



Production of Thermal Axions in the Early Universe

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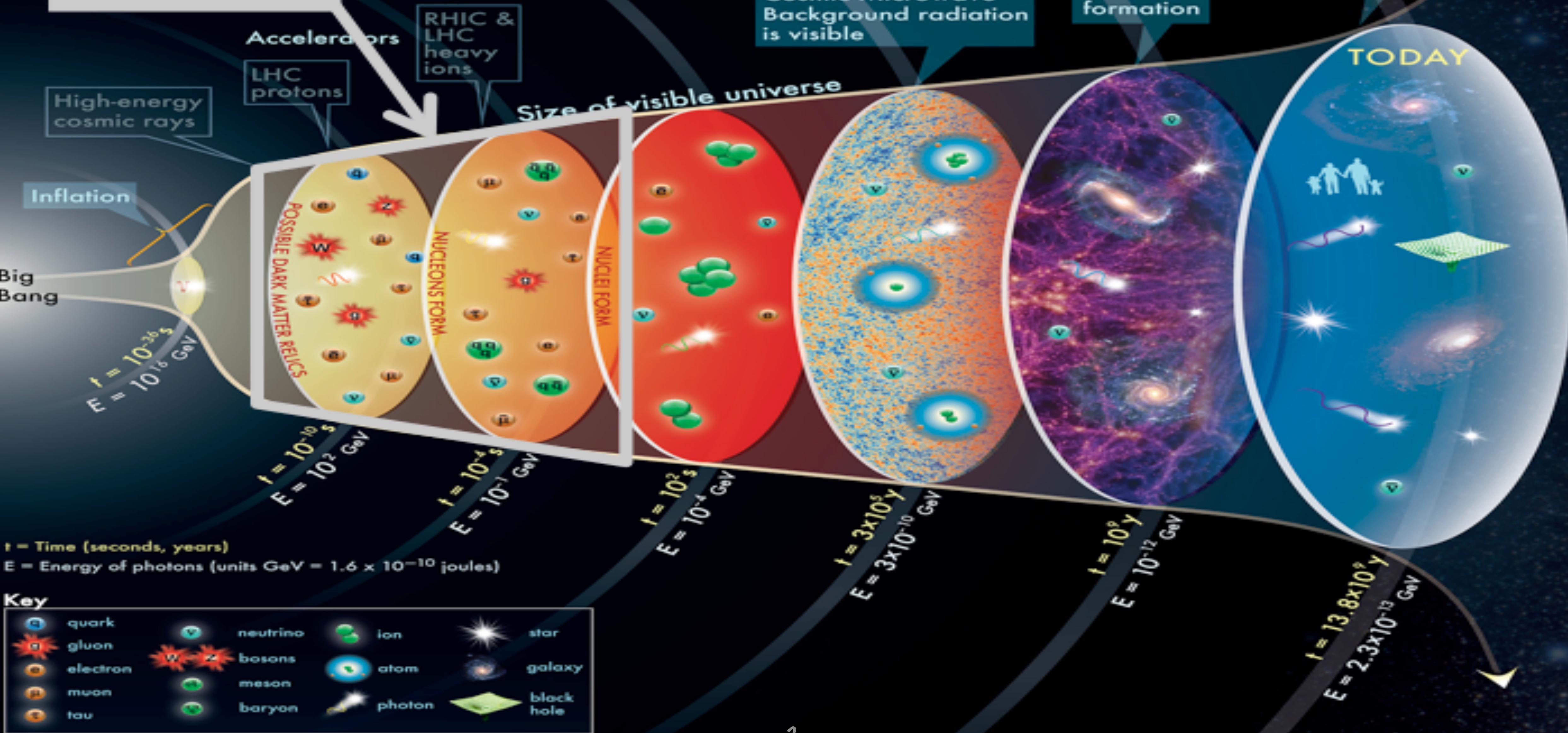
Cosmology from Home, July 2021

