Properties of light relics from cosmological observations

Cosmology in Miramare 2023 - 29 Aug 2023

Martina Gerbino - INFN Ferrara

Image credit: Sara Zollo

Neutrinos and Cosmology

Pioneering and stringent bounds on neutrino properties from Cosmology already competitive with lab

$$m_\nu < 400\,\mathrm{eV} \qquad (\rho_\nu < \rho_{\mathrm{tot}})$$

$$m_\nu < 8\,\mathrm{eV} \qquad (\rho_\nu < \rho_{\mathrm{DM}})$$

Gershtein-Zeldovich (1966)
Cowsik-McClelland (1972)

+ lower bounds for very heavy neutrinos
Szalay&Marx(1976)
Hut; Lee&Weinberg; Sato&Kobayashi(1977)

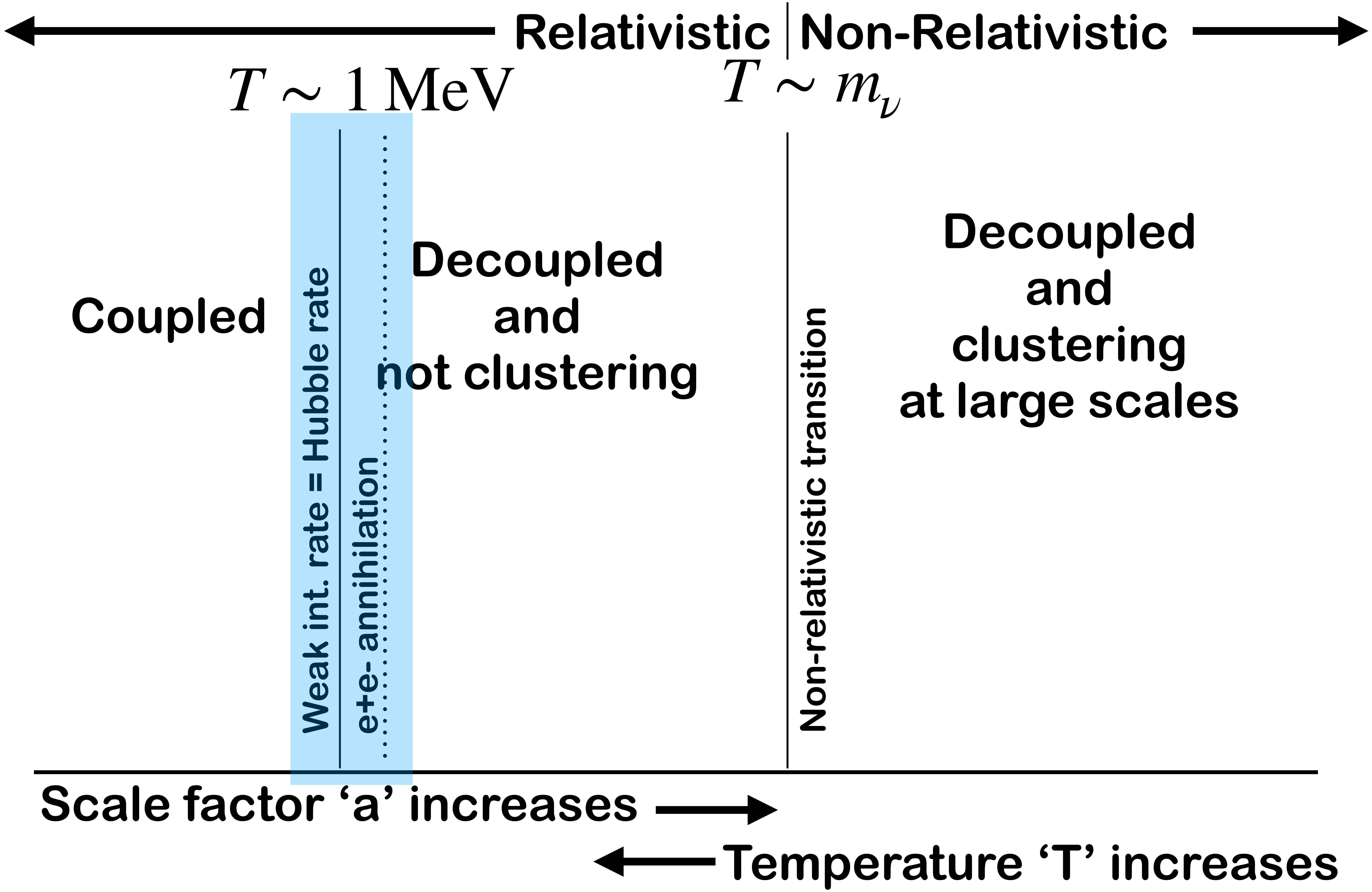
+ from numerical sims
structure formation with hot DM is top-down, incompatible with observations (1980s)

$$N_\nu < 4$$

Schramm&Kawano (1989)
Olive+ (1990)

