UBER-GRAVITY AND THE COSMOLOGICAL CONSTANT PROBLEM

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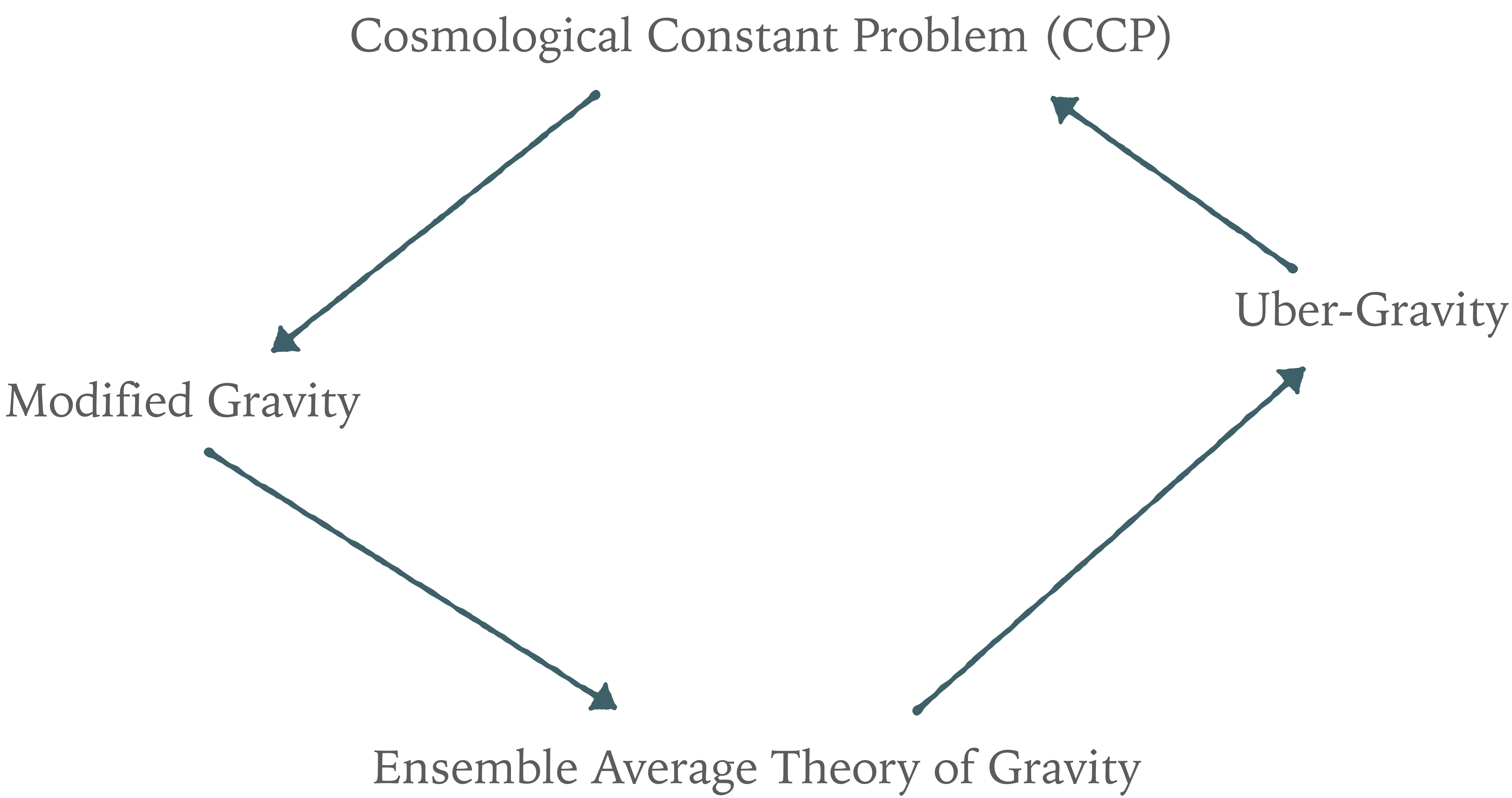

CCP: COSMOLOGICAL CONSTANT PROBLEM

Einstein equation:

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

Einstein tensor — energy-momentum tensor

CCP: COSMOLOGICAL CONSTANT PROBLEM

vacuum energy shows itself in trace of energy momentum tensor

$$G_{\mu\nu} = T_{\mu\nu} + \rho_{vac} g_{\mu\nu}$$

Einstein tensor

vacuum energy

energy-momentum tensor

CCP: COSMOLOGICAL CONSTANT PROBLEM

adding a cosmological constant to GR:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu} + \rho_{vac} g_{\mu\nu}$$

Einstein tensor

vacuum energy

energy-momentum tensor

cosmological constant

CCP: COSMOLOGICAL CONSTANT PROBLEM

$$\Lambda - \rho_{vac} = \Lambda_{obs}$$

a free parameter in the model

observed quantity

calculated by particle physics

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"the worst theoretical prediction in the history of physics."

(MP Hobson, GP Efstathiou & AN Lasenby)

CCP: SOLUTIONS!

- particle physics: vacuum energy calculation?
- gravity: GR should be modified?
- quantum gravity?

