

INSTITUTE FOR ADVANCED STUDY
'IHES@50'
SAT, NOVEMBER 8, 2008

THE CONSTANTS OF NATURE

Thibault Damour

IHES

2008

NOT ONLY THE 50TH ANNIVERSARY OF THE
BIRTH OF IHES, BUT


NOVEMBER 2008

IS THE 60TH ANNIVERSARY OF THE
CONCEPTION OF IHES

14 NOVEMBER 1948

"CÉCILE AMUSED US ALL YESTERDAY BY BRINGING DOWN A FRENCH MILLIONAIRE TO SEE THE INSTITUTE (AN INDUSTRIAL MAGNATE OF SOME KIND). SHE SAID SHE HINTED TO HIM FAIRLY STRONGLY THAT FRANCE COULD DO WITH AN INSTITUTE OF A SIMILAR SORT; SHE SAID IF SHE WERE MADE DIRECTOR OF THE FRENCH INSTITUTE SHE WOULD INVITE ALL OF US TO COME AND LECTURE THERE. IT WILL BE INTERESTING TO SEE IF ANYTHING COMES OF IT."

FREEMAN J. DYSON

IHES'S  GODFATHER, AND ONE OF THE FEW PHYSICISTS FROM IAS WHO VISITED IHES AND INTERACTED WITH IT

(DIMENSIONLESS) CONSTANTS OF NATURE

$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137.03599907}$$

$$\frac{m_p}{m_e} = 1836.152669$$

$$\frac{G m_e m_p}{\hbar c} = 3.216 \times 10^{-42}$$

ABOUT 20 SUCH INDEPENDENT CONSTANTS IN 'STANDARD MODEL'

AND ~ 100 IN MSSM

WHAT DETERMINES THESE CONSTANTS ?

SCIENTIFICALLY UNSATISFACTORY TO PUT THEM BY HAND :

THIS IS AGAINST THE **PRINCIPLE OF REASON**
'NIHIL EST SINE RATIONE' (LEIBNIZ)

COULD THEY VARY (IN TIME AND/OR SPACE) ?

DIRAC '37 $\frac{G(t) m_e m_p}{\hbar c}$ VARIES

FIERZ '56 $\alpha(t)$ VARIES IN JORDAN'S ORIGINAL
THEORY IMPLEMENTING DIRAC'S IDEA

(~ KALUZA-KLEIN) $G \leftrightarrow \varphi(t, \vec{x})$

ASTRONOMICAL LIMITS ON THE VARIATION OF α

SAVEDOFF '56, BAHCALL-SALPETER '65, BAHCALL-SCHMIDT '67, ...

UPPER LIMITS: $\left| \frac{\Delta\alpha}{\alpha} \right| \lesssim 10^{-3}$, THEN 10^{-4}

EXCEPT CLAIM: WEBB, MURPHY ET AL '01 $\frac{\Delta\alpha}{\alpha} = (-0.72 \pm 0.18) \times 10^{-5} \neq 0?$
OVER REDSHIFTS $z \in [0.5, 3.5]$

COUNTER UPPER LIMITS (LEVSHAKOV, ..., PETITJEAN): $\left| \frac{\Delta\alpha}{\alpha} \right| \lesssim 2 \times 10^{-6}$
@ $z \sim 1$

+ UPPER LIMITS ON THE VARIATION OF $\mu \equiv m_p / m_e$

(WENDT, REIMERS '08) $\left| \frac{\Delta\mu}{\mu} \right| < 2.5 \times 10^{-5}$ @ $z_{\text{abs}} = 3.02$

GEOLOGICAL CONSTRAINTS ON 'VARYING CONSTANTS'

β -DECAY LIFETIMES $\left\{ \begin{array}{l} \text{IN THE LAB} \\ \text{IN IRON METEORITES} \\ \text{IN MOLYBDENITE ORES} \end{array} \right.$
 $^{187}\text{Rhenium}$

