Title: BBN and the Unnatural Weak Scale

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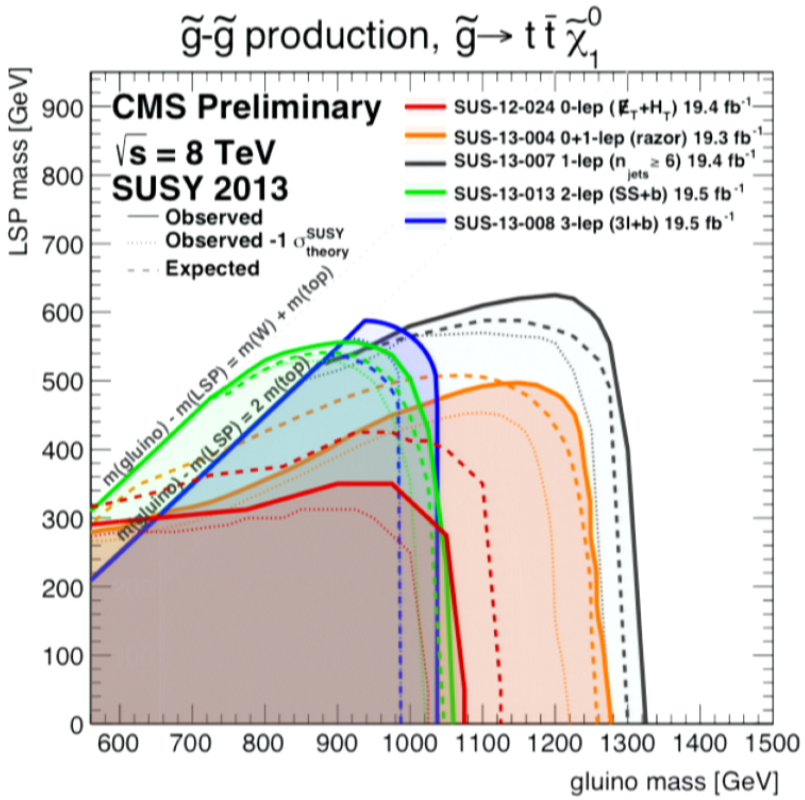
Abstract: The discovery of a perturbatively-coupled, 125 GeV Higgs, together with the absence of LHC signals for supersymmetry, places the principle of naturalness under tension. In this talk I will discuss the possibility that the weak scale is unnatural, with its value determined environmentally in the landscape. In particular, this environmental selection may be driven by BBN: as the weak scale is increased, the abundance of Hydrogen in the early universe is rapidly depleted. That our own universe contains an O(1) fraction of primordial Helium arises as a conspiracy among the weak scale, the neutron-proton mass difference, and the planck scale.

naturalness under siege



$$m_{\tilde{g}} \gtrsim 1 \text{ TeV}$$

(unless no tops, no MET, few high-pT jets)

Evans, et al, 1310.5758

$$\delta m_{H_u}^2 \sim \frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$$

$$\Longrightarrow \Delta \gtrsim 10 - 100$$

environmental selection

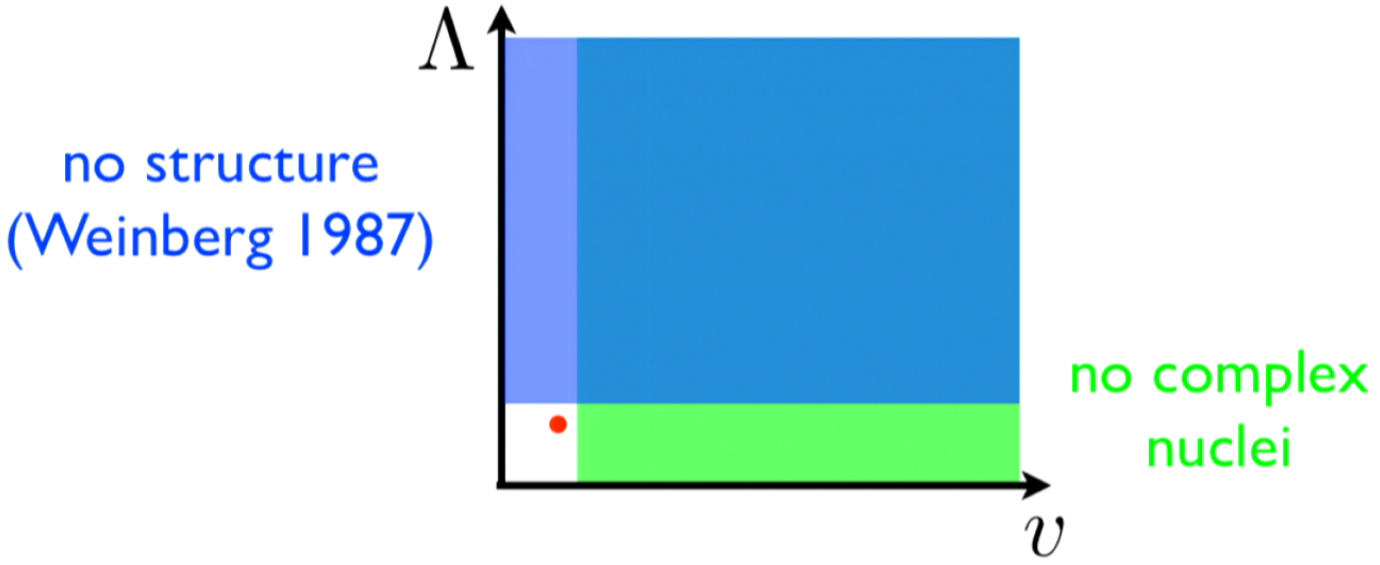
An anthropic "model" consists of:

- scanning parameters
- catastrophic boundaries
- prior distributions

Fixing these, we can ask how likely our universe is in the landscape

minimal landscape

assume only dimensionful parameters scan:

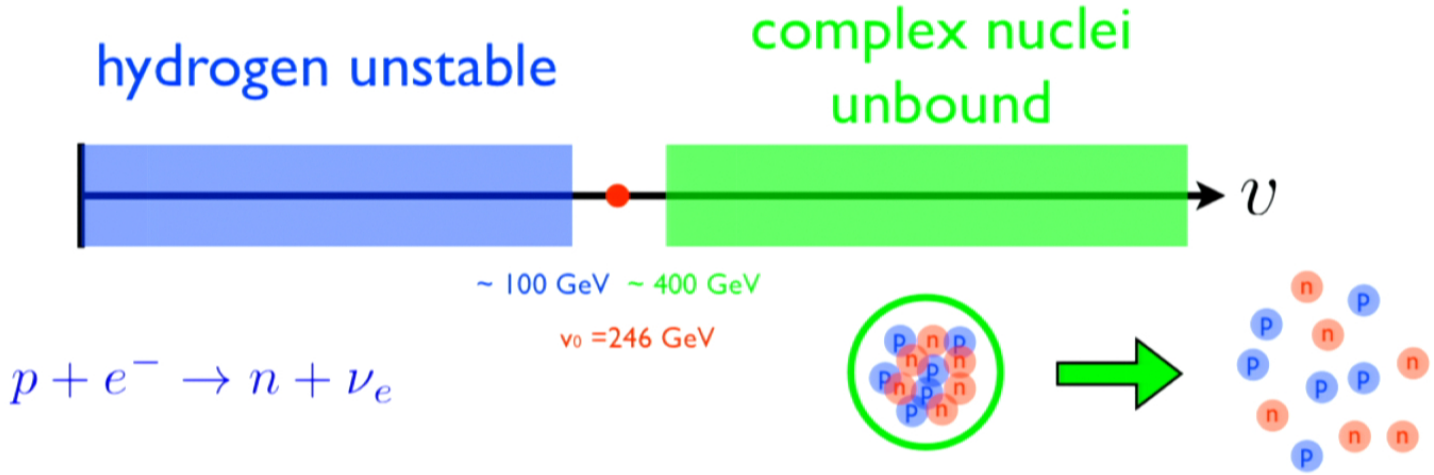


Arkani-Hamed, Dimopoulos, Kachru 0501082

dangers of a variable weak scale

$$m_u = y_u\, v$$

$$m_d = y_d\, v$$

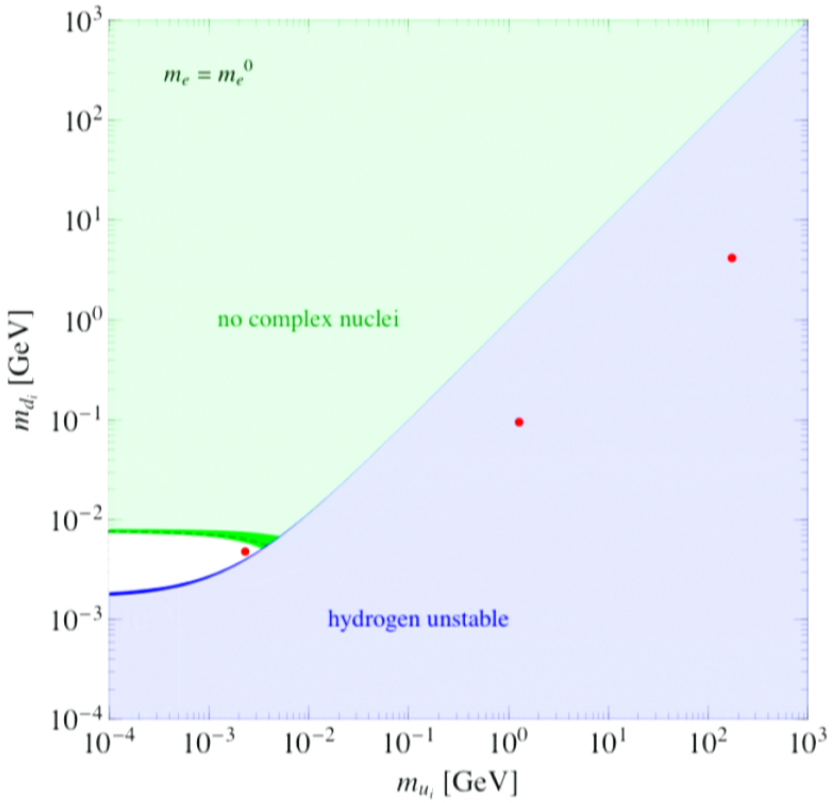


- Agrawal, Barr, Donoghue, Seckel 9707380
- Damour, Donoghue 0712.2968

general landscape

scan:

(y_u, y_d, v)



general landscape

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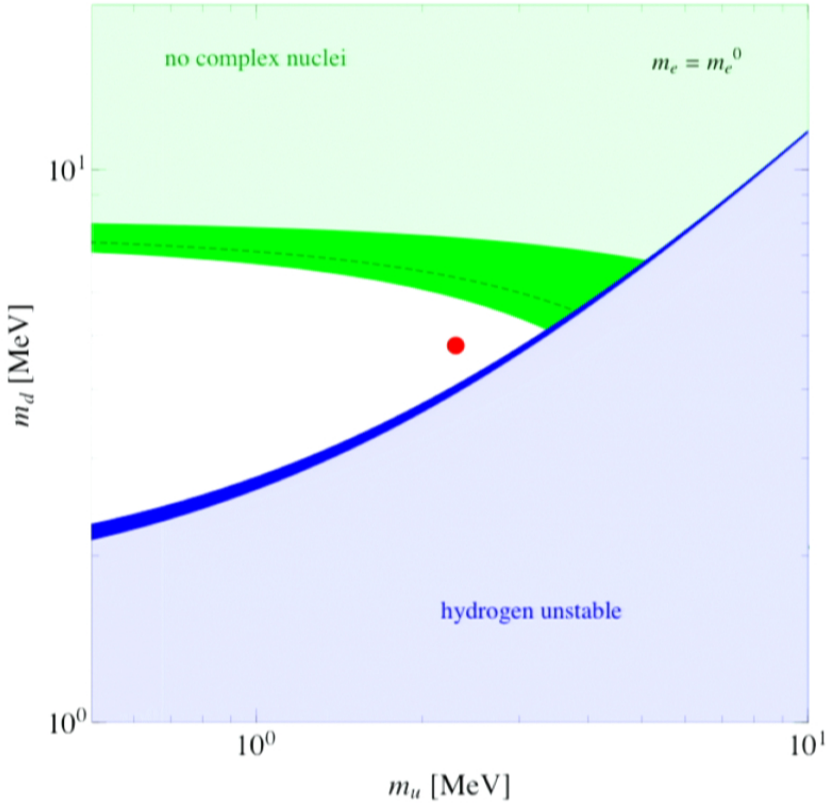


runaway to large v?

scan:

(y_u, y_d, v)

- nuclear physics depends on the quark masses

- runaway: increase v, fixing quark masses,

$$y_{u,d} \to \frac{m_{u,d}}{v}$$

"Weakless Universe," Harnik, Kribs, Perez 0604027

weak-scale physics in our Universe

1. BBN

$$p + \bar{\nu}_e \to n + e^+$$

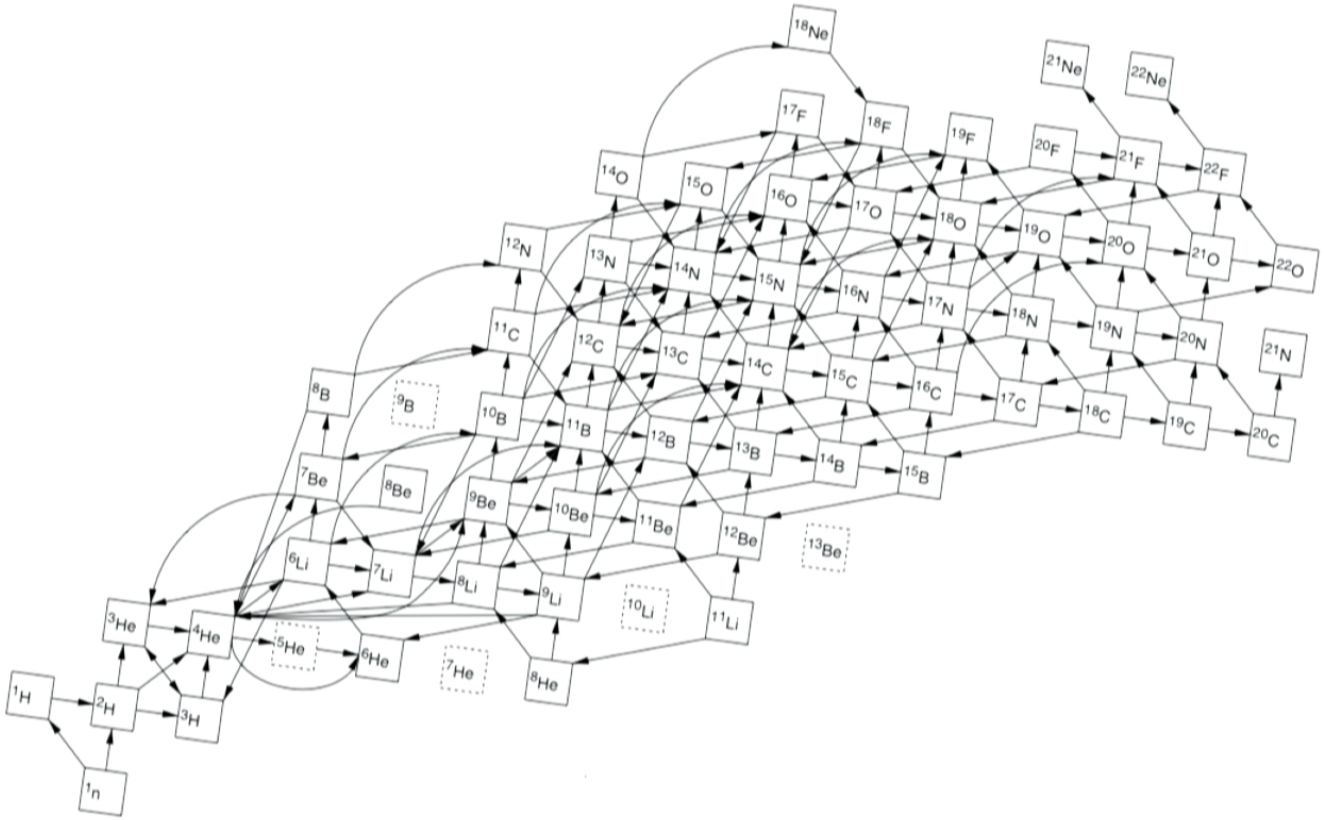
2. pp chain in stars

$$p + p \to d + e^+ + \nu_e$$

3. supernovae

$$e^- + e^+ \to \nu + \bar{\nu}$$
$$\bar{\nu} + p \to n + e^+$$

BBN


^{1}n
^{1}H
^{2}H
^{3}H
^{3}He
^{4}He
^{5}He
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^{6}Li
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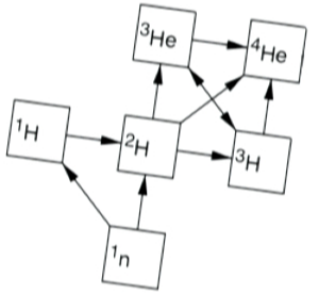
^{22}O
^{17}F
^{18}F
^{19}F
^{20}F
^{21}F
^{22}F
^{18}Ne
^{21}Ne
^{22}Ne

