Implications of Cosmological Dark Matter and Dark Radiation Constraints

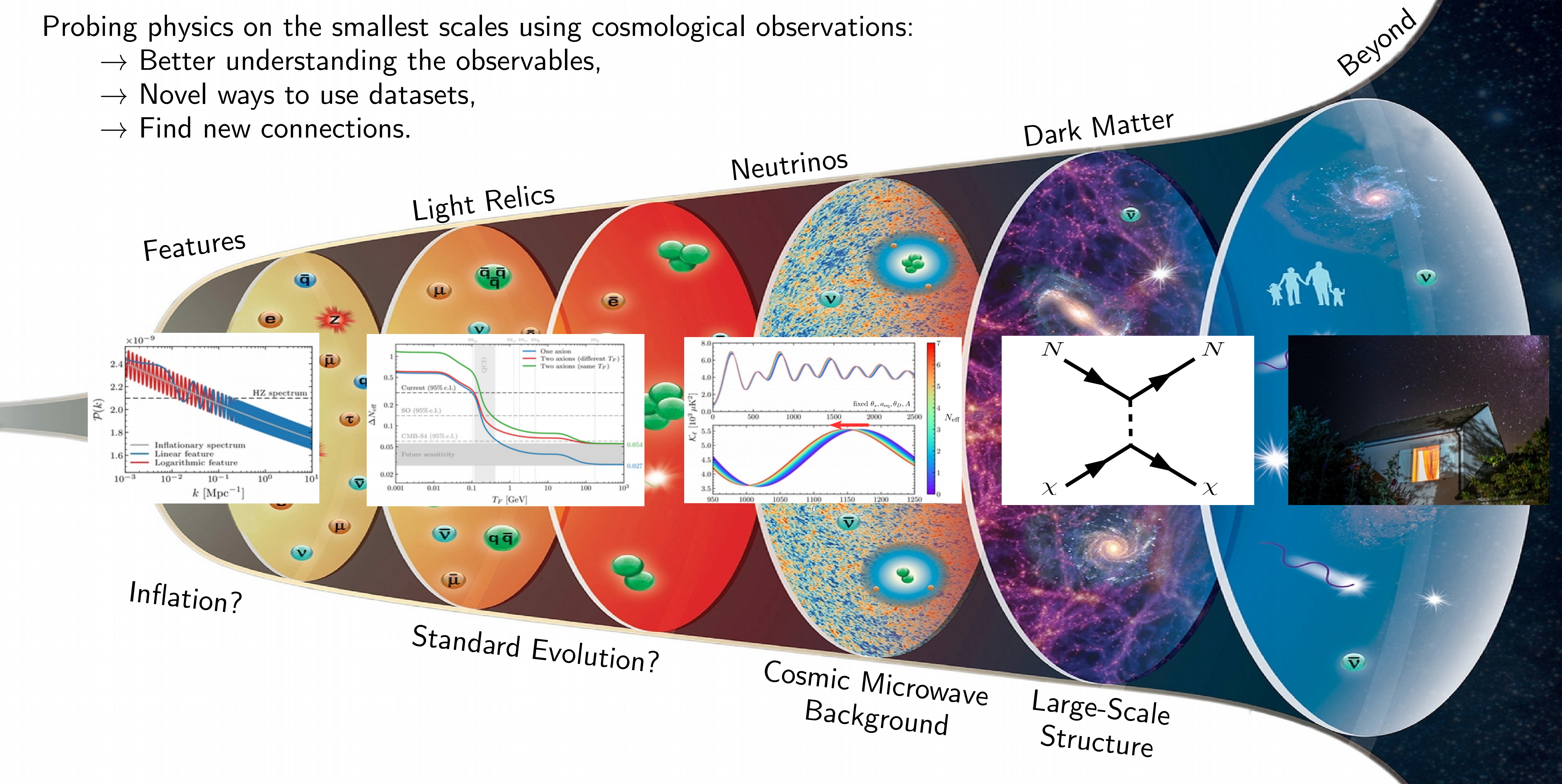
Benjamin Wallisch

Based on work in preparation with Daniel Green
and arXiv:2109.12088 with Daniel Green & Yi Guo

OKC BSM Group Meeting, Stockholm, October 2022

Probing physics on the smallest scales using cosmological observations:

- → Better understanding the observables,
- → Novel ways to use datasets,
- → Find new connections.



Early Universe

Observable Universe

Plan of the Talk

- Cosmic Microwave Background and Large-Scale Structure
- Dark Matter-Baryon Interactions
- Dark Radiation and Axion Couplings
- Conclusions

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Cosmic Sound Waves

In the early universe, photons and baryons were strongly coupled.

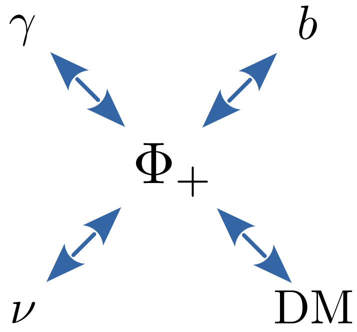
Perturbations excited sound waves in the photon-baryon fluid:

$$\ddot{\delta}_\gamma - c_\gamma^2 \nabla^2 \delta_\gamma = \nabla^2 \Phi_+$$

sound waves

pressure

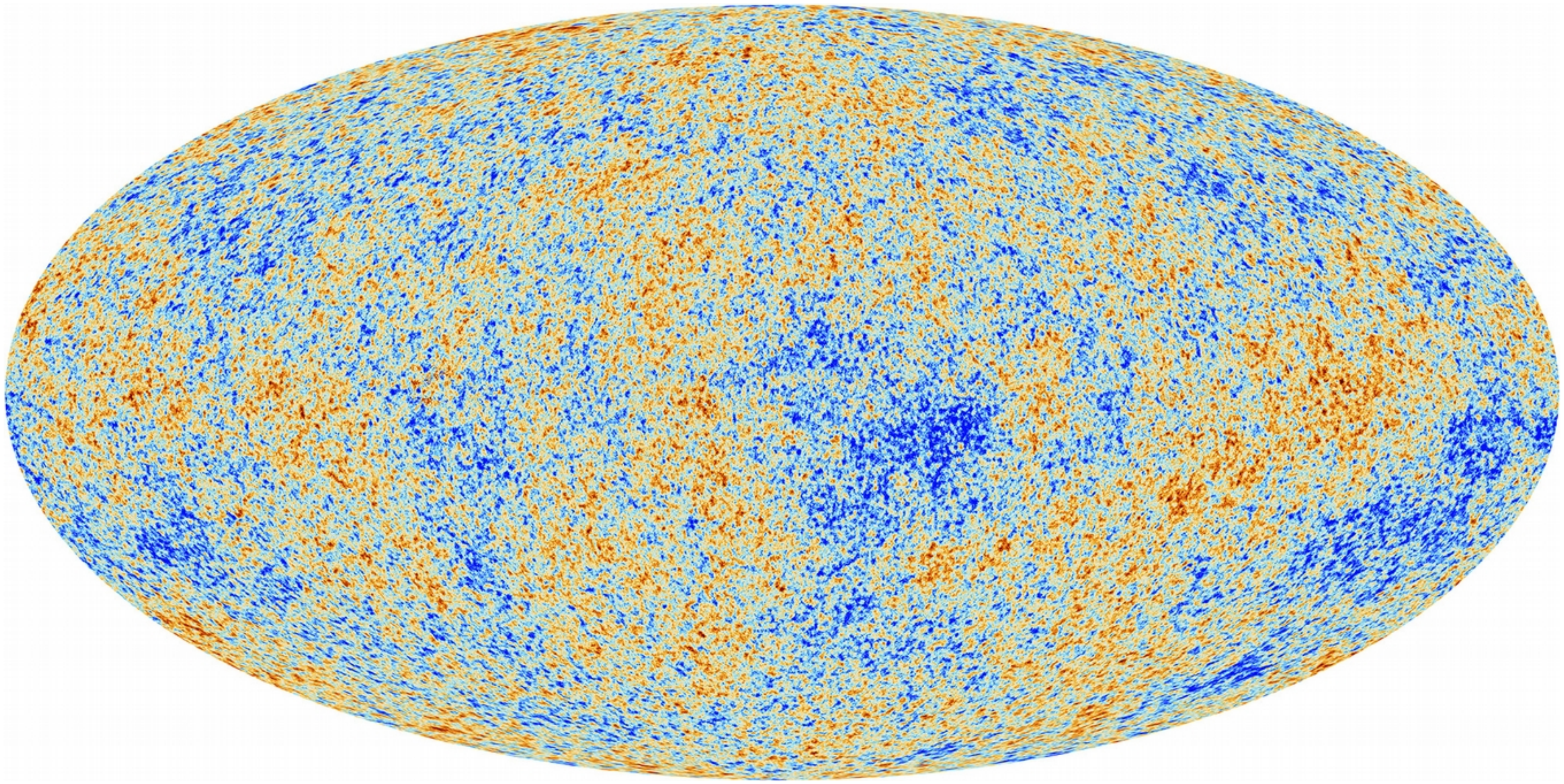
gravity



These acoustic oscillations have been observed...

Cosmic Sound Waves

... in the correlations of the cosmic microwave background (CMB) anisotropies:



Planck (2015)

Cosmic Sound Waves

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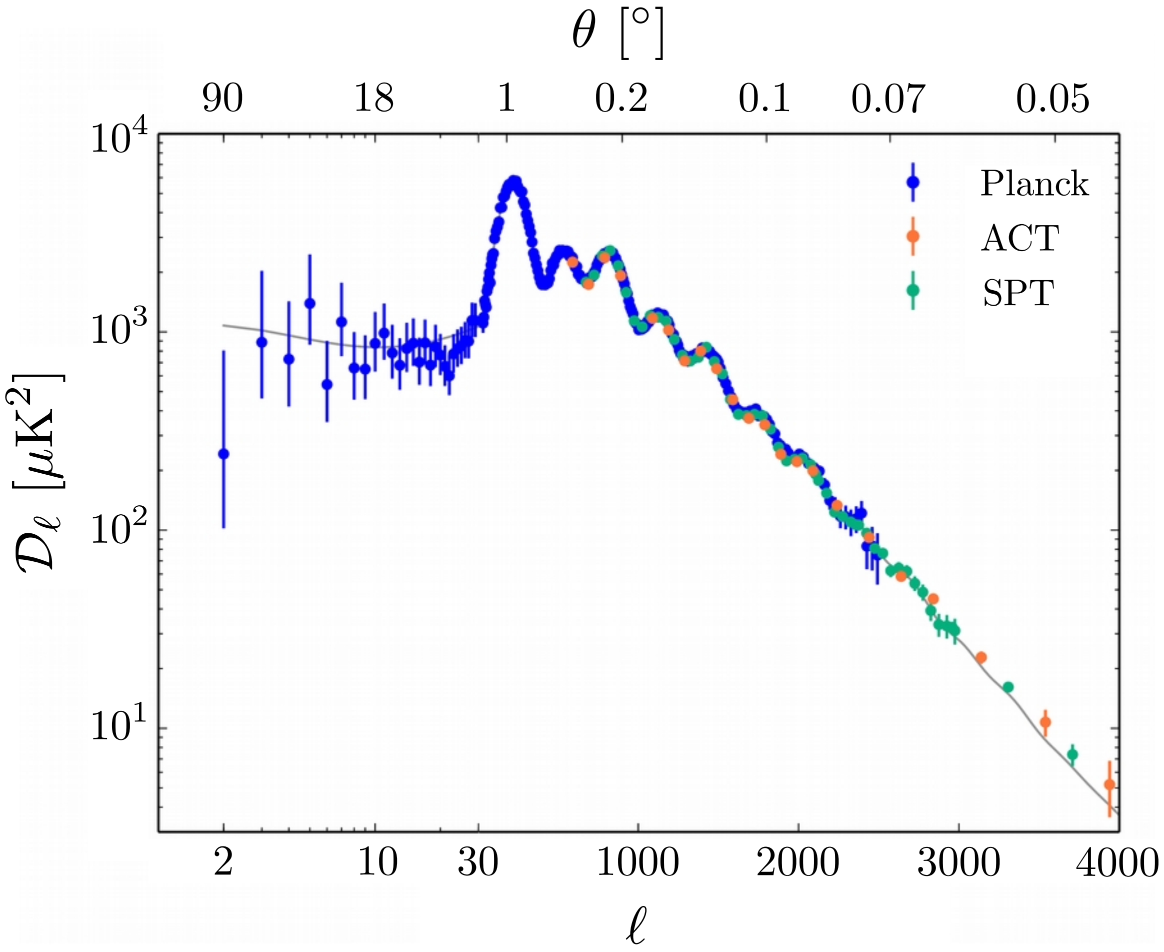
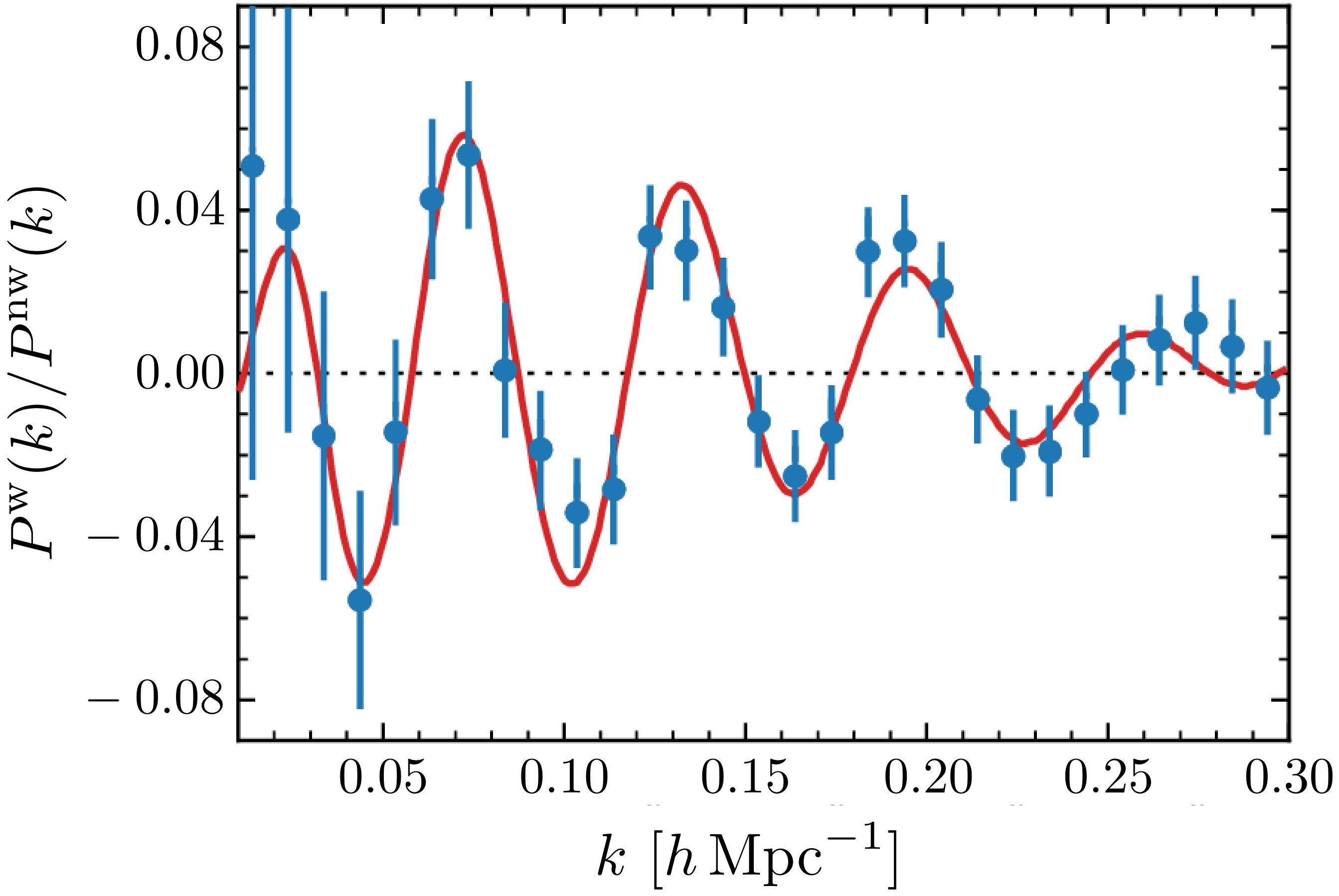


