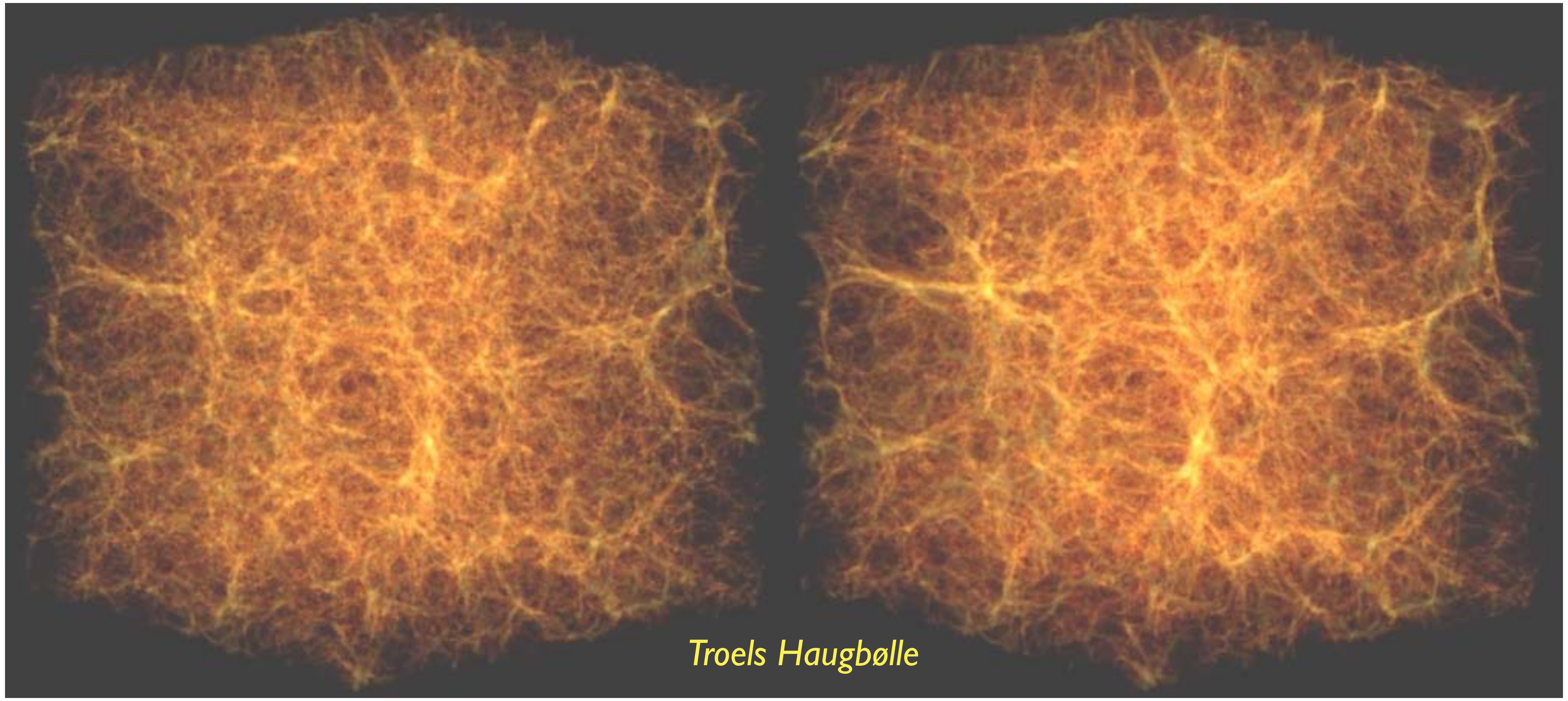
Mini-review on neutrino cosmology
(with comments on massive sterile neutrinos)



Pasquale Dario Serpico (Annecy, France)

Original research presented mostly based on
L. Mastrototaro, PDS, A. Mirizzi and N. Saviano, Phys. Rev. D 104 (2021), 016026 [arXiv:2104.11752]

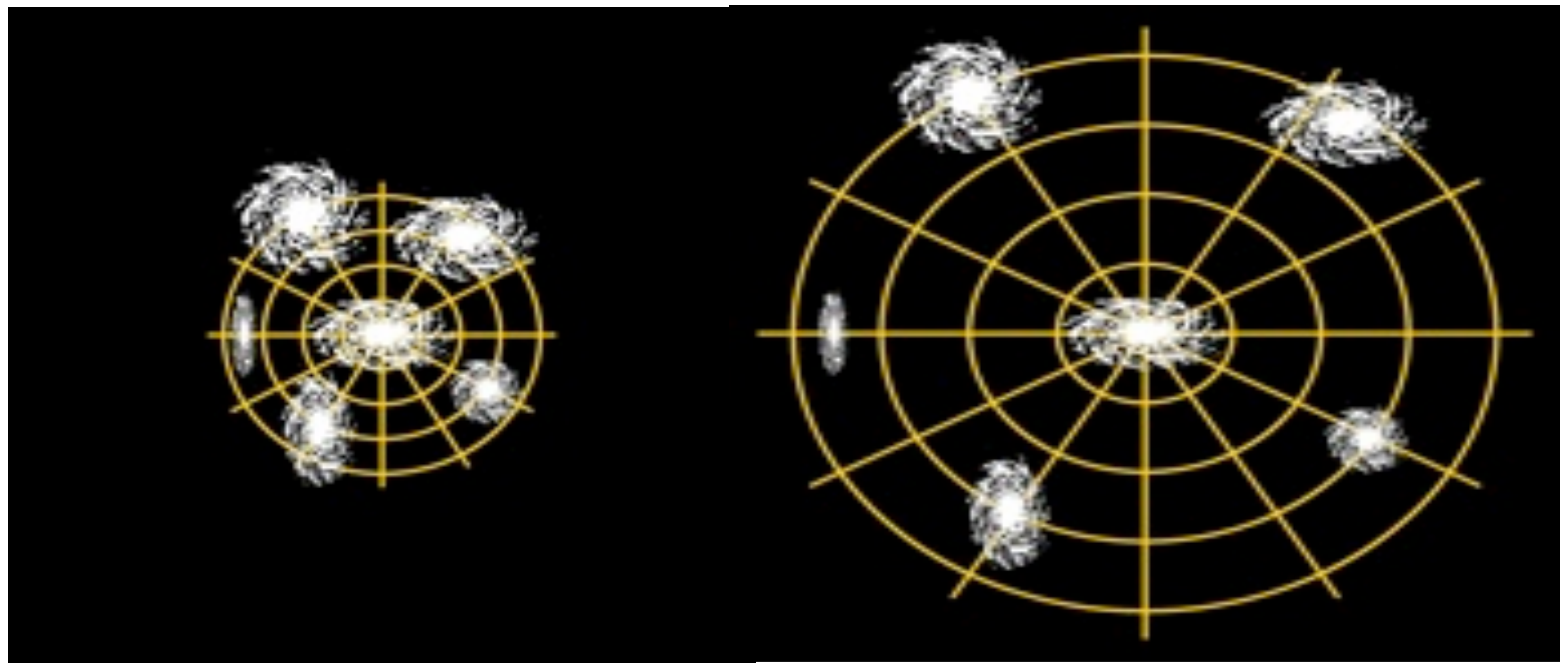
18th Rencontres du Vietnam - Neutrino Physics 21/07/2022

Outline of the talk

- Introduction on cosmology and role of ν's
- ν's main effects and current bounds (N_{eff}, Σ m_i...)
- Some perspectives, role of NP
- One application in more detail: Cosmo bounds on *massive* sterile ν's (~10-150 MeV)
- Conclusions

Some ('pedestrian') cosmology

- Homogeneous & isotropic solution of GR equations (used as first order proxy to describe the Universe aka *Copernican principle*) leads to an ***expanding*** (or contracting) metric, with scale factor $a=a(t)$



- The expansion rate $H=a^{-1}\, da/dt$ depends on the energy content of the Universe (acceleration further depends on the pressure, unlike in Newtonian physics)

$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2}$$

In this framework, the **Hubble-Lemaître law (**Galaxies sufficiently far away from us recede with $v=H_0 d$) makes sense!

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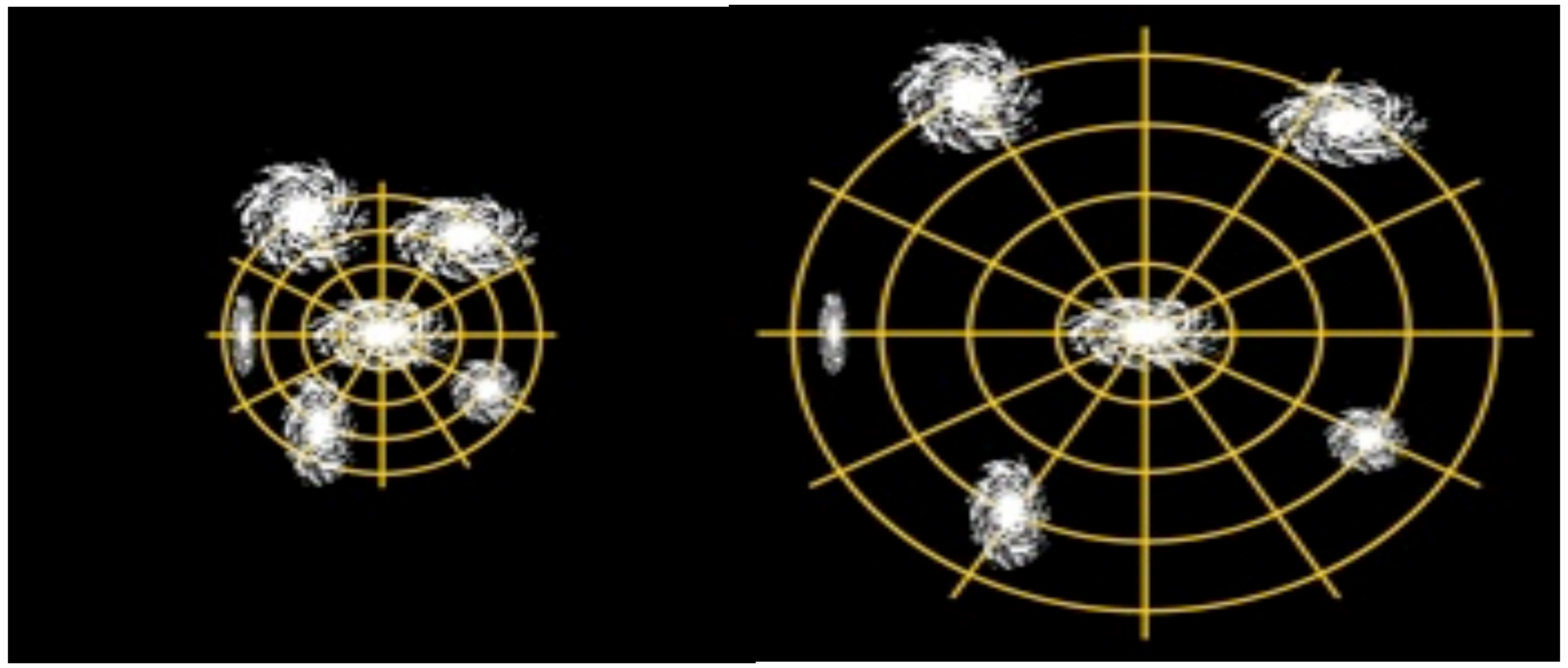

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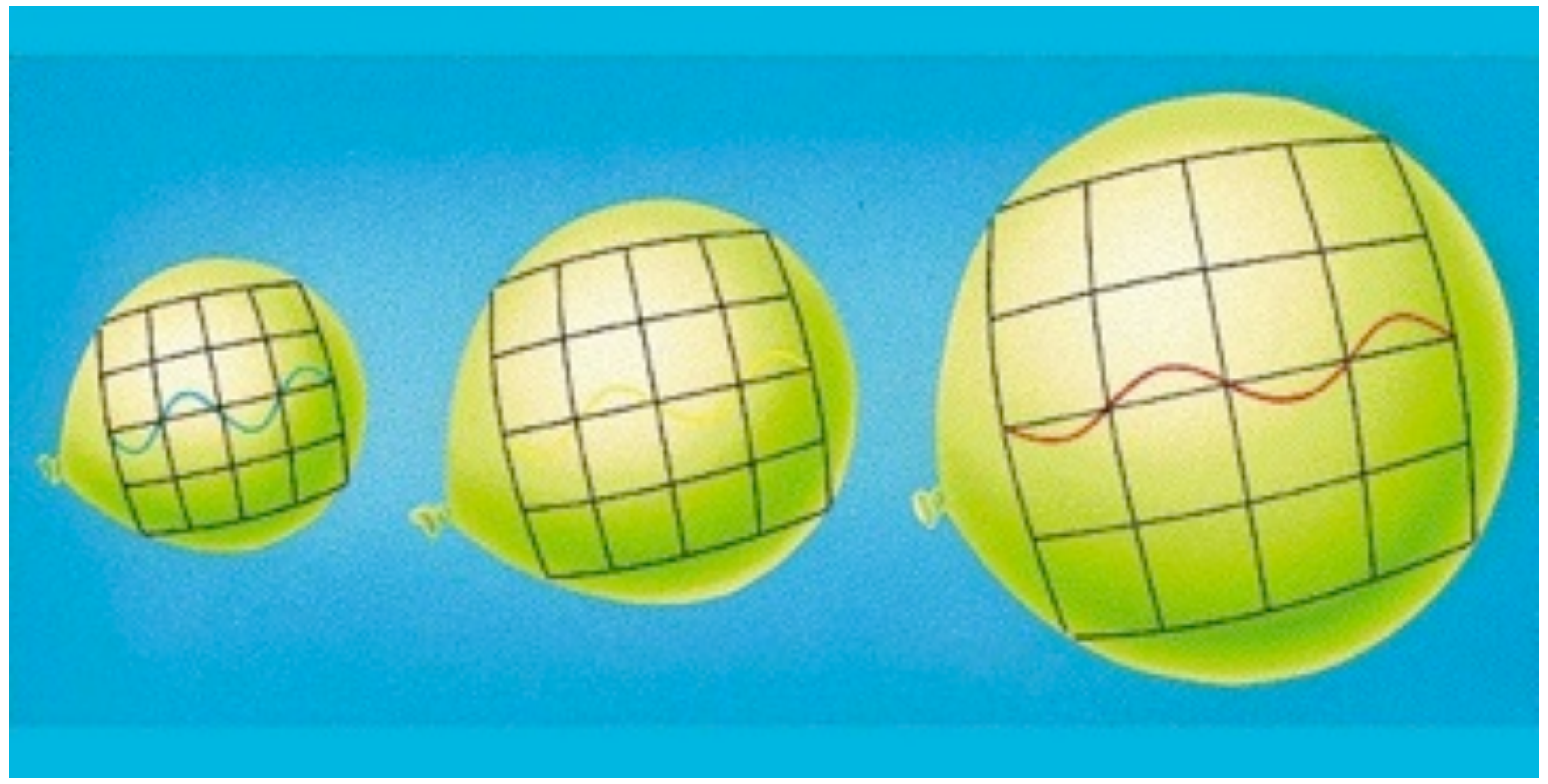
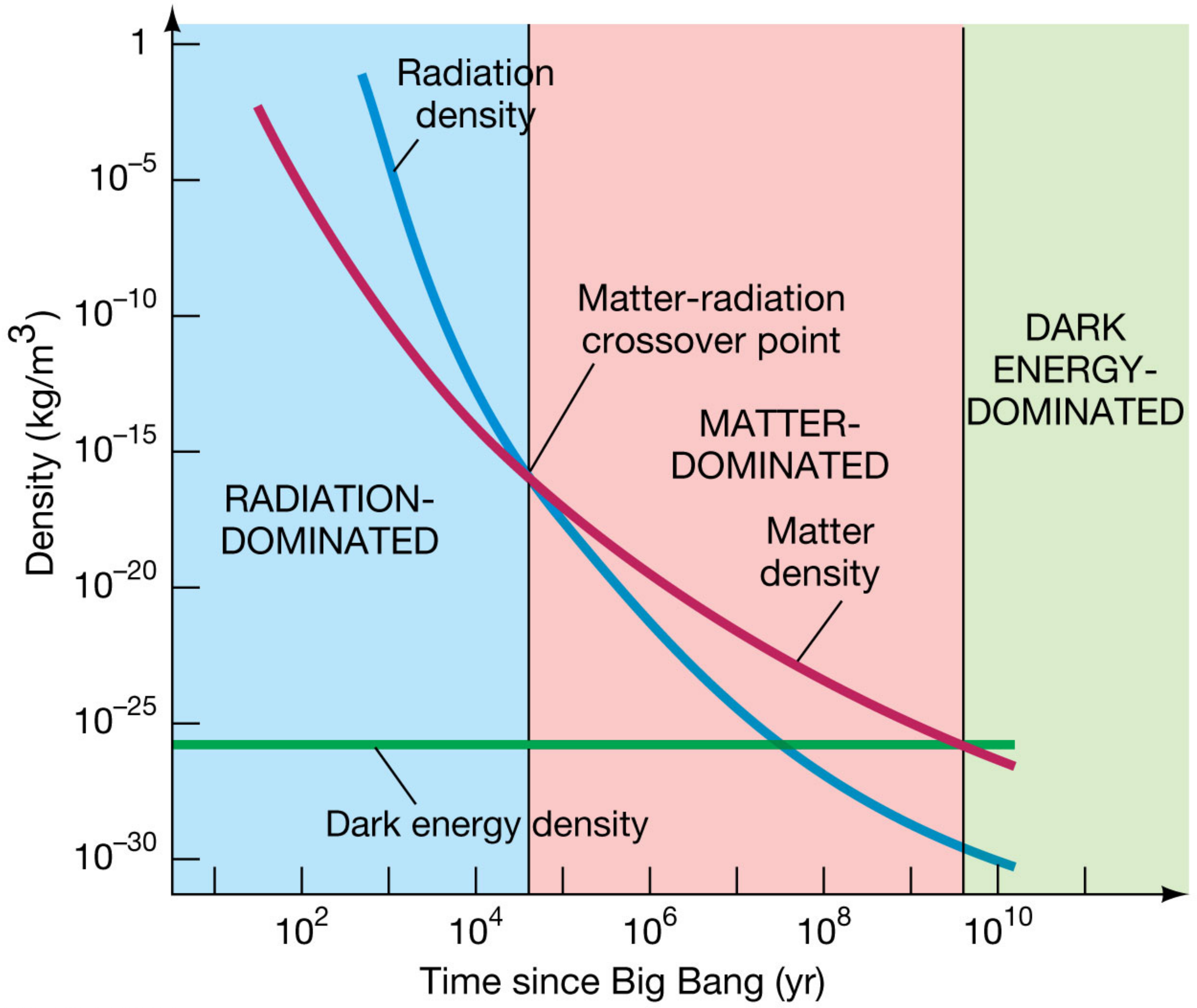
- Not only density higher in the early universe, but radiation wavelength contracted: More energetic! Early universe denser & hotter (eventually a plasma, $E\sim T$) & dominated by relativistic species; even weak interaction at equilibrium when $T>$few MeV !





