New Light Species and the CMB

Chris Brust – 9/9/13

Work done with Matthew T. Walters and David E. Kaplan

Based on arXiv:1303.5379 and ongoing work

Johns Hopkins University and
University of Maryland, College Park

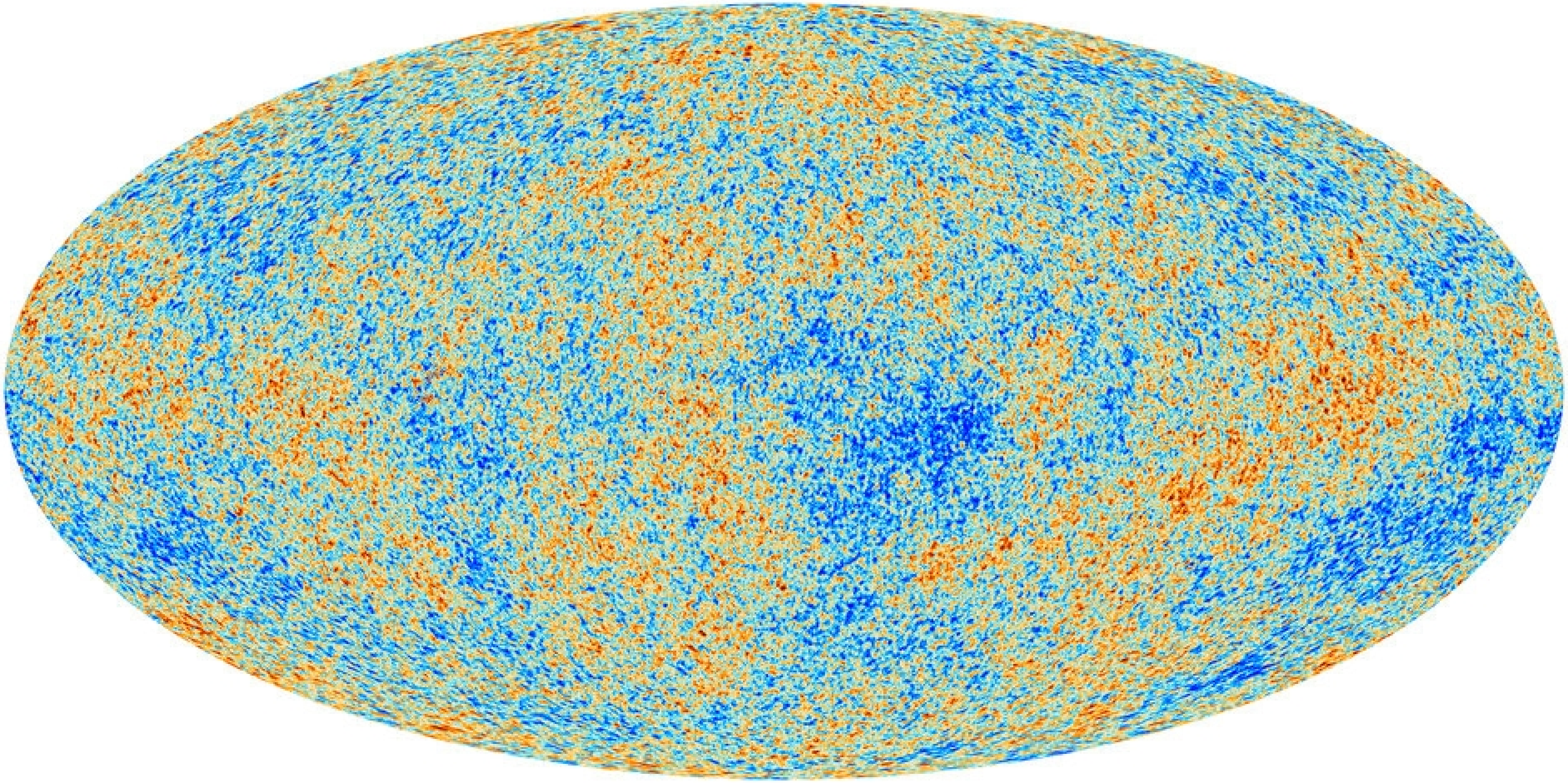
Outline

- Anisotropies in the CMB
- Review of early universe thermodynamics
- BSM physics contributions to g_*/N_{eff}
- Discussion of Planck data analysis

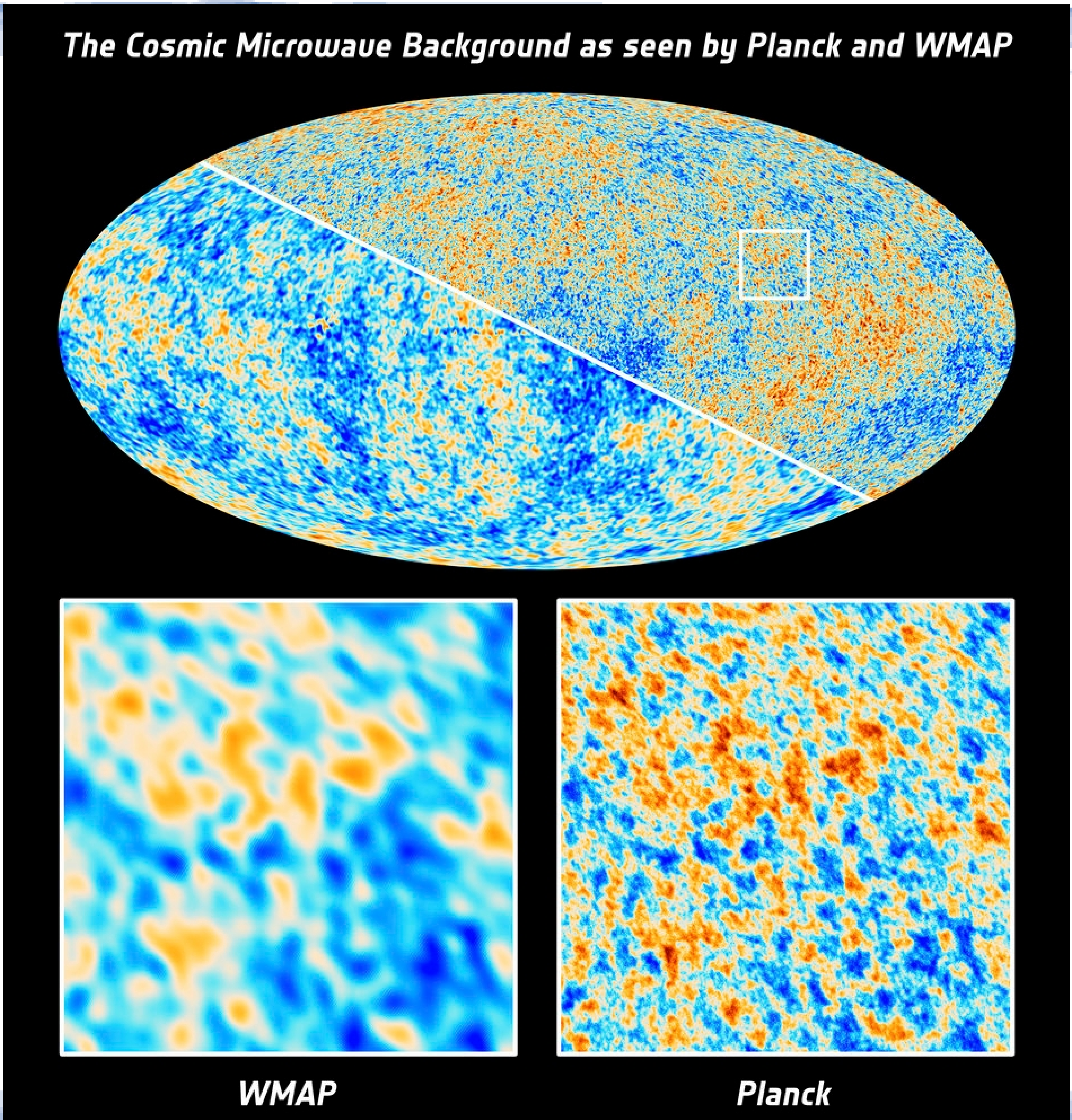
Timeline of Early Universe Physics

T		z
> 1 GeV	Baryogenesis, Inflation and Electroweak symmetry breaking	$> 4 \times 10^{12}$
150-200 MeV	QCD phase transition	$6\text{-}9 \times 10^{11}$
20-100 MeV	Muon and pion annihilation	$8\text{-}40 \times 10^{10}$
~1 MeV	Neutrino decoupling	$\sim 4 \times 10^{9}$
100-500 keV	Electron annihilation	$2\text{-}8 \times 10^{8}$
20-200 keV	Big Bang Nucleosynthesis	$3 \times 10^{7} – 3 \times 10^{8}$
~.75 eV	Matter-radiation equality	~3200
~.25 eV	Recombination	~1100

Anisotropies in the CMB



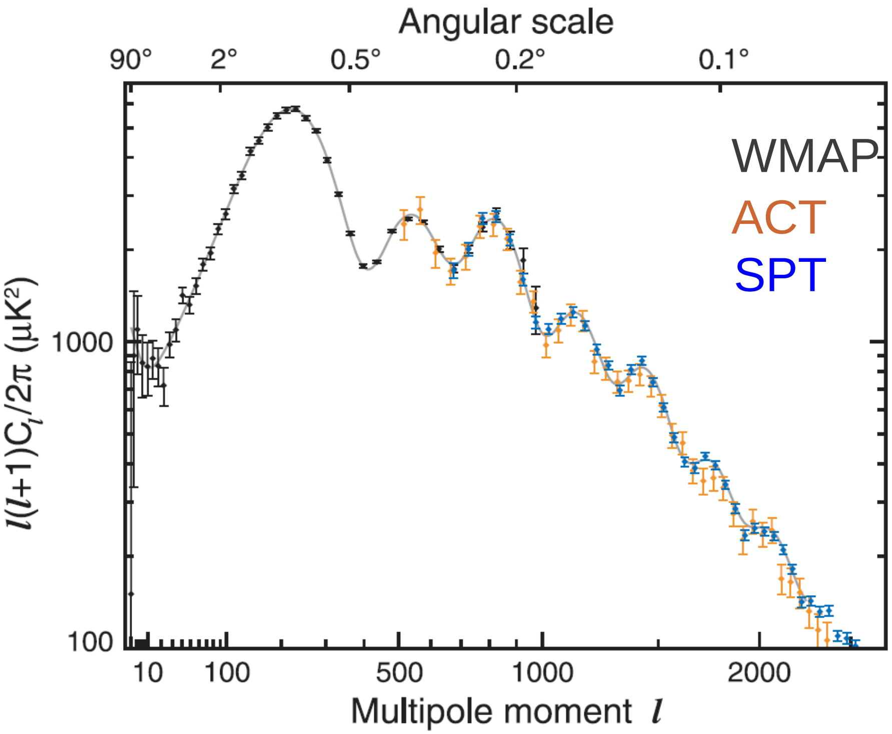
http://www.esa.int/For_Media/Photos/Highlights/Planck

