New Light Species and the CMB

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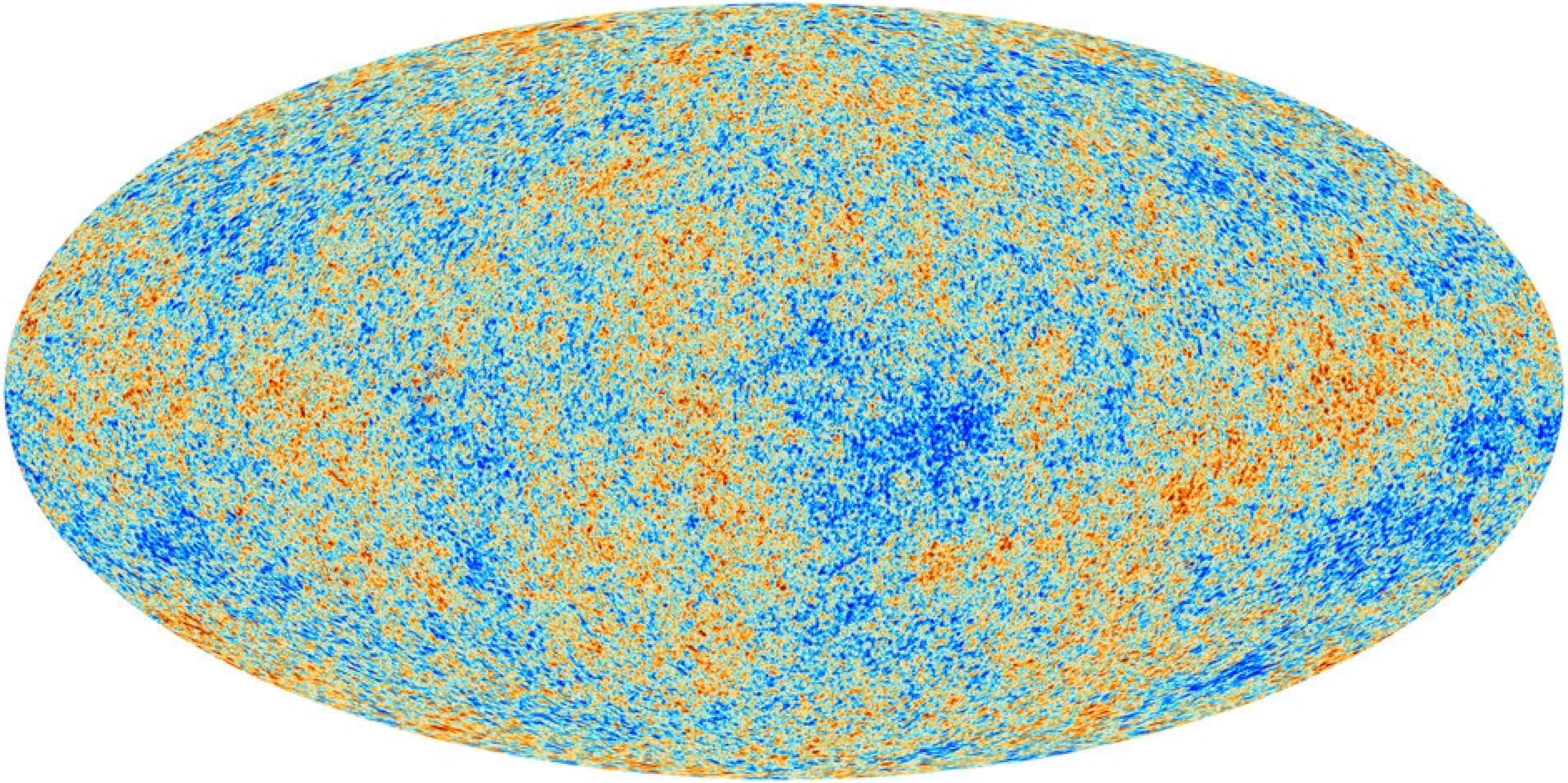
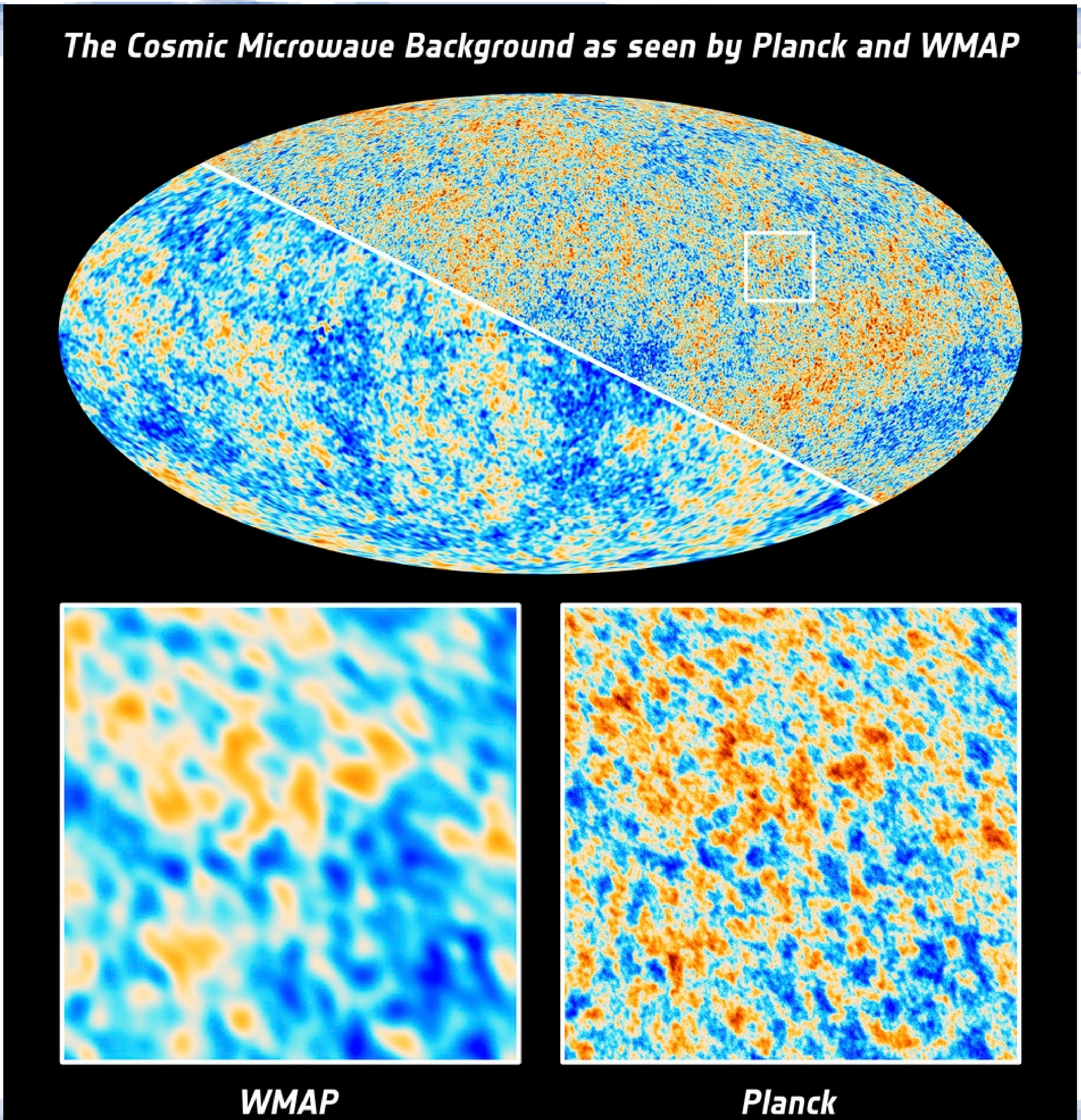
Punchlines

