Theoretical High Energy Physics seminar
University of Toronto, April 20, 2015

Cosmological (non)-Constant Problem: *The case for TeV scale quantum gravity*

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Punchline!

- **Quantum Gravity** is *already* in the **Infrared!**
- **CC problem** (in its various forms) is possibly the single *most significant* theoretical clue as to how to modify UV *and* IR physics

Hierarchy problem(s)

- neutrino mass
- dark energy

Higgs, Electroweak

LHC

GUT…Planck

$10^{-3}\mathrm{eV}$ $\qquad$ $10^{12}\mathrm{eV}$ $\qquad$ $10^{28}\mathrm{eV}$

$\rho_{\mathrm{DE}} \sim \Lambda^4$ $\qquad$ $\delta m_H^2 \sim \Lambda^2$ $\qquad$ $\Lambda ?$

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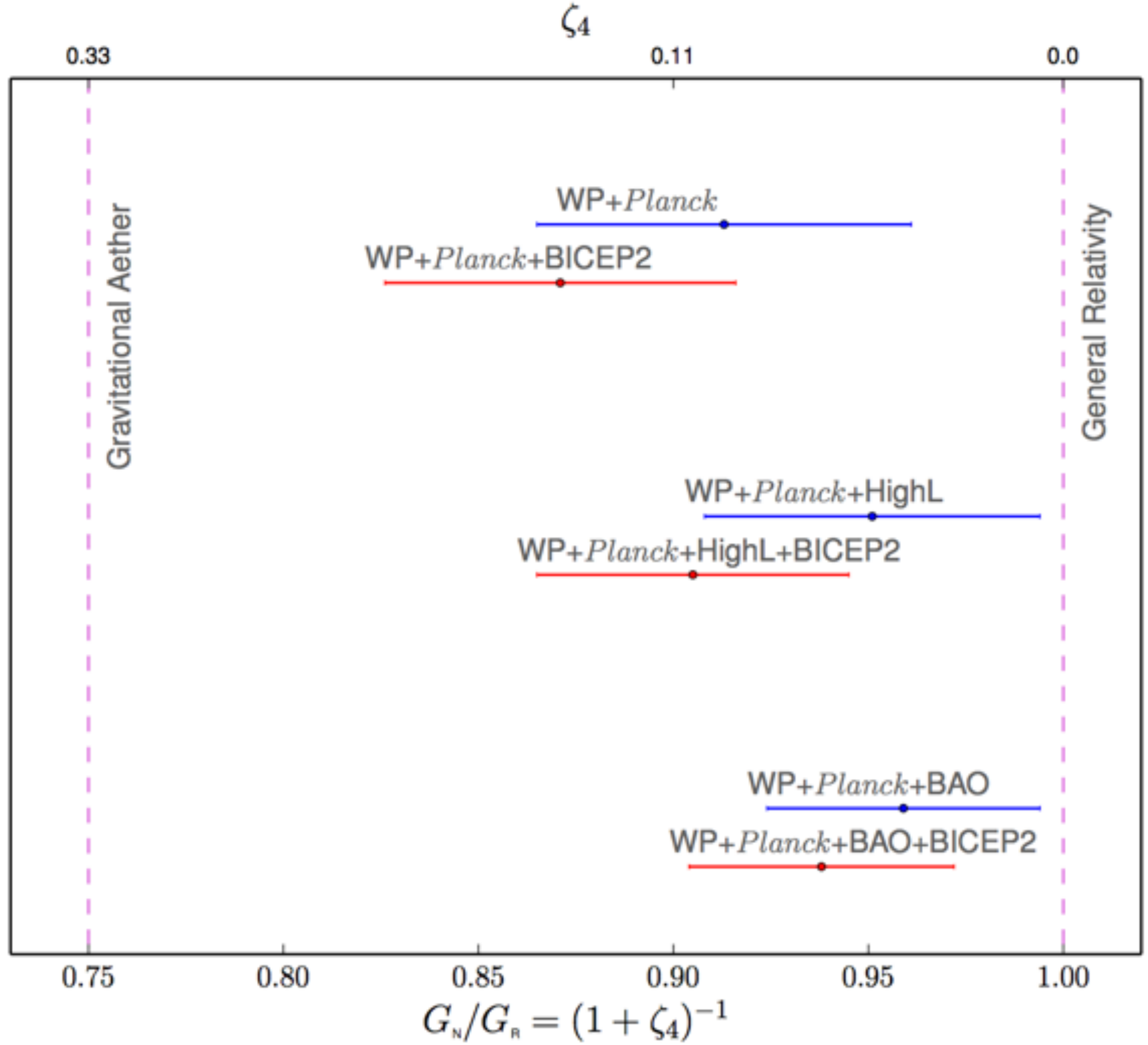
Can modifying gravity solve the old CC problem?



(Narimani, NA & Scott 2014)

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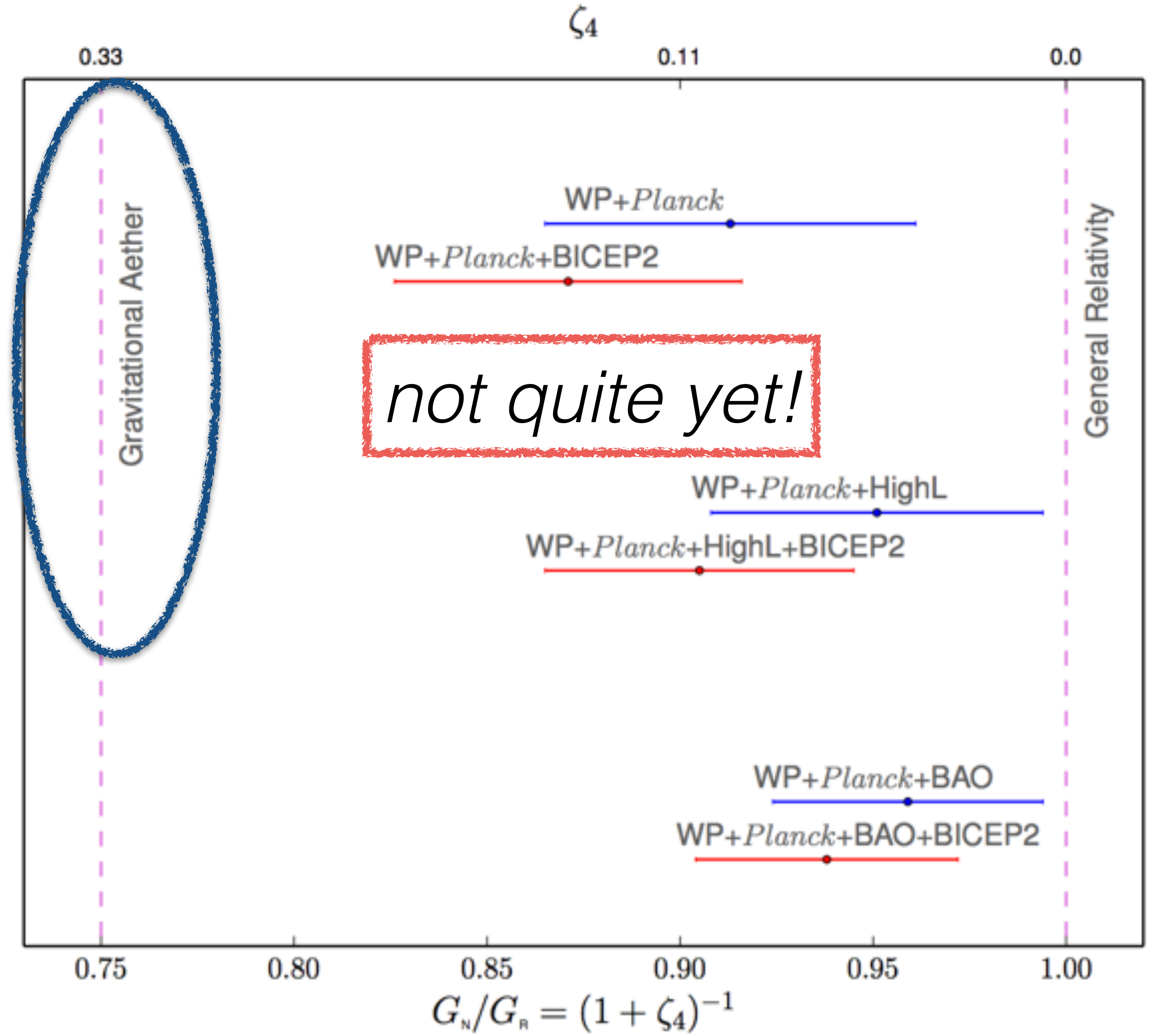

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Outline

- *Prelude:* Cosmological Hierarchy Problems
- Cosmological non-Constant (CnC) Problem *(TeV scale QG!)*
    - *Argument 1:* Poisson Phase Space
    - *Argument 2:* Kallen-Lehmann representation
    - *Argument 3:* Holographic entropy bound
- *Epilogue:* The folly of the Effective Field Theory
    - ➡ *Firewalls!*

Does Quantum Gravity matter in the IR?

- Quantum Fluctuations do fluctuate!

$$\langle T_{\mu\nu} \rangle = 0 \not\Rightarrow \langle T_{\mu\nu} T_{\alpha\beta} \rangle = 0$$

- What is the analog of CC for the covariance of stress fluctuations?

- Can these fluctuations have an observable gravitational signature on large scales?

with Elliot Nelson (Penn-State → PI), 1504.00012

Vacuum Fluctuations in Linear Gravity

- Linearized Perturbations around FRW space-time

$$ds^2 = a^2(\eta)\left[-(1+2\phi)d\eta^2 + 2V_i dx_i d\eta + (1-2\psi)d\mathbf{x}^2\right]$$

- Einstein constraint sector: *scalars in longitudinal gauge and vectors*

$$-k^2\psi = 4\pi G\left(\delta T_{00} - \frac{3\mathcal{H}}{k^2} i k^i \delta T_{i0}\right),$$

$$-k^2\phi = 4\pi G\left(\delta T_{00} - \frac{3\mathcal{H}}{k^2} i k^i \delta T_{i0} + \left(\delta^{ij} - 3\frac{k^i k^j}{k^2}\right)\delta T_{ij}\right),$$

$$k^2 V_i = 16\pi G(\delta_{ij} - \hat{k}_i \hat{k}_j)\delta T_{j0},$$

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- Random stress fluctuations at cut-off scale Λ

$$\langle T_{ij}^{(V)}(\mathbf{x}) T_{kl}^{(V)}(\mathbf{y}) \rangle \sim \delta^3(\mathbf{x}-\mathbf{y})\Lambda^5$$

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- A UV/IR Heisenberg uncertainty relation
  $$\Lambda_{\rm IR} = \frac{\Lambda_{\rm UV}^5}{M_p^4}$$

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$$\Lambda_{\rm IR} = \frac{\Lambda_{\rm UV}^5}{M_p^4}$$

- Cosmology limits the UV scale

$$\Lambda \lesssim (M_{\rm p}^4 H_0)^{1/5} \approx 2 \ {\rm PeV}$$

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- Imagine particles of mass *m,* uniformly sprinkled in the phase space with density $<f_0>$

$$\langle T^{\mu\nu}(\mathbf{y},t')T^{\alpha\beta}(\mathbf{y}+\mathbf{x},t'+t)\rangle = m^5\langle f_0\rangle \frac{x^\mu x^\nu x^\alpha x^\beta}{(-x_\gamma x^\gamma)^{7/2}}\Theta(-x_\gamma x^\gamma)$$

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- We shall see that this structure occurs in generic quantum field theories.

