Cosmological Anisotropies and Neutrino Mass

"2nd Anisotropic Universe Workshop", Amsterdam, 11.04.2016

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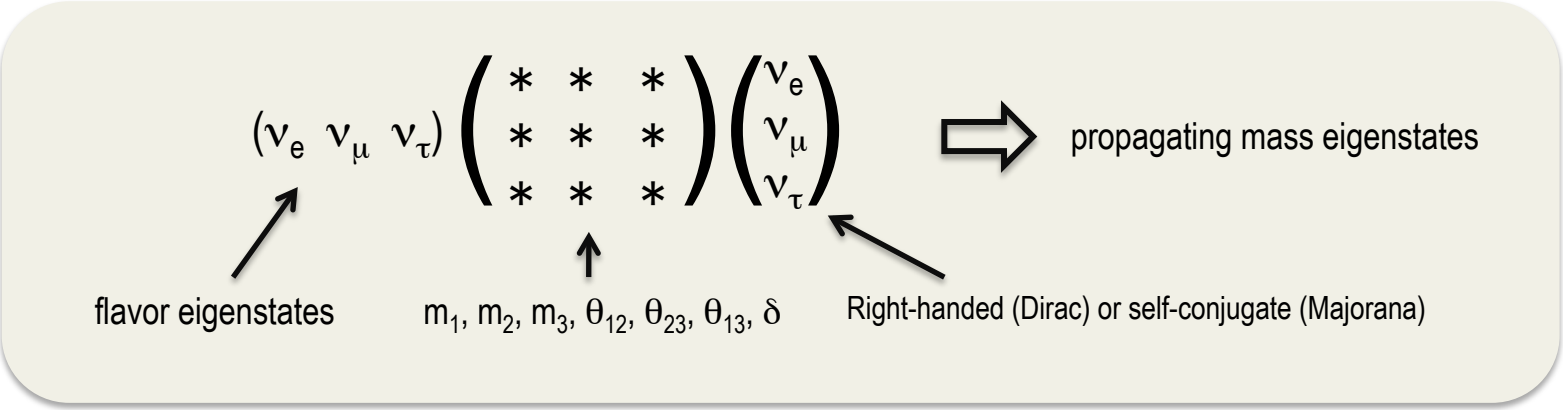
Motivations

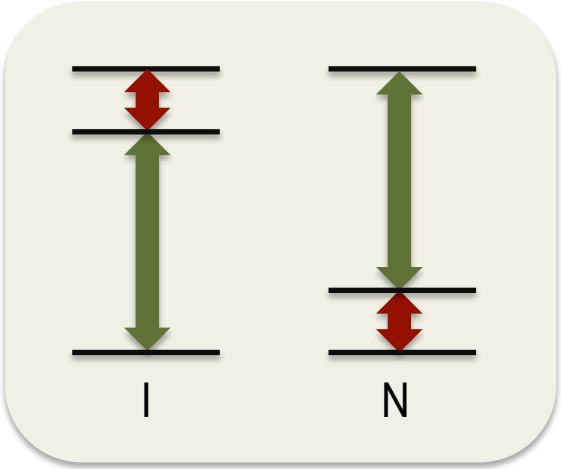
- Neutrino oscillations prove that there is a mass mixing matrix:



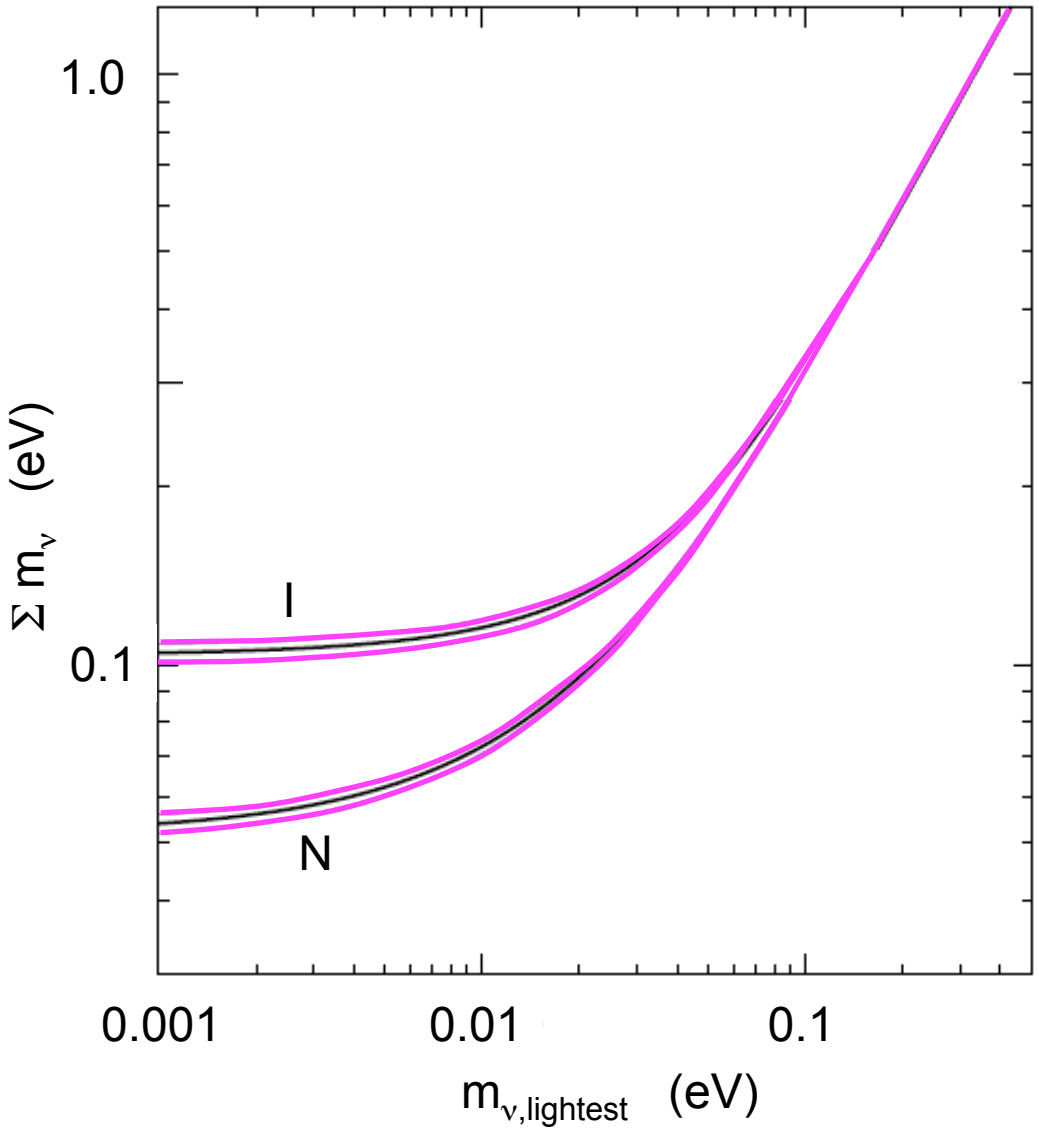
- Laboratory experiments measured:
  - 2 squared mass differences, 3 angles , bounds on phase
  - One missing mass! Knowing one new combination would fix everything (maybe up to ordering option) … “neutrino mass scale” problem

Motivations

- Normal and inverted hierarchy:



$M_\nu > 0.11$ eV 0.06 eV



Motivations

… for measuring total neutrino mass M_ν with cosmology:

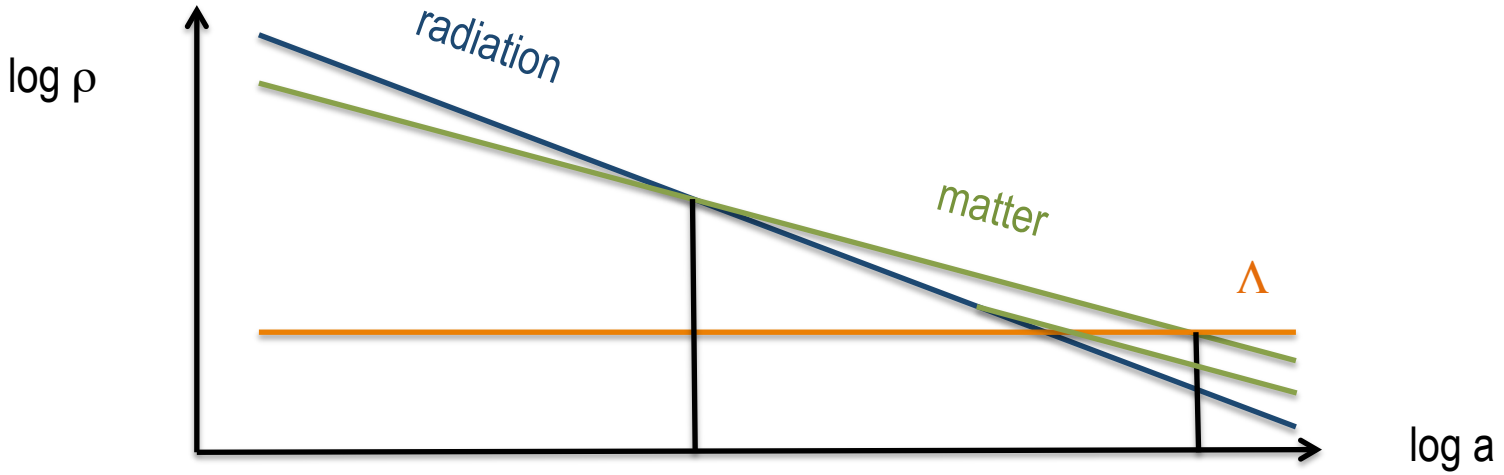
- For particle physicists
  - More sensitive than β- and double-β- decay, works for Dirac and Majorana
  - Complementary to β-decay which contains independent information (on phases, angles, Dirac/Majorana…)
  - Can lead to full understanding of neutrino sector (or give hint of extensions to e.g. sterile neutrinos)
  - Hints on seesaw, leptogenesis, baryogenesis…

Motivations

… for measuring total neutrino mass M_ν with cosmology:

- For cosmologists
  - Safest output/reward of current observational efforts
  - Neglect neutrinos would bias results; e.g.:
    - at least 5% effect in power spectrum would point incorrectly to running, modified gravity etc…
    - At least 1% impact on H_0 value inferred from CMB (through angular diameter distance)
  - Excluding M_ν ~ 0.11eV would rule out IH
  - Excluding M_ν ~ 0.06 eV would point out at new physics or cosmology
    - Neutrinos decay or interact strangely
    - Standard neutrino decoupling does not apply (low-temperature reheating, entropy production, etc.)

