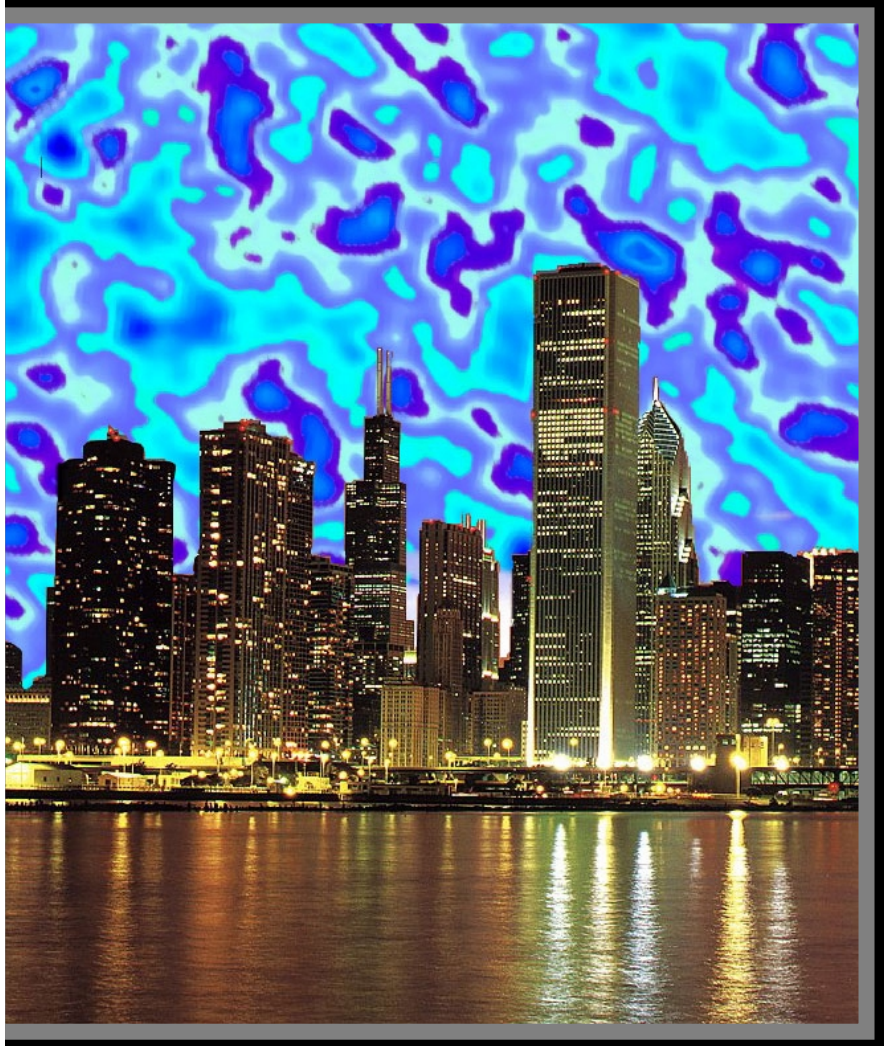

Opening Thoughts

COSMO-02

Wendy Freedman
Carnegie Observatories, Pasadena

Chicago, September 2002

Goals set by our friendly Organizing Committee…

Dear Wendy and David:

Cosmo-02 has proven even more popular than we had anticipated…

> Your two presentations constitute the opening and closing of the conference,… we are asking you for a combination of judgment, advice, inspiration and prognostication for its practictioners.

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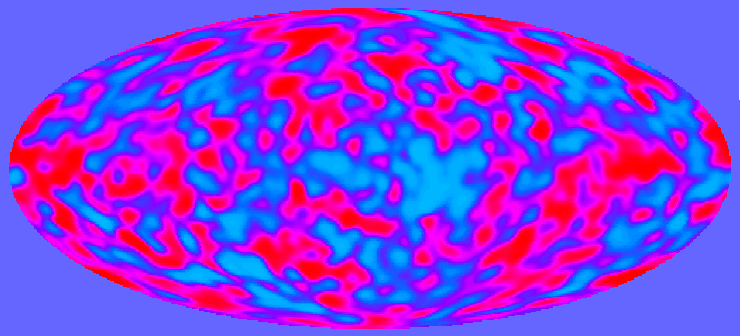
(In particular we are *not* looking for an overview or summary – give us your personal point of view.) The talks are short (25 minutes…) and we realize that we are asking you to do the nearly impossible.

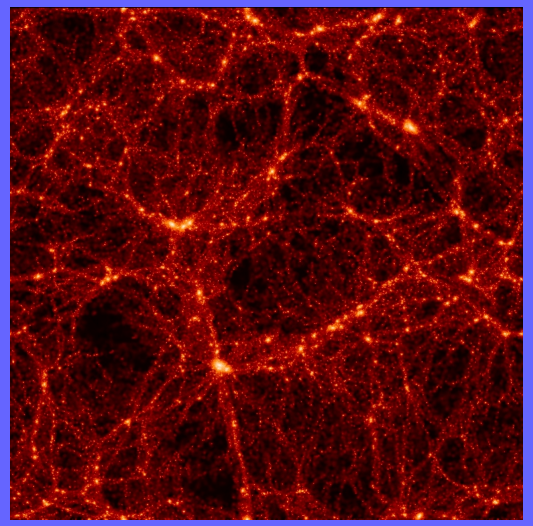
We trust that all of our speakers will make an extra effort to come as close as possible to the unrealistic goals we have set for them.

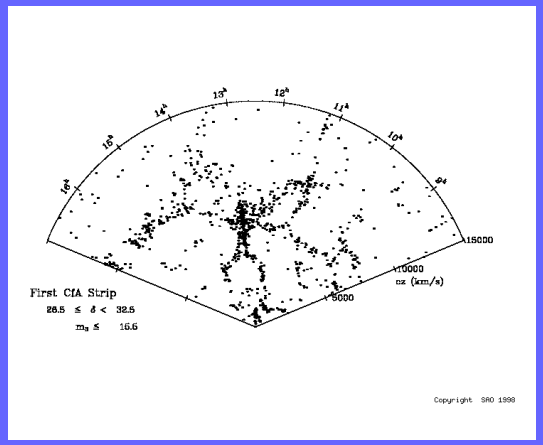
Sincerely,

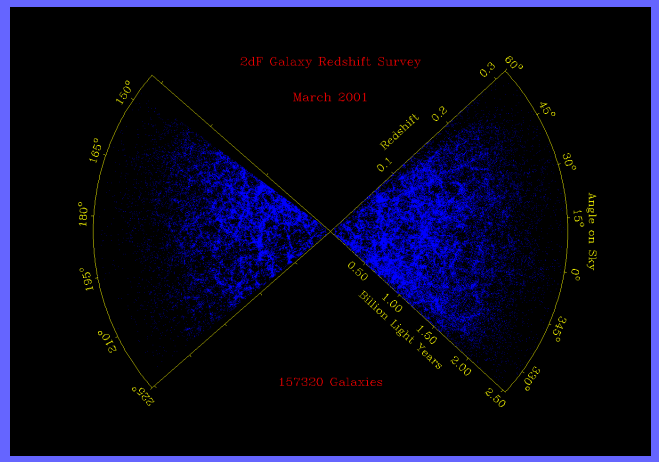
Successes:

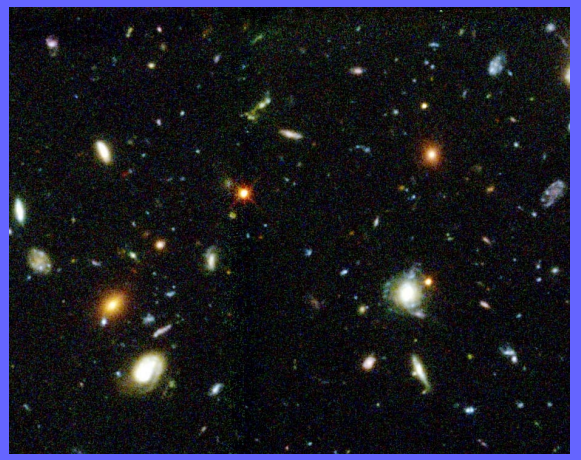
- **Inflation, gravitational instability plus cold dark matter…**