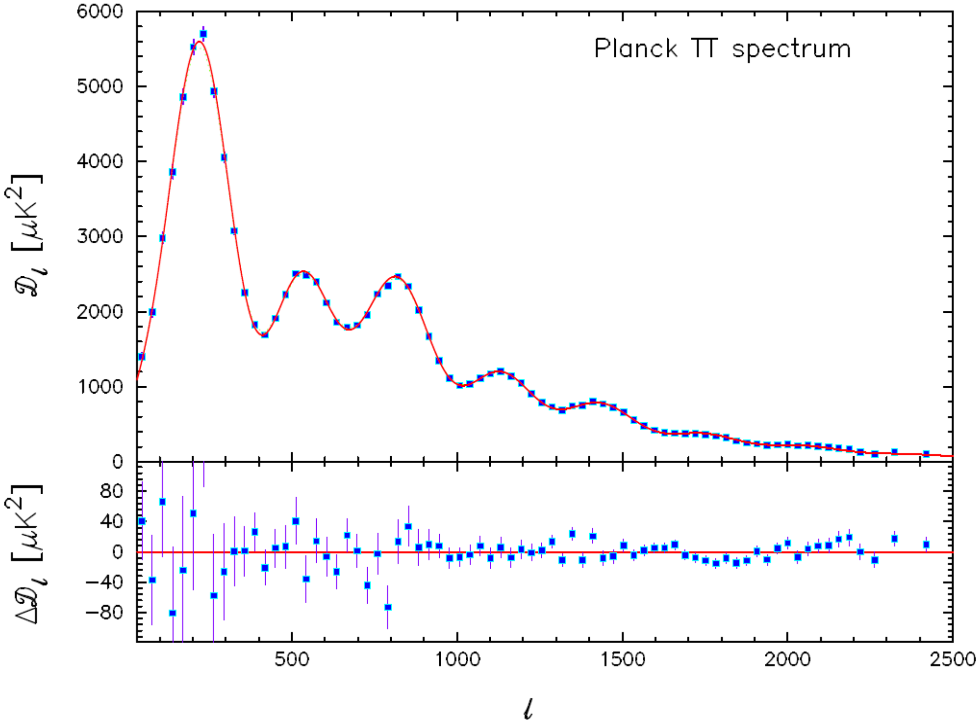


http://www.esa.int/For_Media/Photos/Highlights/Planck

Anisotropies in the CMB

$$\left\langle \frac{\delta T}{\bar{T}}(\mathbf{n})\frac{\delta T}{\bar{T}}(\mathbf{n}')\right\rangle = \sum_l \frac{2l+1}{4\pi} C_l P_l(\cos\theta) \qquad \text{with} \quad \cos\theta = \mathbf{n}.\mathbf{n}'$$





From 1212.5226

From 1303.5076

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:

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

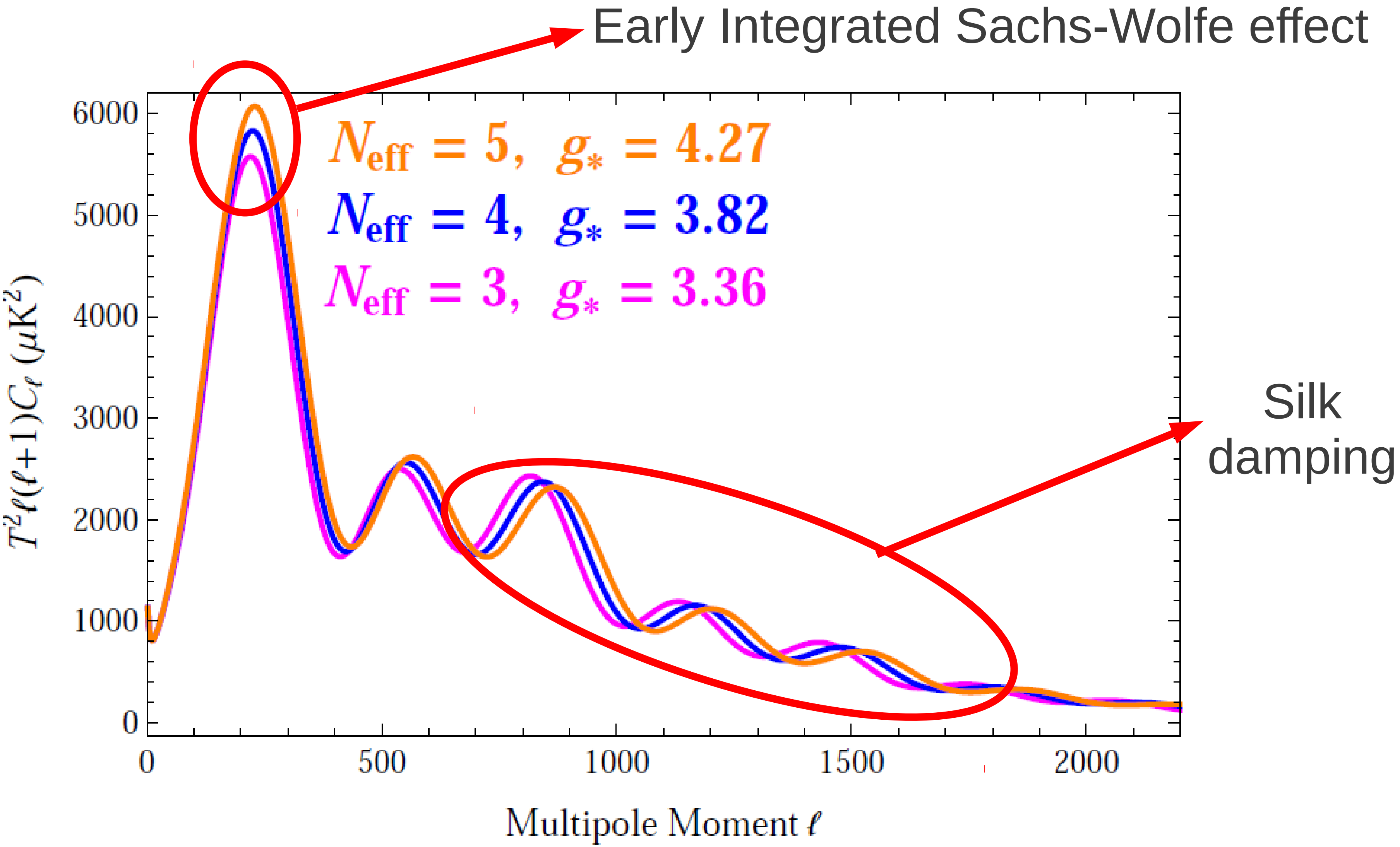
- WMAP nine-year, SPT, ACT:

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

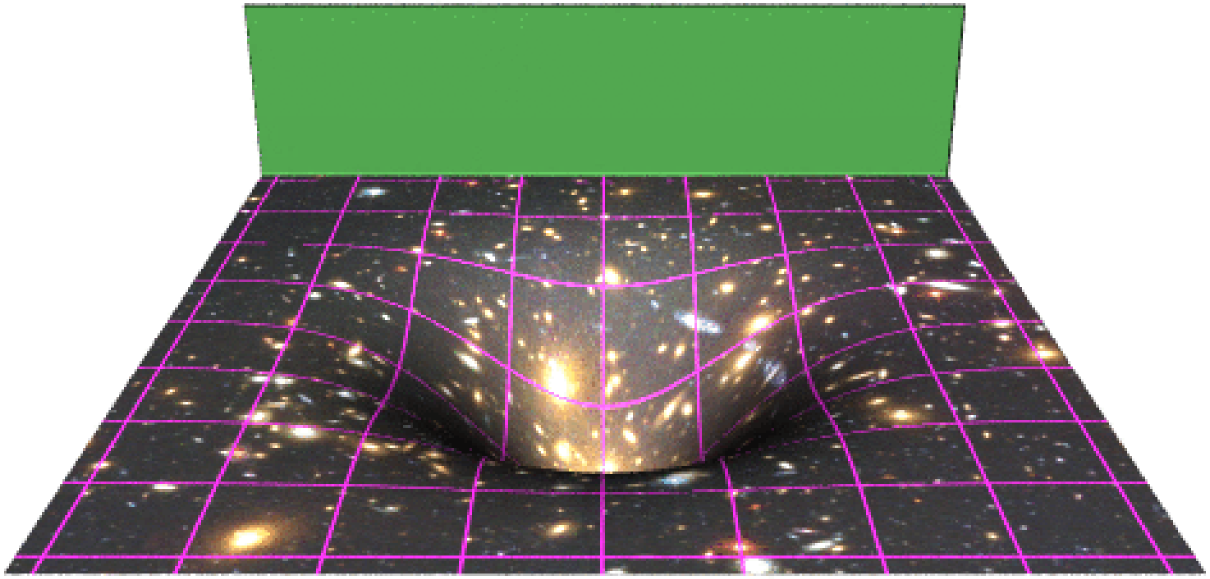
- Planck:

