DARK ENERGY OR MODIFIED GRAVITY?



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A SKY ON A STARRY NIGHT...



NOT SO ACIENT COSMOLOGY: PTOLEMAIC SYSTEM

Schema huius præmissæ diuifionis Sphærarum.



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WE LIVE IN A GOLDEN AGE OF ASTRONOMY!







Subaru Primary Mirror

Plans for TMT

Dark Energy or Modified Gravity?

M51 GALAXY: A COSMIC WHIRLPOOL



OUR COSMIC NEIGHBOURHOOD

A Flight to Virgo Cluster by R. Brent Tully (IfA/Hawaii)

- Solar System
- Orion Nebula
- Horsehead Nebula
- Rosette Nebula
- Crab Nebula
- Milky Way
- Magellanic Clouds
- Andromeda Galaxy
- Messier 33
- Messier 81/82
- Messier 101
- M51 (Whirlpool)
- Ursa Major Cluster
- Virgo Cluster

UNIVERSE IS BIG... AND IT IS GETTING BIGGER!



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929



Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

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WHY DOES IT EXPAND? GRAVITY IS TO BLAME!



EINSTEIN'S GENERAL RELATIVITY DESCRIBES HOW UNIVERSE EXPANDS

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \Longrightarrow$$

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 $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$

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UNIVERSE EXPANSION IS DRIVEN BY MATTER

EXPANSION OF THE UNIVERSE



MEASURE RATE OF EXPANSION VERY ACCURATELY...



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... AND KNOW WHAT THE UNIVERSE IS MADE OF?



DARK MATTER: IT'S THERE, WE JUST DON'T SEE IT



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DARK ENERGY: NO CLUE! JUST PROBLEMS...



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What if instead of curvature in Einstein-Hilbert action we had

$$S = \int \left\{ \frac{f(R)}{16\pi G} + \mathcal{L}_{\rm m} \right\} \sqrt{-g} \, d^4 x$$

UV MODIFICATION:

$$f(R) = R + \frac{R^2}{M^2}$$

Starobinsky (1980)

IR modification:

$$f(R) = R - \frac{\mu^4}{R}$$

Capozziello et. al. [astro-ph/0303041] Carroll et. al. [astro-ph/0306438]

For $F(\mathbf{R})$ theory to make sense we need:

- f' > 0 otherwise gravity is a ghost
- f'' > 0 otherwise gravity is a tachyon

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WMAP: A SATELLITE MISSION TO MEASURE CMB

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Ano	rol	Ero	αv	~	
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CMB: LOOKING AS FAR BACK AS WE CAN SEE

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UNIVERSE STARTS OUT VERY HOMOGENEOUS!



CMB is homogeneous at 10 part per million level!

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GRAVITY MAKES LARGE SCALE STRUCTURE GROW!

				\sim	
Ano	rol	Ero	αv	~	
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N-BODY SIMULATIONS WITH F(R) DARK ENERGY



PRESS-SCHECHTER FORMALISM



Linear density perturbation are a Gaussian Random Field, described by variance $\sigma^2 \equiv \langle \delta^2 \rangle$ and spectrum P(k)(above picture shows scale-invariant fluctuations, actual ones have diffrent spectrum)

Overdense regions with $\delta > \delta_c = \frac{3}{20} (12\pi)^{\frac{2}{3}} \simeq 1.69$ are fully collapsed! Density distribution is very clampy, smooth on scale Rto look for objects of mass $M = \frac{4\pi}{3} R^3 \bar{\rho}$

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WARM-UP: NEWTONIAN COLLAPSE OF A DUST BALL



$$\ddot{r} = -G \frac{M}{r^2}$$

$$E = \frac{\dot{r}^2}{2} - G \frac{M}{r} = \text{const, say} = 0$$

$$\dot{r} = -\left(\frac{r_g}{r}\right)^{\frac{1}{2}}, \quad r_g \equiv 2GM$$

$$\int r^{\frac{1}{2}} dr = -\int r_g^{\frac{1}{2}} dt$$

$$r = \left(\frac{3}{2}r_g^{\frac{1}{2}}(t_* - t)\right)^{\frac{2}{3}}$$

Outer shell of radius *r* collapses under the gravitational pull of mass *M* in the interior

We need to solve a non-linear differential equation:

$$\Box \phi = -\frac{8\pi}{3}G(\rho - 3p) + V'(\phi)$$

How do we understand its solutions?

"EQUILIBRIUM" REGIME:

$$V'(\phi) = \frac{8\pi}{3} G(\rho - 3p)$$

chameleon mechanism

which one is realized depends on environment!

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QUASI-STATIC BALL COLLAPSE IN F(R) GRAVITY



Potential well of a compact object:

$$\Delta \phi = -\frac{8\pi}{3}G\rho + \underbrace{V'(\phi)}_{\text{negligible}}$$

 $\Delta \Phi = 4\pi G \rho$

Excitations of f(R) degree of freedom ϕ and Newtonian potential Φ are related:

$$\phi \approx \phi_* - \frac{2}{3}\Phi$$

Effective Newton's constant changes (non-linearly)!

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BACK TO THE HISTORY OF THE UNIVERSE...



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How Do We See Past Opaque Plasma?



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BIG BANG NUCLEOSYNTHESIS



$$1 \quad n \longrightarrow {}^{1}H + e^{-} + \overline{v}$$

$$2 \quad {}^{1}H + n \longrightarrow {}^{2}H + \gamma$$

$$3 \quad {}^{2}H + {}^{1}H \longrightarrow {}^{3}He + \gamma$$

$$4 \quad {}^{2}H + {}^{2}H \longrightarrow {}^{3}He + n$$

$$5 \quad {}^{2}H + {}^{2}H \longrightarrow {}^{3}He + n$$

$$5 \quad {}^{2}H + {}^{2}H \longrightarrow {}^{4}He + n$$

$$7 \quad {}^{3}H + {}^{4}He \longrightarrow {}^{7}Li + \gamma$$

$$8 \quad {}^{3}He + n \longrightarrow {}^{3}H + {}^{1}H$$

$$9 \quad {}^{3}He + {}^{2}H \longrightarrow {}^{4}He + {}^{1}H$$

$$10 \quad {}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + \gamma$$

$$11 \quad {}^{7}Li + {}^{1}H \longrightarrow {}^{4}He + {}^{4}He$$

$$12 \quad {}^{7}Be + n \longrightarrow {}^{7}Li + {}^{1}H$$

P

BIG BANG NUCLEOSYNTHESIS



INFLATION: AN ANSWER TO COSMIC CONSPIRACY?



inflation wipes the slate clean and re-seeds the structure

... but inflation has to end eventually!



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CMB RIPPLES CARRY LOTS OF INFORMATION!

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STILL UNANSWERED: HOW DOES INFLATION END?

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STILL UNANSWERED: HOW DOES INFLATION END?

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INSTEAD OF A CONCLUSION

