Sequestering the SM Vacuum Energy

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hep-th/1406.0711

Messages:

1) What it is not: soln of CC problem (yet!)
2) What it is: a way around Weinberg no-go
3) Mechanism
   a) Cancelling Vacuum energy loops
   b) Keeping massless mass gap in matter QFT
   c) Symmetries & protection mechanism
4) Comments on features and predictions
5) Questions & future directions

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Cosmological Constant problem

You hear:

1) "Why is it not M_{Pl}^4?"
2) "Why is it not 0?"
3) "Why is it $10^{-120} M_{Pl}^4$?"

THIS IS ALL NONSENSE !!!

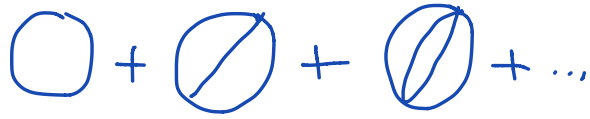
We do not yet have a fully consistent UV complete algorithm for computing vacuum energy; maybe we do not even have a unique vacuum

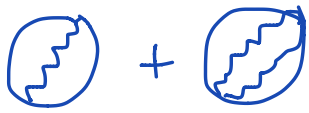
The best we CAN do: compute in QFT coupled to gravity + see what happens

SO DO IT, BUT DO IT "RIGHT": IE USE THE RULES OF QFT TO THE LETTER

(AND, SPIRIT...!)

Cosmological constant - aka vacuum energy diverges:

$\Lambda_{vac} =$  + ... matter loops

+  + ... gravity + matter loops

Must be renormalized! Finite part NOT calculable but <u>MUST</u> be measured!

But: if determined at N-loops level and fitted to observations (like Higgs mass!) it needs to be completely refitted - from skratch - at N+1 loops

JUST LIKE THE HIGGS MASS...

MEASURED CC IS BADLY RADIATIVELY UNSTABLE!

This is the ONLY meaningful formulation of CC problem in QFT of matter + gravity

The problem is very serious due to the famous Weinberg no-go theorem! (1989)

(Alternative philosophy: forget naturalness & use anthropic arguments - giving up ?!)

Weinberg no-go: prohibits dynamical adjustment in EFT + gravity @ a nonzero mass gap

Adjustment + radiative stability $\Longleftrightarrow$ Conformal symmetry

$$\Lambda_{eff} = \left(\Lambda_{vac} + \Lambda_{classical}\right) e^{4\phi}$$

either of the two options is bad:

1) $\Lambda_{vac} + \Lambda_{classical} \ll (\text{cutoff})^4$: TUNING

2) $\phi \to -\infty$: "ADJUSTMENT" ?

But then, since $m_{phys} = m\, e^{\phi}$,

$$m_{phys} \to 0 \,!$$

NOT OUR WORLD!

SEQUESTERING

$$S = \int d^4x \sqrt{g} \left\{ \frac{M_{Pl}^2}{2} R - \Lambda - \lambda^4 \mathcal{L}\left(\frac{g^{\mu\nu}}{\lambda^2}, \phi\right) \right\} + \sigma\left(\frac{\Lambda}{\lambda^4 \mu^4}\right)$$

Postulate: Λ, λ dynamical GLOBAL variables

$\therefore$ LAGRANGE MULTIPLIERS JUST LIKE IN THE ISOPERIMETRIC PROBLEM

$\int d^4x \sqrt{g}\, \Lambda$: Legendre transformation: trades $\int d^4x \sqrt{g}$ for new INDEPENDENT VARIABLE Λ

Variational eqs fix Λ to $\frac{1}{4} \langle T^{\mu\,\text{const}}{}_{\mu} \rangle_{vac}$ because λ is just the engineering scale

$$\therefore \frac{1}{4} \langle T^{\mu\,\text{const}}{}_{\mu} \rangle_{vac} = \Lambda_{vac} = \bigcirc + \bigcirc\!\!\!/ + \bigcirc\!\!\!\!/ + \ldots$$

NO INTERNAL GRAVITON LINES !!!