Background evolution



Non-relativistic transition: $m_\nu = T_\nu \sim (4/11)^{1/3}\, T_\gamma$, $z = (m_\nu/5.3\ \text{eV})\ 10^4$

After CMB decoupling for $m_\nu < 0.57$ eV ($M_\nu < 1.7$ eV)

- for fixed ω_M , change in time of equality
- for fixed ω_{CDM} and equality, peak scale affected by $(M_\nu / 0.06\ \text{eV})$ %
- for fixed equality AND peak scale, i.e. adjusting H_0, Ω_Λ, effect in LISW

Neutrino perturbations

- Neutrino coupled only gravitationally. Mathematical description:
  - f(t,**x**,p,**n**) followed with Boltzmann equation
  - $T_{\mu\nu}$ inferred from f(t,**x**,p,**n**) and mass m_ν ($\delta\rho_\nu$, δp_ν , θ_ν , σ_ν for scalars)
  - Anisotropic stress comes from velocity dispersion (flow superposition)
  - Enters in Einstein equation, and back-reacts on all species

- Relativistic regime:
  - photon-neutrino gravitational interactions responsible for CMB effects (*neutrino drag:* shifts peak location and amplitude)
  - Contributes to sensitivity of CMB to N_{eff} (together with background effects)

- Non-relativistic regime: importance of free-streaming scale

Neutrino perturbations

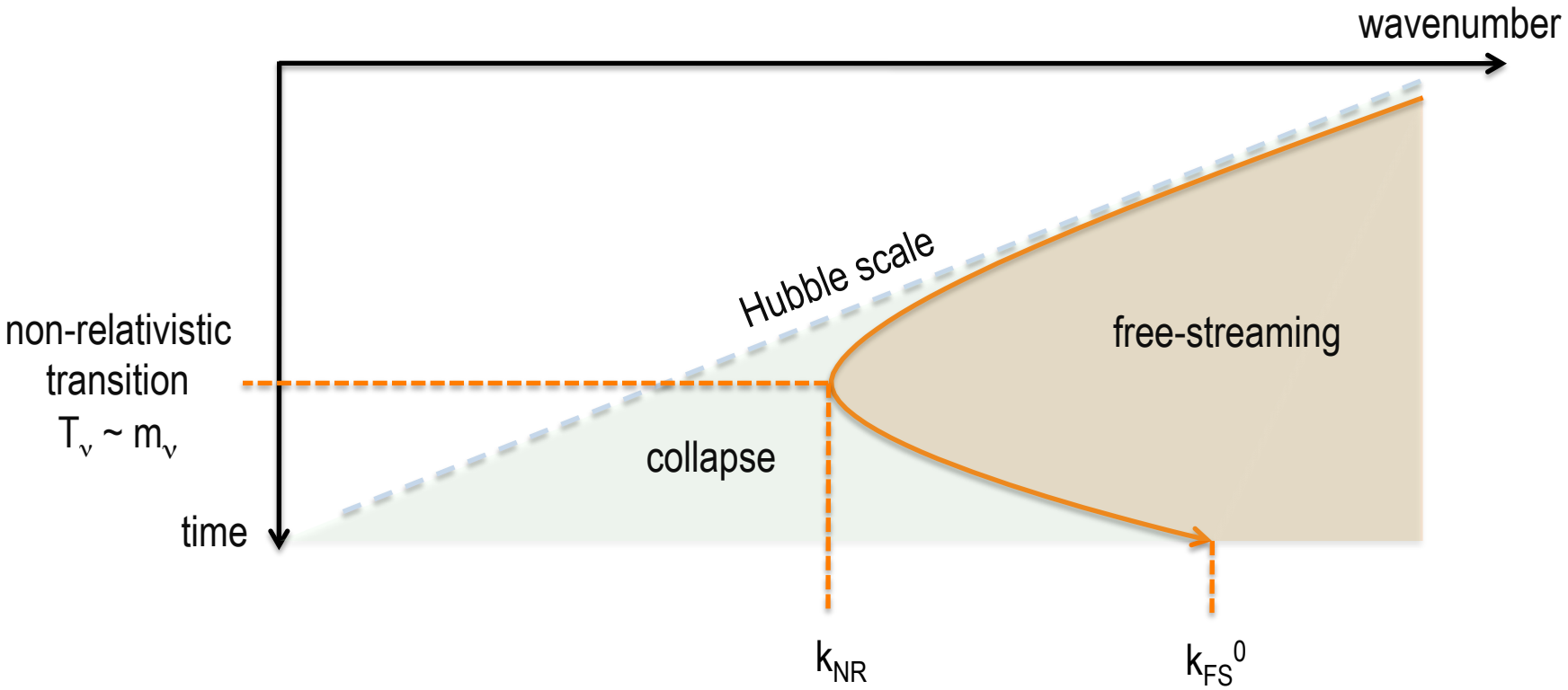
- Non-relativistic regime: importance of free-streaming scale

  - Interacting species with pressure:
    - no gravitational collapse below Jeans length
    - $k_J \sim H/c_s$ (sound speed in fluid)

  - Non-interacting species with velocity dispersion:
    - no collapse below free-streaming length
    - $k_{FS} \sim H/c_\nu$ (average particle velocity: c_ν = first c, second $\langle p \rangle/m = 3.15\, T_\nu/m_\nu$)

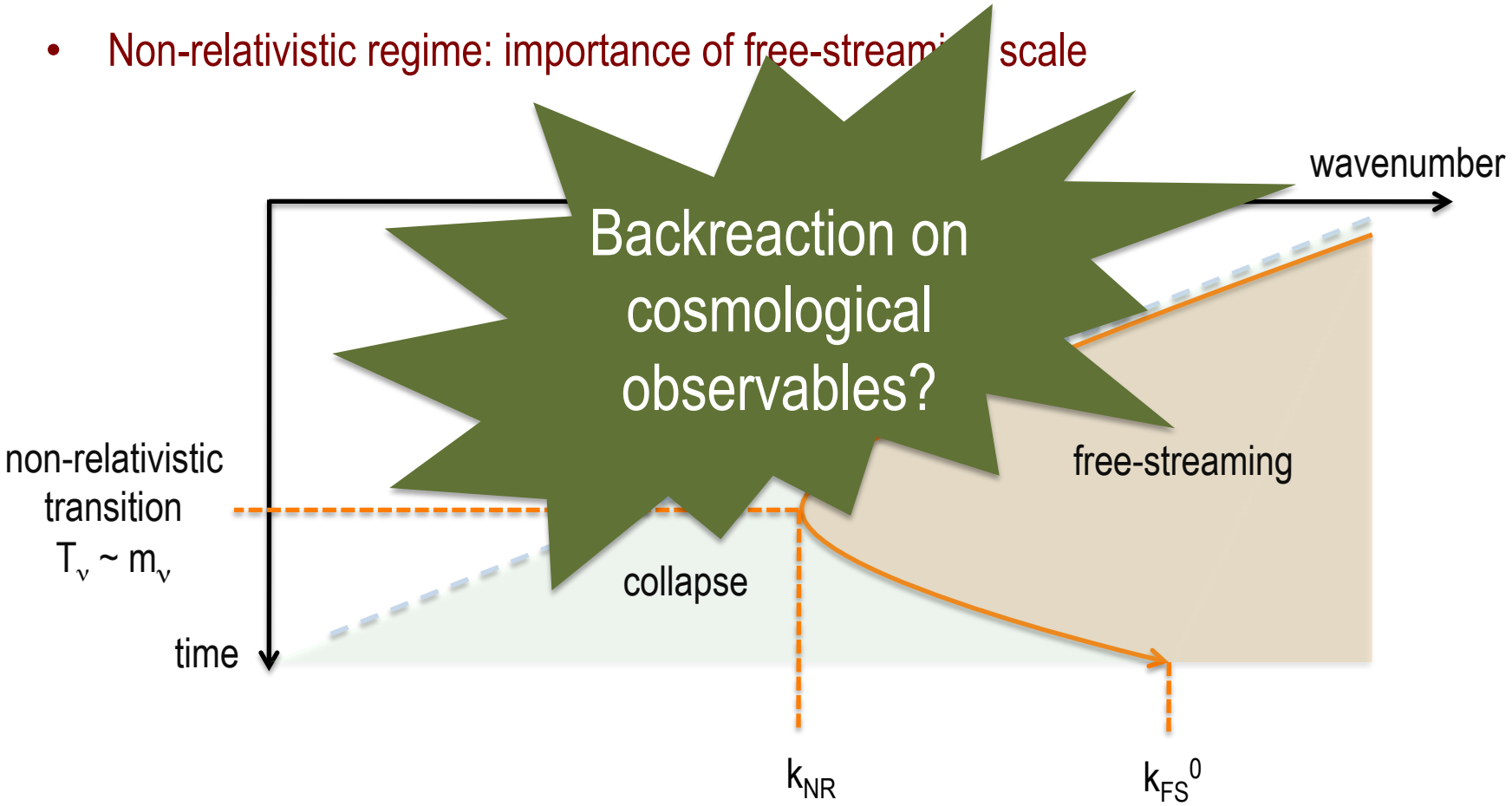
Neutrino perturbations

- Non-relativistic regime: importance of free-streaming scale

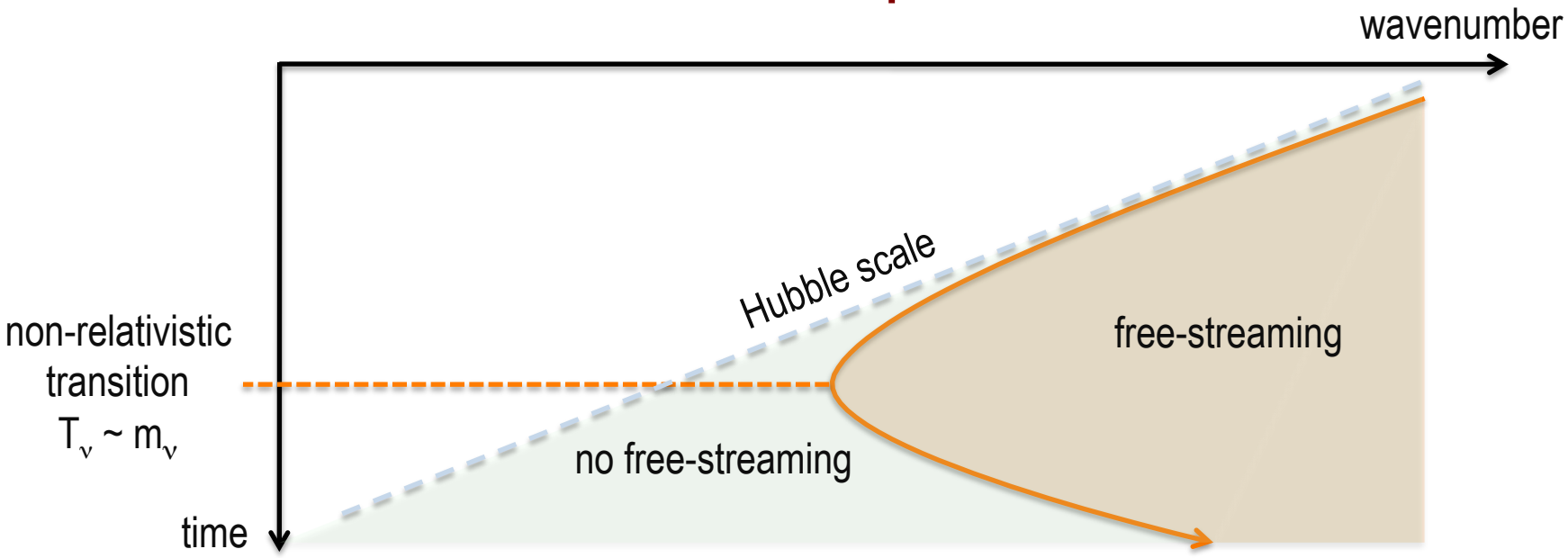


Neutrino perturbations

- Non-relativistic regime: importance of free-streami scale



Effect of Neutrino perturbations



- cdm, baryons, neutrino perturbations identical

$$\delta_m'' + \mathcal{H}\delta_m' + 3/2\mathcal{H}^2\,\delta_m = 0$$

- neutrino perturbations supressed
- cdm, baryon given by:

$$\delta_{bc}'' + \mathcal{H}\delta_{bc}' + 3/2\mathcal{H}^2\,(1-f_\nu)\,\delta_{bc} = 0$$

$f_\nu = \Omega_\nu/\Omega_m$ (minimum 0.006)