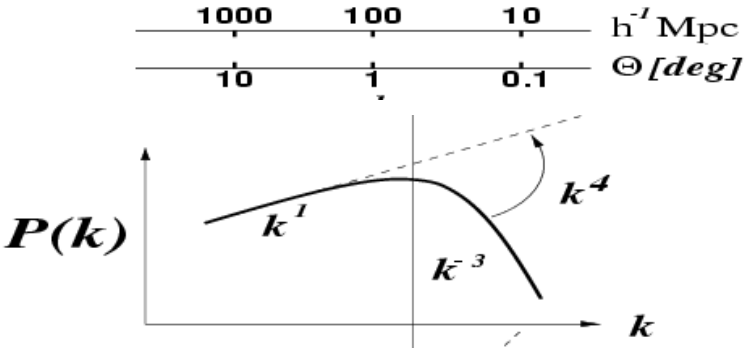


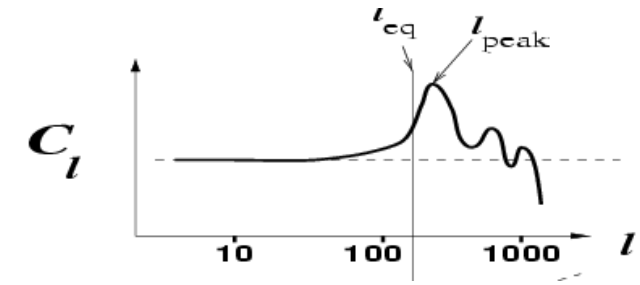


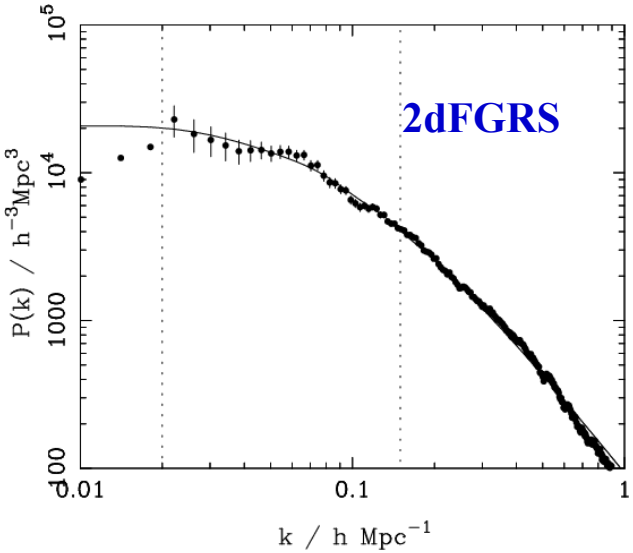


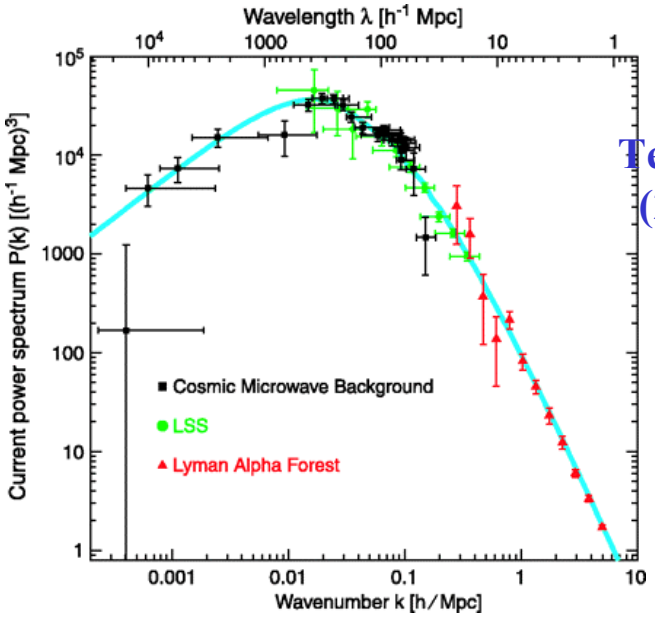


Power Spectrum









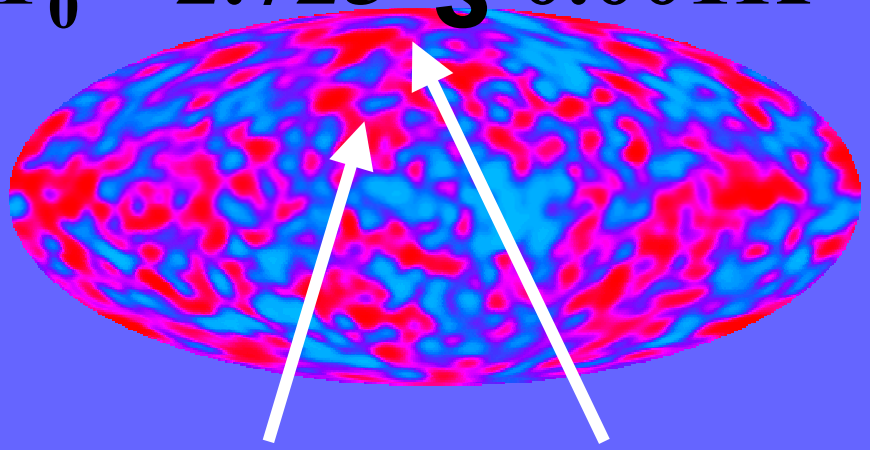
Tegmark (2002)

Primordial power spectrum:
$P(k) / k^n$ (n=1 scale invariant)

$$\Gamma \sim \Omega_m h \sim 0.25 \S 0.05$$

CMB Anisotropies

$T_0 = 2.725 \pm 0.001\mathrm{K}$



$T_1(\theta_1,\phi_1) \quad T_2(\theta_2,\phi_2)$

$$\langle T_1 T_2 \rangle = \sum a_{lm} Y_{lm}(\theta,\phi)$$

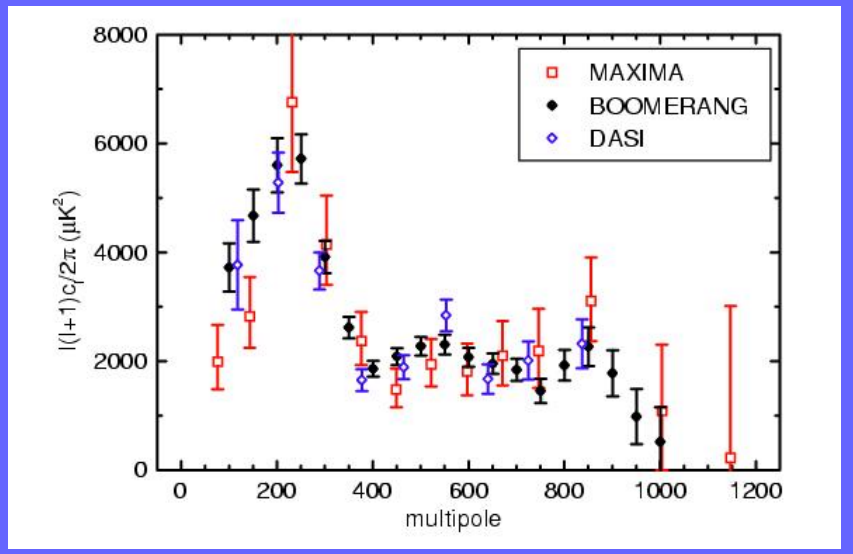
$$\left\langle |a_{lm}|^2 \right\rangle^{1/2} \equiv C_l$$