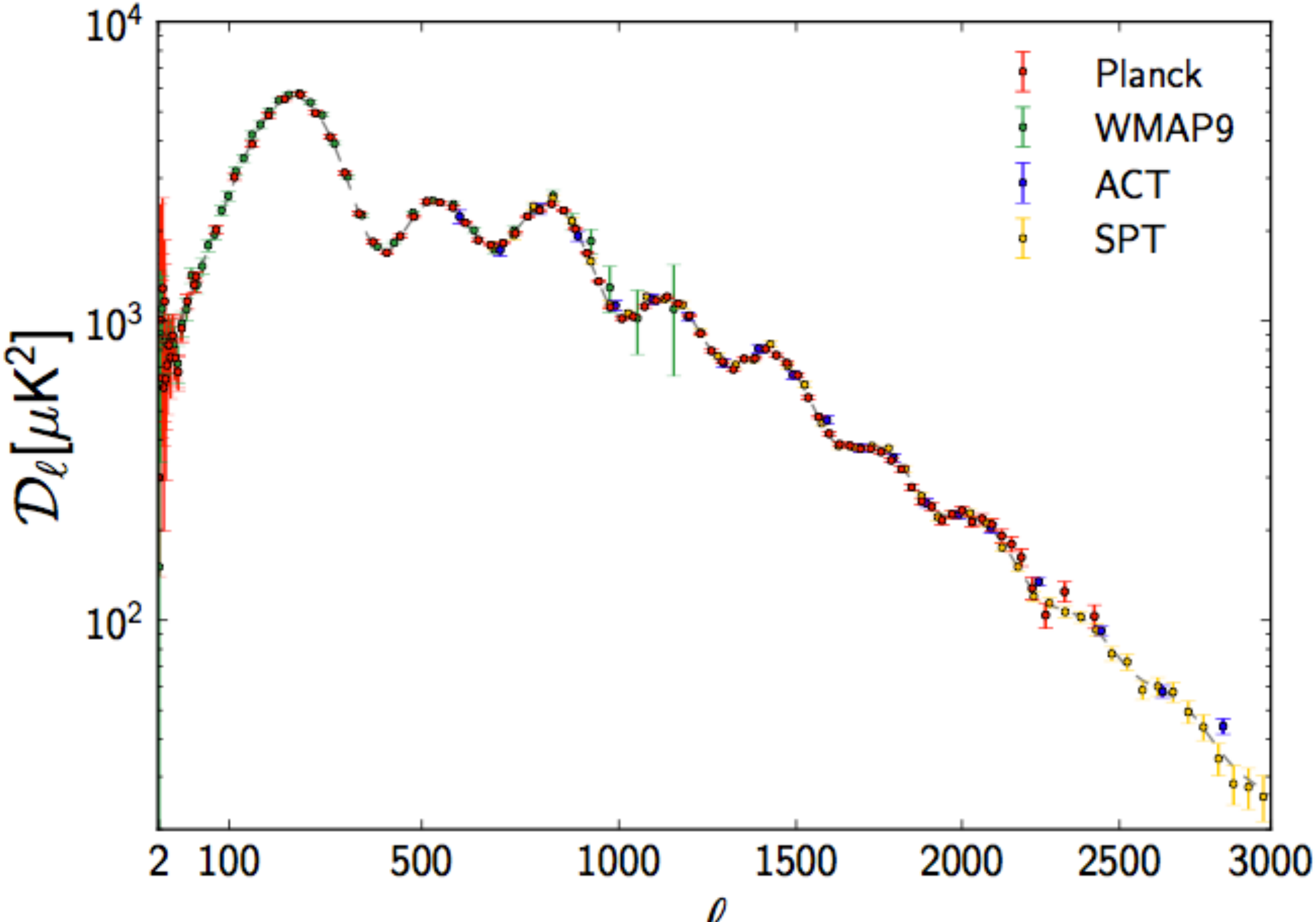
Gravity of Poisson vacuum

- Solving Einstein equations, we find the spectrum of metric perturbations: $\Delta_\phi^2 \simeq \frac{m^5 \langle f_0 \rangle}{M_\mathrm{p}^4 k}$
- or $\Delta_\phi^2 \simeq 4 \times 10^{-9} \left(\frac{m}{50\ \mathrm{TeV}}\right)^5 \left(\frac{\langle f_0 \rangle}{1/2}\right) \left(\frac{k/a}{2 \times\ 10^{-4} \mathrm{Mpc}^{-1}}\right)^{-1}$
- spectrum of CMB anisotropies (Integrated Sachs-Wolfe, or ISW effect):

$$(\Delta_l^2)^{\mathrm{ISW}} \equiv \frac{l(l+1)C_l^{\mathrm{ISW}}}{2\pi} = \frac{49\pi}{720} \frac{m^5 t_0}{M_\mathrm{p}^4} \langle f_0 \rangle$$

(*t_0 = 13.7 billion years*)

power spectrum of CMB



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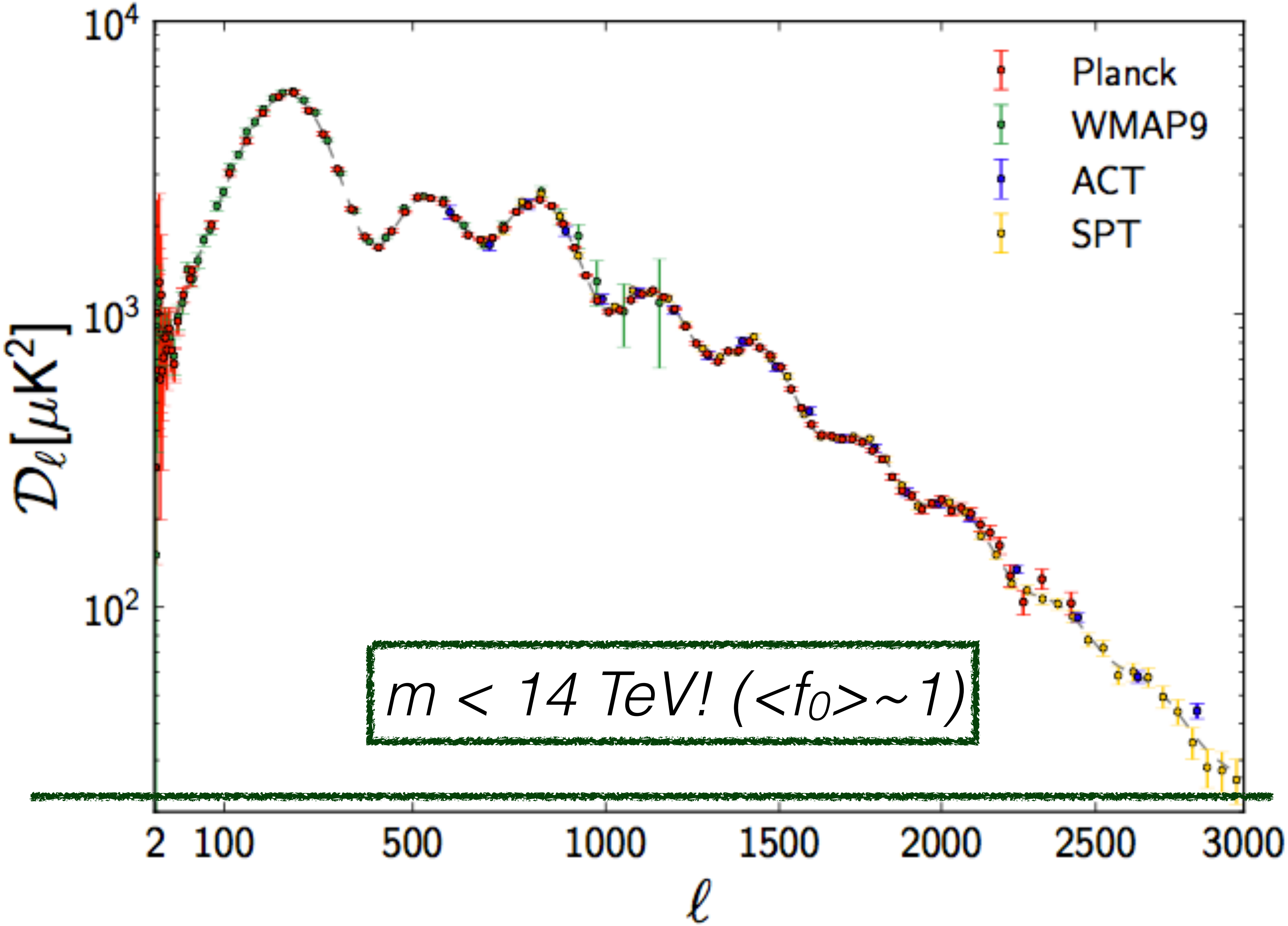

m < 14 TeV! (<f_0>~1)

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Kallen-Lehmann spectral representation

- Most general expectation for stress correlators from *Unitarity* +*Lorentz symmetry*

$$\langle T_{\mu\nu}(x)T_{\alpha\beta}(y)\rangle = \int \frac{d^4k}{(2\pi)^4}e^{ik\cdot(x-y)}\int_0^\infty d\mu \left[\rho_0(\mu)P_{\mu\nu}P_{\alpha\beta}+\rho_2(\mu)\left(\frac{1}{2}P_{\mu\alpha}P_{\nu\beta}+\frac{1}{2}P_{\mu\beta}P_{\nu\alpha}-\frac{1}{3}P_{\mu\nu}P_{\alpha\beta}\right)\right]\theta(k^0)2\pi\delta(k^2+\mu),$$

- ρ's must positive.

$$P_{\mu\nu} \equiv \eta_{\mu\nu} - k_\mu k_\nu/k^2$$

- *Cosmological* constraints will roughly translate to

$$\int \frac{d\mu}{\sqrt{\mu}}\rho_2(\mu) \lesssim (10 \text{ TeV} - 1 \text{ PeV})^5$$

- Metric fluctuations are **high frequency** but **blow up at long wavelength** —> *Observables??*