Neutrinos & Cosmology

- ν's produced (# comparable with photons!) e.g. via $e^+e^- \longleftrightarrow \nu$ anti-ν & attain a FD distribution.

$$f_\nu(p) \simeq \frac{1}{e^{p/T_\nu}+1}$$

- With expansion & cooling below T ~few MeV ν decouple and 'freeze-out': number drops as a^{-3}, average momentum redshifts as a^{-1} (1 eV ~ 10^4 K)

$$H \simeq \sqrt{G_N}T^2 \qquad \Gamma_{\rm eq} = n_{\rm eq}\langle\sigma v\rangle \sim G_F^2 T^5 \quad \langle\sigma v\rangle = \sigma_{\rm weak} \sim G_F^2 E^2 \sim G_F^2 T^2 \qquad \frac{\Gamma_{\rm eq}}{H} \sim \left(\frac{T}{\rm MeV}\right)^3$$

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Key pheno consequences

- *Slightly colder than CMB: ν's decouple before $e^\pm$ annihilations*

$$\frac{T_\nu}{T_\gamma} \simeq \left(\frac{4}{11}\right)^{1/3}$$

- *Abundance*

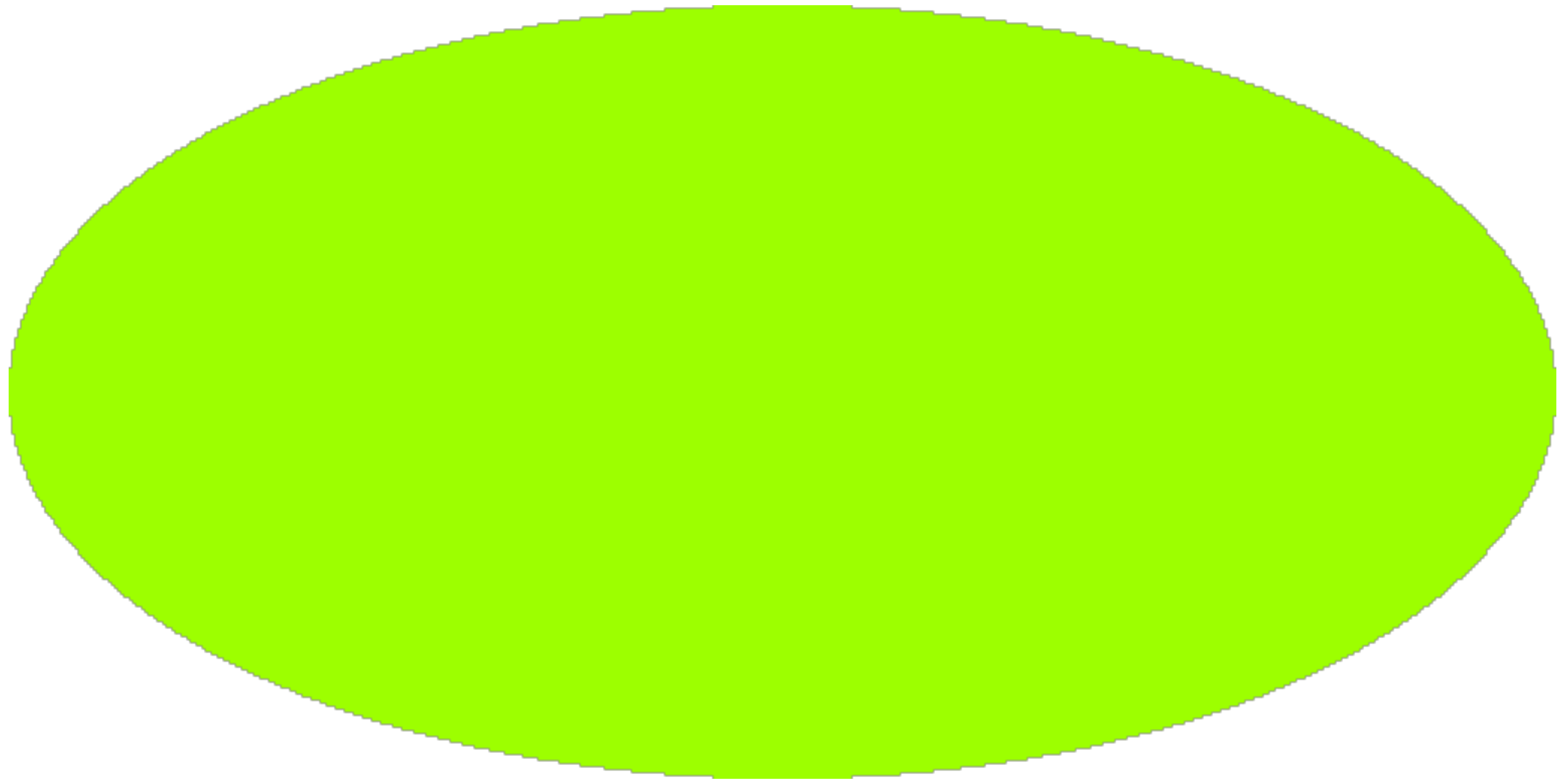
$$n = g\int f_\nu(p)\frac{d^3\mathbf{p}}{(2\pi)^3} = \frac{g}{2\pi^2}\frac{3\zeta(3)}{2}T_\nu^3 \to 110\,\mathrm{cm}^{-3}\ \mathrm{today,\ per\ flavour}$$

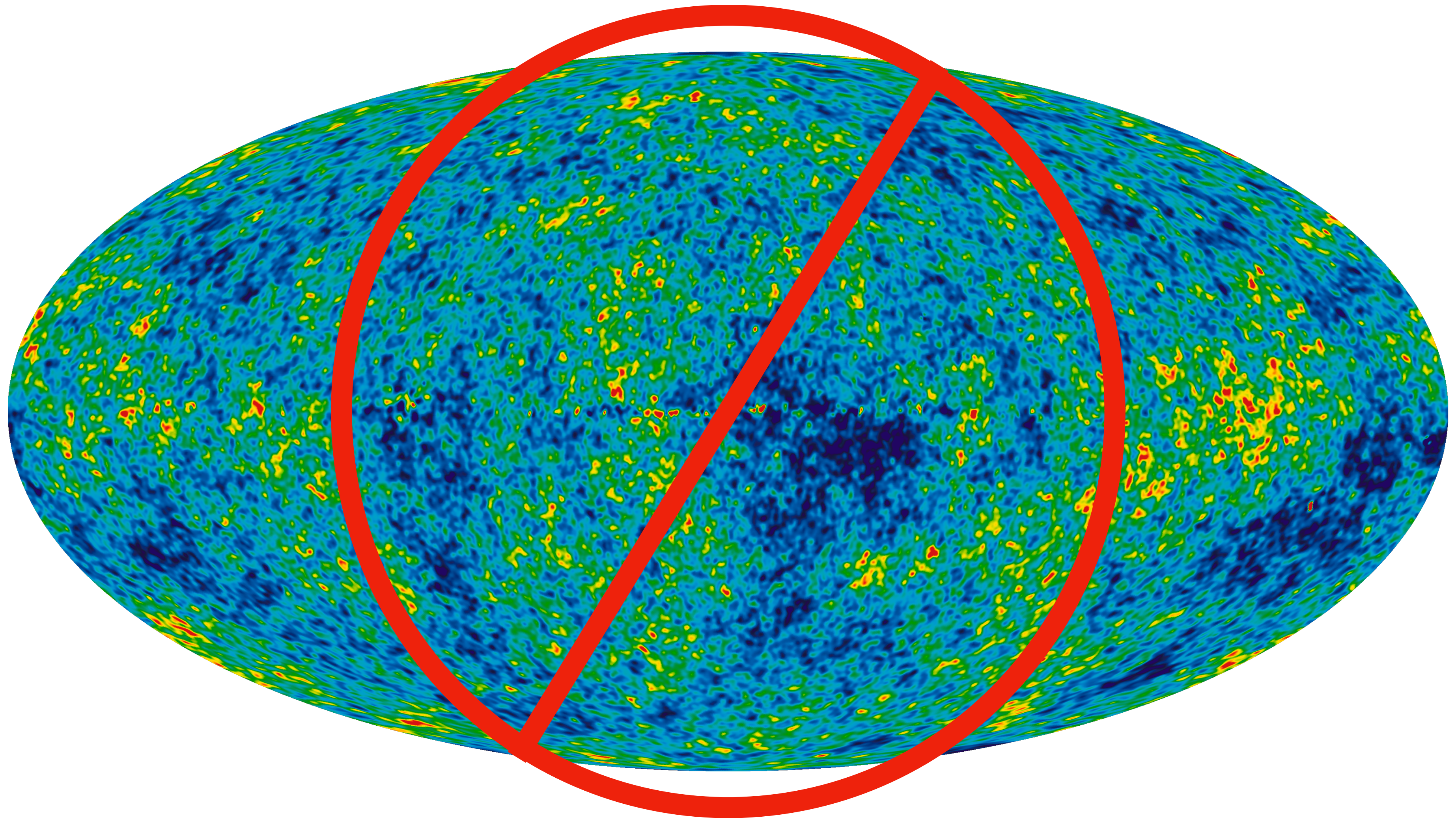
- *Energy density*

$$\rho = \sum_{i=1}^{3}\int [f_{\nu_i}(p) + f_{\bar\nu_i}(p)]\sqrt{m_i^2+p^2}\frac{d^3\mathbf{p}}{(2\pi)^3} \left\{ \begin{array}{l} \equiv \dfrac{7\pi^2}{120}\left(\dfrac{4}{11}\right)^{4/3}\dfrac{T^4}{15} N_{\rm eff}\ (T_\nu \gg m_i) \\ \simeq \sum m_i n_\nu\ (T_\nu \ll m_i) \end{array}\right.$$

Neutrinos in the early universe

- Very close to isotropic and homogeneous (think of the **tiny** anisotropies in the CMB!); relativistic *ν E*-density contributes to the ***expansion of the Universe via H***. Parameterised via $N_{eff.}$ (≃3.045 in the SM)





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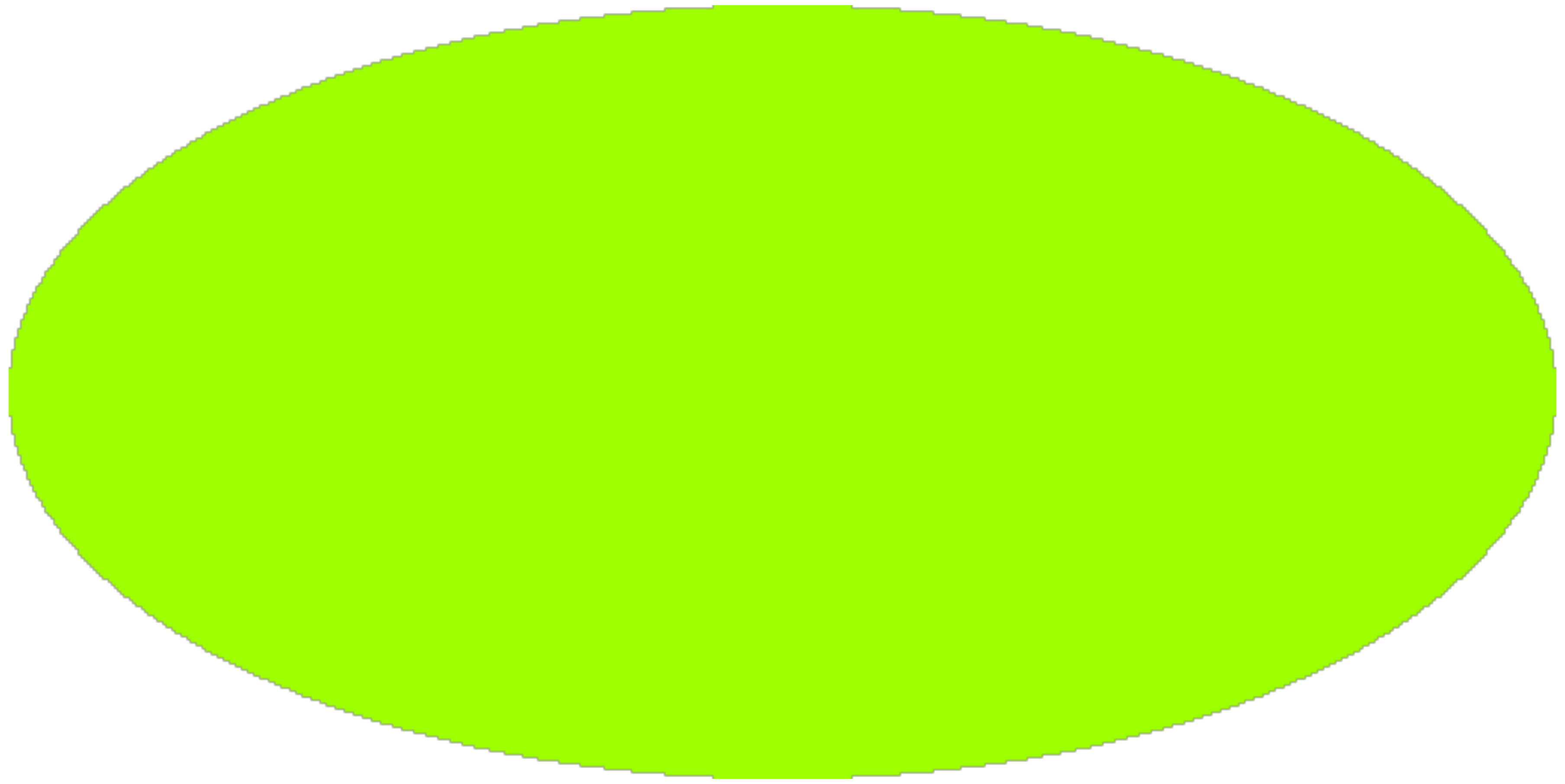
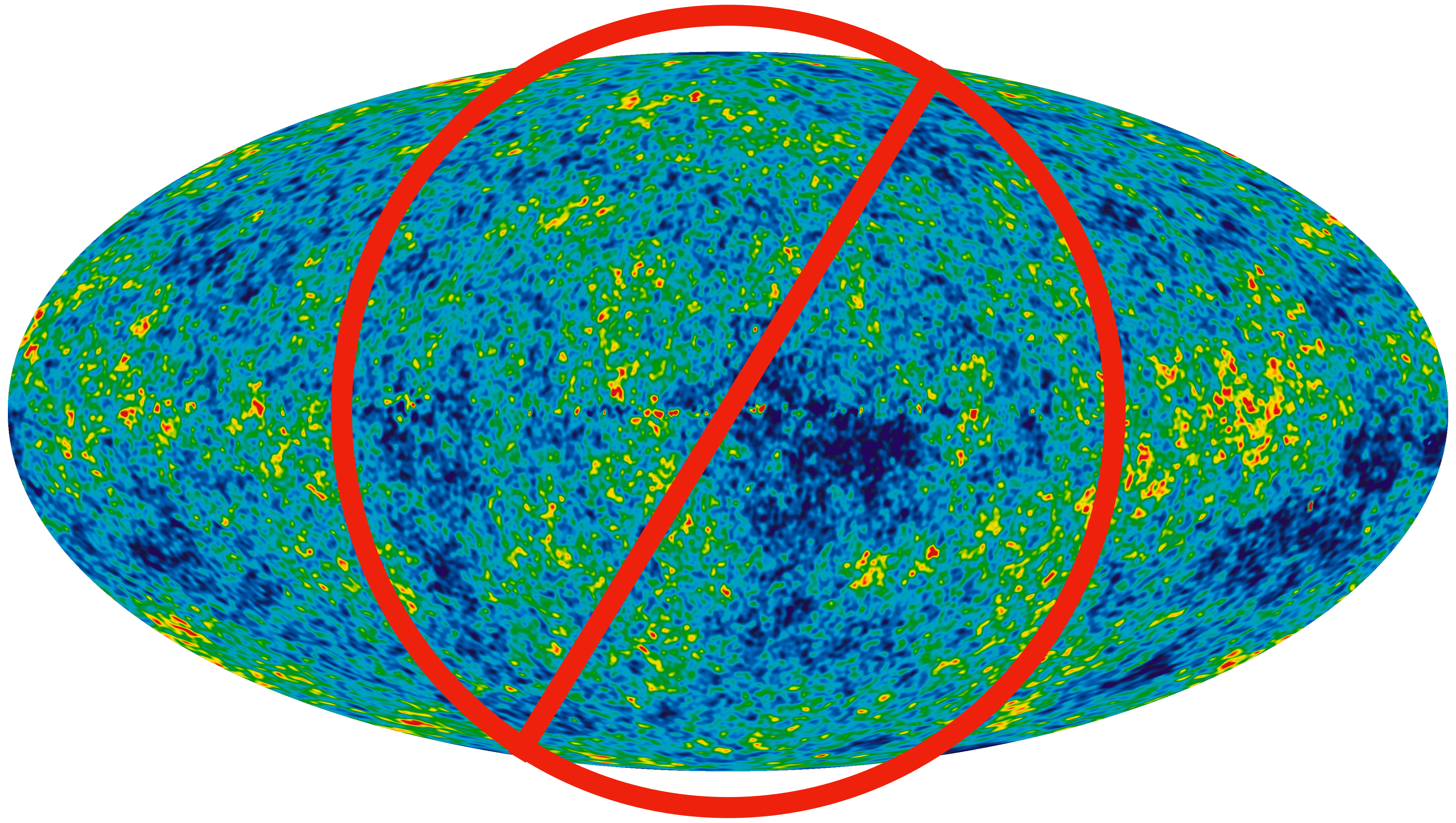




