Cosmology

as a search for neutrinos and new light particles

Amol Upadhye
UNSW Sydney
December 3, 2019

Why look for neutrino masses?

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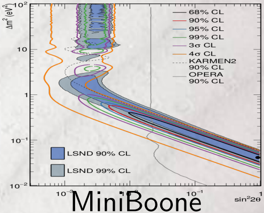

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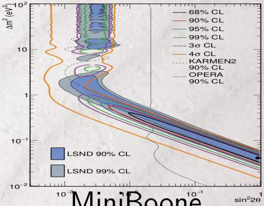
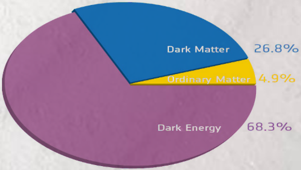


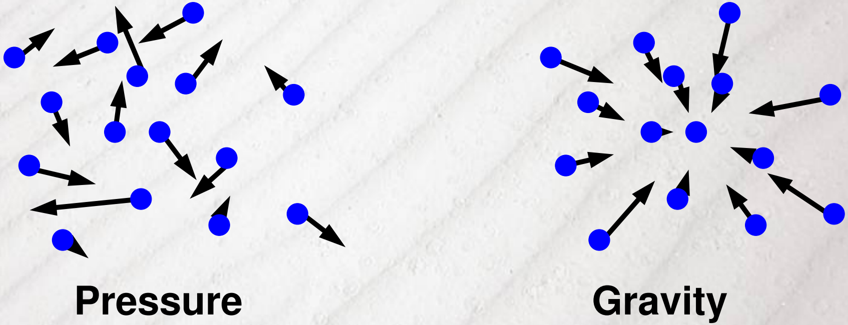
MiniBoone

3. Neutrinos affect overall structure growth, hence constraints on the dark matter and dark energy.



Pressure vs. Gravity

Once a density fluctuation has begun to evolve, its growth is a competition between pressure and gravity.



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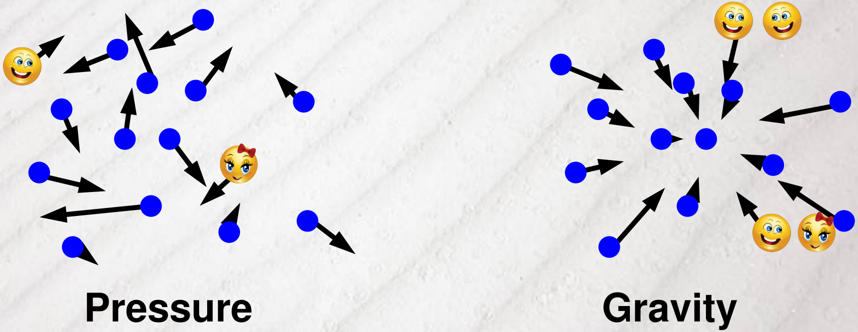

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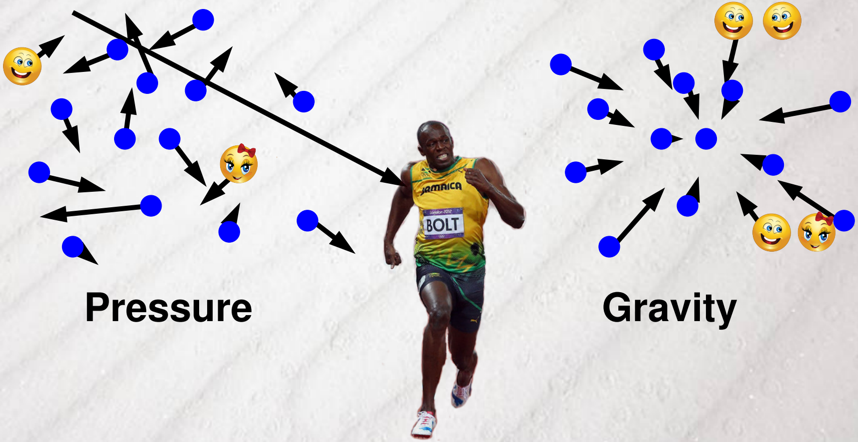
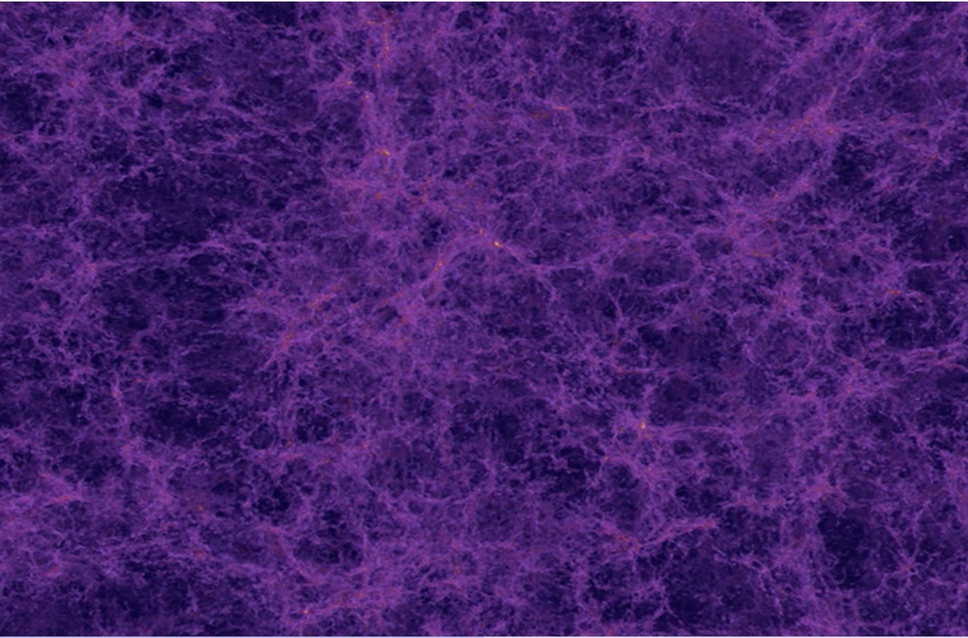
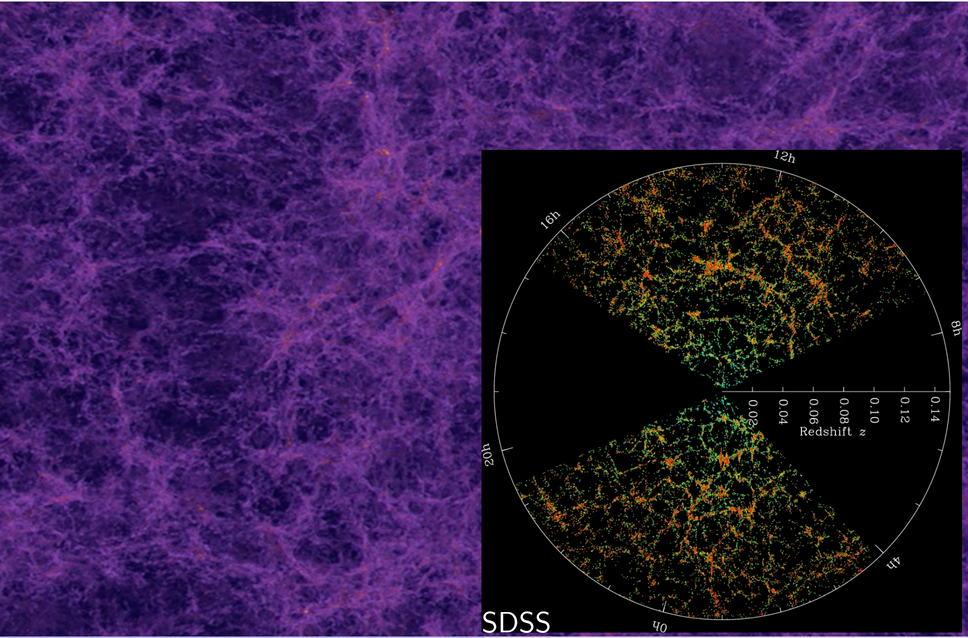


