Probes Dark Energy

- Supernovae Ia
  probing luminosity distance – redshift relation
- Clusters of Galaxies
  number counts N(z),
  # formed clusters of galaxies as function of z sensitive to w & w'
- Cosmic Shear/Weak Lensing
  measures angular diameter distance-redshift relation, in combination with structure growth
- 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"

Standard Candles in Cosmology

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 $\sinh(x)$

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

Comoving radial distance r(z) at redshift z

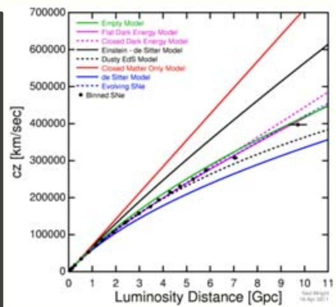
Luminosity Distance

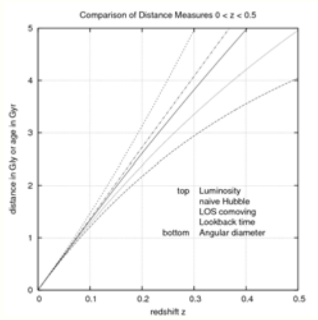
Luminosity Distance at low redshift:

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

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

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



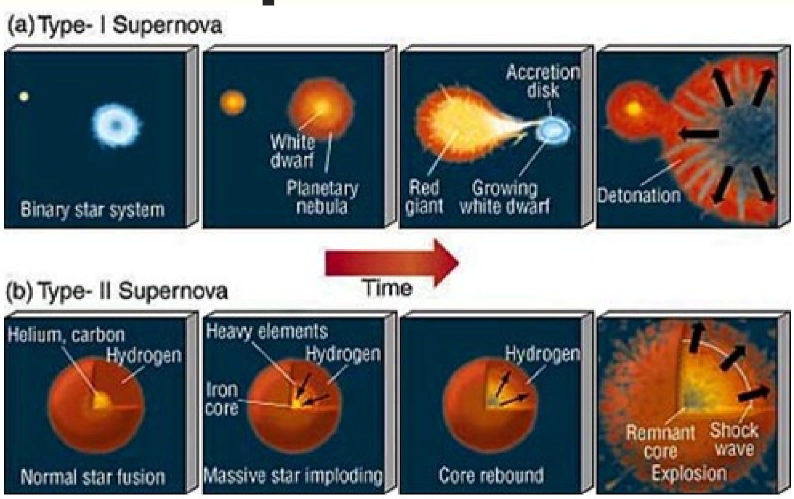


Type Ia Supernovae

Supernova Explosion & Host Galaxy

M51 supernovae