Gravitational effect, but…*

$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2}$$

Statistics

Flavour, NP…

$$\rho_R = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]$$

$0.1\ m_e << T_{dec} << 0.1\ m_\mu$

N_{eff} also sensitive to new dof's e.g. coupled to ν's

N_{eff} = 2.99 ± 0.34 (95% C.L.) Planck 2018 + BAO

N_{eff} = 2.88 ± 0.54 (95% C.L.) BBN; Pitrou et al. 1801.08023

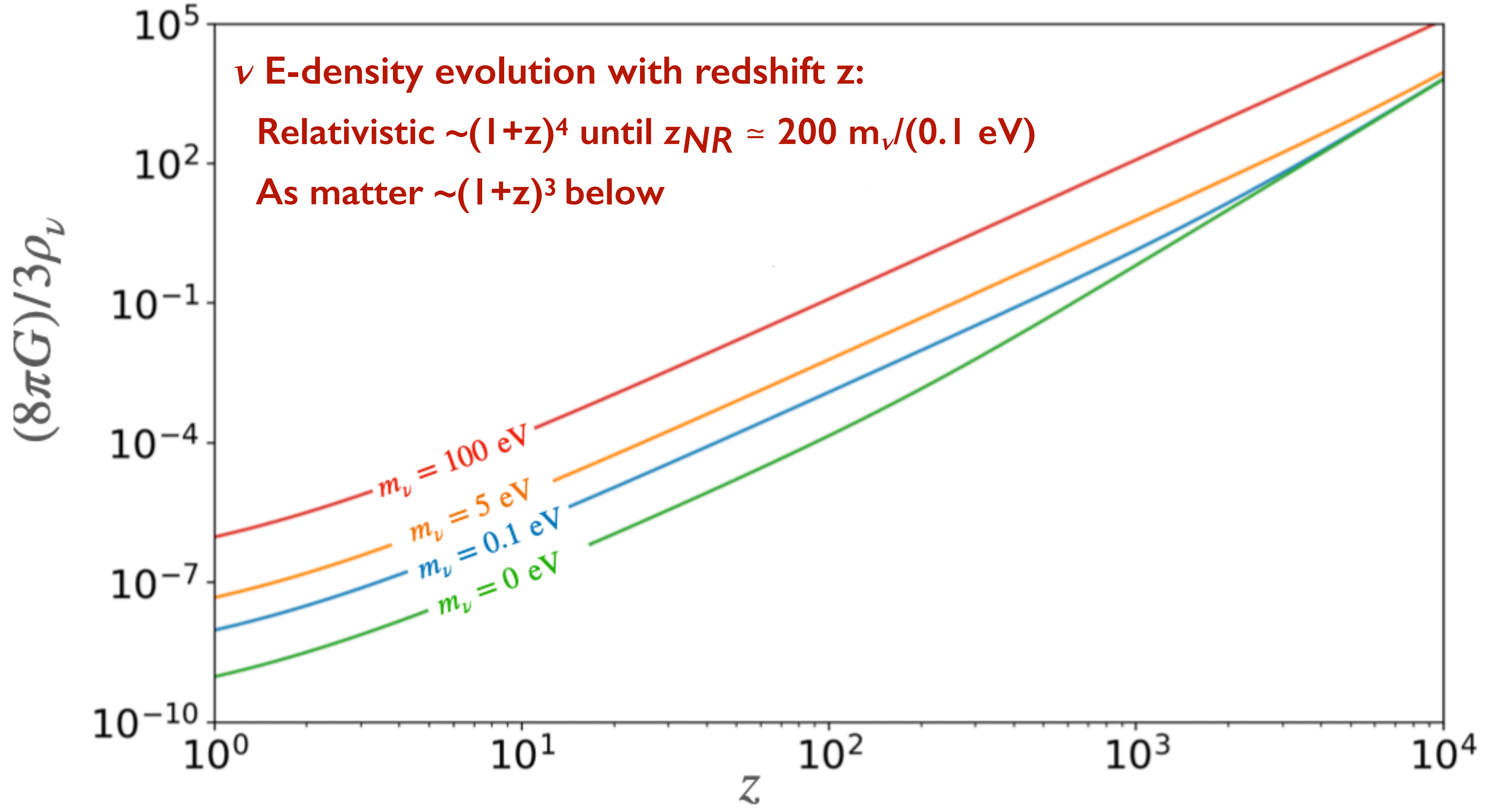
**BBN is also affected by (anti-)ν_e distributions via p-n (departure from) equilibrium*

Neutrinos in the 'late' universe

- In the late universe:

a) ν *E*-density influenced by their mass

$$\rho \simeq \sum m_i n_\nu \; (T_\nu \ll m_i)$$



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- In the late universe:

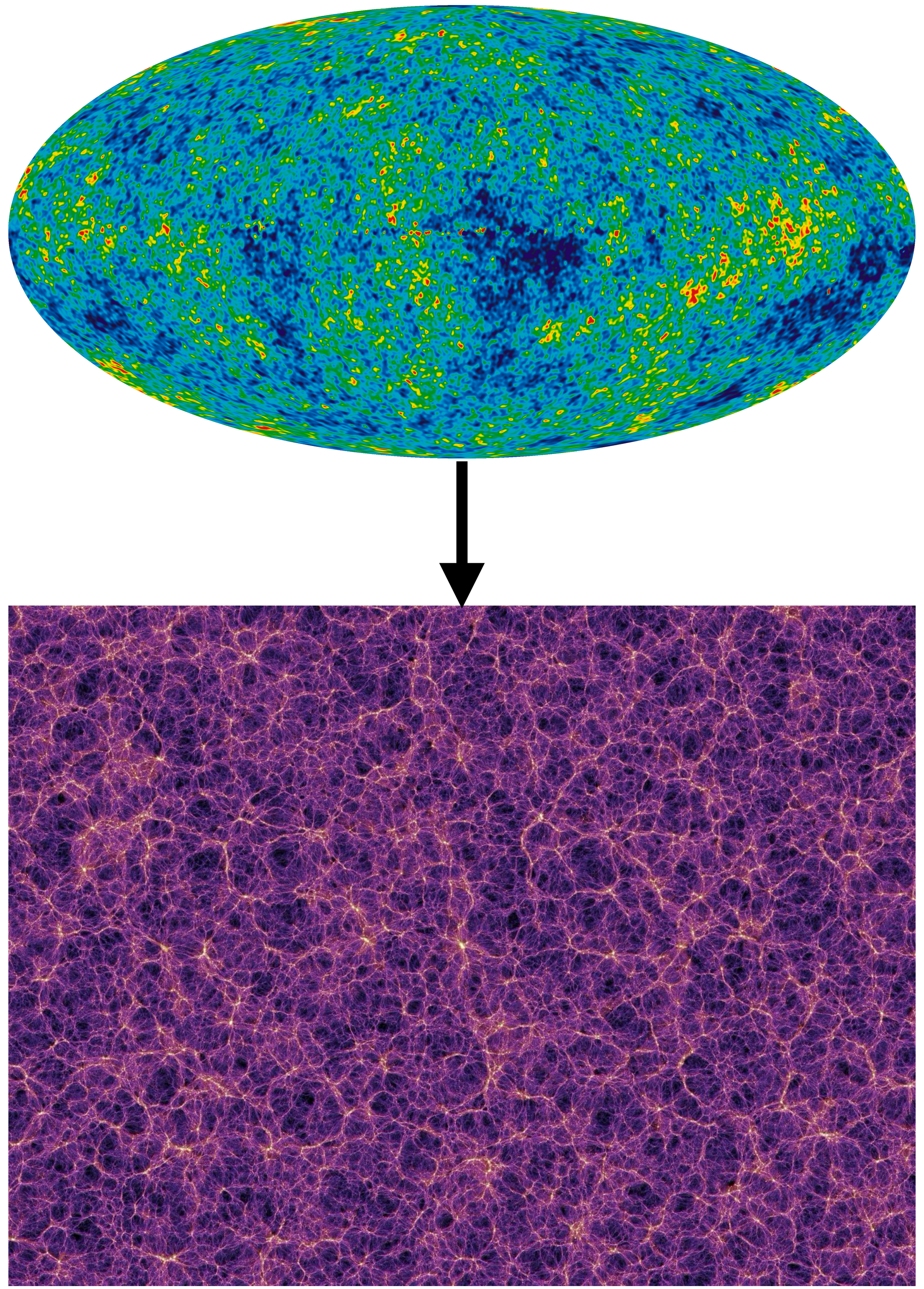
a) ν *E*-density influenced by their mass

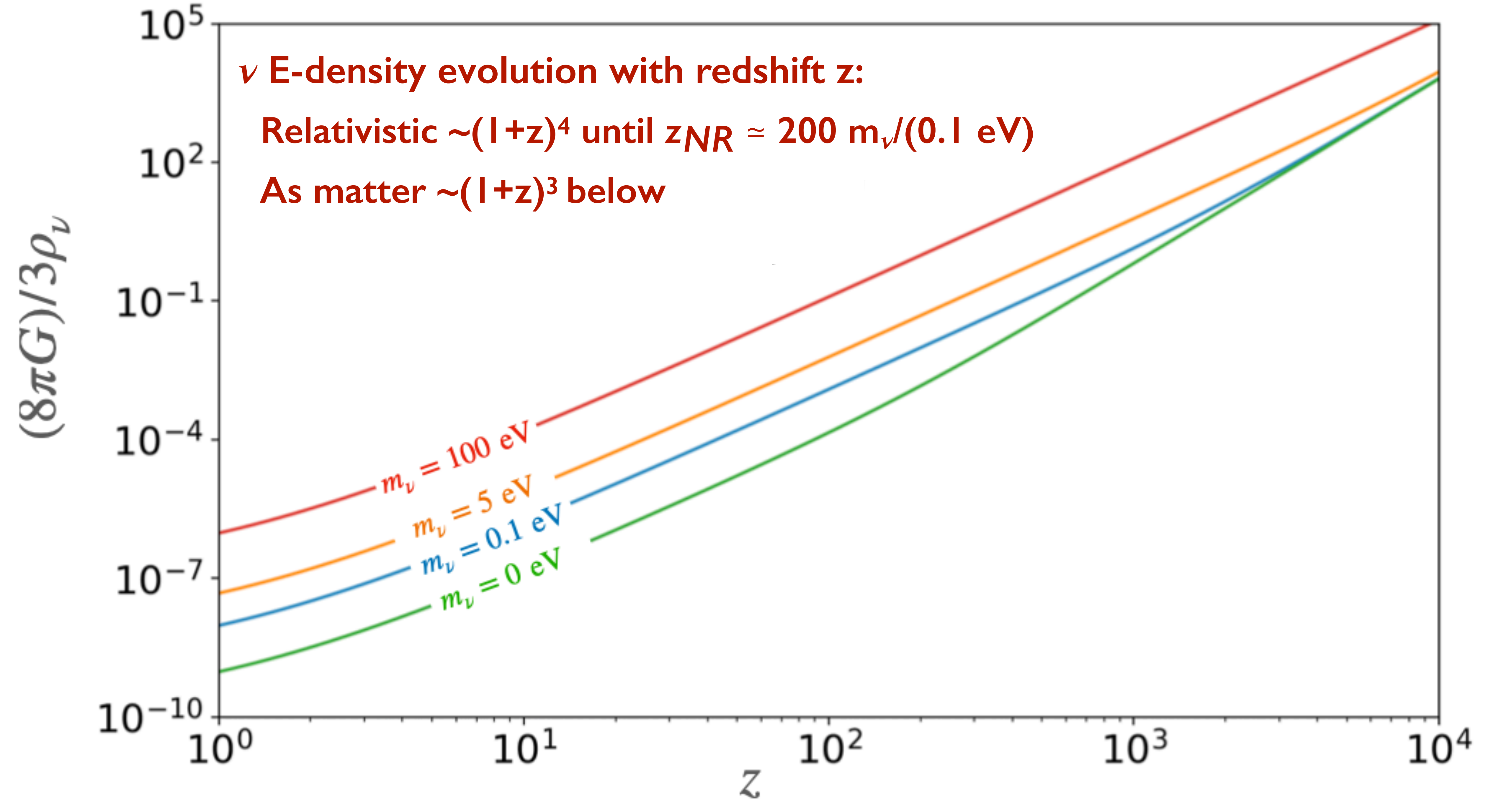
$$\rho \simeq \sum m_i n_\nu \, (T_\nu \ll m_i)$$

b) Formation of structures; $\delta G_{\mu\nu} = 8\pi G_N \delta T_{\mu\nu}$

since ν's have large velocities than typical (both baryonic & dark) matter, they oppose small structure forming.

From the pattern and growth of perturbations, we can constrain (the total) ν mass+exotic interactions (drag, decay…)





Neutrinos & structure growth, some key formulae

For non-relativistic pressureless particles: 2 degrees of freedom describe perturbations $\delta \equiv \delta\rho/\rho, \quad \phi$

Continuity eq. $$\delta'' + \frac{a'}{a}\delta' = -k^2\phi$$

Poisson eq. $$k^2\phi = -4\pi G_N a^2 \rho \sum \delta_i$$

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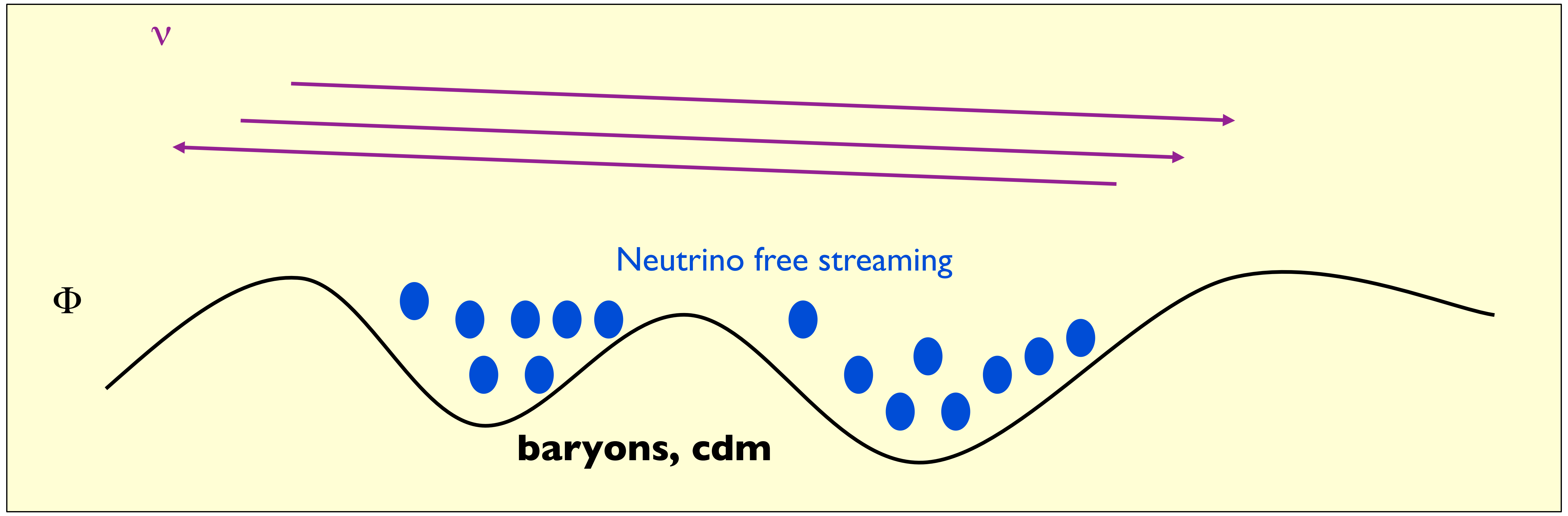
Continuity eq. $\delta'' + \frac{a'}{a}\delta' = -k^2\phi$ *Poisson eq.* $k^2\phi = -4\pi G_N a^2 \rho \sum \delta_i$