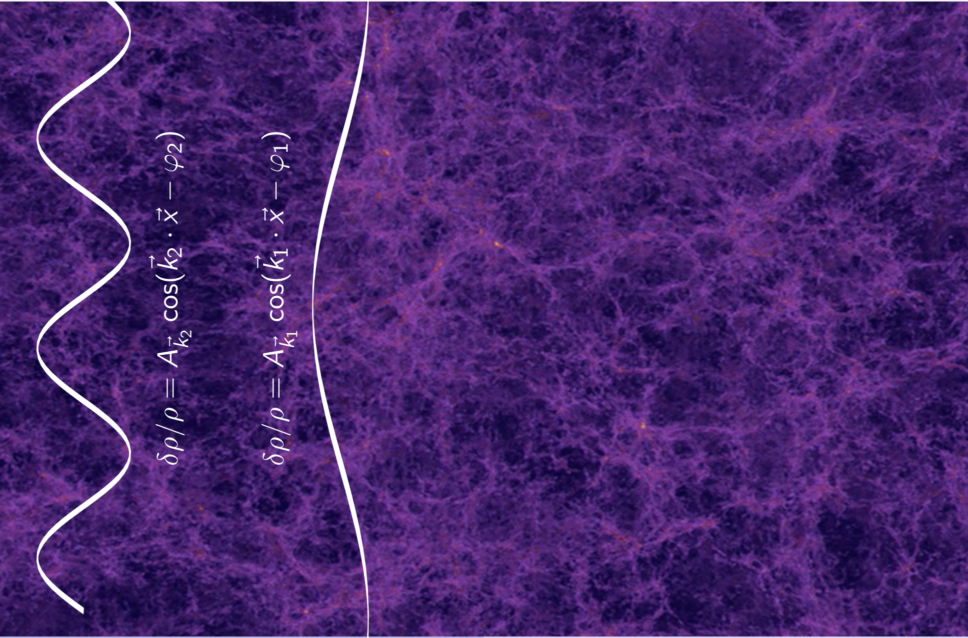
The Cosmic Web



The Cosmic Web has been observed



Amplitudes of individual modes



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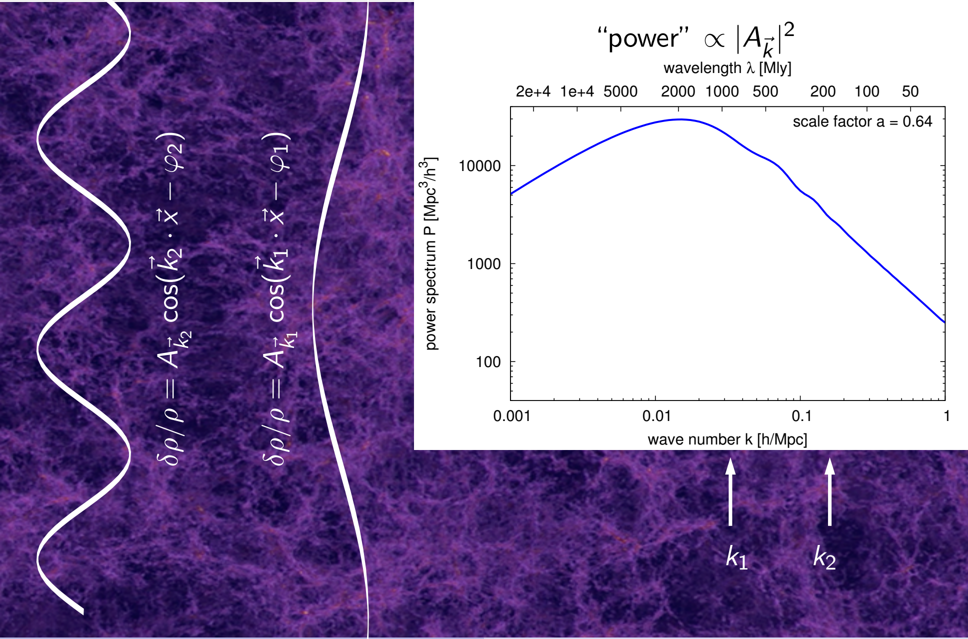

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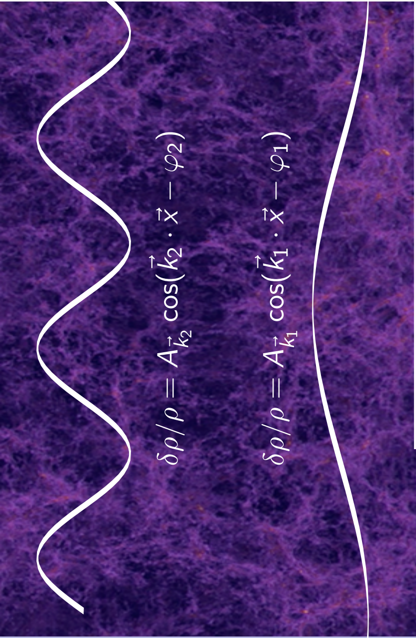

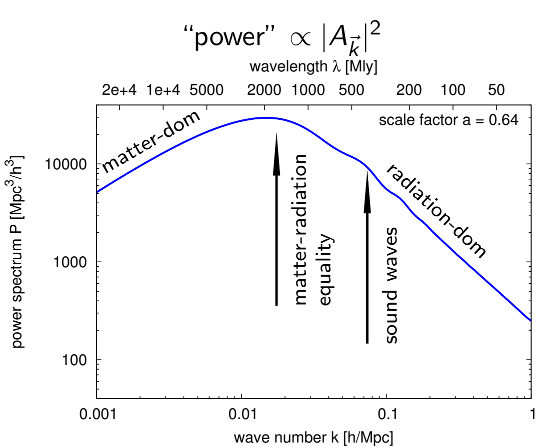

Fluid equations and power spectrum evolution

- Continuity equation: Mass is conserved. A change in density locally must be balanced by an inflow or outflow.

$$\frac{1}{a^3}\frac{\partial(a^3\rho)}{\partial\tau} + \vec{\nabla}\cdot(\rho\vec{v}) = 0$$

- Euler equation: Changes in the velocity of a fluid element are driven by gradients in the gravitational potential.

