Observational Searches for Ultra-Light FIPs with Cosmological Surveys

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Cosmology is Broadly Sensitive to FIPs

- Long time scales and high densities compensate for weak interactions.

- Cosmic microwave background and large-scale structure surveys are and will be providing interesting bounds, both leading and complementary.

- Sensitive to both hot (thermal) and cold (non-thermal) populations.

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Efficient Production in the Universe

Light particles can be efficiently produced in the extreme environments studied in astrophysics and cosmology.

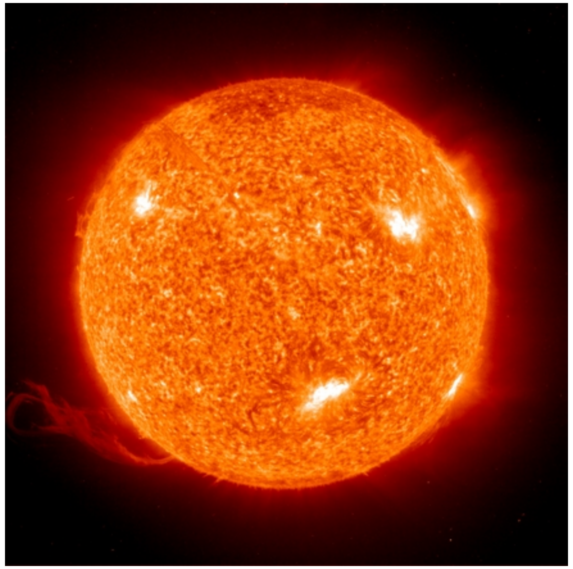
Long time scales Δt and high densities n can compensate small cross sections σ:

$$\frac{\Delta n}{n} \sim n\,\sigma \times \Delta t$$

interaction rate

interaction time

Stellar cooling



$\Delta t \sim 10^{16}\,\mathrm{s}$

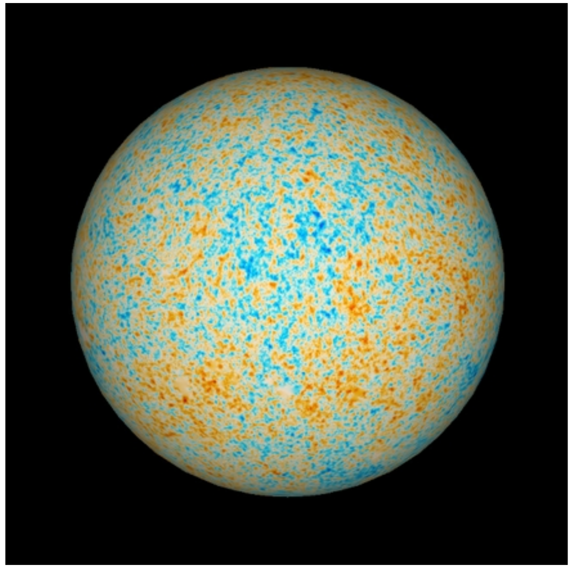
$n \sim T^3 \sim (1\,\mathrm{keV})^3$

Supernovae

$\Delta t \sim 10\,\mathrm{s}$

$n \sim T^3 \sim (10\,\mathrm{MeV})^3$

Early universe



$\Delta t \lesssim 1\,\mathrm{s}$

$n \sim T^3 \gg (1\,\mathrm{MeV})^3$

Above $10^4\,\mathrm{GeV}$, (early universe) cosmology beats astrophysics.

$\longrightarrow$ Probe particle physics and the history of the universe.

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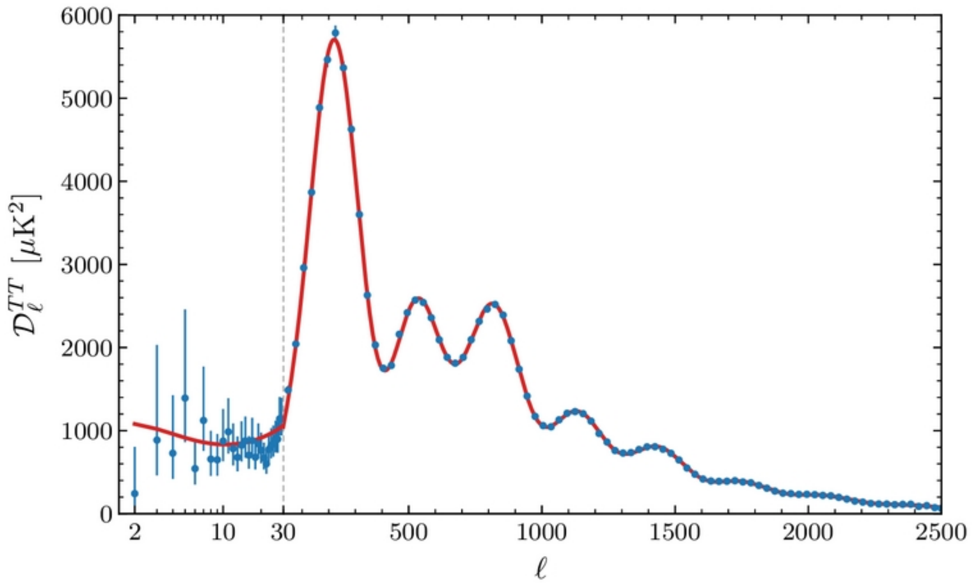
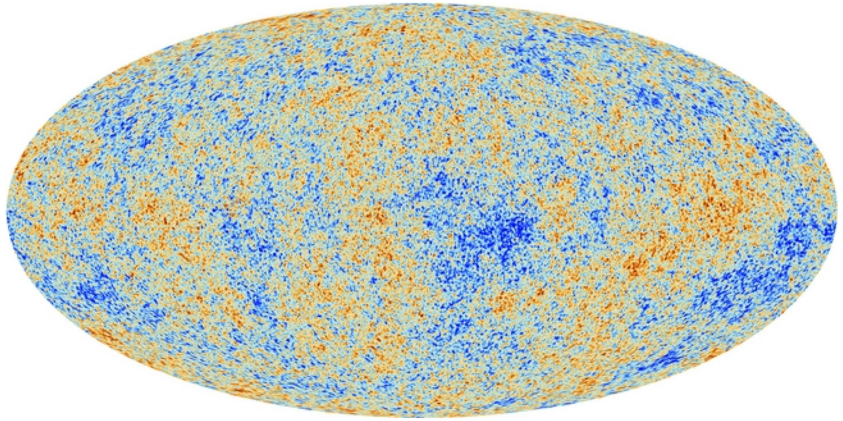
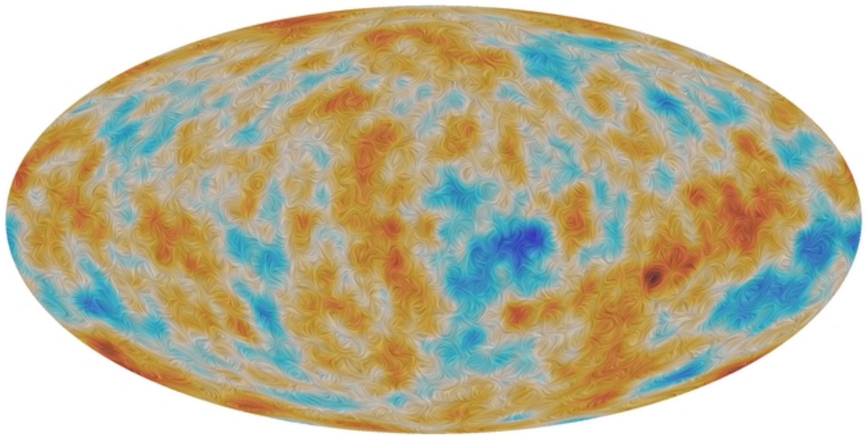
CMB Maps and Power Spectra

