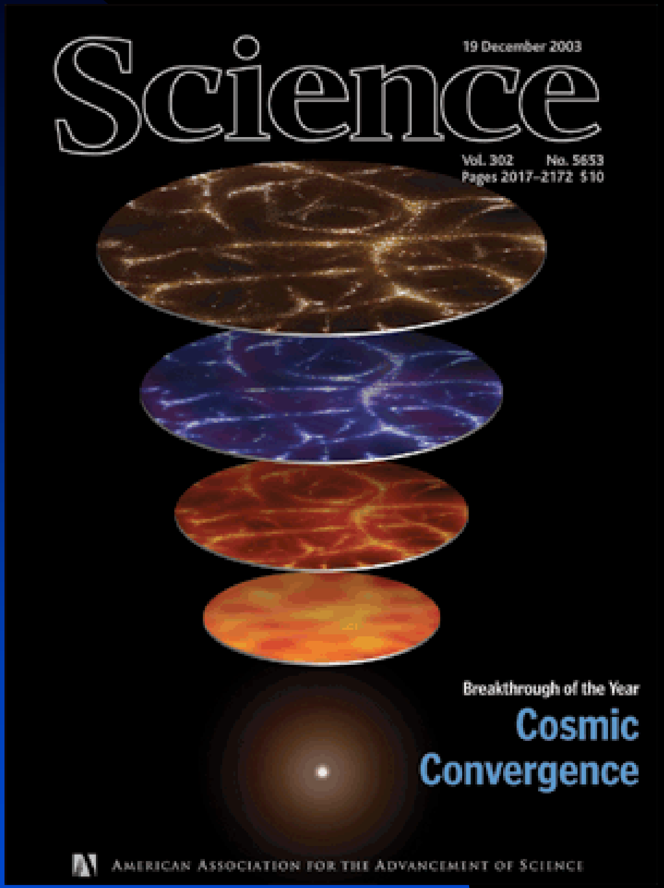
Attempts to explain the nature of dark energy -- How desperate can we get?

Ed Copeland University of Sussex

1. The energy budget.
2. Evidence for dark energy?
3. Problems facing theorists building models of dark energy.

Brijuni, Croatia, Sept 2nd, 2004

Science Magazine -- Breakthrough of the year -Dec 2003

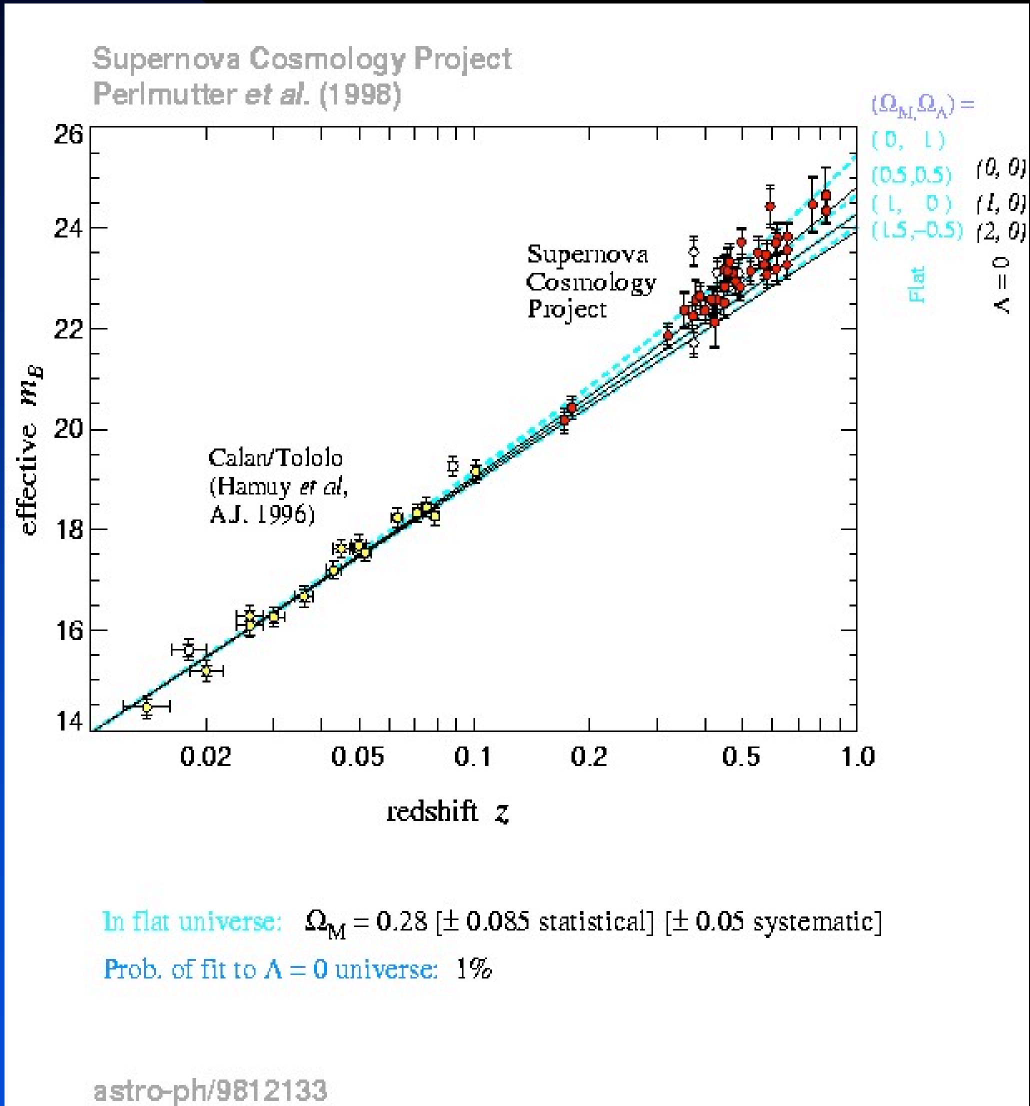


``Disks represent an aging and expanding universe.

Work this year confirmed a bizarre story of how the cosmos was born and what it is made of.

Dark energy is the primary ingredient in a universe whose expansion rate and age are now known with unprecedented precision.''

1. The Big Bang – (1sec → today)



Test 1

- The expansion of the Universe

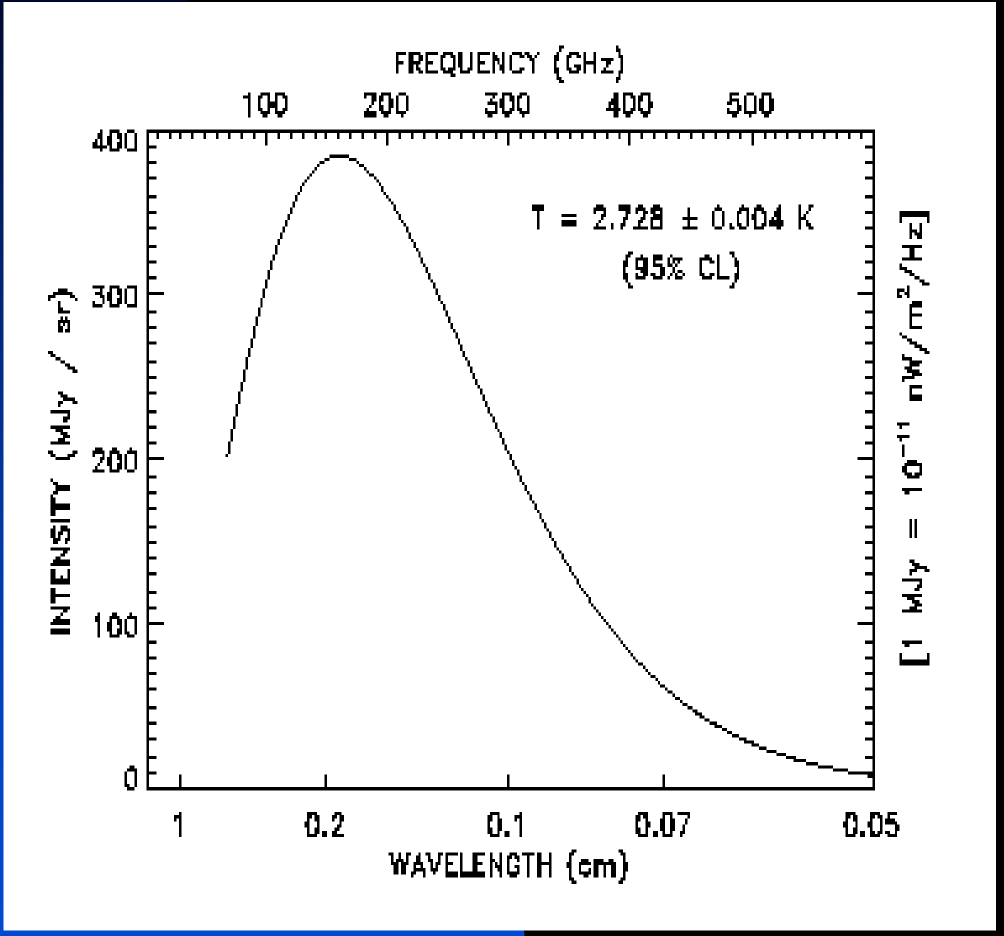
$H_0 = 72^{+}_{-}8$ km s^{-1} Mpc^{-1}

(Freedman et al, 2001)

How far back can we see?

Back to when the Universe was just 1/6 the size it is today – over 11 Billion years ago.

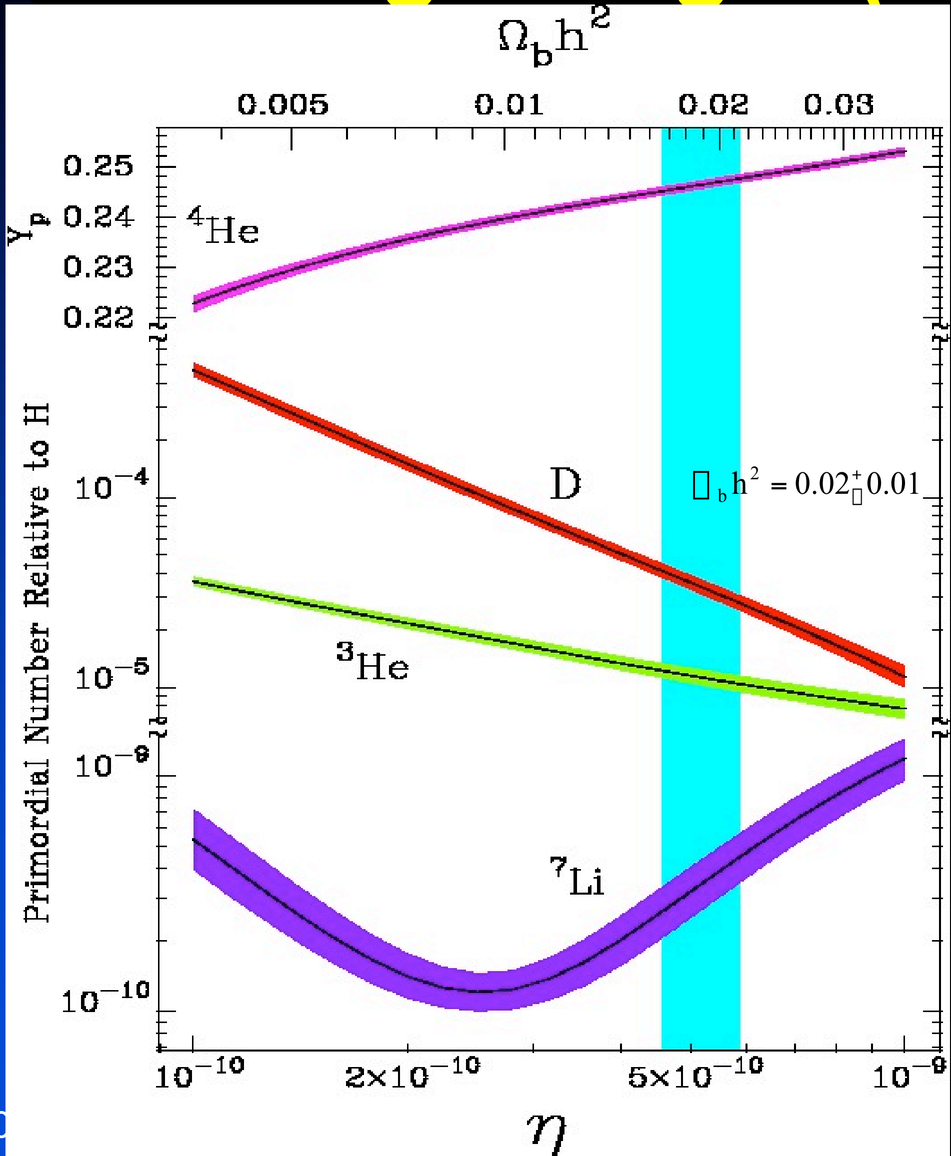
The Big Bang – (1sec → today)



Test 2

- **The existence and spectrum of the CMBR**
- **T_0=2.728 ± 0.004 K**

The Big Bang – (1sec → today)



Test 3

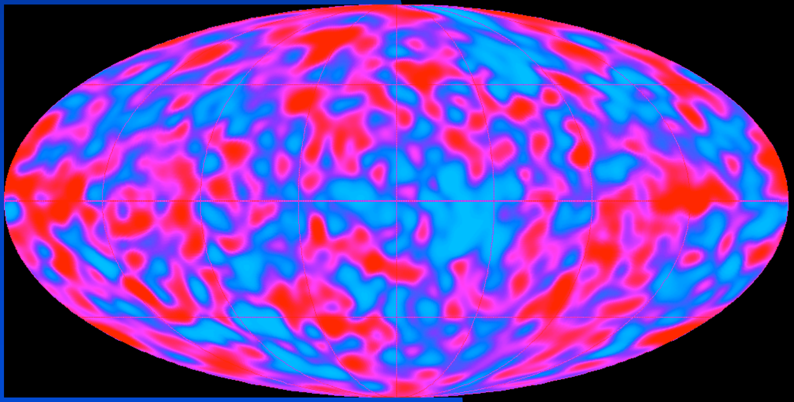
- The abundance of light elements in the Universe.
- Most of the visible matter just hydrogen and helium.