Planck (2015)

Cosmic Sound Waves

... and in the distribution of galaxies in the universe via the spectrum of baryon acoustic oscillations (BAO):



BOSS (2016)

Matter Power Spectrum

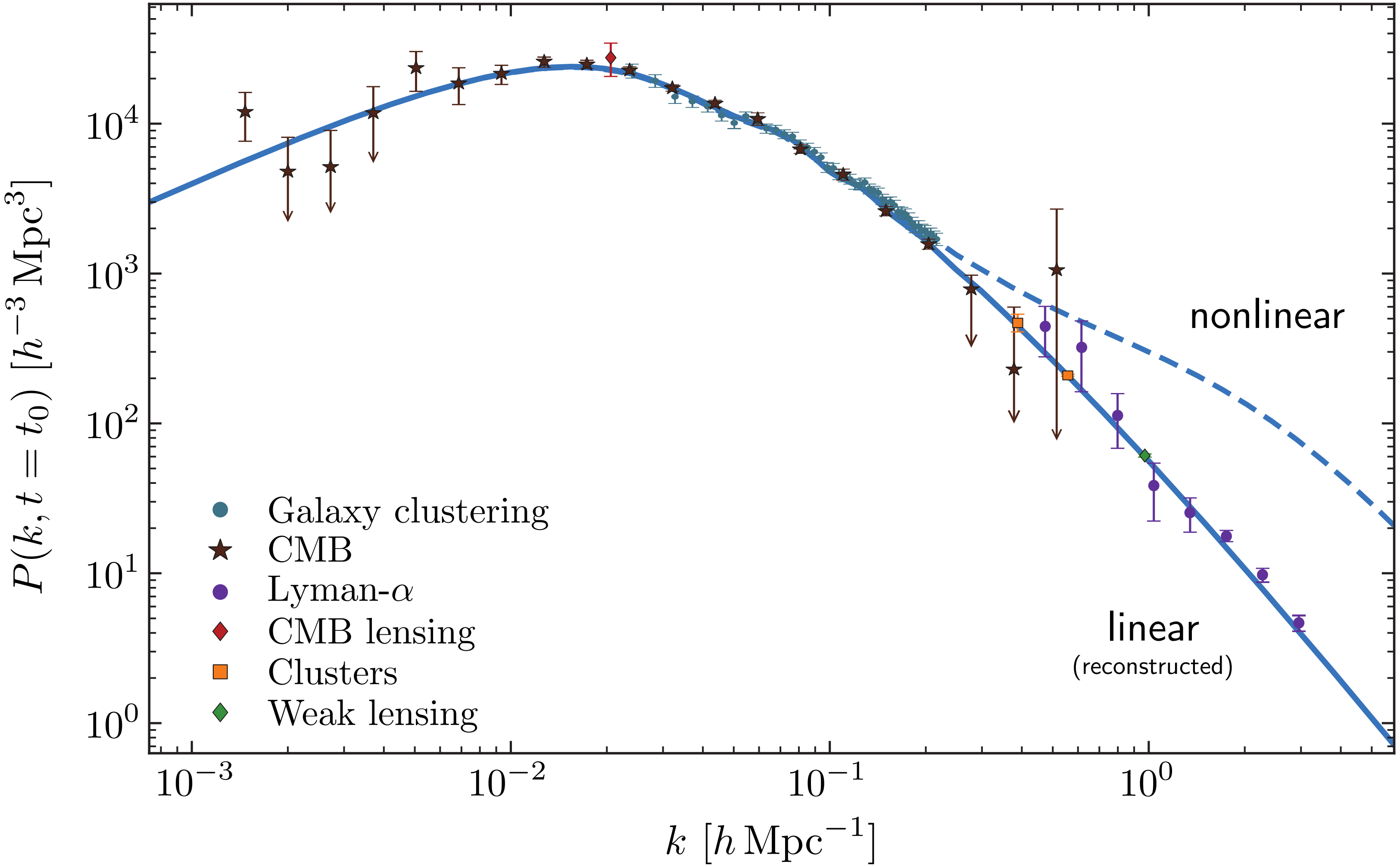
$$\delta(\vec{x},t) \equiv \frac{\rho(\vec{x},t)-\bar{\rho}(t)}{\bar{\rho}(t)}$$

$$\downarrow$$

$$\delta(\vec{k},t) = \int \mathrm{d}^3x\, \mathrm{e}^{-\mathrm{i}\vec{k}\cdot\vec{x}}\, \delta(\vec{x},t)$$

$$\downarrow$$

$$P(k,t) \sim \left\langle \left|\delta(\vec{k},t)\right|^2 \right\rangle \longrightarrow$$



Hložek et al. (2012)

Why Consider Large-Scale Structure?

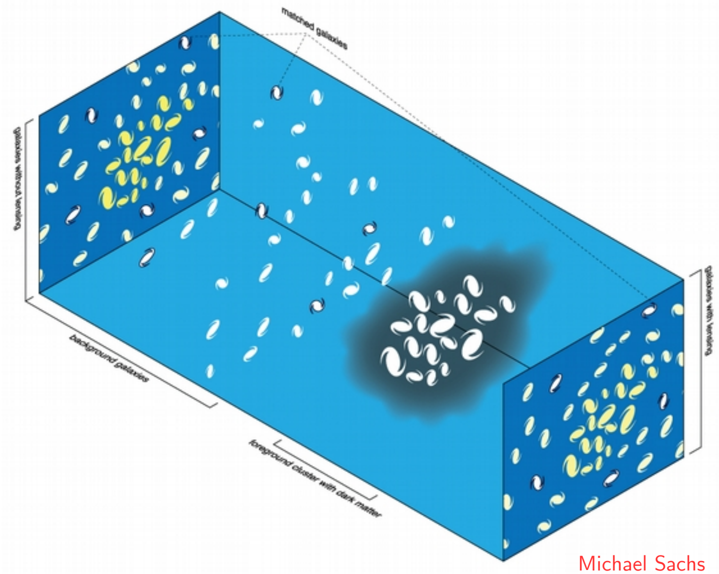
- Additional observational information.
- Complementary to cosmic microwave background observations.
- More observable modes: 2d (CMB) versus 3d (LSS).
- More statistical power (in principle).
- Accessibility of smaller scales (in principle).
- Vast observational effort in next few years:

  DES, DESI, LSST, Euclid, SPHEREx, ...

→ Another window onto our universe!

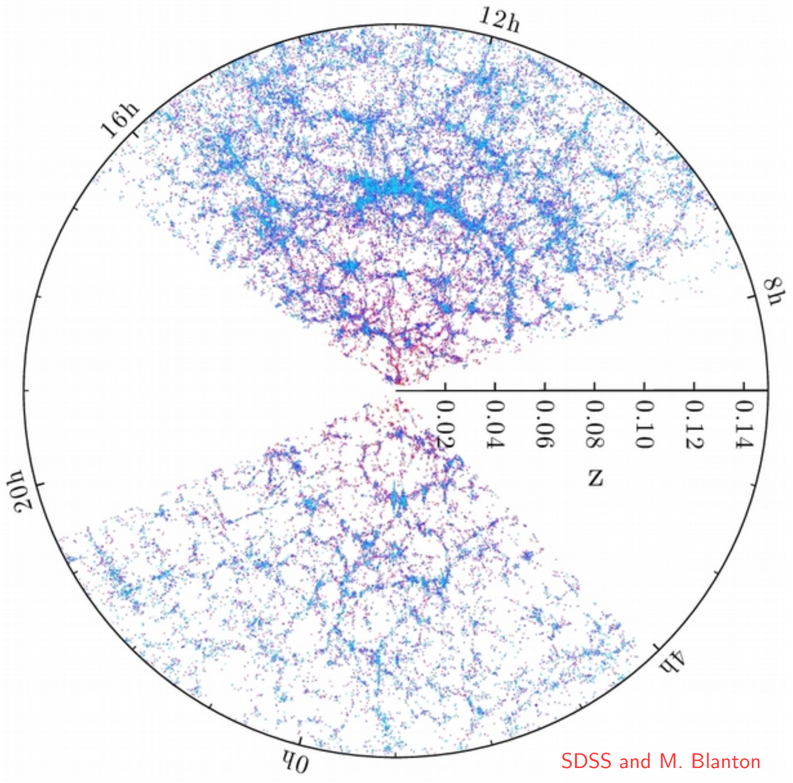
Some Large-Scale Structure Observables

Weak lensing



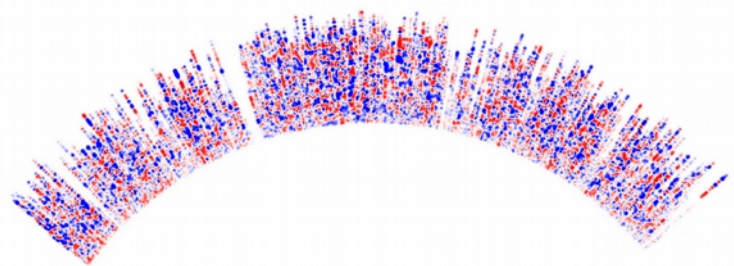
Michael Sachs

Galaxy clustering



SDSS and M. Blanton

Lyman-α forest



SDSS and A. Slosar

Galaxy clusters

NASA, ESA and M. Brodwin

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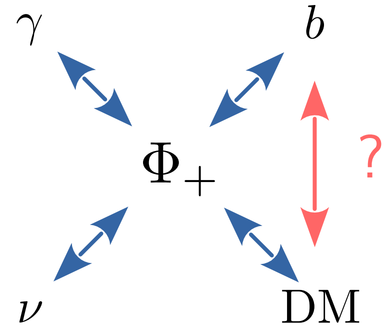
Dark Matter-Baryon Interactions



- Effective field theory:

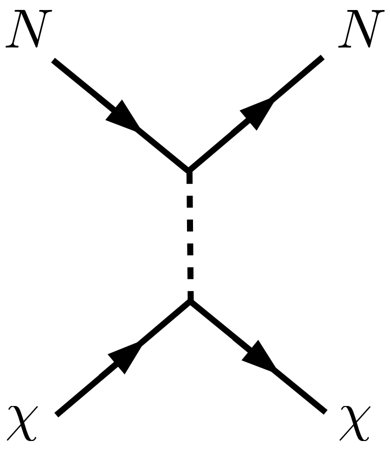
$$\mathcal{L} \sim O_\chi \, O_N$$

operator with dark matter fields

$\bar{\chi}\,\chi$

$\mathrm{i}\bar{\chi}\,\gamma^5\,\chi$

$\vdots$



operator with baryon/nucleon fields

$\bar{N}\,N$

$\mathrm{i}\bar{N}\,\gamma^5\,N$

$\vdots$

- Effective description in terms of velocity-dependent cross-section:

$$\sigma(v) = \sigma_0 v^n$$

Linear Perturbation Theory

- Effective description in terms of velocity-dependent cross-section:

$$\sigma(v) = \sigma_0 v^n$$

- Boltzmann equations:

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}\,, \qquad \dot{\theta}_\chi = -\mathcal{H}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)\,,$$

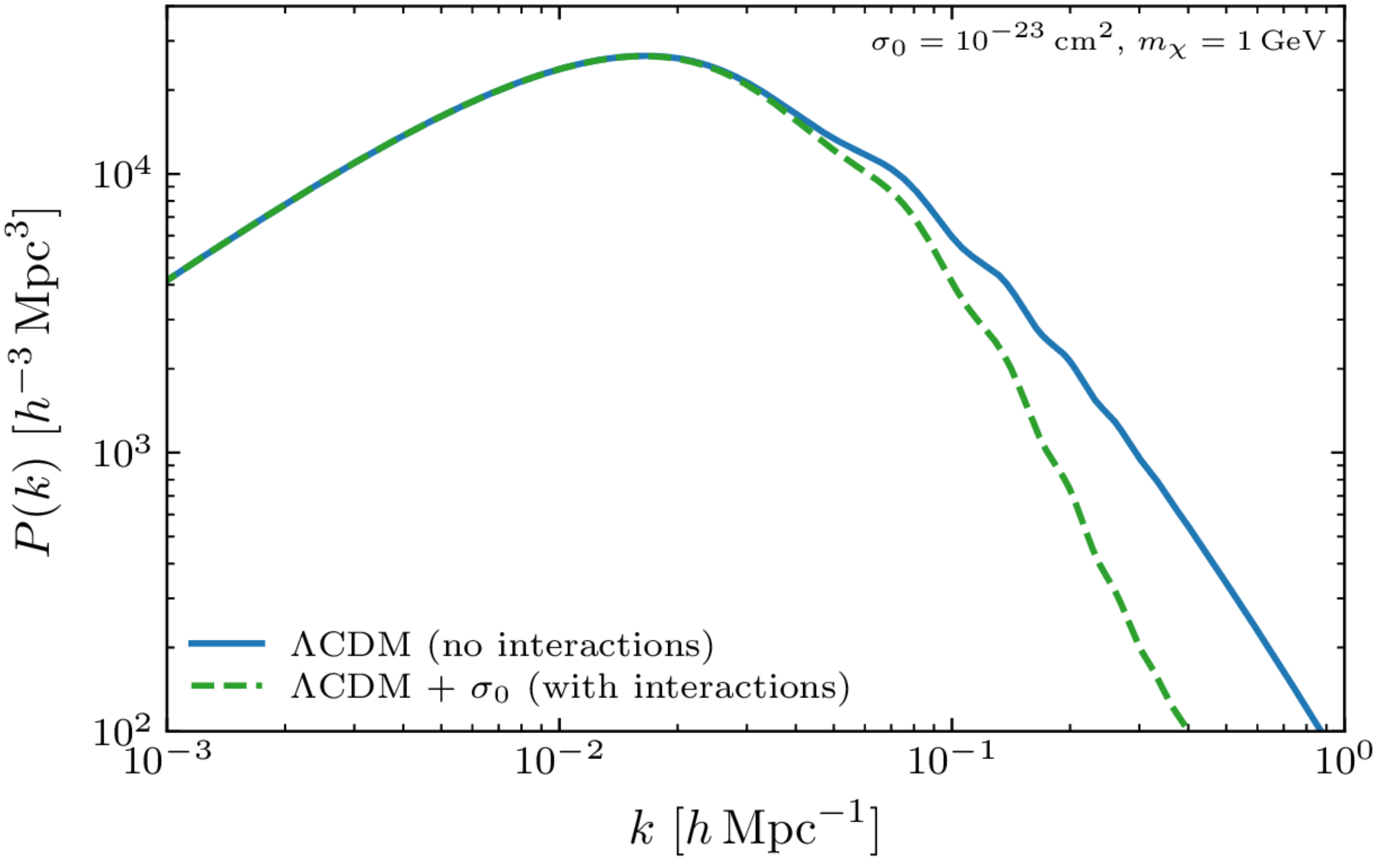
$$\dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2}\,, \qquad \dot{\theta}_b = -\mathcal{H}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b} R_\chi(\theta_\chi - \theta_b)\,.$$

- Dark matter-baryon momentum exchange rate:

