Title: Cosmic Neutrinos and Other Light Relics

Date: Nov 10, 2015 11:00 AM

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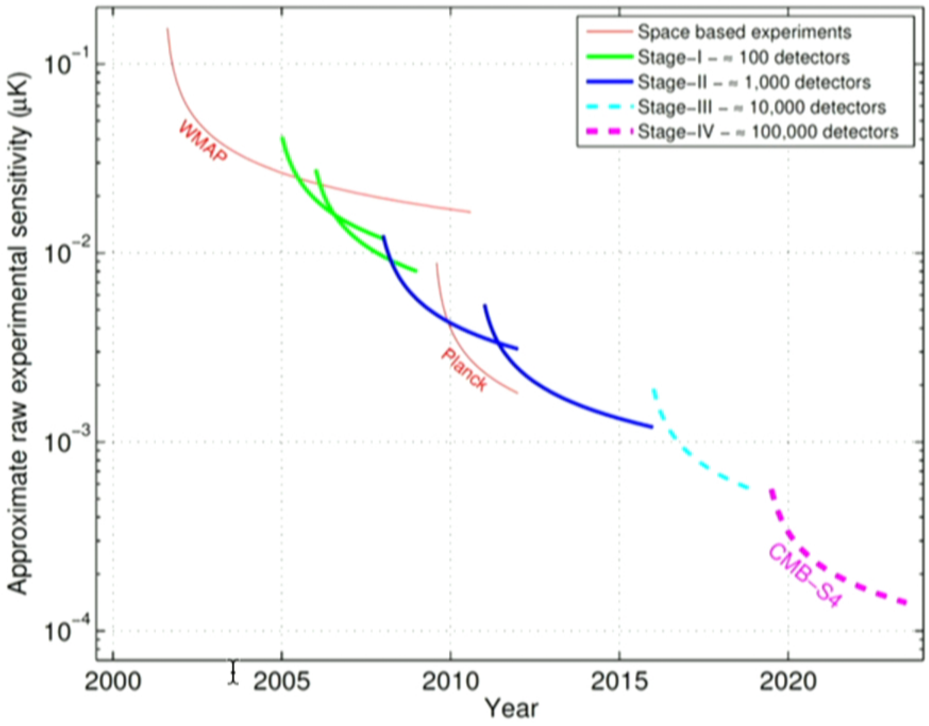
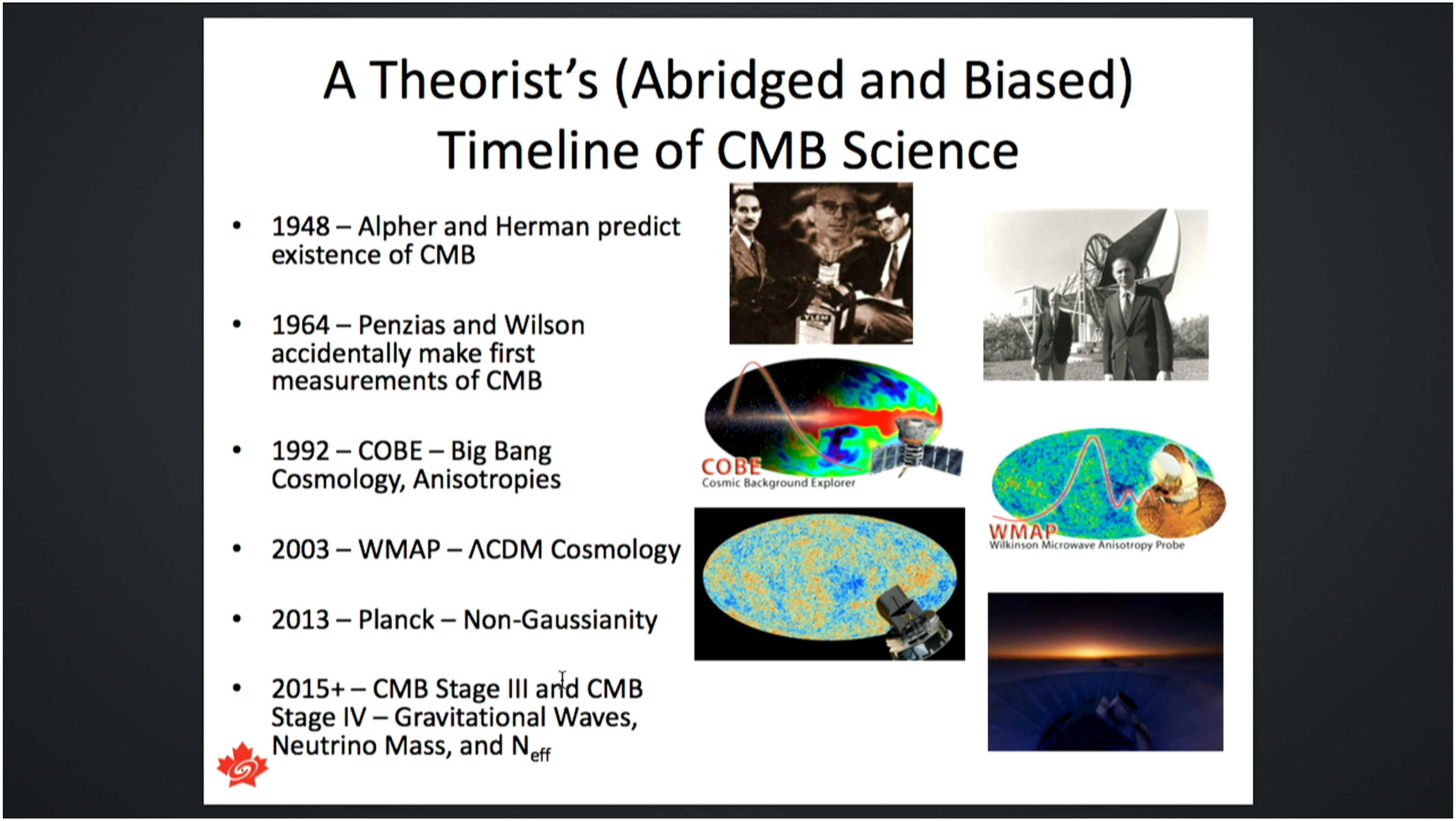
Abstract: <p>Cosmic neutrinos carry a wealth of information about both cosmology and particle physics, but they are notoriously difficult to observe. Rapid advancement in measurements of the cosmic microwave background, however, have allowed us to indirectly constrain some properties of the cosmic neutrino background. I will discuss the current status and future prospects for improving constraints on cosmic neutrinos, focusing in part of the phase shift of acoustic peaks in the cosmic microwave background which results from neutrino fluctuations. I will also discuss how improved measurements from CMB-Stage IV will naturally constrain a wealth of beyond the standard model physics.</p>

Moore’s Law for CMB Experiments

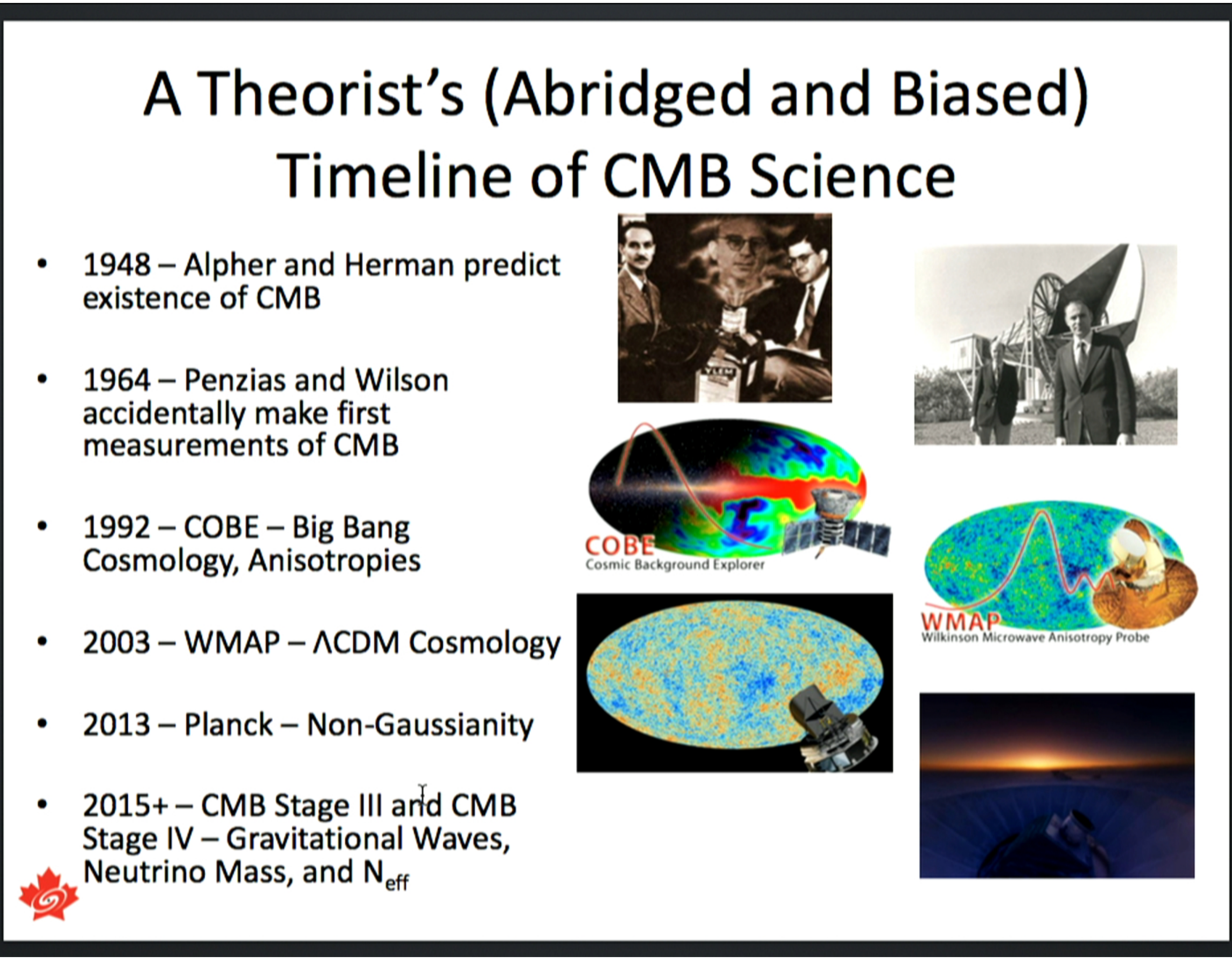


Snowmass (2013)



