RESPONSE FUNCTION AND RECONSTRUCTION FOR ACCURATE TESTS OF DARK ENERGY USING CLUSTERING STATISTICS ON BAO SCALE

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w/ Francis Bernardeau (IAP)
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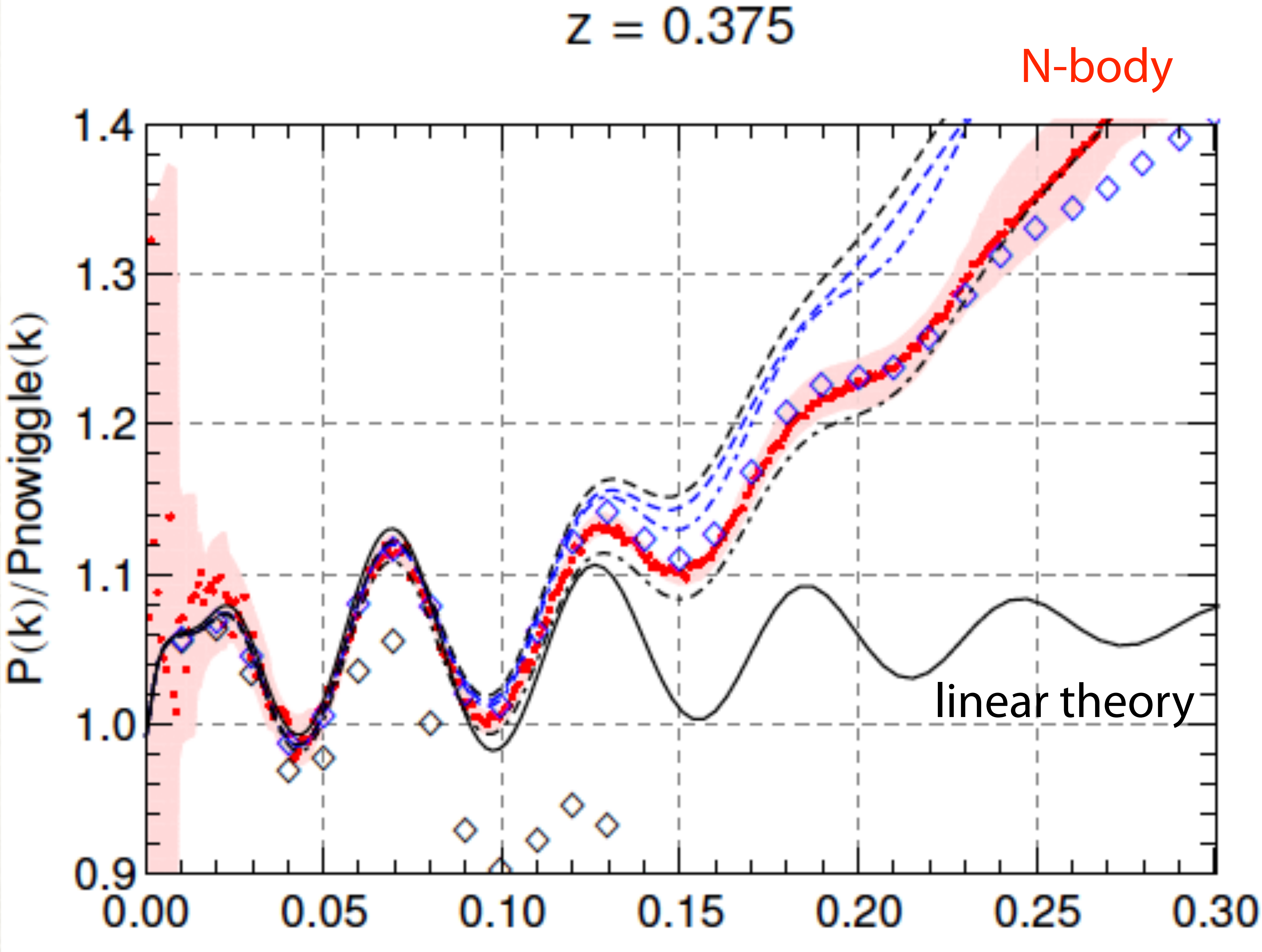
Based on PLB 762 (2016) 247 and arXiv:1708.08946

See also RESPRESSO webpage:
http://www-utap.phys.s.u-tokyo.ac.jp/~nishimichi/public_codes/respresso/

OBJECTIVES

- Let me go back to standard techniques
  - BAO -> expansion history
  - RSD -> growth history
    - Distinguish between DE and MG
- Predict the relevant statistics as accurate and quick as possible
  - Perturbation theory up to high order terms (and its variant)
    - Accuracy: large scale good (?), small scale no
    - Speed: high loop order (2 or 3 loops) takes time
  - N-body simulations
    - Accuracy: good, if you are careful enough (w/ sufficient volume/realizations, only after a careful convergence study)
    - Speed: takes much more time
  - halofit (w/ Takahashi et al. recalibration) is implemented in CAMB, but ~5% accuracy
  - RESPRESSO !
    - A possible integration of the 2 approaches
    - Validated only within ΛCDM, but extension to MG/massive neutrinos in discussion

PERTURBATION THEORY IS IN CRISIS



Blas, Garny, Konstandin '14

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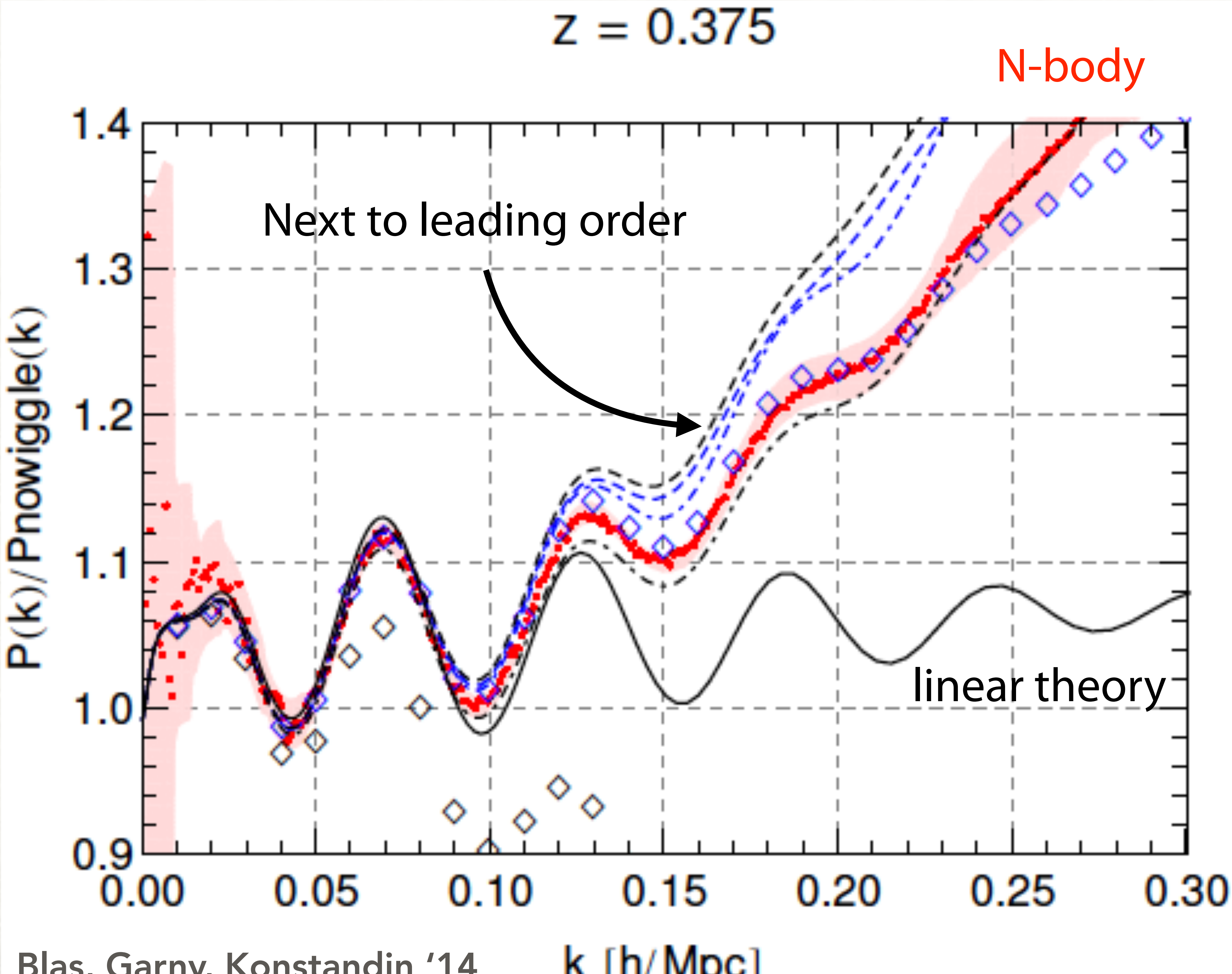

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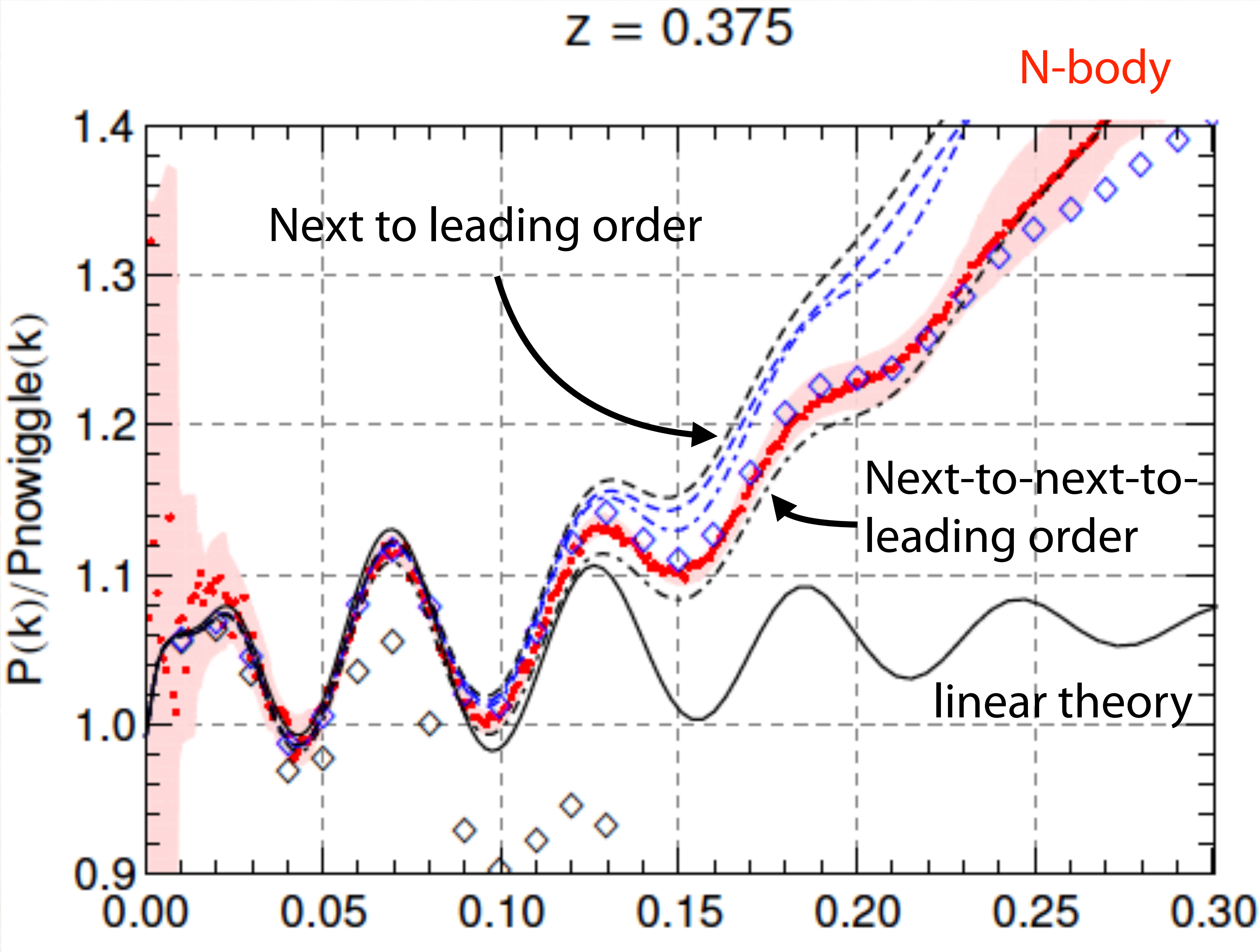

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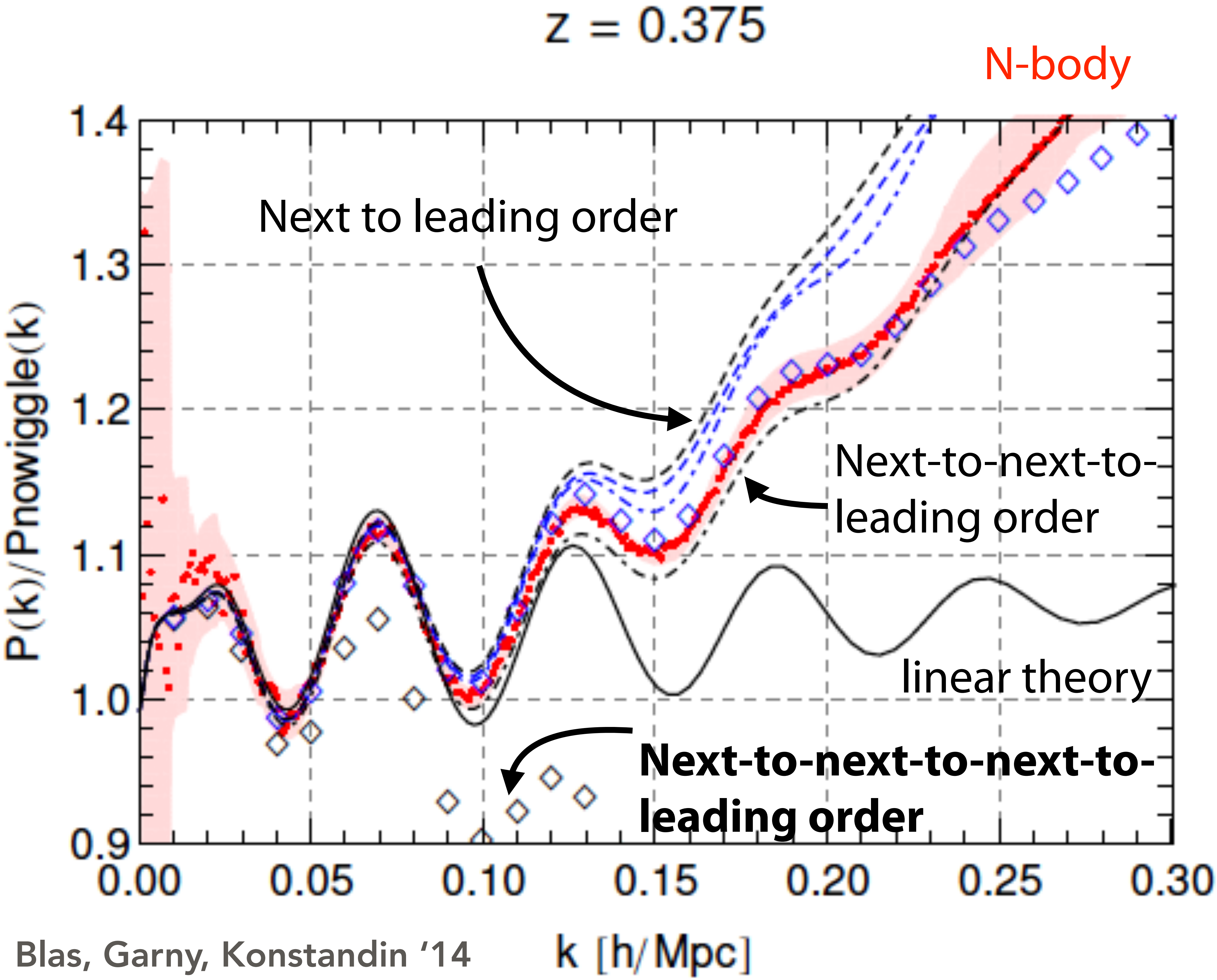