I: An offset in Hubble law

- Particle action $$S_p = -m \int dt \sqrt{1 + 2\phi(\mathbf{x},t) - |\dot{\mathbf{x}}|^2},$$
- To 2nd order in ϕ

$$S_p \simeq m \int d\tau \left[-1 + \frac{1}{2}|\dot{\mathbf{x}}|^2 + \phi(0,t) - \phi(\mathbf{x},t) + \frac{1}{2}\phi(\mathbf{x},t)^2 - \frac{3}{2}\phi(0,t)^2 + \phi(\mathbf{x},t)\phi(0,t) \right].$$

- Effective Newtonian potenial $$\Phi_N(\mathbf{x},t) \simeq -\langle \phi(\mathbf{x},t)\phi(0,t) \rangle$$
- An offset in the Hubble law $$v \simeq Hr - \frac{1}{32\pi H M_p^4} \int \frac{d\mu}{\sqrt{\mu}} \rho_2(\mu)$$
- Planck cluster kSZ monopole

$$\langle v_r \rangle = 72 \pm 60 \text{ km/s},$$

$$\left[\frac{1}{2} \int \frac{d\mu}{\sqrt{\mu}} \rho_2(\mu) \right]^{1/5} < 1.1 \text{ PeV},$$

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II: CMB anisotropies

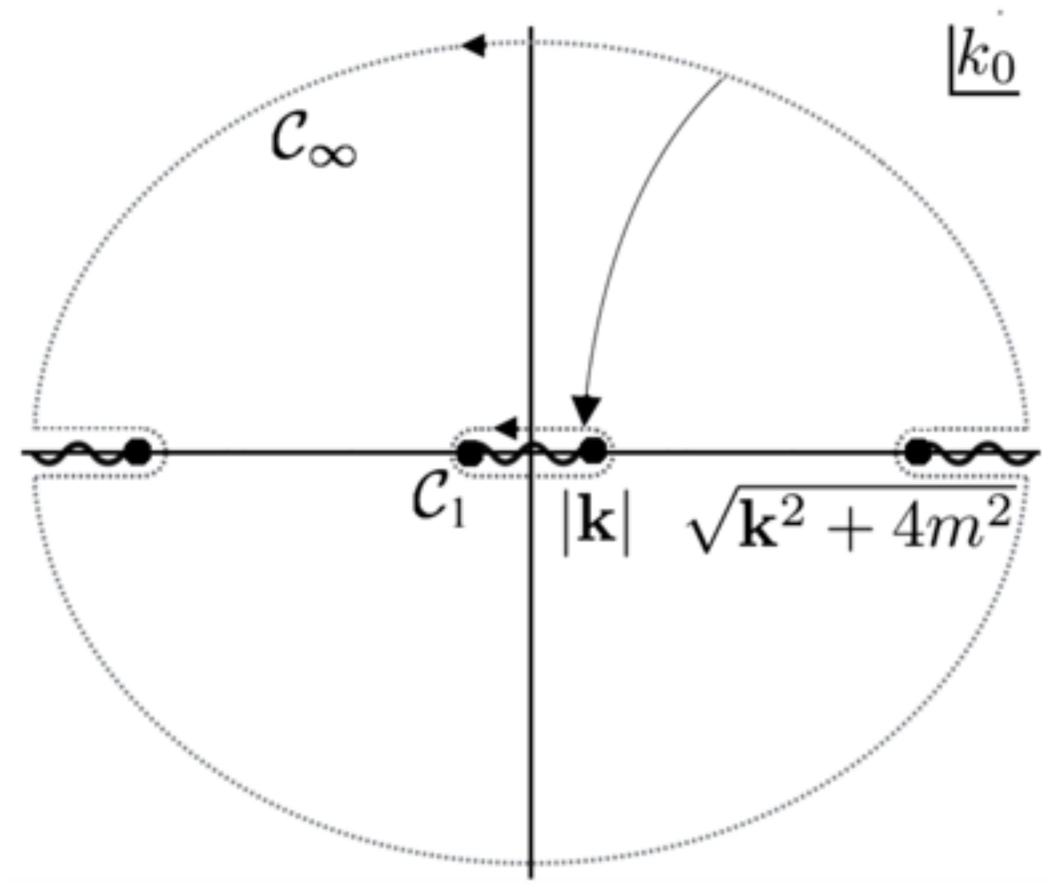
- For a weakly coupled scalar field

$$\rho_2(\mu) = \frac{1}{16\pi^2}\sqrt{\frac{1}{4} - \frac{m^2}{\mu}}\left[\frac{11}{40}\mu^2 + \frac{14}{15}m^2\mu + m^4\right]\Theta(\mu - 4m^2)$$

- For large scale, real-space correlations, one can deform the contour to get

$$\rho_{2,\text{eff}}(\mu) = \frac{m^5}{16\pi^2\sqrt{-\mu}}\Theta(-\mu)$$

- *This is identical to Poisson model, with* $\langle f_0 \rangle = 15/(2\pi)^3$



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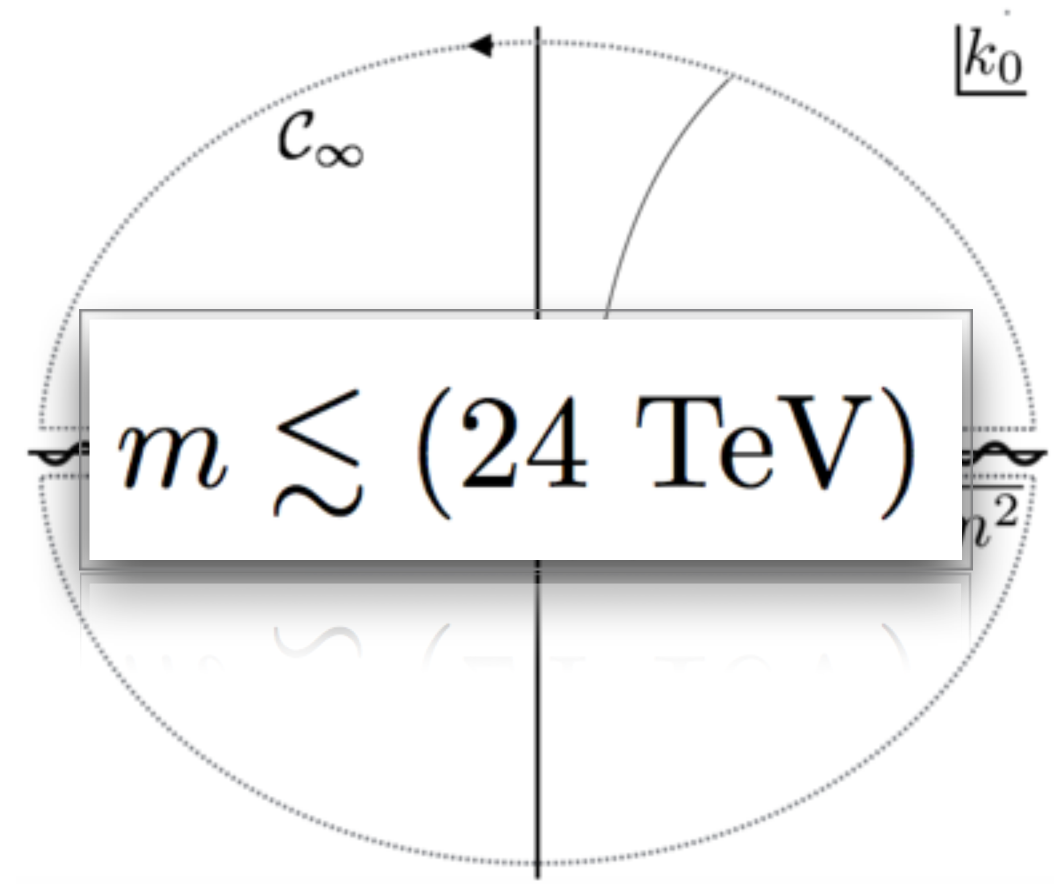

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Interaction entropy

- Imagine a system with Hamiltonian H_o, in its ground state $|0\rangle_\circ$, and zero energy

- Now, turn on H_{int};To 1st order, new eigenstates are

$$\langle n|0\rangle_\circ \simeq -\frac{\langle n|H_{\rm int}|0\rangle}{E_n},$$

- Time-Averaged density matrix:

$$\rho_{\rm int} = \sum_n |\langle n|0\rangle_\circ|^2 |n\rangle\langle n| = \sum_n \frac{|\langle n|H_{\rm int}|0\rangle|^2}{E_n^2} |n\rangle\langle n|,$$

- Entropy of a 2-state system

$$S_{qubit} = -tr(\rho_{\rm int} \ln \rho_{\rm int}) \simeq \alpha\,[1 - \ln(\alpha)] + \mathcal{O}(\alpha^2),$$

- *Fine structure constant*

$$\alpha \equiv \frac{|\langle 1|H_{\rm int}|0\rangle|^2}{E_1^2},$$

A Holographic Bound!

- Gravitational fine structure constant $\alpha_G \sim E^2/M_p^2$
- Number of qubits in a Dirac field

$$\# = 2 \times 2 \times Volume \times \int^{\Lambda} \frac{d^3k}{(2\pi)^3} = \frac{2\Lambda^3}{3\pi^2} \times Volume,$$

- Holographic Bound

$$S_{BH} = 2\pi M_p^2 \times Area > S = \# \times \alpha_G \left[1 - \ln(\alpha_G)\right] \sim \frac{2\Lambda^5 \left[1 + \ln(M_p^2/\Lambda^2)\right]}{3\pi^2 M_p^2} \times Volume.$$

- An IR cut-off for gravity $R \lesssim R_{\max} \sim \frac{3\pi^3 M_p^4}{\Lambda^5 \left[1 + \ln(M_p^2/\Lambda^2)\right]},$

$$\Lambda_{IR} \sim \frac{\pi}{R_{\max}} \sim \frac{\Lambda^5 \left[1 + \ln(M_p^2/\Lambda^2)\right]}{3\pi^2 M_p^4}.$$

$$\boxed{\begin{aligned} &\Lambda_{IR} < H_0 \simeq 9.5 \times 10^{-33} \mathrm{eV} \\ &\Rightarrow \boxed{\Lambda \lesssim 2.4 \ \mathrm{PeV}.} \end{aligned}}$$

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- What about Effective Field Theory?

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- CC problem
- CnC problem
- and firewalls!

