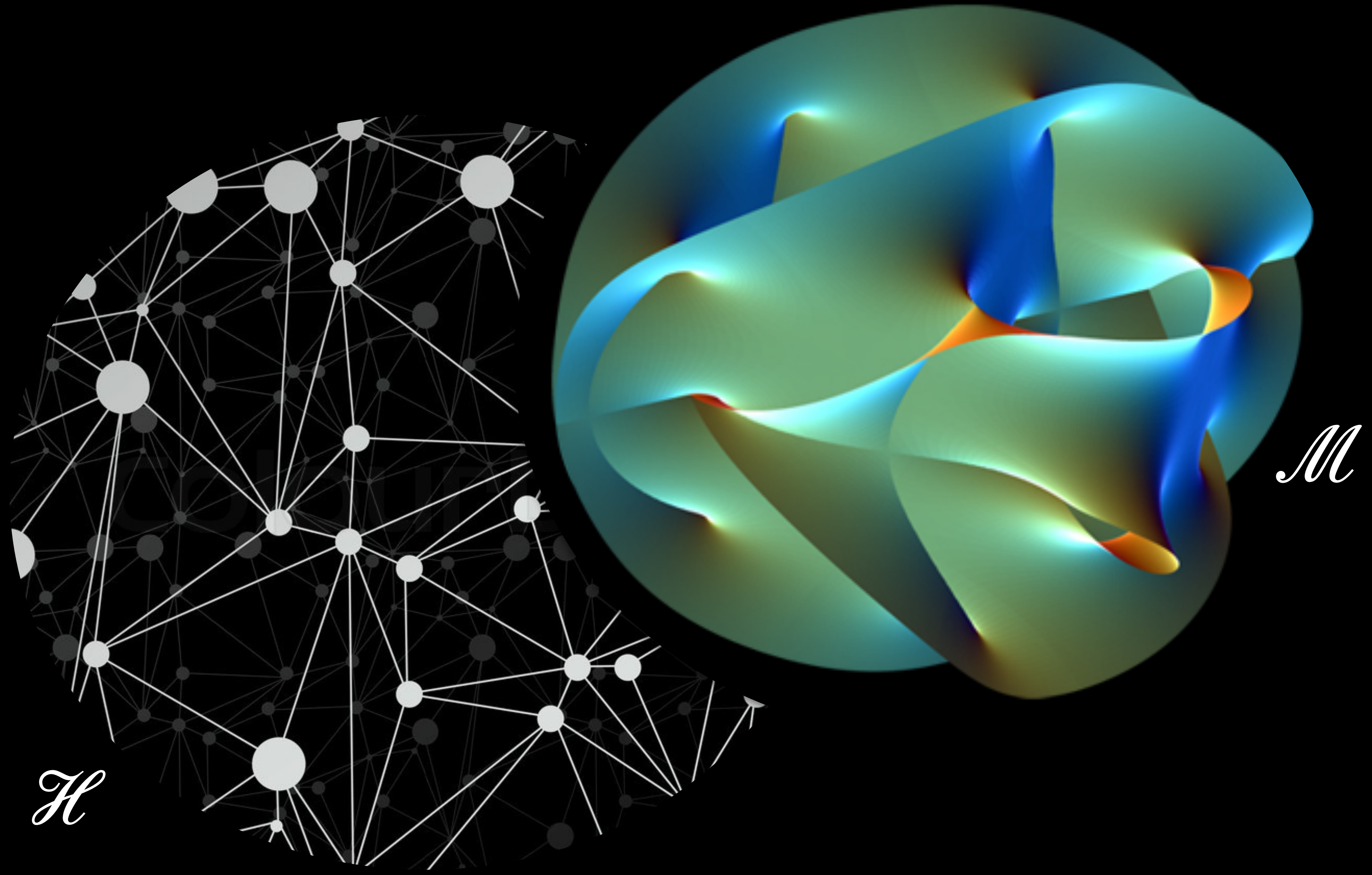
# Is our Universe geometrical after all?

**Guilherme Franzmann**



NORDITA
The Nordic Institute for Theoretical Physics

Oskar Klein
centre

# Foundational Aspects of Dark Energy

## FADE Collaboration

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**Florian Niedermann**
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**Aliki Litsa**
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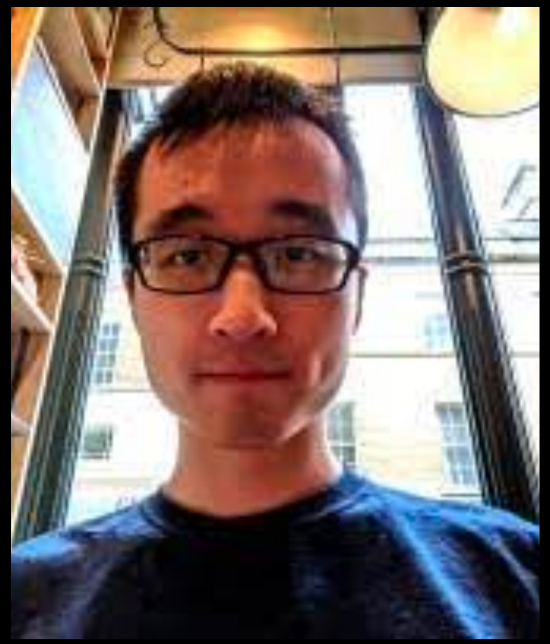

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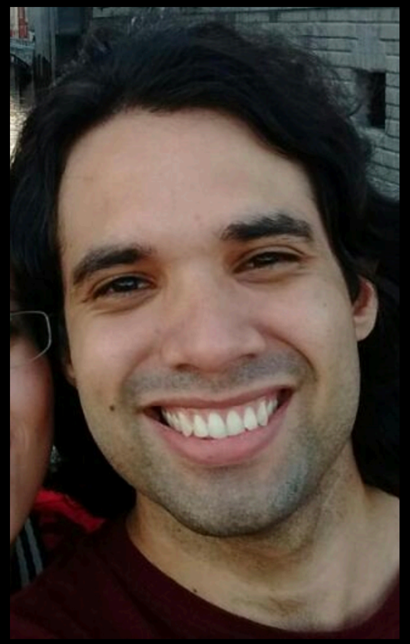

**Heliudson Bernardo**
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**Benjamin Bose**
Hawking Fellow at
the Univ. of Edinburgh

# Modified gravity approaches to the cosmological constant problem

**Foundational Aspects of Dark Energy (FADE) Collaboration**

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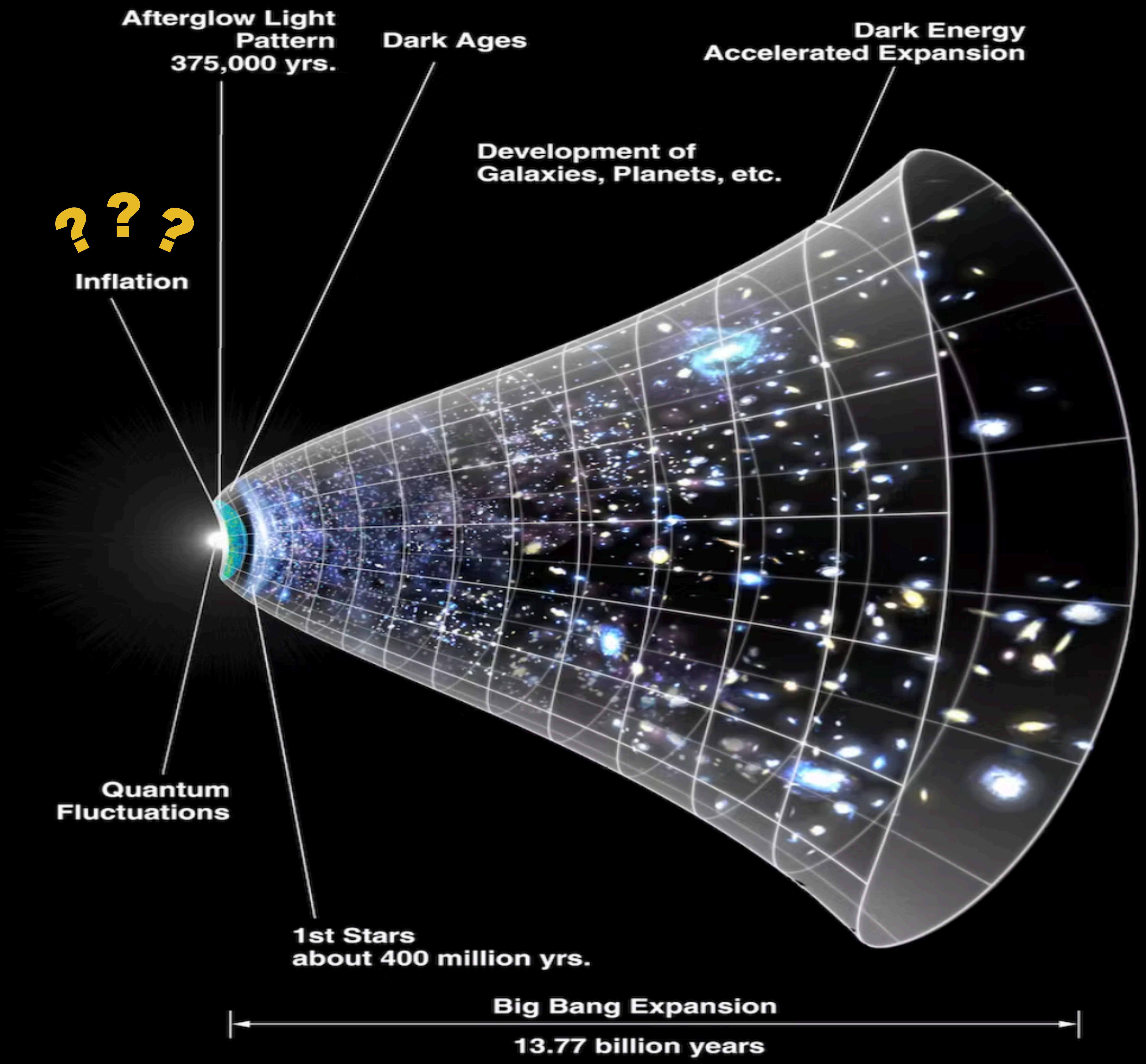
Invited review for Special Issue "Cosmological Constant" in *Universe.*


Afterglow Light Pattern 375,000 yrs.
Dark Ages
Dark Energy Accelerated Expansion
Development of Galaxies, Planets, etc.
? ? ?
Inflation
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.77 billion years

# Standard Model of Particle Physics and Cosmological Standard Model

GR

QFT

# The Cosmological Constant Problem(s)

Scanning the literature, we can find at least four claimed issues attached to the cosmological constant phenomenology:

1. **The Weight of Vacuum.**
2. **Phase Transitions.**
3. **Dark Energy.**

---

4. **UV Sensitivity.**

# The Cosmological Constant Problem(s)

## The Weight of Vacuum.

The gravitating vacuum energy at the level of the Einstein equations receive contributions from the vacuum energy of the fields in the SM. QFT calculations of the vacuum energy of a field with mass $m$ for a given energy scale $\mu$ scales as

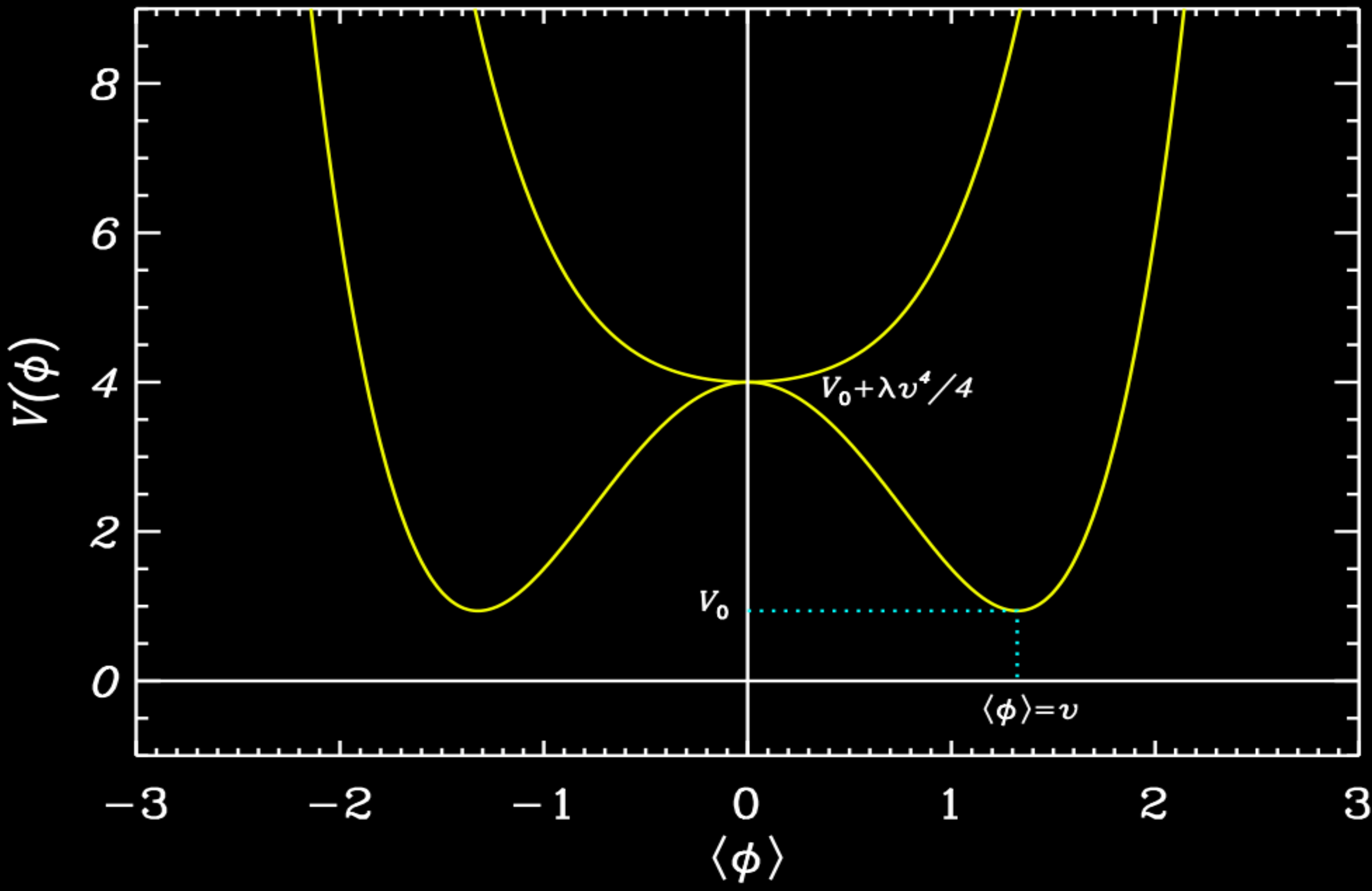
$$\rho_{\mathrm{vac}} \sim m^4 \ln\left(m^2/\mu^2\right).$$

For instance, the mass of the top quark is $10^{11}$ eV while $\rho_\Lambda \sim 10^{-11}\ \mathrm{eV}^4$, leading to a 55-orders-of-magnitude gap!

# The Cosmological Constant Problem(s)

$V(\phi_{\text{const.}}) = \rho_{\text{vac}}^{(\phi)}$, but global minimum shifts as the background temperature of the Universe changes.

