Title: New Light Species and the CMB - Joint Cosmology/Particle Physics Seminar

Date: Nov 19, 2013 01:00 PM

URL: http://pirsa.org/13110051

Abstract: The effective number of neutrino species in our universe, Neff, is capable of probing the presence of new light or massless species in our universe. I will first review relevant facts about both CMB measurements of new light species and thermodynamics in the early universe. Then, I will present the effects of many models of BSM physics containing new light species on the CMB, including models containing eV-scale sterile neutrinos compatible with anomalies in neutrino experiments, and interpret the compatibility of the parameter space of these models in terms of the recent results from the Planck satellite. I will argue that the bounds on couplings obtained from the Planck measurement of the CMB are competitive with bounds coming from other areas of physics.

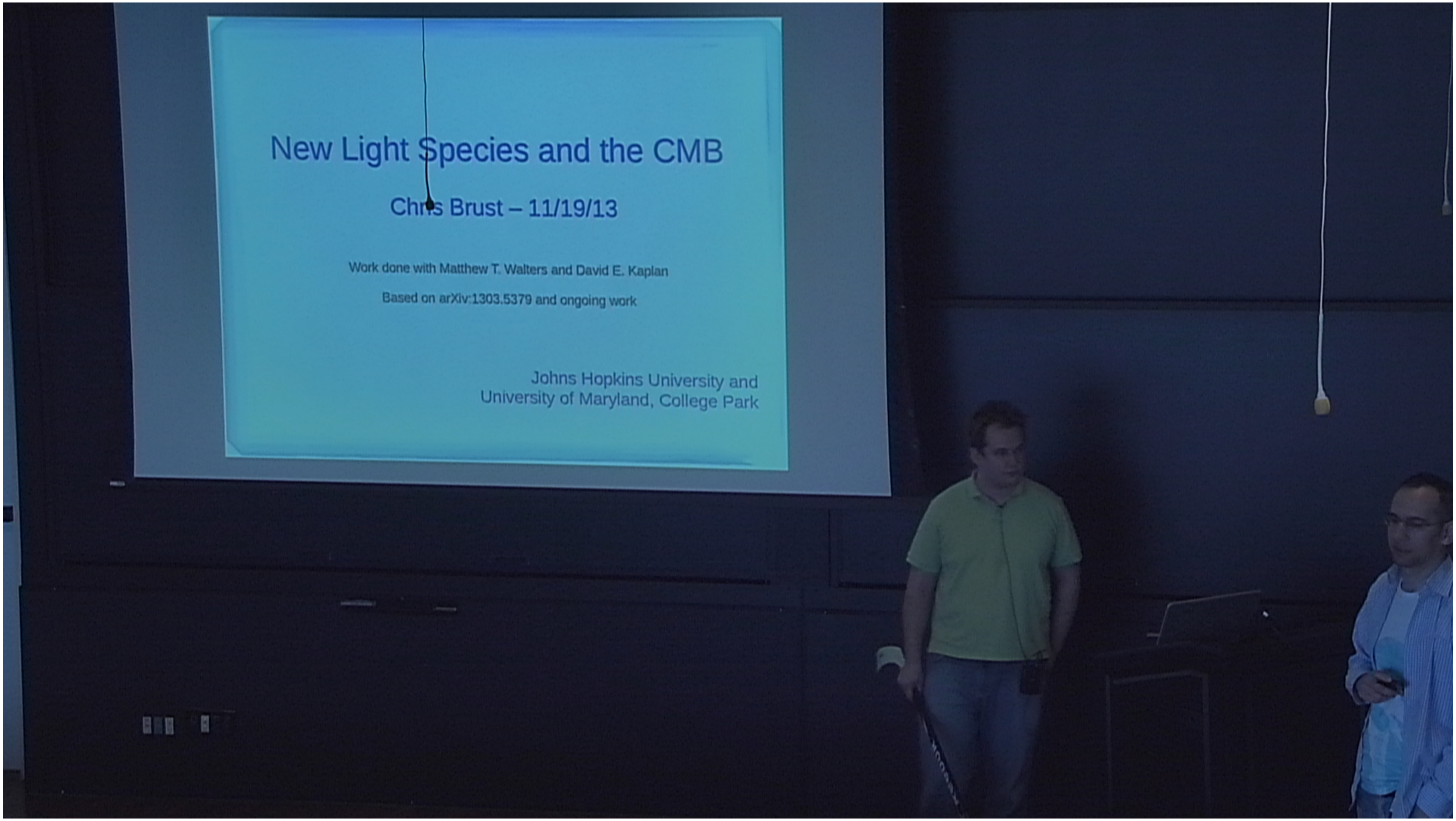
New Light Species and the CMB

Chris Brust – 11/19/13

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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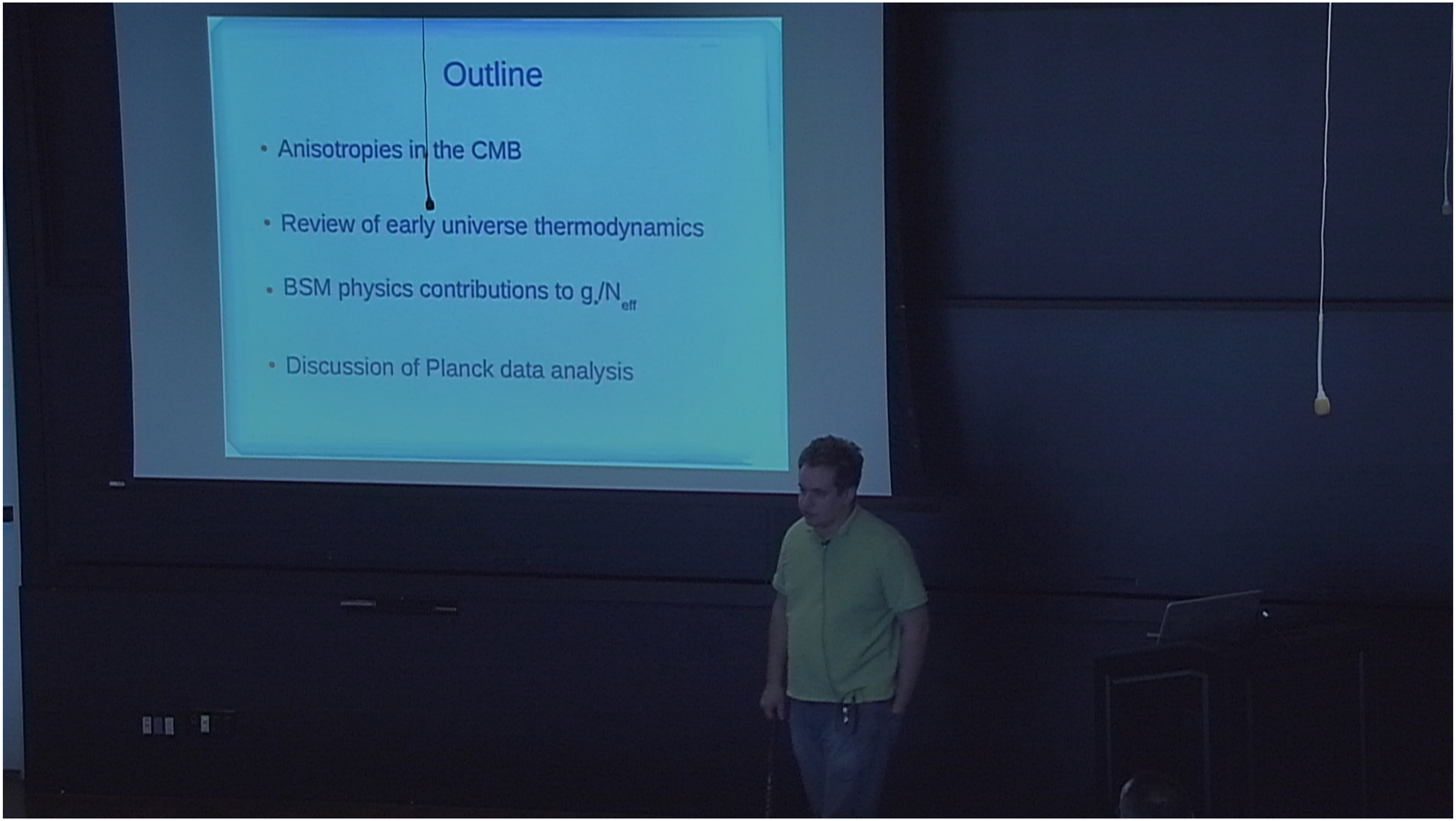
Outline