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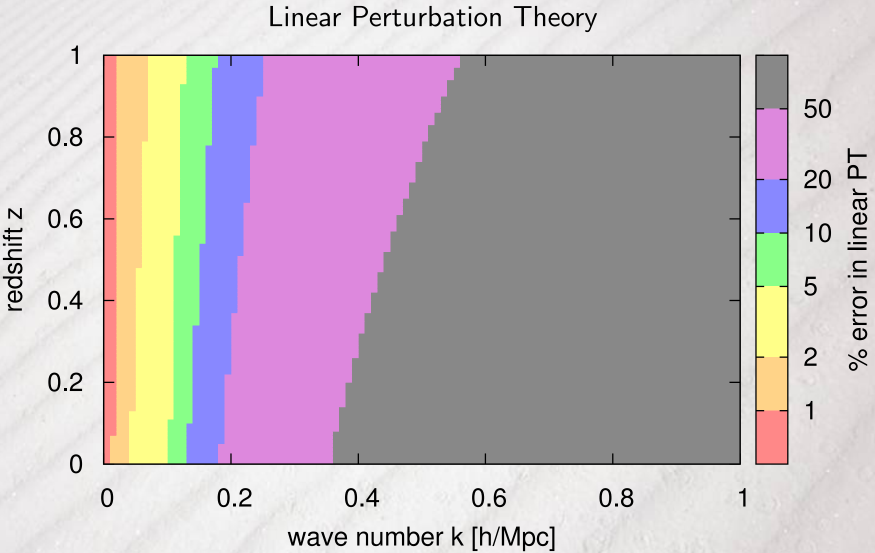
First-order terms give the growth factor (upwards shift).
Second-order terms give smaller higher-order corrections.

How accurate is perturbation theory?



Pietroni, JCAP **0810***:036(2008)*; *Carlson, White, Padmanabhan, PRD* **80***:043531(2009)*; *AU, Biswas, Pope, Heitmann, Habib, Finkel, Frontiere, PRD* **89***:103515(2014)[1309.5872]*

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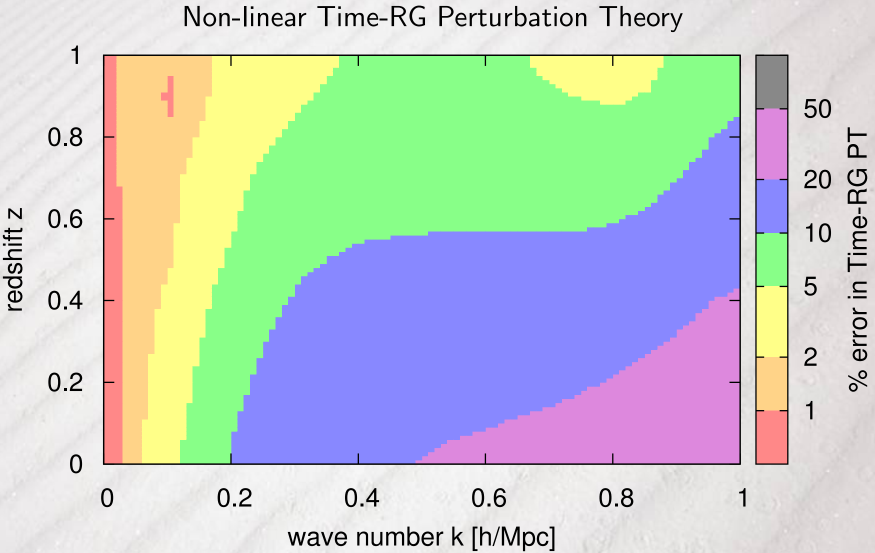

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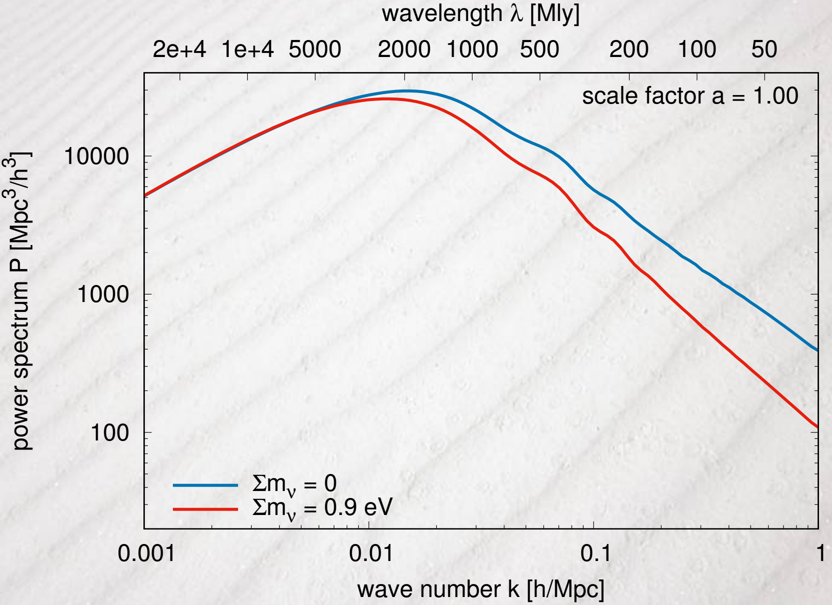
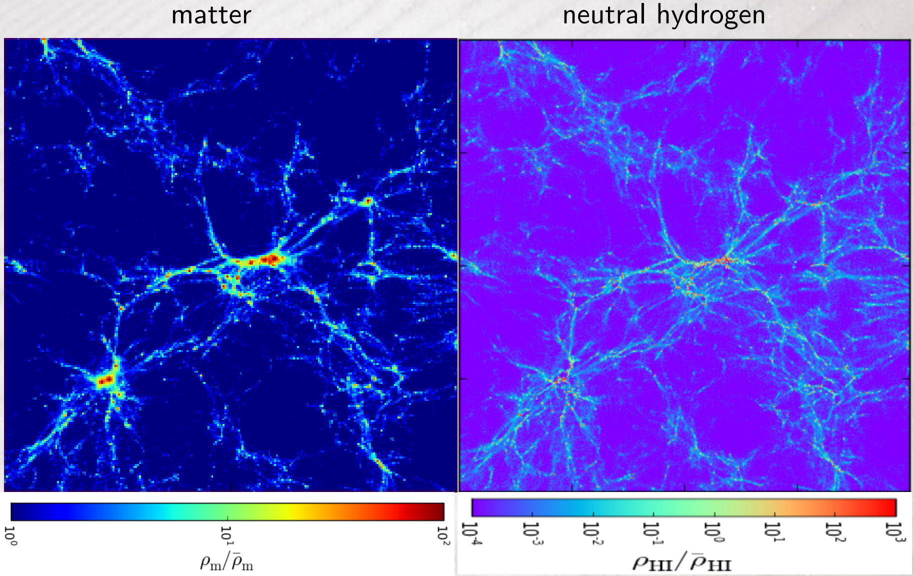
Power spectrum with massive neutrinos



