New Light Species and the Cosmic Microwave Background

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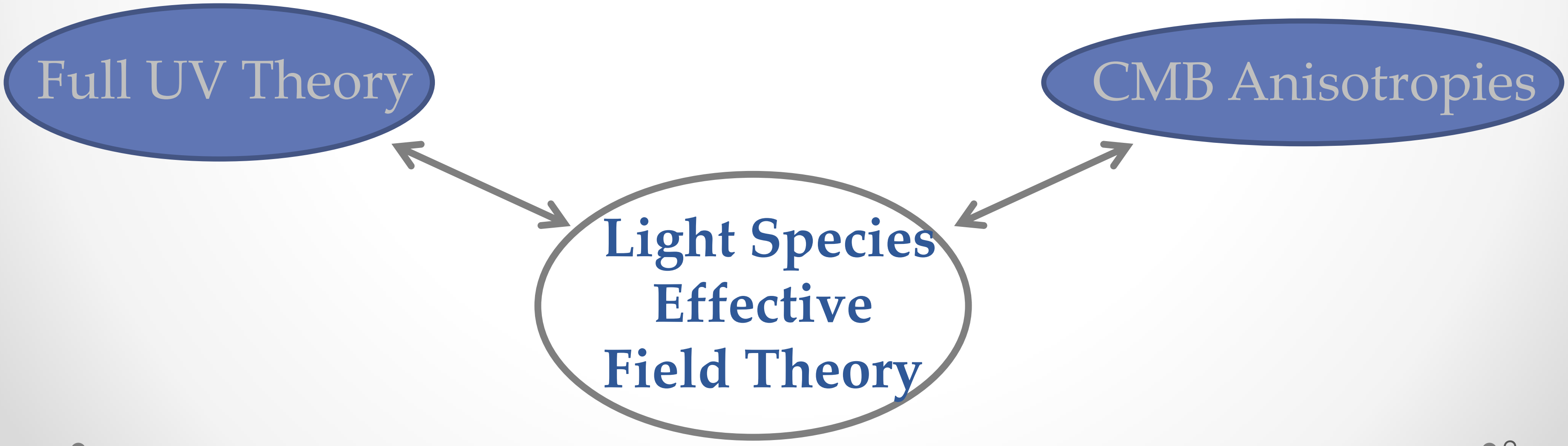
arXiv: 1303.5379 [hep-ph] Brust, Kaplan, MTW

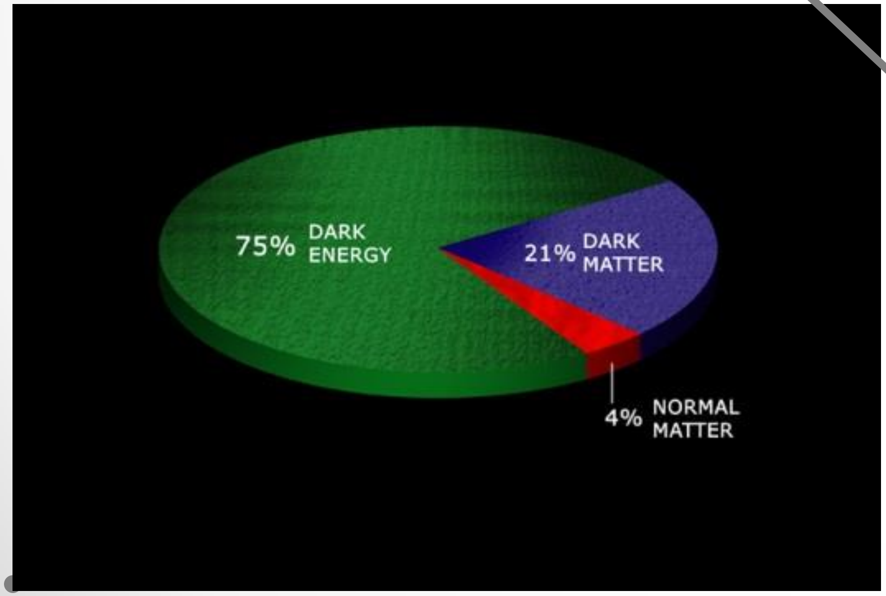
Goal

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

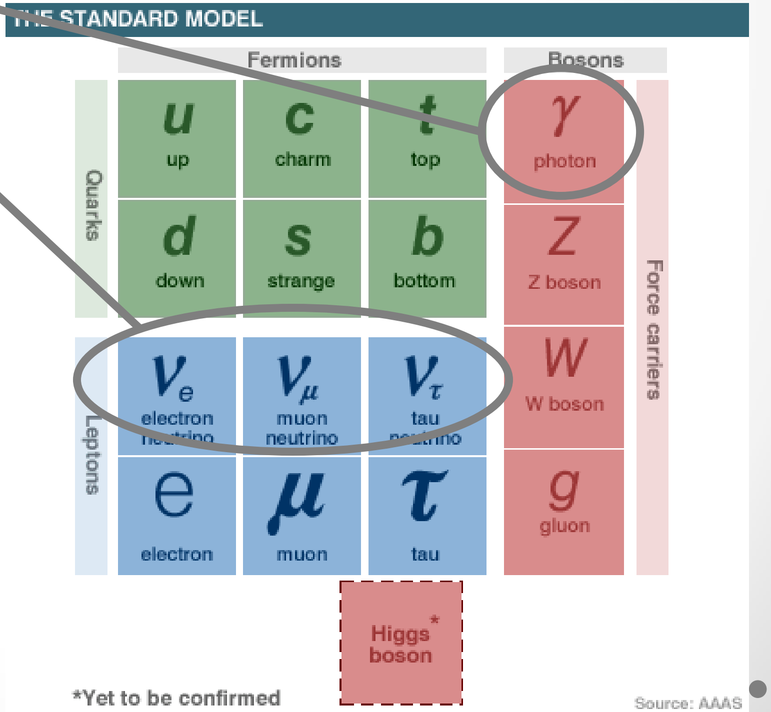


The Big Picture

- Current framework:
  - Standard Model (SM) + Cosmological Constant / Dark Matter (ΛCDM)
- Make and test predictions in early universe (T~eV)
  - Light species: $m \lesssim$ eV
  - 1 eV $\sim 10^4$ K $\sim 10^{-9} m_p$



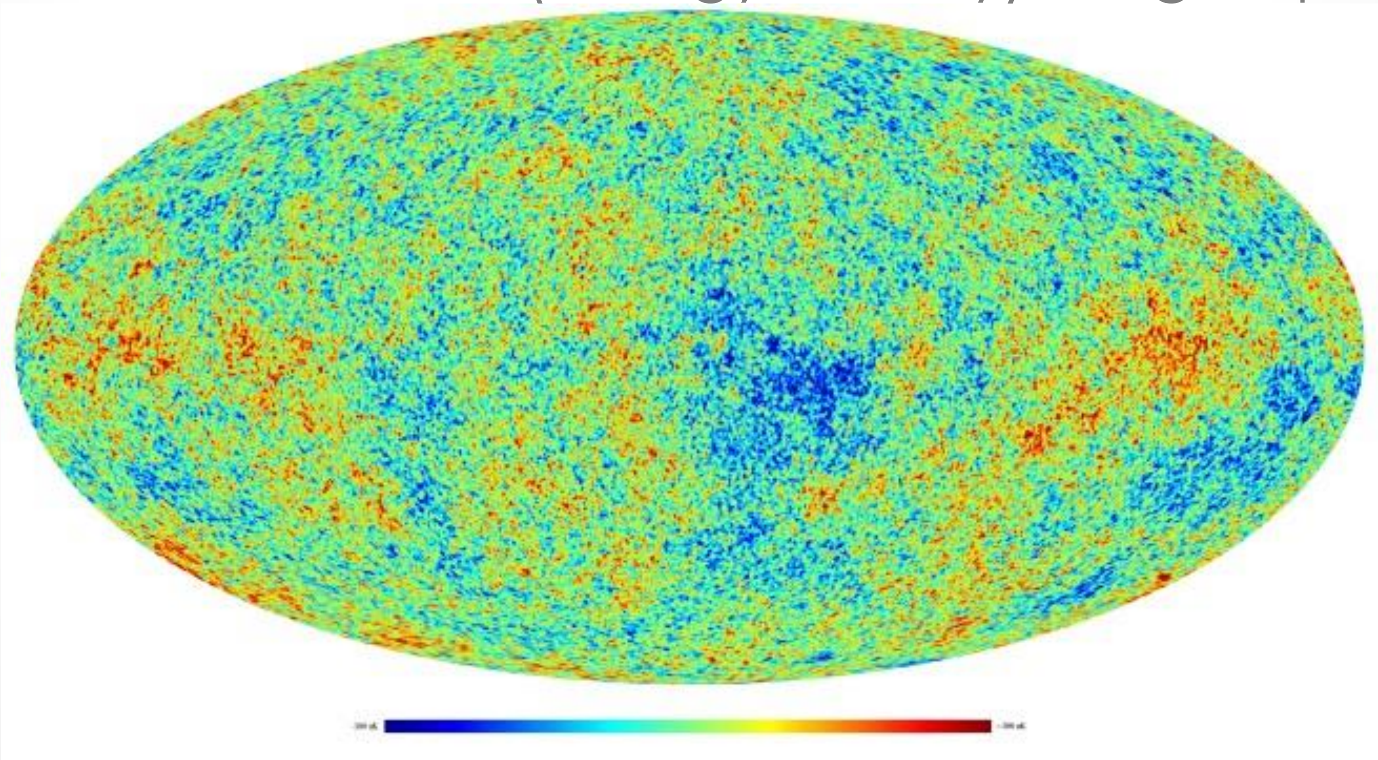
http://physicsforme.files.wordpress.com/2011/08/darkenergy3.jpg



http://www.daviddarling.info/images/Standard_Model.gif

Cosmic Microwave Background (CMB)

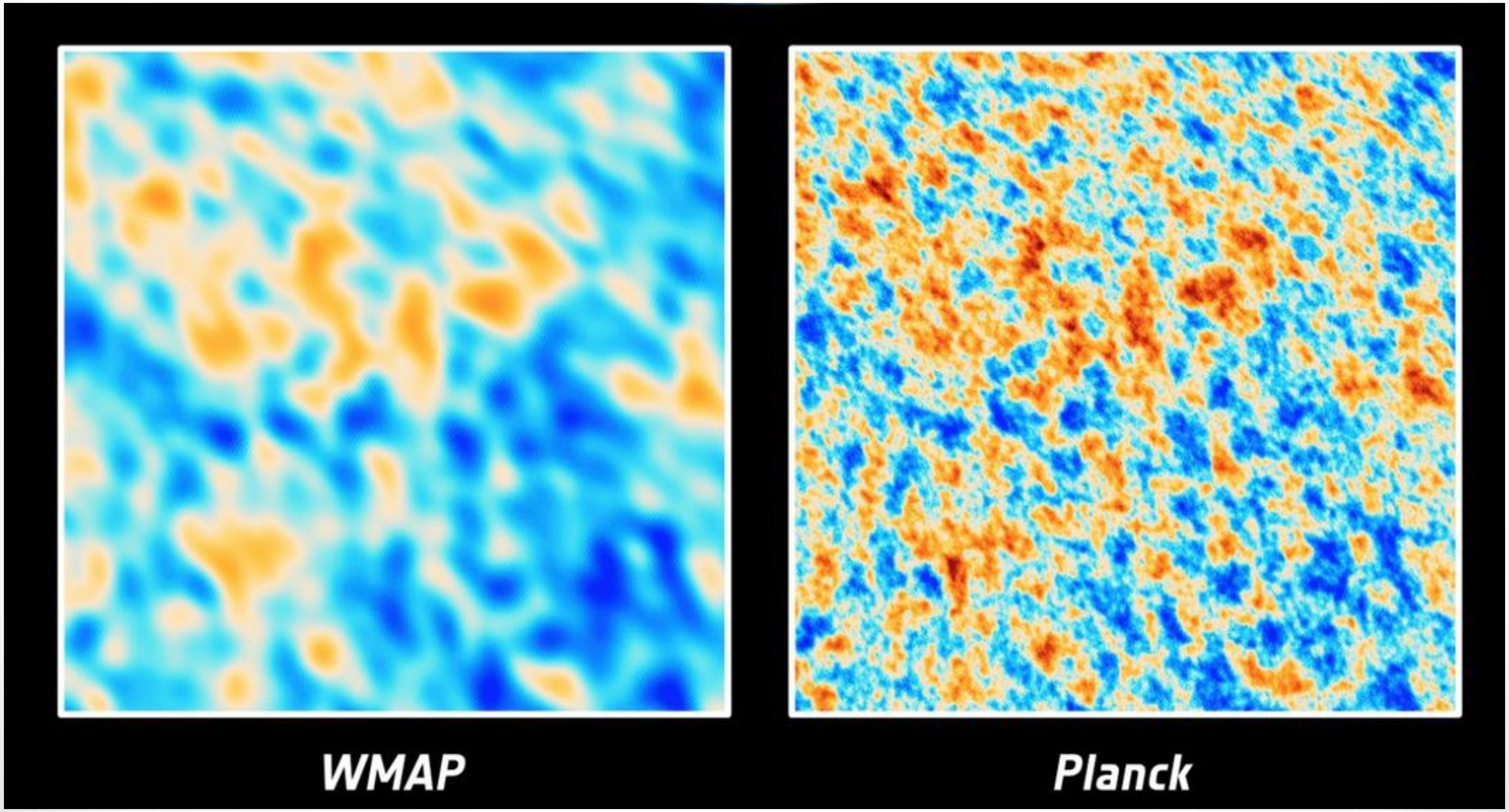
- Residual radiation (from $T \approx 0.1$ eV)
- Anisotropies measure early universe structure
- Sensitive to amount (energy density) of light species