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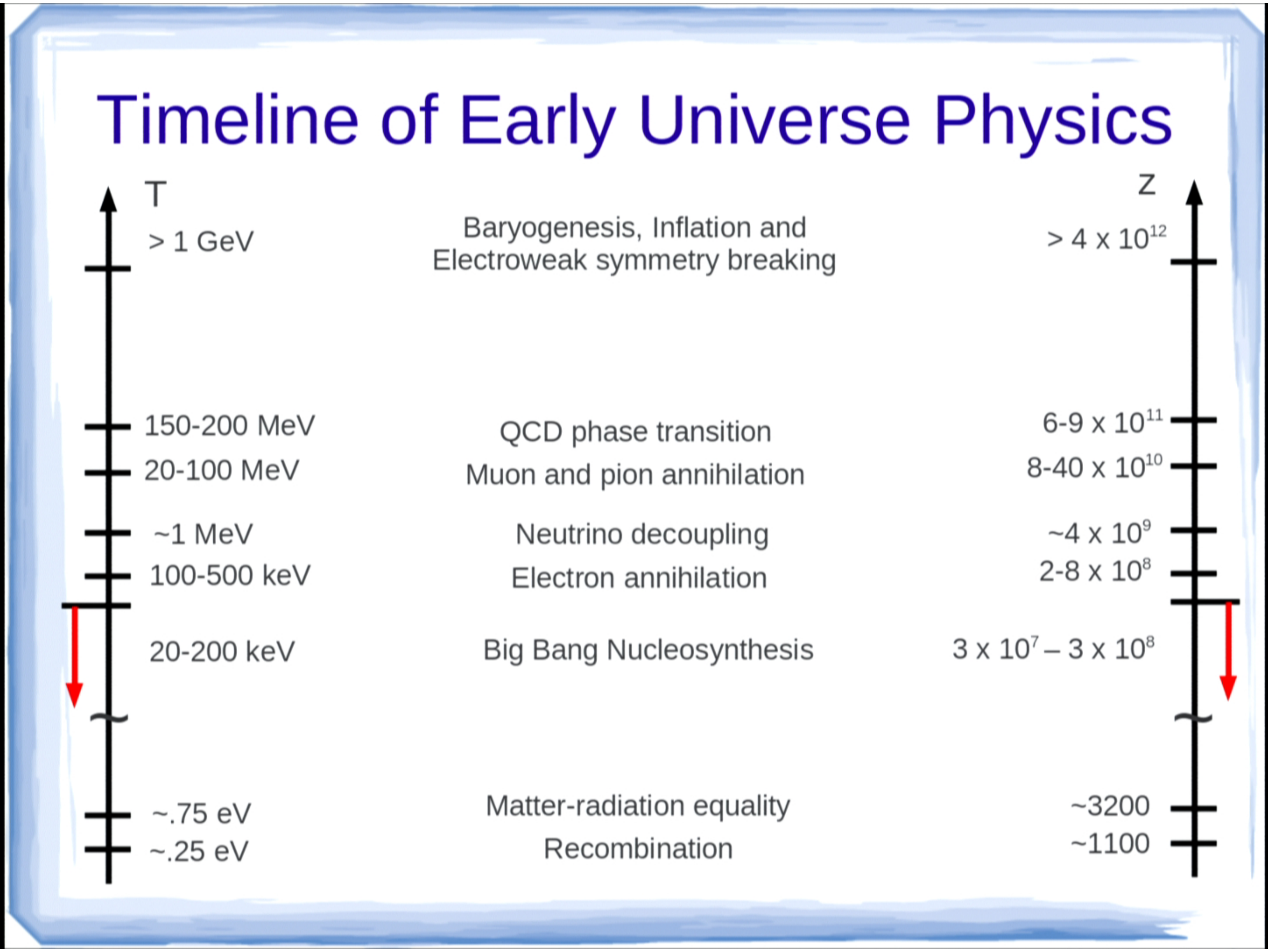
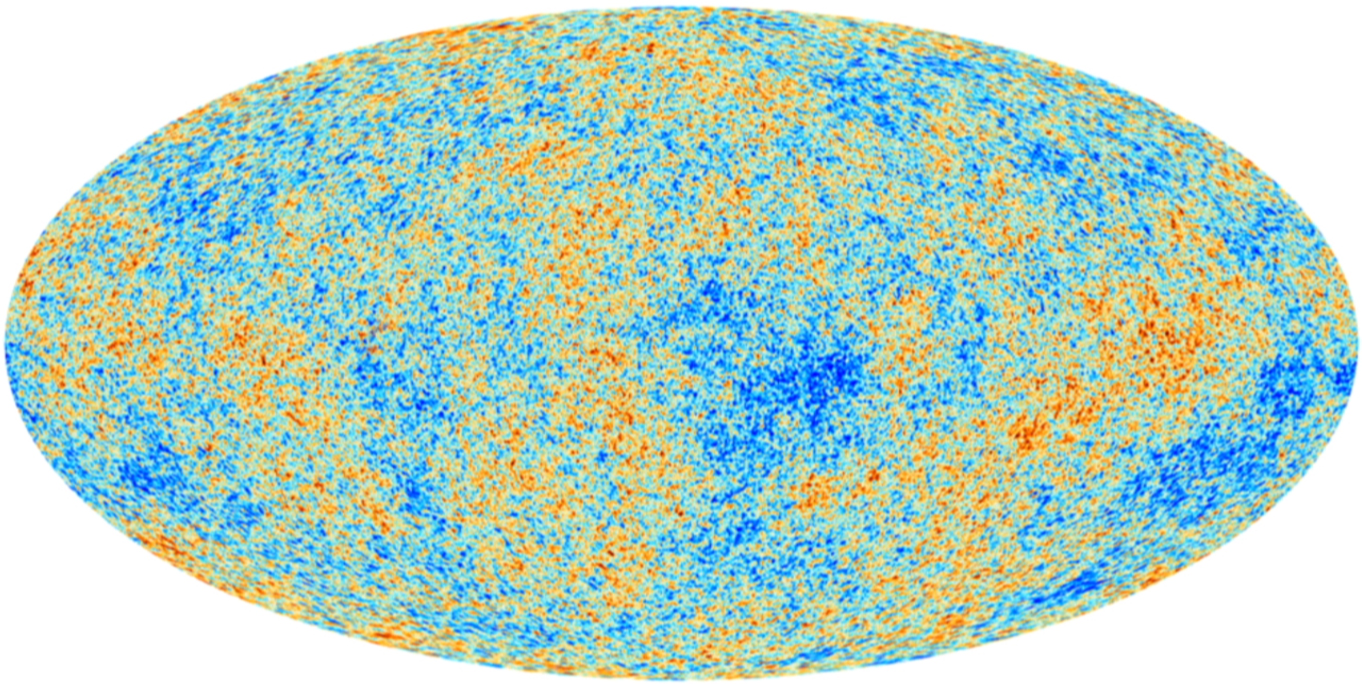