- some specific examples/ideas:
  - degravitation (Arkani-Hamed, Khoury, ….)
  - anthropic principle
  - sequestering (Padilla & Kaloper)
  - …

MODIFIED GRAVITY

- motivations:
  - CCP
  - few tensions between ΛCDM and observations
  - theoretical interests

OBSERVATIONAL HINTS: AN EXAMPLE

The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: Examining the observational evidence for dynamical dark energy

Gong-Bo Zhao,[1,2,*] Marco Raveri,[3,4] Levon Pogosian,[5,2] Yuting Wang,[1,2] Robert G. Crittenden,[2] Will J. Handley,[6,7] Will J. Percival,[2] Jonathan Brinkmann,[8] Chia-Hsun Chuang,[9,10] Antonio J. Cuesta,[11] Daniel J. Eisenstein,[12] Francisco-Shu Kitaura,[13,14] Kazuya Koyama,[2] Benjamin L'Huillier,[15] Robert C. Nichol,[2] Matthew M. Pieri,[16] Sergio Rodriguez-Torres,[9,17,18] Ashley J. Ross,[19,2] Graziano Rossi,[20] Ariel G. Sánchez,[21] Arman Shafieloo,[15,22] Jeremy L. Tinker,[23] Rita Tojeiro,[24] Jose A. Vazquez,[25] and Hanyu Zhang[1]

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We examine the ability of the ΛCDM model to simultaneously fit different types of cosmological observations and apply a recently proposed test, based on the Kullback-Leibler divergence, to quantify the tension between different subsets of data. We find a tension between the distance indicators derived from a ΛCDM model using a combined dataset, and the recent H_0 measurements, as well as the high redshift Baryon Acoustic Oscillations (BAO) obtained from the Lyman-α forest spectra. We then allow for a dynamical dark energy (DE) and perform a Bayesian non-parametric reconstruction of the DE equation of state as a function of redshift. We find that the tension with H_0 and Lyman-α forest BAO is effectively relieved by a dynamical DE. Although a comparison of the Bayesian evidence for dynamical DE with that of ΛCDM shows that the tension between the datasets is not sufficiently strong to support a model with more degrees of freedom, we find that an evolving DE is preferred at a 3.5σ significance level based solely on the improvement in the fit. We also perform a forecast for the upcoming DESI survey and demonstrate that, if the current best fit DE happens to be the true model, it will be decisively supported by the Bayesian evidence.

PACS numbers: 95.36.+x, 98.80.Es

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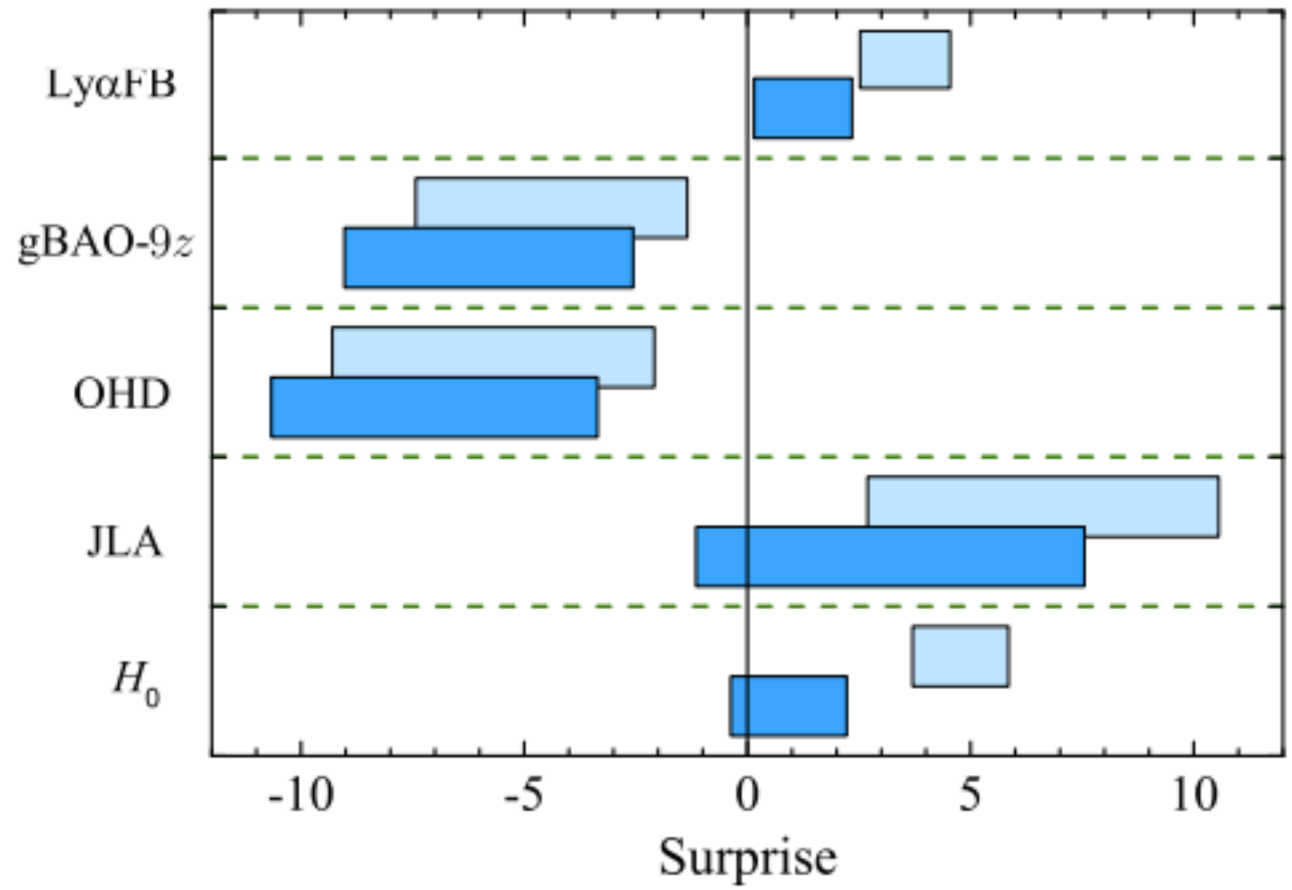

FIG. 1. The Surprise between the PDFs for $D_A(z)$ and $H(z)$ derived from the best fit model using the combined dataset of ALL16, and the directly observed $D_A(z)$ and $H(z)$ from H_0, JLA, OHD, gBAO-9z and LyαFB respectively. The light blue horizontal bars indicate the 68% CL range of Surprise in ΛCDM, while the dark blue bars correspond to $w(z)$CDM.