http://crd-legacy.lbl.gov/~borrill/cmb/planck/CMB_I_217-all.highres.jpg

Planck Satellite

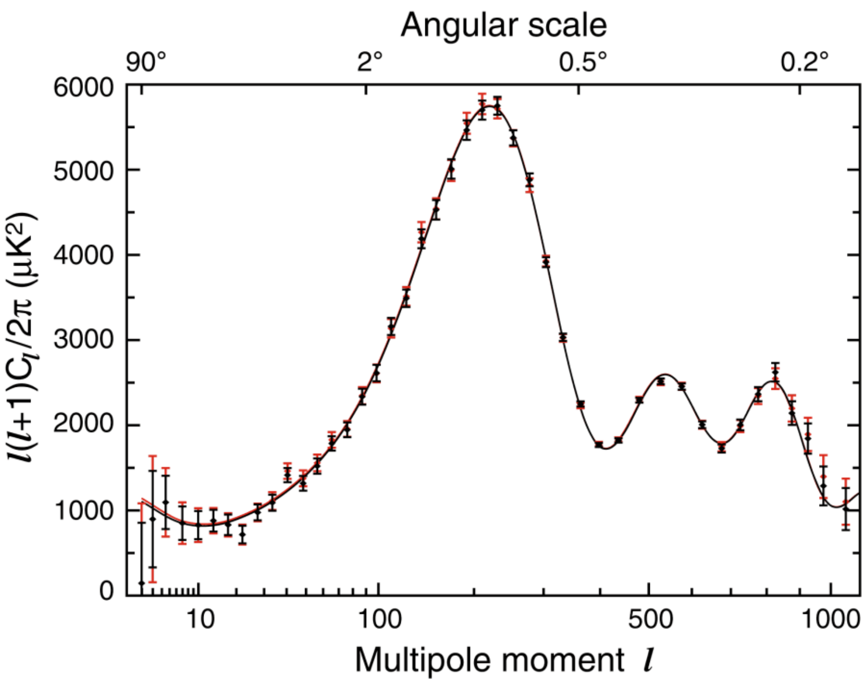
- Large frequency range (~25 – 900 GHz)
- Large angular resolution ($\ell \lesssim 2500$)



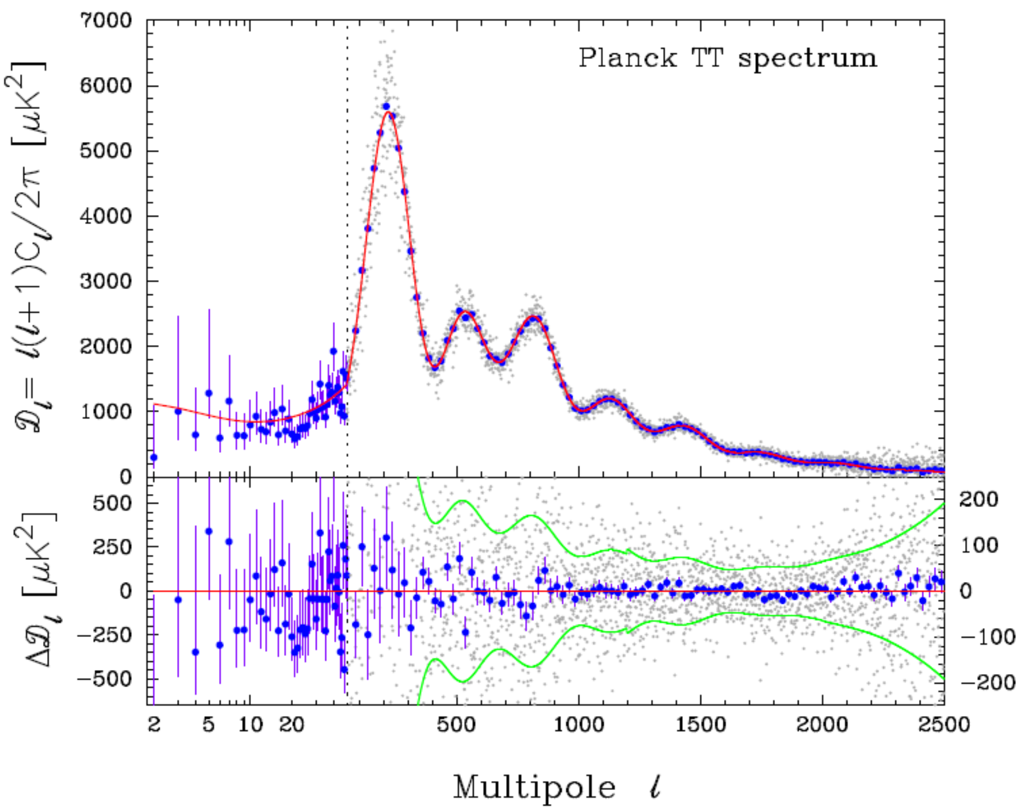
http://spaceinimages.esa.int/Images/2013/03/Planck_WMAP_comparison

CMB Anisotropies

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



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



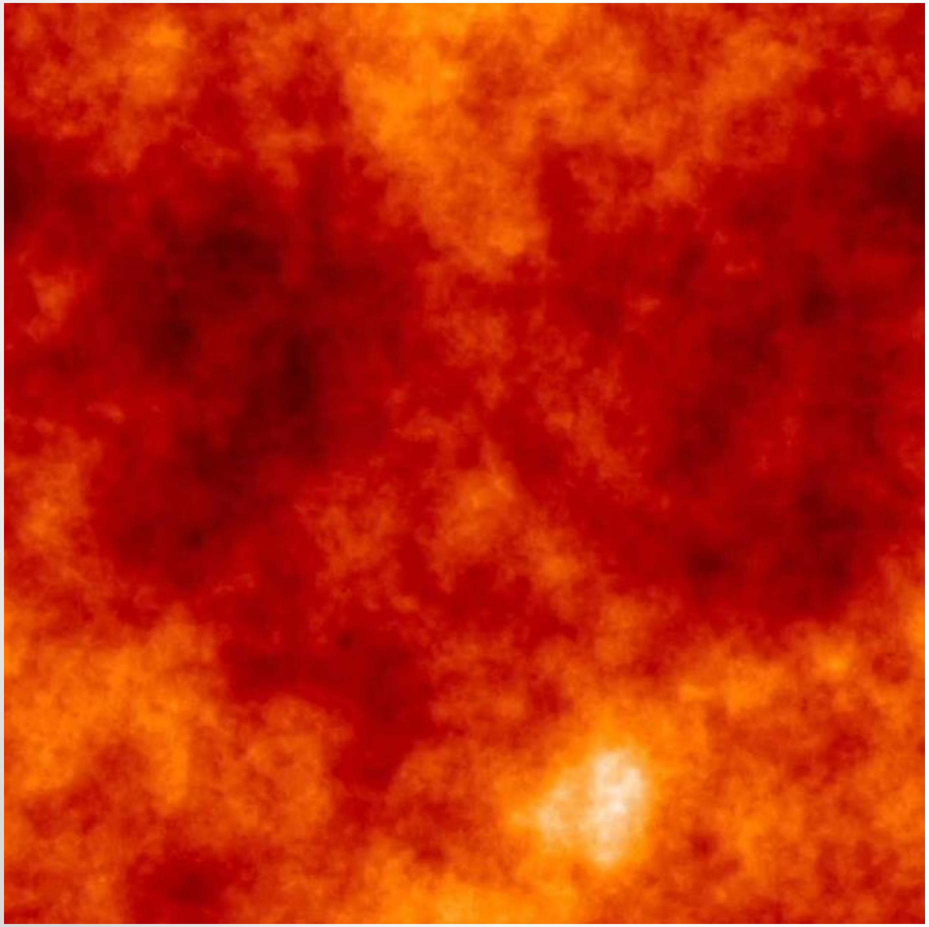
Planck: Ade, *et al*, arXiv:1303.5076 [astro-ph.CO]

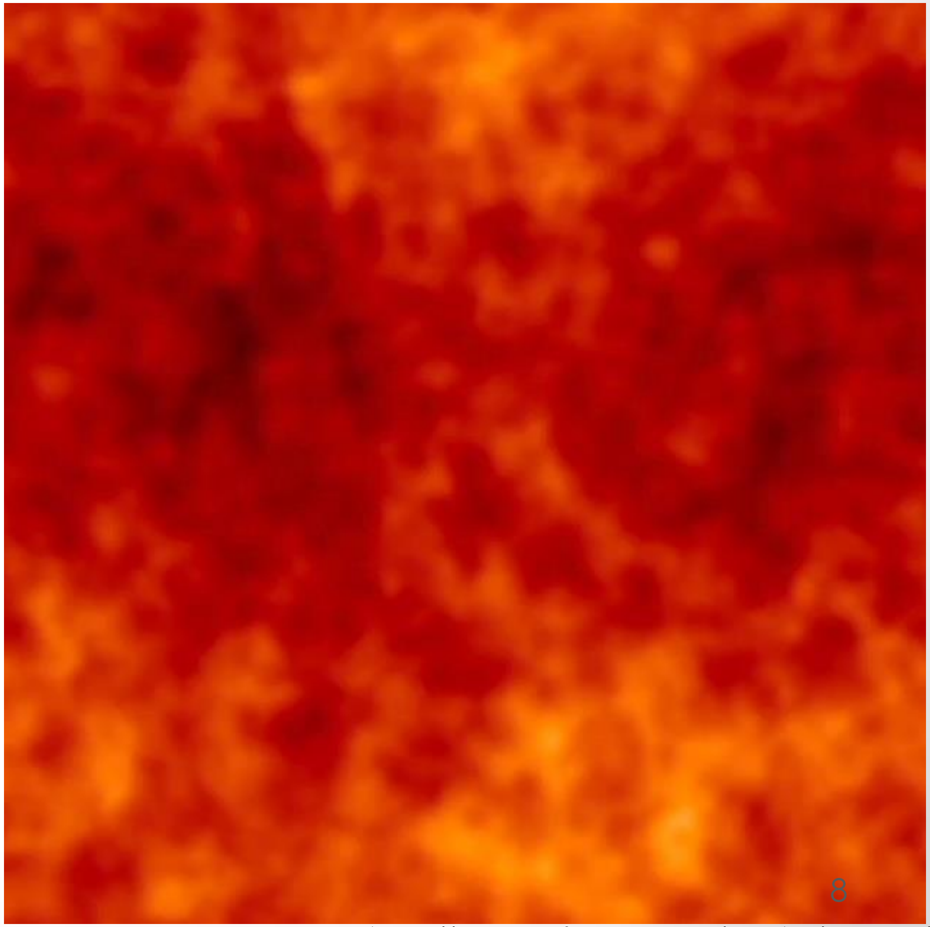
Light Species and CMB

- Massless limit ($m \ll \text{eV}$)
- Energy density and pressure alter expansion rate ($\mathrm{P} = \frac{1}{3}\rho$)
- Two main effects:
  - Silk Damping (before/during recombination)
  - Early Integrated Sachs-Wolfe (during/after recombination)
- Observed significance of effects determines/limits number of light species

Silk Damping

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

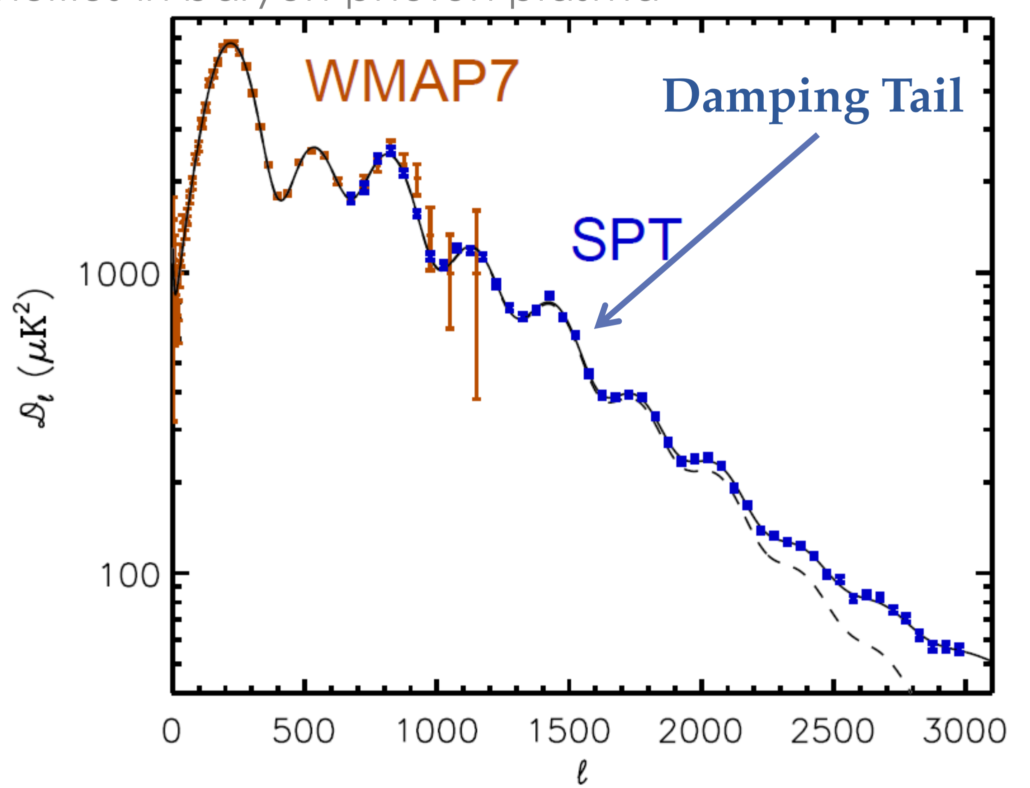




http://map.gsfc.nasa.gov/media/990320/

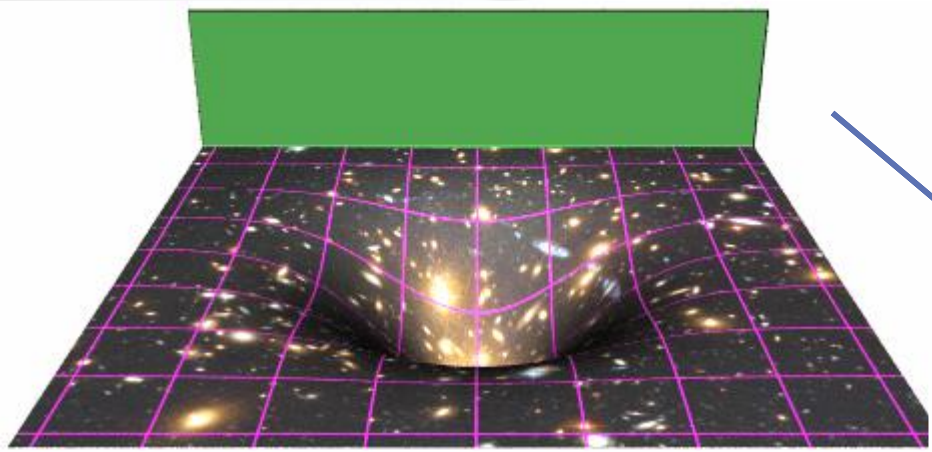
Silk Damping

- 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
- $\frac{\ell_s}{\ell_d} \sim \frac{\theta_d}{\theta_s} \sim \frac{\sqrt{t}}{t} \sim \sqrt{H}$