Timeline of Early Universe Physics
T
Z
> 1 GeV
Baryogenesis, Inflation and
Electroweak symmetry breaking
> 4 x 10^12
150-200 MeV
QCD phase transition
6-9 x 10^11
20-100 MeV
Muon and pion annihilation
8-40 x 10^10
~1 MeV
Neutrino decoupling
~4 x 10^9
100-500 keV
Electron annihilation
2-8 x 10^8
20-200 keV
Big Bang Nucleosynthesis
3 x 10^7 – 3 x 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

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:

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

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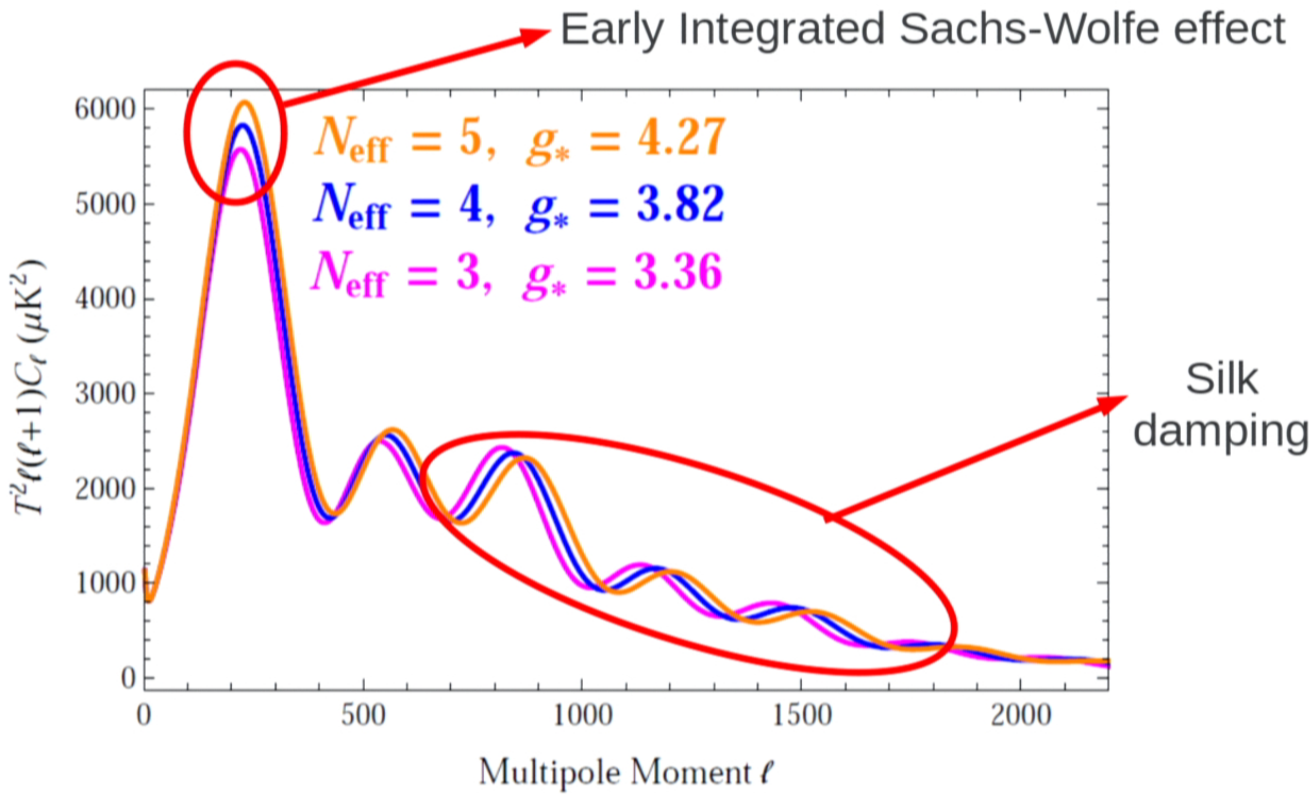
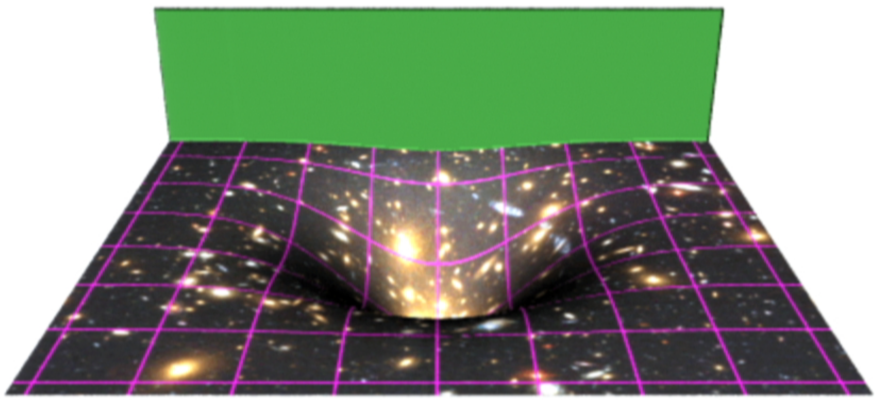