(Stringent) bound on the family number required not to spoil BBN

Neutrino cosmology



← Relativistic | Non-Relativistic →

$T \sim 1\,\mathrm{MeV}$

$T \sim m_\nu$

Coupled

Weak int. rate = Hubble rate

e+e- annihilation

Decoupled
and
not clustering

Non-relativistic transition

Decoupled
and
clustering
at large scales

Scale factor ‘a’ increases →

← Temperature ‘T’ increases

Neutrino cosmology

← Relativistic Non-Relativistic →

T~m_nu

$$\rho_\nu \propto (T_\nu/T_\gamma)^4\, N_{\rm eff}$$

$$\rho_\nu \propto \Sigma m_\nu (T_\nu/T_\gamma)^3$$

$$N_{\rm eff} \equiv \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm st}} = 3.044$$

$$\Sigma m_\nu = \Sigma_{i=1,2,3} m_{\nu,i}$$

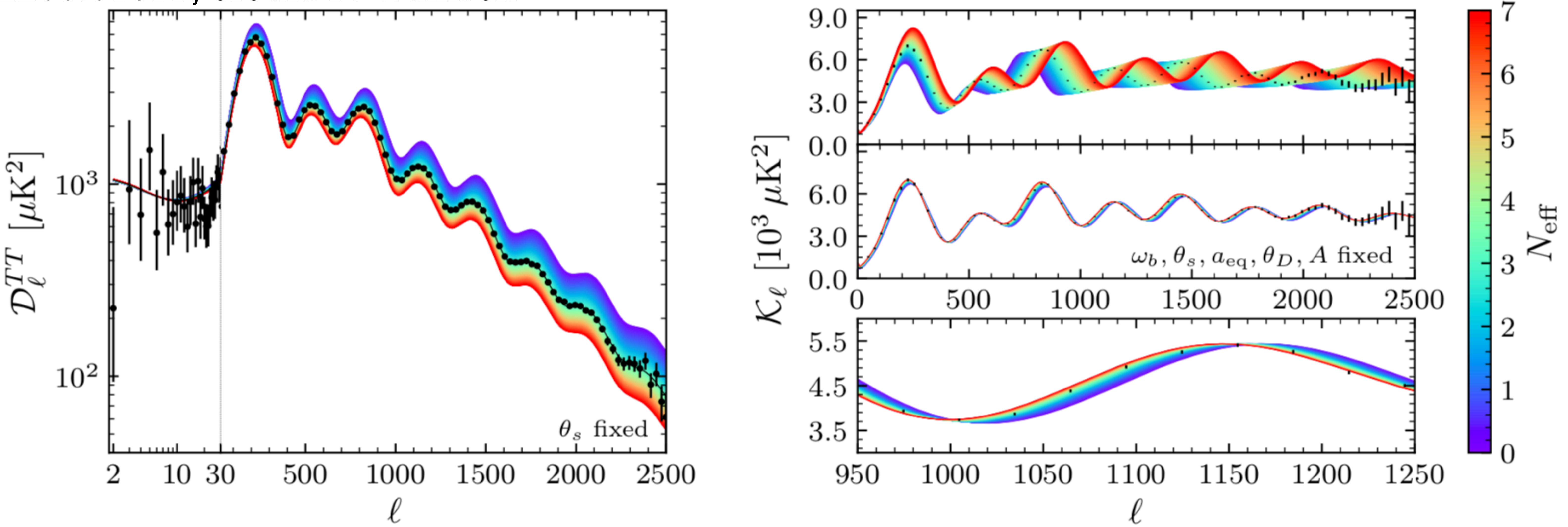
Distorsions due to non-inst decoupling
radiative corrections,
flavour oscillations
Dolgov, 1997, Mangano+,2005
Bennett+2020,Froustey+2020,Akita+2020

Scale factor ‘a’ increases →

← Temperature ‘T’ increases

Neutrino cosmology

2203.07377, credit: B. Wallisch



Damping tail suppression:

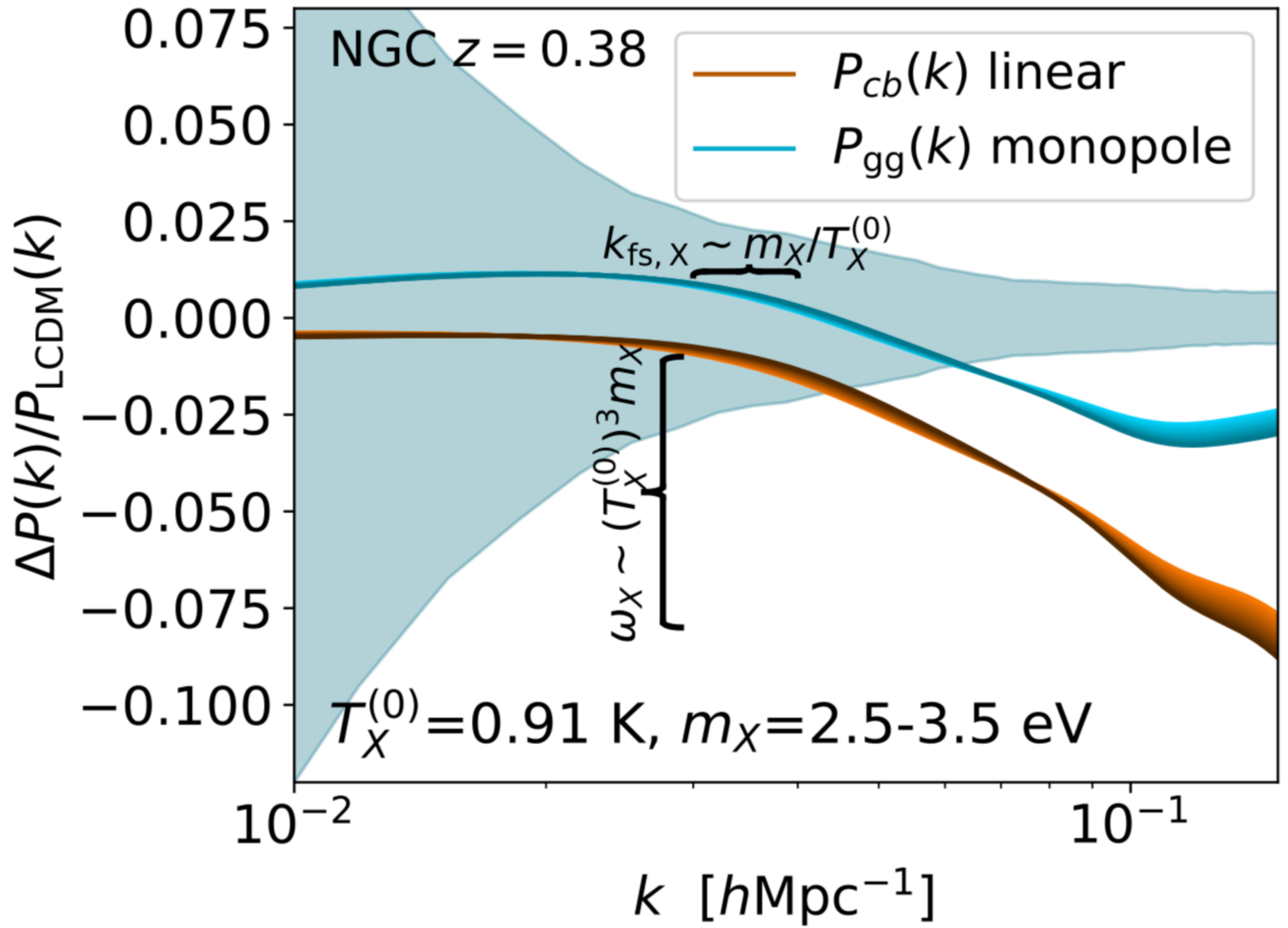
$$\theta_d \sim \sqrt{H(N_{\rm eff})}$$

Shift of acoustic peak position:

$$\phi \sim N_{\rm eff}$$

Amplitude from abundance: $\omega_\nu \propto T_\nu^3 m_\nu$

Suppression from free-streaming scale: $k_{fs} \sim m_\nu / T_\nu$



Xu,Munoz,Dvorkin,2022

What next in neutrino cosmology

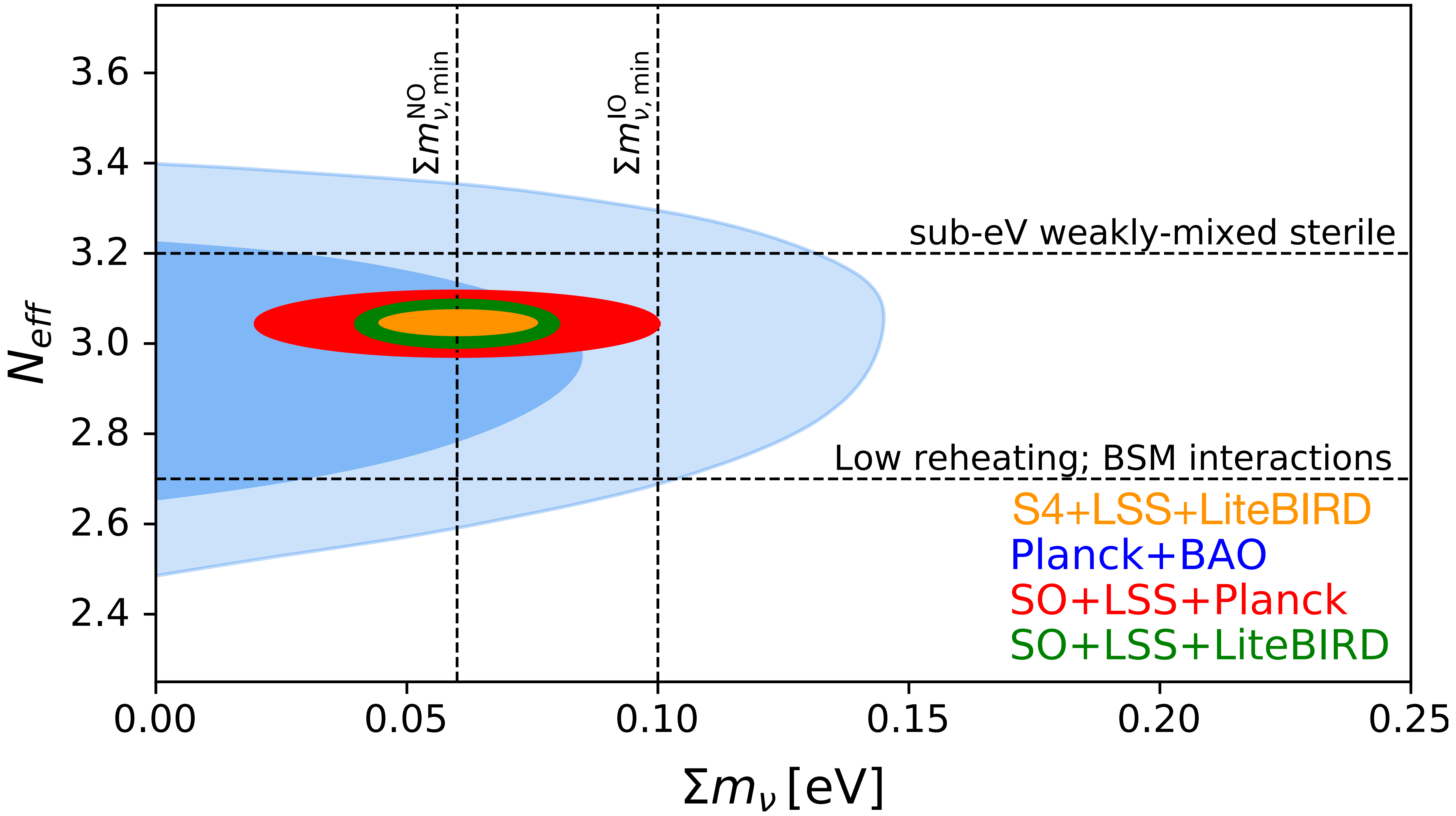
**The new generation of cosmological surveys is approaching: Simons Observatory, Euclid, LiteBIRD, CMB-S4, DESI, Rubin, SPHEREx, SKA …
Does it mean that we are moving:**