**Phase Transitions.**



(Martin, '12)

# The Cosmological Constant Problem(s)

**Dark Energy.**

The Universe is undergoing a period of accelerated expansion that can be explained by a positive cosmological constant, such that

$$\rho_\Lambda \sim 10^{-11}\,\mathrm{eV}^4.$$

Where does this vacuum energy come from?

# The Cosmological Constant Problem(s)

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -\Lambda_{\text{eff}} g_{\mu\nu} + \kappa T^{\text{matter}}_{\mu\nu}$$

These first three problems are all ‘classical’. What really gravitates is

$$\Lambda_{\text{eff}} = \Lambda_{\text{B}} + \kappa \rho_{\text{vac}},$$

that’s the lambda in ΛCDM. That we simply measure, as any other fundamental constant.

# The Cosmological Constant Problem(s)

**UV Sensitivity.**

The vacuum energy computed in QFT is UV sensitive, despite being a constant throughout spacetime:

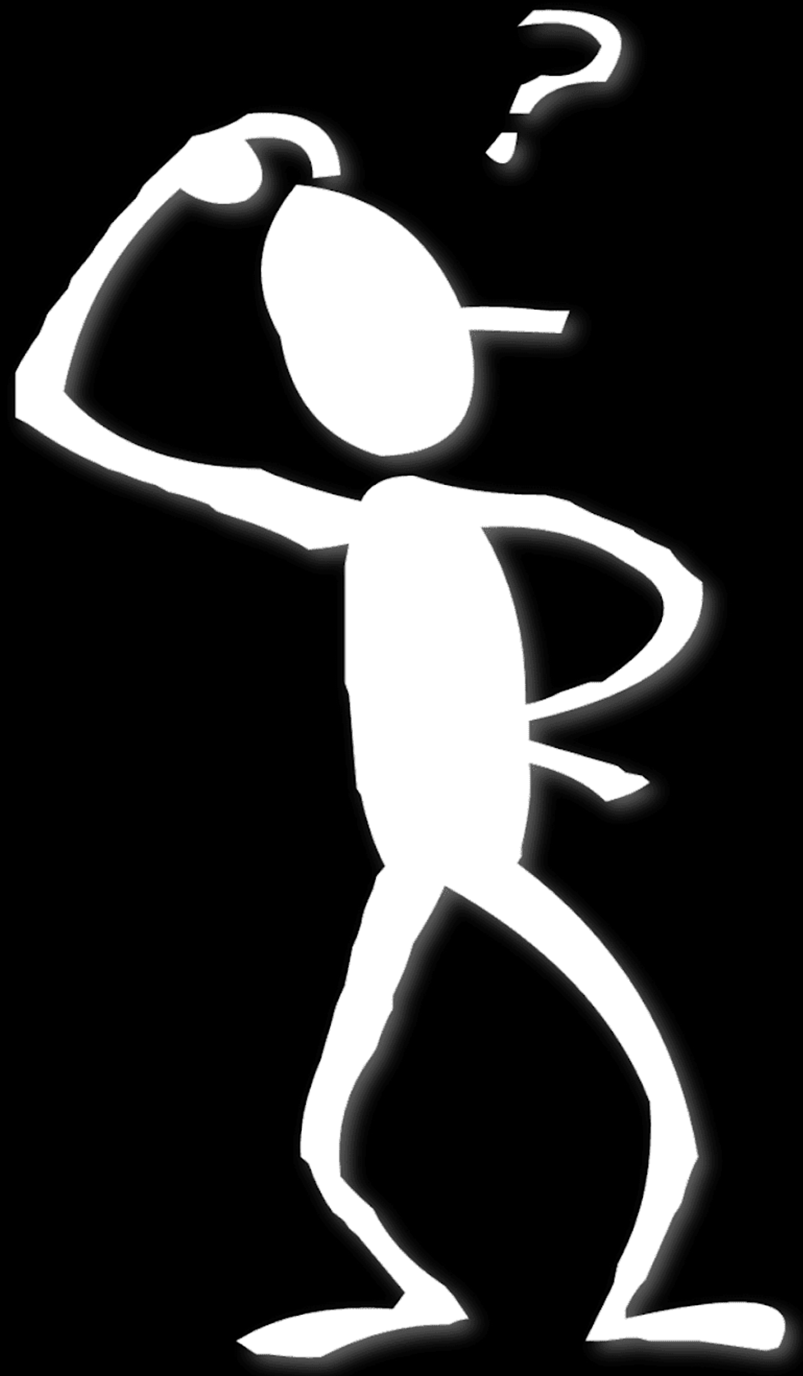
a. The Higgs' mass squared is highly UV sensitive (quadratic in cutoff ). But the vacuum energy scales with the $m^4$, thus an even worse sensitivity;

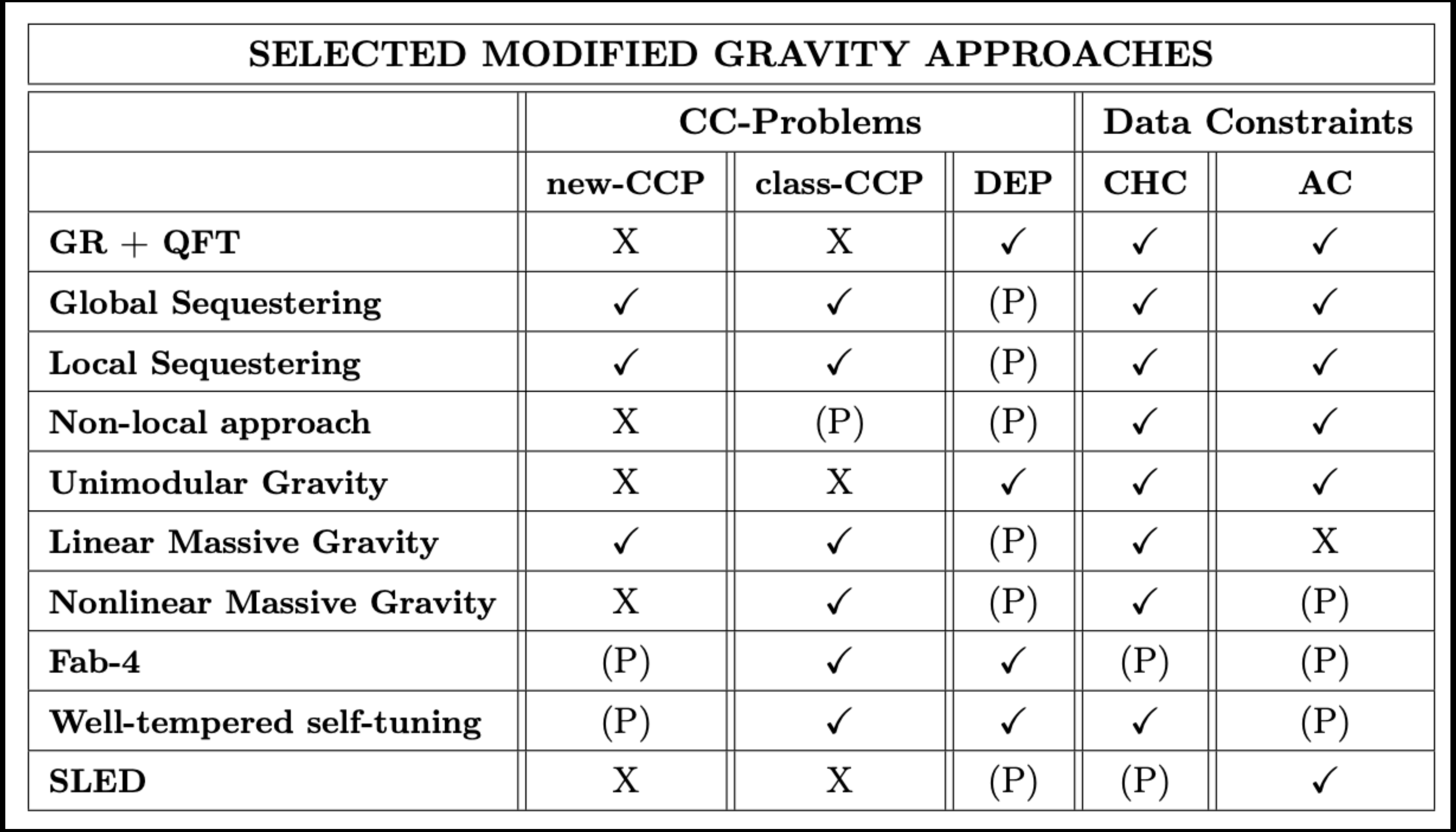
b. As we increase the QFT cutoff, new fields with higher masses can be excited, disturbing the fixing of the CC done at lower scales.

In short, once we change the energy scale in which we are computing the vacuum energy, the radiative corrections from higher-order loop corrections shift the value of $\rho_{\text{vac}}$.

# There have been countless proposals attempting at tackling these issues. What is the best attitude?

a. **Modify GR** (self-tuning)





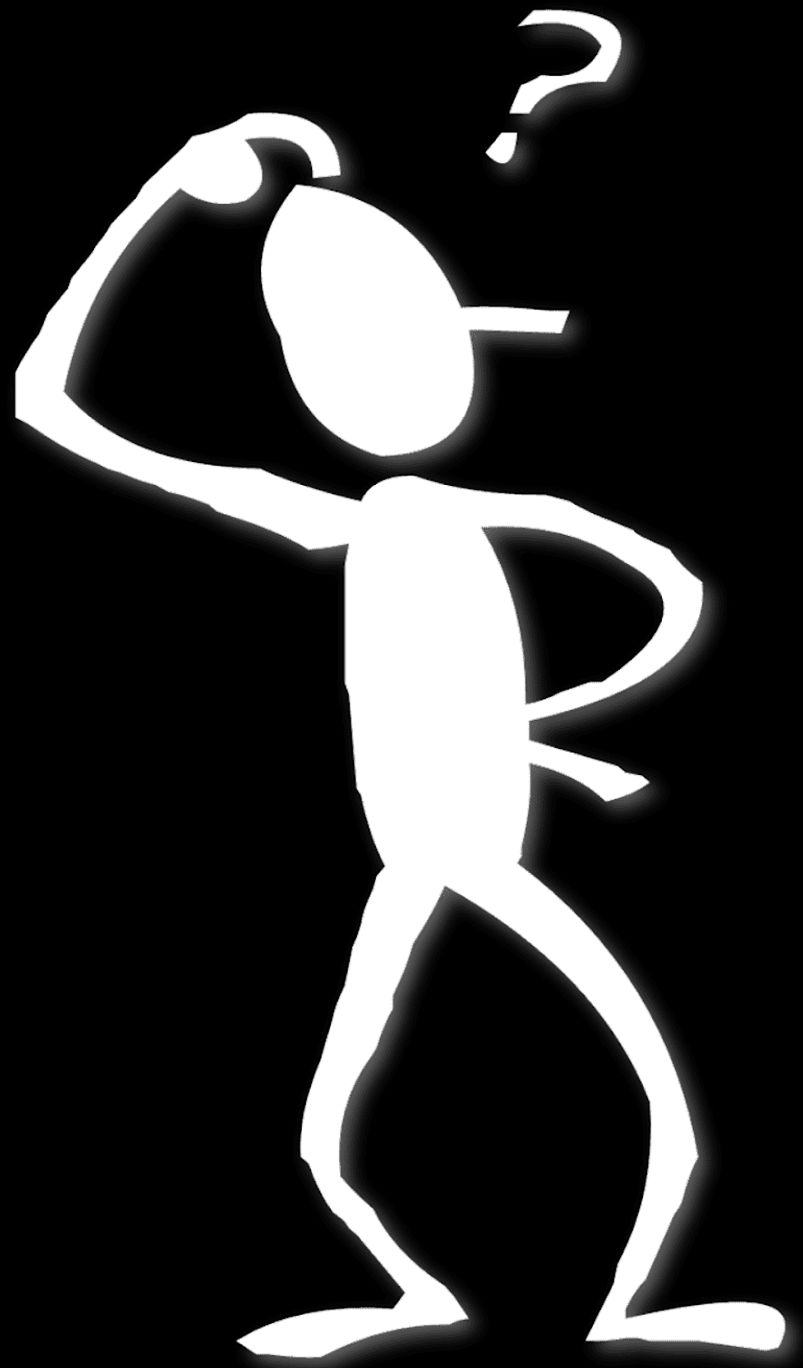
SELECTED MODIFIED GRAVITY APPROACHES

| | CC-Problems | | | Data Constraints | |
|---|---|---|---|---|---|
| | new-CCP | class-CCP | DEP | CHC | AC |
| GR + QFT | X | X | ✓ | ✓ | ✓ |
| Global Sequestering | ✓ | ✓ | (P) | ✓ | ✓ |
| Local Sequestering | ✓ | ✓ | (P) | ✓ | ✓ |
| Non-local approach | X | (P) | (P) | ✓ | ✓ |
| Unimodular Gravity | X | X | ✓ | ✓ | ✓ |
| Linear Massive Gravity | ✓ | ✓ | (P) | ✓ | X |
| Nonlinear Massive Gravity | X | ✓ | (P) | ✓ | (P) |
| Fab-4 | (P) | ✓ | ✓ | (P) | (P) |
| Well-tempered self-tuning | (P) | ✓ | ✓ | ✓ | (P) |
| SLED | X | X | (P) | (P) | ✓ |

There have been countless proposals attempting at tackling these issues. What is the best attitude?

a. **Modify GR** (self-tuning)

b. **Modify the standard model** (SUSY, for instance)

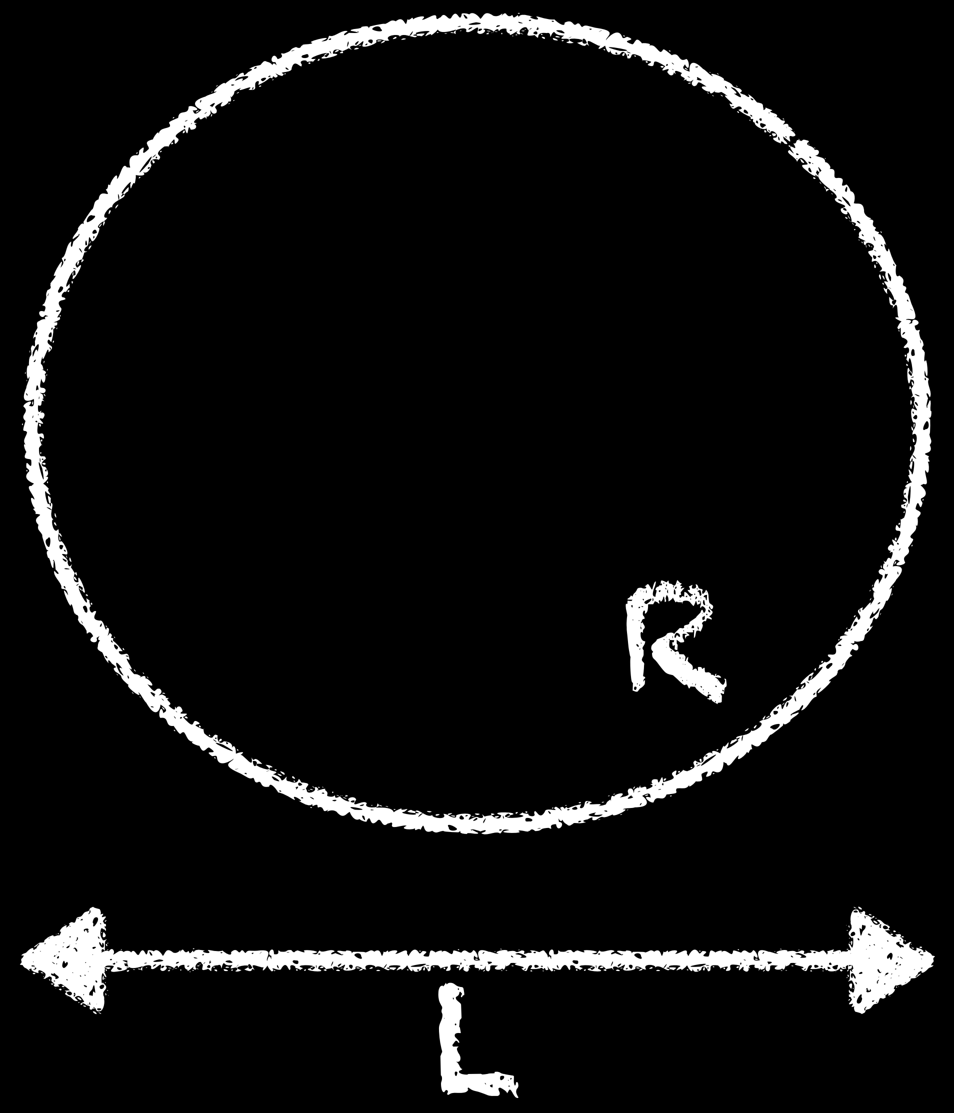


A more radical proposal:

**Take the CCPs as a strong empirical evidence of the breakdown of QFT in the presence of gravity.**

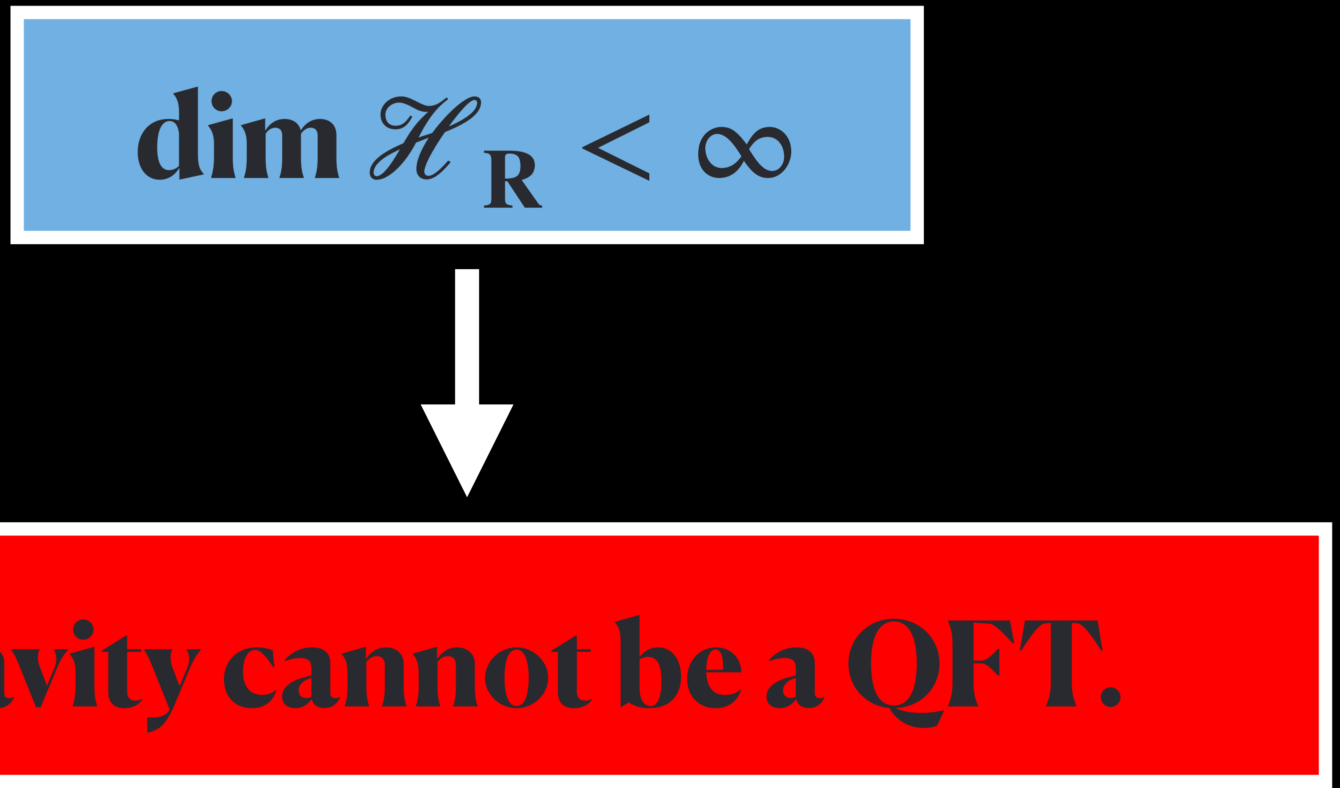
(Bao, Carroll, Singh '17)

# In fact, another argument:



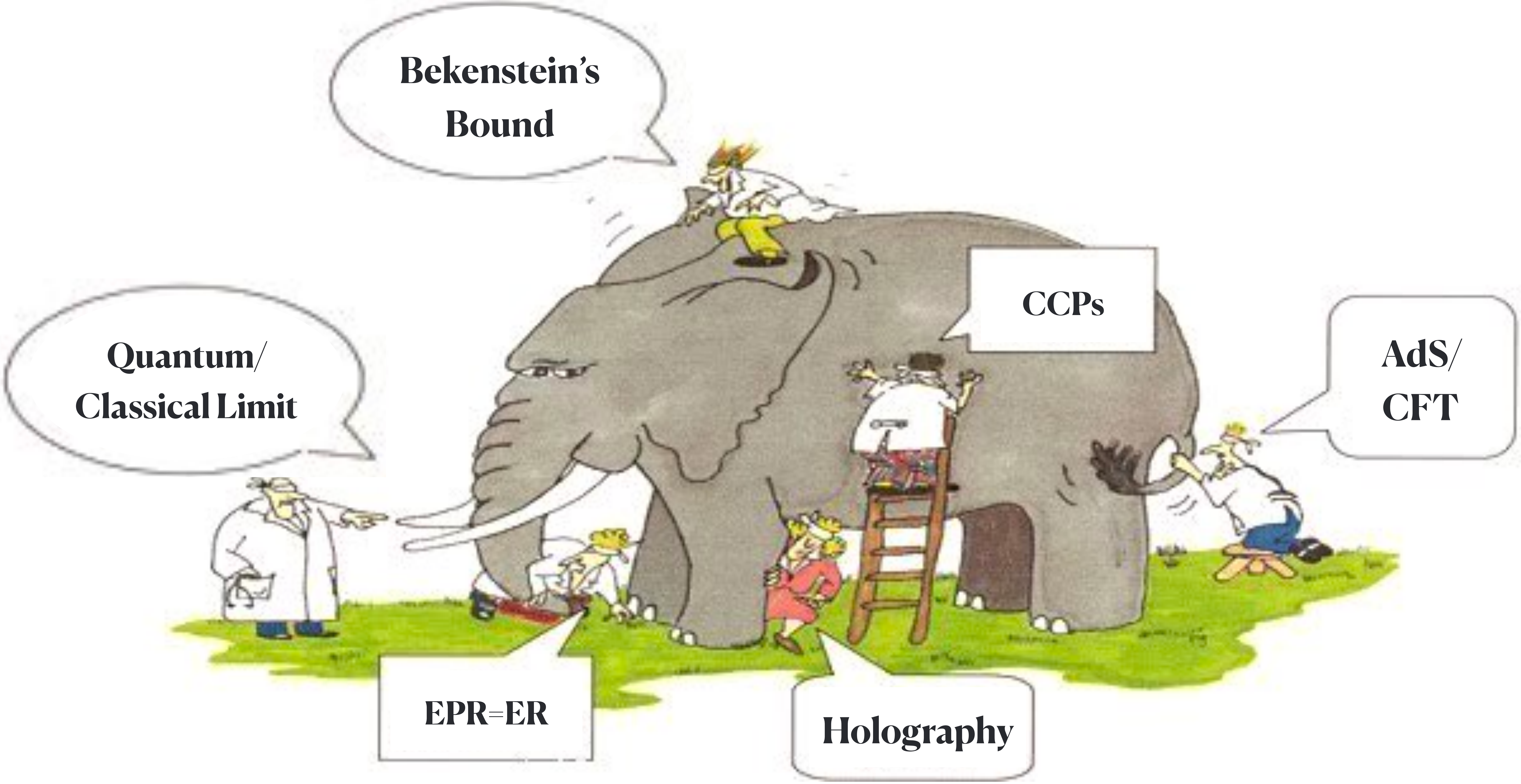
Bekenstein Bound ('81)

$$S_\mathrm{R} \leq \frac{\pi k L E}{\hbar c}$$



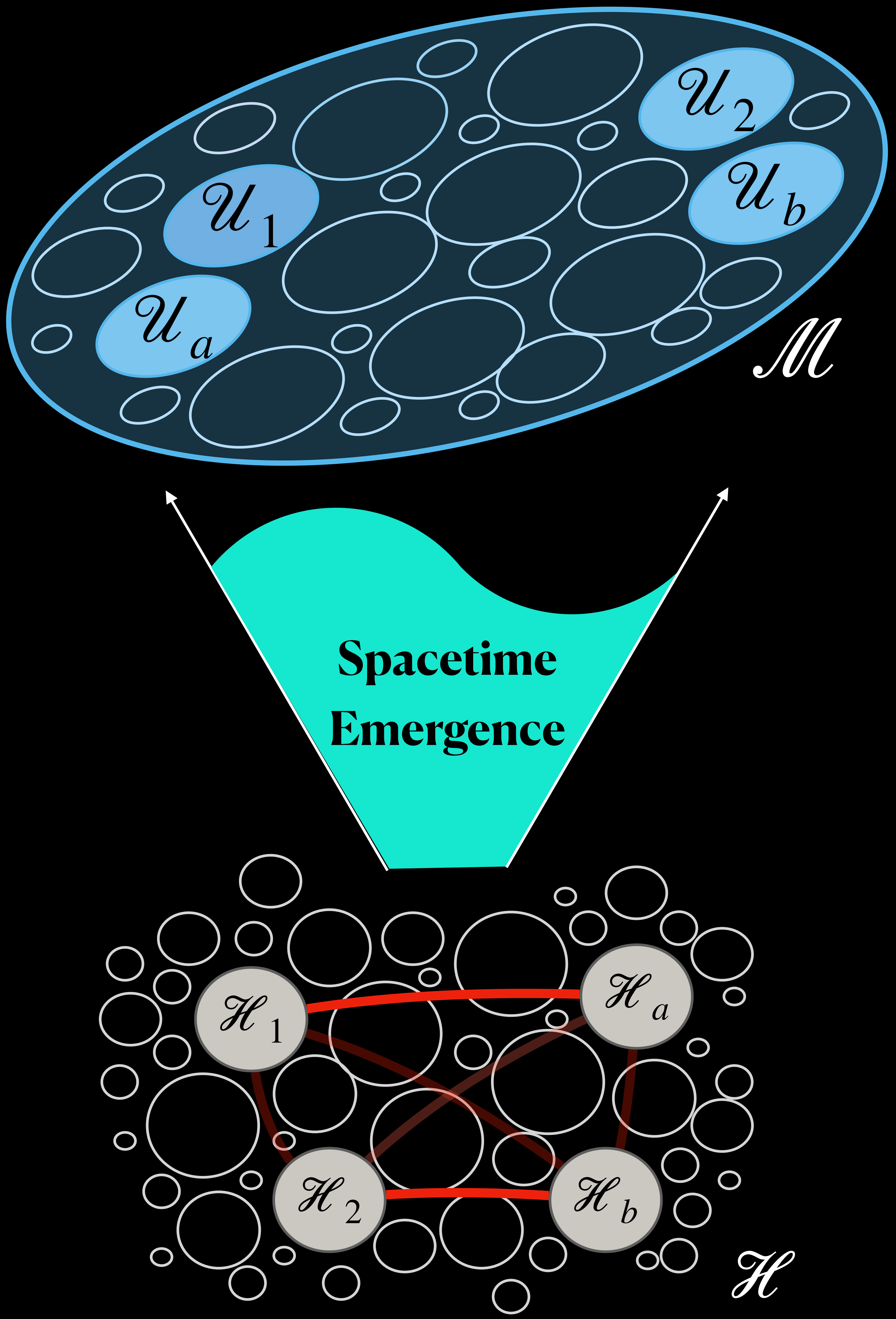
**$\dim \mathscr{H}_\mathrm{R} < \infty$**

**Gravity cannot be a QFT.**



# What is the elephant?

# Questions?



Spacetime Emergence

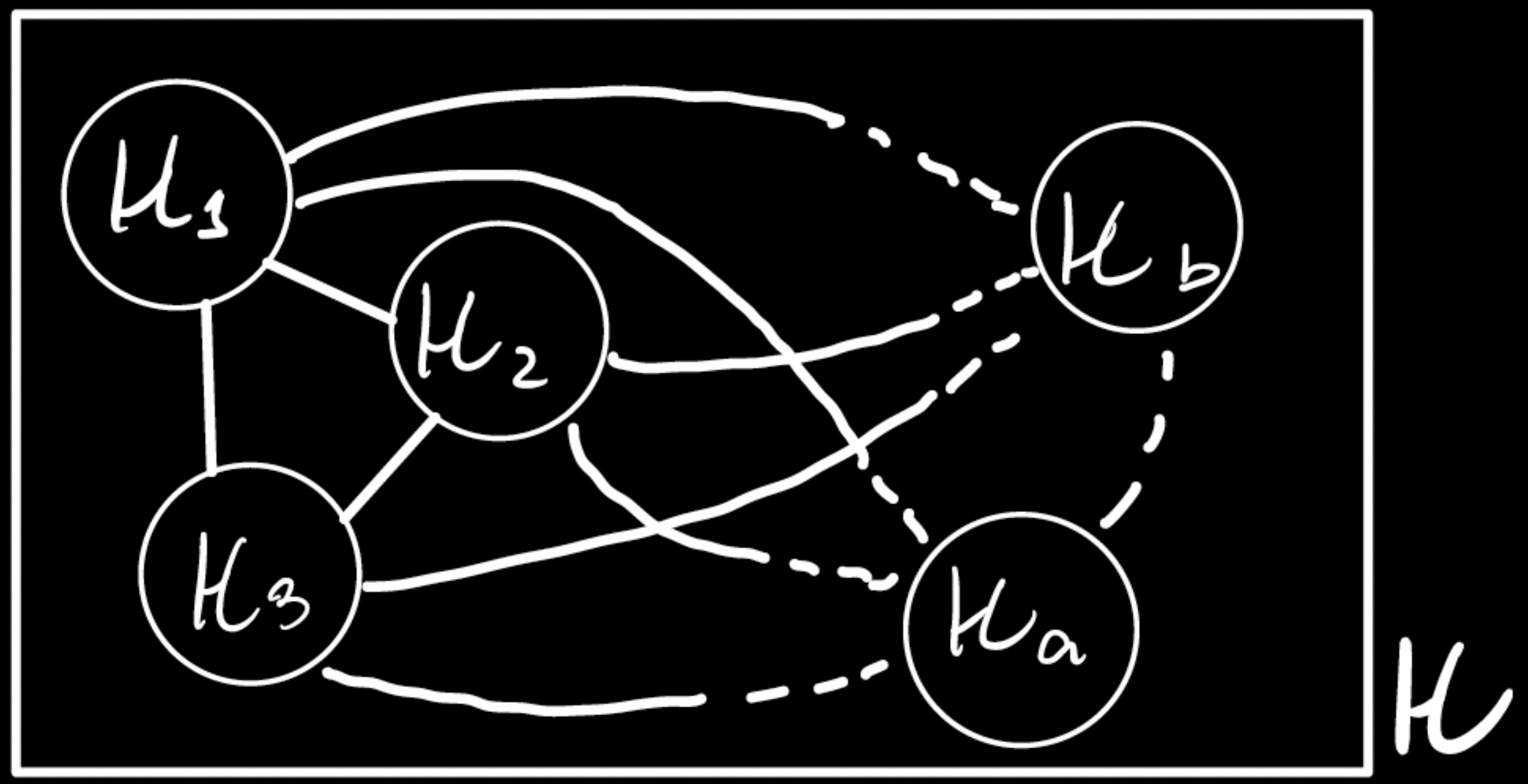
(van Raamsdonk, '10)
(Cao, Carroll, Michalakis, '16)