PEEBLES-DICKE '62

DYSON '72 $|\Delta\alpha/\alpha| < 5 \times 10^{-6}$

OLIVE ET AL '04 $\frac{\Delta\alpha}{\alpha} = (-8 \pm 8) \times 10^{-7}$

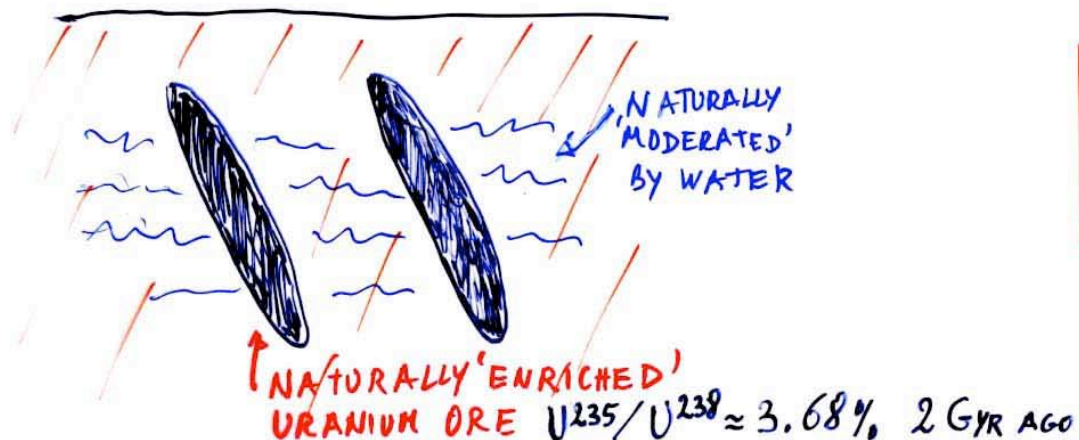
OVER AGE OF SOLAR SYSTEM: $4.6 \text{ Gyr} \leftrightarrow z \approx 0.45$

THE OKLO PHENOMENON: $\sigma: n \rightarrow \text{Sm}^{149}$
CAPTURE

SHLYAKHTER '76

DANOV. DYSON '96 $|\Delta E_r| \lesssim 0.10 \text{ eV}$

FUJII ET AL. 100



$$\left| \frac{\Delta\alpha}{\alpha} \right| \lesssim 10^{-7} \text{ OVER } \sim 2 \text{ Gyr}$$

$$\left| \frac{\dot{\alpha}}{\alpha} \right| \lesssim 5 \times 10^{-17} \text{ yr}^{-1}$$

CONSTRAINTS ON THE VARIATION OF G

LUNAR LASER RANGING

WILLIAMS, NEWHALL, DICKEY '96
TURYSHEV ET AL.

$$\left| \frac{\dot{G}}{G} \right| \lesssim 10^{-12} \text{ yr}^{-1}$$

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BINARY PULSARS

DAMOUR, GIBBONS, TAYLOR '88
DAMOUR, TAYLOR '91
KASPI ET AL '94

$$\left| \frac{\dot{G}}{G} \right| \lesssim 10^{-11} \text{ yr}^{-1}$$

MASSES OF NEUTRON STARS

THORSETT '96

$$\left| \frac{\dot{G}}{G} \right| \lesssim 4 \times 10^{-12} \text{ yr}^{-1}$$

ATOMIC CLOCK LIMITS ON VARYING CONSTANTS

MANY COMPARISONS
OF ATOMIC CLOCKS

HYPERFINE TRANSITIONS $\left\{ \begin{array}{l} \text{Rb} \\ \text{Cs} \end{array} \right.$ SIZE...
MARION...

OPTICAL TRANSITIONS $\left. \begin{array}{l} \text{H} \\ \text{Yb}^+ \\ \text{Hg}^+ \\ {}^{87}\text{Sr} \end{array} \right\} \begin{array}{l} \text{FISHER...} \\ \text{PEIK...} \\ \text{FORTIER...} \\ \text{BLATT...} \end{array} \left. \begin{array}{l} \frac{\dot{\alpha}}{\alpha} = (-3.3 \pm 3.0) \times 10^{-16} \text{ yr}^{-1} \\ \frac{\dot{\mu}}{\mu} = (-1.6 \pm 1.7) \times 10^{-15} \text{ yr}^{-1} \end{array} \right.$

RECENTLY 10^{-17} LEVEL

RATIO TWO SINGLE-ION
OPTICAL CLOCKS

$$\frac{\nu_{\text{Al}^+}}{\nu_{\text{Hg}^+}} = 1.052871833148990438 \pm 5.5 \times 10^{-17}$$

ROSENBERG... '08

$$\frac{\dot{\alpha}}{\alpha} = (-1.6 \pm 2.3) \times 10^{-17} \text{ yr}^{-1}$$

WHAT DETERMINES THE CONSTANTS ?

