Title: The Accelerating Universe: Landscape or Modified Gravity?

Date: Feb 28, 2008 04:00 PM

URL: http://pirsa.org/08020046

Abstract: The most remarkable recent discovery in fundamental physics is that the Universe is undergoing accelerated expansion. A proper understanding of its physical origin forces us to make a hard choice between dynamical and environmental scenarios. The former approach predicts the existence of a new long distance physics in the gravitational sector, while the second relies on the vast landscape of vacua with different values of the cosmological constant. I will discuss achievements and shortcomings of both approaches, and illustrate them in the concrete examples.

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho_0}{M_{Pl}^2}\left(\frac{\Omega_m}{a^3} + \Omega_\Lambda\right)$$

$\Omega_m \sim 0.3$ $\Omega_\Lambda \sim 0.3$ $\rho_0 \sim 10^{-122} M_{Pl}^4$

How to calculate ρ_Λ ?

Why $\Omega_\Lambda \sim \Omega_m$ now ??

Very roughly:

- Modified Gravity: we are trying to save the wrong eq. by adding more and more terms (also DM?)
- Landscape: these questions are not the relevant ones (like calculating a distance from the Earth to the Sun)

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Roughly:

Modified Gravity

- Smth. (symmetry/graviton compositeness) shields vacuum energy either completely, or at least down to $\Lambda_{UV} \sim (0.1\,\mathrm{mm})^{-1}$
- Cosmological acceleration is either due to remaining part, or due to change of gravity in IR

Not too concrete at the moment

Hard to come up with <u>consistent</u> IR modifications of gravity. A reasonable strategy is to try and see what comes out.

New physics in IR $\Rightarrow$ rich phenomenology

Let's see how it works in practice...

Massive Gravity

$$S = M_{Pl}^2 \int d^4x \sqrt{-g} \left(R + m_g^2 F(g_{\mu\nu}, \partial_\lambda) \right)$$

The only condition: flat (de Sitter) space is a solution

NB: Mass term breaks diffs, but a residual subgroup may survive:

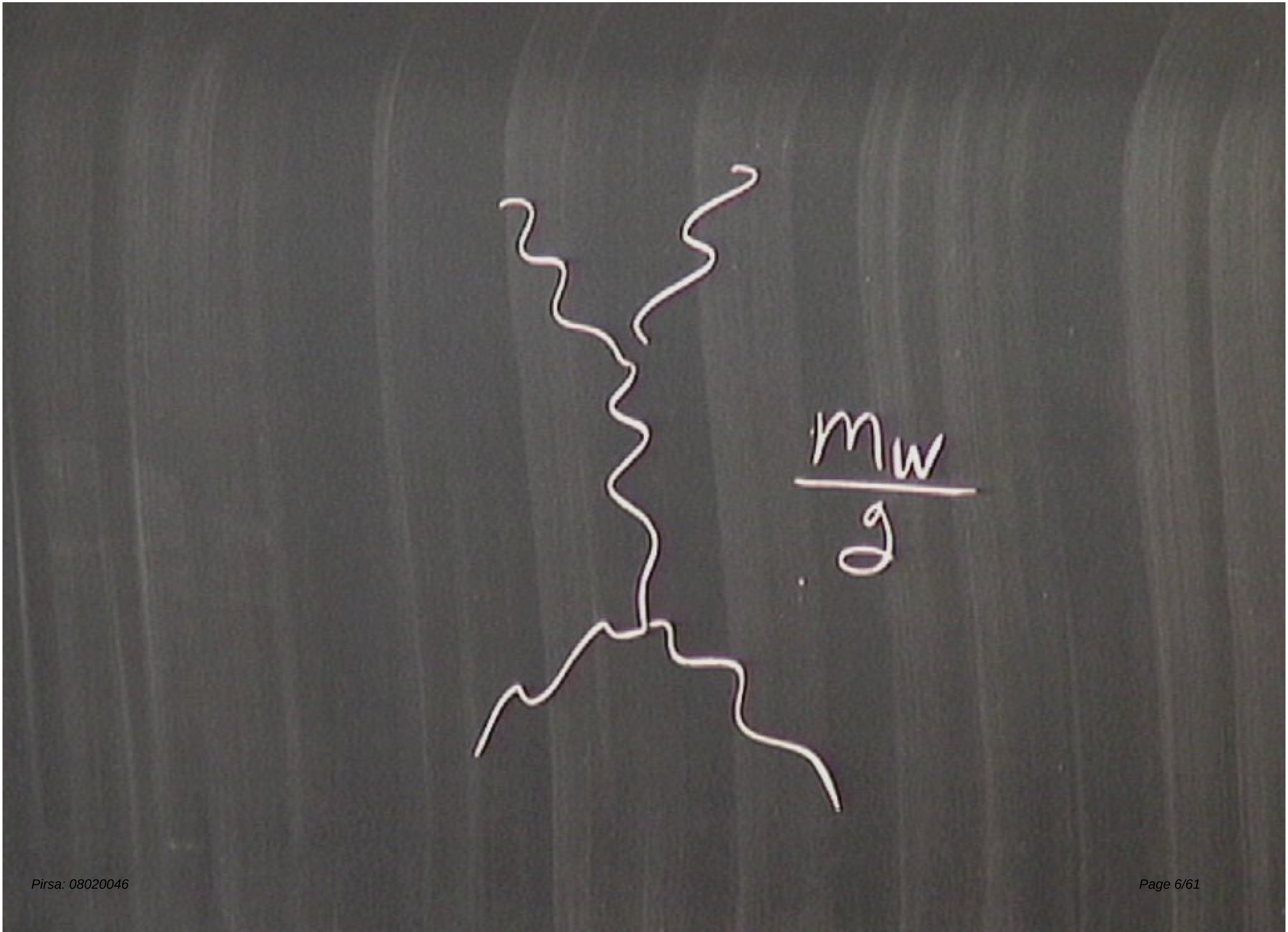
$$x^\mu \rightarrow x^\mu + \xi^\mu(x)$$

Analogy with non-Abelian gauge fields suggests that one has a chance to obtain an effective theory valid up to

$$\Lambda_{UV} \sim \sqrt{m_g M_{Pl}}$$

What are the symmetry breaking patterns, such that this is true?

$\Lambda_{UV} \sim (0.1 \text{ mm})^{-1}$ for $m_g \sim (10^{28} \text{ cm})^{-1}$


$\frac{m_w}{g}$

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Covariant Description

rkani-Hamed, Georgi, Schwartz'02
D'04

$$S = M_{Pl}^2 \int d^4x \sqrt{-g} \left(R + m_g^2 F(\partial_\lambda \phi^\alpha, \ldots) \right)$$

ϕ^α - four scalar fields

Vacuum

$$\phi^\alpha = x^\alpha$$
$$g_{\mu\nu} = \eta_{\mu\nu}$$

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ϕ^α - four <u>scalar</u> fields

Vacuum
+
perturbations

$$\phi^\alpha = x^\alpha + \pi^\alpha$$
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Unitary gauge $\pi^\alpha = 0 \quad \Rightarrow$ "Back" to massive gravity

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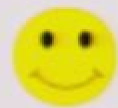
This is a Lagrangian description of a relativistic (super)fluid with

$$T_{\mu\nu} = 0$$

Residual symmetries that work: SD'04

$$x^i \rightarrow x^i + \xi^i(x^j)$$

or → "and" gives ghost condensate

$$x^i \rightarrow x^i + \xi^i(t)$$  --- graviton is massive

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$$t \rightarrow \lambda t$$
$$x^i \rightarrow \lambda^{-\gamma} x^i$$