A Theorist's (Abridged and Biased) Timeline of CMB Science

- 1948 – Alpher and Herman predict existence of CMB
- 1964 – Penzias and Wilson accidentally make first measurements of CMB
- 1992 – COBE – Big Bang Cosmology, Anisotropies
- 2003 – WMAP – ΛCDM Cosmology
- 2013 – Planck – Non-Gaussianity
- 2015+ – CMB Stage III and CMB Stage IV – Gravitational Waves, Neutrino Mass, and N_{eff}



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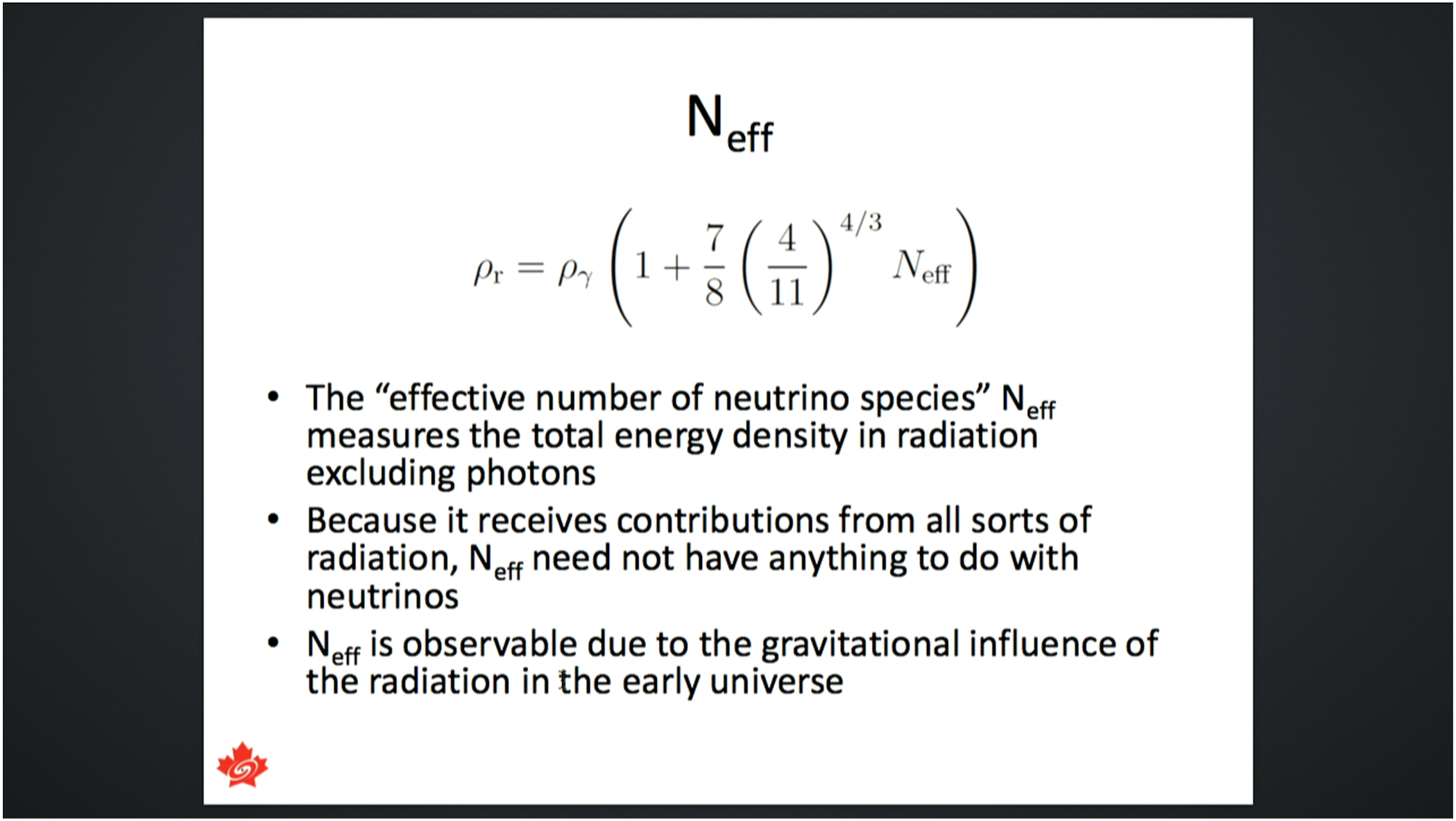
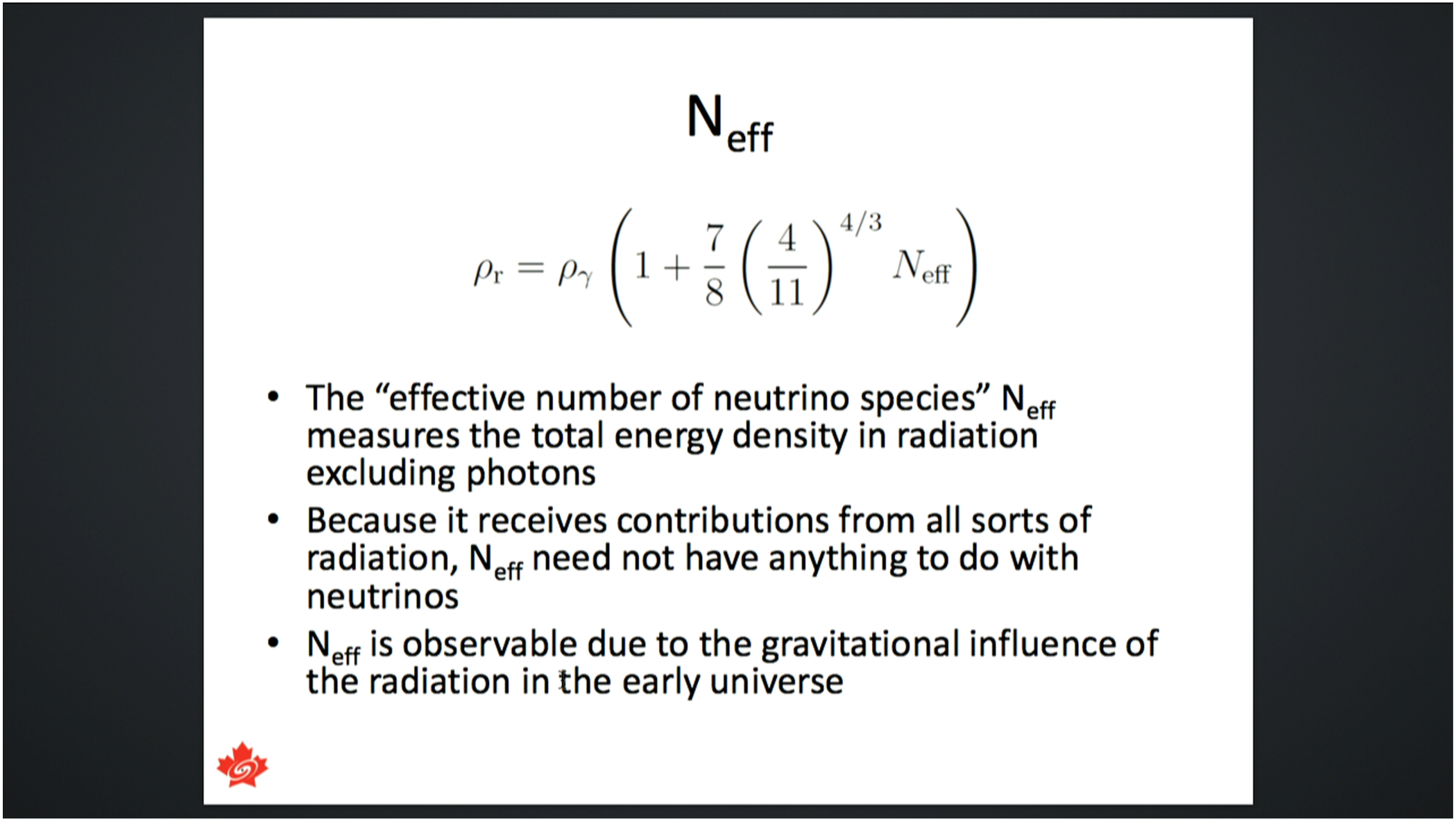


N_{eff}

$$\rho_{\mathrm{r}} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right)$$

- The "effective number of neutrino species" N_{eff} measures the total energy density in radiation excluding photons
- Because it receives contributions from all sorts of radiation, N_{eff} need not have anything to do with neutrinos
- N_{eff} is observable due to the gravitational influence of the radiation in the early universe



