New Light Species and the Cosmic Microwave Background

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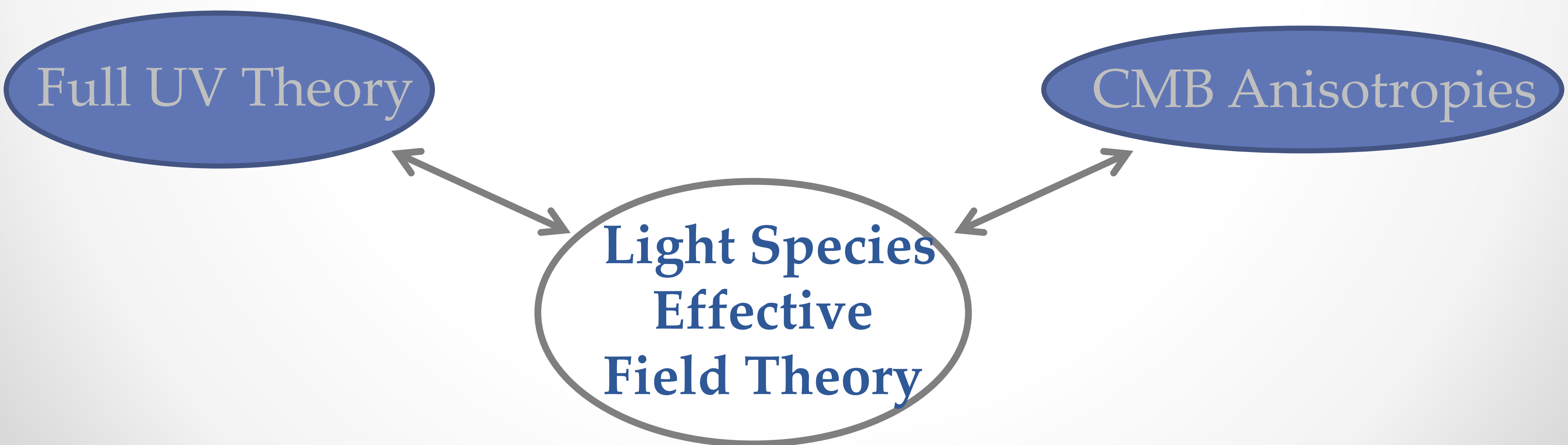
arXiv: 1303.5379 [hep-ph] Brust, Kaplan, MTW

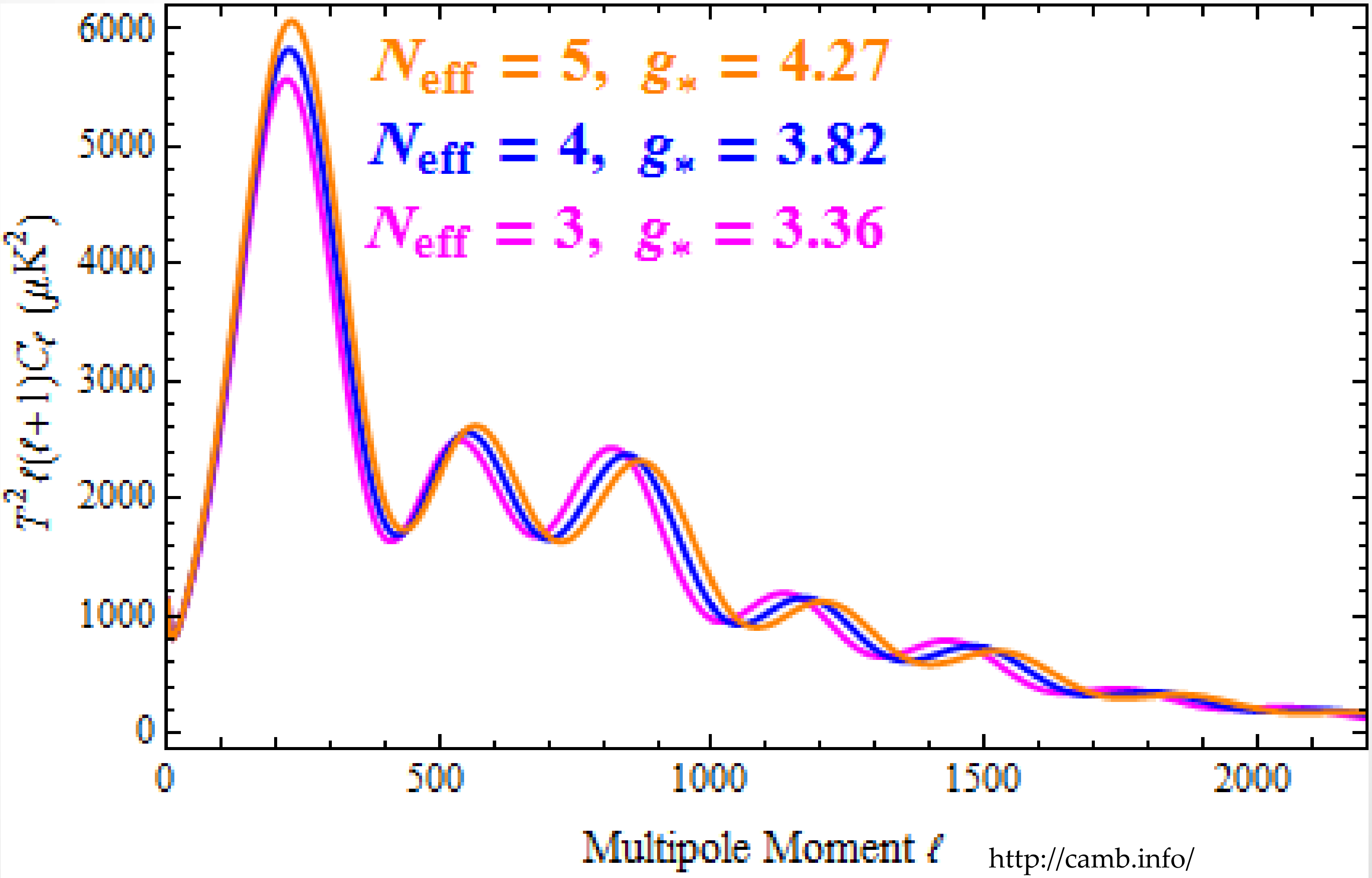
Goal

- Provide map between models with light species and cosmological observations
- Model-independent framework for constraining or confirming theories with CMB
- Complementary results to collider experiments



New Light Species

$$\rho_{rel} = g_* \frac{\pi^2}{30} T_\gamma^4 = 2 + 2 \cdot \frac{7}{8} \cdot N_{eff} \left(\frac{4}{11}\right)^{4/3} \qquad (m \ll \text{eV})$$

