# Neutrinos & Cosmology

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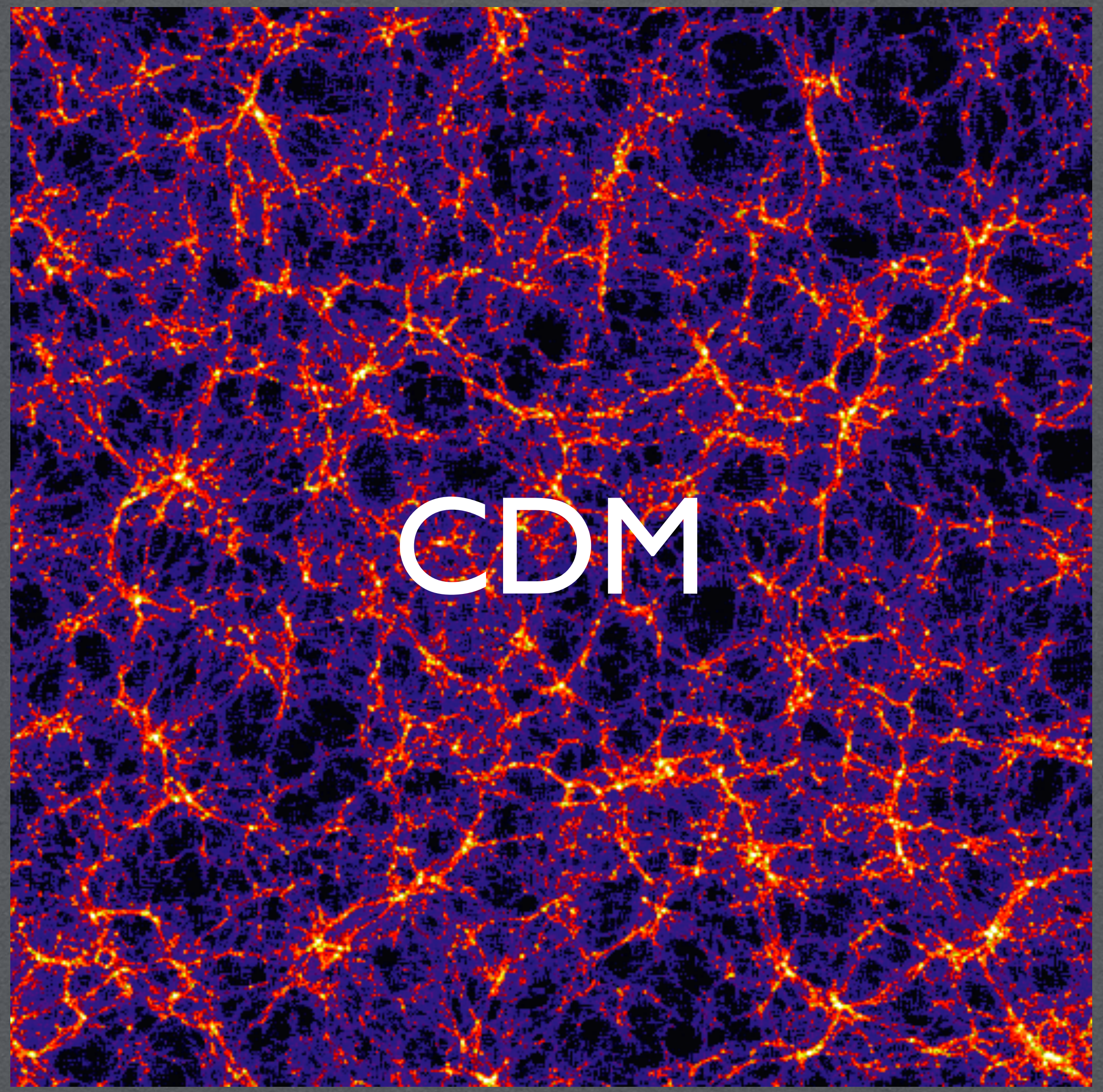
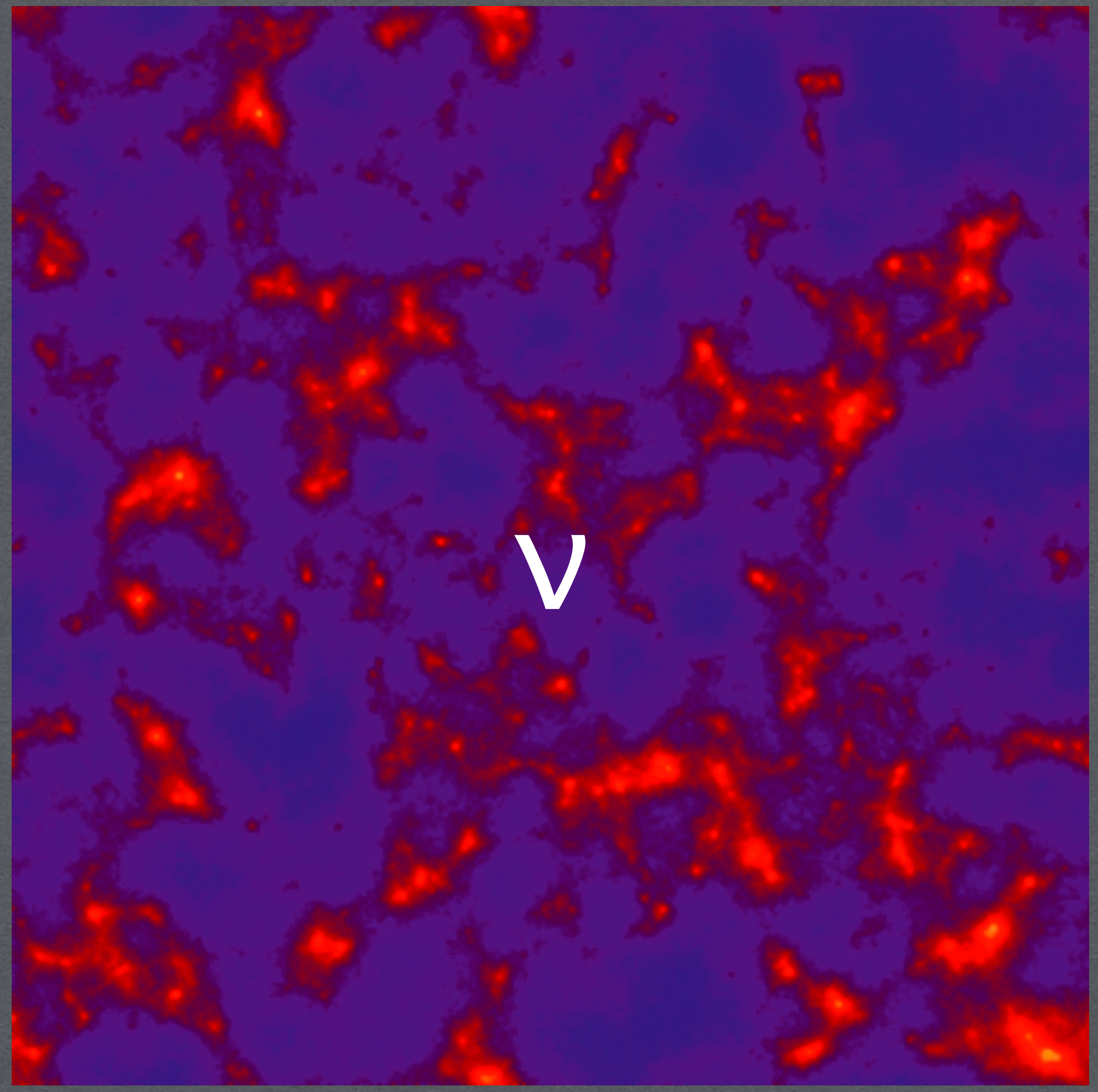
*Neutrino Mass: From the Terrestrial Laboratory to the Cosmos, UMass Amherst, 14-16.12.2015*

# Neutrinos & Cosmology

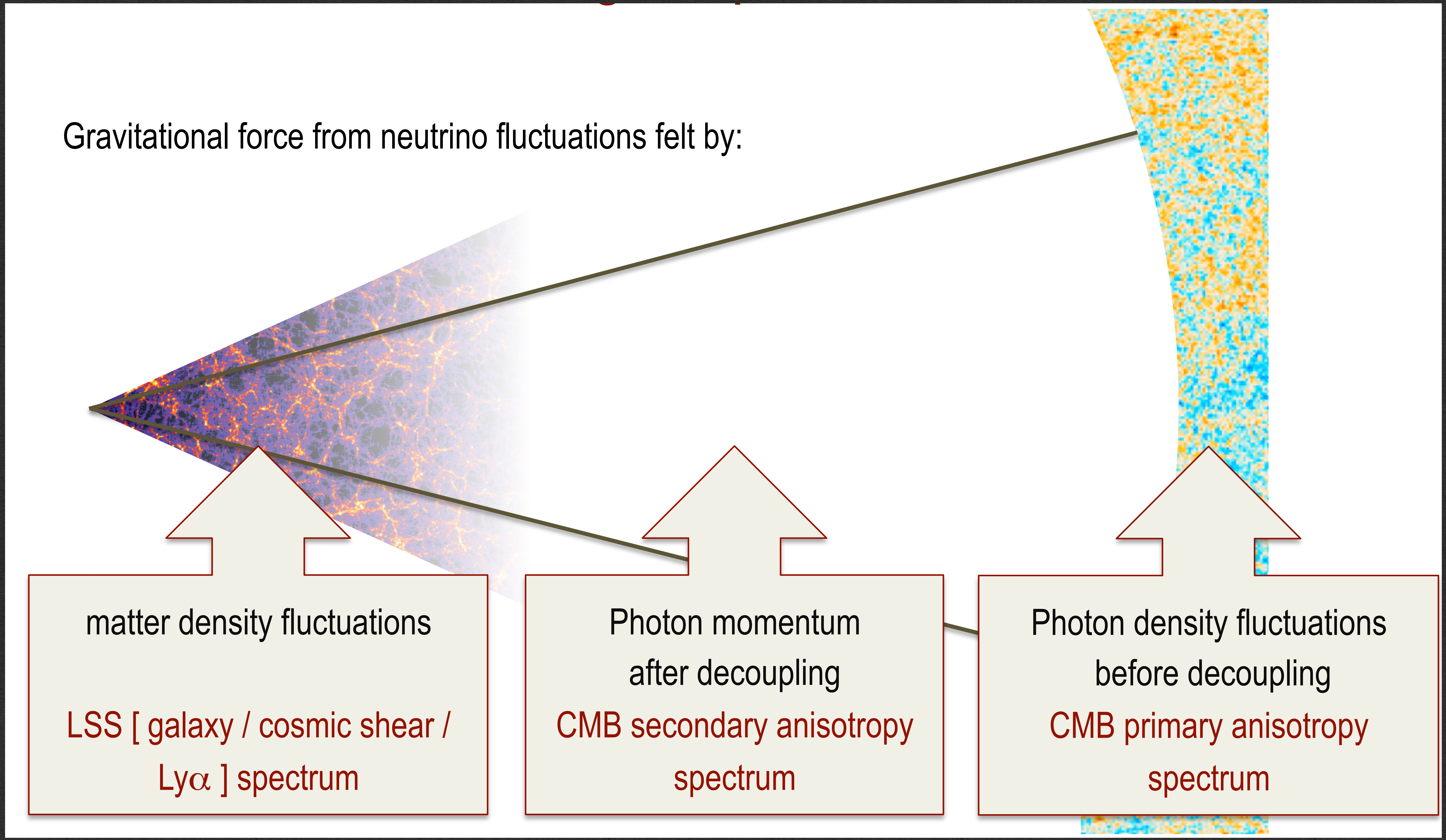



1. Mass impact on CMB : theory
2. Current CMB+LSS bounds
3. Future constraints
4. Complementarity with particle physics experiments
5. Current theoretical challenges in neutrino cosmology




