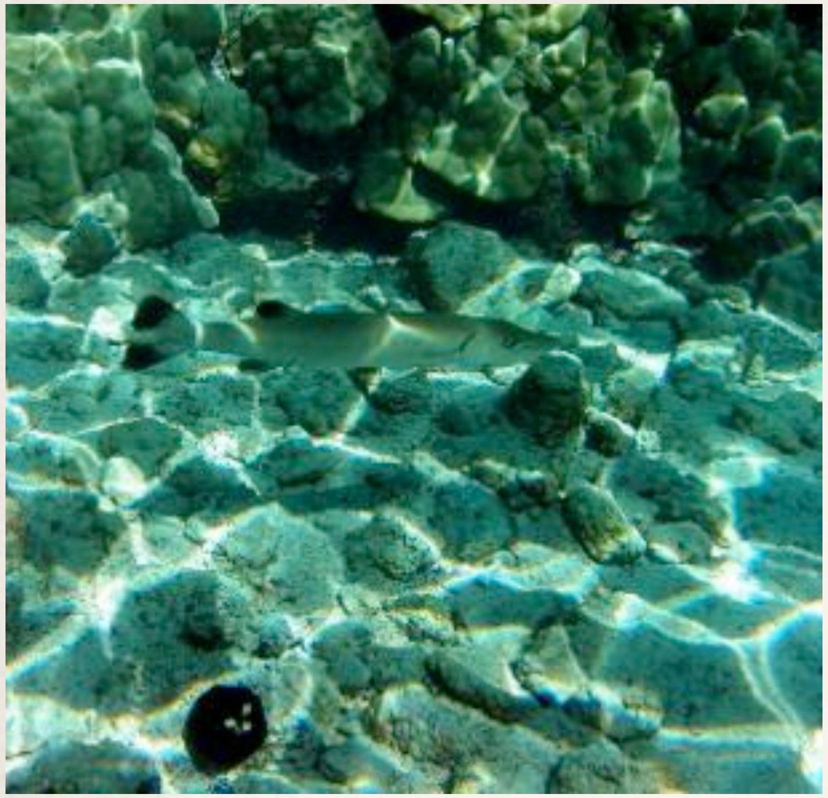
Large scale bulk flows



Redshift space distortions

$$\delta_{RS}(\mathbf{x}) = \mathcal{F}[\delta; \mathbf{v}]$$

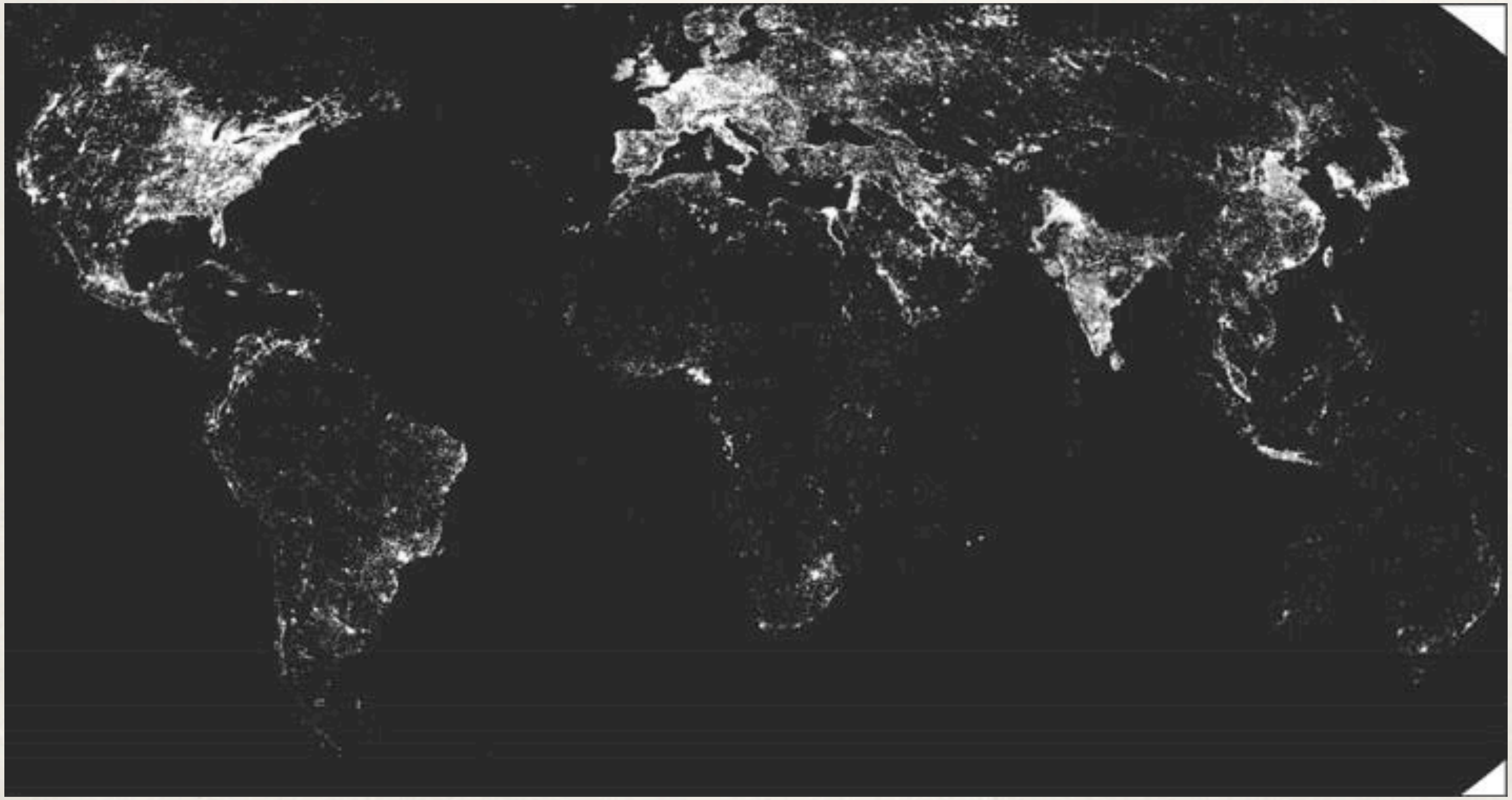
Life is Nonlinear (II)



Multistreaming

$$f(\mathbf{x},\mathbf{v},\tau) \not\propto \rho(\mathbf{x},\tau)\delta_D(\mathbf{v}-\bar{\mathbf{v}}(\mathbf{x},\tau))$$

bias $\delta_g = \mathcal{F}[\delta_{DM}, (\nabla_i\nabla_j\Phi)^2, \cdots]$



Why non linear scales?

- Dark Energy (Baryonic Acoustic Oscillations)
- Neutrino masses
- Primordial non-Gaussianity
- Modifications to General Relativity
- Non standard Dark Matter/Dark Energy
- ...

The future of precision cosmology: non-linear scales

matter density

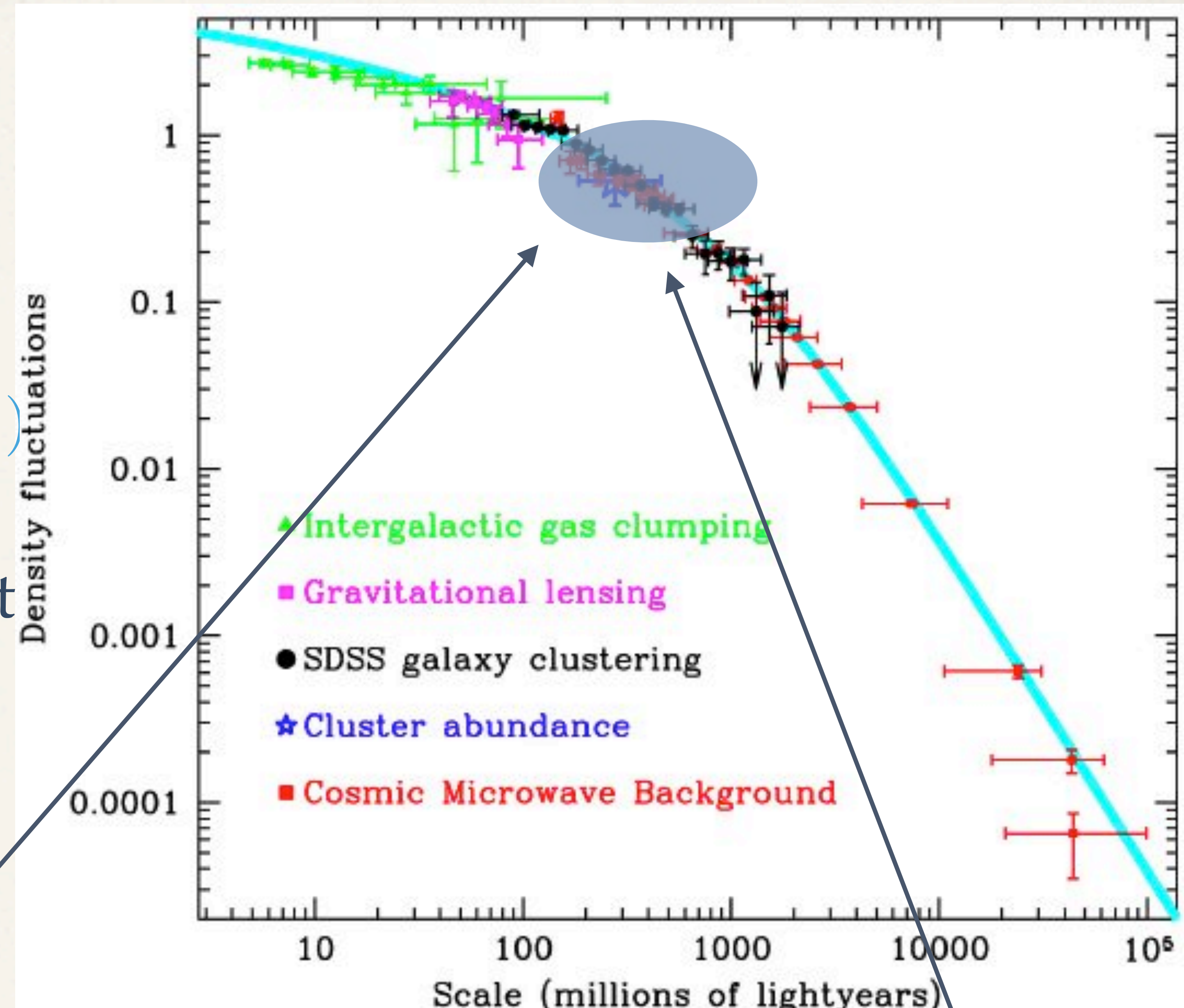
$$\rho(\mathbf{x},\,\tau) \equiv \bar{\rho}(\tau)[1+\delta(\mathbf{x},\,\tau)]$$

power spectrum

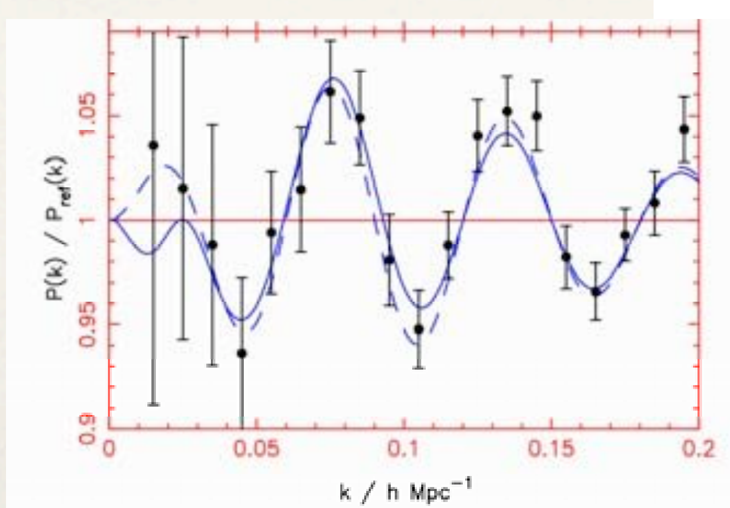
$$\langle \delta(\mathbf{k},\,\tau)\,\delta(\mathbf{k}',\,\tau)\rangle = P(k,\,\tau)\delta^{(3)}(\mathbf{k}+\mathbf{k}')$$

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

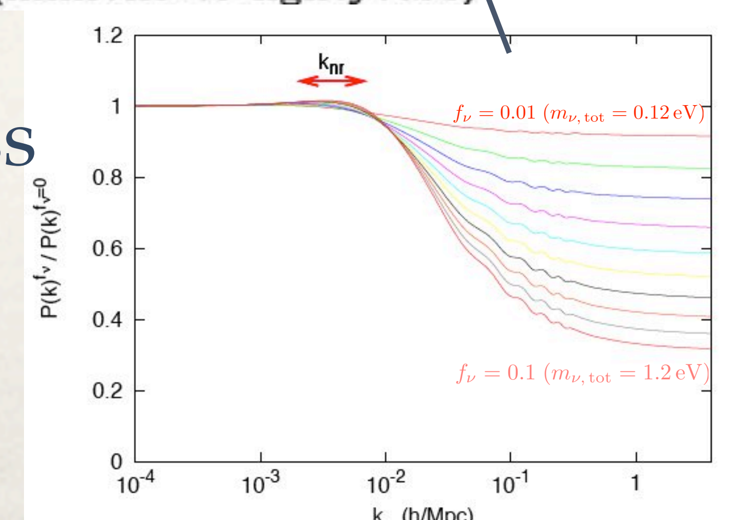
$$\Delta^2(k,\tau) = 4\pi k^3 P(k,\tau)$$