On the folly of EFT

- Gravitational Path Integral

$$\int DgD\varphi \times \mathrm{Diff}^{-1}[g,\varphi] \times \exp\left(i\int d^4x\sqrt{-g}\,\{R[g]+\mathcal{L}_m[\varphi,g]\}\right).$$

- Naive Effective Action

$$\exp(iS_{\mathrm{eff,naive}}[g]) \equiv \exp(iS_{\mathrm{GR}}[g]) \times \int D\varphi \exp\left(i\int d^4x\sqrt{-g}\mathcal{L}_m[\varphi,g]\right)$$

- Ignores GR Constraints :-(

$$\mathrm{Diff}^{-1}[g,0]\exp(iS_{\mathrm{eff,naive}}[g]) \neq \exp(iS_{\mathrm{GR}}[g])\times\int D\varphi\times\mathrm{Diff}^{-1}[g,\varphi]\times\exp\left(i\int d^4x\sqrt{-g}\mathcal{L}_m[\varphi,g]\right)$$

On the folly of EFT

- Low energy scattering CANNOT produce massive particles of mass $\Lambda \rightarrow$ Effective Field Theory
- This is NOT the case for macroscopic systems
- Nearly all macroscopic systems have a fluid description in the IR; UV actions strongly coupled
- Separation of scales is not guaranteed, e.g. turbulent cascade, inverse cascade

Open Questions

- Should we take CnC problem seriously?!
- What about the early universe/inflation?
- Is there a gauge-invariant description of this effect?
- What happens beyond linear order?
- Nature of IR cut-off? massive gravity, Dark Energy?
- What will a 100 TeV collider see?

Final Thoughts

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  - ➡ *A definite target for particle colliders (e.g. 100 TeV collider)*
- **EFT:** Just think outside the box!

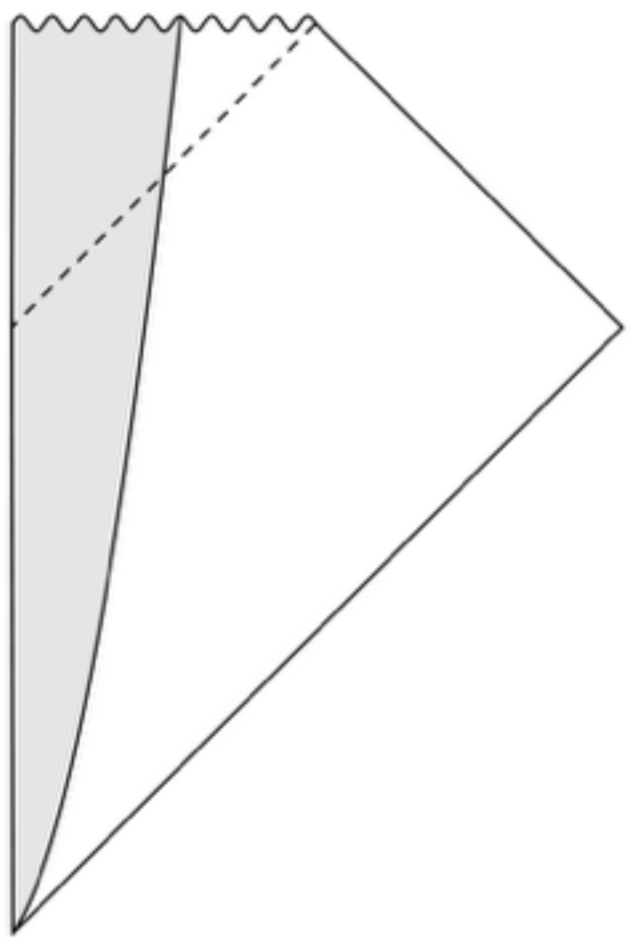
why EFT fails at “horizon”

- **Information paradox:** unitary black hole evaporation, not consistent with local physics +smooth horizon *(Hawking … AMPS 2013)*

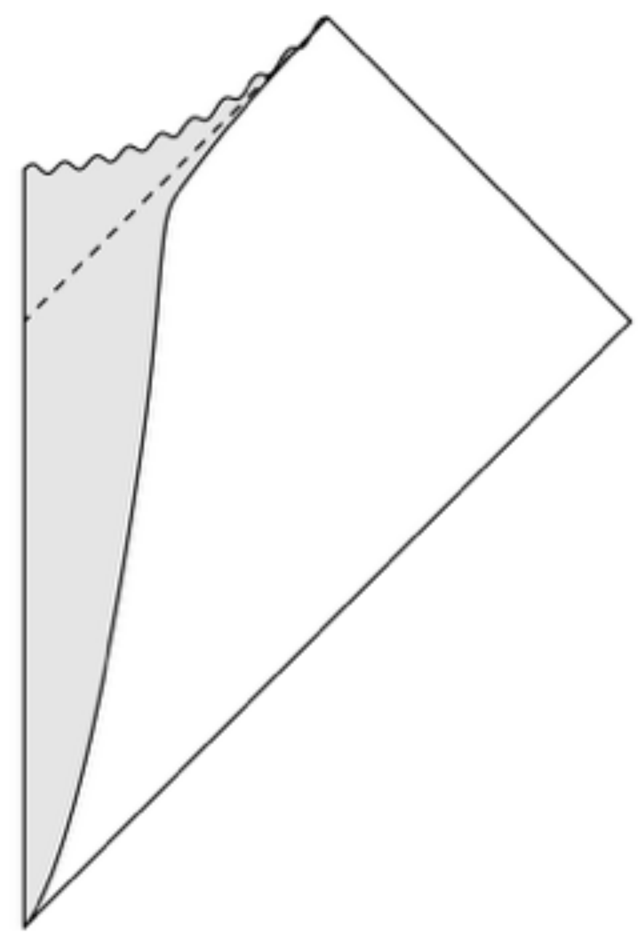
- **Quantum Tunnelling:** *exp(-S_E)x exp(entropy) ~ 1*

- **Fuzzballs:** (*a la* Mathur)**:** classical horizon-less spacetimes, that account for BH entropy

- **Dark Energy:** pressure eq. with stellar BH firewalls, → scale of dark energy *(Presocd-Weinstein, NA, Balogh 2009)*



How to form a Black Hole



How to form a Firewall?!

Firewall entropy & Lorentz violation

- Assume space-time ends at stretched horizon
- Israel Junction condition+Z_2 symmetry:
  - ➡ membrane has vanishing surface density ($c_s \to \infty$)
  - ➡ integrated (surface) pressure: = Unruh Temperature/4
  - ➡ Entropy per unit area = 1/4 *(Bekenstein-Hawking)!*

Saravani, NA, Mann 2012

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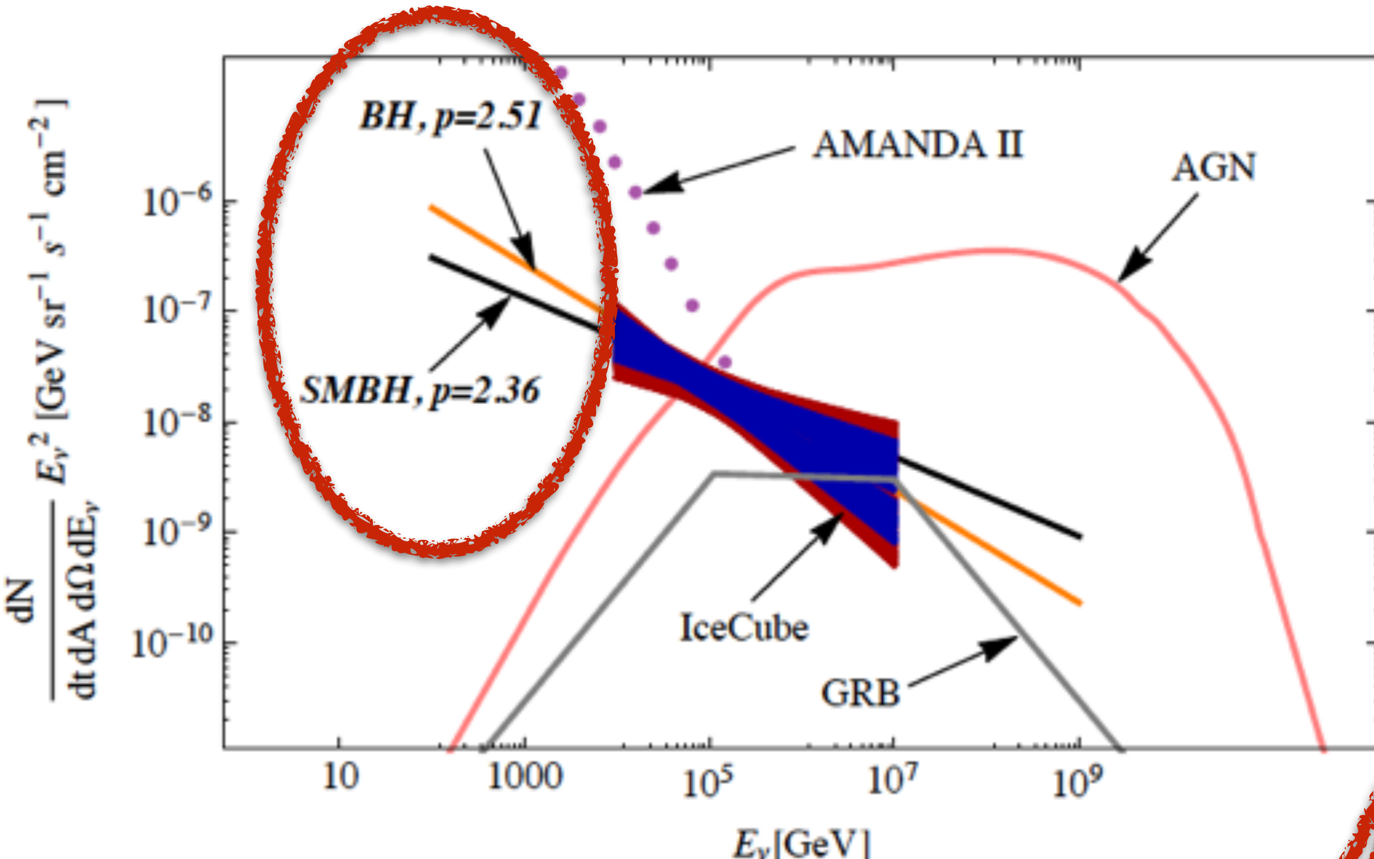
Can we see firewalls?!

