Neutrino in Cosmology

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J. Lesgourgues (EPFL, Lausanne & CERN, Geneva & LAPTh, Annecy)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Plan

I. Neutrino decoupling

II. Relativistic neutrinos
- Impact on background evolution
- Relativistic neutrino perturbations
- Effects of N_{eff} on CMB and LSS
- Measuring N_{eff}

III. Non-relativistic neutrinos
- Impact on background evolution
- Non-relativistic neutrino perturbations
- Effects of masses on CMB and LSS
- Measuring masses (current bounds, future sensitivity)

IV. Other constraints on neutrinos from cosmology

I. Neutrino decoupling

- For T ~ 10 MeV:
  - Thermal bath: γ, p, n, e^+, e^-, $\{\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau\}$
  - DM particle
  - All other particles should have decayed when $T \sim m_i$
  - Neutrinos kept in thermal equilibrium through elastic/inelastic weak interactions:

$$
\begin{array}{ccc}
\nu_e + e^- & \longleftrightarrow & \nu_e + e^- \\
\nu_e + \bar{\nu}_e & \longleftrightarrow & \nu_i + \bar{\nu}_i \\
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\nu_e + \bar{\nu}_i & \longleftrightarrow & \nu_e + \bar{\nu}_i \\
 & \text{etc.} &
\end{array}
\qquad (i = \mu \quad \text{or} \quad \tau)
$$

  - Exchange of W/Z bosons

I. Neutrino decoupling

- For T ~ 1 MeV:
  - thermally averaged cross-section $\langle \sigma v \rangle \sim G_F^2 T^2$
  - Interaction rate $\Gamma = n_{e^-} \langle \sigma v \rangle \sim G_F^2 T^5$
  - Expansion rate $H^2 \sim M_P^{-2} T^4$
  - Ratio $\frac{\Gamma}{H} \sim M_P G_F^2 T^3 \sim \left(\frac{T}{1 \text{ MeV}} \right)^3$
  - Decoupling near 1 MeV, then phase-space distributions frozen very close to

$$f_i(p) = \frac{1}{\exp[p/T_\nu] + 1}$$

with $T_\nu \sim a^{-1}$

  - Tiny flavor-dependent corrections (e^+e^- annihilation, finite-temperature QED, flavor mixing)

I. Neutrino decoupling

- For T < 1 MeV:
  - T_ν scales like a^{-1} but T_γ doesn't ($e^+ + e^- \longrightarrow \gamma + \gamma$)
  - Entropy conservation throughout electron-positron annihilation:
    - Before : $T_\nu = T_\gamma \sim a^{-1}$
    - After : $T_\nu = (4/11)^{1/3}\, T_\gamma \sim a^{-1}$
  - Given $T_\gamma = 2.726$ K, we know the current neutrino number density

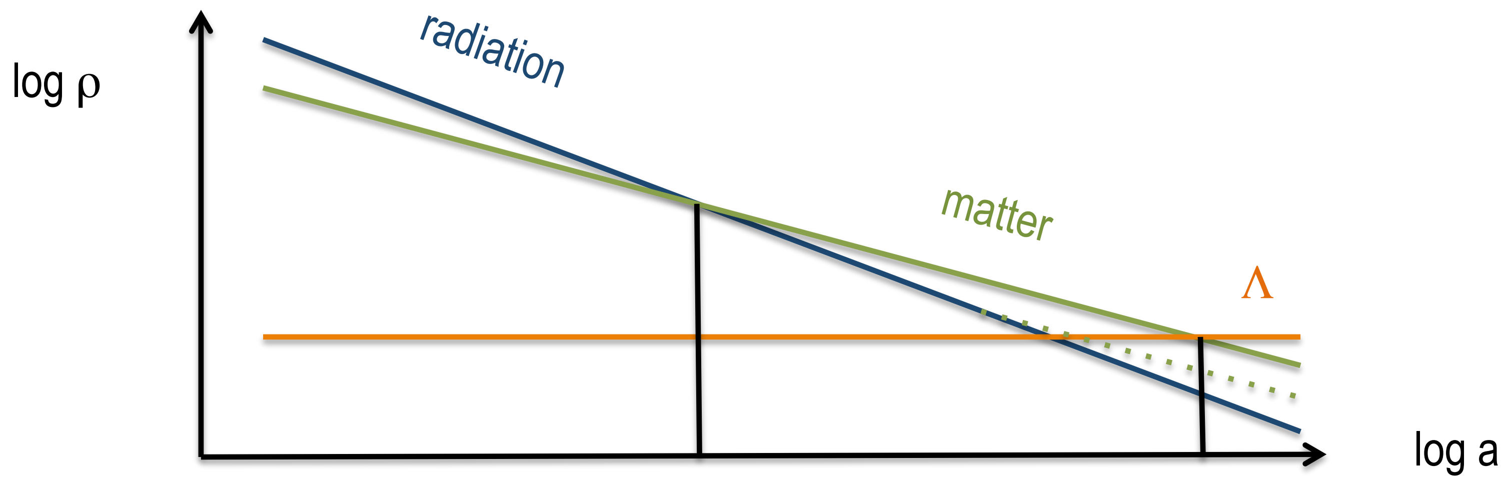
$$n_{\nu_i} = \frac{3}{4}\frac{\zeta(3)}{\pi^2} T_\nu^3 = 56\ \mathrm{cm}^{-3} \quad (\text{for all 6 neutrinos: } 336\ \mathrm{cm}^{-3})$$

  - Independent of Majorana/Dirac
  - Oscillations irrelevant after decoupling due to nearly equal distributions

I. Neutrino decoupling

- Beyond standard model:
  - Distribution can be modified by neutrino-antineutrino asymmetry (chemical potential). If large flavor-dependent asymmetry, then oscillations become important.
  - Non-thermal enhancement due to decay of unstable particle after neutrino decoupling (e.g. Majoron)
  - Overall suppressed, non-thermal distribution for low-temperature reheating
  - Extra population of sterile neutrinos (thermalised or not)

II. Relativistic neutrinos



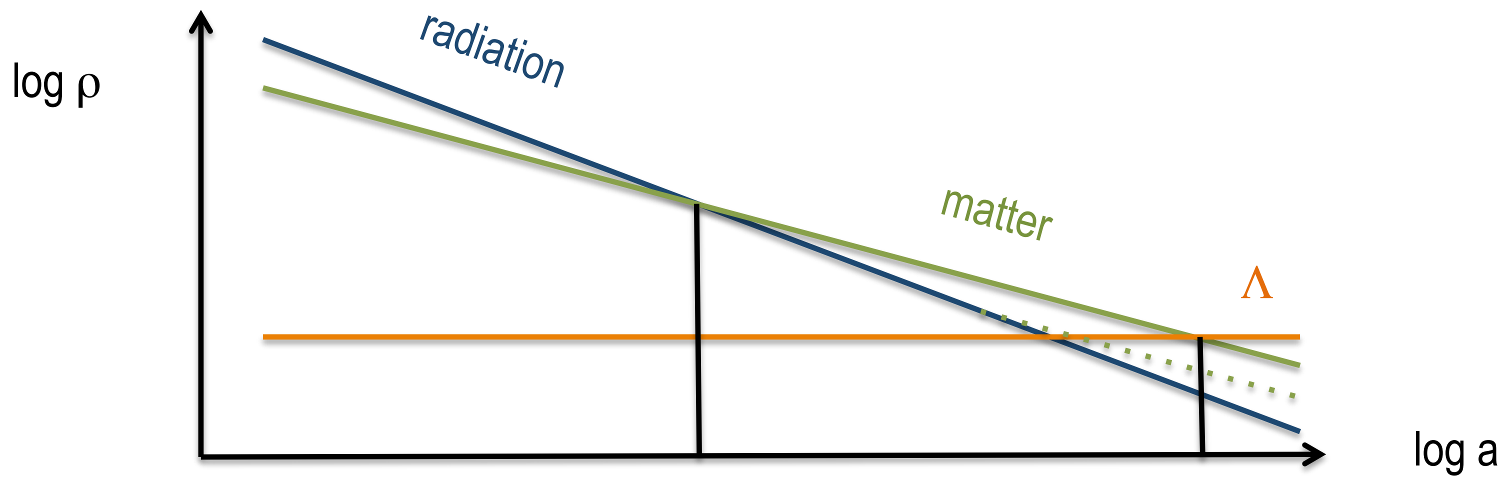
- Background: only $\rho_\nu(a)$ is important

3 standard neutrinos,

Instantaneous decoupling:

$$\rho_R = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} 3\right).$$

II. Relativistic neutrinos



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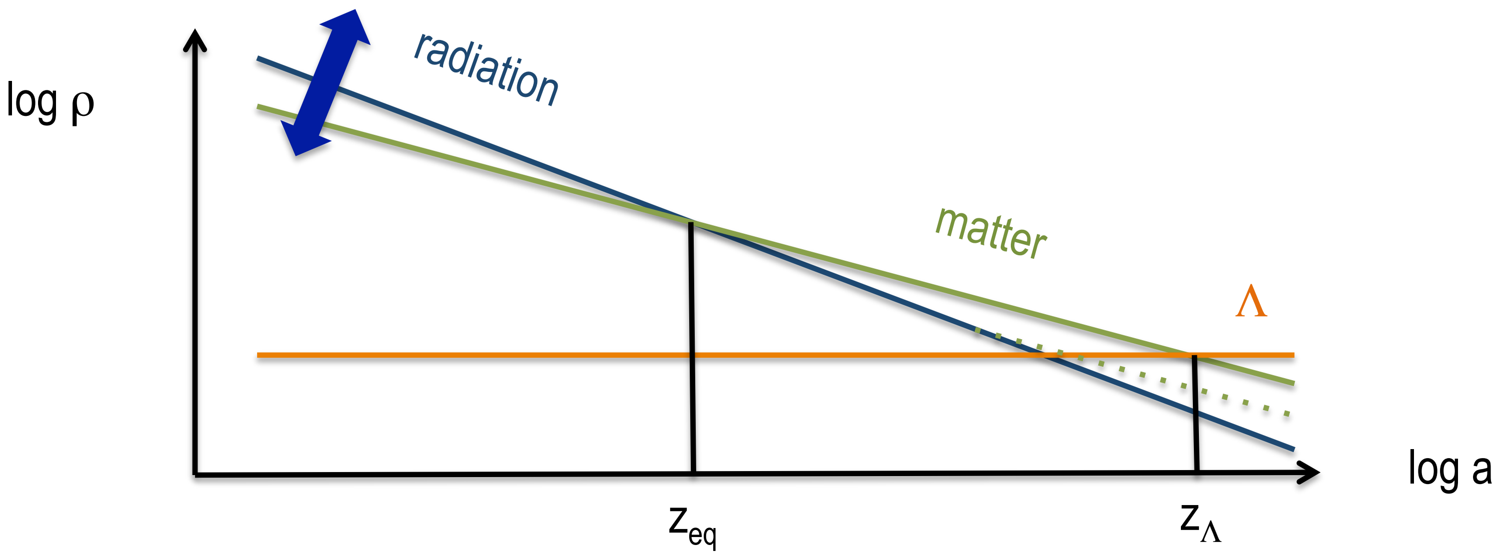
→ N_{eff}

(= 3.046 in standard model)

II. Increasing N_{eff}

- Different background evolution affects CMB and LSS power spectrum



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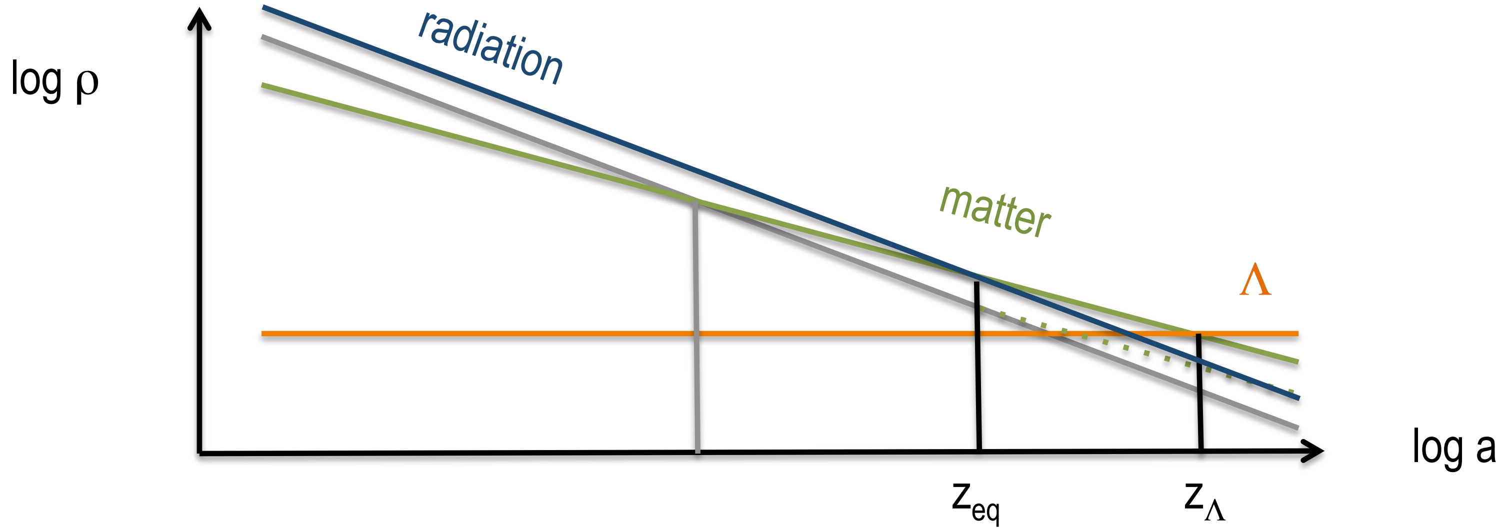

