The gas cosmological power spectrum in RAMSES

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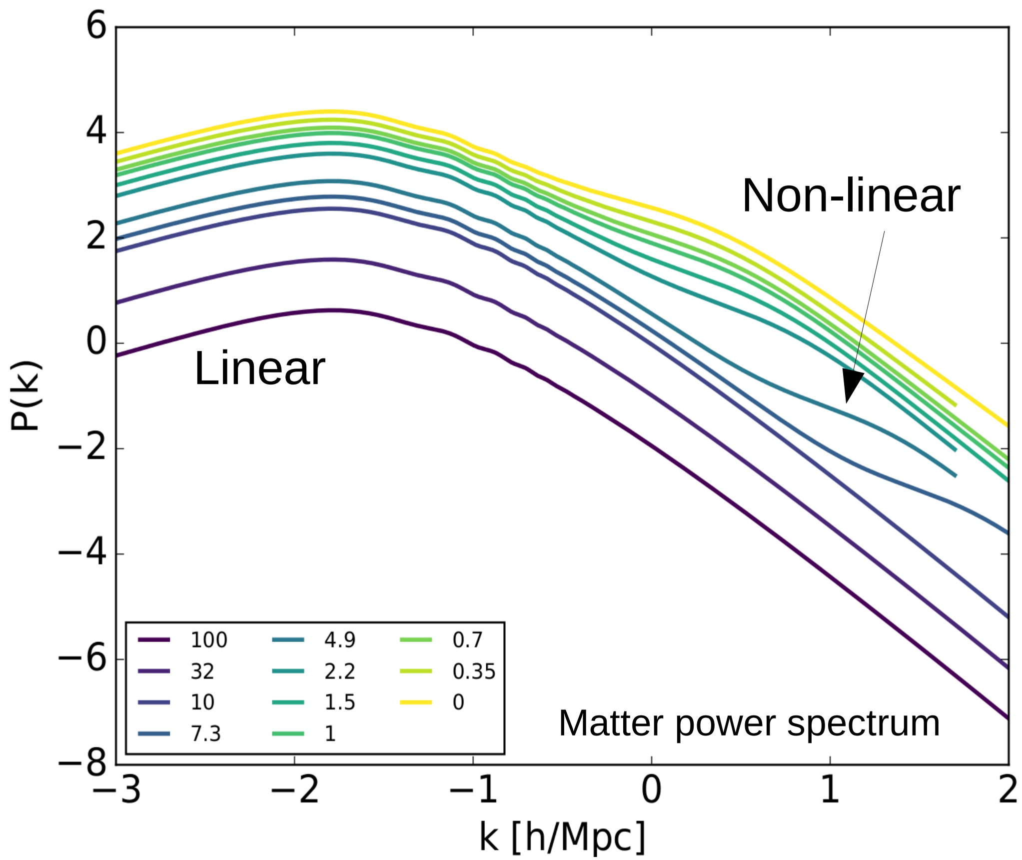
The cosmological power spectrum

- Measure of the contract of the density field on different scales
- Fourier transform on a uniform grid
- Map RAMSES output onto a regular grid (for dark matter and gas)

Initial exploration

- Cosmological simulations include dark matter & baryons
- Matter power spectrum evolves predictably (e.g HALOFIT+, Smith et al. 2003, Takahashi et al. 2012) even in the non-linear



Based on empirical fitting from simulations

Breaks down at high resolution

Tuned using N-body only simulations

Importance of initial resolution (ICs): Which resolution matters?

- **Experiment:** Using ICs with difference coarse grids (initial resolution)
  - set RAMSES to resolve in the same final resolution (max level)
- We can set the maximum refinement level
  - RAMSES only refines when it needs to (i.e. when the number of particles in a cell exceeds a threshold).