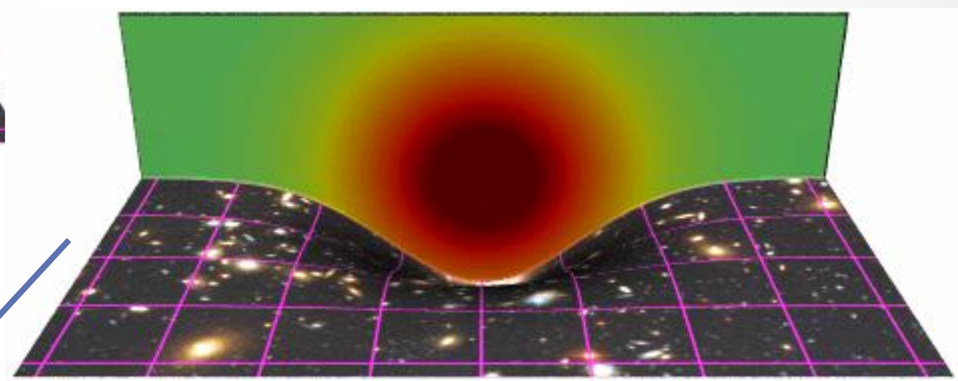


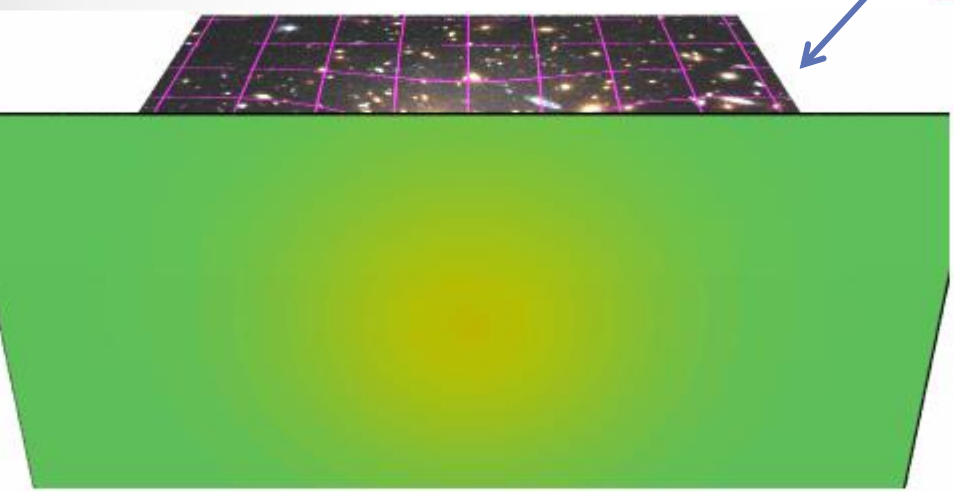
Story, *et al*, arXiv:1210.7231 [astro-ph.CO]

Integrated Sachs-Wolfe



- CMB photons red/blueshifted by matter over/underdensity



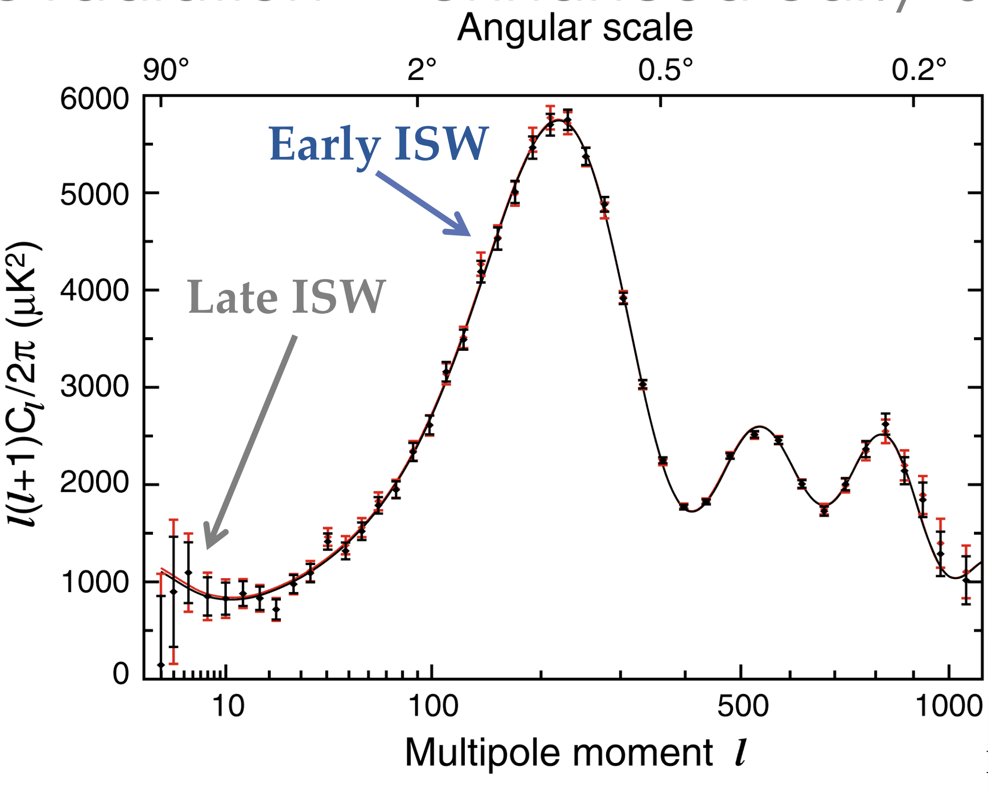


- Occurs when radiation or vacuum energy nonnegligible

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

Integrated Sachs-Wolfe

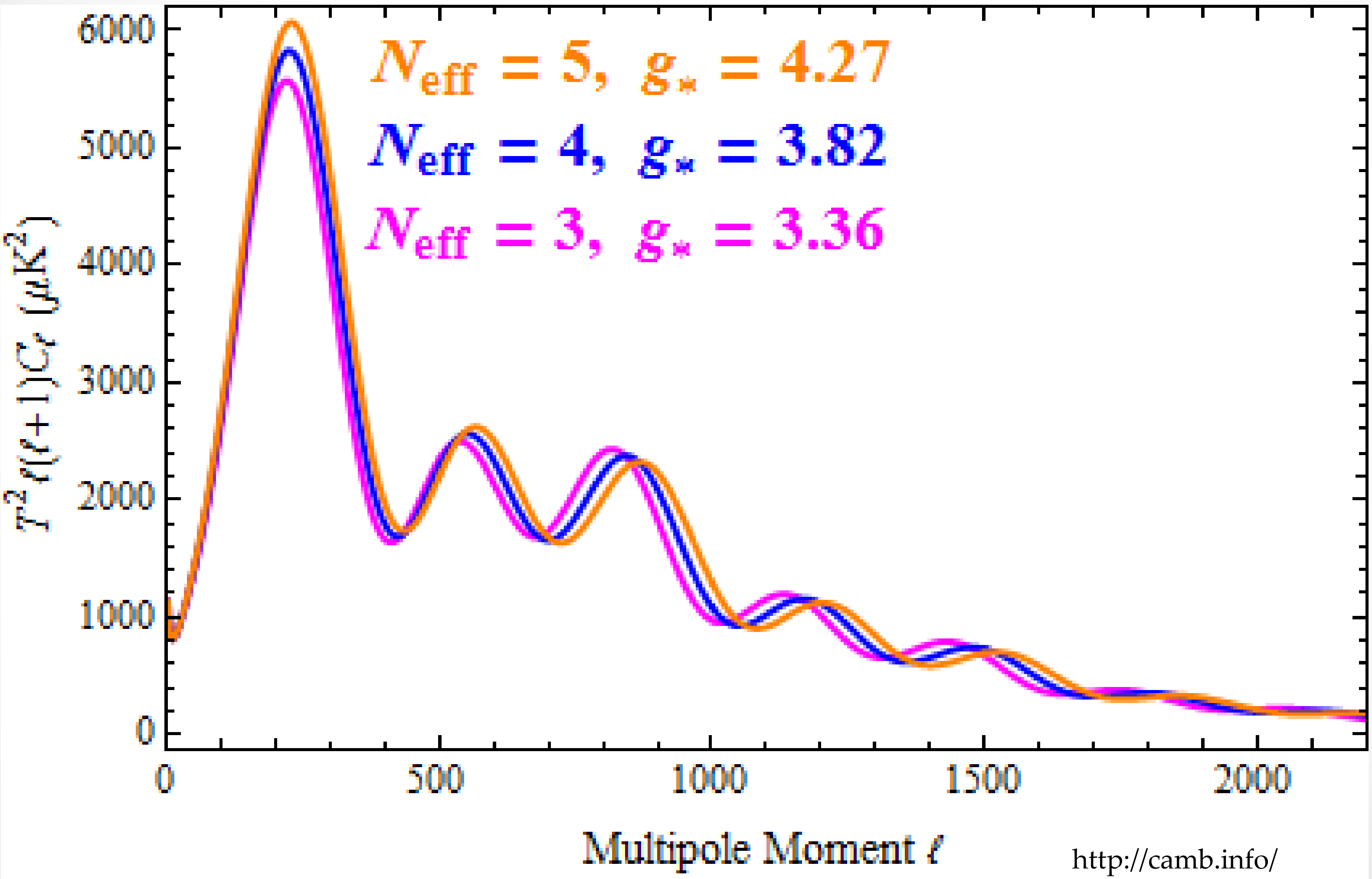
- Following recombination, matter-dominated
- Still large radiation component
- Affects CMB at angular scale of matter inhomogeneities
- More radiation → enhanced early ISW



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

New Light Species

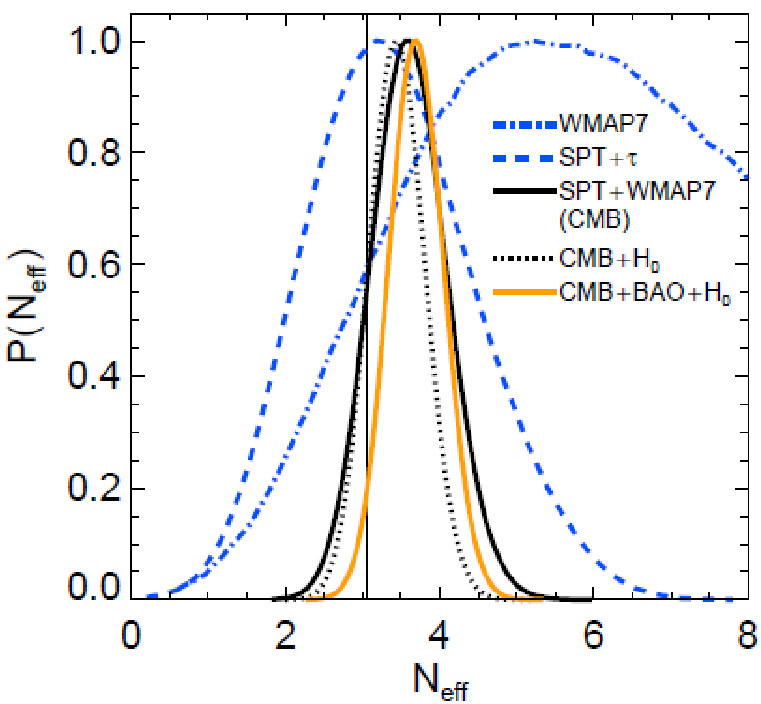
- $\rho_{rel} = g_* \frac{\pi^2}{30} T_\gamma^4 = 2 + 2 \cdot \frac{7}{8} \cdot N_{eff} \left(\frac{4}{11}\right)^{4/3}$