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

Effects of Light (m << eV) Species

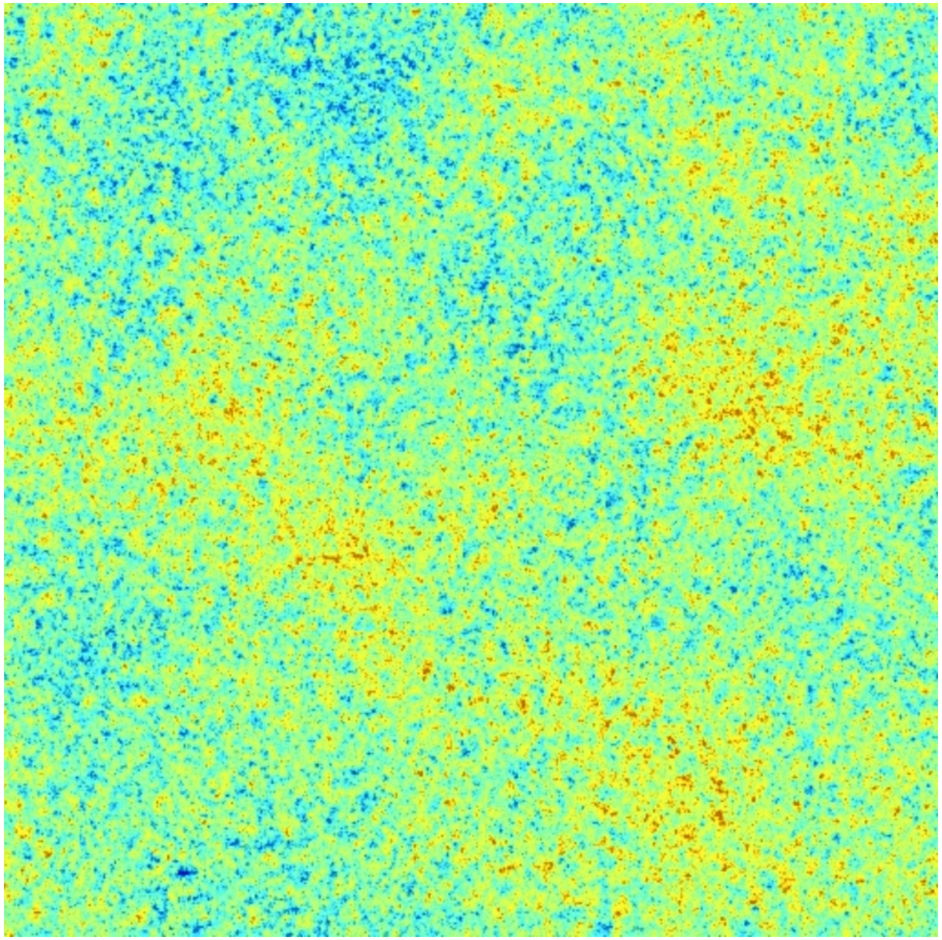


Early Integrated Sachs-Wolfe Effect

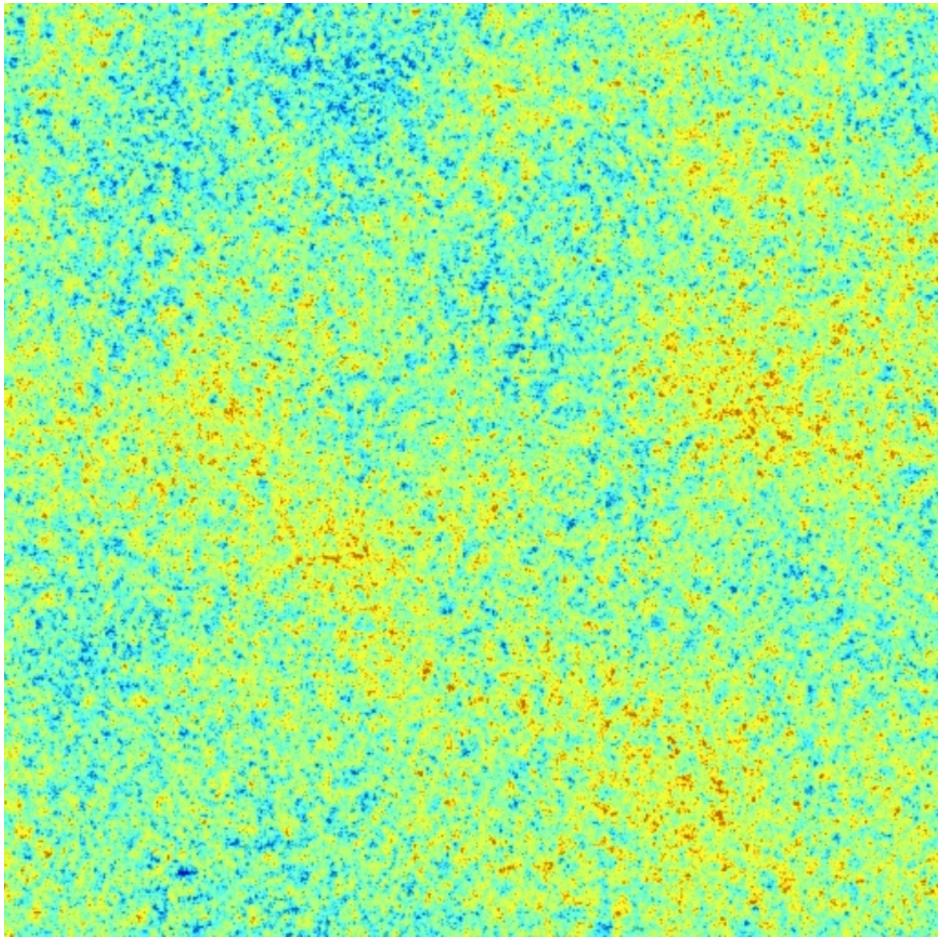


http://ifa.hawaii.edu/cosmowave/supervoids/the-integrated-sachs-wolfe-effect/

Silk Damping



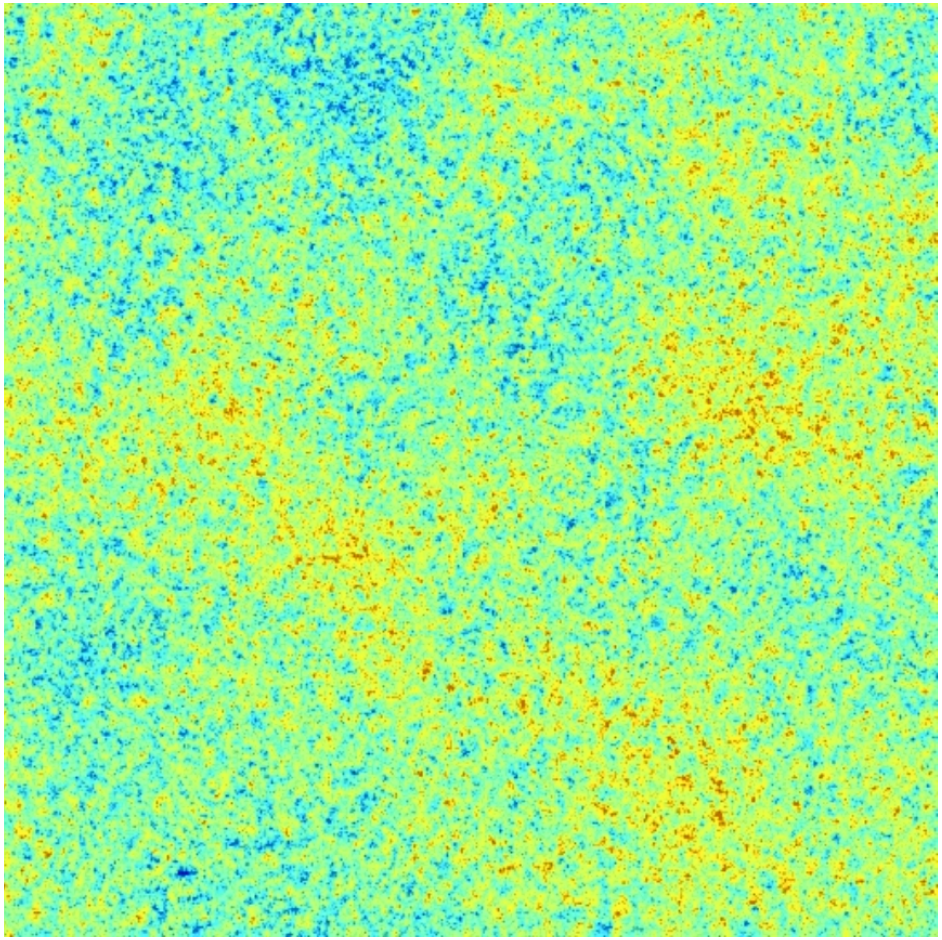
t ~ 100 years



t from 100 to 378,000 years

http://cosmologist.info/notes/cmb_evolve.avi

Silk Damping



t ~ 100 years

t from 100 to 378,000 years

http://cosmologist.info/notes/cmb_evolve.avi

Early Universe Thermodynamics

- Mass eigenstates characterized by distribution function f(p, t)
- Thermal distribution function not always applicable

$$f(p,t) = \frac{1}{e^{E/T} \pm 1}$$

Early Universe Thermodynamics

- f_i of species i determines all other relevant thermodynamic variables:

$$\rho_i = \frac{g_i}{2\pi^2}\int_0^\infty dp\; p^2 E f_i \qquad P_i = \frac{g_i}{2\pi^2}\int_0^\infty dp\; \frac{p^4}{3E} f_i$$

$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty dp\; p^2 f_i$$

- g_* determined through ρ: $g_{*,i} = \dfrac{30\rho_i}{\pi^2 T^4}$

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

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

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

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

- Solve coupled Boltzmann and Friedmann equations

Solutions to Boltzmann Equation

- Sufficiently rapidly interacting:

$$f(p,t) = \frac{1}{e^{E/T} \pm 1}$$

- Non-interacting:

$$f(p,t) = g(pa(t))$$

- Most other cases: Needs numerical solution

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

Instantaneous Decoupling Approximation

- Instantaneous decoupling temperature:
  T at which $\Gamma_X = H$

$$\Gamma_X = \sum_{j,k\to X,i} \frac{n_j n_k}{n_X} \langle \sigma v \rangle_{j,k\to X,i}$$

- Switch from thermal f to decoupled f instantaneously
- Good approximation when no nonequilibrium processes are occuring

Species Annihilation and Entropy Redistributions

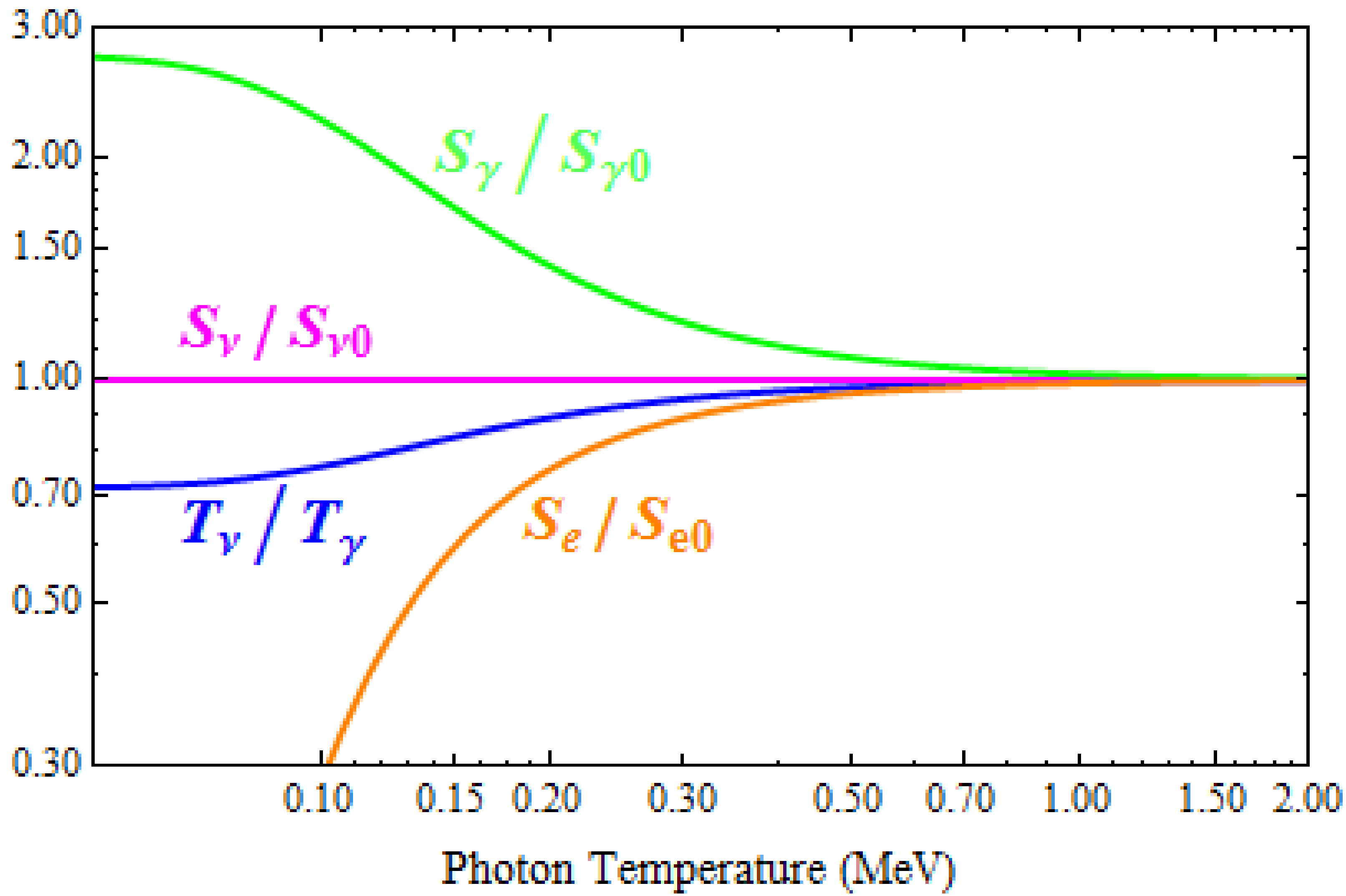
- Annihilation occurs when T ~ m:
  e.g. $e^+e^- \to \gamma\gamma$