LOCAL PARTICLE PHYSICS

$$\sum_a -\frac{1}{g_a^2} \eta^{\alpha\mu} \eta^{\beta\nu} F_{\alpha\beta}^{aA} F_{\mu\nu}^{aA}$$

$$+ \sum_i \bar{\psi}_i [\gamma^\mu (\partial_\mu + A_\mu) + m_i] \psi_i$$

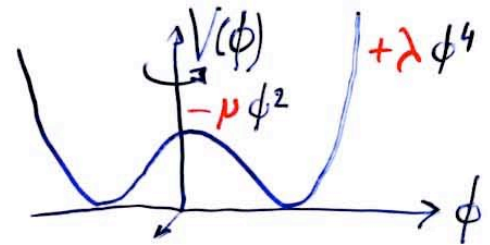
'EXTERNAL' DYNAMICAL EFFECTS

THAT DETERMINE THE STRUCTURE
OF LOCAL 'VACUUM'

$$\eta_{\mu\nu} = [g_{\mu\nu}(x)]^{\text{LOCAL}} \quad \text{EINSTEIN '15}$$

$$m_{e,q} = Y_{e,q} \langle \phi(x) \rangle^{\text{LOCAL}} \quad \text{HIGGS}$$

$$m_p \sim \Lambda_{\text{QCD}} \sim \Lambda_{\text{UV}} e^{-\frac{c}{g_3^2(\Lambda_{\text{UV}})}}$$

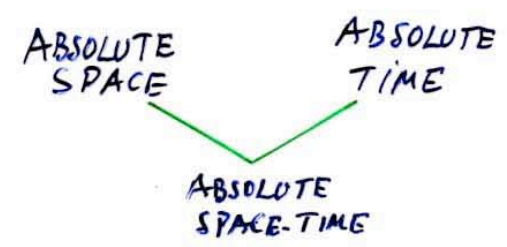


? WHAT DETERMINES $g_a, Y_{e,q}, \lambda, \mu$?

APPEALING IDEA:

∃ NO ABSOLUTE STRUCTURES IN PHYSICS

~ NEWTON



(ABSOLUTE) CONSTANTS OF PHYSICS

EINSTEIN 1905

(ABSOLUTE) CONSTANTS

EINSTEIN 1915

DYNAMICAL SPACETIME $g_{\mu\nu}(x)$

ABSOLUTE CONSTANTS (EQUIVALENCE PRINCIPLE)

