Towards a Measurement of the Cosmic Neutrino Temperature

Bay Area Particle Theory Seminar, 2023

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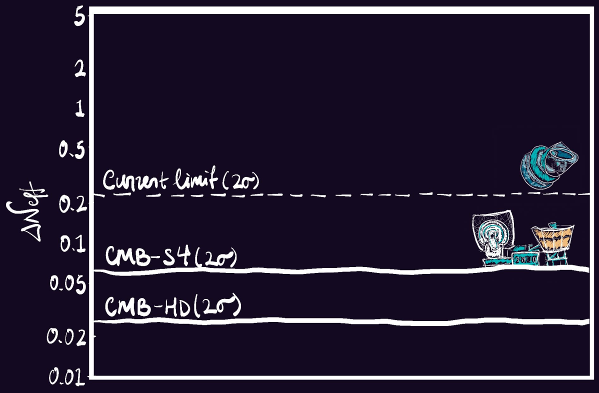
[231x.xxxxx]

This is a short story about dark radiation: the part we think we know, the part we know we don't, and how to ask the next questions

How I got here:



We will soon be performing extremely sensitive measurements of $\Delta N_{\rm eff}$

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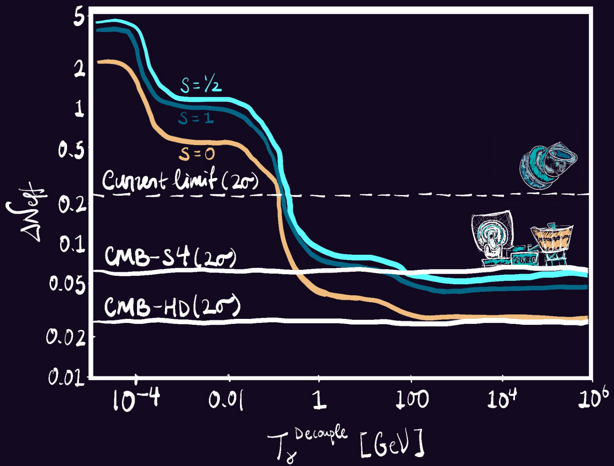

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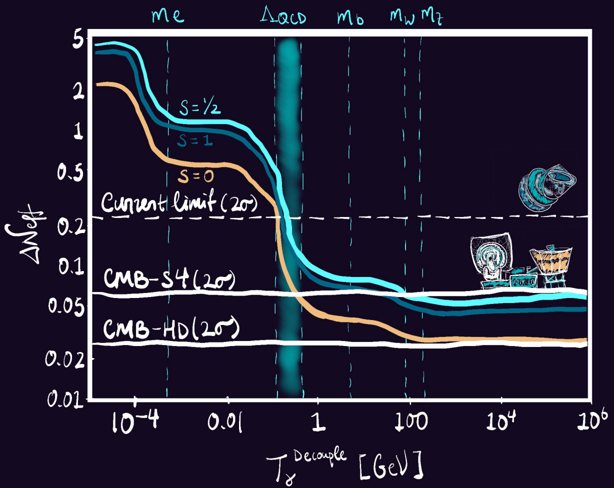

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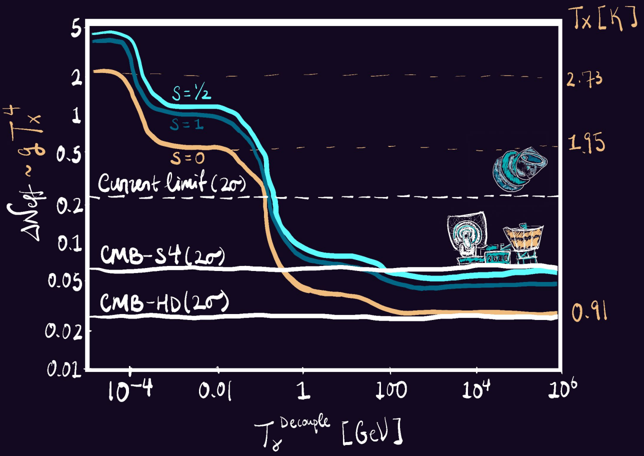