- If firewalls have a dense atmosphere, it could be opaque to photons but transparent to neutrinos

- similar to core-collapse supernovae

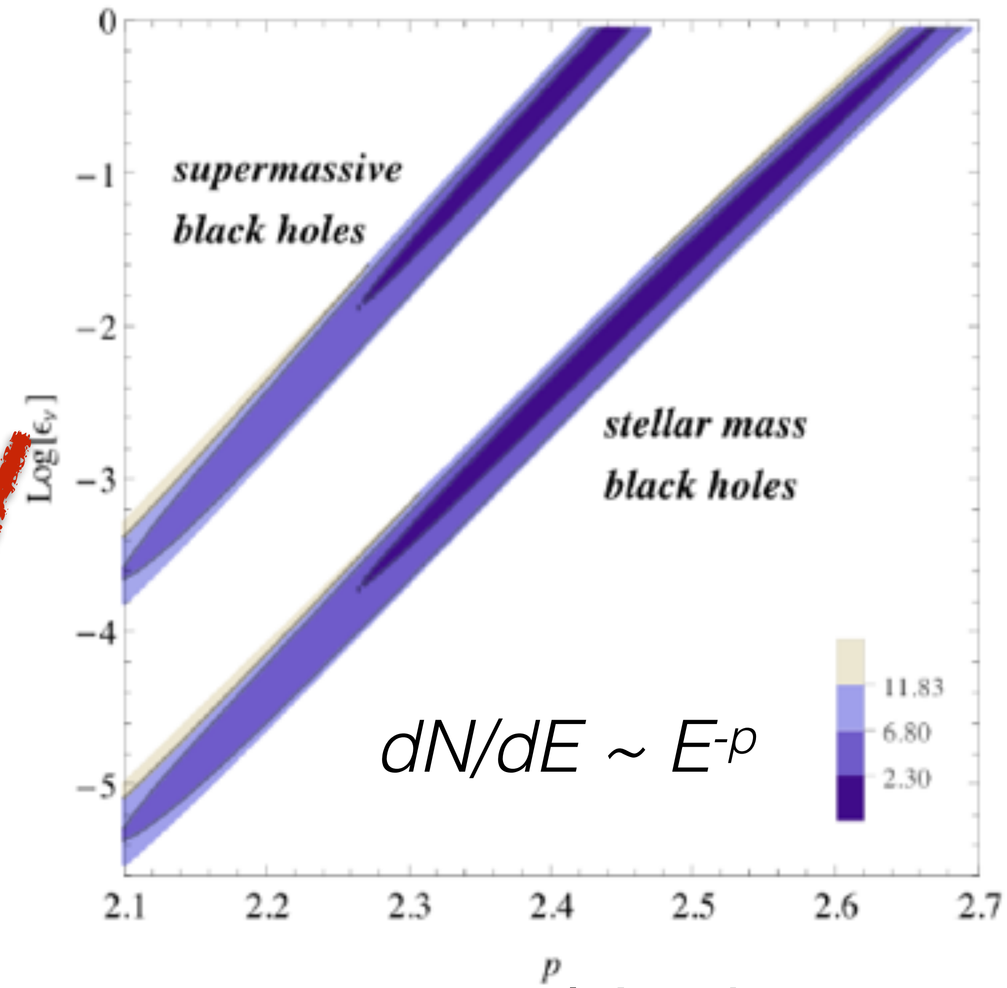
- A fraction of accreted energy into the firewall/BH horizon can be re-radiated as neutrinos

Possibly! *(NA & Yazdi 2015)*



Spectrum of High Energy Neutrinos

IceCube constraints on firewall neutrino spectrum



spectral index

Fraction of accreted energy re-radiated as neutrinos

What if Newton knew quantum field theory

(and special relativity)?!

$$\nabla^2\phi = 4\pi G(\rho)$$

What if Newton knew quantum field theory

(and special relativity)?!

$$\nabla^2 \phi = 4\pi G(\rho + p/c^2)$$

How to do it covariantly?

- Let us propose (*NA 2008*):

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

- The metric is now blind to vacuum energy

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

- In order to satisfy Bianchi identity:

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

- Further assume an *incompressible* fluid (or *gravitational aether*)

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

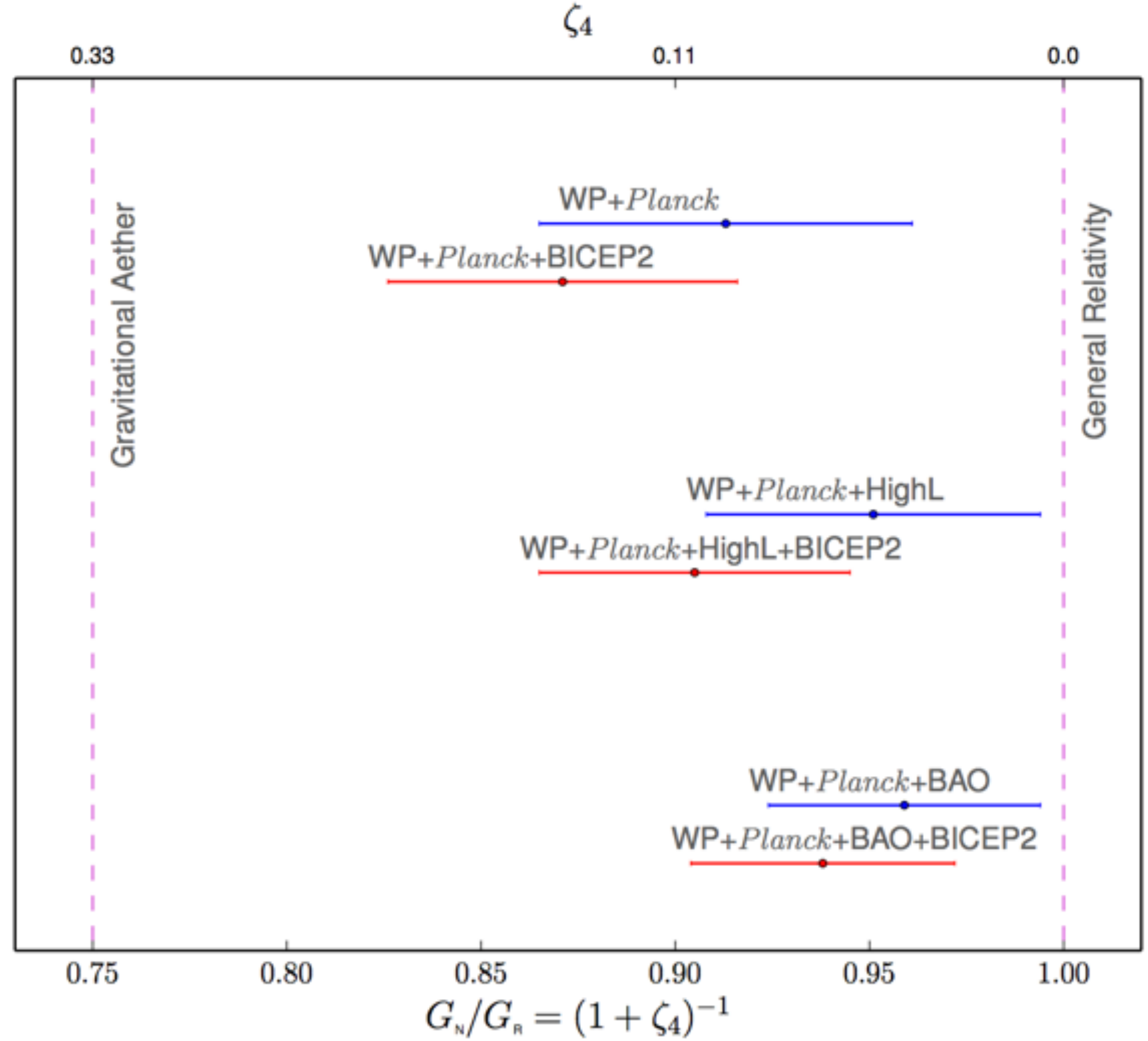
- ***Disclaimer:* The field equations *do not* follow from an *Action principle*

Deviations from GR sourced by **Pressure** or **Vorticity**

(Kamiab & NA, 2011)
(Aslanbeigi, Robbers, Foster, Kohri & NA, 2011)
(Narimani, NA & Scott, 2014)

- Neutron Star Structure (e.g. Adv LIGO)
- Cosmology (CMB, Big Bang Nucleosynthesis)
- *Intrinsic Gravitomagnetic Effect (LAGEOS, GPB)*
- **Vacuum gravity identical to GR****

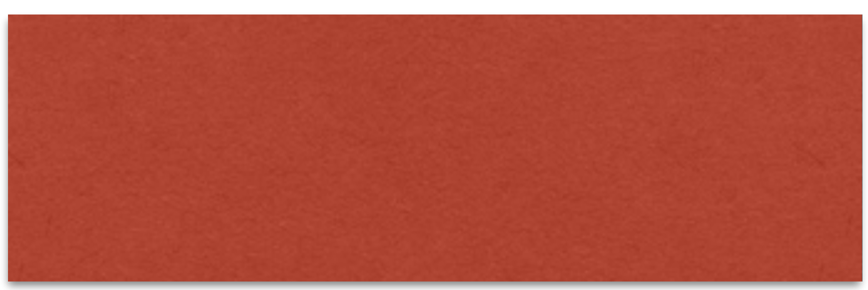
How does pressure gravitate?

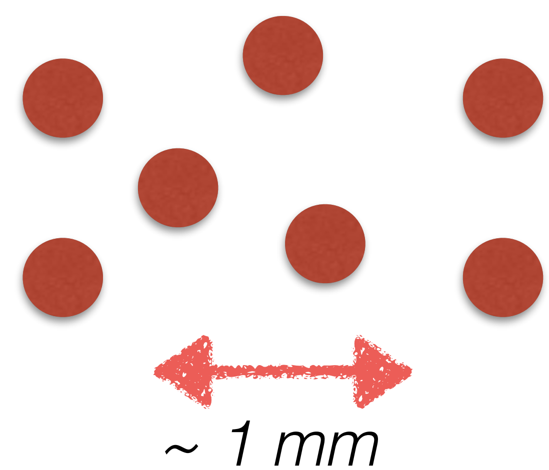


(Narimani, NA & Scott 2014)

What now?