Simulation

- CAMB (Ade et al. 2015) initial conditions
- Uses MUSIC (Hahn et al. 2012)
- Plank cosmology (Lewis et al. 1999)
- Quasi-Lagrangian refinement

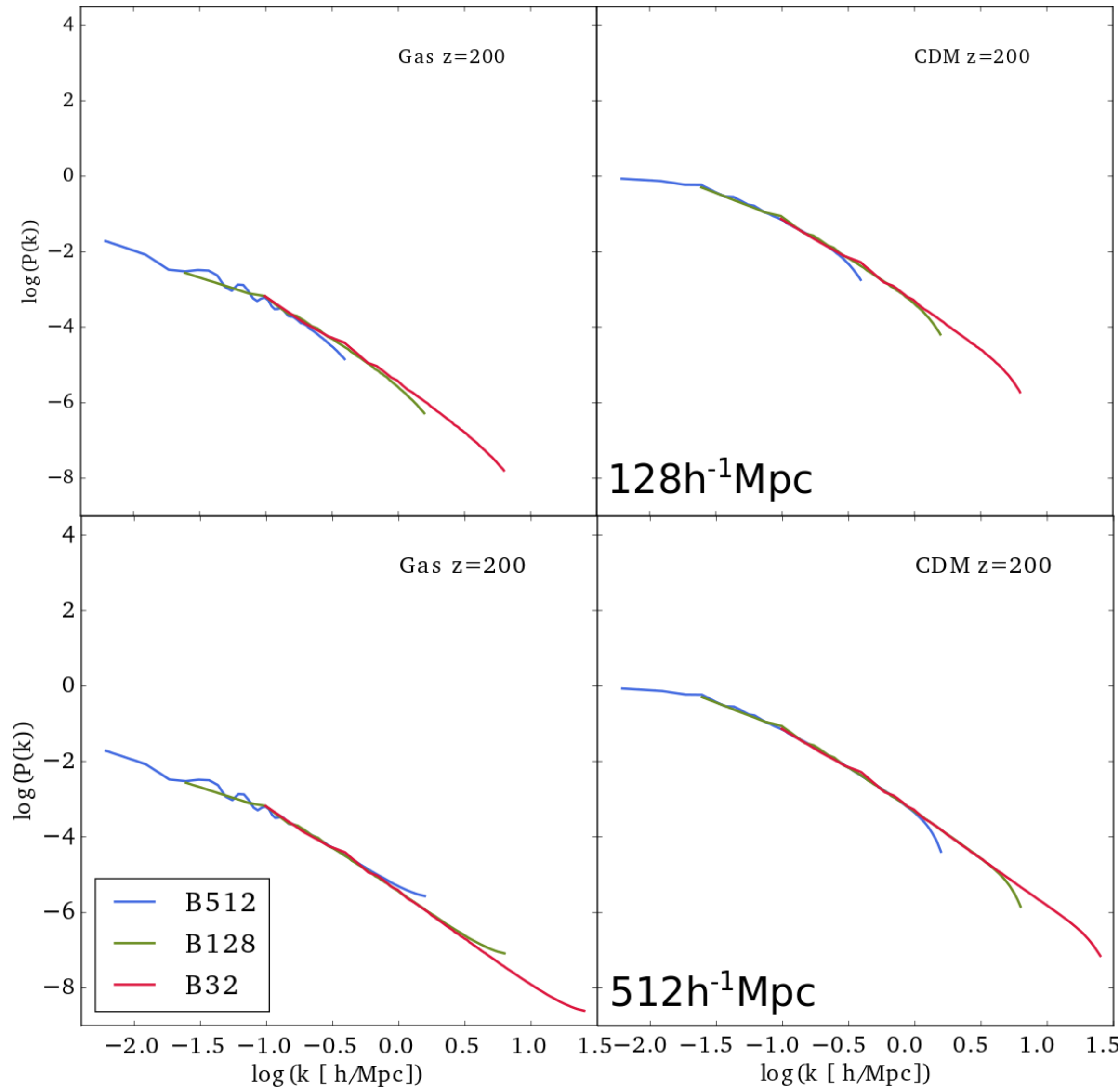
https://lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm

Initial exploration

- Three box sizes:
  - 512h^{-1} Mpc, 128h^{-1} Mpc, 32h^{-1} Mpc
- Set the same levelmax = 9 in each case
- Use different simulation boxes to probe different resolutions
-
- Also run ICs with missing high resolution modes
  - All ICs interpolated from the levelmin=9 ICs)