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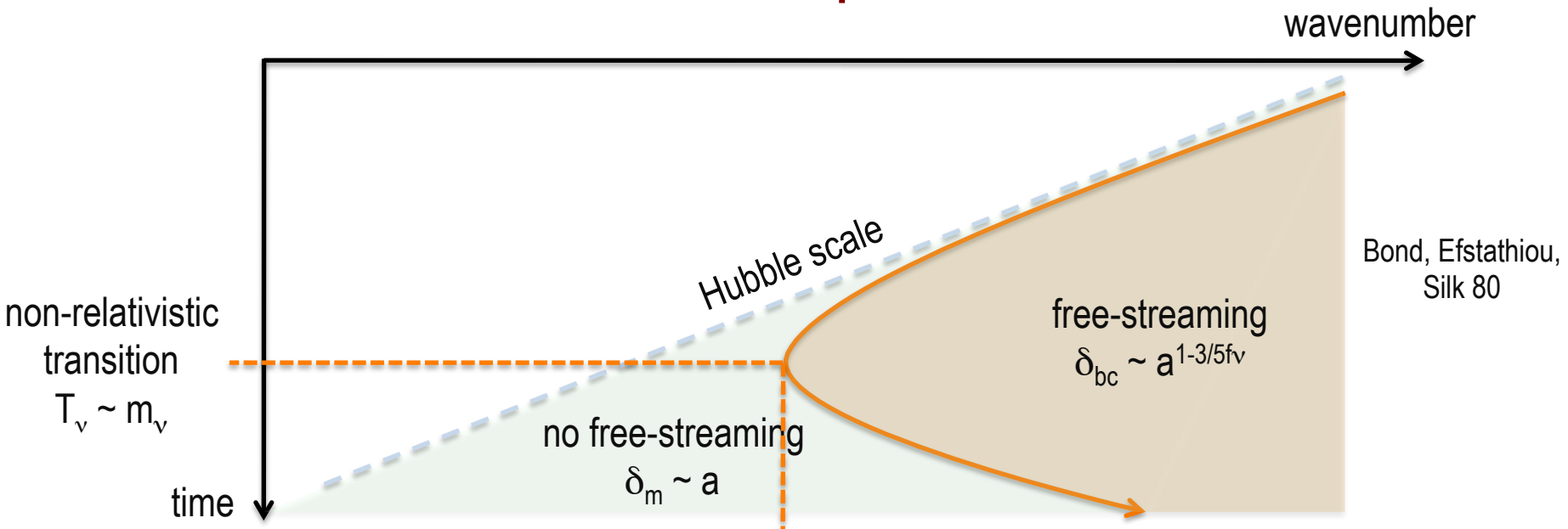

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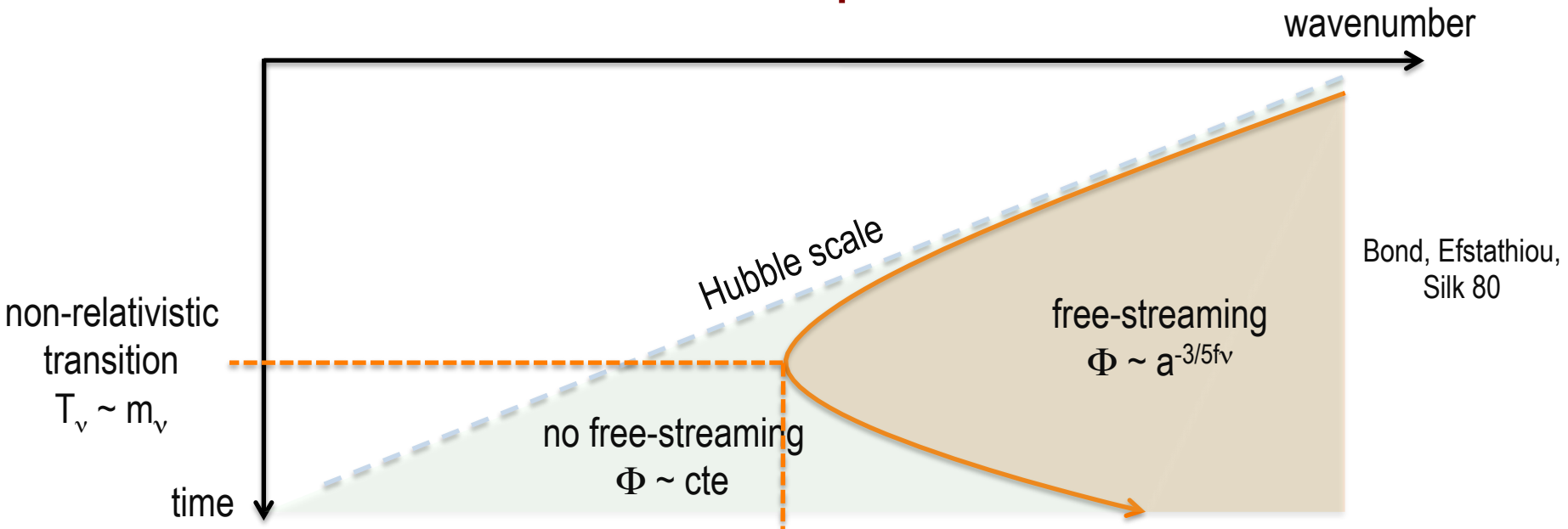

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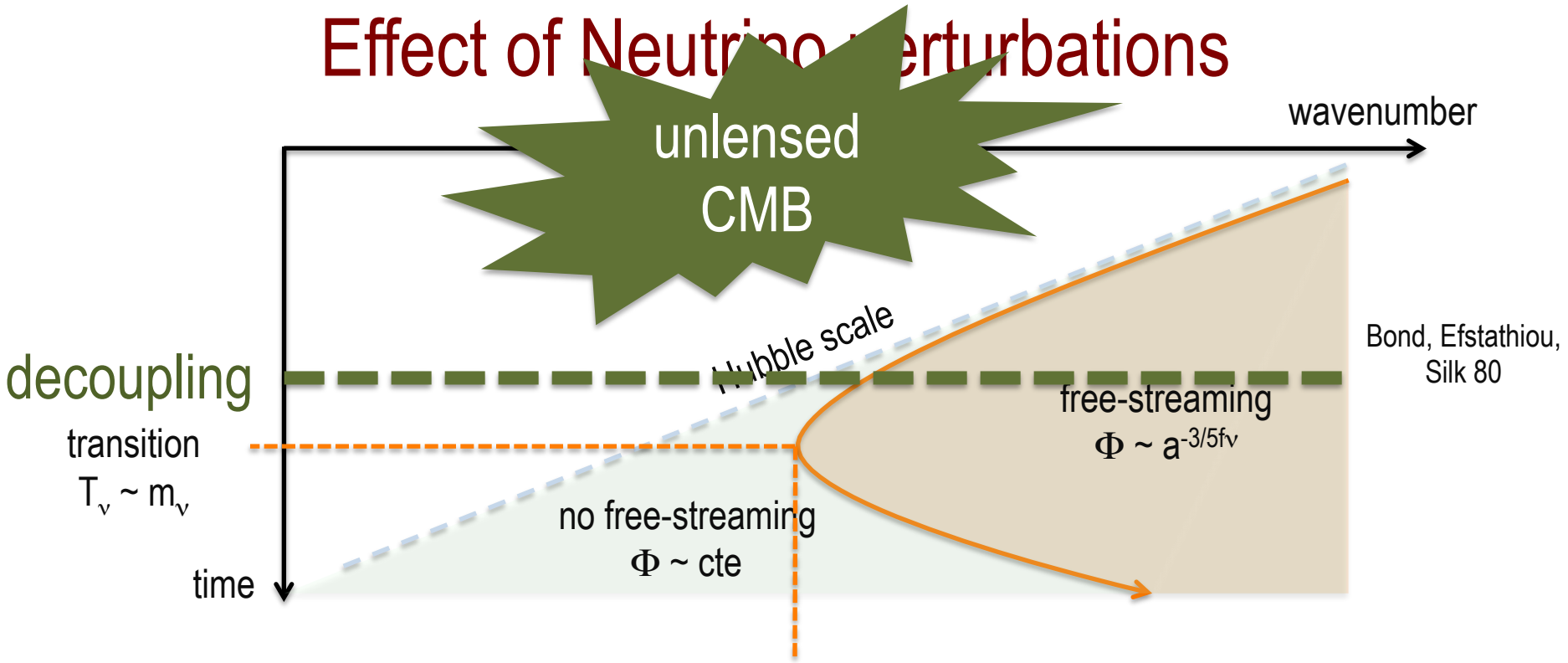

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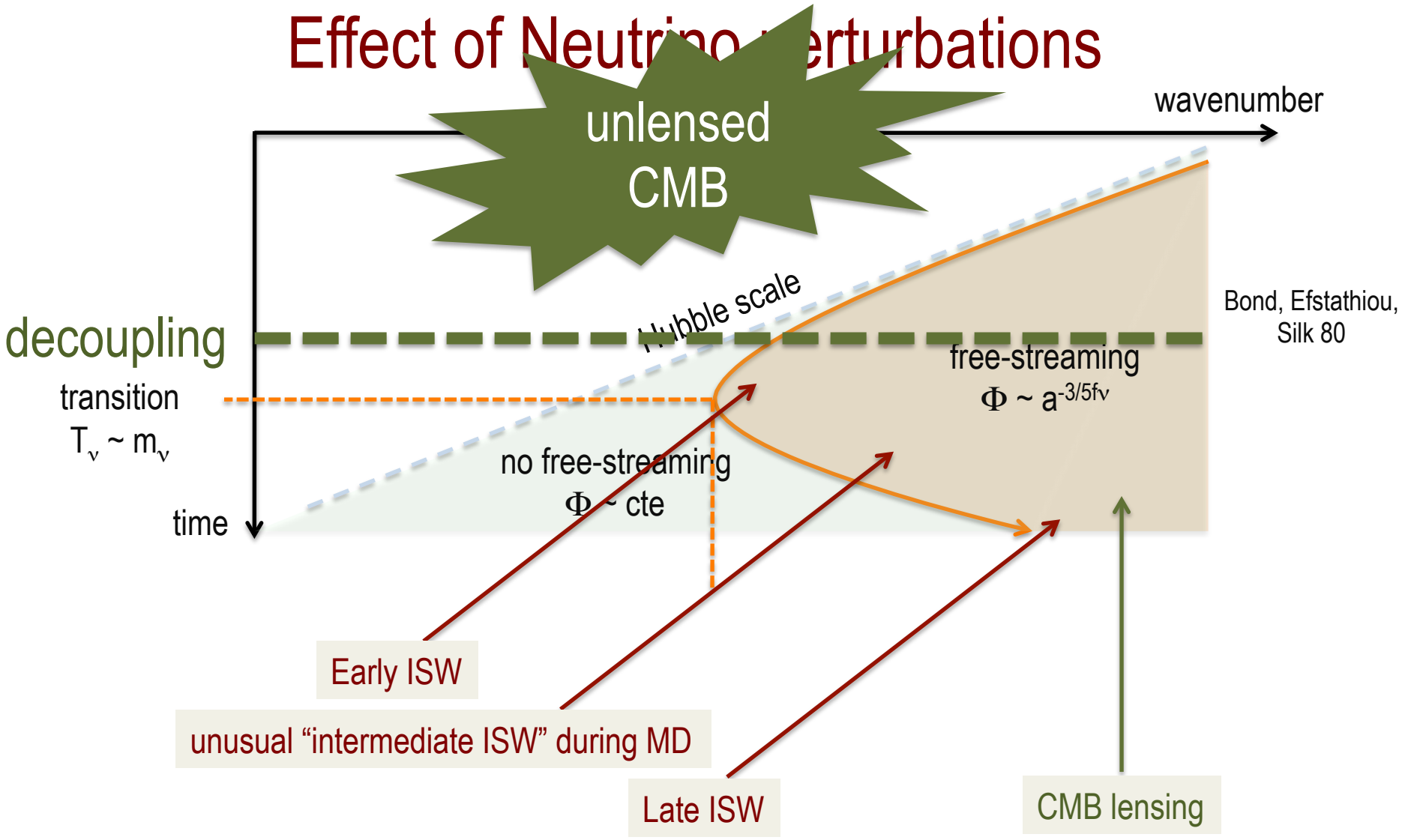