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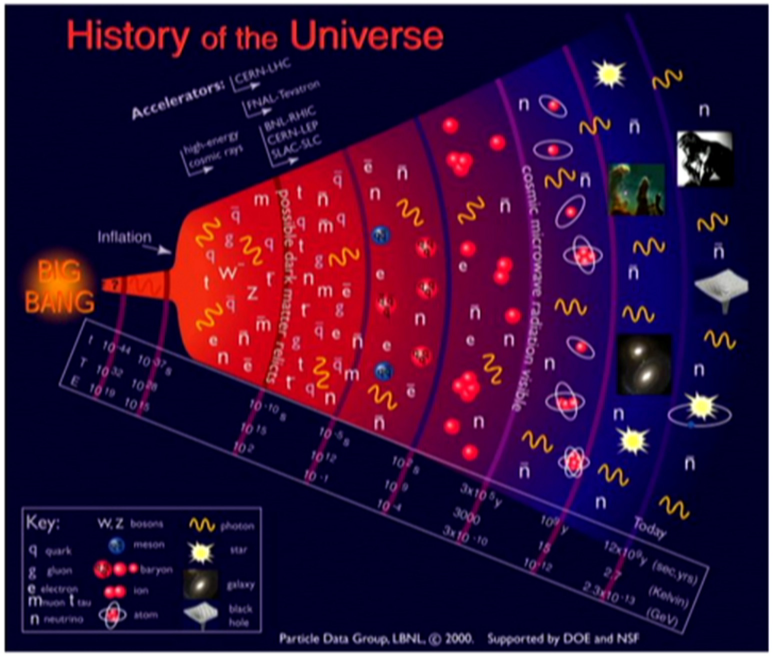
Theoretical Expectation

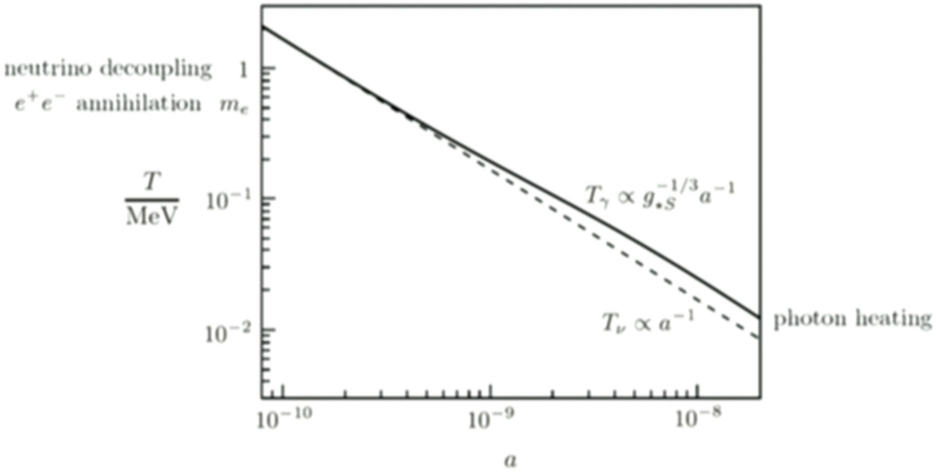
- The standard models of cosmology and particle physics make very definite and detailed predictions about the existence and properties of the cosmic neutrino background
- Neutrinos were in thermal equilibrium, decoupled about 1 second after the end of inflation, and have a nearly perfect Fermi-Dirac distribution

$$f_\nu(p, T_\nu) = \frac{1}{\exp\left(p/kT_\nu\right) + 1}$$



Planck (2015)

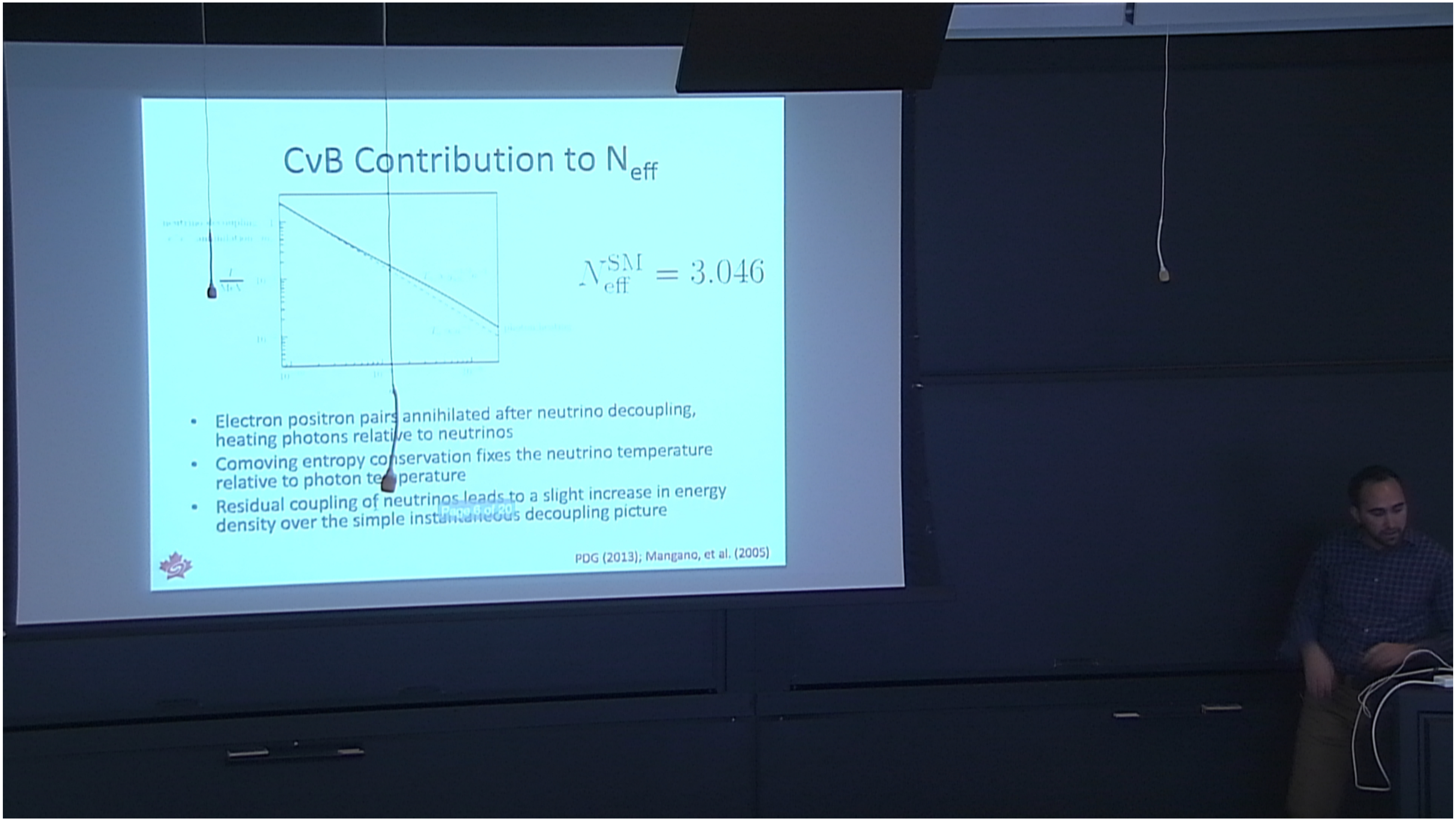
CvB Contribution to N_{eff}



$$N_{\text{eff}}^{\text{SM}} = 3.046$$

- Electron positron pairs annihilated after neutrino decoupling, heating photons relative to neutrinos
- Comoving entropy conservation fixes the neutrino temperature relative to photon temperature
- Residual coupling of neutrinos leads to a slight increase in energy density over the simple instantaneous decoupling picture

PDG (2013); Mangano, et al. (2005)



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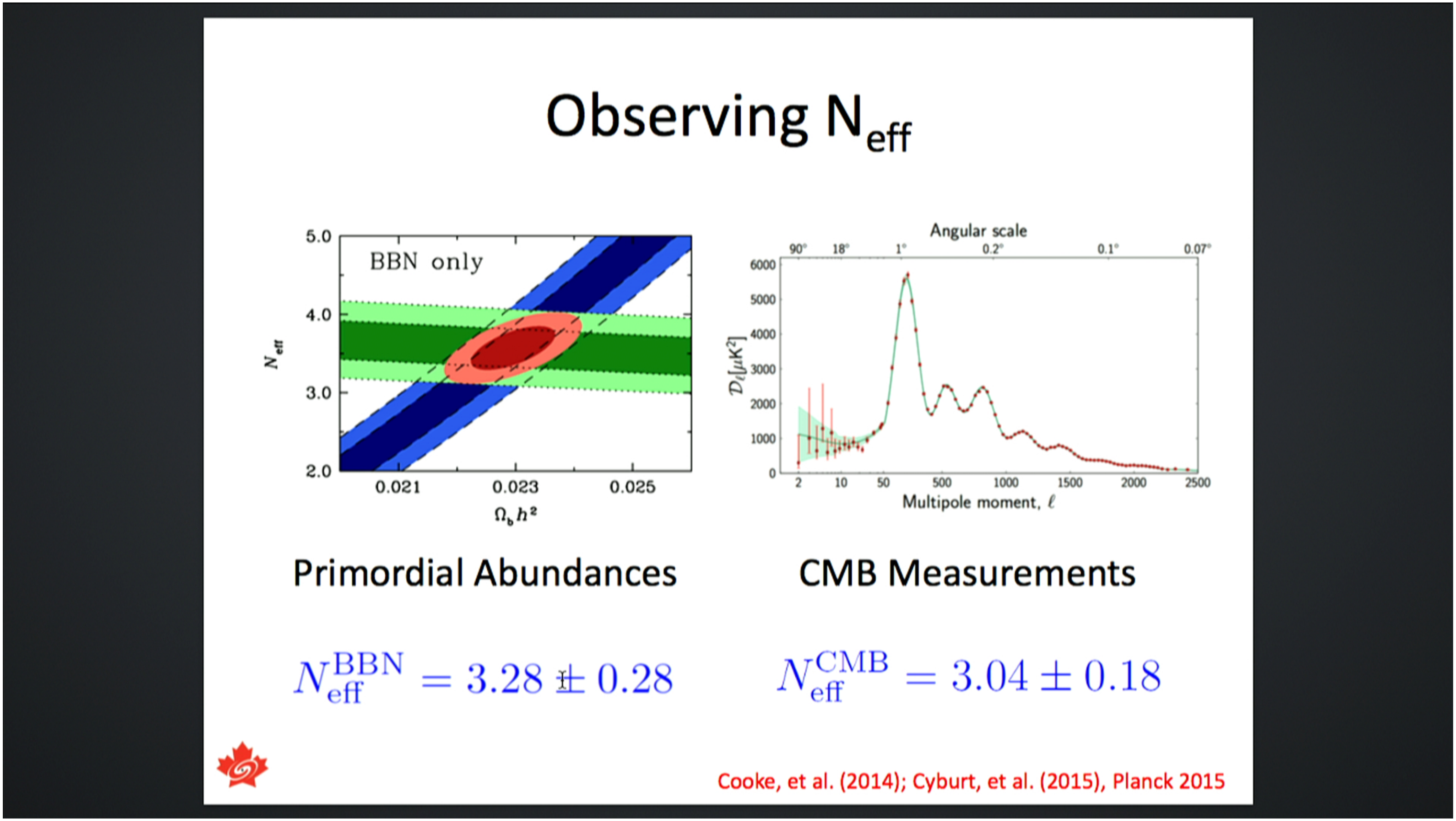


