Vacuum energy, Casimir effect, and Newton's non-constant

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Nottingham
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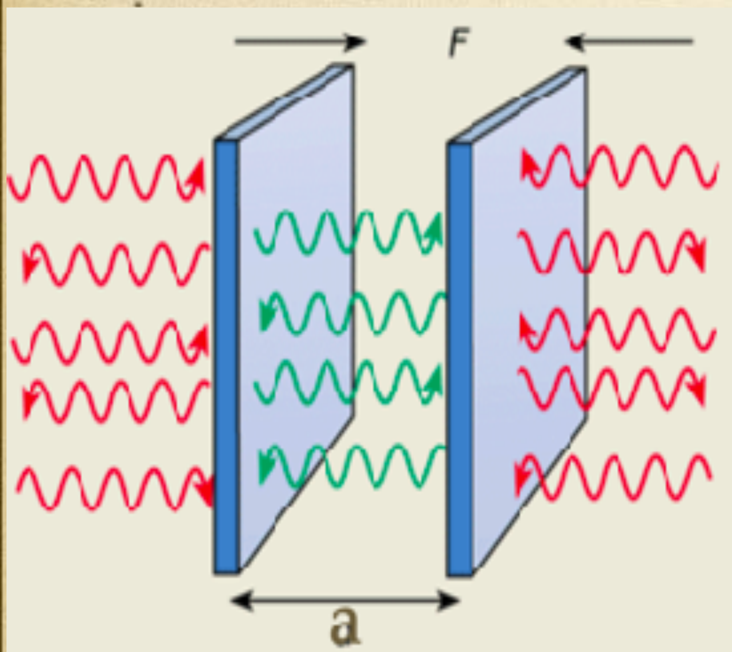
Based on
arXiv:SOON

Content

- What we would like to know
- Vacuum energy density - in the lab
- Vacuum energy density - in the Universe
- Vacuum energy density - combined
- Scale-dependent framework
- Towards experiment
- Discussion and Conclusion

Vacuum energy

What we know so far?



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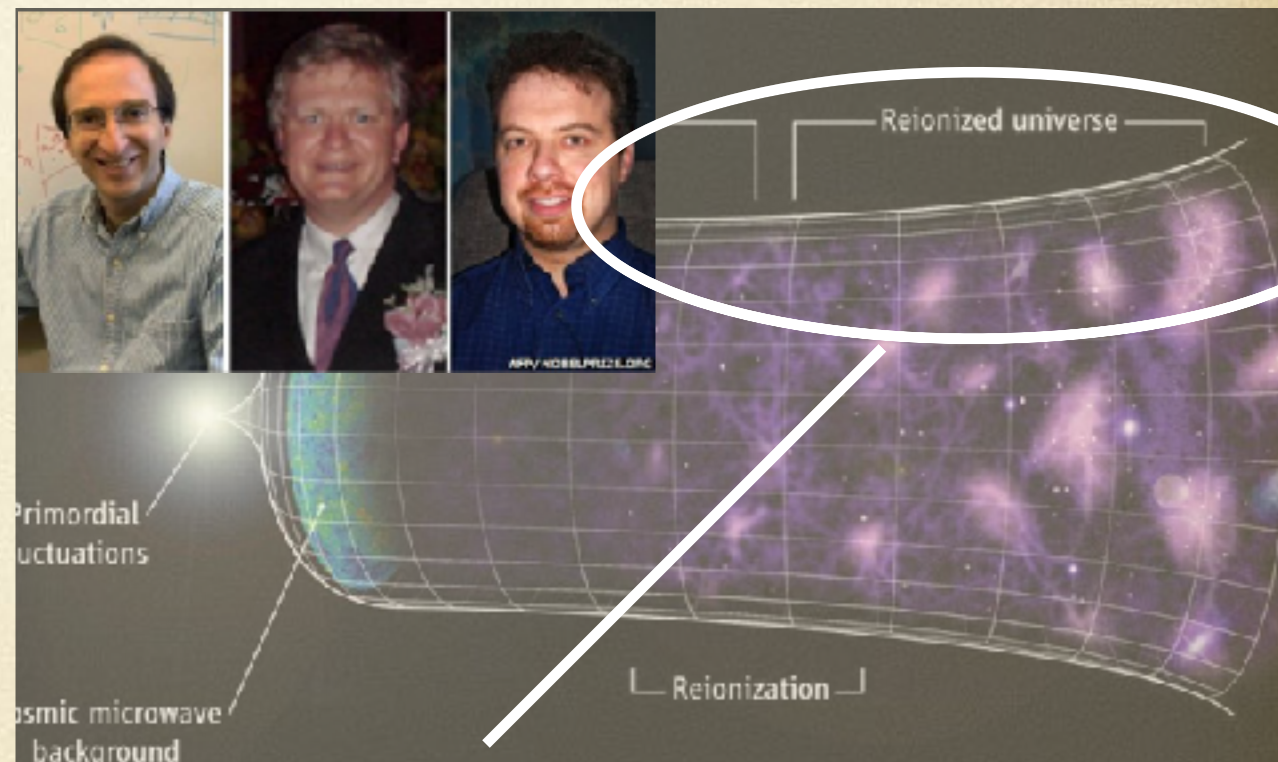


Quantum vacuum:

ρ_Q

accelerates plates

Cosmological vacuum:

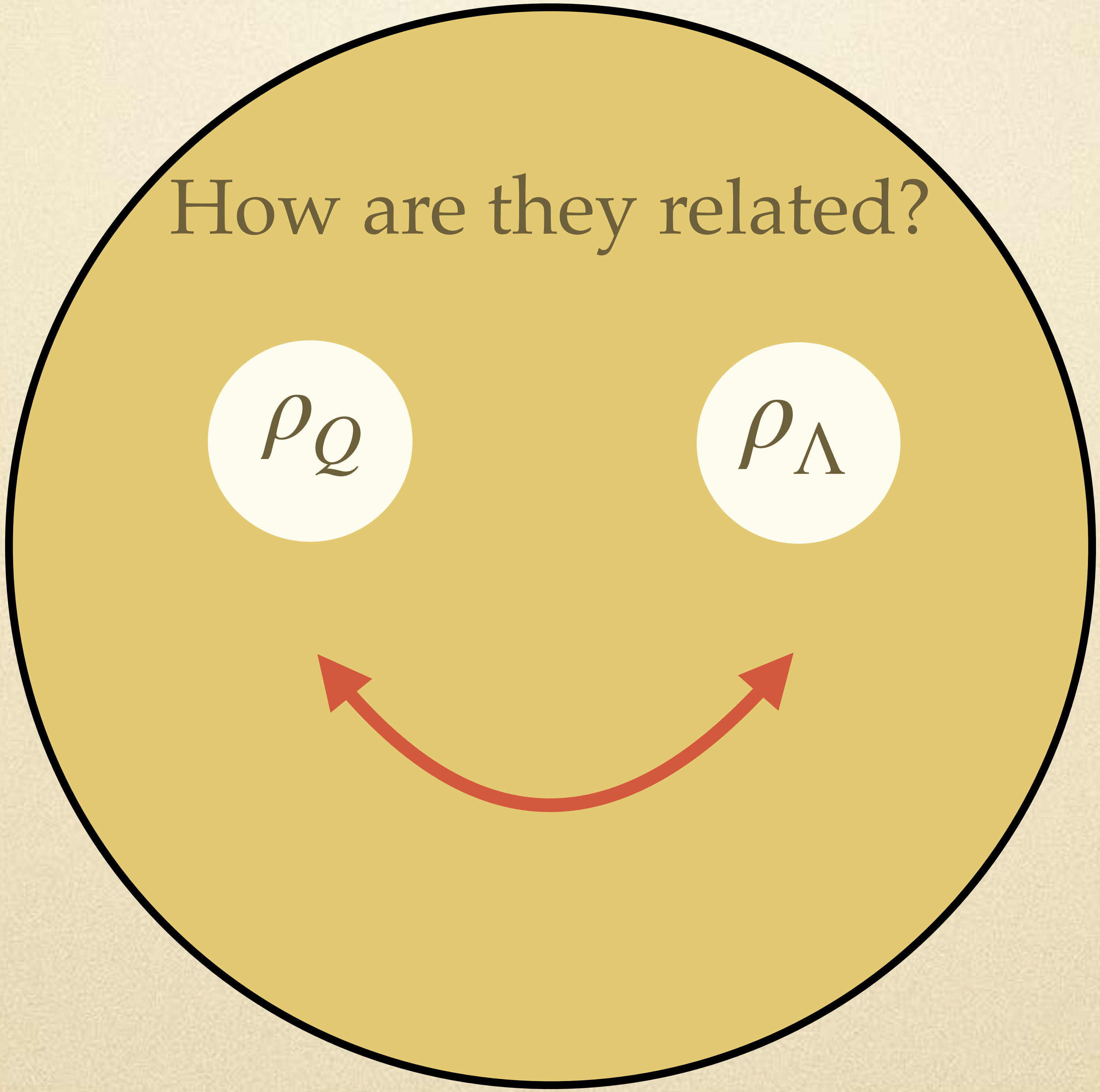
ρ_Λ

accelerates Universe

*https://physicsworld.com/a/the-casimir-effect-a-force-from-nothing/

Vacuum energy

What we would like to know:



Vacuum energy

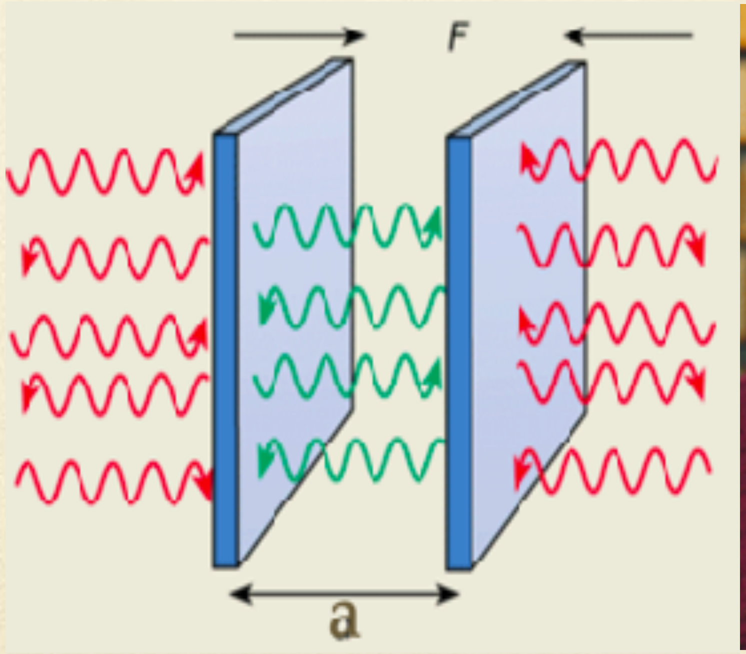
How are they related?

In the lab

Casimir effect

Predicted 1948

Observed 1997 ref [10]

