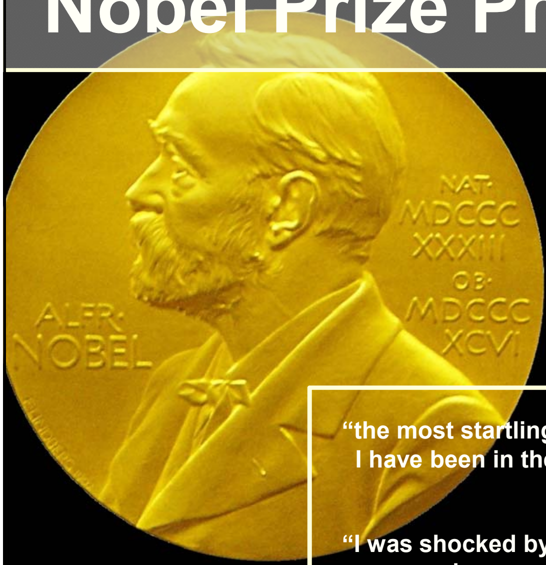

Dark Energy
Caput Lecture Series
Groningen University
November 2013 - January 2014


Nobel Prize Laureates
Adam Riess
Saul Perlmutter
Brian Schmidt

Nobel Prize Physics 2011



"the most startling discovery in physics since I have been in the field."

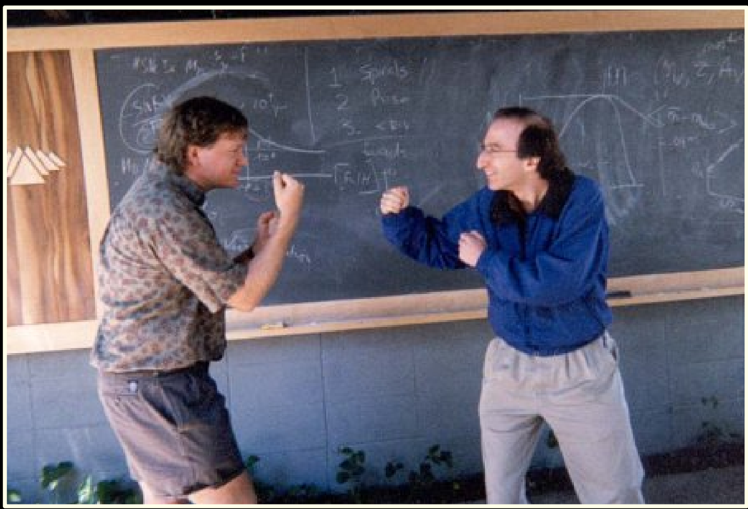
E. Witten

"I was shocked by my discovery, I just assumed we made a mistake"

Brian Schmidt

the Supernova Teams

Supernova Cosmology Project



High-z Supernova Search Team

Supernova Cosmology Project

SCP:
Saul Perlmutter — Lawrence Berkeley National Laboratory

~ 31 members, — Australia, Chile, France, Spain, Sweden, UK, USA
R. Ellis, A. Filippenko, I. Hook, M. Irwin, P. Ruiz-Lapuente, …

HZST:
Brian Schmidt — ANU, Mount Stromlo Observatory, Australia
Adam Riess — JHU, STScI (1998: Harvard)

20 members, — Australia, Chile, Europe, USA
A. Filippenko, M. Hamuy, R. Kirshner, B. Leibundgut, M. Phillips, J. Tonry …

The High-Z SN Search

High-z Supernova Search Team

Supernova Cosmology Project

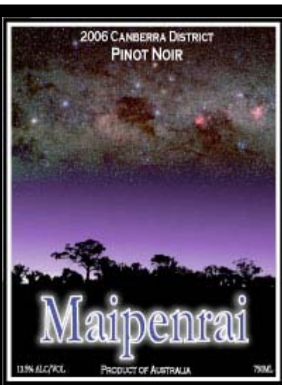
- Riess et al., 1998, Astronomical Journal, 116, 1009
  subm. March 13, 1998; accepted May 1998
  5822 citations (16/11/11)
- Perlmutter et al. , 1999, Astrophysical Journal, 517, 565
  5916 citations (16/11/11)

High-z Supernova Search Team

Supernova Cosmology Project

- 2006: Shaw Prize
- 2007: Gruber Cosmology Prize
- 2011: Nobel Prize
- Jim Peebles, Gruber Prize 2007 ceremony:
  "first, for solving the mass density of the Universe
  secondly, for solving the age crisis"

High-z Supernova Search Team



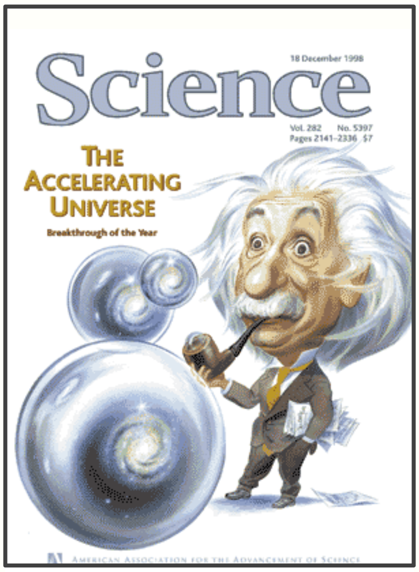
Maipenrai

"I was shocked by my discovery, I just assumed we made a mistake"

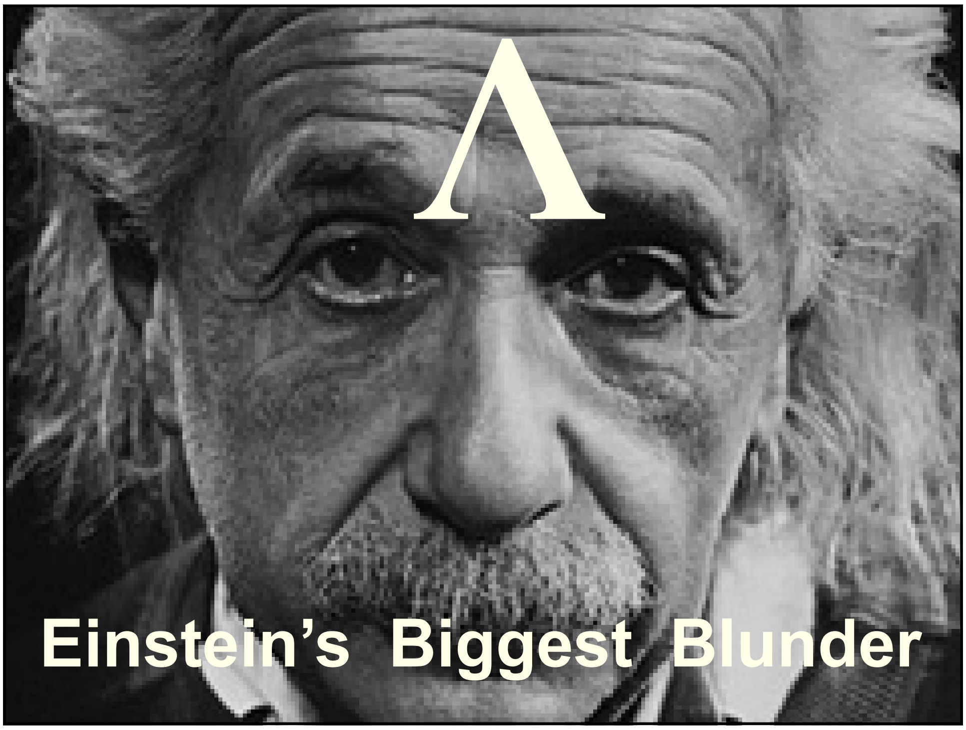
Brian Schmidt

Einstein's Blunder

Science Magazine 1998



Science
Breakthrough of the Year
1998



Cosmic Expansion

Friedmann-Robertson-Walker
Universe:

the Big Bang Universe

Einstein Field Equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

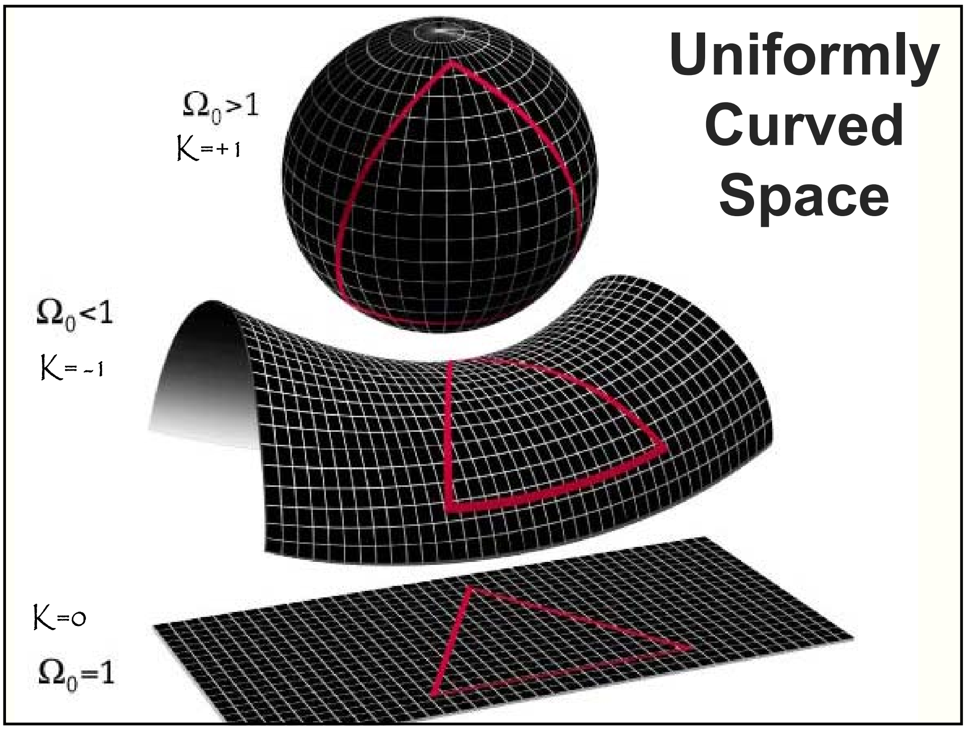
Einstein Field Equation

curvature side

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

energy-momentum side



Friedmann-Robertson-Walker-Lemaitre Universe

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda}{3}a$$

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - \frac{kc^2}{R_0^2} + \frac{\Lambda}{3}a^2$$

Friedmann-Robertson-Walker-Lemaitre Universe

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda}{3}a$$

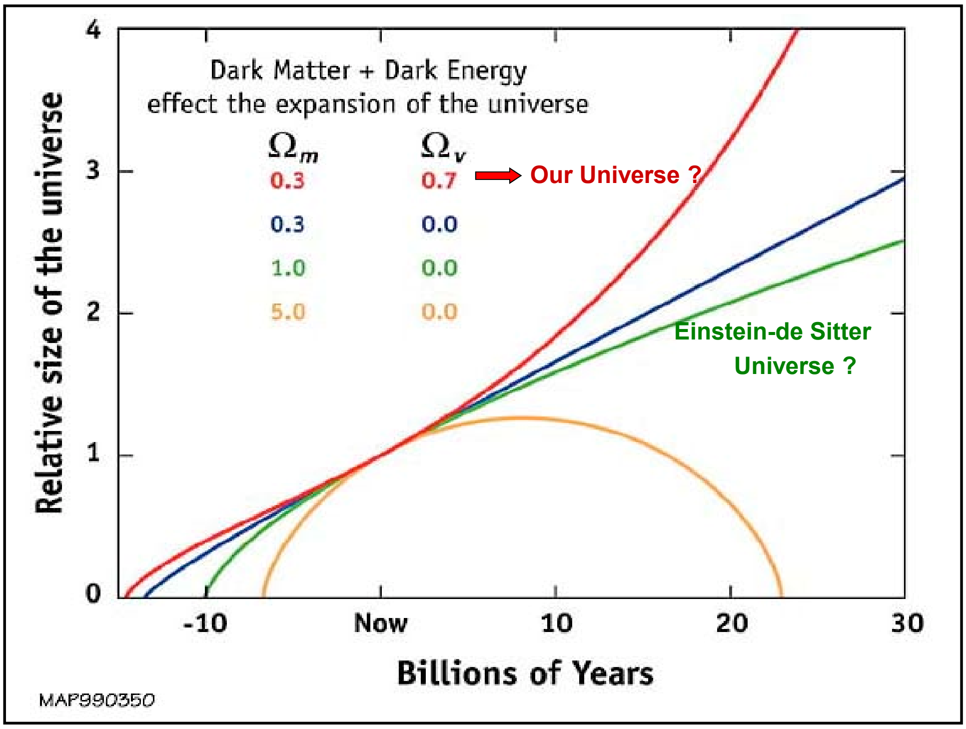
density

pressure

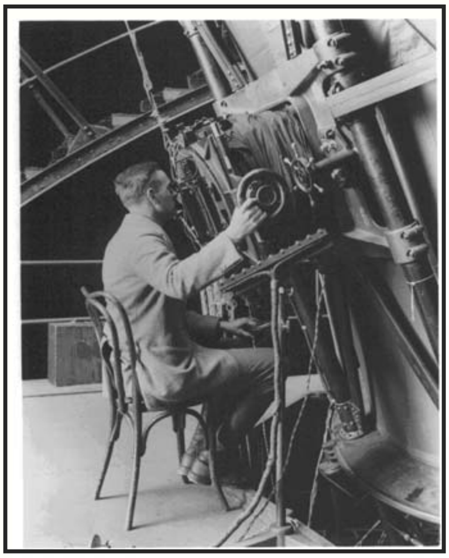
cosmological constant

curvature term

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - \frac{kc^2}{R_0^2} + \frac{\Lambda}{3}a^2$$

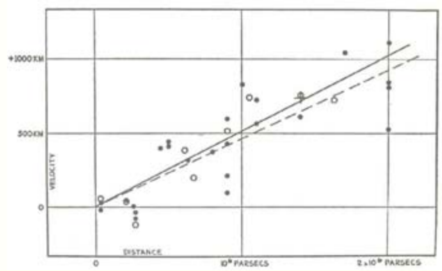


Hubble Expansion



Edwin Hubble

(1889-1953)



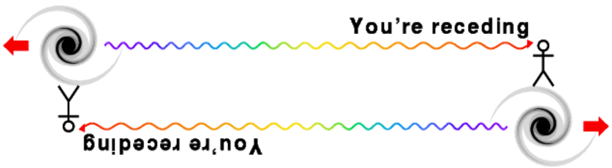
v = H r

Hubble Expansion

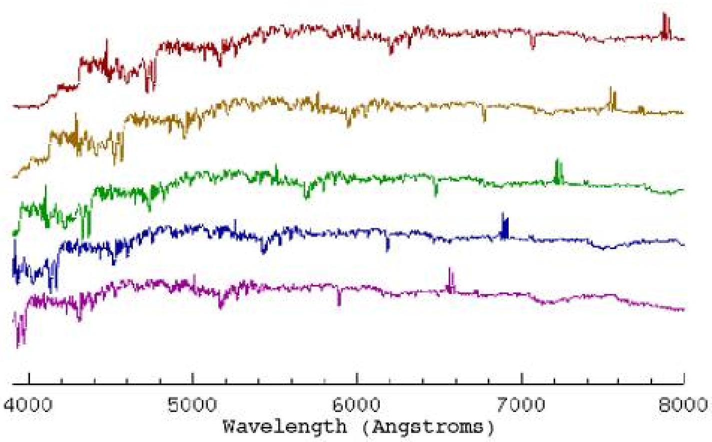
Cosmic Redshift

$$1 + z = \frac{1}{a} \quad \Longleftarrow \quad \begin{cases} \lambda_{em} = \lambda_0 \\ \lambda_{obs} = \dfrac{a(t_{obs})}{a(t_{em})} \lambda_0 \end{cases}$$

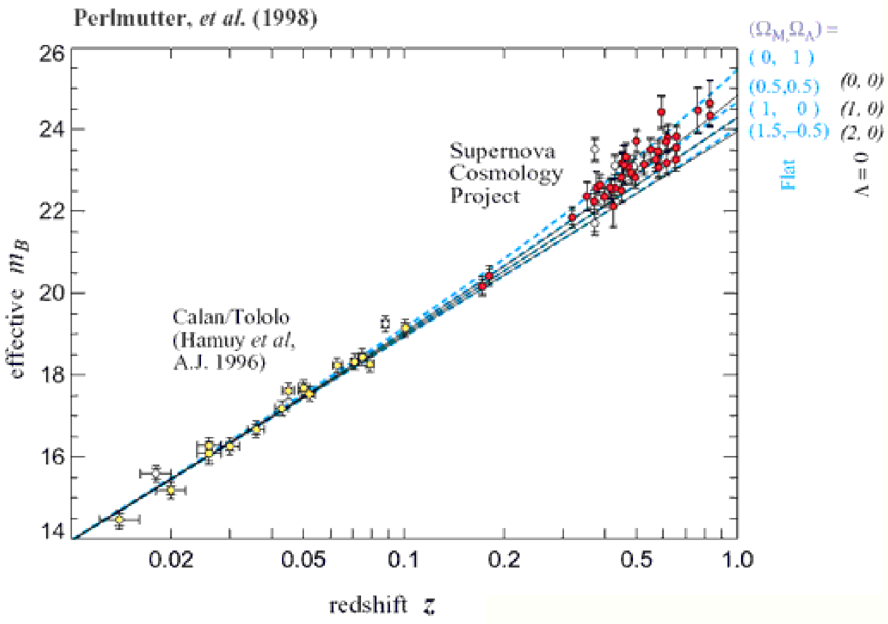
$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$



Redshift & Galaxy Spectra



Examples of redshifted galaxy spectra



FRW Dynamics

The individual contributions to the energy density of the Universe can be figured into the Ω parameter:

- radiation $\Omega_{rad} = \frac{\rho_{rad}}{\rho_{crit}} = \frac{\sigma T^4 / c^2}{\rho_{crit}} = \frac{8\pi G \sigma T^4}{3H^2 c^2}$
- matter $\Omega_m = \Omega_{dm} + \Omega_b$
- dark energy/ cosmological constant $\Omega_\Lambda = \frac{\Lambda}{3H^2}$

$$\Omega = \Omega_{rad} + \Omega_m + \Omega_\Lambda$$

FRW Universe: Curvature

There is a 1-1 relation between the total energy content of the Universe and its curvature. From FRW equations:

$$k = \frac{H^2 R^2}{c^2}(\Omega - 1) \qquad \Omega = \Omega_{rad} + \Omega_m + \Omega_\Lambda$$

$\Omega < 1$	$k = -1$	*Hyperbolic*	*Open Universe*
$\Omega = 1$	$k = 0$	*Flat*	*Critical Universe*
$\Omega > 1$	$k = +1$	*Spherical*	*Close Universe*

FRW Dynamics: Cosmic Acceleration

Cosmic acceleration quantified
by means of dimensionless deceleration parameter q(t):

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

$$q = \frac{\Omega_m}{2} + \Omega_{rad} - \Omega_\Lambda$$

$$q \approx \frac{\Omega_m}{2} - \Omega_\Lambda$$

Examples:

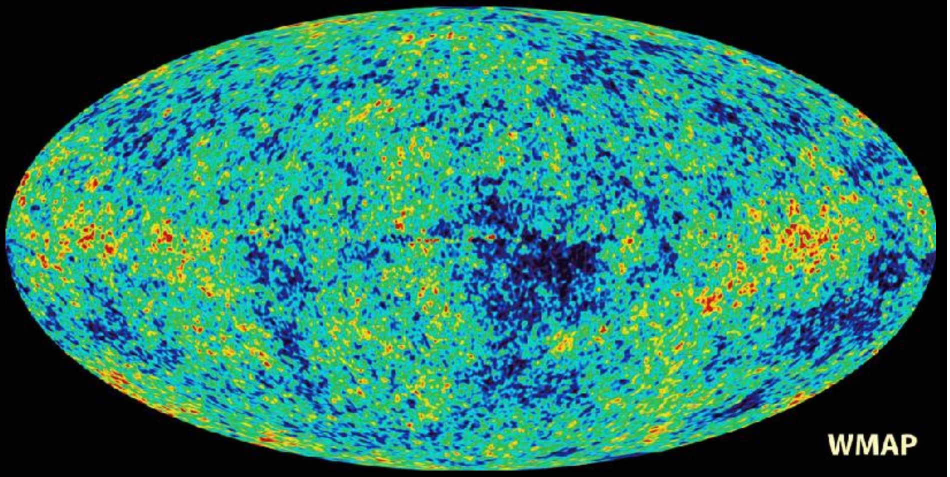
$\Omega_m = 1; \quad \Omega_\Lambda = 0;$
$q = 0.5$

$\Omega_m = 0.3; \quad \Omega_\Lambda = 0.7;$
$q = -0.65$

How Much ?

Cosmic Curvature

Cosmic Microwave Background



Map of the Universe at Recombination Epoch (WMAP, 2003):

- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T$ < 10-5

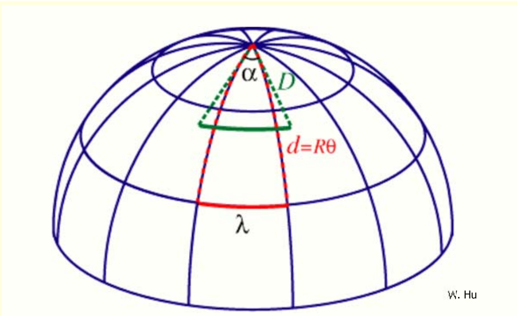
Measuring Curvature

Measuring the Geometry of the Universe:

- Object with known physical size, at large cosmological distance
- Measure angular extent on sky
- Comparison yields light path, and from this the curvature of space

↓

Geometry of Space



In a FRW Universe: lightpaths described by Robertson-Walker metric

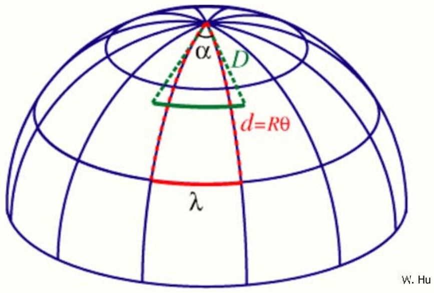
$$ds^2 = c^2dt^2 - a(t)^2\left\{dr^2 + R_c^2 S_k^2\left(\frac{r}{R_c}\right)\left[d\theta^2 + \sin^2\theta\, d\phi^2\right]\right\}$$

Measuring Curvature

- Object with known physical size, at large cosmological distance:
- Sound Waves in the Early Universe !!!!

↓

Temperature Fluctuations CMB



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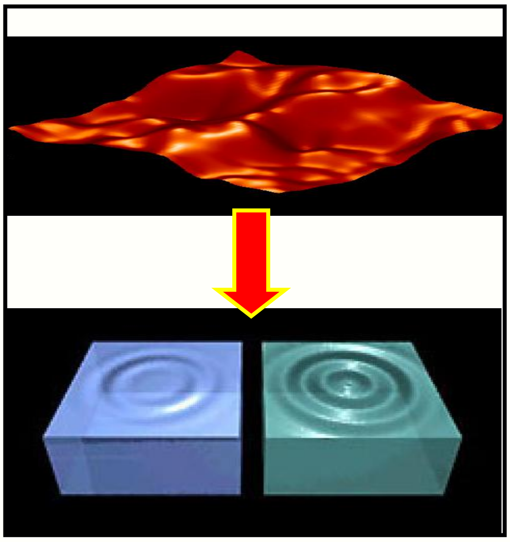
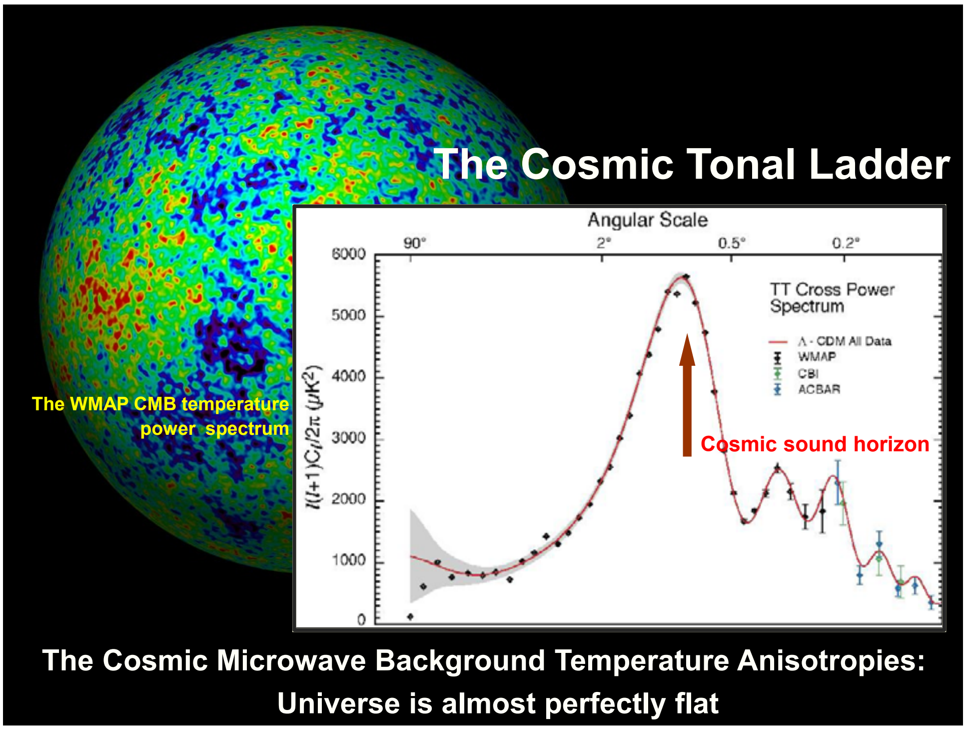
Music of the Spheres

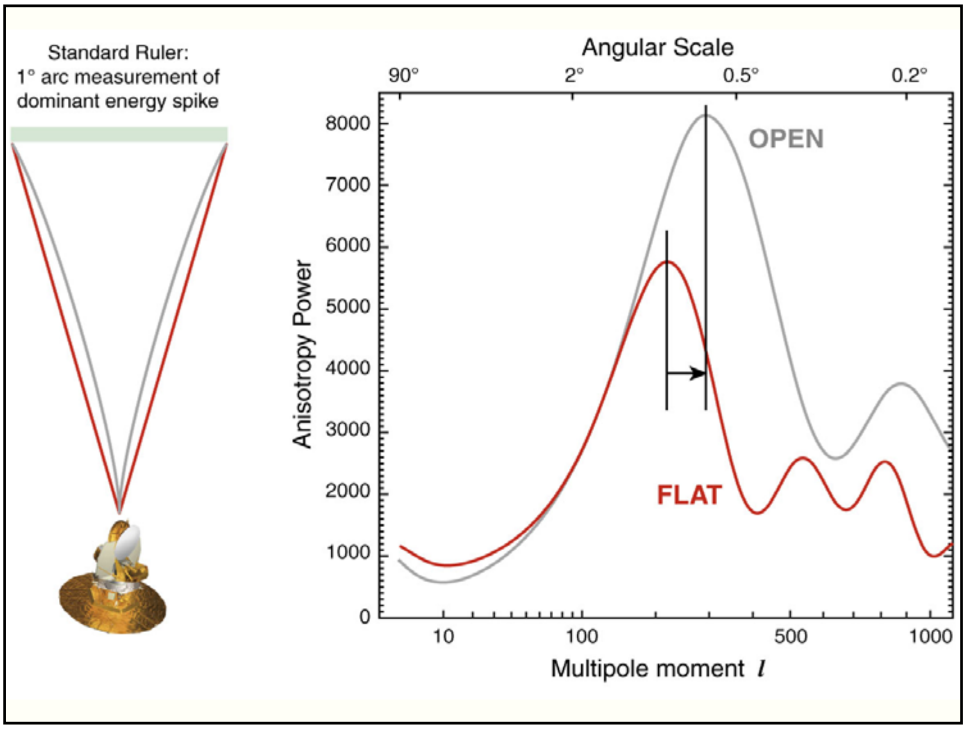
- small ripples in primordial matter & photon distribution
- gravity:
  - compression primordial photon gas
  - photon pressure resists
- compressions and rarefactions in photon gas: sound waves
- sound waves not heard, but seen:
  - compressions: (photon) T higher
  - rarefactions: lower
- fundamental mode sound spectrum
  - size of "instrument":
  - (sound) horizon size last scattering
- Observed, angular size: θ~1°
  - exact scale maximum compression, the "cosmic fundamental mode of music"

W. Hu



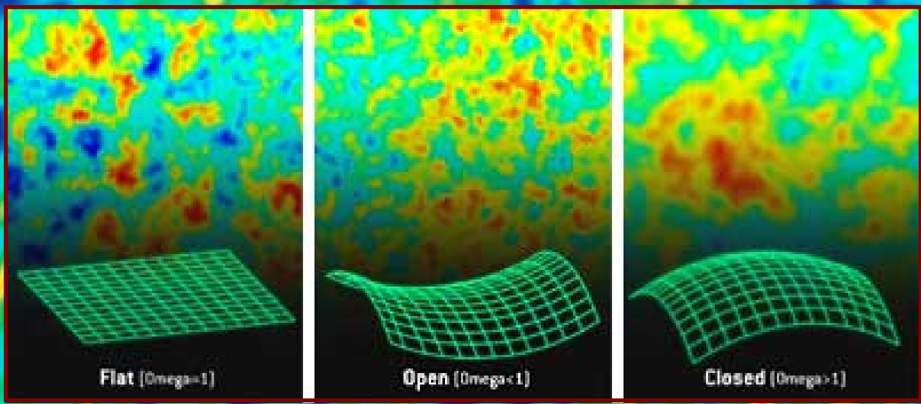


The Cosmic Tonal Ladder
The WMAP CMB temperature power spectrum
Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
Cosmic sound horizon
$l(l+1)C_l/2\pi\ (\mu K^2)$
6000
5000
4000
3000
2000
1000
0
The Cosmic Microwave Background Temperature Anisotropies:
Universe is almost perfectly flat



Standard Ruler:
1° arc measurement of dominant energy spike
Angular Scale
90°
2°
0.5°
0.2°
OPEN
FLAT
Anisotropy Power
8000
7000
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l

Angular CMB temperature fluctuations



CMB: Universe almost perfectly Flat !

Cosmic Constraints

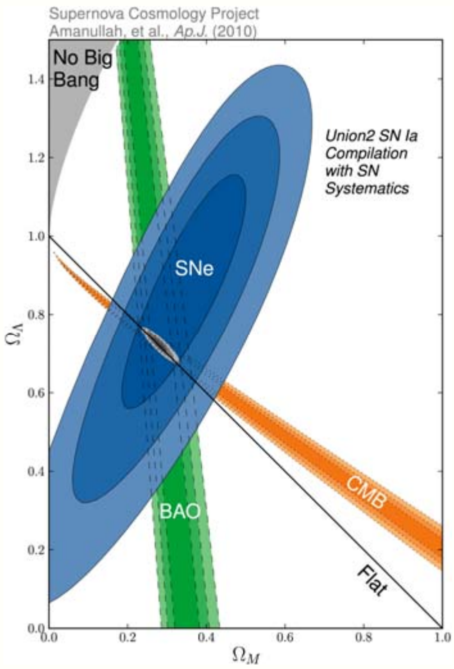
Ω_m vs. Ω_Λ

$$q \approx \frac{\Omega_m}{2} - \Omega_\Lambda$$

$$k = \frac{H^2 R^2}{c^2}(\Omega_m + \Omega_\Lambda - 1)$$

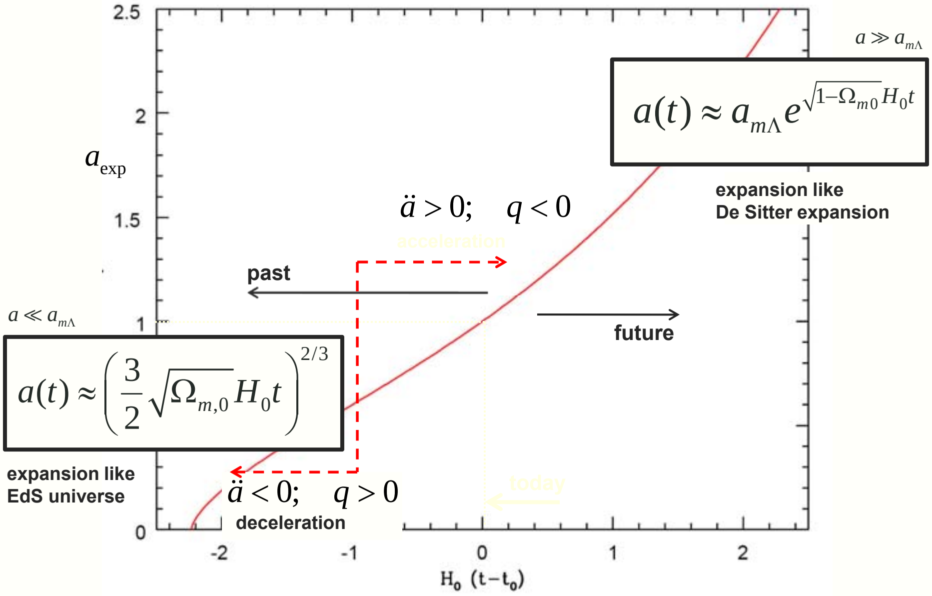
SCP Union2 constraints (2010)

on values of matter density Ω_m
dark energy density Ω_Λ



Concordance Universe

Concordance Expansion

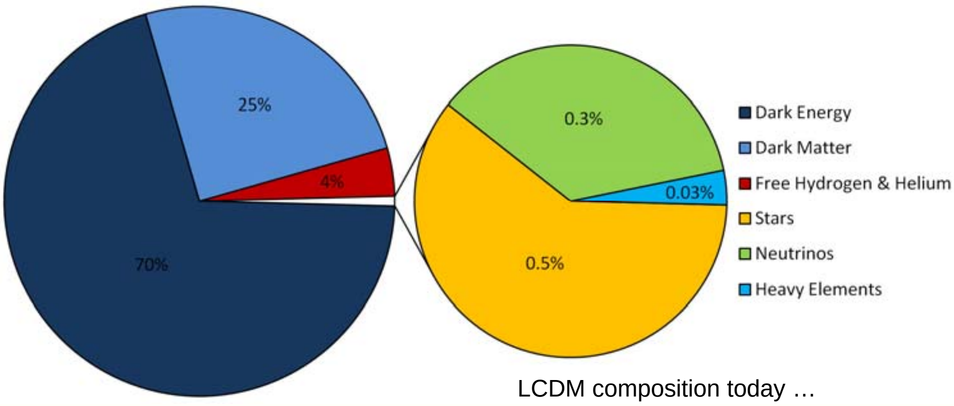


Concordance Universe Parameters

Hubble Parameter		$H_0 = 71.9 \pm 2.6\ km\ s^{-1}\ Mpc^{-1}$	
Age of the Universe		$t_0 = 13.7 \pm 0.12\ Gyr$	
Temperature CMB		$T_0 = 2.725 \pm 0.001\ K$	
Matter	Baryonic Matter Dark Matter	$\Omega_m = 0.27$	$\Omega_b = 0.0456 \pm 0.0015$ $\Omega_{dm} = 0.228 \pm 0.013$
Radiation	Photons (CMB) Neutrinos (Cosmic)	$\Omega_{rad} = 8.4 \times 10^{-5}$	$\Omega_\gamma = 5 \times 10^{-5}$ $\Omega_\nu = 3.4 \times 10^{-5}$
Dark Energy		$\Omega_\Lambda = 0.726 \pm 0.015$	
Total		$\Omega_{tot} = 1.0050 \pm 0.0061$	

LCDM Cosmology

- Concordance cosmology
  - model that fits the majority of cosmological observations
  - universe dominated by Dark Matter and Dark Energy