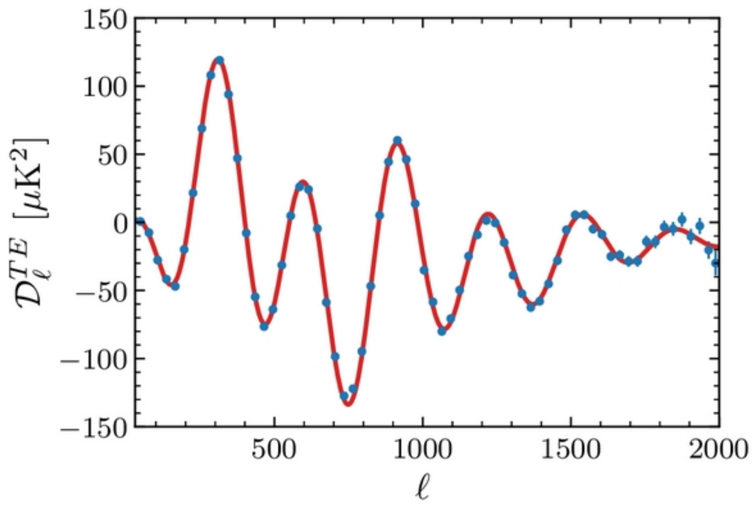


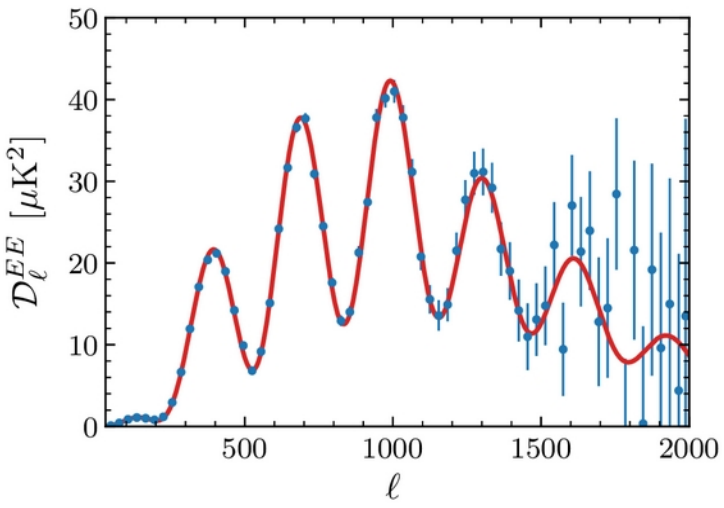


Temperature



Polarization

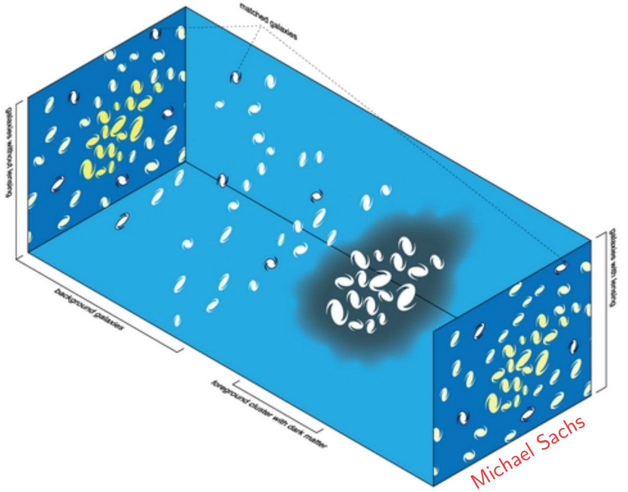




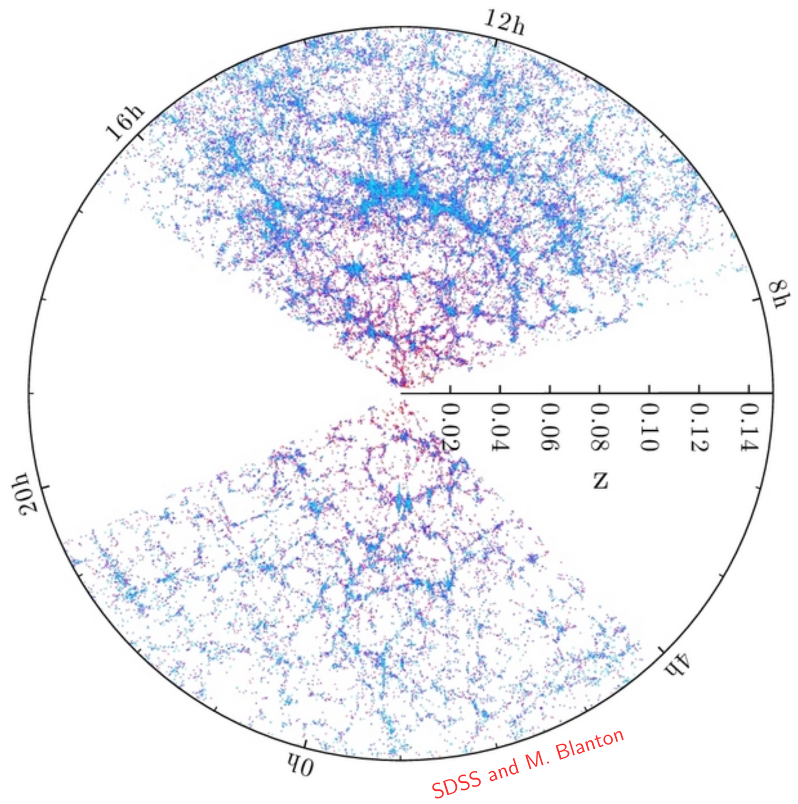
Planck Collaboration (2018)

Some Large-Scale Structure Observables

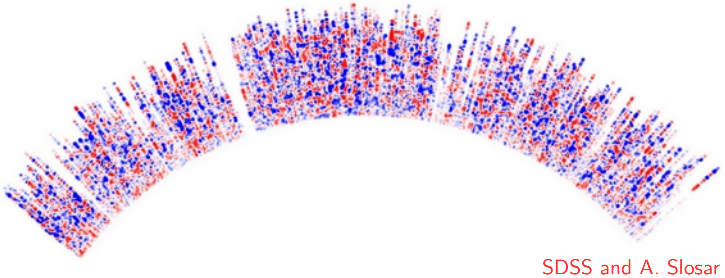
Weak lensing



Galaxy clustering

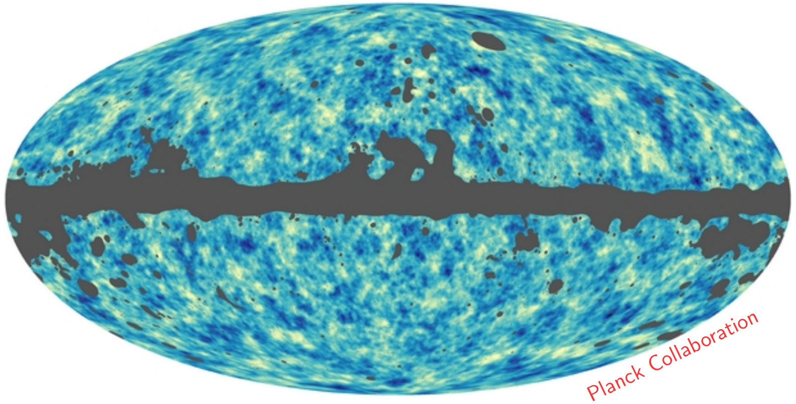


Lyman-α forest



SDSS and A. Slosar

CMB secondaries, e.g. lensing

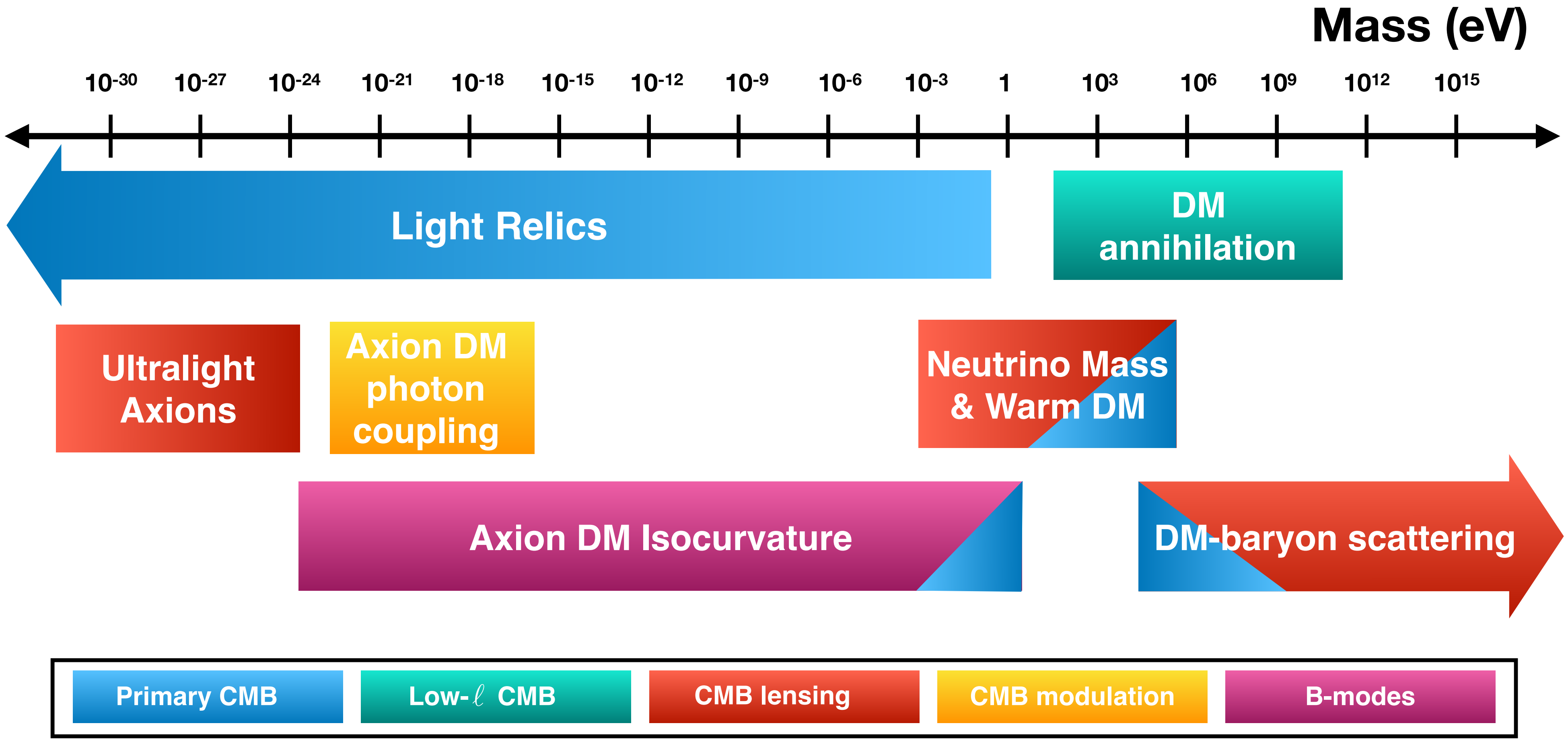


Galaxy clusters

NASA, ESA and M. Brodwin

→ Infer the matter statistics.

Some Targets and Their Driving Observables



+ various large-scale structure observables!

CMB-S4 Collaboration (2019)

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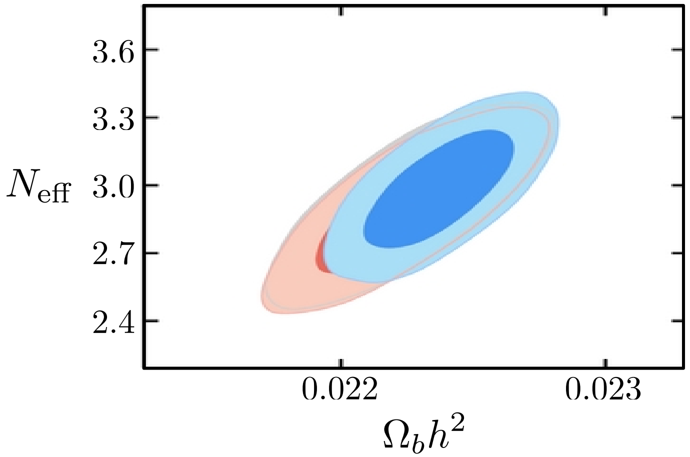
Effective Number of Neutrinos

- Neutrinos: 41% of the radiation density in the universe
  - $\rightarrow$ Leave gravitational imprint,
  - $\rightarrow$ Can detect their energy density.

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

- Observable: "effective number of neutrinos" $N_{\rm eff}^{\rm SM} = 3.044$.

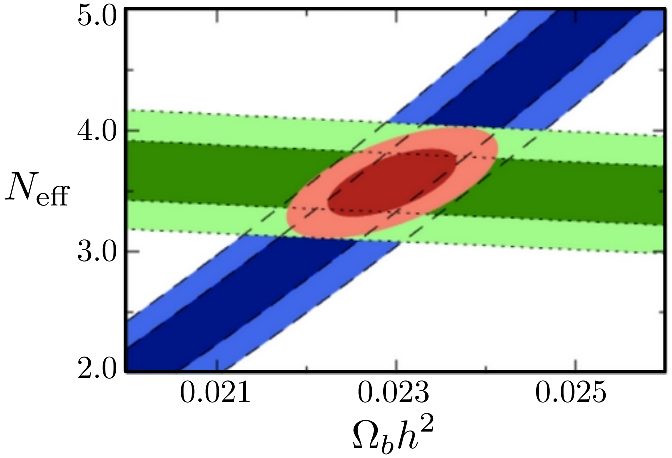
e.g. Akita &Yamaguchi (2020), Froustey et al. (2020), Bennett et al. (2021)



CMB: anisotropy measurements

$$N_{\rm eff}^{\rm CMB} = 2.92 \pm 0.18$$

Planck (2018)