- BSM physics with m << eV species can be probed by CMB
- Obtaining distribution functions requires numerical solution
- Can constrain couplings in wide range of natural, minimal effective theories with recent results from Planck

Anisotropies in the CMB



http://www.esa.int/For_Media/Photos/Highlights/Planck



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Effects of Light (m << eV) Species

- Light species contribute to H, affecting CMB
- Effects parameterized by one number g_* proportional to energy density
- SM contributions to N_{eff} from photons and neutrinos:

$$g_* = 3.38 = 2 + 2 \cdot \frac{7}{8} N_{eff} \left(\frac{4}{11} \right)^{\frac{4}{3}} \qquad N_{eff} = 3.04$$

Measurements of N_{eff}

- SM prediction:

$$g_* = 3.38 \qquad N_{eff} = 3.046$$

- WMAP nine-year, SPT, ACT:

$$g_* = 3.69 \pm 0.16 \qquad N_{eff} = 3.71 \pm 0.35$$

- Planck:

$$g_* = 3.50 \pm 0.12 \qquad N_{eff} = 3.30 \pm 0.27$$

Friedmann Equations

- Einstein equations relate expansion rate to energy density and pressure:

$$H^2 = \frac{8\pi G}{3}\rho$$

$$\frac{\partial \rho}{\partial t} = -3H(\rho + P)$$

Boltzmann Equations

$$E\frac{\partial f}{\partial t} - Hp^2\frac{\partial f}{\partial E} = C[f]$$

$$C[f_X] = \frac{1}{2}\sum_{X,i\to j,k}\int\left(\prod_{s=i,j,k} g_s\frac{d^3p_s}{(2\pi)^3 2E_s}\right)(2\pi)^4\delta^4(p_{in}-p_{out})S\,|\mathcal{M}|^2\,\Omega$$

$$\Omega(f_X, f_i, f_j, f_k) = f_j f_k(1\pm f_X)(1\pm f_i) - f_X f_i(1\pm f_j)(1\pm f_k)$$

- Solve coupled Boltzmann and Friedmann equations

Precision Theory

- Wrote software to numerically solve coupled Boltzmann + Friedmann equations on a momentum x time lattice
- Solves to percent-level accuracy
- Ignores loop corrections, 2 to 3 processes, finite temperature QFT effects (all sub-percent corrections)

Precision Theory

- Cannot compute during QCD phase transition; loop corrections large, etc.

- For all models we considered:
  - Compute Feynman diagrams
  - Perform angular phase space integrations
  - Run code to solve Boltzmann equations
  - Extract Δg_* from distribution functions

Models with New Light Species

- We demand that model is:
  - Natural in t'Hooft sense: $|\frac{\delta\lambda}{\lambda}| < 1$
  - Minimal: as little new physics as possible
  - Contains species with m < eV

- Compute Δg_* for universality classes of models

Summary of Our Models

- Goldstone boson:

$$\mathcal{L} \supset -\frac{\partial_\mu \phi}{\Lambda_f}\bar{\Psi}_f \gamma^\mu \gamma^5 \Psi_f - \frac{e^2}{32\pi^2 \Lambda_\gamma}\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + \pi \text{ couplings}$$

- Four-fermion interactions:

$$\frac{1}{\Lambda^2}\bar{\mathbf{X}}\gamma^\mu \mathbf{X}\bar{\Psi}\gamma_\mu \Psi \text{ or scalar, pseudoscalar, axial couplings}$$

Summary of Our Models

- Light sterile neutrinos:

$$\mathcal{L} \supset -m_{ij}\nu^c_{Ri}\nu_{Lj} - \frac{1}{2}M_{ij}\nu^c_{Ri}\nu^c_{Rj} + h.c.$$

- U(1)' with kinetic mixing with hypercharge:

$$\mathcal{L} \supset -\frac{\epsilon}{2}A'^{\mu\nu}B_{\mu\nu}$$

- U(1)' with dipole couplings to SM fermion:

$$\mathcal{L} \supset -\frac{1}{\Lambda}A'_{\mu\nu}\psi^c_R\sigma^{\mu\nu}\psi_L + h.c.$$

Four-fermion Vector Example

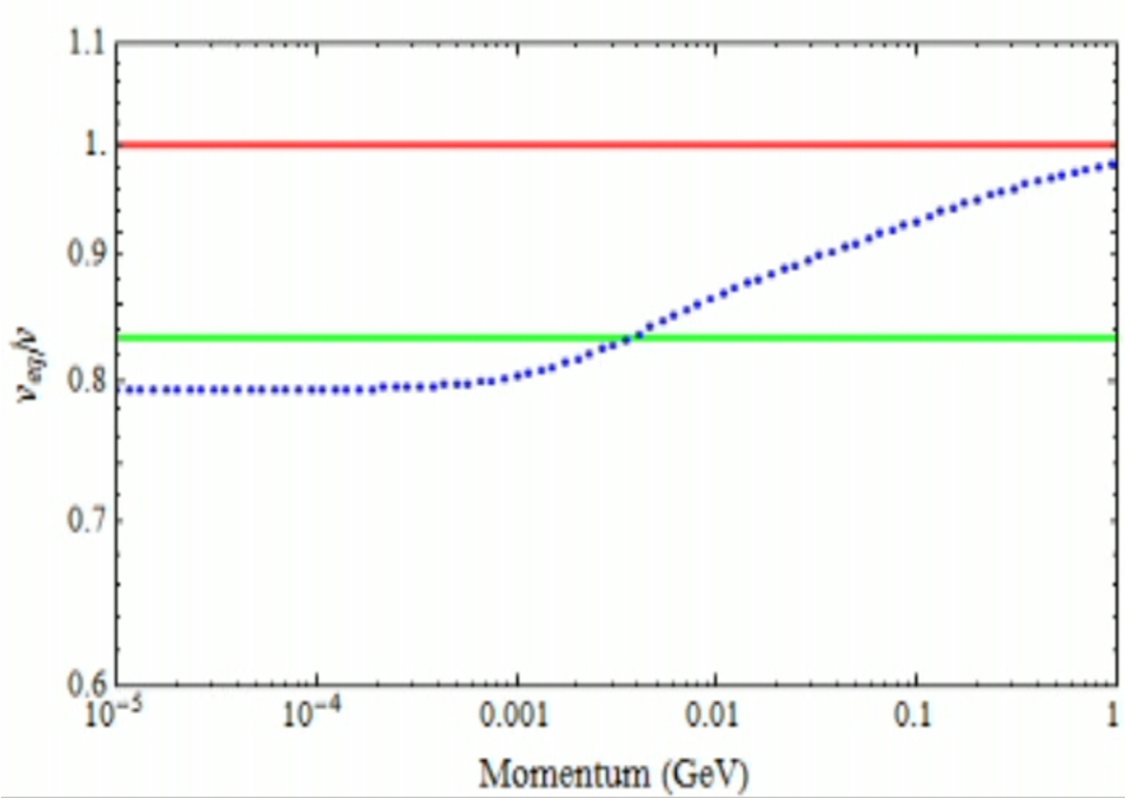
- Λ = 1.4 TeV: Decouples during muon annihilation