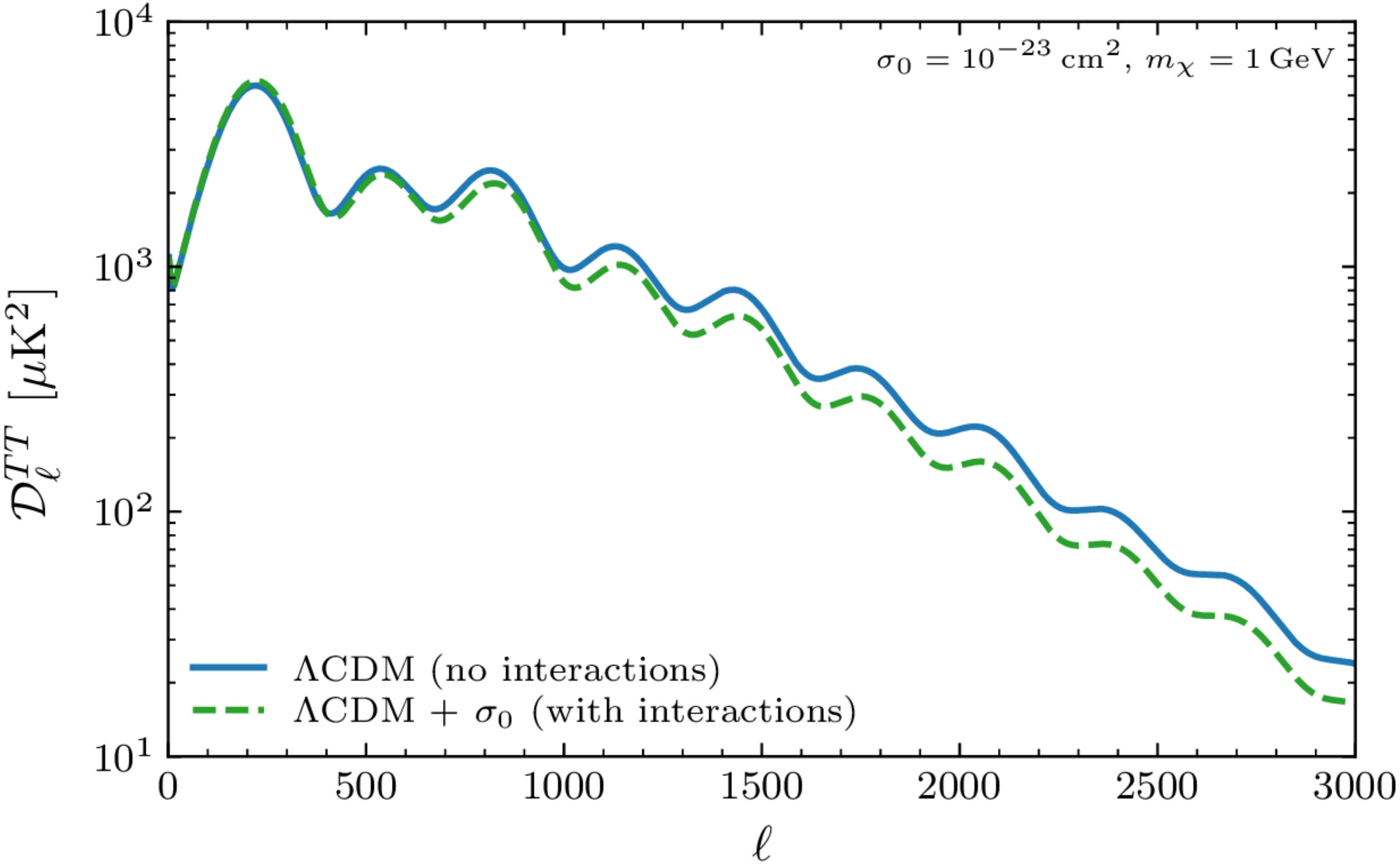
$$R_\chi = \frac{a c_n \rho_b \sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} \right)^{\frac{n+1}{2}} F_{\mathrm{He}}$$

cf. Ma & Bertschinger (1995), Chen et al. (2002), Sigurdson et al. (2004), Dvorkin et al. (2014), Gluscevic & Boddy (2018), ...

Matter Power Spectrum

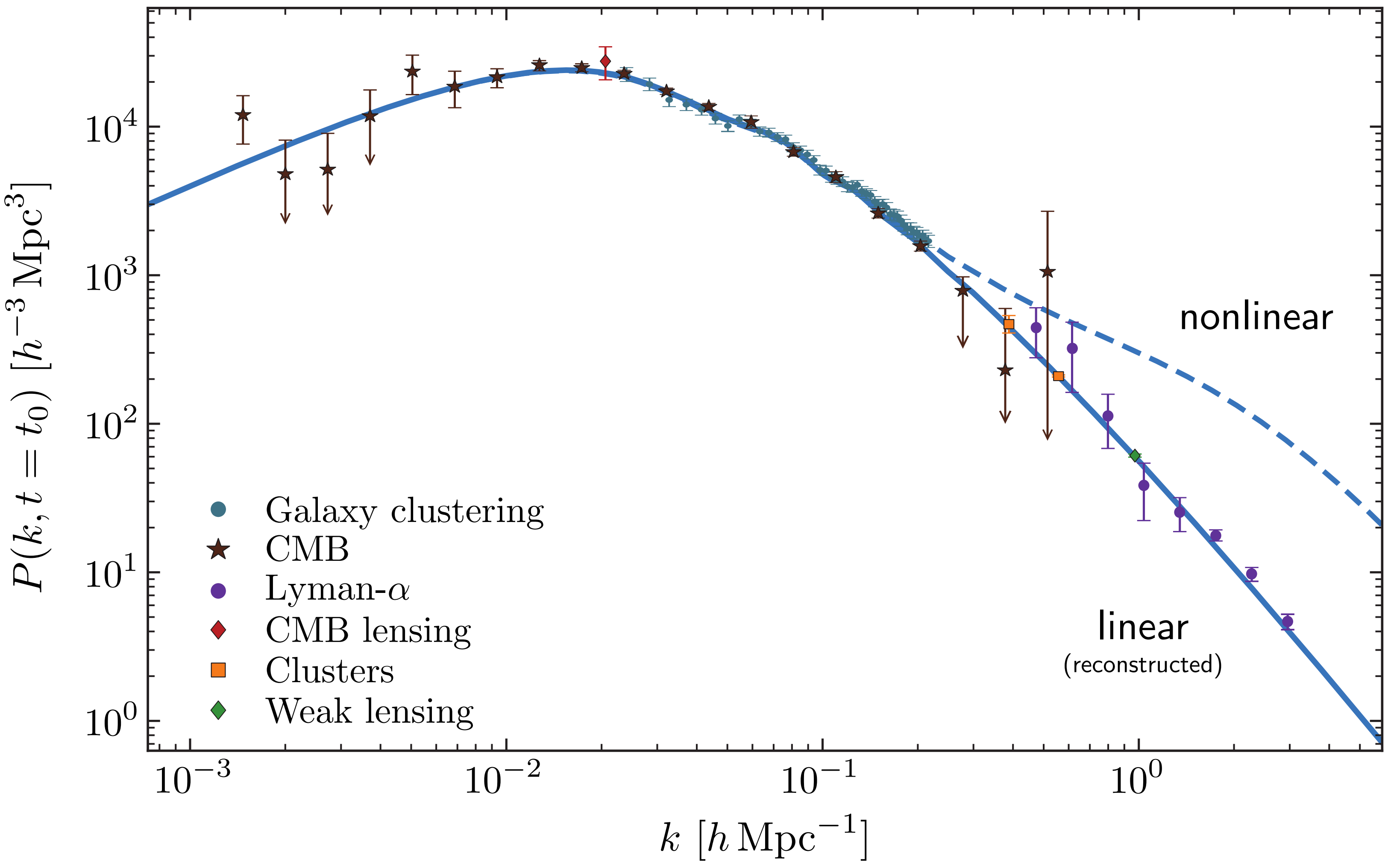


CMB Temperature Power Spectrum



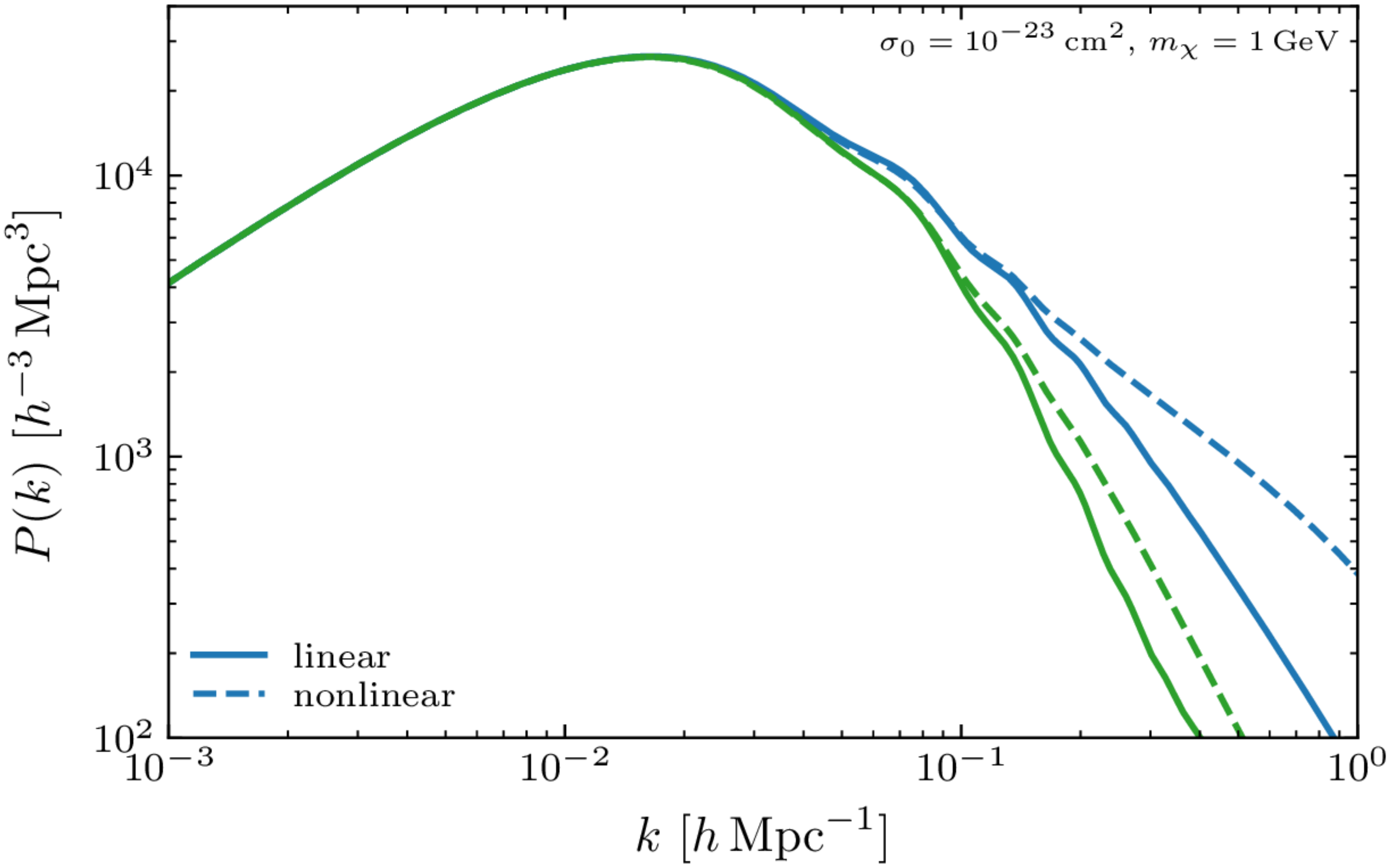
→ Planck constraints by Dvorkin (2014), Boddy & Gluscevic (2018), ...

But Remember: Gravitational Nonlinearities...



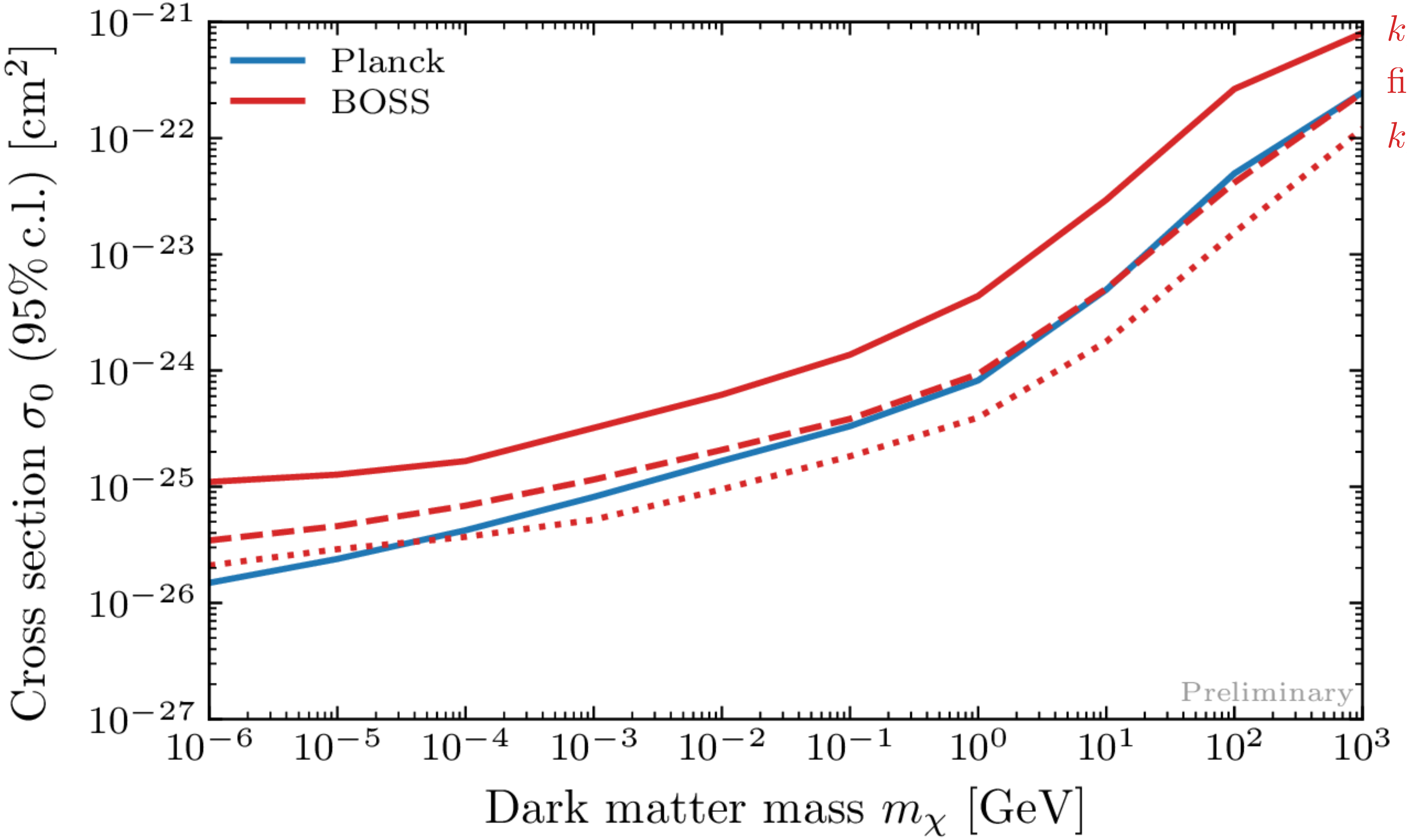
Hložek et al. (2012)

Matter Power Spectrum



Nonlinear spectrum computed using EFTofLSS.

