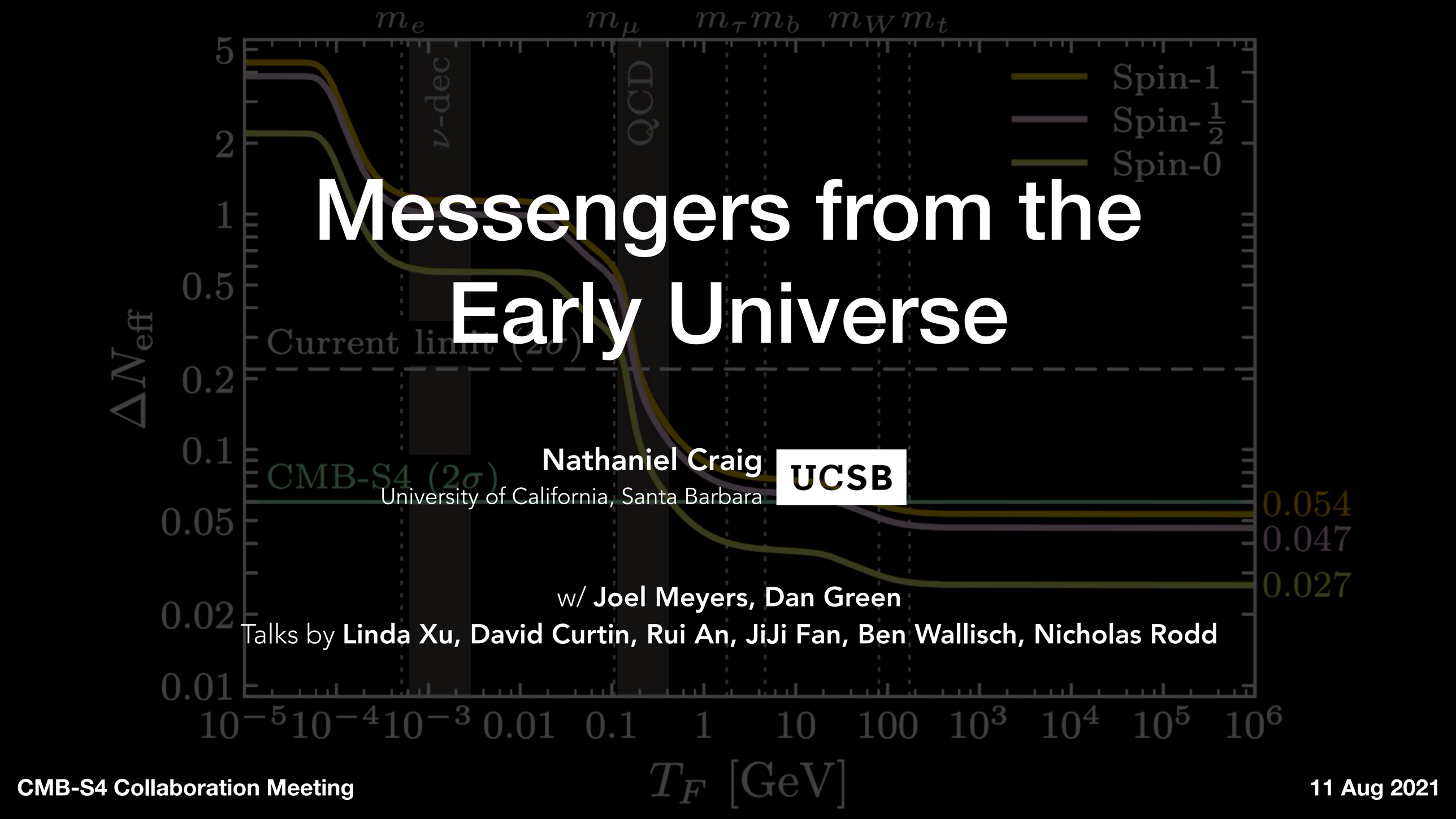


Messengers from the Early Universe

Nathaniel Craig
University of California, Santa Barbara
UCSB

w/ **Joel Meyers, Dan Green**

Talks by **Linda Xu, David Curtin, Rui An, JiJi Fan, Ben Wallisch, Nicholas Rodd**

Dark Energy

Dark Matter

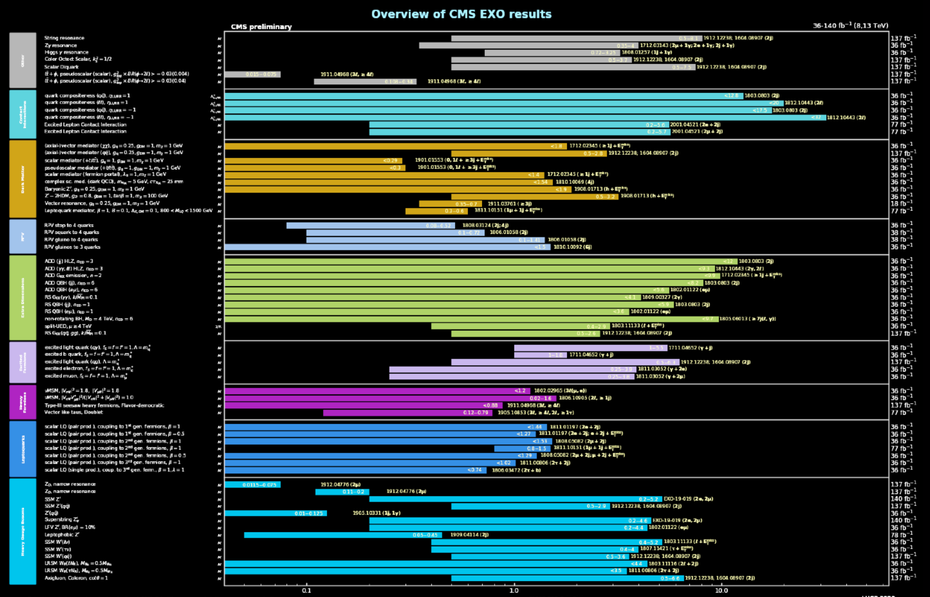
Hierarchy Problem

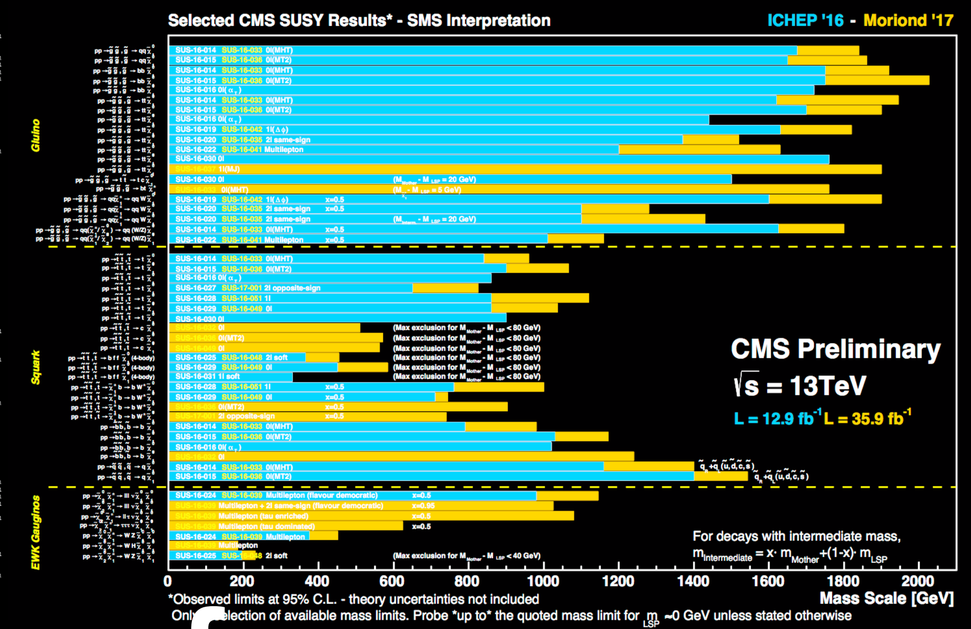
Baryon Asymmetry

Strong CP Problem

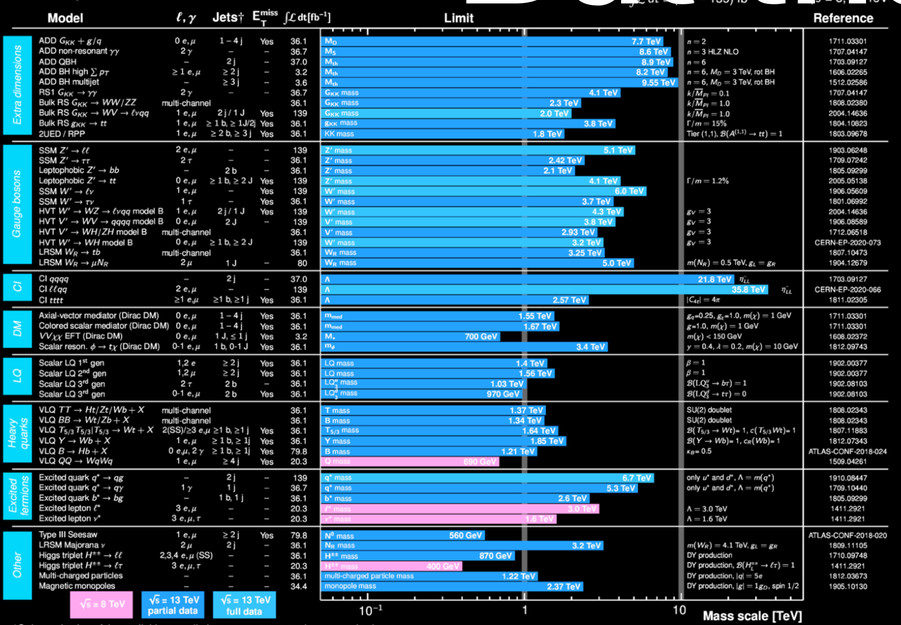
Neutrino Mass

Flavor Puzzle

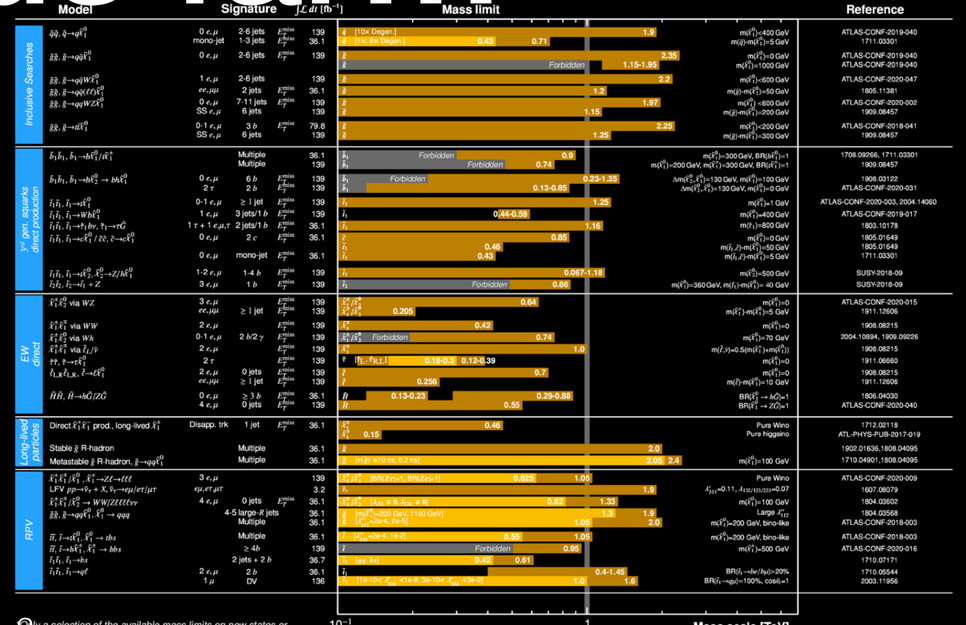




But thus far...