--- gets restored during the cosmological evolution

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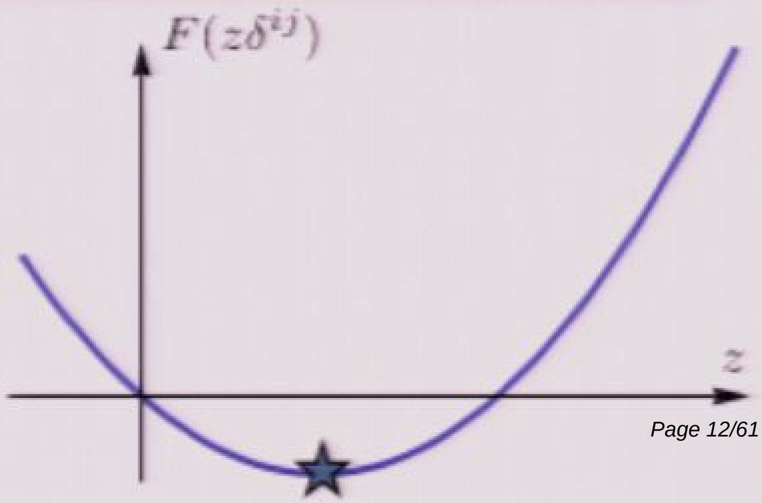
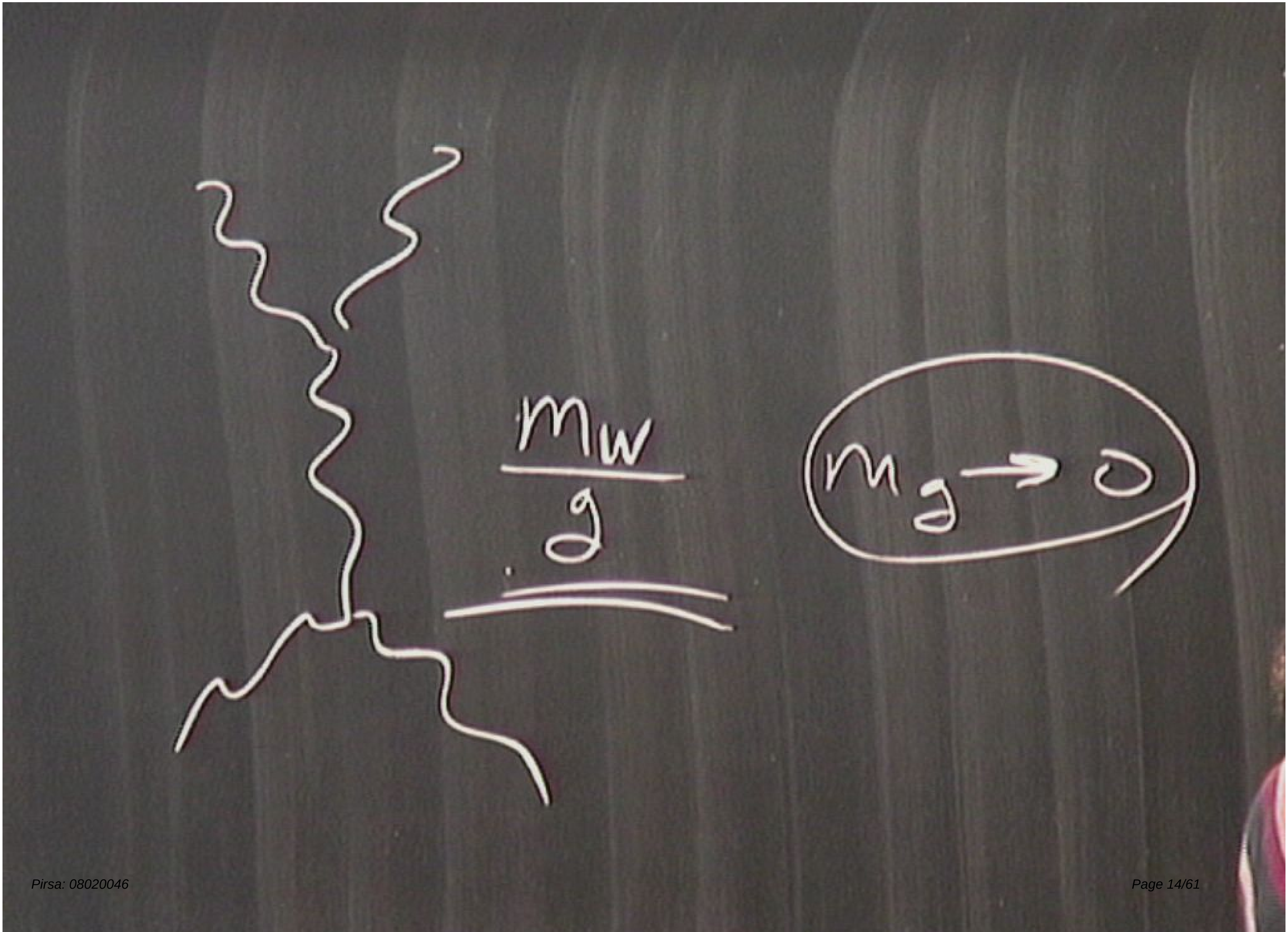
$$\begin{aligned} X &= g^{\mu\nu}\partial_\mu\phi^0\partial_\nu\phi^0 \\ W_{ij} &= G^{\mu\nu}\partial_\mu\phi^i\partial_\nu\phi^j \\ G^{\mu\nu} &= g^{\mu\nu} - \partial^\mu\phi^0\partial^\nu\phi^0/X \end{aligned}$$



Properties of the model

SD'04
SD, Tinyakov, Tkachev'04,'05

- No ghosts or classical UV instabilities
- No vDVZ discontinuity
- Gravitational waves are massive
- Cutoff scale is $\Lambda_{UV} = \sqrt{M_{Pl} m_g}$
- Scalar and vector perturbations are the same as in GR
- Flat cosmological solutions are almost the same as in GR


mw
g
mg → 0

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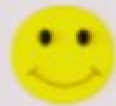

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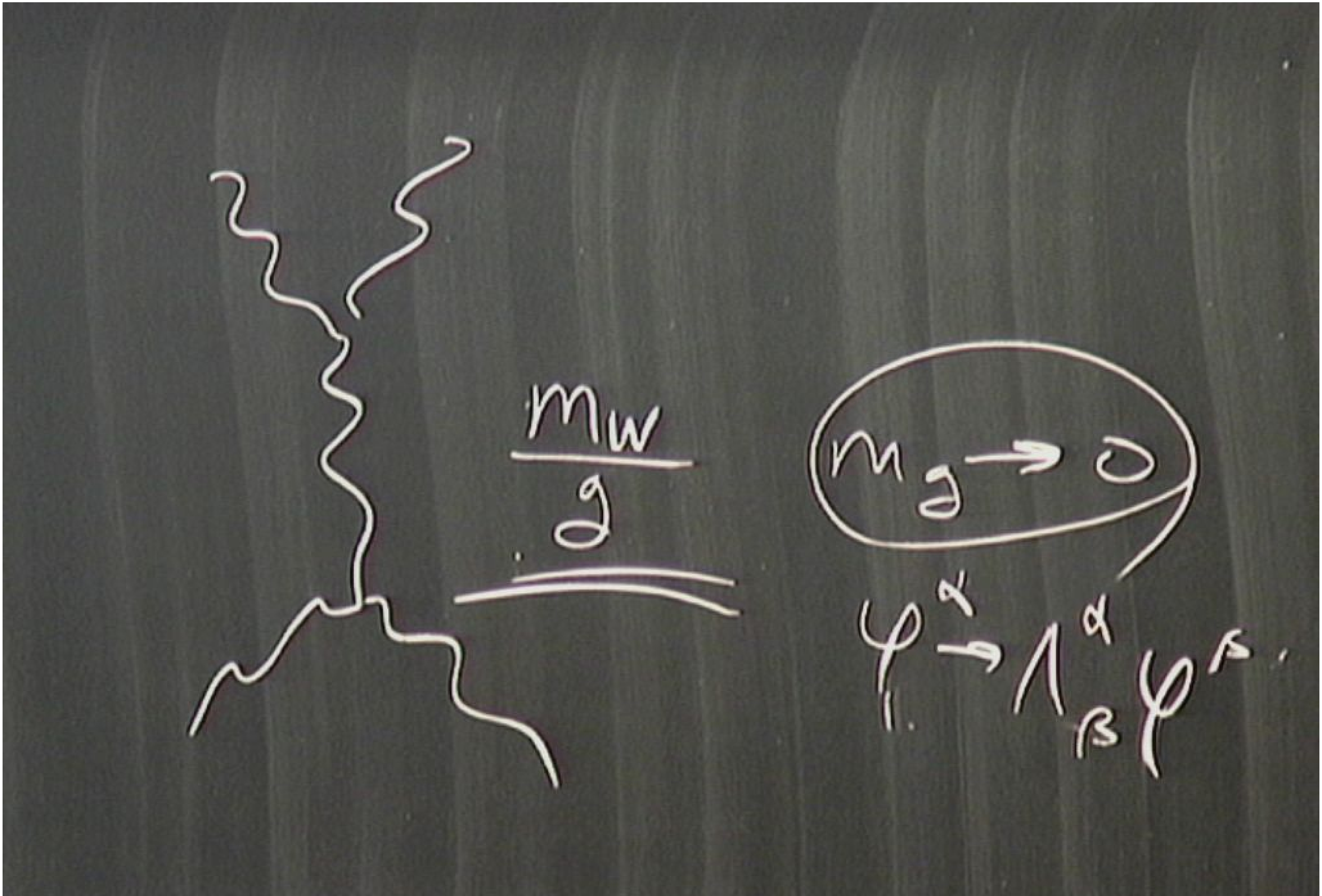
$\frac{m_W}{g}$
$m_g \to 0$
$\varphi^\alpha \to \Lambda^\alpha{}_\beta \varphi^\beta$

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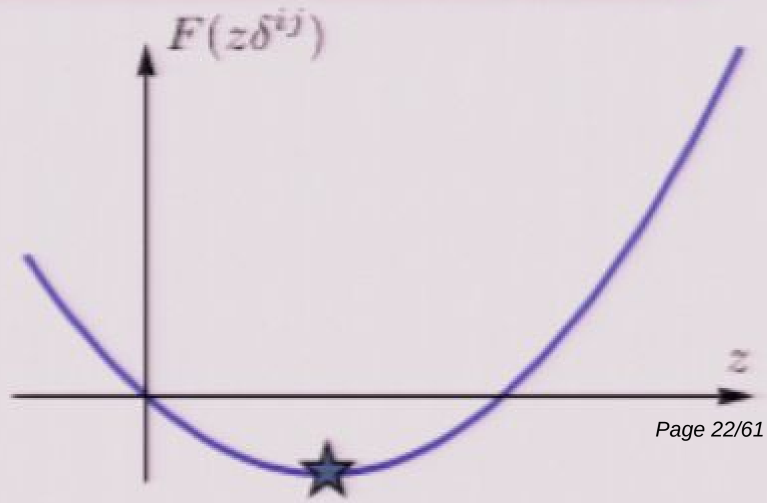