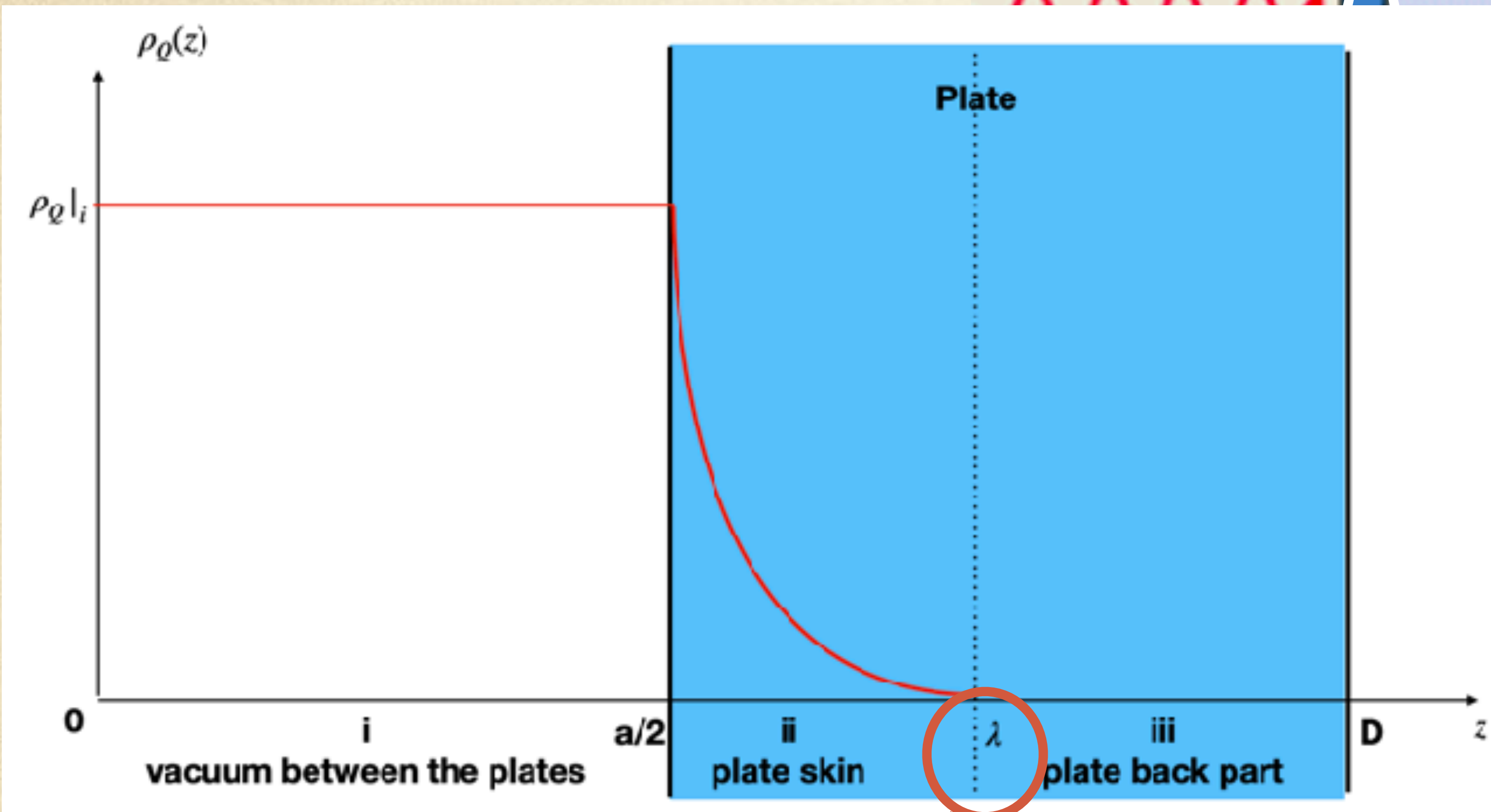


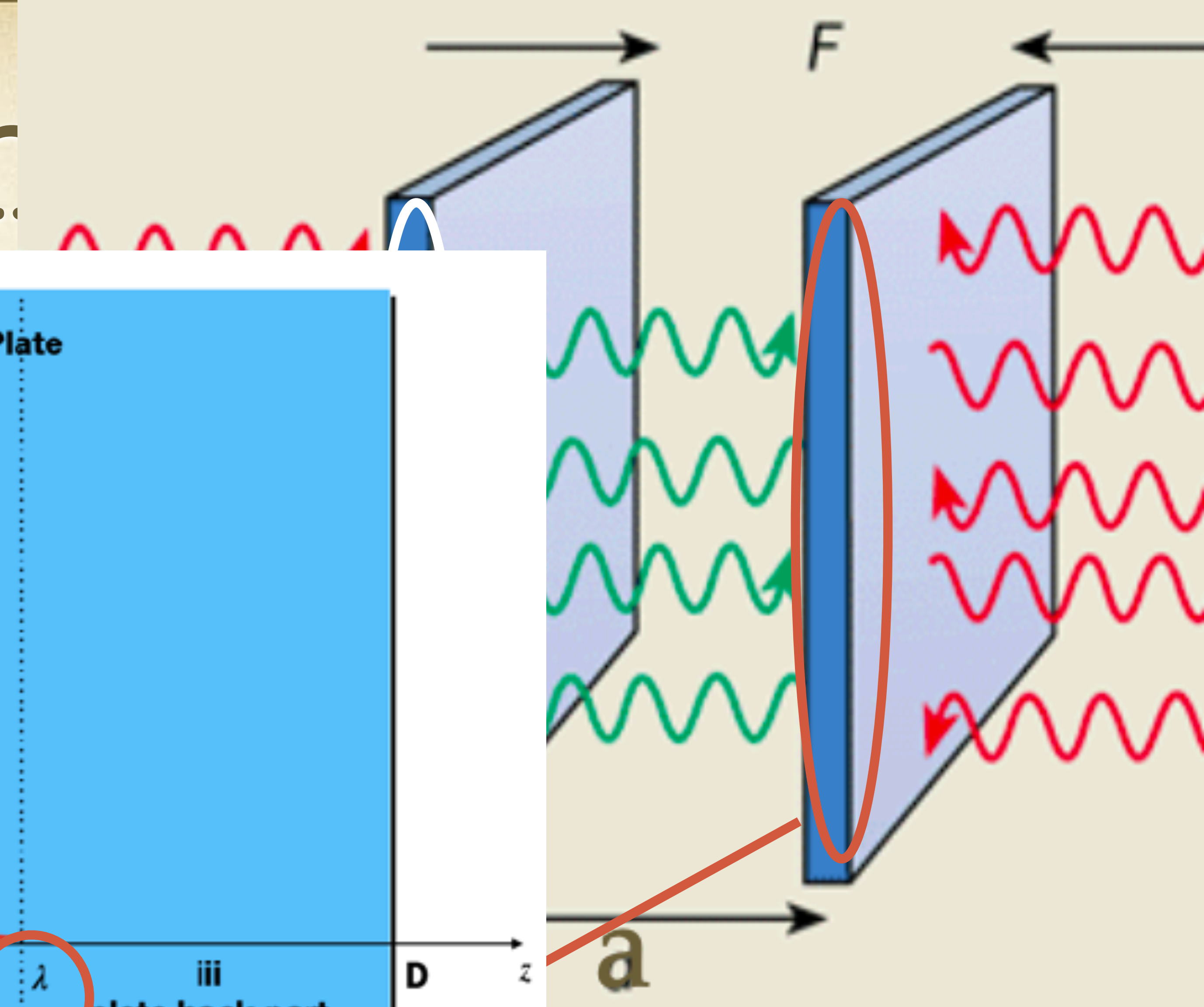
$$\rho_C = -\frac{\hbar \pi^2}{720 a^4}$$

$$\Rightarrow \quad \frac{F_Q}{A} \approx \rho_Q \cdot a$$

In th

In





$$\vec{F}_{G,12} = -\vec{F}_{G,21} = G_0 \int_{V_2} d^3x_2 \int_{V_1} d^3x_1 \frac{\rho_M(\vec{x}_1)\,\rho_M(\vec{x}_2)\,(\vec{x}_2 - \vec{x}_1)}{|\vec{x}_2 - \vec{x}_1|^3}$$

- Finite penetration depth $\lambda \approx 10^{-8} m$, thus $\rho_C = \rho_C(\vec{x})$

remember

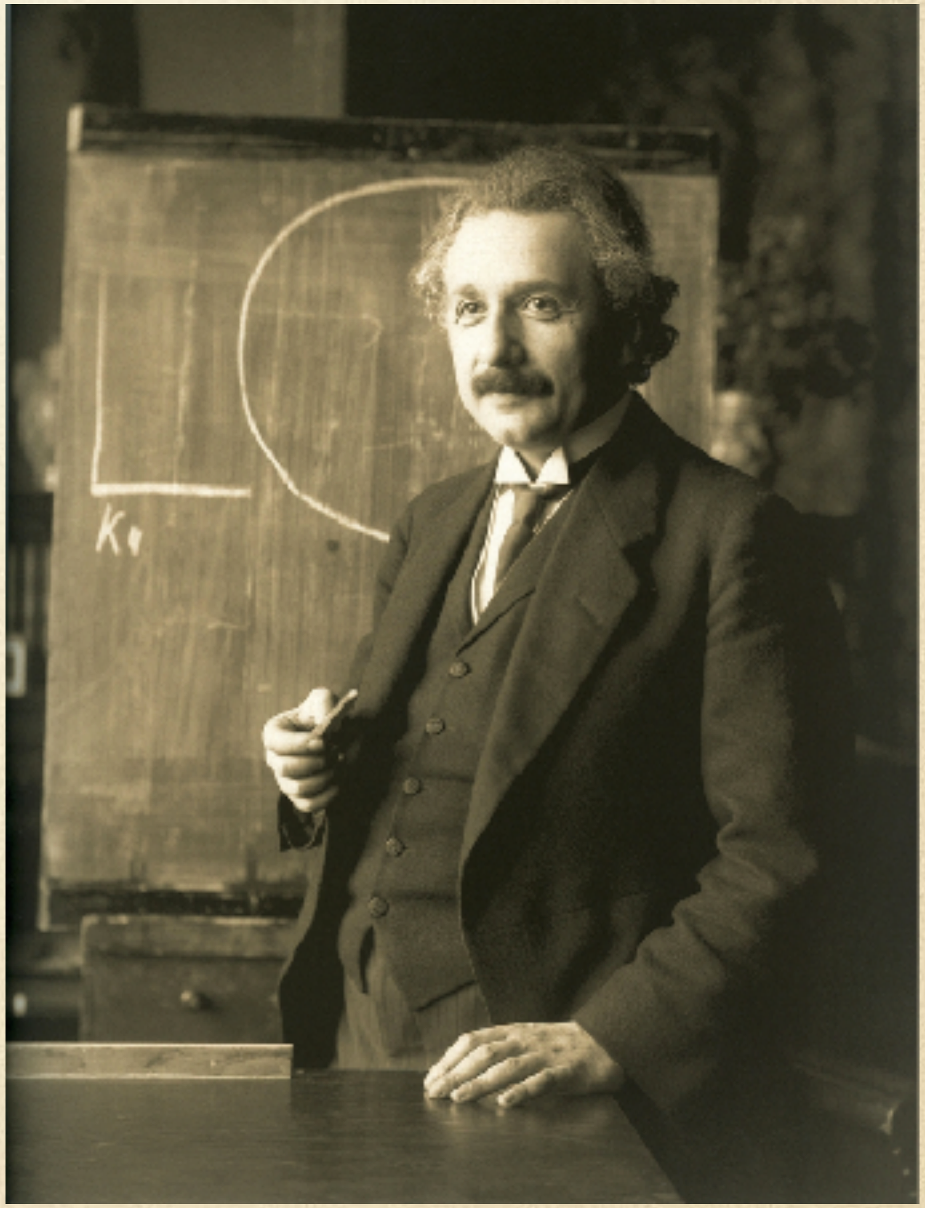
In the Universe

Albert Einstein

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$\Rightarrow$ Friedman eq.

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \equiv 0$$

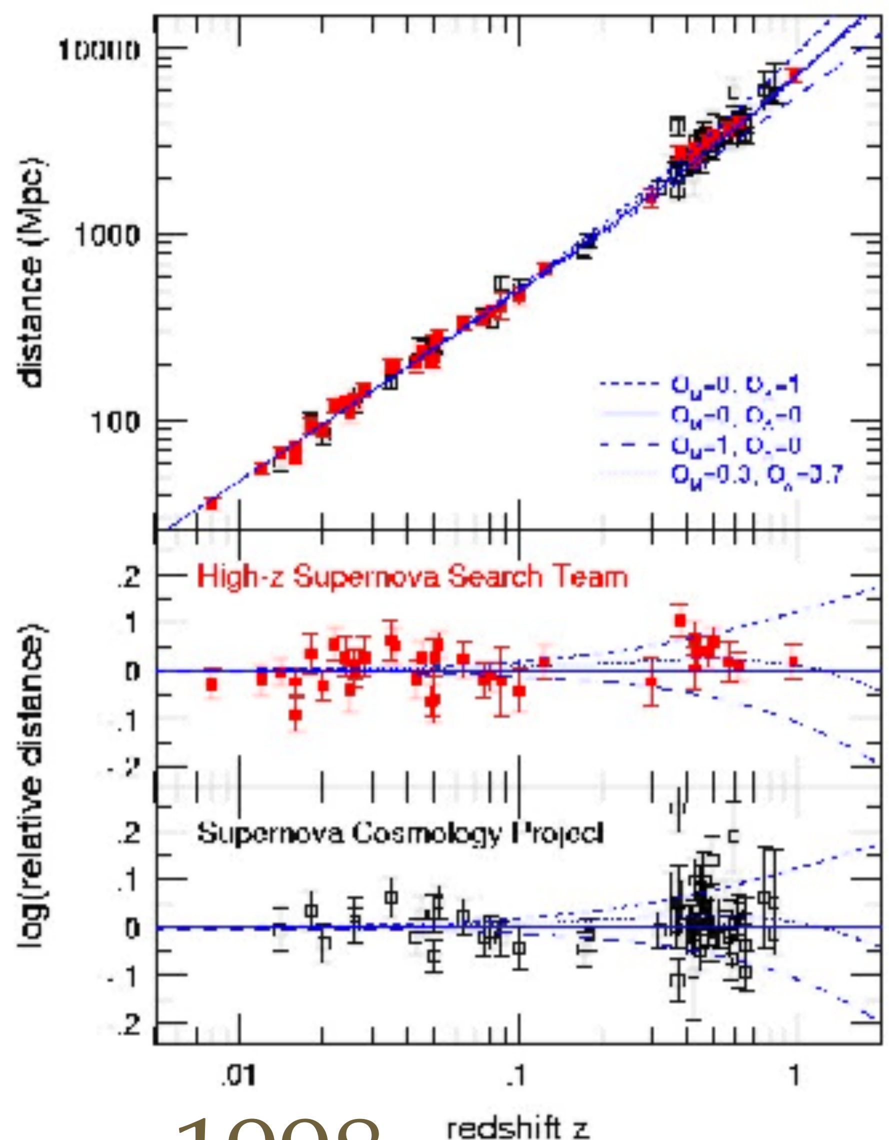


In the Universe

S. Perlmutter, A. Riess, B. Schmidt, & others

mea

ref [2]



1998

NP 2011

$\dot{a} \neq 0$

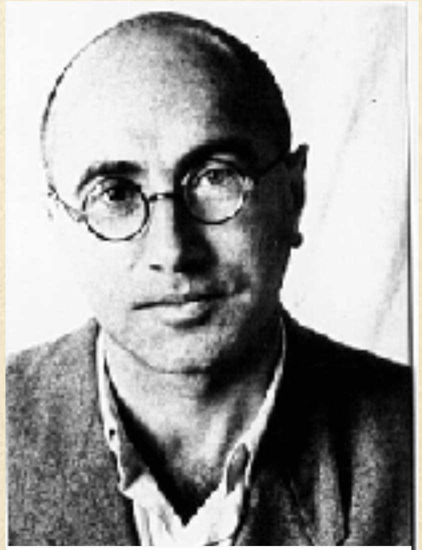
$\ddot{a} > 0 \ \Rightarrow \Lambda > 0$!

In the Universe

Λ as an energy density

$$\rho_{\Lambda,0} = \frac{\Lambda_0 c^4}{8\pi G_0} = 5.35 \times 10^{-10} J/m^3$$

Quantum origin?