ν's 'free stream' (decoupled with *large* velocity dispersion)

$$\delta'' + \frac{a'}{a}\delta' + (k^2 - k_J^2)c_s^2\delta = -k^2\phi \qquad c_s \simeq \frac{3.15 T_\nu}{m_\nu} \qquad k_J^2 = \frac{3a'}{a\, c_s^2}$$

ν's "do not settle" in potential wells that they can overcome by their typical velocity: compared with CDM, they *suppress power at small-scales (perturbations oscillate, do not grow exponentially)*



Can erase the 'free-streaming' feature with (very!) large secret self-coupling~10^{10} G_F: strongly disfavoured even for a single species.

e.g. Schöneberg et al. 2107.10291

Power spectrum of large scale structures

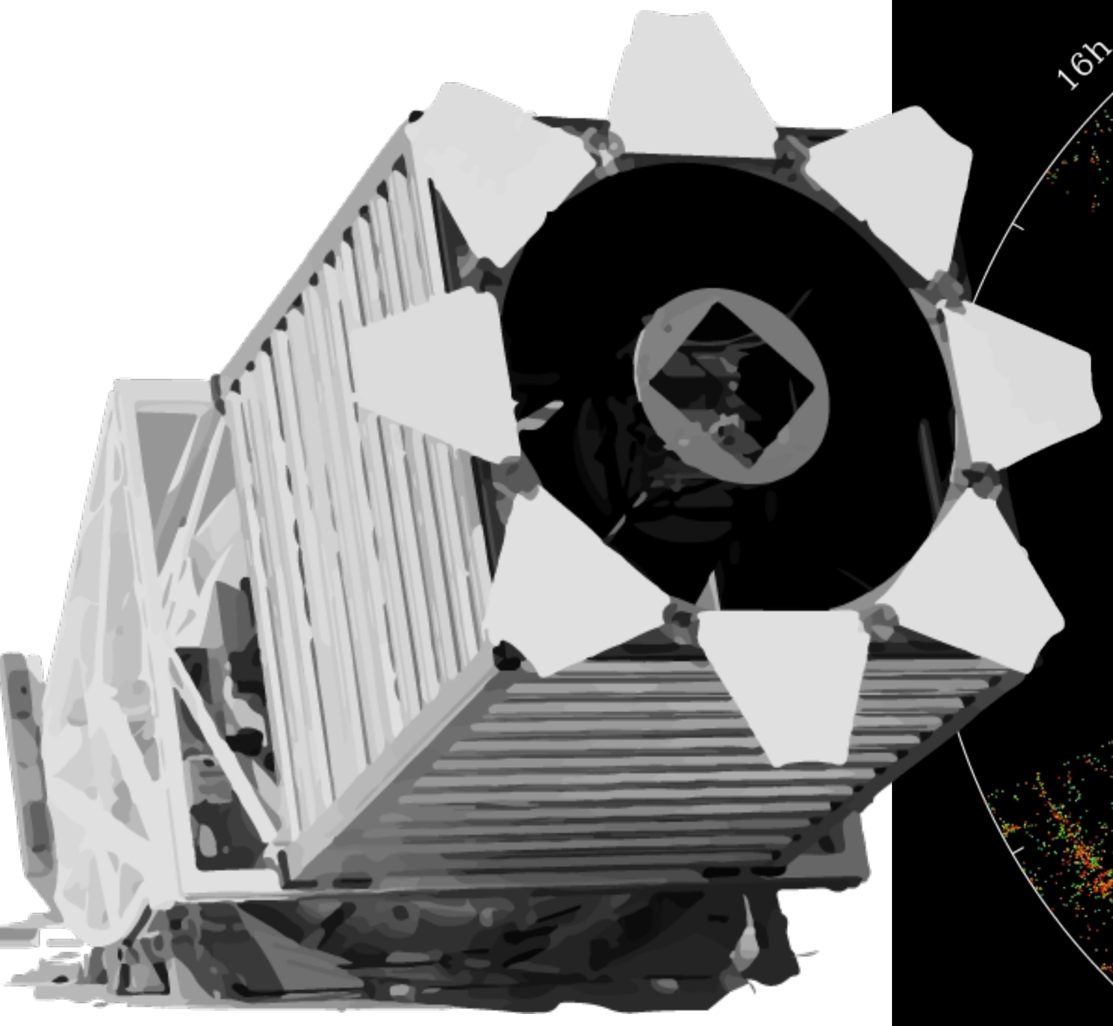
$$\delta = \frac{\rho}{\langle \rho \rangle} - 1$$

Density contrast

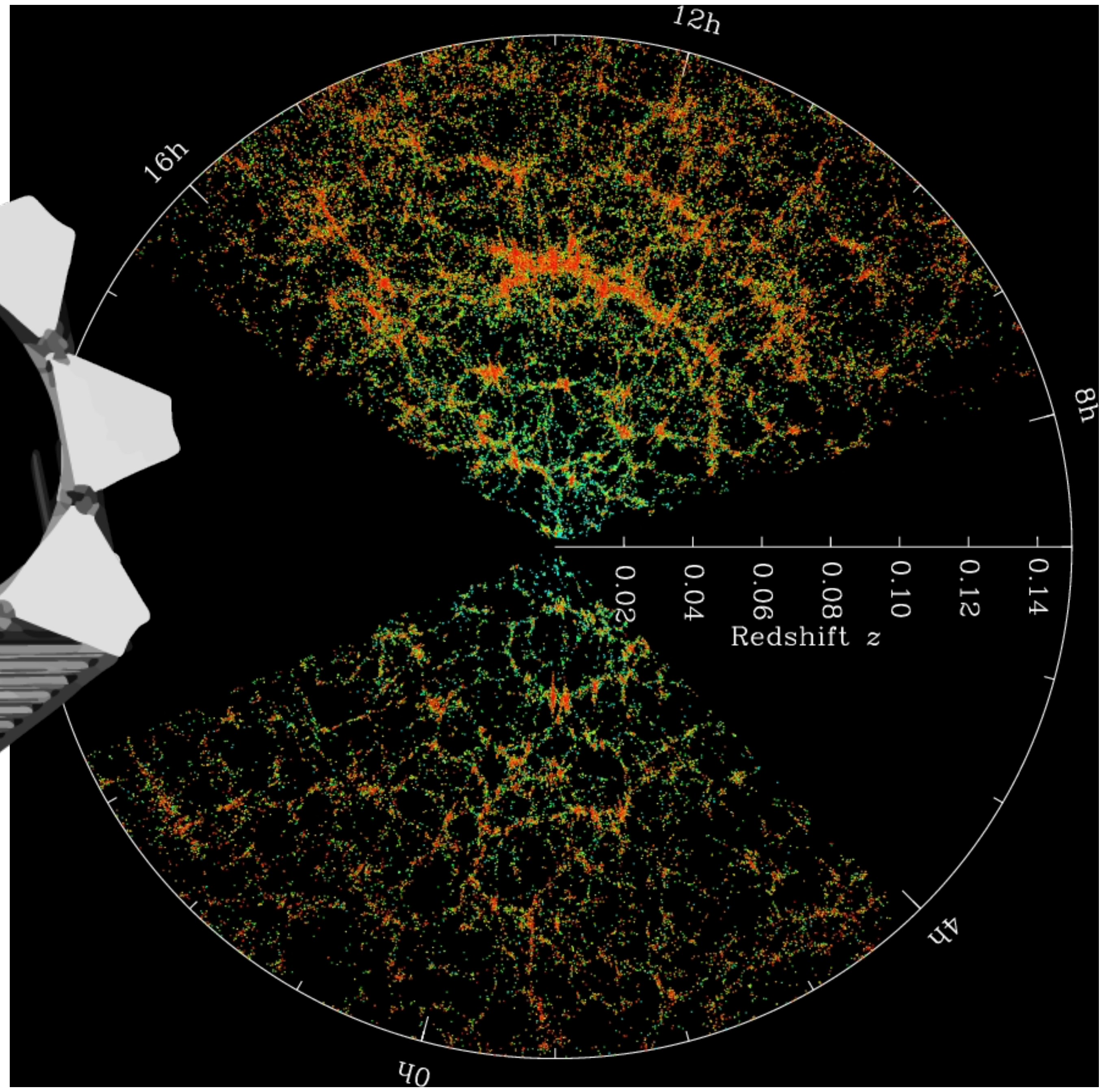
$$= \sum_{\mathbf{k}} \tilde{\delta}_{(\mathbf{k})} \mathrm{e}^{i\mathbf{k}\cdot\mathbf{x}}$$

Can develop in Fourier modes, evolve independently in linear theory

Measured via surveys



e.g. SDSS



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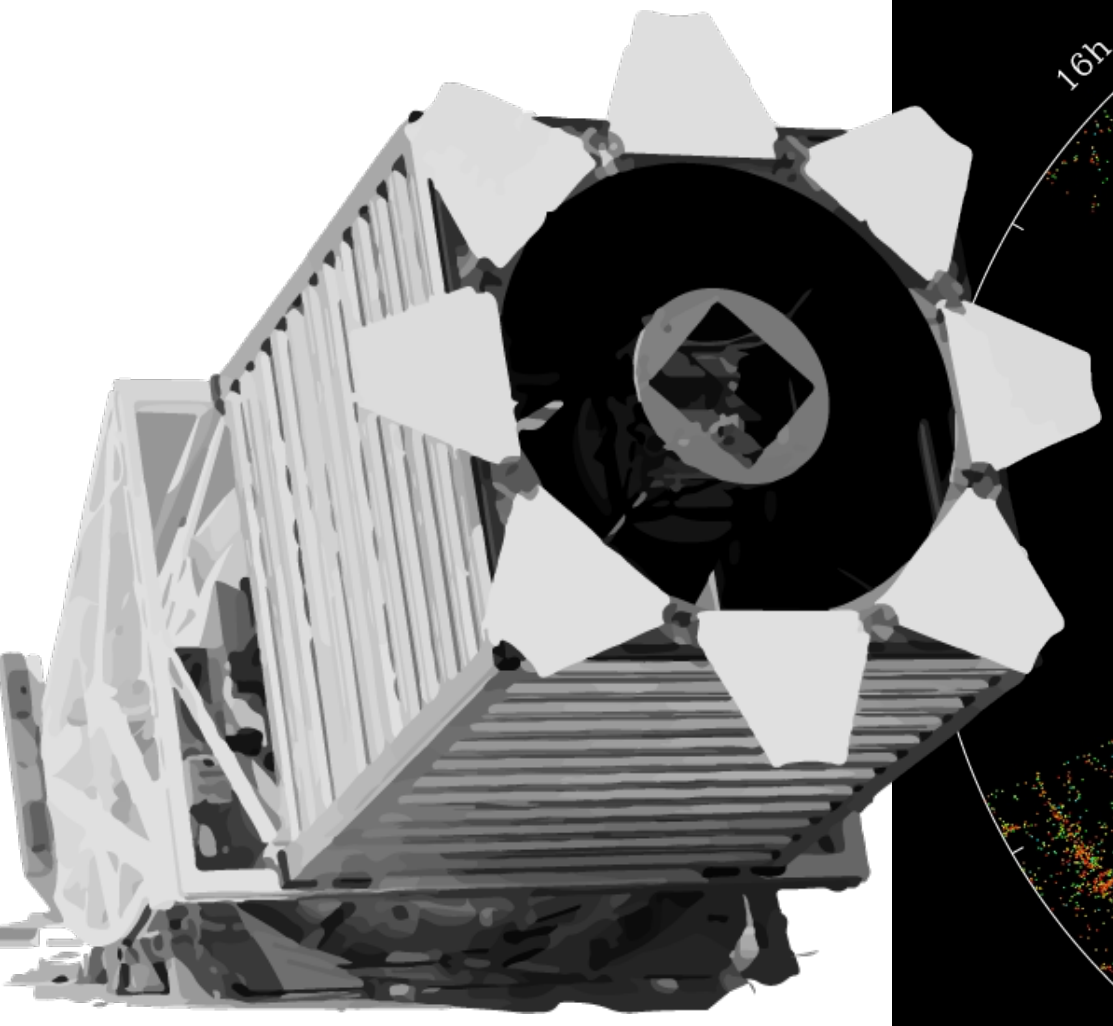
Ensemble variance is the power spectrum *P(k)*

$$\langle\tilde{\delta}(\mathbf{k})\tilde{\delta}^*(\mathbf{k}')\rangle = (2\pi)^3 P(k)\delta^{(3)}(\mathbf{k}-\mathbf{k}')$$

(Simplification for homogeneity and isotropy)

Measured via surveys



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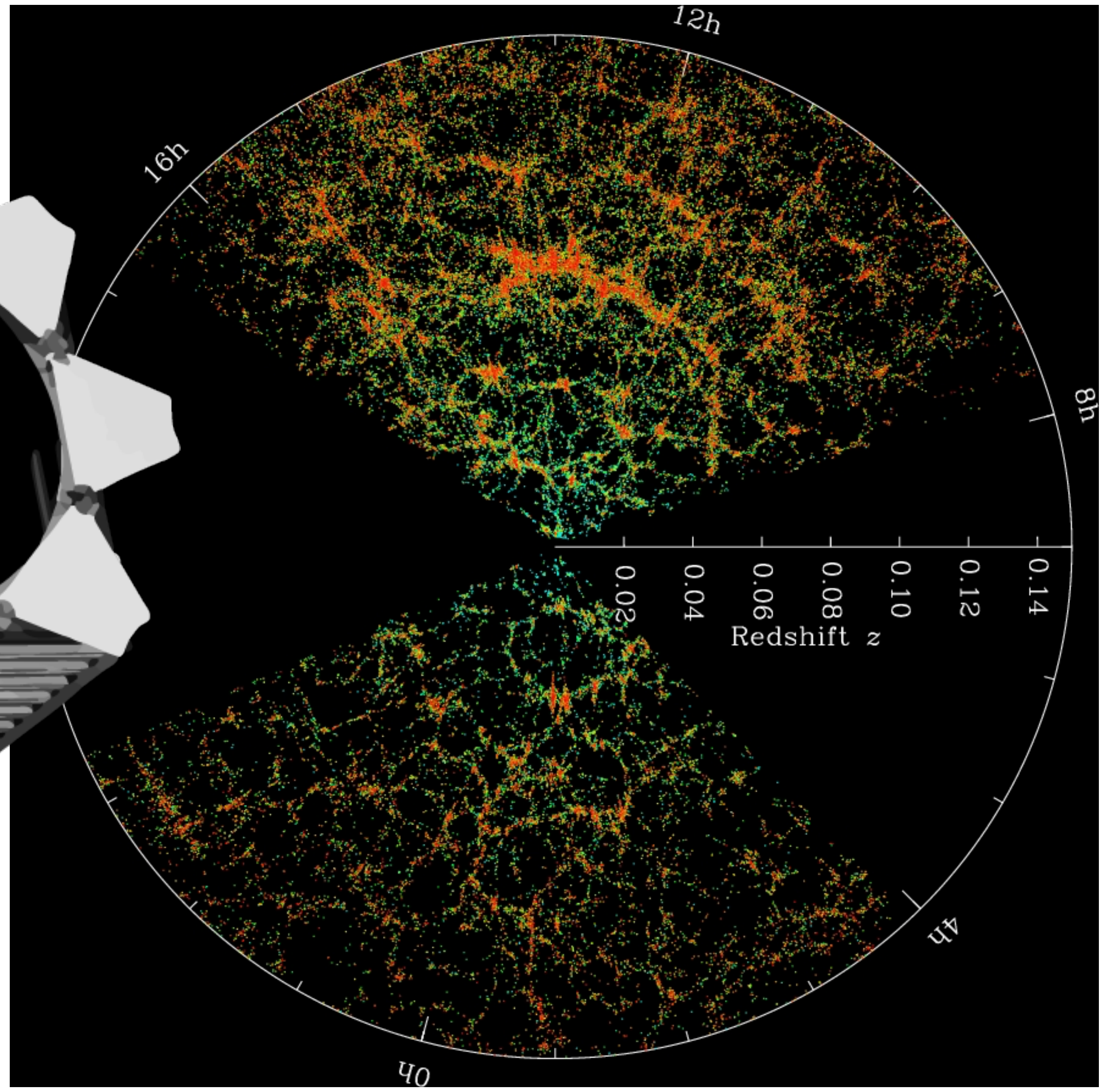
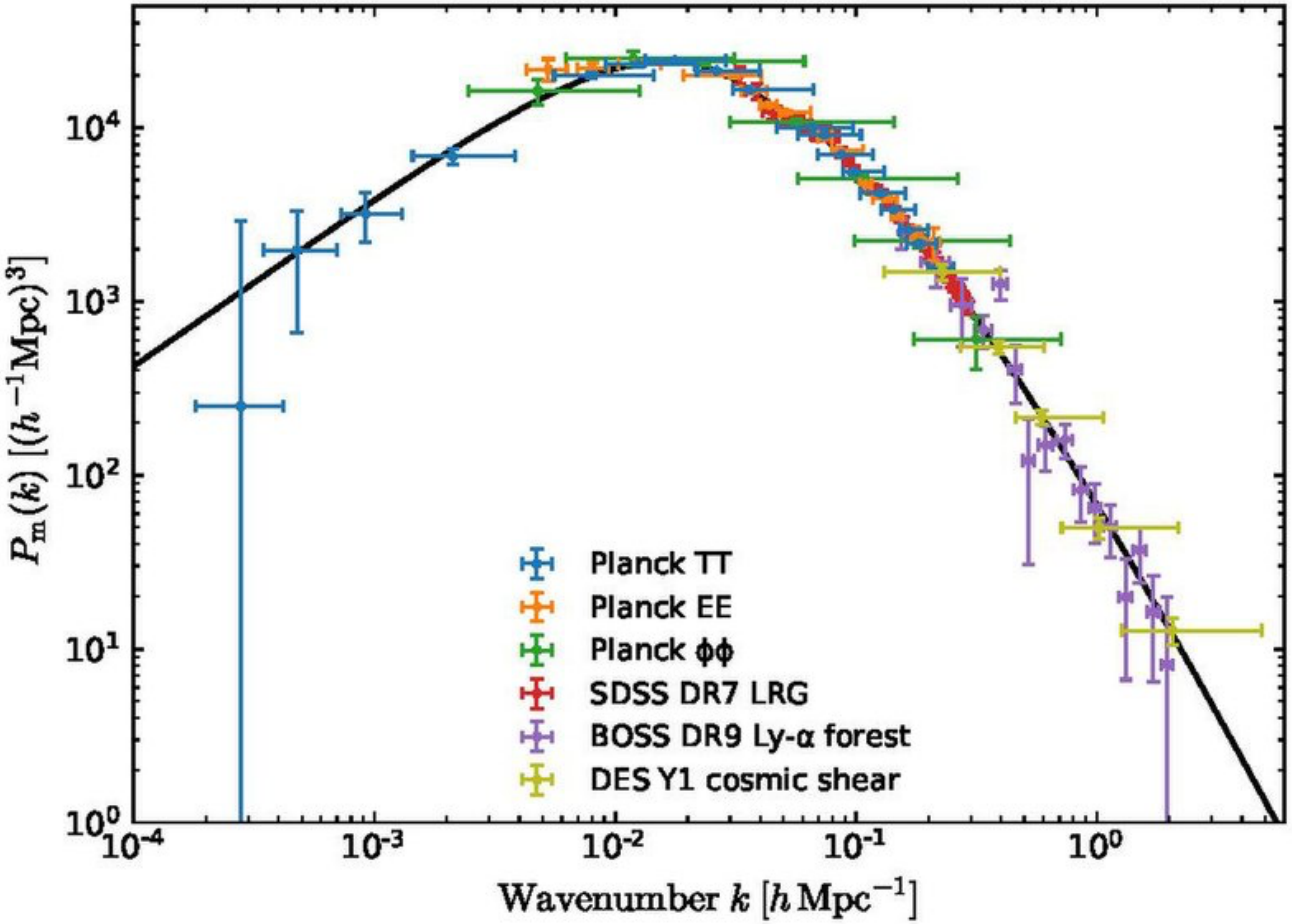