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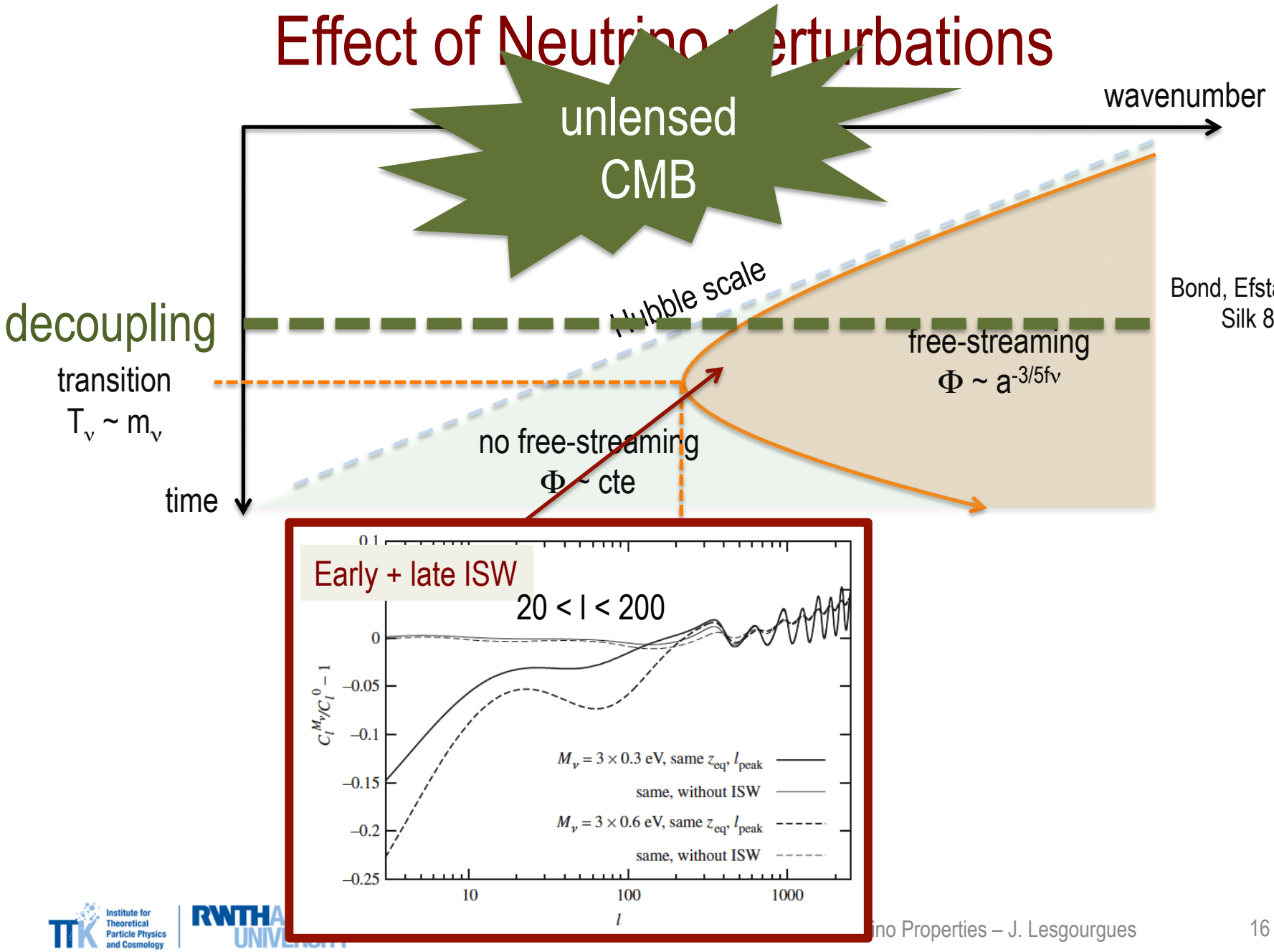

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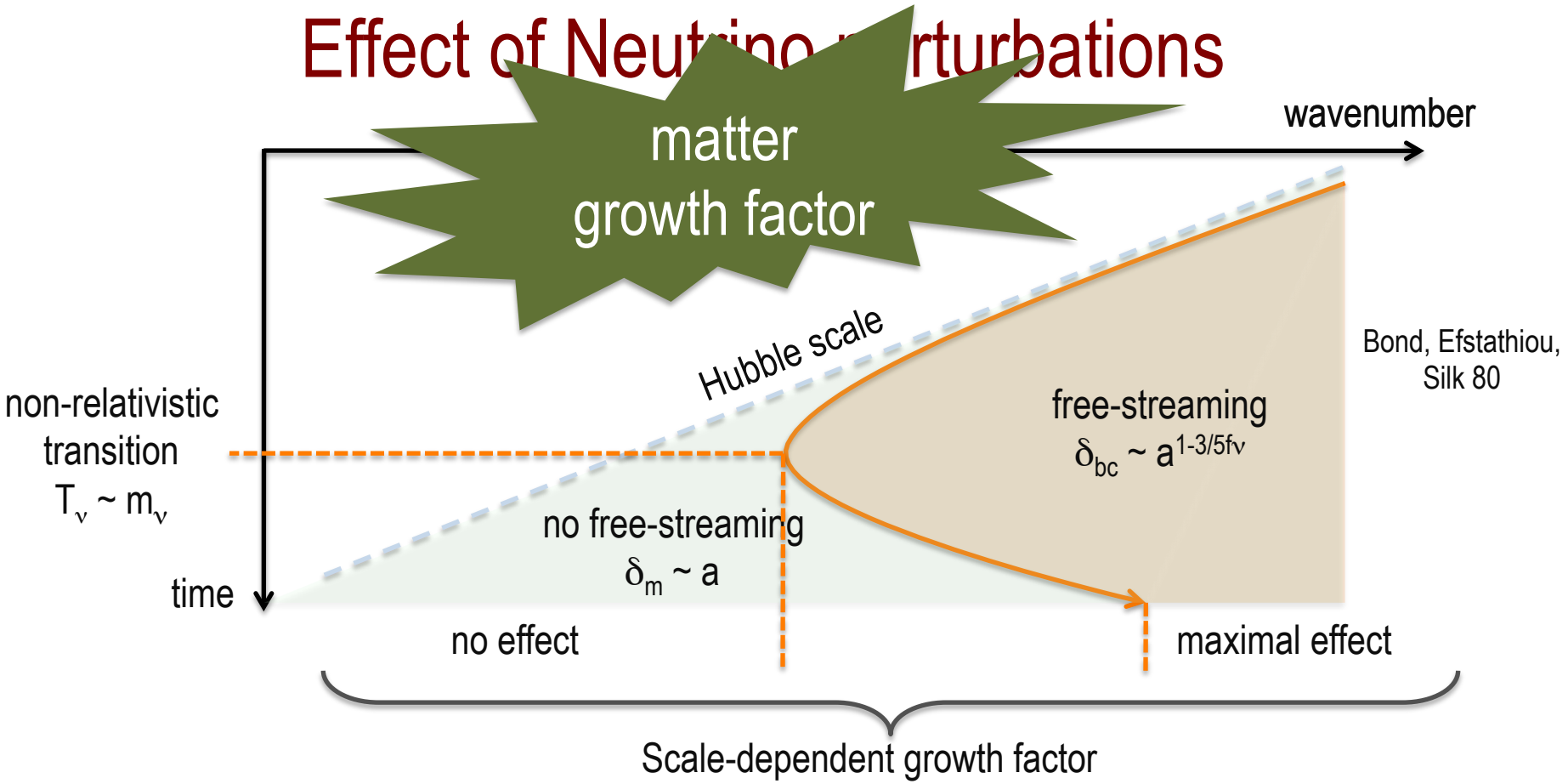

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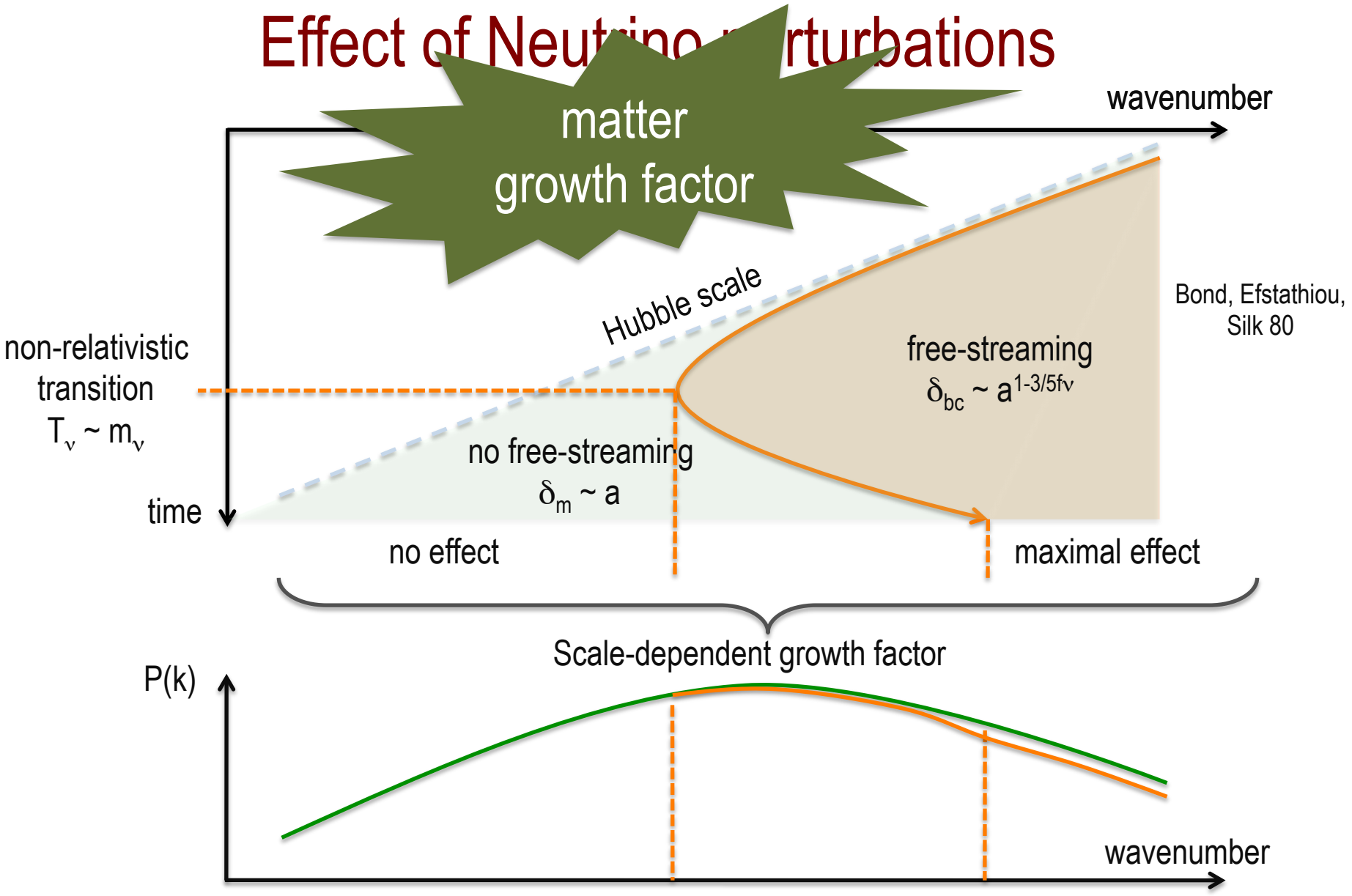
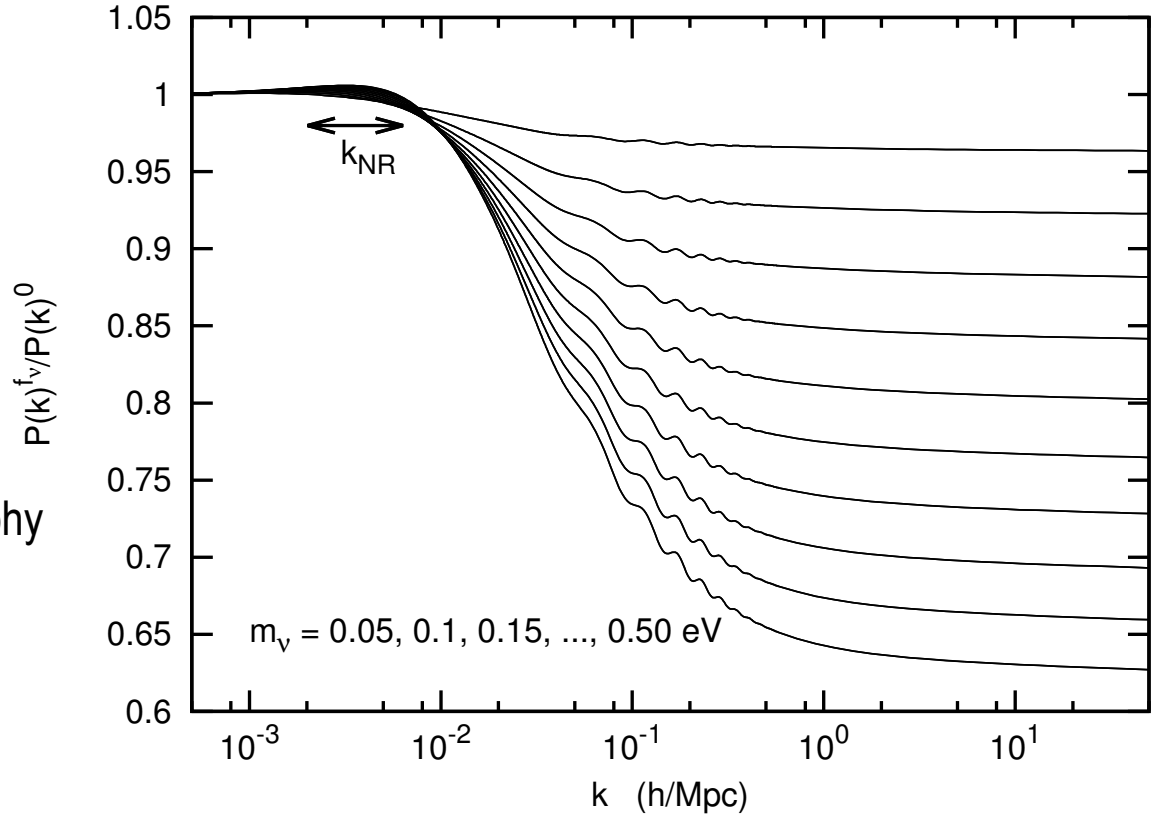