- Go fast on topics previously discussed in this workshop (Fuller, Abazajian, Kaplinghat, Chang, Pan…)
- mention latest results presented yesterday in Neutrino Cosmology session of Texas Symposium
- no sterile / non-standard neutrinos: 3 active neutrinos only

# Neutrinos & Cosmology

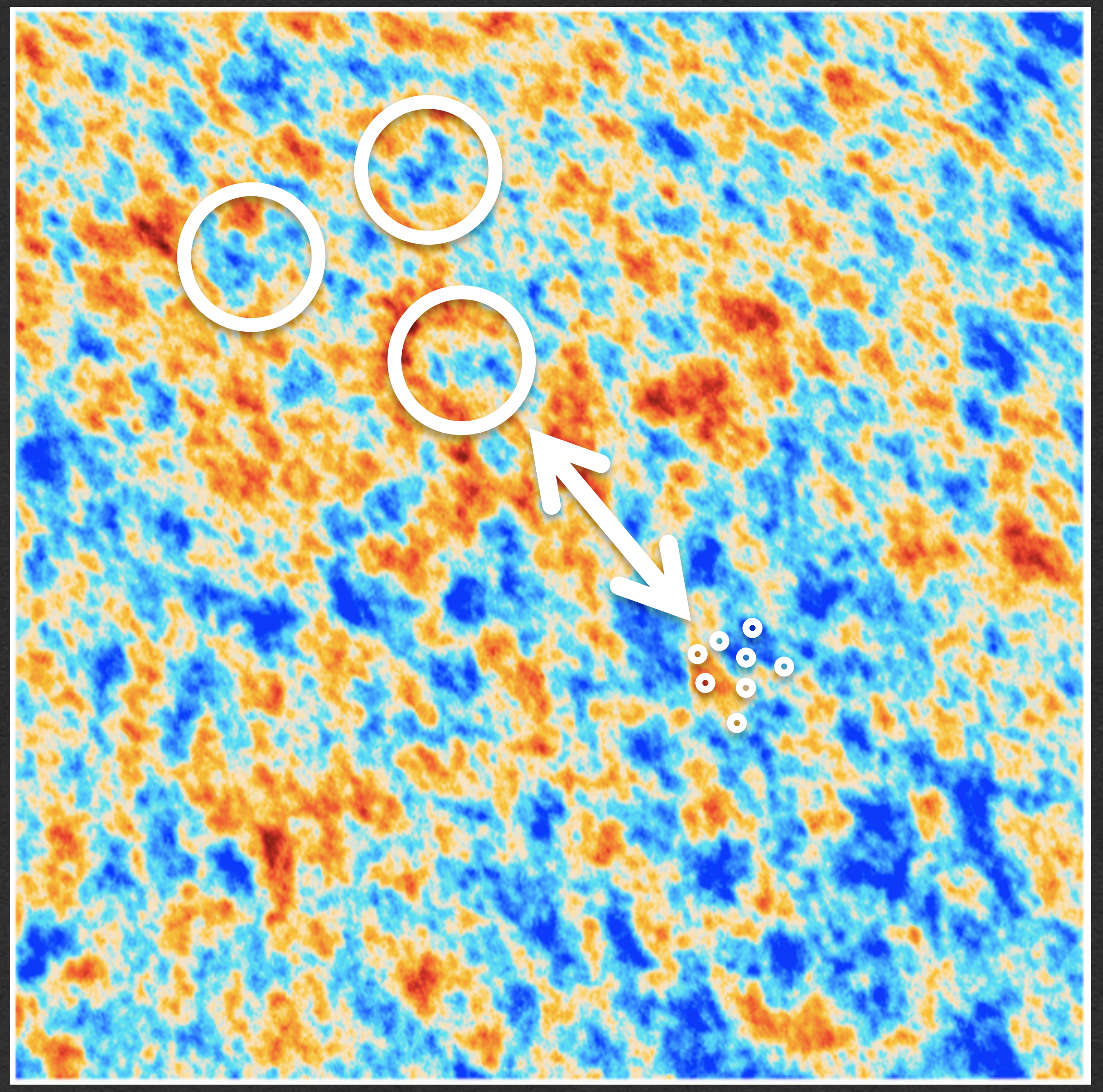


# Mass impact on CMB: theory

- even in relativistic limit ($m_\nu$ << 1 meV) neutrinos would impact CMB:

  1. background: for constant time of radiation-matter equality, ratio of acoustic to diffusion scale (—> damping tail)

  2. perturbations: gravitational interaction between neutrinos and photon-baryon fluid before decoupling: “neutrino drag” (amplitude & phase shift)



- neutrino mass add extra effects even if non-relativistic transition takes place after decoupling

# Mass impact on CMB: theory

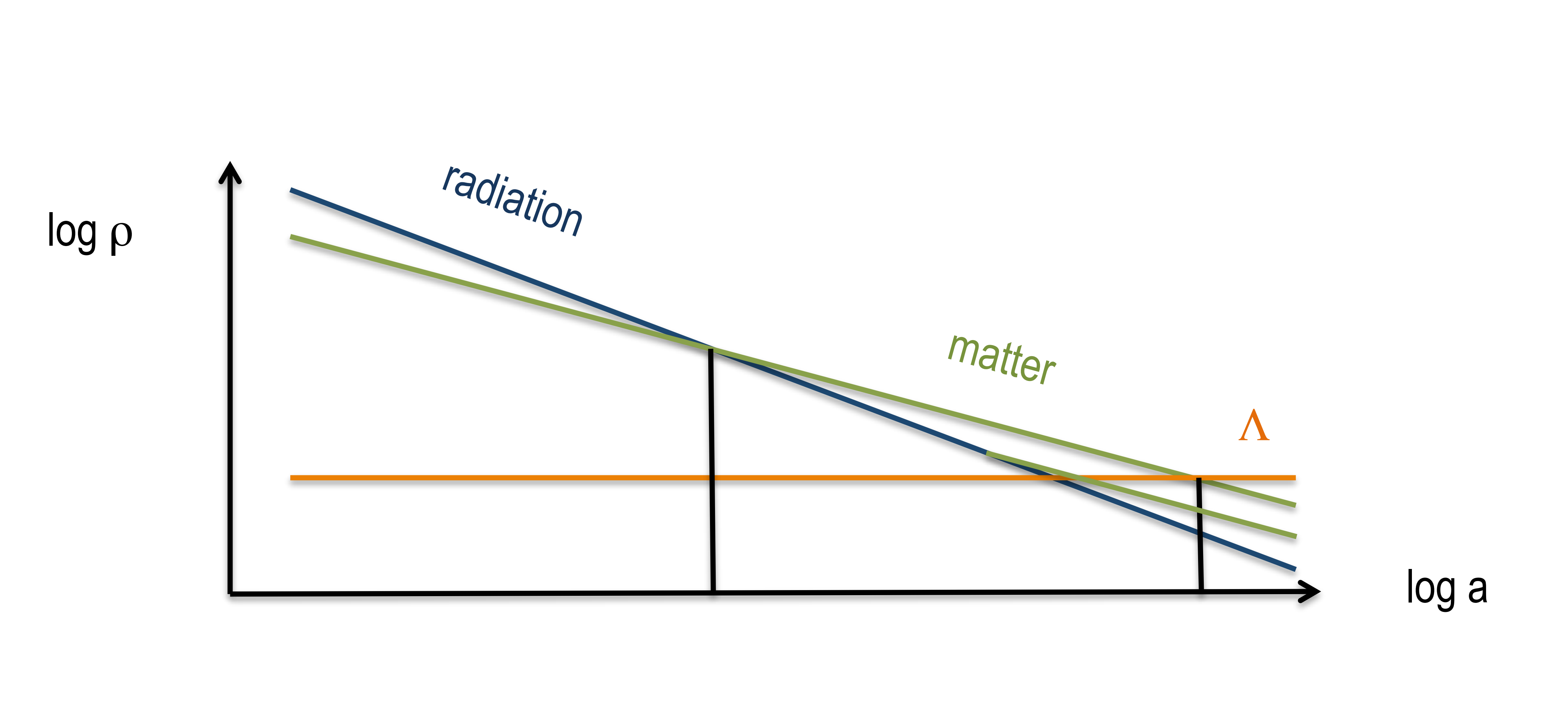
- "trivial" background effects: for same equality time and peak scale, change $H_0$, $\Omega_\Lambda$: late Integrated Sachs-Wolfe (ISW)…

Constant peak angular scale:

$\Delta H_0$ / [1 km/s/Mpc] = - $\Delta M_\nu$ / [0.1eV]

WMAP: $H_0$=69.7+-2.1 km/s/Mpc

Planck15: $H_0$=67.3+-1 km/s/Mpc




$\Delta H_0$=0.6 km/s/Mpc coming from different choice of fiducial model ($M_\nu$ = 0 —> 0.06eV)

