Title: Cosmology

Speakers:

Collection: TRISEP 2023

Date: June 20, 2023 - 2:00 PM

URL: https://pirsa.org/23060065

Lecture 2
Approaches to understanding Dark Energy

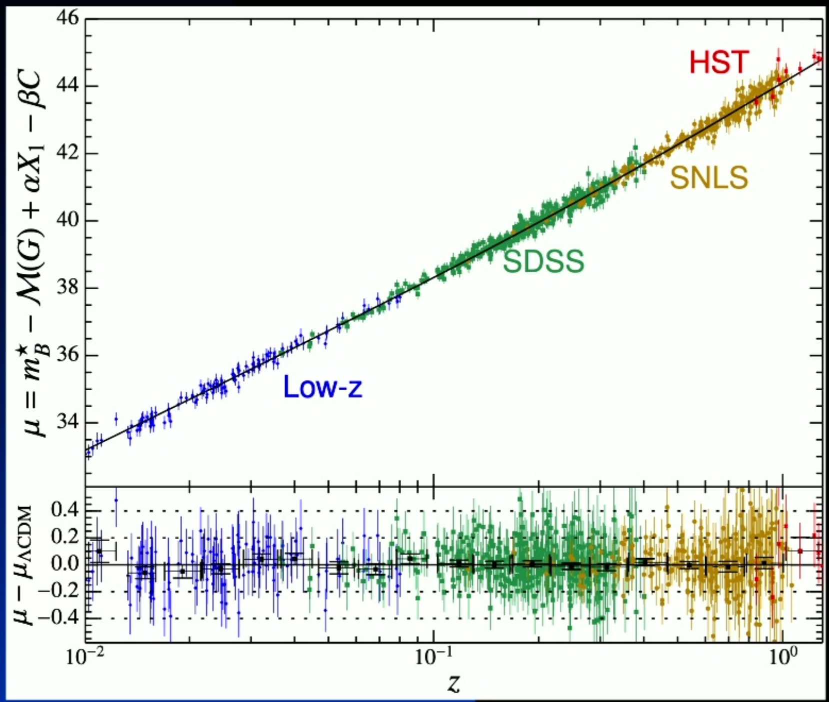
Ed Copeland -- Nottingham University

1. Brief recap of evolution of the universe: assumptions and evidence supporting them - pointing out issues where they may occur.
2. Approaches to Dark Energy and Modified Gravity.
3. Testing screening mechanisms in the laboratory.
4. Hubble tension and approaches to Early Dark Energy
5. Impact of GW discovery on late time cosmology.
6. Dark Energy and the String Swampland
7. Recent large z results if quasars can be standard candles

TRISEP 2023 — Perimeter Institute — June 20th 2023

The Big Bang – (1sec → today)

The cosmological principle -- isotropy and homogeneity on large scales



- **The expansion of the Universe $v=H_0d$**

H_0=73.04±1.04 km s^{-1} Mpc^{-1}

(Riess et al, 2022)

H_0=67.4±0.5 km s^{-1} Mpc^{-1}

(Planck 2018)

Is there a local v global tension ?

Betoule et al 2014

Redshift $1 + z = \frac{a_0}{a}$ $\quad H = \frac{\dot{a}}{a}$

2

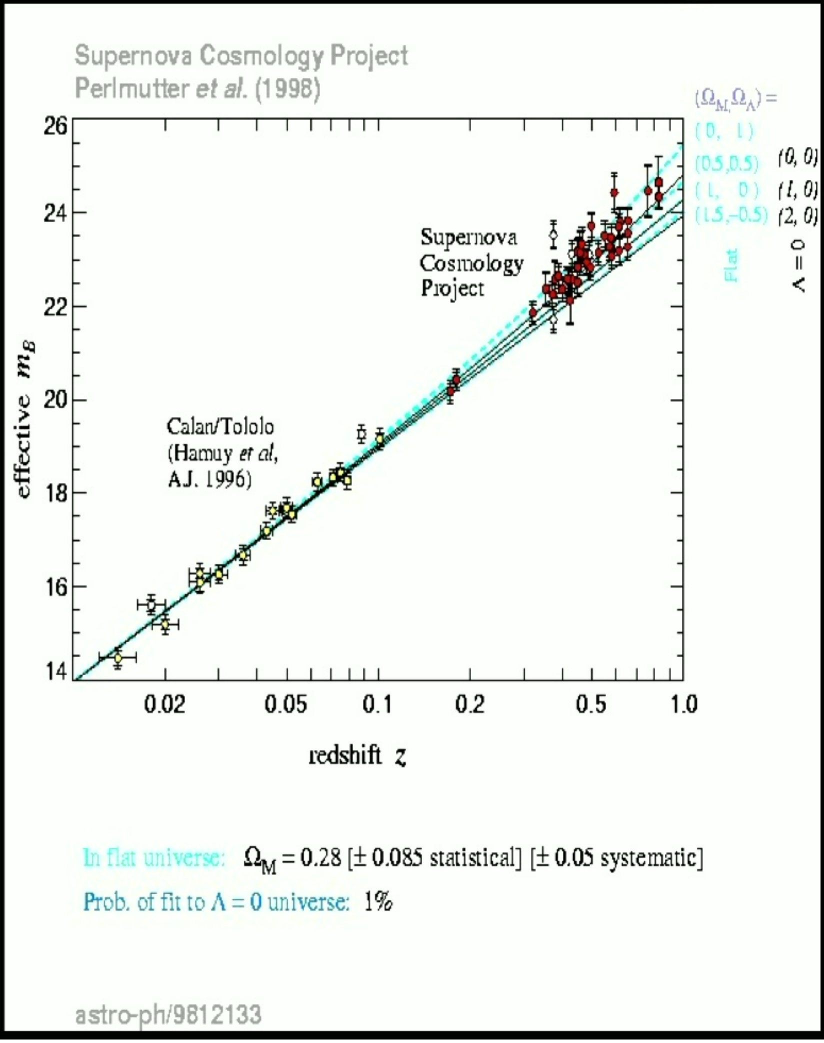
In fact the universe is accelerating !

Observations of distant supernova in galaxies indicate that the rate of expansion is increasing !

Huge issue in cosmology -- what is the fuel driving this acceleration?

We call it Dark Energy -- emphasises our ignorance!

Makes up 70% of the energy content of the Universe



$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$ applied to cosmology

Friedmann - the key bgd equation:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

a(t) depends on matter, $\rho(t)=\Sigma_i \rho_i$ -- sum of all matter contributions, rad, dust, scalar fields ...

Energy density $\rho(t)$: Pressure $p(t)$

Related through : $p = w\rho$

Eqn of state parameters: w=1/3 – Rad dom: w=0 – Mat dom: w=-1– Vac dom

Eqns (Λ=0):

Friedmann + Fluid energy conservation

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

$$\nabla^\mu T_{\mu\nu} = 0$$

4

A neat equation

$$\rho_c(t) \equiv \frac{3H^2}{8\pi G} \quad ; \quad \Omega(t) \equiv \frac{\rho}{\rho_c}$$

$$\Omega > 1 \leftrightarrow k = +1$$

$$\Omega = 1 \leftrightarrow k = 0$$

$$\Omega < 1 \leftrightarrow k = -1$$

Friedmann eqn

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

Ω_m - baryons, dark matter, neutrinos, electrons, radiation ...

Ω_Λ - dark energy ; Ω_k - spatial curvature

$$\rho_c(t_0) \equiv 1.88 h^2 * 10^{-29} \, gcm^{-3}$$

Critical density

5

Bounds on H(z) -- Planck 2018 - (+BAO+lensing+lowE)

$$\mathbf{H^2(z) = H_0^2\left(\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{de}\exp\left(3\int_0^z \frac{1+w(z')}{1+z'}dz'\right)\right)}$$

(Expansion rate) -- H_0=67.66 ± 0.42 km/s/Mpc

(radiation) -- $\Omega_r = (8.5 \pm 0.3) \times 10^{-5}$ - (WMAP)

(baryons) -- $\Omega_b h^2 = 0.02242 \pm 0.00014$

(dark matter) -- $\Omega_c h^2 = 0.11933 \pm 0.00091$ —-(matter) - $\Omega_m = 0.3111 \pm 0.0056$

(curvature) -- $\Omega_k = 0.0007 \pm 0.0019$

(dark energy) -- $\Omega_{de} = 0.6889 \pm 0.0056$ -- Implying univ accelerating today

(de eqn of state) -- $1+w = 0.028 \pm 0.032$ -- looks like a cosm const.

If allow variation of form : $w(z) = w_0 + w' z/(1+z)$ then
$w_0 = -0.961 \pm 0.077$ and $w' = -0.28 \pm 0.31$ (68% CL) — (WMAP)

Important because distance measurements often rely on assumptions made about the background cosmology.

6

Evidence for Dark Energy?

$$3.\ \Omega_0 = \Omega_m + \Omega_\Lambda$$

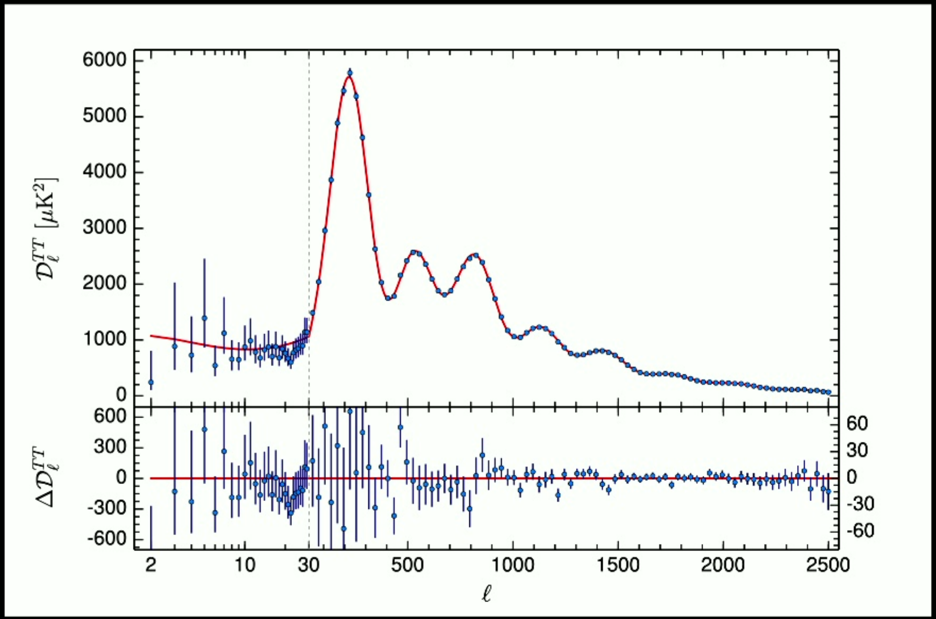
Enter CMBR:

Provides clue. 1st angular peak in power spectrum.