# Quantum-first approach

a. Hilbert space $\left(\mathscr{H}_{<\infty}\right)$, state $\left(|\Psi\rangle\right)$, Hamiltonian $(H)$

b. Schroedinger equation: $i\hbar\partial_t|\psi\rangle = \hat{H}|\psi\rangle$

c. $\mathscr{H} = \otimes_i \mathscr{H}_i \quad \rightarrow \quad H$ local

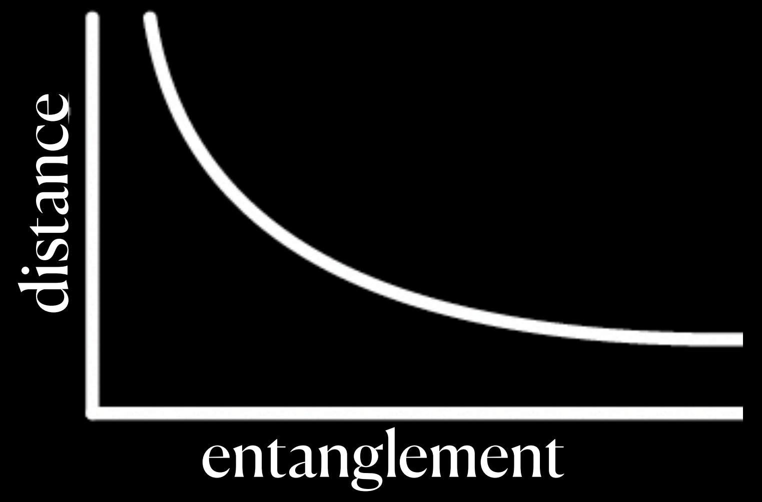


d. compute the mutual information $\left(I_{ab}\right)$

e. define the metric $ds_{ab}\left(I_{ab}\right)$

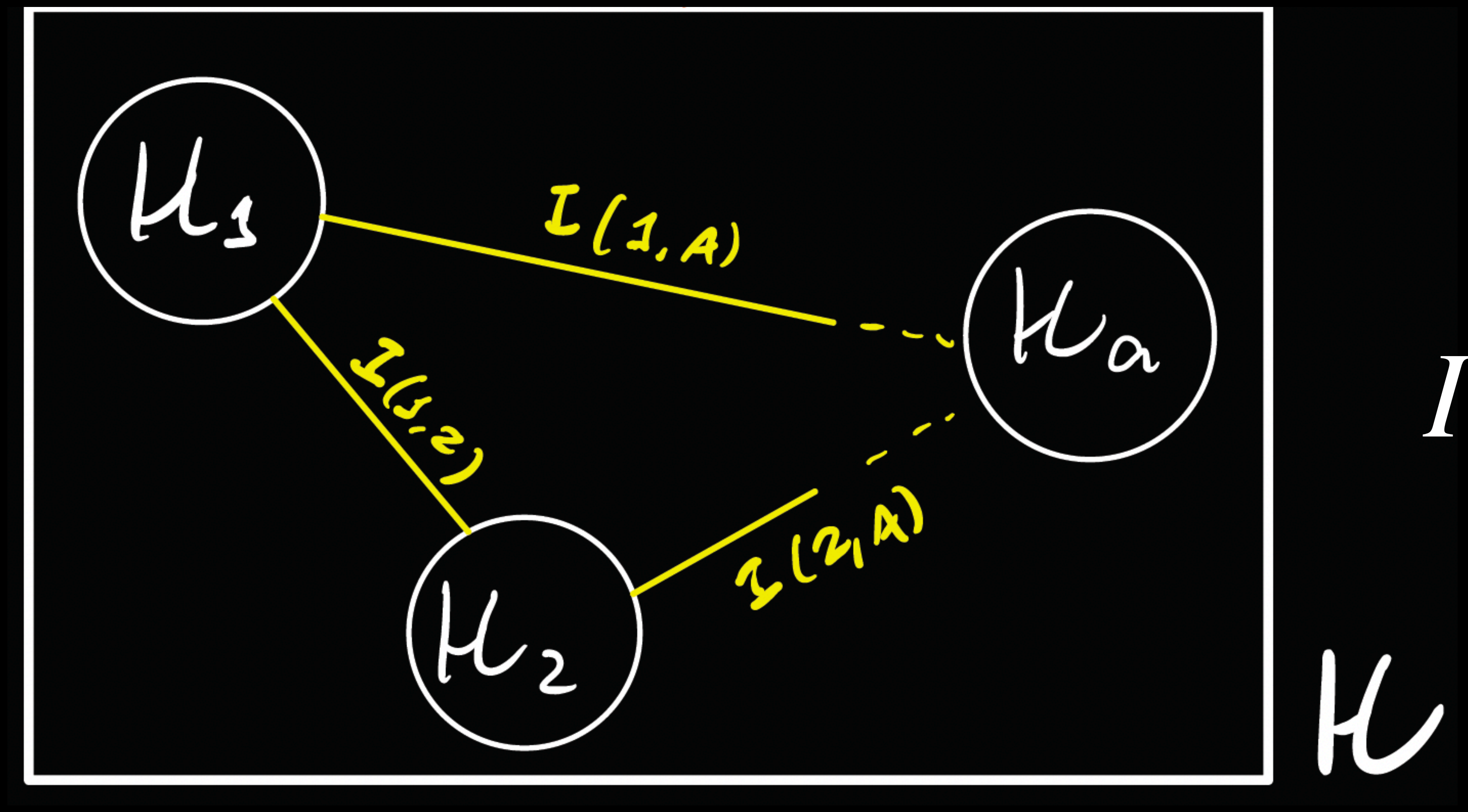
f. reconstruct smooth geometries

g. $\delta|\Psi\rangle \rightarrow \delta I_{ab} \rightarrow \delta ds_{ab} \rightarrow h_{\mu\nu}$ obeying Einstein's equations



(van Raamsdonk, '10)
(Cao, Carroll, Michalakis, '16)

# On the mutual information



$$I(A,B) = S(A) + S(B) - S(A \cup B)$$

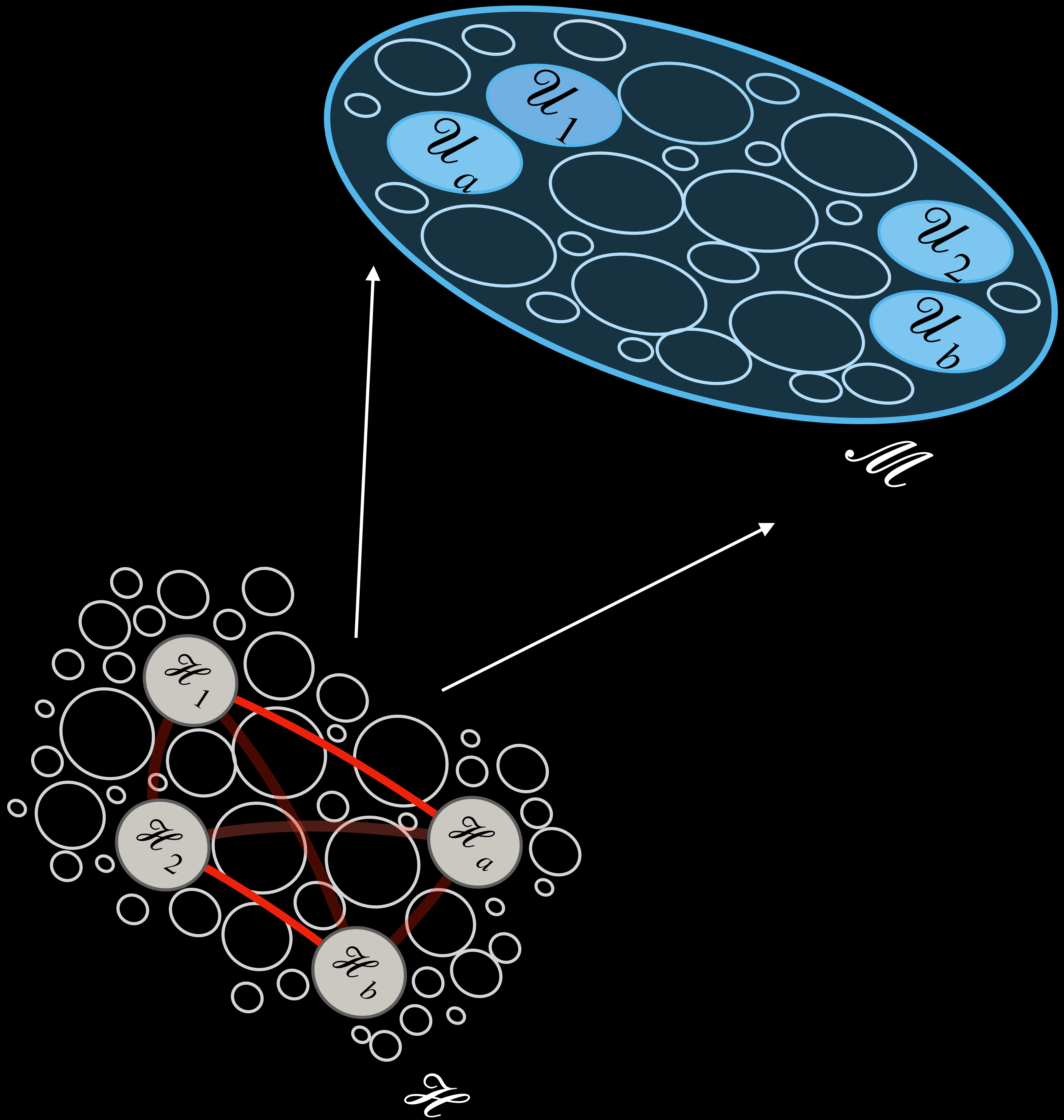
(scalar, symmetric, non-negative)

$$\boxed{I(A,B) \geq \frac{\left(\langle \mathcal{O}_A \mathcal{O}_B \rangle - \langle \mathcal{O}_A \rangle \langle \mathcal{O}_B \rangle\right)^2}{2\,|\mathcal{O}_A|^2\,|\mathcal{O}_B|^2}}$$

(Wolf, Verstraete,
Hastings, Cirac, '18)

$$\langle \mathcal{O}_A(x_A) \mathcal{O}_B(x_B) \rangle \sim e^{-mL}$$

(van Raamsdonk, ’10)



“more entangled” ~
“close together”

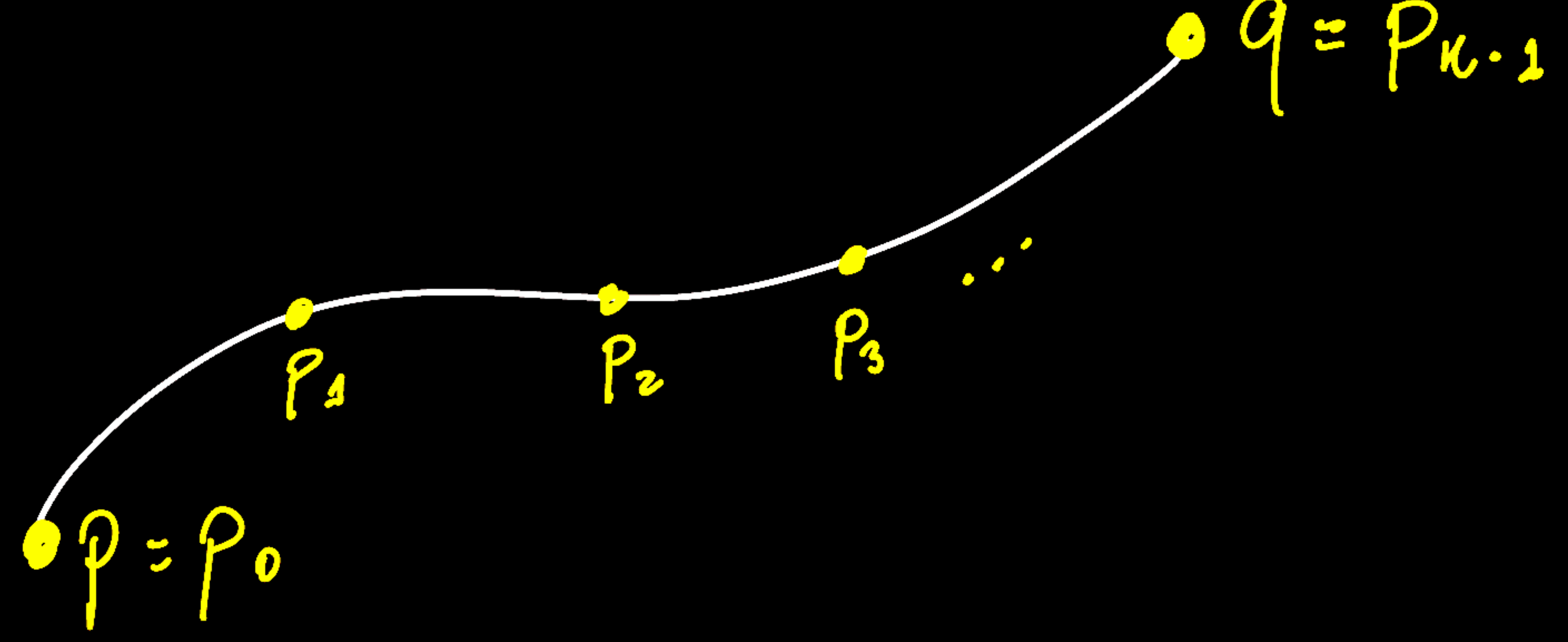
$$\Phi\left(I_{AB}/I_{\max}\right)$$

$$\Phi(1) \to 0$$

$$\Phi(0) \to \infty$$

e.g. $\Phi(x) = -\log(x)$

$$w(p,q) = \begin{cases} l_0 \, \Phi\left( I(A_p, A_q)/I_0 \right), & p \neq q \\ 0, & p = q \end{cases}$$