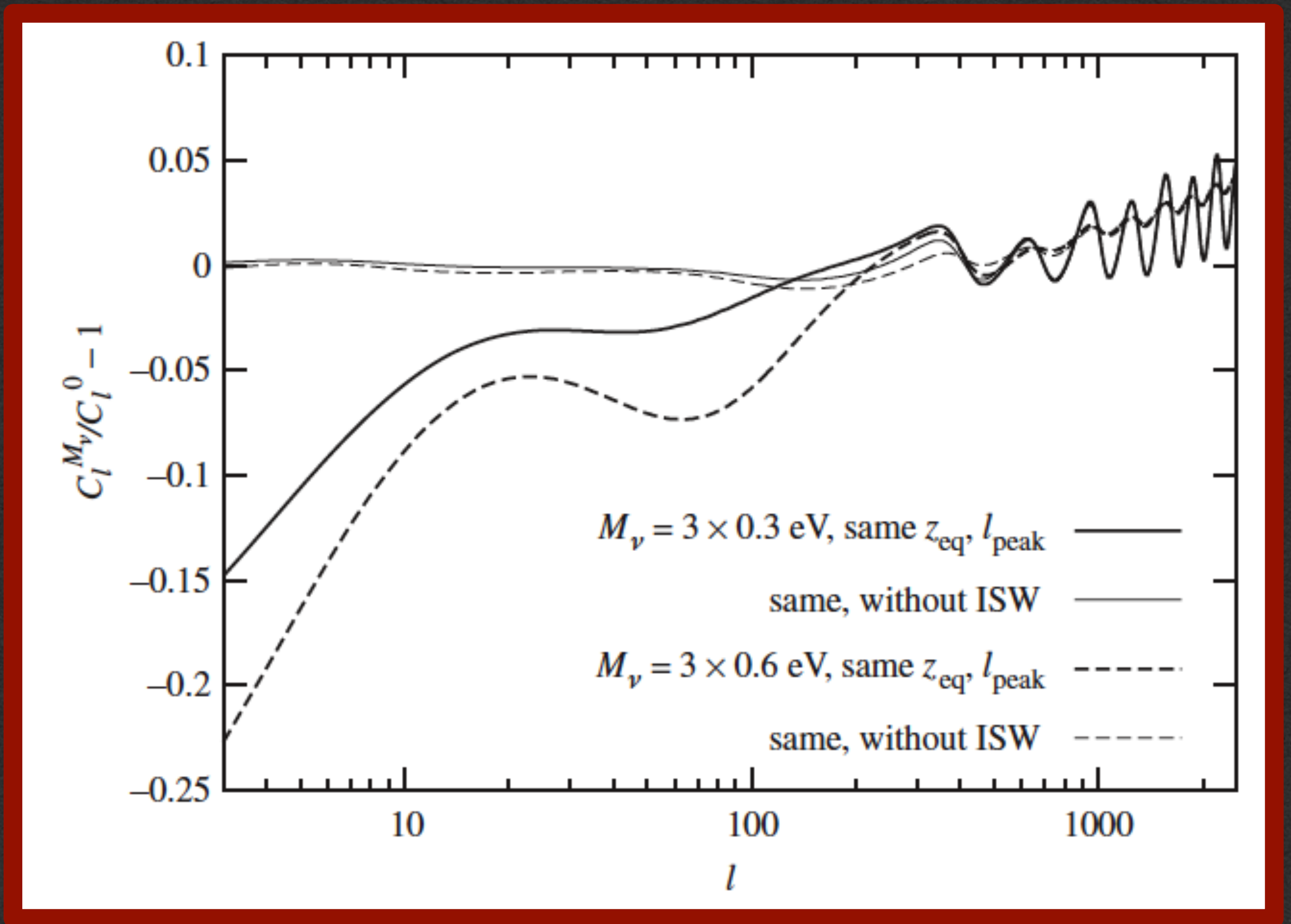
- also small background effect on recombination history [Grohs et al. 1412.6875]

# Mass impact on CMB: theory

- non-trivial perturbation effects at level of primary CMB anisotropies:

1. early Integrated Sachs-Wolfe (ISW) effect when neutrinos become non-relativistic at 500 < z < 1000

   Produces a dip in temperature spectrum for 10 < l < 200



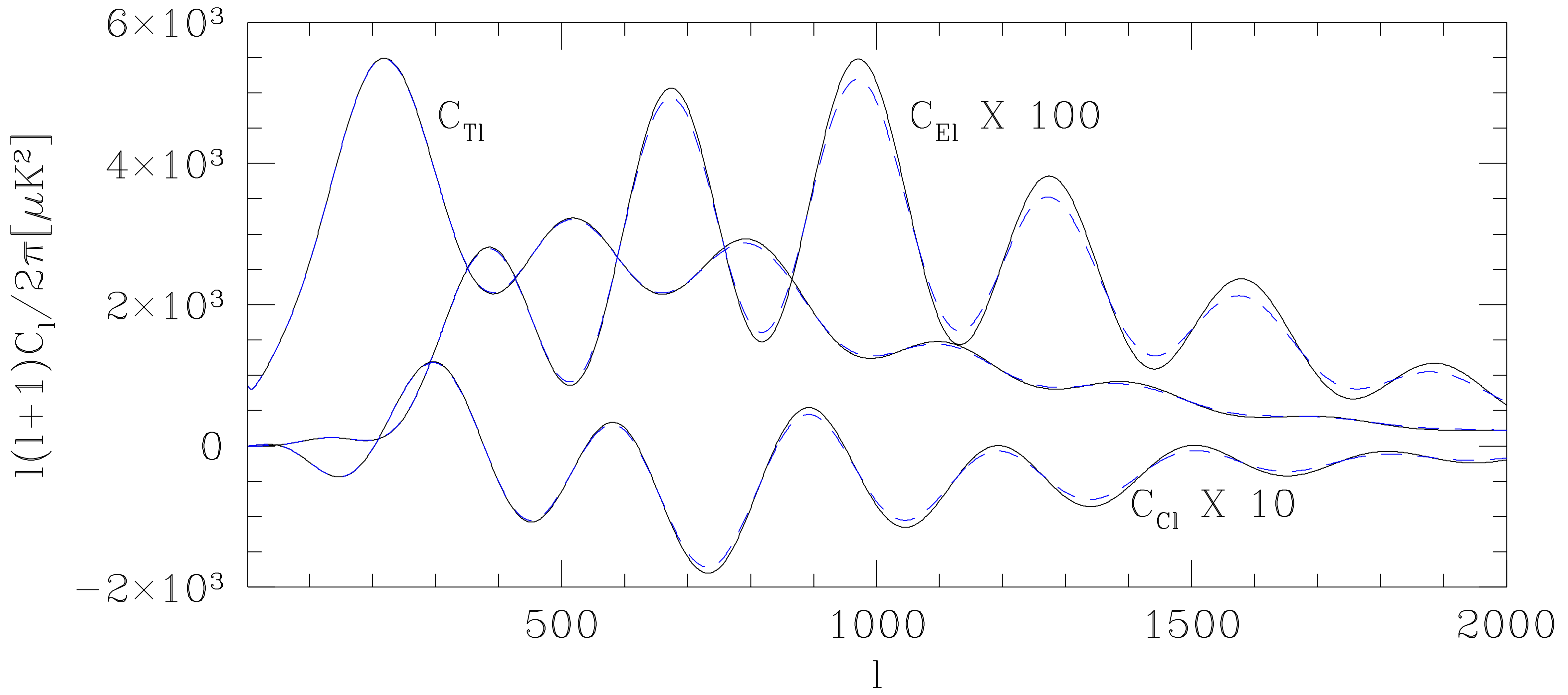

Book "Neutrino Cosmology", Cambridge, JL et al.

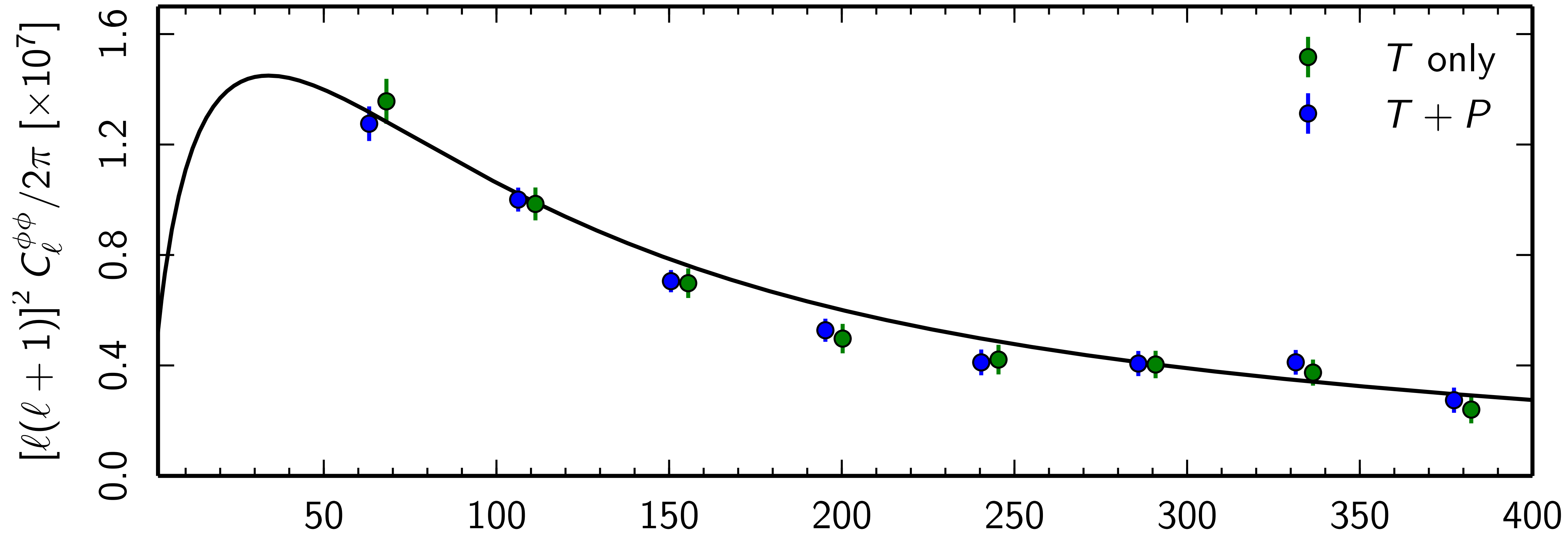
2. fraction of neutrinos already non-relativistic at decoupling: slightly modfied neutrino-photon gravitational interaction (very small)

# Mass impact on CMB: theory

- perturbation effects at level of secondary CMB anisotropies:

  3. reduced CMB lensing (spectrum of temperature, polarisation, extracted lensing potential): dominant effects



