# Probing Fundamental "Constants" with Big Bang Nucleosynthesis

`0705.0696 [astro-ph]`

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Reviews and previous work:

1. J.-P. Uzan, Rev.Mod.Phys. 75 (2003) 403 [hep-ph/0205340], also astro-ph/0409424
2. Springer Lecture Notes 648 (2004) *"Astrophysics, Clocks and Fundamental Constants"*, ed. Karshenboim and Peik (see astro-ph/0310318)
3. C. M. Müller, G. Schäfer and C. Wetterich, *"Nucleosynthesis and the variation of fundamental couplings"*, astro-ph/0405373

# Motivation

Constancy of “constants” (couplings, mass ratios) is an assumption of particle physics
Should be tested!

- Does it make sense?

  Measuring different fundamental constants at different points in spacetime breaks Einstein equivalence principle (Local Position Invariance)

- But generally covariant theories with “varying constants” can easily be constructed

  *eg* GR plus scalar field weakly coupled to radiation and matter

- Doing physics with “varying constants”
  1. Look for signals and set limits
  2. Look for related effects (WEP violation)
  3. A nonzero signal can rule out unified theories, test models of quintessence *etc.*

- Important to consider many probes: different $z$, different environments. . .

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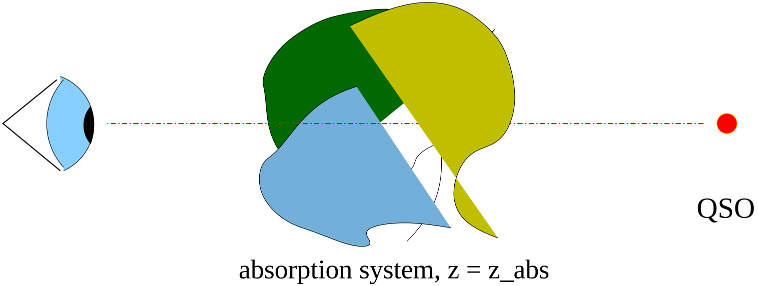
# Alpha: measurement methods




$$\omega_z = \omega_0 + q\left[\left(\frac{\alpha_z}{\alpha}\right)^2 - 1\right]$$

"Many-multiplet" method: different species with different $q$ coefficients enhance sensitivity (Murphy et al., `astro-ph/0209488`)

Latest published result, 143 systems (`astro-ph/0310318`)

$$\frac{\Delta\alpha}{\alpha} = (-0.57 \pm 0.11) \cdot 10^{-5}, \qquad 0.2 < z_{abs} < 4.2$$

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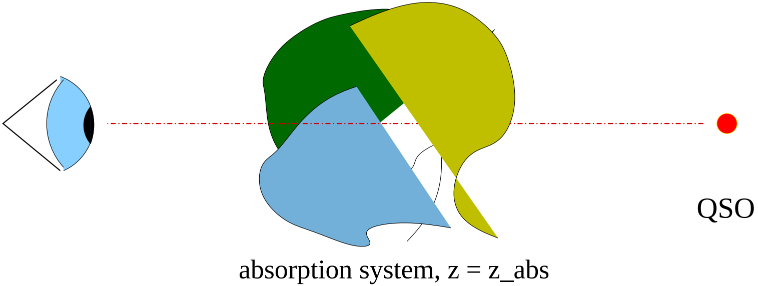


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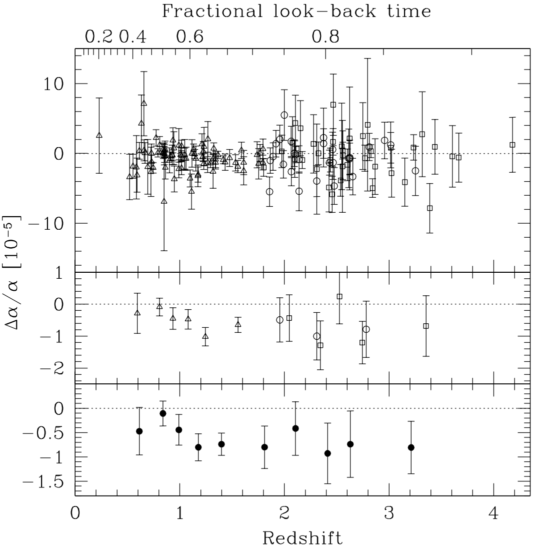
# Alpha data




More spectra still being analyzed...

