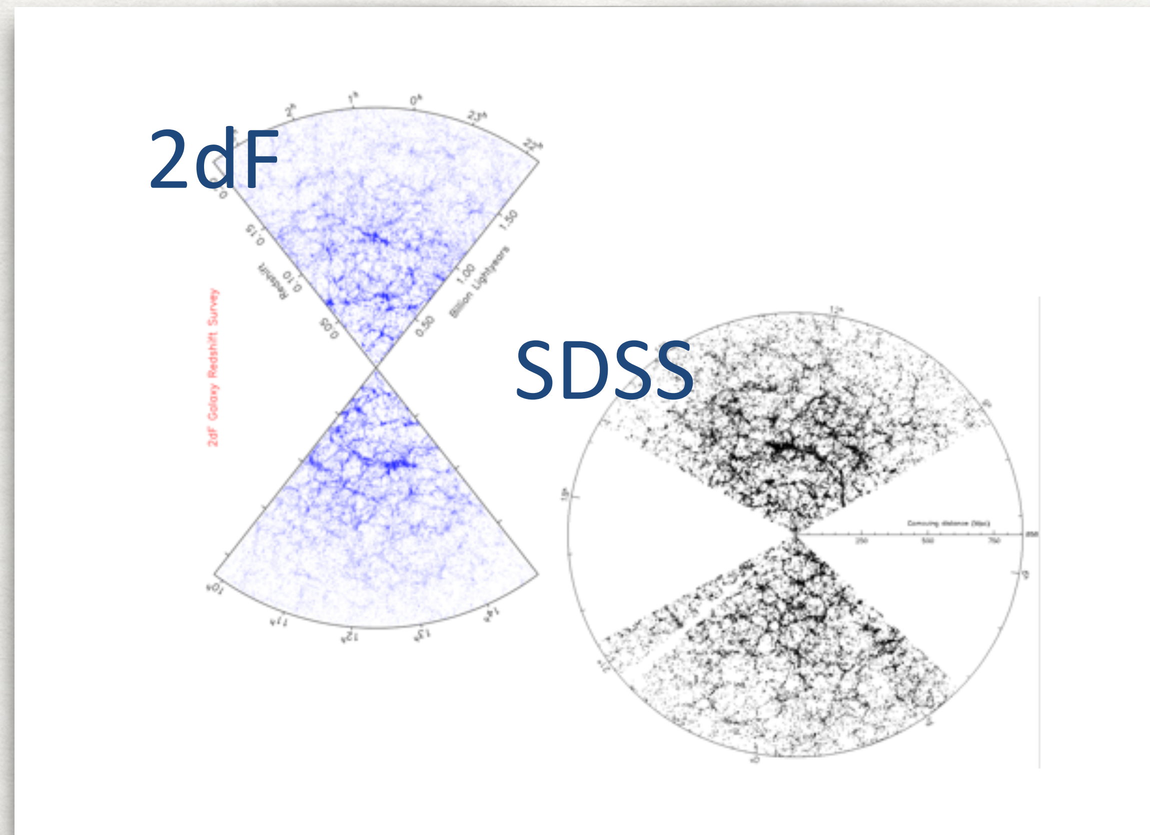
A ROBUST BAO EXTRACTOR: FROM THEORY TO DATA

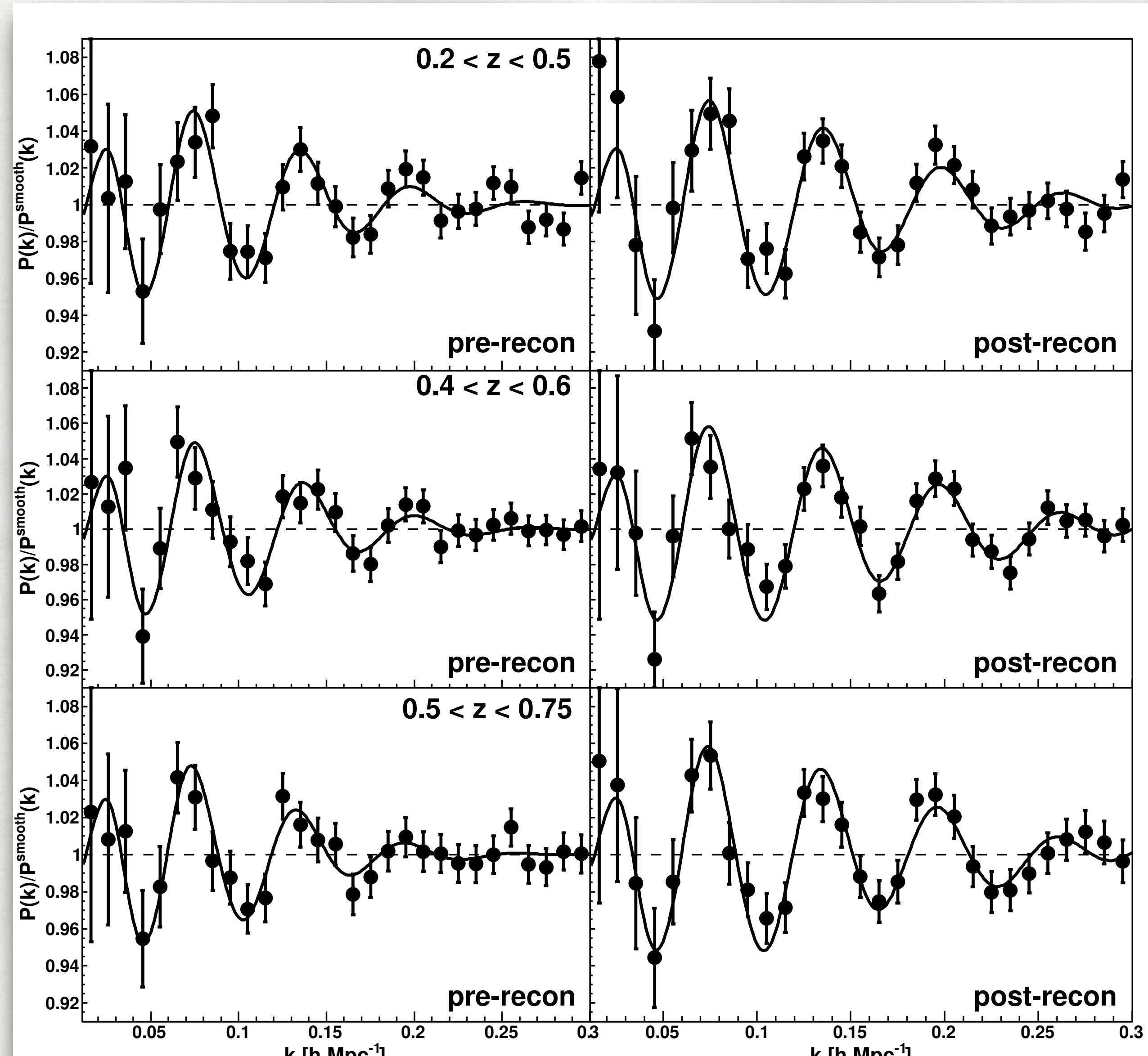
M. Pietroni, University of Parma and INFN-Padova

based on
JCAP 1708 (2017) no.08, 007
JCAP 1801 (2018) no.01, 035
with

Takahiro Nishimichi
Eugenio Noda
Marco Peloso

A TALK ABOUT LARGE SCALE STRUCTURES …





Beutler et al. 2016

… BUT ALSO ABOUT MODIFICATIONS OF GR!

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NGr

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NGr = (Newtonian Gravity)

COARSE-GRAINED VLASOV EQUATION

$$\left[\frac{\partial}{\partial\tau}+\frac{p^i}{am}\frac{\partial}{\partial x^i}-am\frac{\partial\,\phi_{mic}}{\partial x^i}\frac{\partial}{\partial p^i}\right]f_{mic}(\mathbf{x},\mathbf{p},\tau)=0$$

window function

$$f(\mathbf{x},\mathbf{p},\tau)=\int d^3y\,W\left[y/R\right]f_{mic}(\mathbf{x}+\mathbf{y},\mathbf{p},\tau)$$

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

$$am\left[\langle\frac{\partial\phi_{mic}}{\partial x^i}\frac{\partial f_{mic}}{\partial p^i}\rangle_R-\frac{\partial\phi}{\partial x^i}\frac{\partial f}{\partial p^i}\right](\mathbf{x},\mathbf{p},\tau)$$

No divergences from shell-crossing for R > 0

Physics at scale L insensitive to R in the R/L ->0 limit (to be checked!)

BEYOND PRESSURELESS PERFECTION

$$\frac{\partial}{\partial\tau}\delta(\mathbf{x}) + \frac{\partial}{\partial x^i}\left[(1+\delta(\mathbf{x}))v^i(\mathbf{x})\right] = 0$$

$$\frac{\partial}{\partial\tau}v^i(\mathbf{x}) + \mathcal{H}v^i(\mathbf{x}) + v^k(\mathbf{x})\frac{\partial}{\partial x^k}v^i(\mathbf{x}) = -\nabla_x^i\phi(\mathbf{x}) - \underline{J_\sigma^i(\mathbf{x}) - J_1^i(\mathbf{x})}$$

$$\nabla^2\phi(\mathbf{x}) = \frac{3}{2}\Omega_M\mathcal{H}^2\delta(\mathbf{x})$$

Exact dynamics,
including shell-crossing

Need input on the UV
"sources"

$$J_\sigma^i(\mathbf{x}) \equiv \frac{1}{n(\mathbf{x})}\frac{\partial}{\partial x^k}(n(\mathbf{x})\sigma^{ki}(\mathbf{x}))$$

$$J_1^i(\mathbf{x}) \equiv \frac{1}{n(\mathbf{x})}\left(\langle n_{mic}\nabla^i\phi_{mic}\rangle(\mathbf{x}) - n(\mathbf{x})\nabla^i\phi(\mathbf{x})\right)$$

UV INFORMATION ?

