The End & Other Tall Tales

@ A. Padilla, Nottingham — hep-th/1309.6562, hep-th/1406.0711, hep-th/1409.7073 ...

Sequestering:

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 nonzero mass gap in matter QFT
   c) Symmetries & protection mechanism
4) Features & predictions
5) Doomsday cosmology
6) 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 !!!

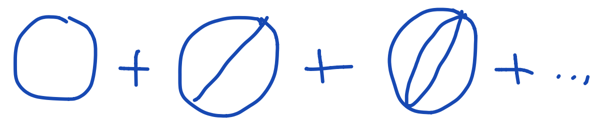
We do not yet have a fully consistent UV Complete algorithm for computing vacuum energy ; maybe we do not even have a unique vacuum

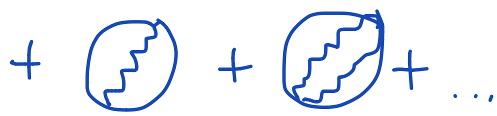
The best we CAN do : compute in QFT coupled to gravity + see what happens

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-loop 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 - but I will ignore this here - we all choose our own poison)

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

Adjustment + radiative stability $\Longleftrightarrow$ Conformal symmetry

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

either of the two options is bad:

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

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

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

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

NOT OUR WORLD!

SEQUESTERING

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

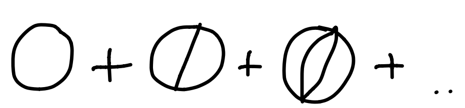
Postulate: Λ, λ dynamical GLOBAL variables

$\therefore$ 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

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



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 NO GO 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 Poincaré 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:

$$\Lambda_{vac} = \bigcirc + \oslash + \oslash + \ldots = \lambda^4 \left(\begin{matrix}\text{dimensionfull}\\ \text{factor}\end{matrix}\right)$$

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

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

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

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

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

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

Recapitulate:

1) Vacuum energy completely cancelled!
2) Residual "c.c." determined by the historic average of all nonconstant matter

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

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), cancells 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!

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

∴ Scaling ensures cancellation happens at all scales

∴ shift performs the cancellation

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

∴ 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 universe's 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?

Yes!

Cosmology:

1) Need a FINITE universe s.t. $\int \sqrt{g} < \infty$ to ensure mass gap $m_{phys} \neq 0$