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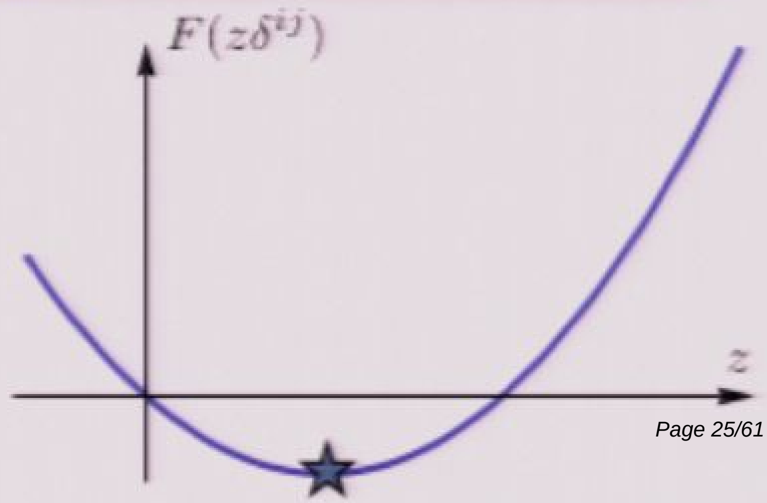

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Cosmology

Ansatz:

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

$$\phi^0 = \phi(t) \quad \phi^i = x^i$$

Cosmological expansion drives the system toward $F' = 0.$

In the vicinity of the attractor one has

$$H^2 = \frac{1}{M_{Pl}^2}\left(\rho_m + \frac{\rho_1}{a^{3-1/\gamma}} + \Lambda_0\right)$$

- Non-conventional source of cosmic acceleration
- "Landscape" at $\gamma = 1/3$

The main conclusion:

Gravitational waves may be "very" heavy

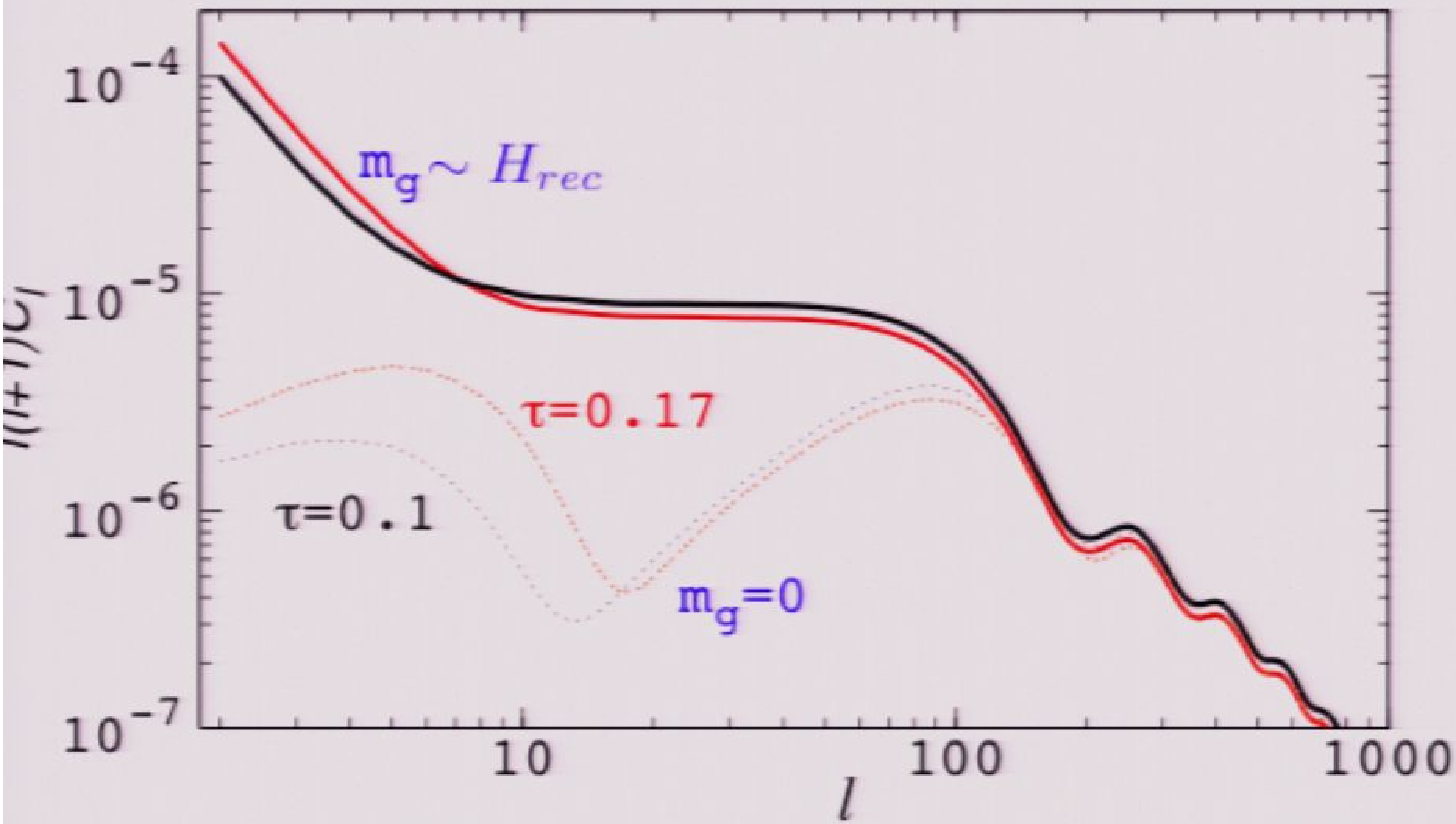
$$\Downarrow$$

Unexpected GW phenomenology

- Upper bound from the binary pulsar timing

$$\frac{m_g}{2\pi} \equiv \nu \lesssim 3 \cdot 10^{-5}\mathrm{Hz} \sim (10\ \mathrm{hr})^{-1} \sim (10^{15}\mathrm{cm})^{-1} \sim 2 \cdot 10^{-20}\mathrm{eV}$$

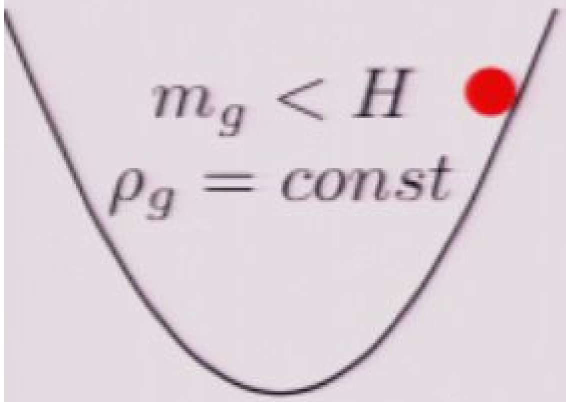
- Sharp cutoff in the GW spectrum
- Time delay between GW and optical signal
- Exotic B-mode spectrum in CMB

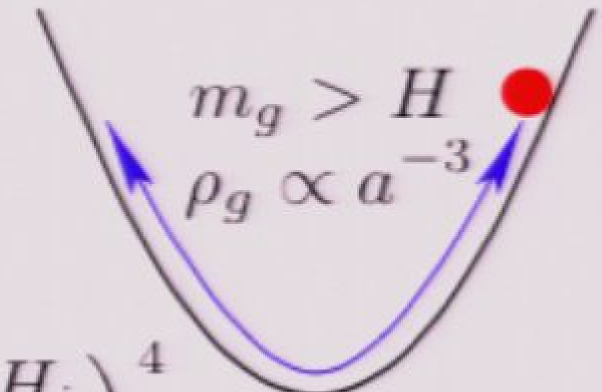


10^{-4}
10^{-5}
10^{-6}
10^{-7}
$m_g \sim H_{rec}$
τ=0.17
τ=0.1
m_g=0
10
100
1000
l

Massive gravitons in the early Universe $(\approx \text{axions})$

$$ds^2 = dt^2 - a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$





$$\Omega_g \sim 3 \cdot 10^3 (m_g \cdot 10^{15}\text{cm})^{1/2} \left(\frac{H_i}{\Lambda}\right)^4$$

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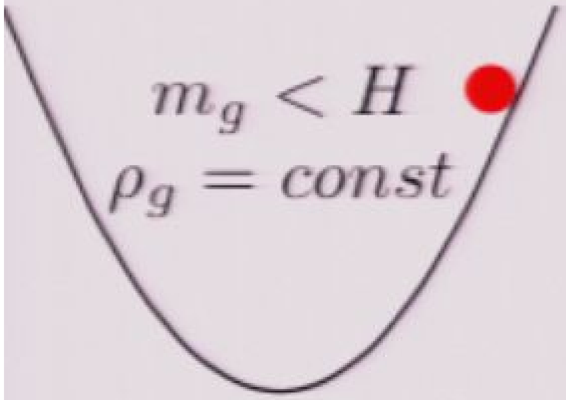

