

Title: Dark Energy and Testing Gravity

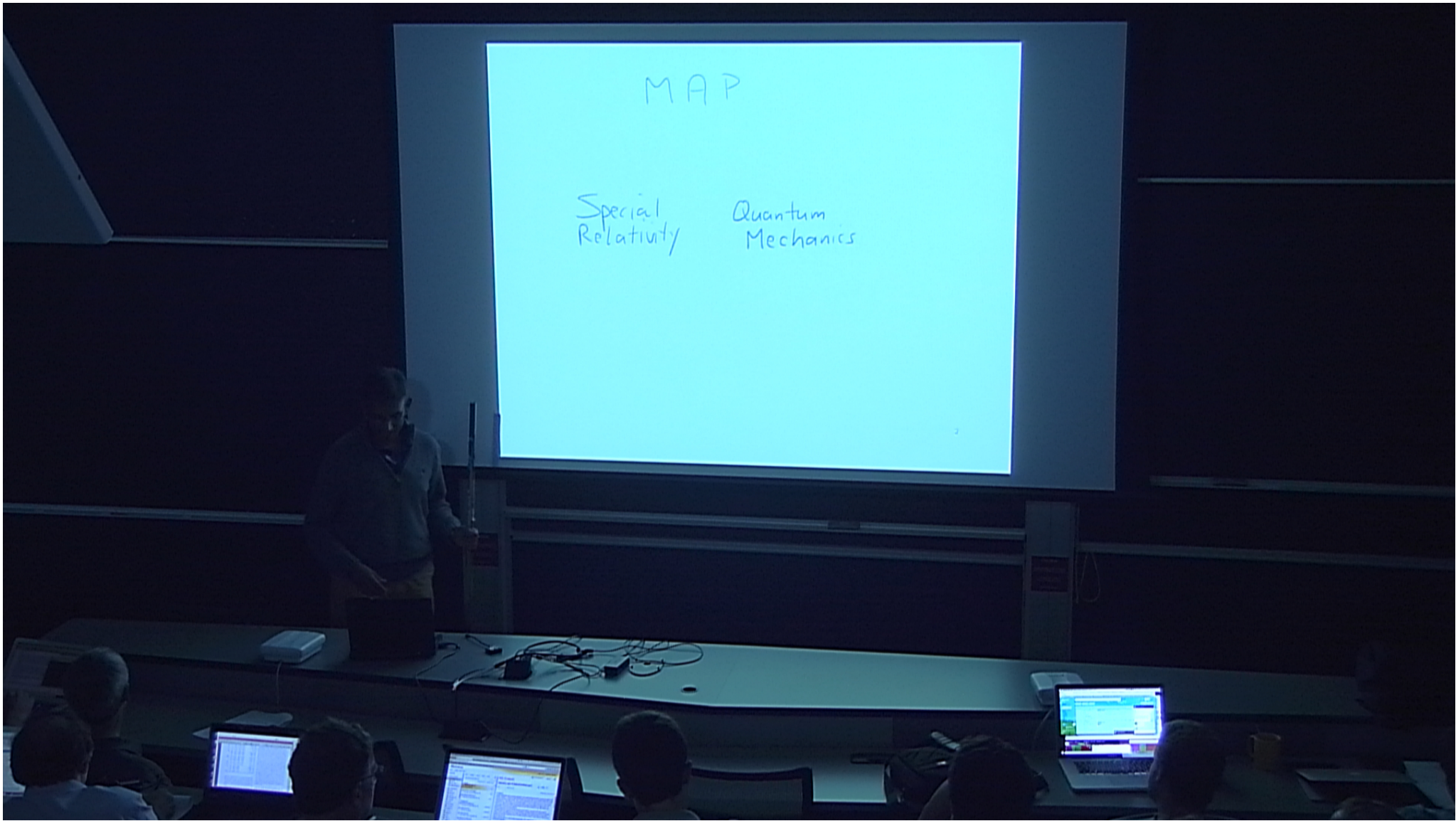
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URL: <http://pirsa.org/14060020>

Abstract: <span>I will review why the mild acceleration of the Universe poses a major puzzle, the Cosmological Constant Problem, for the connection between gravity and matter, suggesting a possible breakdown in the standard general relativistic and field theoretic description. Thus far theorists have failed to provide any very concrete and testable resolution. I will however discuss some simple theoretical ideas that suggest directions for experiments to lead the way.</span>