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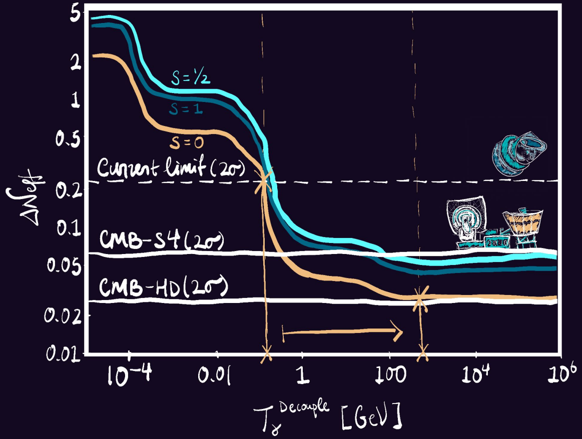

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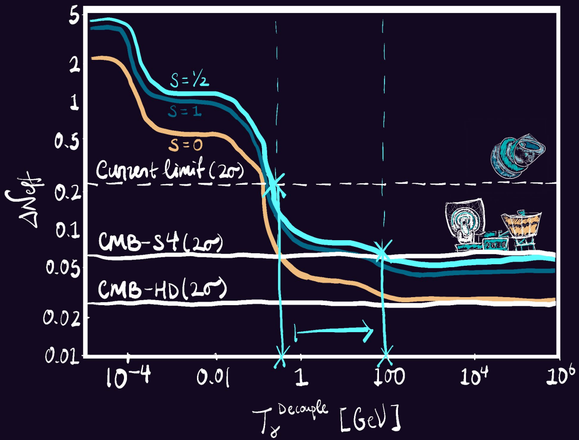


We will soon be performing extremely sensitive measurements of ΔN_{eff}

Decaying heavy Particles.

light thermal dark matter

ΔN_{eff}

Neutrino Interactions

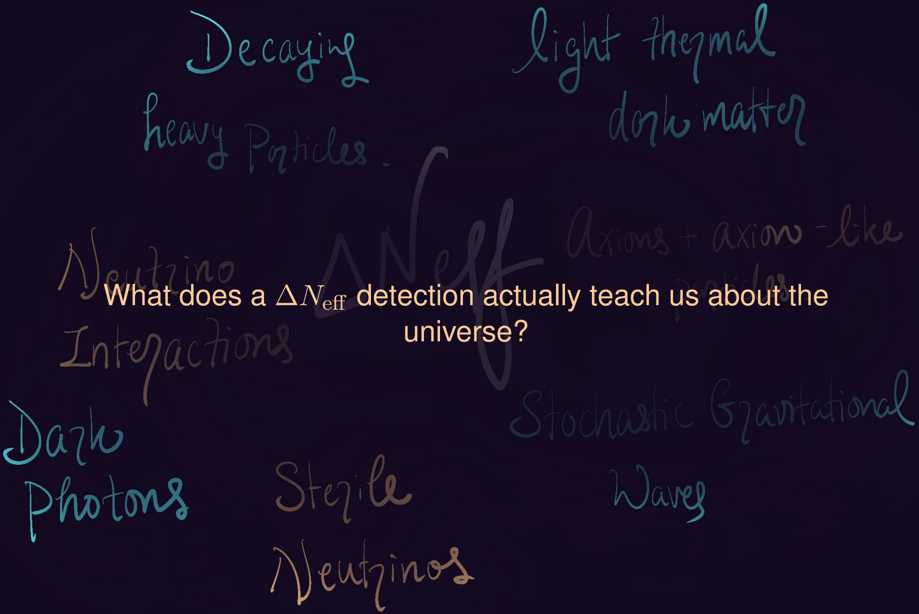
Axions + axion-like particles.

Dark Photons

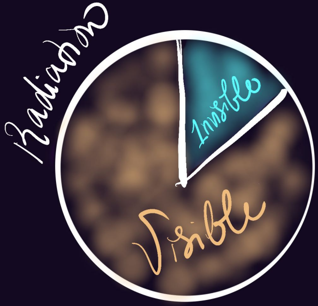
Sterile Neutrinos

Stochastic Gravitational Waves

What does a ΔN_{eff} detection actually teach us about the universe?



Let's back up a bit...



