Title: Modifying Gravity in the Infra-Red by imposing an Ultra-Strong equivalence principle.

Date: May 27, 2009 03:45 PM

URL: http://pirsa.org/04050000

Abstract: I will give account of a work in progress in which I attempt to modify the metric-manifold structure of GR in the infra-red. The proposed modification does not contain any massive parameter as it is effective at length scales comparable with the inverse (extrinsic) curvature. The guiding line for this modification is an "ultra-strong" equivalence principle, according to which even semi-classical gravitational effects (i.e. particle production) are definitely banned from a sufficiently small free-falling elevator. Some cosmological consequences of this modification will be discussed.

Basic Idea: FP, arXiv:0904.4299

Cosmological Implications: FP, to appear

Modifying Gravity in the Infra-Red with an Ultra-Strong Equivalence Principle

Federico Piazza

Invitation: a very well established paradigm...

$$S = \int \sqrt{g}\,\left(R + \mathcal{L}_{matter}\right)$$

Common wisdom:

- We can trust the above up to the semi-classical/low energy effective level
- The only problem with the above is its UV-completion

Invitation: a very well established paradigm...

$$S = \int \sqrt{g}\,(R + \mathcal{L}_{matter})$$

However

There are few UV-insensitive difficulties:

- CC problem
- BH information paradox
- Cosmology (two epochs of accelerating expansion, fine tunings etc...)

IR modification of a very well established paradigm

$$S = \int \sqrt{g}\,(R + \mathcal{L}_{matter})$$

Small scales approximation

Recipe:

- No new mass parameter (Take GR itself as an example)
- IR scale: the curvature! (the Universe looks accelerating at that scale...)
- Start from semi-classical gravity and modify the matter-field operators in the IR. Effectively: breakdown of the metric manifold on large scales.
- Any ``principle"?

Outline

- Introduction, the Ultra-Strong equivalence principle, strategy.
- Modifying the Fourier Modes
- A look at the global picture
- Cosmology

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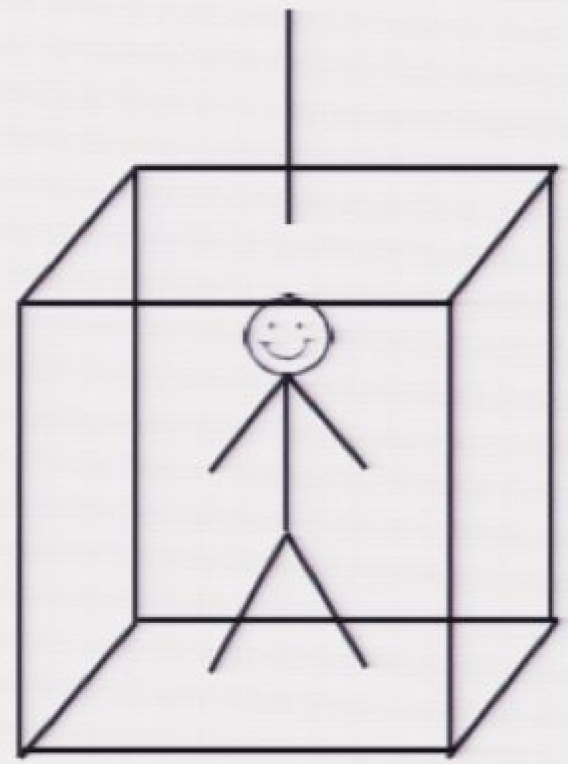
Gravity as an Infra-Red Effect



Equivalence principle: if you are inside a free-falling elevator you can forget about gravity!

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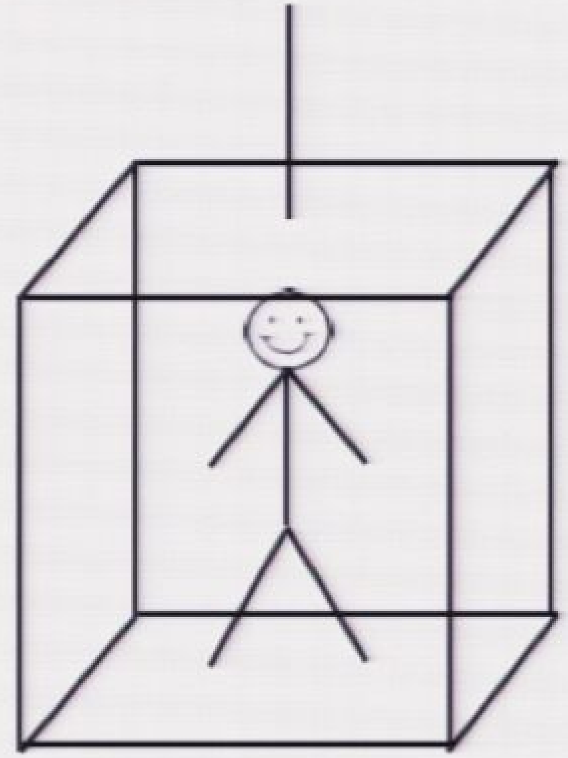

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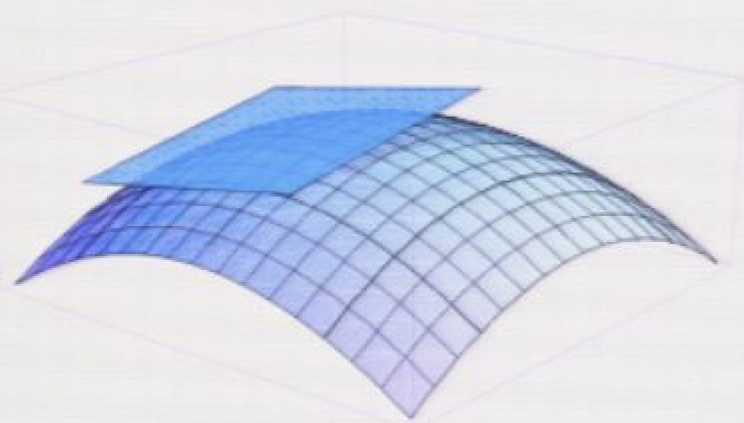

Concrete realization of this idea: General Relativity!

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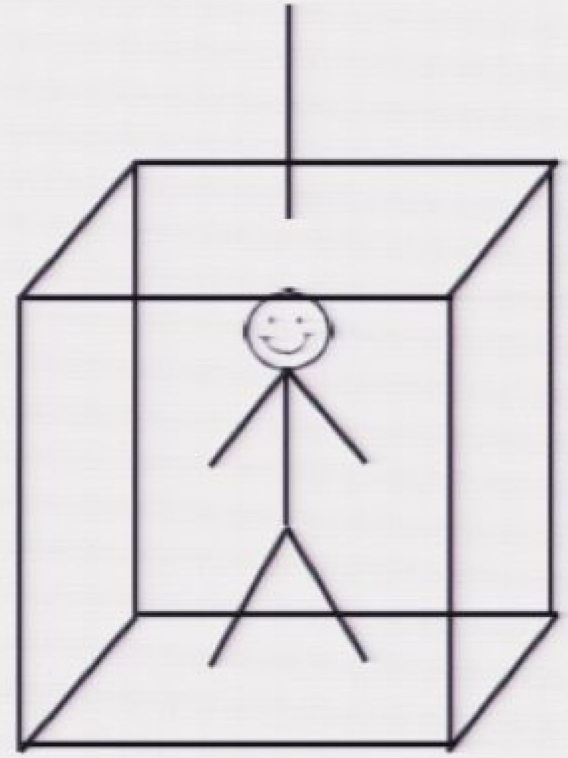
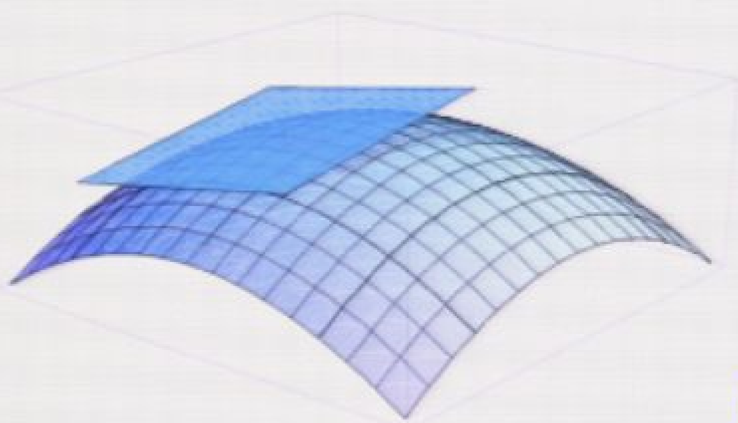


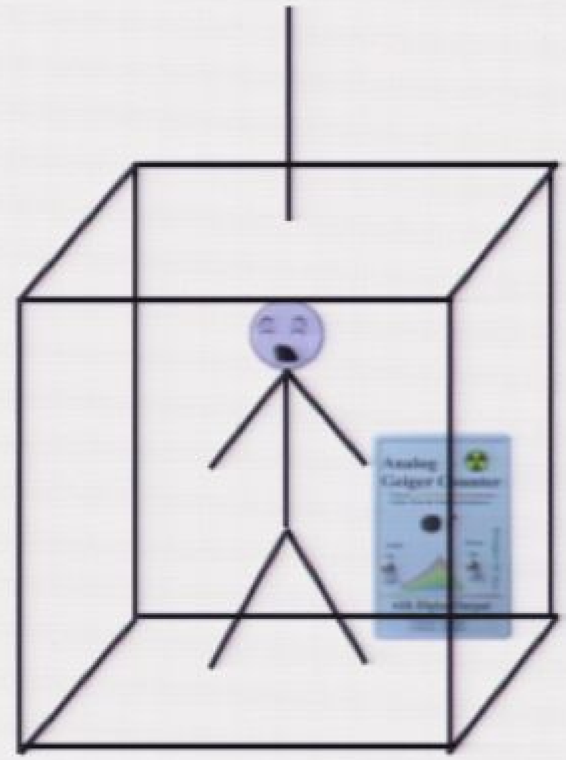


No new mass scale introduced:
the IR-breakdown of non-gravitational physics happens at scales set by the curvature

e.g. $$\mathrm{Area}(d) = 4\pi d^2 \left[1 + \mathcal{O}(R\, d^2)\right]$$

Gravity as an Infra-Red Effect

Things changed after the development of quantum theory. The free falling elevator is no longer immune from gravitational effects