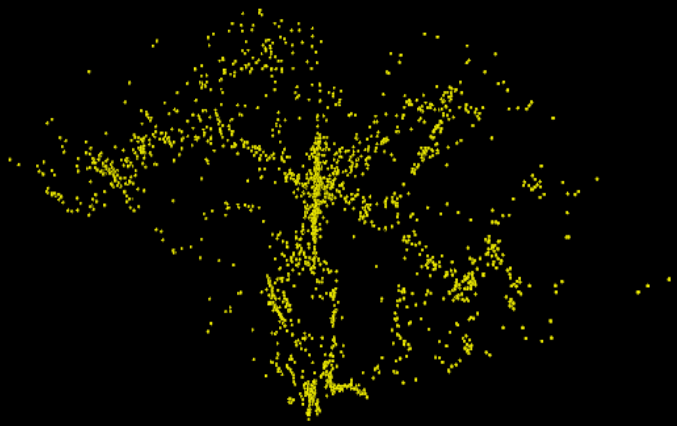
$$\Omega_b h^2 = 0.02^{+0.01}_{-0.01}$$

The Big Bang – (1sec → today)

Test 4

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





Go along way with Sir Isaac

Cosmological principle → Friedmann equation

$$Newton: \quad \ddot{a} = -\frac{GM}{a^2}$$

$$integrate: \frac{\dot{a}^2}{2} - \frac{GM}{a} = -\frac{k}{2} : C\ of\ Energy$$

$$But: M = \frac{4\pi}{3}\rho a^3 = const$$

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

Ok by Birkhoff

a(t): scale factor – physical size of Universe

k– spatial curvature of universe – need GR here

More generally

With cosm const:

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

a(t) depends on matter.

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

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

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

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

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

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

$$\rho(\mathrm{t}) = \rho_0\left(\frac{\mathrm{a}}{\mathrm{a}_0}\right)^{-3(1+\mathrm{w})} \;;\quad \mathrm{a}(\mathrm{t}) = \mathrm{a}_0\left(\frac{\mathrm{t}}{\mathrm{t}_0}\right)^{2/3(1+\mathrm{w})}$$

$$\mathrm{RD}: \mathrm{w} = \frac{1}{3} : \rho(\mathrm{t}) = \rho_0\left(\frac{\mathrm{a}}{\mathrm{a}_0}\right)^{-4} \;;\quad \mathrm{a}(\mathrm{t}) = \mathrm{a}_0\left(\frac{\mathrm{t}}{\mathrm{t}_0}\right)^{1/2}$$

$$\mathrm{MD}: \mathrm{w} = 0 : \rho(\mathrm{t}) = \rho_0\left(\frac{\mathrm{a}}{\mathrm{a}_0}\right)^{-3} \;;\quad \mathrm{a}(\mathrm{t}) = \mathrm{a}_0\left(\frac{\mathrm{t}}{\mathrm{t}_0}\right)^{2/3}$$

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

A neat equation

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

Friedmann eqn

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

$$\rho_c(t_0) \equiv 1.88 h^2 \times 10^{-29} \mathrm{g\,cm^{-3}}$$

Critical density

Weighing the Universe

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

$1. \Omega_m$

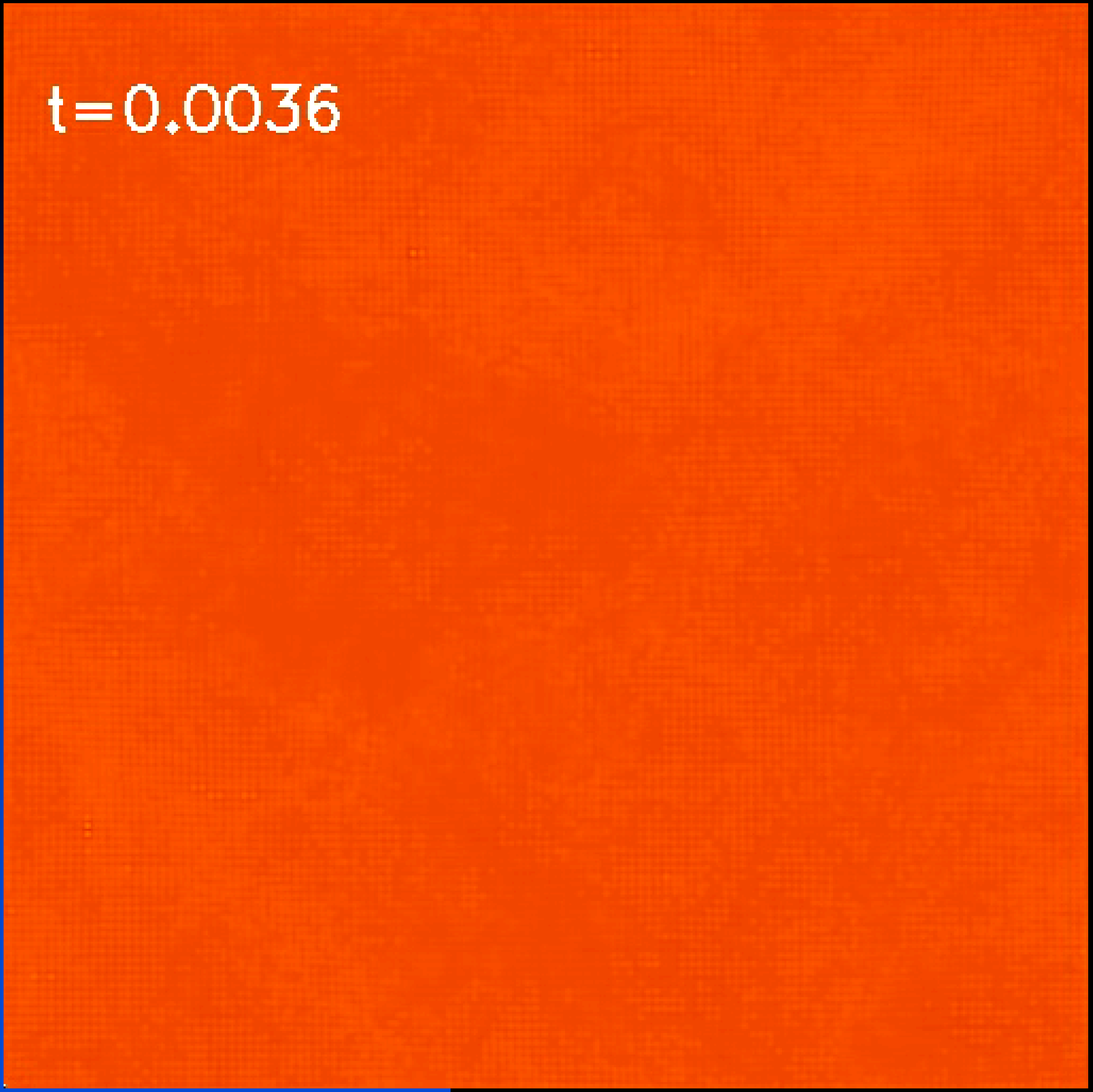
a. Cluster baryon abundance using X-ray measurements of intracluster gas, or SZ measurements.

b. Weak grav lensing and large scale peculiar velocities.

c. Large scale structure distribution.

d. Numerical simulations of cluster formation.

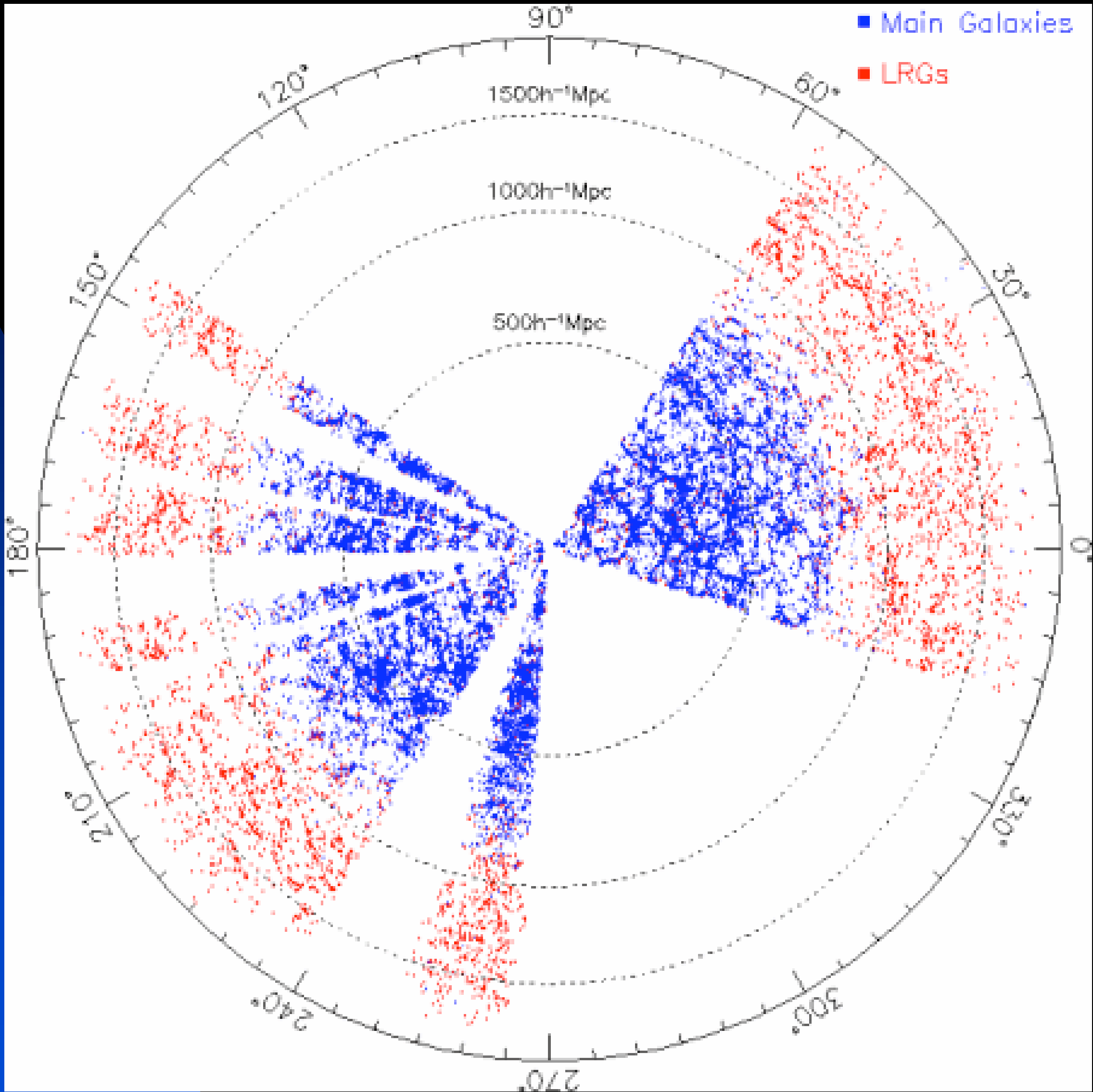
$$\Omega_m = 0.3 \pm 0.05 \qquad \Omega_m << 1$$



Structure formation due to gravitational collapse:

Virgo consortium

Sloan Digital Sky Survey



Homogeneous on large scales?

2. Ω_b

BBN → $\Omega_b h^2 = 0.02^{+0.01}_{-0.01}$

↓

Majority of baryonic matter dark.

$\Omega_b << \Omega_m$

↓

Require Dark matter !!

CDM	HDM – strongly constrained
Axions	Neutrinos
Neutralinos	
PBH's	
Supermassive relics …	

Supersymmetry and dark matter

Neutrinos not likely unless almost degenerate in mass, require 5-40eV.

WIMPS such as neutralinos, axions, axinos, gravitinos…

Interactions with matter vary enormously in strength: neutralinos (10^{-2}) – gravitinos (10^{-33}).