$$f(p,t) = \frac{1}{e^{v(p,t)} \pm 1} = \frac{1}{e^{p/T_{eff}(p,t)} \pm 1}$$

Red: fully coupled

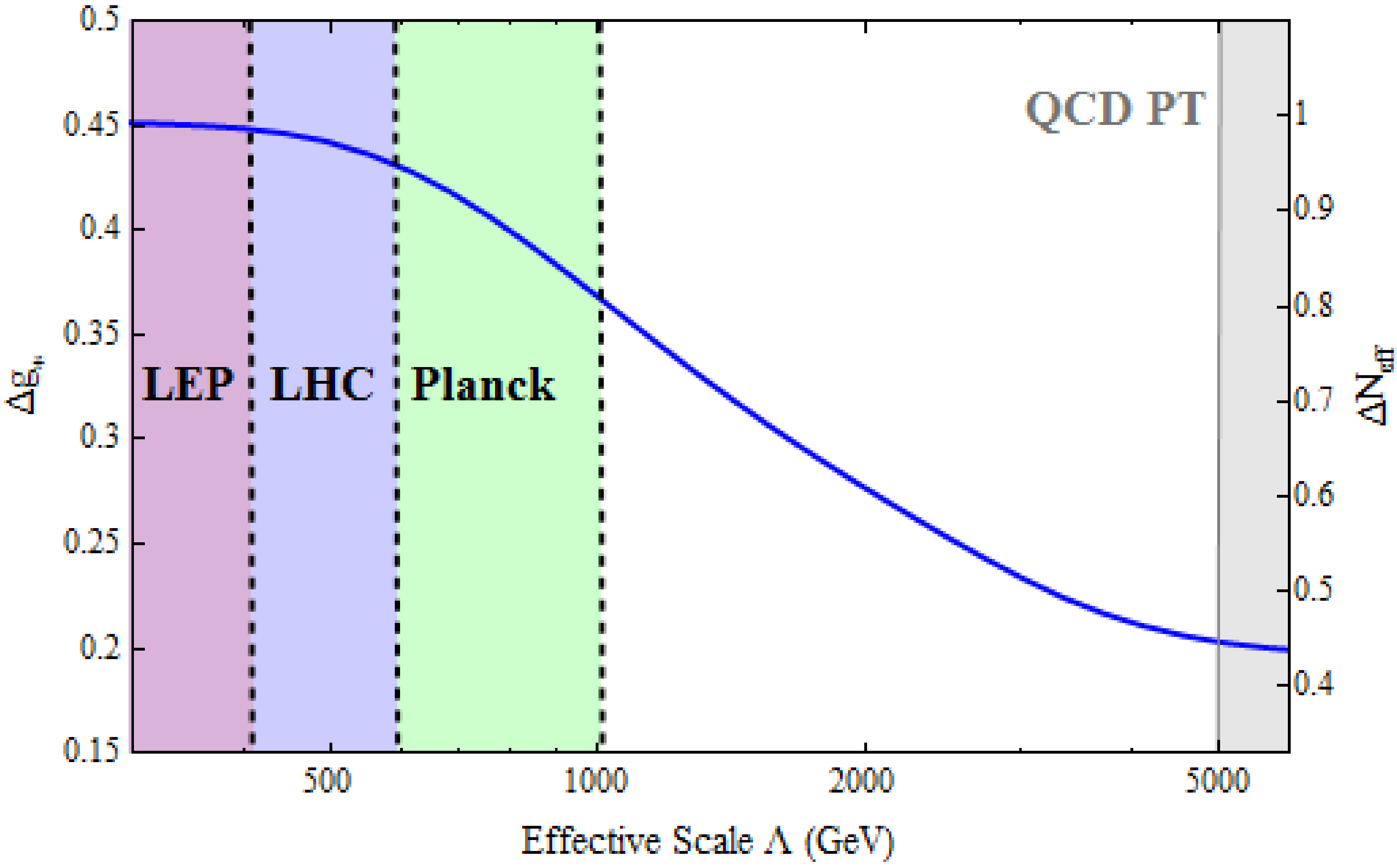
Blue: our code

Green: fully decoupled



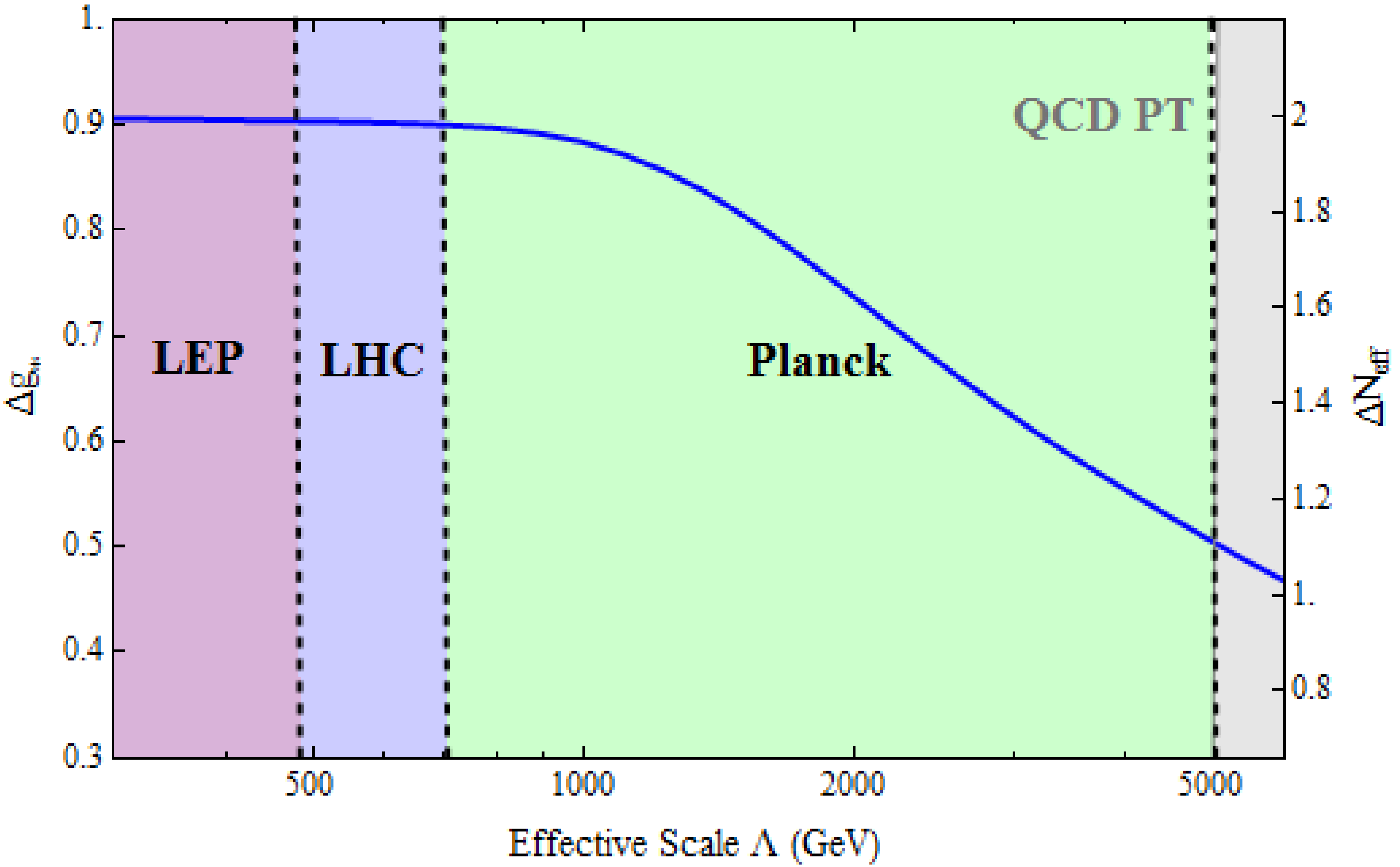