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THEORETICAL INTERESTS:

- studying modified gravity can lead us to better understanding of Einstein GR model

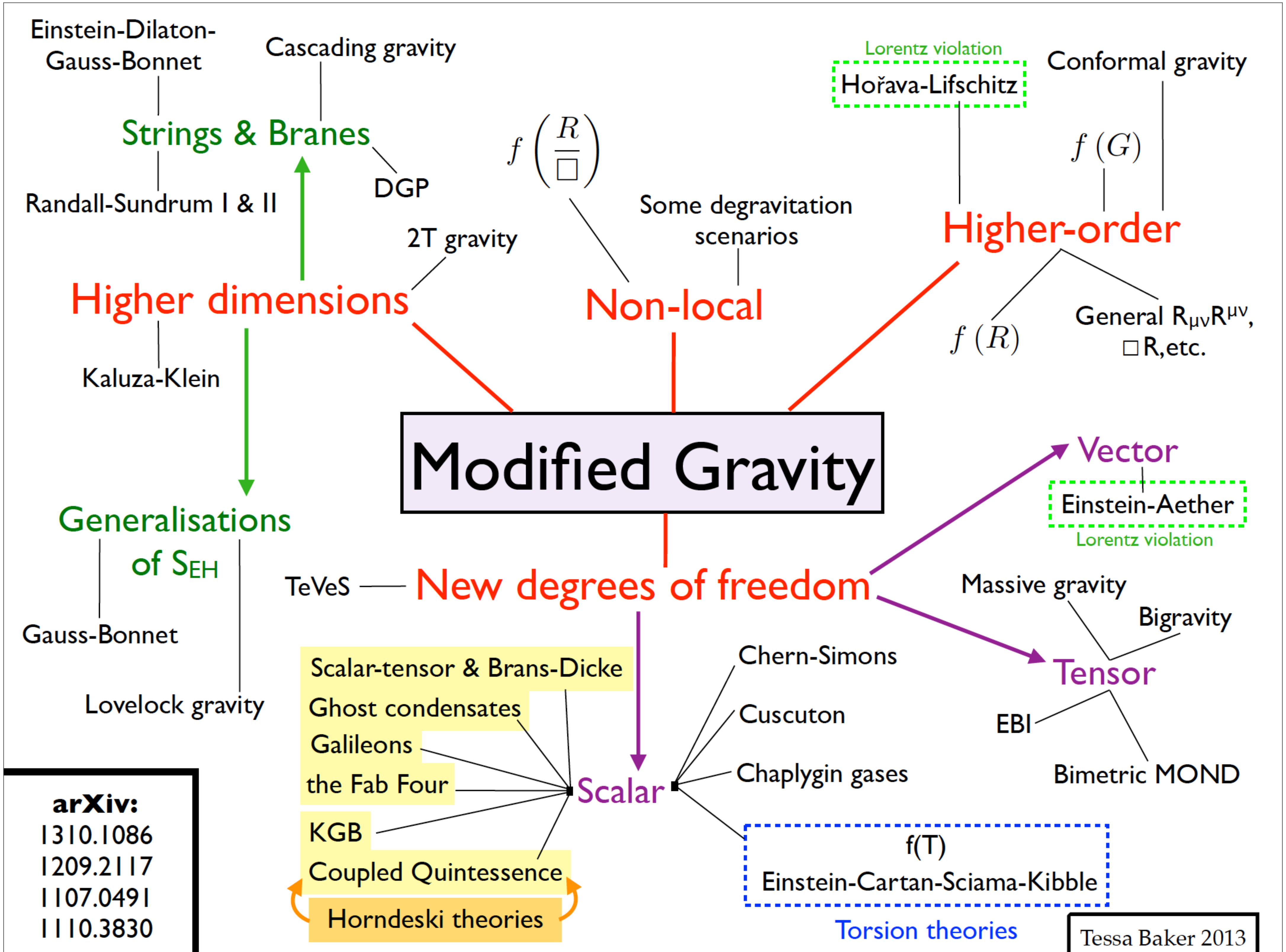
MODIFIED GRAVITY: HOW TO BEGIN?

- modified gravity: adding a new d.o.f. to GR
  - scalar: Galileon, Horndeski, Brans-Dicke, …
  - vector
  - tensor: massive gravity, bi-gravity
- how to do that? some examples:
  - add them to GR by hand (see above)
  - extra-dimensions
  - non-local gravity
  - higher order gravity: Gauss-Bonnet, f(R), …

MODIFIED GRAVITY: HOW TO FINISH?

- check if it is theoretically consistent!
- check it with the observations:
  - background
  - perturbations
- final checks:
  - is your model observationally favored compare with ΛCDM?
  - did you solve the cosmological constant problem?
  - did you solve quantum gravity?
  - is your model more beautiful than GR?