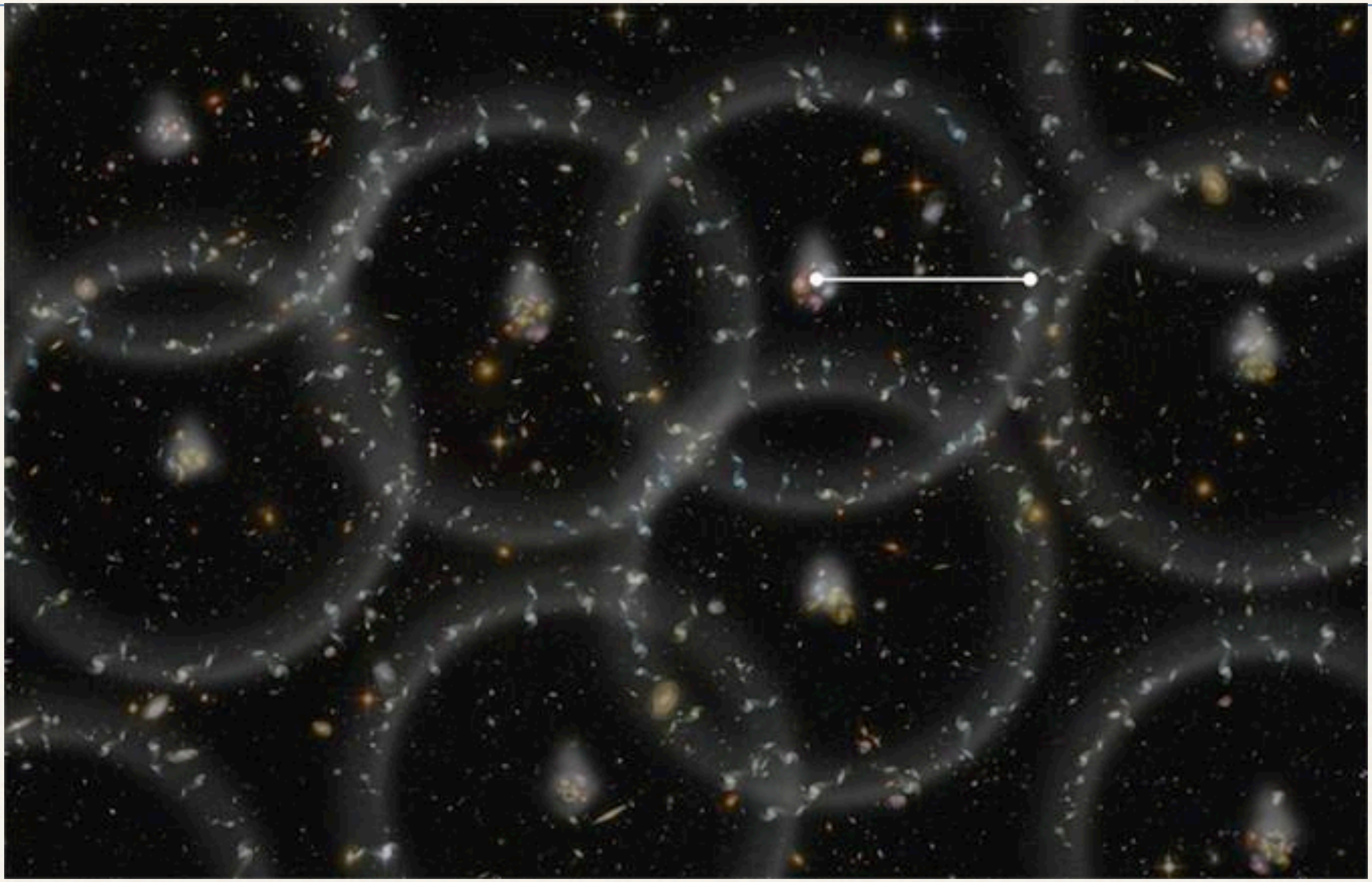
Baryonic Acoustic Oscillations (BAO)



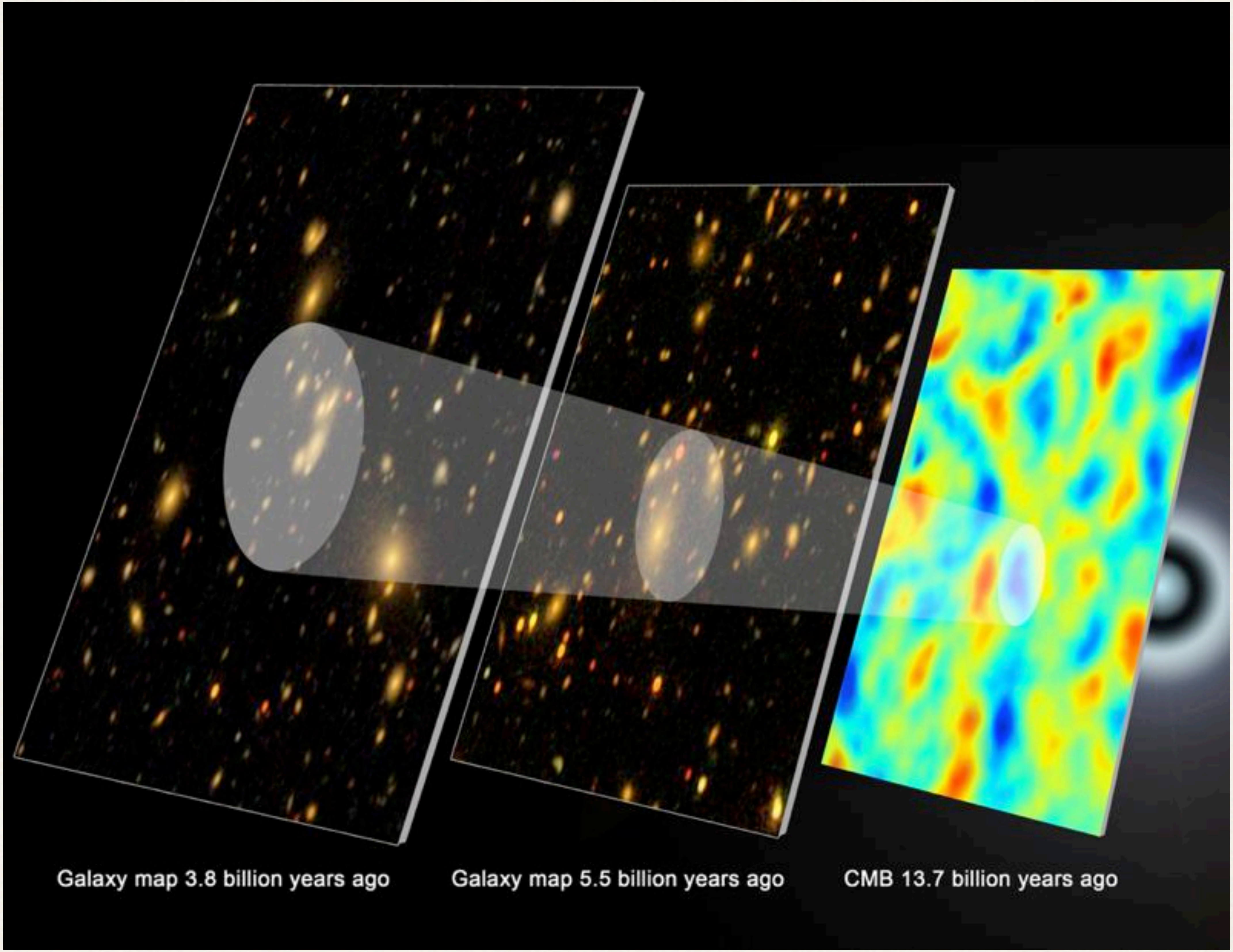
Neutrino mass bounds



Baryonic Acoustic Oscillations



Remnant of the acoustic scale at recombination on the LSS

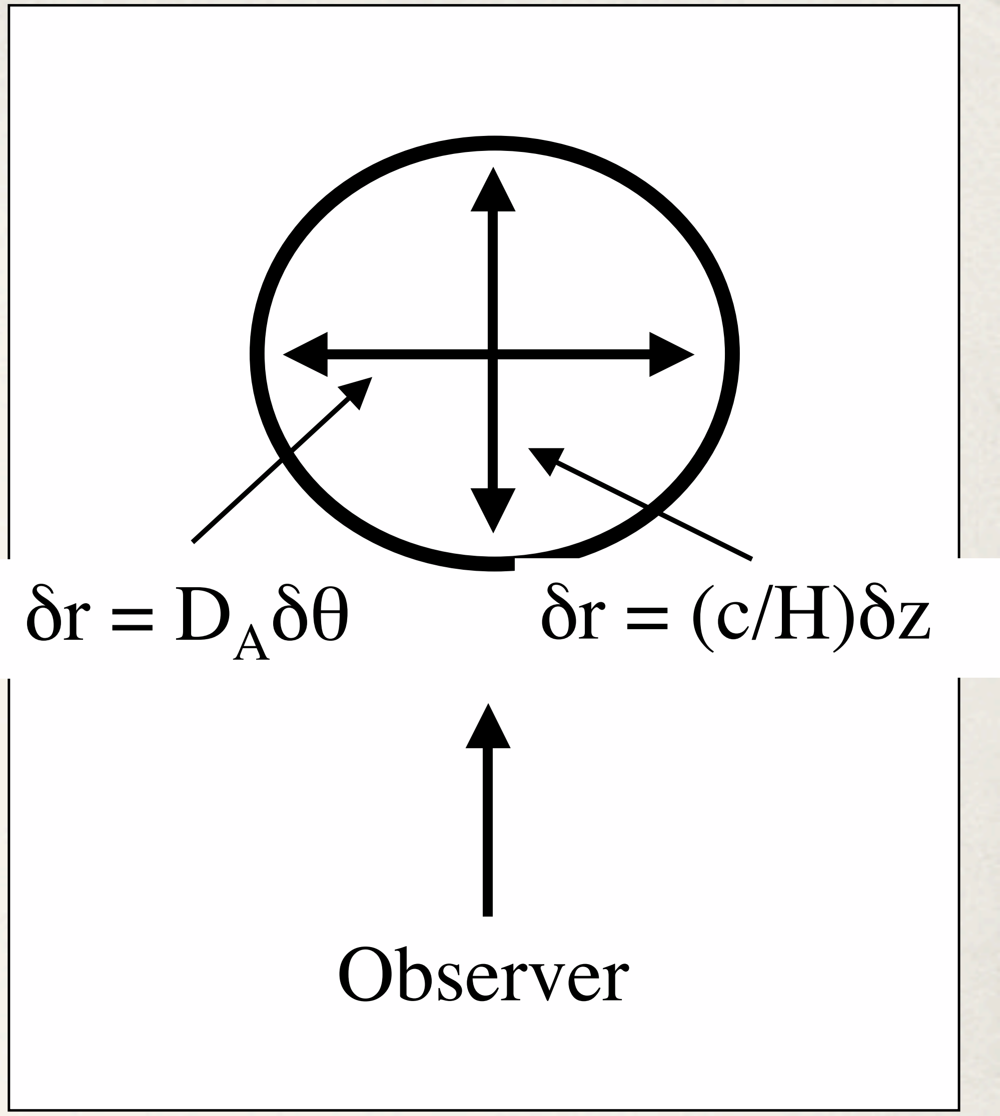

Galaxy map 3.8 billion years ago
Galaxy map 5.5 billion years ago
CMB 13.7 billion years ago

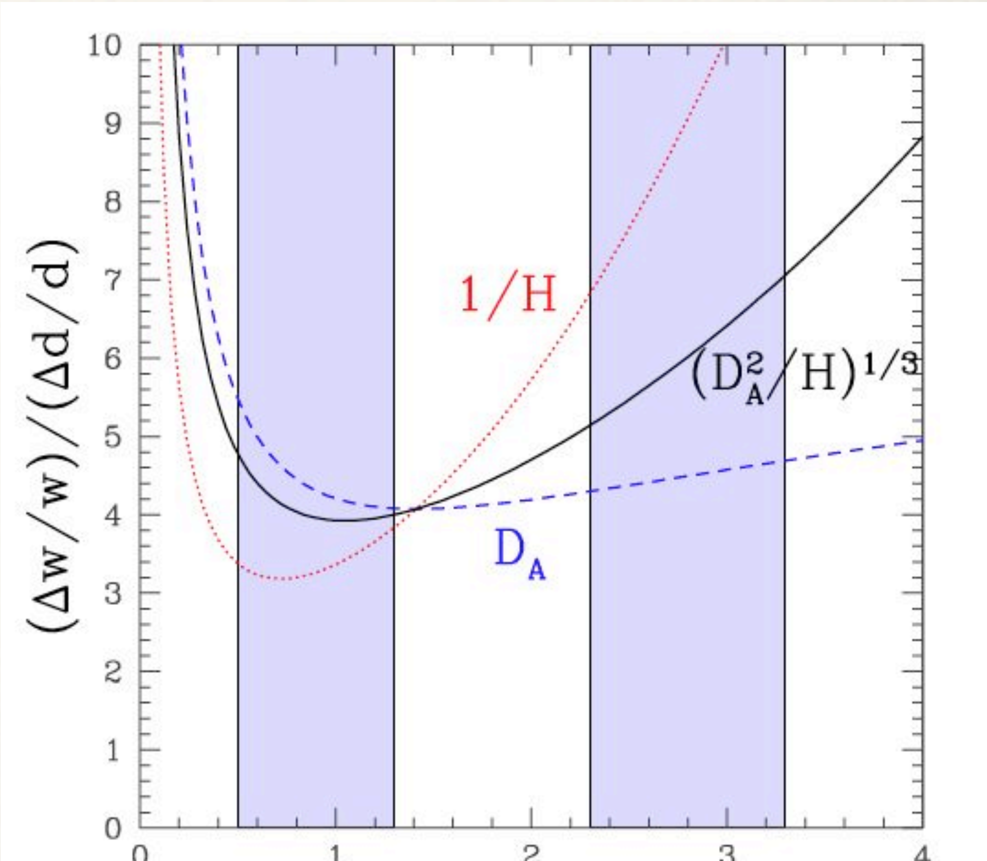
The same acoustic oscillation scale is imprinted on the CMB anisotropies

