Cosmological Probes of Standard Neutrino Scenarios

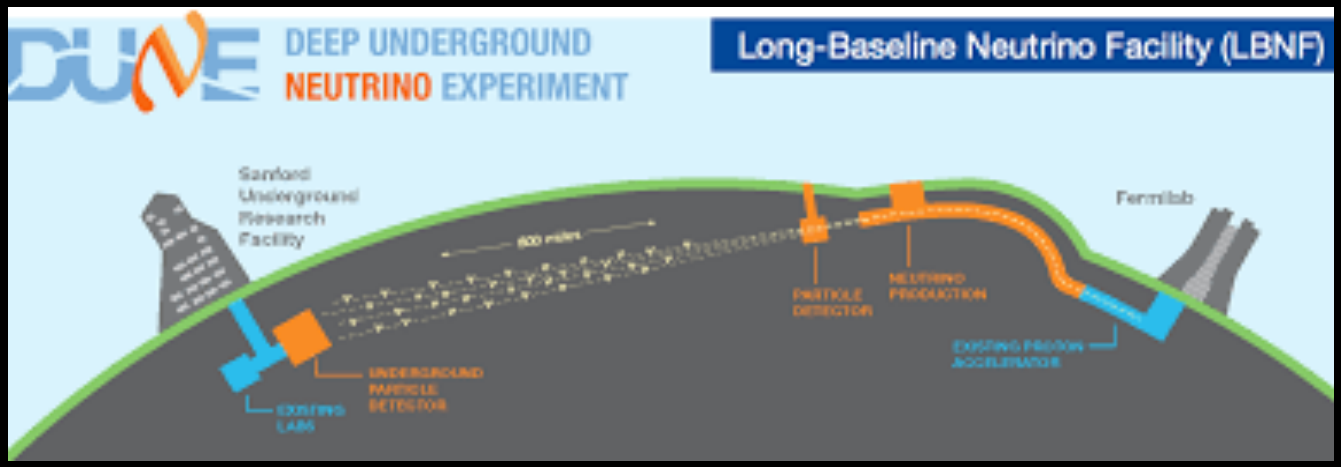
Lloyd Knox
UC Davis

My main goal with this talk

Convince neutrino physicists that cosmology is an **interesting** way to study neutrinos that is **complementary** to laboratory experiments

Perhaps my main obstacle

You are comfortable with this:



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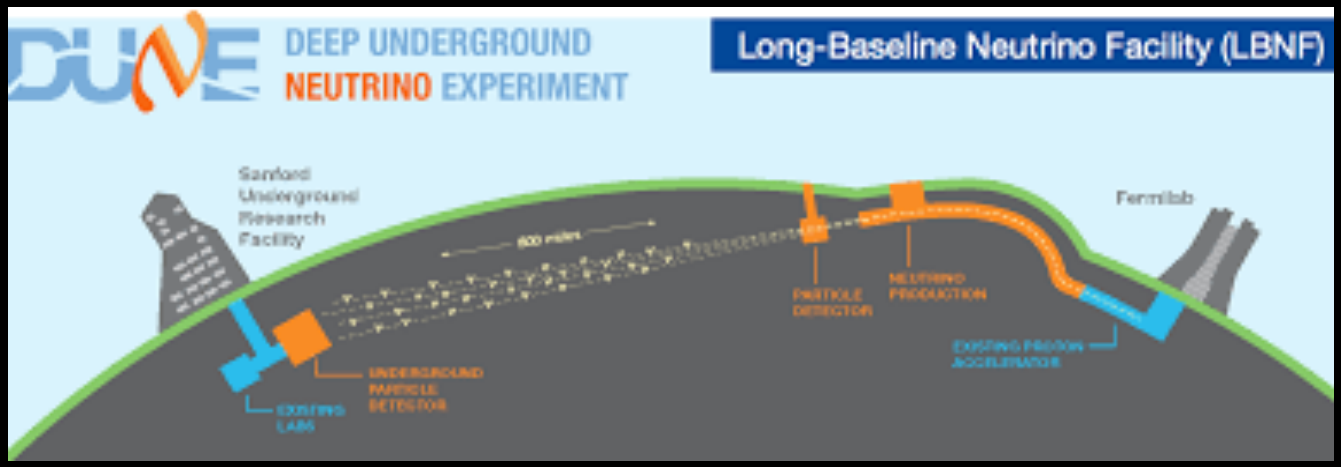

but maybe not this:

"I look up into the sky…
…and I conclude things."

(astronomer explaining their work, as imagined by a neutrino physicist)

Model Dependence

Model Dependence

Complementary to laboratory experiments

Expanded opportunity for discovering new physics

A broad experimental program in neutrino physics

Figure from the Snowmass Neutrino white paper

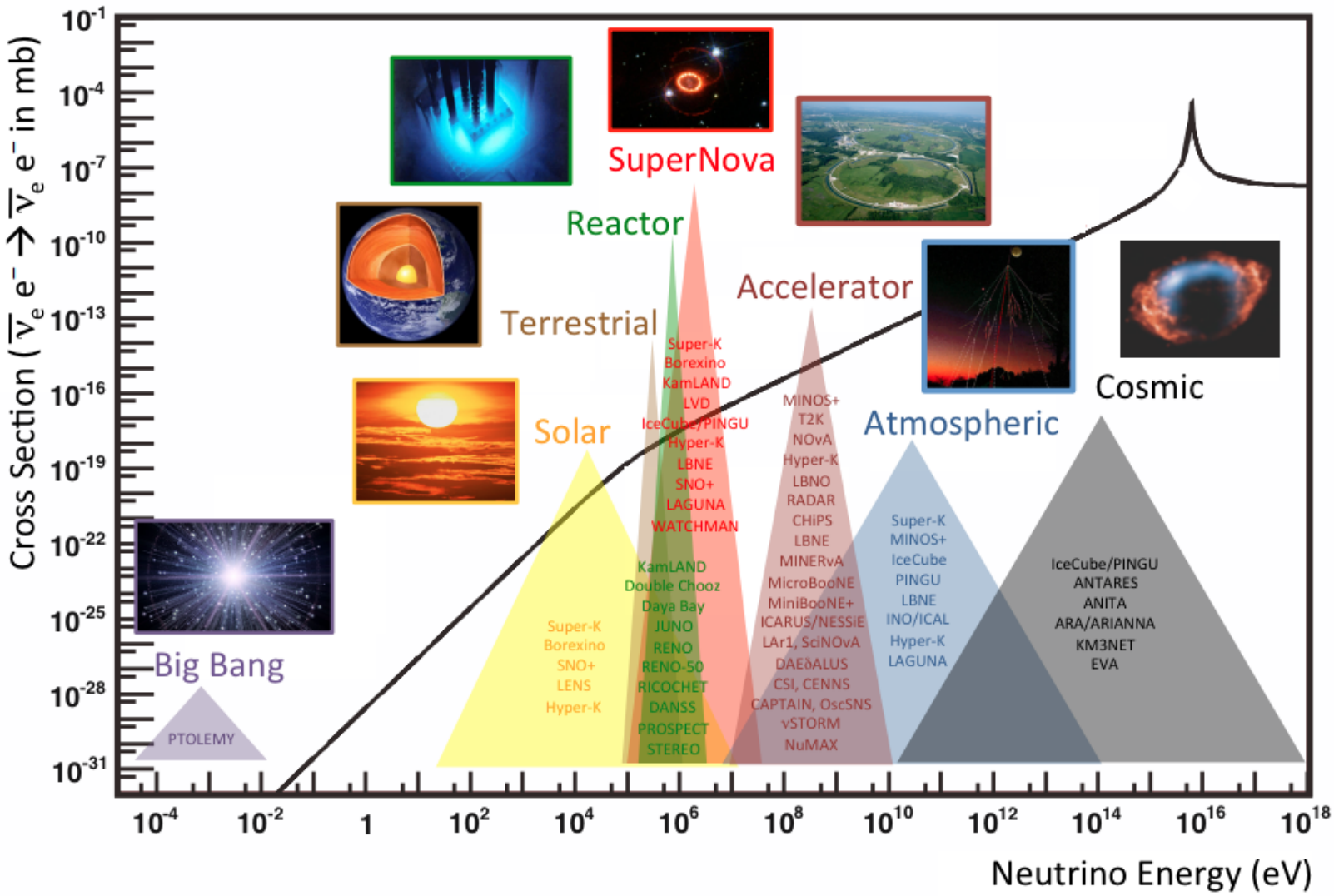

Figure 1: Neutrino interaction cross section as a function of energy, showing typical energy regimes accessible by different neutrino sources and experiments. The curve shows the scattering cross section for $\bar{\nu}_e\, e^- \rightarrow e^-\, \bar{\nu}_e$ on free electrons, for illustration. Plot modified from [1].

A broad experimental program in neutrino physics

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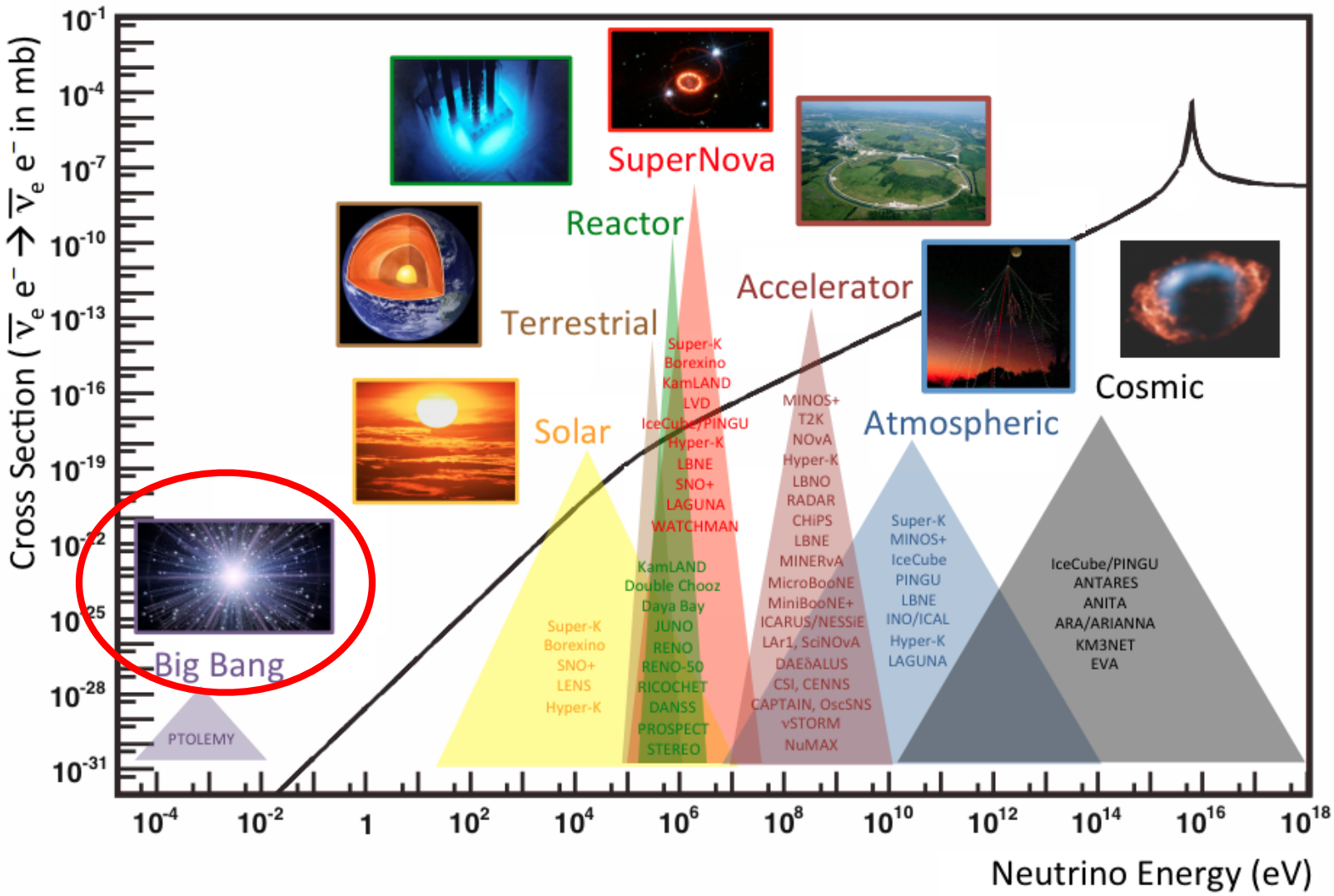

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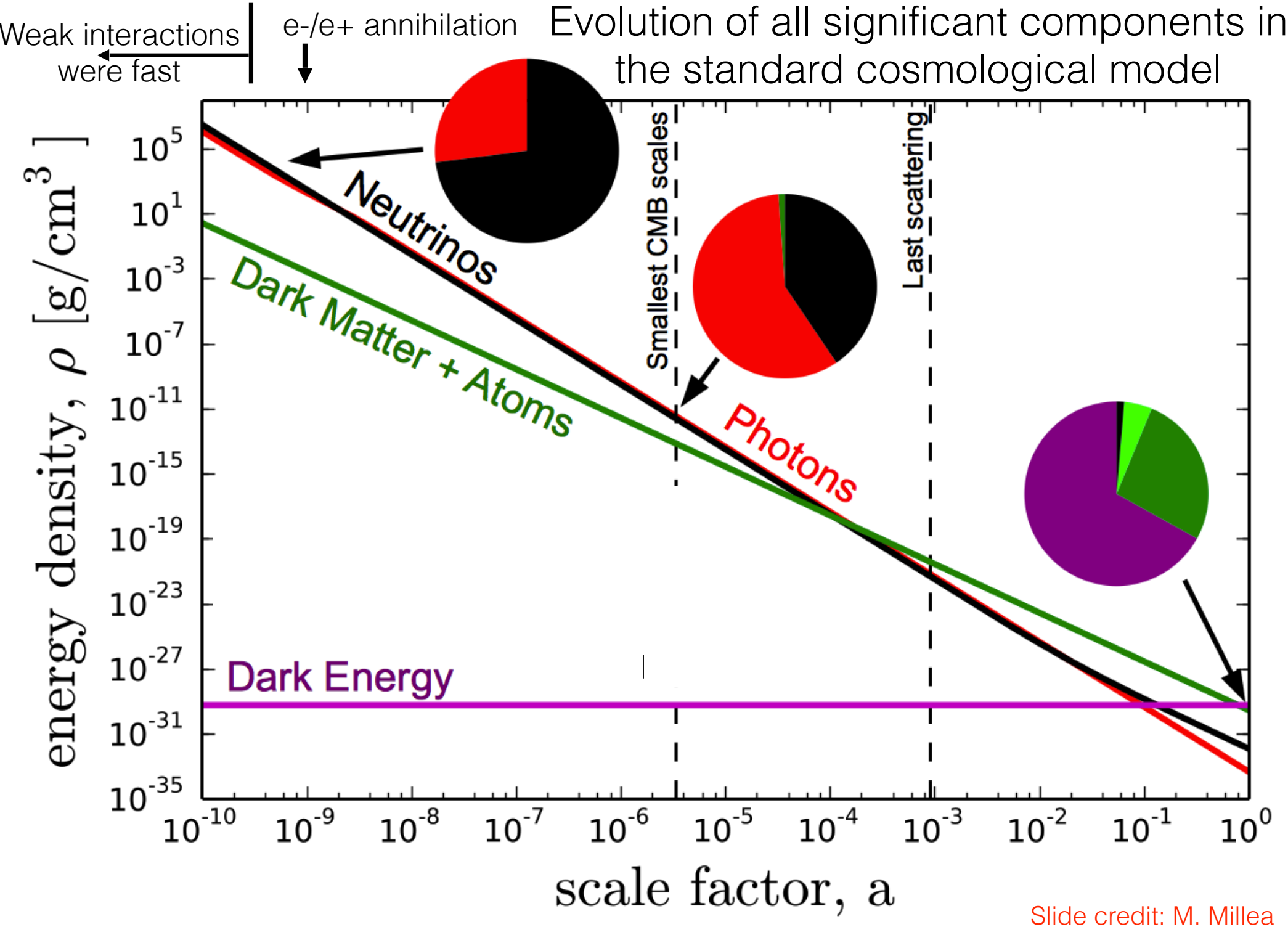
Evolution of all significant components in the standard cosmological model



Slide credit: M. Millea

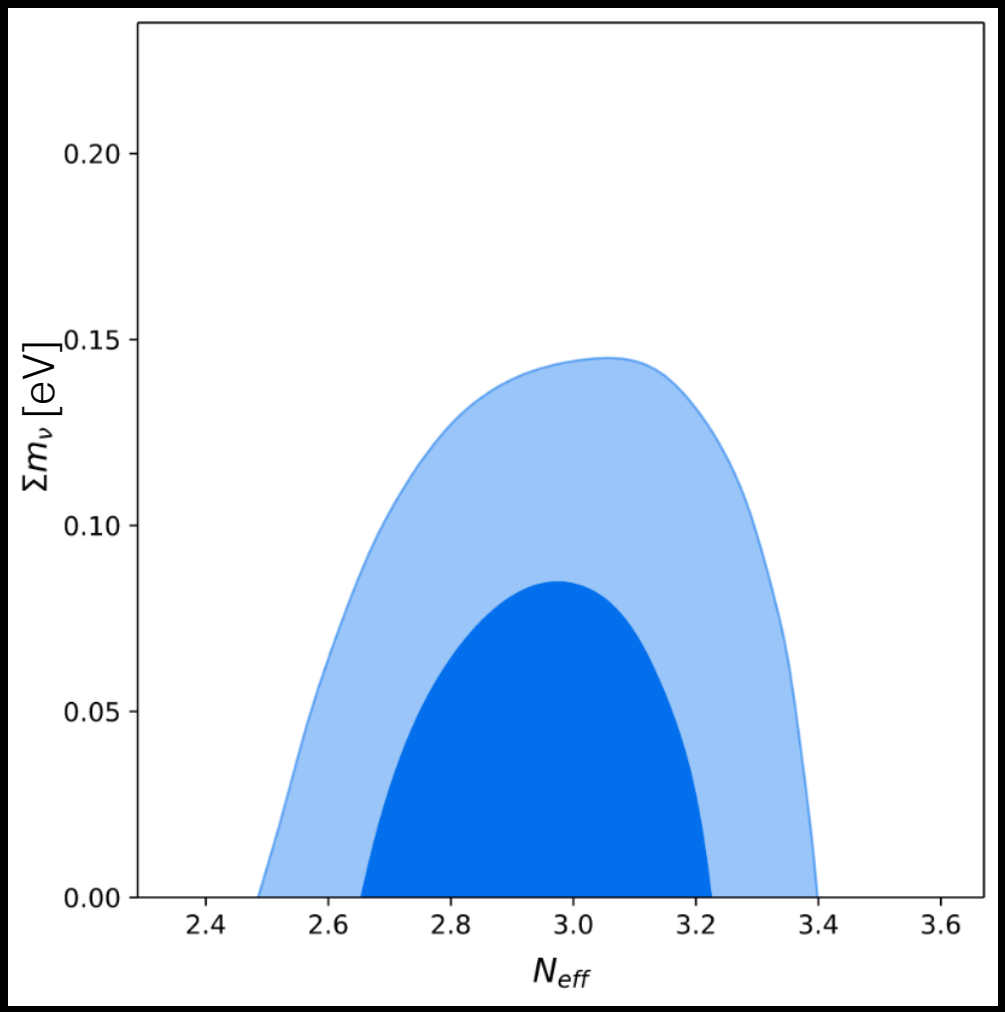
At least for the standard scenario, cosmology is sensitive to two neutrino parameters

$$\Sigma m_\nu$$

$$N_{\rm eff}$$

Current Status: CMB+BAO

sum of neutrino masses



cosmological abundance of neutrinos

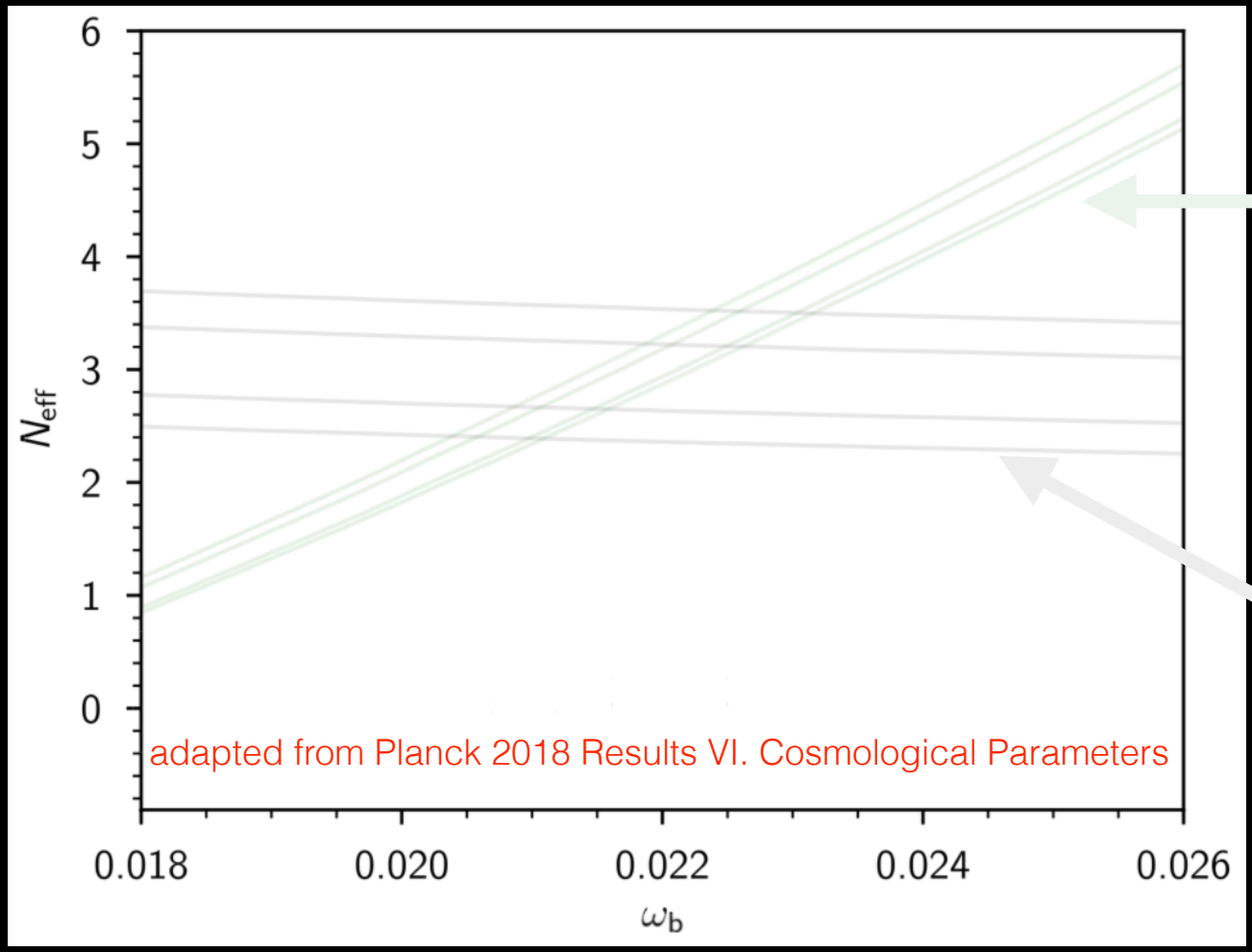
minimum mass for

← inverted hierarchy

← normal hierarchy

Planck 2018 CMB Temperature and Polarization Power Spectra
+ Planck 2018 CMB Lensing Power Spectrum
+ Baryon Acoustic Oscillation (BAO) compilation