Neutrinos & large scale structures, more quantitative

Cosmologies with same total matter Ω_m but massive ν's lead to a $P(k)$ suppression at small scales

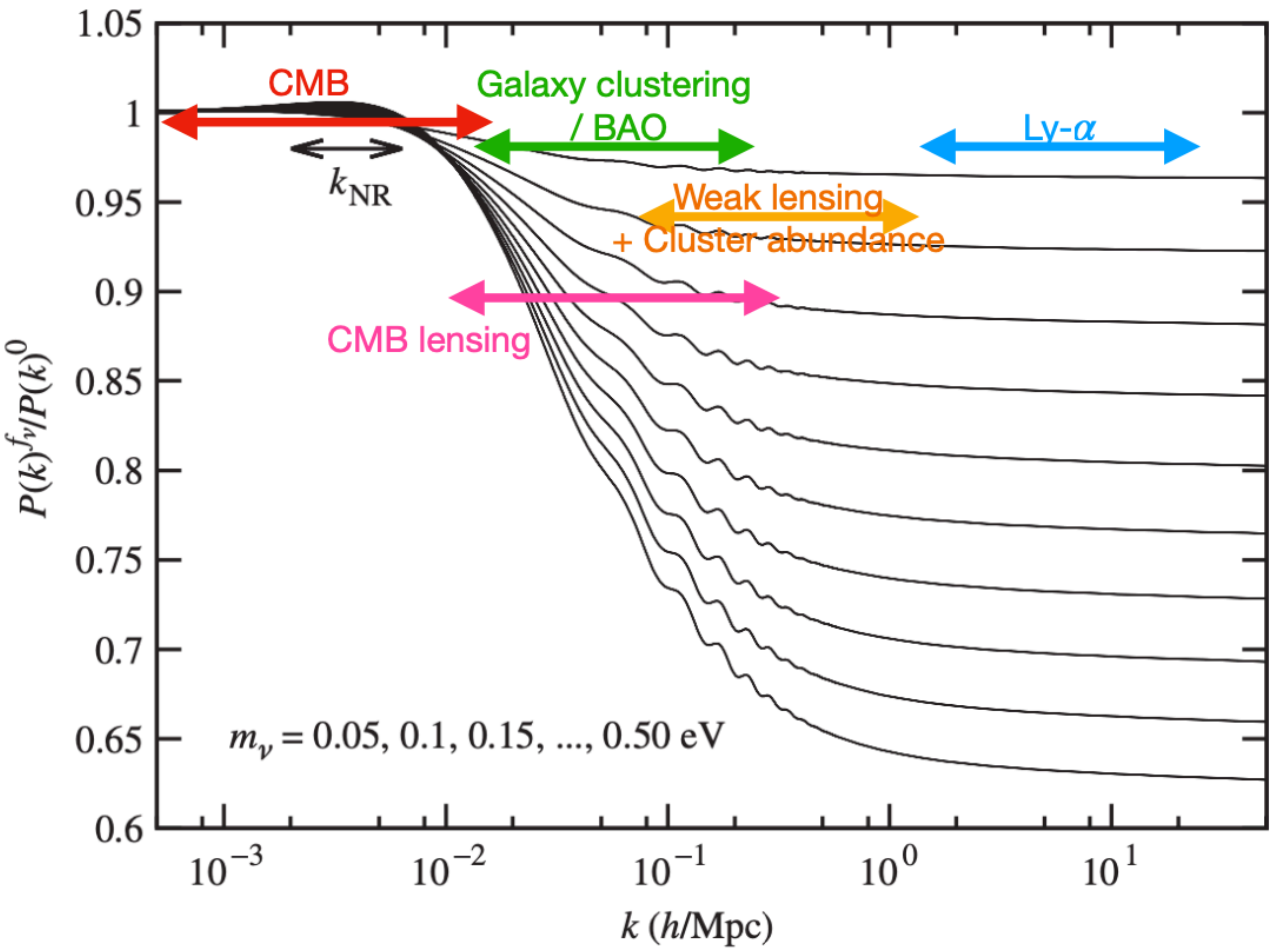
$$k > k_{\rm NR} = 0.01\sqrt{\frac{\sum m_\nu}{\rm eV}}\sqrt{\frac{\Omega_m}{0.3}}\,h\,{\rm Mpc}^{-1}$$

In linear perturbation theory,

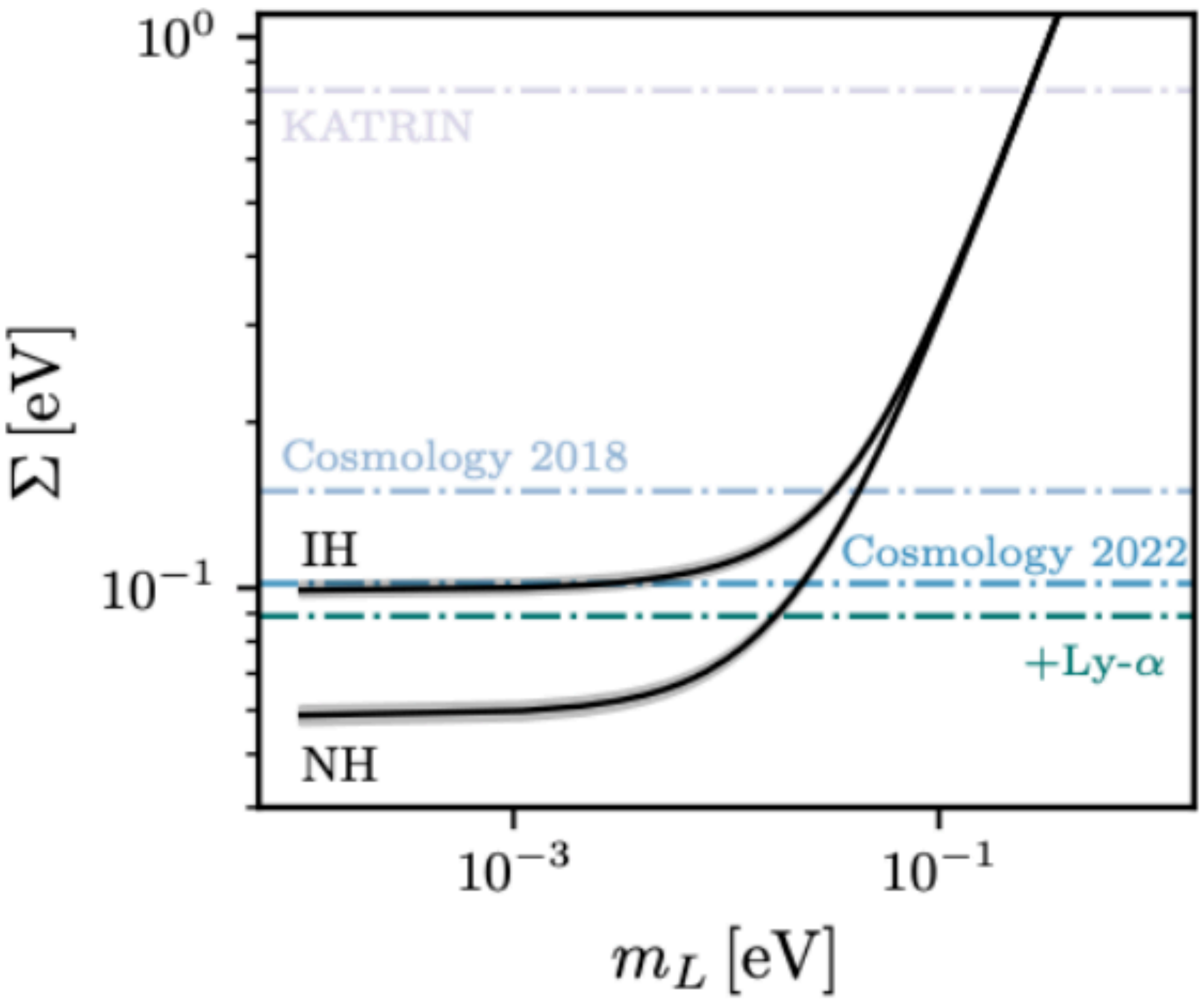
$$\frac{\Delta P}{P} \simeq -\frac{\sum m_\nu}{1.7\,{\rm eV}}\frac{0.3}{\Omega_m}$$

(Improvements exist both via analytical and numerical approaches)

Partial degeneracies with other parameters. Actual bound (mildly) depends on benchmark & on how many (consistent!) datasets are used.



Cosmological neutrino mass bounds (95% CL)



Jimenez et al. 2203.14247

Impact of dataset combination

Planck 2018 (all T and pol, plus lensing) < 0.24 eV

Planck 2018 + BAO < 0.12 eV

(A&A 1807.06209)

Planck 2018 + BAO + Ly−α < 0.089 eV

(Palanque-Delabrouille et al. 1911.09073)

Planck 2018 + BOSS + eBOSS < 0.082 eV

(Brieden et al. 2204.11868)

Impact of cosmological model

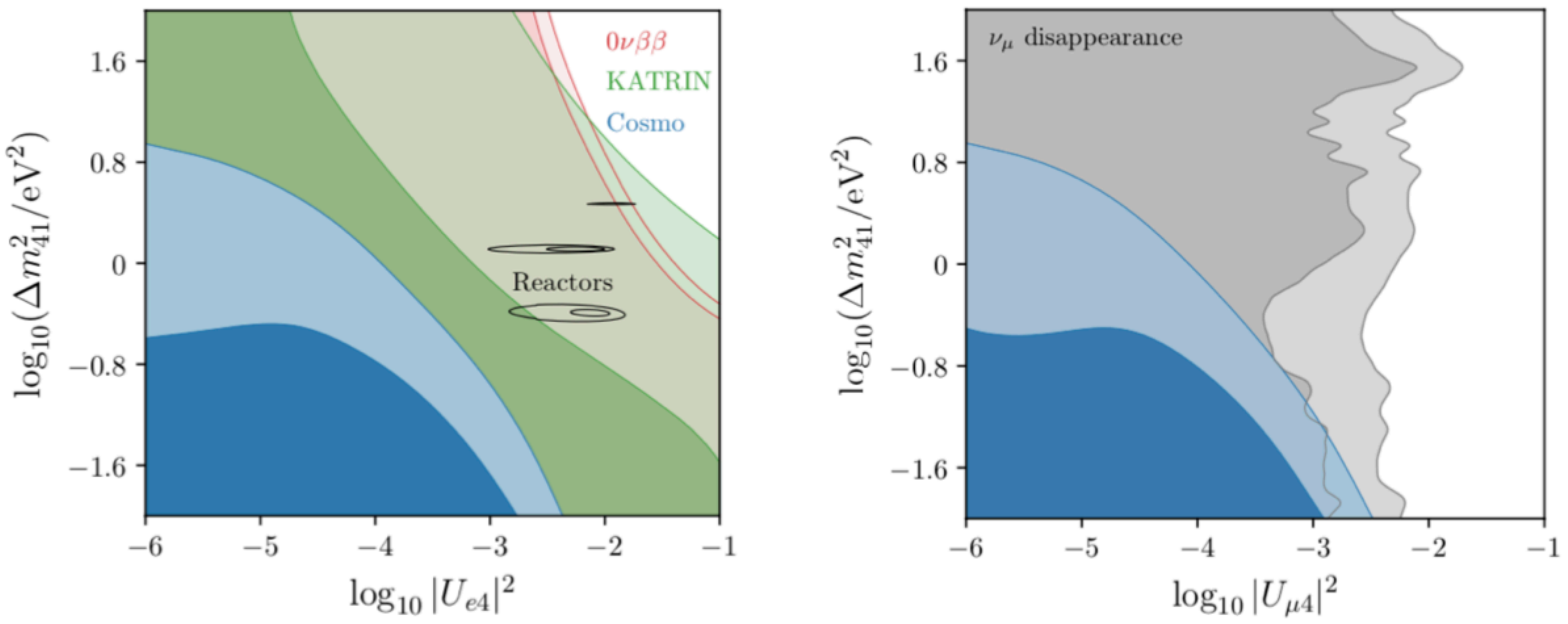
ΛCDM: Planck 2018 + BAO < 0.12 eV

ΛCDM+w+running+N_{eff} : Planck 2018 + BAO < 0.167 eV

(Di Valentino et al. 1908.01391)

Cosmological implications of hinted sterile neutrinos at eV scale

To cut a long story short, for favoured parameters the fourth neutrino fully thermalises, $N_{\rm eff}$ ~4 & ruled out by both BBN & CMB+BAO (although in the latter case some correlation with m_4…)



S. Hagstotz et al. 2003.02289

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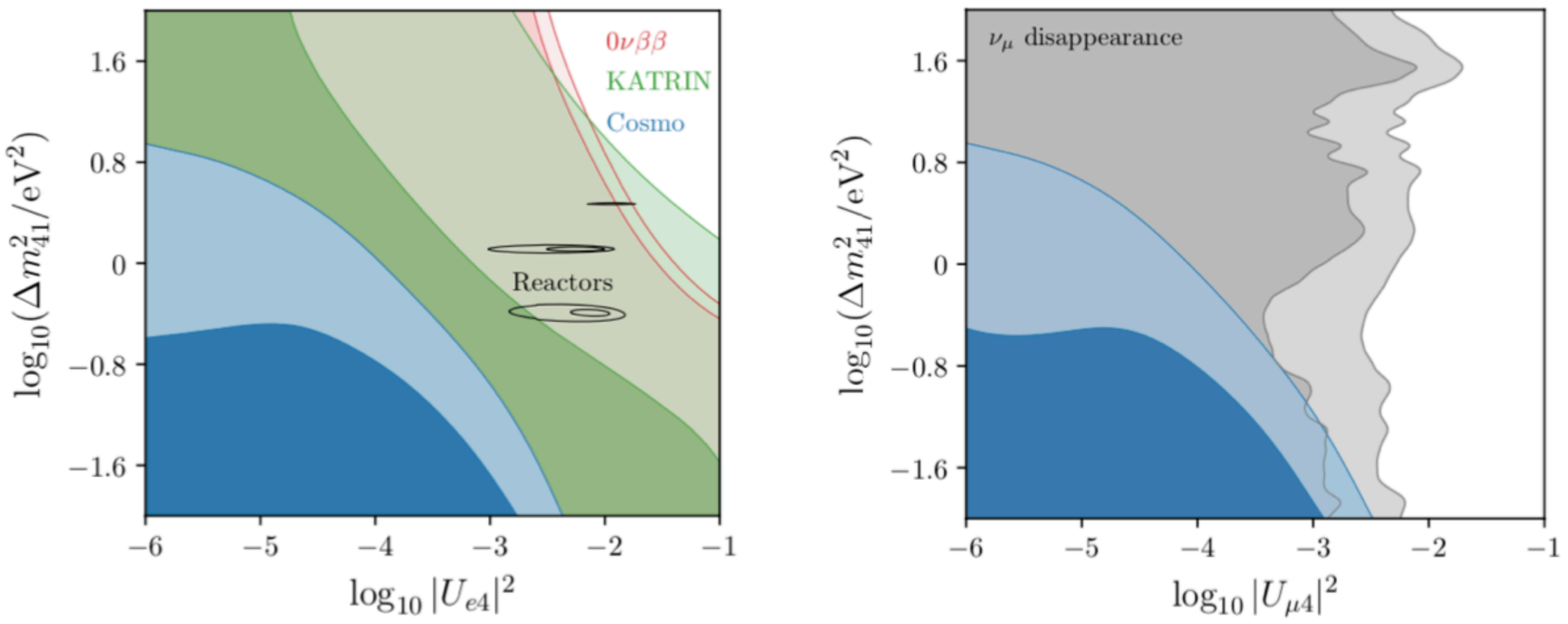