$\Omega_0 = 1.03 \pm 0.03$

$\Rightarrow$ flat geometry

Dasi, Boomerang, MAXIMA, CBI

$n = 1.05 \pm 0.06$

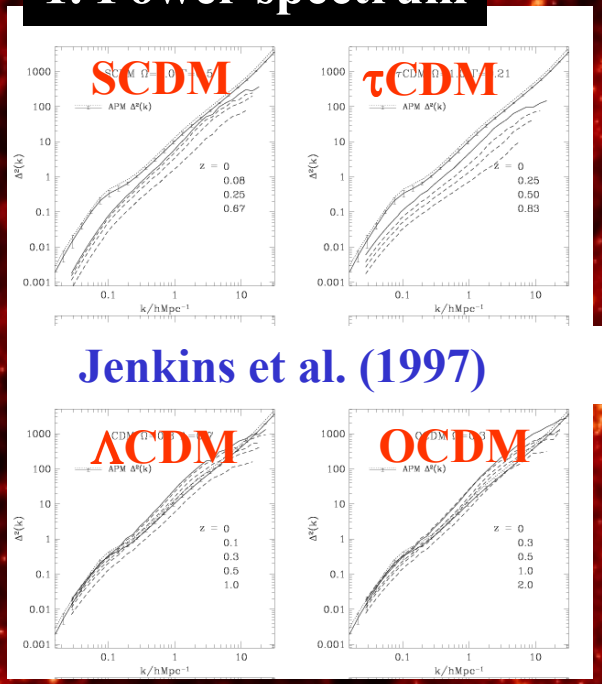


Troubles: Inflation + Cold Dark Matter

1. poor fit to galaxy power spectrum for Einstein-de Sitter model (SCDM: $\Omega_m = 1$, $\Lambda = 0$, $h = 0.5$)
2. predicts excess of small satellites
3. predicts central cusps in density profiles

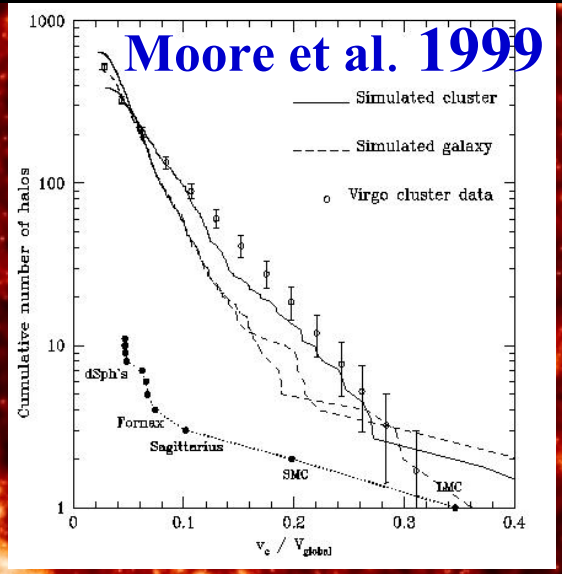
} on small scales

1. Power spectrum

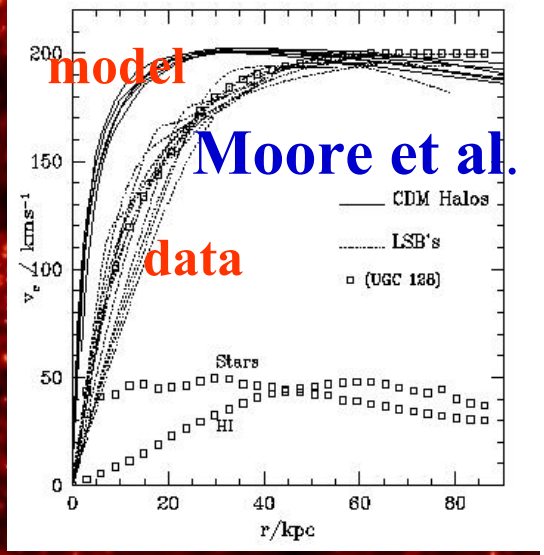


Jenkins et al. (1997)

2. Numbers of satellites



3. Cuspiness of profiles



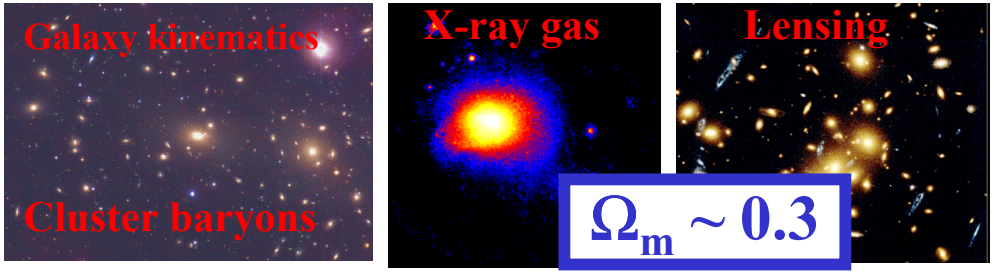
“How wonderful that we have met with a paradox. Now we have some hope of making progress.”

-Neils Bohr

Taking Stock of Where We Are

Einstein-de Sitter model fails because:

- CDM simulations fail to fit distribution of galaxies on large scales
- no evidence for $\Omega_m = 1$
- age discrepancy



Open universe fails because:

- CMB anisotropies yield $\Omega_0 = 1$

Variants to CDM:

Hot dark matter fails because:

- free streaming wipes out seeds for structure formation

Taking Stock of Where We Are

Lambda CDM universe current winner because:

- **excellent fit to galaxy power spectrum on large scales**
- **consistent with faint supernovae at high redshifts**
- **resolves age discrepancy**
- **consistent with LSS+CMB anisotropy results**
- **no single point failure**

Taking Stock of Where We Are

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- **consistent with faint supernovae at high redshifts**
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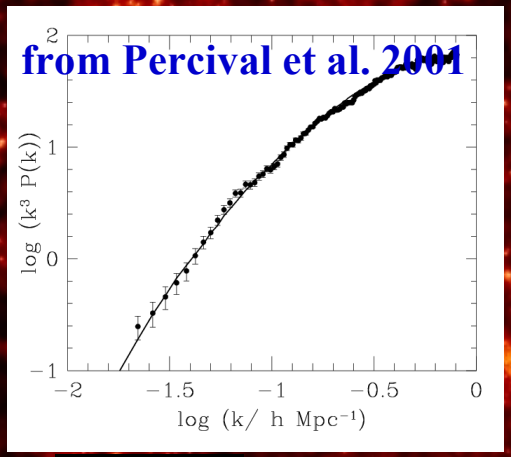
- **consistent with LSS+CMB anisotropy results**
- **no single point failure**

… and no better alternatives!

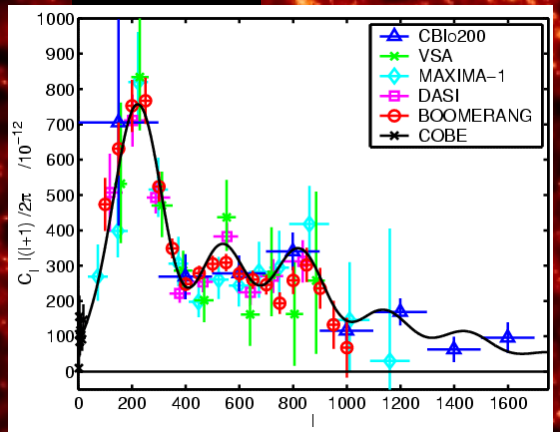
Inflation + Cold Dark Matter+ Dark Energy