$$l_{peak} \approx \frac{220}{\sqrt{\Omega_0}}$$

$$\Omega_k = 0.0007 \pm 0.0019$$

Planck 2018

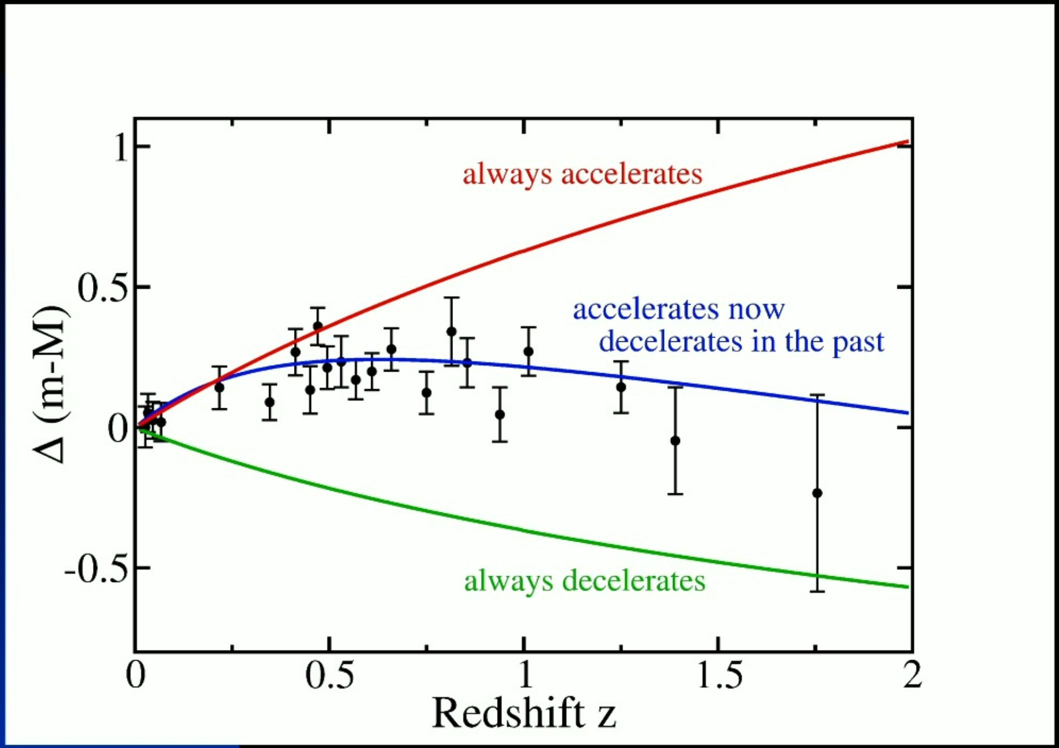


Planck TT spectrum (2015)

01/15/2009

7

The acceleration has not been forever -- pinning down the turnover will provide a very useful piece of information.



Huterer 2010

Help address cosmic coincidence problem ! A region hopefully EUCLID will be able to probe in a few weeks

8

Different approaches to Dark Energy include amongst many:

A true cosmological constant -- but why this value - CCP ?

Time dependent solutions arising out of evolving scalar fields -- Quintessence/K-essence.

Modifications of Einstein gravity leading to acceleration today.

Anthropic arguments.

Perhaps GR but Universe is inhomogeneous.

Hiding the cosmological constant -- its there all the time but just doesn't gravitate and something else is driving the acceleration.

Yet to be proposed ...

Brief reminder why the cosmological constant is regarded as a problem?

The CC gravitates in General Relativity:

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi G} - \rho_{\rm vac}\right)$$

$$G_{\mu\nu} = -8\pi G \rho_{\rm vac} g_{\mu\nu}$$

Now: $\rho_{\rm vac}^{\rm obs} \ll \rho_{\rm vac}^{\rm theory}$

Just as well because anything much bigger than we have and the universe would have looked a lot different to what it does look like. In fact structures would not have formed in it.

Estimate what the vacuum energy should be :

$$\rho_{\text{vac}}^{\text{theory}} \sim \rho_{\text{vac}}^{\text{bare}}$$

$$+$$

zero point energies of each particle

$$+$$

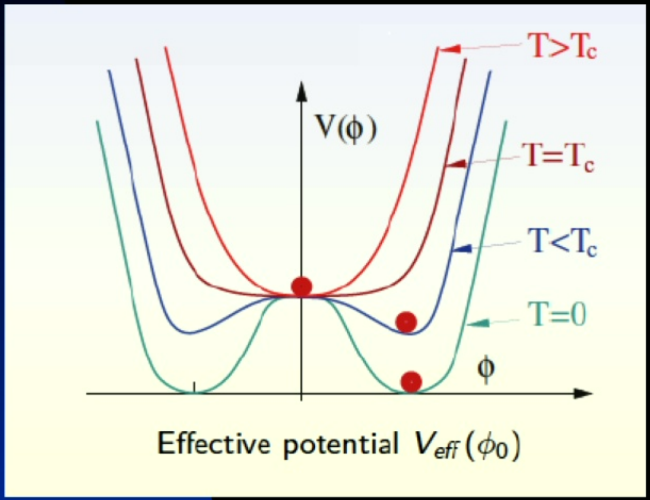
contributions from phase transitions in the early universe zero point energies of each particle

For many fields (i.e. leptons, quarks, gauge fields etc...):

$$< \rho > = \frac{1}{2} \sum_{\text{fields}} g_i \int_0^{\Lambda_i} \sqrt{k^2 + m^2} \frac{d^3k}{(2\pi)^3} \simeq \sum_{\text{fields}} \frac{g_i \Lambda_i^4}{16\pi^2}$$

where g_i are the dof of the field (+ for bosons, - for fermions).

contributions from phase transitions in the early universe



$$\Delta V_{\rm ewk} \sim (200\ \mathrm{GeV})^4$$

$$\Delta V_{\rm QCD} \sim (0.3\ \mathrm{GeV})^4$$

13

Quantum Gravity cut-off	$-(10^{18}\ \mathrm{GeV})^4$	fine tuning to 120 decimal places
SUSY cut-off	$-(\mathrm{TeV})^4$	fine tuning to 60 decimal places
EWK phase transition	$-(200\mathrm{GeV})^4$	fine tuning to 56 decimal places
QCD phase transition	$-(0.3\mathrm{GeV})^4$	fine tuning to 44 decimal places
Muon	$-(100\mathrm{MeV})^4$	
electron	$-(1\ \mathrm{MeV})^4$	fine tuning to 36 decimal places
	$-(\mathrm{meV})^4$	Observed value of the effective cosmological constant today !

14

String - theory -- where are the realistic models?

\`No go' theorem: forbids cosmic acceleration in cosmological solutions arising from compactification of pure SUGR models where internal space is time-independent, non-singular compact manifold without boundary --[Gibbons]

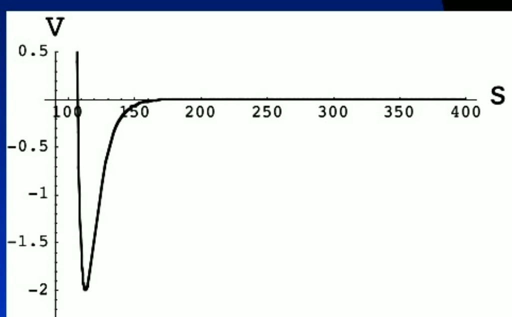
Avoid no-go theorem by relaxing conditions of the theorem.

1. Allow internal space to be time-dependent scalar fields (radion)

2. Brane world set up require uplifting terms to achieve de Sitter vacua hence accn

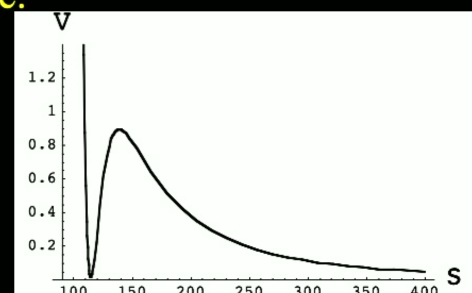
Example of stabilised scenario: Metastable de Sitter string vacua in TypeIIB string theory, based on stable highly warped IIB compactifications with NS and RR three-form fluxes. [Kachru, Kallosh, Linde and Trivedi 2003]

Metastable minima arises from adding positive energy of anti-D3 brane in warped Calabi-Yau space.



AdS minimum

$$V_{\mathrm{KKLT}} = V_{\mathrm{AdS}} + \frac{D}{\sigma^2}$$



Metastable dS minimum

15

The String Landscape approach

Type IIB String theory compactified from 10 dimensions to 4.

Internal dimensions stabilised by fluxes. Assumes natural AdS vacuum uplifted to de Sitter vacuum through additional fluxes !

Many many vacua ~ 10^{500} ! Typical separation ~ $10^{-500}\ \Lambda_{pl}$

Assume randomly distributed, tunnelling allowed between vacua --> separate universes .

Anthropic : Galaxies require vacua < $10^{-118}\ \Lambda_{pl}$ [Weinberg] Most likely to find values not equal to zero!

Landscape gives a realisation of the multiverse picture.

There isn't one true vacuum but many so that makes it almost impossible to find our vacuum in such a Universe which is really a multiverse.

So how can we hope to understand or predict why we have our particular particle content and couplings when there are so many choices in different parts of the universe, none of them special ?

SUSY large extra dimensions and Lambda - Burgess et al 2013, 2015

Soln to 6D Einstein-Maxwell-scalar with chiral gauged sugr.

In more than 4D, the 4D vac energy can curve the extra dimensions.

Proposal: Physics is 6D above 0.01eV scale with SUSY bulk. We live in 4D brane with 2 extra dim. 4D vac energy cancelled by Bulk contributions - quintessence like potential generated by Qu corrections leading to late time accn.

Sequestering Lambda - Kaloper and Padilla 2013-2016

IR soln to the problem - initial version adds a global term to Einstein action

Introduce global dynamical variables Λ, λ

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{pl}^2}{2}R - \Lambda - \lambda^4 \mathcal{L}(\lambda^{-2}g^{\mu\nu}, \Psi)\right] + \sigma\left(\frac{\Lambda}{\lambda^4\mu^4}\right)$$

λ sets the hierarchy between matter scales and M_{pl}

$$\frac{m_{phys}}{M_{pl}} = \frac{\lambda m}{M_{pl}}$$

Padilla 2015

17

Eq of motion:

$$M_{pl}^2 G^\mu{}_\nu = \tau^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu \langle \tau^\alpha{}_\alpha \rangle$$

$$T^\mu_\nu = -V_{vac}\delta^\mu_\nu + \tau^\mu_\nu$$

where: $\Lambda = \frac{1}{4}\langle T^\alpha{}_\alpha \rangle, \qquad \langle Q \rangle = \frac{\int d^4x Q\sqrt{g}}{\int d^4x \sqrt{g}}$ spacetime volume must be finite

Vacuum energy drops out at each and every loop order

Universe has finite spacetime volume

Ends in a crunch
w=-1 is transient
$\Omega_k>0$

collapse triggered by dominating dark energy

Linear potential $V=m^3\varphi$

form protected by shift symmetry,
size of m^3 technically natural

Local version of sequestering can accommodate infinite universe [Kaloper et al 2015]

18

Self tuning - with the Fab Four

with Charmousis, Padilla and Saffin

PRL 108 (2012) 051101; PRD 85 (2012) 104040

In GR the vacuum energy gravitates, and the theoretical estimate suggests that it gravitates too much.