Results

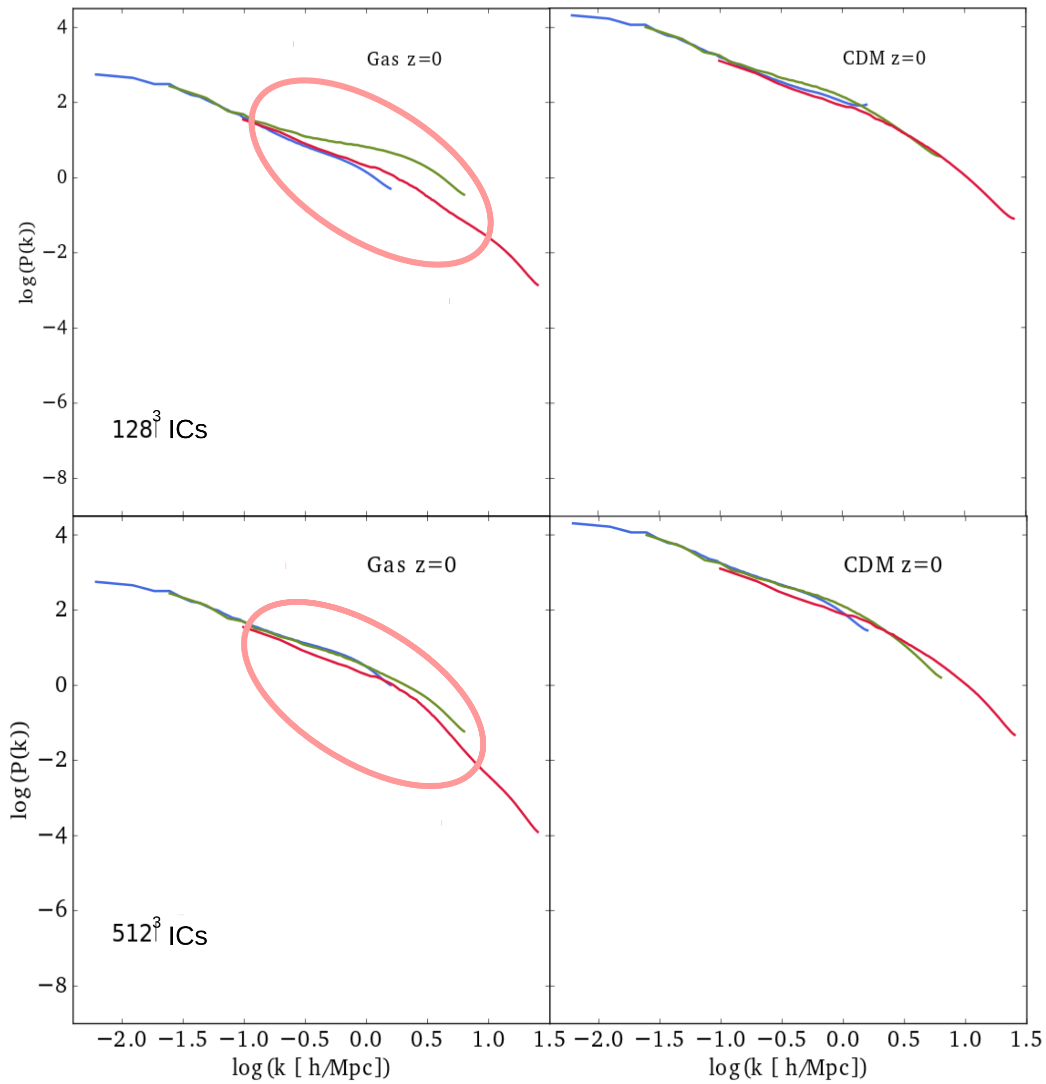
- Calculate P(k) on 512^3 grid
- Power spectra similar – just as we'd hope
- Some differences on small scales