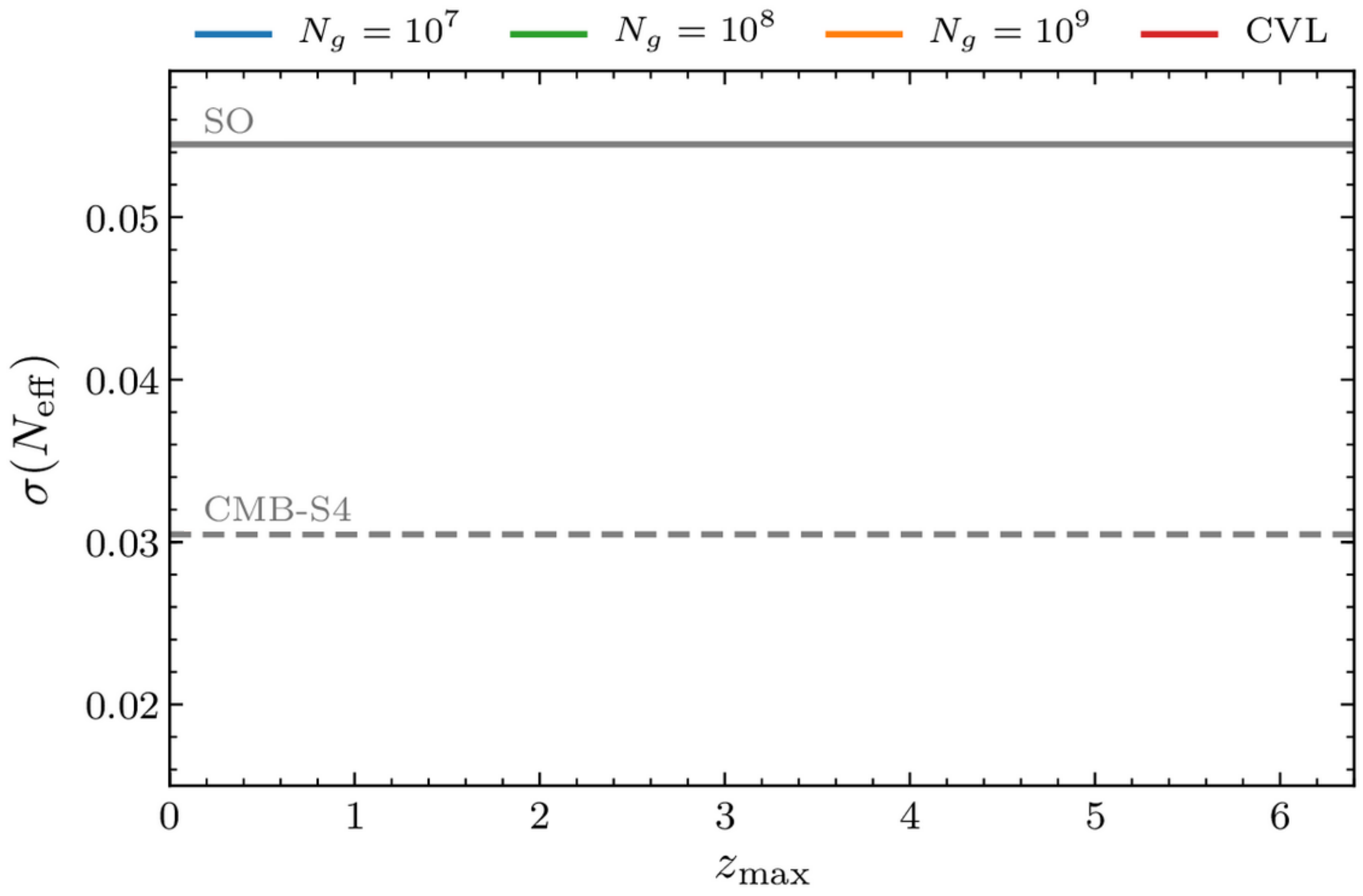


BBN: primordial abundances

$$N_{\rm eff}^{\rm BBN} = 3.28 \pm 0.28$$

Cooke et al. (2015)

Future Constraints from CMB and Large-Scale Structure



$\rightarrow$ Go beyond neutrinos and probe other light relics!

Baumann, Green & BW (2018)

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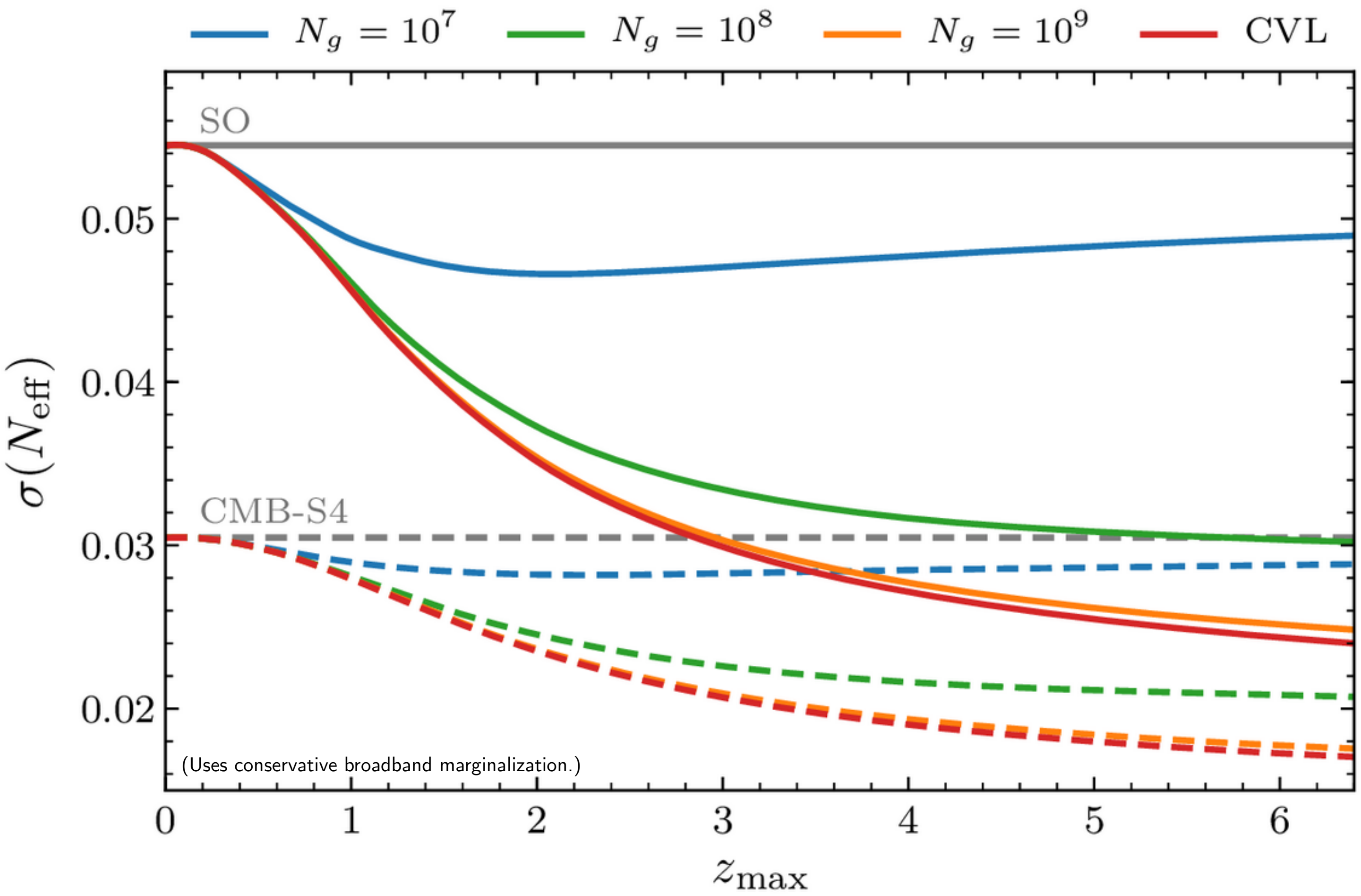

$\rightarrow$ Go beyond neutrinos and probe other light relics!

Baumann, Green & BW (2018)

Light* Thermal Relics

Relic density $\rho_X(\Lambda)$ measured in terms of $N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$:

$$\Delta N_{\rm eff}(T_F) = \frac{\rho_X}{\rho_{\nu_i}} = 0.027\, g_{*,X} \left(\frac{g_{*,\rm SM}}{g_*(T_F)}\right)^{4/3} \gamma^{-4/3}$$

effective number of relativistic degrees of freedom

entropy production

$$g_{*,X} = 1, \frac{4}{7}, 2, \ldots \text{ for spin-0}, \frac{1}{2}, 1, \ldots \qquad g_{*,\rm SM} = 106.75$$

* Light usually refers to massless to roughly sub-eV.

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Assume:

- Negligible entropy production ($\gamma \approx 1$).
- Minimal extension of the Standard Model ($g_*(T \gg m_t) \approx g_{*,SM}$).

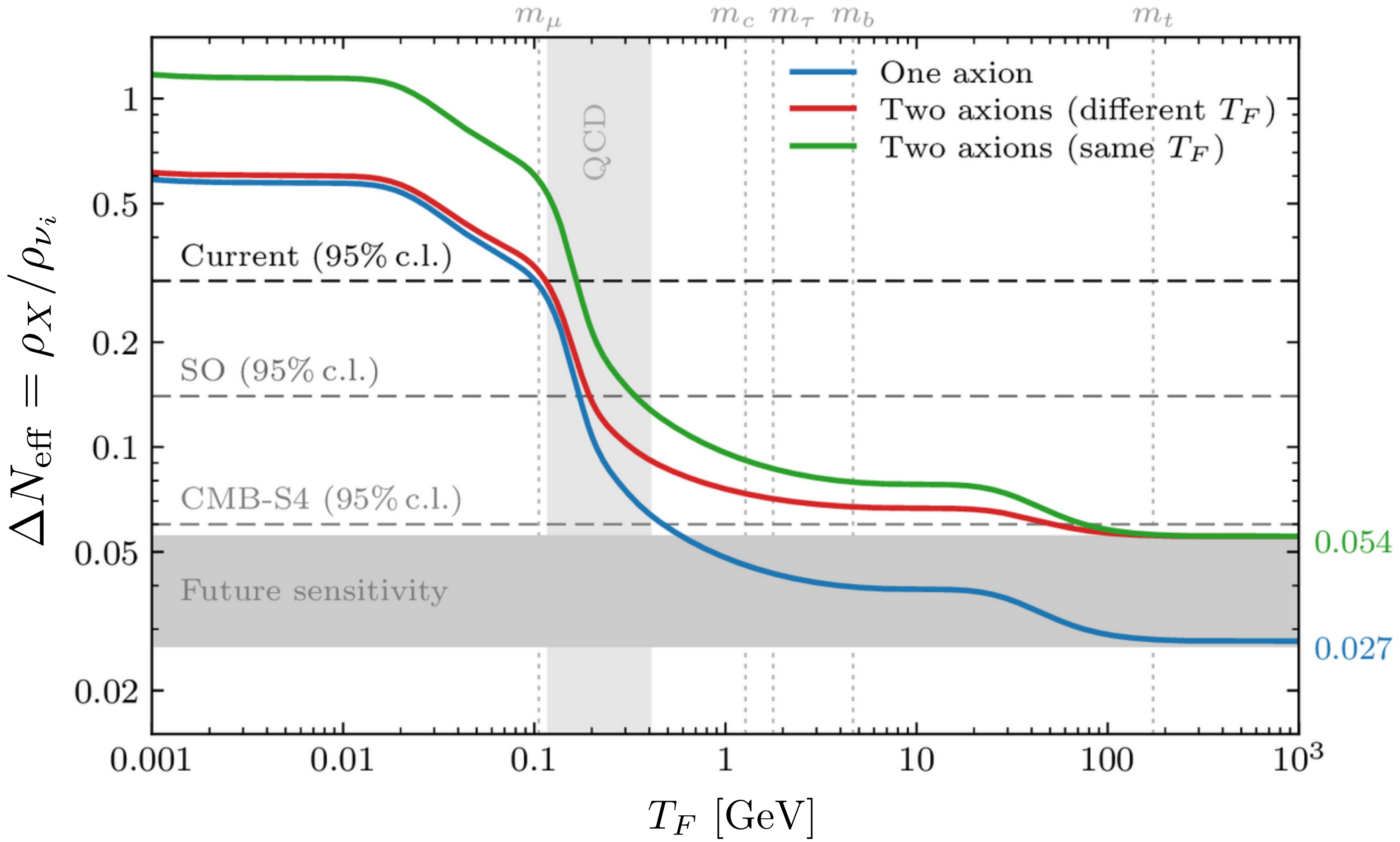
$$\longrightarrow \Delta N_{\rm eff} \geq 0.027\, g_{*,X}$$

* Light usually refers to massless to roughly sub-eV.