Forecasts for Planck and BOSS



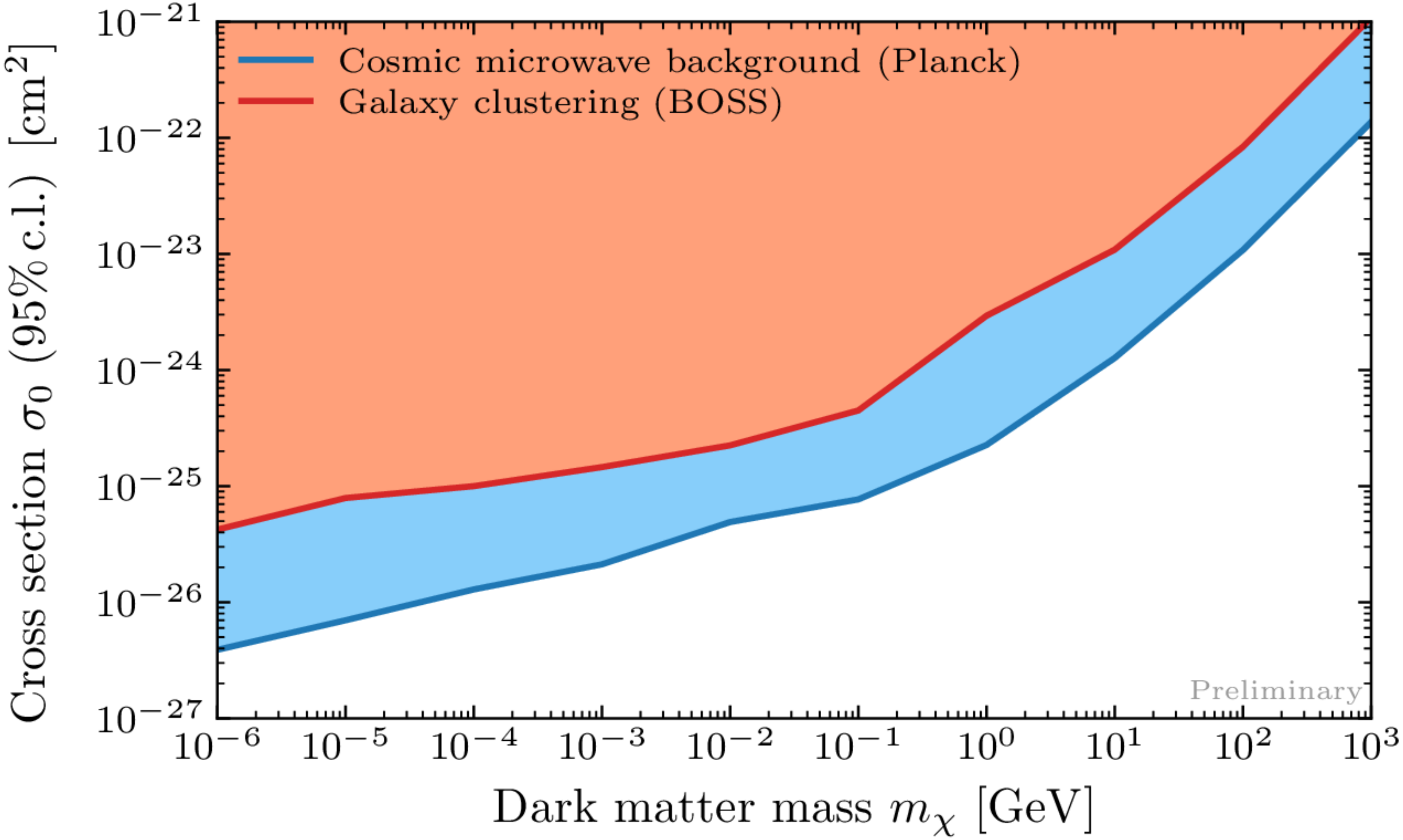
$k_{\max} = 0.25\,h\,\mathrm{Mpc}^{-1}$

fix some parameters

$k_{\max} = 0.5\,h\,\mathrm{Mpc}^{-1}$

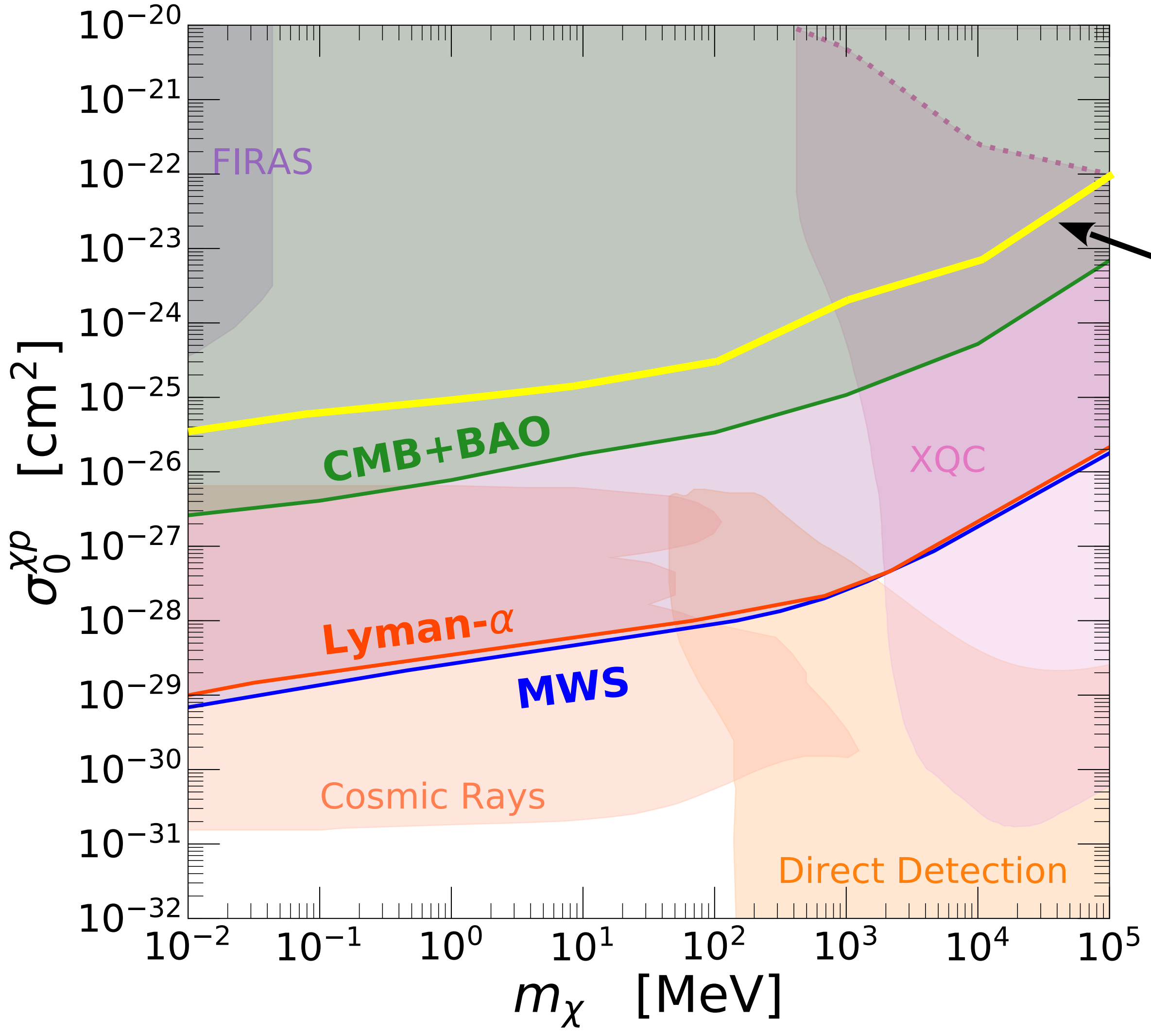
*Cosmology with half of the dark matter interacting with baryons; the other half is collisionless

First Preliminary Bounds from BOSS DR12



*Cosmology with half of the dark matter interacting with baryons; the other half is collisionless

Preliminary Projection on the Comparison Plot



BOSS DR12
galaxy clustering
(preliminary)

Adapted from Buen-Abad et al. (2021); see also Maamari et al. (2021)

Preliminary Forecasts for Future CMB and LSS Surveys

- **CMB**, i.e. Simons Observatory and CMB-S4:
  - could potentially improve the bounds by about 1-2 orders of magnitude,
  - with nonlinear CMB lensing contributing O(1) in sensitivity to linear CMB lensing
  - and a factor of up to 6 over linear unlensed TTTEEE-only.

- **LSS**, i.e. DESI, Euclid and more futuristic surveys:
  - may lead to sizable improvements, at least similar to CMB-S4,
  - details to be verified.

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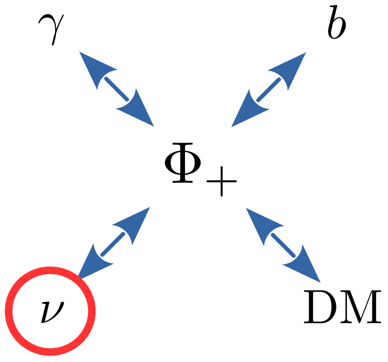
Effective Number of Neutrinos

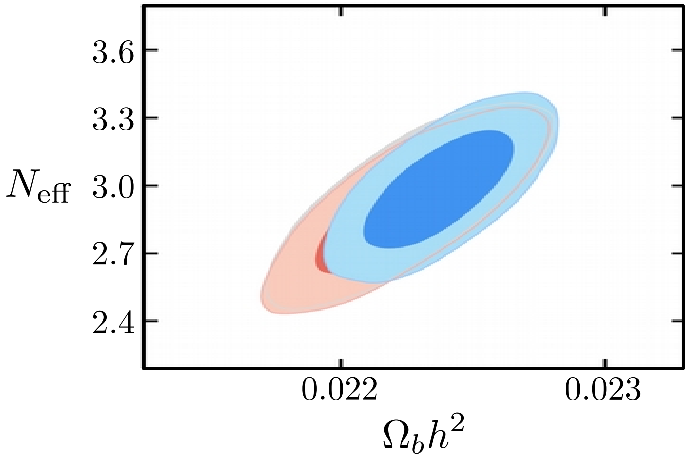


- Neutrinos: 41% of the radiation density in the universe
  - → Leave gravitational imprint,
  - → Can detect their energy density.

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

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

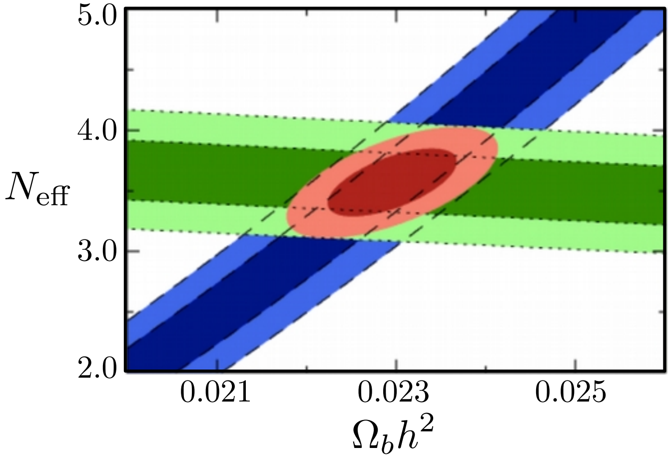
e.g. Akita &Yamaguchi (2020), Froustey et al. (2020), Bennett et al. (2021)



CMB: anisotropy measurements

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

Planck (2018)

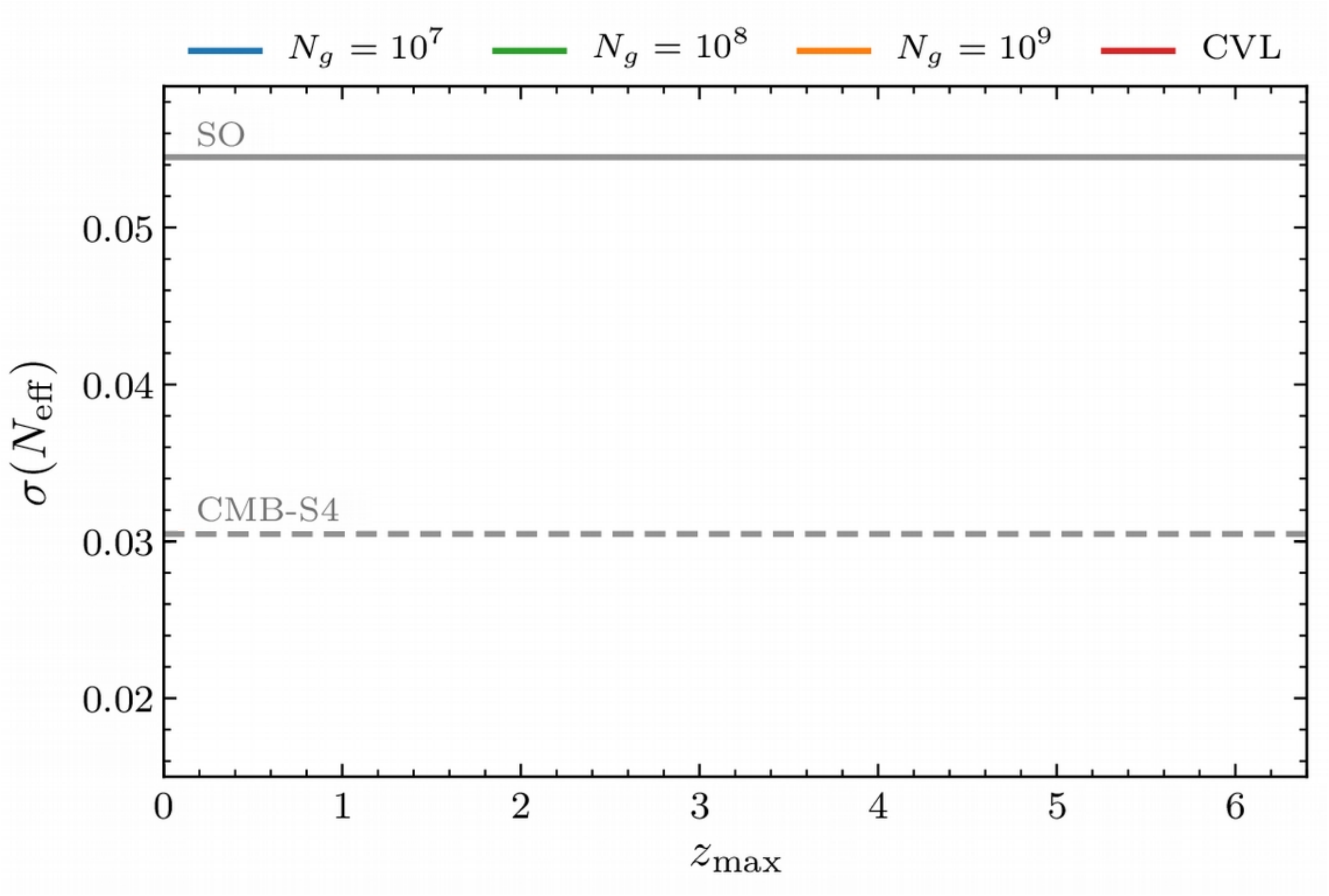


BBN: primordial abundances

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

Cooke et al. (2015)

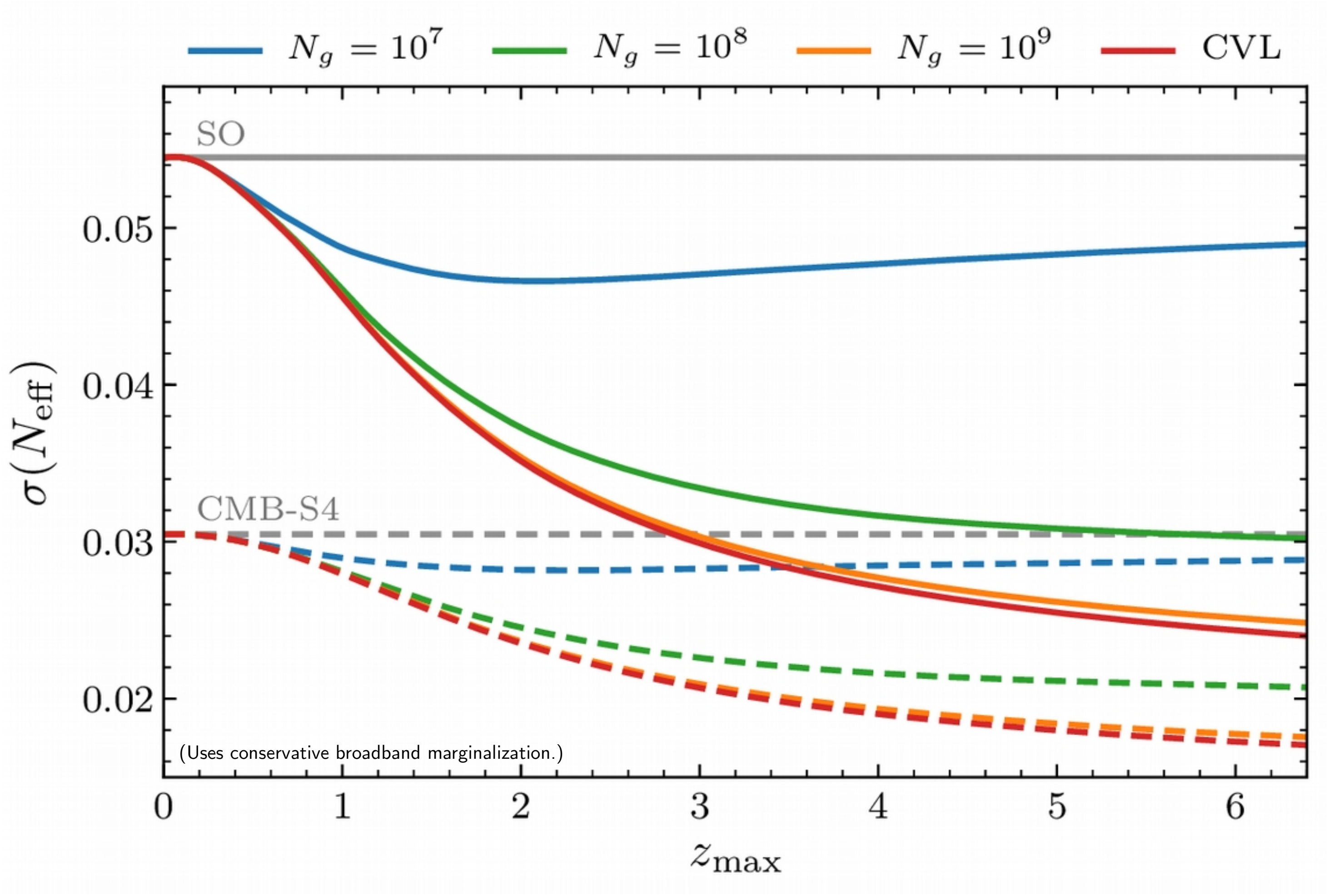
Future Constraints from CMB and Large-Scale Structure



→ Go beyond neutrinos and probe other light relics!

