Conclusions

Particle Physics Side:

- Stability - No Fine-Tunings
- GUT theory
- Good 4D low energy interaction

Cosmology Side:

- Challenging Dynamics
- (Vacuum) Energy Problem

Unknown Physics Anyway

Some More Benefits

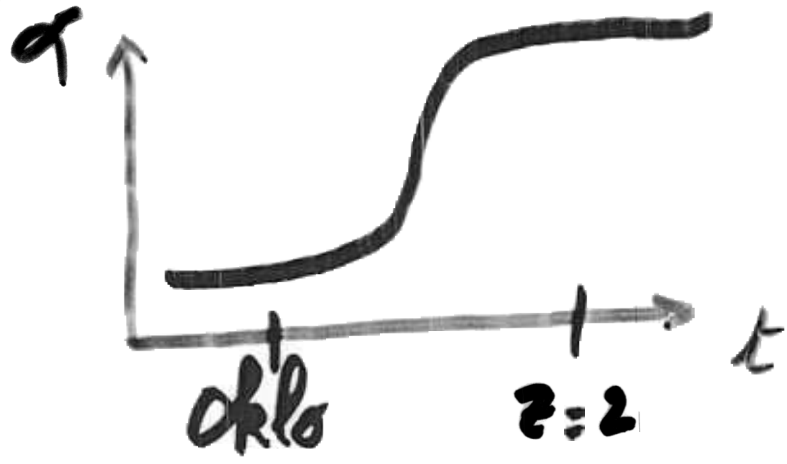
[redacted]

Consider SO(10) broken by Σ $(0\ 0\ 0\ \sigma_2\ \sigma_2)\,v$

$SU(4) \times SU(2) \times U(1)$

$S_{M_{pq}}\ \Sigma\, Q\, Q$ → coupling to SU(2) doublets
→ no coupling to SU(3) triplets

[redacted]



More about Phase Transition

Thermalization

- **Self Interactions** NO!

$\frac{\Delta\alpha}{\alpha} = 10^{-5}$ $\frac{\Delta\Pi}{\Pi} = \frac{\langle S\rangle}{\Pi} \sim 10^{-2}$ $\langle S\rangle \sim 10^{14}$ GeV

S quartic coupling $\lambda \sim \frac{m^2}{S^2} \sim 10^{-52}$

- **Hidden Sector**: $W = ST^2 + TY^2$ Modulus!

decouple at early times but $T_{Hidden} \sim T_\gamma$

Vacuum Energy:

- $V(0) - V(\langle S\rangle) \sim |V''(0)|\langle S\rangle^2 = (10^{-3}\,eV)^2(10^{14}\,GeV)^2 \sim (10^{10}\,eV)^4$

- Requiring $\Delta V < (10^{-3}\,eV)^4$ $\rightarrow$ $\frac{\Delta\alpha}{\alpha} < 10^{-31}$

Facing the C.C. Pb again!

[Banks, Dine, Douglas '01]

Benefits of 10^{-3} eV Mass

- **Stability**: [Arkani-Hamed, Hall, Kolda, Murayama '00]
  - cannot couple to Π $\quad \delta m^2 \quad m_Z^2$
  - couple to hidden massive sector