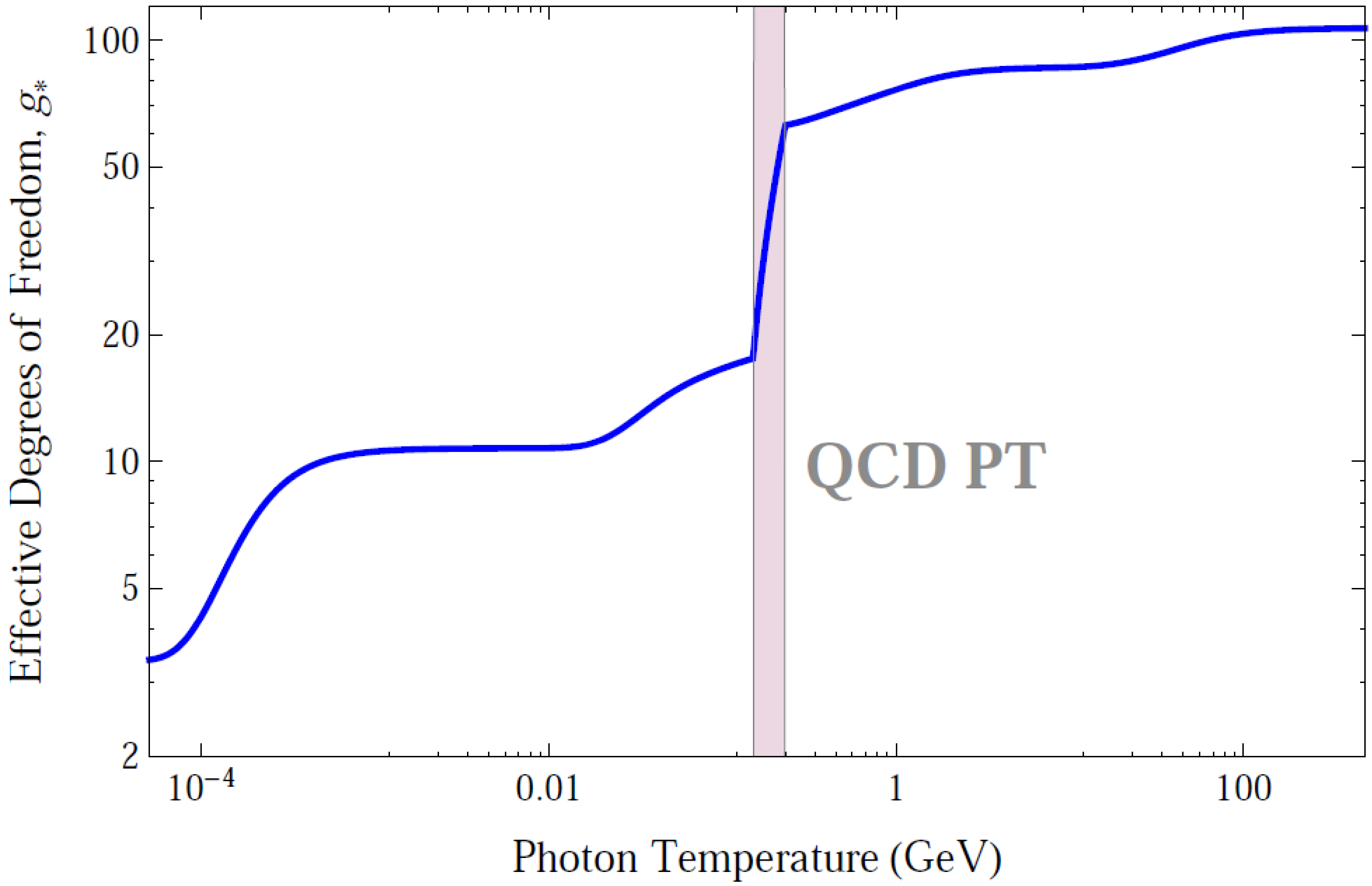
- Species not coupled receive no entropy; e.g. neutrinos

- Conservation of entropy implies

$$\frac{T_\nu^{\rm after}}{T_\gamma^{\rm after}} < \frac{T_\nu^{\rm before}}{T_\gamma^{\rm before}} \longrightarrow \frac{\rho_\nu^{\rm after}}{\rho_\gamma^{\rm after}} < \frac{\rho_\nu^{\rm before}}{\rho_\gamma^{\rm before}} \longrightarrow \Delta g_{*,\nu}^{\rm after} < \Delta g_{*,\nu}^{\rm before}$$

Electron Entropy Redistribution

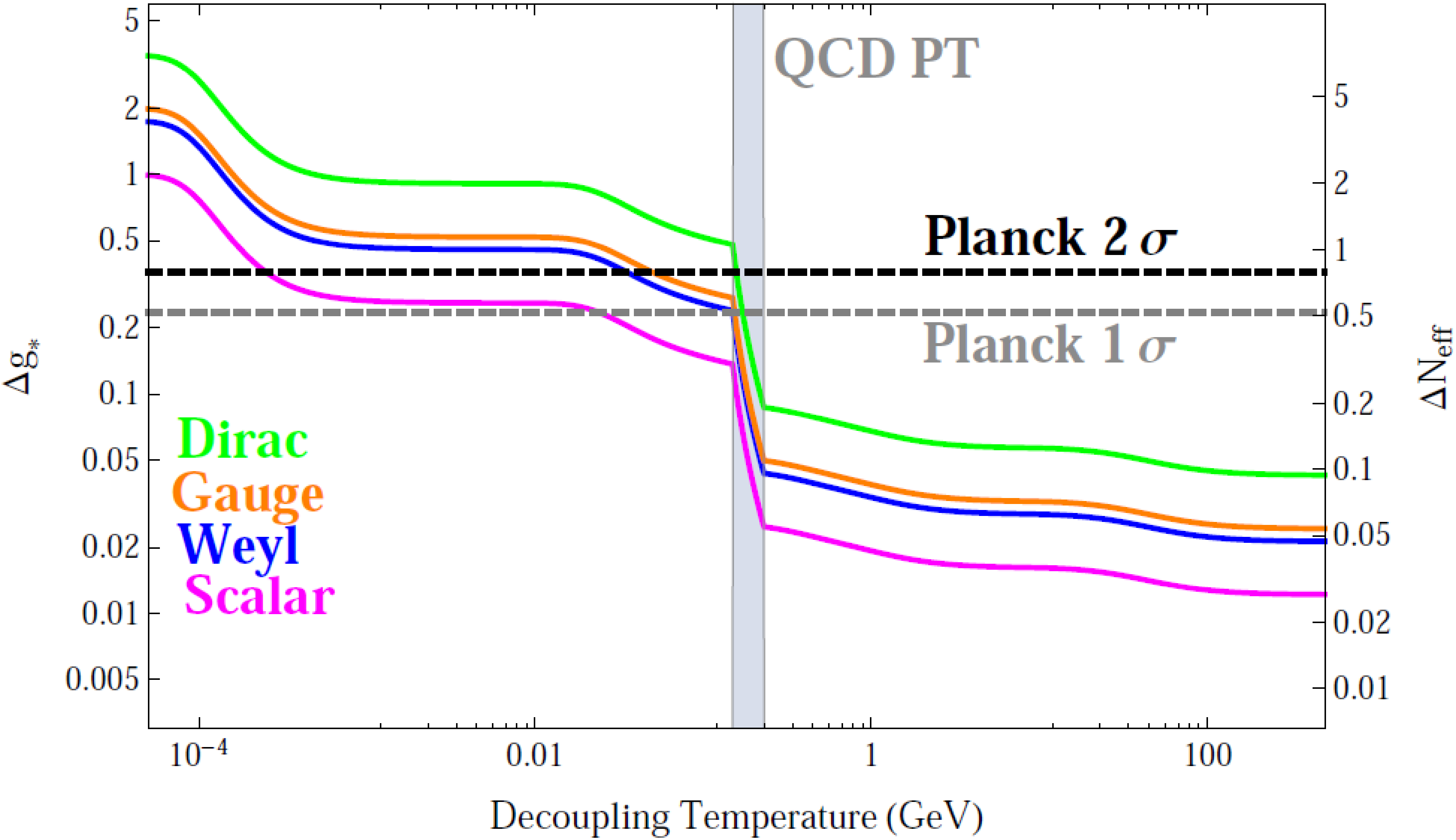



Effective Degrees of Freedom, g_*
100
50
20
10
5
2
10^{-4}
0.01
1
100
Photon Temperature (GeV)
QCD PT

New Physics Contributions

- In instantaneous decoupling framework, can map T_{dec} to contribution to g_* in CMB for any new light species:

$$\Delta g_* = g \left(\frac{3.91}{g_*(T_{dec})} \right)^{\frac{4}{3}} \qquad \text{for } T_{dec} > 1\ \text{MeV}$$


QCD PT
Planck 2 σ
Planck 1 σ
Dirac
Gauge
Weyl
Scalar
Δg*
ΔNeff
Decoupling Temperature (GeV)
10−4
0.01
1
100
5
2
1
0.5
0.2
0.1
0.05
0.02
0.01
0.005
5
2
1
0.5
0.2
0.1
0.05
0.02
0.01

Precision cosmology requires

precision theory!

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

Models with New Light Species

- Two possibilities for having naturally light physics states:
  - Strong dynamics
    - Non-minimal
  - Symmetries
    - Shift symmetry
    - Chiral symmetry
    - Supersymmetry
    - Gauge redundancy

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:

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

Planck Sensitivity

- Resolution of Planck can probe couplings such that species decouples during or after QCD phase transition

- Ran code for all times after QCD phase transition to map effective couplings to g_*

Four-fermion Vector Example

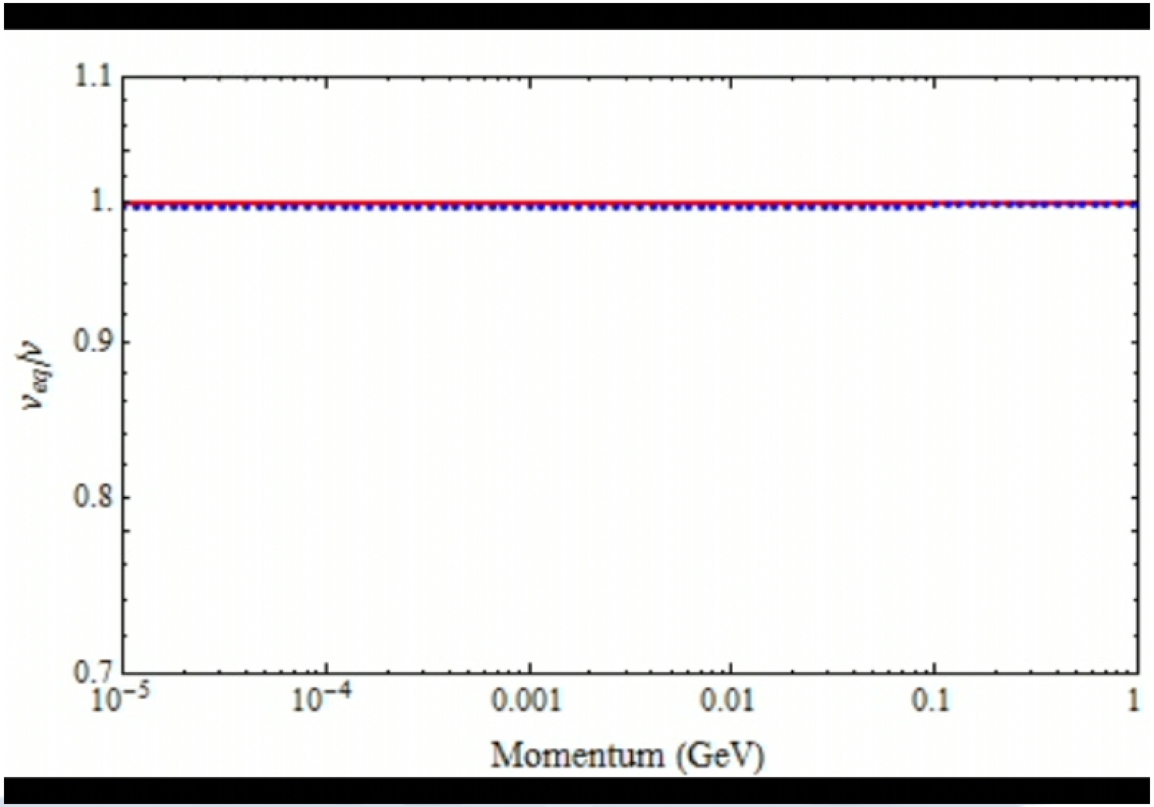
- Λ = 1.4 TeV: Decouples during muon annihilation