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HISTORY OF THE UNIVERSE

Particle era



Dark Radiation

- * There is a discrepancy ΔN_{eff} from the theoretical value number of effective neutrinos: $N_{\text{eff}} = 3.046$ and observed value from cosmic microwave background (CMB) and big bang nucleosynthesis (BBN).
- * Extra degrees of freedom from dark sector can be responsible for dark radiation (DR).
- * Beyond the standard model physics have some proposals for DR like sterile neutrinos, axion, etc. Moreover, gravitational wave background may have a contribution to ΔN_{eff} .
- * Future CMB experiments can put stronger bound on light relics and ΔN_{eff} .
- * Relativistic degrees of freedom depending on their nature can decouple at different temperatures. They may be connected to the new physics!

QCD Axion and Strong CP problem

- * QCD axion is a solution for the strong CP problem
- * Connection to the UV completion physics through Pecci-Quinn symmetry restoration/breaking at high scales \rightarrow giving mass to axions as pseudo Nambu-Goldstone bosons
- * Possible contribution to the dark matter or dark radiation ($m_a \ll 1 \text{ eV}$)
- * There are some constraints from laboratory, astrophysical and cosmological experiments. The supernova constraint put a lower bound on axion decay constant f_a . The upper bound on that comes from the condition on the overclosure of the universe. Axion constraints can be model dependent ...

Axion Production

- * Axion production from scatterings with hadrons using chiral perturbation theory
- * Quarks and gluons scatterings with axions including QCD interactions
- * Interactions from electroweak sector above and below the electroweak transition
- * Possible interaction with leptons for leptophilic models

[arXiv:2003.01100](#)

[arXiv:1303.5379](#)

[arXiv:1008.4528](#)

[arxiv:2012.04736](#)

[arXiv:1604.08614](#)

Axion Interactions with the SM Particles

A general Lagrangian for effective axion models:

$$\mathcal{L}^{(a)} = \mathcal{L}_{\text{gauge}}^{(a)} + \mathcal{L}_{\text{matter}}^{(a)}$$

Invariant under shift symmetry $\leftarrow a \rightarrow a + \text{const}$

Axion field

Fermion coupling

$$\mathcal{L}_{\text{int}} \supset \frac{1}{f_a} \left[a c_X \frac{\alpha_X}{8\pi} X^{a\mu\nu} \widetilde{X}_{\mu\nu}^a + \partial_\mu a c_\psi \bar{\psi} \gamma^\mu \psi \right]$$

Axion decay constant \leftarrow

Gauge boson coupling

SM gauge bosons:

$$X = \{G, W, B(A)\}$$

Quarks and leptons:

$$\psi = \{Q_L, u_R, d_R, L_L, e_R\}$$

Below the QCD confinement chiral perturbation theory for hadrons should be considered for axion-pions interaction $(1/f_a) \partial_\mu a \pi \partial^\mu \pi$.

Computation of Axion Yield

Energy and entropy density of thermal bath:

$$\rho = \frac{\pi^2}{30} g_{\text{eff}} T^4$$

Degrees of freedom

$$s = \frac{2\pi^2}{45} h_{\text{eff}} T^3$$

Boltzmann equation for the evolution of the number density of axions:

$$\frac{d}{dt} n_a + 3Hn_a = \left[\sum_S \bar{\Gamma}_S + \sum_D \bar{\Gamma}_D \right] (n_a^{\text{eq}} - n_a)$$

Number density

Modified Bessel
function 2nd kind

$$n_i^{\text{eq}} = \frac{m_i^2}{2\pi^2} T K_2 \left(\frac{m_i}{T} \right) \propto T^3$$

For relativistic case

$$sHx \frac{dY_a}{dx} = \left(1 - \frac{1}{3} \frac{\ln h_{\text{eff}}}{\ln x} \right) \left(\sum_S \gamma_S + \sum_D \gamma_D \right) \left(1 - \frac{Y_a}{Y_a^{\text{eq}}} \right), \quad x = \frac{m}{T}, \quad Y_a = \frac{n_a}{s}, \quad \gamma_{D,S} \equiv n_a^{\text{eq}} \bar{\Gamma}_{D,S}$$