LCDM composition today …

Matter-Dark Energy Transition

$$a_{m\Lambda} = \sqrt[3]{\frac{\Omega_{m,0}}{\Omega_{\Lambda,0}}}$$

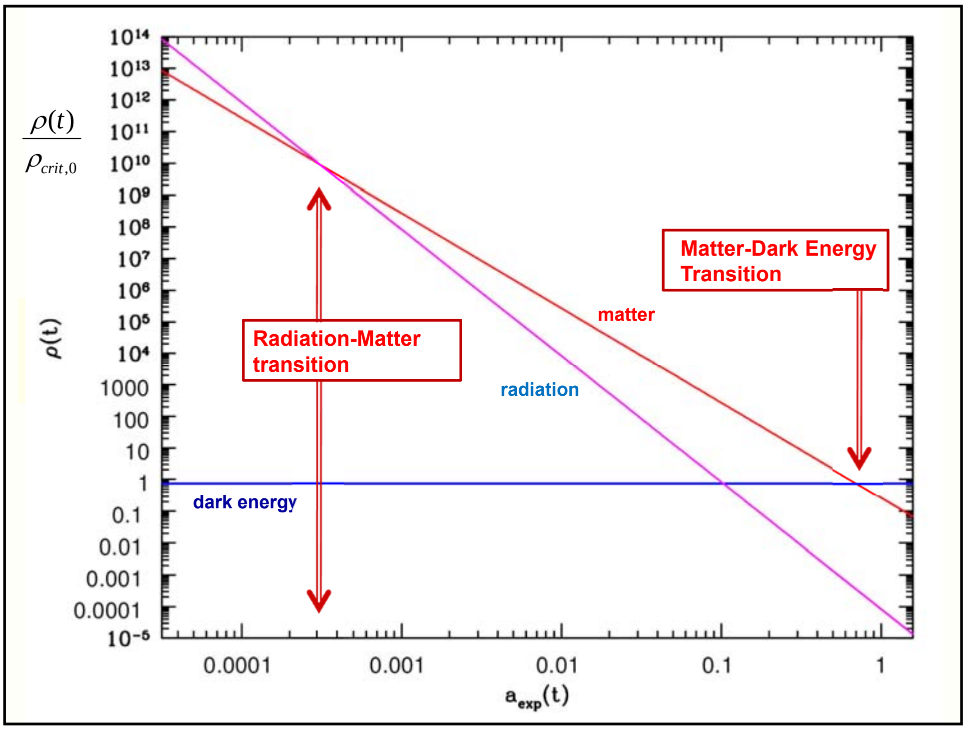
$\Omega_{\Lambda,0} = 0.27$, $\Omega_{m,0} = 0.73$ → $a_{m\Lambda} = 0.72$, $a_{m\Lambda}{}^{\dagger} = 0.57$

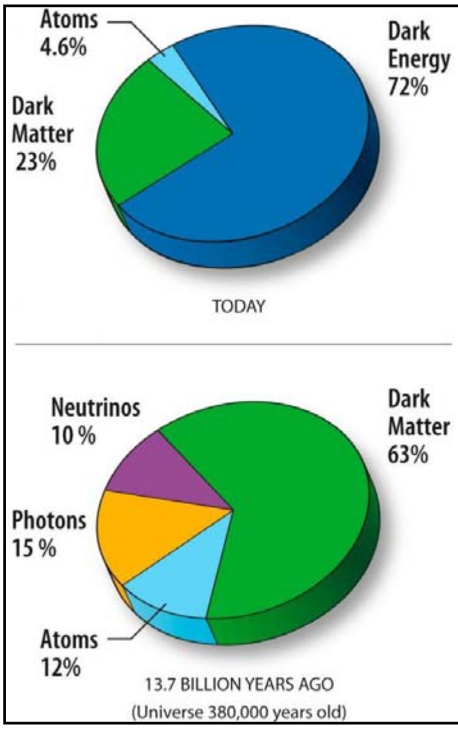
Flat Universe

$$a_{m\Lambda} = \sqrt[3]{\frac{\Omega_{m,0}}{1-\Omega_{m,0}}}$$

Note: a more appropriate characteristic transition is that at which the deceleration turns into acceleration:

$$a_{m\Lambda}{}^{\dagger} = \sqrt[3]{\frac{\Omega_{m,0}}{2\Omega_{\Lambda,0}}} = \sqrt[3]{\frac{\Omega_{m,0}}{2(1-\Omega_{m,0})}}$$





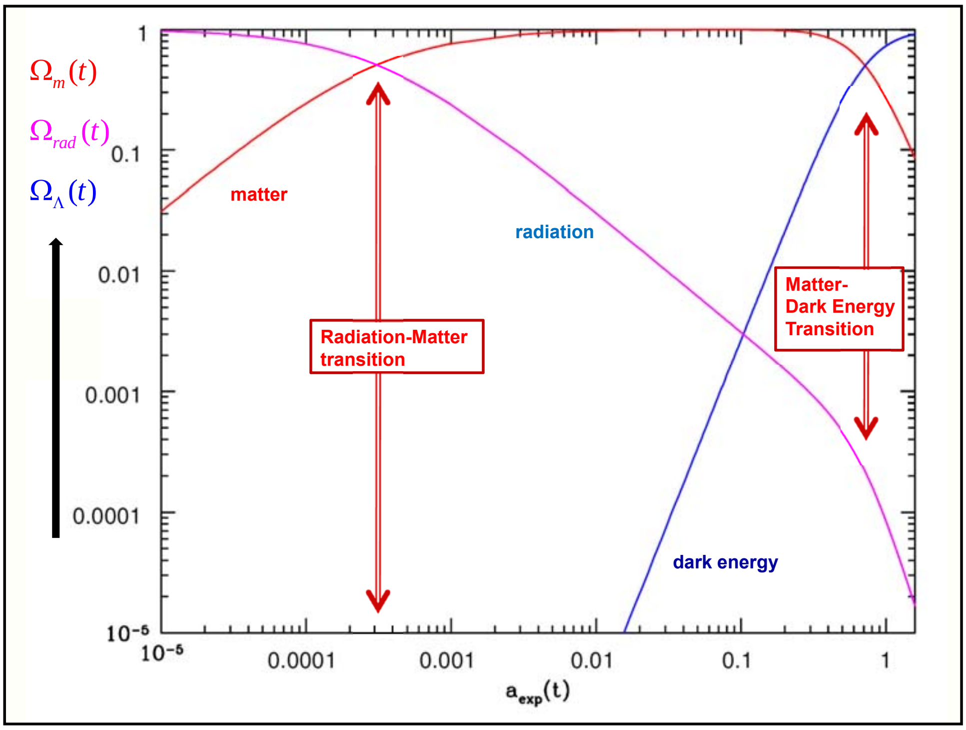
LCDM Cosmology

- with an evolving mixture of Dark Matter and Dark Energy

Universe today

⇕

Universe at recombination

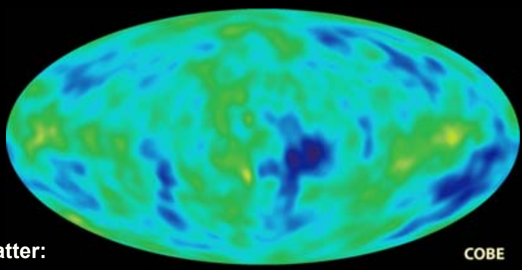


1990s:

the Brewing Crisis

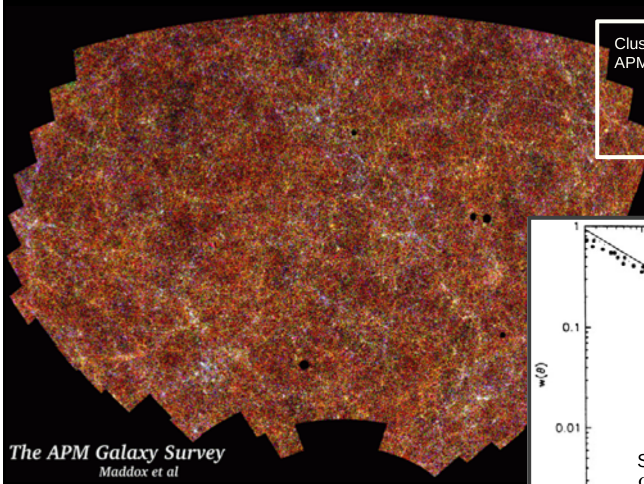
Standard Cosmology ~ 1990

- FRW Universe
- augmented by Inflation
  - solved 4 fine-runing problems
  - accelerated expansion by factor 10^{60} ~ 10^{-36}-10^{-34} sec after Big Bang
  - firm prediction: Universe flat: $k=0$, $\Omega_{tot}=1$



- Universe dominated by Dark Matter:
  - necessary to explain structure growth from primordial fluctuations, which COBE in 1992 had detected at 10^{-5} level
  - would have to make up 96% of matter density Universe
  - SCDM: "standard Cold Dark Matter", $\Omega_m=1.0$
- Succesfully explained large range of astronomical observations (or was made to explain these: "bias")

Galaxy Clustering

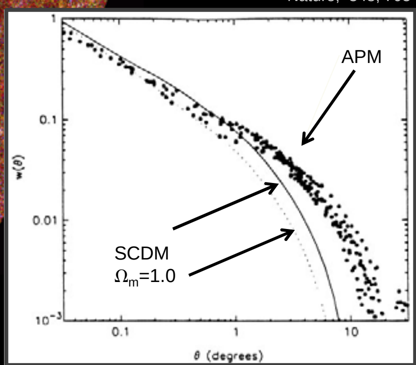


Clustering of galaxies in the plate-scanned APM sky galaxy survey (2 million gals):

$$dP(\theta) = \bar{n}^2\{1 + w(\theta)\}d\Omega_1 d\Omega_2$$

angular 2pt correlation function

Efstathiou, Sutherland & Maddox, 1990 Nature, 348, 705



"the Cosmological Constant and Cold Dark Matter"

"It is argued here that the success of the cosmological cold dark matter (CDM) model can be retained and the new observations of very large scale cosmological structures can be accommodated in a spatially flat cosmology in which as much as 80 percent of the critical density is provided by a positive cosmological constant. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant."

Cluster Baryon fraction

X-ray intracluster gas:

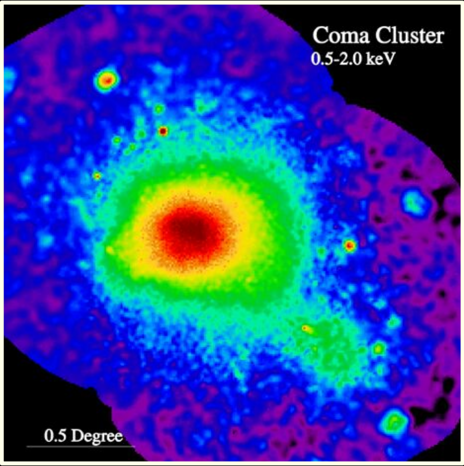
- Mass determination via hydrostatic equilibrium
- fraction mass in baryons (White et al.)

  $f_{baryon} \sim$ 1/6-1/7

- But,

  - if representative for Universe, AND
  - Ω_m=1.0
  - conflict with baryon density suggested by Big Bang nucleosynthesis: Ω_b=0.04

- Many other indications find Ω_m=0.3



ROSAT X-ray image Coma Cluster

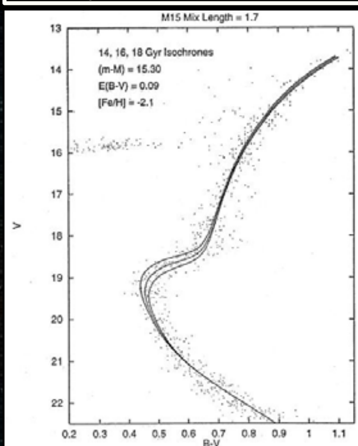
Cosmic Age Crisis

estimated age of the oldest stars in Universe far in excess of estimated age of matter-dominated FRW Universe:

Globular cluster stars:	**13-15 Gyr**
Universe:	**10-12 Gyr**

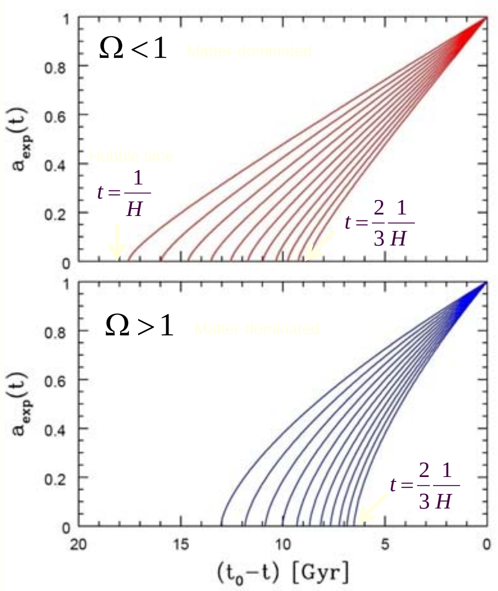
Globular Clusters

- Roughly spherical assemblies of 100,000-200,000 stars
- Radius ~ 20-50 pc: extremely high star density
- Globulars are very old, amongst oldest objects in local Universe
- Stars formed around same time: old, red, population
- Colour-magnitude diagram characteristic: accurate age determination on the basis of stellar evolution theories.



Typical 1980-1990s isochrone fit

Age of the Universe



Age of a FRW universe at
Expansion factor a(t)

$$H\,t = \int_0^a \frac{da}{\sqrt{\frac{\Omega_{rad}}{a^2} + \frac{\Omega_m}{a} + \Omega_\Lambda a^2 + (1-\Omega)}}$$

Cosmic Age Crisis

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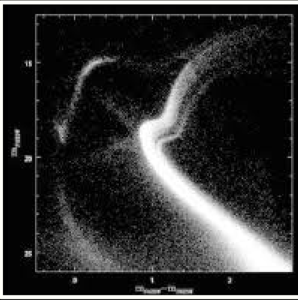
Omega Centauri



Typical 21st century colour-magnitude diagram:

multiple populations in Omega Centauri

1995: Cosmic Confusion

EADN Summerschool, July 1995, Leiden

"Rien, be real … "

John Peacock

the Source:

Dark Energy

Dark Energy & Cosmic Acceleration

Nature Dark Energy:

(Parameterized) Equation of State

$$p(\rho) = w\rho c^2$$

Cosmic Acceleration:

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a$$

Gravitational Repulsion:

$$p = w\rho c^2 \quad \Leftrightarrow \quad w < -\frac{1}{3} \quad \Rightarrow \quad \ddot{a} > 0$$

Dark Energy: Identity & Nature

Huge and ever growing list of suggestions on

identity & nature of Dark Energy:

- **Cosmological Constant**
- **Cosmic Backreaction (inhomogeneities)**
- **Modified Gravity**
- **Quintessence, in a variety of flavours**
- **Phantom Energy**
- **Chameleon Energy**
- **Chaplygin gas**
- **Agegraphic DE**
- **….**

Dark Energy = Vacuum Energy

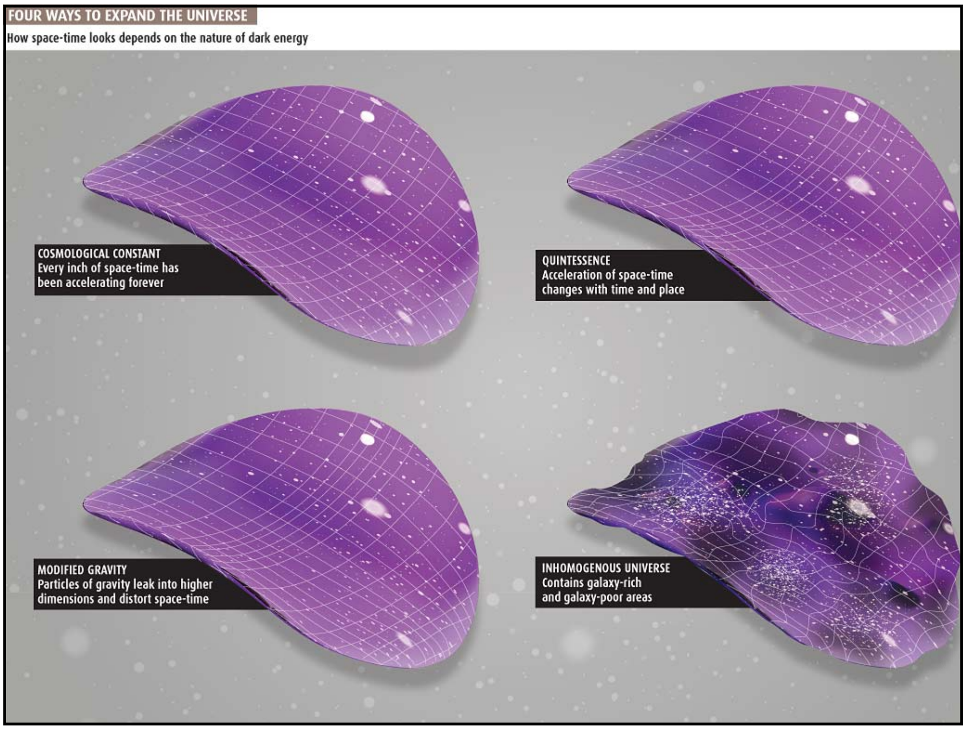
Ya. Zel'dovich - 1960s
S. Weinberg - 1989

Cosmological Constant to be identified with zero-point vacuum energy ?

minor problem:

1st order estimate off by 120 orders magnitude:

~ 10^{120}



Dark Energy & Cosmic Acceleration

DE equation of State

$$p(\rho) = w\rho c^2$$

$$\rho_w(a) = \rho_w(a_0)\, a^{-3(1+w)}$$

Cosmological Constant:

$\Lambda :$ $\quad w = -1 \quad$ $\rho_w = cst.$

-1/3 > w > -1:

$\rho_w \propto a^{-3(1+w)} \quad 1 + w > 0$ **decreases with time**

Phantom Energy:

$\rho_w \propto a^{-3(1+w)} \quad 1 + w < 0$ **increases with time**

Dynamic Dark Energy

DE equation of State

$$p(\rho) = w\rho c^2$$

Dynamically evolving dark energy, parameterization:

$$w(a) = w_0 + (1-a)w_a \approx w_\phi(a)$$

$$\rho_w(a) = \rho_w(a_0)\ \exp\left\{-3\int_1^a \frac{1+w_\phi(a')}{a'}\,da'\right\}$$

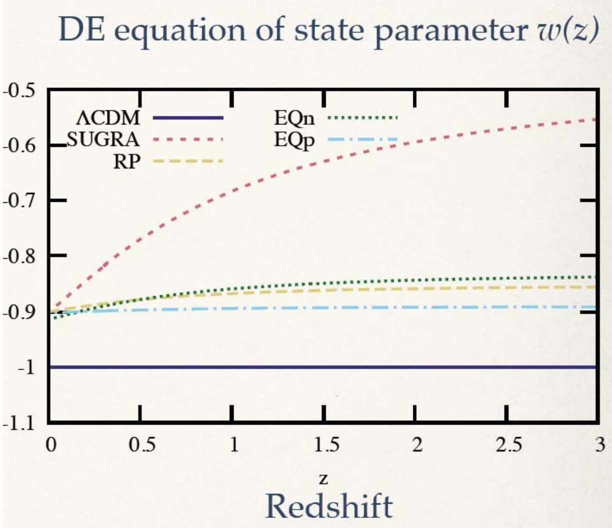
DE Equation of State

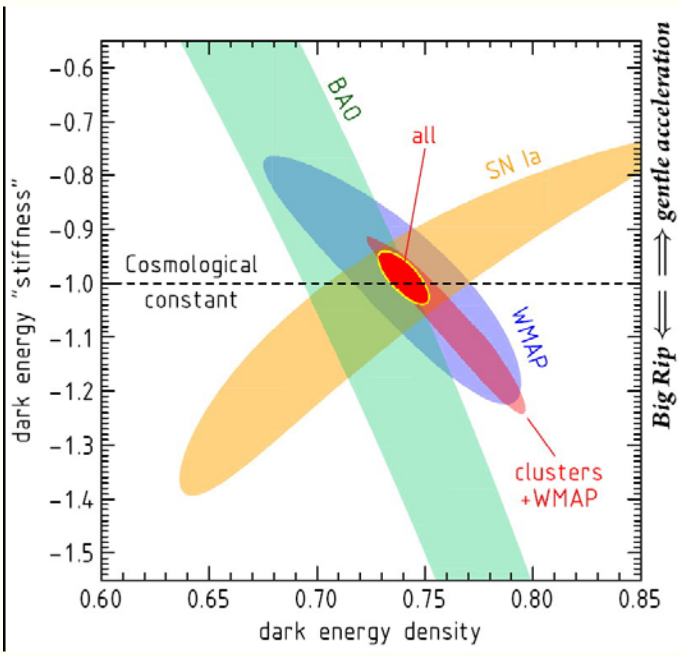
$$w(a) \equiv w_0 + w_a(1-a) \approx w_\phi(a)$$

$$H(a) = H_0\sqrt{\Omega_m a^{-3} + \Omega_\Lambda}$$

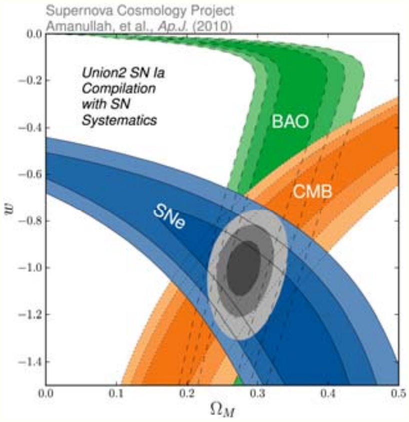
$$\Omega_\Lambda \rightarrow \Omega_w a^{-3(1+w)}$$

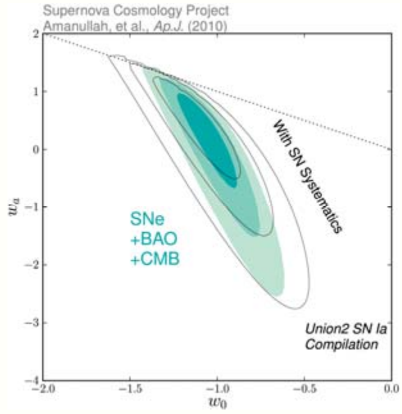
$$\Omega_\Lambda \rightarrow \Omega_\phi \exp\left(-3\int_1^a \frac{1+w_\phi(a')}{a'}da'\right)$$





Dark Energy Eqn.State





SCP Union2 constraints (2010)

on values of matter density Ω_m
dark energy eqn. state w

on dynamical evolution dark energy:

eqn. state parameters w_0 w_a

Take-Home Facts

1. **Strong evidence Accelerated Expansion**
   - since supernova discovery, 100s SNIa observed over broader range redshifts
   - based solely upon supernova Hubble diagram, independent of General Relativity, very strong evidence expansion Universe accelerated recently

2. **Dark energy as cause cosmic acceleration**
   - within general relativity, accelerated expansion cannot be explained by any known form of matter or energy
   - it can be accommodated by a nearly smooth form of energy with large negative pressure, Dark Energy, that accounts for about 73% of the universe.

3. **Independent evidence dark energy**
   - Cosmic Microwave Background and Large Scale Structure data provide independent evidence, within context of CDM model of structure formation, that the universe is filled with a smooth medium accounting for 73% of the total energy content of the universe.
   - that came to dominate the dynamics of the universe once all observed structure had formed

Take-Home Facts

4. Vacuum energy as dark energy

- simplest explanation for dark energy is the energy associated with the vacuum
- mathematically equivalent to a cosmological constant
- However, most straightforward calculations of vacuum energy density from zero-point energies of all quantum fields lead to estimates which are a bit too large, in the order of $\sim 10^{120}$

5. Dark theories of Dark Energy

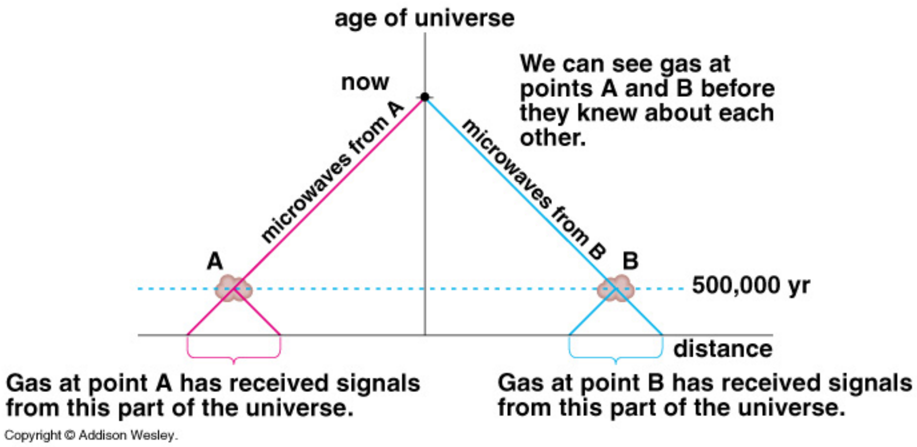
- There is no compelling theory of dark energy
- Beyond vacuum energy, man intriguing ideas: light scalar fields, additional spatial dimensions, etc.
- Many models involve time-varying dark energy

6. New Gravitational Theories ?

- alternatively, cosmic acceleration could be a manifestaation of gravitational physics beyond General Relativity
- however, as yet there is no self-consistent model for new gravitational physics that is consistent with large body of data that constrains theories of graavity.

Cosmic Future

Cosmic Horizons



Particle Horizon of the Universe:
distance that light travelled since the Big Bang

Cosmic Particle Horizon

Light travel in an expanding Universe:

- **Robertson-Walker metric:** $ds^2 = c^2dt^2 - a(t)^2\,dr^2$
- **Light:** $ds^2 = 0$

$$d_{Hor} = \int_0^t \frac{c\,dt'}{a(t')}$$

Horizon distance in comoving space

⇔

$$R_{Hor} = a(t)\int_0^t \frac{c\,dt'}{a(t')}$$

Horizon distance in physical space

Particle Horizon of the Universe:
distance that light travelled since the Big Bang

Cosmic Event Horizon

Light travel in an expanding Universe:

- **Robertson-Walker metric:** $ds^2 = c^2 dt^2 - a(t)^2 dr^2$
- **Light:** $ds^2 = 0$

$$d_{event} = \int_t^\infty \frac{c\,dt'}{a(t')}$$

Event Horizon distance in comoving space

⬌

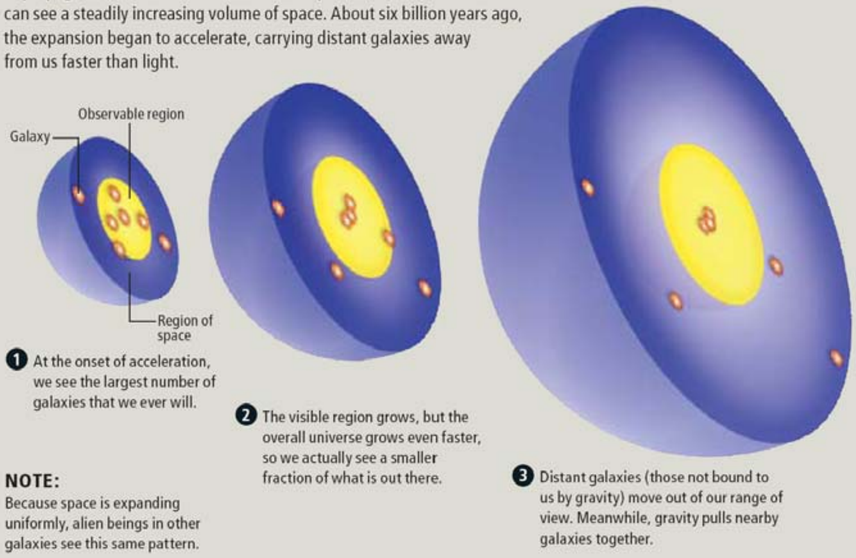
$$R_{event} = a(t)\int_t^\infty \frac{c\,dt'}{a(t')}$$

Event Horizon distance in physical space

Event Horizon of the Universe:
the distance over which one may still communicate …

EXPANDING UNIVERSE, SHRINKING VIEW

The universe may be infinite, but consider what happens to the patch of space around us (*purple sphere*), of which we see only a part (*yellow inner sphere*). As space expands, galaxies (*orange spots*) spread out. As light has time to propagate, we observers on Earth (or our predecessors or descendants) can see a steadily increasing volume of space. About six billion years ago, the expansion began to accelerate, carrying distant galaxies away from us faster than light.



NOTE:
Because space is expanding uniformly, alien beings in other galaxies see this same pattern.

Cosmic Fate

100 Gigayears:
the end of Cosmology

Dark Energy:

Probes

Supernovae Ia

M51 supernovae

Probes DE: additional

- **Clusters of Galaxies**
  - number counts N(z),
  - # formed clusters of galaxies as function of z sensitive to w & w'
- **Baryonic Oscillations (BAO)**
  - cosmic yardstick, curvature: residual imprint in galaxy distribution
  - acoustic oscillations primordial baryon-photon plasma
- **Integrated Sachs Wolfe (ISW)**
  - imprint foreground large scale structure on CMB,
  - via evolving potential perturbations
- **Clustering**
  - clustering correlation function/power spectrum,
  - directly probing cosmological scenario, BAO wiggles
- **Growth of clustering:**
  - evolving growth rate f(Omega,z), probed via influence of
  - redshift distortions on correlation functions
- **Voids:**
  - evolving void shapes,
  - probing tidal force field generated by large scale mass distribution
- **Morphology and Topology**
  - sensitivity of topology, measured by homology (Betti numbers)

Dark Energy Probes: Comparison

Method	Strengths	Weaknesses	Systematics
Weak Lensing	Structure Growth + Geometric Statistical Power	CDM assumption	Image quality Photo-z
Supernovae SNIa	Purely Geometric Mature	Standard Candle assumption	Evolution Dust
BAO (Baryonic Acoustic Oscillation)	Largely Geometric Low systematics	Large samples required	Bias Nonlinearity
Cluster Population N(z)	Structure Growth + Geometric Xray+SZ+optical	CDM assumption	Determining mass Selection function

Standard Candle & Cosmic Distances

Robertson-Walker Metric

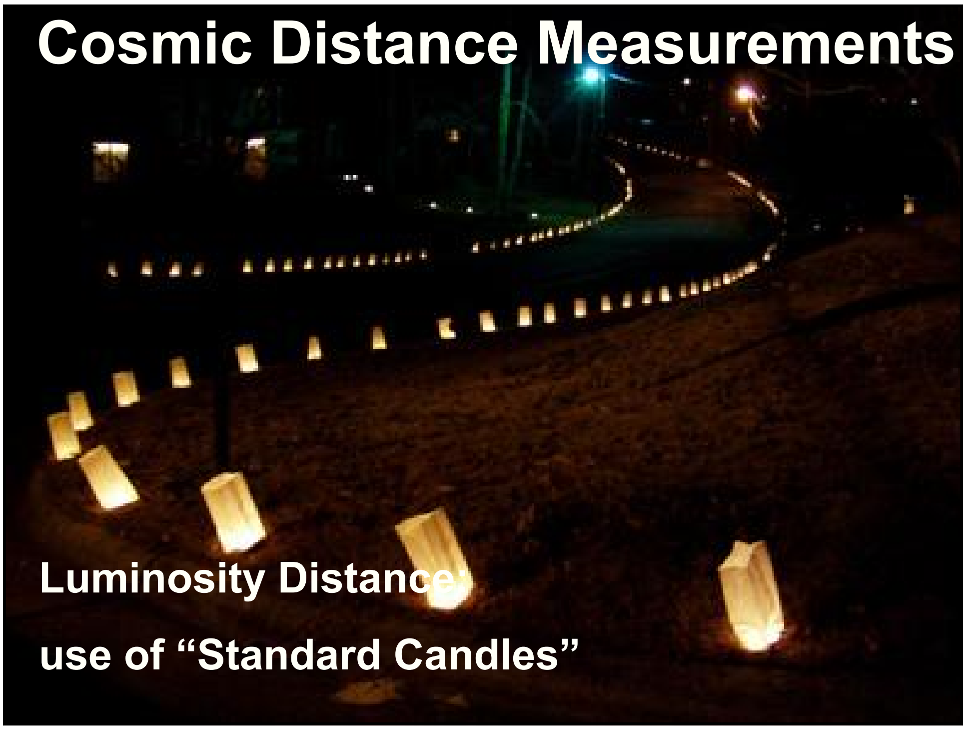
Distances in a uniformly curved spacetime is specified in terms of the Robertson-Walker metric. The spacetime distance of a point at coordinate (r, θ, ϕ) is:

$$ds^2 = c^2 dt^2 - a(t)^2 \left\{ dr^2 + R_c{}^2 S_k{}^2 \left(\frac{r}{R_c} \right) \left[d\theta^2 + \sin^2\theta \, d\phi^2 \right] \right\}$$

where the function $S_k(r/R_c)$ specifies the effect of curvature on the distances between points in spacetime

$$S_k\left(\frac{r}{R_c}\right) = \begin{cases} \sin\left(\frac{r}{R_c}\right) & k = +1 \\ \frac{r}{R_c} & k = 0 \\ \sinh\left(\frac{r}{R_c}\right) & k = -1 \end{cases}$$

Cosmic Distance Measurements



Luminosity Distance:

use of "Standard Candles"

Luminosity Distance

Definition cosmological luminosity distance:

$$l = \frac{L}{4\pi D_L{}^2}$$

for a source with INTRINSIC luminosity L
OBSERVED brightness l

In a Robertson-Walker geometry, luminosity distance is

$$D_L = (1+z)D(z)$$

where D(z) is the cosmological distance measure

Luminosity Distance

Cosmological distance measure:

$$D(z) = R_0\, S_k\left(\frac{r}{R_0}\right)$$

with curvature term S_k(x)=sin(x), x, or sinh(x)

$$r(z) = \frac{c}{H_0}\int_0^z dz' \left[\sum_i \Omega_i \left(1+z'\right)^{3+3w_i} - \frac{kc}{H_0 R_0}\left(1+z'\right)^2\right]^{-1/2}$$

Comoving radial distance r(z) at redshift z

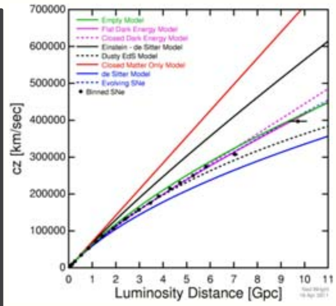
Luminosity Distance

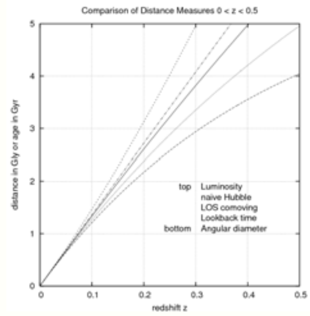
Luminosity Distance at low redshift:

$$D_L = \frac{c}{H_0}\left\{ z + z^2\left(\frac{1-q_0}{2}\right) + O(z^3)\right\}$$