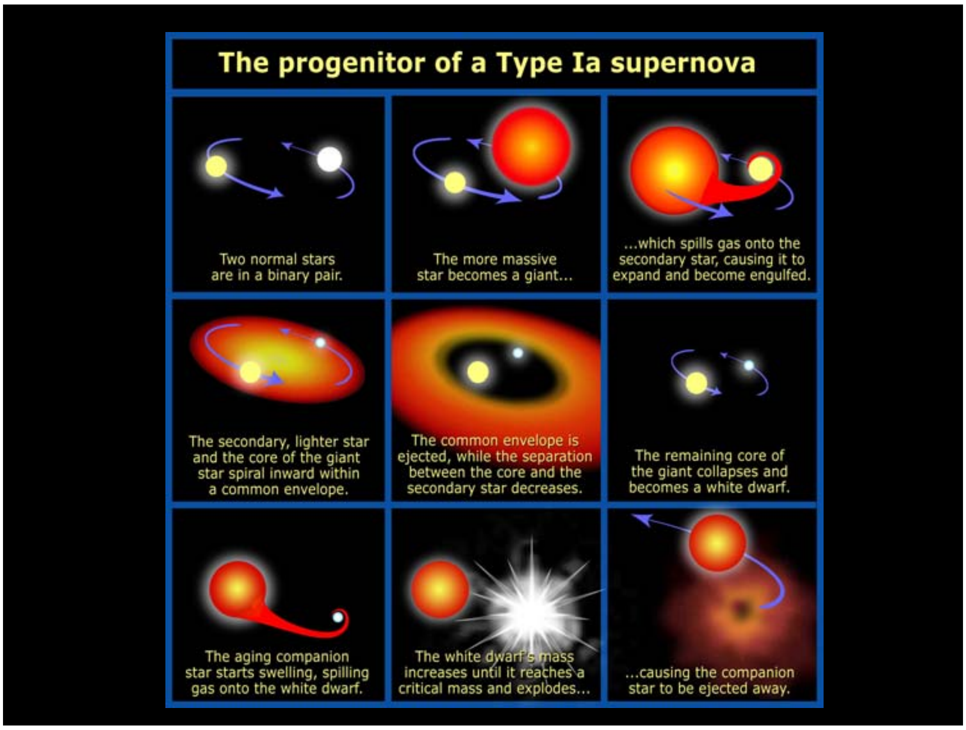
Supernovae



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

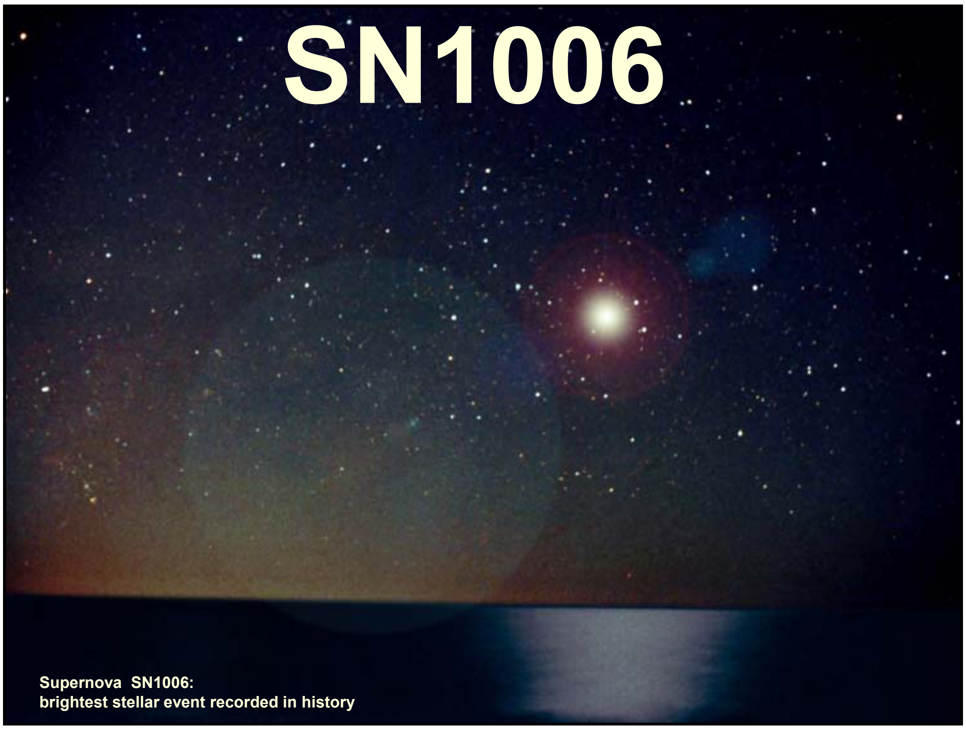


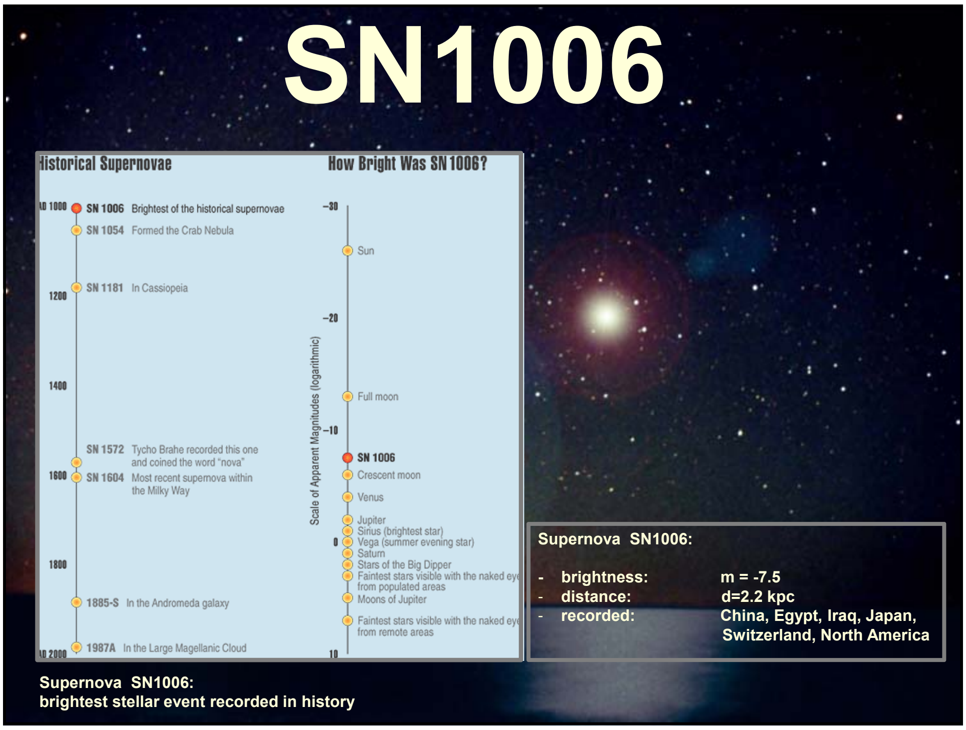
Type Ia Supernova

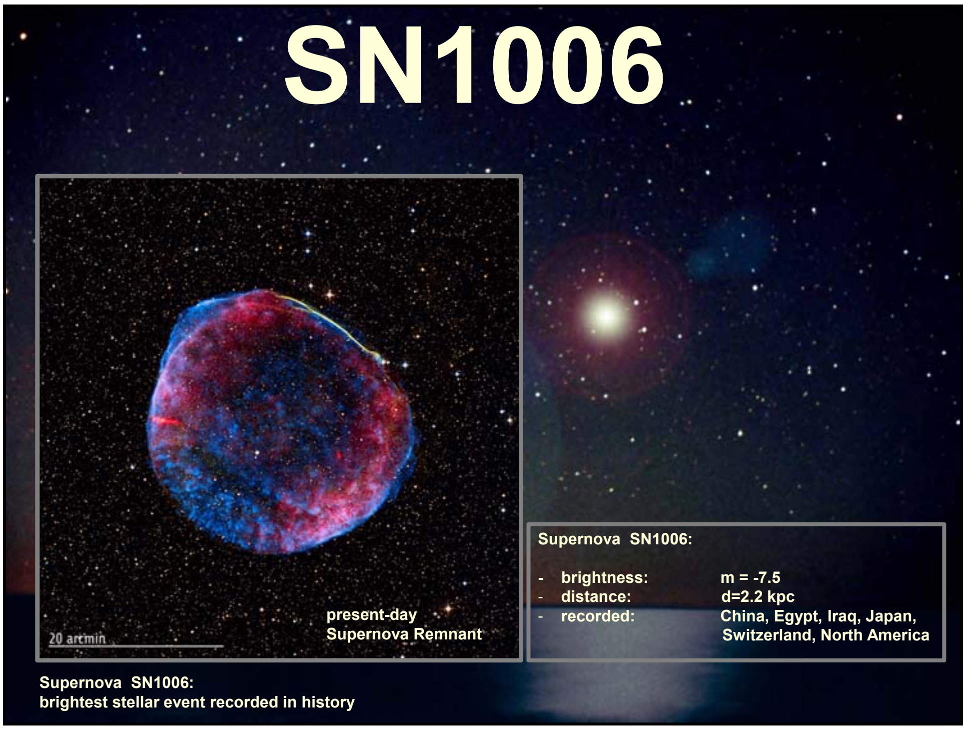
- Amongst the most energetic explosions in our Universe:
  E ~ 10^{54} ergs
- During explosion the star is as bright as entire galaxy ! (ie. 10^{11} stars)

- 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

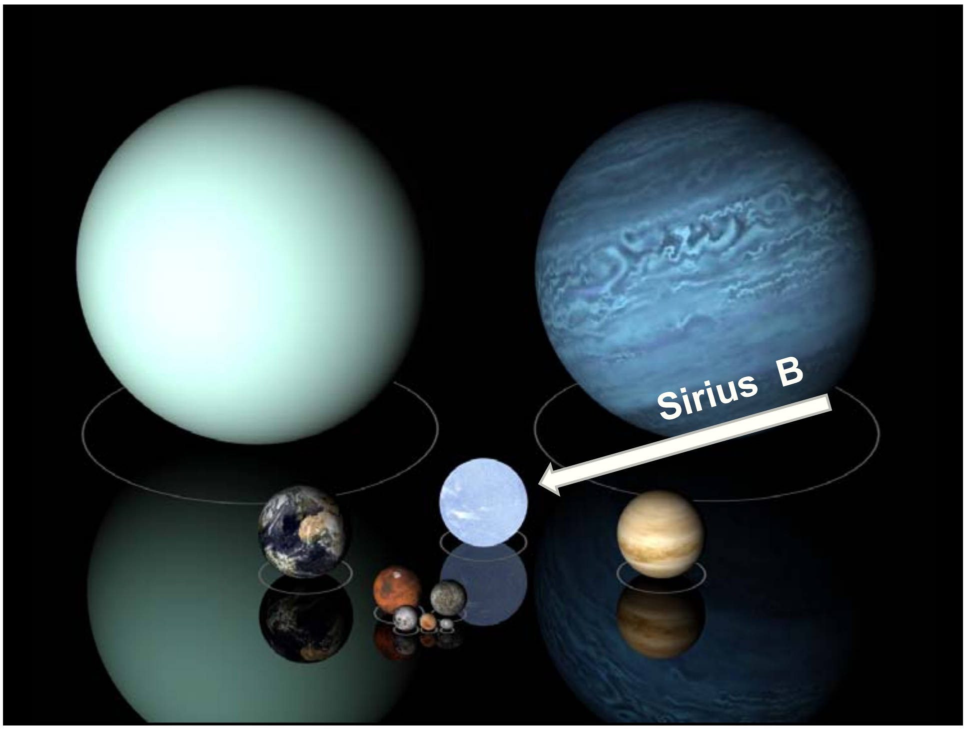
- Because exploding stars have nearly uniform progenitor (~1.38 $M_\odot$ white dwarf), their luminosity is almost the same: M ~ -19.3
  Standard Candle

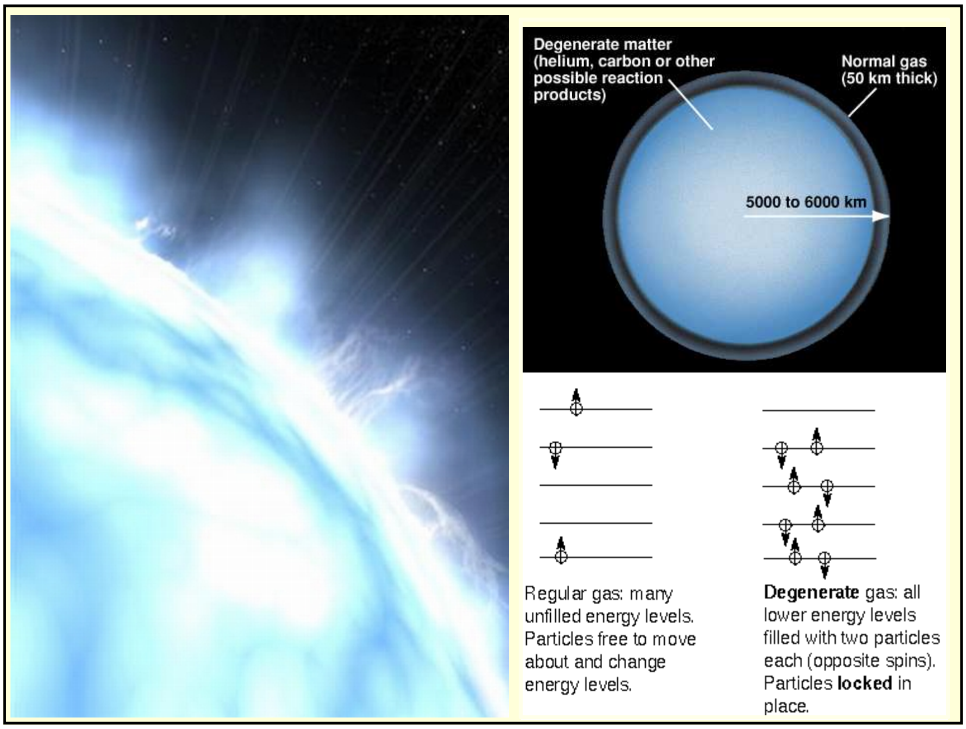

SN1006
Supernova SN1006:
brightest stellar event recorded in history


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
Faintest stars visible with the naked eye from populated areas
Moons of Jupiter
Faintest stars visible with the naked eye 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