Axion yield

[arXiv:2012.04736](https://arxiv.org/abs/2012.04736)

[arXiv:2003.01100](https://arxiv.org/abs/2003.01100)

Entropy degrees
of freedom

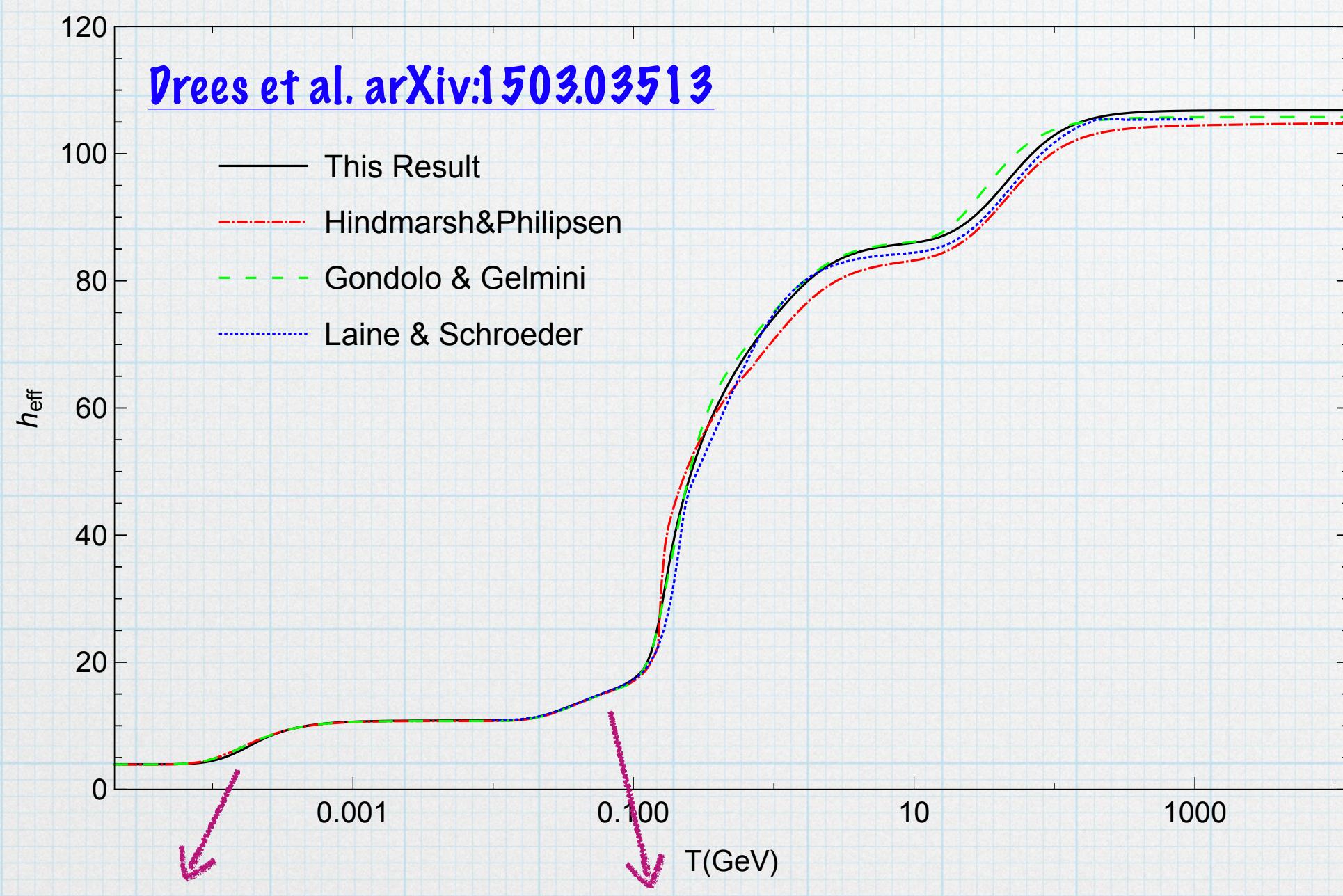
Sum of all
interaction rates

[arXiv:1503.03513](https://arxiv.org/abs/1503.03513)