Basic idea is to use self tuning to prevent the vacuum energy gravitating at all.

The cosmological constant is there all the time but is being dealt with by the evolving scalar field.

Most general scalar-tensor theory with second order field equations:

[G.W. Horndeski, Int. Jour. Theor. Phys. 10 (1974) 363-384]

The action which leads to required self tuning solutions :

$$
\begin{aligned}
\mathcal{L}_{john} &= \sqrt{-g}V_{john}(\phi)G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi \\
\mathcal{L}_{paul} &= \sqrt{-g}V_{paul}(\phi)P^{\mu\nu\alpha\beta}\nabla_\mu\phi\nabla_\alpha\phi\nabla_\nu\nabla_\beta\phi \\
\mathcal{L}_{george} &= \sqrt{-g}V_{george}(\phi)R \\
\mathcal{L}_{ringo} &= \sqrt{-g}V_{ringo}(\phi)\hat{G}
\end{aligned}
$$

In other words it can be seen to reside in terms of the four arbitrary potential functions of ϕ coupled to the curvature terms.

Covers most scalar field related modified gravity models studied to date.

19

fab four cosmology

TABLE I: Examples of interesting cosmological behaviour for various fixed points with $\sigma = 0$.

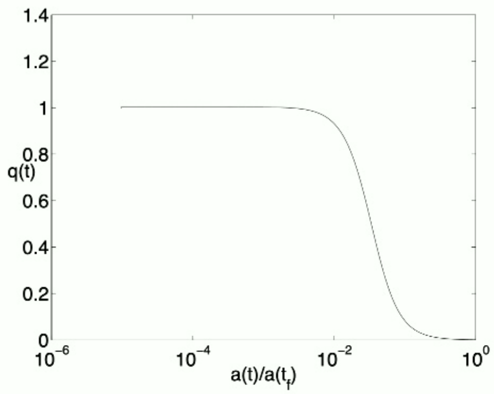
Case	cosmological behaviour	$V_j(\phi)$	$V_p(\phi)$	$V_g(\phi)$	$V_r(\phi)$
Stiff fluid	$H^2 \propto 1/a^6$	$c_1\phi^{\frac{4}{\alpha}-2}$	$c_2\phi^{\frac{6}{\alpha}-3}$	0	0
Radiation	$H^2 \propto 1/a^4$	$c_1\phi^{\frac{4}{\alpha}-2}$	0	$c_2\phi^{\frac{2}{\alpha}}$	$-\frac{\alpha^2}{8}c_1\phi^{\frac{4}{\alpha}}$
Curvature	$H^2 \propto 1/a^2$	0	0	0	$c_1\phi^{\frac{4}{\alpha}}$
Arbitrary	$H^2 \propto a^{2h}, \quad h \neq 0$	$c_1(1+h)\phi^{\frac{4}{\alpha}-2}$	0	0	$-\frac{\alpha^2}{16}h(3+h)c_1\phi^{\frac{4}{\alpha}}$

$$q = -\frac{a\ddot{a}}{\dot{a}^2}$$

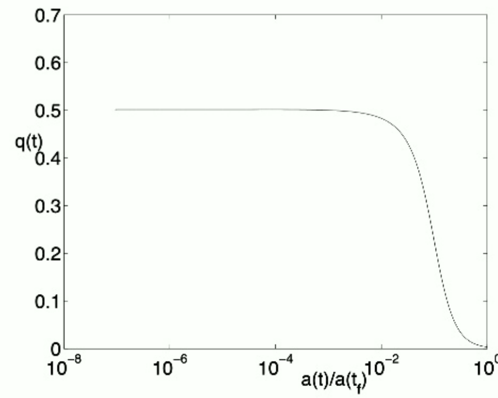
$$a \sim t^p \sim t^{-1/h}$$

$$q = -\frac{p(p-1)}{p^2} = -(1+h)$$

"radiation"



"matter"



See also:

Appleby et al JCAP 1210 (2012) 060; Amendola et al PRD 87 (2013) 2, 023501; Martin-Moruno et al PRD 91 (2015) 8, 084029; Babichev et al arXiv:1507.05942 [gr-qc] ; Emond et al JCAP 05 (2019) 038

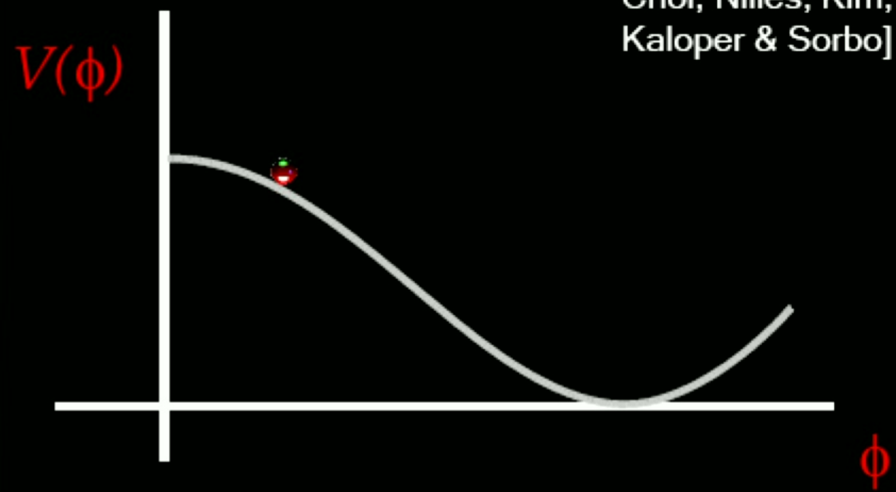
Particle physics inspired models of dark energy ?

Pseudo-Goldstone Bosons -- approx sym ϕ --> ϕ + const.

Leads to naturally small masses, naturally small couplings

[Hill, Freiman, et al;
Choi; Nilles; Kim;
Kaloper & Sorbo]

Barbieri et al



See Yoga model of Burgess et al 2021 for new approach at solving the CCP via relaxation mechanism and obtaining dynamical DE

$$V(\phi) = \lambda^4(1 + \cos(\phi/F_a))$$

Axions could be useful for strong CP problem, dark matter and dark energy — ex. Quintessential Axion.

21

Axions could be useful for strong CP problem, dark matter and dark energy.

Strong CP problem intro axion : $m_a = \frac{\Lambda^2_{\rm QCD}}{F_a}$; F_a $-$ decay constant

PQ axion ruled out but invisible axion still allowed:

$$10^9 \text{ GeV} \leq F_a \leq 10^{12} \text{ GeV}$$

Sun stability CDM constraint

String theory has lots of antisymmetric tensor fields in 10d, hence many light axion candidates.

Can have $F_a \sim 10^{17}$-10^{18} GeV

Quintessential axion -- dark energy candidate [Kim & Nilles].

Requires $F_a \sim 10^{18}$ GeV which can give:

$$E_{\rm vac} = (10^{-3} \text{ eV})^4 \rightarrow m_{\rm axion} \sim 10^{-33} \text{ eV}$$

Because axion is pseudoscalar -- mass is protected, hence avoids fifth force constraints

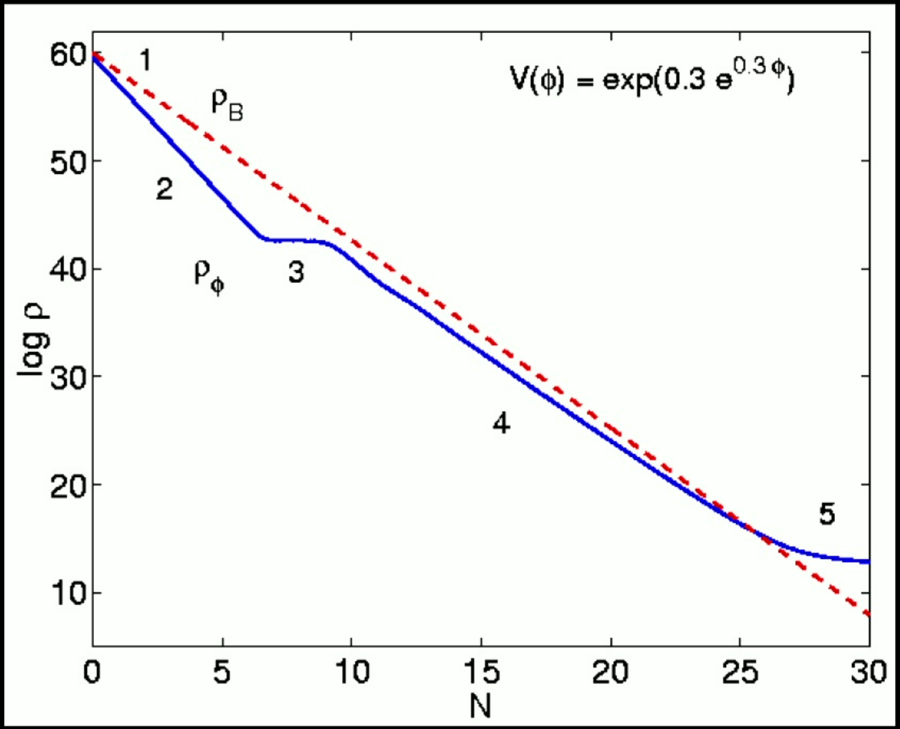
22

Dynamical Dark Energy

Wetterich 1987, Caldwell et al 1998

Slowly rolling scalar fields Quintessence

1. PE → KE
2. KE dom scalar field energy den.
3. Const field.
4. Attractor solution: almost const ratio KE/PE.
5. PE dom.