1) **Towards the first detection of the neutrino mass scale?**

$$\sigma(\Sigma m_\nu) = 0.02\,\mathrm{eV}$$

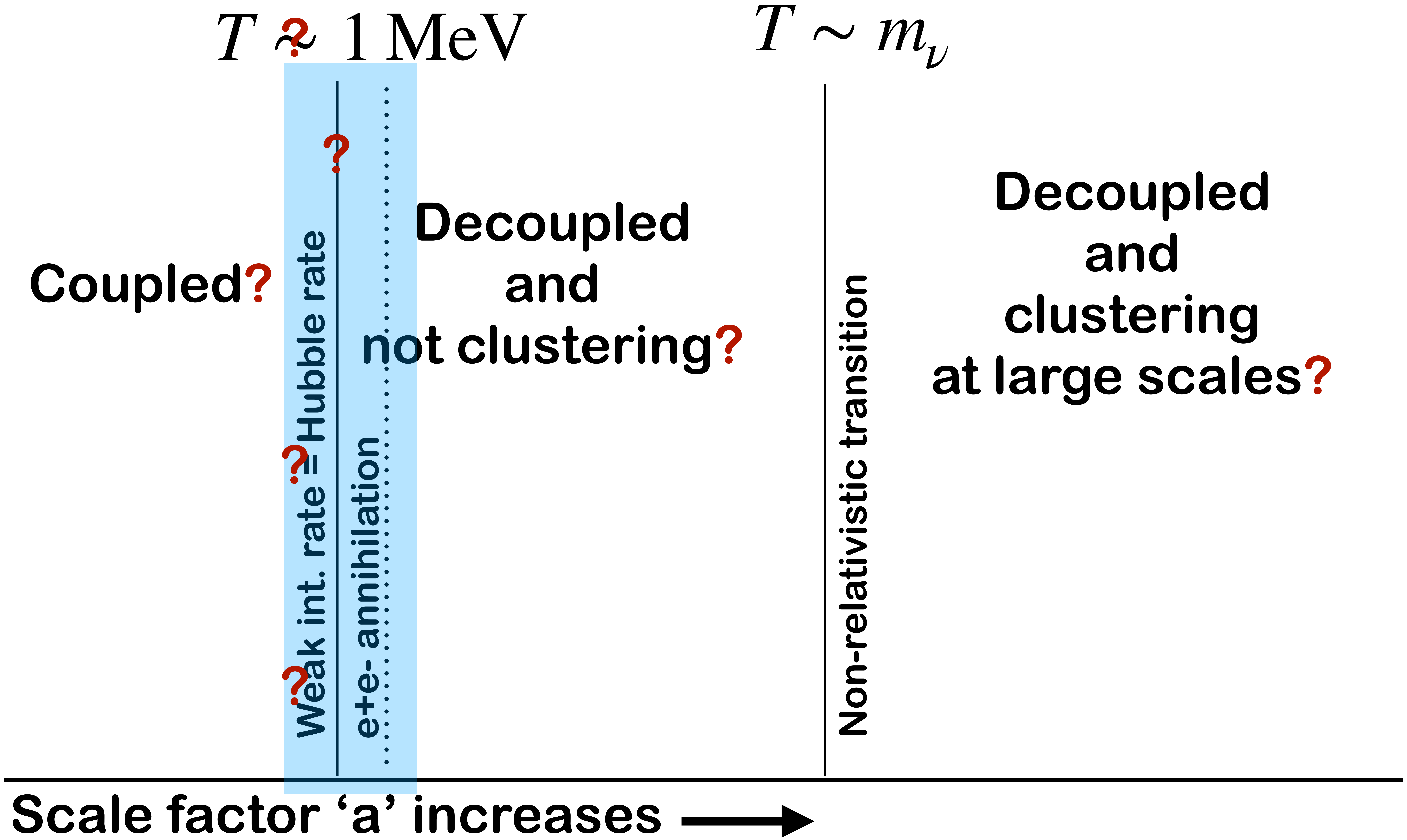
2) **Towards the first probe of the physics of neutrino decoupling, and of BSM content at very early times?**

$$\sigma(N_{\rm eff}) = 0.03$$



BSM neutrinos?

What if they are not what we think?
(or: how sensitive are we to standard assumptions?)



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Coupled?

?Weak int. rate ?= Hubble rate ?

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Non-relativistic transition

Decoupled
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at large scales?

Scale factor ‘a’ increases ⟶

Thanks to many collaborators!