Early Integrated Sachs-Wolfe Effect



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

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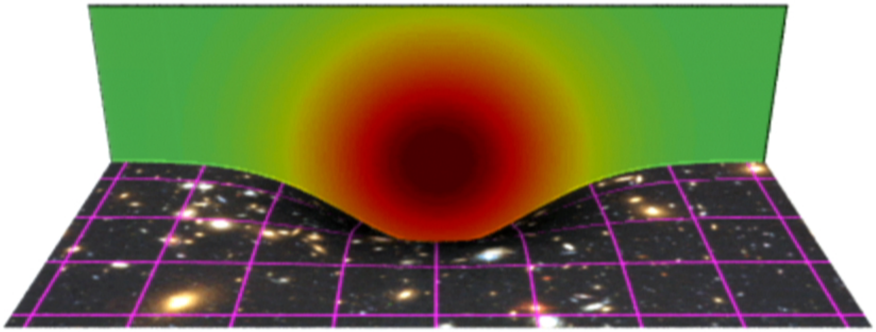

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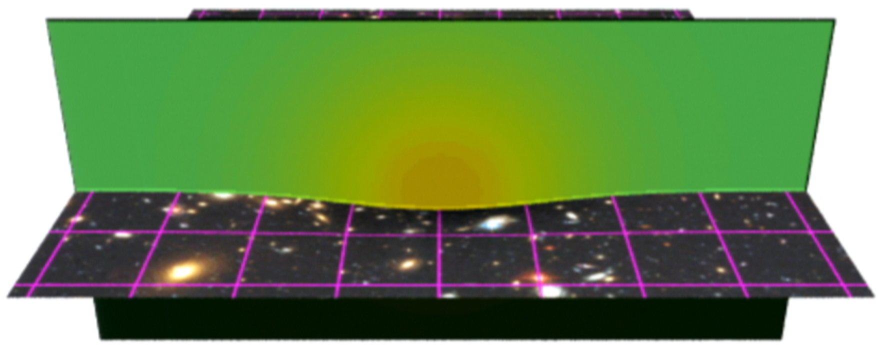

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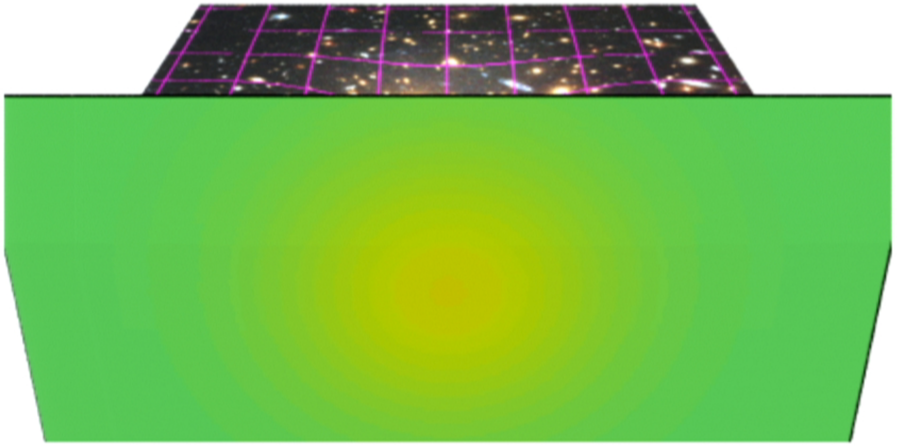

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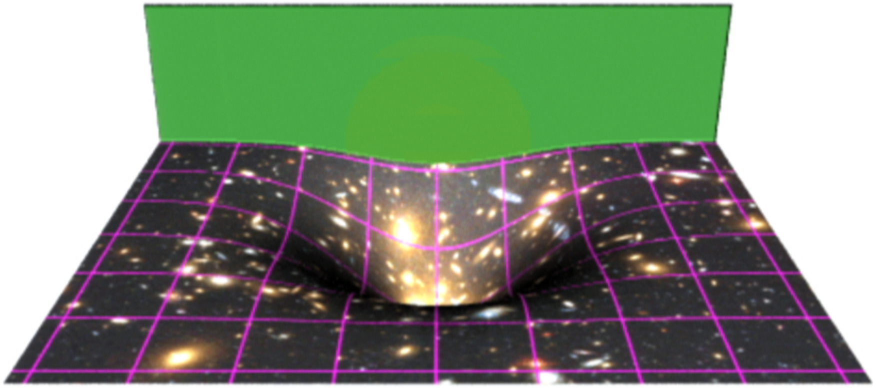

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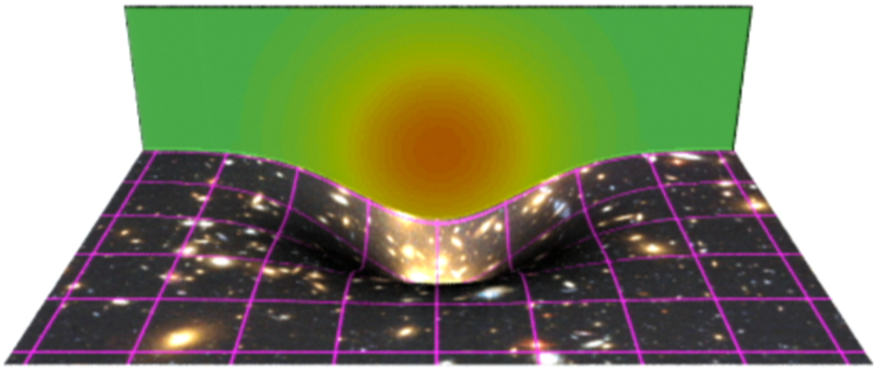

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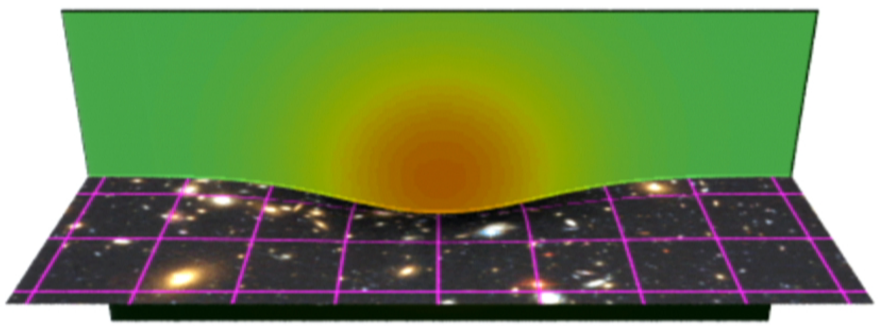