For a detailed discussion on these assumptions and more, see e.g. BW (2018)

Light Thermal Relics

Relic density in units of the neutrino density



Freeze-out temperature

Depends on coupling to the Standard Model

$$\Delta N_{\rm eff}(T_F) = 0.027\, g_{*,X} \left(\frac{g_{*,\rm SM}}{g_*(T_F)}\right)^{4/3}$$

Light Thermal Relics

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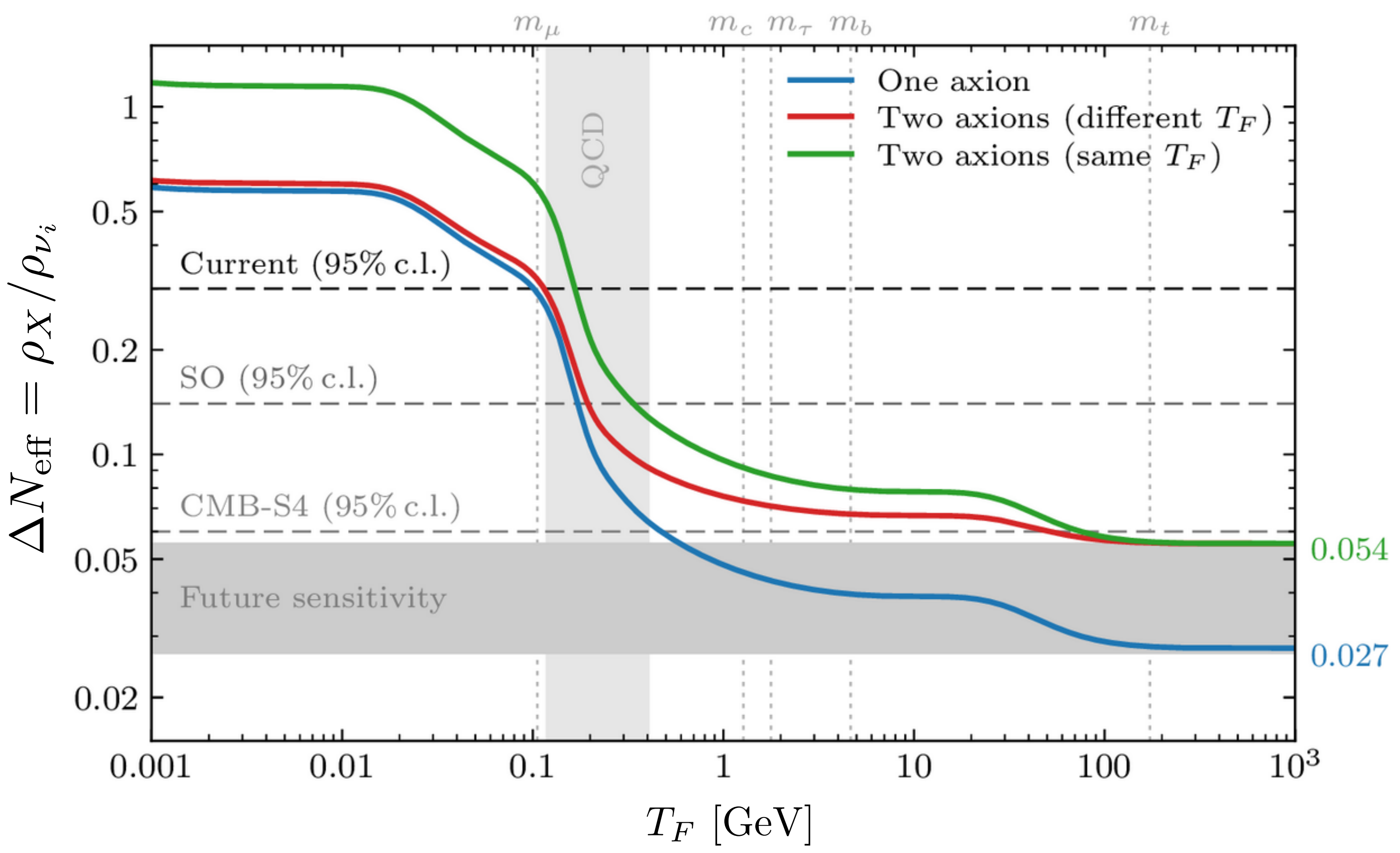


Theoretical Threshold: $\Delta N_{\mathrm{eff}} = 0.027$

Detection

Constraints

Example: Axion-Like Couplings to Standard Model Fermions

General Lagrangian:

$$\mathcal{L} = -\frac{\partial_\mu \phi}{\Lambda_\psi} \bar{\psi}_i \gamma^\mu \left(g_V^{ij} + g_A^{ij} \gamma^5 \right) \psi_j$$

$$\to \frac{\phi}{\Lambda_\psi} \left(\mathrm{i} H \bar{\psi}_{L,i} \left[(\lambda_i - \lambda_j)\, g_V^{ij} + (\lambda_i + \lambda_j)\, g_A^{ij} \right] \psi_{R,j} + \mathrm{h.c.} \right) + \mathcal{O}\big(\phi^2\big)$$

After the electroweak phase transition:

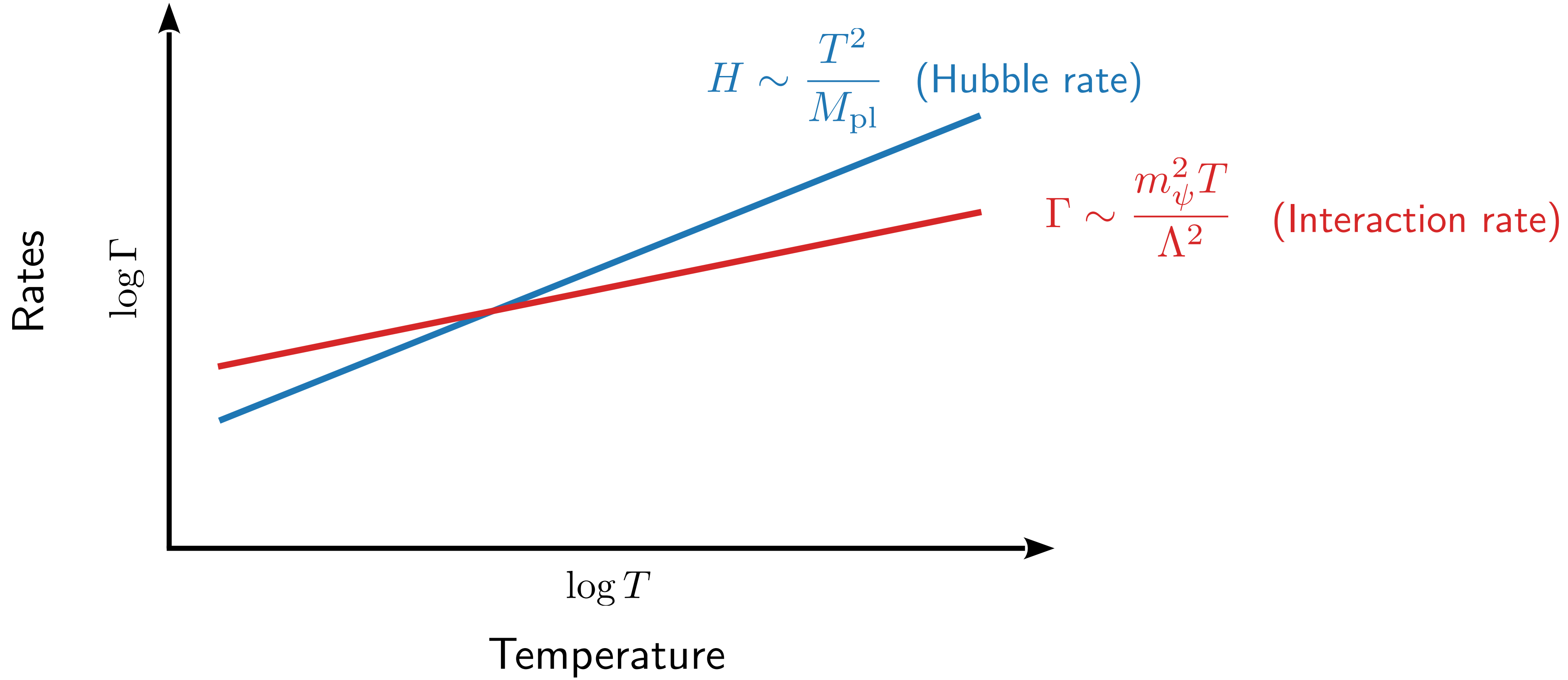
$$\mathcal{L} = \mathrm{i} \frac{\phi}{\Lambda_\psi} \bar{\psi}_i \left[(m_i - m_j) g_V^{ij} + (m_i + m_j) g_A^{ij} \gamma^5 \right] \psi_j$$

Restrict to diagonal couplings:

$$\mathcal{L} = \mathrm{i} \frac{2 m_i}{\Lambda_i} \phi \bar{\psi}_i \gamma^5 \psi_i = \mathrm{i} \tilde{\epsilon}_i \phi \bar{\psi}_i \gamma^5 \psi_i \,, \qquad \Lambda_i \equiv \Lambda_\psi / g_A^{ii} \,,\ \tilde{\epsilon}_i \equiv \frac{2 m_i}{\Lambda_i}$$

Rethermalization

For couplings to SM fermions after the electroweak phase transition:



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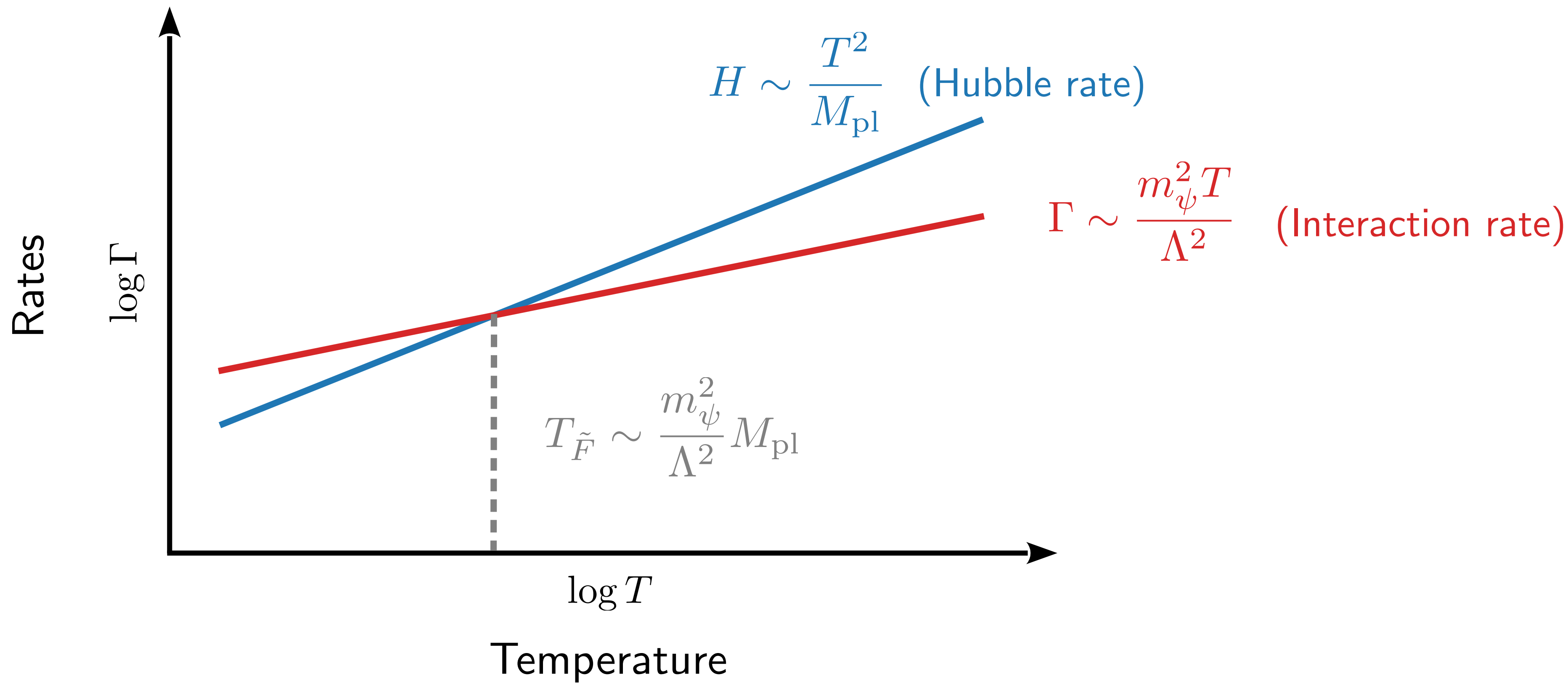
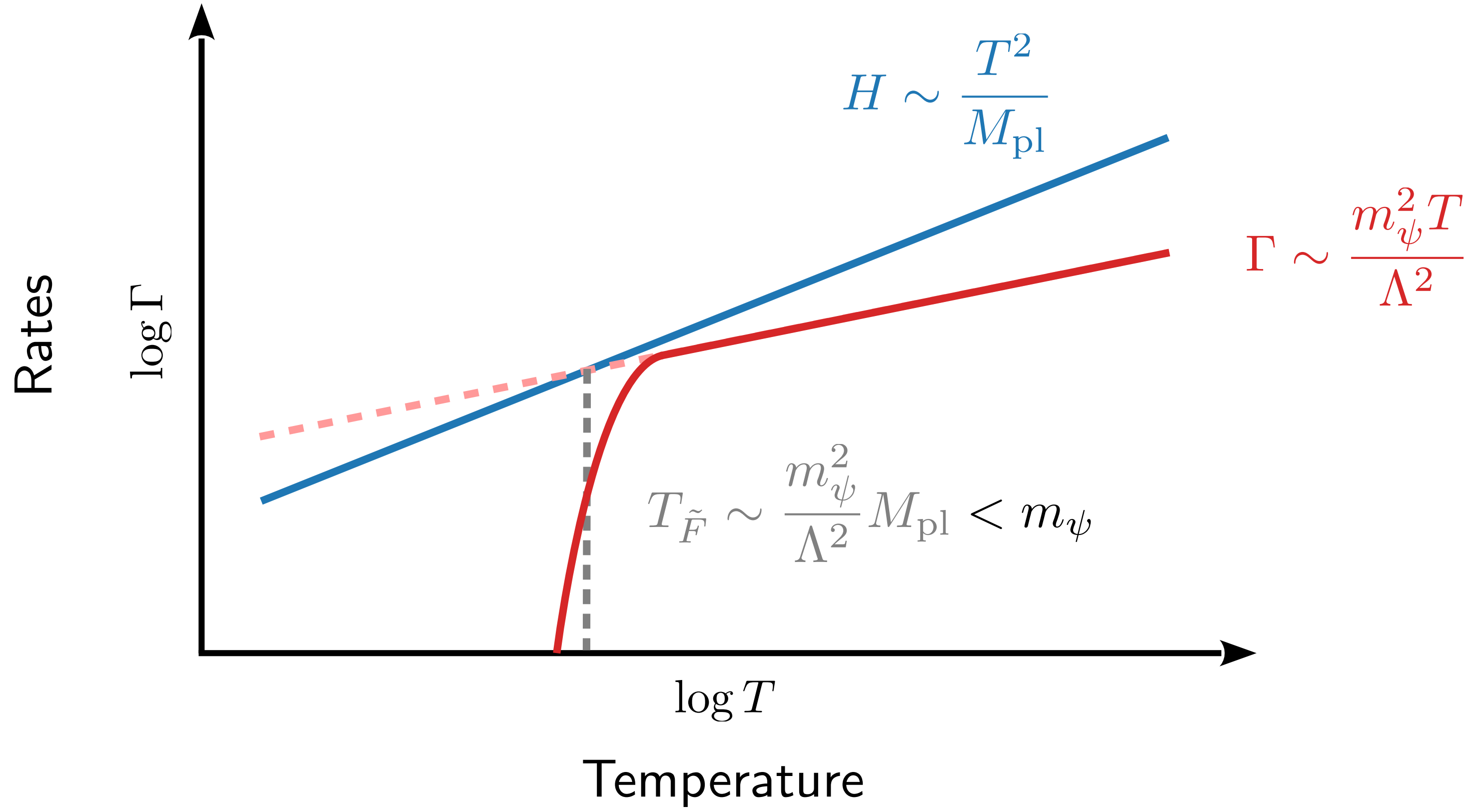


Remember: rethermalization at $H(T) \sim \Gamma(T)$

Avoid Rethermalization Abundance

Boltzmann-suppress the rethermalization abundance by requiring the would-be rethermalization temperature to be below the mass of the coupled SM fermion:



Baumann, Green & BW (2016)

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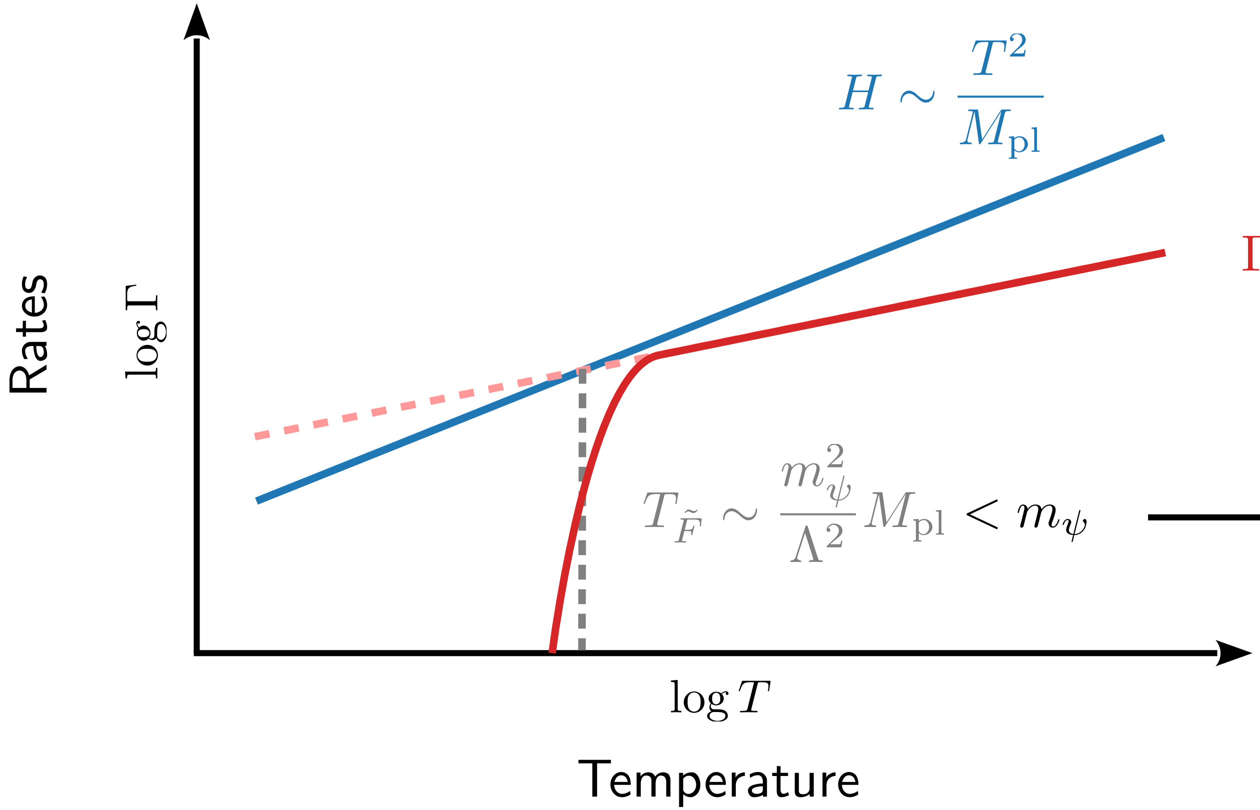
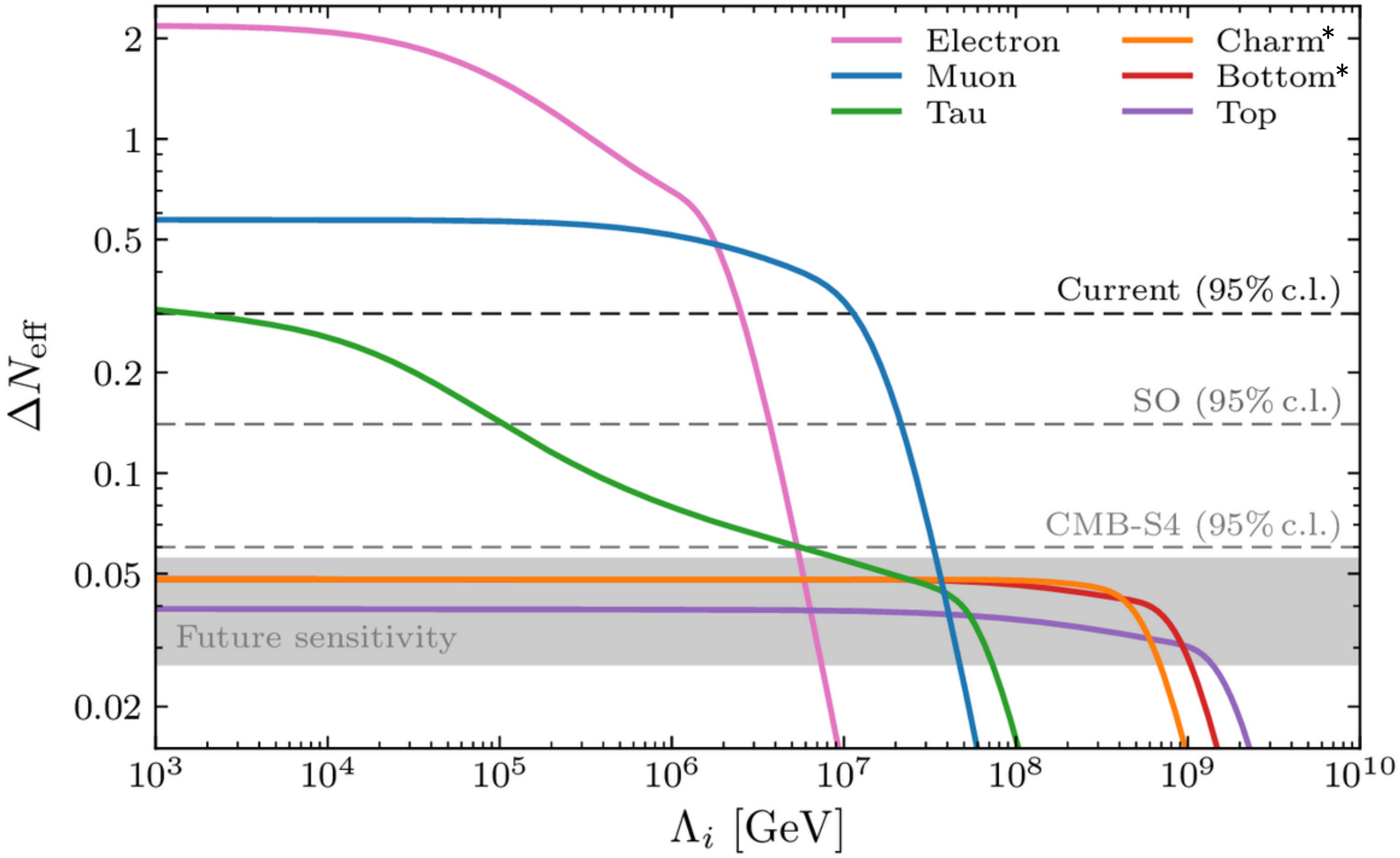