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

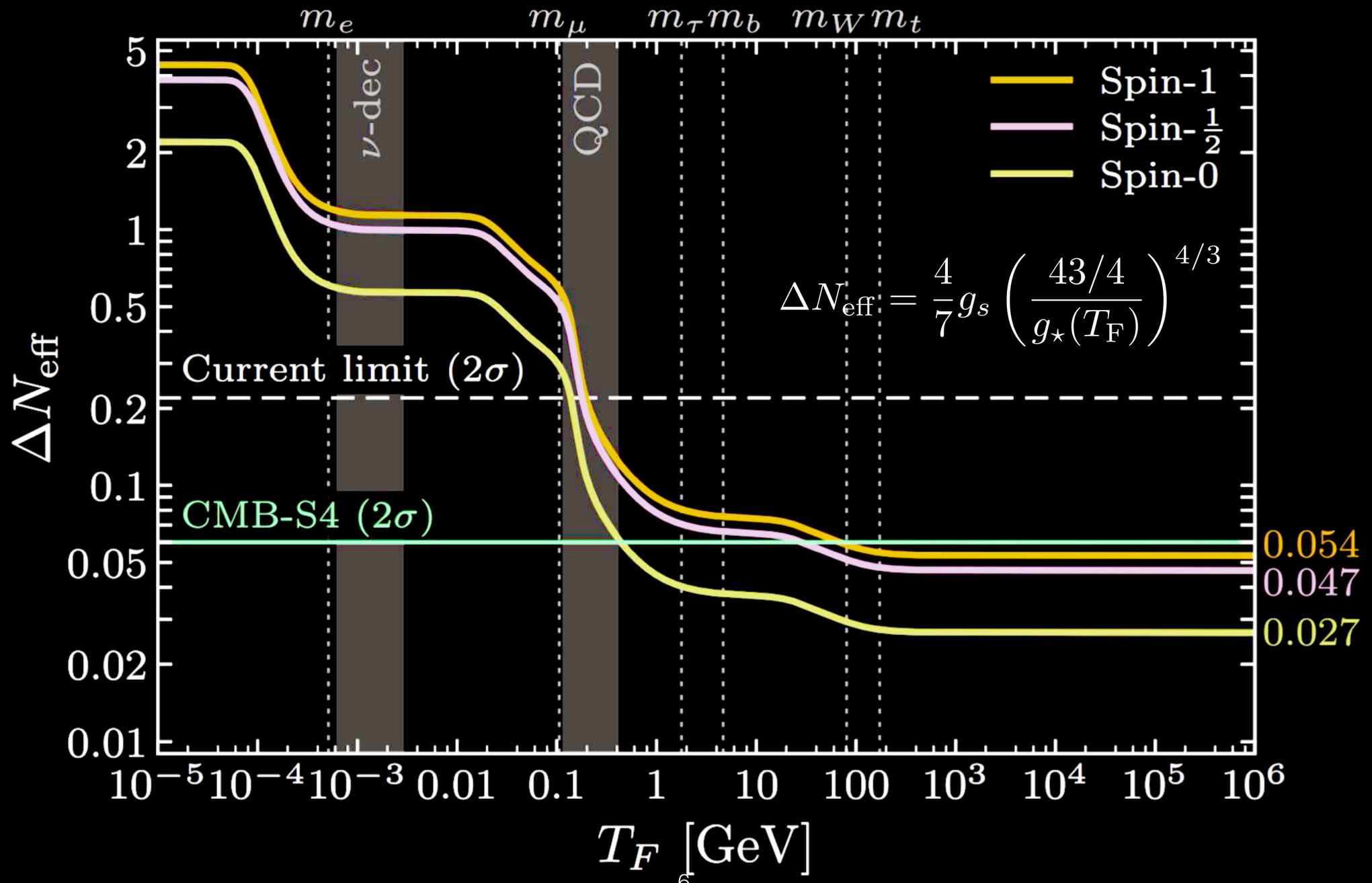


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Jolanda Neff

Tokyo 2020 Olympic gold medalist, MTB

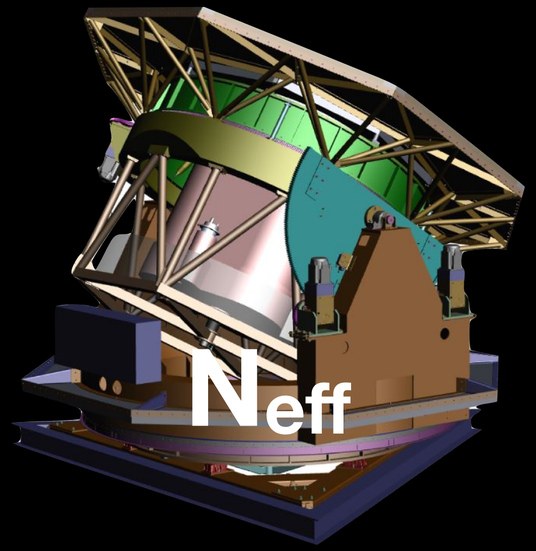
[CMB-S4 DSR (1907.04473), Green, Amin, Meyers, Wallisch (1903.04763)]



Dark Energy

Dark Matter

Hierarchy Problem



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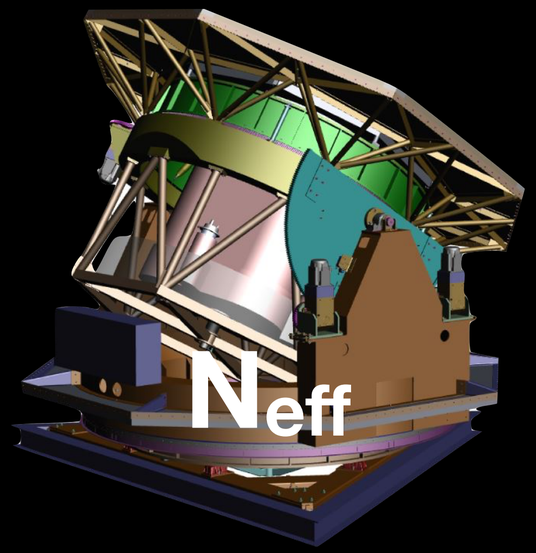

Baryon Asymmetry

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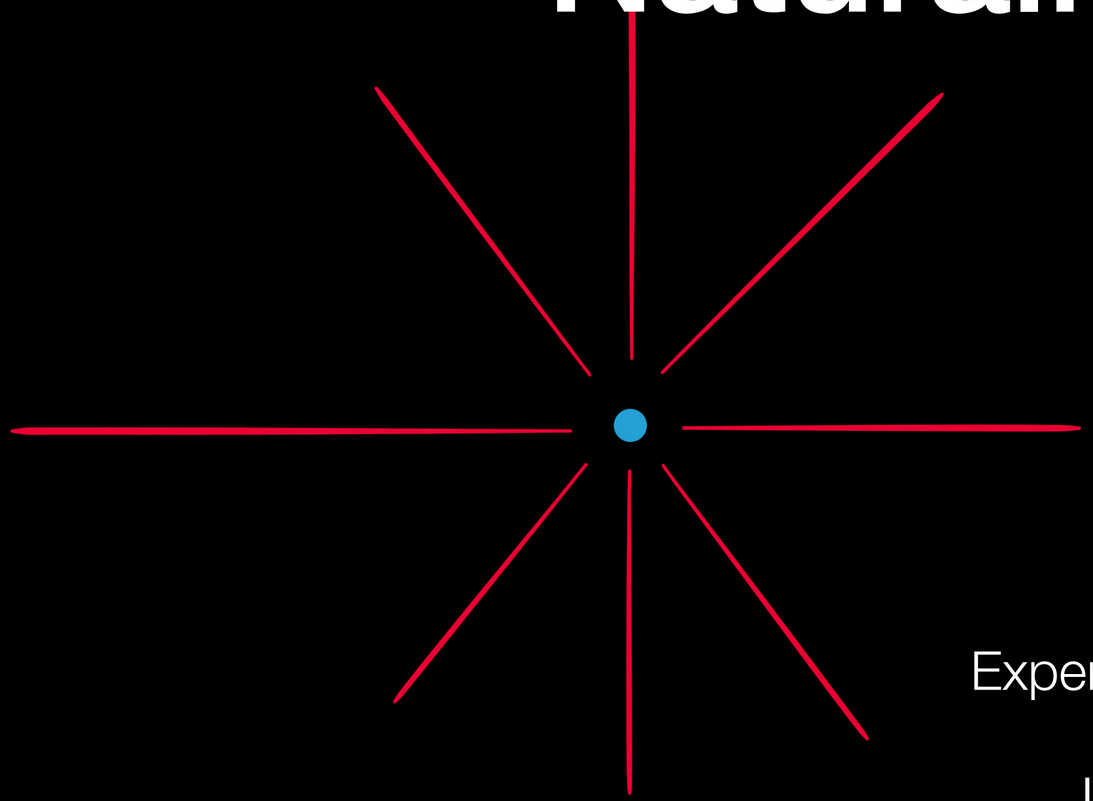
~~Hierarchy Problem~~
Naturalness Strategy



The naturalness strategy: an **analogy** from E&M

$$\Delta E_C = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}$$

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_C$$

Experimentally $r_e \lesssim 10^{-18}\,\mathrm{cm} \Rightarrow \Delta E_C \gtrsim 100\,\mathrm{GeV}$

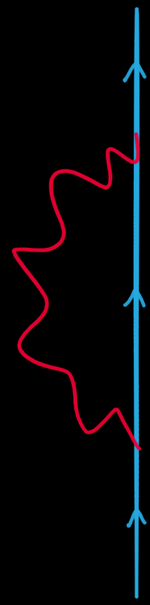
If so, $0.511 = -99999.489 + 100000.000\,\mathrm{MeV}$

To avoid fine-tuning, i.e. for the theory to be “natural”, need picture to change on scales below 2.8×10^{-13} cm

The Naturalness Strategy

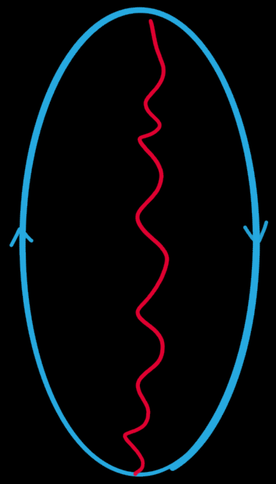
Dirac (1928/29): There is a new state in the relativistic quantum theory