Equation of State of Thermal Bath

Precise equation of state for thermal bath of SM at different temperatures:

Entropy density degrees of freedom

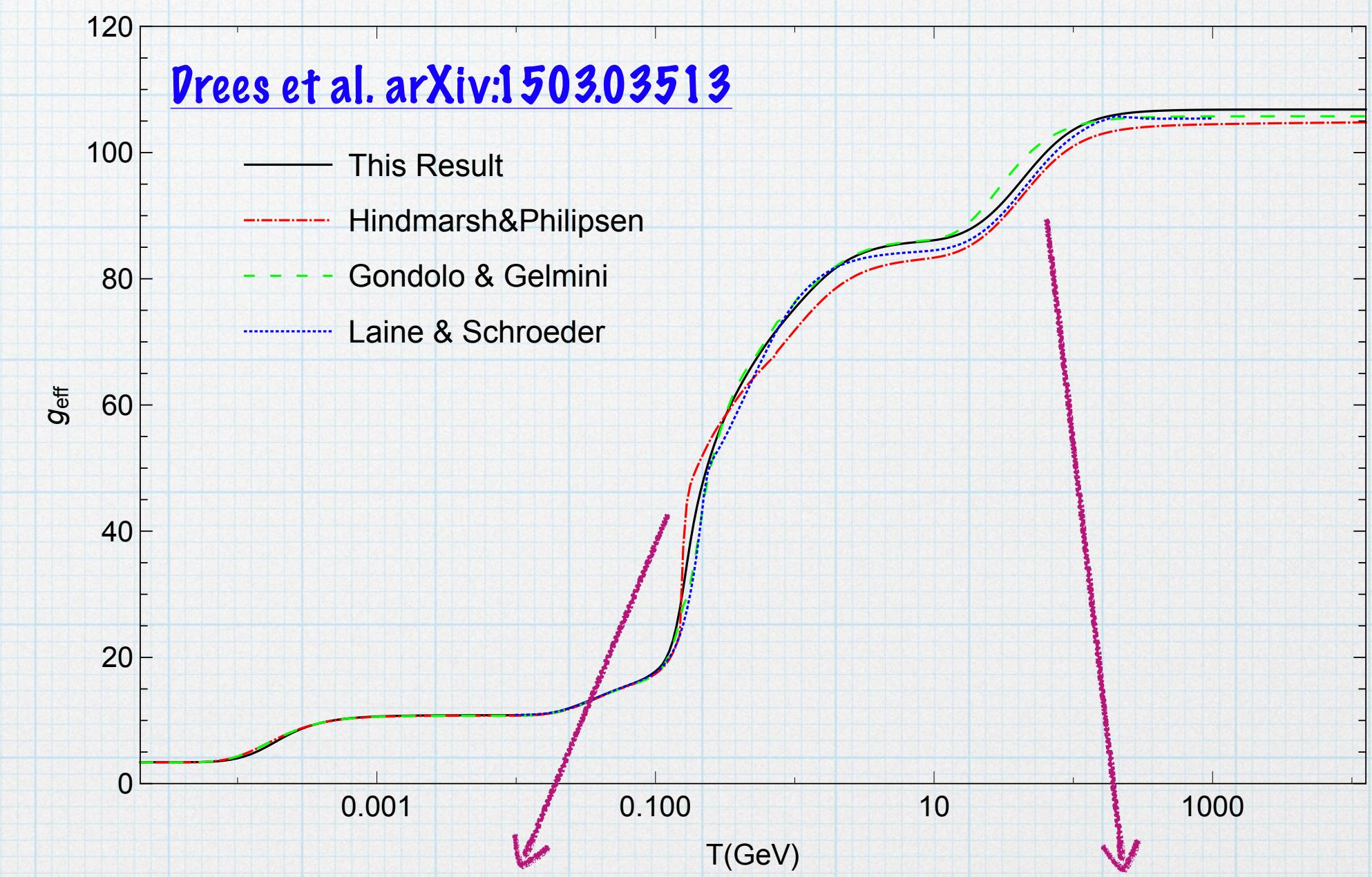


Neutrino decoupling

Hadron resonance
gas model

The rest of SM particles considered free!