KALUZA-KLEIN 1919

PAULI 1953

$g_{\mu\nu}(x)$

DYNAMICAL GAUGE COUPLINGS
 $g^2(x) \sim g_{55}(x)$

STRING THEORY

$g_{\mu\nu}(x)$

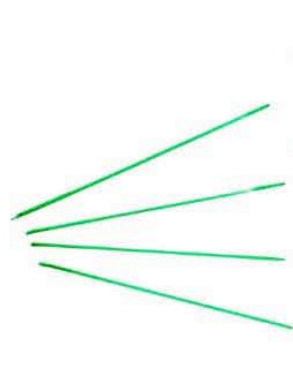
$g_s = e^{\Phi(x)}$ SCHERK SCHWARZ

$g_a^2 = f(\Phi, \Phi_1, \Phi_2, \dots)$ ⋮

$Y = f(\Phi, \Phi_1, \Phi_2, \dots)$

$g_s^2 = (g_{4444}(x))^{3/2}$ WITTEN

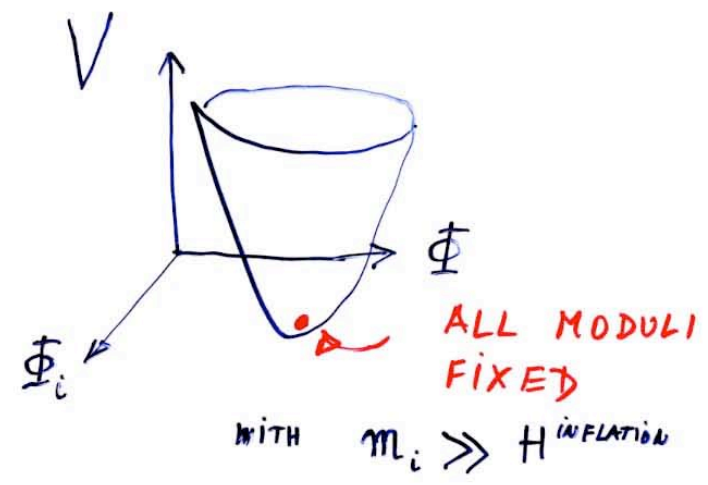
EVERYTHING IS DYNAMICAL



? PROBLEM WITH CONSTRAINTS ON $\dot{\alpha}$
 $\nabla \alpha$

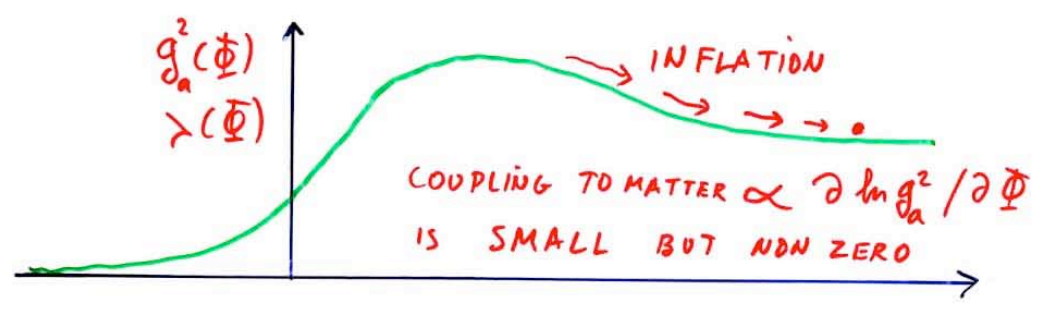
EQUIVALENCE PRINCIPLE TESTS

• GENERALLY ASSUMED THAT



• ANOTHER SCENARIO:
'COSMOLOGICAL ATTRACTOR'

(T.D. POLYAKOV, T.D. PIAZZA-VEVEZIANO)