Weisskopf (1939): Compute the self-energy including the positron

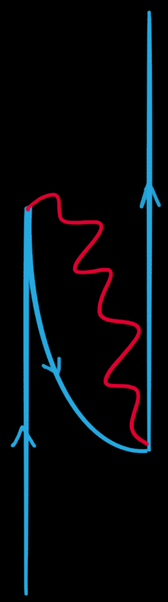


$$\Delta E = \Delta E_C + \dots$$

$$\Delta t \sim \hbar/\Delta E \sim \hbar/(2m_e c^2)$$



$$d \sim c\Delta t \sim 200 \times 10^{-13}\,\mathrm{cm}$$



$$\Delta E = -\Delta E_C + \dots$$

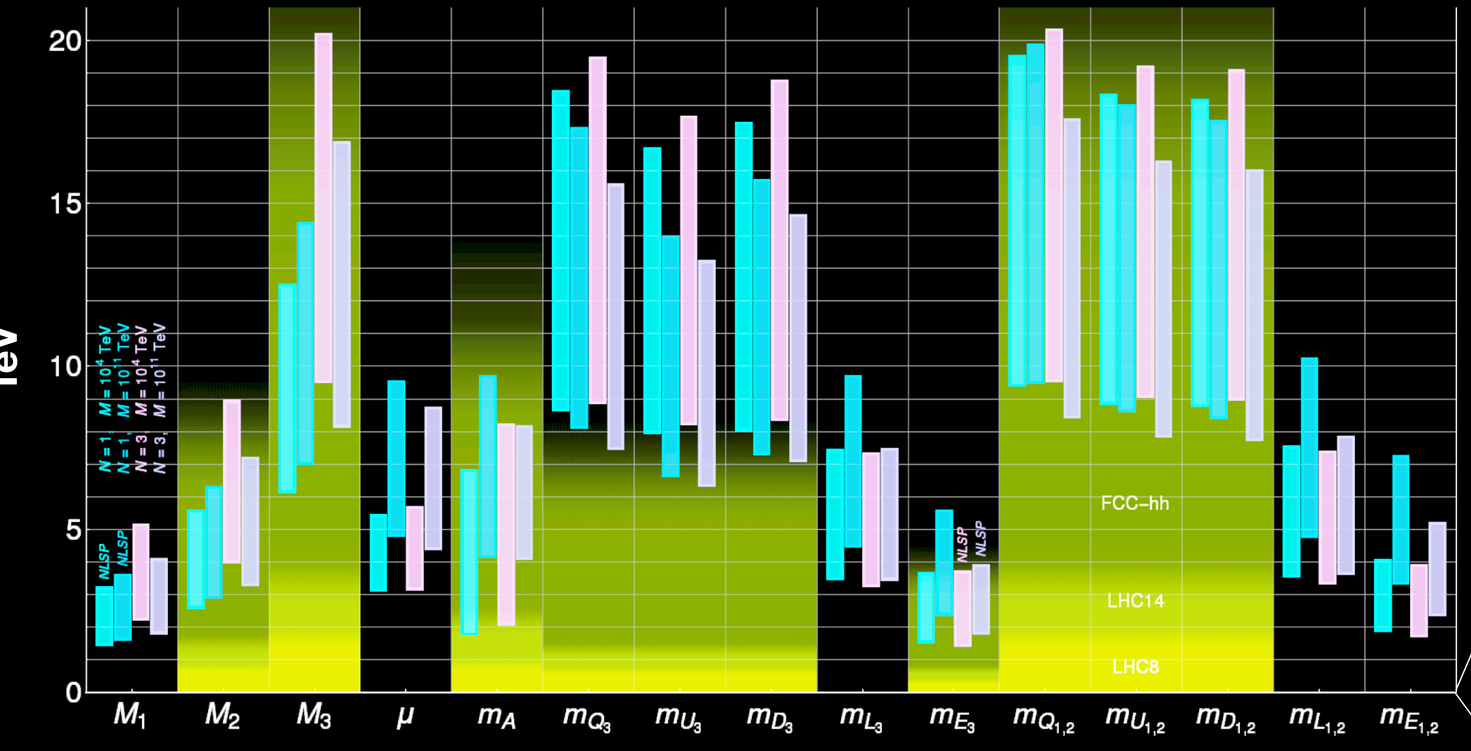
$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

The Naturalness Strategy

Param	UV sensitivity	Natural if	NP	Scale	Natural?
“m_e”	$e^2\Lambda$	$\Lambda \lesssim 5$ MeV	Positron	511 keV	✓
$m_{\pi^\pm}^2 - m_{\pi^0}^2$	$\frac{3\alpha}{4\pi}\Lambda^2$	$\Lambda \lesssim 850$ MeV	Rho	770 MeV	✓
$m_{K_L} - m_{K_S}$	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4}\Lambda^2$	$\Lambda \lesssim 2$ GeV	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2}\Lambda^2 + \dots$	$\Lambda \lesssim 500$ GeV	?	?	?

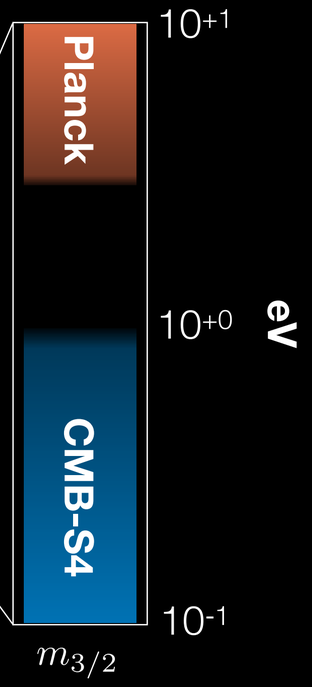
Supersymmetry

[Pardo Vega & Villadoro '15]



Planck bound on hot relics,

$$m_{3/2} < 4.7\,\mathrm{eV}$$

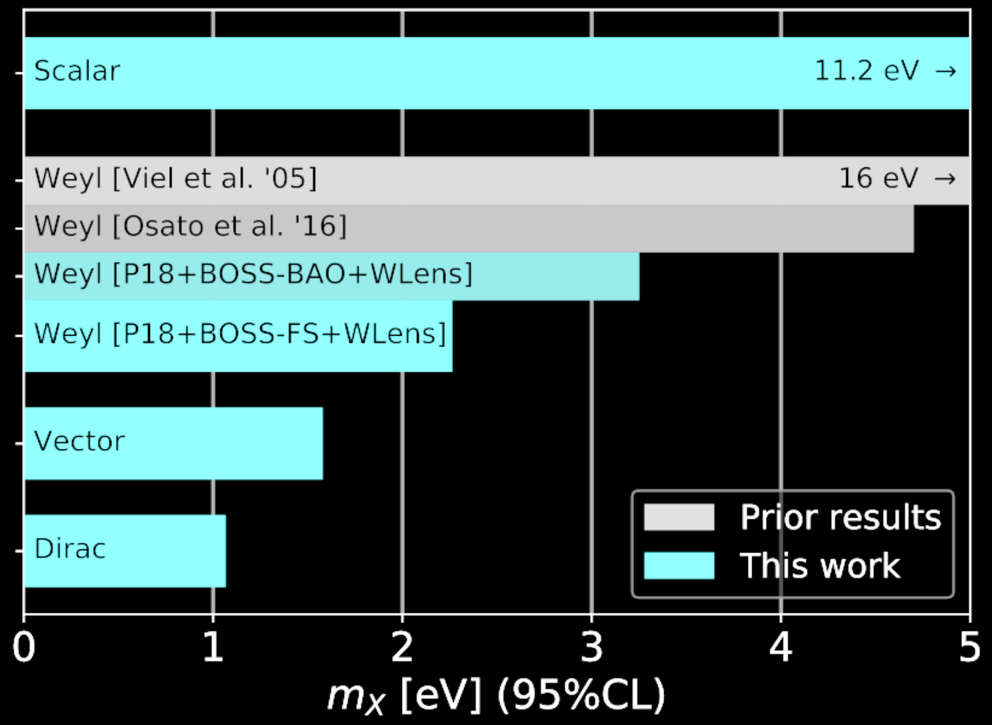


For $m_{3/2} < 1$ eV, gravitinos decouple below 100 GeV; $(\Delta N_{\rm eff})_{3/2} > 0.057$

[CMB-S4 Science Book]

From L. Xu's talk

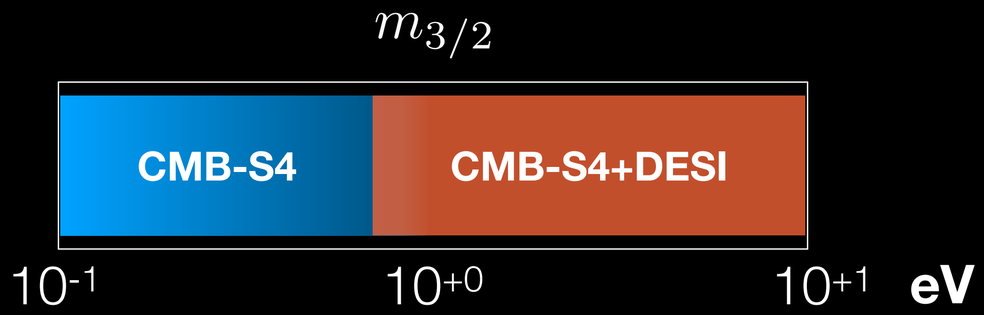
Light but Massive Relics (LiMRs)



$T_X = 0.91$ K

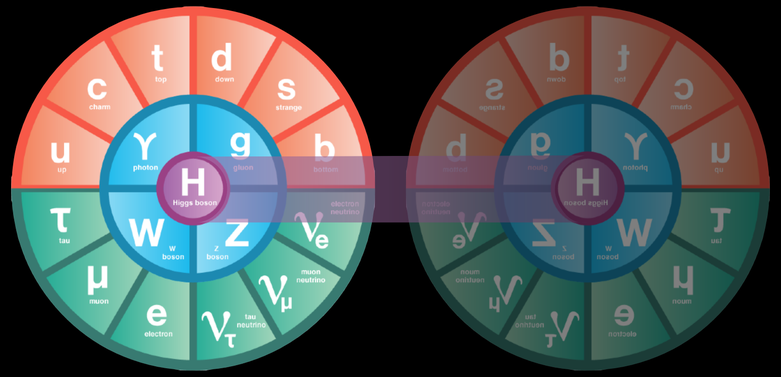
m_X (95% CL)

	BOSS + Planck	DESI + S4
Scalar	11.2 eV	0.94 eV
Weyl	2.26 eV	0.58 eV
Vector	1.58 eV	–
Dirac	1.06 eV	–



Spectrum-independent exclusion/discovery of low-scale SUSY…

Discrete symmetries



E.g. “Twin Higgs” [Chacko, Goh, Harnik ’05, …]
David Curtin’s talk

Consider SM + mirror SM with identical couplings. Combined Higgs potential has an accidental SU(4) global symmetry from SU(2) x SU(2) x Z_2.

Higgs is a pNGB of the accidental SU(4)…

$$\Delta V = -\frac{6y_t^2}{16\pi^2}\Lambda^2\left(\underbrace{|H_A|^2 + |H_B|^2}_{|\mathcal{H}|^2}\right) + \dots$$

$$\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

…but spectrum only respects a Z_2

Still a plethora of new particles corresponding to a symmetry solution, not interacting via SM gauge forces but coupling to Higgs.

