A closed Universe in Hořava-Lifshitz gravity

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Cosmological trouble:

Modern cosmology is rife with trouble

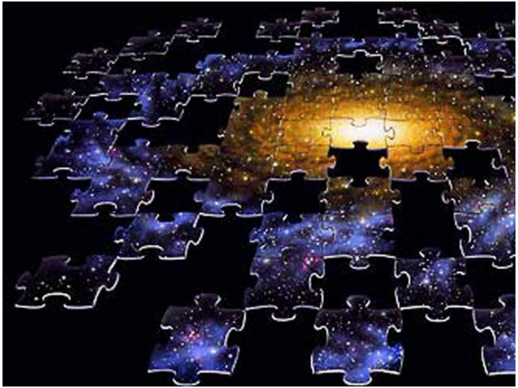
- Horizon problem, flatness problem
- Maybe most significant problem: H_0 **tension** (also S_8)

Open questions:

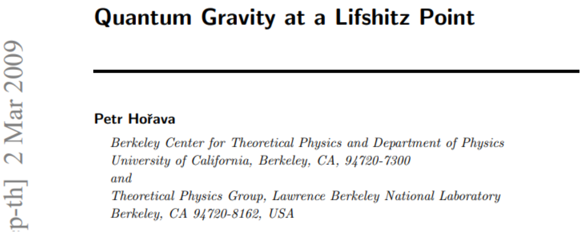
- What is dark matter?
- What is dark energy?

We don't even know whether the Universe is flat! New physics is clearly needed

- How do we reconcile GR and QM?
- Renormalisable gravity theory?



First paper



p-th] 2 Mar 2009

Quantum Gravity at a Lifshitz Point

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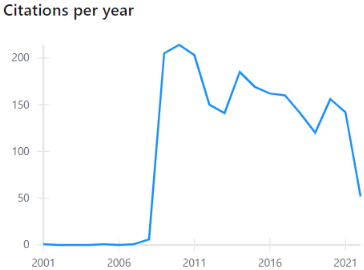


- 200+ citations in the first year
- 7 ghost citations from before it was arXiv'd.
- 2209 citations (in total, yesterday)

"Quantum Gravity at a Lifshitz Point", Petr Hořava, PRD 2009

Hořava-Lifshitz Gravity

Introduce an anisotropic (Lifshitz) scaling:

$$t \to b^{-z} t, \quad x^i \to b^{-1} x^i$$

For Lorentz invariance: $z = 1$
For power-counting renormalisability: $z \geq 3$

Usually assumed to be broken down to: $t \to \xi_0(t), \quad x^i \to (t, x^k)$

Hořava-Lifshitz structure

- Symmetry group: Diff[M,$\mathcal{F}$]
- Preferred foliation on constant time slices, explicit spacetime-symmetry breaking
- Spacetime diffeomorphism symmetry $\longrightarrow$ time-dependent diffeomorphism symmetry + reparametrisation of global time coordinate

The theory

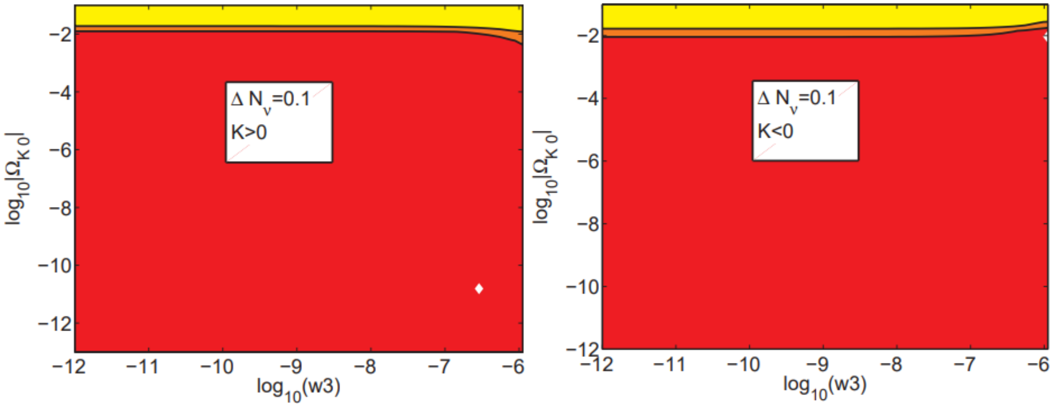
- Once you allow for $\mathcal{O}(\partial_t) > 2$, you can write down an action such as