Need input on the UV "sources"

$$J^i_\sigma(\mathbf{x}) \equiv \frac{1}{n(\mathbf{x})}\frac{\partial}{\partial x^k}(n(\mathbf{x})\sigma^{ki}(\mathbf{x}))$$

$$J^i_1(\mathbf{x}) \equiv \frac{1}{n(\mathbf{x})}\left(\langle n_{mic}\nabla^i\phi_{mic}\rangle(\mathbf{x}) - n(\mathbf{x})\nabla^i\phi(\mathbf{x})\right)$$

Measure them from N-body simulations

(MP, Mangano, Saviano, Viel 1108.5203, Manzotti, Peloso, MP, Viel, Villaescusa-Navarro 1407.1342)

EFToLSS: Expand in terms of long wavelength fields + power law expansion in momentum, with arbitrary coefficients to be fitted

(Carrasco, Hertzberg, Senatore, 1206.2926 ….)

Compute them from first principles. Shell-crossing!

1+1 dim attempts

(Mc Quinn, White, 1502.07389; Taruya, Colombi, 1701.09088; Rampf, Frisch, 1705.08456; McDonald, Vlah, 1709.02834, Pajer, van der Woude, 1710.01736…)

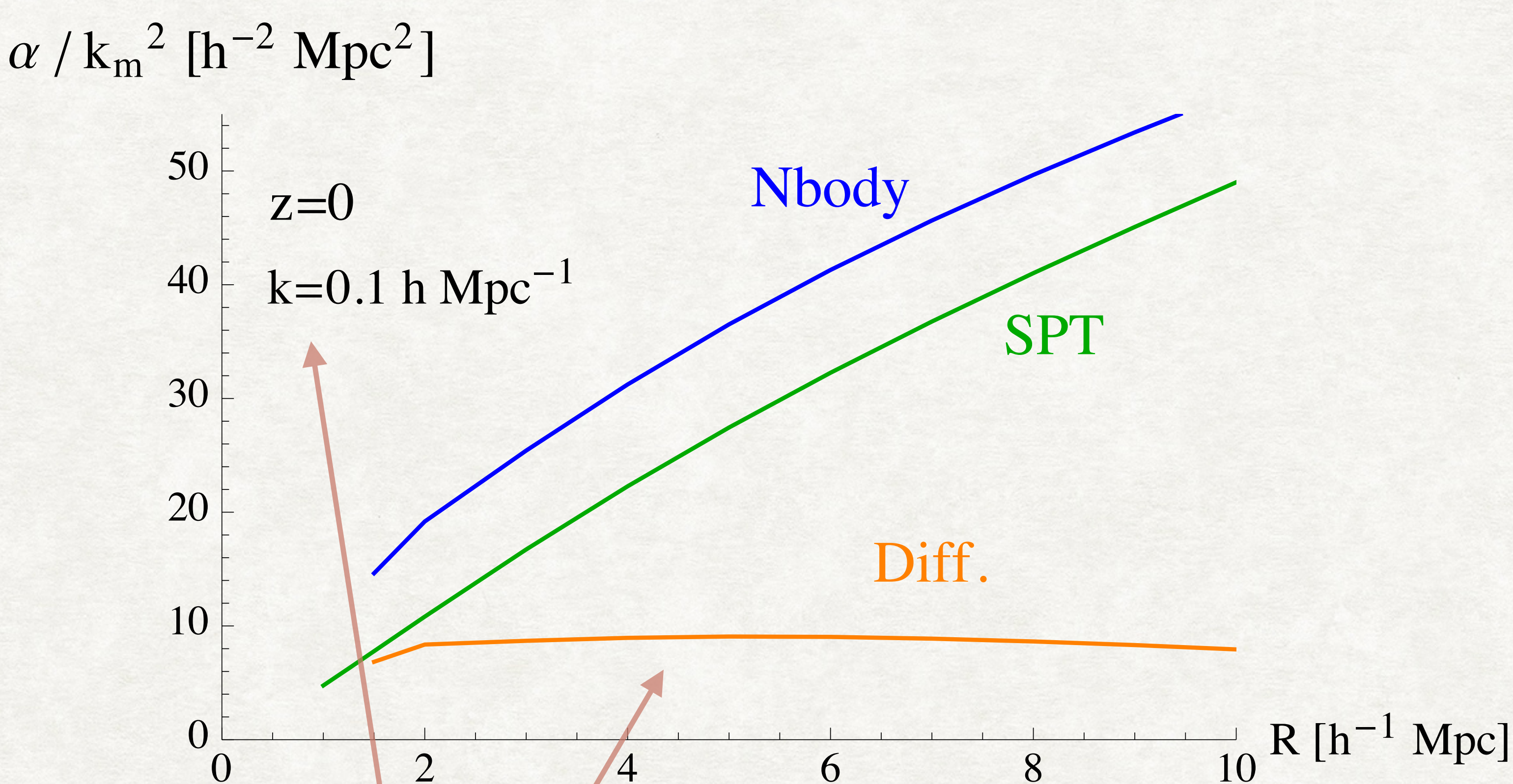
UV SOURCES FROM N-BODY

$$\langle k^i J^i_\sigma(\mathbf{k})\delta(-\mathbf{k})\rangle'_{nb} \propto \alpha_{nb}\frac{k^2}{k_m^2}\langle\delta(-\mathbf{k})\delta(-\mathbf{k})\rangle_{nb}$$

shell crossing,
fully non-linear

$$\langle k^i J^i_\sigma(\mathbf{k})\delta(-\mathbf{k})\rangle'_{pt} \propto \alpha_{pt}\frac{k^2}{k_m^2}\langle\delta(-\mathbf{k})\delta(-\mathbf{k})\rangle_{pt}$$

no shell crossing,
non-linearities up to PT order



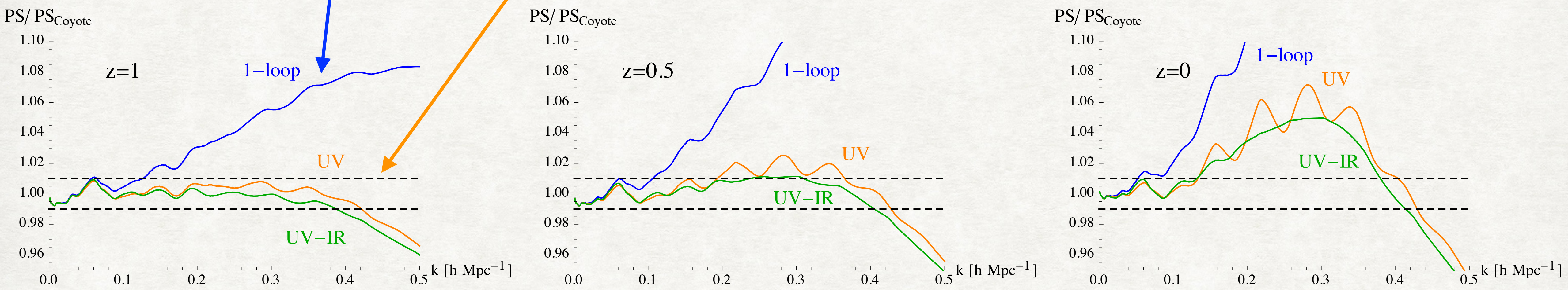
independent on the UV cutoff

("cosmology independent" 1407.1342)

1-LOOP PT + UV

$$P^R_{ab}(k) \simeq \underline{P^{R,1-loop}_{ab}(k) + \Delta P^{R,1-loop}_{ab}(k)}$$

in the R->0 limit
(in practice, on the plateau)

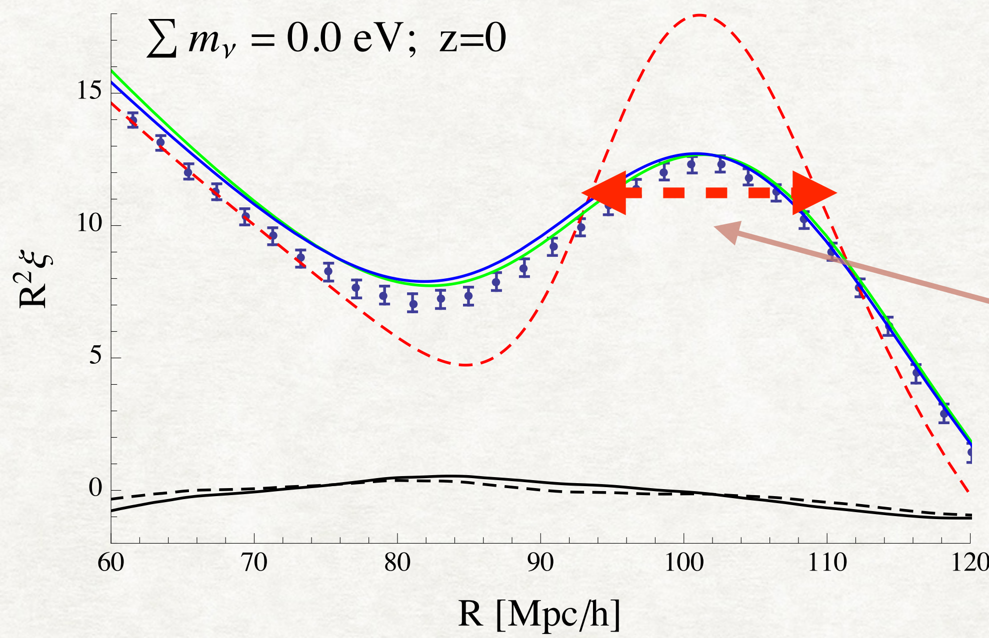


no fitting on the PS

next order: 2-loop PT + $\langle J\,\delta\delta\rangle$ correlators

residual BAO's on the orange curves

BAO ARE LARGELY UV INDEPENDENT



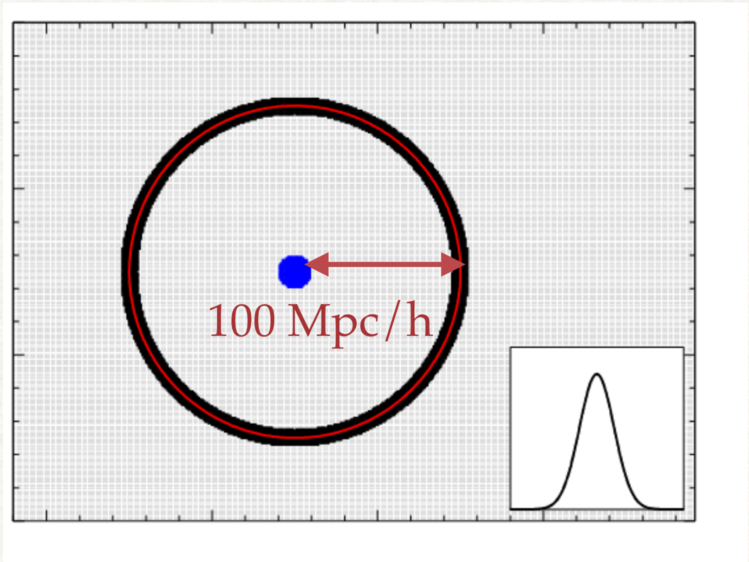
BAO: peak in the corr. function at ~100 Mpc/h