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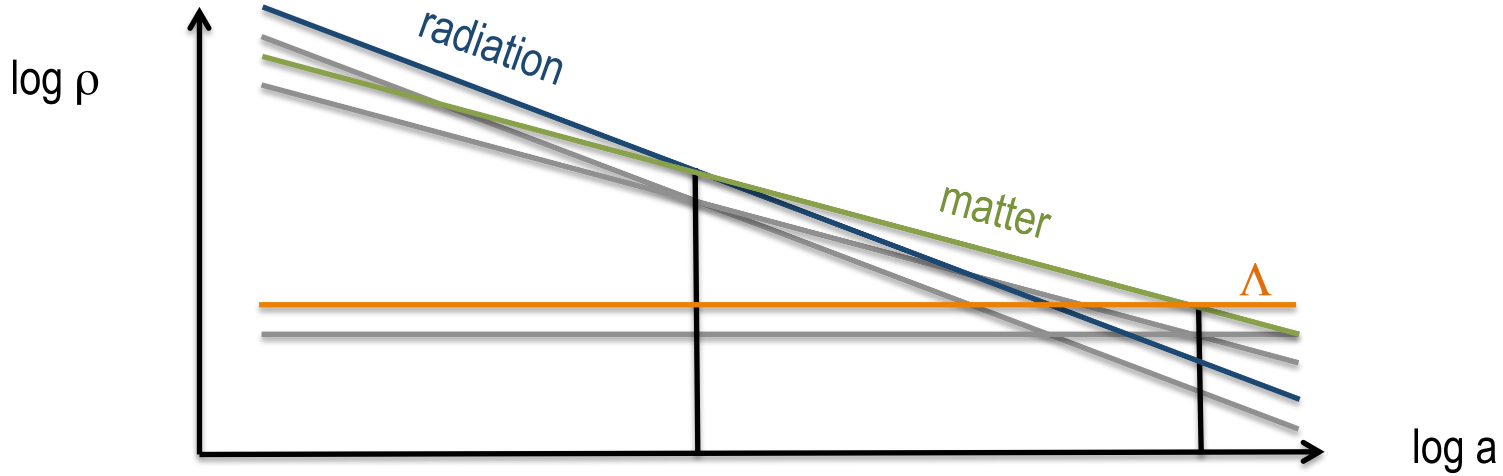

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- Positive correlation between H_0, N_{eff}

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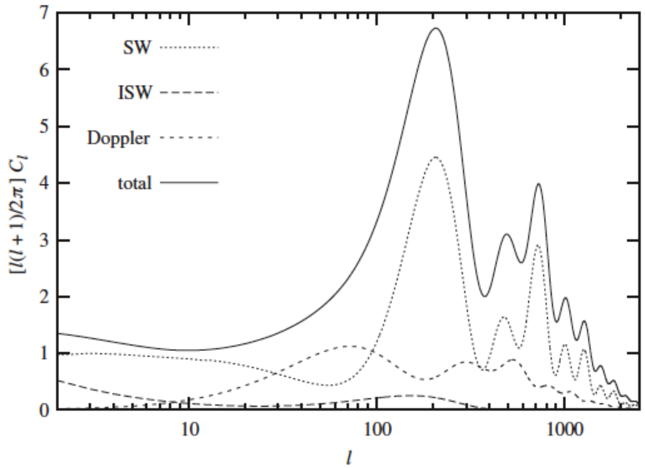

- Sound horizon at decoupling ~ H_0
- Angular diameter distance to decoupling ~ H_0

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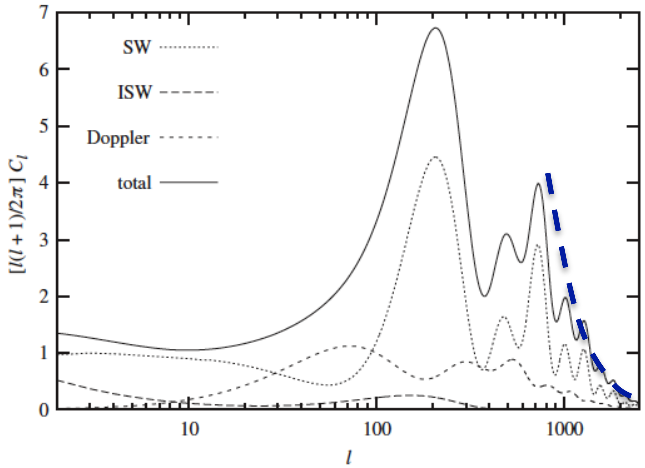

  - Sound horizon at decoupling ~ H_0
  - Angular diameter distance to decoupling ~ H_0
  - Silk damping scale at decoupling ~ H_0^2

II. Increasing N_{eff}

- Keeping Ω_i fixed and increasing H_0, N_{eff} preserves characteristic redshifts
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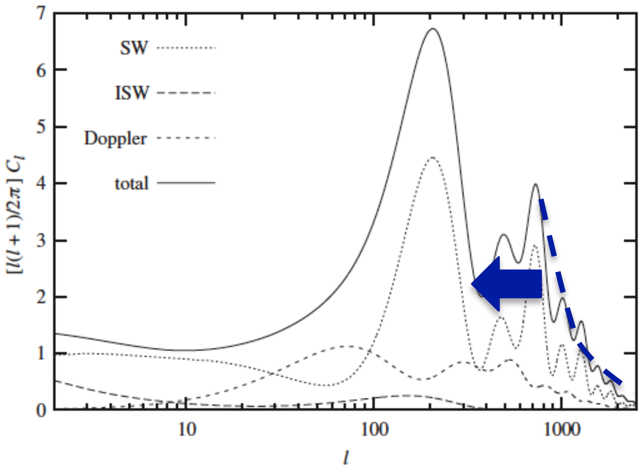
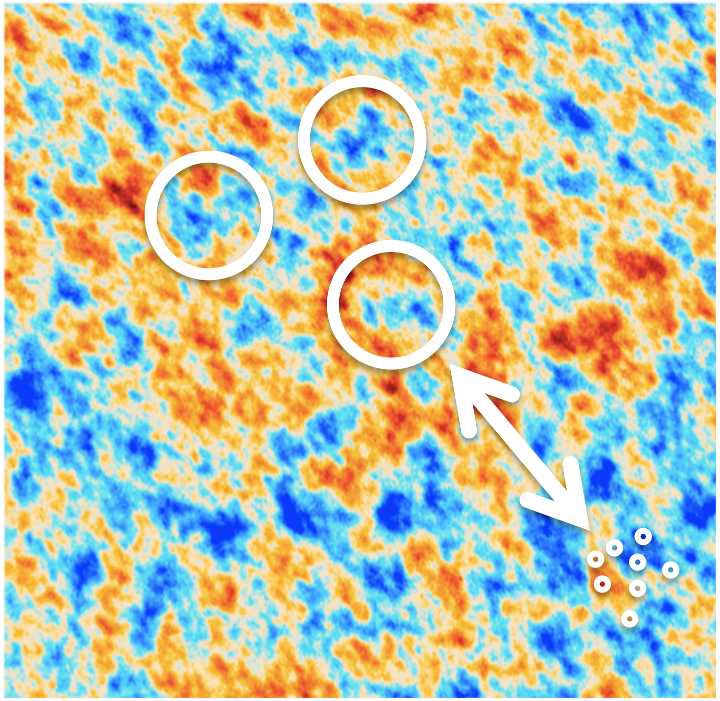
Shift in damping scale relative to peak scale

(larger N_{eff}, more damping)





II. Increasing N_{eff}

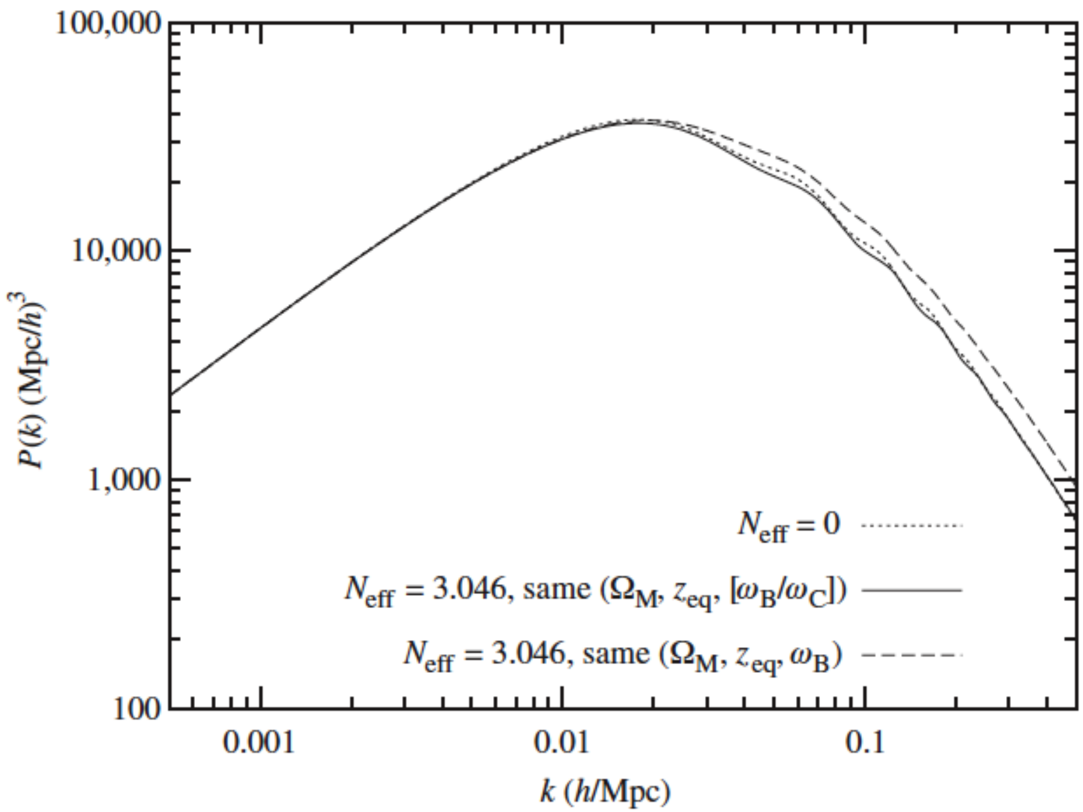
- Keeping Ω_i fixed and increasing H_0, N_{eff} preserves characteristic redshifts
- Positive correlation between H_0, N_{eff}

But in matter spectrum,

in Fourier space,

shift in sound horizon

visible in BAO scale



II. Perturbations of relativistic neutrinos

- Motivation: gravitational interactions between neutrinos and photons, baryons, cdm

  - PSD perturbation $$\Psi_\nu(\eta, \vec{x}, y, \hat{n}) = \frac{f_\nu(\eta, \vec{x}, y, \hat{n})}{f_{\nu 0}(\eta, y)} - 1$$

  - Boltzmann in real space $$\Psi_\nu' + \frac{y}{\epsilon}\hat{n} \cdot \vec{\nabla}\Psi_\nu + \frac{d \ln f_{\nu 0}}{d \ln y}\left[\phi' - \frac{\epsilon}{y}\hat{n} \cdot \vec{\nabla}\psi\right] = 0$$

  - Fourier + Legendre expansion: Boltzmann hierarchy

$$\Psi_{\nu 0}{}' = -\frac{yk}{\epsilon}\Psi_{\nu 1} - \phi' \frac{d \ln f_{\nu 0}}{d \ln y}$$

$$\Psi_{\nu 1}{}' = \frac{yk}{3\epsilon}(\Psi_{\nu 0} - 2\Psi_{\nu 2}) - \frac{\epsilon k}{3y}\psi \frac{d \ln f_{\nu 0}}{d \ln y}$$

$$\Psi_{\nu l}{}' = \frac{yk}{(2l+1)\epsilon}\left[l \Psi_{\nu(l-1)} - (l+1)\Psi_{\nu(l+1)}\right], \qquad \forall\, l \geq 2.$$

II. Perturbations of relativistic neutrinos

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  - Contributions to $T_{\mu\nu}$ in Einstein equations :

$$\delta\rho_\nu = \overline{\rho}_\nu \delta_\nu = 4\pi a^{-4} \int y^2 dy \, \epsilon \, f_{\nu 0}(y) \Psi_0$$

$$\delta P_\nu = \frac{4\pi}{3} a^{-4} \int y^2 dy \, \frac{y^2}{\epsilon} \, f_{\nu 0}(y) \Psi_0$$

$$(\overline{\rho}_\nu + \overline{P}_\nu)\theta_\nu = 4\pi a^{-4} \int y^2 dy \, \epsilon \, f_{\nu 0}(y) \Psi_1$$

$$(\overline{\rho}_\nu + \overline{P}_\nu)\sigma_\nu = 4\pi a^{-4} \int y^2 dy \, \frac{y^2}{\epsilon} \, f_{\nu 0}(y) \Psi_2.$$

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Relativistic particles: shift independent of momentum

