Title: Cosmological constant problem: rethinking quantum and gravity

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Abstract:

Laws of Nature:
Their Nature and Knowability
Perimeter Institute
May 22, 2010

Cosmological Constant Problem:
Rethinking Quantum & Gravity

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Collaborators

- Michael Balogh (U-Waterloo)
- Brendan Foster (FQXi)
- Kazunory Kohri (Tohoku)
- Chanda Prescod-Weinstein (Perimeter → NASA)
- Georg Robbers (MPA, Garching)

NA; arXiv:0807.2639, 1003.4811, 1004.2901

Prescod-Weinstein, NA, & Balogh; Phys. Rev. D 80, 043513 (2009)

NA; Phys.Rev.D 80, 081502 (2009)

…

Outline

- "Why all these prejudices against a constant?"
- Reviving Gravity's Aether
  - quantum gravity
  - degravitating quantum vacuum
  - dark energy
  - initial conditions
- Conclusions

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Why all these prejudices against a constant?

Eugenio Bianchi, Carlo Rovelli
Centre de Physique Théorique de Luminy, Case 907, F-13288 Marseille, EU*
(Dated: April 13, 2010)

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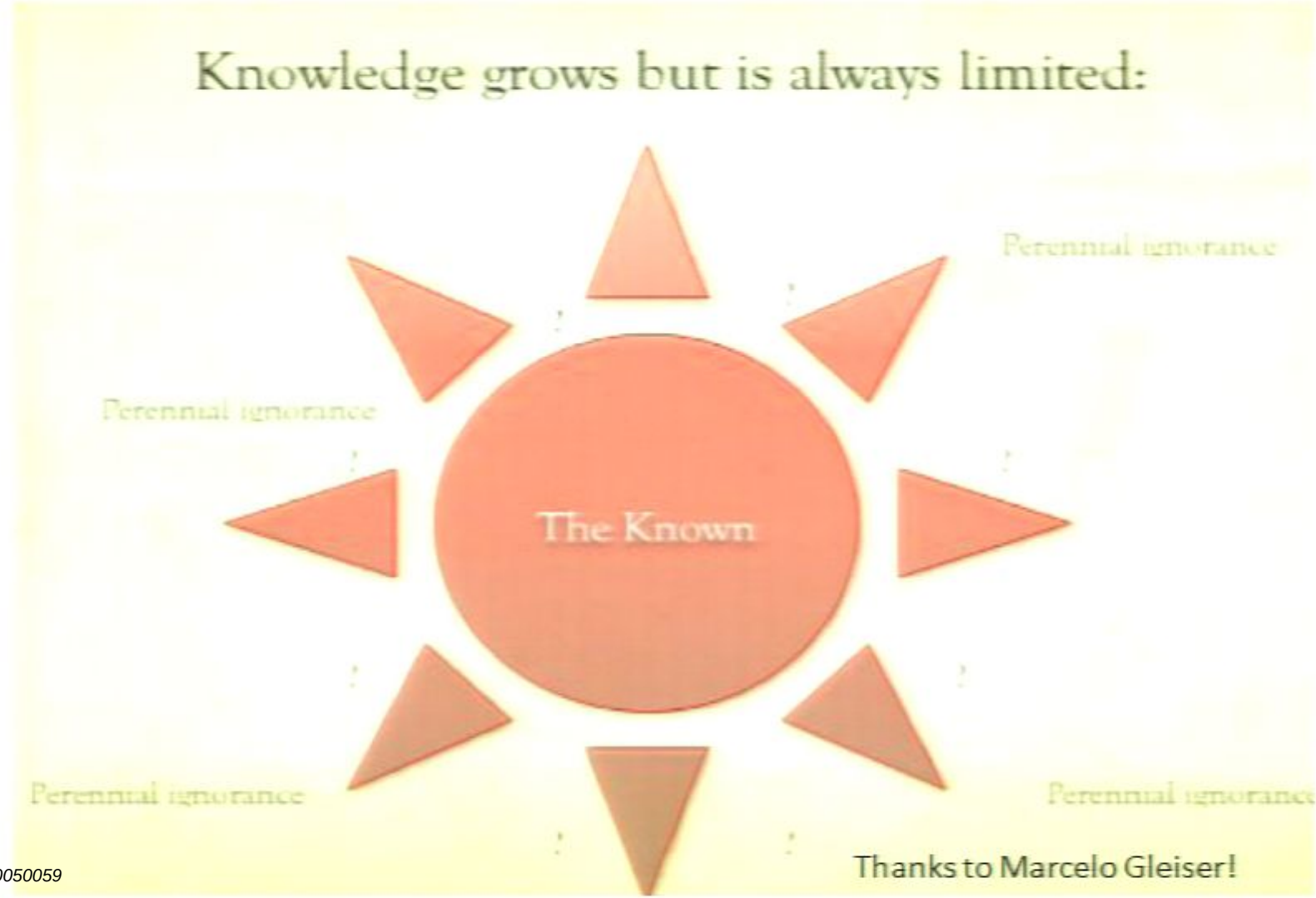
"But to claim that dark energy represents a profound mystery, is, in our opinion, nonsense. "Dark energy" is just a catch name for the observed acceleration of the universe, which is a phenomenon well described by currently accepted theories, and predicted by these theories, whose intensity is determined by a fundamental constant, now being measured. The measure of the acceleration only determines the value of a constant that was not previously measured. We have only discovered that a constant that so far (strangely) appeared to be vanishing, in fact is not vanishing. Our universe is full of mystery, but there is no mystery here."


Knowledge grows but is always limited:
Perennial ignorance
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Thanks to Marcelo Gleiser!

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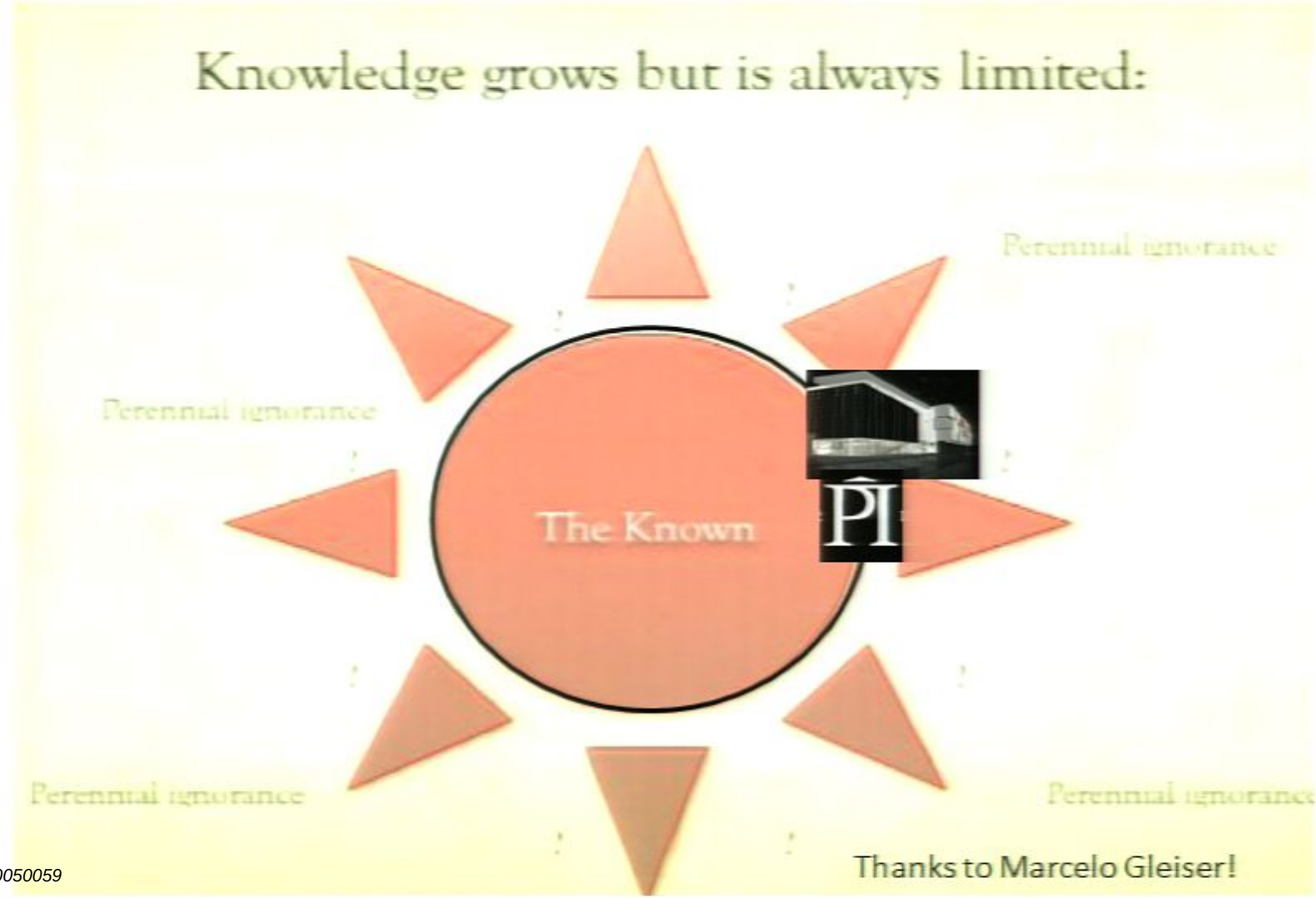
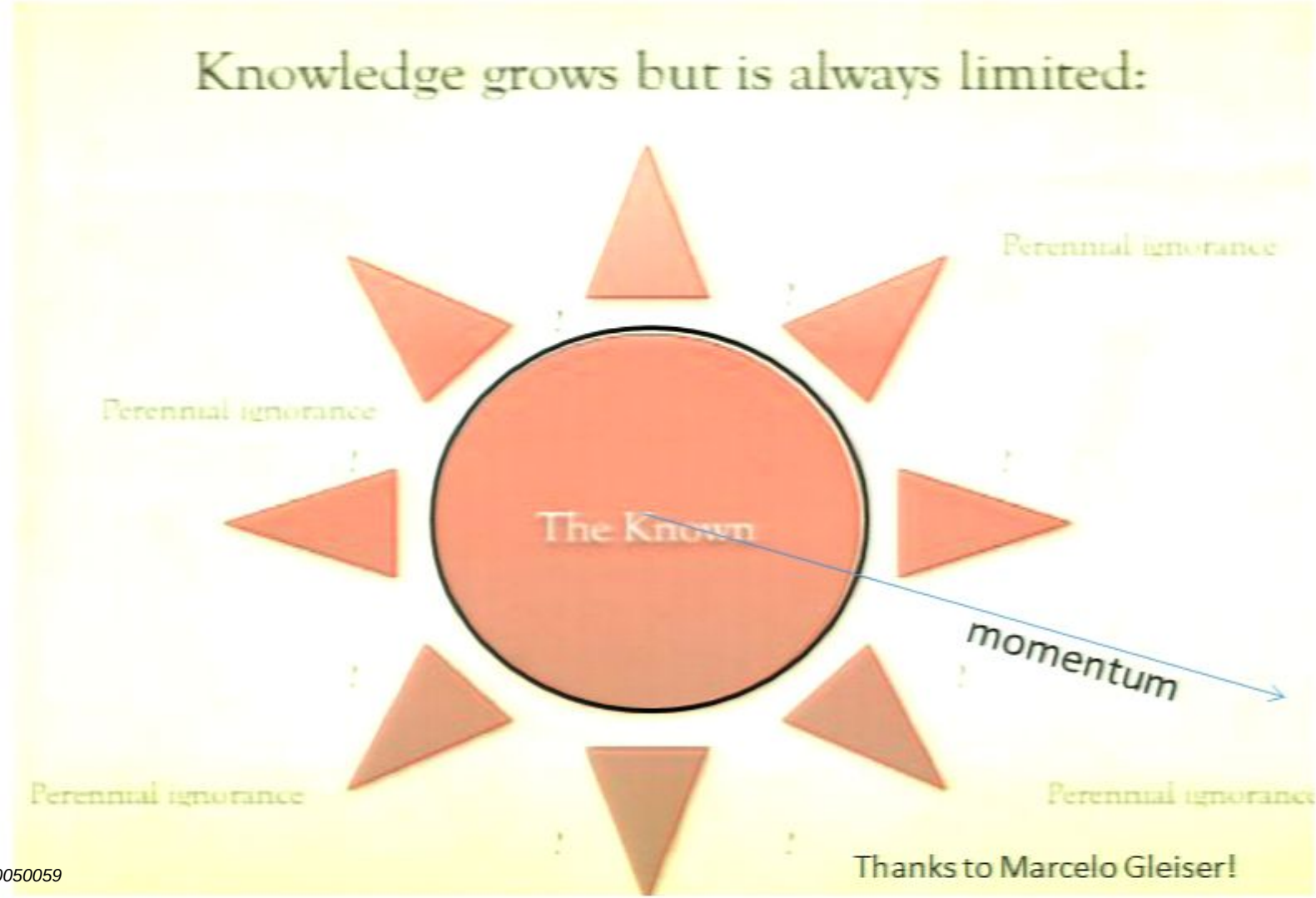
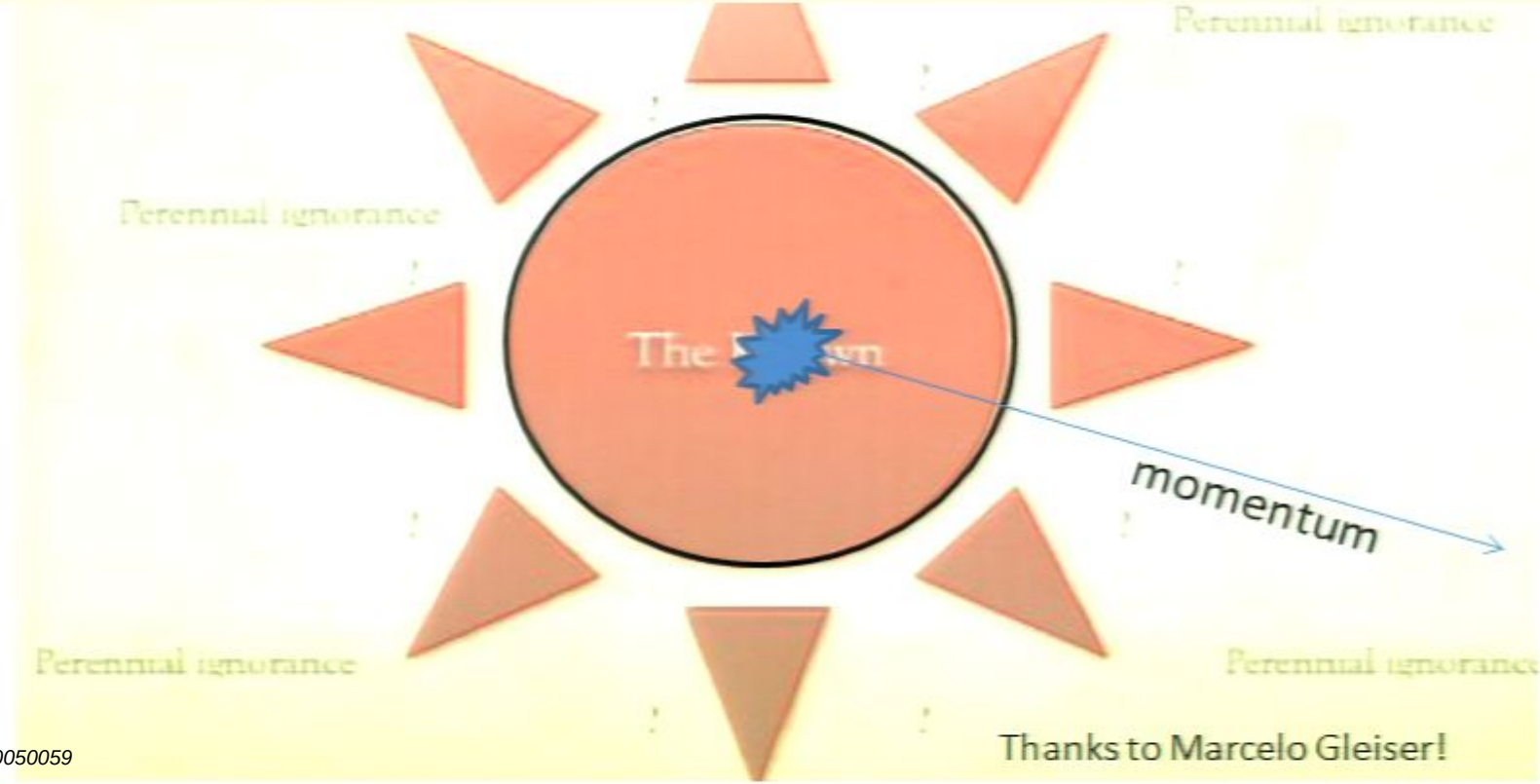


Technical Naturalness



Technical Naturalness

- A *technically natural* effective theory is insensitive to the cut-off



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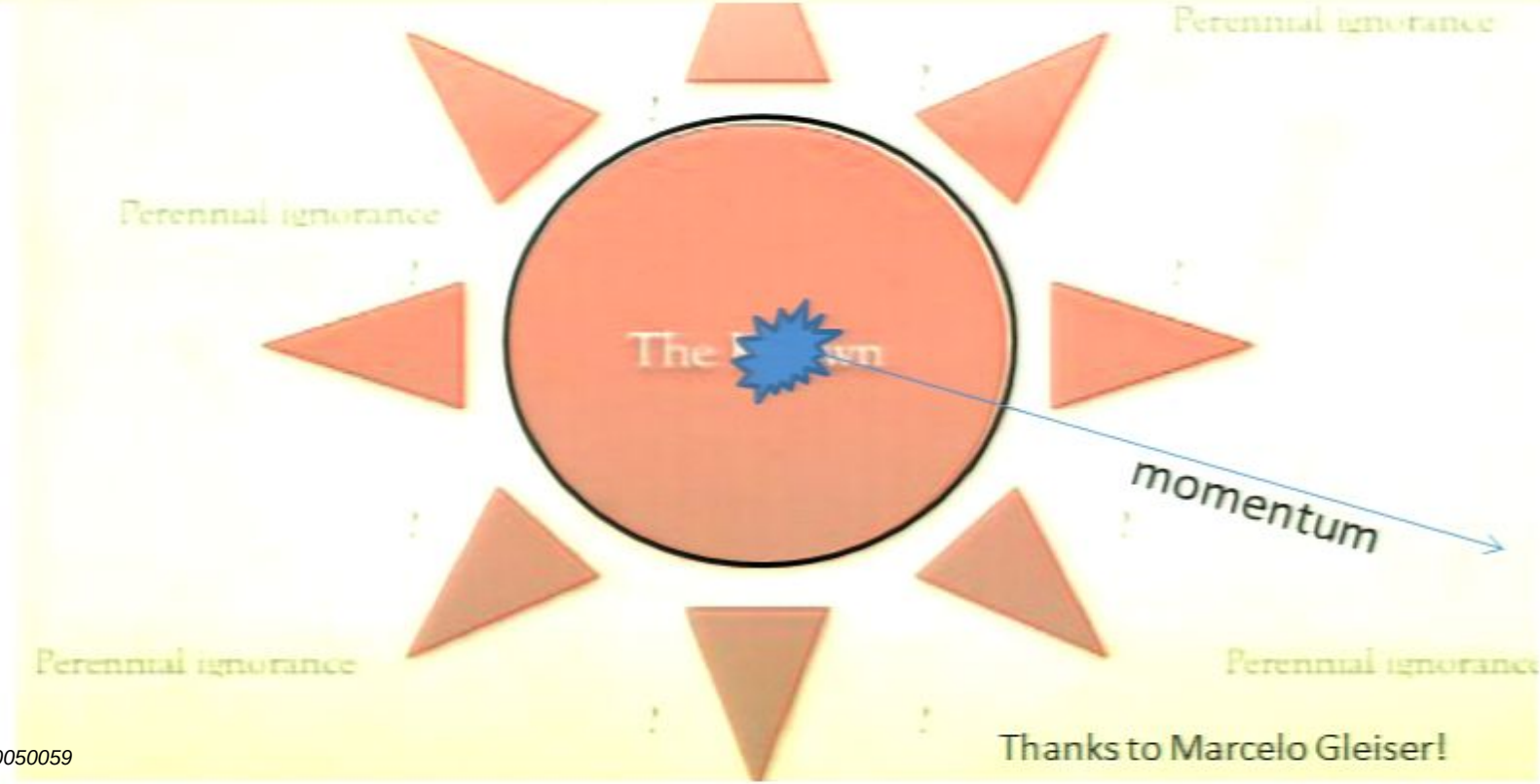
- e.g. Newton's laws, Standard Model
- A theory that is not technically natural requires *fine-tuning*



(Cosmologist's)

Quantum Gravity Problems

- Renormalizability → Big Bang Singularity

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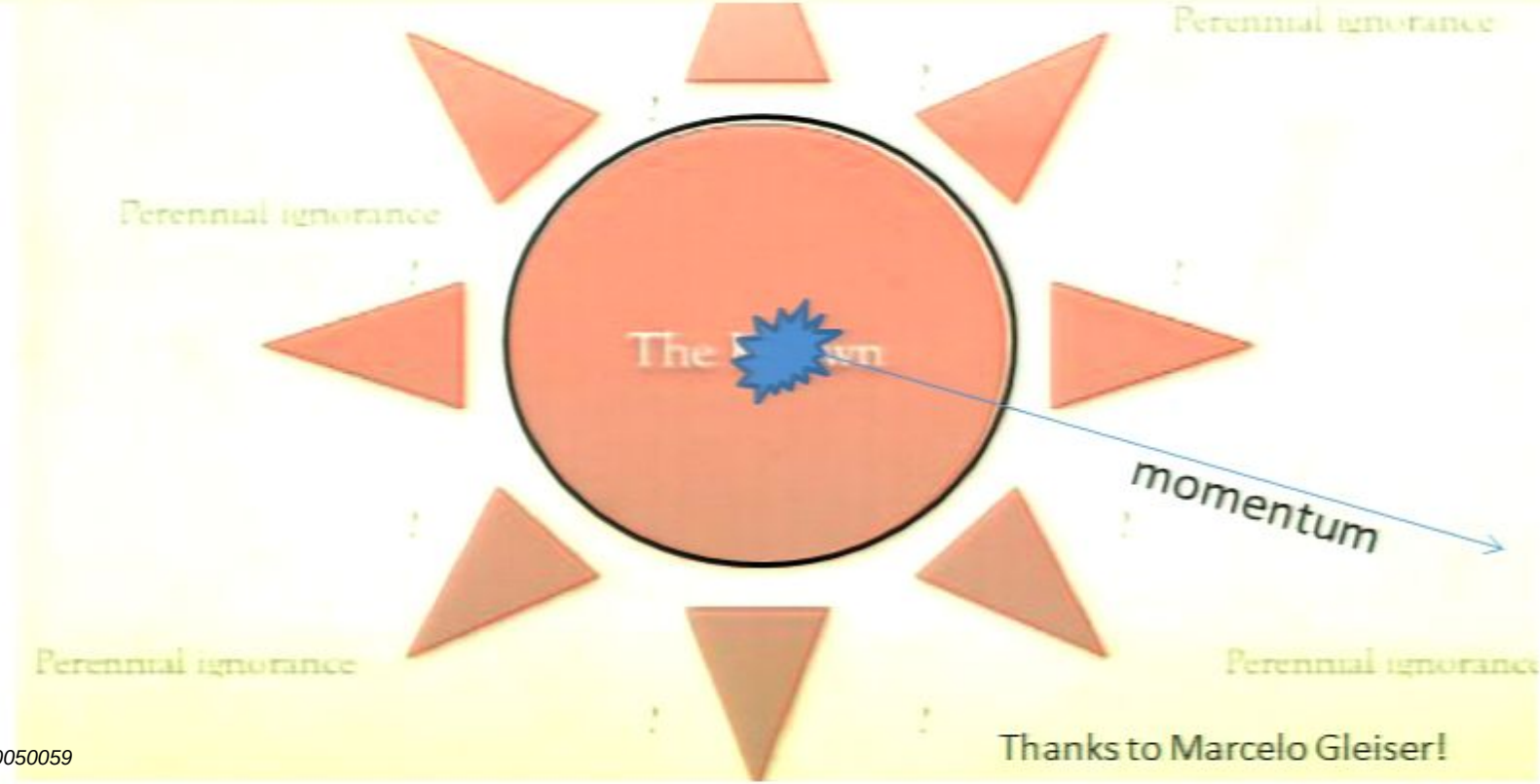

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  - $|\rho_{vac}| \ll 10^{33}$ kg/m^3 (Standard Model of Particle Physics)
- *New* Cosmological Constant Problem: *Dark Energy*
  - $\rho_{vac} = (7.1 \pm 0.9) \times 10^{-27}$ kg/m^3

Landscape/Multiverse "solution" to the CC problem

- All the possible choices of CC are realized in the multiverse, and we happen to live in the universes that are habitable

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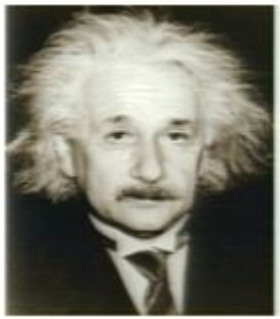
Which Principles to keep?

- Lorentz symmetry
- 4d diff. invariance
- Locality



- Action principle
- Unitarity

- Falsifiability
- Predictivity

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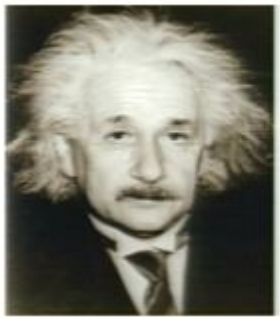

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Possible Quantum Gravities

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- Infinite new degrees of freedom
  - *e.g. string theory*
- Non-perturbative effects, non-standard quantization
  - *e.g. asymptotic safety, loop quantum gravity*
- Break Lorentz Invariance: Emergent Gravity
  - *Gravity is an emergent low energy phenomenon in a condensed matter system* (e.g. Gu & Wen 09)
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→ Aether theories: ~~4-diff. inv.~~ → 3-diff. inv.

(Emergent) Horava-Lifshitz Gravity

- Gravity is renormalizable if
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- Preferred frame behaves like Aether
- Aether should decouple from matter at low energies → *Michaelson-Morely experiment*
- At low energies:

$$S_{HL} = S_{EH} + \frac{1-\lambda}{16\pi G_N}\int d^4x\sqrt{-g}K^2,$$

General Relativity

local expansion (Hubble) rate

Aether → Incompressible Fluid

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Behaves as an incompressible fluid (NA 2009)

- Identical to *cuscuton* field theory
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Lesson:

Renormalizable Emergent Quantum Gravity → GR+Incompressible Aether *(at low energies)*

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mean extrinsic curvature of spatial hypersurfaces

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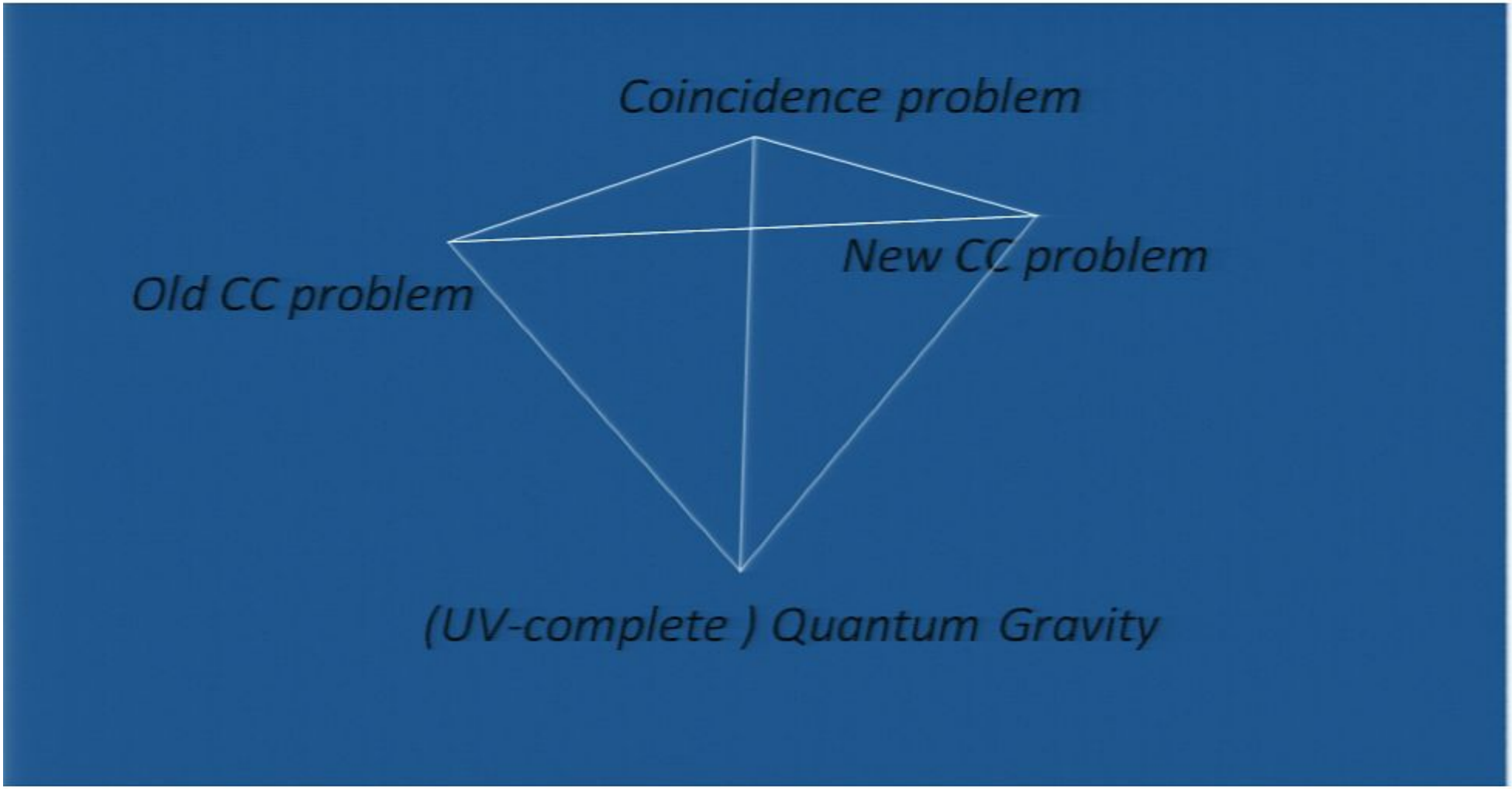
Incompressible Aether in history!

- "Similar to Newton, but mathematically in greater detail, *Bernhard Riemann* assumed in 1853 that the gravitational aether is an incompressible fluid and normal matter represents sinks in this aether …"

http://en.wikipedia.org/wiki/Mechanical_explanations_of_gravitation

Riemann, B. (1876), "Neue mathematische Prinzipien der Naturphilosophie", *Bernhard Riemanns Werke und gesammelter Nachlass* (Leipzig): 528–538

The Cosmological Constant (CC) Conundrum



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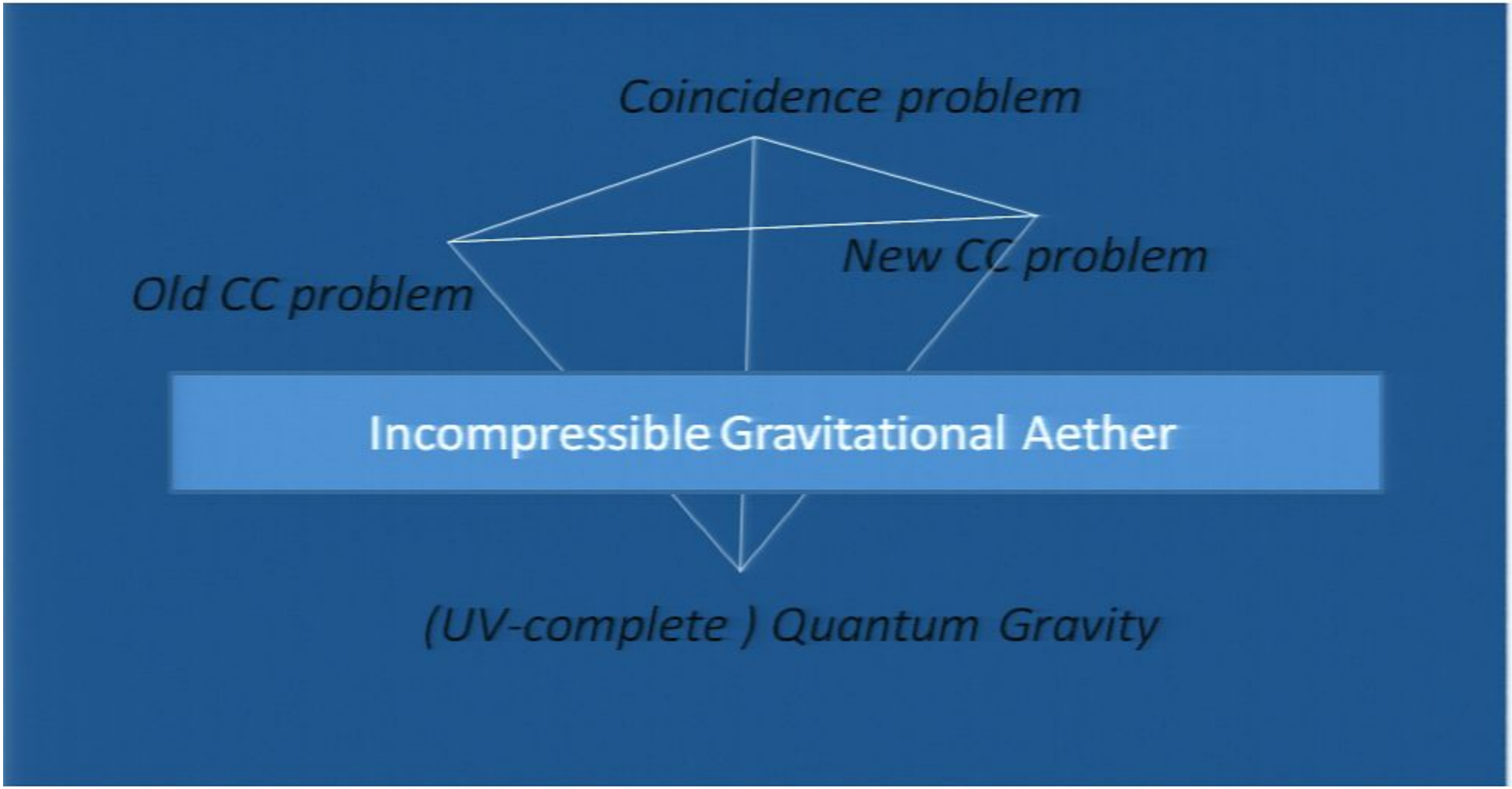

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Gravitational Aether: *(NA 2008)*

solves the old cosmological constant problem

$$(8\pi G')^{-1} G_{\mu\nu}[g_{\mu\nu}] = T_{\mu\nu} - \frac{1}{4} T^{\alpha}_{\alpha} g_{\mu\nu} + \ldots$$

- The metric is now blind to vacuum energy:

$$T_{\mu\nu} = \rho_{\rm vac} g_{\mu\nu} + \text{excitations}$$

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- Further assume incompressible fluid/aether:

$$T'_{\mu\nu} = p'(u'_{\mu} u'_{\nu} + g_{\mu\nu})$$

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Motivation: Tests of gravity severely constrain new deg's of freedom

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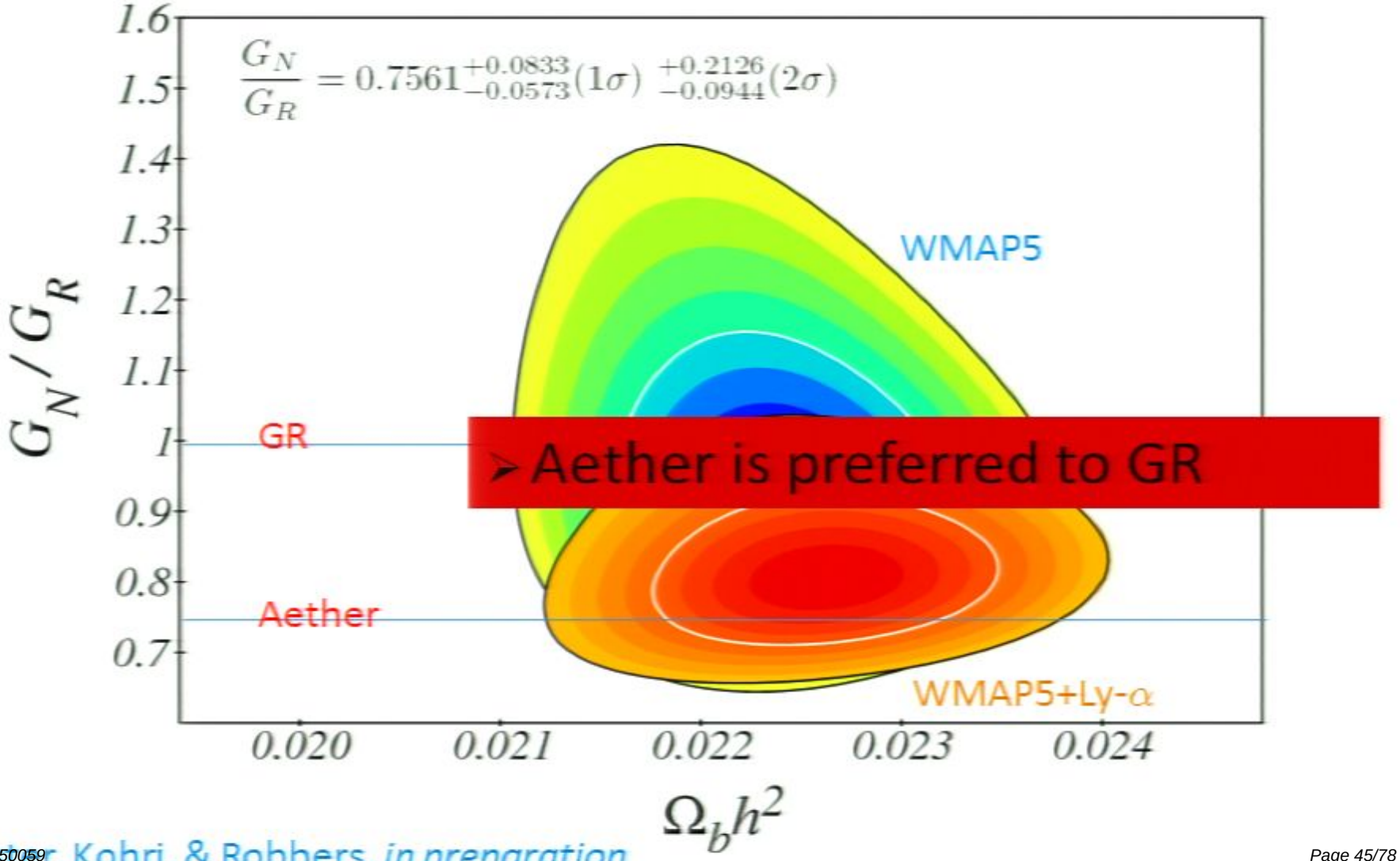
Hořava-Lifshitz gravity

Example of model predictions: Ly-α forest + WMAP5



➢ Aether is preferred to GR

NA, Foster, Kohri, & Robbers, *in preparation*

- Aether has solved the *old* cosmological constant problem.

- How about the *new* cosmological constant problem (Dark Energy)?

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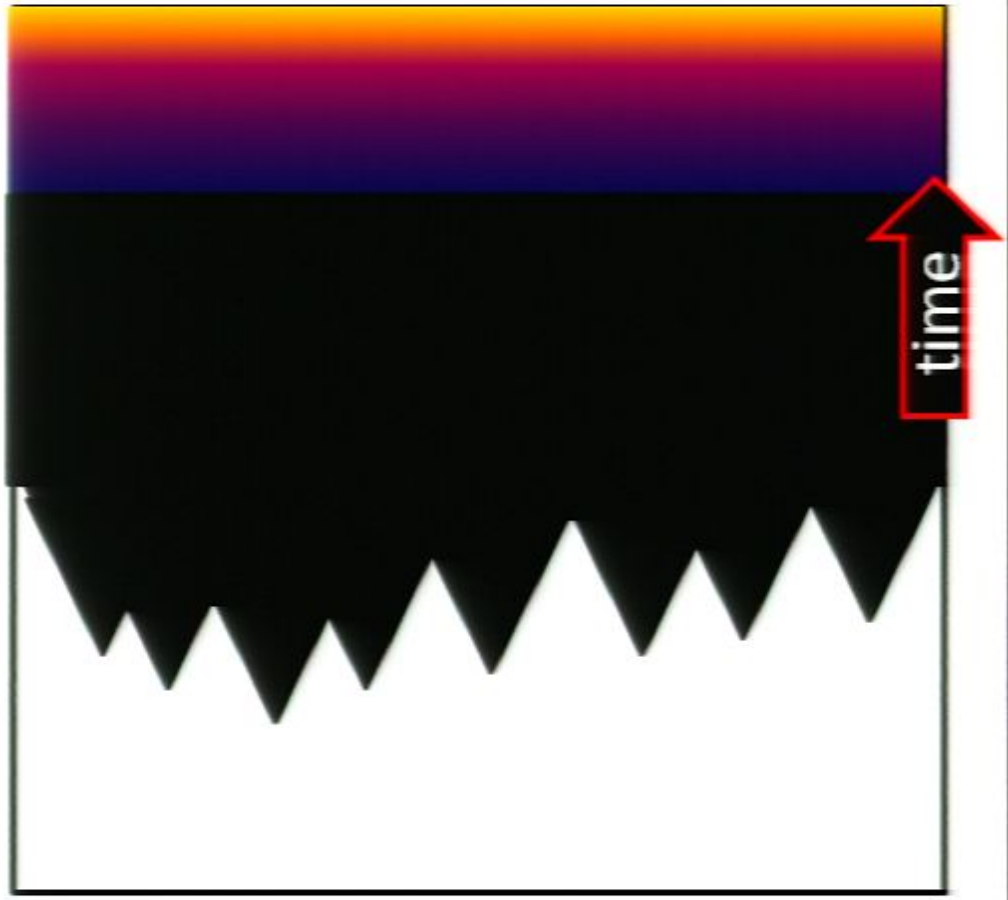
How Black Holes lead to cosmic acceleration



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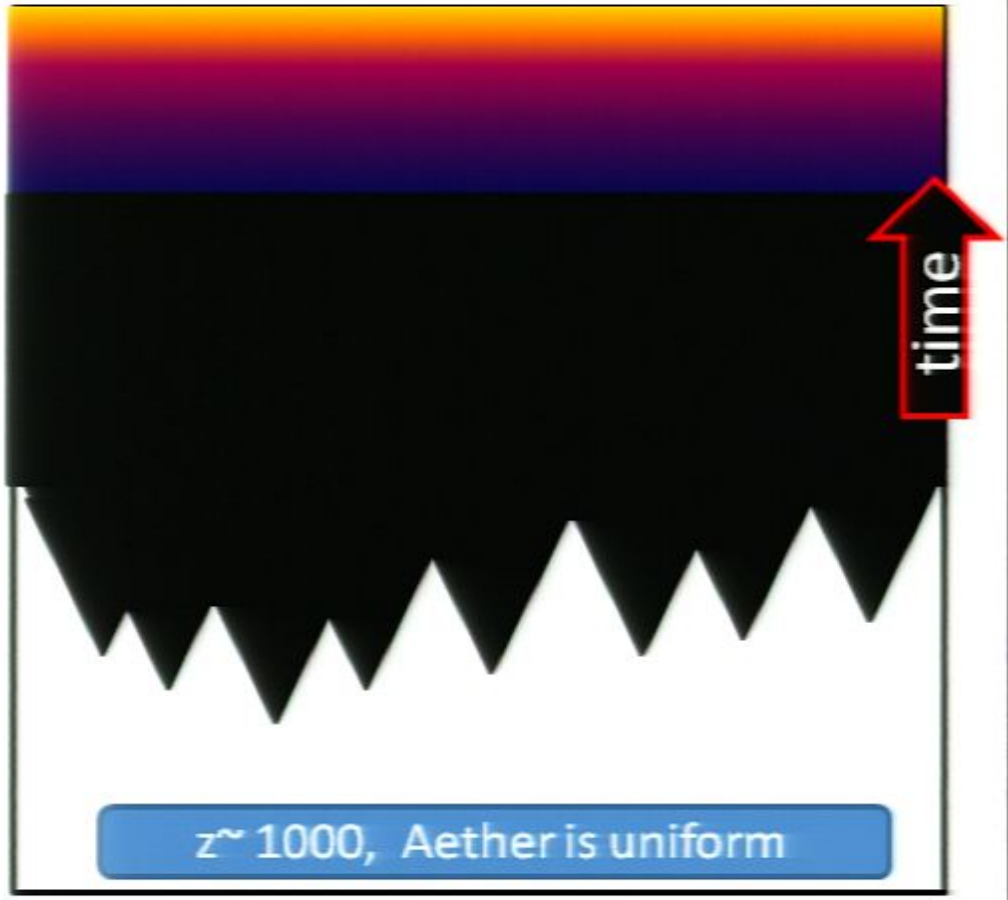

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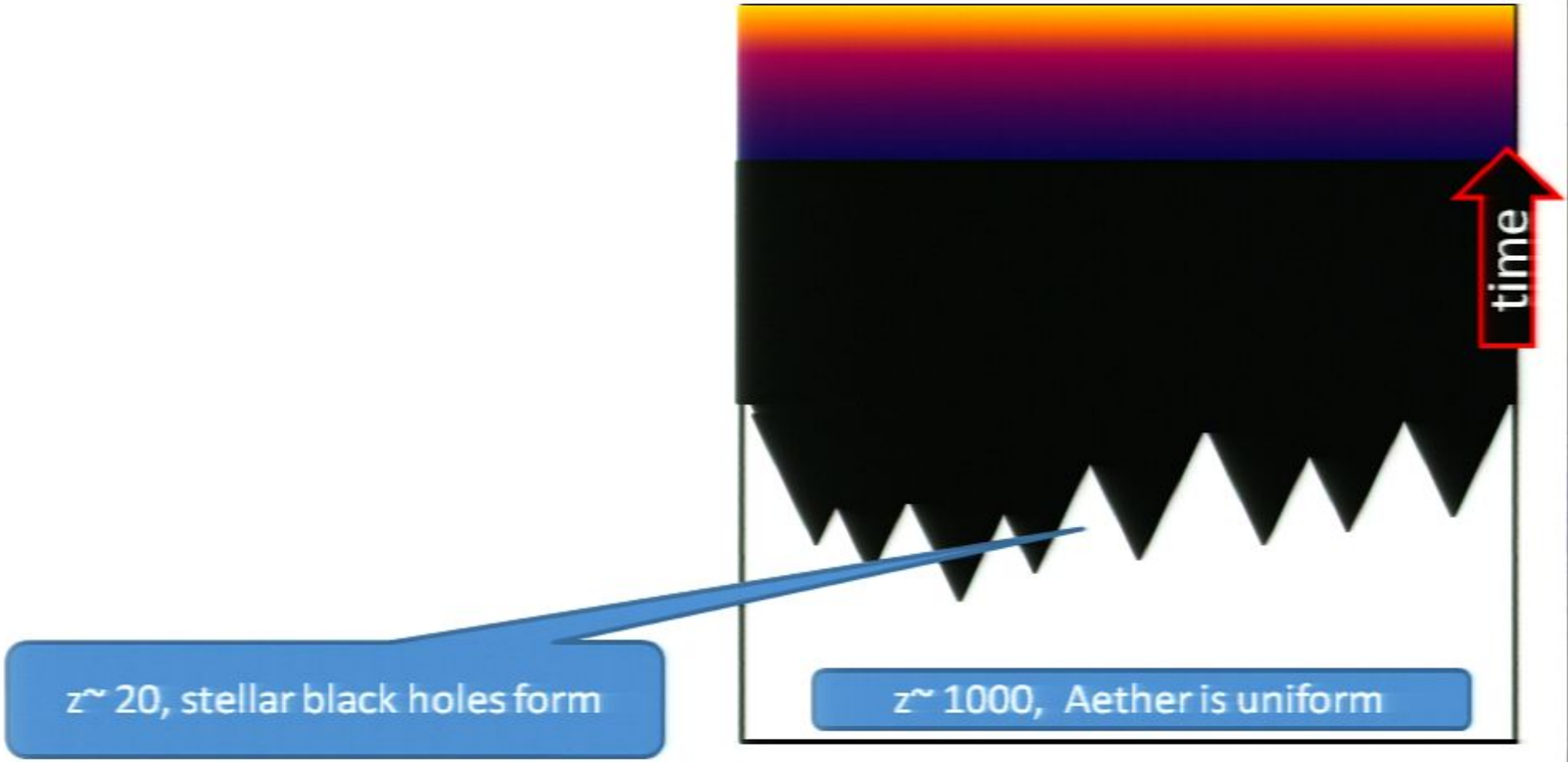

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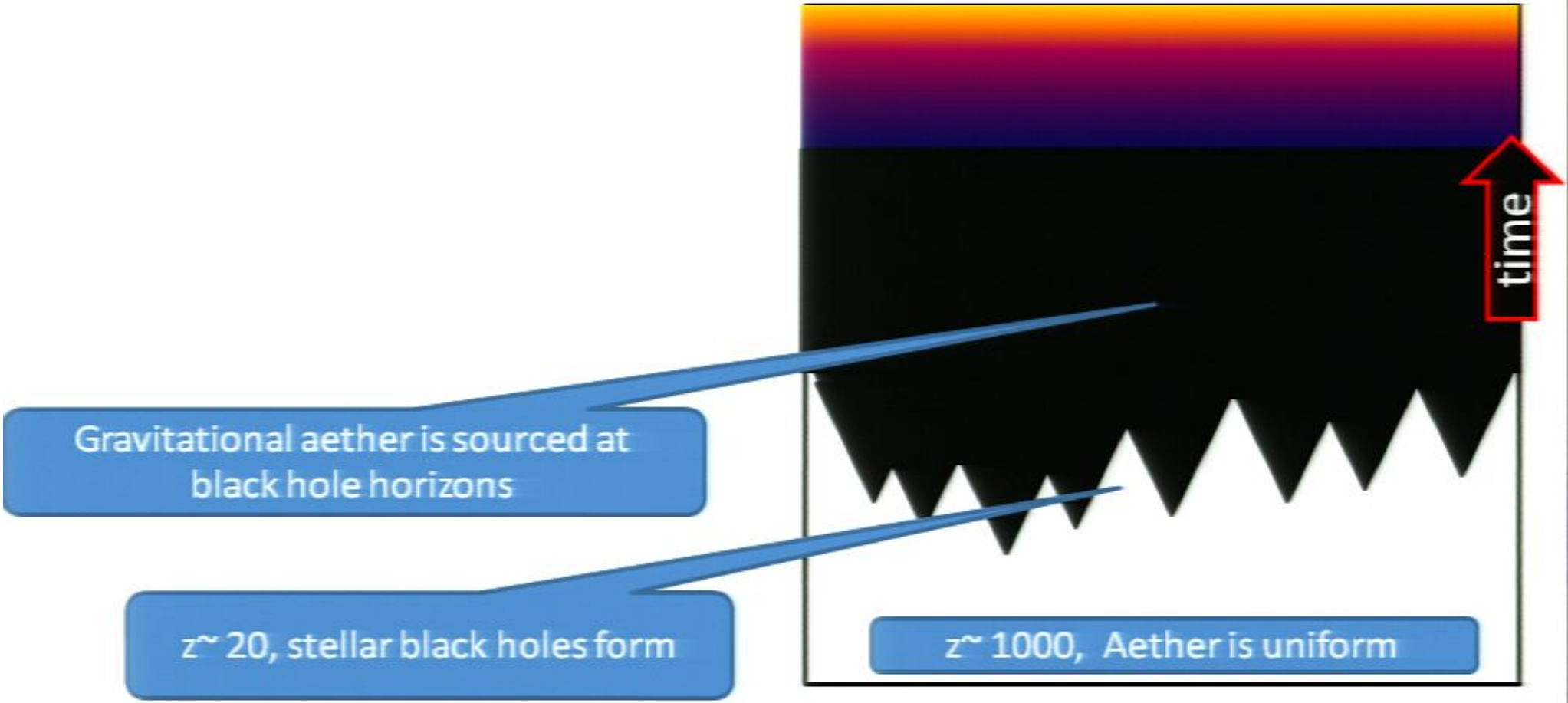

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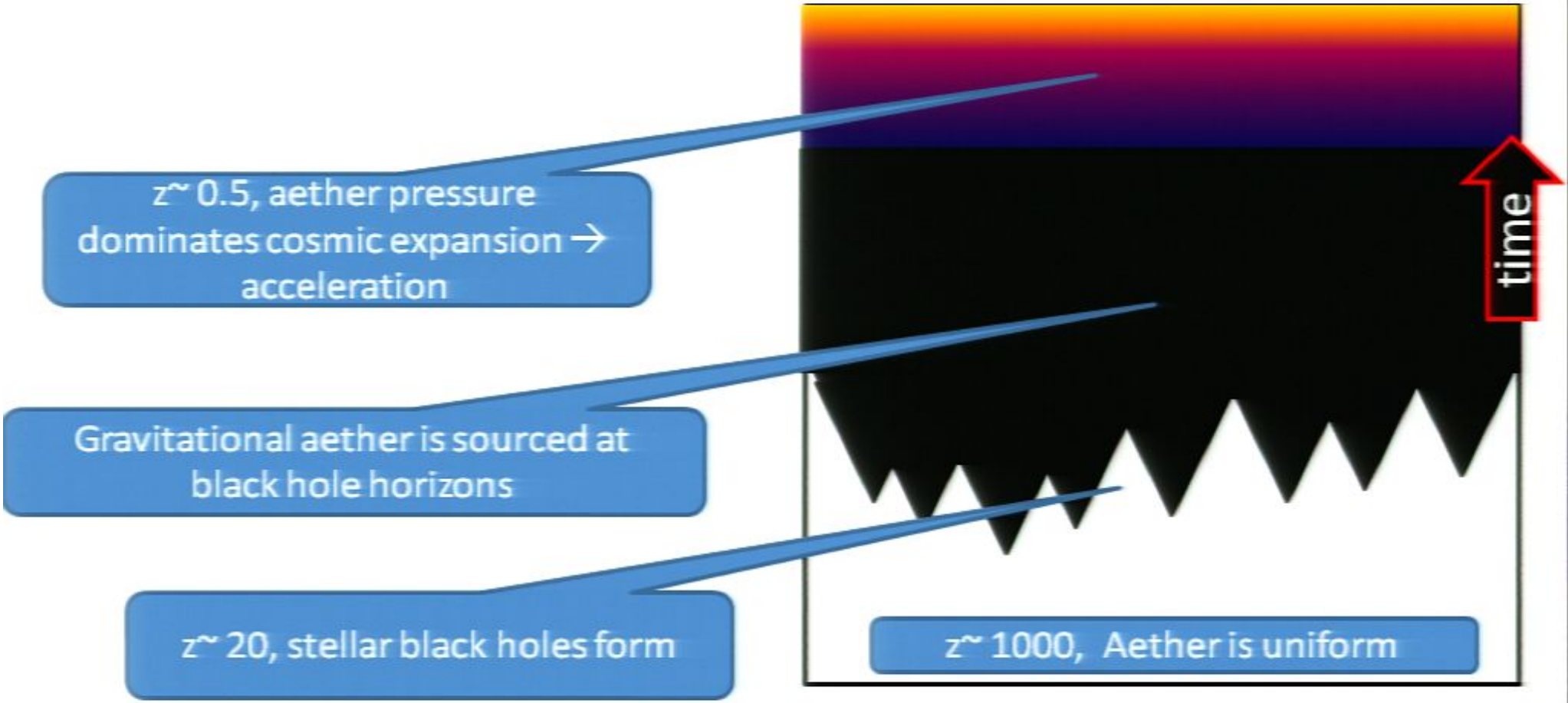

Aether: a thermodynamic theory?!

- Black Hole Thermodynamics:
  - Bardeen, Carter, & Hawking 1973; Bekenstein 1973

$$dM = \left(\frac{\kappa}{8\pi}\right) d\left(\frac{A}{4}\right) + \Omega dJ + \Phi dQ$$

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  - TdS = dQ → $G_{\mu\nu} = T_{\mu\nu}$ (Jacobson 1995)
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- Could gravity be the thermodynamic description of a more fundamental theory?

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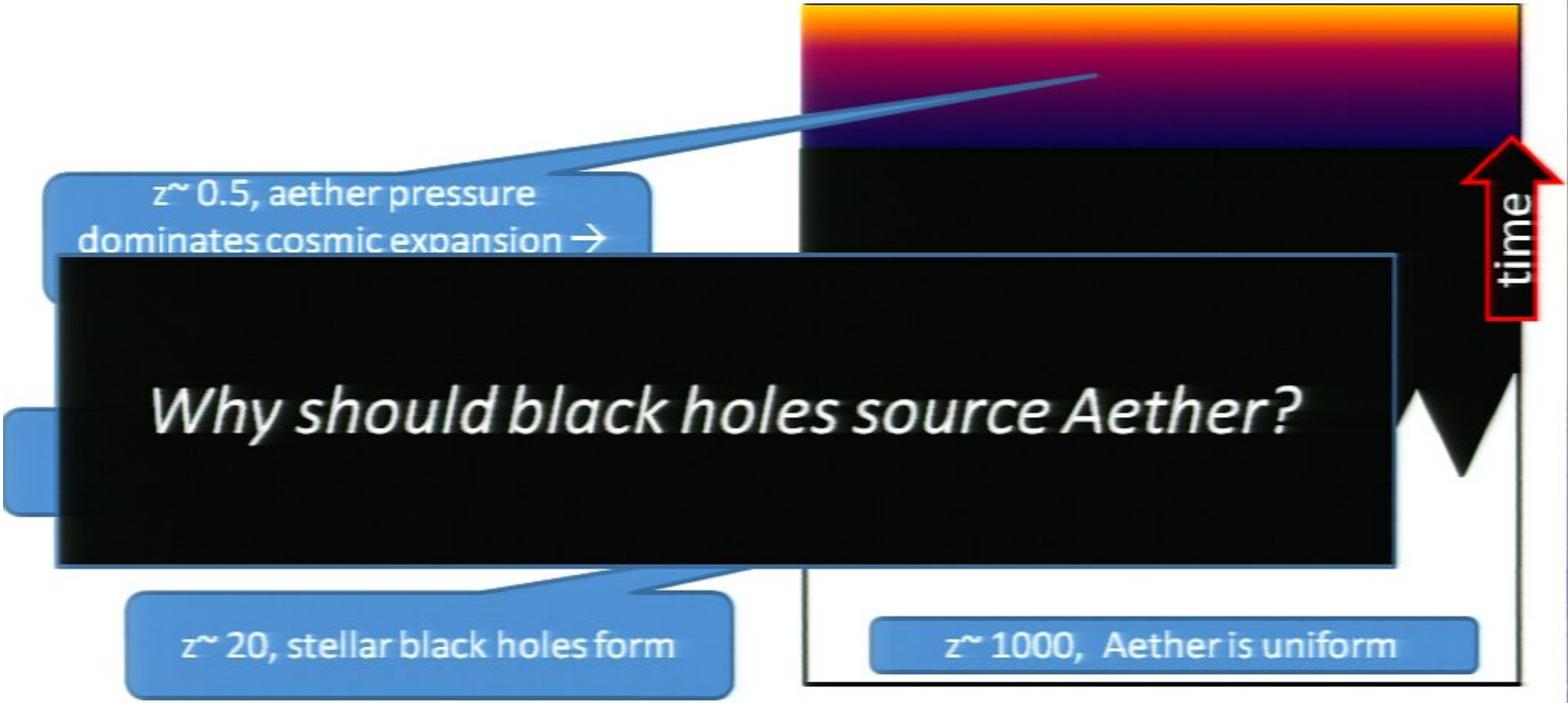

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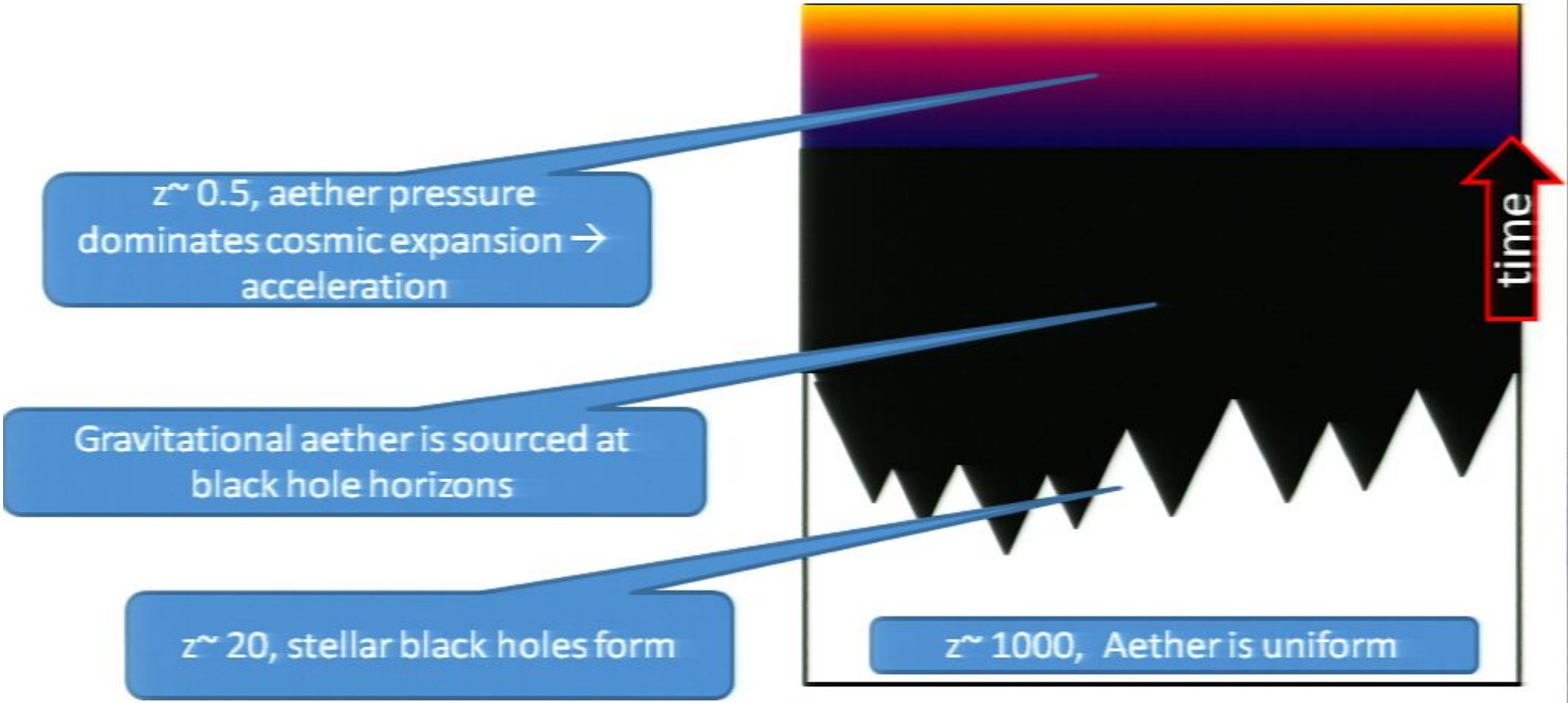

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Back Hole Entropy and Dark Energy

- What if gravitational aether has a thermal pressure? $dM = T_H dS - pdV$

Back Hole Entropy and Dark Energy

Horizon Temperature $\ll$ Planck Energy = 1

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- Pressure becomes:

$$p = \alpha\pi M_P T_H^3$$

Back Hole Entropy and Dark Energy

- Could astrophysical Black Holes source Dark Energy?!
- Cosmic Acceleration, first precision measurement in Quantum Gravity!

$$\alpha = (-3.1 \pm 0.4) \times 10^{-3}\,[M_{BH}/10\,M_{\odot}]^{-3}$$

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- Pressure becomes:

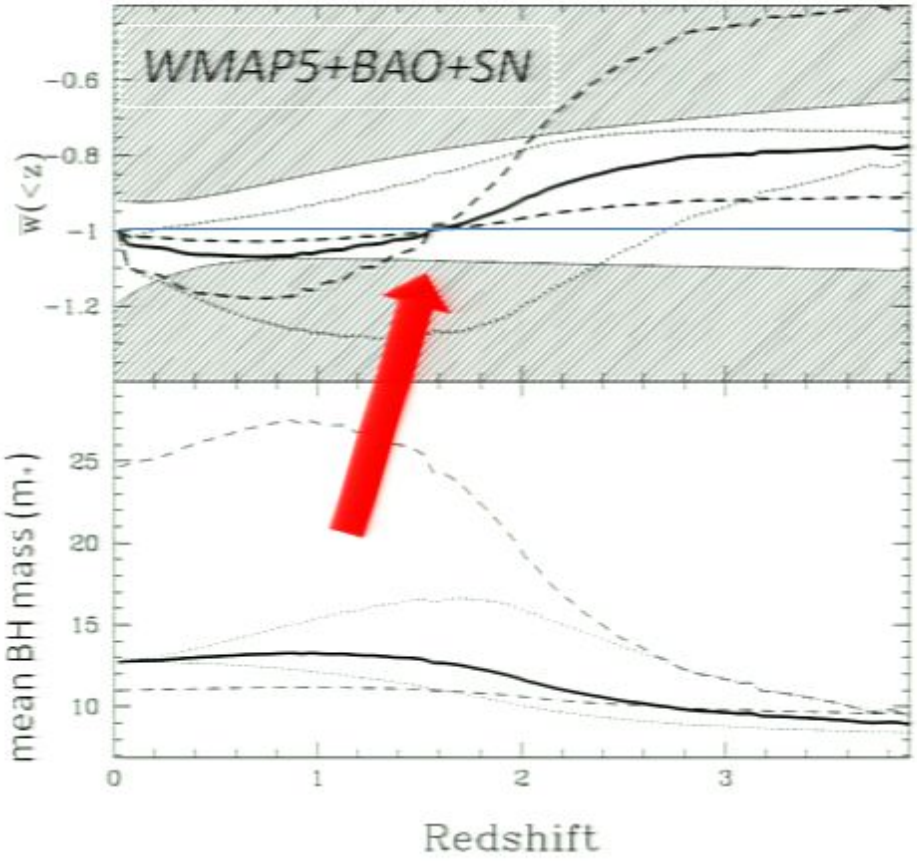
$$p = \alpha\pi M_P T_H^3 = \alpha\rho_{\mathrm{DE},obs}\left(\frac{M}{60\ M_{\odot}}\right)^{-3}$$

Multiple BH's and Effective Dark Energy

- multiple black holes:

  $\log m_* = \langle \log m \rangle_{\text{mass weighted}}$

- As super-massive BH's grow, the effective $\rho_{DE} \propto m_*^{-3}$ decreases
- Using a model for formation of stars/SMBH's



Prescod-Weinstein, N.A. & Balogh 2009

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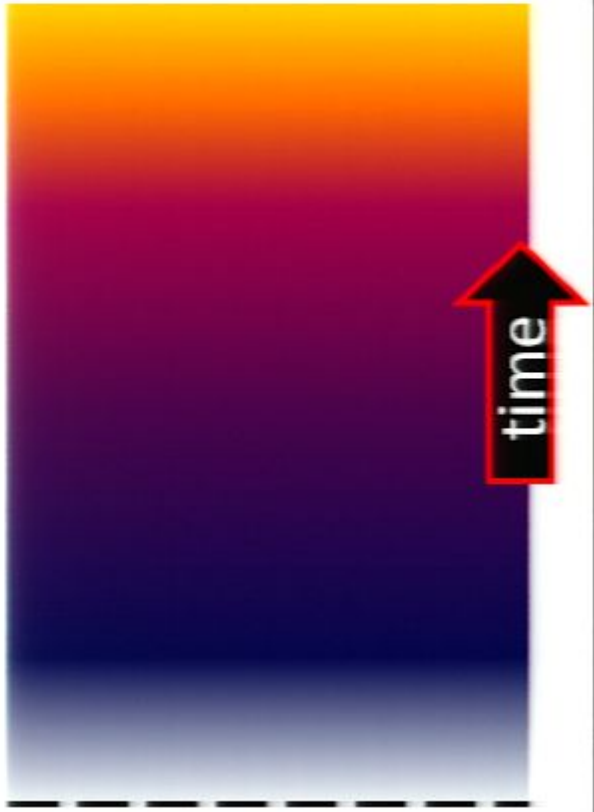
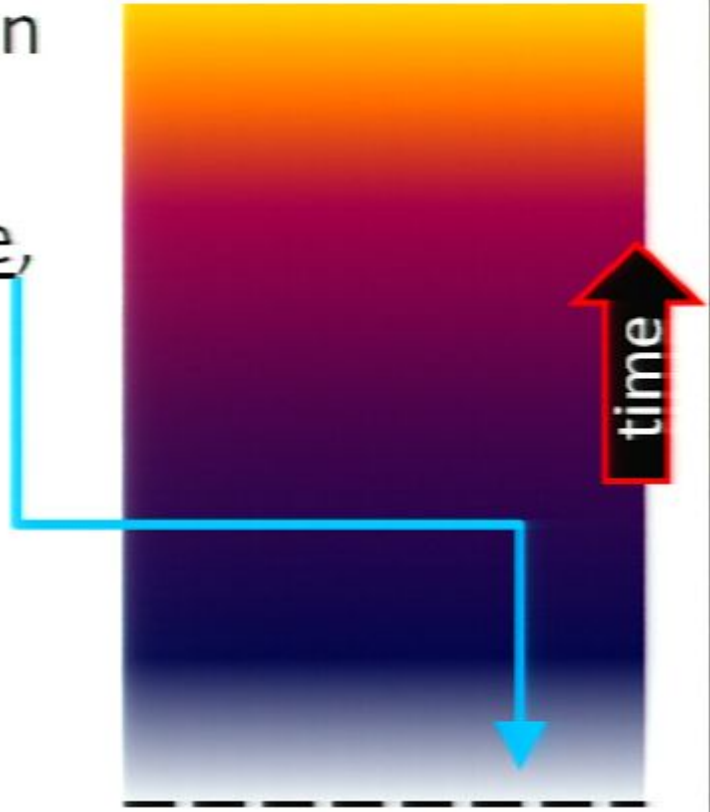
A theory of initial conditions!

- In Horava-Lifshitz gravity, propagation speed diverges at early times



A theory of initial conditions!

- In Horava-Lifshitz gravity, propagation speed diverges at early times
- This yields a natural initial 3d surface, where Bunch-Davies/thermal states can be defined



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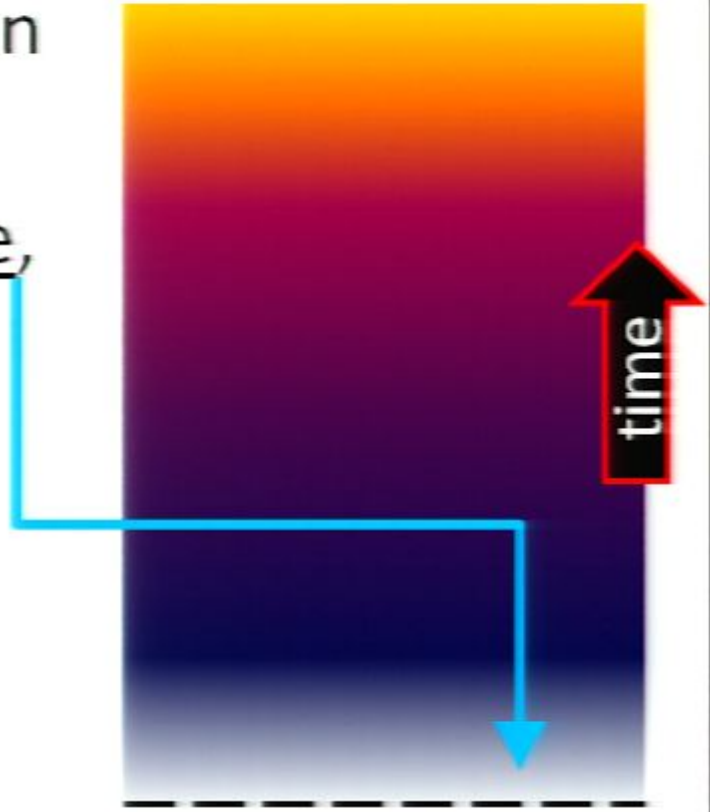
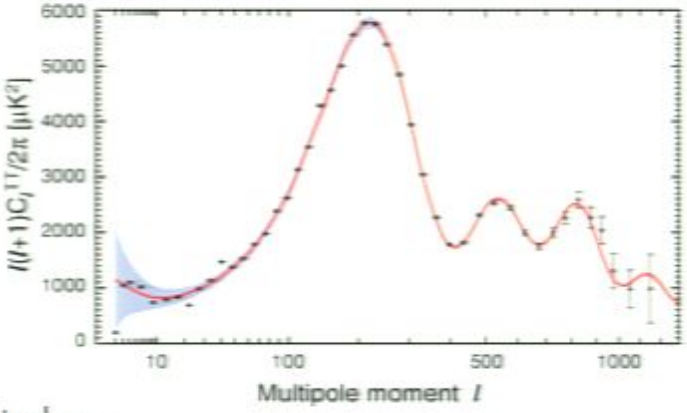
→Scalar-invariant power spectrum

Magueijo 2008, Mukohyama 2009





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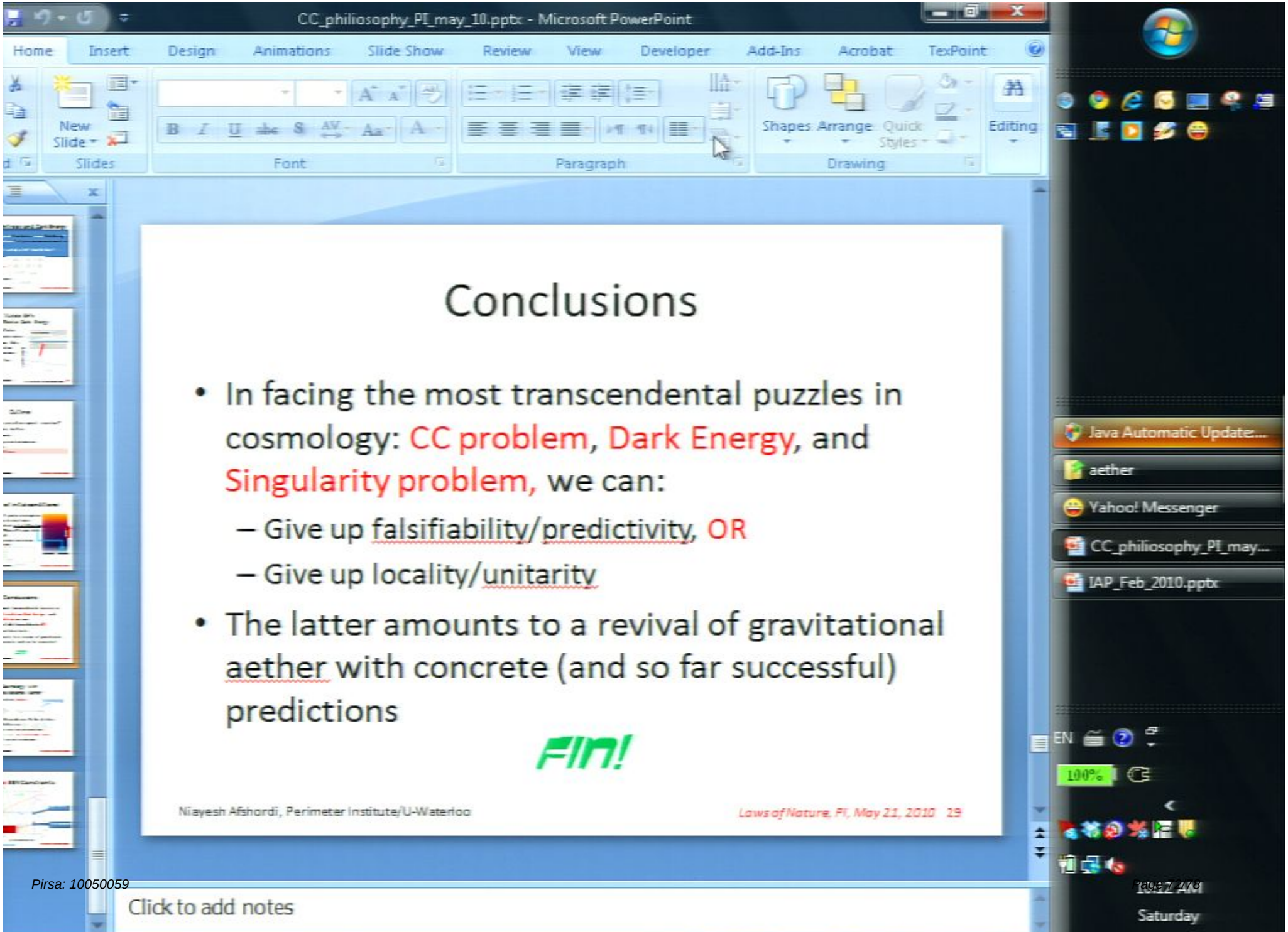