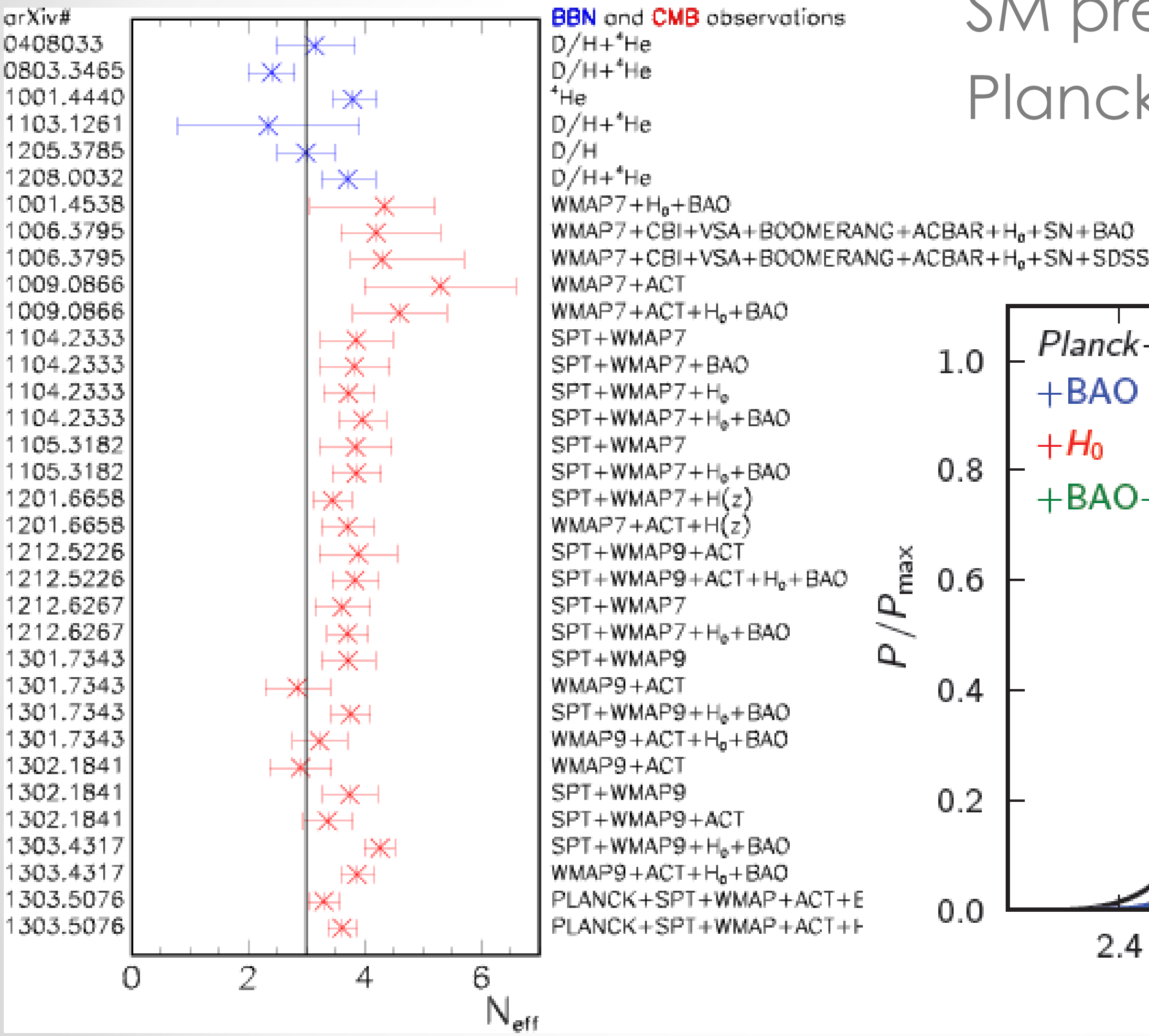


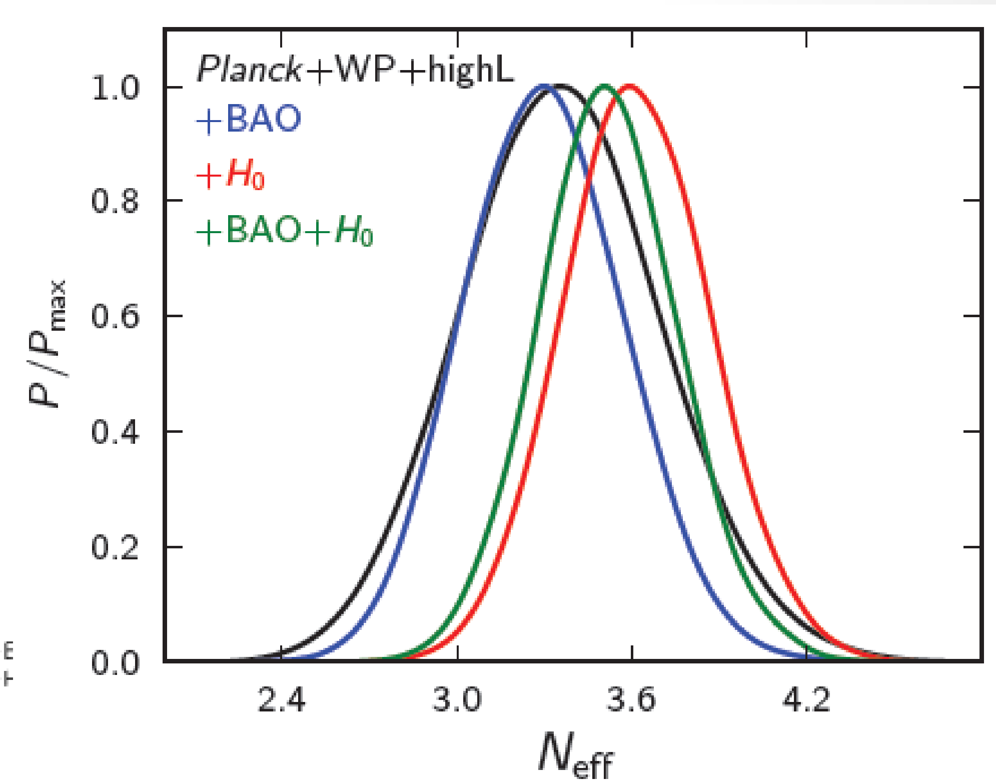
http://camb.info/

Observational Data

SM prediction: $N_{\rm eff} = 3.046$

Planck: $N_{\rm eff} = 3.30 \pm 0.27$



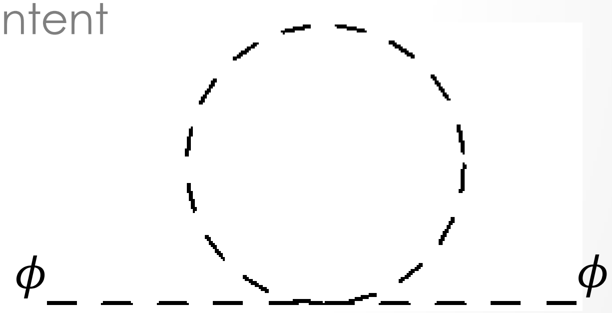


Anchordoqui, *et al*, arXiv:1305.0146 [astro-ph.CO]

Ade, *et al*, arXiv:1303.5076 [astro-ph.CO]

What Could Contribute?

- Assume new light species
    - Couples to SM, Originally in equilibrium
- Effective field theory
    - Connect to UV completions
- Minimal
    - Smallest possible operator and particle content
- Natural
    - $\frac{|\delta\lambda|}{\lambda} \lesssim 1$
    - Mass protected by symmetry
- Detailed calculation of Δg_*
    - Boltzmann, Friedmann equations
- Direct map between theory and experiment

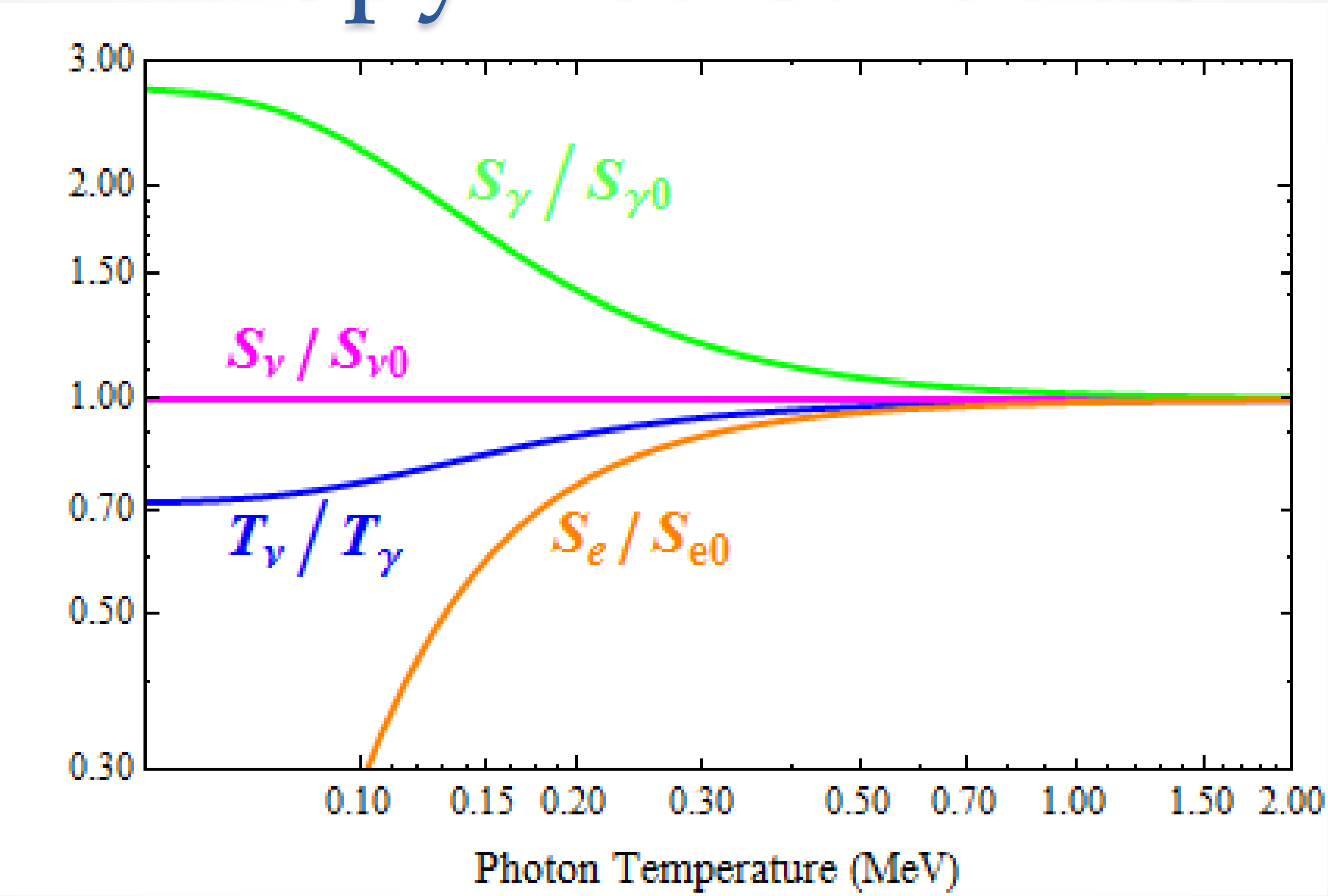


Basic Picture

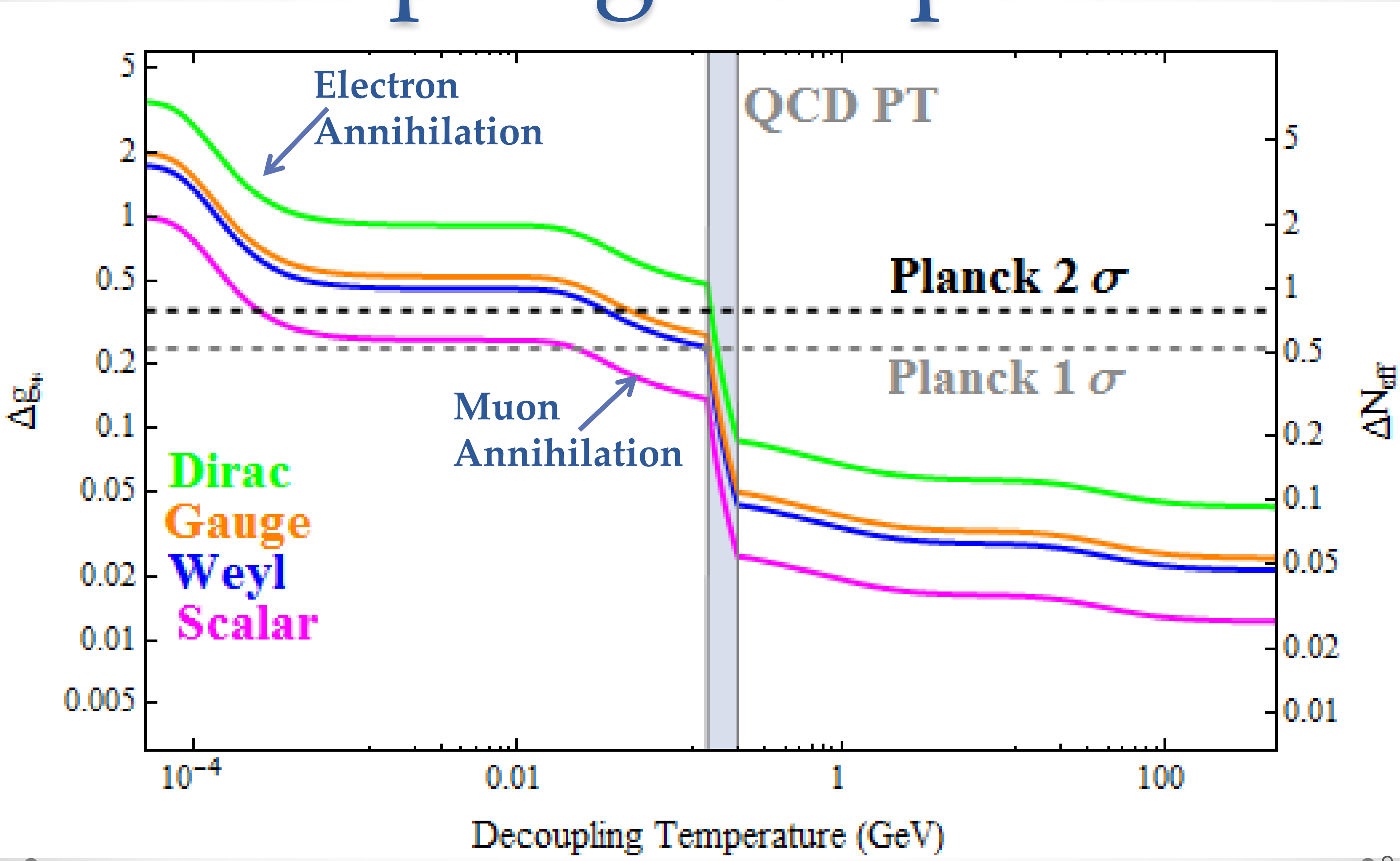
- Assume particular coupling
  - Four-Fermion, Dipole Moment, Goldstone Boson, …
- Equilibrium at high T sets initial condition $\rightarrow f(t,p)$
- Step forward in time, calculate evolution
- Interaction rate falls, species decouples
- SM species annihilate, heating SM relative to new species
- Couplings $\rightarrow T_{dec} \rightarrow$ # of annihilations $\rightarrow \Delta g_*$