PSD remains thermal

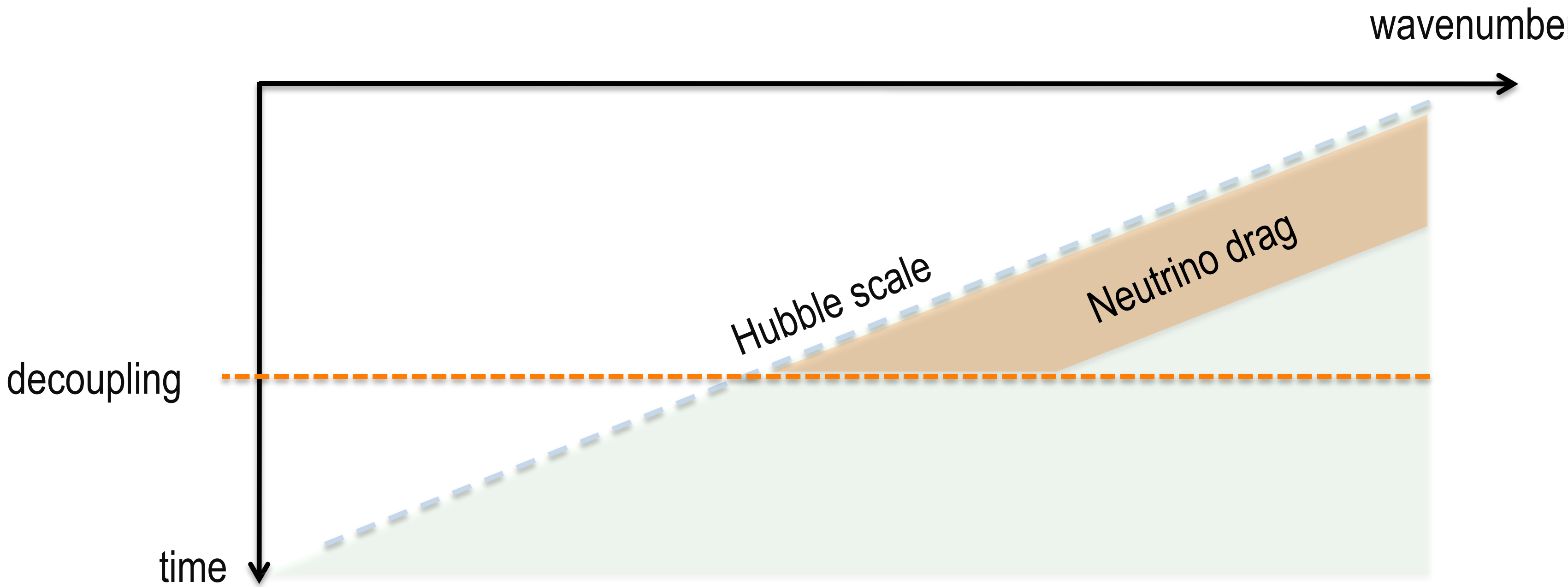
Everything can be integrated over momentum!

II. Perturbations of relativistic neutrinos

- Motivation: gravitational interactions between neutrinos and photons, baryons, cdm
  - PSD perturbation $$F_\nu(\vec{x}, \hat{n}, \eta) = \frac{\int y^2 dy\, y[f_\nu(\vec{x}, y, \hat{n}, \eta) - f_{\nu 0}(y)]}{\int y^2 dy\, y f_{\nu 0}(y)}$$
  - Boltzmann in Fourier space $$F_\nu' + ik\mu F_\nu - 4\phi' - ik\mu 4\psi = 0.$$
  - Legendre expansion: Boltzmann hierarchy $$\begin{cases} {F_{\nu 0}}' = -kF_{\nu 1} + 4\phi' \\ {F_{\nu 1}}' = \frac{k}{3}(F_{\nu 0} - 2F_{\nu 2} + 4\psi) \\ {F_{\nu l}}' = \frac{k}{(2l+1)}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right], \end{cases}$$
  - Contributions to $T_{\mu\nu}$ $$\delta_\nu = F_{\nu 0}, \qquad \theta_\nu = \frac{3}{4}kF_{\nu 1}, \qquad \sigma_\nu = \frac{1}{2}F_{\nu 2}.$$

II. Perturbations of relativistic neutrinos

- N_{eff} increases: more gravitational force ($\delta\rho_{tot} = \rho_\nu \delta_\nu + \ldots$)
- "neutrino drag": CMB (and BAO) peaks shifted to larger scales and amplitude reduced



- Summary: CMB and LSS affected through damping tail + shift in peak scale and amplitude. No exact parameter degeneracy with other effects.

II. Measuring N_{eff}

- Ultimately, constraints driven by CMB damping tail
  - WMAP+SPT see anomalously low tail: $N_{eff} > 3$ at 2 sigma
  - Planck and Planck+BAO well compatible with standard value at 1 sigma
  - Planck (+BAO) + HST : enforce higher H_0, hence also higher N_{eff}

CMB alone (Planck+WP+HighL)

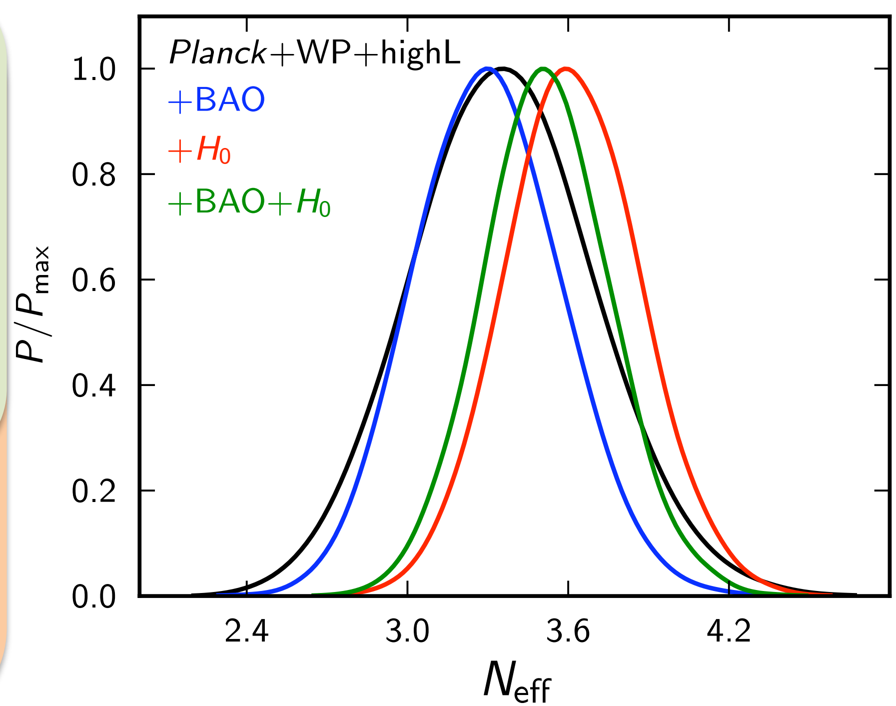
$N_{eff} = 3.36 \pm 0.66$ (95%CL)

With lensing and BAO:

$N_{eff} = 3.30 \pm 0.52$ (95%CL)

With H_0:

$N_{eff} = 3.63 \pm 0.49$ (95%CL)



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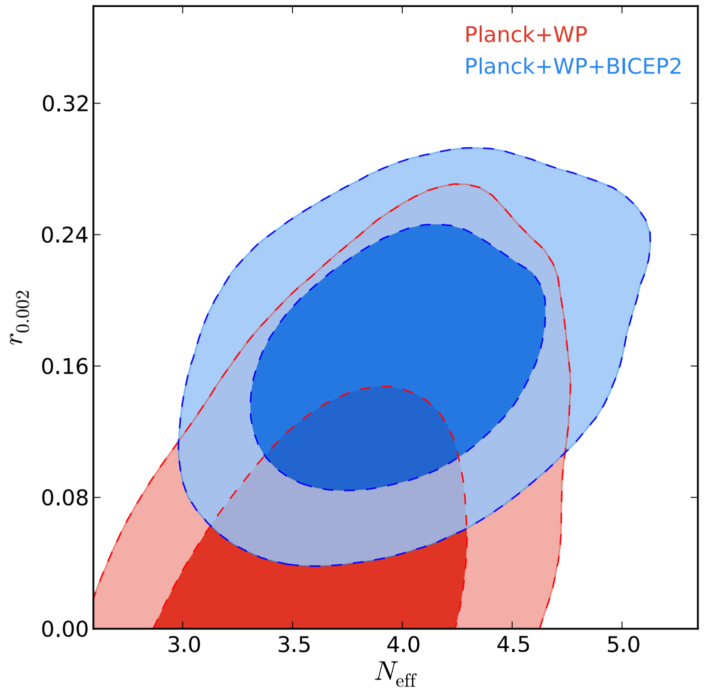
  - Planck + BICEP2 : to decrease r tension, also higher N_{eff}

CMB alone (Planck+WP+HighL+BICEP2)

$N_{eff} = 4.00 \pm 0.82$ (95%CL)

Giusarma et al. 14



Giusarma et al. 1403.4852

II. Future N_{eff} sensitivity

Full Planck data (including lensing)	:	$\sigma(N_{eff}) \sim 0.2$	2014
Planck + LSST, Euclid (cosmic shear, galaxy correlation)	:	$\sigma(N_{eff}) \sim 0.1$	~ 2022
Post-Planck + Euclid	:	$\sigma(N_{eff}) \sim 0.05$	~ 2030

III. Non-relativistic neutrinos

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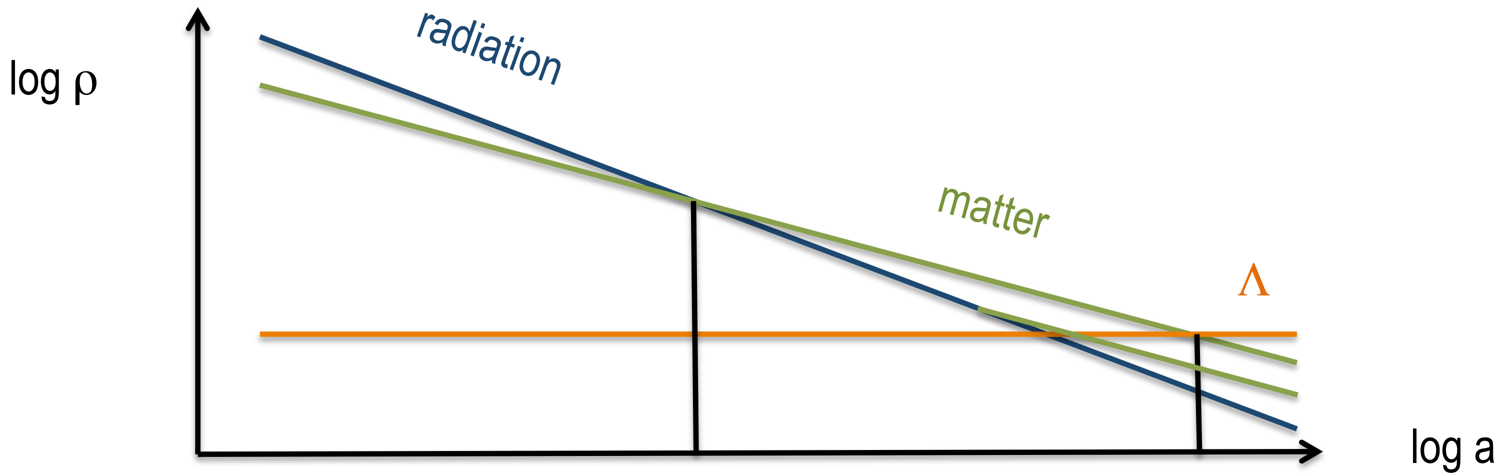

Non-relativistic transition: $m_\nu = T_\nu \sim (4/11)^{1/3}\, T_\gamma$, at $z_\nu = (m_\nu/5.3\ \mathrm{eV})\ 10^4$

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

- for fixed $\omega_M = \omega_B + \omega_{CDM} + \omega_\nu$, change in time of equality
- for fixed $\omega_B + \omega_{CDM}$ and equality, peak scale affected by (M_ν / 0.06 eV) %
- for fixed equality AND peak scale, effect is on z_Λ