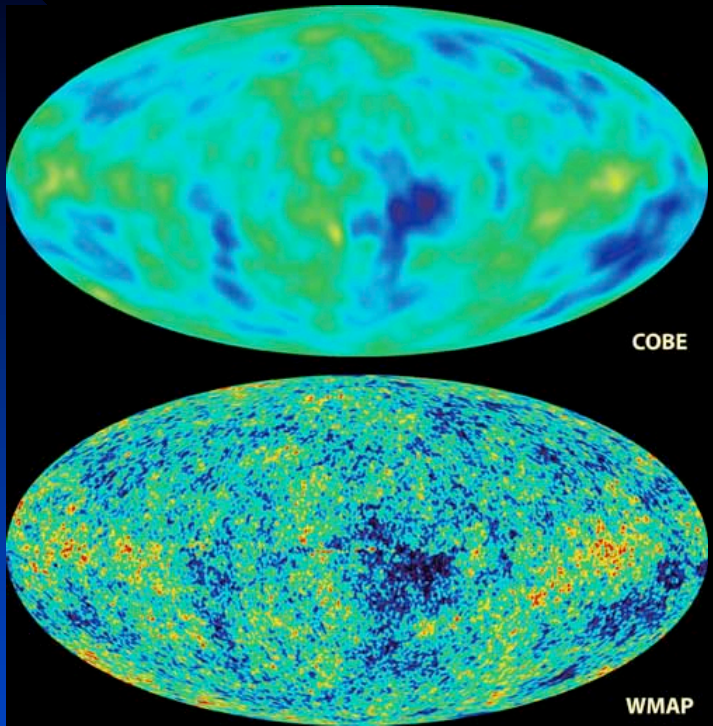
Neutralino- well motivated, LSP (assumption), gives closure for range of SUSY masses below a few TeV.

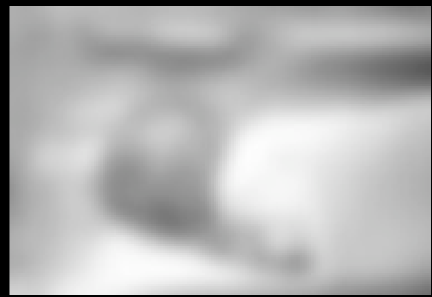
Ex: Gaugino like neutralino has allowed mass in range 30-150 GeV.

Looking for those primordial fluctuations. Ripples in the smooth cosmic microwave background radiation.

1992

2003





Blurred image

Sharp image

Measuring changes of temperature of a few parts in 100,000

Remember the background temp is 2.7Kelvin

Evidence for Dark Energy?

Enter CMBR:

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

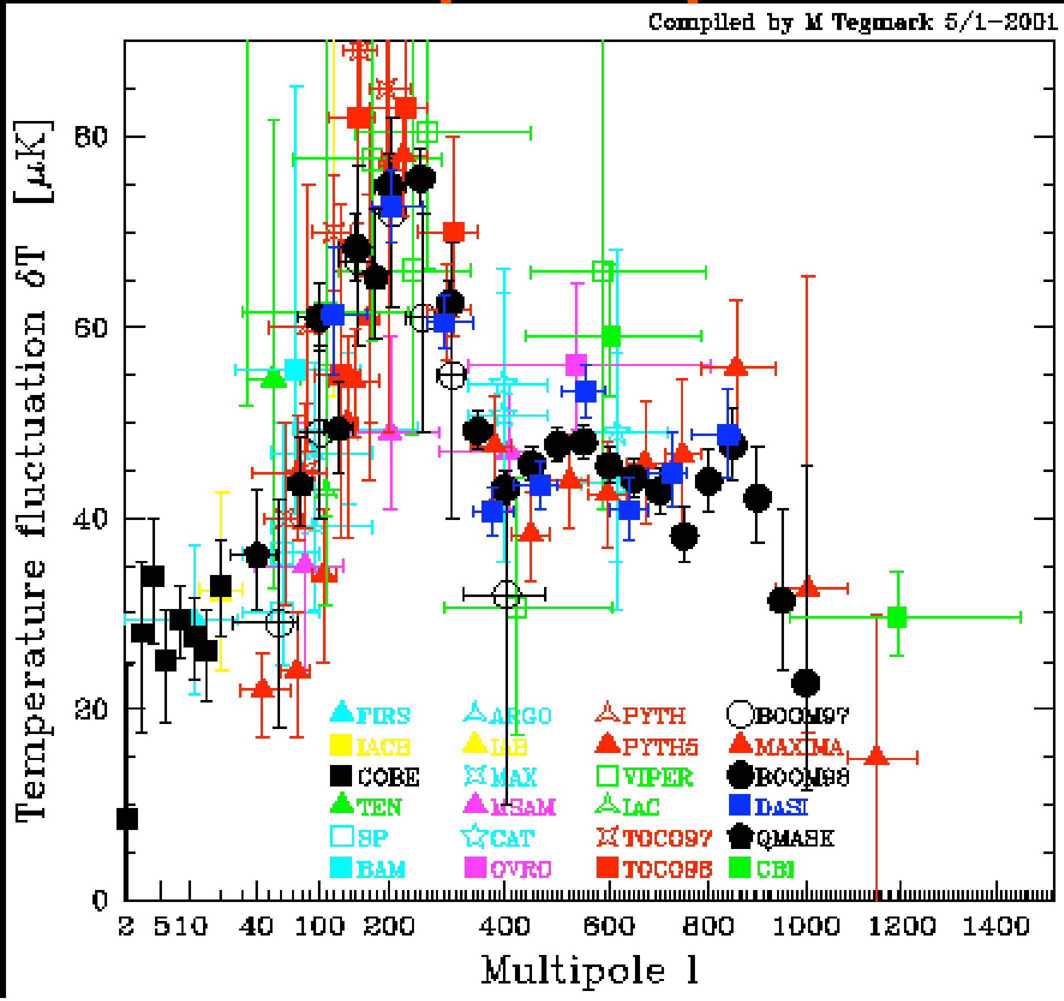
Provides clue. 1st angular peak in power spectrum.

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

$$\Omega_0 = 1.095^{+0.094}_{-0.144}$$

WMAP-Depends on assumed priors

Tegmark et al 2003



The problem with the cosmological constant

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

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

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

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

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

Problem: expect <□> of empty space to be much larger.
Consider summing zero-point energies of all normal modes of some field of mass m up to wave number cut off □>>m:

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

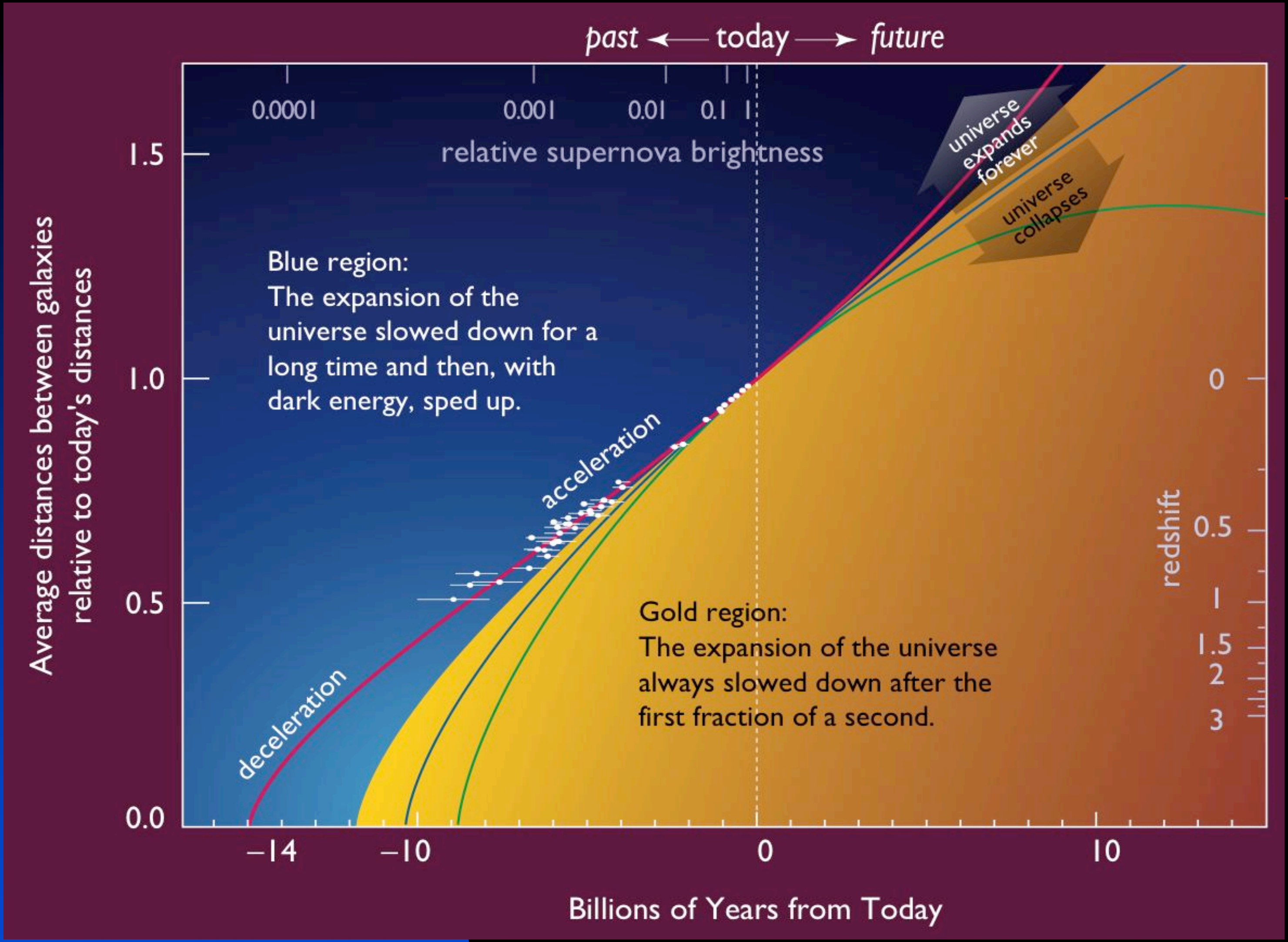
Planck scale: $\Lambda \simeq (8\pi G)^{-1/2} \rightarrow <\rho> \simeq 2 \times 10^{71} GeV^4$

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

Must cancel to better than 118 decimal places.

Even at QCD scale require 41 decimal places!

Evidence for Acceleration



data from Supernova Cosmology Project (LBL)

graphic by Barnett, Linder, Perlmutter & Smoot (for OSTP)

Exploding stars – supernovae –bright beacons that allow us to measure the expansion over the last 10 billion years.

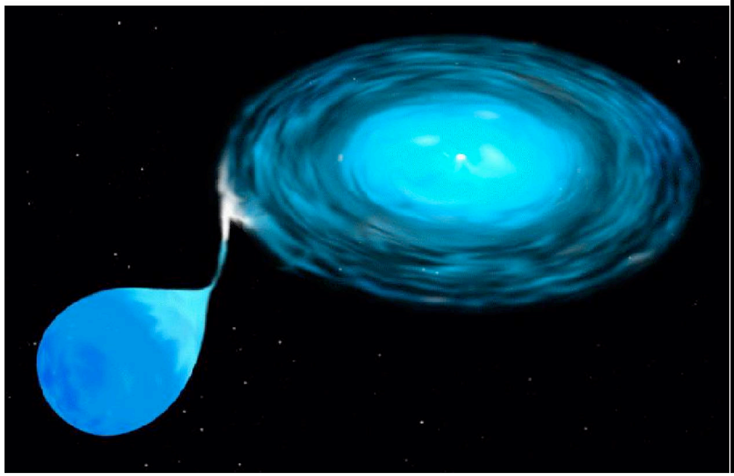
Type Ia Supernovae

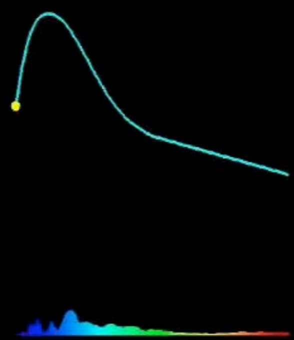
- Exploding star, briefly as bright as an entire galaxy
- Characterized by no Hydrogen, but with Silicon
- Gains mass from companion until undergoes thermonuclear runaway

Standard explosion from nuclear physics

SCP

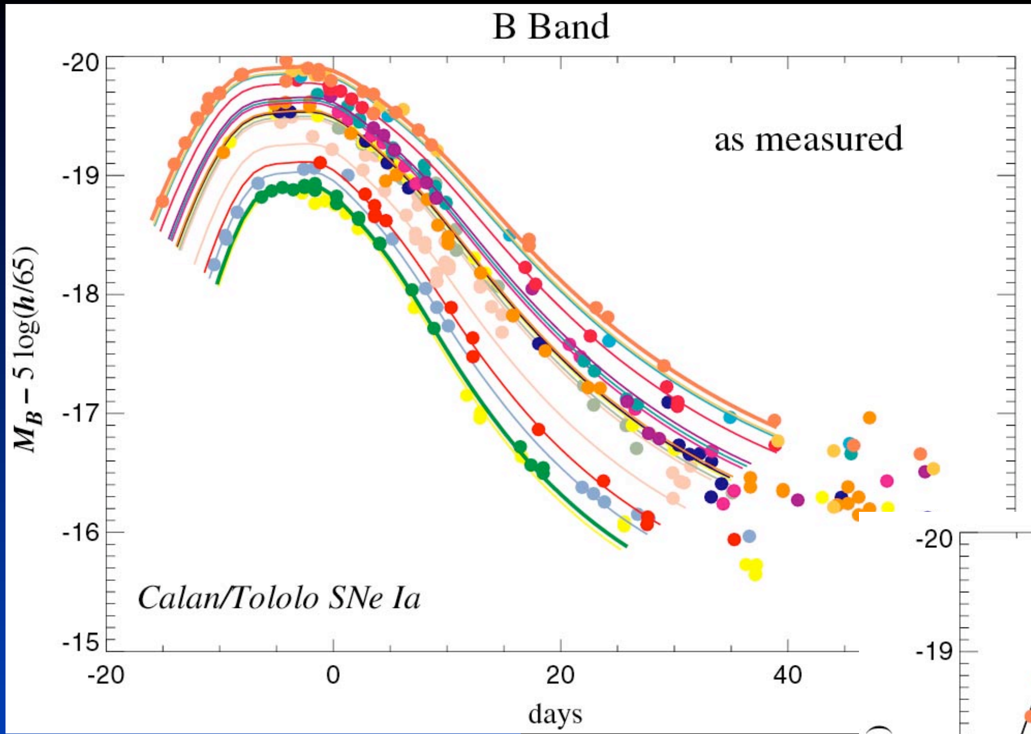
Insensitive to initial conditions:
"Stellar amnesia"
Höflich, Gerardy, Linder, & Marion 2003