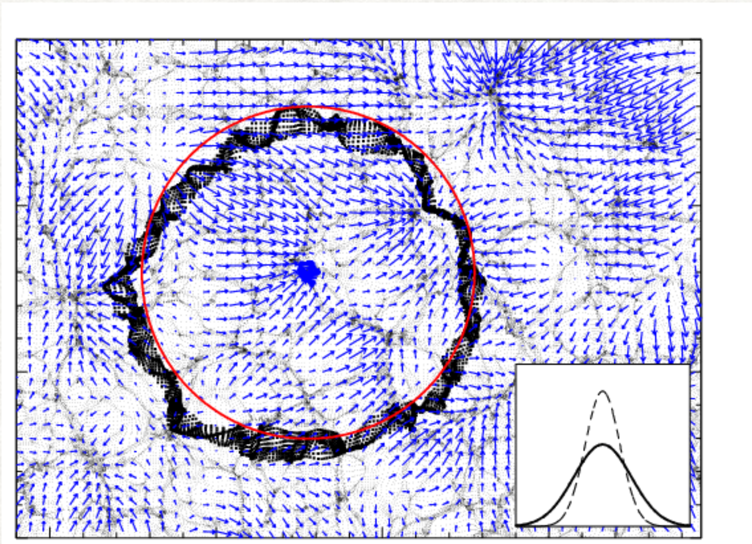
very linear!

width of the linear peak ~ 20 Mpc/h

quasi linear!

Largest nonlinear (in Eulerian space) effect: random displacements (rms~ 6 Mpc/h)





Padmanabhan et al, 1002.0990

CF: peak broadening,   P(k): damping of the peaks

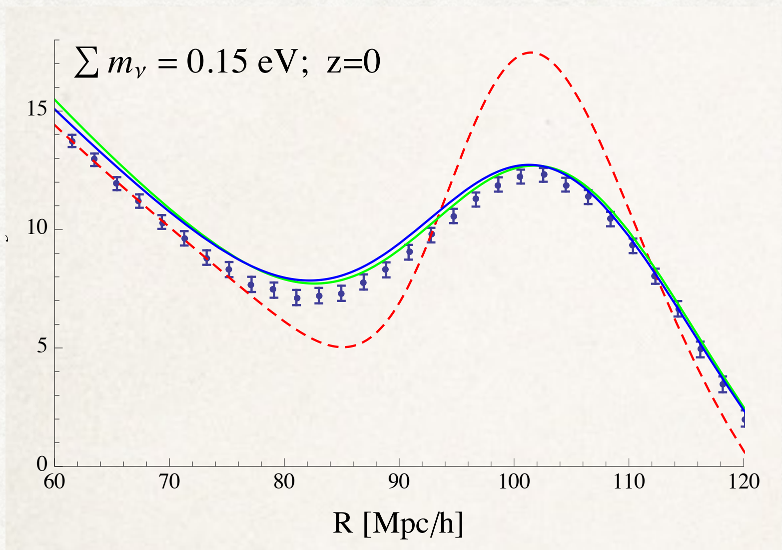
THE BAO DAMPING IS A CONTROLLED PHYSICAL EFFECT!

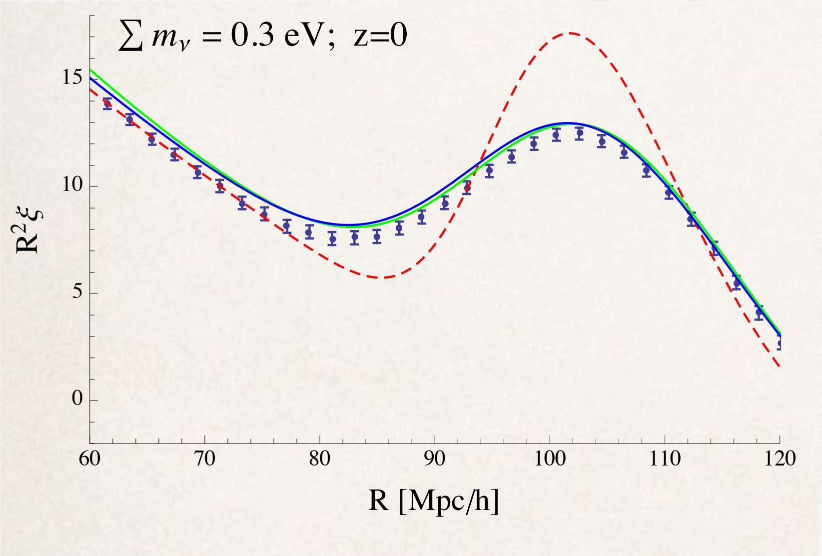
It is largely taken into account in the Zel'dovich approximation:
linear effect in lagrangian space!

It is not a nonlinear "noise" to be marginalised over. It contains physical information!

Ex. Massive neutrinos

(Peloso, MP, Viel, Villaescusa-Navarro 1505.07477)





increasing neutrino masses P(k) decreases, but also velocity dispersion does:

$$\sum m_\nu = 0.15 \quad \text{eV} \qquad \downarrow 0.6\%$$

$$\sum m_\nu = 0.3 \quad \text{eV} \qquad \uparrow 1.2\%$$

CONSISTENCY RELATIONS AND BAO EVOLUTION

evolution equation for P(k)

$$\partial_\eta P^R_{ab}(k) = \Big[-\Omega_{ac} P^R_{cb}(k) + e^\eta I_{\mathbf{k};\mathbf{p}_1,\mathbf{p}_2} \gamma_{acd}(\mathbf{p}_1,\mathbf{p}_2) B^R_{bcd}(k,p_1,p_2) - \langle h^R_a(\mathbf{k}) \varphi^R_b(-\mathbf{k})\rangle' + (a \leftrightarrow b) \Big],$$

UV

$$\langle \varphi_2(\mathbf{q}) \varphi_a(\mathbf{k}-\mathbf{q}) \varphi_b(-\mathbf{k})\rangle' \simeq -e^\eta \frac{\mathbf{k}\cdot\mathbf{q}}{q^2} P^0(q) \left(P_{ab}(k) - P_{ab}(|\mathbf{k}-\mathbf{q}|)\right) + O\left(\left(\frac{q}{k}\right)^0\right)$$

fully nonlinear!!

consistency relations from Galilean invariance
(Peloso, MP 1310.7915)

CONSISTENCY RELATIONS AND BAO EVOLUTION

$$e^{\eta} I_{\mathbf{k},\mathbf{p_1},\mathbf{p_2}} \gamma_{acd} B_{bcd}(k,p_1,p_2) = -2e^{2\eta}\int^{\Lambda(k)} \frac{d^3q}{(2\pi)^3}\left(\frac{\mathbf{k}\cdot\mathbf{q}}{q^2}\right)^2 P^0(q)\,(P_{ab}(k) - P_{ab}(|\mathbf{k}-\mathbf{q}|))$$

$$\simeq -2e^{2\eta}\frac{k^2}{(2\pi)^2}\int^{\Lambda(k)} dq\,P^0(q)\int_{-1}^{1} dx\,x^2\,(P_{ab}(k) - P_{ab}(k-qx)) \quad (*)$$

sensitive to oscillatory features!

if the (nonlinear) P(k) has an oscillatory part: $P_{ab}(k) = P^{nw}_{ab}(k)(1 + A_{ab}(k)\sin(k\,r_{bao})) \equiv P^{nw}_{ab}(k) + P^{w}_{ab}(k)$

then (*) gives $\quad -2e^{2\eta}k^2\,\Xi(r_{bao})P^{w}_{ab}(k) + O\left(P^{nw''}_{ab}\right)$

suppressed as $1/(k^2 r_{bao}^2)$

with $\quad \Xi(r_{bao}) \equiv \dfrac{1}{6\pi^2}\displaystyle\int^{\Lambda(k)} dq\,P^0(q)\,(1 - j_0(q\,r_{bao}) + 2j_2(q\,r_{bao}))$

Physically: large scale displacement act predominantly on P(k) (or CF) *features*