Current Status: BBN



Deuterium abundance + BBN modeling

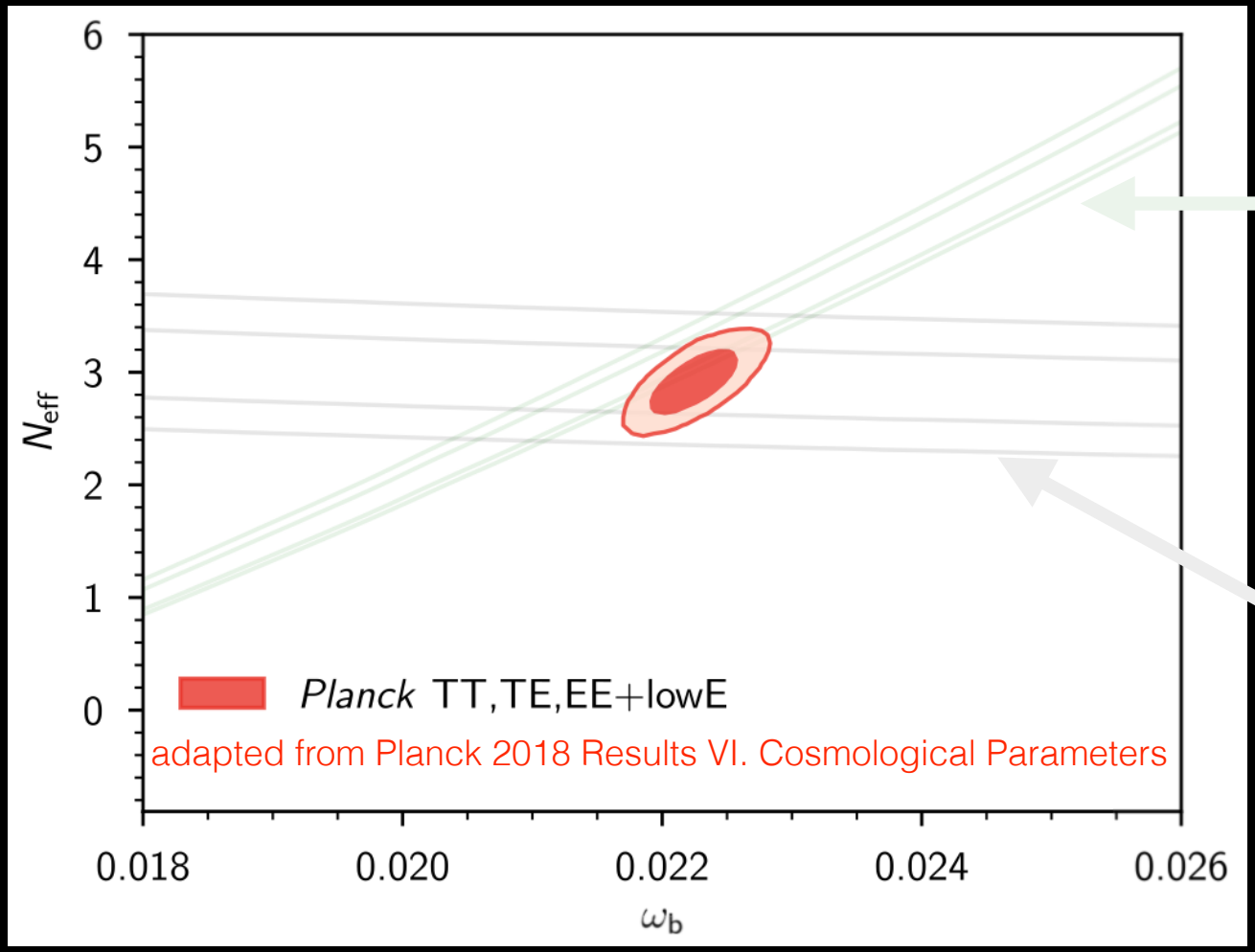
Helium abundance + BBN modeling

baryon density

D/H abundance: Cooke et al. (2018)
D/H BBN model: PArthENoPE + Marcucci et al. (2016)

Helium abundance: Aver et al. (2015)
Helium BBN model: PArthENoPE

Current Status: BBN



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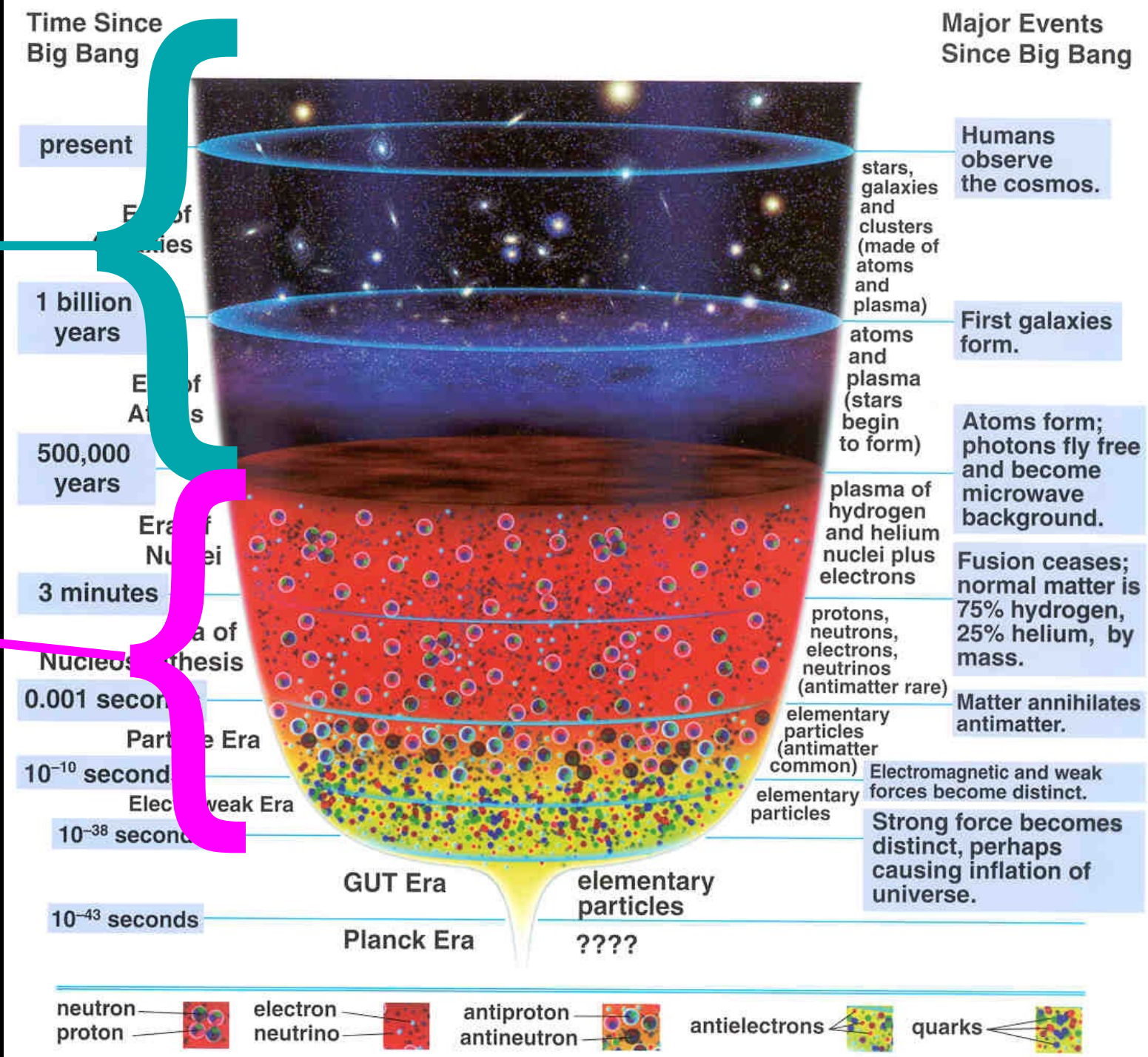
Helium BBN model: PArthENoPE

“I look up into the sky…
…and I conclude things.”

–Cosmologist

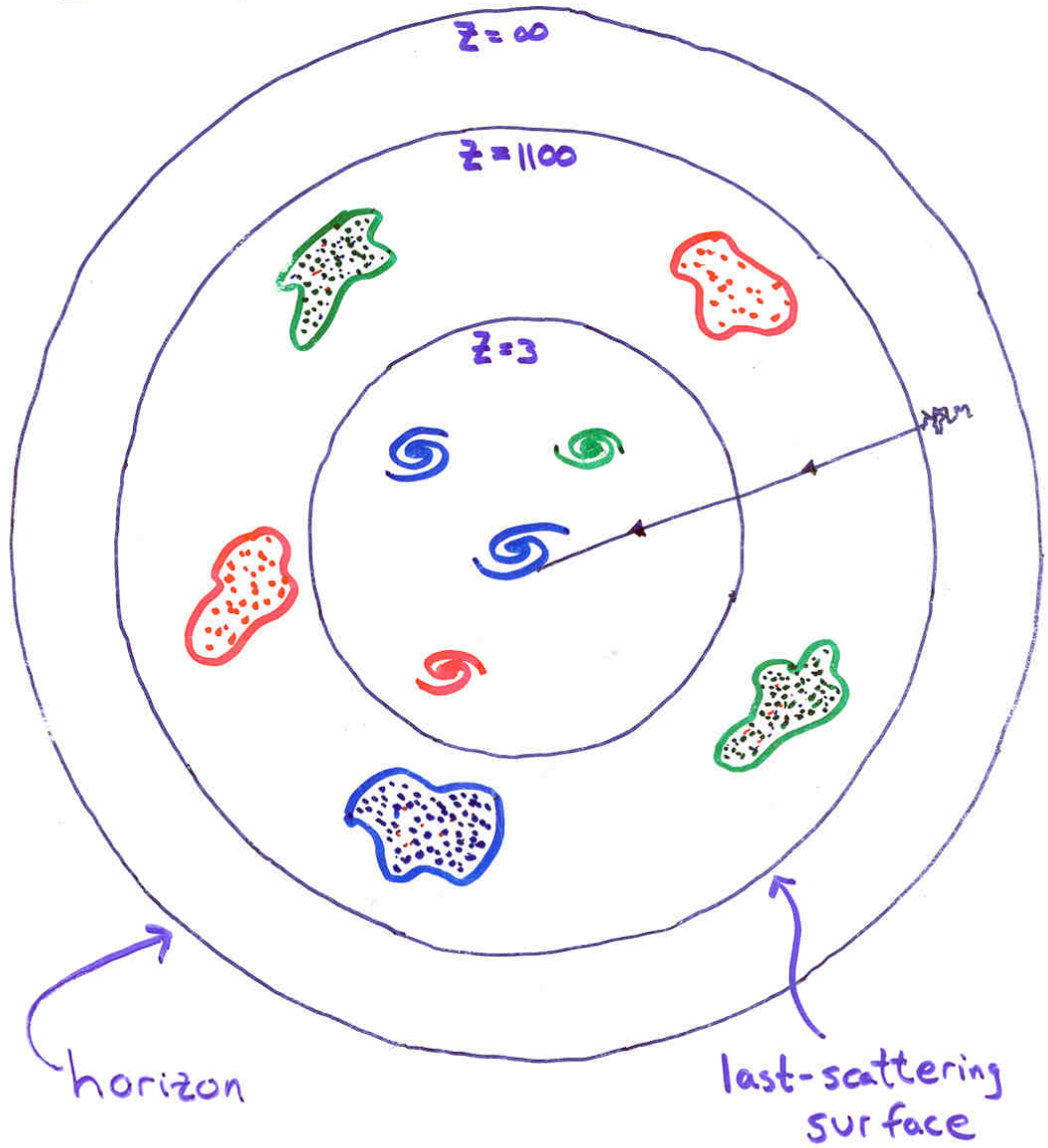
transparent

opaque



Credit: The Cosmic

THE HISTORY OF A SINGLE PHOTON



I look up at the sky…

Optical sky at night

Wavelength = 0.5×10^{-3} mm

I look up at the sky…

(Color here indicates brightness of light)

Optical sky at night

Wavelength = 0.5×10^{-3} mm

Microwave sky

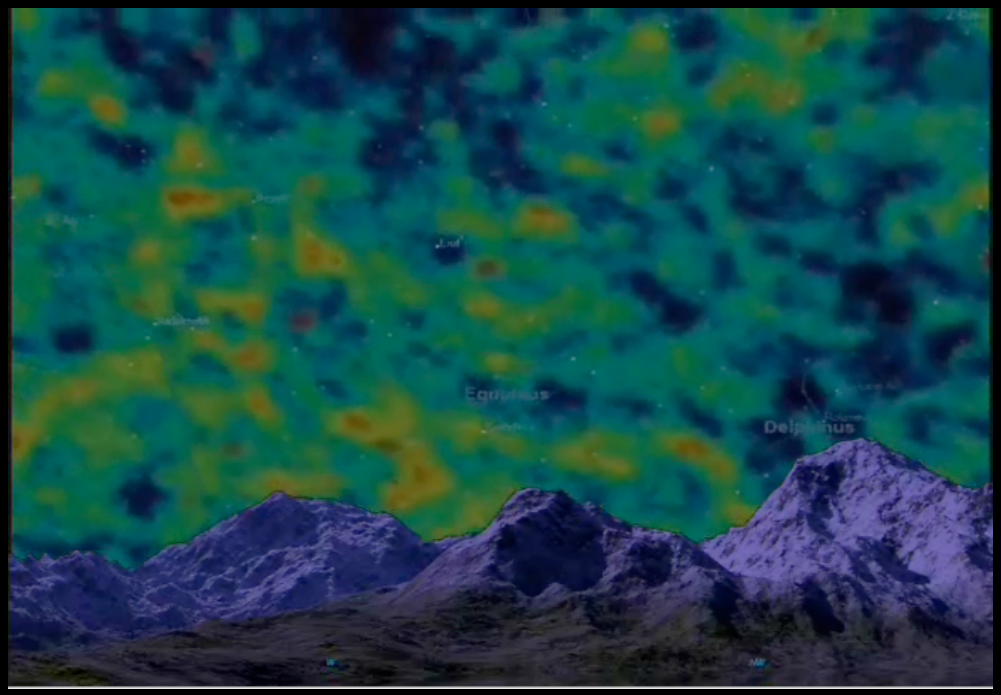
Wavelength = 2 mm

…and I map out the cosmic microwave background

Now with greatly increased contrast, so we can see very small brightness variations

Optical sky at night

Wavelength = 0.5×10^{-3} mm



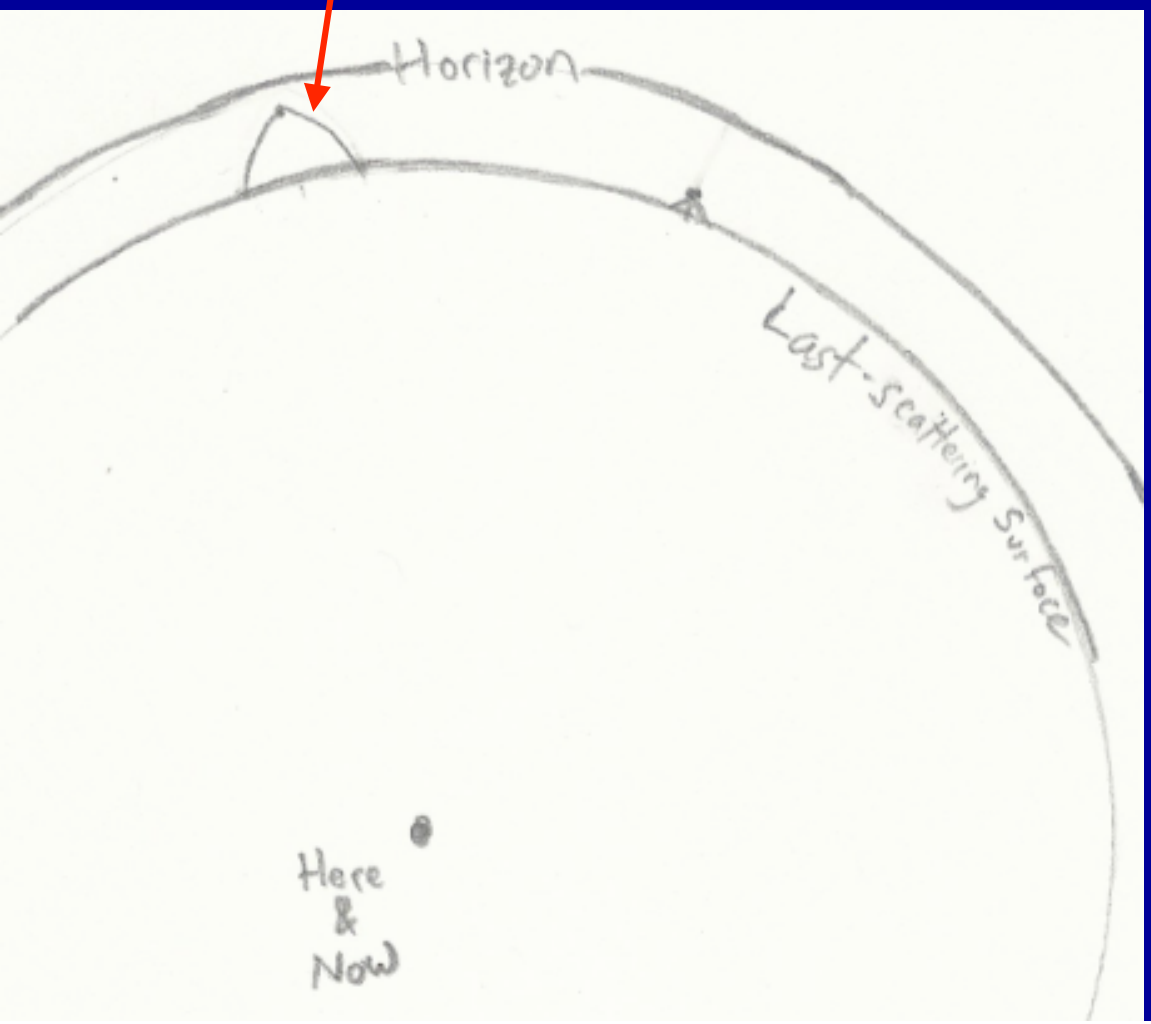
Microwave sky

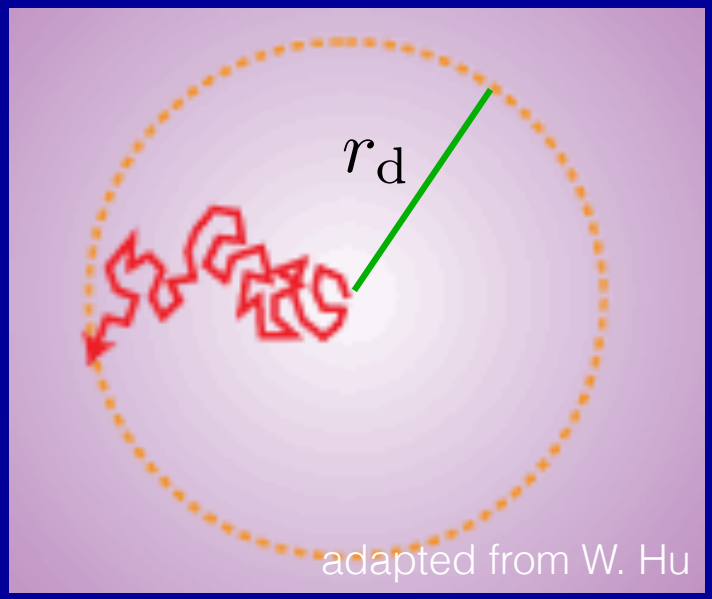
Wavelength = 2 mm

Two important length scales

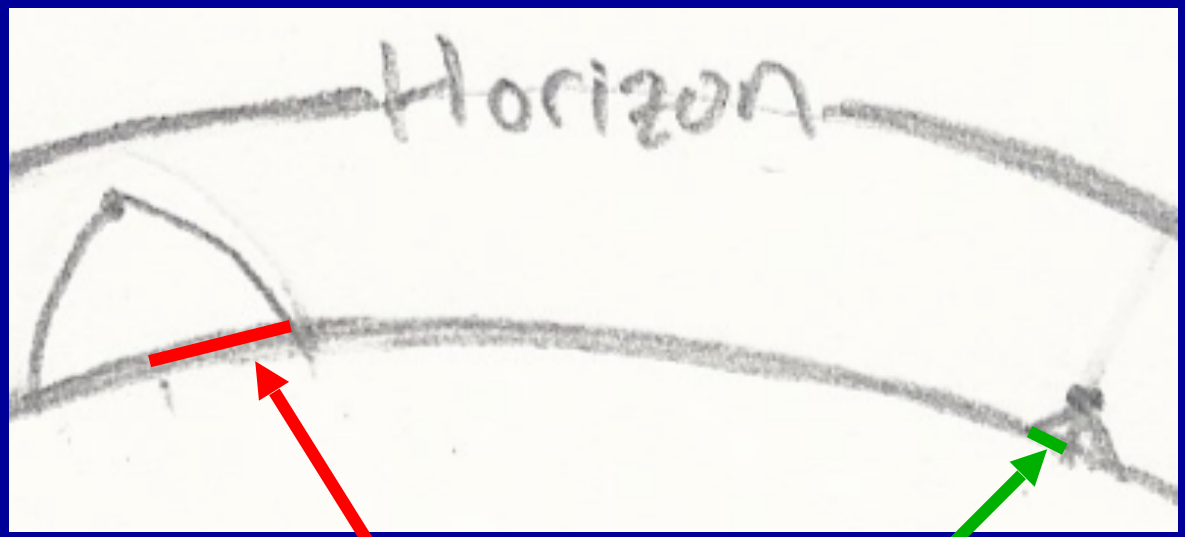
r_s: how far a sound wave travels before the plasma disappears

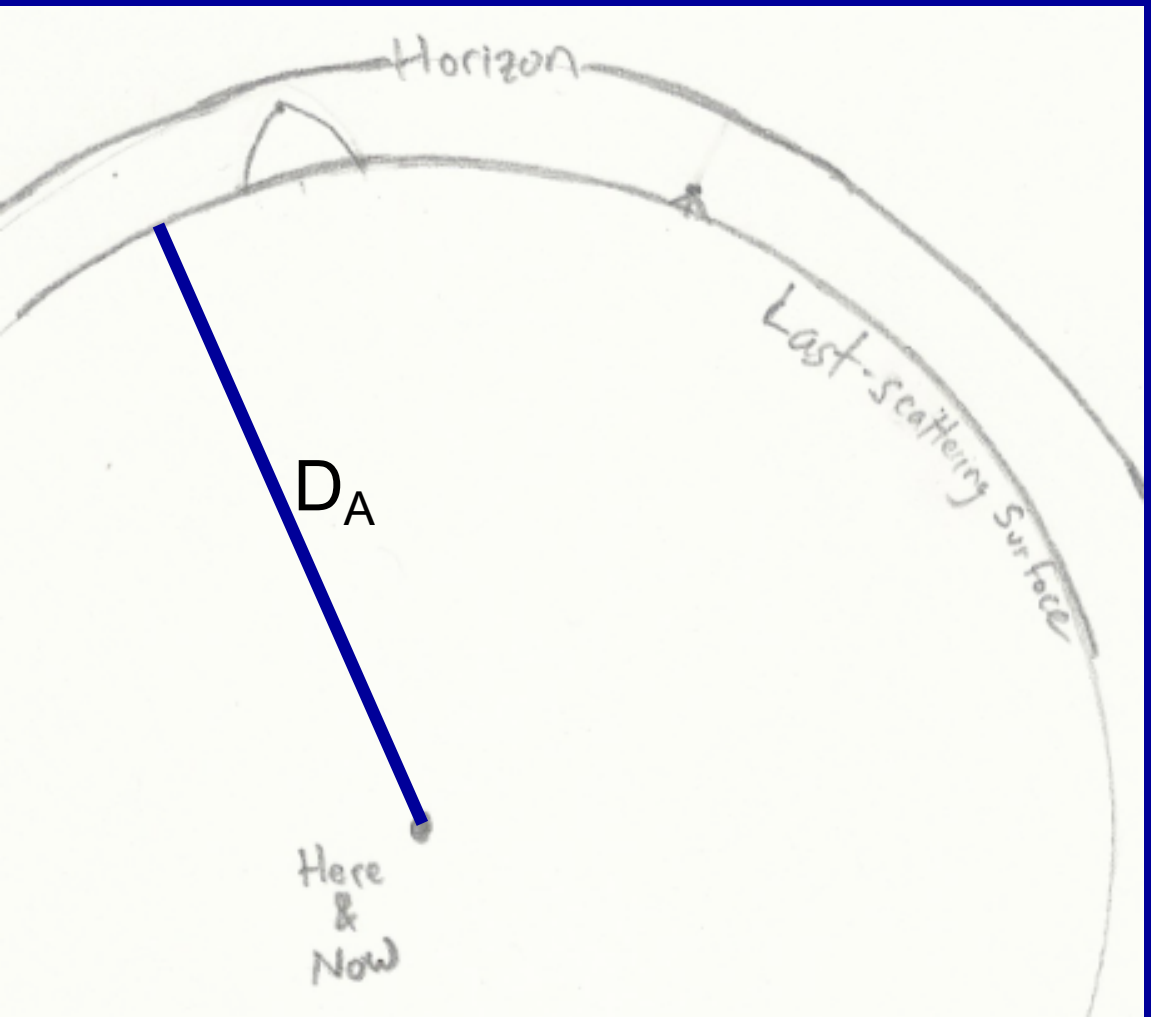
disturbance propagating
through plasma at sound speed