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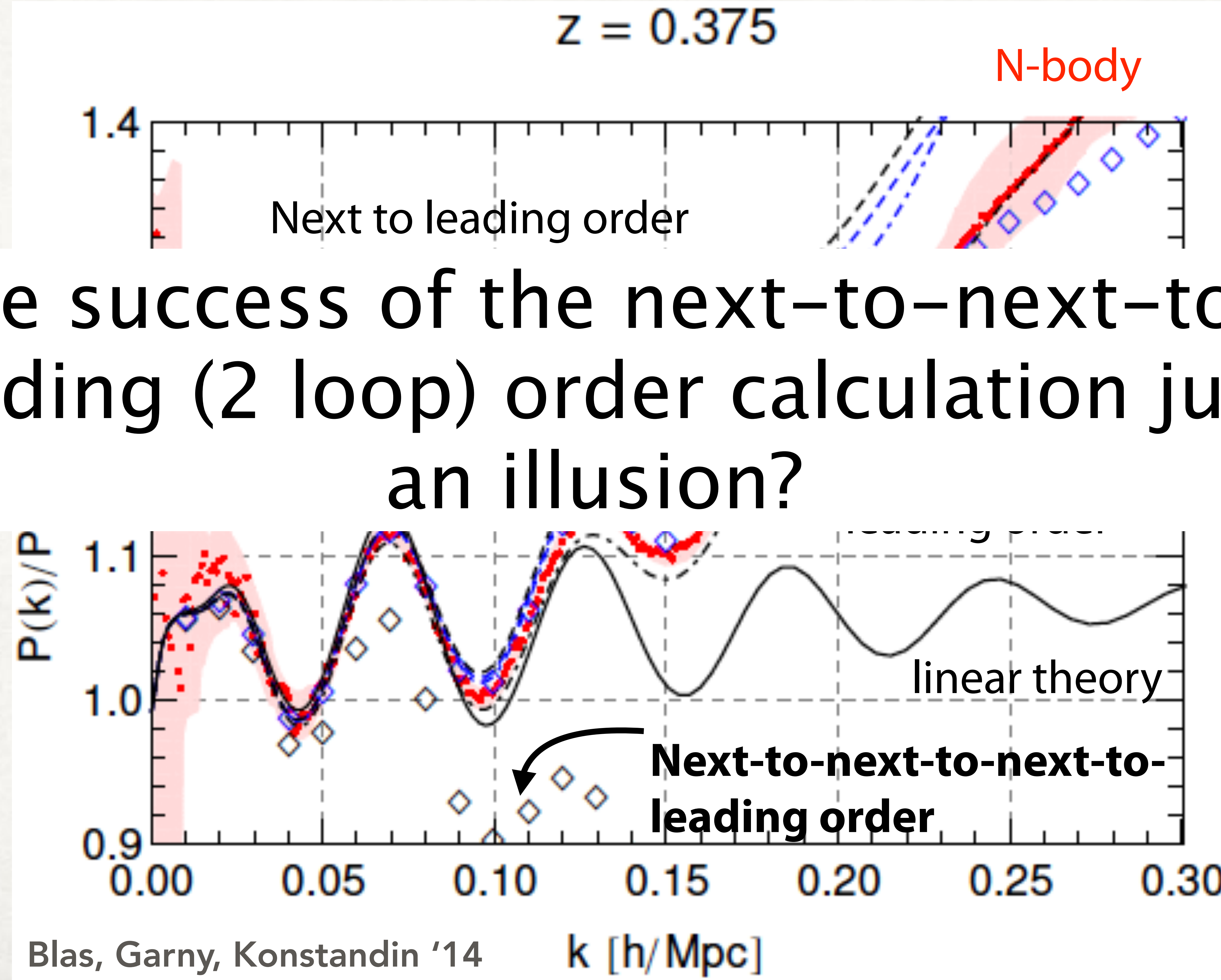
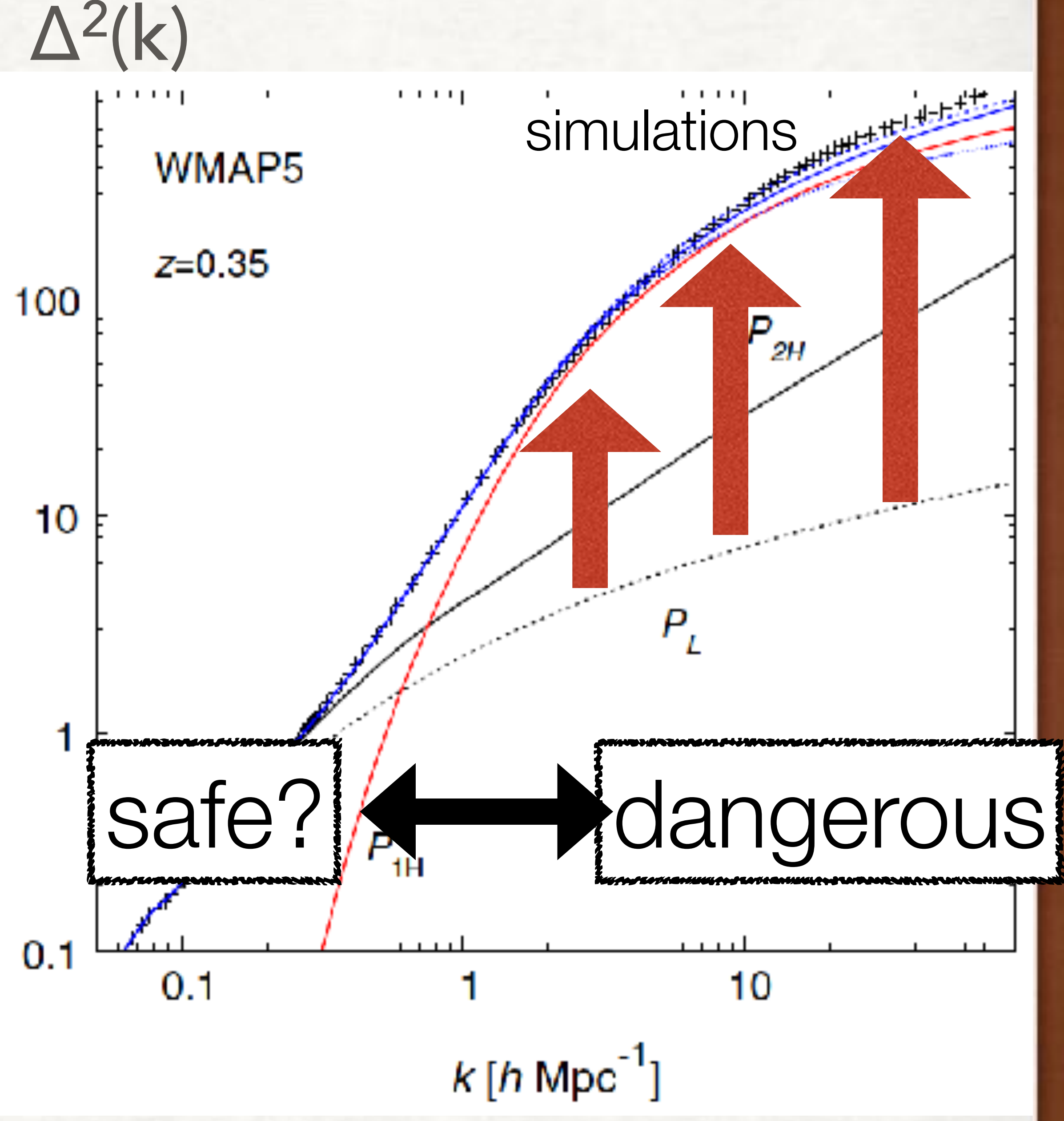


The success of the next–to–next–to–leading (2 loop) order calculation just an illusion?

WHY?

- Perturbation theory works only for a small quantity to have a convergent series expansion
  - δ can be >> 1 at present
- Irrotational single-streaming perfect fluid assumed
  - Enters to multi-streaming phase after shell crossing (even for a cold initial condition)
- Violation of them happens together on small scales at late time
  - The breakdown can propagate to large scales due to **mode coupling**
  - The way how PT breaks down is totally non-trivial —> simulations!



Valageas, TN, Taruya '13

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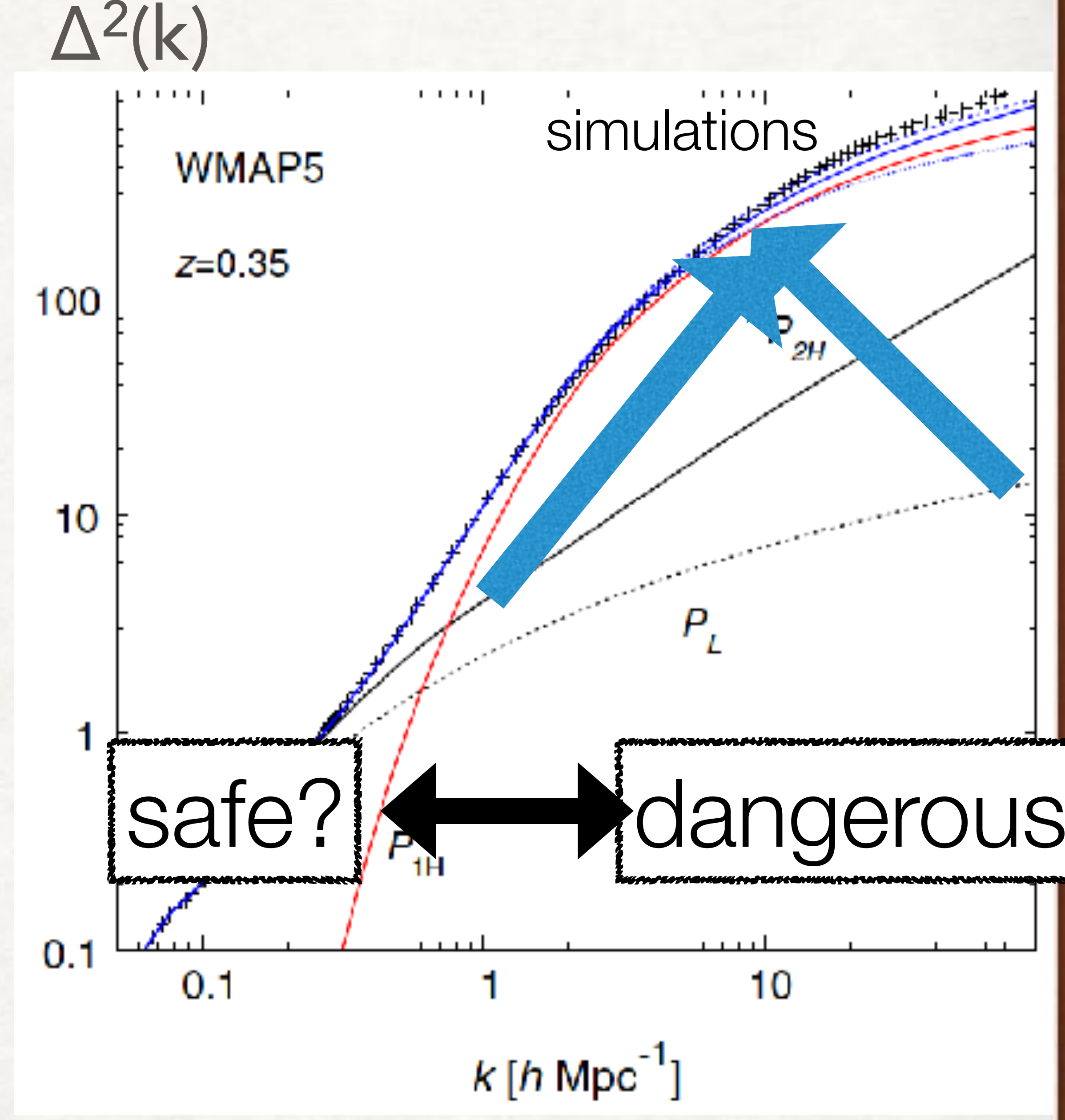