Baumann, Green & BW (2018)

Future Constraints from CMB and Large-Scale Structure

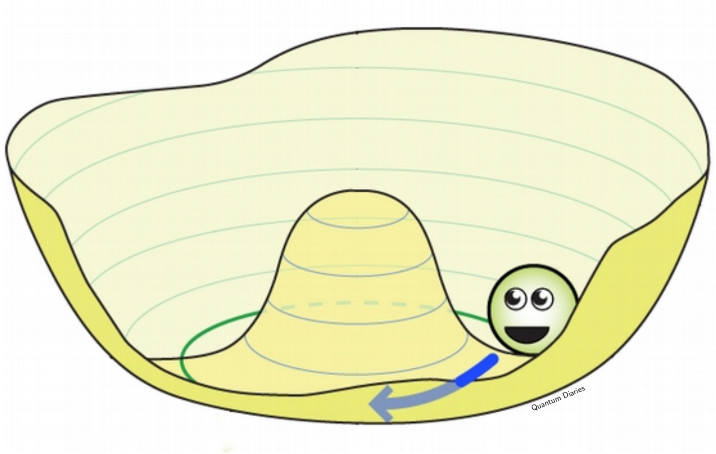


(Uses conservative broadband marginalization.)

→ Go beyond neutrinos and probe other light relics!

Baumann, Green & BW (2018)

Extra Light Species



Light and weakly interacting particles arise in many BSM models, e.g. from spontaneously broken global symmetries.

Classification of their interactions with the Standard Model in effective field theory:

$$\mathcal{L} \supset \sum \frac{\mathcal{O}_X \mathcal{O}_{\text{SM}}}{\Lambda^{\Delta}}$$

allowed interactions constrained by symmetry

symmetry breaking scale

Useful to classify according to spin
→ dark scalars (e.g. axions), dark fermions, dark forces, gravitino.

Brust, Kaplan & Walters (2013)

Light Thermal Relics

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

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

effective number of relativistic degrees of freedom

entropy production

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

Light Thermal Relics

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

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effective number of relativistic degrees of freedom

entropy production

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

Assume:

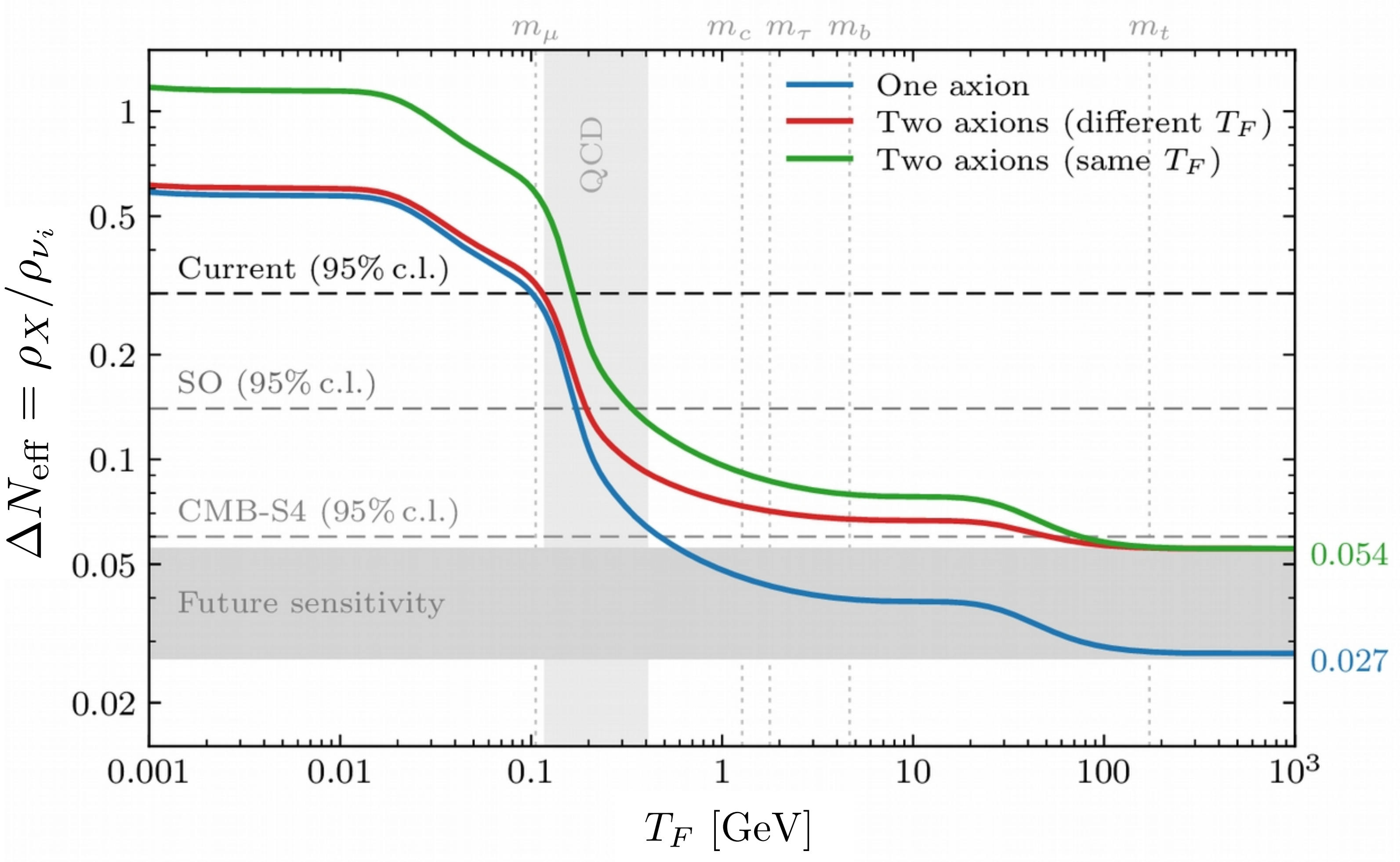
- Negligible entropy production ($\gamma \approx 1$).
- Minimal extension of the Standard Model ($g_*(T \gg m_t) \approx g_{*,SM}$).

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

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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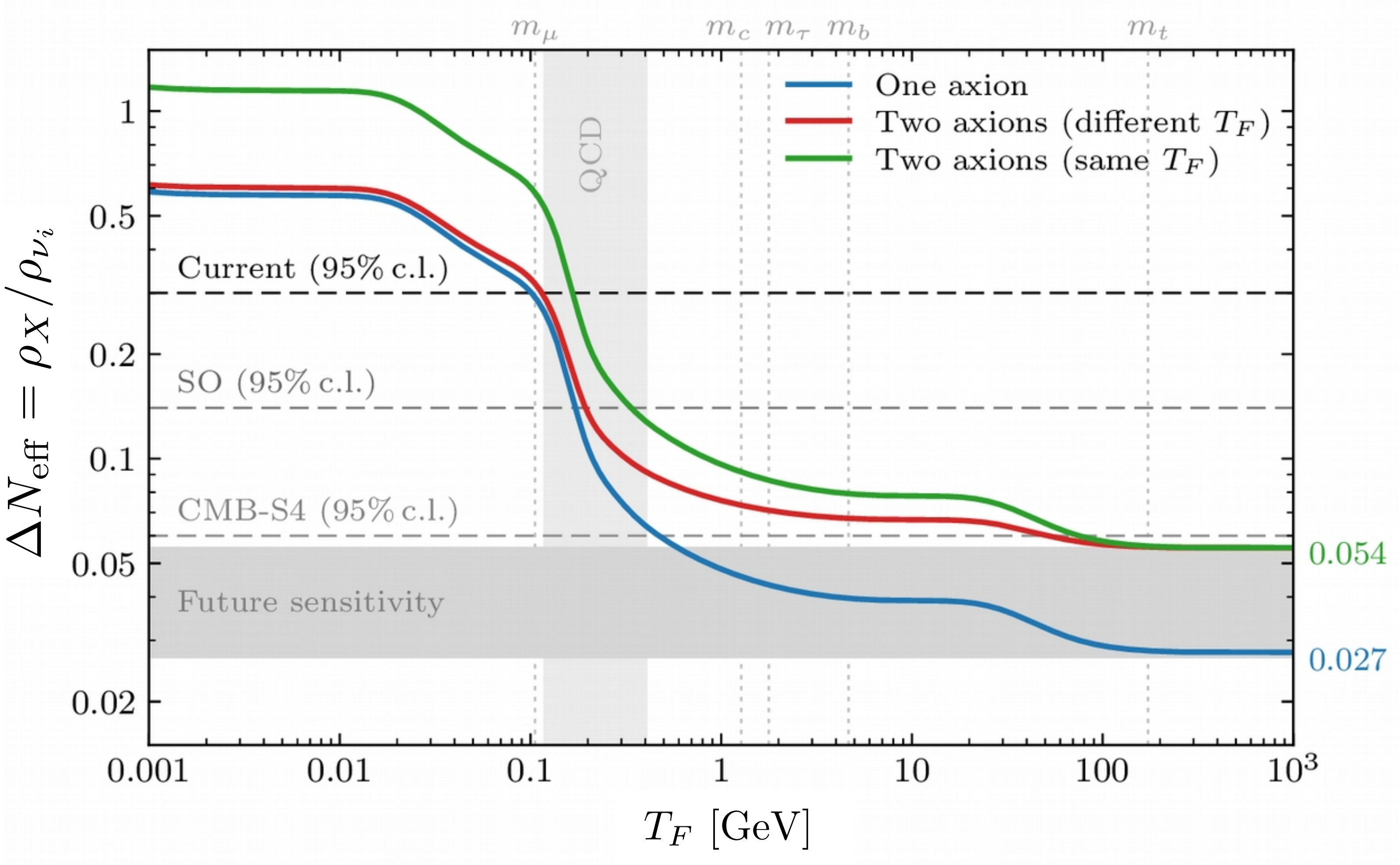


Theoretical Threshold: $\Delta N_{\rm eff} = 0.027$

Detection

Constraints

cf. e.g. Baumann, Green & BW (2016)

Couplings to Standard Model Fermions

General Lagrangian:

$$\begin{aligned}\mathcal{L} &= -\frac{\partial_\mu \phi}{\Lambda_\psi}\bar{\psi}_i \gamma^\mu \left(g_V^{ij} + g_A^{ij}\gamma^5\right)\psi_j \\ &\to \frac{\phi}{\Lambda_\psi}\left(\mathrm{i}H\bar{\psi}_{L,i}\left[\left(\lambda_i - \lambda_j\right)g_V^{ij} + \left(\lambda_i + \lambda_j\right)g_A^{ij}\right]\psi_{R,j} + \mathrm{h.c.}\right) + \mathcal{O}\left(\phi^2\right)\end{aligned}$$

After the electroweak phase transition:

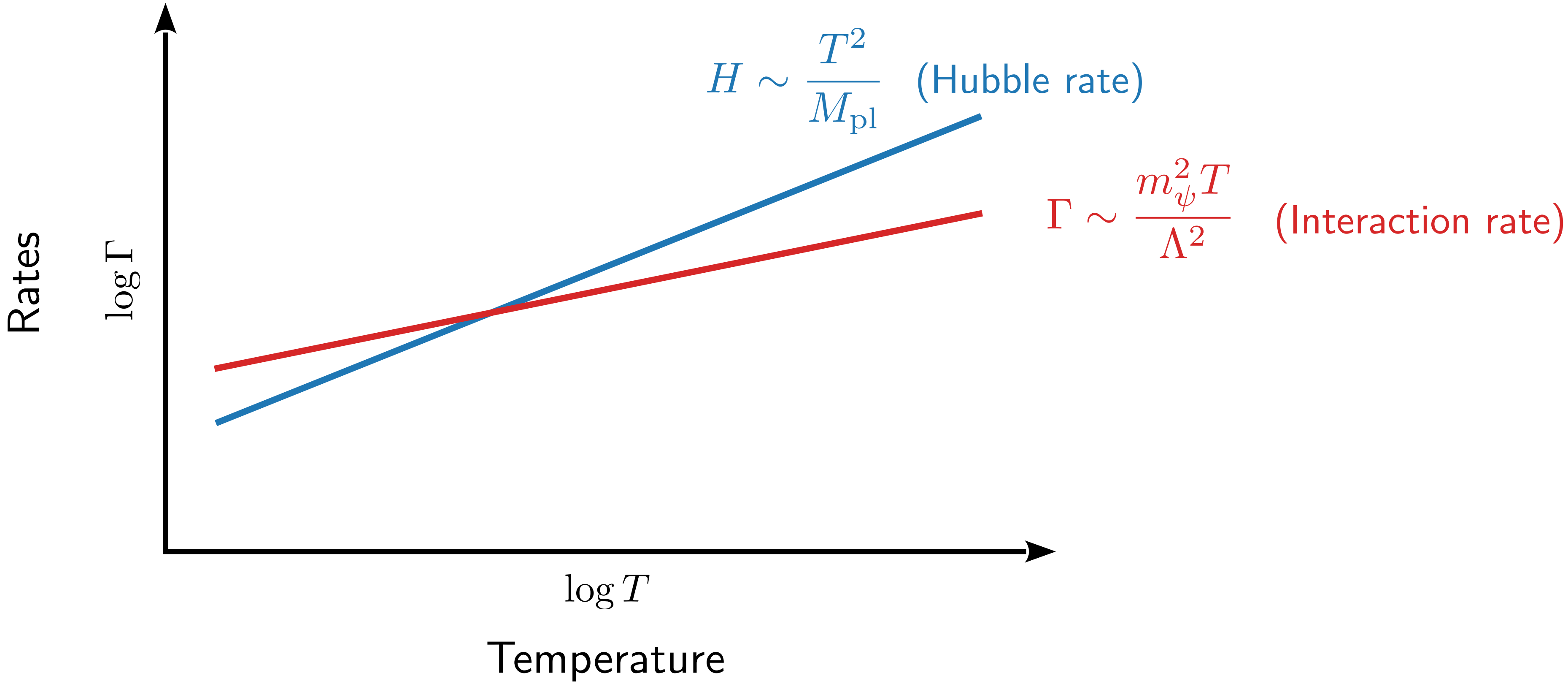
$$\mathcal{L} = \mathrm{i}\frac{\phi}{\Lambda_\psi}\bar{\psi}_i\left[(m_i - m_j)g_V^{ij} + (m_i + m_j)g_A^{ij}\gamma^5\right]\psi_j$$