r_d: typical distance a photon diffuses before last scattering





r_s

r_d

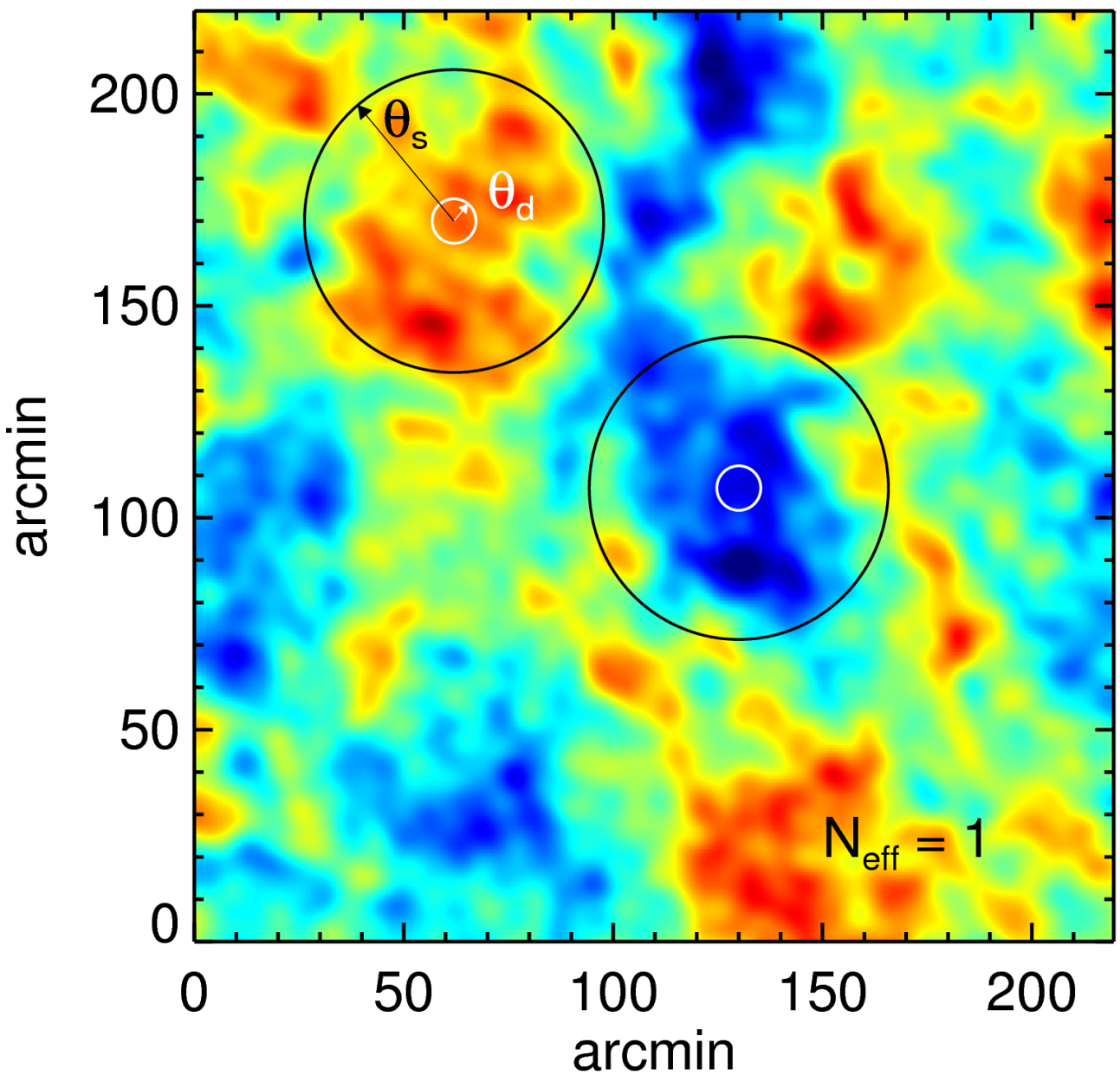
D_A

$\theta_s = r_s/D_A$

$\theta_d = r_d/D_A$

$\theta_{\rm s} = r_{\rm s}/D_A$ typical size of hot or cold spot

$\theta_{\rm d} = r_{\rm d}/D_A$ map is smoothed below this scale



Sensitivity to Neff via impact on H(a)

$$H^2 = 8\pi G\rho/3$$

The sound horizon r_s ~ 1/H

$$\theta_{\rm s} = r_{\rm s}/D_A$$

Sensitivity to Neff via impact on H(a)

$$H^2 = 8\pi G\rho/3$$

The sound horizon $r_s \sim 1/H$

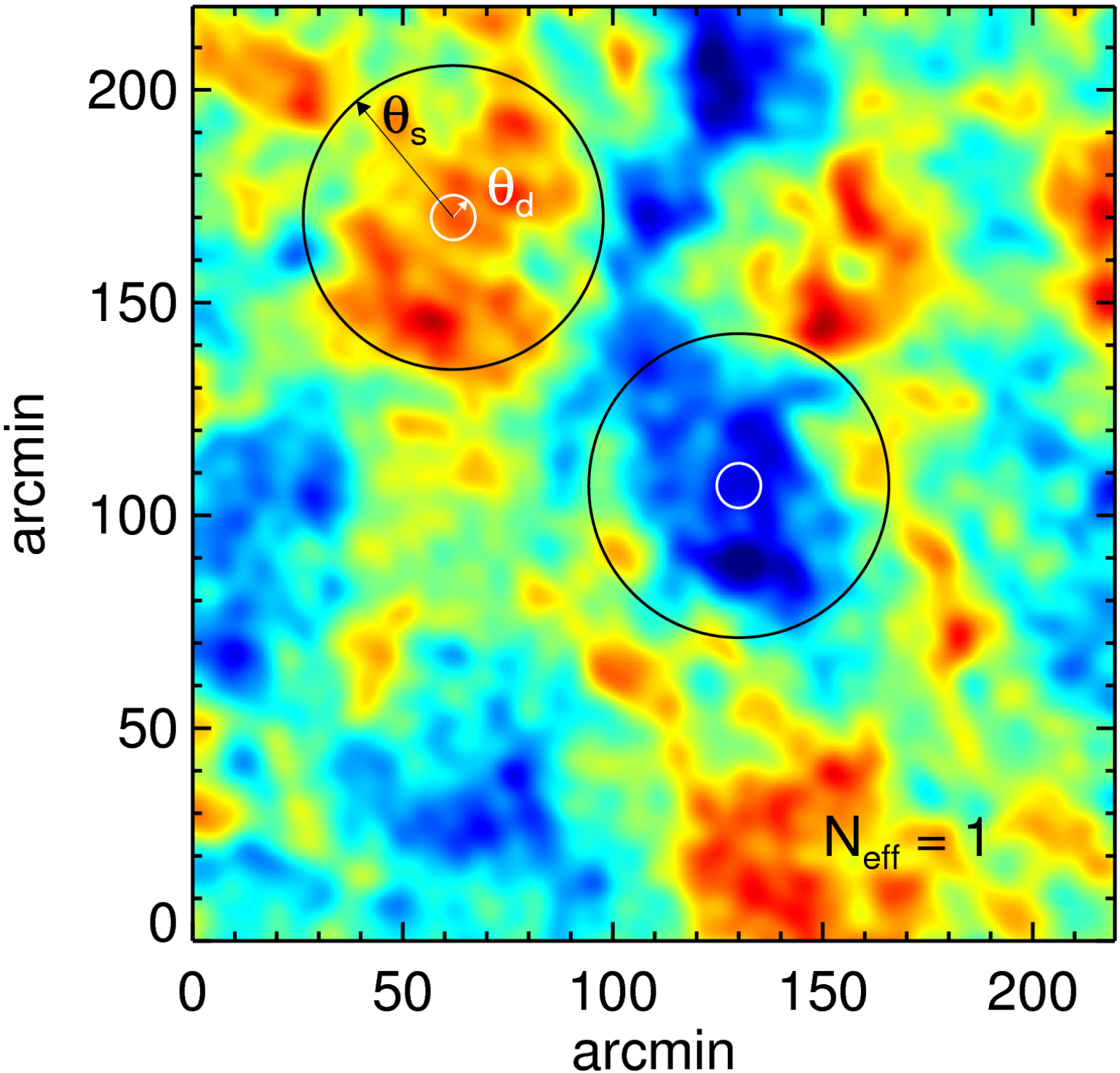
$$\theta_{\rm s} = r_{\rm s}/D_A$$

Photon diffusion is a random walk so $r_d \sim 1/H^{0.5}$

$$\theta_{\rm d} = r_{\rm d}/D_A$$

$$\theta_{\rm d}/\theta_{\rm s} = r_{\rm d}/r_{\rm s} \propto H^{1/2}$$

Neff affects the ratio of sound horizon to diffusion scale



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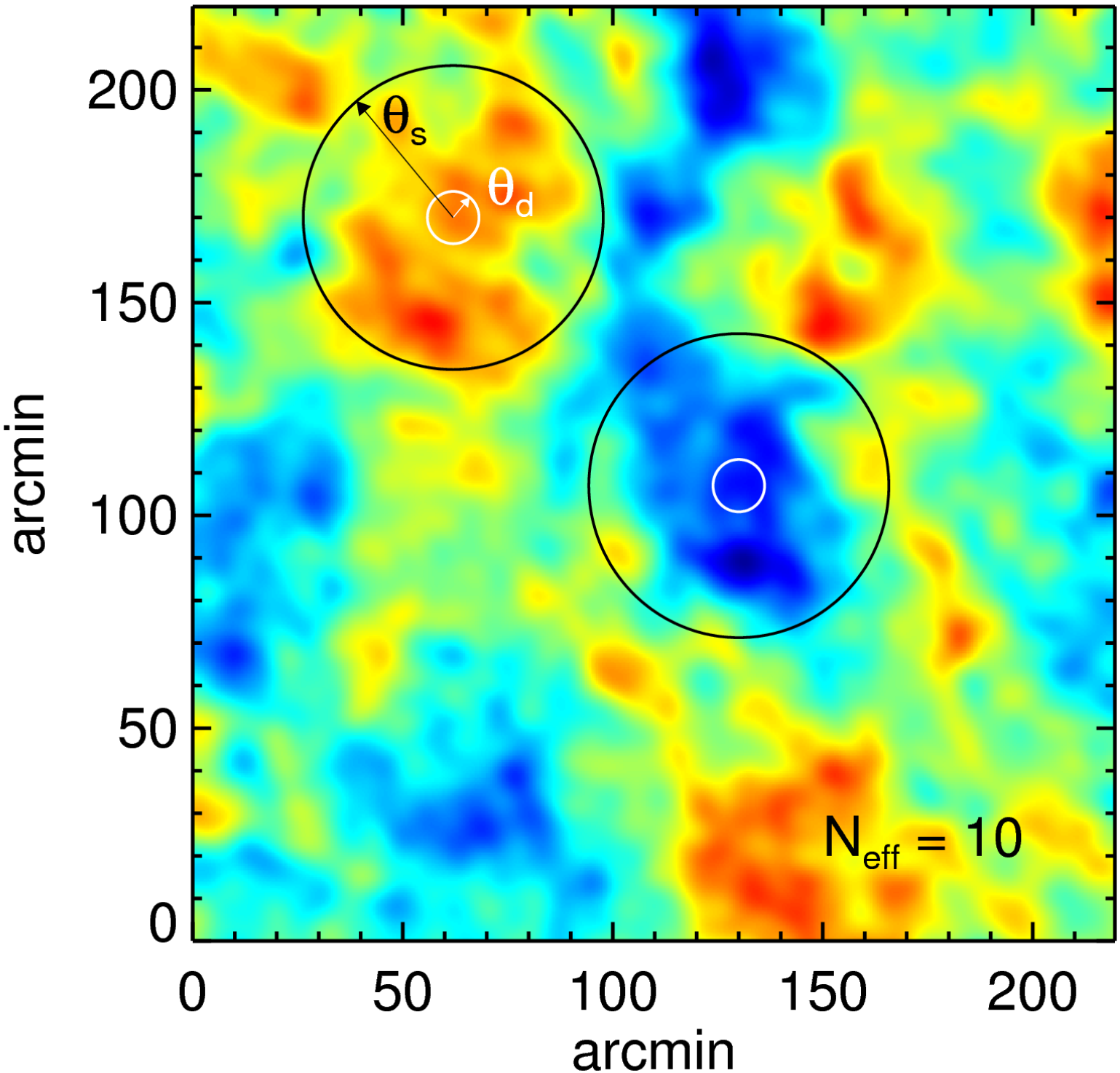


The Future

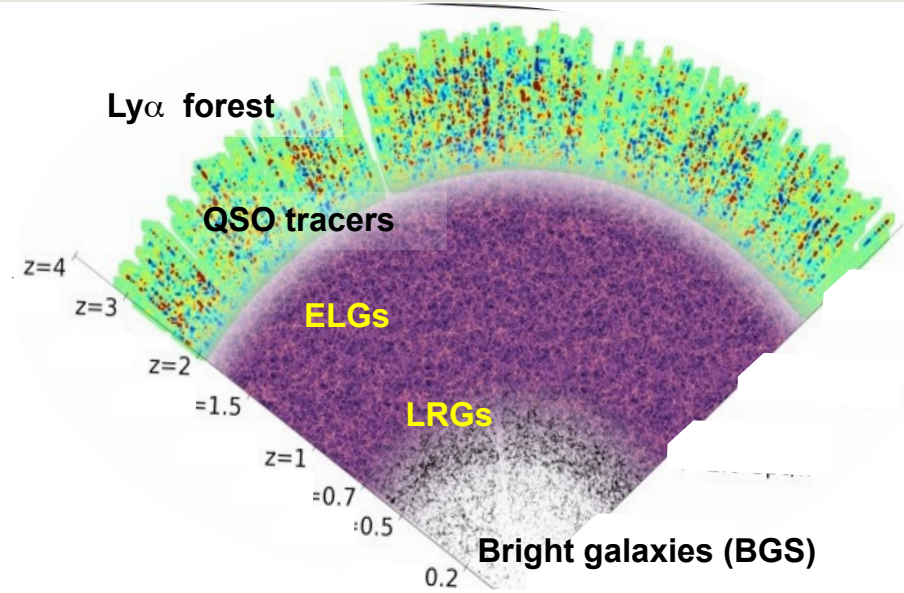
DESI in a nutshell

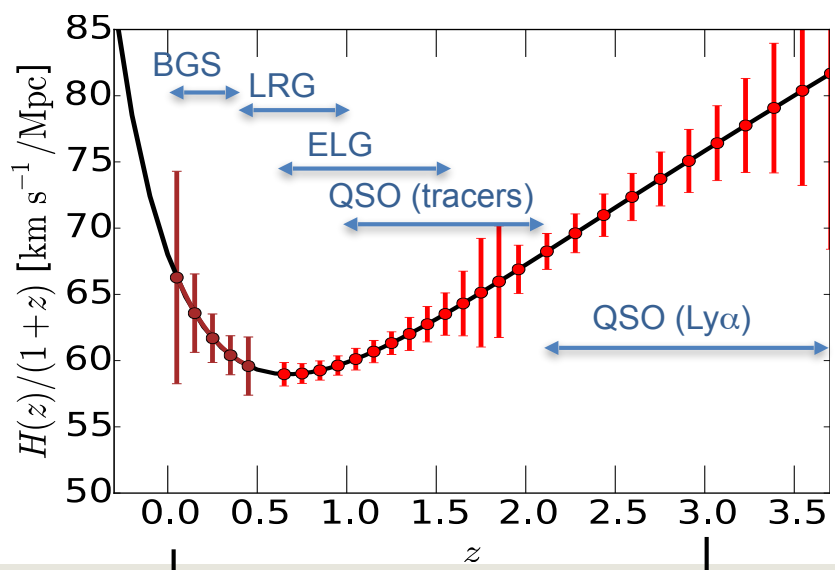
- DESI: Stage-IV dark energy survey
- 35 million redshifts (SDSS x20)
  with 5 target classes

- Requirement on isotropic BAO
  - $\sigma(R) < 0.28\%$ at $z<1.1$
  - $\sigma(R) < 0.39\%$ at $z>1.1$
- Requirement on expansion history
  - $\sigma(H) < 1\%$ at $1.9<z<3.7$

- Commissioning confirmed that the instrument met design requirements

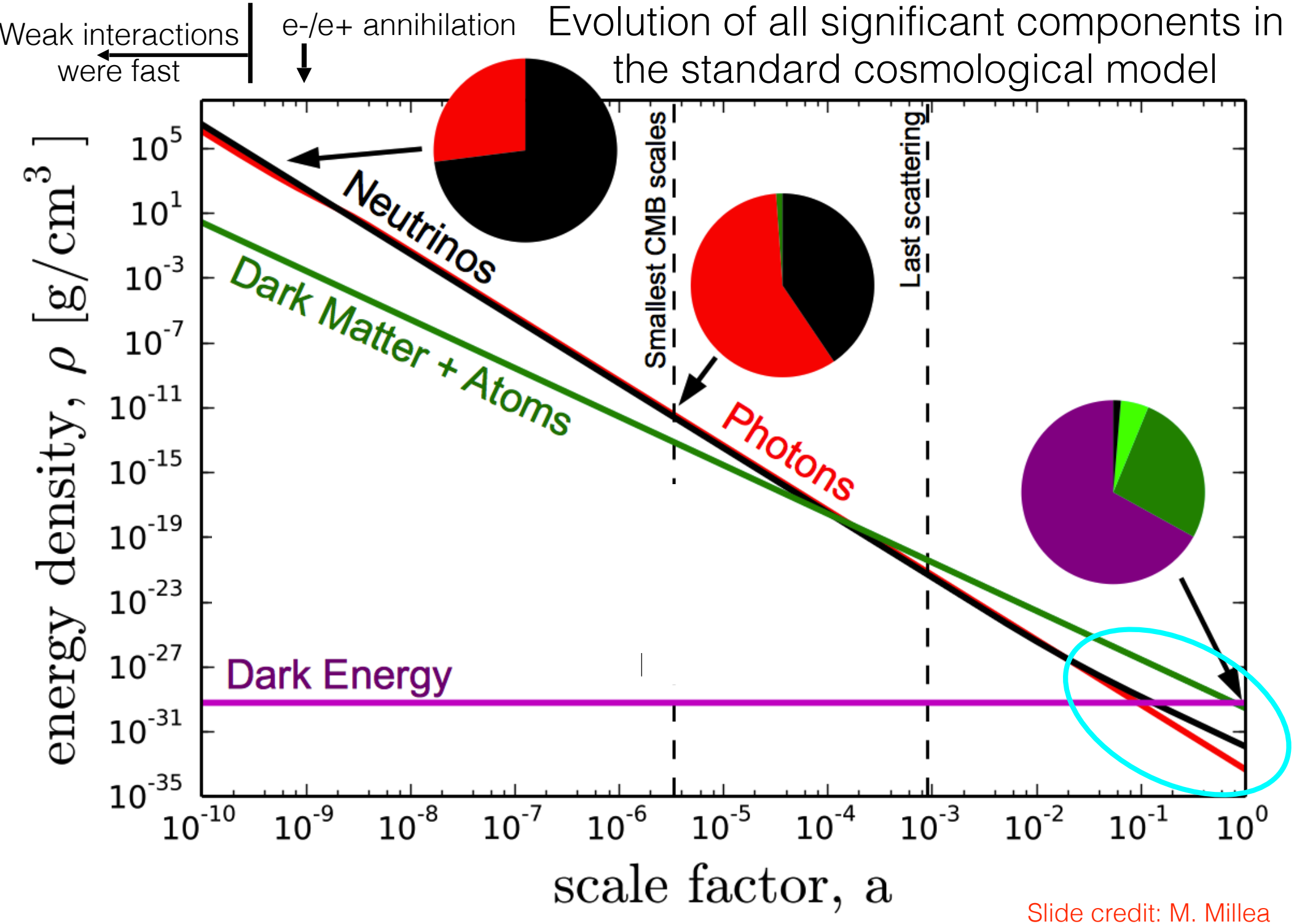
- Science verification will start in fall 2020, and the 5-year survey early 2021





a=1/(1+z) a=1 a=0.25

Evolution of all significant components in the standard cosmological model



Slide credit: M. Millea

See
CMB-S4 Decadal Survey
APC White Paper
1908.01062

DOE MIE

NSF MREFC

Start of Operations:
~2027

Duration:
7 years

Last in-person meeting (Oct 2019)

Last Year:

NSF Mid-Scale Research Infrastructure (**MSRI**) : to support project management and engineering

DOE Critical Decision 0 (**CD-0**) : to support baseline technical design

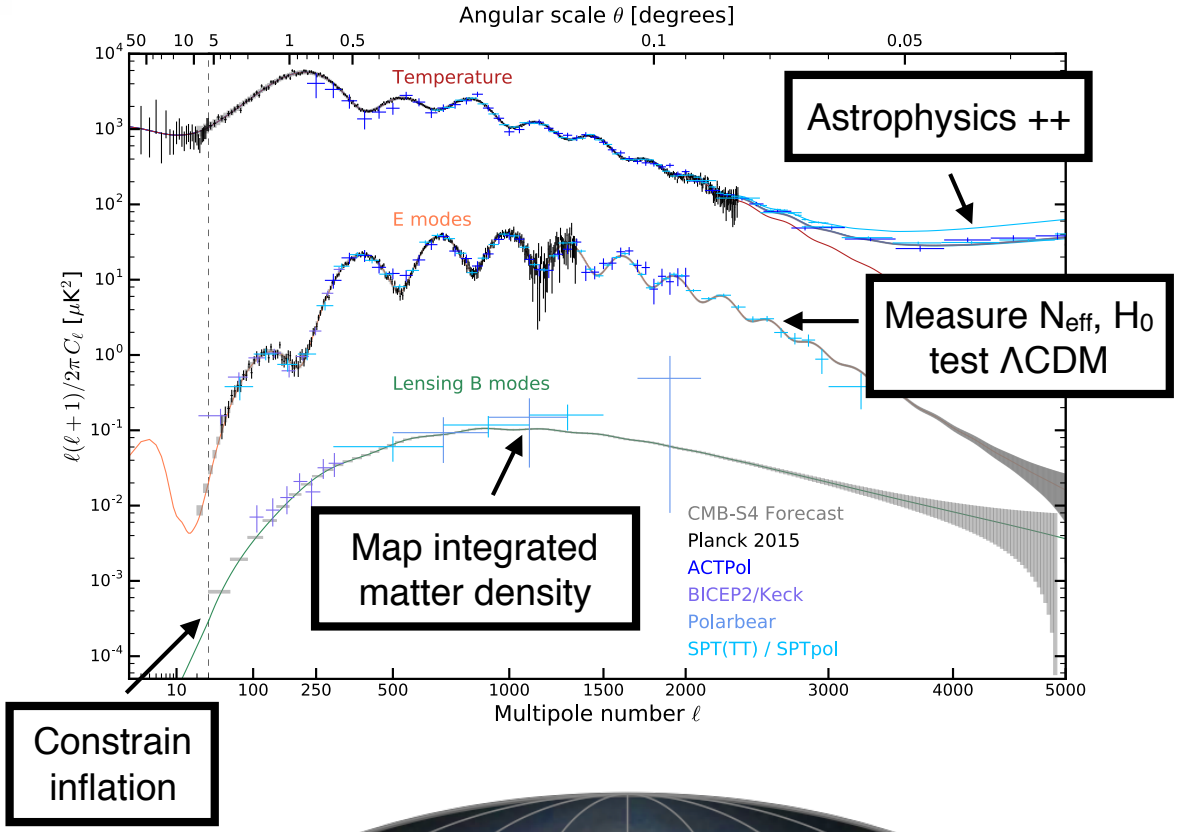
Next :

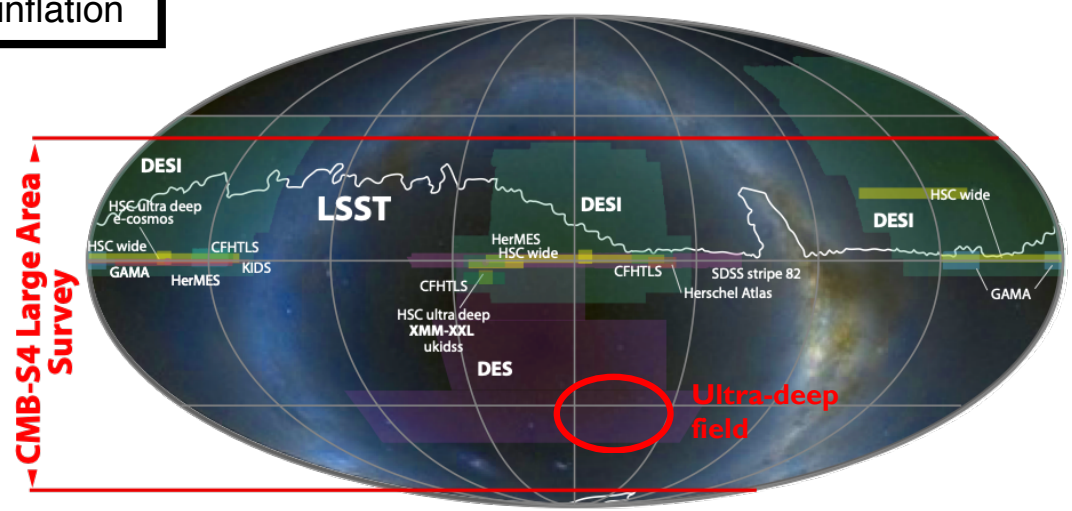
NSF Preliminary Design Review (**PDR**) and DOE **CD-1** in 2021.