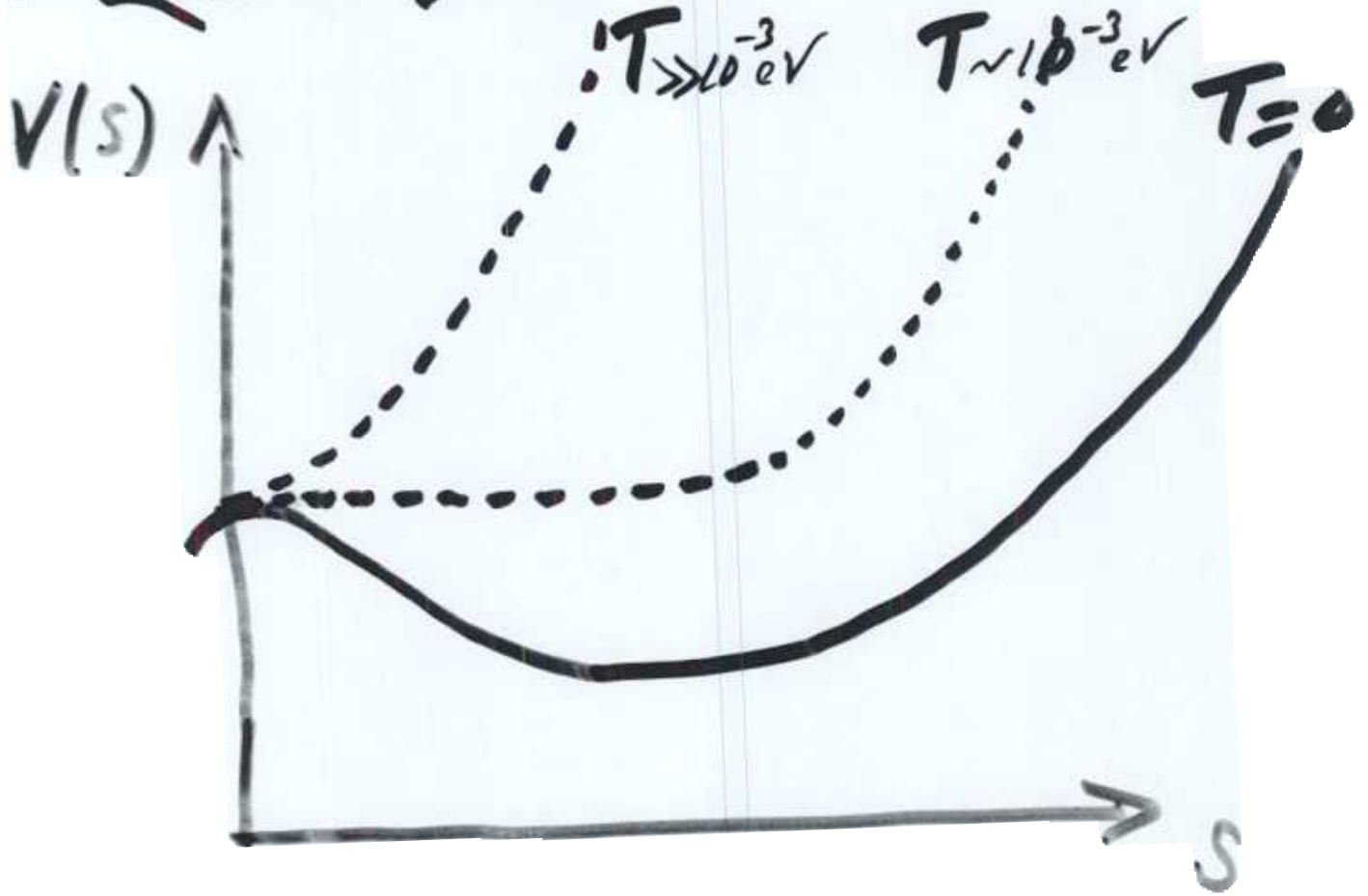
$$\delta m^2 \sim \frac{y^2}{16\pi^2}\left(\frac{e^2}{16\pi^2}\right)^2 \frac{F_{susy}^2}{\Pi^2}$$

- **No Modification of Gravity**

Newton's law: • mm^{-1} mass
• Planck suppressed coupling

No Violations of Equivalence Principle

A Late Phase Transition

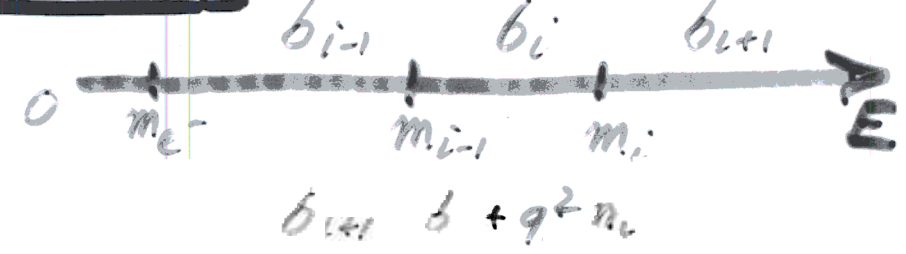


$m_s \sim$ Phase Transition @ $z = 2$

Varying the Thresholds !