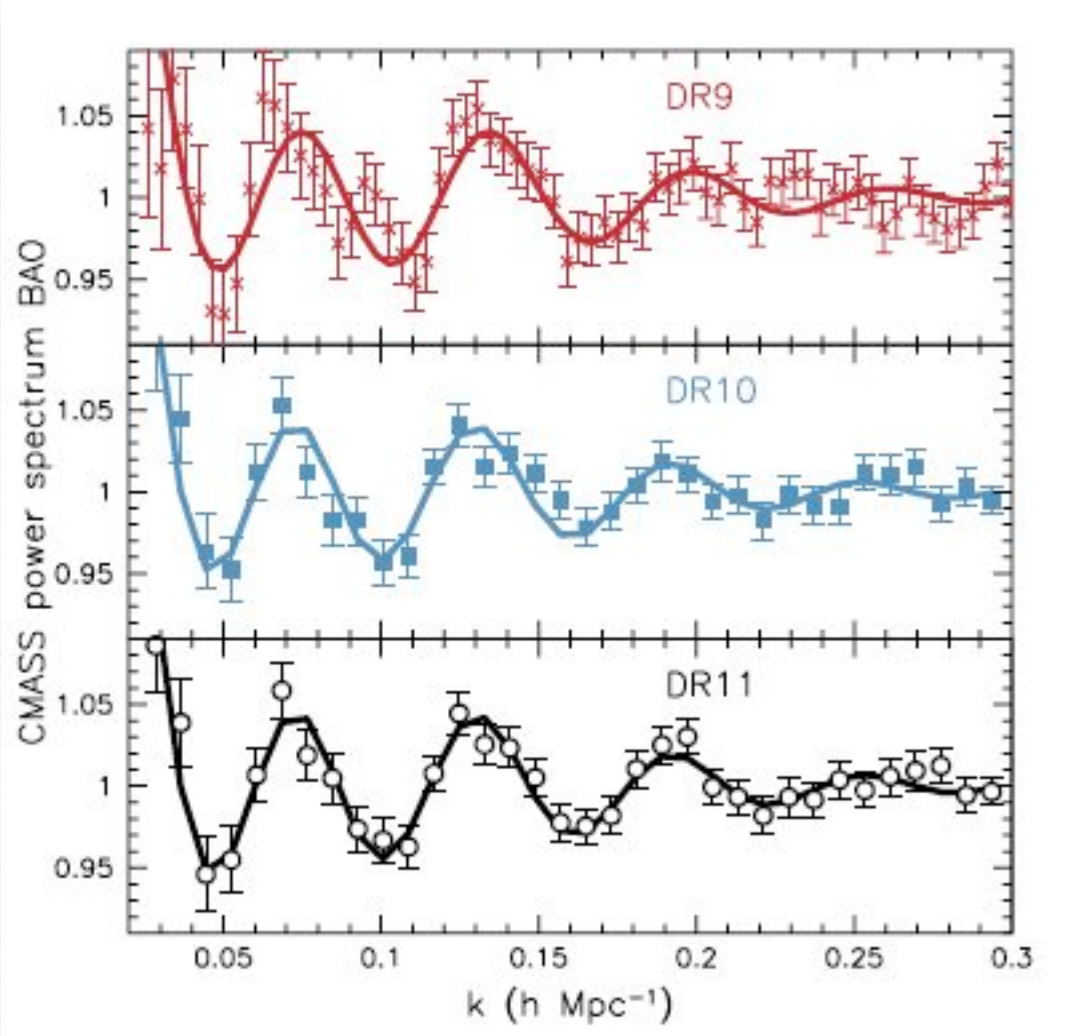
Redshift surveys of galaxies (e.g. Sloan) measure this scale both along and across the line of sight

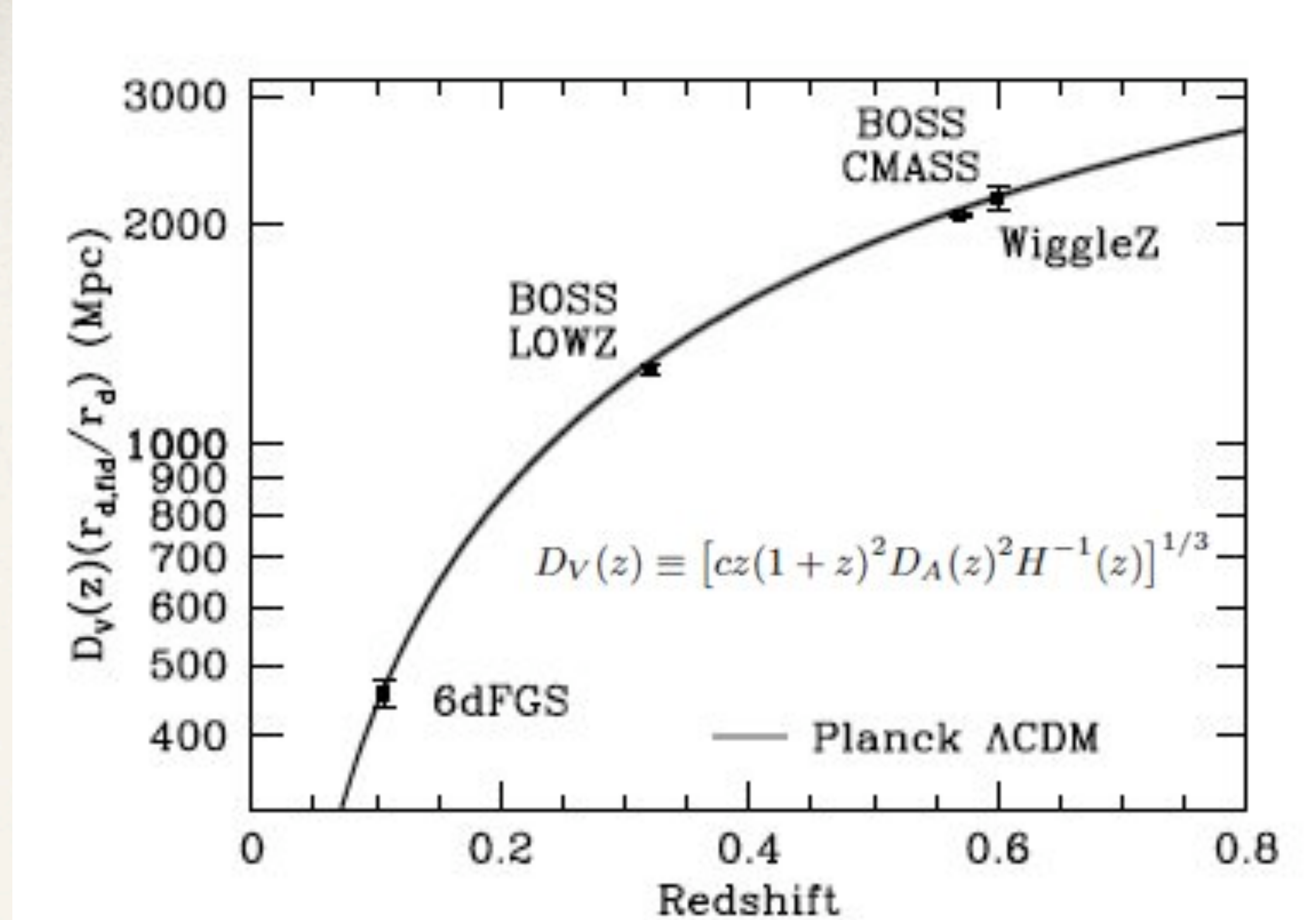
Reconstruct the expansion history of the Universe from z~1000 to today!