Scientific Opportunities

To achieve CMB-S4's ambitious scientific targets:

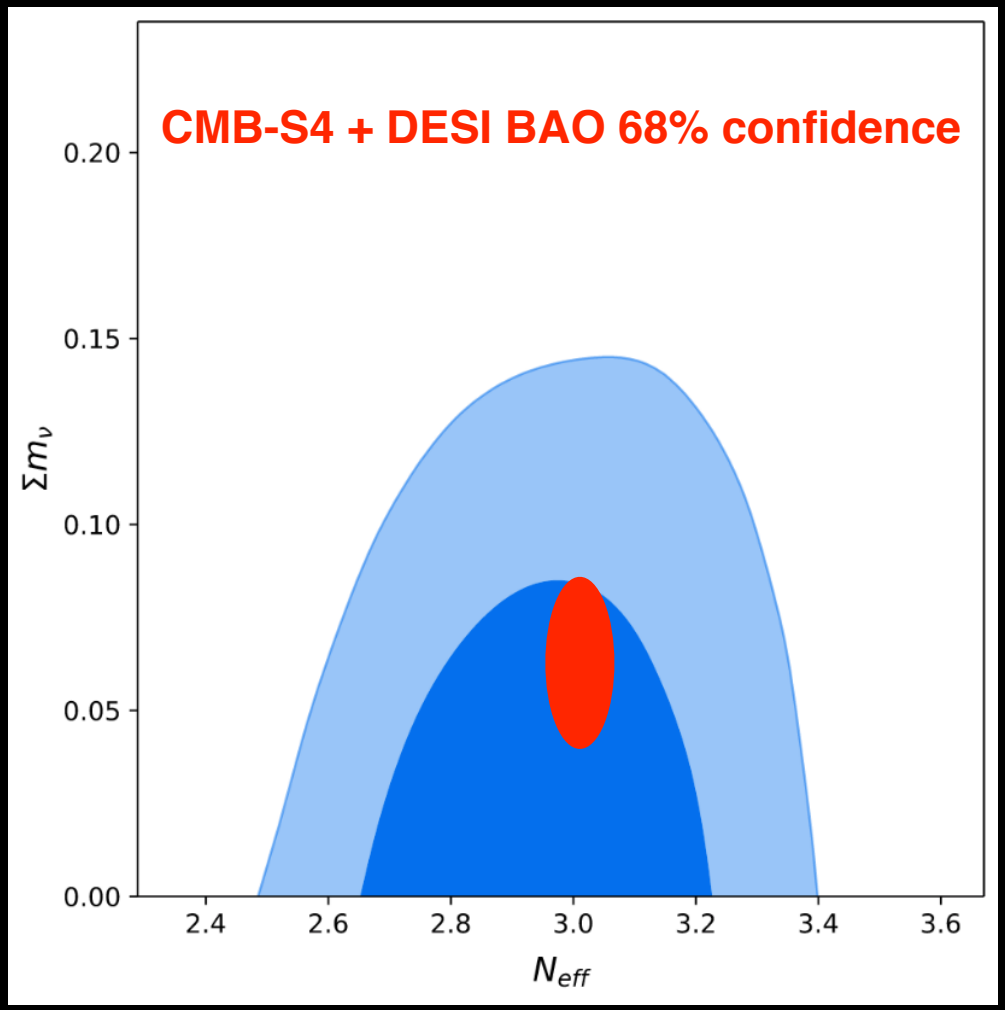
- Sensitivity to both large & small angular scales on the sky
- Increase total instrumental sensitivity by orders of magnitude
- Observe at multiple frequencies to reject foregrounds
- New regime for instrumental characterization, calibration, & systematics control





CMB-S4 science book: https://arxiv.org/abs/1610.02743

Future: CMB+BAO



minimum mass for

inverted hierarchy

normal hierarchy

$\sigma(N_{\rm eff})$ = 0.03 from CMB-S4

$\sigma(\Sigma m_\nu)$ = 0.02 eV from CMB-S4 + DESI BAO (shown above)

$\sigma(\Sigma m_\nu)$ = 0.012 eV from CMB-S4 + DESI BAO (sensitive to reionization modeling)

See the CMB-S4 Science Case, Reference Design and Project Plan (arXiv:1907.04473) and Alvarez et al. 2020

$\sigma(\Sigma m_\nu)$ = 0.026 eV from DESI probes alone (arXiv:1611.00036 updated to Planck 2018)

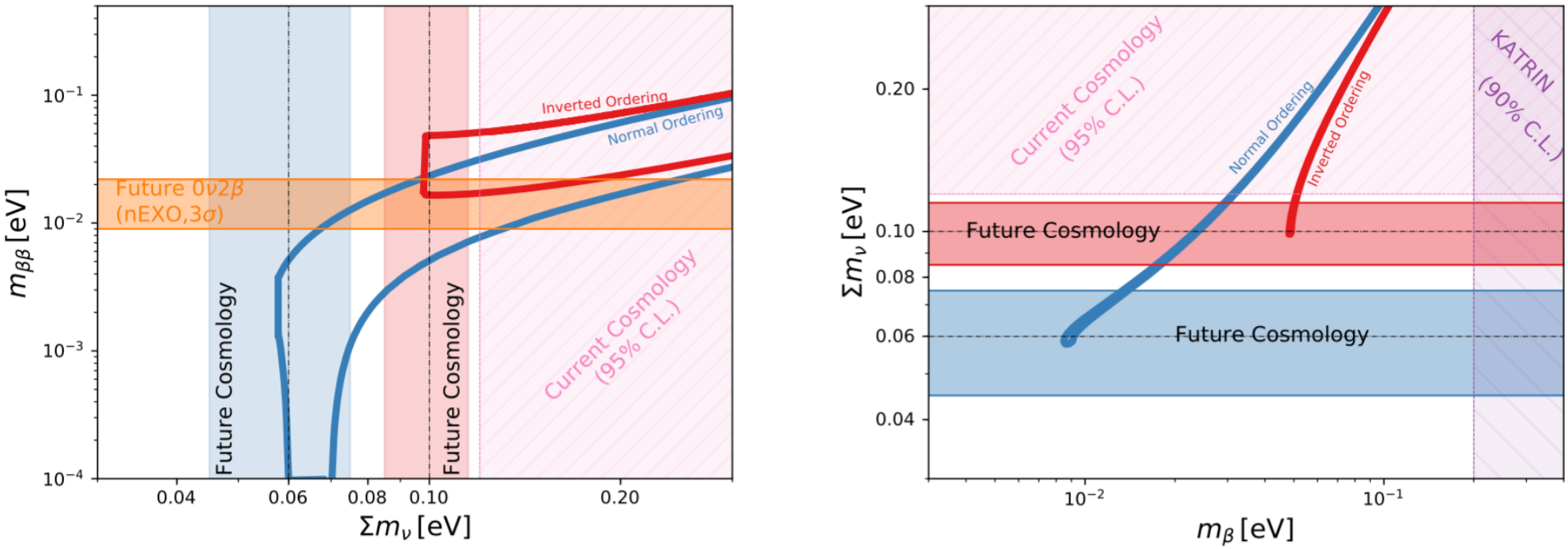
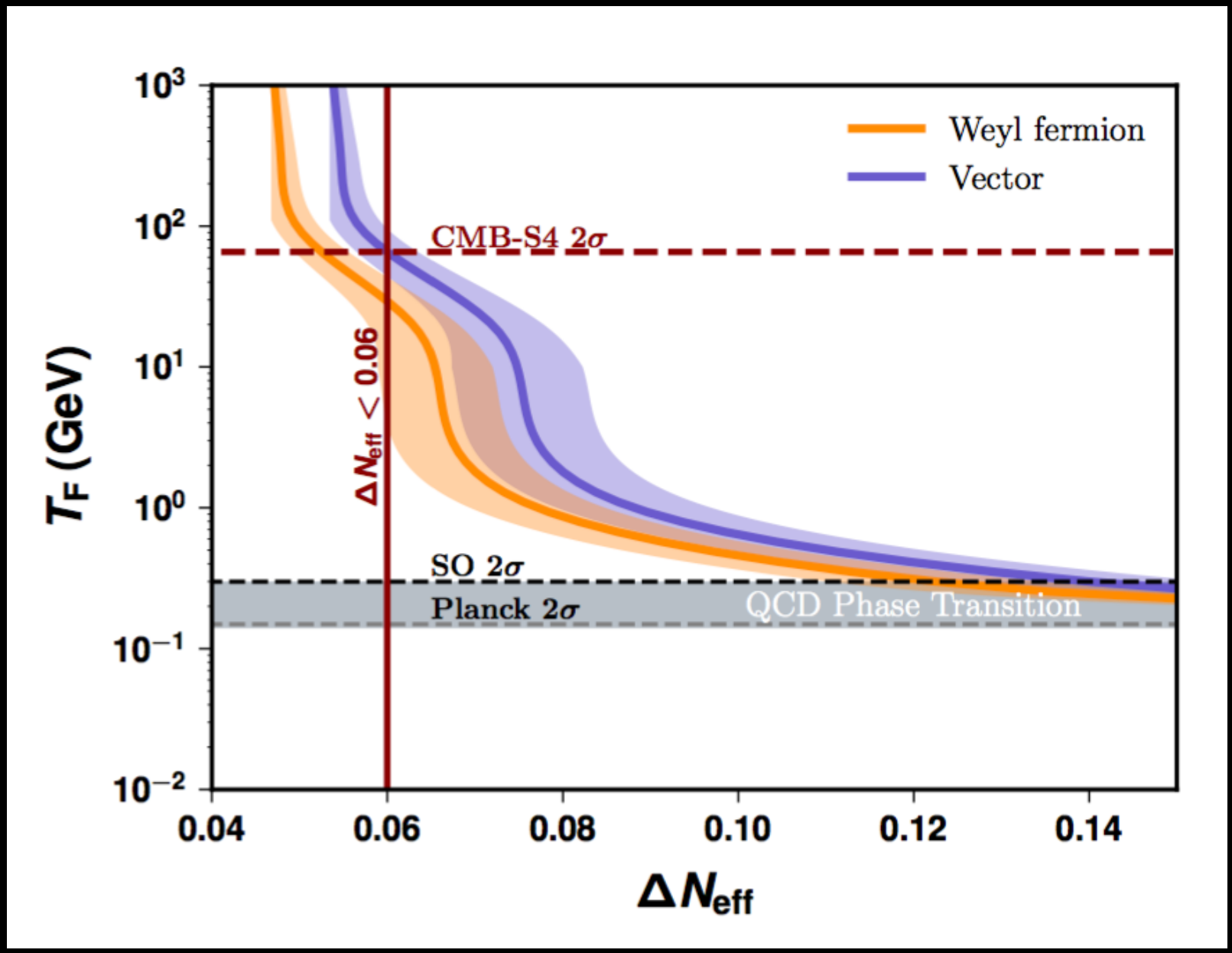


Figure 13. *Left: Majorana effective neutrino mass $m_{\beta\beta}$ versus M_ν in the scenario where NLDBD is mediated by light neutrino exchange. The area enclosed by the blue and red solid lines indicate the allowed 95% ranges from neutrino oscillation experiments [236] for normal ordering (NO) and inverted ordering (IO) assuming complete ignorance of the Majorana phases. The vertical blue and red bands show the forecasted 1σ constraints on M_ν from CMB-S4 for minimal mass NO and IO. The horizontal band shows the sensitivity of future NLDBD experiments. A CMB-S4 detection of M_ν, in combination with a detection of $m_{\beta\beta}$ can constrain the Majorana phases. Right: Sum of individual the neutrino masses as a function of the electron-neutrino effective mass m_β for the NO (blue) and the IO (red). Again, the area enclosed by the blue and red solid lines indicate the allowed 95% ranges from neutrino oscillation experiments [236] for NO and IO. The horizontal bands show the future cosmological constraints around each ordering (assuming the mass of the lightest neutrino state $m_{\rm lightest} = 0\,{\rm eV}$). Also shown are the anticipated limits on m_β from the KATRIN experiment in the case of no detection.*

CMB-S4 Science Case, Reference Design and Project Plan
(https://arxiv.org/abs/1907.04473)

What good is $\sigma(N_{\rm eff})$=0.03?

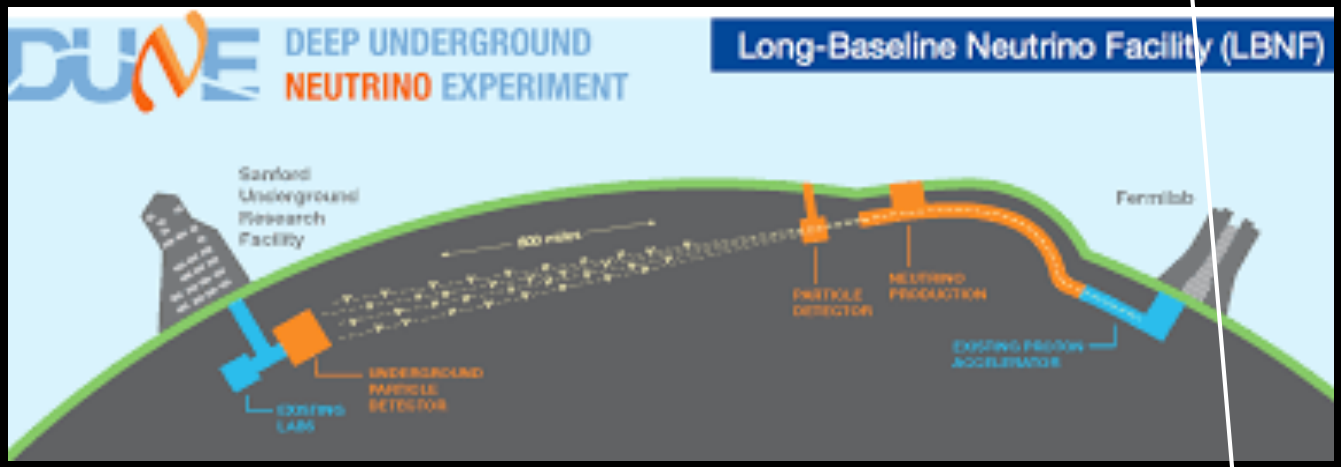


CMB-S4 Science Case, Reference Design and Project Plan
(https://arxiv.org/abs/1907.04473)

To conclude:

I hope you feel encouraged
to talk with cosmologists
and ask them to fill in these dots.

You are comfortable with this:



but maybe not this:

"I look up into the sky…
…and I conclude things."

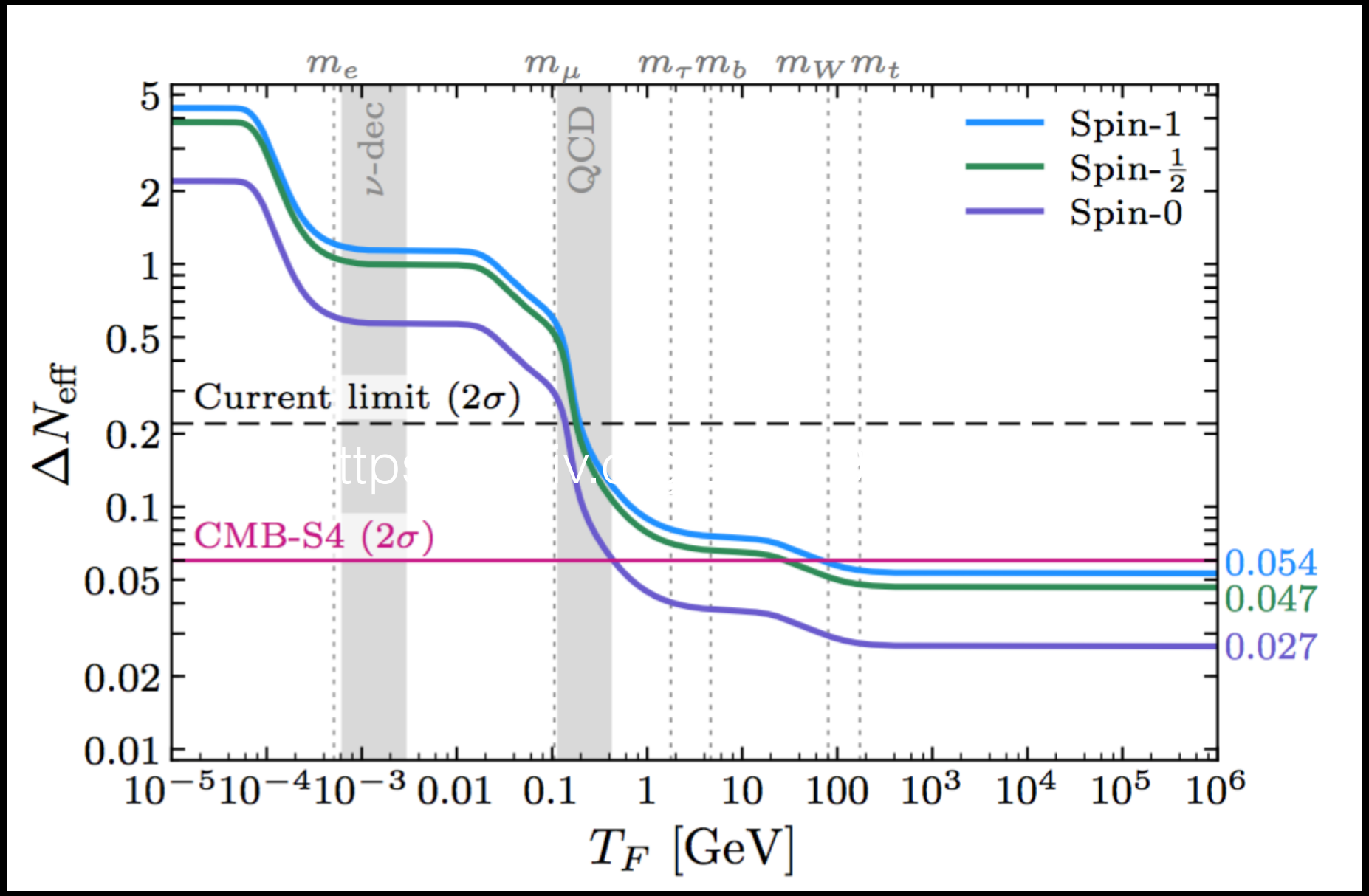
(astronomer explaining their work, as
imagined by a neutrino physicist)

Summary/Conclusions

- In cosmology we study a naturally produced background of neutrinos by exploiting their gravitational influence on other matter and radiation.
- Conclusions are model dependent
- There are a rich variety of ways to check the models (that I did not get to tell you about).
- Results are complementary to constraints from laboratory experiments.
- **Laboratory + cosmology combined ==> improved scope for discovering new physics.**
- For more
  - For a broad, short, overview of cosmological probes of neutrino mass: Neutrino Mass from Cosmology: Probing Physics Beyond the Standard Model (https://arxiv.org/abs/1903.03689)
  - For a broad, short, overview of cosmological probes of light relics: Messengers from the Early Universe: Cosmic Neutrinos and Other Light Relics (https://arxiv.org/abs/1903.04763)

Outtakes

Future probes of light relics



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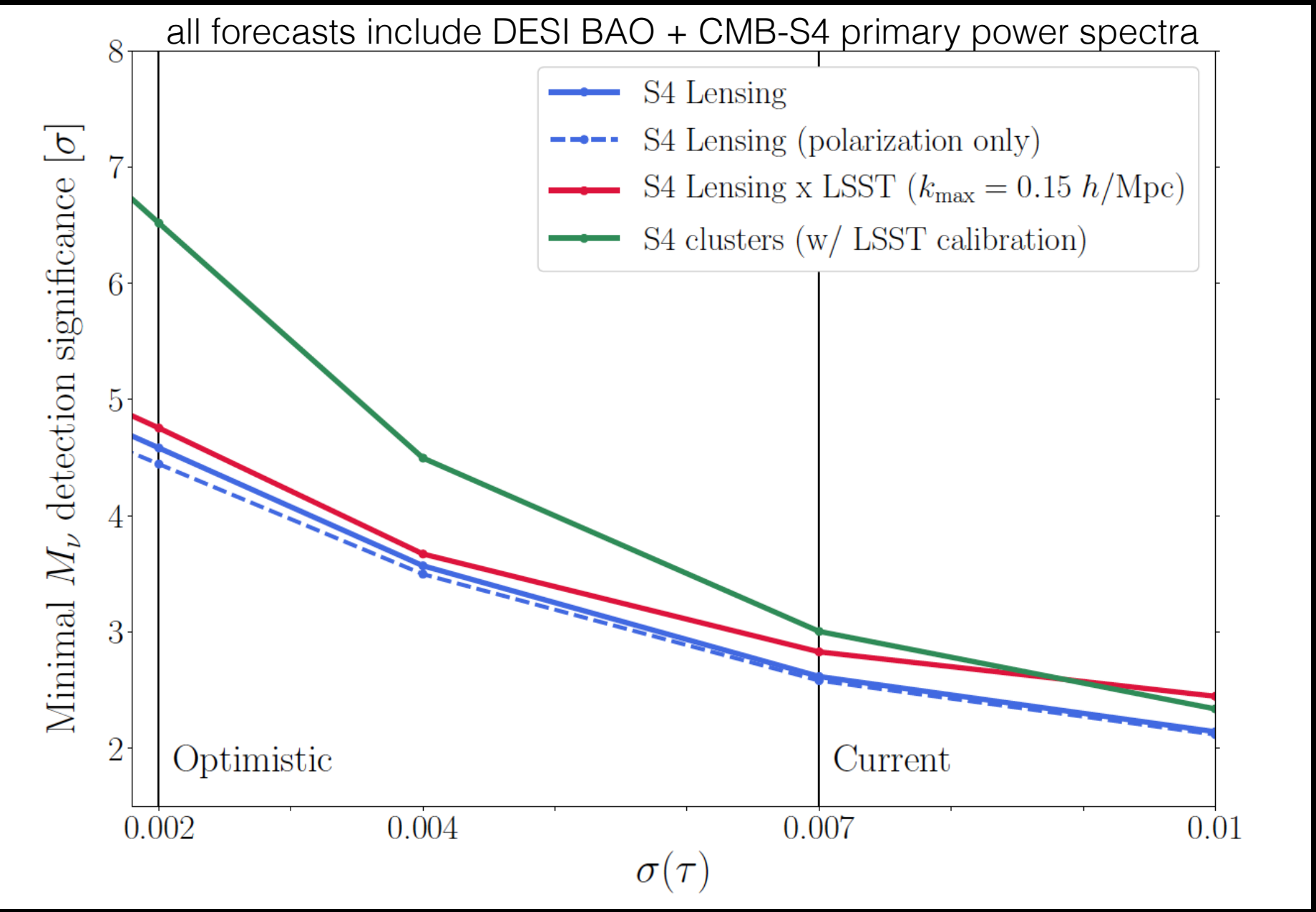
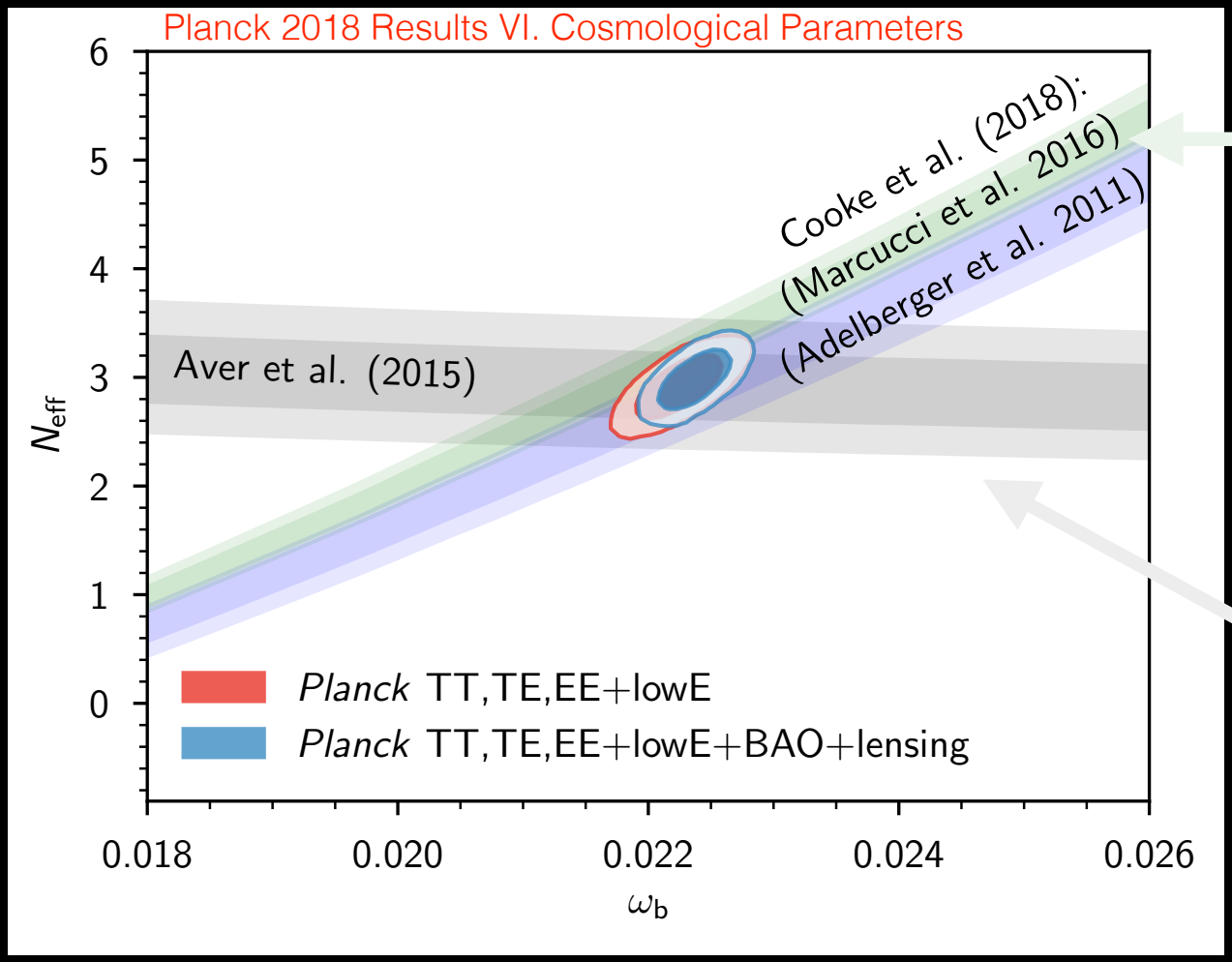


prior on optical depth to Thomson scattering in recognized IGM

Alvarez et al. 2020 claim CMB-S4 can achieve sigma(tau) = 0.002 from using kSZ effect