III. Non-relativistic 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 $\langle p \rangle/m = 3.15\, T_\nu/m_\nu$)

III. Non-relativistic neutrino perturbations

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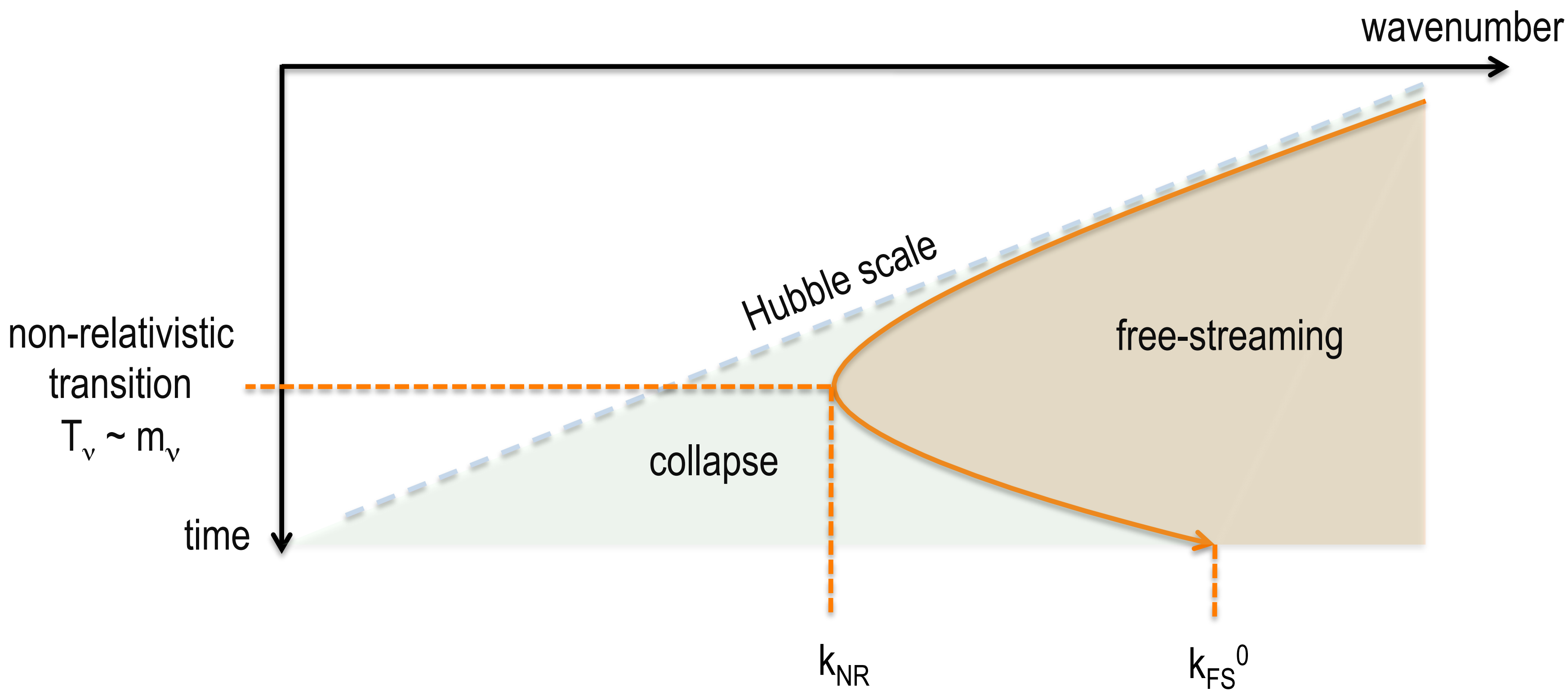

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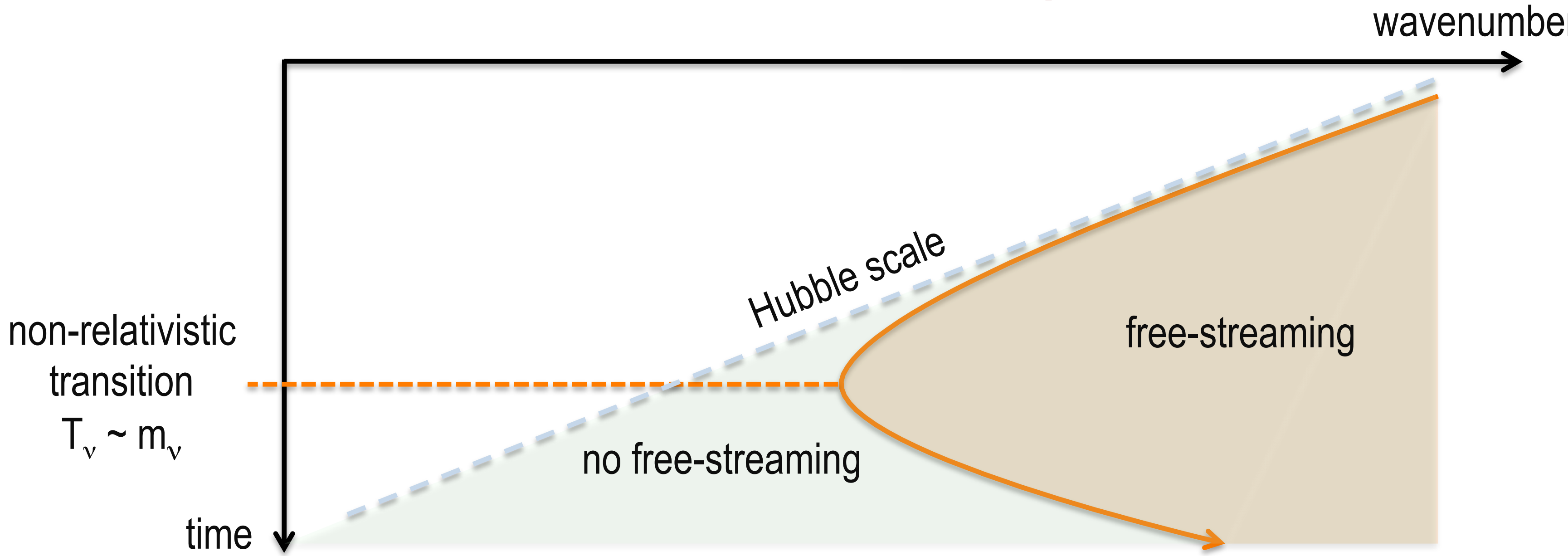

- cdm, baryons, neutrino perturbations identical

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

- 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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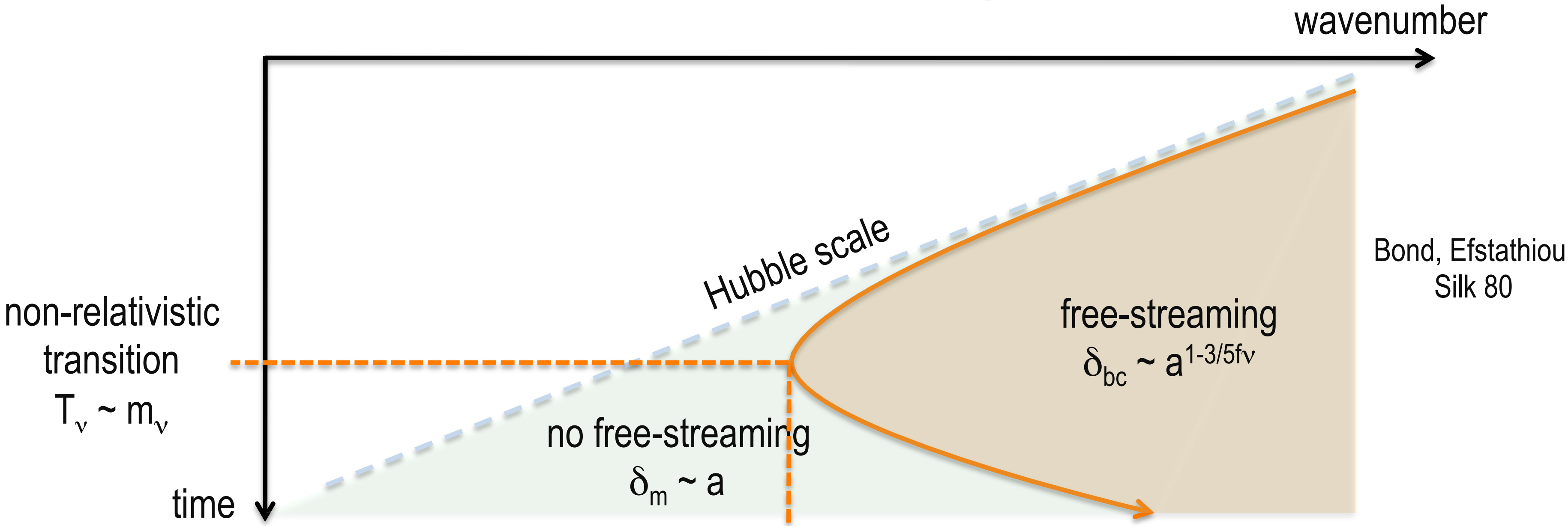

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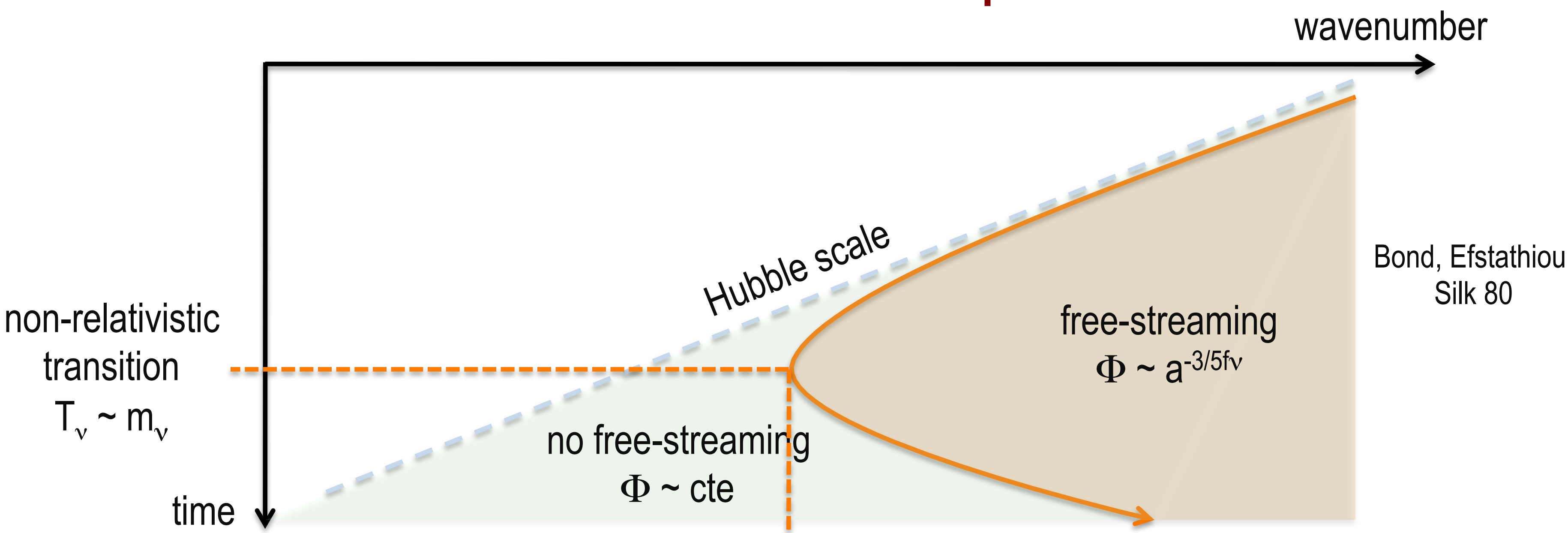

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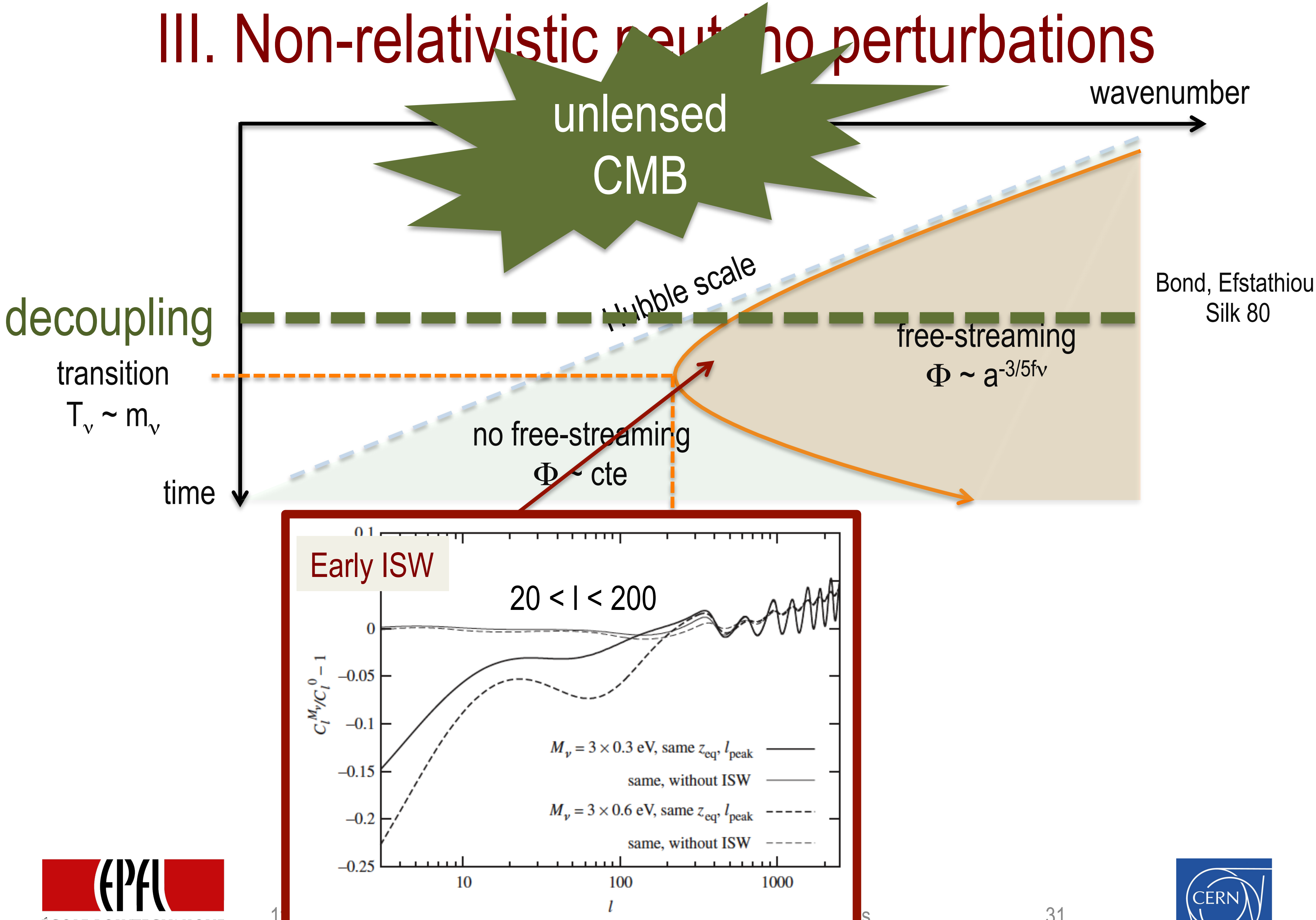