Energy density degrees of freedom



Lattice QCD 2+1+1
For
QCD cross over
transition

Electroweak
crossover transition
= free Higgs and
gauge bosons

Axion Production Rate

Axion production rate from two body interactions in a general case:

Degrees of freedom
of incoming particles

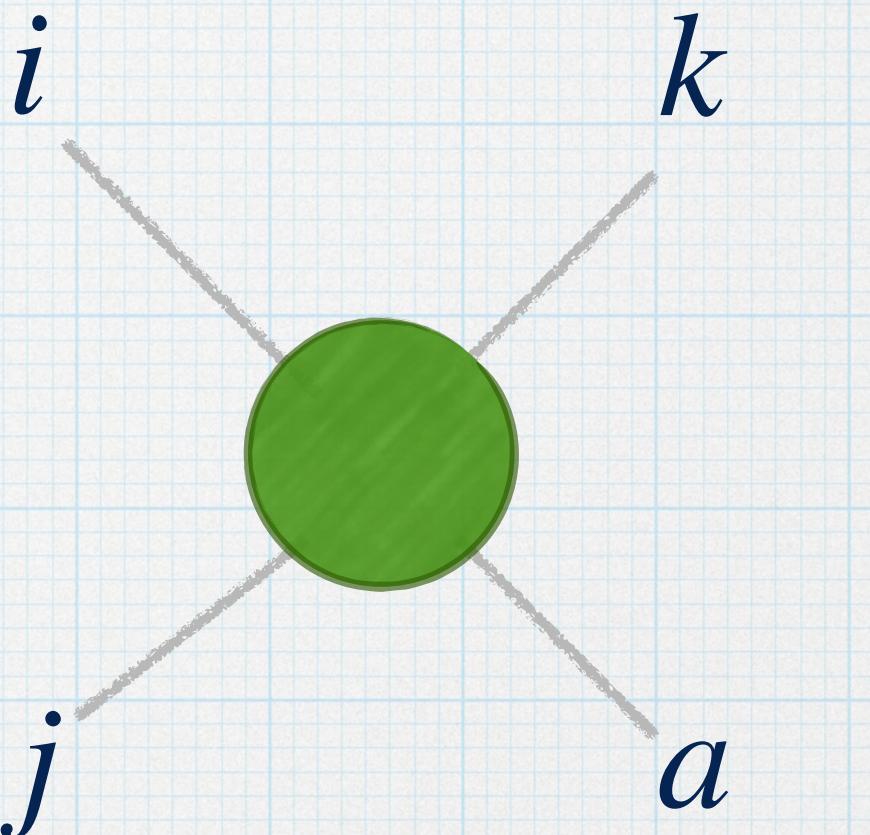
$$\bar{\Gamma}_S = \frac{g_i g_j}{32\pi^4 n_a^{\text{eq}}} T \int_{s_{\min}}^{\infty} ds \frac{\lambda(s, m_i, m_j)}{\sqrt{s}} \sigma_{ij \rightarrow ka}(s) K_1\left(\frac{\sqrt{s}}{T}\right)$$

$$s_{\min} = \text{Max} \left[\left(m_i + m_j \right)^2, m_k^2 \right] \quad \lambda(x, y, z) \equiv [x - (y + z)^2] [x - (y - z)^2]$$

