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THE END OF THE COSMOLOGICAL CONSTANT PROBLEM!

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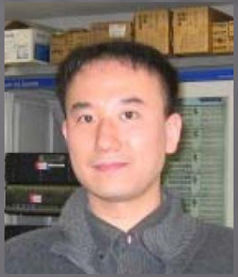
Theory + Data = IPMU

Outline

- History of cosmological constant problem
- Cosmic acceleration and coincidence
- Degravitating the quantum vacuum and the Gravitational Aether
- Testing the Aether
- Stellar black holes and cosmic acceleration
- Conclusions and the Missing Links

My Collaborators

- Kazunory Kohri (Lancaster)



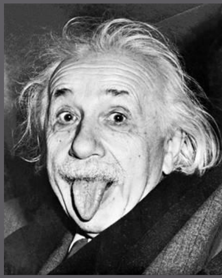
- Georg Robbers (Heidelberg → MPA)

- Tom Giblin (Perimeter/Bates College)

- Chanda Prescod-Weinstein (Perimeter)

History of the C.C. problem

- In 1917, Einstein introduced Λ-term to make Universe static: $G_{\mu\nu} = \Lambda g_{\mu\nu} + T_{\mu\nu}$



- In 1920's, Pauli calculates size of Einstein Universe, including the zero-point quantum fluctuations of the Electromagnetic filed $\sim$ 30 km!

- Meanwhile, Hubble discovers galaxies are at $> 10^{16}$ km! Moreover, Universe isn't static, so no need for Λ.

Revival of Λ

- In 1989, Weinberg provides a "no-go" theorem in his review: No local QFT can naturally give $\Lambda = 0$ without fine-tuning
- Standard Model: $\Lambda \sim (100 \text{ GeV})^4$
- In 1990's, several probes (CMB, galaxy clusters, galaxy correlation function, globular cluster ages, and eventually supernovae) pointed to $\Lambda \sim (10^{-3} \text{ eV})^4$
  - Old CC problem: Why CC is so small?
  - New CC problem: Why does it become important now?

Cosmological constant problem

- Einstein Equation

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

Modified Gravity

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

vacuum energy density : $\gtrsim \pm (100\ \text{GeV})^4$ + excitations

Only known solution: Landscape +Anthropics*

Can Quantum Gravity solve the CC problem?

- No! because:

Quantum Gravity models reduce to GR+ Effective Field Theory at low energies, *by construction*

→solution must change classical gravity

Here is an alternative: Gravitational Aether

$$(8\pi G)^{-1} G_{\mu\nu}[g_{\mu\nu}] = T_{\mu\nu} - \frac{1}{4} T g_{\mu\nu} + \ldots ,$$

- 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:

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

$$T'_{\mu}{}^{\nu}{}_{;\nu} = \frac{1}{4} T_{,\nu}$$

- Further assume:

$$T'_{\mu\nu} = p' \left[(1 + \omega^{-1}) u_\mu u_\nu - g_{\mu\nu} \right] ,$$

FRW cosmology with Gravitational Aether

- Friedmann equation: $$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho_{\rm eff}.$$

$$\rho_{\rm eff} = \rho - \frac{T}{4} + \frac{p'}{\omega} = \frac{3(1+w)(\omega - 1/3)\rho}{4(\omega - w)},$$

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

- Radiation vs. Matter era: $$\frac{G_N}{G_R} \equiv \frac{\rho_{\rm eff}/\rho|_{w=0}}{\rho_{\rm eff}/\rho|_{w=1/3}} = \frac{3}{4} - \frac{1}{4\omega} < 0.75$$
- BBN (Cyburt, Fields, Olive, & Skillman 2005)

$$G_N/G_R = 0.97 \pm 0.09$$

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

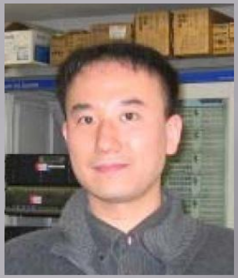
$$G_N/G_R = 0.73 \pm 0.04$$

Incompressible Aether!