BBN and He4

$$p + \bar{\nu}_e \longleftrightarrow n + e^+$$

decouples: $T_{\rm fr} \sim \dfrac{v^{4/3}}{M_p^{1/3}} \approx 1 \text{ MeV}$

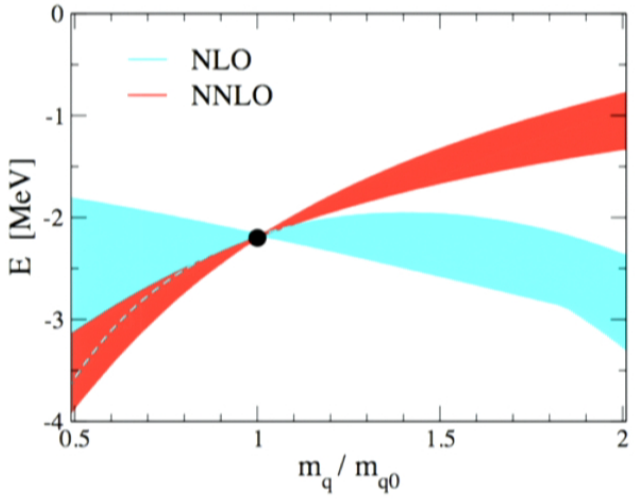
$$\frac{n}{p} = e^{-(m_N - m_P)/T_{\rm fr}} \qquad m_N - m_P \approx 1.3 \text{ MeV}$$



$$Y_4 \approx \frac{2(n/p)}{1 + n/p} \approx 0.25$$

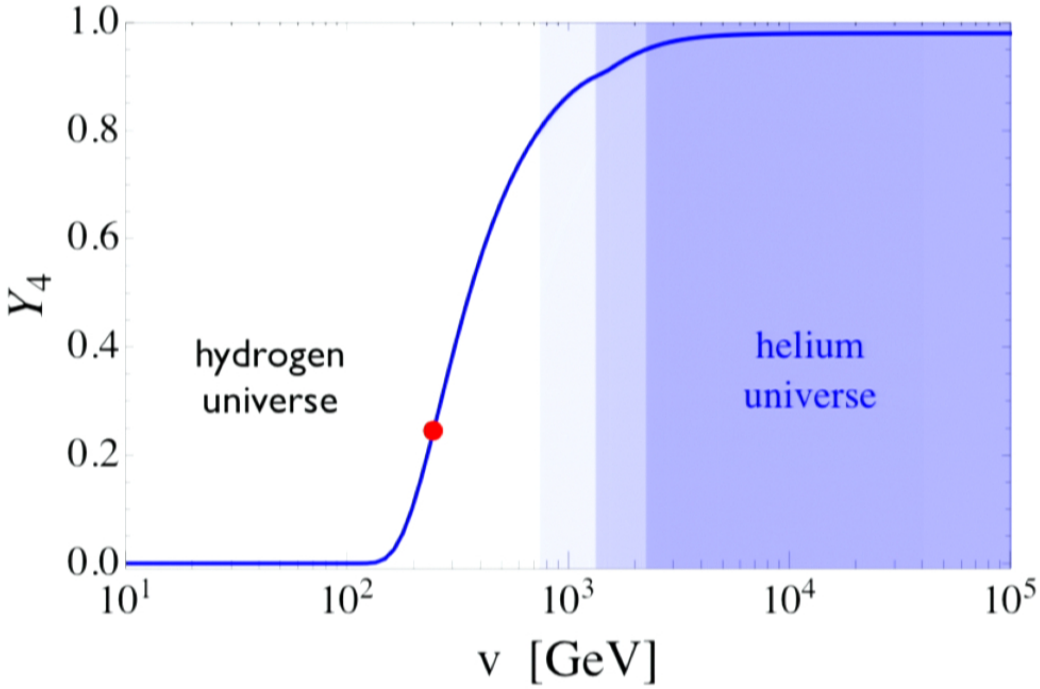
BBN and He4

- also $m_n - m_p = \delta_{\rm EM} + \delta_q (m_d - m_u)$
- $\tau_n \sim \dfrac{v^4}{\delta m^5}$
- $B_d, \sigma(p + n \leftrightarrow d + \gamma)$



Berengut, et al, 1301.1738

BBN and He4



$$(m_N - m_P)^3 M_p \sim v^4$$

dangers of a helium universe

primordial hydrogen is important for:

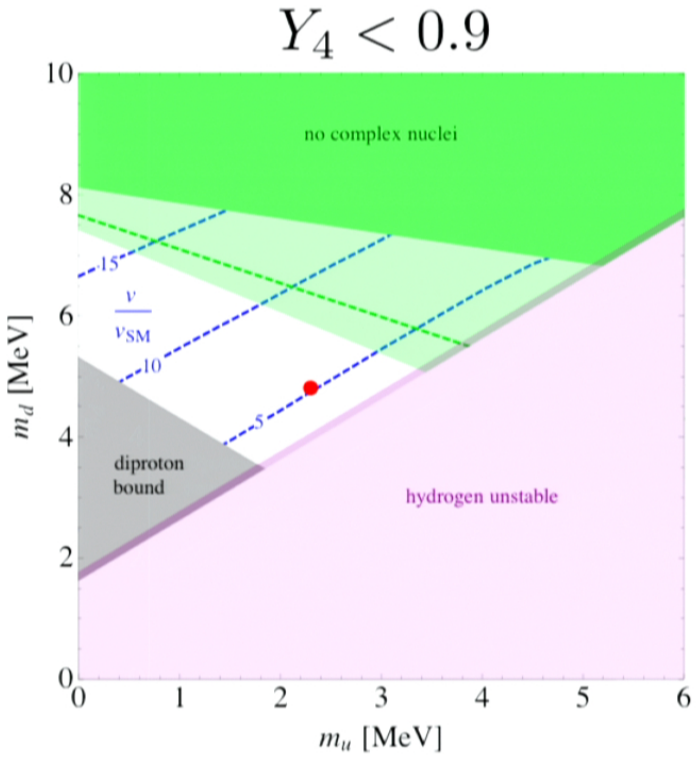
- galactic halo cooling
- stars powered by pp chain
- water

quantifying how much hydrogen is needed for observers we leave for future work...

BBN and the weak scale

scan:

(y_u, y_d, v)



BBN and the weak scale

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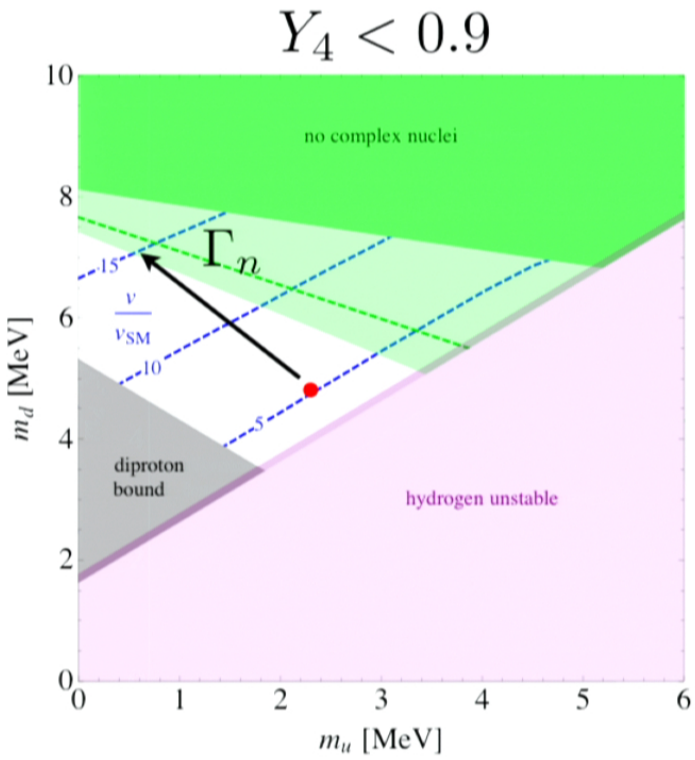


- in a multiverse where (y_u, y_d, v) scan, all three parameters are bounded by requiring stable Hydrogen, complex nuclei, and not too much Helium from BBN

- but what if other parameters scan too?

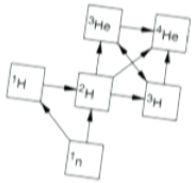
varying the baryon density

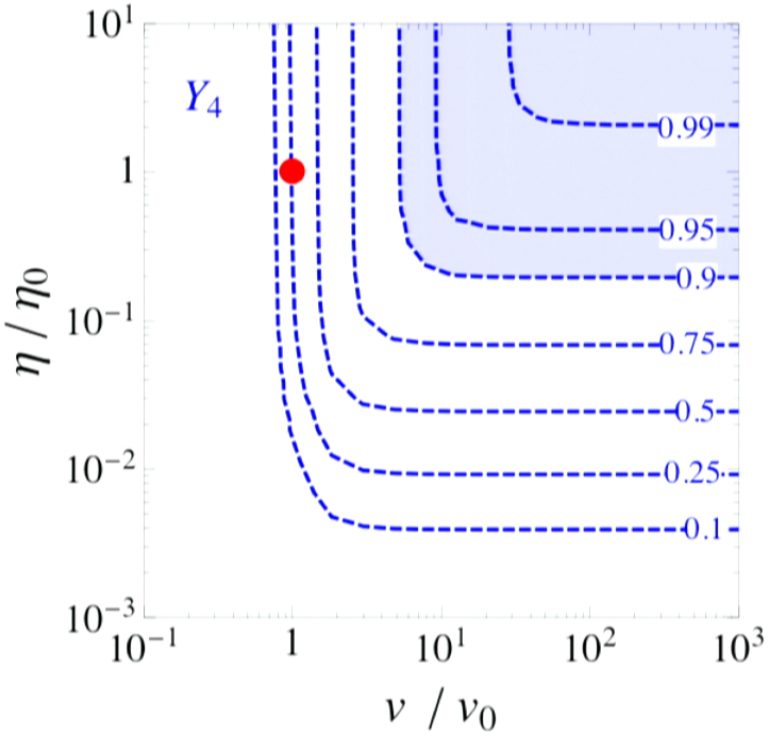
scan:

(v, η)

$p + n \to d + \gamma$

freezes out





varying Mpl

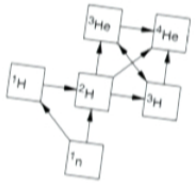
$$T_{\rm fr} \sim \frac{v^{4/3}}{M_{\rm pl}^{1/3}}$$

