# Shedding Light on Dark Energy

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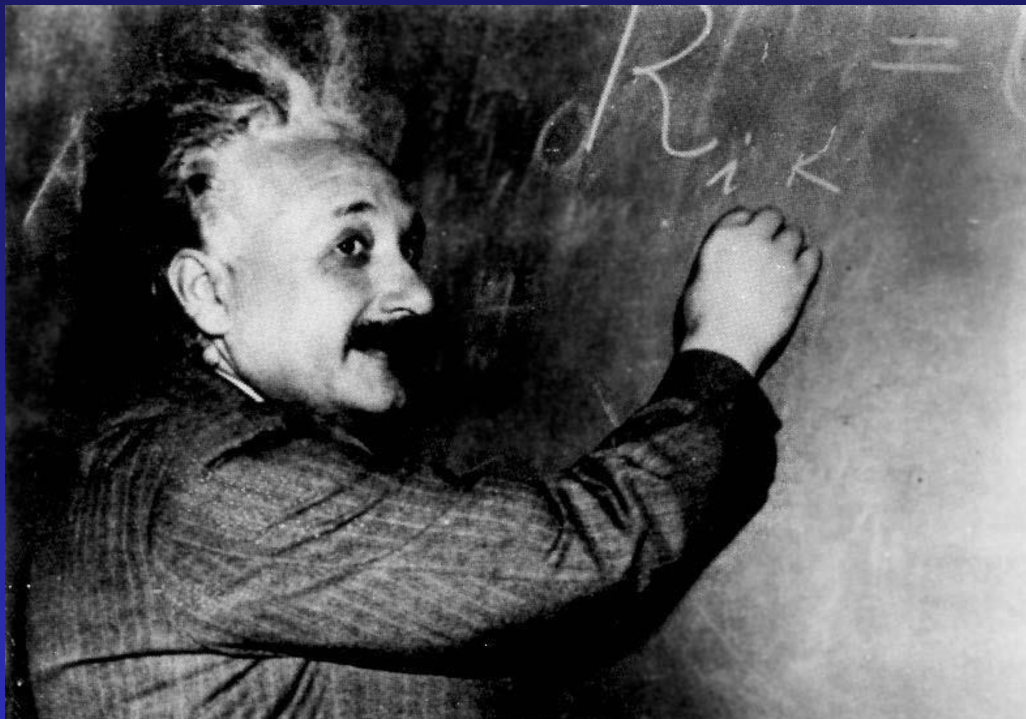
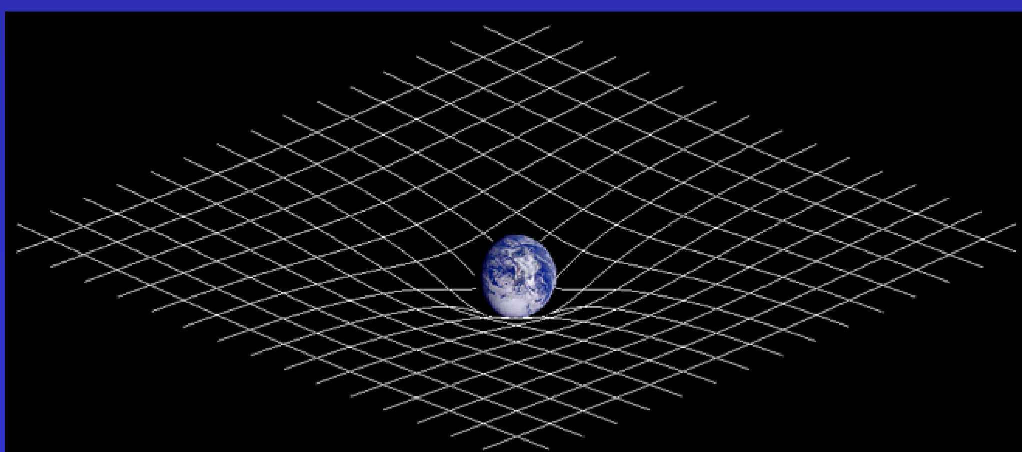
# Outline

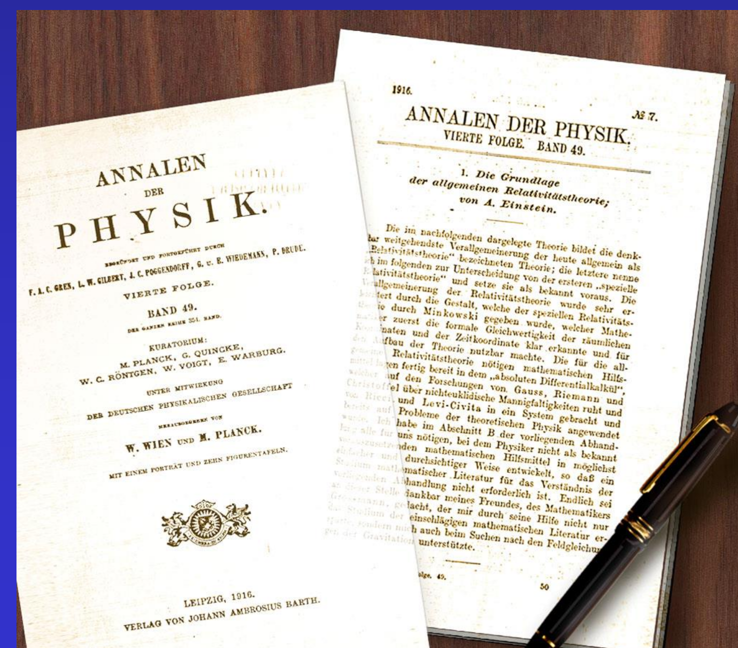
- Introduction
- Cosmological Framework
- Early Signs of Dark Energy
- The Discovery of Dark Energy
- What is Dark Energy?
- Probing Dark Energy
- Dark Energy Projects
- Summary

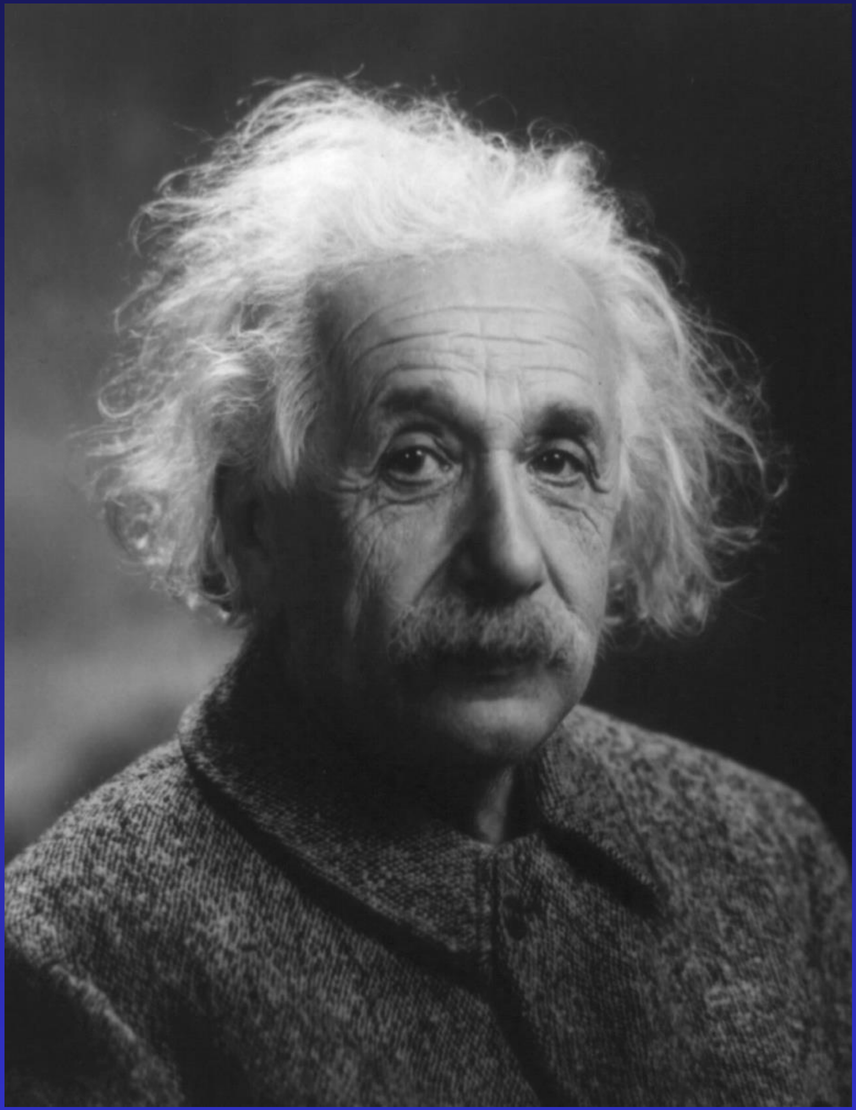
# General Theory of Relativity 1917



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



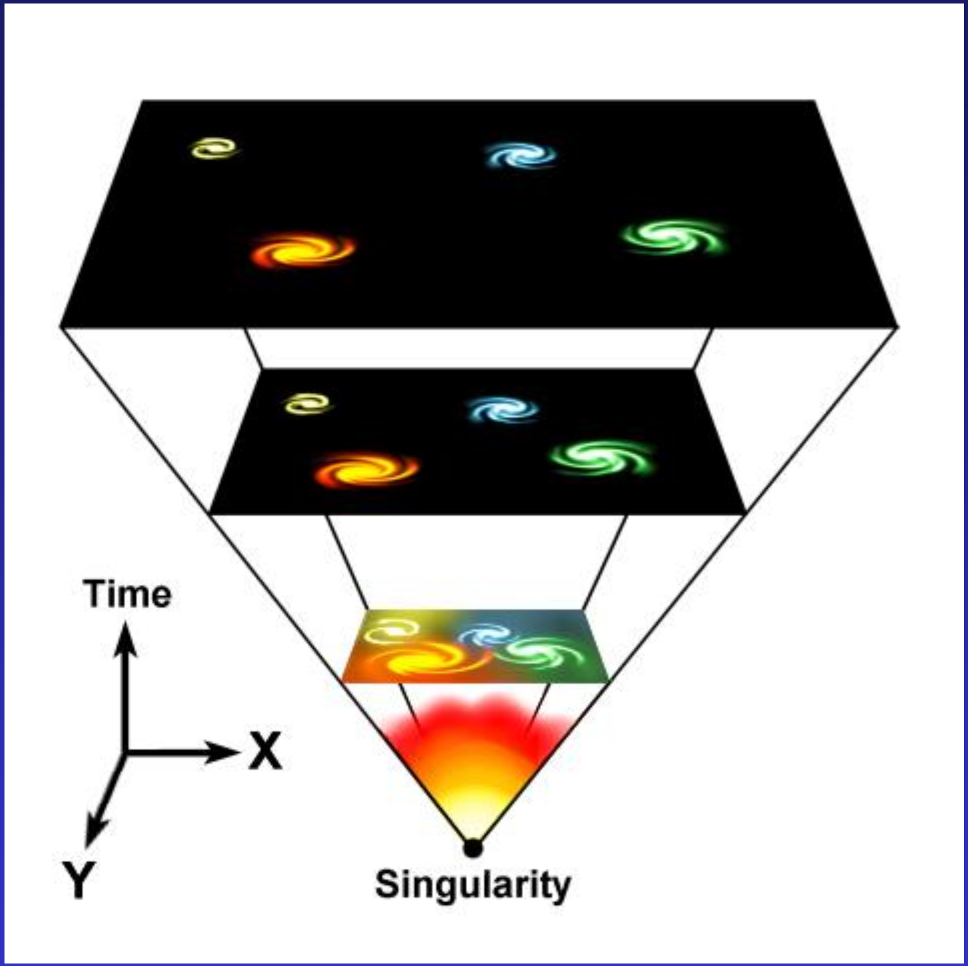




Einstein included the Λ term (cosmological constant) to make a static Universe.

Would later refer to the introduction of Λ as his biggest "blunder"!

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

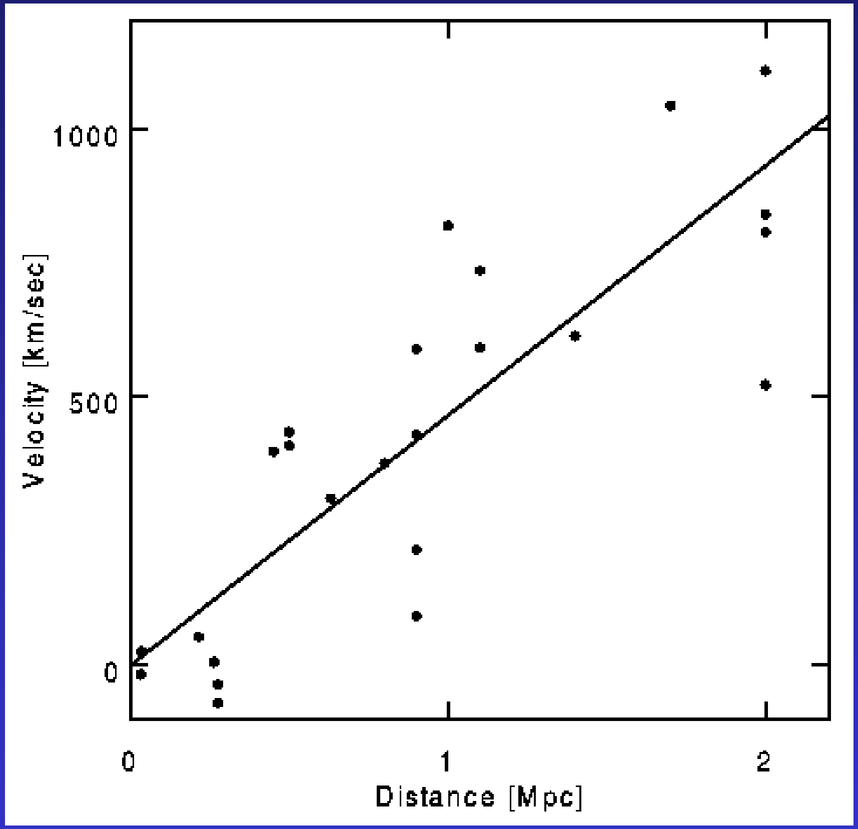



Father Georges Lemaître
(1894-1966)

In 1927, suggested that the Universe is expanding (“hypothesis of the primeval atom”). Early version of the Big Bang Theory.

Edwin Hubble (1889-1953)

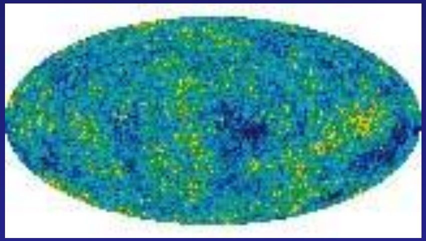

Observational evidence for expansion of the Universe!