Four-Fermion Vector Results

Weyl fermion



Four-Fermion Vector Results

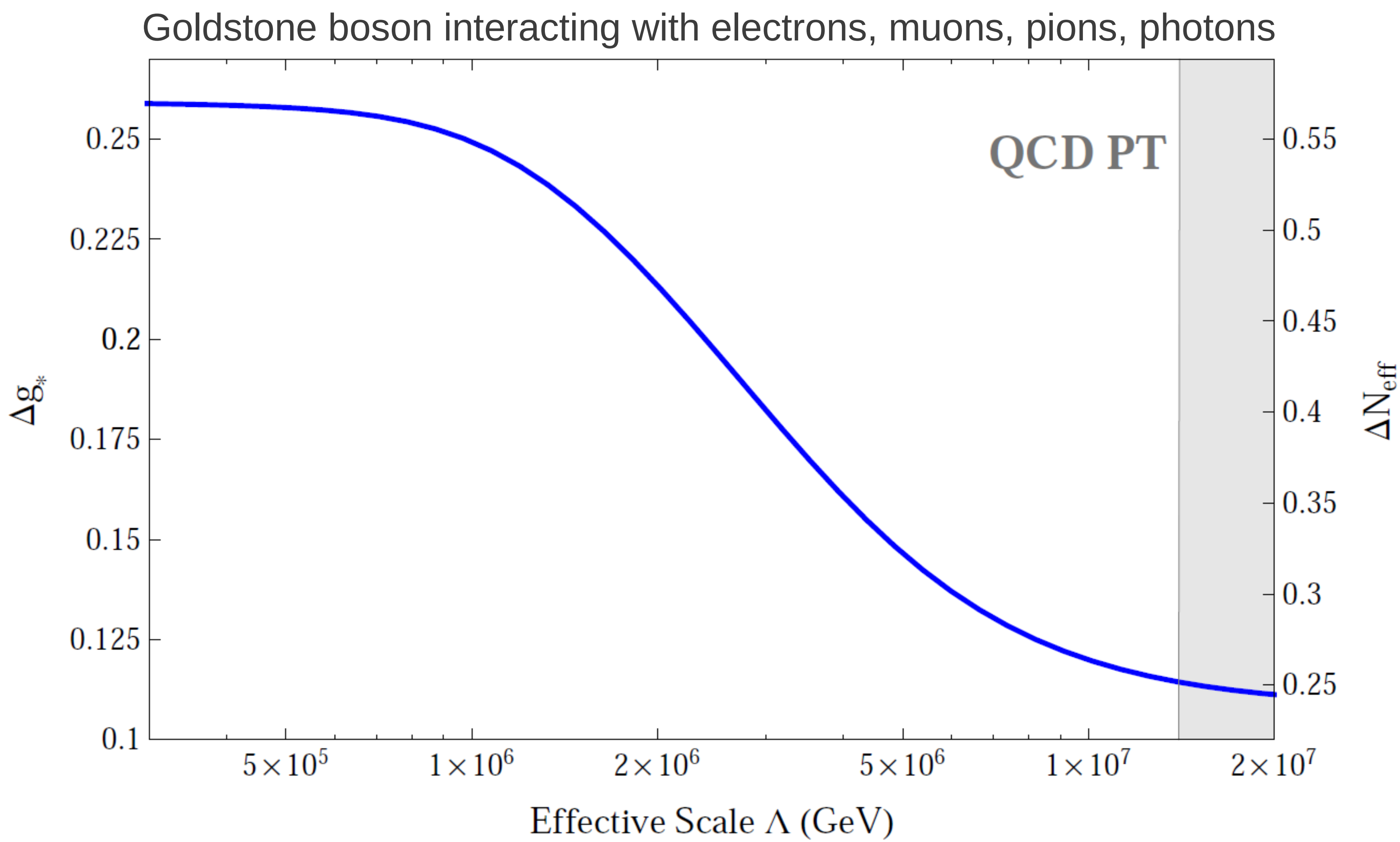
Dirac fermion



Conclusions

- Wrote code to solve Boltzmann equation for nonthermal distribution functions
- Constructed map from parameter space to N_{eff}
- New constraints on parameter space from Planck results
- Potential discovery of new light species with future experimental results