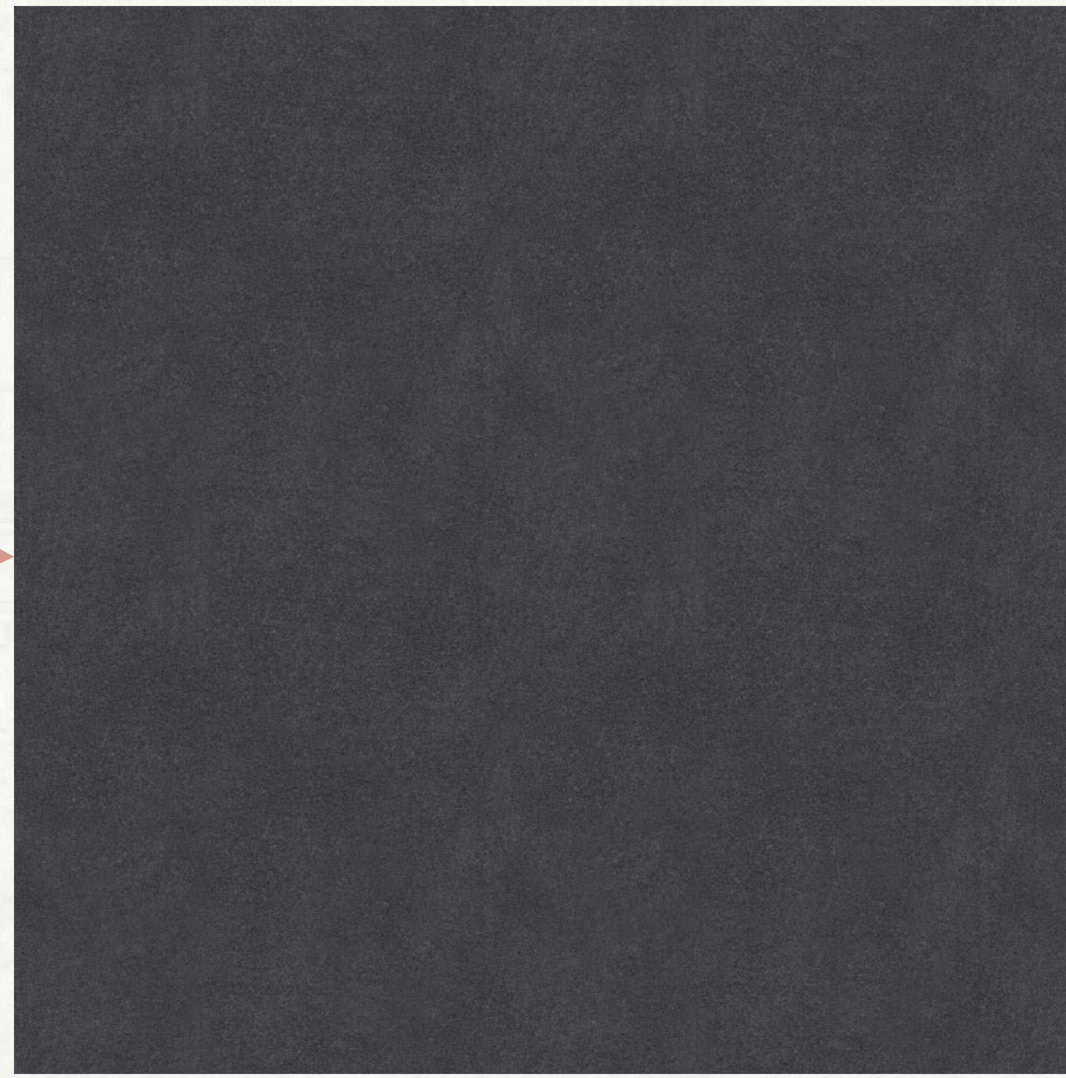
Valageas, TN, Taruya '13

INTUITIVE UNDERSTANDING OF MODE COUPLING? RESPONSE!

large scale structure gravitational evolution

Input

$$(\Omega_m, h, ...; z)$$



$$P_{nl}(k)$$

Output

INTUITIVE UNDERSTANDING OF MODE COUPLING? RESPONSE!

large scale structure gravitational evolution

Input

$$(\Omega_m, h, ...; z)$$

$$P_{lin}(q)$$

$$P_{nl}(k)$$

To a very good approximation

Output

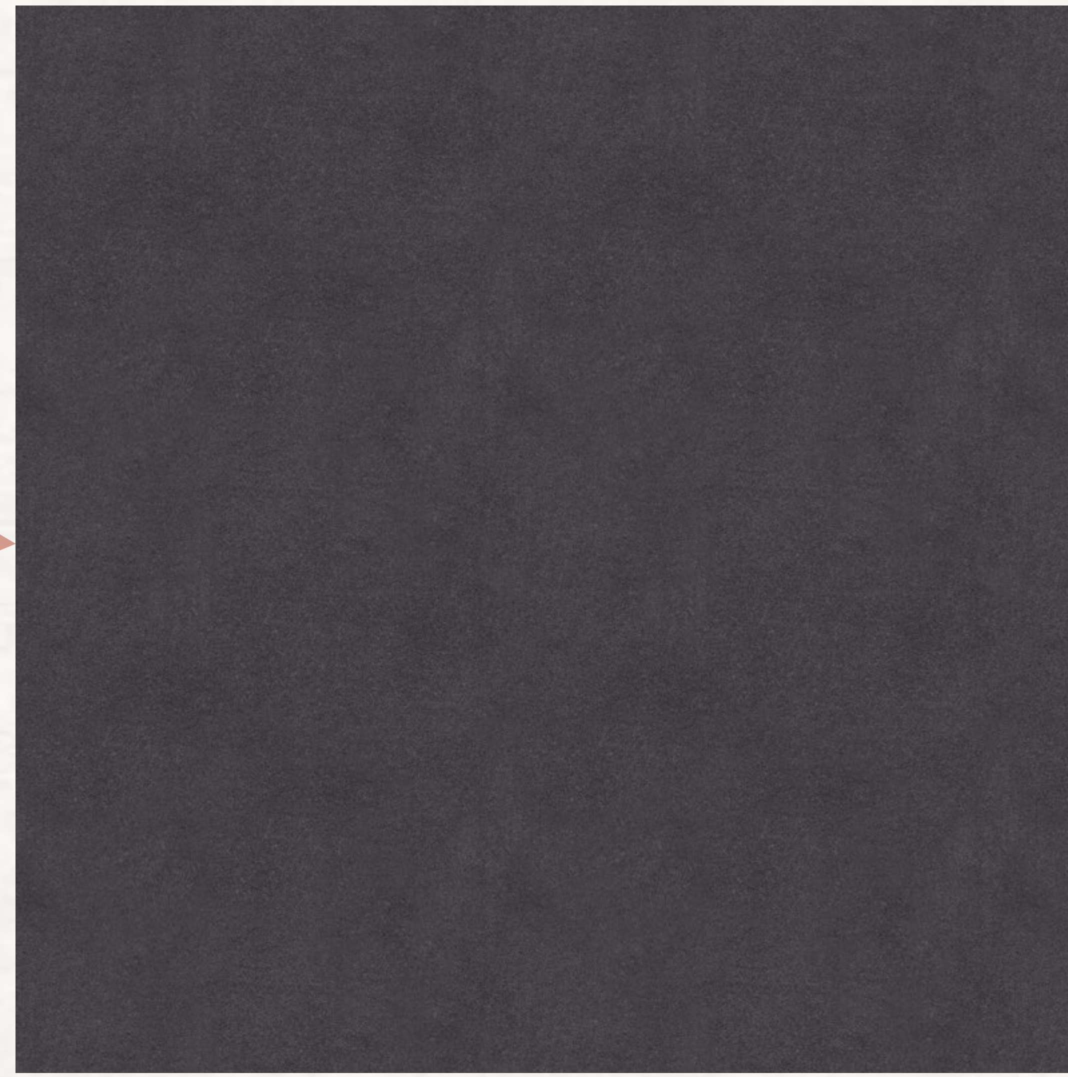
INTUITIVE UNDERSTANDING OF MODE COUPLING? RESPONSE!

large scale structure gravitational evolution

Input

$P_{lin}(q)$

$+\,\delta\,P_{lin}(q)$



$P_{nl}(k)$

Output

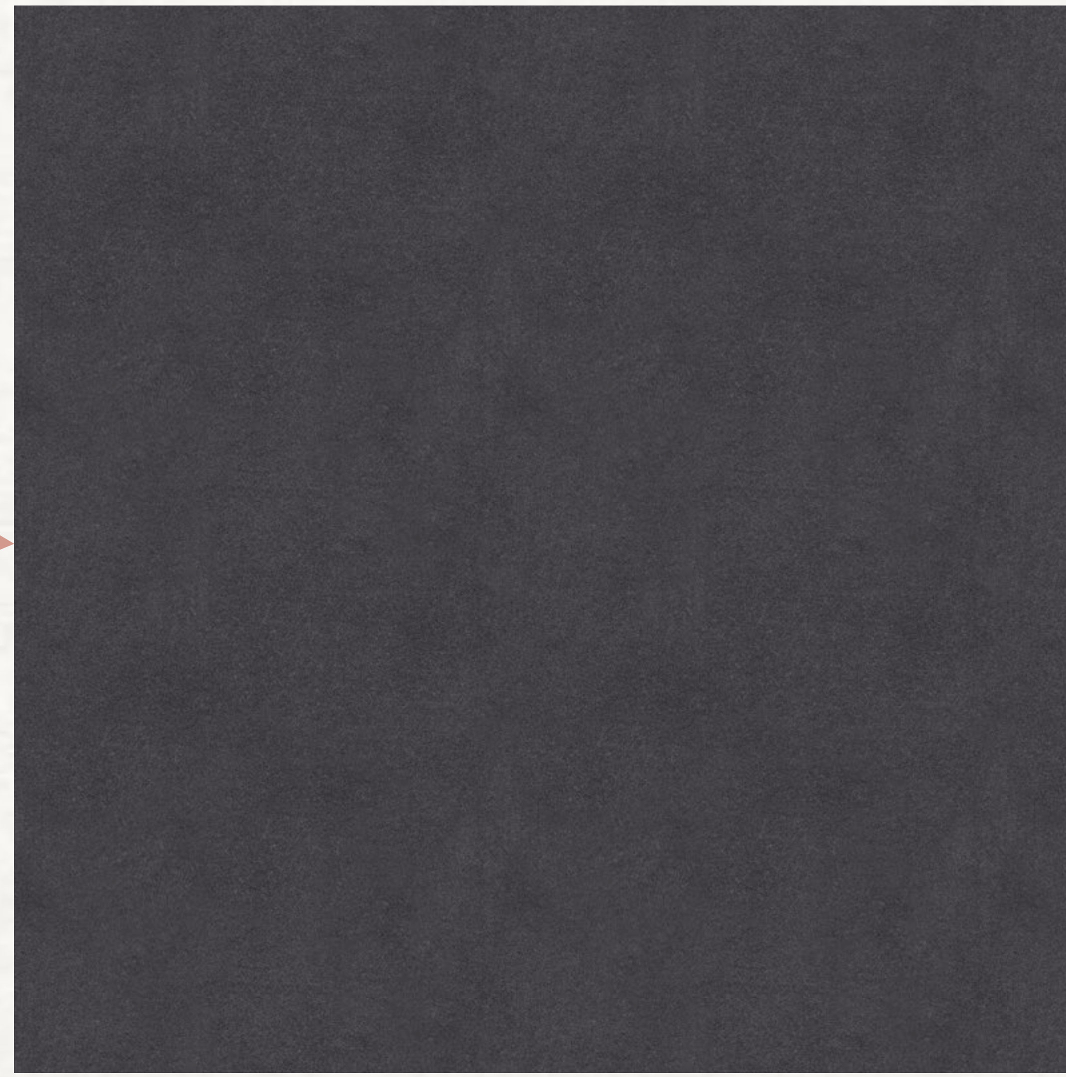
INTUITIVE UNDERSTANDING OF MODE COUPLING? RESPONSE!

large scale structure gravitational evolution

Input

$$P_{lin}(q)$$

$$+\,\delta\, P_{lin}(q)$$



$$P_{nl}(k)$$

Output

$$+\delta P_{nl}(k)$$

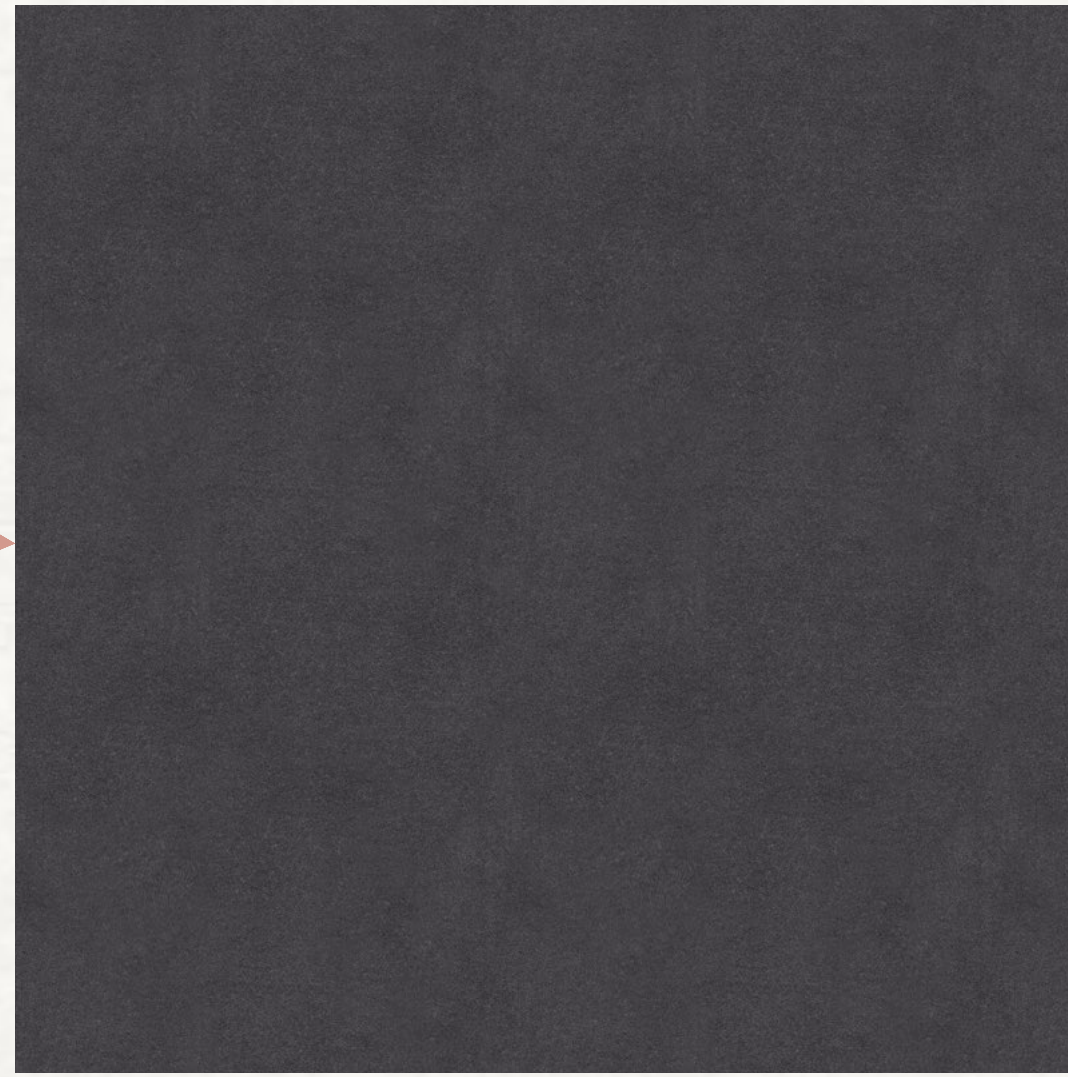
INTUITIVE UNDERSTANDING OF MODE COUPLING? RESPONSE!

