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A Tale of
Two Accelerations

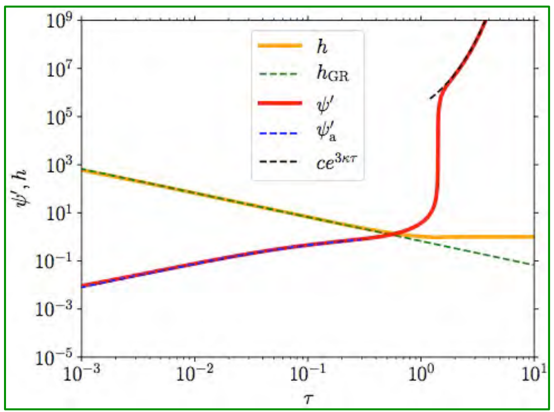
Eric Linder

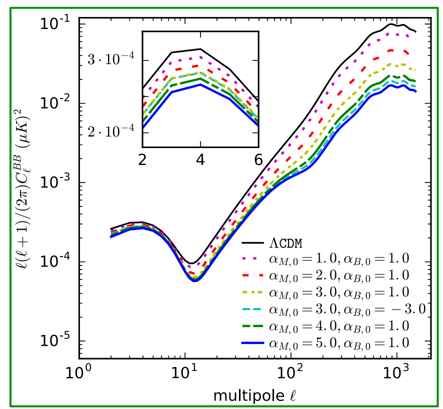
UC Berkeley/KASI

5th Korea-Japan Workshop on Dark Energy

Alexei Starobinsky 70th Birthday Fest

10 August 2018





5 Years Ago

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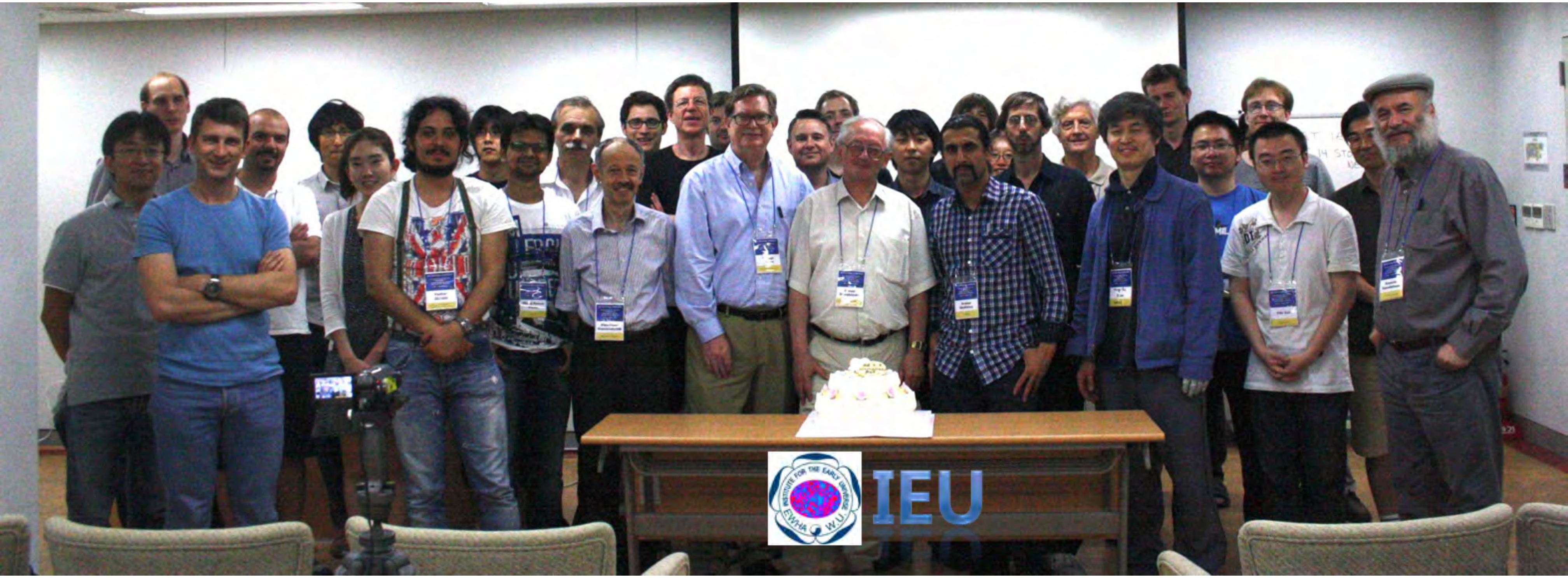
IEU Cosmology Conference 2013