Results shown in the next slides are in collaboration with several amazing people:

Junior: L. Caloni (UniFE), P. Carenza (Stockholm),
F. Forastieri (UniFE), G. Lucente (UniBA -> SLAC)

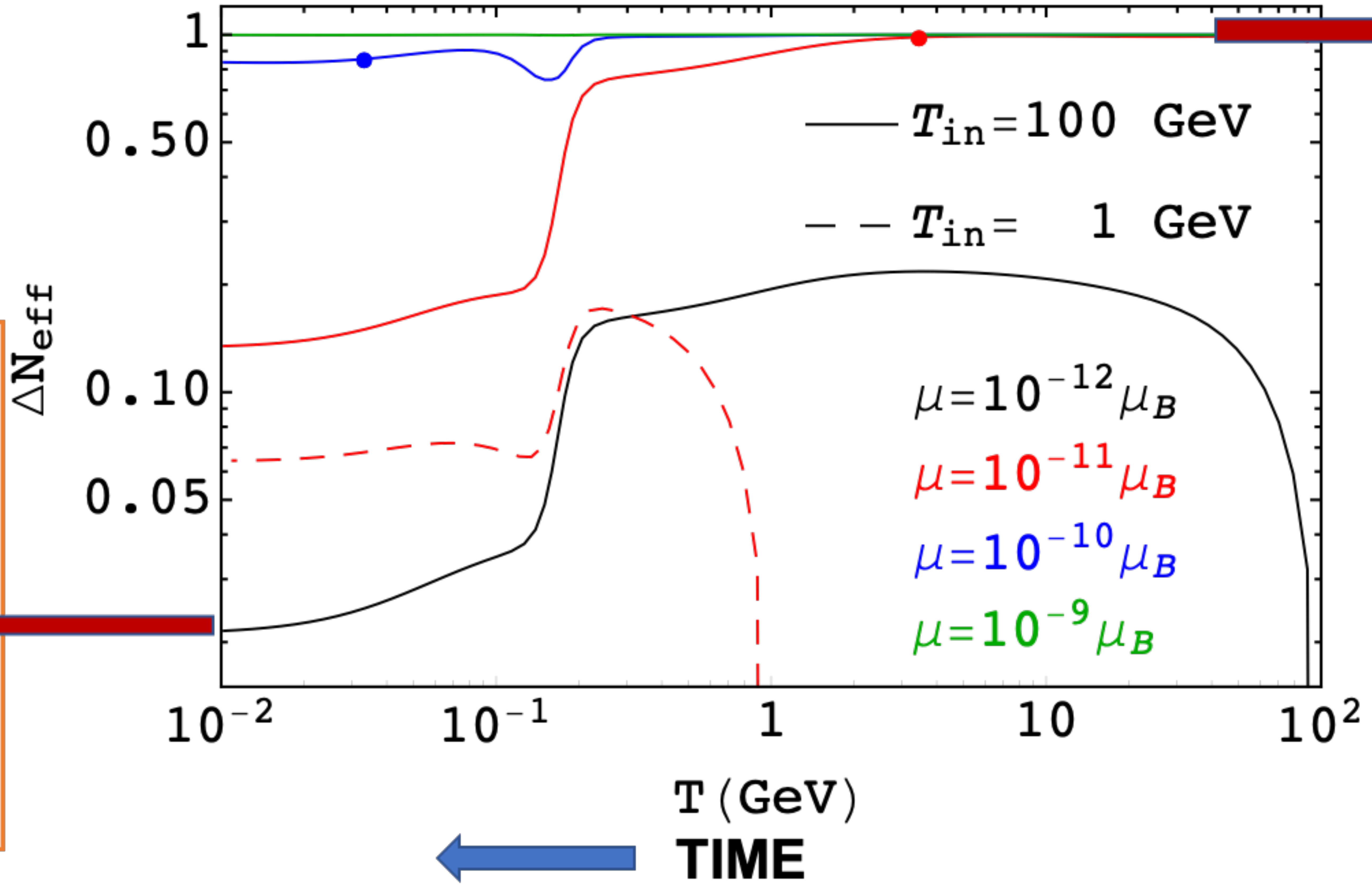
Staff: T. Brinckmann (UniFE), M. Lattanzi (INFN FE),
M. Giannotti (Miami), L. Visinelli (Shanghai)

Neutrino magnetic moment

If neutrinos have a magnetic moment, e.m. interactions in the plasma can flip the ν helicity

A population of right-handed neutrinos is created from a purely left-handed initial ensemble

“Large” magnetic moment: thermal equilibrium is established at early times.



“Small” magnetic moment: thermal equilibrium never established. Freeze-in production. Abundance depends on initial temperature.