large scale structure gravitational evolution

Input

$$P_{lin}(q)$$

$$+\,\delta\, P_{lin}(q)$$



$$P_{nl}(k)$$

Output

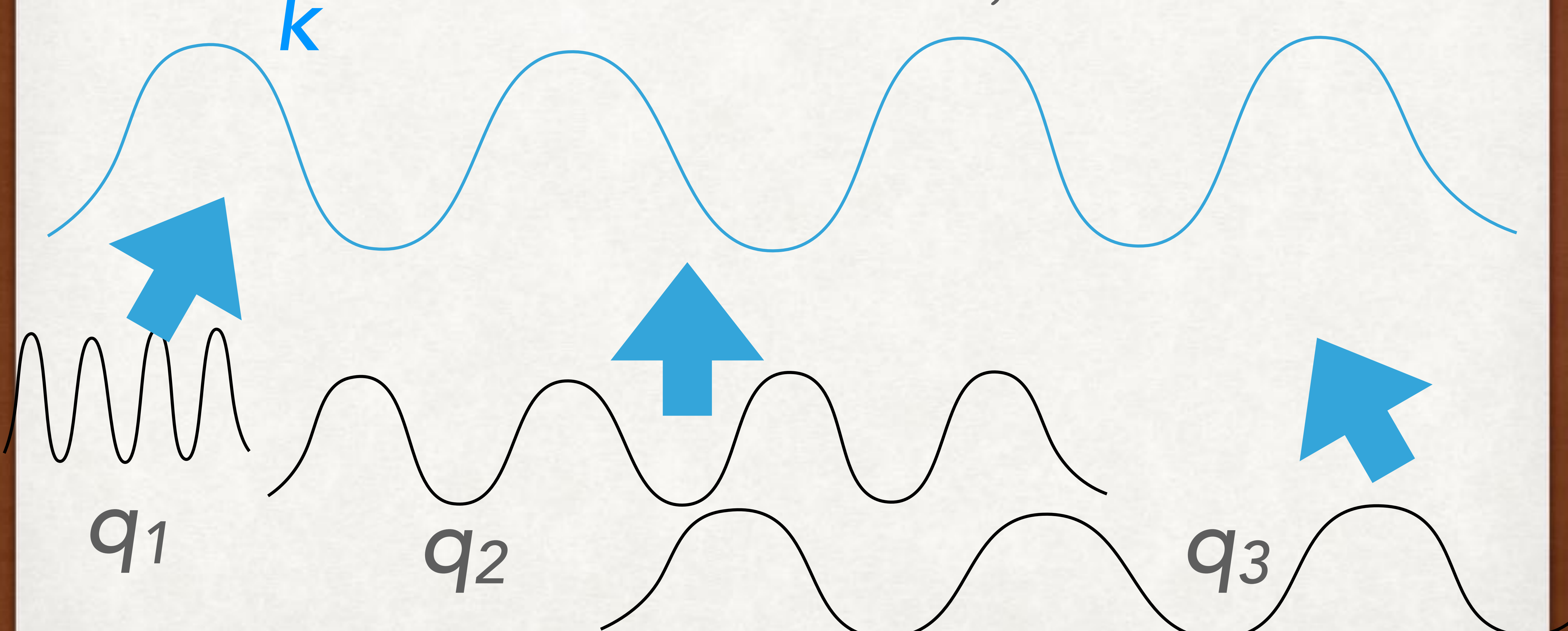
$$+\delta P_{nl}(k)$$

$$\boxed{K(k,q) = q\,\frac{\delta P_{nl}(k)}{\delta P_{lin}(q)}}$$

RESPONSE FUNCTION

$$K(k,q) = q\,\frac{\delta P_{nl}(k)}{\delta P_{lin}(q)}$$

I want to study this mode at some late time t



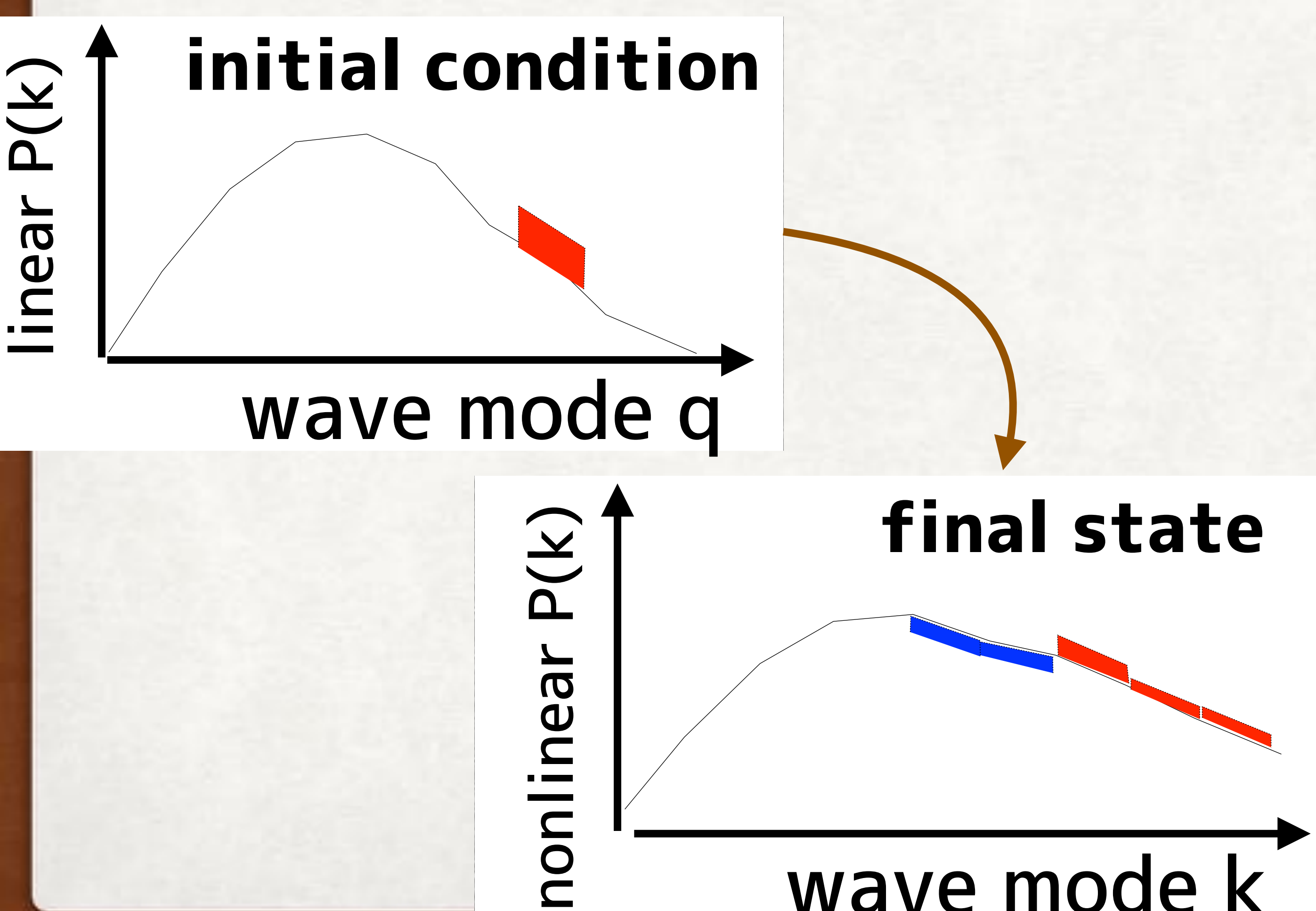
what is the impact from wave mode q at the initial time t_0?

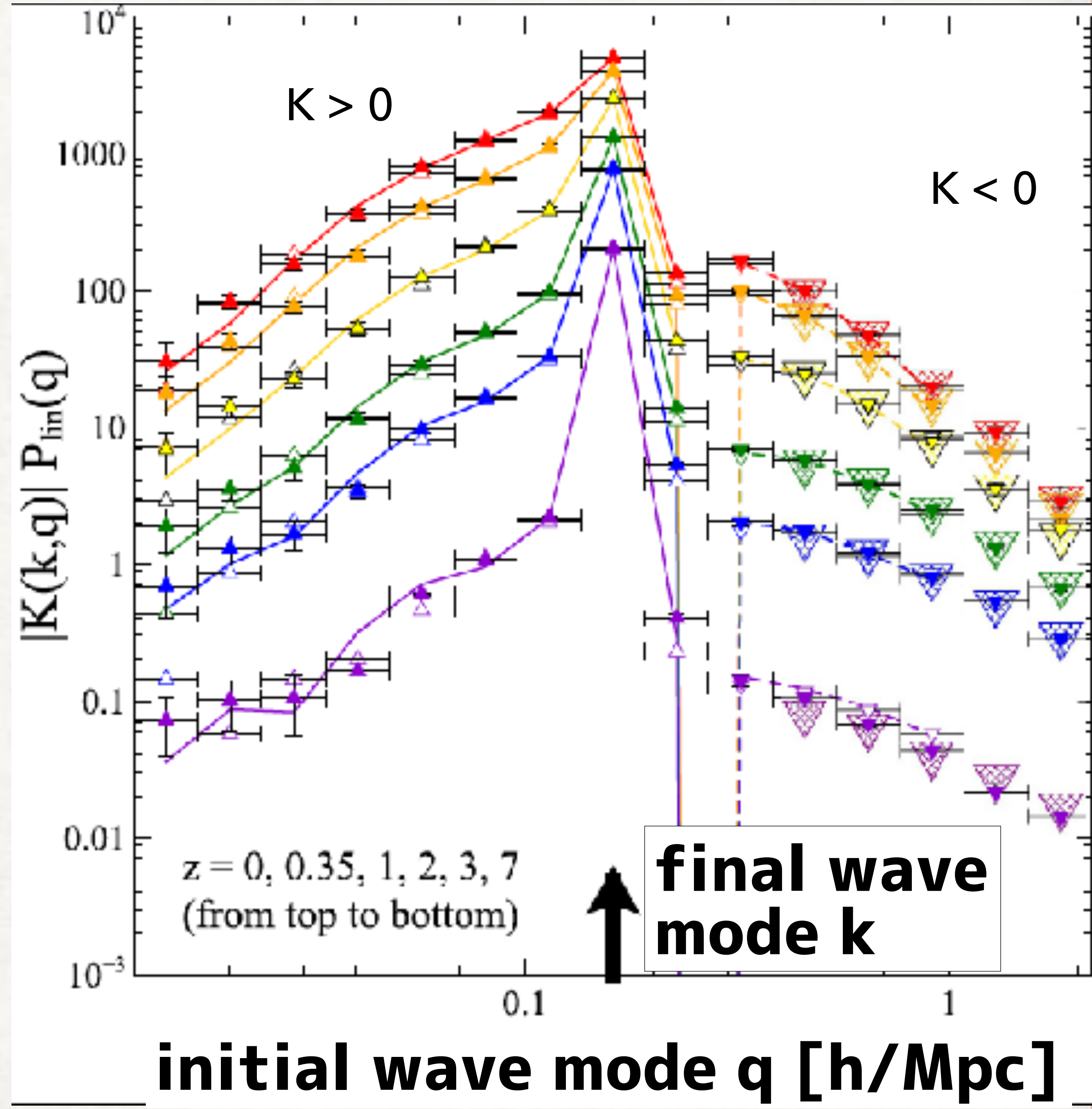
RESPONSE FUNCTION: THE FIRST TRIAL

TN, Bernardeau, Taruya '16 PLB

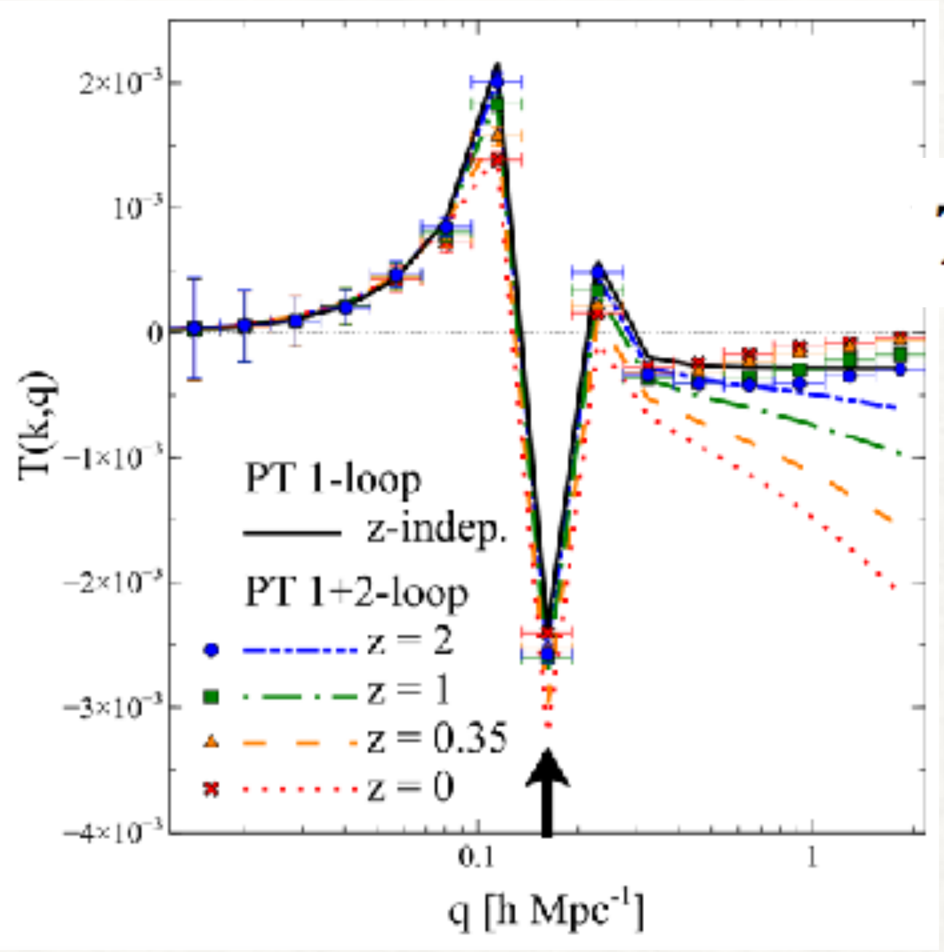
- From order-by-order to the full order discussion possible
- Can estimate the derivative from a simulation ensemble

$$\hat{K}_{i,j} P^{\rm lin}_j \equiv \frac{P^{\rm nl}_i[P^{\rm lin}_{+,j}] - P^{\rm nl}_i[P^{\rm lin}_{-,j}]}{\Delta \ln P^{\rm lin} \Delta \ln q}$$