Current Status: BBN



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Helium abundance + BBN modeling

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Helium abundance: Aver et al. (2015)
Helium BBN model: PArthENoPE

Neutrino bounds with DESI

- Neutrino constraint from galaxy clustering
  - Constraint from BAO position & from scale-dependent broadband
  - Forecast given for 2-pt statistics only (conservative)

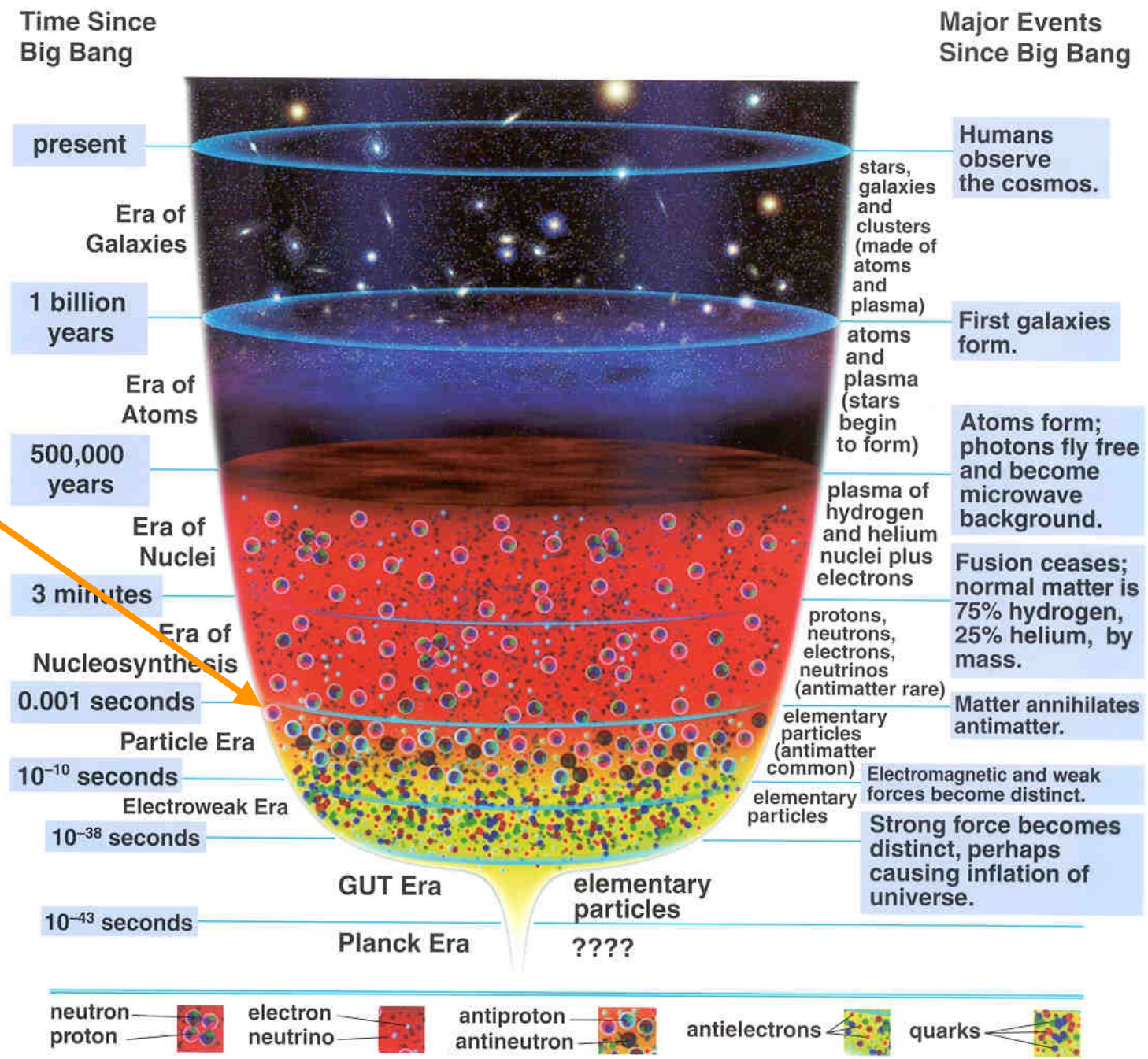
- Neutrino constraint from Lyα forest power spectrum
  - Large redshift lever arm (z=2 to z~5)
  - Sensitivity to small scales ($\lambda/\Delta\lambda$ x1.2 – x1.6 vs. SDSS)

DESI forecast
FDR (arXiv:1611.00036)
updated to Planck 2018

Data (+Planck 2018)	$\sigma(\Sigma m_\nu)$ [eV]
Gal. BAO	0.087
Gal. (k_{max} = 0.1 h Mpc^{-1})	0.034
Gal. (z-optimized k_{max})	0.027
Lyα forest	0.041
Lyα forest + Gal. (k_{max} = 0.1)	0.032
Lyα forest + Gal. (optimized k_{max})	0.026

At kT > 1 MeV, weak reactions that create and destroy neutrinos

are sufficiently rapid that a thermal distribution of neutrinos is created



Credit: The Cosmic Perspective

Extra species in equilibrium ➔ faster expansion rate (at a given temperature)

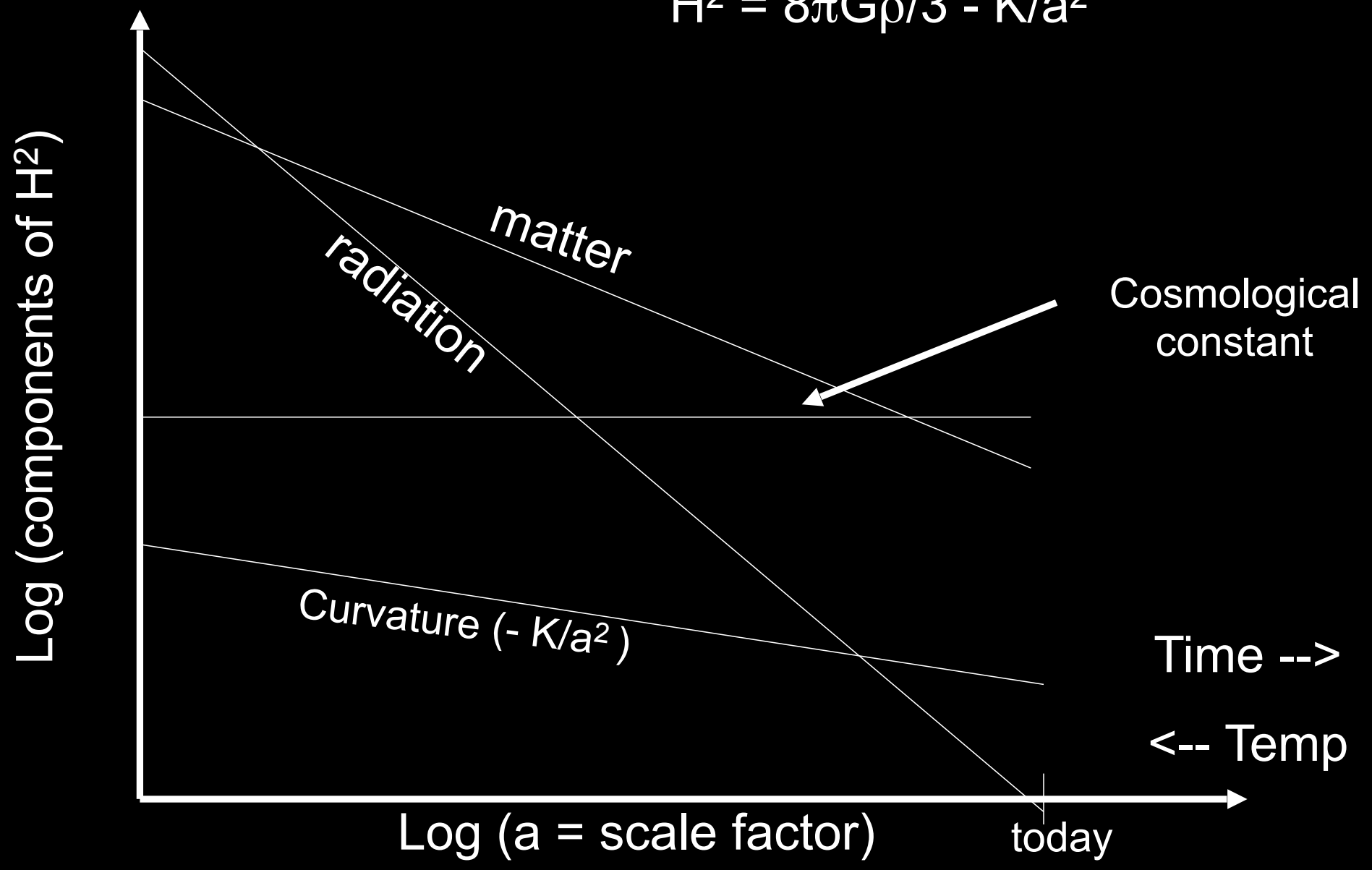
$H^2 = 8\pi G\rho/3$

$\rho = g(\pi^2/30)\, T^4$

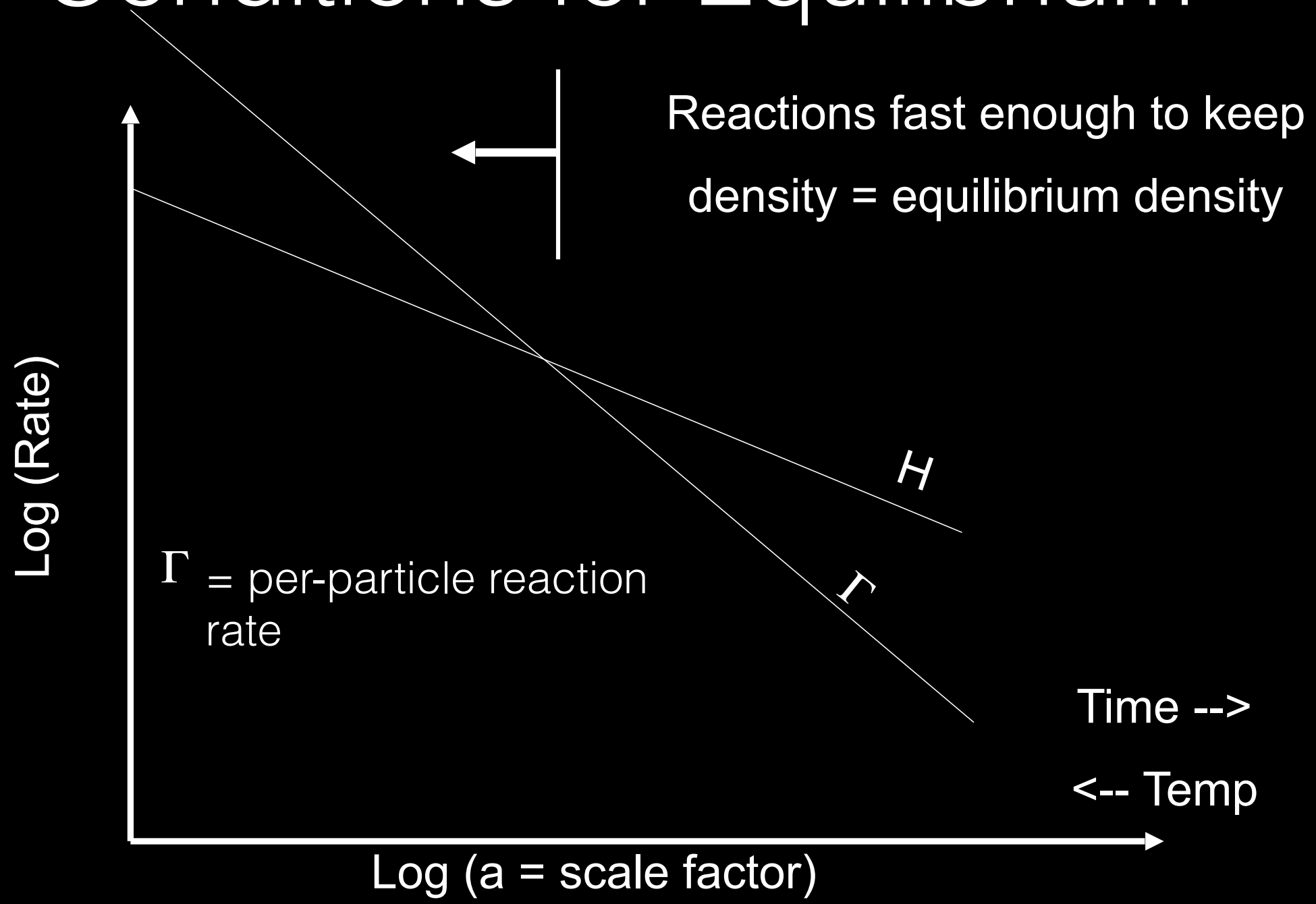
$h/(2\pi) = k_B = c = 1$

History of Contributions to the Expansion Rate

$$H^2 = 8\pi G\rho/3 - K/a^2$$



Conditions for Equilibrium



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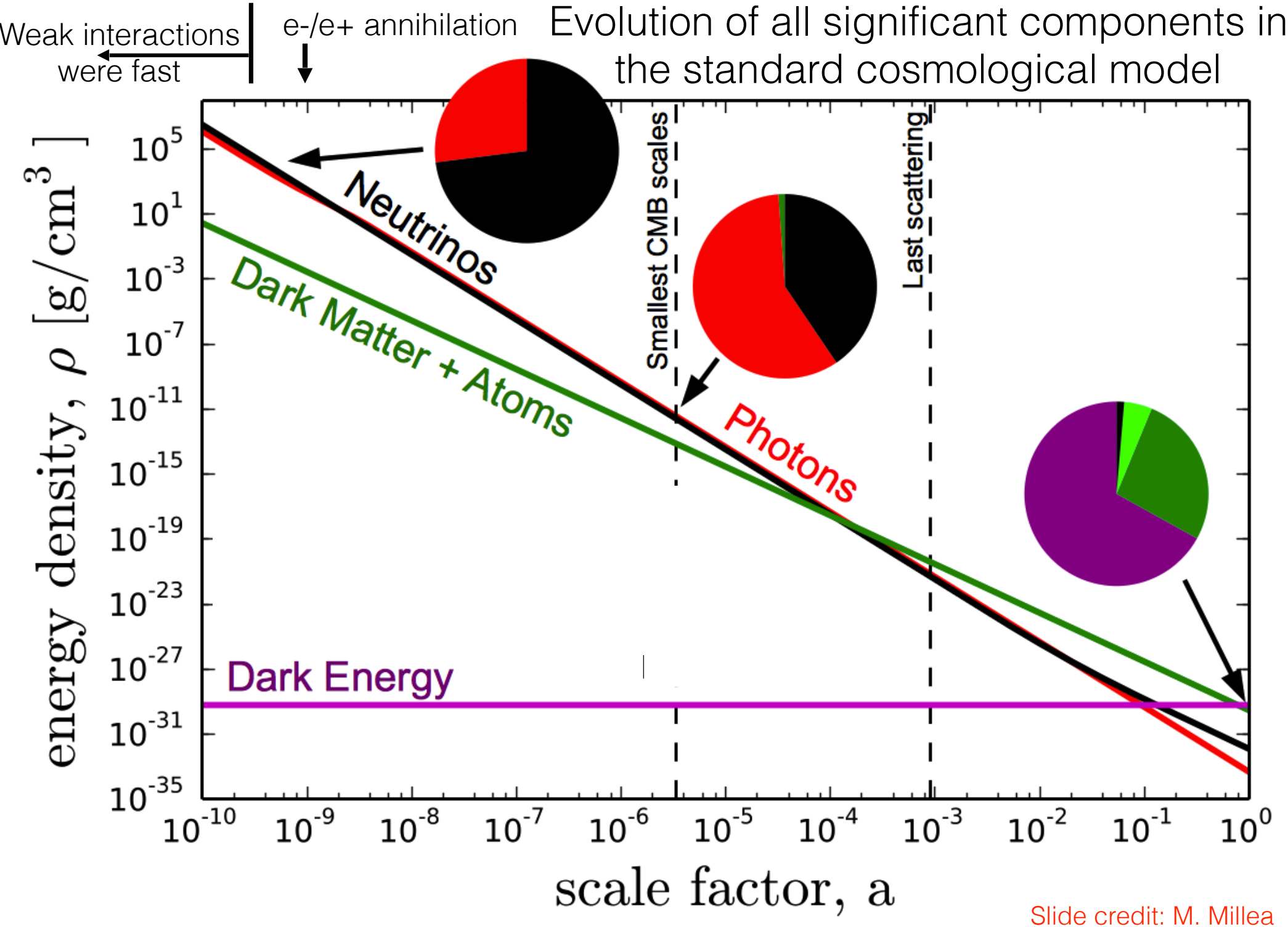

Slide credit: M. Millea

$$\frac{T_{\gamma,\text{after}}}{T_{\nu,\text{after}}} = \left(\frac{11}{4}\right)^{1/3}$$

Approximate result of "electron cooling" of neutrinos

Photons

Fermi statistics

$$\rho_r = \frac{\pi^2 k_B^4}{15\hbar^3 c^3}\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right] T_\gamma^4$$

Neff defined so would be 3 if only 3 known neutrinos and all electron entropy went to photons

Total energy density in relativistic species

Due to reduced temperature

Cosmological standard model has Neff = 3.046 because some of electron/positron entropy does go to neutrinos.

Note: Neff is capturing contributions to energy density that are redshifting like radiation; i.e., no mass!

$$\frac{T_{\gamma,\text{after}}}{T_{\nu,\text{after}}} = \left(\frac{11}{4}\right)^{1/3}$$

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Neff defined so would be 3 if only 3 known neutrinos and all electron entropy went to photons

Total energy density in relativistic species

Due to reduced temperature

If electron/positron cooling did *not* happen $\Delta N_{\text{eff}} \simeq 8$

$$\sigma(N_{\text{eff}}) \simeq 0.3 \rightarrow \sim 25\sigma \text{ detection of electron cooling}$$

Neutrinos (and other light and dark relics) and Cosmology

- The Source
- The Detectors
  - Light element abundances
  - CMB temperature and polarization power spectra
  - Matter power spectrum at late times

Neutron / proton interconversion

The reactions converting neutrons to protons and vice versa are

$$\mathrm{n} + \nu_{\mathrm{e}} \longleftrightarrow \mathrm{p} + \mathrm{e}^{-}$$
$$\mathrm{n} + \mathrm{e}^{+} \longleftrightarrow \mathrm{p} + \bar{\nu}_{\mathrm{e}}$$

where ν_{e} is an electron neutrino and $\bar{\nu}_{\mathrm{e}}$ its anti-particle. As long as these inte

They remain fast until kT is about 0.8 MeV.
While they are fast we have:

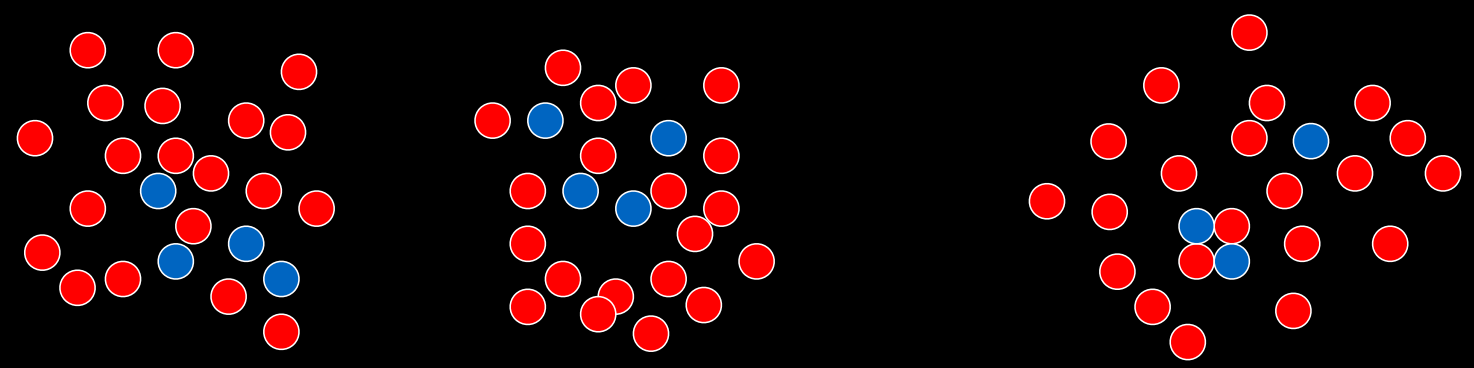
$$n_n/n_p \simeq \exp\left[-(m_n - m_p)c^2/(k_B T)\right]$$

Production of Helium

p
n

If Γ > H then

$n_n = n_p \exp(-\Delta mc^2/kT)$



Cooler ==>

1 MeV

$T_{P,n\ freeze\text{-}out}$

0.1 MeV

T_{nuc}

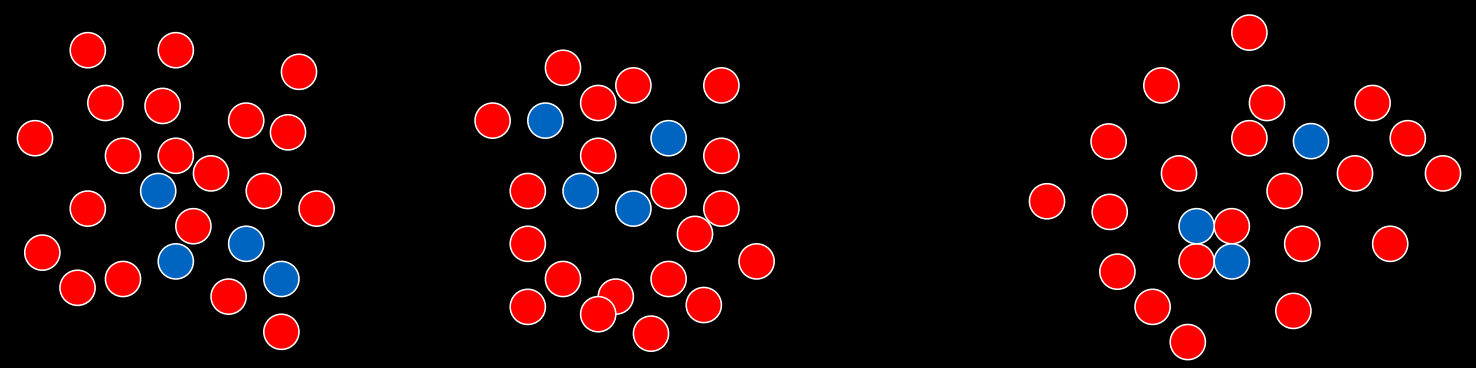
At freeze-out: $n_n/n_p \simeq 1/5 \rightarrow n_n/(n_n + n_p) = 1/6.$