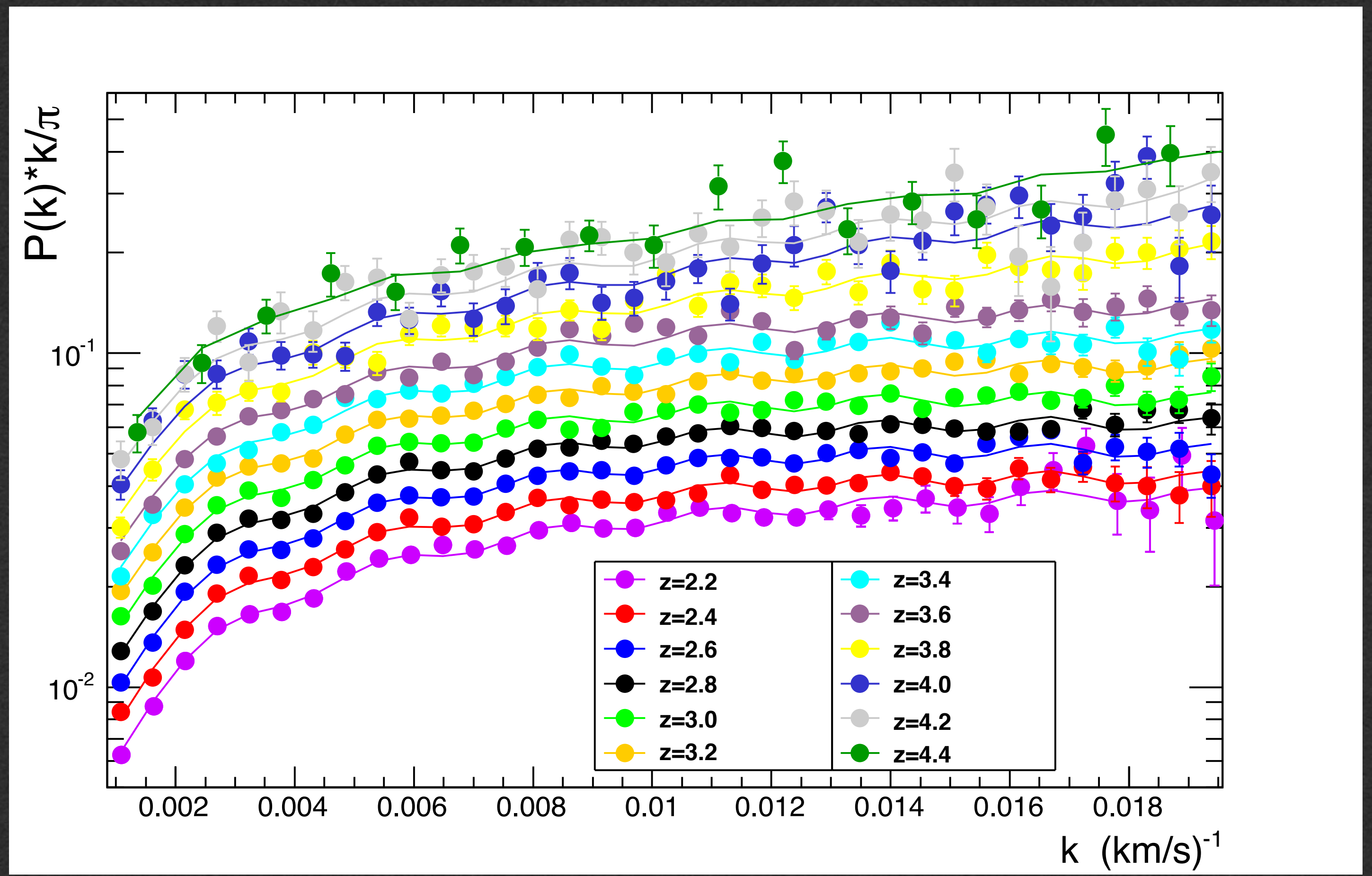



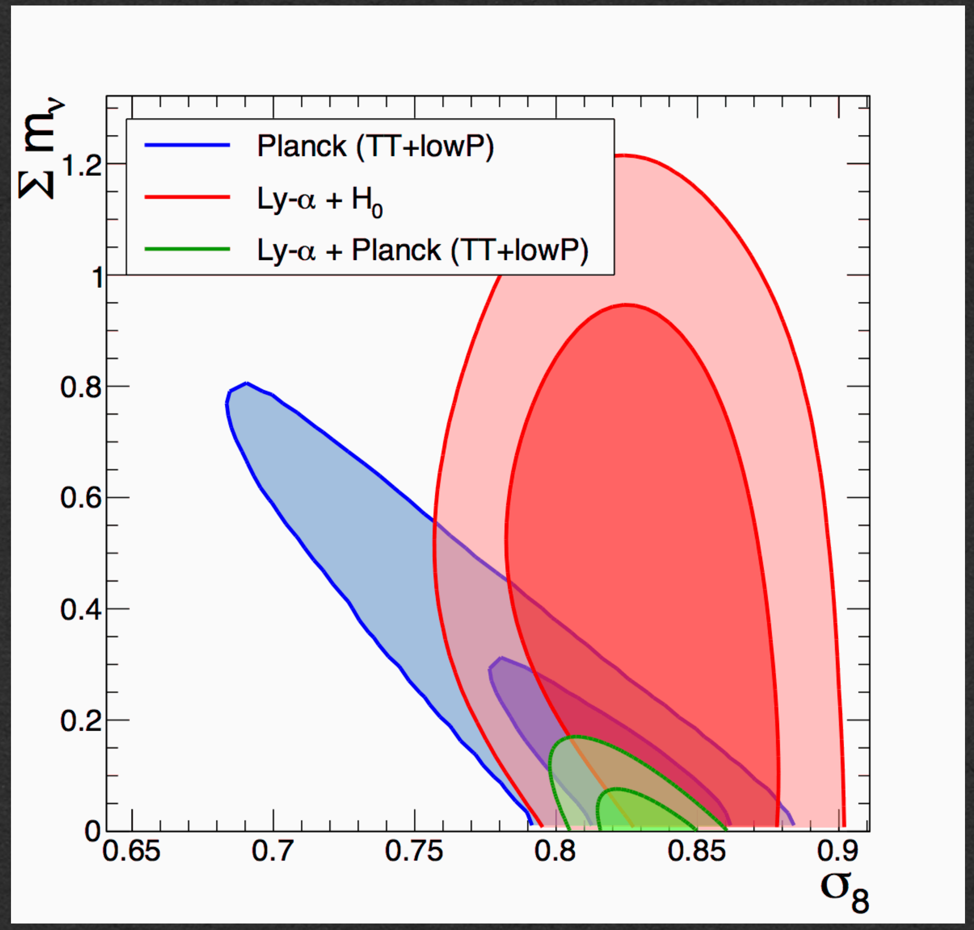
# Current CMB+LSS constraints

- pushing for small neutrino mass:
  - CMB temperature and polarisation (primary ISW effect + temperature lensing) :

    Planck TT,TE,EE + BAO: $M_\nu < 170$ meV (95%CL) [Planck XIII 2015]

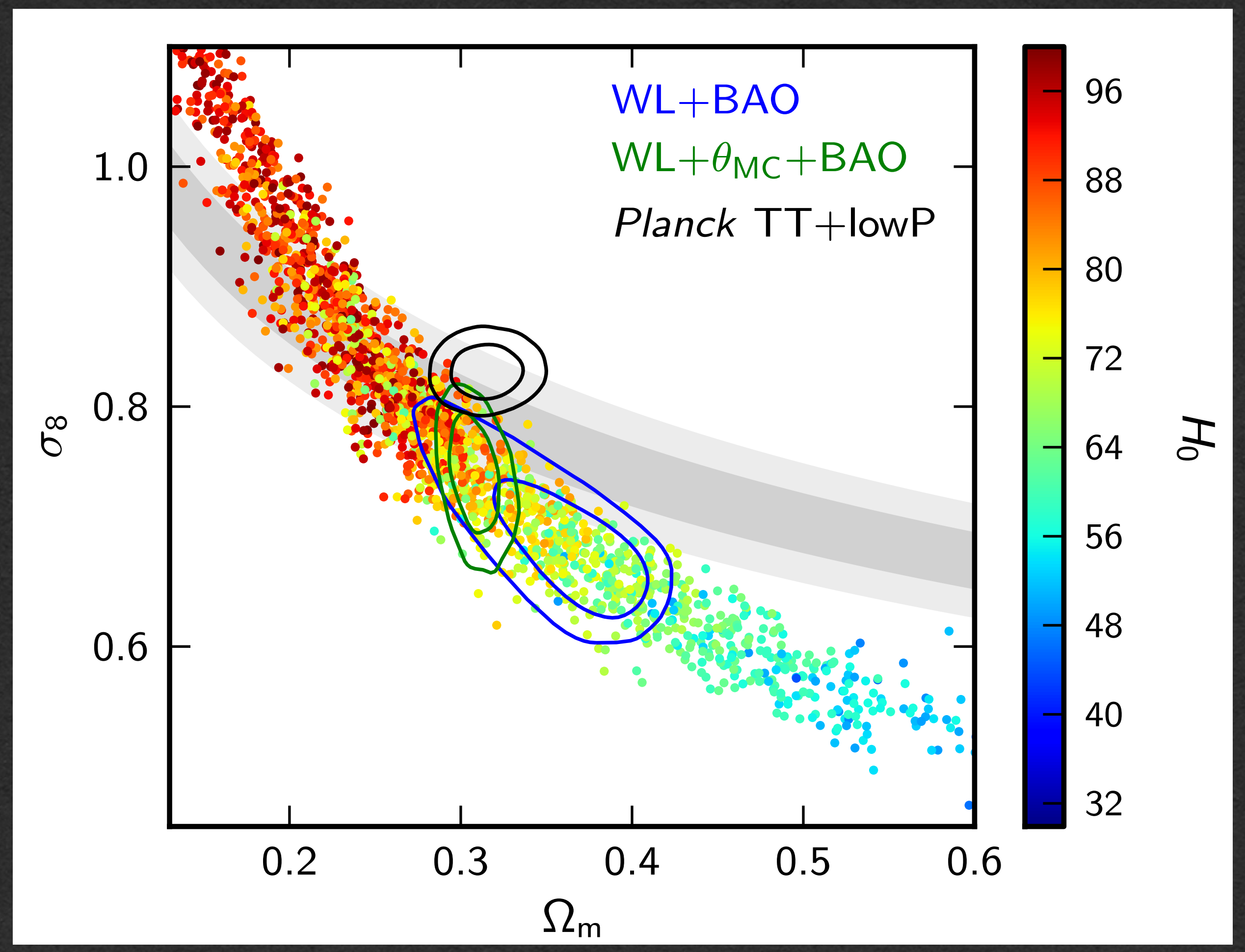
  - BOSS Ly-alpha + Planck 2015 (TT,lowP): $M_\nu < 120$ meV (95%CL) [Palanque-Delabrouille et al. 2015]



# Current CMB+LSS constraints

- pushing for higher neutrino mass: marginal anomalies, reduced LSS amplitude on small scales:
  - clusters counts (Planck SZ, others; issues with bias)
  - cosmic shear experiments (CFHTLens, much less with DES)
  - spectrum of CMB lensing potential on some scales
  - [ also: direct $H_0$ measurement versus CMB $H_0$ measurements ]
  - [ also: low tilt $n_s$ in BOSS Lyman-alpha ]
- No obvious internal contradictions (only when assuming given model)




[Planck XIII 2015]

