

# Observing Dark Matter and Dark Energy

STFC summer school, 1 Sep 2008



Ofer Lahav  
University College London



**Astrophysics**

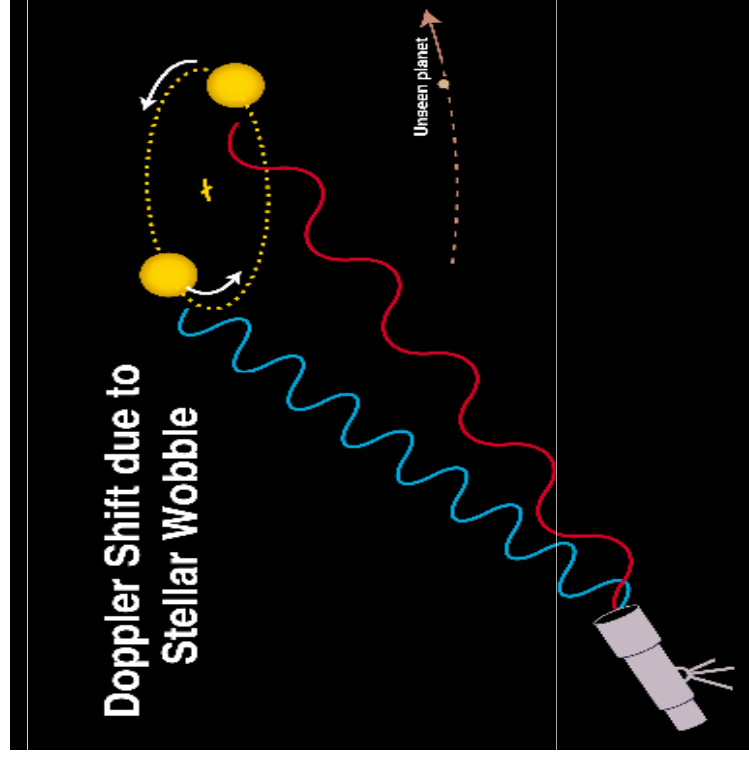
**<http://www.star.ucl.ac.uk>**



**University College London**

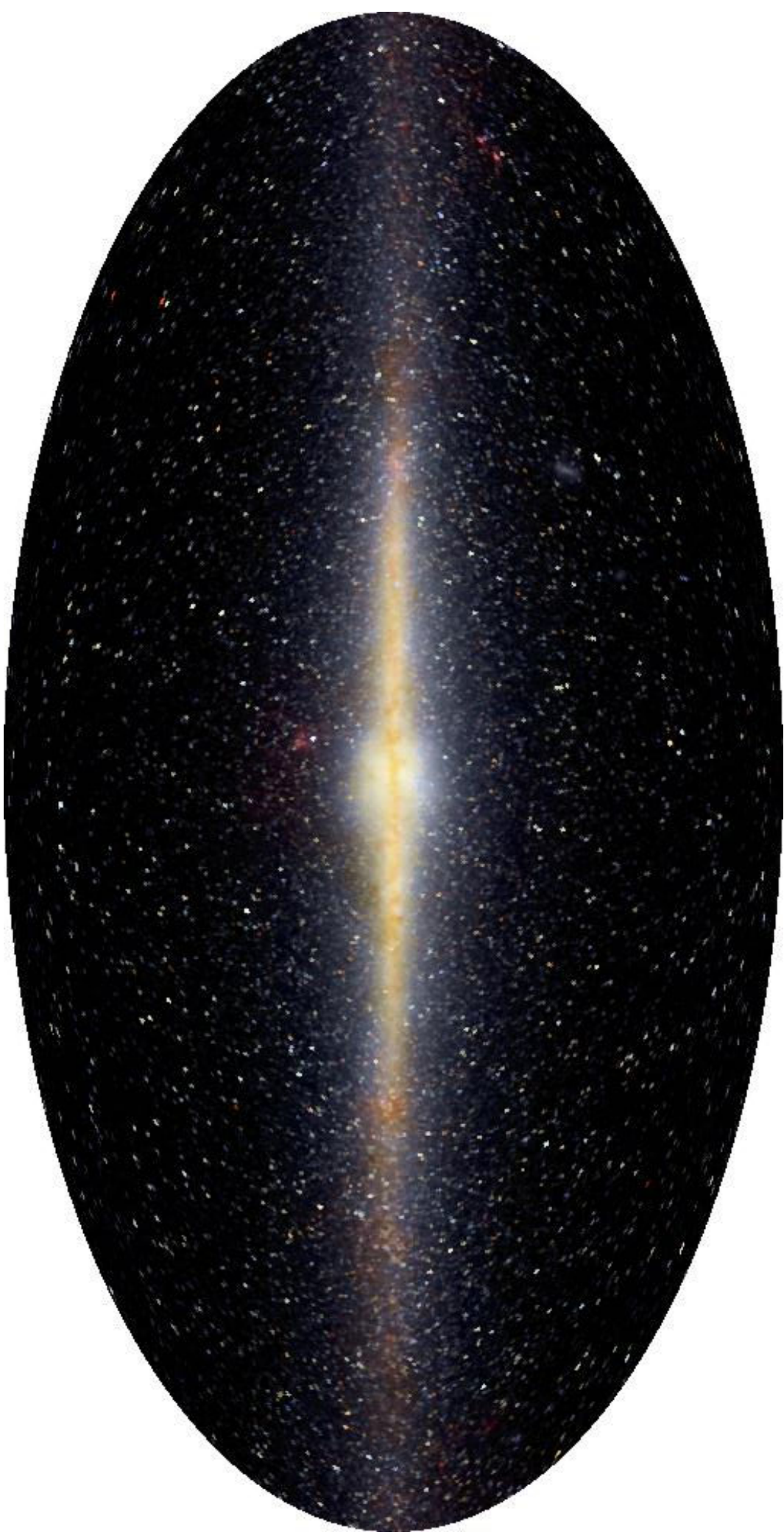


# Extra-solar planets

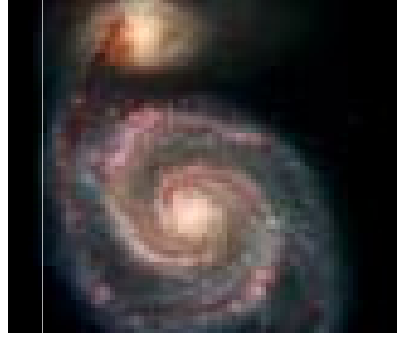


Water on a another planet!