DARK ENERGY  
&  
TESTING  
GRAVITY

Raman Sundrum  
University of Maryland



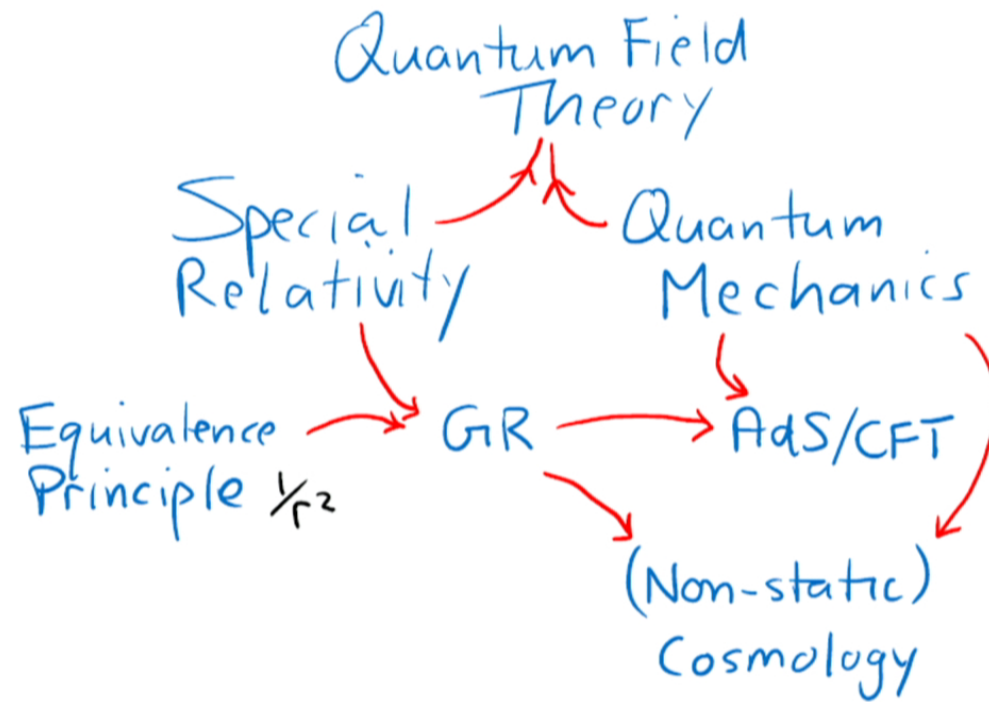
MAP

Special  
Relativity

Quantum  
Mechanics

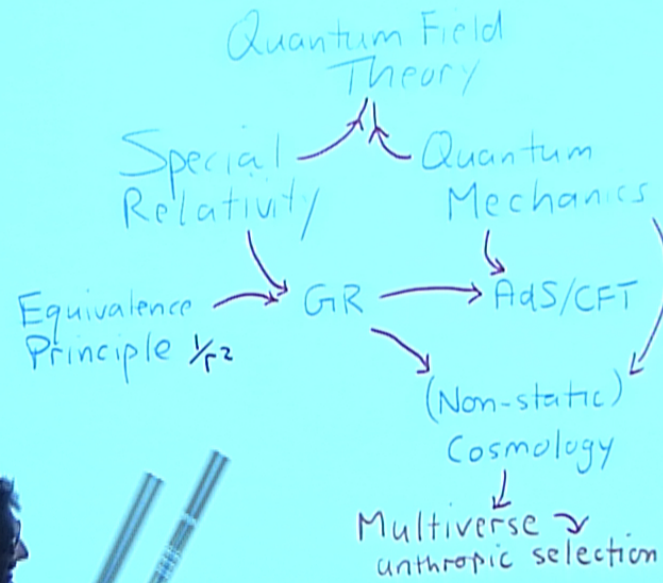
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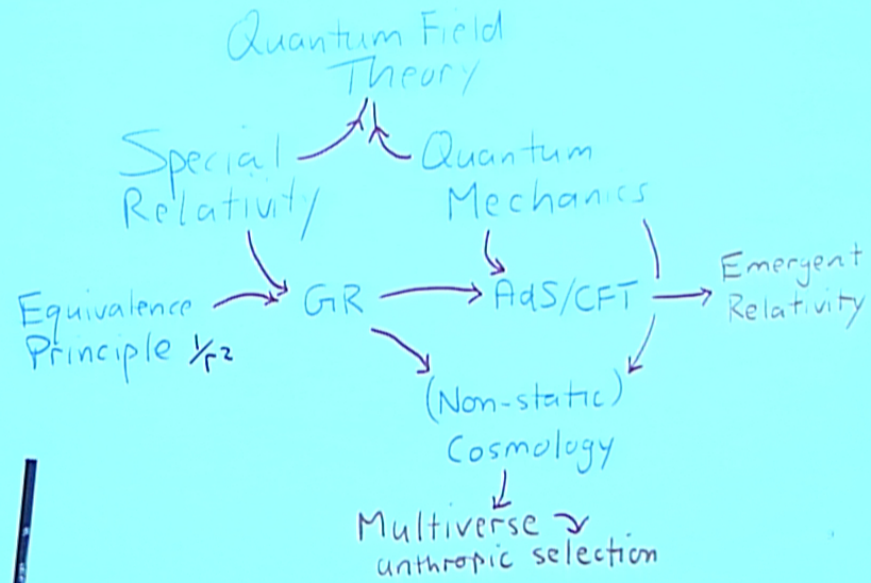