Observing N_{eff}

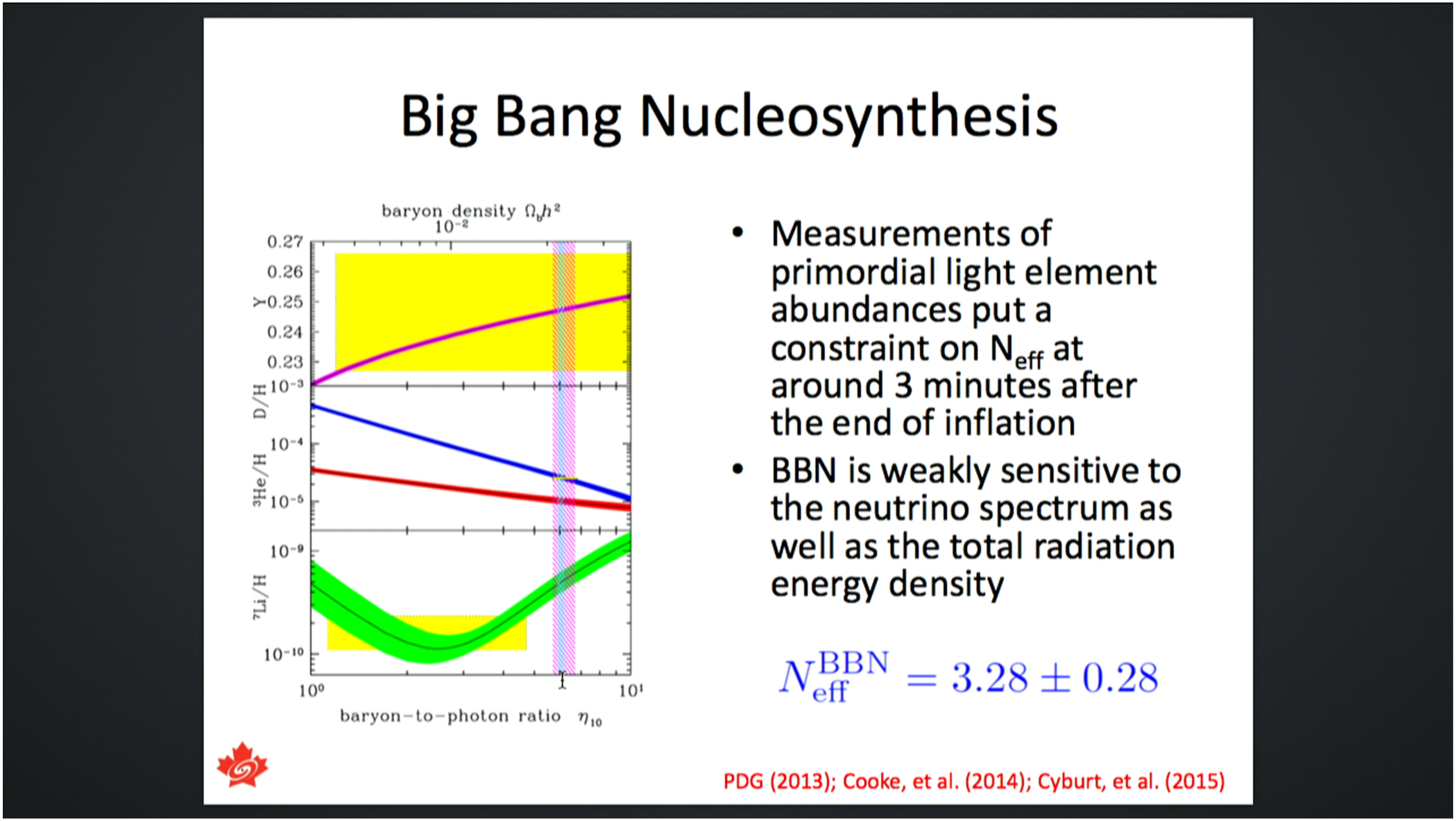
Primordial Abundances

CMB Measurements

$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28$$

$$N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18$$

Cooke, et al. (2014); Cyburt, et al. (2015), Planck 2015



Big Bang Nucleosynthesis

- Measurements of primordial light element abundances put a constraint on N_{eff} at around 3 minutes after the end of inflation
- BBN is weakly sensitive to the neutrino spectrum as well as the total radiation energy density

$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28$$

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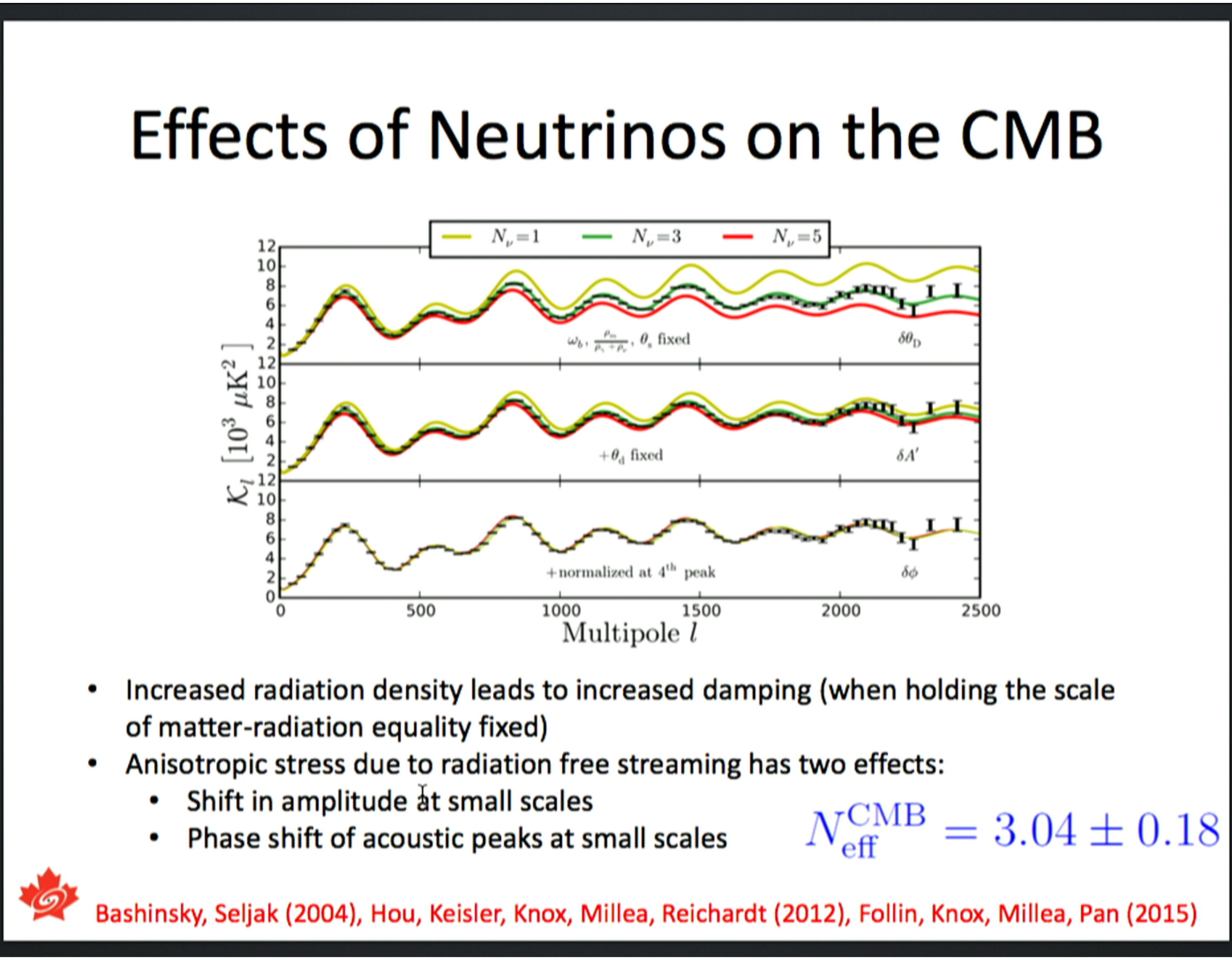
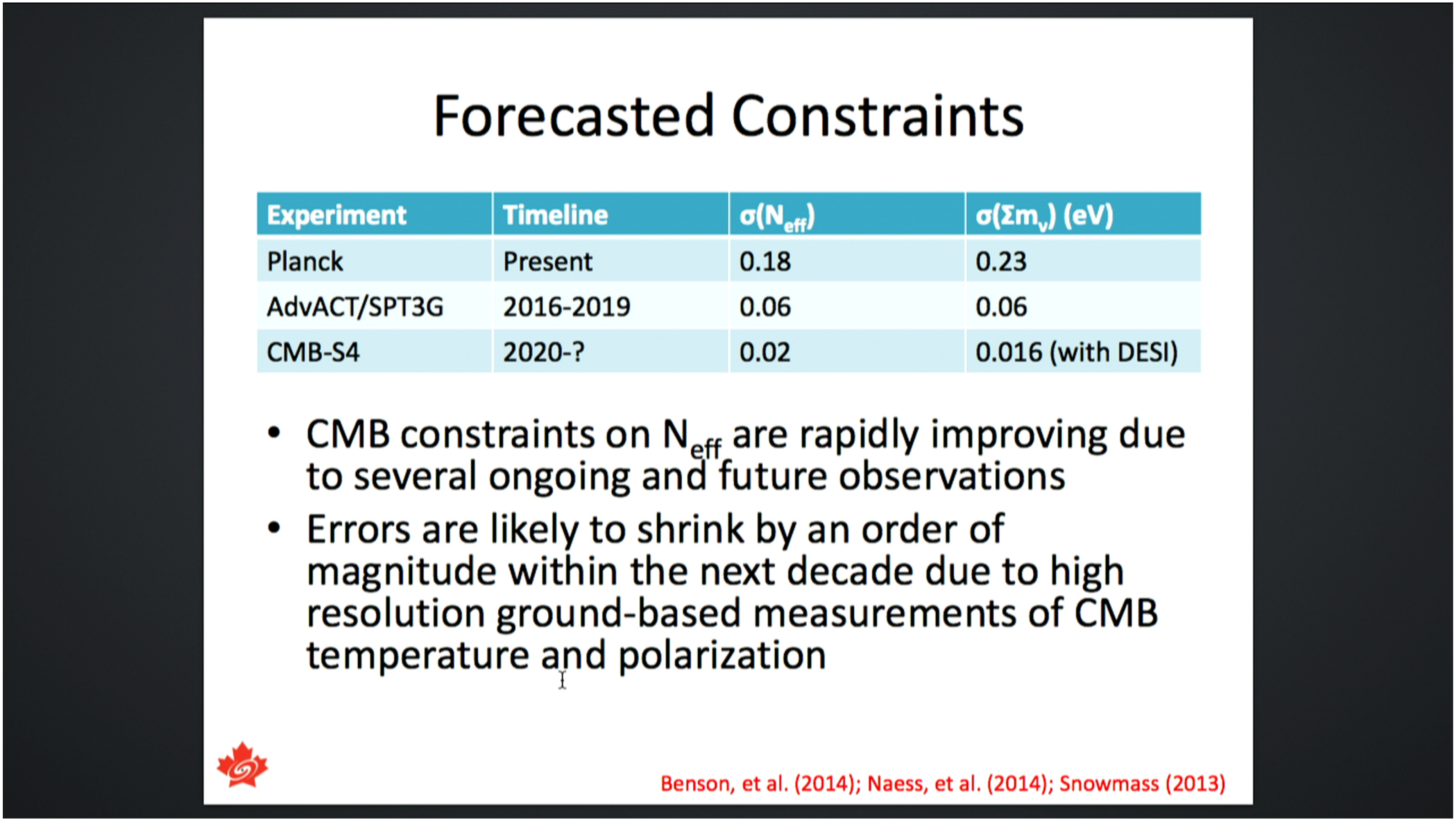