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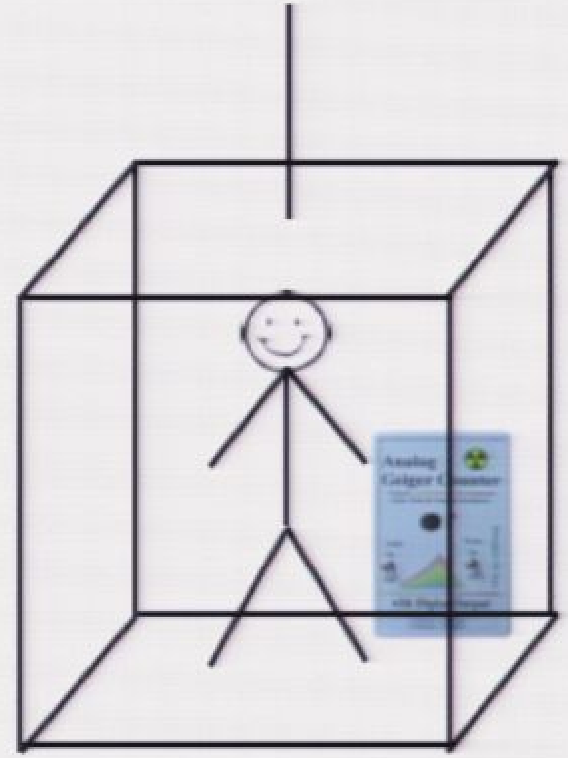

Ultra-Strong Equivalence principle: for each (sufficiently decoupled) matter sector there exists a state (``the vacuum") that is experienced as empty of particles by each free-falling observer

What we want to get rid of?

$$\langle T_0^0 \rangle_{\text{bare}} \;=\; \int d^3k \left(k + \frac{f_{\text{quad}}(t)}{k} + \frac{f_{\log}(t)}{k^3} + \dots \right)$$

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Usual procedure:

Renormalize the local terms with appropriate gravitational counterterms

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The non-local contributions are the effective particle content of the ``vacuum'

The CC problem in semi-classical gravity

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The CC problem in semi-classical gravity

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Is it here?

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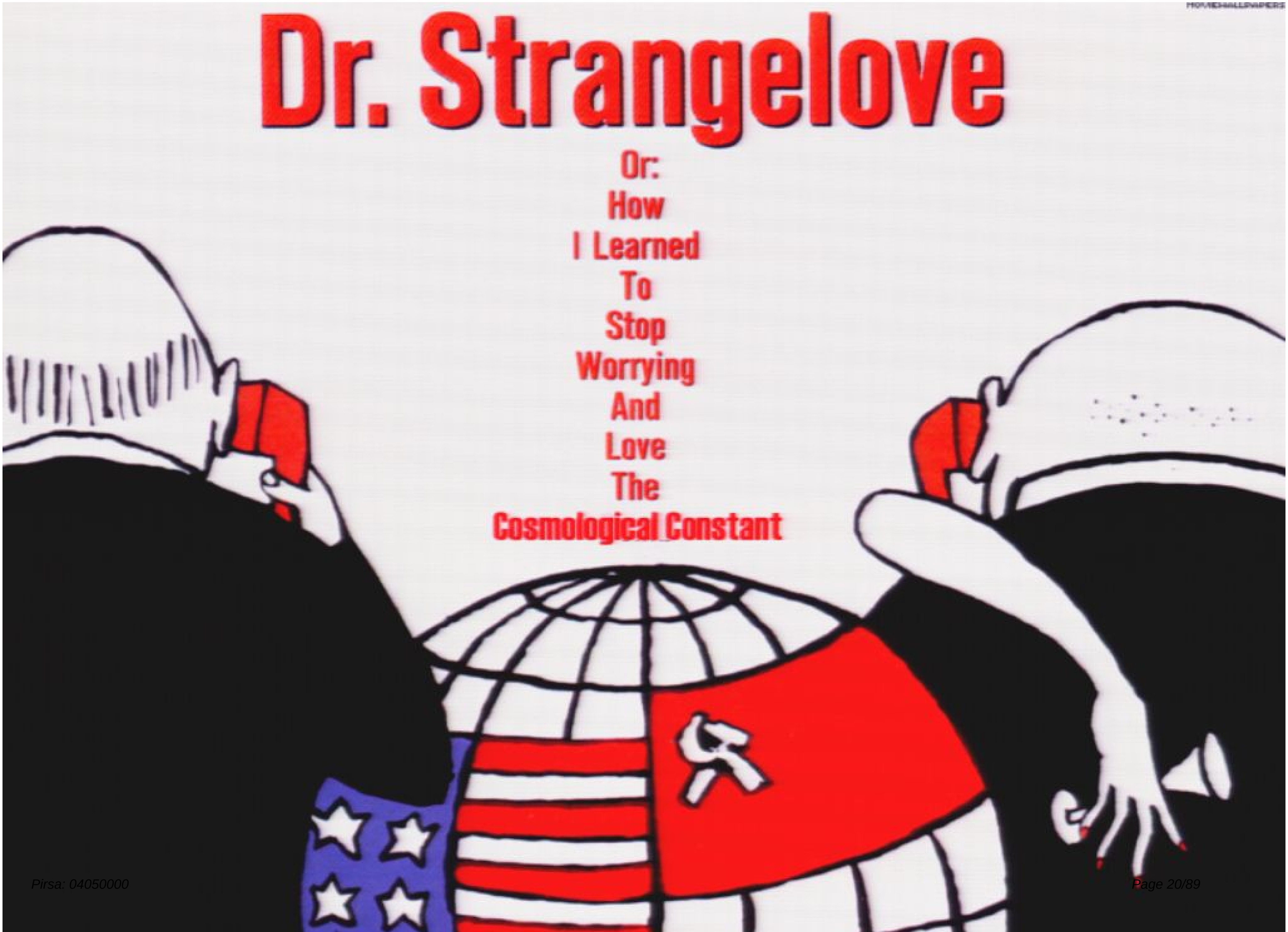
Is it here? (It is because of this terms that we cannot just normal order like in flat space)


MOVIEWALLPAPERS
Dr. Strangelove
Or:
How
I Learned
To
Stop
Worrying
And
Love
The
Cosmological Constant

Ultra-Strong EP: more precisely...

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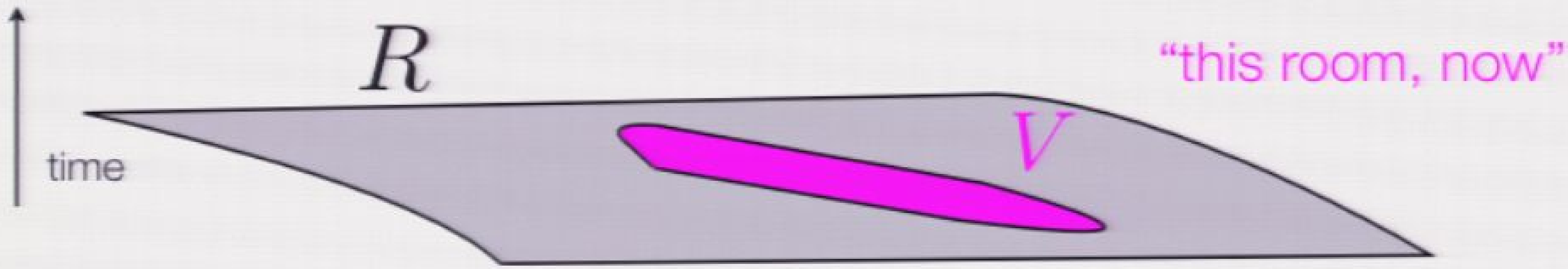
- This can arguably be achieved with a IR modification of the standard paradigm
- CC problem under a new light
- The IR term that cancel the quadratic divergence has the right size to give interesting cosmological implications.

Regions of Space as Quantum Subsystems

In Semiclassical Gravity a region of space has a dual description

F. P. '05 ``Glimmers of a pre-geometric perspective''
F. P. '05
F. P., Costa '07
Cacciatori, Costa, F. P. '08
Costa, F. P., `08



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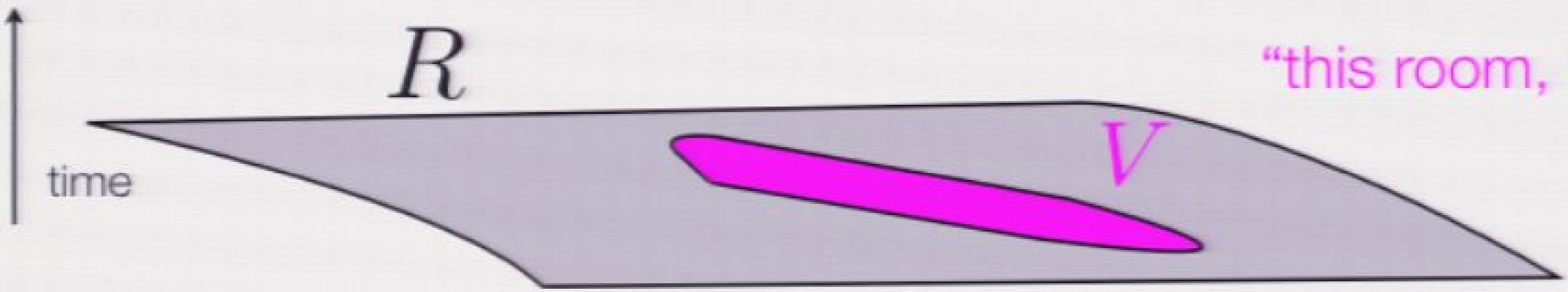

"this room, now"

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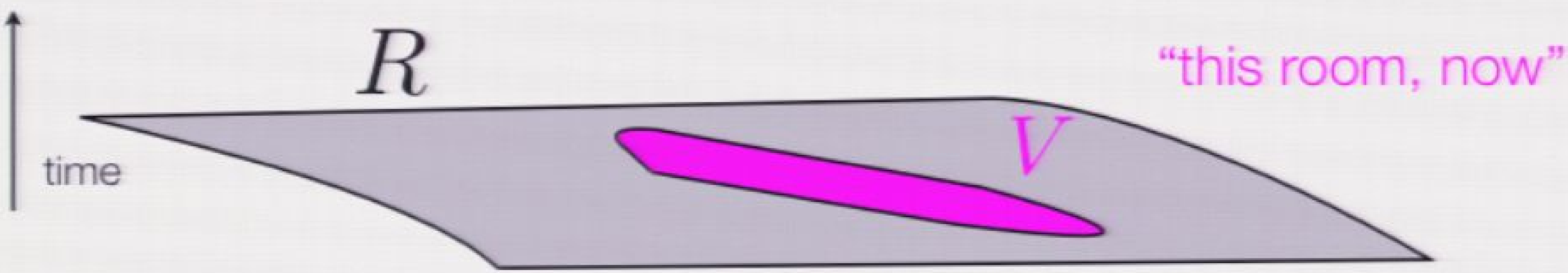