Reconstructing the Universe:

A Celebration of Alexei Starobinsky @ 65, IEU @ 5, and New Research



1 Year Ago

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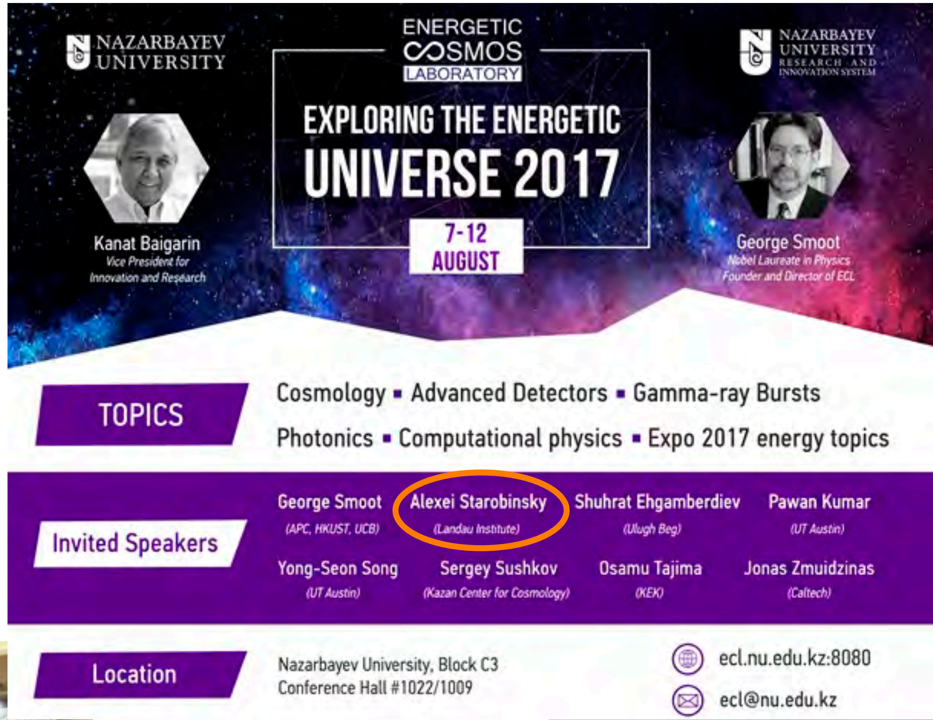
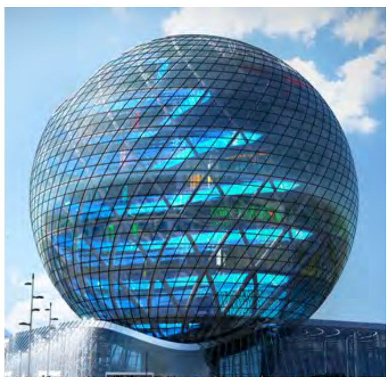


ENERGETIC COSMOS LABORATORY

Astana, Kazakhstan



Outline

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

- **The Well Tempered Cosmological Constant**

  -- The Planck Scale and the Late Λ

- **Inflation and Dark Energy**

  -- Starobinsky Inflation, α attractors, $w \neq -1$

- **CMB B-modes and Modified Gravity**

  -- including Keeping Gravity Stable

- **Gravitational Waves and Cosmic Structure?!**

The Cosmological Constant

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Where does current cosmic acceleration arise from?

But also, why isn't there a high energy (Planck scale, 10^{60}, etc.) cosmological constant that wipes out the whole late time universe?

"Original cosmological constant problem" **Weinberg 1989**

New solution to both problems:

Appleby & Linder, "The Well Tempered Cosmological Constant", JCAP 1807, 034 (2018) [arXiv:1805.00470]

Well Tempering

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Self tuning uses a particular degeneracy in the field equations. We use a different degeneracy condition that we call "well tempered", and an action that preserves $c_{GW}=c$.