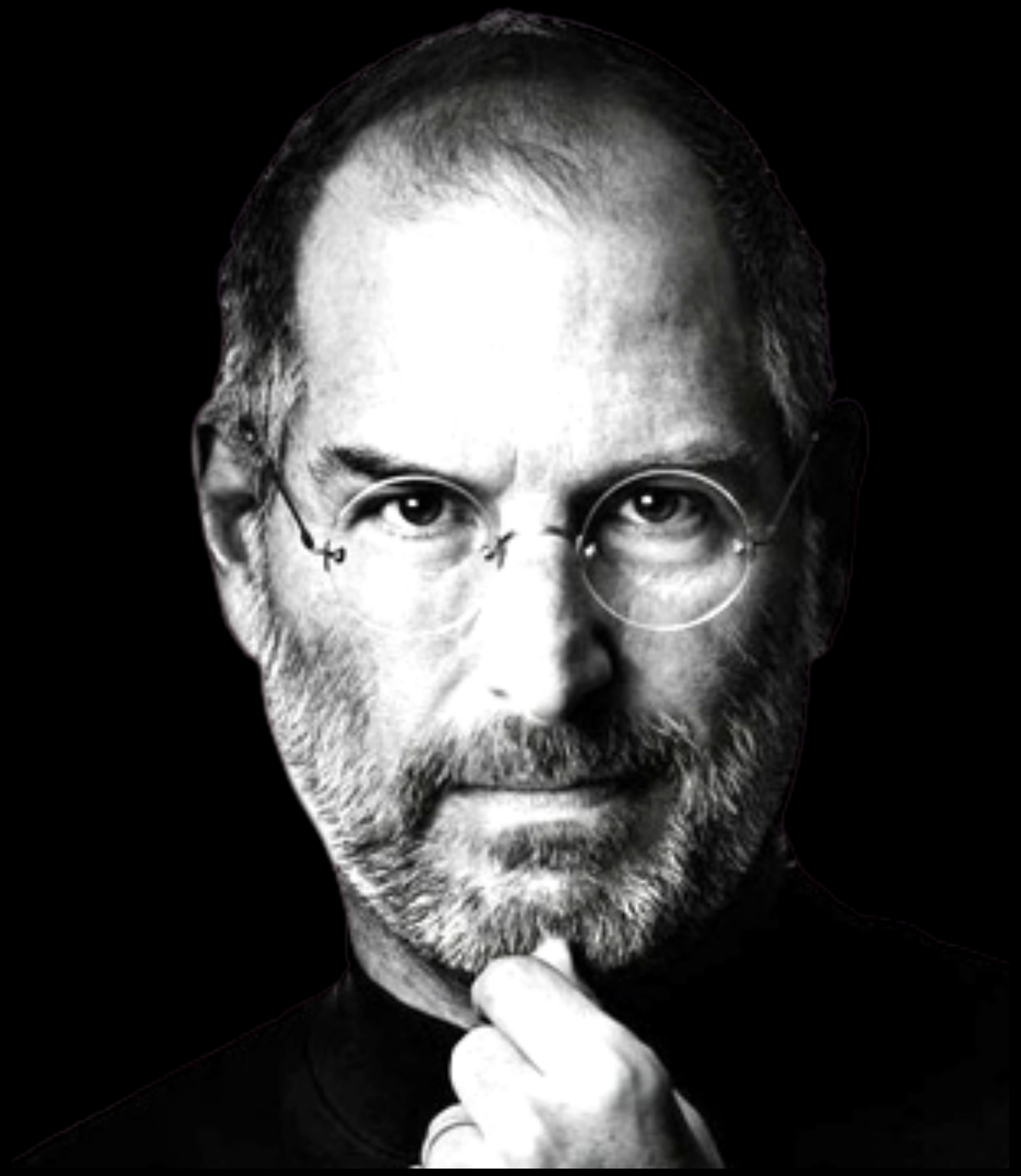
$$d(p,q) = \min_{path\ p} \sum_{n=0}^{k-1} w\left(p_n, p_{n+1}\right)$$

$$\mathbf{A} := \frac{I(A_p, A_q)}{2\alpha}$$

(Cao, Carroll, Michalakis, '16)
(Blanco, Casini, Hung, Myers, '13)
(Faulkner, Guica, Hartman, Myers, Raamsdonk, '13)

$$\begin{tikzcd}
& \delta A \arrow[rr, leftrightarrow, "\mathbf{A} := \frac{I(A_p, A_q)}{2\alpha}"] & & \delta S \arrow[dr, leftrightarrow, "\substack{\text{Entanglement 1st Law} \\ \delta S = \delta\langle \hat{K} \rangle}"] & \\
\mathscr{R} \arrow[ur, leftrightarrow, "\delta A = -\frac{\Omega_{D-1} r^{D-1}}{2D(D+2)} \mathscr{R}_p"] \arrow[dr, leftrightarrow, "\mathscr{R}_p = 2G_{00}(p)"'] & & \boxed{G_{\mu\nu} \propto T_{\mu\nu}} & & \delta\langle \hat{K} \rangle \\
& G_{00} \arrow[rr, leftrightarrow] & {} \arrow[u, "\substack{\text{Lorentz} \\ \text{Invariance}}"'] & T_{00} \arrow[ur, leftrightarrow, "\delta\langle \hat{K} \rangle \to \delta\langle T_{00} \rangle"'] &
\end{tikzcd}$$

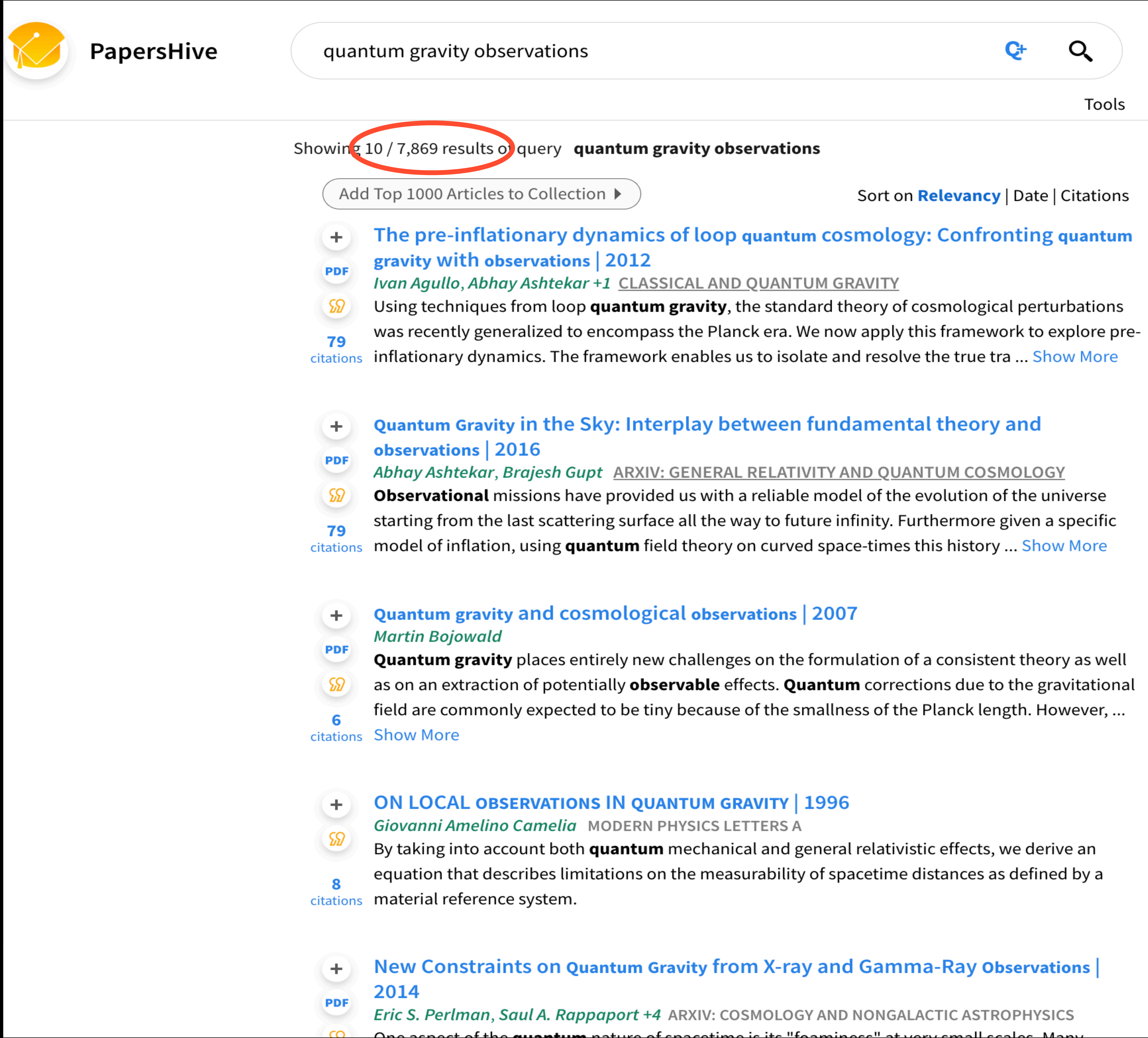
# Questions?



# Space(-time) Emergence

## Experimental Signatures

# Quantum Gravity: observational signatures



quantum gravity observations

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*Ivan Agullo, Abhay Ashtekar +1* CLASSICAL AND QUANTUM GRAVITY
Using techniques from loop **quantum gravity**, the standard theory of cosmological perturbations was recently generalized to encompass the Planck era. We now apply this framework to explore pre-inflationary dynamics. The framework enables us to isolate and resolve the true tra ... Show More
79 citations

**Quantum Gravity** in the Sky: Interplay between fundamental theory and **observations** | 2016
*Abhay Ashtekar, Brajesh Gupt* ARXIV: GENERAL RELATIVITY AND QUANTUM COSMOLOGY
**Observational** missions have provided us with a reliable model of the evolution of the universe starting from the last scattering surface all the way to future infinity. Furthermore given a specific model of inflation, using **quantum** field theory on curved space-times this history ... Show More
79 citations

**Quantum gravity** and cosmological **observations** | 2007
*Martin Bojowald*
**Quantum gravity** places entirely new challenges on the formulation of a consistent theory as well as on an extraction of potentially **observable** effects. **Quantum** corrections due to the gravitational field are commonly expected to be tiny because of the smallness of the Planck length. However, ... Show More
6 citations

ON LOCAL **OBSERVATIONS** IN **QUANTUM GRAVITY** | 1996
*Giovanni Amelino Camelia* MODERN PHYSICS LETTERS A
By taking into account both **quantum** mechanical and general relativistic effects, we derive an equation that describes limitations on the measurability of spacetime distances as defined by a material reference system.
8 citations

New Constraints on **Quantum Gravity** from X-ray and Gamma-Ray **Observations** | 2014
*Eric S. Perlman, Saul A. Rappaport +4* ARXIV: COSMOLOGY AND NONGALACTIC ASTROPHYSICS
One aspect of the **quantum** nature of spacetime is its "foaminess" at very small scales. Many

## Minimal Length Scale Scenarios for Quantum Gravity

Sabine Hossenfelder (Nordita)
Mar, 2012

89 pages
Published in: *Living Rev.Rel.* 16 (2013) 2
Published: 2013
e-Print: 1203.6191 [gr-qc]
DOI: 10.12942/lrr-2013-2
View in: ADS Abstract Service

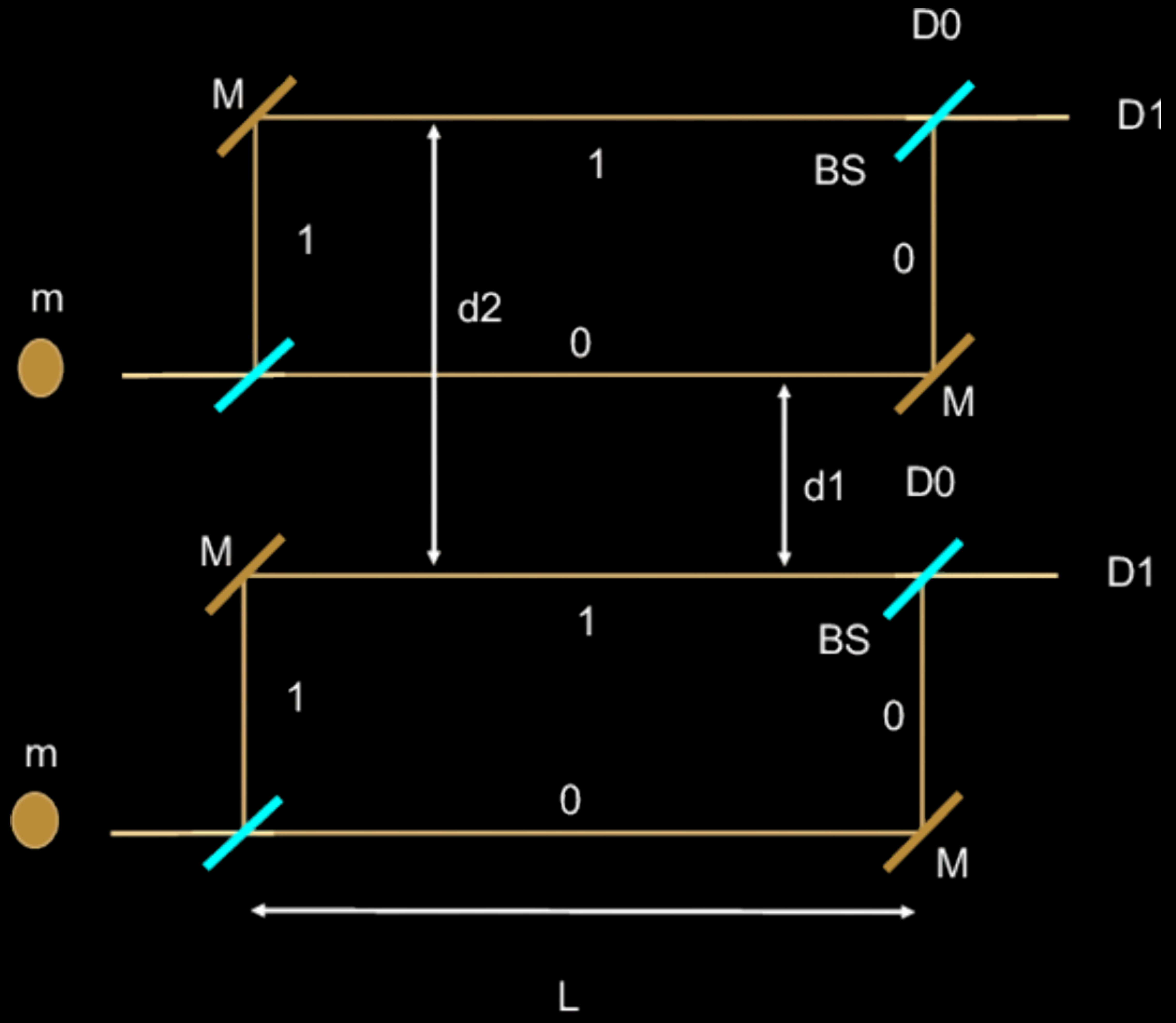
Abstract: (arXiv)
We review the question of whether the fundamental laws of nature limit our ability to probe arbitrarily short distances. First, we examine what insights can be gained from thought experiments for probes of shortest distances, and summarize what can be learned from different approaches to a theory of quantum gravity. Then we discuss some models that have been developed to implement a minimal length scale in quantum mechanics and quantum field theory. These models have entered the literature as the generalized uncertainty principle or the modified dispersion relation, and have allowed the study of the effects of a minimal length scale in quantum mechanics, quantum electrodynamics, thermodynamics, black-hole physics and cosmology. Finally, we touch upon the question of ways to circumvent the manifestation of a minimal length scale in short-distance physics.

(Bose, Mazumdar, Morley, Ulbricth, Toros, '17)
(Marletto, Vedral, '17)
(Carney, Stamp, Taylor, '18)

# Quantum Gravity: table-top gravitational-quantum experiments

It is argued that if gravity can entangle two systems then we should conclude that is indeed quantum (superimposed metric fluctuations).

**Bose-Marletto-Vedral experiment:**
two particles start off in a superposition of two different spatial positions, leading to four different branches of the wavefunction. In each branch the gravitational interaction between the particles yields a different phase shift, entangling them.