[Chacko, C.G Perelstein '02

$$\alpha^{-1} = \alpha_{GUT}^{-1} + \frac{1}{2\pi}\sum_{i=0}^{N} b_{i+1} \ln \frac{m_{i+1}}{m_i}$$



b_{i+1} $b + q^2 n_i$

- **Keep α_{GUT} fixed & Vary m_i**

$$\frac{\Delta\alpha}{\alpha} = -\frac{\alpha}{2\pi}\sum_{i=0}^{N} (b_i - b_{i+1})\frac{\Delta m_i}{m_i}$$

10^{-5} 10^{-2}

- **How to generate Δm_i:**

electrically charged particle

$$(\Pi + y\,\mathbf{S})\, Q\bar{Q}$$

S: scalar field that takes a vev $\in \mathbb{Z}$ 2

Variations of Mass Ratios

$\Delta m_{proton} \sim \Delta \Lambda_{QCD}$
$\quad\;\; proton \qquad\quad \Lambda_{QCD}$

$\hookrightarrow \quad \Delta (m_p/m_e) \sim 30 \cdot 10^{-5}$
$\qquad\quad m_p/m_e$

experimentally $< 8\,10^{-5}$

Ways Out [Langacker Segrè Strassler 01]

- shift of Yukawa Coupling
- shift of Higgs Vev
- shift of Gauge coupling

Possible Cancellation but Fine Tuning
(Not Predicted by GUT Symmetry

Some Problems Anyway ...

- Not natural to vary α_{GUT} @ z 2 since $\alpha_{GUT} \leftrightarrow$ High Ene
- **BBN**: freeze out temperature neutron $\leftrightarrow$ proton is modified
- **Oklo**

$\alpha(t)$ From $\alpha_{GUT}(t)$

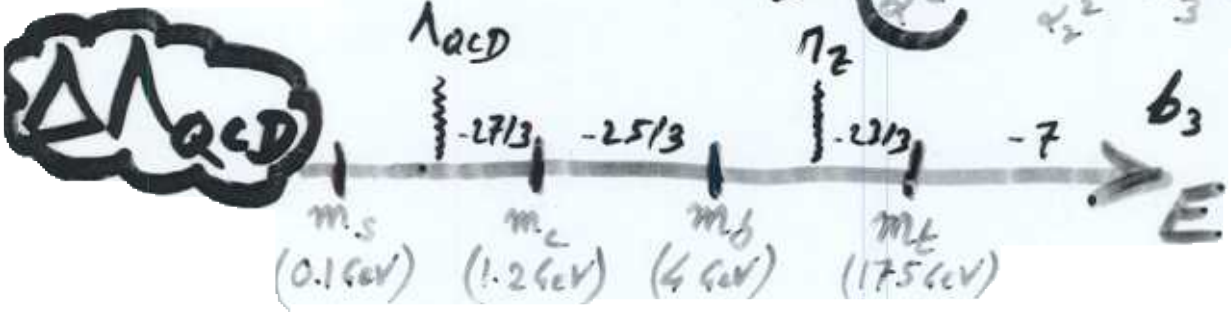
$$\alpha_i^{-1}(\mu) = \alpha_{GUT}^{-1} - \frac{b_i}{2\pi} \ln \frac{\mu}{m_{GUT}}$$

@ m_Z : $SU(2) \times U(1)_Y$ → $U(1)_{e.m.}$

$$q = \tau_3 + \sqrt{\frac{5}{3}}\, Y \quad \rightarrow \quad \frac{1}{\alpha} = \frac{1}{\alpha_2} + \frac{5}{3}\frac{1}{\alpha_1}$$

$$\frac{\Delta\alpha}{\alpha^2} = \frac{\Delta\alpha_2}{\alpha_2^2} + \frac{5}{3}\frac{\Delta\alpha_1}{\alpha_1^2} - \frac{5}{3}\frac{\Delta\alpha_{GUT}}{\alpha_{GUT}^2}$$