Yakov Zeldovich, 1967

Steven Weinberg, 1998

ref [4]

Big theoretical puzzle

In the Universe

Big theoretical puzzle

In short QFT with cutoff $\rho_Q \sim c\kappa_0^4/\hbar^3$

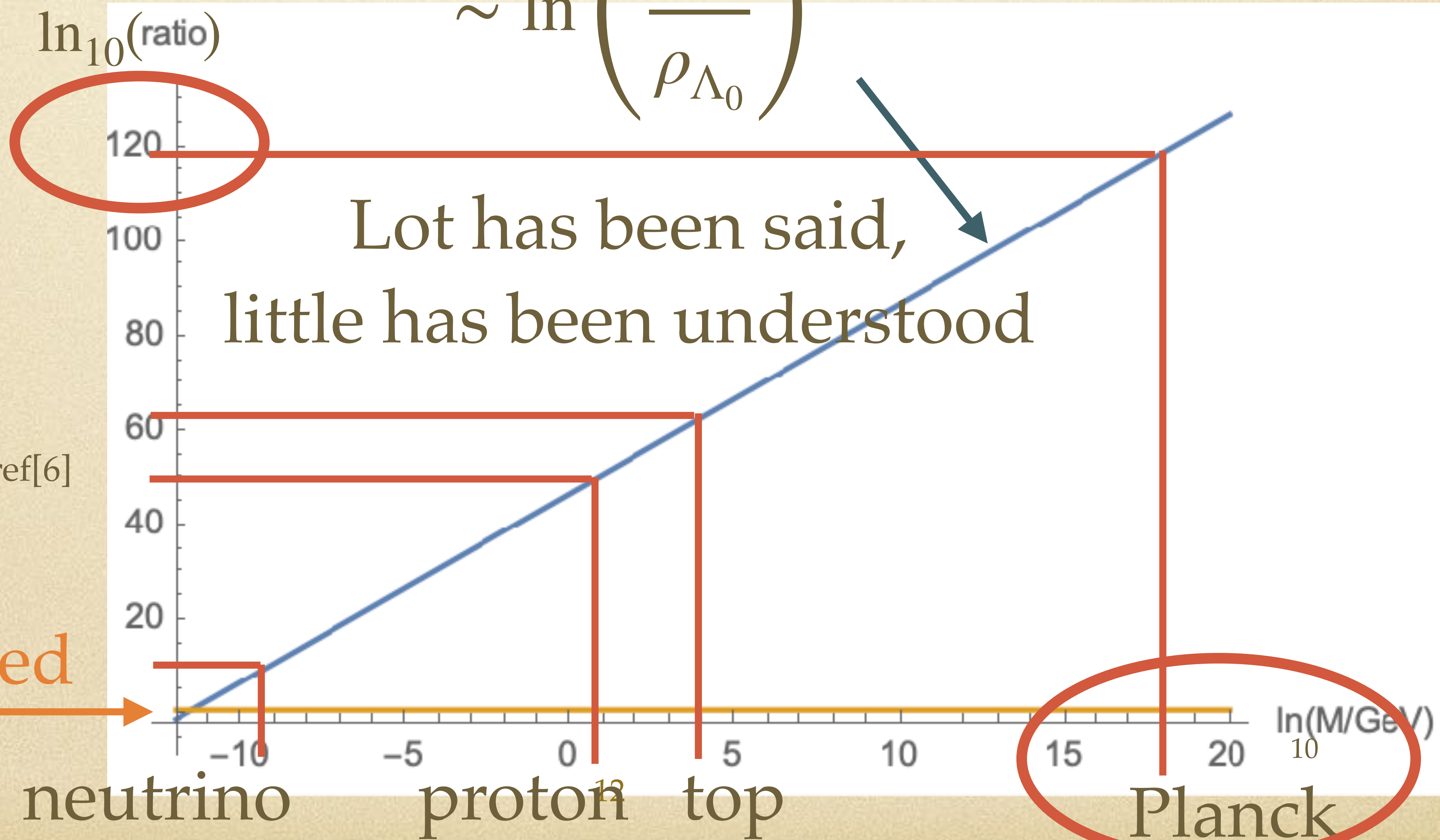
As ratio

$$\Upsilon_0 \equiv \frac{\rho_{\Lambda_0}}{\rho_{Q,0}(\kappa)} = \frac{\Lambda_0 c^3 \hbar^3}{8\pi G_0 \kappa_0^4} = \begin{cases} 10^{-121} & \text{for } \kappa_0 = c\sqrt{\frac{c\hbar}{G_0}} \\ 10^{-55} & \text{for } \kappa_0 = c m_Z. \end{cases}$$

In the Universe

Big theoretical puzzle

Problem as a ratio: $\sim \ln\left(\dfrac{\kappa^4}{\rho_{\Lambda_0}}\right)$



In the Universe

Big theoretical puzzle

experimental input needed

use Casimir experiment to gain insight

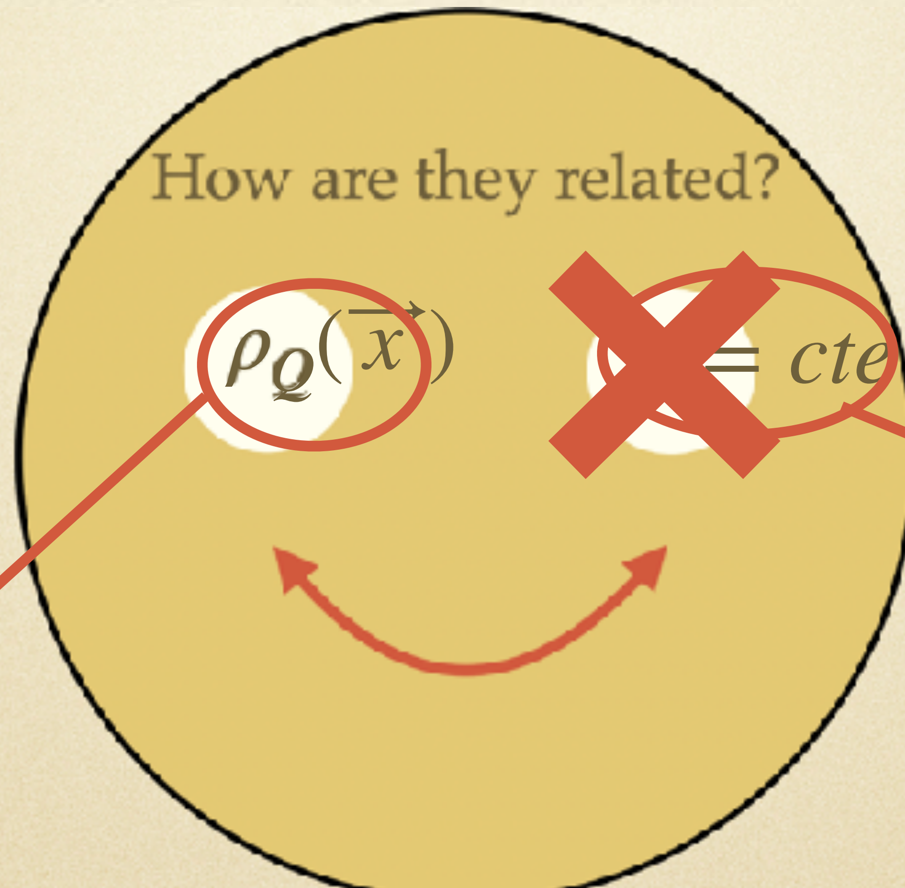
Change ρ_Q See whether ρ_Λ changes

Hypothesis

Parametrize small change

original cosmo → $\rho_{\Lambda_0} - \alpha \cdot \rho_C = \rho_\Lambda$ ← modified cosmo

quantum modification



wait …

universal constant

local variable

need variable, $\rho_\Lambda(\overrightarrow{x})$, $\Lambda(\overrightarrow{x})$, …

Hypothesis

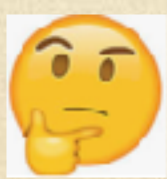
…need variable, $\rho_\Lambda(\overrightarrow{x})$, $\Lambda(\overrightarrow{x})$, but first…

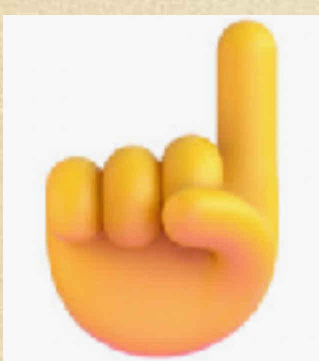
Opinion poll:

What will be found?

$$\rho_{\Lambda_0} - \alpha \cdot \rho_C = \rho_\Lambda$$

huge bounds

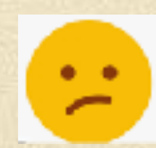
$\alpha < huge$ 

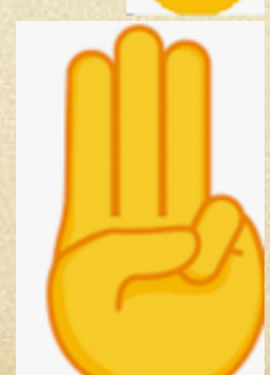


small bounds

$\alpha < small$ 

no bounds

$\emptyset$ 



discovery 

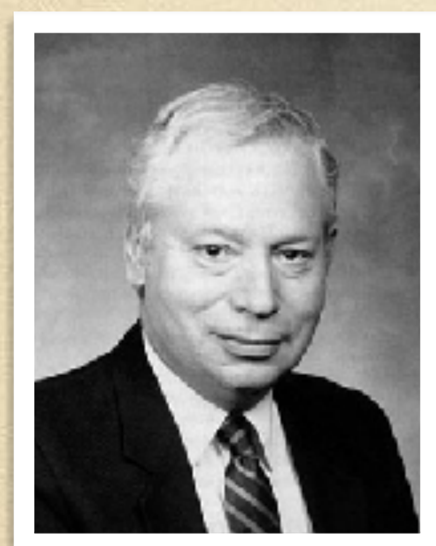
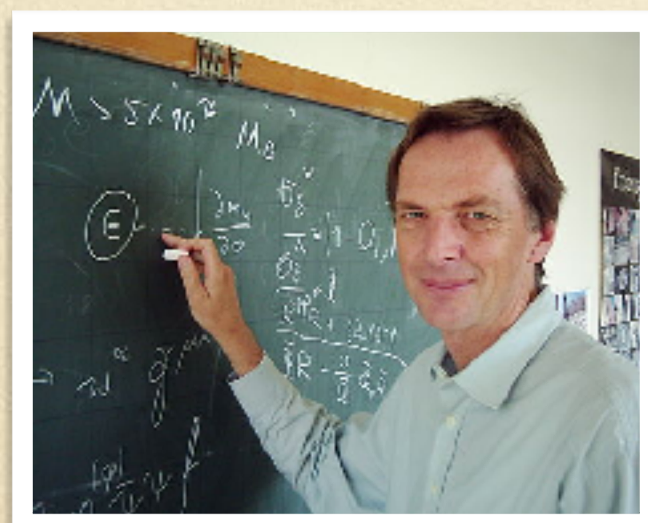
$\alpha \approx some \pm \Delta$

Scale Dependent Framework

Gravity as effective QFT

$$\Gamma_k = \int d^4x \sqrt{-g} \left(\frac{R}{G_k} - 2\frac{\Lambda_k}{G_k} \right) + \dots$$

variable couplings


Weinberg, Wetterich, Donoghue, ...

SD-Framework

scale-dependent (SD) couplings $\Lambda = \Lambda(k)$, $G = G(k)$, two main consequences:

- Modified Einstein equations

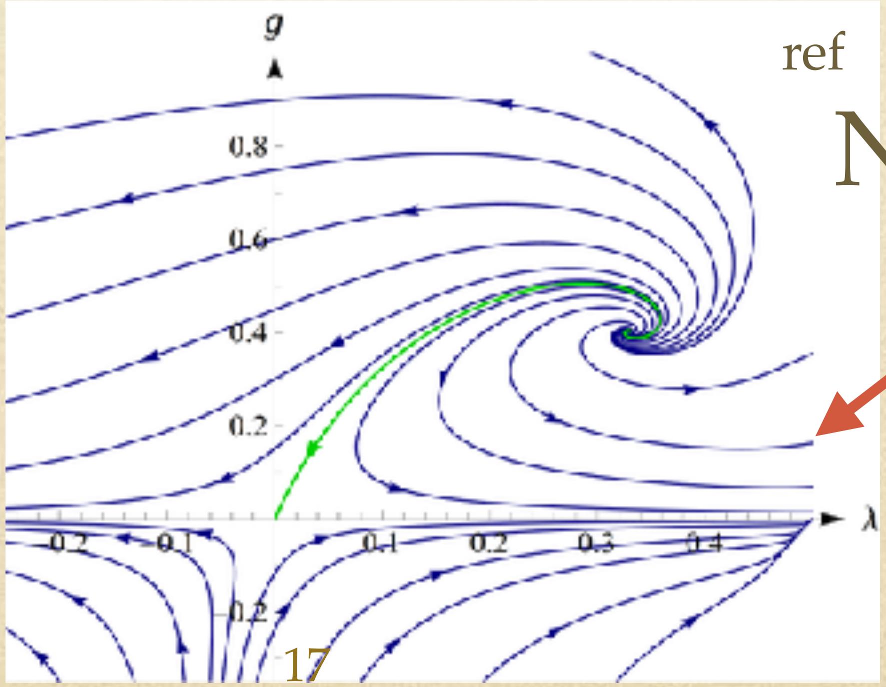
$$G_{\mu\nu} = 8\pi G(k) T_{\mu\nu} - \Lambda(k) g_{\mu\nu} - \Delta t_{\mu\nu}$$

- Couplings are connected in RG flow

example:

$$G_k = \frac{g_k}{k^2}$$

$$\Lambda_k = \lambda_k k^2$$



Not independent

both change
or
none changes

SD-Framework

- Couplings are connected in RG flow

We are only interested in SD small modifications of the couplings in the IR:

Expand:

$$G(k) = G_0(1 + g(k)) = G_0\left(1 + C_1 G_0 k^2\right) + \mathcal{O}(k^4)$$

$$\Lambda(k) = \Lambda_0(1 + \lambda(k)) = \Lambda_0\left(1 + C_3 G_0 k^2\right) + \mathcal{O}(k^4)$$

Theorist: predict

Phenomenologist: use to predict

Experimentalist: measure

SD-Framework

- Couplings are connected in RG flow

We are only interested in SD small modifications of the couplings in the IR:

Expand:

$$G(k) = G_0(1 + g(k)) = G_0\left(1 + C_1 G_0 k^2\right) + \mathcal{O}(k^4)$$

$$\Lambda(k) = \Lambda_0(1 + \lambda(k)) = \Lambda_0\left(1 + C_3 G_0 k^2\right) + \mathcal{O}(k^4)$$

In density

$$\rho_\Lambda(k) = \frac{c^4 \Lambda(k)}{8\pi G(k)} = \rho_0 - k^2 c^4 \frac{(C_1 - C_3)}{8\pi} \Lambda_0 + \mathcal{O}(k^4)$$

?