We also use shift symmetry.

$$
\begin{aligned}
S &= \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R + K(\phi,X) - G(\phi,X)\Box\phi + \rho_\Lambda + \mathcal{L}_m\right] \\
&\to \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R + c_1 M^4\psi + M^4 A(\psi) - M^4 B(\psi)\tilde{\Box}\psi + \rho_\Lambda + \mathcal{L}_m\right]
\end{aligned}
$$

Two free functions $A(\psi)$, $B(\psi)$ with certain conditions on them, providing a family of solutions.

The Well Tempered Cosmological Constant

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This solution

- ✓ Cancels the bare CC
- ✓ Even through phase transitions
- ✓ Preserves matter and radiation
- ✓ Is shift symmetric to protect vs quantum corrections
- ✓ Is ghost free and stable
- ✓ Gives late time acceleration and de Sitter attractor

It does not solve the hierarchy problem, explaining why the residual CC (e.g. mass scale M in action) is so small.

Crescendo!

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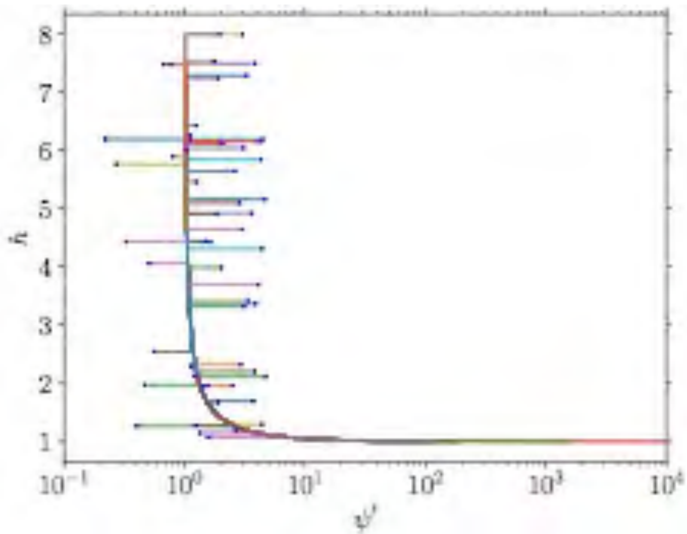
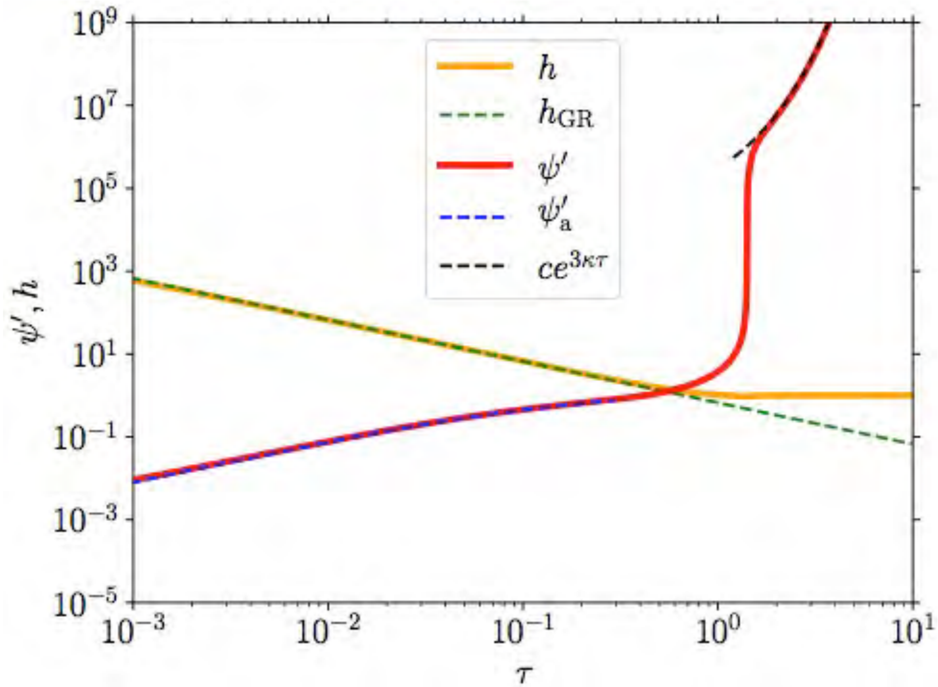
An example where ψ' grows is $A(\psi') = \text{const}$, $B(\psi') = \frac{c_1}{9\kappa^2}\left(\ln\psi' + \frac{1}{\psi'}\right)$



The attractor behavior is clear: many different initial conditions all lead to same trajectory, and to de Sitter state h=constant=1.