# Other results on alpha

$$\frac{\Delta\alpha}{\alpha} = (-0.06 \pm 0.06) \cdot 10^{-5},\ 0.4 \leq z \leq 2.3$$ 23 systems, Srianand et al. 2004

$$\frac{\Delta\alpha}{\alpha} = (-0.007 \pm 0.084) \cdot 10^{-5},\ z_{abs} = 1.15$$ Levshakov et al. 2004

Murphy *et al.* criticize error assignments and fitting methods
`astro-ph/0611080, astro-ph/0612407`

Most recently :

$$\frac{\Delta\alpha}{\alpha} = (0.55 \pm 0.25) \cdot 10^{-5},\ z_{abs} = 1.84$$ Levshakov et al. `astro-ph/0703042`

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# A new mu?

$$\mu \equiv \frac{m_p}{m_e}$$

Vibro-rotational transitions of molecular hydrogen $H_2$, different dependences on reduced mass

$$2005: \frac{\Delta\mu}{\mu} = (3.05 \pm 0.75) \cdot 10^{-5} \text{ (A)},\ (1.65 \pm 0.74) \cdot 10^{-5} \text{ (B)}$$ Ivanchik et al.

Two different sets of lab wavelengths!

New lab measurements:

$$\frac{\Delta\mu}{\mu} = (2.4 \pm 0.6) \cdot 10^{-5},\ z_{abs} = 3.02,\ 2.59$$ Reinhold et al. PRL 2006

Recently: $NH_3$ spectrum constraint on $\Delta\mu/\mu$

$$\frac{\Delta\mu}{\mu} = (0.6 \pm 1.9) \cdot 10^{-6},\ z = 0.685$$ Flambaum and Kozlov, PRL 2007

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# Other dimensionless constants

⋆ $y \equiv \alpha^2 g_p$

$(\mu_p = g_p e/4m_p)$

Probe by comparing 21cm H I line and molecular rotation

$$\frac{\Delta y}{y} = (-0.20 \pm 0.44) \cdot 10^{-5}\ (z = 0.247), \qquad (-0.16 \pm 0.54) \cdot 10^{-5}\ (z = 0.685)$$

Murphy et al. 2001

⋆ $x \equiv \alpha^2 g_p \mu^{-1}$

Compare UV heavy element transitions with H I line

$$\frac{\Delta x}{x} = (0.63 \pm 0.99) \cdot 10^{-5},\ 0.23 \leq z_{abs} \leq 2.35$$

Tzanavaris et al. 2006

⋆ $F \equiv g_p \left[\alpha^2 \mu\right]^{1.57}$

Probe by comparing HI and OH lines

$$\frac{\Delta F}{F} = (0.44 \pm 0.36^{\rm stat} \pm 1.0^{\rm sys}) \cdot 10^{-5}\ (z = 0.765)$$

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# Oklo natural nuclear reactor

2 billion years ago ($z = 0.1$–$0.15$) naturally enriched uranium in a rock formation with a water moderator…

Resulting isotopic ratios in rock samples differ radically from any other terrestrial material

## Samarium

Ratio $^{149}$Sm/$^{147}$Sm : normally 0.9, measured at about 0.02 in Oklo sample

Resonant neutron capture

$$^{149}\mathrm{Sm} + n \rightarrow {}^{150}\mathrm{Sm} + \gamma$$

Today $E_{r,0} = 97.3$ meV, resonance width $\simeq 60$ meV

Resonance energy arises from $\langle H_c + H_n \rangle$ where $H_c \propto \alpha$

$$\alpha \frac{d}{d\alpha} \langle H_c \rangle \simeq 1\,\mathrm{MeV}$$

Neutron fluence and spectrum: estimate from other isotopes e.g.