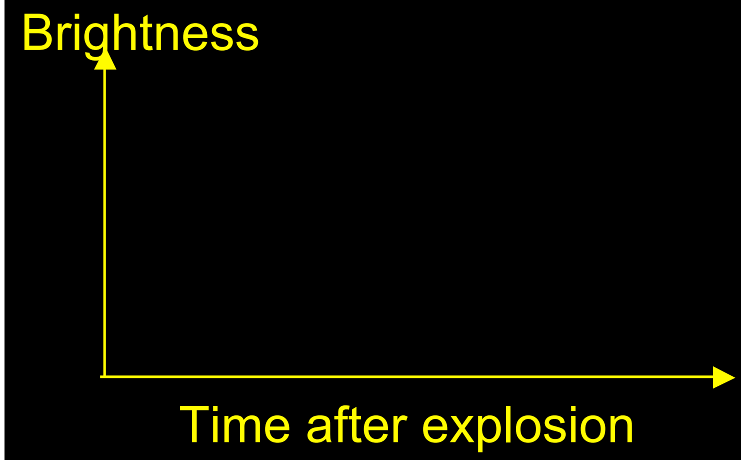




Standard Candle

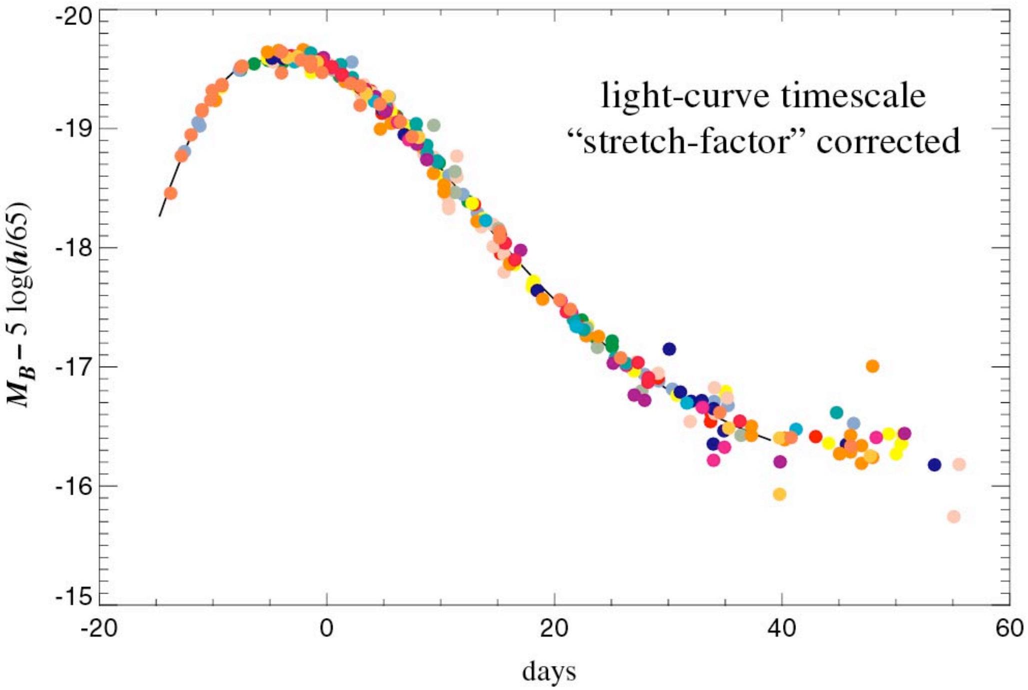
Linder





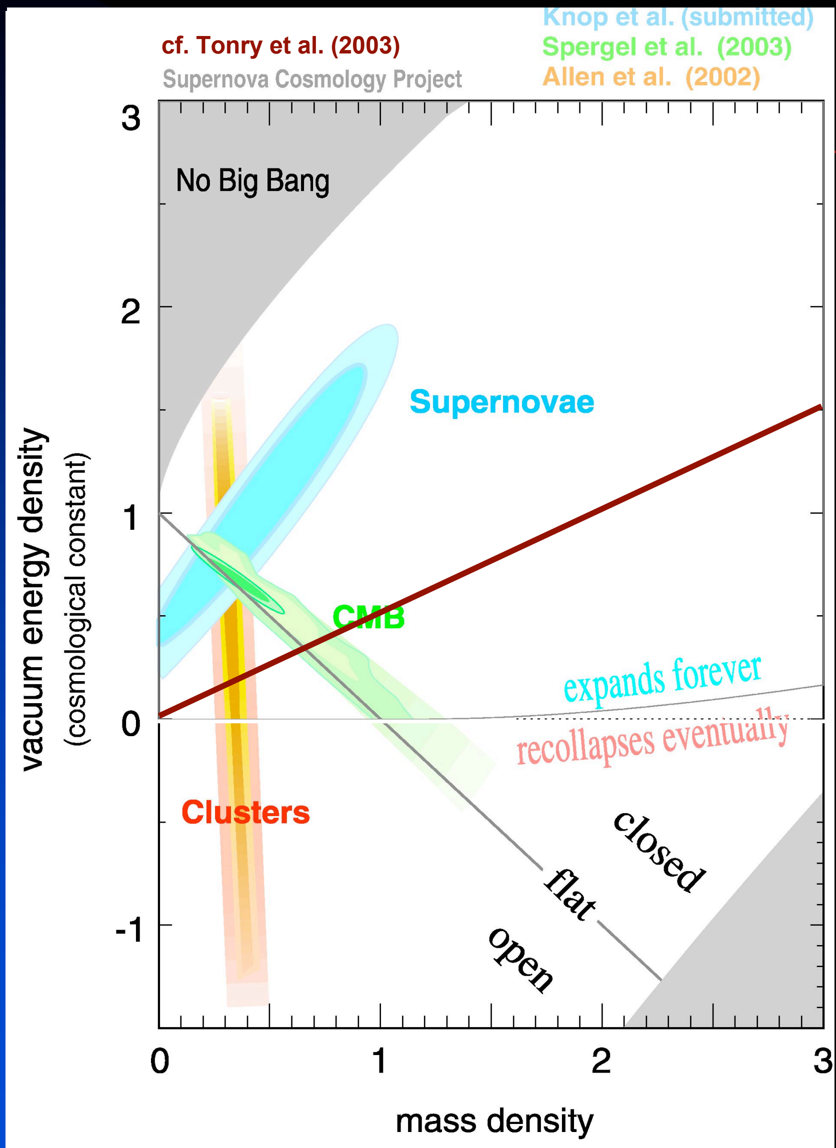
Brightness tells us distance away (lookback time)

Redshift measured tells us expansion factor (average distance between galaxies)



Kim, *et al.* (1997)

Cosmic Concordance



- *Supernovae alone*

□ Accelerating expansion

□ □ > 0

- *CMB (plus LSS)*

□ Flat universe

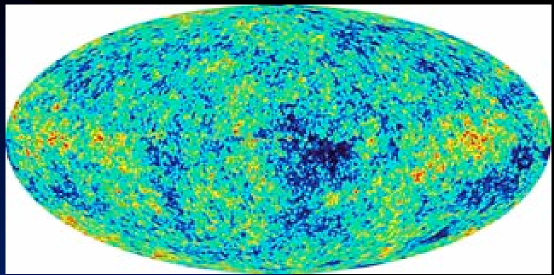
□ □ > 0

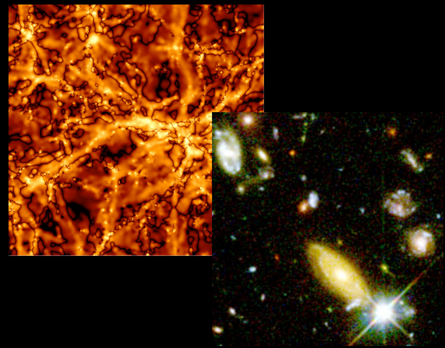
- *Any two of SN, CMB, LSS*

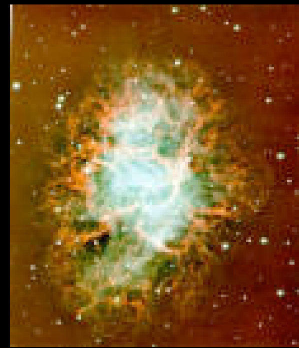
□ Dark energy ~75%

Cosmic probes

Linder







CMB: direct probe of quantum fluctuations

Time: 0.003% of the present age of the universe.

Cosmic matter structures: less direct probes of expansion

Pattern of ripples, clumping in space, growing in time.

3D survey of galaxies and clusters.

Supernovae: direct probe of cosmic expansion

Time: 30-100% of present age of universe

Different approaches to Dark Energy include amongst many:

- A true cosmological constant -- if so, why this value?
- Many possible cosmological constants (false vacua)
- A time-dependent cosmological constant.
- 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.

Over 300 papers on archives since 1998 with dark energy in title.

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

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

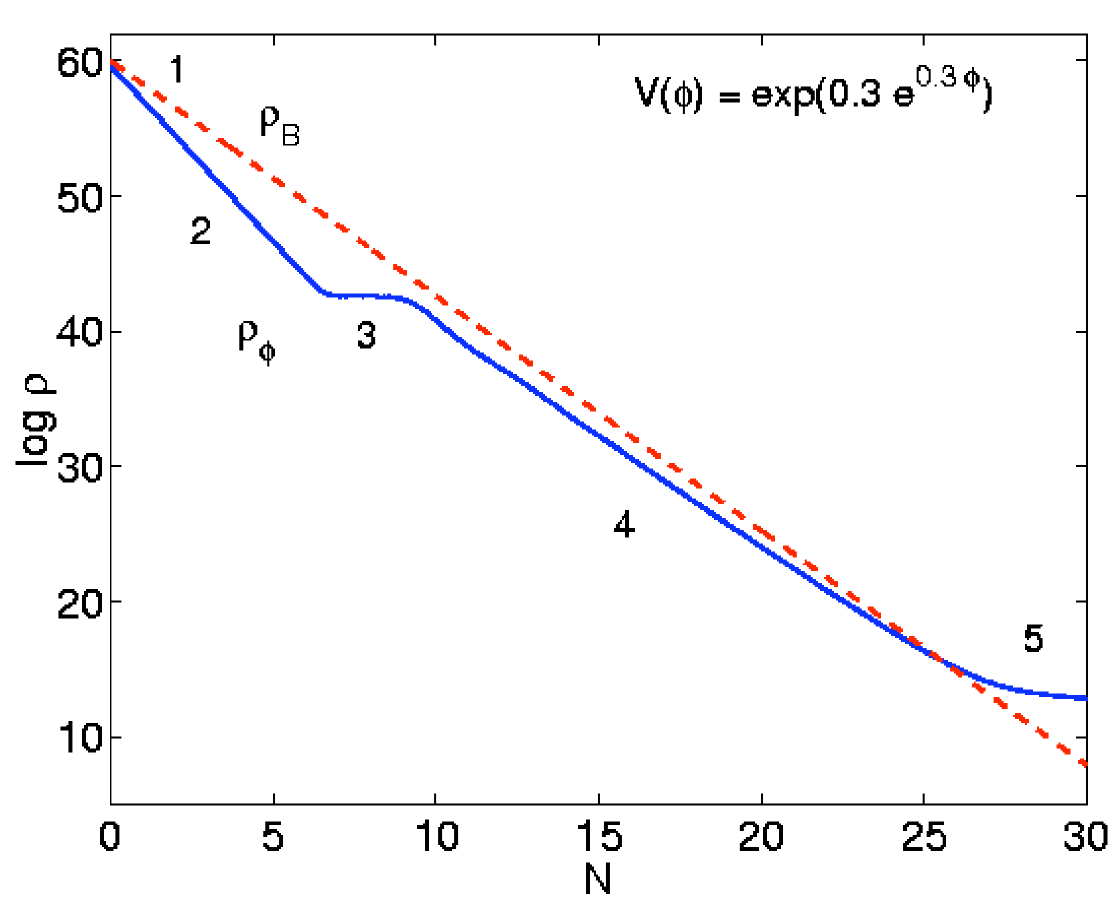
Univ accelerates at: $z_a = \left(-(1+3w_x)\frac{\Omega_x}{\Omega_m}\right)^{\frac{-1}{3w_x}} - 1$

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

Quintessence - Generic behaviour

Ng, Nunes and Rosati

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



Attractors make initial conditions less important

A few models

1. Inverse polynomial – found in SUSY QCD - Binetruy

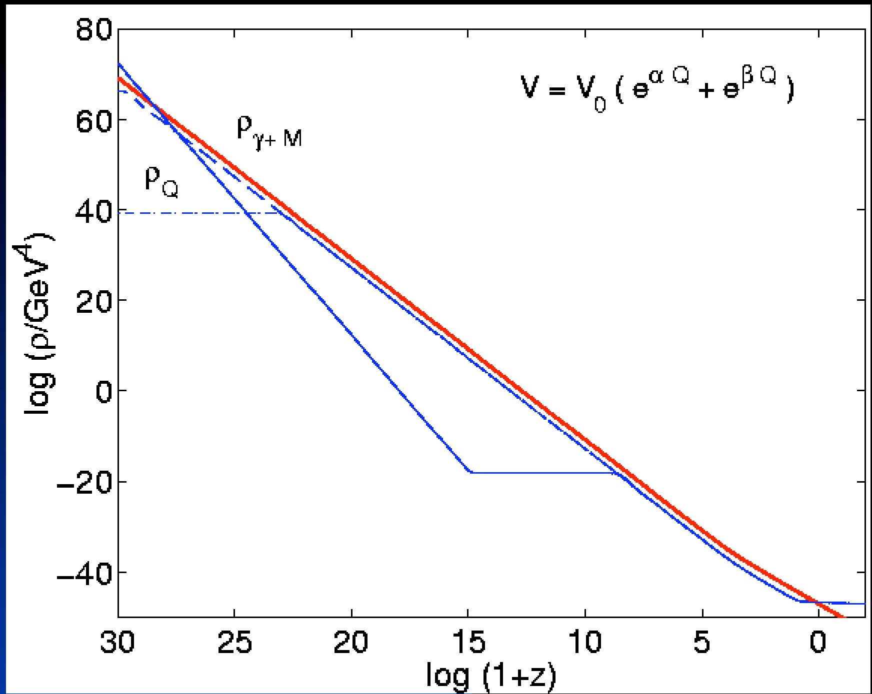
2. Multiple exponential potentials – SUGR and String compactification.