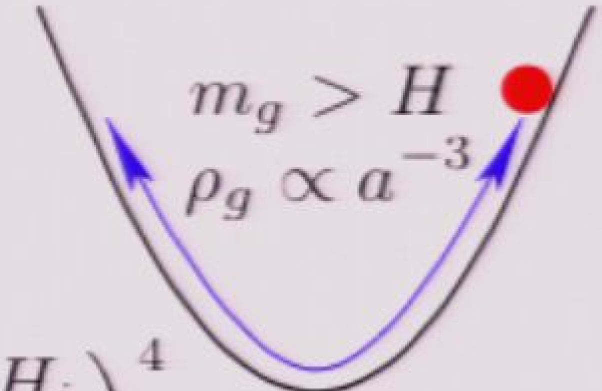

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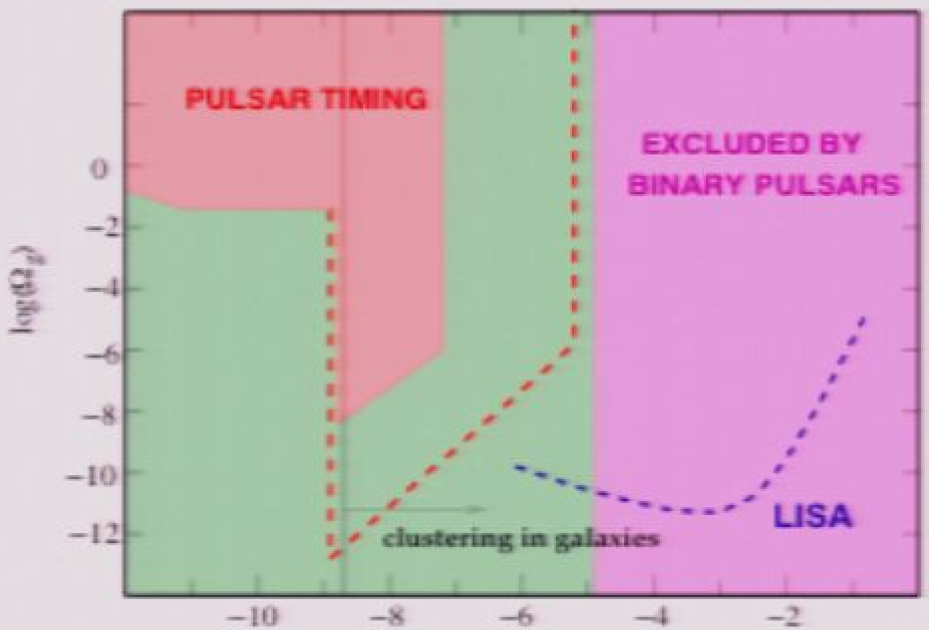
monochromatic
GW signal



Main issue:

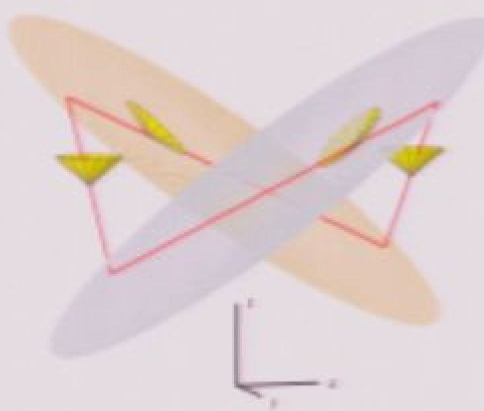
**These are consistent effective field theories.
Is it possible to embed them in a microscopic theory?**

Adams,Arkani-Hamed,SD,Nicolis,Rattazzi'06

Why not?

$$\mathcal{L} = (\partial_\mu\phi)^2 - \frac{1}{\Lambda^4}(\partial_\mu\phi)^4 + \dots$$

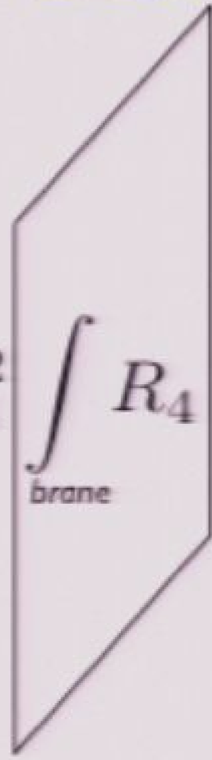
- $2 \to 2$ scattering amplitude has wrong analytical properties
- $\phi = const \cdot t \Rightarrow$ perturbations propagate outside light cone
- Closed time-like curves in more complicated backgrounds



More sophisticated example:

DGP model

Dvali,Gabadadze,Porrati'00



$$S = M_4^2 \int_{brane} R_4 + M_5^3 \int_{bulk} R_5$$

"decoupling" limit

$M_4, M_5 \to \infty$

$\Lambda = \frac{M_5^3}{M_4^2}$ --- fixed

ty,Porrati,Rattazzi'03
icolis,Rattazzi'04

$$\mathcal{L} = (\partial_\mu \phi)^2 + 0 \cdot (\partial_\mu \phi)^4 - \frac{(\partial_\mu \phi)^2 \Box \phi}{\Lambda^3}$$

Same issues...

Adams,Arkani-Hamed,SD,Nicolis,Rattazzi'06

Models above are too unconventional to be killed like that..

For instance, there is no Lorentz invariant vacuum

The closest shot:

SD,Sibiryakov'06

The ground state of our fluid has

$$T_{\mu\nu} = 0 \Leftrightarrow \rho + p = 0$$

$\Rightarrow$ Perturbations can violate the null energy condition

$\rho + p < 0$ ($\approx$ mass can get negative)

What happens with the entropy??

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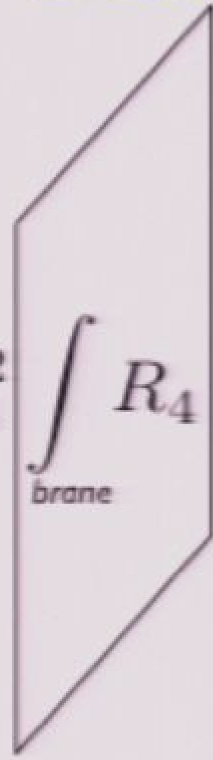

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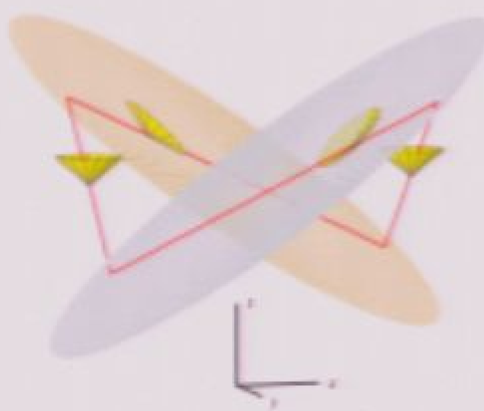

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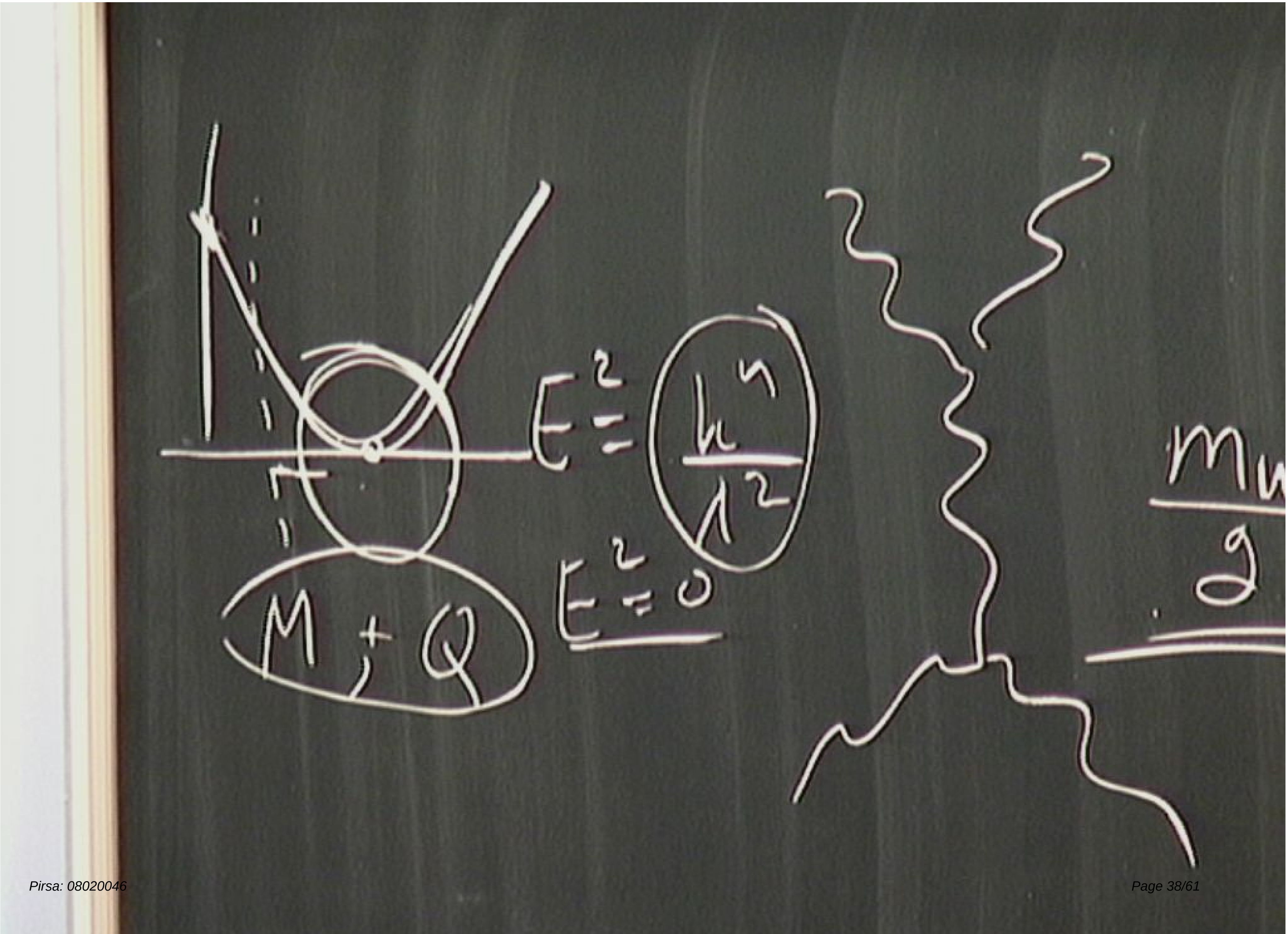
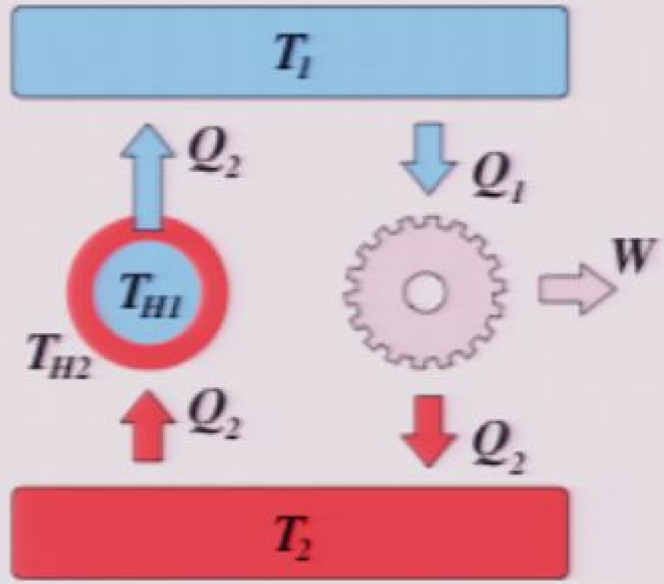