AU, et al., PRD **93***:063515(2016)[1506.07526]*
AU, JCAP 1905:041 (2019)[1707.09354]
`github.com/upadhye/redTime`

What does this suppression do to the cosmic web?



Villaescusa-Navarro, Bull, Viel, Ap.J. **814***:146(2015)[1507.05102]*

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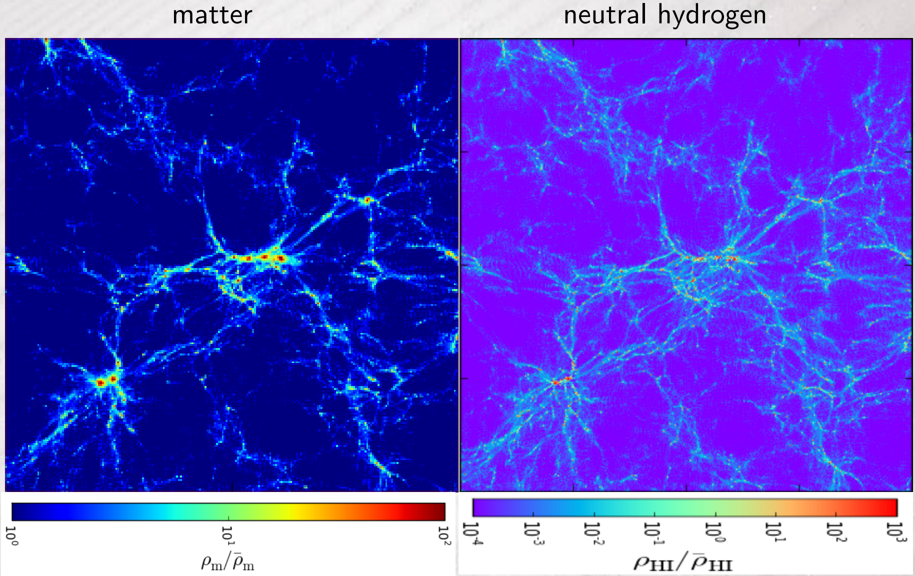
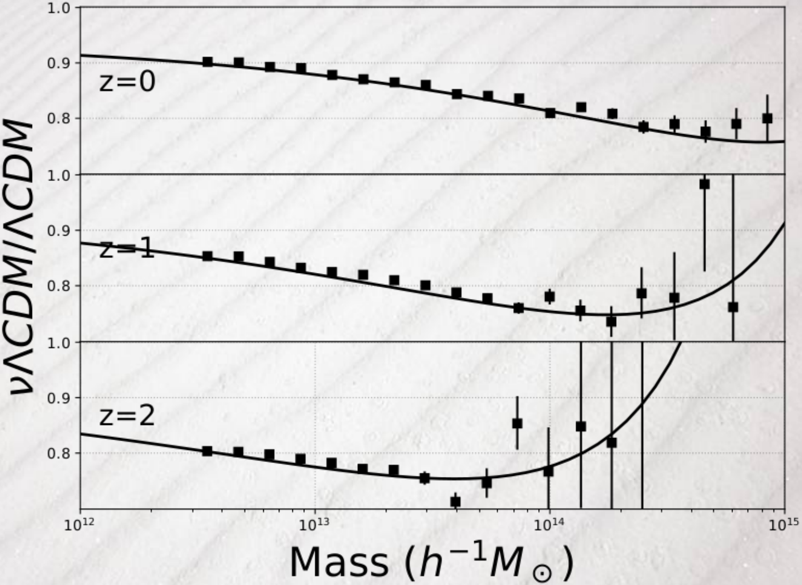


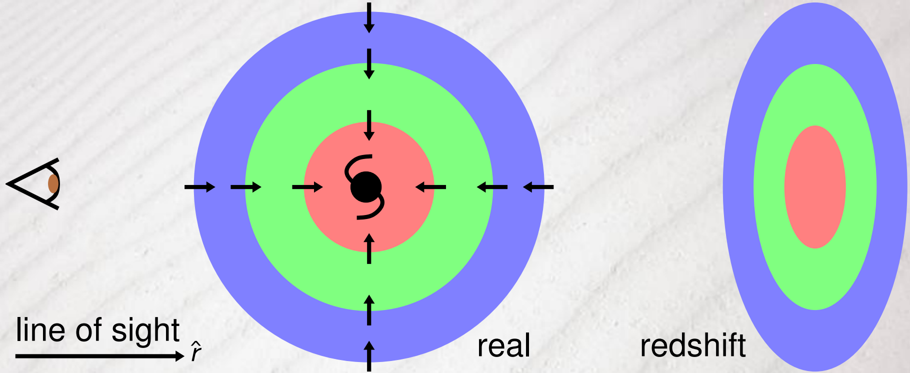
Villaescusa-Navarro, Bull, Viel, Ap.J. **814***:146(2015)[1507.05102]*

What does this suppression do to dark matter halos?