A 1% error on H, D_A, implies ~5% error on $w=p/\varrho$ of the Dark Energy

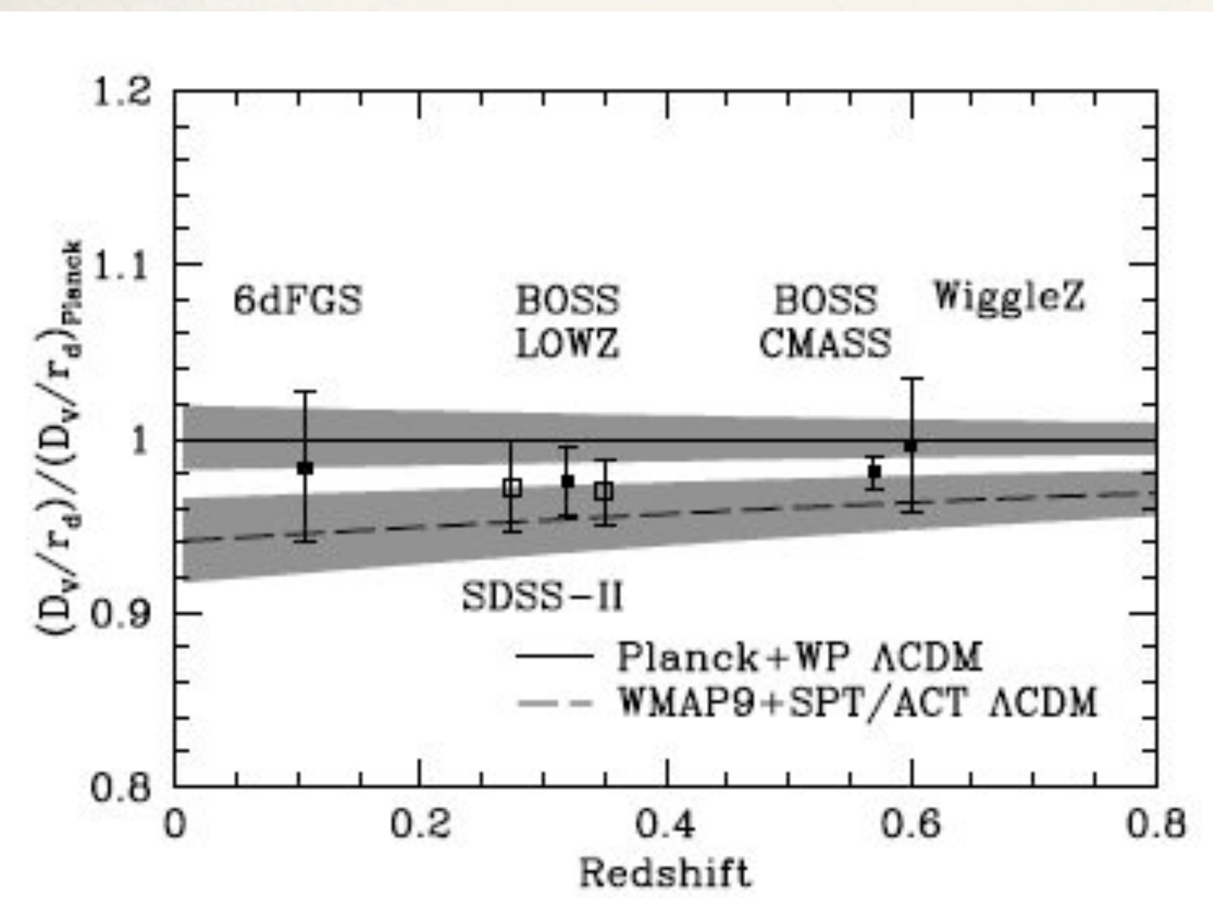


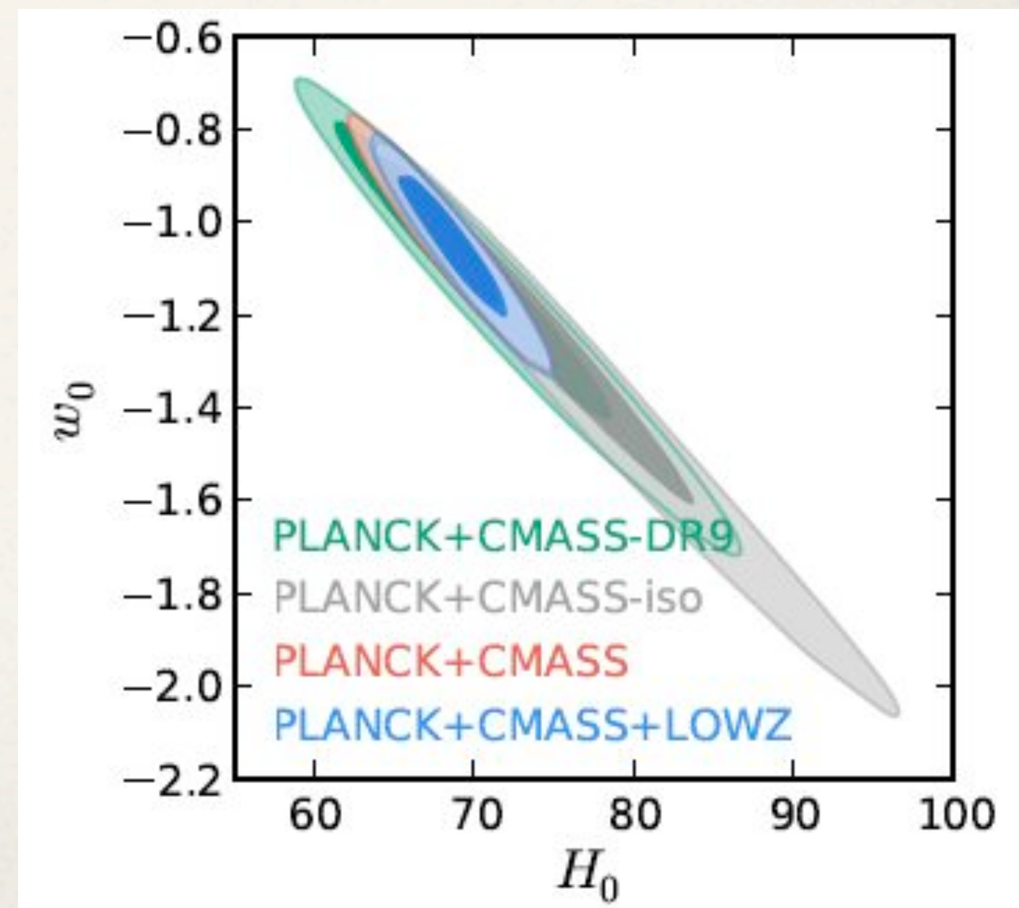




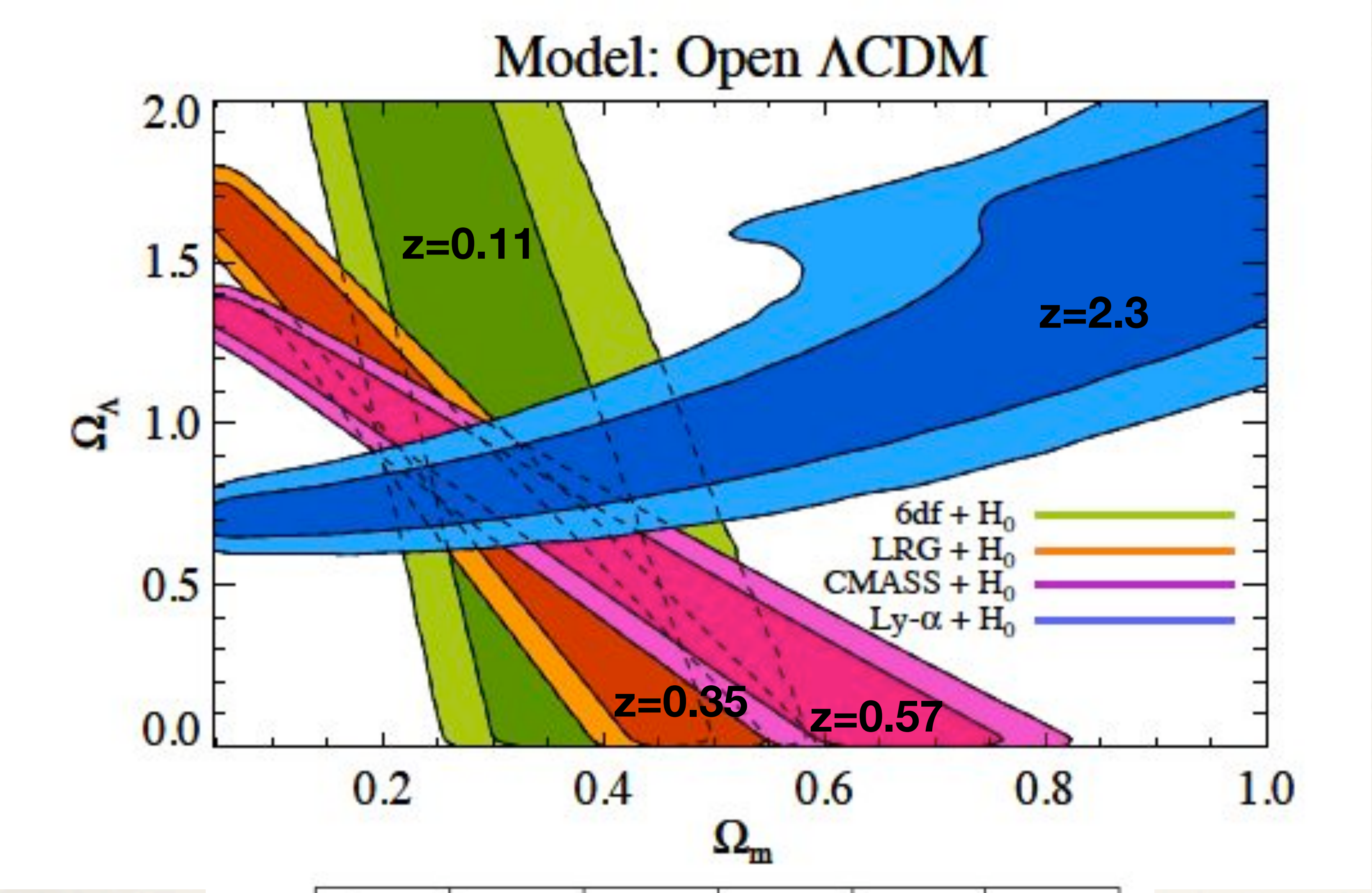


BOSS, 1312.4877



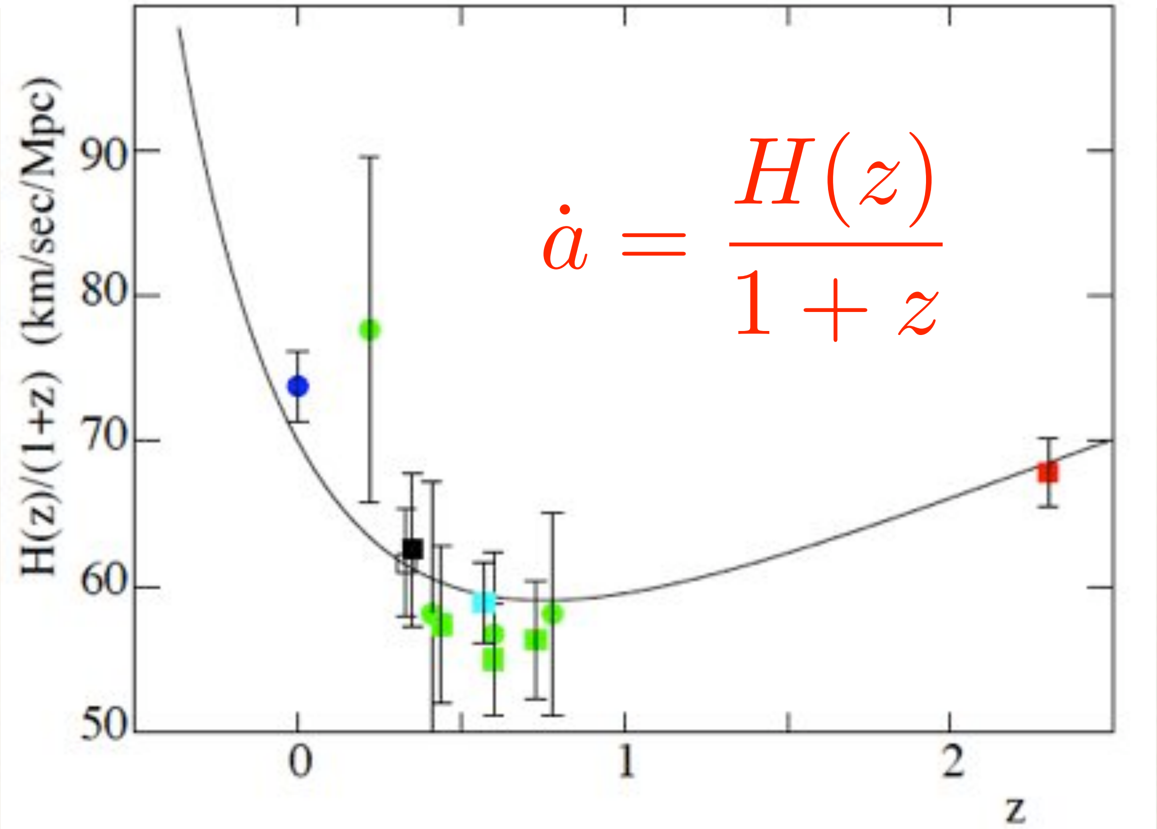


BOSS result: BAO in Lyα



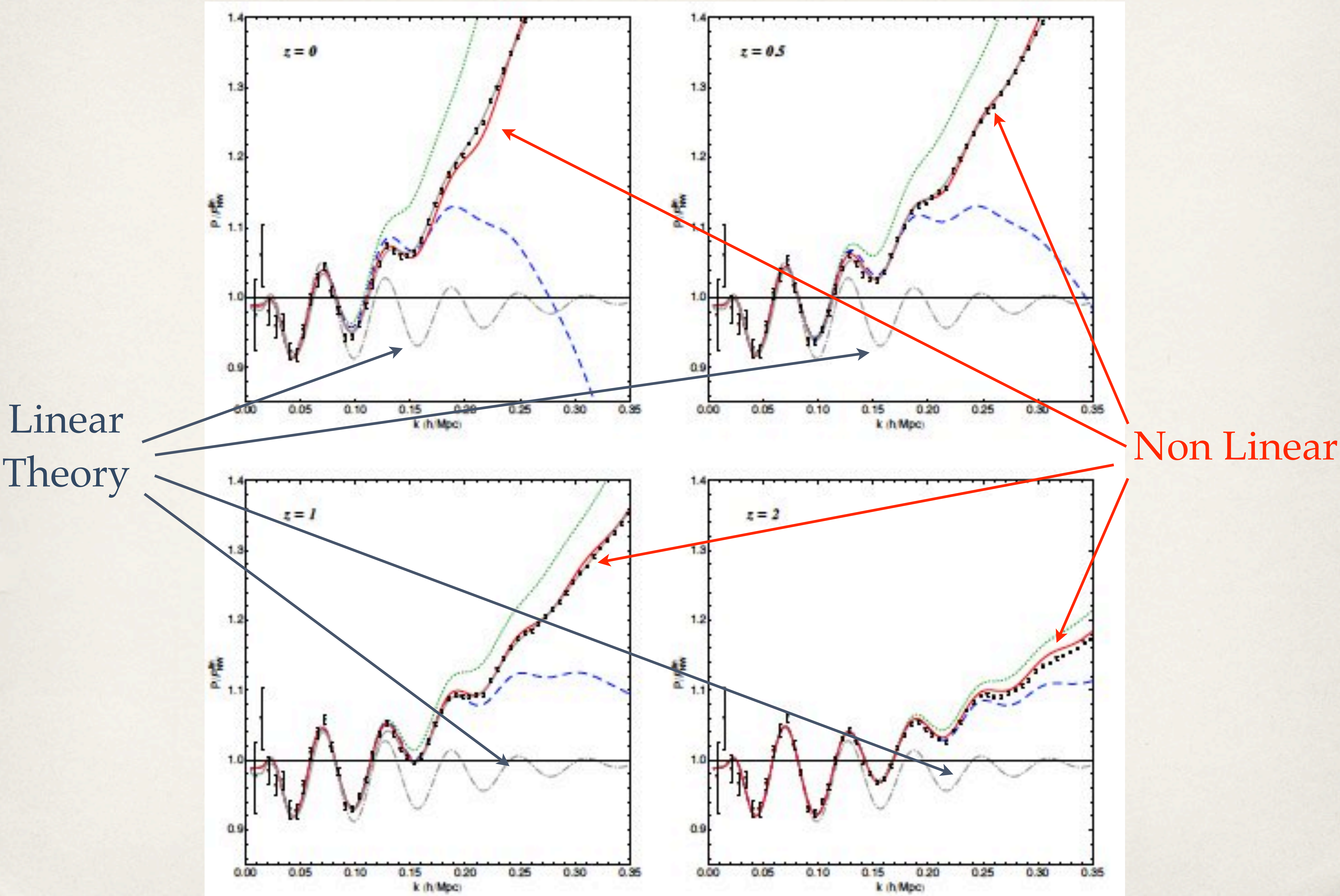
Measurement of Dark Energy from LSS "alone" (+ Ho)!