E² = h^n / Λ²
E² = 0
M + Q
m_w / g

Perpetuum Mobile (2nd kind): Construction Manual



$$T_{H1} > T_1 > T_2 > T_{H2}$$

What should we make of this?

- These theories make no sense?
- The only chance is if black holes have hair...

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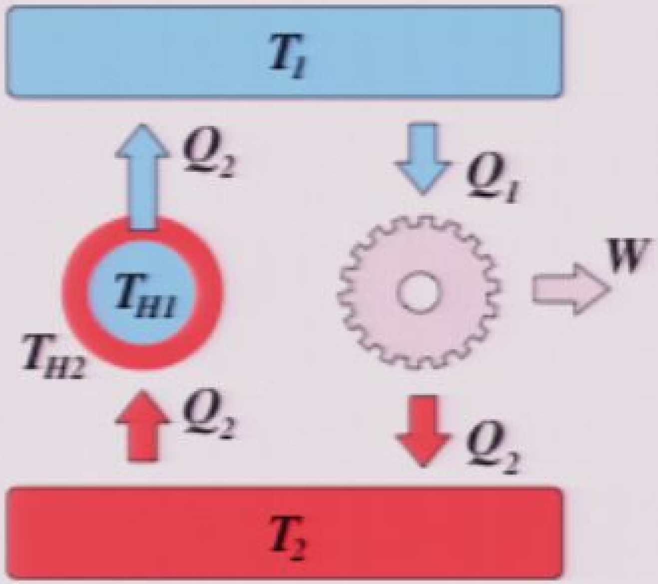

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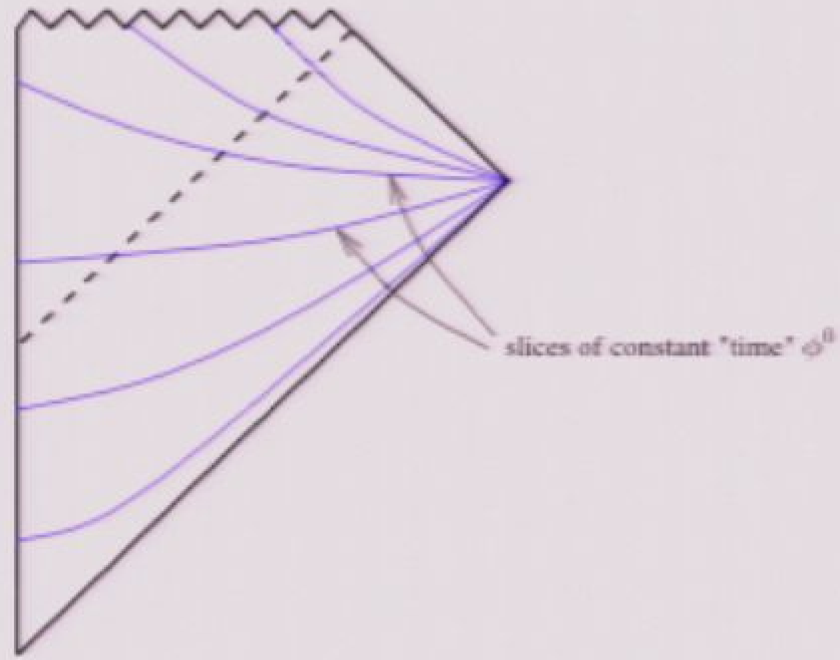
Actually, they do have hair... SD,Tinyakov,Zaldarriaga'07

nstantaneous interactions
long slices of constant ϕ^0

↓

All multipoles are not universal
but depend on the boundary
condition at the singularity



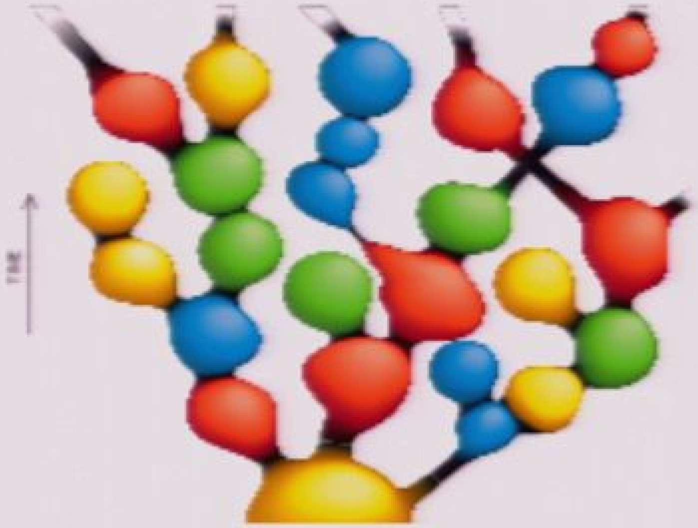
NB: LISA will start "Precision Black Hole Physics"

with Extreme Mass Ratio Inspirals Ryan'97 Hughes'06

Hundreds of events per year. 6-7 multipoles with 1% precision.

At the moment massive gravity models of the type discussed here is the only framework where one may expect surprises.

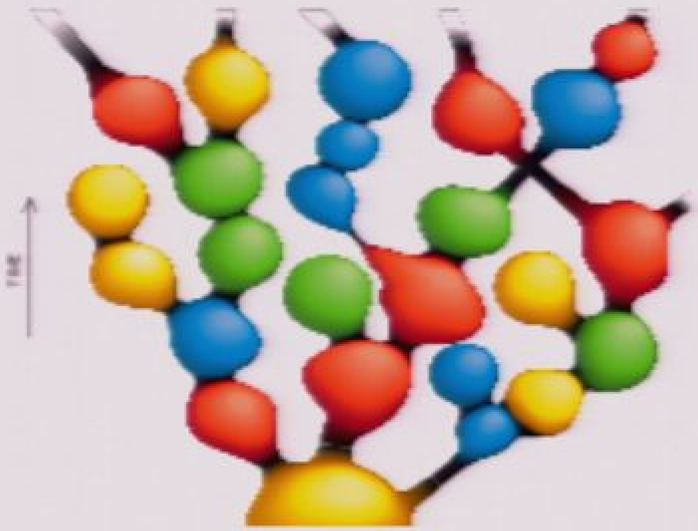
Landscape



or

or even

Landscape



or

or even

In the first approximation solves (eliminates) all CC problems

Forces to talk about causally disconnected regions

$\Downarrow$

Extremely hard to confirm *even in principle*

NB: Easily may be proven wrong: $w_\Lambda \neq -1$, variation of α

Extremely hard to really make sense of

$\Downarrow$

Surprises may be just around the corner...

o get more confidence in this picture:

At the moment, the best we can do is to patiently collect all possible theoretical and observational circumstantial evidence

xample:

The Standard Model Landscape

Arkani-Hamed,SD,Nicolis,Villadoro'07

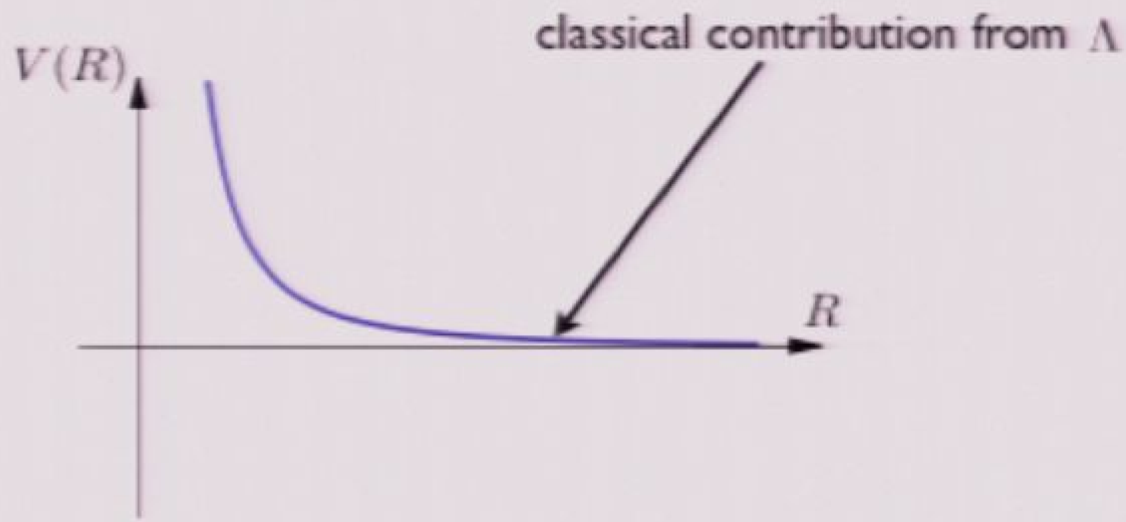
Let's see whether there is a hint of the vast Landscape of vacua in the known IR physics...

