The Accelerating Universe: A Challenge to Fundamental Physics

Ram Brustein

אוניברסיטת בן-גוריון

Irit maor
(BGU→ Cambridge)
P. Steinhardt (Princeton)

PRL 86 (2001),
PRD 65 (2002),
PRD 67 (2003)

- Evidence for accelerated expansion
- Interpretation – "phenomenology"
- Explanation – "theory"

La Recherche
L'ACTUALITÉ DES SCIENCES

01/02/2003 La Recherche

Et pourtant il accélère !

La concordance de toutes ces expériences a fait sursauter plus d'un cosmologiste. À l'aube du XXIe siècle, il devient clair que 95 % de l'Univers nous est totalement étranger ! Les astrophysiciens s'aperçoivent que toutes leurs théories ne se fondent que sur l'observation des cinq petits pour cent visibles de l'énergie totale [fig. 4]. De quoi rendre sceptique le commun des mortels, mais pas les scientifiques, qui continuent à bâtir leur édifice théorique contre vents et marées. Leur plus grand défi est aujourd'hui de dévoiler la nature de cette énergie noire,

מפץ גדול חם : המודל הסטנדרטי

Geometry

$$ds^2 = -dt^2 + a(t)^2 dr^2$$

GR: ↕

$a(t)$, $1 + z = a(now)/a(t)$, $H = \dot{a}/a$

Matter

$\rho(z)$, $p(z)$, $w(z) = p/\rho$.

$$3H^2 = 8\pi G_N \rho$$

$$\dot{H} = -4\pi G_N (\rho + p)$$

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

ρ_C- critical density
(Euclidean space)
Ω_X - ρ_X / ρ_C

Accelerated expansion ?!

$$3H^2 = 8\pi G_N \rho$$

$$\dot{H} = -4\pi G_N (\rho + p)$$

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

Radiation

$\rho = 3p$, $w = 1/3$

Matter

(normal and dark)

$p=0$, $w = 0$

$$\ddot{a}/a = \dot{H} + H^2$$

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

$$w < -1/3$$

Attractive gravity + "normal" matter → decelerated expansion

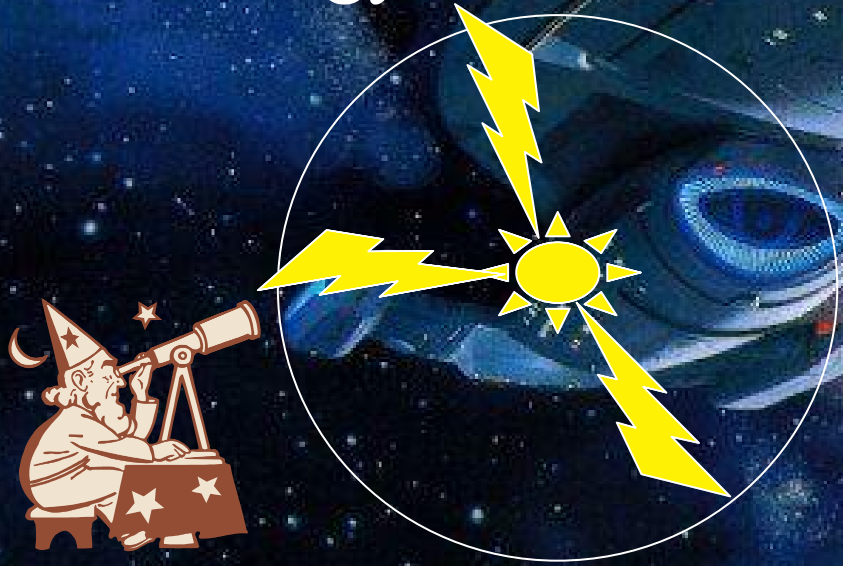
Mapping the Universe

ratio of luminosity $\mathcal{L}$ to flux $\mathcal{F}$

$$d_L = \sqrt{\frac{\mathcal{L}}{4\pi\mathcal{F}}} = (1+z)r$$

Luminosity – energy/time emitted by source

Flux – energy /time/area absorbed by detector



Due to expansion:

Energy/time ▼ $(1+z)^2$

(1+z) – red shift of energy

Need "standard candles"

Luminosity distance d_L vs. redshift z: Hubble Diagram

$$d_L = \sqrt{\frac{\mathcal{L}}{4\pi\mathcal{F}}} = (1+z)r$$

For light $-dt^2 + a^2 dr^2 = 0$

$$H = \frac{1}{a}\frac{da}{dt}$$

$$dz = -\frac{da}{a^2}$$

$$\Rightarrow \quad r = \int_1^{1+z} \frac{dx}{H}$$

Example:
SNIa

Angular distance d_A vs. redshift z

Proper diameter - d

Observed angular diameter – θ

$\theta = d/(a\,r)$

$$d_A \equiv \frac{d}{\theta} = a(t_1)r \rightarrow d_L = (1+z)^2 d_A$$

Example:

Peaks in CMB spectrum

Need
"standard feature"

Evidence for Accelerated Expansion

Direct and Indirect

- **C**osmic **M**icrowave **B**ackground : inhomogeneities in radiation
- **L**arge **S**cale **S**tructure :

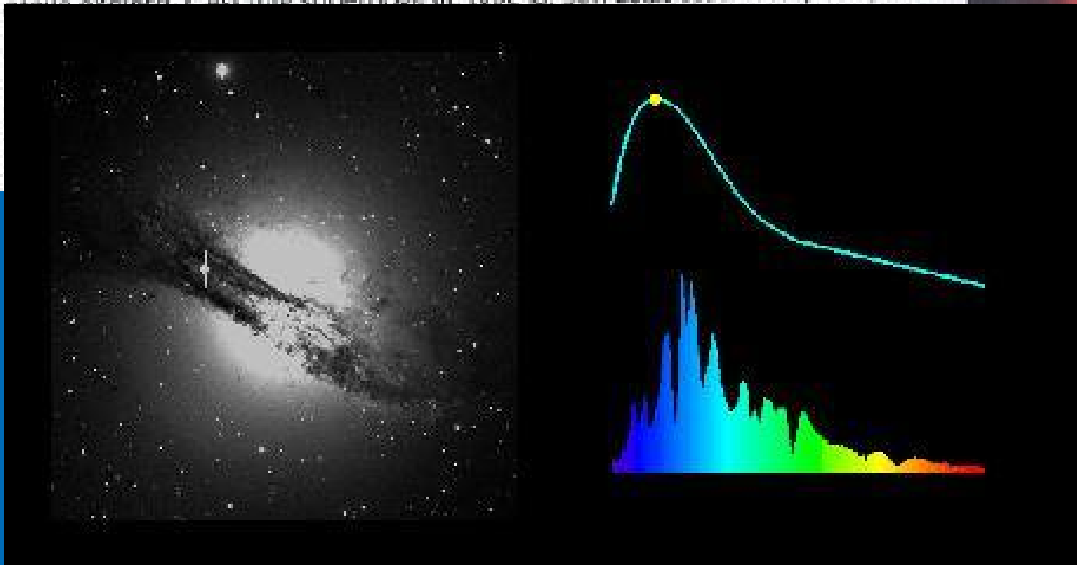
  inhomogeneities in matter

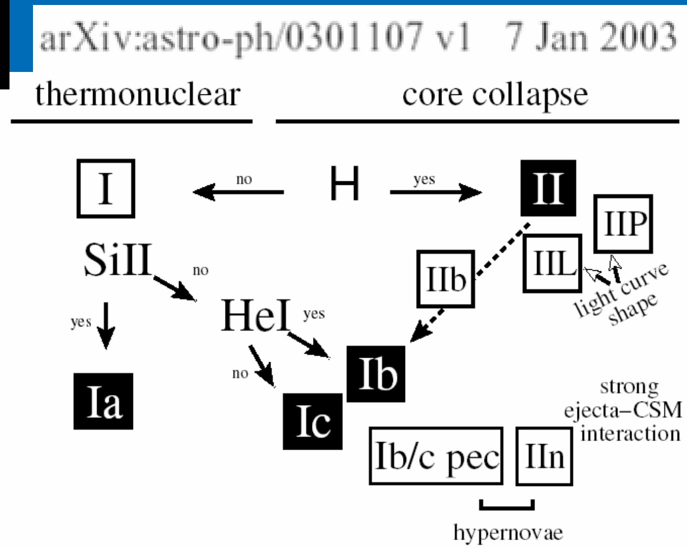
  object counts: galaxies, clusters, weak lensing, strong lensing, …
- **S**uper**N**ovae **Ia** – most direct

