Astrophysics Seminar
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# **Stellar Black Holes**, and the *thermodynamic origin* of **Cosmic Acceleration**

Niayesh Afshordi


UNIVERSITY OF Waterloo

# Outline

- Introduction
- Reviving Aether
- Cosmological Constant Problem and Aether
- Testing Aether
- Stellar Black Holes and Cosmic Acceleration
- Conclusions

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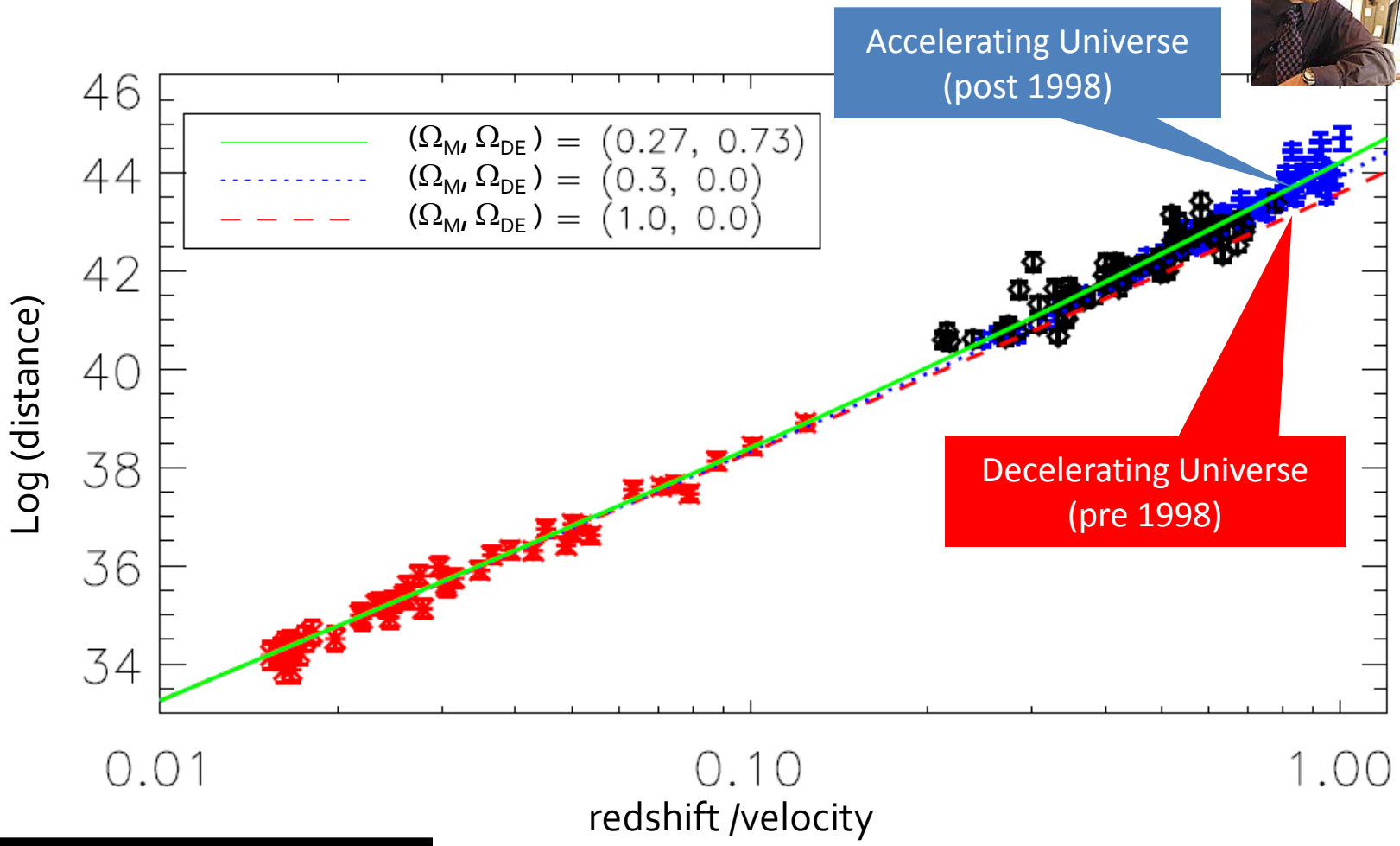
*(Cosmologist's)*

# Quantum Gravity Problems

- Renormalizability → Big Bang Singularity
- *Old* Cosmological Constant Problem (Pauli 1920's)
  - $|\rho_{vac}| \lesssim 10^{33}\ kg/m^3$ (Standard Model of Particle Physics)