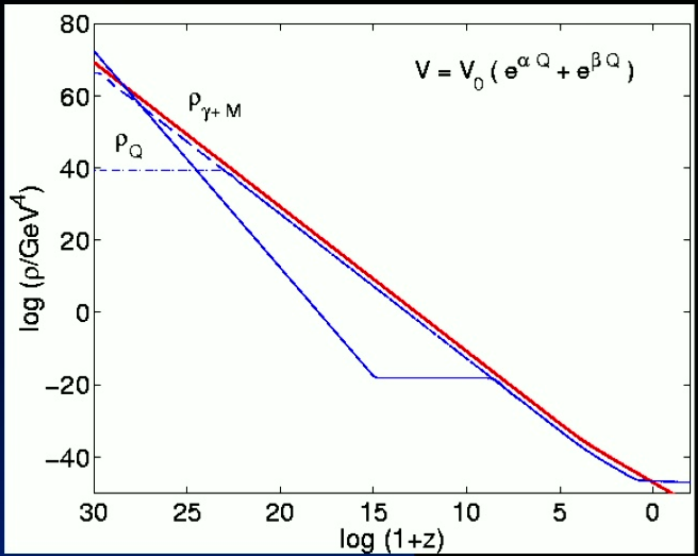
Nunes

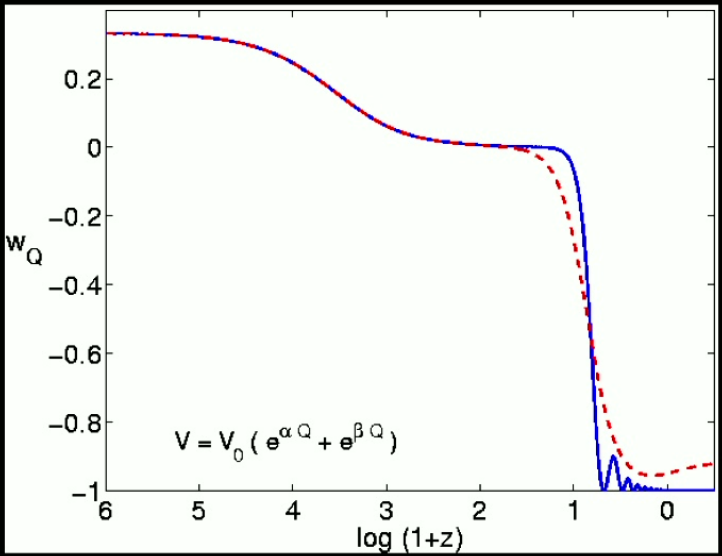
Attractors make initial conditions less important

23

$$V(\phi) = V_1 + V_2 = V_{01}e^{-\kappa\lambda_1\phi} + V_{02}e^{-\kappa\lambda_2\phi}$$

Barreiro, EJC and Nunes 2000





$\alpha = 20; \beta = 0.5$

Scaling for wide range of i.c.

Fine tuning: $V_0 \approx \rho_\phi \approx 10^{-47}\ \mathrm{GeV}^4 \approx (10^{-3}\ \mathrm{eV})^4$

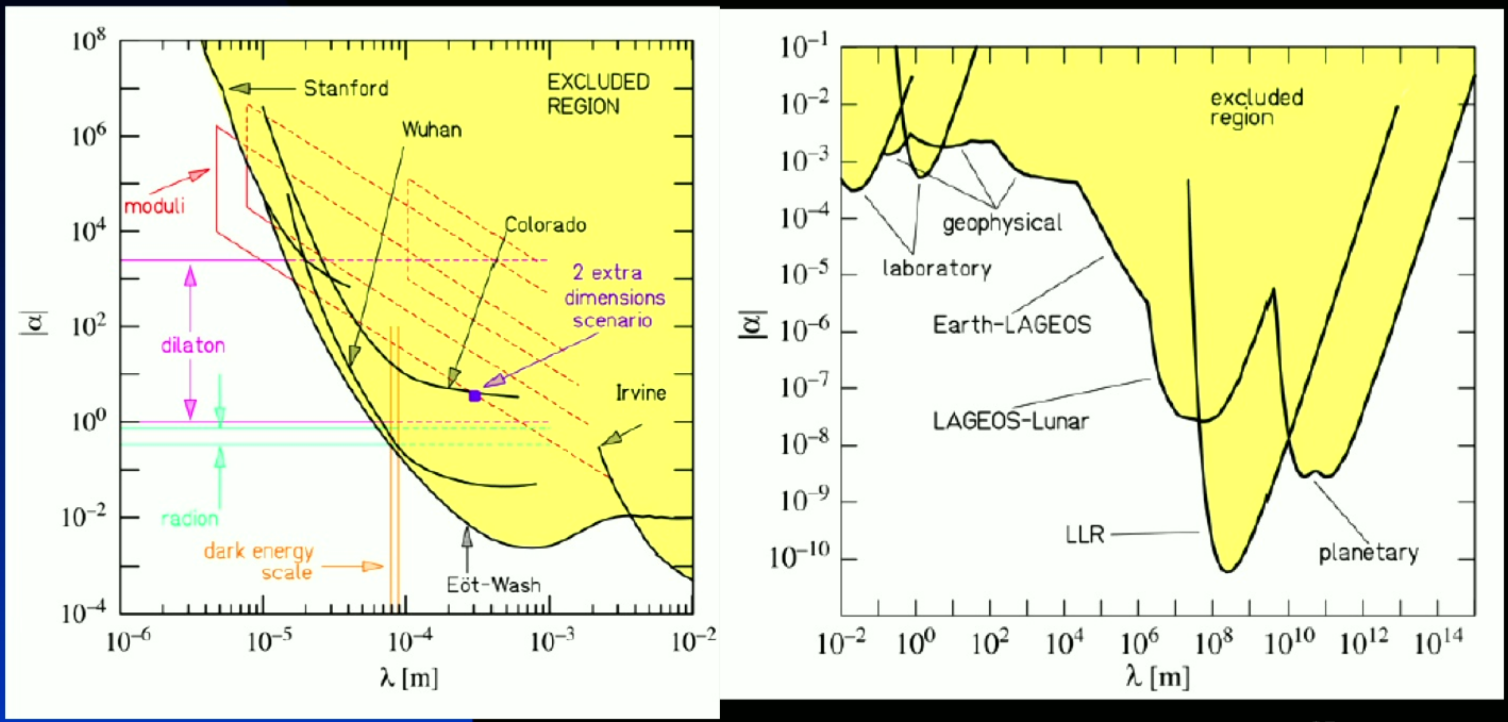
Mass: $m \approx \sqrt{\dfrac{V_0}{M_{pl}^2}} \approx 10^{-33}\ \mathrm{eV}$

Generic issue Fifth force - require screening mechanism!

24

Quintessence tends to lead to existence of Yukawa Fifth Force - very tightly constrained.

$$F(r) = G\frac{m_1 m_2}{r^2}\left[1+\alpha\left(1+\frac{r}{\lambda}\right)e^{-r/\lambda}\right]$$



25

Adelberger 2009.

Screening mechanisms - a route to hide the fifth forces

1. Chameleon fields [Khoury and Weltman (2003) ...]

Non-minimal coupling of scalar to matter in order to avoid fifth force type constraints on Quintessence models: the effective mass of the field depends on the local matter density, so it is massive in high density regions and light (m~H) in low density regions (cosmological scales).

2. K-essence [Armendariz-Picon et al ...]

Scalar fields with non-canonical kinetic terms. Includes models with derivative self-couplings which become important in vicinity of massive sources. The strong coupling boosts the kinetic terms so after canonical normalisation the coupling of fluctuations to matter is weakened -- screening via Vainshtein mechanism

Similar fine tuning to Quintessence -- vital in brane-world modifications of gravity, massive gravity, degravitation models, DBI model, Galileon's, ...

3. Symmetron fields [Hinterbichler and Khoury 2010 ...]

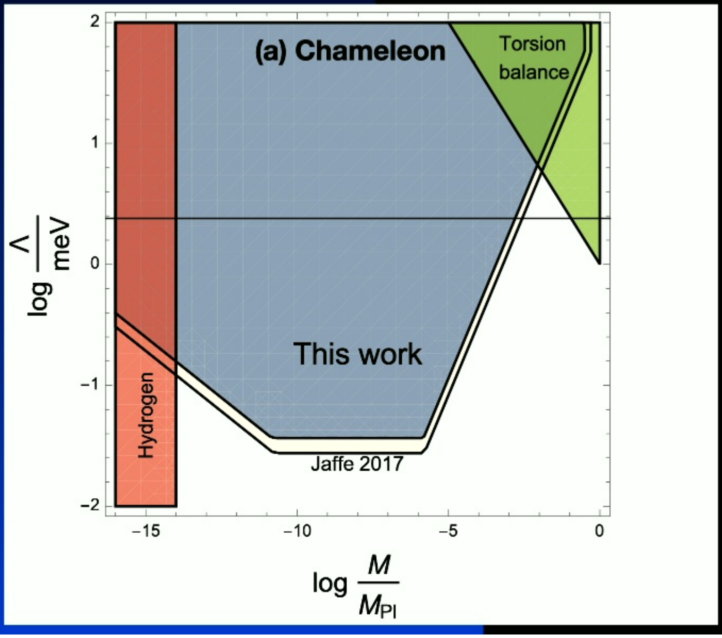
vev of scalar field depends on local mass density: vev large in low density regions and small in high density regions. Also coupling of scalar to matter is prop to vev, so couples with grav strength in low density regions but decoupled and screened in high density regions.

Dark Energy Direct Detection Experiment [Burrage, EC, Hinds 2015,Hamilton et al 2015]

We normally associate DE with cosmological scales but here we use the lab !

Atom Interferometry - testing Chameleons Idea: Individual atoms in a high vacuum chamber are too small to screen the chameleon field and so are very sensitive to it - can detect it with high sensitivity. Can use atom interferometry to measure the chameleon force - or more likely constrain the parameters !

$$\nabla^2\phi = -\frac{\Lambda^2}{\phi^2} + \frac{\rho}{M}$$



$$F_r = \frac{GM_A M_B}{r^2}\left[1 + 2\lambda_A\lambda_B\left(\frac{M_P}{M}\right)^2\right]$$

$$\lambda_i = 1 \text{ for } \rho_i R_i^2 < 3M\phi_{bg}$$

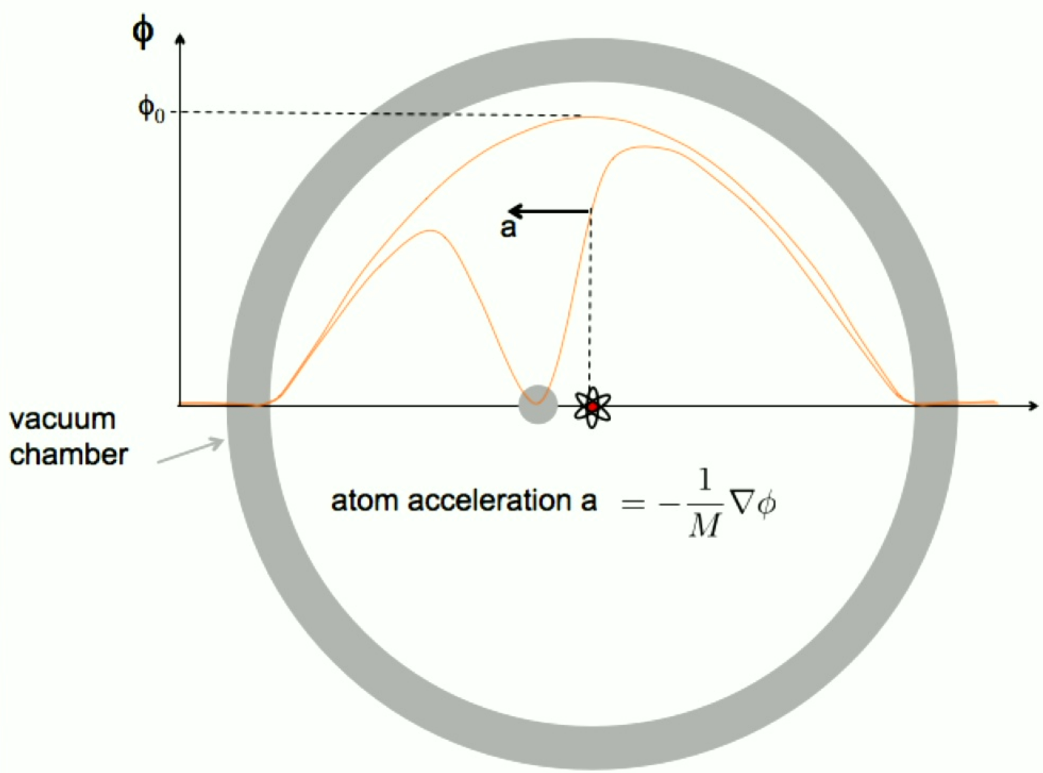
$$\lambda_i = \frac{3M\phi_{bg}}{\rho_i R_i^2} \text{ for } \rho_i R_i^2 > 3M\phi_{bg}$$