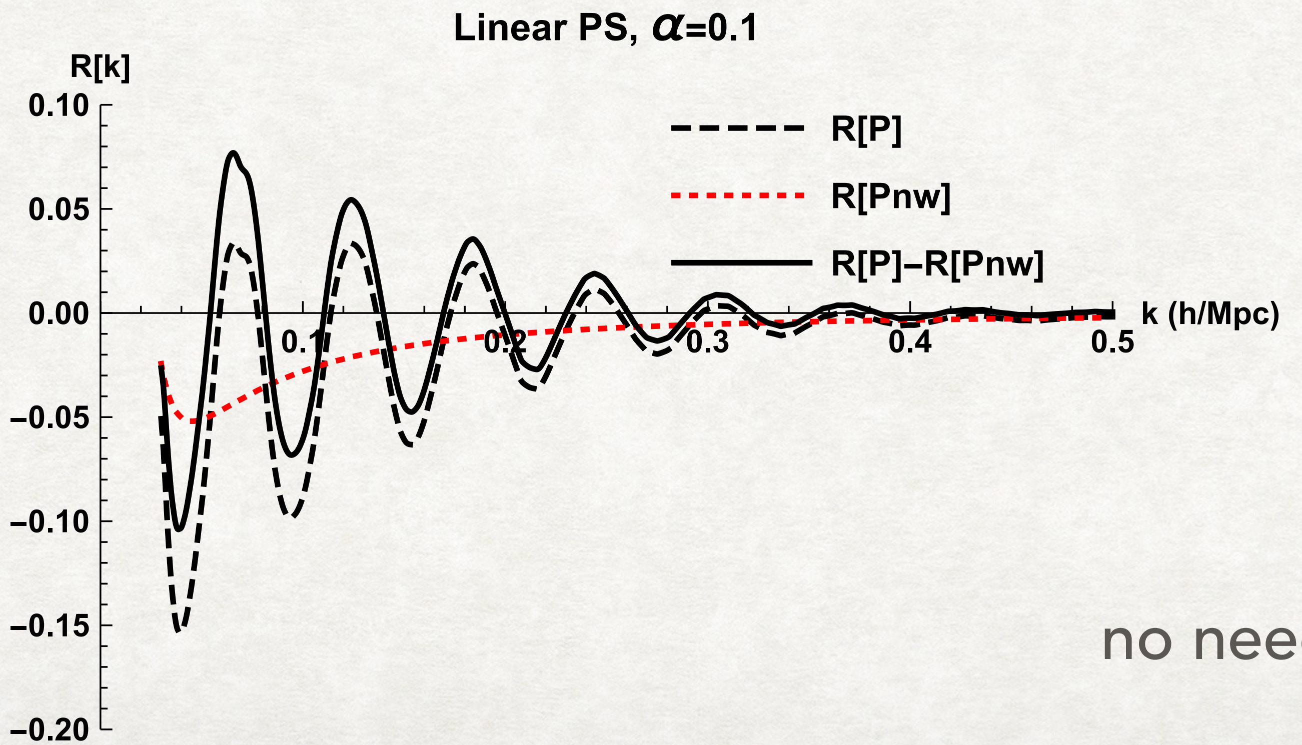
TWO BENEFITS

1) A nonlinear evolution equation for the oscillating part of P(k)
(including subdominant UV effects)

2) A tool to extract the BAO feature from a given (nonlinear) P(k)

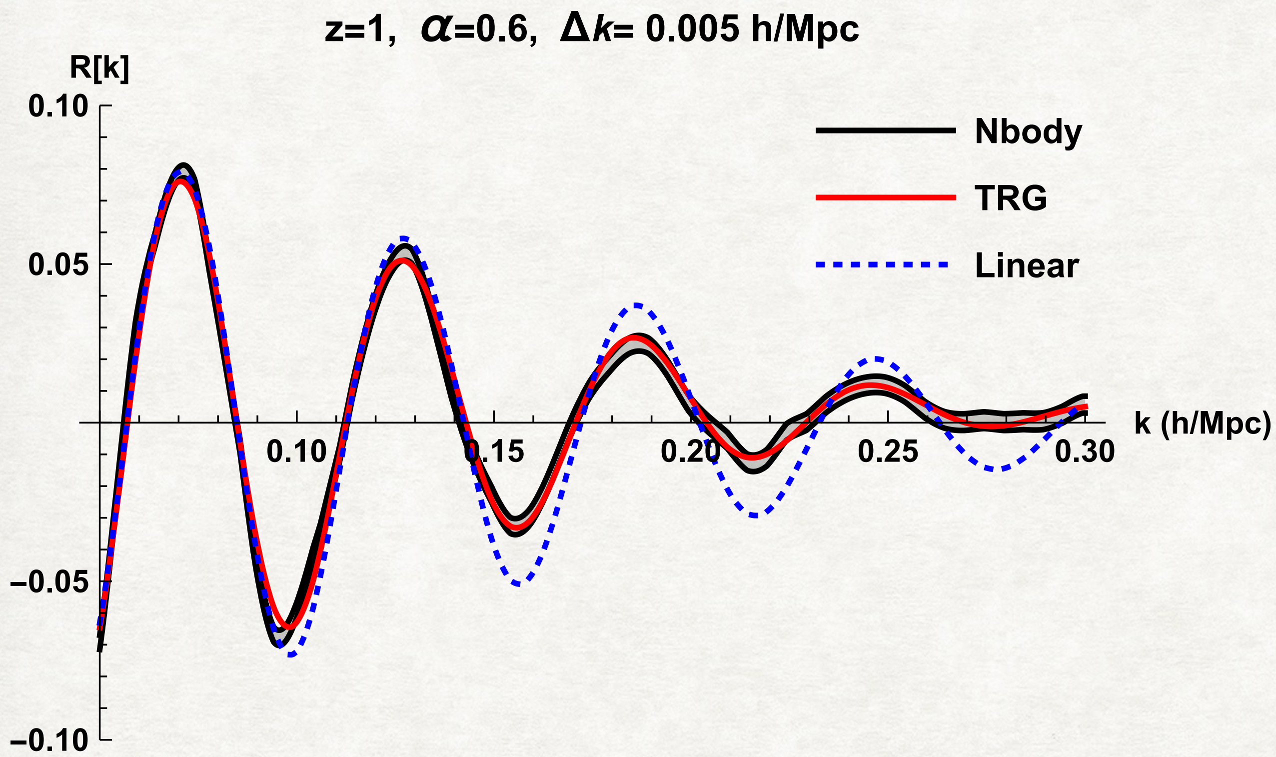
$$R\left[P\right](k;\Delta,\,n)\equiv\frac{\int_{-\Delta}^{\Delta}dx\,x^{2n}\left(1-\frac{P(k-x\,k_s)}{P(k)}\right)}{\int_{-\Delta}^{\Delta}dx\,x^{2n}\left(1-\cos(2\pi x)\right)}\qquad k_s\equiv 2\pi/r_s,$$