In both cases, abundance is diluted by entropy production after decoupling

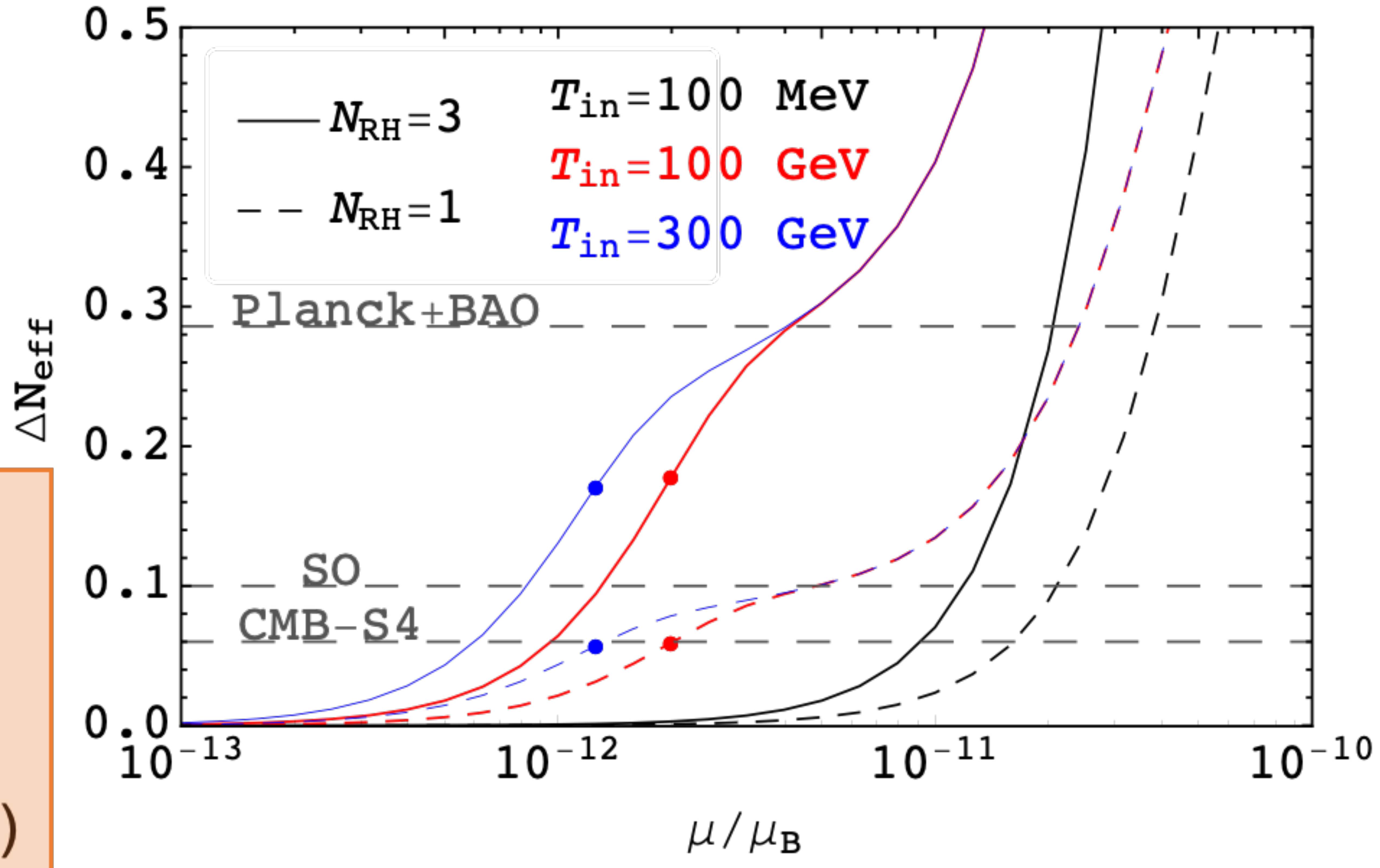
Carenza+(incl. MG), 2022; Slide: courtesy of M. Lattanzi

Neutrino magnetic moment

CMB experiments can provide competitive constraints on the neutrino magnetic moment

$\mu < 4.6 \times 10^{-12}\ \mu_b$ (Planck+BAO)
$\mu < 1.7 \times 10^{-12}\ \mu_b$ (Planck+BBN)
($T_{max} \geq 100$ GeV)
Carenza+ (incl ML, arXiv:2211.0432)

Compare with
$\mu < 6 \times 10^{-11}\ \mu_b$ (cosmo, EERS87, assumes th. eq)
$\mu < 2.7 \times 10^{-12}\ \mu_b$ (cosmo, Li&Xu arXiv:2211.04669) (assumes th. eq)
$\mu < 6.4 \times 10^{-11}\ \mu_b$ (lab, XENONnT arXiv:2207:11330)
$\mu < 1.2 \times 10^{-12}\ \mu_b$ (astro, Capozzi&Raffelt PRD2020)



(95% CL bounds)

Carenza+(incl. MG), 2022; Slide: courtesy of M. Lattanzi

Axion-like Particles (ALPs)

QCD axions introduced to solve the strong CP problem

(Peccei&Queen,77; Weinberg,78; Wilczek,78; Georgi+,76)

Axions are light and weakly coupled **->** $g_a \propto m_a \propto 1/f_a$

Generic axion-like particles are common in many theories (e.g., string theory)

Mass and couplings decoupled

ALPs can be produced in the early Universe. Cosmology can help constrain their properties