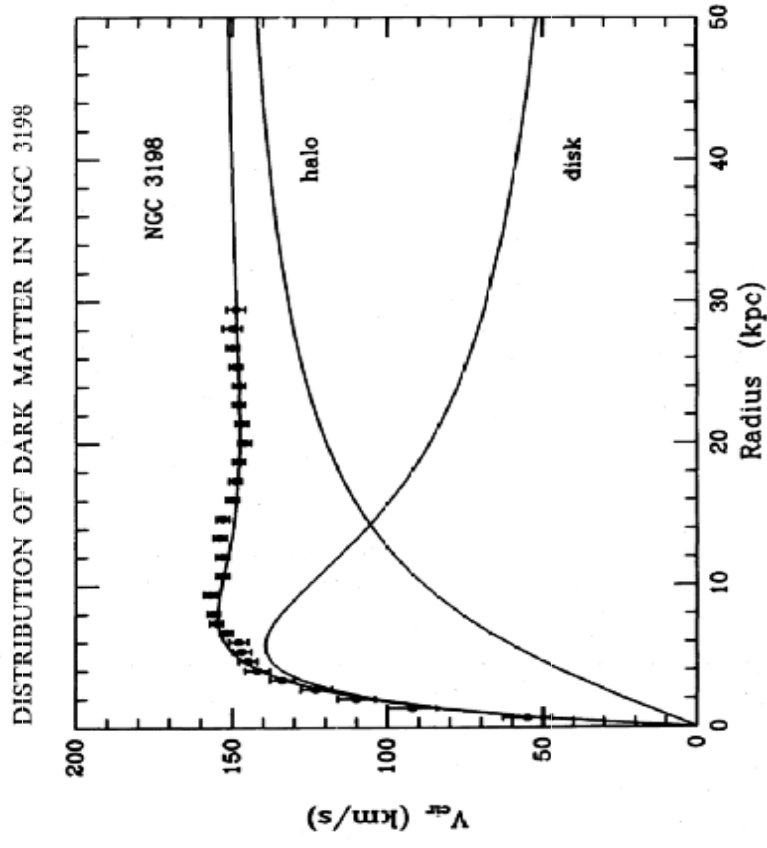
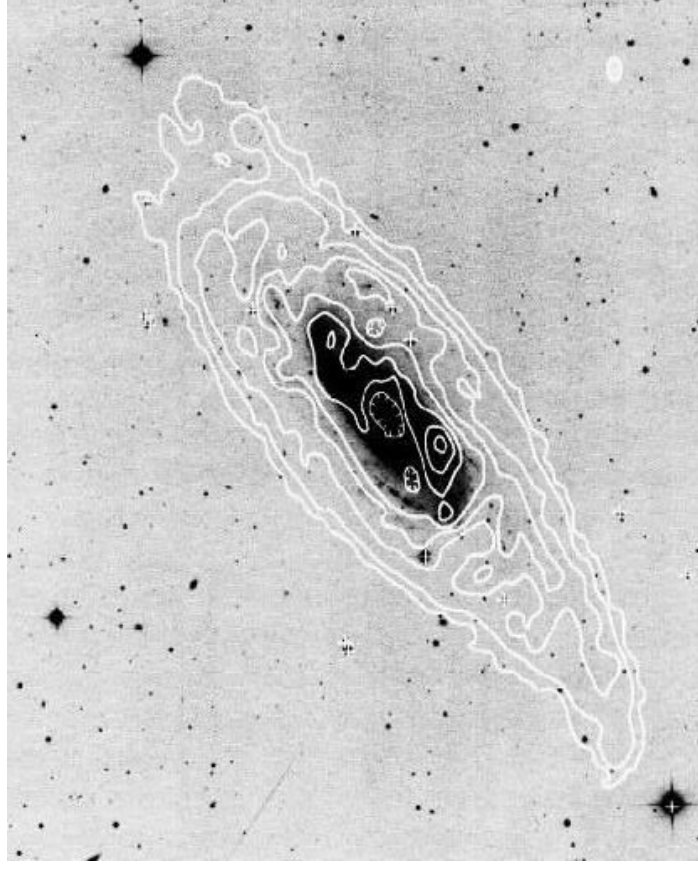
# Our Galaxy – The Milky Way

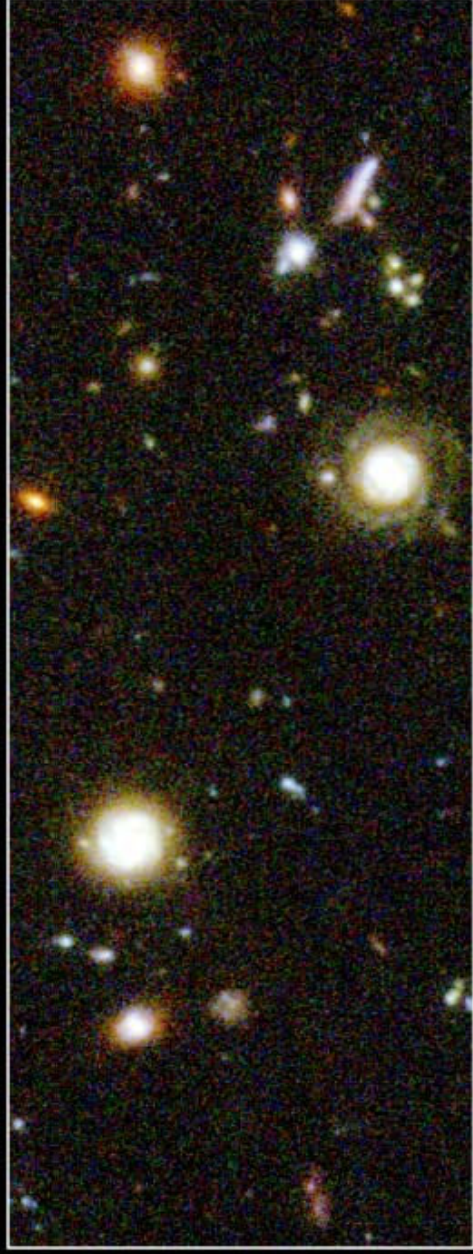
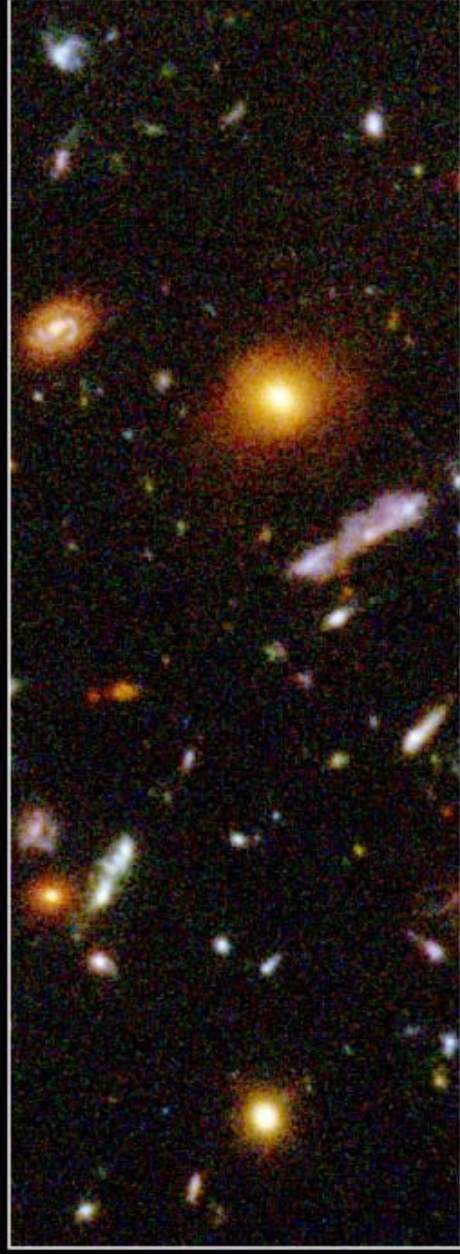