- Original Gravitational Aether proposal (NA 2008) is ruled out at 3-4σ (still better than 10^{60}-10^{120}σ!)
- **But, vacuum is smooth** **matter is lumpy**





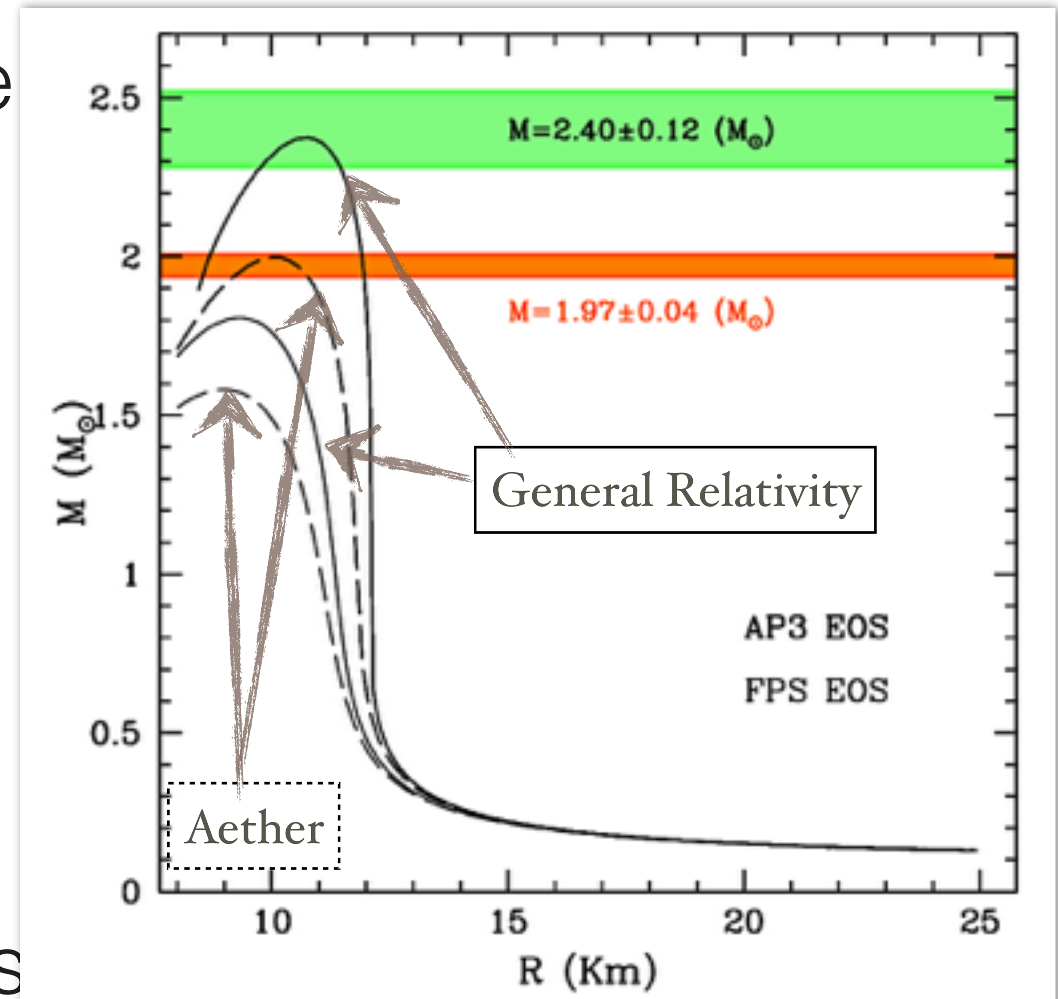
- Does that make a difference?
- The theory ***must*** have a cut-off/coarse-graining scale

neutron stars and aether

- Deviations from Einstein gravity are
  pressure

- *Neutron Stars*

- Aether
  EOS)
  it out



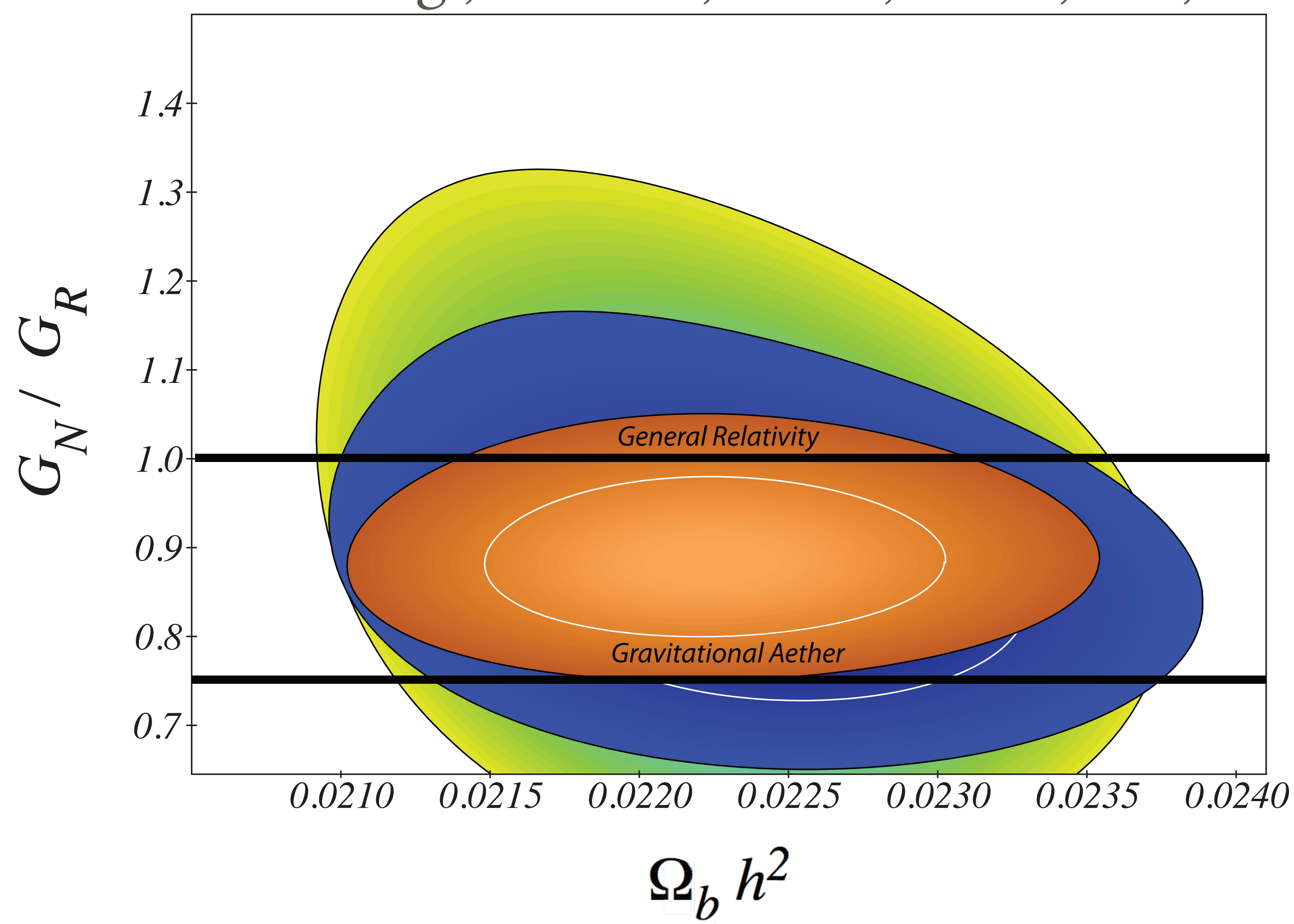
Kamiab & NA 2011

- Uncertainty in nuclear equation of s

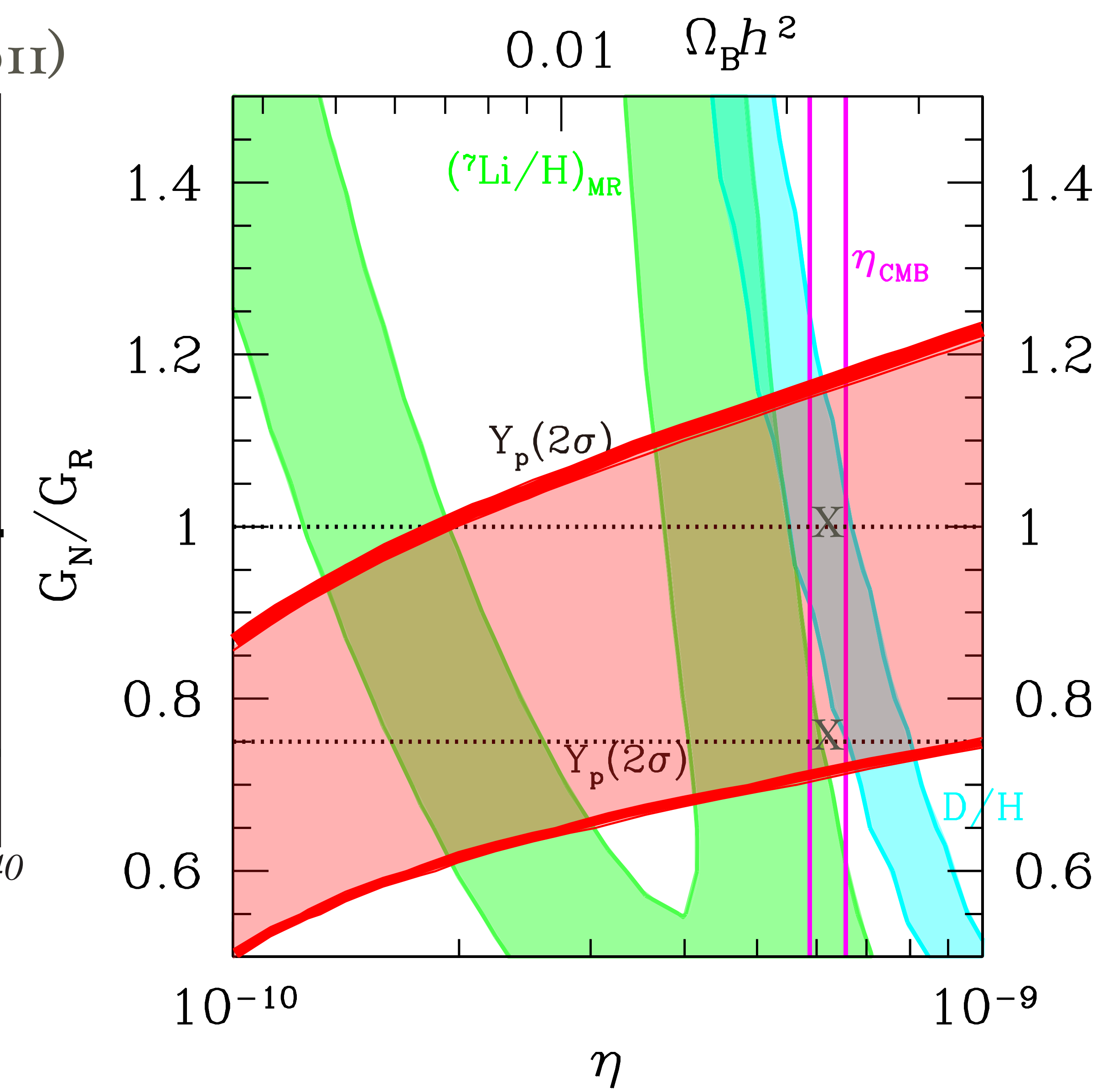
- Can test with Gravitational Wave detection from NS-NS mergers

Cosmology (G_N/G_R = 0.75 or 1?)