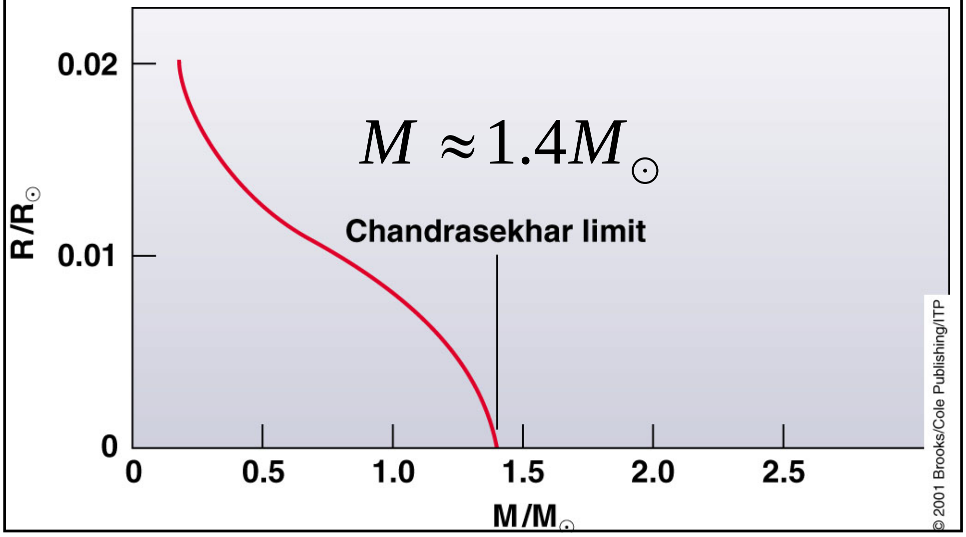
White Dwarfs


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?



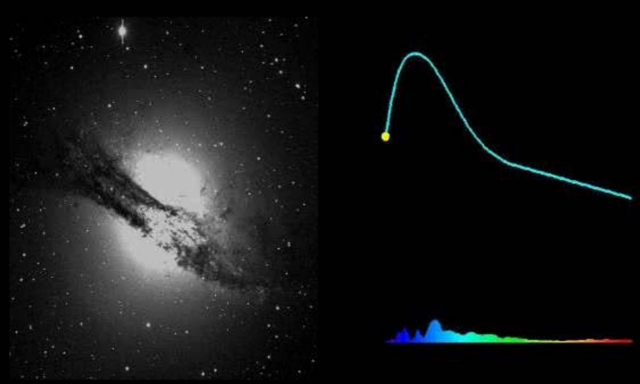
Supernova Lightcurves

SN 2007uy

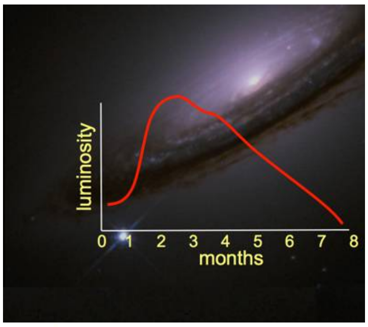
Supernova SN 2007uy in NGC2770

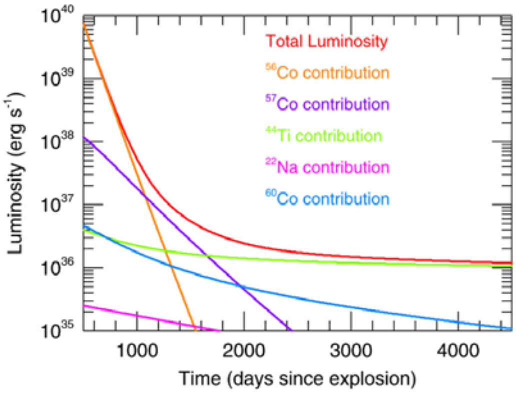
while fading, another supernova, SN2008D, went off in same galaxy

Supernova Lightcurve & Spectrum



Supernova Lightcurve



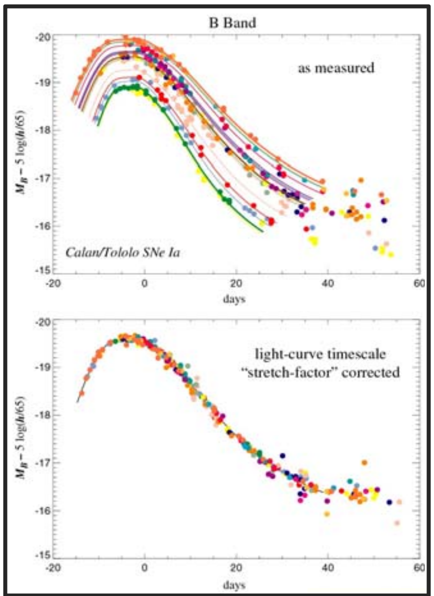


Type Ia supernovae follow a characteristic light curve
—the graph of luminosity as a function of time—after the explosion.

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

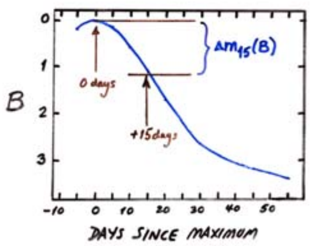
Maximum absolute magnitude of about -19.3.

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:

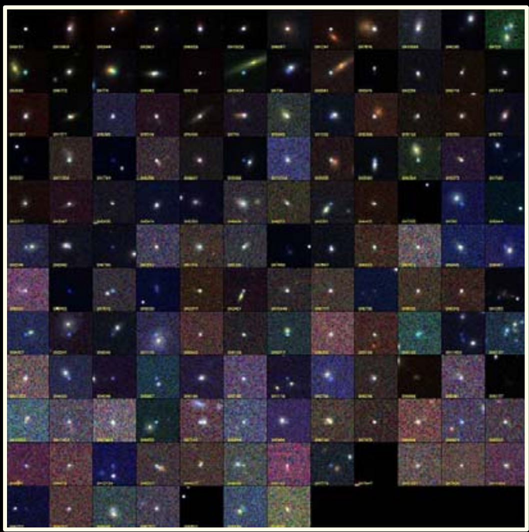
  - enabling vast amount of data processing for automated search of supernovae amongst the huge number of galaxies monitored

- 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

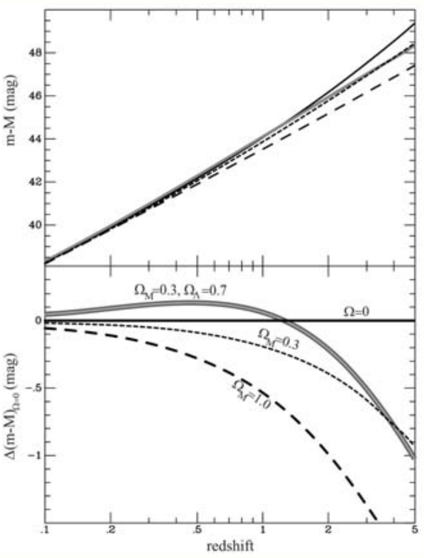
Challenges to be dealt with by Supernova Teams:

- 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

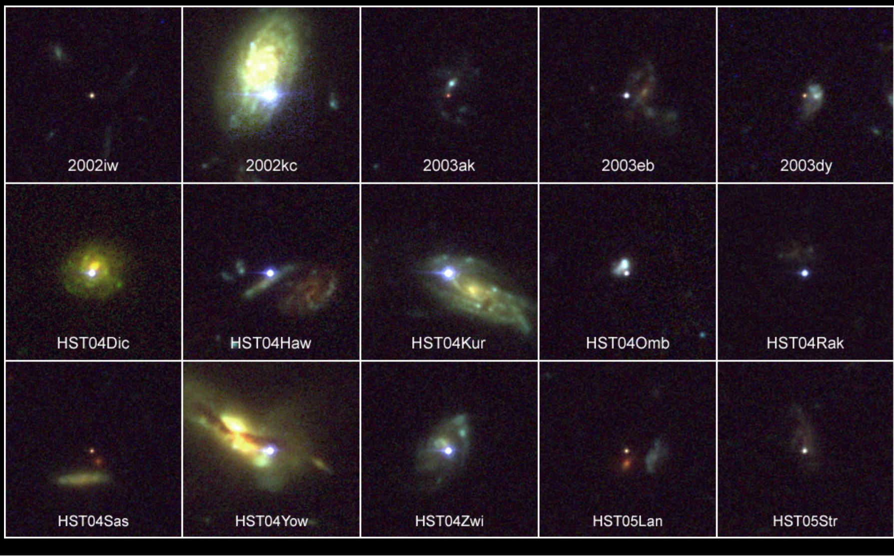
Cosmic Acceleration



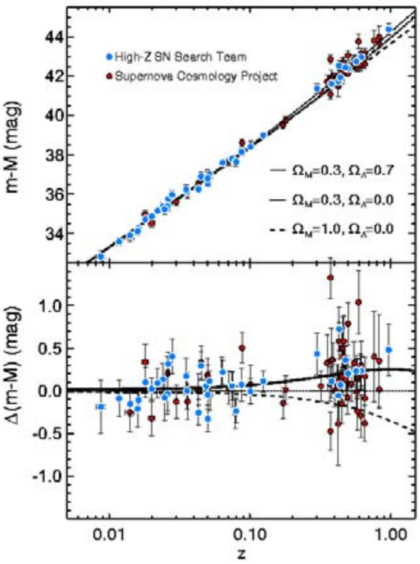
Hubble Diagram high-z SNIa

- 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



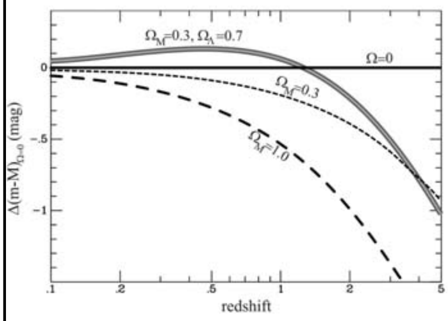
Cosmic Acceleration

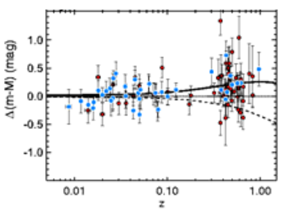


Hubble Diagram high-z SNIa

- 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

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:

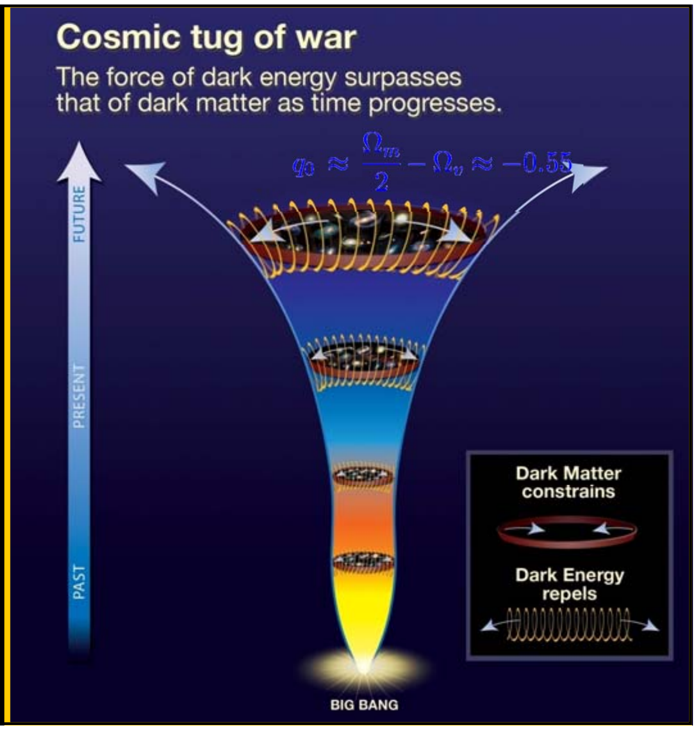
$$q_0 \approx \frac{\Omega_m}{2} - \Omega_v \approx -0.55$$

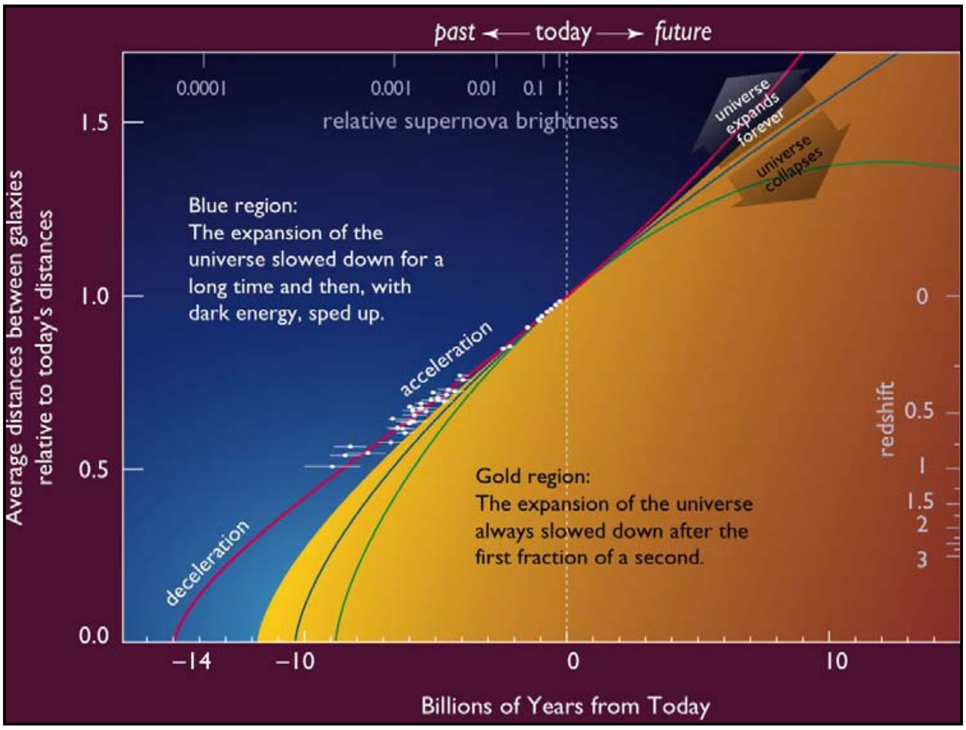
Present:

ACCELERATION

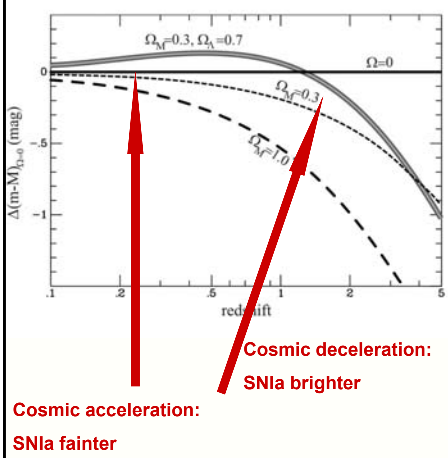
Past:

DECELERATION





Cosmic Deceleration



Before current Dark Energy epoch

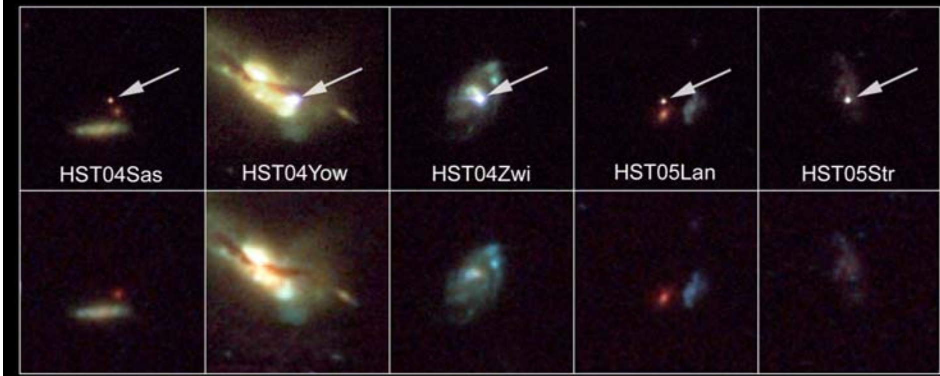
- **Universe dominated by matter:**

  Decelerating Expansion

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

  z > 0.73

Beyond Acceleration: SNe Ia at z > 0.7

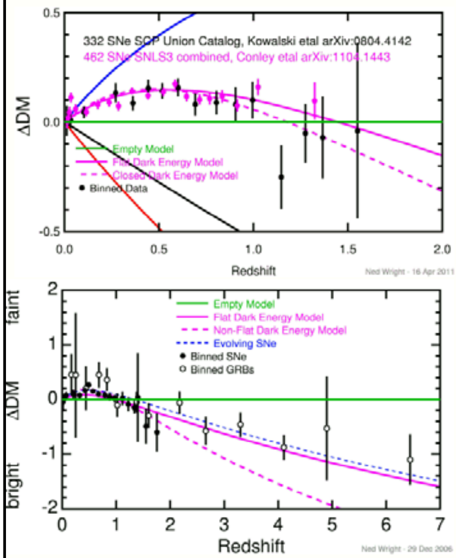


Five high-z SNIa, images HST-ACS camera

SNIa and host galaxies lower panel: before

top panel: after explosion)