Biswas, Heitmann, Habib, AU, Pope, Frontiere (2019) [1901.10690]

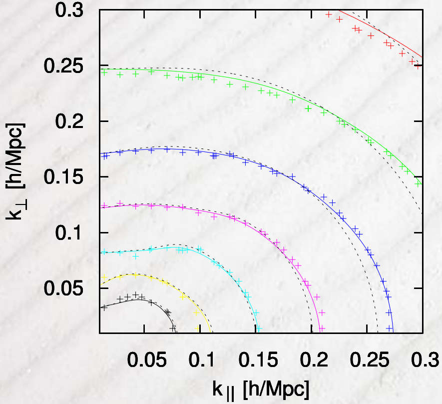
Redshift-Space Distortions (RSD)



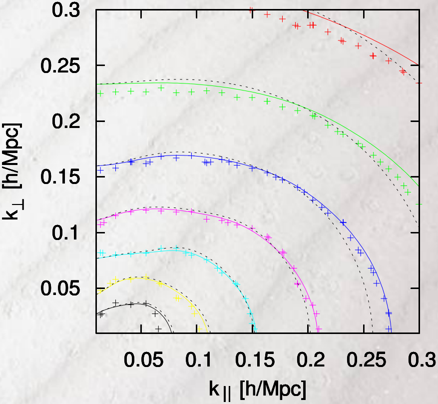
Redshift-space position: $\vec{s} = \underbrace{\hat{r}\int_0^z \frac{dz'}{H(z')}}_{\text{homogeneous-universe distance}} + \underbrace{\frac{\hat{r}\cdot\vec{v}_{\rm pec}}{aH}}_{\text{distortion}}$

RSD in massive neutrino models ($z = 1$)

ΛCDM
$\Sigma m_\nu = 0.94$ eV



$w_0 + (1 - a)w_a$ with
$w_0 = -1.2,\ w_a = -1.1$
$\Sigma m_\nu = 0.29$ eV



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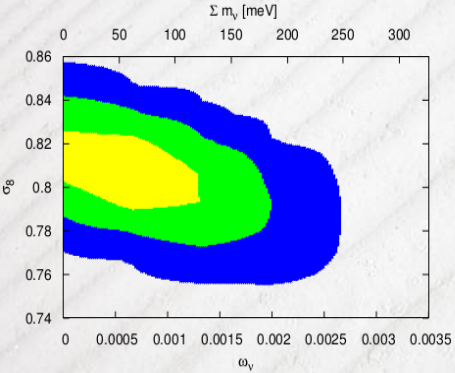
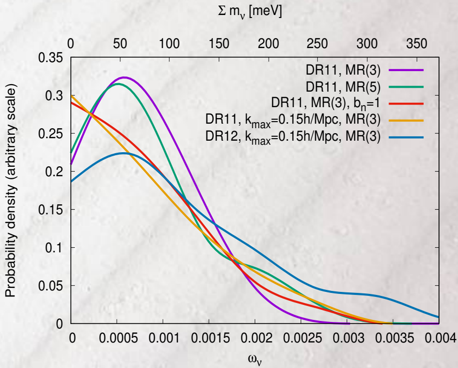
Massive neutrino constraints I

Application of `redTime` to BOSS DR11 and DR12 galaxy redshift data plus Planck data for the $\nu\Lambda$CDM model: $\sum m_\nu < 0.18$ eV (95%CL)

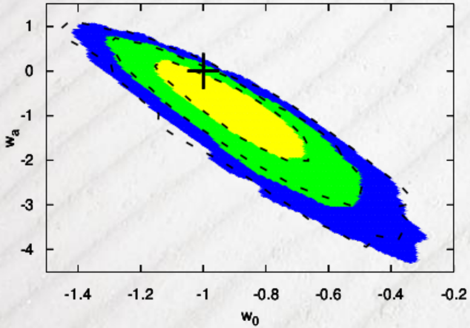


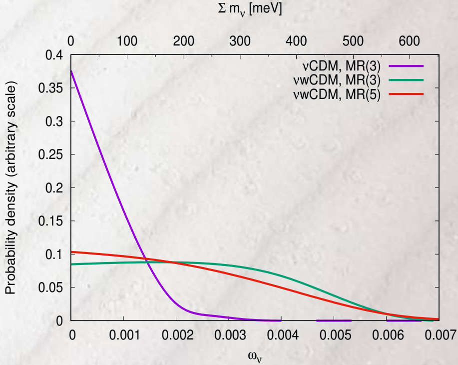


AU, JCAP 1905:041 (2019)[1707.09354]

Massive neutrino constraints II

Application of `redTime` to BOSS DR11 galaxy redshift data, Planck, and SN Ia for the νwCDM model: $\sum m_\nu < 0.54$ eV (95%CL)