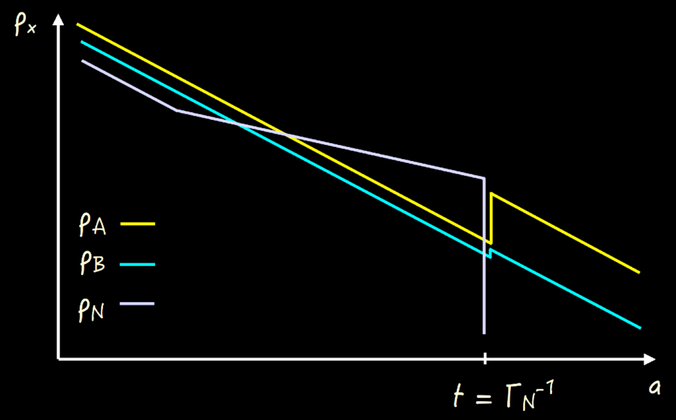
Cosmology is Key

The problem: thermal history of Z_2-symmetric theory has too much energy density in twin ν, γ

$$\Delta N_{\rm eff} \approx 7.4 \left.\frac{\rho_B}{\rho_A}\right|_{\rm BBN} \approx 5.6$$

Preserve symmetry & reconcile w/ current limits if energy density set by neutral particle *N* that

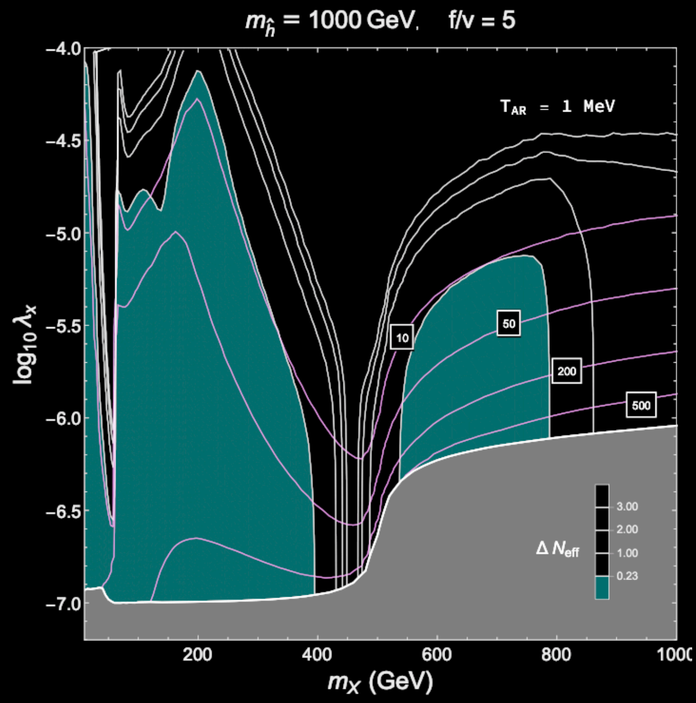
- decouples while relativistic
- decays some time thereafter
- decays primarily to A (SM)



Easy to do w/ symmetric coupling to H_A, H_B

[Chacko, NC, Fox, Harnik '16; NC, Koren, Trott '16]

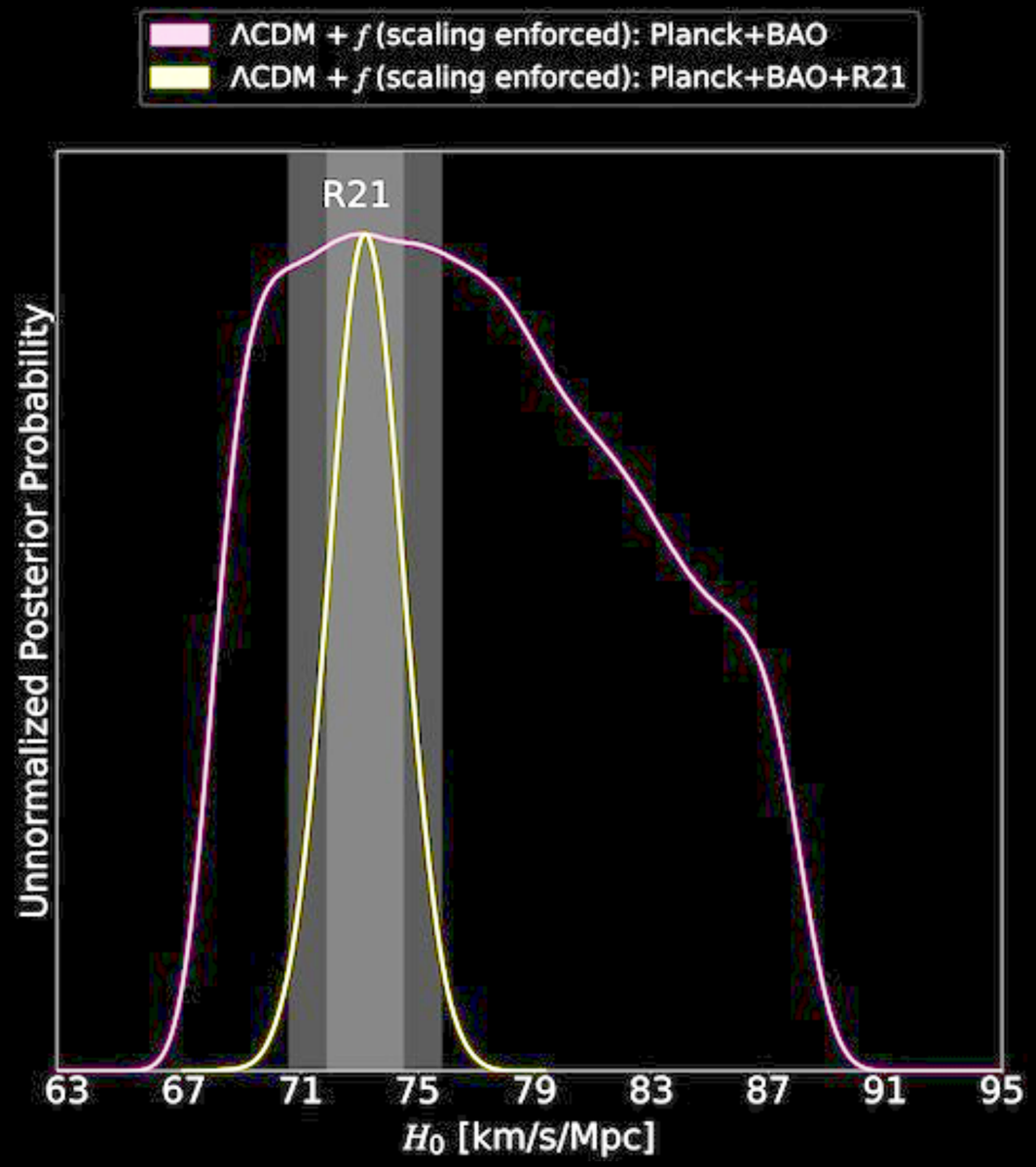
Signals predominantly in CMB-S4



[Curtin, Gryba '21]

D. Curtin's talk: plethora of exotic astrophysical signals if CMB-S4 sees anomalous $N_{\rm eff}$

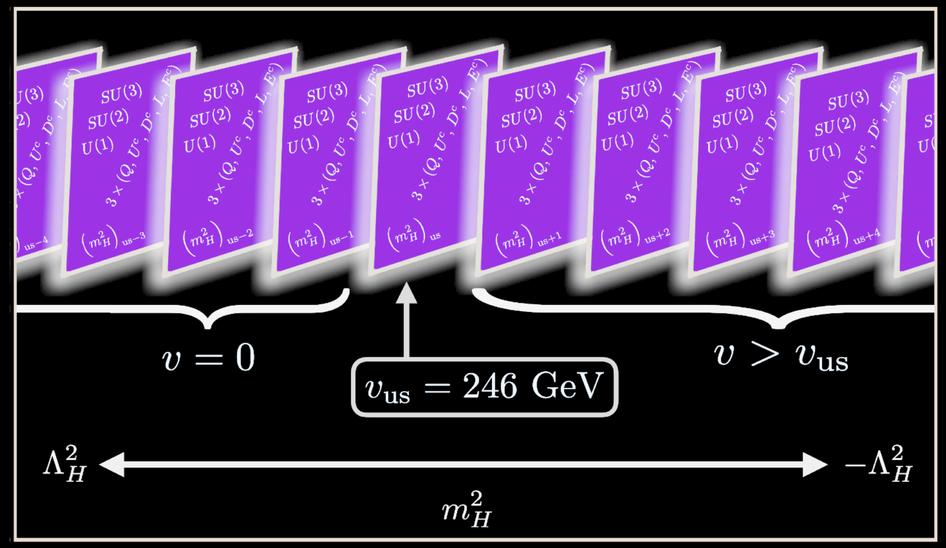
[Cyr-Racine, Ge, Knox ’21]



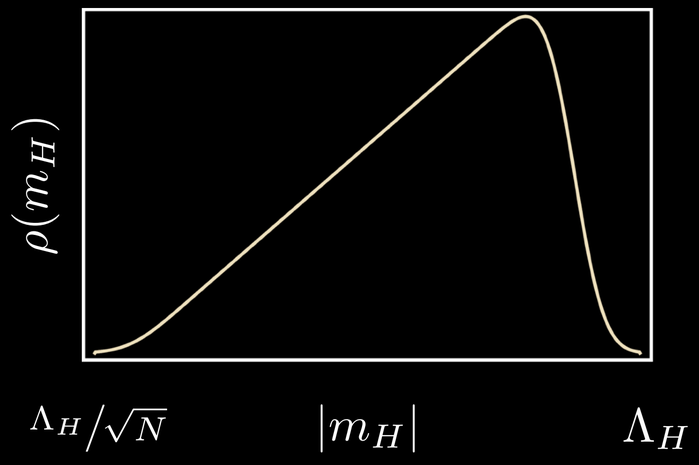
NNaturalness

[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]

N copies of the SM w/ UV scale Λ_H



Random UV contributions to Higgs mass-squared → distribution of m_H^2 between $\pm\Lambda_H^2$

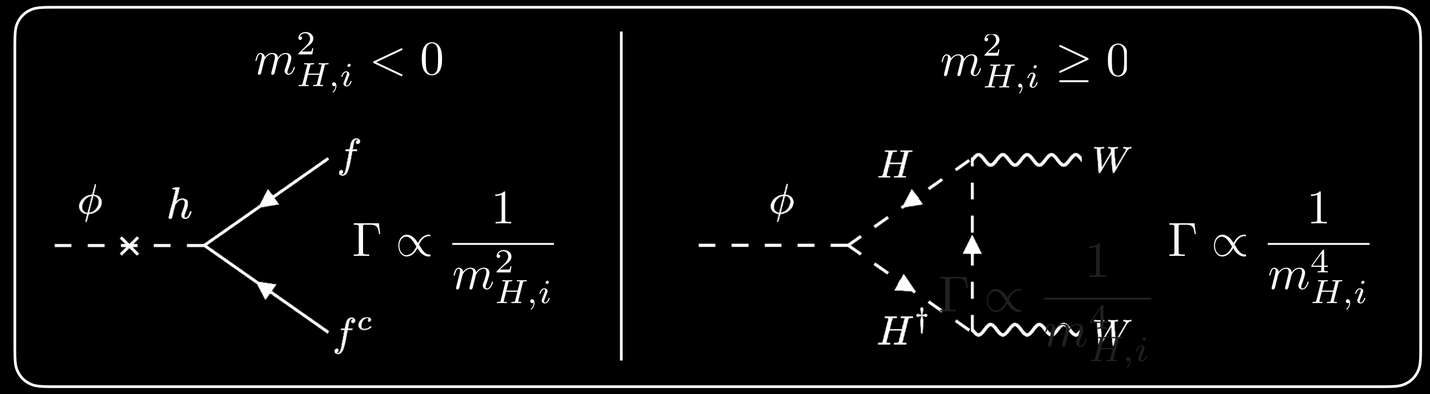


At least 1 copy w/ $|m_H| \sim \Lambda_H/\sqrt{N}$

Why does copy w/ smallest m_H dominate? *Cosmology.*

Reheaton ϕ starts universe via $\phi\,|H_i|^2$ couplings

Decays (provided $m_\phi < |m_{H_i}|$)