# Galaxies



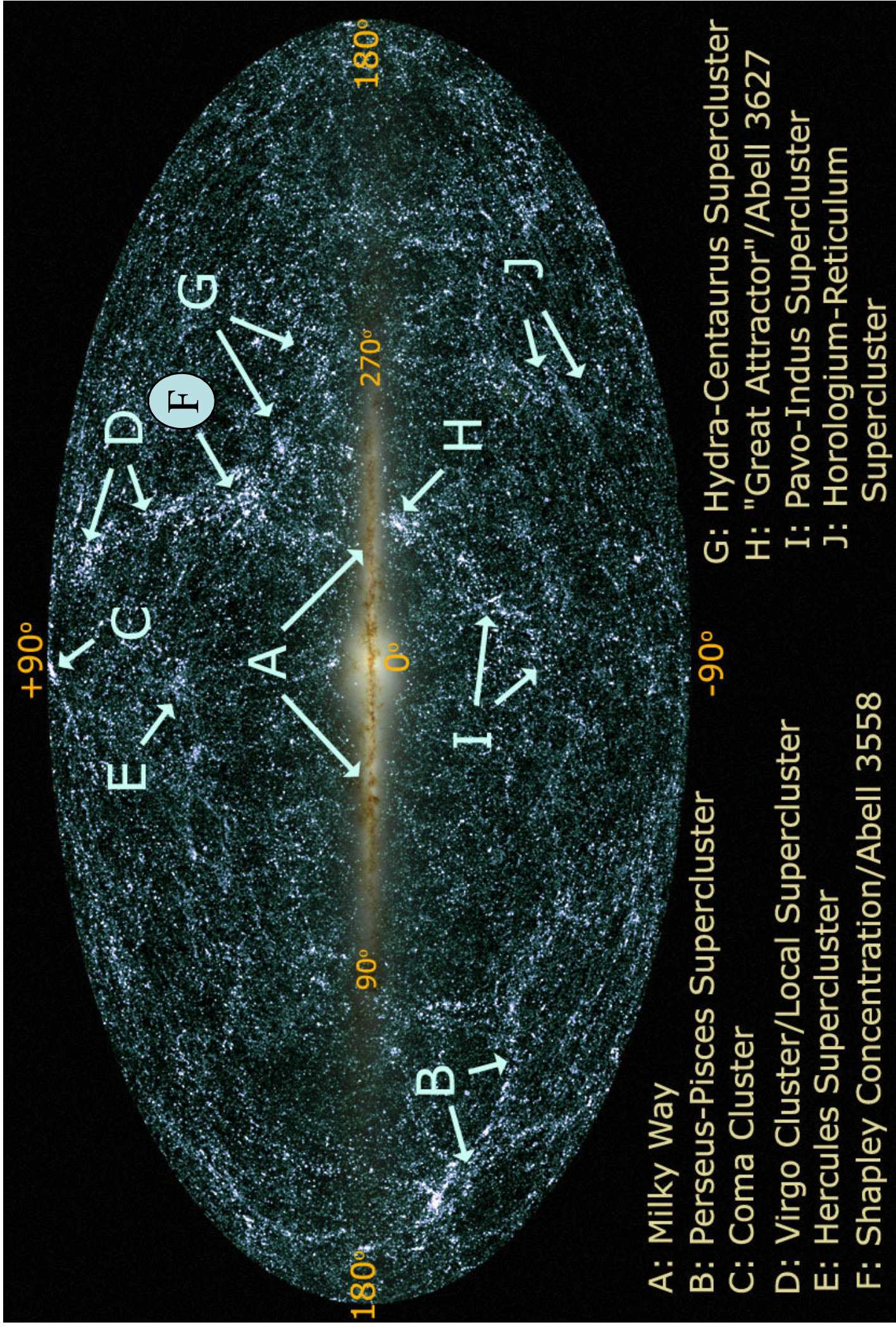
# Rotation curves of spirals are flat- Dark matter halos (or MOND?)





**Hubble Deep Field Details** HST · WFPC2

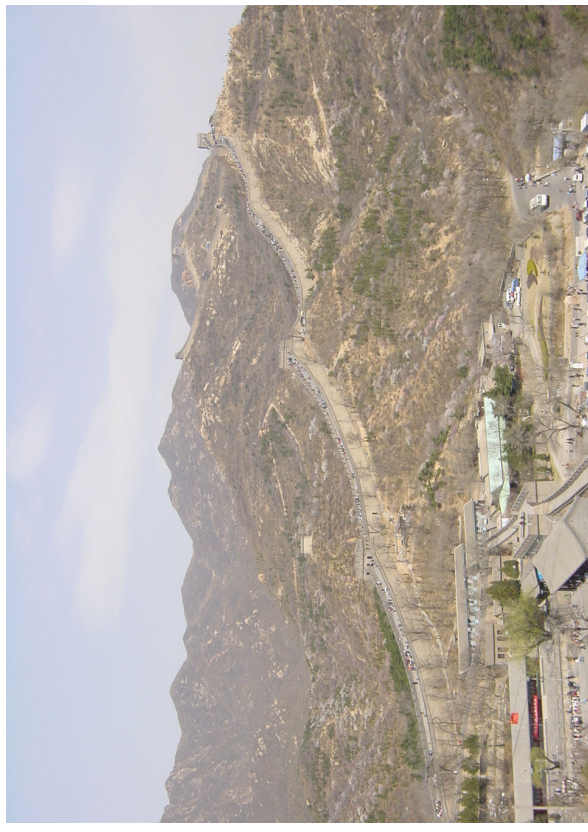
PRC96-01b · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA



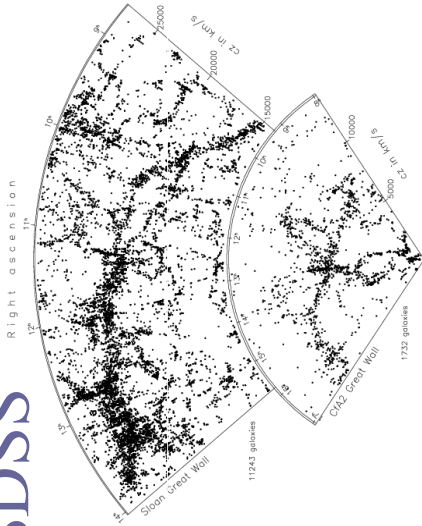
## 2MASS Galactic chart



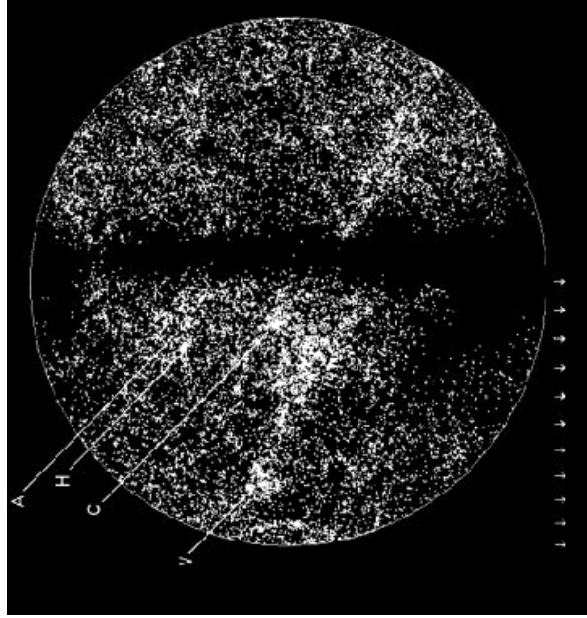
# The Cosmic Web



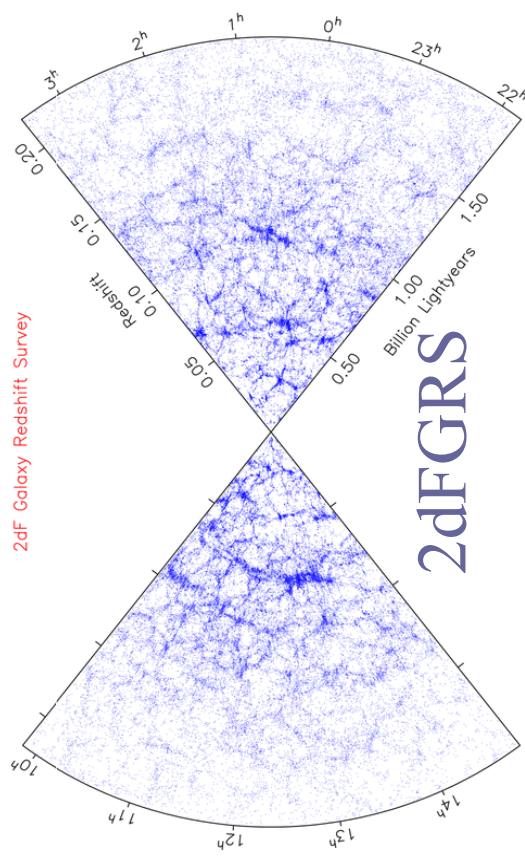
SDSS



CfA Great Wall

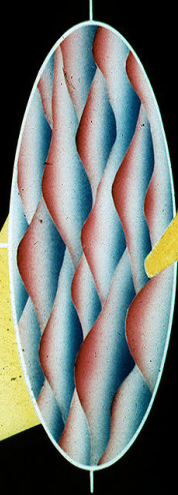


Great Attractor



# Early Development of the Universe

**BIG BANG**



**BIG BANG PLUS TINIEST  
FRACTION OF A SECOND  
( $10^{-43}$ )**

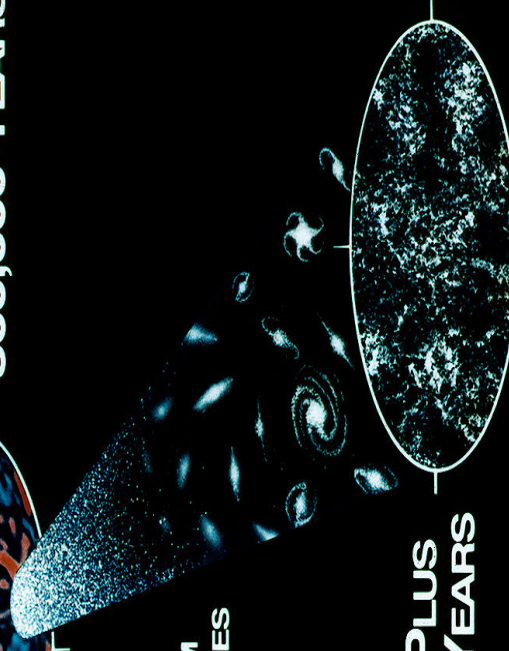
**INFLATION**

**COBE  
SKY MAP**

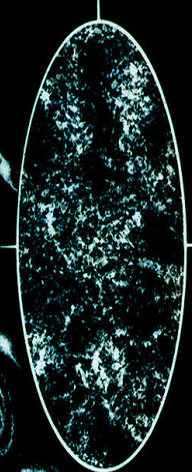


**BIG BANG PLUS  
300,000 YEARS**

**LIGHT FROM  
FIRST GALAXIES**



**BIG BANG PLUS  
15 BILLION YEARS**



# “Evidence” for Dark Energy

## Observational data

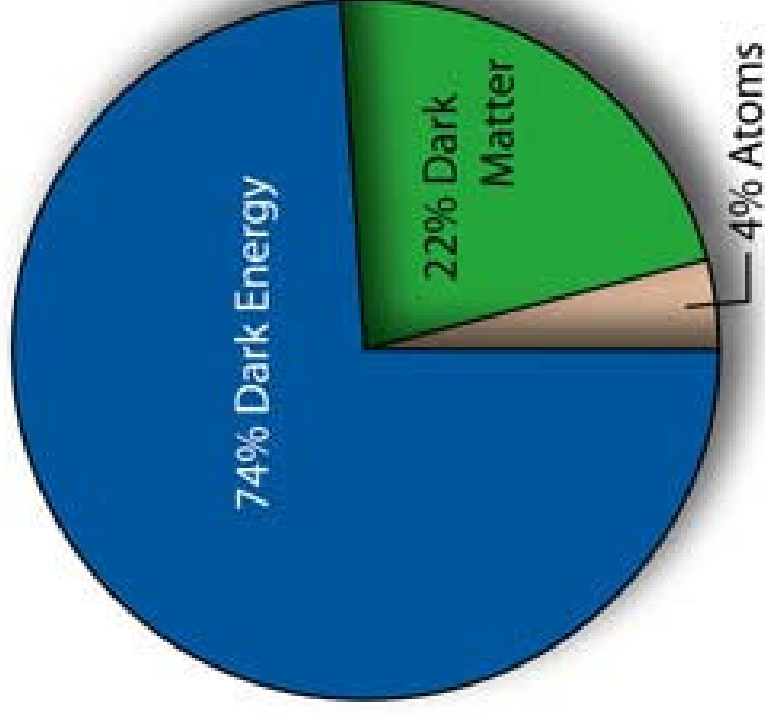
- ◆ Type Ia Supernovae
- ◆ Galaxy Clusters
- ◆ Cosmic Microwave Background
- ◆ Large Scale Structure
- ◆ Gravitational Lensing

## Physical effects:

- ◆ Geometry
- ◆ Growth of Structure


Both depend on the Hubble expansion rate:

$$H^2(z) = H_0^2 [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}] \quad (\text{flat})$$




# The Chequered History of the Cosmological Constant $\Lambda$


**A Chequered History**  
 Since Einstein's calculations, a constant of spatial curvature,  $\Lambda$ , has been proposed, refuted and abandoned. It has returned in various guises.



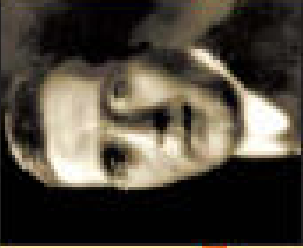
**FEB. 1917:** Einstein introduces the cosmological term into his general relativity theory, allowing for a static model of the universe. The model is later abandoned in favor of an expanding universe.



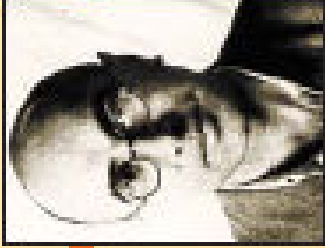
**MAR 1931:** Dutch cosmologist Willem de Sitter proposes a model with a cosmological term. This model is later abandoned in favor of an expanding universe.



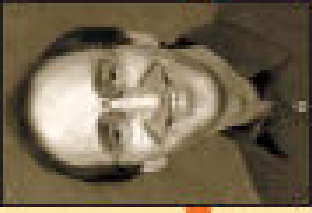
**1922:** Soviet physicist Alexander Friedmann considers models in which  $\Lambda$  is not zero, but is a cosmological term.




**1927:** American astronomer Edwin Hubble discovers that galaxies are receding from Earth at a rate proportional to their distance, a discovery that leads to the cosmological term, at first it is usually called the "receding velocity".



**1927:** Belgian physicist Georges Lemaître introduces the cosmological term into his equations, which is later called the "receding velocity".



**1928:** The amount of expansion has been being studied (Hubble's law) and the cosmological term is required to account for the expansion. It is later called the "receding velocity".



The old CC problem:

Theory exceeds observational limits on  $\Lambda$  by  $10^{120}$ !

The new CC problem:

Why are the amounts of Dark Matter and Dark Energy so similar?

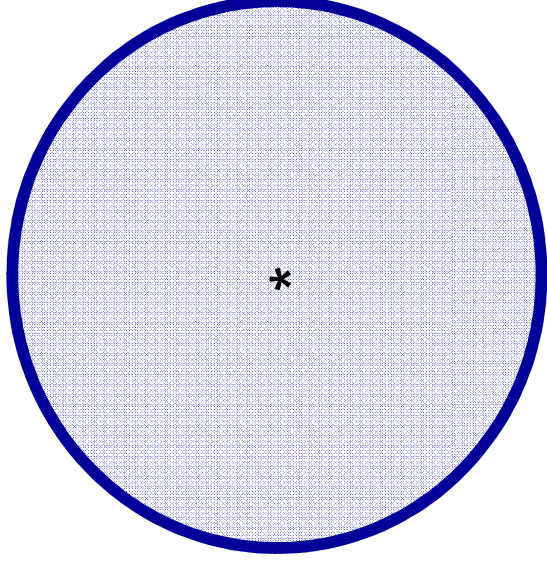
# Back to

# Newton's Principia?

Weak field limit of GR:

$$F = -GM/r^2 + \Lambda/3 r$$

X



Lucy Calder & OL

A&G Feb 08 issue

<http://www.star.ucl.ac.uk/~lahav/CLrev.pdf>

(revised)

18 December 1998  
**Science**

Vol. 282 No. 5397  
Pages 2141-2336 \$7

**THE  
ACCELERATING  
UNIVERSE**  
Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE



# Newton, Principia (1687, Book I, Proposition 77, Theorem 37)

QuickTime™ and a  
TIFF (Uncompressed) decompressor  
are needed to see this picture.