Initial power spectra for dark matter and gas

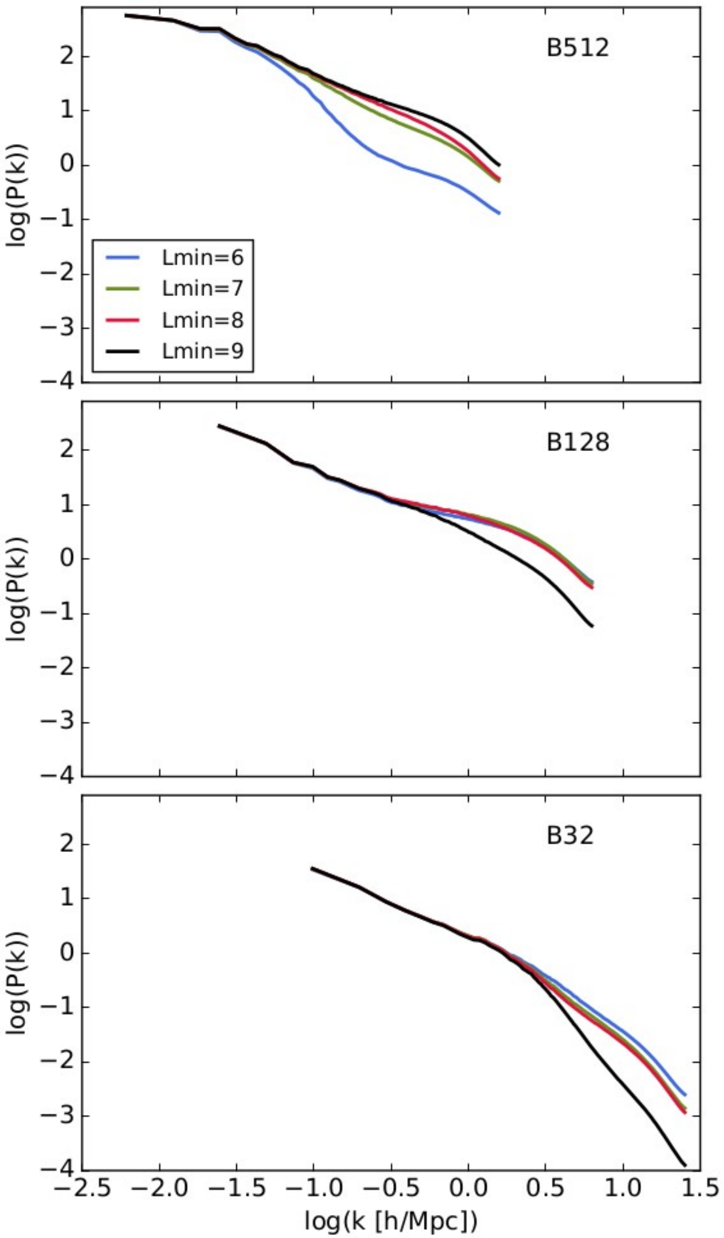
Results

- For the dark matter:
  - Good match between different volumes
  - Similar results at different resolutions
- For the gas:
  - Low resolution shows excess at low resolution
  - No-AMR case shows reasonable fit.



Results

- In the largest box increasing the IC resolution results in convergence towards the Lmin=9 (no-AMR) case
- On smaller scales there is a distinct separation



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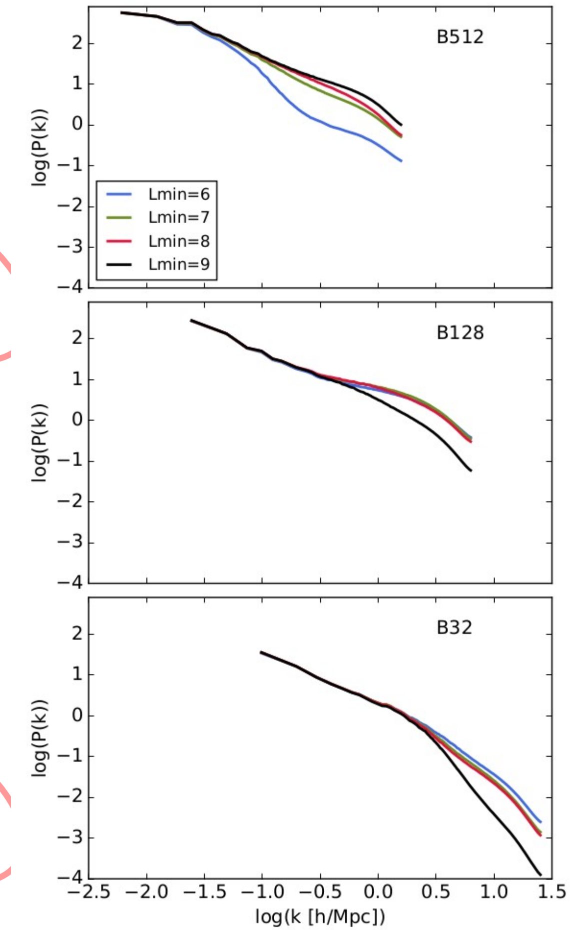