Map

Entropy Redistribution



Decoupling Temperature

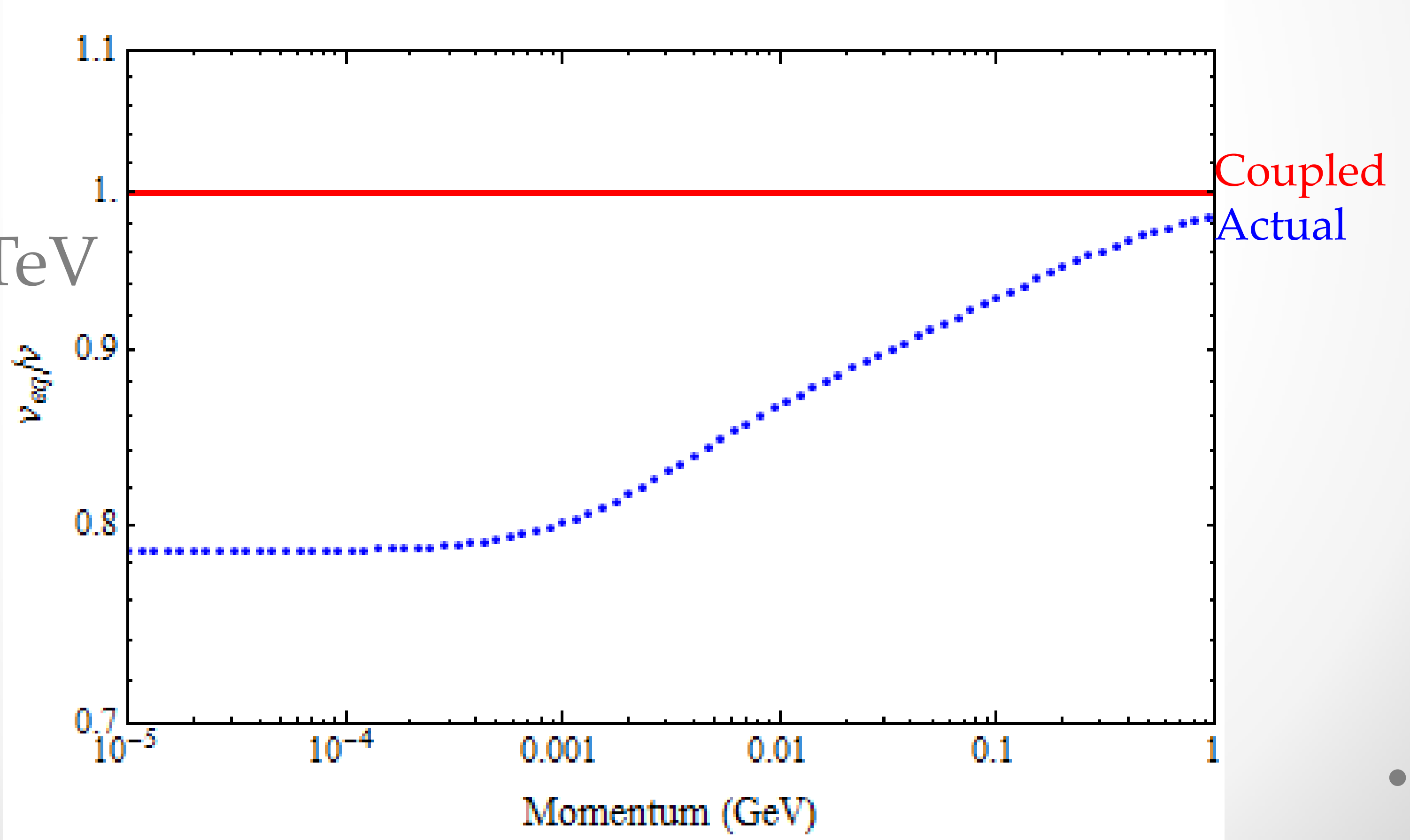


Results: Four-Fermion

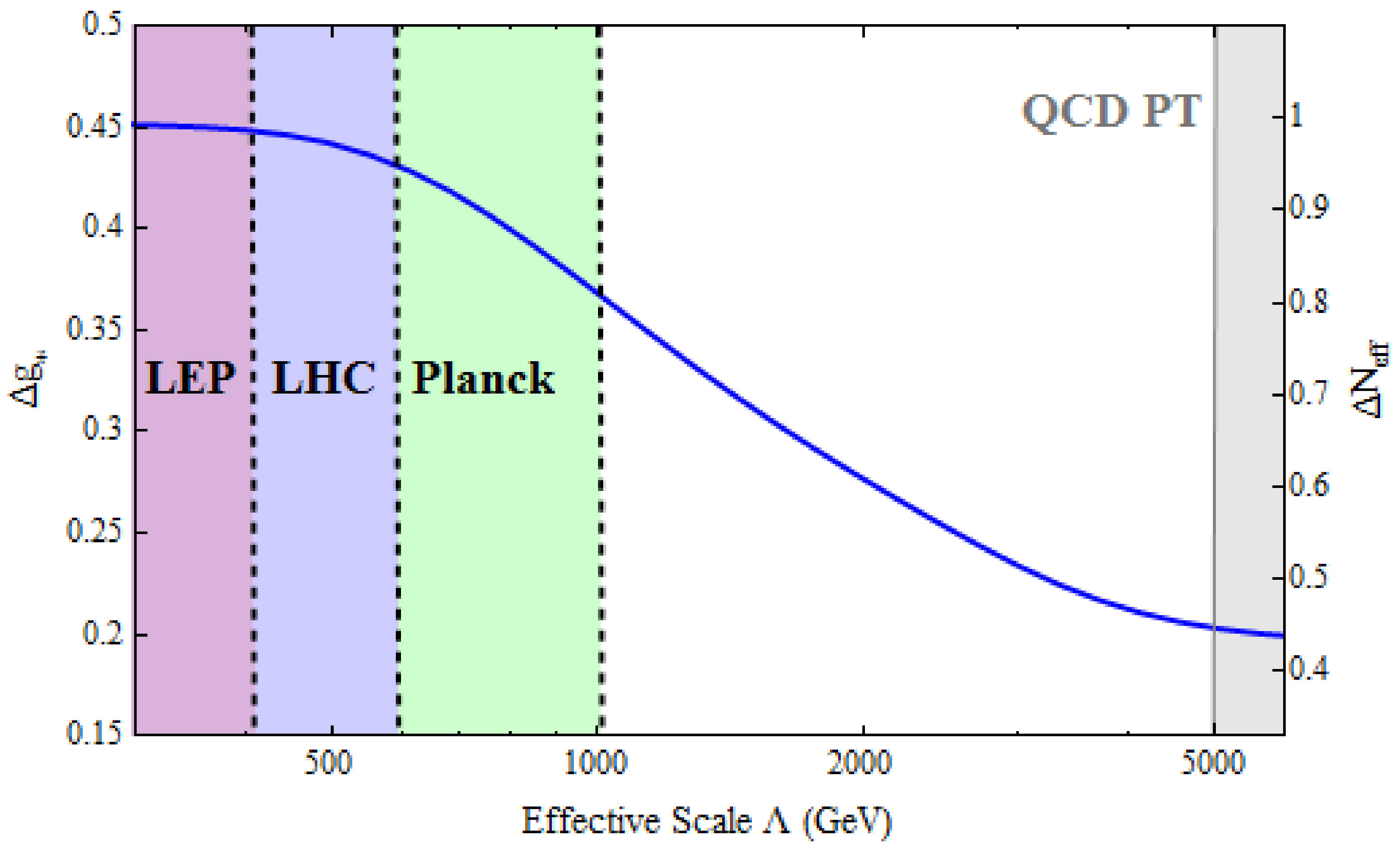
- Calculated distribution vs. Equilibrium distribution

$$f(t,p) = \frac{1}{e^{v(t,p)}+1} \rightarrow \frac{v_{eq}}{v} = \frac{p/T_{SM}}{v} \sim \frac{T_{eff}(t,p)}{T_{SM}(t)}$$

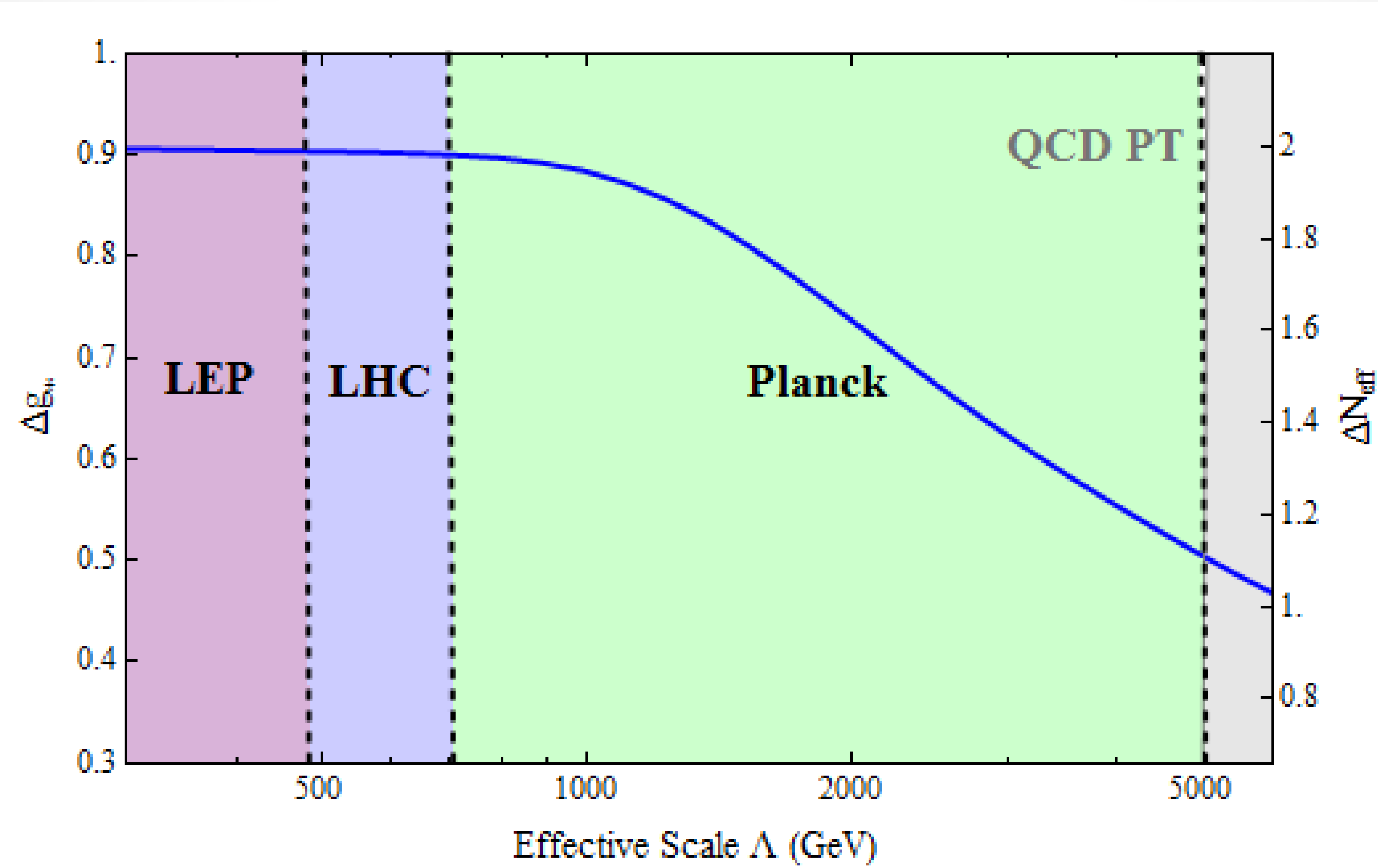
$\Lambda = 1.4$ TeV



Results: Four-Fermion (Weyl)



Results: Four-Fermion (Dirac)