Neutrino masses and linear growth of structure

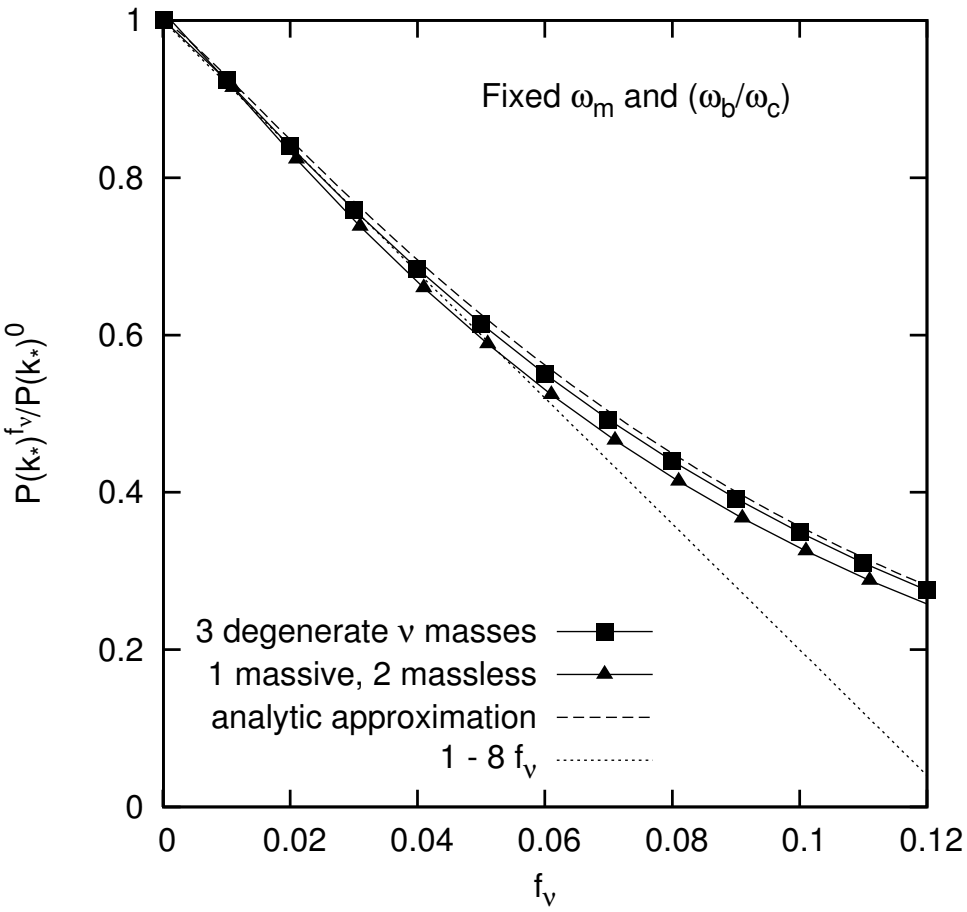
- Step-like effect
- Depends on redshift!
  Smaller at high z
- Importance of tomography



Neutrino Cosmology, CUP 2013, Lesgourgues, Pastor, Mangano, Miele
Physics Reports (2006), JL, Pastor

Neutrino masses and linear growth of structure

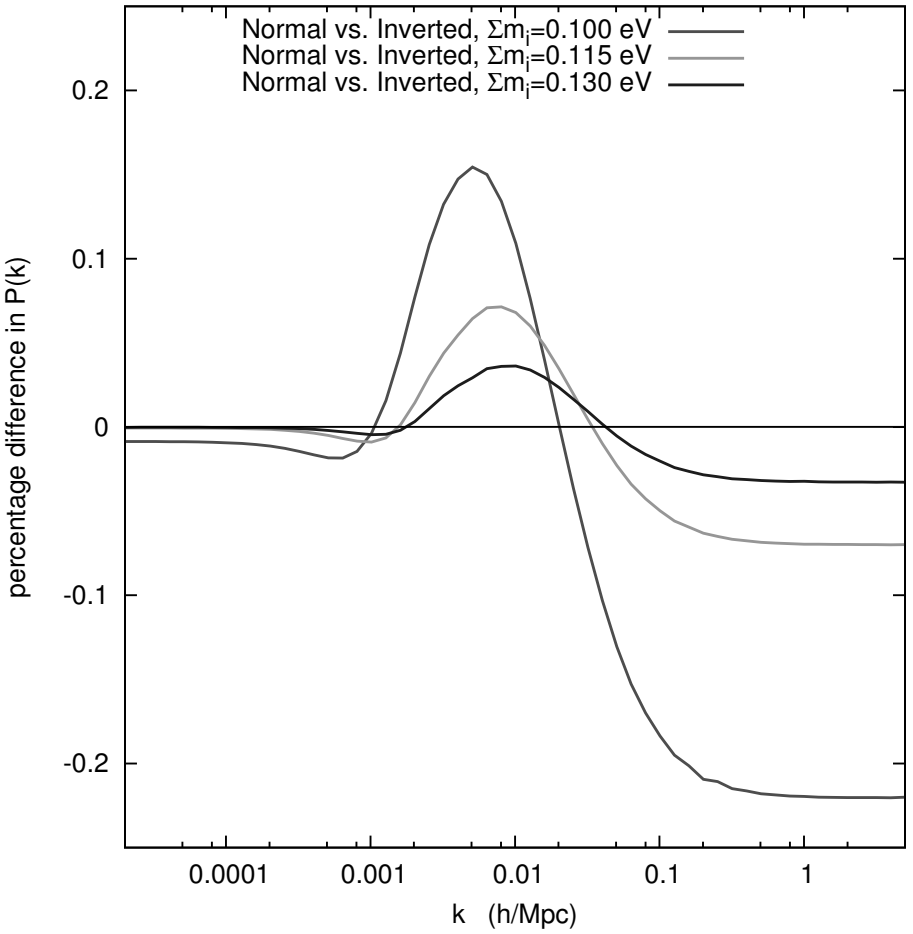
- Today: $\Delta P/P \sim 1\text{-}8 f_\nu$
- At least 4.5% suppression
- Depends mainly on total mass.
- But k_{NR} depends on individual mass



Neutrino Cosmology, CUP 2013, Lesgourgues, Pastor, Mangano, Miele

Neutrino masses and linear growth of structure

- Mass splitting: effects of order 0.1%
- Undetectable

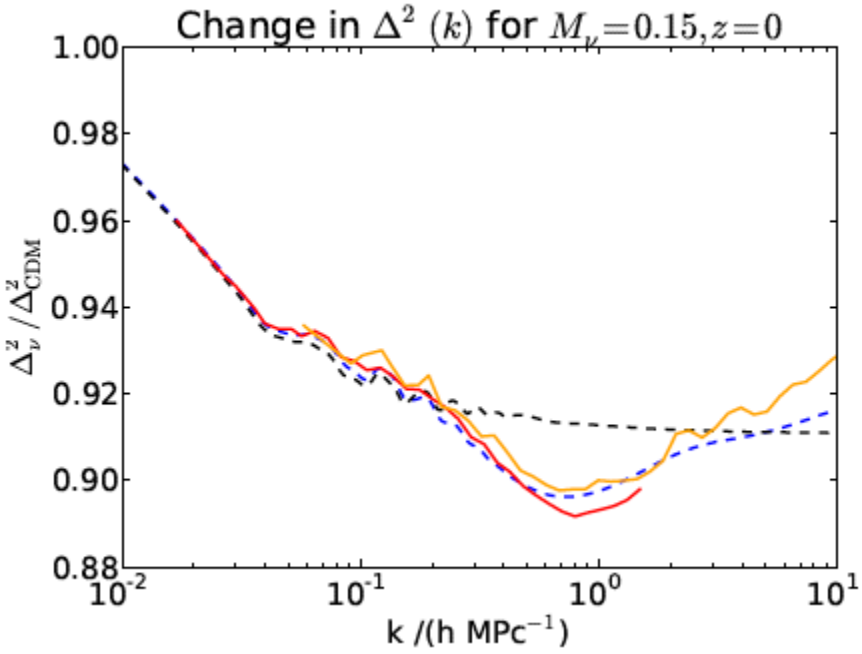


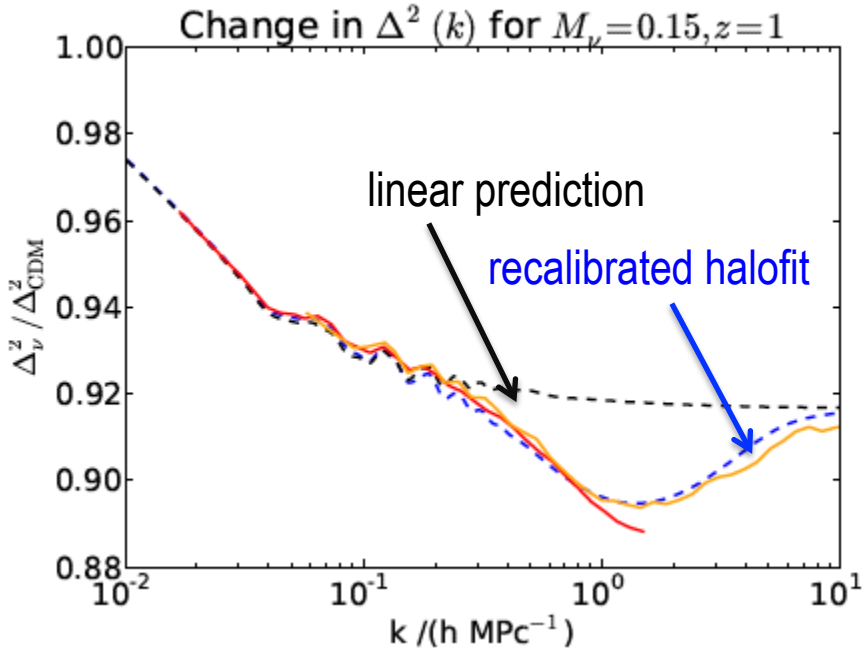
Neutrino Cosmology, CUP 2013, JL, Pastor, Mangano, Miele Tram, Lesgourgues, 2011

Neutrino masses and non-linear growth of structure

- Effect enhanced by non-linear evolution

Bird et. al 2011, see also Brandbyge et al., Wagner et al., Villaescusa et al., Castorina et al.