$\Delta\Lambda_{QCD}$



$$\alpha_3^{-1}(m_t) = \alpha_3^{-1}(m_Z) + \frac{23}{3}\frac{1}{2\pi}\ln\left(\frac{m_t}{m_Z}\right)$$

$$\alpha_3^{-1}(m_c) = \alpha_3^{-1}(m_b) + \frac{25}{3}\frac{1}{2\pi}\ln\left(\frac{m_c}{m_s}\right)$$

$$0 = \alpha_3^{-1}(\Lambda_{QCD}) - \alpha_3^{-1}(m_c) - \frac{27}{3}\frac{1}{2\pi}\ln\left(\frac{\Lambda_{QCD}}{m_c}\right)$$

$$\Lambda_{QCD}^9 = m_Z^{23/3}\, m_c^{2/3}\, m_b^{2/3}\, e^{-\frac{2\pi}{\alpha_3(m_Z)}}$$

$$\frac{\Delta\Lambda_{QCD}}{\Lambda_{QCD}} = \frac{2\pi}{9}\frac{\Delta\alpha_3}{\alpha_3^2(m_Z)} \simeq$$

[Langacker, Segre Strassler '01
Calmet, Fritzsch '01
Dent, Fairbairn '01]

Time Variation and Running

$\alpha_{e.m.}$ varies BECAUSE T varies ?

NO!

- QED is IR free : $\alpha \searrow$ when $E \searrow$
- α doesn't run below $m_e = 0.5$ MeV ie

RGE

$$\frac{d\alpha_i}{d\ln\mu} = \frac{b_i}{2\pi}\alpha_i^2$$

$$b_i = -\frac{11}{3}T_2(G) + \frac{2}{3}T_2(\text{Weyl}) + \frac{1}{6}T_2($$

< 0 for uv fre

$$\frac{1}{\alpha_i(\mu)} = \frac{1}{\alpha_i(\mu_0)} - \frac{b_i}{2\pi}\ln\frac{\mu}{\mu_0}$$

Unification

If unification @ M_{GUT}

$$B_{ijkl} = \frac{\alpha_i^{-1}(\mu) - \alpha_j^{-1}(\mu)}{\alpha_k^{-1}(\mu) - \alpha_l^{-1}(\mu)} = \frac{b_j - b_i}{b_l - b_k} \quad \#$$

[redacted]

$b_{3-2-1} = -7, -\frac{19}{6}, \frac{41}{10}$ & $\alpha_i(m_z)$ $\quad B_{exp} = 0.69$ $B_{SM} = 0.53$

$b_{3-2-1} = -3, 1, \frac{33}{5}$ & $\alpha_i(m_z)$ $\quad B_{exp} = 0.69$ $B_{mssm} = 0.71$

$(2,3,1,2)$

Some Ways out ?

• Coupling to Dark Matter [Olive, Pospelov '01]

- suppress coupling of ϕ to SM matter
- couple ϕ to Dark Matter

(⚠ D.M. is neutral

but susy $\phi F^2 \leftrightarrow \phi \bar{\chi} \partial \chi$ LSP ⊃ gaugino.

• Attractor Solution: [Damour, Polyakov '94] [Damour, Veneziano '02]

- $f'(\phi_0) = 0$ i.e. $\lambda = 0$ oscillatory solution
- Require all couplings of ϕ to matter to have the same extremum ⊕ some fine-tuning

• No Violation of Equivalence Principle

New source of violation that exactly compensate the naive one ... [Bekenstein, last week]

Instability Radiative Cor. Remains !