However, suppose space(-time) is emergent from more fundamental quantum degrees of freedom.

**Then, it is unclear what to conclude from these experiments, as we do expect that these more fundamental degrees of freedom are ruled by interactions that produce entanglement, despite not being gravitational.**

One way to parse out this “degeneracy" about the nature of gravity is probing its emergent nature.

# Curvature and Entanglement Perturbations

Consider a quantum state, $\rho = |\psi\rangle\langle\psi|$. Then,

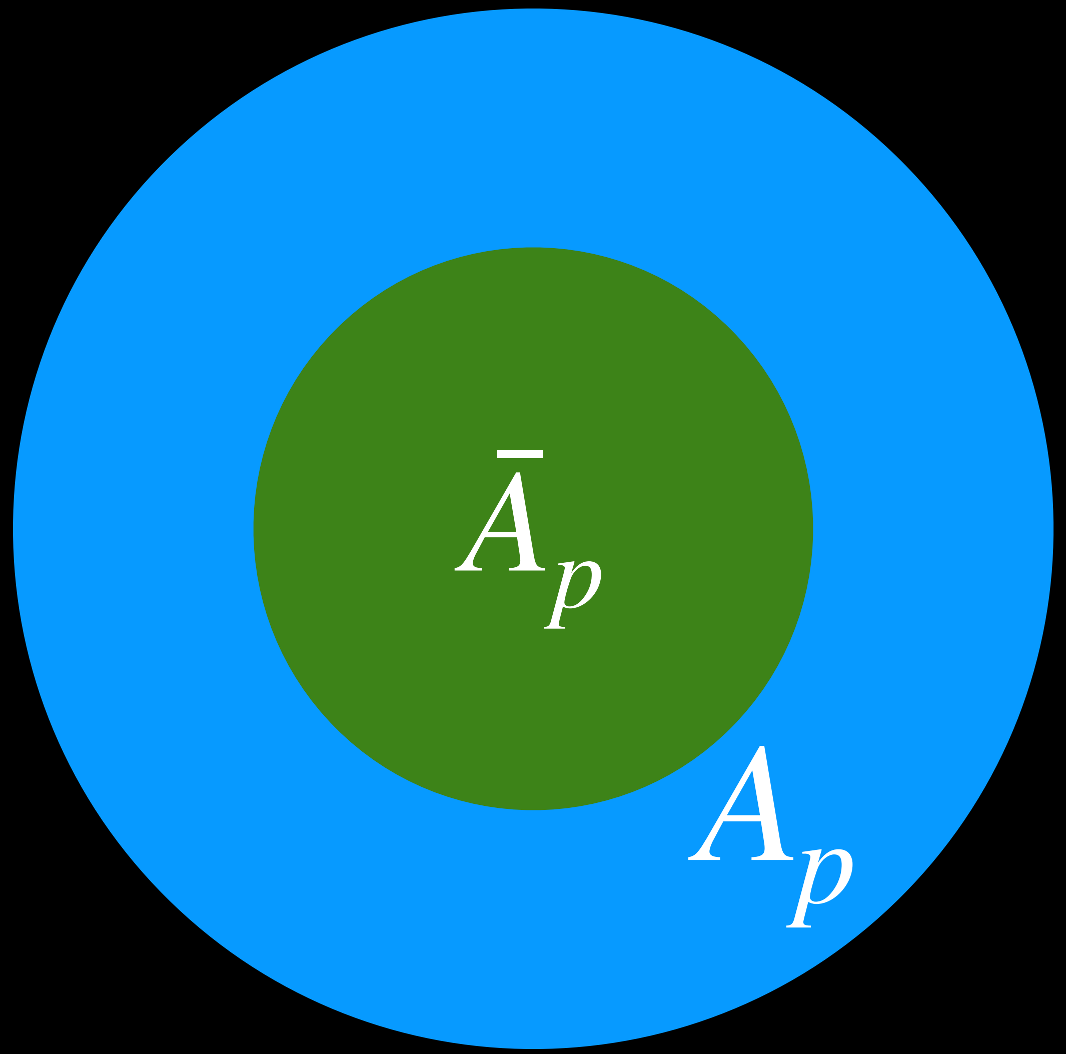
$$\rho_{A_p} = \mathrm{Tr}_{\bar{A}_p}\,\rho \qquad \text{and} \qquad \boxed{\alpha A = I\left(A_p, \bar{A}_p\right)/2}$$

Now perturb the state locally by changing entanglement

between $A_p$ and $\bar{A}_p$:

$$\rho' = U^{\dagger}_{A_p\bar{A}_p}\,\rho\, U_{A_p\bar{A}_p} \quad \rightarrow \quad \delta I(A_p, \bar{A}_p) = 2\delta S(A_p).$$

$$\mathscr{H} = \mathscr{H}_{A_p} \otimes \mathscr{H}_{\bar{A}_p}$$



# What about the geometry?

a. Introduce Riemann coord. around $A_p$: $h_{ij} = \delta_{ij} - \frac{1}{3} r^2 \mathscr{R}_{ijkl} x^k x^l + \mathcal{O}(r^3)$

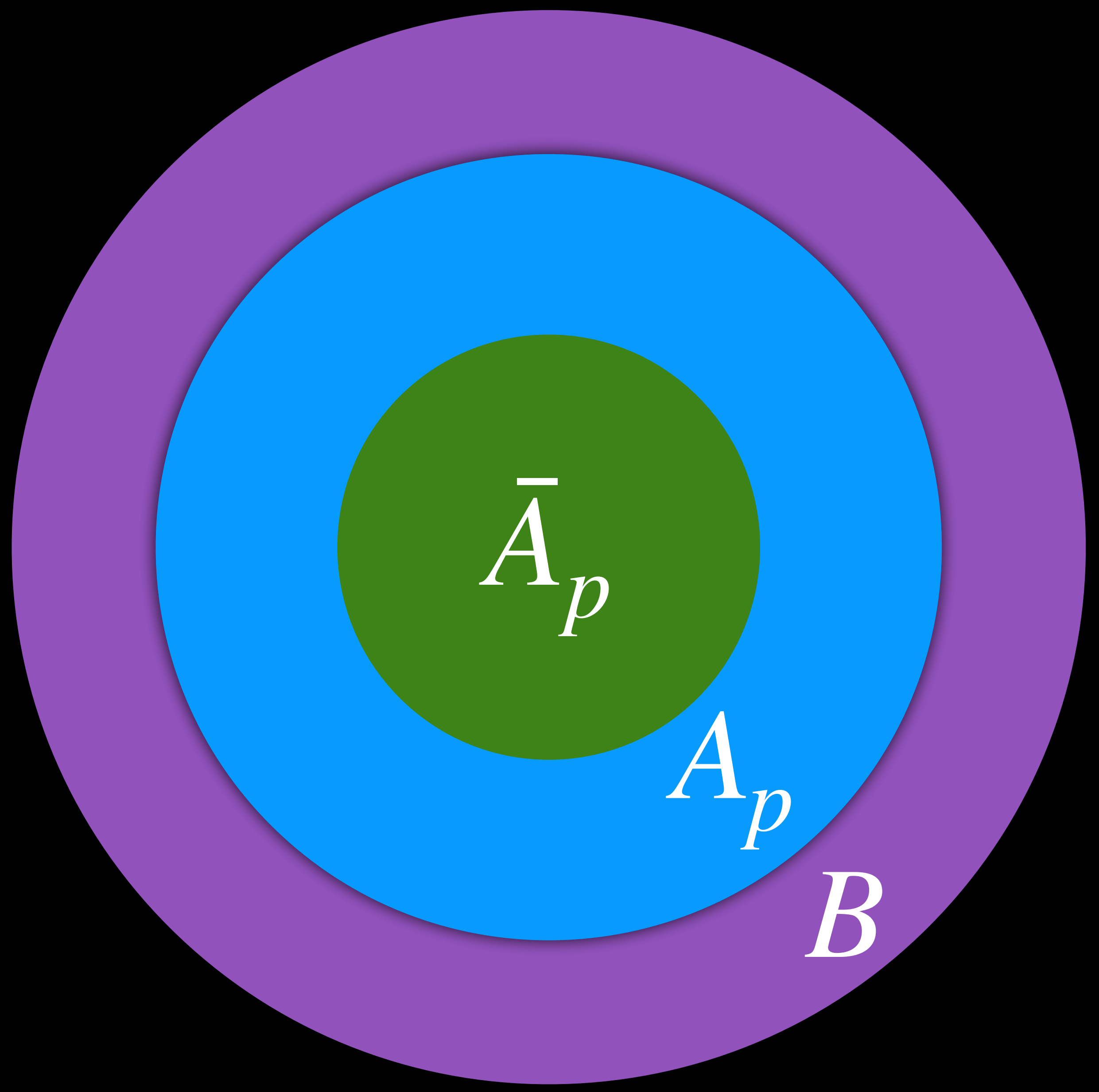
b. For fixed volume: $\delta A = -\frac{\Omega_{D-1} r^{D-1}}{2D(D+2)} \mathscr{R}_p,$

c. But $\alpha A = I\left(A_p, \bar{A}_p\right)/2$

d. Thus:

$$\mathscr{R}_p = -\frac{2D(D+2)}{\alpha \Omega_{D-1} r^{D-1}} \delta S_{A_p} \Rightarrow \boxed{\begin{array}{l} \delta S_{A_p} < 0 \to \mathscr{R}_p > 0 \\ \delta S_{A_p} > 0 \to \mathscr{R}_p < 0 \end{array}}$$

$$\mathscr{H} = \mathscr{H}_{A_p} \otimes \mathscr{H}_{\bar{A}_p} \otimes \mathscr{H}_{B}$$



Now perturb the state non-locally,

$$U_{A_p\bar{A}_pB} = U_{A_pB} \otimes I_{\bar{A}_p}\,.$$

Then,

$$\delta I(A_p, \bar{A}_p) < 0 \quad \Longrightarrow \quad \boxed{\mathscr{R}_p > 0!}$$

Thus, the induced curvature is always positive.

(In collab. w/ Florian Niedermann)

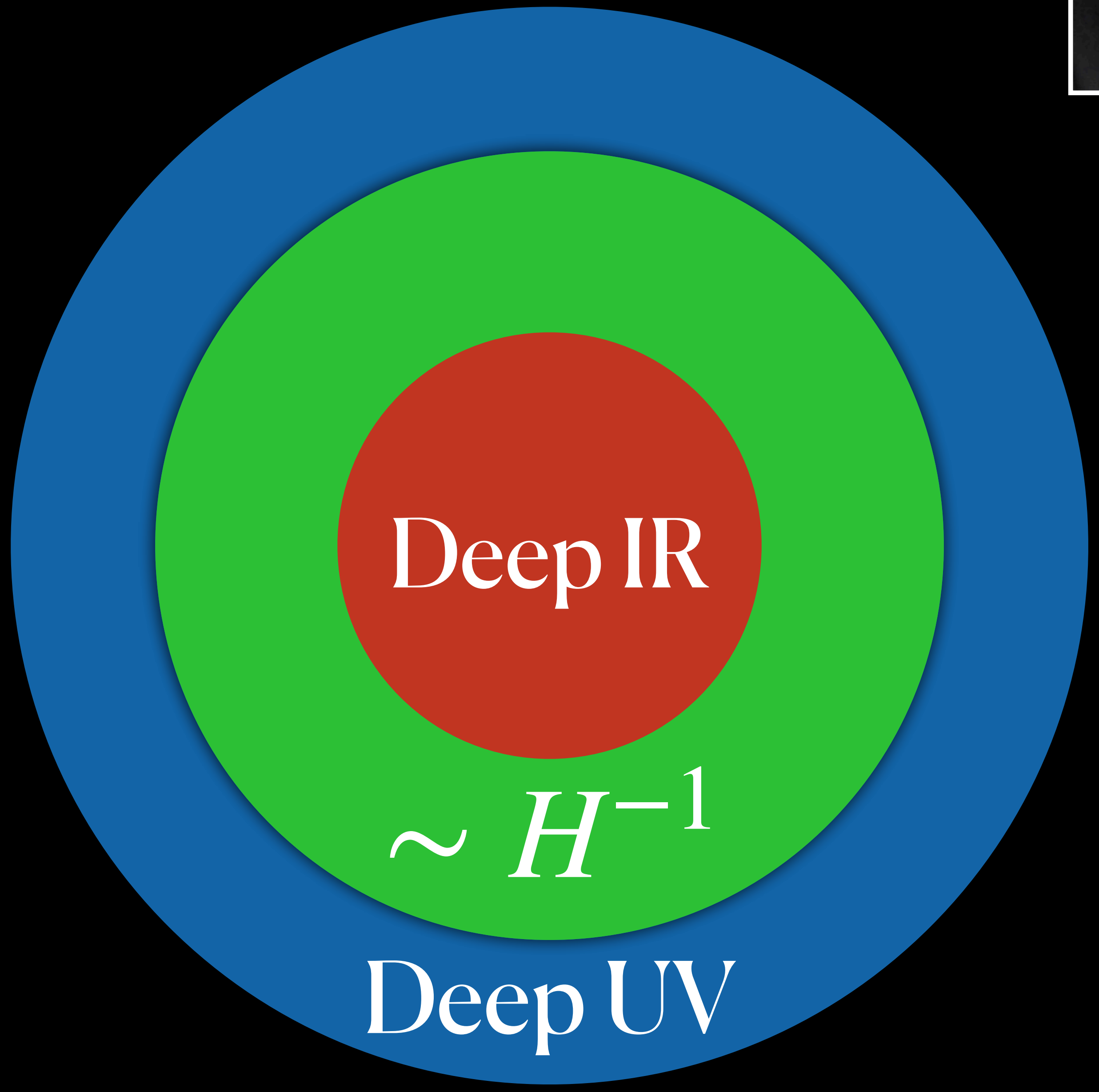
# Cosmological Signatures

At any given time, there are three different sort of modes:

a. Deep UV ($B$)

b. Sub- and supper-Hubble ($A_p$)

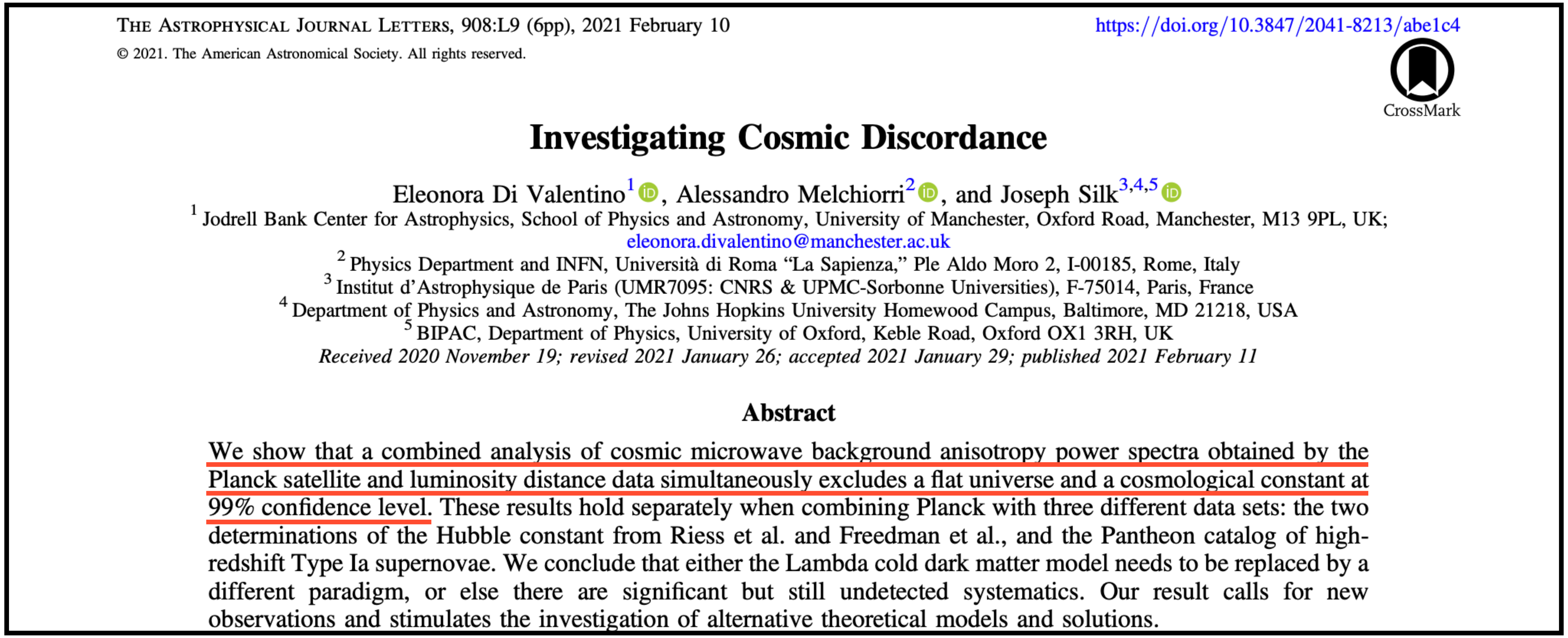
c. Deep IR (beyond horizon) ($\bar{A}_p$)



1. Apply formalism to FRW's spatial hypersurfaces, which seems to lead to positive spatial curvature. Then consider that in the context of current expansion and inflation;

2. Covariantize it for Lorentzian manifolds and see what the implications would be for the full scalar curvature (and dark energy). One needs to understand better what kind of areas are to be considered (covariant entropic bounds).