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A number of modifications of cosmology (e.g. late reheating) and/or particle physics (strongly self-interacting neutrinos) that were superficially thought to lift these constraints proven ineffective

E.g. we tested large lepton asymmetries in *Mirizzi et al. 1206.1046, 1302.1200* B. Dasgupta & J. Kopp, arXiv:2106.05913

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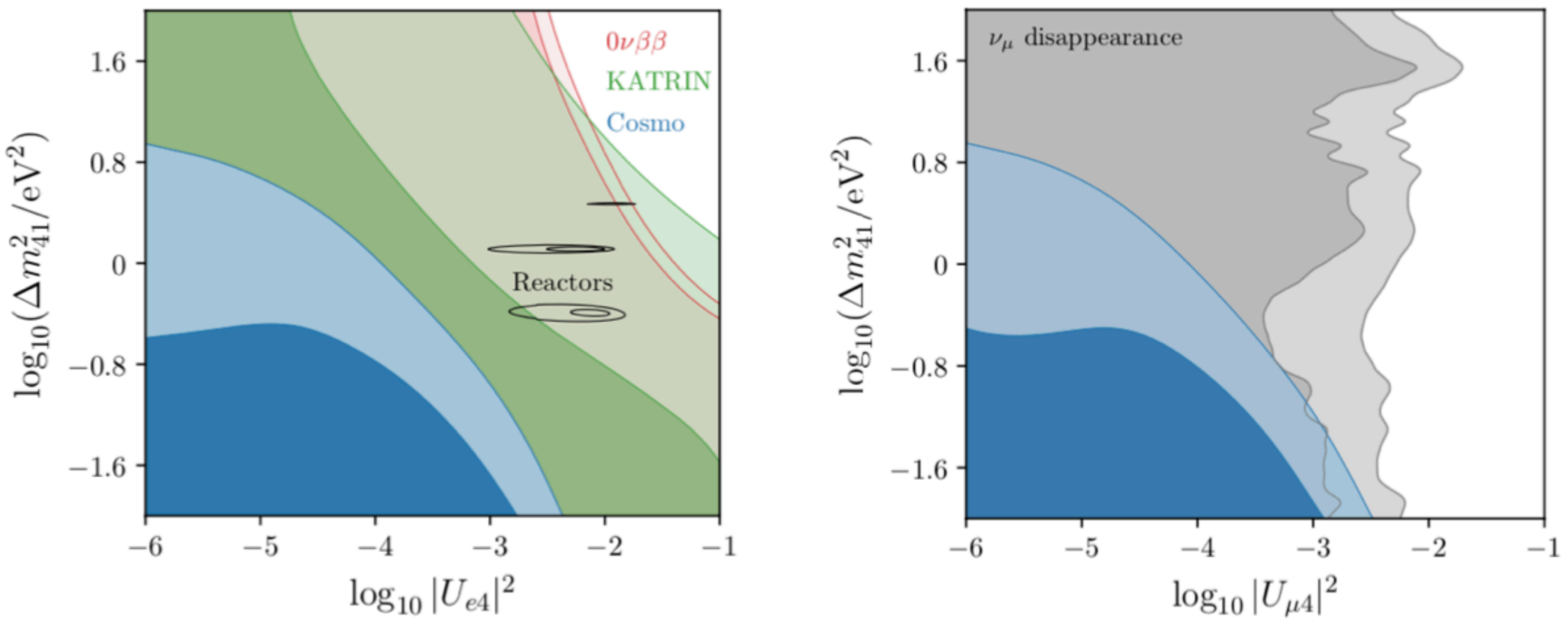

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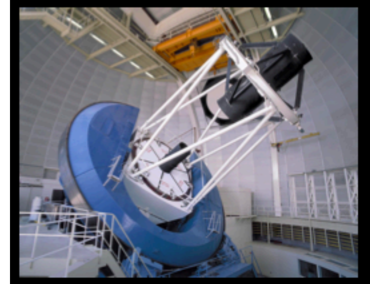
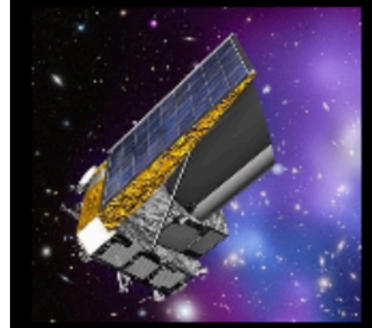
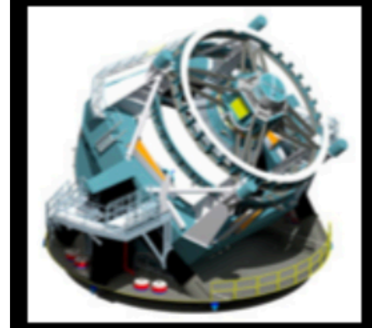
Rather robust conclusion: Cosmology 'does not like' these states

If confirmed in the Lab, *radical* changes needed in both cosmology *and* particle physics

Perspectives & room for surprises?

In the coming decade, expected to reach sensitivity to measure the minimum NH mass at 3-4 sigma
e.g. *T. Brinckmann et al. arXiv:1808.05955*

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to N_{eff}
	DESI	2023	0.02-0.03 eV	0.08-0.13
	**ESA Euclid**	2024 ?	0.011 – 0.02 eV	0.05
	**LSST**	2024	0.015 eV	0.05
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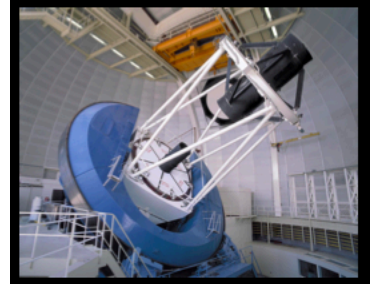
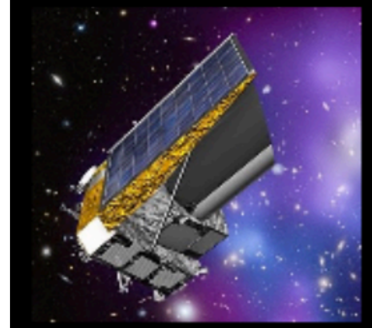
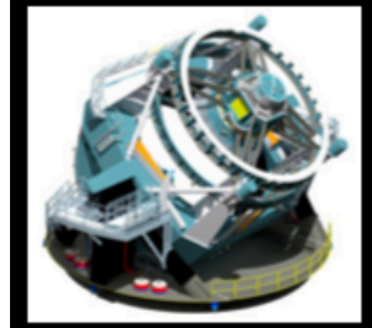
	DESI	2023	0.02-0.03 eV	0.08-0.13
	**ESA Euclid**	2024 ?	$0.011 - 0.02$ eV	0.05
	**LSST**	2024	0.015 eV	0.05
	**CMB-S4**	2027	0.015 eV	$0.02 - 0.04$

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What if null detection? The cosmological model must be modified, likely new physics!

E.g. ν decay into massless dark radiation.

Could reconcile a positive detection e.g. at KATRIN or conversely, bound ~10^{17} s level if detecting mass

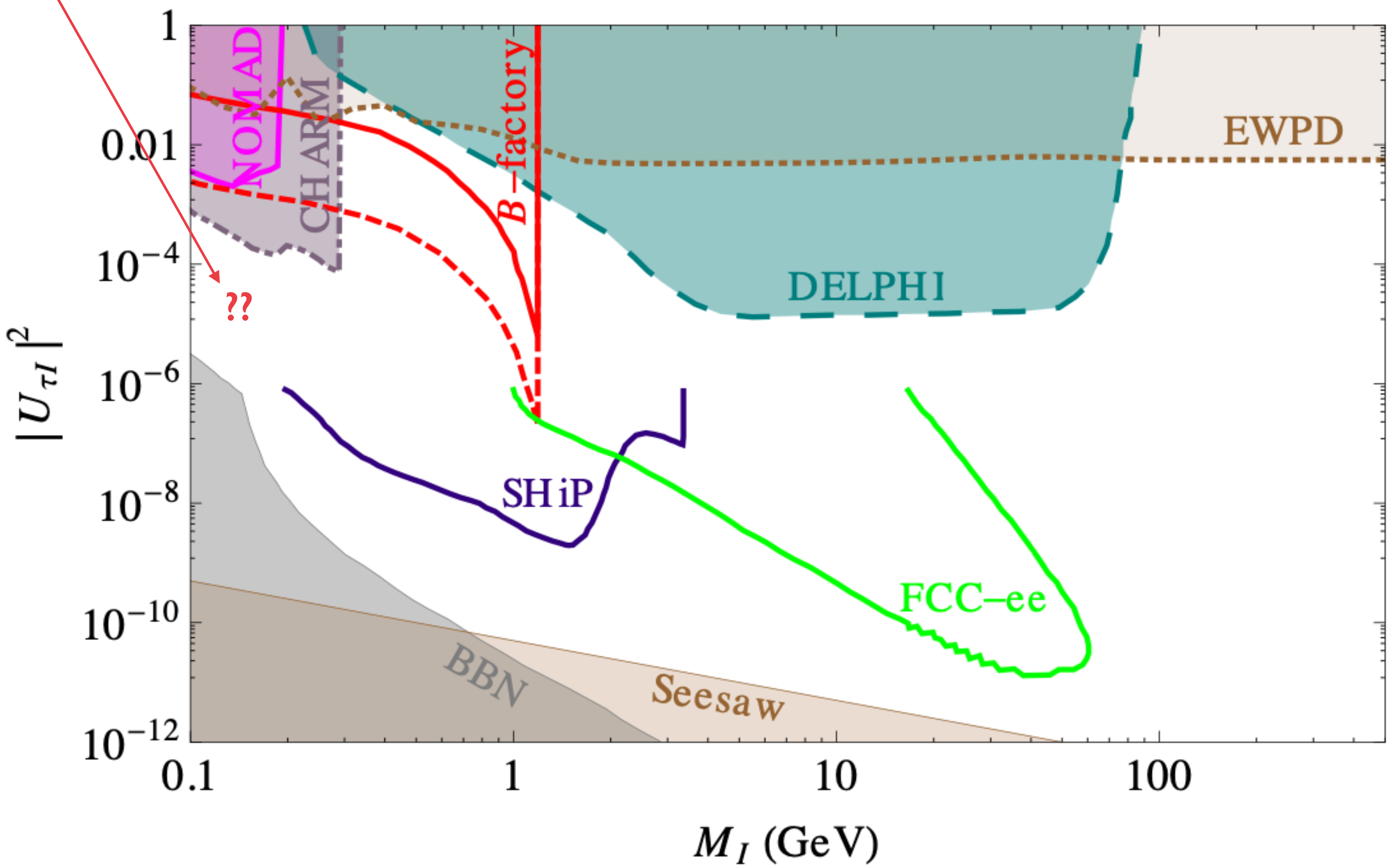
PDS astro-ph/0701699…Funcke et al. 1905.01264, Aalberts et al. 1803.00588, Chacko et al. 1909.05275, Escudero et al. 2007.04994, Chen et al. 2203.09075, Abellán et al. 2112.13862…

An example of the cosmological constraining power, in detail

Massive sterile states in the Early universe

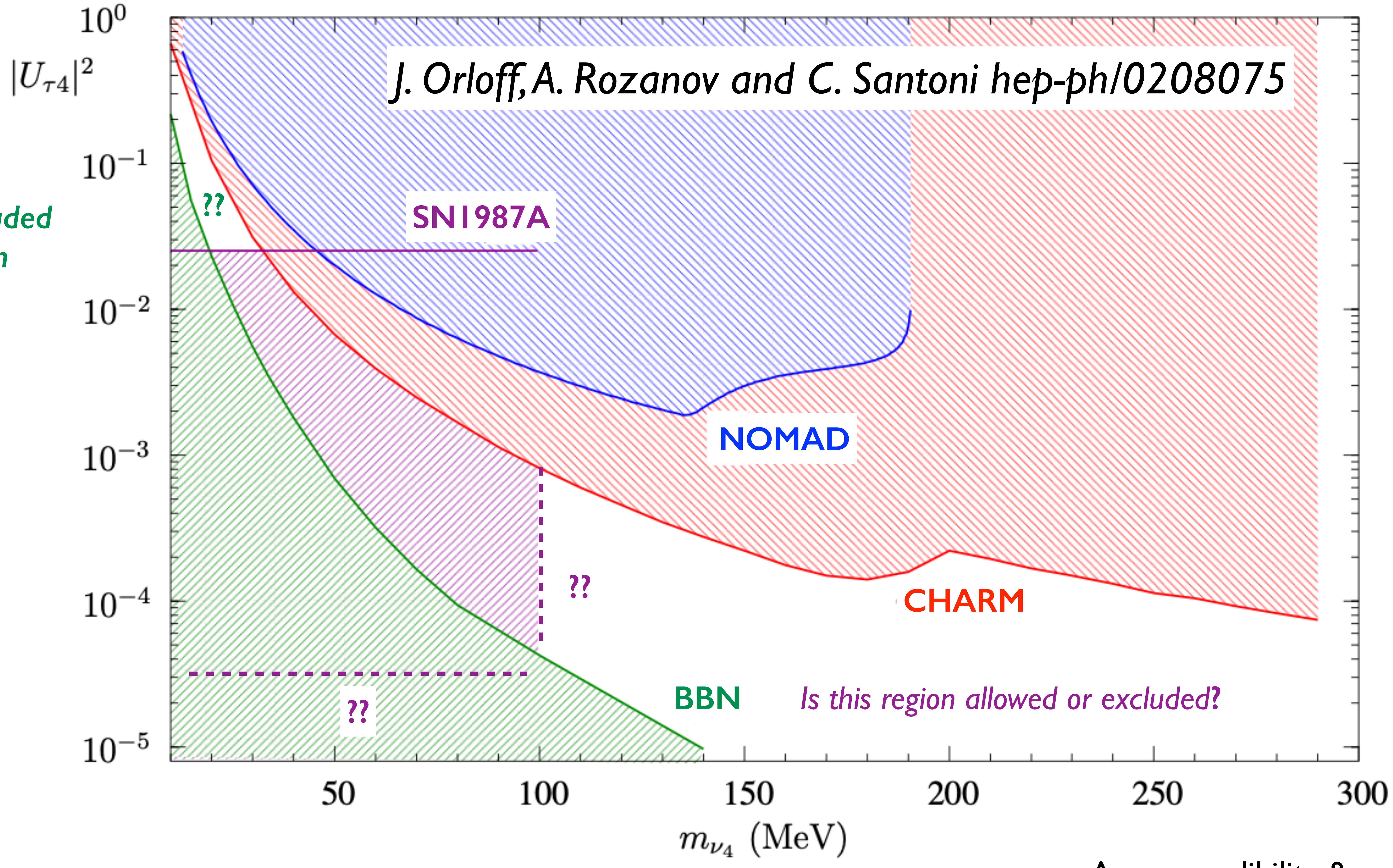
- Sterile state in the O(10-100) MeV mass range (mostly) mixing with ν_τ hard to probe in the lab
- Range kinematically accessible ***(collisional, not oscillation production!)*** in supernova cores and in the early universe, which are ~ "flavour-universal" environments
- Some peculiar phenomenology to be studied, chances for serendipitous discoveries

??



Zooming in - Region of interest

Is this region excluded or testable with cosmology?



Astroparticle bounds from A.D. Dolgov et al., Nucl. Phys. B 590 (2000) 562

Assess credibility & update ~20 yr later

Evolution equations in terms of dimensionless parameters

$$t \to x = m\,a \qquad p \to y = p\,a \qquad T_{\mathrm{e.m.}} \to z = T\,a$$

Here [a]=[L]=[m]$^{-1}$, measured in MeV^{-1}, proxy for neutrino 'temperature' when that notion makes sense; henceforth, m=1 MeV

Boltzmann equation for active and sterile neutrinos writes

(Initial condition: thermal FD, x=z)

$$\boxed{\frac{\mathrm{d}f(x,y)}{\mathrm{d}x} = \frac{I[f]}{x\,H}}$$

where the ***Hubble expansion rate*** is

includes γ,e, μ,π, ν (including sterile ones) & antiparticles.