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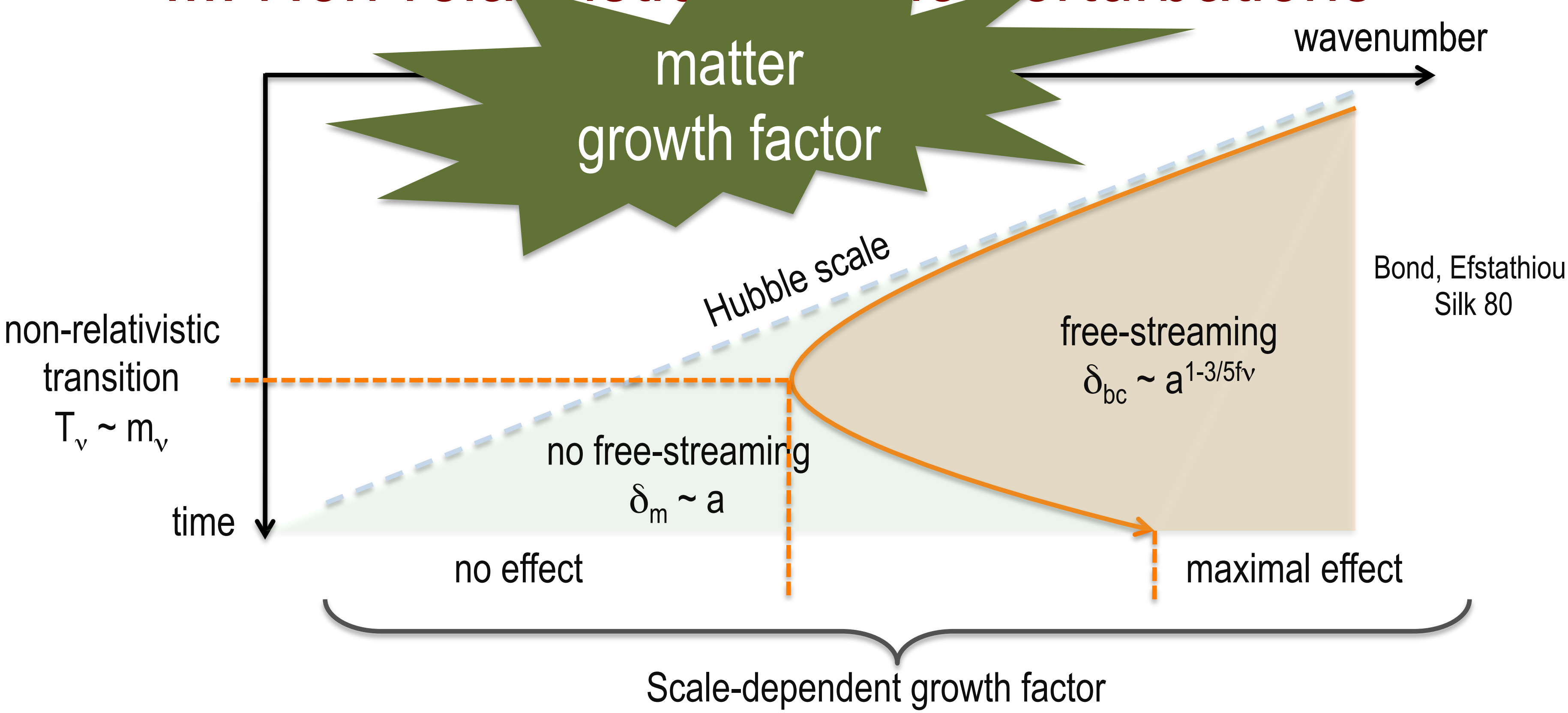

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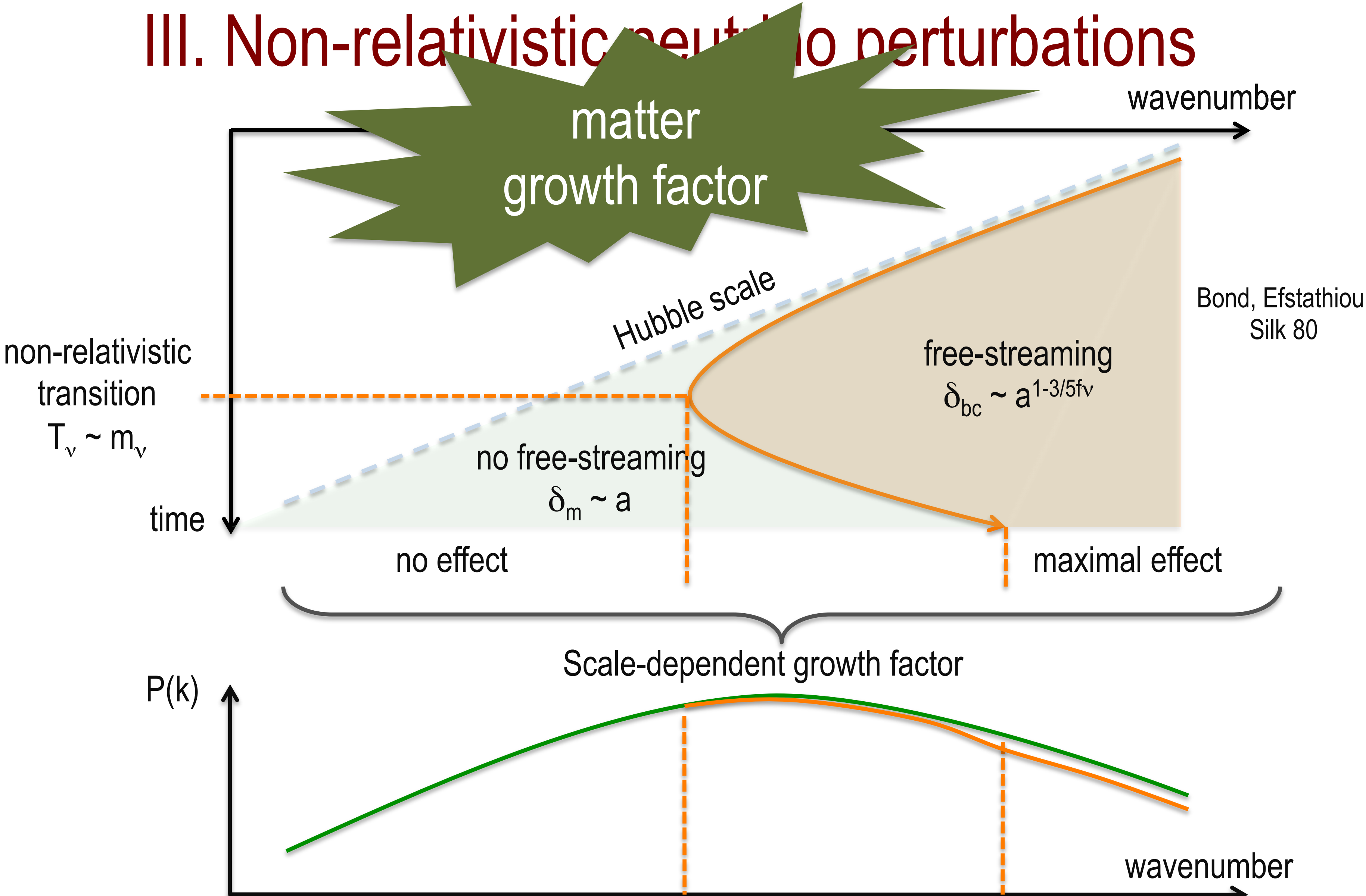
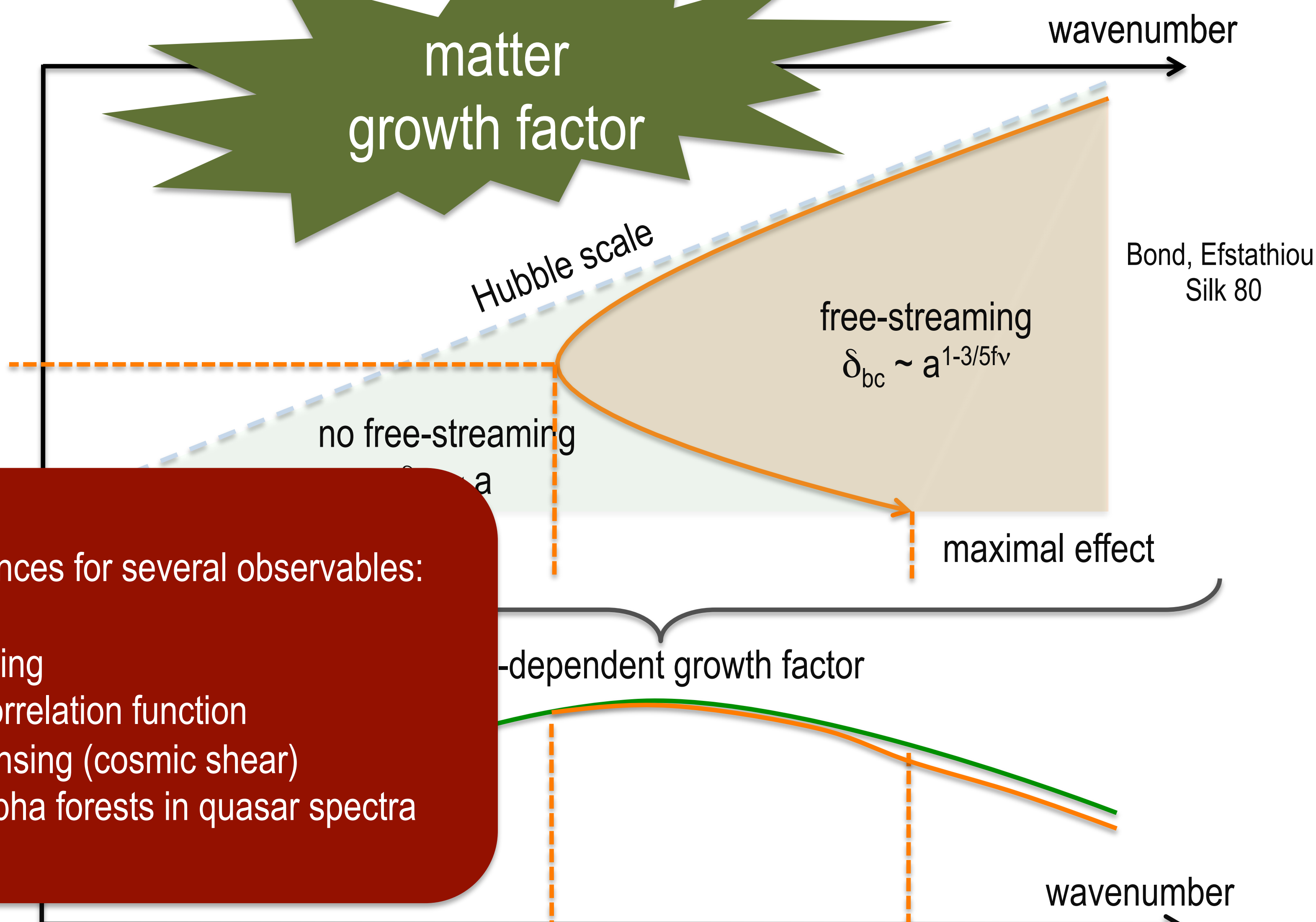


III. Non-relativistic neutrino perturbations

matter
growth factor

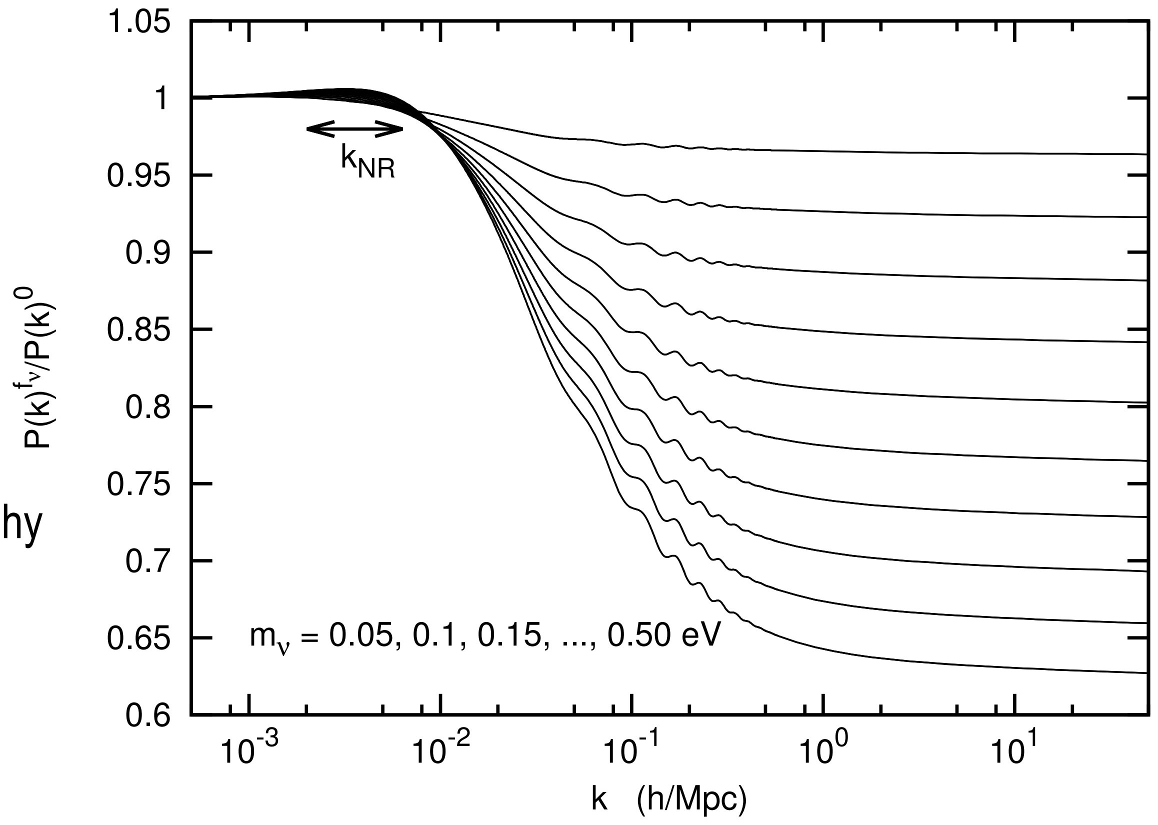


Consequences for several observables:

- CMB lensing
- Galaxy correlation function
- Galaxy lensing (cosmic shear)
- Lyman-alpha forests in quasar spectra

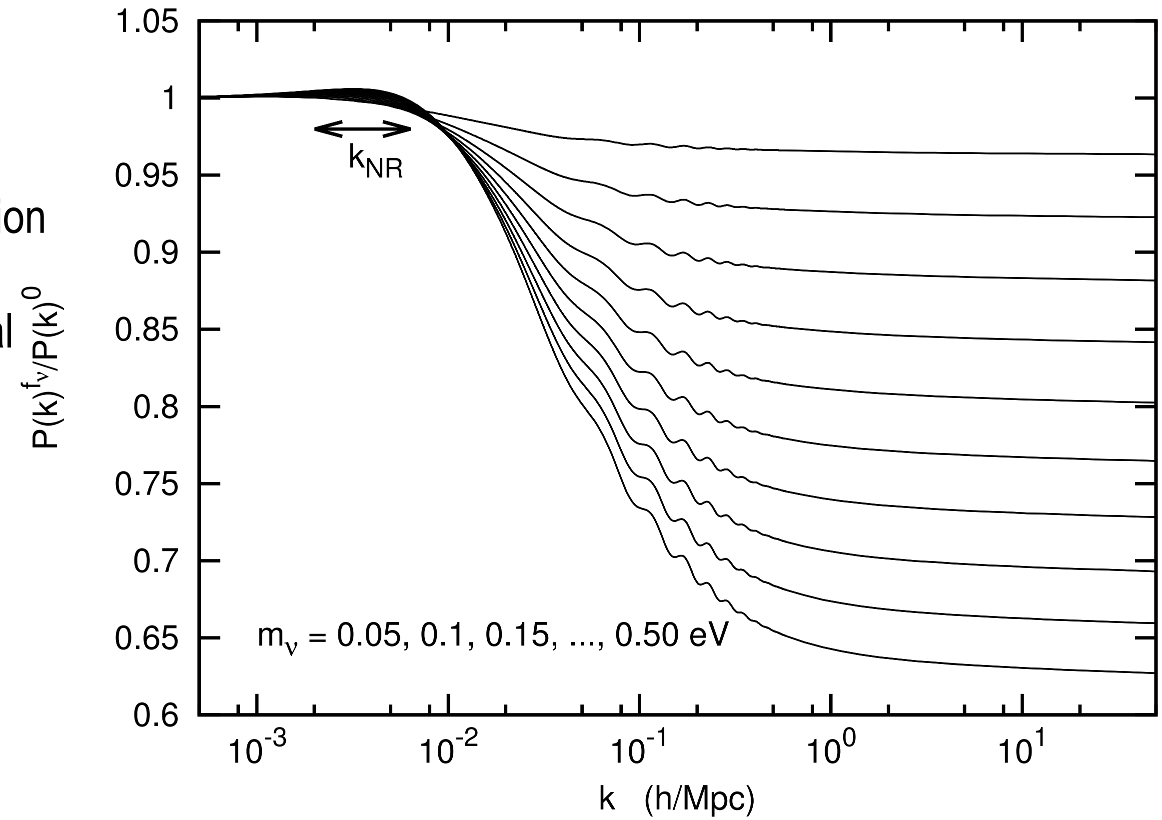
III. Neutrino masses and linear growth of structure

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



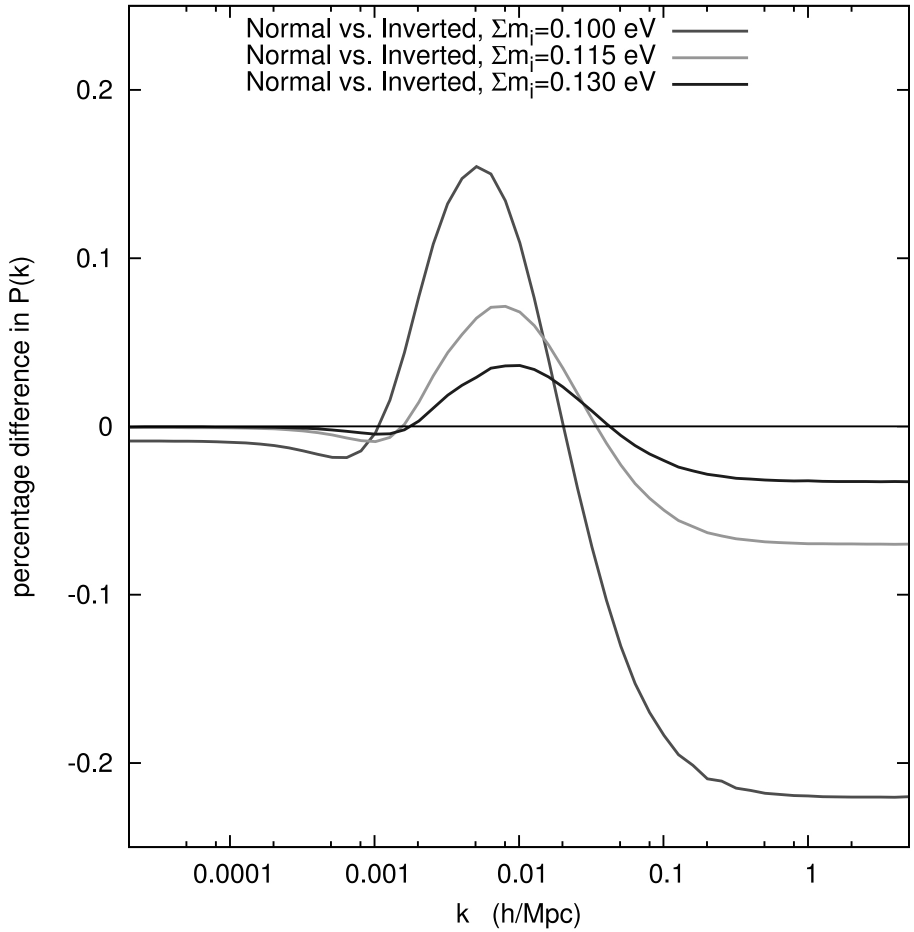
III. Neutrino masses and linear growth of structure

- 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



III. Neutrino masses and linear growth of structure

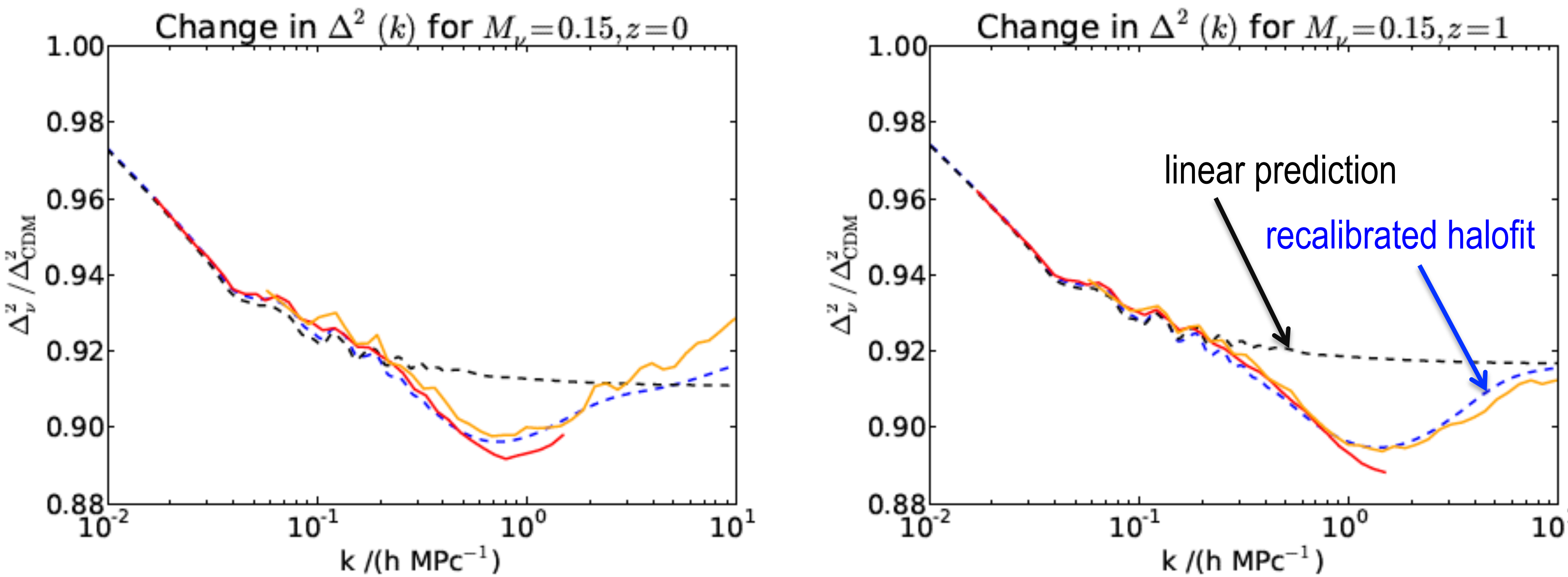
- Mass splitting: effects of order 0.1%
- Undetectable



III. Neutrino masses and non-linear growth of structure

- Effect enhanced by non-linear evolution

Bird et. al 2011, see also
Brandbyge et al., Hannestad et al., Wagner et al.



- Tree-PM, $N_\nu >> N_{cdm}$, ν in tree only
- (or SPH with imperfect fluid)

III. So what do we actually measure?

Assuming three standard active neutrinos, and no other light relic:

- Equivalently: ρ_ν , ω_ν , $\Sigma m_i = M_\nu = 93.14\ \omega_\nu$ eV
- Mass splitting inaccessible
- No sensitivity to Dirac/Majorana, mixing angles, CP phases, etc.

Assuming three standard active neutrinos, and no other light relic:

- Equivalently: ρ_{HDM} , ω_{HDM} , $M_{\nu eff} = 93.14\ \omega_{HDM}$ eV
- plus N_{eff} defined during radiation domination
- Mass splitting could be accessible : depends on model

III. Measuring M_ν

CMB:

- Not observed by Planck (within error bars)!
- Planck + WP alone: $M_\nu < 0.66$ eV (95% CL)
- adding BAO: $M_\nu < 0.23$ eV

Planck XVI paper, 2013

CMB + LSS:

- Contradictions: compatible with $M_\nu < 0.23$ eV or pointing at ~0.3-0.4 eV

III. Measuring M_ν

CMB + LSS:

- Vulnerable to systematics and parameter degeneracies due to limited number of: scales, redshifts, independent tracers of dark matter

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Any experiment seeing low amplitude favors high neutrino mass but conflicts CMB TT

- CMB lensing,
- (SZ) clusters,
- CFHTLens weak lensing,
- BOSS red.-space dist.