# Dark Energy:
## 73% of cosmic energy is vacuum!



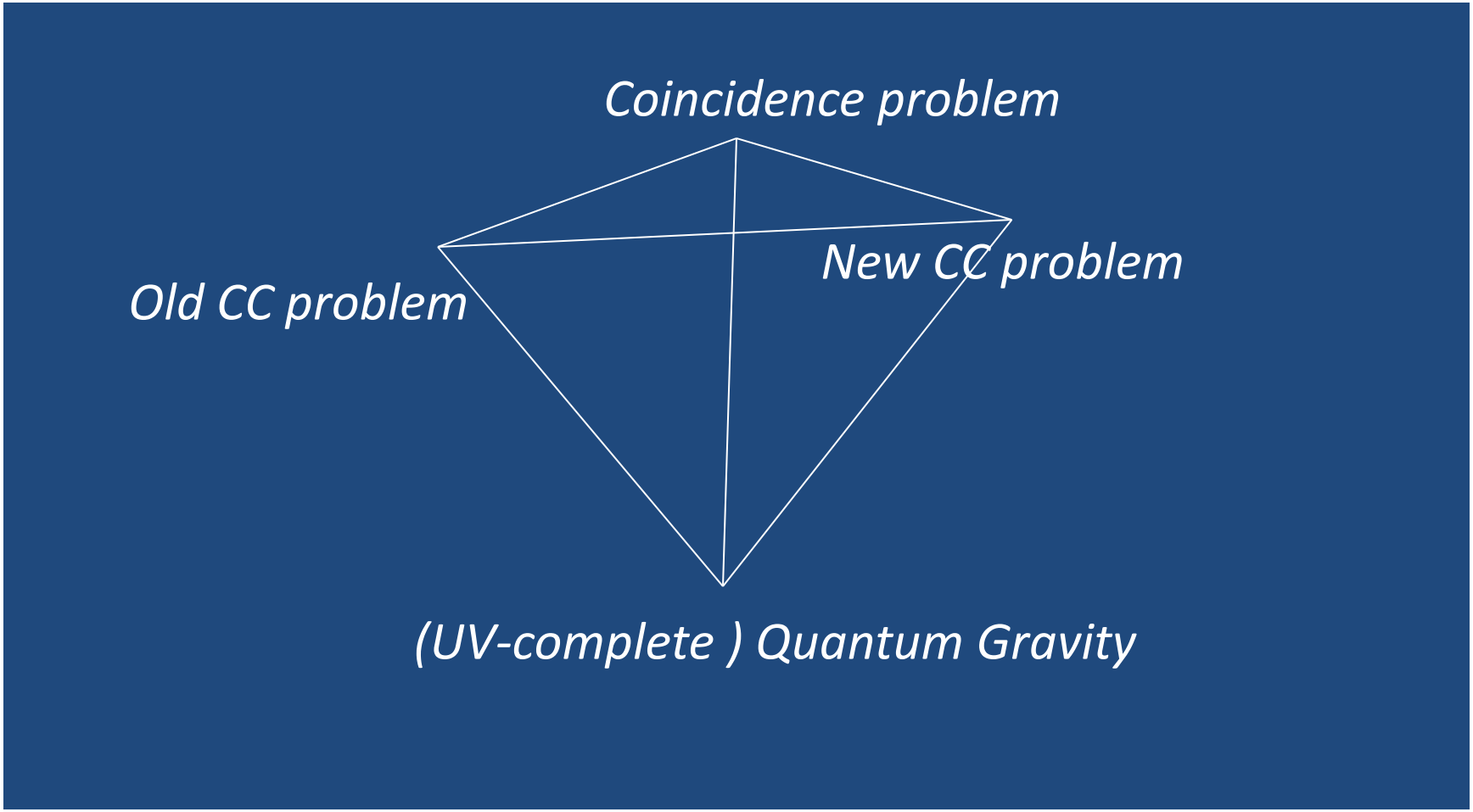

Supernovae Ia (Wood-Vasey et al. 2007)

*(Cosmologist's)*

# Quantum Gravity Problems

- Renormalizability → Big Bang Singularity
- *Old* Cosmological Constant Problem (Pauli 1920's)
  - $|\rho_{vac}| \sim 10^{33}\ kg/m^3$ (Standard Model of Particle Physics)
- *New* Cosmological Constant Problem: *Dark Energy*
  - $\rho_{vac} = (7.1 \pm 0.9) \times 10^{-27}\ kg/m^3$
- *Coincidence* Problem
  - $\rho_{vac} \simeq 2.7\, \rho_{m,0}$

# The Cosmological Constant (CC) Conundrum



# Possible Quantum Gravity Theories

- 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)
  - *e.g. Horava-Lifshitz gravity* (Horava 09)

  → Cosmologist's favorite! *Cosmological (FRW) spacetime maximally breaks Lorentz symmetry!*

  → Scalar-Tensor or Aether theories

# Aether: a thermodynamic theory?!

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

$$dm = \left(\frac{\kappa}{2\pi}\right) d\left(\frac{A}{4}\right) + \Omega dJ + \Phi dQ$$

- Einstein's gravity and 2nd law:
  - TdS = dQ → $G_{1o} = T_{1o}$ (Jacobson 1995)
  - Newtonian gravity as an entropic force (Verlinde 2010)
- Could gravity be the thermodynamic description of a more fundamental theory?

# Back Hole Entropy and Dark Energy

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

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

- Entropy: $$S = \frac{1}{16\pi T_H^2}\left[1 + \alpha T_H + \mathcal{O}(T_H^2)\right]$$
- Energy/Mass: $$m = \frac{1}{8\pi T_H}\left[1 + \beta T_H + \mathcal{O}(T_H^2)\right]$$
- Volume: $$V = \frac{4}{3}\pi(2m)^3 = \frac{1}{48\pi^2 T_H^3}$$

- Pressure becomes: $$p = \alpha\pi T_H^3$$

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# *(Emergent)* Horava-Lifshitz Gravity

- Gravity is renormalizable if
  - frequency / wavelength$^{-3}$ (! / $k^3$); Horava 09
- Lorentz invariance is broken at high energies
- 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

mean extrinsic curvature of spatial hypersurfaces
local expansion (Hubble) rate

# Aether → Incompressible Fluid

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

Behaves as an incompressible fluid (NA 2009)

- Identical to *cuscuton* field theory
  - (*NA, Chung, & Geshnizjani 2007)*

Lesson:

Renormalizable Emergent Quantum Gravity → Incompressible Aether

# 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

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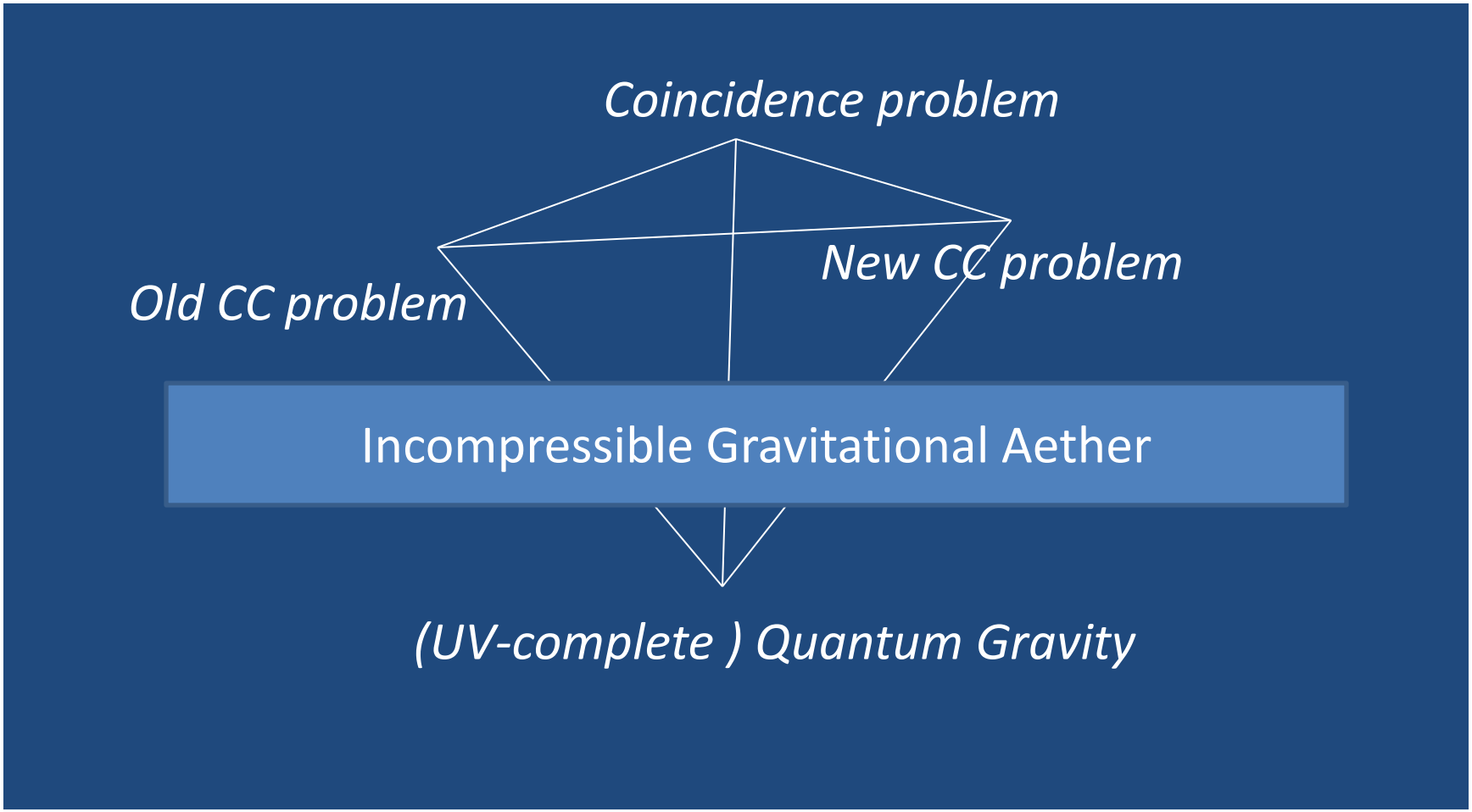
# The Cosmological Constant (CC) Conundrum



# Cosmological Constant problem

- Einstein Equation

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

Modified Gravity

space-time curvature
$(10^{-3}\ \mathrm{eV})^4$

vacuum energy density : &
§ $(100\ \mathrm{GeV})^4$
+ excitations

*e.g.*, Degravitation: Dvali, Hofmann, & Khoury 2007

# 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:

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

- 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

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# Cosmology with Gravitational Aether

- Friedmann equation *(NA 2008)*:

$$H^2 + \frac{k}{a^2} = \frac{8\pi G_{\rm eff}}{3}\rho \qquad G_{\rm eff} = (1+w)G_N$$

$p/\rho$=½ for matter

i.e., effective *G* depends on the Eq. of state.

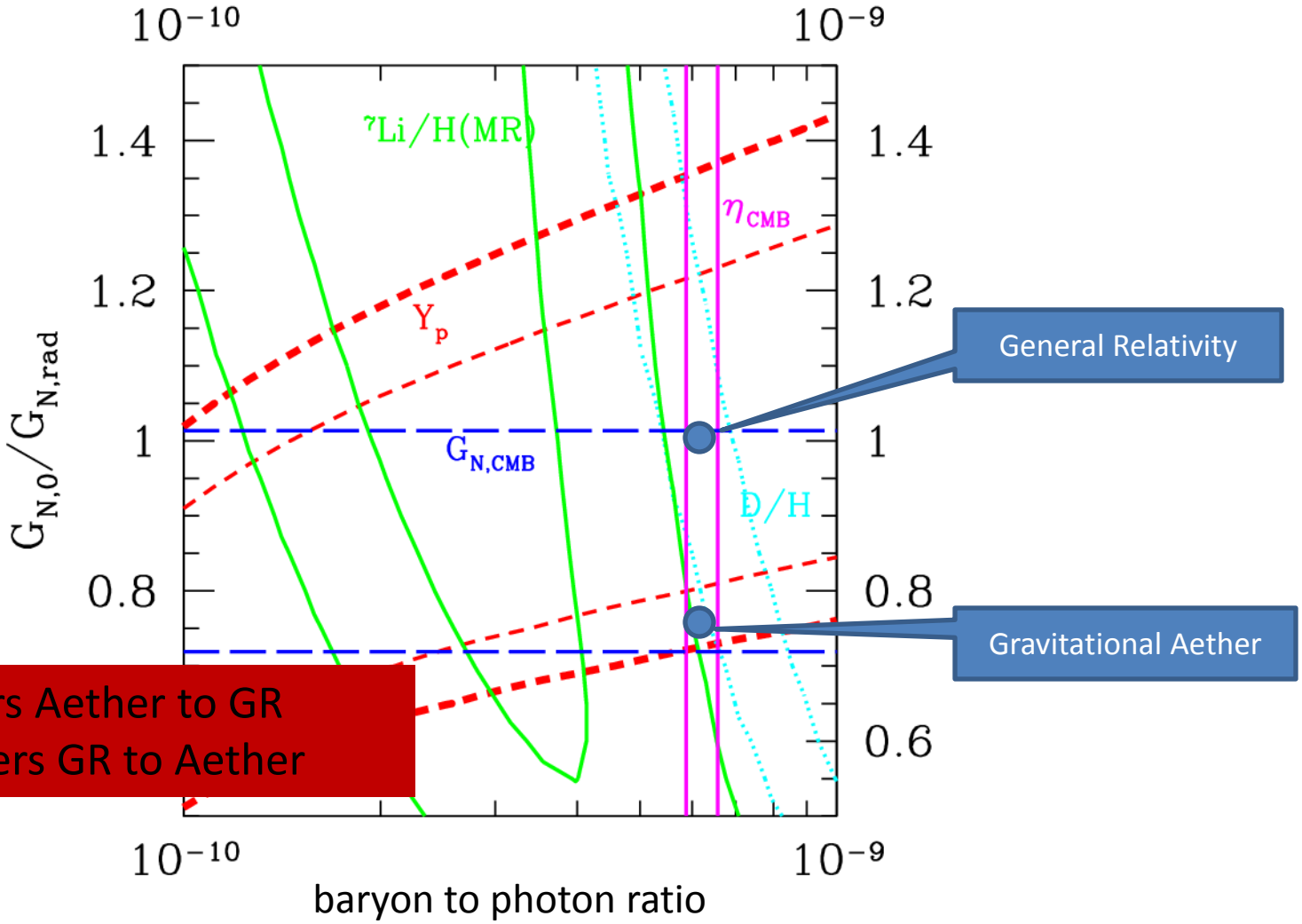
- Radiation vs. Matter era: $\frac{G_N}{G_R} = \frac{G_{\rm eff}(w=0)}{G_{\rm eff}(w=1/3)} = \frac{3}{4}$
- BBN ($^4$He abundance) (Cyburt, Fields, Olive, & Skillman 2005)