Cosmic Deceleration



Before current Dark Energy epoch

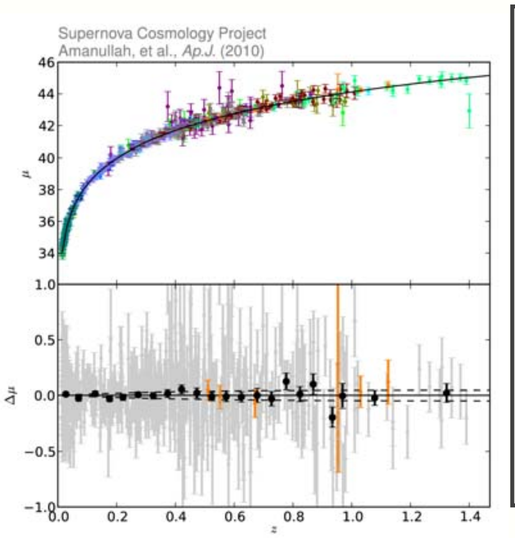
- Universe dominated by matter:

  Decelerating Expansion

- Observable in SNIa at very high z:

  z > 0.73

Union2:
state-of-the-art SNIa compilation



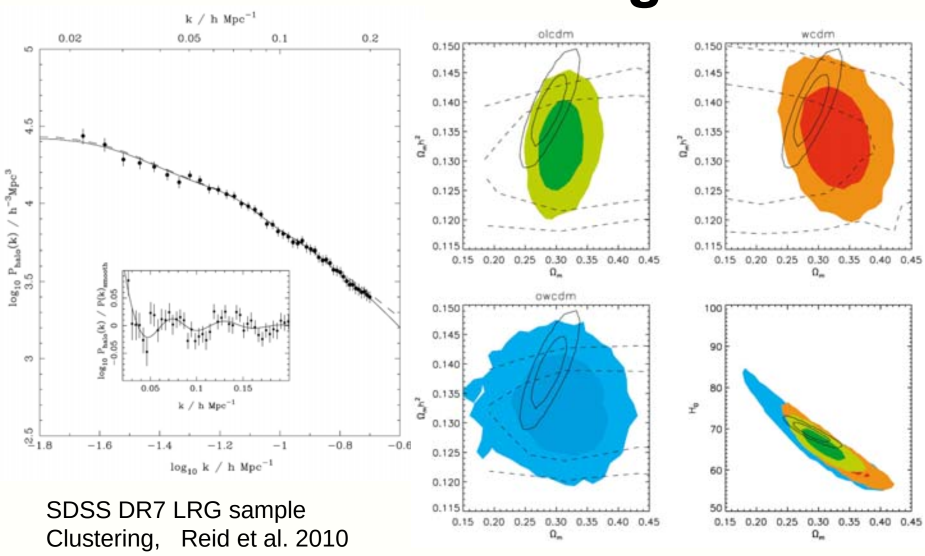
SCP Union2.1 SN Ia compilation:

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

Amanullah et al. 2010

Clustering

Cosmic Constraints
LSS Clustering



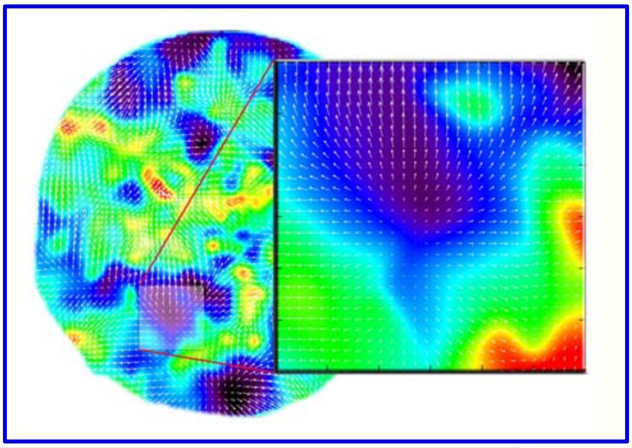
SDSS DR7 LRG sample
Clustering, Reid et al. 2010

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

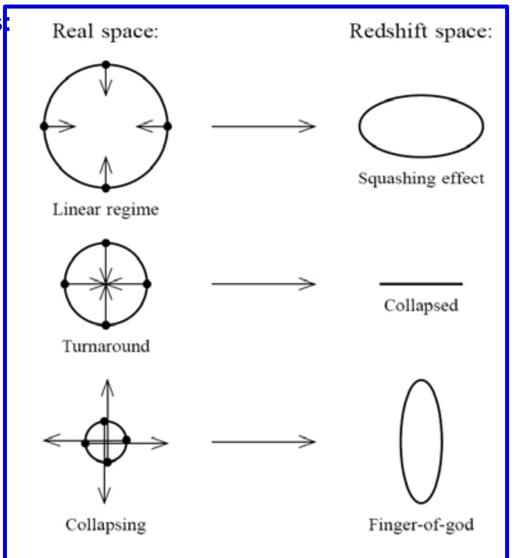
Origin of peculiar velocities:

three regimes

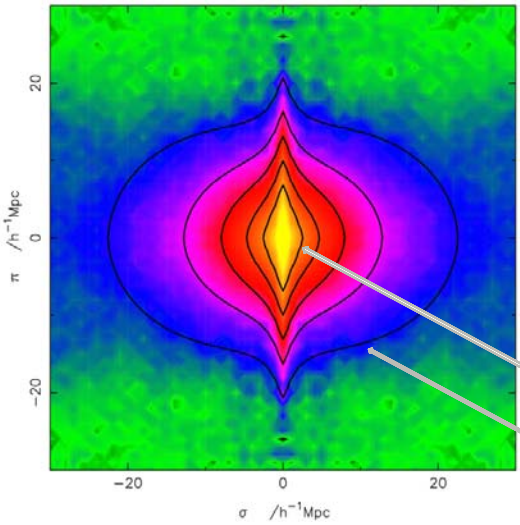
- very high-density virialized cluster (core) regions: "thermal" motion in cluster, up to > 1000 km/s

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



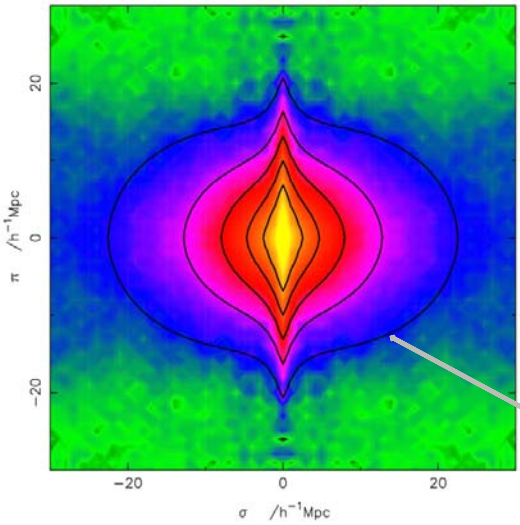
Correlation function determined in sky-redshift space:

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

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



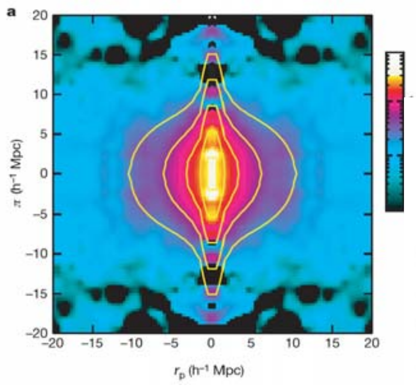
On average, $\xi_s(s)$ gets amplified wrt. $\xi_r(r)$