The expansion history h(t) is simply that of ΛCDM, despite a large early CC. The matter epoch is preserved and gives way to current acceleration.



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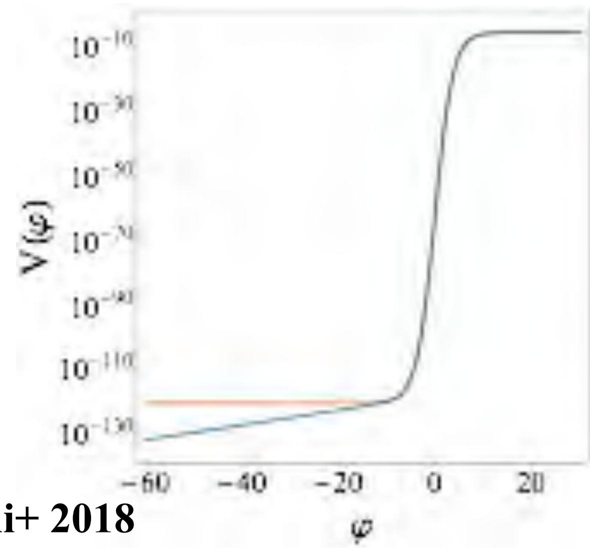
Inflation and Dark Energy

The last remaining unobserved prediction from inflation is primordial gravitational waves. The tensor-scalar ratio r<0.064 (95% CL). Planck X 2018

Starobinsky inflation predicts $r=12\alpha/N^2=0.0033$ ($\alpha=1$).

α attractors can explain why $r\sim1/N^2$.

One can also use them to connect inflation with current cosmic acceleration. Akrami+, Dimopoulos+, van den Bruck+



Akrami+ 2018

Exponential drop $e^{-2\gamma}$ with $\gamma\sim125$.

At late times, $V \sim e^{2\varphi/\sqrt{6\alpha}}$

$$w \to -1 + \frac{2}{9\alpha}$$

Inflation and Dark Energy

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Extraordinary prediction:

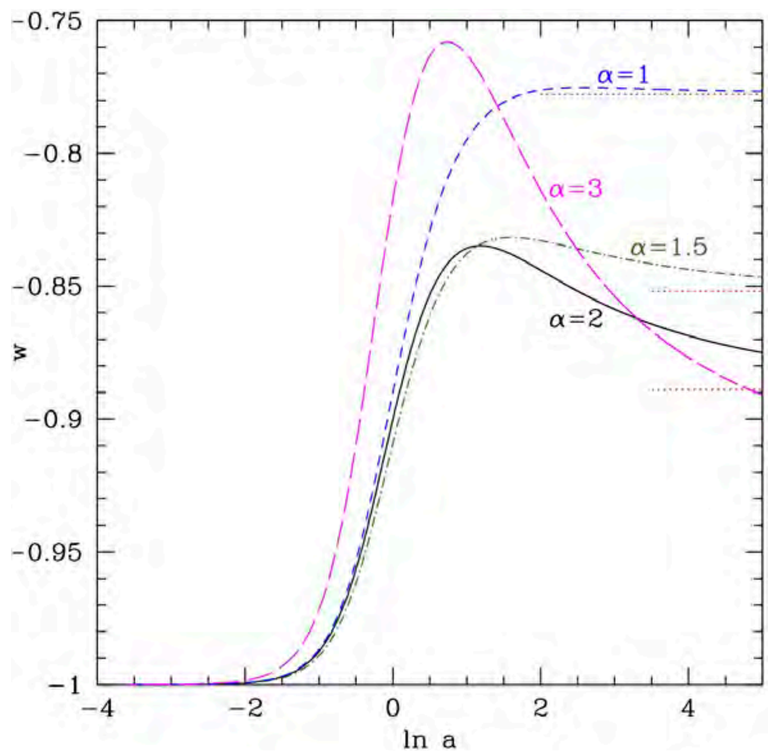
$$1 + w \sim \frac{1}{\alpha} \qquad\qquad r \sim \alpha$$

We must win at something! Either α is large enough to see GW in CMB, or small enough that we see distinction of DE from Λ.