∴ We work @ QFT of matter @ (semi)classical gravity: gravity is a spectator, a probe only

∴ OK: this is the original version of the problem recognized by Pauli & by Zeldovich

∴ The Weinberg NoGo precludes a dynamical soln even in this restricted setup

NOTE: can define $\bar{g}_{\mu\nu} = \lambda^2 g_{\mu\nu}$ to rewrite the QFT of matter as

$$S_{matter} = -\int d^4x \sqrt{\bar{g}}\, \mathcal{L}_{matter}\left(\bar{g}^{\mu\nu}, \phi\right)$$

Since the theory is Poincare invt & Diffeo invt — as long as we insist that the UV regulator is also included in $\mathcal{L}_{matter}$ — the form of the matter action is PRESERVED by all loop corrections

So:

$$\Lambda_{vac} = \bigcirc + \bigcirc\!\!\!/ + \bigcirc\!\!\!\!/ + \ldots = \lambda^4 \begin{pmatrix}\text{dimensionful} \\ \text{factor}\end{pmatrix}$$

Thus: $\Lambda_{vac} = \langle 0 | \mathcal{L}_{matter} | 0 \rangle = \frac{1}{4} \langle 0 | T^{\mu}{}_{\mu} | 0 \rangle$

Variational Eqs

$$M_{Pl}^2 G^\mu{}_\nu = T^\mu{}_\nu - \Lambda \delta^\mu{}_\nu$$

$$\frac{\sigma'}{\lambda^4 \mu^4} = \int d^4x \sqrt{g} \qquad \Lambda \frac{\sigma'}{\lambda^4 \mu^4} = \frac{1}{4}\int d^4x\, T^\mu{}_\mu$$

In the vacuum, $T^\mu{}_\mu \to \langle 0 | T^\mu{}_\mu | 0 \rangle_{\text{regularized}}$; so elimination of σ' gives us

$$\Lambda = \frac{1}{4} \frac{\int d^4x \sqrt{g} \langle 0 | T^\mu{}_\mu | 0 \rangle}{\int d^4x \sqrt{g}} = \frac{1}{4} \langle T^\mu{}_\mu \rangle$$

$\therefore$ Λ is SPACETIME average of the $T^\mu{}_\mu$ — integrated over all times, past & future! (GLOBAL CONSTRAINT!)

$$M_{Pl}^2 G^\mu{}_\nu = T^\mu{}_\nu - \frac{1}{4} \langle T^\alpha{}_\alpha \rangle \delta^\mu{}_\nu$$

Define now $T^\mu{}_\nu = -\Lambda_{vac} \delta^\mu{}_\nu + \tau^\mu{}_\nu$ → NONCONST PART

Since $\langle \Lambda_{vac} \rangle \equiv \Lambda_{vac} \equiv -\frac{1}{4} T^\alpha{}_\alpha$ (const) :

$$M_{PL}^2 G^\mu{}_\nu = \tau^\mu{}_\nu - \frac{1}{4}\langle \tau^\alpha{}_\alpha \rangle \delta^\mu{}_\nu$$

Λ_{vac} completely cancelled from the source of the curvature irrespective of the loop order

IN THIS THEORY VACUUM ENERGY INVISIBLE TO $G^\mu{}_\nu$

$\therefore$ Trick: global variable Λ is tied to Λ_{vac} and always exactly cancels it; the residual finite part is $-\frac{1}{4}\langle \tau^\alpha{}_\alpha \rangle$ - historic average of energy density of all NONCONSTANT sources (γ, B, DM, ...)