QuickTime™ and a  
TIFF (Uncompressed) decompressor  
are needed to see this picture.

# Forces inside and outside a spherical shell

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

# “Dark Energy”: 10, 90 or 320 years old?

QuickTime™ and a  
TIFF (Uncompressed) decompressor  
are needed to see this picture.

QuickTime™ and a  
TIFF (Uncompressed) decompressor  
are needed to see this picture.



Matter and Dark Energy tell space how to curve:

$$\Omega_k = \Omega_m + \Omega_\Lambda - 1$$

*Curvature*                      *Matter*                      *Dark (Vacuum) Energy*

# Einstein's GR: Matter and Dark Energy

tell space how to curve:

$$\Omega_{\text{K}} = \Omega_{\text{m}} + \Omega_{\Lambda} - 1$$

*Curvature*                      *Matter*                      *Dark (Vacuum)*  
*Energy*

*OR modified curvature*

$$\Omega_{\text{K}} - \Omega_{\Lambda} = \Omega_{\text{m}} - 1$$

The Universe accelerates at present if

$$\Omega_m/2 - \Omega_\Lambda < 0$$

e.g. For  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$   
 $\Omega_k = 0$  (the U. is flat!) and  
the U. is accelerating!  
(only ‘recently’,  $z < 0.7$ )

# Just Six numbers (?)

- ◆ Baryons  $\Omega_b$
- ◆ Matter  $\Omega_m$
- ◆ Dark Energy (Cosmological Constant)  $\Omega_\Lambda$
- ◆ Hubble parameter  $H_0$
- ◆ Amplitude  $A$
- ◆ Initial shape of perturbations  $n$

# Probing Dark Matter & Dark Energy

- ◆ Through the **history of the expansion rate**:

$$H^2(z) = H_0^2 \left[ \Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)} \right]$$

matter                      dark energy

(flat Universe)  
(constant  $w$ )

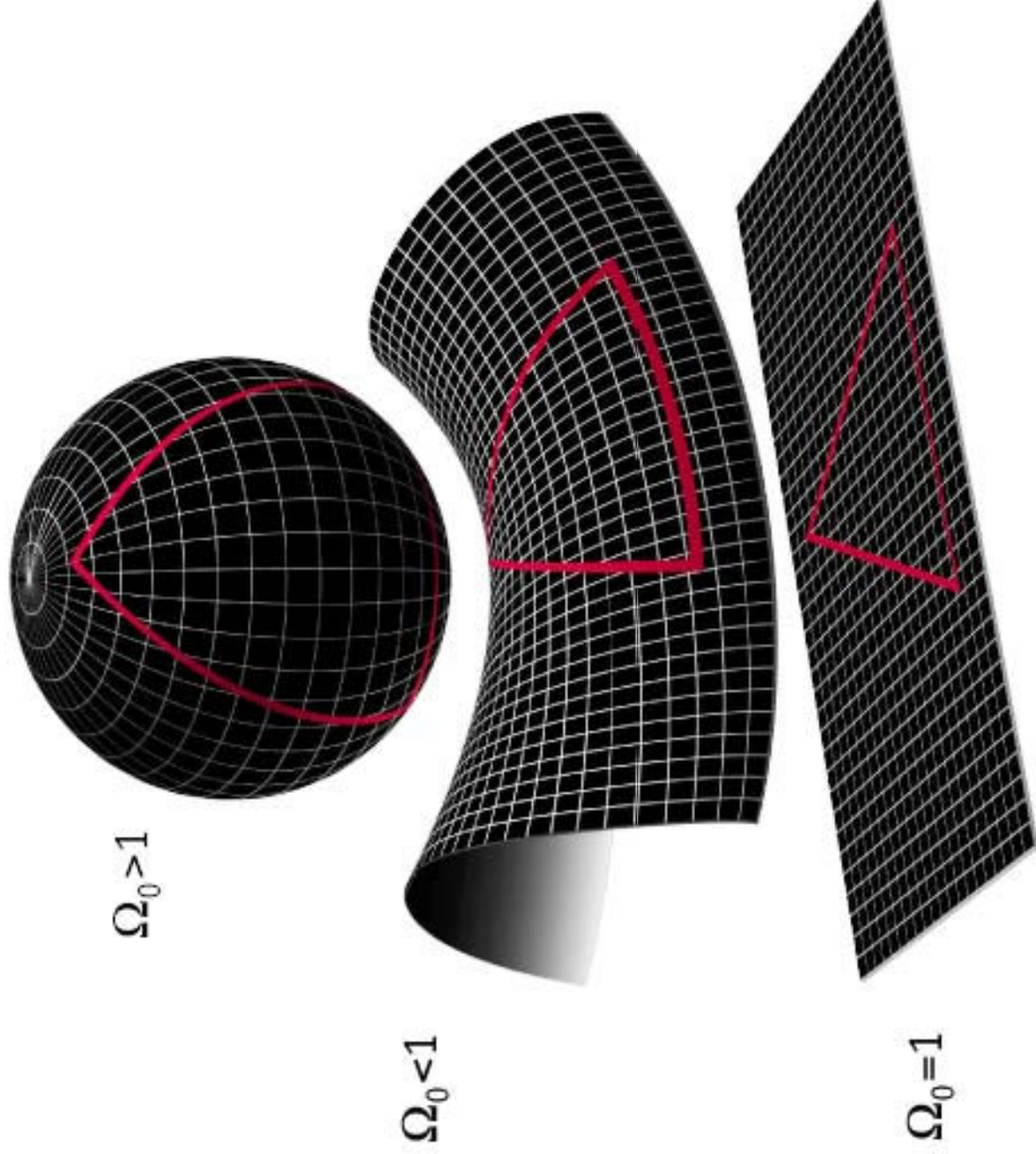
$$P = w \rho$$

- ◆ Comoving distance
- ◆ Standard Candles
- ◆ Standard Rulers

$$r(z) = \int dz/H(z)$$
$$d_L(z) = (1+z) r(z)$$
$$d_A(z) = (1+z)^{-1} r(z)$$

- ◆ The **rate of growth of structure** also determined by  $H(z)$  and by any modifications of gravity on large scales