Connect to DE flow formalism, model independent potential

Akrami, Linder, Vardanyan in progress

DE observations imply α~1-2, recall α=1 is Starobinsky model.



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CMB B-modes and Gravity

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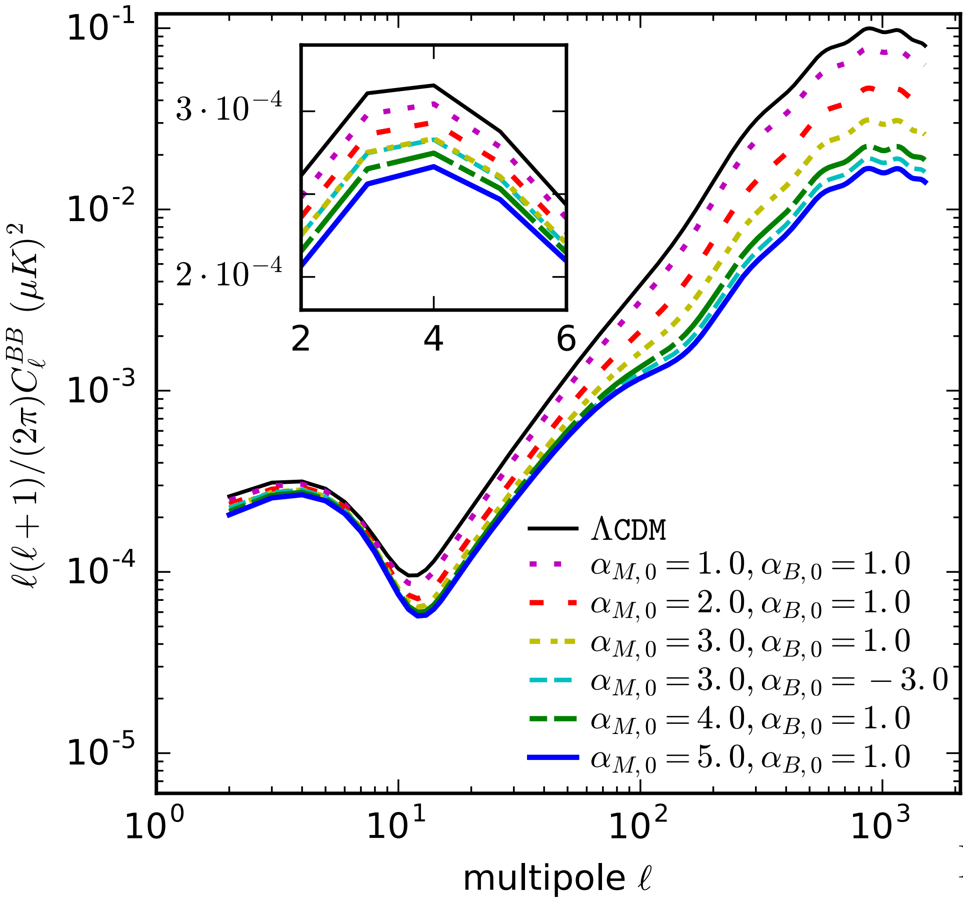
Effective field theory approach to modified gravity defines property functions α_B, α_K, α_M, α_T. We know* α_T=0, and α_K is only important on horizon scales.

Even with α_T=0, GW propagation affected by α_M.



Low l bump is primordial GW. Clear impact of (only) α_M.

High l bump is lensing. Matter growth suppression by α_M, α_B.