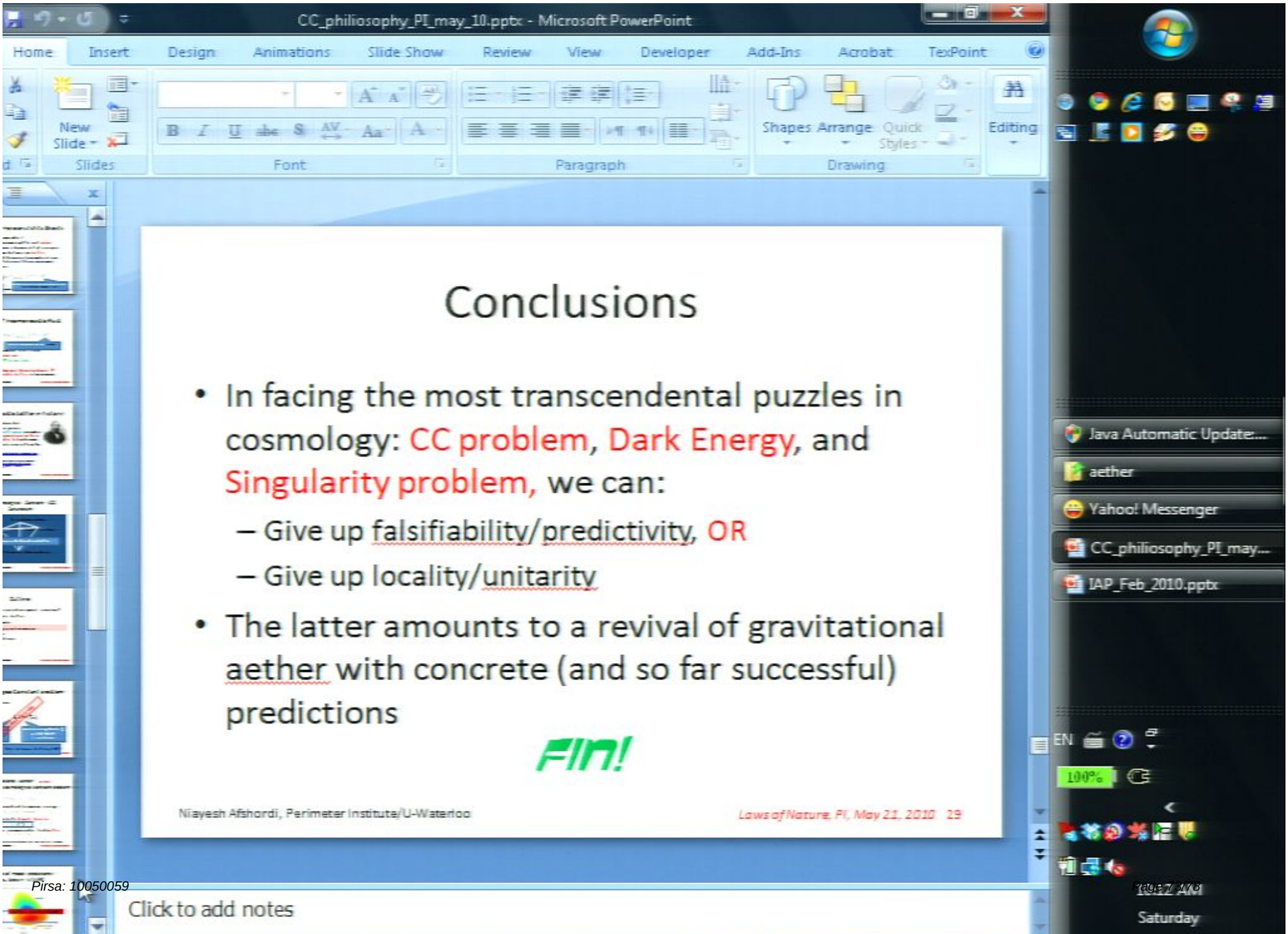
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FIN!
Niayesh Afshordi, Perimeter Institute/U-Waterloo
Laws of Nature, PI, May 21, 2010 29
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Gravitational Aether: *(NA 2008)*

solves the old cosmological constant problem

$$(8\pi G')^{-1} G_{\mu\nu}[g_{\mu\nu}] = T_{\mu\nu} - \frac{1}{4} T^{\alpha}_{\alpha} g_{\mu\nu} + \ldots$$

- The metric is now blind to vacuum energy:

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

- In order to satisfy the Bianchi identity:

$$(8\pi G')^{-1} G_{\mu\nu}[g_{\mu\nu}] = T_{\mu\nu} - \frac{1}{4} T^{\alpha}_{\alpha} g_{\mu\nu} + T'_{\mu\nu} \qquad T'^{\mu}{}_{\nu;\mu} = \frac{1}{4} T^{\alpha}{}_{\alpha;\nu}$$

- Further assume incompressible fluid/aether:

$$T'_{\mu\nu} = p'(u'_{\mu} u'_{\nu} + g_{\mu\nu})$$

Motivation: Tests of gravity severely constrain new deg's of freedom

+ Horava-Lifshitz gravity

Gravitational Aether: *(NA 2008)*

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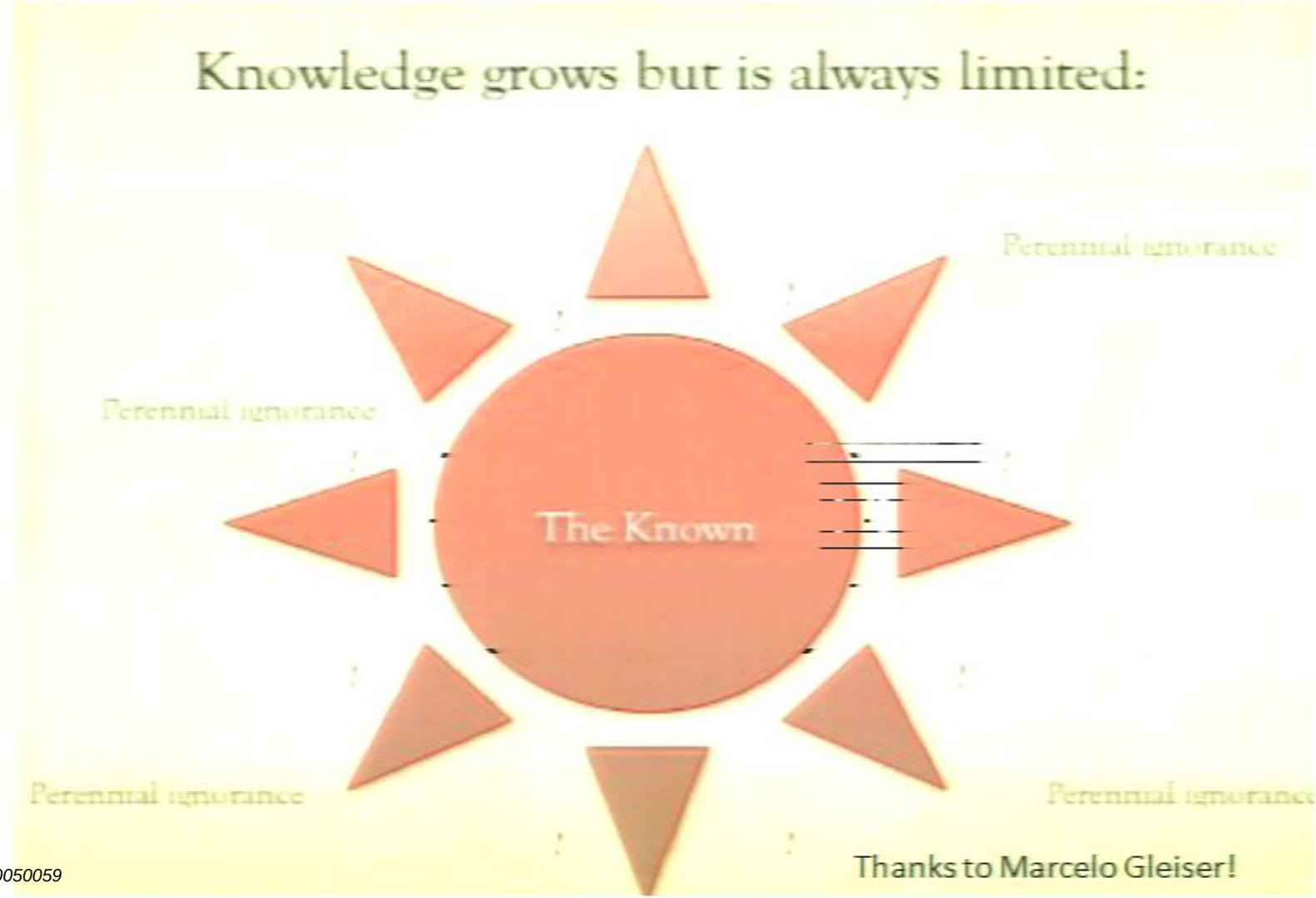
Landscape/Multiverse "solution" to the CC problem

- All the possible choices of CC are realized in the multiverse, and we happen to live in the universes that are habitable


Knowledge grows but is always limited:
Perennial ignorance
Perennial ignorance
The Known
Perennial ignorance
Perennial ignorance
Thanks to Marcelo Gleiser!

Technical Naturalness