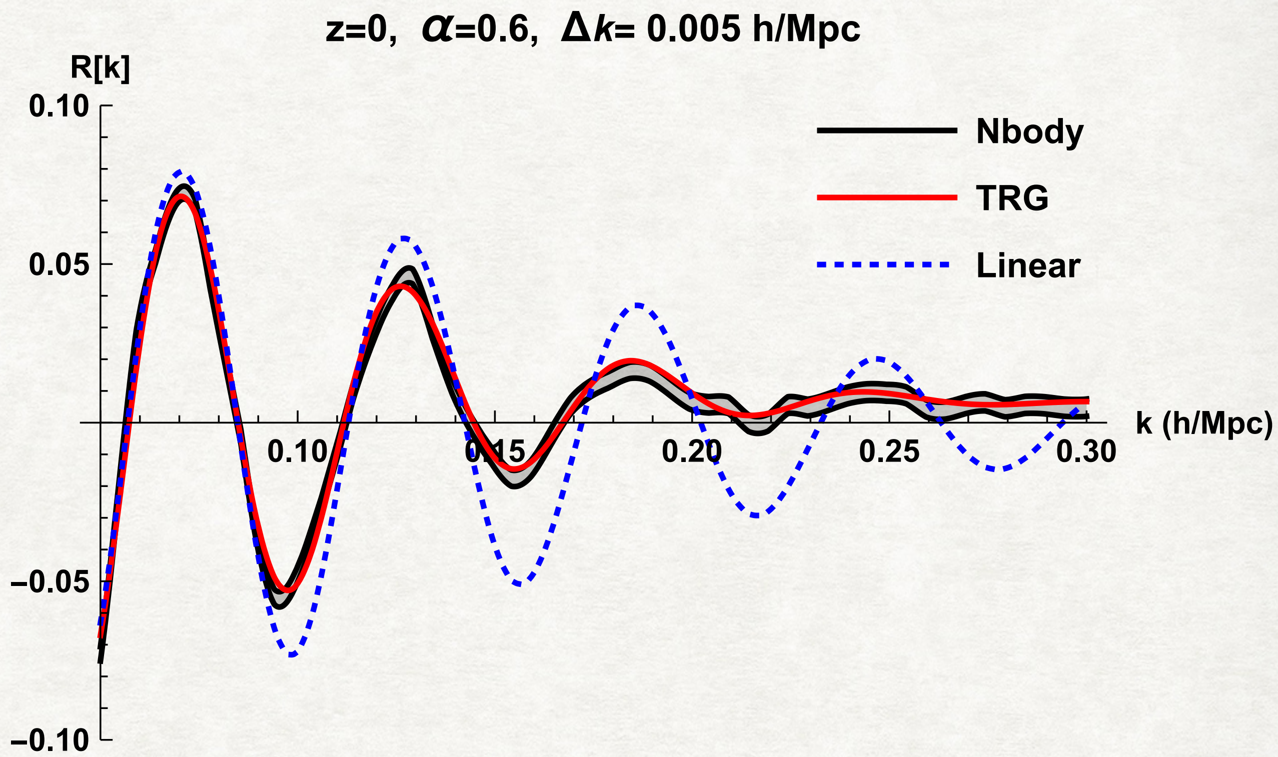
BAO extractor



no need of "nw" fitting functions

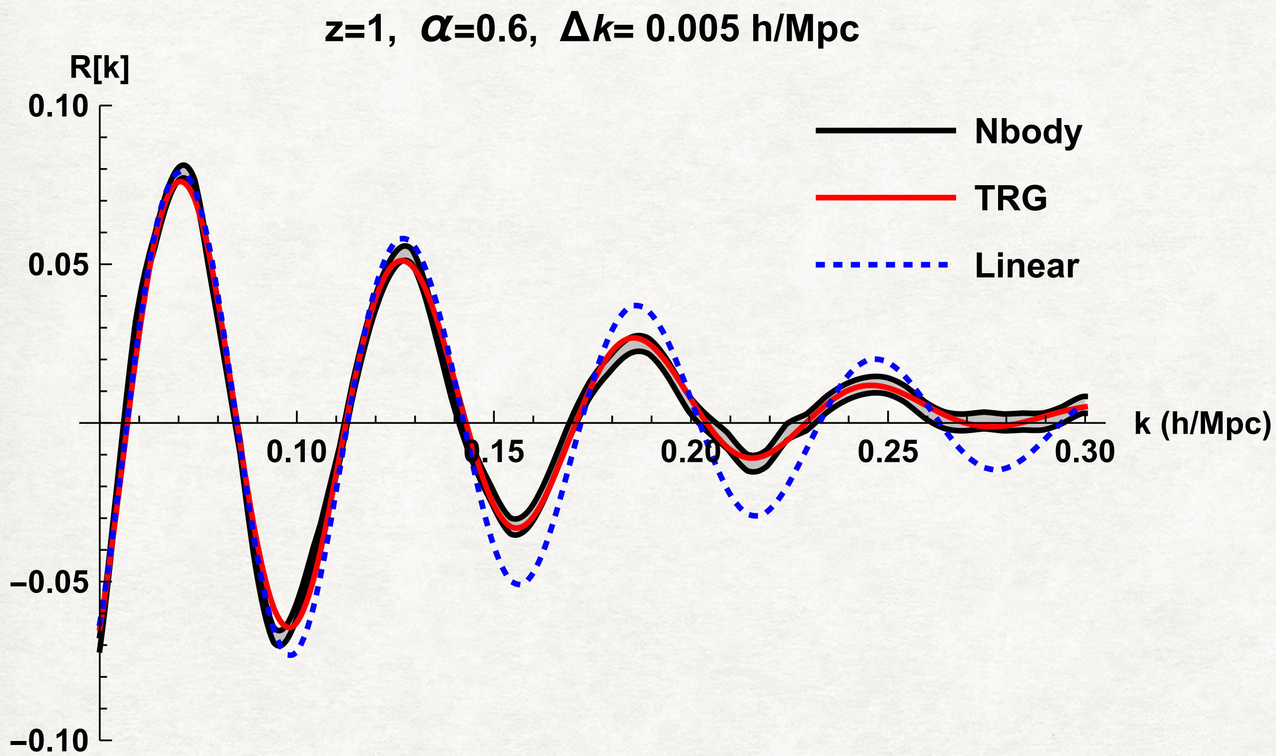
IR+UV EVOLUTION OF BAO

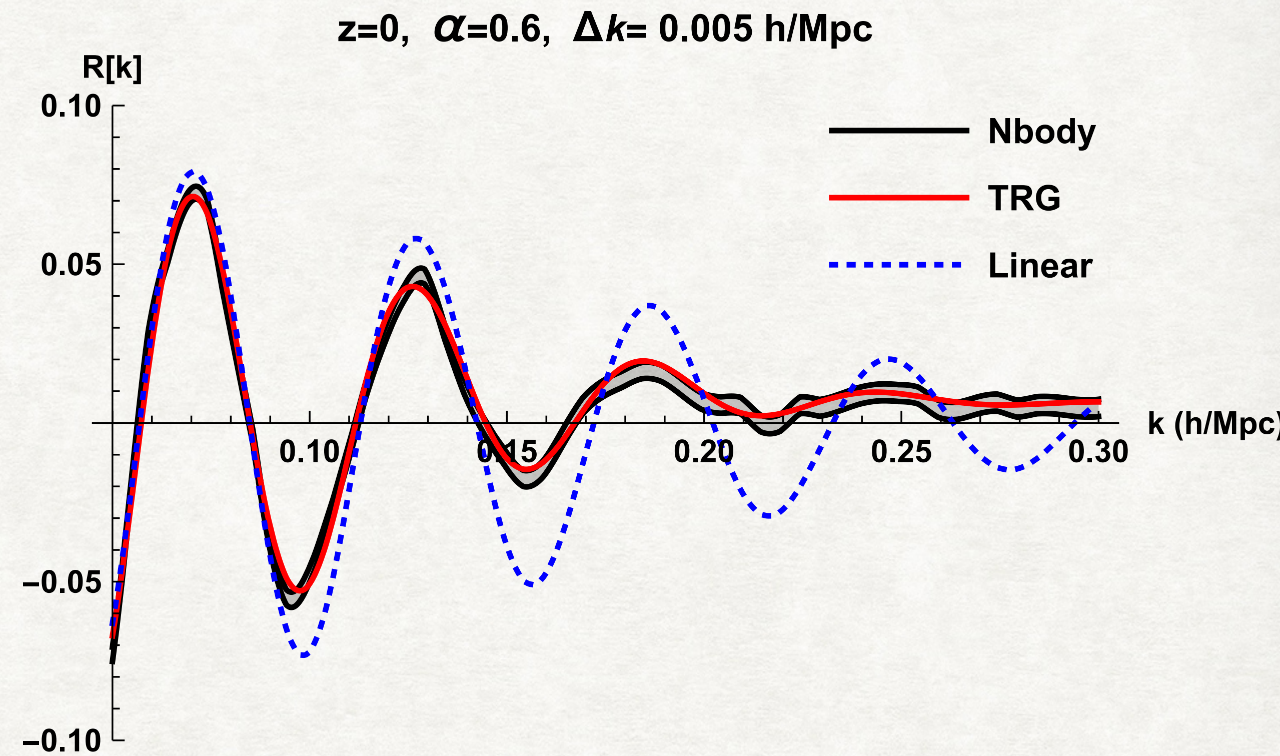




BAO's match with N-body at all scales down to z=0!

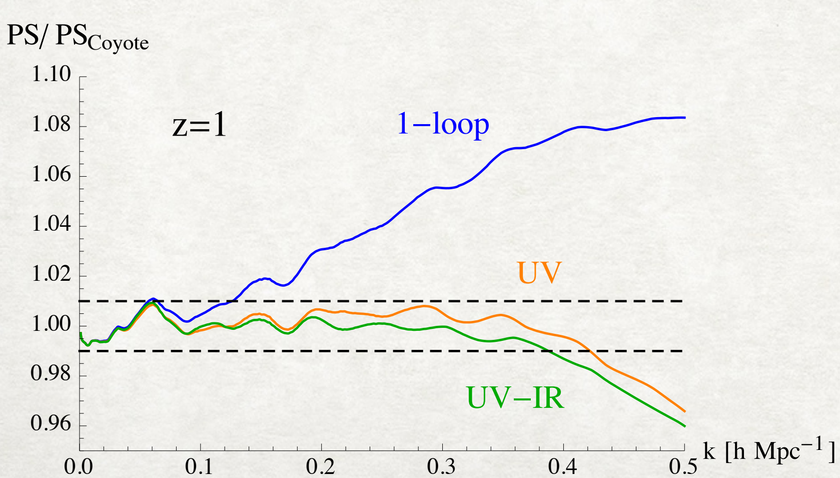
IR+UV EVOLUTION OF BAO

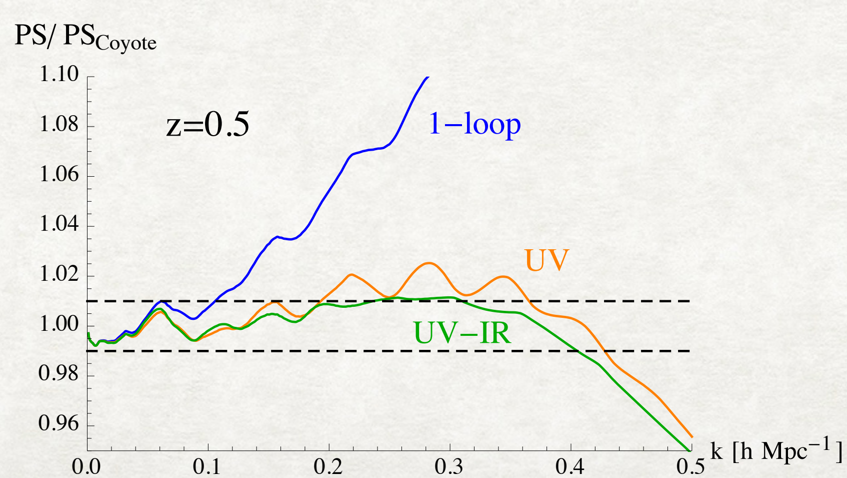


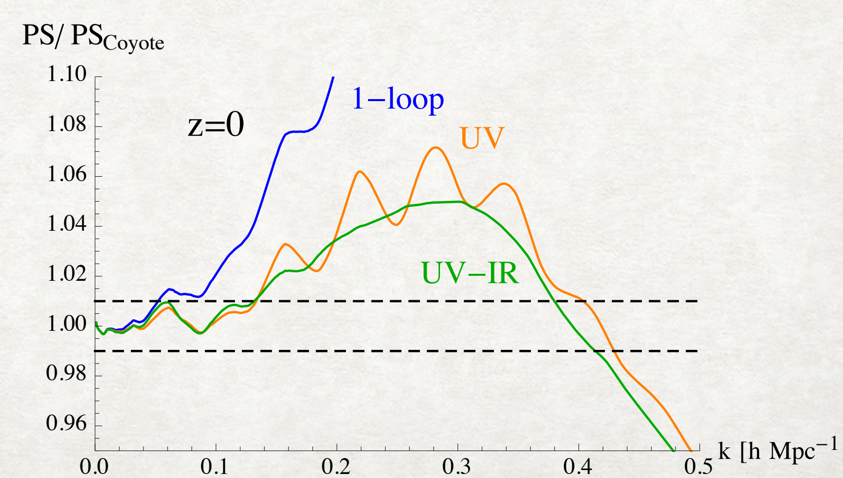


BAO's match with N-body at all scales down to z=0!