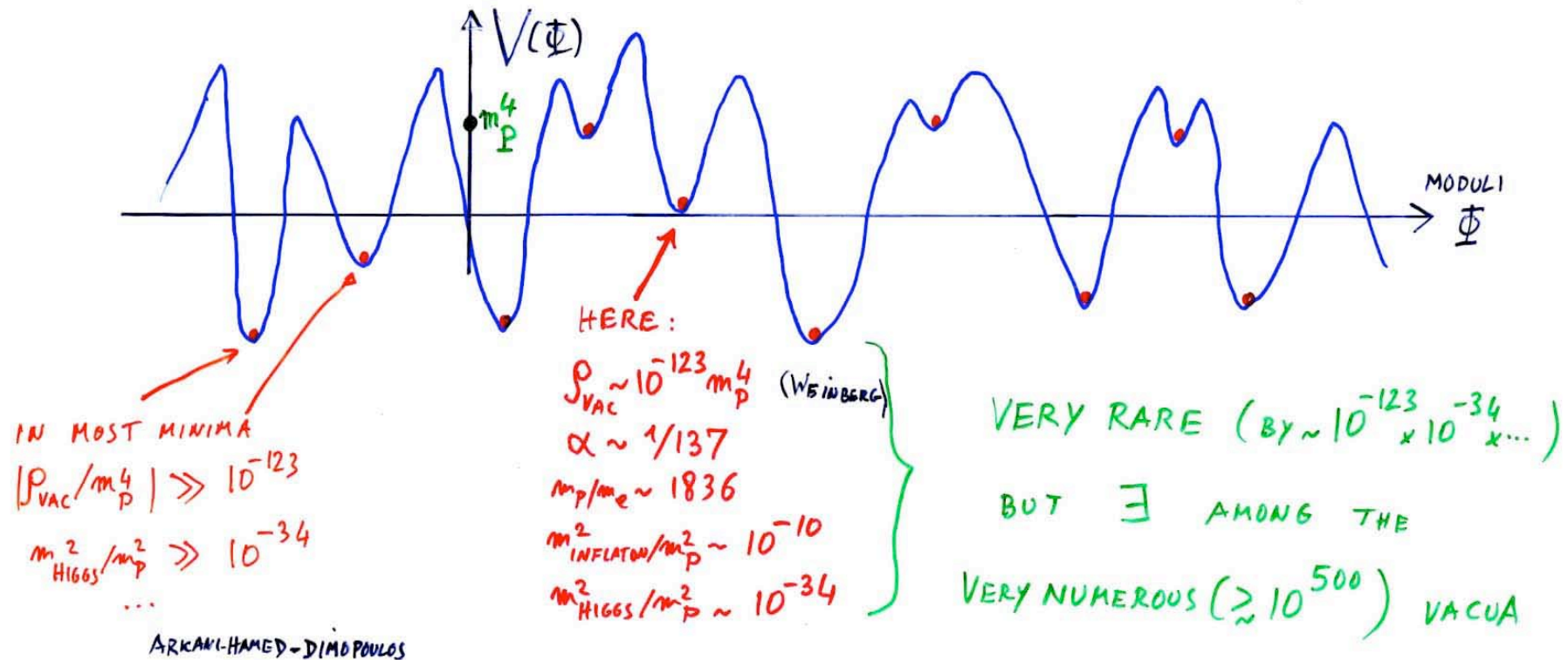


PREDICTS NATURALLY SMALL $\dot{\alpha} / \nabla \alpha \lesssim$ BELOW CURRENT LIMITS

DYNAMICS VS ANTHROPICS

DIRAC $\frac{G m_e m_p}{e^2} \sim \frac{t^{\text{ATOMIC}}}{t^{\text{UNIVERSE NOW}}}$ VS DICKE $\frac{G m_e m_p}{e^2} \sim \frac{t^{\text{ATOMIC}}}{t^{\text{TYPICAL MS STAR}}}$

? VAST 'LANDSCAPE OF STRING VACUA' POLCHINSKI-BOUSSO, SUSSKIND, DOUGLAS, DENEF, ... ARKANI-HAMEZ



WELL-POSED SCIENTIFIC QUESTIONS RELATED TO ANTHROPICS

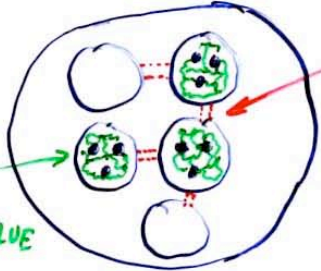
EFFECT OF VARYING CONSTANTS ON KNOWN PHYSICS

E.G. 'ATOMIC PRINCIPLE' (AGRAWAL, BARR, DONOGHUE, SECKEL; ARKANI-HAMBD, DIMOPOULOS)

WHAT RANGE OF VALUES OF $\left\{ \begin{array}{l} m_q / \Lambda_{QCD} \\ v_{HIGGS} \end{array} \right\} \Leftrightarrow \exists \text{ H AND/OR HEAVY ATOMS}$

RECENT PROGRESS (DONOGHUE '06; DAMOUR-DONOGHUE '08)

HEAVY NUCLEI



WEAK VANDERWAALS-LIKE FORCES BETWEEN COLORLESS NUCLEONS

ATTRACTION SCALAR $V_S(q^2) = -\frac{2}{\pi} \int_{2m_\pi}^{\infty} d\mu \mu \frac{\rho_S(\mu)}{\mu^2 + q^2}$

REPULSIVE VECTOR $V_V(q^2) = +\frac{2}{\pi} \int_{3m_\pi}^{\infty} d\mu \mu \frac{\rho_V(\mu)}{\mu^2 + q^2}$

SENSITIVE DEPENDENCE ON $m_\pi^2 \sim \Lambda_{QCD}^2 (m_u + m_d)$

NUCLEAR BINDING ENERGY PER NUCLEON $\approx -10 \text{ MeV} \approx -100 \text{ MeV}_S + 50 \text{ MeV}_V + 40 \text{ MeV}_{KIN+...}$

IF $V_S \downarrow$ BY 10%
HEAVY NUCLEI WOULD UNBIND!

$$\frac{m_u + m_d}{(m_u + m_d)_{\text{PHYS}}} < 1.36 \pm 0.14$$

$$0.39 < \frac{v_{\text{HIGGS}}}{v_{\text{PHYS}}} < 1.64$$

FOR H TO \exists FOR NUCLEI TO \exists

RE CECILE'S REMARK TO FREEMAN OF 60 YRS AGO

" SHE SAID IF SHE WERE MADE DIRECTOR OF THE FRENCH INSTITUTE
SHE WOULD INVITE ALL OF US TO COME ... THERE !!

SHE WAS NEVER MADE DIRECTOR OF IHES ,
BUT PLEASE KEEP IN MIND THAT
THE INVITATION IS VALID !

LOOKING FORWARD TO MORE PHYSICS-RELATED
IAS - IHES INTERACTIONS IN THE FUTURE.