SD-Framework

To identify k^2 compare

$$\rho_\Lambda(k) = \rho_{\Lambda_0} - k^2 c^4 \frac{(C_1 - C_3)}{8\pi} \Lambda_0$$

$$\rho_\Lambda = \rho_{\Lambda_0} - \alpha \cdot \rho_C(\overrightarrow{x})$$

$$\Rightarrow \qquad k^2(\overrightarrow{x}) = \alpha \frac{8\pi \rho_C(\overrightarrow{x})}{c^4 (C_1 - C_3)\Lambda_0}$$

Insert in couplings

$$G\left(k(\overrightarrow{x})\right) = G_0 \left(1 + C_1 G_0 \alpha \frac{8\pi \rho_C(\overrightarrow{x})}{c^4 (C_1 - C_3)\Lambda_0} \right)$$

Thus, ρ_Q modifies Newton coupling!

SD-Framework

- Modified Einstein equations

Derivatives of $G\left(k(\overrightarrow{x})\right)$

$$G_{\mu\nu} = 8\pi G(k)T_{\mu\nu} - \Lambda(k)g_{\mu\nu} - \Delta t_{\mu\nu}$$

Does Casimir/SD affect Newton?

Trace trick

$$R^{\mu}_{\ \nu} = 8\pi\frac{G(k)}{c^4}\left(T^{\mu}_{\ \nu} - \frac{1}{2}g^{\mu}_{\ \nu}T\right) + \Lambda(k)g^{\mu}_{\ \nu} + G(k)\left(\frac{1}{2}g^{\mu}_{\ \nu}\nabla^2 + \nabla^{\mu}\nabla_{\nu}\right)\frac{1}{G(k)}\,.$$

With non-relativistic matter

$$\left(T^{\mu}_{\ \nu} - \frac{1}{2}g^{\mu}_{\ \nu}T\right) = \frac{\rho_M}{2}\mathrm{diag}(-1,1,1,1)$$

SD-Framework

- Modified Einstein equations

$$G_{\mu\nu} = 8\pi G(k) T_{\mu\nu} - \Lambda(k) g_{\mu\nu} - \Delta t_{\mu\nu}$$

Derivatives of $G\left(k(\overrightarrow{x})\right)$

Weak field and weak SD expansion…

$$ds^2 = -(1 + 2\epsilon_\Phi \Phi(r,\theta,\phi))c^2 dt^2 + (1 - 2\epsilon_\Phi \Psi(r,\theta,\phi))dr^2 + (1 + 2\epsilon_\Phi \Xi(r,\theta,\phi))r^2 d\Omega^2 + \mathcal{O}(\epsilon_\Phi^2)$$

$$G(k) = \epsilon_\Phi \left(G_0 + \epsilon_G \Delta G(k) + \mathcal{O}(\epsilon_\Phi^2)\right)$$

$$\Lambda(k) \to \epsilon_\Phi \Lambda(k)$$

R_0^0 component

$$\overrightarrow{\nabla}^2 \Phi(r,\theta,\phi) = \frac{4\pi}{c^4} G_0 \rho_M(r,\theta,\phi) + \frac{\epsilon_G}{\epsilon_\Phi} \frac{\overrightarrow{\nabla}^2 \Delta G(k)}{2G_0} - \Lambda(k) + \mathcal{O}(\epsilon_\Phi, \epsilon_G)$$

Solution…

SD-Framework

- Modified Einstein equations

$$G_{\mu\nu} = 8\pi G(k)T_{\mu\nu} - \Lambda(k)g_{\mu\nu} - \Delta t_{\mu\nu}$$

Derivatives of $G\left(k(\overrightarrow{x})\right)$

Solution

$$\Phi(\overrightarrow{x}) = \frac{G_0}{c^4}\int_{V_1} d^3x_1 \frac{\tilde{\rho}_M(\overrightarrow{x}_1)}{|\overrightarrow{x} - \overrightarrow{x}_1|} + \mathcal{O}(\epsilon_\Phi)$$

with

$$\tilde{\rho}_M = \rho_m + c^2\frac{\overrightarrow{\nabla}^2 G(k)}{8\pi G_0^2}$$

For extended objects…

$$\alpha c^2 C_1 \frac{\overrightarrow{\nabla}^2 \rho_C(\overrightarrow{x})}{c^4(C_1 - C_3)\Lambda_0}$$

SD-Framework

- Modified Einstein equations

Derivatives of $G\left(k(\overrightarrow{x})\right)$

$$G_{\mu\nu} = 8\pi G(k) T_{\mu\nu} - \Lambda(k) g_{\mu\nu} - \Delta t_{\mu\nu}$$

For extended objects: Newton

$$\overrightarrow{\mathscr{F}}_{G,12} = - \overrightarrow{\mathscr{F}}_{G,21} = G_0 \int_{V_2} d^3x_2 \int_{V_1} d^3x_1 \frac{\tilde{\rho}_M\left(\overrightarrow{x}_1\right)\tilde{\rho}_M\left(\overrightarrow{x}_2\right)\left(\overrightarrow{x}_2 - \overrightarrow{x}_1\right)}{|\overrightarrow{x}_2 - \overrightarrow{x}_1|^3}$$

with

$$\tilde{\rho}_M = \rho_m + c^2 \frac{\overrightarrow{\nabla}^2 G(k)}{8\pi G_0^2}$$

$$\alpha c^2 C_1 \frac{\overrightarrow{\nabla}^2 \rho_C(\overrightarrow{x})}{c^4 (C_1 - C_3)\Lambda_0}$$

SD-Framework

- Modified Einstein equations &
- Couplings are connected in RG flow

$\Rightarrow$ Gravitational attraction between plates changes

$$\alpha c^2 C_1 \frac{\vec{\nabla}^2 \rho_C(\vec{x})}{c^4 (C_1 - C_3)\Lambda_0} \rightarrow \vec{\mathscr{F}}_{G,12} \neq \vec{F}_{G,12}$$

Hypothesis
can be tested by experiment:
Verify, or set bounds on α …

SD-Framework

Gravitational attraction between plates changes

$$\alpha c^2 C_1 \frac{\vec{\nabla}^2 \rho_C(\vec{x})}{c^4 (C_1 - C_3)\Lambda_0} \rightarrow \vec{\mathscr{F}}_{G,12} \neq \vec{F}_{G,12}$$

What that means

Change ρ_Q

Hypothesis

ρ_Λ not measurable

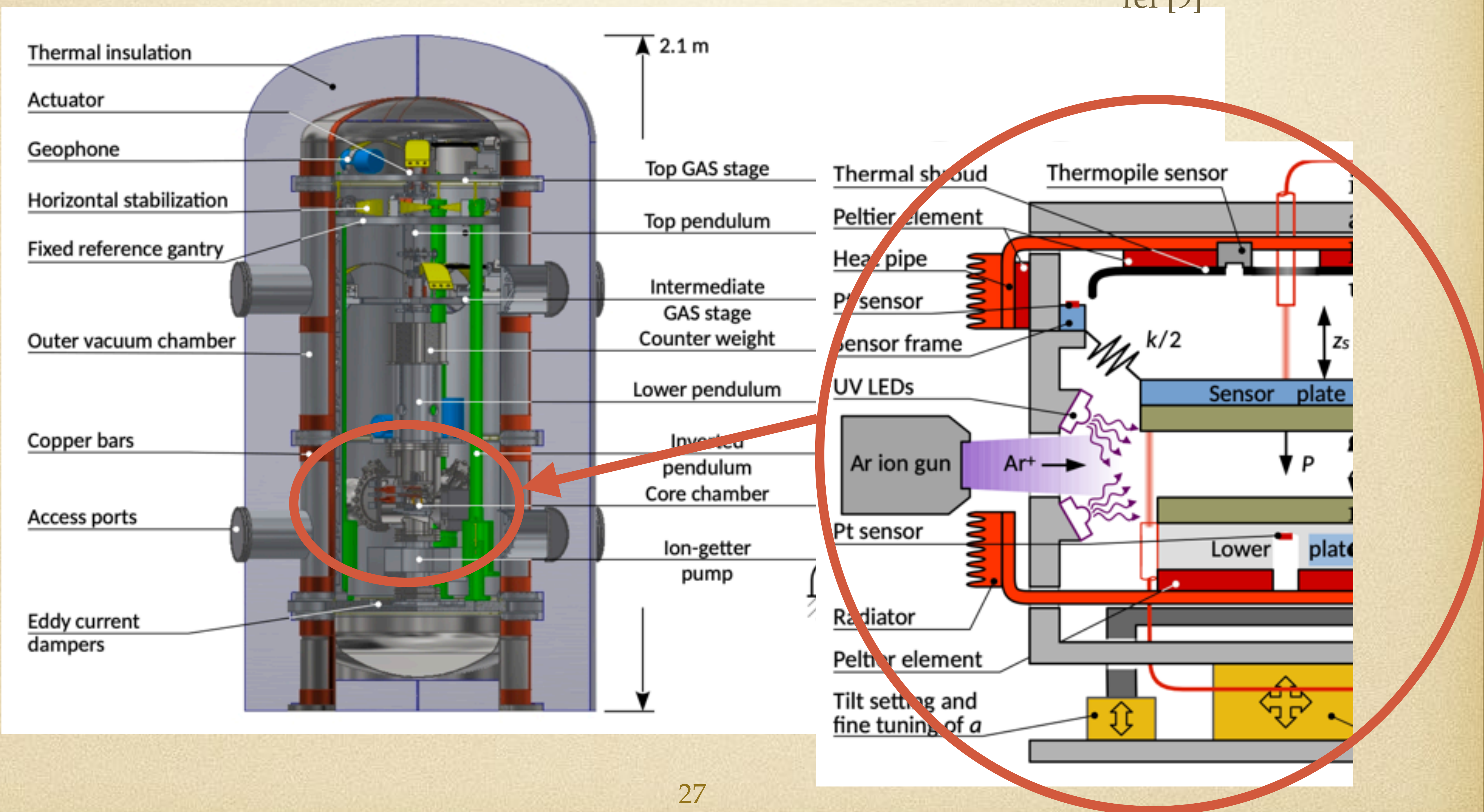
SD & flow

$\rho_M \rightarrow \tilde{\rho}_M$ measurable

Towards experiment

Cannex planned experiment

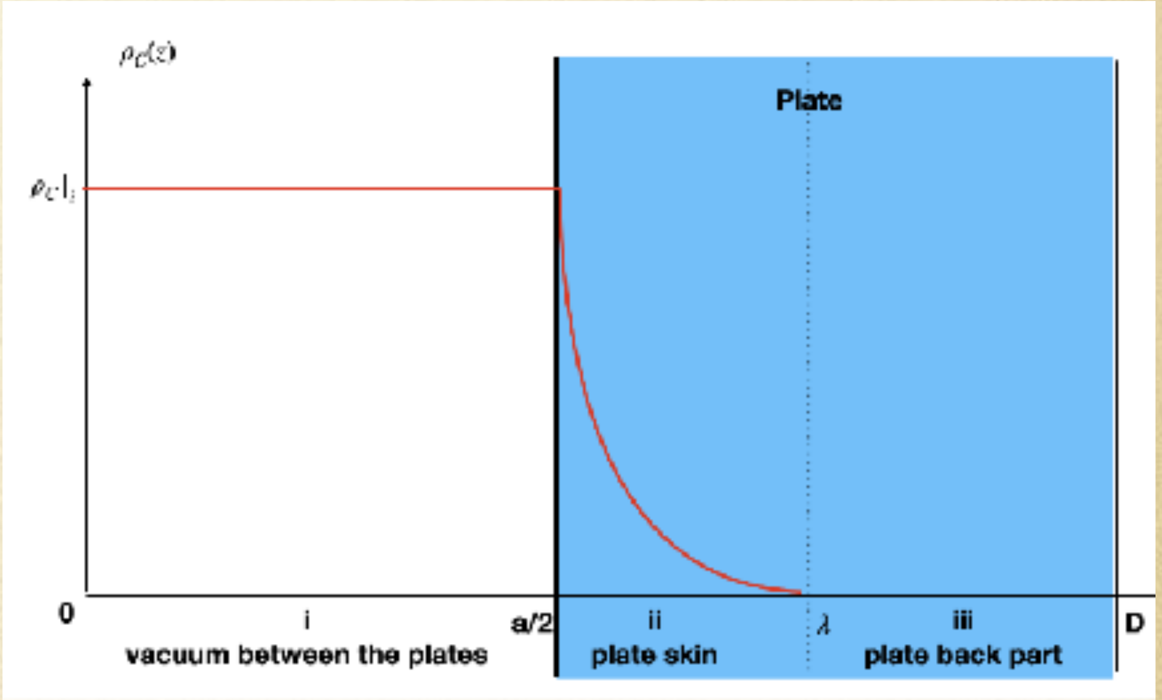
ref [9]



Towards experiment

Results (preliminary estimate):

$$1 \ll (8\pi G_0^2)\frac{\int_{a/2}^{D} dz\ \rho_M(z)}{\int_{a/2}^{D} dz c^2 \vec{\nabla}^2 G}$$



$$\alpha \frac{C_1}{C_1 - C_3} \ll 10^{-32}$$

$$\alpha < small$$

heading towards ultra small

potentially excludes models

Interpretation

$$\alpha \frac{C_1}{C_1 - C_3} \ll 10^{-32}$$

A. ρ_Q contribution to ρ_Λ strongly suppressed ($\alpha \ll 1$)

B. $\Lambda(k)$ has very weak RG coupling to $G(k)$

C. Effective Einstein equations have additional fields, contributions, stuff, leading to cancellations…

For each interpretation many possible subcategories, e.g.