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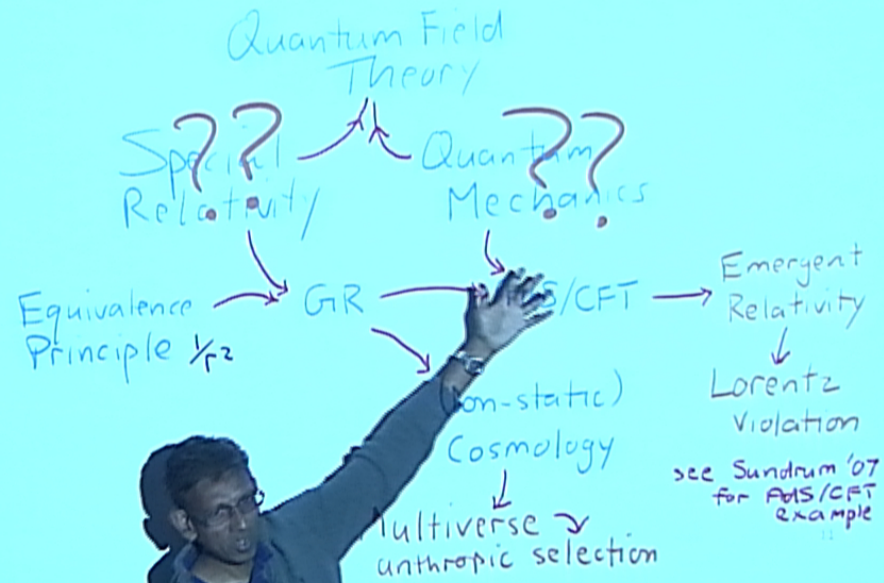
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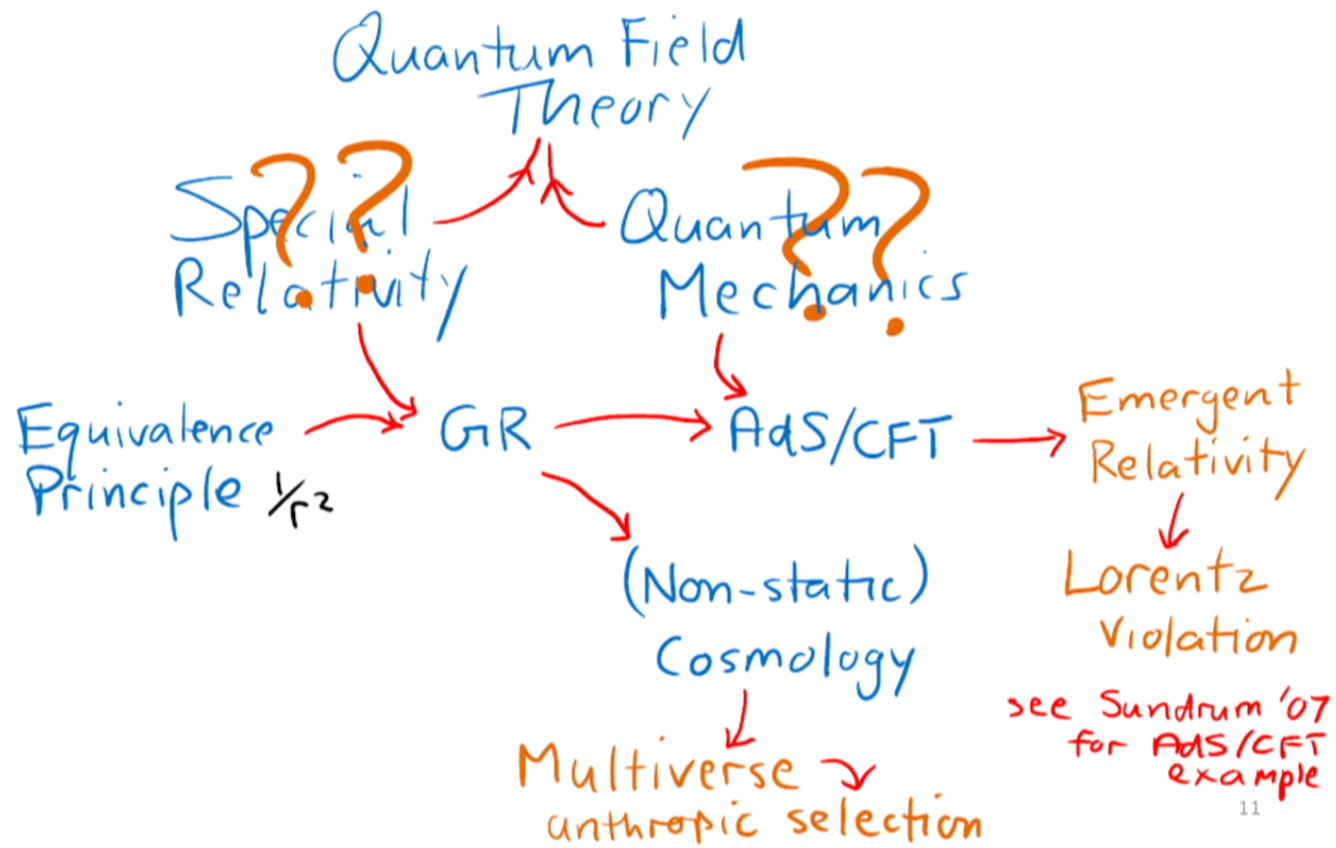


# MAP





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WHY SHOULD THERE BE ANY  
CRACKS IN MOST FUNDAMENTAL  
PHYSICAL PRINCIPLES  
**NOW?**

Special  
Relativity

Quantum  
Mechanics

GR

Reasonable if there are tremendous  
advances in sensitivity or into  
new regimes.

Example: <sup>Inflation</sup> BICEP2 (attempts to be) sensitive  
huge extrapolation of Quantum Mechanics & GR.

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# CRISIS

"DARK ENERGY" = source that accelerates expanding Universe.