$$G_N/G_R = 0.97 \pm 0.09$$ (but $^7$Li prefers lower values)

- Ly-®+WMAP3 (Seljak, Slosar, McDonald 2006):

$$G_N/G_R = 0.73 \pm 0.04$$

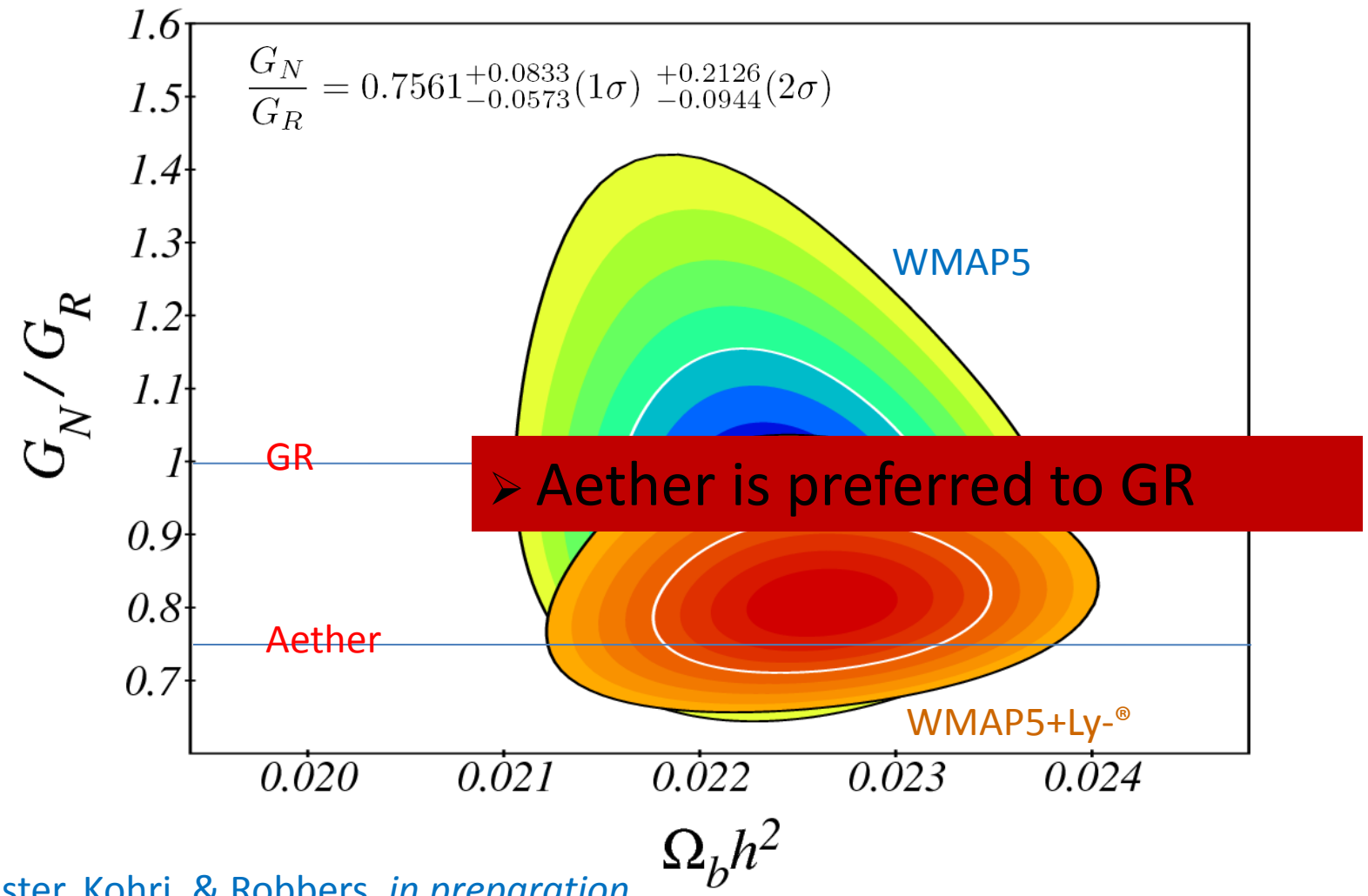
# The *Real* BBN Constraints




- $^7$Li prefers Aether to GR
- $^4$He prefers GR to Aether

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

# Ly-® forest + WMAP5




- Aether is preferred to GR

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

# How does aether affect tests of gravity?

- If:
  - Aether tracks matter
  - Internal pressure is negligible

→ Aether is indistinguishable from GR

- But:
  - Aether is irrotational → e.g. observing gravito-magnetic effect due to earth rotation can test it (→Gravity Probe B, LAGEOS)
  - Internal structure of self-gravitating objects with relativistic pressure (e.g. neutron stars, supernovae) will be sensitive to aether