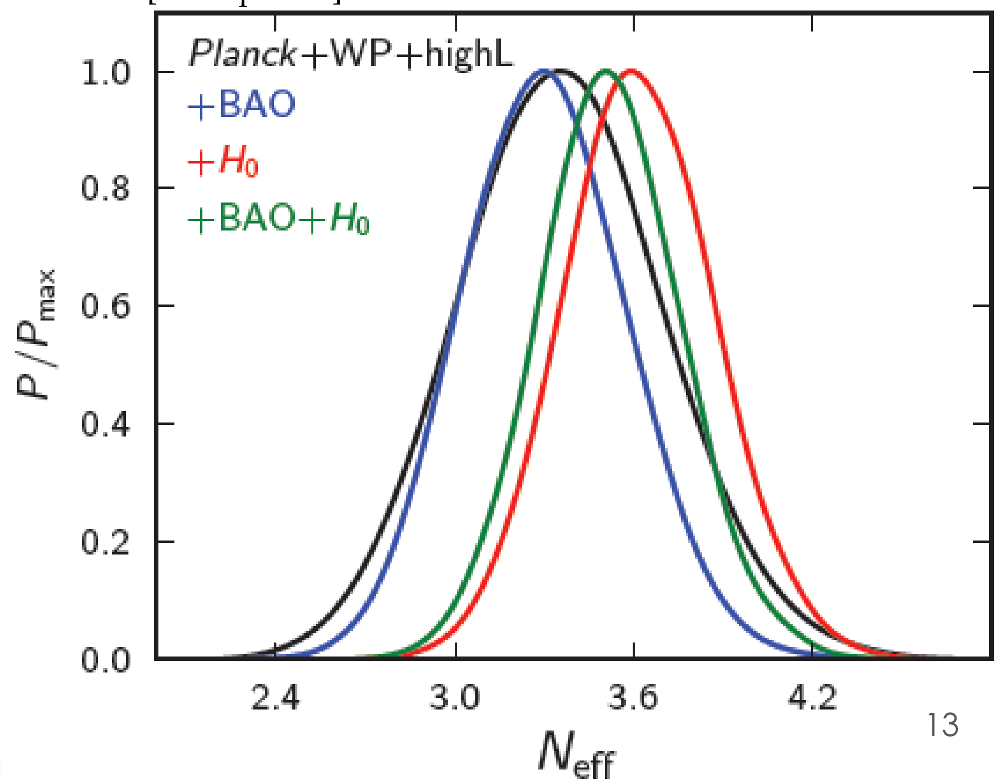


http://camb.info/

Observational Data

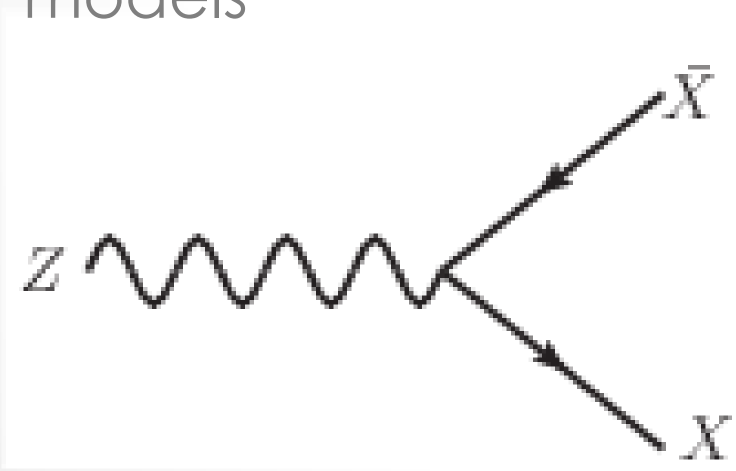
- SM prediction: 3.046
- WMAP: 3.55 ± 0.49 Hinshaw, *et al*, arXiv:1212.5226 [astro-ph.CO]
- ACT: 3.50 ± 0.42 Sievers, *et al*, arXiv:1301.0824 [astro-ph.CO]
- SPT: 3.71 ± 0.35 Hou, *et al*, arXiv:1212.6267 [astro-ph.CO]
- Planck: 3.30 ± 0.27 Ade, *et al*, arXiv:1303.5076 [astro-ph.CO]

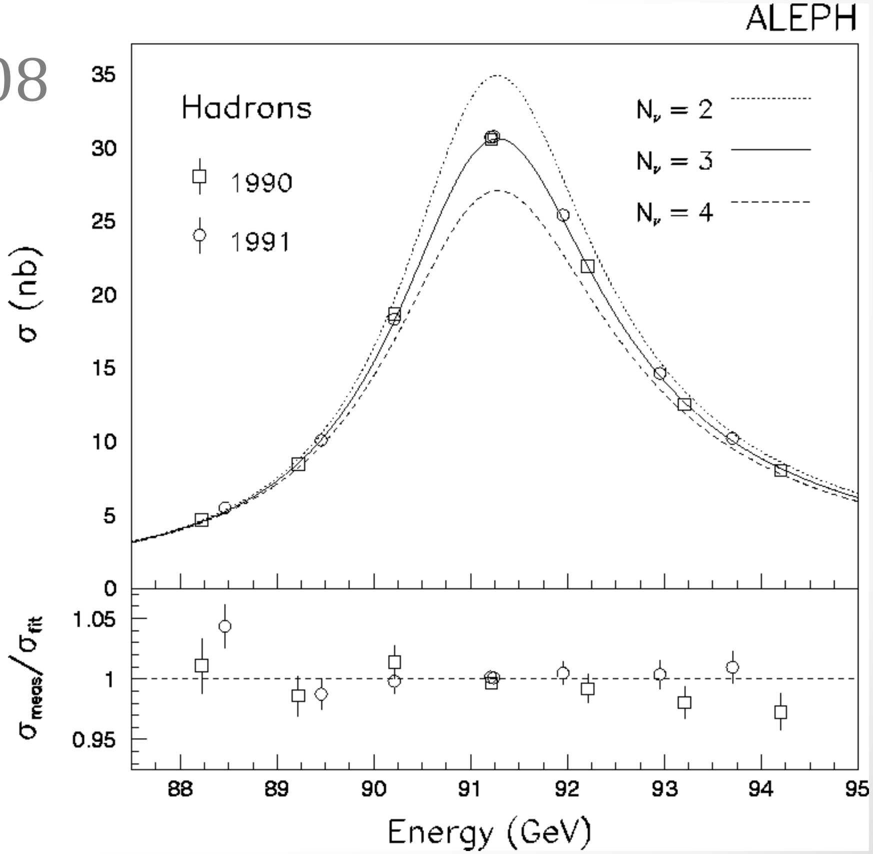




Are There More Neutrinos?

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

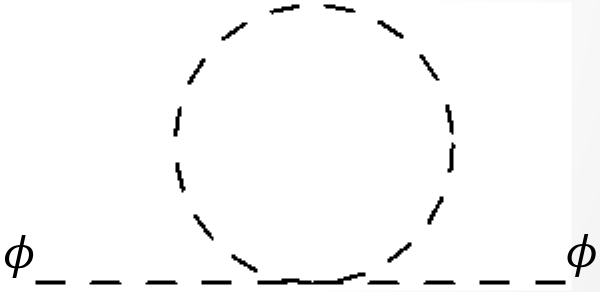




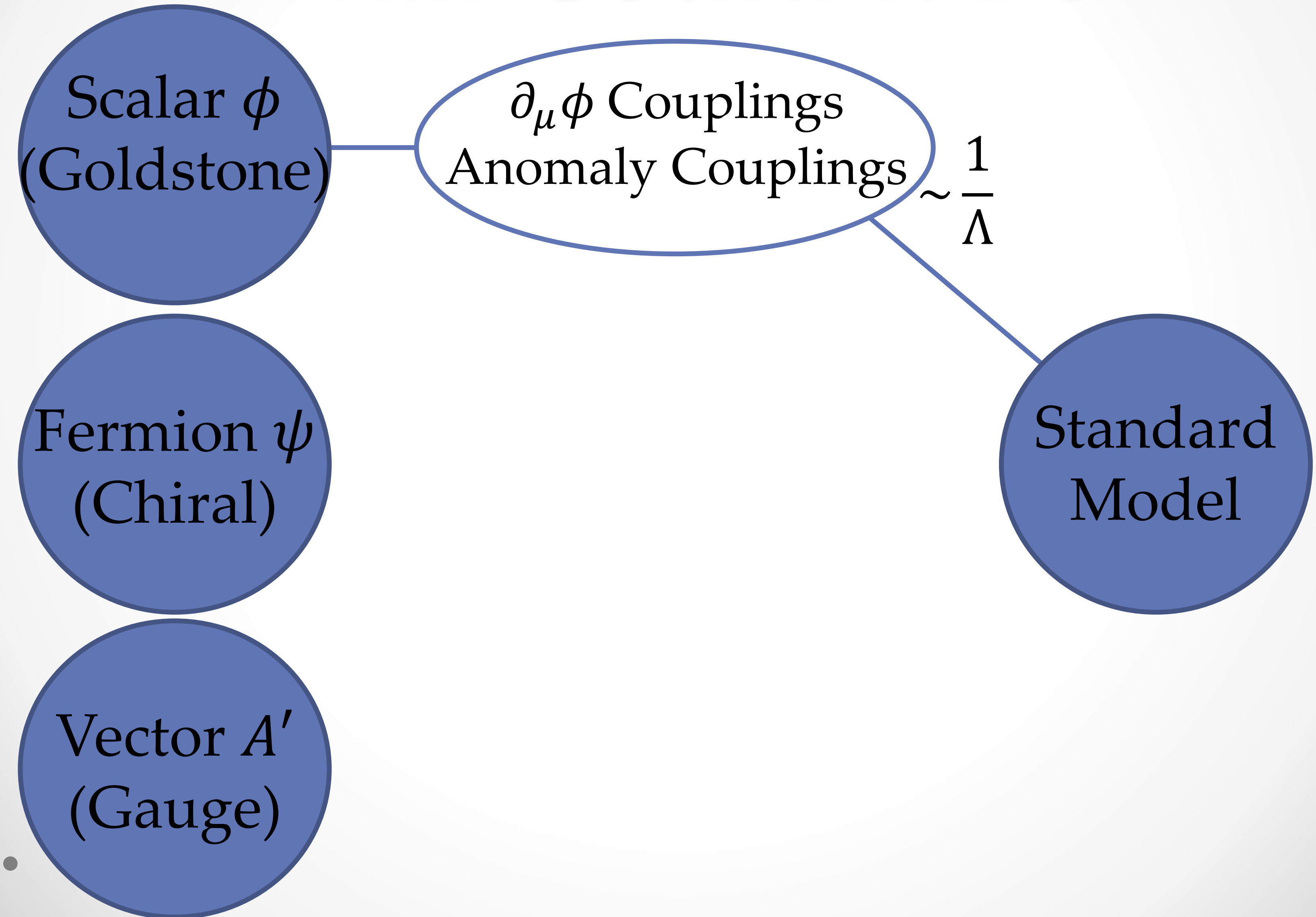
http://lappweb.in2p3.fr/neutrinos/neutimg/nhistory/alephneutrino2.gif

What Could 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
  - Insensitive to quantum corrections, $\frac{|\delta\lambda|}{\lambda} \lesssim 1$
  - Mass protected by symmetry
- Detailed calculation of Δg_*
- Direct map between theory and experiment



What Could It Be?



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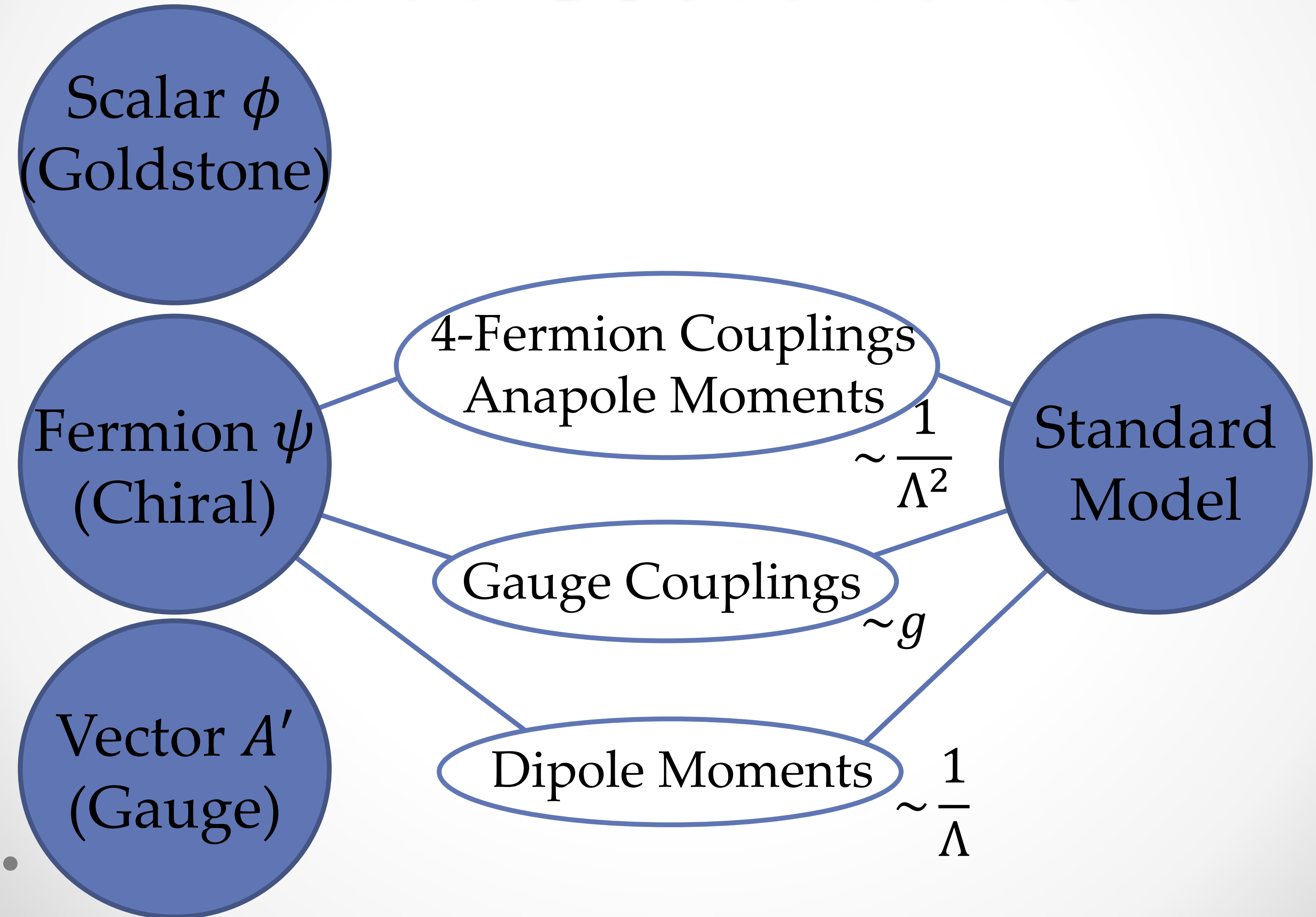