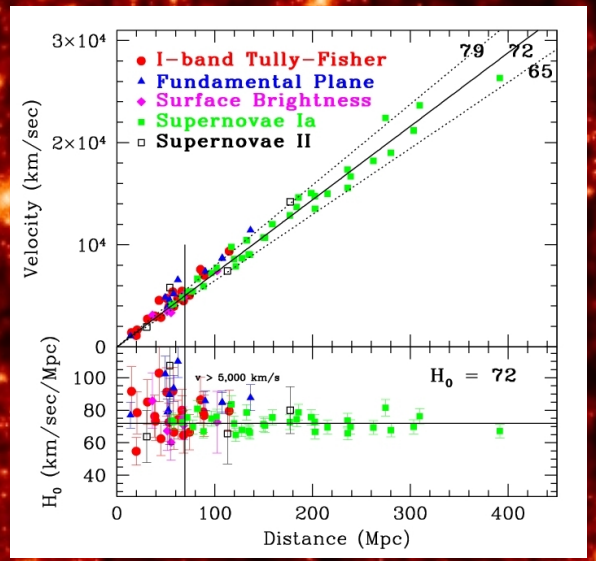
2Df Power Spectrum + Λ CDM



$\Omega_m = 0.3$
$\Omega_\Lambda = 0.7$
$h = 0.7$

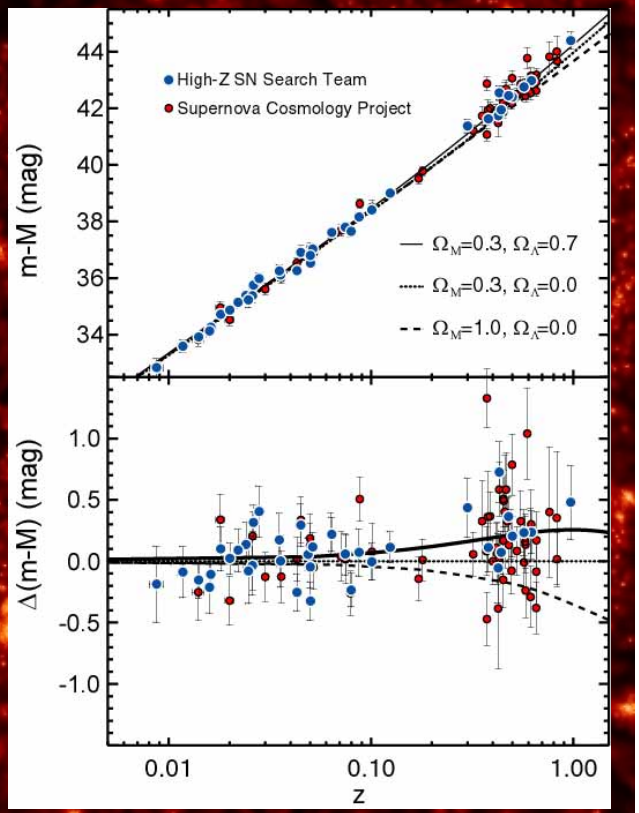
CMB





H_0 Key Project

Supernovae



Critical Missing Pieces to the Current "Standard Model"

- **Cold dark matter dominates the matter density and is in an unknown form**
- **The overall mass-energy density is dominated by dark energy, for which there is currently no explanation**
- **The dynamics of inflation depends on particle physics at high energy, and nothing is known of the hypothetical scalar field that drives inflation**

The Challenge:

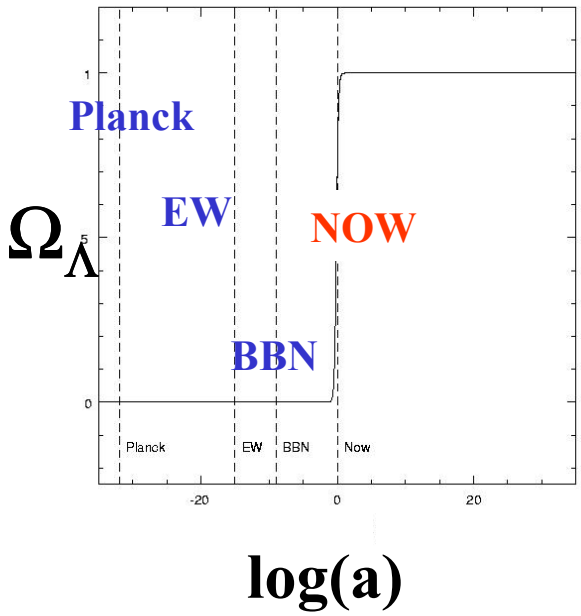
1. Why the small value?

Observed:	$\rho \cdot 10^{-30}$ g cm^{-3}
Quantum field theory:	$\rho = 1$
Quantum gravity:	$\rho \cdot 10^{+90}$ g cm^{-3}
Supersymmetry:	$\rho \cdot 10^{+30}$ g cm^{-3}

"The mystery of the cosmological constant is probably the most pressing obstacle to significantly improving the models of elementary particle physics derived from string theory."

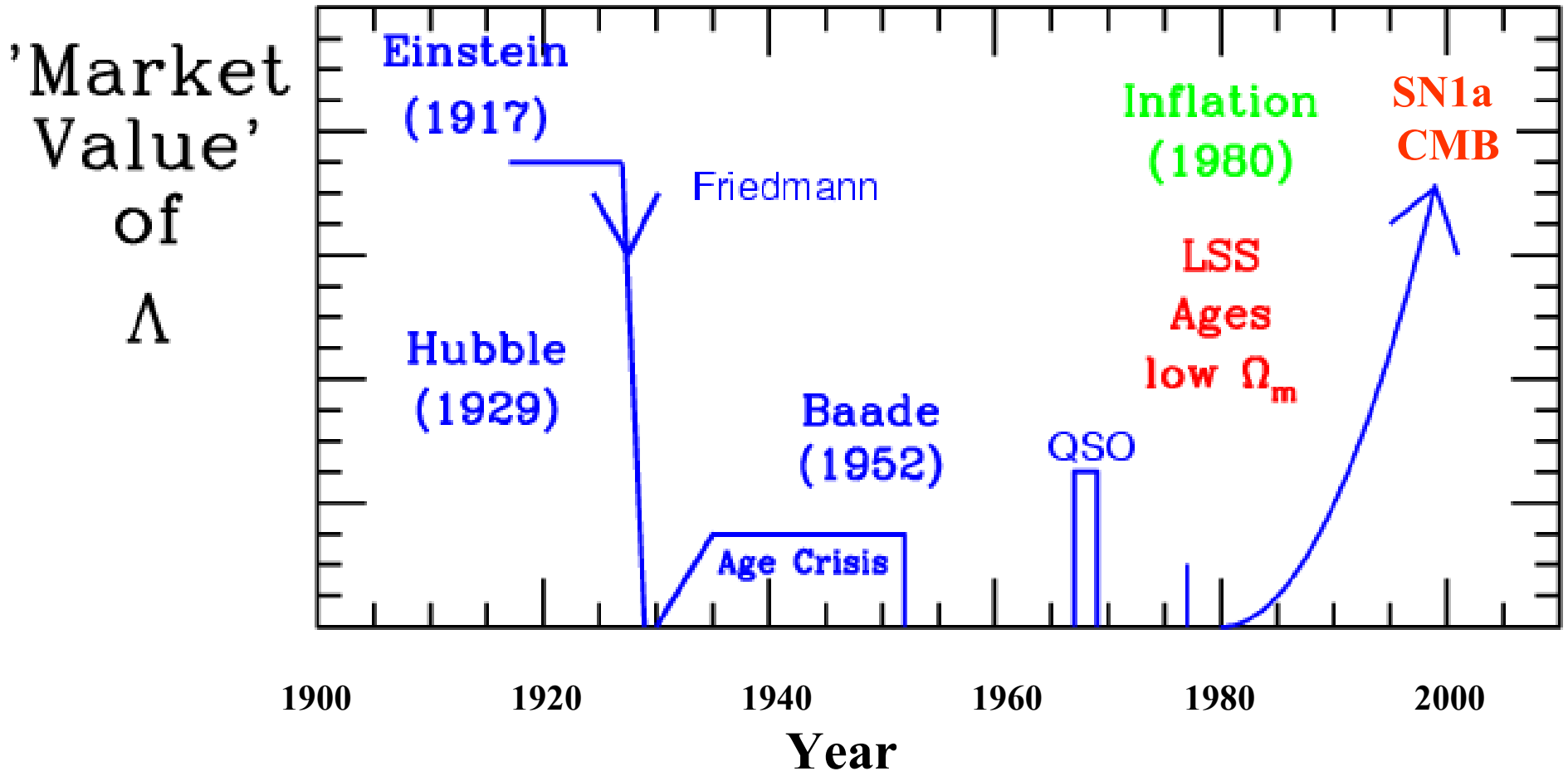
Witten (2000)

2. Why now?



Carroll (2001)

Λ : Blunder, Convenient, or Correct?