NA 2008; NA, Foster, Kohri, & Robbers, *in preparation*

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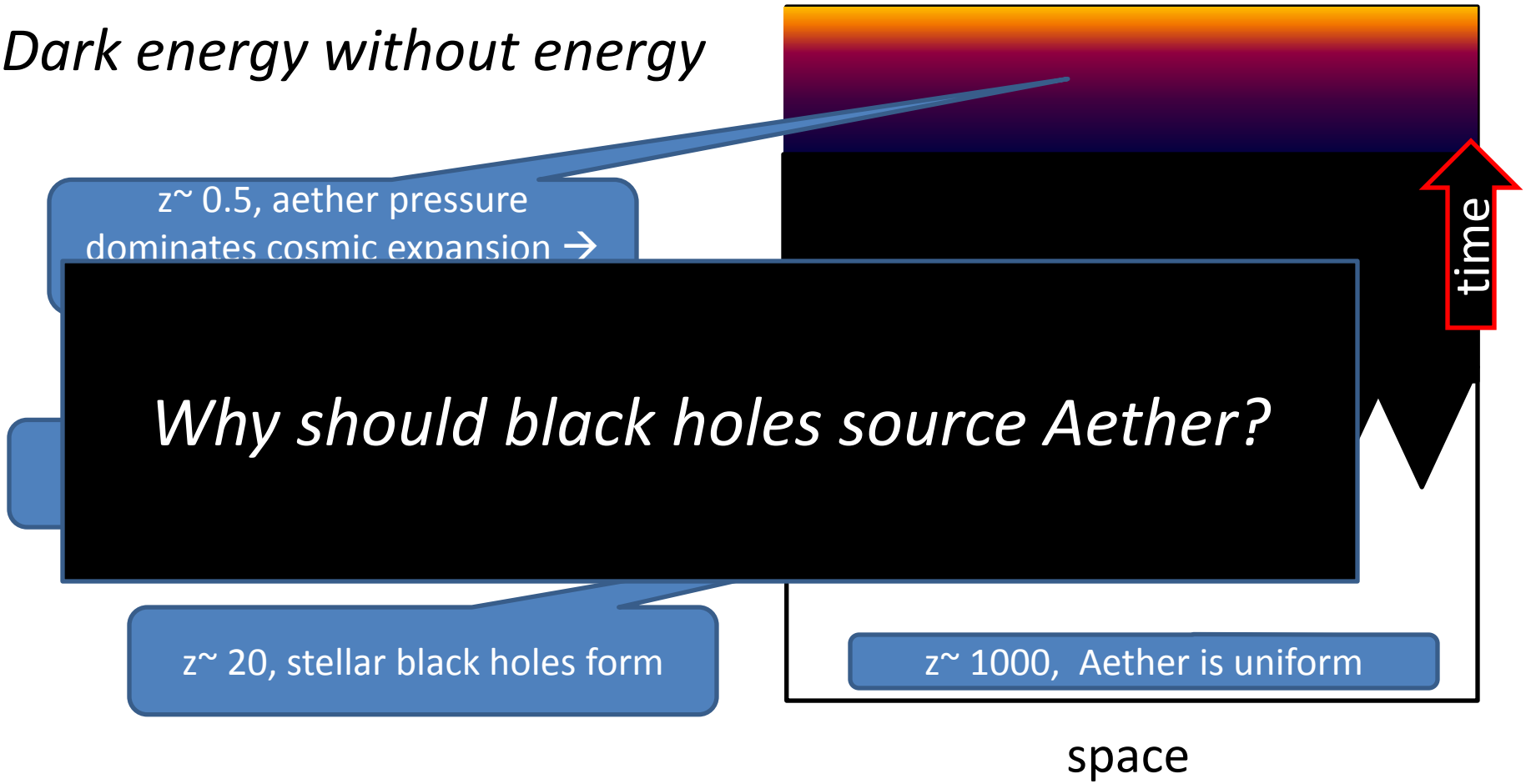
- Aether has solved the *old* cosmological constant problem.

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

# How Black Holes lead to cosmic acceleration

- Gravitational Aether:

*Dark energy without energy*



Prescod-Weinstein, NA, & Balogh 2009

# Aether and Black Holes

- Aether around a spherical Black Hole:

$$ds^2 = -e^{2\phi}dt^2 + \left(1 - \frac{2m}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

$$e^{\phi(r)} = \left(1 - \frac{2m}{r}\right)^{\frac{1}{2}} [4\pi p_0 f(r) + 1] \qquad P = p_0 e^{-\phi}$$