(Bousso, '02)



The Astrophysical Journal Letters, 908:L9 (6pp), 2021 February 10 https://doi.org/10.3847/2041-8213/abe1c4

# Investigating Cosmic Discordance

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*Received 2020 November 19; revised 2021 January 26; accepted 2021 January 29; published 2021 February 11*

## Abstract

We show that a combined analysis of cosmic microwave background anisotropy power spectra obtained by the Planck satellite and luminosity distance data simultaneously excludes a flat universe and a cosmological constant at 99% confidence level. These results hold separately when combining Planck with three different data sets: the two determinations of the Hubble constant from Riess et al. and Freedman et al., and the Pantheon catalog of high-redshift Type Ia supernovae. We conclude that either the Lambda cold dark matter model needs to be replaced by a different paradigm, or else there are significant but still undetected systematics. Our result calls for new observations and stimulates the investigation of alternative theoretical models and solutions.

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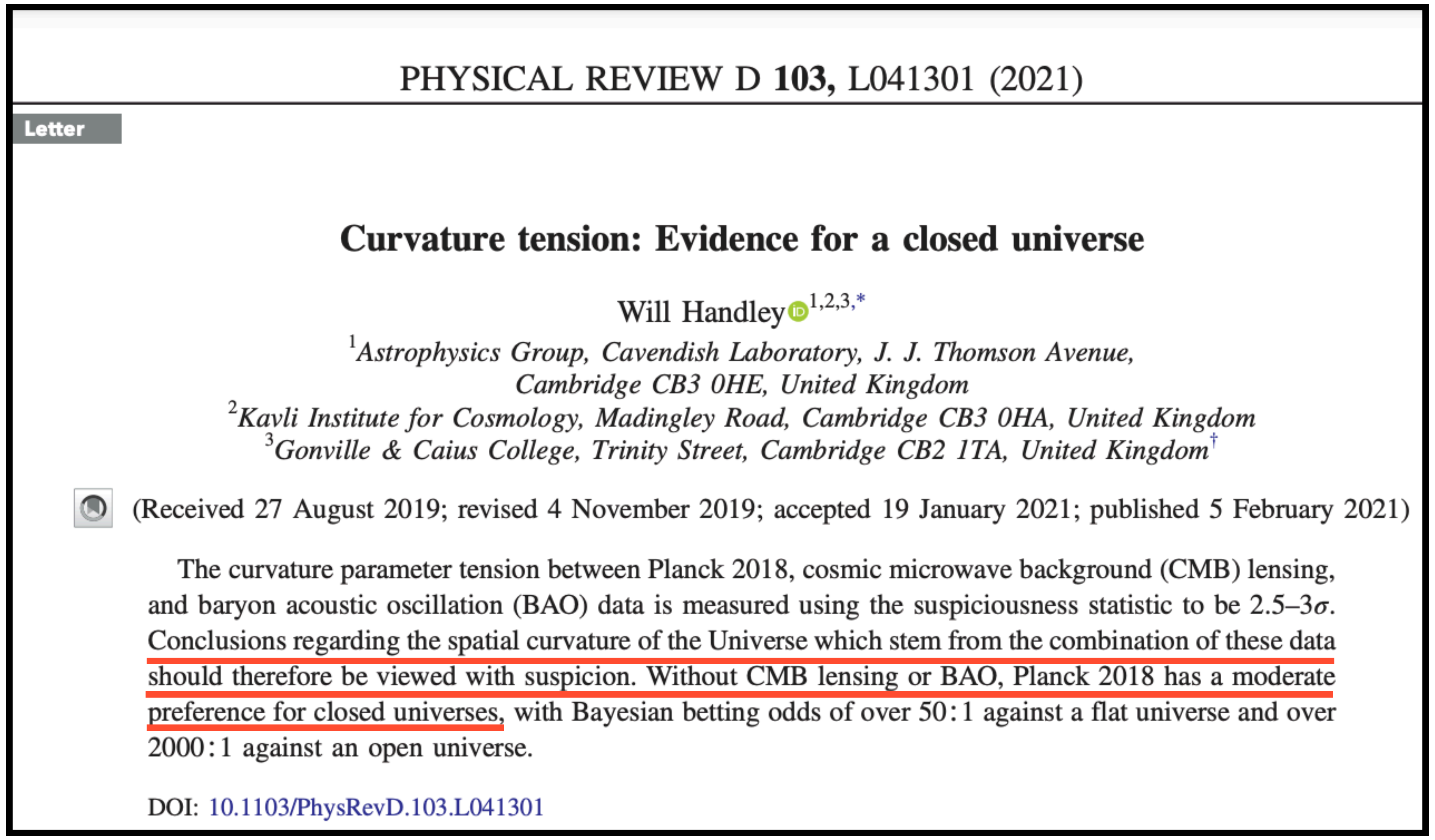

PHYSICAL REVIEW D **103,** L041301 (2021)

# Curvature tension: Evidence for a closed universe

Will Handley[1,2,3,*]
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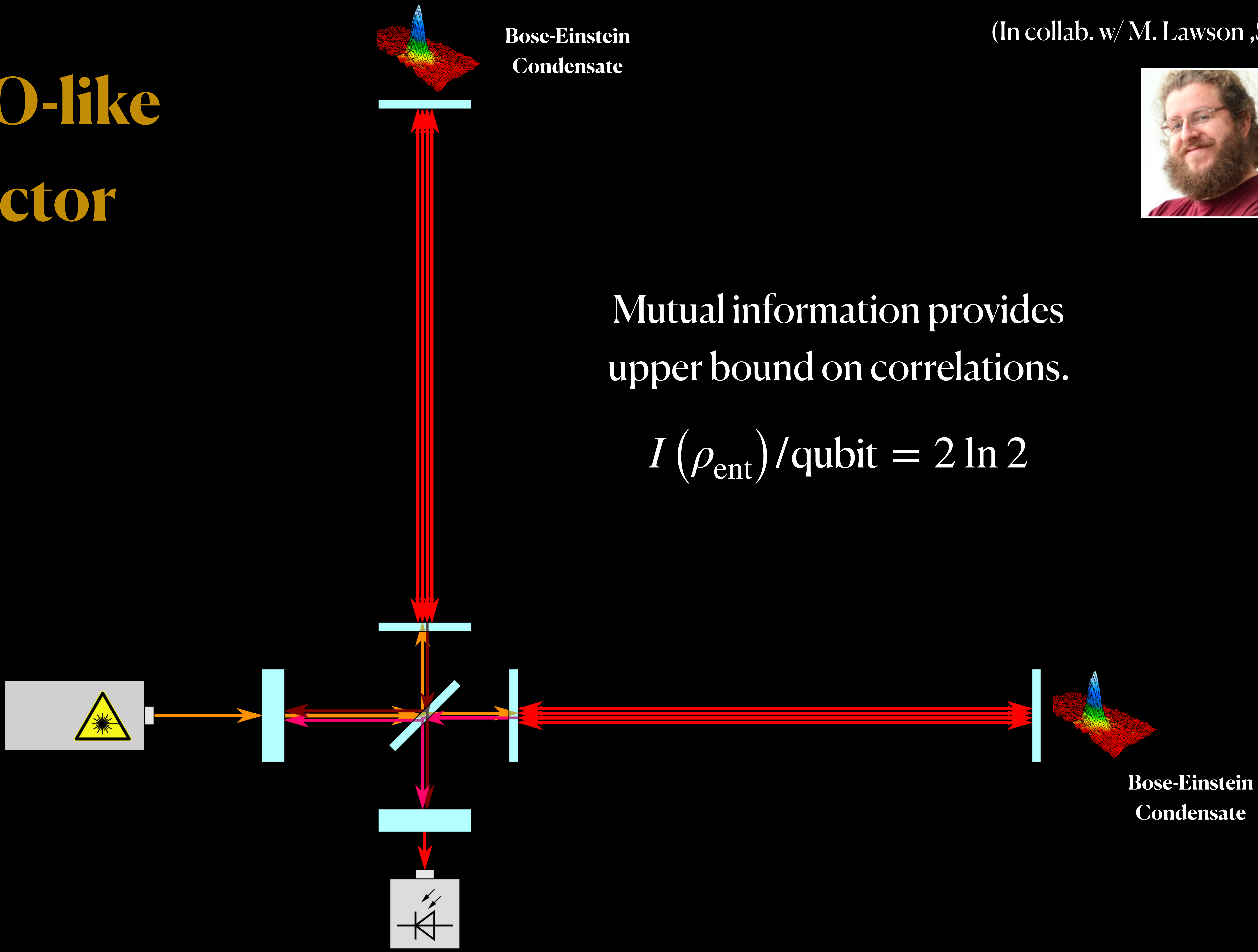
(Received 27 August 2019; revised 4 November 2019; accepted 19 January 2021; published 5 February 2021)

The curvature parameter tension between Planck 2018, cosmic microwave background (CMB) lensing, and baryon acoustic oscillation (BAO) data is measured using the suspiciousness statistic to be 2.5–3$\sigma$. Conclusions regarding the spatial curvature of the Universe which stem from the combination of these data should therefore be viewed with suspicion. Without CMB lensing or BAO, Planck 2018 has a moderate preference for closed universes, with Bayesian betting odds of over 50 : 1 against a flat universe and over 2000 : 1 against an open universe.

DOI: 10.1103/PhysRevD.103.L041301

# LIGO-like detector

(In collab. w/ M. Lawson ,S. Baum, S. Qvarfort)



Mutual information provides upper bound on correlations.

$$I\left(\rho_{\text{ent}}\right)/\text{qubit} = 2\ln 2$$

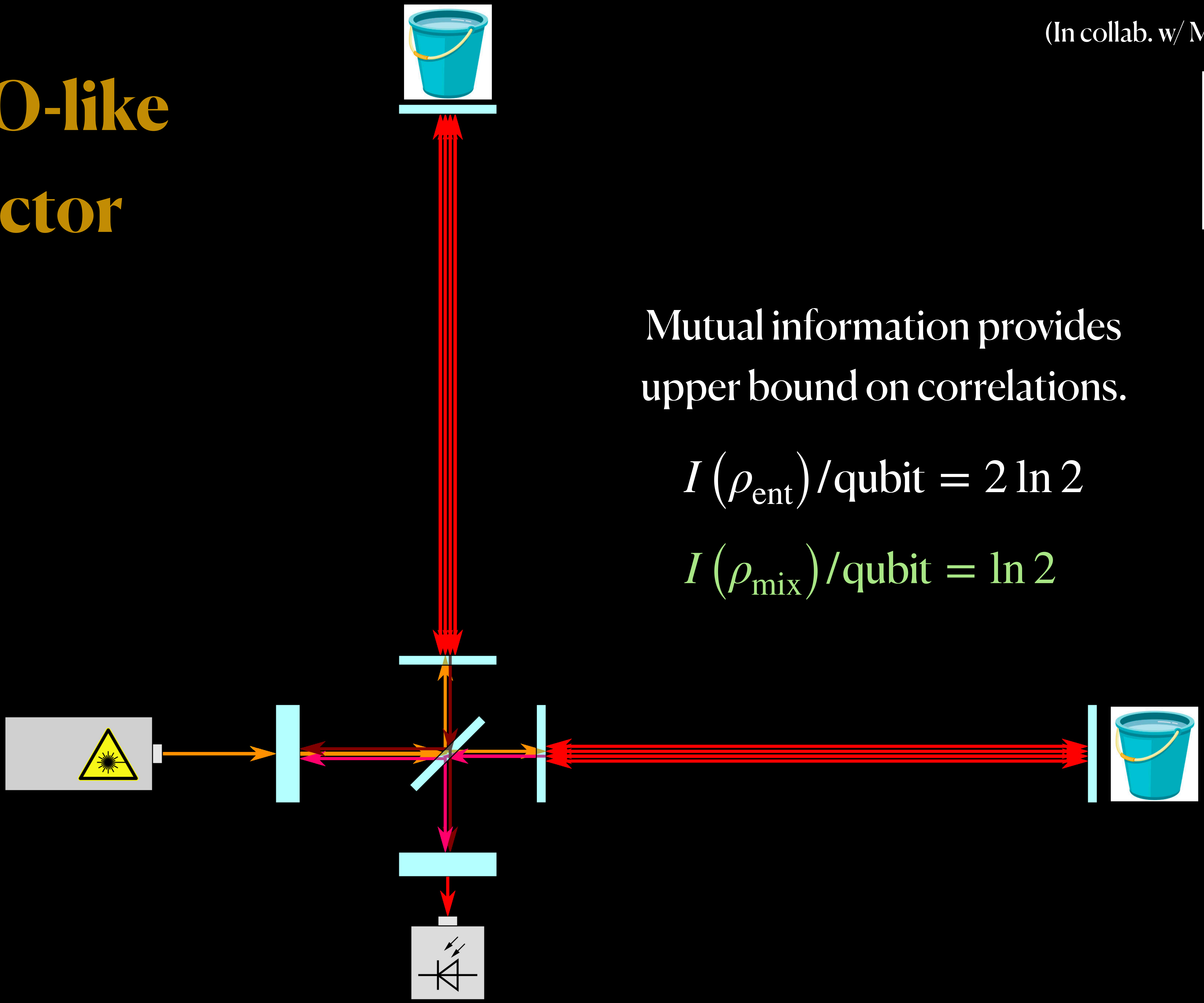
(In collab. w/ M. Lawson ,S. Baum, S. Qvarfort)

# LIGO-like detector

Mutual information provides upper bound on correlations.