Goldstone Boson Results



Bound from supernova/star cooling: $\Lambda_e \gtrsim 2.9 \times 10^9$ GeV

Sterile Neutrino Results

- LSND and MiniBooNE anomalies:
  - 3+2 framework
  - Best-fit point

- Mass basis: induced gauge couplings of new neutrino states

- Normal hierarchy: m = 0.7 and 0.9 eV
  Inverted hierarchy: m = 0.8 and 1.2 eV

Sterile Neutrino Results

- Result: new states decouple just after muon annihilation with nonthermal distributions
- Contribute to measurements of Ω_{DM} today
- Mass effects subtle; requires further study

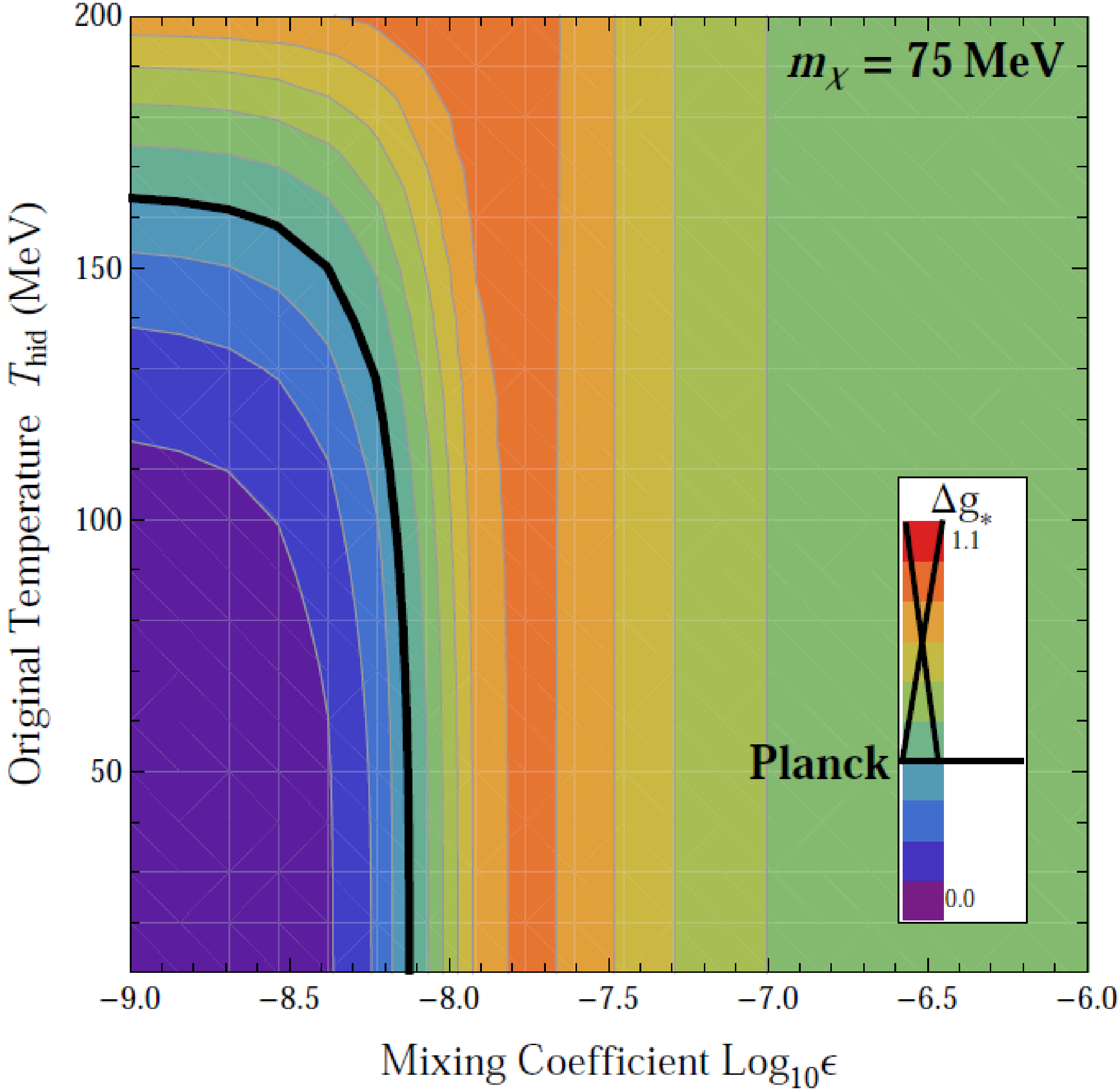
U(1)' Kinetic Mixing Results

- No fermions charged under U(1)':
  - Can always redefine away kinetic mixing term
  - No contribution to g_*
- Dirac fermion χ charged under U(1)':
  - Redefinition introduces couplings of χ to photons proportional to ϵ