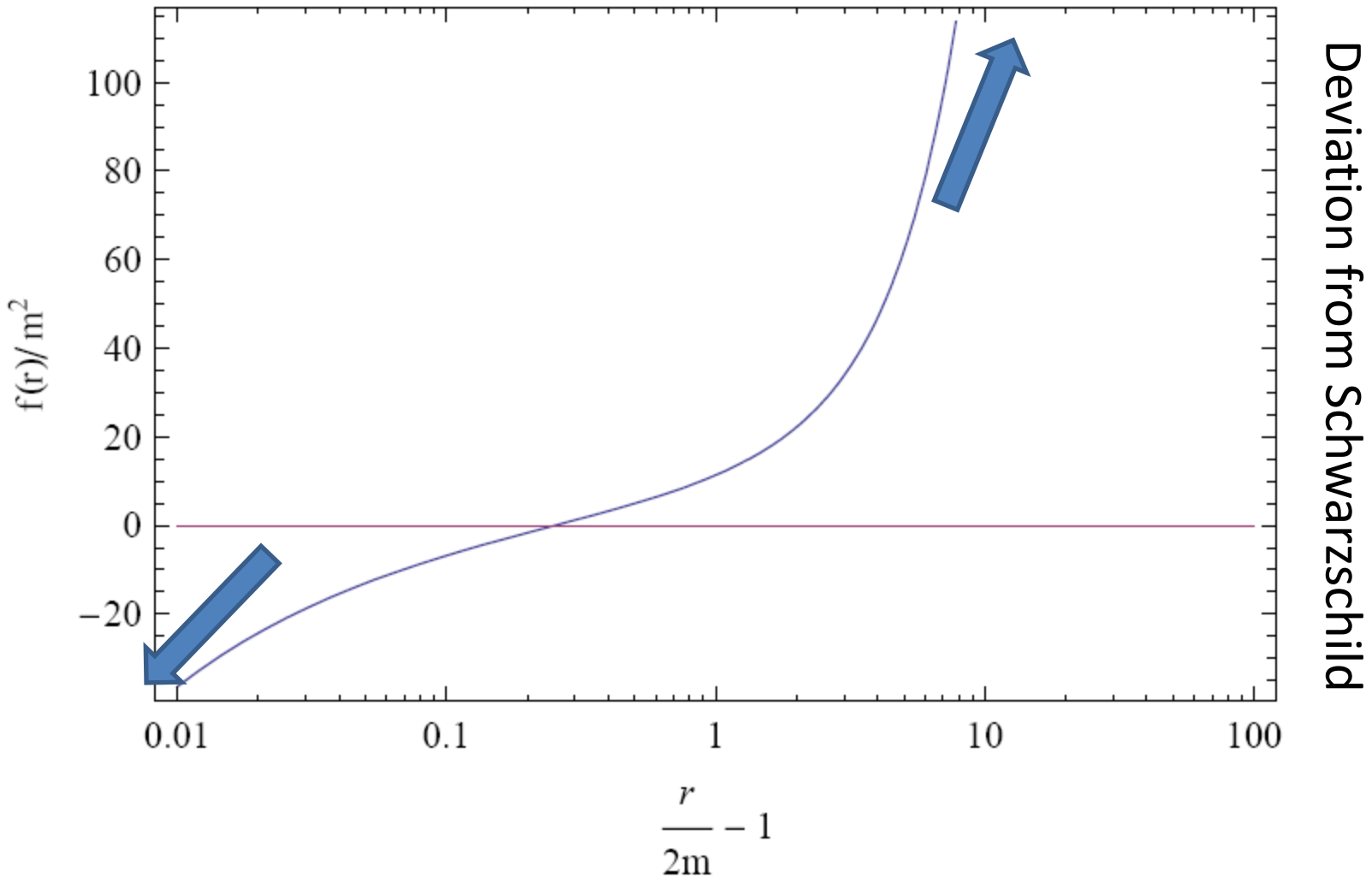
Aether pressure at large distances

- Limits far from and close to the horizon:

$$f(r) = \frac{r^2}{2} + 3mr + \mathcal{O}[m^2]. \quad r \gg 2m$$

$$f(r) = -8\frac{\sqrt{2}m^{5/2}}{\sqrt{-2m+r}} + \mathcal{O}[m^{3/2}(r-2m)^{1/2}]. \quad r - 2m \ll 2m$$

# Distance from Black Hole horizon



Prescod-Weinstein, NA, & Balogh 2009

# A single stellar BH and cosmic acceleration

- The same integration constant describes solution close to and far from the BH "horizon"

  *UV-IR coupling*
- Maximum redshift: $-\frac{1}{32\pi p_0 m^2}$
- Assuming this to be = *Planck Energy/Hawking Temperature*

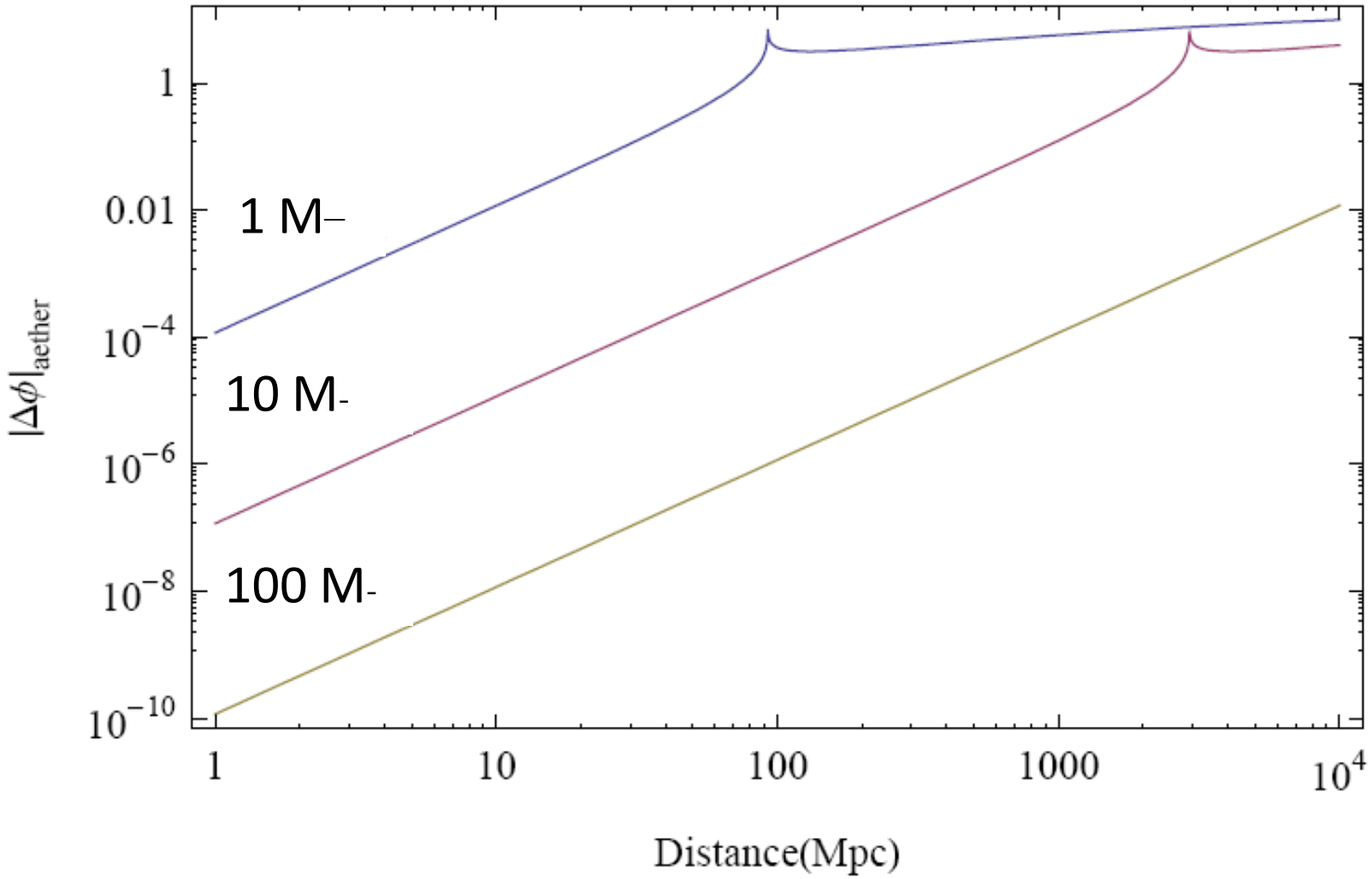
→ $$p_0 = -\frac{1}{256\pi^2 m^3} = -\text{observed } \rho_{DE}, \text{ for } m = 7 \; M_\odot \text{ !!!!}$$