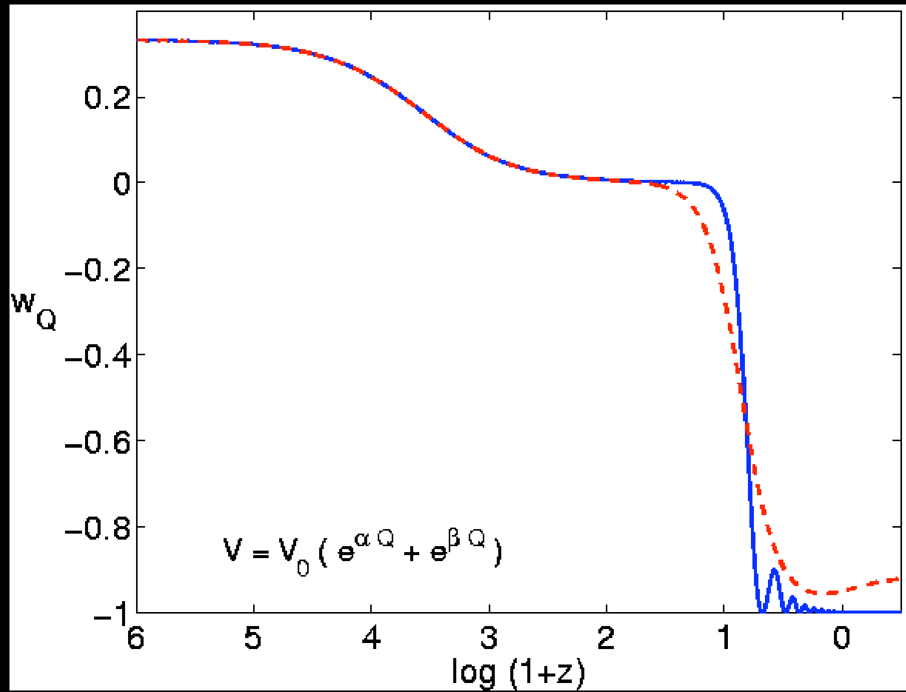
$$V(\phi) = V_1 + V_2$$
$$= V_{01} e^{-\kappa\lambda_1\phi} + V_{02} e^{-\kappa\lambda_2\phi}$$

Barreiro, EC, Nunes

Enters two scaling regimes depends on lambda, one tracking radiation and matter, second one dominating at end. Must ensure do not violate nucleosynthesis constraints.

□ = 20; □ = 0.5





Scaling for wide range of i.c.

Fine tuning: $V_0 \square \square_{\square} \square 10^{\square 47}\ \mathrm{GeV}^4 \square (10^{\square 3}\ \mathrm{eV})^4$

Mass: $m \square \sqrt{\frac{V_0}{M_{pl}^2}} \square 10^{\square 33}\ \mathrm{eV}$

Fifth force !

Acceleration from new Gravitational Physics? Starobinski 1980, Carroll et al 2003

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

Modify Einstein

Const curv vac solutions: $\nabla_\mu R = 0, \rightarrow R = \pm\sqrt{3}\mu^2$ de Sitter or Anti de Sitter

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

Also, any modification of Einstein-Hilbert action needs to be consistent with classic solar system tests of gravity. Not obvious these models are!

Quintessence and 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]

Must avoid no-go theorem by relaxing conditions of the theorem.

Problems that emerge:

Difficult to obtain sustained period of inflation.

Current realistic potentials are too steep

These models have kinetic domination, not matter domination before entering accelerated phase.

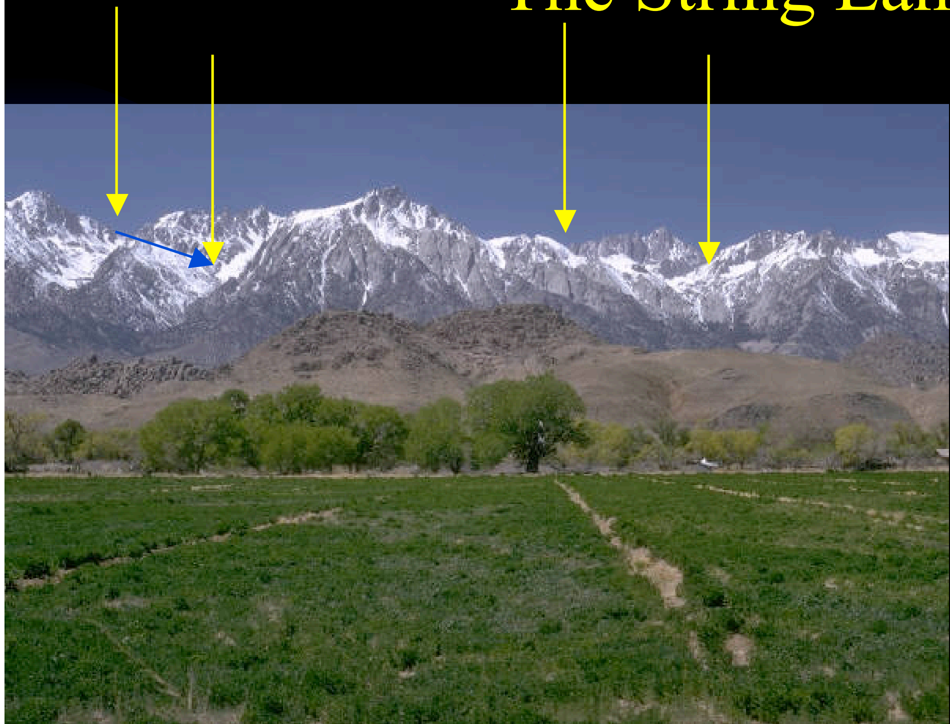
However progress is being made to obtain early and late time inflation in string theory:

Some evolve modifying the Friedmann eqn.

Metastable de Sitter string vacua in TypeIIB string theory, based on stable highly warped IIB compactifications with NS and RR three-form fluxes. [Kachru et al 2003]

Still early days for inflation in string/M-theory.

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} □$_{pl}$

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

Anthropic : Galaxies require vacua < 10^{-118} □ $_{pl}$ [Weinberg]

Most likely to find values not equal to zero!

Evidence for dynamical dark energy ?

Ideally look for evidence in evolution of equation of state as go back in time.

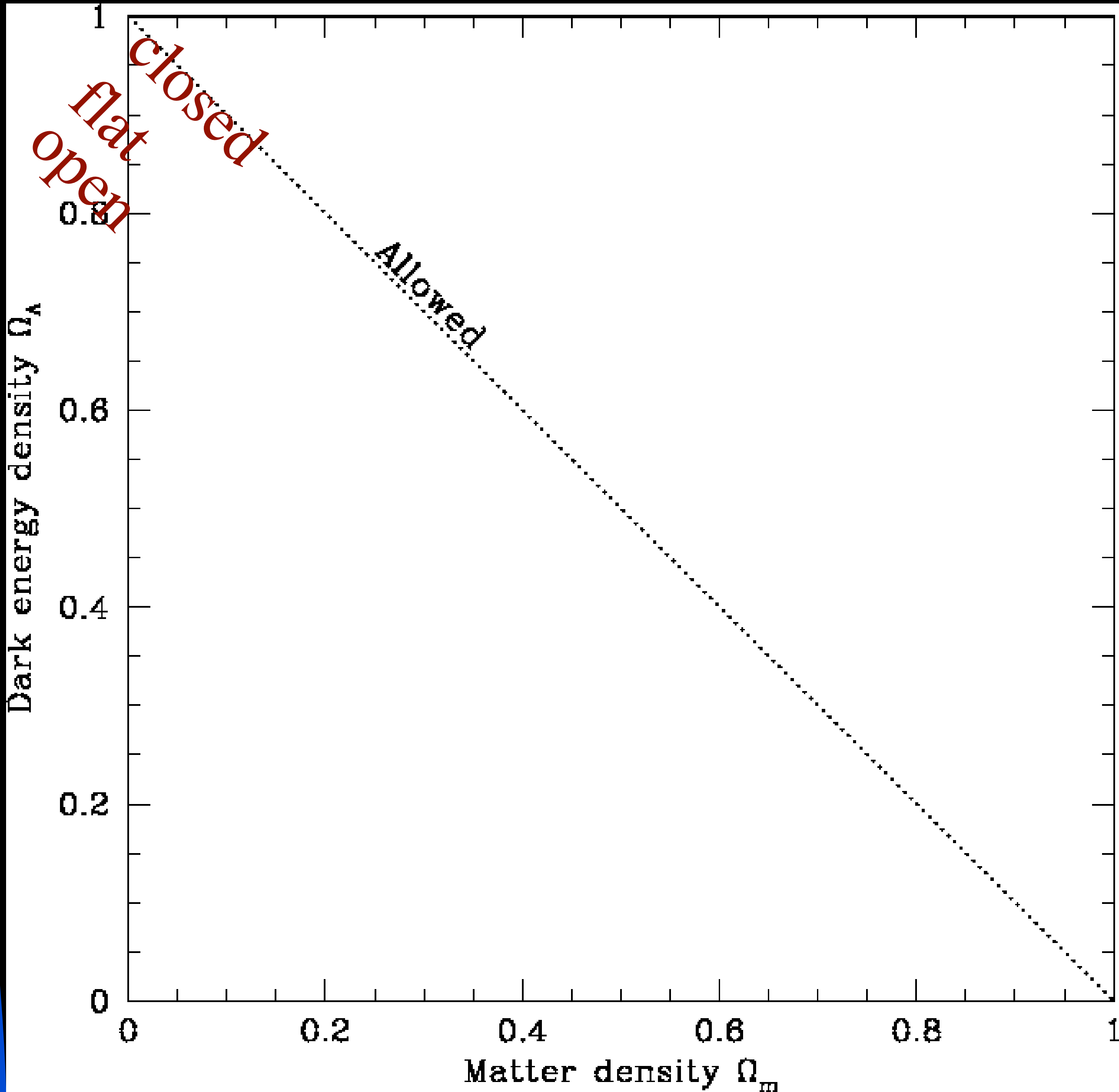
1. Precision CMB anisotropies – lots of models currently compatible.
2. Combined LSS , SN1a and CMB data – tend to give $w_Q<-0.85$ → difficult to tell from cosmological constant.
3. Look for more SN1a – SNAP will find over 2000 at large redshift – can then start to constrain eqn of state.
4. Constraining eqn of state with SZ cluster surveys – compute number of clusters for given set of cosm parameters.
5. Probing the Dark Energy with Quasar clustering – redshift distortions constrain cosm parameters –sensitive to matter-lambda combination.
6. Reconstruct eqn of state from observation – offers hope of method indep of potentials – example is Statefinder method.
7. Look for evidence in variation of fine structure constant.

How much dark energy is there?

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

Tegmark et al.