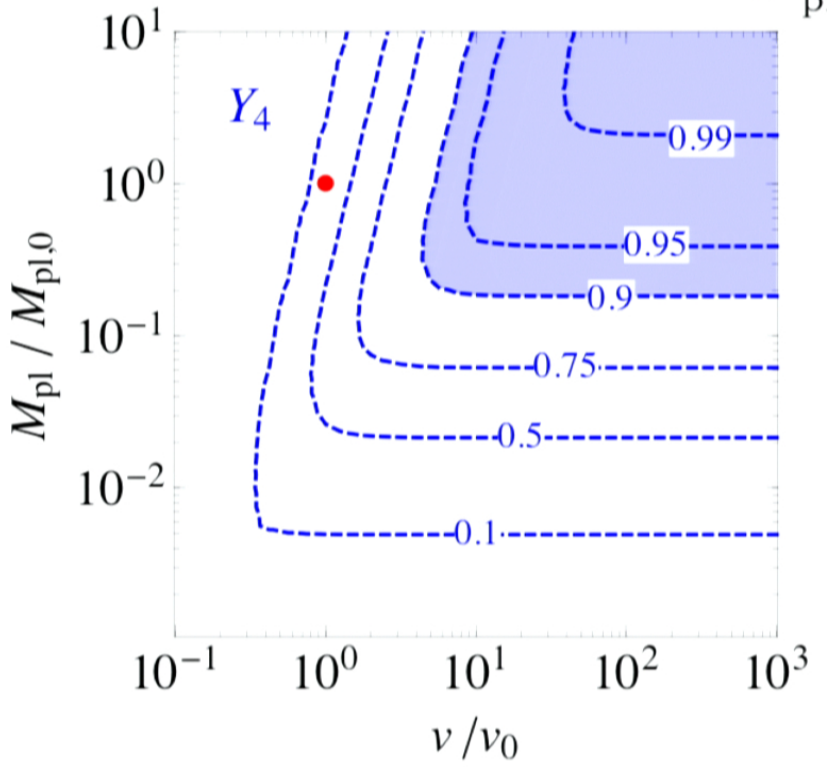
scan:

$(v, M_{\rm pl})$

$p + n \to d + \gamma$

freezes out





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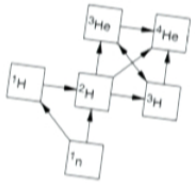

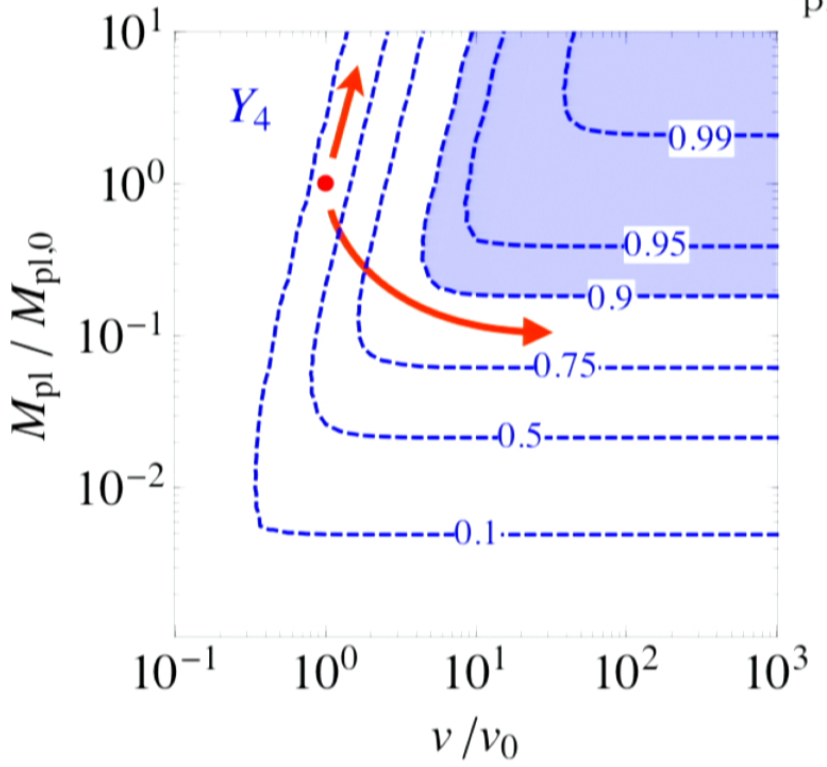

Scanning cosmology

- $M_{\rm pl}, \rho_b, \rho_c$
- structure formation boundaries
- WIMP DM $\Longrightarrow \quad \rho_c \propto v^2$

Tegmark, Aguirre, Rees, Wilczek 0511774

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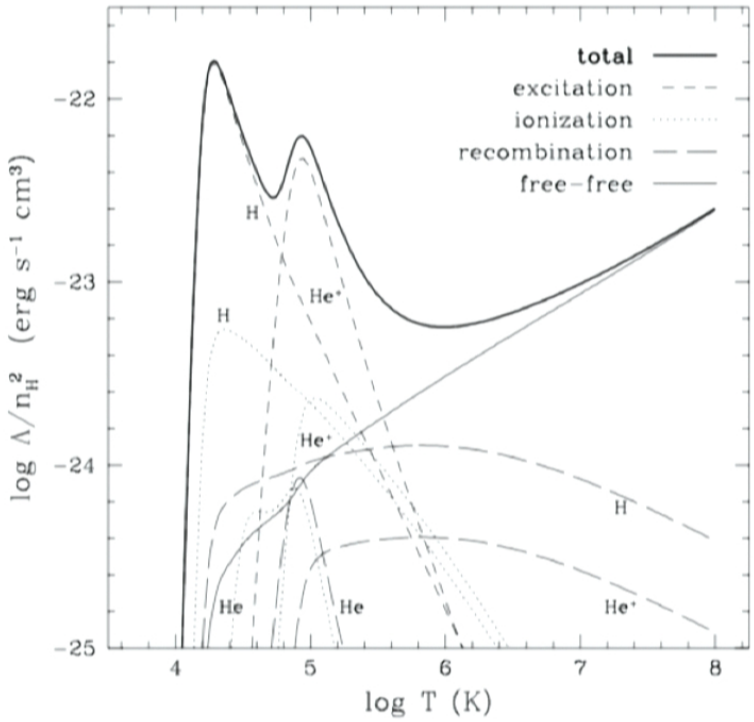
cooling