Restrict to diagonal couplings:

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

Rethermalization

For couplings to SM fermions after the electroweak phase transition:



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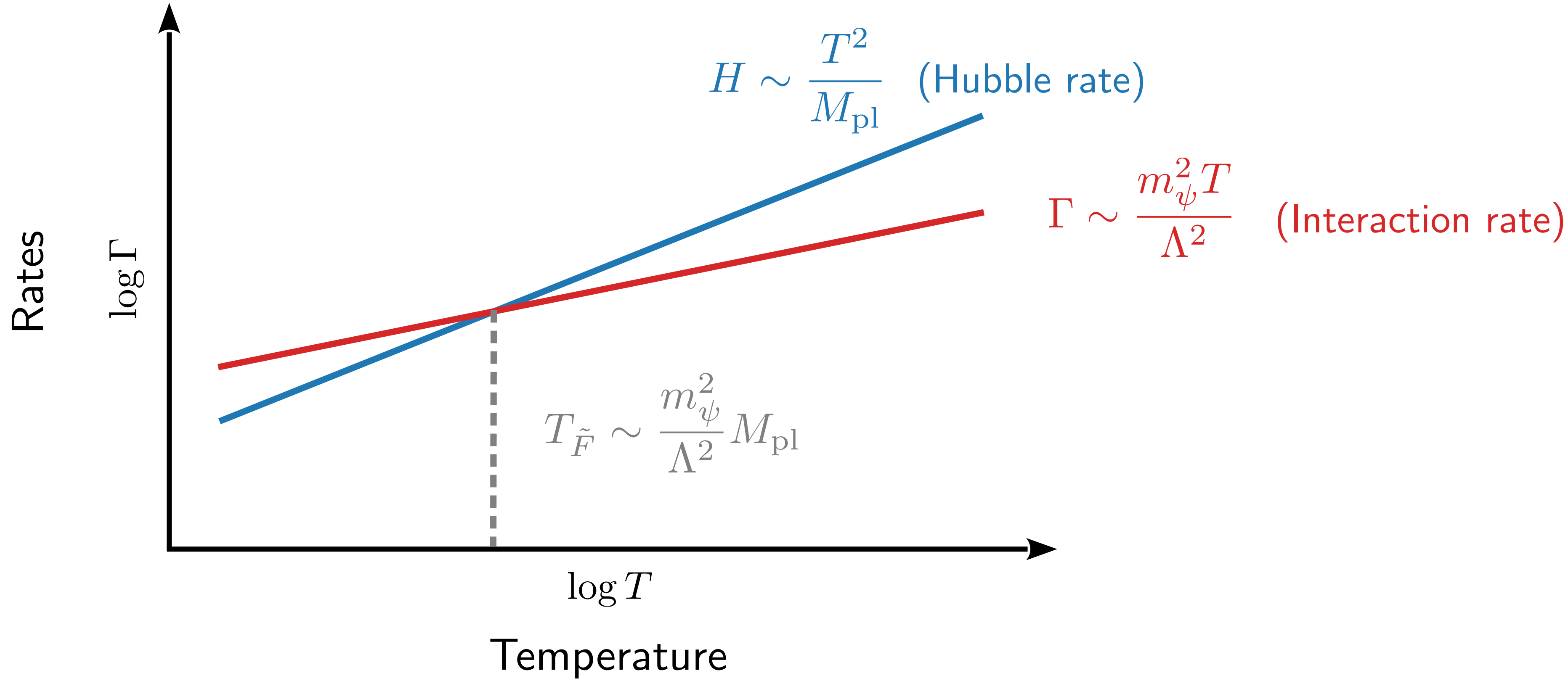
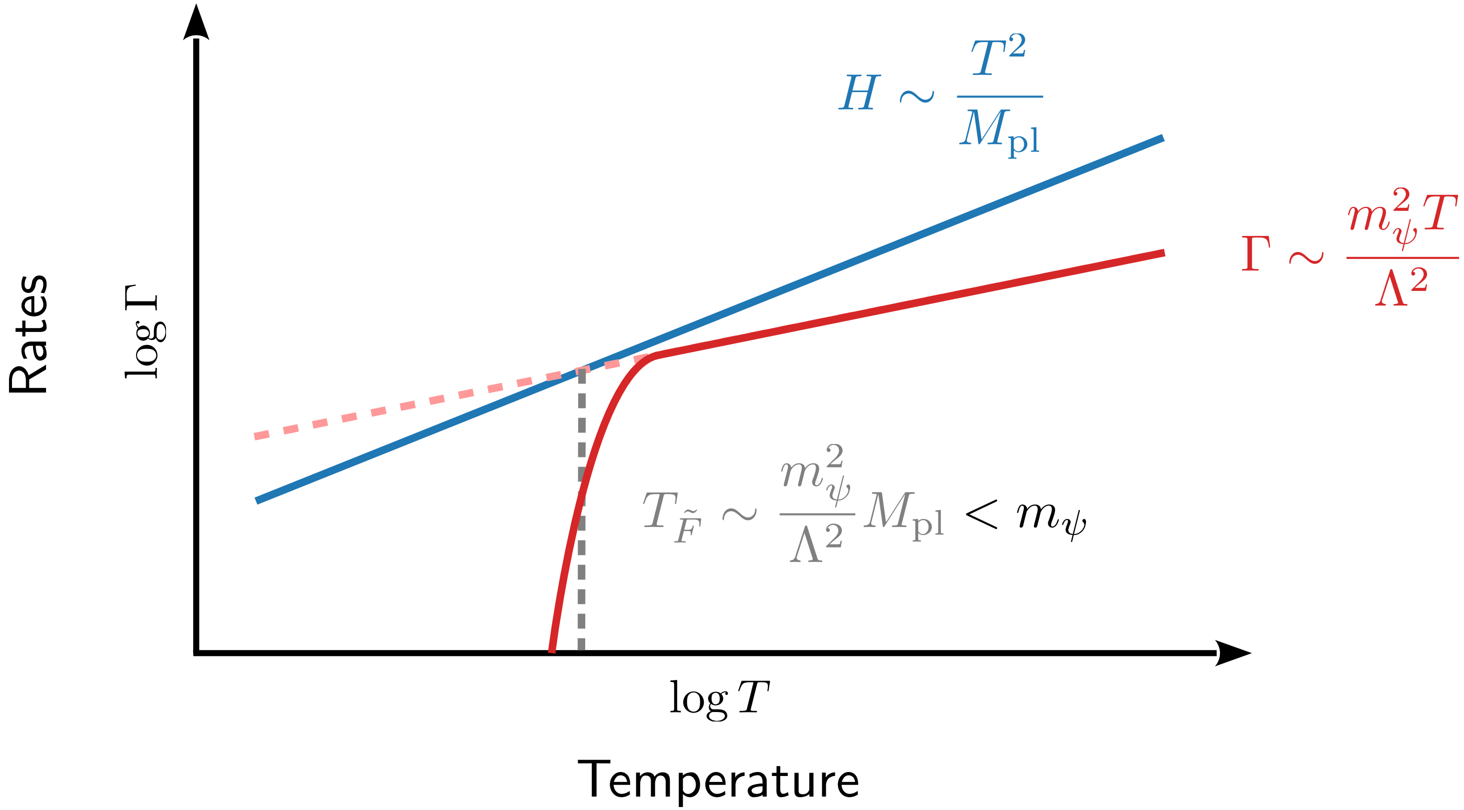


Remember: rethermalization at $H(T) \sim \Gamma(T)$

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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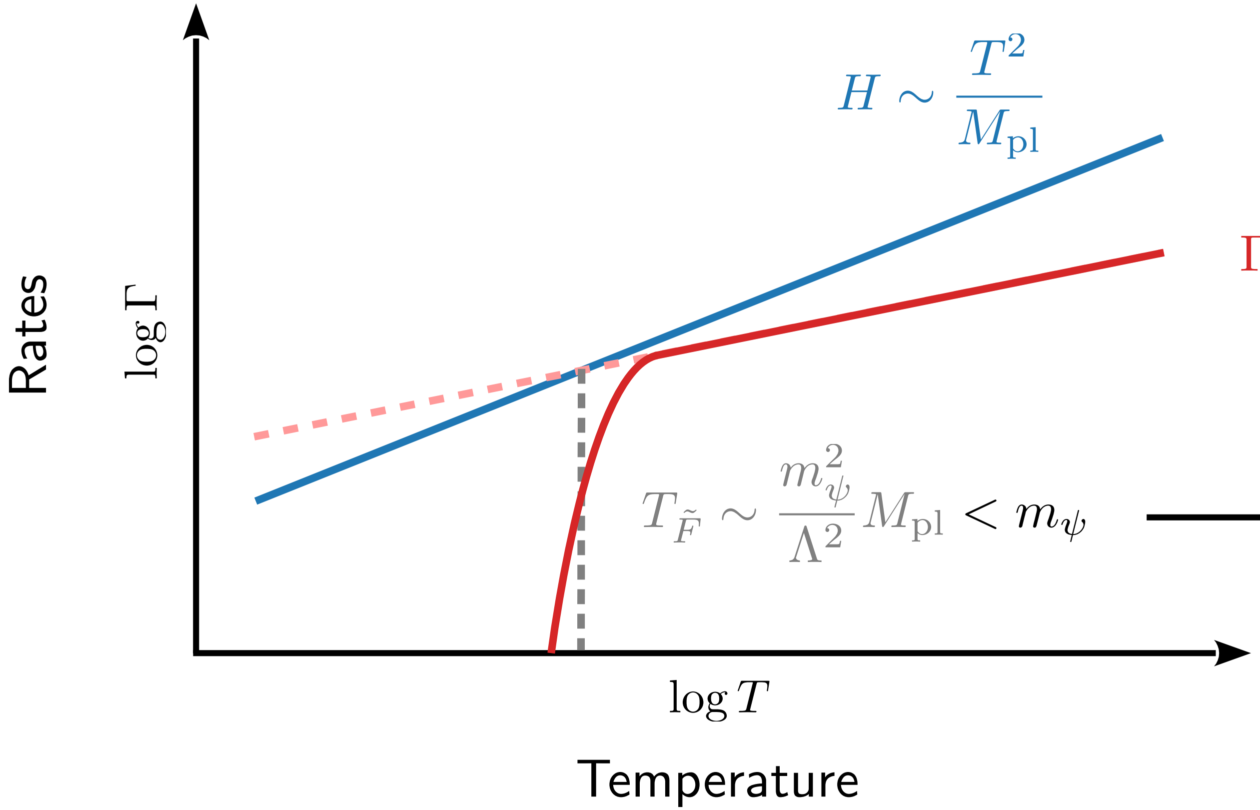
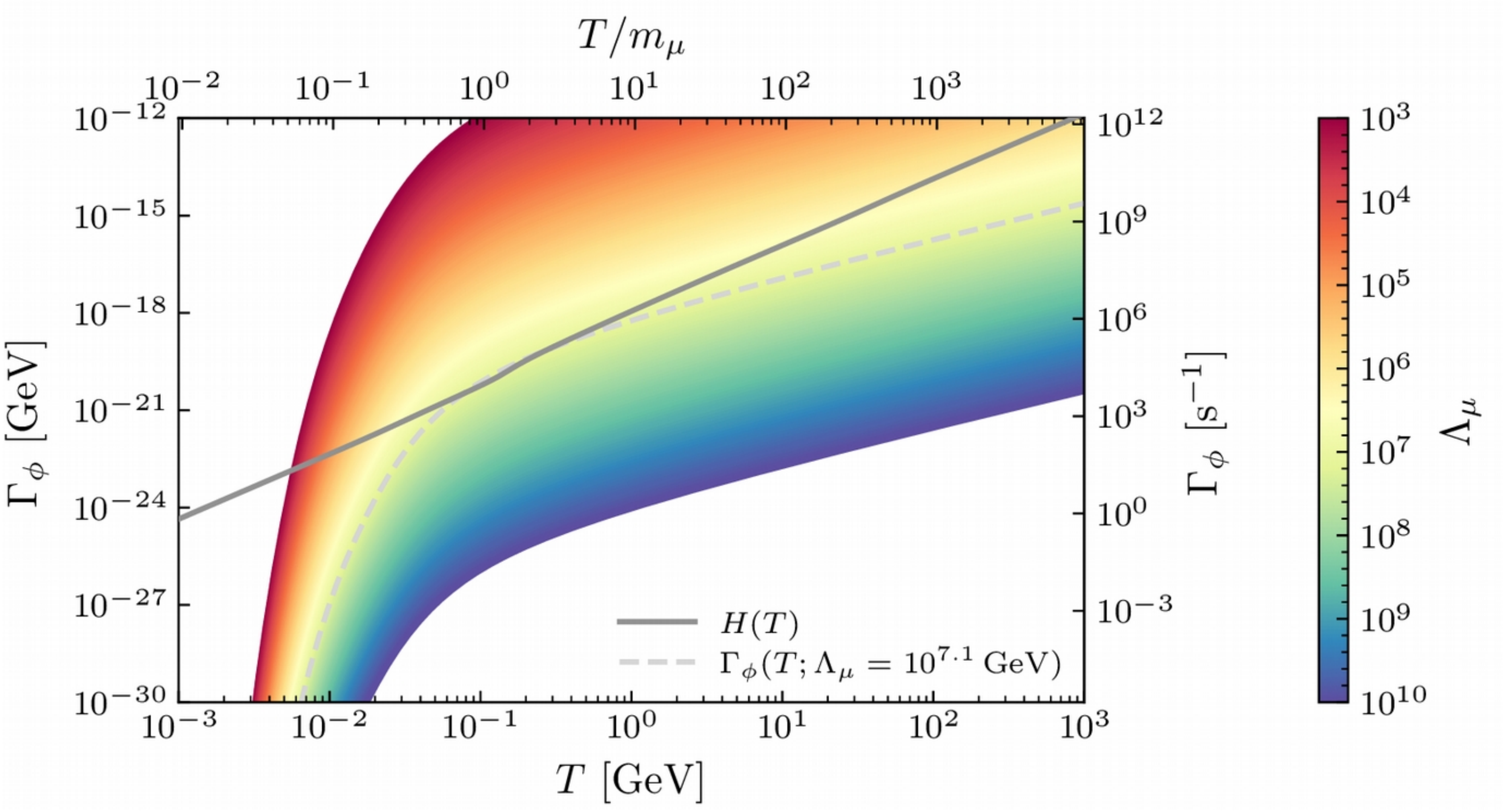


$$T_{\tilde F} \sim \frac{m_\psi^2}{\Lambda^2} M_{\rm pl} < m_\psi \longrightarrow \Lambda \gtrsim c\sqrt{m_\psi\, M_{\rm pl}}$$

Baumann, Green & BW (2016)

Axion-Fermion Interaction Rate

Calculation of the interaction rate without common approximations:

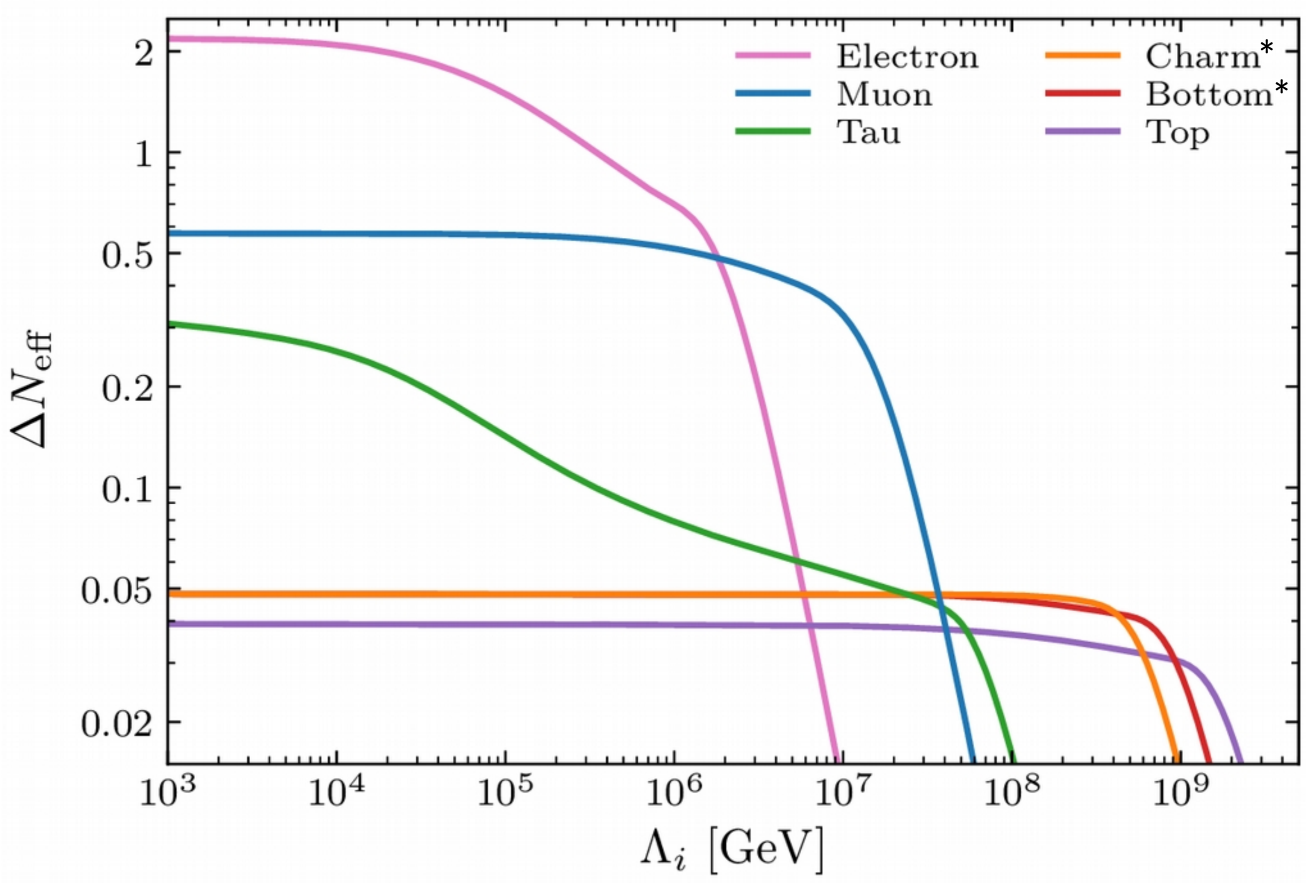


Here: muons, but similar for couplings to other massive SM fermions.