2) This universe needs to get large and old - since it is large and old

3) This can be done @ inflation - NONETERNAL

4) then some time in the future collapse can occur

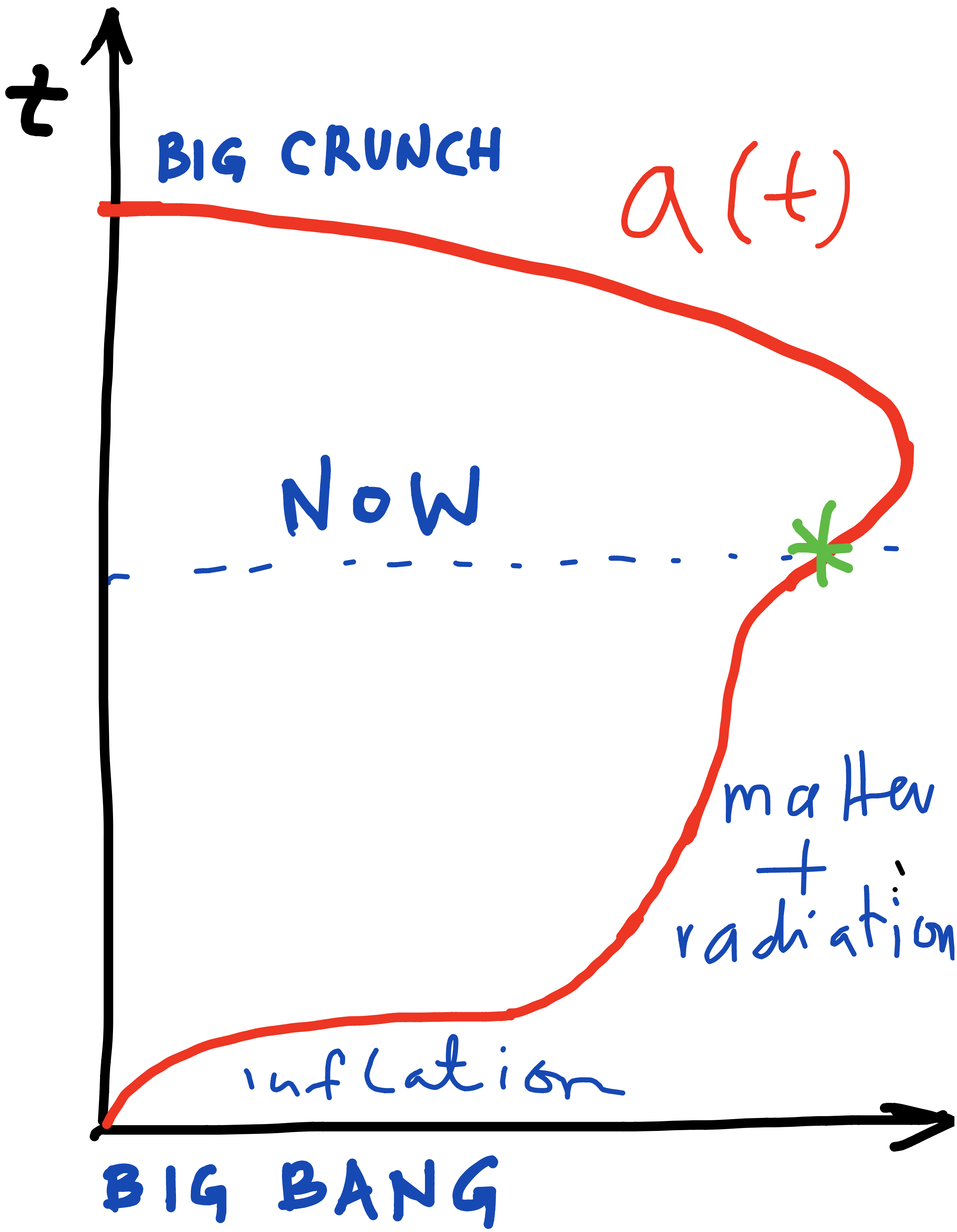
Getting the collapse to happen at the right time is tuned, to be sure

But: the choice of the time of cosmic doom is

1) Radiatively stable

2) Predicts epoch of acceleration before collapse

This can explain "why now" problem!


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

To condense the universe one needs $\rho < 0$

$$3M_p^2\left(H^2 + \frac{1}{a^2}\right) = \rho_{usual} + \rho_{trigger}$$

Having $\rho_{trigger} < 0$ and dominating can flip $H > 0 \longrightarrow H < 0$: eq an unstable V

A generic potential is radiatively unstable which can reintroduce loop sensitivity

Linde '87 : LINEAR POTENTIAL: $V = m_*^3\varphi$

1) form & slope are radiatively stable

2) $\varphi \to \varphi + c$ & $\Lambda \to \Lambda - m_*^3 c$ shift symmetry $\longrightarrow$ loop corrections DO NOT move the initial value of φ

The point is that field eqs are

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

so the shift of $\varphi \equiv$ shift of $\Lambda \to$ it cancells out !!!

$t \nearrow \quad \varphi \nearrow \quad V \searrow$: when $V < 0$ sufficiently, collapse occurs $\rightarrow H = 0$

If m_* is big this will happen too soon

So we need small m_*

Hence for most of the expansion

1) φ & $V(\varphi)$ are negligible

2) φ is in slow roll $\rightarrow$ changes little

Near the onset of collapse - by definition - φ dominates; before this time $\Delta\varphi$ is

$$\frac{\varphi_f - \varphi_{in}}{M_{PL}} = \int_{t_{in}}^{t_f} dt \, \frac{\dot{\varphi}}{M_{PL}} \simeq -\,\mathcal{O}(1)\, \frac{m_{slope}^3 M_{PL}}{M_{PL}^2 H_f^2}$$

$$\therefore \Delta\varphi < M_{PL}$$

since $m_{slope}^3 = M_{PL} H_0^2$ @ $H_0 < H_f$ and $H_0 \lesssim$ Hubble now

Since $\left(\dot{\varphi}^2 / m_{slope}^3 \varphi\right)_+ = O(1)\, m_{slope}^6 / M_{PL}^2 H_+^4 < 1$

when this happens the universe is dominated by a slowly rolling scalar field : DE!