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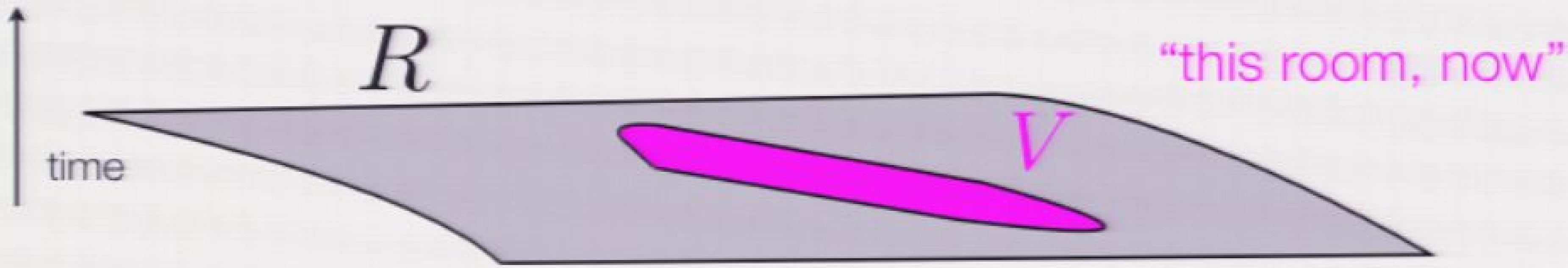

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QFT: Quantum subsystem! $\mathcal{H} = \mathcal{H}_V \otimes \mathcal{H}_R$

Hilbert space of the field theory (matter fields)

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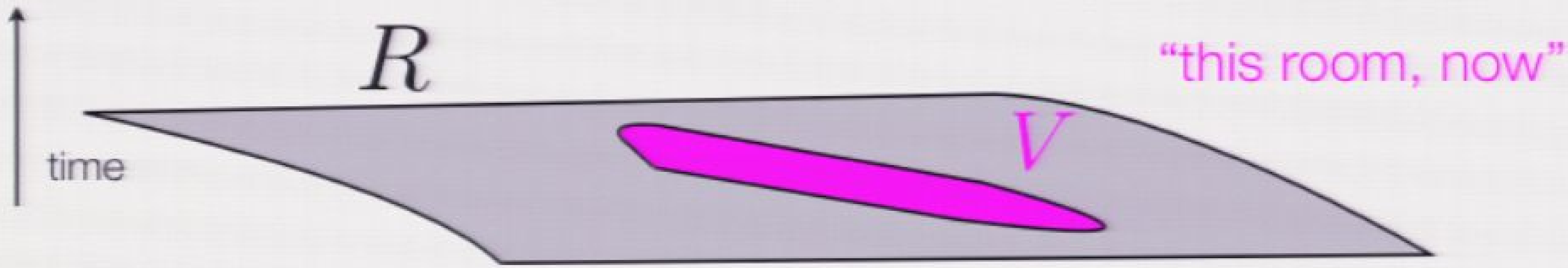

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Much more general description!

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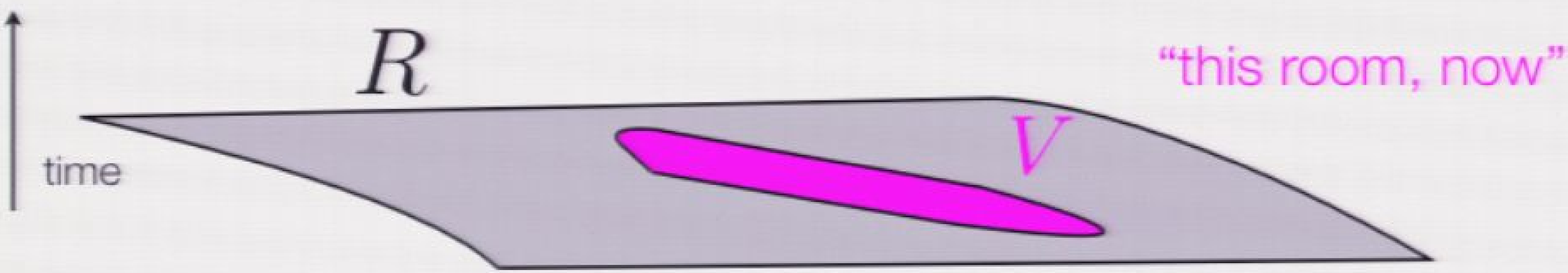
Hilbert space of the field theory (matter fields)

The correspondence Submanifold/Subsystems

It is assigned once and for all by the local operators $\phi(x, t)$



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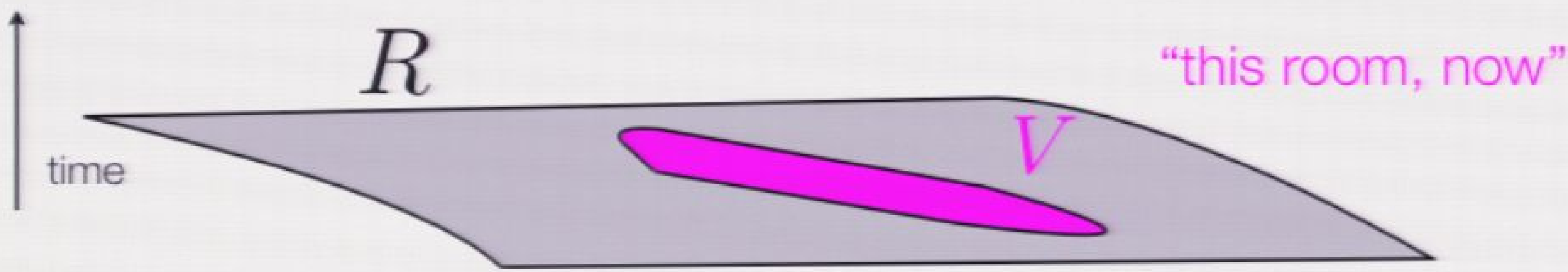

$$O(V,t) = \int_V d^3x \sqrt{-g}\, \phi(x,t)$$

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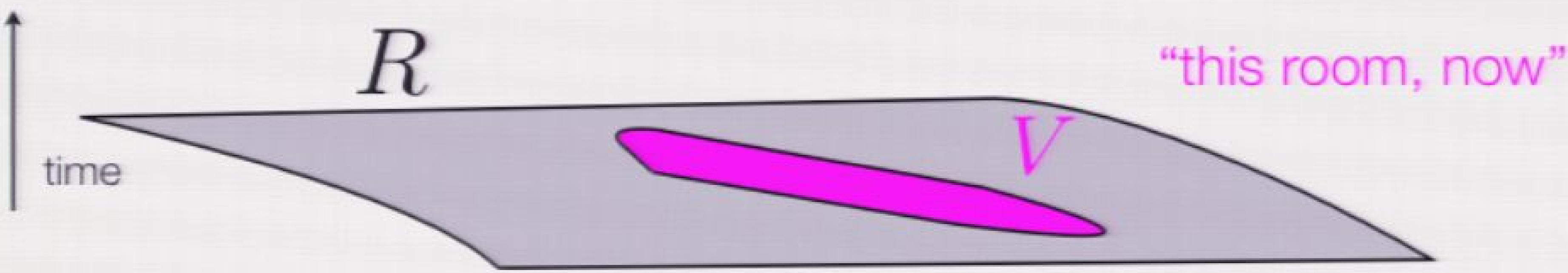

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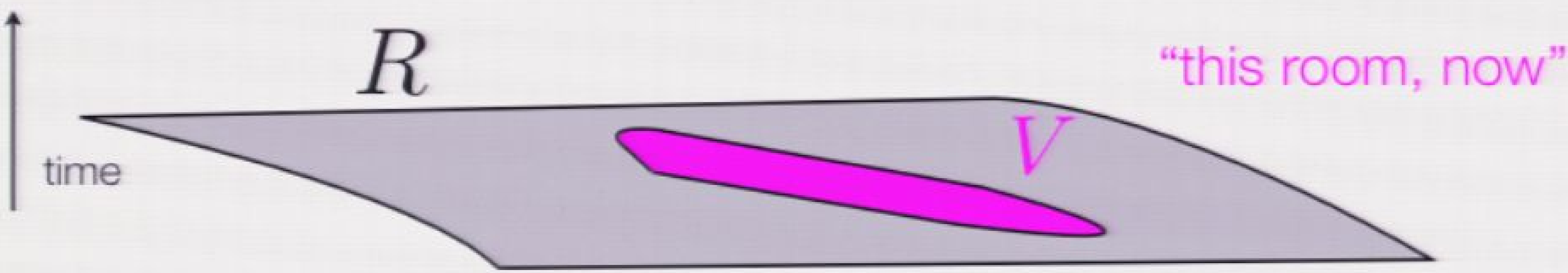

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But act on the QFT Hilbert space and **define** the partition $\mathcal{H} = \mathcal{H}_V \otimes \mathcal{H}_R$

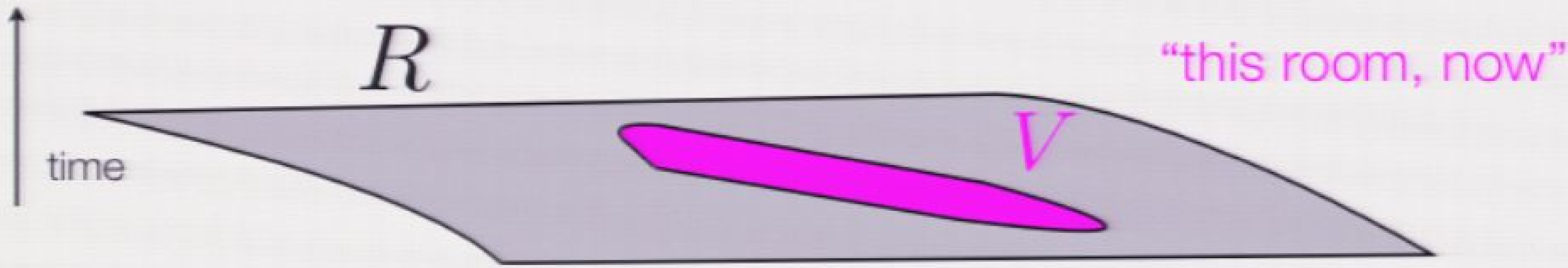
Zanardi '01

Remember: the area of a sphere in GR...