compare with results for the broadband shape





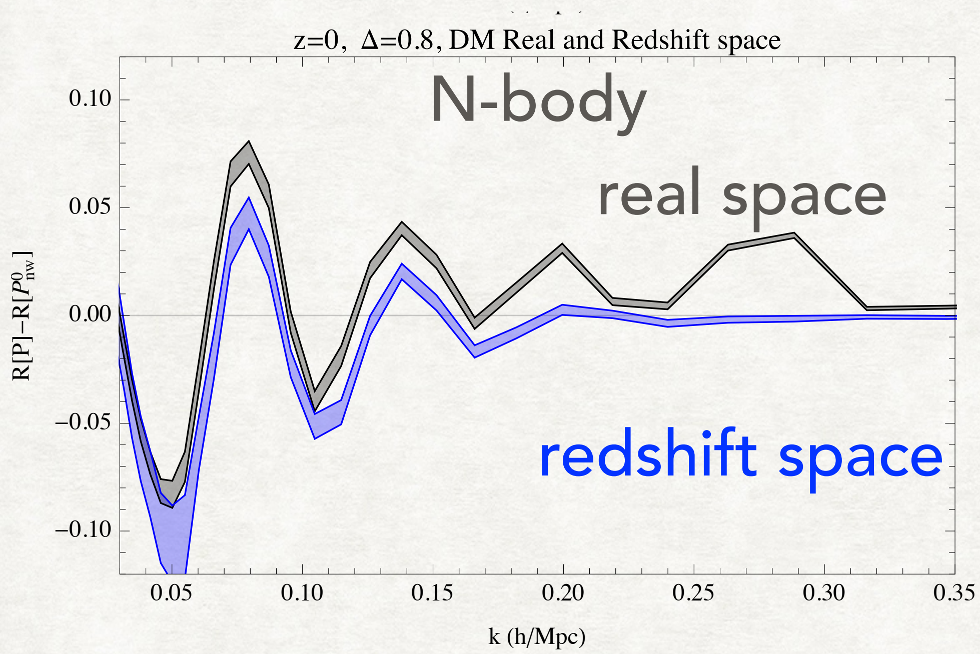


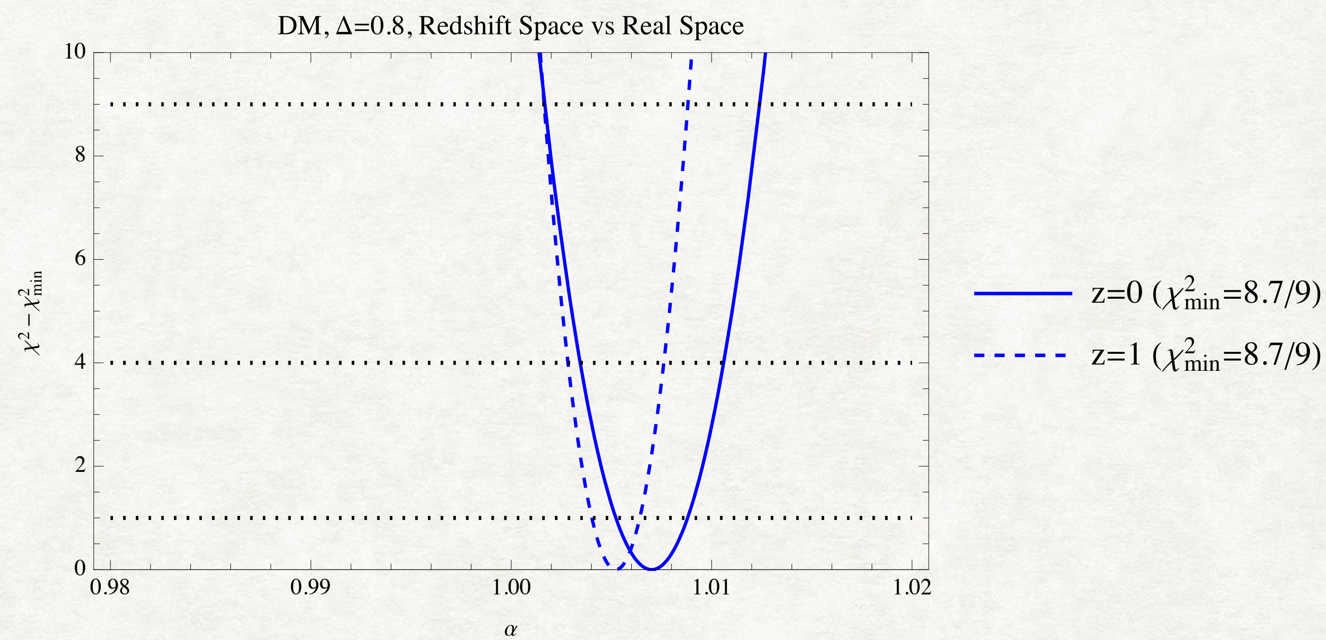
ROBUSTNESS: REDSHIFT SPACE

shift of the BAO scale

$$\delta R[P_a](k_n;\alpha,\Delta) \equiv R[P_a](k_n/\alpha;\Delta) - R[P_{data}](k_n;\Delta)$$

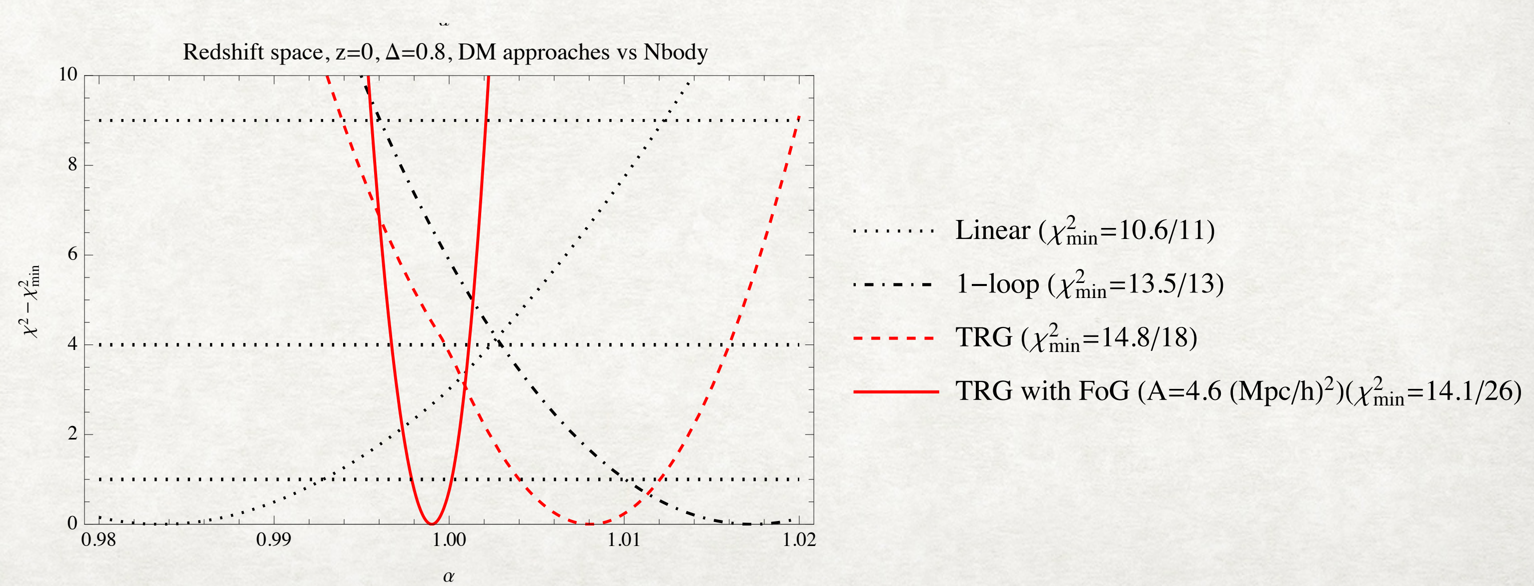
$$\chi^2_a(\alpha) = \sum_{n,m=n_{min}}^{n_{max}} \delta R[P_a](k_n;\alpha,\Delta) C^{-1}_{n,m}(\Delta)\delta R[P_a](k_m;\alpha,\Delta)$$