Sph source A and test object B near middle of chamber experience force between them - usually ƛ<<1 in cosmology but for atom ƛ=1 - reduced suppression

27

[Sabulsky et al 2019]

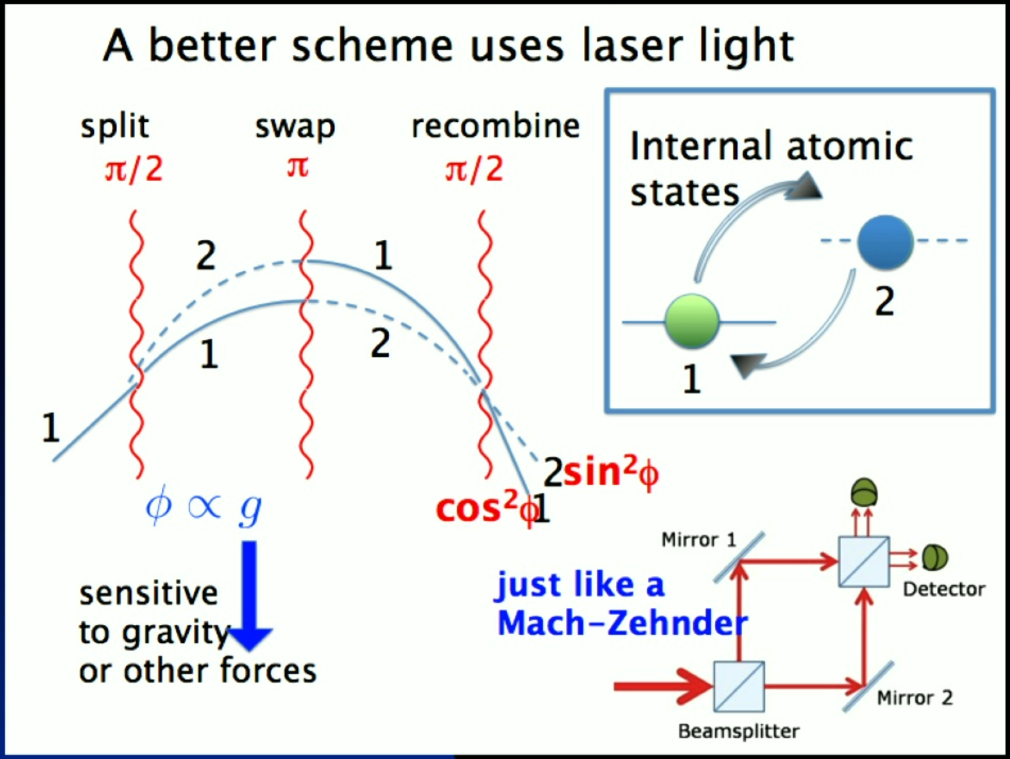
Measure ϕ in a high vacuum chamber



Ed Hinds

28

Use Atom Interferometry of atoms in free fall [Burrage, EC, Hinds 2015]



Ed Hinds

Raman interferometry uses a pair of counter-proagating laser beams, pulsed on three times, to split the atomic wave function, imprint a phase difference, and recombine the wave function.

The output signal of the interferometer is proportional to $\cos^2\varphi$, with

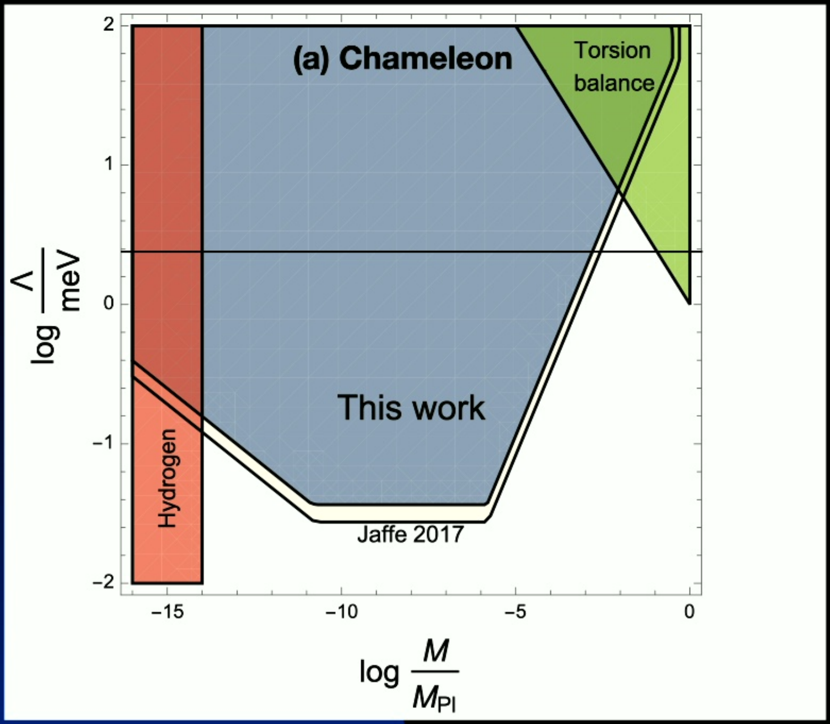
$$\varphi = (\underline{k}_1 - \underline{k}_2).\underline{a}T^2$$

$\underline{k}_{1,2}$ − −wavevectors of the 2 beams

T − −time interval between pulses

$\underline{a}$ − −acceleration of the atom

Sensitivity to acc'n of rubidium atoms due to sphere placed in Chamber radius 10cm, Pressure 10^{-10} Torr



[Sabulsky et al 2019]

$$V_{\text{eff}}(\phi) = V(\phi) + \left(\frac{\phi}{M}\right)\rho$$

$$V(\phi) = \frac{\Lambda^5}{\phi}$$

Systematics:

Stark effect, Zeeman effect, Phase shifts due to scattered light, movement of beams - negligible at 10^{-6} g and controllable for 10^{-9} g

Accn due to chameleon force outside an Al sphere of radius R_A = 19mm and screening factor $\lambda_A \ll 1$.

Λ-M area above solid black line excluded by atom interferometry expt measuring 10^{-6} g - easy !

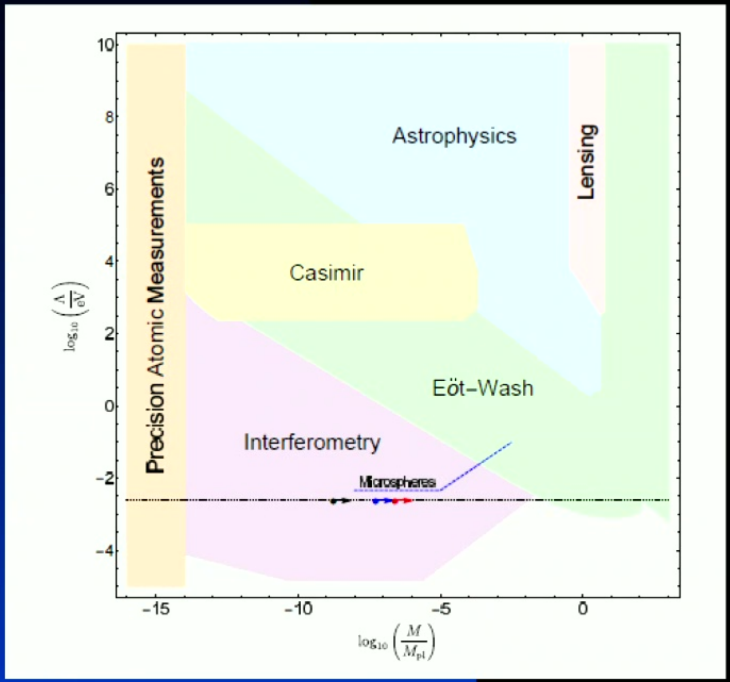
Our result indicates acceleration due to chameleon < 18 x10^{-9} g (90% CL) - can reach M_P !