hi_class with $\alpha_i=\alpha_{i,0}a^1$

Denissenya & Linder 1808.00013

CMB B-modes and Gravity

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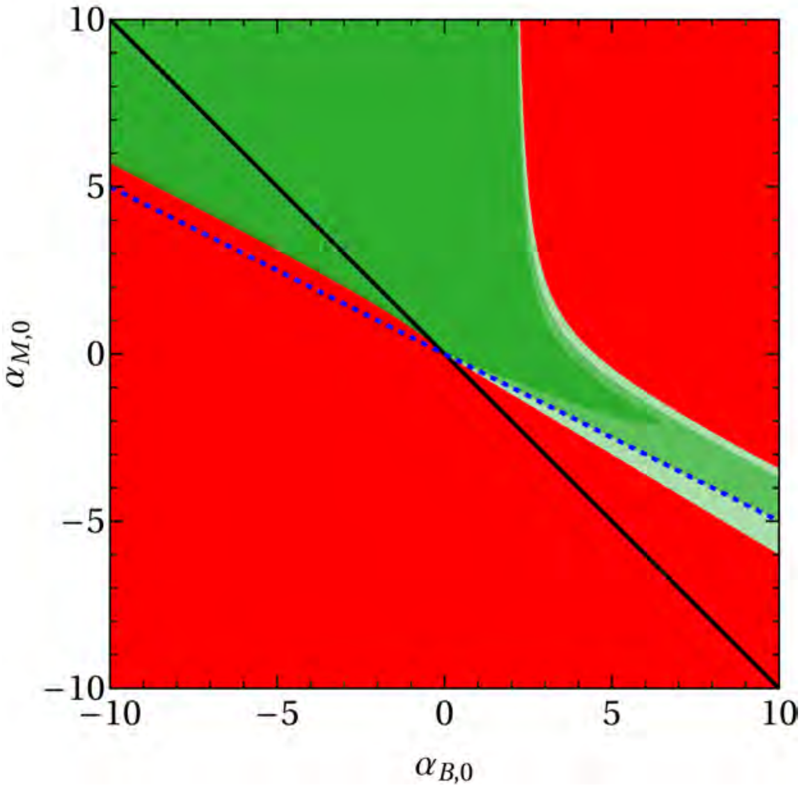
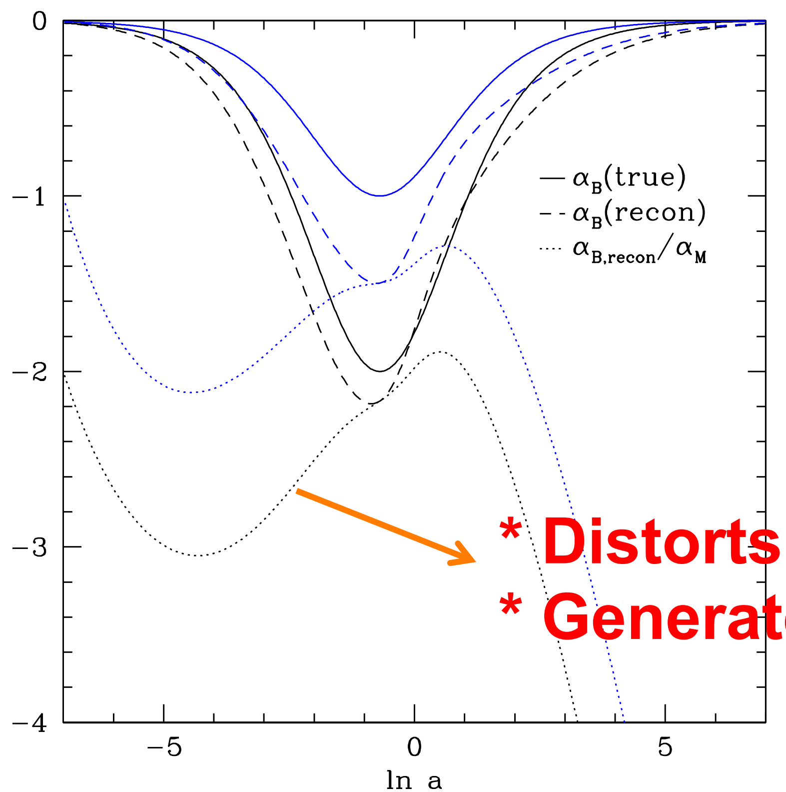
Physics results very sensitive to parametrization of property functions – not good!

Parametrization also affects stability.



a^s with s=1.3, 1.5, 1.7



* Distorts the theory
* Generates slip

Fit exact c_s^2 with 3 parameters, then reconstruct theory – fails!