MODIFIED GRAVITY: WHAT WE HAVE



ENSEMBLE AVERAGE THEORY OF GRAVITY

- A. Einstein:

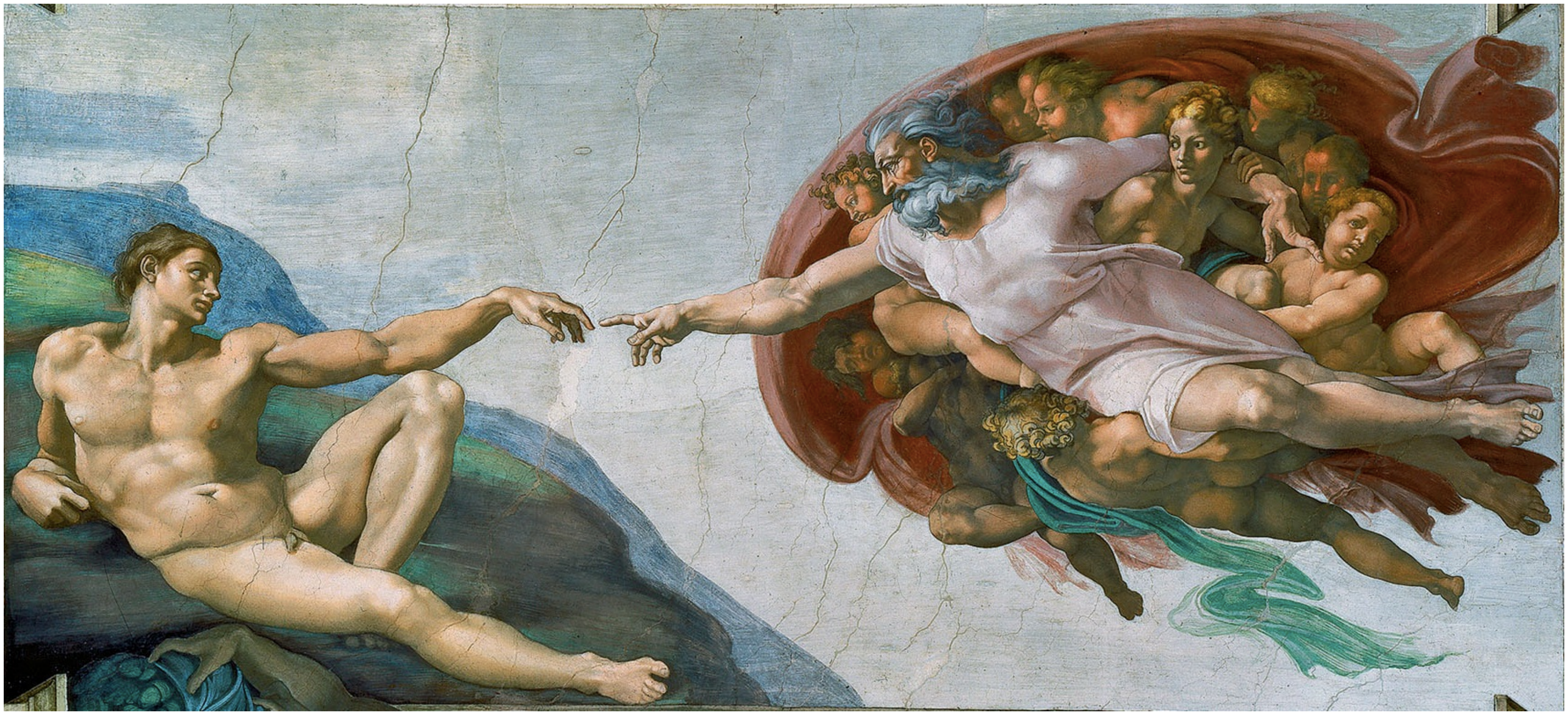
  “What really interests me is whether God had any choice in the creation of the World”

A TRUE STORY:

- I am telling a story while you are enjoying art!

— THE FIRST DAY: IT WAS ASKED FOR A THEORY!

the creation of Adam, Michelangelo:



A. Einstein:
"What really interests me is whether God had any choice in the creation of the World"

— THEN, MANY THEORIES WERE PROPOSED BY THINKERS!

the school of Athens, Raphael:

— EUREKA: THE ANSWER IS AVERAGING!

ENSEMBLE AVERAGE THEORY OF GRAVITY

- let's recall Einstein quote:
  "What really interests me is whether God had any choice in the creation of the World"

- what is your answer to his question?
  - no! → why not? why GR is unique?
  - yes! → how can we check this "yes"?
  - it is not a well-defined question! → see you at break!

ENSEMBLE AVERAGE THEORY OF GRAVITY

A. Einstein:
"What really interests me is whether God had any choice in the creation of the World"

- what is my answer to his question?
    - my answer to this question is "yes" and "no" both!
    - "yes": all the theoretically consistent models have been used in the creation of the World!
    - "no": at the end there is just a "unique model" which is the "ensemble average" of all the theoretically possible models!
- based on PRD 94 (2016) no.12, 124035, arXiv:1606.01887

ENSEMBLE AVERAGE THEORY OF GRAVITY

$$\mathbb{M}$$

the space of all the (consistent) models for gravity!

- we take average over all the models
- to do this we need to assigned to each model a probability

$$\mathcal{M} = \sum_i p_i \mathcal{M}_i = \frac{1}{\sum_j e^{-\mathcal{S}_j}} \times \sum_i e^{-\mathcal{S}_i} \mathcal{M}_i$$

ENSEMBLE AVERAGE THEORY OF GRAVITY

- practically I will assign to each model a Lagrangian
- the averaged Lagrangian will be like

$$\mathcal{L} = \sqrt{-g}\left(\sum_{i=1}^{N} L_i e^{-\beta L_i}\right) \Big/ \left(\sum_{j=1}^{N} e^{-\beta L_j}\right)$$

i'th Lagrangian

its weight

averaged Lagrangian

normalization factor

ENSEMBLE AVERAGE THEORY OF GRAVITY

- an example: higher order gravity
- in 4-dimension we have Ricci scalar and Gauss-Bonnet term

$$\mathcal{L} = \sqrt{-g}\left[\frac{M^2 R\, e^{-\beta M^2 R}}{e^{-\beta M^2 R} + e^{-\beta \alpha G}} + \frac{\alpha G\, e^{-\beta \alpha G}}{e^{-\beta M^2 R} + e^{-\beta \alpha G}}\right]$$

Ricci scalar

Gauss-Bonnet term

temperature of model space??