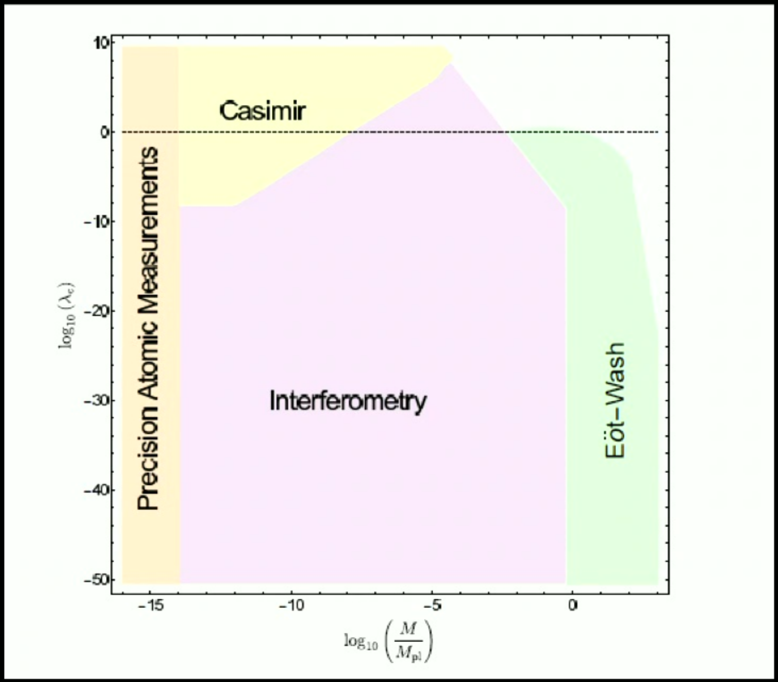
30

Combined chameleon constraints [Burrage & Sakstein 2017]

$$V_{\rm eff}(\phi) = V(\phi) + \left(\frac{\phi}{M}\right)\rho$$

$$V(\phi) = \frac{\Lambda^5}{\phi} \qquad V(\phi) = \frac{\Lambda}{4}\phi^4$$





31

Modifying Gravity rather than looking for Dark Energy - non trivial

Any theory deviating from GR must do so at late times yet remain consistent with Solar System tests. Potential examples include:

•f(R), f(G) gravity -- coupled to higher curv terms, changes the dynamical eqns for the spacetime metric. Need chameleon mechanism [Starobinski 1980, Carroll et al 2003, Joyce et al 2015…]

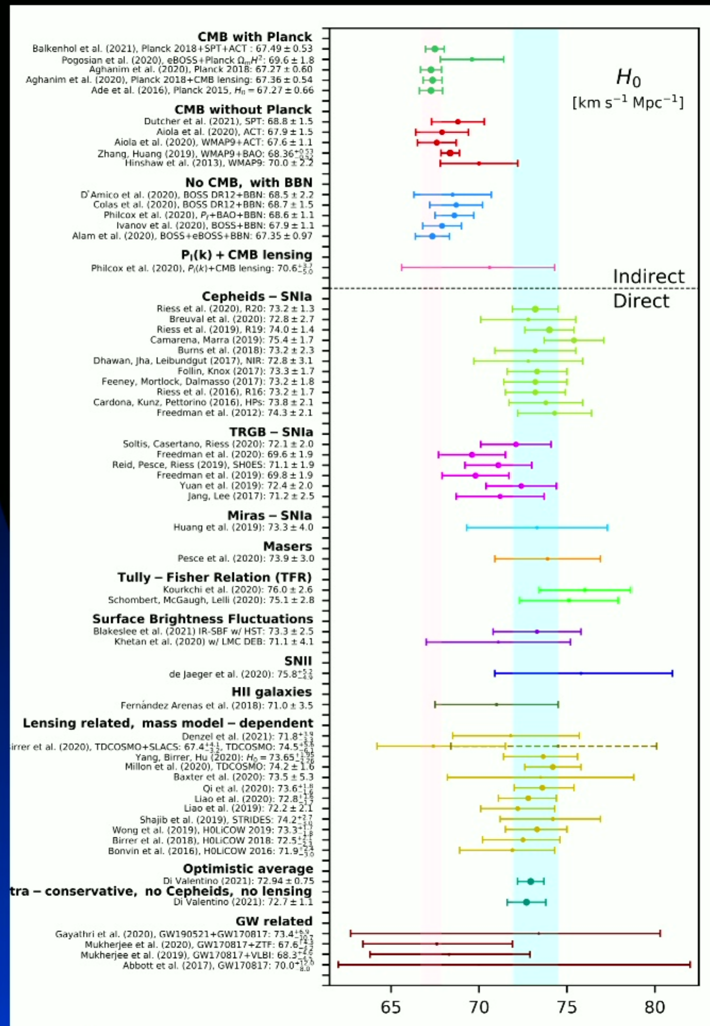
- Modified source gravity -- gravity depends on nonlinear function of the energy.
- Gravity based on the existence of extra dimensions -- DGP gravity

We live on a brane in an infinite extra dimension. Gravity is stronger in the bulk, and therefore wants to stick close to the brane -- looks locally four-dimensional.

Tightly constrained -- both from theory [ghosts] and observations

- Scalar-tensor theories including higher order scalar-tensor lagrangians -- examples include Galileon models
- Massive gravity theories dRGT [de Rham et al 2011…]

Return to Hubble tension - local v global - Early Dark Energy



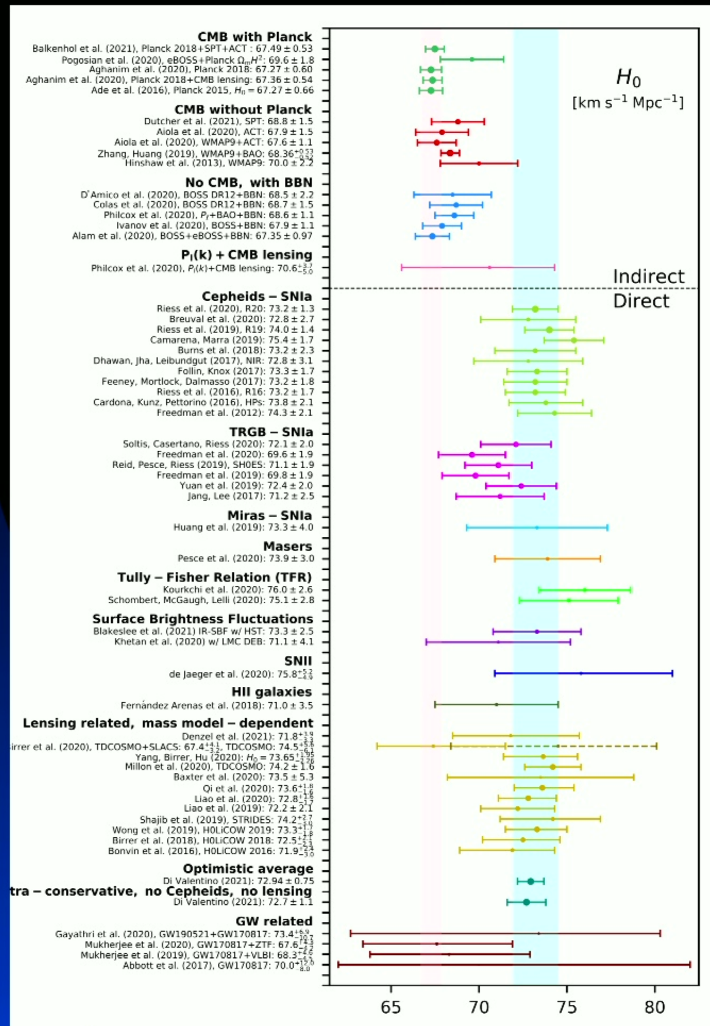
[Di Valentino et al 2019]

Lots of approaches being taken to determine H_0

33

H_0=67.4±0.5 km s^{-1} Mpc^{-1} (Planck) v H_0=73.2±1.3 km s^{-1} Mpc^{-1} (SHOES)

Return to Hubble tension - local v global - Early Dark Energy



[Di Valentino et al 2019]

Lots of approaches being taken to determine H_0

33

H_0=67.4±0.5 km s^{-1} Mpc^{-1} (Planck) v H_0=73.2±1.3 km s^{-1} Mpc^{-1} (SHOES)

Assuming the tension is a sign of new physics - many theoretical approaches.

Most of them make use of the standard ruler imprinted in the cmb maps - the Sound Horizon - the distance sound waves could propagate in a plasma from t=0 to t=1100.

Measure the angular size on the cmb, so have a distance and redshift to cmb.

One approach - use new physics early on to reduce the physical size of the sound horizon, hence decrease the distance we infer to the cmb (rem we measure the angular separation) - implying the H_0 we infer increases !

$$r_s^* = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(z) \quad \rightarrow D_A \sim \frac{r_s^*}{\theta_s^*} \quad \rightarrow H_0$$

Recall $D_A \sim 1/H_0$

So the idea, have new physics early on, alter the energy density, change H(z). Concentrate here on EDE but also possible to have late time modifications to resolve the tension [Zhao et al, Nature Ast 2017; Wang et al, Astro J. Lett 2018]

34

The particle cosmologists tool of choice — a (pseudo) scalar field - ϕ

ϕ initially frozen on its potential c/o Hubble friction - like DE with w=-1

As H~m, rolls down potential and oscillates.

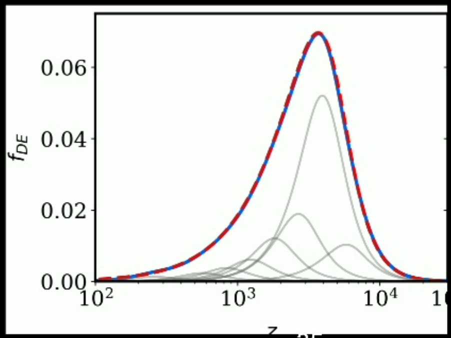
Need late time w>0, so EDE energy density decays faster than matter.

Three EDE examples:

axion EDE [Poulin et al, PRL 2019]

$$V(\phi) = m^2 f^2 (1 - \cos(\phi/f))^n, \quad m \sim 10^{-27} eV, \ f \sim 10^{26} eV, \ n = 3$$

Near minimum - eos - $w_\phi = \dfrac{n-1}{n+1} = \dfrac{1}{2} > 0$



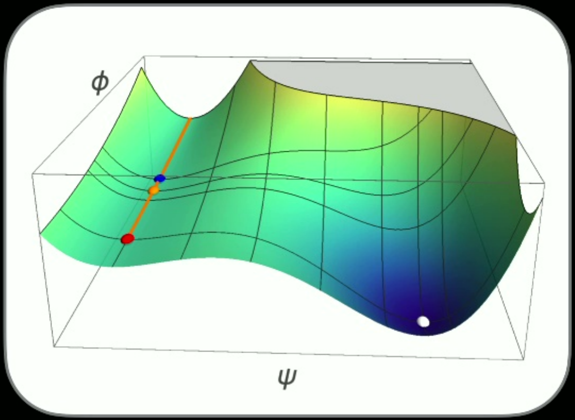
[Moss et al, 2021]

Note occurs around matter radiation equality

35

New EDE — driven by a first order phase transition [Niedermann and Sloth, PRD 2021]

$$V(\psi,\phi) = \frac{\lambda}{4}\psi^4 + \frac{1}{2}\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\tilde{\lambda}\phi^2\psi^2,$$ ψ is tunneling field, ϕ trigger field



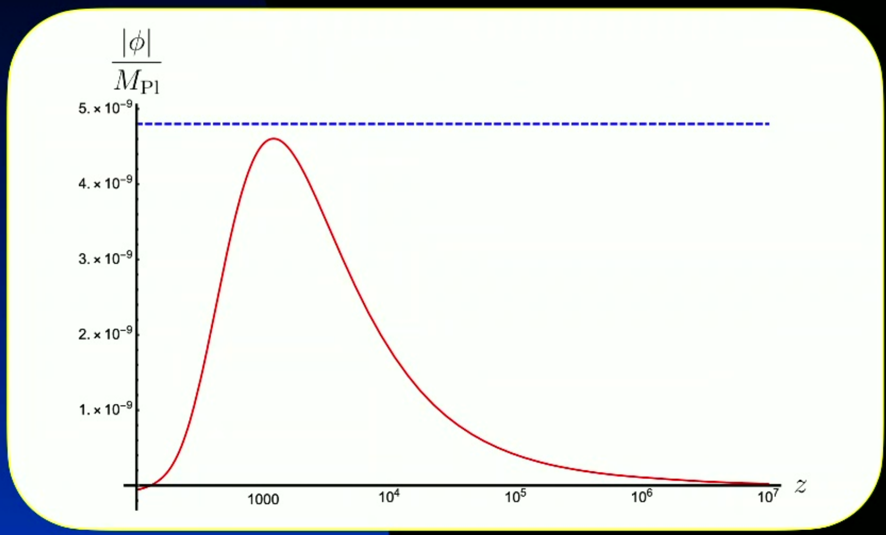
False vacuum decay of ψ from cosm const source to decaying field with const eos w>0 around eV scale.