$$A(V) = (36\pi V^2)^{1/3}(1 + \mathcal{O}(RV^{2/3}))$$

The Rule of Thumb:

Regions of space are still perfectly defined as quantum subsystems. However,



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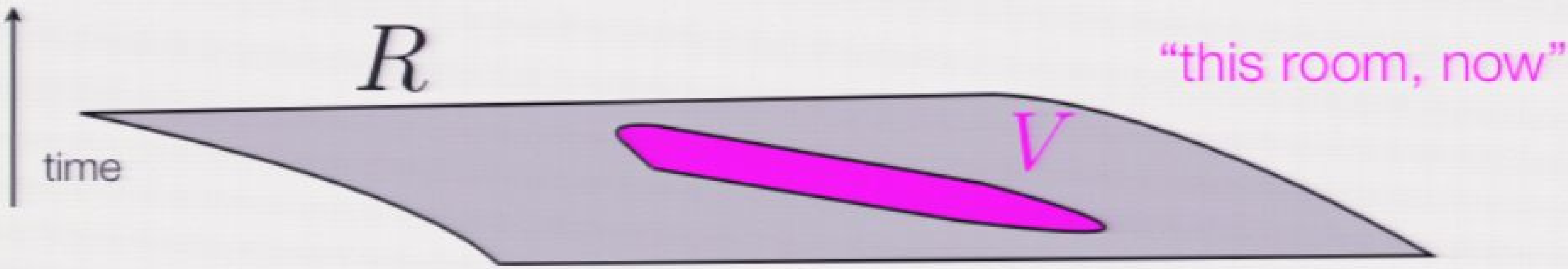

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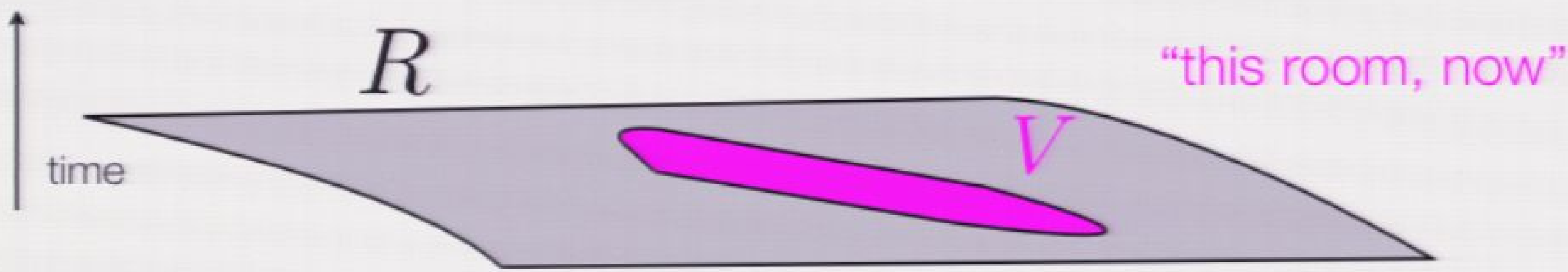

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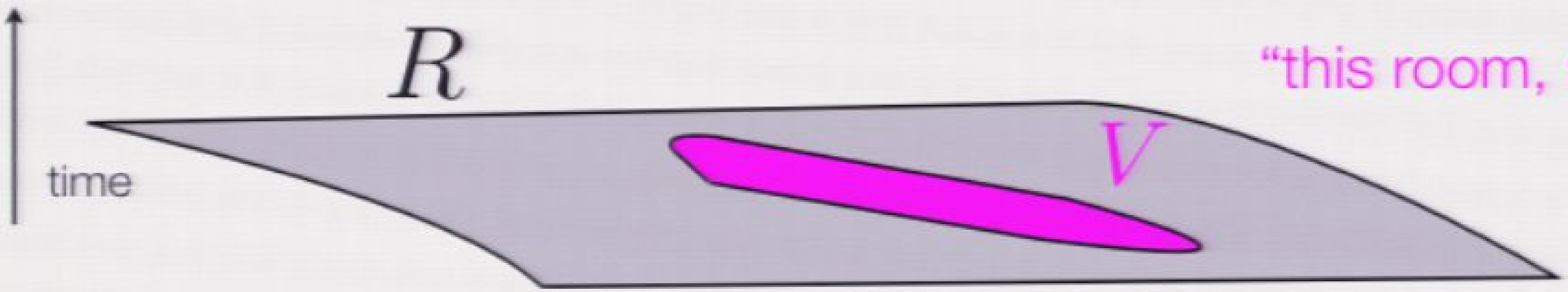

"this room, now"

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Zanardi '01

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A massless scalar field in a flat FRW

Preserve local physics

$$\ddot{\phi}(t, \vec{x} \approx 0) + 3H\dot{\phi}(t, \vec{x} \approx 0) - \nabla^2\phi(t, \vec{x} \approx 0) = 0$$

$$T_0^0 = \mathcal{H} = \frac{1}{2}\left(a(t)^3\, \dot{\phi}^2(t, \vec{x} \approx 0) + a(t)\, \vec{\nabla}\phi^2(t, \vec{x} \approx 0)\right)$$

Introduce global operators

$$\phi(t, \vec{x} \approx 0) = \frac{1}{(2\pi L)^3} \sum_{\vec{k}} \left[\psi_k(t)\tilde{A}_{\vec{k}} + \psi_k^*(t)\tilde{A}^{\dagger}{}_{-\vec{k}}\right]\, e^{i\vec{k}\cdot\vec{x}}.$$

The commutator of the global fields is proportional to the volume; therefore, (ansatz)

$$[\tilde{A}_{\vec{k}}, \tilde{A}^{\dagger}_{\vec{k}'}] = (2\pi L)^3 \ \delta_{\vec{k},\vec{k}'} \ \left(1 - \gamma \frac{H^2}{k^2_{\rm phys}} + \text{higher order}\right)$$

To be fixed by the USEP

A general equation of state

$$w = -(2\nu+3)/(6\nu-3); \quad a(\tau) \propto \tau^{1/2-\nu}; \quad H(\tau)a(\tau) = \frac{1-2\nu}{2\tau}$$

The mode functions can be choosen as

$$\psi_k(\tau) = \tau^\nu H_\nu^{(1)}(k\tau), \qquad \psi_k^*(\tau) = \tau^\nu H_\nu^{(2)}(k\tau)$$

Calculate $\langle 0| T_0^0(0) |0\rangle$ and expand at high momenta

$$\langle 0| T_0^0(0) |0\rangle \propto \sum_{\vec{k}} \left(\frac{k}{a}\right) \left(4 + \frac{(2\nu-1)^2}{2(k\tau)^2} + \mathcal{O}(k\tau)^{-4}\right) \left(1 - \gamma \frac{(2\nu-1)^2}{4(k\tau)^2}\right)$$

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$$\sum_{\vec{k},\vec{k}'} \left(\dot{\psi}_k \dot{\psi}^*_{\vec{k}'} - \frac{\vec{k}\cdot\vec{k}'}{a(\tau)^2} \psi_{\vec{k}} \psi_{\vec{k}'}\right) \qquad [A_{\vec{k}}\,, A^\dagger_{-\vec{k}'}]$$

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Introduce ``manifold operators"
satisfying usual comm. rel.

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$$= \sum_{\vec{n}} \vec{k}\, A^{\dagger}_{\vec{n}} A_{\vec{n}}$$

$\vec{k}$ is the physical (comoving) momentum associated to infinitesimal translations

(sort of) Modified Dispersion Relations

$\vec{n}$ → ``Manifold"- Fourier comoving labels. They are conserved during evolution. Fourier space is flat in these labels

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$$\vec{k} = \vec{n}\left(1 - \frac{H^2 a^2}{2n^2}\right)$$ → Physical comoving momenta

Cosmological Implication (I)

Physical comoving momenta are conserved only approximately. What is conserved is the quantity

$$\vec{k}\left(1 + \frac{H^2 a^2}{2k^2} + \text{higher orders}\right)$$

Defining local field operators elsewhere

Exponentiate the momentum operator and make a translation operator

$$T_i(\lambda) = e^{-i\lambda P_i}; \qquad P_i = \int d^3n\, \vec{k}(\vec{n})\, A^\dagger_{\vec{n}} A_{\vec{n}}$$

$$\phi(t,*) \equiv T_i(\lambda)\, \phi(t,0)\, T_i^{-1}(\lambda) = \frac{1}{(2\pi)^{3/2}} \int d^3n\, \phi_{\vec{n}}\; e^{-i\,\lambda\, n_i\left(1-\frac{H^2 a^2}{2n^2}\right)}$$

`at comoving distance λ if one keeps going in the i direction"

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`at comoving distance λ if one keeps going in the i direction"

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$$w = -(2\nu + 3)/(6\nu - 3); \quad a(\tau) \propto \tau^{1/2-\nu}; \quad H(\tau)a(\tau) = \frac{1-2\nu}{2\tau}$$

The mode functions can be choosen as

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$$\sum_{\vec{k},\vec{k}'} \left(\dot{\psi}_k \dot{\psi}^*_{k'} - \frac{\vec{k}\cdot\vec{k}'}{a(\tau)^2} \psi_{\vec{k}} \psi_{\vec{k}'}\right)$$

$$[A_{\vec{k}},\, A^{\dagger}_{-\vec{k}'}]$$

(sort of) Modified Dispersion Relations

$\vec{n}$ → ``Manifold''- Fourier comoving labels. They are conserved during evolution. Fourier space is flat in these labels

$$\vec{k} = \vec{n}\left(1 - \frac{H^2 a^2}{2n^2}\right)$$

→ Physical comoving momenta

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What about time derivatives? If we derive after translating we get a spurious contribution

$$\pi(\vec{\lambda}) \;\; = \;\; \frac{a^3}{(2\pi)^{3/2}} \int d^3n \, \left[\dot{\psi}_n(t) e^{i\vec{k}\cdot\vec{\lambda}} A_{\vec{n}} + \dot{\psi}^*_n(t) e^{-i\vec{k}\cdot\vec{\lambda}} A^\dagger_{\vec{n}} \right]$$

$$+ \;\; i \frac{a^3}{(2\pi)^{3/2}} \int d^3n \, (\vec{k}\cdot\vec{\lambda})^{\cdot} \left[\psi_n \; e^{i\vec{k}\cdot\vec{\lambda}} A_{\vec{n}} - \psi^*_n \; e^{-i\vec{k}\cdot\vec{\lambda}} A^\dagger_{\vec{n}} \right]$$