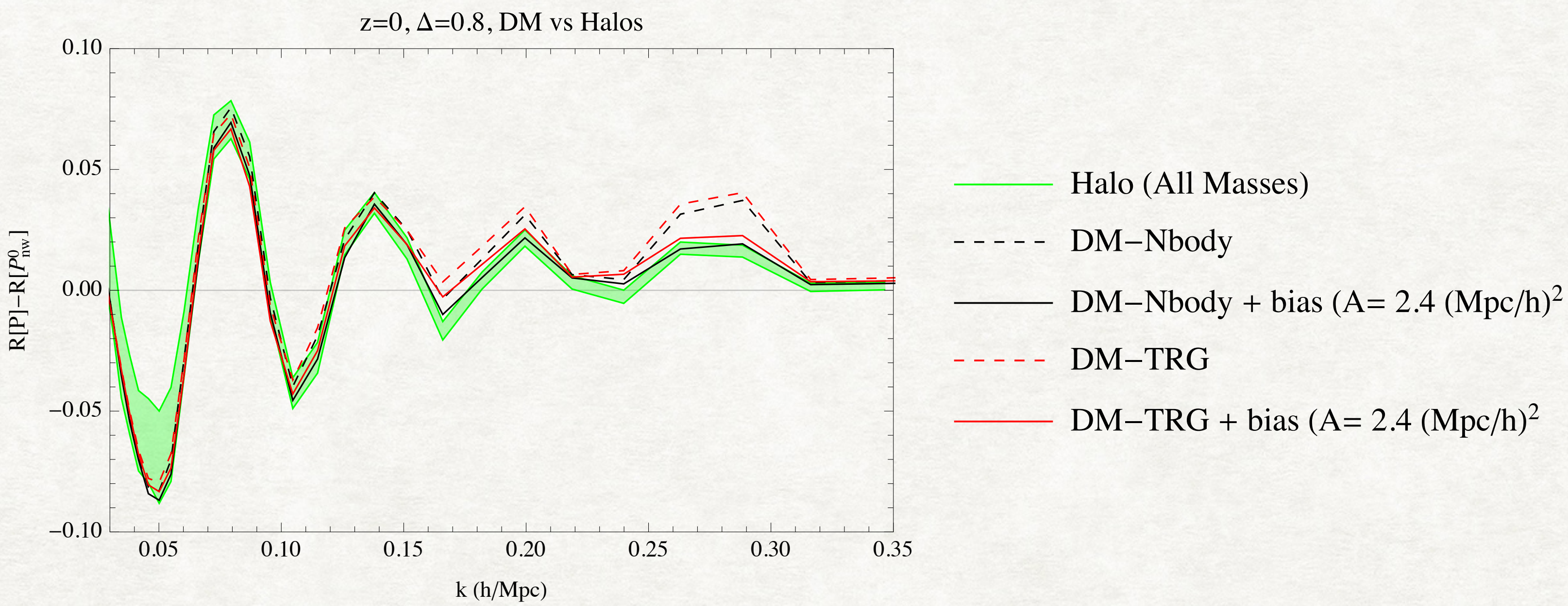


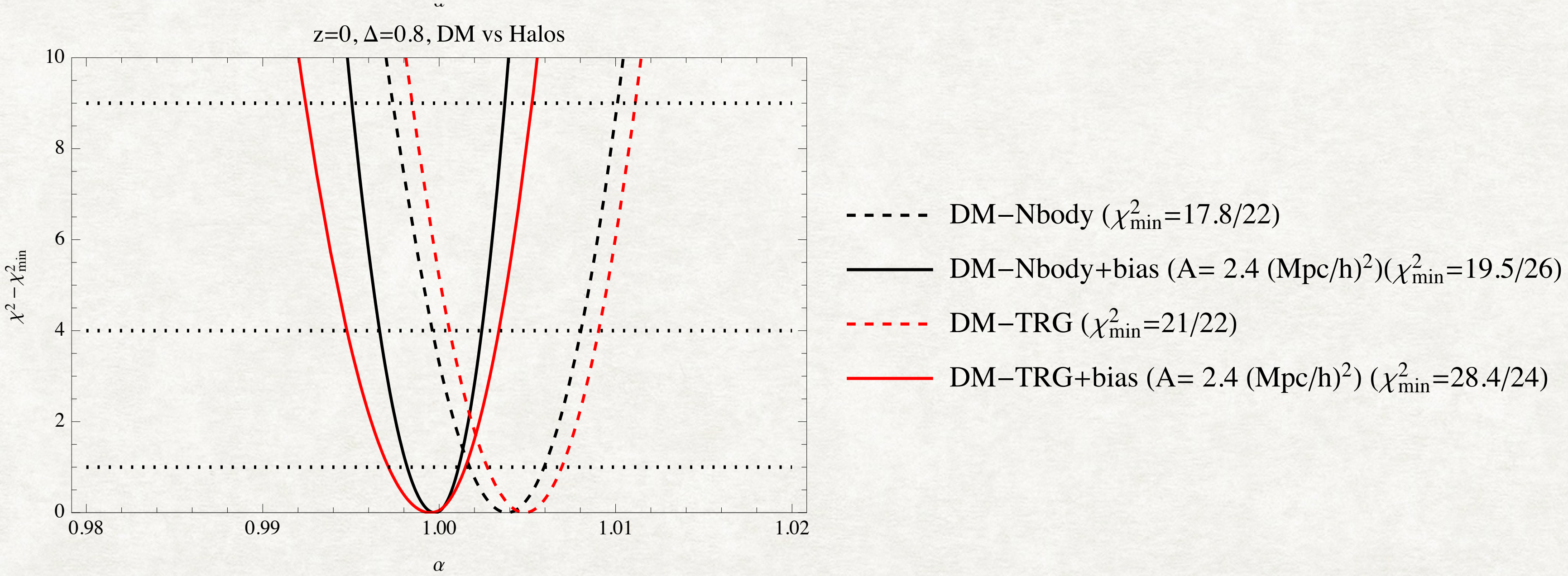
~ 0.5% shift in the BAO scale due to redshift effects