(Aslanbeigi, Robbers, Foster, Kohri, NA, 2011)



Cosmic Microwave Background



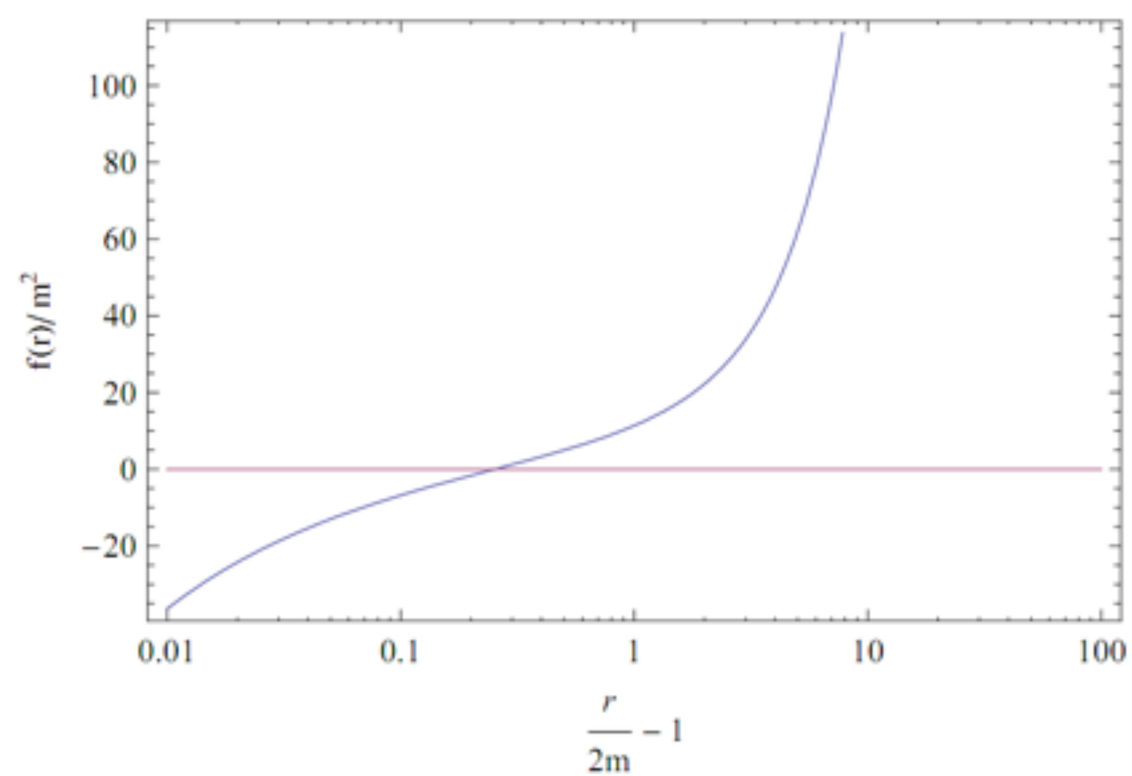
Big Bang Nucleosynthesis

aether and black holes

- We can solve for the black hole spacetime in this theory

$$ds^2 = \left(1 - \frac{2m}{r}\right)\left[1 + 4\pi p_0 f(r)\right]^2 dt^2 - \left(1 - \frac{2m}{r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

- p_0 is the aether pressure at infinity
- *f(r)* is an analytic function of *r* that diverges at $r \approx 2m$ & $r \to \infty$
- ➥ *UV-IR coupling thru aether press*
- ➥ *Finite redshift at r=2m*
- ➥ *No Horizon(similar to Fuzzball r*



... and dark energy!

- Let us propose that maximum redshift at "horizon" is set to *Planck Temperature/Hawking Temperature* by quantum gravity effects:

$$p_0 = -\frac{1}{256\pi^2 m^3} \simeq \left(\frac{m}{74\ M_\odot}\right)^{-3} p_{\rm DE,obs}!!$$

- *Aether pressure* has the same sign and magnitude as *Dark Energy* for stellar mass black holes!

- ➥Conjecture: Formation of stellar black holes causes cosmic acceleration

- ➥Conjecture: Evolution of Astrophysical black holes leads to dynamical Dark Energy

... and dark energy!

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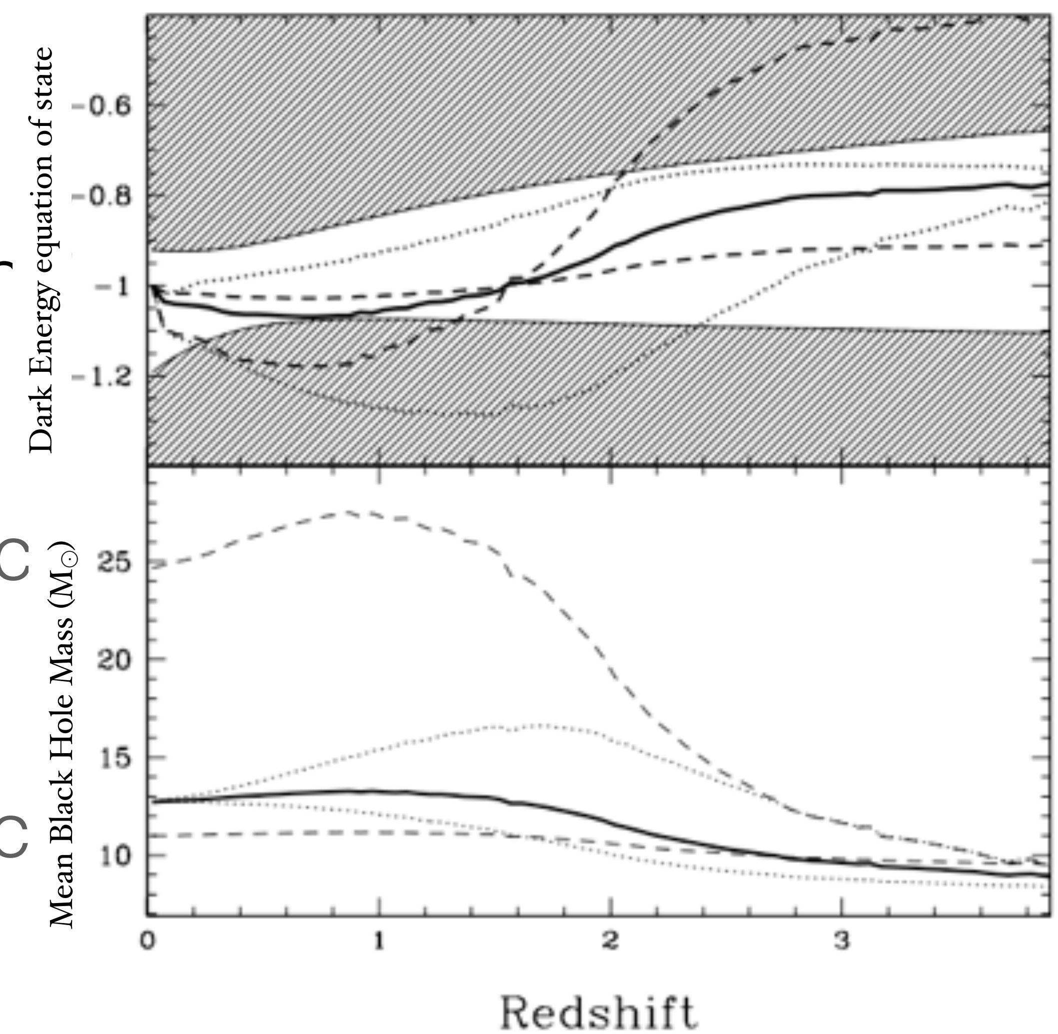
Prescod-Weinstein, NA, Balogh 2009

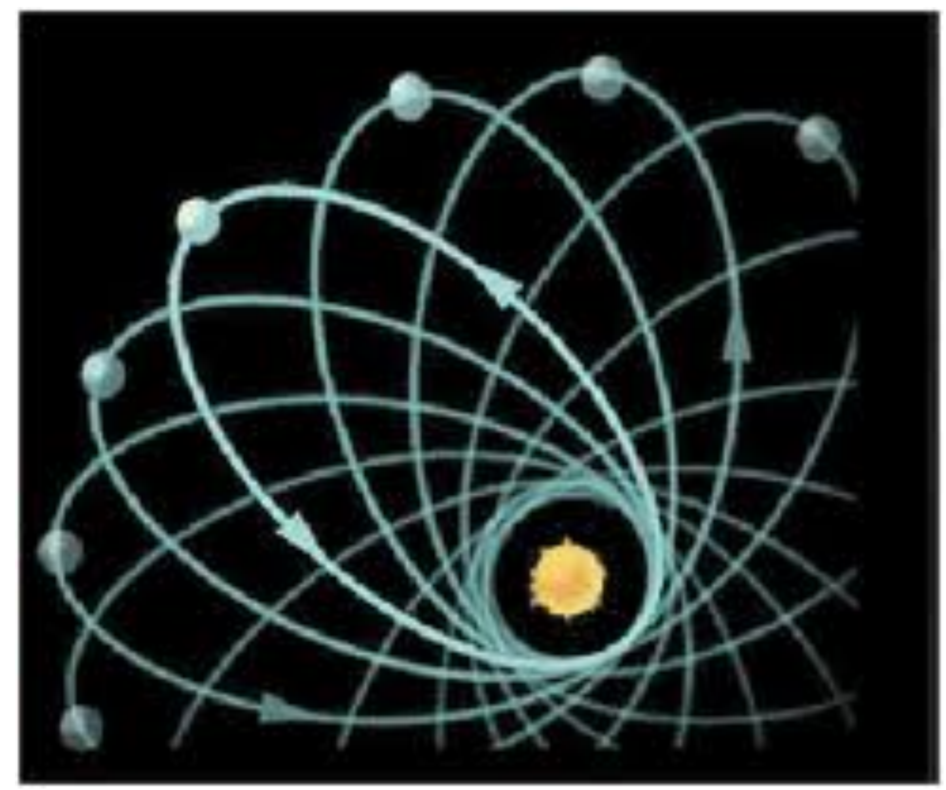


“a glorious historical accident!”