This goes on until the end of slow roll $\varphi \leq M_{PL}$, which happens at

$$t_{age} \sim \frac{1}{H_{age}} \simeq \frac{1}{H_+} + O(1)\sqrt{\frac{M_{PL}}{m_{slope}^3}} \gtrsim \frac{1}{H_0}$$

$\therefore$ # of efolds $N \simeq H_+ / H_0$!

More importantly:

$$\frac{\varphi_{age} - \varphi_{in}}{M_{pl}} = -O(1)\frac{m_{slope}^3 M_{PL}}{M_{PL}^2 H_{age}^2} \simeq -O(1)\frac{H_0^2}{H_{age}^2}$$

$\therefore$ $\varphi_{age} - \varphi_{in} > M_{PL}$!

In GR φ_{in} is arbitrary, and so when it is small the late stage of acceleration will not last long enough

Initial condition tuning for quintessence models

Not so here! At the onset of collapse

$$\langle \rho_\varphi \rangle = \langle \dot{\varphi}^2 \rangle - 4 m_{slope}^3 \langle \varphi \rangle \simeq -O(1)\, m_{slope}^3 \varphi_{age}$$

AND

$$\langle T \rangle = \langle 3p - \rho \rangle \simeq -O(1) M_{pl}^2 H_{age}^2$$

$$\therefore \quad \frac{\varphi_{age}}{M_{pl}} \simeq -O(1) \frac{M_{pl} H_{age}^2}{m_{slope}^3} \simeq -O(1) \frac{H_{age}^2}{H_0^2} \lesssim -1$$

Therefore

$$\varphi_{in} \simeq \left[O(1) \frac{H_0^2}{H_{age}^2} + O(1) \frac{H_{age}^2}{H_0^2} \right) M_{pl} \gtrsim M_{pl}!$$

Consistency requires $\varphi_{in} \gtrsim M_{pl} \to$ tuning the age of the universe automatically yields a prediction ~~that~~ prior to collapse there is a stage of accelerated expansion for an efold or few

But ... there is more ...

field eqs require that $\langle R \rangle = 0$

FRW: $\int dt\, a^3 \left(\dot{H} + 2H^2 + \frac{k}{a^2} \right) = 0$

Integrate by parts:

$$a^3 H \Big|_{t_{bang}}^{t_{crunch}} = \int dt\, a^3 \left(H^2 - \frac{k}{a^2} \right)$$

In big old universes LHS is small, < 0

So there must be a cancellation on the RHS as well! $\longrightarrow$ $k = +1$!

So: we have 2 predictions for cosmology:

1) $w \neq -1$ DE: Linear potential

$$w = -1 + O(1)\frac{H_0^4}{H_+^4}$$

2) $K = +1 \rightarrow \Omega_K\big|_{now} < 0 \rightarrow \Omega_K\big|_{age} \simeq -1$

But there is only ONE dimensional parameter!