Production of Helium

p
n

If Γ > H then

$n_n = n_p \exp(-\Delta mc^2/kT)$



Cooler ==>

1 MeV

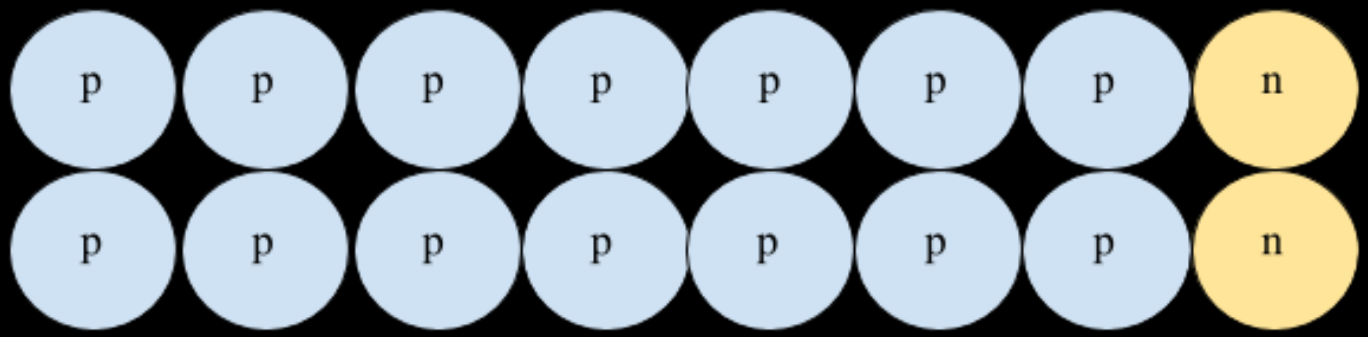
$T_{P,n\ freeze\text{-}out}$

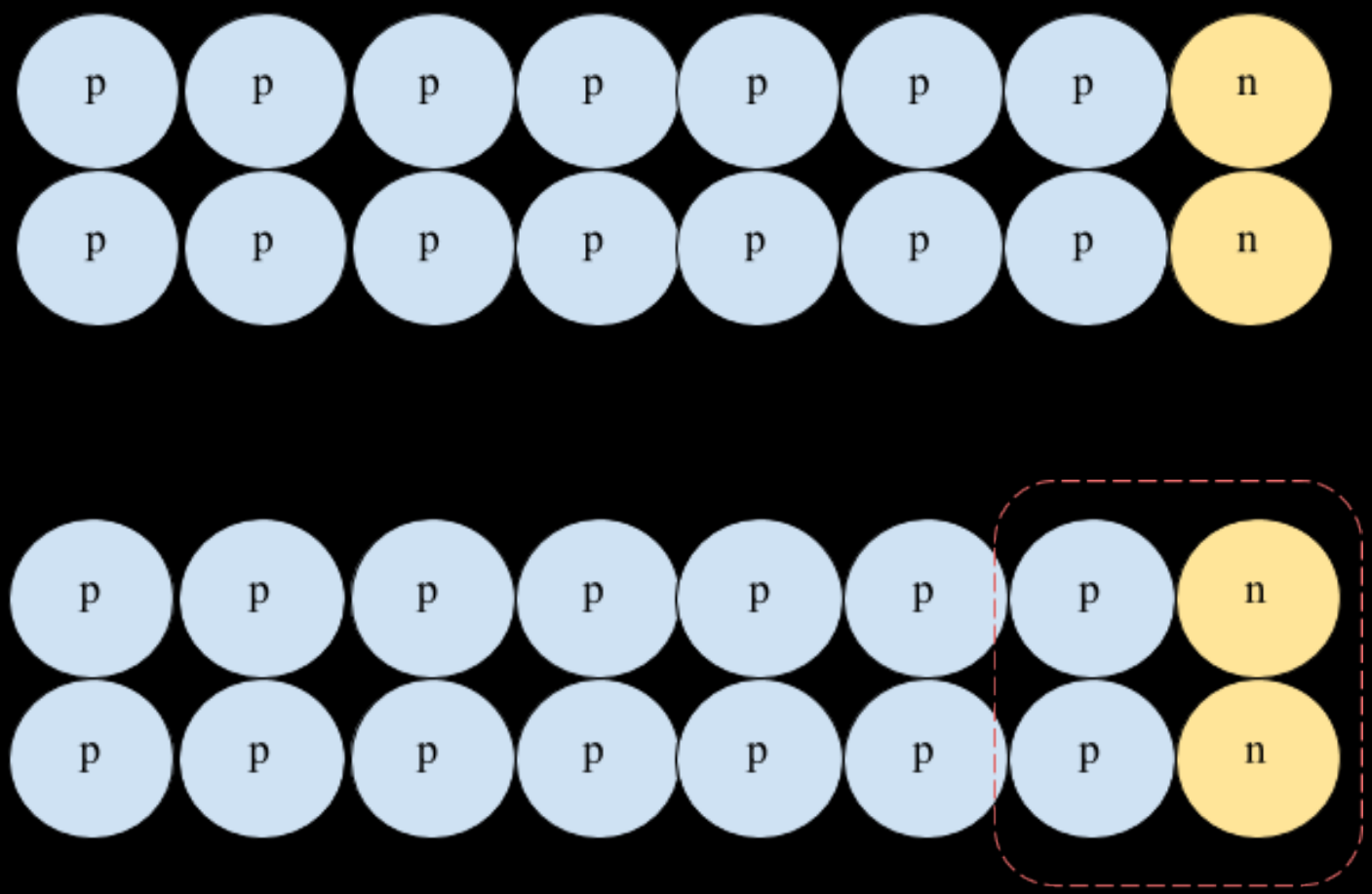
0.1 MeV

T_{nuc}

At freeze-out: $n_n/n_p \simeq 1/5 \rightarrow n_n/(n_n + n_p) = 1/6.$

At Tnuc: $n_n/n_p \simeq 1/7 \rightarrow n_n/(n_n + n_p) = 1/8.$


p p p p p p p n
p p p p p p p n



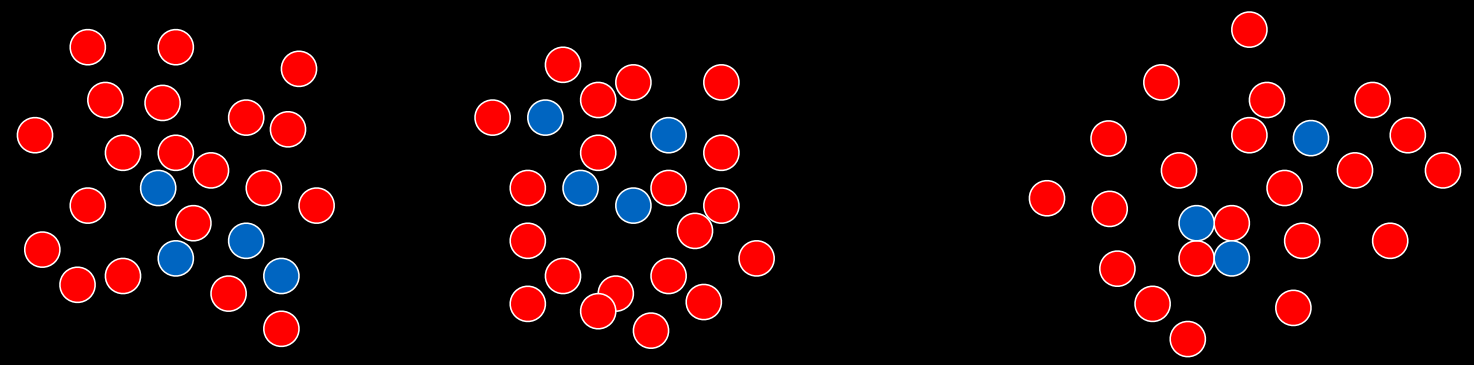
1/8 nucleons is a neutron ==> 1/4 of mass in 4He

Production of Helium

p
n

If $\Gamma > H$ then

$$n_n = n_p \exp(-\Delta mc^2/kT)$$



Cooler ==>

1 MeV

$T_{P,n\ freeze\text{-}out}$

0.1 MeV

T_{nuc}

Quiz: what is impact of extra neutrino species (or extra light and dark relics?)

Dependence of Helium production on neutrinos

p

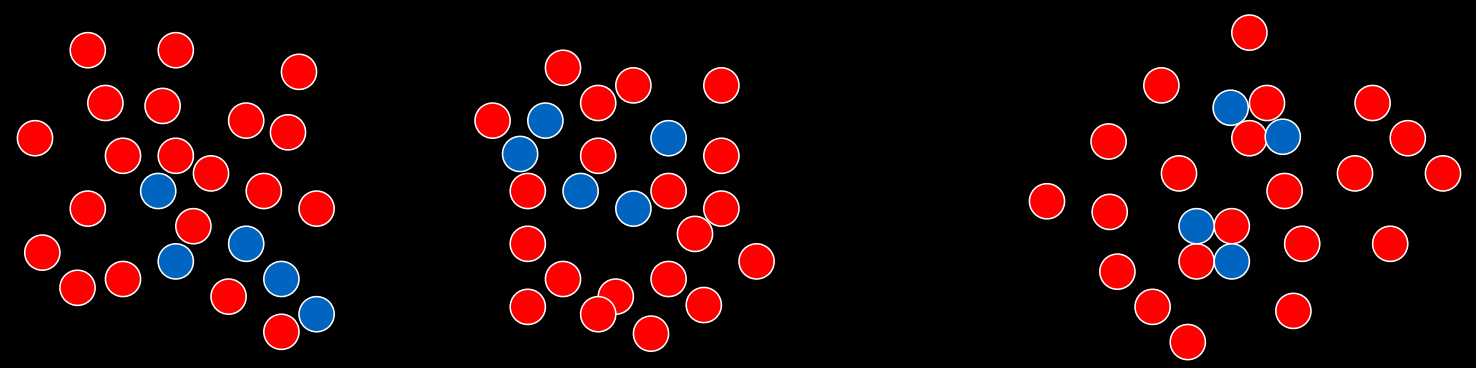
n

Γ here is per-neutron rate of

$p + e \leftrightarrow n + \nu_e$

If $\Gamma > H$ then

$n_n = n_p \exp(-\Delta mc^2/kT)$



Cooler ==>

1 MeV

$T_{P,n\ freeze\text{-}out}$

0.1 MeV

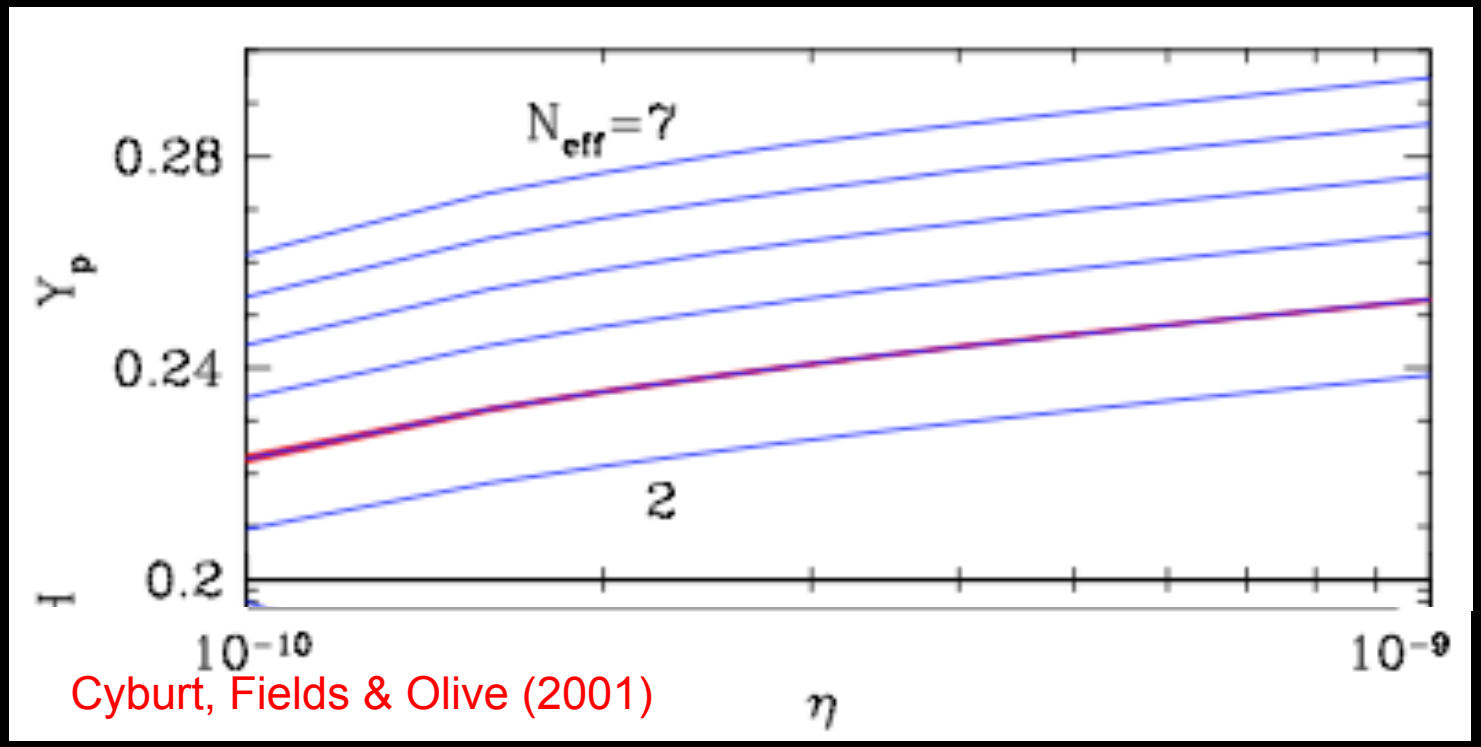
T_{nuc}

More ν species ==> higher total ρ (at given T) ==> higher H (at given T) ==> Γ = H at higher T ==> more neutrons around ==> more Helium

(also less time for neutron decay)

$H^2 = 8\pi G\rho/3$

Dependence of Primordial Helium on the number of neutrino species, N_{eff}

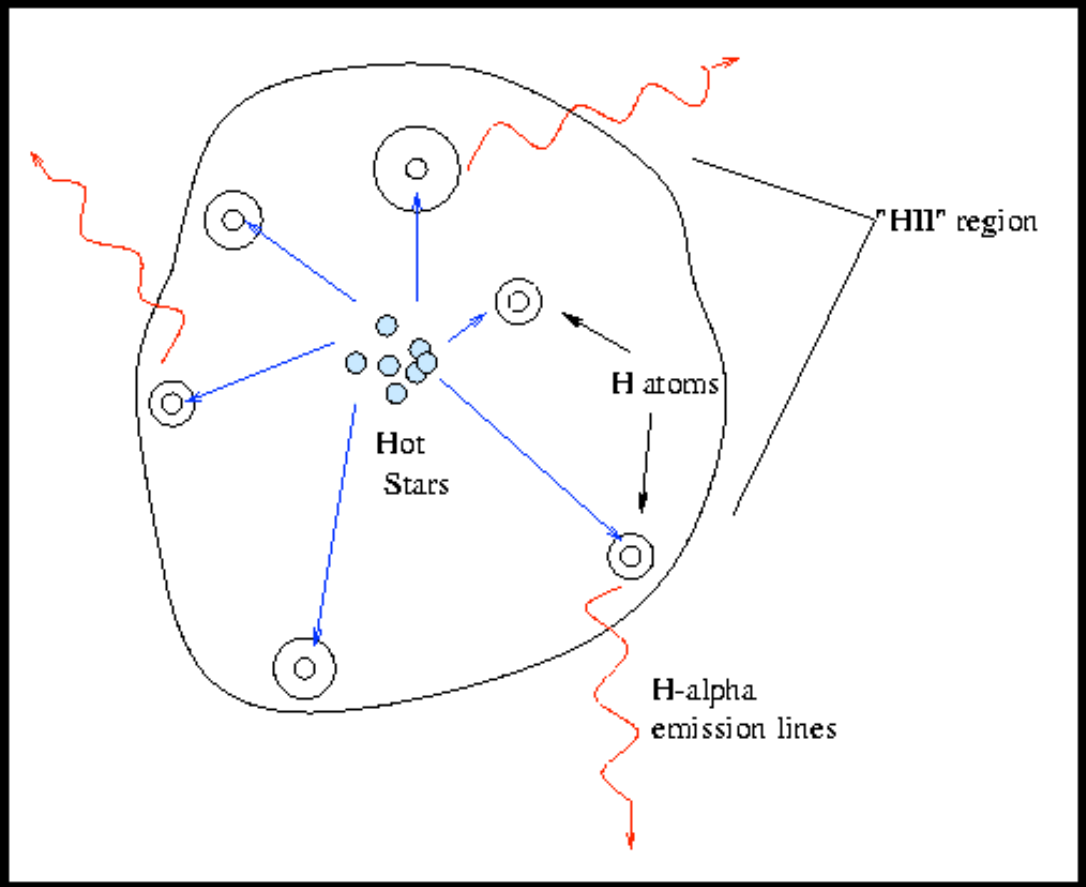


Cyburt, Fields & Olive (2001)

baryon-to-photon ratio

Y = fraction of baryonic mass in Helium

An HII region is one where there is ionized Hydrogen (HII), usually from young stars that pump out ultraviolet light.



Spectrum of an HII region

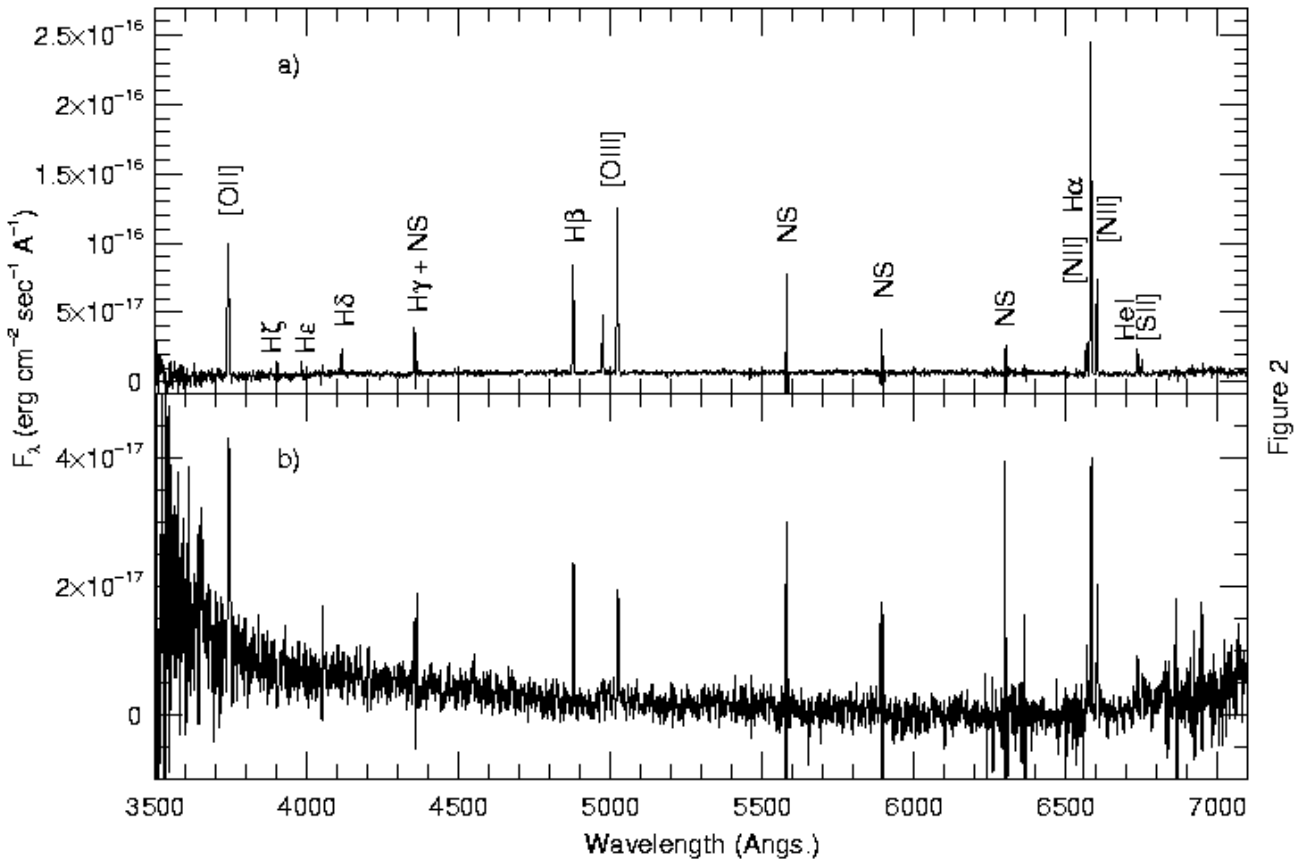


Figure 2

Inference of He/H from data like this is challenging!

An interesting history of Y_P inferences

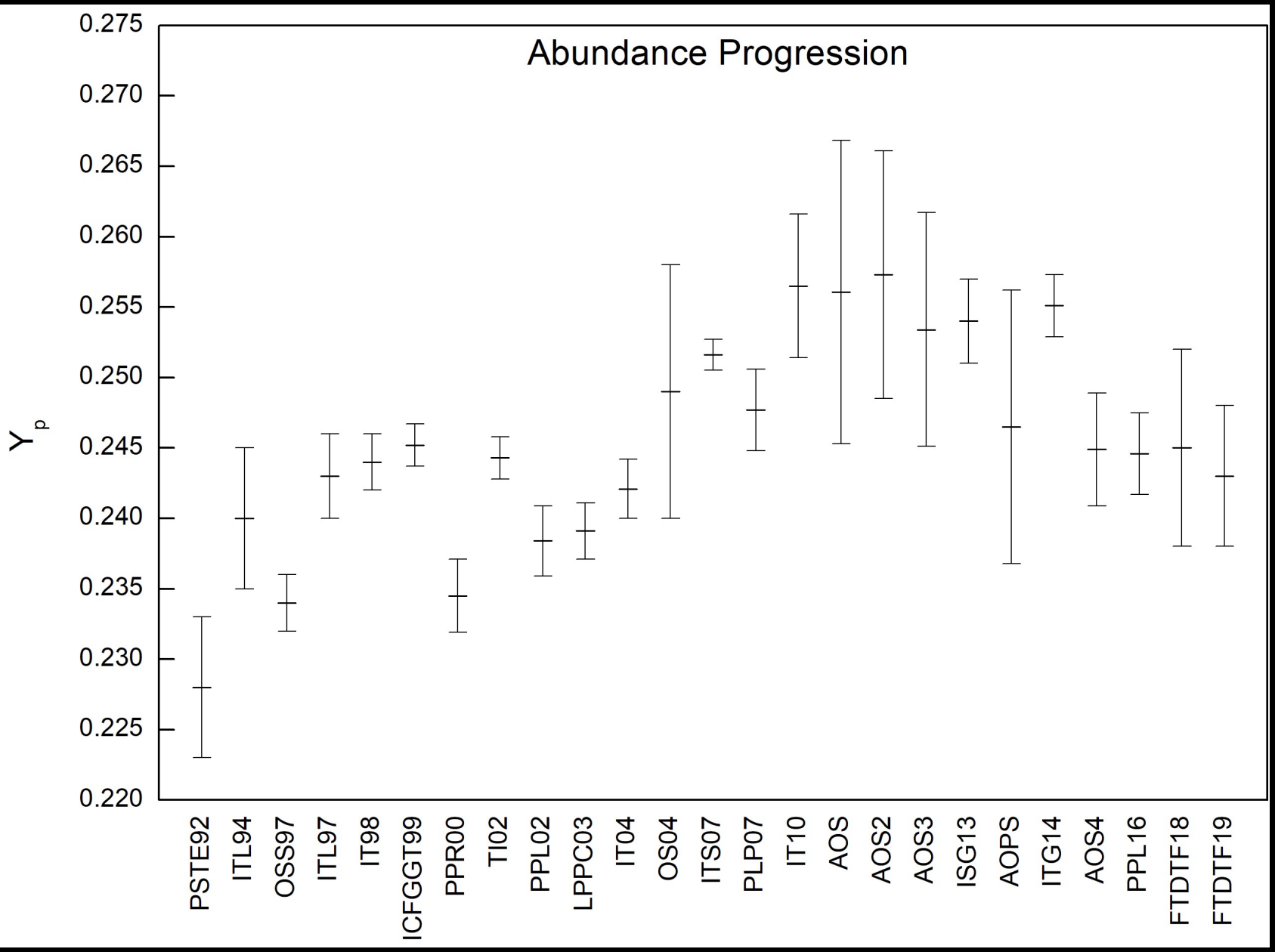
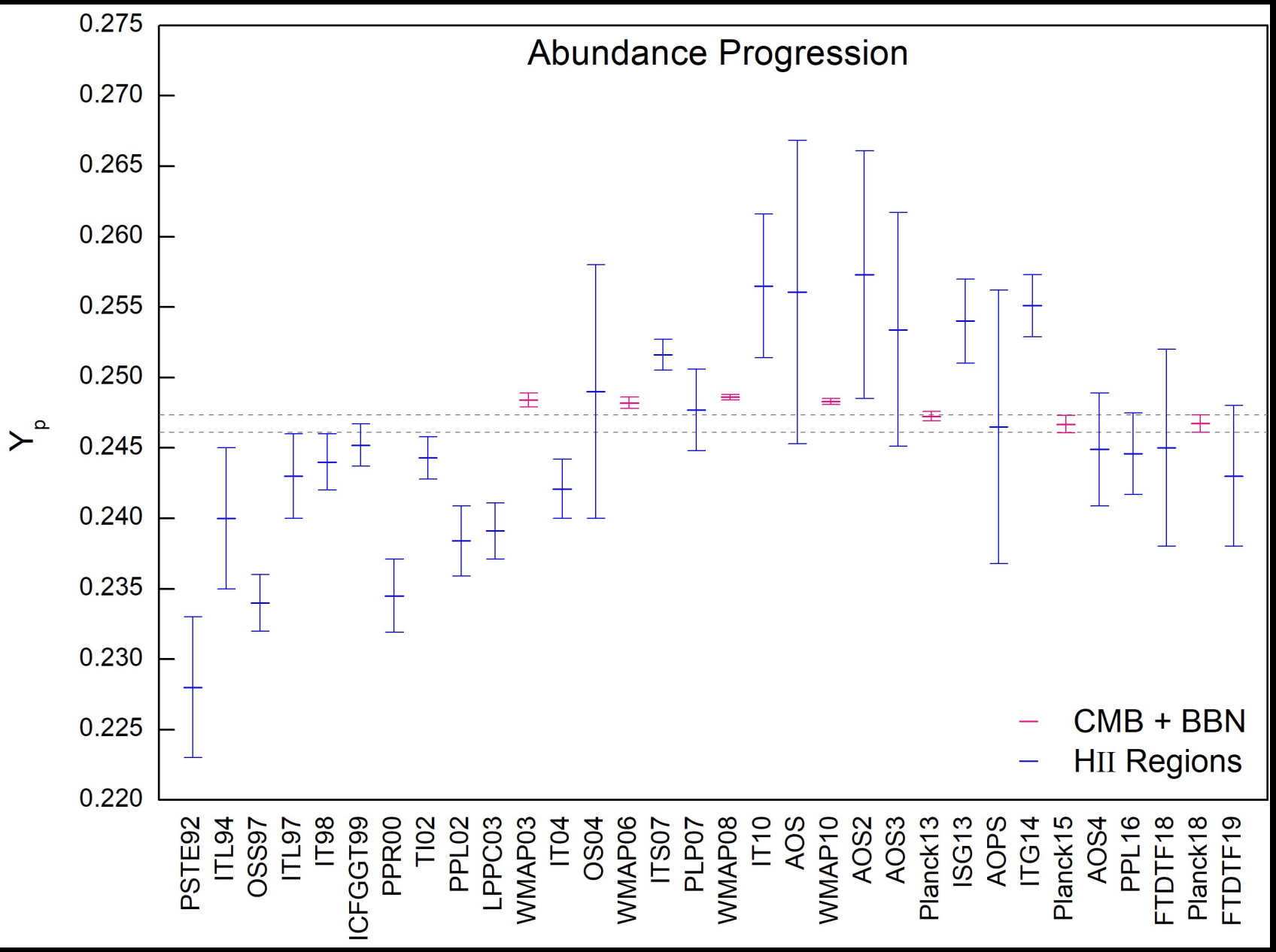