1211.2616
(1404.1801)



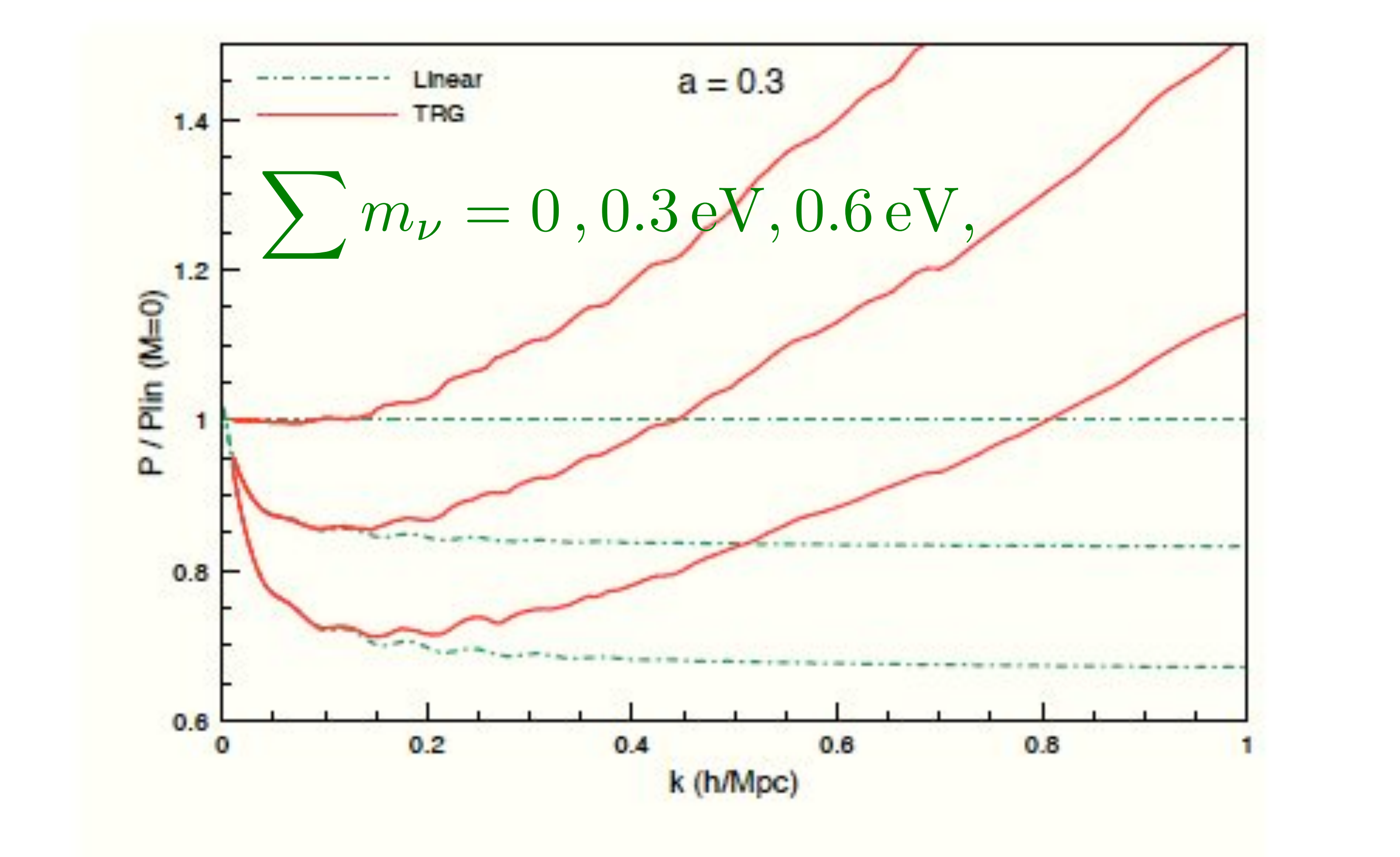
Deceleration to acceleration transition seen!!

BAO scales

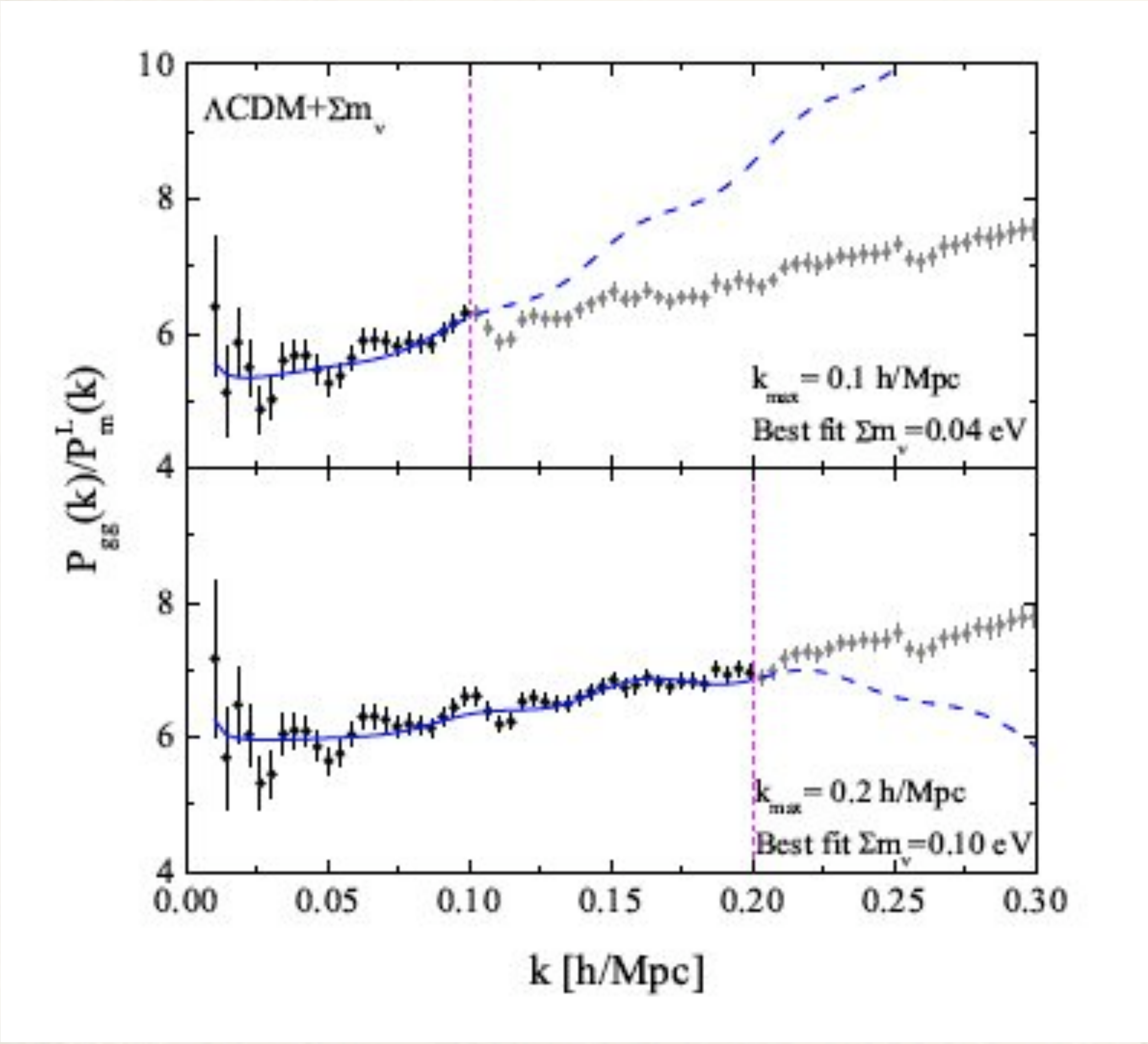


Neutrino masses

nonlinearities crucial to increase the sensitivity!!