Preferentially reheats copy w/ smallest $|m_H|$ & $m_H^2<0$

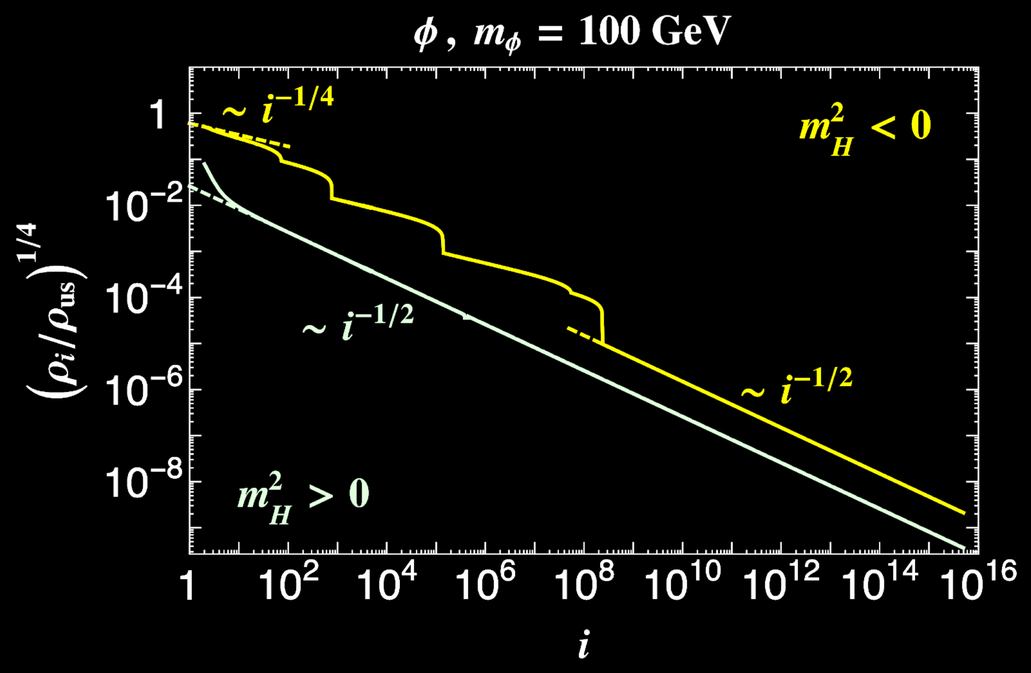
N Higgses…in the sky

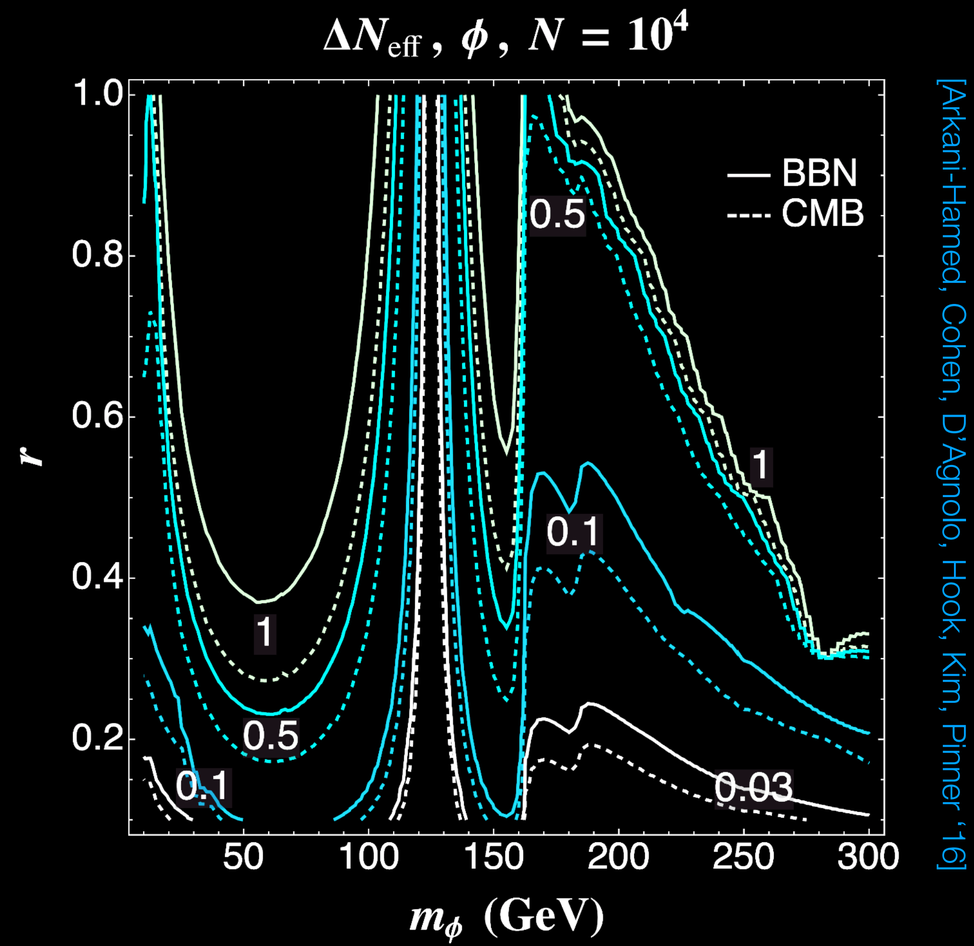
All sectors reheated by some amount ⇒ dark radiation

$$\frac{\rho_i}{\rho_{\rm us}} \equiv \frac{\Gamma_i}{\Gamma_{\rm us}}$$

Dominated by sectors with similar scales

[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]





[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]

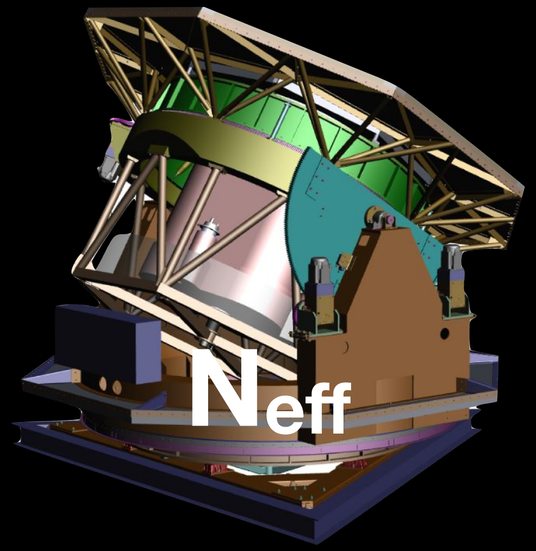
Primary signals in dark radiation, extensive coverage by CMB-S4
See also [Choi, Chiang, Loverde '18]

(r=1 ↔ flat m_H^2; r<1 ↔ larger splitting)

Dark Energy

Dark Matter

Hierarchy Problem

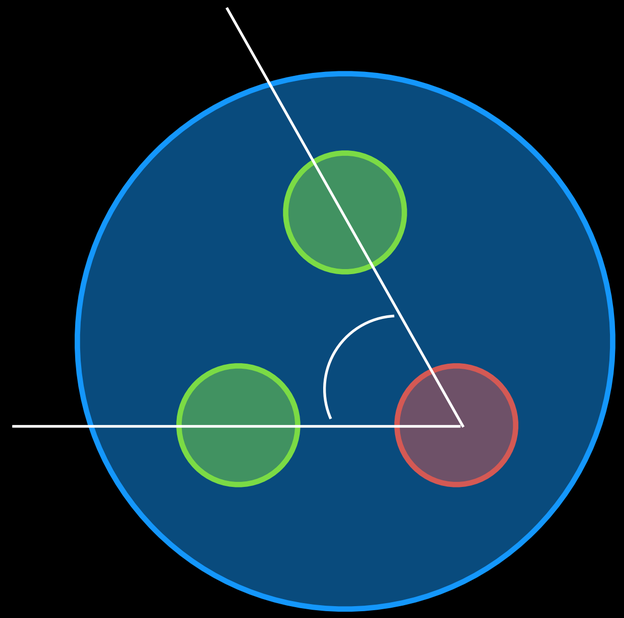


Baryon Asymmetry

Strong CP Problem

Neutrino Mass

Flavor Problem



Strong CP Problem

Classical version: bound on neutron EDM

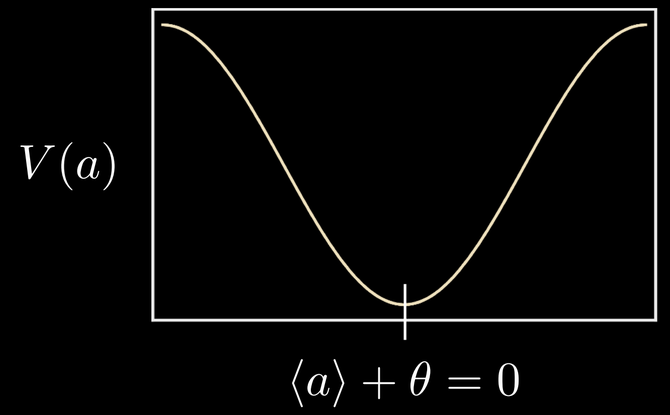
$$|d_n| \lesssim 3 \times 10^{-26}\, e\,\mathrm{cm}$$

"implies" up, down quarks aligned to within 10^{-12}

Quantum version: naively O(1) CP-violating θ parameter $\mathcal{L} \supset \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$ is actually < 10^{-10}

Many solutions; **axion** preferred because it can relax away all contributions to θ, furnish a DM candidate, etc.

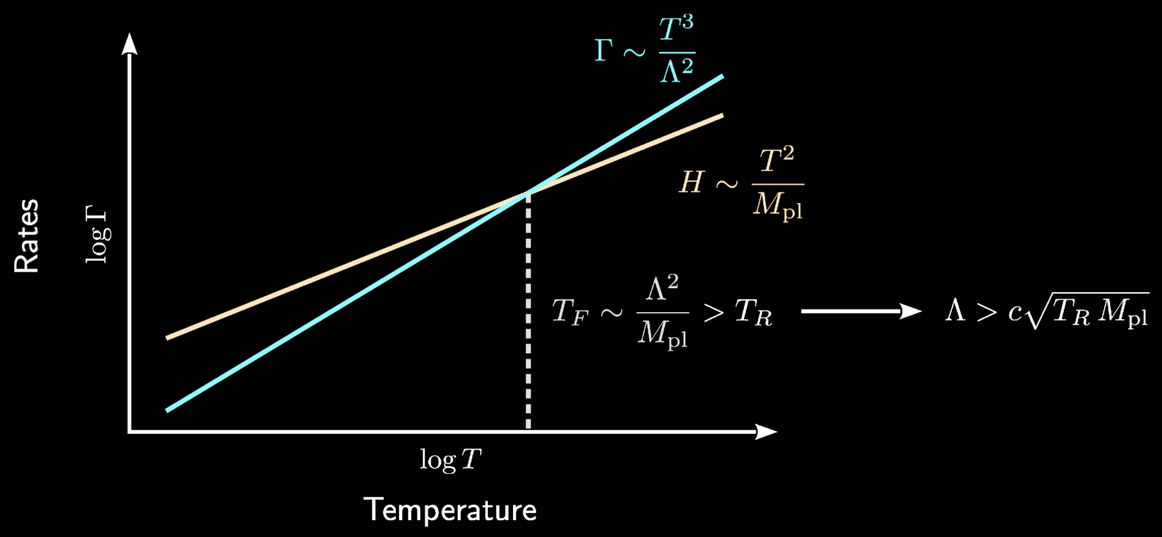
$$\underbrace{\frac{a}{f_a}\frac{1}{32\pi^2} G\tilde{G}}_{\text{Model independent}} \qquad \underbrace{\frac{a}{f_\gamma}\frac{1}{32\pi^2} F\tilde{F}}_{\text{Model dependent}} \quad \frac{\partial_\mu a}{f_Q} Q^\dagger \bar{\sigma}^\mu Q$$