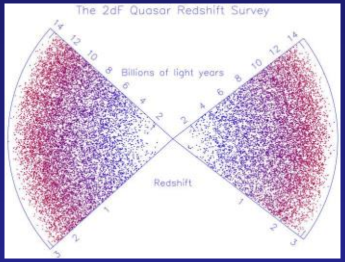



January 17, 1927

# Cosmological Framework

## Universe is homogeneous and isotropic






FLRW Metric

$$ds^2 = dt^2 - a^2(t)\,[dr^2/(1-kr^2) + r^2 d\theta^2 + r^2 \sin^2\theta\, d\varphi^2]$$

$r, \theta, \varphi$ = comoving spatial coordinates

$t$ = time

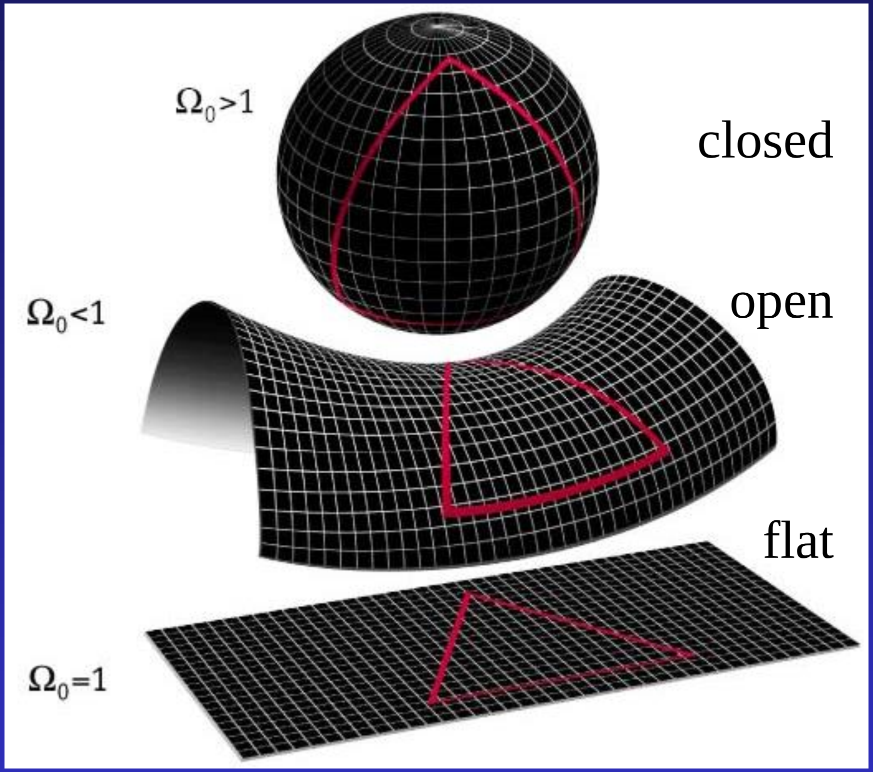
$a(t)$ = scale factor ($a$=1 today)

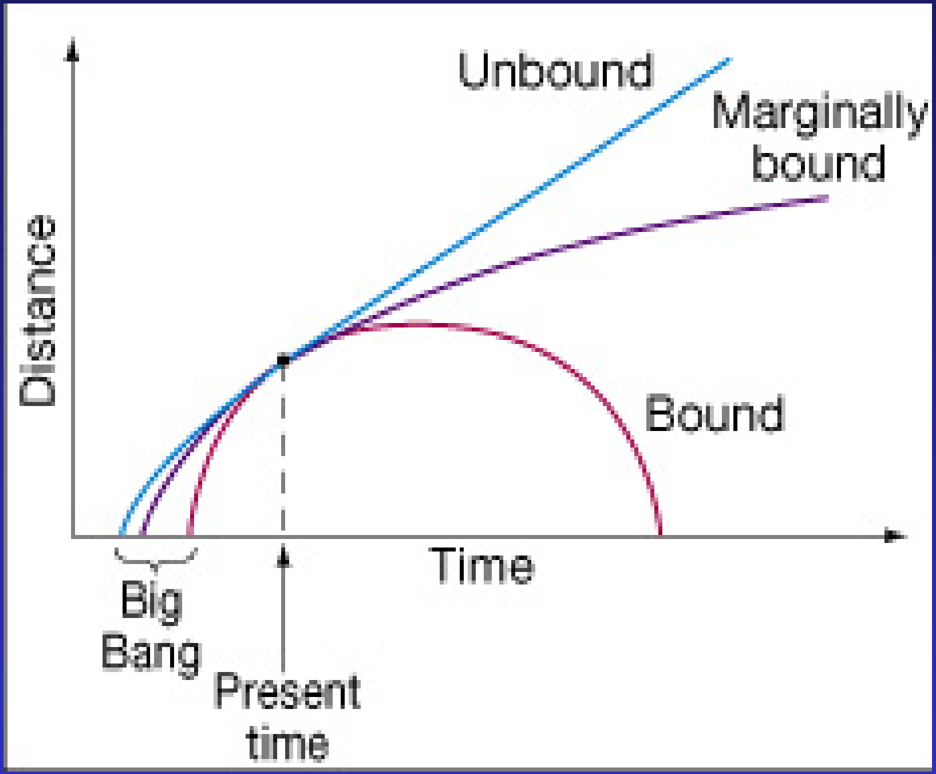
k = 0 (zero curvature)

k = +1 (positive curvature)

k = –1 (negative curvature)

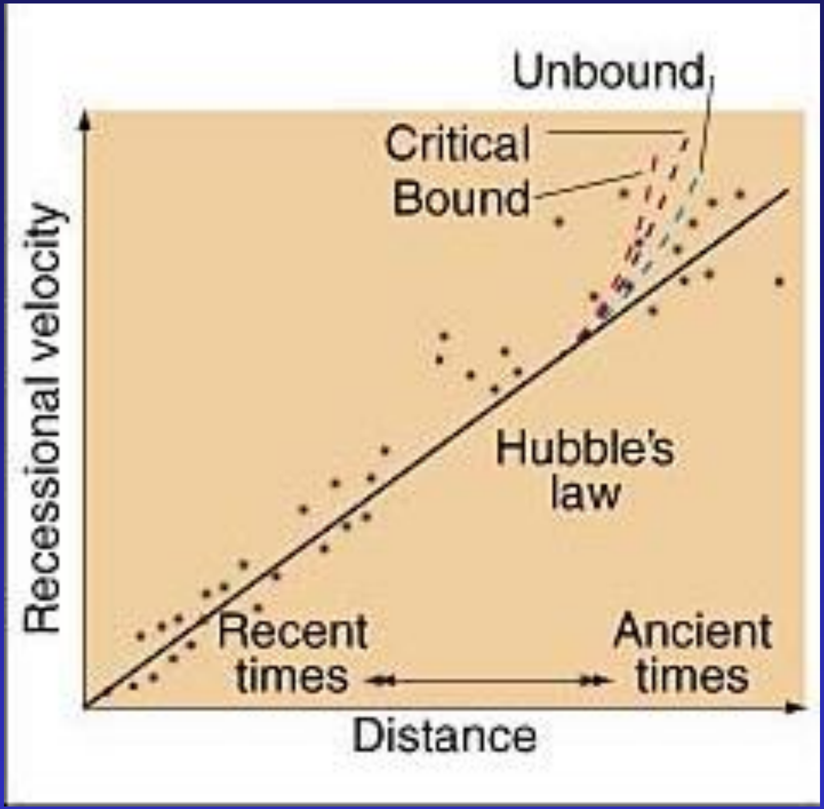
# Geometry of the Universe




$\Omega$ = (total density/critical density)

# Measuring the Universe




Cosmology is the search of new numbers:

Hubble Parameter ($H_0$)
Deceleration parameter ($q_0$)

# Early Signs of Dark Energy

- Einstein Cosmological constant (Einstein 1917)
- Eddington-Lemaitre model (Eddington 1930)
- Quasar peak at z~2 (Petrosian *et al.* 1967)
- Energy density of quantum vacuum (Zel'dovich 1968)
- Hubble diagram of BCGs (Gunn & Tinsley 1975)
- Inflationary prediction for $\Omega=1$ (Peebles 1984; Turner *et al.* 1984)
- $\Lambda$CDM (Efstathiou et al. 1990; Turner 1991)
- Globular clusters ages (Frieman et al. 1995; Krauss & Turner 1995)

# Consequence of Dark Energy

## Friedmann Equations:

Application of GR field equations to FLRW metric

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho + \Lambda}{3} - K\frac{c^2}{a^2}$$

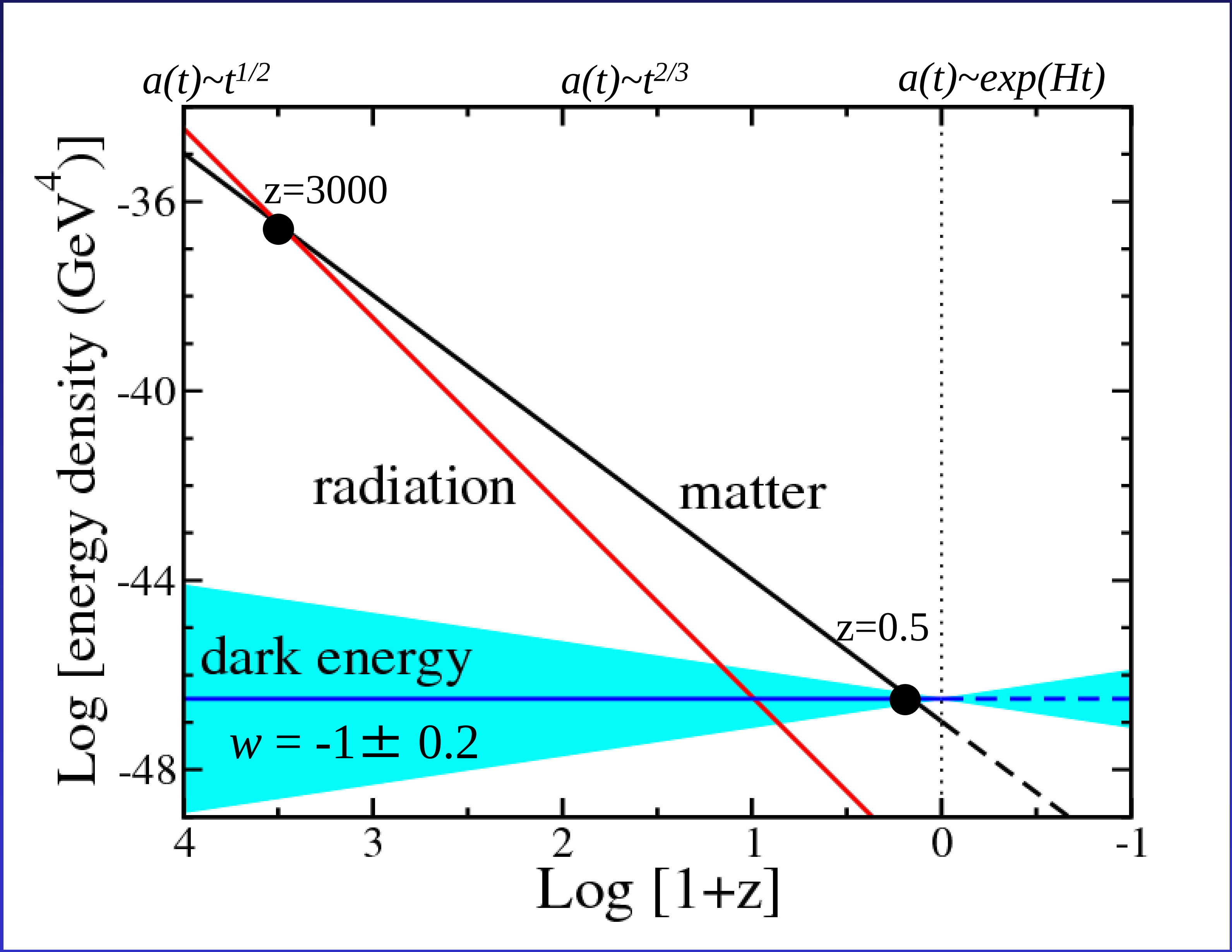
$$3\frac{\ddot{a}}{a} = \Lambda - 4\pi G\left(\rho + \frac{3p}{c^2}\right)$$

$\Lambda \Rightarrow p_{vac} = -\rho_{vac} = -\Lambda/8\pi G = \text{constant}$

Equation of state $w = \frac{P}{\rho} = -1$ (cosmological constant)

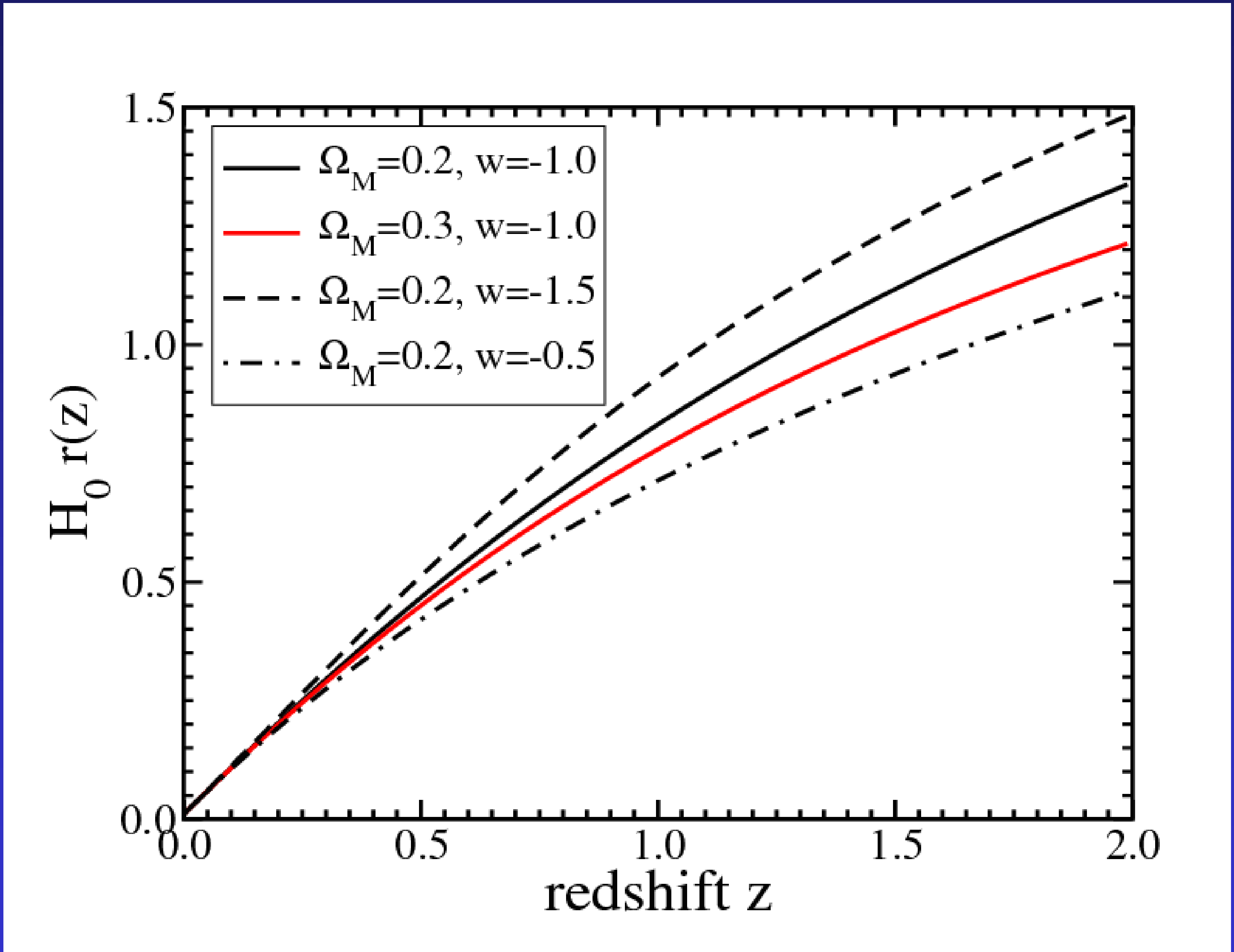
$P < -\rho/3 \Rightarrow w < -1/3 \Rightarrow d^2(a)/dt^2 > 0!$