B.
1. Λ is not a coupling but a field
2. G is not a coupling but a field
3. RG group is not universal
4. Hierarchy in QG parameters: $C_3 \gg C_1$
5. …

Interpretation

A: $(\alpha \ll 1)$

Implications for the CCP

$$\Upsilon_0 \equiv \frac{\rho_{\Lambda_0}}{\rho_{Q,0}(\kappa)} = \frac{\Lambda_0 c^3 \hbar^3}{8\pi G_0 \kappa_0^4} = \begin{cases} 10^{-121} & \text{for } \kappa_0 = c\sqrt{\frac{c\hbar}{G_0}} \\ 10^{-55} & \text{for } \kappa_0 = c m_Z. \end{cases}$$

Problem comes from the ambition

$$\rho_\Lambda = \Upsilon(\rho_Q) \cdot \rho_Q,$$

Casimir can contribute to both

$$\rho_Q = \rho_{Q,0} + \beta \cdot \rho_C$$

Should be $\beta = 1$, but who knows …

$$\rho_\Lambda = \rho_{\Lambda_0} - \alpha \cdot \rho_C$$

hypothesis, α

Interpretation

A: ($\alpha \ll 1$)

Implications for the CCP

Look at changes of the CCP

Find

$$\Upsilon_0' \equiv \left.\frac{d\Upsilon(\rho_Q)}{d\rho_C}\right|_{\rho_C=0}$$

Measuring α

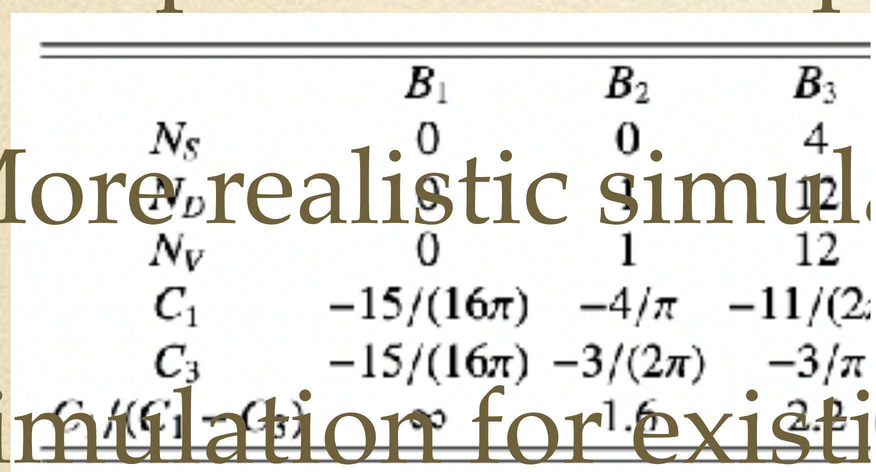
$$\alpha = \Upsilon_0' + \beta\,\Upsilon_0$$

$\Rightarrow$

Measure changes in CCP

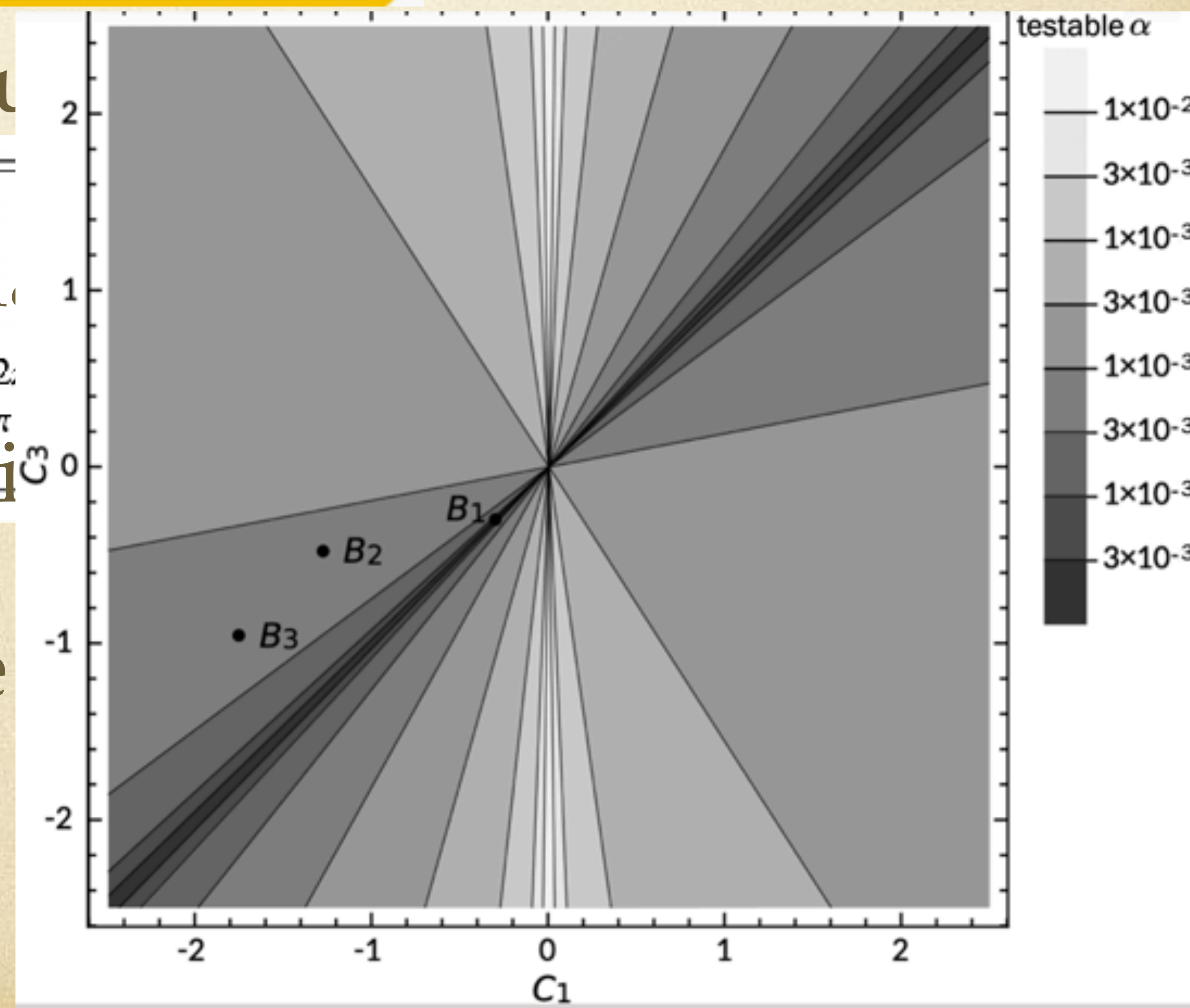
Under construction

- Comparison with qu



	B_1	B_2	B_3
N_S	0	0	4
N_D	0	1	12
N_V	0	1	12
C_1	$-15/(16\pi)$	$-4/\pi$	$-11/(2$
C_3	$-15/(16\pi)$	$-3/(2\pi)$	$-3/\pi$
$C_3/(C_1-C_3)$	∞	[illegible]	[illegible]

- More realistic simul
- Simulation for existi
- Implications for the
- …



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Thank You!

Backup stuff

Scale-Dependent
& FRG

Scale Dependent Framework

Gravity as effective QFT

$$\Gamma_k = \int d^4x \sqrt{-g} \left(\frac{R}{G_k} - 2\frac{\Lambda_k}{G_k} \right) + \ldots$$

Non renormalizable?

Yes, but …

Could still be predictive QFT
(Asymptotic Safety)

Asymptotic Safety in a nutshell

$$\Gamma_k = \int d^4x\sqrt{-g}\left(\frac{R}{G_k} - 2\frac{\Lambda_k}{G_k}\right) + \ldots$$

- Idea: works if non trivial UV-fixed points for finite number of couplings (S.W)

Asymptotic Safety in a nutshell

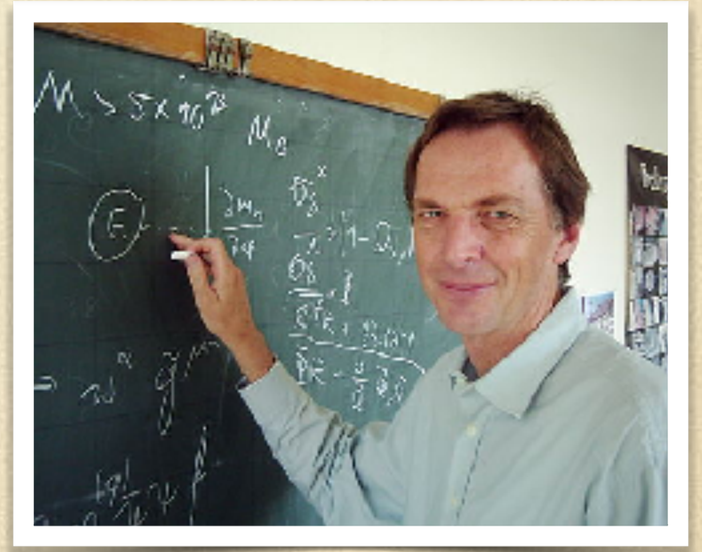
$$\Gamma_k = \int d^4x \sqrt{-g} \left(\frac{R}{G_k} - 2\frac{\Lambda_k}{G_k} \right) + \dots$$

- Tool: Functional renormalization group equation

$$\partial_k \Gamma_k = \frac{1}{2} Tr \left(\frac{\partial_k R_k}{\Gamma_k^{(2)} + R_k} \right)$$

two point function

regulator



C. Wetterich

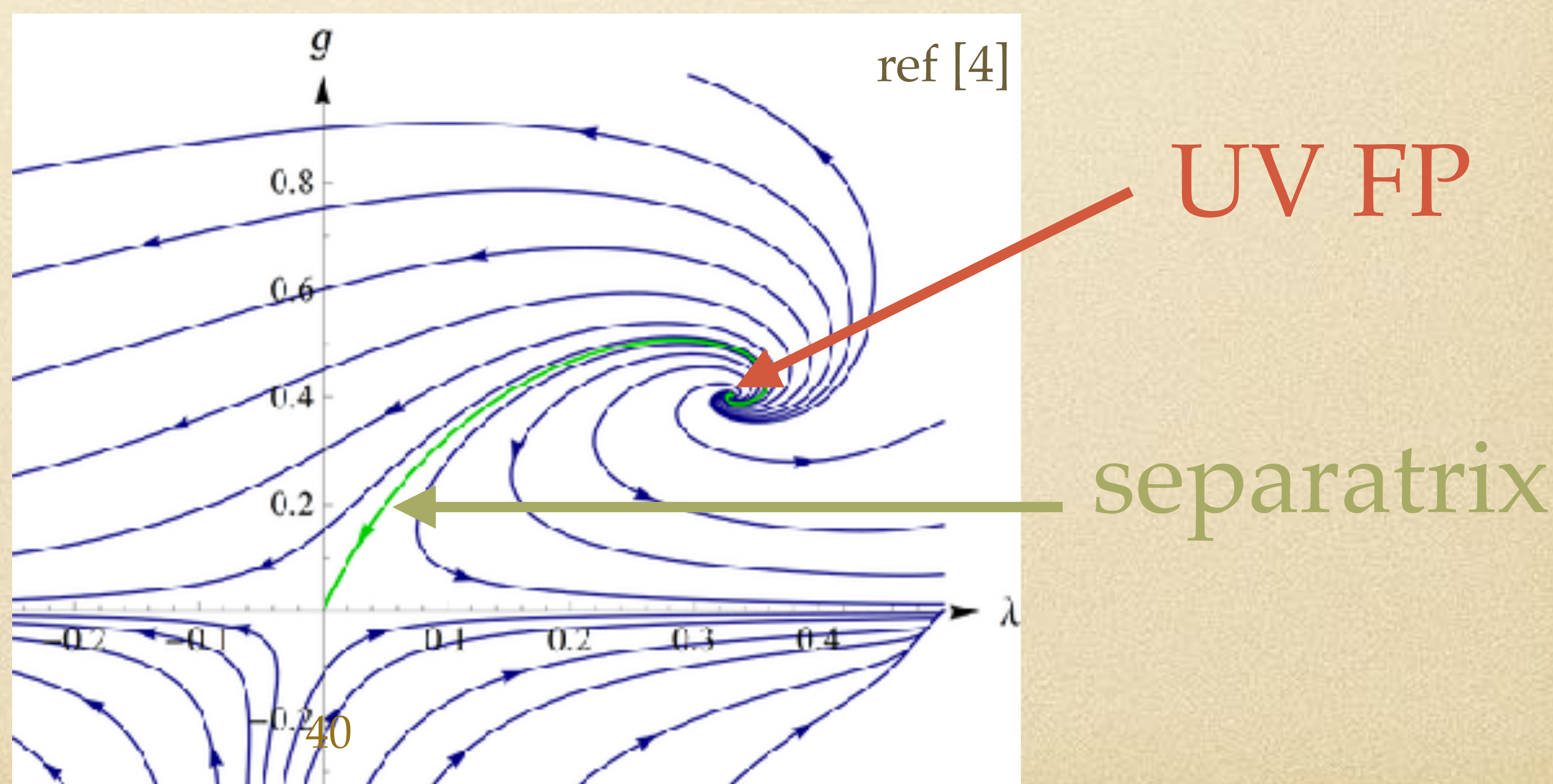
Asymptotic Safety in a nutshell

$$\Gamma_k = \int d^4x \sqrt{-g} \left(\frac{R}{G_k} - 2\frac{\Lambda_k}{G_k} \right) + \dots$$