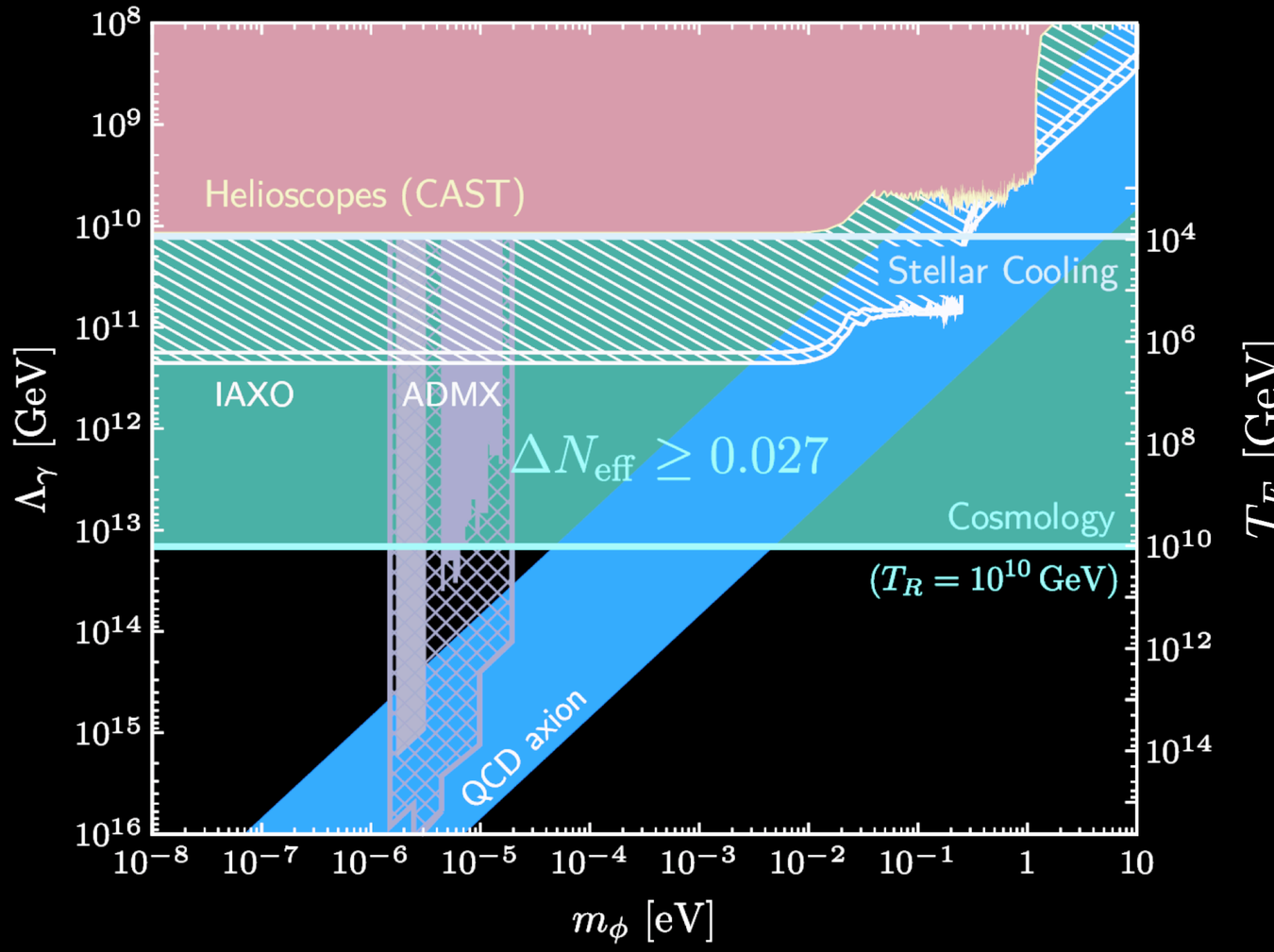
Strong CP Problem

From B. Wallisch's talk

If ever in thermal equilibrium w/ SM, sub-eV axions constrainable by $\Delta N_{\rm eff}$; only alternative is to have $T_F > T_R$



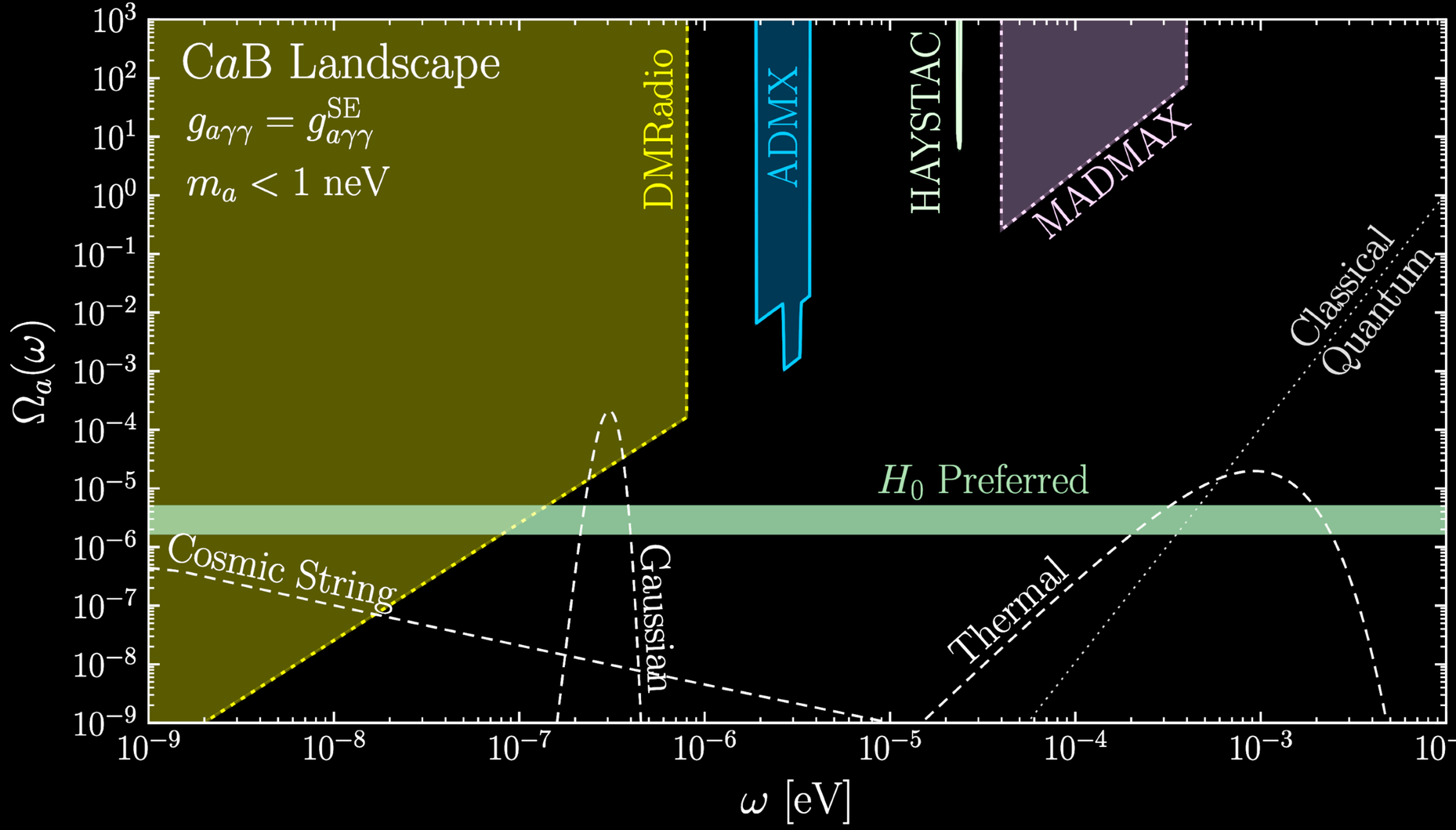
[Baumann, Green, Wallisch '16]



Cosmic Axion Background

From N. Rodd's talk

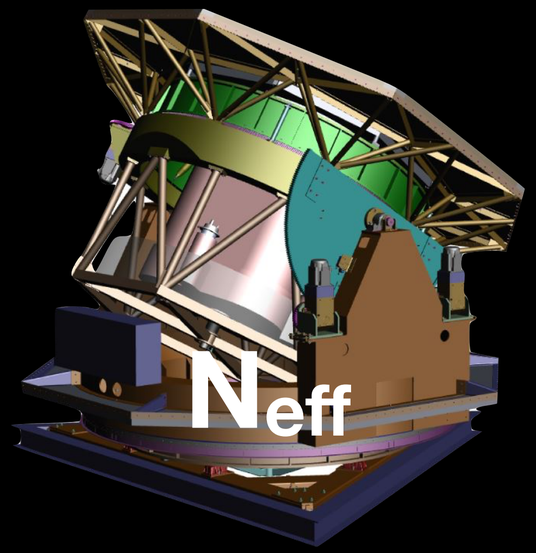
[Dror, Murayama, Rodd '21]



Dark Energy

Dark Matter

Hierarchy Problem



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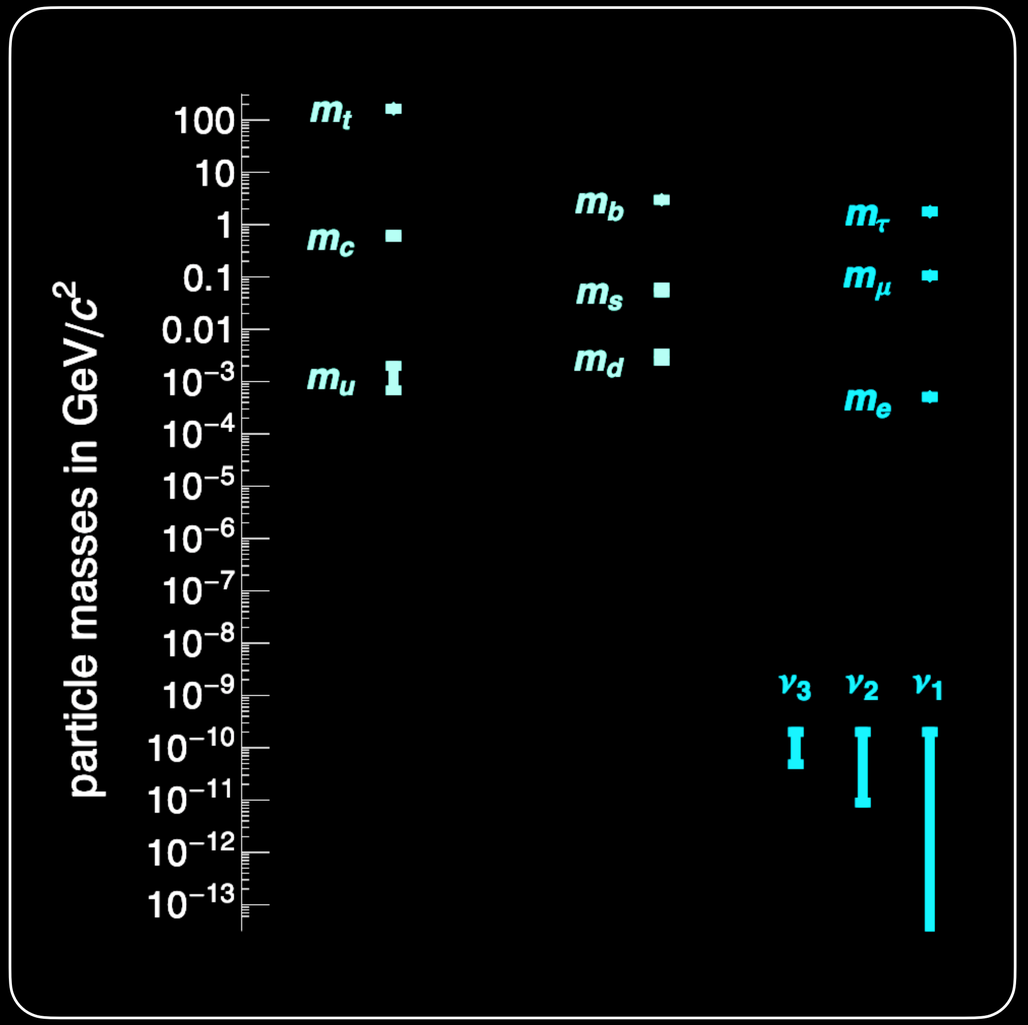
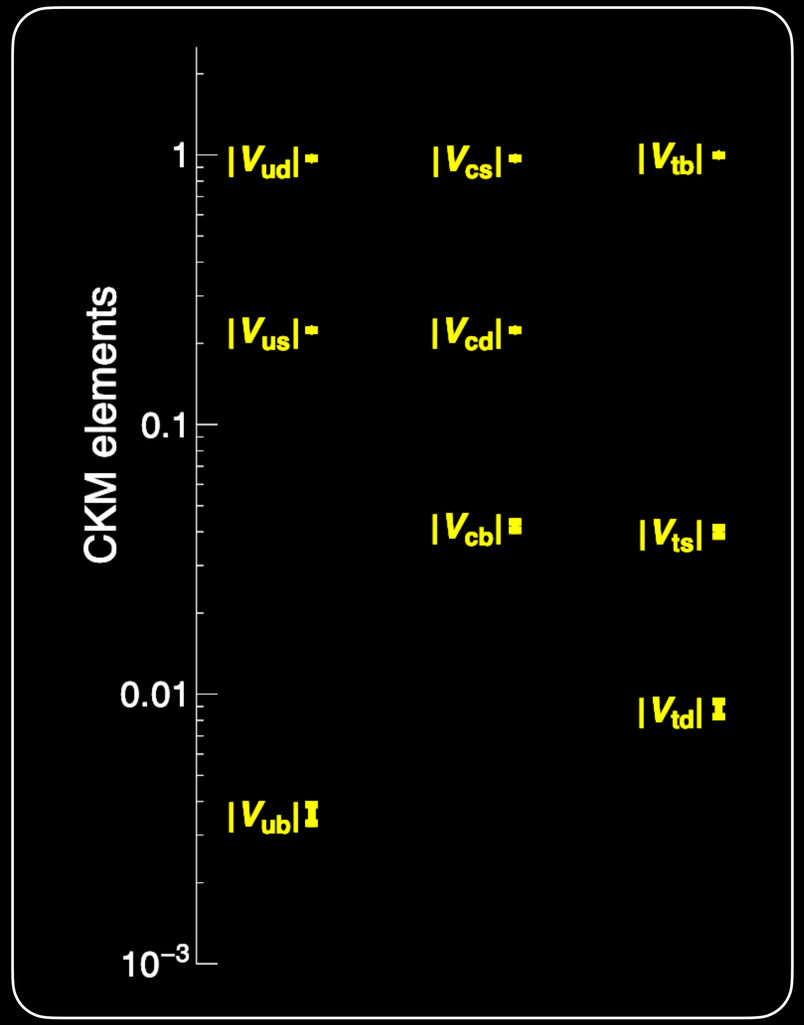