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

Red: fully coupled

Blue: our code

Green: fully decoupled



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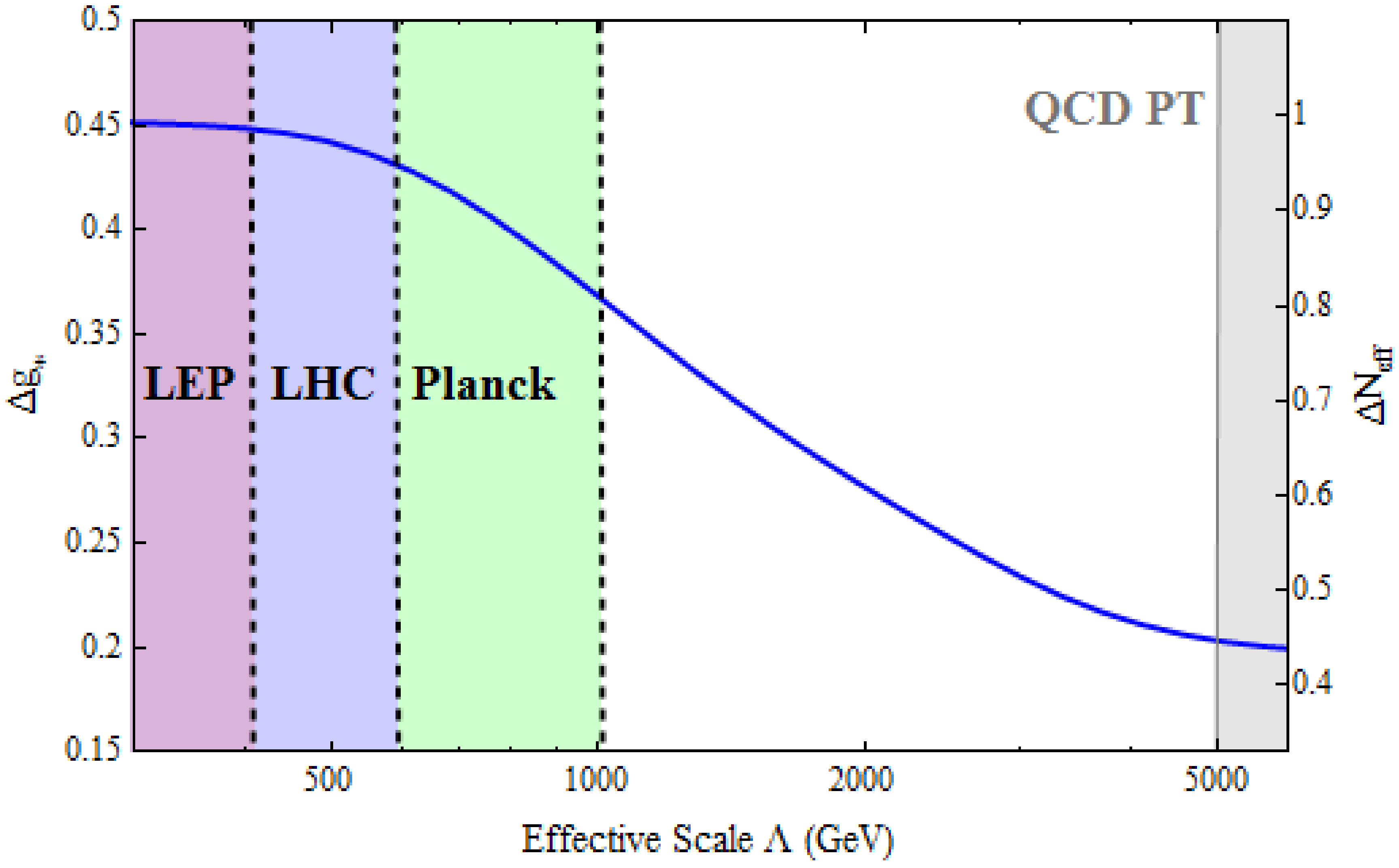
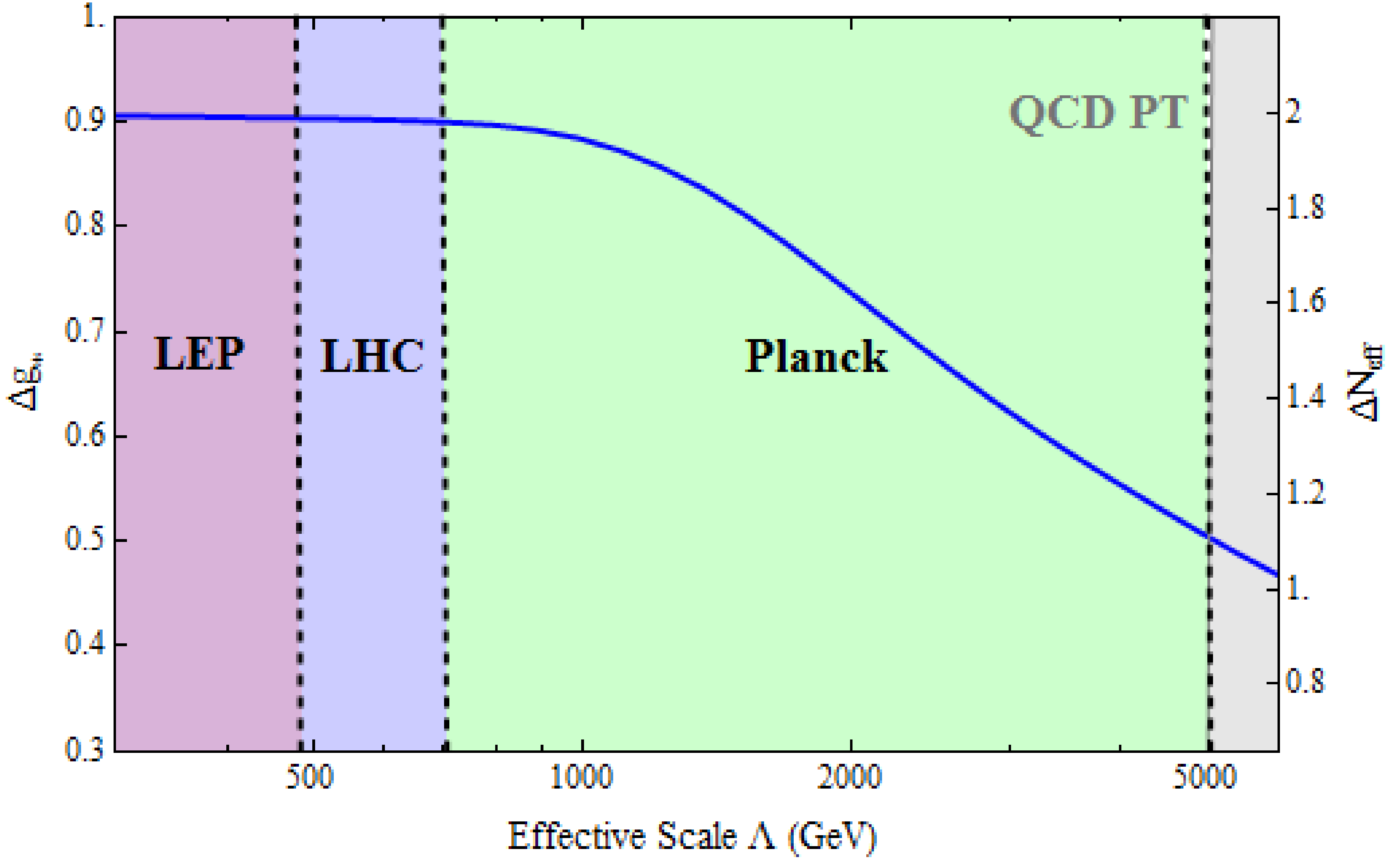
Four-Fermion Vector Results

Weyl fermion

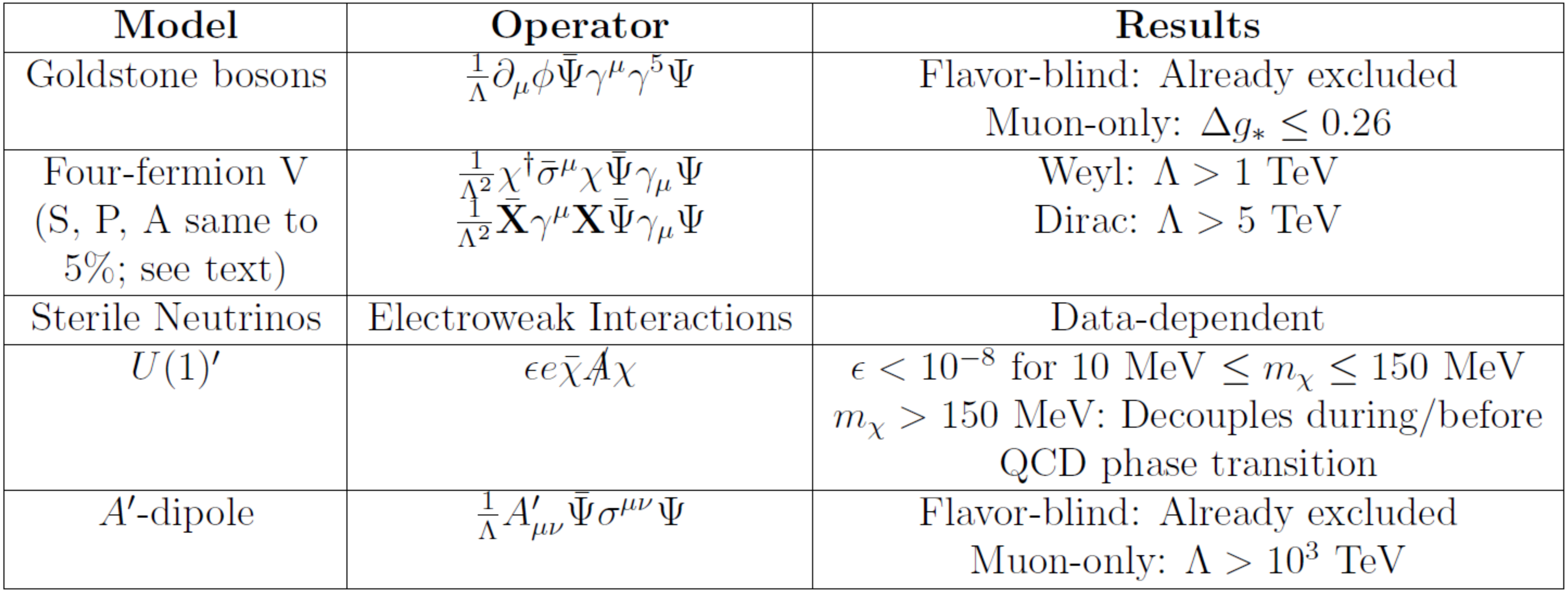


Four-Fermion Vector Results

Dirac fermion



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	Data-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

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
- Lensing through eV-scale species is qualitatively new effect on CMB