Freedman (2000)

Cosmological Framework

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \qquad H \equiv \frac{\dot{a}}{a}$$ expansion rate

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \qquad q \equiv -\frac{\ddot{a}}{a}\frac{1}{H^2}$$ deceleration parameter

$\rho = \rho_b + \rho_{CDM} + \rho_\nu + \rho_{rad} + \rho_X + \cdots$

$\Omega_0 \equiv \rho / \rho_{crit}$

$\rho_{crit} = 3H_0^2/8\pi G$

Essential to determine equation of state for dark energy:

Cosmological Framework

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$\Omega_0 \equiv \rho / \rho_{crit}$

$\rho_{crit} = 3H_0^2/8\pi G$

Essential to determine equation of state for dark energy :

$$w = P(z) / \rho(z)$$

$$\rho(z) / (1+z)^{3(1+w)}$$

Matter: $\rho_m / (1+z)^3$ $w = 0$
Radiation: $\rho_r / (1+z)^4$ $w = 1/3$
Vacuum: $\rho_\Lambda / (1+z)^0$ $w = -1$

16 Cosmological Parameters

2 sets of parameters:

- **first set: 10 parameters describing FLRW model**
  - **-- the expansion**
  - **-- global geometry**
  - **-- age**
  - **-- composition**

$$H_0,\ q_0,\ w,\ t_0,\ T_0,\ \Omega_0,\ \Omega_b,\ \Omega_{CDM},\ \Omega_\nu,\ \Omega_x$$

Freedman & Turner (Science, 2002)

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  - -- the expansion
  - -- global geometry
  - -- age
  - -- composition

$$H_0,\ q_0,\ w,\ t_0,\ T_0,\ \Omega_0,\ \Omega_b,\ \Omega_{CDM},\ \Omega_\nu,\ \Omega_x$$

- second set: 6 parameters describing the deviations from exact homogeneity

$$S,\ T,\ \sigma_8,\ n,\ n_T,\ dn/d\ln k$$

Freedman & Turner (Science, 2002)

Table of Cosmological Parameters

Part I: 9 global FLRW parameters:

H_0	72§7km/sec/Mpc	Present expansion rate
q_0	-0.67 § 0.25	Deceleration parameter
t_0	13 § 1.5	Age of the Universe
T_0	2.725 § 0.001K	CMB temperature
Ω_0	1.03 § 0.03	Density parameter
Ω_b	0.039 § 0.008	Baryons
Ω_{CDM}	0.3 § 0.05	CDM
Ω_ν	0.002 – 0.05	Massive neutrinos
Ω_X	0.7 § 0.1	Dark energy

Freedman & Turner (Science, 2002)

Table of Cosmological Parameters

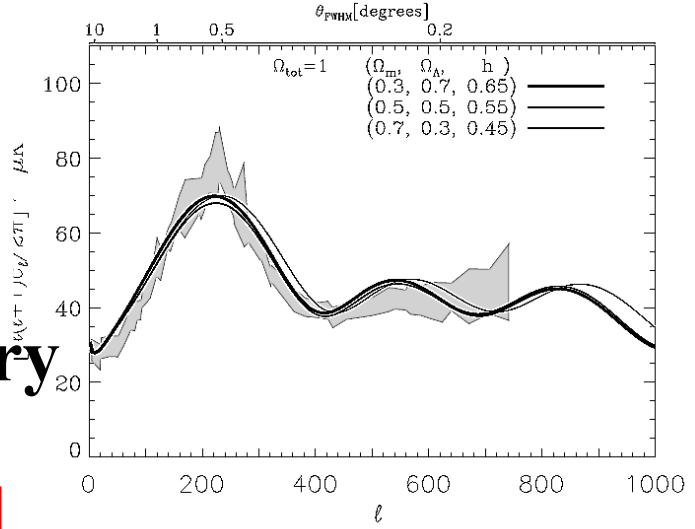
Part II: 6 fluctuation parameters:

S	10^{-10}	Scalar amplitude
T	< S	Tensor amplitude
σ_8	0.9 § 0.1	Mass fluctuations (8 Mpc)
n	1.05 § 0.09	Scalar index
n_T	------	Tensor index
dn/d ln k	-0.02 § 0.04	Running of scalar index

Freedman & Turner (Science, 2002)

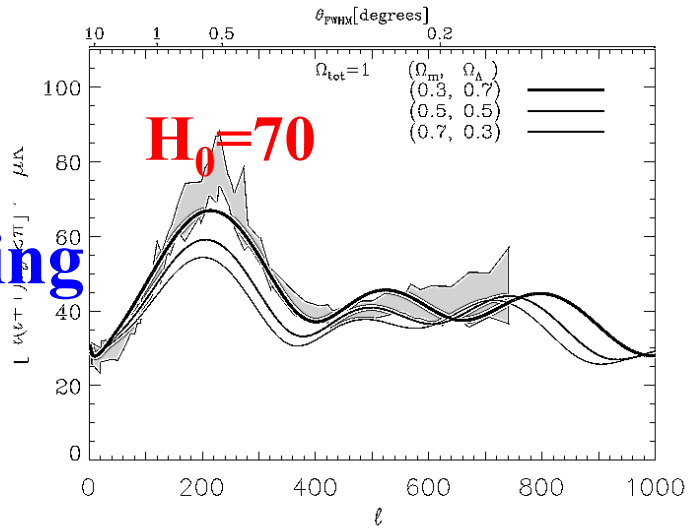
CMB Anisotropies

- Robust measure of Ω_0
- But large degeneracies



• Can have same geometry, but very different matter content

Ω_m and Ω_Λ are not measured independently from the CMB alone.