Hints of an organizing principle…

$$|V| \simeq \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

+ signs of lepton flavor universality violation?

Familons

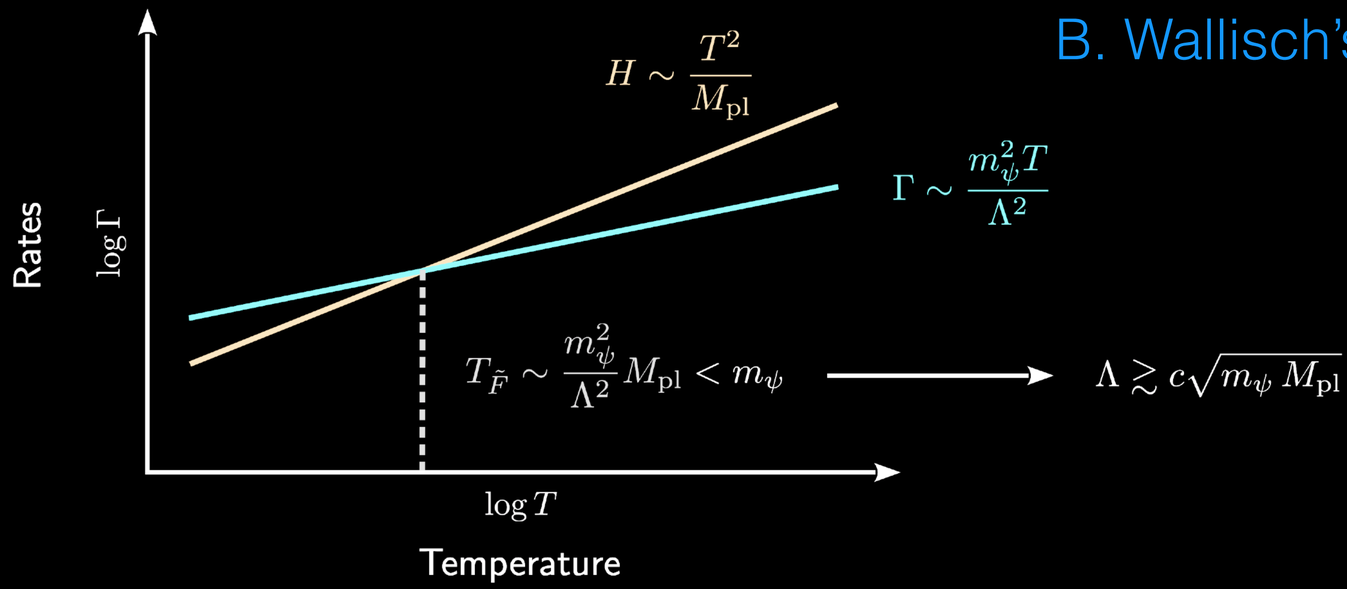
What if some of the pattern of SM flavor symmetry breaking

$$U(3)^5 \to U(1)_B \times U(1)_L$$

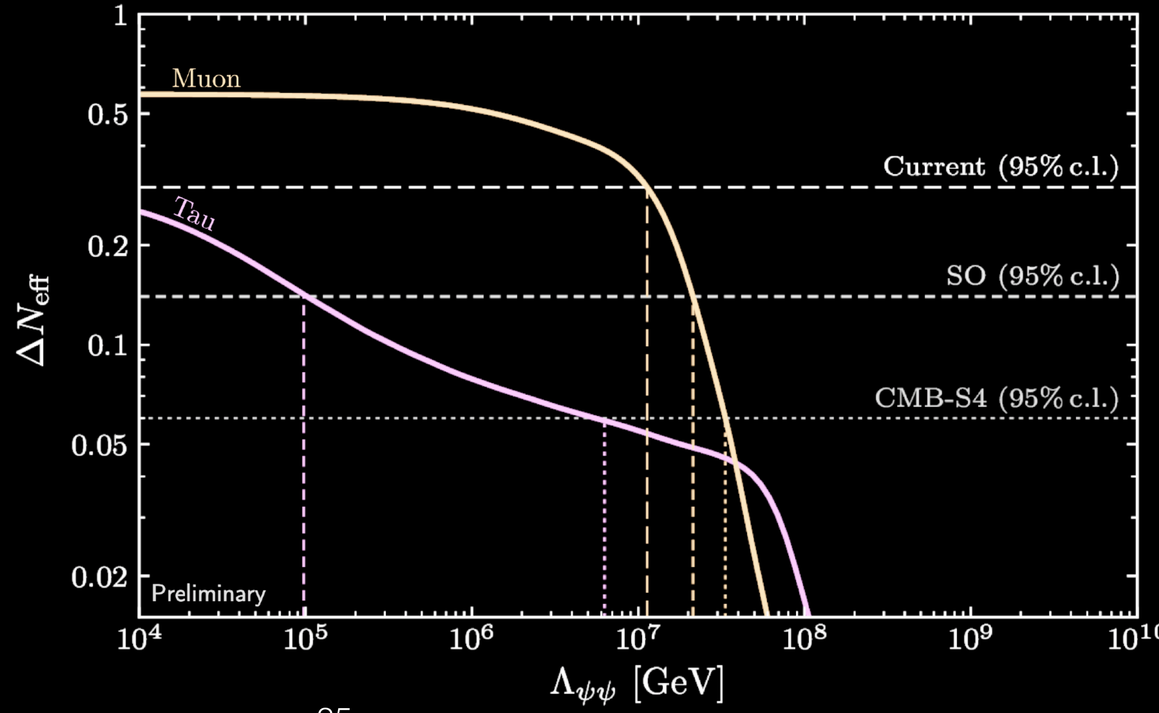
is spontaneous? Expect goldstone bosons (familons) coupling to SM fermions via

$$\mathcal{L} = \frac{1}{\Lambda} \partial_\mu f^a J^{\mu a}$$

Generate thermal population via freeze-in; sub-eV axions constrainable by $\Delta N_{\rm eff}$



B. Wallisch's talk



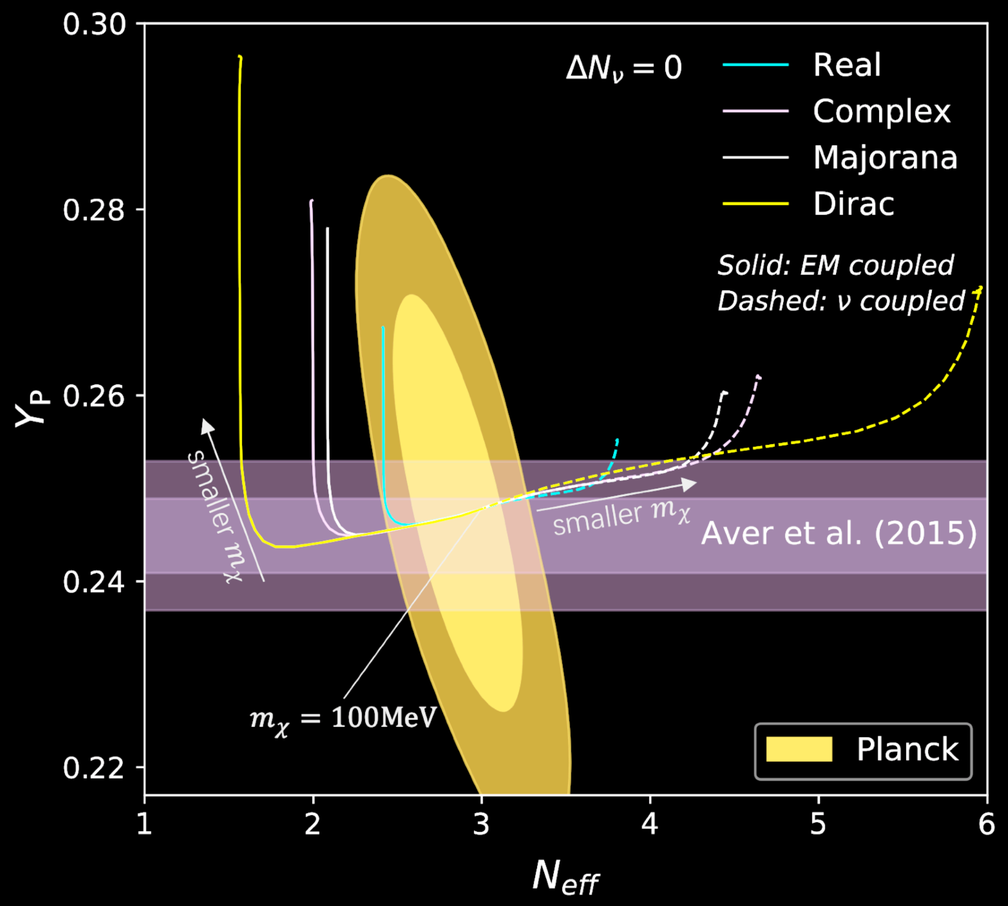
Current:
$\Lambda_{\mu\mu} > 10^{7.1}$ GeV
$\Lambda_{\tau\tau} > 10^{3.2}$ GeV