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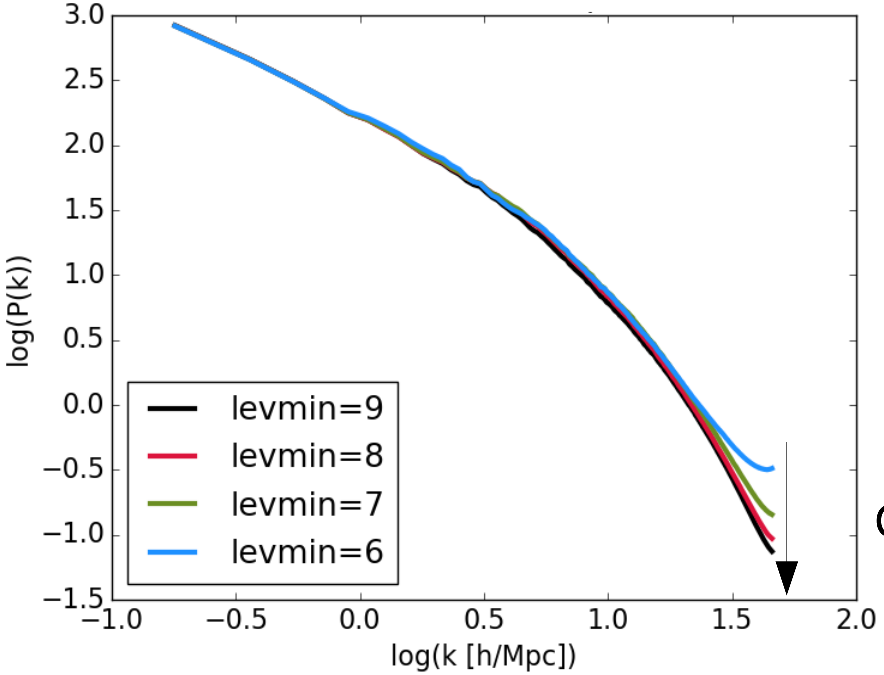


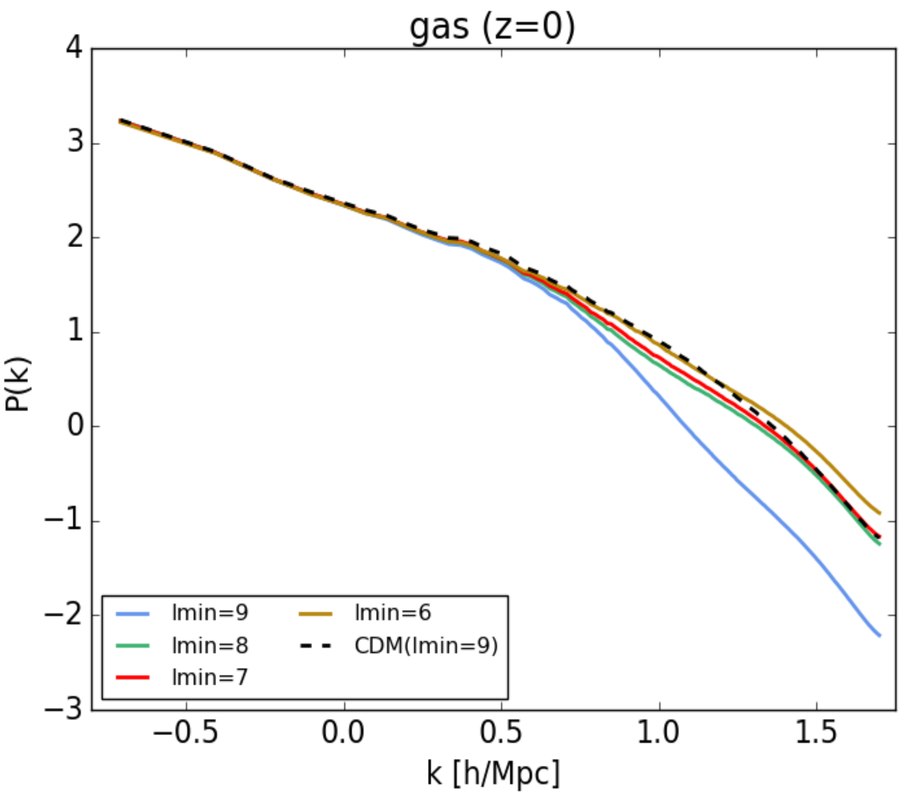
Dark Matter power spectrum at z=0 for the 4 simulations with coarse grids 2^levmin