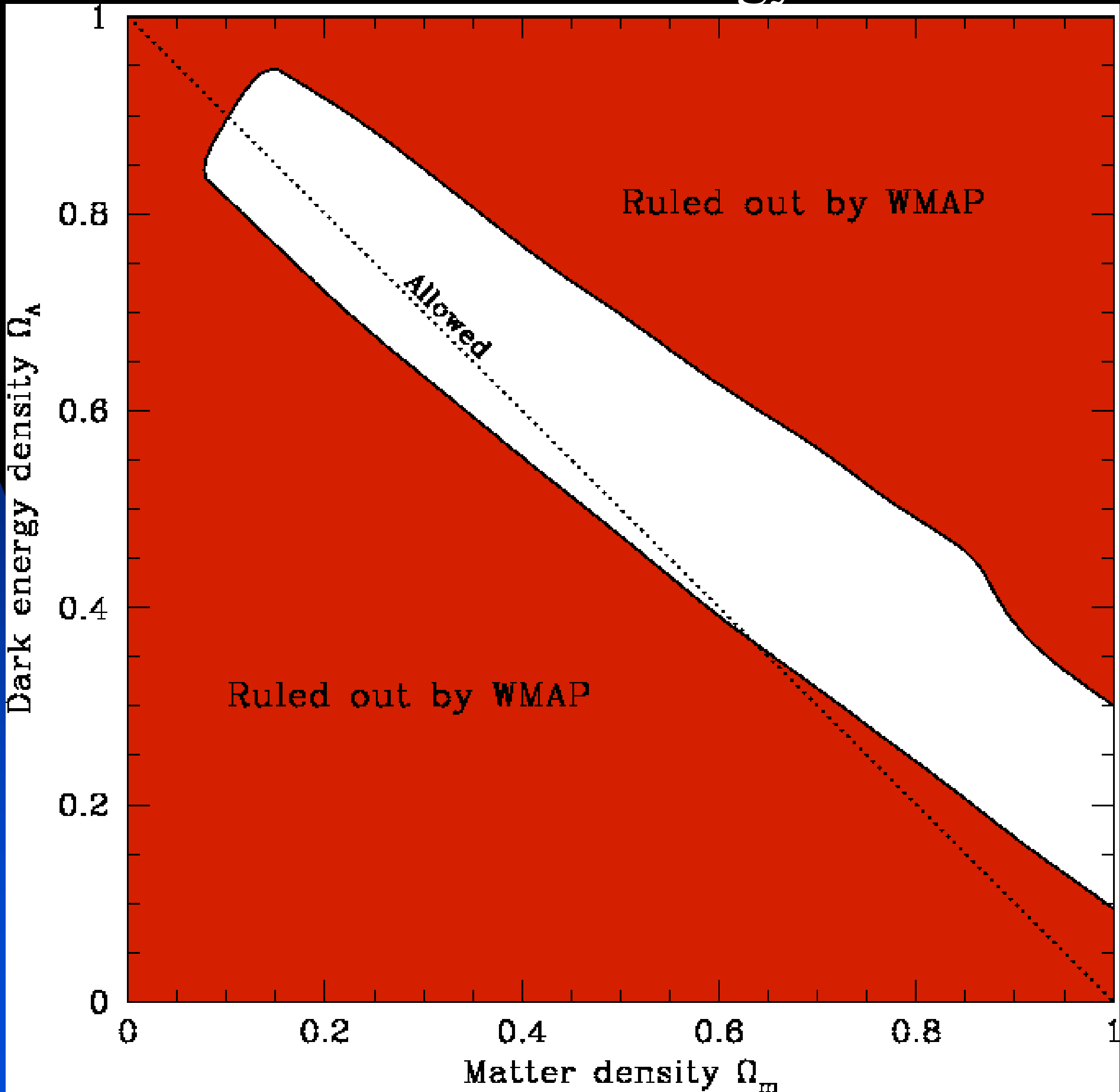
astro-ph/0310723



WMAP + SDSS: lots

How much dark energy is there?

CMB



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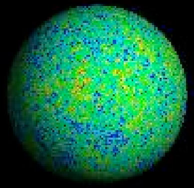
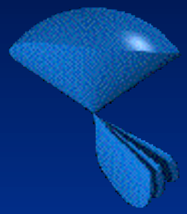
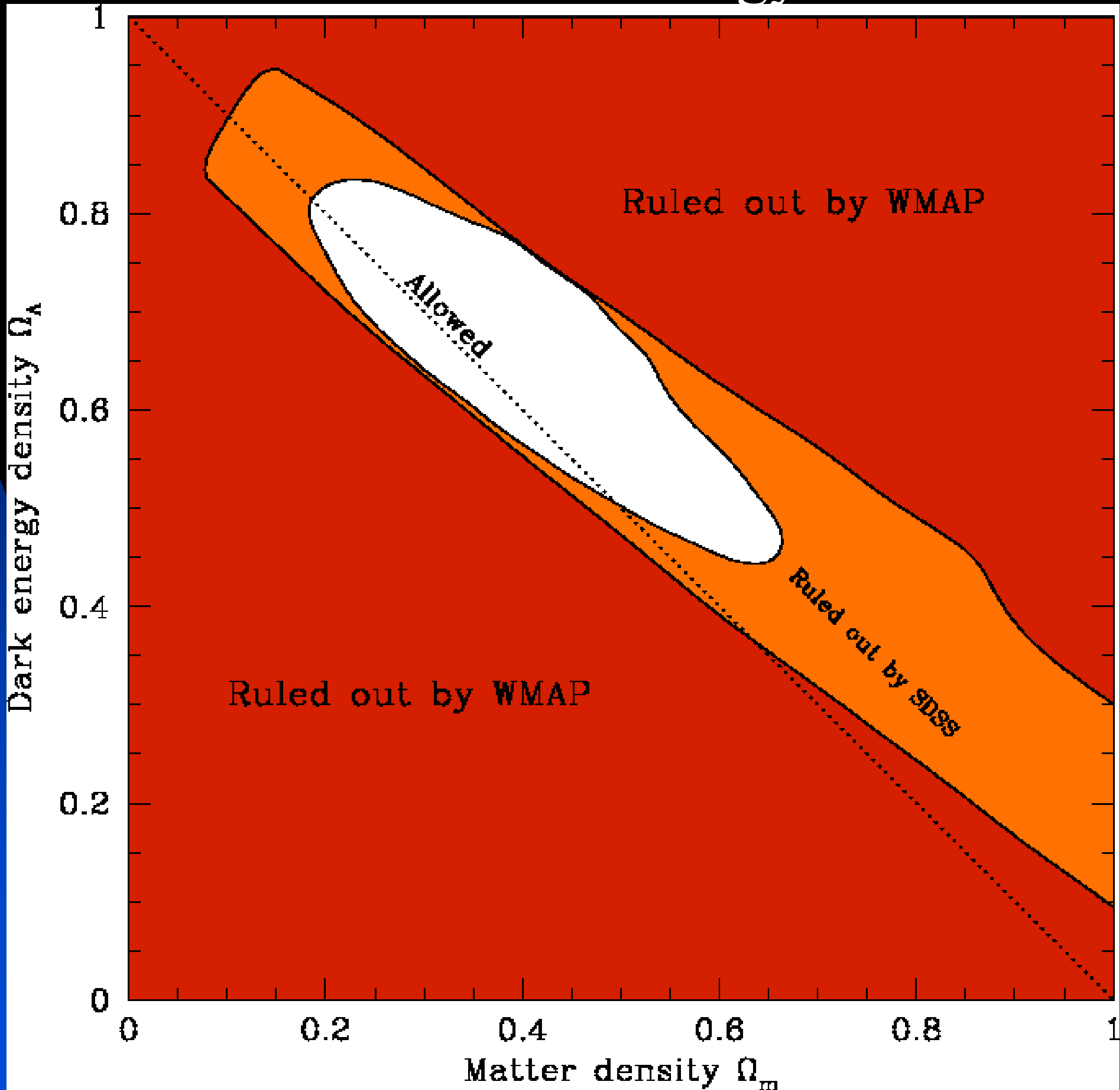


CMB

+

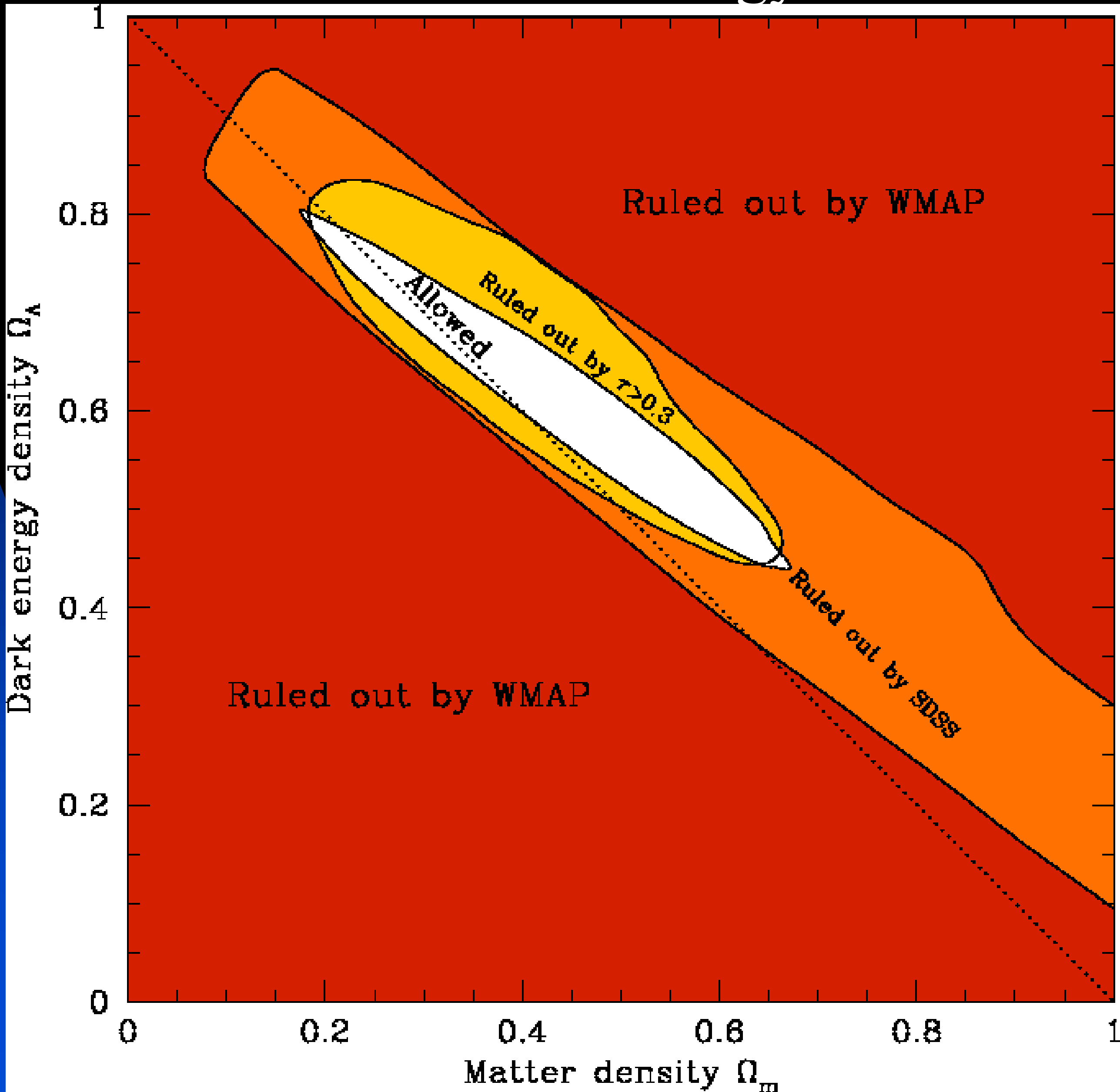


LSS



WMAP + SDSS: lots

How much dark energy is there?



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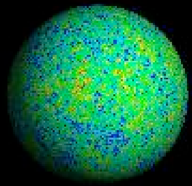
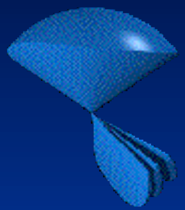


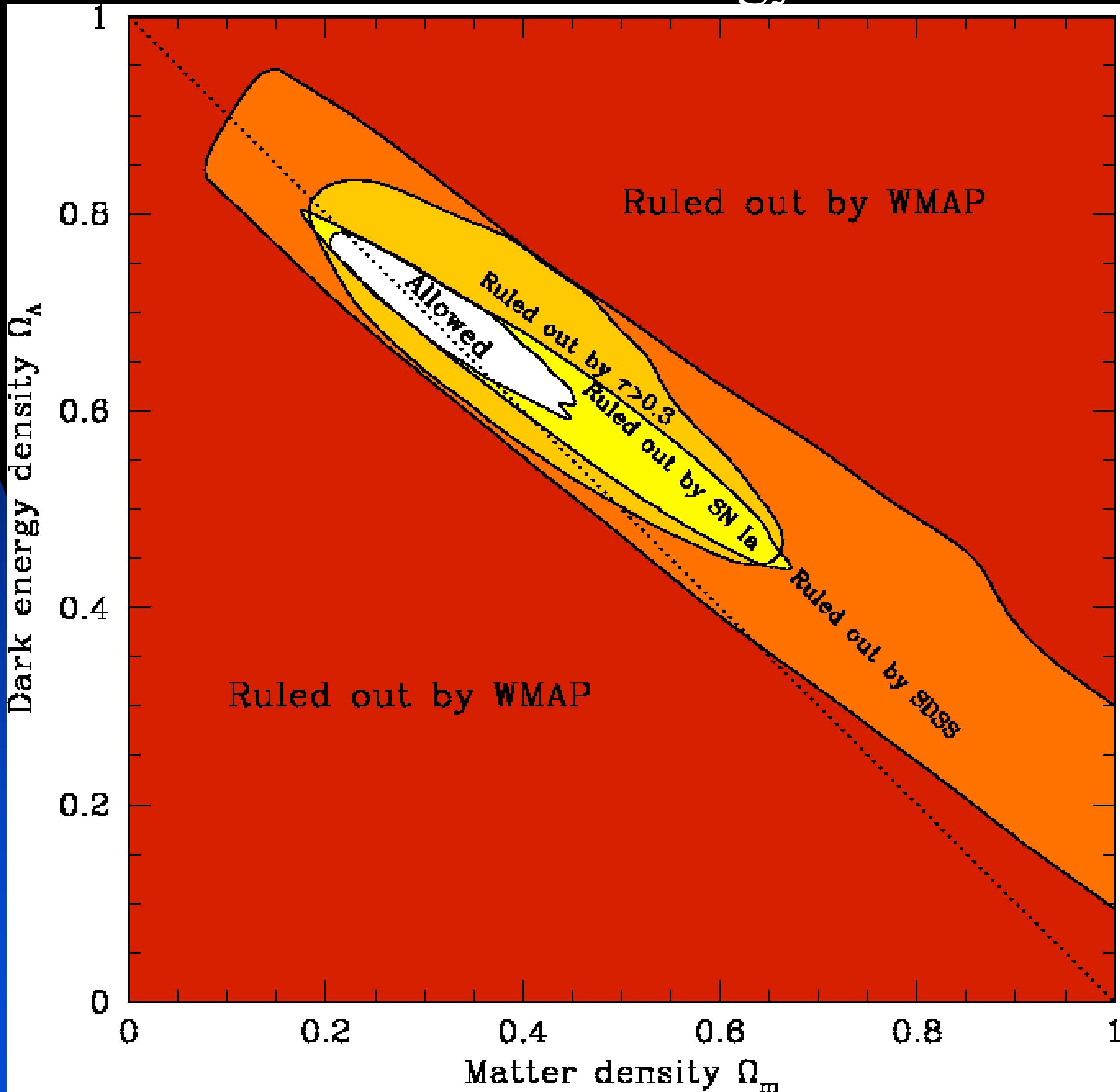
CMB

+



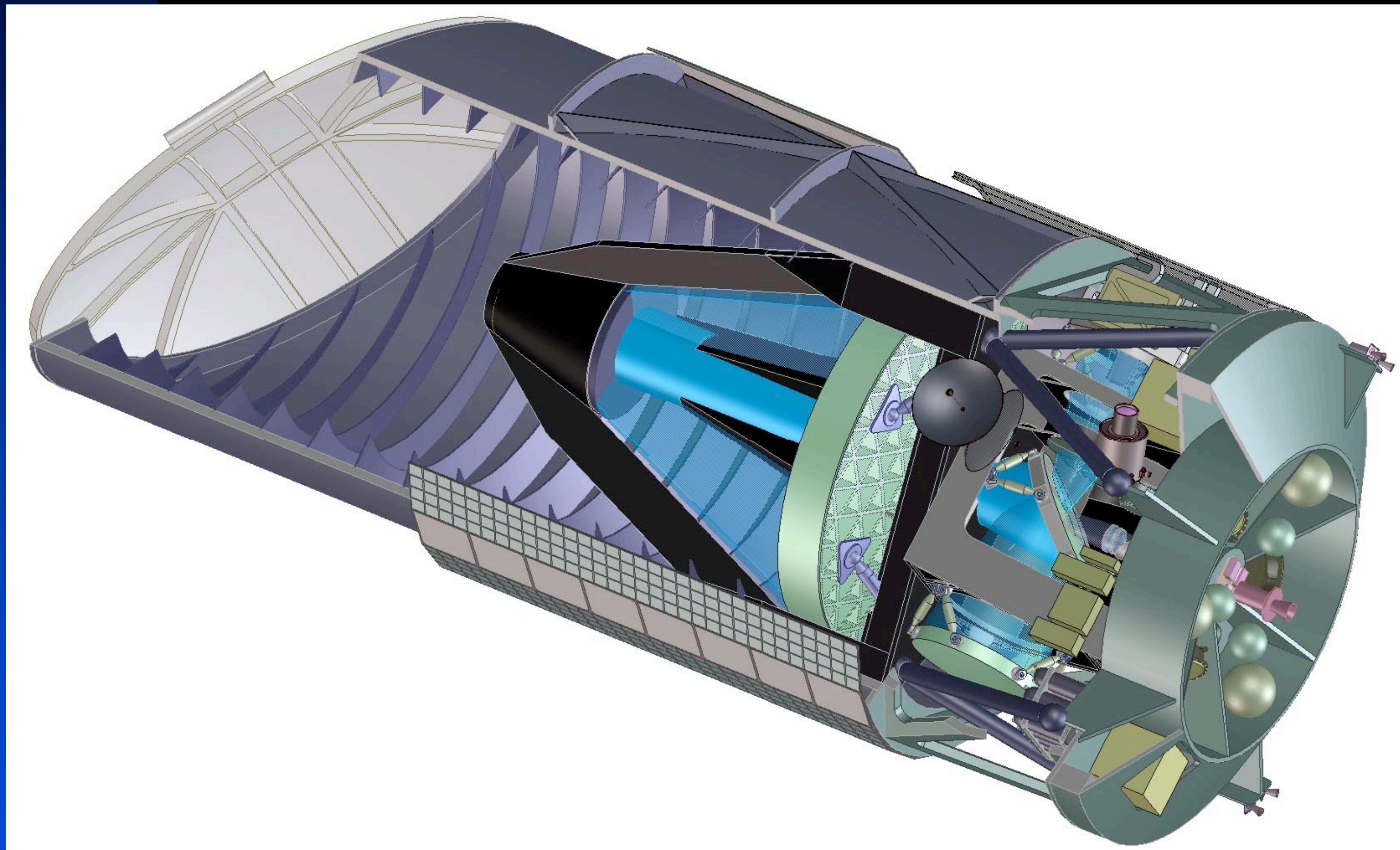
LSS

Note impact of SN 1a -- if excluded parameter space opens up



Dark Energy - future expts

Dedicated dark energy probe



SNAP: Supernova/Acceleration Probe

Dynamical evolution of w?

Weller and Albrecht; Kujat et al; Maor et al; Gerke and Efstathiou, Kratochvil et al

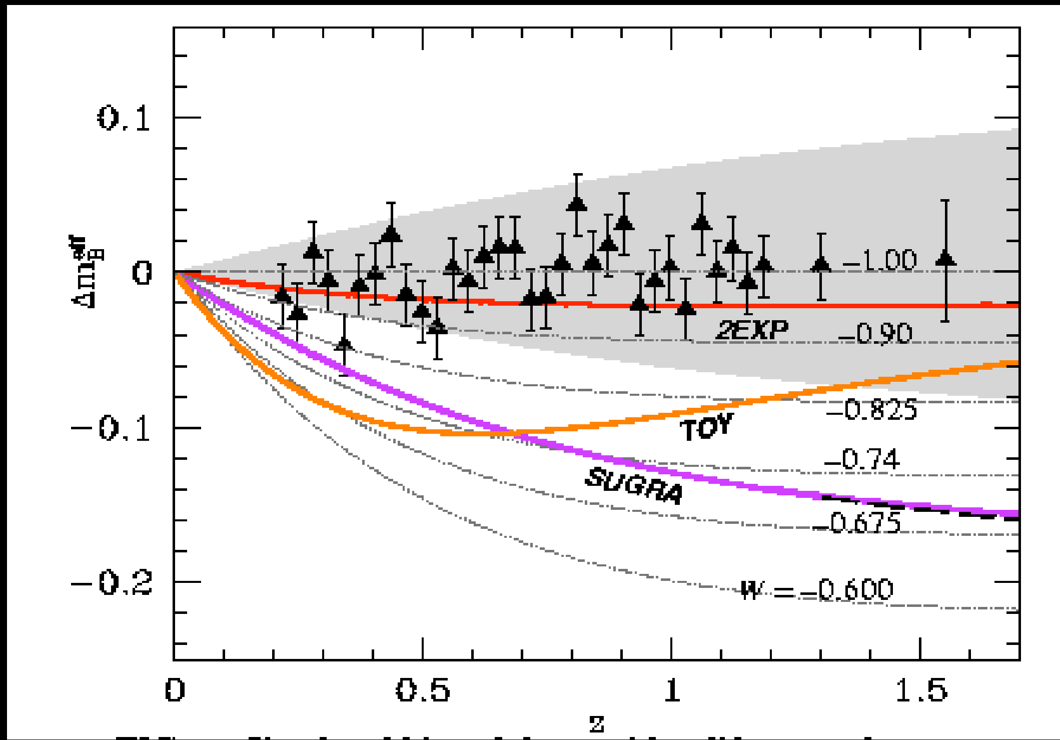
SNAP as a discriminator

Write:

$$w(z) = \sum_{i=0}^{N} w_i z^i$$

or:

$$w(z) = \sum_{i=0}^{N} w_i \ln(1+z)^i$$



Evaluate magnitude difference for each model and compare with Monte Carlo simulated data sets.

Evolution of Fine Structure Constant

Olive and Pospelov

Non-trivial coupling to emg: $L_m = \square \frac{1}{4} B_F(\square) F_{\square\square} F^{\square\square}$

Expand about current value of field: $B_F(\square) = 1 + \square_F \square + \frac{1}{2} \square_F \square^2$

Eff fine structure const depends on value of field

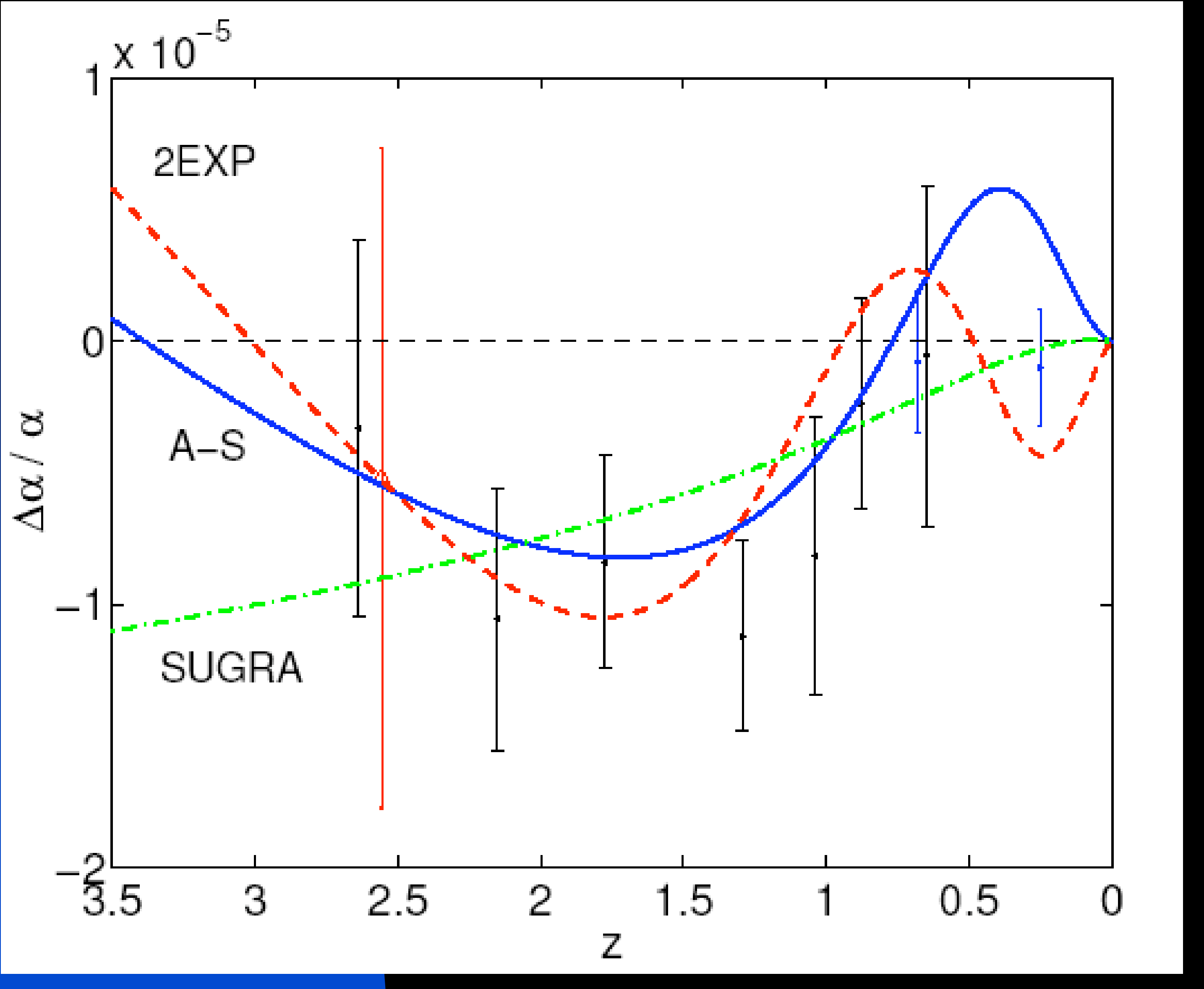
$$\square(\square) = \frac{e_0^2}{4\square B_F(\square)}$$

$$\frac{\square\square}{\square} = \square_F \square + \frac{1}{2}(\square_F \square 2\square_F^2)\square^2$$

Claim from analysing quasar absorption spectra:

$$\frac{\square\square}{\square}(z = 0.5 \square 3.5) \square 10^{\square 5}$$

Webb et al



EJC, Nunes, Pospelov,

A way of constraining the eqn of state?