- with first term the linear Hubble expansion term
- second term the first accelerarion/deceleration term:

$$D_L = \frac{1}{2}\sum_i \Omega_i (1+3w_i)$$

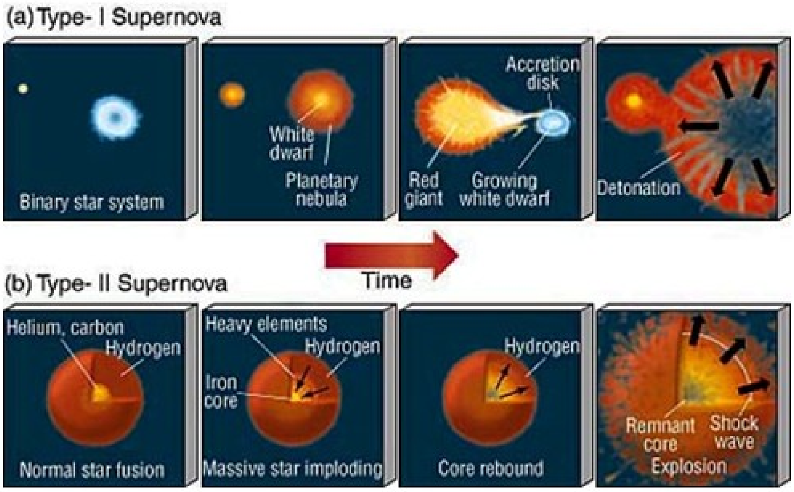




Standard Candles in Cosmology

Type Ia Supernovae

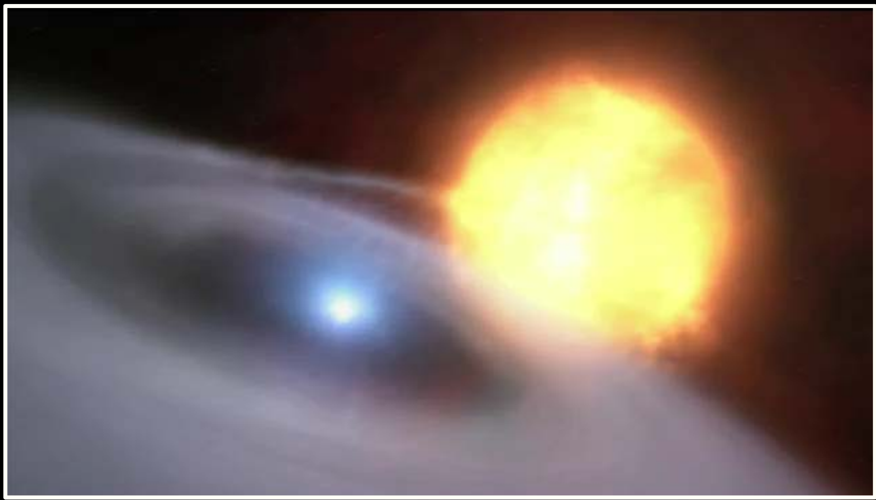
Supernovae

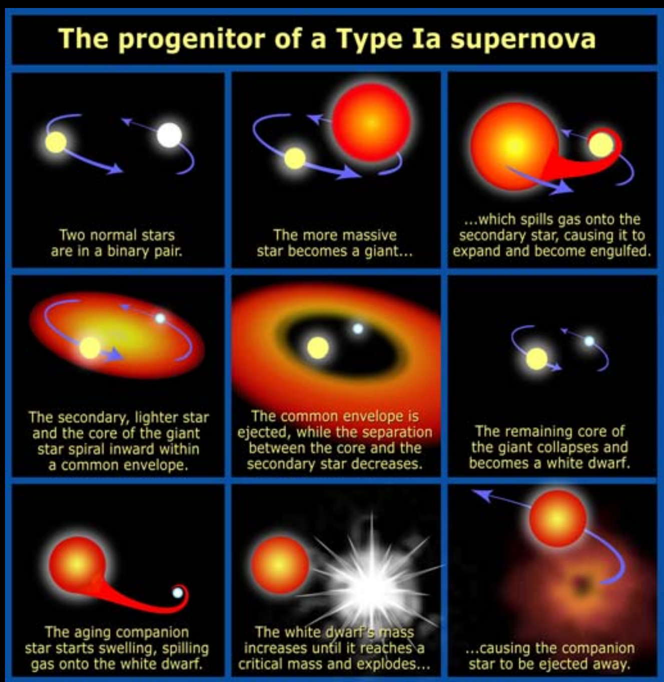


Supernovae:
- gigantic stellar explosions
- within few months more radiation than Sun over entire lifetime
- shockwaves 5,000-30,000 km/s
- enrichment interstellar medium
- triggers star formation in surrounding ISM

Supernovae, 4 types (spectral absorption lines):
- SN II
- SN Ia - no hydrogen
- SN Ib
- SN Ic - no helium

Type Ia Supernova Explosion





Type Ia Supernova

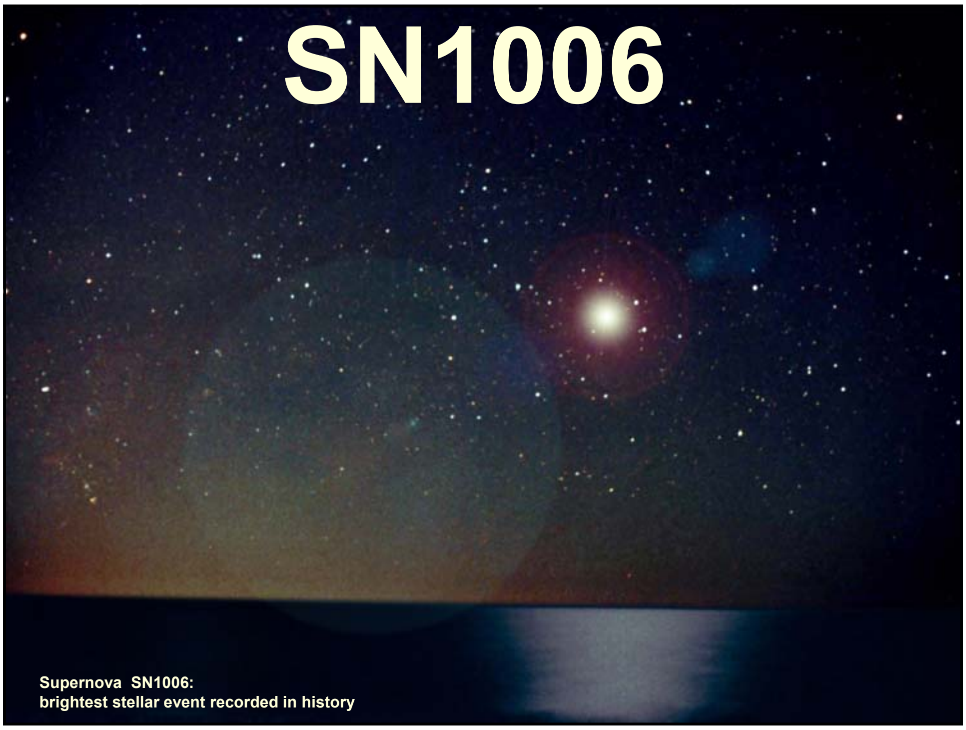
- Amongst the most energetic explosions in our Universe:
  E ~ 10^{54} ergs
- During explosion the star is as bright as entire galaxy ! (ie. 10^{11} stars)

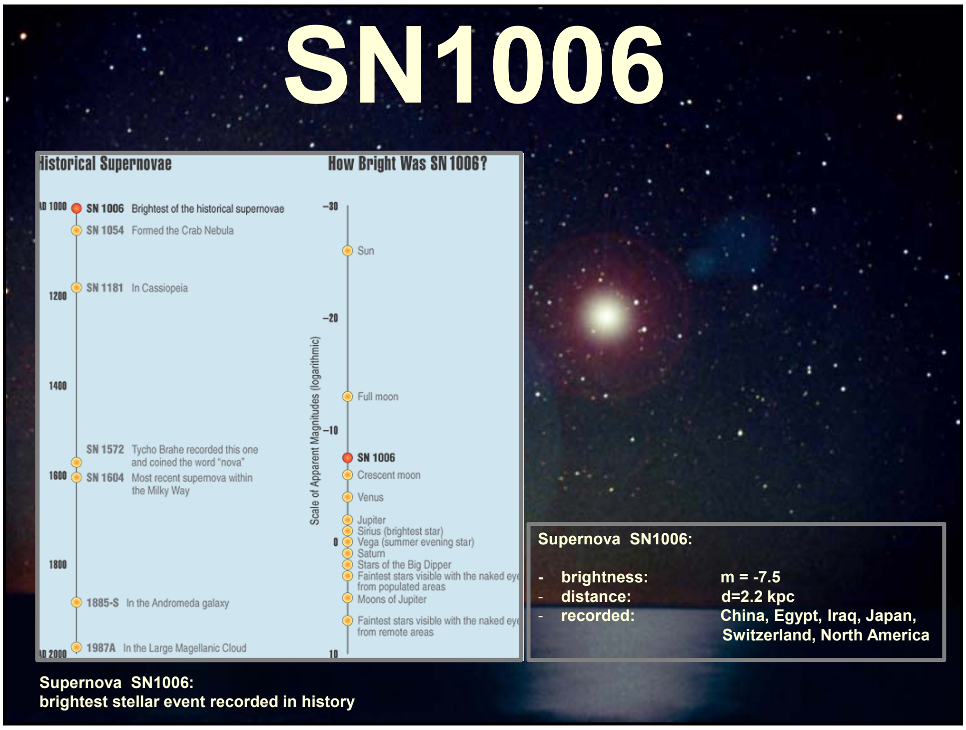
- Violent explosion Carbon-Oxygen white dwarfs:
- Embedded in binary, mass accretion from companion star
- When nearing Chandrasekhar Limit (1.38 $M_{\odot}$), electron degeneracy pressure
- can no longer sustain star.
- while contracting under its weight, carbon fusion sets in, powering a
- catastrophic deflagration or detonation wave,
- leading to a violent explosion, ripping apart entire star

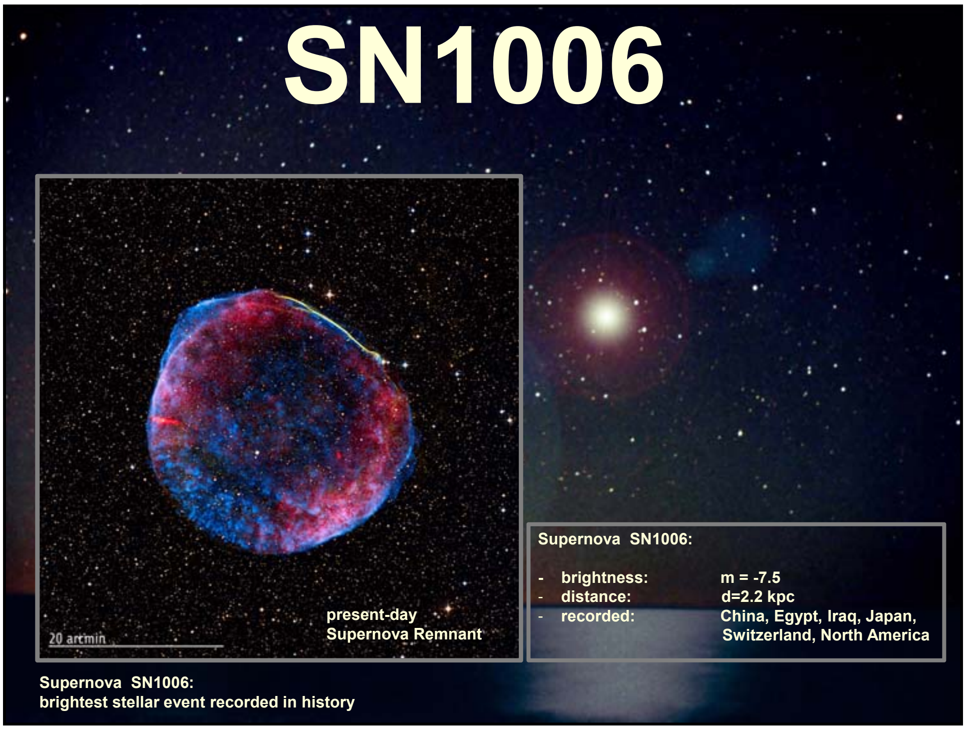
- Because exploding stars have nearly uniform progenitor (~1.38 $M_{\odot}$ white dwarf), their luminosity is almost the same: M ~ -19.3
  Standard Candle

Supernova Explosion & Host Galaxy

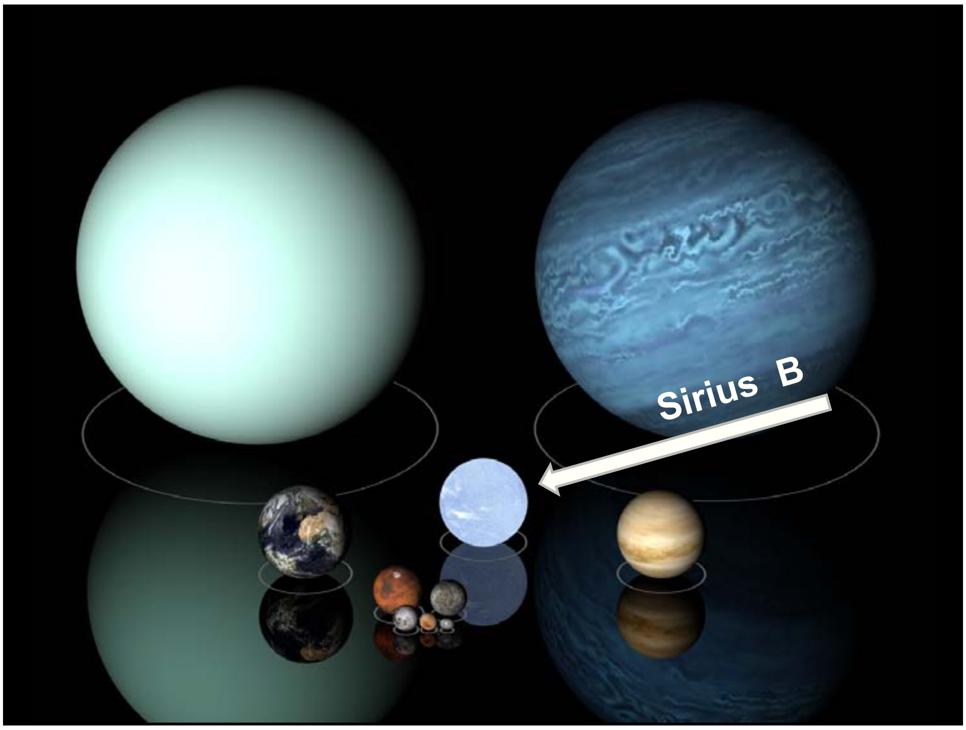
M51 supernovae

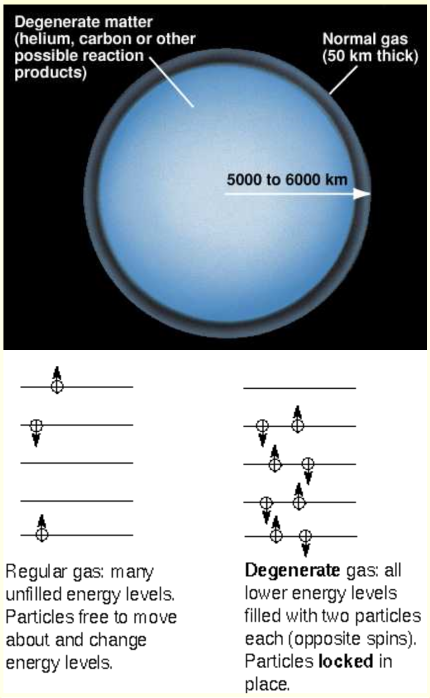

SN1006
Supernova SN1006:
brightest stellar event recorded in history


SN1006
Historical Supernovae
How Bright Was SN 1006?
SN 1006 Brightest of the historical supernovae
SN 1054 Formed the Crab Nebula
1200
SN 1181 In Cassiopeia
1400
SN 1572 Tycho Brahe recorded this one and coined the word "nova"
1600
SN 1604 Most recent supernova within the Milky Way
1800
1885-S In the Andromeda galaxy
1987A In the Large Magellanic Cloud
Scale of Apparent Magnitudes (logarithmic)
−30
Sun
−20
Full moon
−10
SN 1006
Crescent moon
Venus
Jupiter
Sirius (brightest star)
0
Vega (summer evening star)
Saturn
Stars of the Big Dipper
from populated areas
Moons of Jupiter
from remote areas
10
Supernova SN1006:
- brightness: m = -7.5
- distance: d=2.2 kpc
- recorded: China, Egypt, Iraq, Japan, Switzerland, North America
Supernova SN1006:
brightest stellar event recorded in history



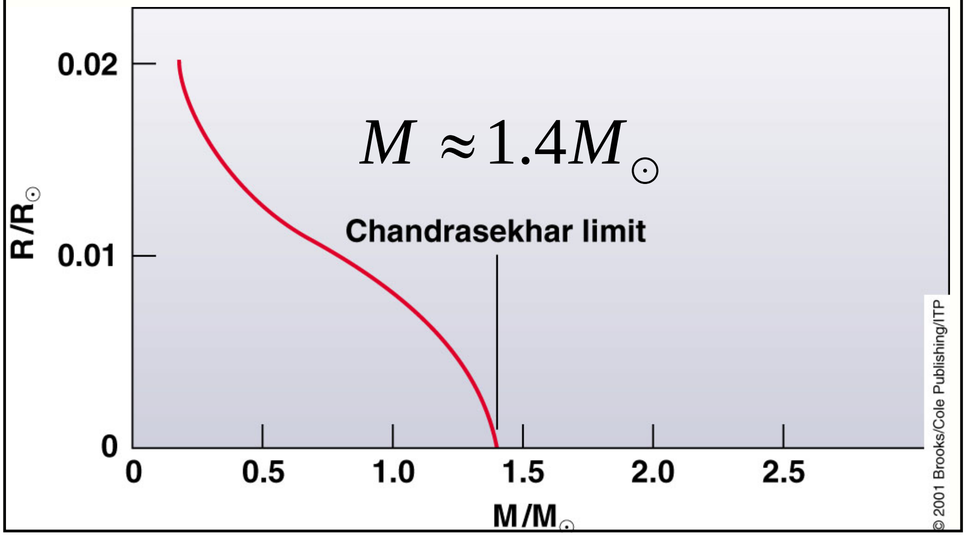
White Dwarfs


Sirius B


Degenerate matter (helium, carbon or other possible reaction products)
Normal gas (50 km thick)
5000 to 6000 km
Regular gas: many unfilled energy levels. Particles free to move about and change energy levels.
Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

Chandrasekhar Mass Limit

What is the maximum mass that can be supported by the dense compact material of a white dwarf star?