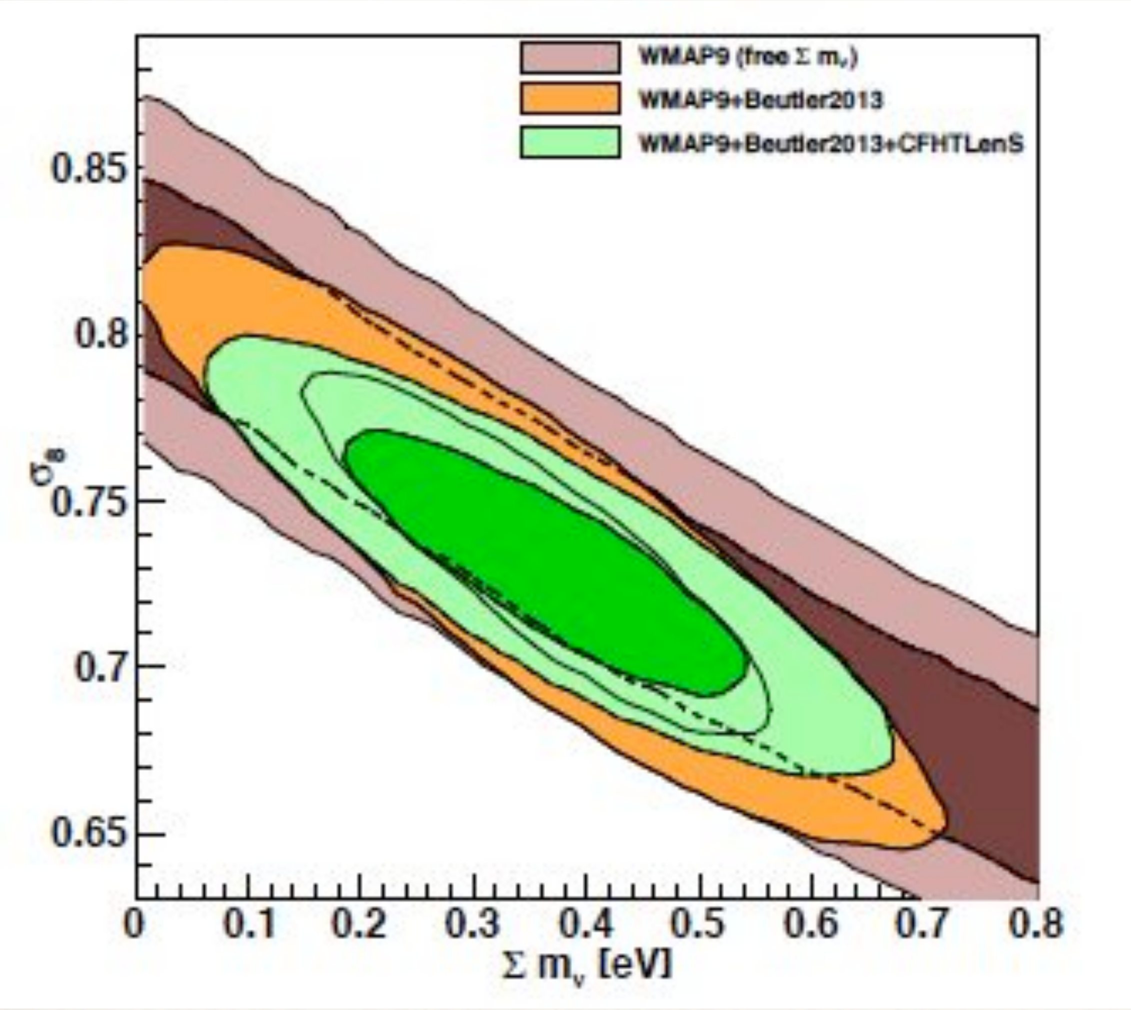


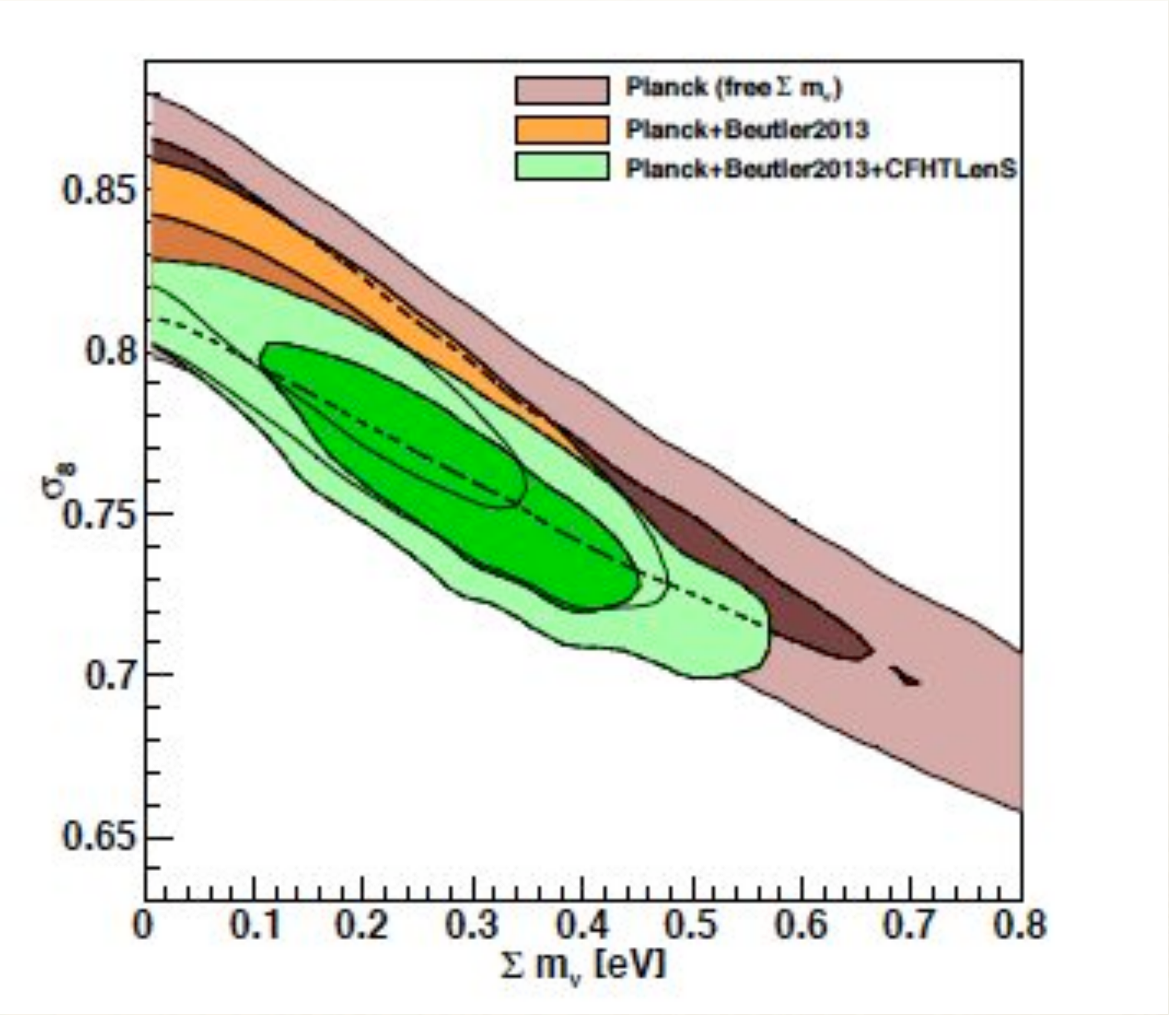
Lesgourgues, Matarrese, MP, Riotto, ’09



Zhao et al 1211.3741

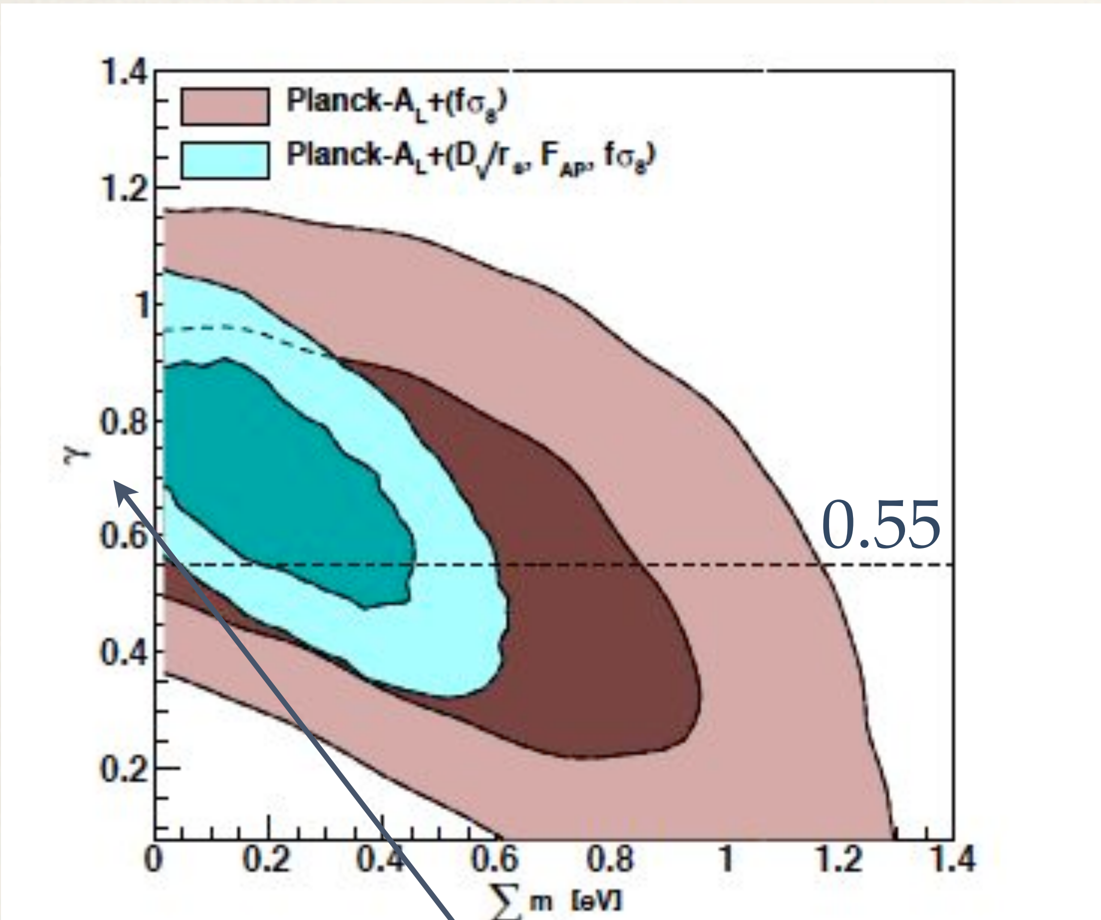
Hints for nonzero neutrino masses (?)

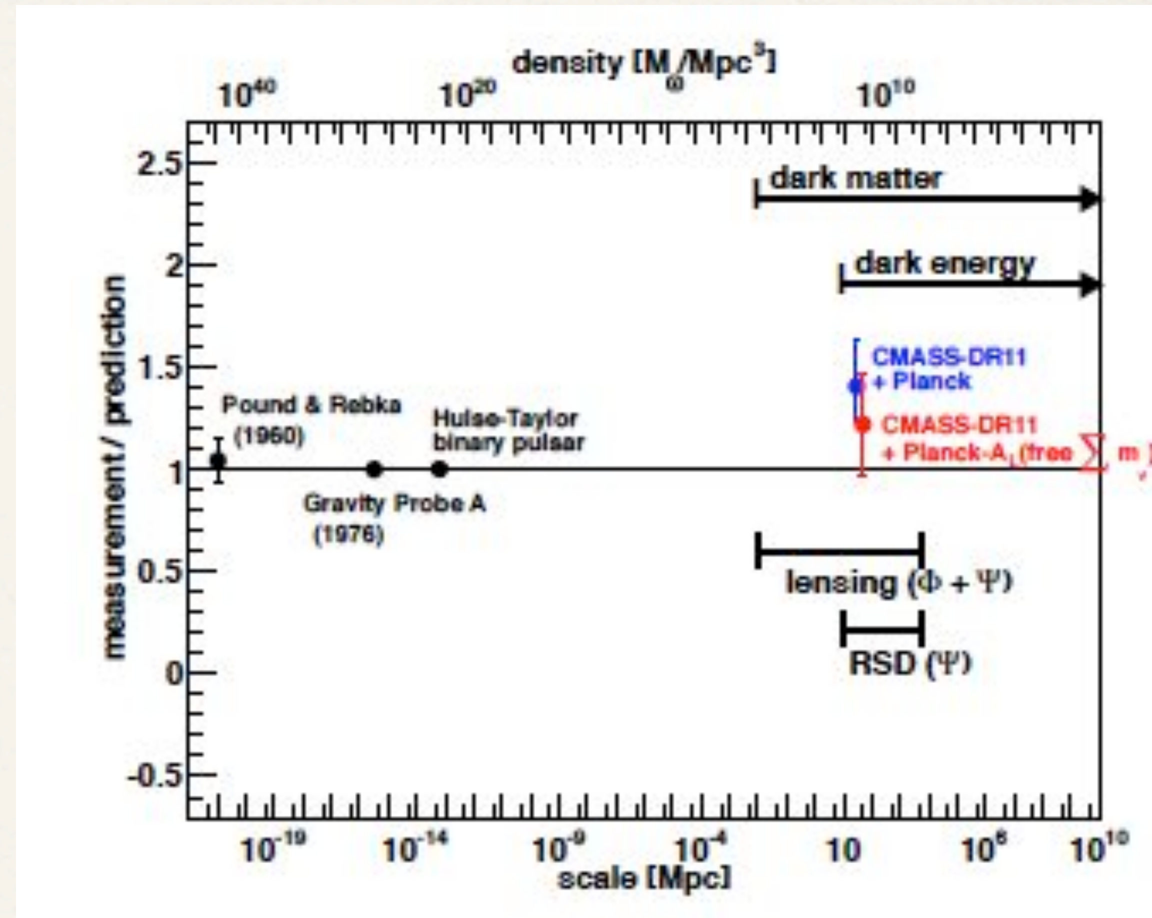




SDSSIII 1403.4599

TESTS OF General Relativity





SDSSIII 1403.4599

$$f \equiv \frac{d\log\delta}{d\log a} \simeq \Omega_m^{\gamma}$$

The LSS mantra

%

... and fast

→ scan over different cosmologies

... not trivial even for N-body

- 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

More General Cosmologies

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

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

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

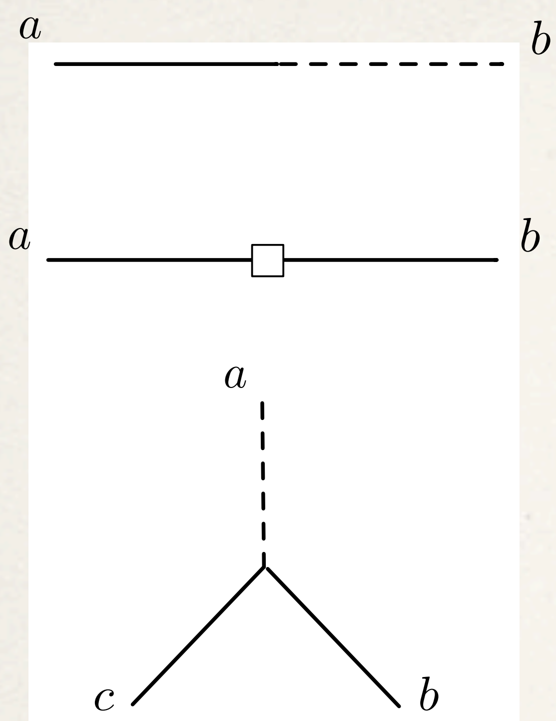
$$\nabla^2\phi = 4\pi G\,(1 + B(\vec{x},\tau))\,\rho\,a^2\,\delta$$

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

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

Ex: Massive neutrinos: $\mathcal{A} = 0 \quad \mathcal{B} \simeq \dfrac{\Omega_\nu \delta_\nu}{\Omega_c \delta_c}$

Beyond Linear Theory: loops

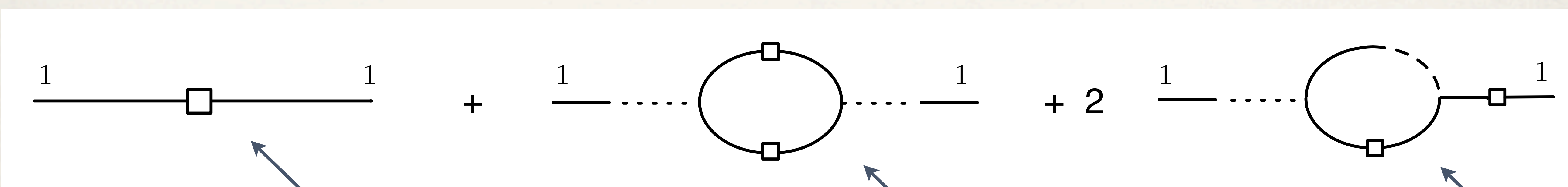


propagator (linear growth factor): $-i\, g_{ab}(\eta_a,\, \eta_b)$

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:



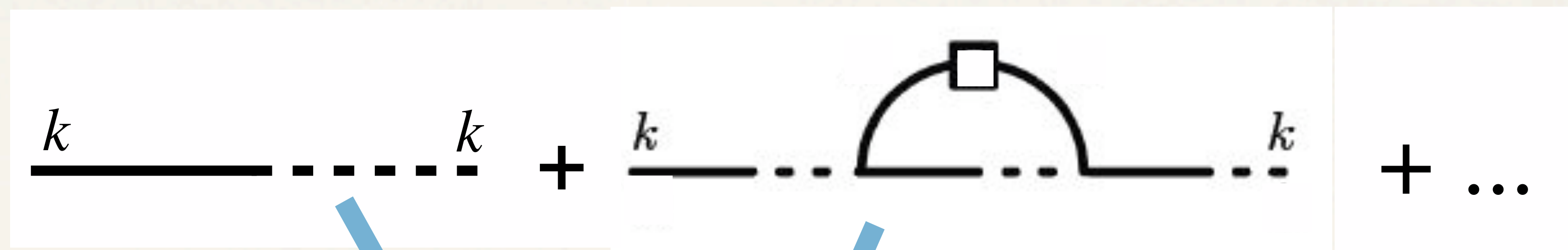
Linear Power spectrum

"P22"

"P13"

PT in the BAO range

1-loop propagator
@ large k:



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

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

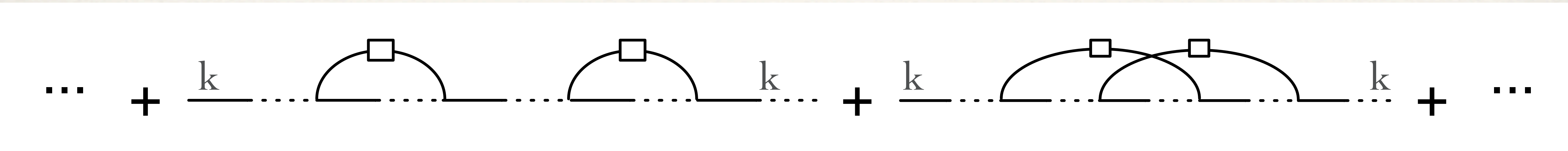
$(\sigma\, e^{\eta_a})^{-1} \simeq 0.15\,\mathrm{h\,Mpc}^{-1}$
in the BAO range!