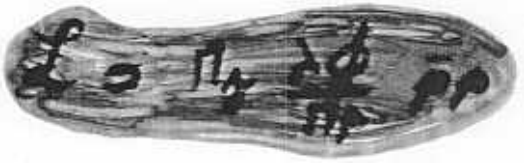
Violations of 4D Gravity

- **[redacted]**: [redacted]

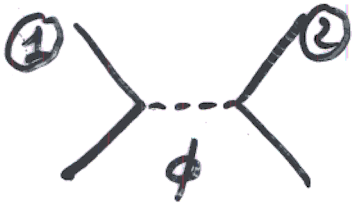
ϕ "massless" scalar coupled to S.M. Sub-Planckian Coupling

- **Equivalence Principle**

- $\Pi_{proton} = 3\Lambda_{QCD} + 2m_u + m_d + \alpha\Pi_\gamma$
- $\Pi_{Neutron} = 3\Lambda_{QCD} + m_u + 2m_d$



$$\frac{m_1 m_2}{\Pi_P^2 r^2}$$



$$\frac{\#_\phi^2 \lambda \Pi_\gamma \#_P^2 \lambda \Pi_\gamma}{\Pi_P^2 r^2}$$

② & ②'

same mass

different composition

$$\eta = \frac{a_2 - a_2'}{a_2 + a_2'} = \lambda^2 \frac{\Pi_\gamma^2 \#_\phi^2 (\#_P^2 - \#_P^{2'})}{m_1 m_2} \simeq$$

Experimental Bound: [redacted]

(MICROSCOPE) $\eta < 10^{-12}$

(STEP) $\eta < 10^{-15}$

$\eta < 10^{-18}$

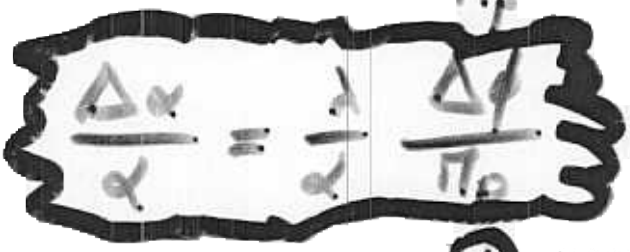
[redacted]

Quintessential Models

$$\mathcal{L} \supset \frac{1}{16\pi\alpha} F^2 \longrightarrow \frac{1}{16\pi} f\left(\frac{\phi}{M_p}\right) F^2$$

. dilaton vev
. size of X dim
...

$$\alpha(t) = \alpha_0 + \lambda \frac{\phi(t)}{M_p} + \dots$$



[Bekenstein '82
. Dvali, Zaldarriaga
. Olive, Pospelov '01

$$\left(\frac{\Delta\phi}{M_p}\right)^2 = \left(\frac{\dot\phi}{H_0 M_p}\right)^2 = \frac{(1+w_\phi)\rho_\phi}{\rho}$$

$\rho_\phi = \frac{1}{2}\dot\phi + V$
$p_\phi = \frac{1}{2}\dot\phi - V$

1. $\Delta\phi \sim M_p \rightarrow \rho_\phi \sim \rho$

2. $\Delta\phi \ll M_p \rightarrow$

$$\ddot\phi + 3H\dot\phi + m^2\phi + \dots = 0$$

1. $m \ll H_0$ ... exponential dumping
2. $m \gg H_0$ ... oscillations in the past & equilibrium now

$$m \sim H_0 \sim 10^{-33}\ eV$$

Unstable under Radiative Corrections

Experimental Results

Absorption lines in spectra of distant quasars

$$\frac{\alpha_{\text{today}} - \alpha_{z=2}}{\alpha_{\text{today}}} \quad (.7 \pm .8)\,10^{-5}$$

[Webb et al '00]

and also Oklo

$$\left| \frac{\alpha_{\text{today}} - \alpha_{z=0.07}}{\alpha_{\text{today}}} \right| < 10^{-7}$$

[Shlyakhter '7
[Damour/Dyson '9

Can we understand/explain these results in particle physics ?

more fields, more dim BUT 4D SM Gravity

Modify electromagnetic coupling

Modify α running

What can we learn in Particle Physics from a Time Variation of $\alpha_{e.m}$?

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