$$S = \int dtd^3x\sqrt{\gamma}\alpha\Big[K_{ij}K^{ij} - \lambda K^2 - \mathcal{V}[\gamma_{ij}]\Big],$$

$$\mathcal{V}[\gamma_{ij}] = \frac{\kappa^4}{2}\Big[\frac{1}{2\nu^4}C_{ij}C^{ij} - \frac{\mu}{2\nu^2}\epsilon^{ijk}R_{il}D_jR^l{}_k\frac{\mu^2}{8}R_{ij}R^{ij} - \frac{\mu^2}{8(3\lambda-1)}\Big(\frac{4\lambda-1}{4}R^2 - \Lambda_w R + 3\Lambda_w^2\Big) - \frac{\mu^2\omega}{8(3\lambda-1)}R\Big]$$

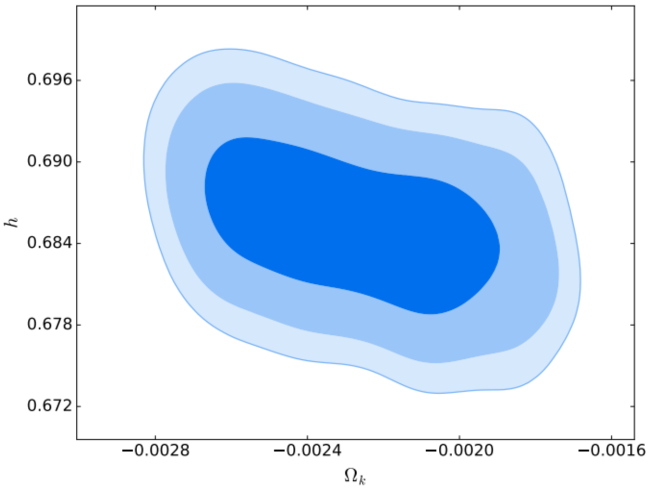
Previous results

- First constraints from 2009



Dutta, Saridakis JCAP 2010

Previous results



NAN, Czuchry, Phys.Dark Univ. 2018

Cosmology

- We start from FLRW:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2)\right]$$

$$H^2 = \frac{\kappa^2}{6(3\lambda-1)}\left[\rho + \frac{3\kappa^2\mu^2}{8(3\lambda-1)}\left(\frac{2k(\Lambda_w-\omega)}{a^2} - \Lambda_w^2\right)\right]$$

$$\dot{H} + H^2 = \frac{\kappa^2}{6(3\lambda-1)}\left[-\frac{1}{2}(\rho+3p) + \frac{3\kappa^2\mu^2}{8(3\lambda-1)}\left(\frac{k^2}{a^4} - \Lambda_w^2\right)\right],$$

- This can be recast in a very convenient form!

$$\frac{H^2}{H_0^2} = \Omega_m^0 a^{-3} + \Omega_r^0 a^{-4} + \Omega_k^0 a^{-2} + \Omega_{\mathrm{DE}}$$

Cosmology

- The dynamical dark energy term is highly sensitive to Ω_k^0

$$\Omega_{\mathrm{DE}} = \frac{(\Omega_k^0)^2}{4\Omega_\Lambda^0} a^{-4} - \Omega_k^0 \left(\frac{\Omega_\omega^0}{\Omega_\Lambda^0} \right) a^{-2} + \Omega_\Lambda^0$$

- The dark-radiation term has a constraint from BBN:

$$\Omega_{\mathrm{DR}} = \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \Delta N_{\mathrm{eff}} \Omega_\gamma a^{-4}, \quad \Omega_\Lambda = \frac{\Omega_k^2}{4 \cdot 0.13424 \Delta N_{\mathrm{eff}} \Omega_r}$$

Models

Model A: Use the BBN constraint

Model B: **Do not use** the BBN constraint

NAN, Park arXiv:2108.07986

The final Friedmann equations

- Model A

$$\left(\frac{H}{H_0}\right)^2 = (1 + 0.13424\Delta N_{\mathrm{eff}})\Omega_r a^{-4} + \Omega_m a^{-3} + \left[\Omega_k - 4 \cdot 0.13424\Delta N_{\mathrm{eff}} \left(\frac{\Omega_\omega \Omega_r}{\Omega_k}\right)\right] a^{-2} + \frac{\Omega_k^2}{4 \cdot 0.13424\Delta N_{\mathrm{eff}} \Omega_r}$$