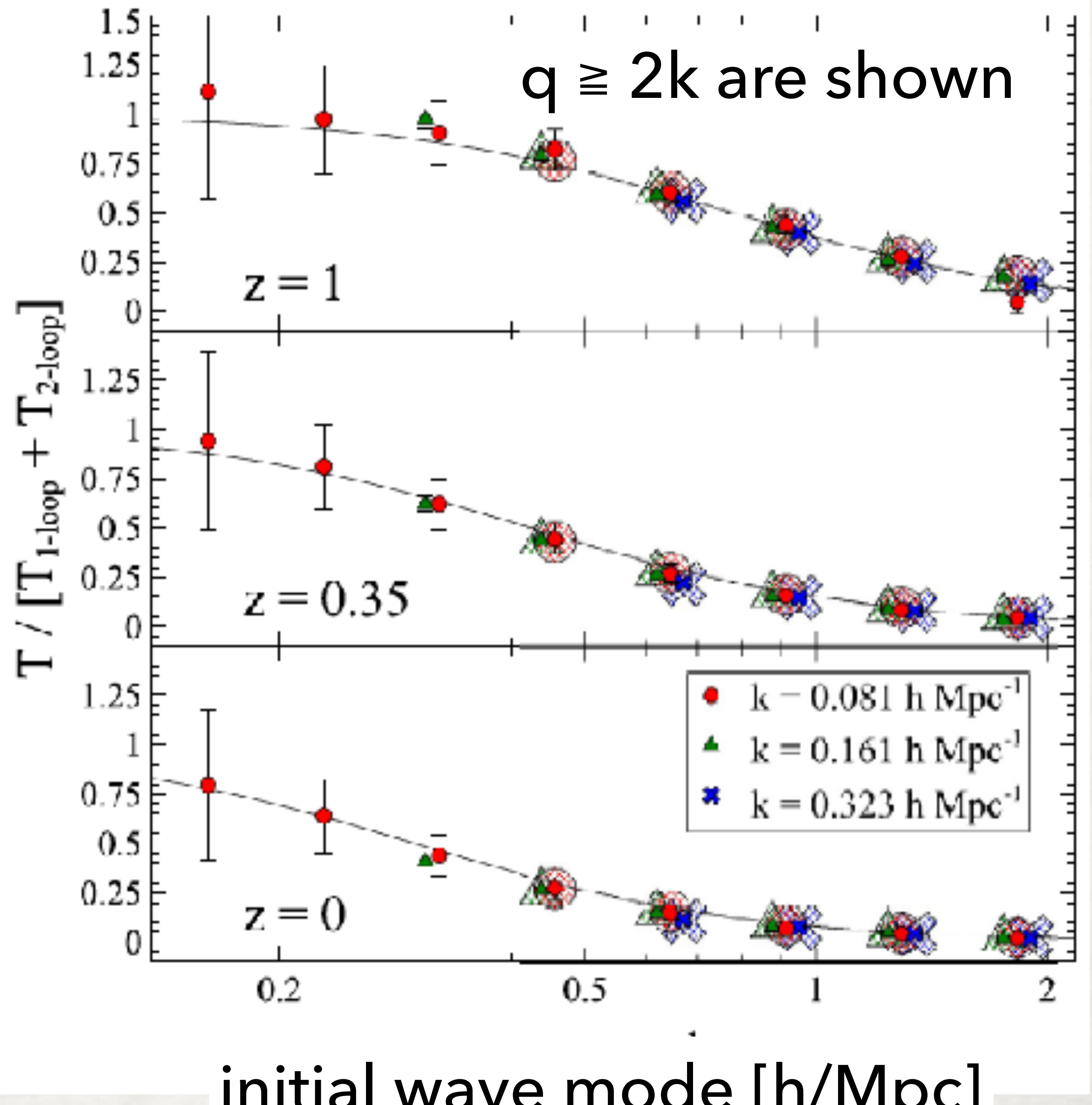


RESPONSE FUNCTION: SIM VS PT



Rescaled quantity:

$$T(k,q) \equiv [K(k,q) - K^{\mathrm{lin}}(k,q)]/[q P^{\mathrm{lin}}(k)]$$



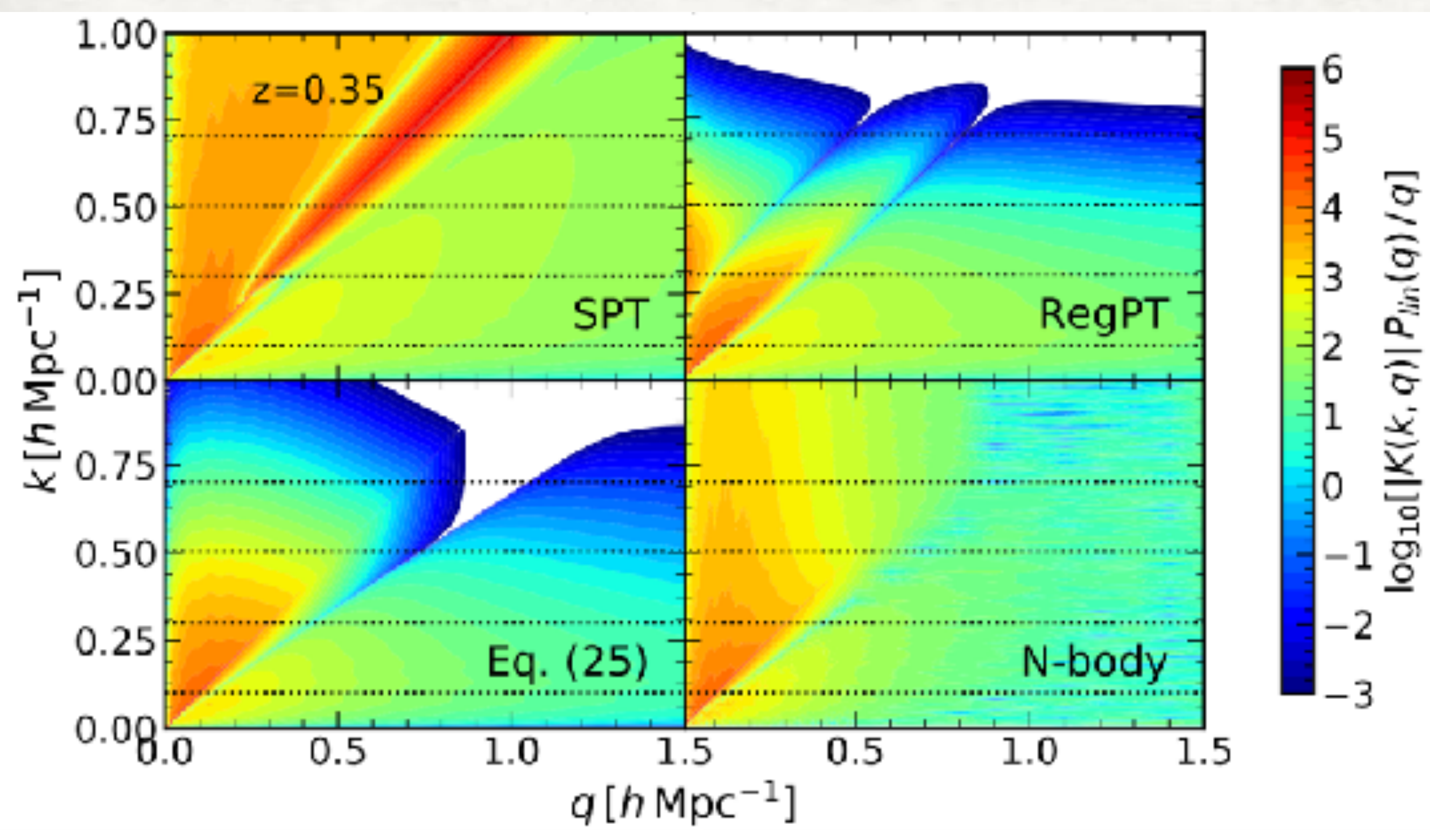
- SPT (2-loop) >> N-body @ high q
- This is exactly where PT breaks down
- What N-body tells us is:

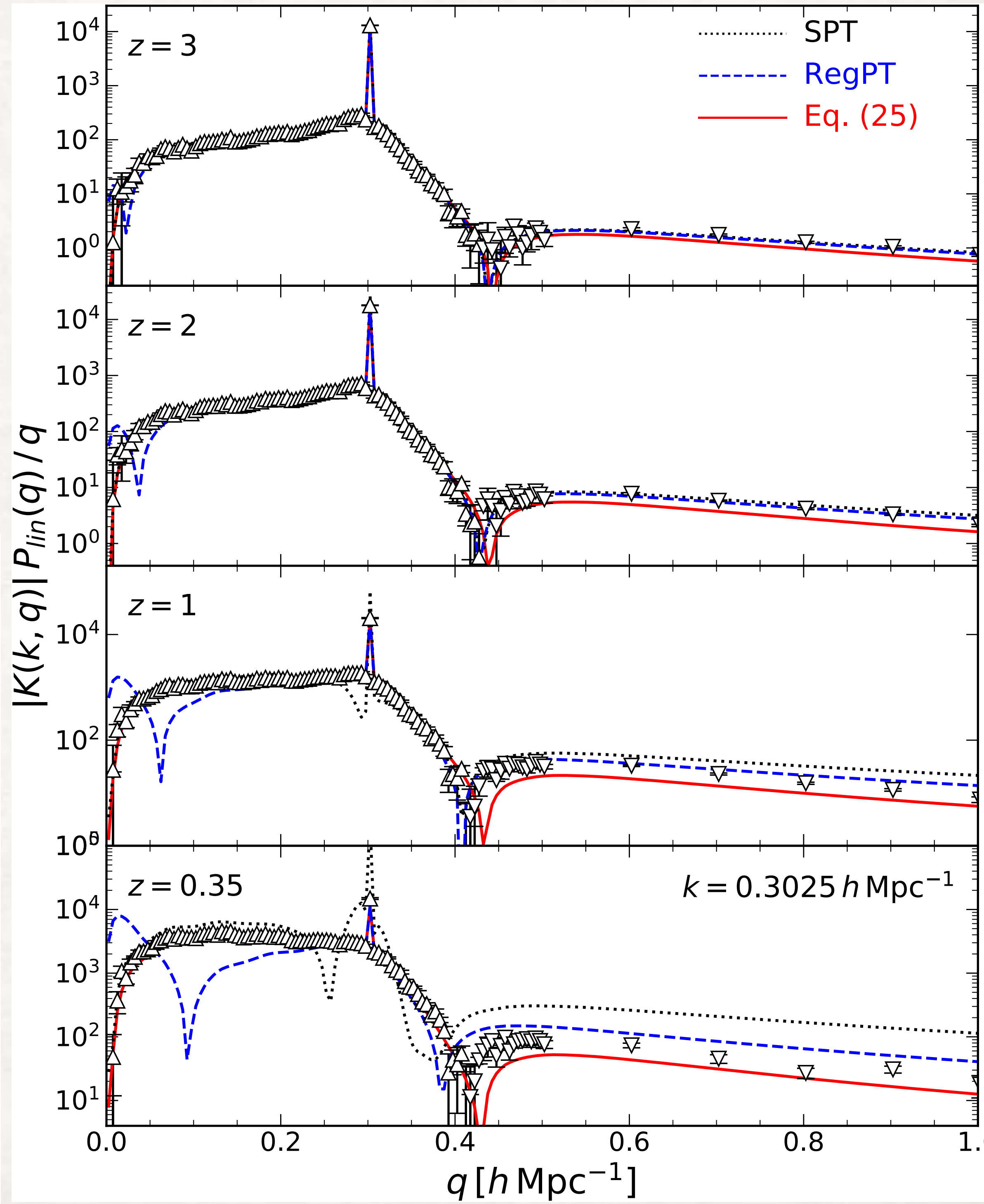
"Physics at strongly nonlinear regime does not propagate to large scales"

HIGH RES RESPONSE FUNCTION

- 1400 N=512^3 simulations to study fine structures of the response function
- Vs 2-loop calculation based on different schemes (SPT and RegPT)
- New phenomenological model introduced

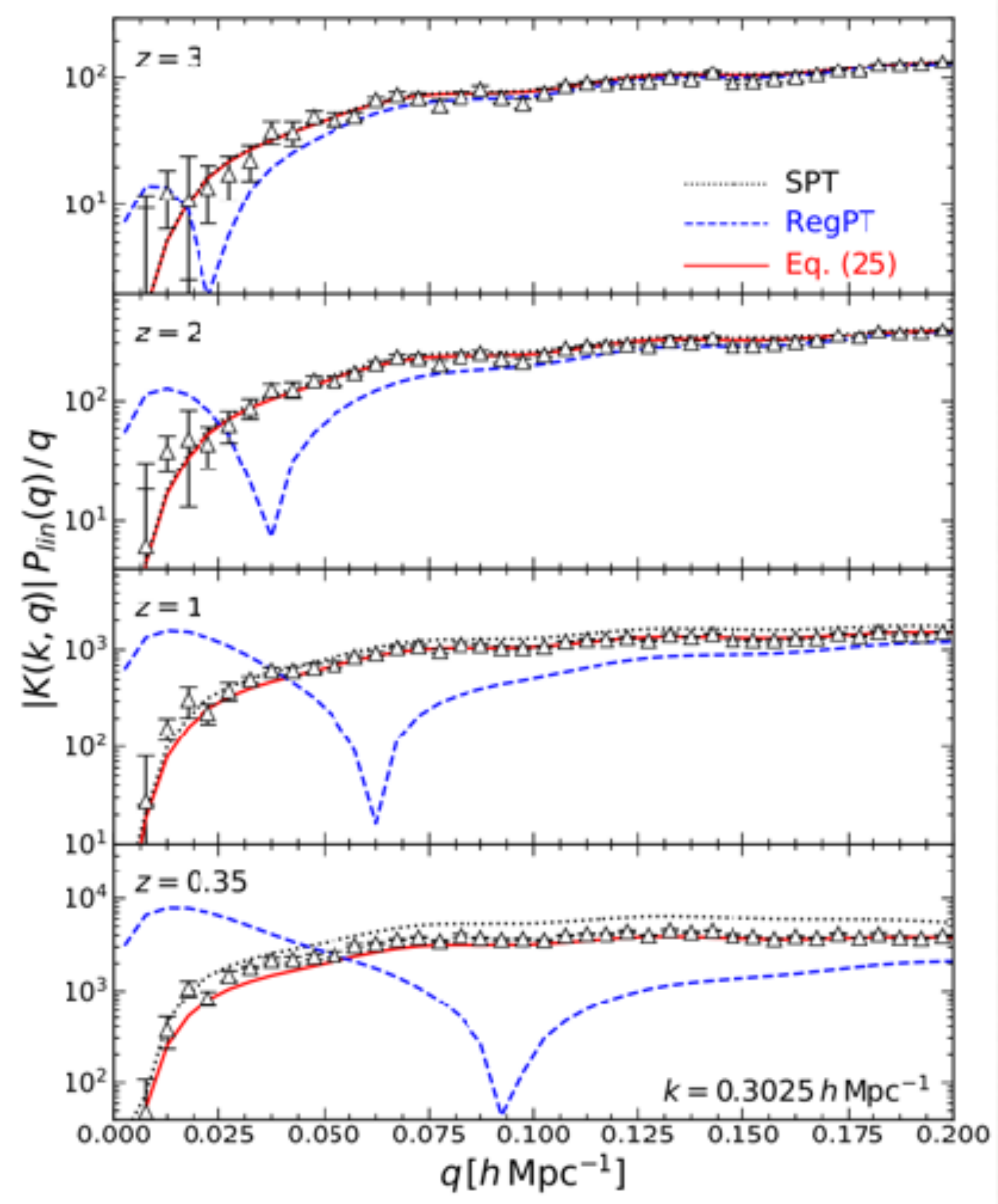
TN, Bernardeau, Taruya '17 (arXiv:1708.08946)