Center of mass
energy

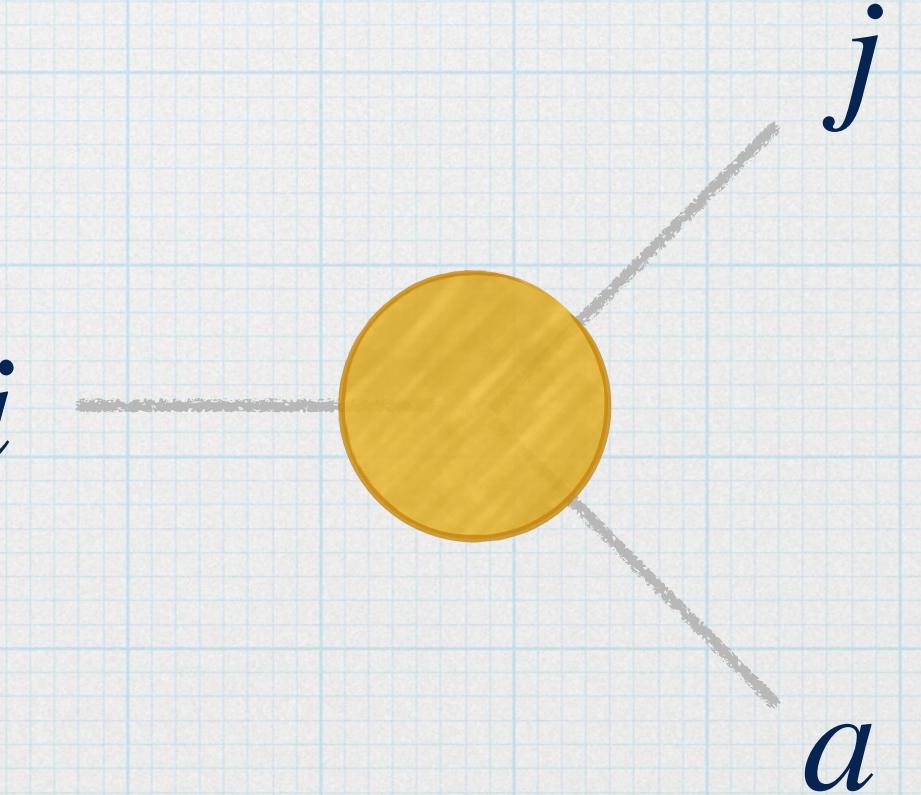
Modified Bessel
function 1st kind

Kaellen function



Axion production rate from decay e.g in case of flavour violating interactions:

$$\bar{\Gamma}_D = \frac{n_i^{\text{eq}}}{n_a^{\text{eq}}} \frac{K_1\left(\frac{m_i}{T}\right)}{K_2\left(\frac{m_i}{T}\right)} \Gamma_{i \rightarrow ja}$$

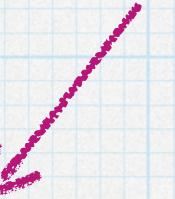


Effective Number of Extra Radiation ΔN_{eff}

By calculating all axion interactions for any given model the number of effective extra degrees of freedom dominated by axions can be evaluated:

$$\Delta N_{\text{eff}} \equiv N_{\text{eff}} - N_{\text{eff}}^{\text{SM}} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_a}{\rho_\gamma}$$