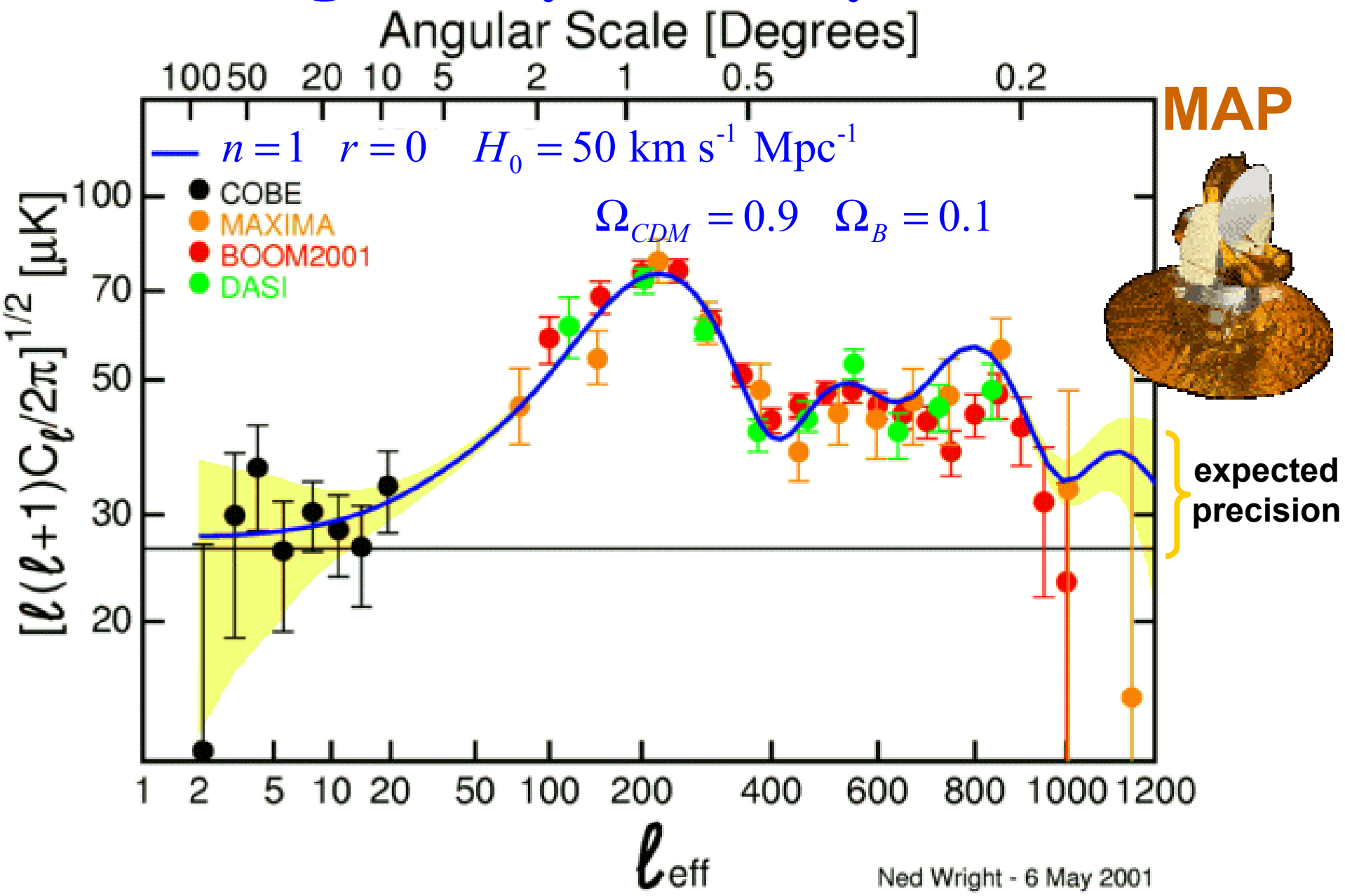


•To break degeneracies: H_0, SNIa, galaxy power spectrum, weak lensing

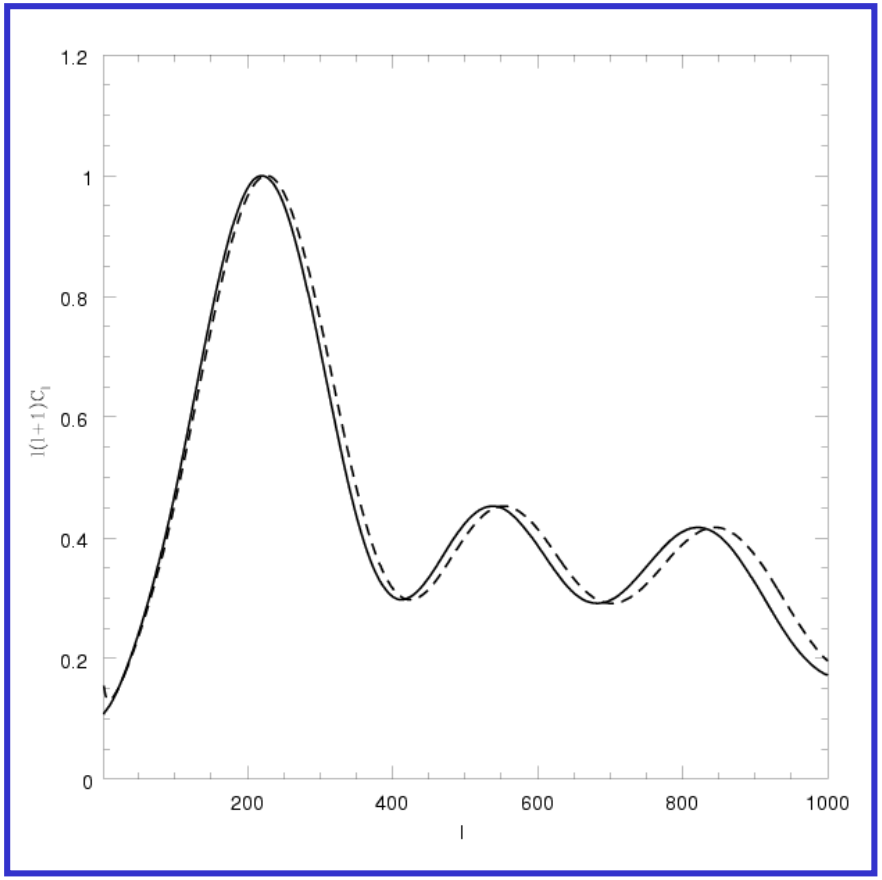
• CMB measurements give no information on w(z)

Lineweaver (2001)

Angular power spectrum



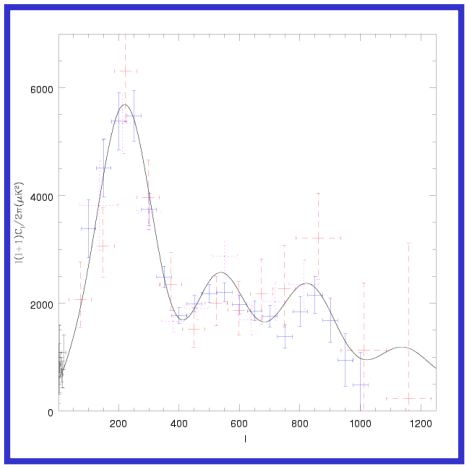
Constraining Quintessence



Baccigalupi et al. 2001

Solid line: $w_q = -0.8$
Dashed line: $w = -1$

A Challenge!!!



Best fit: $w_q = -0.8$
$\Omega_q = 0.72$

Prognostication***

*** Beware of observers willing to tell the future....

Prognostication***

Einstein will turn out to be right about the cosmological constant

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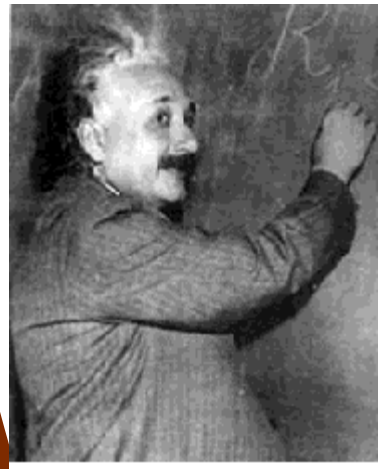
Prognostication***

Einstein will turn out to be right about the cosmological constant



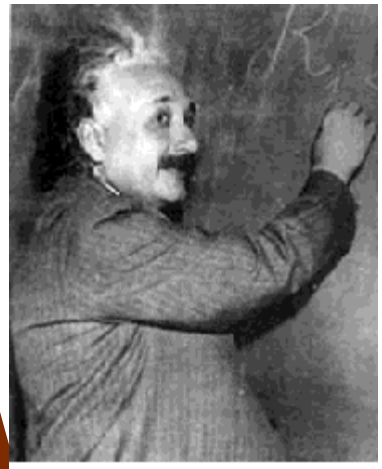
$$R_{\mu\nu} - 1/2 \mathcal{R} g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

"My biggest blunder"

*** Beware of observers willing to tell the future....

Prognostication***

Einstein will turn out to be right about the cosmological constant



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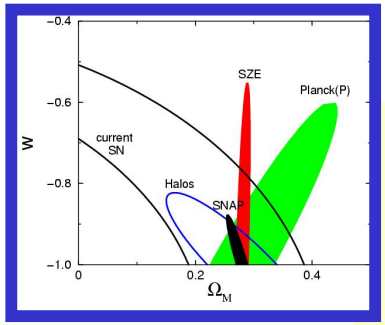
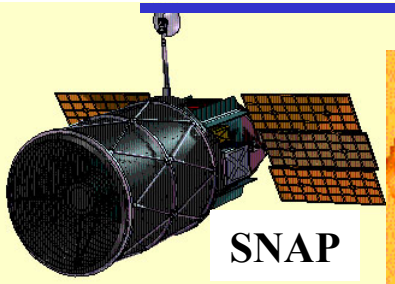
"My biggest blunder"

*** Beware of observers willing to tell the future....

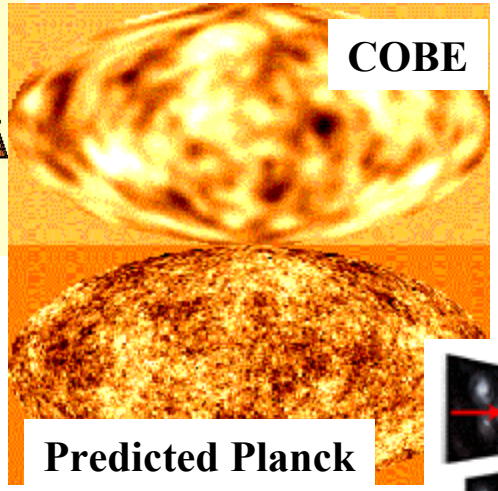
Either way!...