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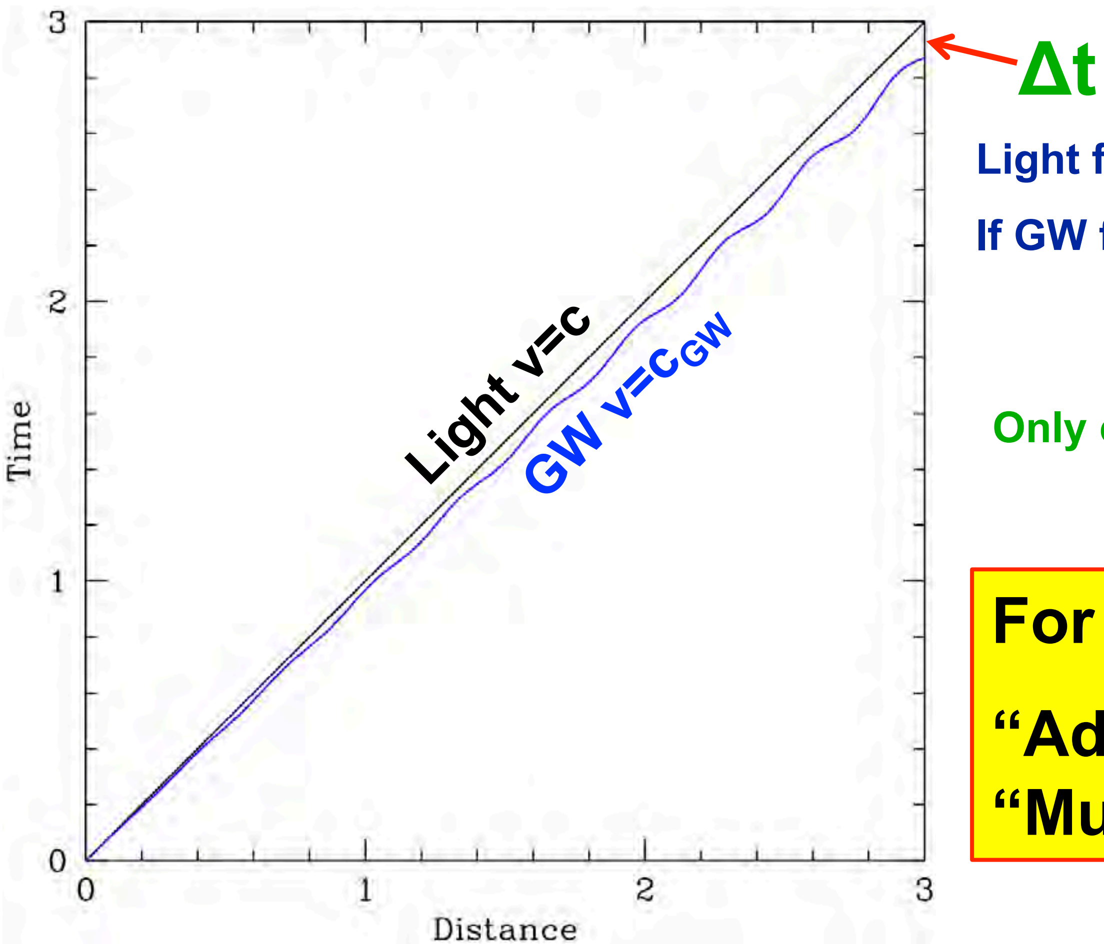
Implications of $c_T = c$

GW170817 + GRB1070817A: synchronicity of GW and photon arrival within 2 seconds after signal propagation for 130 My (400 x 10^{13} s) limits $c_T/c - 1 < 10^{-15}$.

Any theory with $c_T \neq c$ is essentially* ruled out.



Light follows null geodesics. $g_{\mu\nu} dx^\mu dx^\nu = 0$

If GW follows disformal → Δt. $\mathcal{G}_{\mu\nu} dx^\mu dx^\nu = 0$

$$\mathcal{G}_{\mu\nu} = g_{\mu\nu} + D(\phi, X)\, \partial_\mu \phi \partial_\nu \phi$$

Only conformal theories survive.

$$\mathcal{G}_{\mu\nu} = C(\phi, X)\, g_{\mu\nu}$$

For nonrelativists:

"Additive" gravity is dead
"Multiplicative" gravity is ok

Gravitational Wave Distances

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Just because c_T=c doesn't mean no effect on GW propagation.

$$\ddot{h} + (2+\alpha_M)\mathcal{H}\dot{h} + c_T^2 k^2 h = 0$$

GW amplitude is proportional to 1 / distance
(energy goes as inverse square)

$$h \sim 1/D_L^{GW}$$

So we can measure changes in gravity by comparing the GW distance to the photon luminosity distance to the same object.