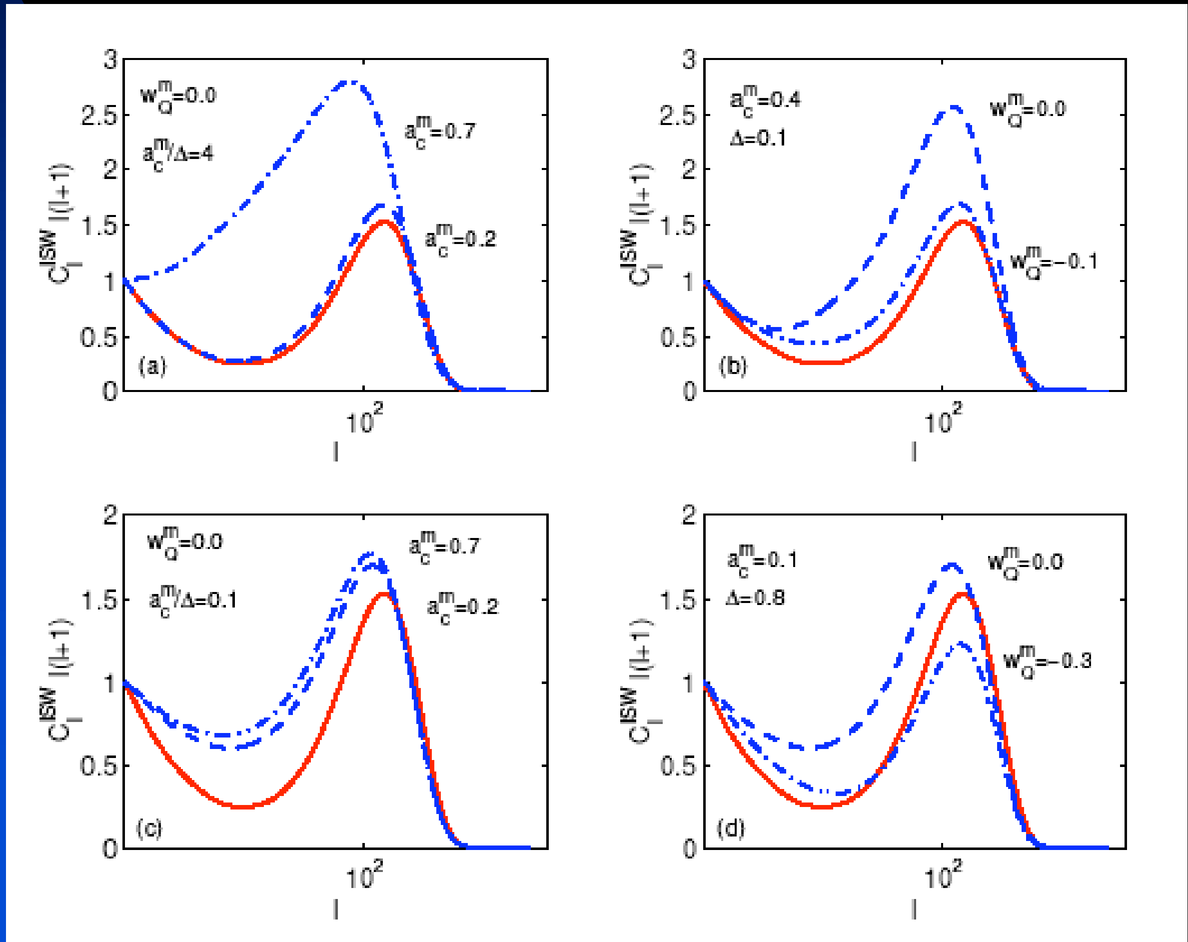
Probing Quintessence with the cmb through the ISW effect-- Corasaniti et al

$$\left[\frac{\delta T(e)}{T}\right]_{SW} = \frac{1}{3}\Phi(ex_{ls}) + 2\int_{\tau_{ls}}^{\tau_0} \frac{\partial \Phi(ex,\tau)}{\partial \tau} d\tau$$

Use parameterisation of w(z) to test whether we can see difference with Lambda CDM

Rapid transition

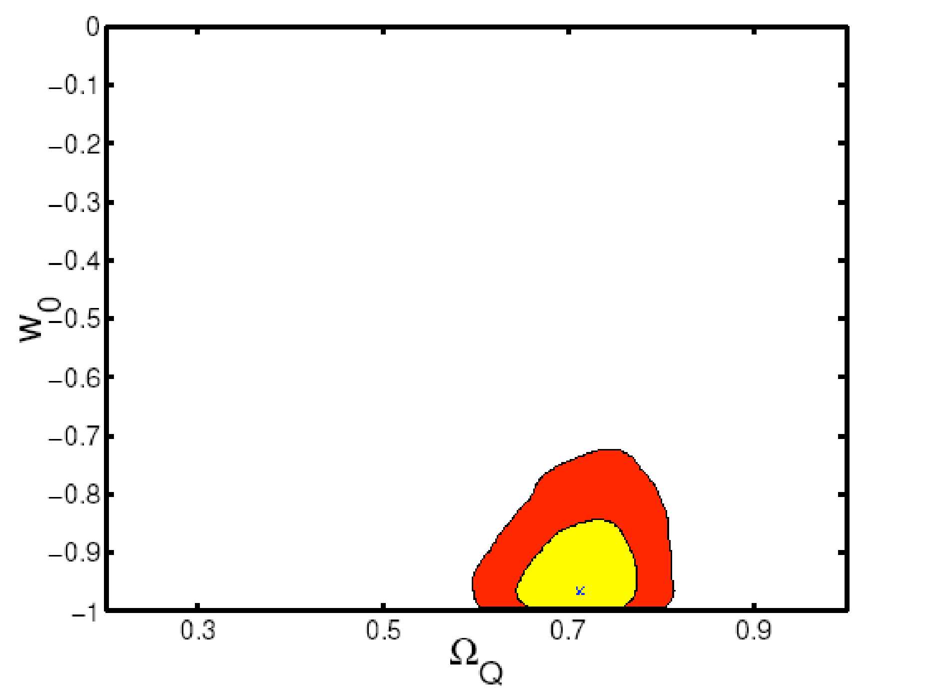
Slow transition



—— Λ

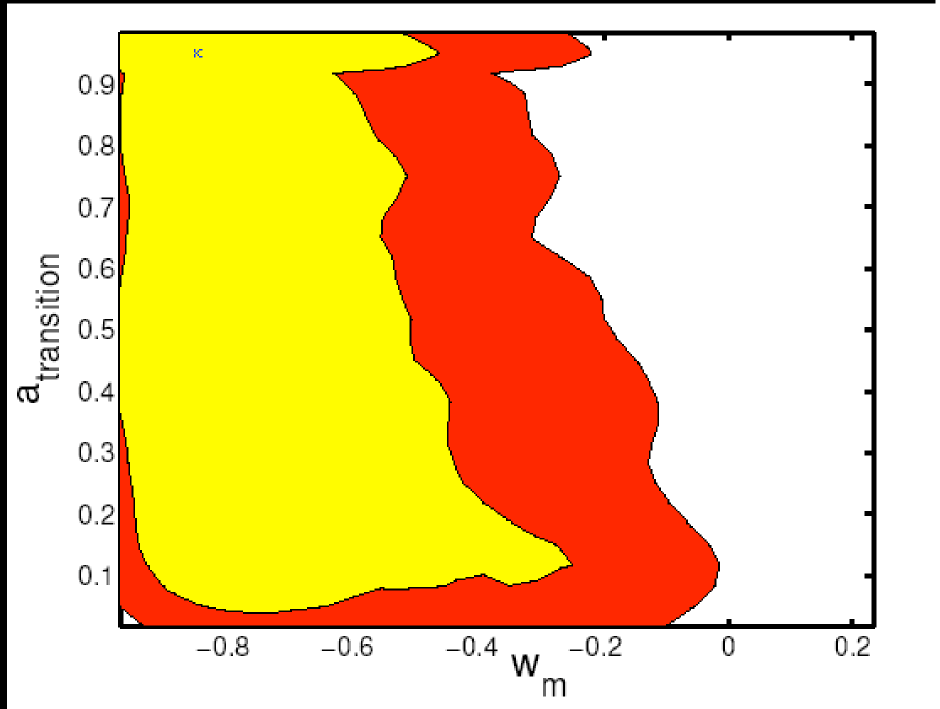
Need late rapid transition to differentiate

Probing Quintessence with WMAP and SN1a -- Kunz et al

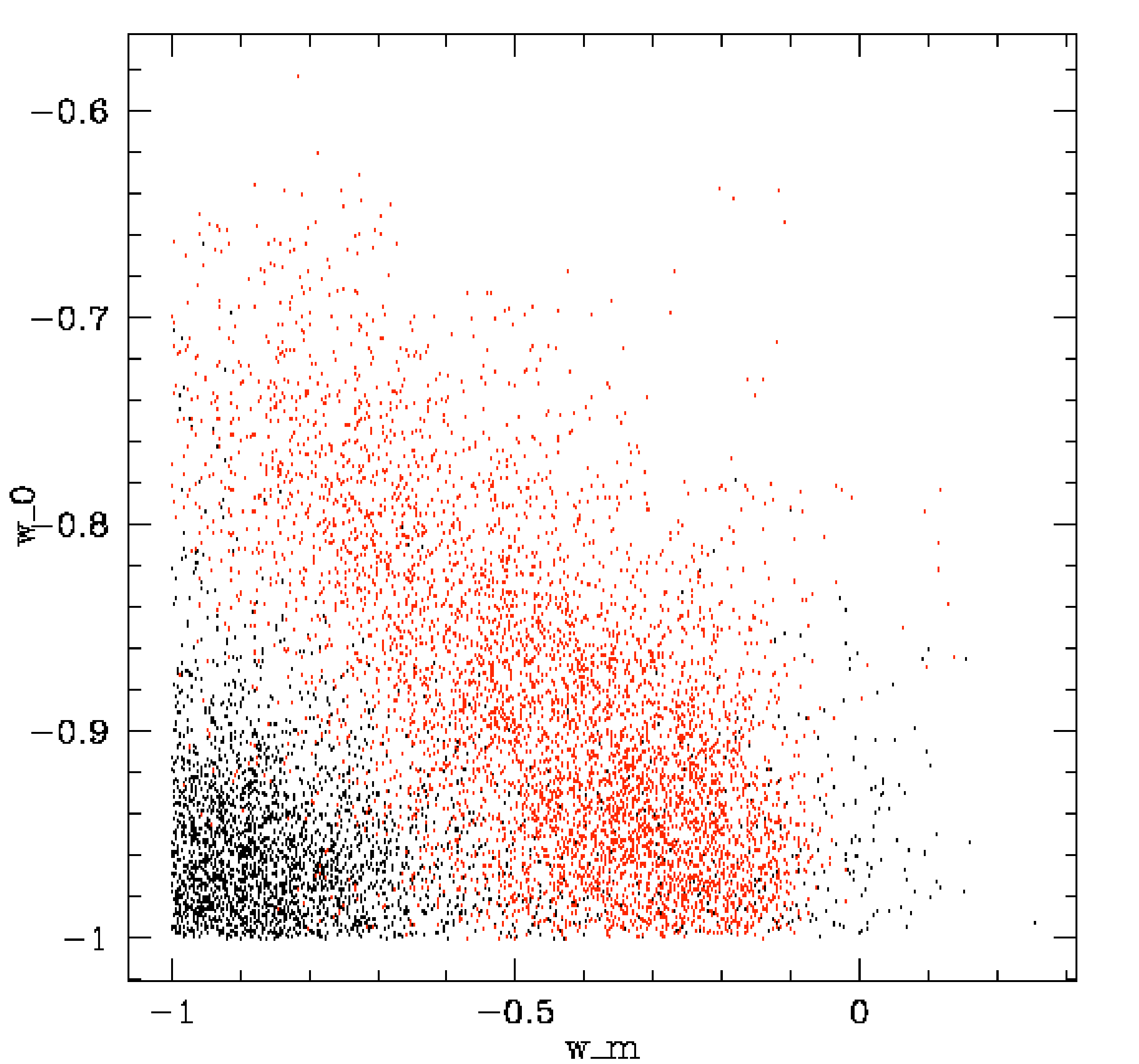


← 2D Likelihood shows that today w very close to - 1, as expected.

This is not the same though as saying it always had to be -1. →



Using σ_8



Black dots: $\sigma_8 > 0.8$

Red dots: $\sigma_8 < 0.6$

Pointing towards lambda if sigma8 turns out to be large.

Summary

- Observations transforming field, especially CMBR and LSS. Constraining the cosmological parameters, even before Planck arrives on the scene.
- Why is the universe inflating today?
- Is w=-1 which is a cosmological constant type term? If not, then what?
- Is w(z) -- dynamical?
- New Gravitational Physics -- perhaps modifying Friedmann equation on large scales?
- Lots of models of dark energy but may yet prove too difficult to separate one from another such as cosmological const – need to try though!
- or -- could we all be wrong and we do not need a lambda term?

Harry's quote: `Be careful of your conclusions if you can only be sure of 95% of your model'

Here we have a basic model which fits the available data very well but we do not know what 95% of the energy density is comprised of!

So, we will need to be careful as we search for an explanation!