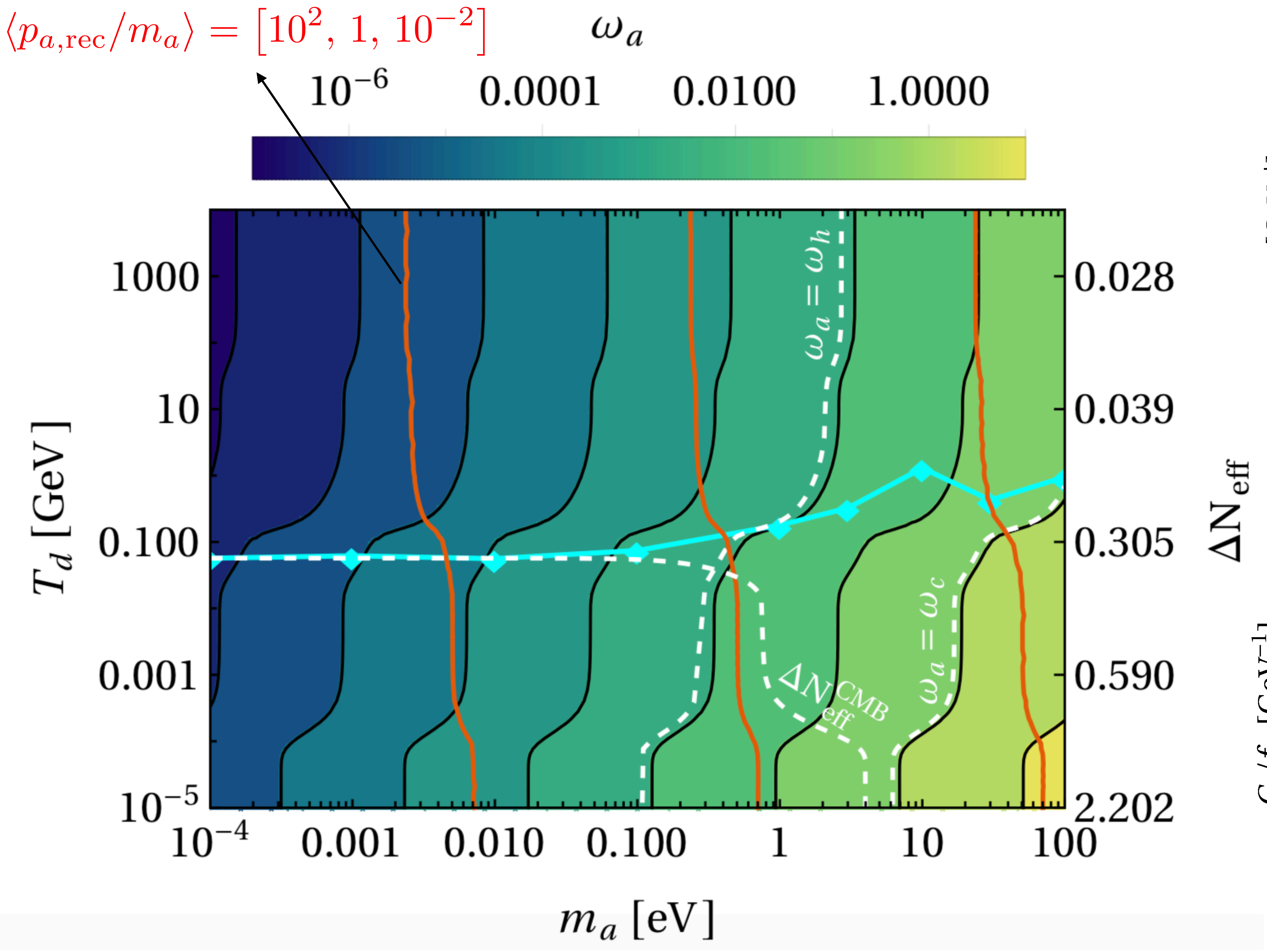
Thermally produced axions via coupling with gluons and photons in the early Universe

Freeze-out condition $H(T_d) \simeq \Gamma(T_d)$

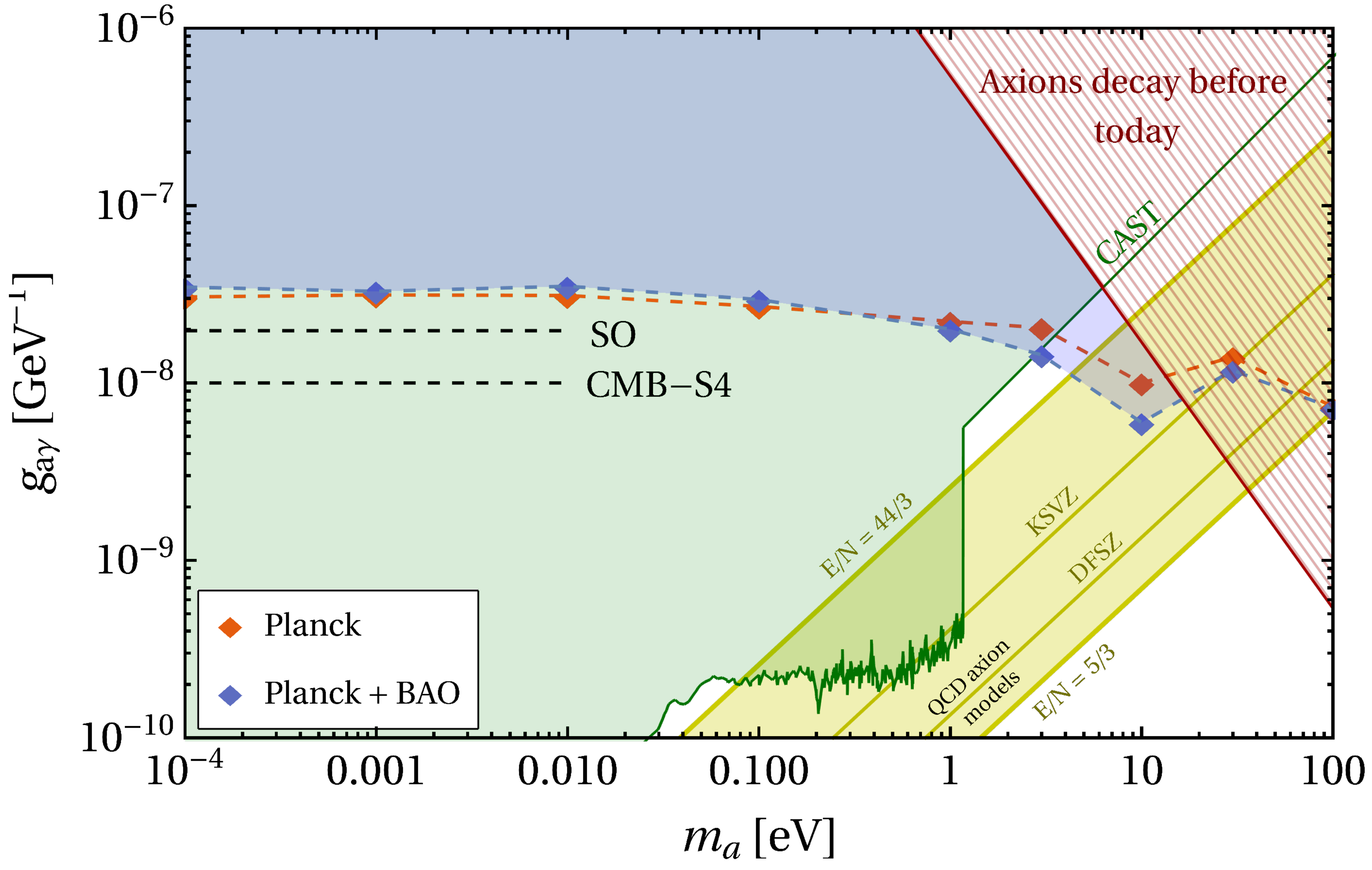
Decoupling temperature Td sets axion abundance:

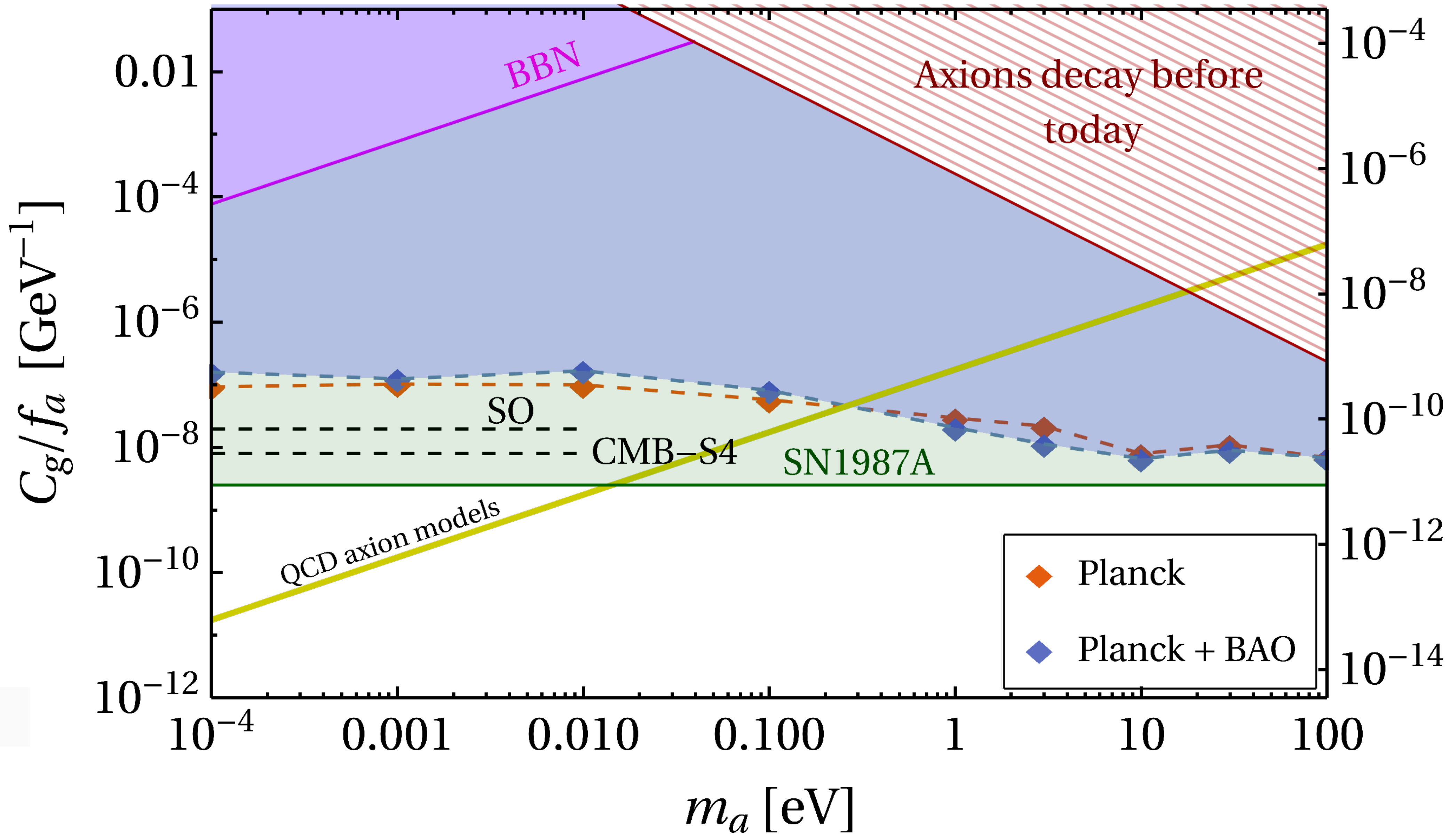
$$\Delta N_{\rm eff}^{\rm CMB} \equiv \frac{\rho_a(m_a)}{\rho^{\rm mless}} \propto m_a g_{*s}(T_d)^{1/3} \qquad \omega_a \simeq m_a n_a \simeq \left(\frac{m_a}{130\,{\rm eV}}\right)\left(\frac{g_{*,s}(T_d)}{10}\right)^{-1} = 0.011\left(\frac{m_a}{\rm eV}\right)\Delta N_{\rm eff}^{3/4}$$

Axion-like Particles (ALPs)



$\langle p_{a,\mathrm{rec}}/m_a \rangle = [10^2,\, 1,\, 10^{-2}]$





Caloni, MG,+, 2022

Conclusions?

Massive light relics: very similar phenomenology (contribution to energy density). How to disentangle?

Enhanced sensitivity of future surveys demands enhanced accuracy: is it possible and feasible to achieve?

Entering the synergy epoch: CMB alone can do a lot for BSM particle physics; can do much more when combined with LSS; can do even more when cosmology meets astro&lab searches