Horndeski α_M (running of Planck mass) damps h.

Nishizawa 1710.04825
Arai & Nishizawa 1711.03776
Belgacem+ 1712.08108
Amendola+ 1712.08623
Linder 1801.01503

Gravitational Wave Distances

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Modified gravity α_M (running of Planck mass)

$$\alpha_M = \frac{d\ln M_\star^2}{d\ln a}$$

damps h

$$\begin{aligned} h &= h^{GR} e^{-(1/2)\int_{\rm em}^{\rm obs} d\ln a\,\alpha_M(a)} = h^{GR} e^{-(1/2)\int_{\rm em}^{\rm obs} d\ln M_\star^2(a)} \\ &= h^{GR}\left[\frac{M_{\star,\rm em}^2}{M_{\star,\rm obs}^2}\right]^{1/2} \end{aligned}$$

So

$$d_{L,GW}(a) = d_L^{GR}(a)\,\left[\frac{M_\star^2(a=1)}{M_\star^2(a)}\right]^{1/2}$$

but M_* also affects growth, so GW distance tied to growth!

Linder 1801.01503

e.g. in No Slip Gravity

$$d_{L,GW}(a) = d_L^{GR}(a)\,\left[\frac{G_{\rm matter}(a)}{G_{\rm matter}(a=1)}\right]^{1/2}$$

(also in nonlocal gravity)

Gravitational Waves and Cosmic Growth

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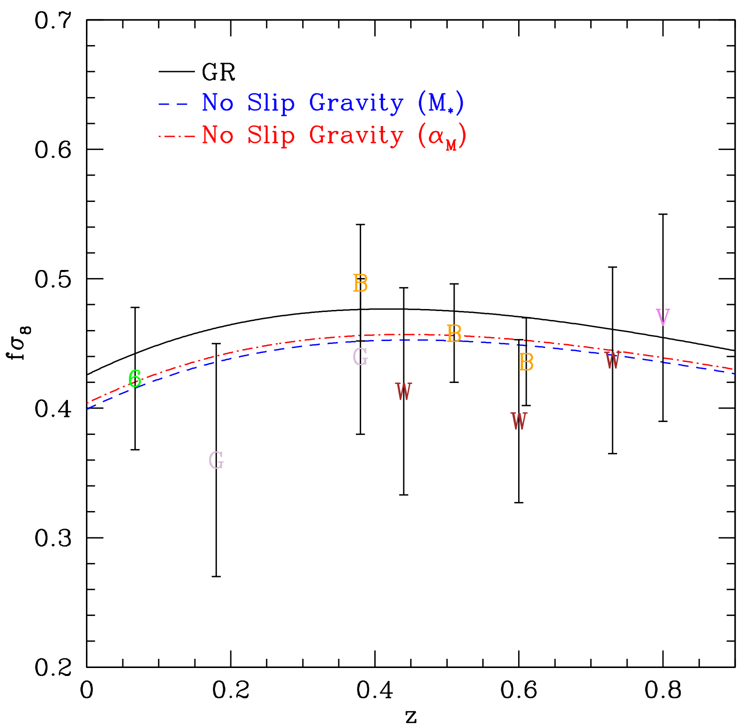
GW distance tied to growth!

If we detect, e.g., a suppression in growth, then this can be checked vs GW distances different than GR.



Example: No Slip Gravity (1 free function) fits growth from redshift space distortions, better than GR.

It predicts ~5% deviation in GW distances.

Galaxy surveys have deep complementarity with GW and CMB surveys.

Summary

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The well tempered cosmological constant is a solution to the original cosmological constant problem, improving on self tuning.

$$\Lambda \to \Lambda$$

Inflation may be tied to dark energy in a win or win situation: either we find primordial GW or w≠-1.

$$r \leftrightarrow 1 + w$$

Modified gravity stability and interpretation can be very sensitive to parametrization. Parametrize Poisson equations not EFT.

$$G_{\rm eff} \to {\rm EFT}$$

The tensor sector of modified gravity can be probed by interferometers, and CMB, and cosmic surveys. Crosscheck between gravitational wave distance and structure growth!

$$d_L^{GW} \to G_{\rm eff}$$