- tree-PM, $N_\nu \sim N_{cdm}$, ν in tree only, not in mesh (Trieste, Milano: DEMUni);
  or ν on a grid, evolved using linear equations sourced by non-linear Φ, δ_{cdm} (Bird & Ali-Haimoud 2012)
- Recalibrated Halofit (Bird et al.), or Halofit on cdm component only (Castorina et al.)

Sensitivity of current and future experiments

- Best current bounds

Planck 2015; Palanque-Delabrouille et al. 2015; Niro et al. 2015

Planck 2015 TT,TE,EE + BAO : $M_\nu < 0.17$ eV (95%CL)
Planck 2015 TT,lowP + BOSS-[Lyα or gal.cor.] : $M_\nu < 0.12$ eV (95%CL)

2015: disfavor IH

- published forecasts for
  - Galaxy redshift surveys
  - Cluster redshift surveys
  - Lyman-alpha flux spectrum
  - Cosmic shear surveys
  - CMB lensing extraction
  - 21cm surveys
  - + various combinations

Perotto et al. 06; Sekiguchi et al. 10; Gratton et al. 08; Lahav et al. 09; Namikawa et al. 10; Kitching et al. 08; Debono et al. 09; Cabone et al. 11, 12; Hannestad et al. 06, 12, 13; Lesgourgues et al. 04; Pritchard & Pierpaoli 08; Wang et al. 05; Jimenez et al. 10; …

Full Planck + DES : $\sigma(M_\nu) \sim 0.06$ eV
Full Planck + LSST : $\sigma(M_\nu) \sim 0.04$ eV
Full Planck + Euclid : $\sigma(M_\nu) \sim 0.02$ - 0.03 eV
Full Planck + 21cm (SKA/FFTT) : $\sigma(M_\nu) \sim 0.075$ / 0.0075 eV
Core+ / LiteCore : $\sigma(M_\nu) \sim 0.03$ eV

2022: detect or disfavor NH

ISW x LSS with massive neutrinos

analytical/numerical computations and forecast in JL, Valkenburg & Gaztanaga, PRD 2008 (0710.5525)

Limber approximation:

$$C_l^{GG} \sim < \Phi(k,z)\ \Phi(k,z) > \qquad C_l^{TG} \sim < \Phi'(k,z)\ \Phi(k,z) >$$

- Trivial effect: $\Phi(k,z)$ step-like suppressed for large k / small l (identical for GG and TG)
- Interesting effect: $|\Phi'|$ enhanced by neutrino mass (mass effect enhanced in TG w.r.t GG)

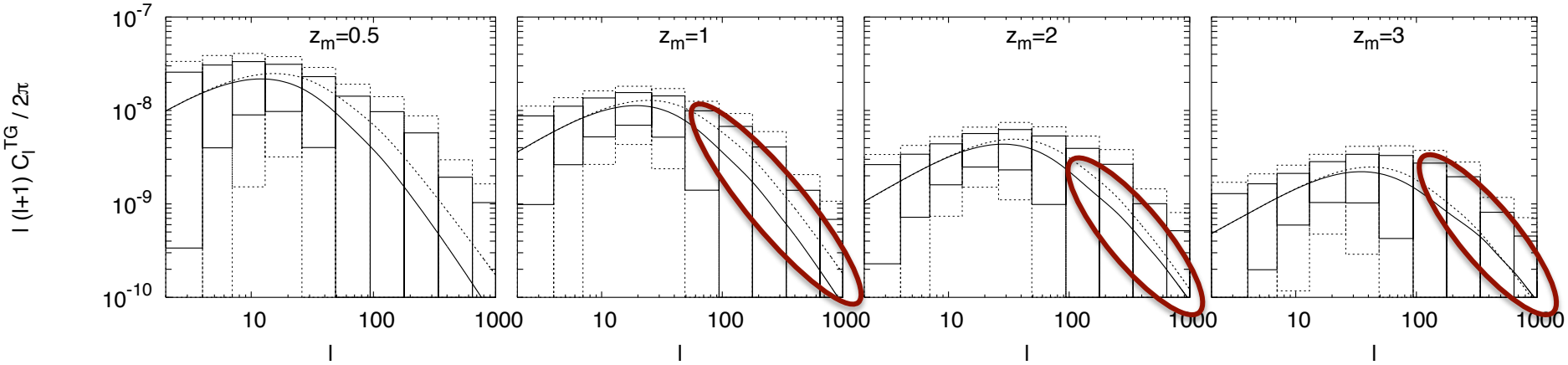
Interesting effect expected to dominate:

- for small scales (probing neutrino free-streaming)
- at large redshift (for $z >> z_\Lambda$, otherwise subdominant w.r.t Λ/DE effect)

… hence at large l, for which primary CMB = large noise

ISW x LSS with massive neutrinos

JL, Valkenburg & Gaztanaga, PRD 2008 (0710.5525)



Planck x Euclid – like errors

… but ``interesting effect'' dominated by experimental + irreducible noise

ISW x LSS with massive neutrinos

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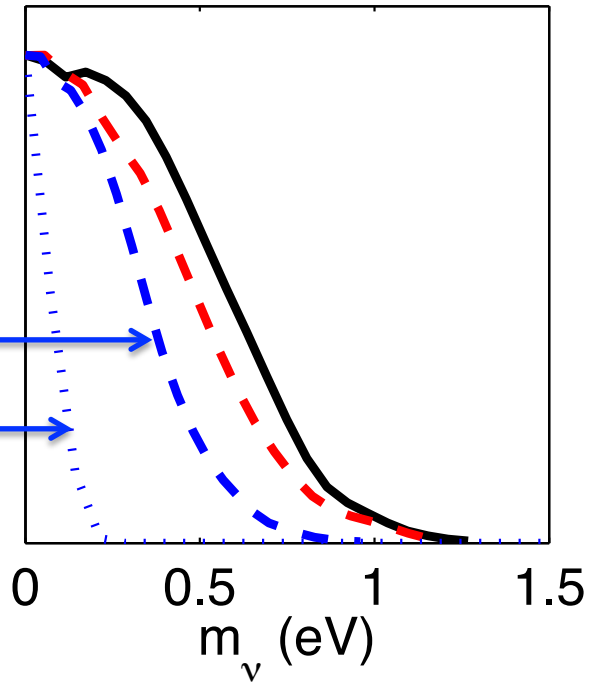
MCMC forecast for:

Planck

(+ Planck x DES)

(+ Planck x LSST)

(+ LSST x LSST)



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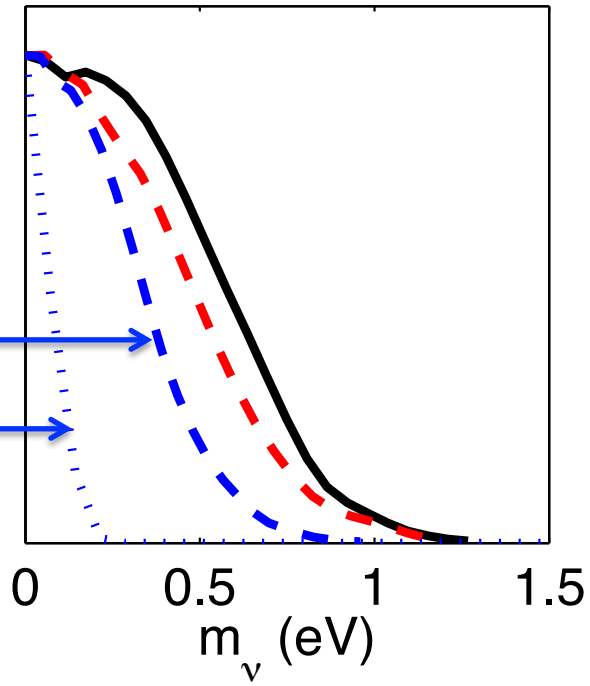


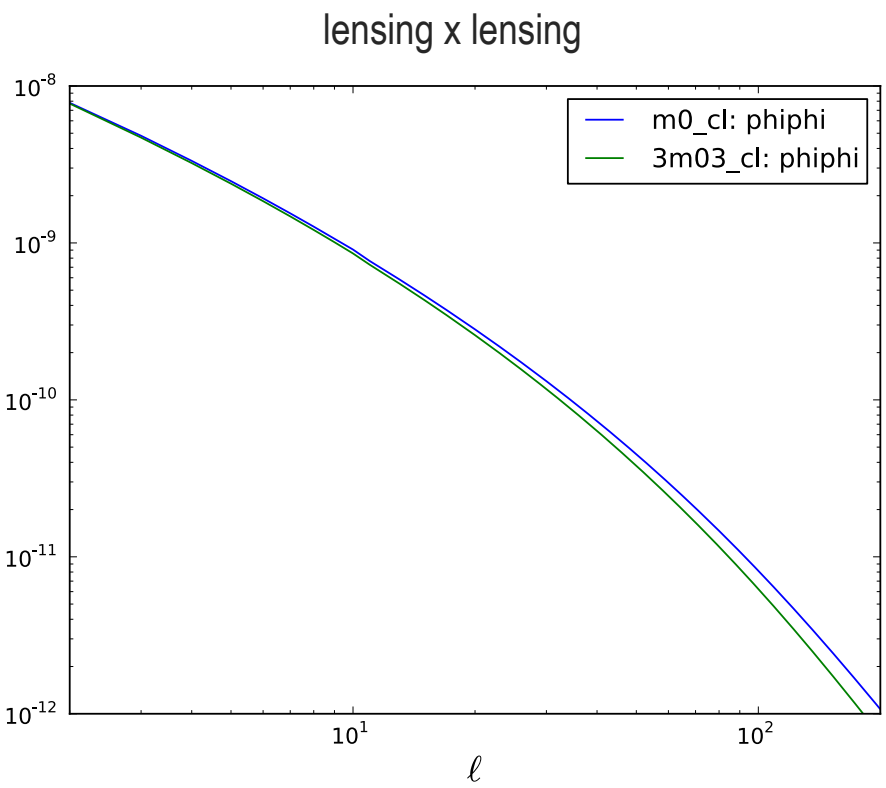
Assumes no systematics, linear bias… in real life cross-correlation more valuable than in forecast!