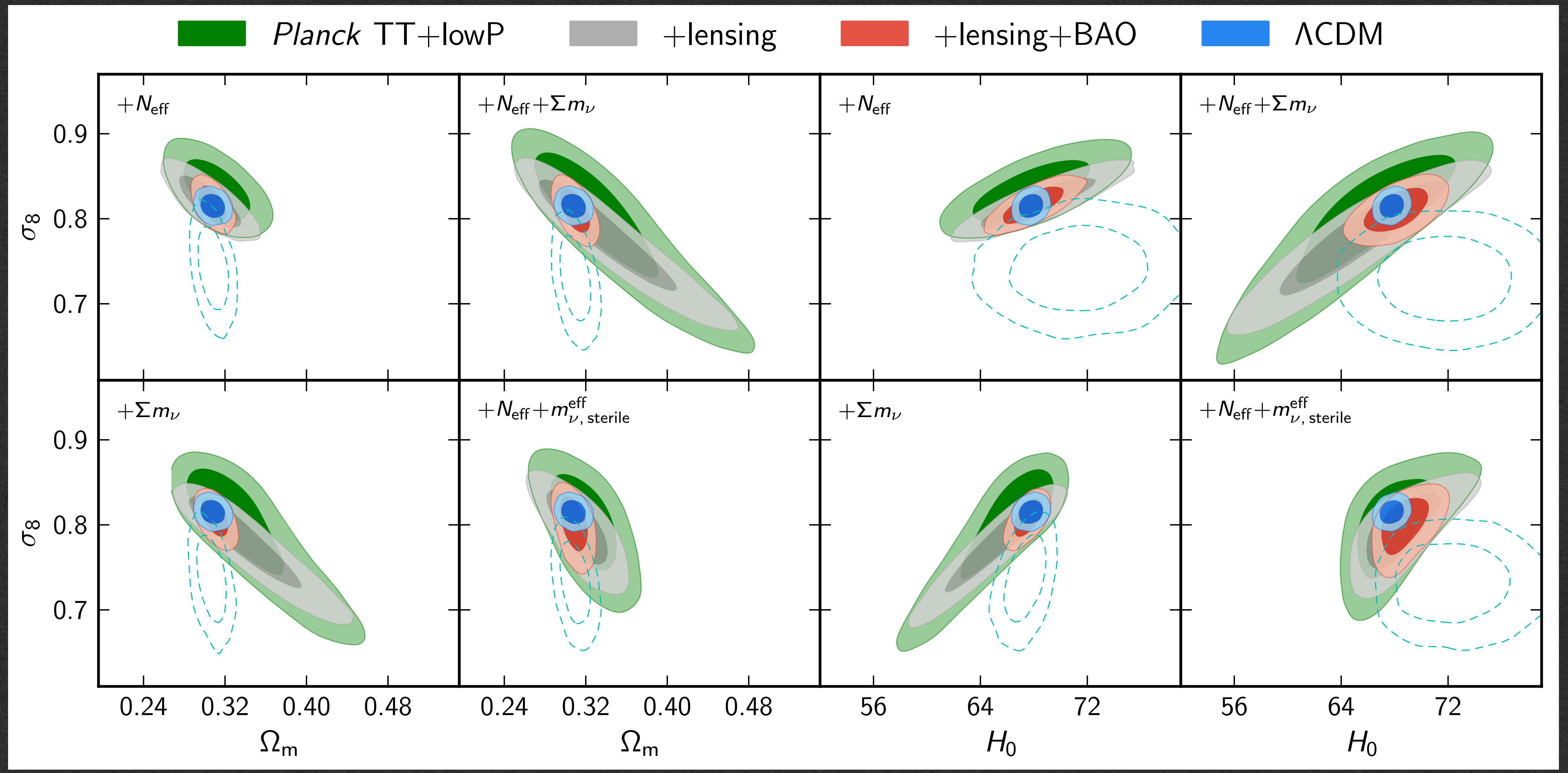
# Current CMB+LSS constraints

- My opinion:

  1. systematics in LSS, anomalies will go away

  2. or non-neutrino explanation…

     - active neutrino mass, light sterile neutrinos: would bring contradiction. No massive neutrino fit increases goodness of fit significantly




[Planck XIII 2015]

- can accommodate everything with other models, e.g. with non-WIMP dark matter: small dark matter-dark radiation interaction [JL, Marques-Tavares, Schmaltz 2015]

# Future constraints

- target of next 10 years: e.g. Planck & Euclid: $\sigma(M_\nu)$ = 25-30 meV
- with new CMB satellite: e.g. Core+ & Euclid: $\sigma(M_\nu)$ = 15-20 meV
- but this assumes that issues in theoretical cosmo/astrophysics can be solved (see later)
- target of 21cm surveys: more controversial.

[Villaescusa et al. 2015]: N-body + hydro simulations including massive neutrino and hydrogen power spectrum computation. Planck + SKA: also $\sigma(M_\nu)$ = 30 meV

# Complementarity with laboratory experiments

- cosmology more sensitive to absolute neutrino mass scale than laboratory experiments (now; or even with Katrin; Gerda I,II); comparable bounds in future (Planck+Euclid versus Holmes, nEXO) [Gerbino et al. 1507.08614]

- no direct information on individual masses, CP phases, Dirac/Majorana…

- what if we find a contradiction, e.g. $M_\nu << 0.06$eV with cosmo data ?

  - non-standard neutrino interactions? Mass varies with time/spaces?

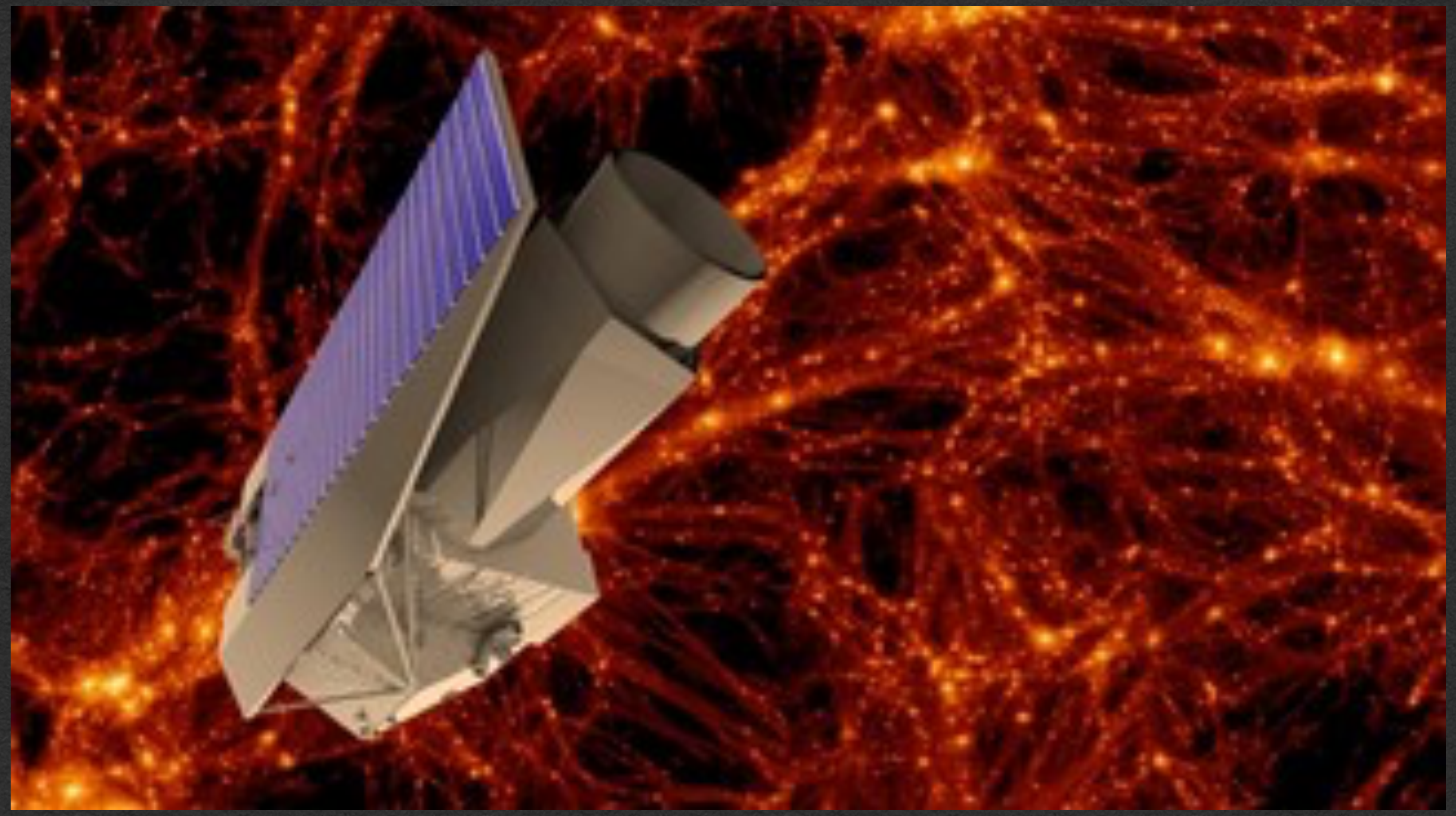
  - neutrinos decay into massless dark species? (result: $N_{eff} \sim 3$ massless species)

  - reheating at T ~ 1-10 MeV + other particles contributing to $N_{eff}$

- interesting in all cases (like Higgs search at LHC)

# Open challenges in neutrino cosmology

- Precise LSS observations require precise theoretical predictions of observable quantities: full non-linear matter power spectrum, cosmic shear spectrum, including non-linear bias, redshift space distorsions…



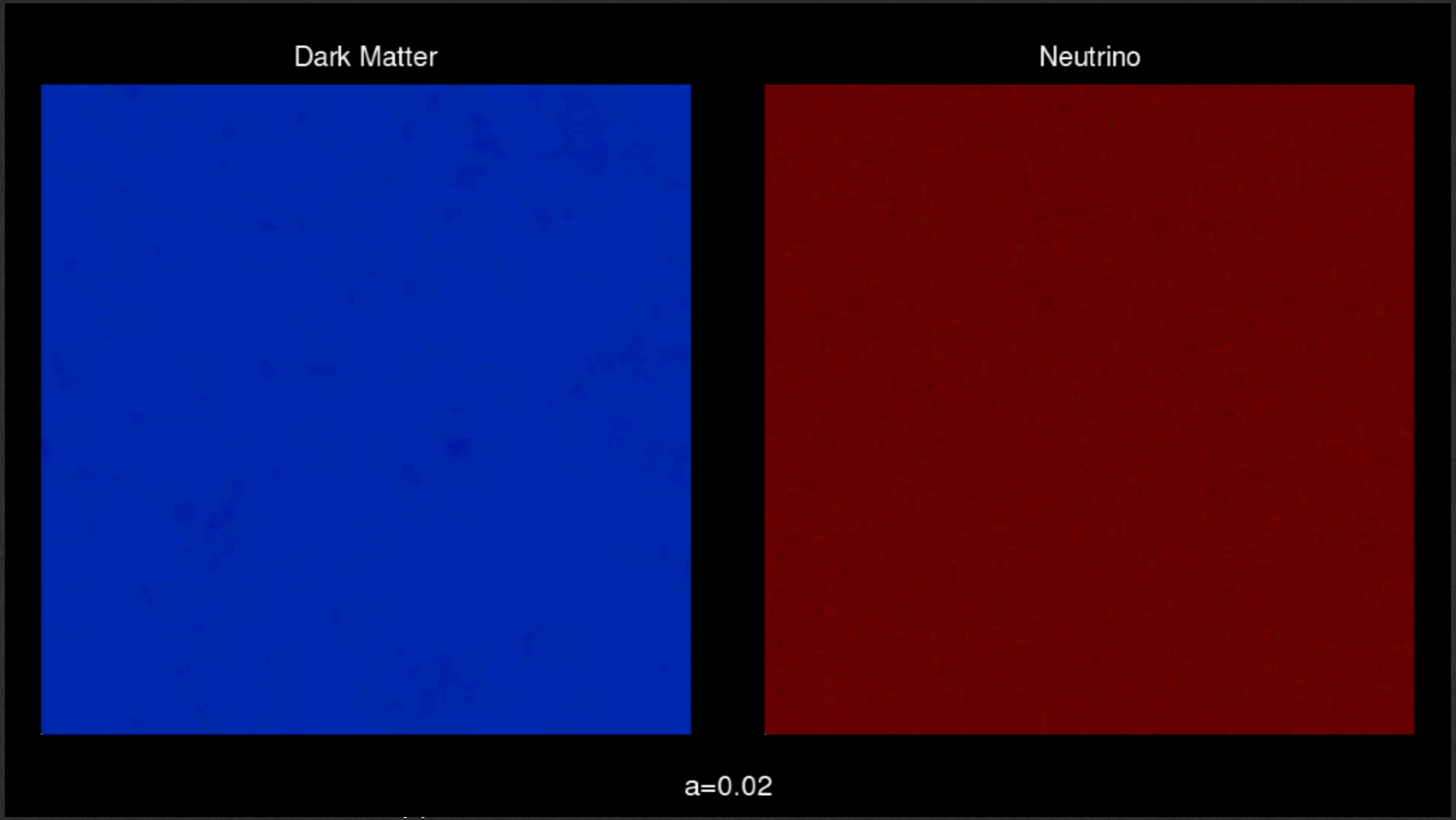
- target: 1% precision on all non-linear observables up to scale k=1 h/Mpc [Audren et al. 2012]

# Open challenges in neutrino cosmology

- N-body simulation challenge: neutrinos go fast and fill large volume in phase space. Solved by brute force and appropriate modifications of Gadget-III for $m_\nu > 100$ meV. Computationally expensive.