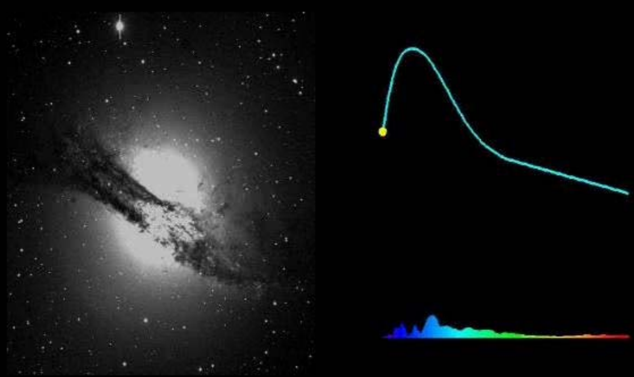
Supernova Lightcurves

SN 2007uy

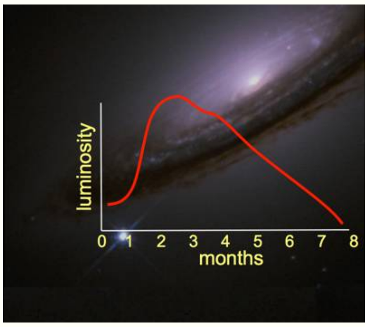
Supernova SN 2007uy in NGC2770

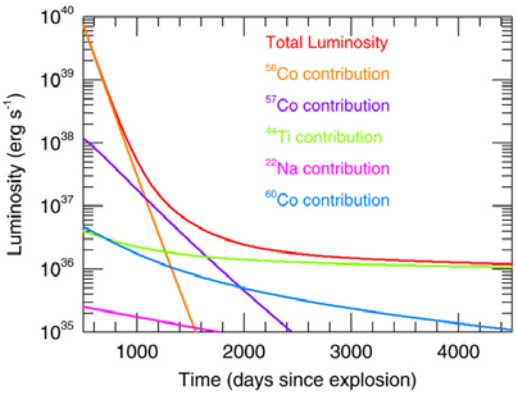
while fading, another supernova, SN2008D, went off in same galaxy

Supernova Lightcurve & Spectrum



Supernova Lightcurve



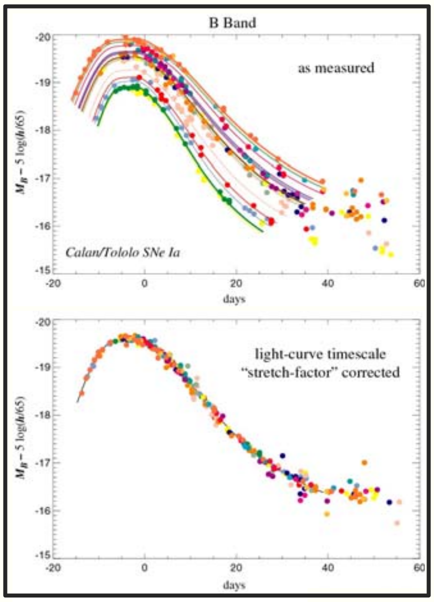


Type Ia supernovae follow a characteristic light curve
—the graph of luminosity as a function of time—after the explosion.

This luminosity is generated by the radioactive decay of Nickel-56 through Cobalt-56 to Iron-56.

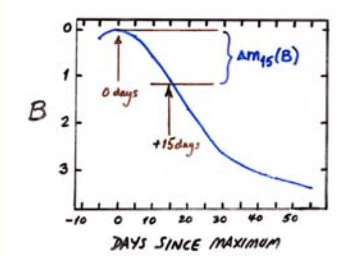
Maximum absolute magnitude of about -19.3.

the Phillips Relation



Relationship between

- peak luminosity of a Type Ia supernova
- speed of luminosity evolution after maximum light.



Mark Phillips (1993):
- on the basis of Calan/Tololo Supernova Survey

- the faster a supernova fades after peak,
- the fainter its intrinsic peak luminosity

- reduces scatter in Hubble diagram to σ<0.2 mag
- heuristic relationship, as yet not theoretically "understood"

Supernova Teams:

Practical Aspects

Supernova Cosmology Project

Success of Supernova Projects built on 3 major developments:

- the introduction in the 1980s of large mosaic charge-coupled device (CCD) cameras on 4-meter class telescopes:

  - systematic search of thousands of galaxies over large area of sky for rare supernova events

- dramatic increase in computing power in the 1980s:

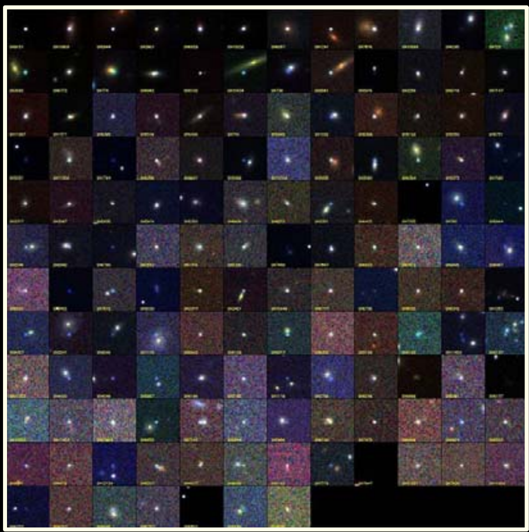
  - enabling vast amount of data processing for automated search of supernovae amongst the huge number of galaxies monitored

- Supernovae Ia as standard candles

  - Calan/Tololo Supernova Search: accurate light curves & spectra
  - Phillips relation

High-z Supernova Search Team

Supernova Cosmology Project



diligently monitoring millions
of galaxies, in search for that
one explosion …

High-z Supernova Search Team

Supernova Cosmology Project

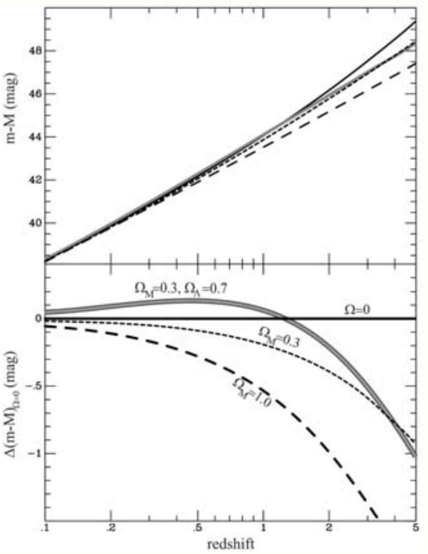
Challenges to be dealt with by Supernova Teams:

- Huge logistic (and political) issue of assuring vast amounts of (strongly contested) observing time on a range of telescopes (incl. 4-m ones for probing high-z universe)
- Dealing with a range of astronomical effects that would render any subtle cosmological signature insignificant:
  - Influence of dust: affecting brightness of supernovae
  - Abundance effects: poorly understood influence of heavy chemical elements on supernova lightcurves
  - ….
- Results put under heavy scrutiny through large range of tests dealing with each imaginable pitfall and artefact
- Absolutely crucial that two competing teams reached same conclusion independently !!!!

High-z Supernova Search Team

Cosmic Acceleration

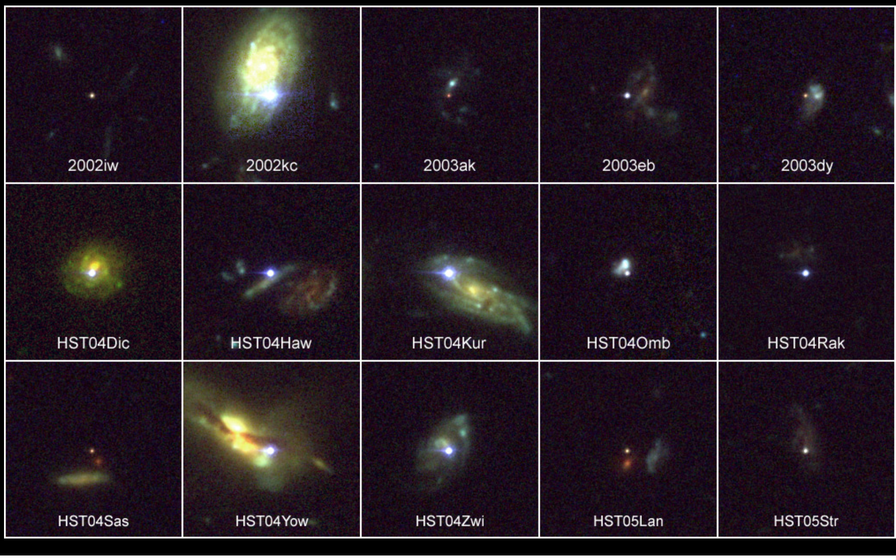
Cosmic Acceleration



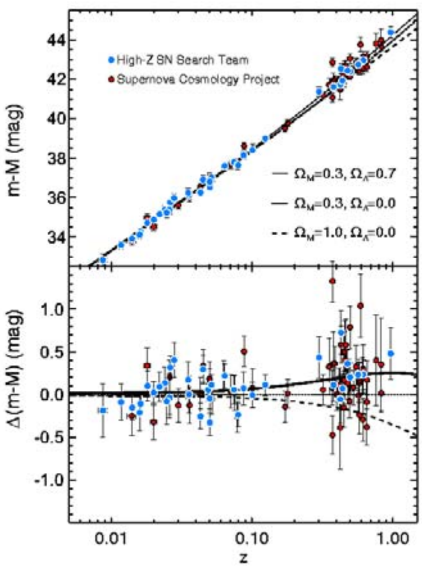
Hubble Diagram high-z SNIa

- distance vs. redshift z
  m-M vs. redshift z
- determine:
  - absolute brightness of supernova Ia
  - from dimming rate (Phillips relation)
- measure:
  - apparent brightness of explosion
- translates into:
  - luminosity distance of supernova
  - dependent on acceleration parm. q

High-z SNIa: sample



Cosmic Acceleration



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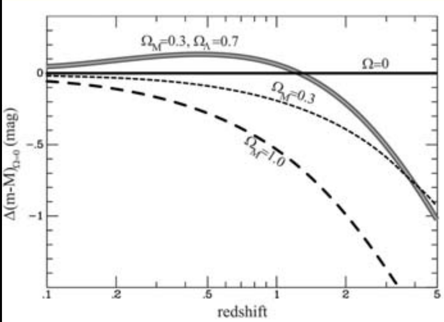
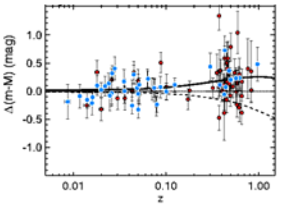
Cosmic Acceleration





Relative Hubble Diagram

Δ(m-M) vs. Redshift z

with Hubble diagram for empty Universe

Ω_m=0.0, Ω_Λ=0.0

as reference.

Acceleration of the Universe:

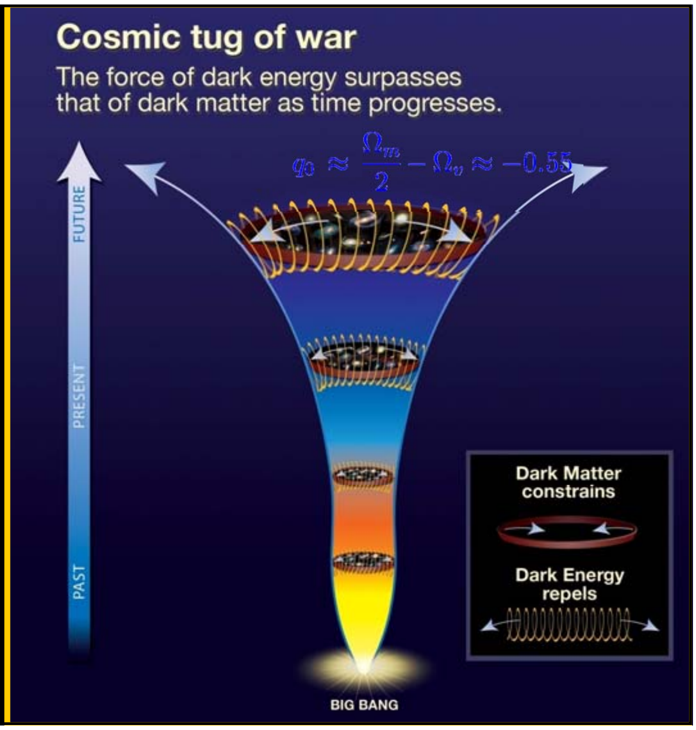
$$q_0 \approx \frac{\Omega_m}{2} - \Omega_v \approx -0.55$$

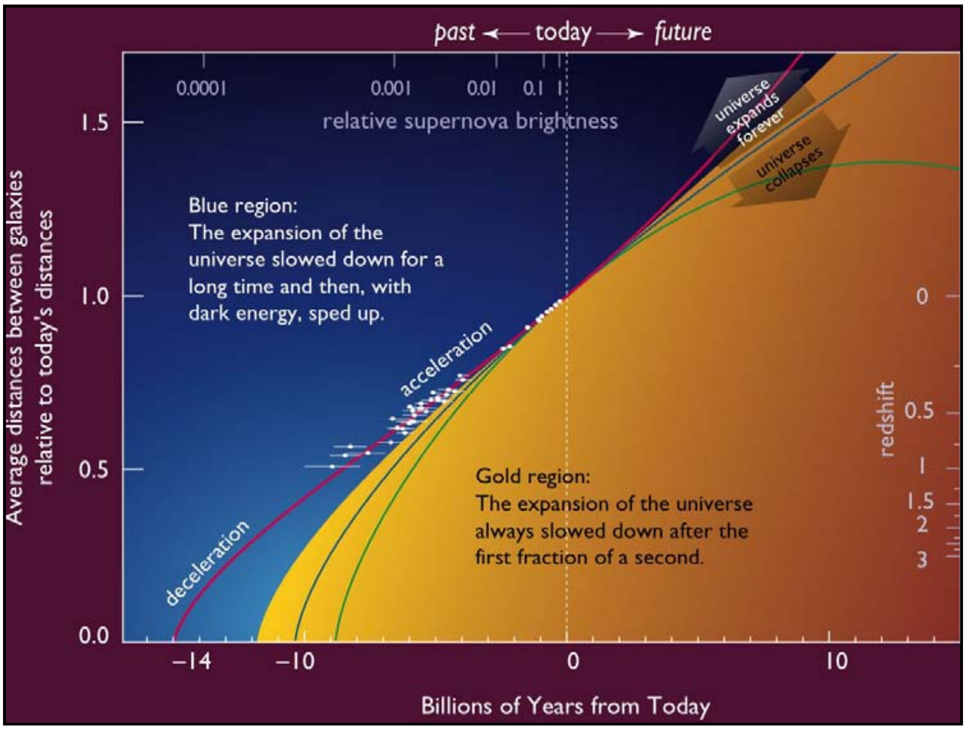
Present:

ACCELERATION

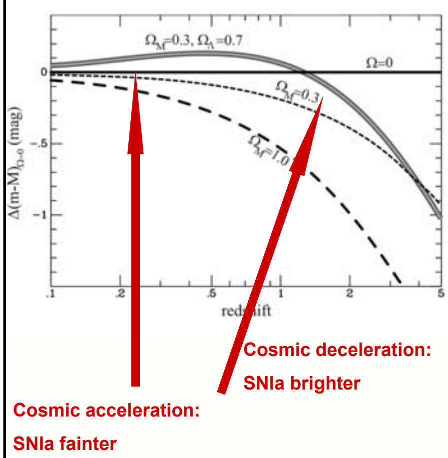
Past:

DECELERATION





Cosmic Deceleration



Before current Dark Energy epoch

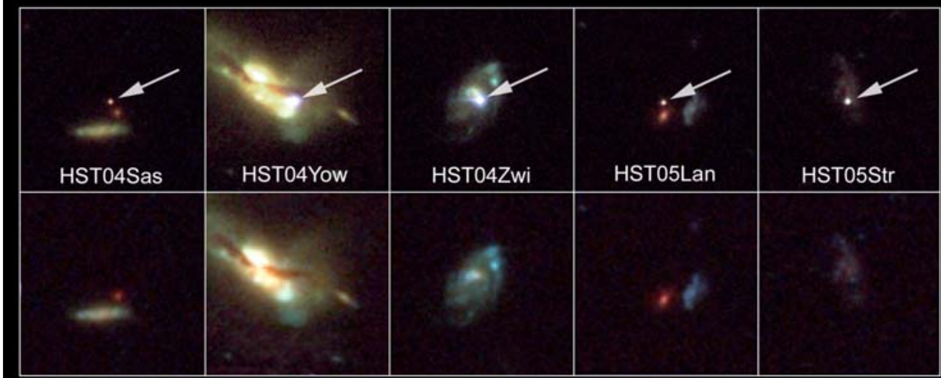
- **Universe dominated by matter:**

  Decelerating Expansion

- **Observable in SNIa at very high z:**

  z > 0.73

Beyond Acceleration: SNe Ia at z > 0.7

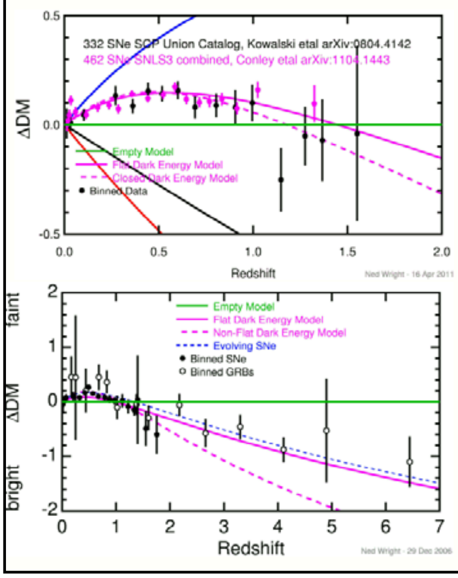


Five high-z SNIa, images HST-ACS camera

SNIa and host galaxies lower panel: before

top panel: after explosion)