Convergence

- At z=0 the dark matter profiles are similar
- No strong effect due to oversmoothing (e.g. O’Shae et al. 2005)
- Converge to 512^3 on small scales

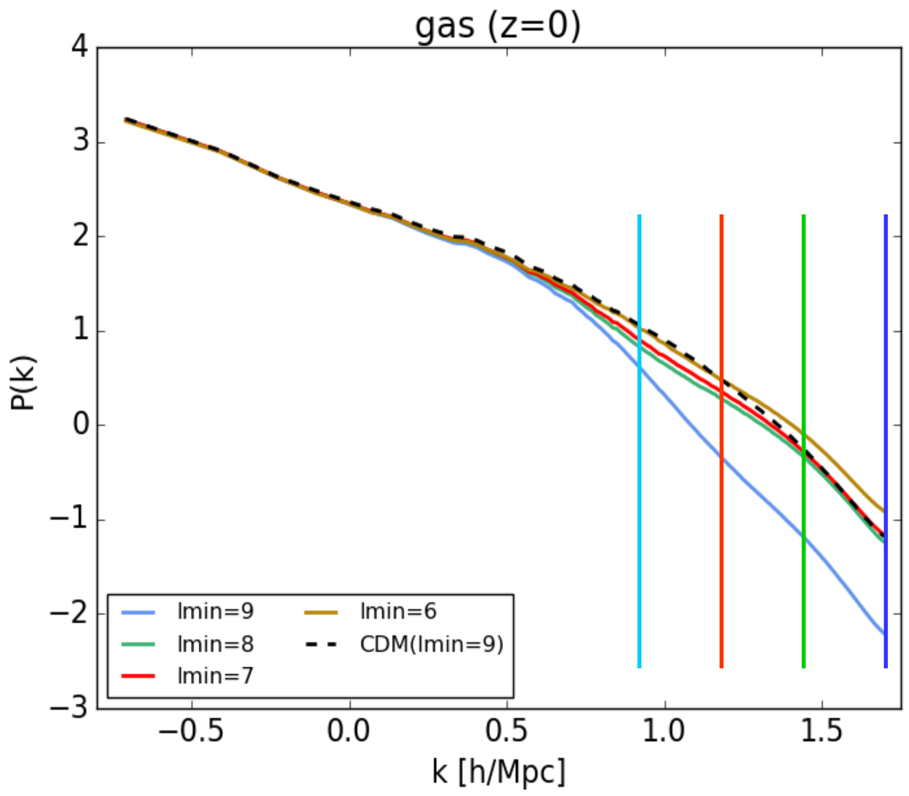
Results

- From the 32 Mpc box →
- With AMR cases match
- Diverge from the no-AMR case by a factor of 10
- Gas matches DM in AMR case
- Origin of discrepancy?