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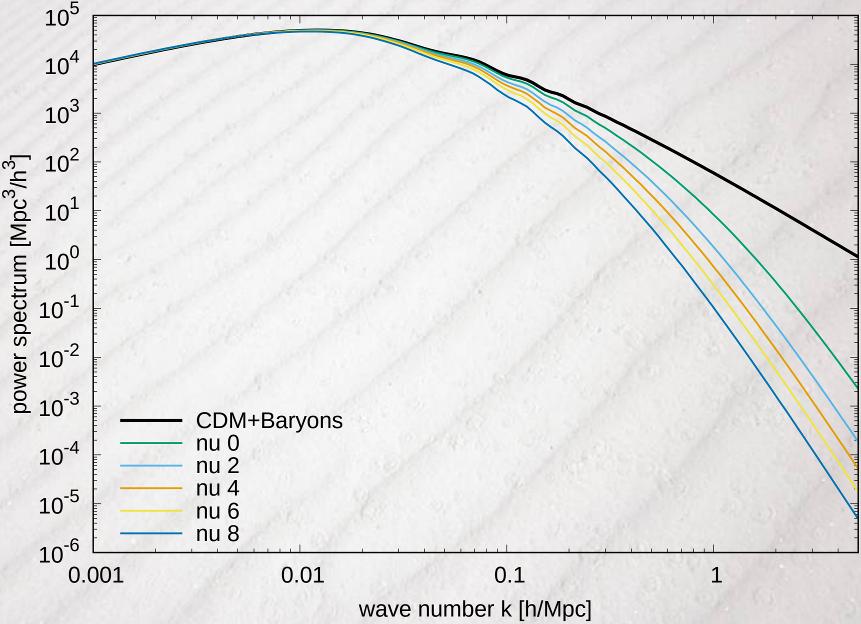
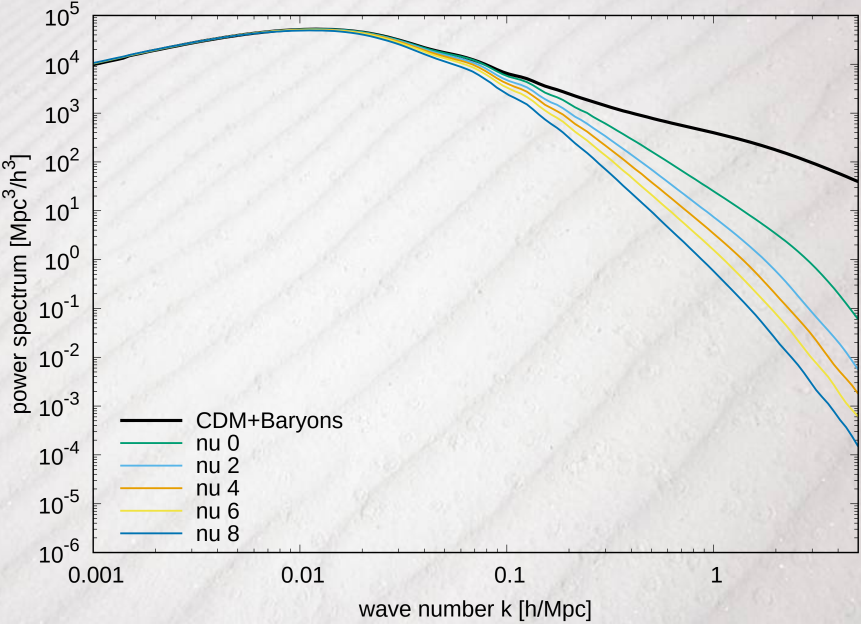
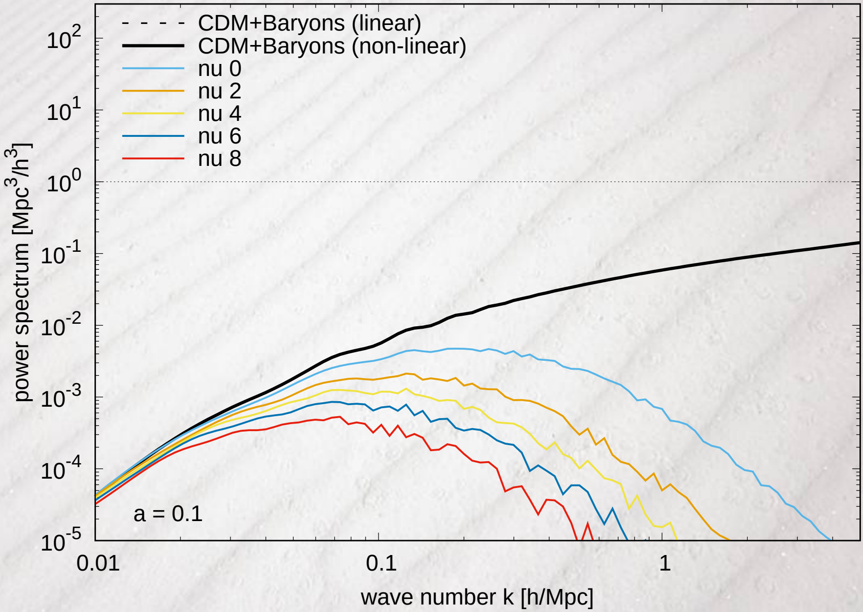
Next step: Neutrinos as multiple fluids



Next step: Neutrinos as multiple fluids: Linear response



But when do neutrinos go non-linear?



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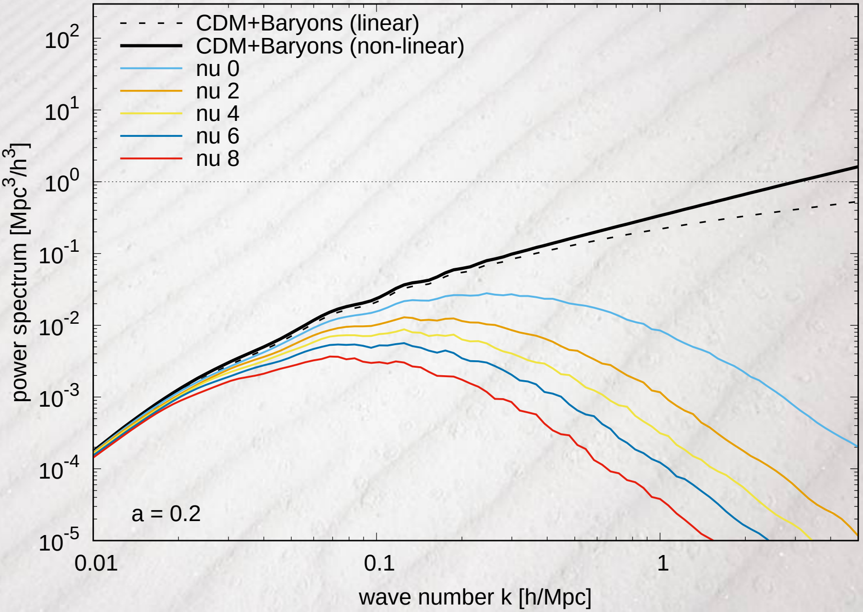

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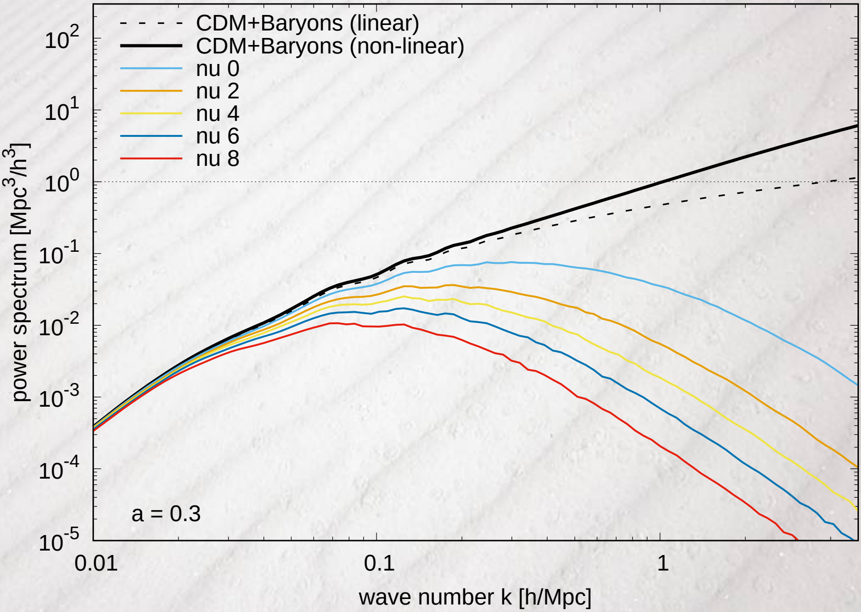