$w(a) = w_0 + w_a(1-a)$ (time evolution)

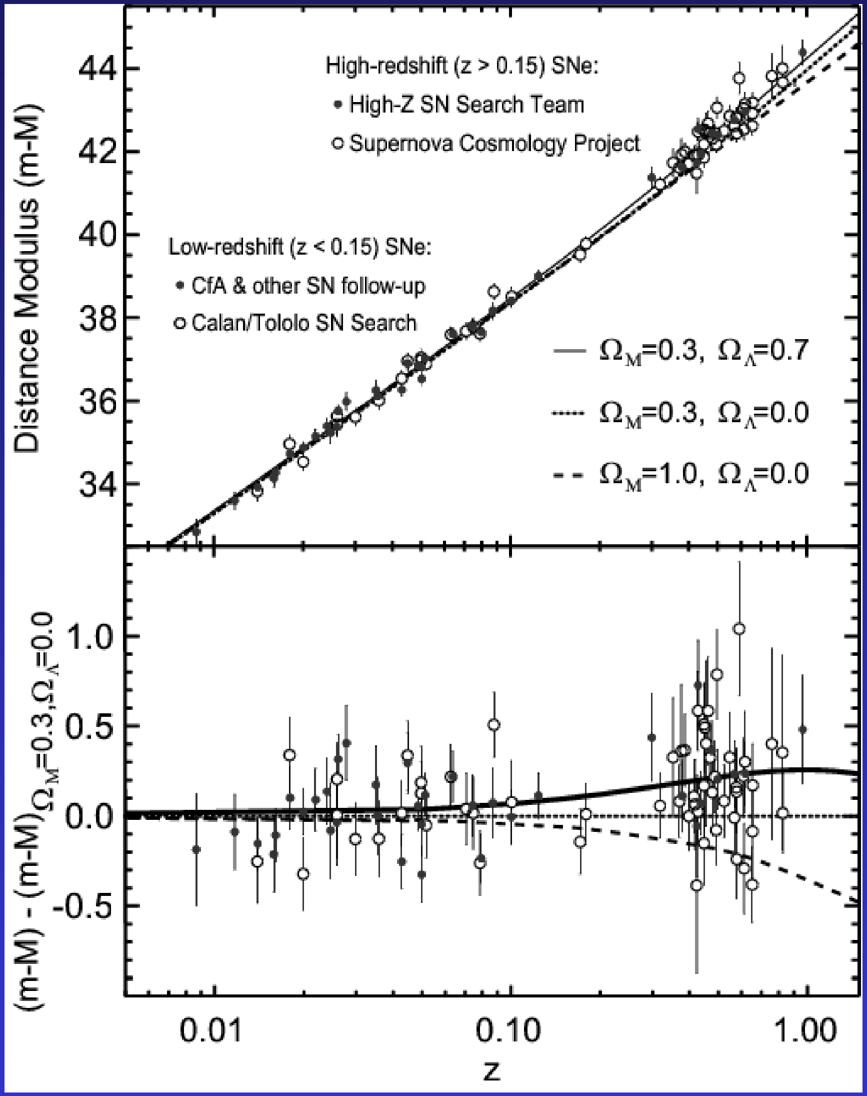


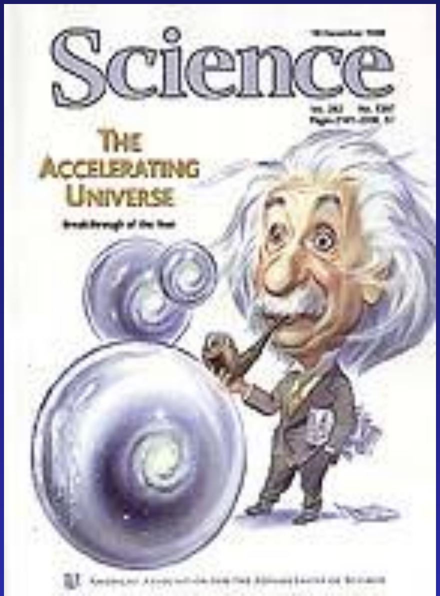
a(t)~t^1/2
a(t)~t^2/3
a(t)~exp(Ht)
Log [energy density (GeV^4)]
-36
-40
-44
-48
z=3000
radiation
matter
dark energy
z=0.5
w = -1± 0.2
4
3
2
1
0
-1
Log [1+z]

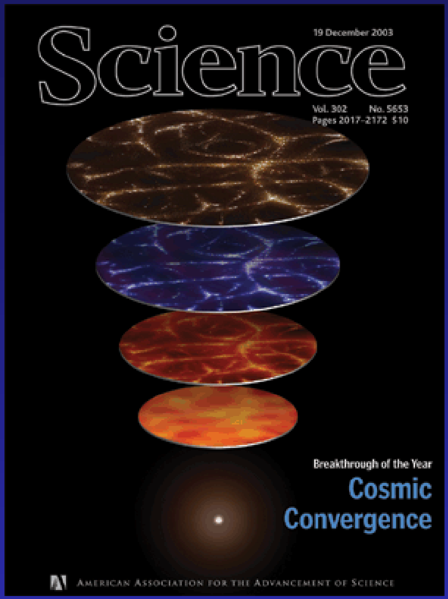
Recall the use of the Hubble diagram to measure deceleration:



# The Discovery of Dark Energy (1998)



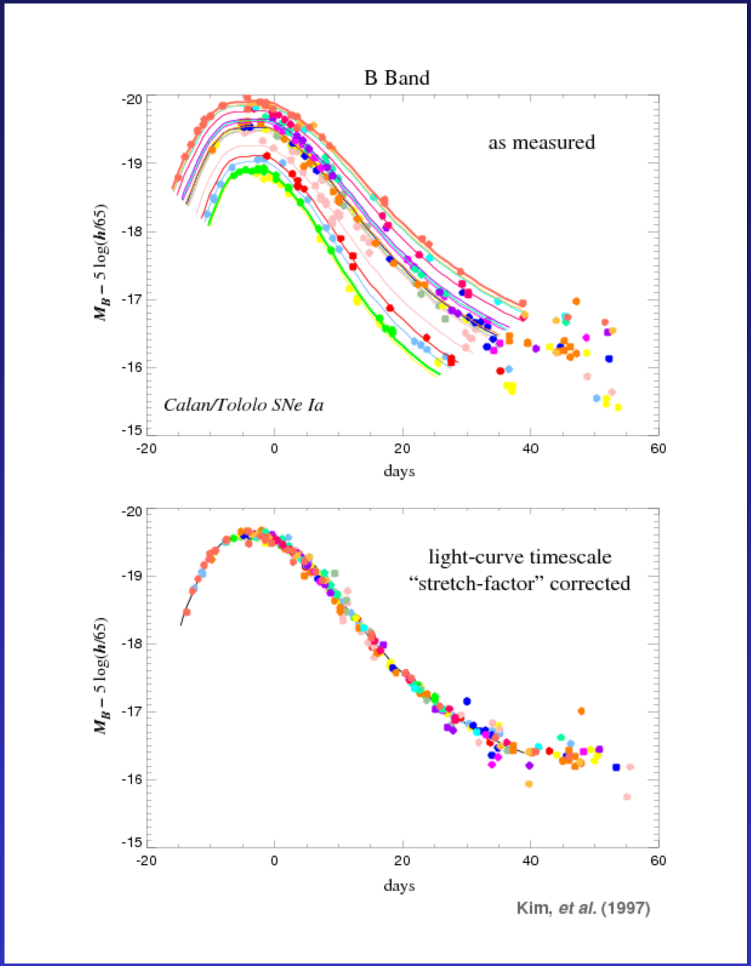



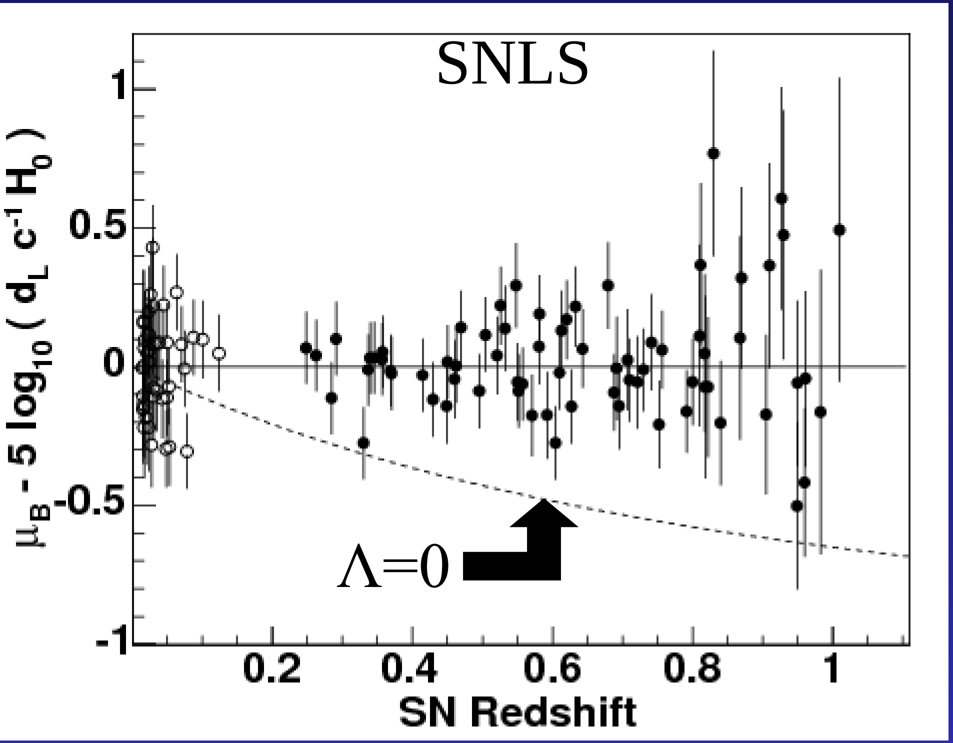




SNe Ia ~0.25 mag dimmer than expected

Riess *et al.* 1998
Perlmutter *et al.* 1999

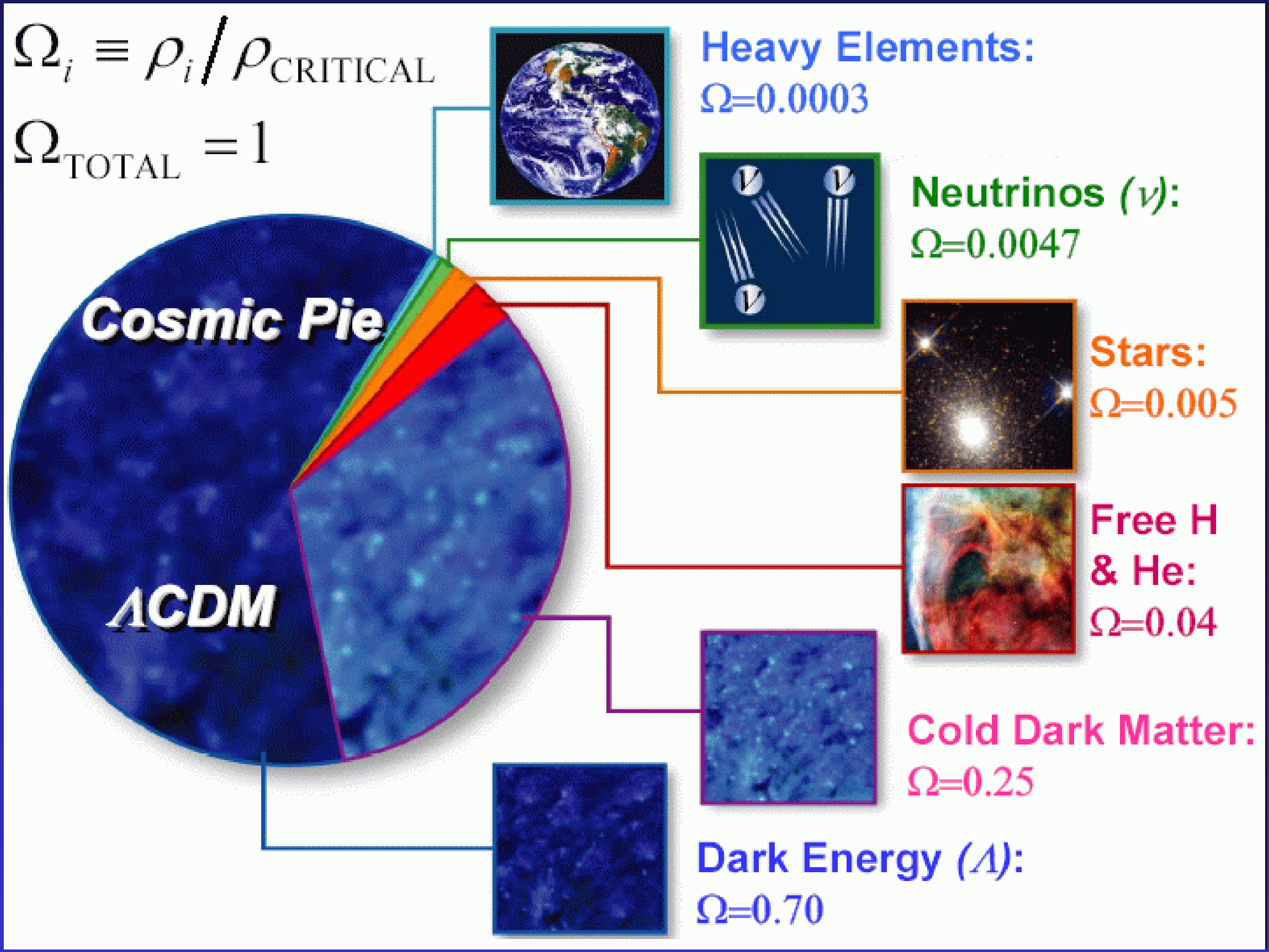
*Einstein's cosmological constant is back!*




Astier *et al.* (2006)