$$S = \int d^4x\sqrt{-g}\Big\{M_{Pl}^2 R + \mathcal{L}(\gamma, \nu_i, \ldots) - \Lambda\Big\}$$

Let's proceed as in string/M theory: compactify and look for (meta)stable vacua

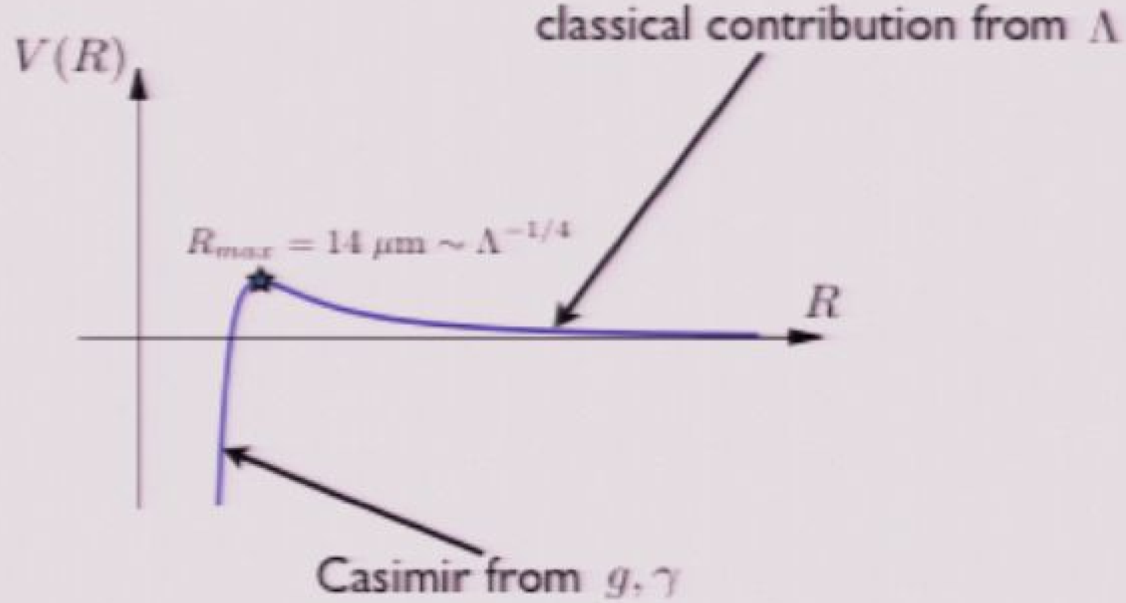
$$ds^2 = \left(\frac{R_0}{R}\right)^2 ds_3^2 - R^2 d\phi^2$$

Radion Potential



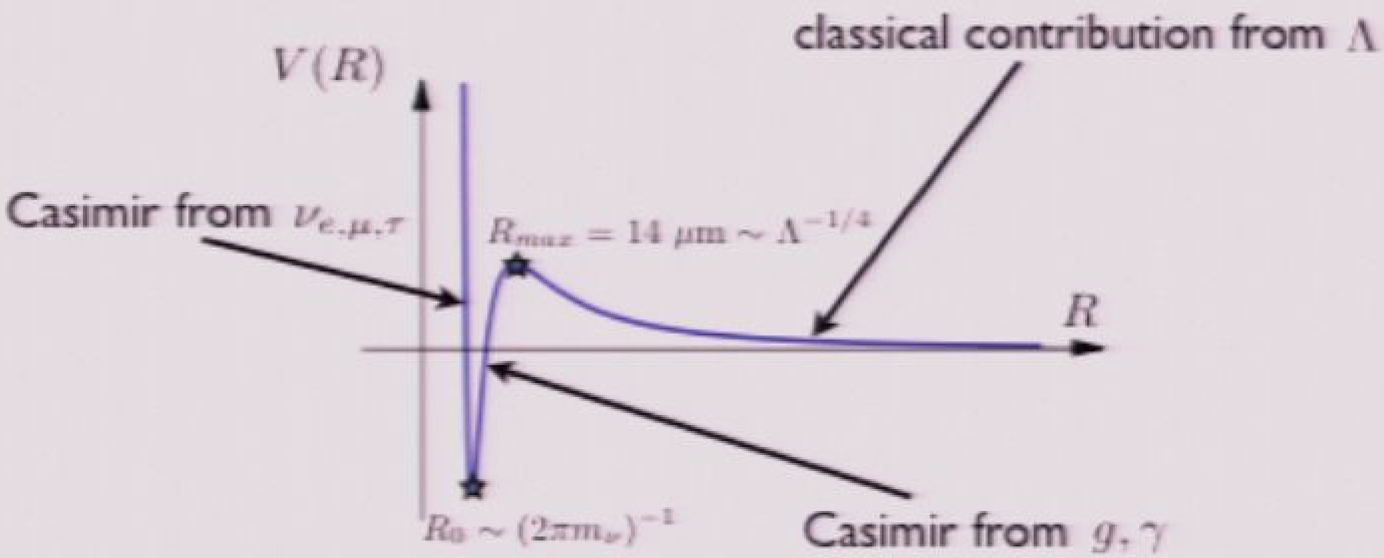
End of story if Λ were natural ($\sim M_{Pl}$)

Radion Potential



Λ is fine-tuned, so quantum effects have a chance to compete

Radion Potential



$m_\nu \sim \Lambda^{1/4}$ so one should take care...

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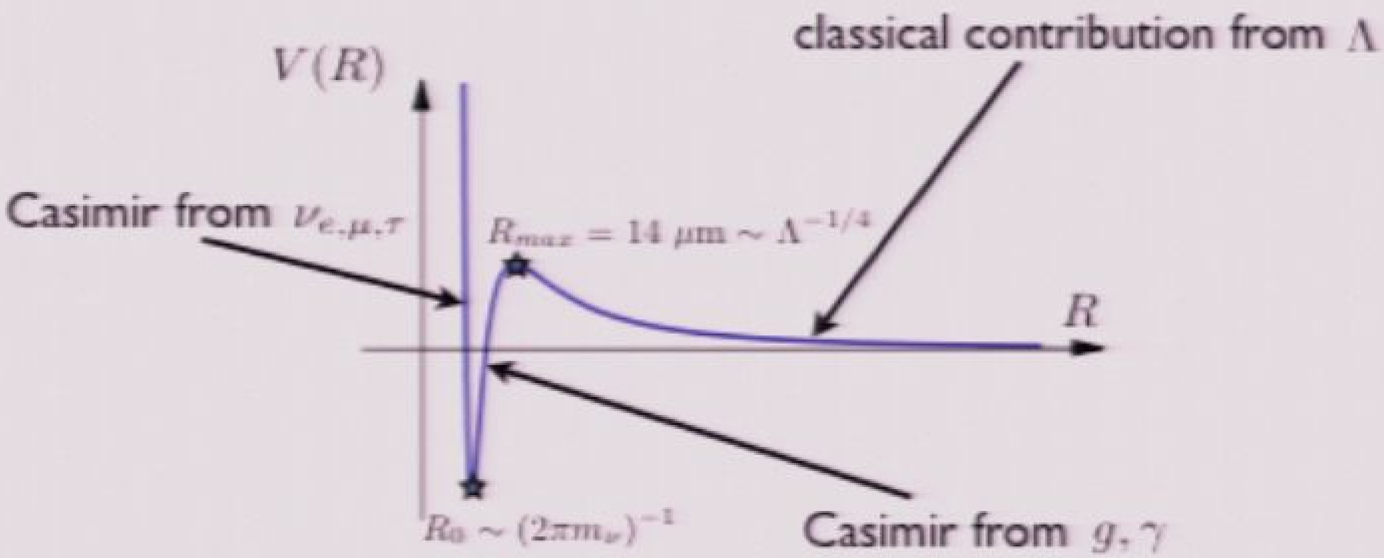

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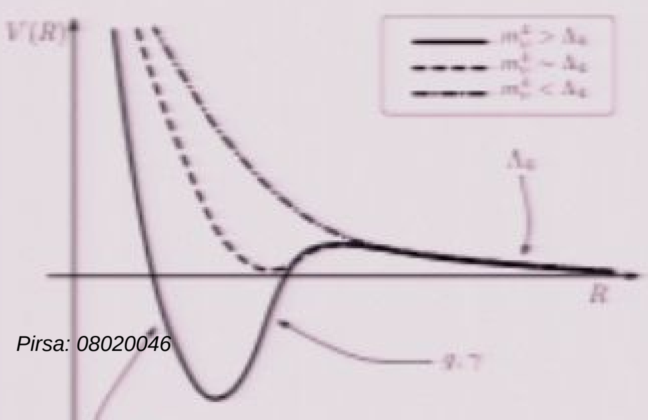
what really matters is a mass of the second lightest neutrino