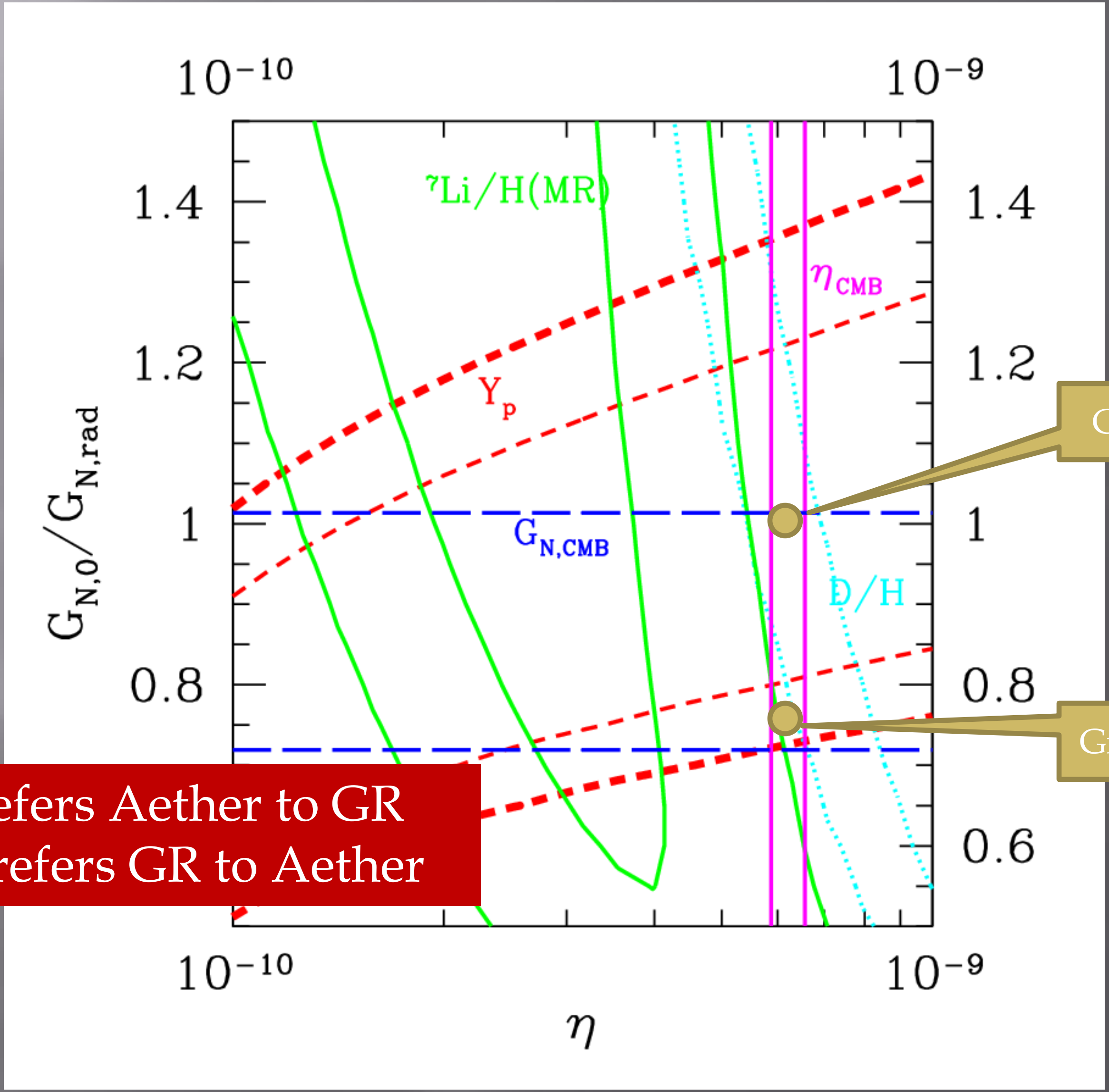
- We require $\omega \gtrsim 5$
- Superluminal propagation: $c_s = \omega^{1/2} > 1$?
- Does not necessarily violate causality
  - c.f. K-essence: Mukhanov et al., Stenihardt et al.
- Cuscuton ($c_s = \infty$) : does not propagate information (Afshordi, Chung, Geshnizjani 2007)