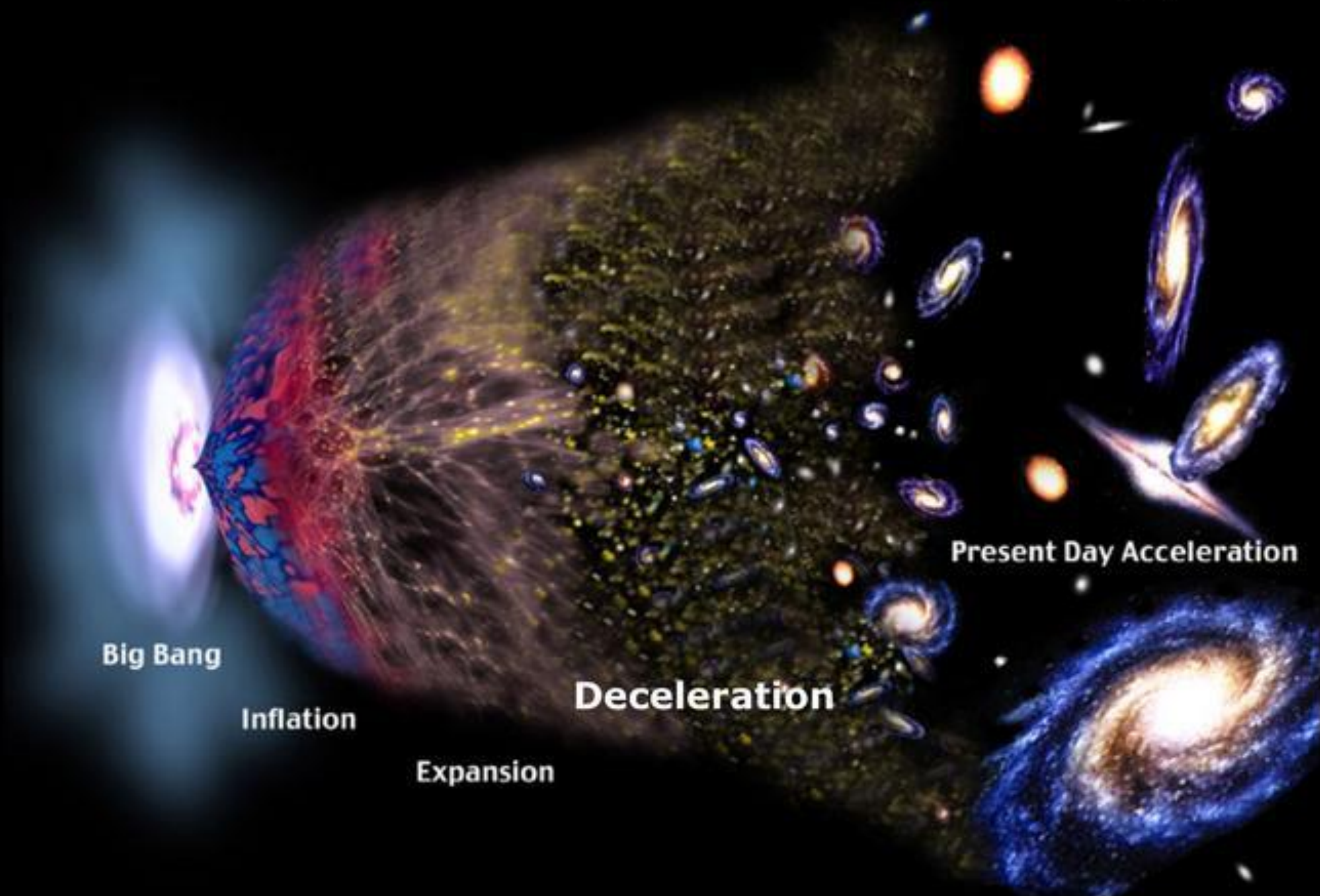
SNe Ia are standardizable candles.



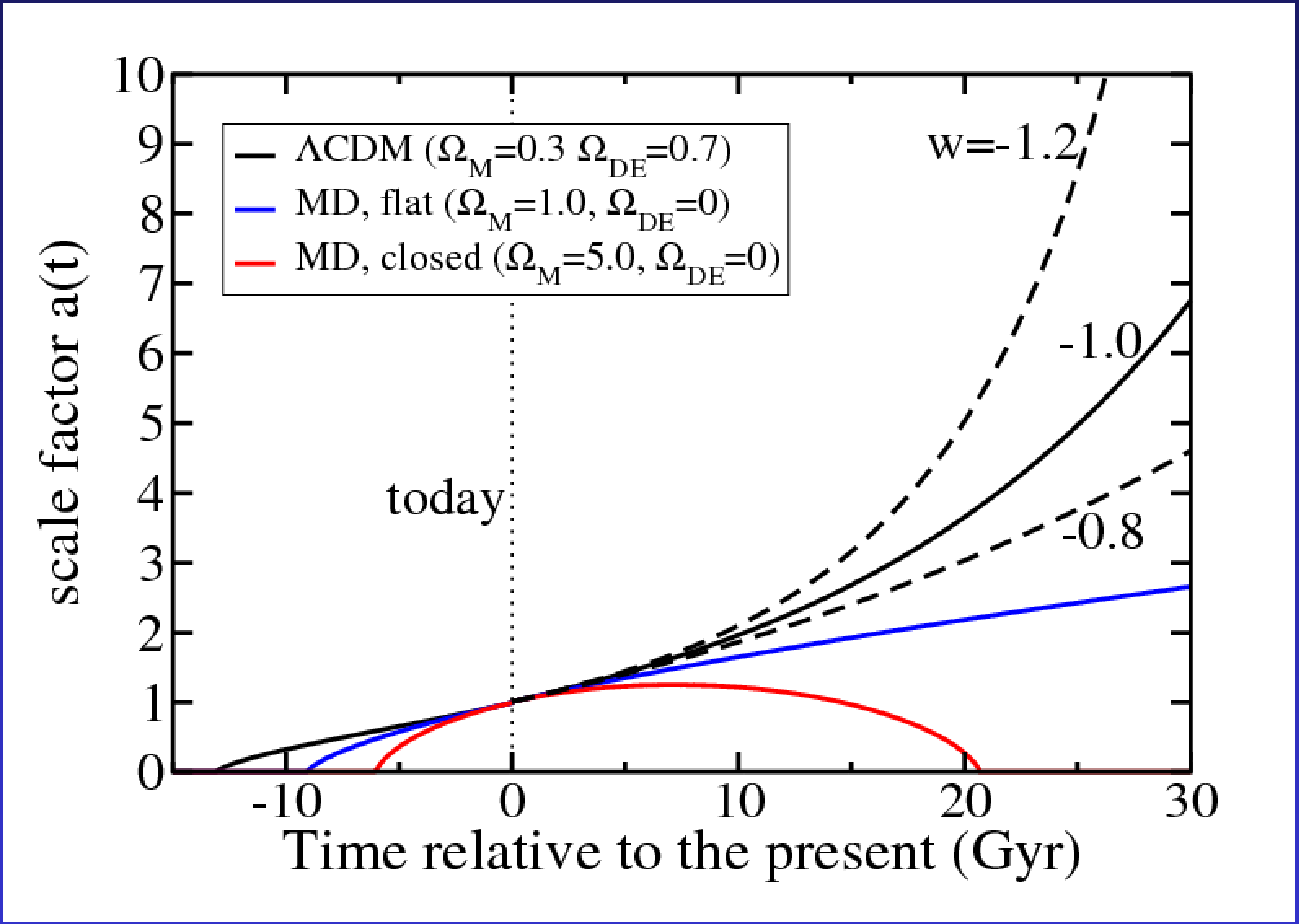

Everything you can see (i.e., ordinary matter) is only ~5% of Universe!

95% of the Universe is unknown!!!

# Cosmic Deceleration from Dark Matter, then Acceleration from Dark Energy!



# Is the Future Knowable?



# What is Dark Energy?

1) Vacuum Energy:

- zero point energy of the vacuum
- quantum field theory yield $\Omega_{DE} > 10^{120}\ \rho_{critical}$
- SUSY or string theory doesn't help (LHC may yield info)

2) Scalar Field:

- additional degree of freedom (*w* varies between -1 and +1)
- related to inflation?
- vacuum energy is dynamical – why is DE just becoming important now?
- may give rise to new long-range force
- does not address cosmological constant problem

# What is Dark Energy?

3) New Gravitational Physics:

- cosmic acceleration could point towards a theory of gravity that supersedes General Relativity
- no self-consistent model available

4) Old Gravitational Physics:

- no compelling solution

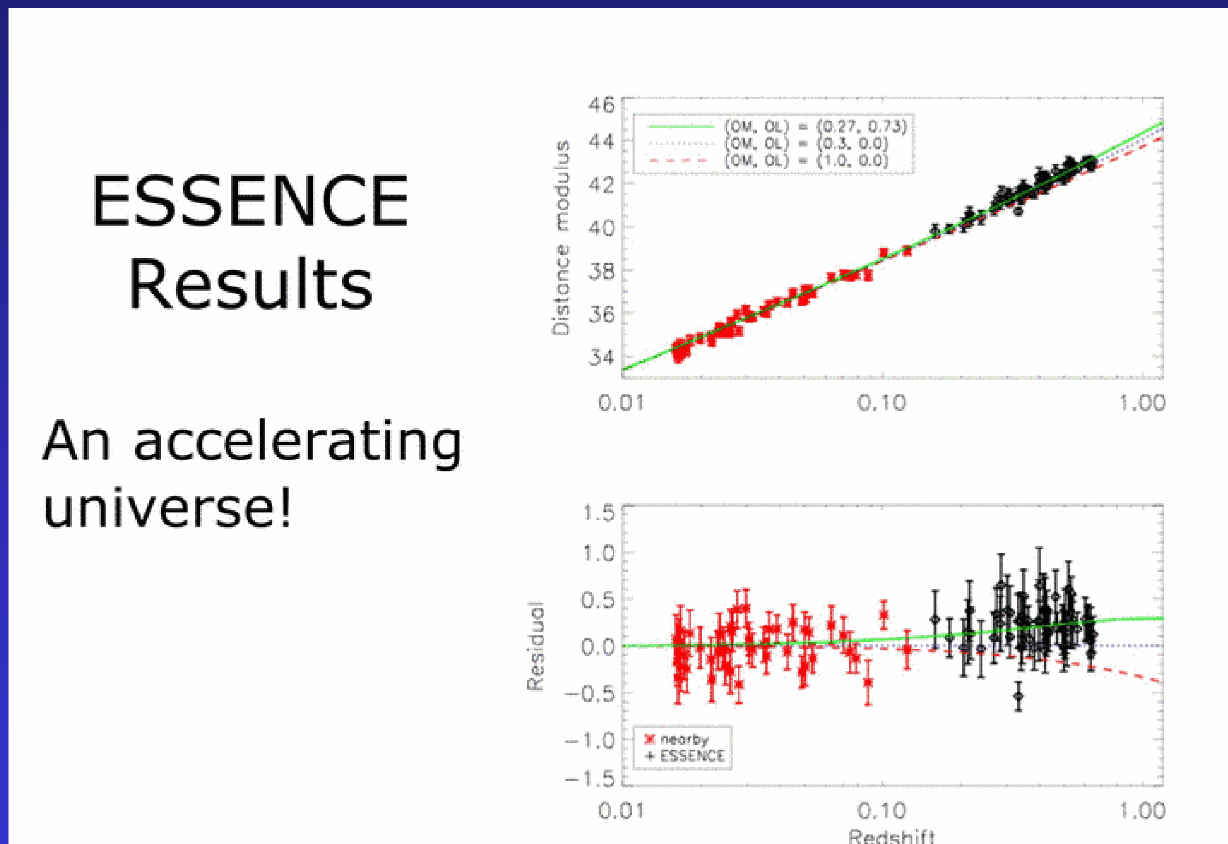
5) String Theory:

- no unique solution (invoke the anthropic principle?)

Dark energy has the potential of revolutionizing physics!

# Probing Dark Energy

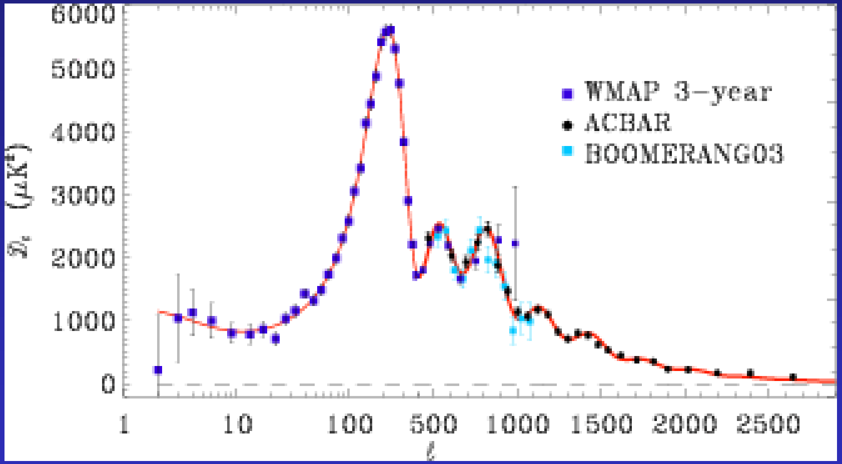
1) Supernovae Type Ia:

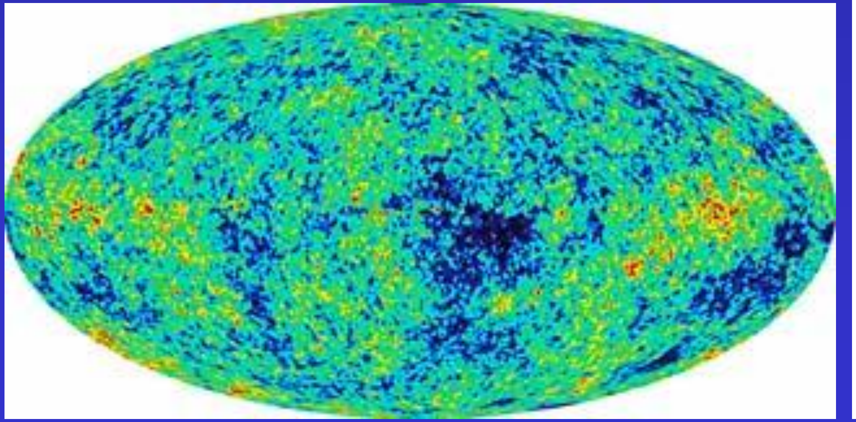


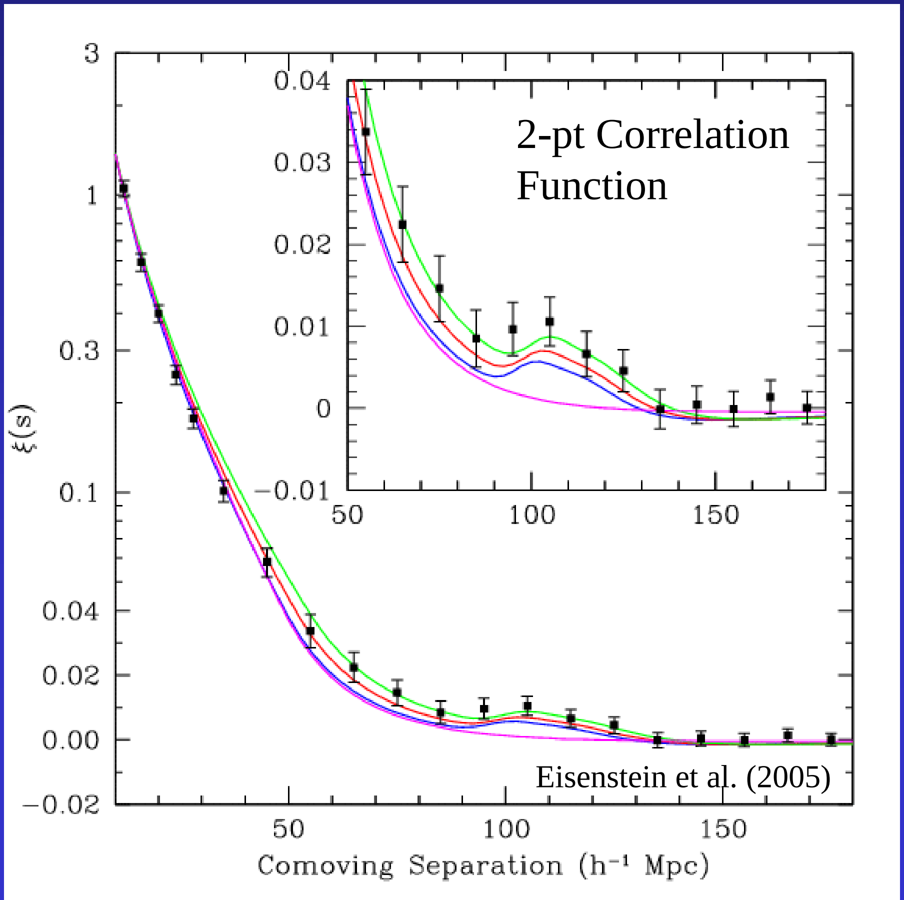
# Probing Dark Energy

2) Baryon Acoustic Oscillations:

- gravity-driven acoustic oscillations of the coupled baryon/photon fluid (sound horizon at recombination)

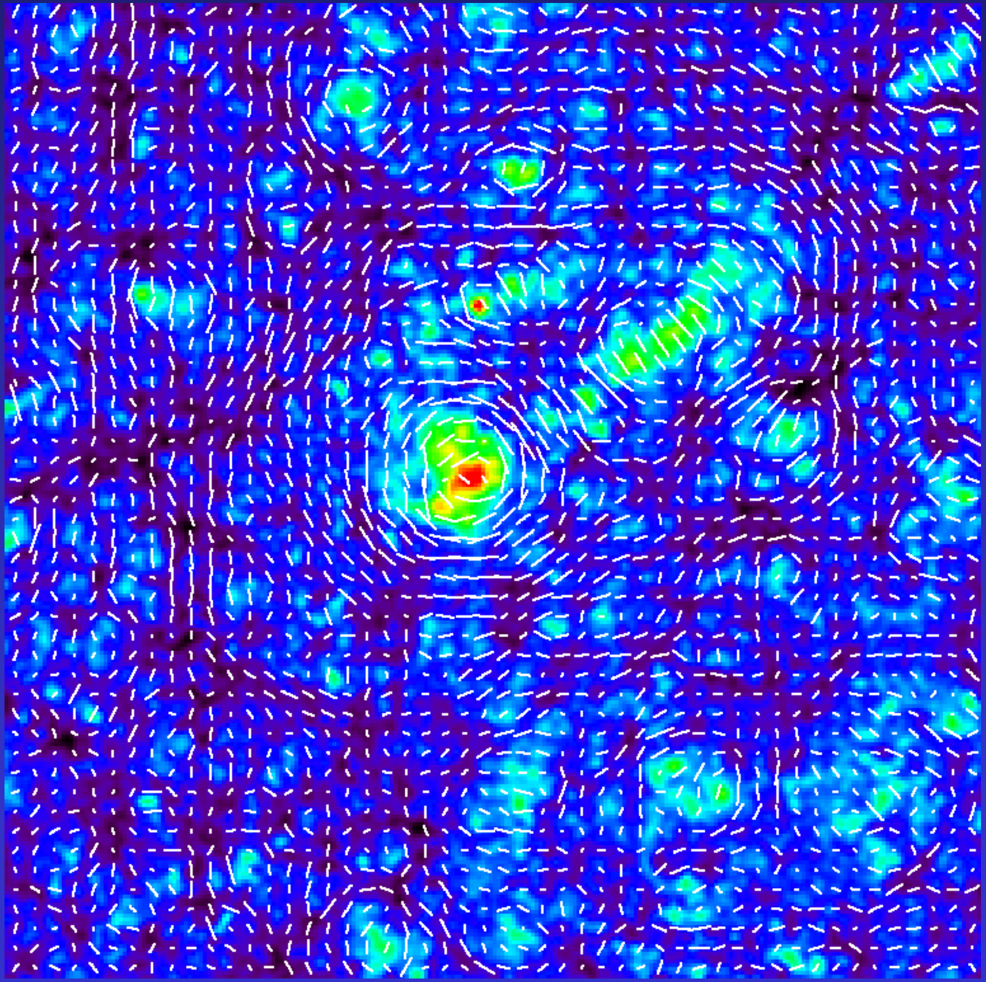




# Probing Dark Energy

3) Weak Gravitational Lensing:

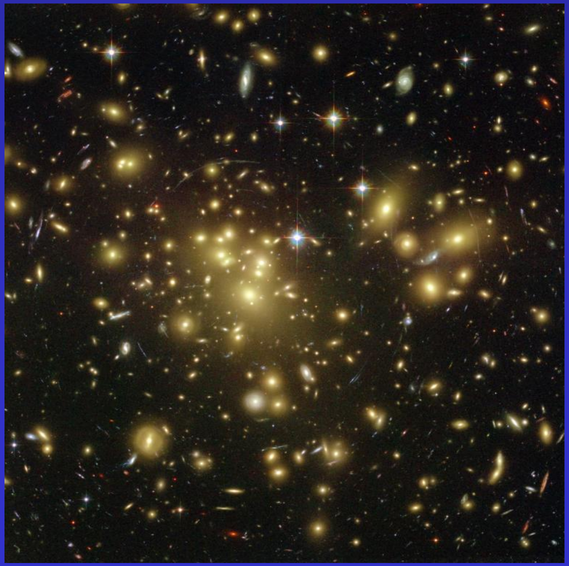


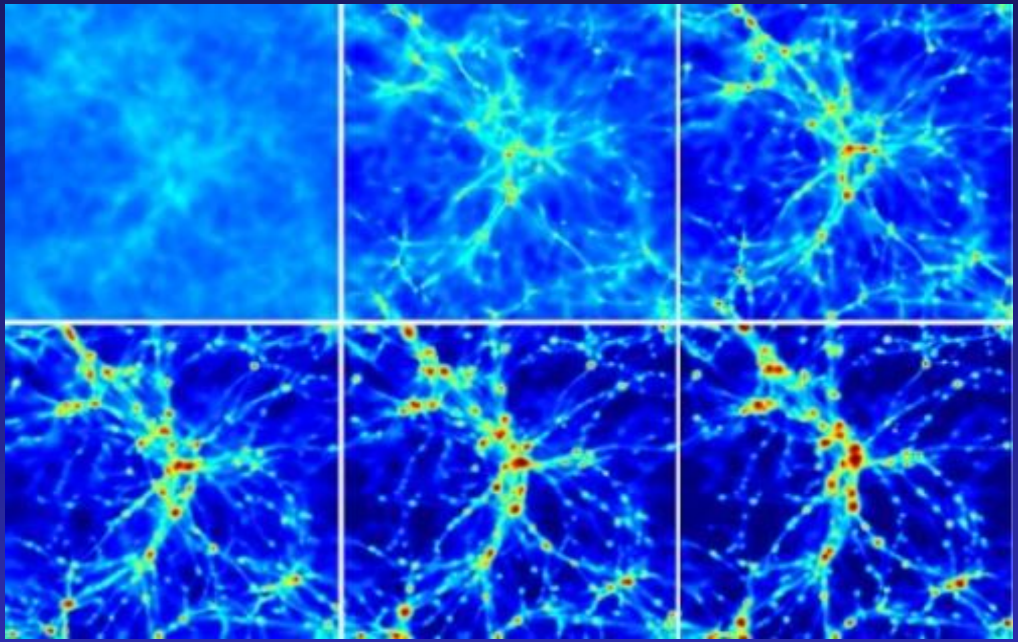
The distortion or shear of galaxy shapes due to the gravitation bending of light probes the distribution of dark matter and its evolution with time (sensitive to DE).

Need very large area coverage to reduce shot-noise.

# Probing Dark Energy

4) Galaxy Clusters:



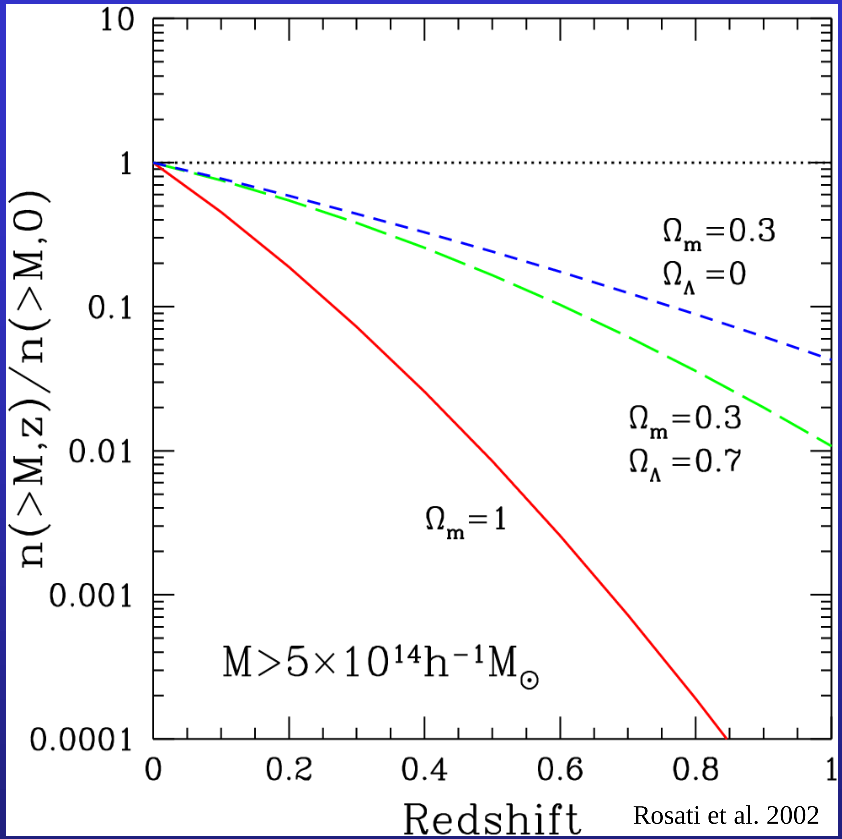


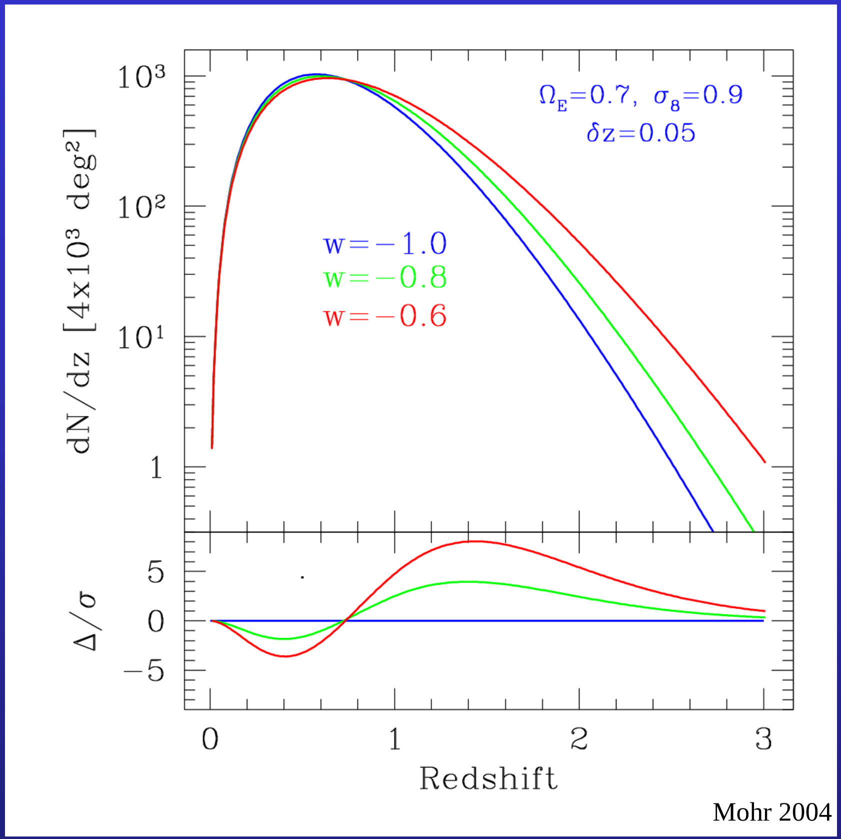
Mass: ~$10^{14}$ – $10^{15}$ solar masses
(solar mass = $1.99 \times 10^{30}$ kg)

Composition: 85% dark matter
10% hot gas (~$10^{6}$ – $10^{8}$ K)
~5% stars

Richness: 10 – 1000 galaxies

# Sensitivity of Cluster Mass Function to Cosmology




$$\frac{d^2N}{dz\,d\Omega} = \frac{c}{H(z)}\, d_A^2(z)(1+z)^2 \int_o^\infty dM\, \frac{dn}{dM}(M,z)\, f(M,z)$$

Volume surveyed × cluster abundance

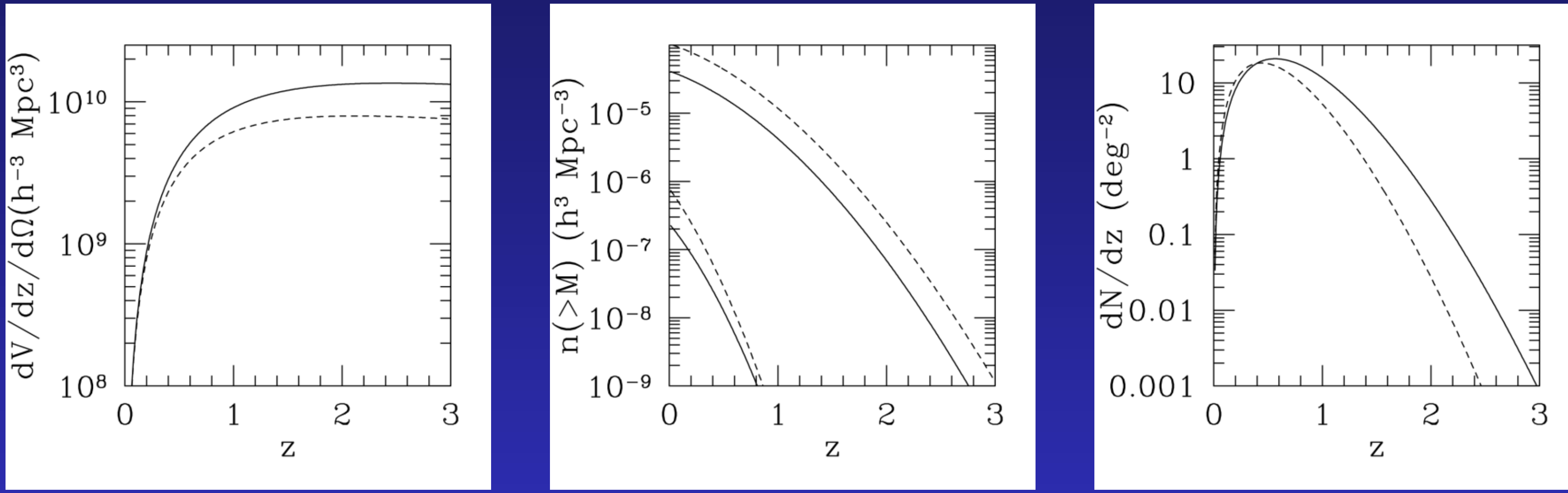
Expansion history and growth rate of structure is sensitive to Dark Energy.