- Results: Plenty of evidence supporting idea

$$G_k = \frac{g_k}{k^2}$$

$$\Lambda_k = \lambda_k k^2$$

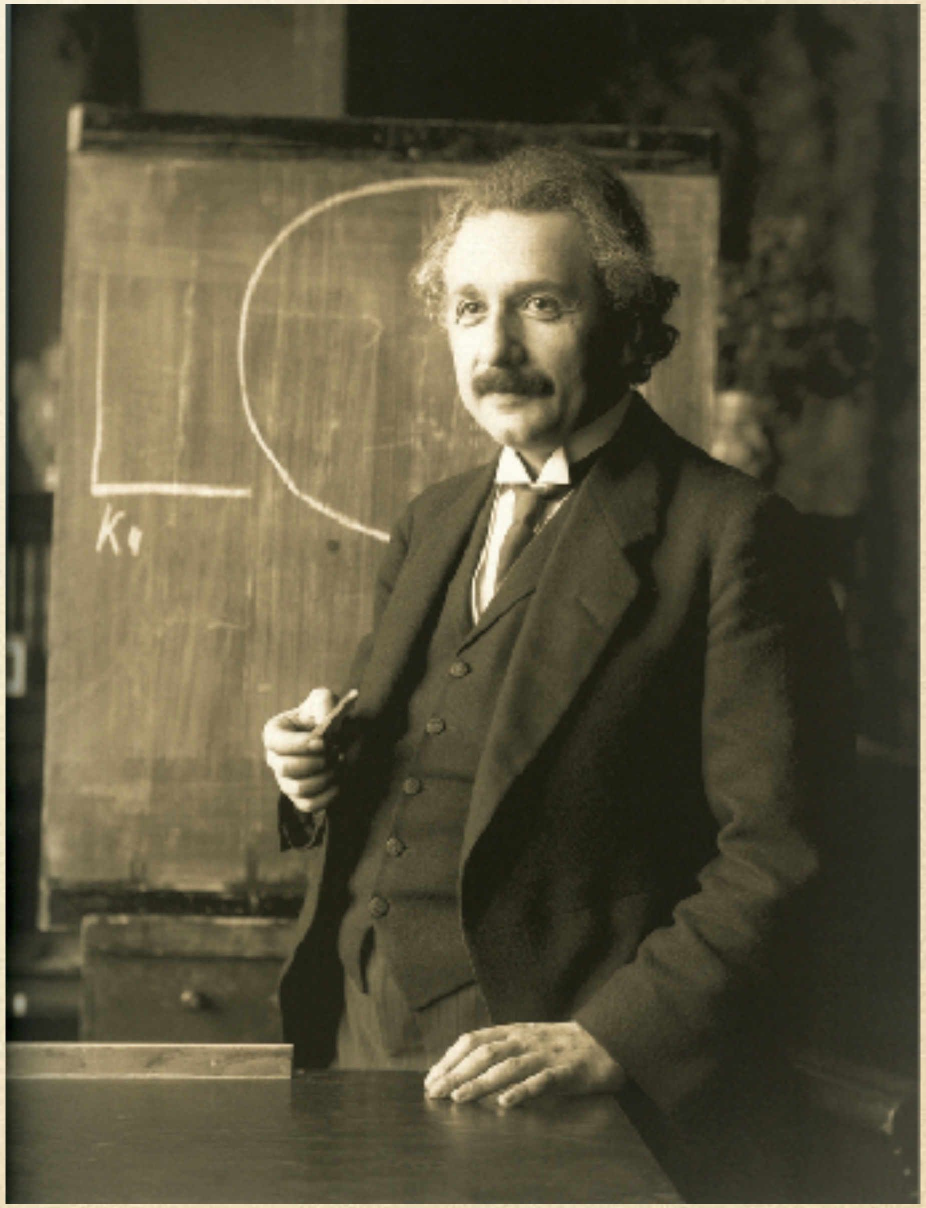


The CCP 1.0

The CCP 1.0

Albert Einstein

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$



NP 1921

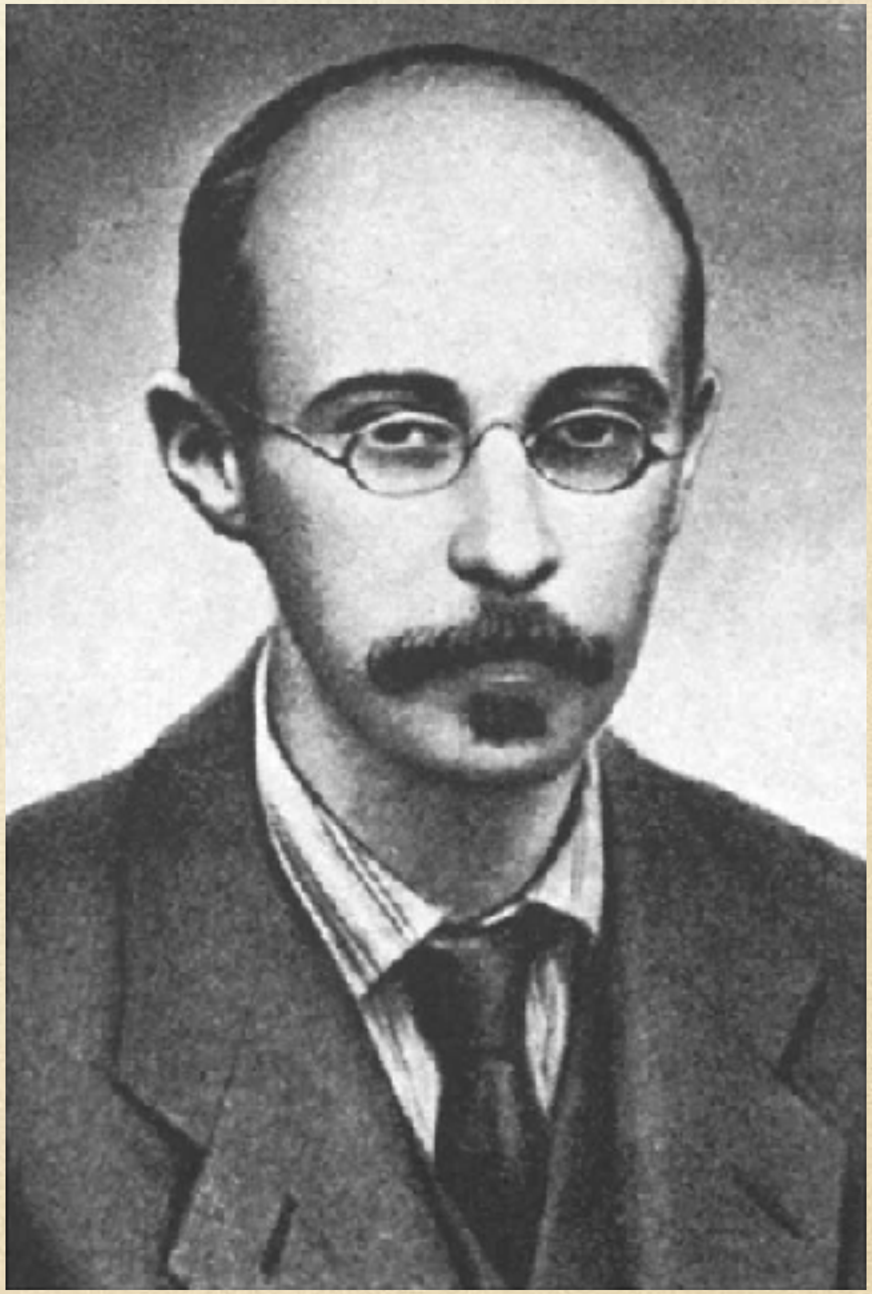
The CCP 1.0

Alexander Friedmann

$$ds^2 = a(t)ds_3^2 - dt^2$$

$$\frac{\dot{a}^2 + k}{a^3} = \frac{1}{3}8\pi G\rho$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$



The CCP 1.0

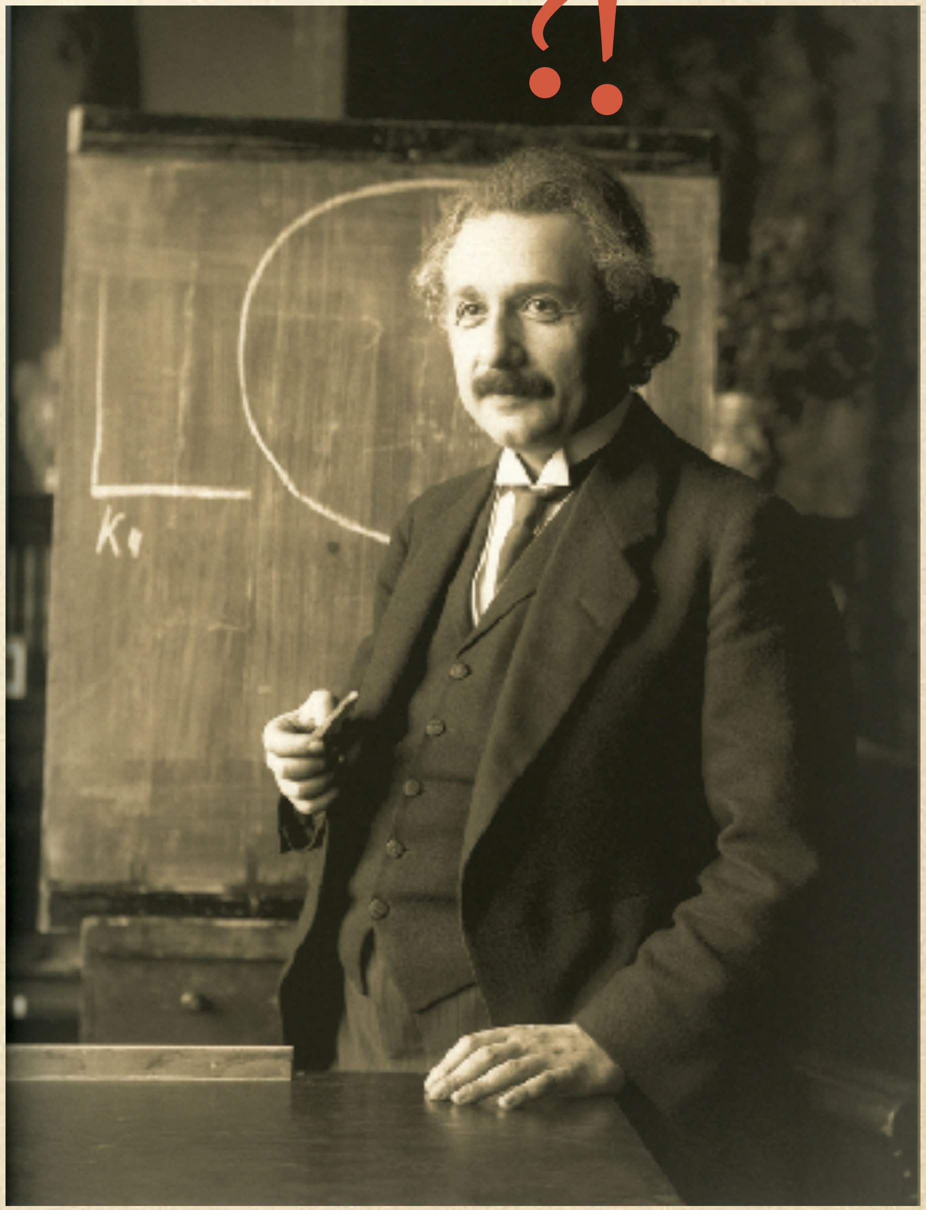
Albert Einstein

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \neq 0$$

$$\Rightarrow \dot{a} \neq 0$$ not static

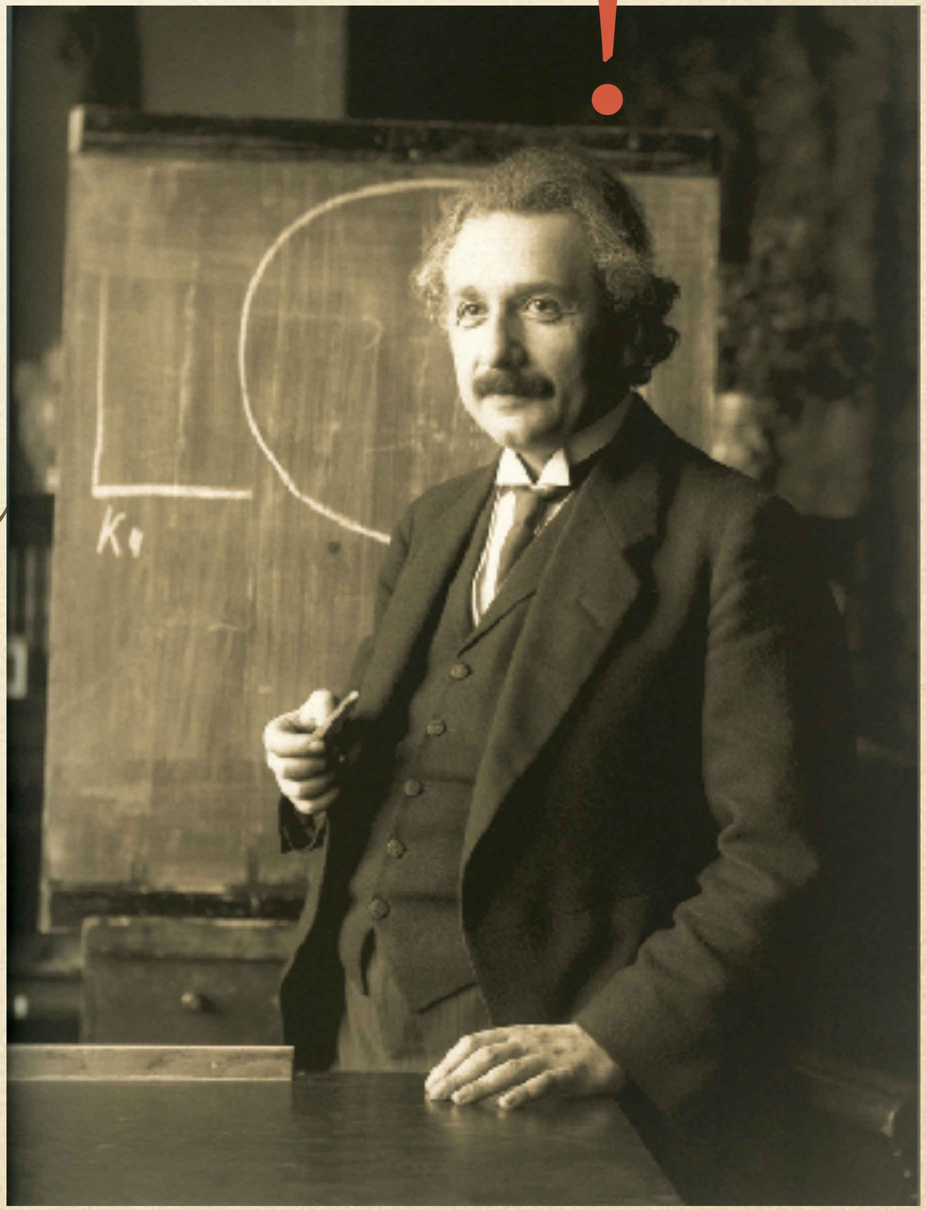
?!