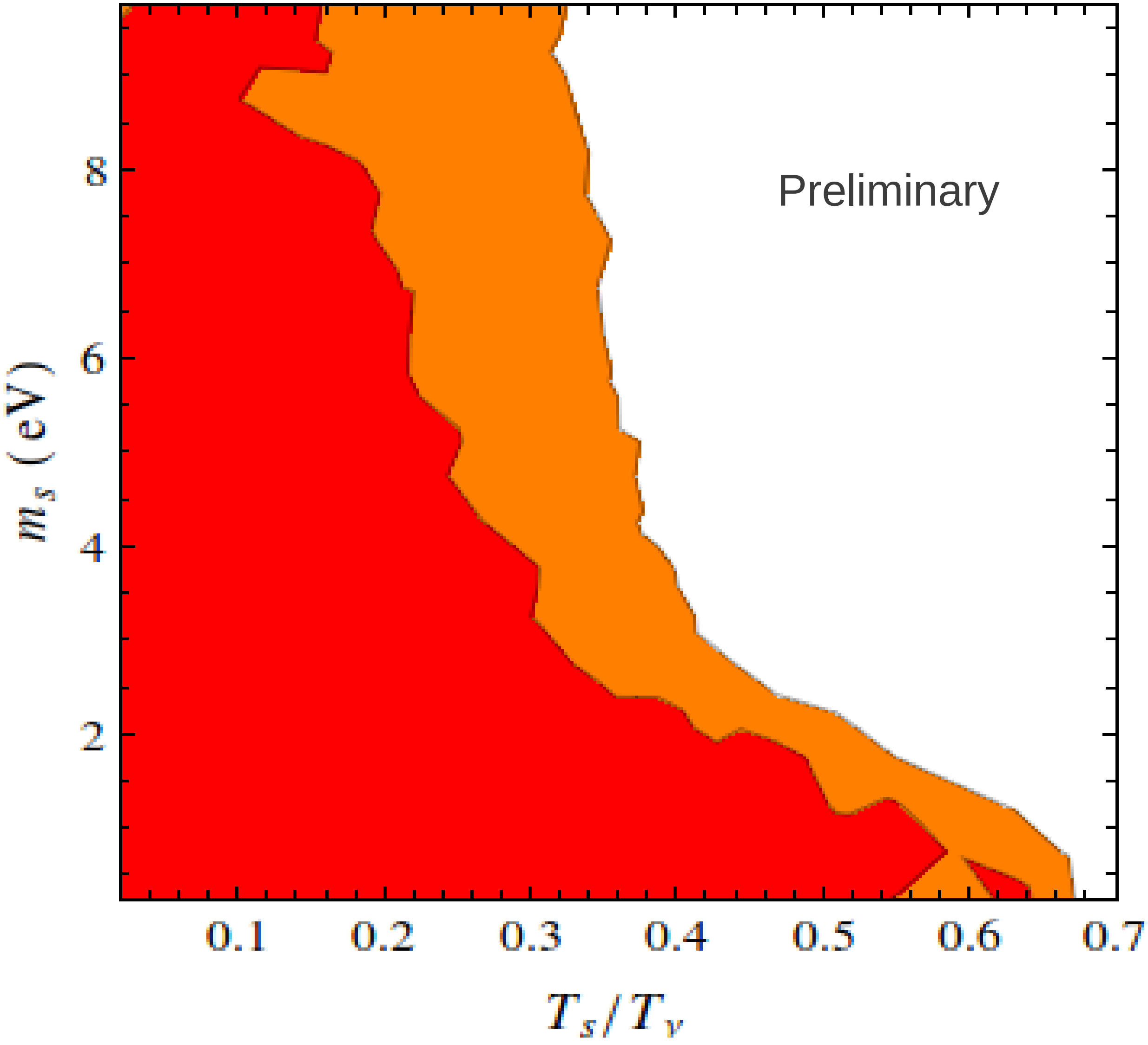
Sterile Neutrinos

- Attempt to exclude even one decoupled sterile neutrino at temperature T_s
- Analyze full effects of eV-scale state with CLASS and MontePython
- Use ΛCDM + ν_s framework with m_s and T_s parameters

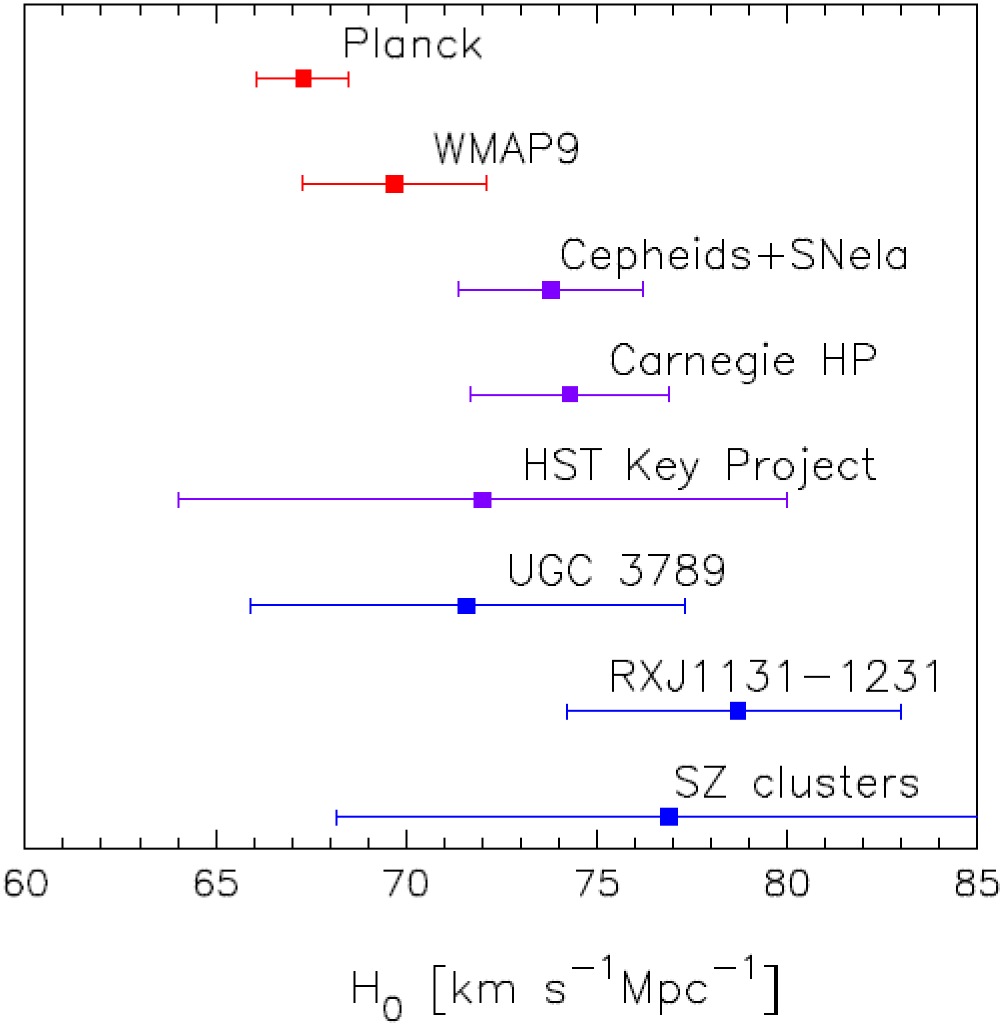
Sterile Neutrinos

- Use following likelihoods, following Planck:
  - Planck
  - WMAP polarization
  - BAO data from SDSS and WiggleZ
  - High-l data from ACT and SPT