$$\frac{d^2N}{dz\,d\Omega} \propto \text{Volume} \bullet \text{number density}$$

$$\text{volume surveyed} = \frac{d^2V}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2(z)(1+z)^2$$

$$\text{number density} = n(z) = \int_0^\infty dM \frac{dn}{dM}(M,z) f(M,z)$$

*dn/dM*= cluster mass function; *f(M,z)*= survey selection function

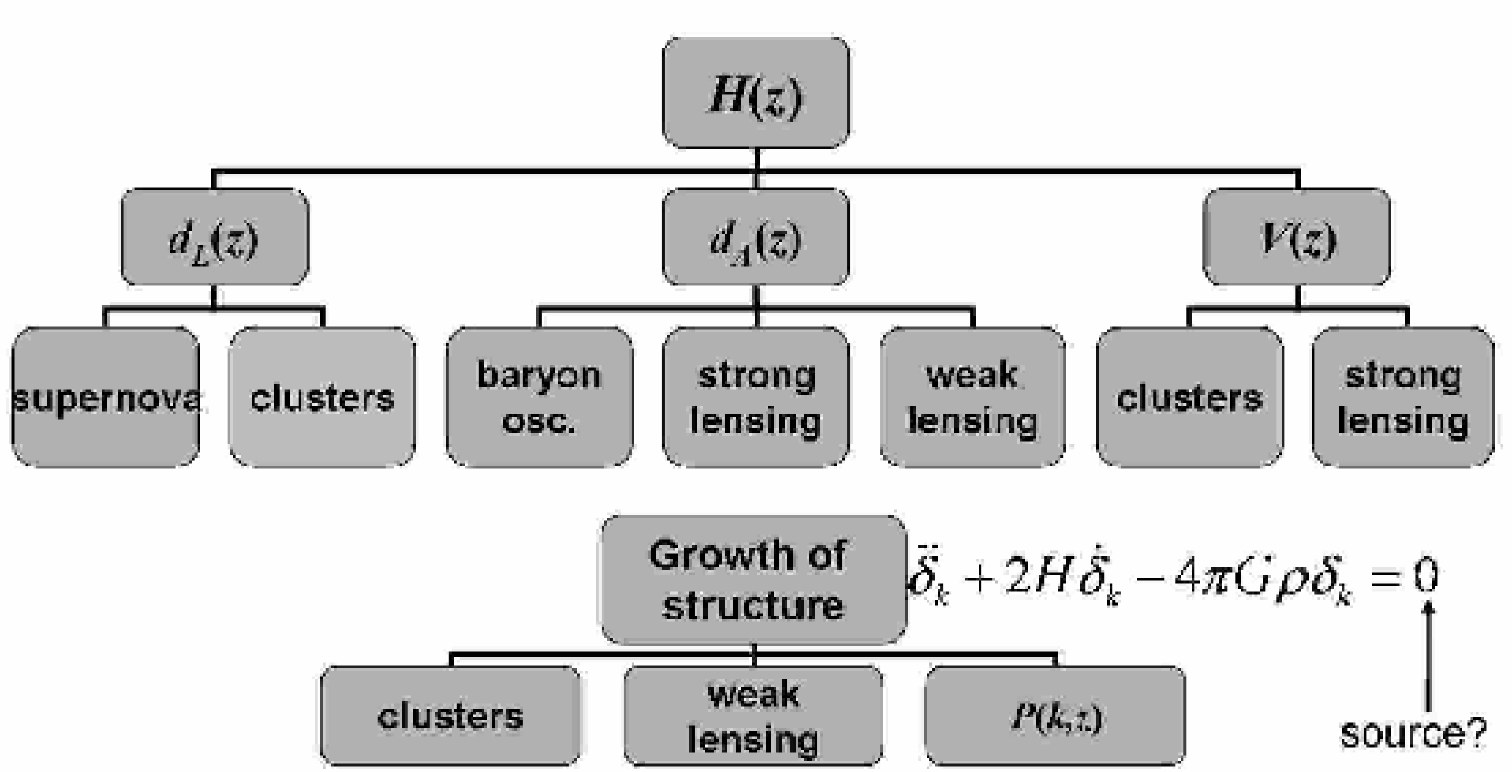



Carlstrom et al. 2002

Co-moving volume for $(\Omega_M,\Omega_\Lambda)=(0.3,0.7)$ solid $(\Omega_M,\Omega_\Lambda)=(0.5,0.5)$ dashed.

Co-moving number density ($\sigma_8=0.9$). Lower lines= $> 10^{15}\,M_\odot$ Upper lines= $> 10^{14}\,M_\odot$

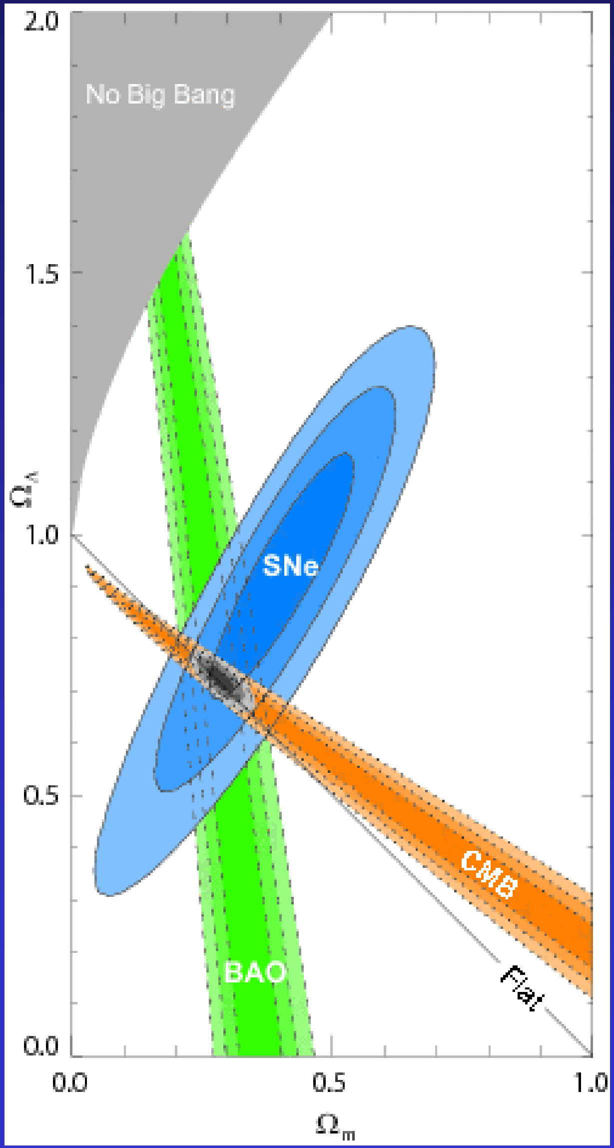
Redshift distribution per sq. deg for $M > 10^{14}\,M_\odot$

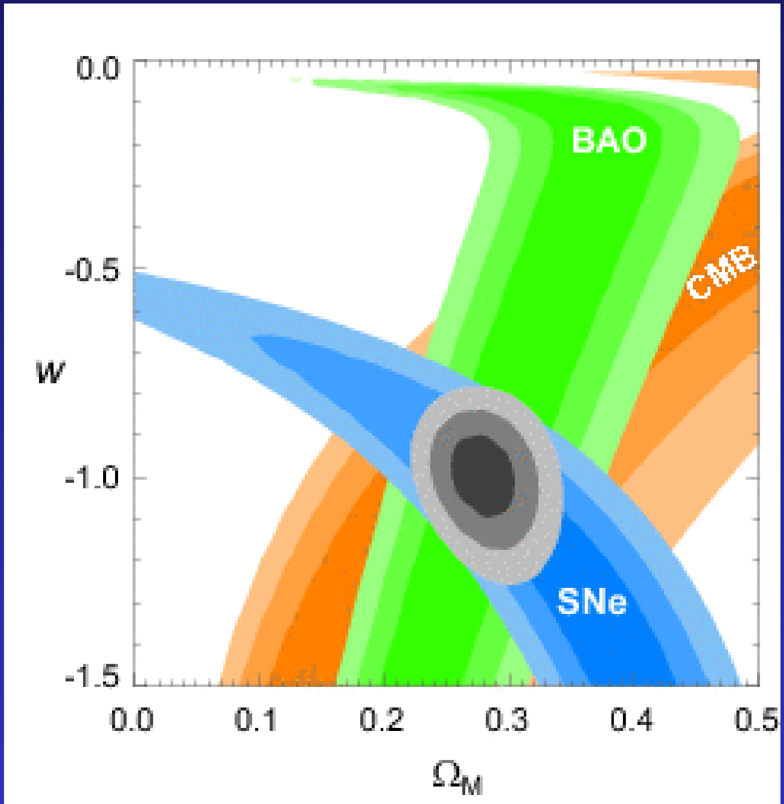


$H(z)$
$d_L(z)$
$d_A(z)$
$V(z)$
supernova
clusters
baryon osc.
strong lensing
weak lensing
clusters
strong lensing
Growth of structure
$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho\delta_k = 0$
clusters
weak lensing
$P(k,z)$
source?


Kolb (2007)

# Cosmological Parameters




Kowalski *et al.* (2008)

$w = -0.94 \pm 0.1$

# Dark Energy Projects

Need to measure $w_0$ and $w_a$ to within a few percent accuracy in order to discriminate various dark energy ideas.

$$w(a) = w_0 + w_a(1-a)$$

## Ground-based Surveys

| | | |
|---|---|---|
| ACT | Hyper Suprime Cam | SDSS BOSS |
| APEX | ALPACA | WFMOS |
| SPT | LSST | HSHS |
| VST | AAT WiggleZ | SKA |
| Pan-STARRS | HETDEX | DES |
| PAU | | |

# Dark Energy Projects

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$$w(a) = w_0 + w_a(1-a)$$

Space-based Surveys

| | | | |
|---|---|---|---|
| ADEPT | DESTINY | SNAP | DUNE |
| SPACE | eROSITA | Planck | Constellation-X |

# The Dark Energy Survey

- A study of the dark energy using four independent and complementary techniques
  - Galaxy cluster surveys
  - Galaxy power spectrum (BAO)
  - Weak lensing
  - SNe Ia distances
- Two linked, multi-band optical surveys (~24 - 25 mag)
  - 5000 $deg^2$ *g*, *r*, *i* and *z (Z & Y)*
  - Repeated observations of 40 $deg^2$

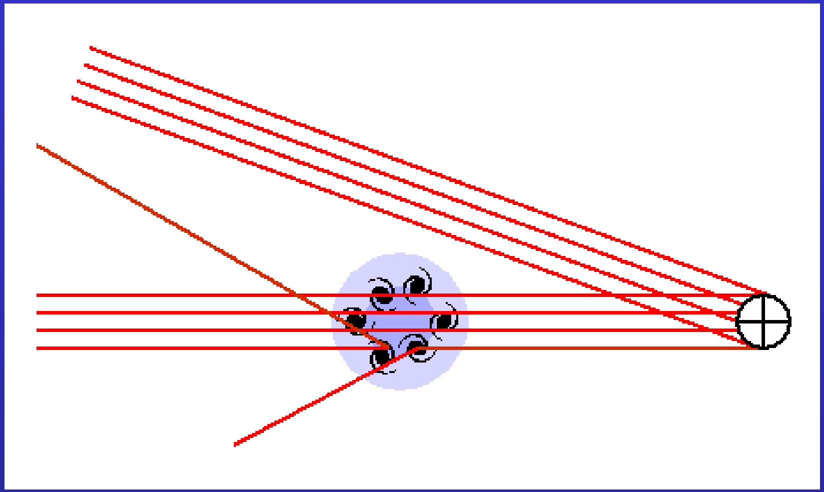
    (*J*,*H*,*Ks* from VISTA)
- Instrument and schedule
  - New 3 $deg^2$ camera on the Blanco 4m on Cerro Tololo (Chile)
  - Construction: 2004-2010
  - Survey Operations: 30% of telescope time over 5 years

Blanco 4m on Cerro Tololo

Image credit: Roger Smith/NOAO/AURA/NSF

Multi-institutional collaboration

# The South Pole Telescope



- a sub-mm cluster survey based on a new 10m telescope located in Antarctica

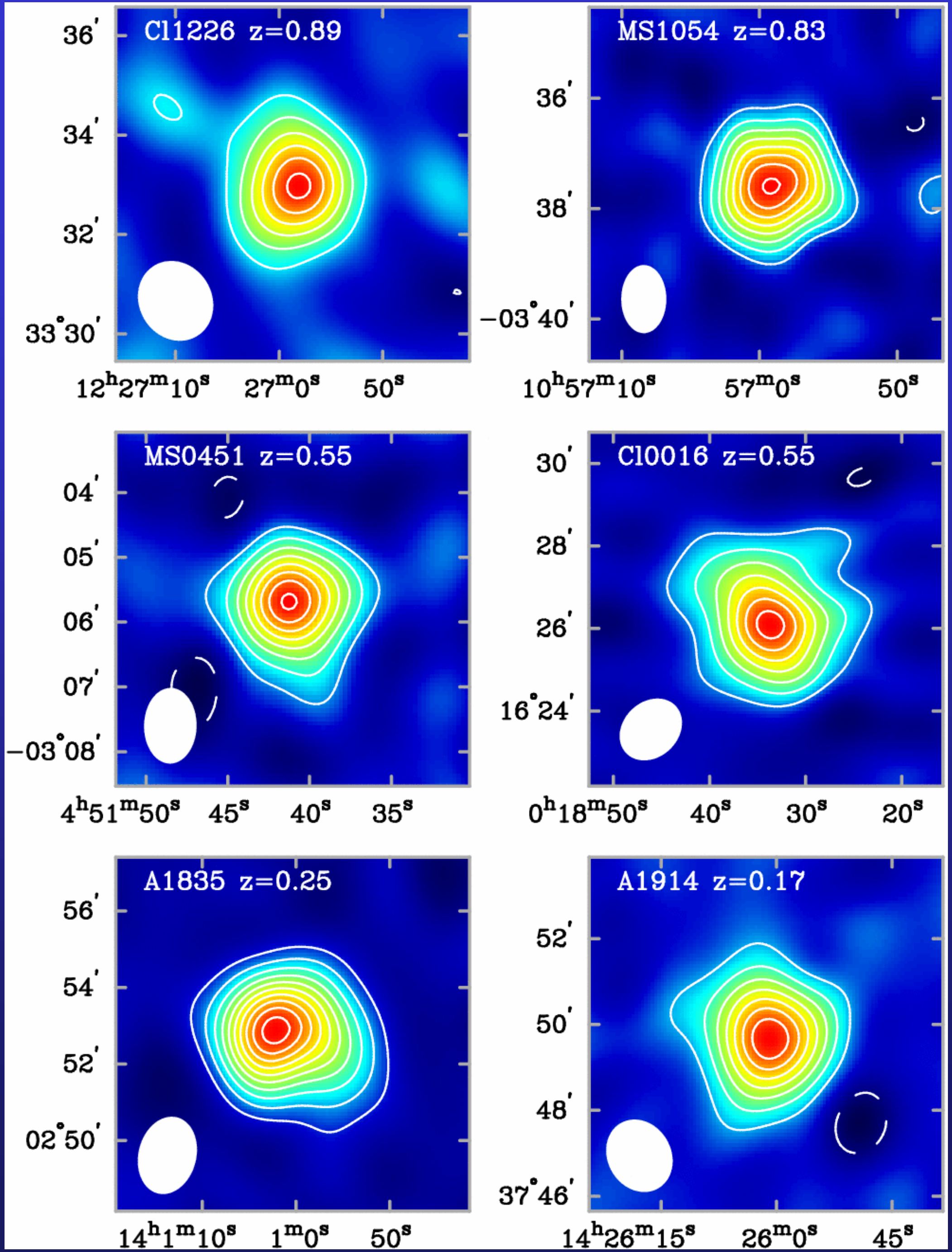
- ~20,000 rich clusters expected from 4000 sq deg detected using the Sunyaev-Zel'dovich Effect