Claims for $M_\nu \sim 0.3$ eV – 0.8 eV

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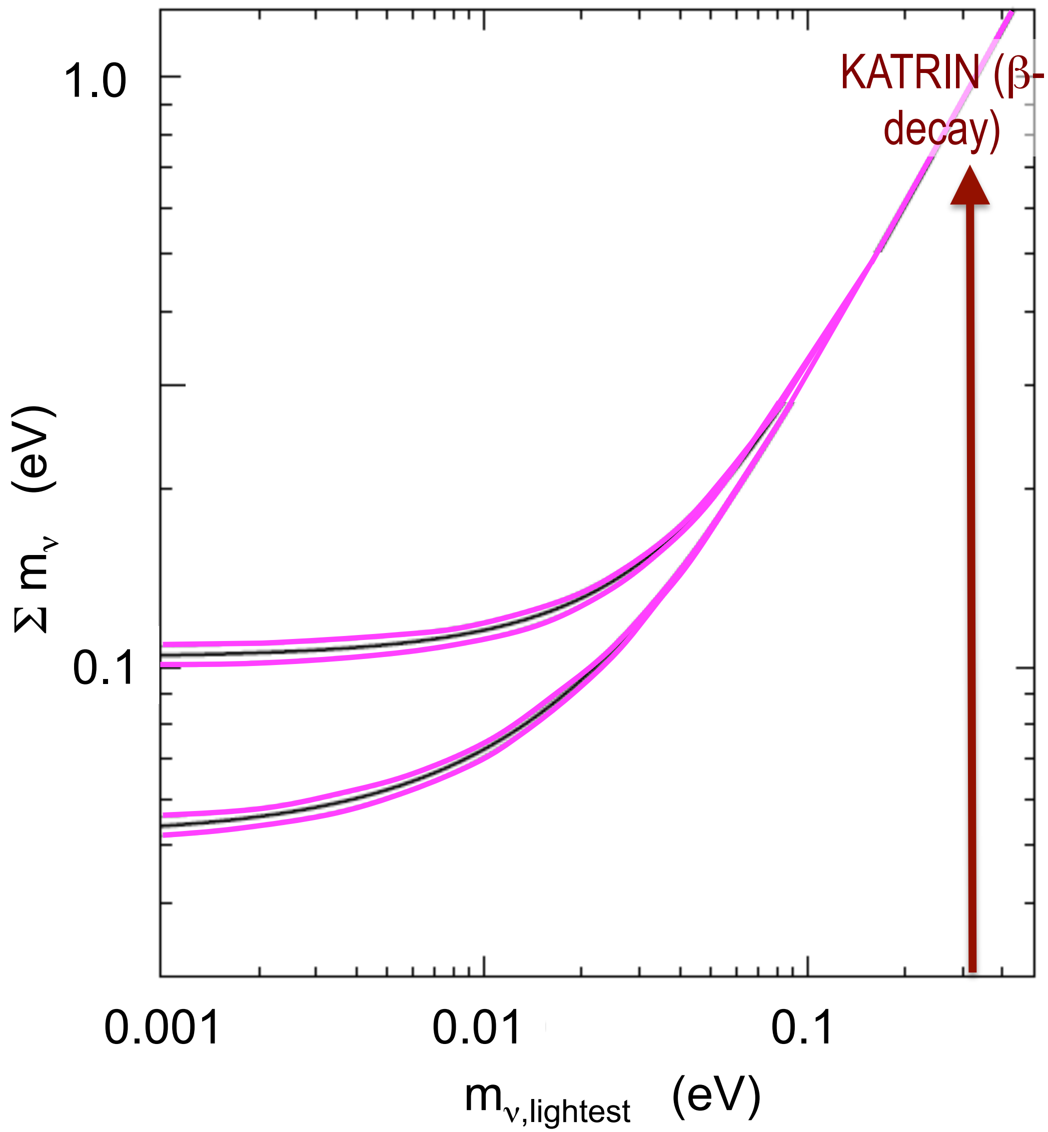
Claims for $M_\nu \sim 0.3$ eV – 0.8 eV

Any experiment seeing high amplitude disfavors high neutrino mass:

- SDSS Ly-α of 2006

  $M_\nu < 0.17$ eV (95%)

III. Future mass sensitivity



2σ error bars

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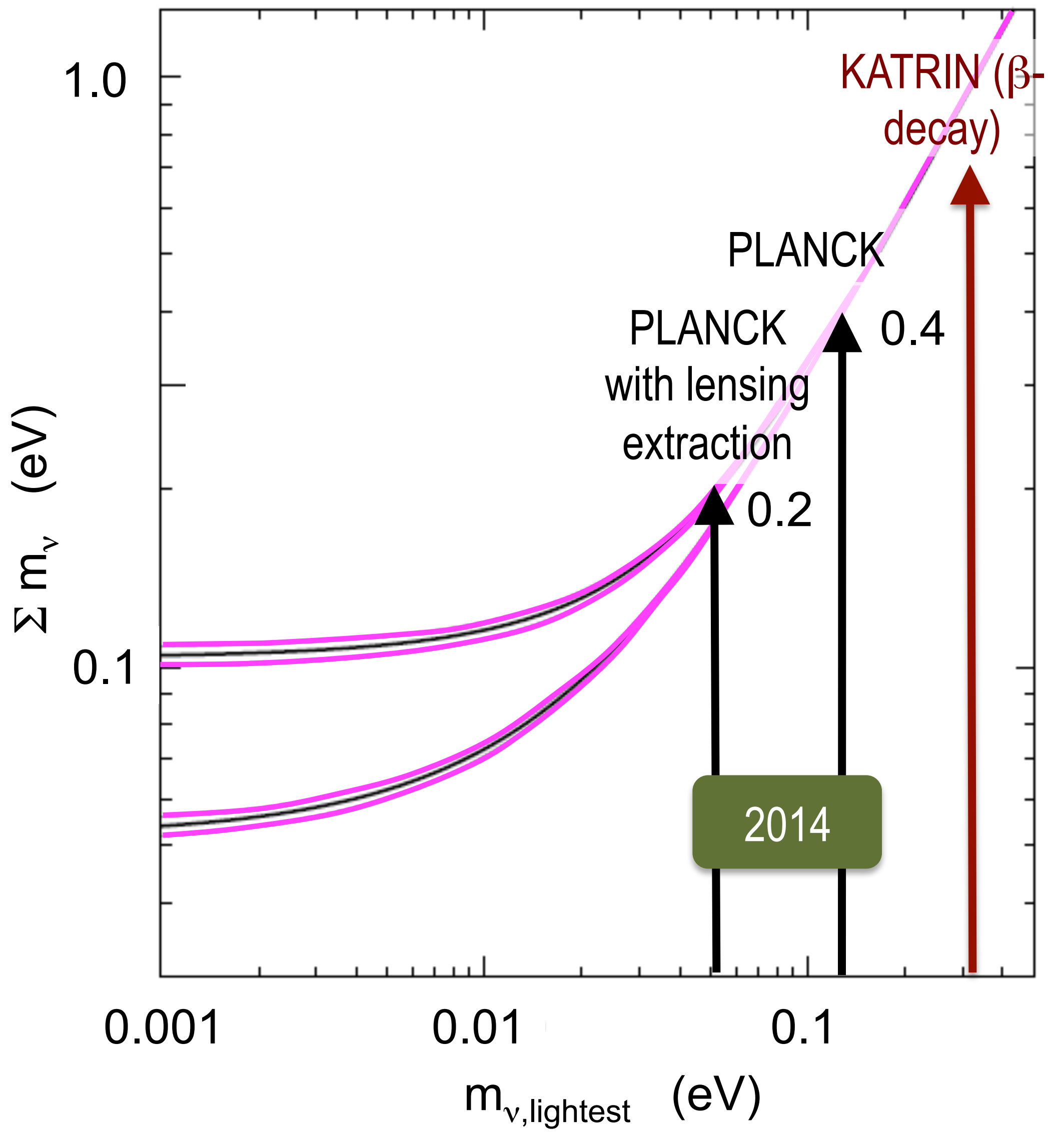

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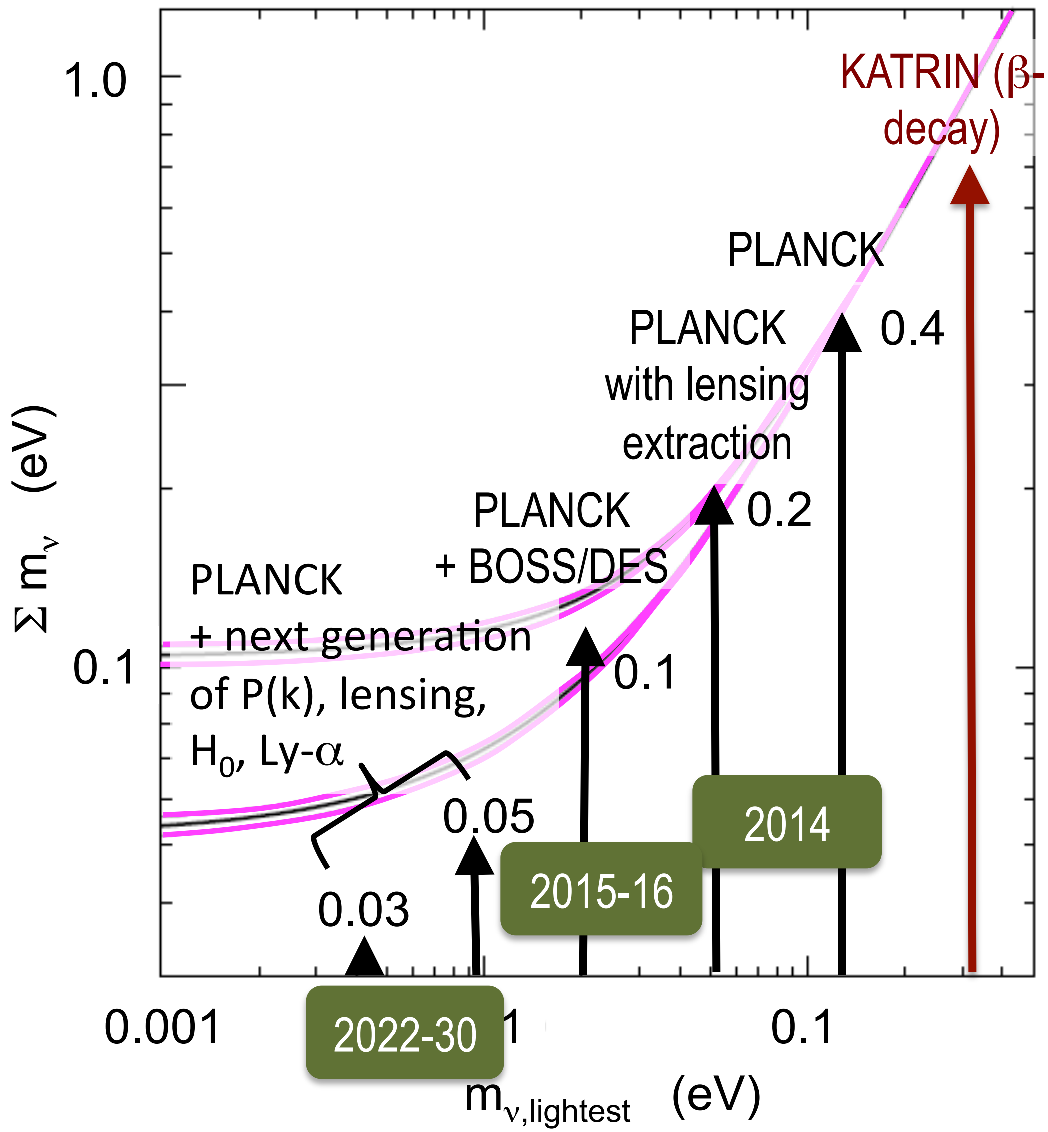
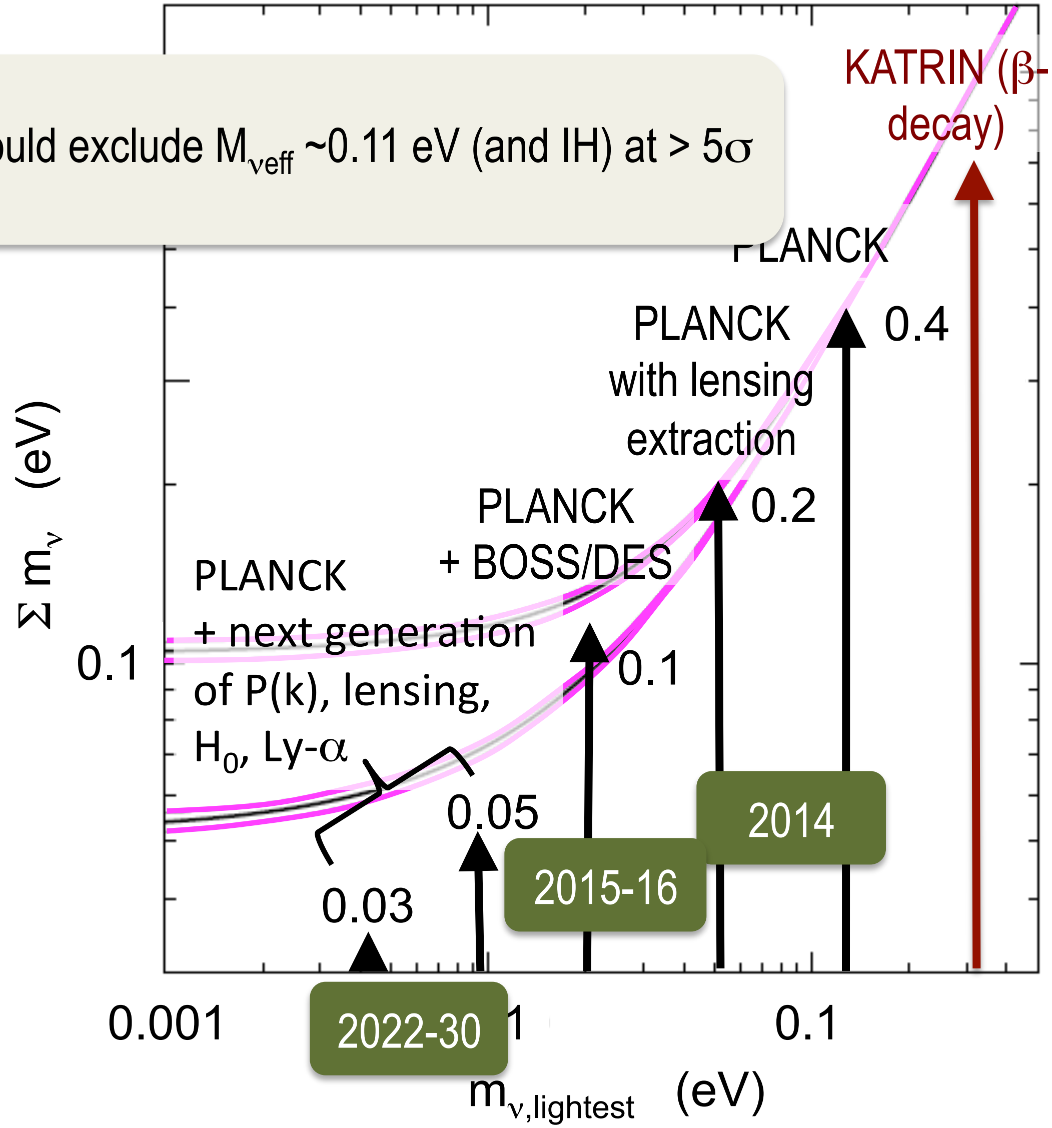


2σ error bars

III. Future mass sensitivity

cosmology could exclude $M_{\nu eff}$ ~0.11 eV (and IH) at > 5σ



2σ error bars

III. Model-dependence of bounds ?

- Bounds obtained by fitting given model (minimal 6-parameter ΛCDM, extensions with curvature, dark energy, more freedom in primordial spectrum, etc.)