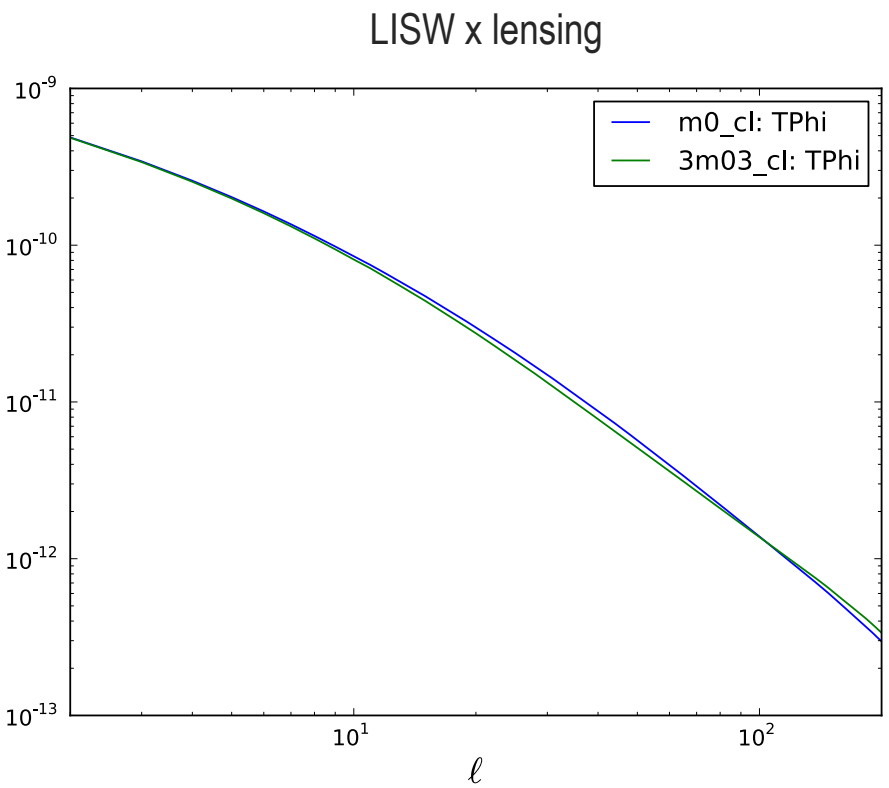
Other correlations

- This was [ISW x density]
- Same conclusions for [ISW x lensing]
- More obvious effects on [LSS x LSS]

ISW x Lensing with massive neutrinos

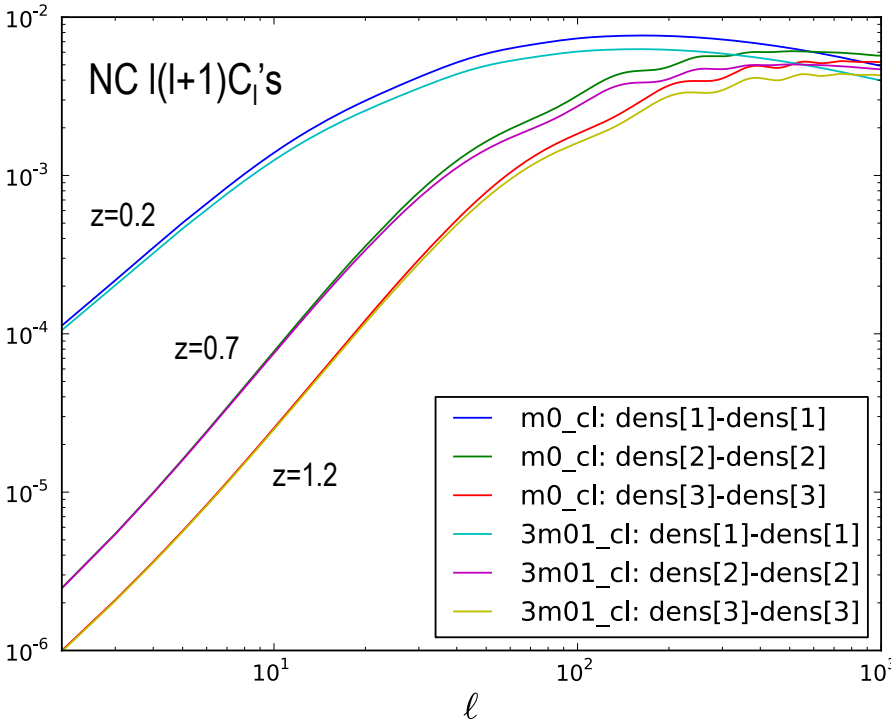
- For temperature x CMB lensing (= LISW x lensing) : (3 x 0.3 eV versus massless)

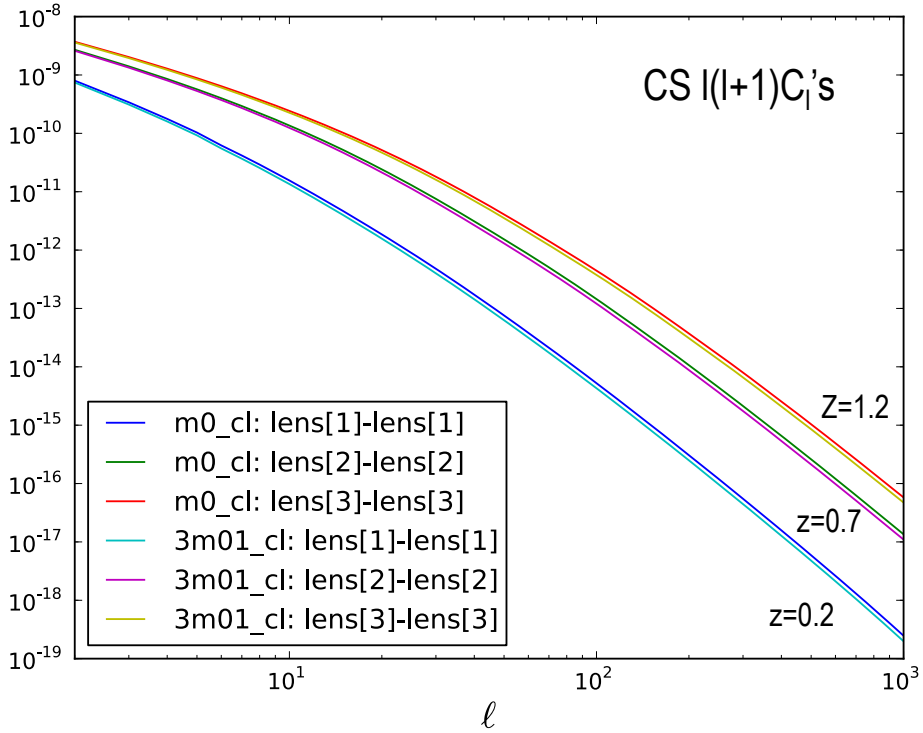




LSS x LSS with massive neutrinos

- NC (number count) and CS (cosmic shear), z = 0.2,0.7,1.2, Δz=0.1: (3 x 0.1 eV versus massless)





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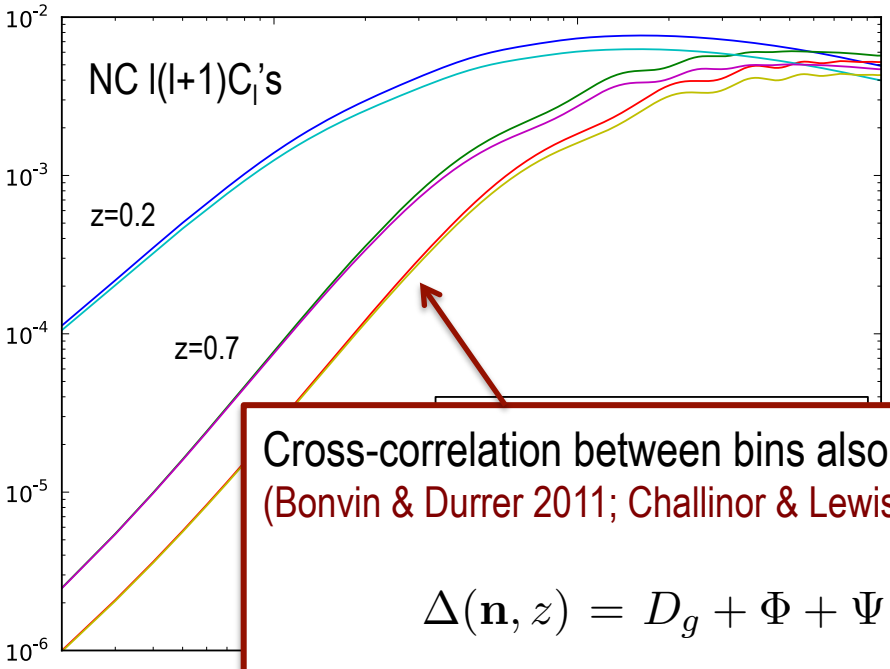

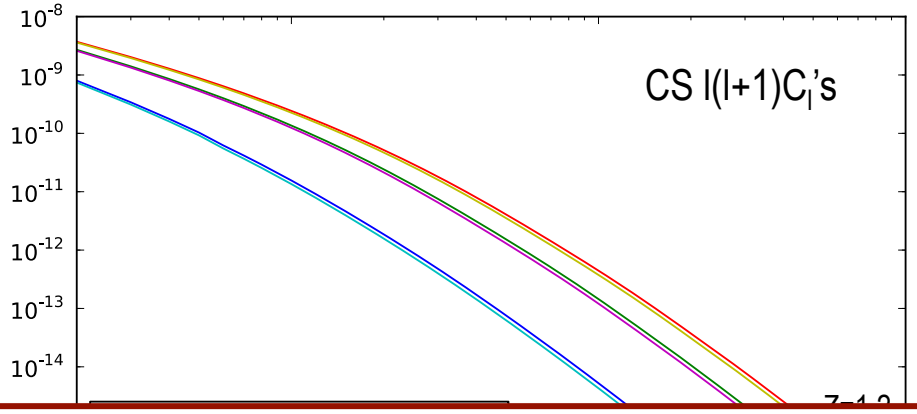

Cross-correlation between bins also interesting: probes lensing of one bin by another bin
(Bonvin & Durrer 2011; Challinor & Lewis 2011; Di Dio et al. 2013; Durrer & Montanari 2015)

$$\Delta(\mathbf{n},z) = D_g + \Phi + \Psi + \frac{1}{\mathcal{H}}\left[\Phi' + \partial_r(\mathbf{V}\cdot\mathbf{n})\right] + \left(\frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2}{r_S\mathcal{H}}\right)\left(\Psi + \mathbf{V}\cdot\mathbf{n} + \int_0^{r_S} dr(\Phi' + \Psi')\right) + \frac{1}{r_S}\int_0^{r_S} dr\left[2 - \frac{r_S - r}{r}\Delta_\Omega\right](\Phi + \Psi).$$