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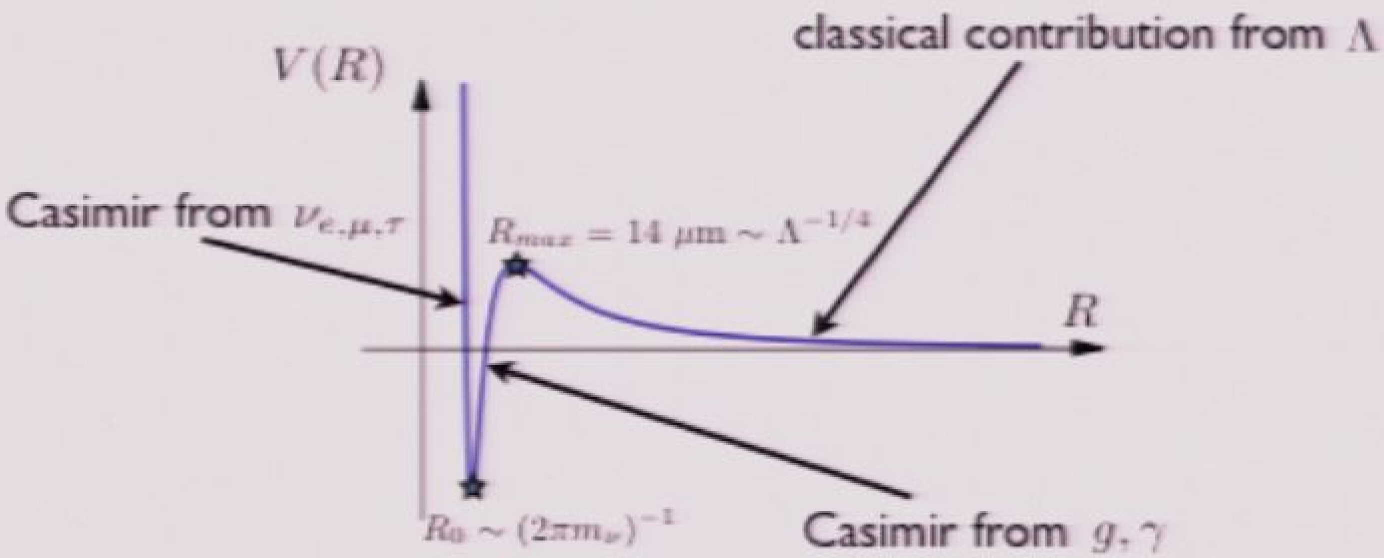

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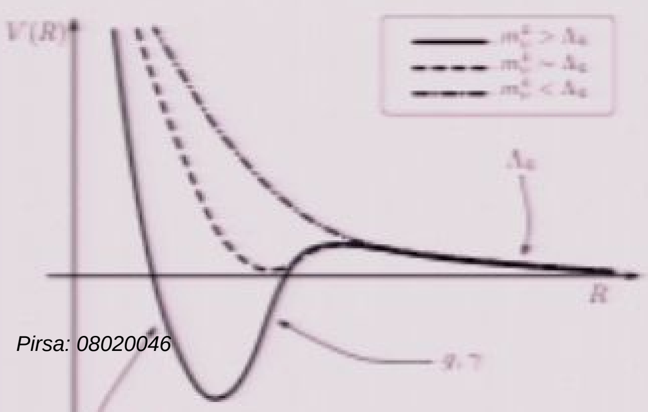
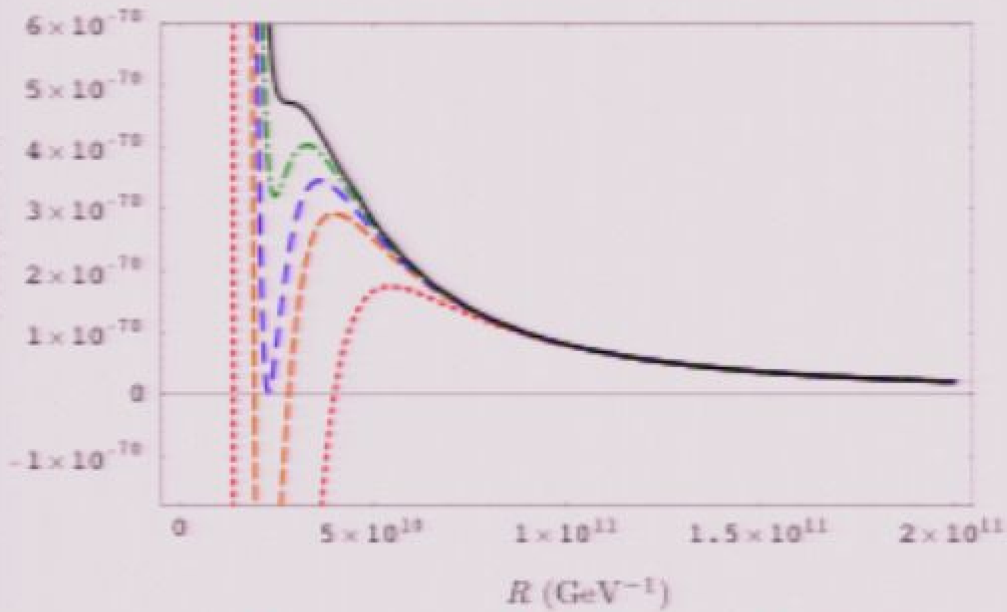


$$\Delta m^2_{\text{atm}} \simeq (1.9 \div 3.0) \cdot 10^{-3}\,\text{eV}^2$$
$$\Delta m^2_{\odot} \simeq (8.0 \pm 0.5) \cdot 10^{-5}\,\text{eV}^2$$
$$\Downarrow$$

in the Majorana case

$$2\pi m_{\nu_2} > (3.5\mu m)^{-1}$$

For Majorana neutrinos $AdS_3 \times S_1$ minimum exists



Trichamoeba sp.

typical habitant of the SM Landscape

$\Delta m^2_\odot = 8.0 \cdot 10^{-5}\mathrm{eV}^2$ (actual value)

$\Delta m^2_\odot = 2.0 \cdot 10^{-5}\mathrm{eV}^2$

$\Delta m^2_\odot = 1.5 \cdot 10^{-5}\mathrm{eV}^2$

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$$2\pi R_0 \approx 20\mu\mathrm{m}$$
$$l_{AdS} \approx 3.7 \cdot 10^{27} cm$$

Photon Wilson line (Aharonov-Bohm flux)

$\Downarrow$

There is a valley with a slope $\propto \mathrm{e}^{-m_e/m_\nu} \sim \mathrm{e}^{-10^8}$

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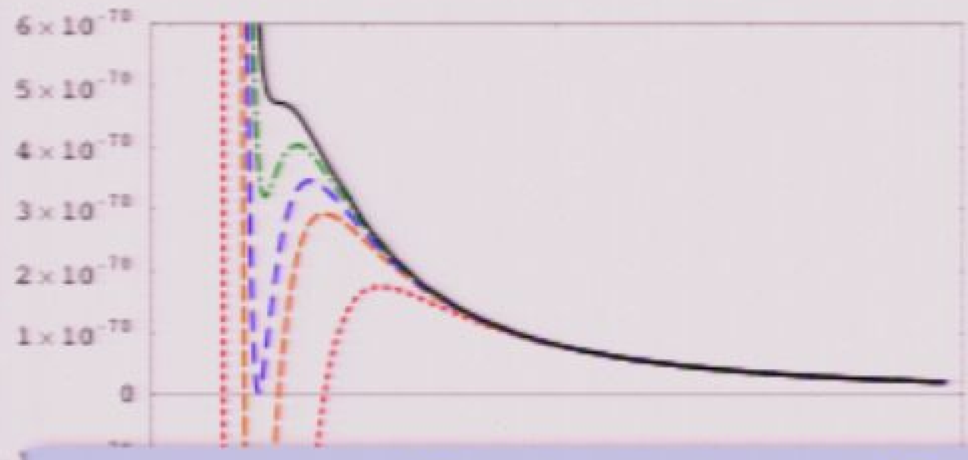

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Casimir is an IR calculable effect.
All this discussion does not rely on any assumptions on the UV.
SM Landscape *does exist in the real world!*

$\Delta m^2_\odot = 1.2 \cdot 10^{-5} \mathrm{eV}^2$

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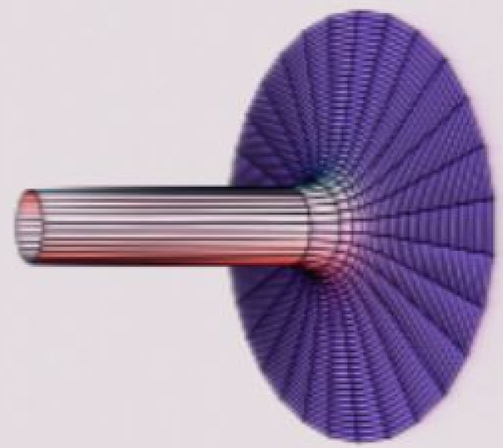
Are these vacua connected to ours?