The amount of invisible radiation relative to the photon bath is parametrized by $N_{\rm eff}$

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_{\rm DR} \equiv \rho_\gamma \left(1 + \alpha N_{\rm eff}\right)$$

$$\alpha \equiv \frac{\rho_{1\nu}^{SM}(T)}{\rho_\gamma^{SM}(T)}$$

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_{\rm DR} \equiv \rho_\gamma \left(1 + \alpha N_{\rm eff}\right)$$

In the late universe (after e^+e^- annihilation)

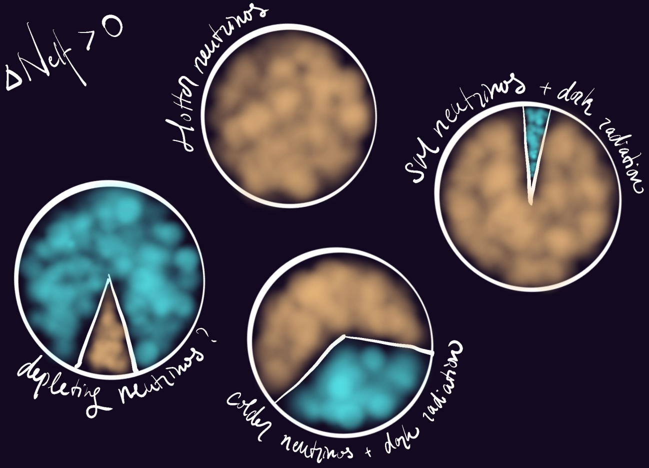
$$\alpha = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \approx \frac{7}{8}\left(\frac{1.95\,\mathrm{K}}{2.73\,\mathrm{K}}\right)^{4}$$

$$\Delta N_{\text{eff}} \equiv N_{\text{eff}} - N_\nu^{SM} \qquad N_\nu^{SM} = 3.044$$

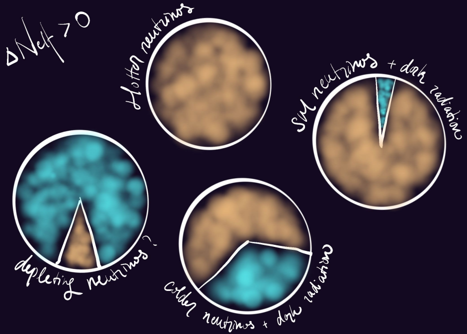
The $\Delta N_{\rm eff} = 0$ prediction of ΛCDM is actually two separate null hypotheses

$$N_{\rm eff} = N_\nu \quad \& \quad N_\nu = 3.044$$

How do we make progress upon a detection?



Can we start distinguishing between these various scenarios?



$$N_{\mathrm{eff}} \equiv N_\nu + N_{\mathrm{DR}}$$

How are neutrinos different from other dark radiation?

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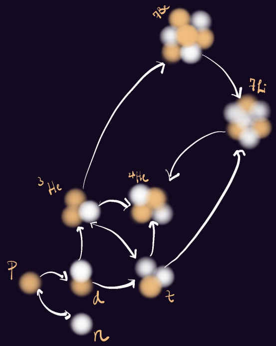
How are neutrinos different from other dark radiation?

- Neutrinos participate in weak interactions
  - Injecting neutrinos is different from injecting sterile DR at BBN
  - Rich science, but model dependent
  - See [Giovanetti et al. 2109.03246, Sabti et al. 1910.01649, Burns et al. 2307.07061] + separate upcoming work!



$$N_{\text{eff}} \equiv N_\nu + N_{\text{DR}}$$

How are neutrinos different from other dark radiation?

- Neutrinos participate in weak interactions
- Neutrinos have (a specific) mass
  - We expect them to become non-relativistic at $z \sim 100$
  - We have some priors on their mass hierarchies
  - ...and we might have a measurement of the total soon!

We can actually hope to see a mass detection relatively soon

$$\sum m_\nu \geq 60 \text{ meV}$$

$$\sigma(\Sigma m_\nu) = \begin{cases} 20 \text{ meV} & \text{SO} + \text{LiteBIRD } \tau + \text{ DESI} \\ 24 \text{ meV} & \text{S4} + \textit{Planck } \tau + \text{ DESI} \\ 14 \text{ meV} & \text{PICO} + \textit{Euclid} \\ 13 \text{ meV} & \text{CMB-HD} \end{cases}$$

This is also an interesting time to ask the question: in what sense is this a neutrino detection?