Effects of Neutrinos on the CMB

- Increased radiation density leads to increased damping (when holding the scale of matter-radiation equality fixed)
- Anisotropic stress due to radiation free streaming has two effects:
  - Shift in amplitude at small scales
  - Phase shift of acoustic peaks at small scales

$$N_{\mathrm{eff}}^{\mathrm{CMB}} = 3.04 \pm 0.18$$

Bashinsky, Seljak (2004), Hou, Keisler, Knox, Millea, Reichardt (2012), Follin, Knox, Millea, Pan (2015)

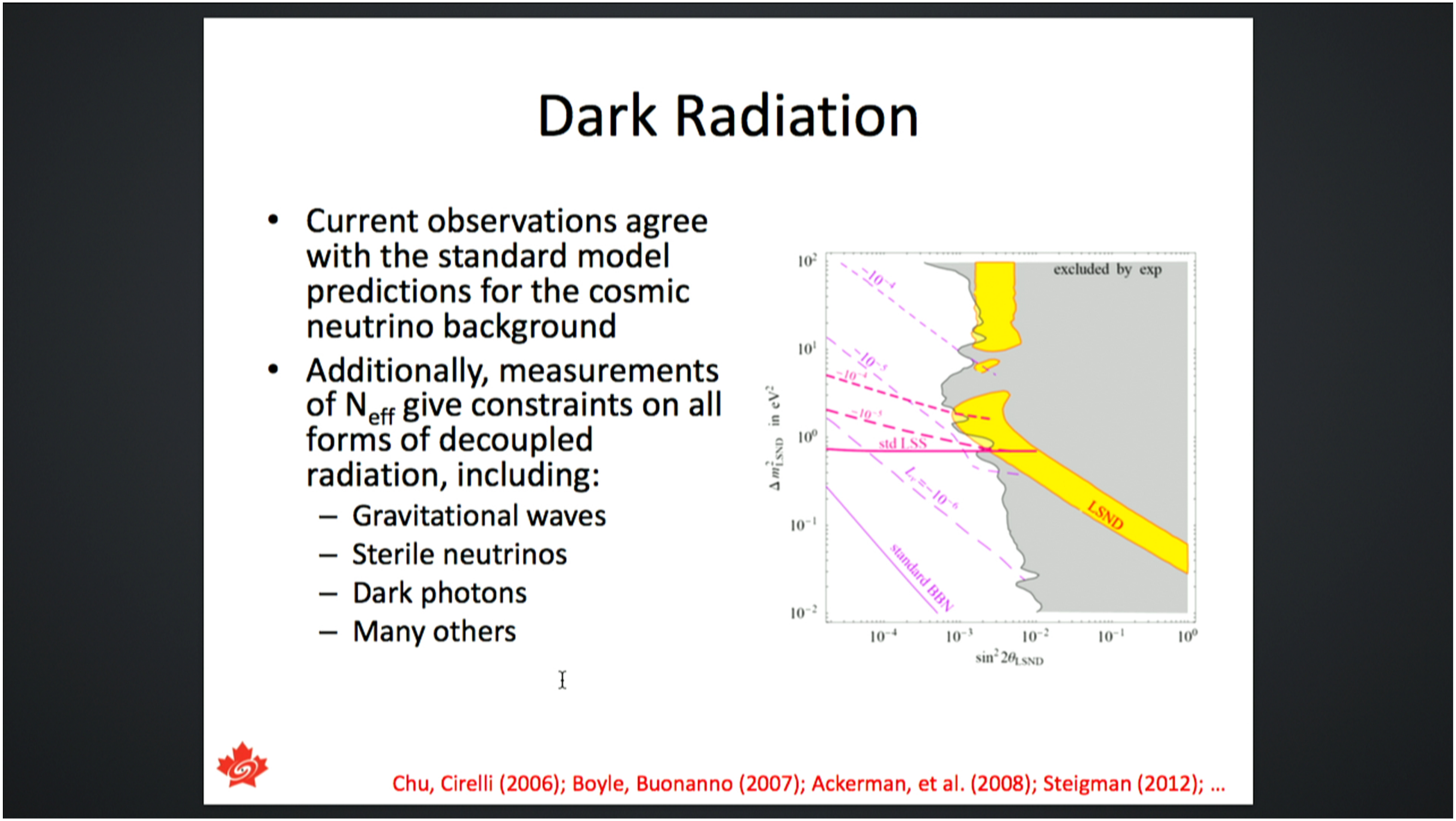


Forecasted Constraints

Experiment	Timeline	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$ (eV)
Planck	Present	0.18	0.23
AdvACT/SPT3G	2016-2019	0.06	0.06
CMB-S4	2020-?	0.02	0.016 (with DESI)

- CMB constraints on N_{eff} are rapidly improving due to several ongoing and future observations
- Errors are likely to shrink by an order of magnitude within the next decade due to high resolution ground-based measurements of CMB temperature and polarization

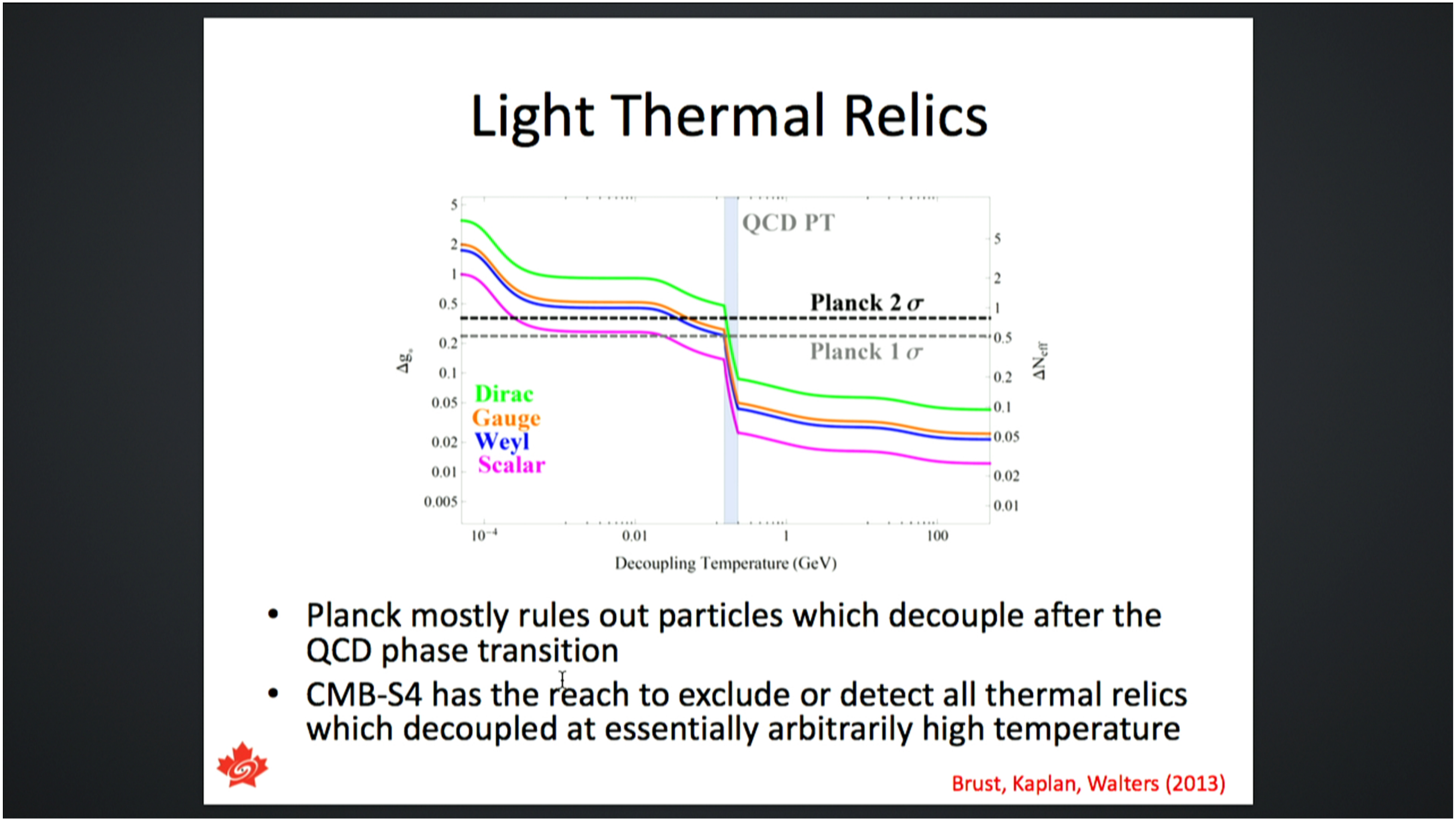
Benson, et al. (2014); Naess, et al. (2014); Snowmass (2013)