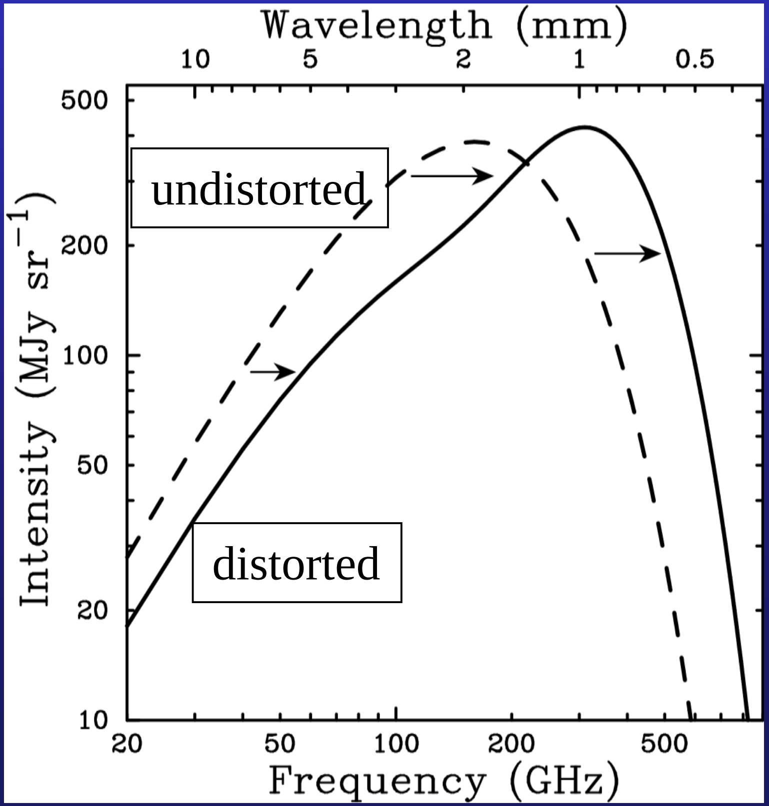
(inverse compton scattering of CMB photons from electrons in the cluster ICM)

- SPT has just completed one year of operation

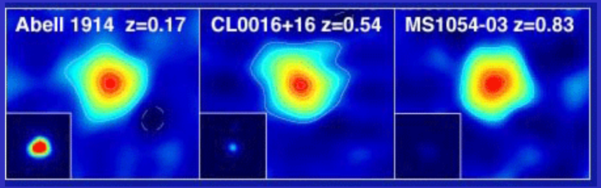
• SZE detection of known clusters (Carlstrom et al. 2002)

• detection weakly coupled to redshift



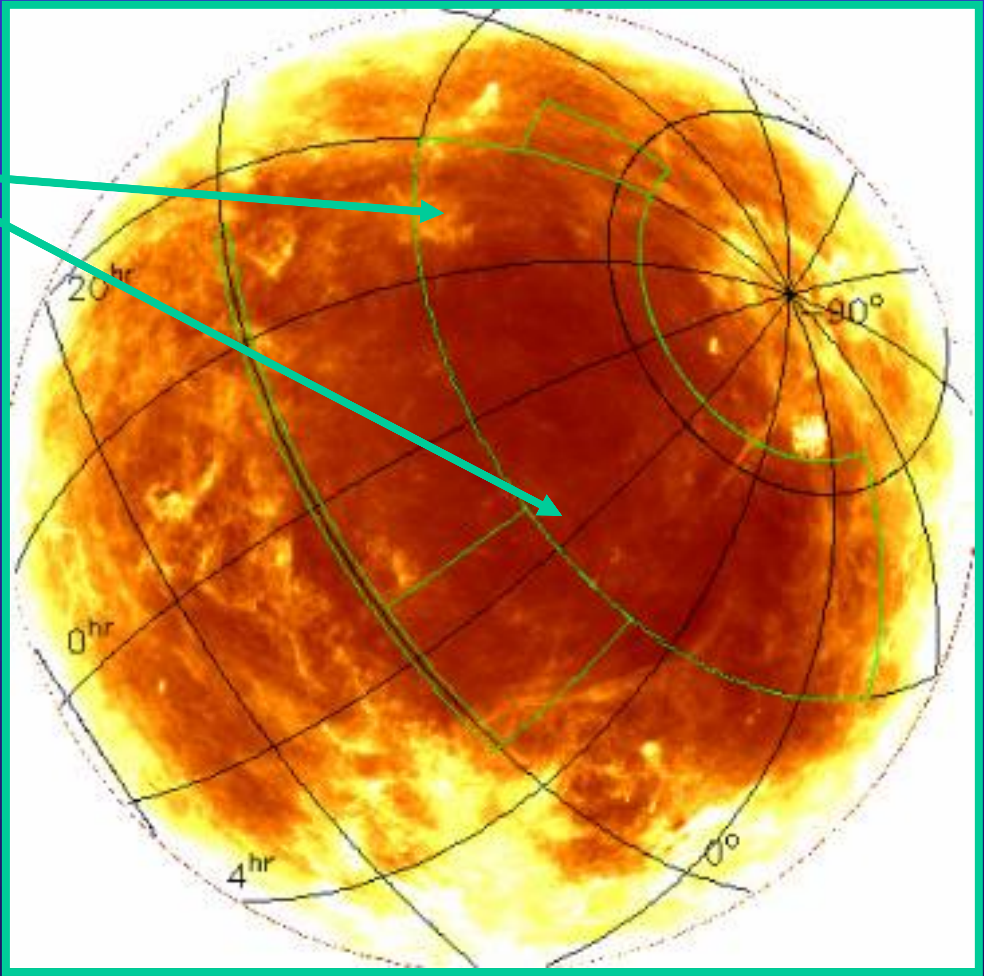



# SPT Survey Region



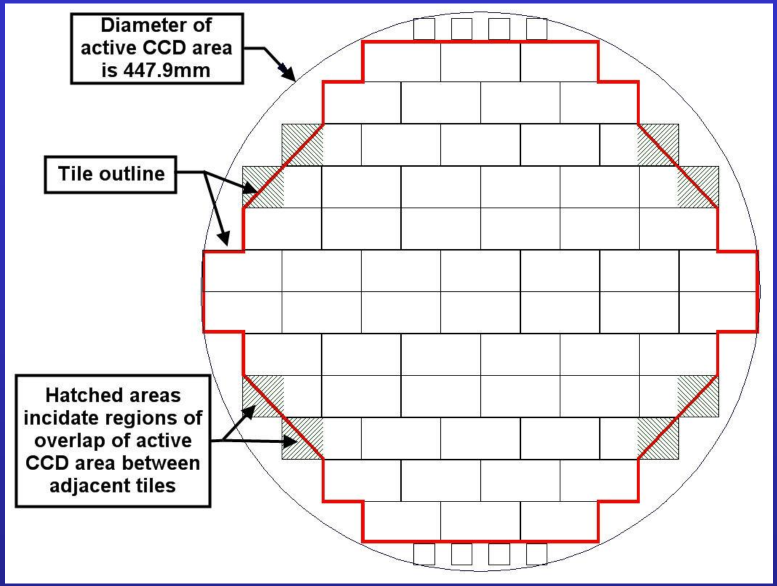

- SPT will survey all the extragalactic sky south of declination $\delta = -30^{\circ}$
- This corresponds to approximately 4000 $deg^2$ of reasonably clean sky
  - north of $\delta = -75^{\circ}$
  - $20hr < \alpha < 7hr$
- This region is easily observable with the Blanco 4m on Cerro Tololo

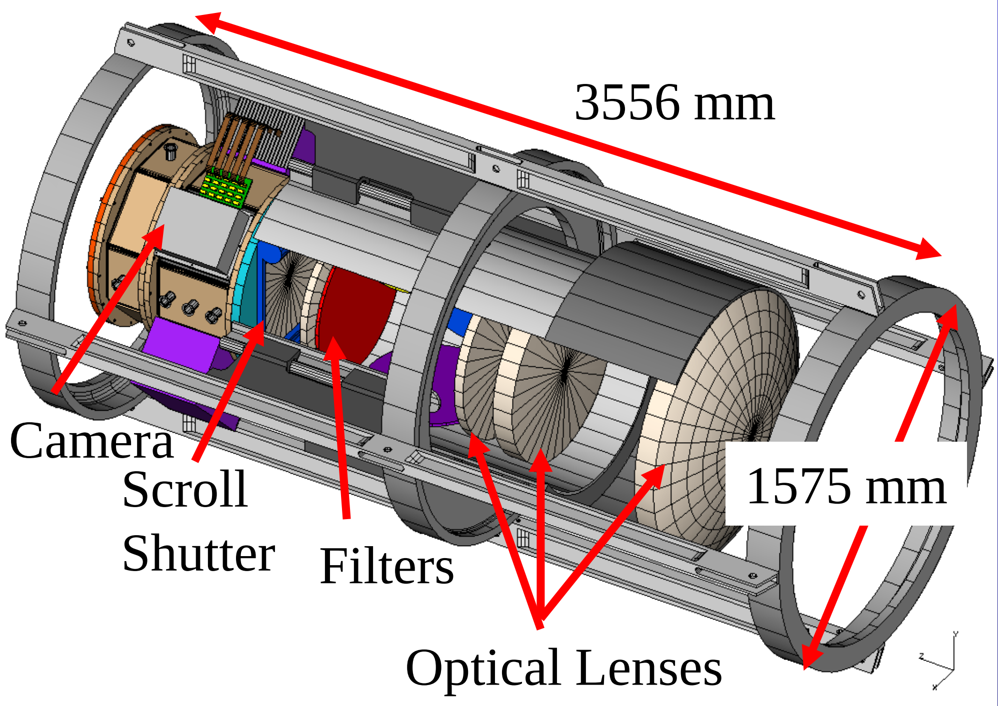
- DES will provides redshifts for SZE clusters



# DES Instrument Design

Focal Plane




3 $deg^2$ FOV

62 2k x 4k CCDs for main image,
4-side buttable, 15 micron pixels
8 1k x 1k guide and focus CCDs

971 MB per image
Read-out ~ 20 sec

New Prime Focus Cage, Camera and Corrector for the CTIO Blanco 4m Telescope

# TeraGrid Processing

National Center for Supercomputing Applications

NCSA:

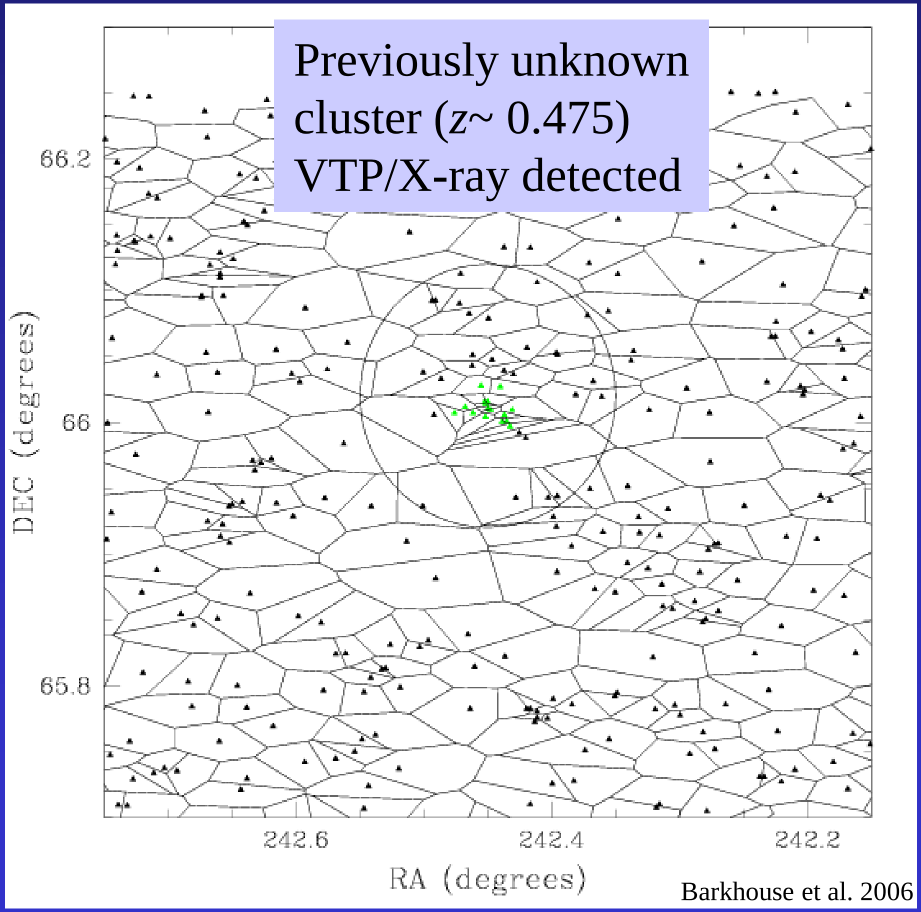
Phase I: 128 node (256 CPU)
Phase II: 631 nodes (1262 CPU)

Data Rate: ~370 GB/night
Total Survey:
~100 TB raw data
~500 TB - 1 PB raw+reduced
Database: 5 - 50 TB

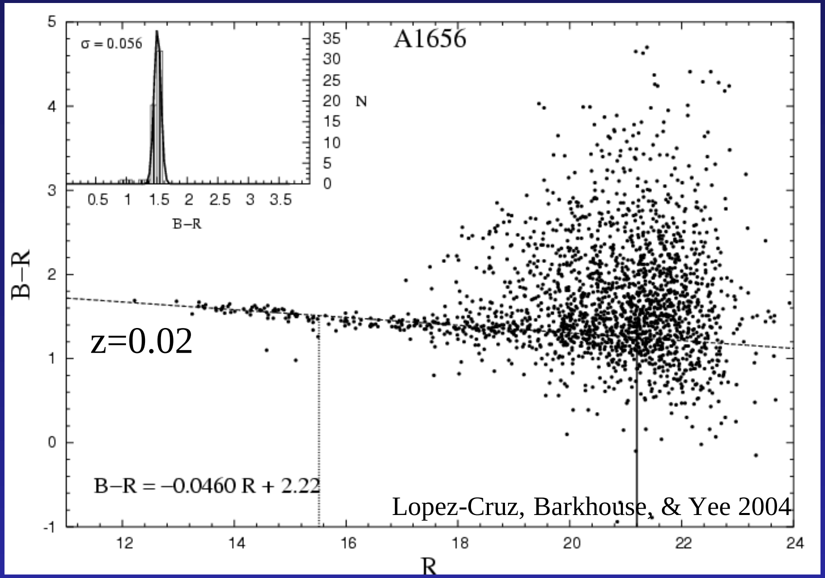
# Finding Galaxy Clusters
# Voronoi Tessellation and Percolation Technique