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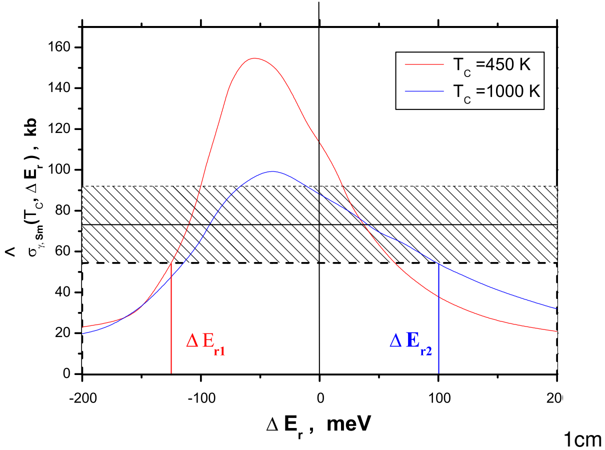
## Oklo bound




Recent bound

$$-5.6 \times 10^{-8} < \Delta\alpha/\alpha < 6 \times 10^{-8}, \qquad \dot{\alpha}/\alpha \leq 3.5 \times 10^{-17}\,\text{y}^{-1}$$

Petrov et al. `hep-ph/0506186`, see also Damour & Dyson 1996

# Interpreting Oklo, other nuclear physics bounds

Nuclear physics parameters $m_n, m_\pi, \ldots$ may also vary!

Can we calculate dependence of $\langle H_n \rangle$ from first principles – QCD, quark masses?

No

- use phenomenological models *e.g.* Walecka model, $\chi$PT...

- only order-of-magnitude estimates of dependence

*e.g.* claimed Oklo bounds:

$$\Delta \ln \frac{m_\pi}{\Lambda_{\rm QCD}} = 0.5 \Delta \ln \frac{m_q}{\Lambda_{\rm QCD}} \leq 7 \times 10^{-10}$$ Flambaum & Shuryak 2002

$$\Delta \ln \frac{m_q}{\Lambda_{\rm QCD}} \leq \text{few} \times 10^{-8}$$ Olive et al. 2002

Also use beta decays *e.g.* $^{187}$Re

$$\Gamma_{187} \propto Q_\beta^3 \propto \alpha^{2\times 10^4}$$

compare with less sensitive U $\rightarrow$ Pb in meteorites of similar age:

$$-2.4 \times 10^{-6} < \frac{\Delta\alpha}{\alpha} < 0.8 \times 10^{-6}, \; t = 4.6\,\text{Gyr}$$ Olive et al. 2003

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# Atomic clocks

Absolute frequency standard: $^{133}$Cs ground state hyperfine transition

Measure some other transition in the lab over years $\Rightarrow$
bound on fundamental "constant" variations (up to variation of $\mu_{\rm Cs}$)

## Example

- Atomic hydrogen 1S-2S transition $\nu_H \propto$ Ry
- Mercury electric quadrupole transition $\nu_{\rm Hg} \propto {\rm Ry}\alpha^{-3.2}$
- Caesium hyperfine transition $\nu_{\rm Cs} \propto {\rm Ry}\alpha^2 \frac{\mu_{\rm Cs}}{\mu_{\rm B}} \alpha^{0.8}$

Eliminate $\mu_{\rm Cs}$ to obtain $\dot{\alpha}/\alpha = (-0.9 \pm 2.9) \cdot 10^{-15}\,{\rm y}^{-1}$ Fischer et al. PRL 2004

Update: Peik et al. physics/0611088

$$d\ln\alpha/dt = (-0.26 \pm 0.39) \times 10^{-15}\,{\rm y}^{-1}, \qquad d\ln\mu/dt = (-1.2 \pm 2.2) \times 10^{-15}\,{\rm y}^{-1}$$

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# Spacetime dependence of variations

"Spontaneous" violation of LPI: cosmologically varying scalar $\varphi(x^\mu)$

"Constants" are functions of $\langle\varphi\rangle$

General theoretical framework: introduce action

$$\int d^4x\, \mathcal{L}(g_{\mu\nu}, \varphi, \text{matter})$$

Questions:

- Does variation of $\varphi$ inside virialized systems track cosmological evolution? (Yes! Wetterich 2002, Shaw & Barrow 2005)
- Does the value of $\varphi$ differ in different environments? (Yes – but not much!)
- Does $\varphi(t)$ vary monotonically or oscillate? (Fujii 2003)
- What drives the variation? (potential $V(\varphi)$, coupling to matter, . . . )
- What is the mass of the field?
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# WEP