Dark Radiation

- Current observations agree with the standard model predictions for the cosmic neutrino background
- Additionally, measurements of $N_{\rm eff}$ give constraints on all forms of decoupled radiation, including:
  - Gravitational waves
  - Sterile neutrinos
  - Dark photons
  - Many others

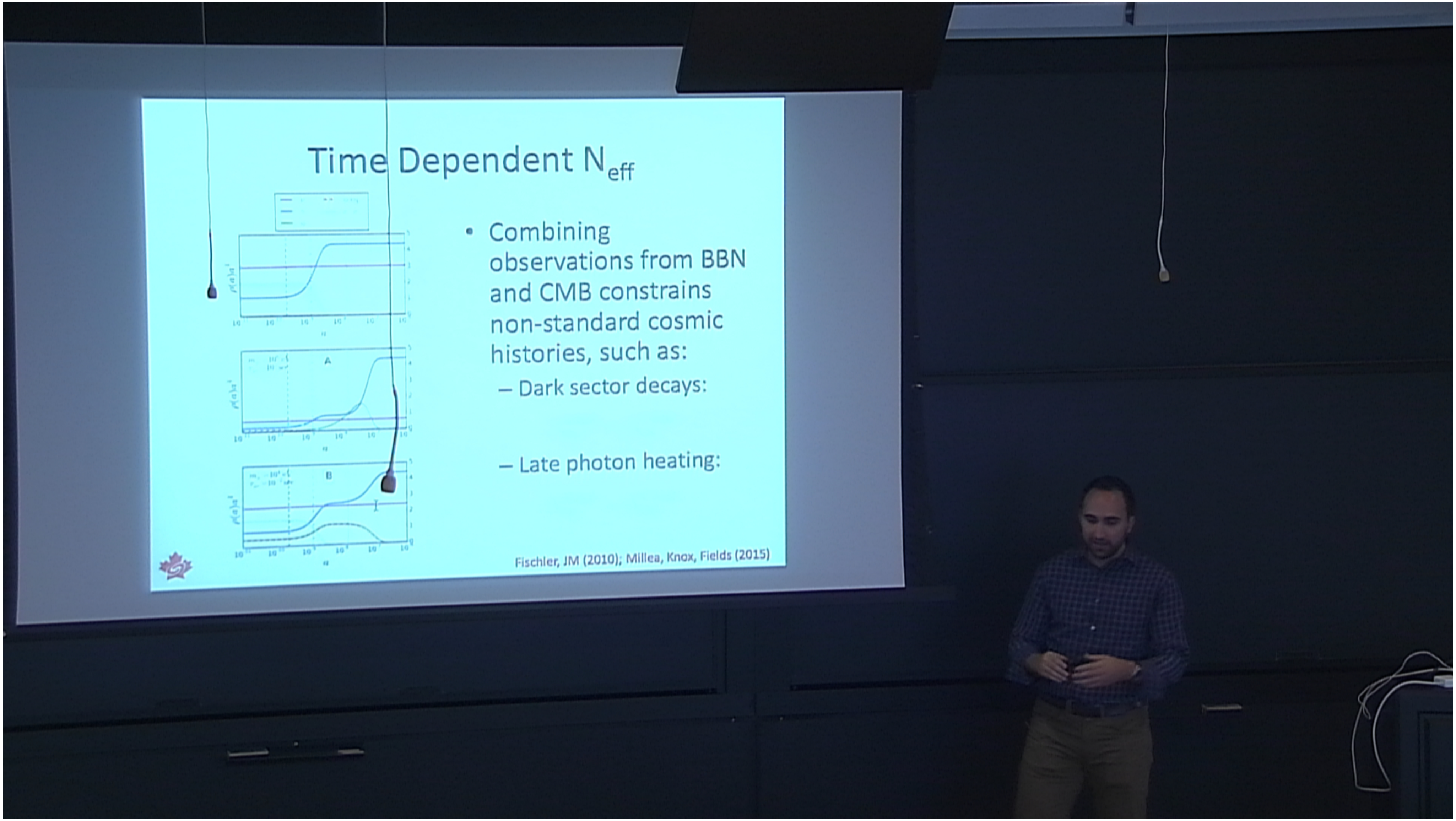
Chu, Cirelli (2006); Boyle, Buonanno (2007); Ackerman, et al. (2008); Steigman (2012); …



Light Thermal Relics

- Planck mostly rules out particles which decouple after the QCD phase transition
- CMB-S4 has the reach to exclude or detect all thermal relics which decoupled at essentially arbitrarily high temperature

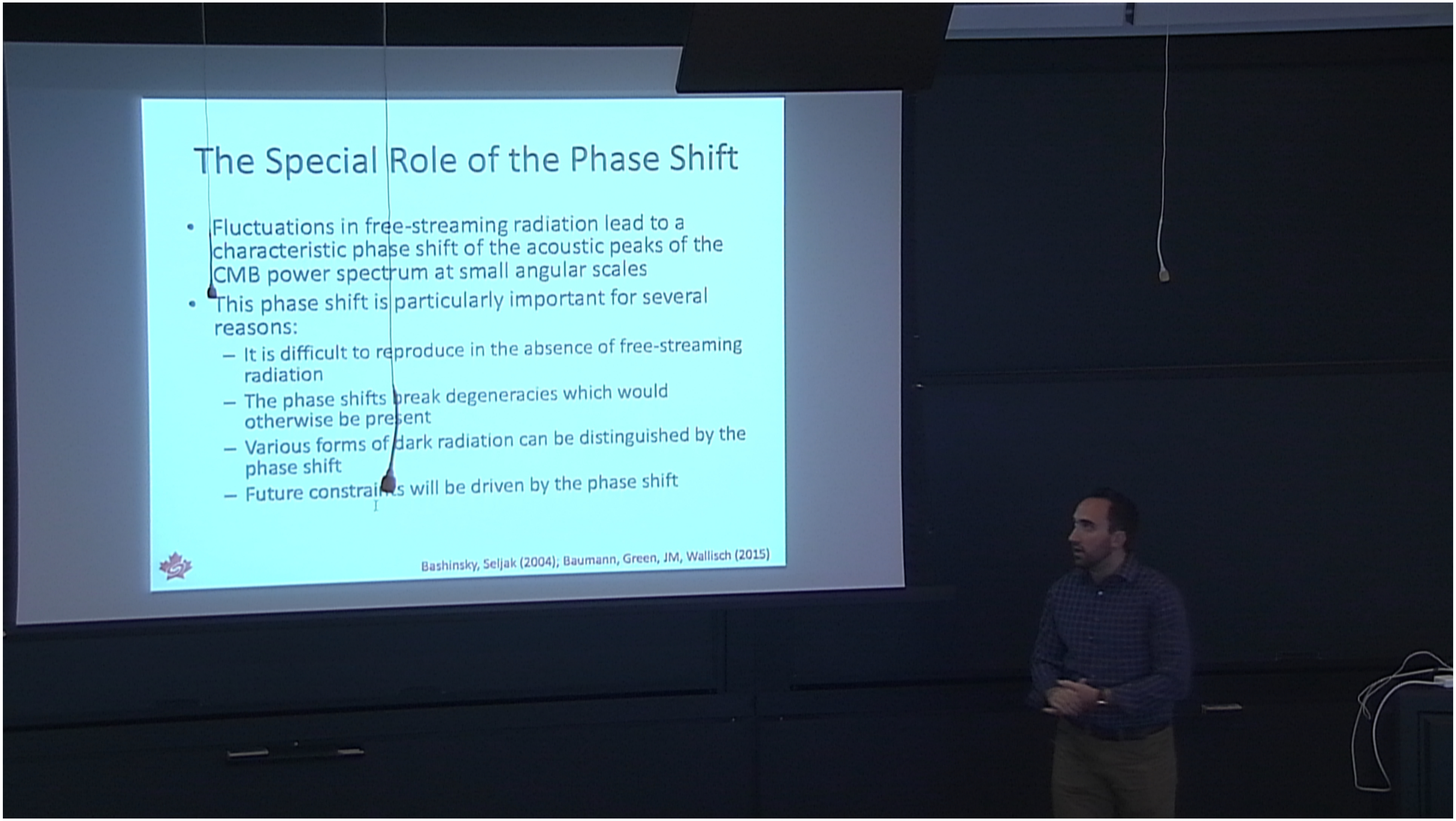
Brust, Kaplan, Walters (2013)