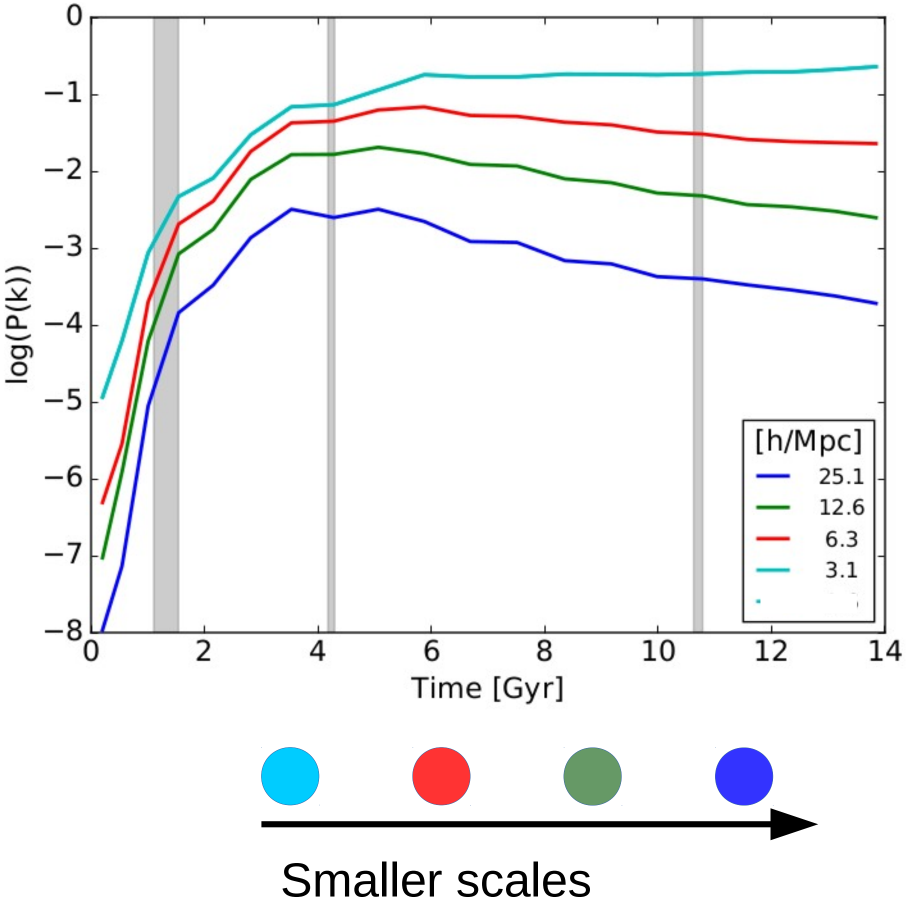
Results

- Evolution
  - Pick certain k values and see how they evolve through time
  - When does the difference between AMR and non-AMR manifest?