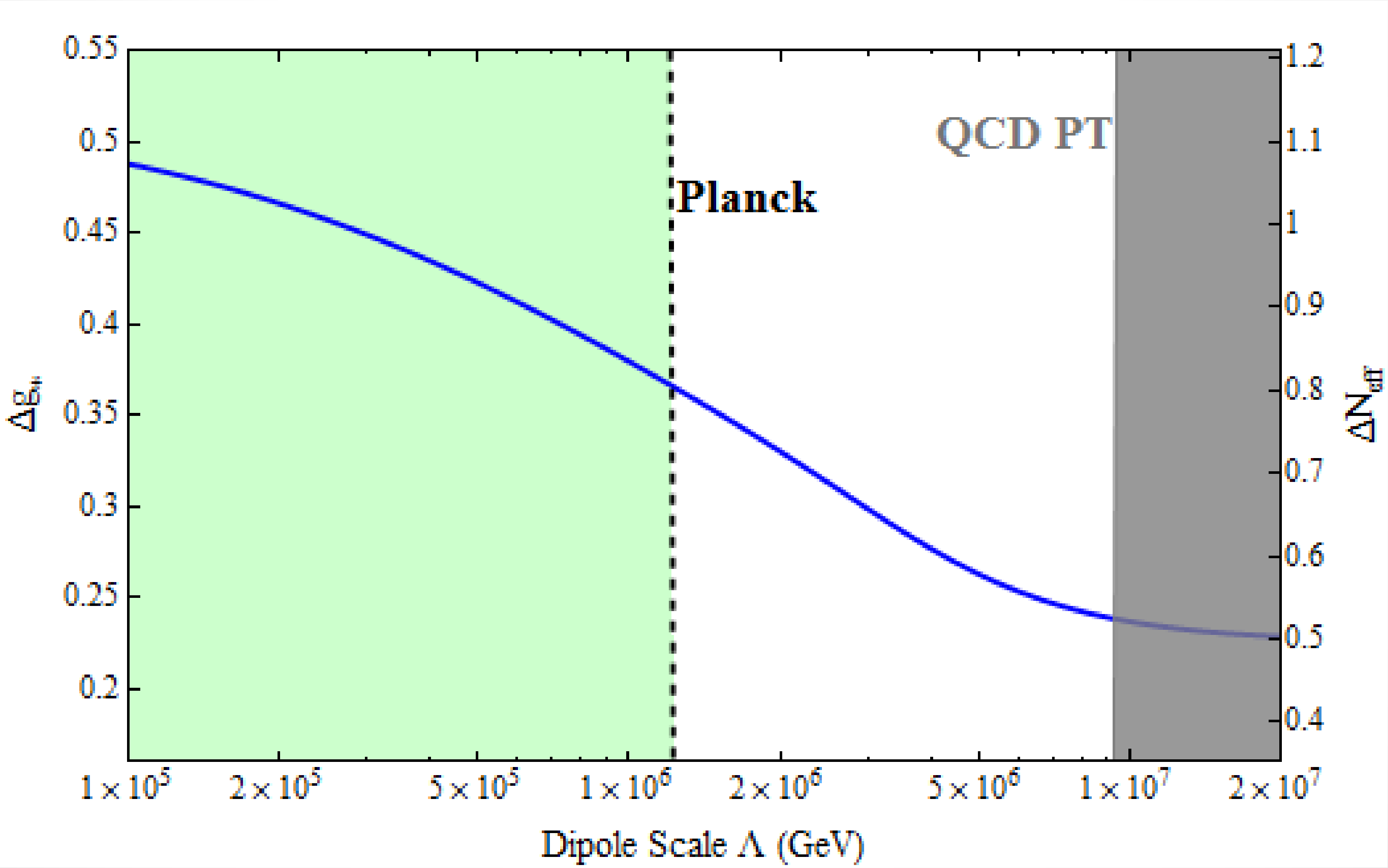


Future Work

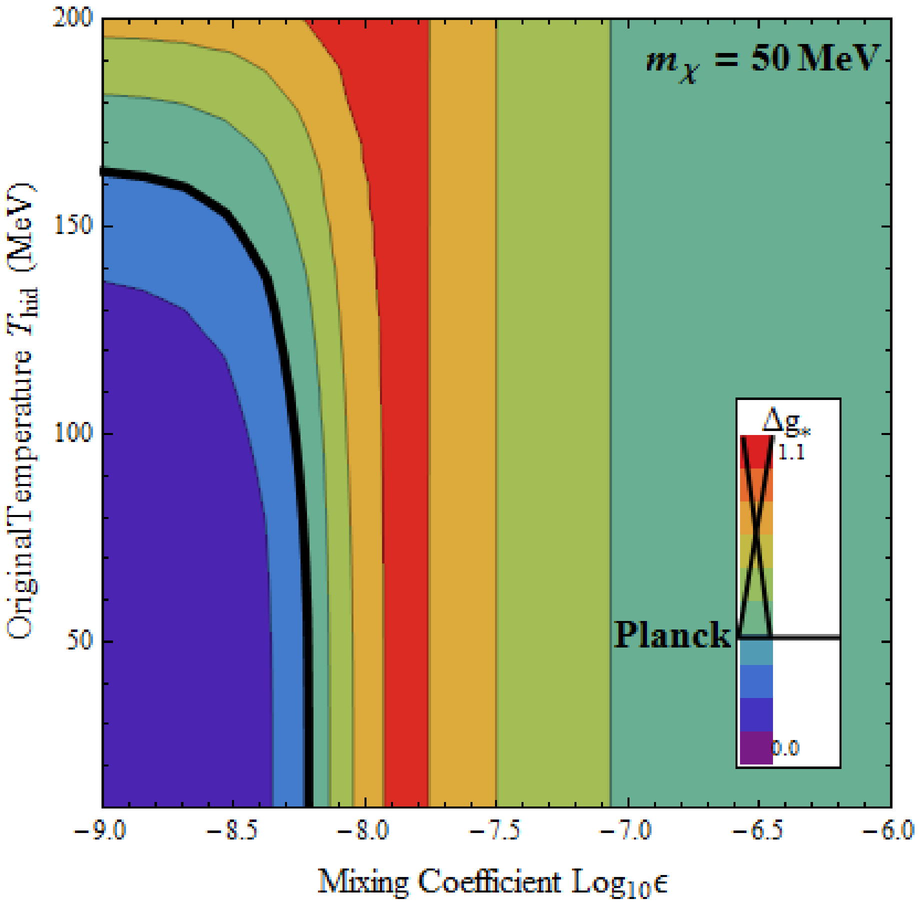
- Effects of non-zero masses on CMB
- Future constraints with polarization data
- Independent means of exclusion/discovery
- Well-motivated UV completions

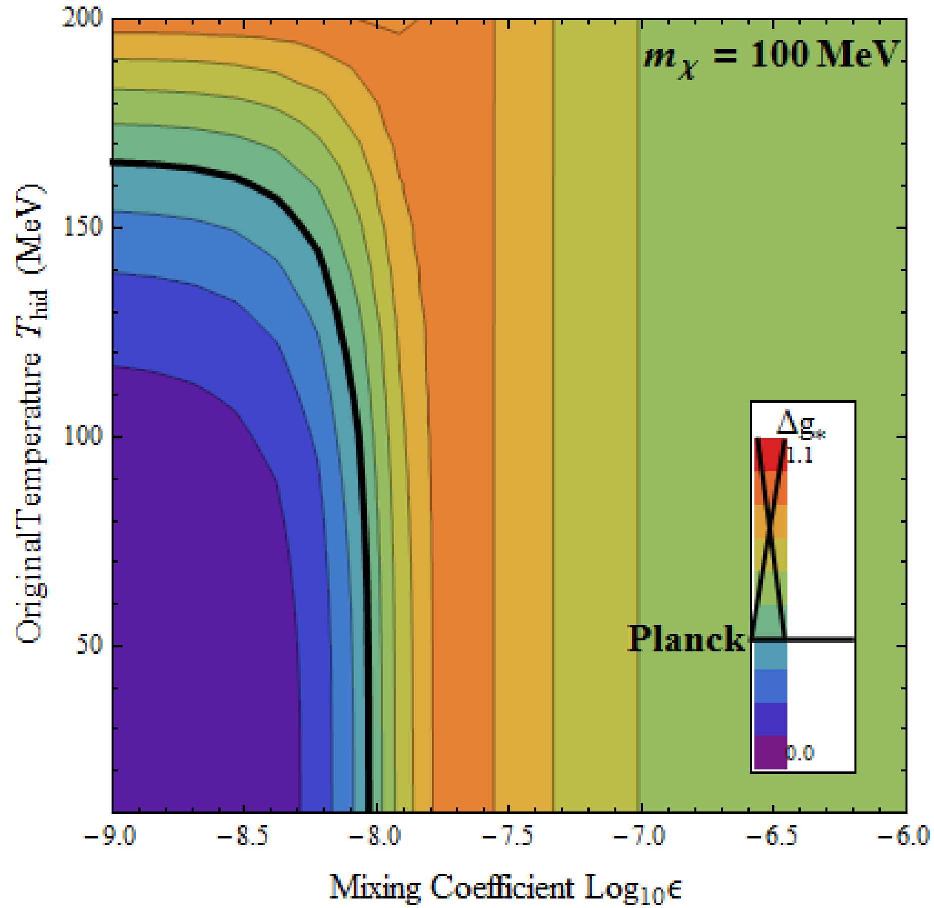
BACKUP SLIDES

Results: Dipole Moment (Gauge)