GR  $\Rightarrow$  Cosmological Constant  
(Vacuum Energy Density)  
is simplest possibility for dark energy.

but Cosmological Constant Problem  
struggles with  $(\text{dark energy density})^{1/4} \sim \text{meV} \ll_{13} \text{TeV}$

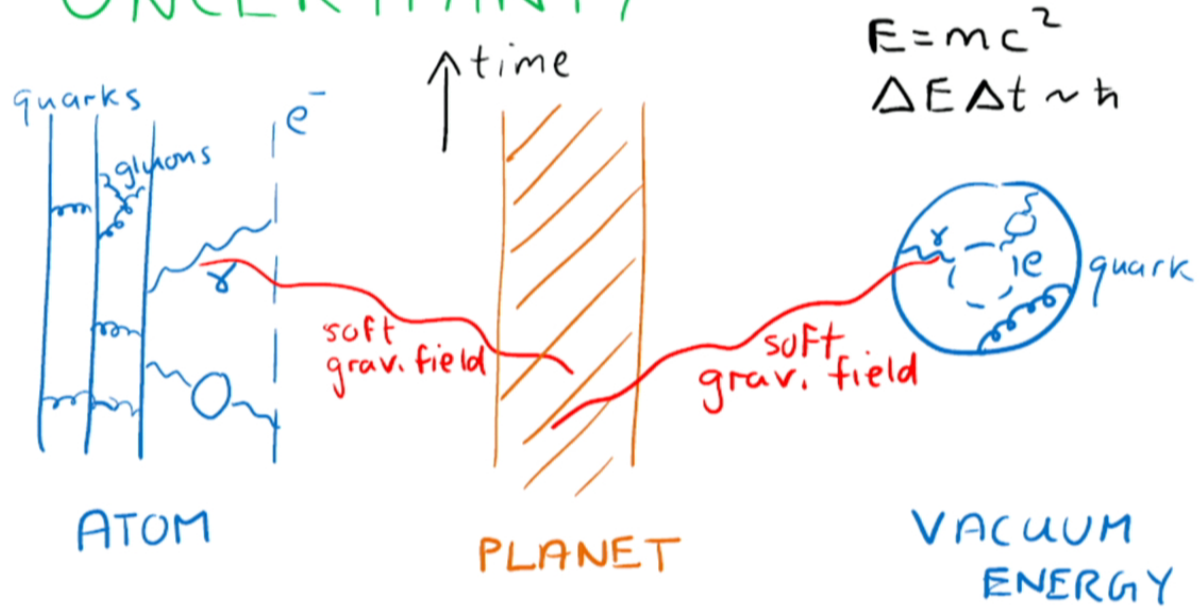
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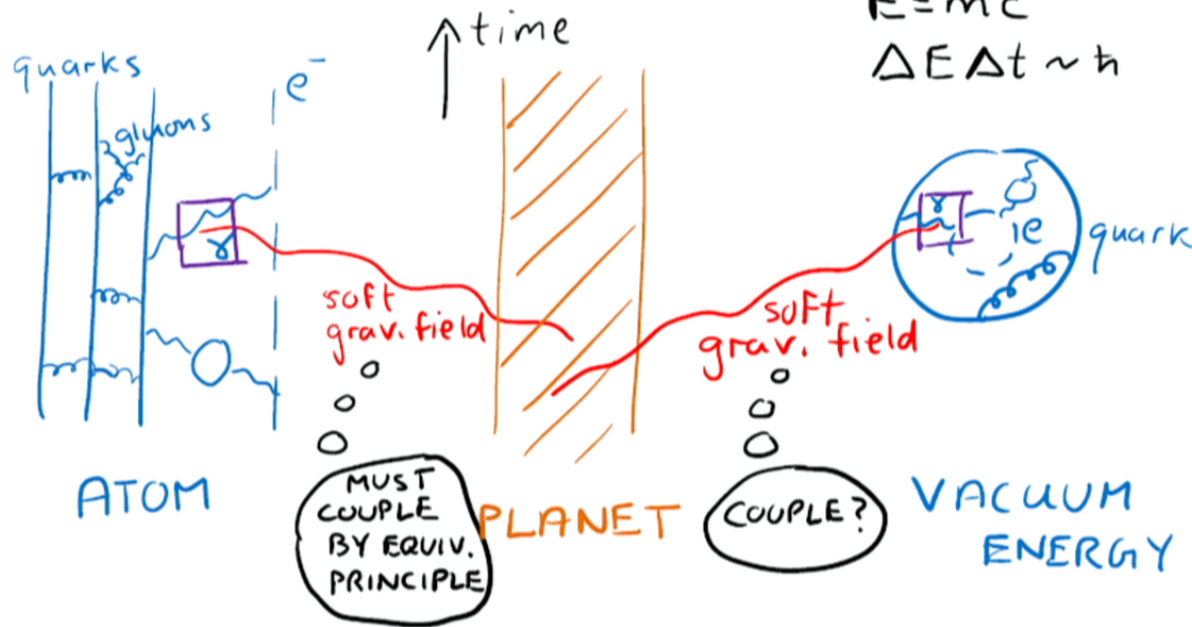
# UNCERTAINTY