[Snowmass 2022, incl. 1907.08284, 2203.08093, 1902.10541, 2203.05728]

The behavior of neutrinos, as radiation and as free-streaming matter, relate to the neutrino temperature as

$$\rho_\nu \approx T_\nu^3 E_\nu \sim \begin{cases} T_\nu^4 & \to N_\nu \\ \sum m_\nu T_\nu^3 & \to \omega_\nu \end{cases}$$

This has always been an assumed value at

$$T_\nu = T_\nu^{\mathrm{SM}} = 1.95\ \mathrm{K} \qquad \text{at } z = 0$$

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Can we measure the neutrino temperature?

$\sim$ can we simultaneously measure $T_\nu,\ \sum m_\nu$, and N_{DR}?

Why care?

For the SM:

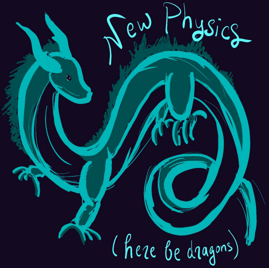
- Cosmology can *measure* this SM prediction instead of *assuming* it. That's cool!
- Verification that the thing galaxy surveys measure is neutrino-like (decoupled around e^+e^- annihilation)

Why care?

For the SM

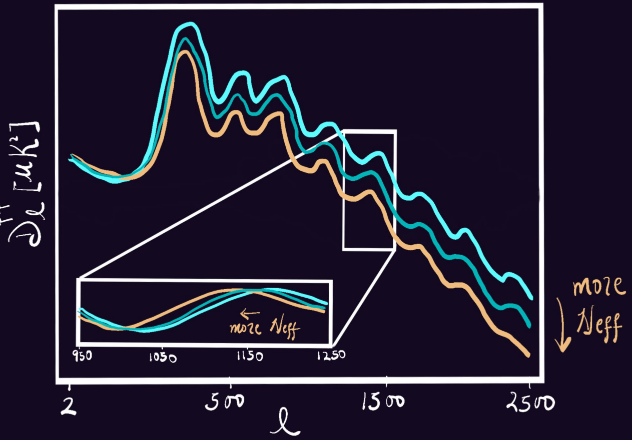
...And beyond:

- Understand what the viable model landscape actually looks like for dark radiation
- ... and how far we'd need to go to get answers



Let's talk observables... $\{T_\nu,\ \sum m_\nu,\ N_{DR}\}$

What does altering T_ν do to the CMB anisotropies?



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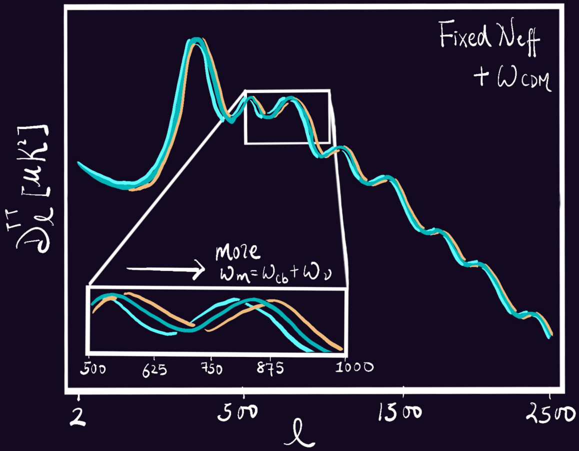
$$N_{\rm DR} \to N_{\rm eff}^{\rm fid} - N_\nu$$



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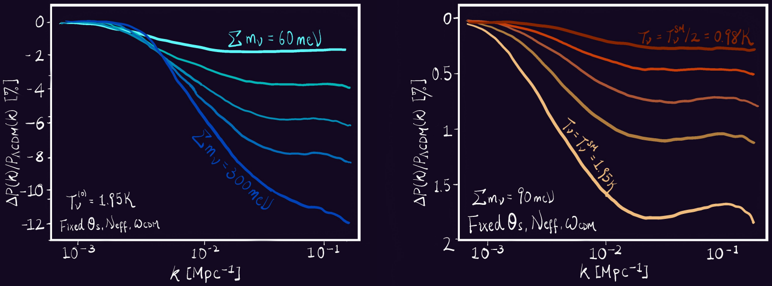
What does altering T_ν do to the matter power spectrum?