**→Formation of stellar Black Holes can trigger late-time cosmic acceleration**

**→Cosmic acceleration: first concrete signature of quantum gravity!**

Trans-Planckian ansatz → quantum gravity near BH horizon

# Effect of Aether at large disances

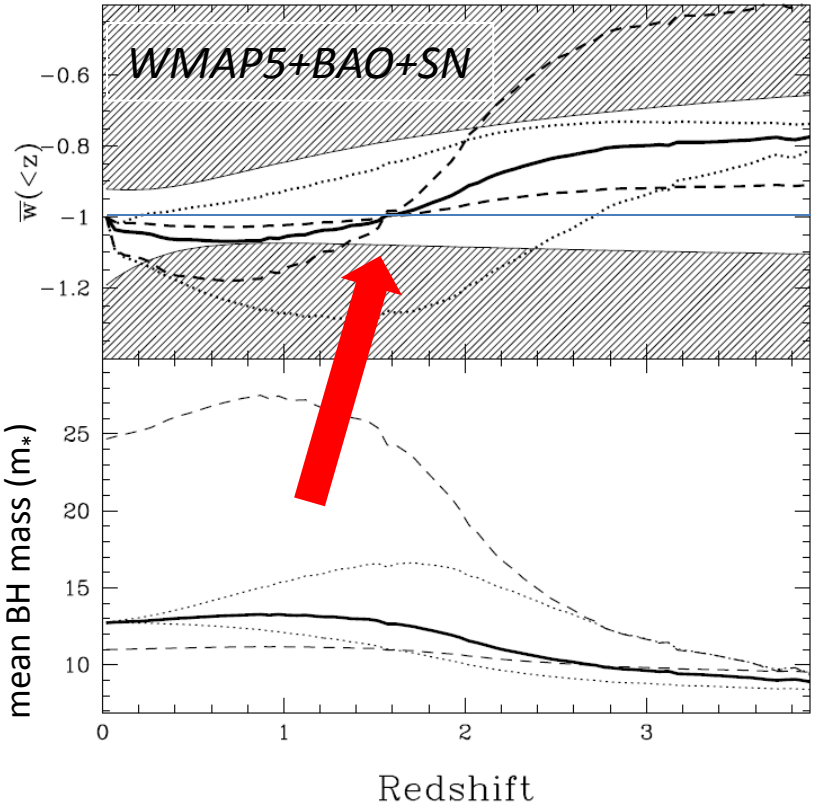


# Multiple BH's and Effective Dark Energy

- multiple black holes:

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

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






Prescod-Weinstein, NA, & Balogh 2009

# How about other modified gravity models?

- Models such as scalar-tensor, f(R), DGP, etc. are purely phenomenological
- They do not address cosmological constant problem(s)
- They have extra deg's of freedom

  → (unlike aether model) either very fine-tuned or inconsistent with data

# Conclusions I

- Incompressible Gravitational Aether:
  - arises in renormalizbale Quantum Gravity

  → Horava-Lifshitz gravity
  - decouples gravity from vacuum energy

  → solving the old cosmological constant problem
  - BH formation leads to cosmic acceleration

  → solving the new cosmological constant problem

# Conclusions II

- Aether ($G_{mat.}/G_{rad.}=3/4$) is preferred by cosmological observations (Ly-®, WMAP, SDSS); BBN constraints remain inconclusive
- Follows dust matter, and satisfies current tests of General Relativity (possible exception: gravito-magnetic effect)
- Ties horizon physics of astrophysical black holes to cosmology, explaining late-time cosmic acceleration *without any fine-tuning*
- *First precision measurement in Quantum Gravity!*

# Future Directions

- Observational:
  - Future CMB/LSS surveys will constrain $G_{mat.}/G_{rad.}$ with 10 times better precision *(Planck/ACT/SPT/SDSS3)*
  - Precision tests of gravity: Rotation *(Gravity Probe B/LAGEOS)*

  →Correlations between star formation/AGN activity and cosmic acceleration *(JDEM/Euclid)*
- Theoretical:
  - Fundamental theory/action and quantization
  - Aether →Emergent Gravity/Quantum Graphity
  - Dynamical picture of BH formation

- *Should we revisit our assumptions for constructing Effective Theories? (e.g. locality/action)*
- *Should we re-evaluate our Dark Energy program?*

# *(Emergent)* Horava-Lifshitz Gravity

- Gravity is renormalizable if ! / $k^3$ (Horava 09)

$$ds^2 = -N^2 dt^2 + g_{ij}(dx^i + N^i dt)(dx^j + N^j dt), \quad K_{ij} = \frac{1}{2N}\left(g_{ij} - \nabla_i N_j - \nabla_j N_i\right)$$

$$S = \int dt\, d^3\mathbf{x}\, \sqrt{g}\, N \left\{ \frac{2}{\kappa^2}\left(K_{ij}K^{ij} - \lambda K^2\right) - \frac{\kappa^2}{2w^4} C_{ij}C^{ij} + \frac{\kappa^2\mu}{2w^2}\varepsilon^{ijk} R_{i\ell}\nabla_j R^{\ell}_{k} \right.$$
$$\left. - \frac{\kappa^2\mu^2}{8} R_{ij}R^{ij} + \frac{\kappa^2\mu^2}{8(1-3\lambda)}\left(\frac{1-4\lambda}{4}R^2 + \Lambda_W R - 3\Lambda_W^2\right)\right\}.$$

- At low energies, if N=N(t,x):

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

General Relativity

mean extrinsic curvature

# Horava-Lifshitz → Cuscuton

$$\frac{1-\lambda}{16\pi G_N}\int d^4x\sqrt{-g}K^2 \rightarrow \int d^4x\sqrt{-g}\left(\mu^2\sqrt{\partial^\nu\varphi\partial_\nu\varphi}-\frac{1}{2}m^2\varphi^2\right)$$