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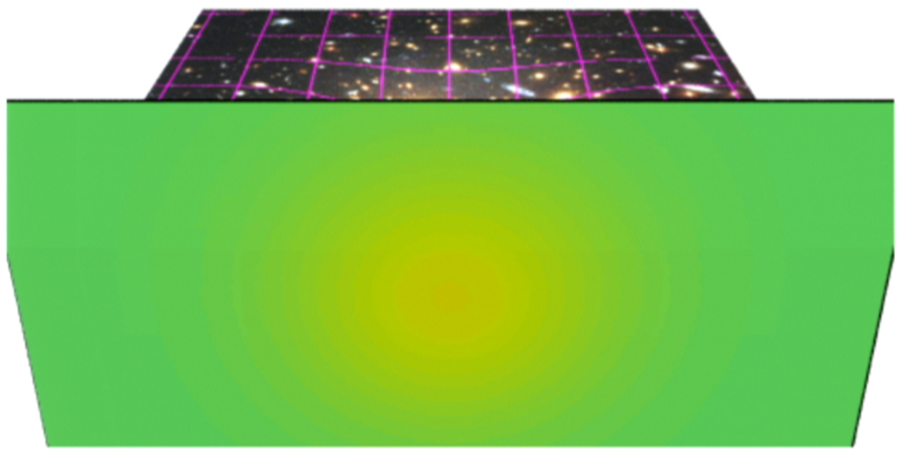

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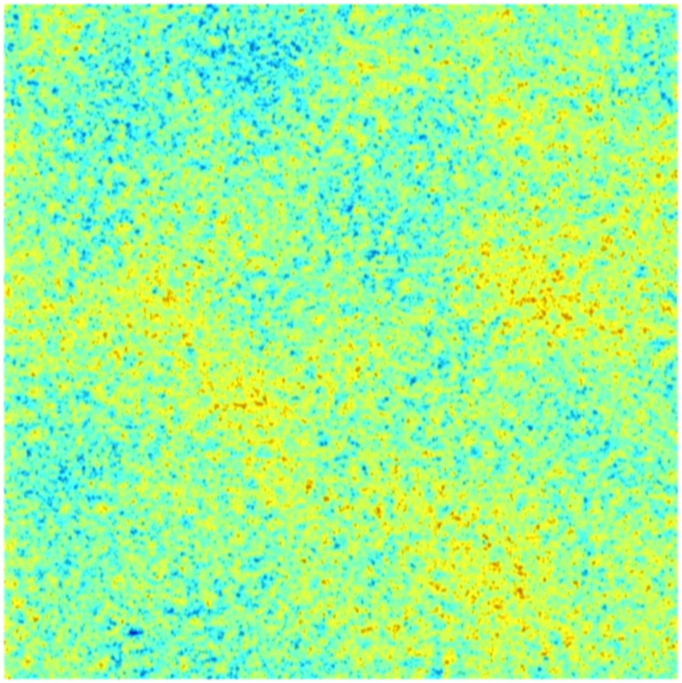
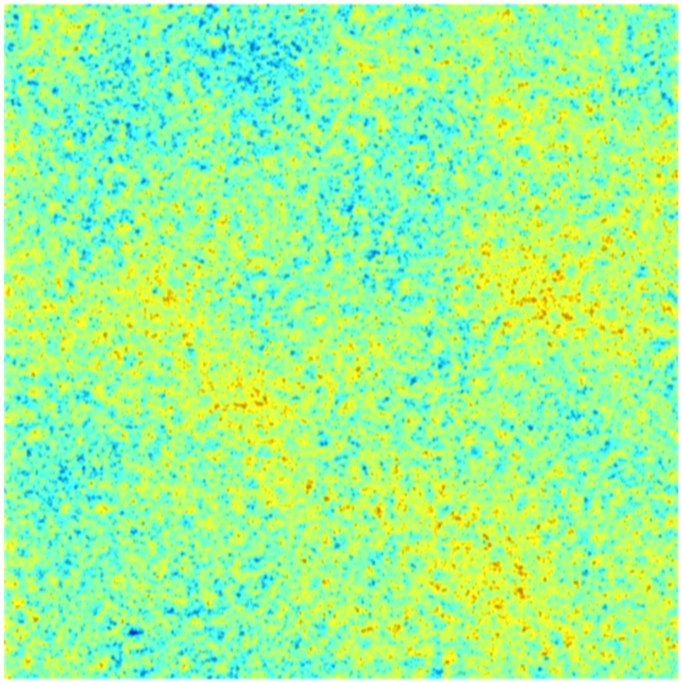
Silk Damping



t ~ 100 years



t from 100 to 378,000 years

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

Friedmann Equations

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

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

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

Solutions to Boltzmann Equation

- Sufficiently rapidly interacting:

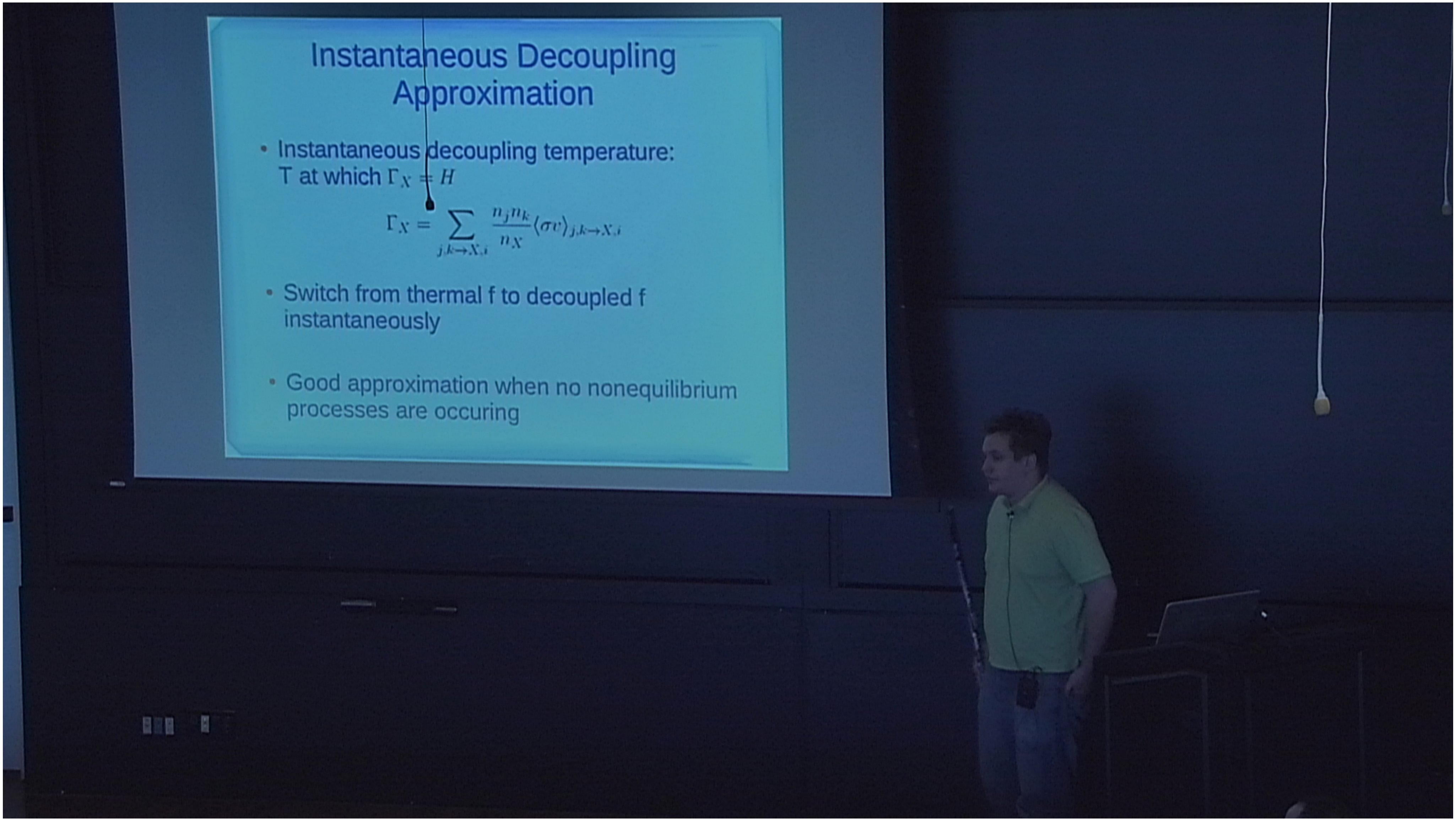
$$f(p,t) = \frac{1}{e^{E/T} \pm 1}$$

- 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

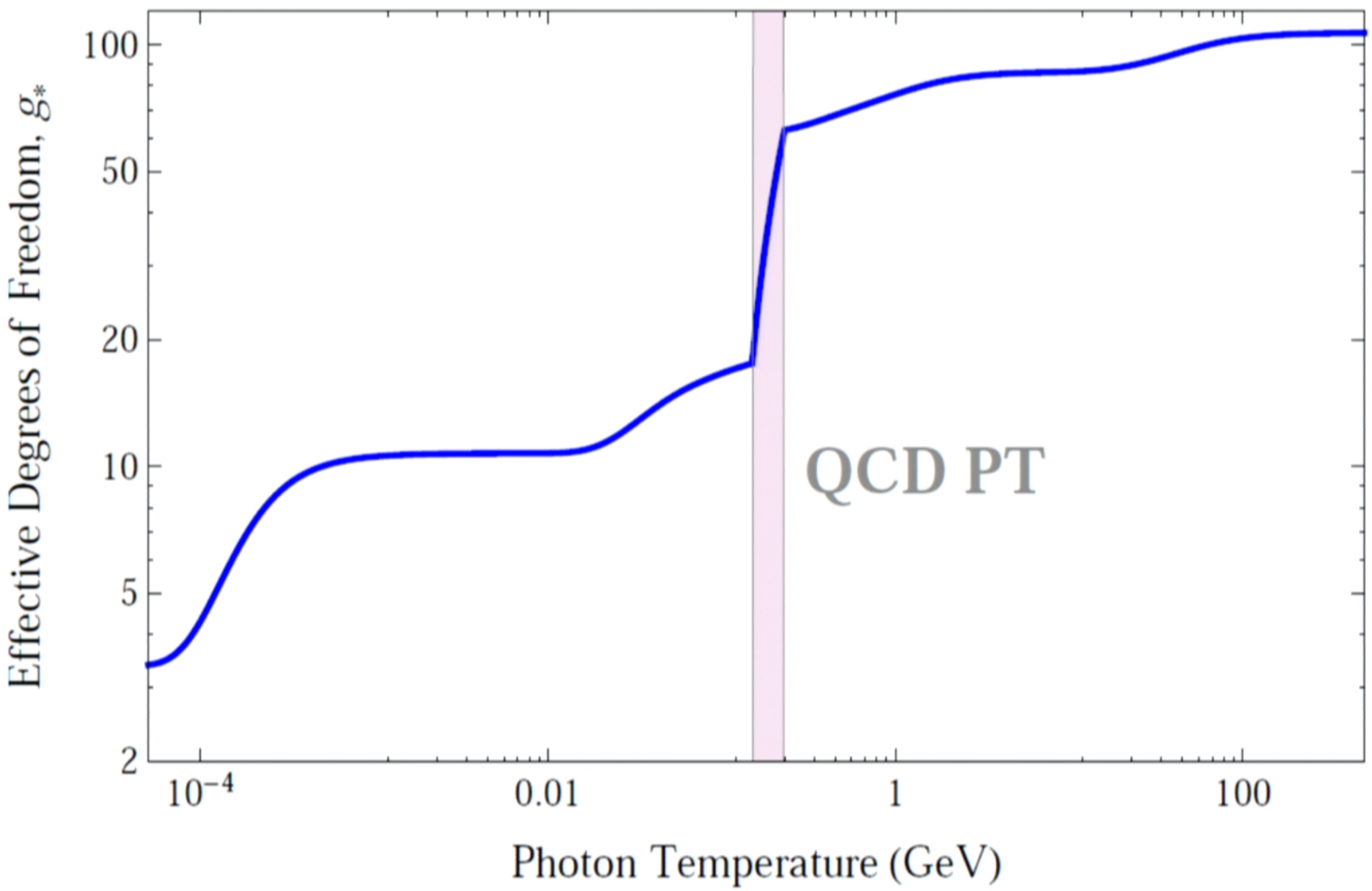
Species Annihilation and Entropy Redistributions

- 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

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



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:

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

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

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

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

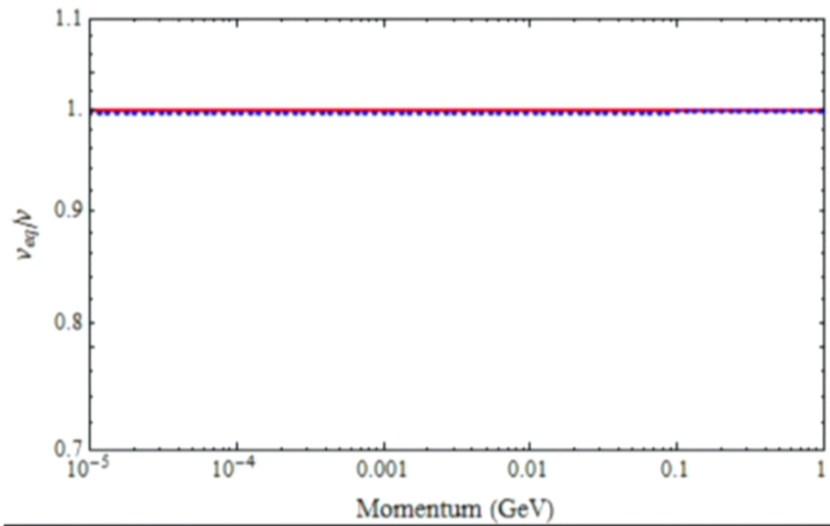
- Λ = 1.4 TeV: Decouples during muon annihilation