2-loop

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

Partial list of contributors

<u>"traditional" P.T.</u>:
see Bernardeau et al, Phys. Rep. 367, 1, (2002), and refs. therein; Jeong-Komatsu; Saito et al; Sefusatti;...

<u>resummation methods</u>:
Valageas; Crocce-Scoccimarro; McDonald; Matarrese-M.P.; Matsubara; Anselmi-M.P.; Taruya-Hiratamatsu; Bernardeau-Valageas; Bernardeau-Crocce-Scoccimarro; Tassev-Zaldarriaga,...

Physical meaning of the IR resummation

$$\frac{\partial}{\partial\tau}\delta_\alpha(\mathbf{x},\tau)+\frac{\partial}{\partial x^i}[(1+\delta_\alpha(\mathbf{x},\tau))v^i_\alpha(\mathbf{x},\tau)]=0\,,$$

$$\mathbf{v}_\alpha(\mathbf{x},\tau)=\mathbf{v}_{\alpha,\mathrm{short}}(\mathbf{x},\tau)+\mathbf{v}_{\alpha,\mathrm{long}}(\mathbf{x},\tau)$$

$$\frac{\partial}{\partial\tau}\delta_\alpha(\mathbf{x},\tau)+\frac{\partial}{\partial x^i}[(1+\delta_\alpha(\mathbf{x},\tau))v^i_{\alpha,\mathrm{short}}(\mathbf{x},\tau)]+v^i_{\alpha,\mathrm{long}}(\mathbf{x},\tau)\frac{\partial}{\partial x^i}\delta_\alpha(\mathbf{x},\tau)\simeq 0$$

$$\bar\delta_\alpha(\mathbf{x},\tau)=\delta_\alpha(\mathbf{x}-\mathbf{D}_\alpha(\mathbf{x},\tau),\tau)$$

$$\mathbf{D}_\alpha(\mathbf{x},\tau)\equiv\int_{\tau_{in}}^{\tau}d\tau'\mathbf{v}_{\alpha,\mathrm{long}}(\mathbf{x},\tau')\simeq\mathbf{D}_\alpha(\tau)$$

$$\frac{\partial}{\partial\tau}\bar\delta_\alpha(\mathbf{x},\tau)+\frac{\partial}{\partial x^i}[(1+\bar\delta_\alpha(\mathbf{x},\tau))v^i_{\alpha,short}(\mathbf{x},\tau)]\simeq 0$$

similar for the Euler equation!
(Extended Galilean Invariance)

$$\langle\delta_\alpha(\mathbf{k},\tau)\delta_\alpha(\mathbf{k}',\tau')\rangle=\langle\bar\delta_\alpha(\mathbf{k},\tau)\bar\delta_\alpha(\mathbf{k}',\tau')\rangle\langle e^{-i\mathbf{k}\cdot(\mathbf{D}_\alpha(\tau)-\mathbf{D}_\alpha(\tau'))}\rangle$$
$$=\langle\bar\delta_\alpha(\mathbf{k},\tau)\bar\delta_\alpha(\mathbf{k}',\tau')\rangle e^{\frac{-k^2\sigma_v^2(D(\tau)-D(\tau'))^2}{2}}$$

$$\sigma_v^2=-\frac{1}{3}\int^\Lambda d^3q\langle v^i_{in}(q)v^i_{in}(q)\rangle'$$

Resummations take into account the
Large scale bulk motions

Consistency Relations for the LSS

M. Peloso, M.P. 1302.0223/1310.7915
A. Kehagias, A. Riotto et al 1302.0130
Creminelli et al. 1309.3557
P. Valageas 1311.1236
....

$$\mathrm{v}_\alpha(\mathrm{x},\tau) = \mathrm{v}_{\alpha,\mathrm{short}}(\mathrm{x},\tau) + \mathrm{v}_{\alpha,\mathrm{long}}(\mathrm{x},\tau)$$

$$\bar{\delta}_\alpha(\mathrm{x},\tau) = \delta_\alpha(\mathrm{x} - \mathbf{D}_\alpha(\mathrm{x},\tau),\tau)$$

$$\mathrm{D}_\alpha(\mathrm{x},\tau) \equiv \int_{\tau_{in}}^{\tau} d\tau' \mathrm{v}_{\alpha,\mathrm{long}}(\mathrm{x},\tau') \simeq \mathbf{D}_\alpha(\tau)$$

the effect of a long wavelength (time dependent) velocity mode can be exactly reabsorbed by a change of coordinates in the uniform limit

$$\lim_{k \ll q} B_{abc}^{L,S,S}(k, q, |\mathbf{q}+\mathbf{k}|; \eta, \eta', \eta'') = \frac{\mathbf{k}\cdot\mathbf{q}}{k^2} P_{bc}(q;\eta',\eta'')\, u_2 u_a\, P^0(k) \left(\mathrm{e}^{\eta'} - \mathrm{e}^{\eta''}\right)$$

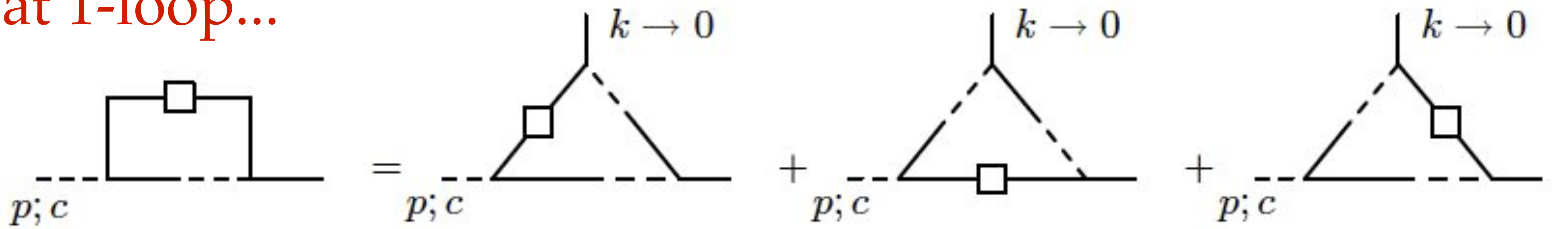
<u>exact</u> relations between N and N+1 point function in the soft limit

extension to multi-species (velocity bias)
and non-gaussian initial conditions
(Peloso, M.P. 1310.7915)

Ward identities

$$G^{-1}_{cb}(p;\eta'',\eta')\,\mathbf{p}\cdot\mathbf{w}\,\left(e^{\eta'}-e^{\eta''}\right) + \int d\eta\, d^3\mathbf{k}\,\mathbf{k}\cdot\mathbf{w}\;\delta_D(\mathbf{k})\,\Gamma^{\chi\varphi\varphi}_{cb2}(-\mathbf{p}-\mathbf{k},\mathbf{p},\mathbf{k};\eta'',\eta',\eta) = 0$$

at 1-loop...



Non-trivial checks for resummation schemes

Peloso, M.P.

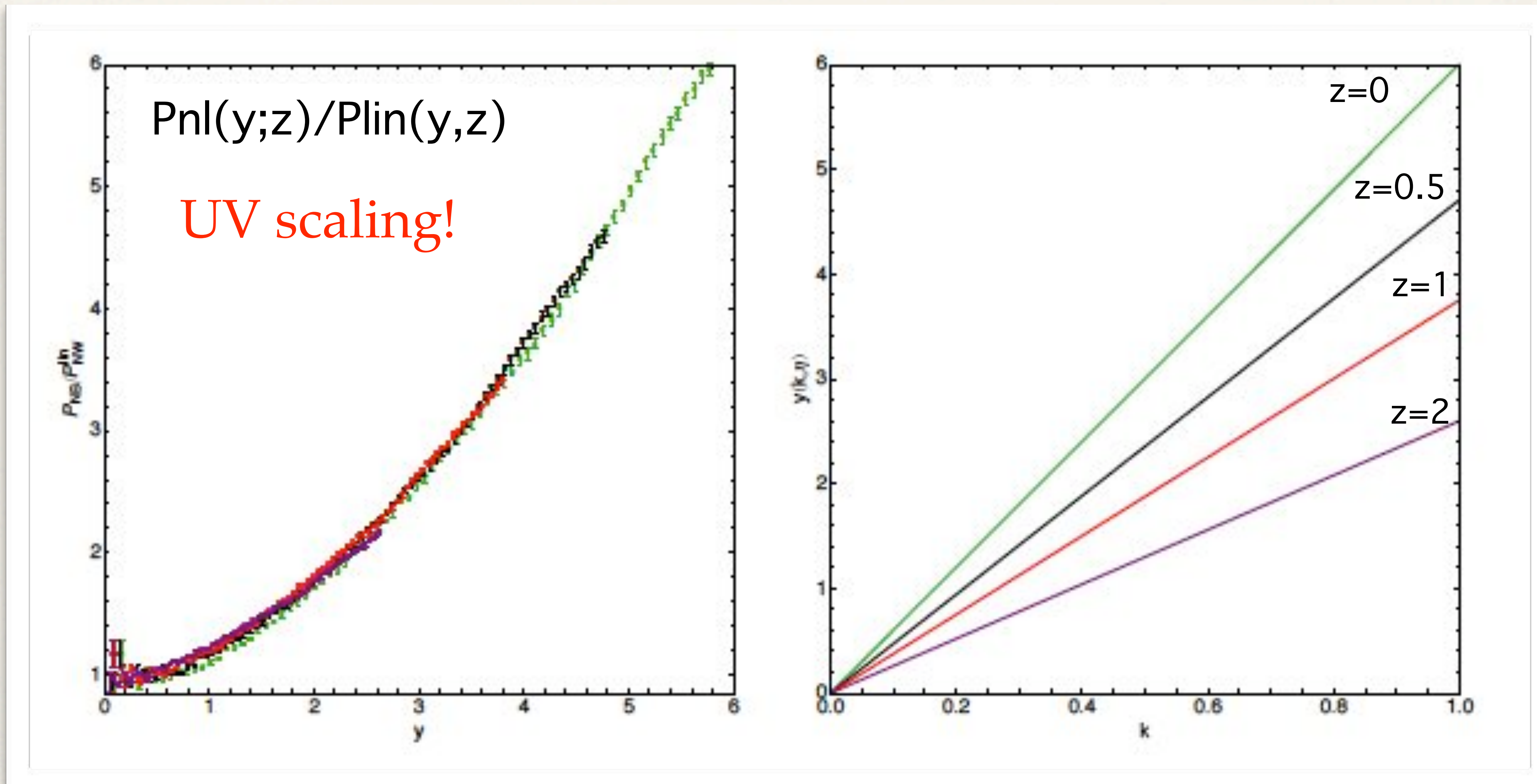
A consistent resummation scheme

The large k regime for the PS

Anselmi, MP, 1205.2235

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

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

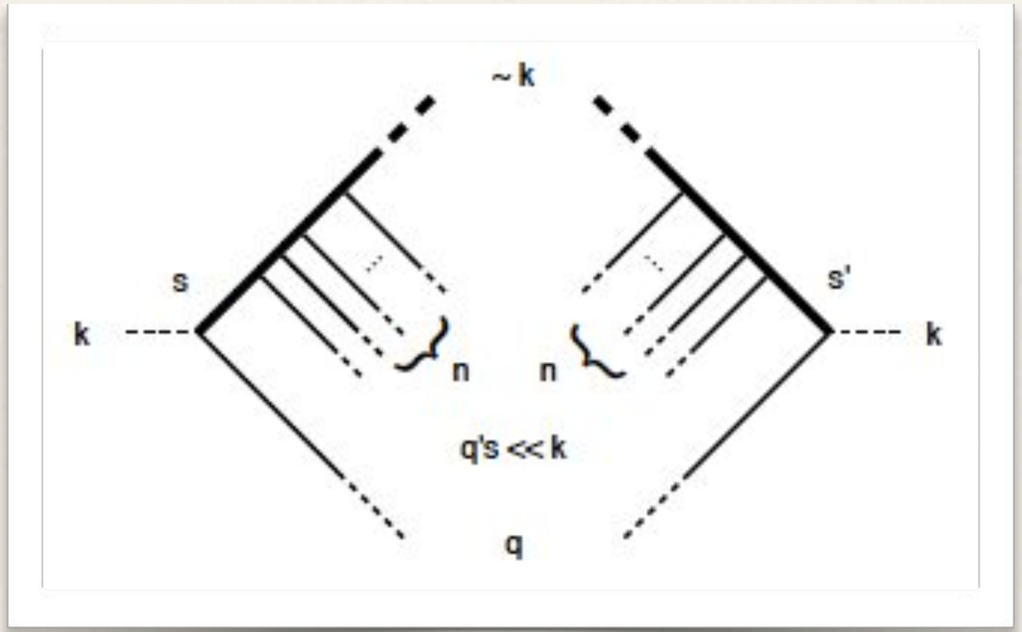


The non-linear PS is y-dependent too. resummation possible !!