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

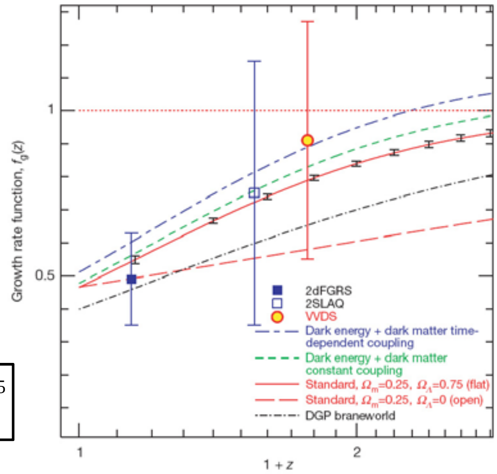
Evolution Growth Rate



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

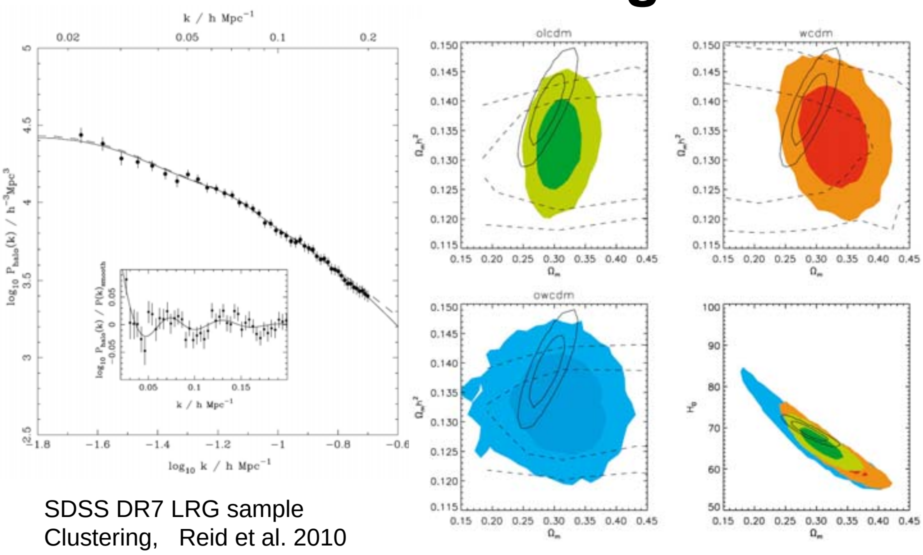
Peebles growth rate factor

Linder 2008
Guzzo et al. 2008



Galaxy & Cluster Clustering

Cosmic Constraints
LSS Clustering



SDSS DR7 LRG sample
Clustering, Reid et al. 2010

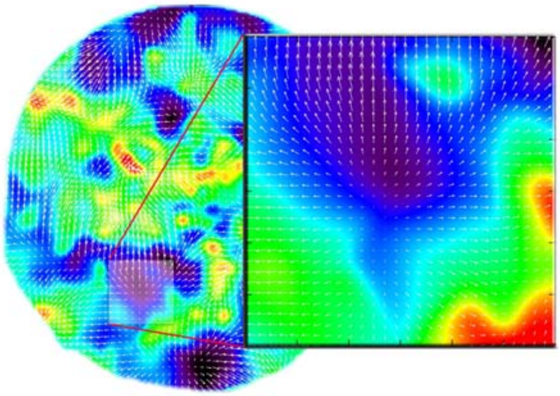
Structure

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



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

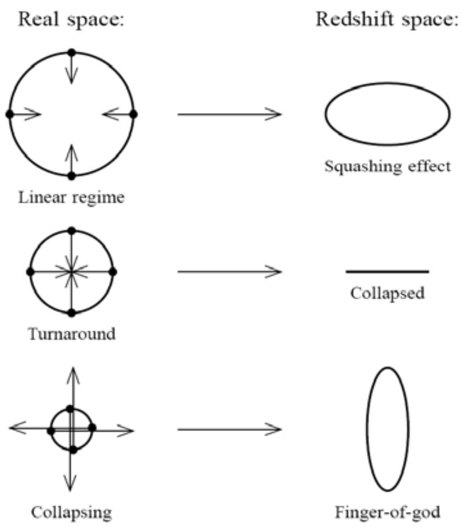
Redshift Distortions

Origin of peculiar velocities:

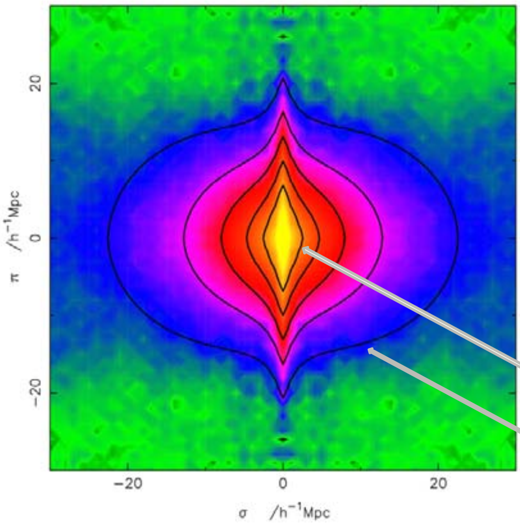
three regimes

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

  "Fingers of God"
- 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 $\xi(\sigma,\pi)$



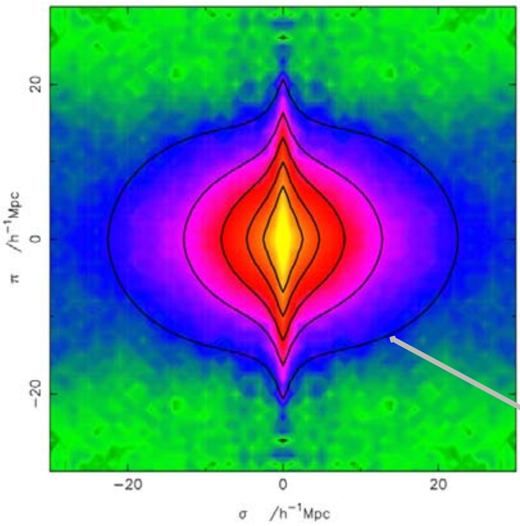
Correlation function determined in sky-redshift space:

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

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



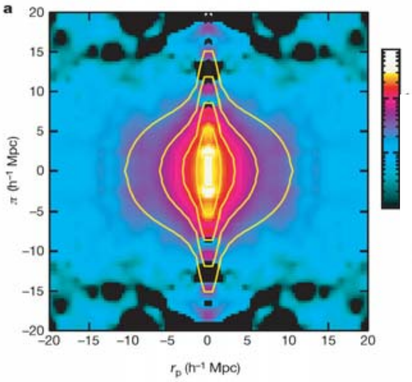
On average, $\xi_s(s)$ gets amplified wrt. $\xi_r(r)$

Linear perturbation theory (Kaiser 1987):

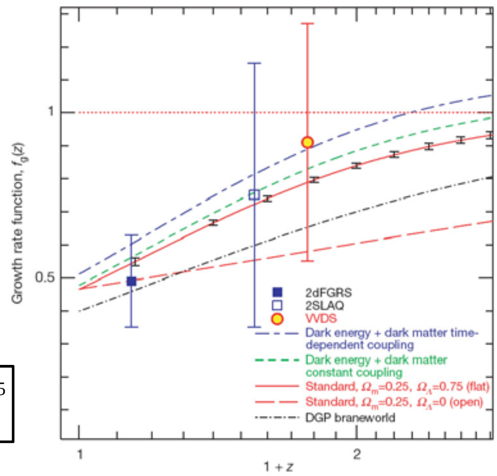
$$\xi_s(s) = (1 + \frac{2}{3}\Omega^{0.6} + \frac{1}{5}\Omega^{1.2})\xi_r(s)$$

Large distances:
distortions due to large-scale flows

Evolution Growth Rate



Linder 2008
Guzzo et al. 2008



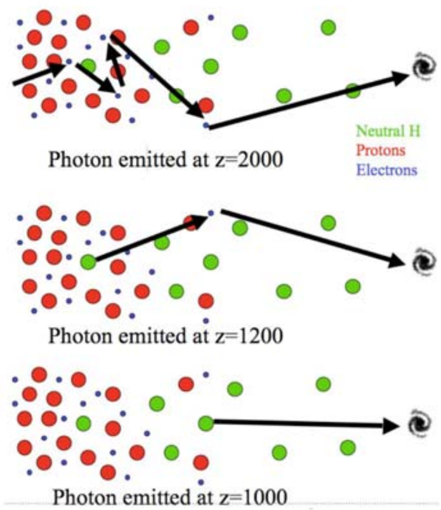
$$f(\Omega_m, \Omega_\Lambda) = \frac{a}{D}\frac{dD}{da} \approx \Omega_m^{0.55}$$

Peebles growth rate factor

BAO:

Baryonic Acoustic Oscillations

BAO

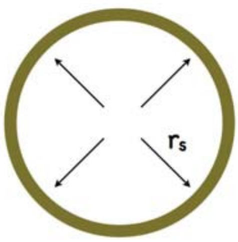


Before recombination, universe is opaque, so photons & baryons couple; interplay of gravity (DM, baryons) and photon pressure ⇒ acoustic waves propagate

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

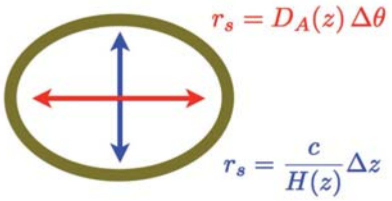
After recombination, the universe is transparent, so photons can stream freely ⇒ acoustic waves frozen

BAO as cosmological tools



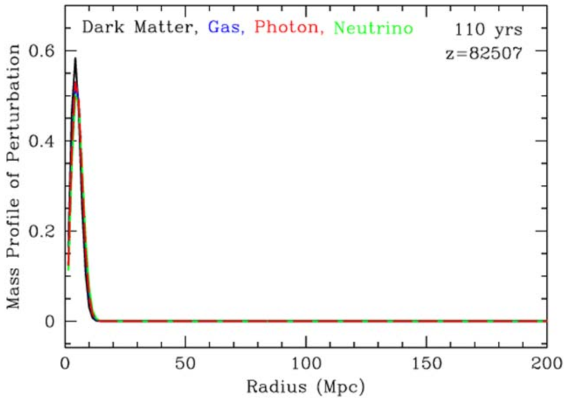
Until recombination, the sound wave travels a distance of:

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

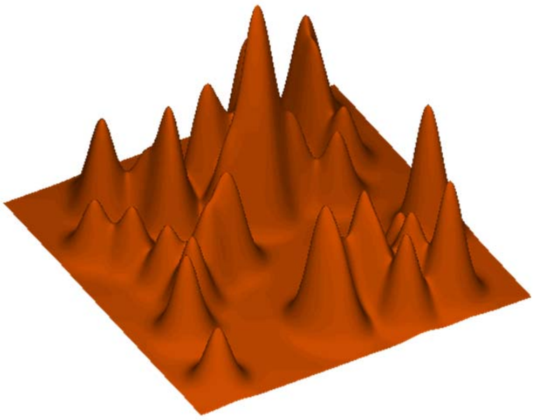


This distance can be accurately determined from the CMB power spectrum, and was found to be 147±2 Mpc.

Measuring BAO



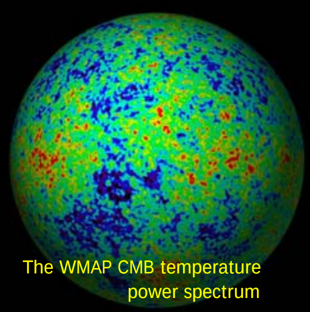
Measuring BAO



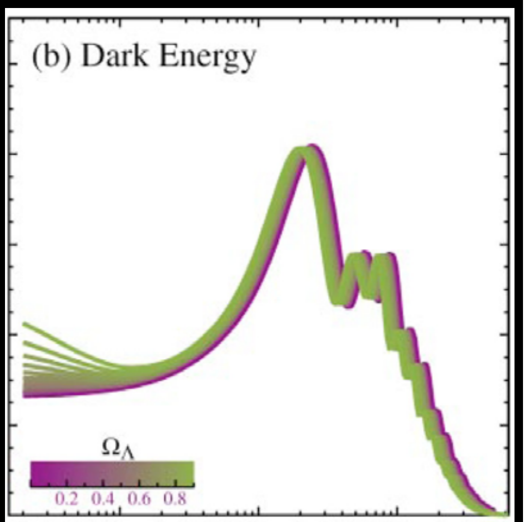
ISW:

Integrated Sachs Wolfe Effect

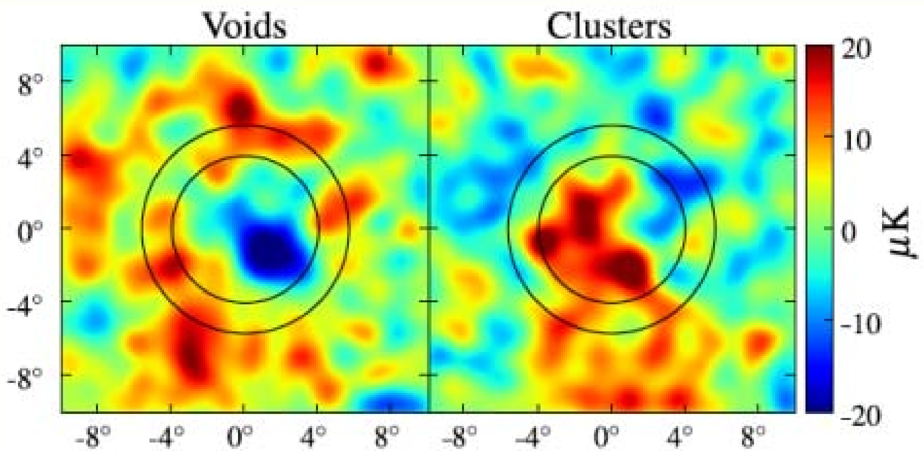
Dark Energy & CMB: ISW



Dark Energy modifies evolution potential wells

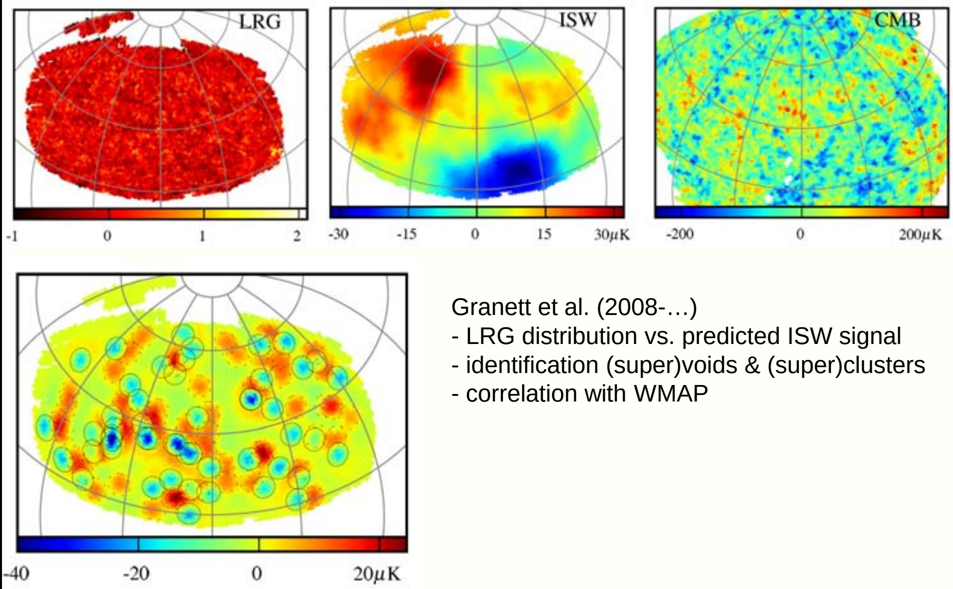


Dark Energy: ISW



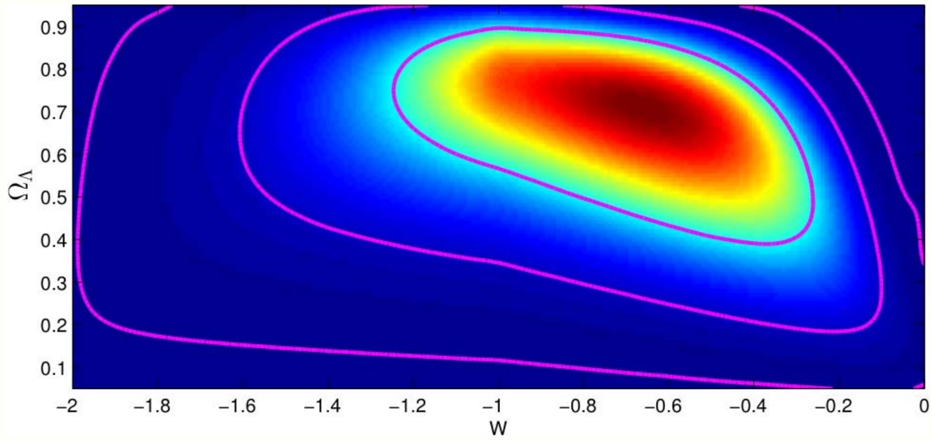
Dark Energy modifies evolution potential wells