# Curvature of the Universe bends light



# Supernovae

- Geometric Probe of Dark Energy



SDSS

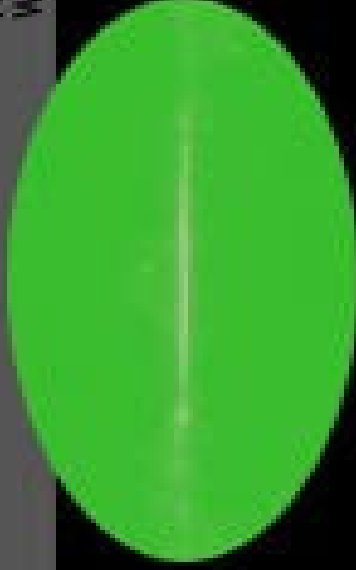
# The History of CMB observations

1965

1965



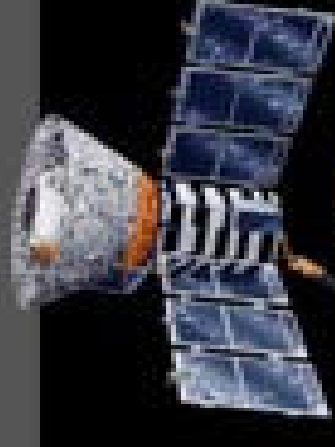
Penzias and  
Wilson



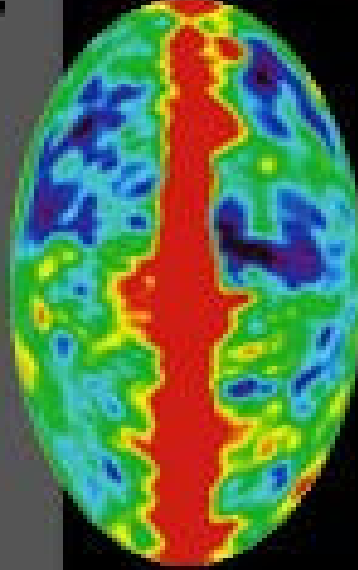
Discovery

1992

1992



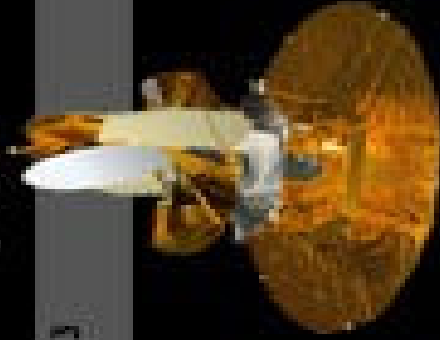
COBE



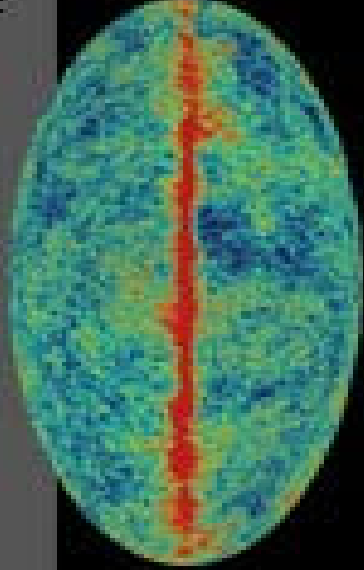
COBE

2003

2003



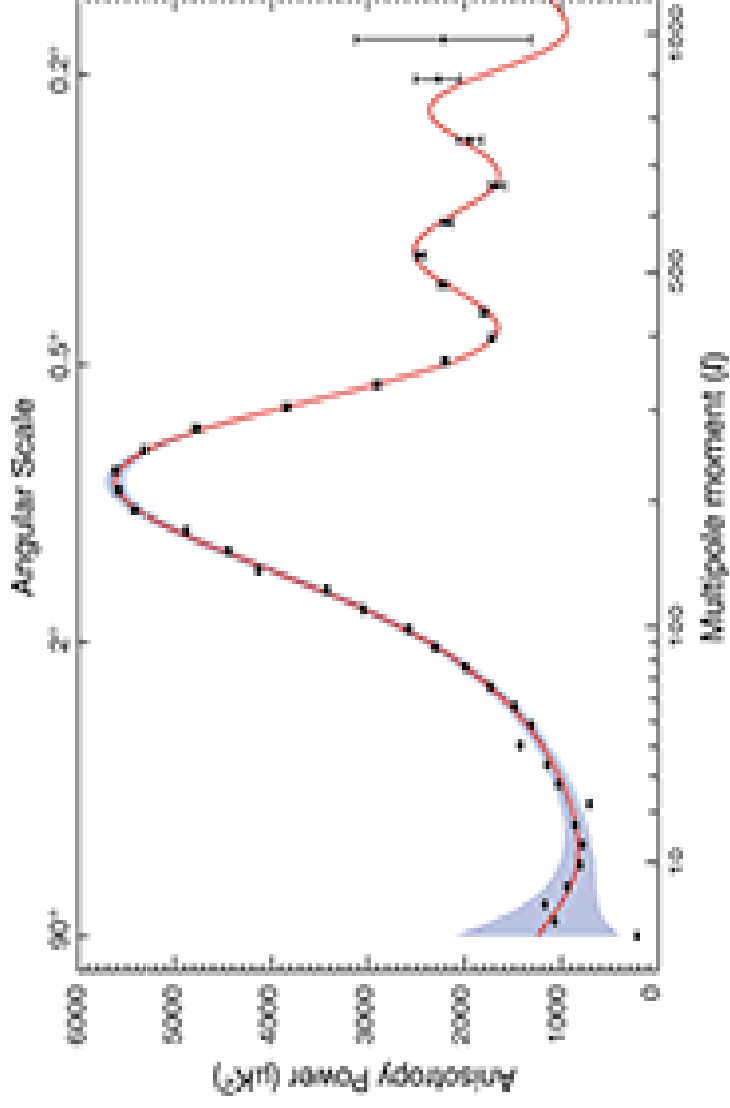
WMAP



WMAP



# WMAP3



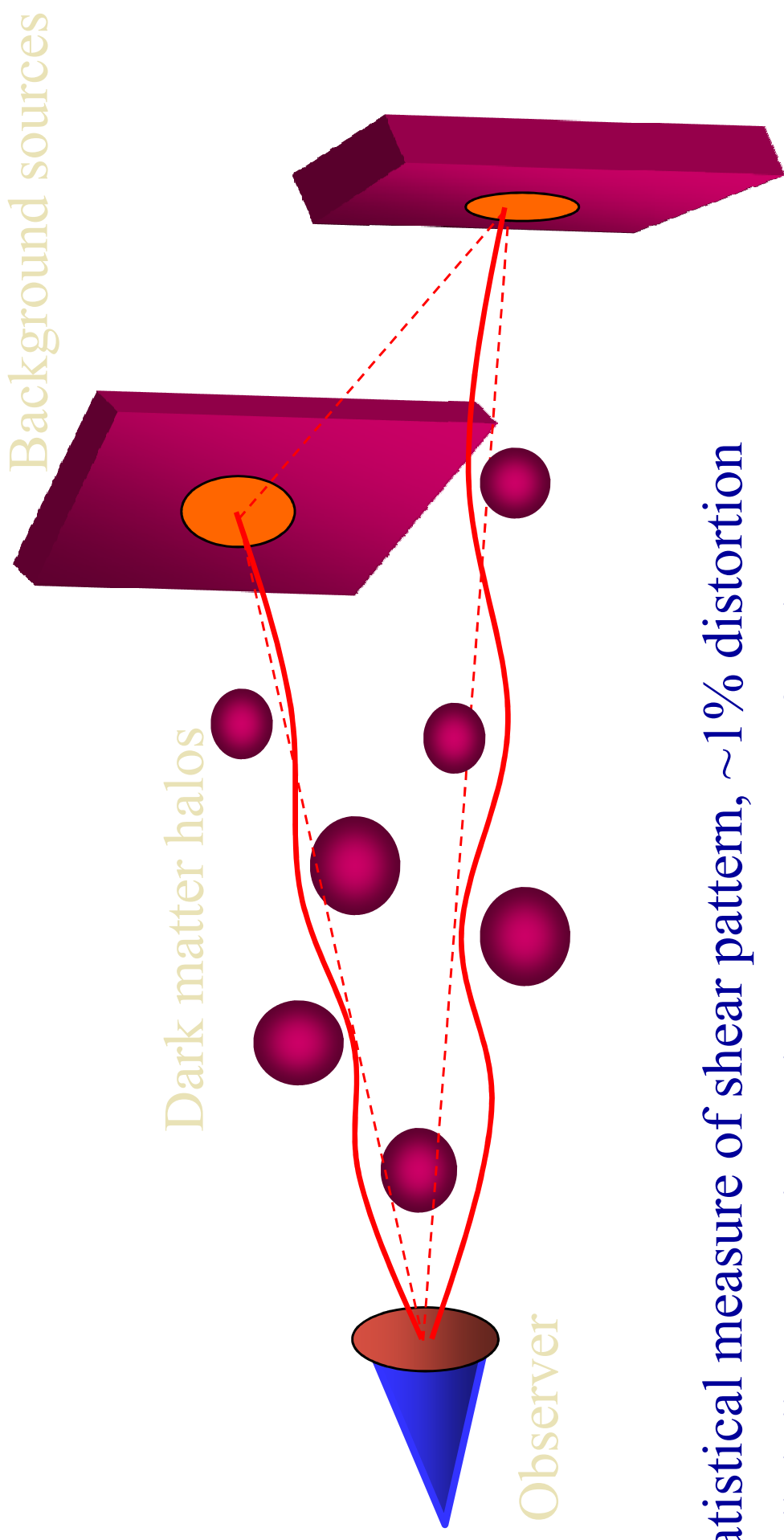
$$\Omega_m = 0.24 \pm 0.04$$

$$\sigma_8 = 0.74 \pm 0.06$$

$$n = 0.95 \pm 0.02$$

$$\tau = 0.09 \pm 0.03$$

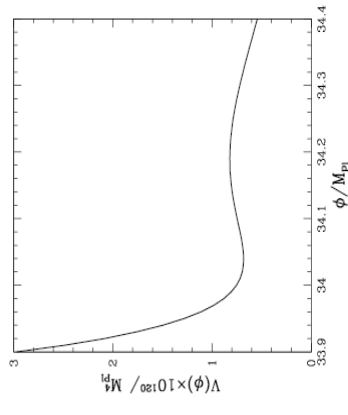
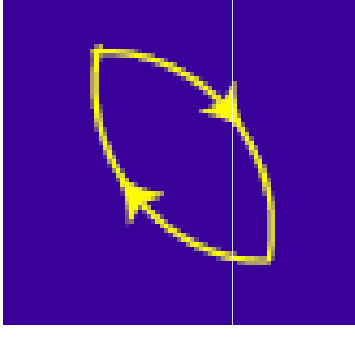
# Weak Lensing: Cosmic Shear



- Statistical measure of shear pattern,  $\sim 1\%$  distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

# What is Dark Energy?

- ◆ Vacuum energy (cosmological constant)?
- ◆ Dynamical scalar field?
  - $w=p/\rho$
  - for cosmological constant:  $w = -1$
- ◆ Manifestation of modified gravity?
- ◆ Inhomogeneous Universe?
- ◆ What if cosmological constant after all?
- ◆ Multiverse - Landscape?
- ◆ The Anthropic Principle?