Killing the spurious

$$[\phi(0), \pi(\vec{\lambda})] = -[\pi(0), \phi(\vec{\lambda})] - 2i \frac{a^3}{(2\pi)^3} \int d^3n \, e^{-i\vec{k}\cdot\vec{\lambda}} \, |\psi_n|^2 \, (\vec{k} \cdot \vec{\lambda})$$

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High momenta, small distances

$$\int d^3n\, e^{-i\vec{n}\cdot\vec{\lambda}}\,\frac{1}{n}\left[\dot{\vec{\lambda}}\cdot\vec{n}\left(1-\frac{H^2a^2}{2n^2}\right) - \vec{\lambda}\cdot\vec{n}\frac{(H^2a^2)^{\cdot}}{2n^2}\right]$$

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Ansatz: $\dot{\vec{\lambda}} = \beta\lambda^2(H^2a^2)^{\cdot}\,\vec{\lambda}$

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Ansatz: $\dot{\vec{\lambda}} = \beta \lambda^2 (H^2 a^2)^{\cdot} \vec{\lambda}$

$$\Rightarrow \qquad \beta = \frac{1}{4}$$

Cosmological Implication (2)

The comoving distance between two comoving observers is conserved only when it is small compare to Hubble. In general,

$$\dot{\lambda} = \lambda^3 \frac{(H^2 a^2)^{\cdot}}{4} + \text{higher order}$$

Their proper distance $d = a(t)\lambda$, equivalently, scales as

$$\frac{d(t)}{d(t')} = \frac{a(t)}{a(t')} \left[1 + \frac{d^2(t')}{4} \left(H^2(t) \frac{a^2(t)}{a^2(t')} - H^2(t') \right) + \text{higher orders} \right]$$

Outline

- Introduction, the Ultra-Strong equivalence principle, strategy.
- Modifying the Fourier Modes
- A look at the global picture
- Cosmology

Light-like trajectories and Luminosity Distance

We get a correction from the modified global expansion

$$\frac{dr}{d\tau} = 1 + r^3 \frac{(H^2 a^2)'}{4}$$

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Cosmological Implication (3)

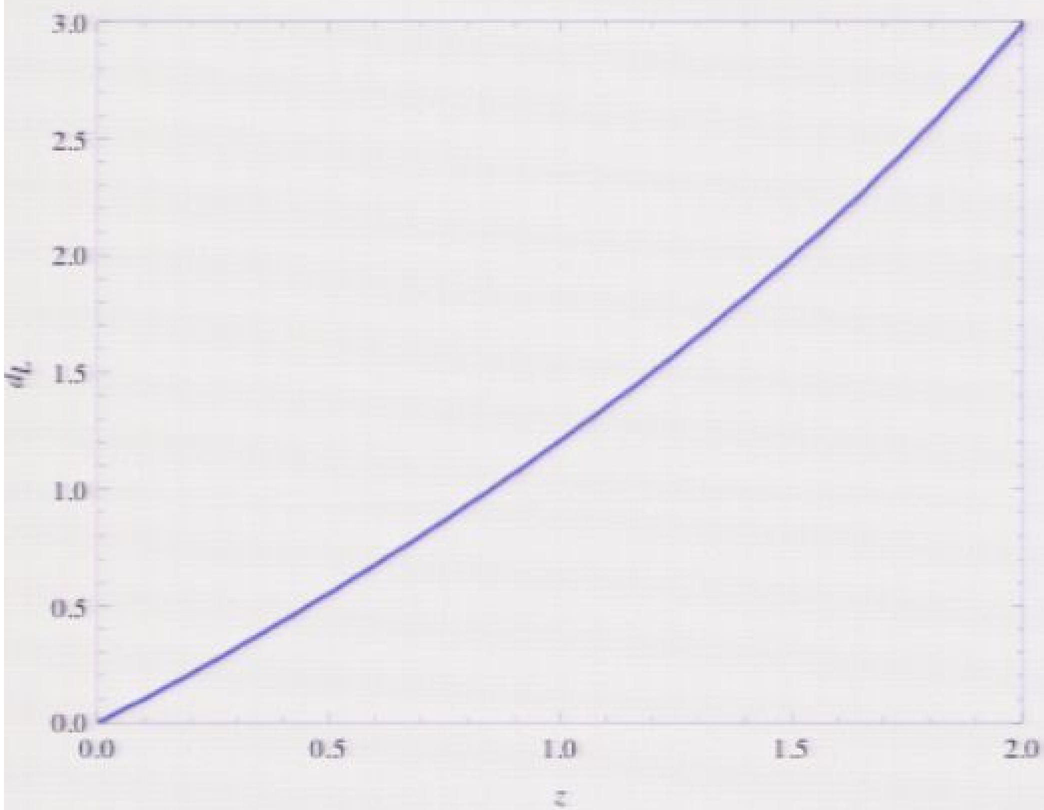
In a matter-dominated universe the luminosity reads