Light scalar coupled to electromagnetic energy mediates composition-dependent force

$$m_{p,n} = m_{N,\mathrm{QCD}} + B_{p,n}\alpha_0(1+\lambda\varphi) + \cdots$$

$\varphi$-mediated force between Earth / Sun and different atoms

- Proton fraction $f_p$ is $0.456$ for Cu, $0.385$ for U
- Different electromagnetic binding energies $B_{\mathrm{nucl}}$
  $\Rightarrow$ differential acceleration

$$\eta \equiv 2\frac{|a_1-a_2|}{|a_1+a_2|} \qquad \propto \frac{\lambda^2}{m_N^2} B_{\mathrm{source}}(\Delta f_n B_n + \Delta f_p B_p + \Delta B_{\mathrm{nucl}})$$

Current limit $\eta \lesssim 10^{-13}$ (Eöt-Wash experiments)

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# WEP vs. variations plus cosmology

- Cosmological variation in $\varphi$ is $\leq 1$ (kinetic energy)
  If $\Delta\varphi$ is the source of $\Delta\alpha$ then $\lambda \gtrsim 10^{-5}$
  $\eta \geq 10^{-18}$, STEP will see a signal (Dvali & Zaldarriaga 2001)
- Couple $\varphi$ to QCD, fermion masses: $\mu$ also varies
  Earth's $\varphi$ field may be 2 orders of magnitude larger (Wetterich 2002) . . .
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- Cosmological limits on scalar kinetic energy
  Direct relations between $\Omega_\varphi$, $w_\varphi$, $\partial_t\alpha$, $\partial_t\mu$ today: TD, hep-ph/0608067
- Elliptical orbit $\rightarrow$ seasonal variation in "constants"? (Flambaum, Shaw)

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# Cosmology: CMB & after

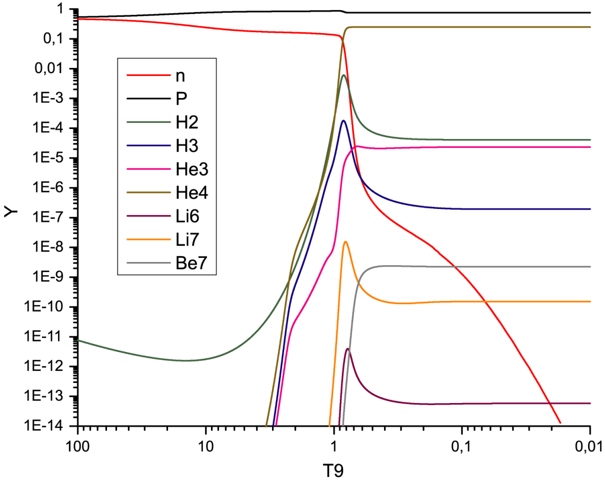
$\alpha$ affects CMB through Thomson scattering, recombination history

$$0.95 < \frac{\alpha_{\rm CMB}}{\alpha_0} < 1.02\ (1\sigma),\ z \sim 10^3$$ (Martins et al. 2004)

Relatively weak bound, degenerate with variations in other cosmological parameters

Effect of $\alpha$ on 21cm emissions?

# BBN: what is it?




$T_9 \equiv T/10^9\,\mathrm{K} \simeq T/0.1\,\mathrm{MeV}$

# BBN motivation

- (Space)time-dependence of $\varphi$ not known

  Test "constants" at many different redshifts, different astrophysical conditions

  BBN is extremely hot, dense, early compared to any other probe of particle physics
- More than one observable: D, $^4$He, $^7$Li, . . . ?

  WMAP determination of baryon density helps to fix one parameter
- Drawbacks: BBN sensitive to many parameters, degeneracy

  Astrophysical abundances have systematic issues

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# Cosmology: BBN ($z \sim 10^{10}$)

Simple treatment: All neutrons end up in $^4$He ⇒ Helium abundance

$$Y_{4\mathrm{He}} = 2\frac{(n/p)_f e^{-t_N/\tau}}{1 + (n/p)_f e^{-t_N/\tau}}$$

- $(n/p)_f = e^{-Q/T_f}$: freezeout of weak interactions, compare $\Gamma(n \leftrightarrow p)$ with $H$
- $t_N$: "nucleosynthesis time", compare $T$ with deuterium binding energy $B_{\mathrm{D}}$
- $\tau$: neutron lifetime