Sterile Neutrinos

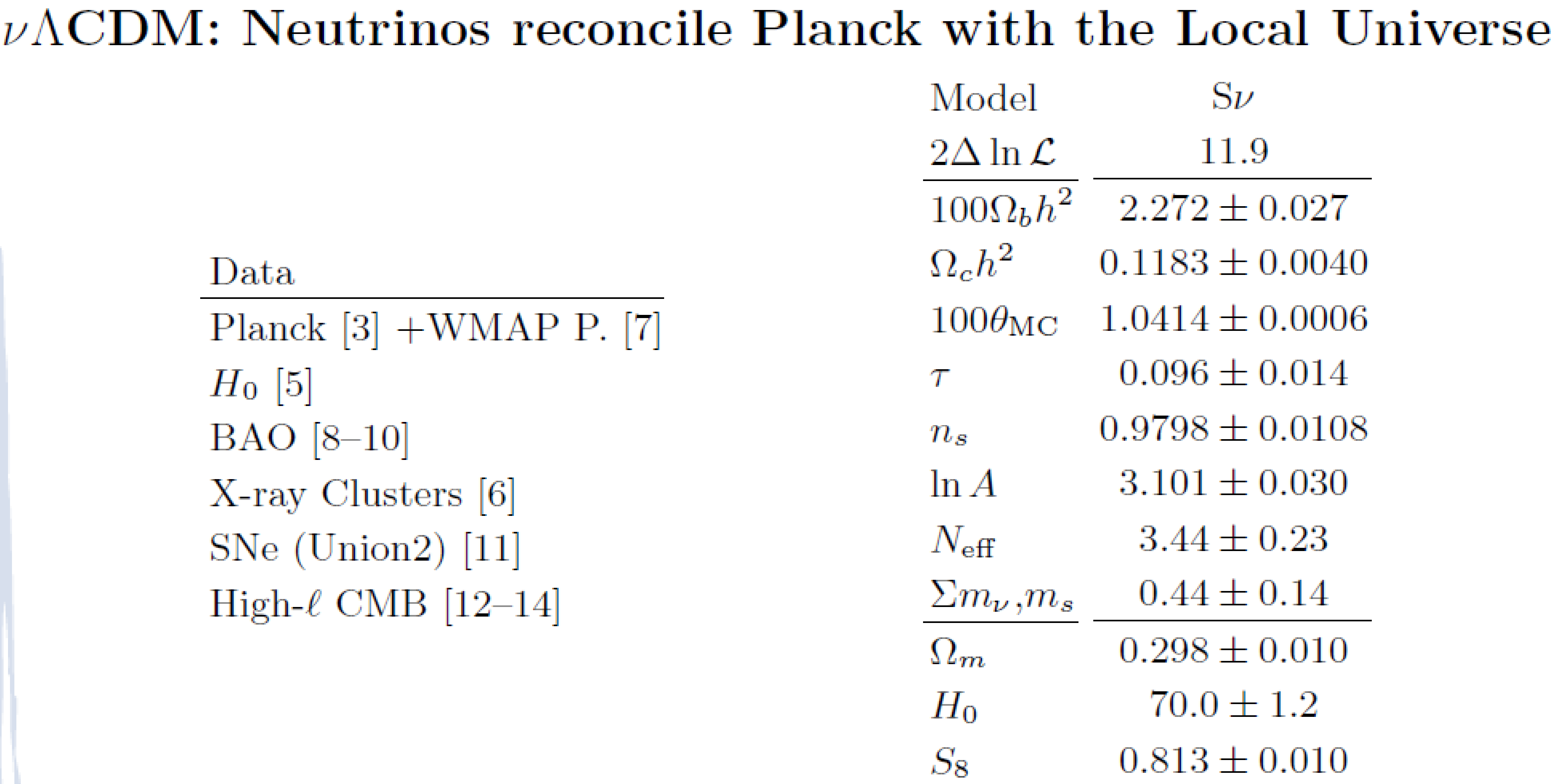


Tension in Hubble Parameter



Planck Collaboration, 1303.5076

Sterile Neutrinos



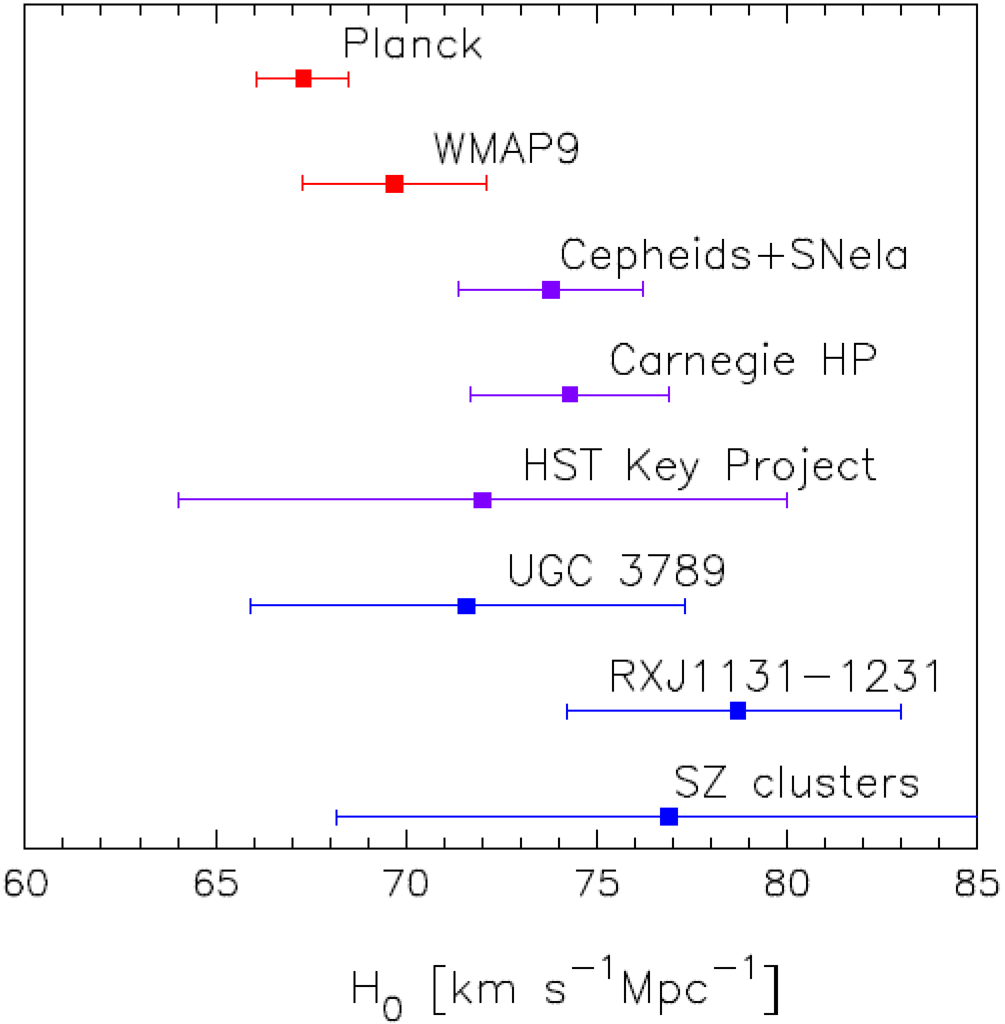
$\nu\Lambda$CDM: Neutrinos reconcile Planck with the Local Universe

Data
Planck [3] +WMAP P. [7]
H_0 [5]
BAO [8–10]
X-ray Clusters [6]
SNe (Union2) [11]
High-ℓ CMB [12–14]

Model	Sν
$2\Delta \ln \mathcal{L}$	11.9
$100\Omega_b h^2$	2.272 ± 0.027
$\Omega_c h^2$	0.1183 ± 0.0040
$100\theta_{\rm MC}$	1.0414 ± 0.0006
τ	0.096 ± 0.014
n_s	0.9798 ± 0.0108
$\ln A$	3.101 ± 0.030
$N_{\rm eff}$	3.44 ± 0.23
$\Sigma m_\nu, m_s$	0.44 ± 0.14
Ω_m	0.298 ± 0.010
H_0	70.0 ± 1.2
S_8	0.813 ± 0.010

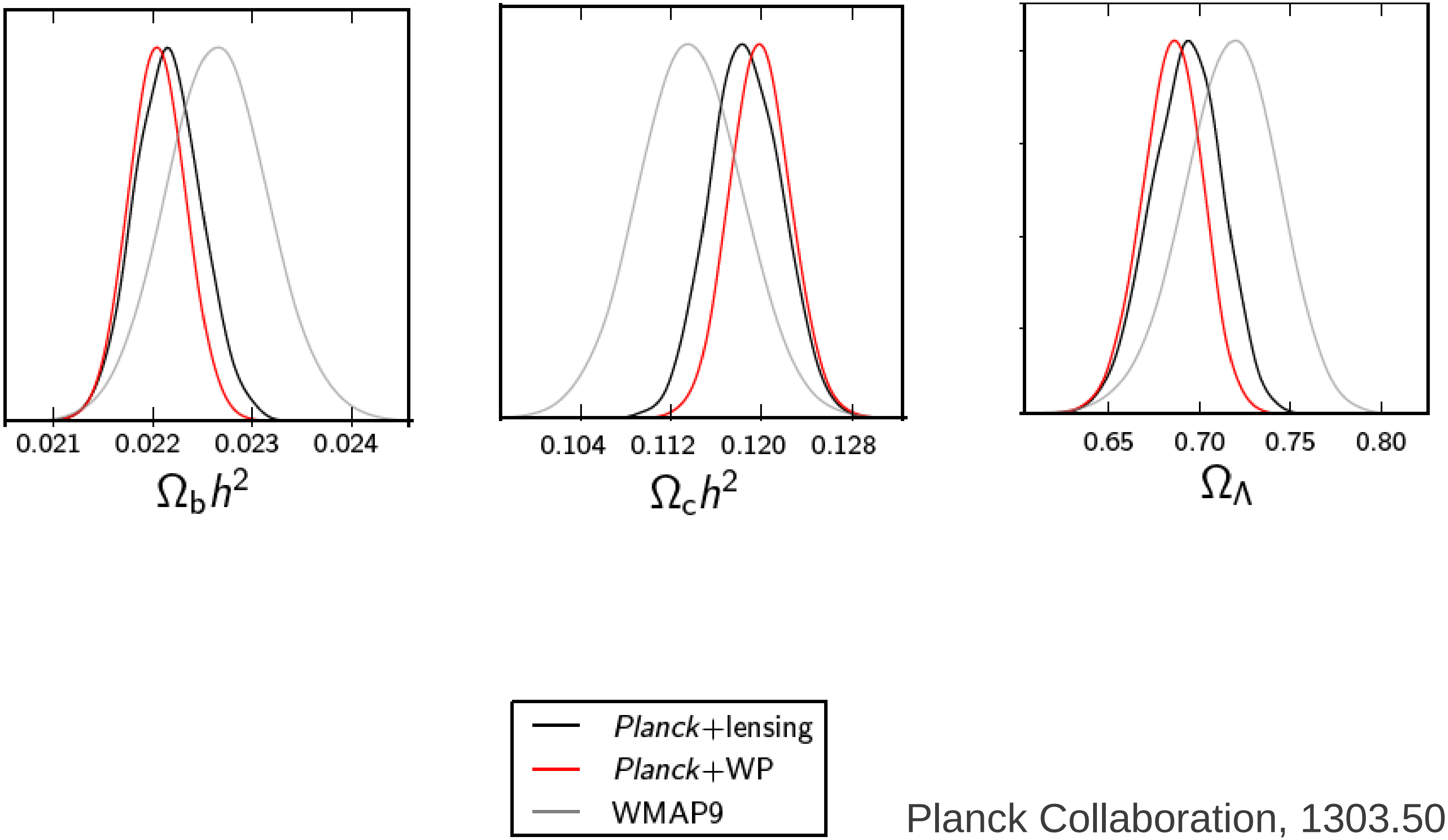
Wyman et al, 1307.7715

Critical Look at Planck



Planck Collaboration, 1303.5076

Critical Look at Planck



Planck Collaboration, 1303.5076

Critical Look at Planck

$$N_{\rm eff} = 3.30^{+0.54}_{-0.51} \quad (95\%;\ \textit{Planck}\text{+WP+highL+BAO})$$

$$N_{\rm eff} = 3.62^{+0.50}_{-0.48} \quad (95\%;\ \textit{Planck}\text{+WP+highL+}H_0).$$

$$N_{\rm eff} = 3.52^{+0.48}_{-0.45} \quad (95\%;\ \textit{Planck}\text{+WP+highL+}H_0\text{+BAO})$$

Planck Collaboration, 1303.5076

Critical Look at Planck

- Planck TT spectrum comes from 100, 143 and 217 GHz bands
- N_{eff} measurement sensitive to high-l data
- High-l data dominated by 217 GHz band
- Higher frequencies more susceptible to details of foreground modeling

Critical Look at Planck

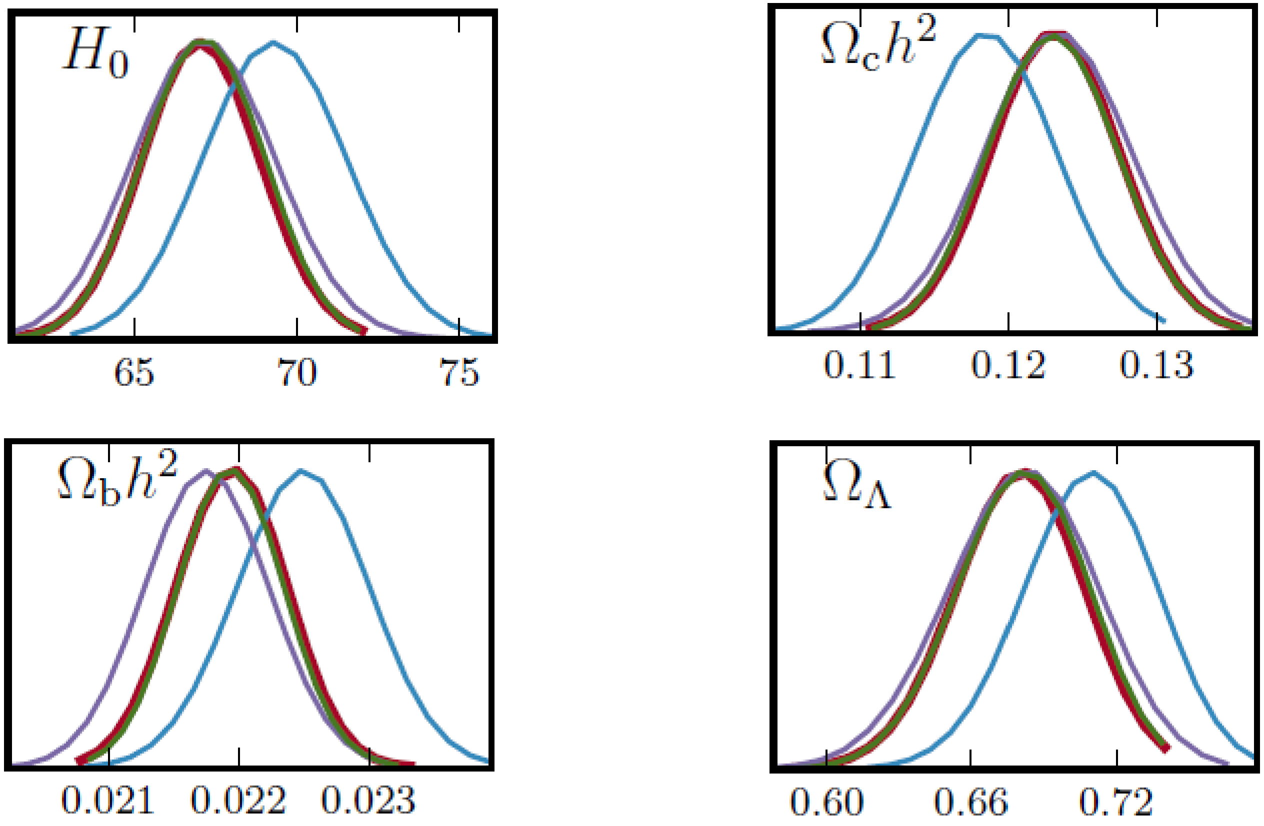


Figure D.8. Impact on parameters of removing one single frequency channel (i.e., *all* spectra with at least one frequency in the removed channel). Results are shown removing the 100 GHz (green), 143 GHz (purple), or 217 GHz (blue) channels, compared to the reference case (red). Where the 217 GHz channel is removed, the CIB spectral index is held fixed at $\gamma^{\rm CIB} = 0.6$.