Cosmic Deceleration



Before current Dark Energy epoch

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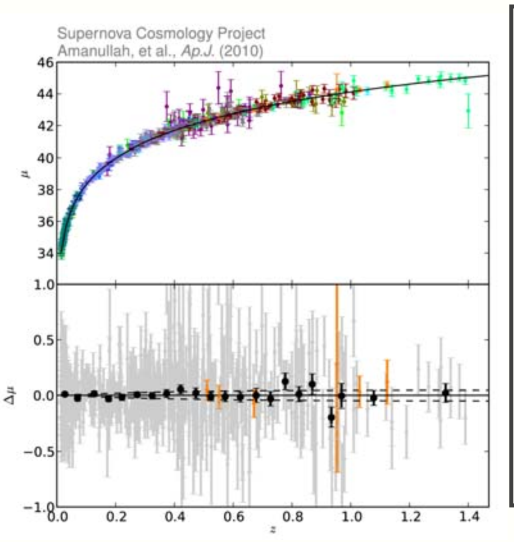
  Decelerating Expansion

- Observable in SNIa at very high z:

  z > 0.73

Union2:
state-of-the-art SNIa compilation



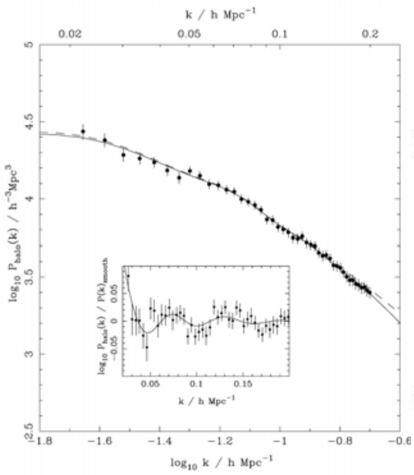
SCP Union2.1 SN Ia compilation:

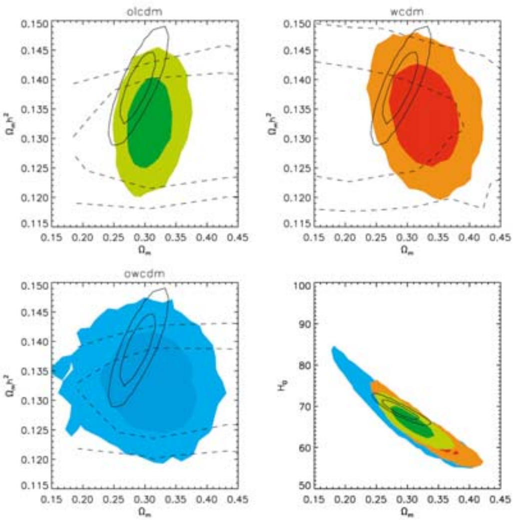
719 SNe, 17 datasets (557 used)
6 z>1 SN Ia

Amanullah et al. 2010

Clustering

Cosmic Constraints
LSS Clustering





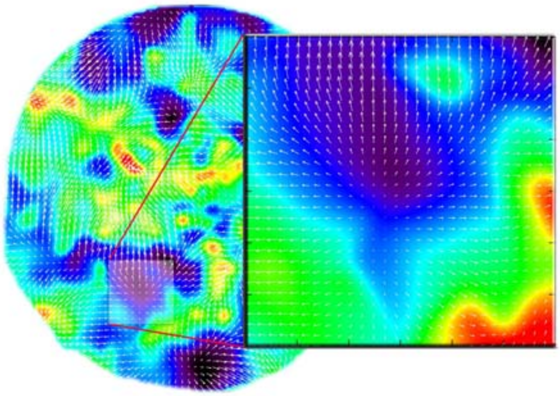
SDSS DR7 LRG sample
Clustering, Reid et al. 2010

Structure Growth Factor

Large Scale Flows

Large-Scale Flows:

- On large (Mpc) scales, structure formation still in linear regime
- Structure buildup accompanied by displacement of matter: - Cosmic flows
- Directly related to cosmic matter distribution



$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}a\int d\mathbf{x}'\,\delta_{gal}(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Redshift Distortions

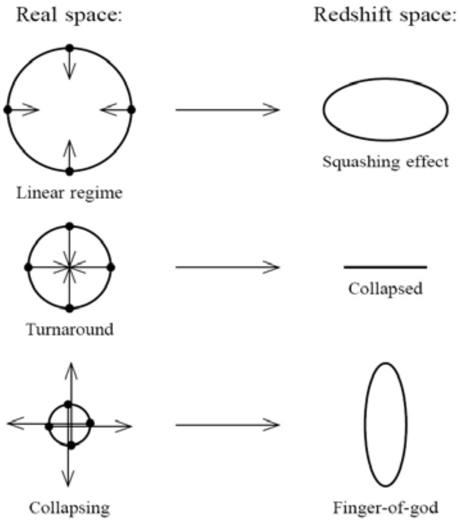
Origin of peculiar velocities:

three regimes

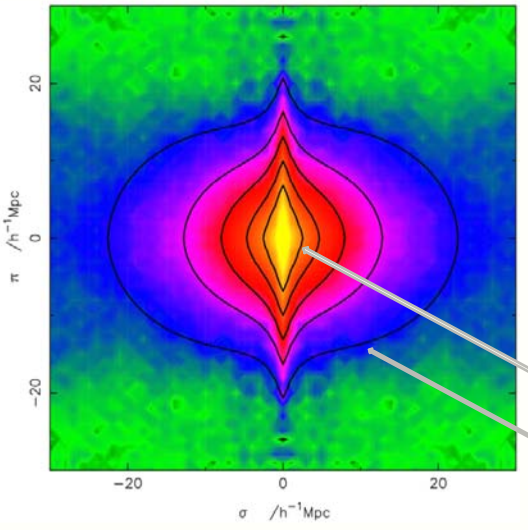
- very high-density virialized cluster (core) regions: "thermal" motion in cluster, up to > 1000 km/s

  "Fingers of God"

- collapsing overdensity (forming cluster): inflow/infall velocity
- Large scales: (linear, quasi-linear) cosmic flow, manifestation of structure growth



sky-redshift space
2-pt correlation function $\xi(\sigma,\pi)$



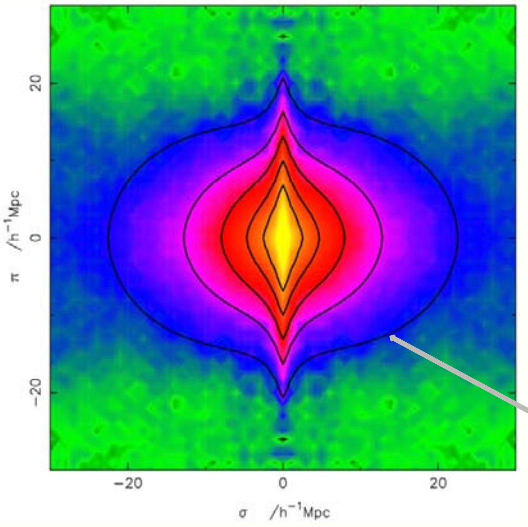
Correlation function determined in sky-redshift space:

$$\xi(\sigma,\pi)$$

sky position: $\sigma = (\alpha, \delta)$
redshift coordinate: $\pi = cz$

Close distances:
distortion due to non-linear Finger of God
Large distances:
distortions due to large-scale flows

Redshift Space Distortions
Correlation Function



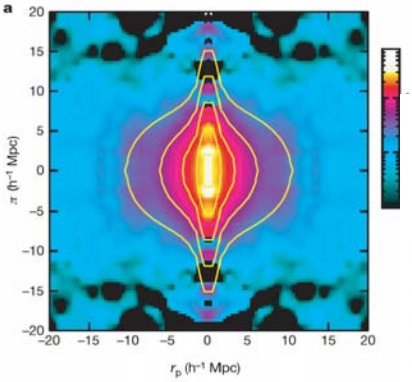
On average, $\xi_s(s)$ gets amplified wrt. $\xi_r(r)$

Linear perturbation theory (Kaiser 1987):

$$\xi_s(s) = (1 + \frac{2}{3}\Omega^{0.6} + \frac{1}{5}\Omega^{1.2})\xi_r(s)$$

Large distances:
distortions due to large-scale flows

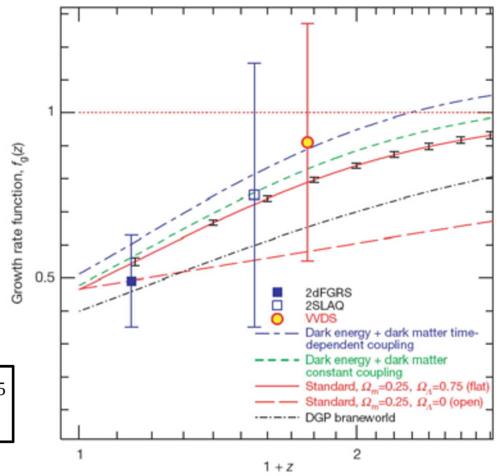
Evolution Growth Rate



$$f(\Omega_m, \Omega_\Lambda) = \frac{a}{D}\frac{dD}{da} \approx \Omega_m^{0.55}$$

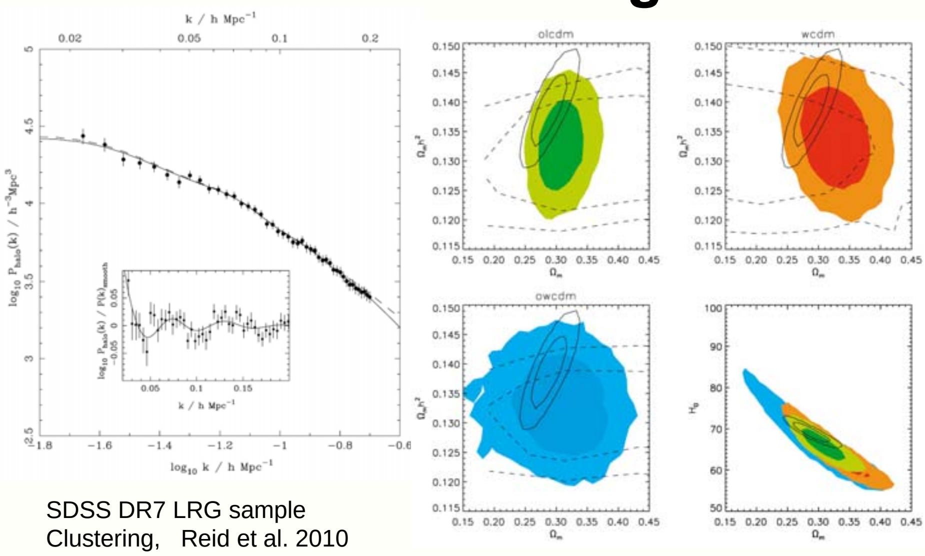
Peebles growth rate factor

Linder 2008
Guzzo et al. 2008



Galaxy & Cluster Clustering

Cosmic Constraints
LSS Clustering



SDSS DR7 LRG sample
Clustering,   Reid et al. 2010

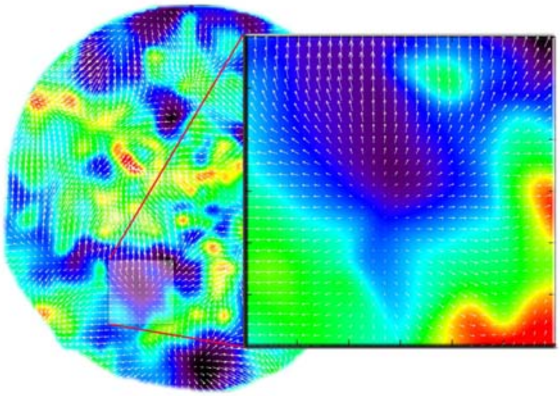
Structure

Growth Factor

Large Scale Flows

Large-Scale Flows:

- On large (Mpc) scales, structure formation still in linear regime
- Structure buildup accompanied by displacement of matter: - Cosmic flows
- Directly related to cosmic matter distribution



$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}a\int d\mathbf{x}'\,\delta_{gal}(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Redshift Distortions

Origin of peculiar velocities:

three regimes

- very high-density virialized cluster (core) regions: "thermal" motion in cluster, up to > 1000 km/s

  "Fingers of God"

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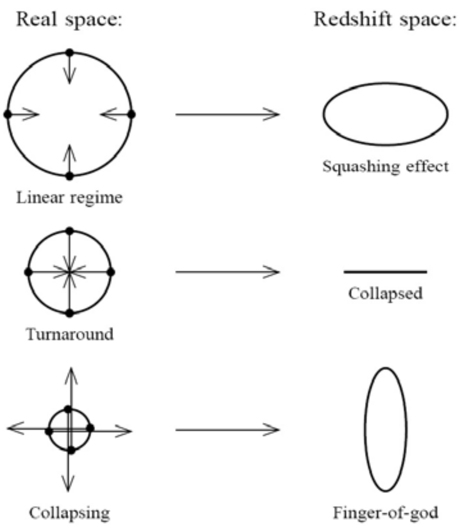
- Large scales: (linear, quasi-linear) cosmic flow, manifestation of structure growth



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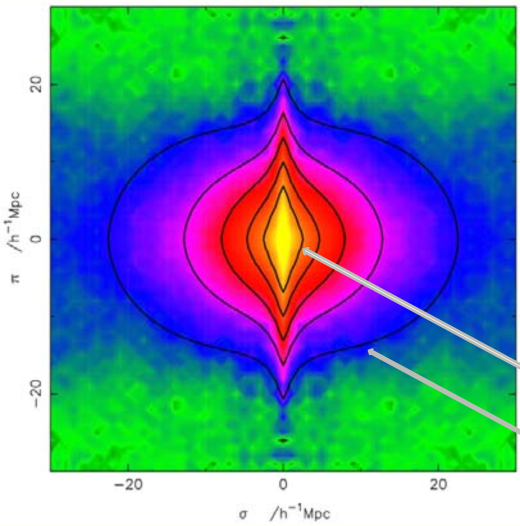

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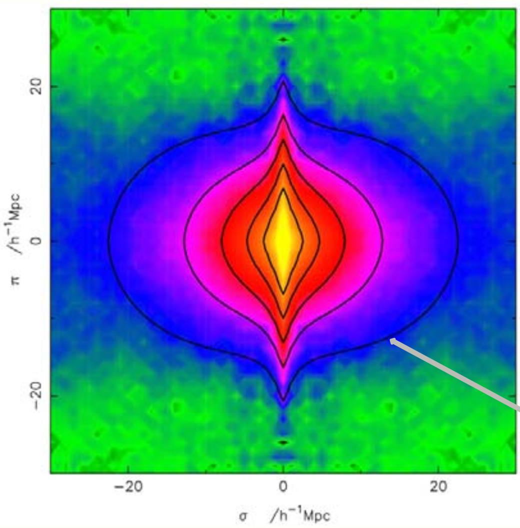

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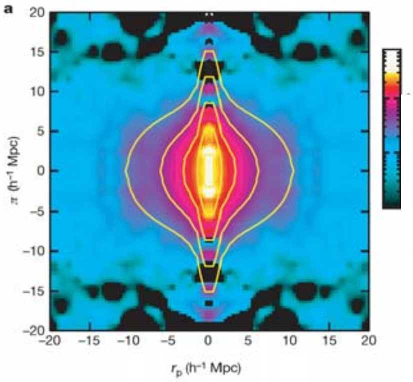

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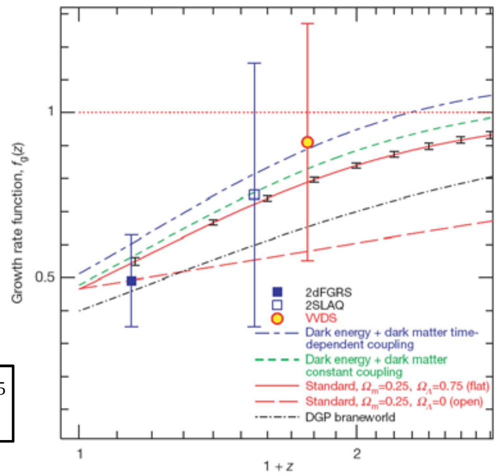
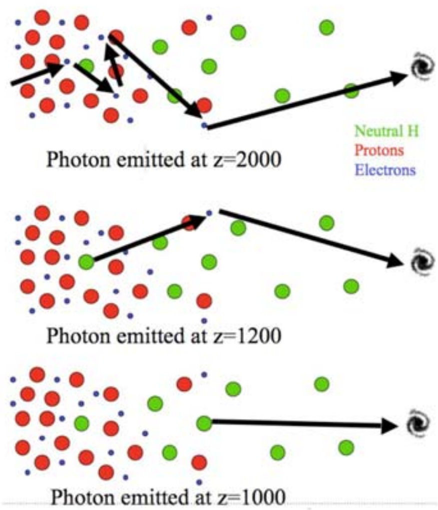


BAO:

Baryonic Acoustic Oscillations

BAO

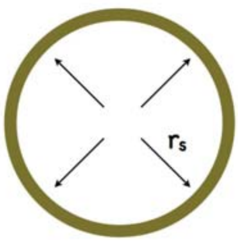


Before recombination, universe is opaque, so photons & baryons couple; interplay of gravity (DM, baryons) and photon pressure ⇒ acoustic waves propagate

At recombination, photons scatter for the last time ('surface of last scattering')

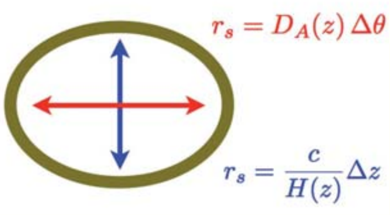
After recombination, the universe is transparent, so photons can stream freely ⇒ acoustic waves frozen

BAO as cosmological tools



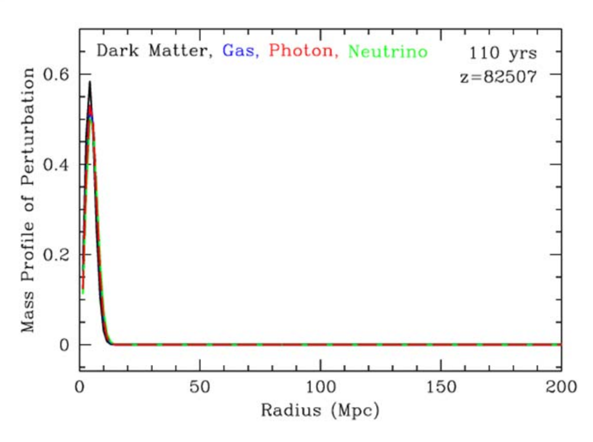
Until recombination, the sound wave travels a distance of:

$$r_s = \int_{z_{rec}}^{\infty} \frac{c_s(z)}{H(z)} dz$$

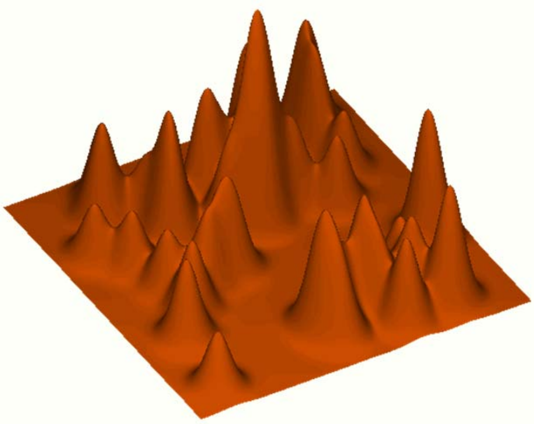


This distance can be accurately determined from the CMB power spectrum, and was found to be 147±2 Mpc.