Green, Guo & BW (2021)

Predictions for $\Delta \mathrm{N}_{\mathrm{eff}}$

Solving the Boltzmann equation, we predict:



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

Green, Guo & BW (2021)

Predictions for $\Delta N_{\rm eff}$

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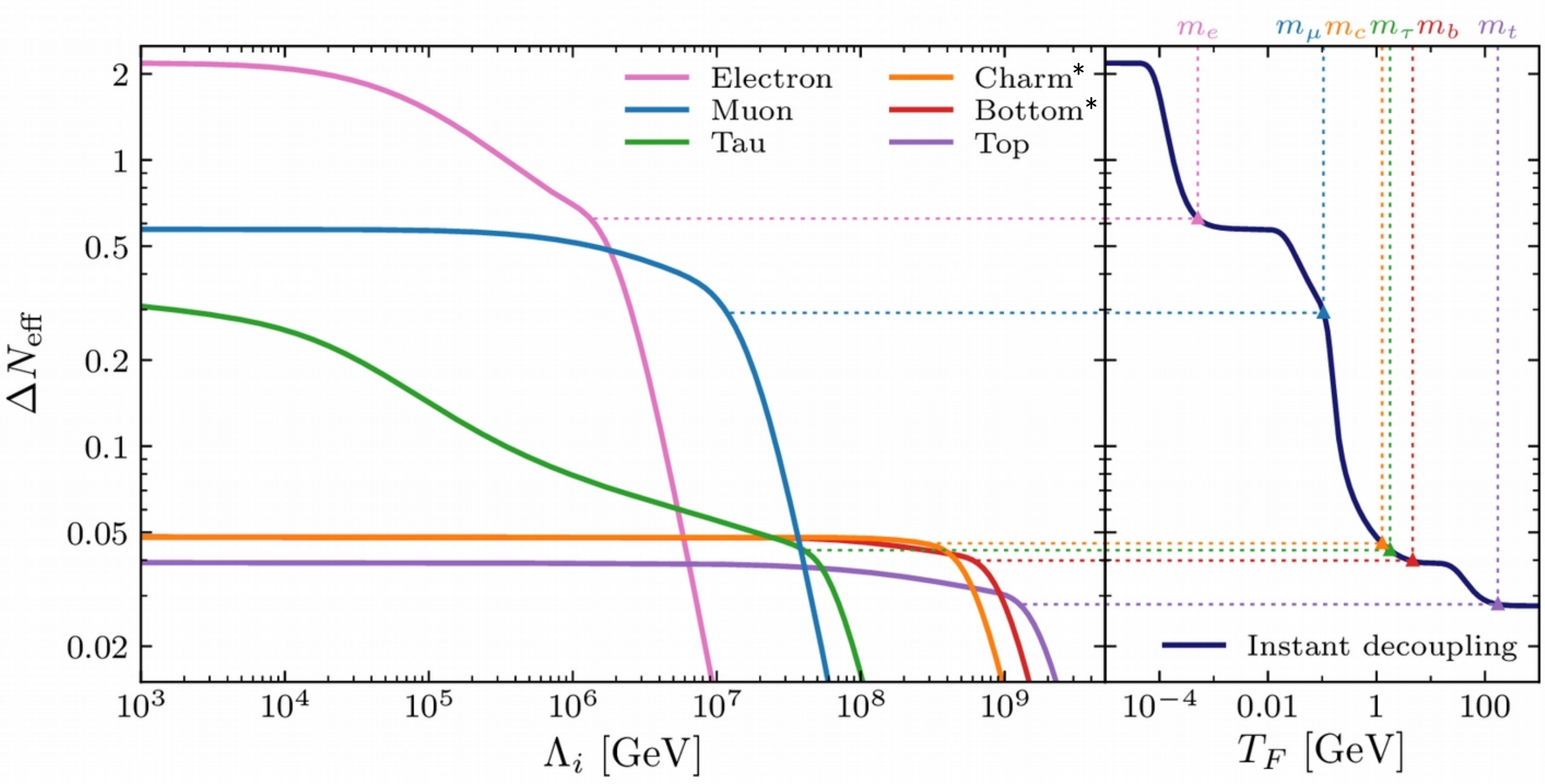

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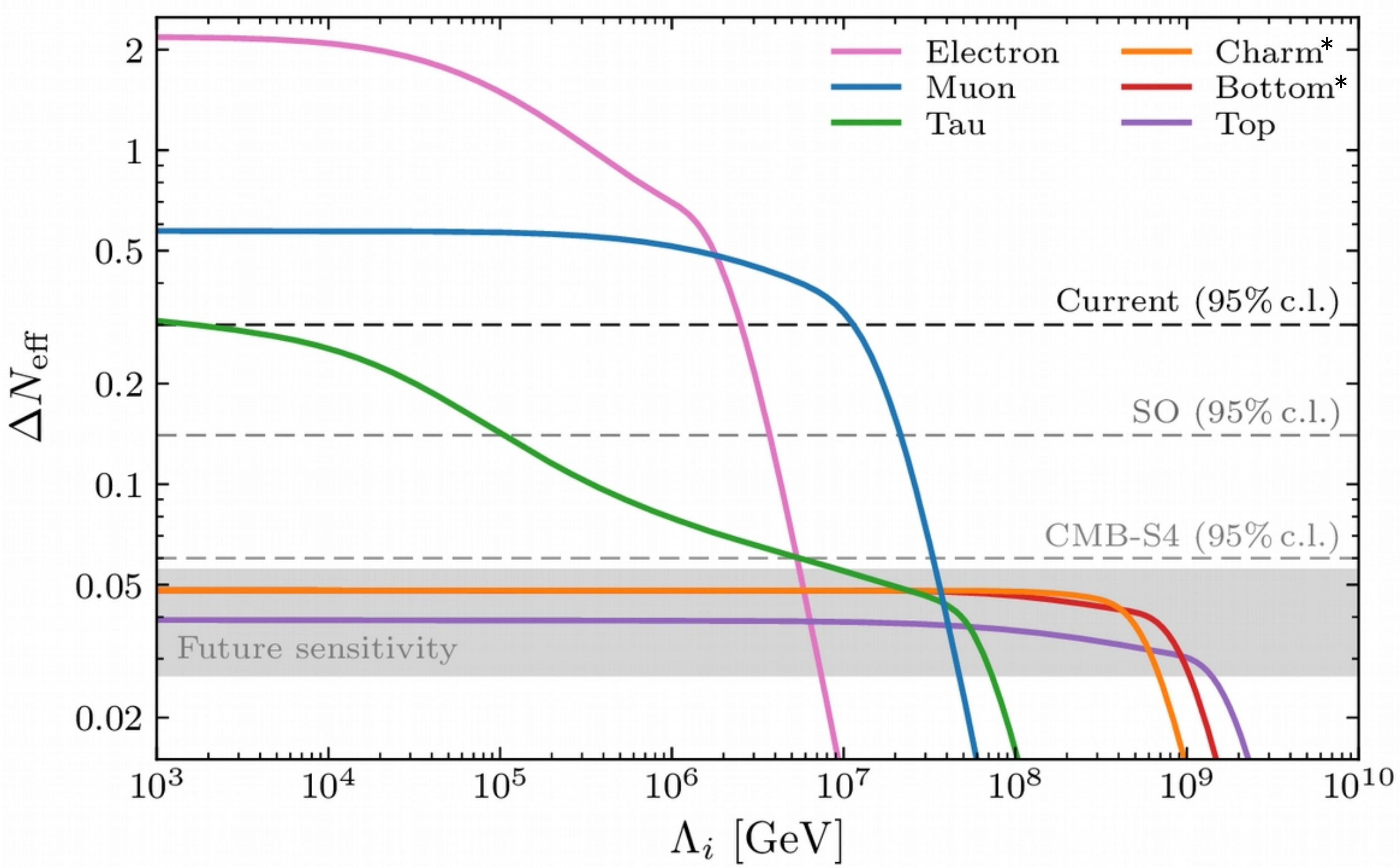
Green, Guo & BW (2021)

Predictions for $\Delta N_{\rm eff}$

Our predictions in comparison to current and future constraints:



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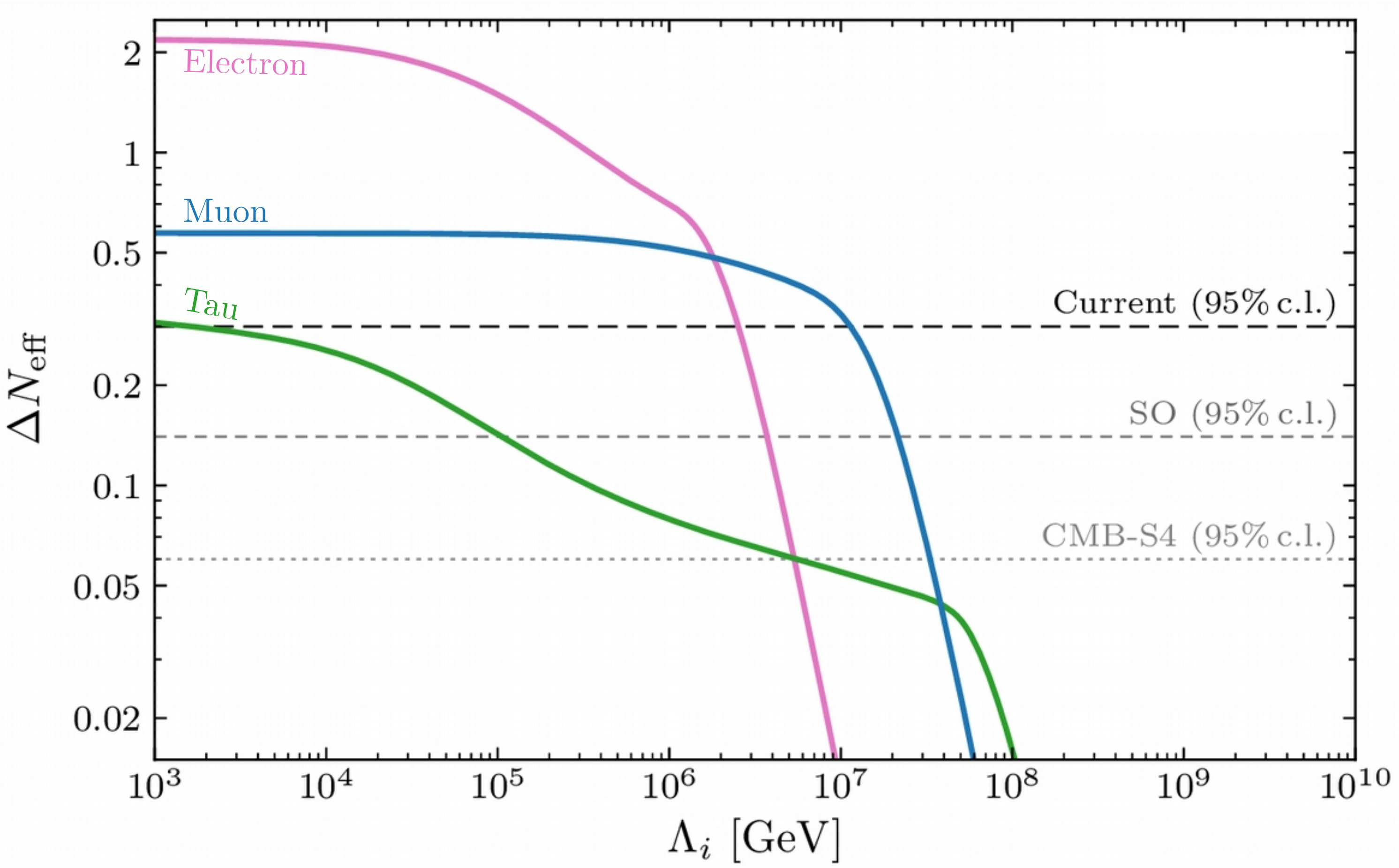
Green, Guo & BW (2021)