DÉFINITION

La supernova de type Ia

UNE ÉTOILE NAINE BLANCHE, RÉSIDU D'UN VIEUX SOLEIL, qui cohabite avec une étoile géante rouge, va progressivement happer la matière de cette dernière. Quand la masse de la naine blanche atteint 1,4 fois celle du Soleil (masse de Chandrasekhar), des réactions thermonucléaires s'enchaînent, et la petite

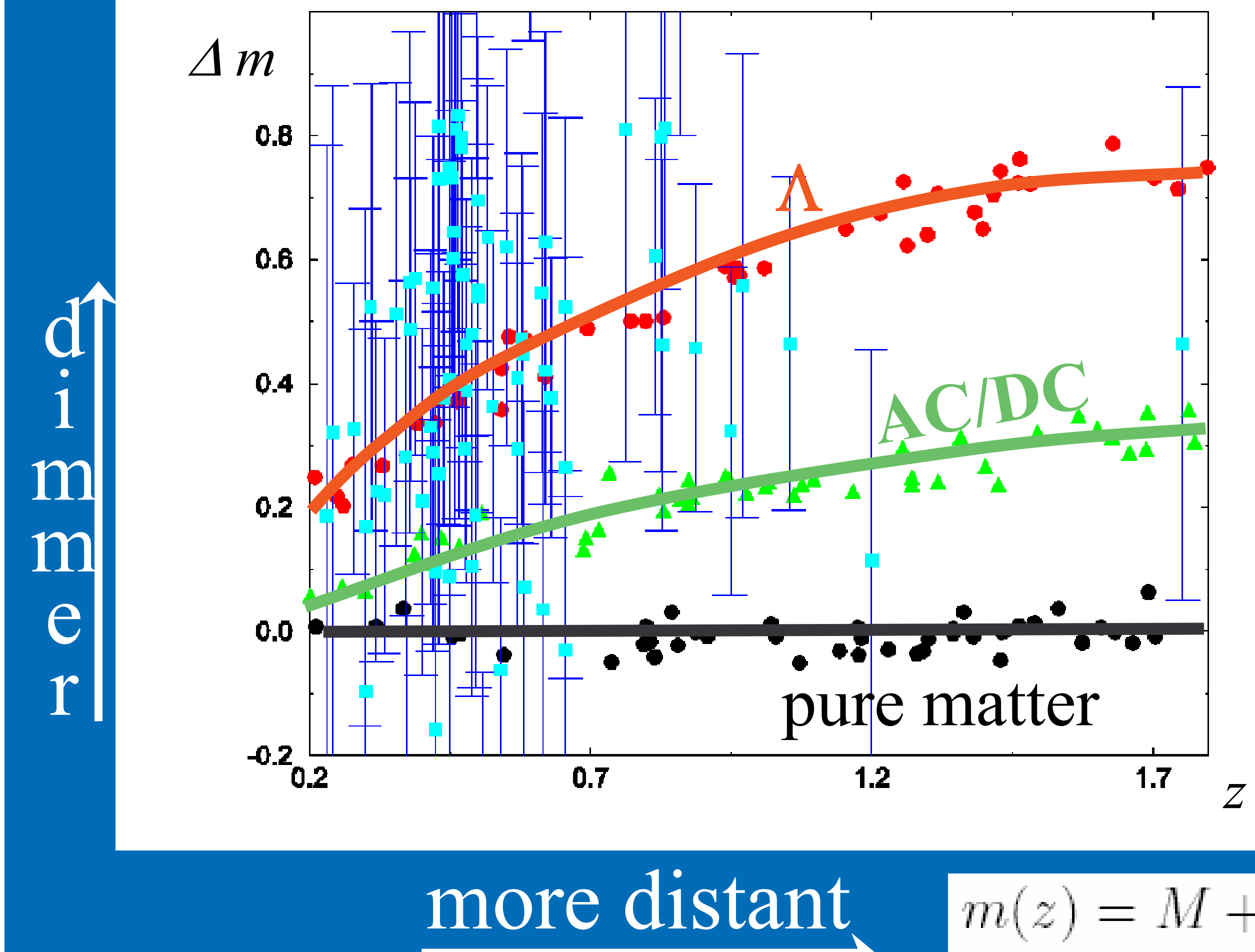




מתאם בין בהירות שיא, צורה
וספקטרום של עקומת האור ←
~ 10 % פיזור בבהירות שיא

Current SNIa Data

Cosmological Results from High-z Supernovae[1,2]
arXiv:astro-ph/0305008 v1 1 May 2003



Λ preferred

$$\Delta m = \frac{5}{\ln 10}\frac{\Delta d_L}{d_L}$$

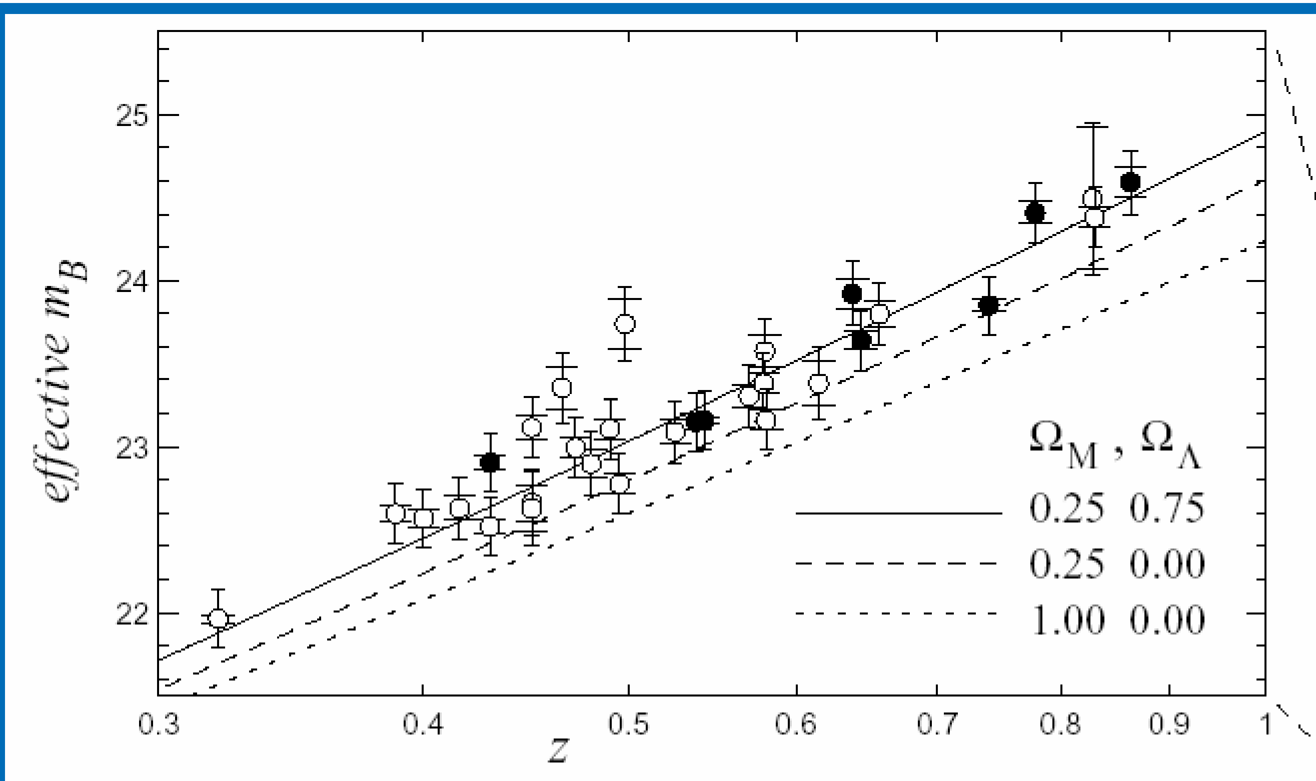
$$\Delta m \approx \frac{\Delta L}{L}$$

fiducial models:
$\Omega_m = 0.3$
$w_Q = \text{const.}$

$$m(z) = M + 25 + 5\log_{10}\left[H_0 d_L(z)\right]$$

Key issue:systematic errors

Previous version: Sci. Am. 1/2001


effective m_B
25
24
23
22
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z
Ω_M , Ω_Λ
0.25 0.75
0.25 0.00
1.00 0.00