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

large k

leading contributions to Phi:

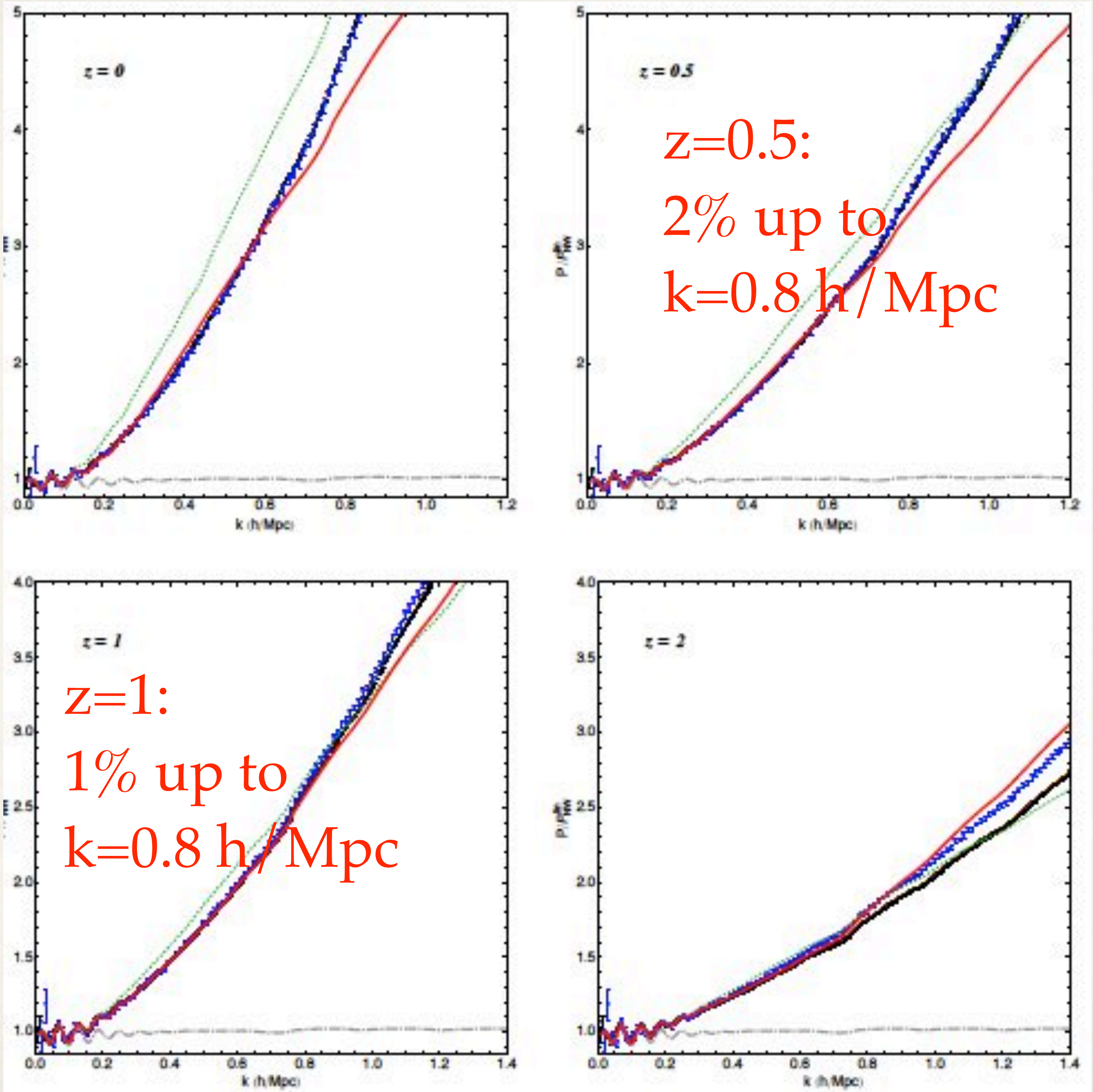


1 "hard" loop momentum, n-1 "soft" ones

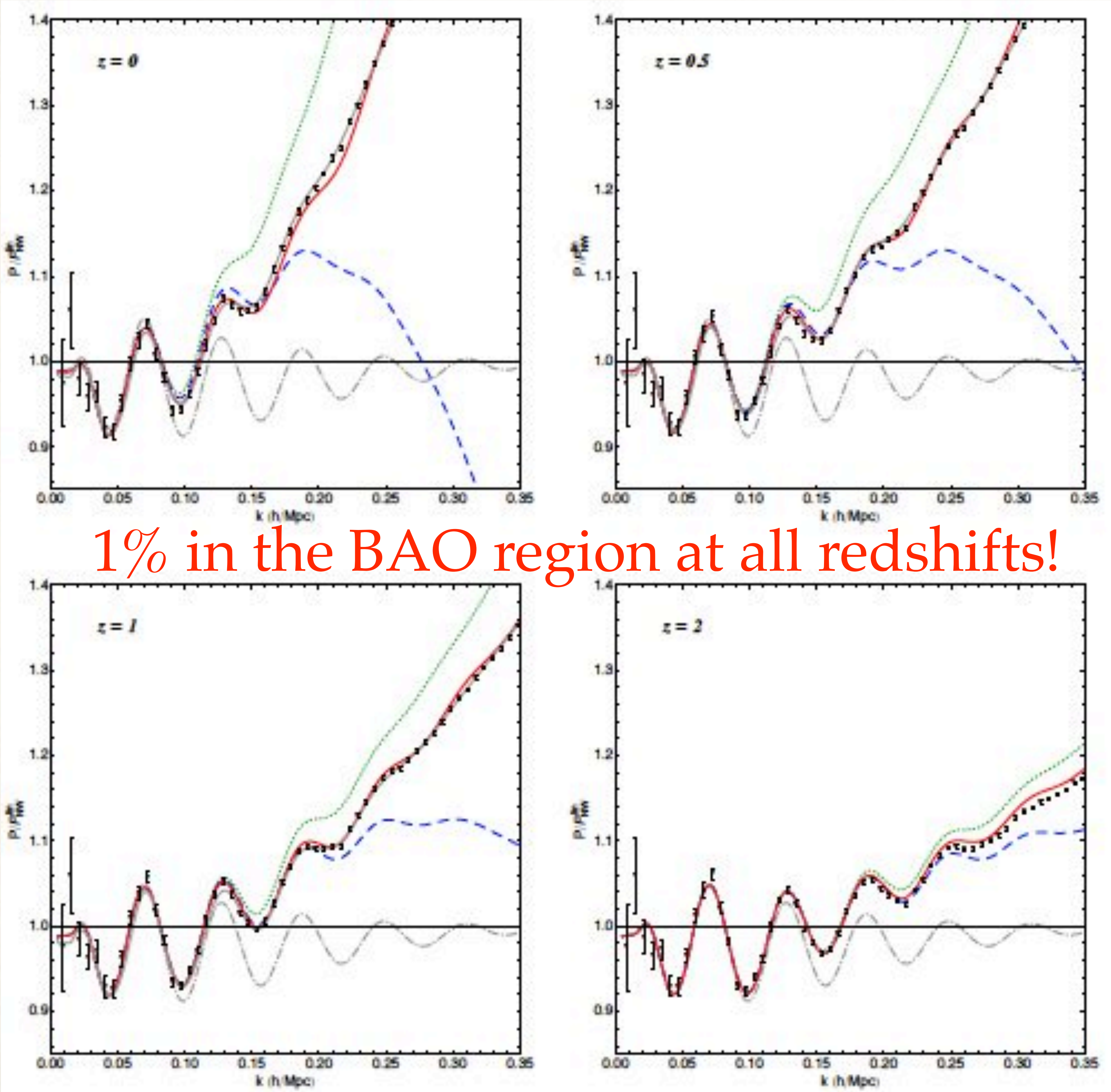
$$\tilde{\Phi}_{ab}(k;s,s') \to e^{-\frac{k^2\sigma_v^2}{2}(e^s-e^{s'})^2}\left[\Phi^{(1)}_{ab}(k;s,s') + \left(k^2\sigma_v^2\, e^{s+s'}\right)^2 P(k)u_a u_b\right]$$

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

large k

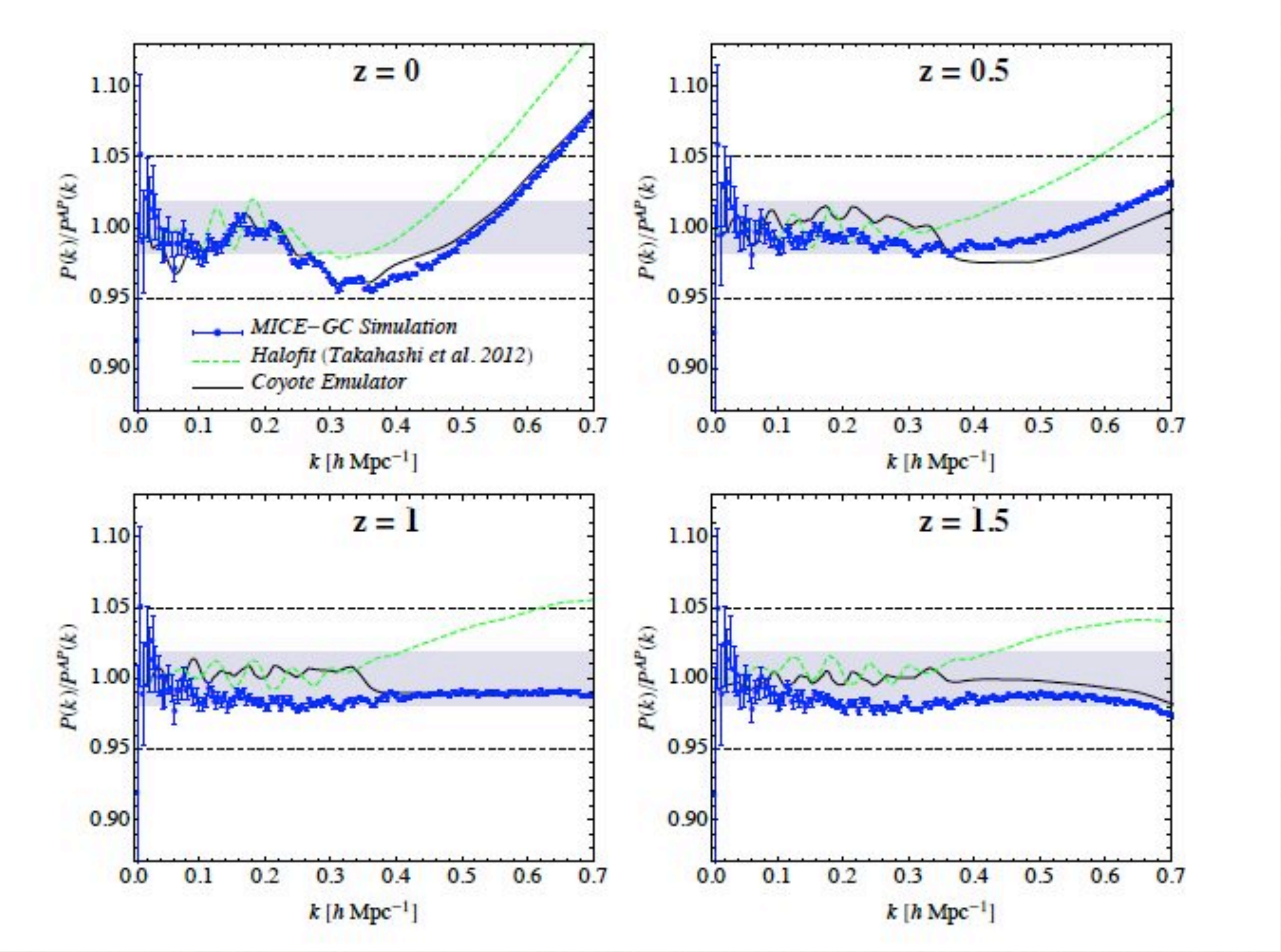


BAO scales



1% in the BAO region at all redshifts!

~% agreement with MICE simulation



Anselmi, Lopez-Nacir, Sefusatti, 2014

Practical Implementation

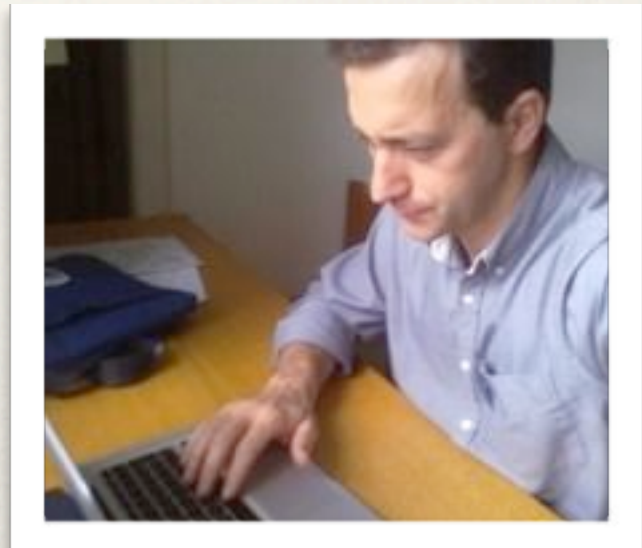
- linear PS at zin
- compute 5 momentum integrals:

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

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

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

O(1 min) for PS at all z



Conclusions, Future work

- The precision cosmology program is moving from the CMB to the LSS
- O(%) is the goal both for theory and observations
- N-body simulations should not be left alone: resolution, transients, non-standard cosmologies, neutrinos, ...
- Semi-analytical schemes close to the goal: non-perturbative non-trivial checks available (consistency relations, Ward identities)
- More non-linearities ahead: redshift space distortions, bias.