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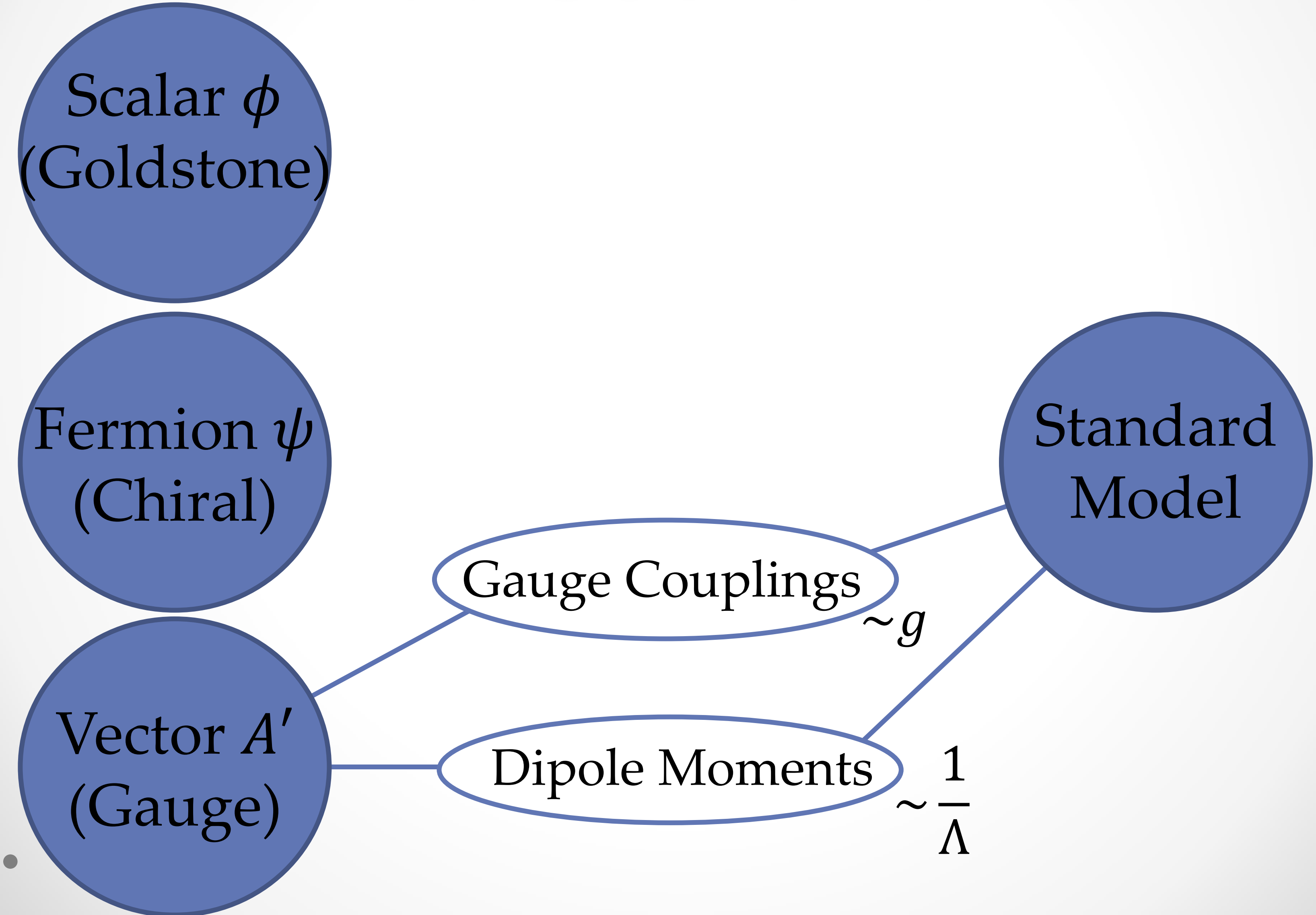
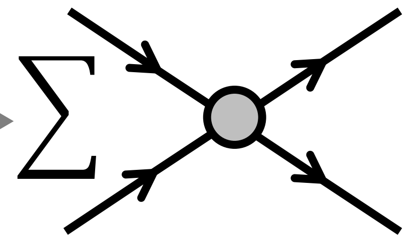
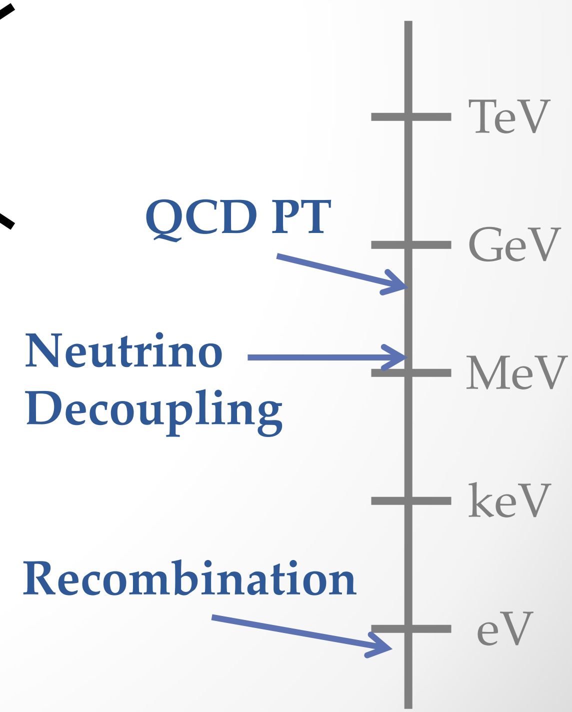


Early Universe Thermodynamics

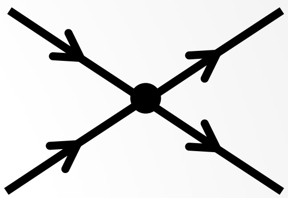
- Particle species described by phase space density: $f(x^\mu, p^\mu)$
- Evolution governed by Boltzmann equations, Friedmann equations
- $E\frac{\partial f}{\partial t} - Hp^2\frac{\partial f}{\partial E} = C[f] \longrightarrow$



- $H^2 = \frac{8\pi G}{3}\rho$
- $\frac{d\rho}{dt} = -3H(\rho + P)$



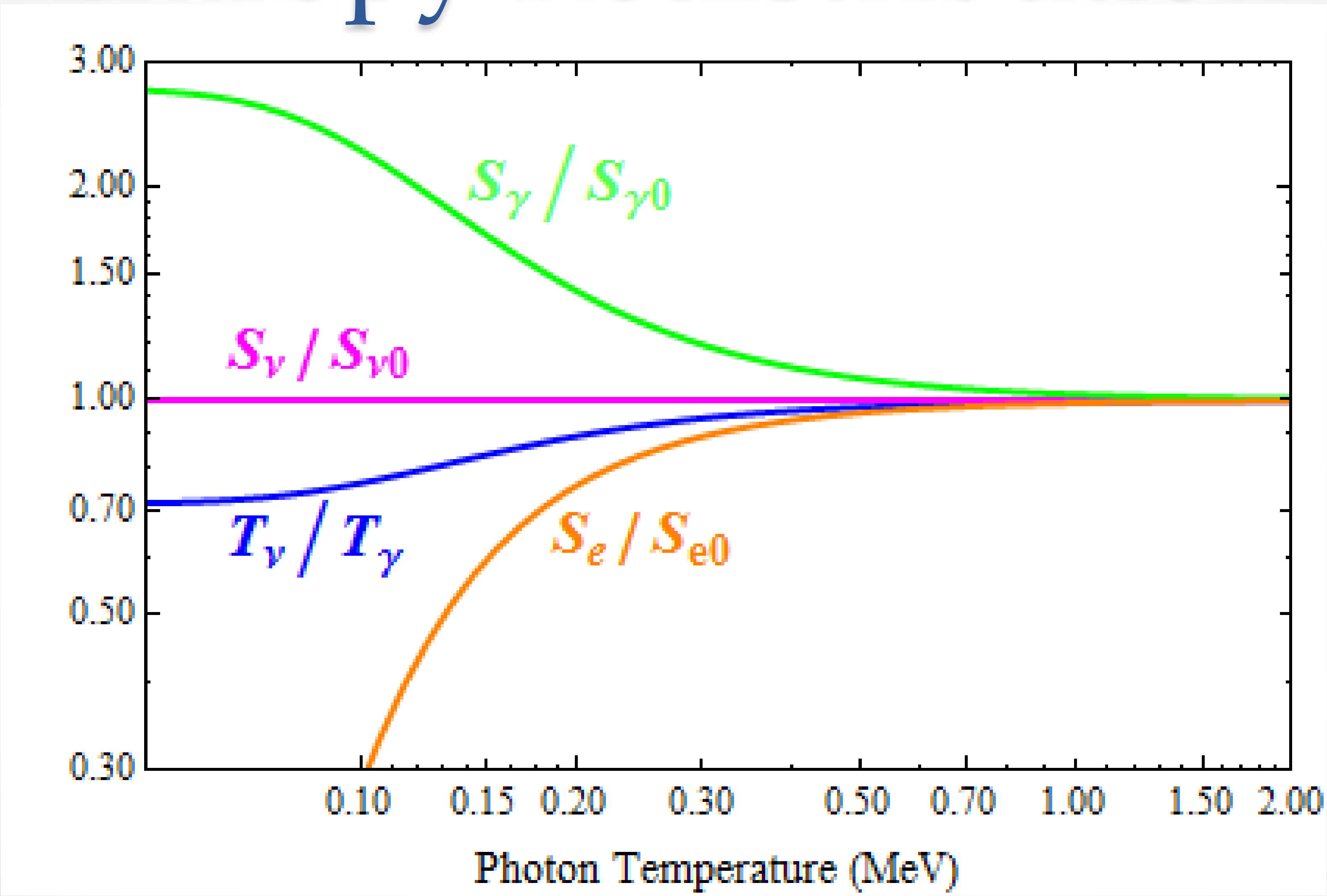
Example: Neutrinos



- Interact with weak force
- Interaction rate comparable to expansion rate near $T{\sim}$MeV (begin to freeze-out)
- Instantaneous decoupling approximation:

$$\Gamma \sim G_F^2 T^5 \sim H \sim \frac{T^2}{M_{Pl}}$$

Entropy Redistribution



Entropy Redistribution

- Photon energy density at recombination fixed experimentally
- Contribution of other species expressed relative to photons
- Earlier decoupling → More redistributions → Smaller Δg_*

$$\Delta g_* = \Delta g_{*0} \left(\frac{g_{*after}}{g_{*before}} \right)^{4/3}$$

Example: Neutrinos

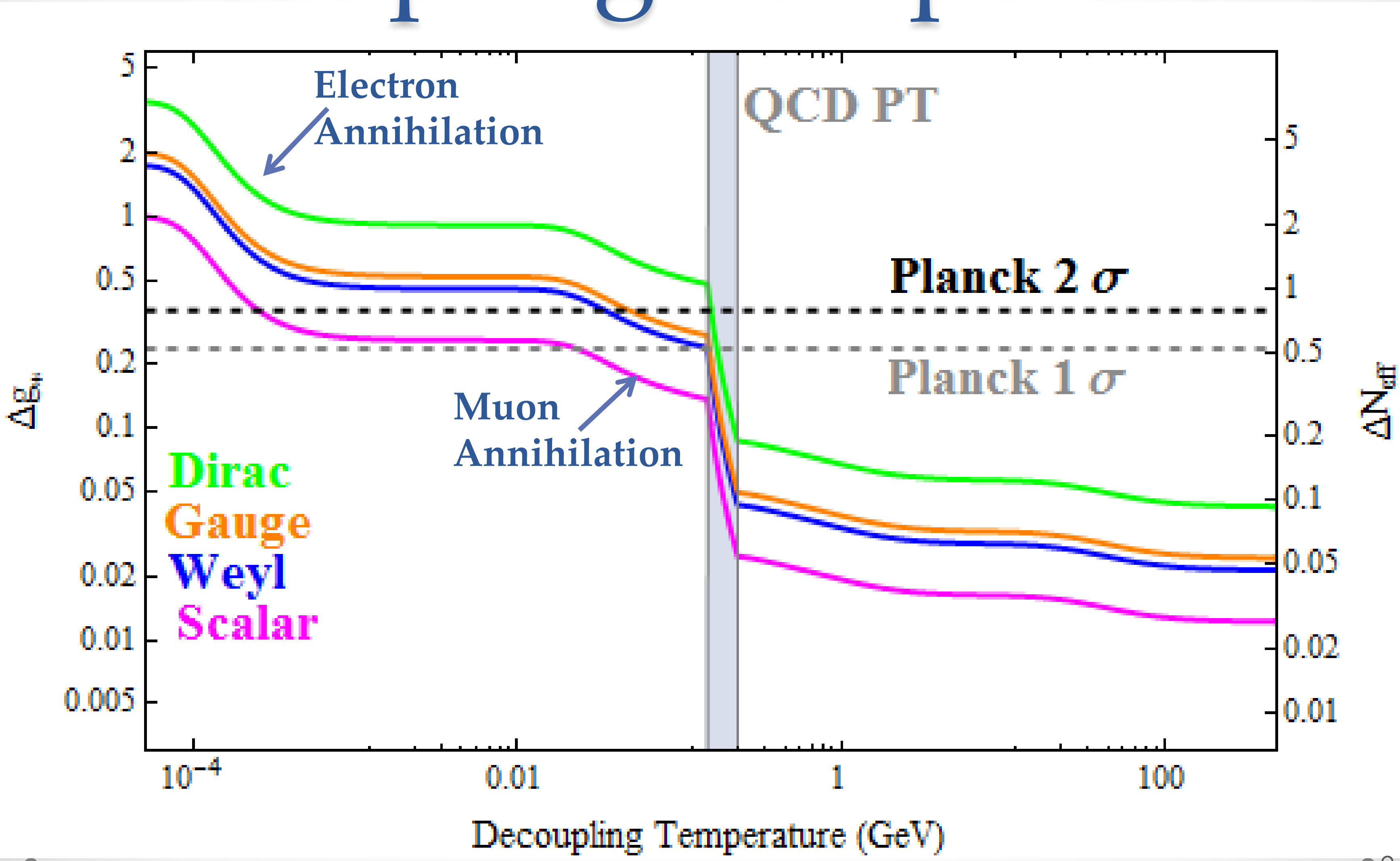
- Applying instantaneous decoupling:

$$\Delta g_* = 2 \cdot \frac{7}{8} \cdot N_\nu \left(\frac{2}{2 + 4 \cdot \frac{7}{8}} \right)^{\frac{4}{3}} = 2 \cdot \frac{7}{8} \cdot N_\nu \left(\frac{4}{11} \right)^{\frac{4}{3}}$$

- Numerical non-instantaneous correction:

$$N_{eff} = 3.046$$

Decoupling Temperature



Precision Cosmology Requires Precise Theory

- Planck sensitive to species decoupling during muon annihilation
- Instantaneous approximation insufficient for detailed constraints
- Numerically solve:

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

$$H^2 = \frac{8\pi G}{3}(\rho_{SM} + \rho_X)$$

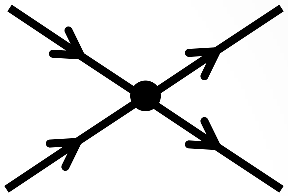
$$\frac{d\rho_{SM}}{dt} + \frac{d\rho_X}{dt} = -3H(\rho_{SM} + P_{SM} + \rho_X + P_X)$$

- Determine contribution of any species decoupling after QCD phase transition
-

Example: New Fermion

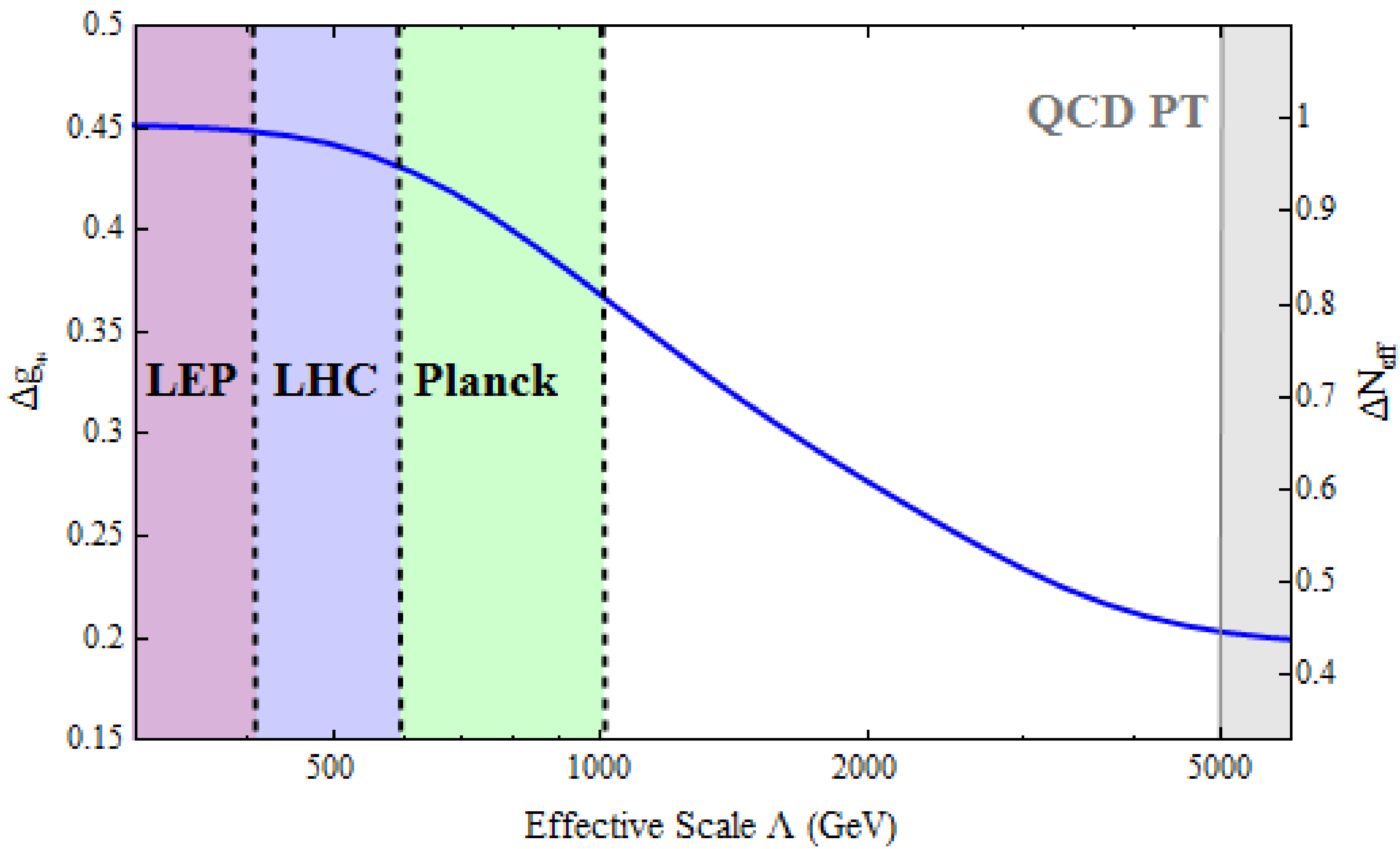
- Interacts with effective operator:

$$\frac{1}{\Lambda^2}\bar{\chi}\Gamma^\mu\chi\,\bar{\psi}\Gamma_\mu\psi$$

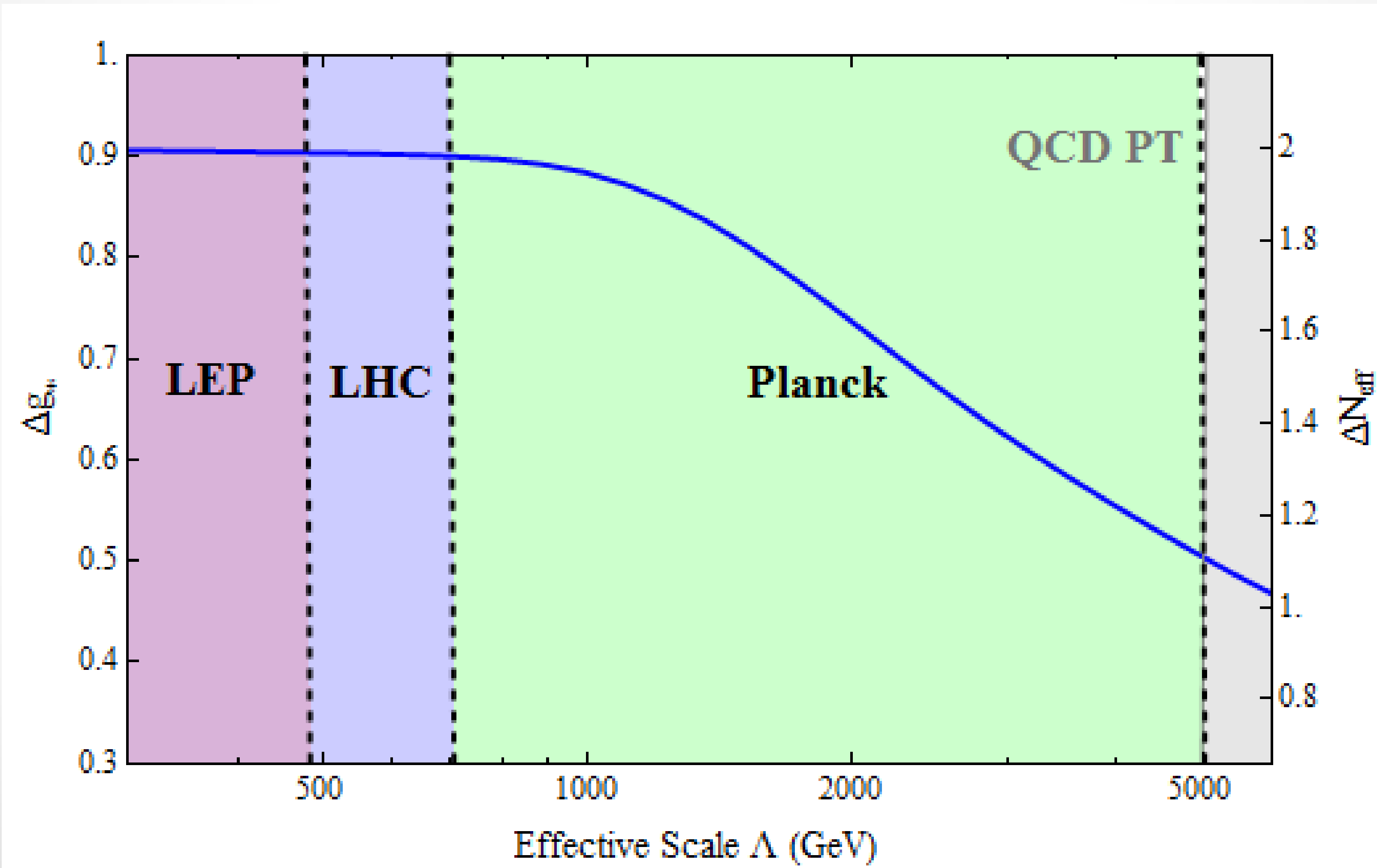


- Options: Scalar, Pseudoscalar, Vector, Axial
- Assume universal coupling to SM
- In equilibrium at high T
- Decoupling temperature determined by Λ