Katz, Weinberg, Hernquist, 9509107

$$T_{\rm vir} \sim \frac{M m_p}{M_{\rm pl}^2 R_{\rm vir}}$$

$$\sim \frac{m_p}{M_{\rm pl}^2} \left(\rho_{\rm vir} M^2\right)^{1/3}$$

$$t_{\rm brem} \sim \frac{nT}{\Lambda} \propto \frac{\sqrt{T_{\rm vir}}}{f_b \rho_{\rm vir}}$$

Inefficient cooling unless

$$10^6 M_\star \lesssim M \lesssim 10^{13} M_\star$$

$$(t_{\rm cool} > H^{-1})$$

disk fragmentation

- necessary for star formation
- Jeans instability in the z-direction
- $M_{\rm disk} \gtrsim 120 M_{\rm pl}^2 v_p v_c R_{\rm disk}$

Fall & Efstathiou (1980)

$$\Longrightarrow \quad f_b \gtrsim 0.1 \sqrt{\frac{T_{\rm min}}{T_{\rm vir}}}$$

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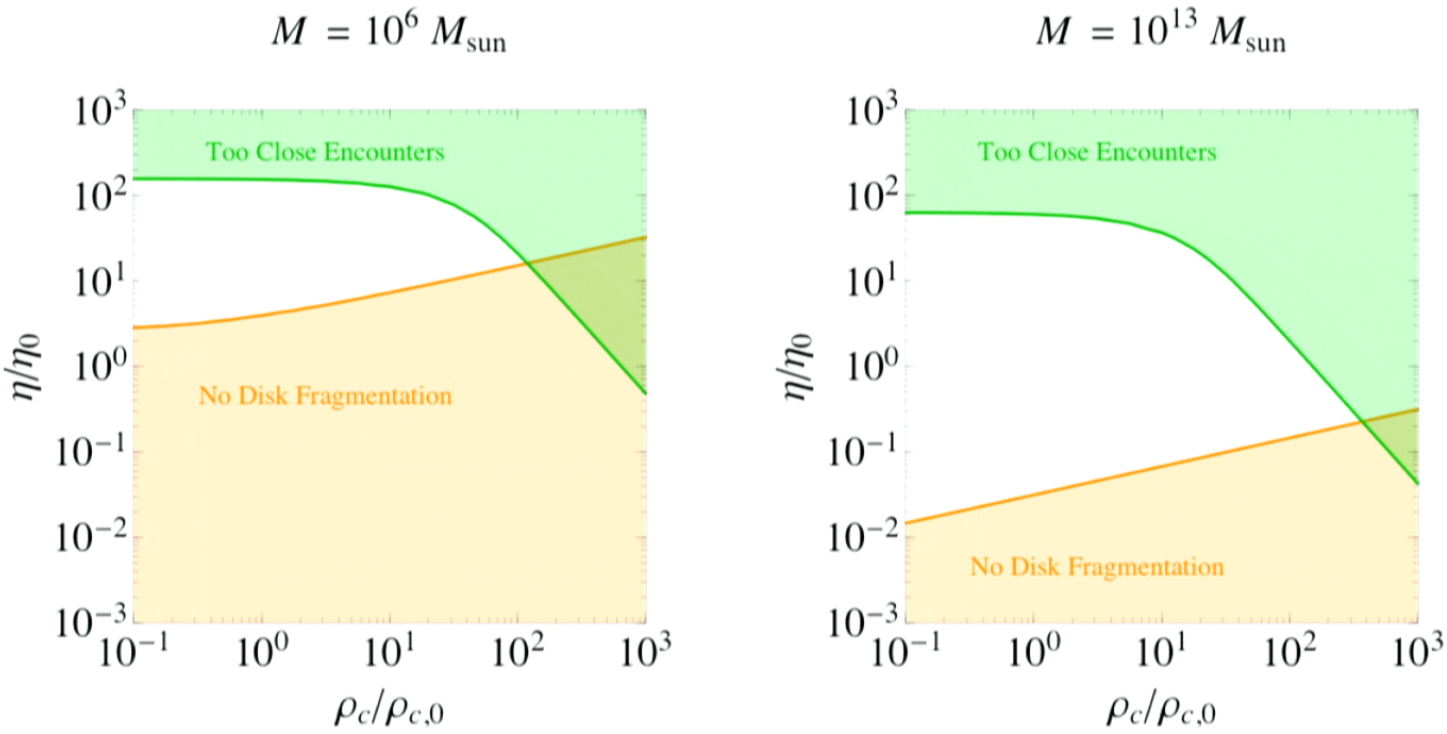
close encounters

- stellar collision rate
- $\gamma \equiv n_\star \sigma v_p \lesssim (10^9 \text{ years})^{-1}$
- $n_\star \sim \rho_{\rm disk}/M_\star, \sigma \sim (1 \text{ AU})^2$
- "Goldilocks" relates cross-section to fundamental parameters