Current Data

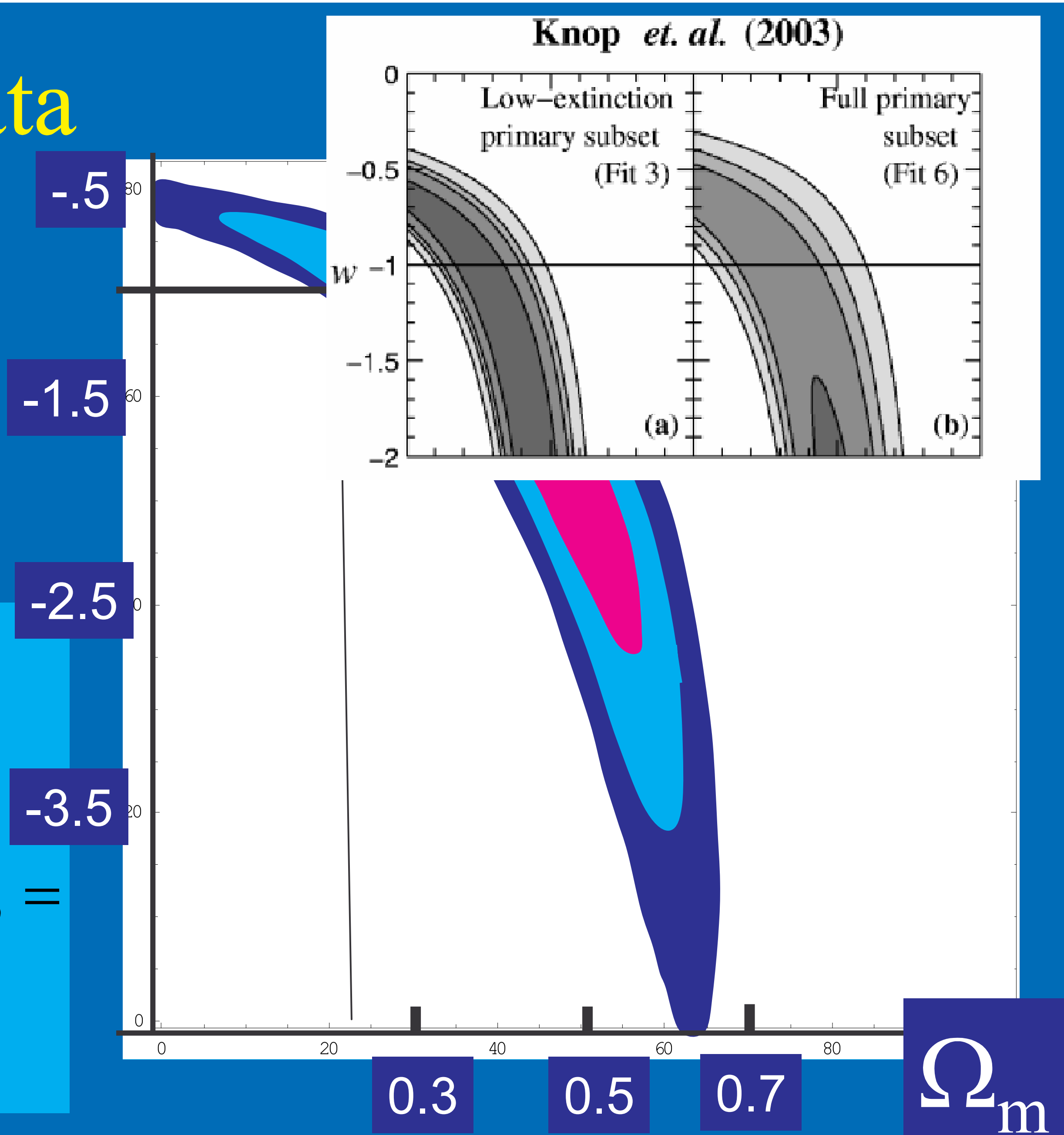
- Ω_m vs. w_Q

(assume flat U.)

$$w_T = \frac{p_T}{\rho_T} =$$

$$\frac{p_m + p_Q}{\rho_m + \rho_Q} = w_Q \Omega_Q =$$

$$w_Q(1 - \Omega_m)$$



$$DM \equiv 5 \log \left(\frac{D_L}{10 \text{ pc}} \right)$$

$$z \approx \frac{v}{c} = \frac{d}{D_H}$$

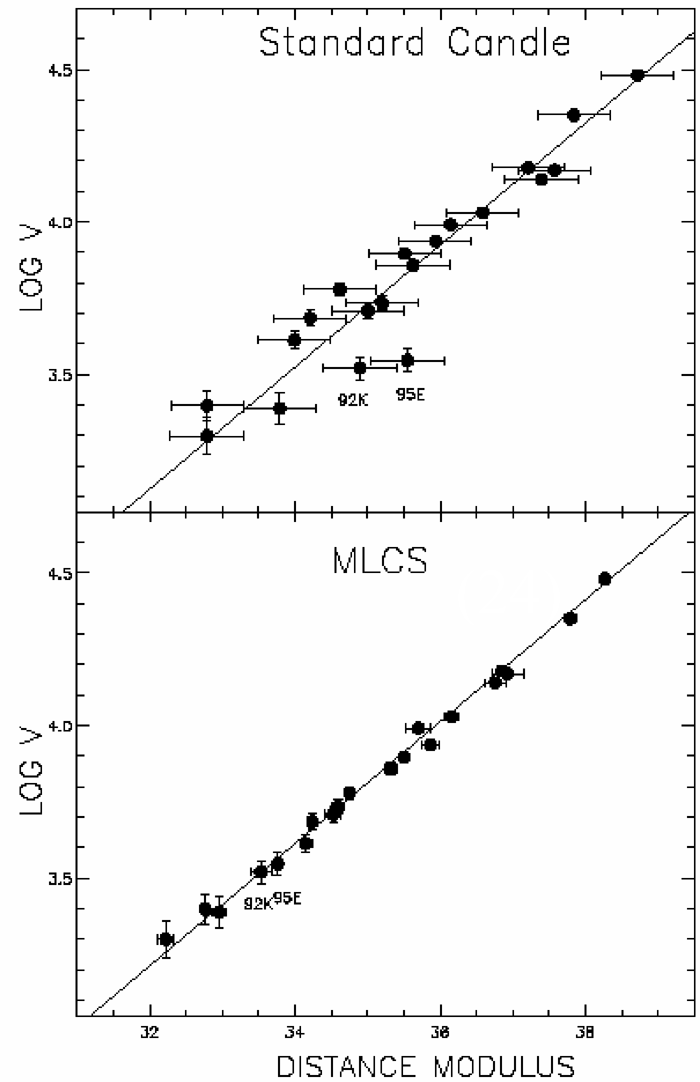
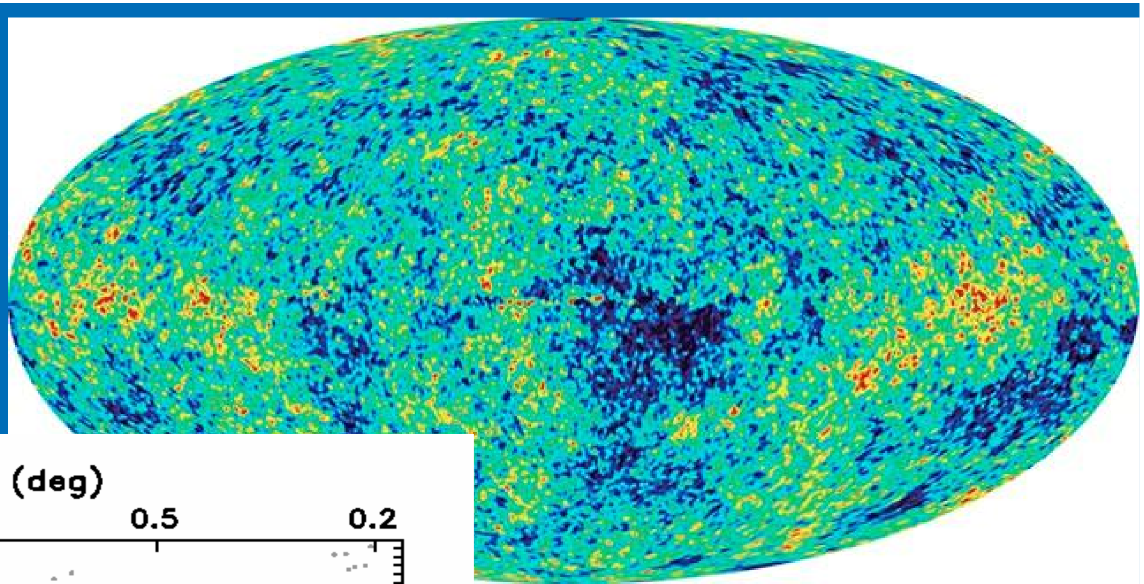
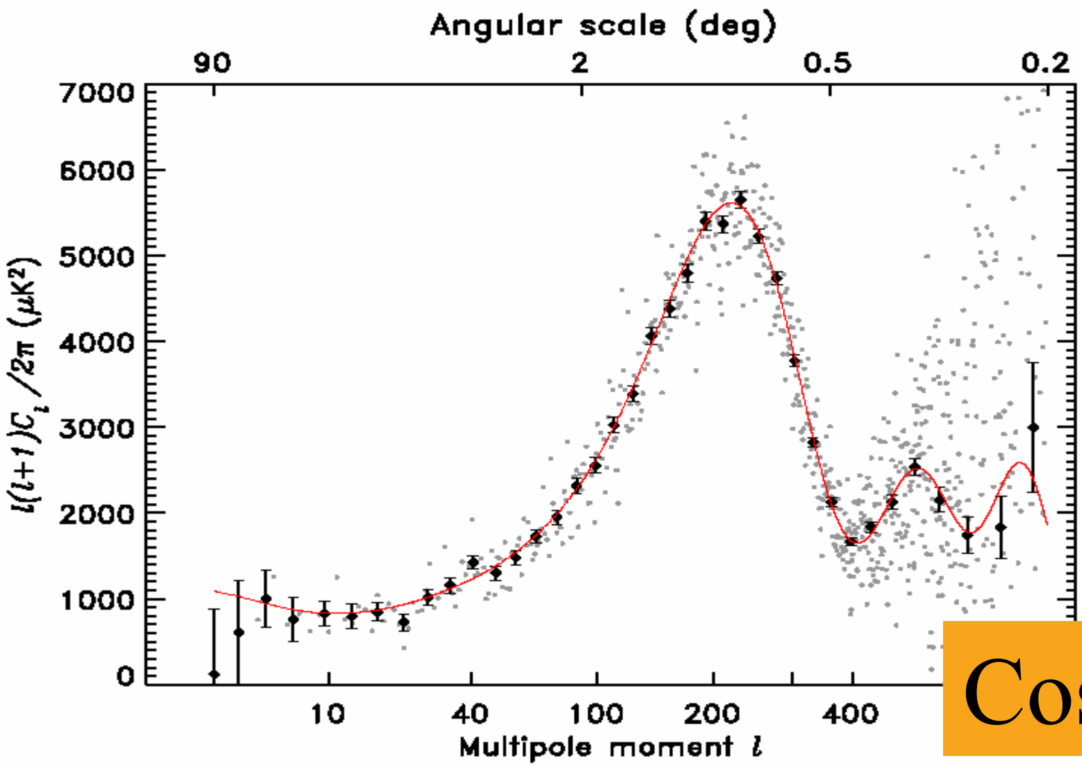