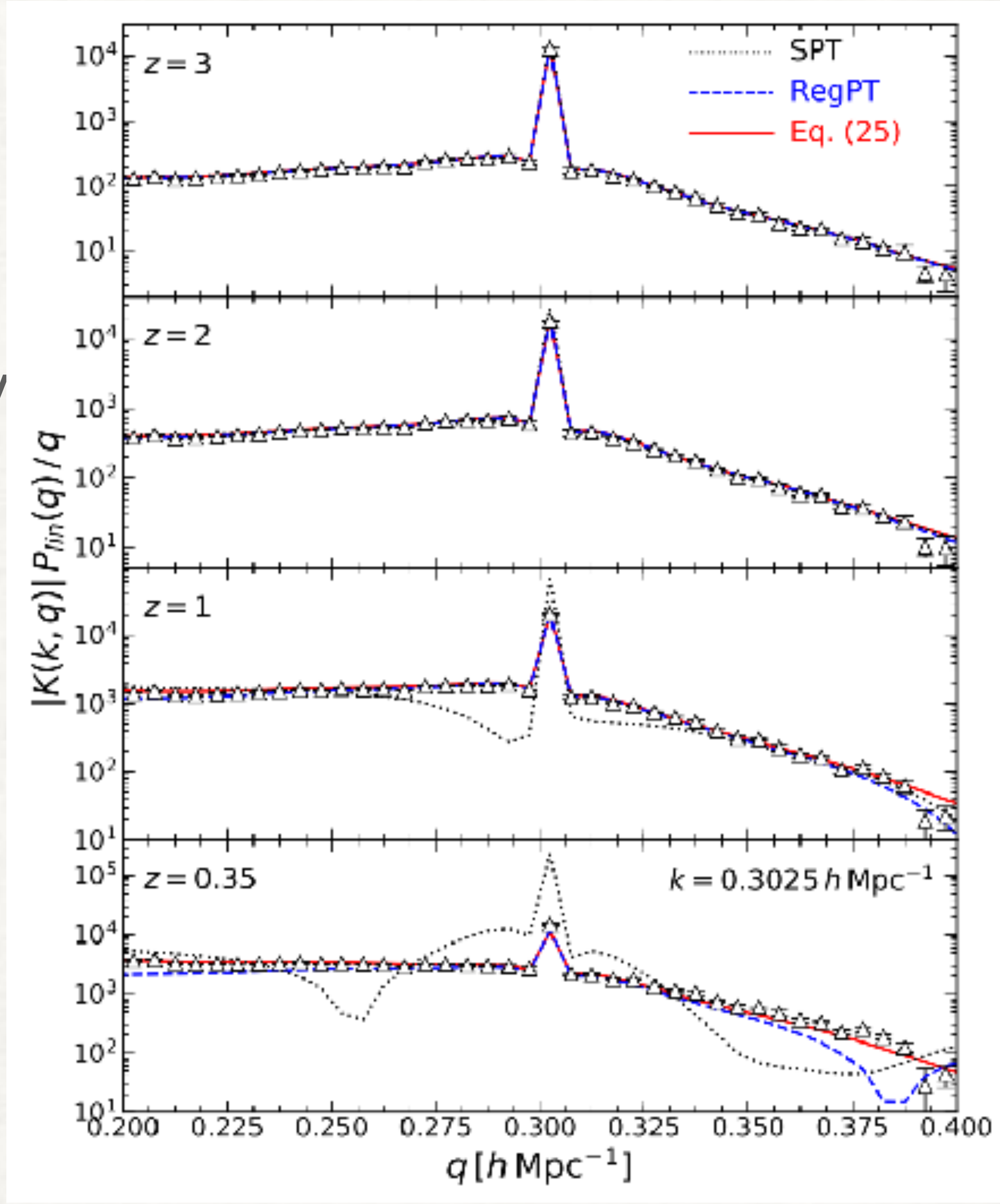
RESPONSE FUNCTION AT q << k

- Response function goes to zero from simulations
    - **Extended galilean invariance**
- This is nicely explained by SPT
- Not the case for RegPT



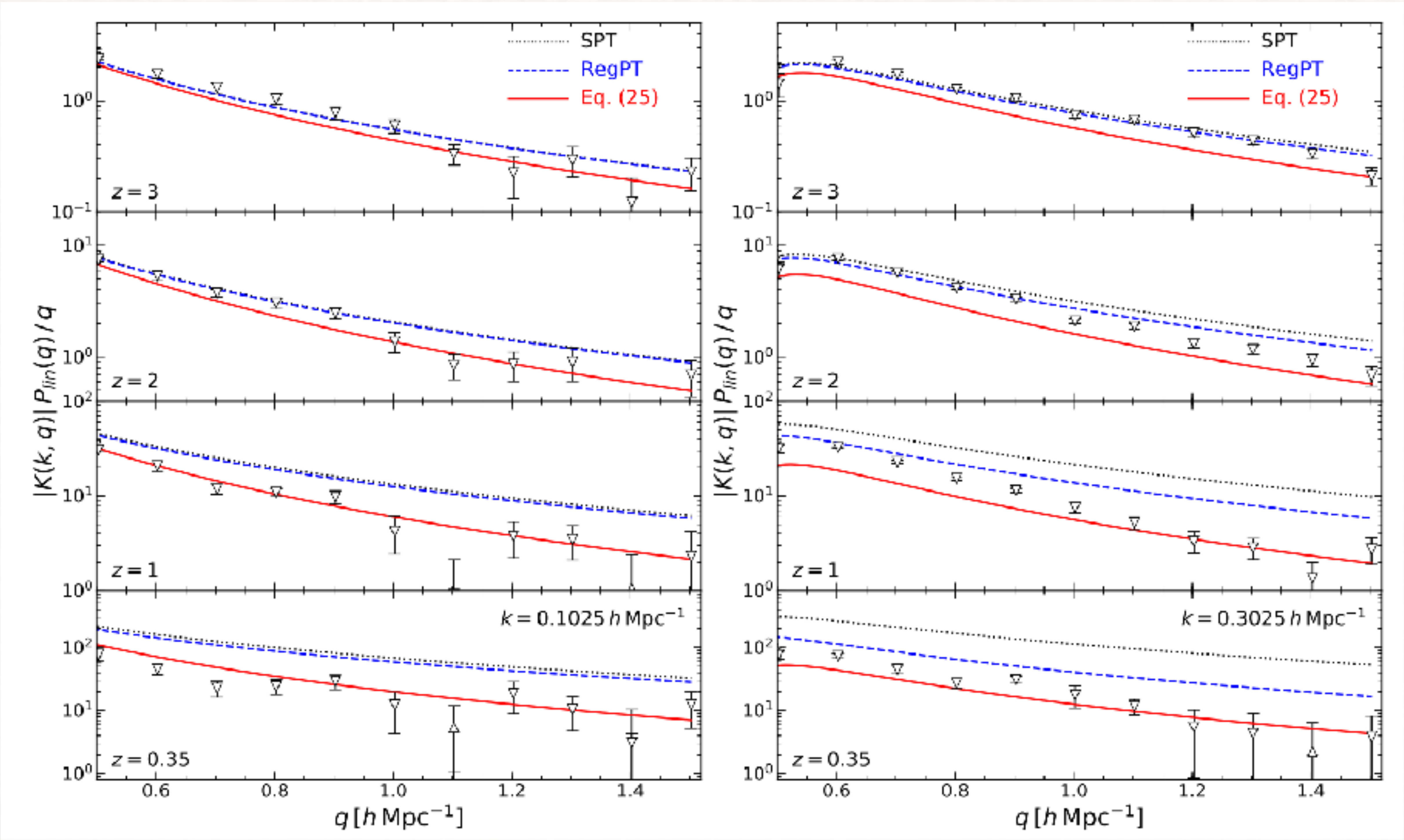
RESPONSE FUNCTION AT q~k

- Peaky structure decay as time goes by
- SPT behaves weirdly at late time
- RegPT has its strength in this regime
    - Efficiently captures mode transfer between nearby modes



RESPONSE FUNCTION AT k << q

- We need phenomenology here anyway!



OUR MODEL

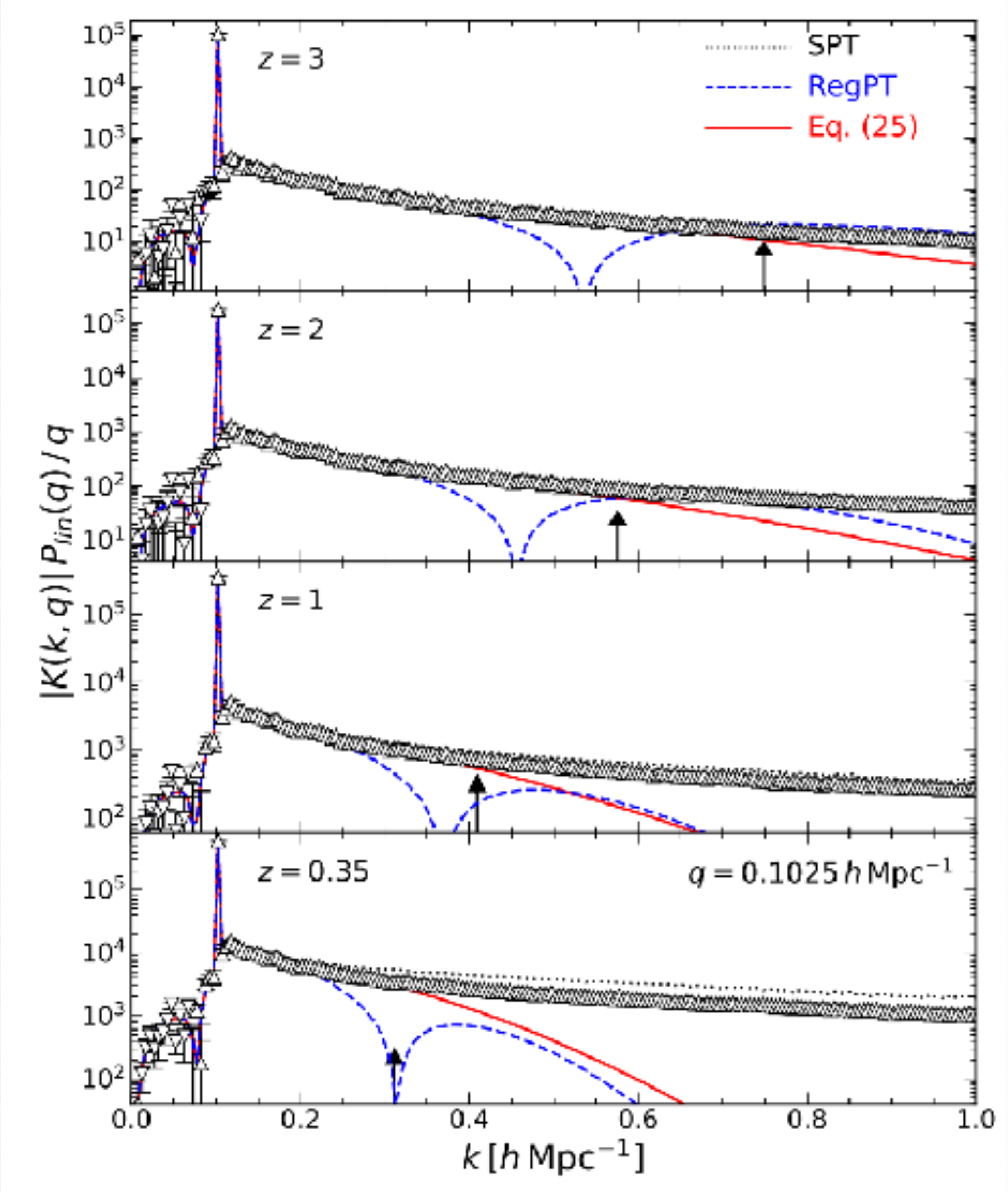
$$K_{\rm model}(k,q) = \Big[\big(1+\beta_{k,q}+\frac{1}{2}\beta_{k,q}^2\big)K^{\rm SPT}_{\rm tree}(k,q) + (1+\beta_{k,q})\,K^{\rm SPT}_{\rm 1\text{-}loop}(k,q) + K^{\rm SPT}_{\rm 2\text{-}loop}(k,q)\Big]D(\beta_{k,q}),$$

$$D(x) = \begin{cases} \exp(-x)\,, & \text{if } K_{\rm model}(k,q) > 0, \\ \dfrac{1}{1+x}, & \text{if } K_{\rm model}(k,q) < 0. \end{cases}$$

$$\beta_{k,q} = \alpha_k + \alpha_q$$ Regularize both in k and q

$$\alpha_k = \frac{1}{2}k^2\sigma_{\rm d}^2\,; \quad \sigma_{\rm d}^2 = \int \frac{dq}{6\pi^2}\,P_{\rm lin}(q),$$