- *Barbour:* Mach suggested that Physic
  depends on the change in observabl
  (and Lorentz Invariance) emerges as
  condition

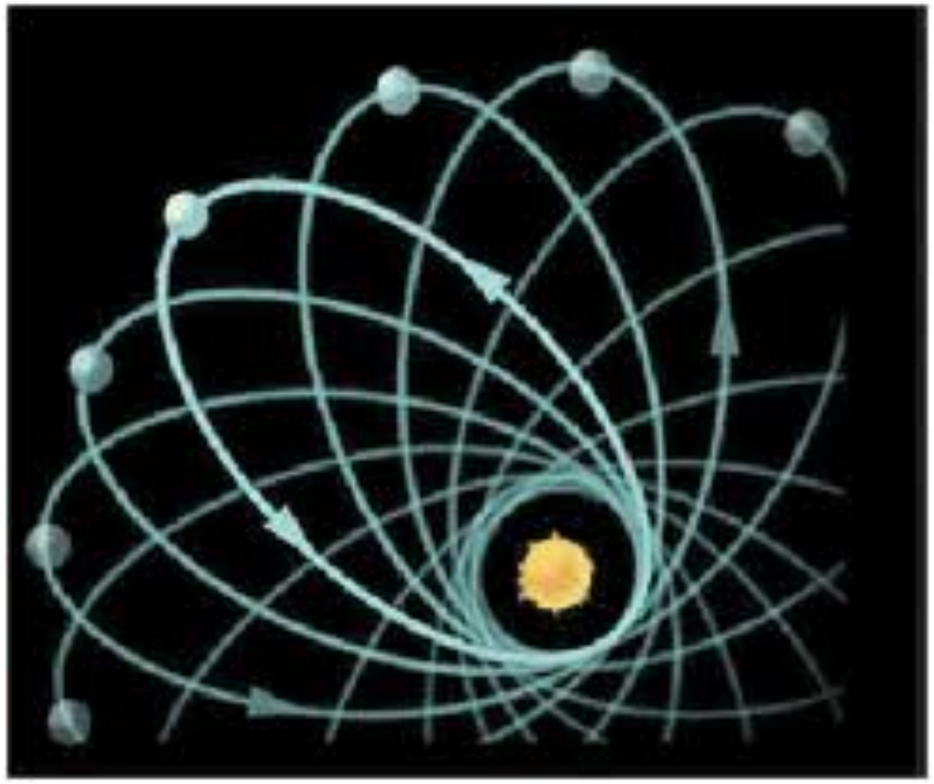
- *Horava:* A transition to Lifshitz symmetr
  makes gravity power-counting renorma

A lesson from
perihelion precession of Mercury



A lesson from perihelion precession of Mercury

- Newtonian Gravity has a symmetry between angular and radial coord's: $r \leftrightarrow \theta$, $\Omega_r = \Omega_\theta$



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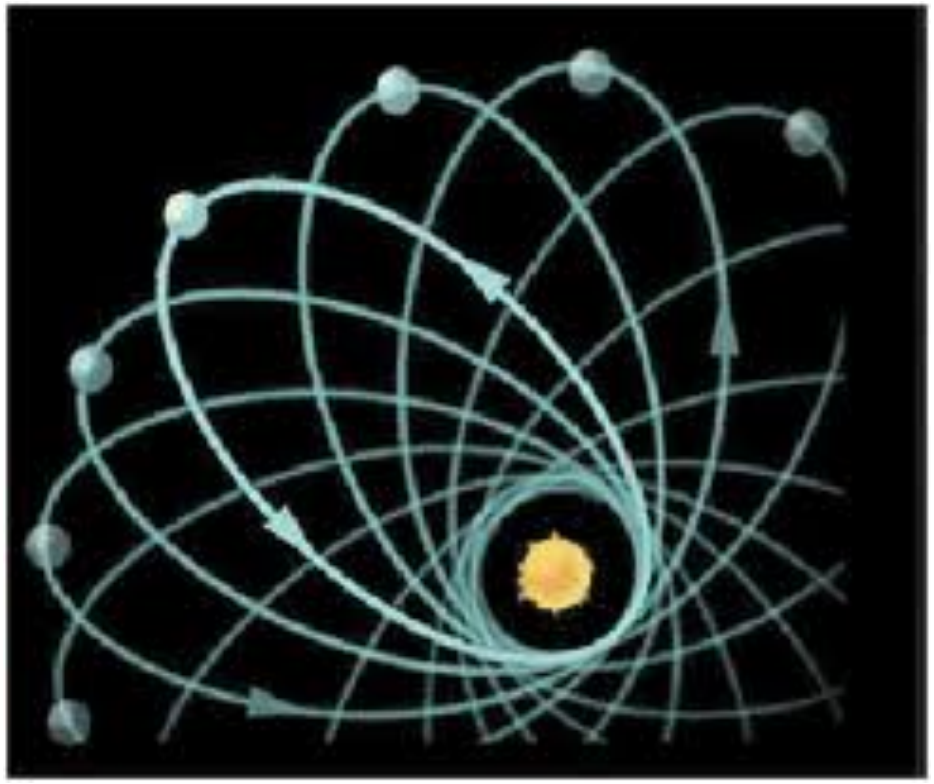

- Is this fundamental?

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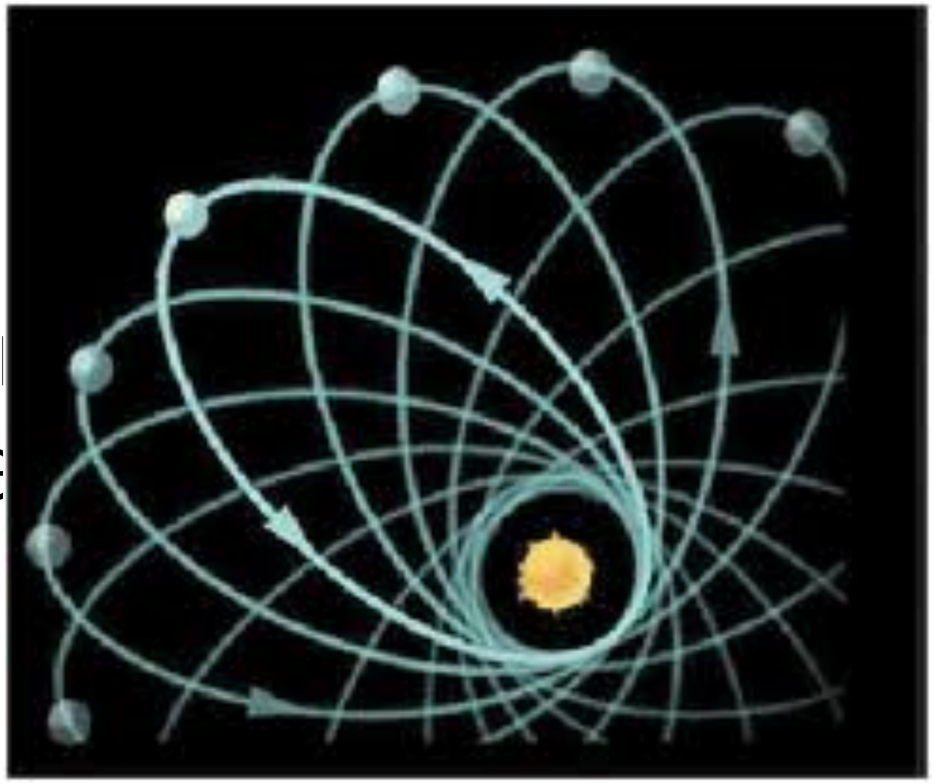

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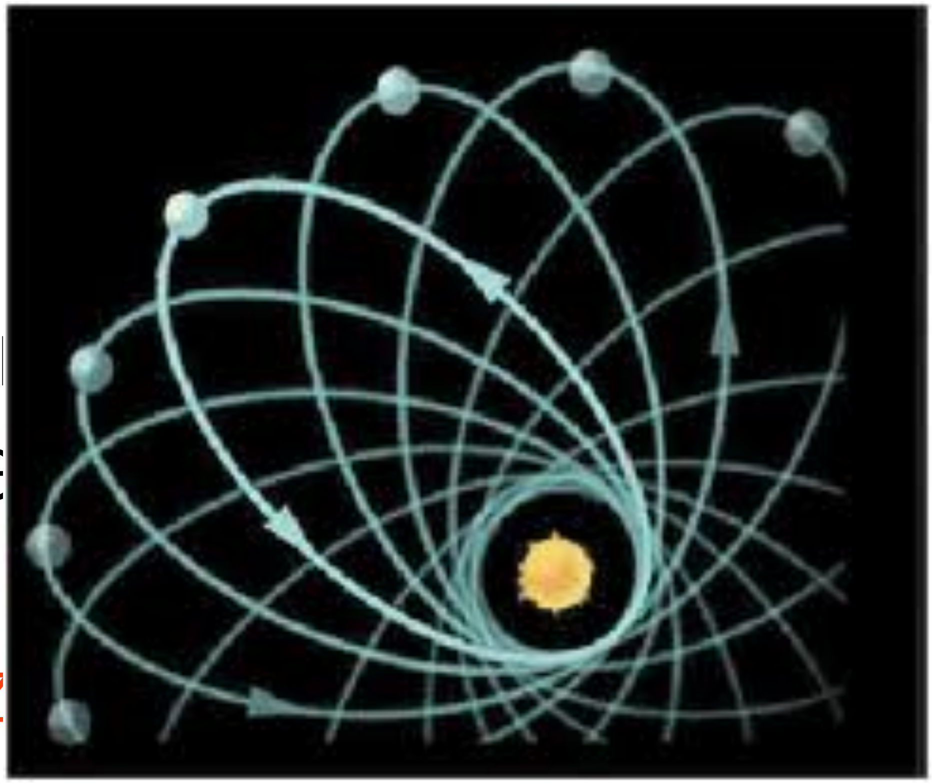

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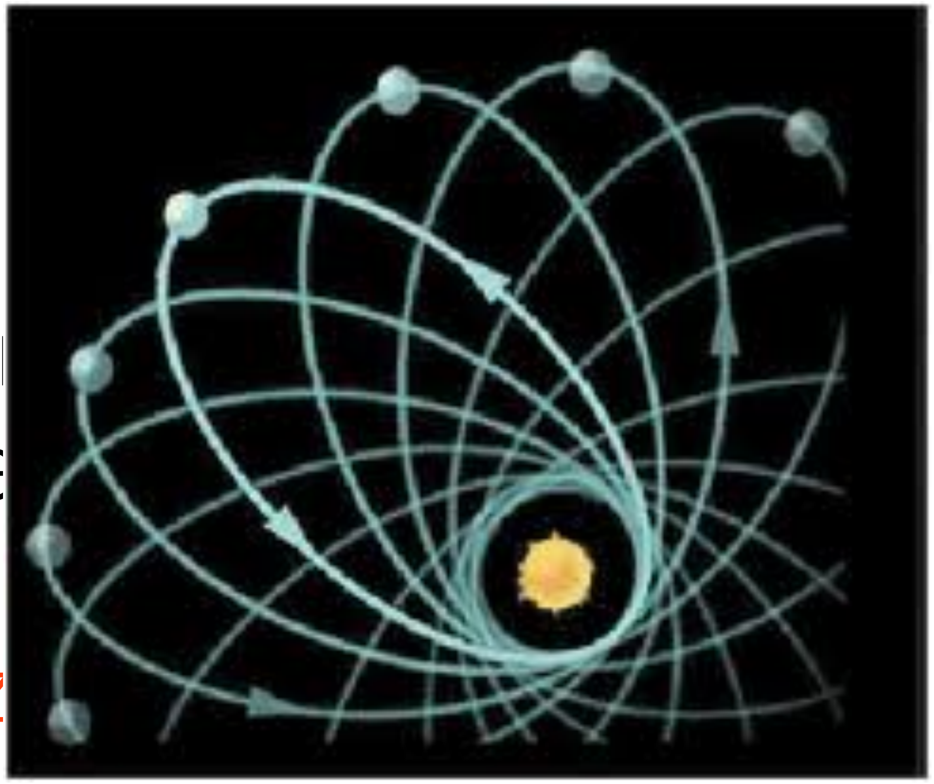

- *Cosmologist: Universe has already done this!*