# UNCERTAINTY & HARD CHOICES

$$E=mc^2$$

$$\Delta E \Delta t \sim \hbar$$

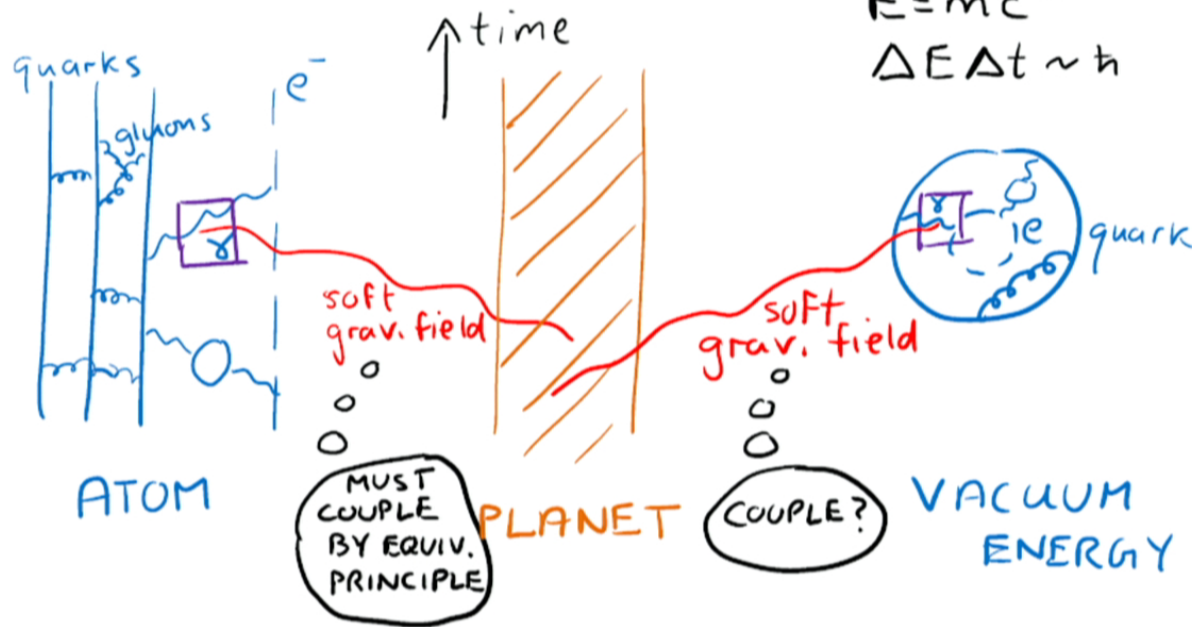


SOFT GRAV. FIELD  $\ni$  SOFT GRAVITONS, BUT  
WITH POINTLIKE COUPLINGS  
MUST COUPLE TO VACUUM ENERGY<sup>17</sup>

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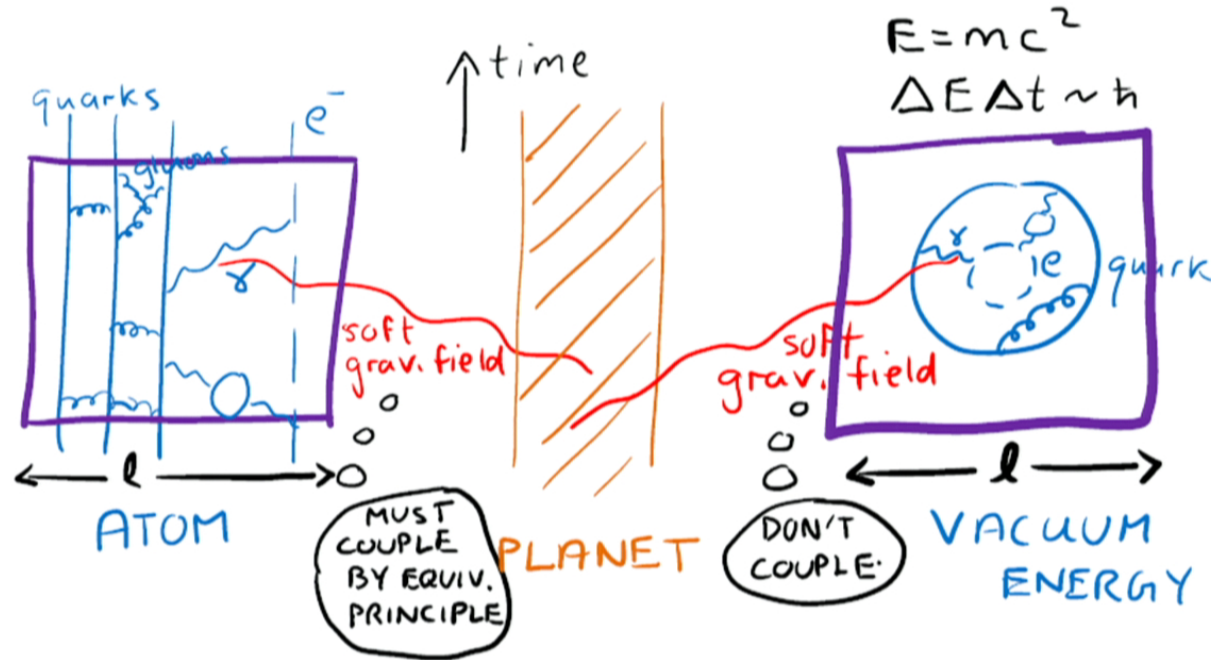
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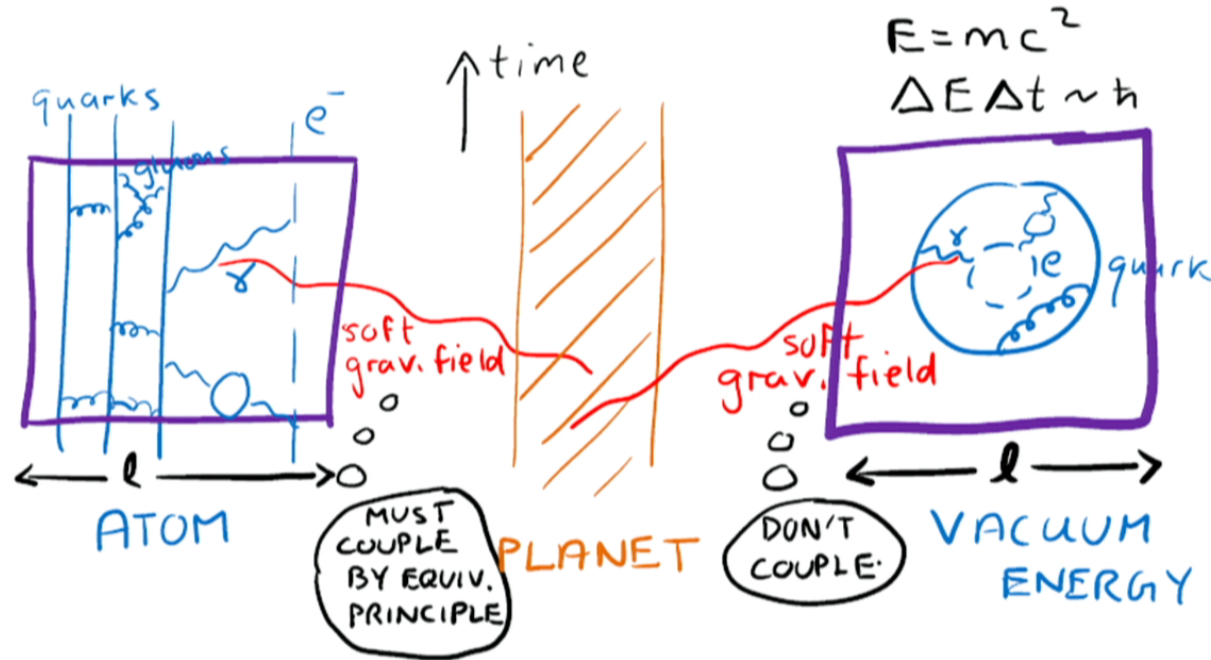