Measuring BAO



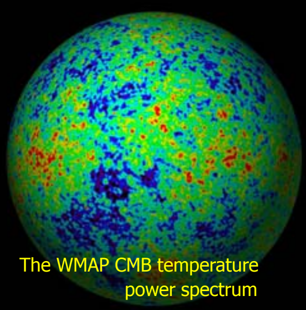
Measuring BAO

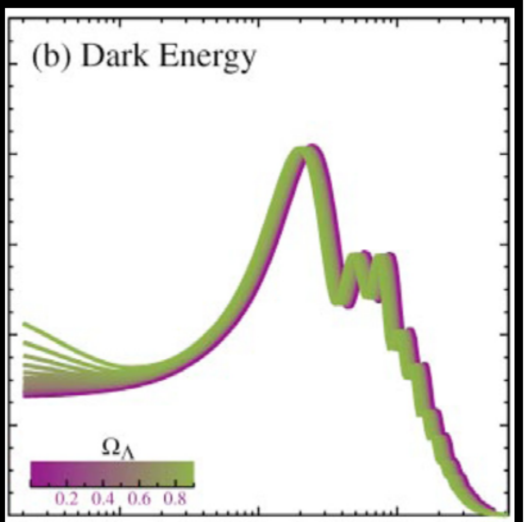


ISW:

Integrated Sachs Wolfe Effect

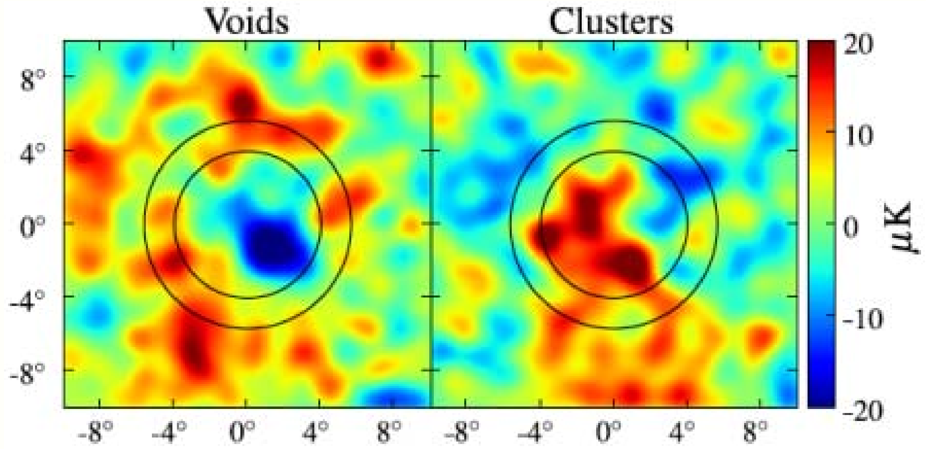
Dark Energy & CMB: ISW





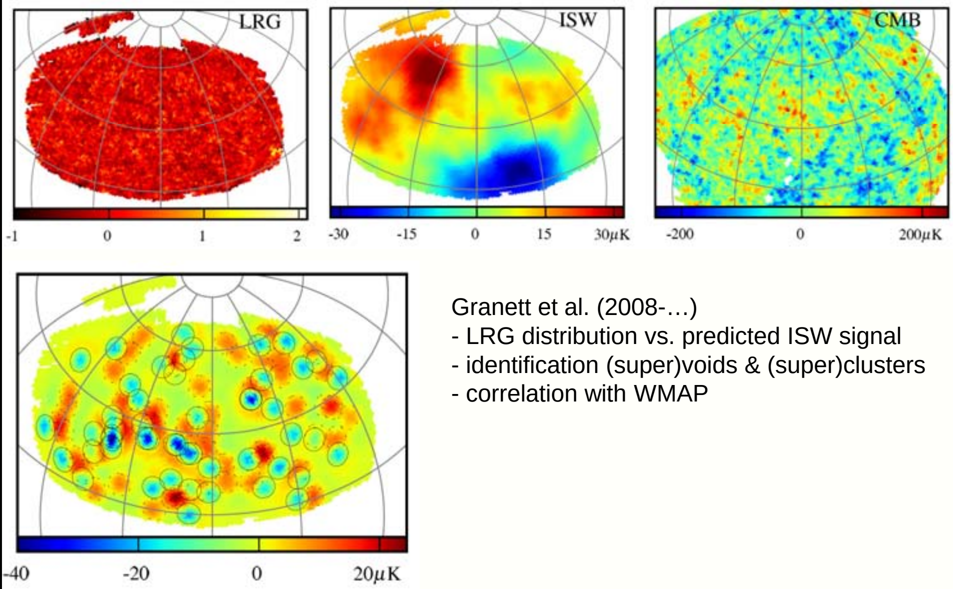
Dark Energy modifies evolution potential wells

Dark Energy: ISW



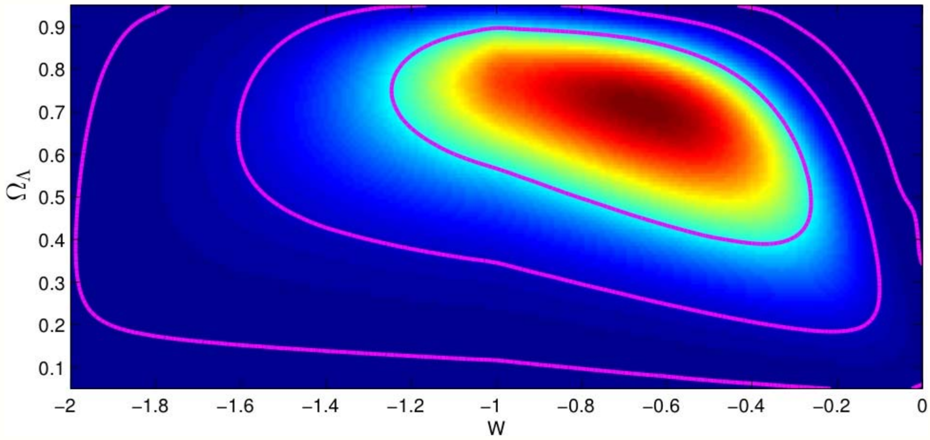
Dark Energy modifies evolution potential wells

ISW & identified voids/clusters



Granett et al. (2008-…)
- LRG distribution vs. predicted ISW signal
- identification (super)voids & (super)clusters
- correlation with WMAP

Dark Energy: ISW

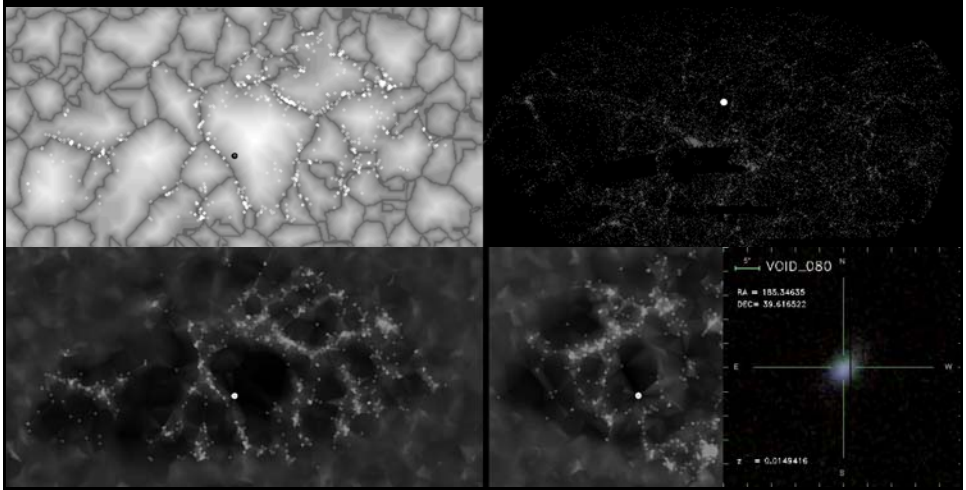


Dark Energy modifies evolution potential wells

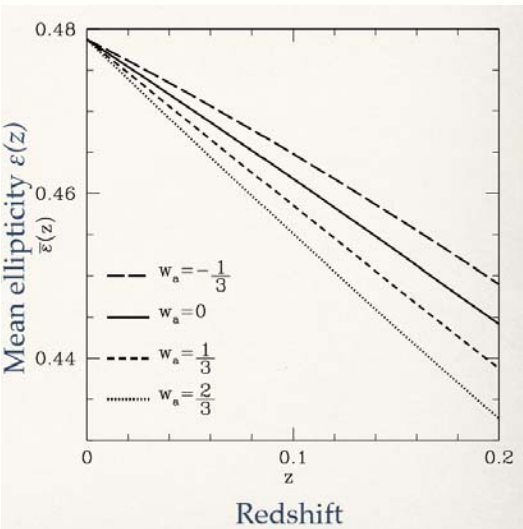
Cosmic Voids:

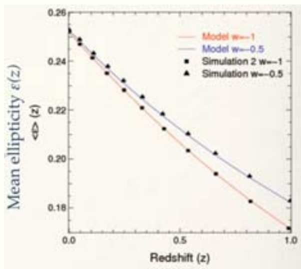
Shape of Voids

Cosmic Voids



Evolving Void Shapes

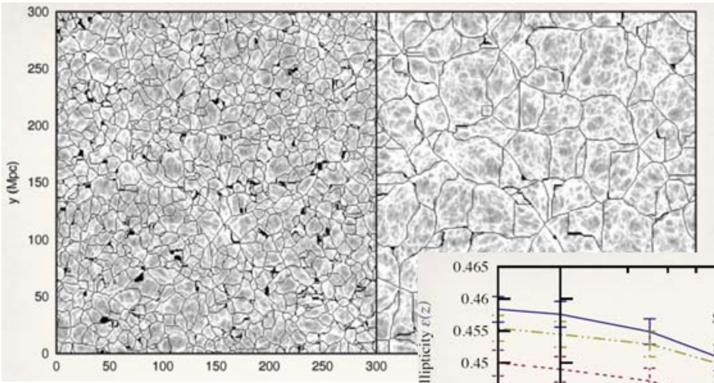


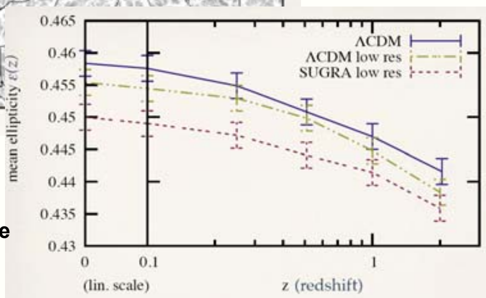


Evolution of void shape sensitive probe of dark energy:

Park & Lee 2007
Lavaux & Wandelt 2010

Evolving Void Shapes





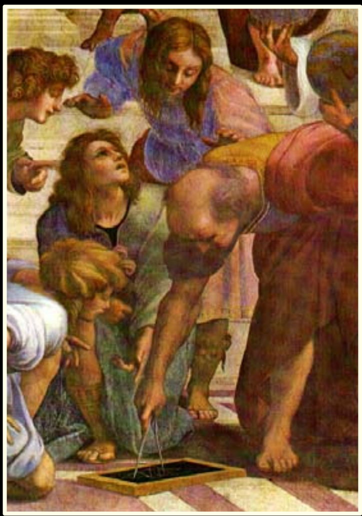
Bos et al. 2011:

Trend of evolving void shape as function of dark energy eqn.state confirmed.

Future Experiments

Euclid

Euclid:
father of geometry



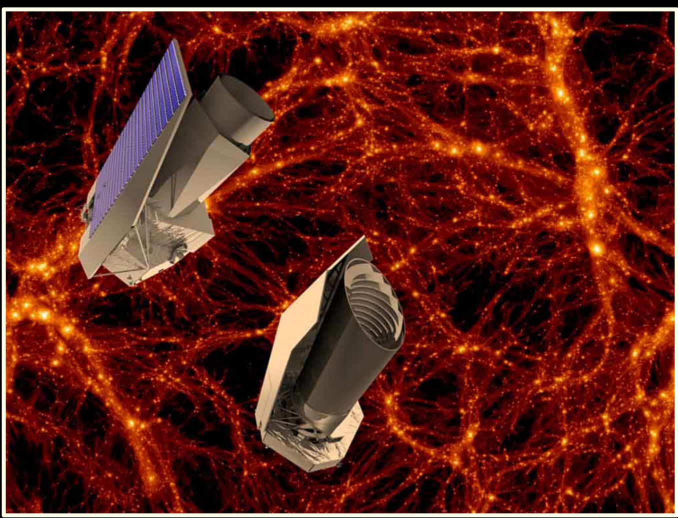
ESA
Cosmic Vision
2020-2025

- 1.2 m Korsch telescope
- visible light:
  m=24.5 CCD imaging
- IR (Y,J,H) band photometer
- spectrometer 108 bright gals

- 15,000 sq. deg. survey
- 40 sq. deg. deep survey

- Combination:
  - DUNE grav. Lensing
  - SPACE BAO

Euclid



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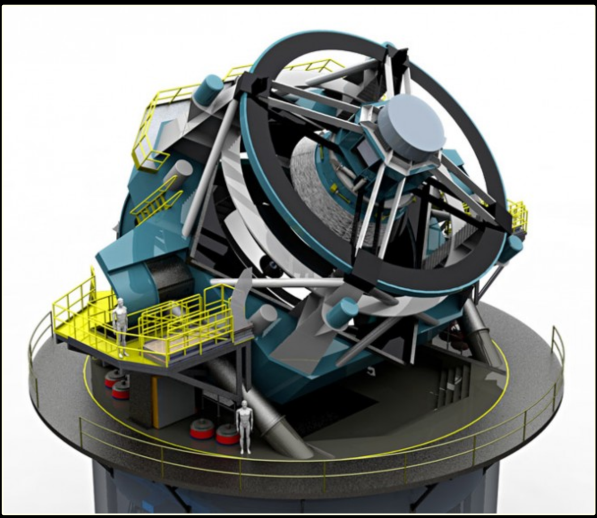
LSST:
Large Synoptic Survey Telescope



8.4 m primary mirror widefield survey telescope

- El Penon, Chile
  2682 m. mountain
- start operation: 2015
- 3.5 deg. angle of view
- 3.2 Gigapixel prime focus digital camera
- 200,000 images per year
- 30 Tbyte per night
- partial funding Bill Gates

Summary

Take-Home Facts

1. **Strong evidence Accelerated Expansion**
   - since supernova discovery, 100s SNIa observed over broader range redshifts
   - based solely upon supernova Hubble diagram, independent of General Relativity, very strong evidence expansion Universe accelerated recently

2. **Dark energy as cause cosmic acceleration**
   - within general relativity, accelerated expansion cannot be explained by any known form of matter or energy
   - it can be accommodated by a nearly smooth form of energy with large negative pressure, Dark Energy, that accounts for about 73% of the universe.

3. **Independent evidence dark energy**
   - Cosmic Microwave Background and Large Scale Structure data provide independent evidence, within context of CDM model of structure formation, that the universe is filled with a smooth medium accounting for 73% of the total energy content of the universe.
   - that came to dominate the dynamics of the universe once all observed structure had formed

Take-Home Facts

4. **Vacuum energy as dark energy**
   - simplest explanation for dark energy is the energy associated with the vacuum
   - mathematically equivalent to a cosmological constant
   - However, most straightforward calculations of vacuum energy density from zero-point energies of all quantum fields lead to estimates which are a bit too large, in the order of $\sim 10^{120}$

5. **Dark theories of Dark Energy**
   - There is no compelling theory of dark energy
   - Beyond vacuum energy, man intriguing ideas: light scalar fields, additional spatial dimensions, etc.
   - Many models involve time-varying dark energy

6. **New Gravitational Theories ?**
   - alternatively, cosmic acceleration could be a manifestaation of gravitational physics beyond General Relativity
   - however, as yet there is no self-consistent model for new gravitational physics that is consistent with large body of data that constrains theories of graavity.

Take-Home Facts

7. Dark destiny

8. At the nexus of many physical mysteries

9. Two big questions

a) Is dark energy something different than vacuum energy
b) Does General Relativity self-consistently describe cosmic acceleration ?

10. Probing Dark Energy

Maipenrai

Oct 5, 2011:

"We Are Sold out
We were down to our last few cases before the announcement of Maipenrai's Brian Schmidt winning the Nobel Prize, and what remained has literally gone in 60 seconds.

Stay tuned for our next release in December of the 2009 Maipenrai Pinot Noir."