$H_0 = 71.4 \pm 1.0 kms^{-1}Mpc^{-1}$, with decay at $z_* = 4920^{+620}_{-730}$ and with $f_{NEDE} = 0.126^{+0.03}_{-=.03}$

Massive neutrino driven EDE — [Sakstein and Trodden, PRL 2020, for earlier related work see Amendola et al 2008]

Idea: If EDE field ϕ is coupled to neutrinos with strength β, it receives a large injection of energy around the time that neutrinos become non-relativistic, which is when their temp ~ their mass, just before matter-rad equality.

Nice feature - neutrino decoupling provides trigger for EDE by displacing ϕ from min of it's potential $V(\phi) = \lambda\phi^4/4$.



$m_\nu = 0.5eV,\ \beta = 4 \times 10^{-4},\ \lambda = 10^{-75}$

For approaches resolving the Hubble tension using impact of screened fifth forces on the distance ladder see [Desmond et al, PRD 2019, Baker et al, Rev Mod Phys 2021]

More general approach to DE - spike model

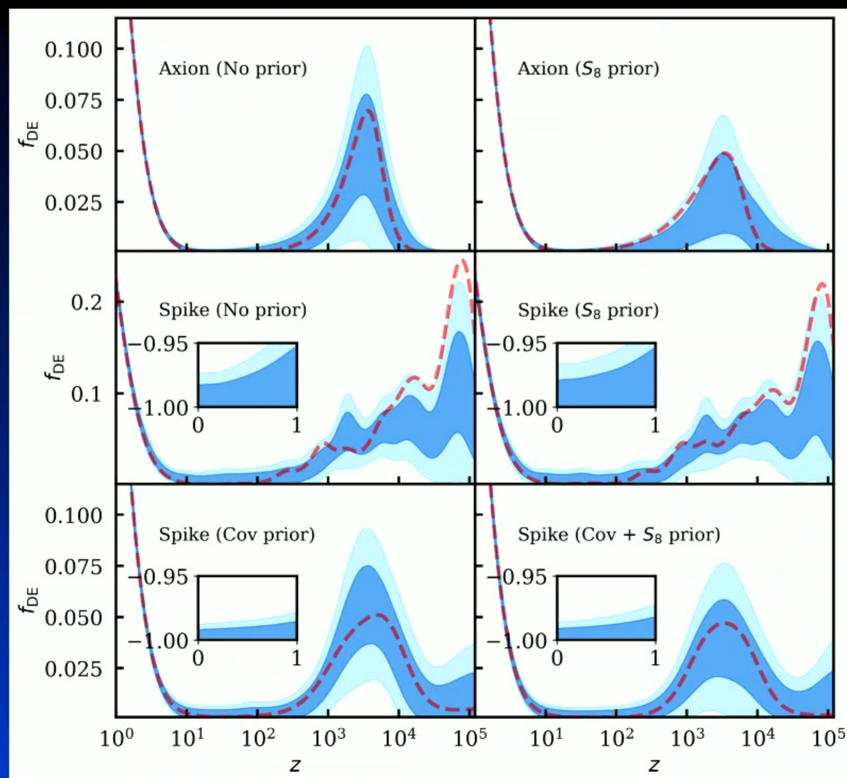
[Moss, EJC, Bamford and Clarke 2021 - for similar approach see also Lin et al 2019 and Hojjati et al 2013]

Model DE by perfect fluid with series of bins in energy density, with eos $-1 \leq w \leq 1$. Combine with cmb, BAO and local H_0 data obtain improvement over ΛCDM with DE contributing significantly between $z \sim 10^4 - 10^5$ and $c_s^2 \sim 1/3$.

$\Delta\chi^2 = -10.8$

$\Delta\chi^2 = -34.4$

$\Delta\chi^2 = -14.0$



inc DES S_8 prior

$S_8 = 0.776 \pm 0.017$

38

A few details

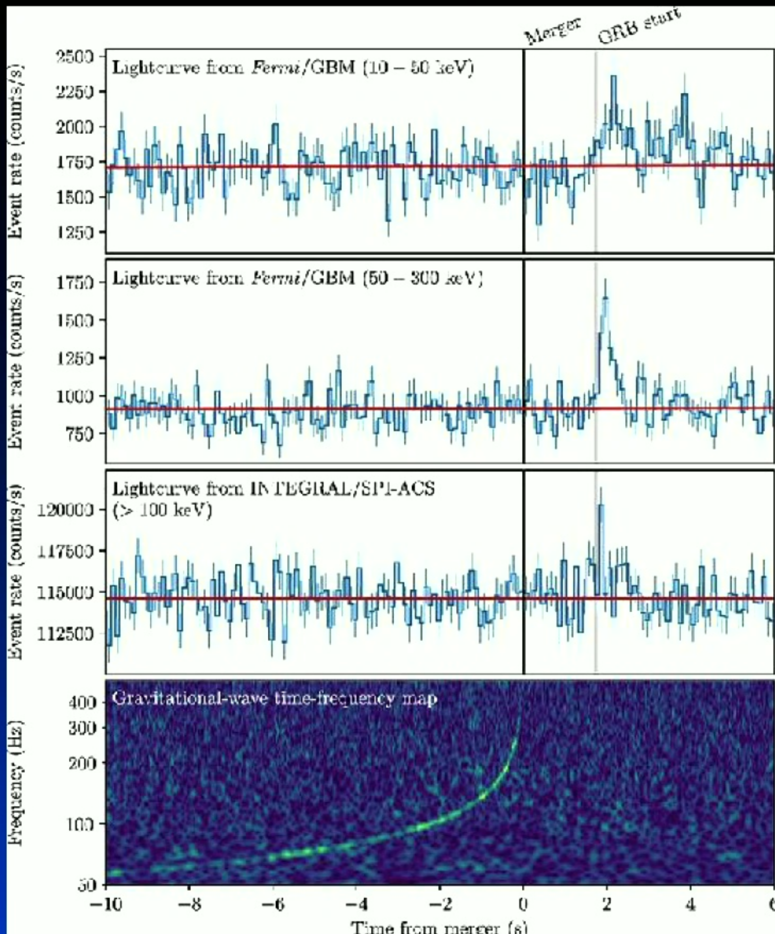
Parameter	ΛCDM	Axion Fluid	Spike	Spike (+ Covariance Prior)
H_0	68.48 ± 0.32 (68.44)	$70.03^{+0.81}_{-1.1}$ (70.95)	$72.25^{+0.93}_{-1.2}$ (73.59)	$70.9^{+1.0}_{-1.3}$ (71.29)
$\Omega_{\rm m}$	0.3001 ± 0.0041 (0.3006)	$0.2975^{+0.0044}_{-0.0049}$ (0.2950)	$0.3027^{+0.0062}_{-0.0055}$ (0.2978)	0.2948 ± 0.0054 (0.2952)
$n_{\rm s}$	0.9729 ± 0.0030 (0.9728)	$0.9810^{+0.0060}_{-0.0073}$ (0.9834)	0.9703 ± 0.0083 (0.9636)	$0.9805^{+0.0081}_{-0.0063}$ (0.9833)
$c_{\rm s}^2$	-	-	$0.334^{+0.021}_{-0.039}$ (0.3125)	$0.401^{+0.10}_{-0.090}$ (0.4153)
$w_{\rm n}$	-	$0.475^{+0.087}_{-0.18}$ (0.3523)	-	-
$z_{\rm c}$	-	10240^{+2000}_{-8000} (5460)	-	-
$f_{\rm EDE}(z_{\rm c})$	-	$0.0272^{+0.0097}_{-0.021}$ (0.03609)	-	-
S_8	0.8075 ± 0.0077 (0.8073)	0.814 ± 0.010 (0.8133)	0.8182 ± 0.0099 (0.8183)	$0.812^{+0.011}_{-0.0094}$ (0.8151)
$\chi^2_{\rm H0}$	15.5	4.7 (**-10.8**)	0.1 (**-15.4**)	3.7 (**-11.8**)
$\chi^2_{\rm Planck}$	1017.0	1020.0 (3.0)	1009.2 (**-7.8**)	1018.3 (1.3)
$\chi^2_{\rm ACT}$	240.7	235.3 (**-5.4**)	225.3 (**-15.4**)	234.4 (**-6.3**)
$\chi^2_{\rm S8}$	3.4	4.8 (1.4)	6.2 (2.8)	5.3 (1.9)
$\chi^2_{\rm data}$	2316.7	2305.9 (**-10.8**)	2281.4 (**-35.4**)	2302.8 (**-14.0**)
$\chi^2_{\rm prior}$	0.0	0.0	0.0	3.8
$\Delta \ln E$	-	-	-	5.0

The high z behaviour of EDE changes the radiation driving envelope that modifies the high *l* CMB power spectrum, potentially alleviating the tension between Planck and ACT data -see [Hill et al 2021]

Note - none of these models really address the S_8 tension - cmb v lss

Once the 33 spike parameters inc, find moderate Bayesian evidence for EDE [following the approach developed in [Crittendon et al, JCAP 2012; Zhao et al, PRL 2012]]

The impact of the simultaneous detection of GWs and GRBs on Modified Gravity models !



Credit: LIGO-VIRGO Collaboration.

GW 170817 and GRB 170817A

speed of GW waves

$$c_T^2 = 1 + \alpha_T$$

$$\Delta t \simeq 1.7s$$

$$\rightarrow |\alpha_T| \leq 10^{-15}$$

40

Implication for scalar-tensor theories - [Horndeski (1974), Deffayet et al 2011]

Lagrangian couples field and curvature terms: $\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_i$

$$\mathcal{L}_2 = K \qquad\qquad \mathcal{L}_3 = -G_3 \Box\phi$$

$$\mathcal{L}_4 = G_4 R + G_{4,X}[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi]$$

$$\mathcal{L}_5 = G_5 G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,X}[(\nabla\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi + 2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi]$$

where $G_i = G_i(\phi, X)$ and $X = -\nabla^\mu\phi\nabla_\mu\phi/2$

Linearise theory and map to alpha parameter :

$$M_*^2\alpha_T = 2X\left[2G_{4,X} - 2G_{5,\phi} - (\ddot{\phi} - H\dot{\phi})G_{5,X}\right]$$

$$M_*^2 = 2(G_4 - 2XG_{4,X} + XG_{5,\phi} - H\dot{\phi}XG_{5,X})$$

Recall:

$$|\alpha_T| \leq 10^{-15}$$

Many authors assumed the following saying they held barring fine-tuned cancellation:

$$G_{4,X} = G_{5,\phi} = G_{5,X} = 0$$

This of course satisfies the bound meaning any model that satisfies those conditions (such as GR, f(R), Quintessence) is perfectly viable.