UBER-GRAVITY

- based on “Uber-Gravity and the CPP”, arXiv:1703.02052
- a generalization of EAT-of-Gravity for all analytical functions of f(R). so we have

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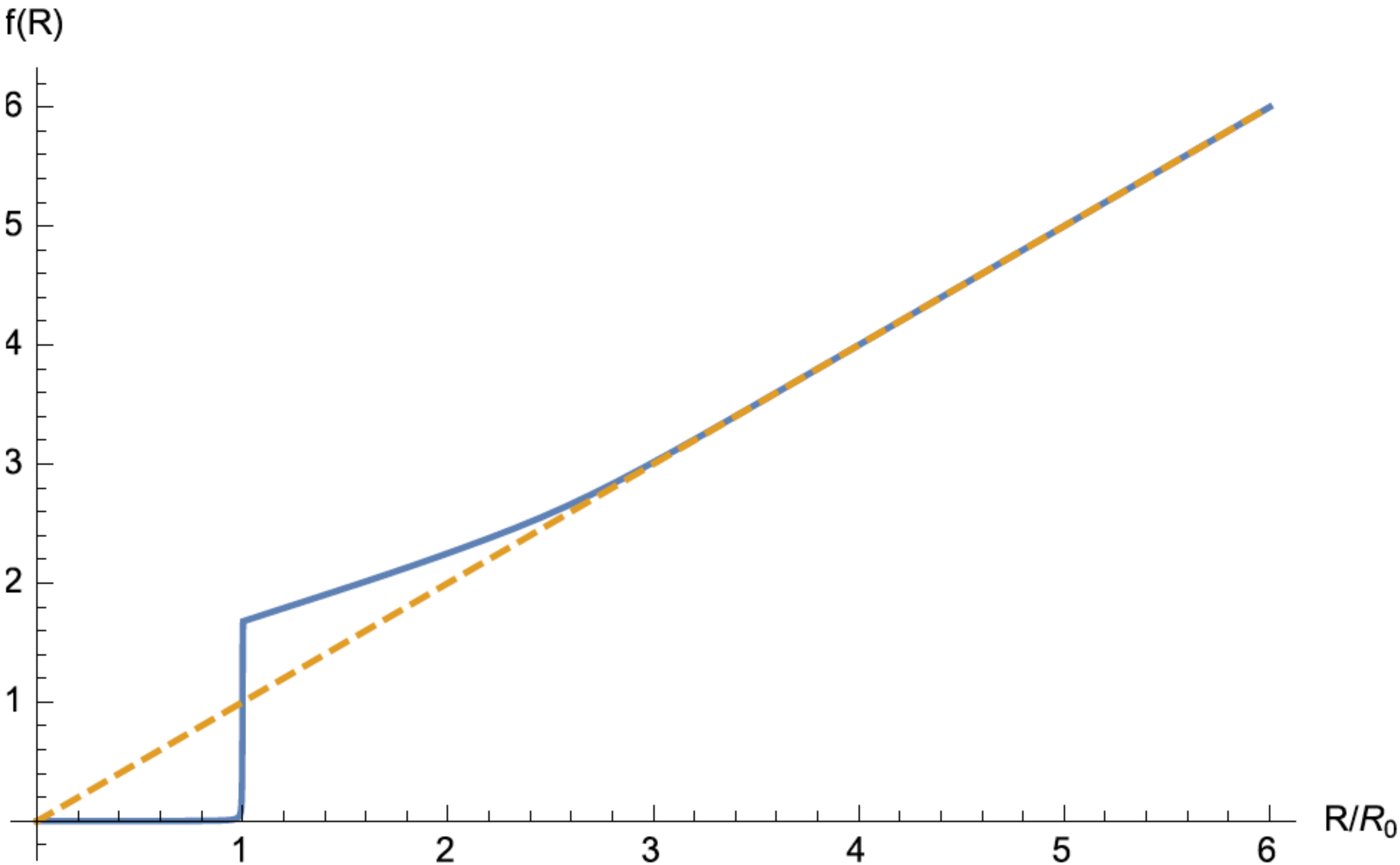
$$\mathbb{M} = \{R^n \mid \forall\, n \in \mathbb{N}\}$$