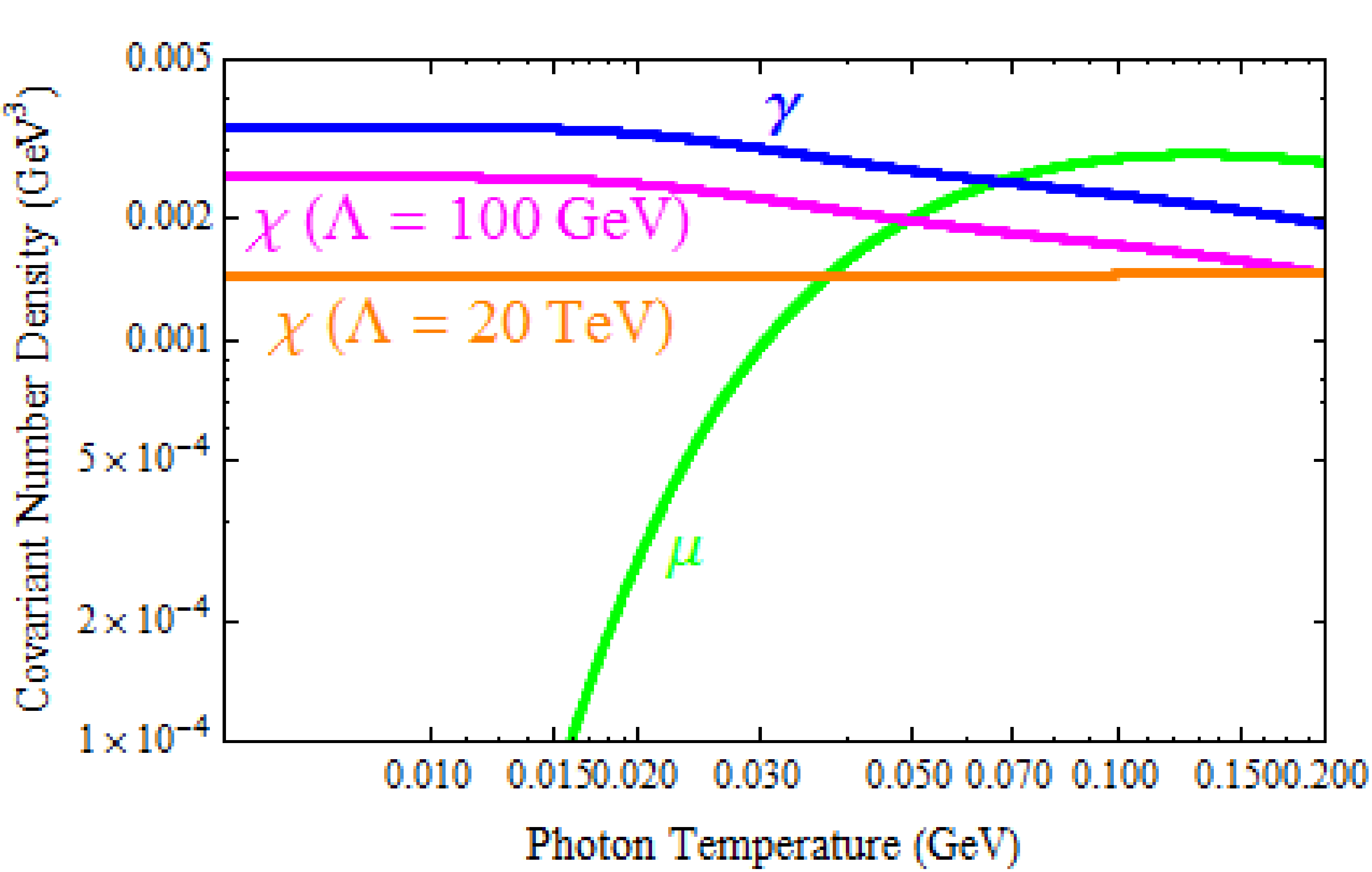
Results: Weyl Fermion



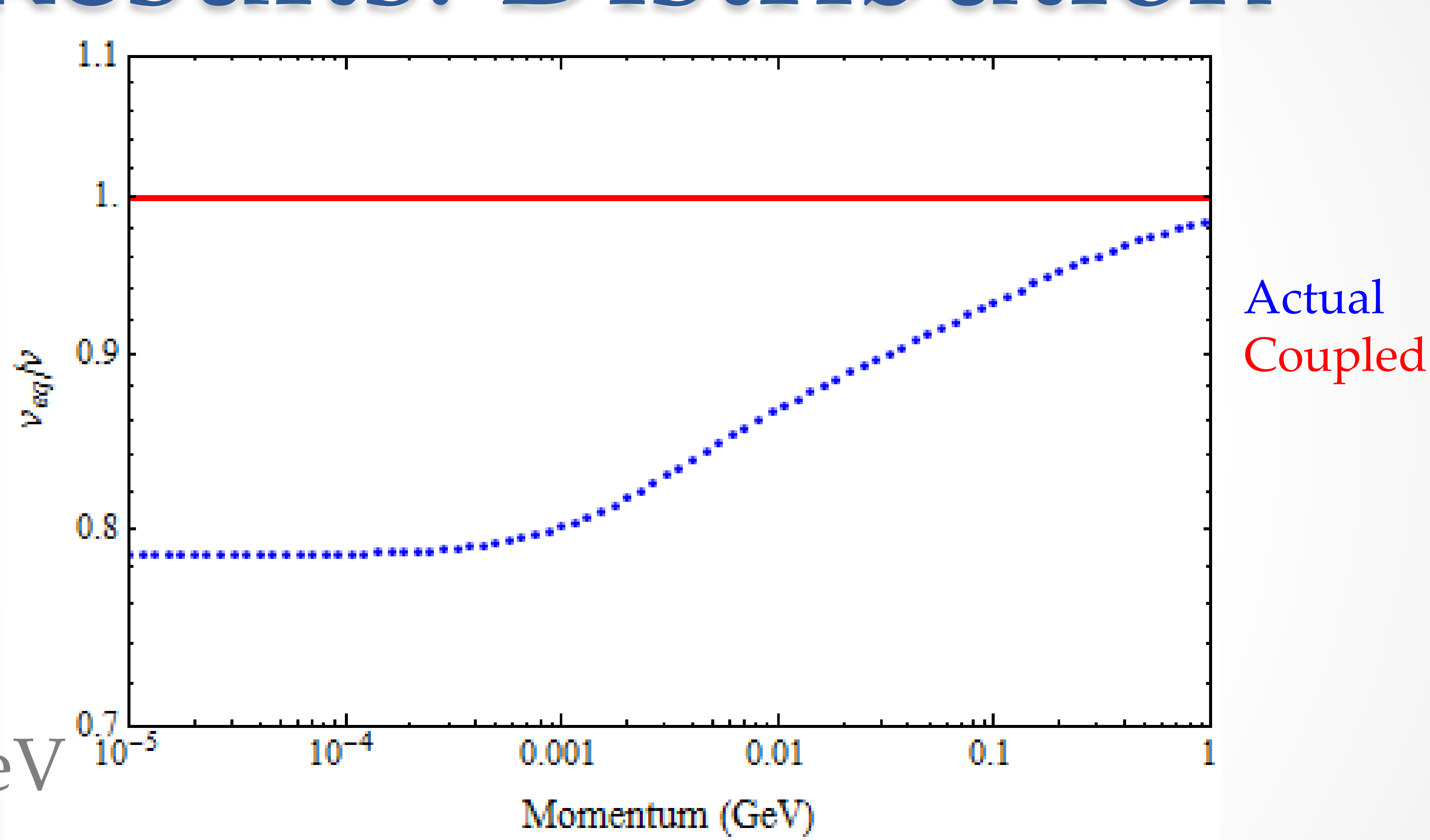
Results: Dirac Fermion



Results: Number Density



Results: Distribution

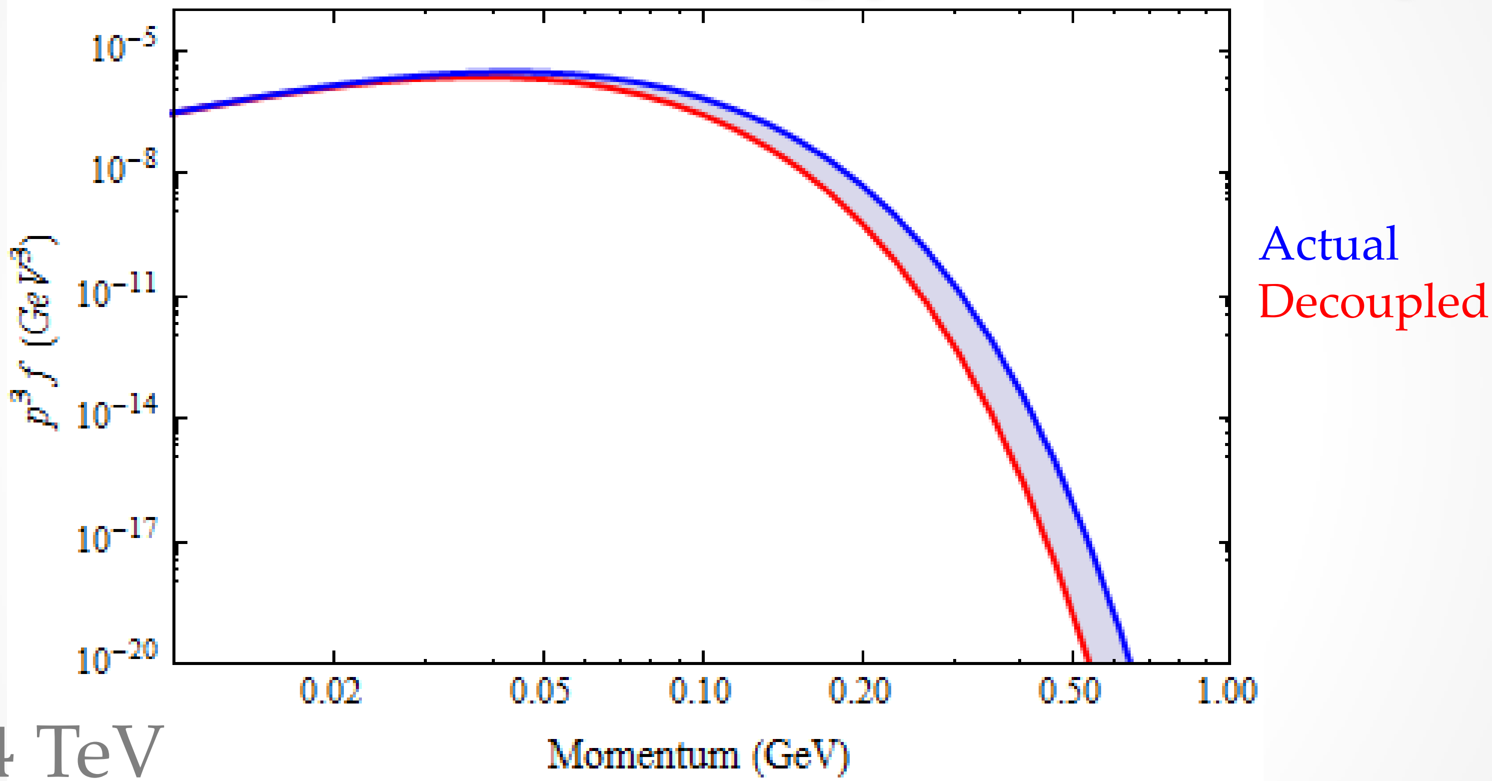


$\Lambda = 1.4$ TeV

- Calculated distribution vs. Equilibrium distribution

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

Results: Energy Density



$\Lambda = 1.4$ TeV

- Calculated vs. Decoupled Energy Density

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

Future Work

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

Summary

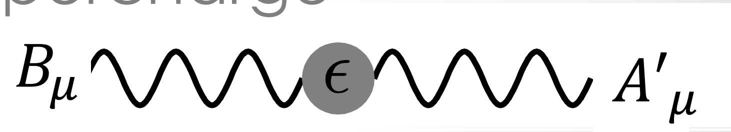
- CMB measurements can potentially discover/constrain new light species
- Can map between couplings of theory and contribution to g_*, N_{eff}
- Planck data places new constraints on multiple models

BACKUP SLIDES

Kinetic Mixing

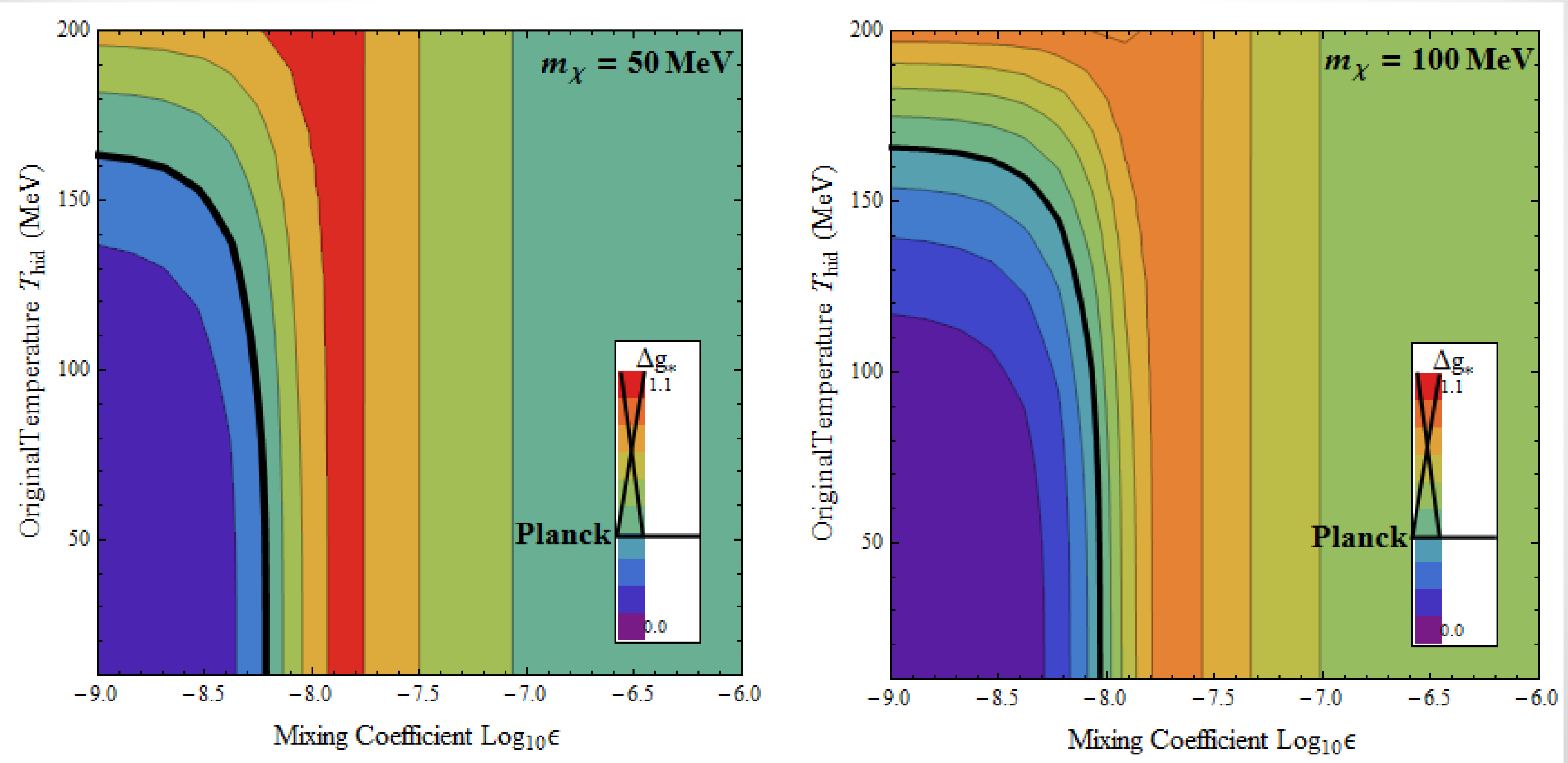
- New gauge boson mixes with hypercharge

$$\epsilon A'^{\mu\nu} B_{\mu\nu}$$



- Can generically be rotated away
- If A' couples to other fermion χ, results in millicharged fermion
- Nonnegligible contribution to g_* for $m_\chi \sim$ MeV
- Millicharged χ recouples with SM, depending on initial temperature