Figure credit: Erik Aver

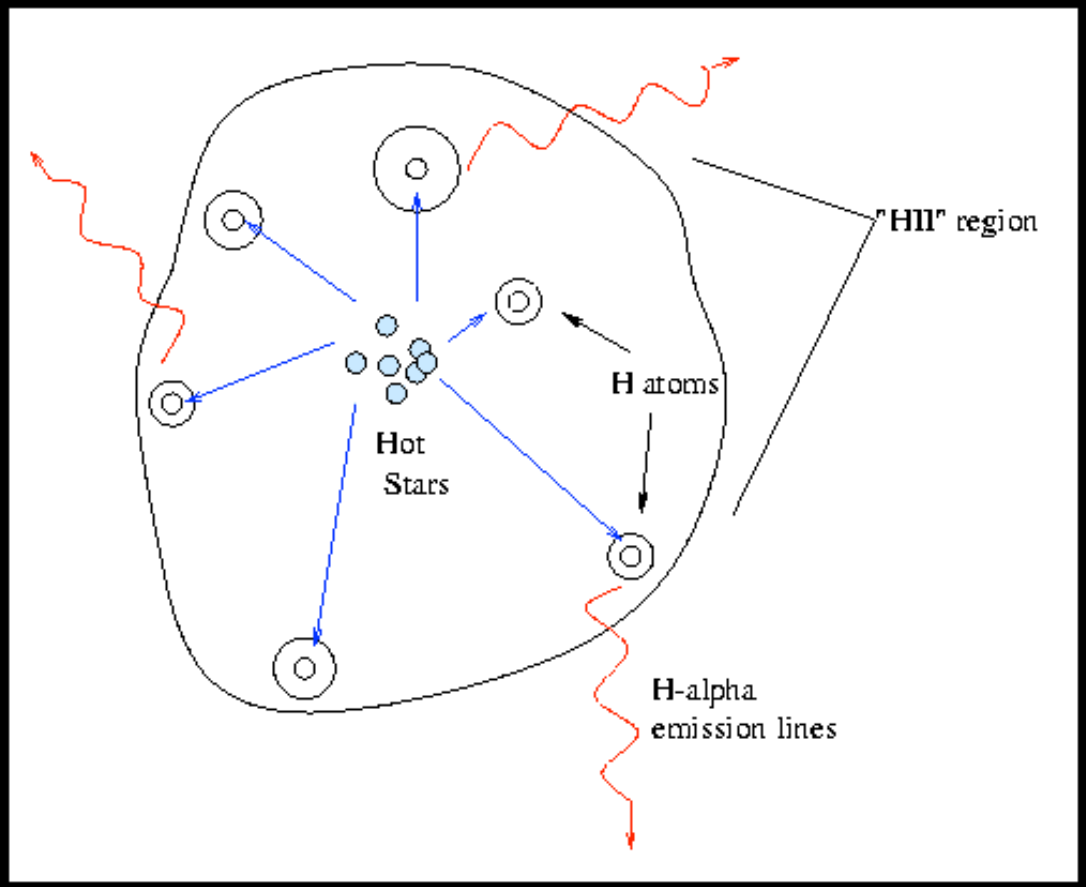
An interesting history of Y_P inferences



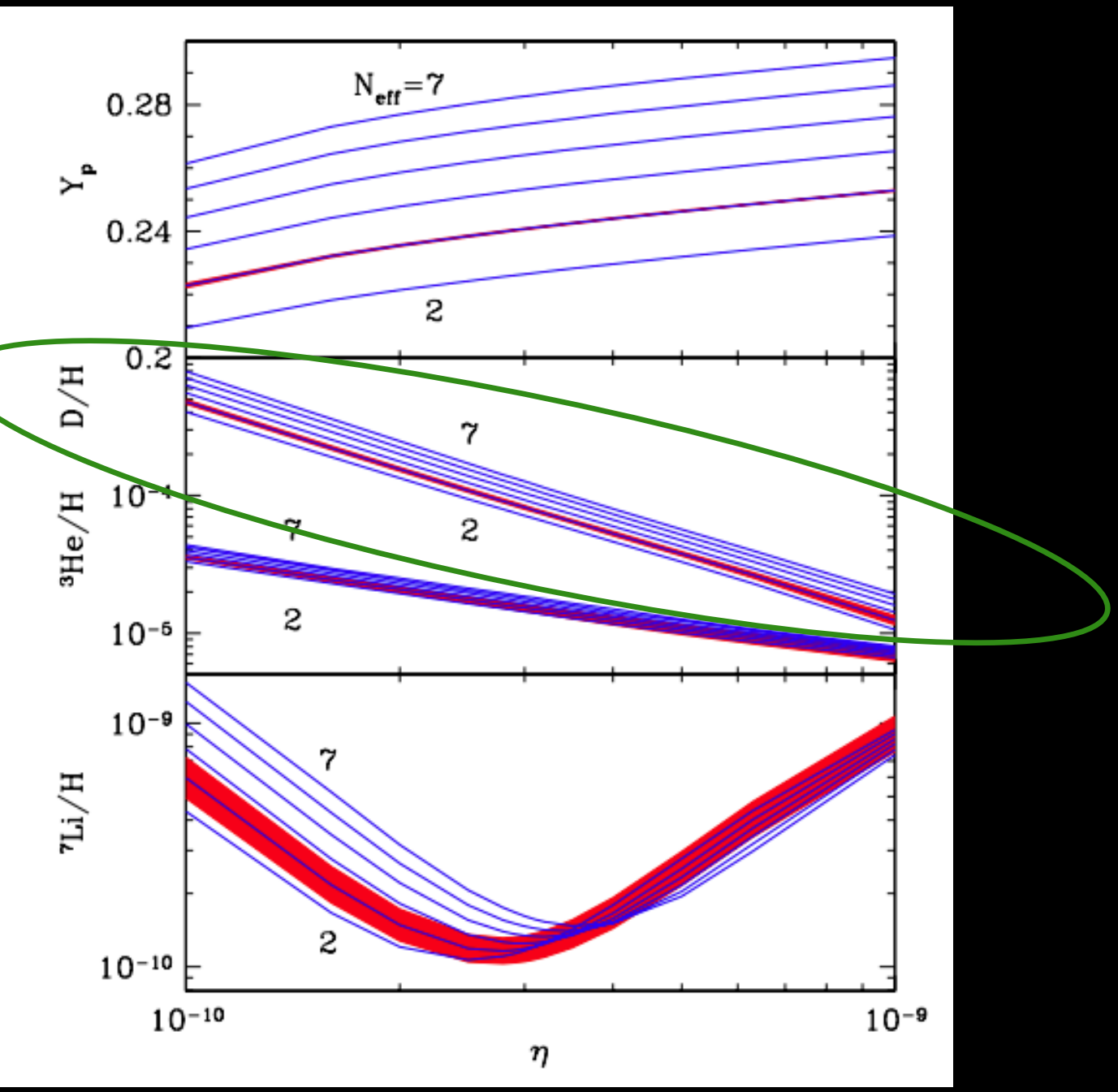
prediction of Yp

Figure credit: Erik Aver

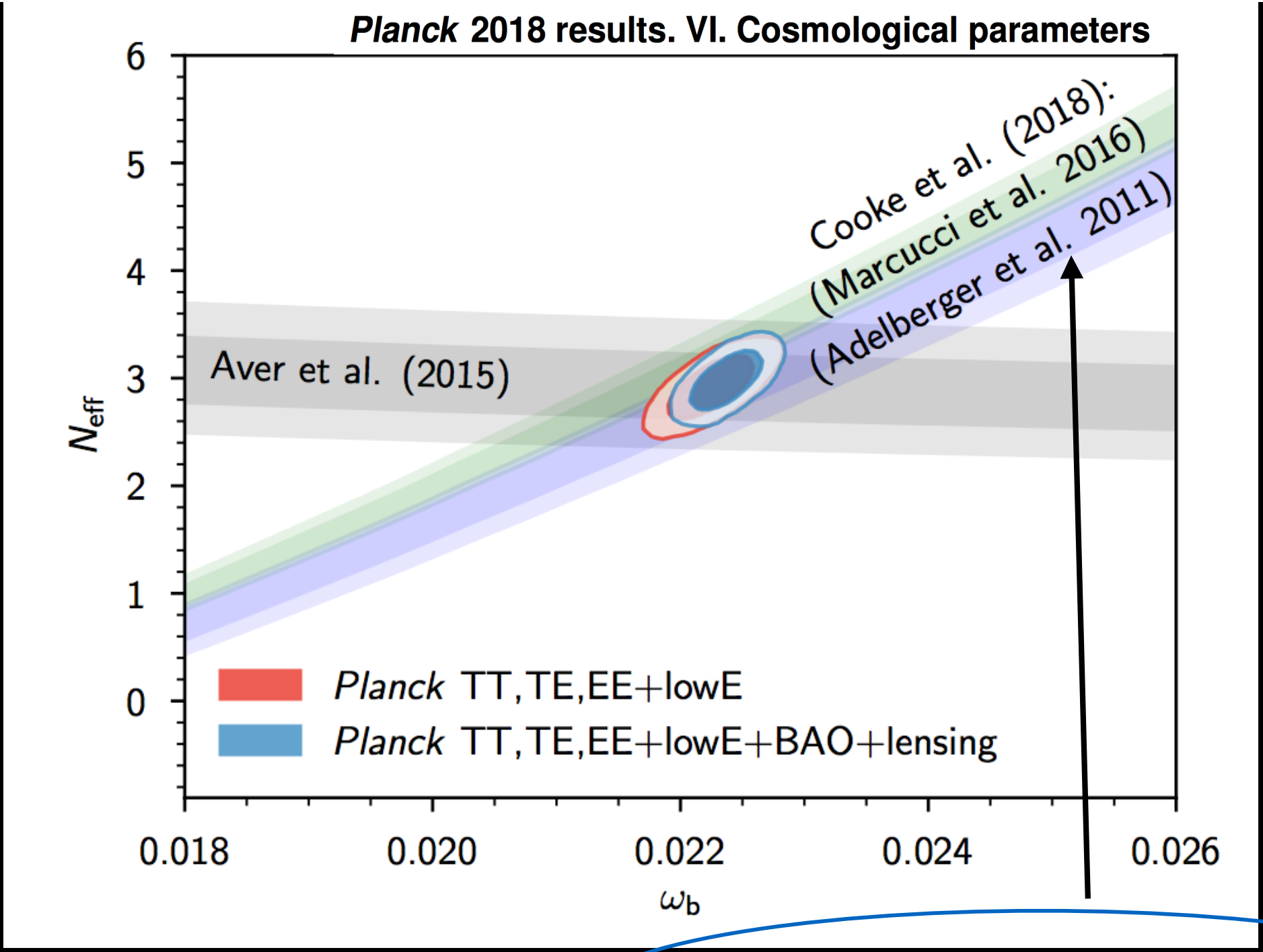
Is the modeling still overly simplistic?



Cyburt, Olive & Fields (2001)



baryon-to-photon ratio



Based on Deuterium/Hydrogen inferred from quasar absorption line systems

Neutrinos (and other light and dark relics) and Cosmology

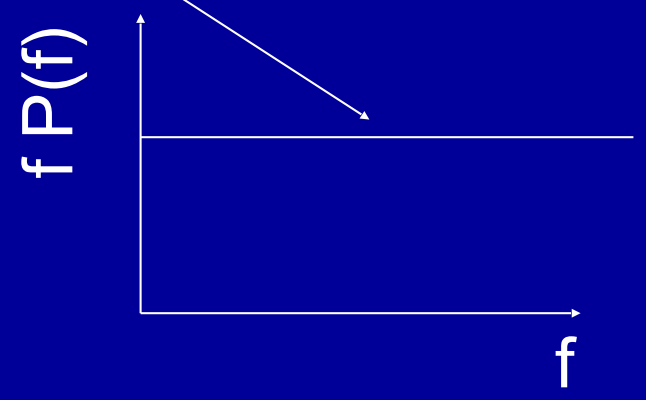
- The Source
- The Detectors
  - Light element abundances
  - CMB temperature and polarization power spectra
  - Matter power spectrum at late times

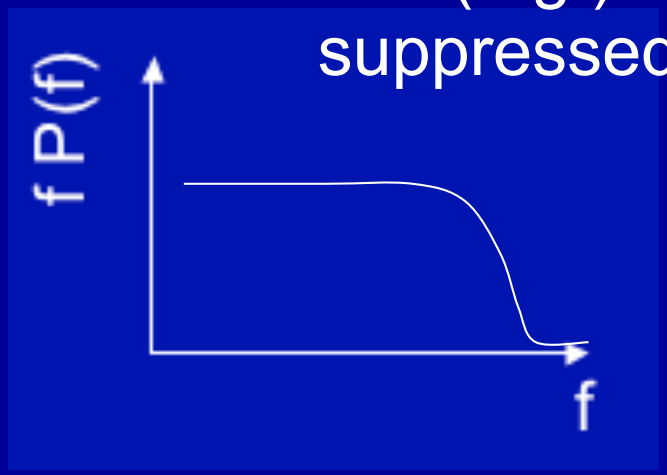
The CMB is Like a Detector of Some Noise Source

1/f noise

Transfer function has (e.g.) suppressed high f

detector





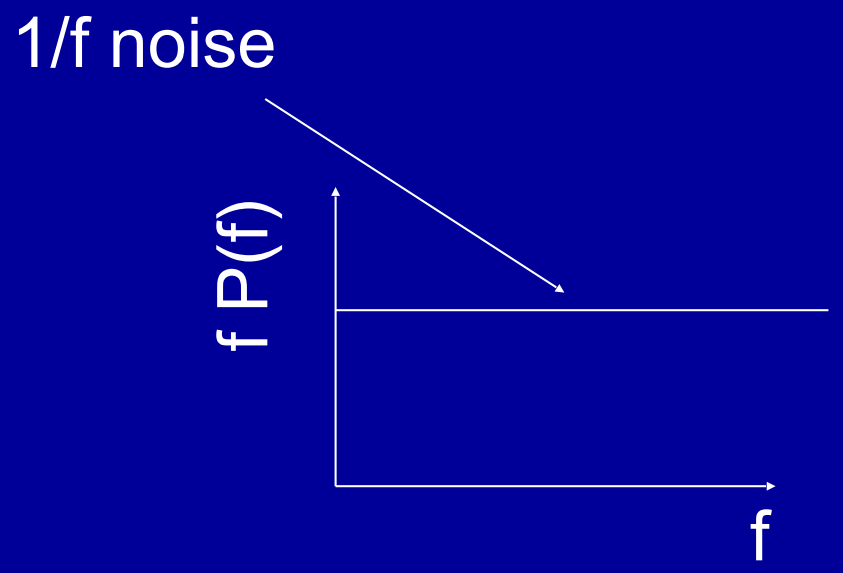
CMB

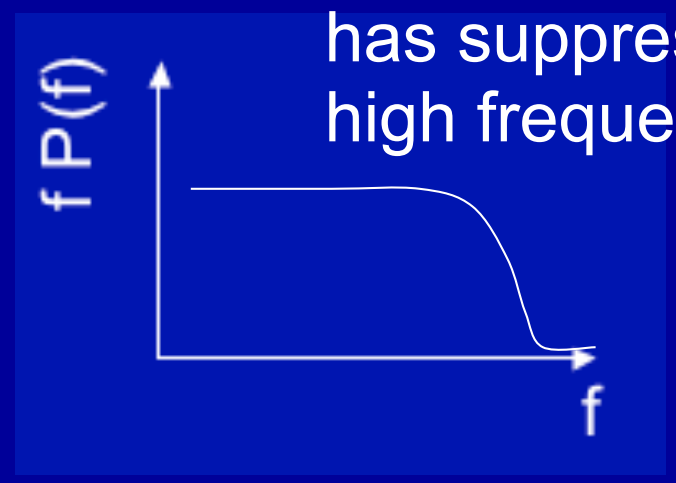
Noise source (input)

Detector output

The CMB is Like a Detector of Some Noise Source

detector





Transfer function has suppressed high frequencies

CMB

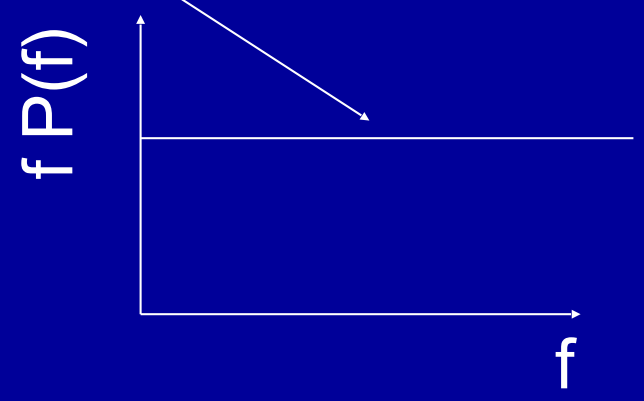
Noise source (input)

Detector output

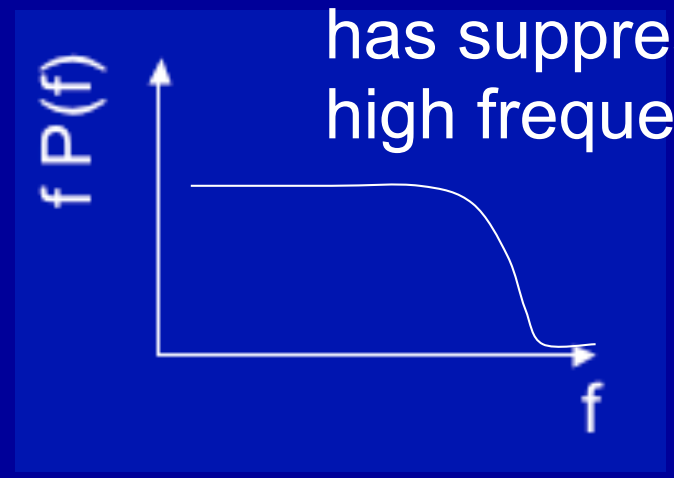
The CMB is Like a Detector of Some Noise Source

detector

1/f noise

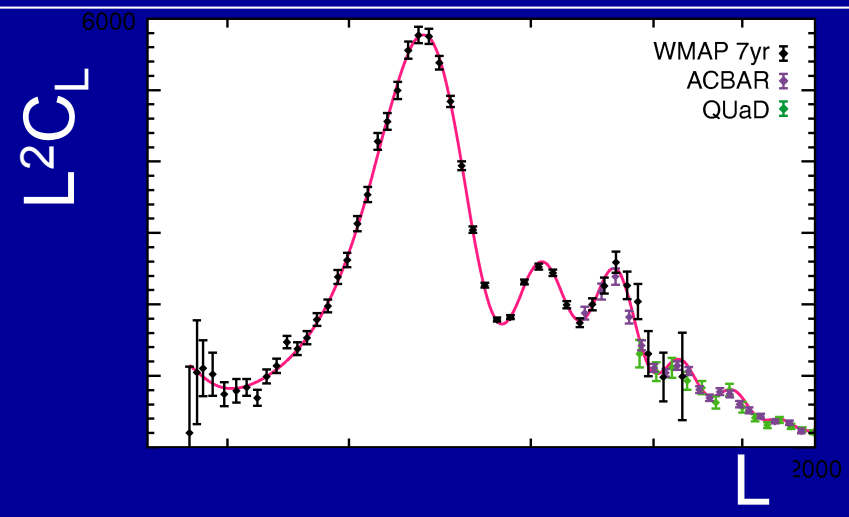


Transfer function has suppressed high frequencies



CMB

Noise source (input)



Detector output

Impact of Neff on CMB power spectra

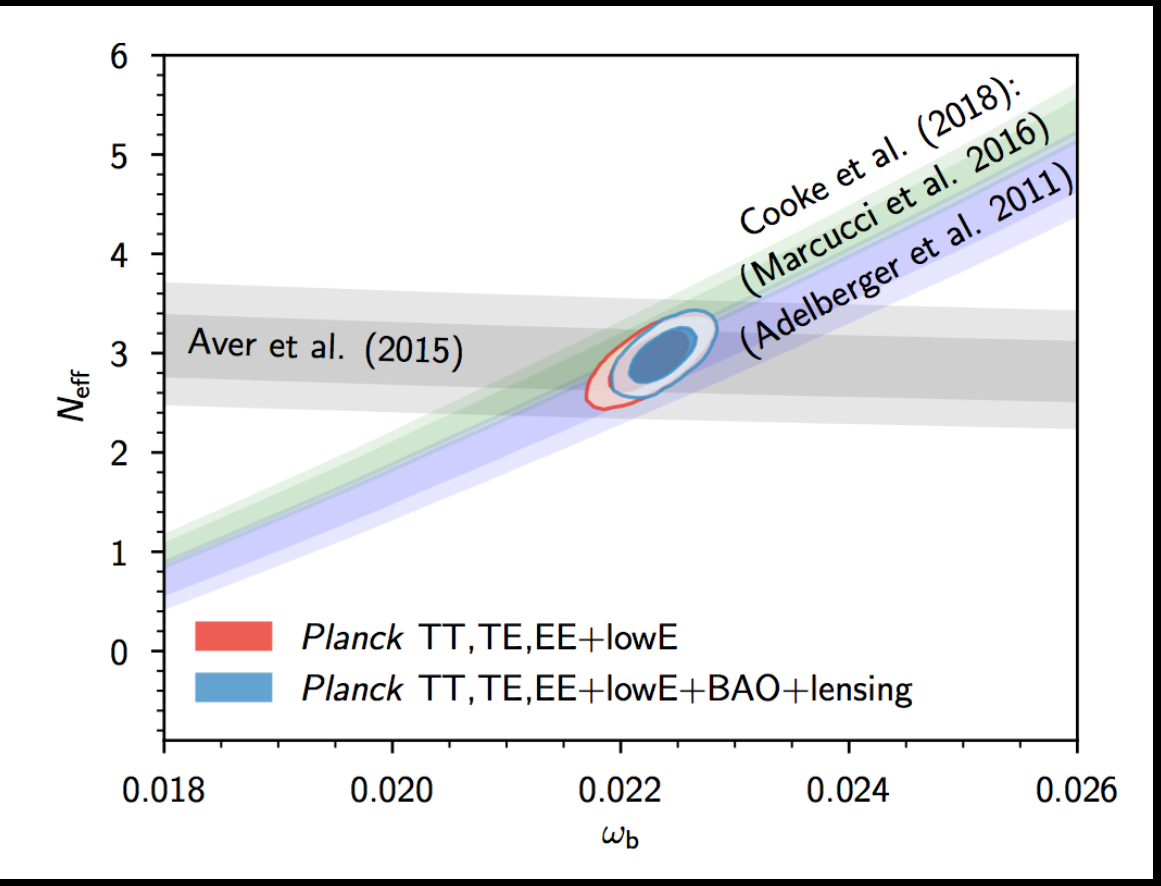
- Via background cosmology
  - Sound horizon
  - Photon diffusion scale