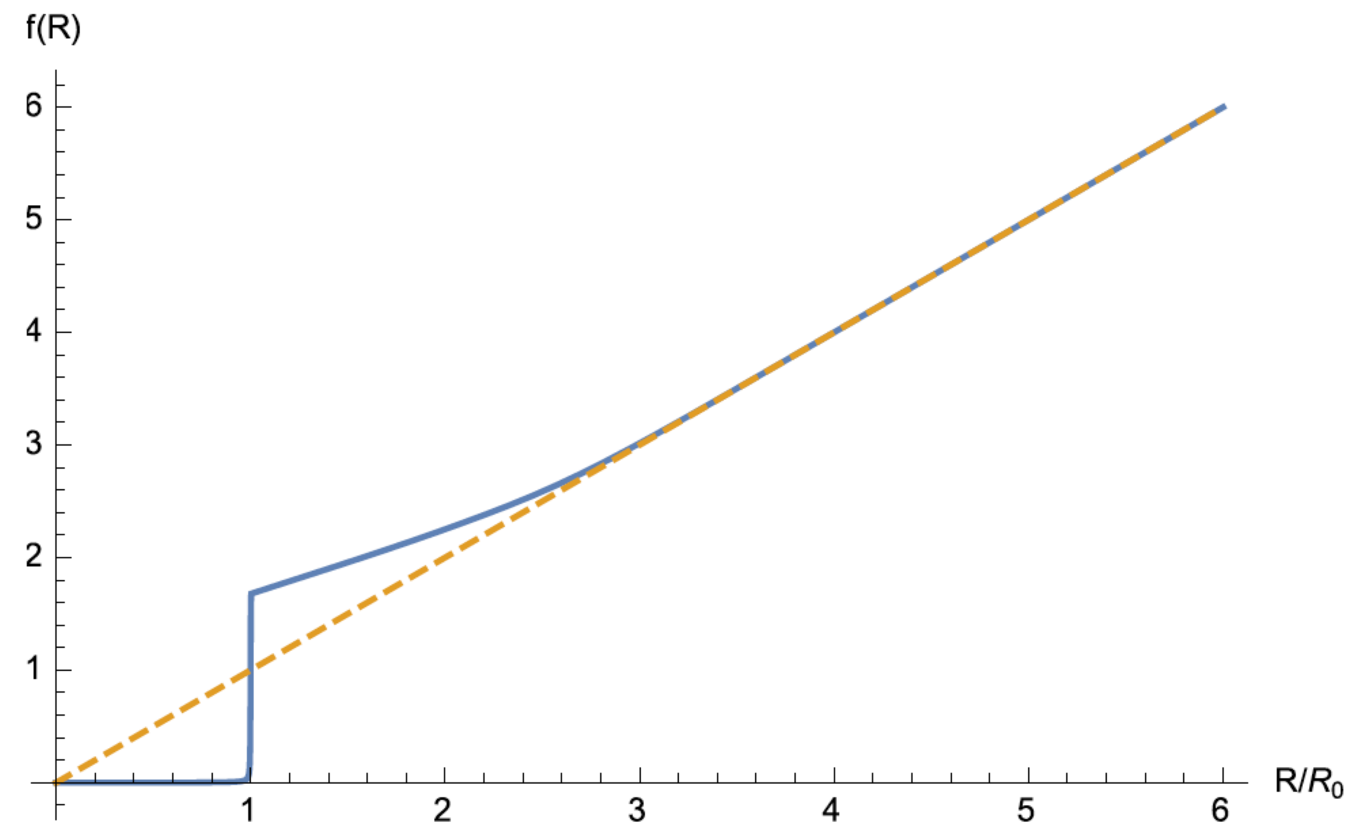
$$\mathcal{L} = \left(\sum_{n=1}^{\infty} \bar{R}^n e^{-\beta \bar{R}^n}\right) \Big/ \left(\sum_{n=1}^{\infty} e^{-\beta \bar{R}^n}\right)$$

UBER-GRAVITY



UBER-GRAVITY: UNIVERSAL PROPERTIES

- for high-curvature regime it reduces to GR
- for intermediate-curvature regime it predicts stronger gravity than GR
- it is vanishing for low-curvature regime (R < R_0)
- there is a sharp transition at R_0



UBER-GRAVITY: A SIMPLIFIED MODEL

$$f(R) = \begin{cases} \bar{R}^n & R \leq R_0 \\ \bar{R} + e^{-(\bar{R}-0.7)} & R_0 < R \end{cases}$$