Results: Kinetic Mixing

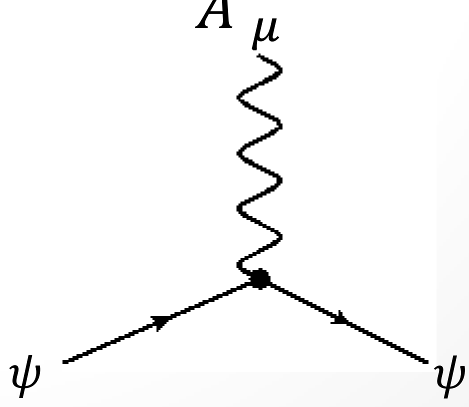


New Dipole Moment

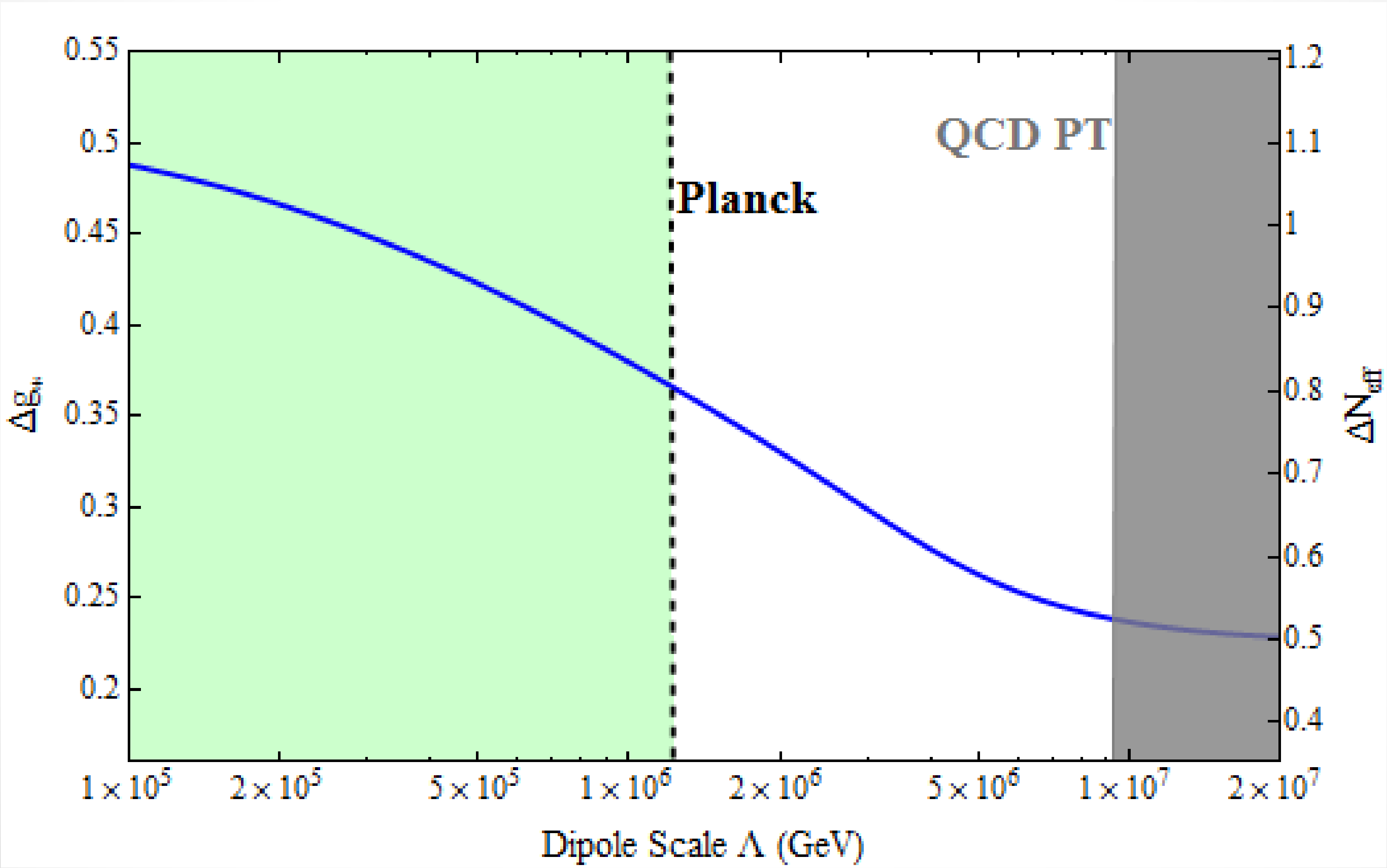
- New gauge boson interacts with effective operator:

$$\frac{1}{\Lambda}A'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}(c_M + c_E\gamma^5)\psi$$

- Universal coupling to SM ruled out by stellar cooling
    - $\Lambda \gtrsim 10^{10}$ GeV
- Hierarchical coupling still allowed
- Decoupling temperature determined by coupling to muon



Results: Dipole Moment



Sterile Neutrinos

- New SM singlet fermions which mix with neutrinos:
$$y^{\nu}_{ij} h^{\dagger} l_i \nu^c_{Rj} \rightarrow m^{\nu}_{ij} \nu_{Li} \nu^c_{Rj}$$
- 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:
$$f(t,p) = \left(exp\left(\frac{1}{T_d} \sqrt{\left(\frac{ap}{a_d}\right)^2 + m_\nu^2} \right) + 1 \right)^{-1}$$

Thermodynamics

- Boltzmann Equation: $E\frac{\partial f}{\partial t} - Hp^2\frac{\partial f}{\partial E} = C[f]$
- $C[f_i] = \frac{1}{2}\sum_{i,j\to a,b}\int d^3\Pi(2\pi)^4\delta^4(p)|M|^2\Omega(f)$
- $\Omega(f) = (f_a f_b(1 \pm f_i)\left(1 \pm f_j\right) - f_i f_j(1 \pm f_a)(1 \pm f_b))$
- 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 keV $\lesssim p \lesssim 10$ 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: $\frac{1}{2} \bar{\chi} \sigma^{\mu\nu} (\mu + i d \gamma^5) \chi F_{\mu\nu}$
- 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

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

Inhomogeneities

- Inhomogeneous Universe:

$$g_{\mu\nu} = a^2 \begin{pmatrix} 1 + 2\phi & 0 \\ 0 & -(1 - 2\psi)\delta_{ij} \end{pmatrix}$$

Einstein Field Equations:

- $-3\left(\frac{\dot{a}}{a}\right)^2 \phi - 3\frac{\dot{a}}{a}\dot{\psi} - k^2\psi = 4\pi G a^2 \delta\rho$
- $\left(2\frac{\ddot{a}}{a} - \left(\frac{\dot{a}}{a}\right)^2\right)\phi + \frac{\dot{a}}{a}\left(\dot{\phi} + 2\dot{\psi}\right) + \ddot{\psi} - \frac{k^2}{3}(\phi - \psi) = 4\pi G a^2 \delta P$
- $k^2(\phi - \psi) = 12\pi G a^2(\rho_0 + P_0)\sigma$
- Perfect Fluid $\rightarrow \sigma = 0 \rightarrow \phi = \psi$

Evolution of Inhomogeneities

- $\left(2\frac{\ddot{a}}{a} - \left(\frac{\dot{a}}{a}\right)^2\right)\phi + 3\frac{\dot{a}}{a}\dot{\phi} + \ddot{\phi} = \frac{\delta P}{\delta\rho}\left(-3\left(\frac{\dot{a}}{a}\right)^2\phi - 3\frac{\dot{a}}{a}\dot{\phi} - k^2\phi\right)$

Radiation-/Matter-Dominated:

- $H^2 = \frac{8\pi G}{3}\rho \to a \sim \tau^n$ (R: $n = 1$, M: $n = 2$)
- $\frac{\dot{a}}{a} \to \frac{n}{\tau}, \frac{\ddot{a}}{a} \to \frac{n(n-1)}{\tau^2}$
- $\ddot{\phi} + 3\frac{n}{\tau}\left(1 + \frac{\delta P}{\delta\rho}\right)\dot{\phi} + \frac{\delta P}{\delta\rho}k^2\phi = 0$
- $\frac{\delta\rho}{\rho} = -2\frac{\tau}{n}\dot{\phi} - 2\left(1 + \frac{k^2\tau^2}{3n^2}\right)\phi$

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
  - $Y_P \gtrsim 0.227 \; (N_{eff} = 2)$
  - $Y_P \gtrsim 0.242 \; (N_{eff} = 3)$
  - $Y_P \gtrsim 0.254 \; (N_{eff} = 4)$

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

   Decay, Annihilation
3) New interactions with SM particles

   Dipole moment, Four-fermion

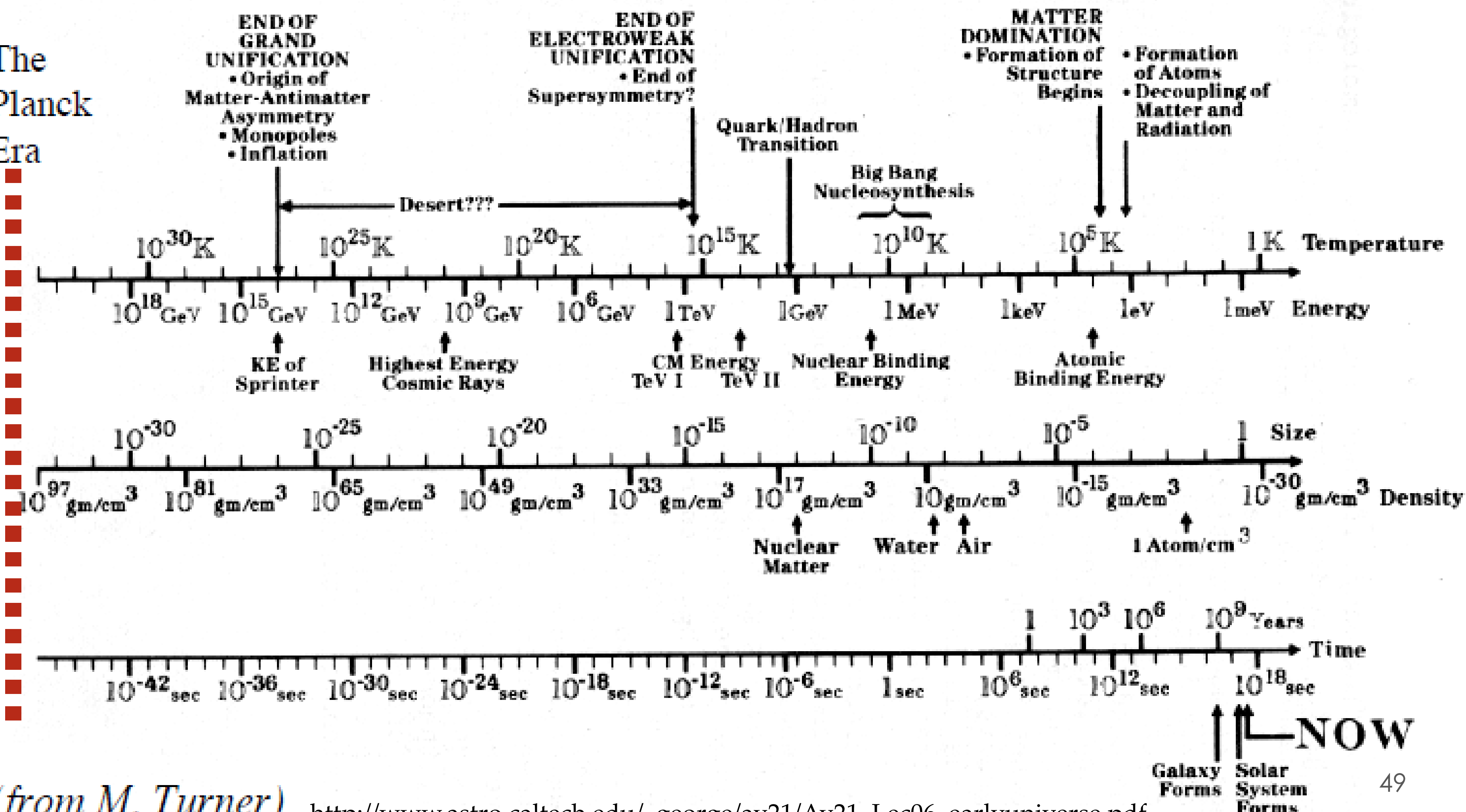
Matter-Radiation Equality

- Matter: $\rho_m \sim m n_m \sim \frac{\Omega_m h^2}{a^3} \sim \Omega_m h^2 (1+\mathrm{z})^3$
- Radiation: $\rho_r \sim g_* T_\gamma^4 \sim \frac{g_* \Omega_\gamma h^2}{g_\gamma a^4} \sim \frac{g_*}{g_\gamma} \Omega_\gamma h^2 (1+z)^4$
- M-R Equality: $\rho_r = \rho_m \rightarrow g_* = g_\gamma \frac{\Omega_m h^2}{\Omega_\gamma h^2} \frac{1}{1+z_{eq}}$
- $N_{eff} = \frac{(g_* - g_\gamma)}{g_\nu} \left(\frac{T_\gamma}{T_\nu}\right)^4 = \frac{g_\gamma}{g_\nu} \left(\frac{T_\gamma}{T_\nu}\right)^4 \left(\frac{\Omega_m h^2}{\Omega_\gamma h^2} \frac{1}{1+z_{eq}} - 1\right)$

$$= \frac{8}{7} \left(\frac{11}{4}\right)^{4/3} \left(\frac{\Omega_m h^2}{\Omega_\gamma h^2} \frac{1}{1+z_{eq}} - 1\right)$$

Thermal History

The
Planck
Era



(from M. Turner) http://www.astro.caltech.edu/~george/ay21/Ay21_Lec06_earlyuniverse.pdf