# SOFT POWER



If graviton coupling spread out over distance  $l$ , it can filter out most UV vacuum energy  $\Rightarrow P_{\text{vacuum}} \sim 1/l^4$  Example: string theory  $l \sim l_{\text{string}}$

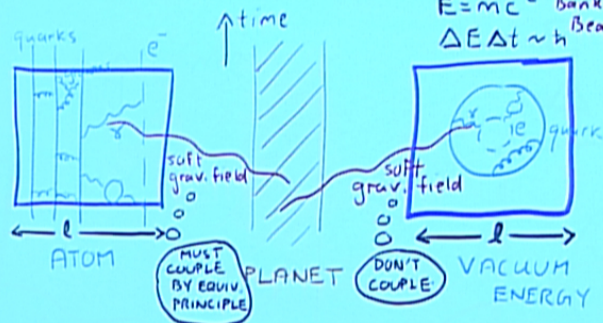
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# FAT GRAVITON

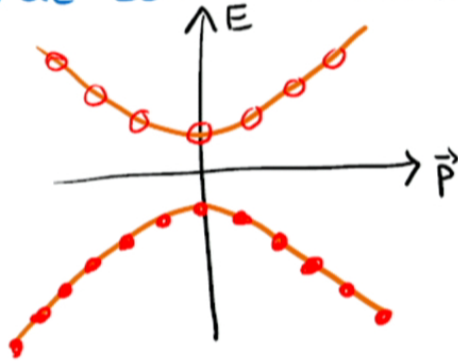
Sundrum '97; '03  
 earlier related:  
 $E=mc^2$  Banks '88  
 $\Delta E \Delta t \sim \hbar$  Beane '97



$P_{\text{Dark Energy}} \sim \text{meV}^4 \Rightarrow l_{\text{grav}} \sim 10 \mu\text{m} \gg l_{\text{matter}} < 10^{-18} \text{m}$   
 not standard string theory  
 don't have concrete model

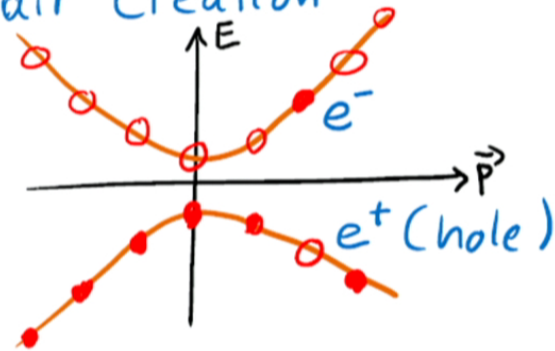
# SYMMETRY FOR COSMOLOGICAL CONSTANT?