Baryons negligible…

$$\boxed{H = \sqrt{\frac{8\pi\rho(x,z)}{3m_{\mathrm{Pl}}^2}}}$$

Bianchi identity ("energy conservation") is

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}x}\bar{\rho}(x) = \frac{1}{x}(\bar{\rho} - 3\bar{P})}$$

where $\quad \bar{\rho} = \rho\left(\frac{x}{m}\right)^4 \qquad \bar{P} = P\left(\frac{x}{m}\right)^4$

Collisional term

$$I = I_{\rm coll} + I_{\rm dec} = \frac{1}{2E} \int \prod_i \left(\frac{d^3 p_i}{2E_i (2\pi)^3} \right) \prod_f \left(\frac{d^3 p_f}{2E_f (2\pi)^3} \right) (2\pi)^4 \delta^{(4)} \left(\sum_i p_i - \sum_f p_f \right) |M_{fi}|^2 F(f_i, f_f)$$

$$F(f_i, f_f) = -\prod_i f_i \prod_f (1 - f_f) + \prod_i (1 - f_i) \prod_f f_f$$

Exact results can be reduced to 3-4 D integrals as shown in *Hannestad & Madsen, astro-ph/9506015*

Process		$G_F^{-2} \lvert U_{\alpha s} \rvert^{-2} \lvert M \rvert^2$	
$\nu_s \to \nu_\alpha + \bar{\nu}_\alpha + \nu_\alpha$	decay	$32 (p_1 \cdot p_4)(p_2 \cdot p_3)$	(b.r.≳1%)
$\nu_s \to \nu_\alpha + \nu_\beta + \bar{\nu}_\beta$		$16 (p_1 \cdot p_4)(p_2 \cdot p_3)$	
$\nu_s \to \nu_\alpha + e^+ + e^-$		$64 [\tilde{g}_L^2 (p_1 \cdot p_4)(p_2 \cdot p_3) + g_R^2 (p_1 \cdot p_3)(p_2 \cdot p_4) - \tilde{g}_L g_R m_e^2 (p_1 \cdot p_3)]$	

Process		$G_F^{-2} \lvert U_{\tau s} \rvert^{-2} \lvert M \rvert^2$	
$\nu_s + \bar{\nu}_\alpha \to \nu_\alpha + \bar{\nu}_\alpha$	scattering	$64 (p_1 \cdot p_4)(p_2 \cdot p_3)$	
$\nu_s + \nu_\alpha \to \nu_\alpha + \nu_\alpha$		$32 (p_1 \cdot p_2)(p_3 \cdot p_4)$	(Tree level)
$\nu_s + \bar{\nu}_\alpha \to \nu_\beta + \bar{\nu}_\beta$		$16 (p_1 \cdot p_4)(p_2 \cdot p_3)$	
$\nu_s + \bar{\nu}_\beta \to \nu_\alpha + \bar{\nu}_\beta$		$16 (p_1 \cdot p_4)(p_2 \cdot p_3)$	
$\nu_s + \bar{\nu}_\alpha \to e^+ + e^-$		$64 [\tilde{g}_L^2 (p_1 \cdot p_4)(p_2 \cdot p_3) + g_R^2 (p_1 \cdot p_3)(p_2 \cdot p_4) - \tilde{g}_L g_R m_e^2 (p_1 \cdot p_3)]$	
$\nu_s + e^- \to \nu_\alpha + e^-$		$64 [\tilde{g}_L^2 (p_1 \cdot p_2)(p_3 \cdot p_4) + g_R^2 (p_1 \cdot p_4)(p_2 \cdot p_3) - \tilde{g}_L g_R m_e^2 (p_1 \cdot p_3)]$	
$\nu_s + e^+ \to \nu_\alpha + e^+$		$64 [g_R^2 (p_1 \cdot p_2)(p_3 \cdot p_4) + \tilde{g}_L^2 (p_1 \cdot p_4)(p_2 \cdot p_3) - \tilde{g}_L g_R m_e^2 (p_1 \cdot p_3)]$	

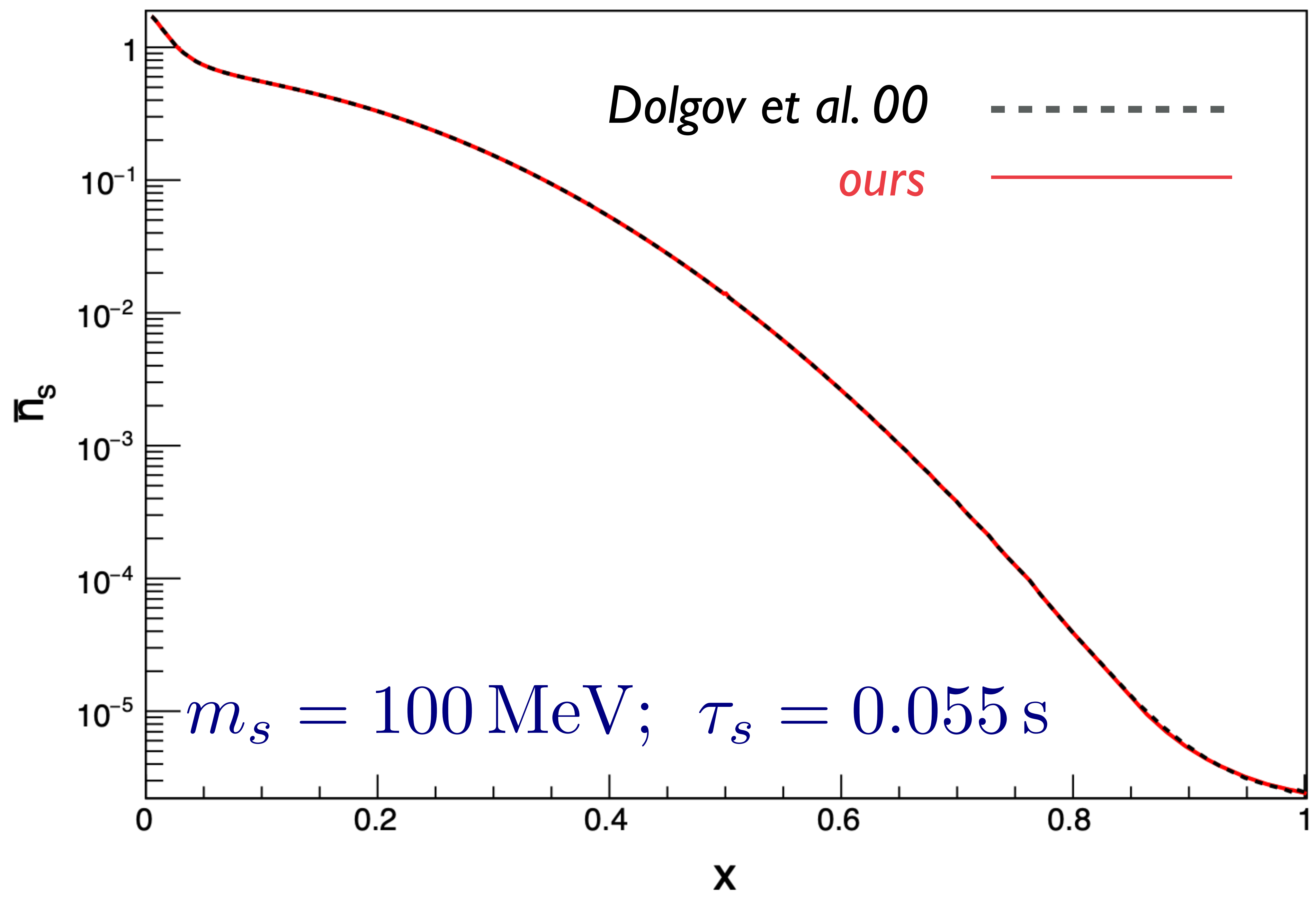
Scattering, analytical approximation

Fermi-Dirac →Maxwell-Boltzmann, neglecting Pauli blocking factors & m_e

$$I_{\rm scatt} \to 192\,\Gamma_{\nu_s}\,\left(f^{\rm eq}(E_1) - f(E_1)\right)\left[\frac{3\zeta(3)}{2}\frac{T^3}{m_s^3} + \frac{7\pi^4}{72}\frac{T^4 E_1}{m_s^5}\left(1 + \frac{p_1^2}{3E_1^2}\right)\right]$$

Under the same approximation, we agree with the final results of the seminal paper

A. D. Dolgov, S. H. Hansen, G. Raffelt and D.V. Semikoz, hep-ph/0008138



Decoupling of thermal sterile states

Numerical vs. analytical results of freeze-out condition *I=H*

Sterile ν distribution evolved from

min(150MeV, 2m_s)

m_s [MeV]	$\sin^2\theta_{\tau 4}$	τ [s]	T_D^n [MeV]	T_D^a [MeV]
20.0	2.6×10^{-2}	3.0×10^{-1}	4.35	4.26
40.0	2.8×10^{-3}	8.8×10^{-2}	9.24	10.00
60.0	5.5×10^{-4}	6.0×10^{-2}	16.83	16.20
80.0	1.5×10^{-4}	5.0×10^{-2}	26.53	25.22
100.0	5.8×10^{-5}	4.4×10^{-2}	37.10	37.65
130.0	1.6×10^{-5}	4.2×10^{-2}	59.13	59.00

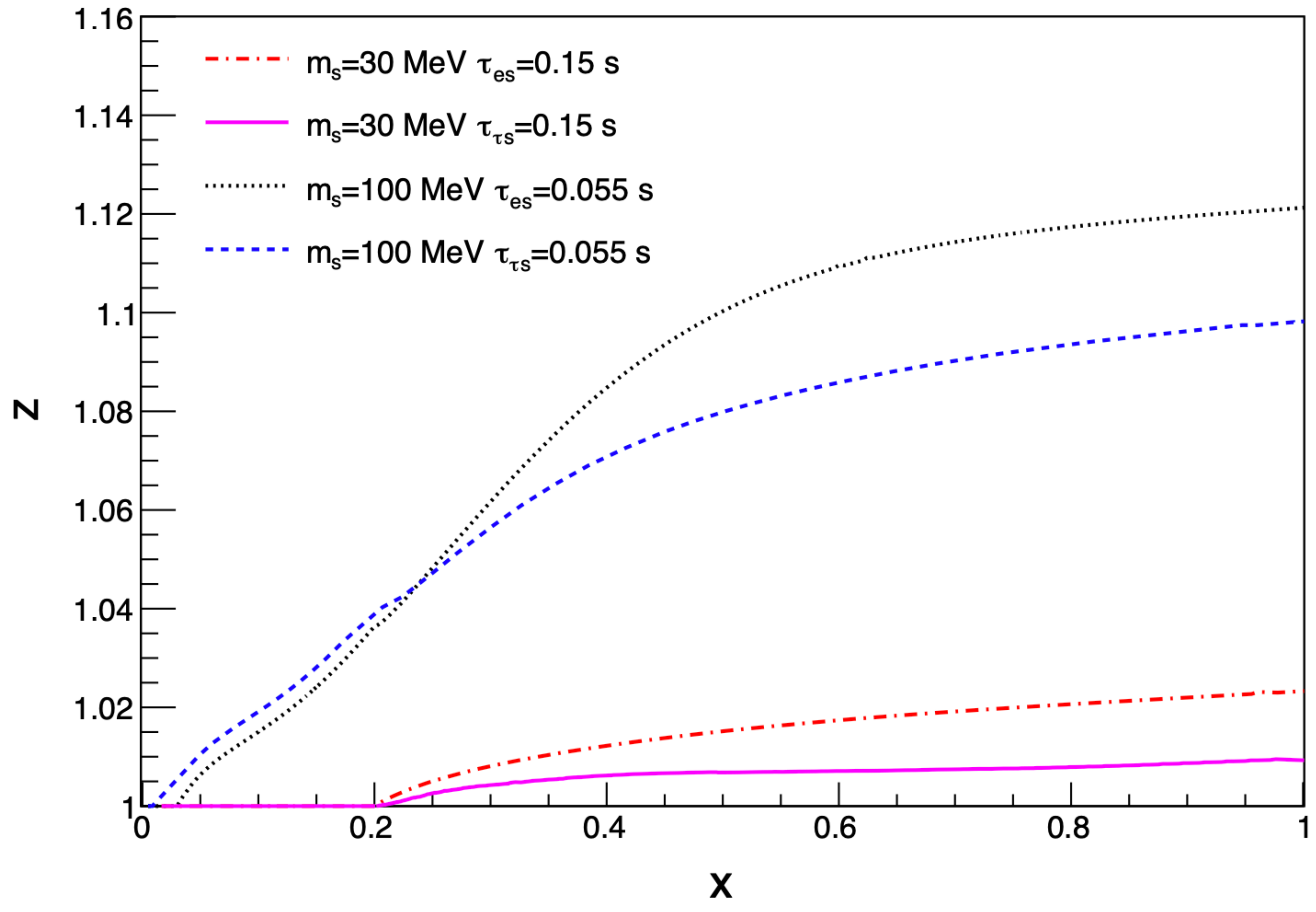
Like photons warm up compared to active ν's,

Active ν's warm up (a little) compared to sterile ν's

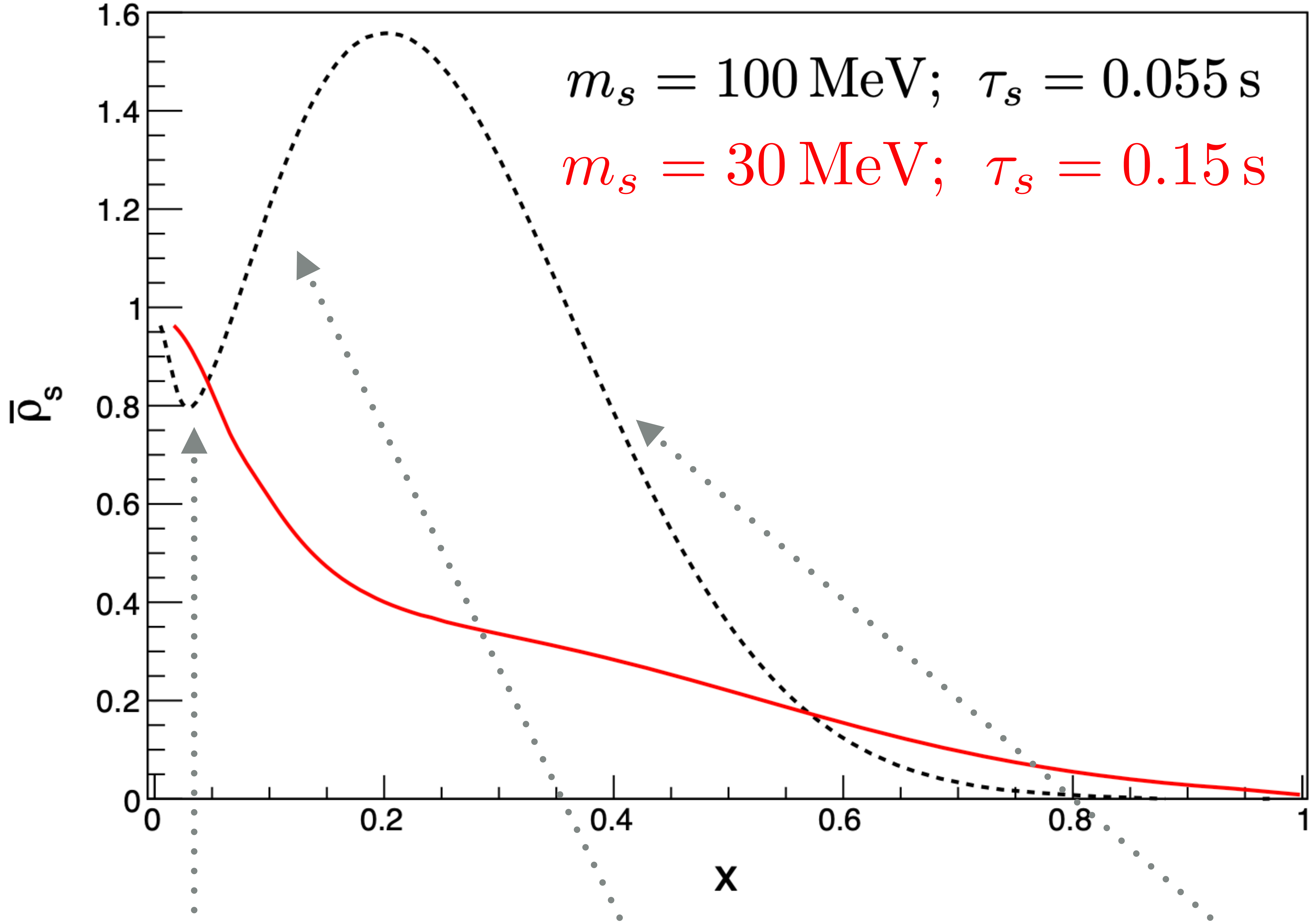
z starts evolving from ν decoupling

(0.02≲*x*≲ 0.2 for range of interest)

(Effect of e^+e^- annihilation happens later, not visible on this plot)



Energy density evolution (sterile species)