- Well-behaved over all q
- Eventually fails at high k



PRACTICAL USAGE? RECONSTRUCTION

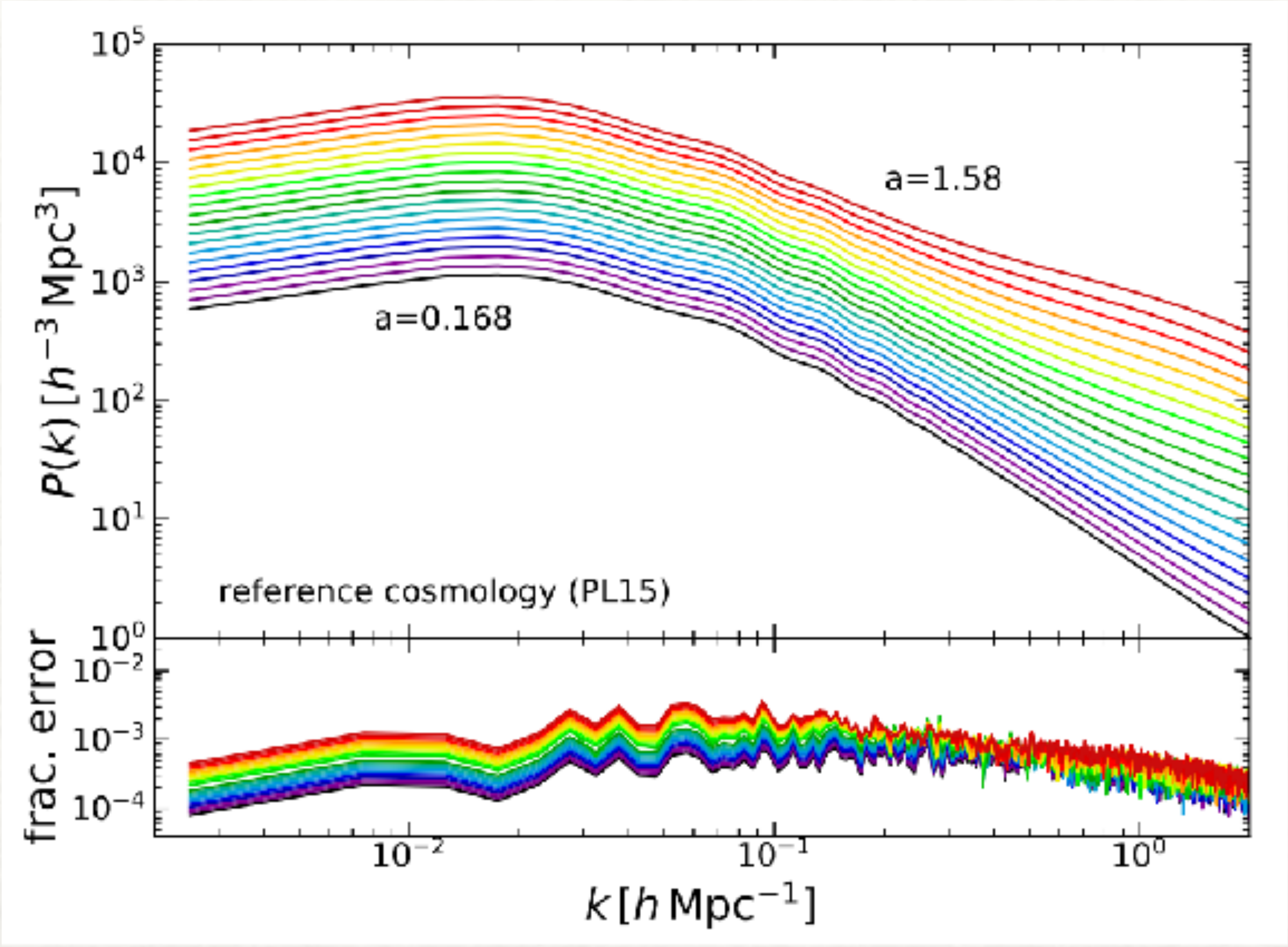
- From the definition of a functional derivative

$$P_{\rm nl}(k;\boldsymbol{p}_1) \approx P_{\rm nl}(k;\boldsymbol{p}_0) + \int {\rm d}\ln q\, K(k,q) \times \left[P_{\rm lin}(q;\boldsymbol{p}_1) - P_{\rm lin}(q;\boldsymbol{p}_0)\right],$$

- Use this to predict P_{nl} for cosmological model $\mathbf{p_1}$ given P_{nl} for another model $\mathbf{p_0}$

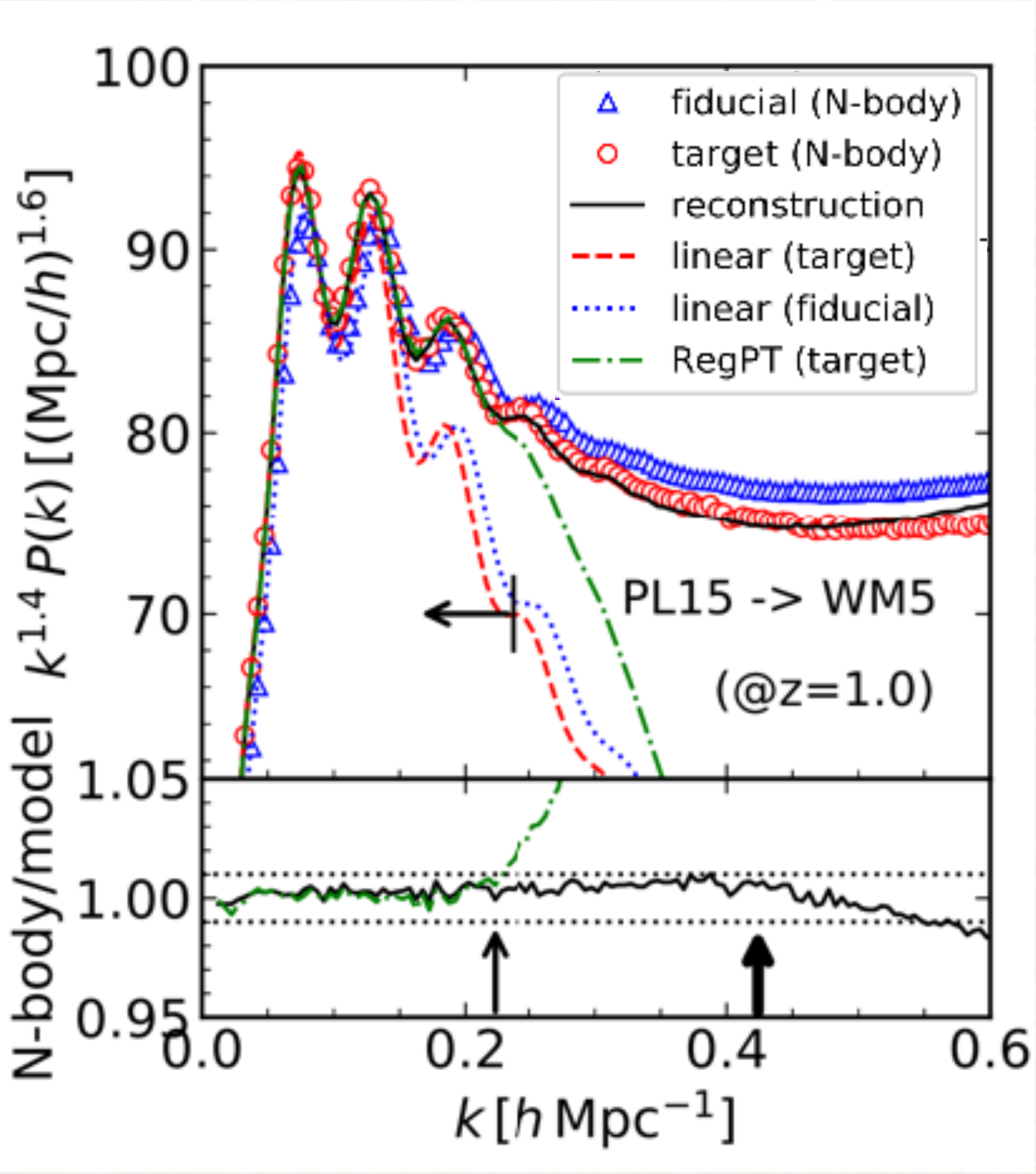
STARTING POINT: SIMULATION DATABASE

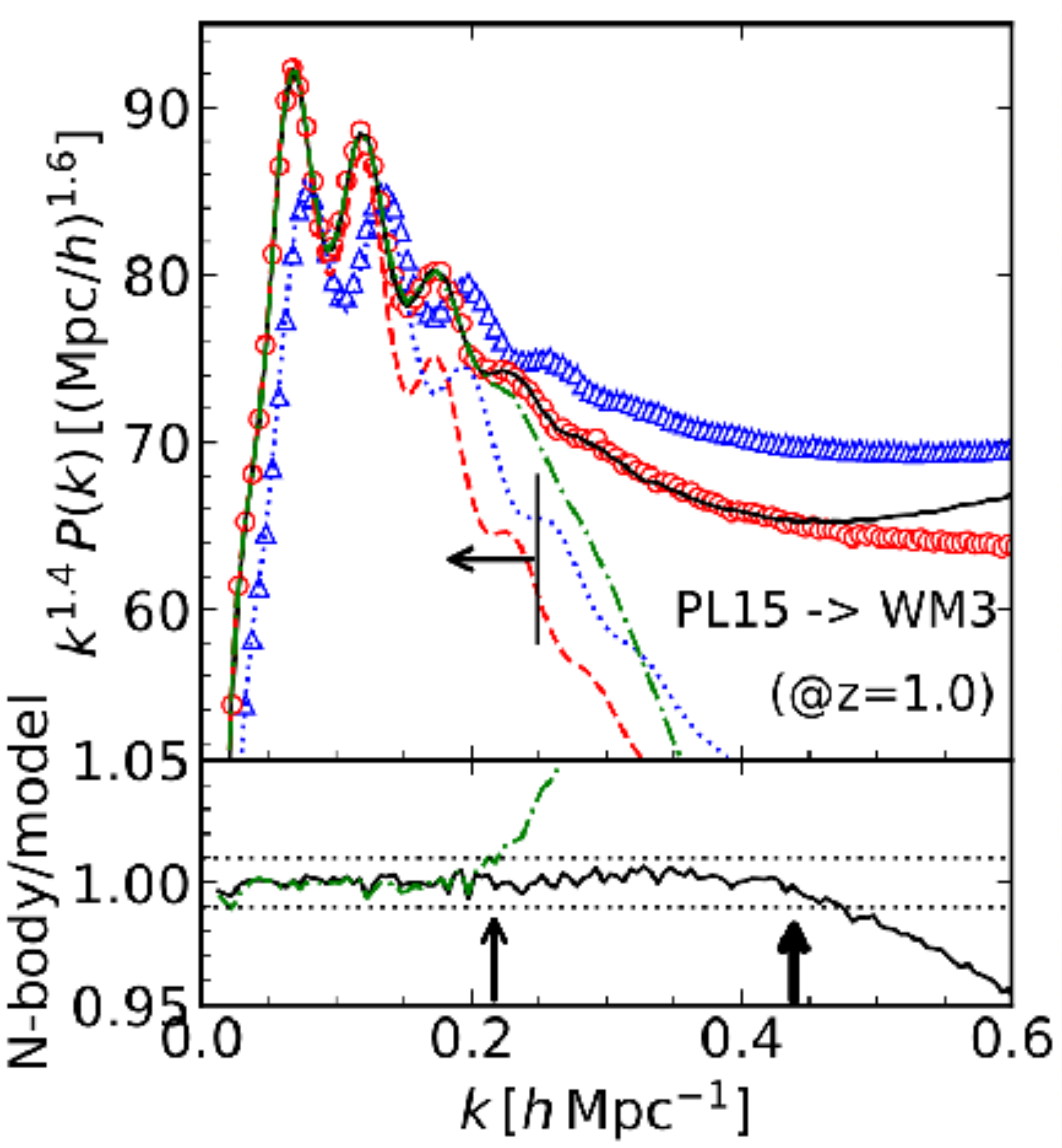
- P_{nl} database for the fiducial Planck 2015 cosmology from 10 x 2048^3 sims
  - Cosmic variance suppressed with Angulo-Pontzen technique
  - Fractional error < 0.1%
- Can smoothly interpolate over k and time



A SIMPLE IMPLEMENTATION

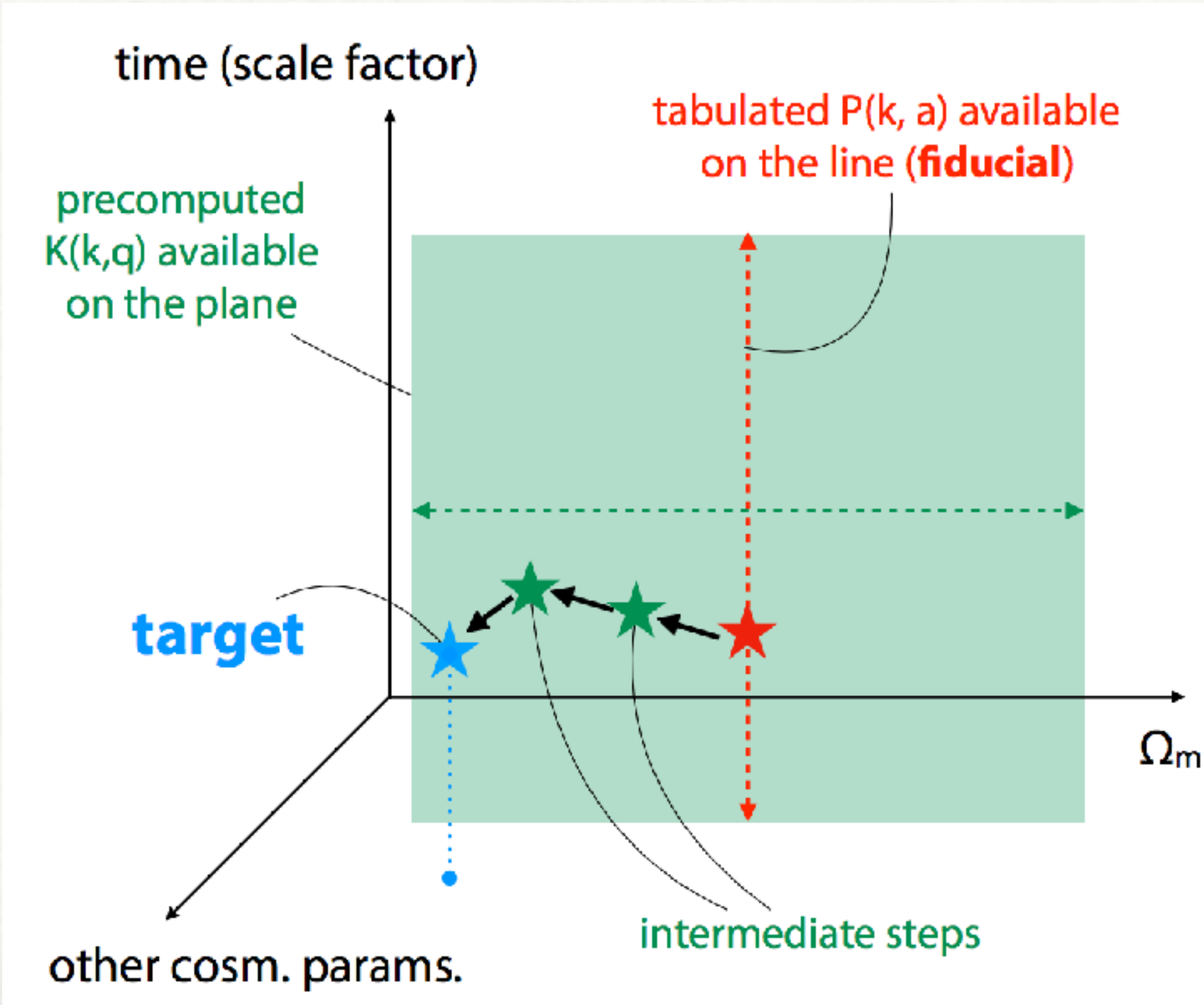
- Double the reliable k range from the pure RegPT prediction