Note: canonically normalizing all matter fields shows that physical dimensional parameters are

$$\frac{m_{phys}}{M_{PL}} = \lambda \frac{m_{bare}}{M_{PL}}$$

So $m_{phys} \neq 0 \iff \lambda \neq 0$; but by

$$\lambda^4 \mu^4 = \frac{\sigma'}{\int d^4x \sqrt{g}} \implies \int d^4x \sqrt{g} < \infty \quad \text{FINITE UNIVERSE!}$$

Recapitulate:

1) Vacuum energy completely cancelled!

2) Residual "c.c." determined by the historic average of all nonconstant matter

$$\Lambda_{eff} = \frac{1}{4} \langle T^{\alpha}_{\alpha} \rangle$$

This is NONLOCAL IN TIME! — but: NO PATHOLOGIES in (semi) classical gravity

Recall QFT: if Q is divergent, it CANNOT be predicted: one regulates it (Λ'_{vac}!), picks the counterterm (Λ), cancels the divergent part and MEASURES the finite remainder!

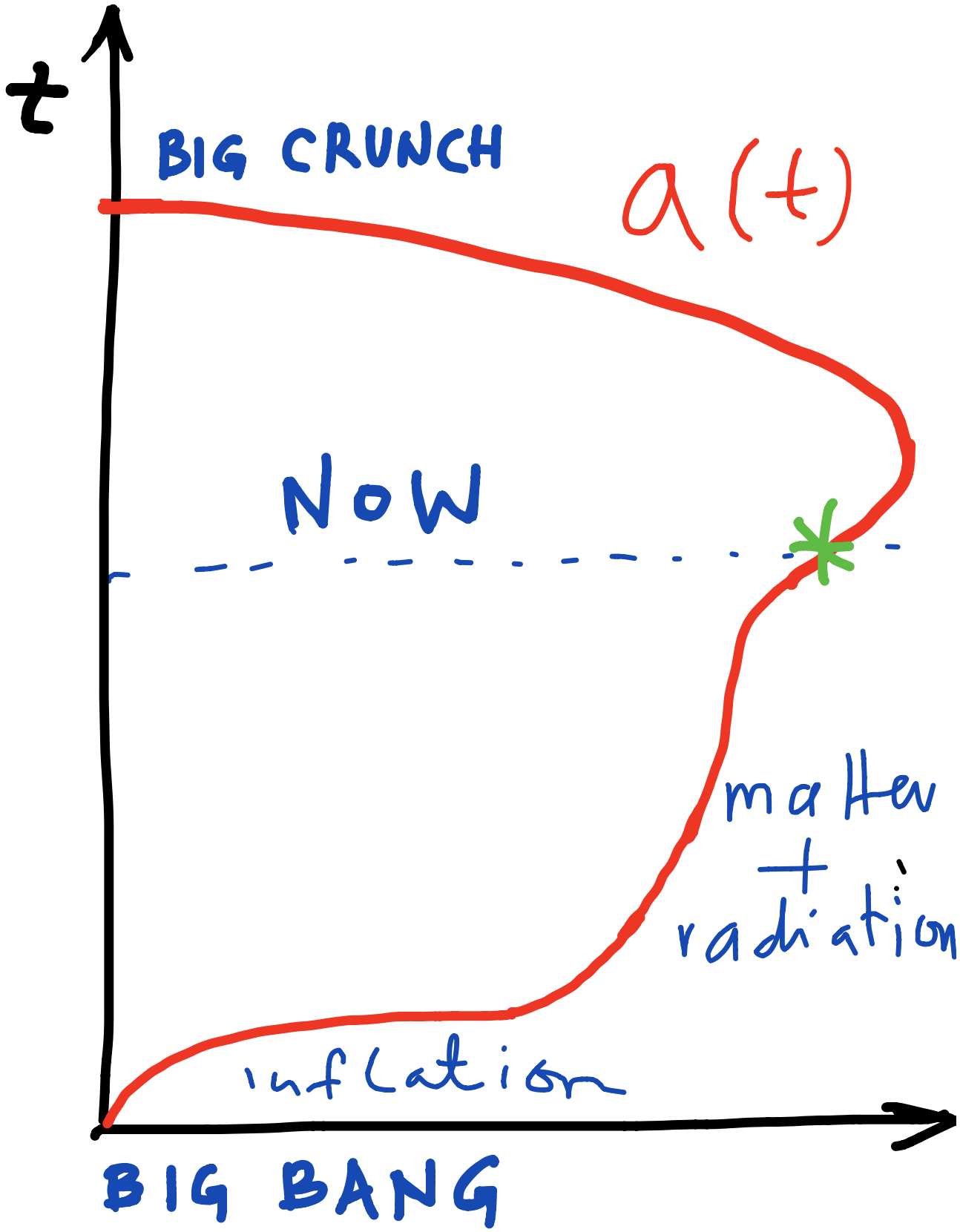
Λ: codimension-0 parameter — need cod. 0 detector to measure