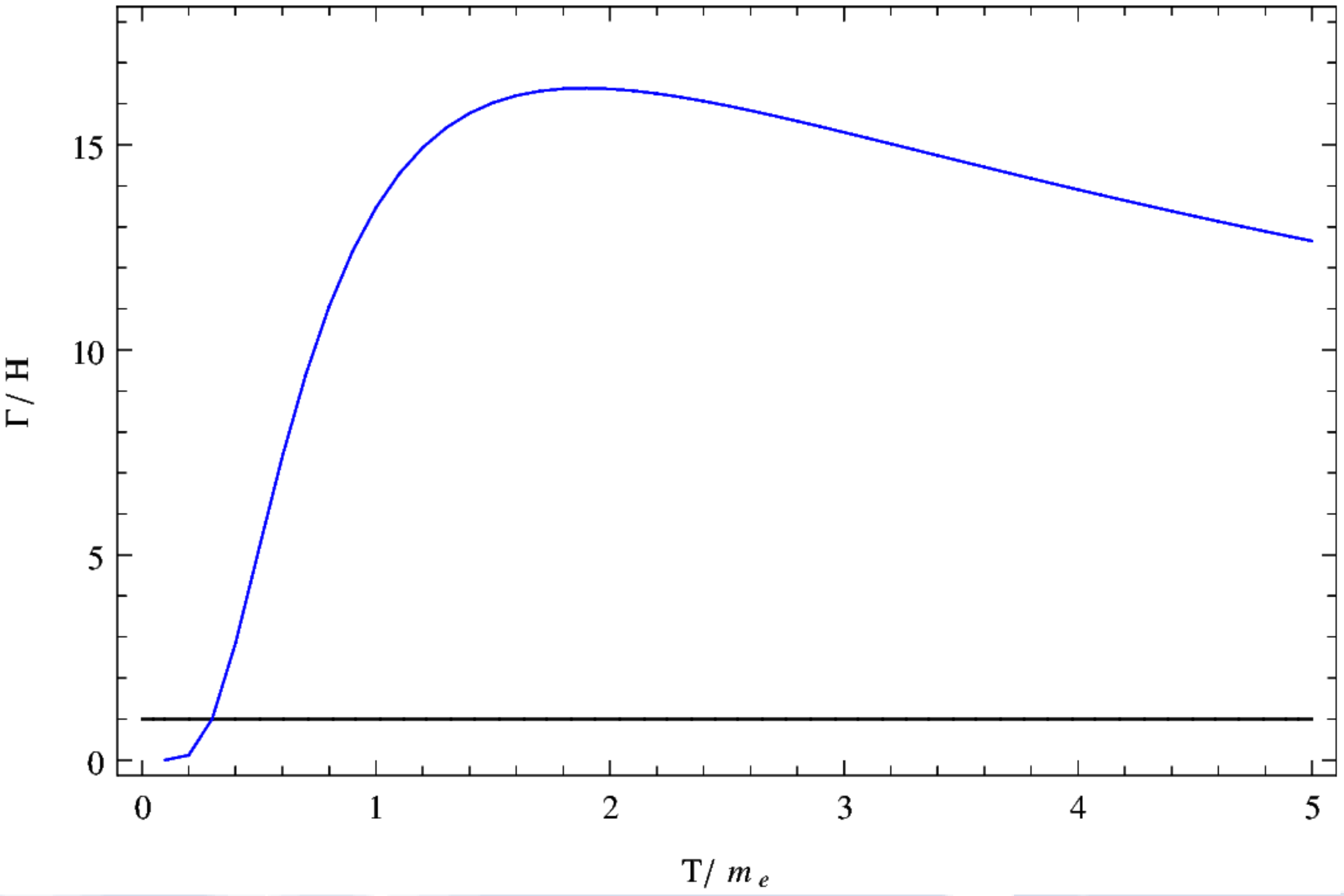
Planck Collaboration, 1303.5075

Conclusions

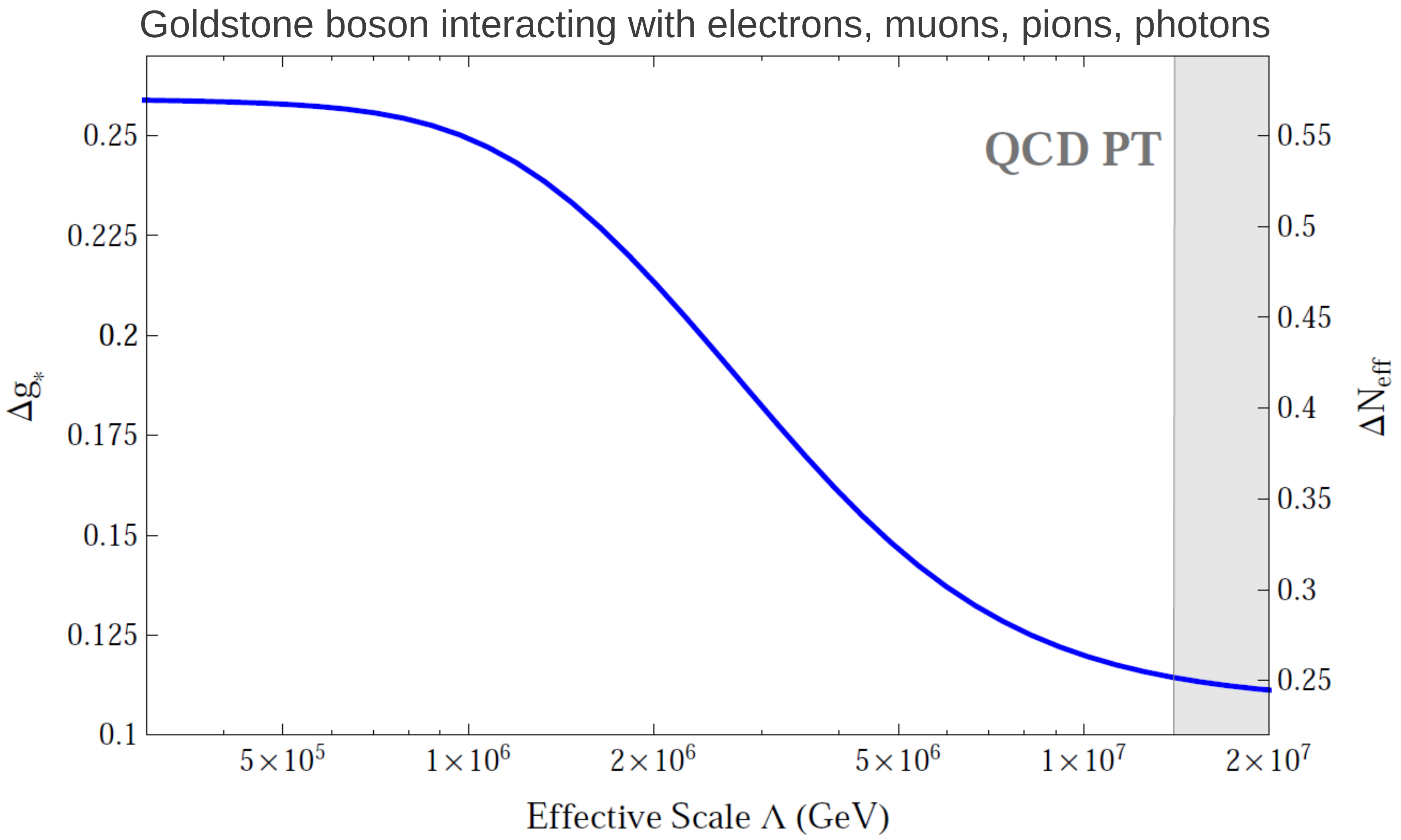
- Wrote code to solve Boltzmann equation for nonthermal distribution functions
- Constructed map from parameter space to N_{eff}
- Look for news regarding 217 GHz band from Planck and hopefully a discovery of new light species!

Recoupling

- Species out of equilibrium with SM can come into equilibrium before species annihilation



Goldstone Boson Results



Bound from supernova/star cooling: $\Lambda_e \gtrsim 2.9\times10^9\ \mathrm{GeV}$

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

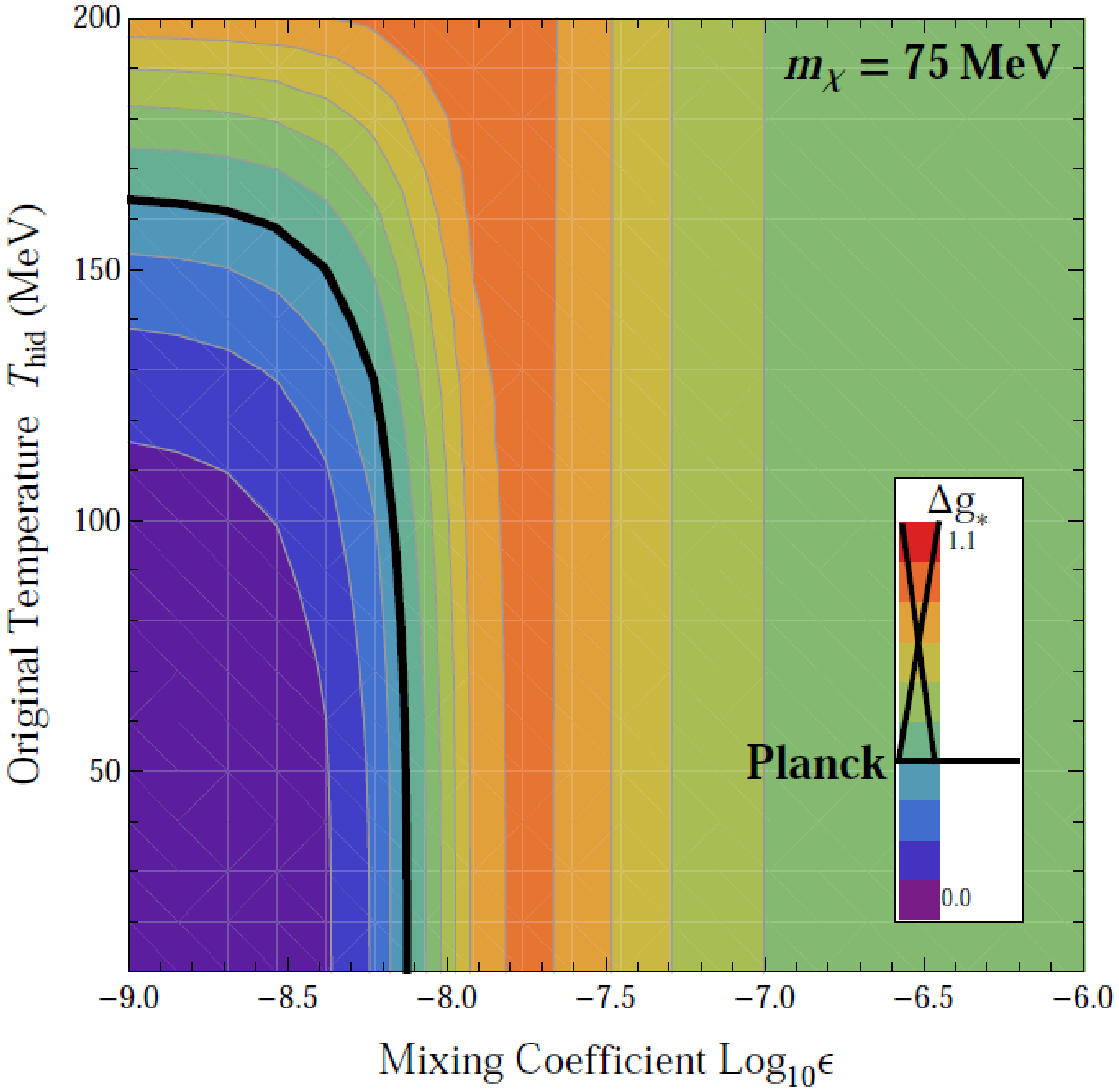
U(1)' Kinetic Mixing Results

- $m_\chi \lesssim 10\ \mathrm{MeV}$: 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: