Particle Astrophysics and Cosmology !

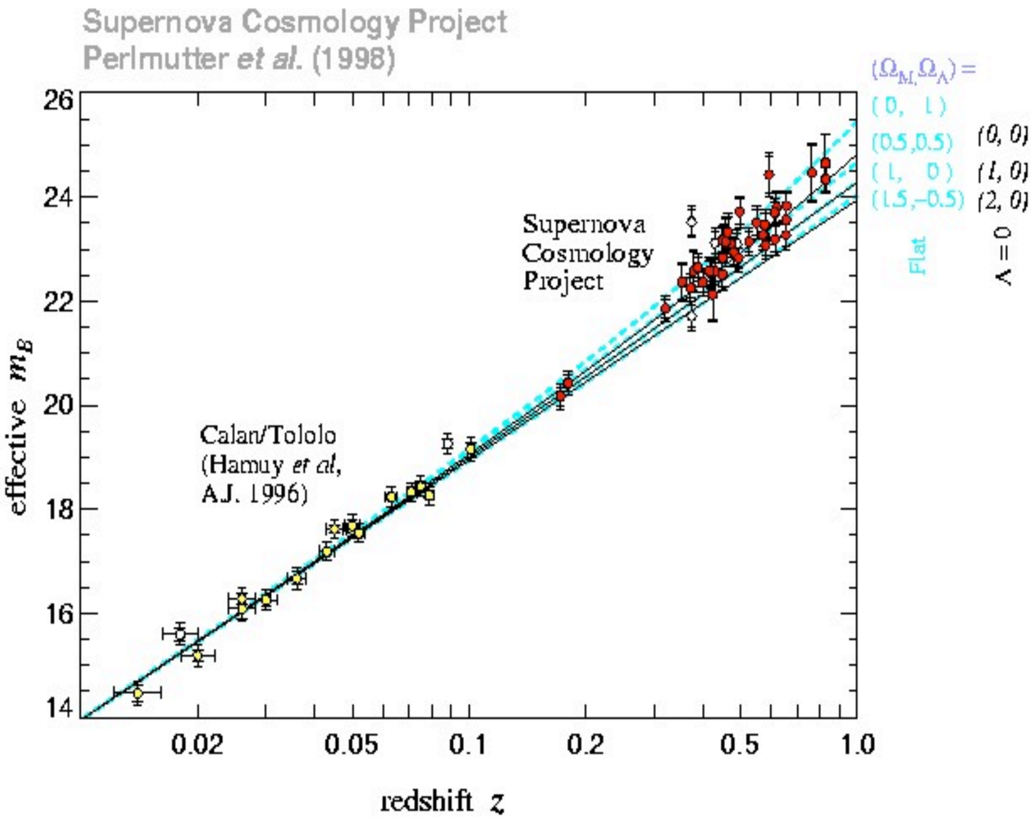
Ed Copeland -- Nottingham University

1. The general picture, assumptions and evidence supporting them.
2. Dark Energy - Dark Matter - Modified Gravity
3. Origin of Inflation and the primordial density fluctuations.
4. Searching for string theory in cosmology.

Durham -- Annual Theory Meeting -- Dec 17th 2010

1. The Big Bang – (1sec → today)

The cosmological principle -- isotropy and homogeneity on large scales



In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%

astro-ph/9812133

Test 1

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

$H_0=74.2\pm3.6$ km s^{-1} Mpc^{-1}

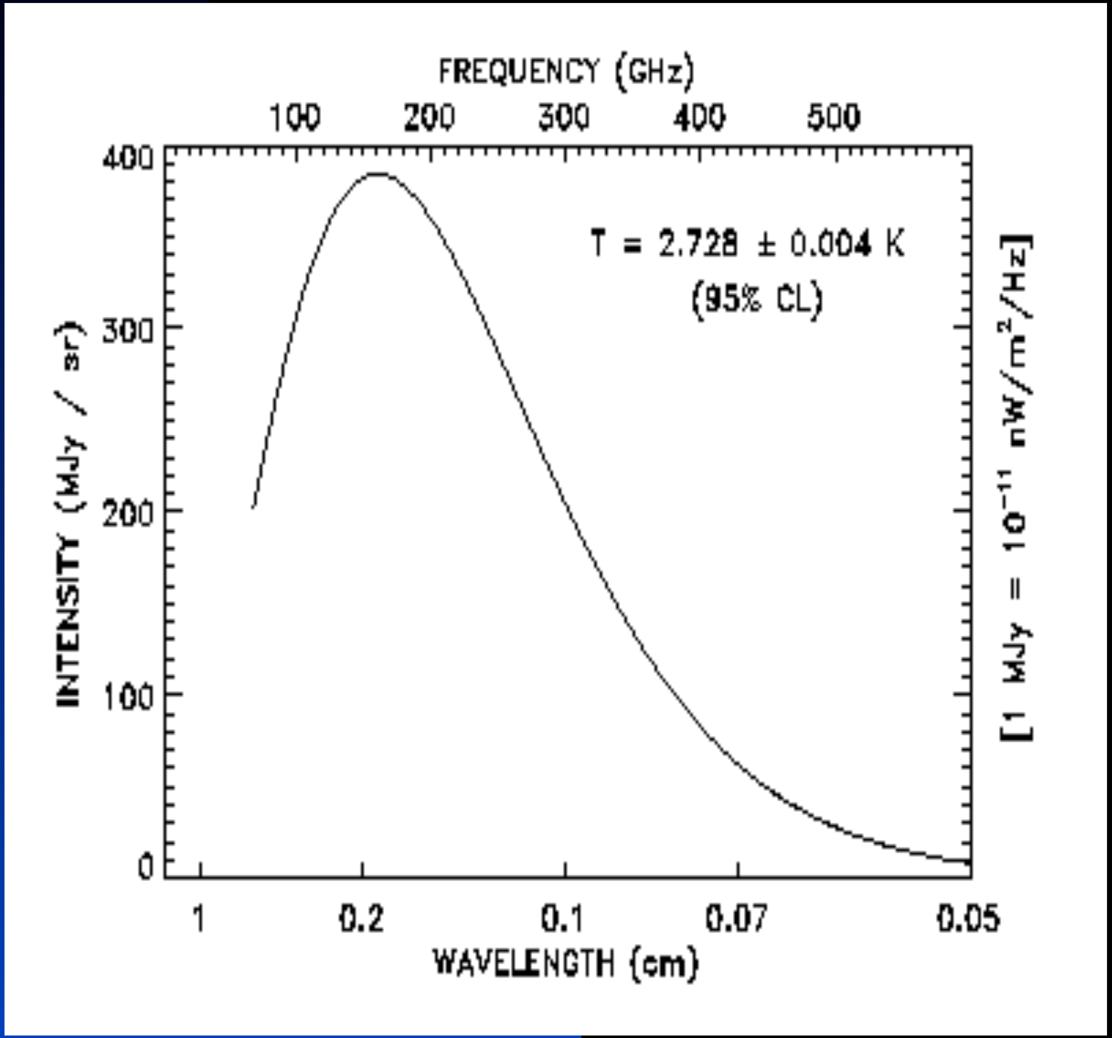
(Riess et al, 2009)

Distant galaxies receding with vel proportional to distance away.

Relative distance at different times measured by scale factor a(t) with

$$H = \frac{\dot{a}}{a}$$

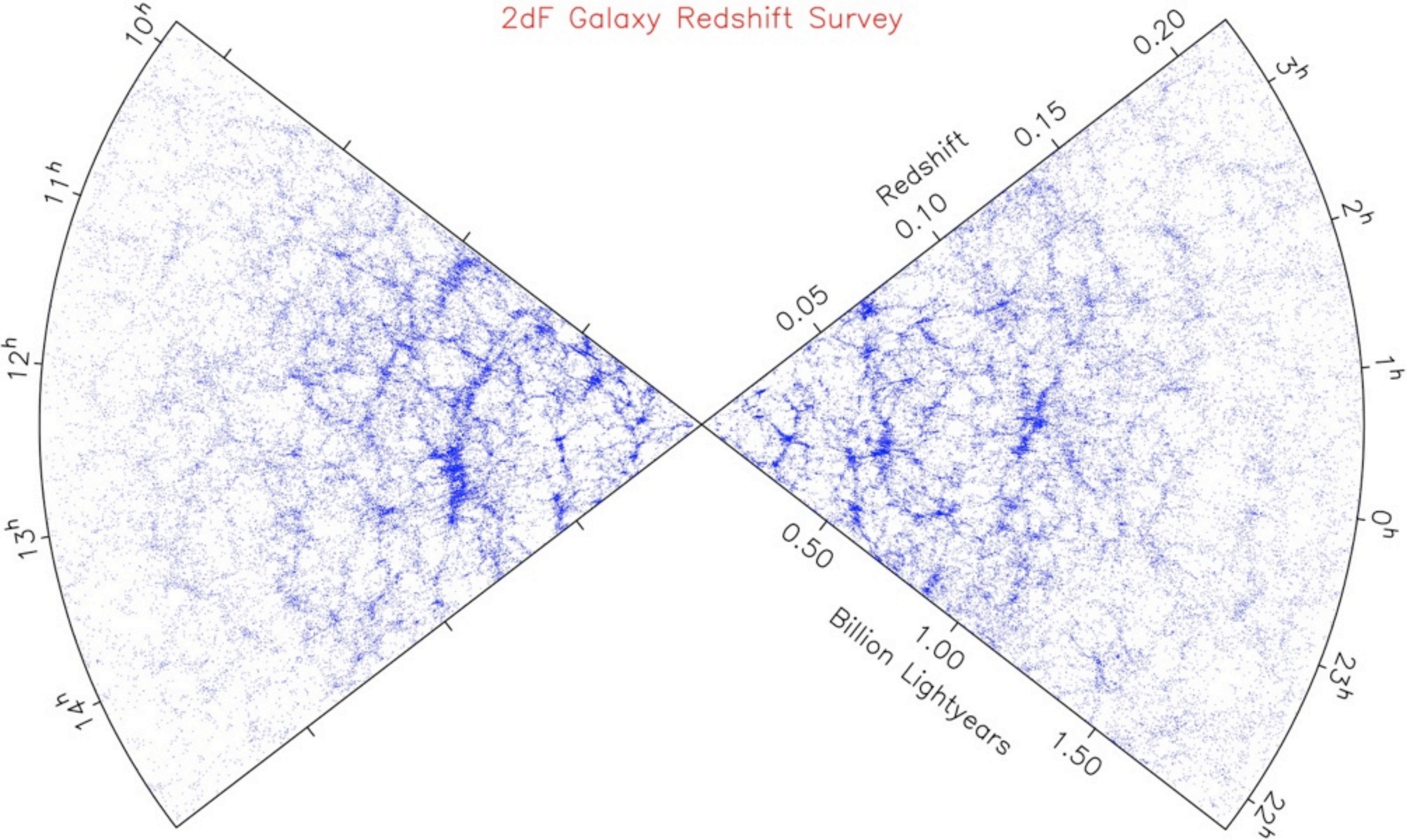
The Big Bang – (1sec → today)



Test 2

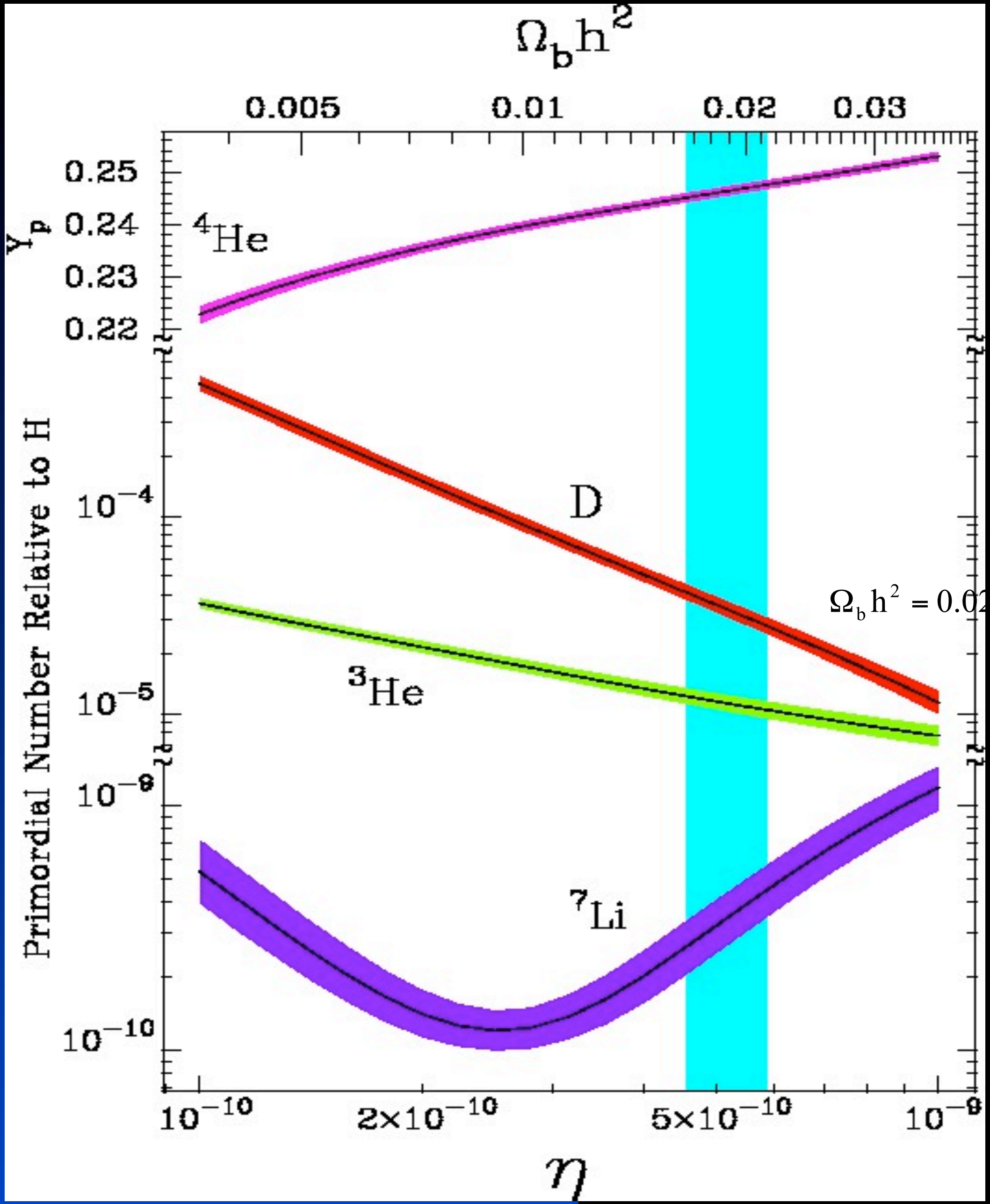
- **The existence and spectrum of the CMBR**
- **T_0=2.728 ± 0.004 K**
- Evidence of isotropy -- detected by COBE to such incredible precision in 1992
- Nobel prize for John Mather 2006

2dF Galaxy Redshift Survey



Homogeneous on large scales?

The Big Bang – (1sec → today)



Test 3

- **The abundance of light elements in the Universe.**
- **Most of the visible matter just hydrogen and helium.**

WMAP7 - detected effect of primordial He on temperature power spectrum, giving new test of primordial nucleosynthesis.

$$Y_P = 0.326 \pm 0.075$$

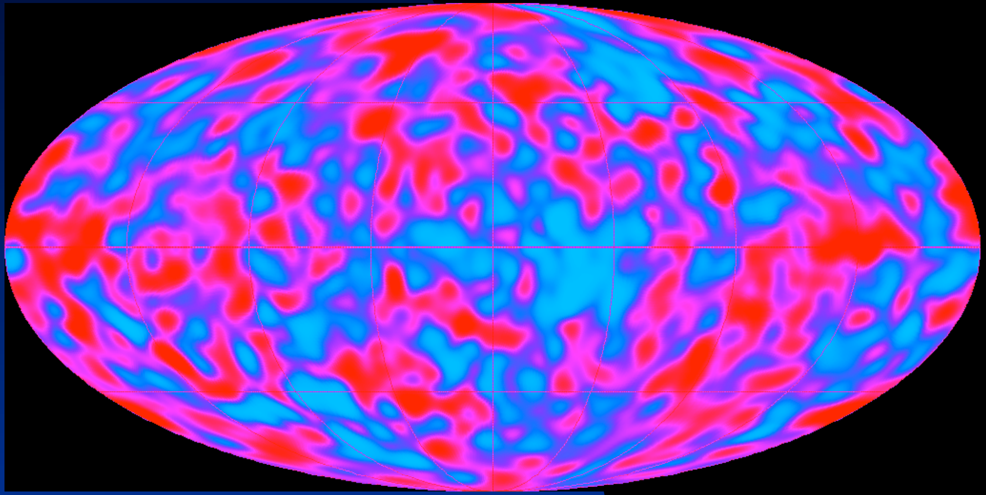
(Komatsu et al, 2010)

$$\Omega_b h^2 = 0.0225 \pm 0.0005 \ (68\% \ CL)$$

The Big Bang – (1sec → today)

Test 4

- Given the irregularities seen in the CMBR, the development of structure can be explained through gravitational collapse.

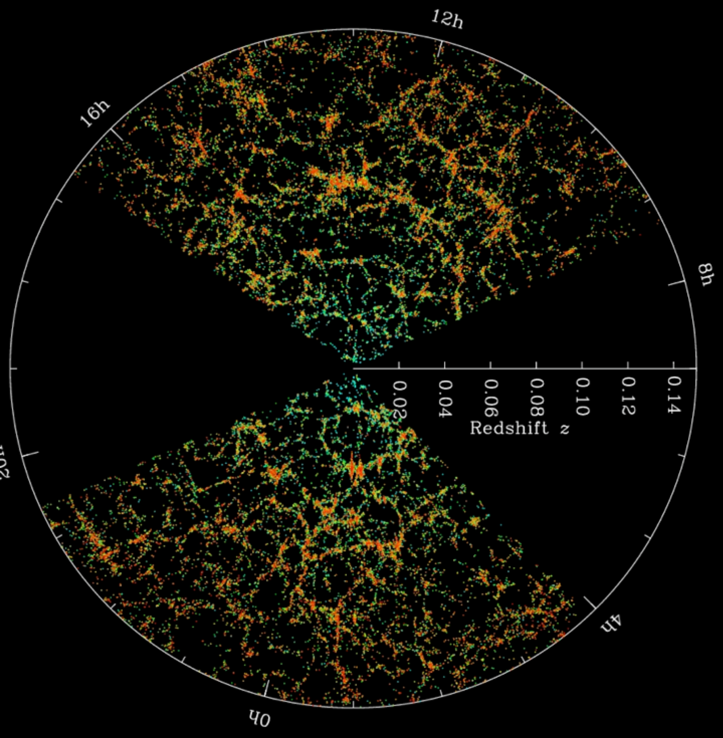


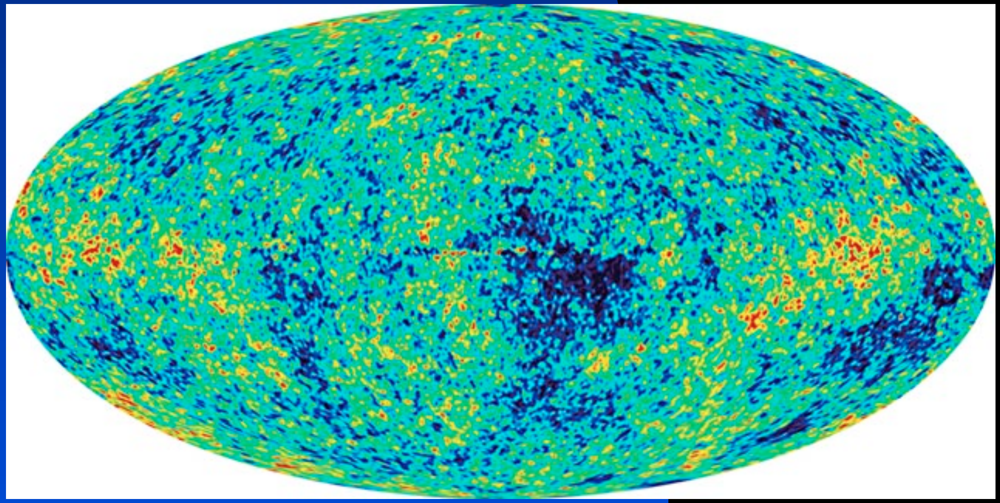
COBE - 1992, 2006

Nobel prize for

George Smoot

SDSS





WMAP-2010

Some basic equations

Friedmann:

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

a(t) depends on matter.

$$\text{Energy density } \rho(t): \quad \text{Pressure } p(t)$$

$$\text{Related through}: p = w\rho$$

w=1/3 – Rad dom: w=0 – Mat dom: w=-1– Vac dom

Eqns (Λ=0):

Friedmann +
Fluid
conservation

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

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

Combine

$$\frac{\ddot{a}}{a} = -\frac{8\pi}{3}G\left(\rho + 3p\right) --- Accn$$

$$If\ \ \rho + 3p < 0 \Rightarrow \ddot{a} > 0$$

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

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

$$\rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3(1+w)} \qquad ; a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+w)}}$$

$$\mathrm{RD} \quad : \quad w = \frac{1}{3} : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-4} \quad ;\ a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{1}{2}}$$

$$\mathrm{MD} \quad : \quad w = 0 : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3} \quad ;\ a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3}}$$

$$\mathrm{VD} \quad : \quad w = -1 : \rho(t) = \rho_0 \ \ ;\ a(t) \propto e^{Ht}$$

A neat equation

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

Friedmann eqn

$$\Omega_{\mathrm{m}} + \Omega_{\Lambda} + \Omega_{\mathrm{k}} = 1$$

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

Ω_Λ - dark energy ; Ω_k - spatial curvature

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

Current bounds on H(z) -- Komatsu et al 2010 - (WMAP7+BAO+SN)

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

(Expansion rate) -- H_0=70.4 ± 1.3 km/s/Mpc

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

(baryons) -- $\Omega_b = 0.0456 \pm 0.0016$

(dark matter) -- $\Omega_m = 0.227 \pm 0.014$

(curvature) -- $\Omega_k < 0.008$ (95%CL)

(dark energy) -- $\Omega_{de} = 0.728 \pm 0.015$

(de eqn of state) -- $1+w = 0.001 \pm 0.057$ -- looks like a cosm const.

If allow variation of form : $w(z) = w_0 + w' z/(1+z)$ then
$w_0 = -0.93 \pm 0.12$ and $w' = -0.38 \pm 0.65$ (68% CL)

Weighing the Universe

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

$1. \Omega_m$

a. Cluster baryon abundance using X-ray measurements of intracluster gas, or SZ measurements.

b. Weak grav lensing and large scale peculiar velocities.

c. Large scale structure distribution.

d. Numerical simulations of cluster formation.

$$\Omega_m h^2 = 0.1369 \pm 0.0037$$

$$\Omega_m << 1$$

(Komatsu et al, 2008) (WMAP5)

H_0=70.4±1.3 km s^{-1} Mpc^{-1}

2. Ω_b

$$\xrightarrow{\text{BBN}} \Omega_b h^2 = 0.0225 \pm 0.0005 \; (68\% \; CL)$$

$$\downarrow$$

Majority of baryonic matter dark.

$$\boxed{\Omega_b << \Omega_m} \rightarrow$$

Require Dark matter !!

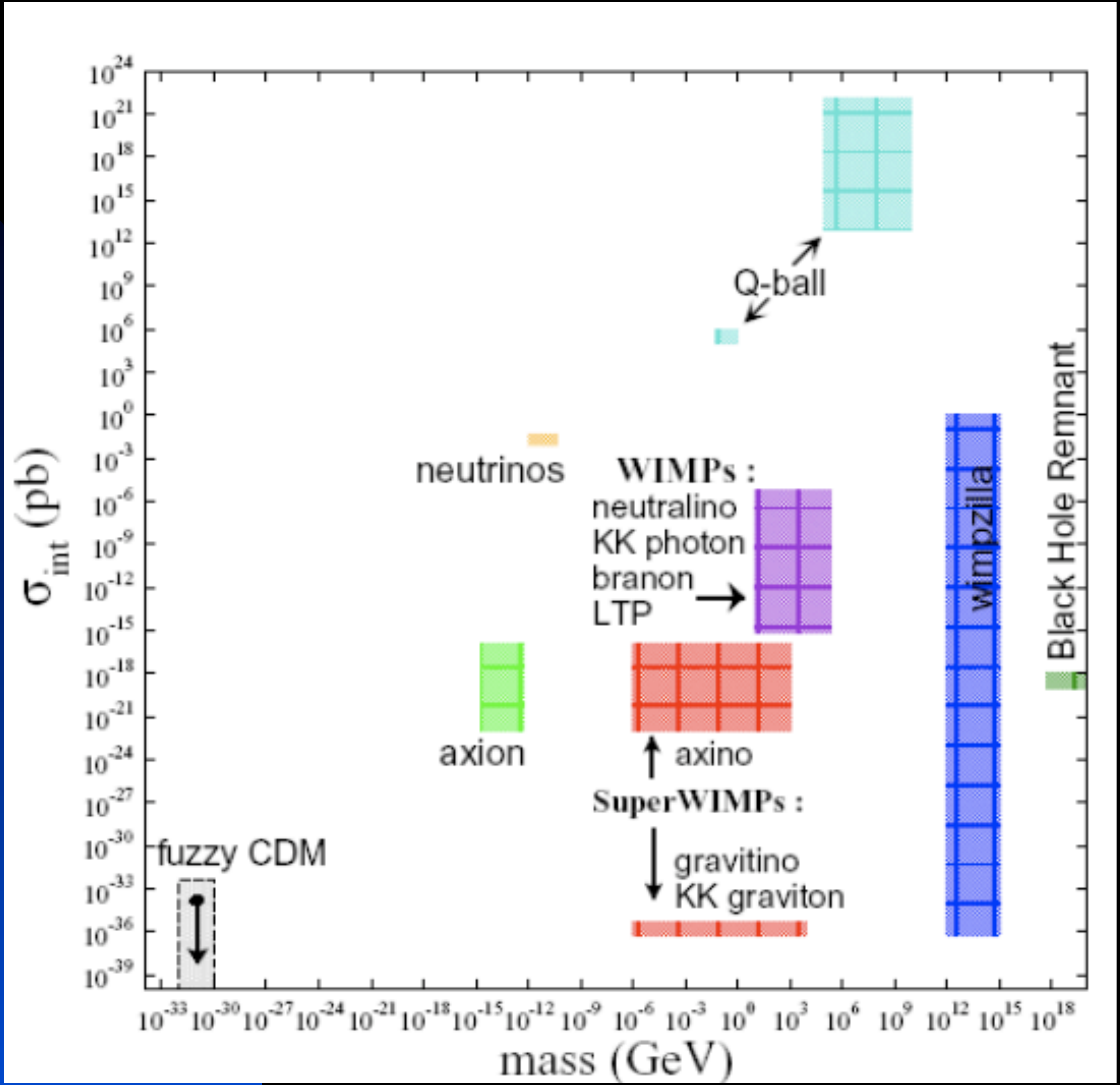
Candidates: WIMPS (Neutralinos, Kaluza Klein Particles, Universal Extra Dimensions...)

Axinos, Axions, Axion-like light bosons, Sterile neutrinos, Q-balls, WIMPzillas, Elementary Black Holes...

Search for them is on:

1. **Direct detection -- 20 expts worldwide**
2. **Indirect detection -- i.e. Bullet Cluster !**
3. **LHC -- i.e. missing momentum and energy**

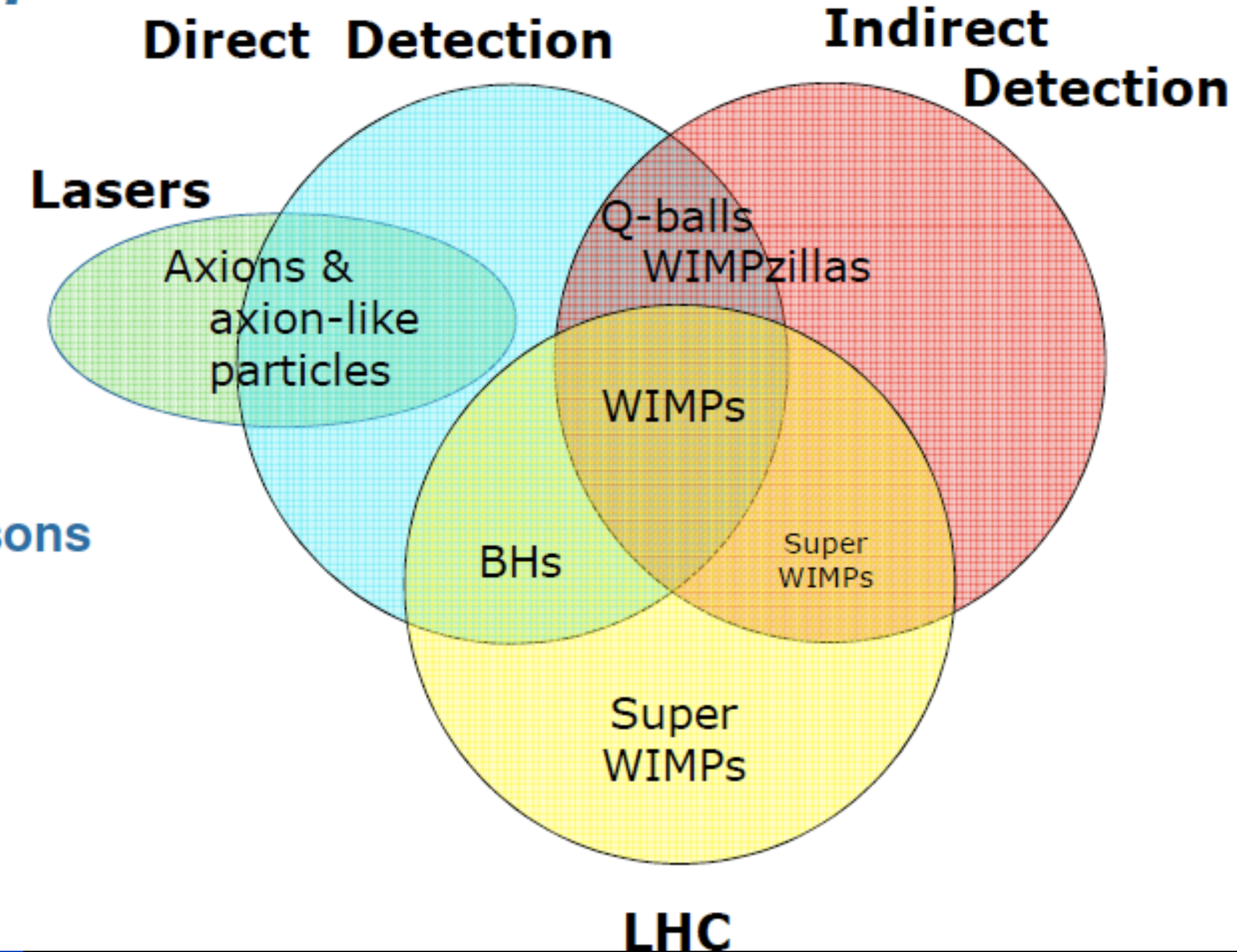
Dark Matter Candidates



C. Spiering, Cosmo 09

DM candidates:

- **WIMPs**
  - Neutralinos
  - Kaluza-Klein particles
  - …
- **Axinos**
- **Super-WIMPs**
- **Axions**
- **Axion-like light bosons**
- **Sterile neutrinos**
- **Q-balls**
- **WIMPzillas**
- **Elementary BHs**
- **…**

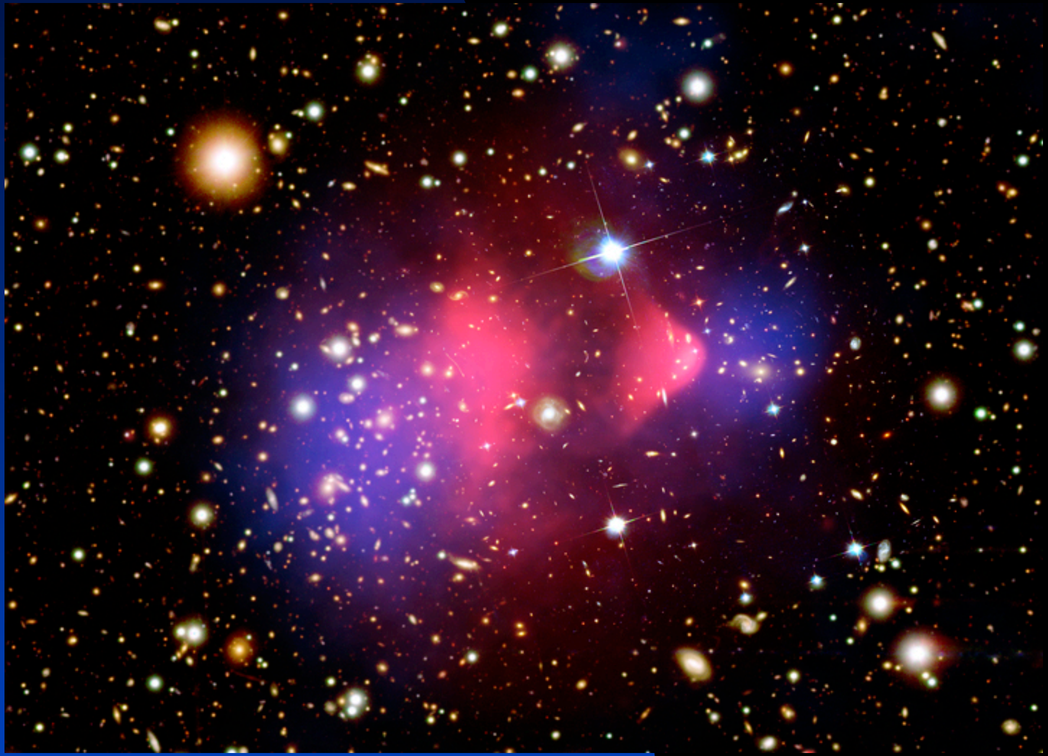


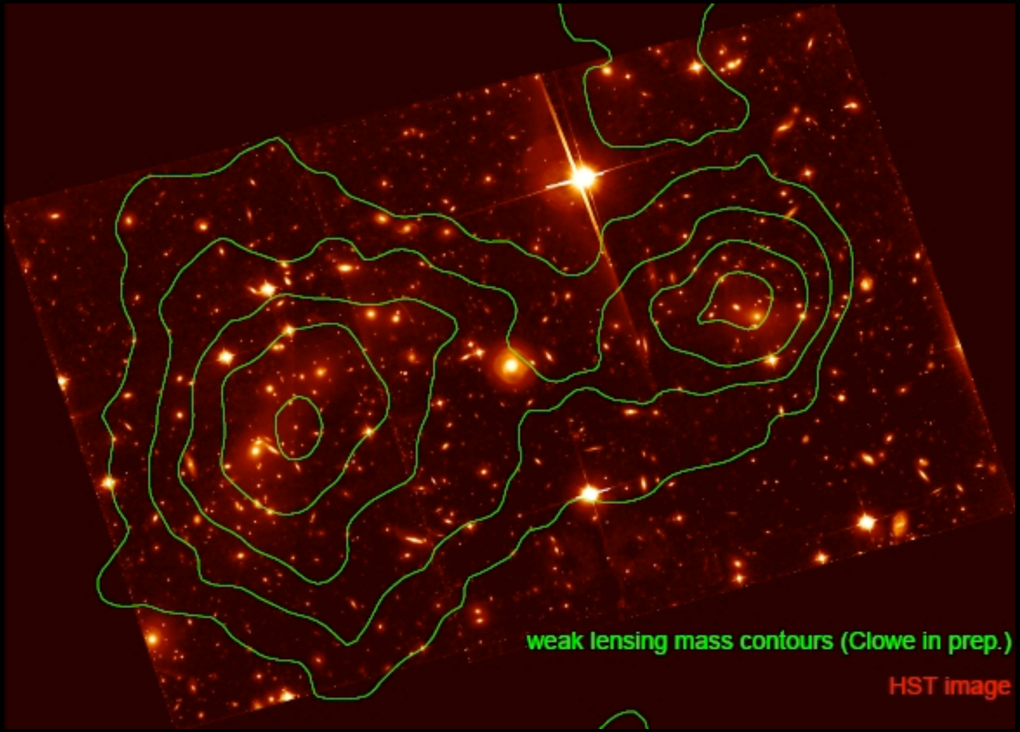
Indirect evidence for Dark Matter -- Bullet Cluster

Two clusters of galaxies colliding.

Dark matter in each passes straight through and doesn't interact -- seen through weak lensing in right image.

Ordinary matter in each interacts in collision and heats up -- seen through infra red image on left.





Clowe et al 2006

However if Tom Shanks is here I'm sure he will have something to say on the interpretation of the data.

Evidence for Dark Energy?

Enter CMBR:

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

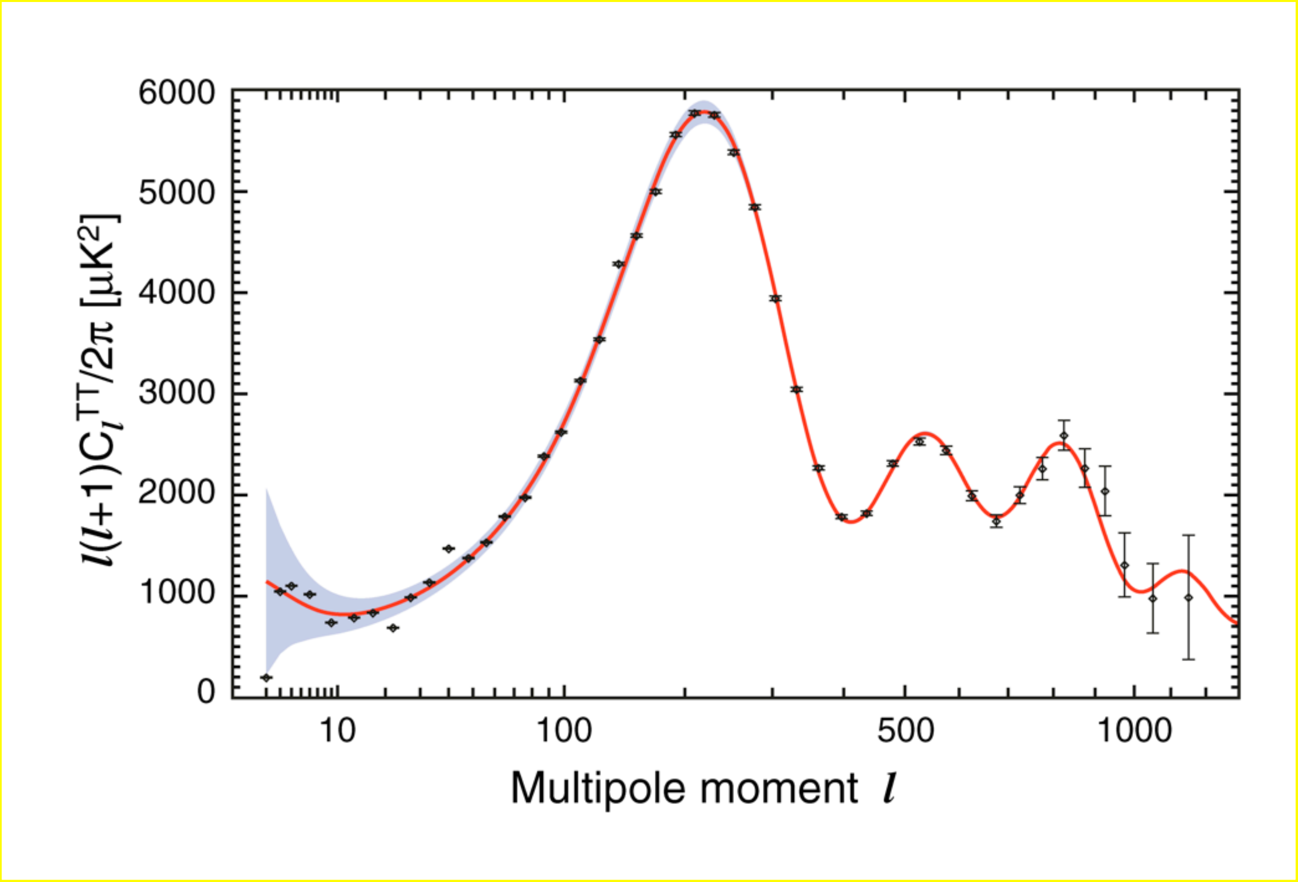
Provides clue. 1st angular peak in power spectrum.

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

$$|1 - \Omega_0| = 0.03^{+0.026}_{-0.025}$$

WMAP3-Depends on assumed priors

Spergel et al 2006



$$-0.0175 < \Omega_k < 0.0085$$

Dunkley et al 2008 (WMAP5)

WMAP7 and dark energy

(Komatsu et al, 2010)

Assume flat univ +
+BAO+ SNLS:

$$w = -0.980 \pm 0.053$$

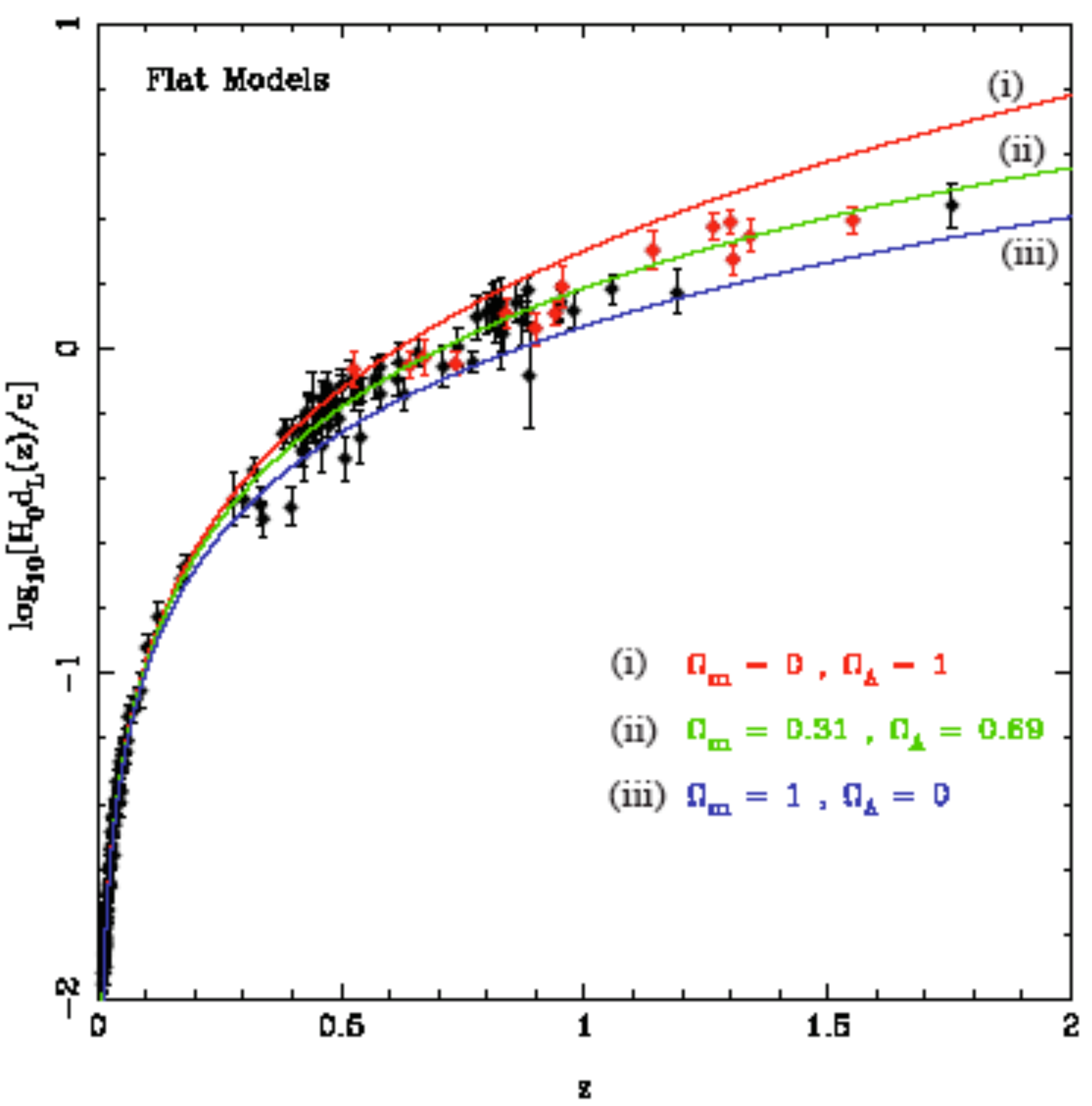
Drop prior of flat
univ: WMAP + BAO
+ SNLS:

$$w = -0.999^{+0.057}_{-0.056} \quad \Omega_k = -0.0057^{+0.0067}_{-0.0068}$$

Drop assumption of
const w but keep flat
univ: WMAP + BAO
+ SNLS:

$$\begin{aligned} w_0 &= -0.93 \pm 0.12 \\ w_a &= -0.38^{+0.66}_{-0.65} \end{aligned}$$

Type Ia Luminosity distance v z [Reiss et al 2004]



Flat model
Black dots -- Gold data set
Red dots -- HST

$$(i)\Omega_m = 0,\ \Omega_\Lambda = 1 \quad (ii)\Omega_m = 0.31,\ \Omega_\Lambda = 0.69 \quad (iii)\Omega_m = 1,\ \Omega_\Lambda = 0$$

Coincidence problem – why now?

Recall: $$\frac{\ddot{a}}{a} \geq 0 < - > = (\rho + 3p) \leq 0$$

If: $$\rho_x = \rho_x^0 \, a^{-3(1+w_x)}$$

Universe dom by dark energy at:

$$z_x = \left(\frac{\Omega_x}{\Omega_m}\right)^{\frac{1}{3w_x}} - 1$$

$$\left(\frac{\Omega_x}{\Omega_m}\right) = \frac{7}{3} \rightarrow z_x = 0.5,\ 0.3 \text{ for } w_x = -\frac{2}{3},\ -1$$

Univ accelerates at:

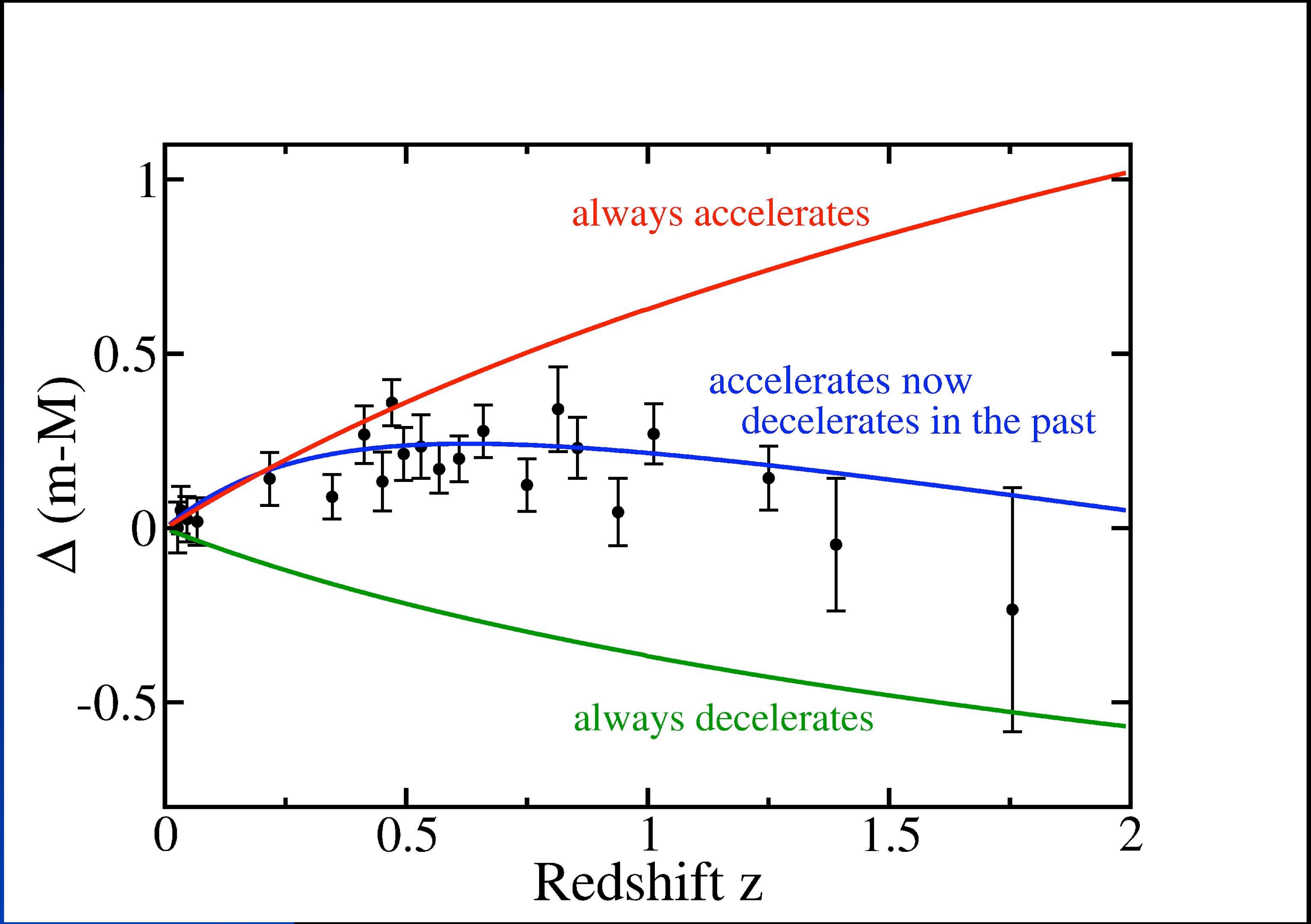
$$z_a = \left(-(1+3w_x)\frac{\Omega_x}{\Omega_m}\right)^{\frac{-1}{3w_x}} - 1$$

$$z_a = 0.7,\ 0.5 \text{ for } w_x = -\frac{2}{3},\ -1$$

Constraint: $-0.11 < 1 + w < 0.14$

Komatsu et al 2008 (WMAP5)

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



What is making the Universe accelerate?

Dark energy -- a weird form of energy that exists in empty space and pervades the universe -- also known as vacuum energy or cosmological constant.

Smoothly distributed, doesn’t cluster.

Constant density or very slowly varying

Doesn’t interact with ordinary matter -- only with gravity

Big problem though. When you estimate how much you expect there to be, from the Quantum world, the observed amount is far less than expected.

Theoretical prediction = 10^{120} times observation

Different approaches to Dark Energy include amongst many:

- A true cosmological constant -- but why this value?
- Solid –dark energy such as arising from frustrated network of domain walls.
- 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.

Over 2500 papers on archives since 1998 with dark energy in title !

Early evidence for a cosmological constant type term.

1987: Weinberg argued that anthropically ρ_{vac} could not be too large and positive otherwise galaxies and stars would not form. It should not be very different from the mean of the values suitable for life which is positive, and he obtained $\Omega_{vac} \sim 0.6$

1990: Observations of LSS begin to kick in showing the standard $\Omega_{CDM} = 1$ struggling to fit clustering data on large scales, first through IRAS survey then through APM (Efstathiou et al).

1990: Efstathiou, Sutherland and Maddox - Nature (238) -- explicitly suggest a cosmology dominated today by a cosmological constant with $\Omega_{vac} < 0.8$!

1998: Type Ia SN show striking evidence of cosm const and the field takes off.

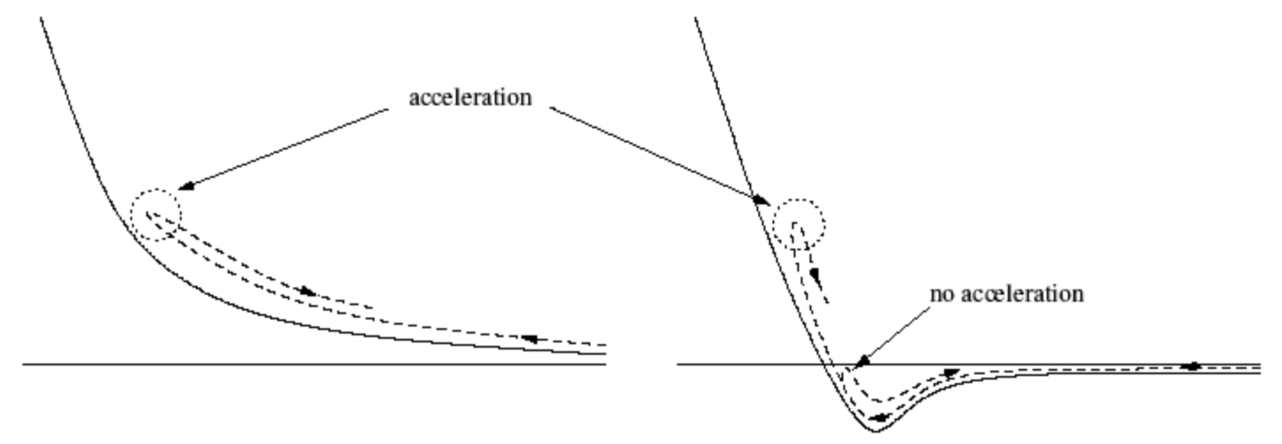
String/M-theory -- where are the realistic models?

`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]

Recent extension: forbids four dimensional cosmic acceleration in cosmological solutions arising from warped dimensional reduction --[Wesley 08]

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

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



Current realistic potentials are too steep

Models kinetic, not matter domination before entering accelerated phase.

Four form Flux and the cosm const: [Bousso and Polchinski]

Effective 4D theory from M^{4}xS^7 compactification

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{2\kappa^2}R + \Lambda_b - \frac{1}{2\cdot 4!}F_4^2\right)$$

Negative bare cosm const: $-\Lambda_b$

EOM: $\nabla_\mu\left(\sqrt{-g}F^{\mu\nu\rho\sigma}\right) = 0$ $\rightarrow F^{\mu\nu\rho\sigma} = c\epsilon^{\mu\nu\rho\sigma}$

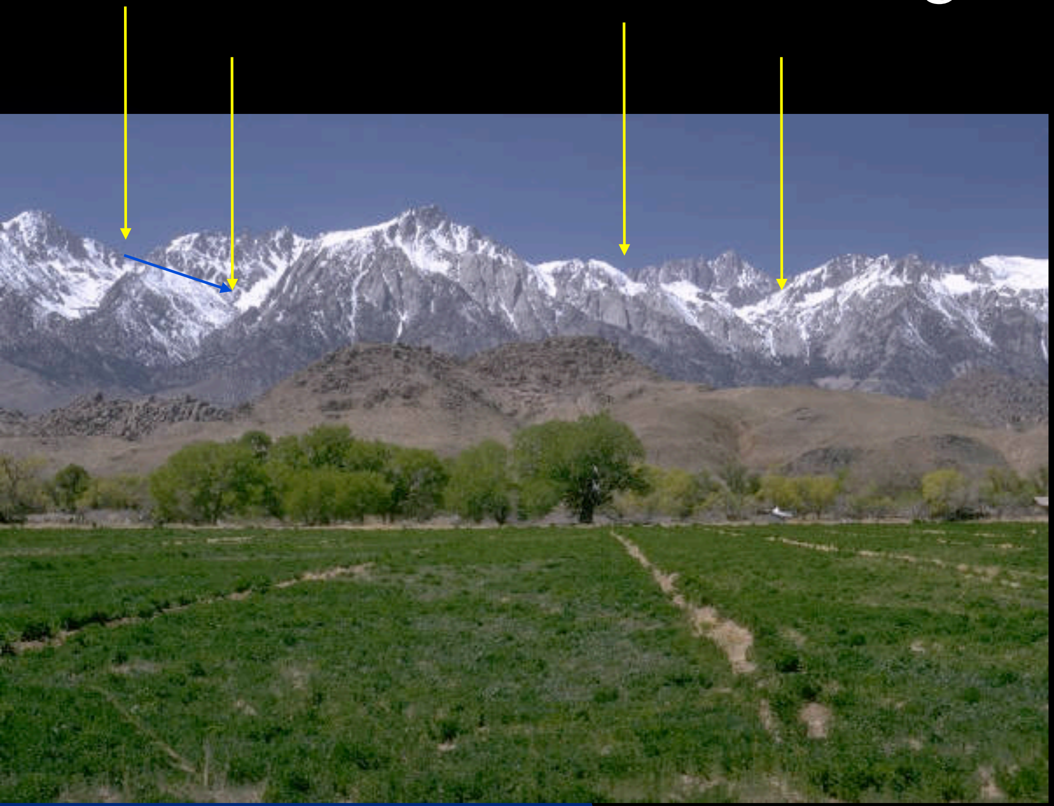
Eff cosm const: $\Lambda = -\Lambda_b - \frac{1}{48}F_4^2 = -\Lambda_b + \frac{c^2}{2}$

Quantising c and considering J fluxes $\Lambda = -\Lambda_b + \frac{1}{2}\sum_{i=1}^{J} n_i^2 q_i^2$

Observed cosm const with J~100

Still needed to stabilise moduli but opened up way of obtaining many de Sitter vacua using fluxes -- String Landscape in which all the vacua would be explored because of eternal inflation.

1.The String Landscape approach



Type IIB String theory compactified from 10 dimensions to 4.

Internal dimensions stabilised by fluxes.

Many many vacua ~ 10^{500} !

Typical separation ~ $10^{-500}\ \Lambda_{pl}$

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

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

[Witten 2008]

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.

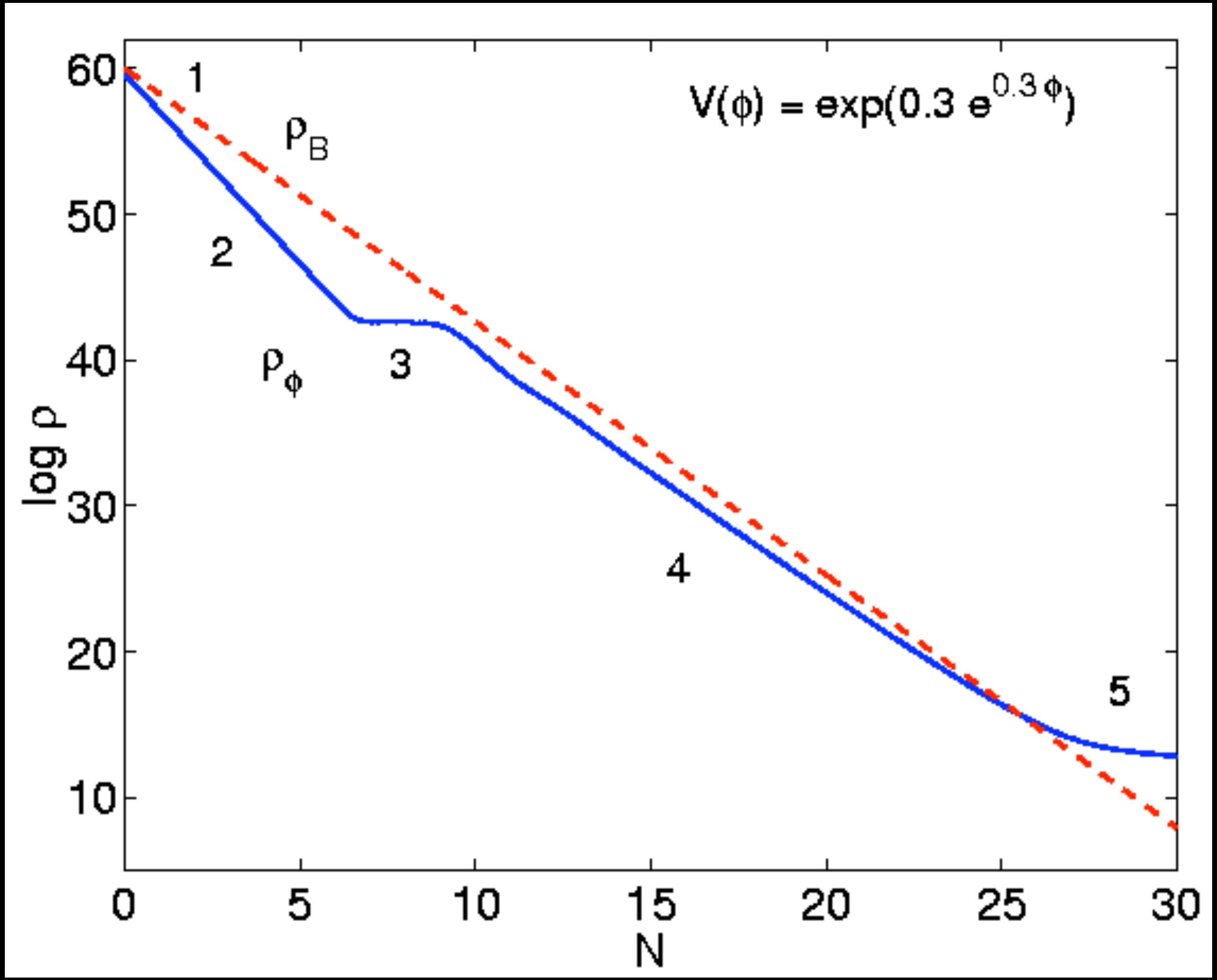
So how can we hope to understand or predict why we have our particular particle content and couplings when there are so many choices in different parts of the universe, none of them special ?

This sounds like bad news, we will rely on anthropic arguments to explain it through introducing the correct measures and establishing peaks in probability distributions.

Or perhaps, it isn’t a cosmological constant, but a new field such as Quintessence which will eventually drive us to a unique vacuum with zero vacuum energy -- that too has problems, such as fifth force constraints, as we will see.

Slowly rolling scalar fields Quintessence - Generic behaviour

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



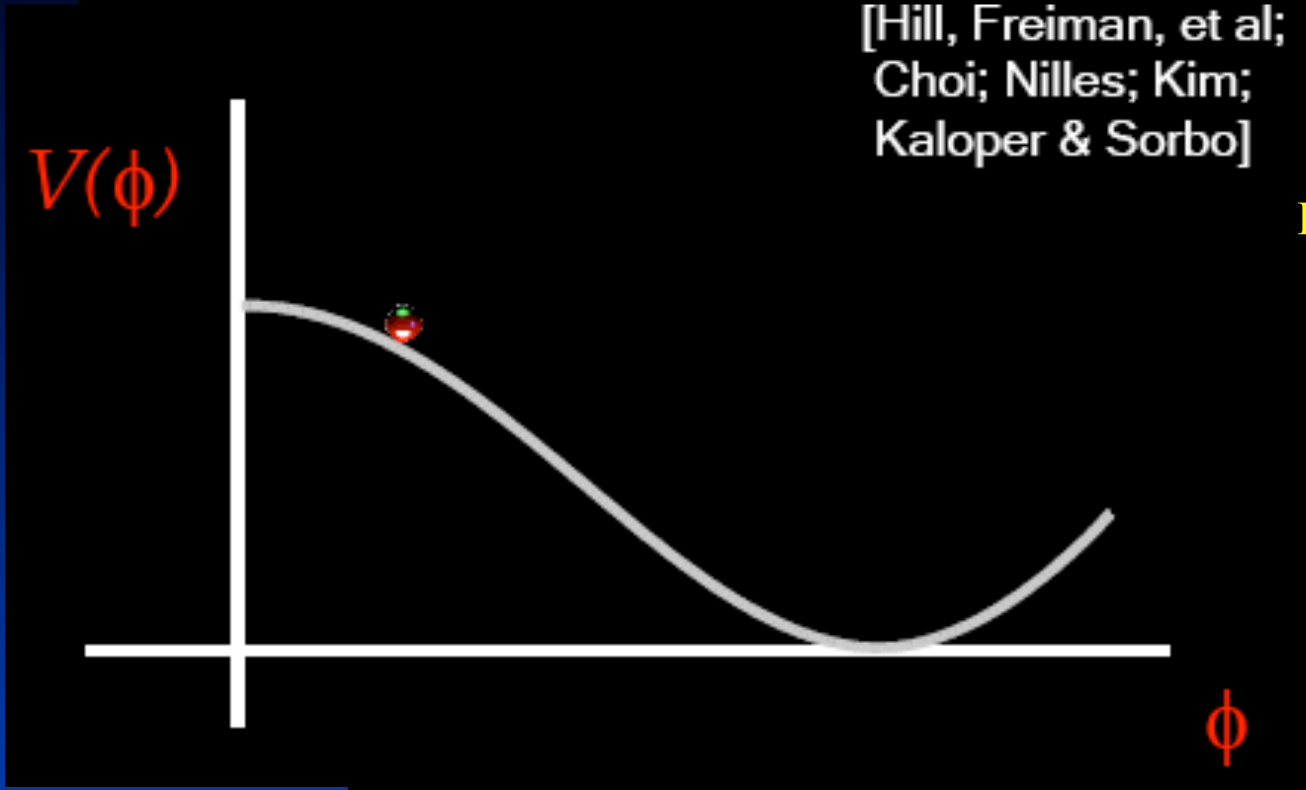
Nunes

Attractors make initial conditions less important

Particle physics inspired models?

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

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

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

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

Key idea: in order to avoid fifth force type constraints on Quintessence models, have a situation where the 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. Phantom fields [Caldwell (2002) …]

The data does not rule out w<-1. Can not accommodate in standard quintessence models but can by allowing negative kinetic energy for scalar field (amongst other approaches).

3. K-essence [Armendariz-Picon et al …]

Scalar fields with non-canonical kinetic terms. Advantage over Quintessence through solving the coincidence model?

Long period of perfect tracking, followed by domination of dark energy triggered by transition to matter domination -- an epoch during which structures can form. Similar fine tuning to Quintessence.

4. Interacting Dark Energy [Kodama & Sasaki (1985), Wetterich (1995), Amendola (2000) + many others…]

Idea: why not directly couple dark energy and dark matter?

$$\begin{aligned} \text{Ein eqn} &: \quad G_{\mu\nu} = 8\pi G T_{\mu\nu} \\ \text{General covariance} &: \quad \nabla_\mu G^\mu_\nu = 0 \rightarrow \nabla_\mu T^\mu_\nu = 0 \end{aligned}$$

$$T_{\mu\nu} = \sum_i T^{(i)}_{\mu\nu} \rightarrow \nabla_\mu T^{\mu\,(i)}_\nu = -\nabla_\mu T^{\mu\,(j)}_\nu \ \text{ is ok}$$

Couple dark energy and dark matter fluid in form:

$$\begin{aligned} \nabla_\mu T^{\mu\,(\phi)}_\nu &= \sqrt{\frac{2}{3}}\kappa\beta(\phi)T^{\alpha\,(m)}_\alpha \nabla_\nu\phi \\ \nabla_\mu T^{\mu\,(m)}_\nu &= -\sqrt{\frac{2}{3}}\kappa\beta(\phi)T^{\alpha\,(m)}_\alpha \nabla_\nu\phi \end{aligned}$$

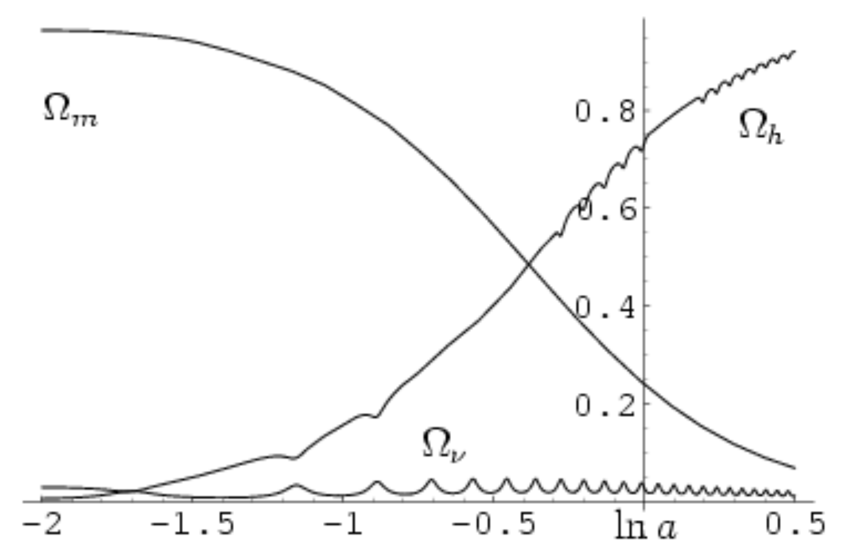
Including neutrinos -- 2 distinct DM families -- resolve coincidence problem [Amendola et al (2007)]

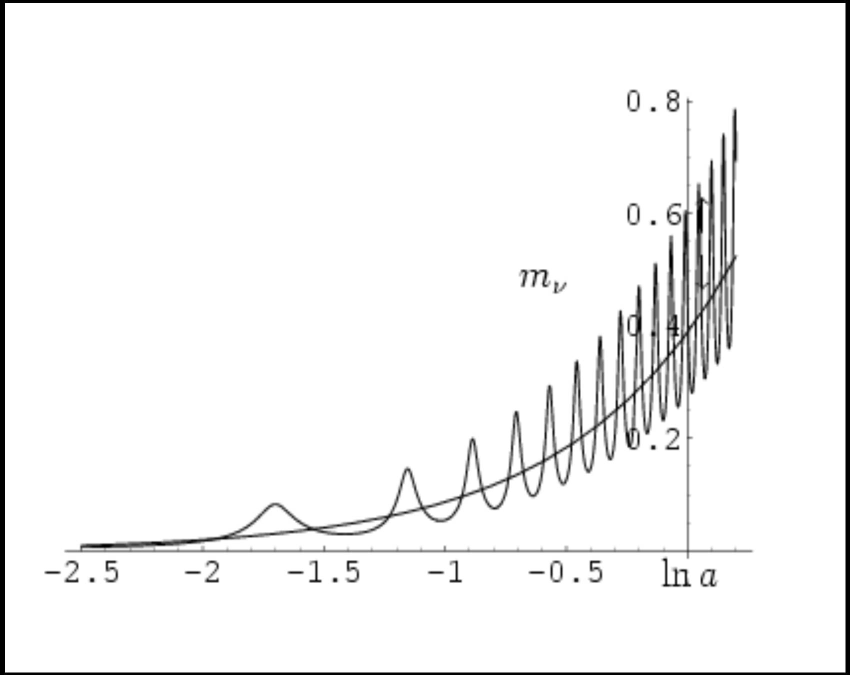
Depending on the coupling, find that the neutrino mass grows at late times and this triggers a transition to almost static dark energy.

Trigger scale set by when neutrinos become non-rel

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.07 \left(\frac{\gamma m_\nu(t_0)}{eV}\right)^{\frac{1}{4}} 10^{-3} eV$$

$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\text{eV}}$$





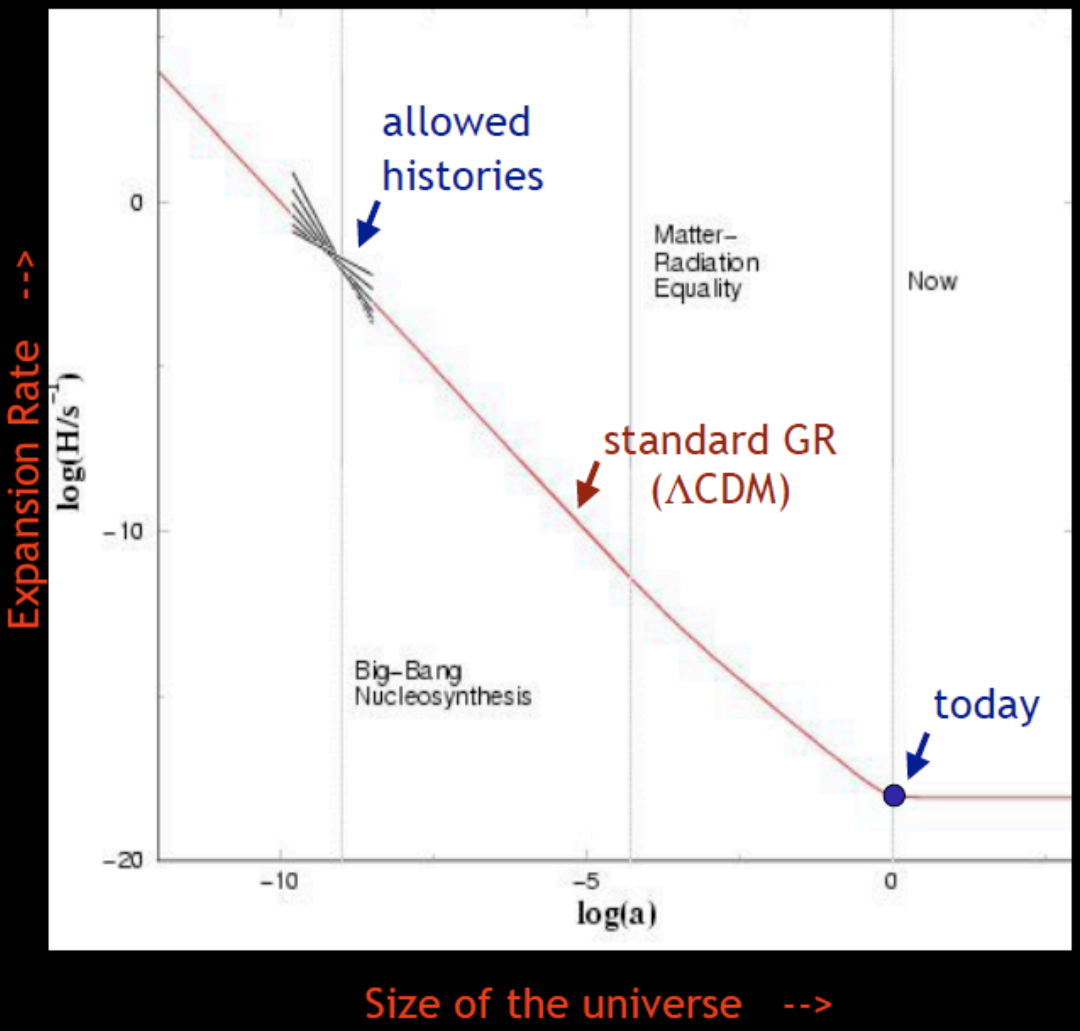
m_ν

Perhaps we are wrong -- maybe the question should be not whether dark energy exists, rather should we be modifying gravity?

Has become a big industry but it turns out to be hard to do too much to General Relativity without falling foul of data.

BBN occurred when the universe was about one minute old, about one billionth its current size. It fits well with GR and provides a test for it in the early universe.

Any alternative had better deliver the same successes not deviate too much at early times, but turn on at late times .



[Carroll & Kaplinghat 2001]

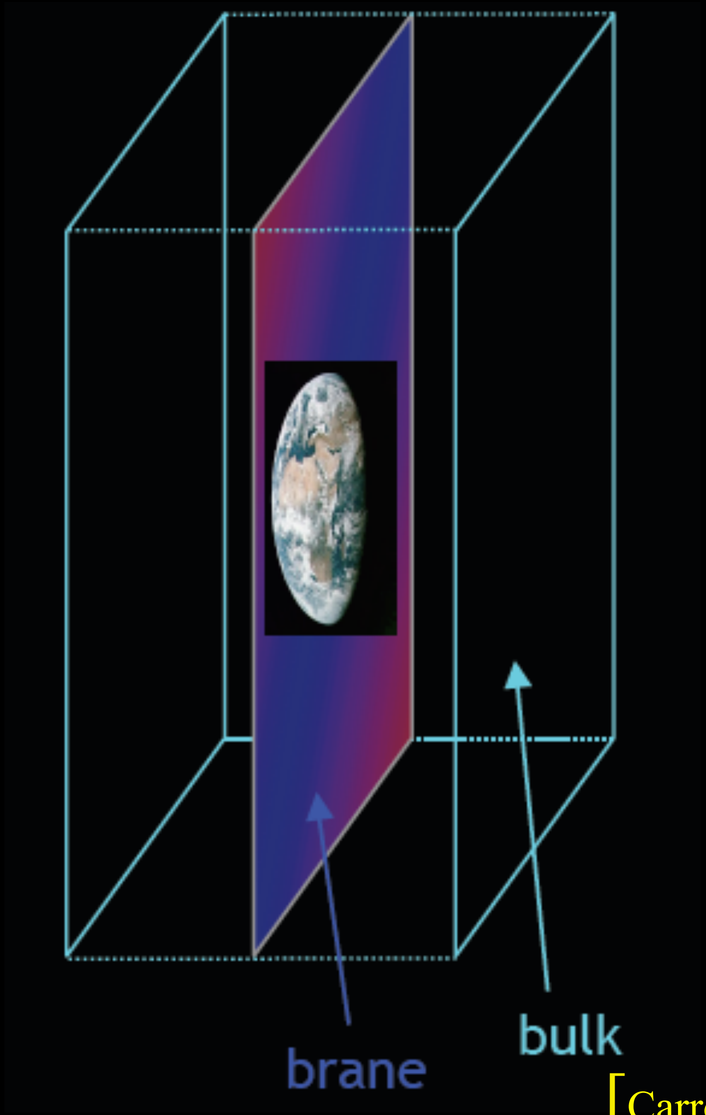
Any theory deviating from GR must do so at late times yet remain consistent with Solar System tests. Potential examples include:

- f(R) gravity -- coupled to higher curv terms, changes the dynamical equations for the spacetime metric.

[Starobinski 1980, Carroll et al 2003, ...]

- Modified source gravity -- gravity depends on nonlinear function of the energy.

- Gravity based on the existence of extra dimensions -- DGP gravity



[Carroll]

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 and observations -- ghosts !

Example of Galileon fields -- [Nicolis et al 08]

To test GR on cosmological scales compare kinematic probes of dark energy to dynamical ones and look for consistency.

Kinematic probes: only sensitive to a(t) such as standard candles, baryon oscillations.

Dynamical probes: sensitive to a(t) and structure growth such as weak lensing and cluster counts.

Determining the best way to test for dark energy and parameterise the dark energy equation of state is a difficult task, not least given the number of approaches that exist to modeling it .

Dark Energy Task Force review: Albrecht et al : astro-ph/0609591

Findings on best figure of merit: Albrecht et al: arXiv:0901.0721

Return to the beginning -- Brief intro to Inflation

A period of accelerated expansion in the early Universe

Explains the homogeneity and spatial flatness of the Universe

and also explains why no massive relic particles predicted in say GUT theories

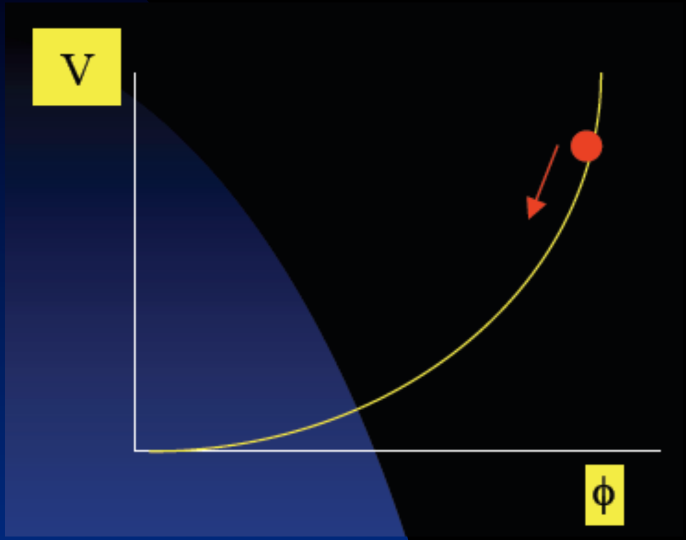
Leading way to explain observed inhomogeneities in the Universe

$$\boxed{\frac{\ddot{a}}{a} = -\frac{8\pi}{3} G\,(\rho + 3p) - - - Accn}$$

$$\boxed{If\ \ \rho + 3p < 0 \Rightarrow \ddot{a} > 0}$$

Intro fundamental scalar field -- like Higgs

If Universe is dominated by the potential of the field, it will accelerate!



$$\begin{aligned}\rho &= \frac{1}{2}\dot{\phi}^2 + V(\phi)\\ p &= \frac{1}{2}\dot{\phi}^2 - V(\phi)\end{aligned}$$

Of course no fundamental scalar field ever seen.

We aim to constrain potential from observations.

During inflation as field slowly rolls down its potential, it undergoes quantum fluctuations which are imprinted in the Universe. Also leads to gravitational wave production.

Prediction -- potential determines important quantities

Slow roll parameters [Liddle & Lyth 1992]

$$\epsilon = \frac{1}{16\pi G}\left[\frac{V'(\phi)}{V(\phi)}\right]^2$$

$$\eta = \frac{1}{8\pi G}\left[\frac{V''(\phi)}{V(\phi)}\right]$$

Inflation occurs when both of these are << 1

Density perturbations

$$\delta_H^2(k) \simeq \delta_H^2(k_0)\left(\frac{k}{k_0}\right)^{n-1}$$

$$\delta_H^2(k_0) \simeq \frac{32}{75}\frac{VG^2}{\epsilon}, \quad n-1 = 6\epsilon - 2\eta$$

Gravitational waves

$$\delta_g^2(k) \simeq \delta_g^2(k_0)\left(\frac{k}{k_0}\right)^{n_G}$$

$$r \equiv \frac{\delta_g^2(k_0)}{\delta_H^2(k_0)} = 16\epsilon, \quad n_G = -2\epsilon = -\frac{r}{8}$$

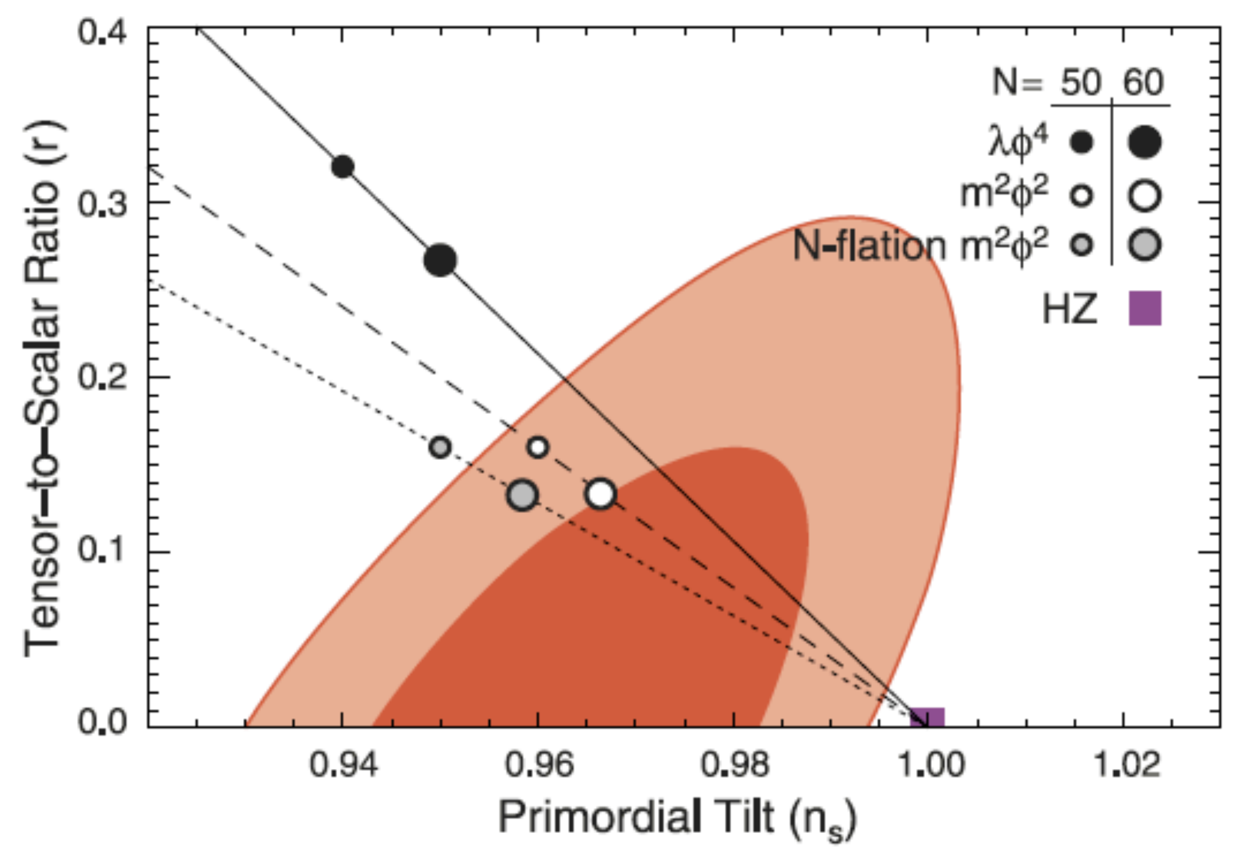
Example if include WMAP7+BAO+H0 constraints:

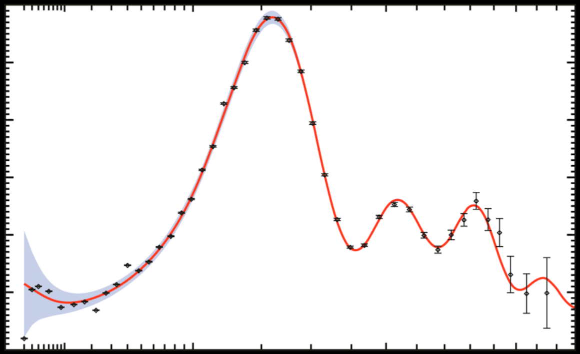
$$k_0 = 0.002\mathrm{Mpc}^{-1}$$

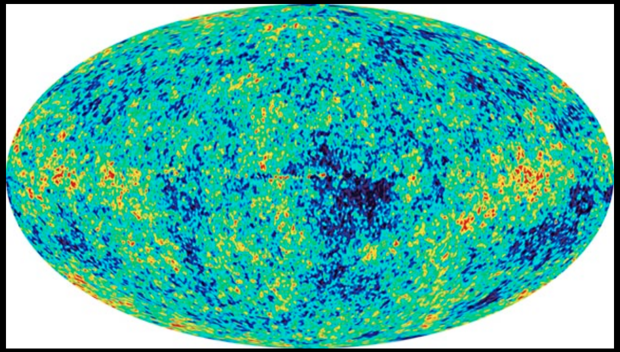
No GW assumed: $n_s = 0.963 \pm 0.012$

Allow for GW:

$$\begin{aligned} n_s &= 0.973 \pm 0.014 \\ r &< 0.24\ (95\%\ CL) \end{aligned}$$







(Komatsu et al, 2010)

Inflation model building -- big industry

Multi-field inflation

Inflation in string theory and braneworlds

Inflation in extensions of the standard model

Cosmic strings formed at the end of inflation

The idea is clear though:

Use a combination of data (CMB, LSS, SN, BAO ...) to try and constrain models of the early universe through to models explaining the nature of dark energy today.

Inflation in string theory -- non trivial
The η problem in Supergravity -- N=1 SUGR Lagrangian:

$$\mathcal{L} = -K_{\varphi\bar\varphi}\partial\varphi\partial\bar\varphi + V_F,$$

with

$$V_F = e^{K/M_p^2}\left[K^{\varphi\bar\varphi}D_\varphi W\overline{D_\varphi W} - \frac{3}{M_p^2}|W|^2\right]$$

and

$$D_\varphi = \partial_\varphi W + \frac{1}{M_p^2}\partial_\varphi K$$

$$K(\varphi,\bar\varphi) = K_0 + K_{\varphi\bar\varphi}\varphi\bar\varphi + \ldots$$

Expand K about φ=0

$$\begin{aligned}\mathcal{L} &\approx -K_{\varphi\bar\varphi}\partial\varphi\partial\bar\varphi - V_0\left(1 + K_{\varphi\bar\varphi}|_{\varphi=0}\frac{\varphi\bar\varphi}{M_p^2} + \ldots\right)\\ &= -\partial\phi\partial\bar\phi - V_0\left(1 + \frac{\phi\bar\phi}{M_p^2} + \ldots\right),\end{aligned}$$

Canonically norm fields ϕ

Have model indep terms which lead to contribution to slow roll parameter η of order unity

$$\Delta\eta = M_p^2\frac{\Delta V''}{V_0} = 1.$$

So, need to cancel this generic term possibly through additional model dependent terms.

Ex 1: Warped D3-brane D3-antibrane inflation where model dependent corrections to V can cancel model indep contributions

[Kachru et al (03) -- KLMMT].

Find:

$$V(\phi) = V_0(\phi) + \beta H^2 \phi^2$$

β relates to the coupling of warped throat to compact CY space. Can be fine tuned to avoid η problem

Ex 2: DBI inflation -- simple -- it isn't slow roll as the two branes approach each other so no η problem

Ex 3: Kahler Moduli Inflation [Conlon & Quevedo 05]

Inflaton is one of Kahler moduli in Type IIB flux compactification. Inflation proceeds by reducing the F-term energy. No η problem because of presence of a symmetry, an almost no-scale property of the Kahler potential.

$$V_{inf} = V_0 - \frac{4\tau_n W_0 a_n A_n e^{-a_n \tau_n}}{\mathcal{V}^2},$$

Inflaton moduli: τ_n

$$V_{inf} = V_0 - \frac{4\tau_n W_0 a_n A_n e^{-a_n \tau_n}}{\mathcal{V}^2},$$

Find:

$$\begin{array}{rcl} 0.960 & < n < & 0.967, \\ -0.0006 & < \frac{dn}{d\ln k} < & -0.0008, \\ 0 & < |r| < & 10^{-10}, \end{array}$$

with large volume modulus

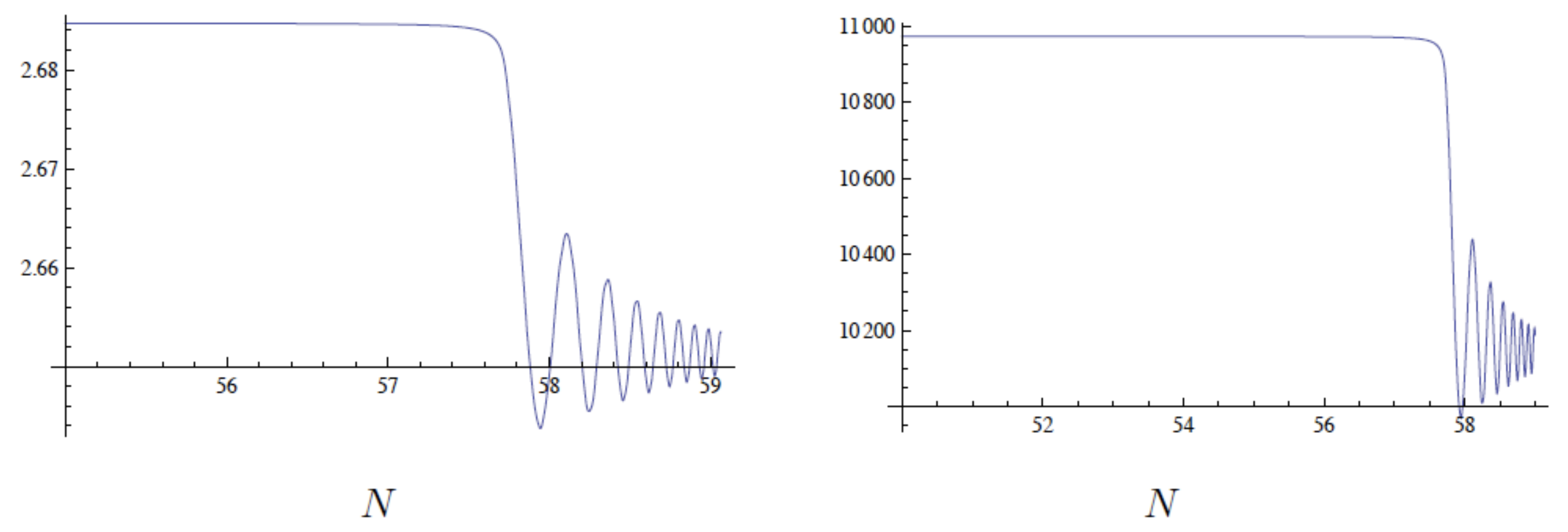
$$10^5 l_s^6 \leq \mathcal{V} \leq 10^7 l_s^6,$$

and

$$\begin{array}{rcl} \eta & \approx & -\frac{1}{N_e}, \\ \epsilon & < & 10^{-12}, \end{array}$$

for N_e ≈50-60 efolds with low energy scale

$$V_{inf} \sim 10^{13}\text{GeV}.$$



Inflaton [Blanco-Pillado et al 09] **Volume modulus**

Can include curvaton as second evolving moduli -- Burgess et al 2010

Todays update : see Kallosh et al -- arXiv 1011.5945

Key inflationary parameters:

n: Perhaps Planck will finally determine whether it is unity or not.

r: Tensor-to-scalar ratio : considered as a smoking gun for inflation but also produced by defects and some inflation models produce very little.

dn/dln k : Running of the spectral index, usually very small -- probably too small for detection.

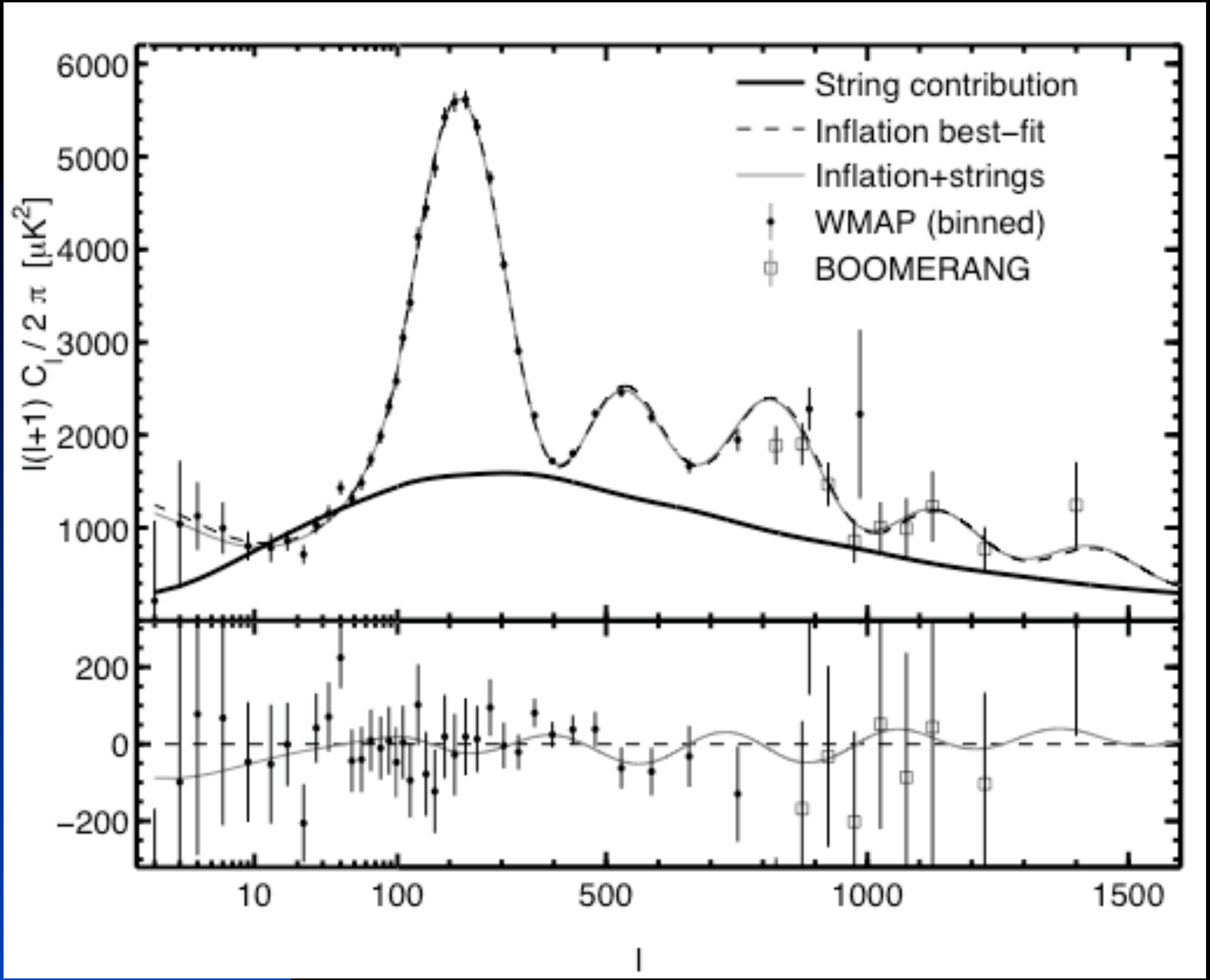
f_{NL}: Measure of cosmic non-gaussianity. Still consistent with zero, but tentative evidence of a non-zero signal in WMAP data which would provide an important piece of extra information to constrain models. For example, it could rule out single field models -- lots of current interest.

$G\mu$: string tension in Hybrid models where defects produced at end of period of inflation.

Also new perturbation generation mechanisms (e.g. Curvaton)

Perturbations not from inflaton but from extra field and then couple through to curvature perturbation

Cosmic strings - may not do the full job but they can still contribute



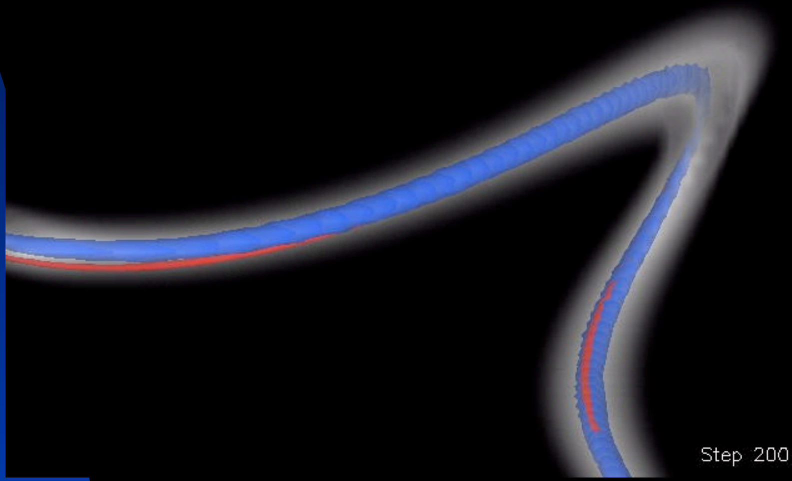
Hybrid Inflation type models

String contribution < 11% implies $G\mu < 0.7 * 10^{-6}$.

Bevis et al 2007,2010.

Any smoking guns signals ?

Possibly through strong non-gaussian nature of stochastic gravitational wave emission from loops which contain kinks and cusps. [Damour & Vilenkin 01 and 04]



[Blanco-Pillado and Olum]

Cusp: x’=0 for instant in an oscillation

Kink: x’ discontinuous, occurs every intercommuting -- common

Both produce beams of GW, cusps much more powerful. Cusps and kinks act quickly and can have significant consequences.

The power of kinks!

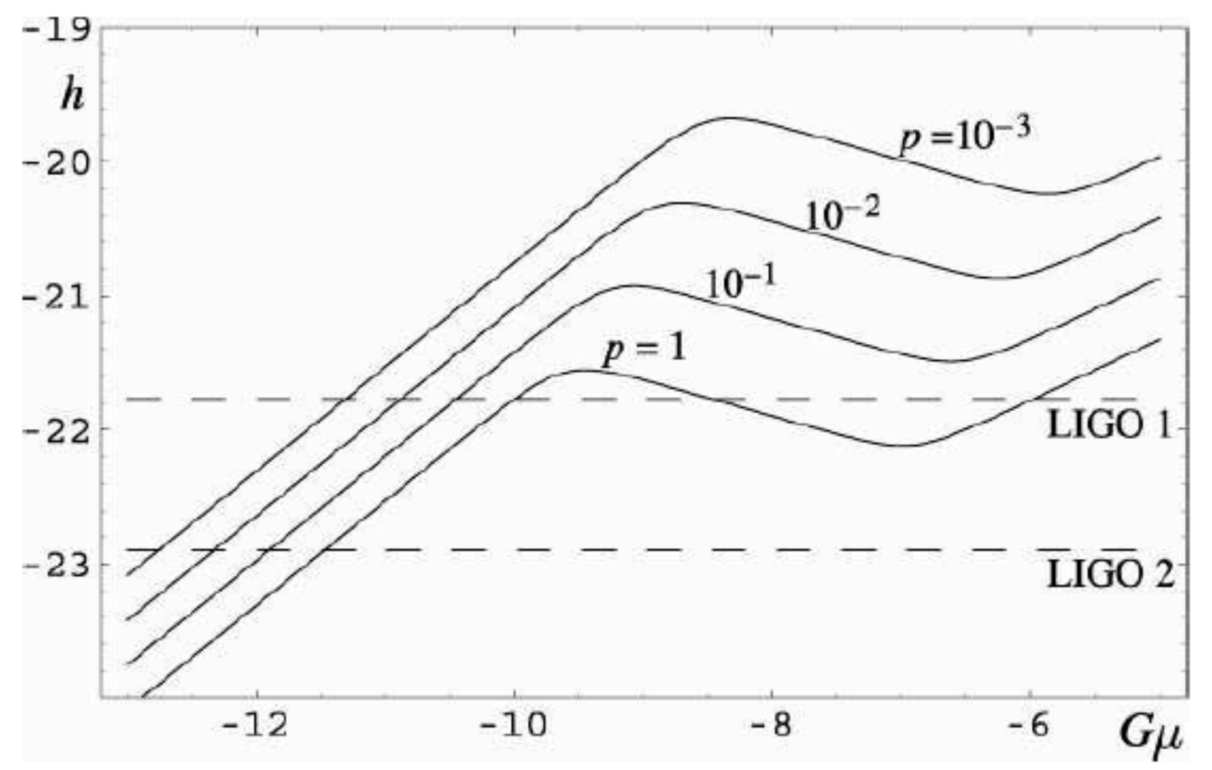
In loop network, if only 10% of loops have cusps, bursts of GW above `confusion' GW noise could be detected by LIGO and LISA for Gμ ~10^{-12} !

$\log_{10} h$

strain

LIGO I

LIGO II



[Damour & Vilenkin 04]

Noise levels

Bursts emitted by cusps in LIGO frequency range f_{ligo}=150 Hz

Recent work says results optimistic because extra dimensions round off cusps, reduce likelihood of formation so significantly dmapen the gravity wave signal - [O'Callaghan et al 2010]

In 1980's Fundamental (F) strings excluded as being cosmic strings [Witten 85]:

1. F string tension close to Planck scale (e.g. Heterotic)

$$G\mu = \frac{\alpha_{GUT}}{16\pi} \geq 10^{-3}$$

Cosmic strings deflect light, hence constrained by CMB:

$$G\mu \propto \frac{\delta T}{T} \leq 10^{-6}$$

Consequently, cosmic strings had to be magnetic or electric flux tubes arising in low energy theory

2. Why no F strings of cosmic length?

a. Diluted by any period of inflation as with all defects.

b. They decay ! (Witten 85)

1990's: along came branes --> new one dimensional objects:

1. Still have F strings
2. D-strings
3. Higher dimensional D-, NS-, M- branes partly wrapped on compact cycles with only one non-compact dimension left.
4. Large compact dimensions and large warp factors allow for much lower string tensions.
5. Dualities relate strings and flux tubes, so can consider them as same object in different regions of parameter space.

What do they imply for cosmic strings?

Strings surviving inflation:

D-brane-antibrane inflation leads to formation of D1 branes in non-compact space [**Dvali & Tye; Burgess et al; Majumdar & Davis; Jones, Sarangi &Tye; Stoica & Tye**]

Form strings, not domain walls or monopoles.

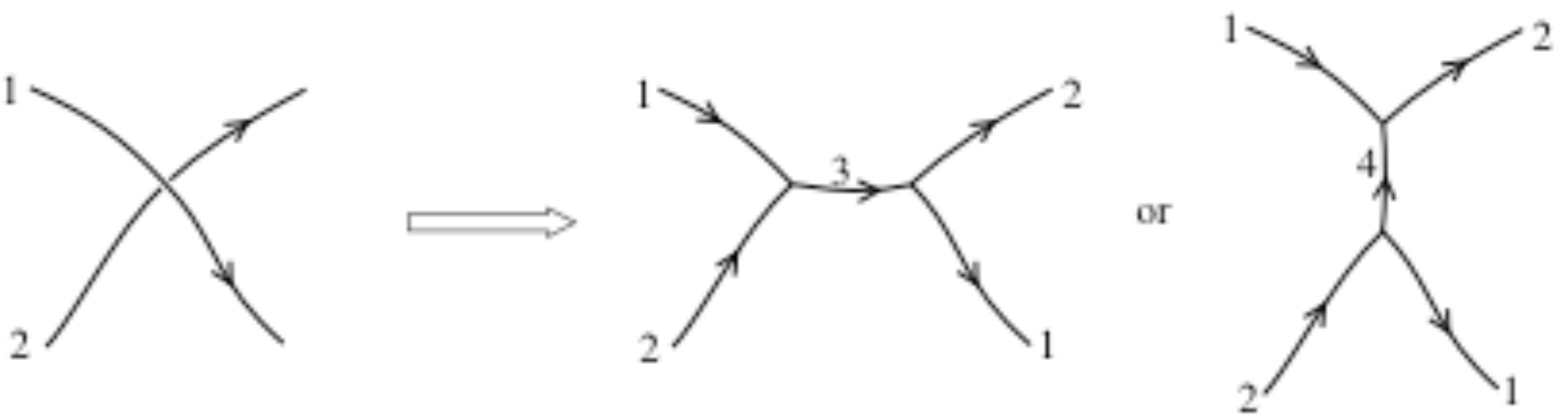
$$10^{-11} \lesssim G\mu \lesssim 10^{-6}$$

In general for cosmic strings to be cosmologically interesting today we require that they are not too massive (from CMB constraints), are produced after inflation (or survive inflation) and are stable enough to survive until today [**Dvali and Vilenkin (2004); EJC,Myers and Polchinski (2004)**].

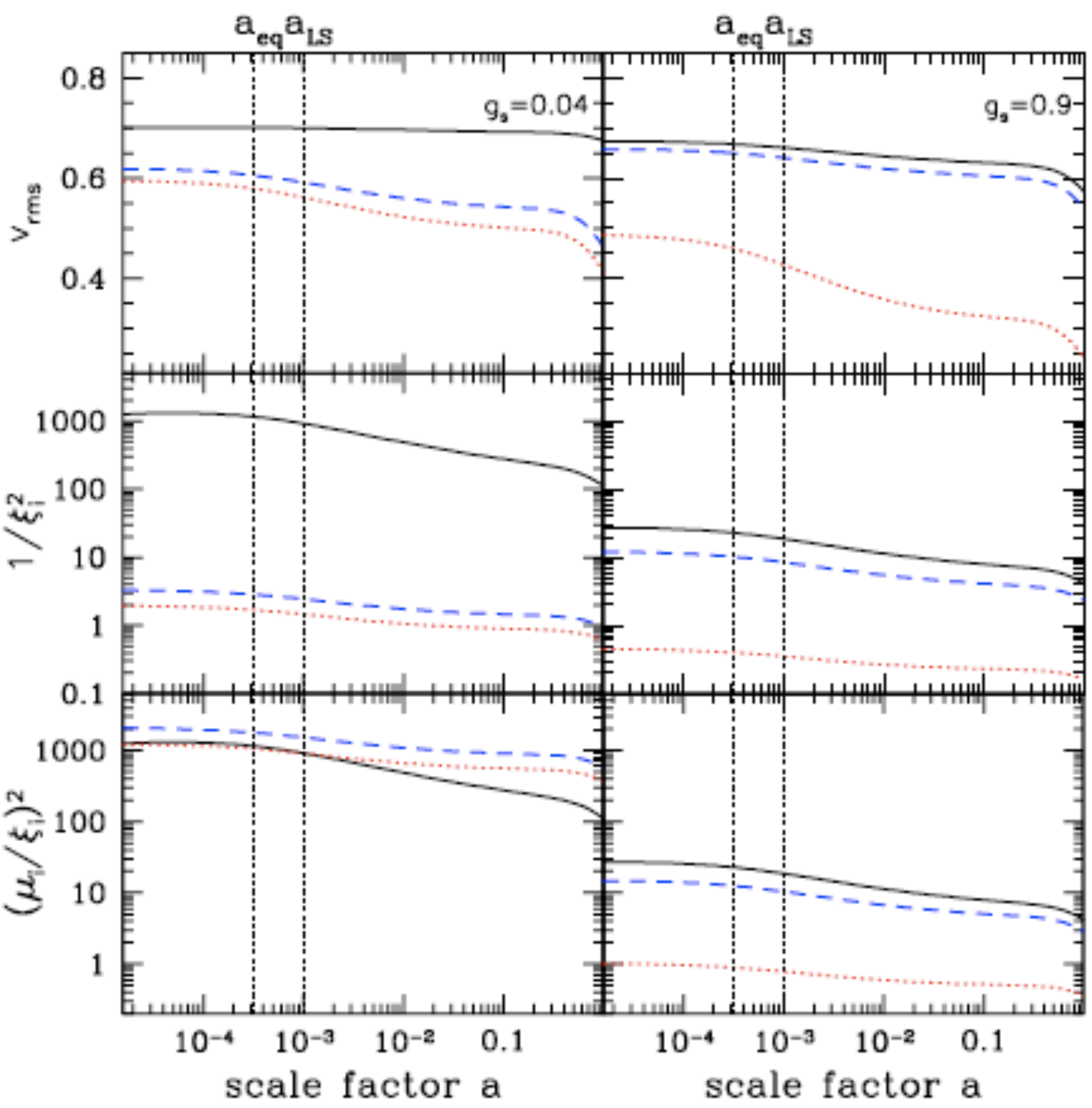
Distinguishing cosmic superstrings through cosmology

1. Intercommuting probability for gauged strings P~1 always ! In other words when two pieces of string cross each other, they reconnect. Not the case for superstrings -- model dependent probability [Jackson et al 04].

2. Existence of new `defects' D-strings allows for existence of new hybrid networks of F and D strings which could have different scaling properties, and distinct observational effects.



Case of network of F,D and FD strings: [Pourtsidou et al 2010]



Velocities:

F and D strings dominate both the number density and the energy density for larger values of g_s

Black -- (1,0) -- Most populous
Blue dash -- (0,1)
Red dot dash -- (1,1)

Deviation from scaling at end as move into Λ domination.

Note: Dominant CMB contribution switches as go from small to large string coupling because of changing balance between number density and energy density.

Strings and the CMB

Modified CMBACT (Pogosian) to allow for multi-tension strings.
Shapes of string induced CMB spectra mainly obtained form large scale properties of string such as correlation length and rms velocity given from the earlier evolution eqns.

Normalisation of spectrum depends on:

$$C_l^{strings} \propto \sum_{i=1}^{N} \left(\frac{G\mu_i}{\xi_i} \right)^2$$

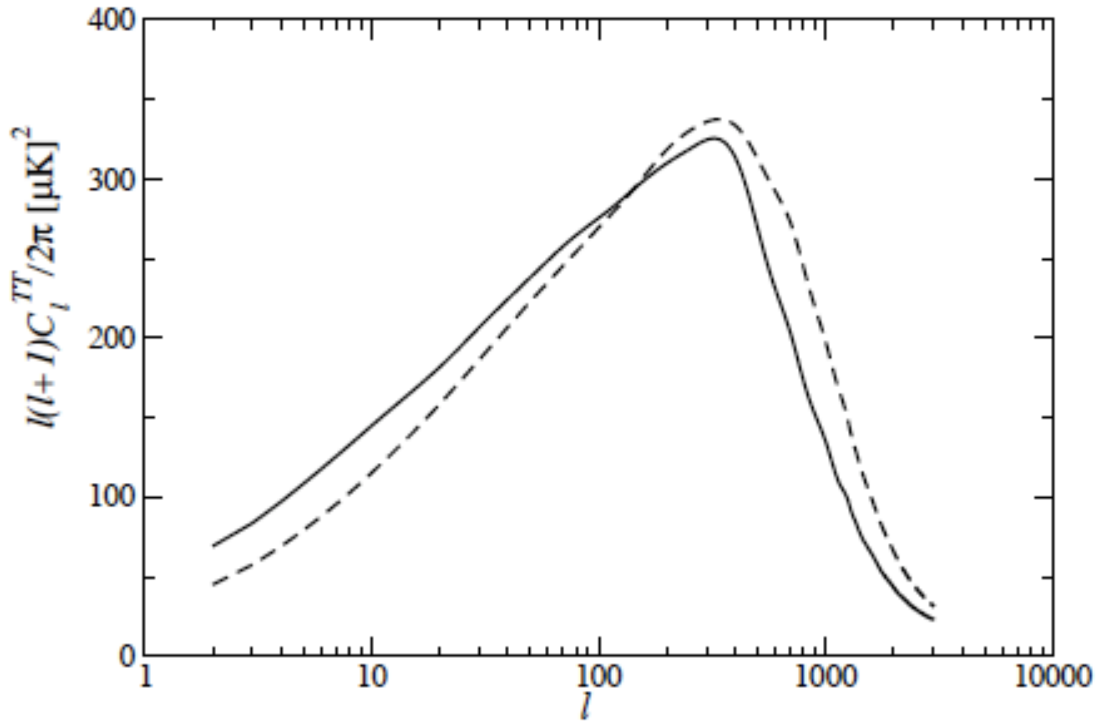
i.e. on tension and correlation lengths of each string

Since strings can not source more than 10% of total CMB anisotropy, we use that to determine the fundamental F string tension which is otherwise a free parameter. So μ_F chosen to be such that:

$$f_s = C^{TT}_{strings}/C^{TT}_{total} = 0.1$$

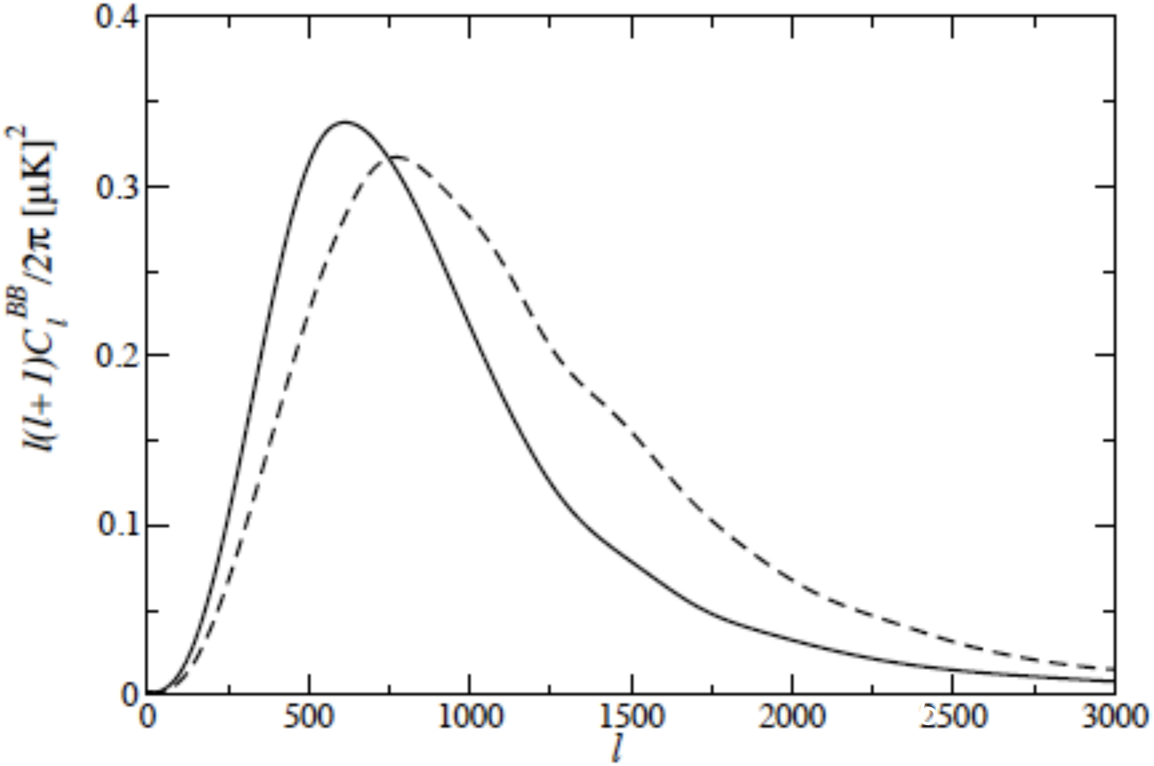
where

$$C^{TT} \equiv \sum_{\ell=2}^{2000} (2\ell+1) C^{TT}_{\ell}$$



Left:
Normalised TT power spectra (w=1, normalised to give 10% fractional contribution from strings).

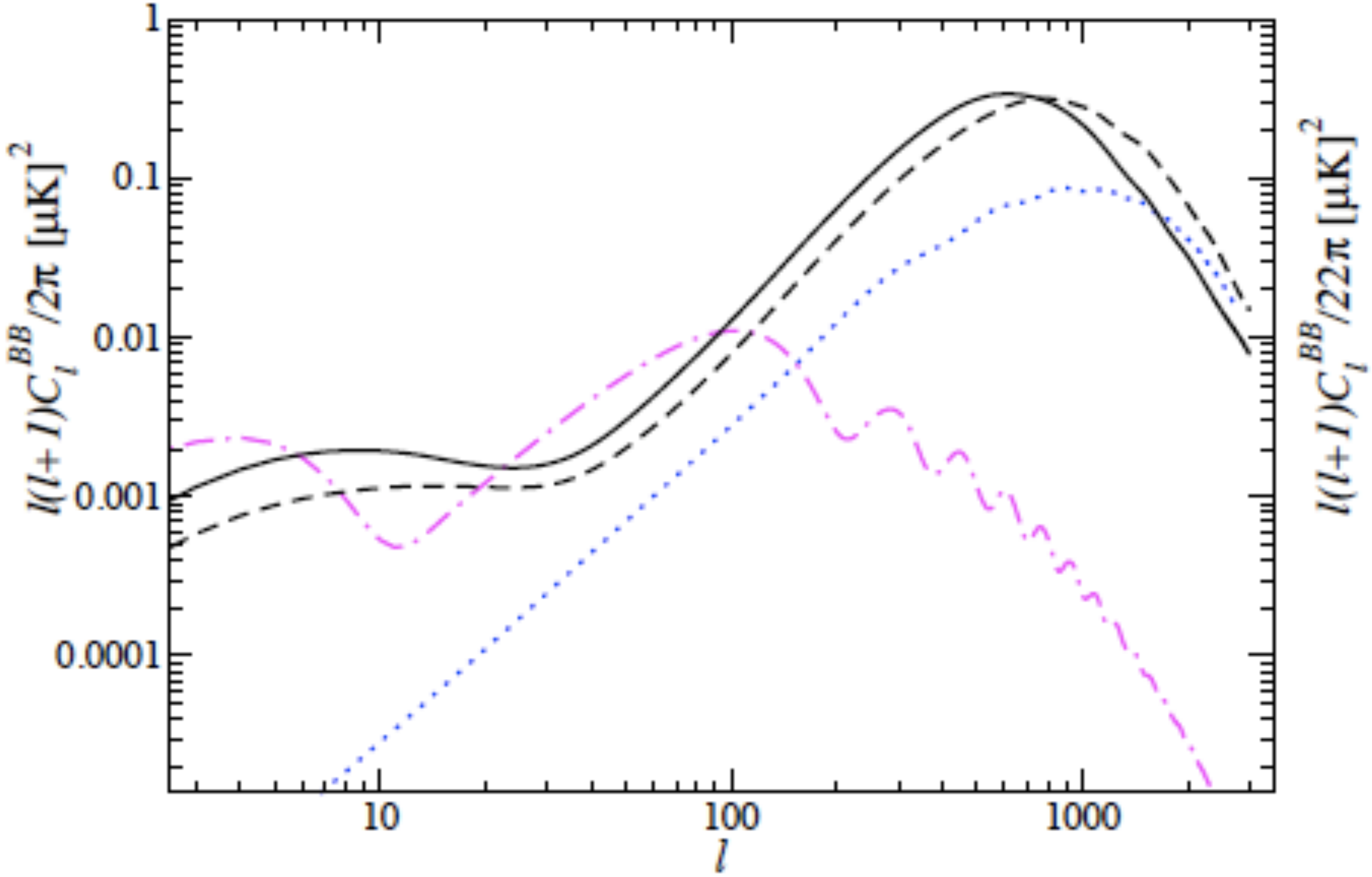
Solid black is g_s=0.04
Dotted line is g_s=0.9



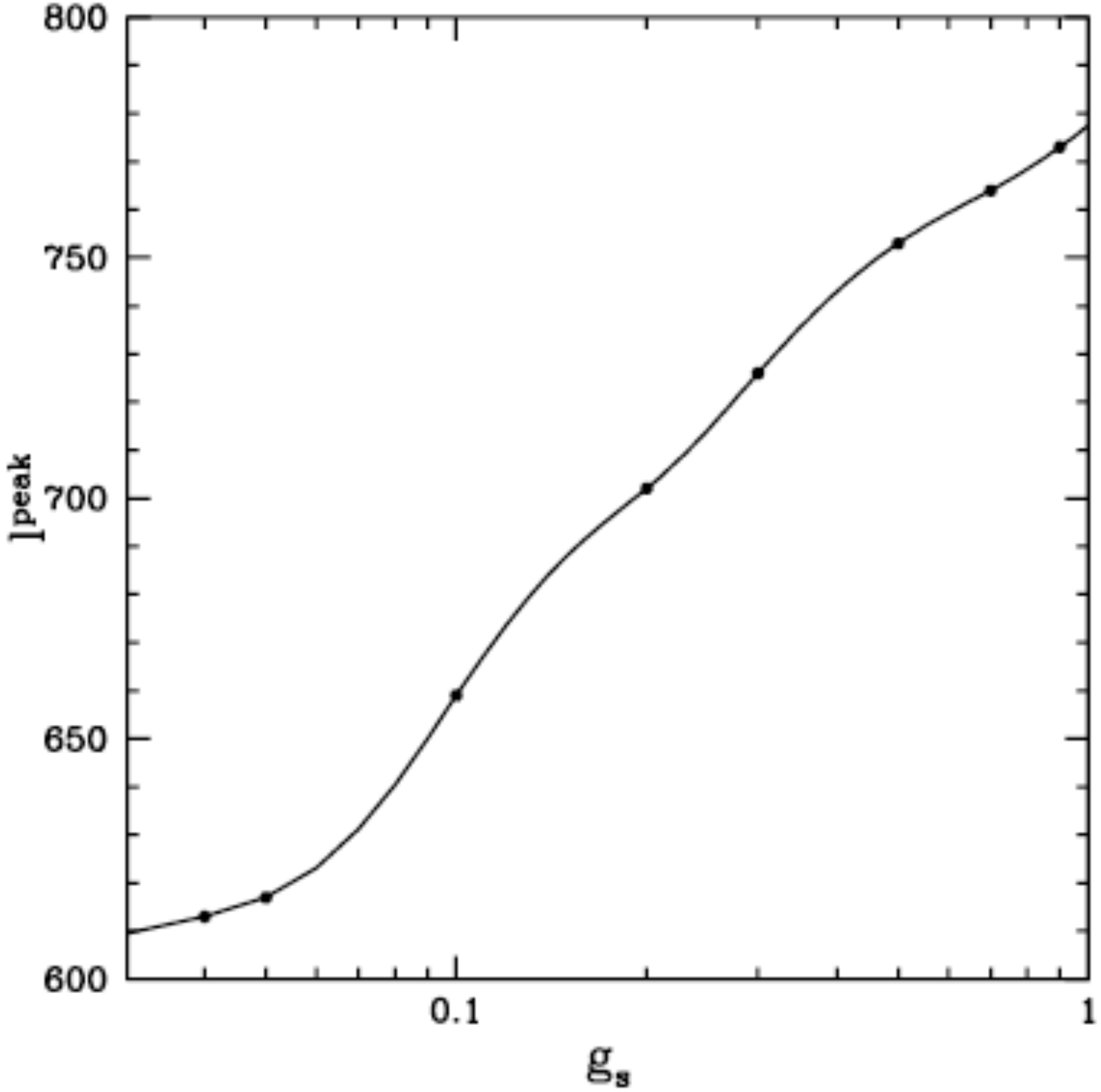
Right:
Normalised TT power spectra (w=1, normalised to give 10% fractional contribution from strings).

Solid black is g_s=0.04
Dotted line is g_s=0.9

Note smaller string coupling leads to discernible move in the peak of the BB spectra to small l -- showing impact of changing scaling solutions wrt light and heavy strings.



B type polarisation spectra due to cosmic superstrings assuming 10% string contribution. Solid black (g_s=0.04) and dashed black line (g_s=0.9). Expected spectra for E to B lensing (blue dot) and primordial grav waves assuming r=0.1 (magenta-dot-dash) also shown.



Example of peak position dependence on g_s.

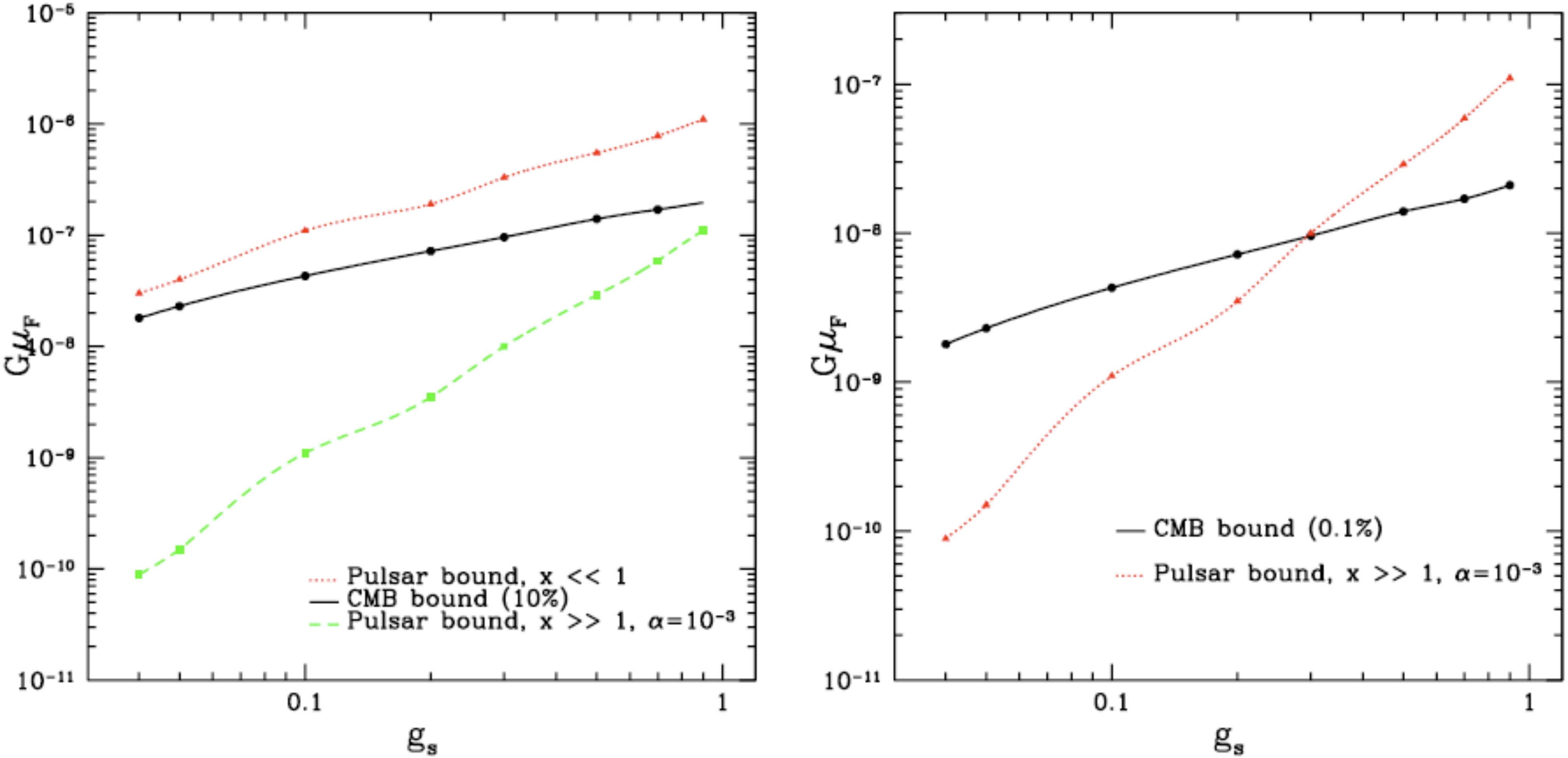
Precise change depends on assumptions about intercommuting prob. Still working on this aspect.

Position of the peak of the BB spectrum as a function of the string coupling g_s. The transition from high l values to lower values occurs when the density of string becomes dominated by the heavy rarer strings. w=1

Using cosmology to constrain μ_F and g_s

Aim use a combination of measurements to constrain the allowed parameter space making use of the fact they have different dependencies on the parameters. For example combining CMB and pulsar timing (Battye and Moss 10)

$$\Omega_{\rm g} h^2 = 1.17\times 10^{-4}\sum_{i=1}^{3} G\mu_i \left(\frac{1-\langle v^2_{\rm rad,i}\rangle}{\xi^2_{\rm rad,i}\Omega_{\rm m}}\right)\frac{(1+1.4x_i)^{3/2}-1}{x_i} \qquad x_i = \alpha/(\Gamma\, G\mu_i)$$



The Future

- Particle physicists engaged since the beginning.
- Implications for fundamental physics are profound.

Europe

CMBR: Planck

- **USA**

Summary

- Observations transforming field, especially SN1a, CMBR and LSS. Theory struggling to keep up.
- Why is the universe inflating today?
- Is w = - 1, the cosmological constant ?
- Is w(z) -- dynamical?
- New Gravitational Physics -- perhaps modifying Friedmann equation on large scales?
- Where is the inflaton in physics?
- Will we see evidence of strings in cosmology?
- Of course not touched the beginning of it all !
- Exciting period to be working in cosmology -- lots still to do.

Extra stuff -- in case of emergency

The problem with the cosmological constant

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Einstein (1917) -- static universe with dust

Not easy to get rid of it, once universe found to be expanding.

Anything that contributes to energy density of vacuum acts like a cosmological constant

$$< T_{\mu\nu} > = < \rho > g_{\mu\nu}$$

Lorentz inv

$$\lambda_{eff} = \lambda + 8\pi G < \rho >$$

or

$$\rho_V = \lambda_{eff}/8\pi G$$

Effective cosm const

Effective vac energy

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

$$H_0 \simeq 10^{-10} yr^{-1} : \frac{|k|}{a_0^2} \leq H_0^2 : |\rho - < \rho > | \leq \frac{3H_0^2}{8\pi G}$$

Age

Flat

Non-vac matter

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

$$H_0 \simeq 10^{-10} yr^{-1} : \frac{|k|}{a_0^2} \leq H_0^2 : |\rho - <\rho>| \leq \frac{3H_0^2}{8\pi G}$$

Hence: $\lambda_{eff} \leq H_0^2\ or |\rho_V| \leq 10^{-29} gcm^{-3} \simeq 10^{-47} GeV^4$

Problem: expect <ρ> of empty space to be much larger. Consider summing zero-point energies (ħω/2) of all normal modes of some field of mass m up to wave number cut off Λ>>m:

$$<\rho> = \int_0^{\Lambda} \frac{4\pi k^2 dk}{2(2\pi)^3}\sqrt{k^2+m^2} \simeq \frac{\Lambda^4}{16\pi^2}$$

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).

Imagine just one field contributed an energy density $\rho_{cr} \sim (10^{-3}\text{ eV})^4$. Implies the cut-off scale Λ<0.01 eV -- well below scales we understand the physics of.

Planck scale: $\Lambda \simeq (8\pi G)^{-1/2} \rightarrow <\rho> \simeq 2\times 10^{71} GeV^4$

But: $|\rho_V| = |<\rho> + \lambda/8\pi G| \leq 2\times 10^{-47} GeV^4$

Must cancel to better than 118 decimal places.

Even at QCD scale require 41 decimal places!

Very unlikely a classical contribution to the vacuum energy density will cancel this quantum contribution to such high precision

Not all is lost -- what if there is a symmetry present to reduce it? Supersymmetry does that. Every boson has an equal mass SUSY fermion partner and vice-versa, so their contributions to $<\rho>$ cancel.

However, SUSY seems broken today - no SUSY partners have been observed, so they must be much heavier than their standard model partners. If SUSY broken at scale M, expect $<\rho>\sim M^4$ because of breakdown of cancellations. Current bounds suggest M~1TeV which leads to a discrepancy of 60 orders of magnitude as opposed to 118 !

Still a problem of course -- is there some unknown mechanism perhaps from quantum gravity that will make the vacuum energy vanish ?

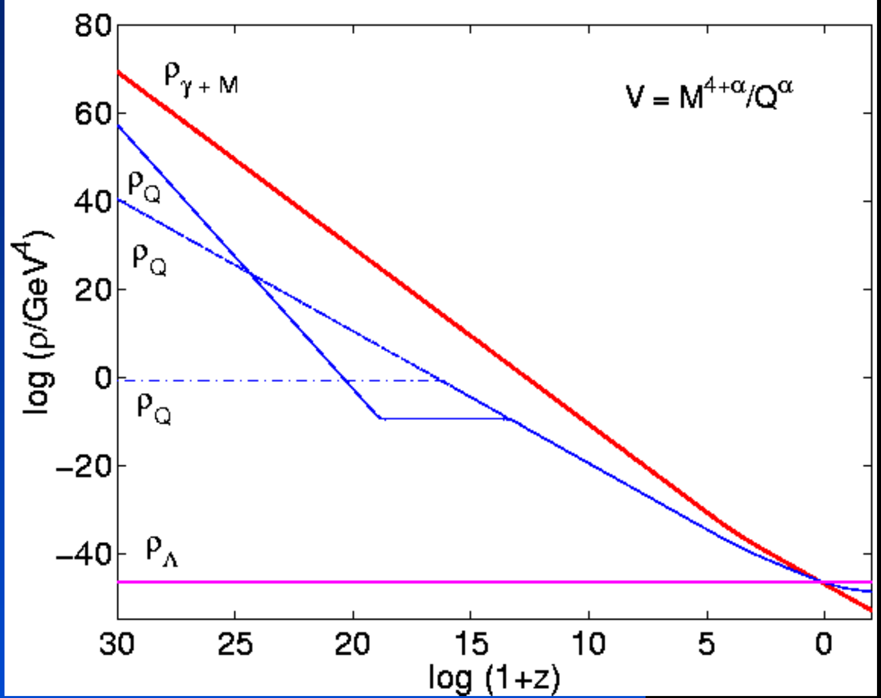
Original Quintessence model

Peebles and Ratra;

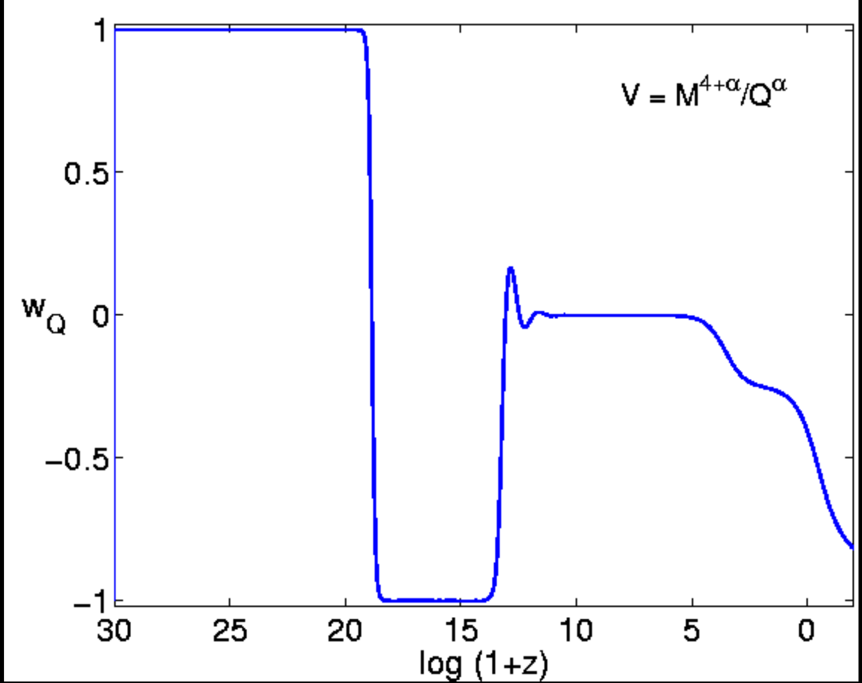
Zlatev, Wang and Steinhardt

$$\boxed{V(\phi)=\frac{M^{4+\alpha}}{\phi^{\alpha}}}$$

Find: $\phi = \phi_i \left(\frac{a}{a_i}\right)^{\frac{3(1+w_B)}{2+\alpha}}$ and $\boxed{w_\phi = \frac{\alpha w_B - 2}{2+\alpha}}$



$\boxed{\alpha = 6}$



And so where are we today?

- Exciting time in cosmology -- Big Bang huge success.
- String - theory suggests we can consistently include gravity into particle physics.
- What started the big bang ?
- How did inflation emerge – if at all ?
- How did the spacetime dimensions split up?
- Where did the particle masses come from?
- Why are there just three families of particles?
- Why is the Universe accelerating today?
- What is the dark matter
- Where is all the anti-matter?

A few issues over the cosmological constant:

Is the observed dark energy really representing the energy of the vacuum or is it just that we have not yet reached it and it is a dynamical process?

The cosmological constant is the simplest addition, requires nothing other than one more fundamental constant and requires no modification of GR or addition of new fields.

How does it relate to early universe inflation? That lasted a finite time, perhaps this will imply there is nothing special about our vacuum.

Maldacena has shown stable QG vacuum of negative vacuum energy can exist (AdS/CFT), as can vacuum of zero energy (include SUSY). No one has shown a stable positive vacuum energy is possible in theories of QG. [Witten 2008]

This would imply our Universe is unstable - perhaps a bit drastic!

Acc^n from new Gravitational Physics? [Starobinski 1980, Carroll et al 2003, ...]

$$S = \frac{M_{\rm P}^2}{2}\int d^4x\,\sqrt{-g}\left(R - \frac{\mu^4}{R}\right) + \int d^4x\,\sqrt{-g}\,\mathcal{L}_M$$

Modify Einstein

Const curv vac solutions:

$$\nabla_\mu R = 0, \rightarrow R = \pm\sqrt{3}\mu^2$$

de Sitter or Anti de Sitter

Transform to EH action:

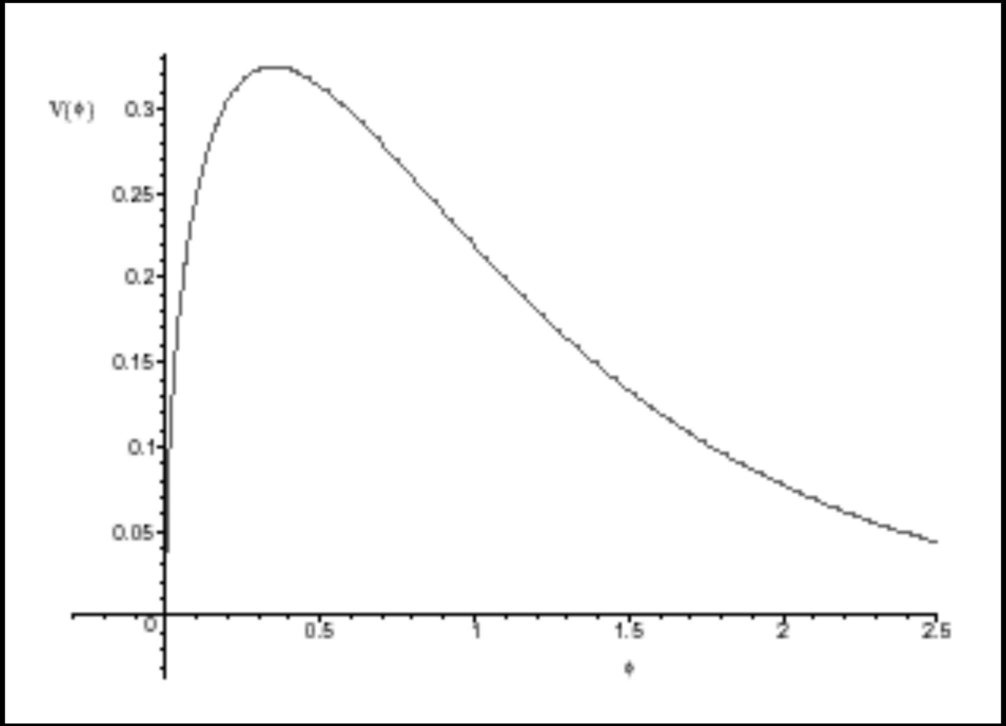
$$\tilde{g}_{\mu\nu} = p(\phi)g_{\mu\nu}\ , \quad p \equiv \exp\left(\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm P}}\right) \equiv 1 + \frac{\mu^4}{R^2}$$

Scalar field minimally coupled to gravity and non minimally coupled to matter fields with potential:

$$V(\phi) = \mu^2 M_{\rm P}^2 \frac{\sqrt{p-1}}{p^2}$$

Cosmological solutions:

1. **Eternal de Sitter - ϕ just reaches V_{max} and stays there. Fine tuned and unstable.**
2. **Power law inflation -- ϕ overshoots V_{max}, universe asymptotes with $w_{DE}=-2/3$.**
3. **Future singularity-- ϕ doesn't reach V_{max}, and evolves back towards $\phi=0$.**



1.Fine tuning needed so acceleration only recently: $\mu \sim 10^{-33}$eV

2. Also, not consistent with classic solar system tests of gravity.

3. Claim that such R^{-n} corrections fail to produce matter dom era [Amendola et al, 06]

But recent results based on singular perturbation theory suggests it is possible [Evans et al, 07 -- see also Carloni et al 04]

Designer f (R) or f(G) models [Hu and Sawicki (2007), ...]

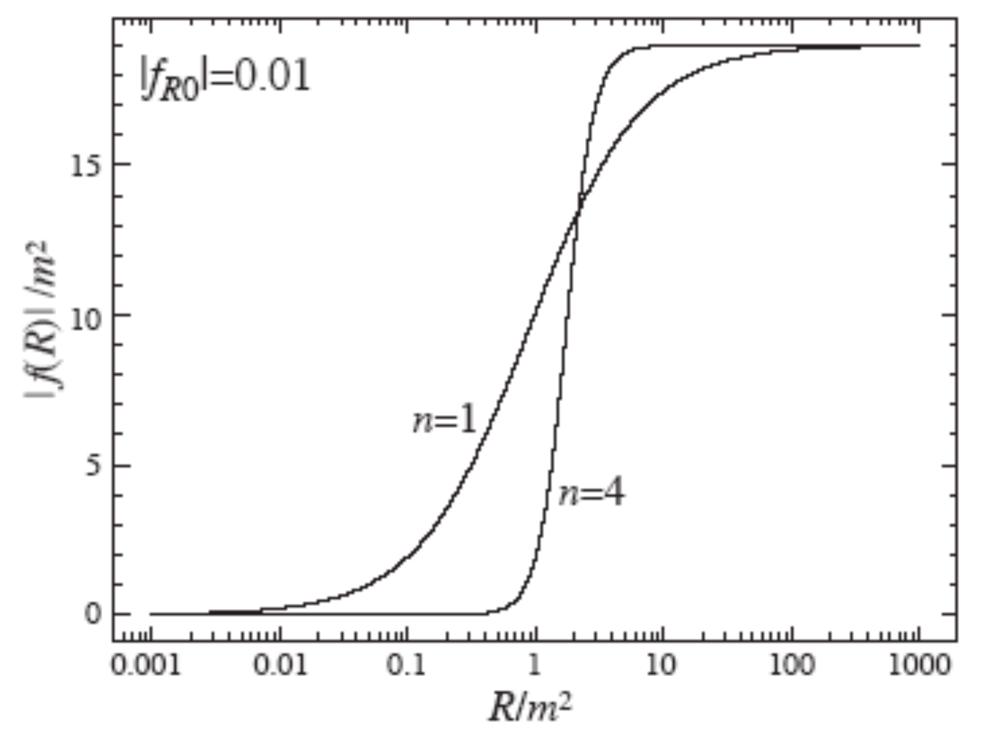
Construct a model to satisfy observational requirements:

1. Mimic LCDM at high z as suggested by CMB
2. Accelerate univ at low z
3. Include enough dof to allow for variety of low z phenomena
4. Include phenom of LCDM as limiting case.
5. Quantum corrections?

$$\lim_{R\to\infty} f(R) = \text{const.}\,,$$
$$\lim_{R\to 0} f(R) = 0\,,$$

$$f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1}\,,$$

$$f_{RR} \equiv \frac{d^2 f(R)}{dR^2} > 0$$



More general f (R) models [Gurovich & Starobinsky (79); Tkachev (92); Carloni et al (04,07,09); Amendola & Tsujikawa 08; Bean et al 07; Wu & Sawicki 07; Appleby & Battye (07) and (08); Starobinsky (07); Evans et al (07); Frolov (08)…]

$$S = \int d^4x\sqrt{-g}\left[\frac{R + f(R)}{2\kappa^2} + \mathcal{L}_m\right]$$

No Λ

Usually f (R) struggles to satisfy both solar system bounds on deviations from GR and late time acceleration. It brings in extra light degree of freedom --> fifth force constraints.

Ans: Make scalar dof massive in high density solar vicinity and hidden from solar system tests by chameleon mechanism.

Requires form for f (R) where mass of scalar is large and positive at high curvature.

Issue over high freq oscillations in R and singularity in finite past.

In fact has to look like a standard cosmological constant [Song et al, Amendola et al]

Modifications of Friedmann equation in 4D:

Write: $$H^2 = \frac{8\pi}{3m_4^2}\rho L^2(\rho)$$

$$L(\rho) = 1$$

Standard Friedmann

$$L(\rho) = \sqrt{1 + \frac{\rho}{2\sigma}}; \quad \sigma^{1/4} > 2.0 MeV$$

Randall-Sundrum II: co-dimension one brane, embedded in 5D AdS space.

$$L(\rho) = \sqrt{1 - \frac{\rho}{2|\sigma|}}; \quad \sigma < 0$$

Shtanov-Sahni: co-dimension one brane, negative tension embedded in 5D conformally flat Einstein space where signature of 5th dim is timelike

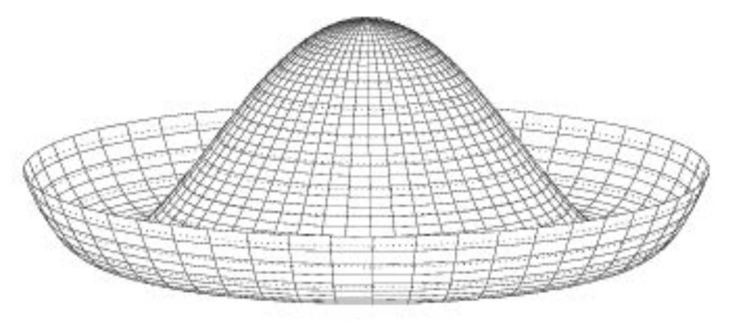
$$L(\rho) = \sqrt{1 + A\rho^n}; \quad n < -1/3$$

Cardassian: only matter present --> late time acceleration. Freese & Lewis

$$L = \frac{1}{\sqrt{B\rho}}\left[\mp 1 + \sqrt{1 + B\rho}\right]; B \equiv \frac{8\pi m_4^2}{3m_5^6}$$

Dvali-Gabadadze-Porrati: 3-brane embedded in flat 5D Minkowski with Ricci scalar term included in brane action. Bulk empty.

Searching for strings in cosmology
Original cosmic strings, in gauge theory :



Spontaneously broken $U(1)$ symmetry, has magnetic flux tube solutions (Nielsen-Oleson vortices).

Network would form in early universe phase transitions where $U(1)$ symmetry *becomes* broken. Higgs field roles down the potential in different directions in different regions (Kibble 76).

String tension : μ Dimensionless coupling to gravity : G μ
GUT scale strings : G $\mu \sim 10^{-6}$ -- size of string induced metric perturbations.

Observational consequences : 1980's and 90's

Single string networks evolve with Nambu-Goto action, decaying primarily by forming loops through intercommutation and emitting gravitational radiation and possibly particles.

For gauge strings, reconnection probability P~1

Scaling solutions are reached where energy density in strings reaches constant fraction of background energy density:

$\rho_{string}/\rho_{rad} \sim 400G\mu$

$\rho_{string}/\rho_{mat} \sim 60G\mu$

[Albrecht &Turok; Bennett & Bouchet; Allen & Shellard]

Density increases as P decreases because takes longer for network to lose energy to loops. Recent re-analysis of loop production mechanisms suggest two distributions of long and small loops.