The CCP 1.0

Albert Einstein

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$



!

!

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \equiv 0$$

static possible $\dot{a} \equiv 0$

The CCP 2.0

The CCP 2.0

Edwin Hubble, Georges Lemaítre

measurement:

ref [1]

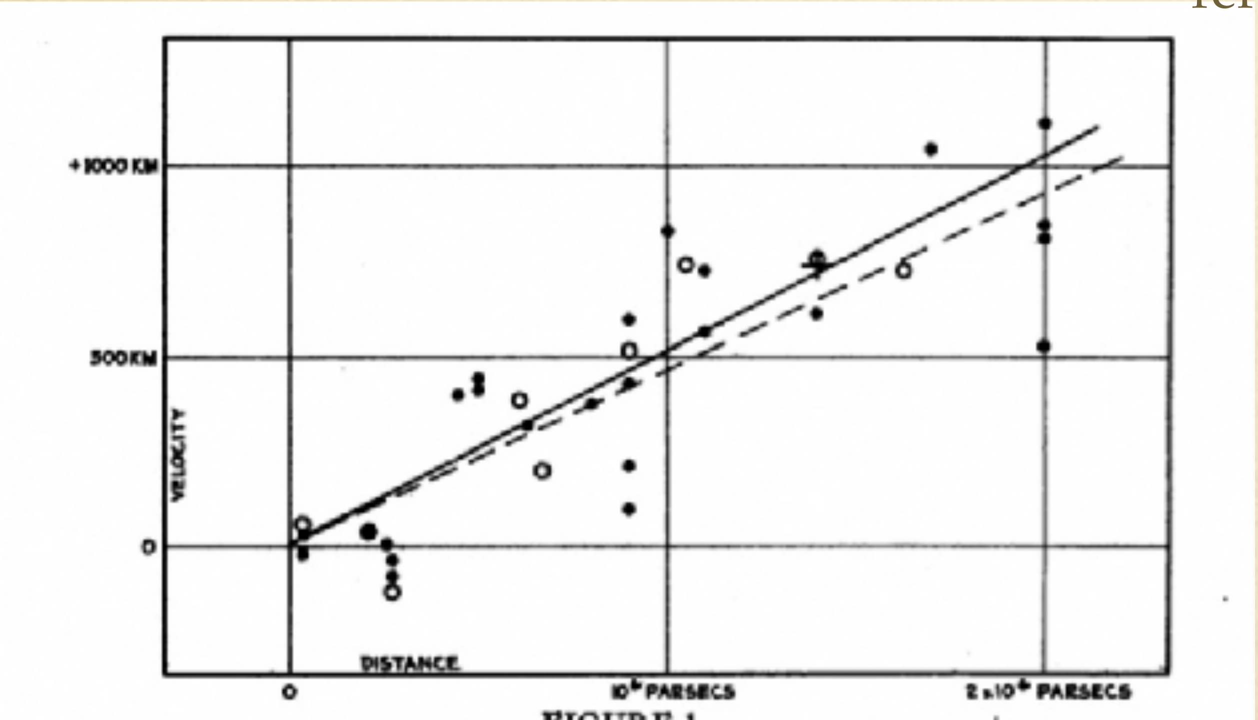


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

1927,1929

The CCP 2.0

Edwin Hubble

measurement:

$\dot{a} > 0$ not static

later:

$$\dot{a} = 67.66 \pm 0.42 \frac{km/s}{Mpc}$$

(Planck collaboration 2018)

The CCP 2.0

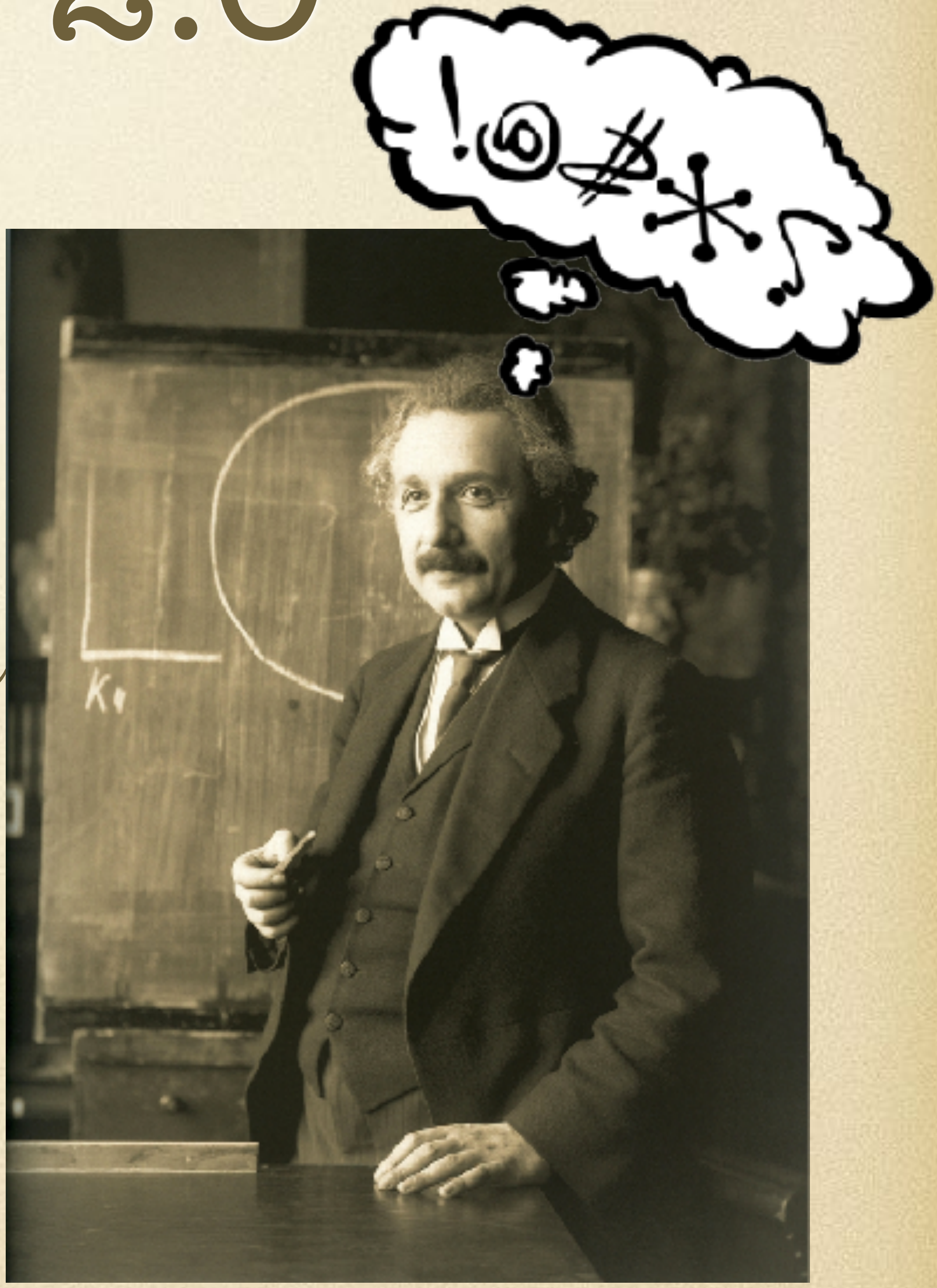
Albert Einstein

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} = 0$$

not static $\quad \dot{a} \neq 0$

$\ddot{a} < 0$



“biggest blunder”

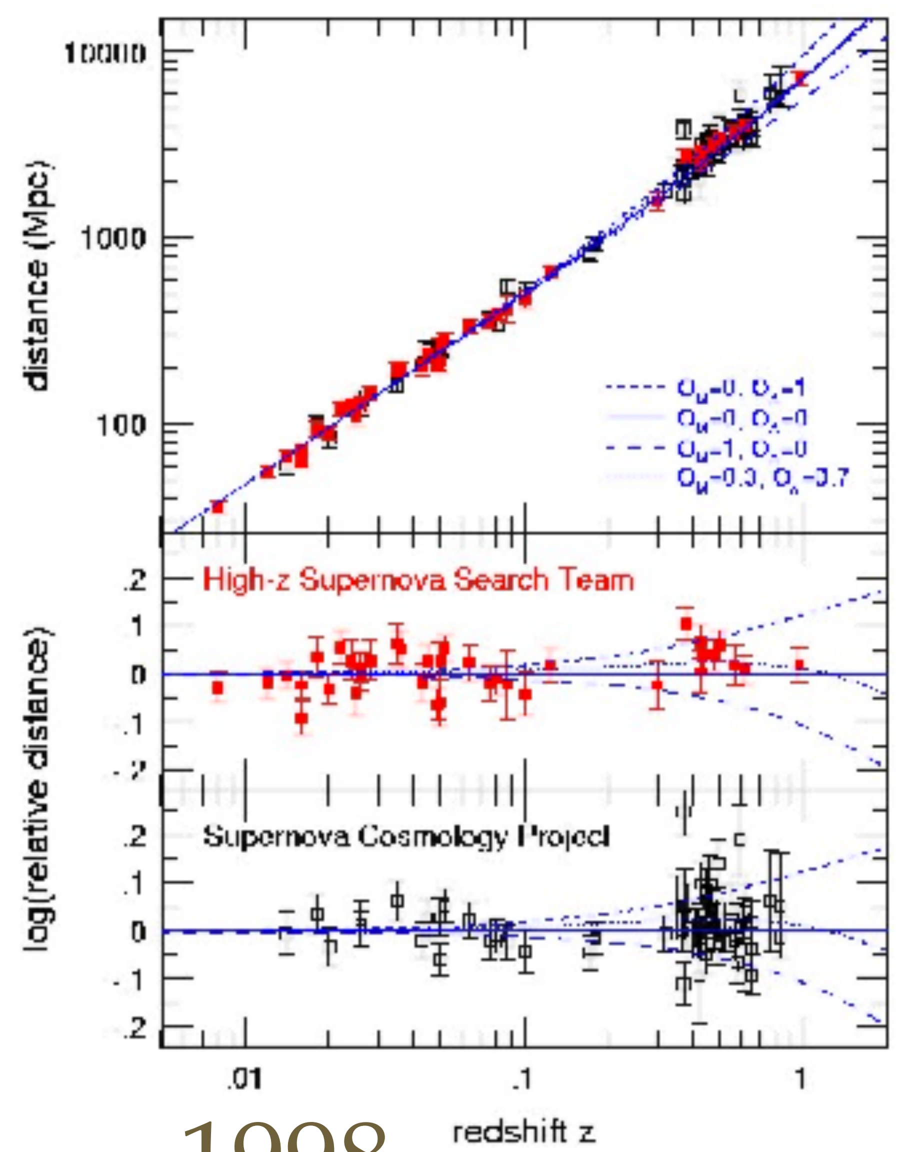
The CCP 3.0

The CCP 3.0

S. Perlmutter, A. Riess, B. Schmidt, & others

mea

ref [2]



1998

NP 2011

$\dot{a} \neq 0$ $\dot{a}$ 0

$\ddot{a} > 0$!