Ramella et al. 2001

CXOMP J160948.4+660057

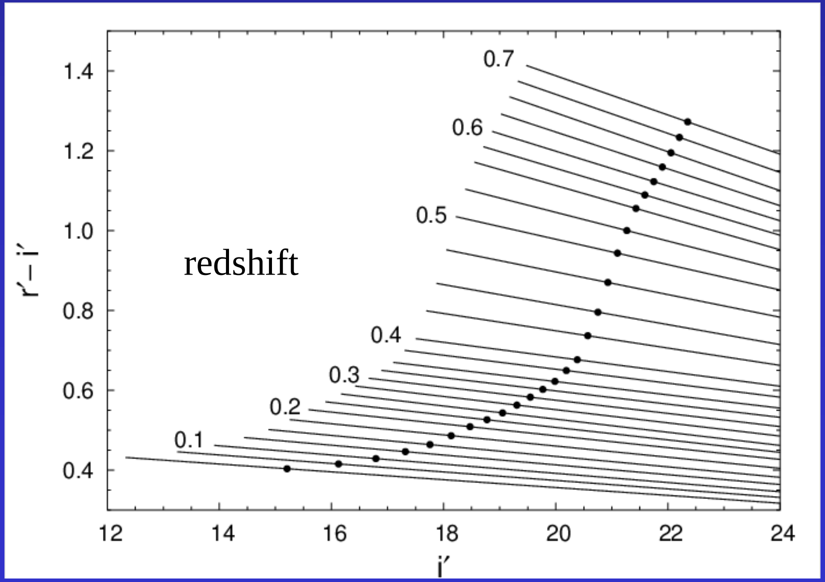


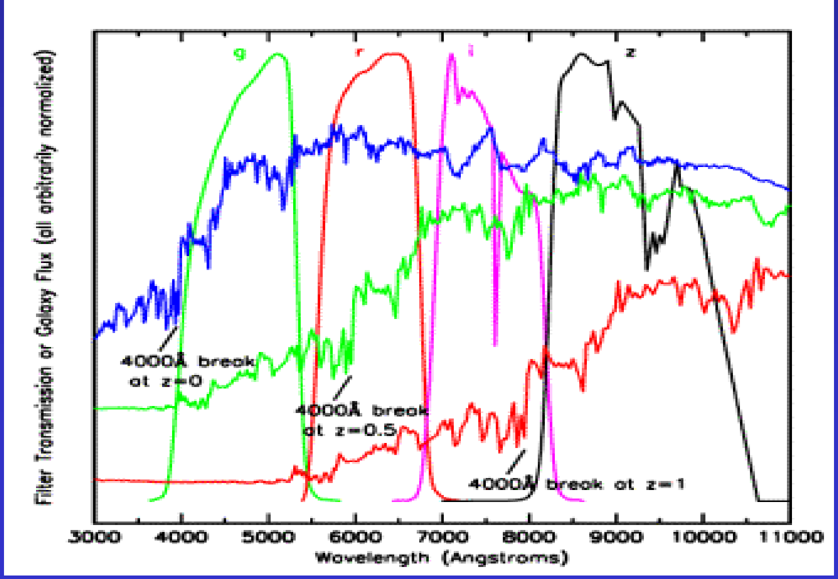

- Galaxy plane divided into cells containing a unique galaxy
- clusters selected as over-densities in cell numbers grouped using percolation technique
- detection significance derived from comparison to random field
- Independent of cluster shape (irregular + symmetric clusters)




- early-type E/S0 galaxies evolve passively and pile-up on the red sequence ridgeline
- color-magnitude relation defines a unique region for a given redshift
- *griz* filters provide redshift estimate for clusters with 0 < z < 1.1

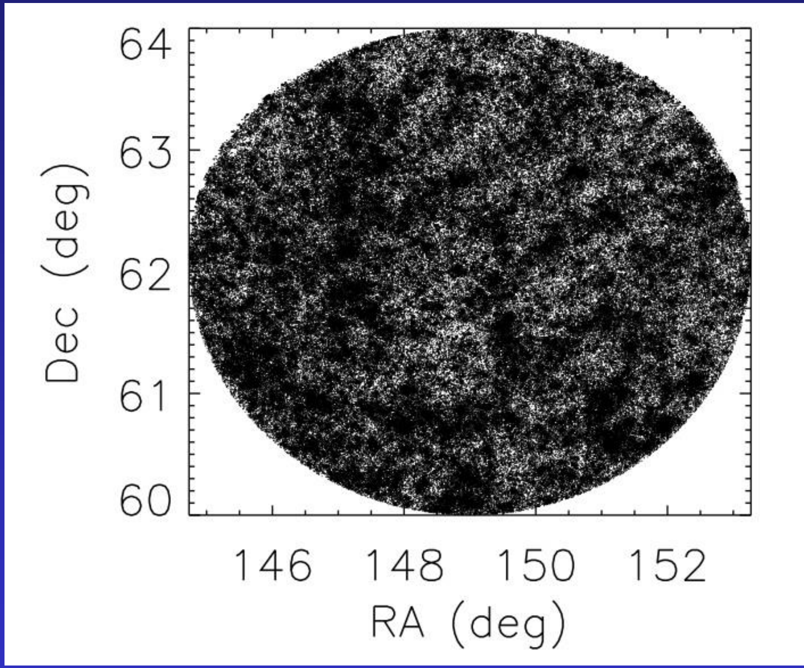
  (*Z, Y, J,H,Ks* => z~2)



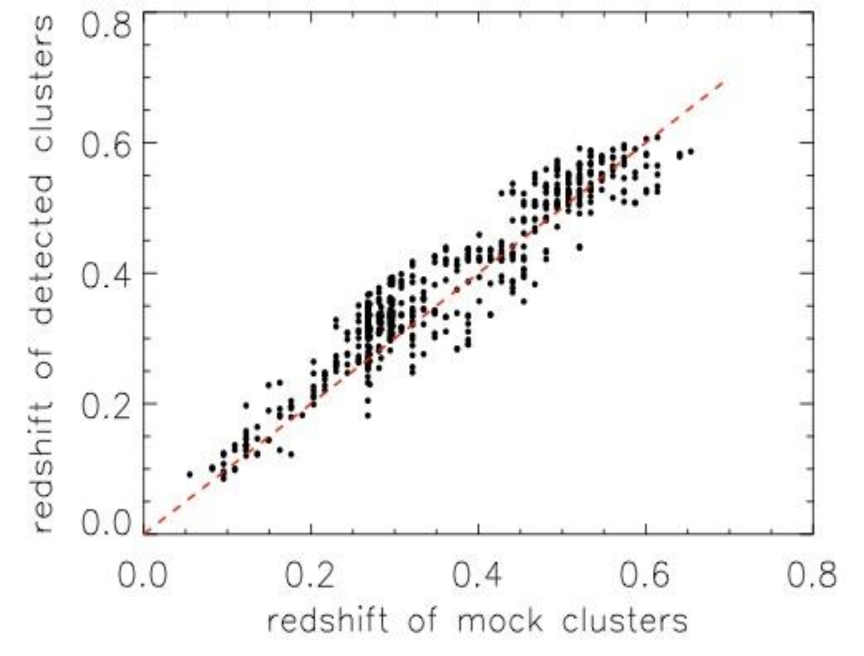



# N-body Simulations

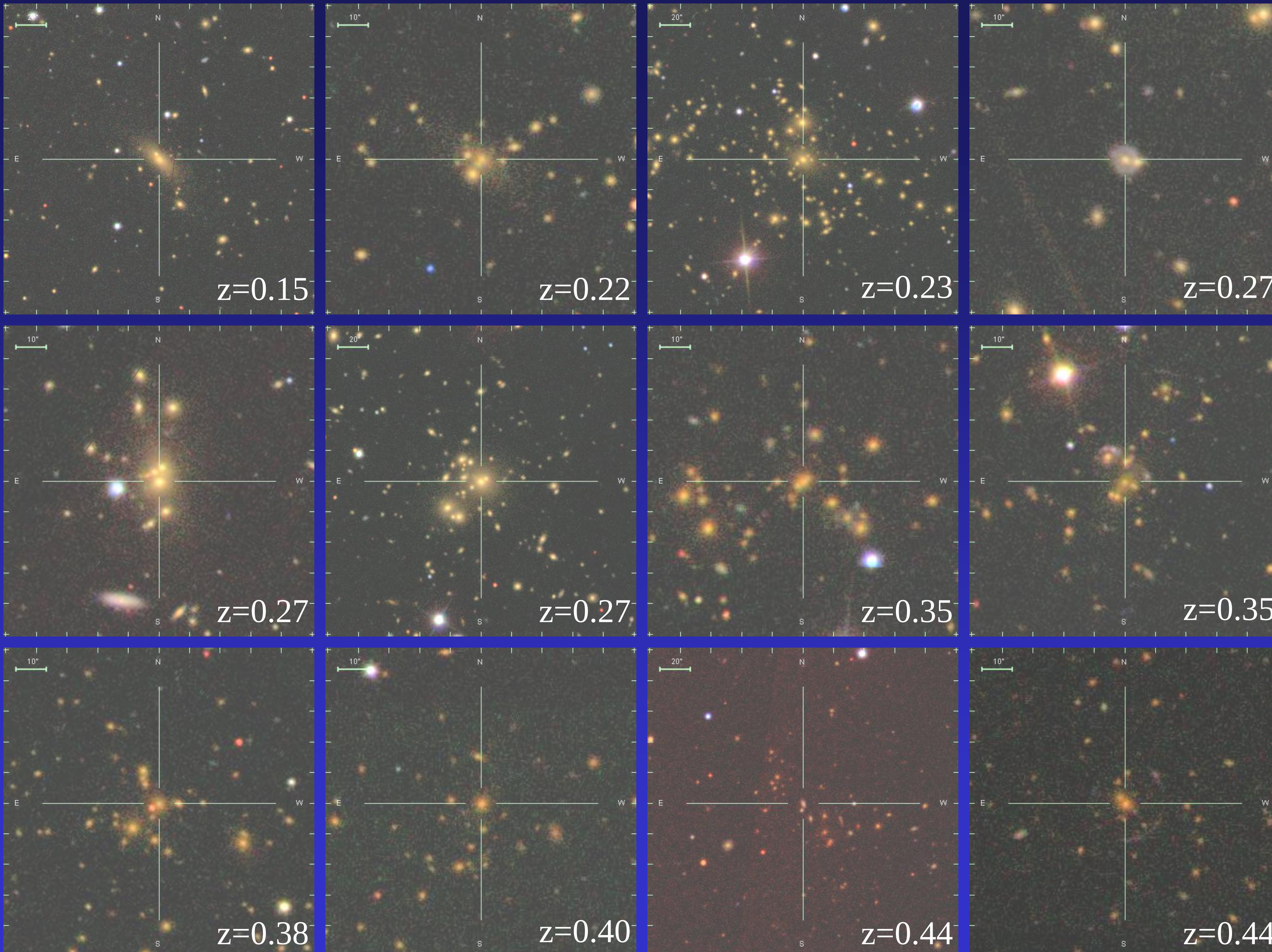
- $10^{10}$ particles in a 250 $Mpc^3$ box (co-I's: UIUC, LANL)
- cluster selection functions measured from extensive simulations

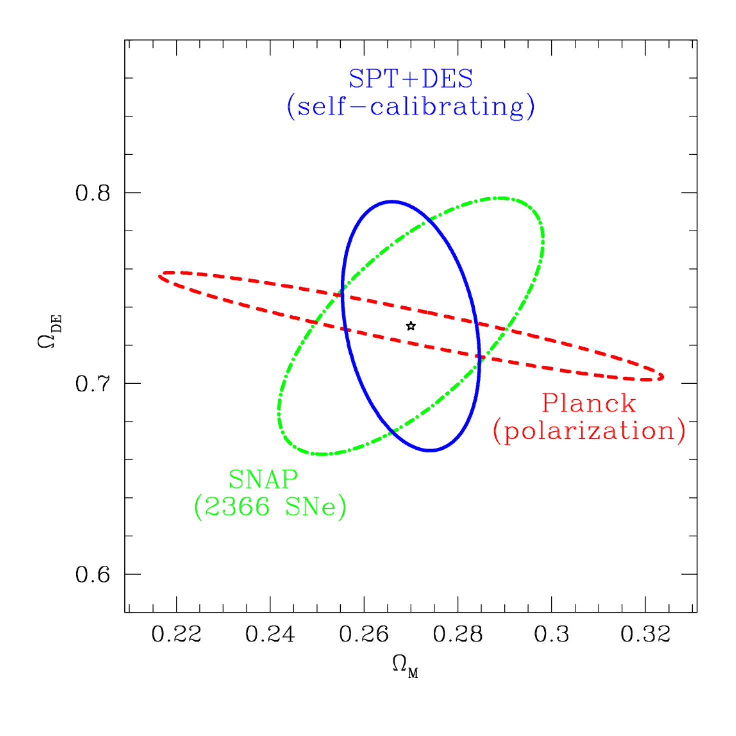


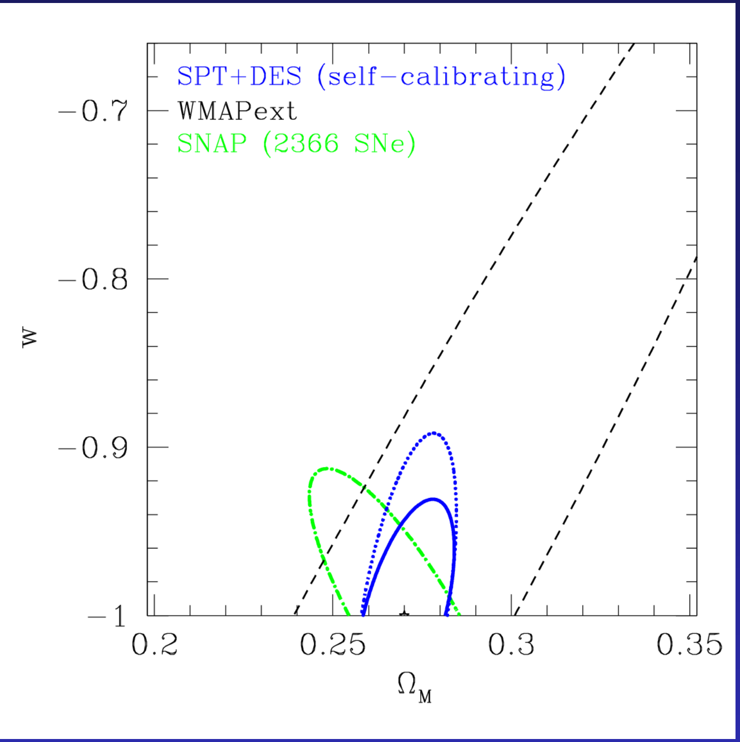

2D sky distribution of galaxies from the mock catalog. Real data from DR5 of the same region has been stacked on top of the mock galaxies to simulate the background.




Redshifts of mock vs. VTP-detected clusters. The small offset is likely due to the difference in $z_f$ (z=3 for the mock data and z=5 for VTP).


z=0.15
z=0.22
z=0.23
z=0.27
z=0.27
z=0.27
z=0.35
z=0.35
z=0.38
z=0.40
z=0.44
z=0.44




Majumdar & Mohr 2004

DES Forecast: 68% CL => $\sigma(\Omega_{DE}) = 0.004\ (0.012)$

$\sigma(w_0) = 0.061\ (0.112)$

$\sigma(w_a) = 0.217\ (0.498)$

* parentheses represent current results

# The Next Step Forward

# Summary

- Strong evidence for accelerated expansion
- Dark Energy as the cause of cosmic acceleration
- Independent evidence for Dark Energy
- Vacuum energy as Dark Energy
- Current observational status: $w \sim -1 \pm 0.1$ (stat) $\pm\ 0.1$ (sys)
- The Dark Energy Survey and other ground- and space-based surveys will provide tight constraints on dark energy

"At the last dim horizon, we search for ghostly errors of observations for landmarks that are scarcely more substantial."

Edwin Hubble, *The Realm of the Nebulae* (1936)