Already depends on every fundamental force: electroweak, strong, gravitational

Cosmological parameter: baryon abundance from WMAP3

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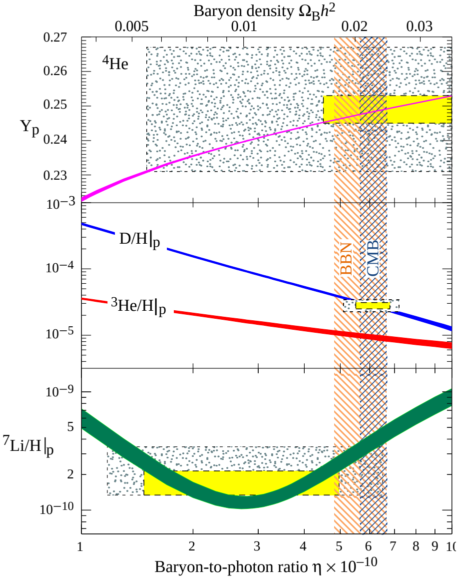
# Observation *vs.* theory (Fields and Sarkar, PDG 2006)



# Observation vs. theory: the numbers

| Nuclide | SBBN theory | Observation |
|---|---|---|
| D/H ($10^{-5}$) | $2.61 \pm 0.04$ | $2.82 \pm 0.26$ O'Meara et al. 2006 |
| $^3$He/H ($10^{-5}$) | $1.03 \pm 0.03$ | $< 1.1 \pm 0.2$ Bania et al. 2002<br>Complex post-BBN development $\Rightarrow$ no clear limit |
| $Y_{^4\mathrm{He}}$ | $0.2478 \pm 0.0002$ | $0.2474 \pm 0.0028$ Peimbert et al. 2007<br>$0.2472 \pm 0.0012$ Izotov et al. 2007<br>$0.2516 \pm 0.0011$ Izotov et al. 2007<br>$0.232 \leq Y_{^4\mathrm{He}} \leq 0.258$ Olive/Skillman 2004 |
| $^7$Li/H ($10^{-10}$) | $4.5 \pm 0.4$ | $1.26 \pm 0.3$ Bonifacio et al. 2007<br>"Lithium problem": questions in stellar astrophysics |

Table: Primordial abundances: number fraction or mass fraction $Y_i$

# BBN: current project

Use elements other than $^4$He to constrain more parameters

Problem: Dependence of binding energies and reaction rates ($A > 2$) on QCD

1. Define "nuclear parameters" $X_i$: inputs to the BBN integration code
   - $\eta$
   - $G_N$
   - $\alpha$
   - $\tau_n$
   - $m_e$
   - $Q_N \equiv m_n - m_p$
   - $m_N \equiv (m_n + m_p)/2$
   - Binding energies D, ..., $^7$Be
2. Find leading dependence of abundances on $X_i$ and forward reaction rates
   - Only 8 important reactions
   - $^4$He insensitive to rates
   - No abundance very sensitive to rates: $\partial \ln Y_a / \partial \ln \langle sigma \rangle \leq 1$
   - Very large dependence of $^7$Li on binding energies ($Q$-values)
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Units defined with $\Lambda_{\mathrm{QCD}}$ set to constant

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# Results

| $\partial \ln Y_a / \partial \ln X_i$ | D | $^3$He | $^4$He | $^6$Li | $^7$Li |
|---|---|---|---|---|---|
| $\eta$ | $-1.6$ | $-0.57$ | $0.04$ | $-1.5$ | $2.1$ |
| $G_{\rm N}$ | $0.94$ | $0.33$ | $0.36$ | $1.4$ | $-0.72$ |
| $\alpha$ | $2.3$ | $0.79$ | $0$ | $4.6$ | $-8.1$ |
| $\tau_n$ | $0.41$ | $0.15$ | $0.73$ | $1.4$ | $0.43$ |
| $m_e$ | $-0.16$ | $-0.02$ | $-0.71$ | $-1.1$ | $-0.82$ |
| $Q_N$ | $0.83$ | $0.31$ | $1.5$ | $2.9$ | $1.0$ |
| $m_N$ | $3.5$ | $0.11$ | $-0.07$ | $2.0$ | $-12$ |
| $B_{\rm D}$ | $-2.8$ | $-2.1$ | $0.68$ | $-6.8$ | $8.8$ |
| $B_{\rm T}$ | $-0.22$ | $-1.4$ | $0$ | $-0.20$ | $-2.5$ |
| $B_{\rm 3He}$ | $-2.1$ | $3.0$ | $0$ | $-3.1$ | $-9.5$ |
| $B_{\rm 4He}$ | $-0.01$ | $-0.57$ | $0$ | $-59$ | $-56$ |
| $B_{\rm 6Li}$ | $0$ | $0$ | $0$ | $69$ | $0$ |
| $B_{\rm 7Li}$ | $0$ | $0$ | $0$ | $0$ | $-6.9$ |
| $B_{\rm 7Be}$ | $0$ | $0$ | $0$ | $0$ | $81$ |

Table: Dependence of abundances on nuclear parameters

# Translating to fundamental parameters

Dependence on electromagnetic and weak interactions: relatively straightforward

Quark mass dependence of $m_{n,p}$ under control (strangeness content?)