Predictions for ΔN_{eff}

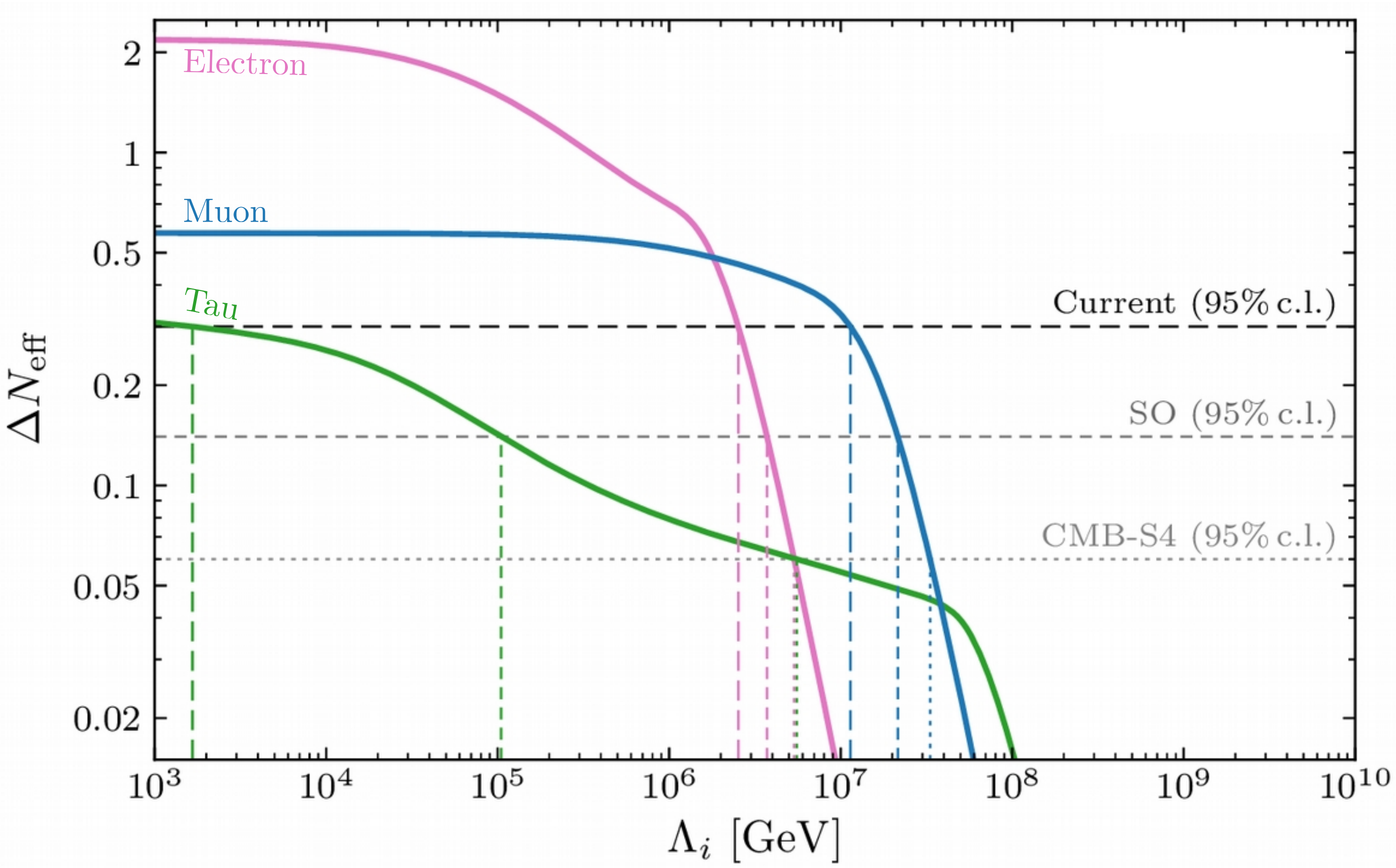
Focusing on the couplings to leptons:



Green, Guo & BW (2021)

Constraints on Axion Couplings to Matter Fields

Exclusion of certain levels of ΔN_{eff} leads to constraints on these axion couplings:



Current:

$\Lambda_e > 10^{6.4}$ GeV
$\Lambda_\mu > 10^{7.1}$ GeV
$\Lambda_\tau > 10^{3.2}$ GeV

SO:

$\Lambda_e > 10^{6.6}$ GeV
$\Lambda_\mu > 10^{7.3}$ GeV
$\Lambda_\tau > 10^{5.0}$ GeV

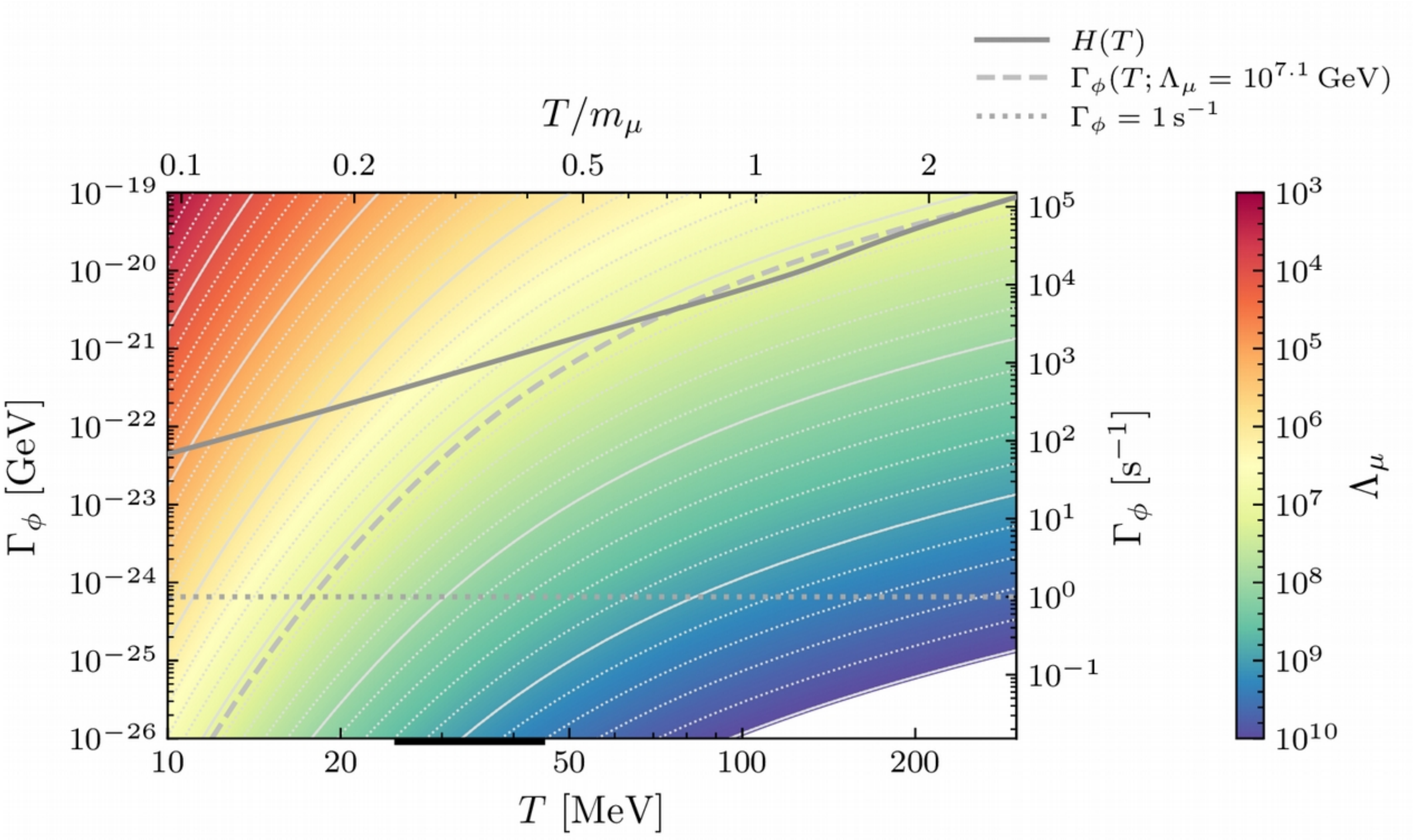
CMB-S4:

$\Lambda_e > 10^{6.7}$ GeV
$\Lambda_\mu > 10^{7.5}$ GeV
$\Lambda_\tau > 10^{6.7}$ GeV

Green, Guo & BW (2021)

Axion-Fermion Interaction Rate

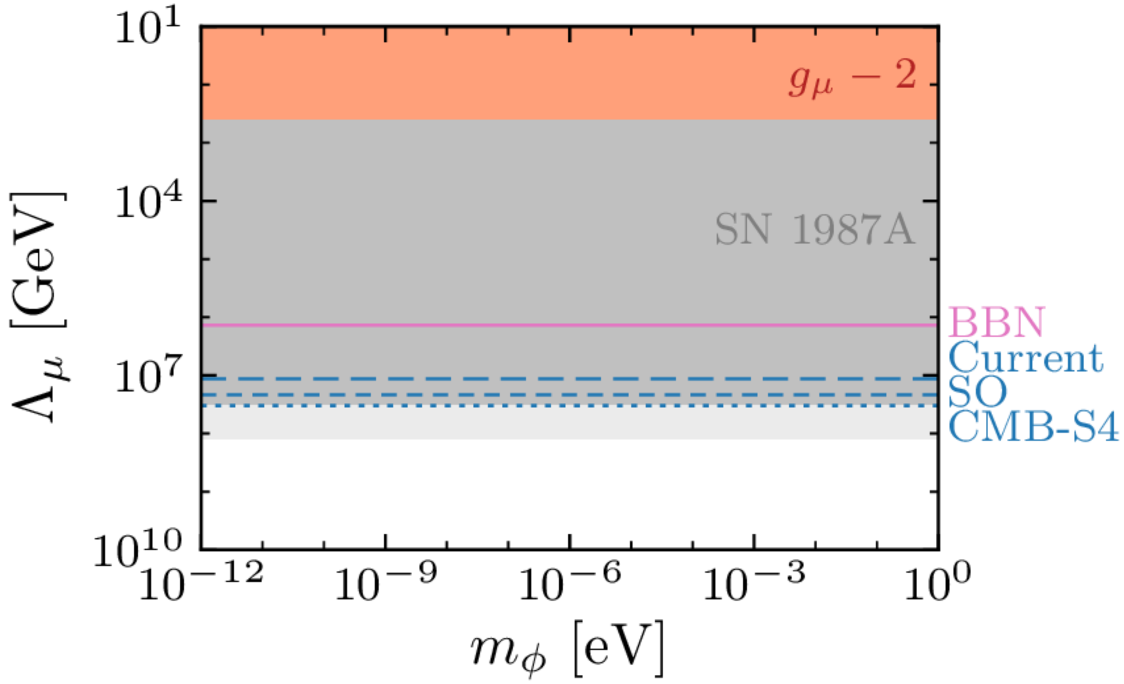
To compare the cosmological bounds to those from supernova cooling:

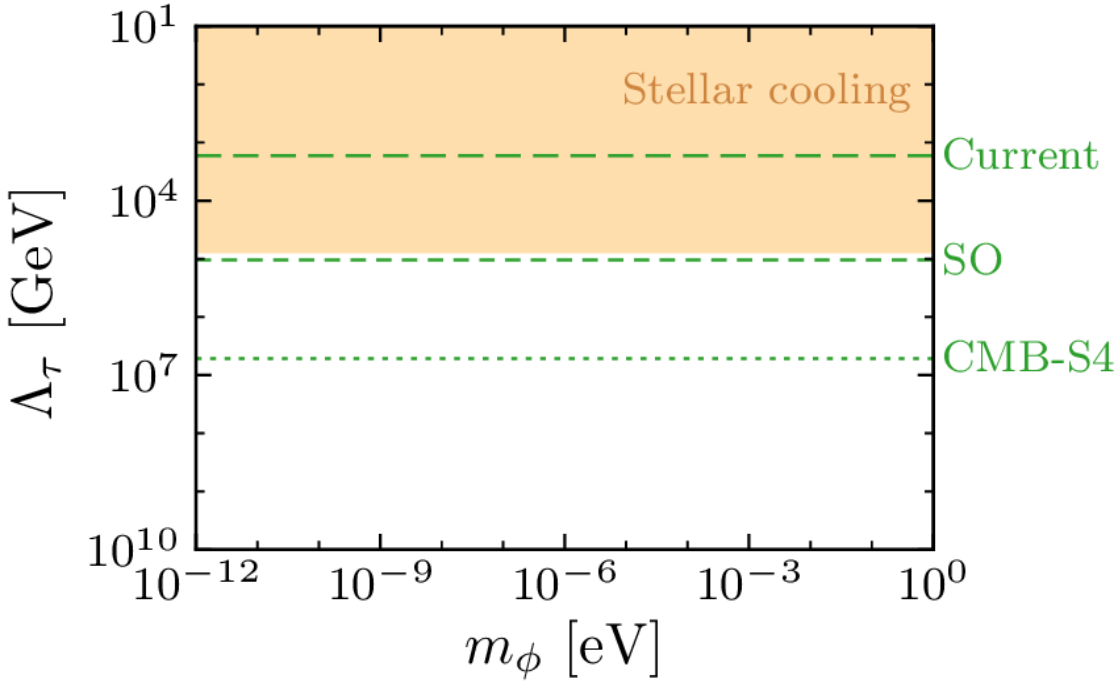


Green, Guo & BW (2021)

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. (2021)

Green, Guo & BW (2021)

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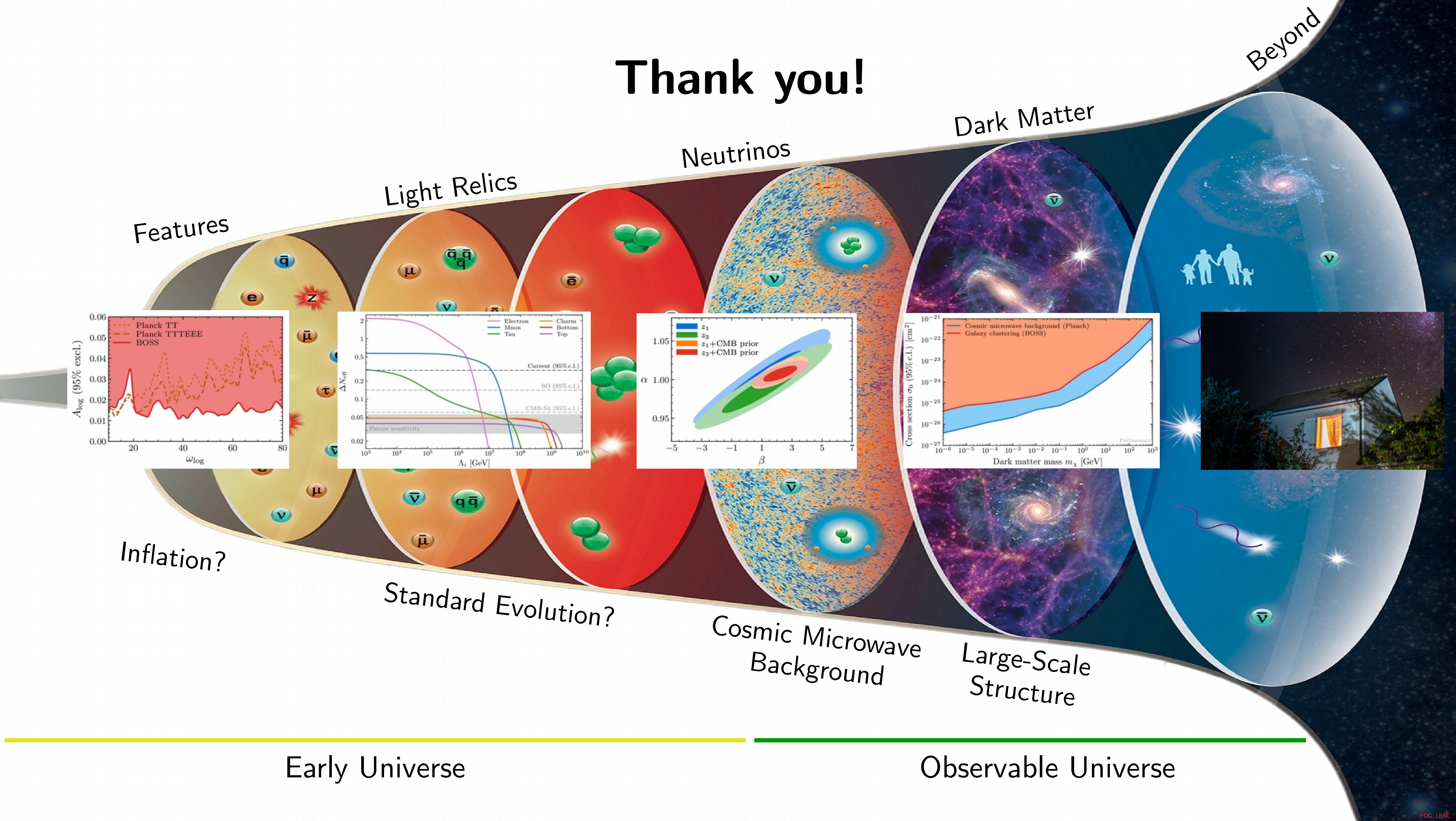
Conclusions

- CMB and LSS observations (and underlying theory) are now precise enough to put interesting constraints on fundamental physics, e.g. inflation, neutrinos, light relics and dark matter.

- EFT-of-LSS treatment allows for first bounds on dark matter-baryon scattering from BOSS galaxy clustering.

- Constraints on $\Delta N_{\rm eff}$ do not only have implications on particle physics via freeze-out, but couplings to SM fermions can also be competitively constrained.

Thank you!



Features

Light Relics

Neutrinos

Dark Matter

Beyond

Inflation?

Standard Evolution?

Cosmic Microwave Background

Large-Scale Structure

Early Universe

Observable Universe

PDG, LBNL