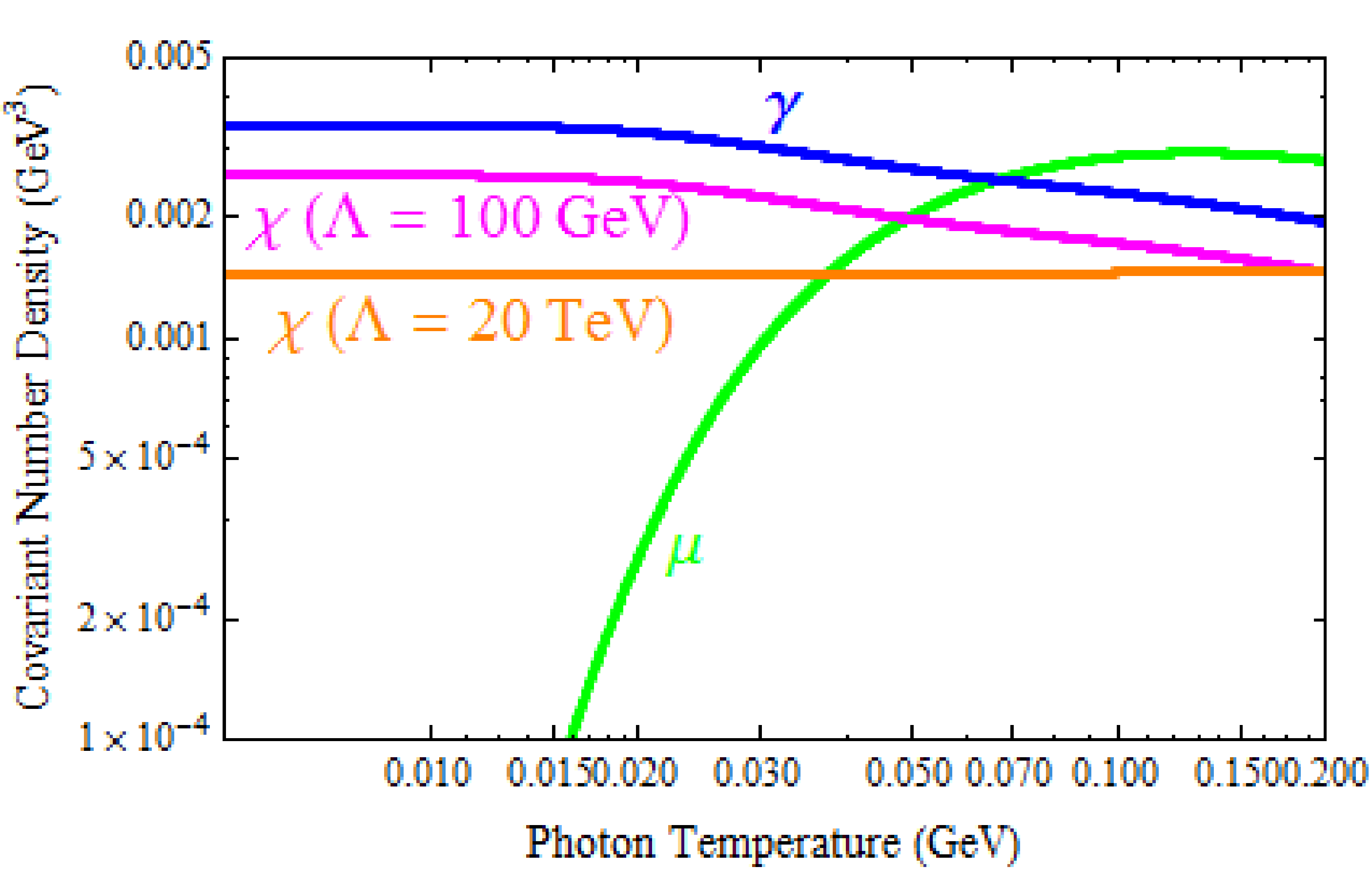


Results: Kinetic Mixing

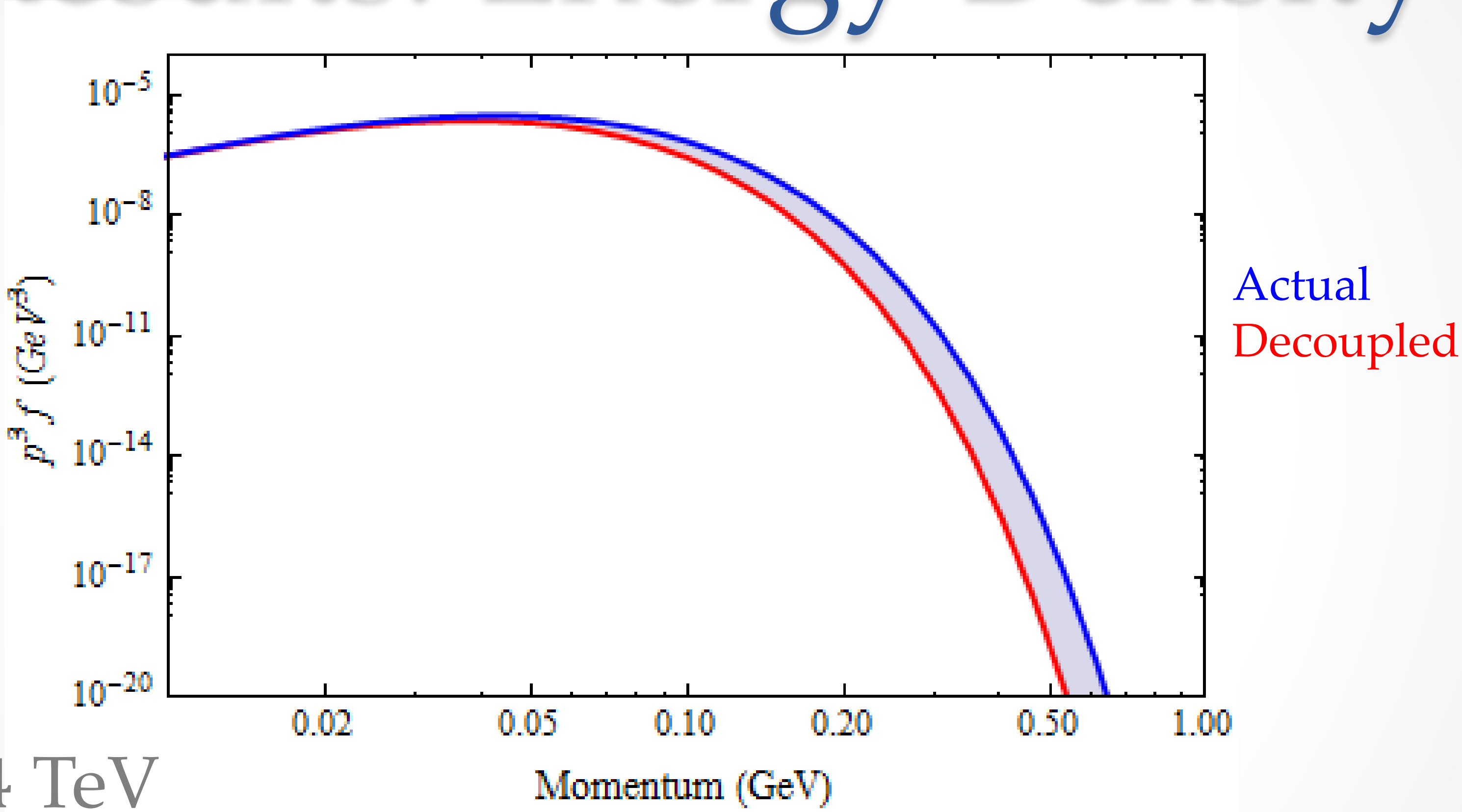




Results: Number Density



Results: Energy Density



$\Lambda = 1.4$ TeV

- Calculated vs. Decoupled Energy Density

$$\rho(t) = \frac{g}{2\pi^2}\int dp\, p^2 E\, f(t,p) \rightarrow p^3 f(t,p)$$

-

Sterile Neutrinos

- New SM singlet fermions which mix with neutrinos:

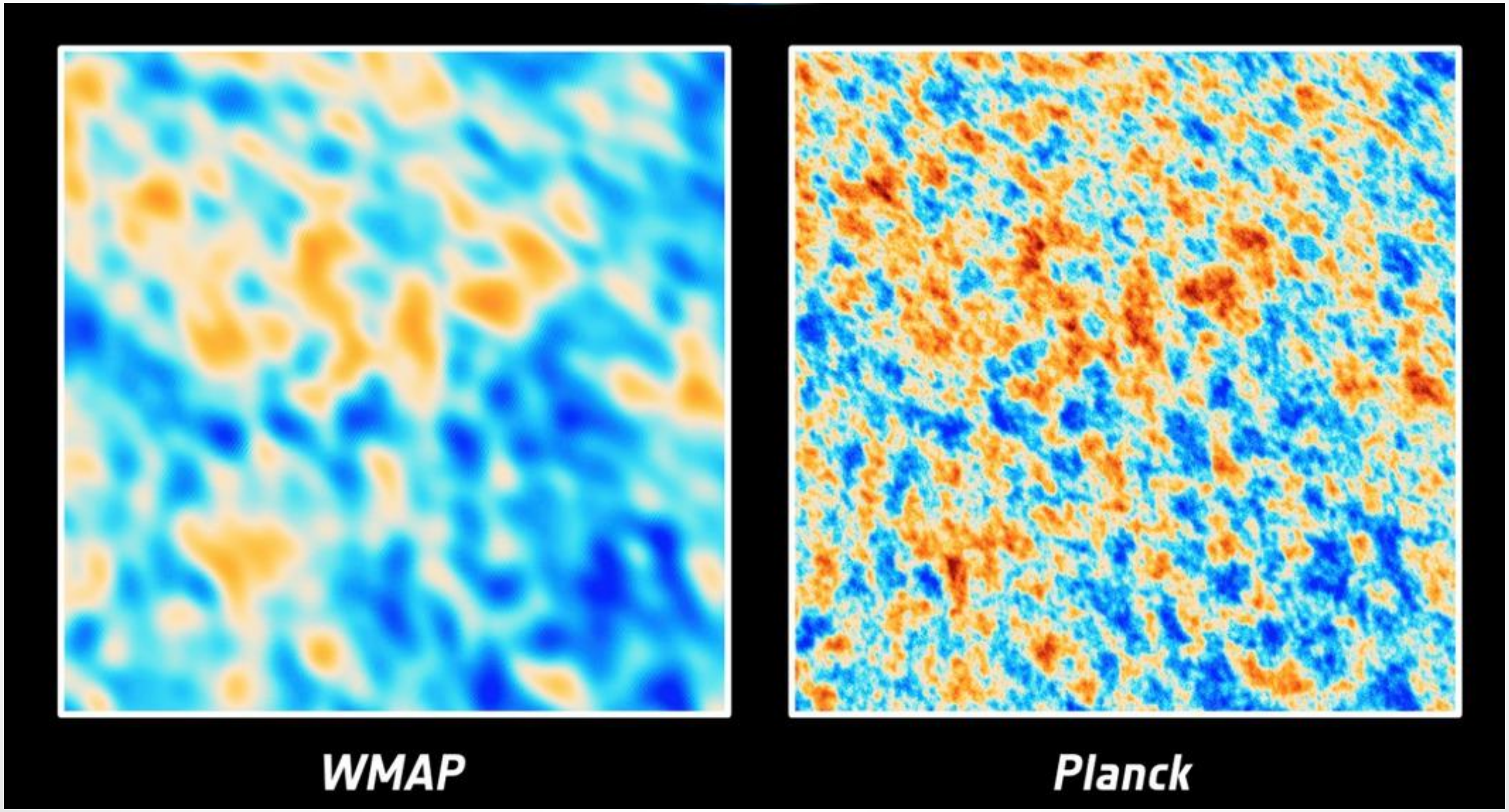
$$y_{ij}^{\nu} h^{\dagger} l_i \nu_{Rj}^{c} \rightarrow m_{ij}^{\nu} \nu_{Li} \nu_{Rj}^{c}$$

- Diagonalize mass basis to find couplings
- Short baseline experiments favor states with m~eV
- Requires more detailed analysis of massive species effects on CMB
- Nonrelativistic species evolve away from standard Fermi-Dirac distribution
- Free massive species: $\frac{\partial f(a(t)p)}{\partial t} = 0$
- Thermalized solution:

$$f(t,p) = \left(exp\left(\frac{1}{T_d} \sqrt{\left(\frac{ap}{a_d}\right)^2 + m_\nu^2} \right) + 1 \right)^{-1}$$

Planck Satellite

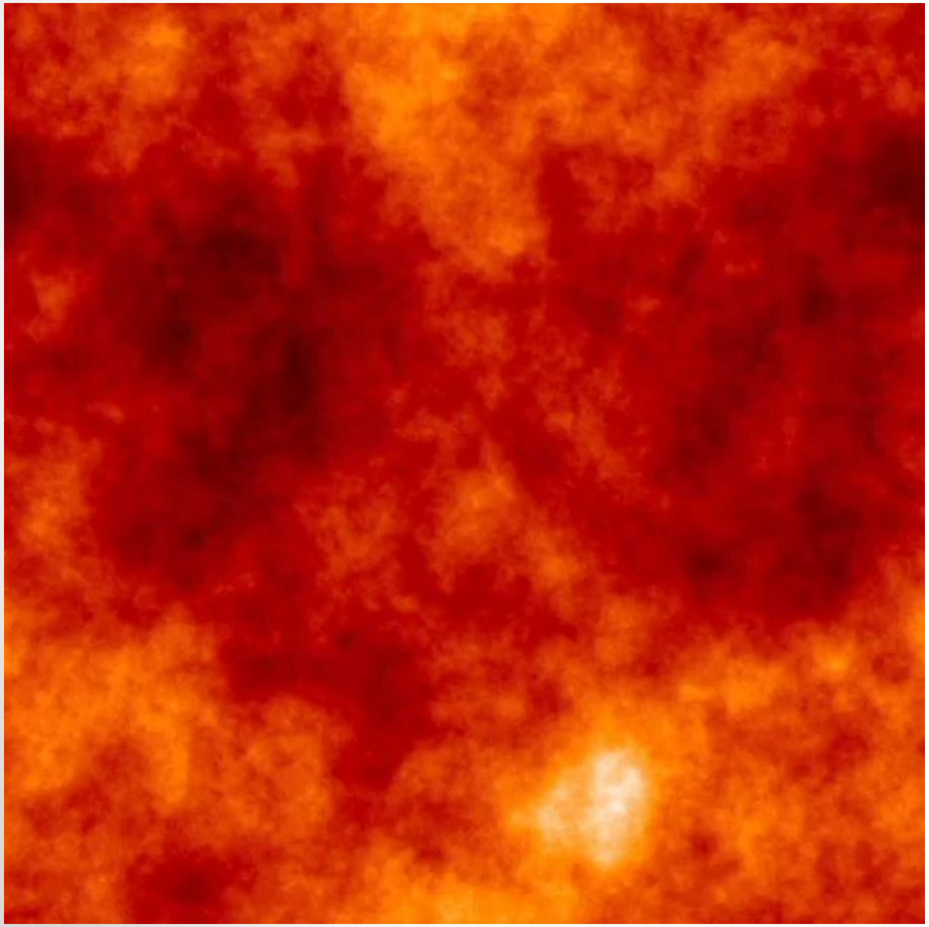
- Large frequency range (~25 – 900 GHz)
- Large angular resolution ($\ell \lesssim 2500$)