Several group, especially Trieste and Milano

[movie from Francisco Villaescusa-Navarro]

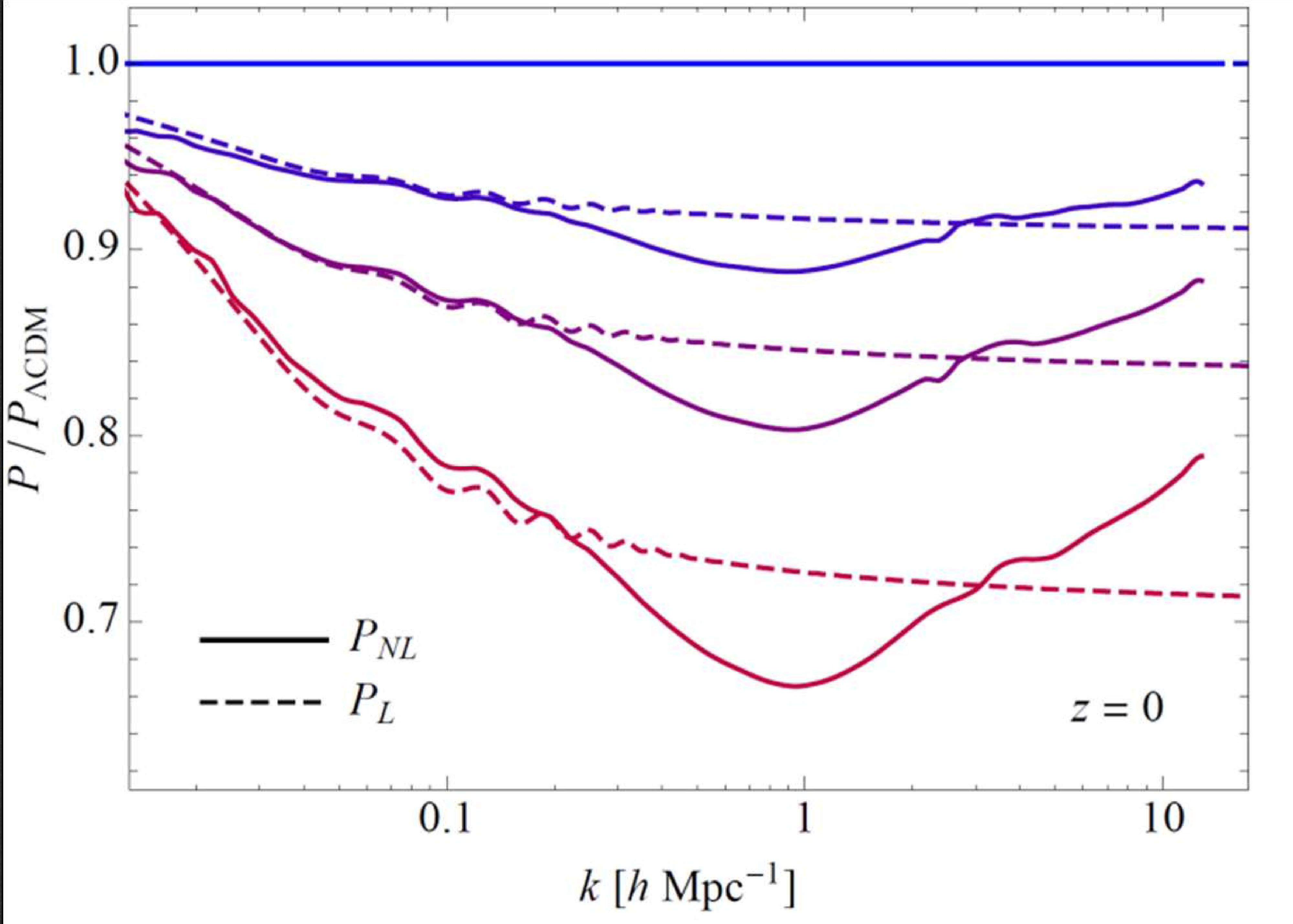


# Open challenges in neutrino cosmology

- N-body simulation challenge: neutrinos go fast and fill large volume in velocity space. Solved by brute force and appropriate modifications of Gadget-III for $m_\nu > 100$meV. Computationally expensive.

Several group, especially Trieste and Milano

[matter spectrum ratio from DEMNUni, Carbone et al. 2015]

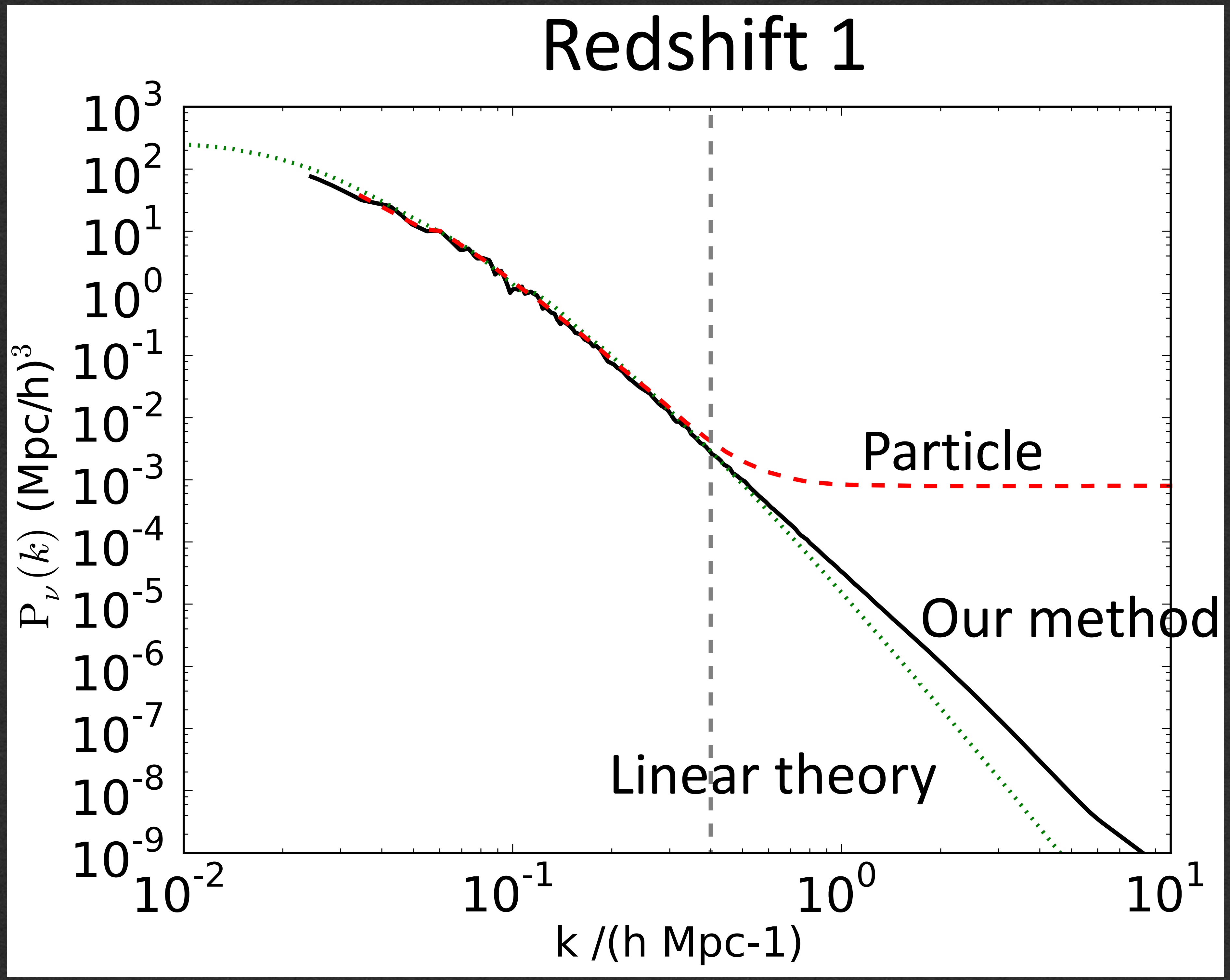


# Open challenges in neutrino cosmology

- N-body simulation challenge: small mass more difficult for N-body (high velocities, difficult to sample phase space, shot noise…).