Time Dependent N_{eff}

- Combining observations from BBN and CMB constrains non-standard cosmic histories, such as:
  - Dark sector decays:
  - Late photon heating:

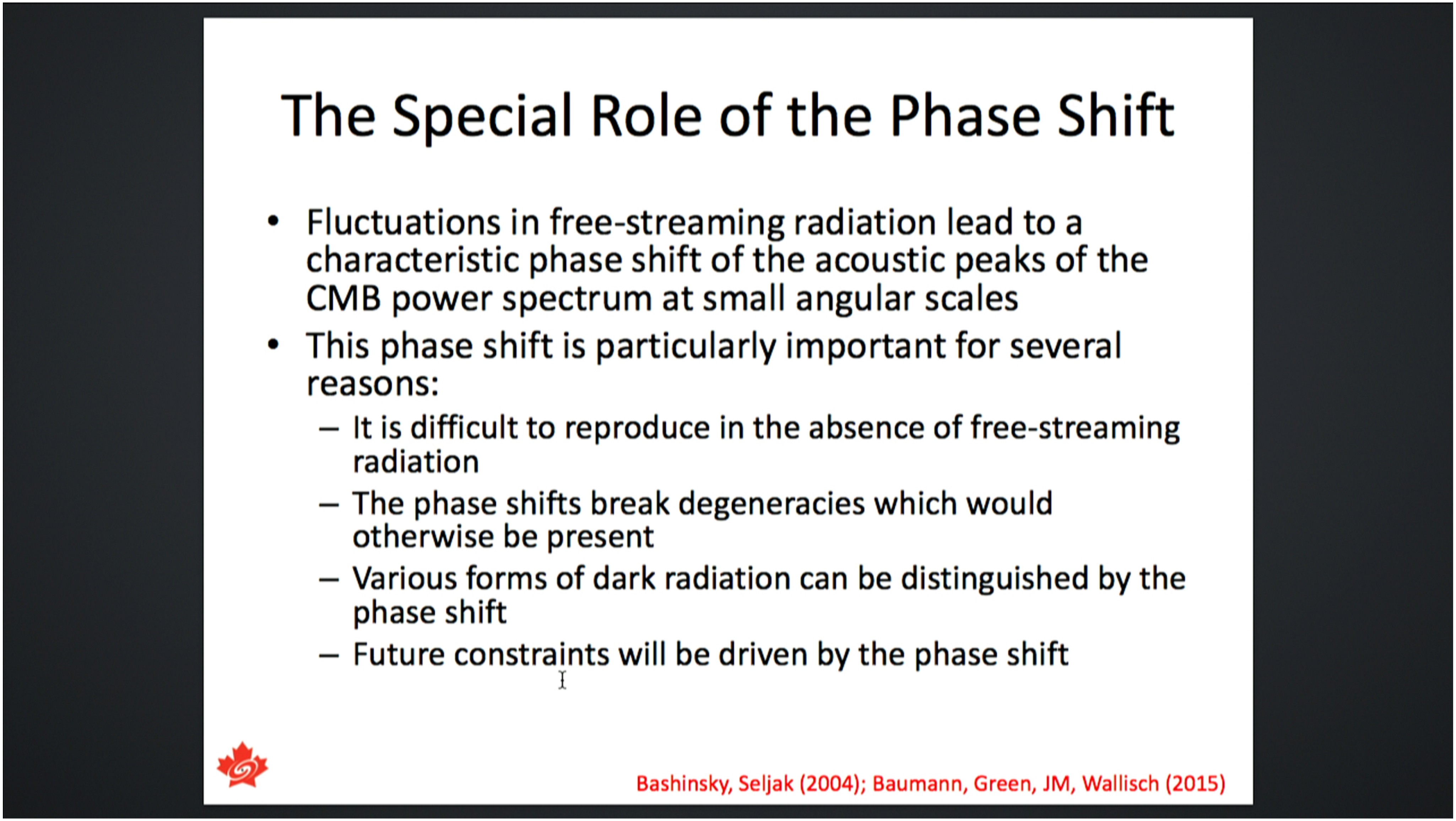
Fischler, JM (2010); Millea, Knox, Fields (2015)



The Special Role of the Phase Shift

- Fluctuations in free-streaming radiation lead to a characteristic phase shift of the acoustic peaks of the CMB power spectrum at small angular scales
- This phase shift is particularly important for several reasons:
  - It is difficult to reproduce in the absence of free-streaming radiation
  - The phase shifts break degeneracies which would otherwise be present
  - Various forms of dark radiation can be distinguished by the phase shift
  - Future constraints will be driven by the phase shift

Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2015)



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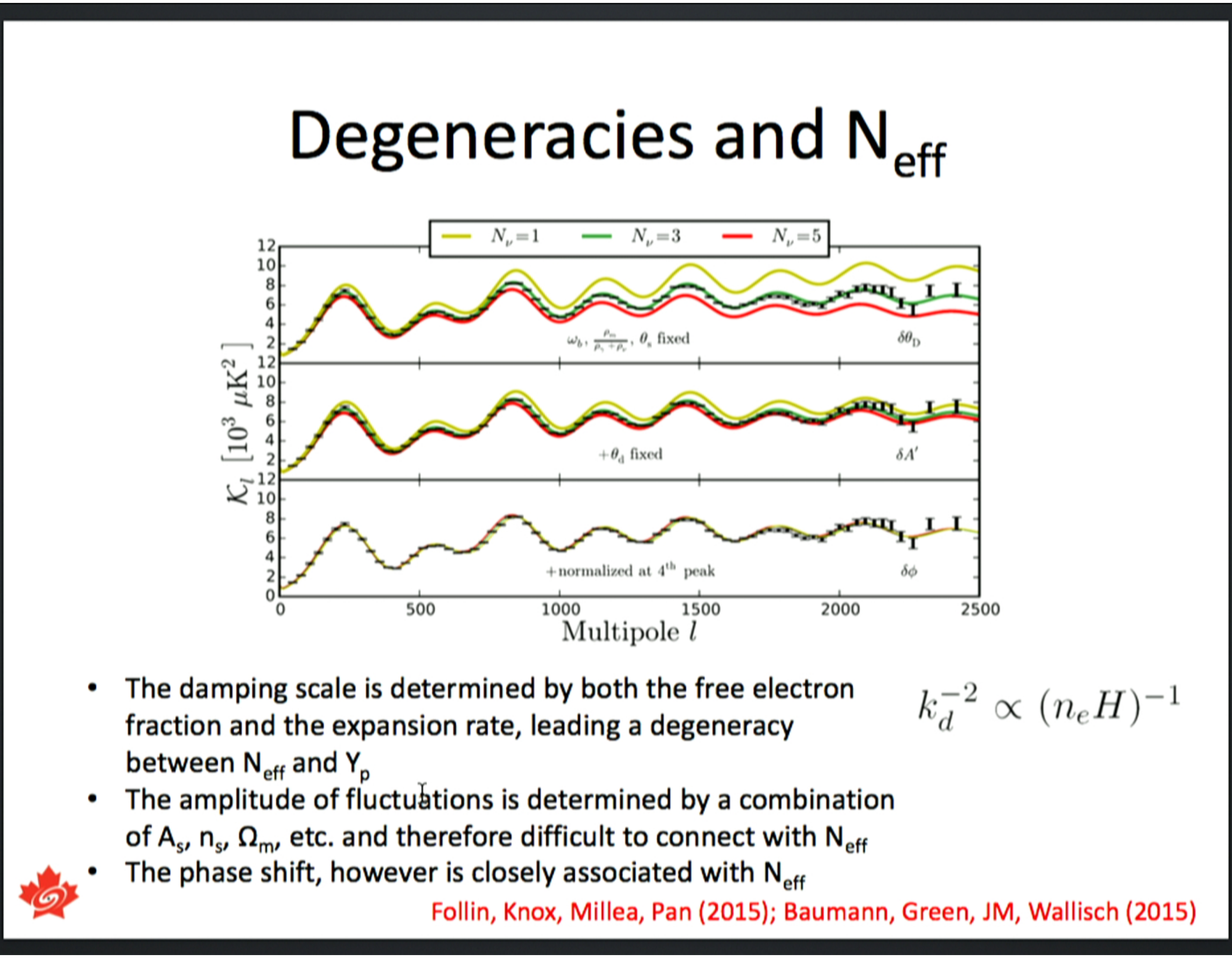


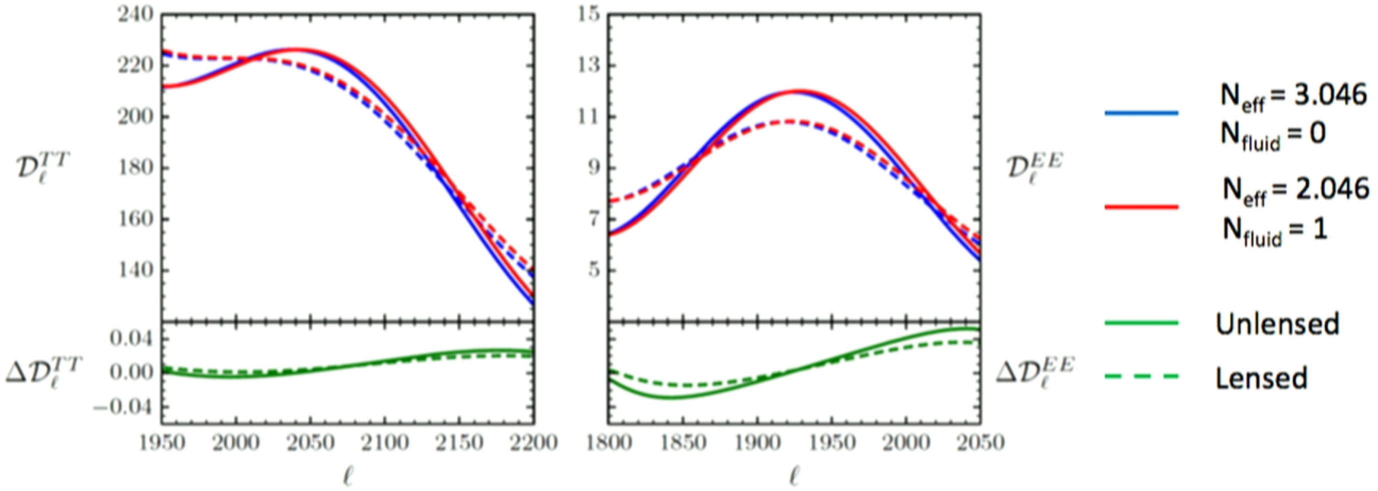
Degeneracies and N_{eff}

- The damping scale is determined by both the free electron fraction and the expansion rate, leading a degeneracy between N_{eff} and Y_p
- The amplitude of fluctuations is determined by a combination of A_s, n_s, Ω_m, etc. and therefore difficult to connect with N_{eff}
- The phase shift, however is closely associated with N_{eff}