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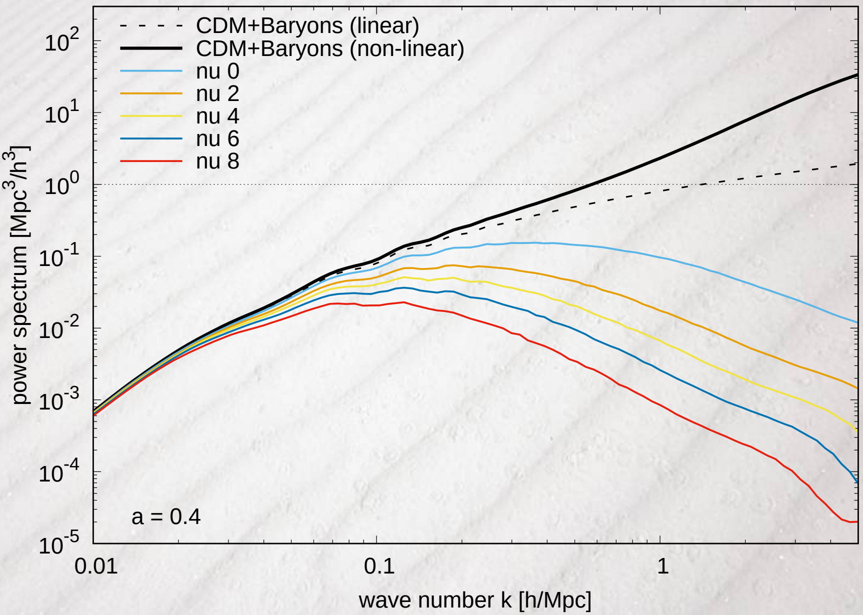

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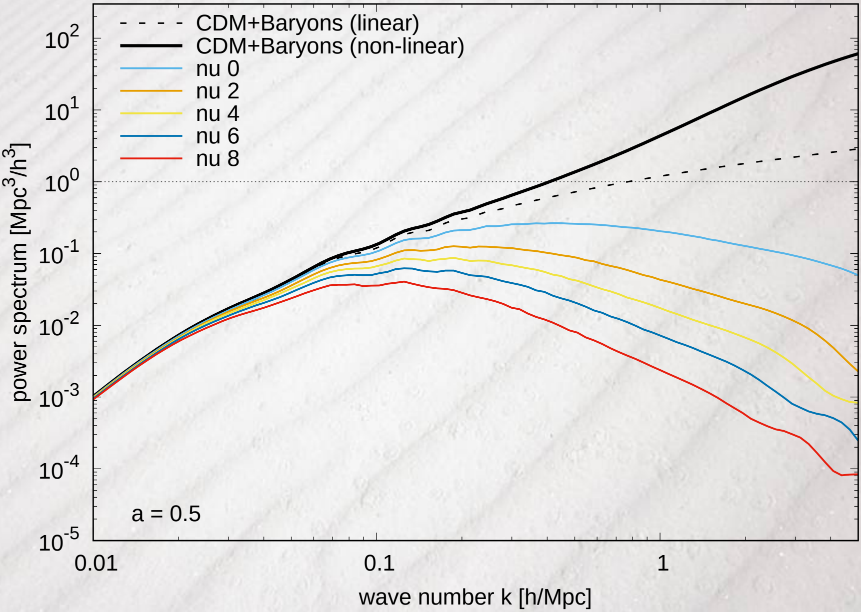

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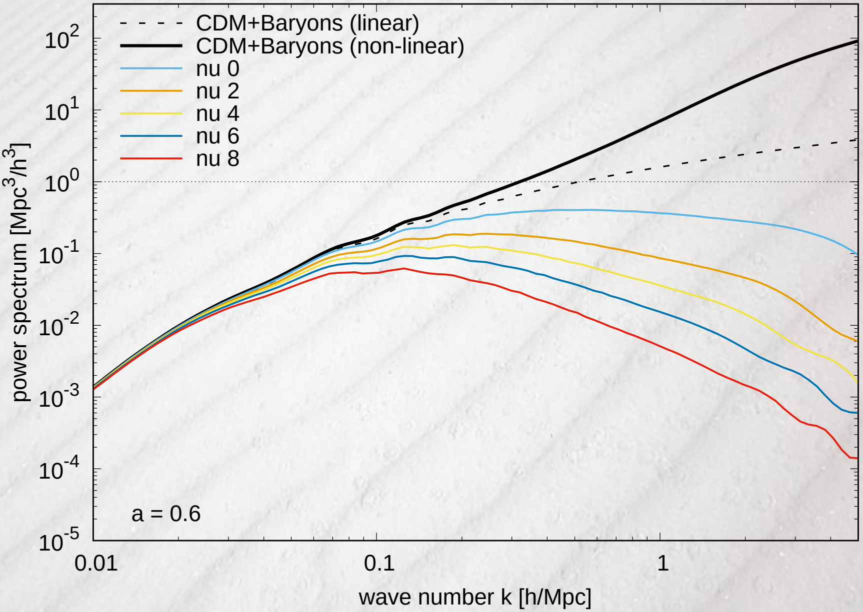

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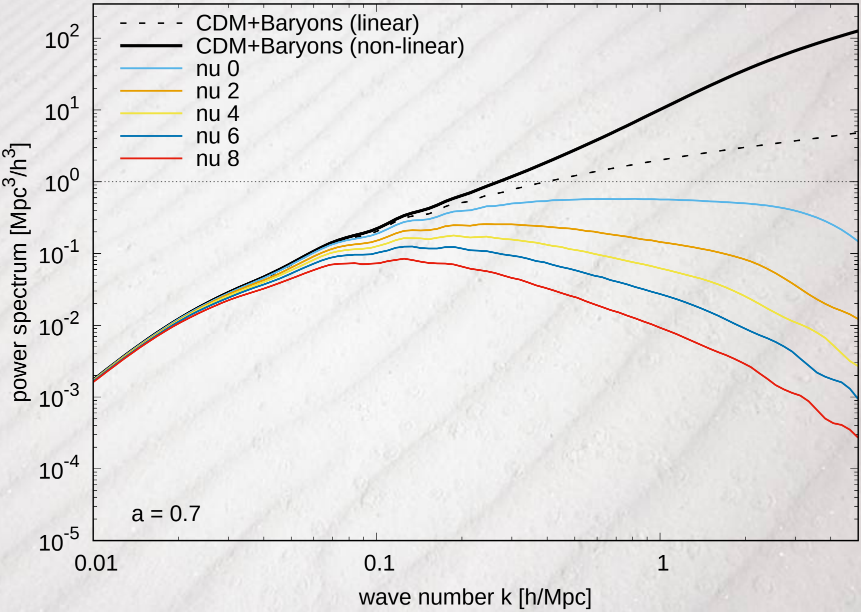