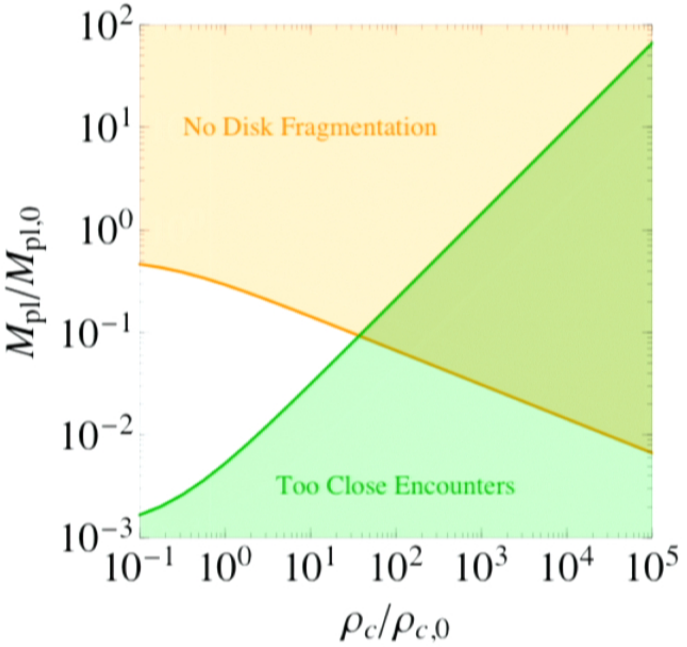
$$\gamma \propto f_b^2 \frac{\rho_{\rm vir}^{4/3} M^{2/3}}{M_{\rm pl}^4 m_e}$$

varying baryon asymmetry

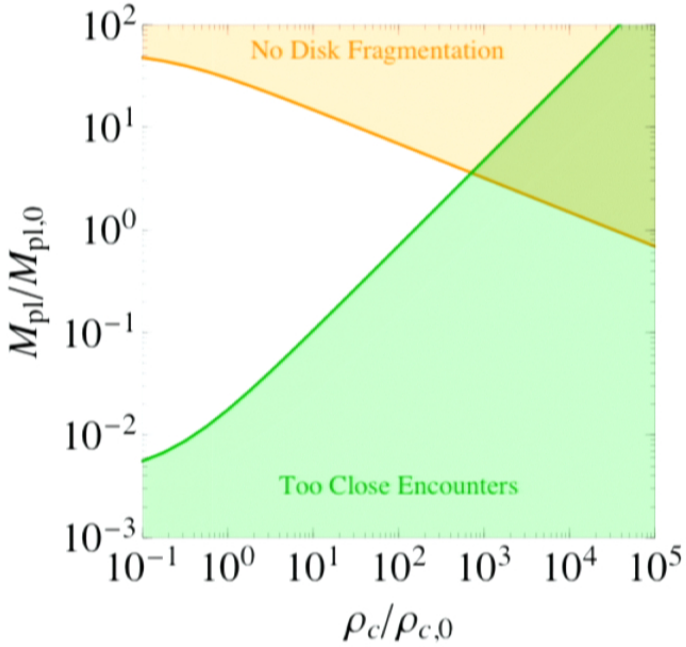


varying planck mass

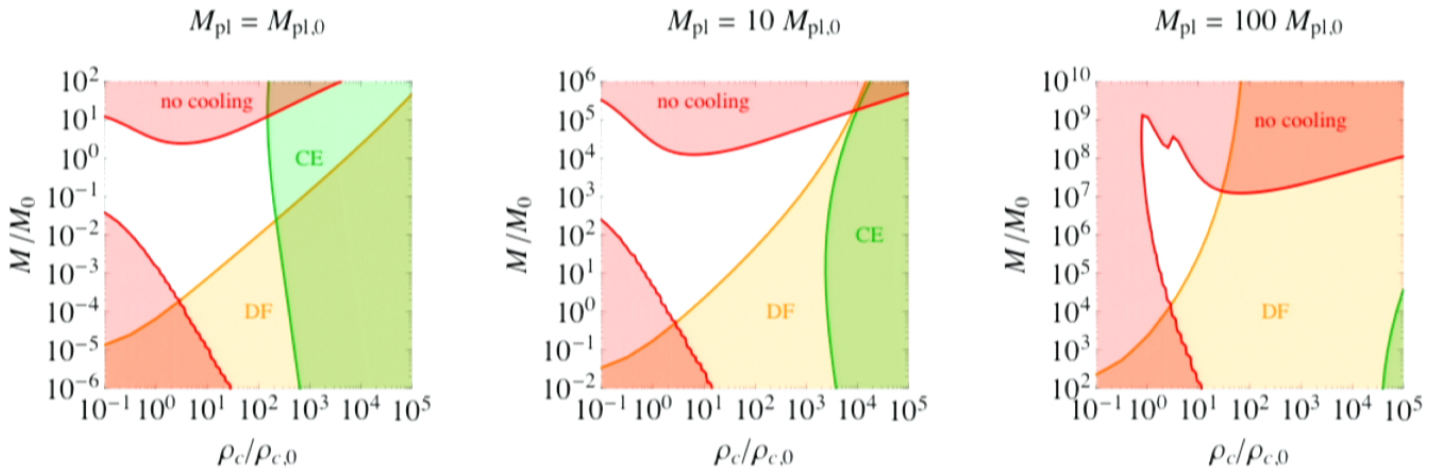
$M = 10^6\, M_{\rm sun}$



$M = 10^{13}\, M_{\rm sun}$



add in cooling



conclusions

- atomic principle bounds quark masses, not v
- EW fine tuning may be explained by He, unless baryon asymmetry, Mpl scan
- close stellar encounters, disk fragmentation, cooling bound virial density
  - restores Weinberg's solution to CC problem
  - explains EW fine tuning for WIMP DM
- more to do: $m_e, \delta\rho/\rho$, Silk damping, etc.