$$\Lambda \gtrsim c\sqrt{m_\psi M_{\rm pl}}$$

Baumann, Green & BW (2016)

Predictions for ΔN_{eff}

Solving the Boltzmann equation, we predict:

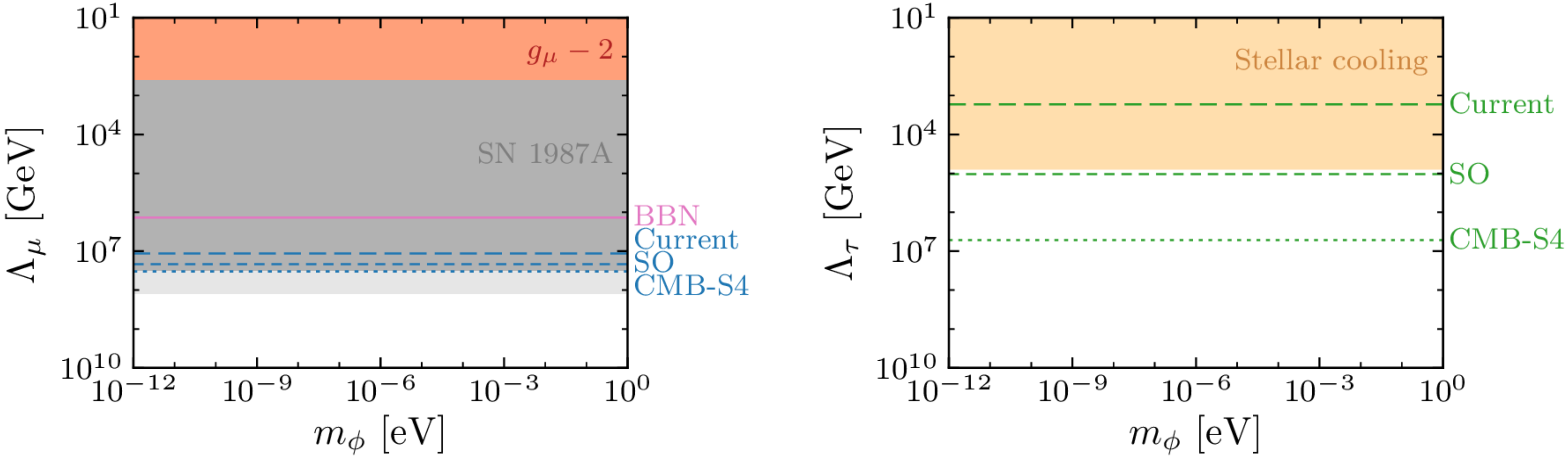


* Calculations for charm and bottom couplings are impacted by the QCD phase transition. Here: conservative estimate.

Green, Guo & BW (2021); cf. also D'Eramo et al.

Comparison to Astrophysical and Terrestrial Constraints

Current and upcoming CMB surveys can put complimentary and competitive constraints on axion-fermion couplings by avoiding freeze-in:



cf. Feng et al. (1998); Andreas et al. (2010); Bollig et al. (2020); Croon et al. (2020)

Green, Guo & BW (2021)

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Example: Non-Thermal Ultra-Light Axions

- Non-thermally produced axions can contribute to dark matter and dark energy:
  - standard dark energy for $m_\phi \lesssim 10^{-33}\,\mathrm{eV}$,
  - early dark energy for $m_\phi \lesssim 10^{-27}\,\mathrm{eV}$,
  - dark matter for $m_\phi \gtrsim 10^{-27}\,\mathrm{eV}$.

- Gravitational ultra-light axion window: $10^{-33}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-10}\,\mathrm{eV}$.

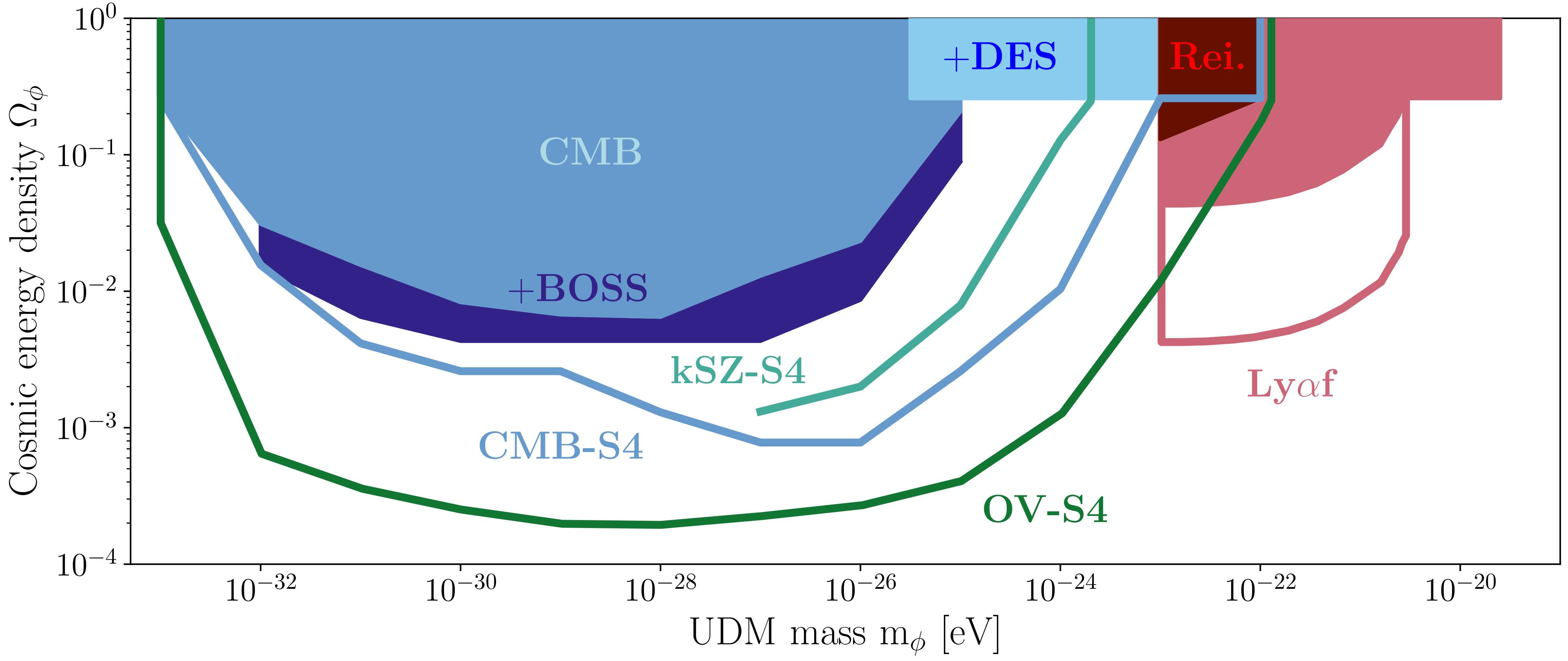
- Various observable implications, including suppression of density fluctuations below the (comoving) Jeans scale $\lambda_J = 0.1\,\mathrm{Mpc}\,(m_\phi/10^{-22}\,\mathrm{eV})^{-1/2}\,(1+z)^{1/4}$.

- Isocurvature modes are also excited if $U(1)$ symmetry breaking before the end of inflation.

- Coupling to photons leads to birefringence and resonant conversion.

For reviews see e.g. Marsh (2018), Grin et al. (2019), Jaeckel et al. (2022), ...

Example: Non-Thermal Ultra-Light Axions



Dvorkin et al. (2022) [Hložek et al. (2015), Poulin et al. (2018), Rogers & Peiris (2021), Farren et. al. (2021), Laguë et al. (2022), Dentler et al. (2022), ...]