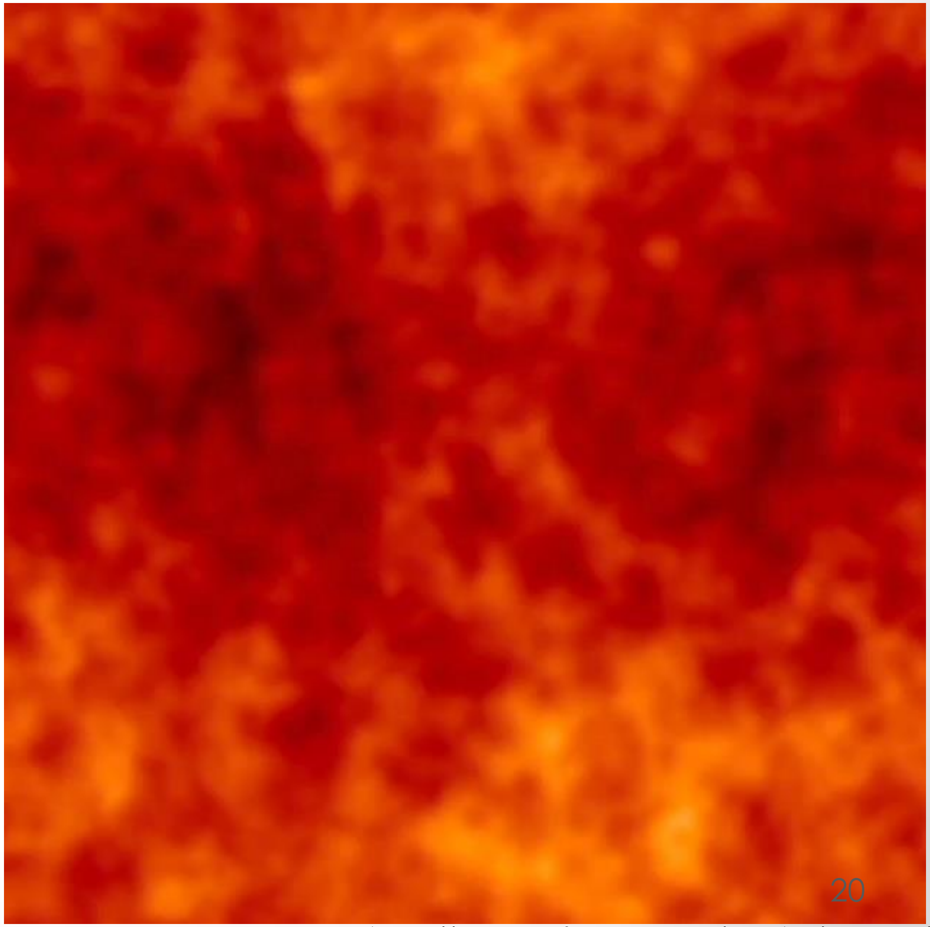


http://spaceinimages.esa.int/Images/2013/03/Planck_WMAP_comparison

Silk Damping

- Diffusion of photons → Damping of inhomogeneities
- Partial thermalization of baryon-photon plasma
- Expansion rate → Diffusion time → Damping scale

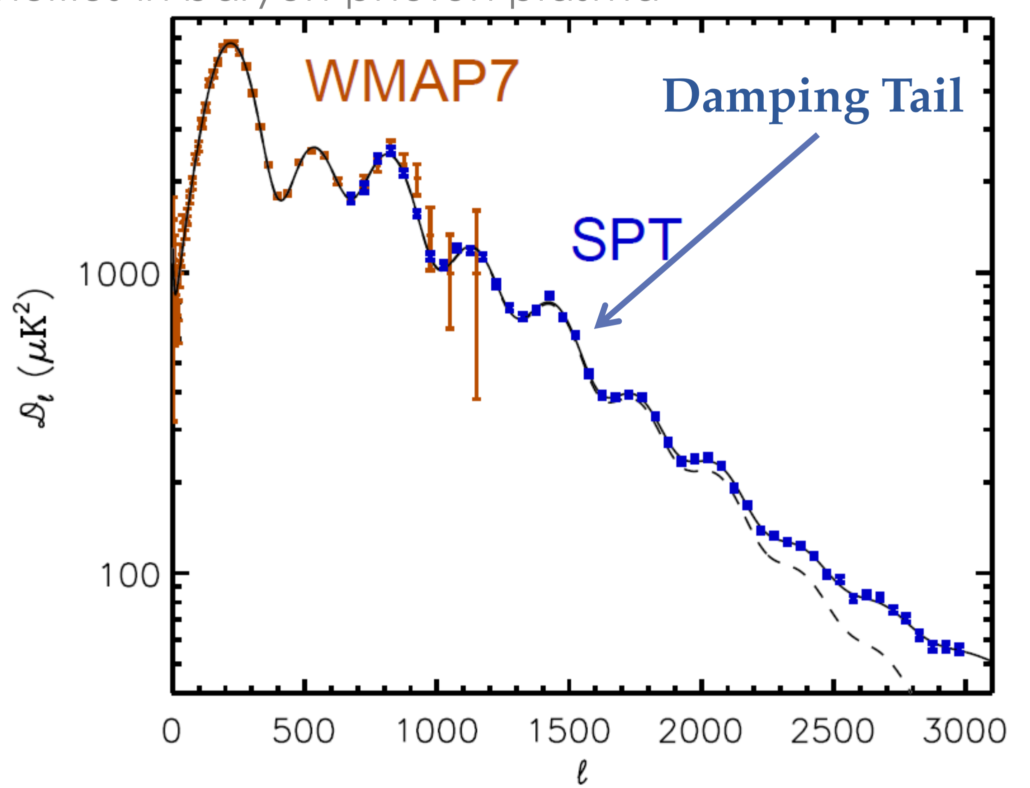




http://map.gsfc.nasa.gov/media/990320/

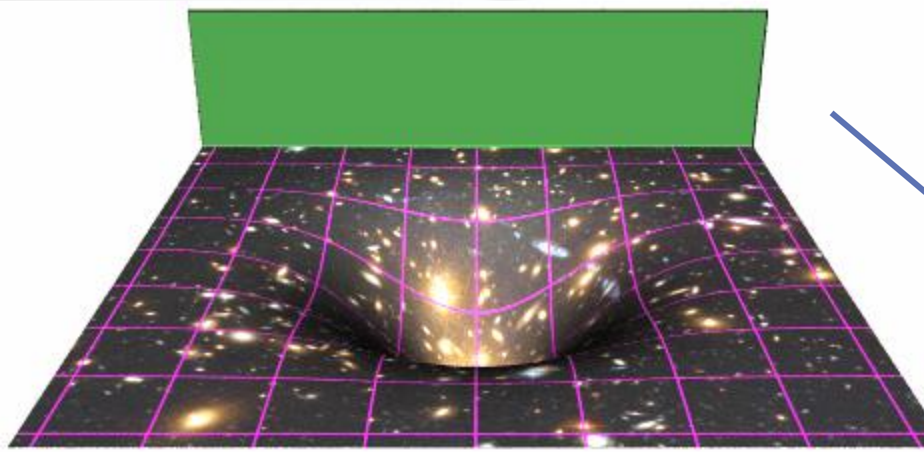
Silk Damping

- More light species → Faster expansion → Less damping
- Diffusion length determines damping moment ℓ_d
- Simpler to compare to sound horizon ℓ_s
    - Spread of inhomogeneities in baryon-photon plasma
- $\frac{\ell_s}{\ell_d} \sim \frac{\theta_d}{\theta_s} \sim \frac{\sqrt{t}}{t} \sim \sqrt{H}$

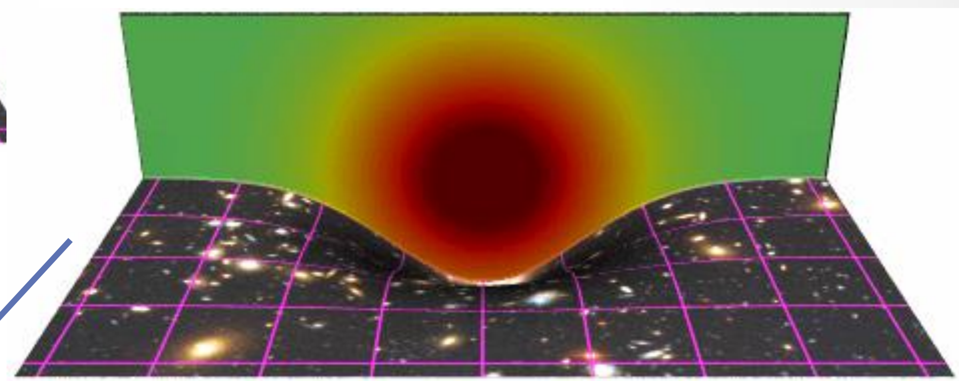


Story, *et al*, arXiv:1210.7231 [astro-ph.CO]