Deuteron binding $B_{\rm D}$: systematic treatment in $\chi$PT

$$\Delta \ln B_D = (-8 \pm 2) \Delta \ln m_\pi = (-4 \pm 1) \Delta \ln \hat{m}$$

Beane & Savage, Epelbaum et al.

Other binding energies: parameterise pion contribution to $B_i$ as scaling with $(A_i - 1)$ times fudge factors $f_i$ (order 1)

| $\partial \ln Y_a / \partial \ln G_k$ | D | $^4$He | $^7$Li |
|---|---|---|---|
| $G_{\rm N}$ | $0.94$ | $0.36$ | $-0.7$ |
| $\alpha$ | $3.6$ | $1.9$ | $-11$ |
| $\langle \phi \rangle$ | $1.6$ | $2.9$ | $1.7$ |
| $m_e$ | $0.46$ | $0.40$ | $-0.17$ |
| $\delta_q$ | $-2.9$ | $-5.1$ | $-2.8$ |
| $\hat{m}$ | $\gtrsim 10$ | $\simeq -2.7$ | $\gtrsim -60$ |

Table: Dependence on fundamental parameters

Quark mass dependences via $\delta_q \equiv m_d - m_u$ and binding energies dominate!

Investigation of nuclear binding energy from first principles should be a priority!

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# Fundamental parameters related by unification

Write variation of “fundamental” parameters as

$$\Delta \ln G_k = d_k \Delta\bar{\varphi} \equiv \frac{d_k}{d_\alpha} \Delta \ln \alpha$$

vector $d_k$ depends on choice of model

Enforce gauge unification and define $\gamma$

$$\frac{\langle\phi\rangle}{M_X} = \text{const.} \left(\frac{\Lambda_c}{M_X}\right)^\gamma$$

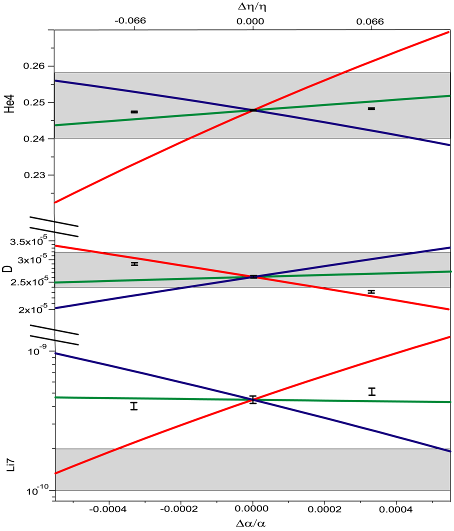
Three scenarios: $\gamma = 0, 1, 1.5$

Neglect variation in $M_{\rm P}/M_X$ and Yukawas

1. $\Delta \ln(G_N, \alpha, \langle\phi\rangle, m_e, \delta_q, \hat{m}) \simeq (64, 1, -32, -32, -32, -32)\Delta \ln \alpha$
2. $\Delta \ln G_k \simeq (78, 1, 0, 0, 0, 0)\Delta \ln \alpha$
3. $\Delta \ln G_k \simeq (87, 1, 22, 22, 22, 22)\Delta \ln \alpha$

Current observational values might (just?) be reconciled

# Three unified scenarios



# Summary

Many methods exist to investigate EEP and constancy of fundamental “constants”:

- ⋆ Astrophysical spectra
- † Nuclear reactions and decays
- ∘ Atomic clocks
- ∗ Cosmology
- • WEP violation

Unlikely source of new physics, but huge implications of any positive result

BBN probes “constants” at earliest time, conditions most different from today

Complex system, observations need to be clarified

We disentangle dependence on nuclear / fundamental parameters and find stringent bounds (percent level)

TD, Stern, Wetterich 0705.0696 [astro-ph]

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"Lithium problem": questions in stellar astrophysics

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