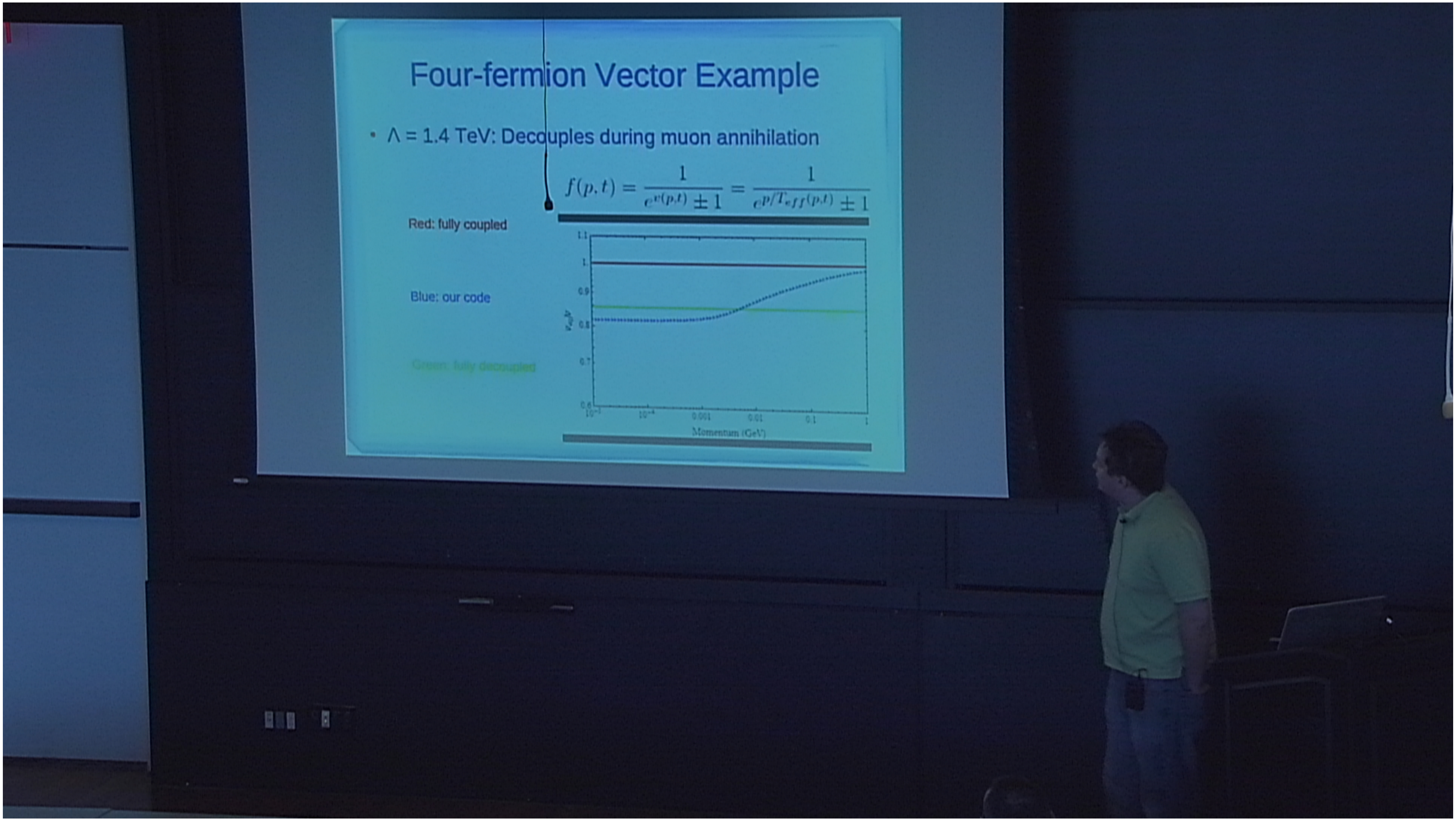
$$f(p,t) = \frac{1}{e^{v(p,t)} \pm 1} = \frac{1}{e^{p/T_{eff}(p,t)} \pm 1}$$

Red: fully coupled

Blue: our code

Green: fully decoupled





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Momentum (GeV)

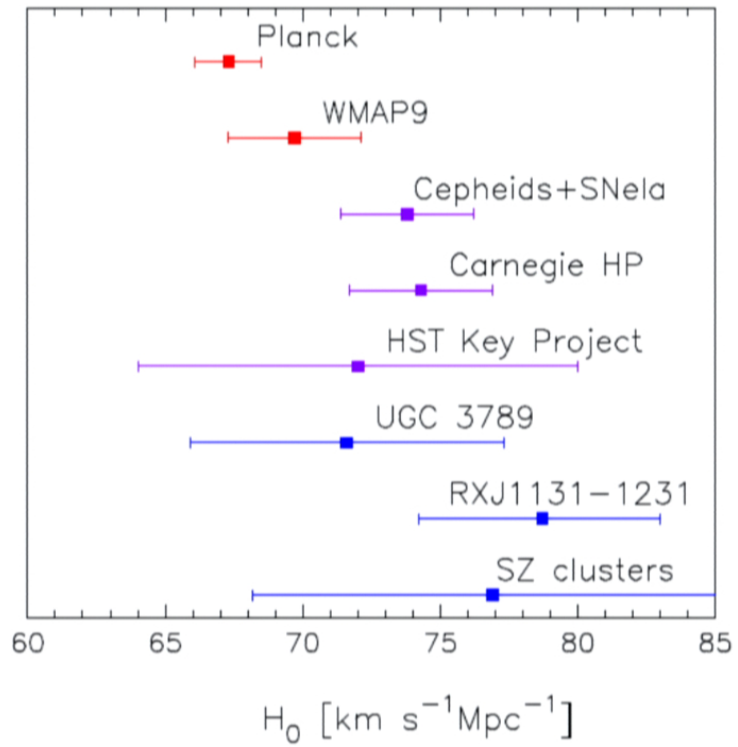
Summary of Results

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 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