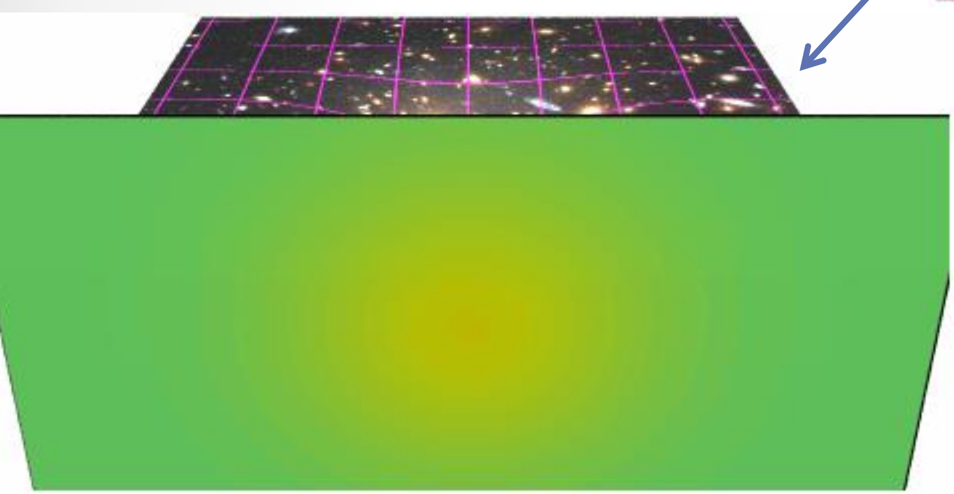
Integrated Sachs-Wolfe



- CMB photons red/blueshifted by matter over/underdensity



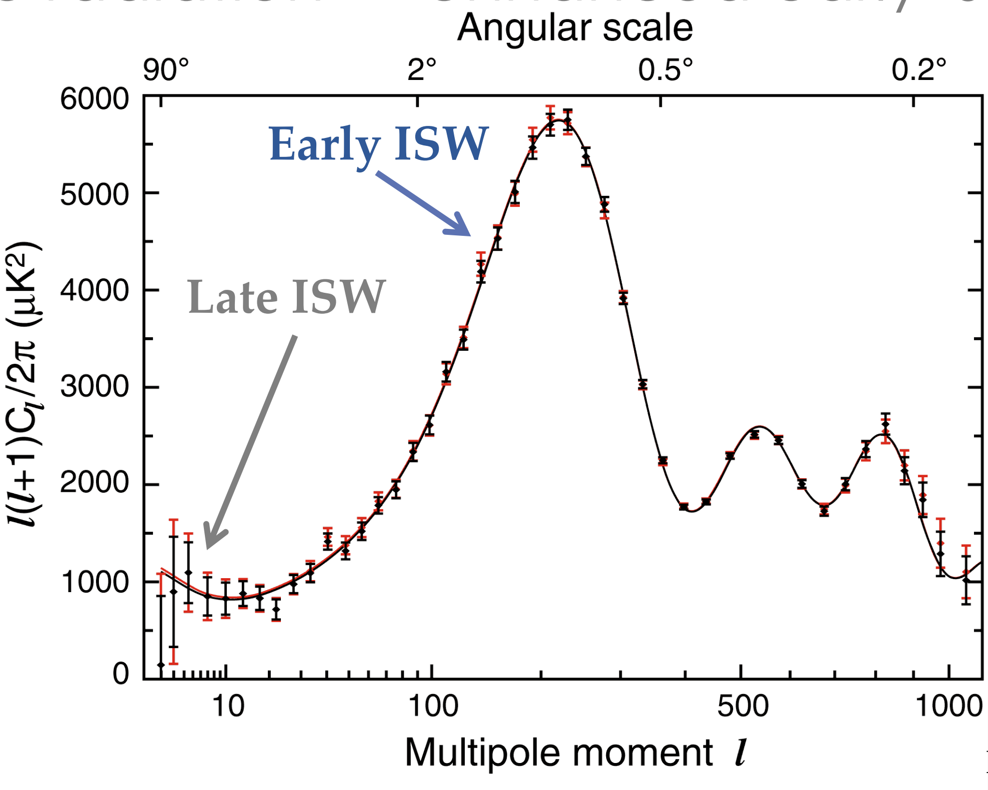
- Occurs when radiation or vacuum energy nonnegligible



http://ifa.hawaii.edu/cosmowave/supervoids/the-integrated-sachs-wolfe-effect/

Integrated Sachs-Wolfe

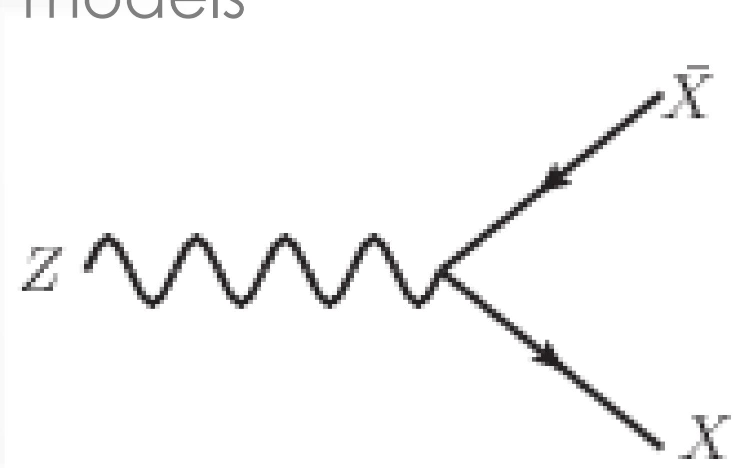
- Following recombination, matter-dominated
- Still large radiation component
- Affects CMB at angular scale of matter inhomogeneities
- More radiation → enhanced early ISW

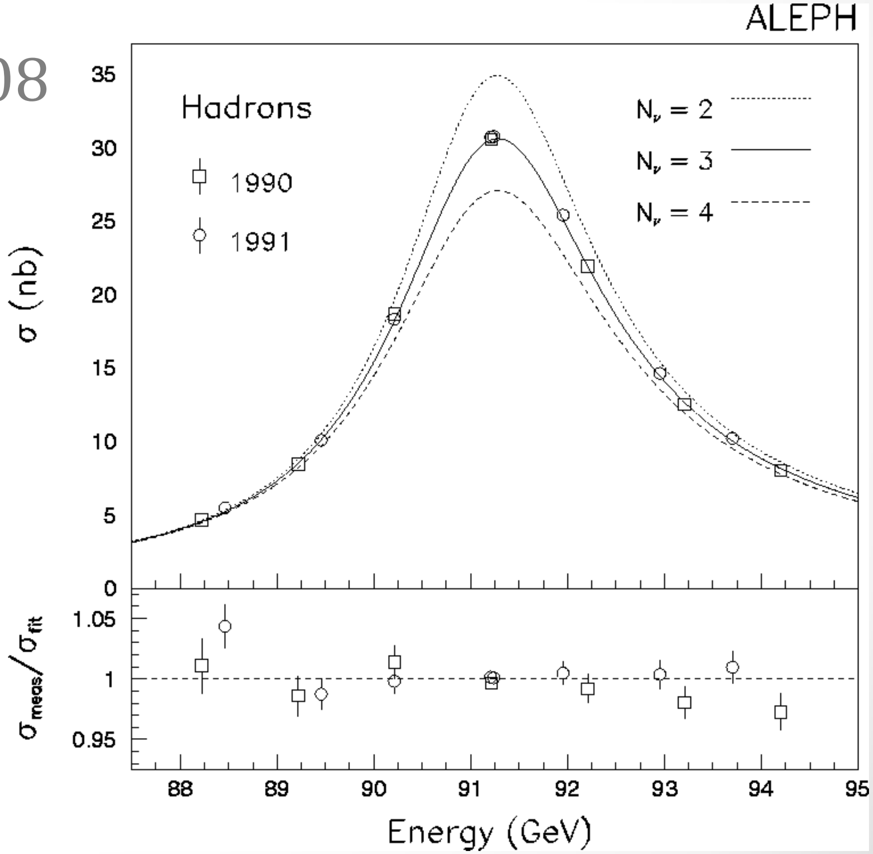


Hinshaw, *et al*, arXiv:1212.5226 [astro-ph.CO]

Are There More Neutrinos?

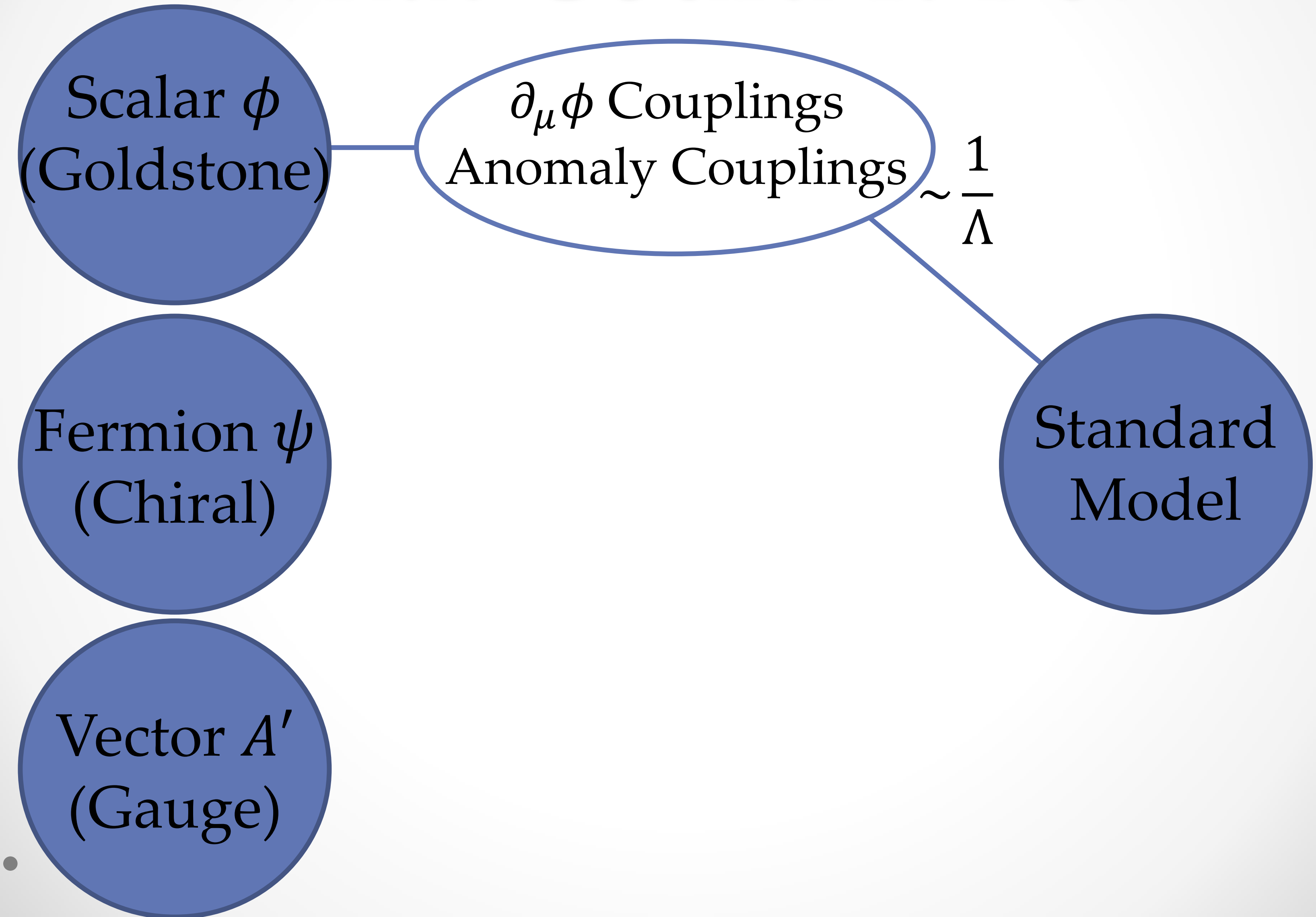
- Neutrino: light, electrically neutral fermion with weak force interactions
- Z-width: $N_\upsilon = 2.984 \pm 0.008$
- Need more general models





http://lappweb.in2p3.fr/neutrinos/neutimg/nhistory/alephneutrino2.gif

What Could It Be?



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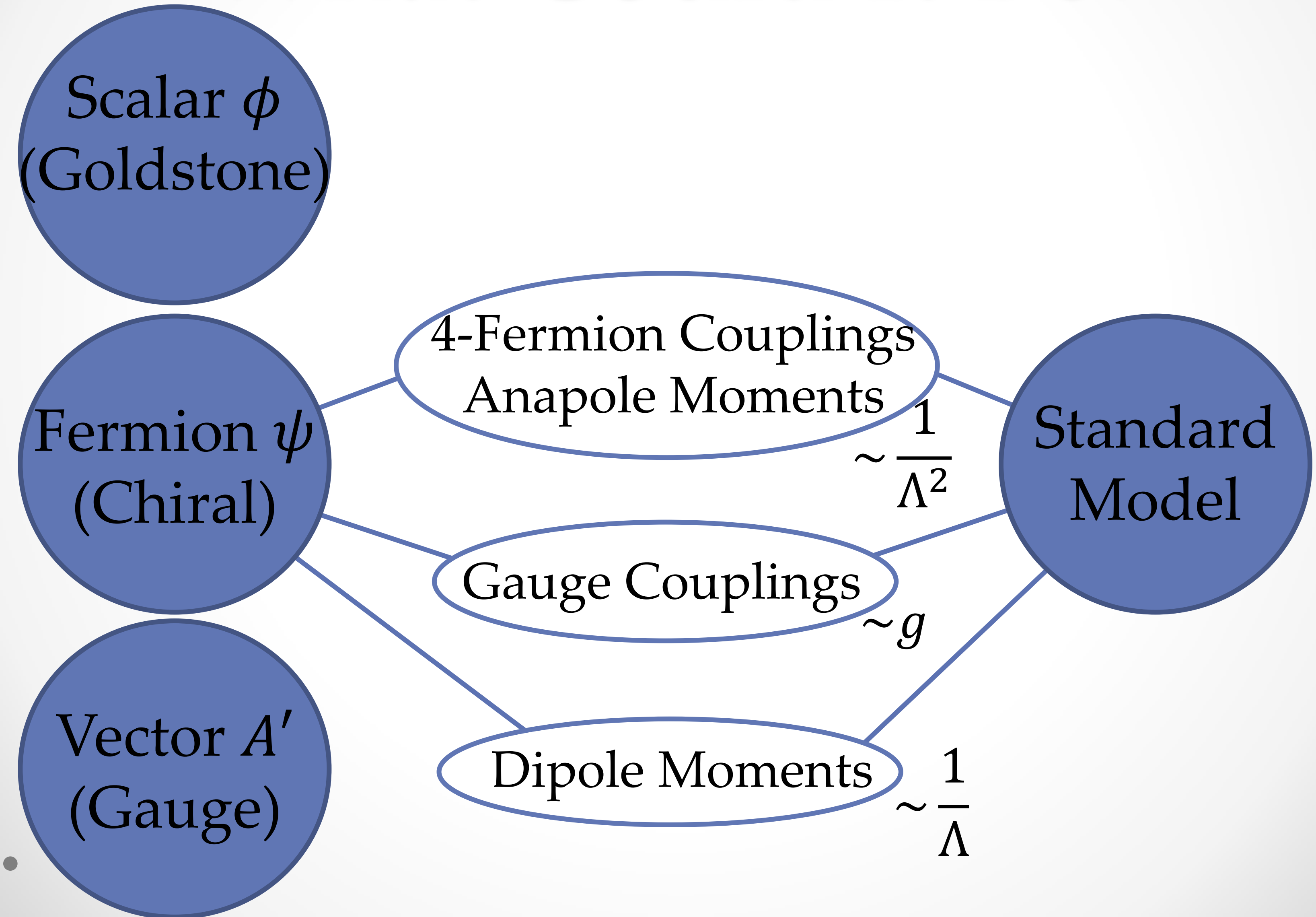