we focus on low-curvature regime. we have

$$(n-2)\bar{R}^n + 3\,n\,R_0^{-1}\,\Box\,\bar{R}^{n-1} = \kappa^2 T$$

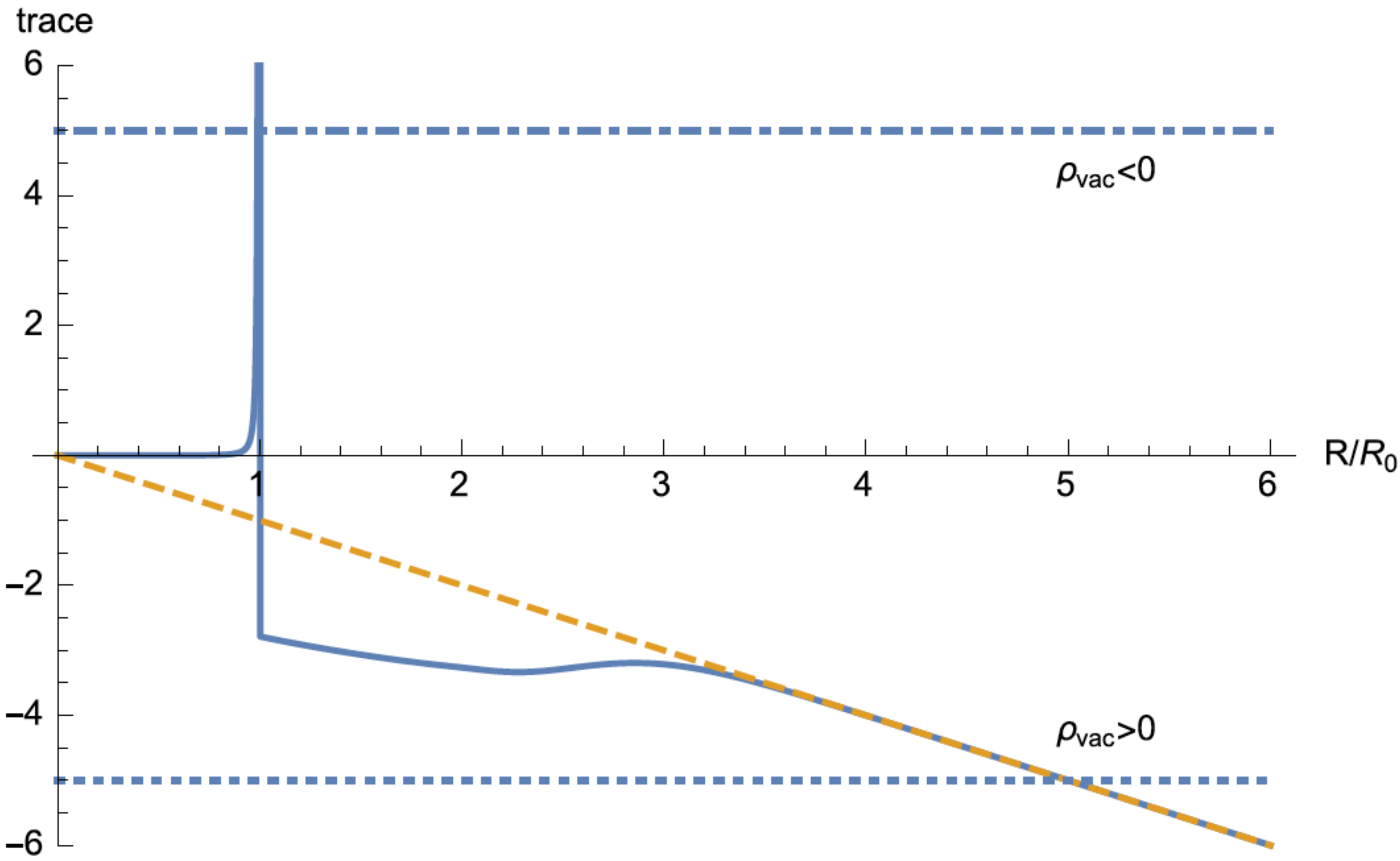
and for R = const. we have

$$\frac{R}{R_0} = \left(\frac{\kappa^2\,T}{n-2}\right)^{\frac{1}{n}}$$

which means for $n \to \infty$ results in $R \to R_0$!!

this means there is no need to fine-tuning since this model is not sensitive to vacuum energy.

UBER-GRAVITY: FULL MODEL



UBER-GRAVITY: FINAL REMARKS/DISCUSSIONS

- to be fully consistent we need negative value for vacuum energy. this is achievable if number of bosonic d.o.f. be larger than ferminonic ones.
  - a suggestion: dark matter is axion! or …
- ensemble average idea can be a way to think about hierarchy problems!
- uber-gravity idea can be a way to think about CCP.