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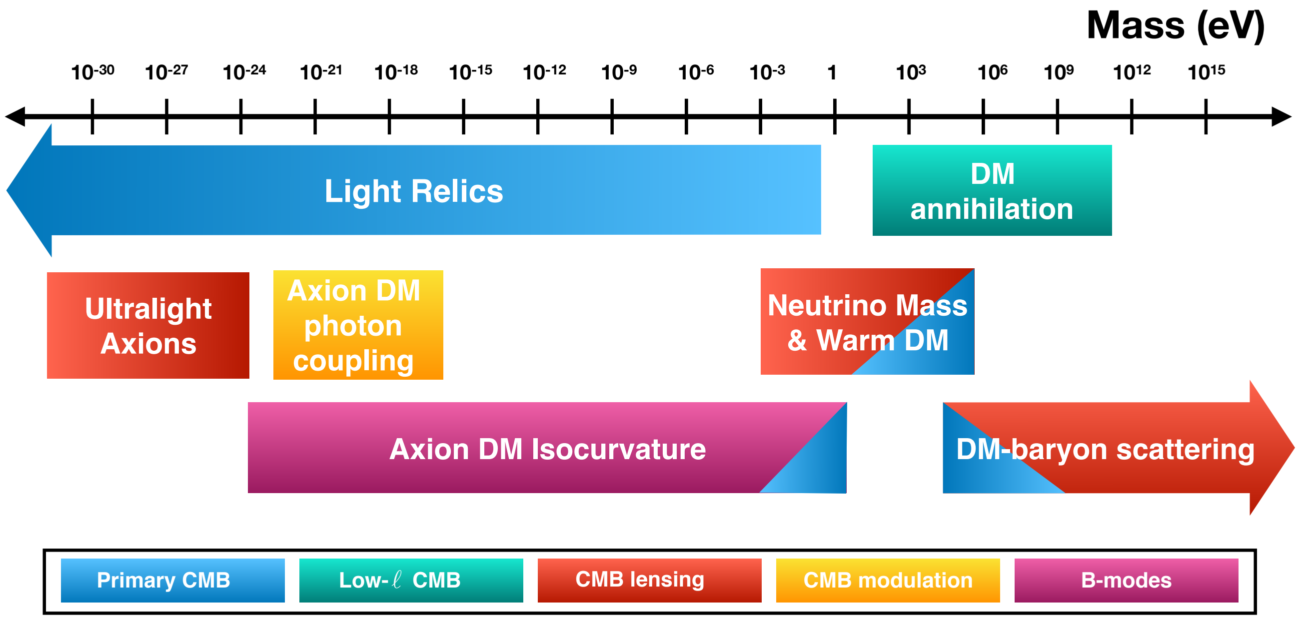
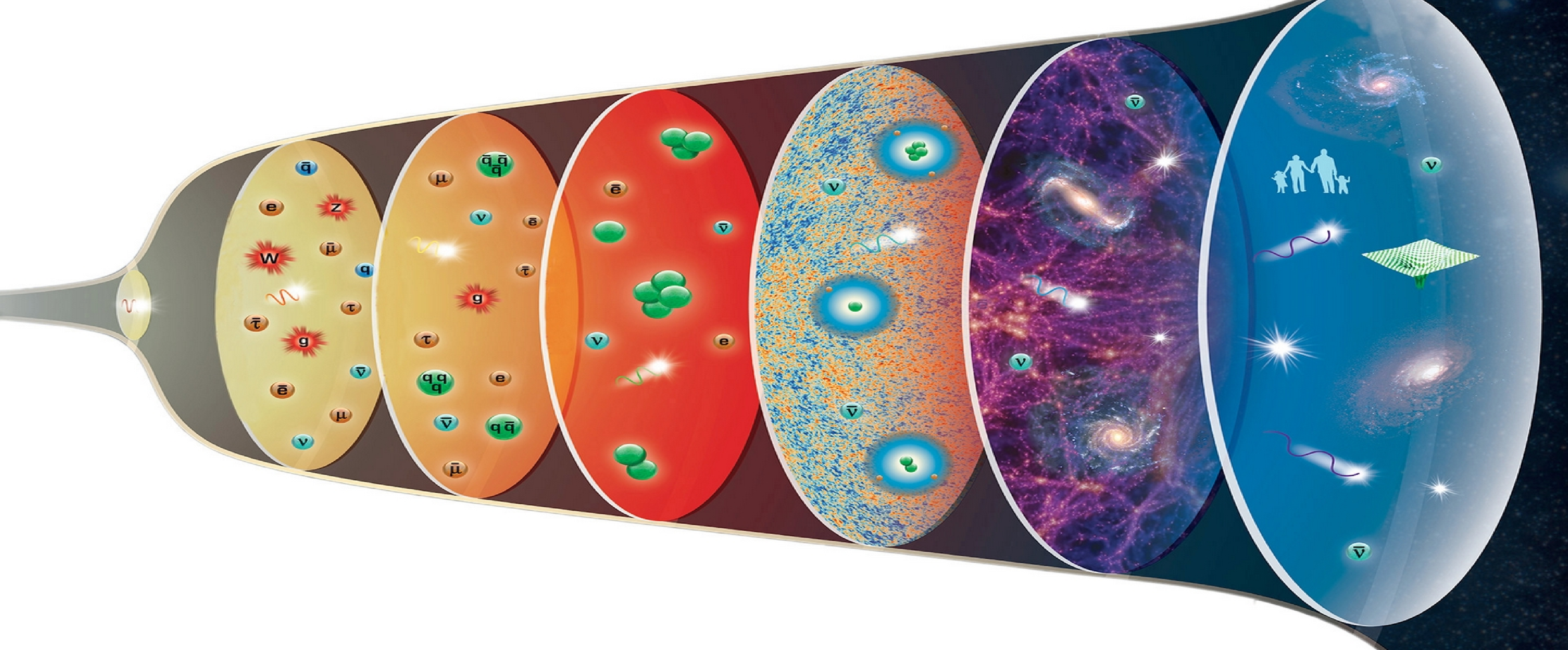


+ various large-scale structure observables!

CMB-S4 Collaboration (2019)

Thank you!



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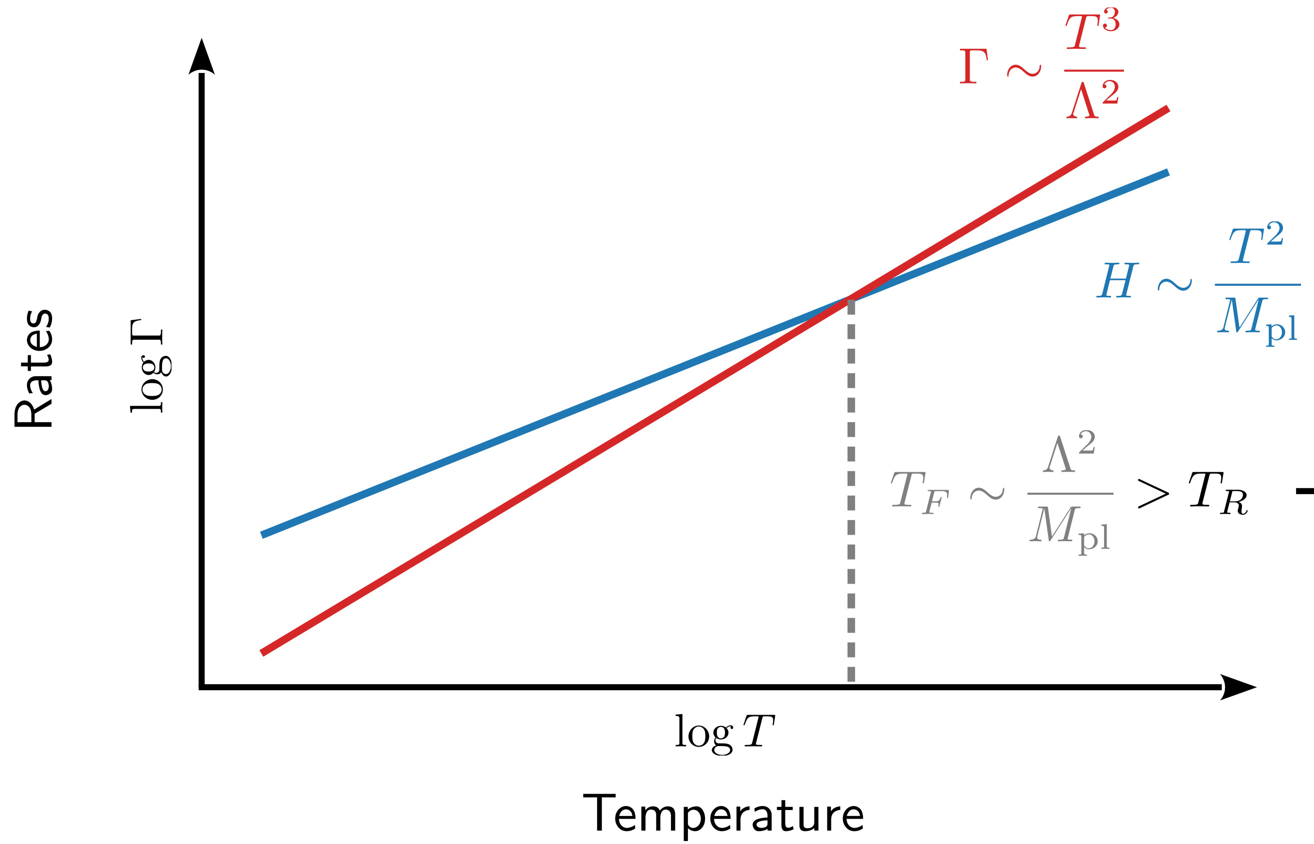
Backup Slides

Avoid Freeze-Out Abundance

Suppress the freeze-out abundance from a dimension-5 coupling to massless SM particles by requiring the would-be freeze-out temperature to be above the reheating temperature*:



$$T_F \sim \frac{\Lambda^2}{M_{\rm pl}} > T_R \longrightarrow \Lambda > c\sqrt{T_R\, M_{\rm pl}}$$

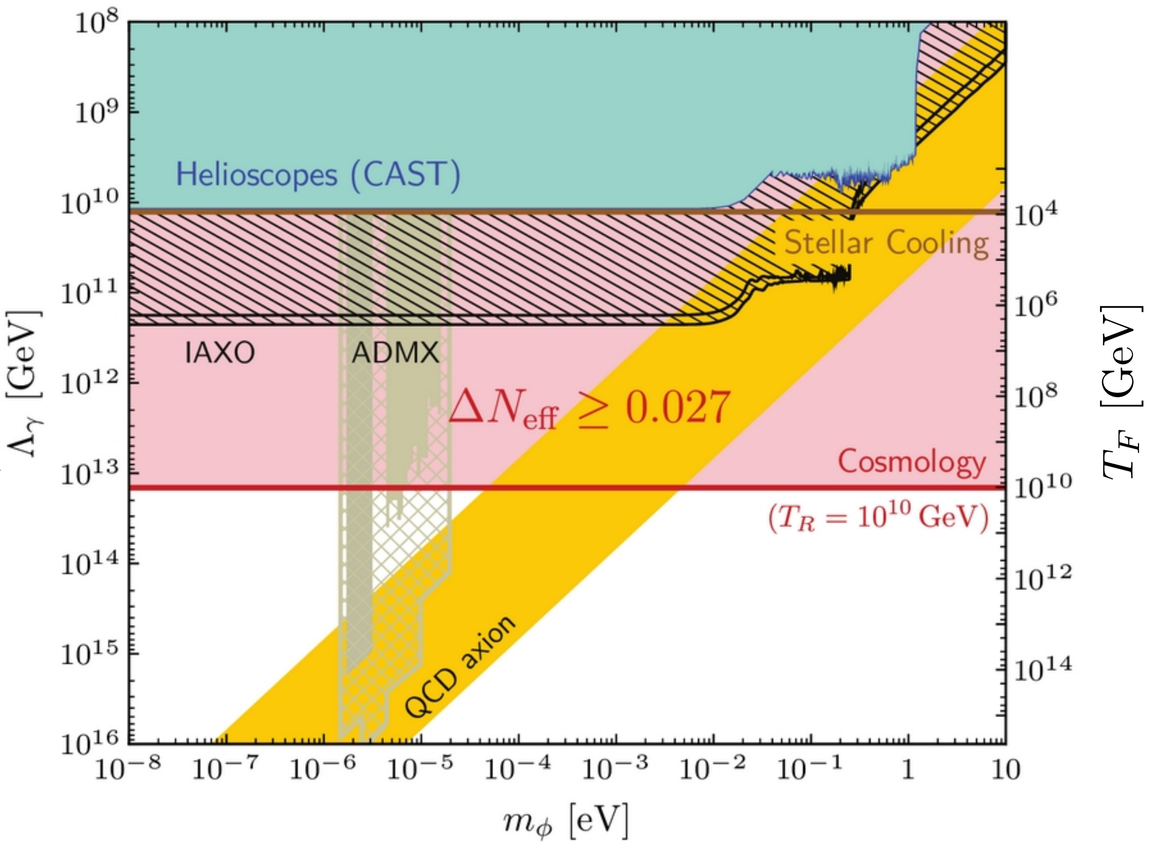
* Alternatively, weaker constraints can be derived by excluding a given freeze-out temperature.