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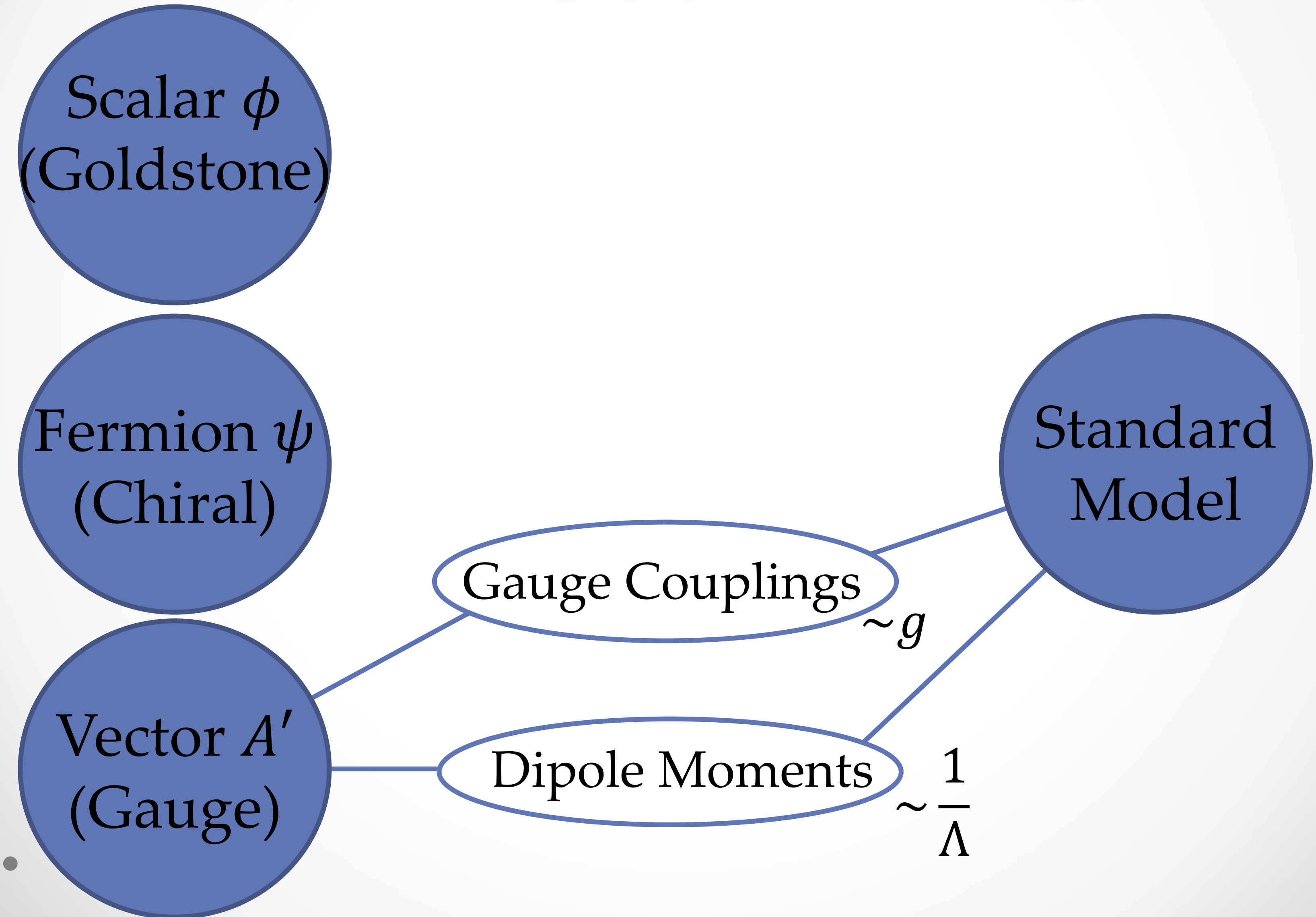
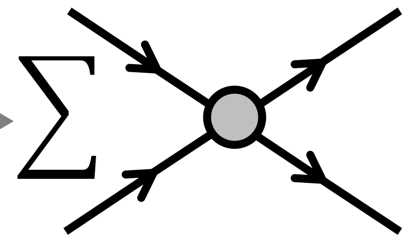
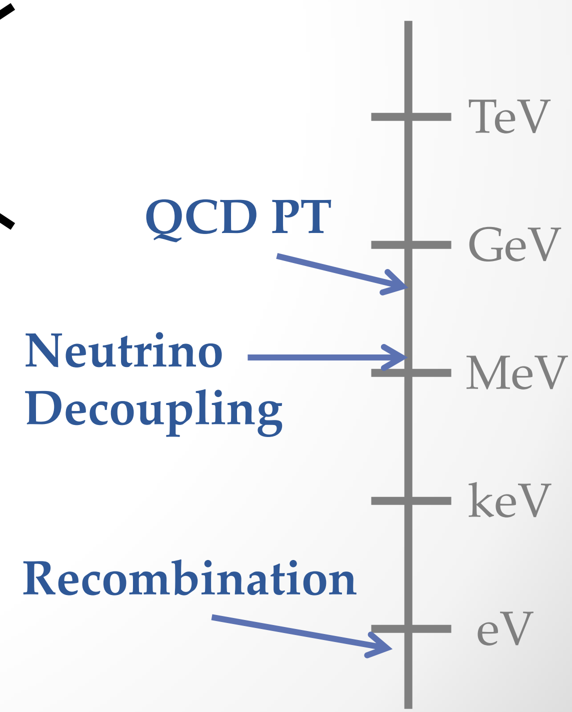


Early Universe Thermodynamics

- Particle species described by phase space density: $f(x^\mu, p^\mu)$
- Evolution governed by Boltzmann equations, Friedmann equations
- $E\frac{\partial f}{\partial t} - Hp^2\frac{\partial f}{\partial E} = C[f] \longrightarrow$
- $H^2 = \frac{8\pi G}{3}\rho$
- $\frac{d\rho}{dt} = -3H(\rho + P)$





Thermodynamics

- Boltzmann Equation: $E\frac{\partial f}{\partial t} - Hp^2\frac{\partial f}{\partial E} = C[f]$
- $C[f_i] = \frac{1}{2}\sum_{i,j\to a,b}\int d^3\Pi(2\pi)^4\delta^4(p)|M|^2\Omega(f)$
- $\Omega(f) = (f_a f_b(1\pm f_i)(1\pm f_j) - f_i f_j(1\pm f_a)(1\pm f_b))$
- Hubble: $H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G}{3}\rho} \approx \frac{T^2}{M_{Pl}}\sqrt{\frac{4\pi^3 g_*}{45}}$
- Conservation of Energy: $\frac{d\rho}{dt} = -3H(\rho + P)$
- $T^{\mu\nu} = g\int\frac{d^3p}{(2\pi)^3}\frac{p^\mu p^\nu}{E}f$

Calculational Method

- New species distribution function defined on momentum grid covering $10\ \text{keV} \lesssim p \lesssim 10\ \text{GeV}$
- Assume equilibrium following QCD phase transition
- Step forward in time, solving Boltzmann equation for new species with predictor-corrector method, based on evolution of SM
- Continue until after muon annihilation ($T \sim 1$ MeV)
- Resulting distribution function used to calculate energy density at recombination

Interaction Terms

- Gauge Coupling: $A'_\mu \bar{\chi}\gamma^\mu(c_V + c_A\gamma^5)\chi$
- Dipole Moment: $\frac{1}{2}\bar{\chi}\sigma^{\mu\nu}(\mu + id\gamma^5)\chi F_{\mu\nu}$
- Goldstone-Fermion Coupling: $\frac{1}{\Lambda}\partial_\mu\phi\, \bar{\psi}\gamma_\mu\gamma^5\psi$
- Goldstone-Gauge Coupling: $\frac{1}{\Lambda}\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$
- Four-Fermion Coupling: $\frac{1}{\Lambda^2}\bar{\chi}\Gamma^\mu\chi\, \bar{\psi}\Gamma_\mu\psi \quad (1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5)$
- Anapole Moment: $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu(c_V + c_A\gamma^5)\chi\partial^\nu F_{\mu\nu}$

CMB Anisotropies

$$\left.\frac{\delta T}{T}\right|_{obs} = \left.\frac{\delta T}{T}\right|_{emit} + \left.\phi\right|_{emit} - \left.\phi\right|_{obs} + \left.\hat{n}\cdot\vec{v}\right|_{emit} + 2\int d\tau\ \dot{\phi}$$

Observed Spectrum

Original Spectrum

Gravitational Redshift

Relative Vel. Doppler

Changing Potential

$$\left\langle \frac{\delta T}{T}(\hat{n})\frac{\delta T}{T}(\hat{0})\right\rangle = \sum_{l,m} a_{lm}Y_{lm}(\theta,\phi) \rightarrow \langle |a_{lm}|^2\rangle = C_l$$

Big Bang Nucleosynthesis

- More radiation implies faster expansion, which increases neutron abundance (earlier decoupling) and thus helium abundance
- CMB measurements (and some recent observational analyses) imply potentially larger helium abundance than predicted, consistent with more light species
    - $Y_P \gtrsim 0.227 \left(N_{eff} = 2\right)$
    - $Y_P \gtrsim 0.242 \left(N_{eff} = 3\right)$
    - $Y_P \gtrsim 0.254 \left(N_{eff} = 4\right)$

Alternatives to Light Species

- **Two choices:**

1) Increased neutrino energy density (number, temperature, distribution)

2) Additional light particles beyond the SM

- Neutrino energy density can be altered by:

1) Neutrino asymmetry: $\rho_\nu = \frac{7N_\nu \pi^2 T_\nu^2}{120}\left(1 + \frac{30\xi^2}{7\pi^2} + \frac{15\xi^4}{7\pi^4}\right)$
2) Interactions with new massive species:

   Decay, Annihilation
3) New interactions with SM particles

   Dipole moment, Four-fermion