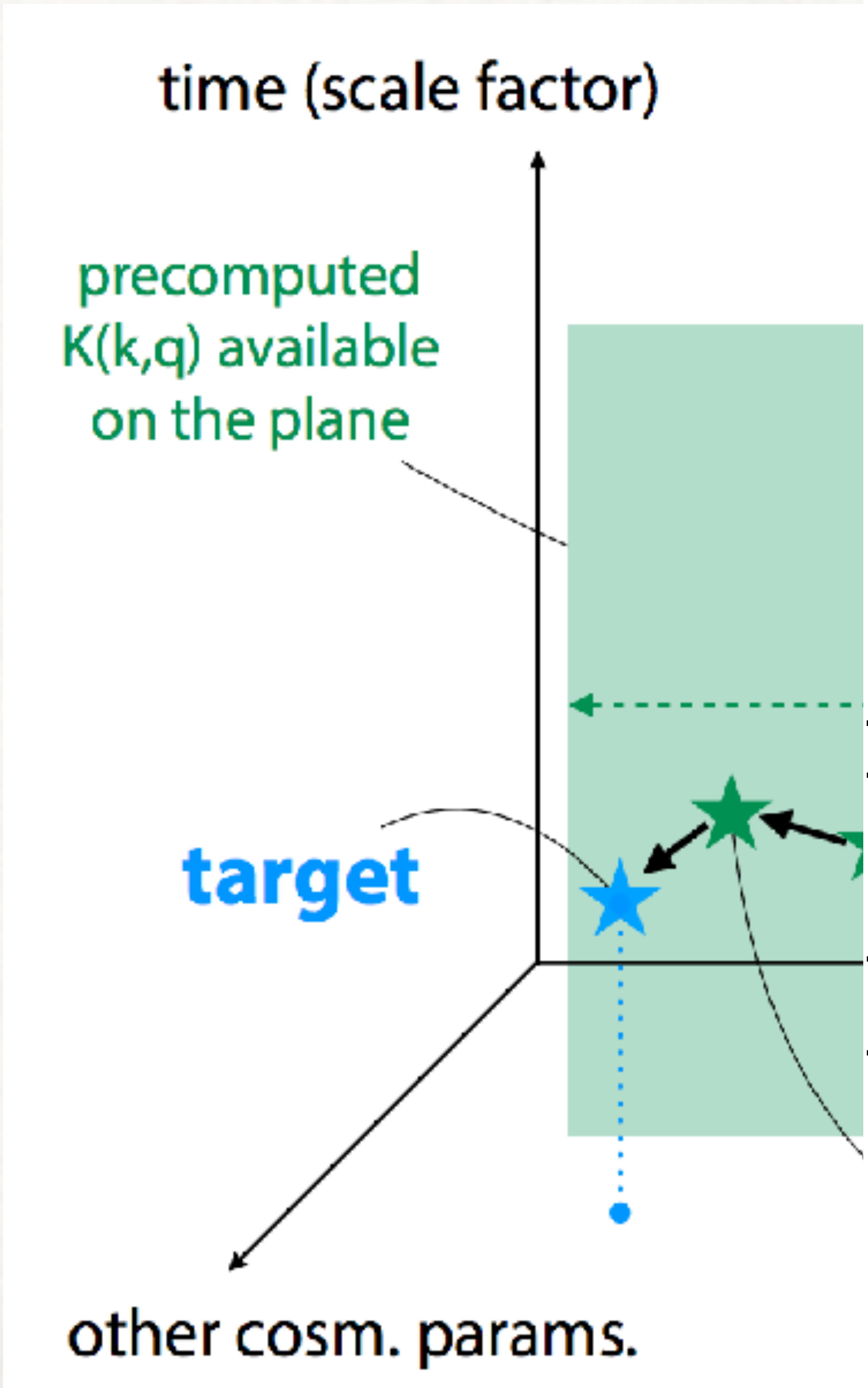
MORE EXTREME MODELS

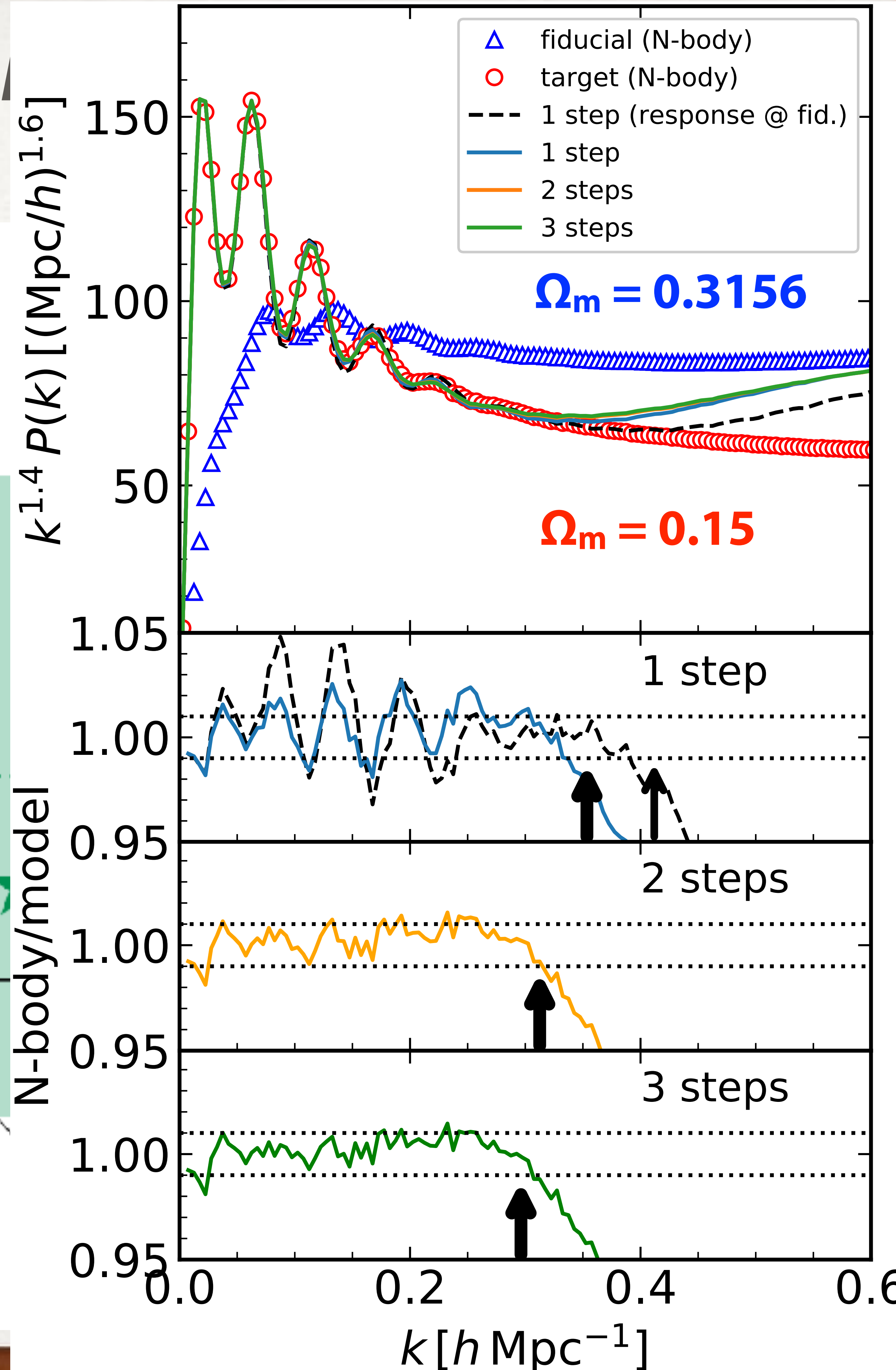
- Employ multi-steps



MORE EXTRE

- Employ multi-steps

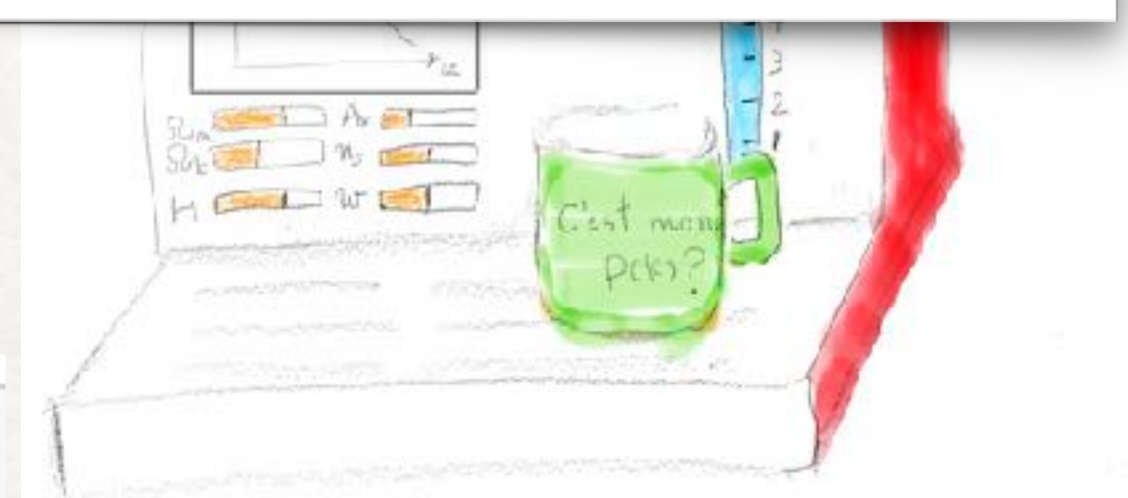




RESPRESSO PYTHON PACKAGE AVAILABLE!


```
In [7]: respresso_obj.find_path()
```

```
In [9]: kwave = respresso_obj.get_kinternal()
        pnl_rec = respresso_obj.reconstruct()
```



http://www-utap.phys.s.u-tokyo.ac.jp/~nishimichi/public_codes/respresso/

RESPRESSO PYTHON PACKAGE AVAILABLE!

(Rapid and Efficient SPectrum calculation based on RESponSe functiOn)

```
In [1]: %pylab inline
        import respresso
```

```
In [3]: respresso_obj = respresso.respresso_core()
        Hello. This is RESPRESSO.
        Load precomputed data files...
        RESPRESSO ready.
```

```
In [6]: respresso_obj.set_target(plin_target_spl)
```

```
In [7]: respresso_obj.find_path()
```

```
In [9]: kwave = respresso_obj.get_kinternal()
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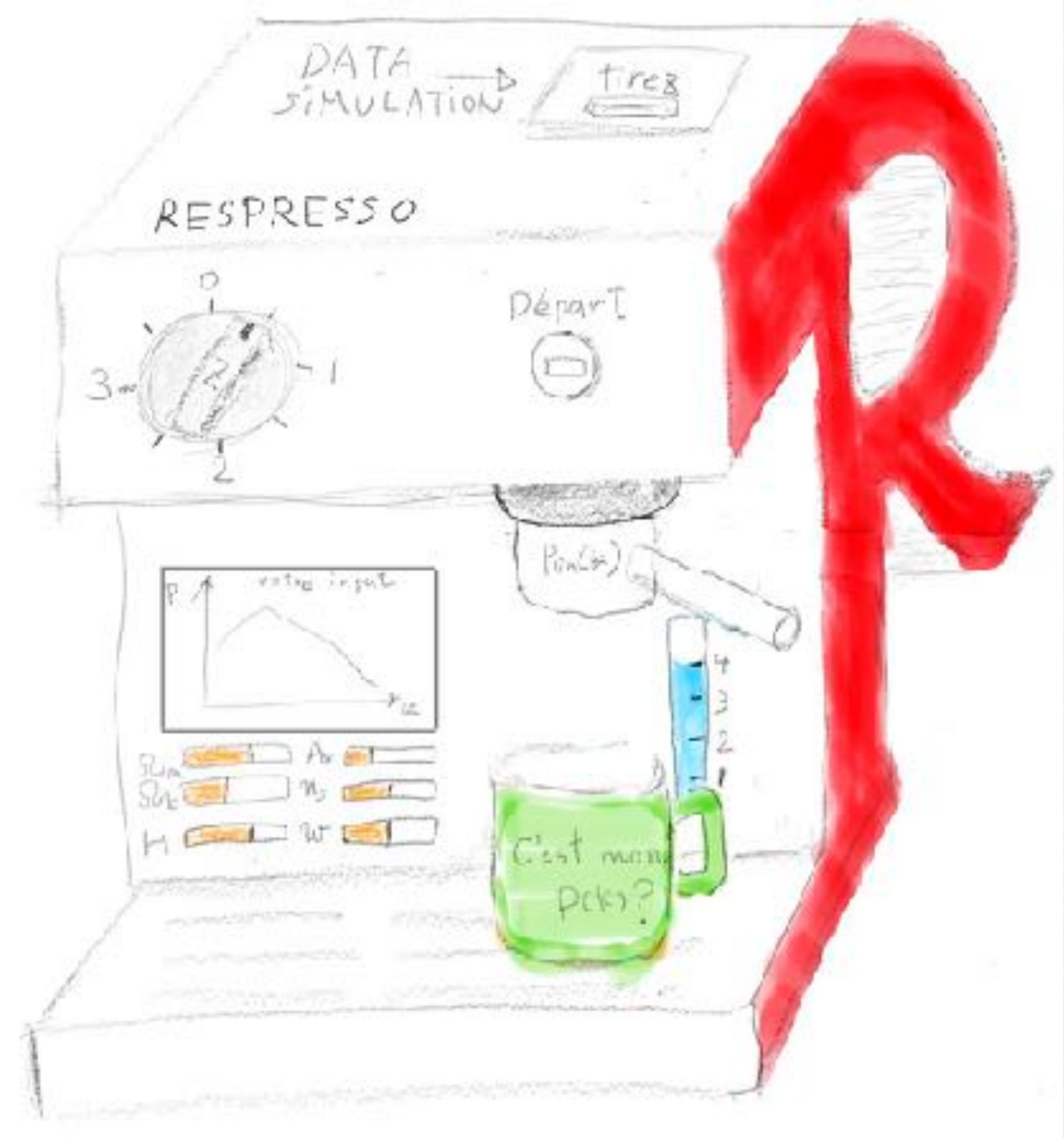

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SUMMARY

- P(k) to a 2D quantity K(k,q): more physical insight
  - MG simulations?
- Difficulty in perturbative approaches
  - Suppress small to large scale mode transfer!
  - SPT and RegPT behavior differently in different regimes
- RESPRESSO package available
  - Response function is a natural interpolator over the cosmological parameter space
  - Can go to k ~ 0.44 (0.35) h/Mpc at z=1 (0.5) within 1%
  - Can be generalized to general DE models (and maybe MG models, less obviously) as long as the linear power spectrum is close to the baseline model

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