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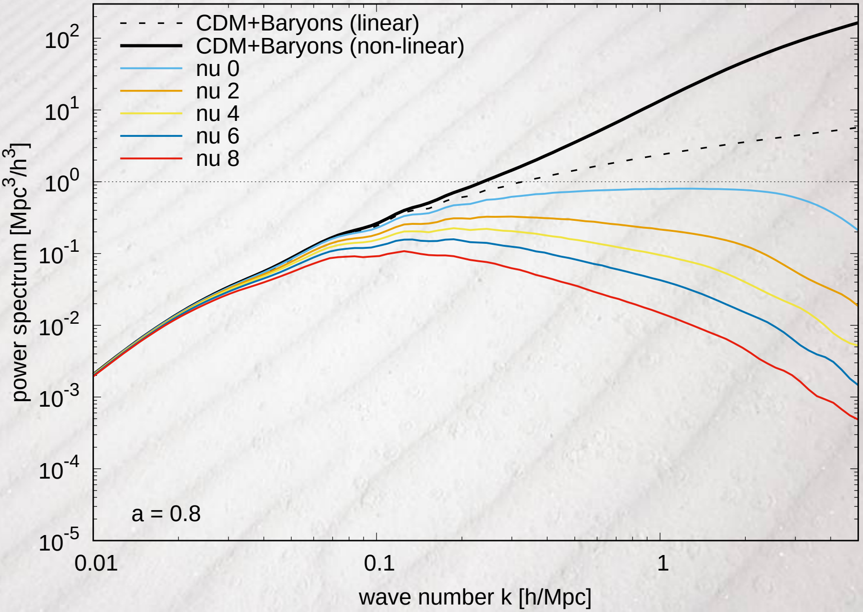

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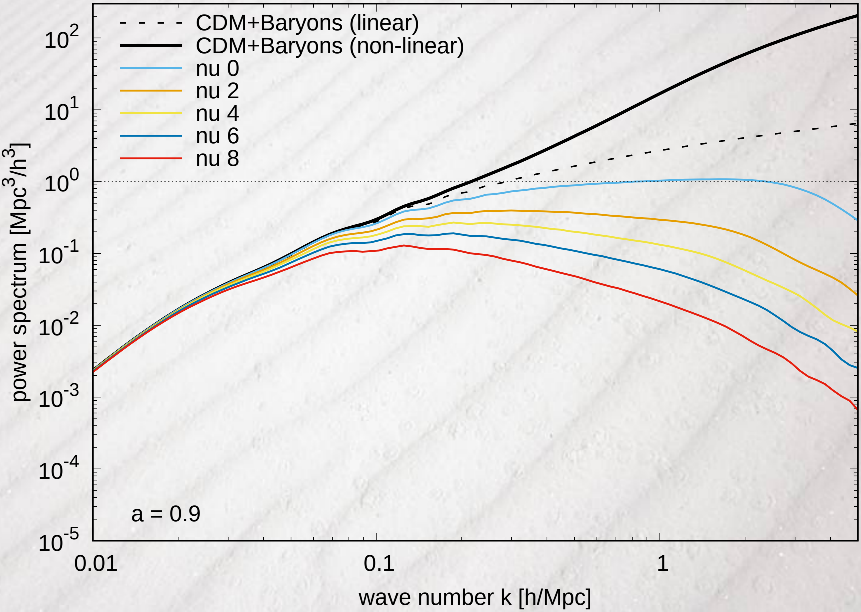

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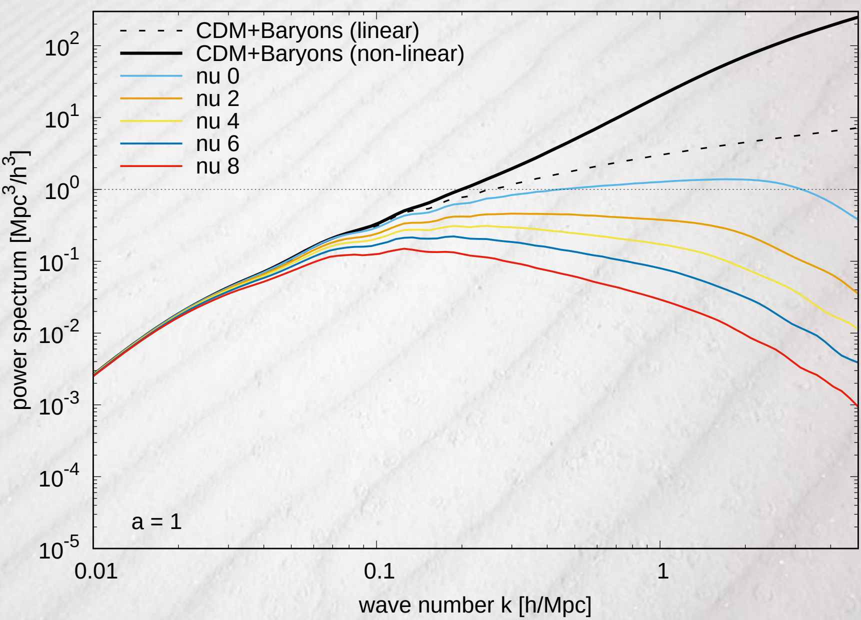

Future work

My goal is a fast, efficient multi-fluid perturbation theory for massive neutrinos and other light particles. This work sits at the intersection of several important advances in theoretical cosmology:

1. perturbation theory for DM in presence of massive ν:
   Pietroni, JCAP **0810***:036(2008)*; *AU,* et al., *PRD* **93***:063515(2016)[1506.07526]*
2. many-fluid perturbation theory for large velocity dispersion:
   Dupuy and Bernardeau, JCAP **1401***:030(2014)*
3. Fast Fourier Transform acceleration of perturbation theory:
   McEwen, Fang, Hirata, Blazek, JCAP **1609***:015(2016)[1603.04826]*;
   AU, JCAP 1905:041 (2019)[1707.09354]
4. combination of perturbation theory and N-body simulations:
   Lawrence, Heitmann, Kwan, AU, et al., Ap. J. **847***:50(2017)[1705.03388]*
5. perturbation theory applied to data analysis:
   AU, JCAP 1905:041 (2019)[1707.09354]
6. future: higher-redshift data!

Conclusions

1. The cosmological power spectrum represents the interplay between pressure and gravity for density fluctuations on a range of wavelengths.
2. Massive neutrinos, which alter the pressure and suppress matter clustering, have unique signatures in the redshift-space power spectrum.
3. Current data impose powerful constraints on the sum of neutrino masses. Over the next several years we will measure, and not just bound, their masses.
4. A convergence of modern theoretical tools allows us to address major challenges to power spectrum prediction in massive neutrino models.