Looking Ahead





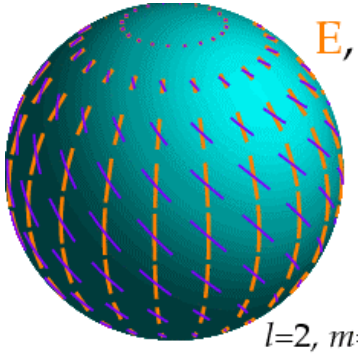
SNAP



COBE

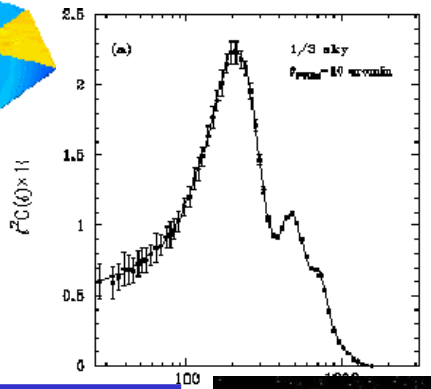
Predicted Planck

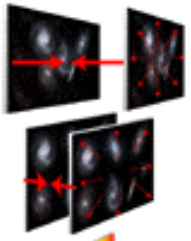
Fermilab



CMB Polarization

Planck

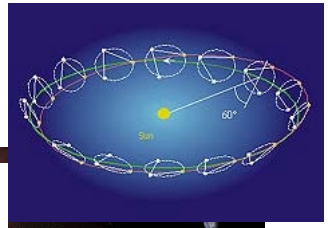




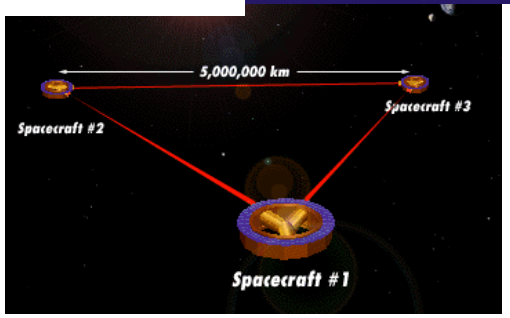
Cyclic Branes ???

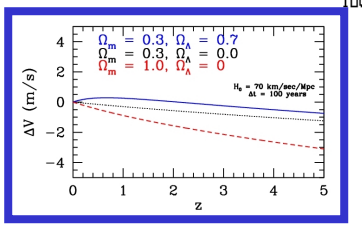
CERN

LHC prototype beam collider

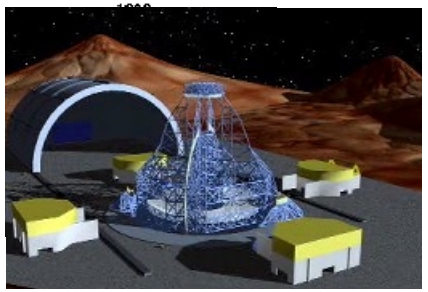


LISA orbit





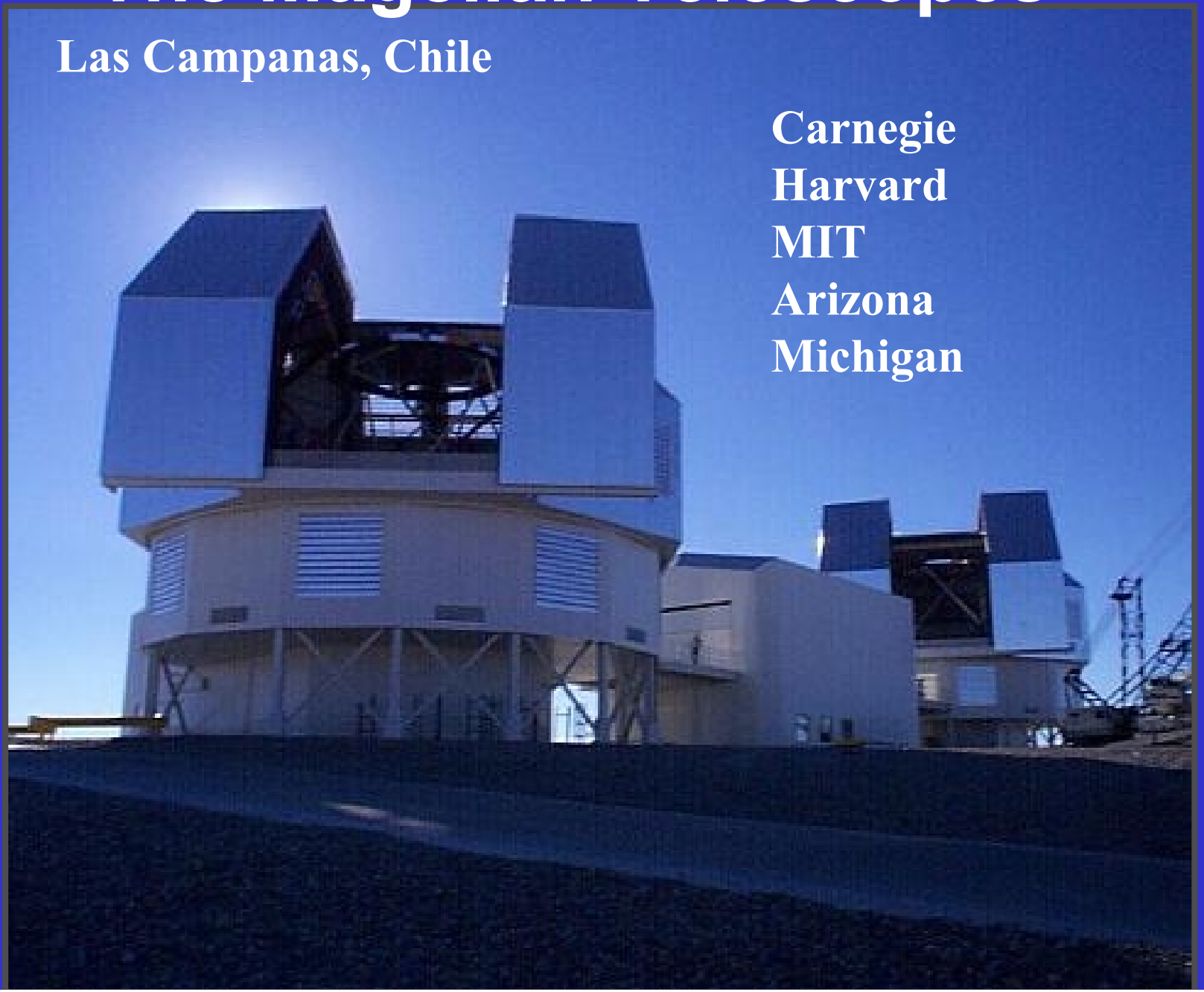
Direct expansion rate: 2 m/s/century!



OWL – 100m telescope

CDMS in the Soudan mine

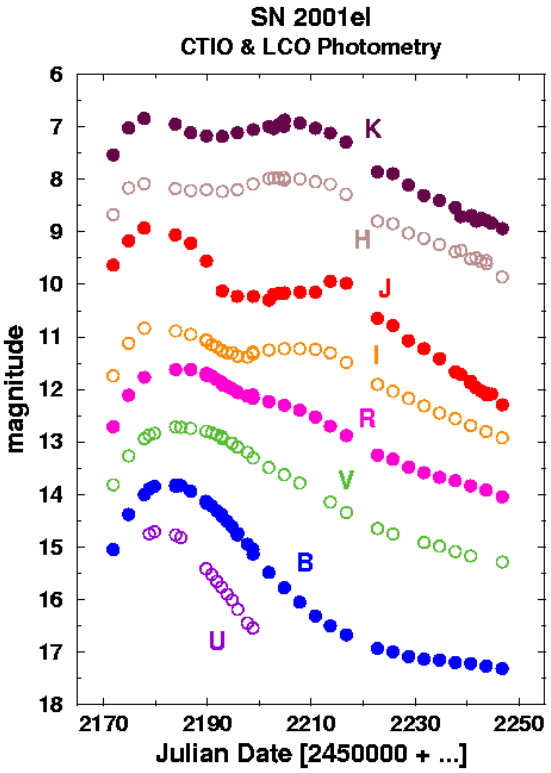
The Magellan Telescopes



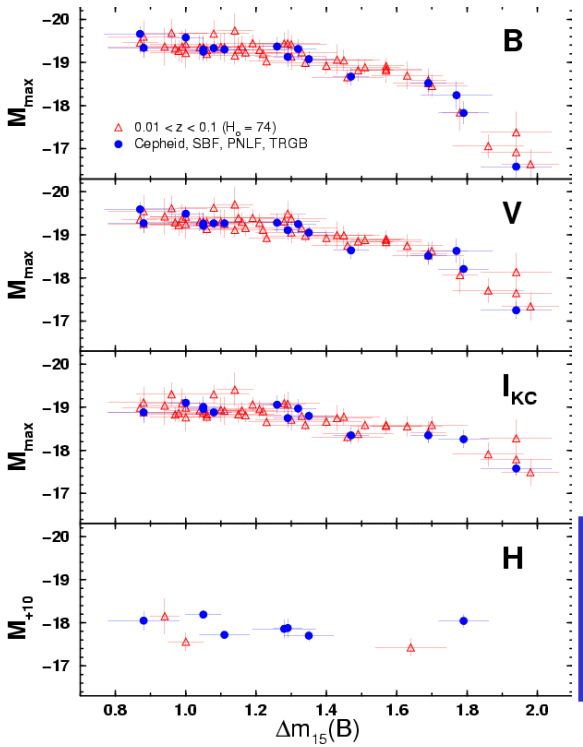
Carnegie/Las Campanas Infrared SN Survey