Solution of [Bird & Ali-Haimoud 1209.0461] :

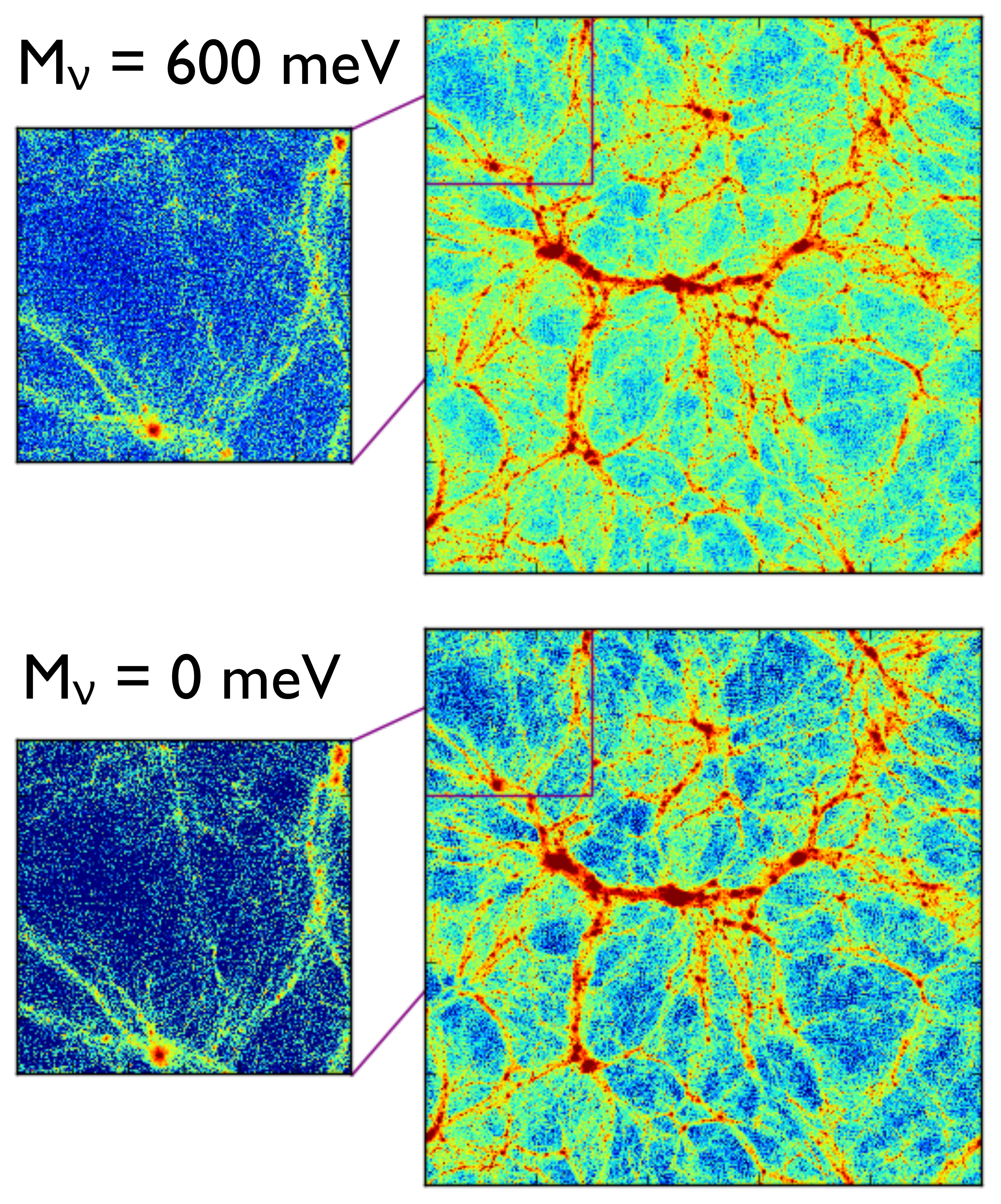
mix of CDM particles + analytic linear equations for neutrinos in Fourier space sourced by nonlinear gravitational field



# Open challenges in neutrino cosmology

- gives in sight on clustering of neutrinos around halos, in voids, etc.

void density sensitive to neutrino mass
[Massara et al. 2015]



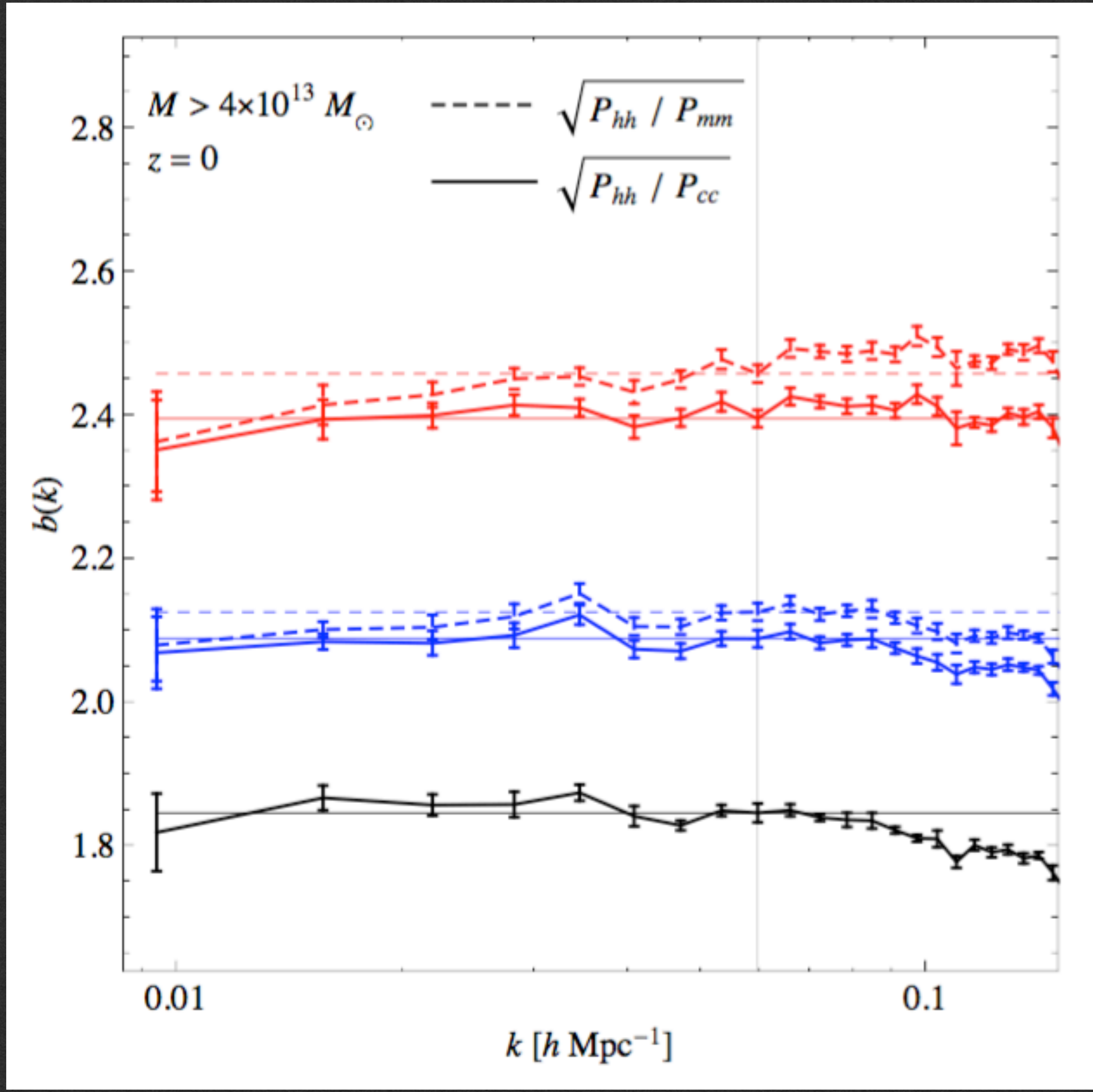
# Open challenges in neutrino cosmology

- gives in sight on clustering of neutrinos around halos, in voids, etc.

[Castorina et al. 2013, 2015, Villaescusa et al. 2013]

galaxy-to-mass bias : galaxies and virialised halos trace $P_{cdm}$, not $P_{tot} = P_{cdm} + P_{\nu} + P_{cross}$

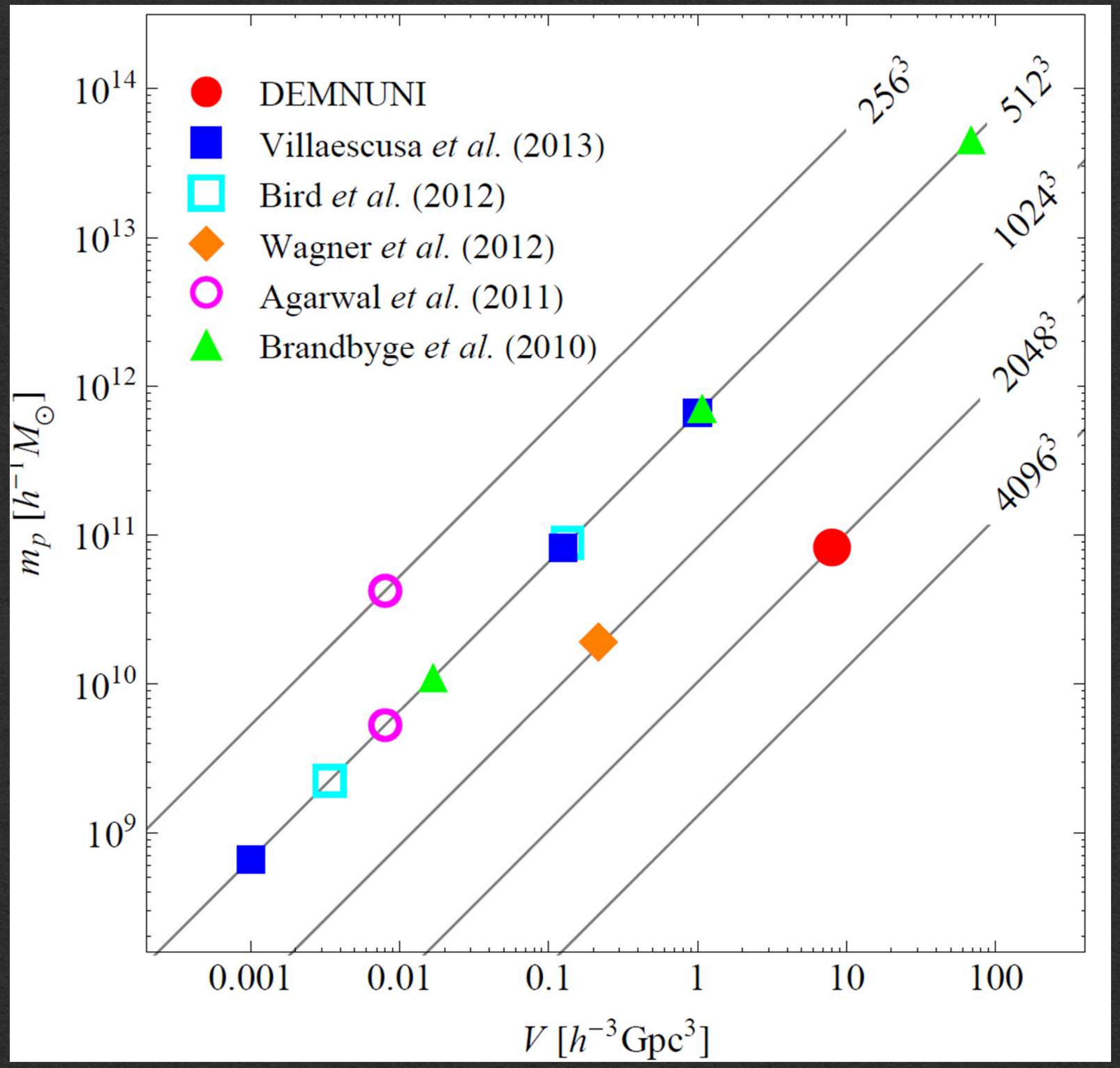
Similar conclusions on: halo mass function and cluster count, halo model, application of ΛCDM N-body fitting functions (HALOFIT), redshift space distorsions…