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

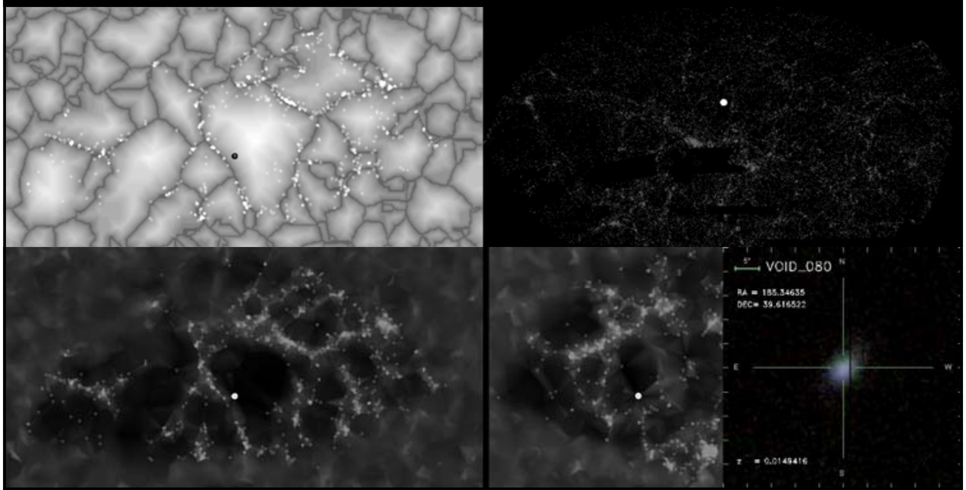


Dark Energy modifies evolution potential wells

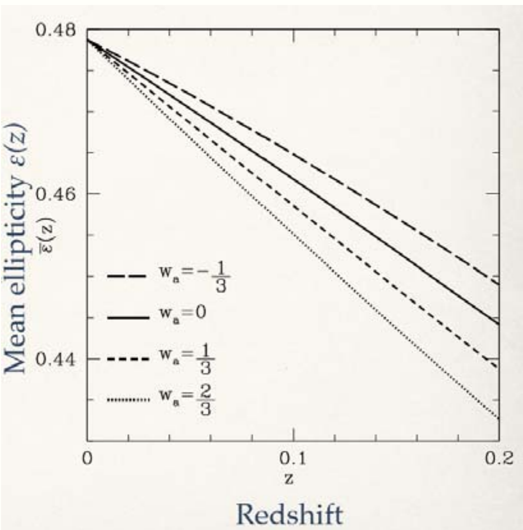
Cosmic Voids:

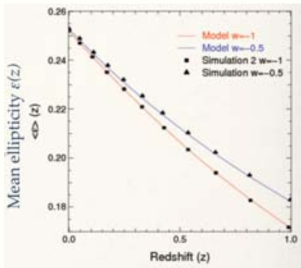
Shape of Voids

Cosmic Voids



Evolving Void Shapes

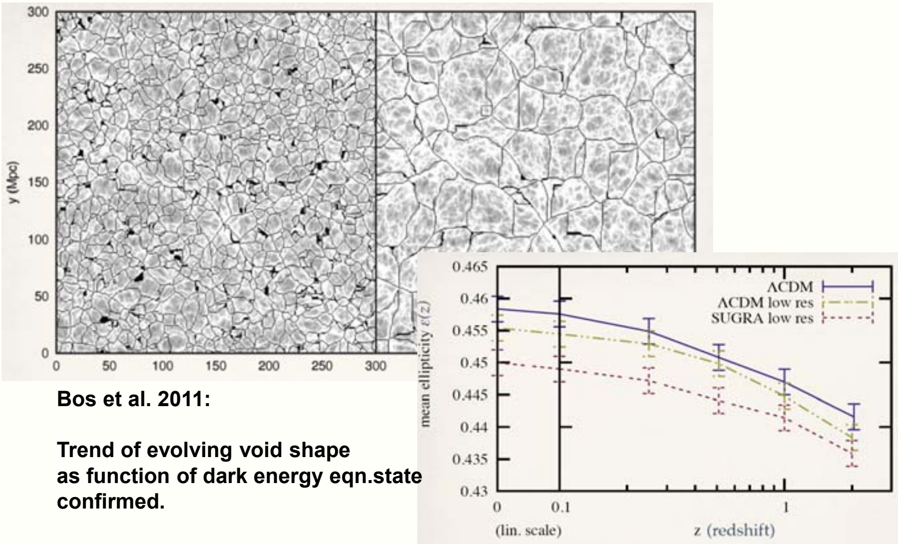




Evolution of void shape
sensitive probe of dark energy:

Park & Lee 2007
Lavaux & Wandelt 2010

Evolving Void Shapes



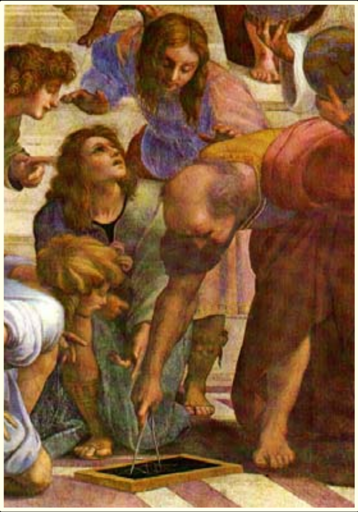
Bos et al. 2011:

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

Future Experiments

Euclid

Euclid:
father of geometry



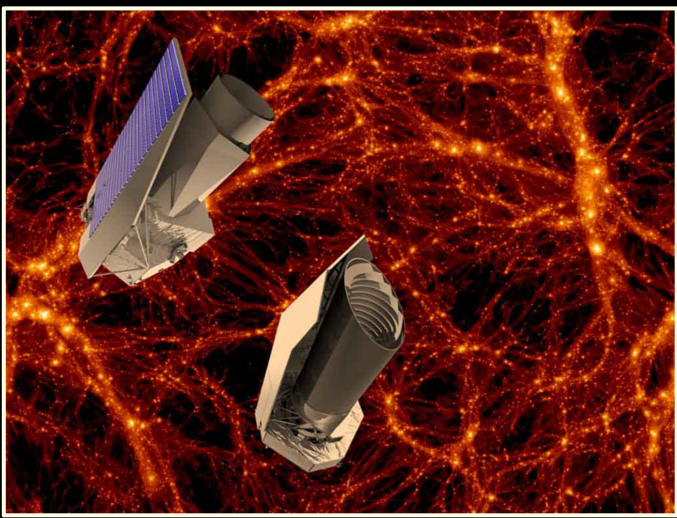
ESA
Cosmic Vision
2020-2025

- 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



ESA
Cosmic Vision
2020-2025

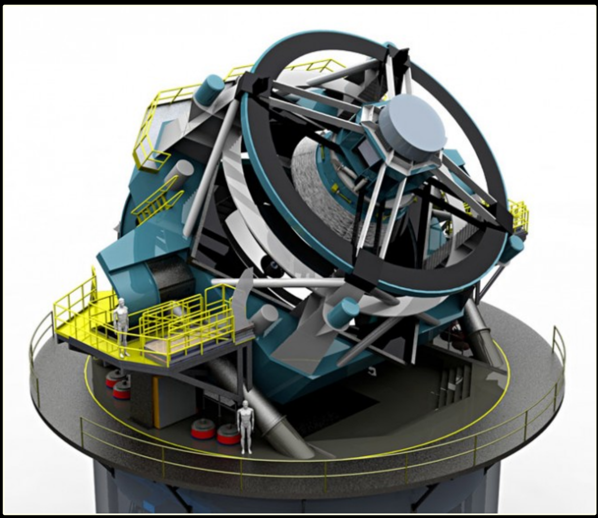
- 1.2 m Korsch telescope
- visible light:
  m=24.5 CCD imaging
- IR (Y,J,H) band photometer
- spectrometer 108 bright gals

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

- Combination:
  - DUNE grav. Lensing
  - SPACE BAO

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