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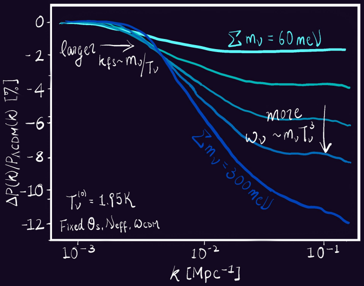
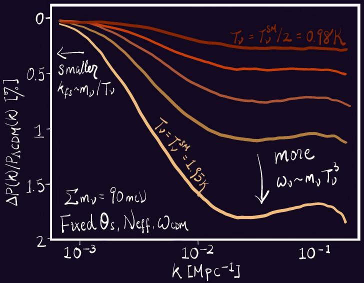
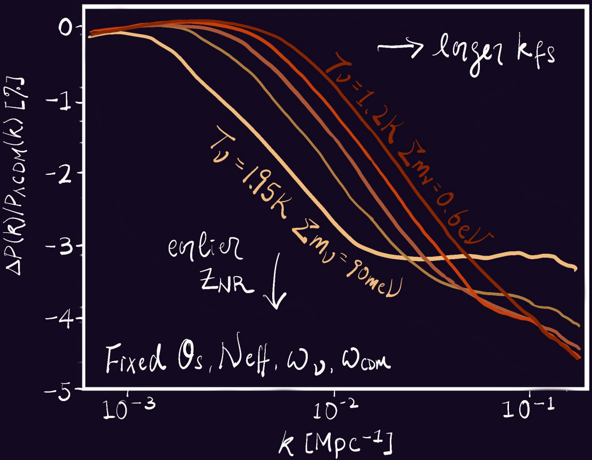
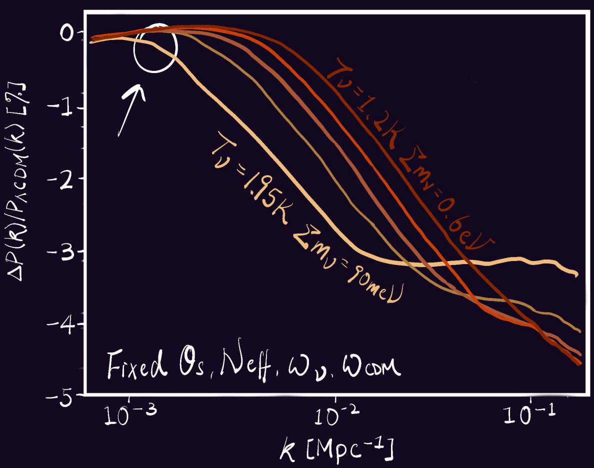




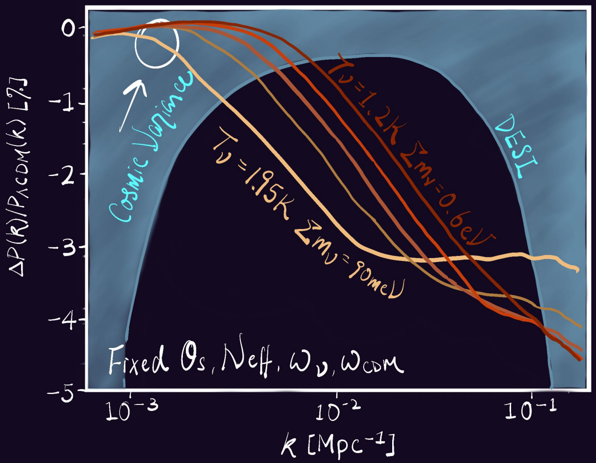
$$N_{\rm DR} \to N_{\rm eff}^{\rm fid} - N_\nu \qquad m_\nu \to m_\nu^{\rm fid}\left(\frac{T_\nu^{\rm fid}}{T_\nu}\right)^3$$



$$N_\nu \sim T_\nu^4 \qquad \omega_\nu \sim \sum m_\nu T_\nu^3 \qquad k_{\rm fs} \sim m_\nu / T_\nu$$



want to precisely measure both $\omega_\nu \sim \sum m_\nu T_\nu^3$ & $k_{\rm fs} \sim m_\nu / T_\nu$