Creminelli & Vernizzi (2017), Baker et al (2017), Sakstein & Jain (2017), Ezquiaga & Zumalacárregui (2017)

Crucially though it does not imply that models that do not satisfy the assumptions are ruled out !

42

Copeland et al, PRL (2019)

Ex: Fab Four - self tuning solutions with a large Cosmological Constant:

$$G_X^{(2)} = V^{(J)} - 2V_\phi^{(P)} X + 4V_{\phi\phi}^{(R)} \left(1 - \ln|8\pi G X|\right)$$
$$G_\phi^{(3)} = \frac{1}{2} V_\phi^{(P)} X + \frac{2}{3} V_{\phi\phi}^{(R)} \ln|8\pi G X|$$
$$G_X^{(3)} = \frac{1}{2} V^{(P)} + \frac{2}{3} V_\phi^{(R)} \frac{1}{X}$$

Four arbitrary potentials-
John, Paul, Ringo, George

$$|\alpha_T| \leq 10^{-15}$$

$$\left[\frac{3}{2} V^{(P)} X + 2V_\phi^{(R)}\right] \left(\ddot{\phi} - H\dot{\phi}\right) = -V^{(J)} X - V_\phi^{(P)} X^2 - 4V_{\phi\phi}^{(R)} X$$

Cosmological Solutions : [EJC,Padilla, Saffin and Skordis 2018]

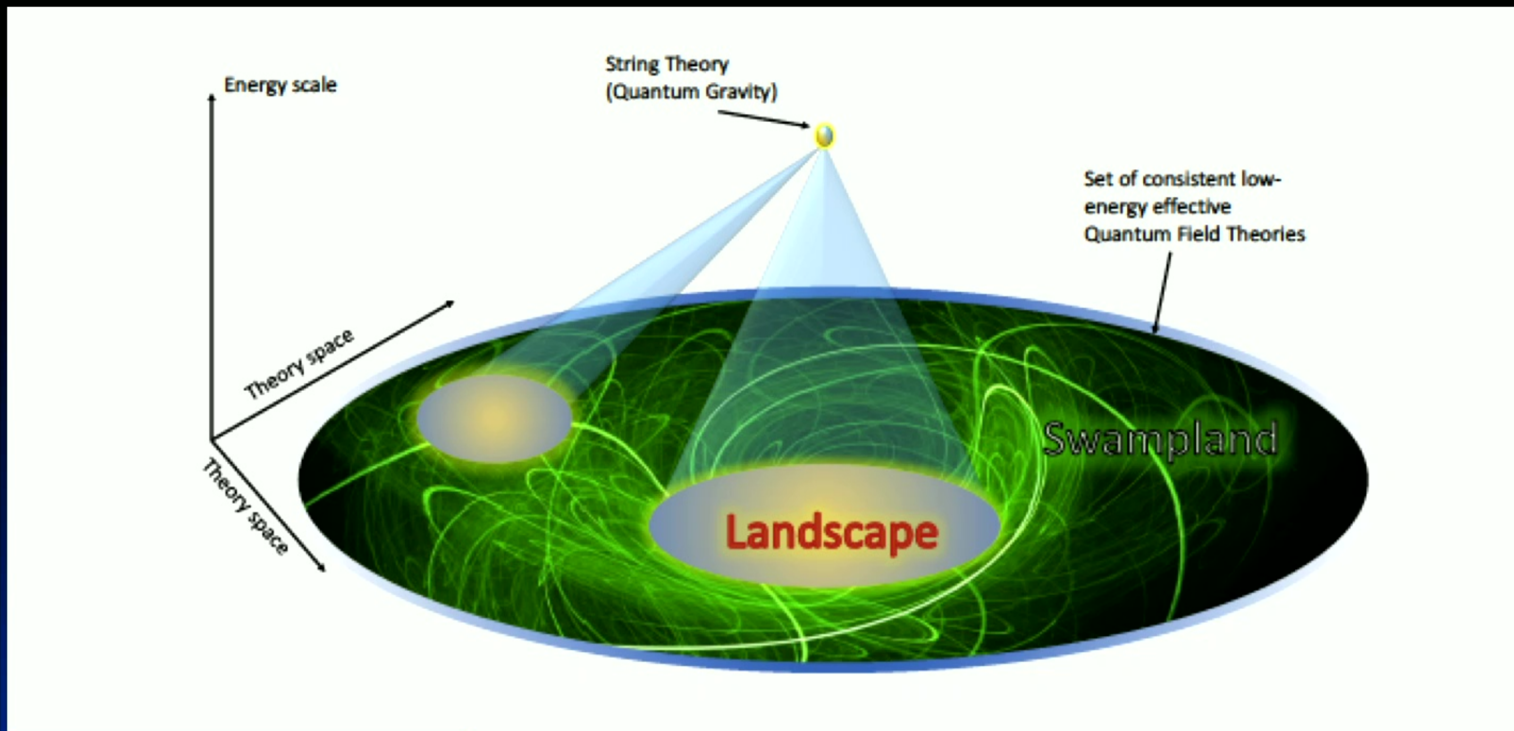
Case	behaviour	$V^{(J)}$	$V^{(P)}$	$V^{(G)}$	$V^{(R)}$
Stiff	$H^2 = H_0^2/a^6$	$c_1\phi^{4/\alpha-2}$	$c_2\phi^{6/\alpha-3}$	0	0
Radiation	$H^2 = H_0^2/a^4$	$c_1\phi^{4/\alpha-2}$	0	$c_2\phi^{2/\alpha}$	$-\frac{\alpha^2}{8}c_1\phi^{4/\alpha}$
Curvature	$H^2 = H_0^2/a^2$	0	0	0	$c_1\phi^{4/\alpha}$
Arbitrary $w \neq -1$	$H^2 = H_0^2 a^{-3(1+w)}$	$-\frac{1}{2}c_1(1+3w)\phi^{4/\alpha-2}$	0	0	$\frac{9\alpha^2(1-w^2)}{64}c_1\phi^{4/\alpha}$
Matter-I	$H^2 = H_0^2 a^{-3}$	$c_1\phi^{n+4}$	$c_2\phi^{n+6}$	0	$\frac{2n-3}{16(2n+7)(n+6)}c_1\phi^{n+6}$
Matter-II	$H^2 = H_0^2 a^{-3}$	$c_1\phi^{n+4}$	0	$c_2\phi^{n+3}$	$-\frac{(n+3)(2n+5)}{8(2n+7)(n+6)}c_1\phi^{n+6}$
Matter-III	$H^2 = H_0^2 a^{-3}$	$-\frac{1}{2}c_1\phi^4$	0	0	$\frac{1}{16}c_1\phi^6$
Matter-IV	$H^2 = H_0^2 a^{-3}$	$-45\sqrt{2}\phi^5$	$-\frac{75067}{225}\frac{1}{M^2}\phi^7$	$-M^2\phi^4$	$\frac{143}{168}\sqrt{2}\phi^7$

Table 1: Table of solutions from Copeland-Padilla-Saffin

All of these solutions except Stiff fluid satisfy the GW bound and in doing so determine either the coefficient alpha or n in the potentials.

43

Dark Energy and the String Swampland [Agrawal et. al. 2018]



[Credit: E. Palti 2018]

String Swampland [Vafa 2005]

The class of theories that appear perfectly acceptable as low energy QFT but can not be in the Landscape of string theories at high energies.

Symmetrons & rotation curves - screening in galaxies [Burrage, EC & Millington 2017]

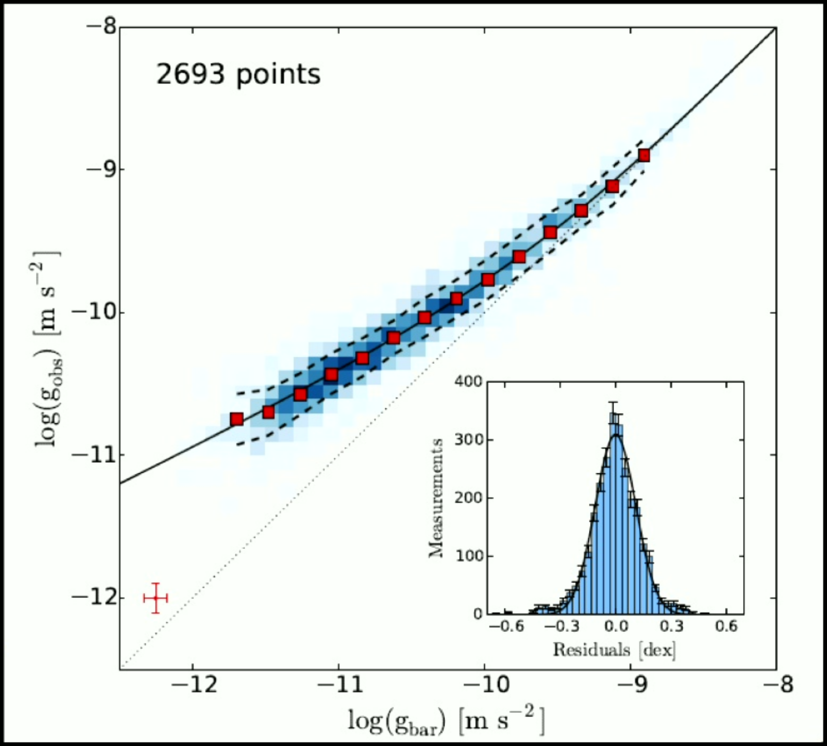
Radial acceleration relation from 153 galaxies (also known as mass discrepancy acceleration relation) [McGaugh et al PRL 2016]

$$g_{\mathrm{obs(bar)}}(r) = \frac{V^2_{\mathrm{obs(bar)}}(r)}{r} = \frac{GM_{\mathrm{obs(bar)}}(r)}{r^2}$$

Empirical fit:

$$g_{\mathrm{obs}} = \frac{g_{\mathrm{bar}}}{1 - e^{-\sqrt{g_{\mathrm{bar}}/g_\dagger}}}$$

where $g_\dagger = 1.20 \pm 0.02(\mathrm{rand}) \pm 0.24(\mathrm{sys}) \times 10^{-10}\ \mathrm{ms}^{-2}$.



Explanations include: MOND [Milgrom 2016], MOG [Moffat 2016], Emergent Gravity [Verlinde 2016], Dissipative DM [Keller & Waldsley 2016], Superfluid DM [Hodson et al 2016], some weird thing called ΛCDM [Ludlow et al PRL 2017] + us + others …

59