$$w = -1 + O(1)\left[\Omega_K(now)\right]^2$$

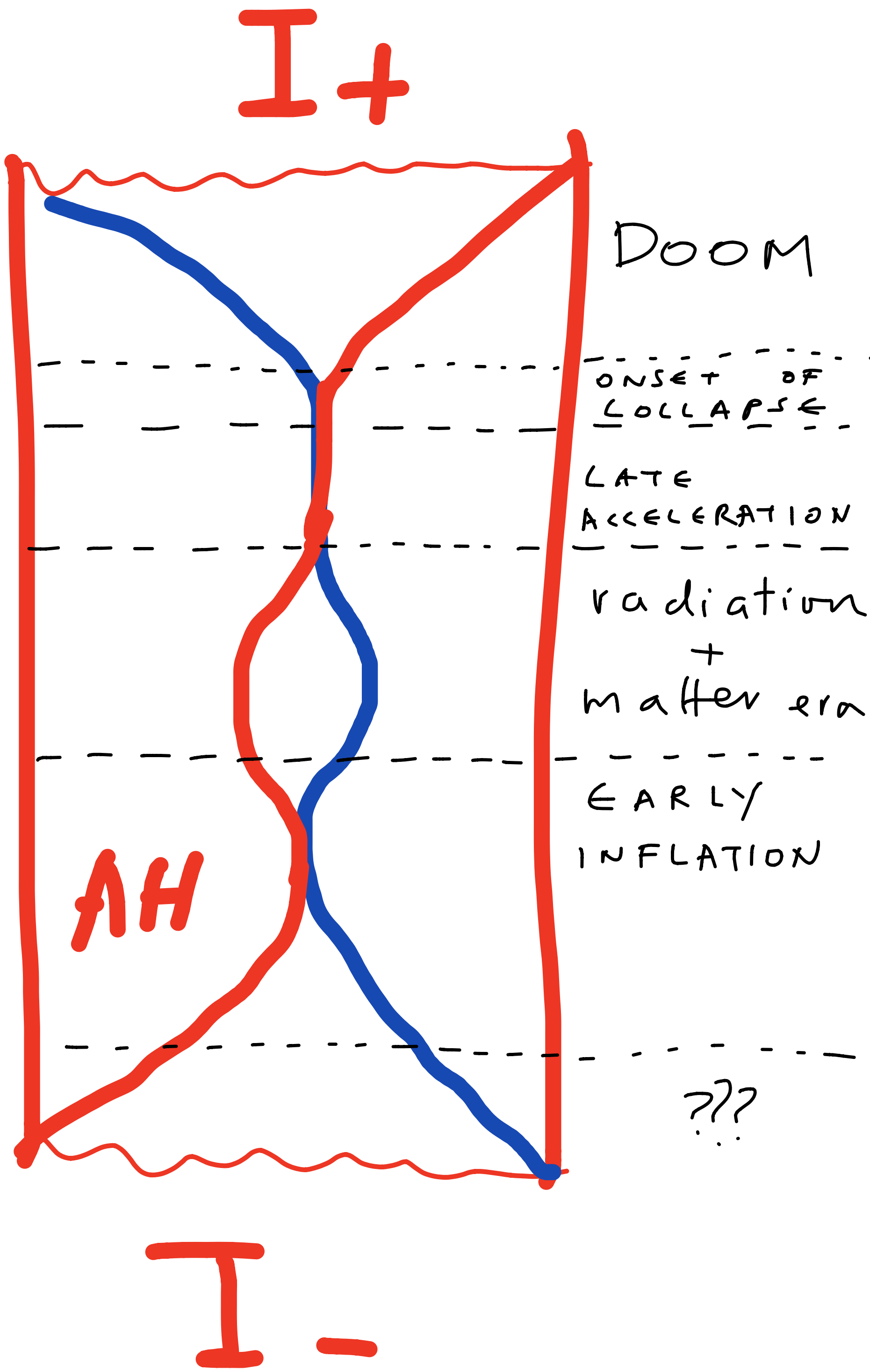
This is a strong prediction of the setup

Could be tested observationally

Note: this was sloppy, a more precise estimate needed

Work in progress, @ A. Moss, A. Padilla, J. Pearson

The portrait of the world



SUMMARY

∴ FOUND A WAY AROUND WEINBERG NO GO

1) Cancells all loop corrections to Λ
2) Maintains $M_{phys} \neq 0$
3) Radiatively stable – aka technically natural
4) Maximally minimal modification of GR+QFT

∴ Poincare & diff. invariant

∴ No new local DOFs

∴ Cosmology differs: $w \neq -1$, $\Omega_K < 0$, universe finite, will collapse

5) phase transitions tamed
6) Inflation (finite!) ok!
7) Cosmic coincidence → why accelerating now!

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