$$k_d^{-2} \propto (n_e H)^{-1}$$

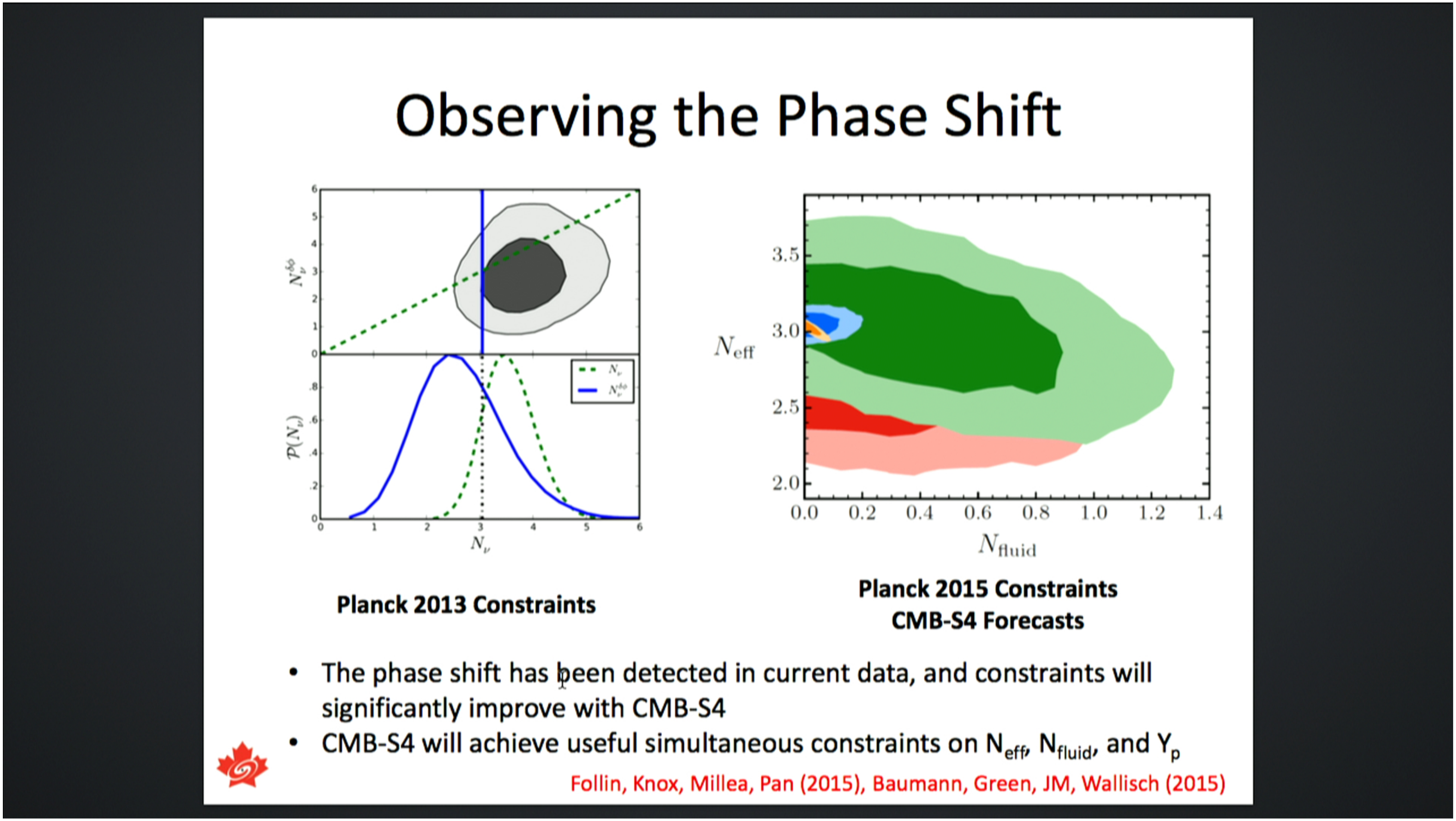
Follin, Knox, Millea, Pan (2015); Baumann, Green, JM, Wallisch (2015)

Free Streaming and the Phase Shift



- The phase shift can be used to distinguish between free streaming and non-free streaming radiation species
- The phase shift is most easily detectable in the delensed EE spectrum due to the sharper peaks

Baumann, Green, JM, Wallisch (2015)



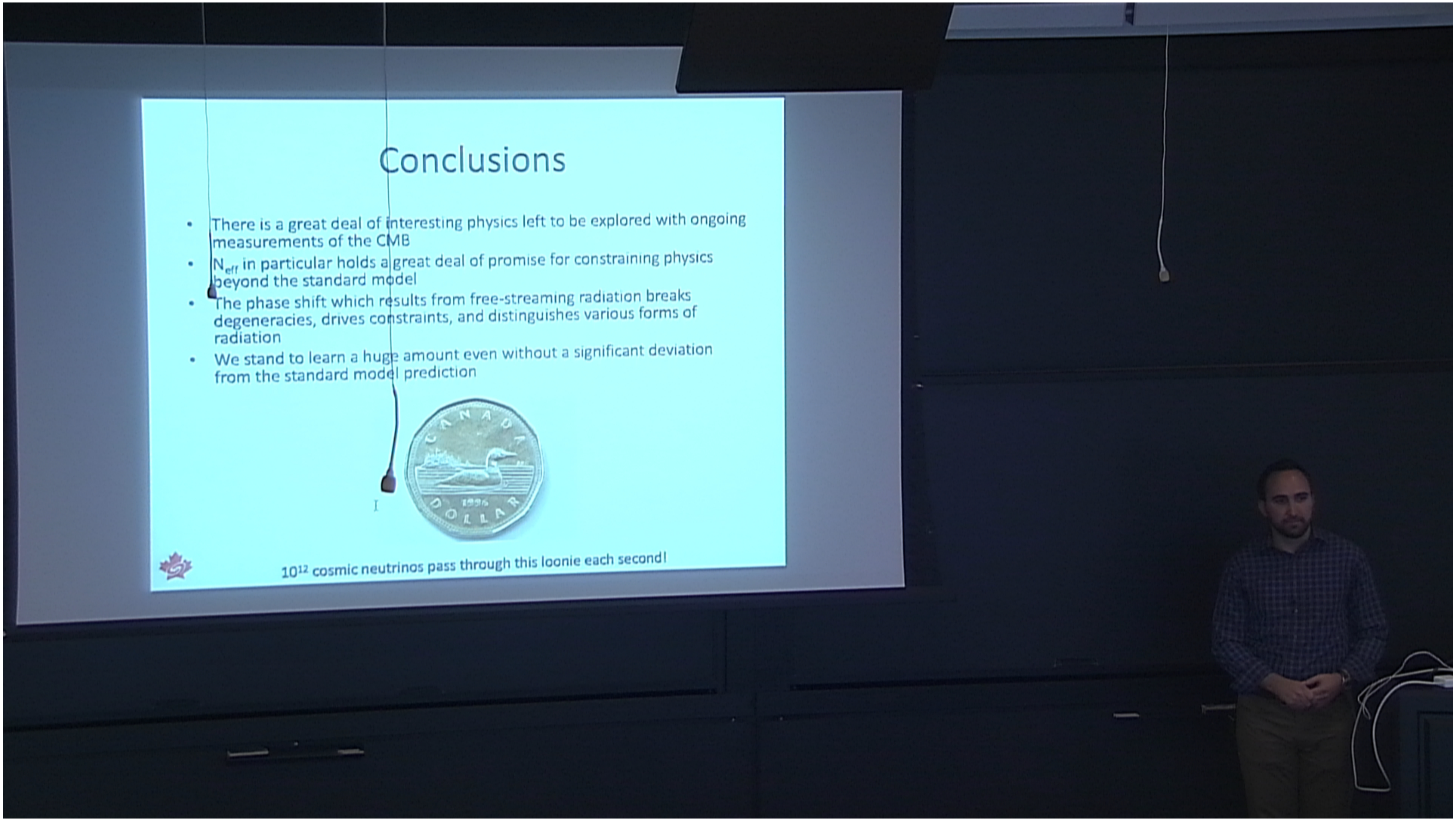
Observing the Phase Shift

Planck 2013 Constraints

Planck 2015 Constraints
CMB-S4 Forecasts

- The phase shift has been detected in current data, and constraints will significantly improve with CMB-S4
- CMB-S4 will achieve useful simultaneous constraints on $N_{\rm eff}$, $N_{\rm fluid}$, and Y_p

Follin, Knox, Millea, Pan (2015), Baumann, Green, JM, Wallisch (2015)



Conclusions

- There is a great deal of interesting physics left to be explored with ongoing measurements of the CMB
- N_{eff} in particular holds a great deal of promise for constraining physics beyond the standard model
- The phase shift which results from free-streaming radiation breaks degeneracies, drives constraints, and distinguishes various forms of radiation
- We stand to learn a huge amount even without a significant deviation from the standard model prediction

10^{12} cosmic neutrinos pass through this loonie each second!