shift correctly reproduced
by TRG equations



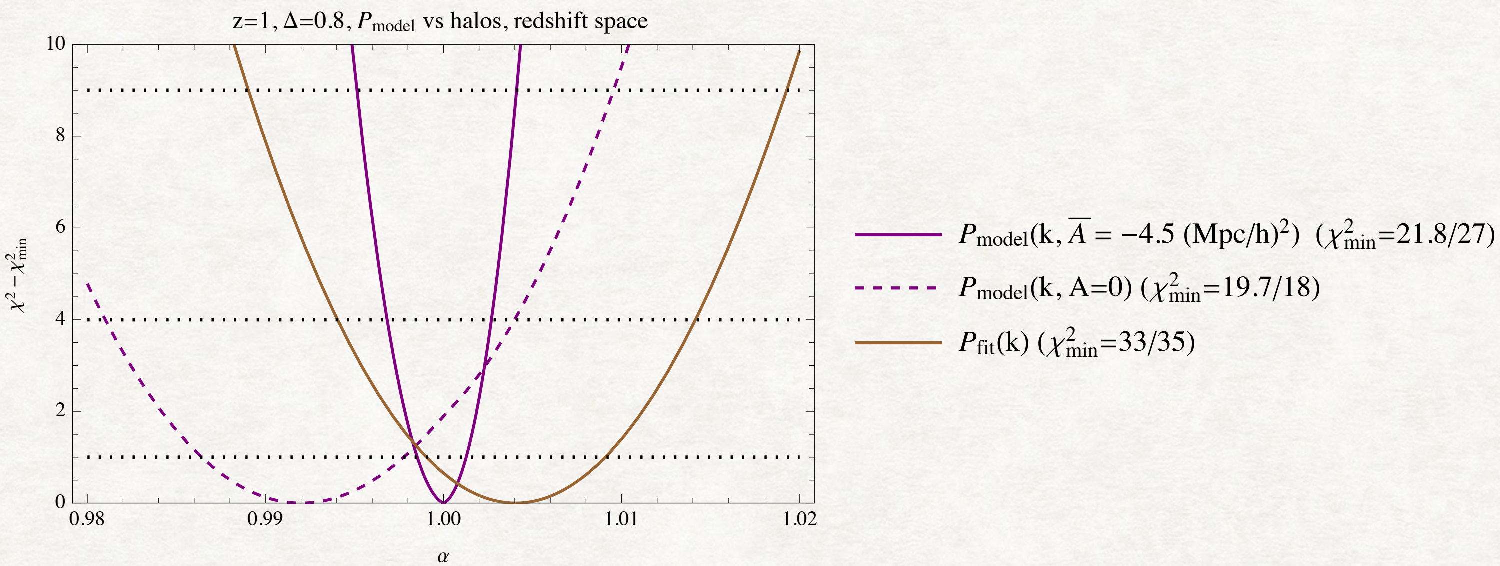
ROBUSTNESS: HALO BIAS

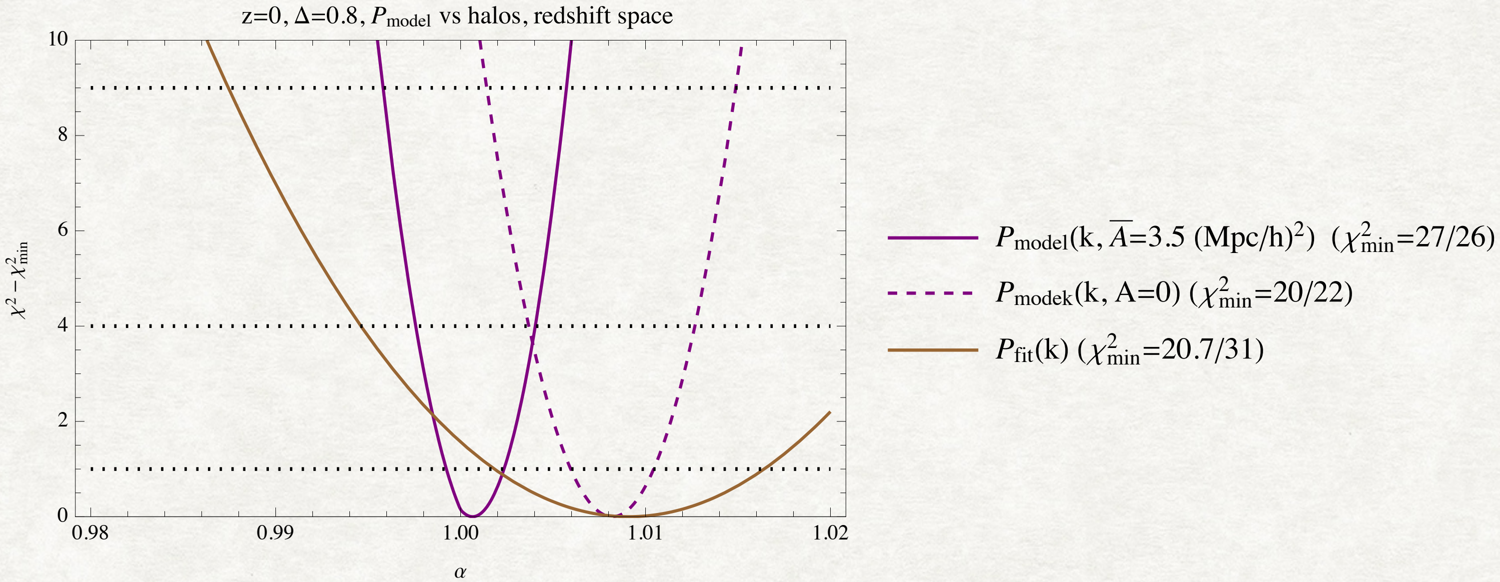




Extractor is only sensitive to scale-dependent bias

ROBUSTNESS: REDSHIFT SPACE+HALO BIAS





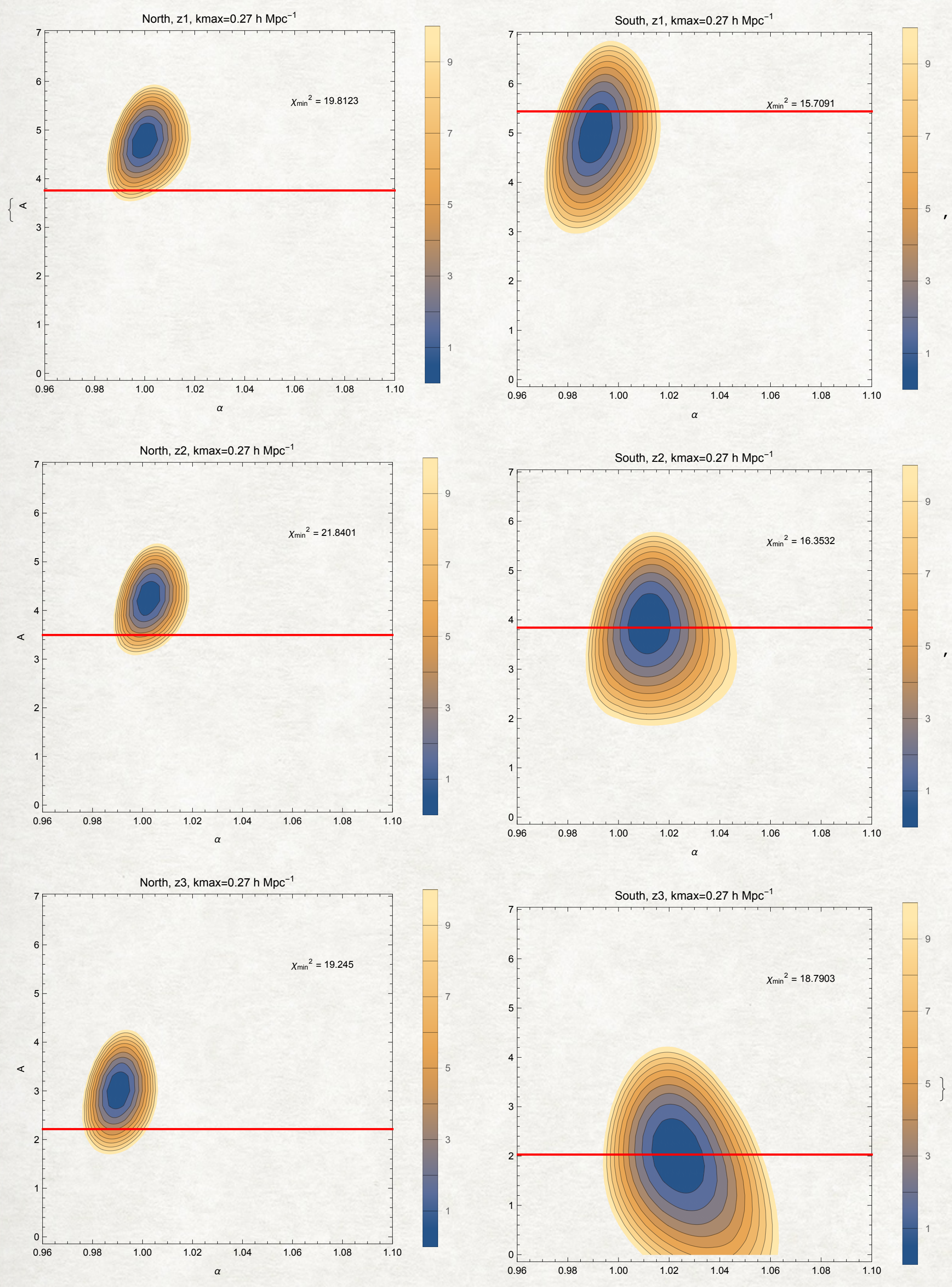
compare to "standard" analysis:

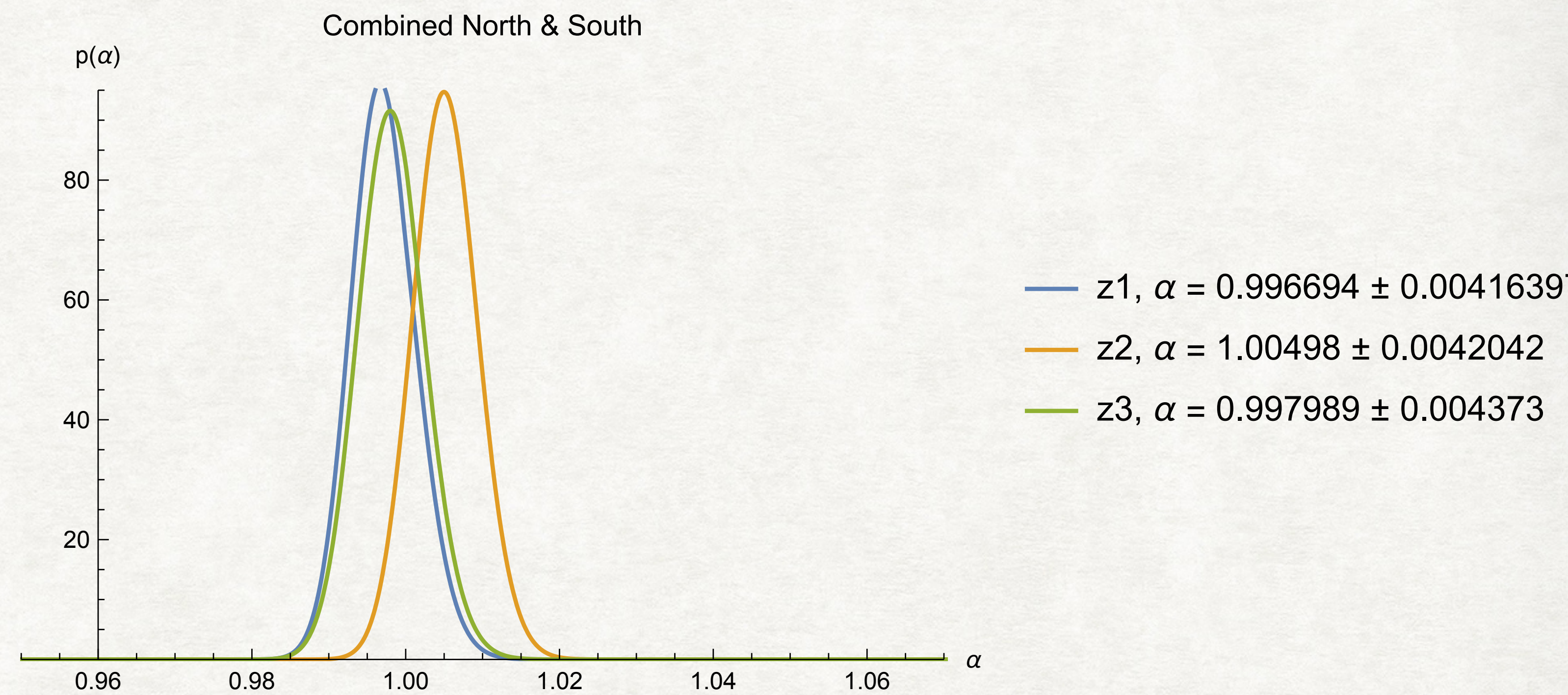
$$P_{\mathrm{fit}}\left(k;\alpha\right) = P^{\mathrm{smooth}}\left(k\right)\left\{1+\left[O^{\mathrm{linear}}\left(\frac{k}{\alpha}\right)-1\right]e^{-\frac{k^2\Sigma_{\mathrm{nl}}^2}{2}}\right\}$$

$$P_{\mathrm{smooth}}\left(k\right) \equiv B_P^2 P^{0,nw}\left(k\right) + A_1\,k + A_2 + \frac{A_3}{k} + \frac{A_4}{k^2} + \frac{A_5}{k^3} \qquad O^{\mathrm{linear}}\left(k\right) \equiv \frac{P^0\left(k\right)}{P^{0,nw}\left(k\right)}$$

need: P^nw(k) + 7 nuisance parameters+ α

EXTRACTOR ON BOSS DATA (preliminary)





compare to Beutler et al. 1607.03149

$$z1, \quad \alpha = 1.000 \pm 0.010$$
$$z2, \quad \alpha = 0.9936 \pm 0.0082$$
$$z3, \quad \alpha = 0.9887 \pm 0.0087$$

Notice, no TRG used here, only simple model+extractor

CONCLUSIONS

- IR and UV nonlinear effects clearly separated in TRG approach
- UV effects require external input (or nonperturbative breakthrough)
- IR effects are well understood and contain physical information
- BAO extractor is robust: can be efficiently computed and measured

SCALE DEPENDENCE OF SOURCES

$$\langle k^i J^i_\sigma(\mathbf{k})\delta(-\mathbf{k})\rangle'_{nb} \propto \alpha_{nb}\frac{k^2}{k_m^2}\langle\delta(-\mathbf{k})\delta(-\mathbf{k})\rangle_{nb}$$

$$\langle k^i J^i_\sigma(\mathbf{k})\delta(-\mathbf{k})\rangle'_{pt} \propto \alpha_{pt}\frac{k^2}{k_m^2}\langle\delta(-\mathbf{k})\delta(-\mathbf{k})\rangle_{pt}$$