LSS x LSS with massive neutrinos

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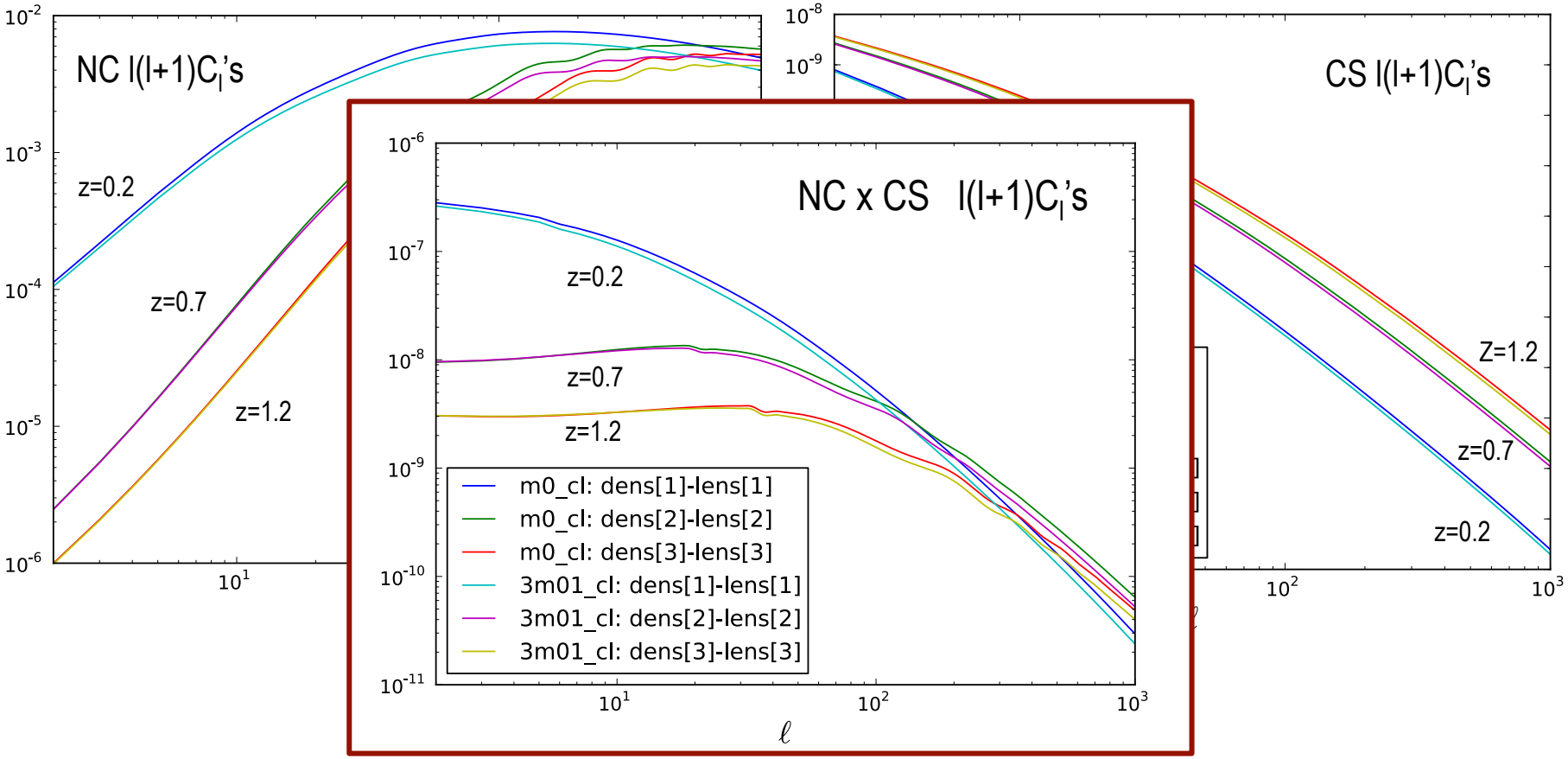


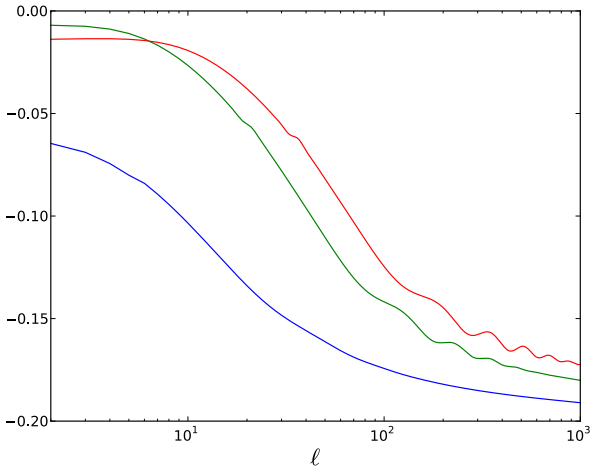
Conclusions

- Neutrino masses are a robust and realistic target
- Cross-correlation help for the same reason that they help with the rest (DE, MG, …)
- Not talking of testing sterile neutrinos, active neutrino decoupling and asymmetry, etc…

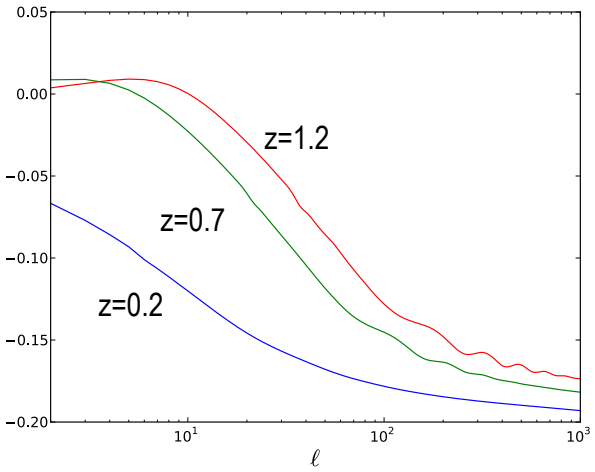
LSS x LSS with massive neutrinos

- NC (number count) and CS (cosmic shear), z = 0.2,0.7,1.2, Δz=0.1: (3 x 0.1 eV versus massless)

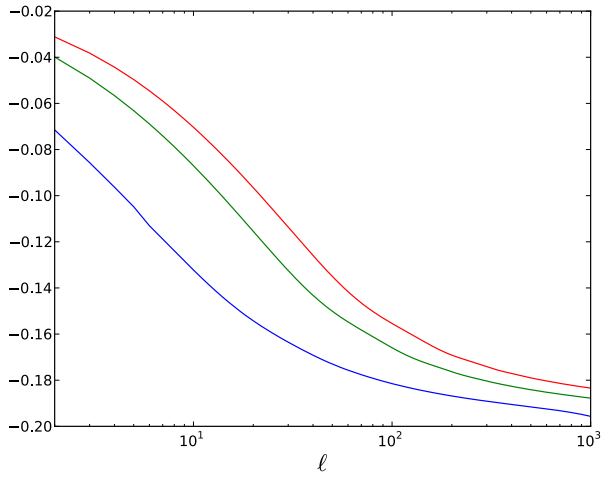
density $l(l+1)C_l$ ratios



cross-correlation $l(l+1)C_l$ ratios

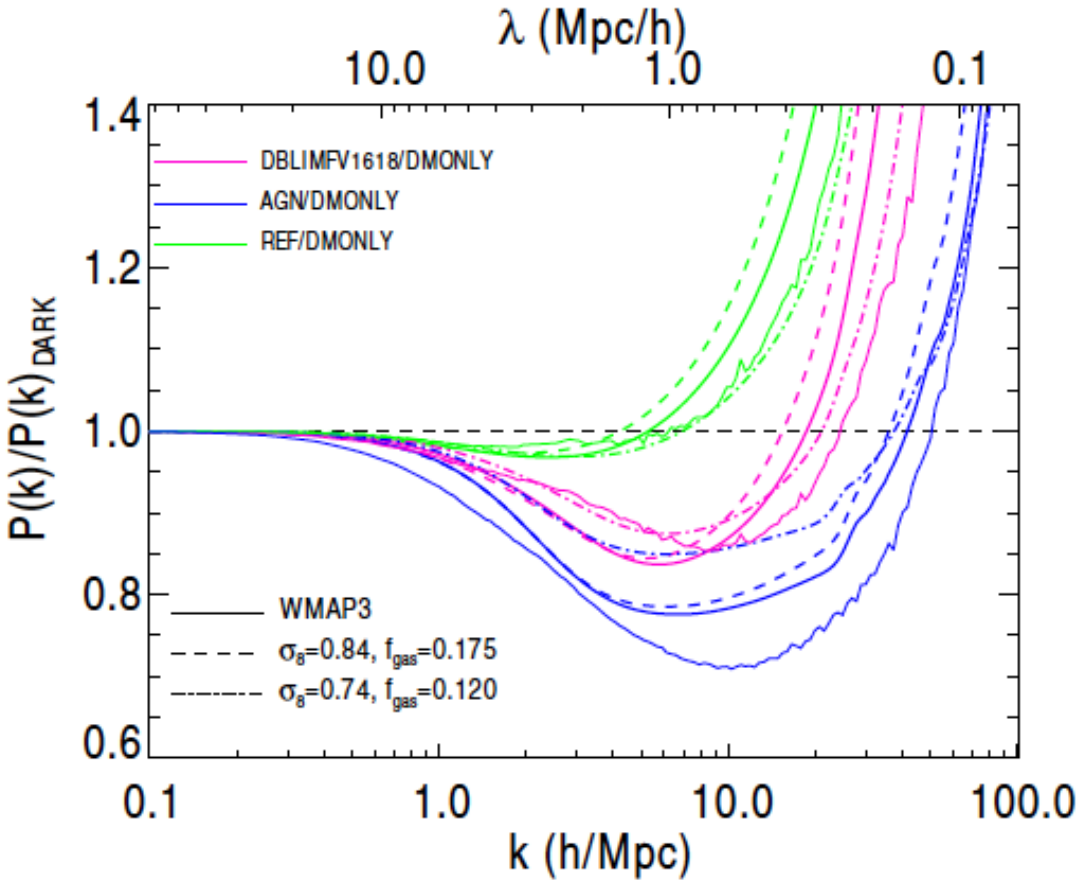


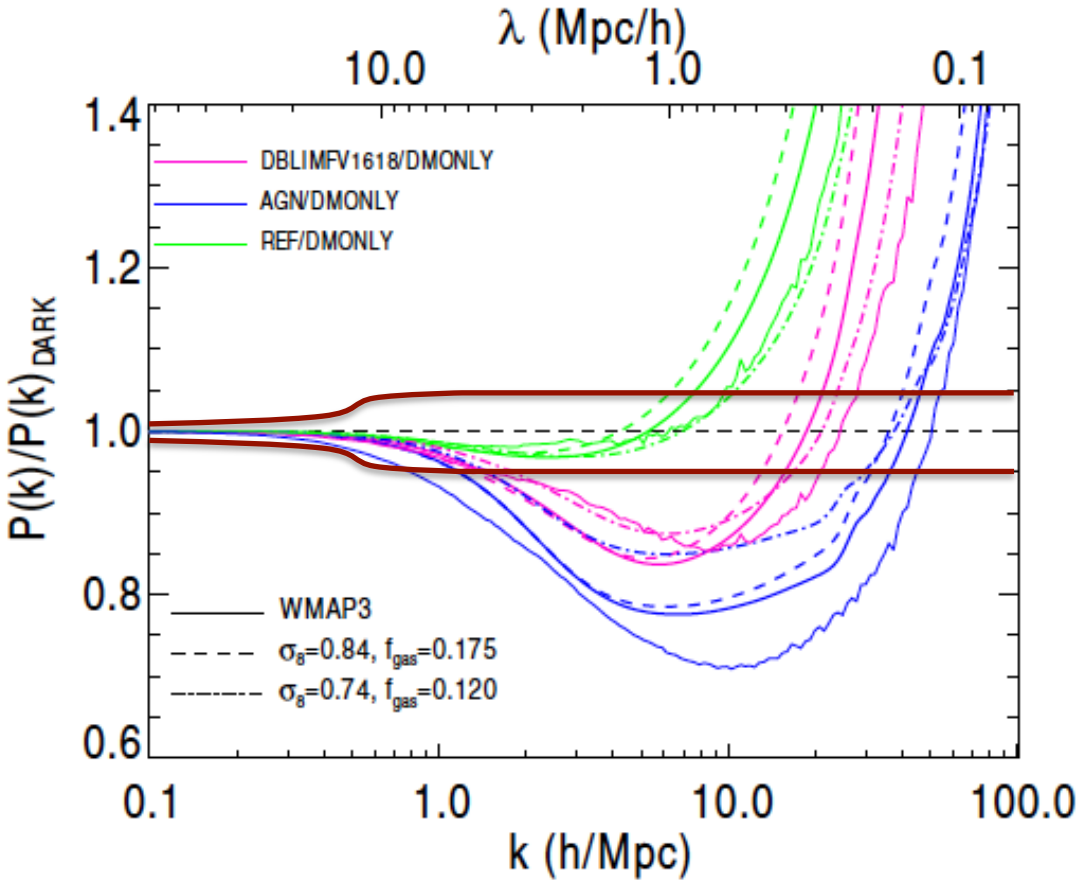
lensing potential $l(l+1)C_l$ ratios



Baryonic effects

- Semboloni et al. 2011, 2012



Baryonic effects

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