Dirac Sea = Vacuum



$$E = \pm \sqrt{\vec{p}^2 + m^2}$$

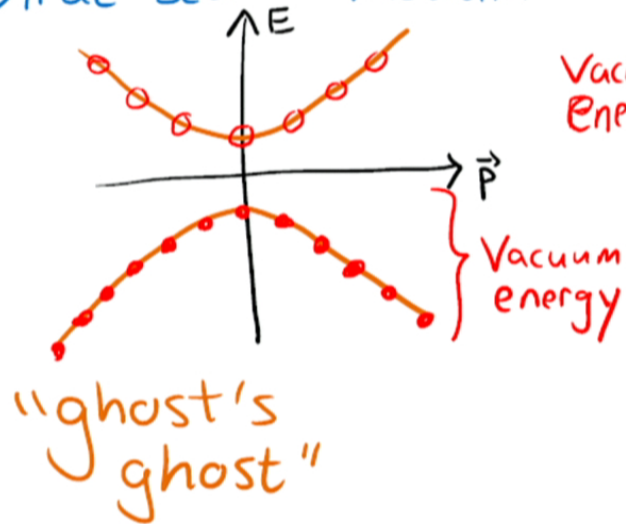
Pair Creation



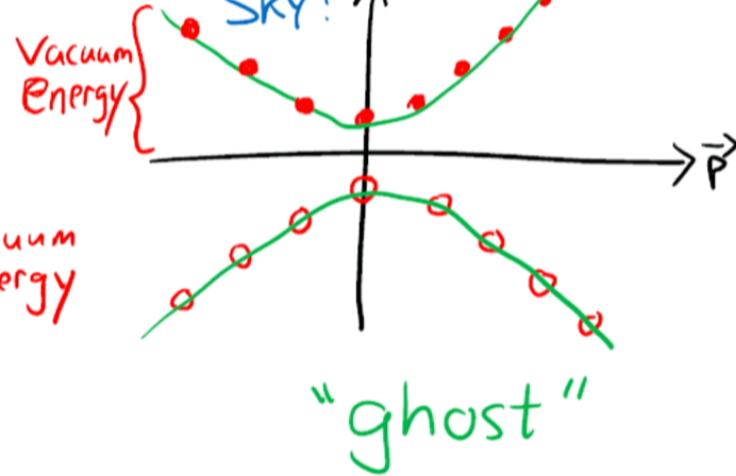
$$\Delta E > 2mc^2$$

# SYMMETRY FOR COSMOLOGICAL CONSTANT

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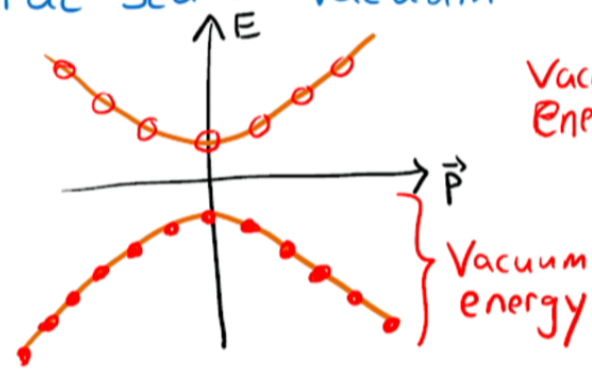


Dirac SKY!



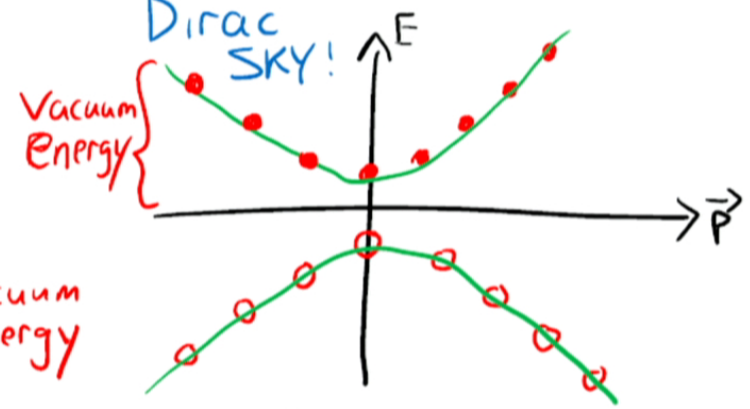
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Dirac Sea = Vacuum



"ghost's ghost"

Dirac SKY!



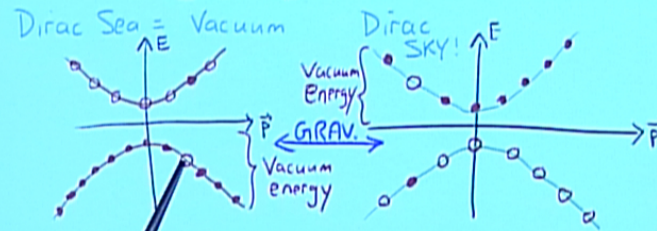
"ghost"

Discrete Energy-Parity Symmetry

Kaplan, Sundrum '05  
based on earlier classical Linde '84

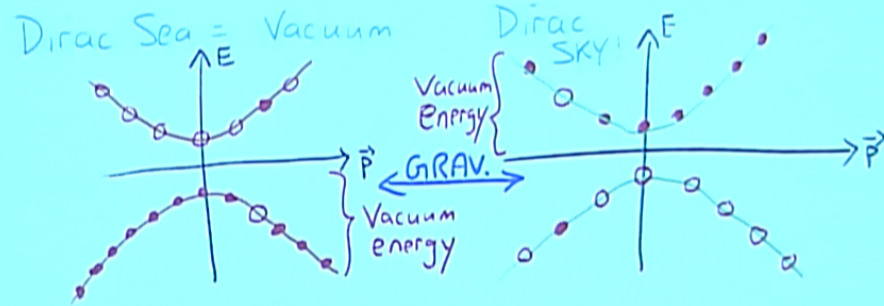
⇒ Vacuum energy cancellation<sup>24</sup>

# SYMMETRY FOR COSMOLOGICAL CONSTANT



Unorthodox "vacuum" stable only if standard & ghost sectors decoupled. But gravity must connect them.  $\Rightarrow$  Vacuum Decay.