•Infrared Hubble diagram

- •UBVRIJHK observations
- •3 telescopes, coordinated followup, 5 years



•Decline-rate relation



• H-band may be insensitive to decline rate

>300 6.5m Magellan nights (2003-2008)

Carnegie Centennial Symposium

Measuring and Modeling the Universe

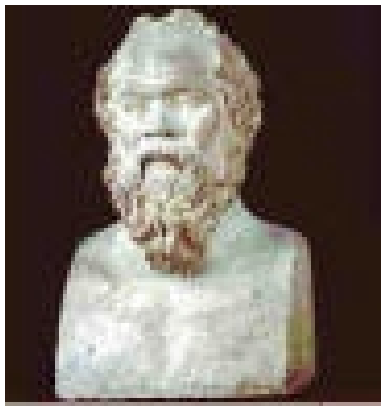
November 18-22, 2002

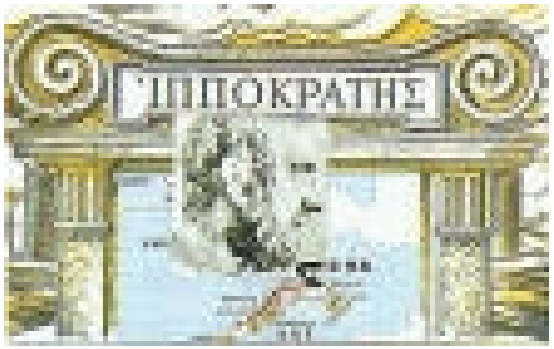
Pasadena, CA

Malcolm Longair	John Schwarz
Lisa Randall	Michael Turner
Alan Guth	Steven Weinberg
Marc Kamionkowski	Wendy Freedman
John Carlstrom	Chris Kochanek
John Tonry	Joe Silk
David Spergel	Andrew Lange
Matias Zaldiarraga	Tony Readhead
Lyman Page	Sandy Faber
Roger Blandford	Alex Filippenko

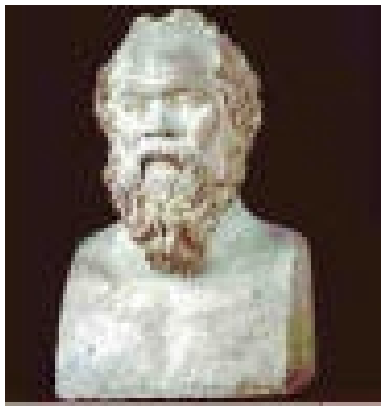
http://www.ociw.edu/ociw/symposia/symposium2

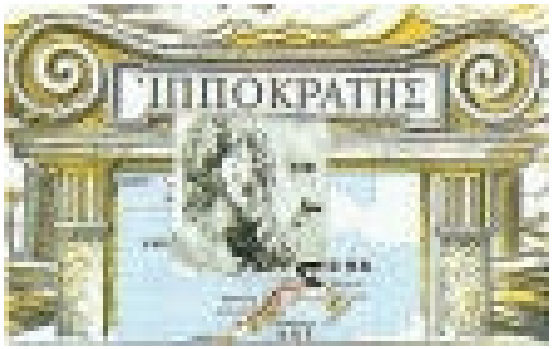
Are We Living in a Golden Age?





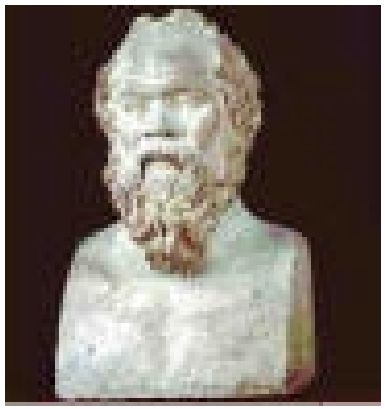
Are We Living in a Golden Age?

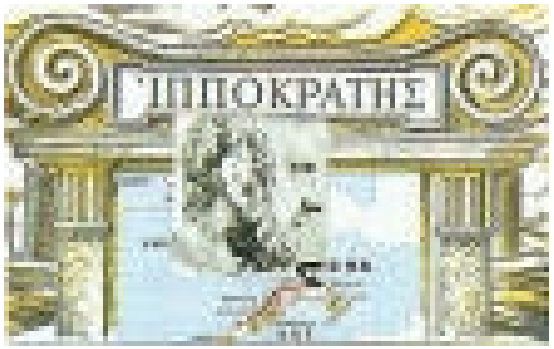




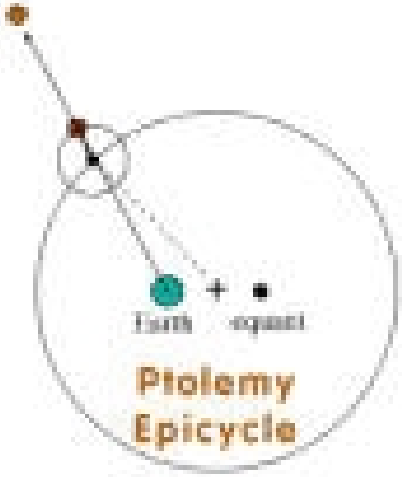
Or are we still living in a Bronze Age?…

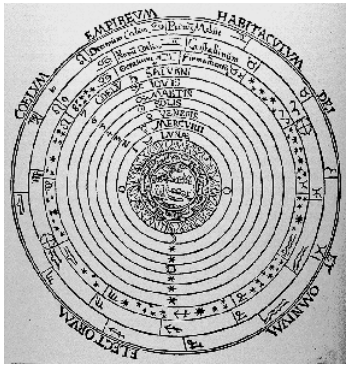
Are We Living in a Golden Age?





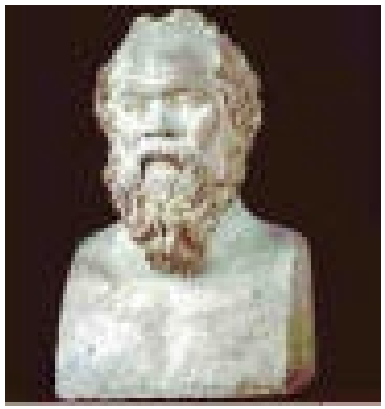
Or are we still living in a Bronze Age?…

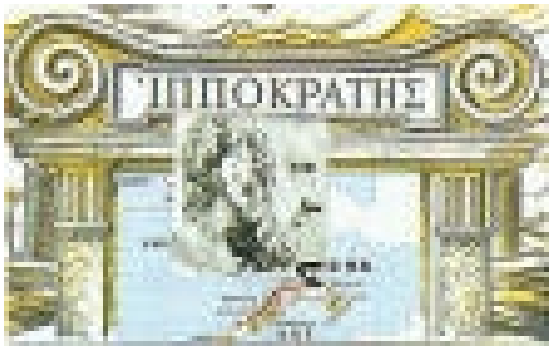




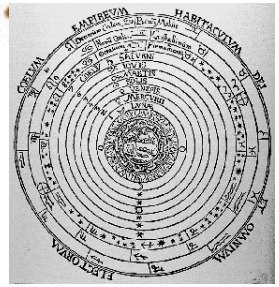
Or taken to epicycles?…

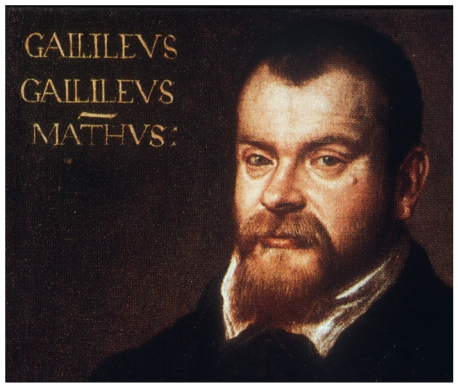
Are We Living in a Golden Age?





Or are we still living in a Bronze Age?…





Let us look forward to an Age of Reason and understanding!…