$$\Delta N_{\text{eff}} \simeq 74.85 Y_a^{4/3} \propto f_a^{-8/3}$$



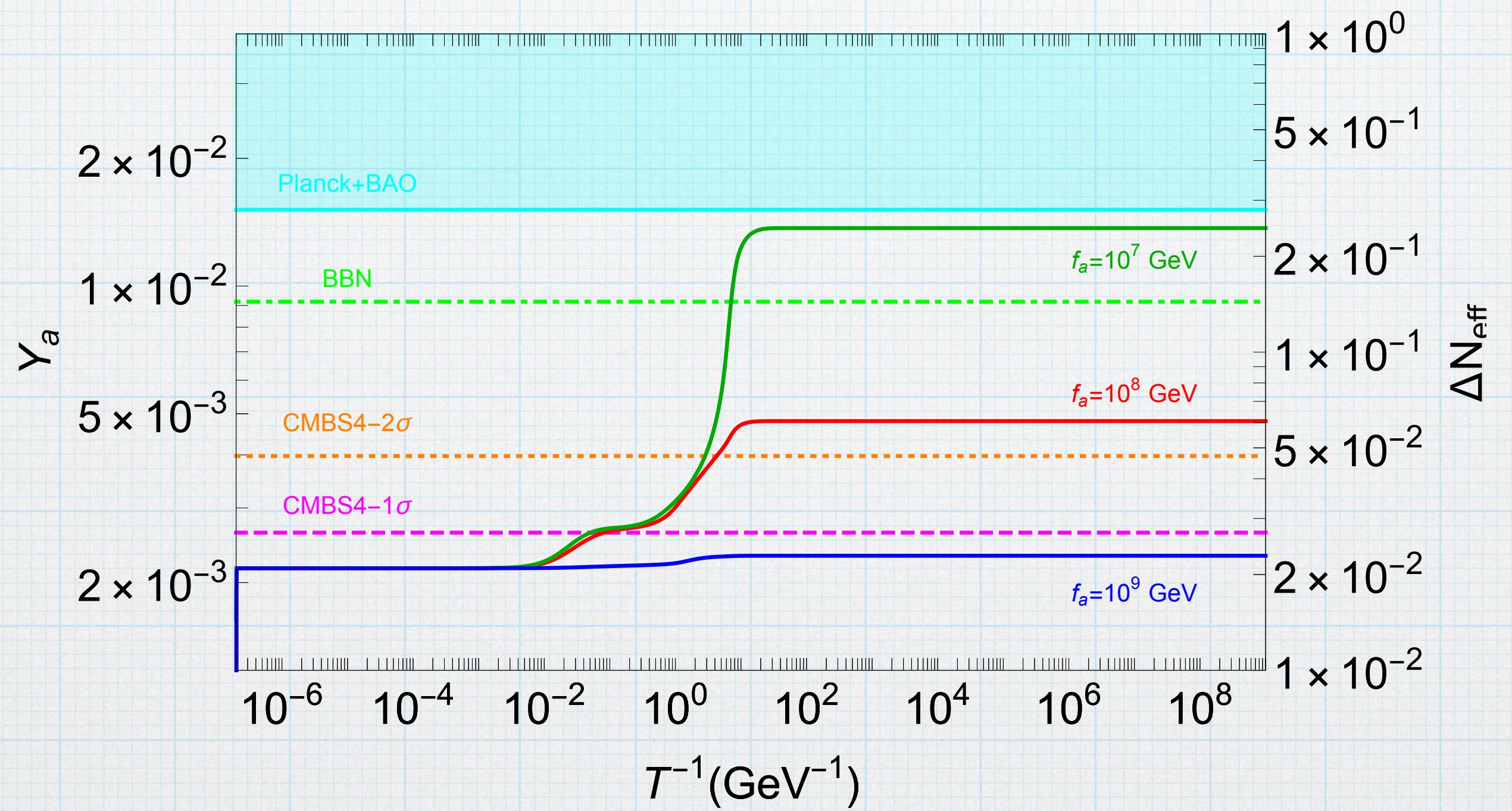
It can be constrained by CMB experiments which can falsify different axion models!

When axions thermalize ($\Gamma_a \gtrsim H$) the value of ΔN_{eff} gets its maximum. If axions do not reach the thermal equilibrium the final value of ΔN_{eff} depends on the initial abundance of them!

KSVZ Model

Vanishing couplings to SM fermions \rightarrow production rate from gluons dominant, here $c_g = 1$