- Effect of N_{eff}, M_ν could be confused with that of other parameters

- true with past experiments (e.g. degeneracies N_{eff}-M_ν, N_{eff}-H_0, w-M_ν, etc.)

- Less and less true: thousands of independent data points, at many different scales AND redshift; only ~10-20 model parameters

- Unique effect of M_ν : scale-dependent growth factor, signature of free-streaming particles (different from changing primordial spectrum)

- Unique effects of N_{eff} : e.g. baryon drag shifting peaks because $c > c_s$, signature of ultra-relativistic particles

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- Unique effect of M_ν: scale-dependent growth factor, signature of free-streaming particles (different from changing primordial spectrum)
- Unique effects of N_{eff} : e.g. baryon drag shifting + damping tail

III. Complementarity with laboratory ?

- assuming $N_{eff} = 3$, $M_{\nu eff} = m_1+m_2+m_3$, independently of mixing angles, CP phases, Dirac/Majorana mass : different from β- and double β-decay

- What if there is a tension between cosmology and laboratory bounds? E.g. KATRIN find m ~ 0.3 eV and cosmology M < 0.1 eV?

- After checking for systematics and degeneracies, would bring evidence for non-standard interactions (decay into lighter species, effective mass from coupling with other fields, etc…) or strong deviation from standard cosmological model (low-scale reheating / entropy production after BBN and conspiracy with other light relics …) : NEW PHYSICS

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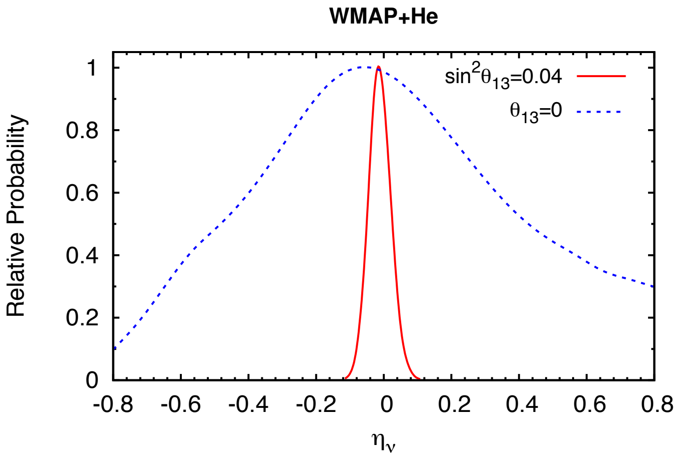
IV. Beyond minimal model

- Extra production of neutrinos; low temperature reheating;
  - N_{eff} constraints from CMB, LSS, BBN

- Neutrino-antineutrino asymmetry
  - Similar, but non-trivial effects from oscillations and BBN leading to much stronger bound!
  - Very constrained by θ_{13}
  - At T~10 MeV , $\eta_\nu < 0.06$
  - $\Delta N_{eff} < 0.4$



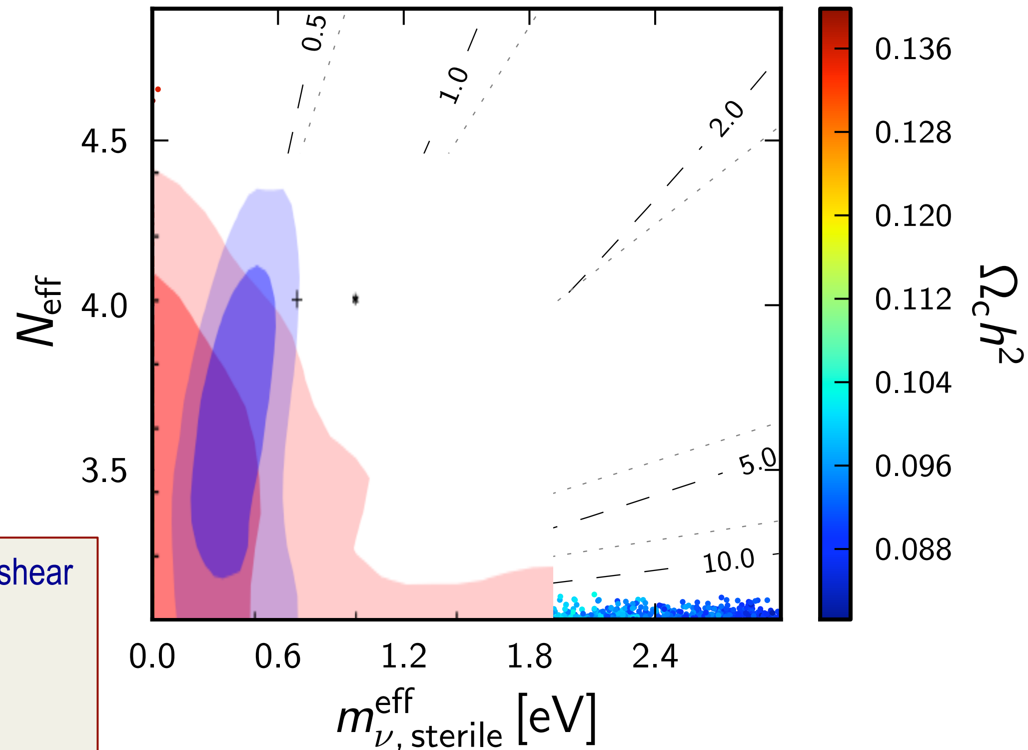
Franca et al., PRD86 023517 (2012)

- Non-standard neutrino interactions: very model-dependent
  - Interactions with themselves, dark matter, scalar field, quintessence, dark radiation
  - (see e.g. e.g. Archidiacono & Hannestad 13, Wilkinson et al. 13, Serra 10, …)

- Light sterile neutrinos: see next

IV. Light sterile neutrinos

CMB only (Planck + WP + highL) analysis for 3+1 case:



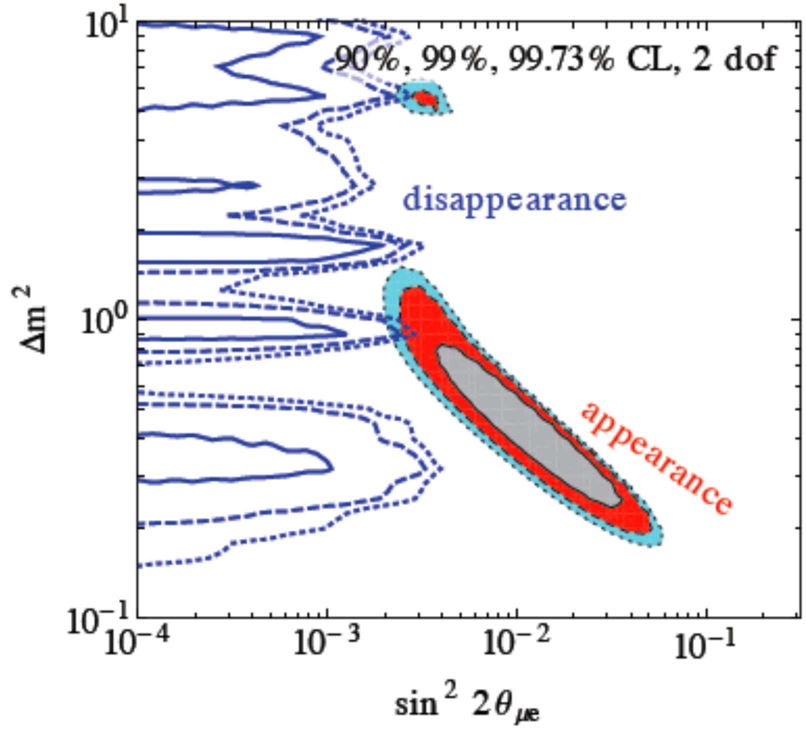
Using H0 + BAO + clusters + gal.shear

From Hamann & Hasenkamp
See also Wyman et al.,
Archidiacono et al.,
Giusarma et al.

IV. Light sterile neutrinos

Motivations: anomalies in short-baseline neutrino oscillation experiments

3+1 analysis in
Kopp et al. 2013



Appearance: LSND, MiniBoone, NOMAD, KARMEN, ICARUS, E776

Disappearance: reactor, Gallium, MiniBoone, CDHS, Minos, KARMEN

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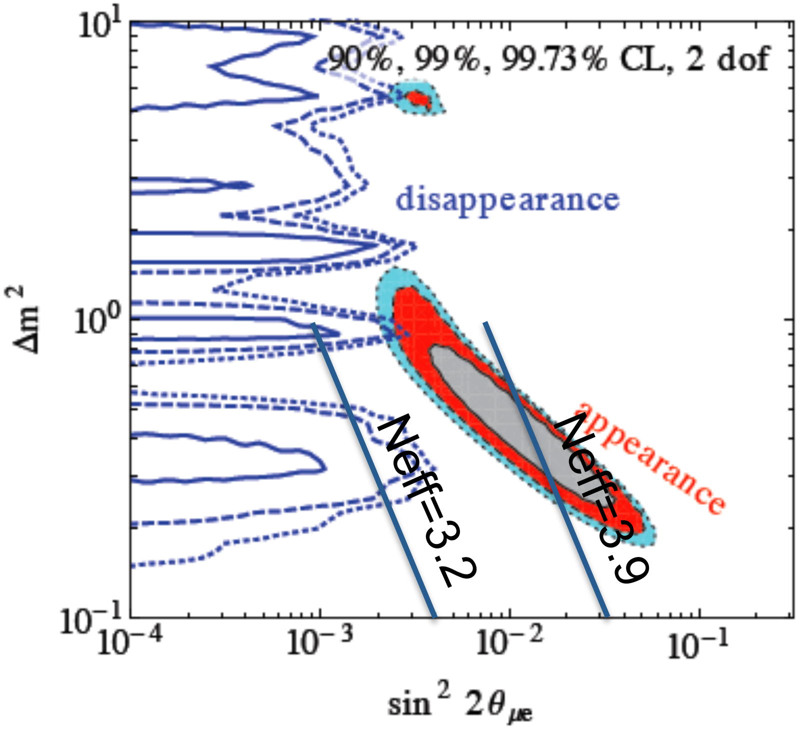

N_{eff} isocontours are model-dependent (leptonic asymmetry: Saviano et al., Mirrizi et al., Tambora et al.; NSI: Archidiacono et al.,…)

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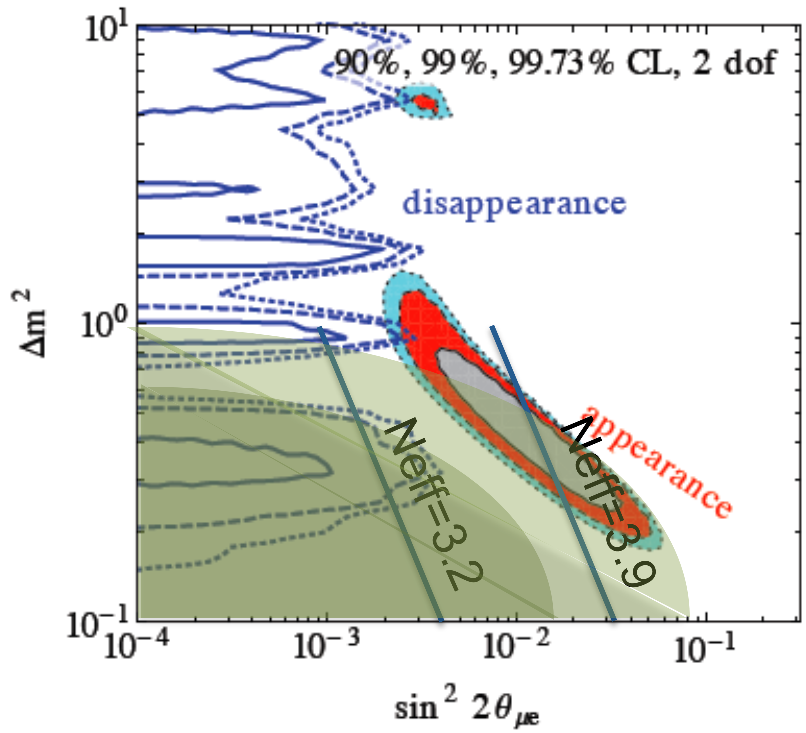

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