Extremal Reissner-Nordstrom black holes connect between flat and $AdS_2 \times S_2$ vacua

$$ds^2 = (1 - \frac{r_h}{r})^2 dt^2 - \frac{dr^2}{(1 - \frac{r_h}{r})^2} - r^2 d\Omega_2^2$$



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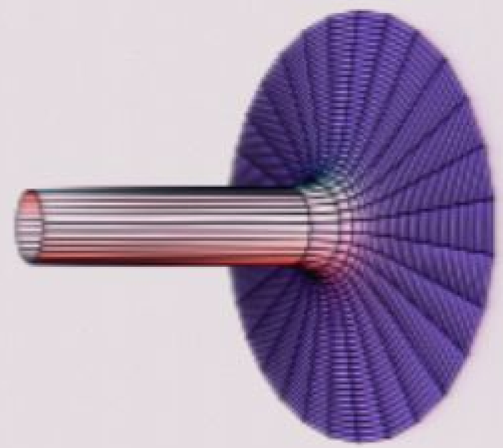
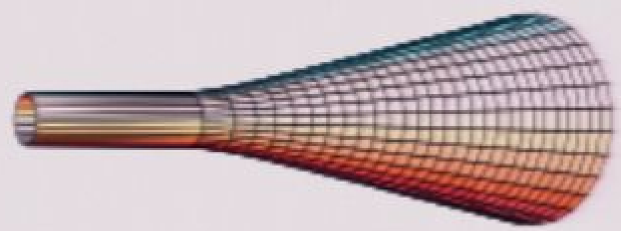


New "quantum" black strings interpolate to neutrino vacua

$$ds^2 = f^2(r)(dt^2 - dx^2) - h^2(r)dr^2 - \epsilon \cdot r^2 d\phi^2$$

tiny opening angle $\theta \sim \frac{m_\nu}{M_{Pl}}$



Does a naive picture of the Landscape makes sense?

BH: after $t = t_{ev} \sim r_s^3 M_{Pl}^2$ global description breaks down and information comes out

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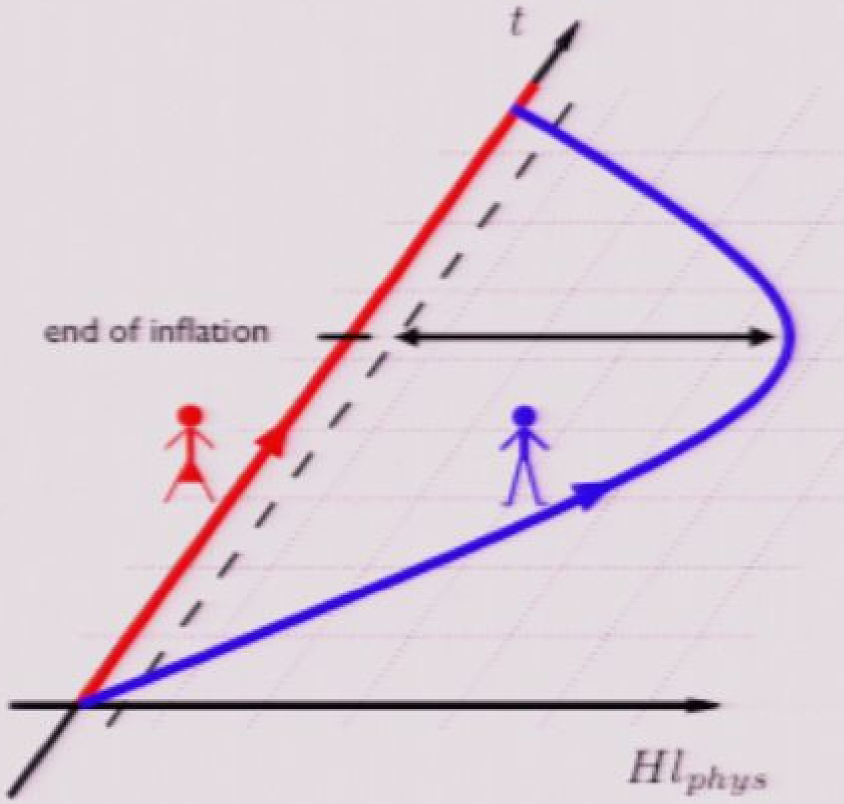
BH: after $t = t_{ev} \sim r_s^3 M_{Pl}^2$ global description breaks down and information comes out

- Global description fails in the dS case as well after $t \sim H^{-3} M_{Pl}^2 \Leftrightarrow N_e = S_{dS}$ e-foldings?

- Information comes out of the dS horizon after that time??

These ideas would be trivially wrong if inflation could last for an arbitrary large number of e-foldings, without ever being eternal



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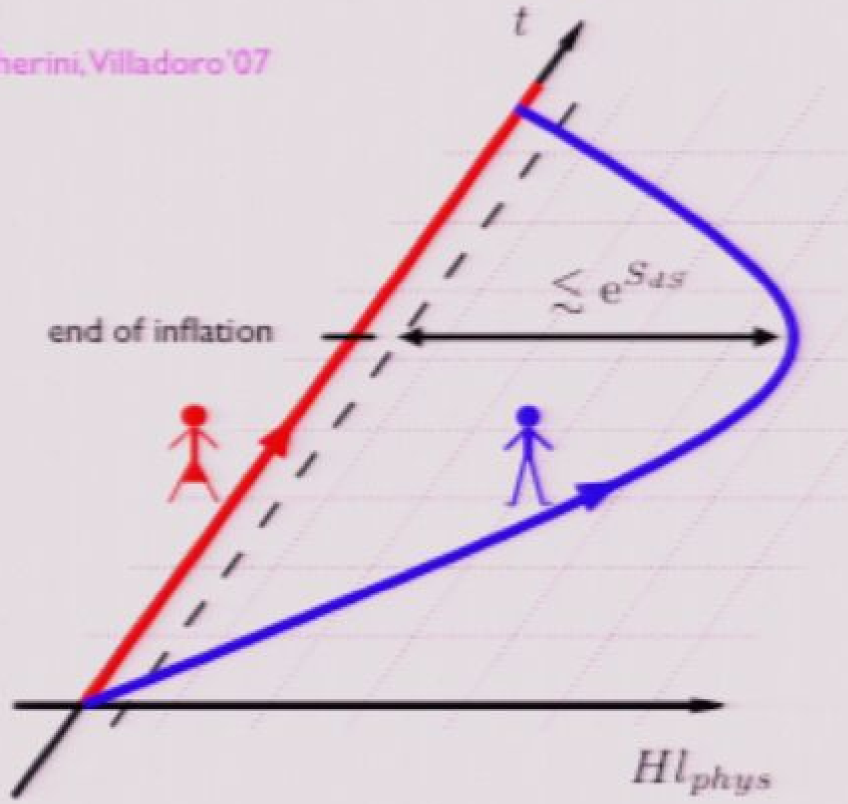
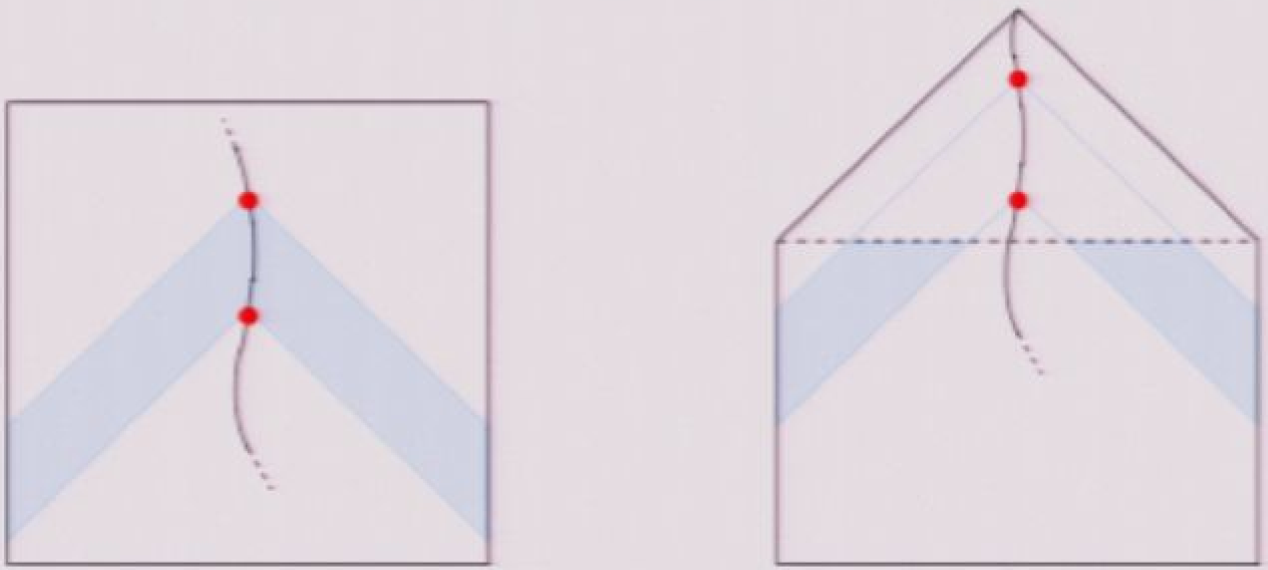


However, if non-eternal inflation preserves NEC, it satisfies

$$N_e \lesssim S_{dS}$$



Effective field theory properly describes spacetime regions only for spacetime volumes smaller than

$$H^{-4}e^{S}$$

Eternal de Sitter ⟶ Poincare recurrence time

Slow roll inflation ⟶ Our bound

Modified Gravity	Landscape
Eventually pretends to solve CC	‣Eliminates CC
Consistent effective field ıeories...UV completion???	‣Present in ST, not clear how to deal with
Rich phenomenology	‣Hard to confirm, surprises may be around the corner

It's encouraging that in both cases the most important issues are related to the same set of questions: BH thermodynamics, physics of horizons...

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MG trivializes this physics, while the naive picture of the Landscape ignores it. Perhaps the truth is in between?