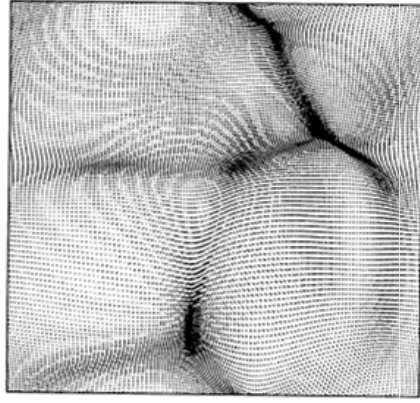
# Brief History of 'Hot Dark Matter'

- \* **1970s** : Top-down scenario with massive neutrinos (HDM) –  
Zeldovich Pancakes
- \* **1980s**: HDM - Problems with structure formation
- \* **1990s**: Mixed CDM (80%) + HDM (20%)
- \* **2000s**: Baryons (4%) + CDM (26%) + Lambda (70%):

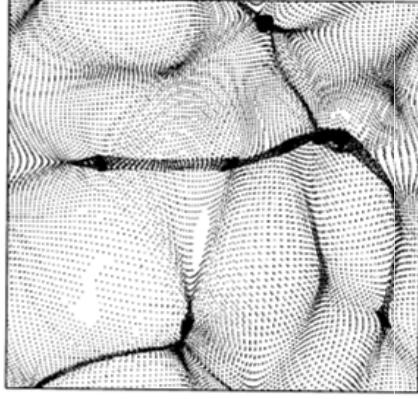
But now we know HDM exists!  
How much?

Neutrinos decoupled when they were still relativistic,  
hence they wiped out structure on small scales

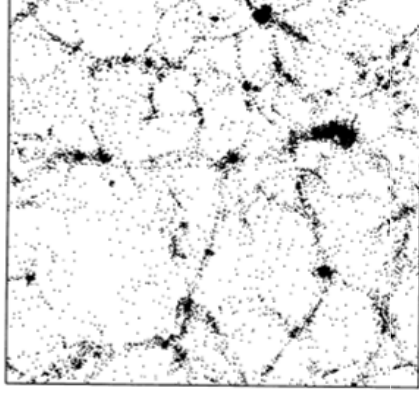
112 neutrinos per  $\text{cm}^3$



CDM+HDM



WDM



CDM

*From 2dF  $\Omega_\nu < 0.04$  ;  $M_\nu < 1.8 \text{ eV}$  (Elgaroy & OL 2003)*

*From Ly- $\alpha$ +SDSS +CMB  $M_\nu < 0.17 \text{ eV}$  (Seljak et al. 2006)*

# Sources of uncertainties

- Cosmological (parameters and priors)
- Astrophysical (e.g. cluster M-T, biasing)
- Instrumental (e.g. “seeing”)

# Bayes' Theorem

- ◆  $P(A|B) = P(B|A) P(A) / P(B)$
- ◆  $P(\text{model} | \text{data}) = \frac{P(\text{data} | \text{model}) P(\text{model})}{P(\text{data})}$ 
  - ↑ Likelihood
  - ↑ Prior
  - ↑ Evidence

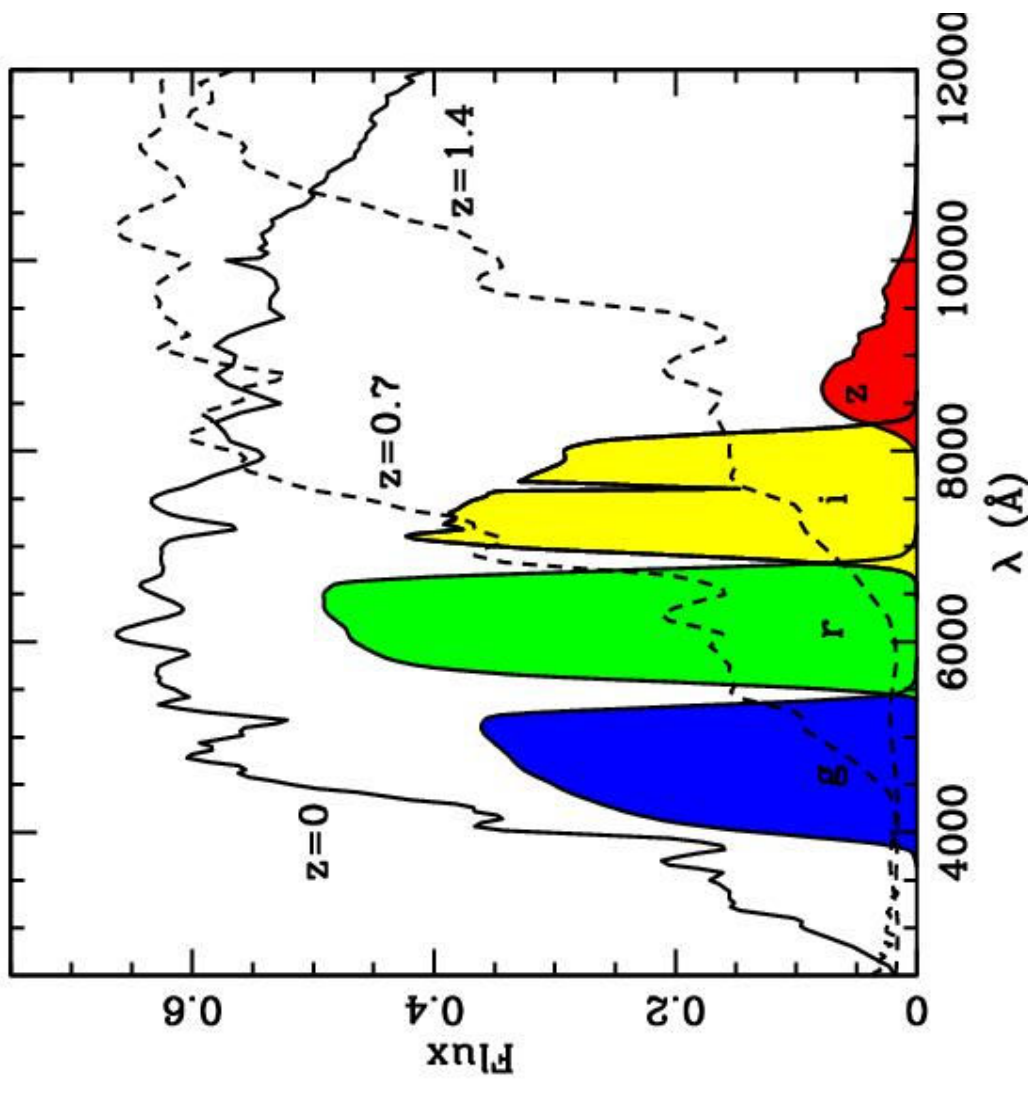
$\exp(-\chi^2 / 2)$



1702-1761  
(paper only published in  
1764)