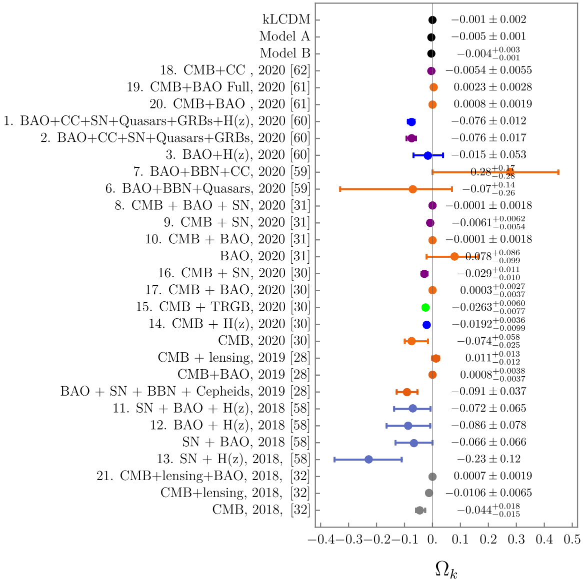
- Model B

$$\left(\frac{H}{H_0}\right)^2 = \left(\Omega_r + \frac{\Omega_k}{4\Omega_\Lambda}\right) a^{-4} + \Omega_m a^{-3} + \left(1 - \frac{\Omega_\omega}{\Omega_\Lambda}\right) \Omega_k a^{-2} + \Omega_\Lambda$$

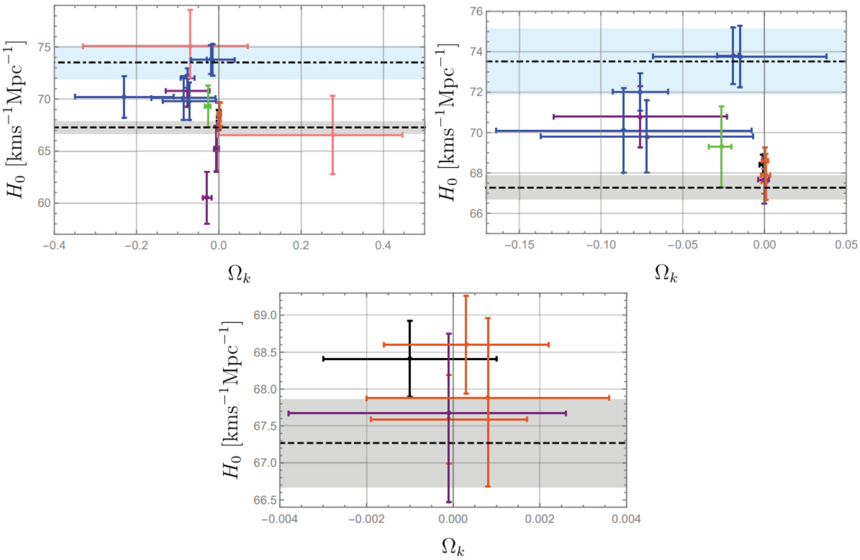
The data

- We use **background level** data only, no CMB power spectrum, only the shift parameters of *Planck* 2018 (location of first peak in angular power spectrum)
- Baryon Acoustic Oscillations
  - SDSS-BOSS DR12 release
  - SDSS-eBOSS
  - SDSS-BOSS-Lyman-α
  - WiggleZ dark-energy survey
- Type Ia Supernovae, PANTHEON sample
- Gamma-ray bursts, Mayflower sample
- H0liCOW lensed quasar sample
- Cosmic chronometers (elliptical and lenticular galaxies) $H(z)$ measurements