THE WHOLE UNIVERSE IS THE ONLY DETECTOR

3) Need $\int d^4x \sqrt{g} < \infty$ to keep nonzero QFT mass gap

UNIVERSE LARGE, BUT FINITE IN SPACE-TIME!

predictions:
1) will collapse
2) finite spatial sections (CMB?)
3) cannot accelerate forever!


t
BIG CRUNCH
a(t)
NOW
matter
+
radiation
inflation
BIG BANG

Symmetries & Naturalness

Whenever $\exists$ magical cancellation look for symmetries

There are 2 approx sy etries

1) approx scaling symm

$$\lambda \to \Omega \lambda$$
$$g_{\mu\nu} \to g_{\mu\nu}/\Omega^2$$
$$\Lambda \to \Lambda \Omega^4$$

2) approx shift symmetry

$$\Lambda \to \Lambda + \alpha \lambda^4$$
$$\mathcal{L} \to \mathcal{L} - \alpha$$

Weakly broken by anity: $\delta S \sim \alpha \lambda^4 \int d^4x \sqrt{g} \sim \alpha \left(\frac{m_{phys}}{M_{Pl}}\right)^4$

$\therefore$ Scaling ensures cancellation happens at all scales

$\therefore$ shift performs the cancellation

$\therefore$ Since symmetri are approx, $\Lambda_{eff} \neq 0 \ll M_{Pl}^4$

$\therefore$ It is naturally small since in the conformal limit $m_{phys} \to 0$ symmetries enhanced!

PROTECTION MECHANISM!

Further properties & consequences

1) Consistent w/ inflation - can make a big old universe w/ slowly rolling ϕ

2) Phase transition contributions to Λ_{eff} automatically small! (Reason: PT takes only a fraction of universes lifetime and its correction to Λ_{eff} is weighted by $\int d^4x \sqrt{g}$!)

3) $\Lambda_{eff} = \frac{1}{4}\langle T^\alpha{}_\alpha \rangle \lesssim M_{pl}^2 H_*^2$ where H_* is the Hubble at the onset of collapse: $H_* \lesssim H_{now}$

$$\Lambda_{eff} \lesssim 10^{-12}\, eV^4$$

as long as we live in a big old universe (we do!)

4) Offers a new perspective on the cosmic coincidence "problem": can we explain cosmic acceleration NOW?

(WORK IN PROGRESS; IT SEEMS YES!)

SUMMARY

∴ FOUND A WAY AROUND WEINBERG NO GO

1) Cancells all loop corrections to Λ
2) Maintains $M_{plys} \neq 0$
3) Radiatively stable – aka technically natural
4) Maximally minimal modification of GR+QFT
   - ∴ Poincare & diff. invariant
   - ∴ No new local DOFs
   - ∴ Locally theory behaves the same as usual
   - ∴ Cosmological predictions differ: $w \neq -1$, universe finite, with collapse
5) Phase transitions tamed
6) Inflation OK!

a) Microscopic origin & UV completion?
b) Protection from gravity loops?
c) Uniqueness? Or not? Further predictions?

" THE END "