$$d_L(z) = (1+z)r(z)$$

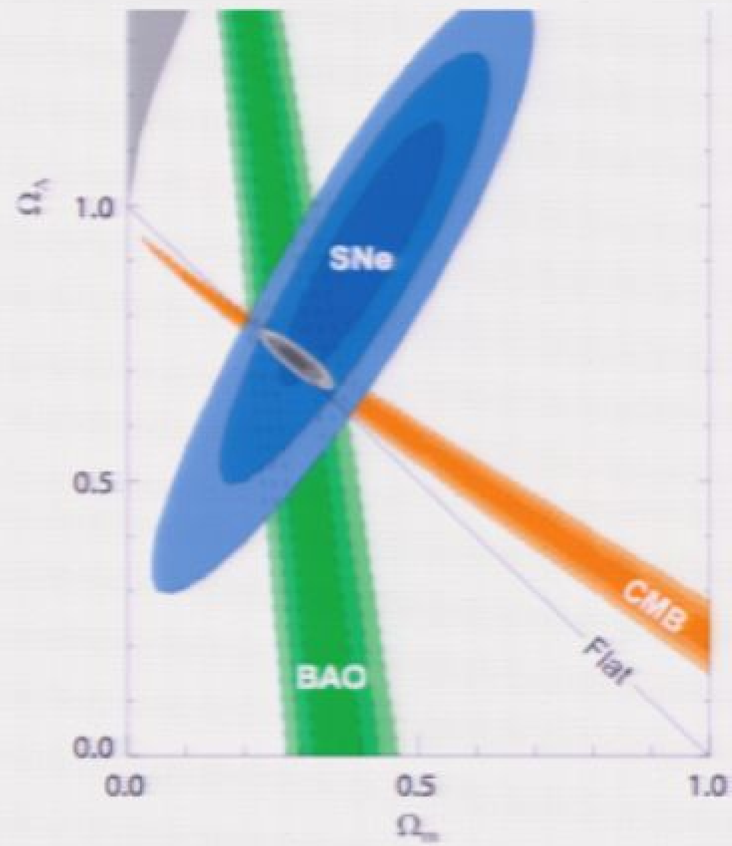
where

$$H_0(1+z)^{3/2}\frac{dr(z)}{dz} = 1 + (1+z)^{3/2}\frac{r^3(z)H_0^3}{4}$$

USEP v.s. LCDM



Kowalski et al. 2008



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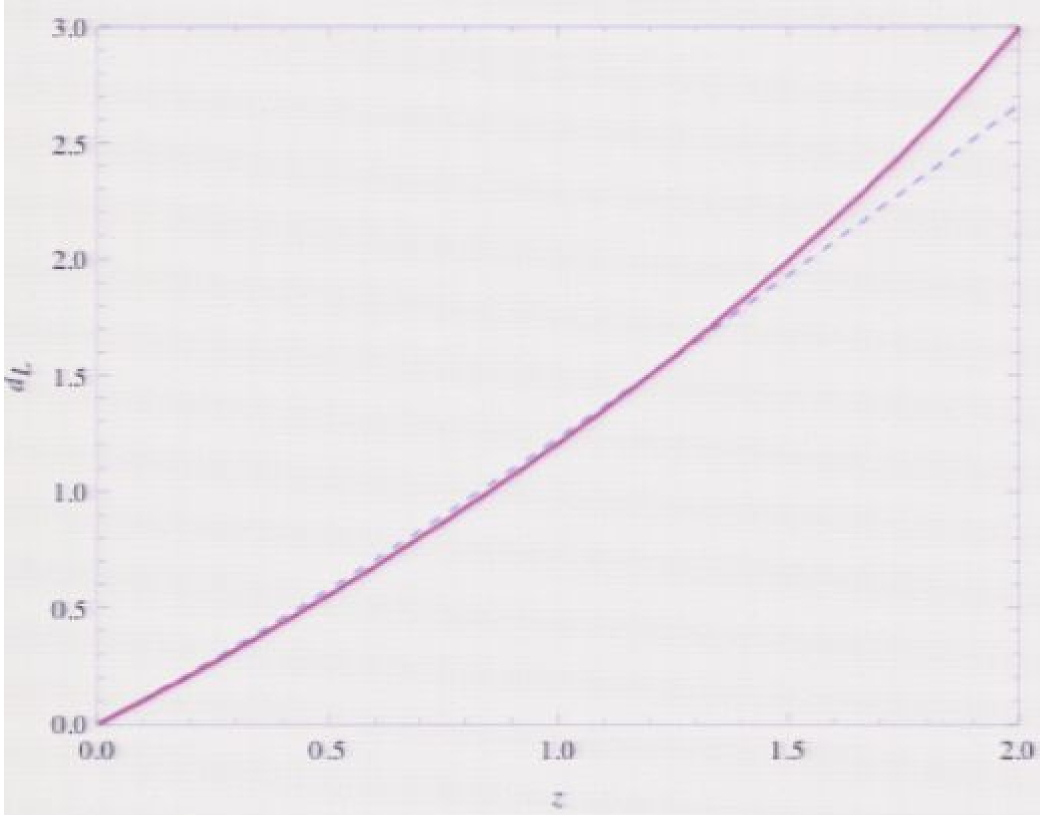
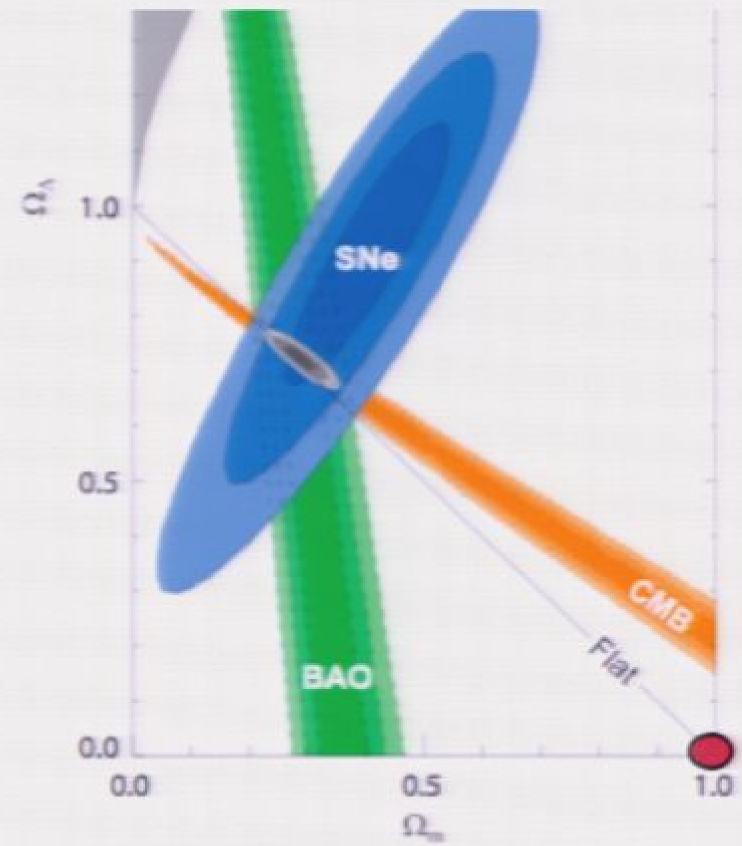
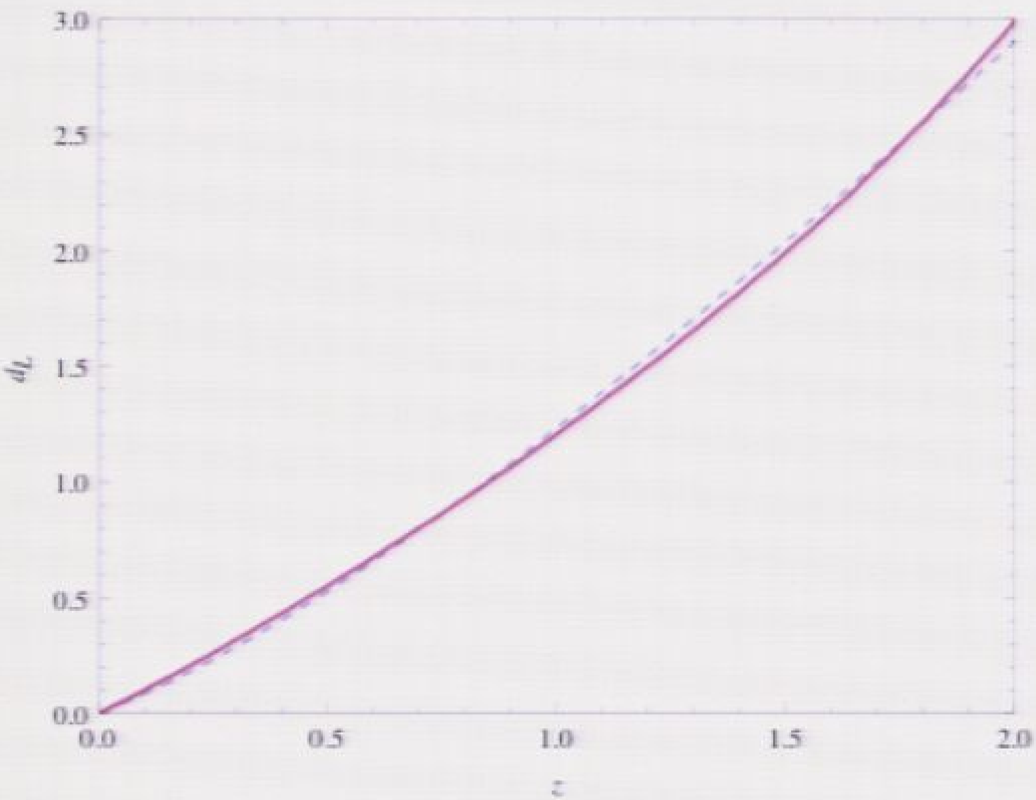