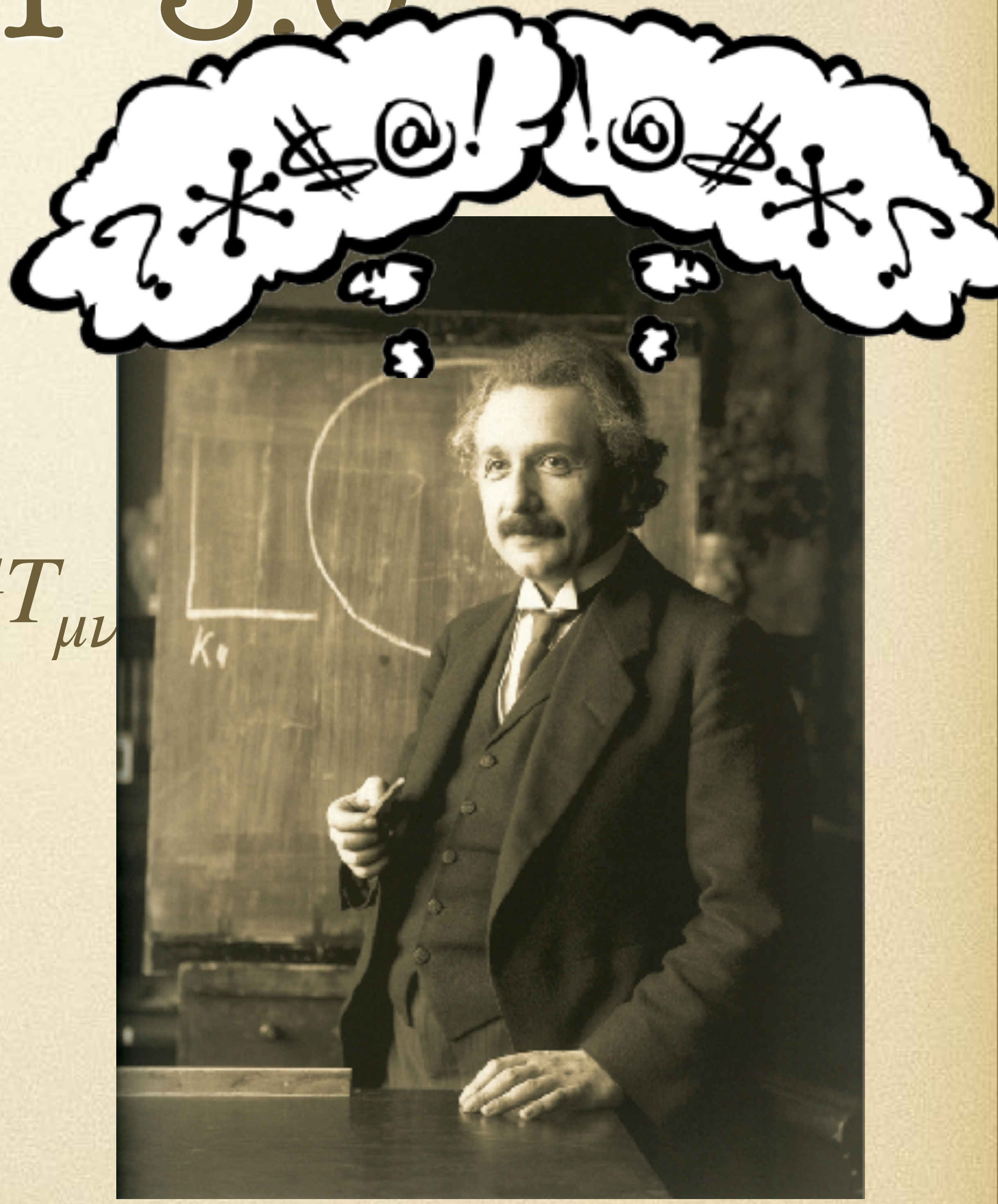
The CCP 3.0

Albert Einstein

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

$$\Lambda > 0 \Rightarrow \ddot{a} > 0$$



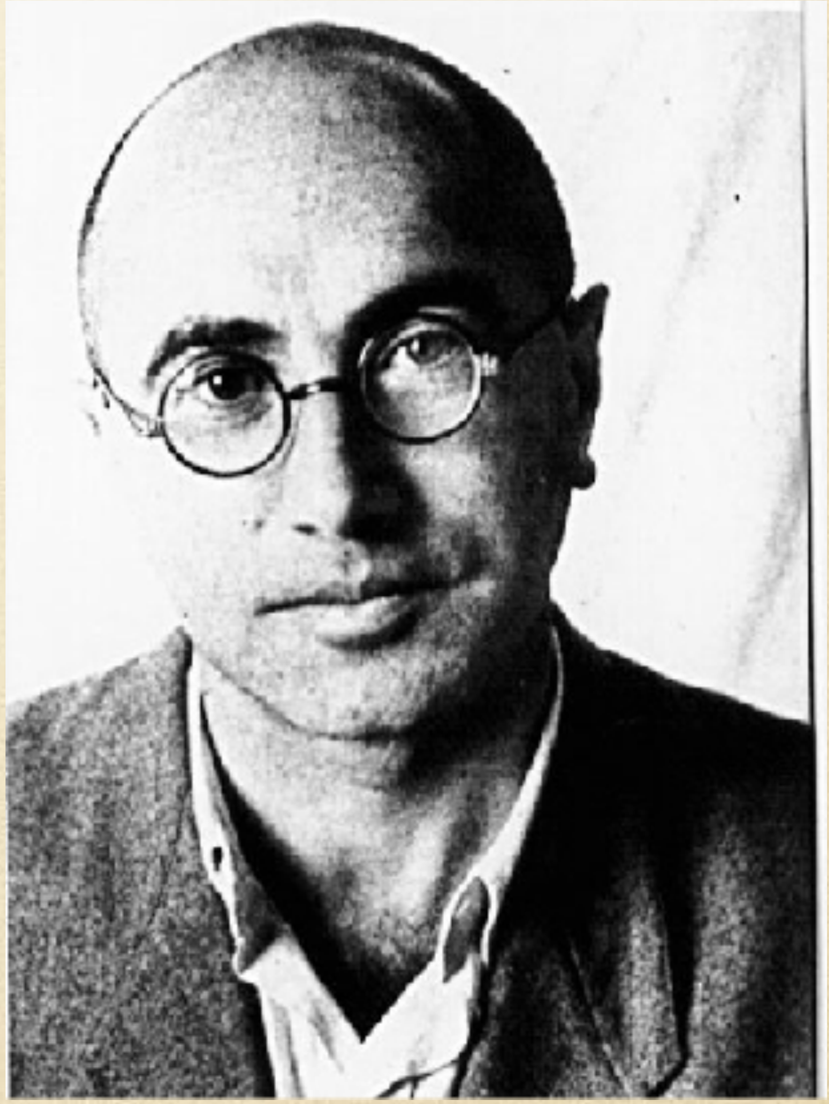
“???”

The CCP 3.0

Yakov Zeldovich

Quantum fluctuations predict value of Λ

1967



The CCP 3.0

Steven Weinberg

Quantum fluctuations predict value of Λ

Problem since 1998 ref [3]

NP 1979

The CCP 3.0

Quantum fluctuations
predict value of Λ

ref [3]

$$\left(\frac{\Lambda}{G}\right)_{eff} \sim M^4(1 + \ldots)$$

effective
quantum value

different
methods

cut-off
mass scale of QFT

use: $G \sim \dfrac{1}{M_P^2}$

The CCP 3.0

Quantum fluctuations
predict value of Λ

$$(\Lambda)_{eff} \sim \frac{M^4}{M_P^2}(1 + \dots)$$

effective
quantum value

different
methods

cut-off
mass scale of QFT

Planck mass

The CCP 3.0

Quantum fluctuations predict value of Λ

Highest physical mass scale

$$(\Lambda)_{eff} \sim \frac{M^4}{M_P^2}(1 + \ldots)$$

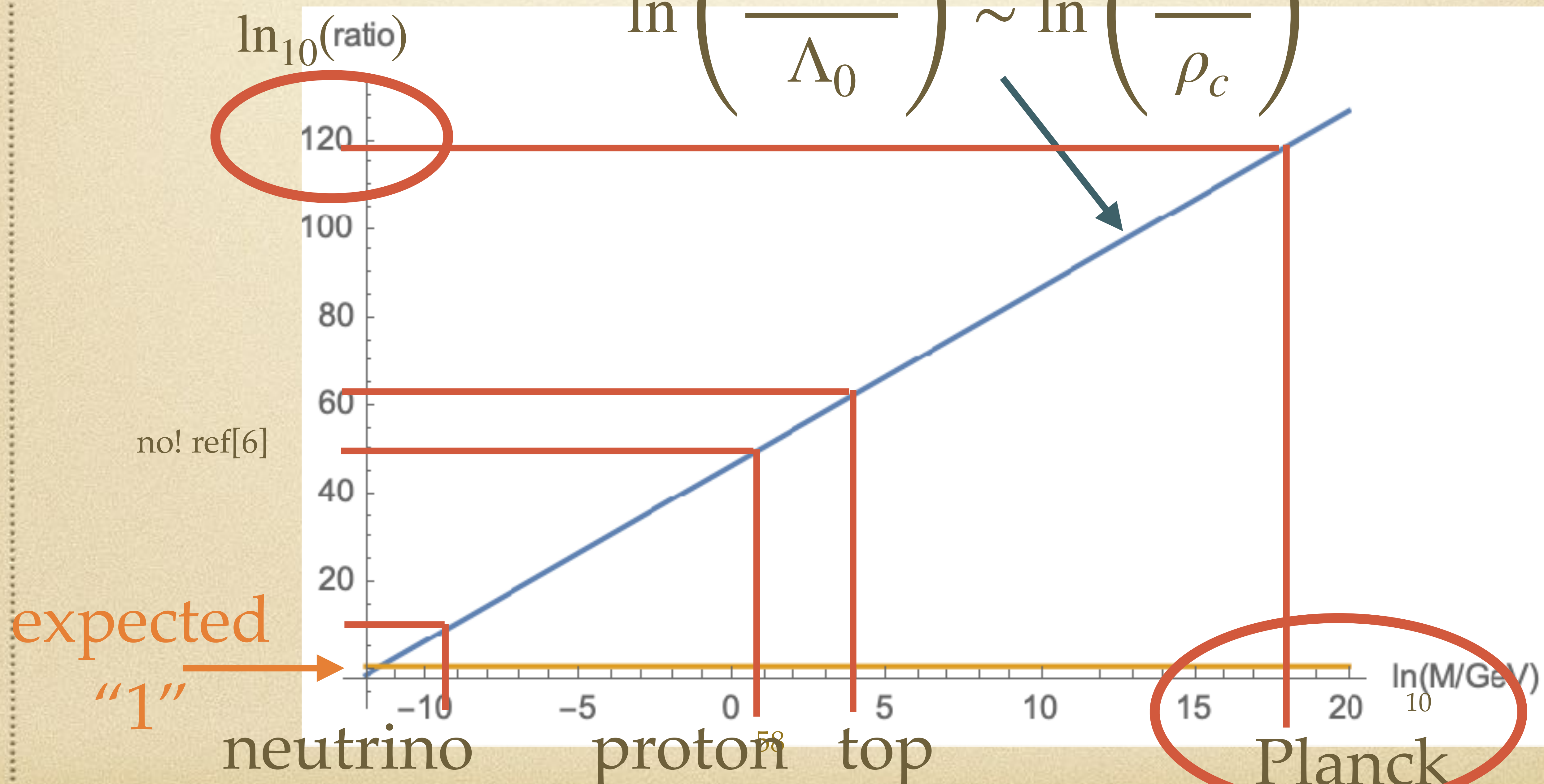
Observed value

$$\Lambda_o = \frac{\rho_c}{M_P^2} \approx \frac{10^{-47} GeV^4}{M_P^2}$$

observed critical energy density

The CCP 3.0

Problem as a ratio: $\ln\left(\frac{(\Lambda)_{eff}}{\Lambda_0}\right) \sim \ln\left(\frac{M^4}{\rho_c}\right)$



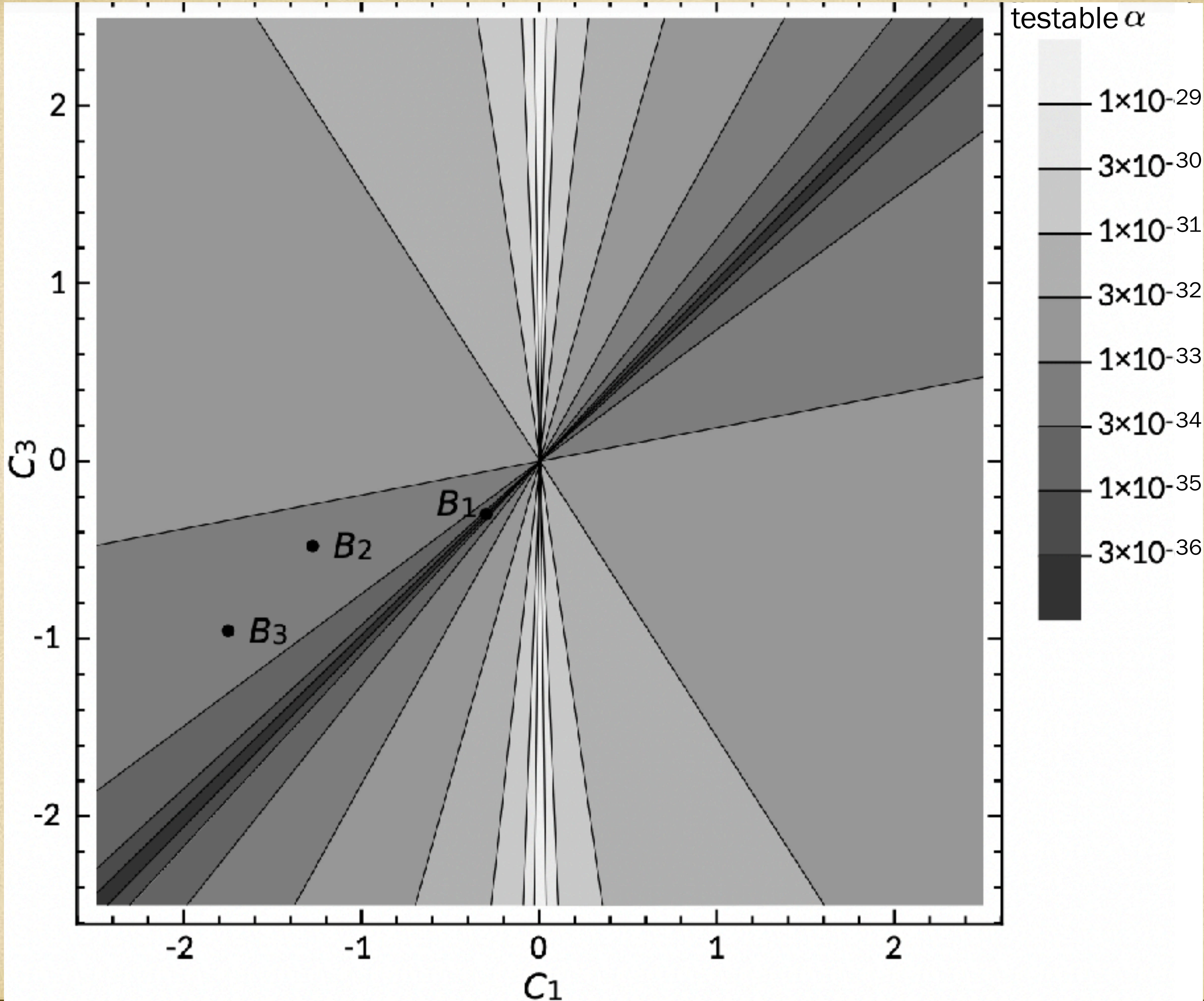
The CCP 3.0

Problem as a ratio:

$$\frac{(\Lambda)_{eff}}{\Lambda_0} \sim \frac{1}{G_N \cdot \Lambda_0} \sim \frac{M_P^4}{\rho_c} \approx 10^{120}$$

we try to address
this problem

assuming there are quantum fluctuations
of gravity associated to the Planck scale


testable α
1×10^-29
3×10^-30
1×10^-31
3×10^-32
1×10^-33
3×10^-34
1×10^-35
3×10^-36
B_1
B_2
B_3
2
1
0
-1
-2
C_3
-2
-1
0
1
2
C_1