# Open challenges in neutrino cosmology

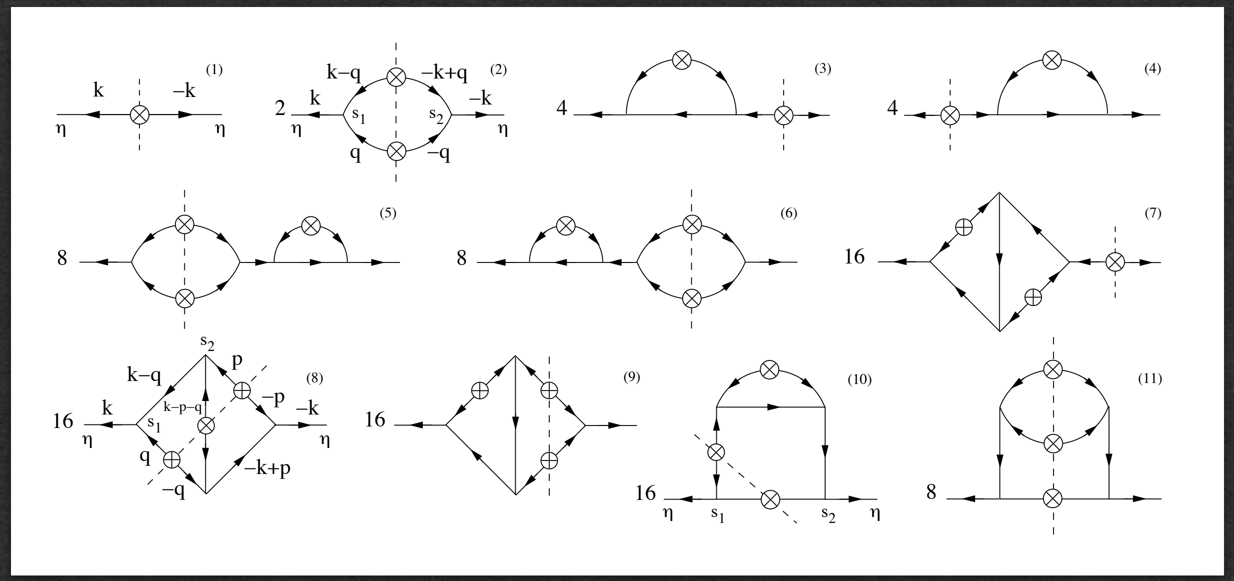
- so we now learn how to derive many non-linear astrophysical observables once non-linear $P_{cdm}$ computed in presence of massive neutrinos

- remains computationally challenging: many N-body simulations with 1% accuracy, for ΛCDM + $M_\nu$ + many other extensions…

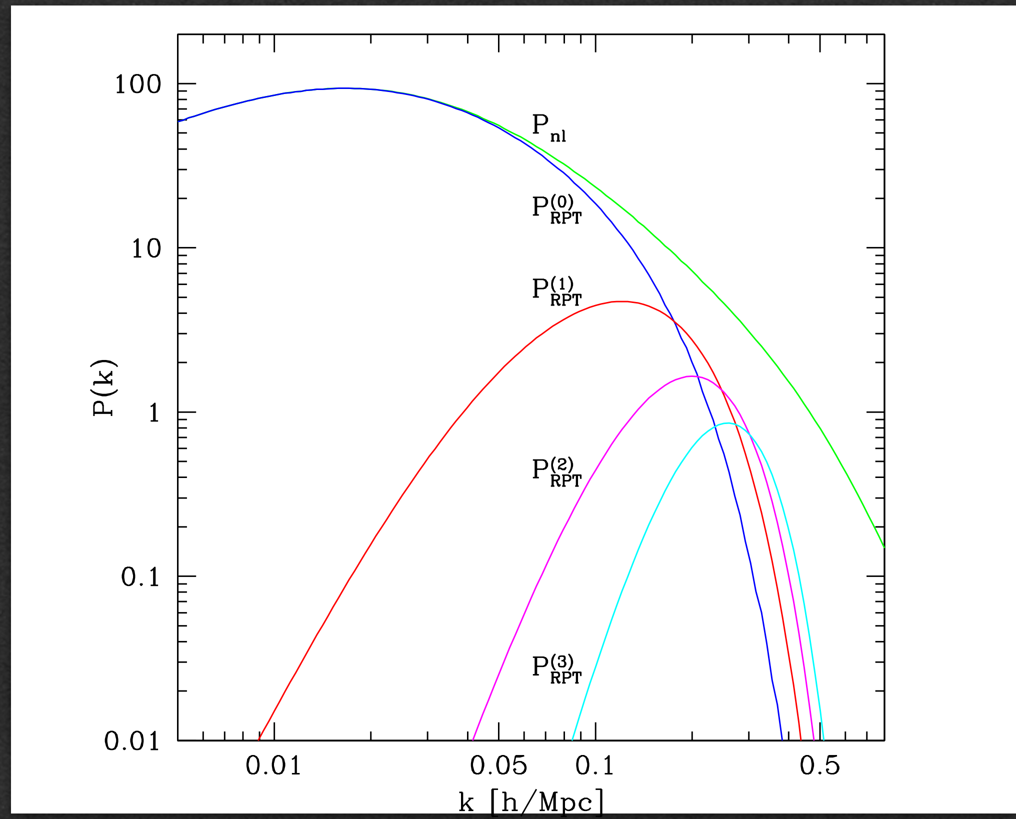


# Open challenges in neutrino cosmology

- Progress on modelling of non-linear perturbations



  - no satisfactory approach yet even for pure ΛCDM
    - SPT (standard perturbation theory) : order 2,3,… : break very early
    - RPT (renormalised perturbation theory): many competing formulations; issue of convergence; doomed to fail on small scales (based on equations valid for single flow; no shell-crossing) [Crocce, Soccimarro, many others]



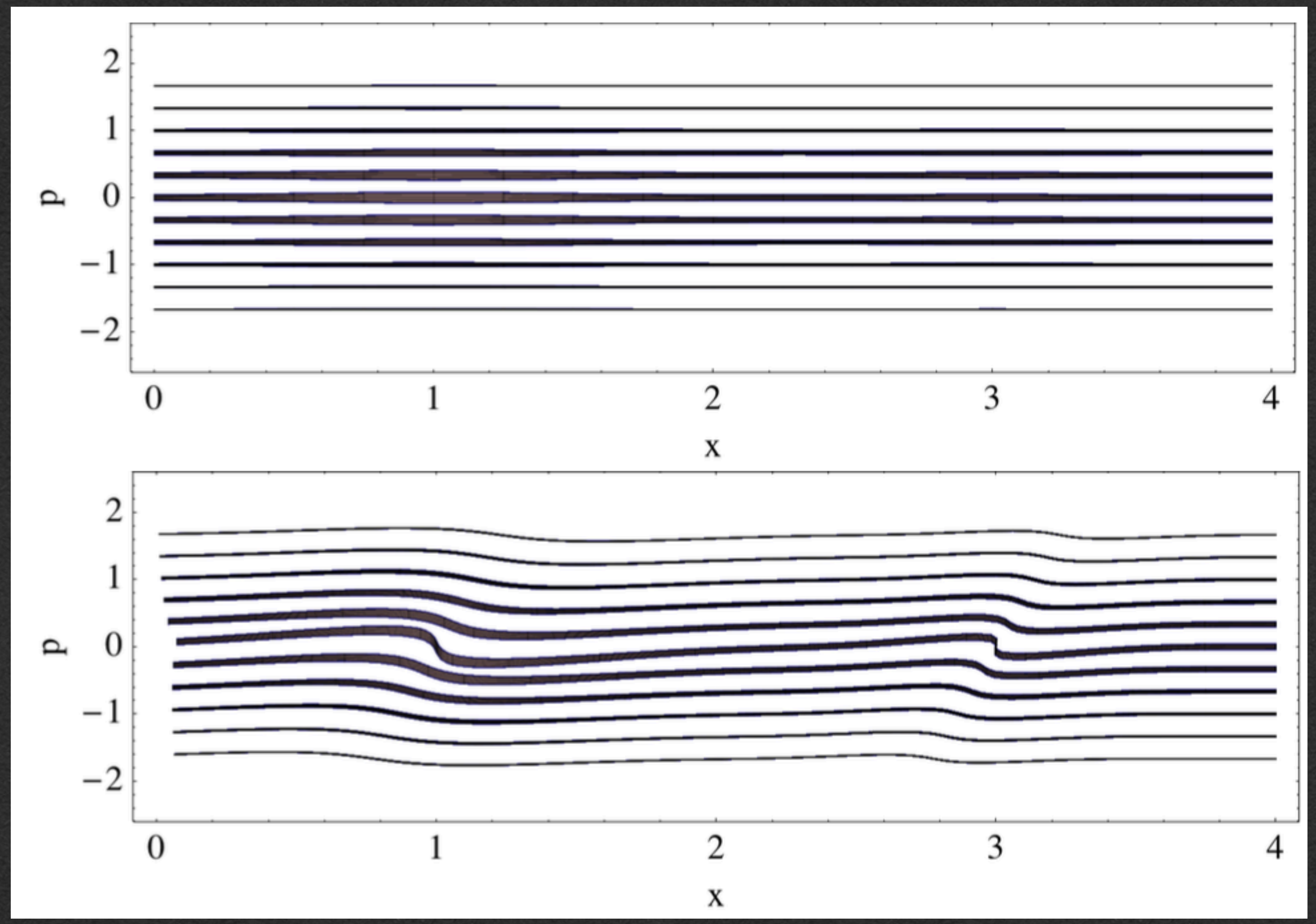

    - EFT (EFfective theory): arbitrary coefficients depending on model parameters [Senatore et al.]
    - new hope with TSPT (Time-Slicing Perturbation theory)? [Sibiryakov et al. in prep.]

# Open challenges in neutrino cosmology

- Progress on modelling of non-linear perturbations
  - assuming good solution exists for ΛCDM, what about extension to massive neutrinos?
    - problem: which equations to start with? non-linear CDM + linear ν lead to inconsistencies. [Garny et al. 2014]
    - treat massive neutrinos as second fluid with non-zero sound speed and viscosity effects: totally wrong at CMB time (used by [Audren et al. 2015; Planck 2015; Durrer & Sellentin 2015] to claim indirect CNB detection in CMB)
    - fluid approximation OK at late times (sub-Hubble scales), provides convenient equations for non-linear neutrino perturbations in PT/RPT/etc. methods [JL & Tram 2011; Garny et al. 2014, Führer et al. 2015]

# Open challenges in neutrino cosmology

- Progress on modelling of non-linear perturbations
  - assuming good solution exists for ΛCDM, what about extension to massive neutrinos?
    - reformulate equations. Cut phase space in momentum bins. Each bin = fluid with given sound speed and no velocity dispersion/viscosity. Central bin = CDM, other bins more and more linear… all PTs might work better. [Dupuy & Bernardeau 2014, 2015]



# Open challenges in neutrino cosmology

Summary of challenges to match ambitious targets like $\sigma(M_\nu)$ = 15-20 meV:

- numerical progress in simulations
- theoretical progress on theory of (non-linear) large-scale structure in presence of massive neutrinos
- analytical modelling of non linear observables
- find new observables relevant for $M_\nu$ (cross correlations: CMB x LSS due to ISW [JL et al. 2008; Carbone et al. in prep.], LSSxLSS due to lensing…)