Figure 2. The Hubble diagram for SNe Ia before (top panel) and after (bottom panel) correction of the width–absolute brightness relationship. The figure is from Riess, Press & Kirshner (1995a).

CMB data : WMAP





February 2003

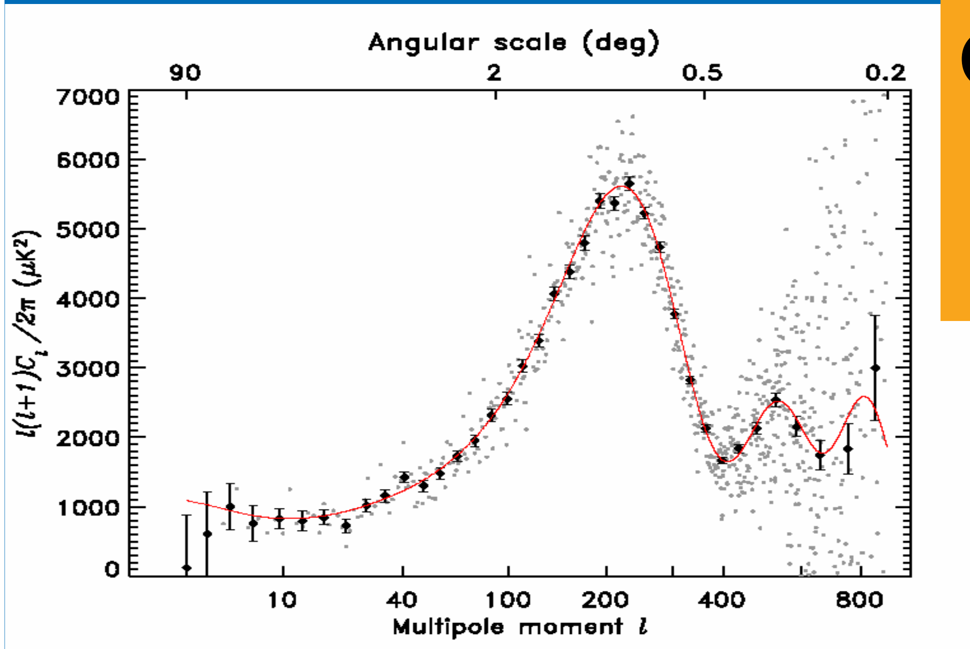
$$\Theta(\hat{\mathbf{n}}) = \Delta T/T.$$

$$\langle \Theta^*_{\ell m} \Theta_{\ell' m'} \rangle = \delta_{\ell\ell'}\delta_{mm'}C_\ell$$

$$\Delta_T^2 \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell T^2$$

Cosmic variance!

$$\Delta C_\ell = \sqrt{\frac{2}{2\ell+1}} C_\ell.$$



One more point on the Hubble diagram (z ~ 1,000)

$\ell_1 = 220.1 \pm 0.8$

~ Flat U.

Cosmic variance!

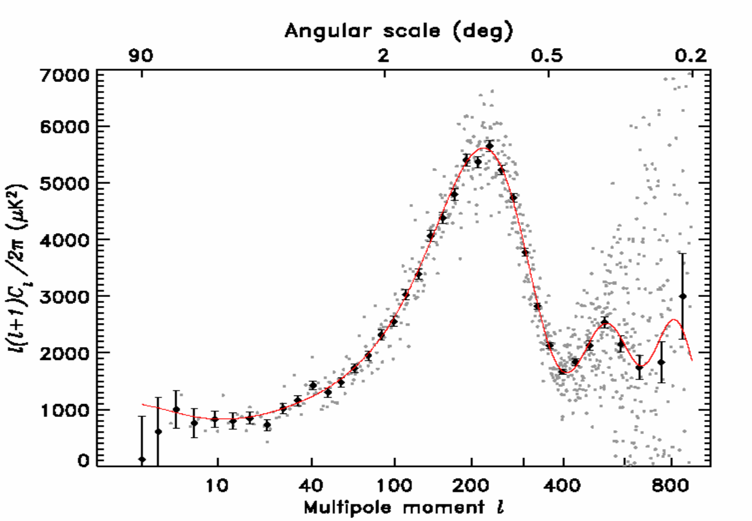
$$\Delta C_\ell = \sqrt{\frac{2}{2\ell+1}} C_\ell .$$

Last scattering: U. becomes transparent

$$\frac{X_e^{\,2}}{1-X_e} = \frac{Z_e Z_p}{Z_H} \sim 1.4\times10^{17}\,\frac{1}{\Omega_b^{\,0.05}h_{75}^{\,2}}\left(\frac{1eV}{T}\right)^{3/2} e^{-13.6eV/kT}$$

$$\Rightarrow kT_{90\%} \sim 0.3eV,\; kT_{ls} \sim 0.26eV$$

$$z_{ls} = T_{ls} / T_{today} = .26\ eV / 2.72\ K \sim 1100$$



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A picture of the state of CMB photons @ ls convoluted with their motion through the (whole) universe

Acoustic peaks

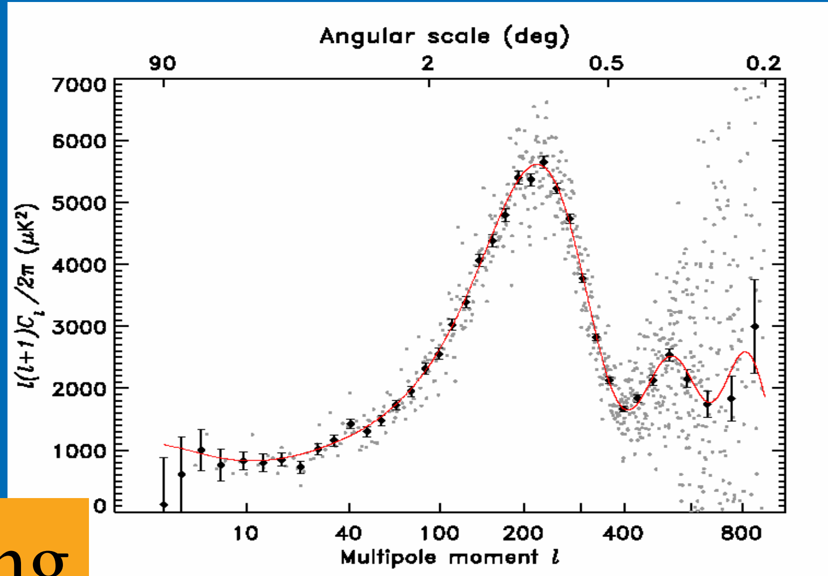
From: Hu & Dodelson (2002)

eq. without gravity

$$\ddot{\Theta} + c_s^2 k^2 \Theta = 0,$$

$$c_s \equiv \sqrt{\dot{p}/\dot{\rho}} = 1/\sqrt{3}$$

$\eta \equiv \int dt/a(t)$. for light $r = \eta$



fluid wave heating & cooling

solution $\Theta(\eta_{ls}) = \Theta(0)\cos(ks_{ls})$ no initial velocity

Sound horizon $s_{ls} = c_s \eta_{ls}$

$$\ell_n \approx n\pi D_{ls} / s_{ls}$$

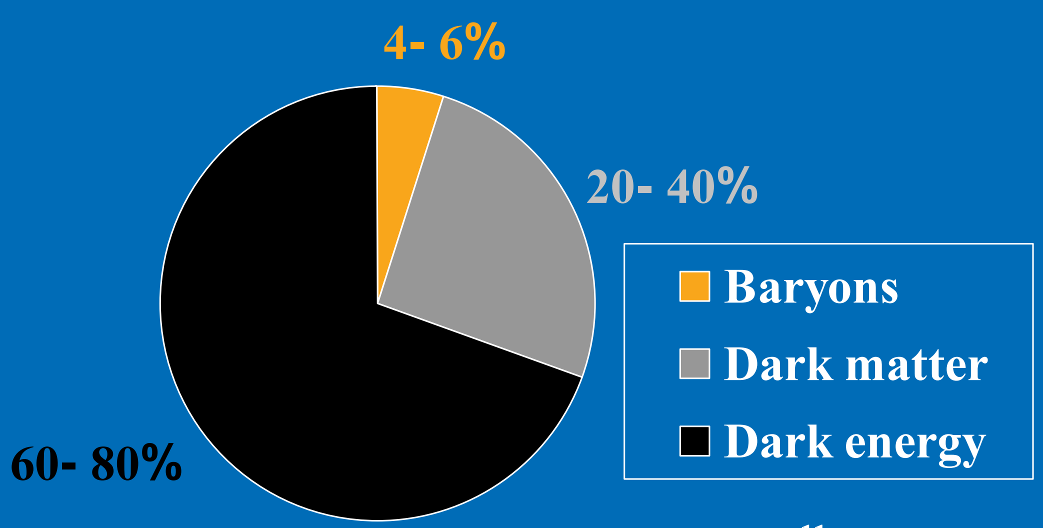
Modes "caught" at max./min.@ ls ➔ peaks in PS

With gravity: Θ ➔ $\Theta + \Psi$

Combined results

astro-ph/0302209 Table 7. Best Fit Parameters: Power Law Λ CDM

	WMAP	WMAPext[16]a	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
A	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	$0.75^{+0.08}_{-0.07}$
n_s	0.99 ± 0.04	0.97 ± 0.03	0.97 ± 0.03	0.96 ± 0.02
τ	$0.166^{+0.076}_{-0.071}$	$0.143^{+0.071}_{-0.062}$	$0.148^{+0.073}_{-0.071}$	$0.117^{+0.057}_{-0.053}$
h	0.72 ± 0.05	0.73 ± 0.05	0.73 ± 0.03	0.72 ± 0.03
$\Omega_m h^2$	0.14 ± 0.02	0.13 ± 0.01	0.134 ± 0.006	0.133 ± 0.006
$\Omega_b h^2$	0.024 ± 0.001	0.023 ± 0.001	0.023 ± 0.001	0.0226 ± 0.0008
χ^2_{eff}/ν	1431/1342	1440/1352	1468/1381	b



ν small

<u>Interim report I</u>

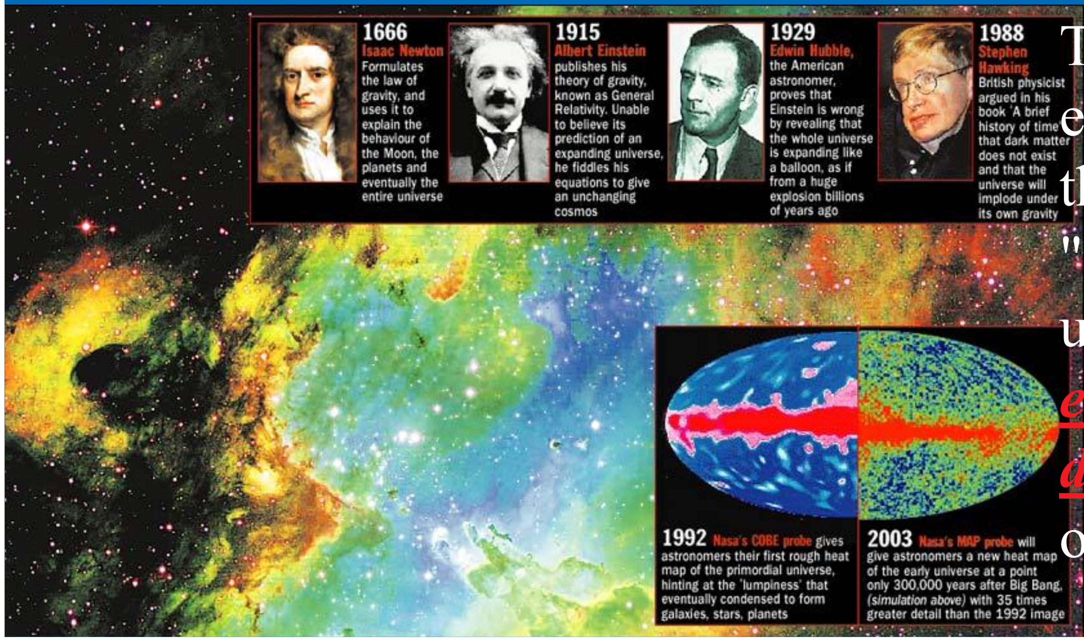
- flat universe
- acceleration
- consistent
- reasonable ?!

The end of the universe is cancelled

By Robert Matthews, Science Correspondent

(Filed: 09/02/2003)

Professor Hawking, we have a problem. Nasa, the American space agency, is expected to announce this week that it has proved the existence of "dark energy", a cosmic force that counteracts gravity and will keep the universe expanding forever.



The announcement will effectively demolish the theory that life will be wiped out in a "Big Crunch" when the universe collapses, ***and should end decades of academic dispute*** over the forces at work on the universe

Interpretation: theoretical expectations

- Dark energy is not just Λ
- Dynamical field (s):
  - Kinetic & potential energies
  - Interactions with other particles
  - Cosmic friction
  - Very small mass

→ time-dependence

Dark Energy **EOS**

- Parametrization in terms of (time-dependent)

  Energy density $\rho_Q(z)$

  Pressure $p_Q(z)$

  EOS $w_Q(z)=p_Q(z)/\rho_Q(z)$

- previously : $w_Q = -1$ → Λ

  $w_Q = 0$ → cold matter

oscillations, “sudden start”, “decay to a constant”

Luminosity distance d_L vs. redshift z

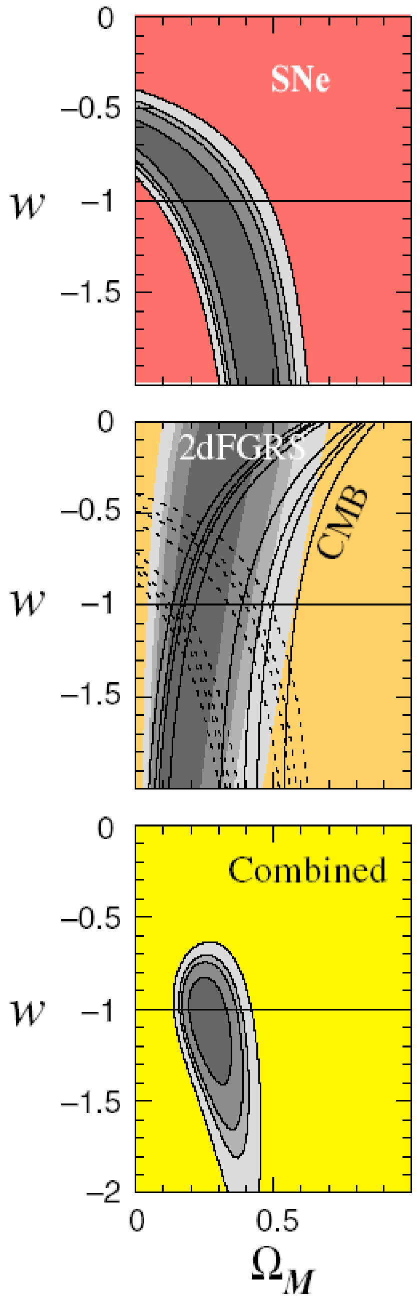
$$d_L = \frac{(1+z)}{H_0}\int_1^{1+z} dx\, exp\left[-\frac{3}{2}\int_1^x (1+w_T(y))\frac{dy}{y}\right] =$$

$$= \frac{(1+z)}{H_0}\int_1^{1+z} \frac{dx}{x^{3/2}} exp\left[-\frac{3}{2}\int_1^x \left(\frac{w_Q(y)}{1+g\, exp\left[-3\int_1^y w_Q(u)\frac{du}{u}\right]}\right)\frac{dy}{y}\right]$$

Maor et al.

$g = \Omega_m/(1-\Omega_m)$

Current SnIA data: some acceleration in the last 8 billion years ($0 < z < 1$)



Supernova Cosmology Project
Knop *et al.* (2003)

Assuming constant w

With limits from;
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003, Spergel et al. 2003)

$w = -1.05 \; ^{+0.15}_{-0.20}$ (statistical)

± 0.09 (systematic)

Current SNIa Data

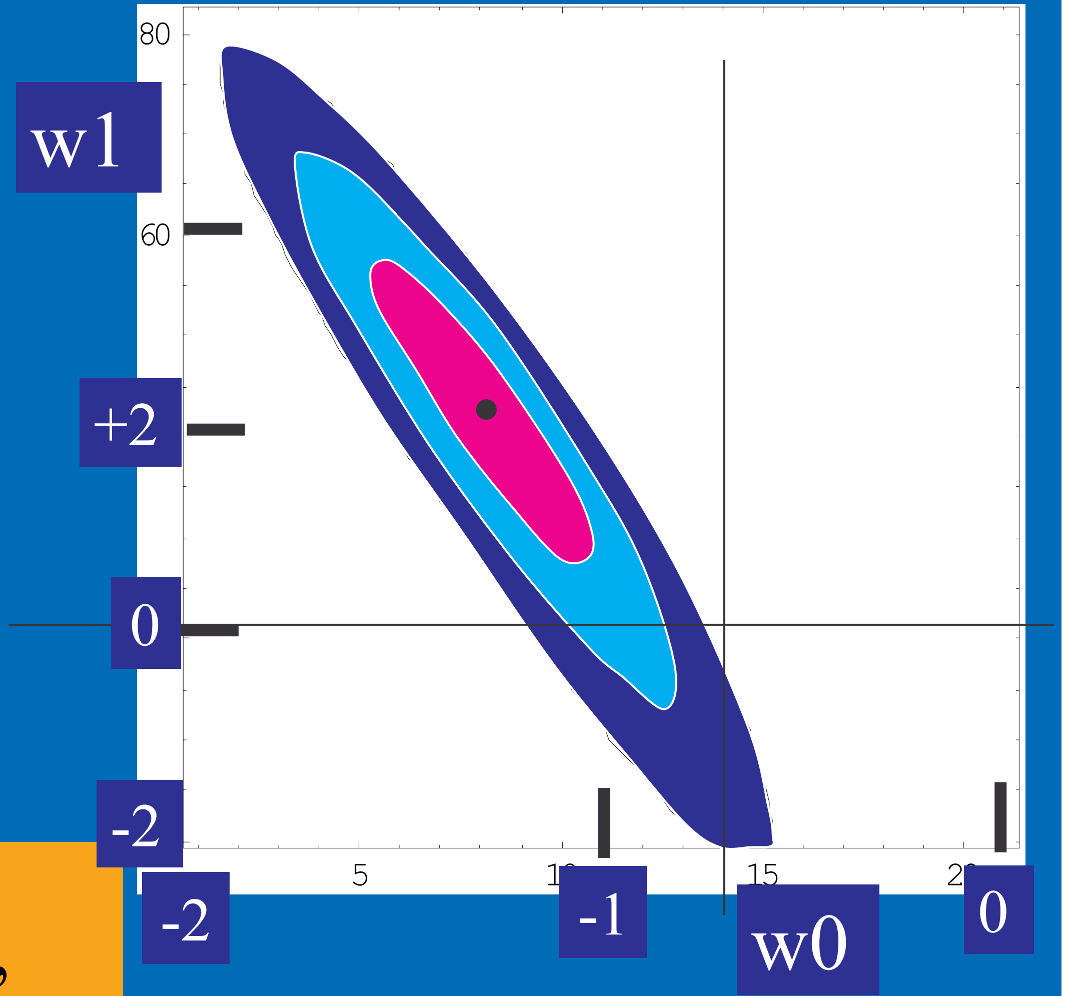
Fit to

$w_Q = w0 + w1z$

* Fixed Ω_m=0.23

(Fixed Ω_m=0.32,

0< w1< +4,1σ)



W_Q< -.7 for some z,

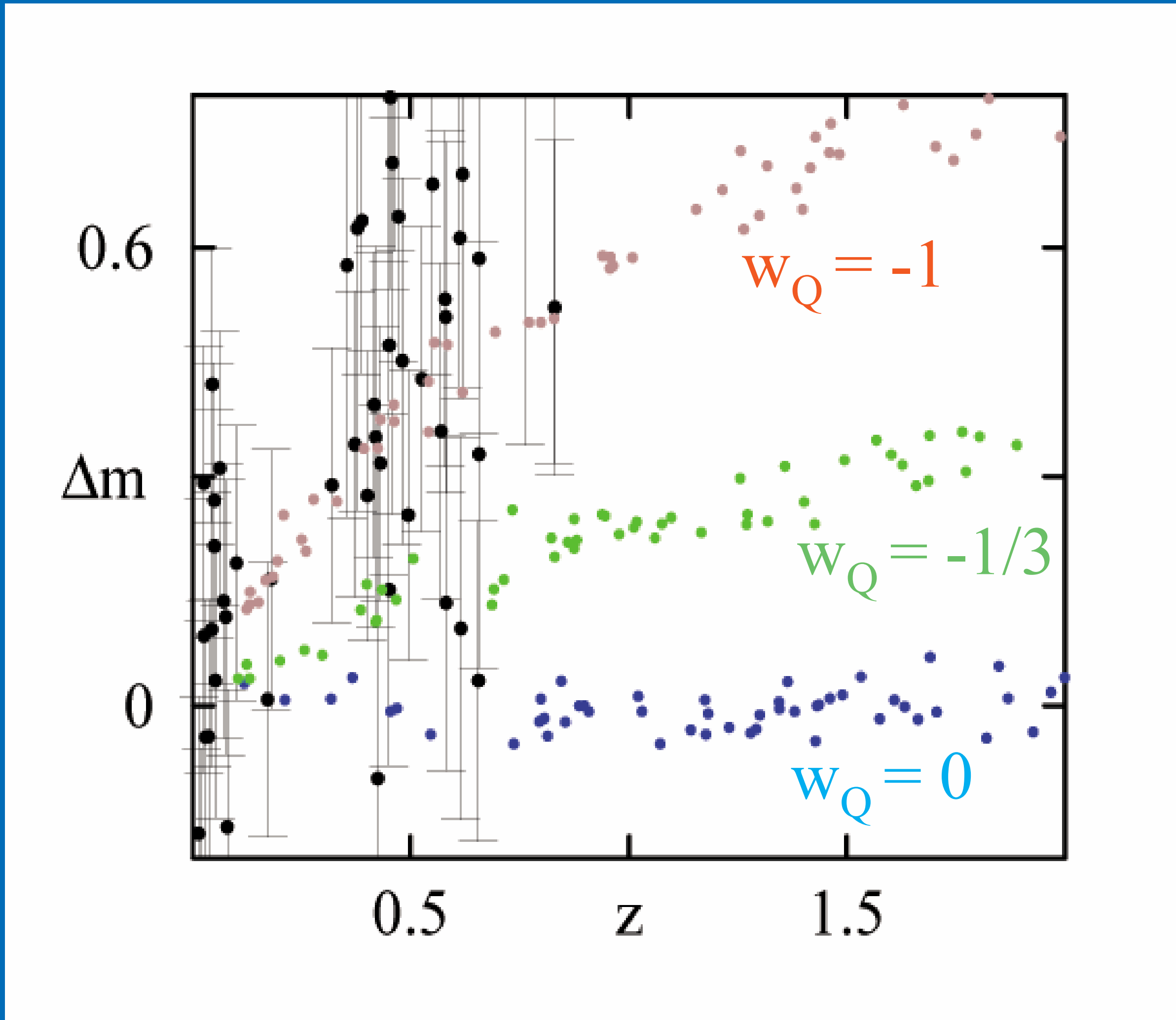
0< z < 1

l'avenir: SNAP (F)

snap.lbl.gov

SNAP proposal:
1000's de SNIa,
surtout $0 < z < 1.2$,
quelques-uns $1.2 < z < 1.7$

Also:
ESSENCE
CFHLS (F)
GOODS,
SNFactory (F)



fiducial models:

$\Omega_m = 0.3$

$w_Q = $ const.

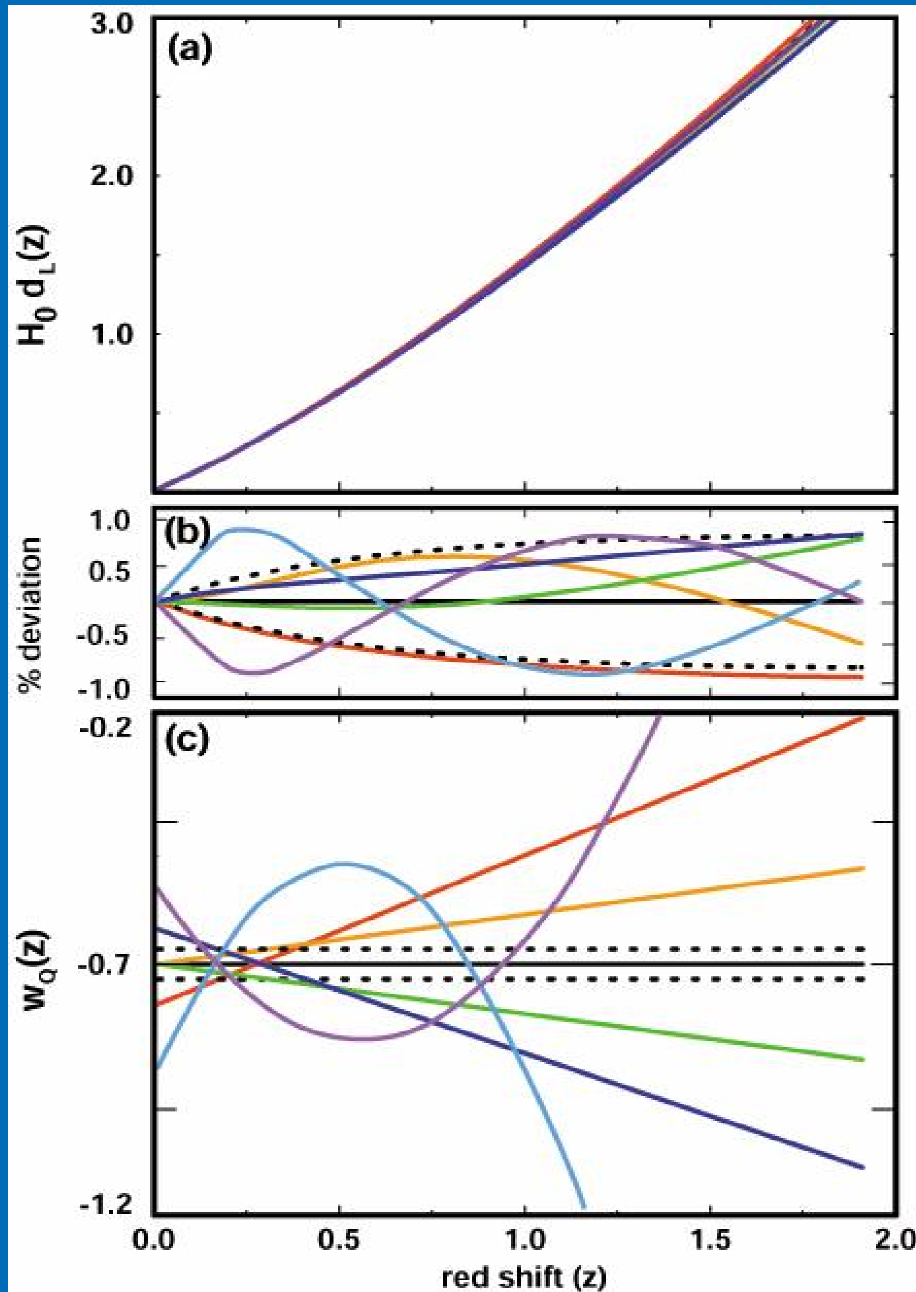
See: Sci. Am. 1/2001

Degeneracy!

Maor et al.

a) DL
b) Δ DL/DL
c) $w_Q(z)$

For 9 different EOS



CMB cannot help much …

Maor & Brustein

- Dark energy expected to “disappear” for $z > 2$
- CMB photons propagate most of the way through matter dominated U.

→ No gain compared to “low z” probes

- Best accuracy for d_L from CMB ~ 1%

→ CMB comparable to other probes

- CMB cannot help much … Maor & Brustein

$$
\begin{aligned}
d_L(x_{ls}) &= x_{ls}\int_1^{x_{ls}} \frac{dx}{H(x)} \\
&= x_{ls}\int_1^{3} \frac{dx}{H(x)} + x_{ls}\int_3^{x_{ls}} \frac{dx}{H(x)} \\
&= \frac{x_{ls}}{3} d_L(3) + \frac{x_{ls}}{H(3)} \int_3^{x_{ls}} \frac{dx}{H(x)/H(3)} \\
&= \frac{x_{ls}}{3} d_L(3) + \frac{x_{ls}}{H(3)} \int_3^{x_{ls}} \frac{dx}{(x/3)^{3/2}} \\
&= \frac{x_{ls}}{3} d_L(3) + 2x_{ls}\left(\frac{1}{\sqrt{3}} - \frac{1}{\sqrt{x_{ls}}}\right)\left(\frac{3^{3/2}}{H(3)}\right),
\end{aligned}
$$

$x=z+1$

$$d'_L(3) = c_1 \frac{d_L(3)}{3}$$

$$\Delta d'_L(3) = c_2 \frac{\Delta d_L(3)}{3}$$

$$\left(\frac{\Delta d_L}{d_L}\right)_{x_{ls}} \simeq \frac{2c_2 - 1}{2c_1 - 1}\left(\frac{\Delta d_L}{d_L}\right)_{x=3}$$

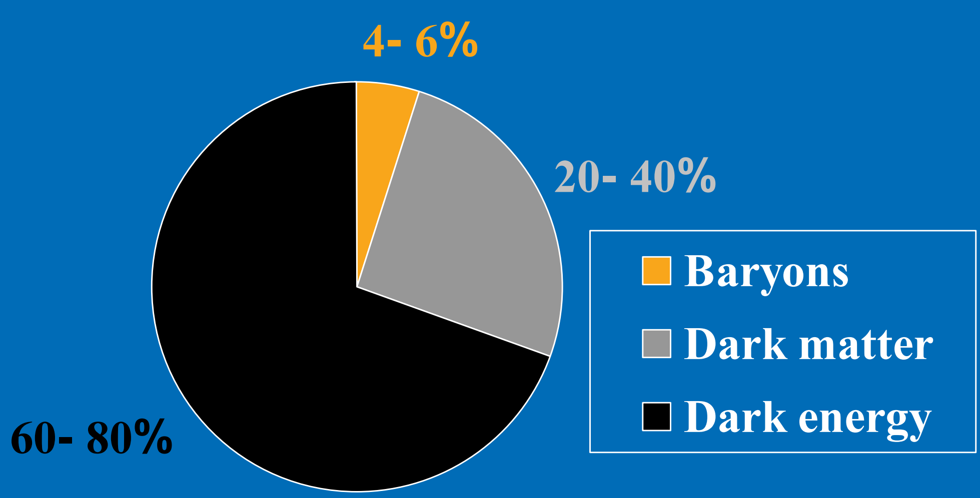
Interim report II

- recent acceleration

($0 < z < 1$, today $< t <$ 8 billion years)

- evidence from many sources, consistent.
- qualitative information only (on fundamental physics) from most accurate planned experiments

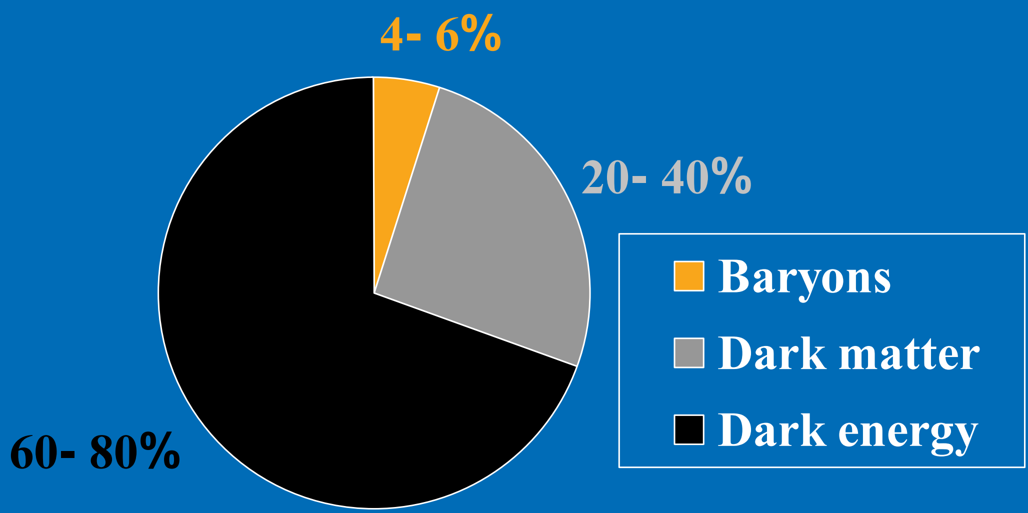
Dark sector
&
the standard model of particle physics



arXiv:hep-ph/0211065 v1 5 Nov 2002

$$\begin{aligned}
M_H &= 86^{+49}_{-32}\ \mathrm{GeV}, \\
m_t &= 174.2 \pm 4.4\ \mathrm{GeV}, \\
\alpha_s &= 0.1210 \pm 0.0018, \\
\hat{\alpha}(M_Z)^{-1} &= 127.922 \pm 0.020 \\
\hat{s}^2_Z &= 0.23110 \pm 0.00015, \\
\bar{s}^2_\ell &= 0.23139 \pm 0.00015, \\
s^2_W &= 0.22277 \pm 0.00035 \\
s^2_{M_Z} &= 0.23105 \pm 0.00008
\end{aligned}$$

Dark sector
&
gravity and quantum mechanics



$$\rho_{Vacuum} = \sum_{\omega} \frac{1}{2} \hbar \omega$$

$$G_{00} = 8\pi G_N \rho$$

Does not make sense as a normal source

P. J. E. Peebles :

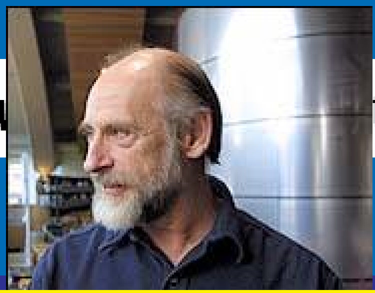
arXiv:astro-ph/0209403 v1 19 Sep 2002

Abstract. Physical science has changed in the century since Lord Kelvin's celebrated essay on *Nineteenth Century Clouds over the Dynamical Theory of Heat and Light*, but some things are the same.

Cloud No. I: the Dark Sector

Cloud No. II: Strong Spacetime Curvature

Clou... the Me...



"We live where we can live,"
NYT: 2 Sept. 2003

Something has to give

- Gravity

$$\rho_{Vacuum} = \sum_{\omega} \frac{1}{2}\hbar\omega$$

$$G_{00} = 8\pi G_N \rho$$

- Matter – additional fields, light, extremely weakly coupled – "quintessence"
- Quantum mechanics
- More space dimensions
- Cherished principles: causality, …

and the ugliest(?) of them all:
the Anthropic principle

The “boring” option: Quintessence

- “Tracker” fields
- Many other possibilities

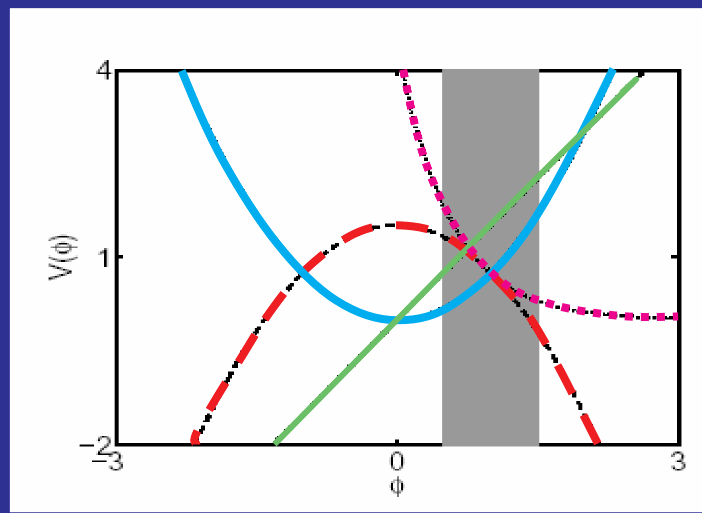
$m \sim H = 10^{-33}$ eV
$V \sim \rho_{crit} \sim (10^{-3}\ eV)^4$

Steinhardt + …
Rhatra+Peebles
Wetterich …

Maor & Brustein

Degeneracies

$$w_Q = \frac{p_Q}{\rho_Q} = \frac{x^2 H^2 \phi'^2 - 2V}{x^2 H^2 \phi'^2 + 2V}.$$



The Anthropic Principle

R. Dicke (1961): " carbon-based life can only arise when the Dirac large numbers hypothesis is true because this is when burning stars exist"

B. Carter (Early 1970's): "what we can expect to observe must be restricted by the conditions necessary for our presence as observers" (Leslie ed. 1990). The word "anthropic" was intended as applying to intelligent beings.

A possible argument for preferring the God hypothesis: think in terms of many possible fundamental theories, God selecting a theory which permitted life's requirements to be fulfilled without contradictions.

Conclusions

- **Excellent measurements are not good enough as clues for fundamental physics !**
- **A large source of error: theory**
- **Need:**
  - **either a new "local" test -what is it?**
  - **or radically new theoretical input -what is it ?**
- **Theory situation in a nut-shell**

  "we don't have a clue"
- **Personal hope: revolutionary resolution**