Kowalski et al. 2008

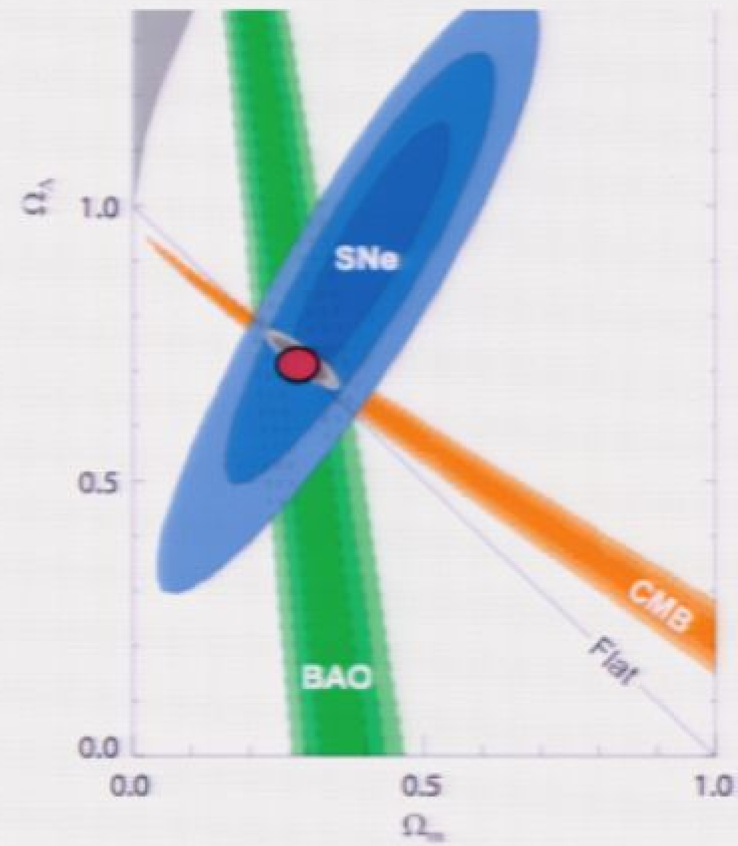


$$\Omega_m = 1; \Omega_\Lambda = 0$$

USEP v.s. LCDM

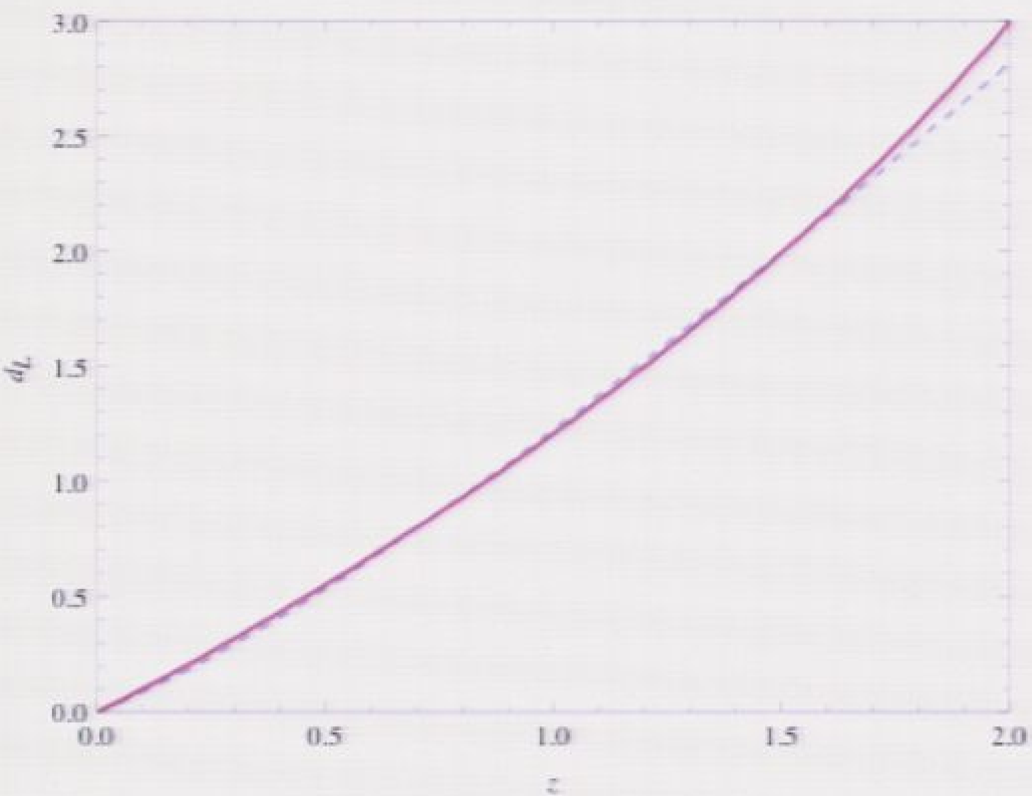


Kowalski et al. 2008



$$\Omega_m = 0.3; \Omega_\Lambda = 0.7$$

USEP v.s. LCDM



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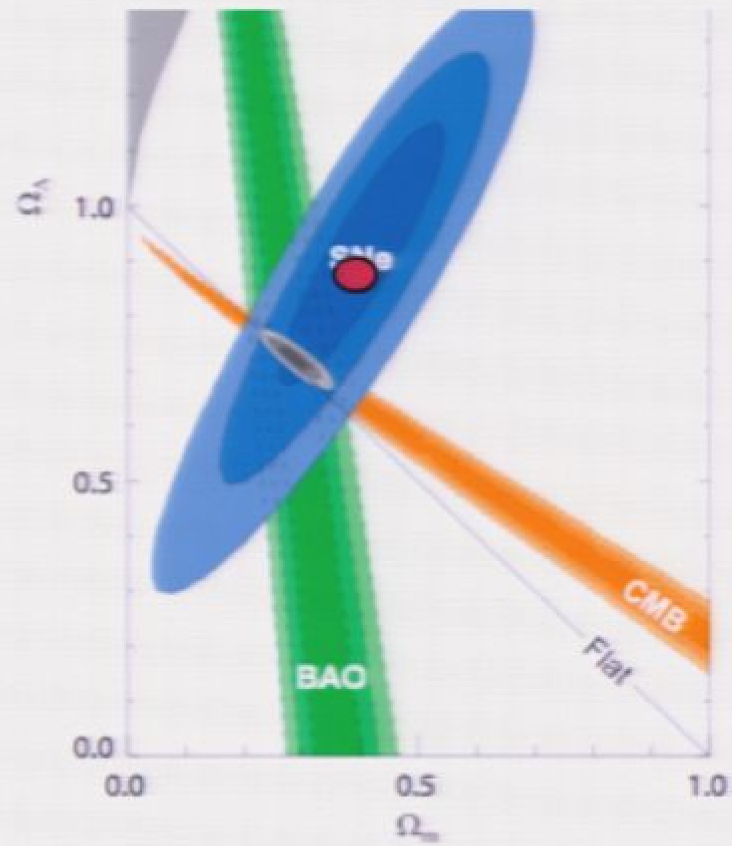
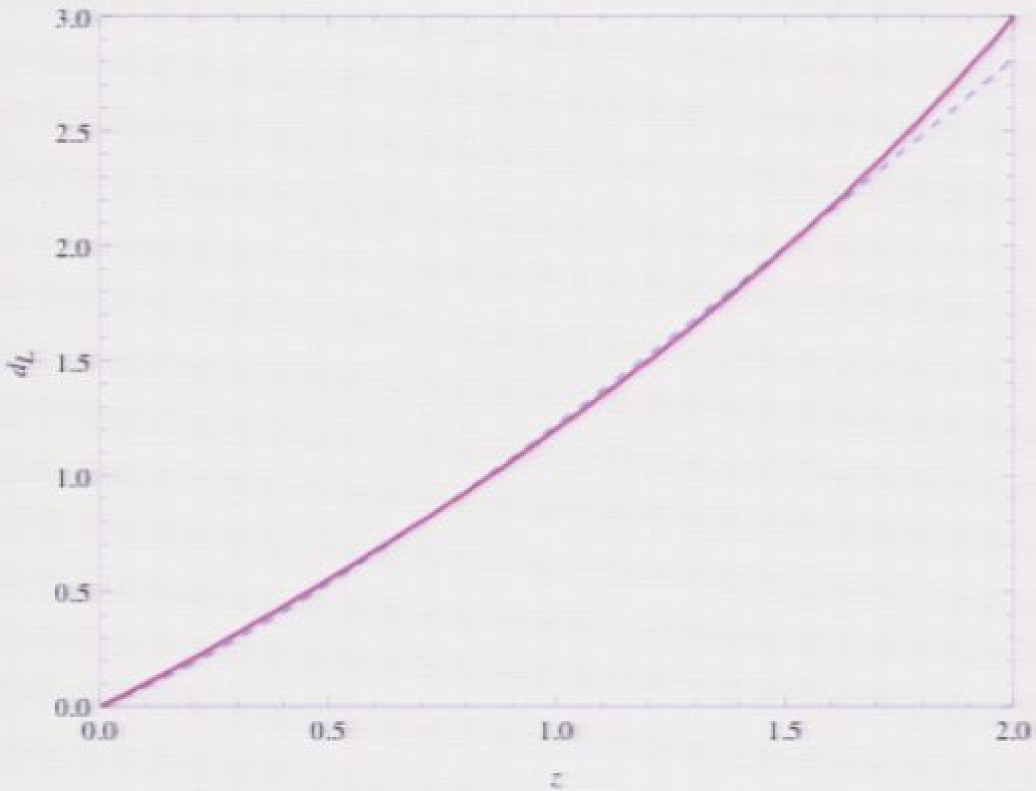


$$\Omega_m = 0.4; \Omega_\Lambda = 0.9$$

CONCLUSIONS

- IR-modification with no freedom left (does not go to GR in some limit).
- A genuinely new theoretical framework (exciting, but also worring...)
- Much more to understand and double-check
- Promising Cosmological Implications

USEP v.s. LCDM



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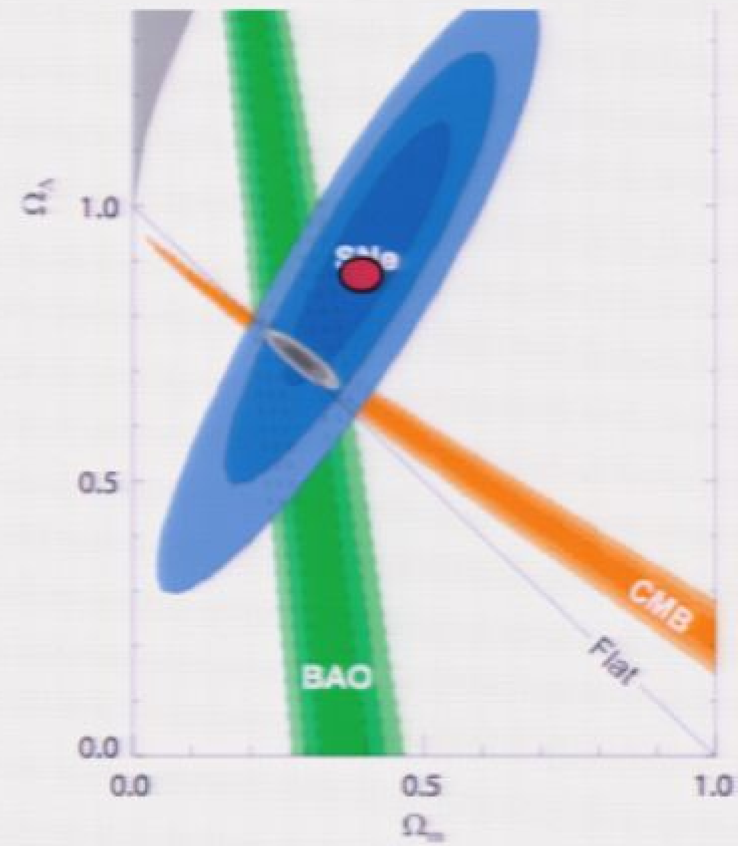

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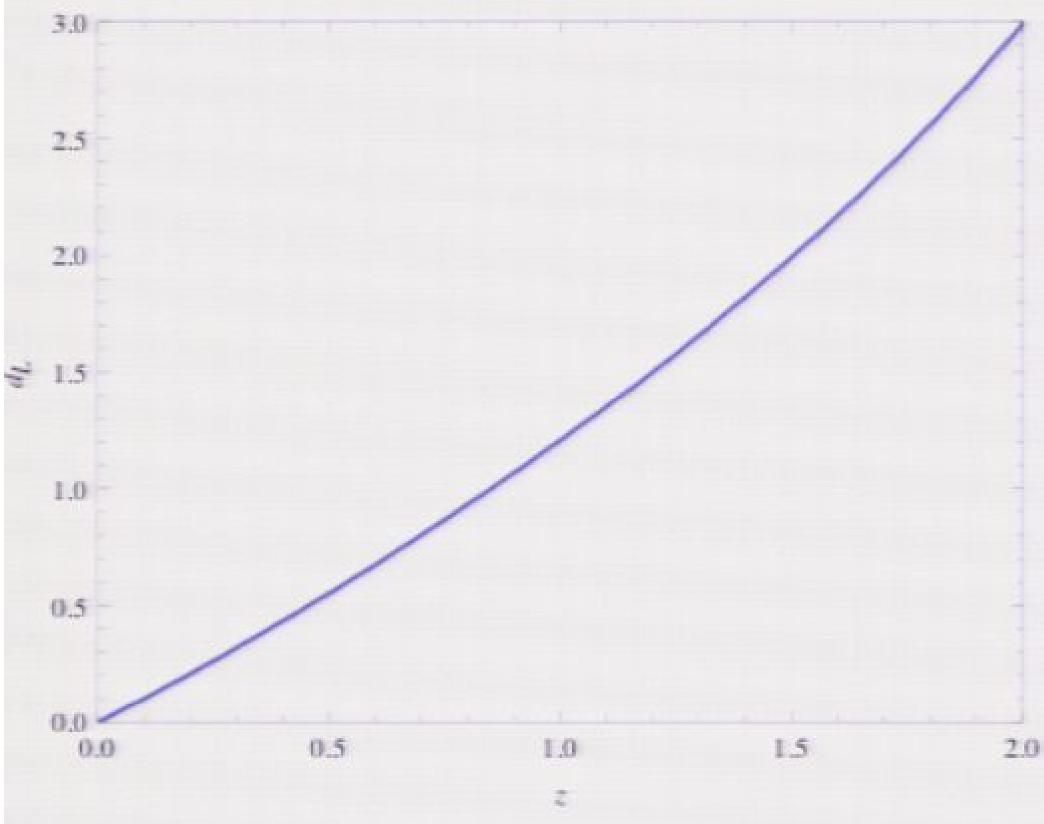

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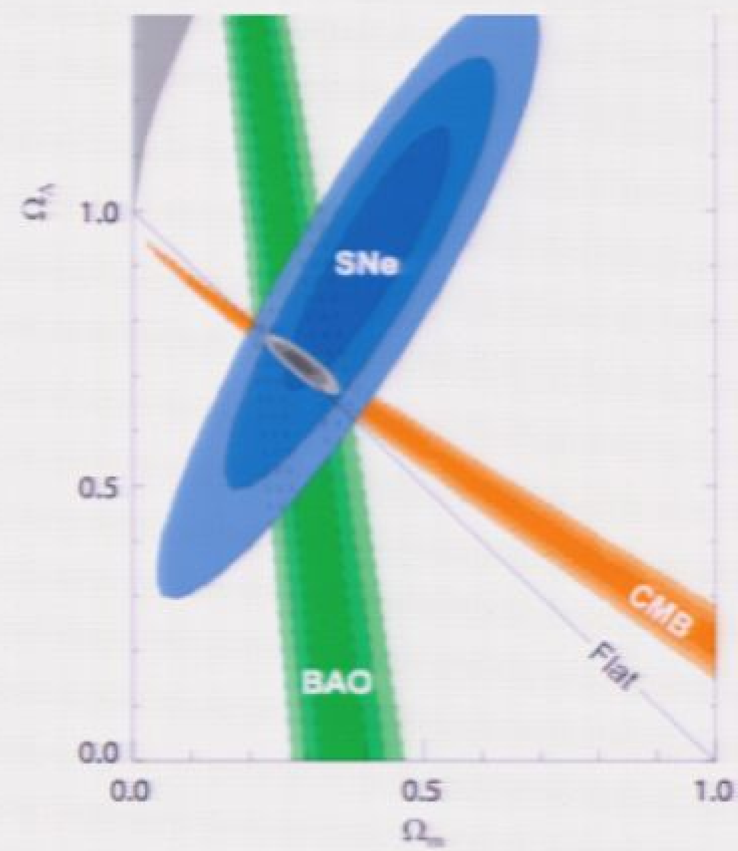