- Via Perturbations
  - Shift in temporal phase of acoustic oscillations

Prediction: Bashinsky & Seljak (2004)

Detection: Follin, LK, Millea and Pan (2015)

Planck 2018 results. VI. Cosmological parameters



$N_{\rm eff} = 3.00^{+0.57}_{-0.53}$ (95 %, *Planck* TT+lowE),

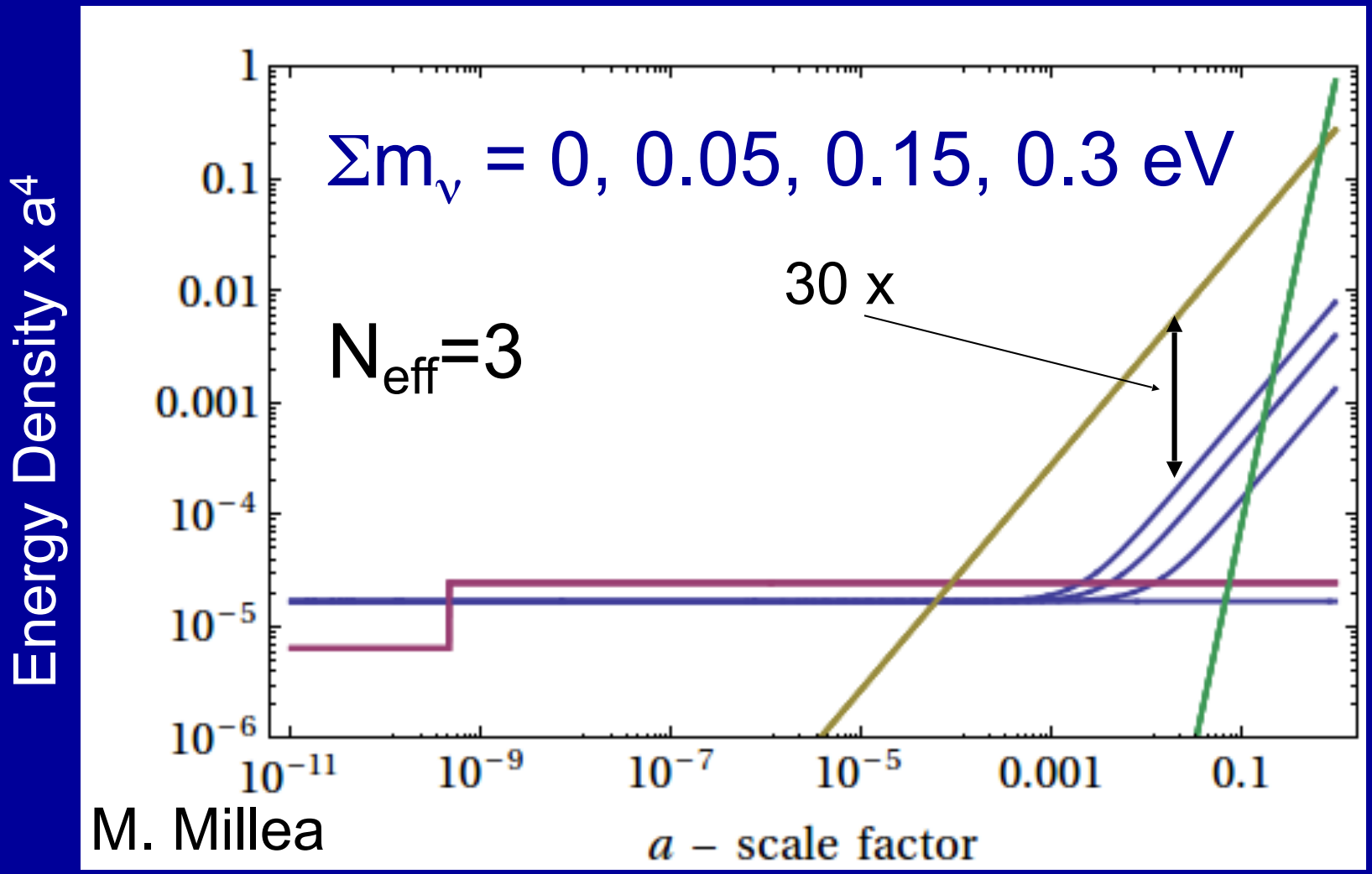
$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95 %, *Planck* TT,TE,EE+lowE),

$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (95 %, TT,TE,EE+lowE+lensing +BAO).

Neutrinos (and other light and dark relics) and Cosmology

- The Source
- The Detectors
  - Light element abundances
  - CMB temperature and polarization power spectra
  - Matter power spectrum at late times

Impact of Σm_ν



M. Millea

Planck 2018 results. VI. Cosmological parameters

$\sum m_\nu < 0.16$ eV (95 %, *Planck* TT+lowE+BAO),

$\sum m_\nu < 0.13$ eV (95 %, *Planck* TT,TE,EE+lowE +BAO),

and combining with lensing the limits further tighten to

$\sum m_\nu < 0.13$ eV (95 %, *Planck* TT+lowE+lensing +BAO),

$\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

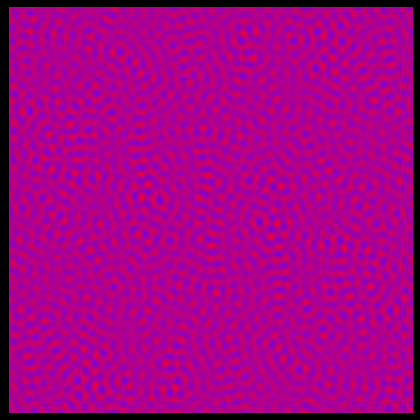
Neff + mnu constraints important for model building

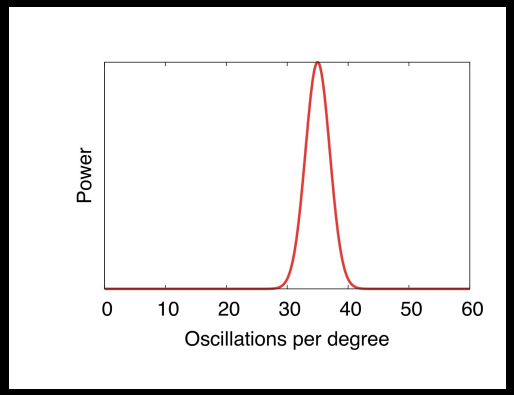
Example: m ~ eV extensions motivated by neutrino oscillation experiments

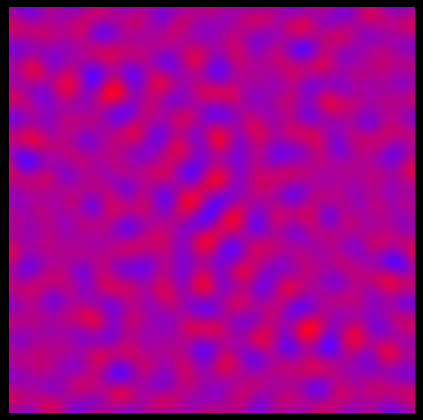
Typically thermal production is disastrous, but that's model dependent.

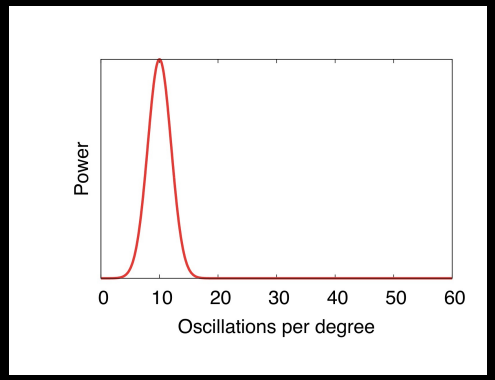
e.g., Cherry, Friedland & Shoemaker: https://arxiv.org/abs/1605.06506

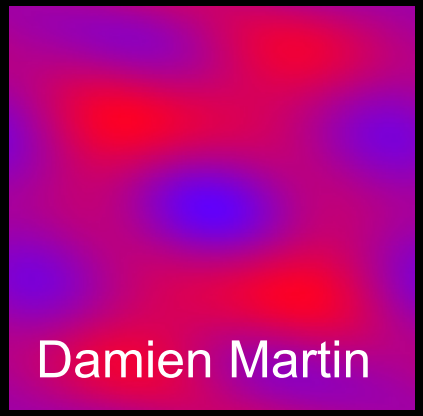
Understanding Power Spectra

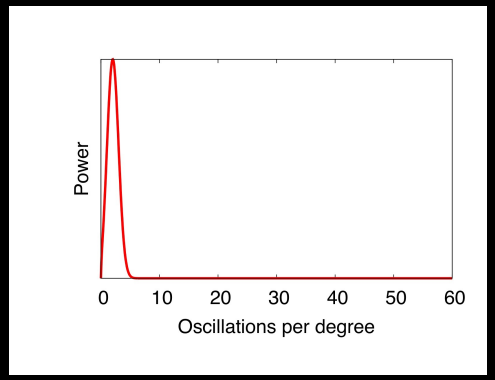








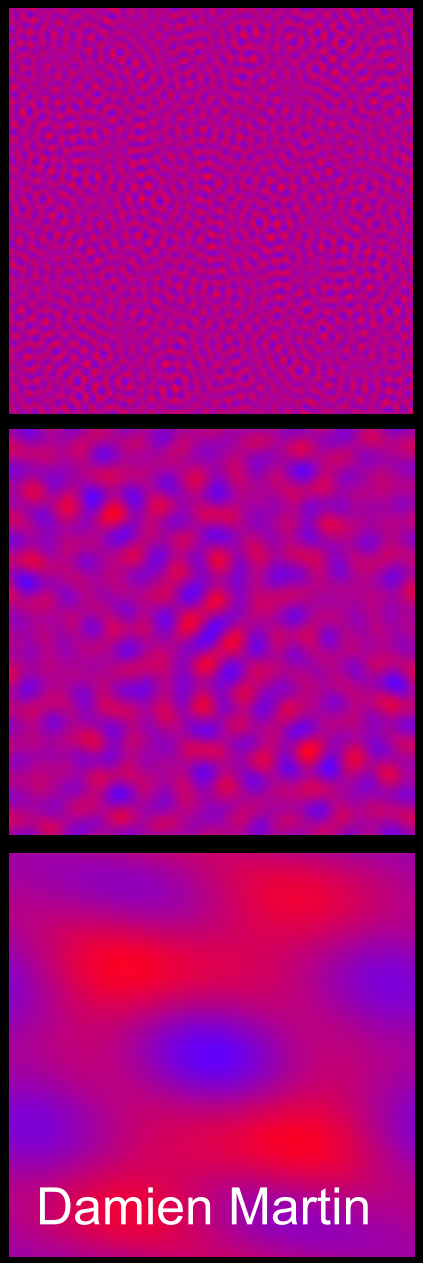




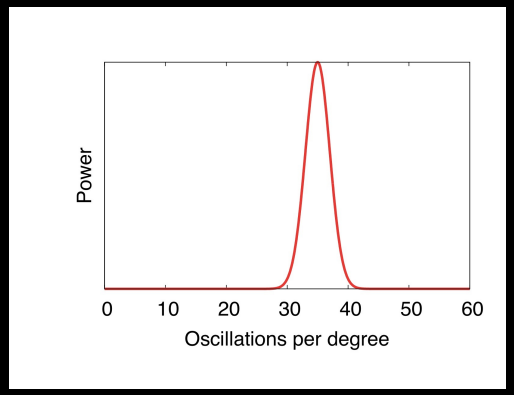
Sky map

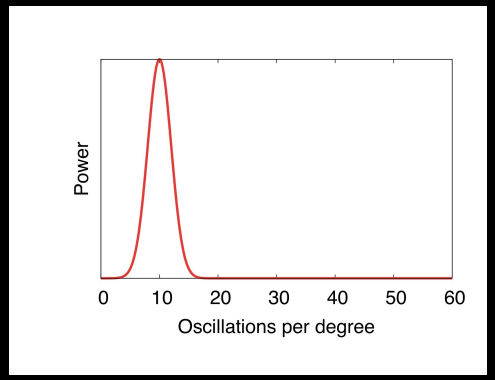
Power spectrum

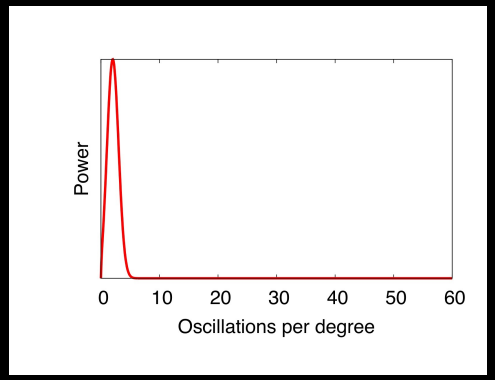
Understanding Power Spectra



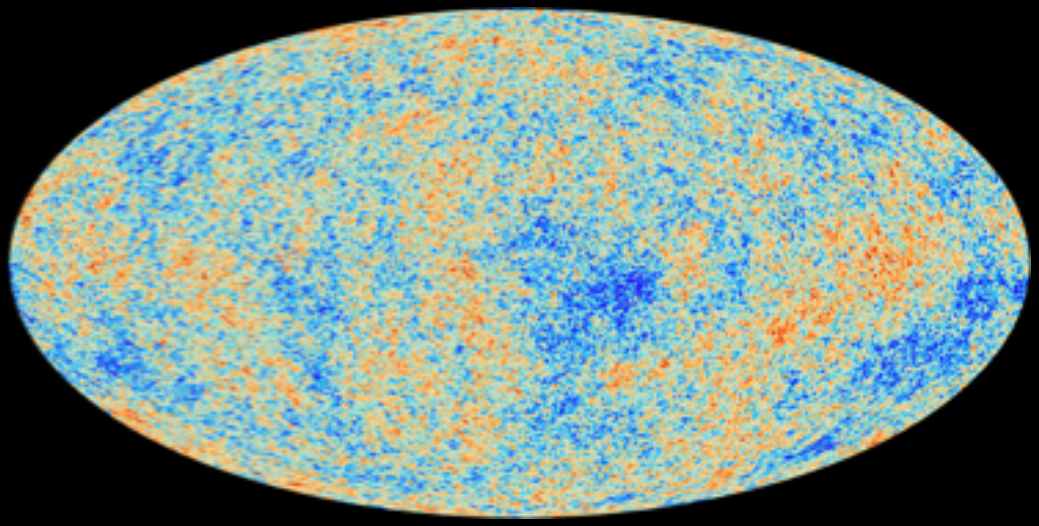
Sky map

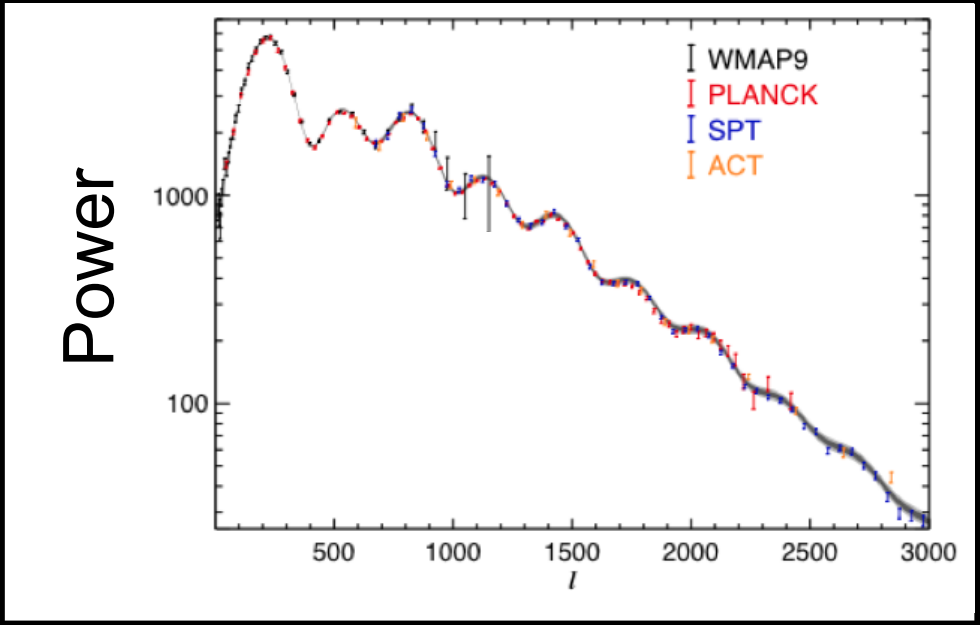




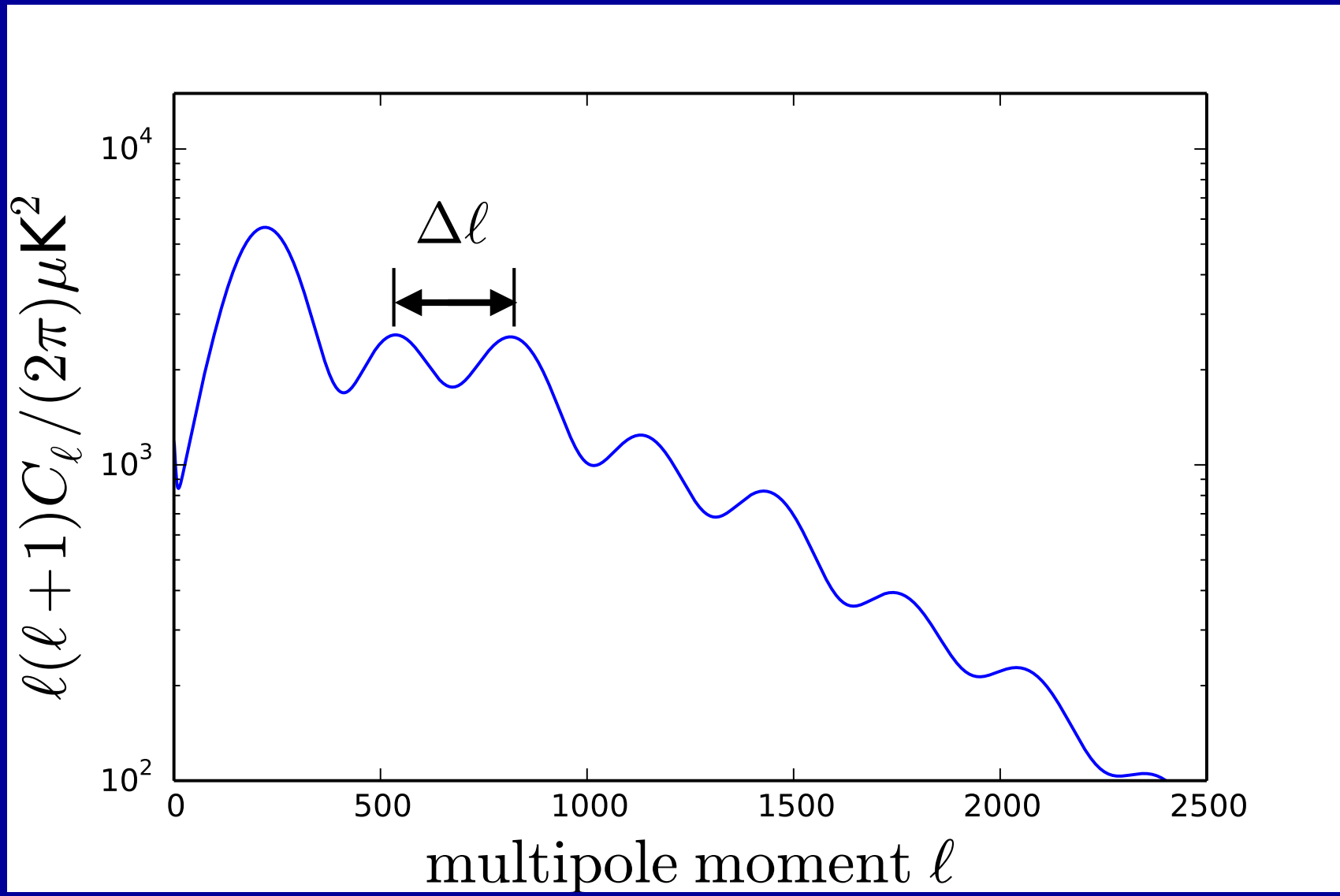


Power spectrum

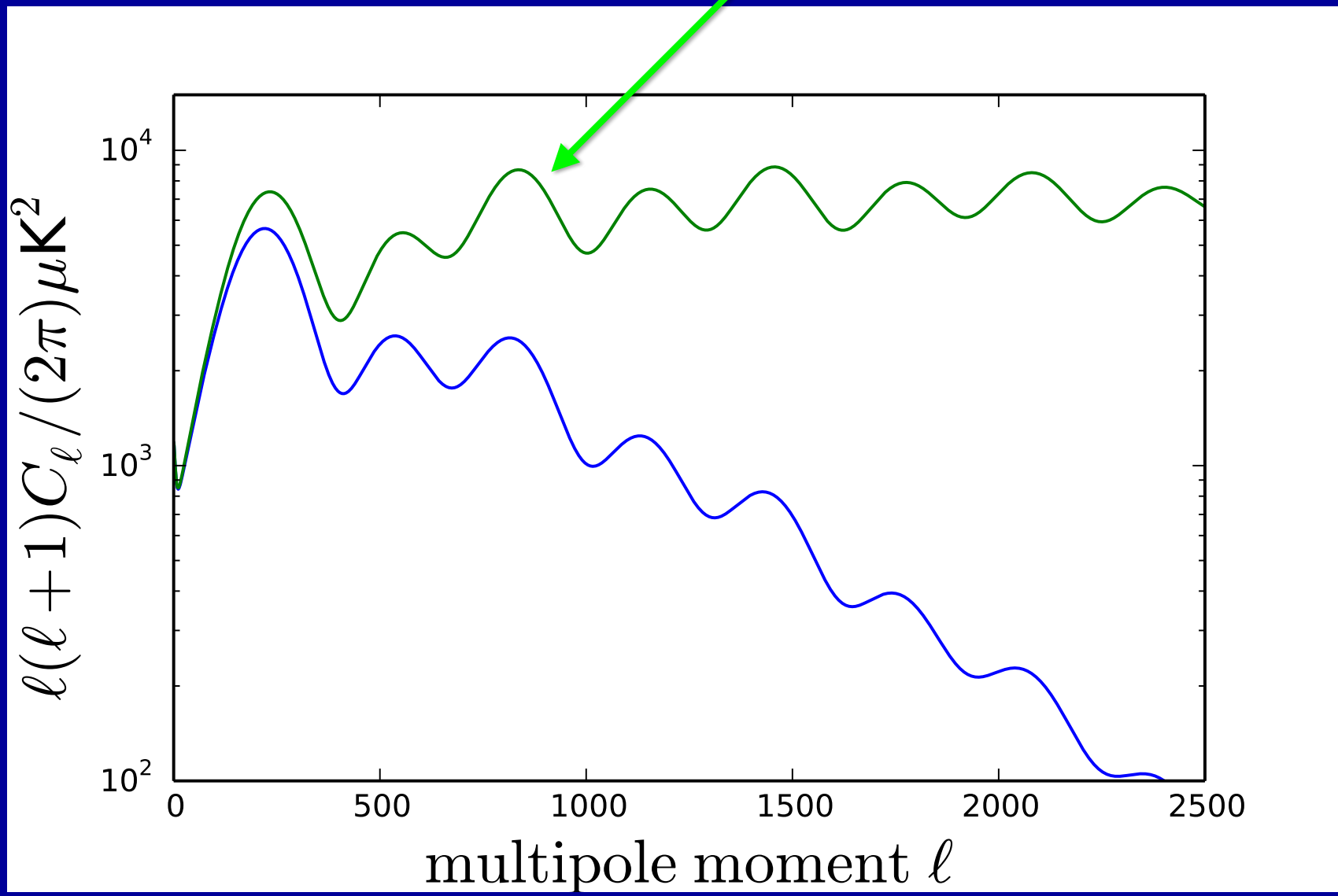




l = oscillations per great circle



Can infer $\theta_{\rm s}$ from peak spacing: $\theta_{\rm s} \simeq \pi/\Delta\ell$



angular scale of photon diffusion: θ_{d}

Short-baseline neutrino oscillations, Planck, and IceCube

John F. Cherry (Virginia Tech.), Alexander Friedland (SLAC), Ian M. Shoemaker (Penn State U.)

(Submitted on 20 May 2016)

We examine a framework with light new physics, which couples to the Standard Model only via neutrino mixing. Taking the hints from the short-baseline anomalies seriously and combining them with modern cosmological data and recent IceCube measurements, we obtain surprisingly effective constraints on the hidden force: keV $\lesssim M \lesssim 0.3$ GeV for the mediator mass and $g_h > 10^{-6} - 10^{-3}$ for the coupling constant. Flavor equilibration between the hidden and active neutrinos can be delayed until temperatures of ~ 1 MeV, but not below ~ 100 keV. This scenario can be tested with next-generation Cosmic Microwave Background, IceCube, and oscillation experiments.