Tension in Hubble Parameter



Planck Collaboration, 1303.5076

Sterile Neutrinos

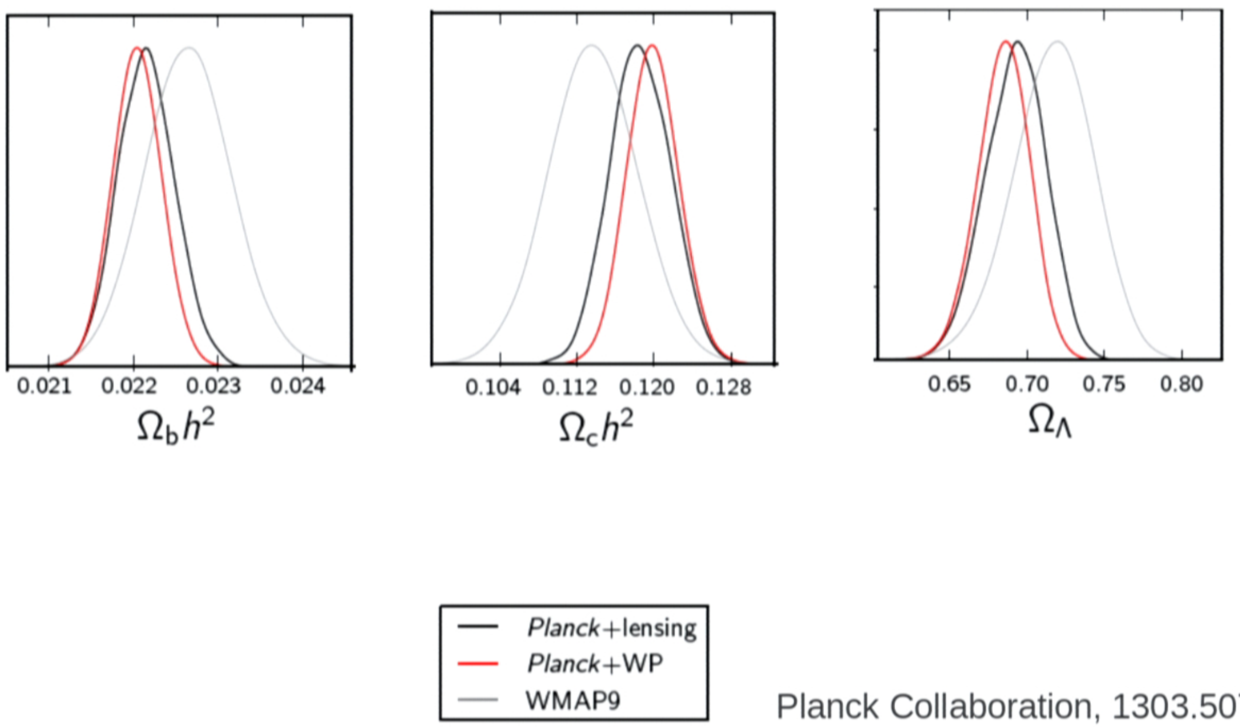
$\nu\Lambda$CDM: Neutrinos reconcile Planck with the Local Universe

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
$100\theta_{MC}$	1.0414 ± 0.0006
τ	0.096 ± 0.014
n_s	0.9798 ± 0.0108
$\ln A$	3.101 ± 0.030
N_{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

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

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

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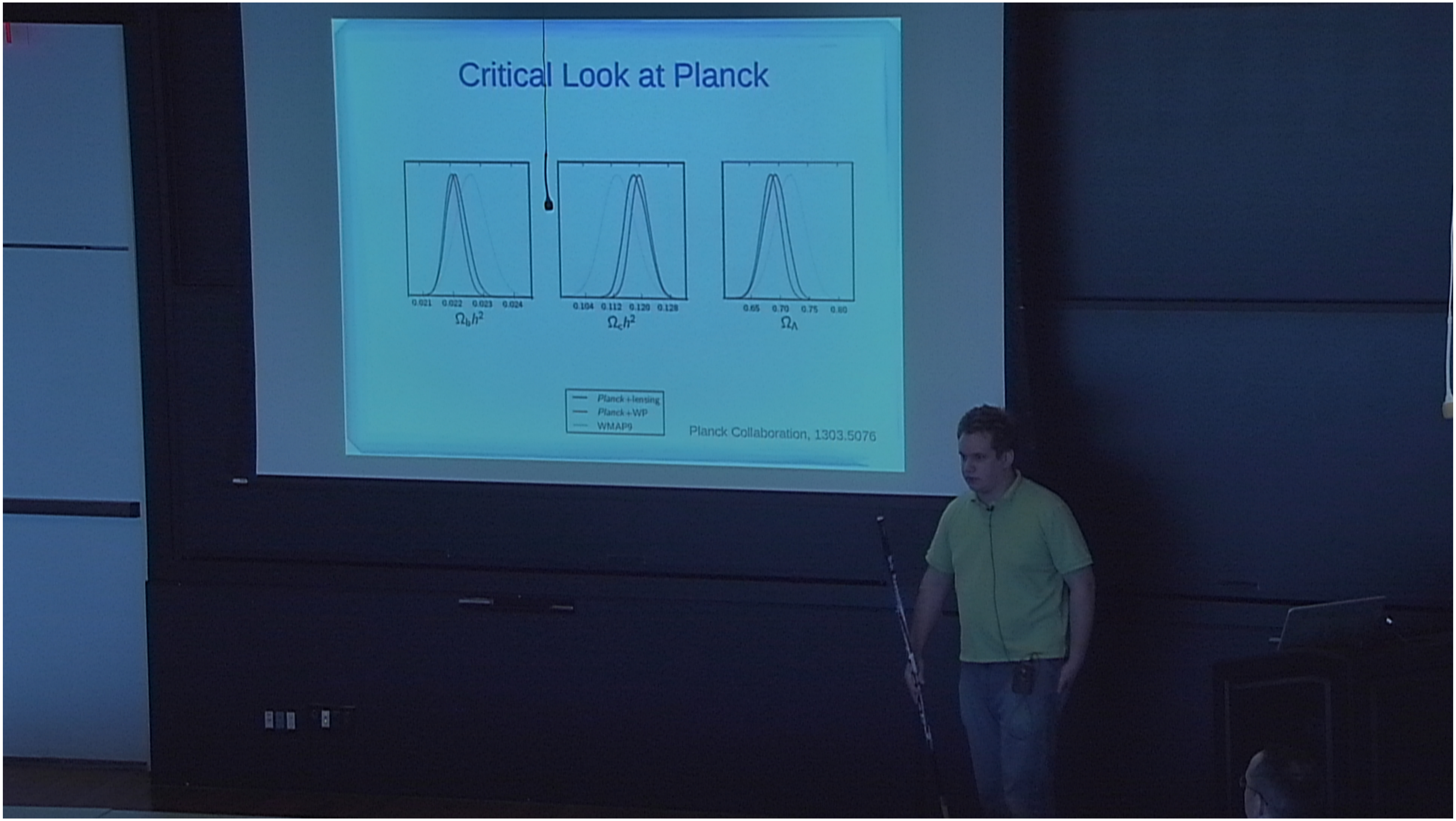
Critical Look at Planck
0.021
0.022
0.023
0.024
$\Omega_b h^2$
0.104
0.112
0.120
0.128
$\Omega_c h^2$
0.65
0.70
0.75
0.80
Ω_Λ
Planck+lensing
Planck+WP
WMAP9
Planck Collaboration, 1303.5076

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