→ Field/Fluid equation becomes a constraint equation

The *Real* BBN Constraints



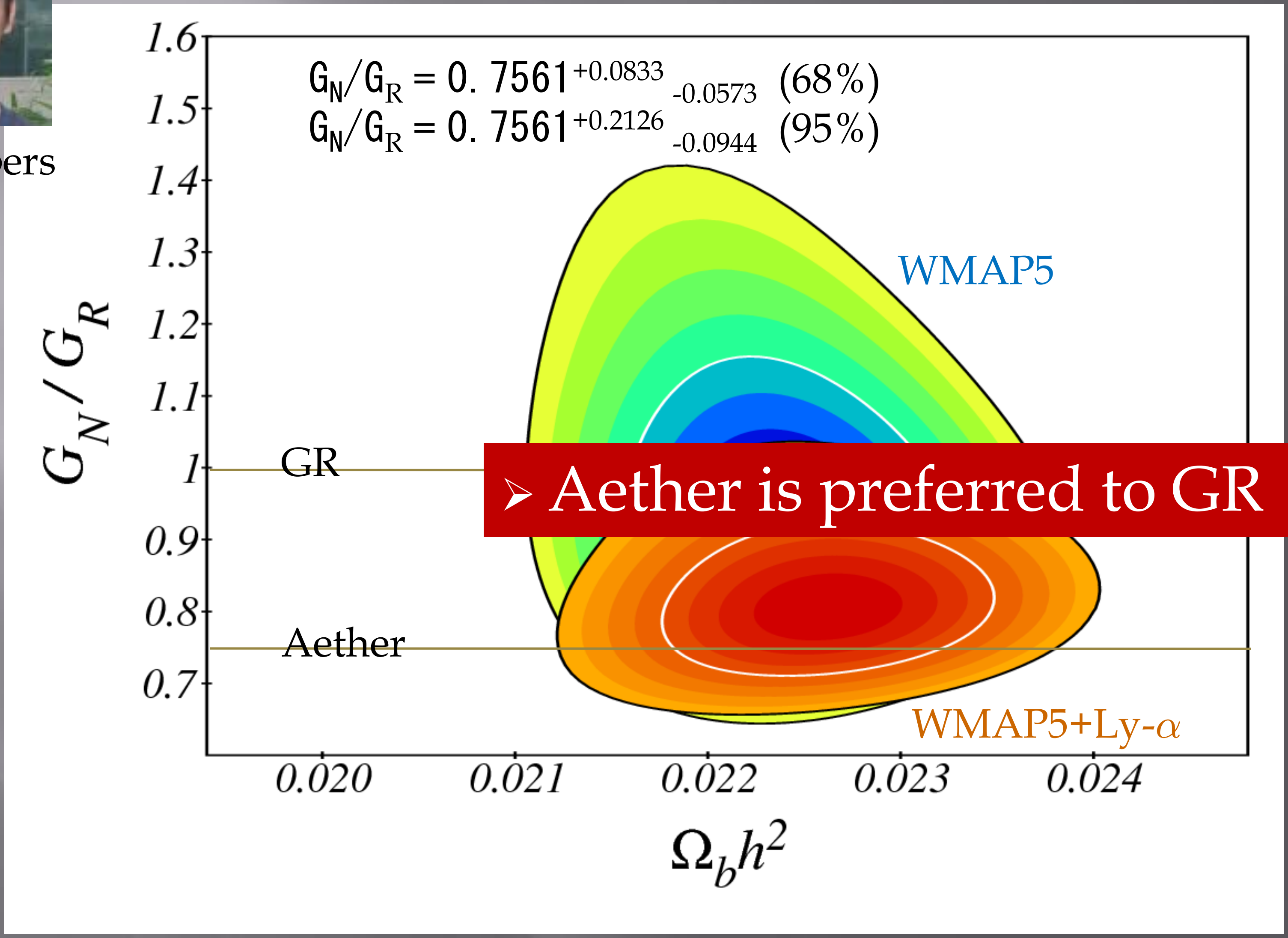
K. Kohri



- Li7 prefers Aether to GR
- He4 prefers GR to Aether

Ly-α forest + WMAP5

G. Robbers



- Aether is preferred to GR

Non-relatvistic Perturbations:

- Euler + continuity equations →

$$p' + \frac{1}{4}T = p'\mathcal{O}(u^2, \phi) + \text{const.}$$

- Perturbations around a static background:

$$\frac{\partial^2 T\mathbf{u}}{\partial t^2} = \omega \nabla\nabla \cdot (T\mathbf{u})$$

  - Longitudinal modes propagate superluminally/disperse
  - What about rotation/gravito-magnetic effect?
- Aether follows the velocity of non-relativistic matter
- Gravitational constant depends on pressure: $G_{eff} \propto (1+w)\, G$, (modifies ζ_4: unconstrained PPN parameter)

How does aether affect tests of gravity?