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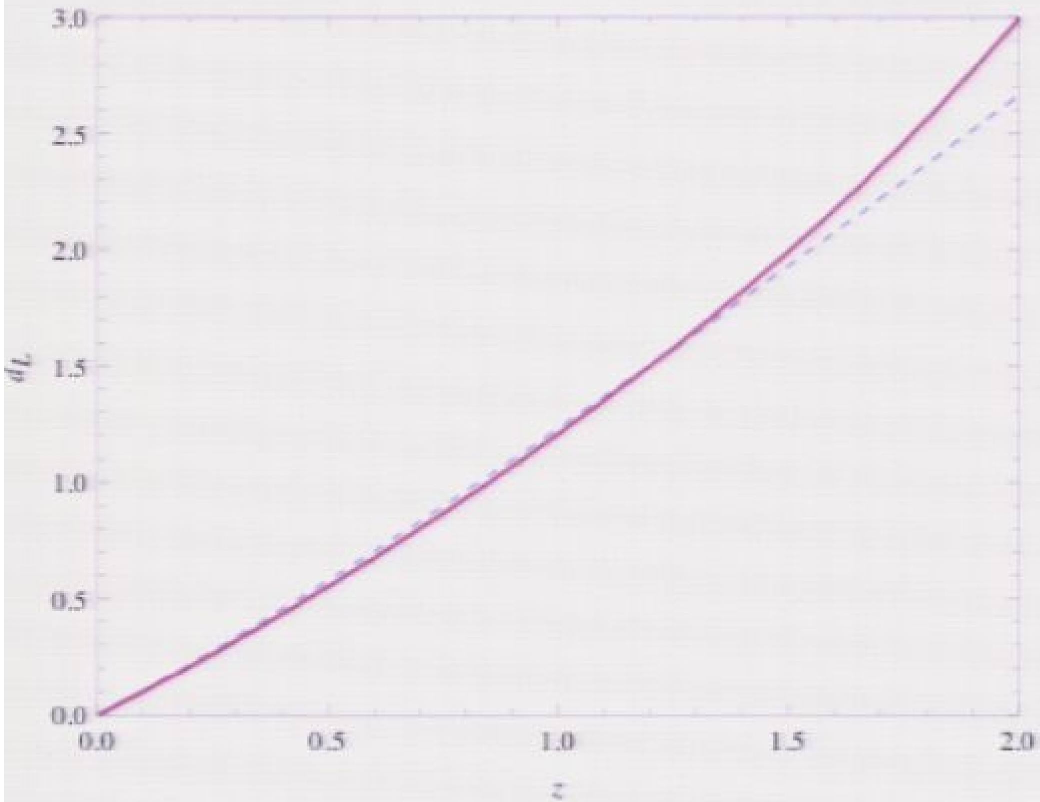

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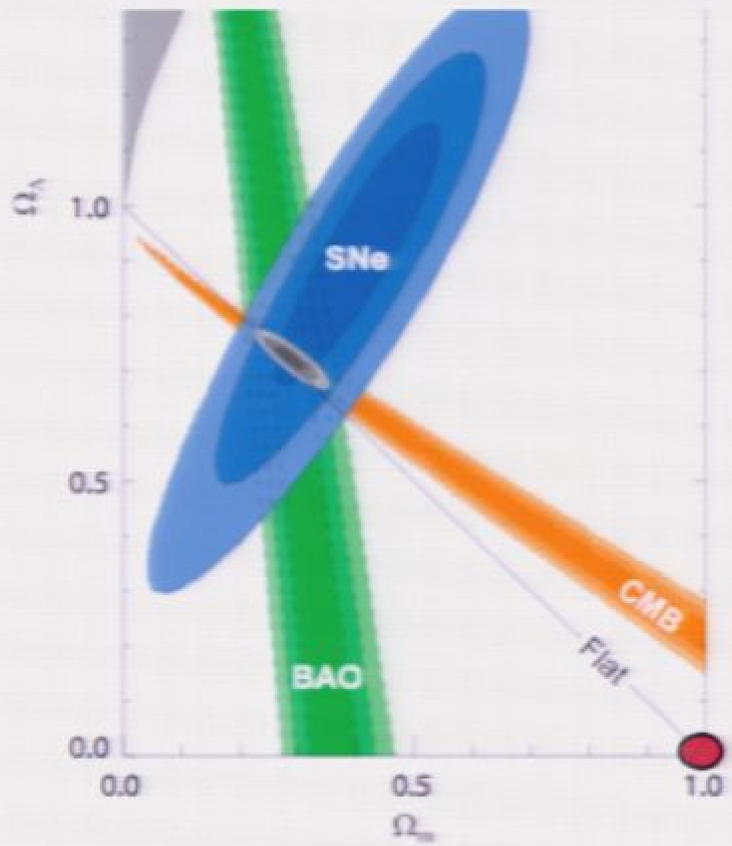

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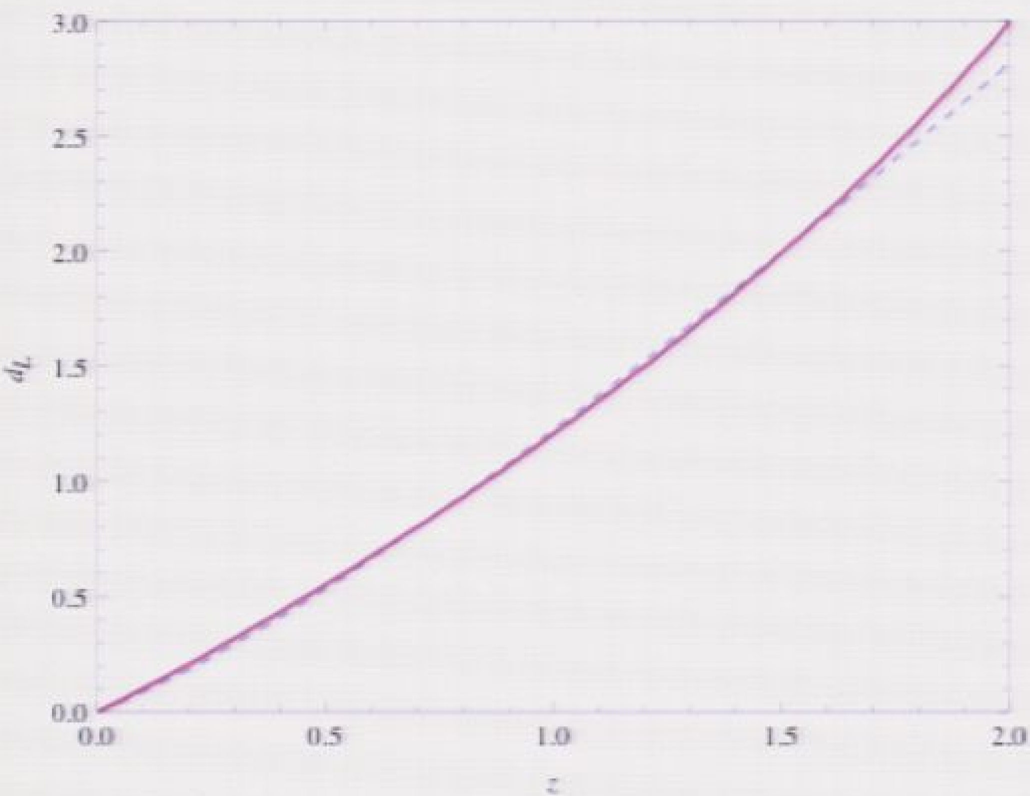

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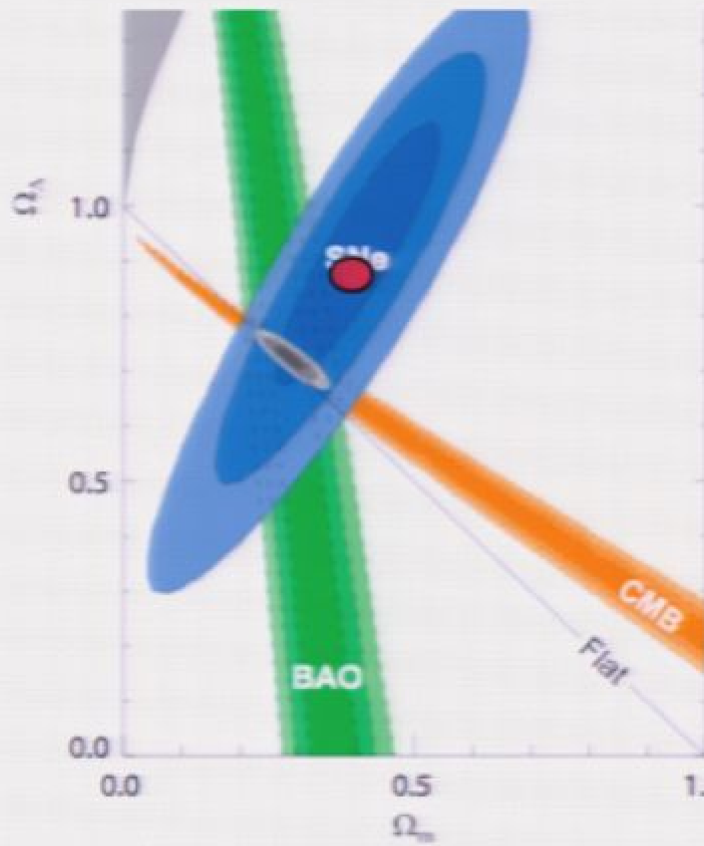

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Ultra-Strong EP: more precisely...

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- This can arguably be achieved with a IR modification of the standard paradigm
- CC problem under a new light
- The IR term that cancel the quadratic divergence has the right size to give interesting cosmological implications.