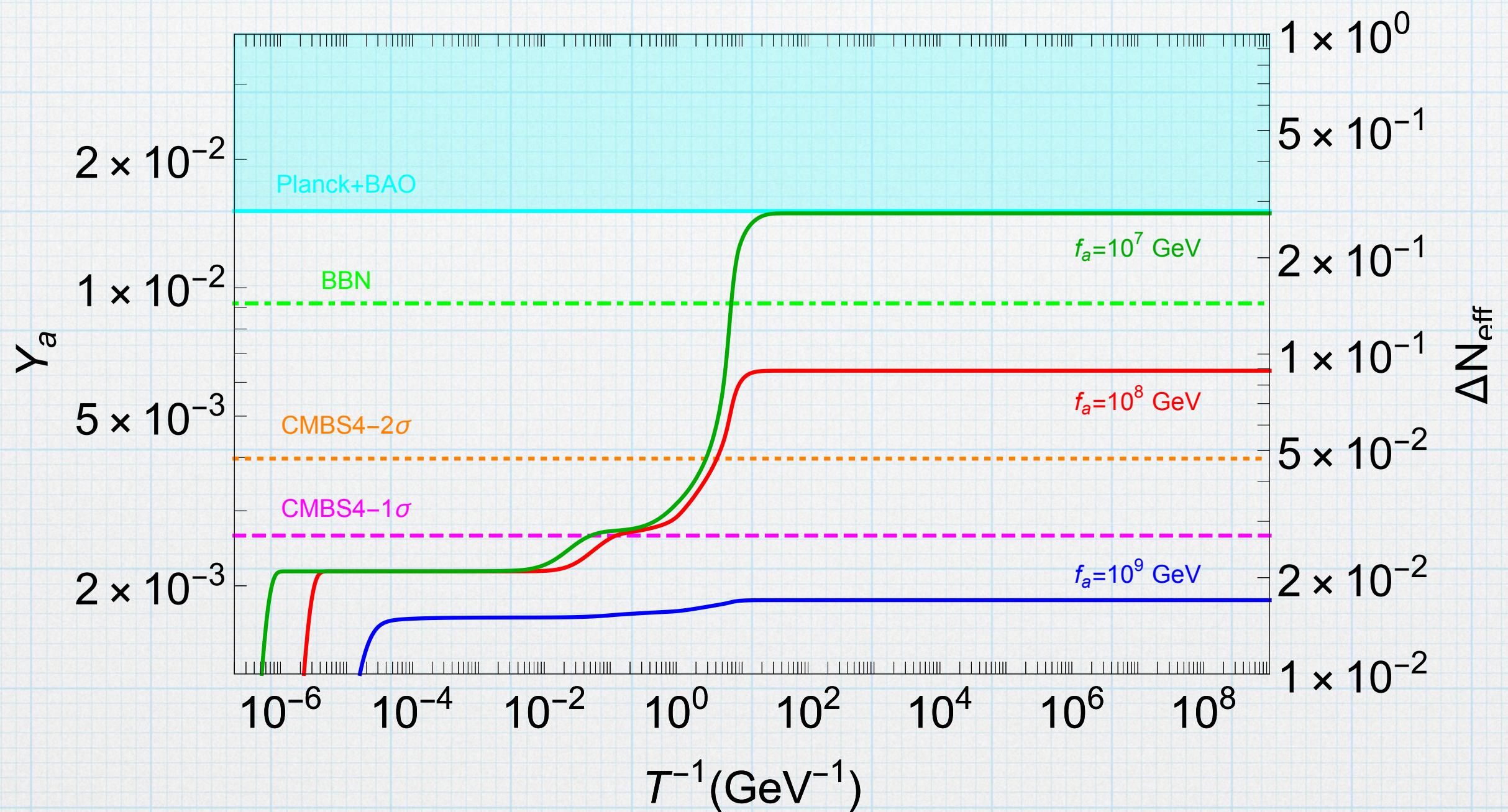
To compute the rate \rightarrow consider all axion interactions with hadrons, quarks, gluons



DFSZ Model

Nonvanishing couplings to SM fermions, e.g. here $c_u = 0$, $c_d = 1/3$.

To compute the rate -> consider all axion interactions with hadrons, quarks, gluons, electroweak sector



This can be similar to a model with two Higgs doublet with $\tan\beta \simeq 10$.

Remarks

- * Considering precise interaction rates of axion at different scales improves theoretical prediction for axionic DR
- * Accurate treatment of thermal bath at different temperatures is necessary to have a correct estimation of axion abundance
- * Predicting the precise value of ΔN_{eff} in different axion models is complementary for future experiments
- * Axions may also explain the Hubble tension and the recent XENON1T anomaly!

Thank you for your attention!