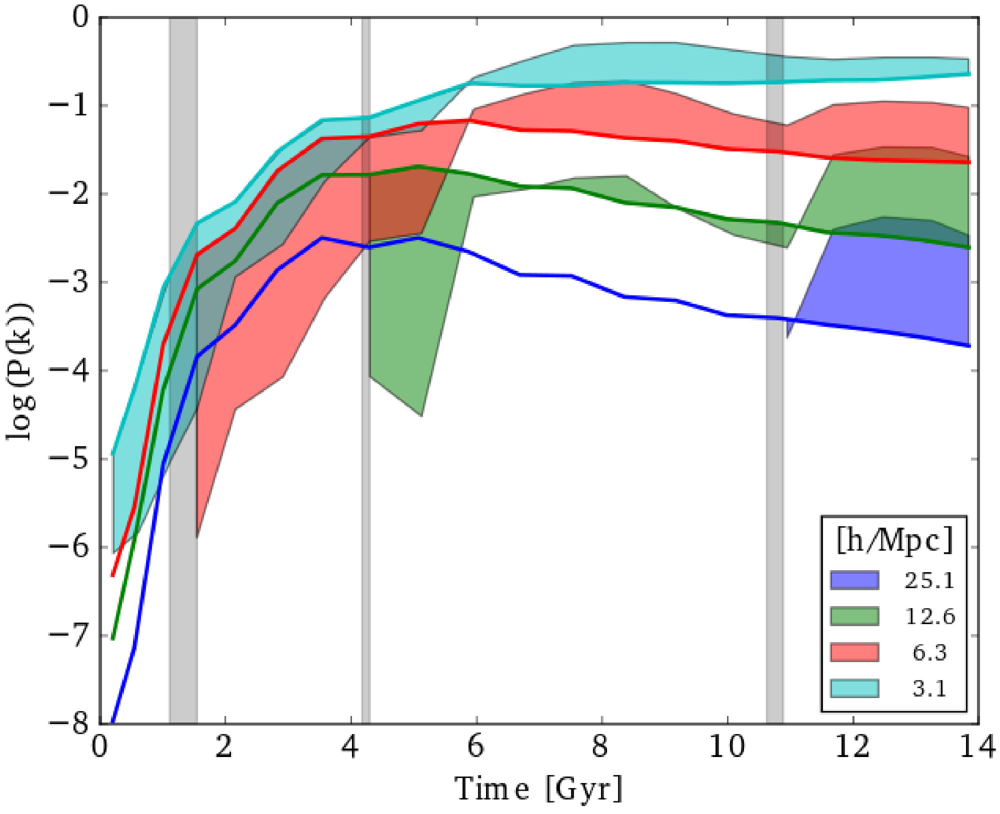
Results

- For the no-AMR simulation in the $32h^{-1}$ Mpc box
- Well behaved evolution at different scales
- On small scales maximum power is at 4 Gyr



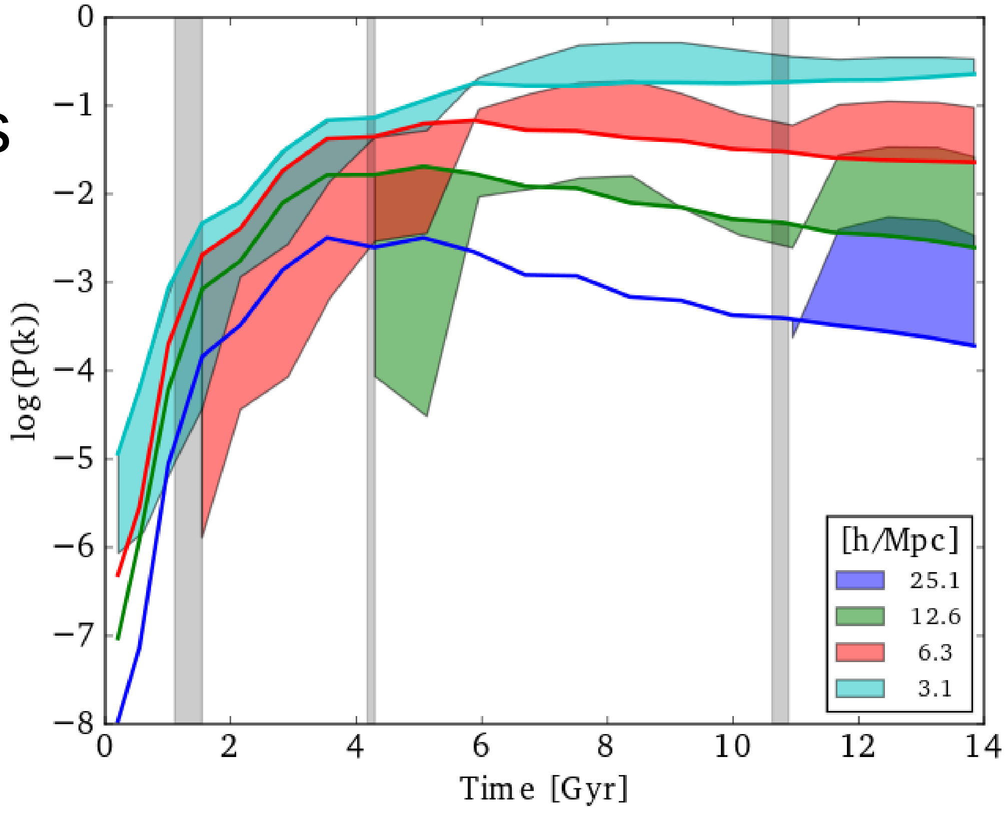
Results

- Evolution
  - Compare the Lmax=6 wit the no-AMR case
  - Grey lines show when refinement occurs
  - Shade region is the difference between the AMR and non-AMR case



Results

- Evolution
  - When refinement occurs the gas distribution is strongly affected
  - The last refinement 'kicks' the power spectrum away from the non-AMR case
  - Earlier refinement kicks the power spectrum towards the non-AMR case



Cause

- Cooling!
- Refinement based on physical units so refines as time advances
- Causes increase in density
- Density = cooling
- Need feedback etc. to mitigate this – or improved cooling

Conclusions

- Gas and dark matter power spectra are different in the non-AMR case
- Similar in the with-AMR case
- Gas sensitive to refinement strategy & cooling