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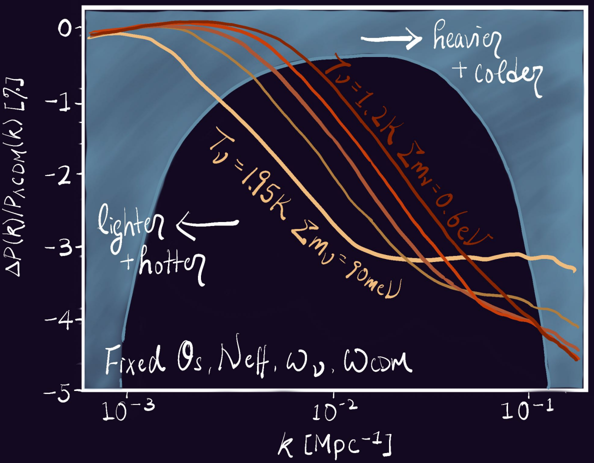
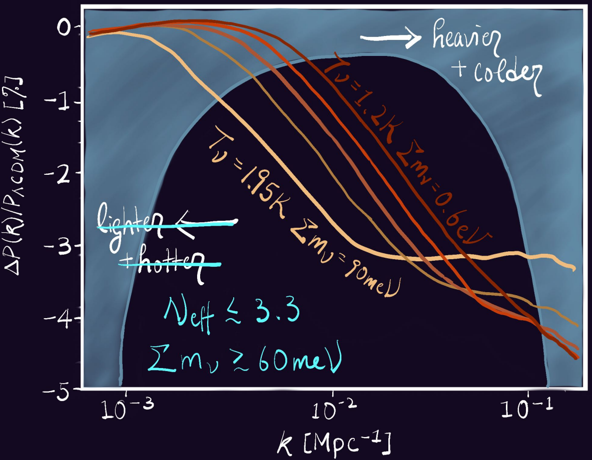
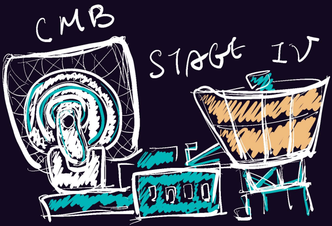


Viable parameter choices push $k_{\rm fs}$ *into* the sensitivity window



$$\{\omega_b, \omega_c, h, A_s, n_s, \tau_{\text{reio}}\} + \{m_\nu,\ T_\nu,\ N_{\text{DR}}\}$$



Fiducial :

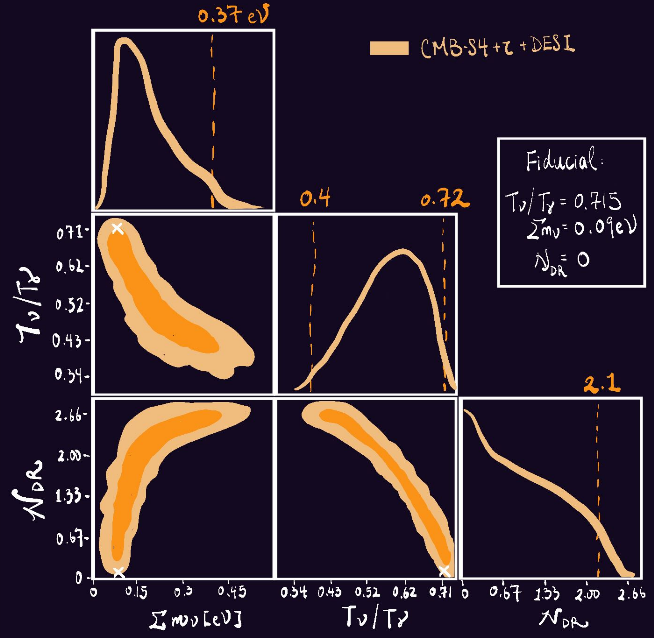
- LCDM
- $\sum m_\nu = 90$ meV (degenerate)
- $\dfrac{T_\nu^{(0)}}{T_\gamma^0} = 0.715 \quad (T_\nu^0 = 1.95\,\text{K})$
- $N_{\text{DR}} = 0$