Baumann, Green & BW (2016)

Example: Constraints on the Axion Coupling to Photons

Exclusion of $\Delta N_{\rm eff} = 0.027$ implies strong constraints on couplings to the Standard Model:

$$-\frac{\phi}{4\Lambda_\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Similar constraints apply to couplings to gluons, charged fermions and neutrinos.

Baumann, Green & BW (2016)

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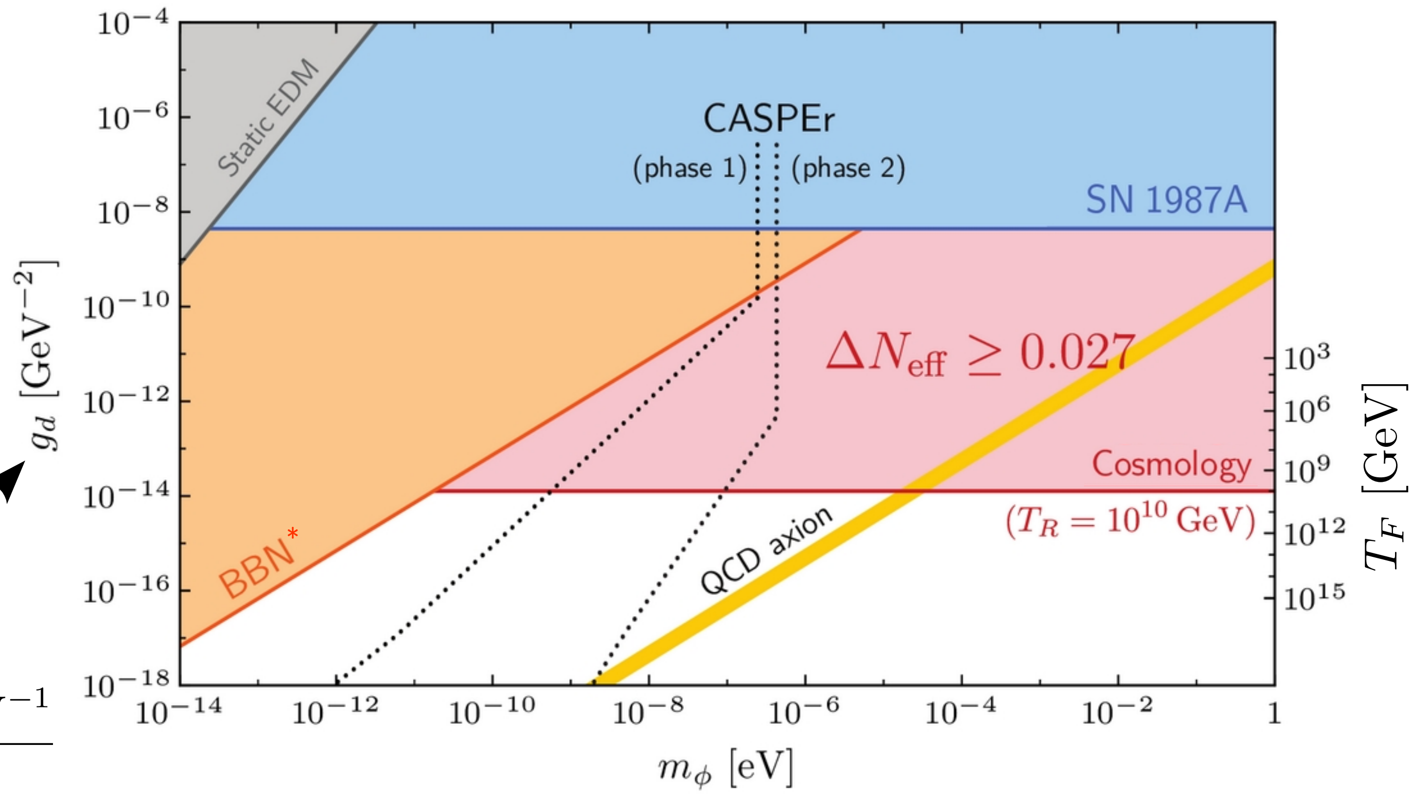
$$-\frac{\phi}{4\Lambda_g}\mathrm{tr}\{G_{\mu\nu}\tilde{G}^{\mu\nu}\}$$

$$g_d \approx \frac{2\pi}{\alpha_s} \times \frac{3.8\times 10^{-3}\,\mathrm{GeV}^{-1}}{\Lambda_g}$$



Similar constraints apply to couplings to photons, charged fermions and neutrinos.

Baumann, Green & BW (2016)

Constraints on Axion Couplings to Matter Fields

Similar constraints apply to couplings of Goldstone bosons to charged fermions and neutrinos:

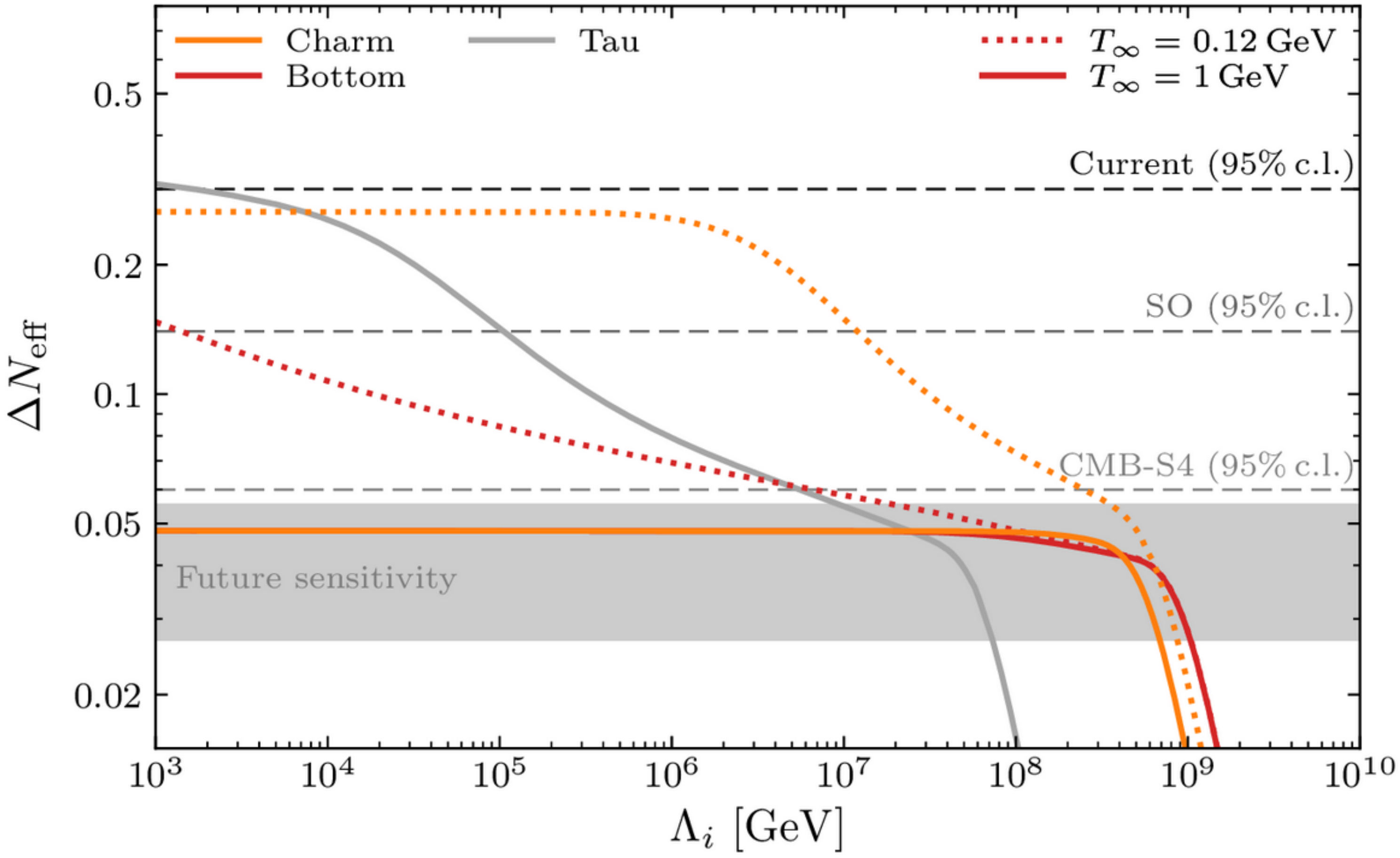
	Current Constraints		Future CMB Constraints		
Coupling	Bound [GeV]	Origin	Freeze-Out [GeV]	Freeze-In [GeV]	$\Delta\tilde{N}_{\rm eff}$
Λ_{ee}	1.2×10^{10}	White dwarfs	6.0×10^{7}	2.7×10^{6}	1.3
$\Lambda_{\mu\mu}$	2.0×10^{6}	Stellar cooling	1.2×10^{10}	3.4×10^{7}	0.5
$\Lambda_{\tau\tau}$	2.5×10^{4}	Stellar cooling	2.1×10^{11}	9.5×10^{7}	0.05
Λ_{bb}	6.1×10^{5}	Stellar cooling	9.5×10^{11}	–	0.04
Λ_{tt}	1.2×10^{9}	Stellar cooling	3.5×10^{13}	–	0.03
$\Lambda^{V}_{\mu e}$	5.5×10^{9}	$\mu^+ \to e^+ \phi$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+ \to e^+ \phi \gamma$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^- \to e^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
$\Lambda_{\tau\mu}$	3.2×10^{6}	$\tau^- \to \mu^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
Λ^{A}	6.9×10^{5}	D^0–$\bar{D}^0$	1.3×10^{11}	2.0×10^{8}	0.05

Feng et al.; Brust et al.; Hansen et al.; Archidiacono & Hannestad; ...

Baumann, Green & BW (2016)

Predictions for ΔN_{eff}

Predictions for the charm and bottom couplings are affected by the QCD phase transition:



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