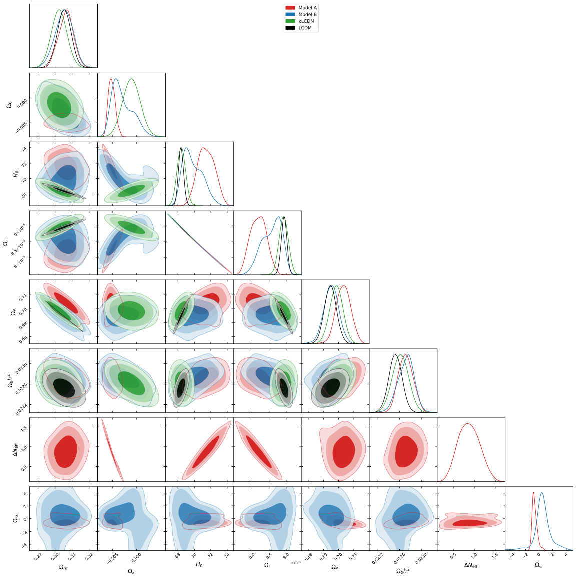
Curvature measurements



Curvature measurements



Curvature measurements



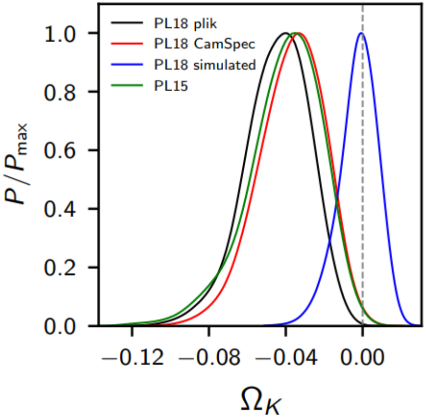
Numbers

Model Parameters	Model **A**	Model **B**	kLCDM	LCDM
$\Omega_b h^2$	0.0227 ± 0.0001	0.0227 ± 0.0001	0.0226 ± 0.0001	0.0225 ± 0.0001
Ω_m	$\mathbf{0.307 \pm 0.004}$	$\mathbf{0.306^{+0.005}_{-0.006}}$	$\mathbf{0.302 \pm 0.005}$	$\mathbf{0.305 \pm 0.004}$
$\Omega_r \cdot 10^5$	$\mathbf{8.20^{+0.22}_{-0.27}}$	$\mathbf{8.64^{+0.23}_{-0.38}}$	$\mathbf{8.93^{+0.14}_{-0.13}}$	$\mathbf{8.94^{+0.08}_{-0.08}}$
Ω_k	-0.005 ± 0.001	$-0.004^{+0.003}_{-0.001}$	-0.001 ± 0.002	-
Ω_Λ	$\mathbf{0.70 \pm 0.01}$	0.695 ± 0.005	0.699 ± 0.004	0.695 ± 0.004
H_0 [km s^{-1} Mpc^{-1}]	$71.38^{+1.19}_{-0.93}$	$69.53^{+1.57}_{-0.91}$	$68.41^{+0.52}_{-0.51}$	$68.36^{+0.32}_{-0.30}$
Ω_ω	$-0.75^{+0.46}_{-0.24}$	$0.34^{+1.15}_{-0.31}$	-	-
ΔN_{eff}	$0.87^{+0.28}_{-0.26}$	-	-	-
$\chi^2_{\min}$	1143.6	1150.1	1155.0	1157.9
$\Delta\chi^2_{\min}$	-14.3	-7.8	-2.9	0
$\ln E$	-573.8	-576.9	-578.9	-580.0
$\ln B_{ij}$	$+6.2$	$+3.1$	$+1.1$	0

Other hints

E.D.Valentino et al, Nature Astronomy 2019 finds:

- $\Omega_k = 0.0438$ (*Planck* only) as best fit, closed Universe at 99.985%
- adding BAO data brings a flat Universe back into agreement: $\Omega_k = 0.037^{+0.032}_{0.034}$ 95%.



Conclusions

- In IR-modified Hořava-Lifshitz gravity, there seems to be evidence for a closed Universe
- Consistent with previous Hořava work (Dutta+Saridakis & NAN+Czuchry), as well as GR (E.D.Valentino et al)
- It seems like Hořava maintains preference for a closed Universe even when adding BAO
- Perturbation-level analysis needed for final word on this (in progress...)

Thank you

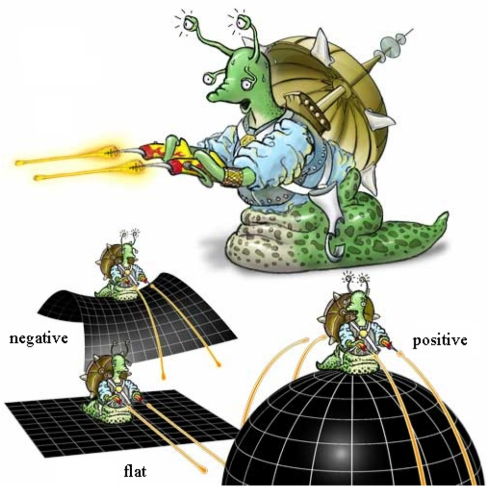


Image credit: James Schombert, University of Oregon