# VACUUM DECAY $\Rightarrow$ LORENTZ VIOLATION



$\rightarrow$  particle  
 $\rightarrow$  grav.  
 $\rightarrow$  ghost particle

Phase space integral includes  $\int$  c.o.m. frame  
 $= \infty$  if Lorentz-invariant laws

$\Rightarrow$  EMERGENT RELATIVITY  
 UV ~~LORENTZ~~

Cosmic ray bounds  $\Rightarrow \Lambda_{UV} < \text{few MeV}$  Cline, Jeon, Moore '03



# GHOST OF NEWTON

$$L_{\text{non-rel.}} = \frac{1}{2} m_1 \dot{\vec{r}}_1^2 + \frac{1}{2} m_2 \dot{\vec{r}}_2^2 + \frac{G_N m_1 m_2}{|\vec{r}_1 - \vec{r}_2|}$$

$m > 0$  regular particle

$m < 0$  ghost particle

$$m_1 = -m_2$$

$\uparrow t$



Simple inflation mechanism can explain absence of ghosts today.

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# SIMPLER ANALOGY

Sundrum '03

Special  
Relativity

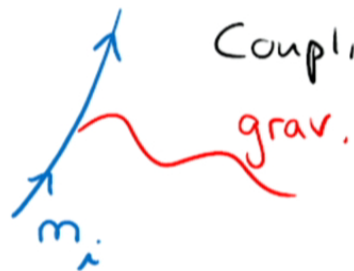
Equivalence  
Principle  $\frac{1}{r^2}$

Nordstrom (Scalar)  
Gravity Nordstrom 1907  
= Curved Spacetime (too)  
Einstein, Fokker 1913

EMERGENT EQUIV. PRINCIPLE not exact!

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# DEVIATIONS FROM EQUIVALENCE PRINCIPLE (in Scalar Gravity) NOT REAL WORLD!!


 Coupling =  $\frac{m_i}{M_{Pl}} (1 + \epsilon_i)$ ,  $\epsilon_i \ll 1$

$\Rightarrow \rho_{\text{dark energy}} \sqrt{-g} \sim \Lambda^4 a^4(t) - \Lambda^4 a^{4-\epsilon}(t)$

Rattazzi, PLANCK '10 talk  
 Coradeschi, Lodone, Pappadopoulos, Rattazzi,  
 Vitale '13  
 Sundrum, Agrawal, to appear

↑ Cosmological scale  
 factor of expanding  
 Universe

$\Rightarrow a_{\text{min.}} \sim \left(\frac{\Lambda^4}{\Lambda^4}\right)^{1/\epsilon}$

near which  $\rho_{\text{dark energy}} \sqrt{-g} \sim \epsilon \Lambda^4 a^4 \ln a / a_{\text{min.}}$

# ~~EQUIVALENCE~~ SIGNALS SUGGESTED BY ANALOGY

Very small deviations, anomalous accelerations.

But significant impact on gravity / structure on largest length scales of Universe

In scalar gravity,  $w \equiv -\frac{p}{\rho} = -1 + \frac{1}{\underbrace{\ln \epsilon}_{\%}}$

# CONCLUSIONS

"Dark energy" may well be fine-tuned cosmological constant (perhaps via anthropic selection in Multiverse), & GR very standard.

[Other long wavelength physics still interesting]

More ambitiously, there may be a deep mechanism at work. Theory is still poor. Experiments in short distance gravity, ~~Lorentz~~, ~~Equivalence~~, dark energy equation of state, largest structures... might lead the way!

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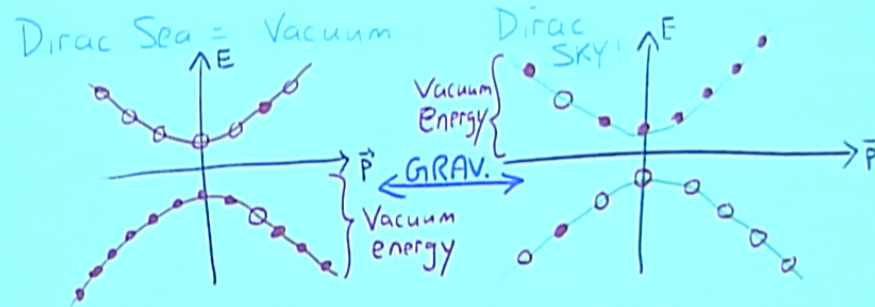
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GRAVITY  $\Rightarrow$  ~~weak ENERGY-PARITY~~



Gravity itself a quantum field,  
 either a ghost or regular,  
 asymmetrizing physics.  $\rho_{\text{vacuum}} \sim \text{meV}^4$   
 $\sim \Lambda_{\text{UV}}^4 / M_{\text{Pl}}^2 \Rightarrow \Lambda_{\text{UV}} \sim 10 \text{ MeV}$