U(1)' Kinetic Mixing Results

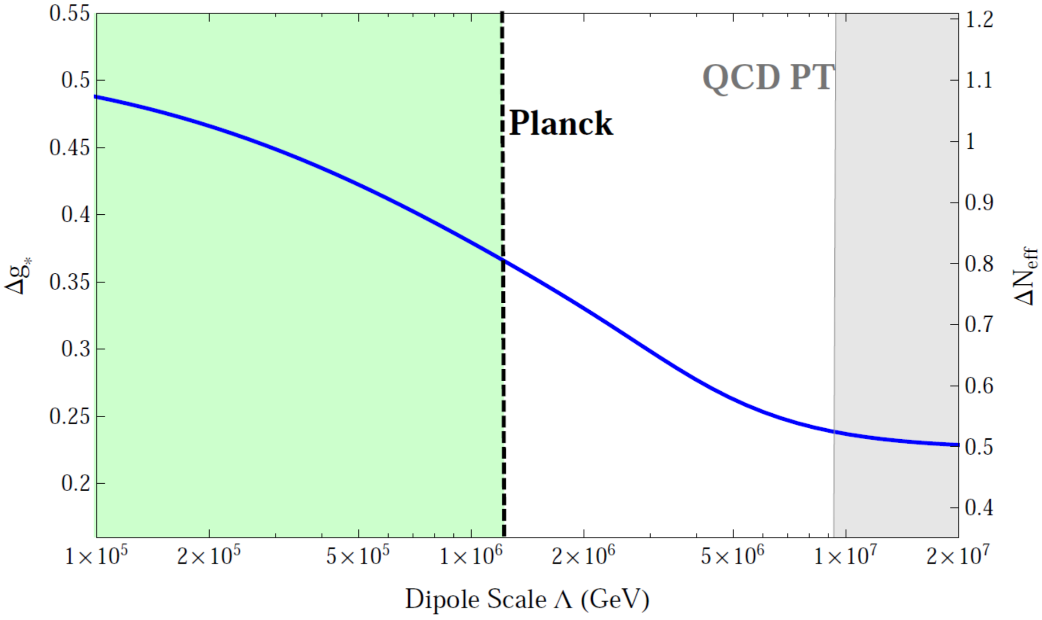
- $m_\chi \lesssim 10\ \mathrm{MeV}$: star/supernova cooling prevents hidden sector from ever coupling to SM
- $m_\chi \gtrsim 150\ \mathrm{MeV}$: hidden sector decouples before/during QCD phase transition
- Otherwise, answer depends on initial hidden sector temperature

U(1)' Kinetic Mixing Results



U(1)' Dipole Results

- Flavor-blind parameter space which decouples after QCD phase transition:
  - Excluded by supernova/star cooling
- Muon-only couplings constrained by Planck at 95% CL:



Summary of Results

Model	Operator	Results
Goldstone bosons	$\frac{1}{\Lambda}\partial_\mu\phi\bar{\Psi}\gamma^\mu\gamma^5\Psi$	Flavor-blind: Already excluded Muon-only: $\Delta g_* \leq 0.26$
Four-fermion V (S, P, A same to 5%; see text)	$\frac{1}{\Lambda^2}\chi^\dagger\bar{\sigma}^\mu\chi\bar{\Psi}\gamma_\mu\Psi$ $\frac{1}{\Lambda^2}\bar{\mathbf{X}}\gamma^\mu\mathbf{X}\bar{\Psi}\gamma_\mu\Psi$	Weyl: $\Lambda > 1$ TeV Dirac: $\Lambda > 5$ TeV
Sterile Neutrinos	Electroweak Interactions	Inconclusive; mass-dependent
$U(1)'$	$\epsilon e\bar{\chi}\not{A}\chi$	$\epsilon < 10^{-8}$ for 10 MeV $\leq m_\chi \leq$ 150 MeV $m_\chi >$ 150 MeV: Decouples during/before QCD phase transition
A'-dipole	$\frac{1}{\Lambda}A'_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi$	Flavor-blind: Already excluded Muon-only: $\Lambda > 10^3$ TeV