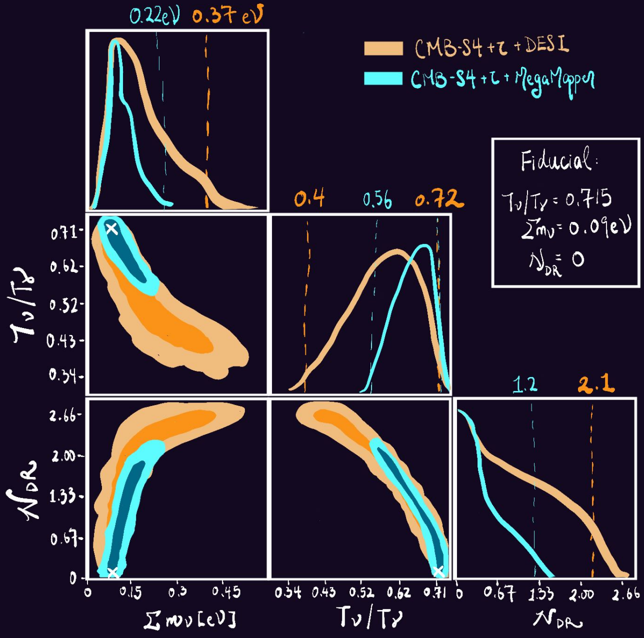
$$\{\omega_b, \omega_c, h, A_s, n_s, \tau_{\text{reio}}\} + \{m_\nu,\ T_\nu,\ N_{\text{DR}}\}$$

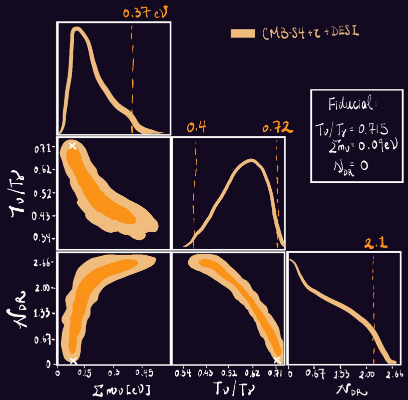
- CMB-S4 TT, TE, EE, lensing, prior on $\tau = 0.06 \pm 0.006$
- DESI: $\sim 10^6$ galaxies, $14000\ \text{deg}^2\,\text{survey}, z \in [0.65, 1.65]$
- Also, MegaMapper: $10^6 \to 10^8$ targets, $z \in [2, 5]$
- Burying details...
  RSD, AP, bias prescriptions $\{\beta_0, \beta_1, \sigma_{\text{NL}}\}$:

$$\tilde{P}(k, z, \mu) = \left(b + f_{\text{cb}}\mu^2\right)^2 \exp\left[-\mu^2 k^2 \sigma_v^2\right] P_{\text{cb}}(k, z)$$

$$b = \beta_0(1+z)^{\beta_1} \qquad \sigma_v^2 = (1+z)\frac{\sigma_0^2}{H^2} + \sigma_{\text{NL}}^2$$

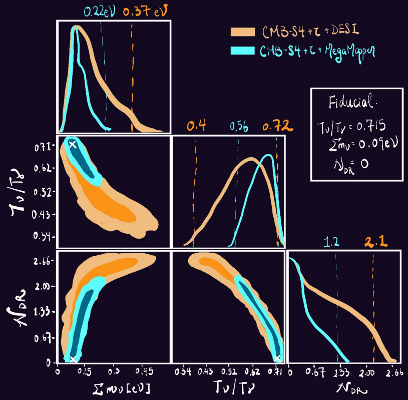

0.37 eV
CMB-S4 + τ + DESI
Fiducial:
Tν/Tγ = 0.715
Σmν = 0.09eV
N_DR = 0
0.4
0.72
2.1
Tν/Tγ
0.71
0.62
0.52
0.43
0.34
N_DR
2.66
2.00
1.33
0.67
0
0
0.15
0.3
0.45
Σ mν [eV]
0.34
0.43
0.52
0.62
0.71
Tν/Tγ
0
0.67
1.33
2.00
2.66
N_DR


0.22eV
0.37 eV
CMB-S4 + τ + DESI
CMB-S4 + τ + MegaMapper
Fiducial:
$T_\nu/T_\gamma = 0.715$
$\Sigma m_\nu = 0.09$ eV
$N_{DR} = 0$
0.4
0.56
0.72
1.2
2.1
T_ν/T_γ
N_{DR}
Σm_ν [eV]
T_ν/T_γ
N_{DR}



For near future experiments (S4, DESI), expect

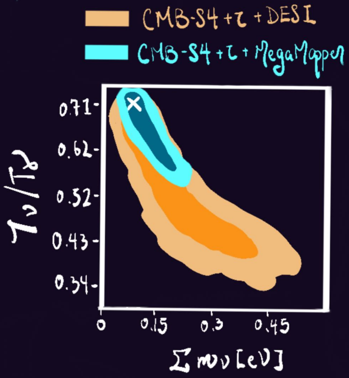
$$1.14\,\mathrm{K} \leq T_\nu \leq 1.954\,\mathrm{K}$$