- K=φ = K(t) is the preferred frame
- HL gravity reduces to GR in the Constant Mean Curvature (CMC) gauge+cuscuton

$$\mu^2=-m^2=-\frac{1-\lambda}{8\pi G_N},$$

*NA 2009 [arXiv:0907.5201]*

$$|\lambda-1|<0.014$$

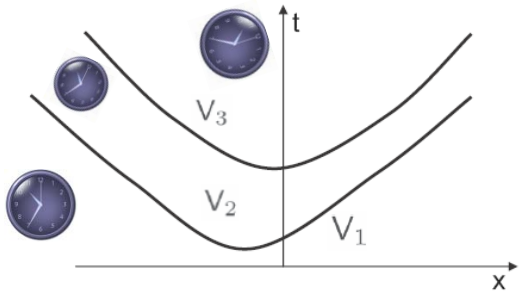
from cosmological observations

# Cuscuton: *a Discrete Clock Field*

- Imagine a discrete clock field

Cuscuton Action

$$S_\varphi = \int d^4x\sqrt{-g}\left[\mu^2\sqrt{|g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi|} - V(\varphi)\right].$$




continuous limit

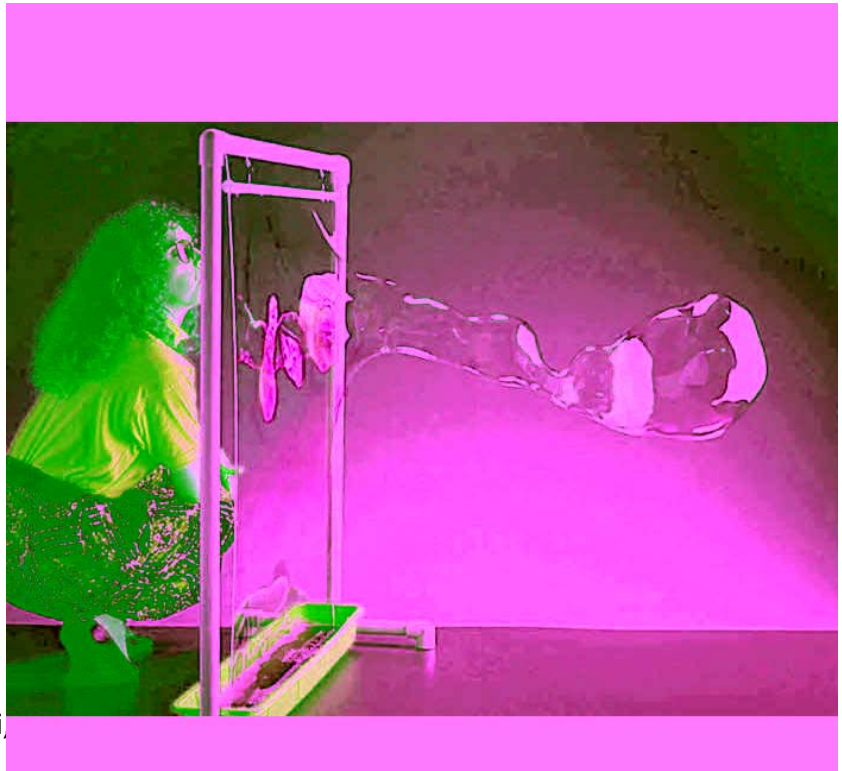
$$S_{\rm eff} \simeq \mu^2 \sum_i (\varphi_{i+1} - \varphi_i) \int d\Sigma_i - \int d^4x\ V(\varphi),$$

interface areas

volumes

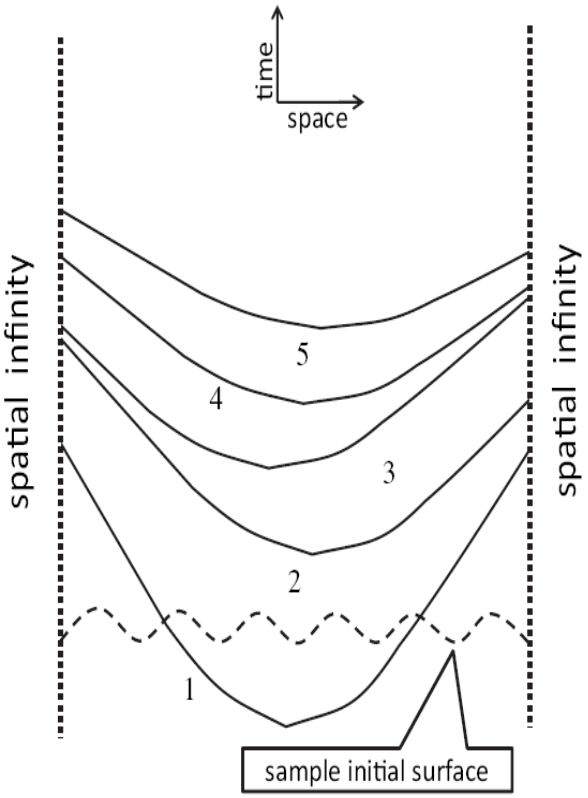
# Cuscuton: *a parasite?!*

- Only modification of GR that does not introduce new perturbative degrees of freedom ($c_s = 1$ ) *NA, Chung, & Geshnizjani 2007*



# Cuscuton: *non-dynamics*

- no propagating d.o.f/no violation of causality
- no coupling between different $\varphi$-surfaces
- scalar mode in HL gravity is non-dynamical
- Fixed by spatial boundary condition
- Non-dynamical nature is protected by symmetry



# Late-time Acceleration scenario

$$\text{deSitter}: \quad ds^2 = -(1-4\pi\rho_\Lambda r^2)dt^2 + (1-4\pi\rho_\Lambda r^2)^{-1}dr^2 + r^2 d\Omega^2$$
$$\text{Aether}: \quad ds^2 = -(1+2\pi p_0 r^2)^2 dt^2 + dr^2 + r^2 d\Omega^2$$

- $g_{00}$ around the black hole (m ¿ r ¿ $H^{-1}$) looks like de-Sitter space, so slow-moving particles (i.e. stars/galaxies) accelerate away from the center
- As this happens around every BH, the coarse-grained universe should look like ¤ + matter with ½ = $-p_0$

# But didn't you just kill Inflation?!

**No!**

- $G_{eff}$ / (1+w) G
- →since w ≠ -1 during inflation, one could still get inflation with slight modifications
- For Inflation:
  - $w_{eff}$ = dP/d½' -1 (rather than P/½)
  - ³ » H/$M_P$ » $10^{-5}$ (no ² in the denominator)
  - similar slow-roll conditions, but with V'(φ) instead of V(φ)
  - Gravity waves ??, need an action for the theory