$$I\left(\rho_{\mathrm{ent}}\right)/\mathrm{qubit} = 2\ln 2$$

$$I\left(\rho_{\mathrm{mix}}\right)/\mathrm{qubit} = \ln 2$$



# Gravimetry through non-linear optomechanics

(In collab. w/ M. Lawson ,S. Baum, S. Qvarfort)



$$H = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{b}^\dagger \hat{b} - \hbar k \hat{a}^\dagger a(\hat{b} + \hat{b}^\dagger)$$

$$-m_S g_0[a + \epsilon(\omega_g t + \phi_g)](\hat{b}^\dagger + \hat{b})$$

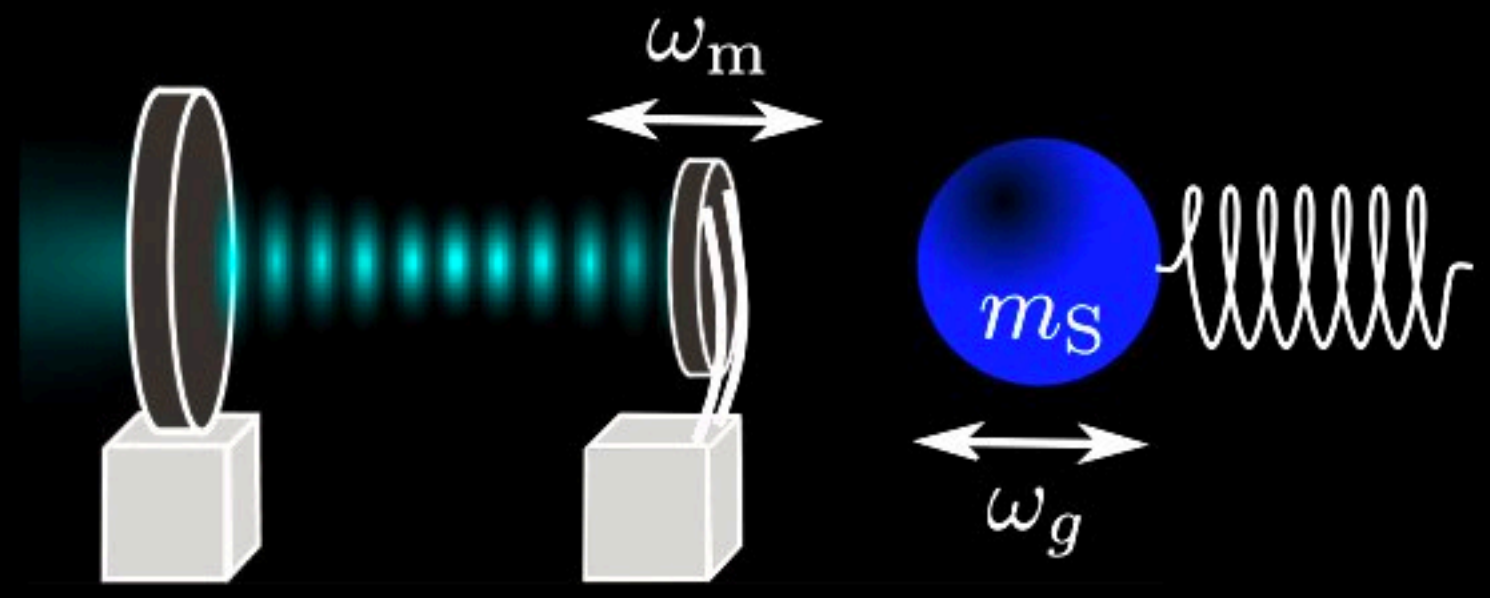
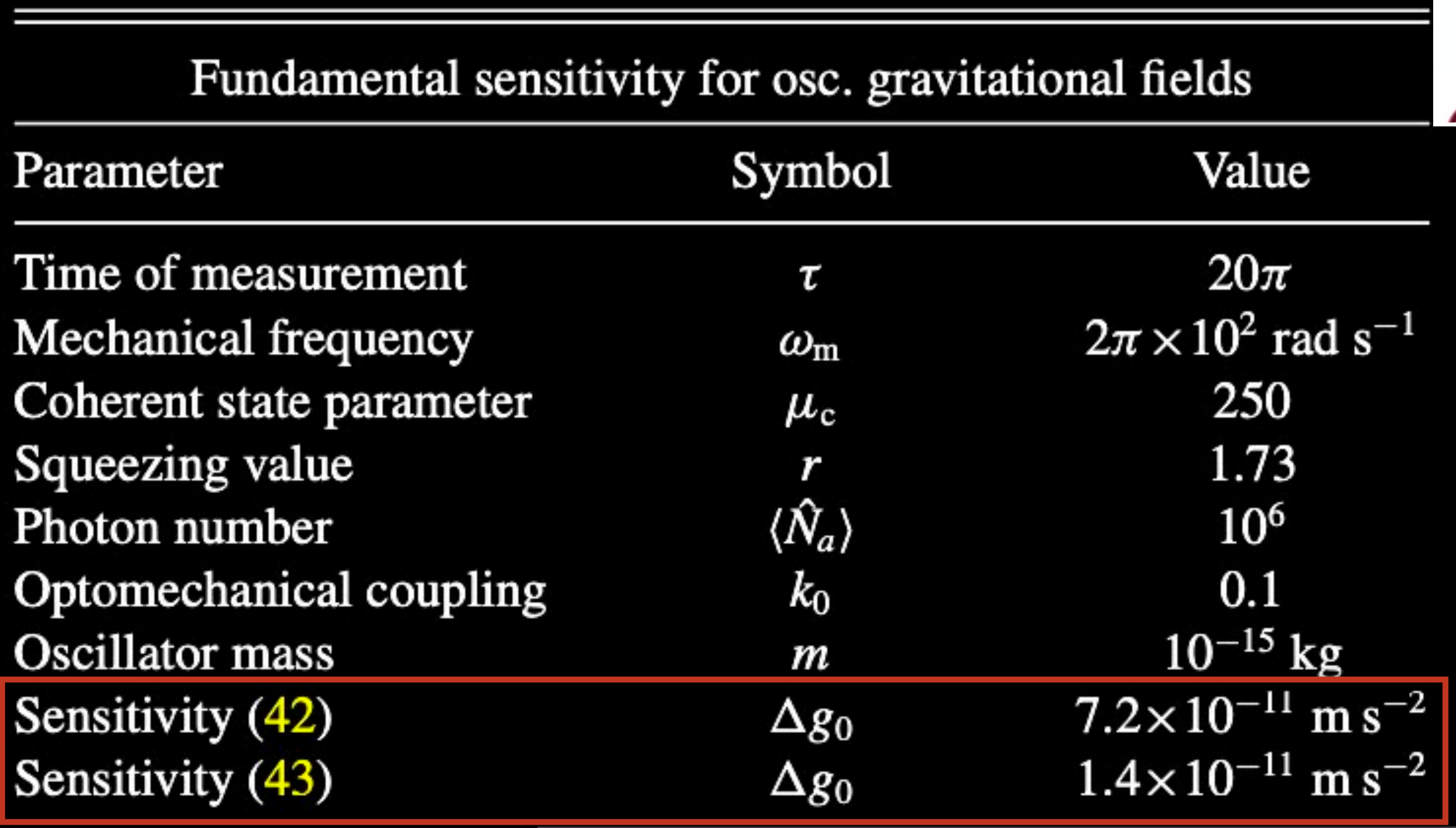


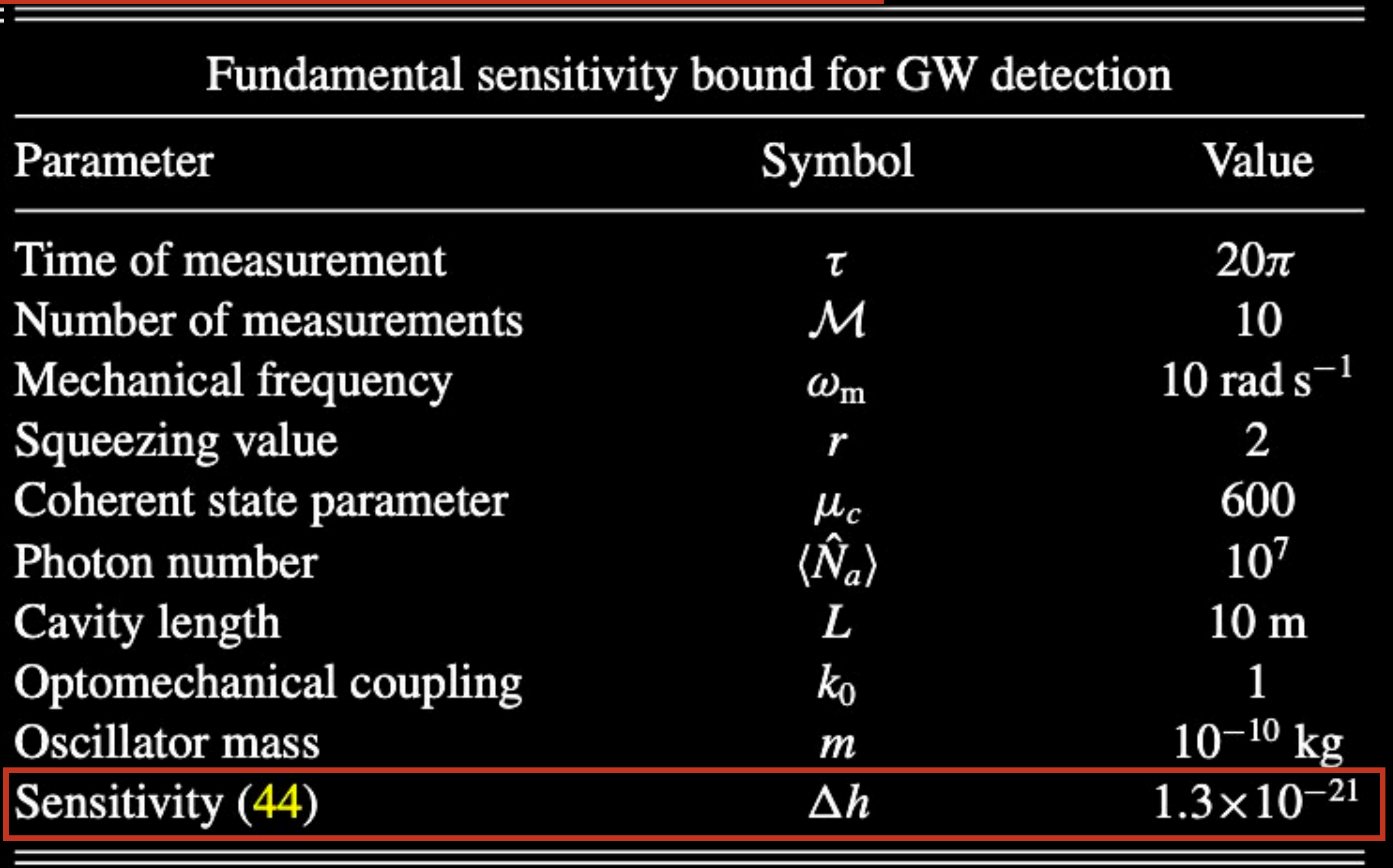
FIG. 1. The influence of a time-dependent gravitational acceleration on a Fabry-Pérot moving-end mirror. A small source sphere with mass $m_S$ oscillates with frequency $\omega_g$ and creates an oscillating gravitational field, which drives the center of mass motion of the mechanical part of the optomechanical system with frequency $\omega_\mathrm{m}$.

(Qvarfort, Plato, Bruschi, Schneiter, Braun, Serafini, Rätzel, ’21)



Fundamental sensitivity for osc. gravitational fields

| Parameter | Symbol | Value |
|---|---|---|
| Time of measurement | $\tau$ | $20\pi$ |
| Mechanical frequency | $\omega_\mathrm{m}$ | $2\pi \times 10^2$ rad s$^{-1}$ |
| Coherent state parameter | $\mu_\mathrm{c}$ | 250 |
| Squeezing value | $r$ | 1.73 |
| Photon number | $\langle \hat{N}_a \rangle$ | $10^6$ |
| Optomechanical coupling | $k_0$ | 0.1 |
| Oscillator mass | $m$ | $10^{-15}$ kg |
| Sensitivity (42) | $\Delta g_0$ | $7.2\times 10^{-11}$ m s$^{-2}$ |
| Sensitivity (43) | $\Delta g_0$ | $1.4\times 10^{-11}$ m s$^{-2}$ |



Fundamental sensitivity bound for GW detection

| Parameter | Symbol | Value |
|---|---|---|
| Time of measurement | $\tau$ | $20\pi$ |
| Number of measurements | $\mathcal{M}$ | 10 |
| Mechanical frequency | $\omega_\mathrm{m}$ | 10 rad s$^{-1}$ |
| Squeezing value | $r$ | 2 |
| Coherent state parameter | $\mu_c$ | 600 |
| Photon number | $\langle \hat{N}_a \rangle$ | $10^7$ |
| Cavity length | $L$ | 10 m |
| Optomechanical coupling | $k_0$ | 1 |
| Oscillator mass | $m$ | $10^{-10}$ kg |
| Sensitivity (44) | $\Delta h$ | $1.3\times 10^{-21}$ |

# Emergent Geometries from Entanglement

## EmerGE Collaboration

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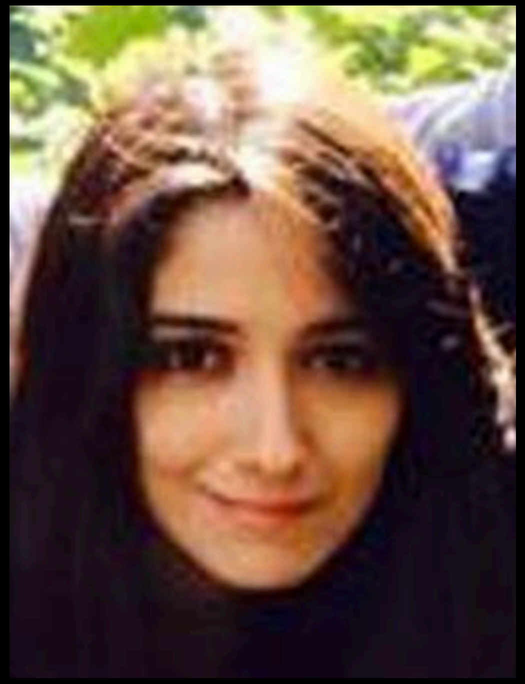

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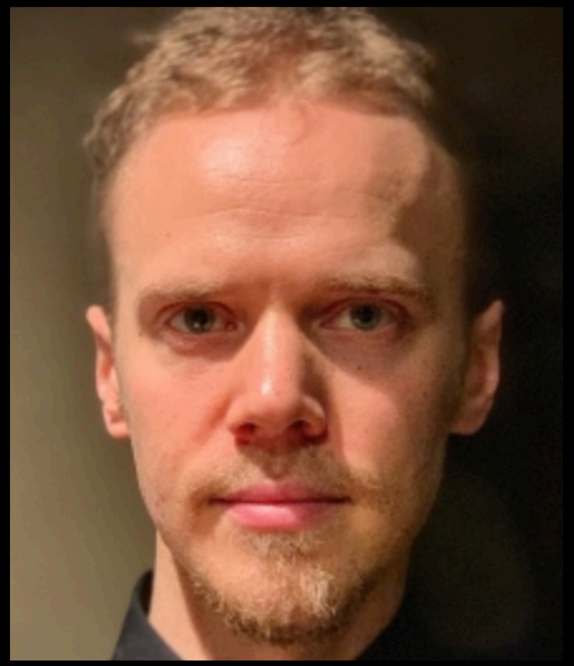

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# Thank you!