Thermal decoupling

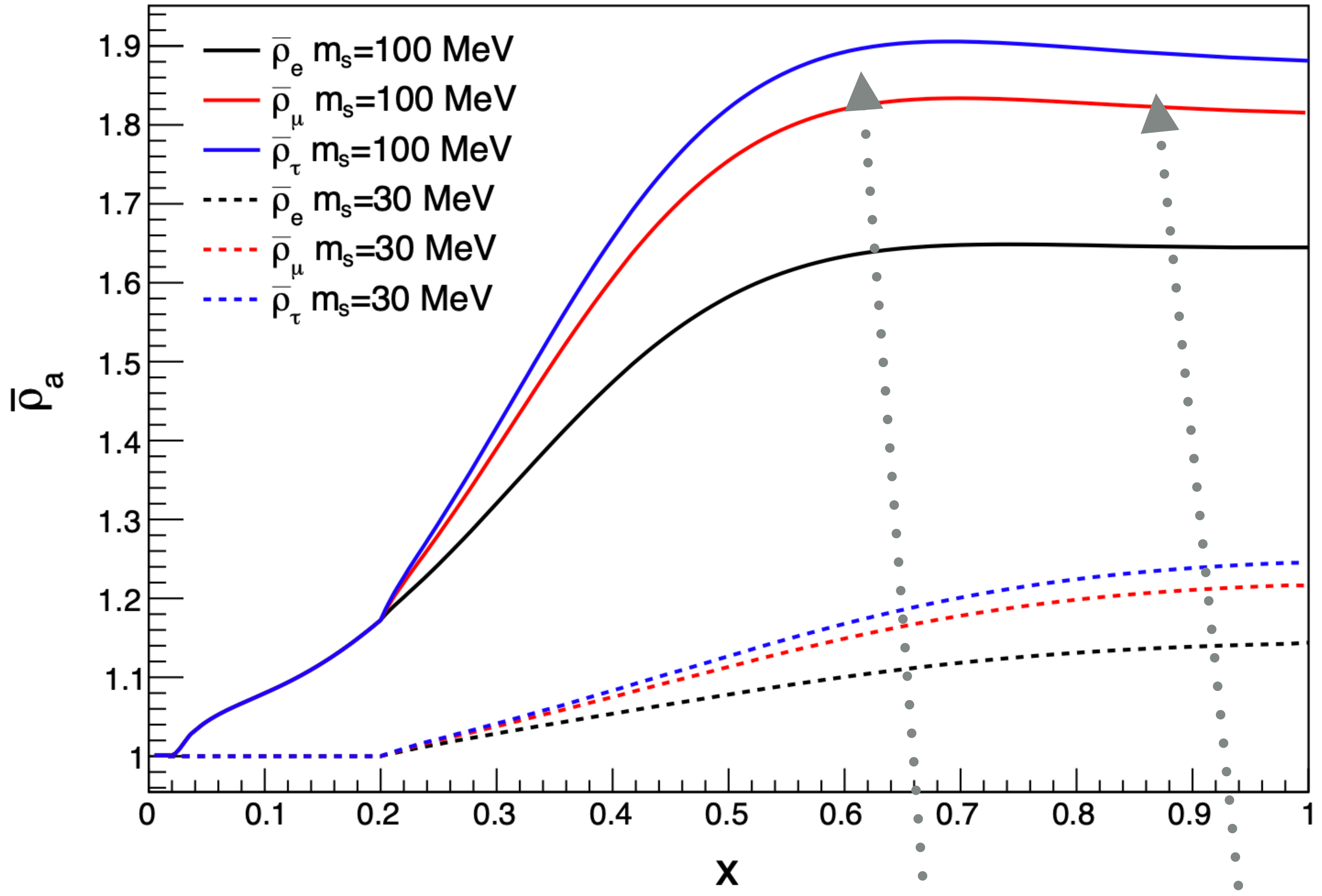
(Boltzmann suppression responsible for declining tail)

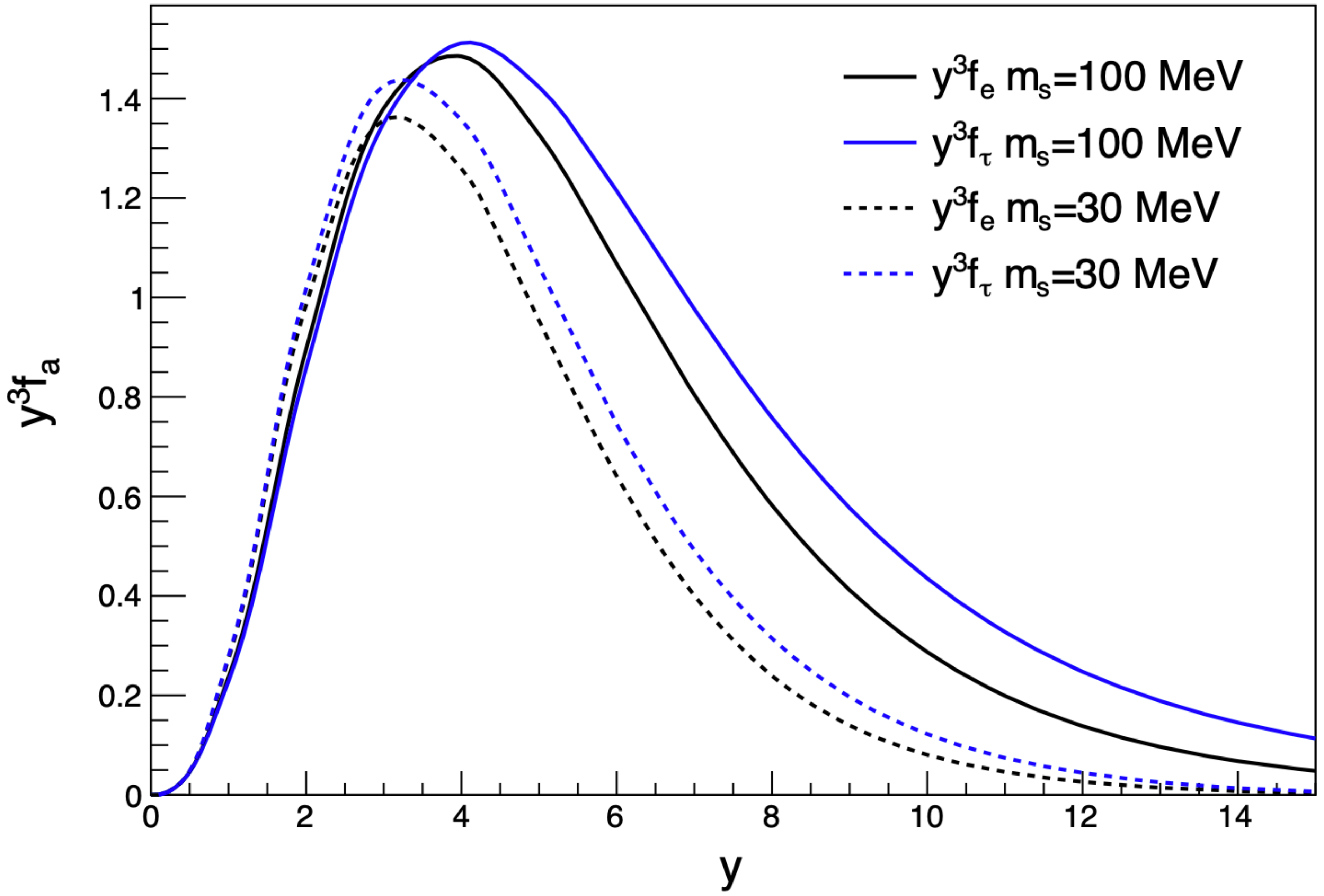
Comoving energy density growth

(as matter vs. radiation)

Decay takes over

Energy evolution and spectral distortion (active species)





Impact on energy density in active species

Spectral distortions in active species at x=1

Bulk of contribution from sterile decays

Partial transfer to e.m. sector

Impact on observables - $N_{\rm eff}$

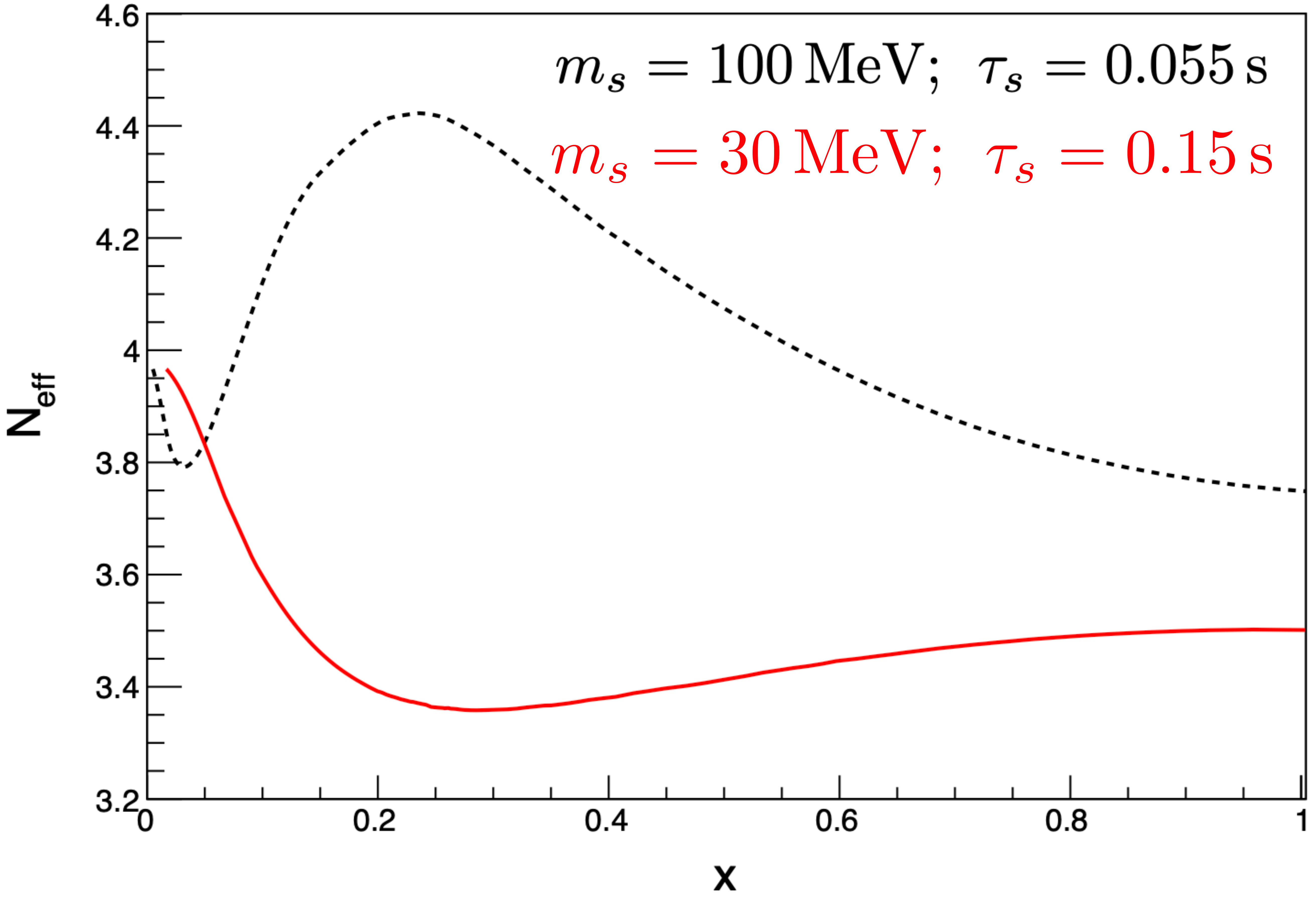
$$N_{\rm eff}(x) = \frac{\rho_\gamma^{\rm inst}}{\rho_\gamma} \sum_{i \neq {\rm e.m.}} \frac{\rho_i}{\rho_{\nu_0}} = \left(\frac{z_0(x)}{z(x)}\right)^4 \left(3 + \frac{\Delta\rho_{\nu_e}}{\rho_{\nu_0}} + \frac{\Delta\rho_{\nu_\mu}}{\rho_{\nu_0}} + \frac{\Delta\rho_{\nu_\tau}}{\rho_{\nu_0}} + \frac{\rho_{\nu_s}}{\rho_{\nu_0}}\right)$$

$z_0 \to (11/4)^{1/3} \simeq 1.4$ $\qquad$ $\rho_{\nu_s} \to 0$

N_{eff}=4 at the beginning.

Evolution phases match the phases of sterile decay.

Entropy transfer to e.m. sector non-negligible, but sub-leading



Impact on observables - Helium-4 mass fraction Y_p

$$Y_p = 2X_n(t_{\rm on})e^{-t_{\rm on}/\tau_n} \qquad X_n = \frac{n_n}{n_p + n_n} \;,$$

$$\frac{dX_n}{dx} = \frac{\left[\omega_B(p \to n)\,(1 - X_n) - \omega_B\,(n \to p)\,X_n\right]}{xH} \;,$$

We estimate the effect perturbatively, rescaling the precise numerical results obtained via $\mathtt{Parthenope}$ with the ratio of the results obtained with Born approximations (which depend on ν_e distributions)

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We compare BBN results with the range

$$Y_p = 0.245 \pm 0.006 \ (2\sigma)$$

M. Tanabashi et al. [Particle Data Group] Phys. Rev. D 98 (2018) no.3, 030001

Effects on other nuclei much more modest, can be neglected

N. Sabti, A. Magalich and A. Filimonova, arXiv:2006.07387

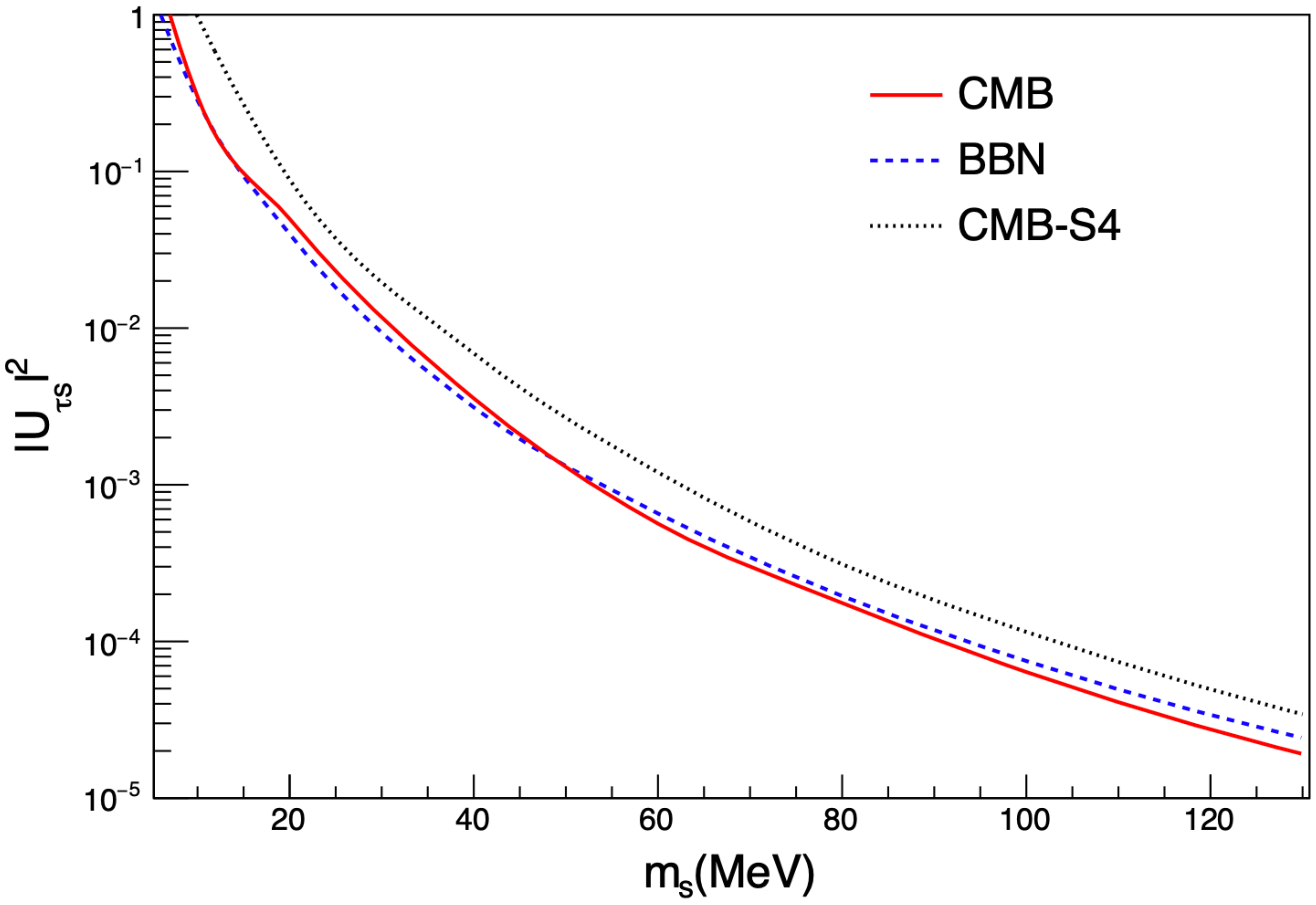
CMB [Planck] sensitive mostly to N_{eff} but also Y_p (correlations taken into account)

$$\chi^2_{\rm CMB} = (\Theta - \Theta_{\rm obs})\,\Sigma^{-1}_{\rm CMB}\,(\Theta - \Theta_{\rm obs})^T \ ,$$

$$\Theta = (N_{\rm eff}, Y_p)$$

95% CL bounds/forecasts for mixing with ν_τ

(excluded region below the curves)



↓ Eventually, pre-QCD freeze-out and/or non-thermal relic…

CMB already comparable to BBN bounds, will definitely surpass them with S-4 observatories

(CMB-S4 expected sensitivity from Baumann et al, 1508.06342)

Closing most of the allowed edge in parameter space at small *m* within reach!

Conclusions

- Reviewed the role of ν's in cosmology, notably the origin of the effects constraining their number density and their mass, discussing the current bounds, the forecasted sensitivity, and some effects of (constraint on) new physics

- Numerical calculation of the decoupling and decay of a massive sterile ν thermal relic (in the particularly interesting mass range $m < m_\pi$) also checking the analytical approximations available in the literature.

- We re-evaluated the impact on N_{eff} and Y_p . Contrarily to 'historical' results, dominated by BBN, CMB has now comparable constraining power

- Future CMB-S4 should surpass BBN constraints (barring systematic reductions in Y_p!) and probe the residual parameter space open at low-m for mixing with ν_τ