UBER-GRAVITY: A DIFFERENT VIEWPOINT

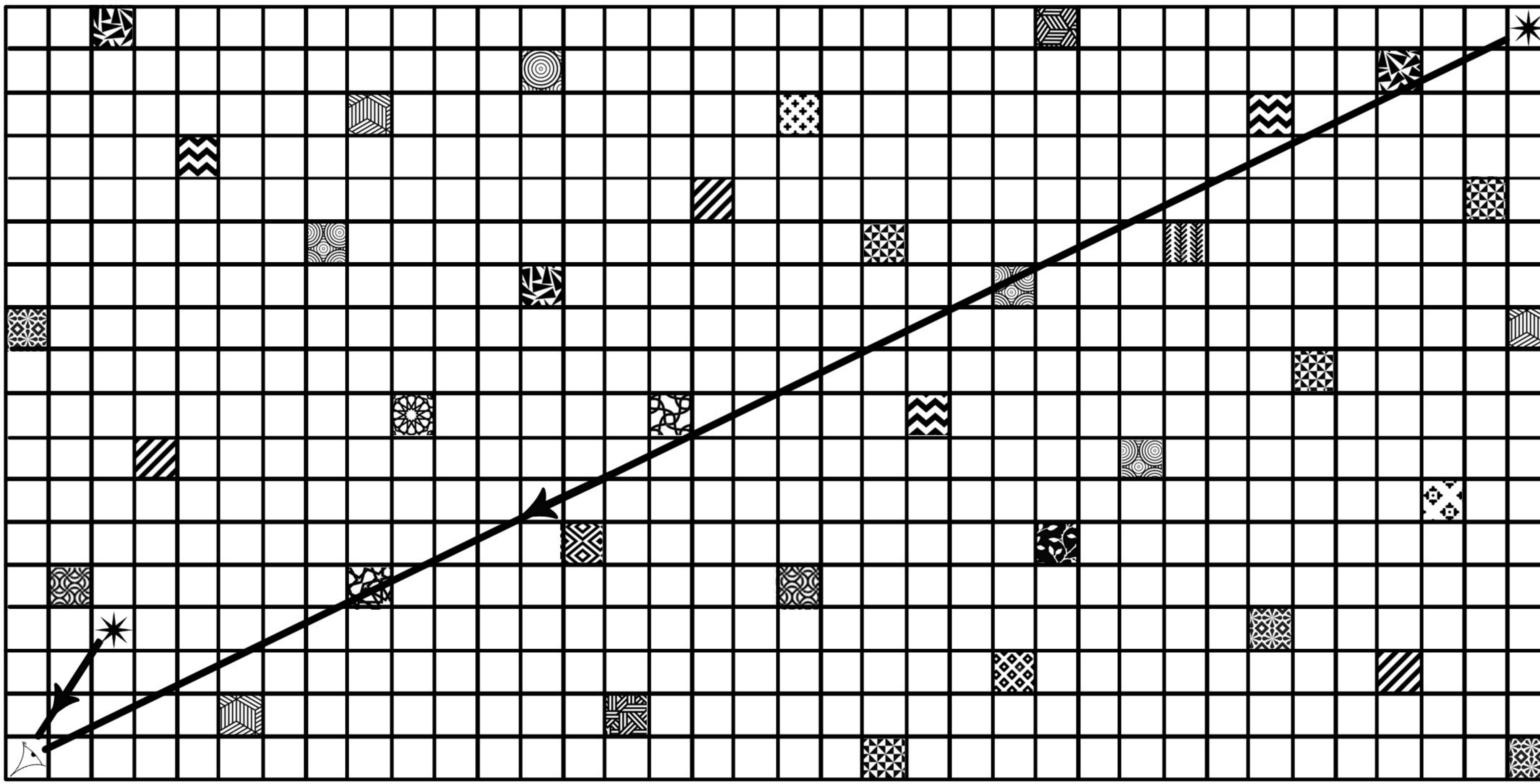


figure by Elham Salmanzadeh

A CONJECTURE:

- picking just one model from model space is highly fine-tuned which shows itself in both gravity and particle physics.
- maybe we need to change our viewpoint on the way we describe the nature!

THINK OUTSIDE THE BOX:

maybe we need more artistic approach?!

photo taken at kunsthaus zurich, and don’t forget Einstein was at ETH zurich

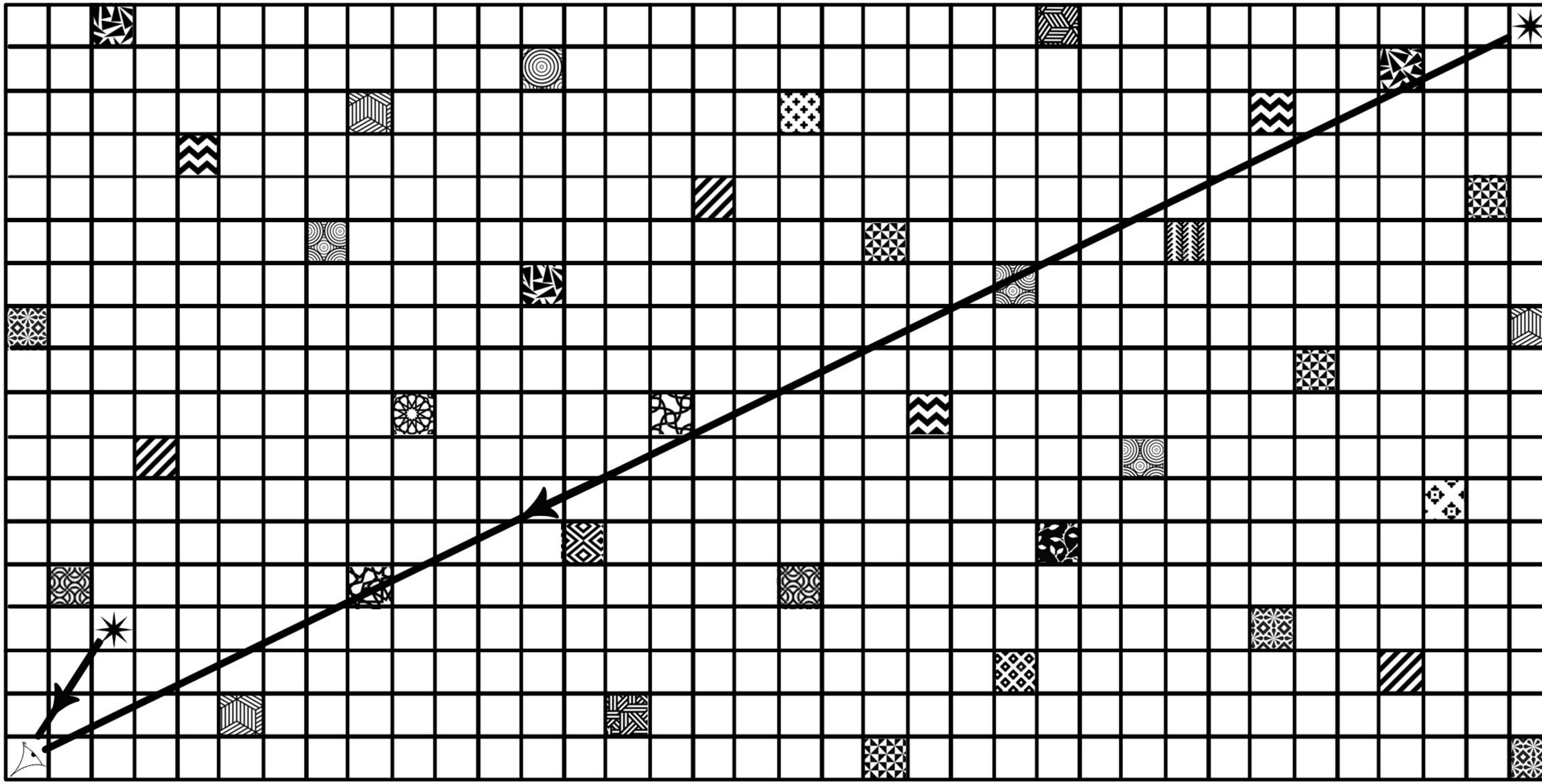


figure by Elham Salmanzadeh

گیسوی تو پیچیده ترین معضل دنیا ست؛

و الا مساله ثابت کیهان شناسی حل شدنی ست!