SO:
$\Lambda_{\mu\mu} > 10^{7.3}$ GeV
$\Lambda_{\tau\tau} > 10^{5.0}$ GeV

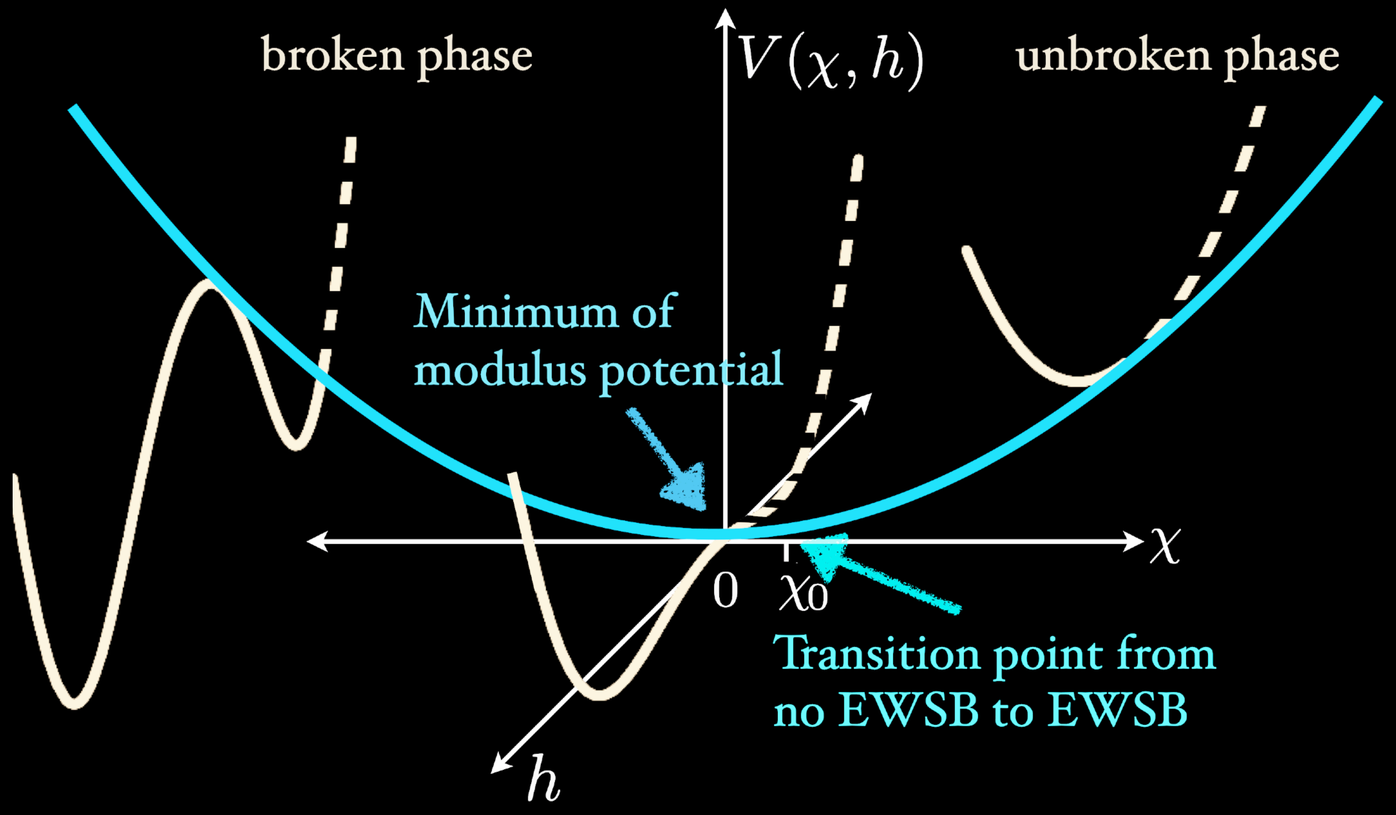
CMB-S4:
$\Lambda_{\mu\mu} > 10^{7.5}$ GeV
$\Lambda_{\tau\tau} > 10^{6.8}$ GeV

(Preliminary)

Rui An's talk: CMB and BBN constraints on light thermally coupled WIMPs



JiJi Fan's talk: Modulating Fields and the CMB



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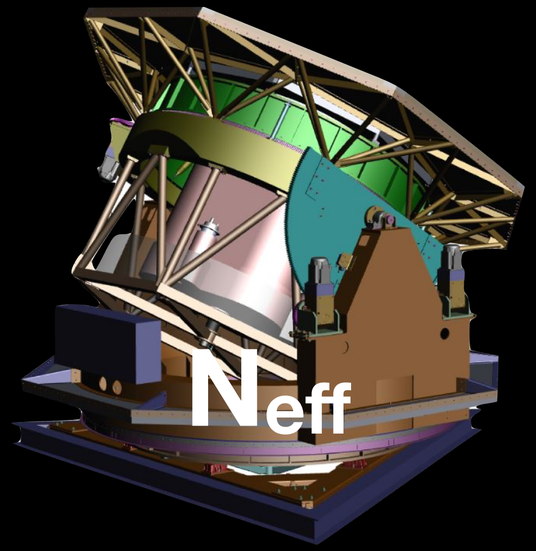

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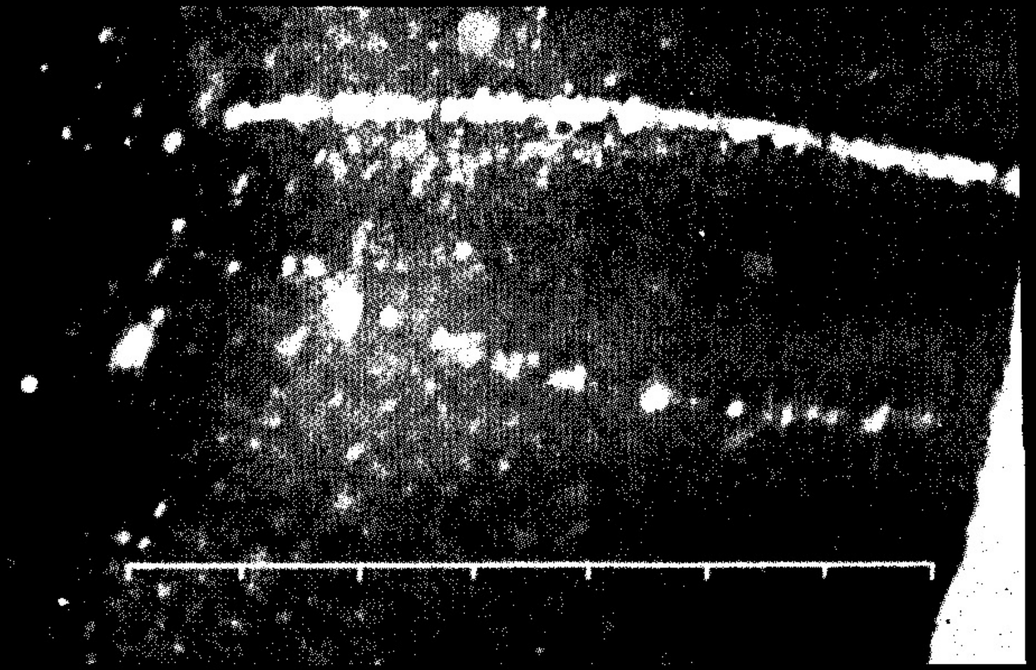
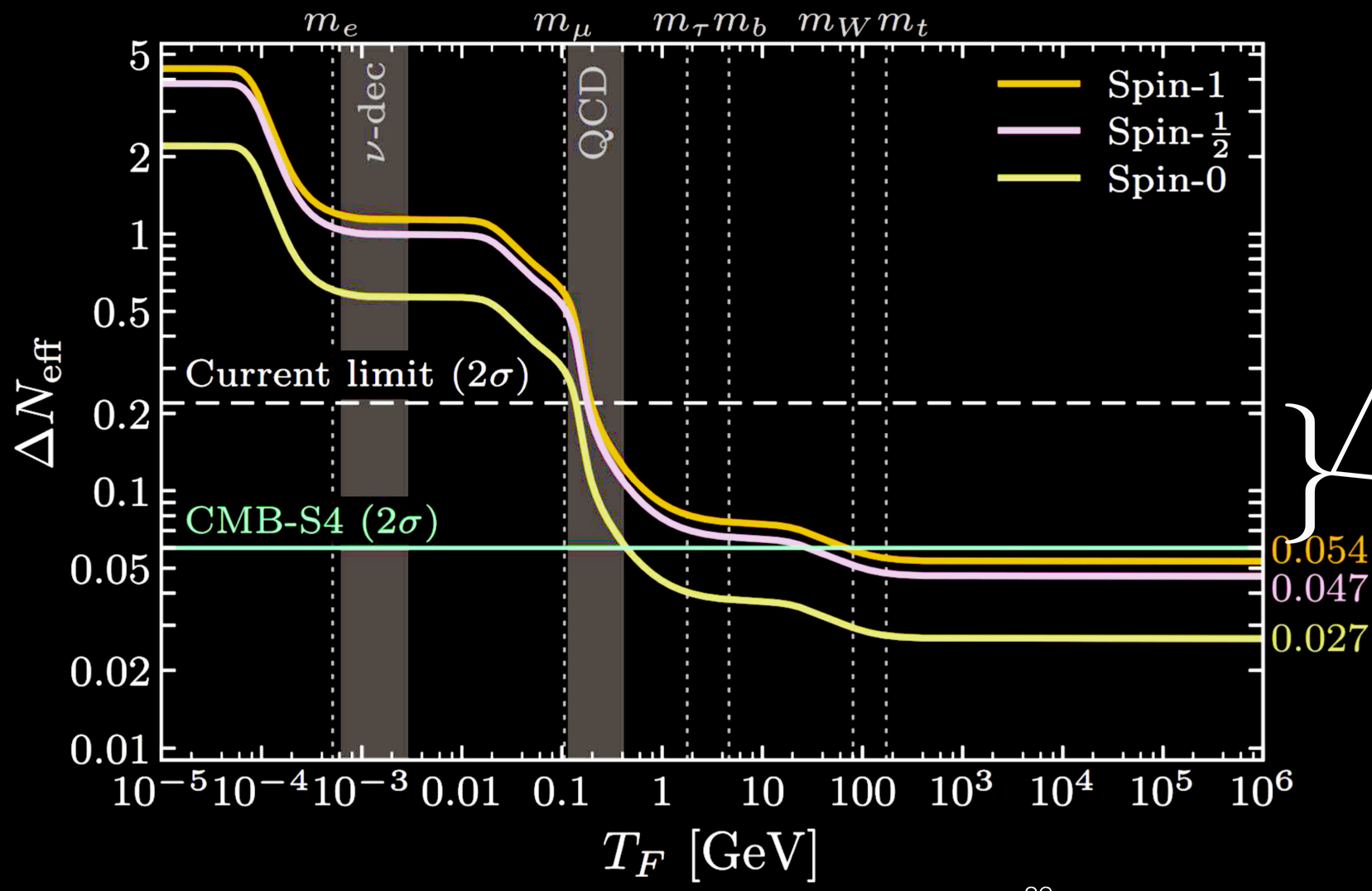


"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

Who Ordered That?



CMB-S4 sensitive to:

- Any sub-eV particle decoupling from SM between EW phase transition and QCD phase transition.
- More than ~one copy of any sub-eV particle ever in thermal equilibrium with the SM.

Extraordinary opportunity for "who ordered that"…

Thank you!