- As long as:
  - 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)
  - Internal structure of self-gravitating objects with relativistic pressure (e.g. neutron stars, supernovae) will be sensitive to aether

But Physical theories should have an action!

- *Not Necessarily!*
- *E.g.* coarse-grained theories have information-loss → they're not unitary → no action
- *E.g.* Fluid mechanics does not have an action: c.f. viscosity, turbulence, diffusion
- ***Gravity Action is only necessary for Quantization (i.e. Quantum Gravity)***
- In contrast, our model describes quantum field theory in *classical* curved space-time

two related works

- De-Gravitation, Cascading gravity

  (Dvali, Khoury, Hofmann, Tolley, de Rham, …)
  - decouples ρ_{vac} through a massive graviton/induced gravity
  - No non-linear + tractable realization
- Einstein-Aether theory

  (Ted Jacobson, et al.)
  - Lorentz breaking vector field: u_μ

  Minimal coupling to gravity

  → does not address the cosmological constant problem

Aether and Black Holes


C. Prescod-Weinstein

- Aether around a spherical Black Hole:

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

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

$$P = p_0 e^{-\phi}$$

- Limits far from and close to the horizon:

$$f(r) = \frac{r^2}{2} + 3mr + O[\frac{1}{r}]^0$$

r ≫ 2m

$$f(r) = -8\frac{\sqrt{2}m^{5/2}}{\sqrt{-2m+r}} + \frac{15}{2}m^2\ln[2m] + \sqrt{O[-2m+r]}$$

r -2m ≪ 2m

Stellar BH's and cosmic acceleration

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

→ *UV-IR coupling*

- Maximum redshift: $1/(-32\pi p_0 m^2)$
- Assuming this to be = *Planck Energy/Hawking Temp.*

→ $p_0 = -1/(256\,\pi^2 m^3) = -\rho_\Lambda$, for m = 1.45 $M_\odot$!!!!

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

Tras-Planckian corrections to gravity

C. Prescod-Weinstein

Late-time Acceleration scenario

- g_{00} around the black hole looks like de-Sitter space, so dust particles (i.e. stars/galaxies) accelerate away from the center
- As this happens around every BH, the coarse-grained Universe should look like Λ + matter
- With 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

But didn't you just kill Inflation?!

No!

- $G_{eff} \propto (1+w)\, G$
- → since $w \neq -1$ during inflation, one could still get inflation with slight modifications
- For Inflation:
  - $w_{eff} = dP/d\rho \simeq -1$ (rather than P/ρ)
  - $\zeta \sim H/M_P \sim 10^{-5}$ (no ϵ in the denominator)
  - similar slow-roll conditions, but with $V'(\varphi)$ instead of $V(\varphi)$
  - Gravity waves ??, need an action for the theory

Conclusions

- Decouple gravity from vacuum energy by introducing an incompressible gravitational aether
- Aether ($G_{mat.}/G_{rad.}=3/4$) is preferred by cosmological observations (Ly-α, WMAP, SDSS); BBN constraints remain inconclusive
- Ties horizon physics of stellar black holes to cosmology, explaining late-time cosmic acceleration
- Follows dust matter, and can satisfy tests of General Relativity *
- Inflationary scenarios are only slightly modified

missing links and future prospects

- Future CMB/LSS surveys will constrain $G_{mat.}/G_{rad.}$ with 10 times better precision
- Precision tests of gravity: Rotation
- Fundamental theory and quantization
- How to patch BH space-times to make an accelerating FRW?
- Correlations between star formation/AGN activity and cosmic acceleration?
- *Should we re-evaluate our Dark Energy program?*