DESI → MegaMapper,

$$1.53\,\mathrm{K} \ \leq T_\nu \leq 1.952\,\mathrm{K}$$

40% → 20% measurement

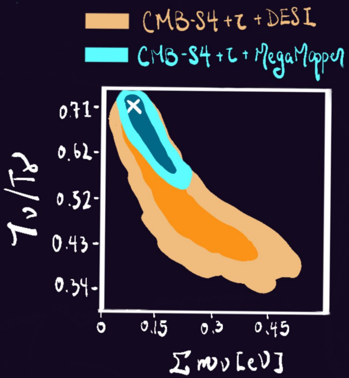


How well can we measure $\sum m_\nu$ and T_ν simultaneously?

- Still get a measurement for $\sum m_\nu > 0$

$$0.07\,\mathrm{eV} \leq \sum m_\nu \leq 0.22\,\mathrm{eV}$$

albiet degraded sensitivity

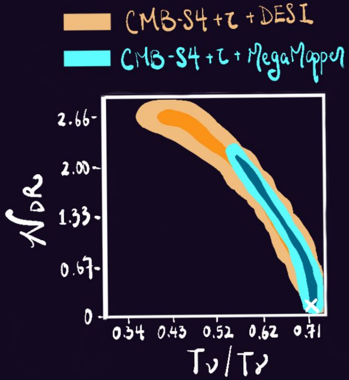


How well can we measure $\sum m_\nu$ and T_ν simultaneously?

- Still get a measurement for $\sum m_\nu > 0$

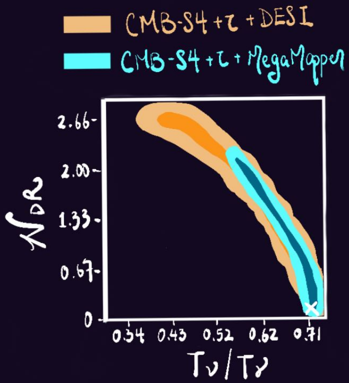
$$0.07\,\mathrm{eV} \ \leq \sum m_\nu \leq 0.22\,\mathrm{eV}$$

  albiet degraded sensitivity
- Still below KATRIN reach ($m_\nu \lesssim 0.2$ eV)



How well can we distinguish neutrinos and dark radiation?

- The data allows up to $\sim$ 60% of ρ_ν displaced by DR
- Requires heavy neutrinos



How well can we distinguish neutrinos and dark radiation?

- The data allows up to $\sim$ 60% of ρ_ν displaced by DR
- Requires heavy neutrinos
- Complementary with BBN:
  - Sensitive to the "most ν_e" neutrinos

In conclusion:

- We're starting to be sensitive to neutrino temperatures.
- 20% measurements in future, probably room to improve
- Go wild on the model building for now...
- Happy birthday BAPTS!

Side note about prior volumes: we need a detection to talk about this

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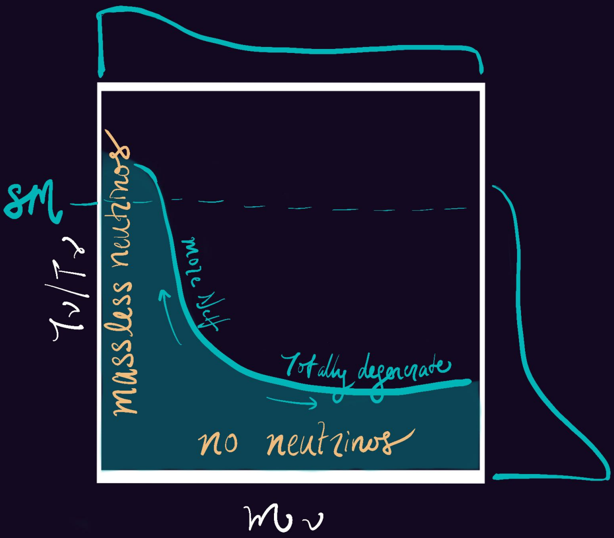

Side note about prior volumes: we need a detection to talk about this