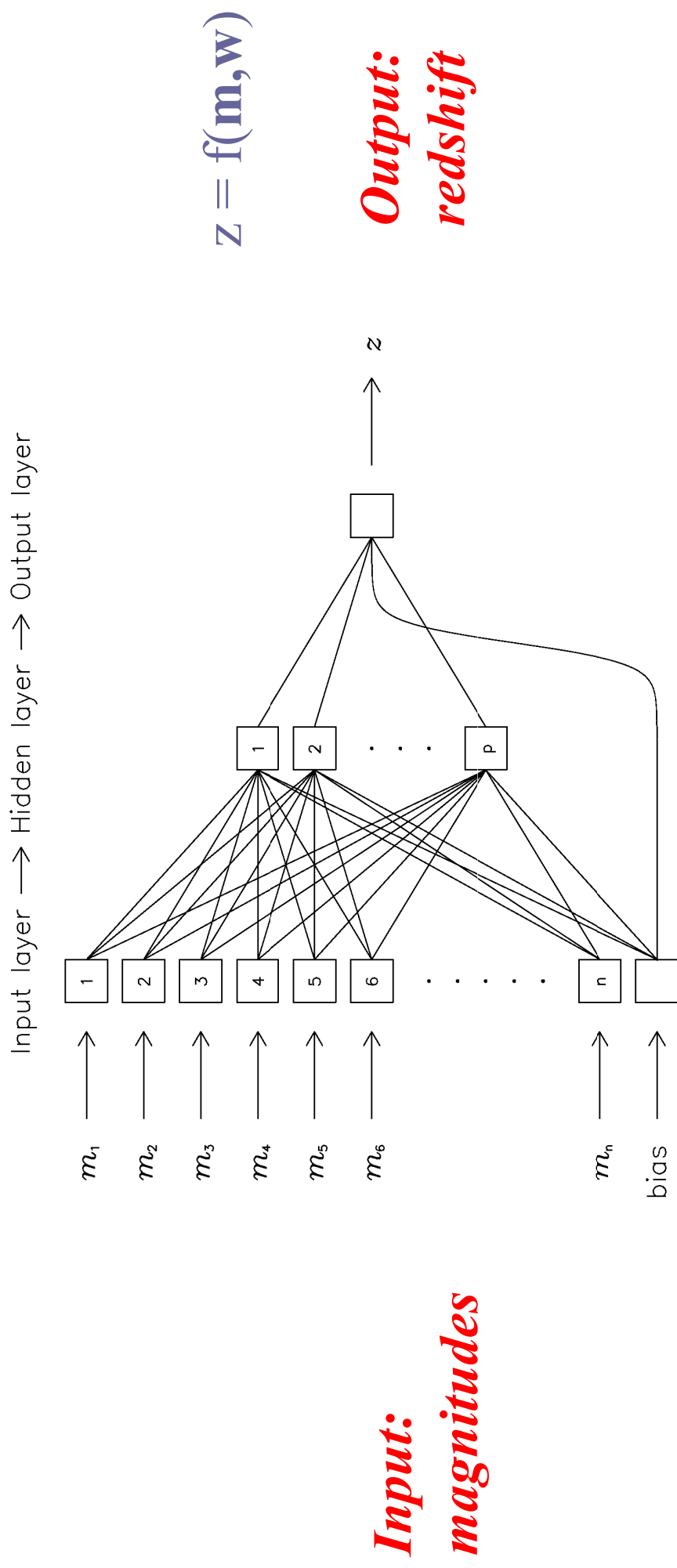
# Photometric redshift

- Probe strong spectral features (4000 break)
- Difference in flux through filters as the galaxy is redshifted.





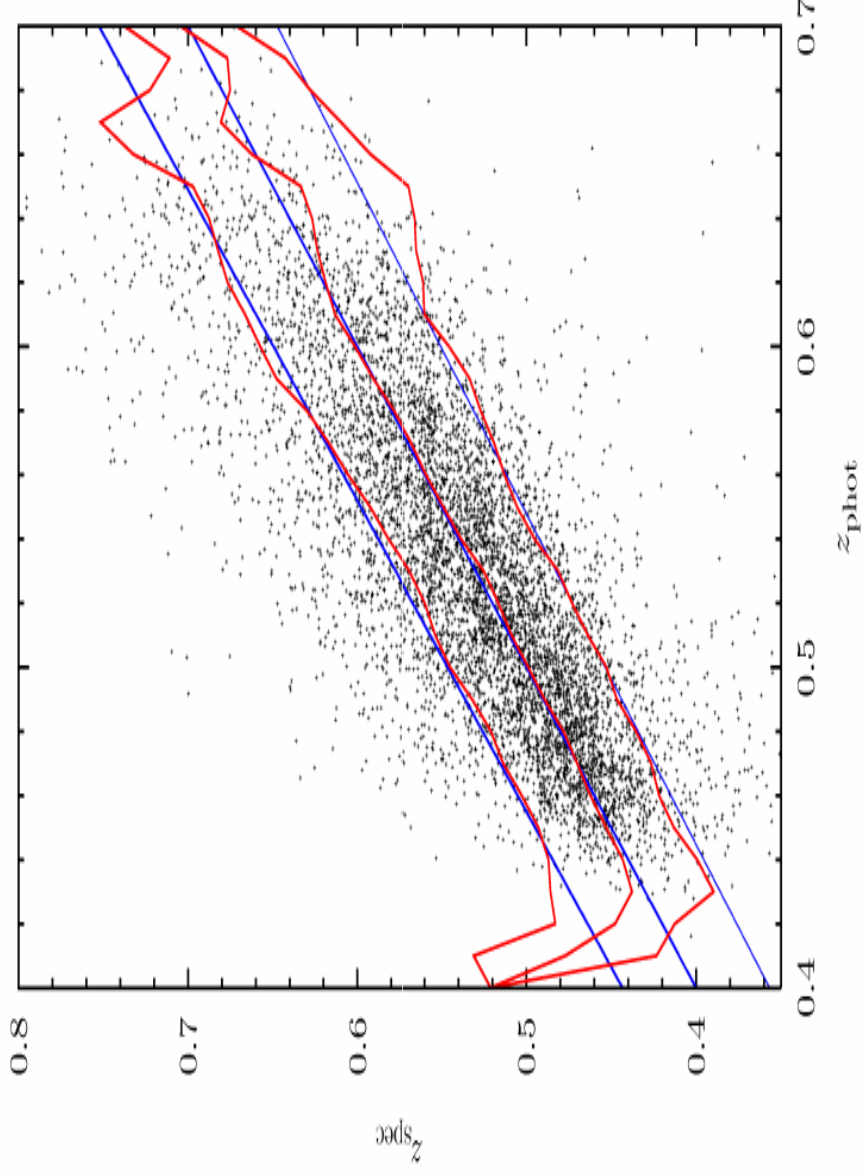
# ANNz - Artificial Neural Network



*Collister & Lahav 2004*

<http://www.star.ucl.ac.uk/~lahav/annz.html>

\*Training on  $\sim 13,000$  2SLAQ  
\*Generating with ANNz  
Photo-z for  $\sim 1,000,000$  LRGs  
MegaZ-LRG

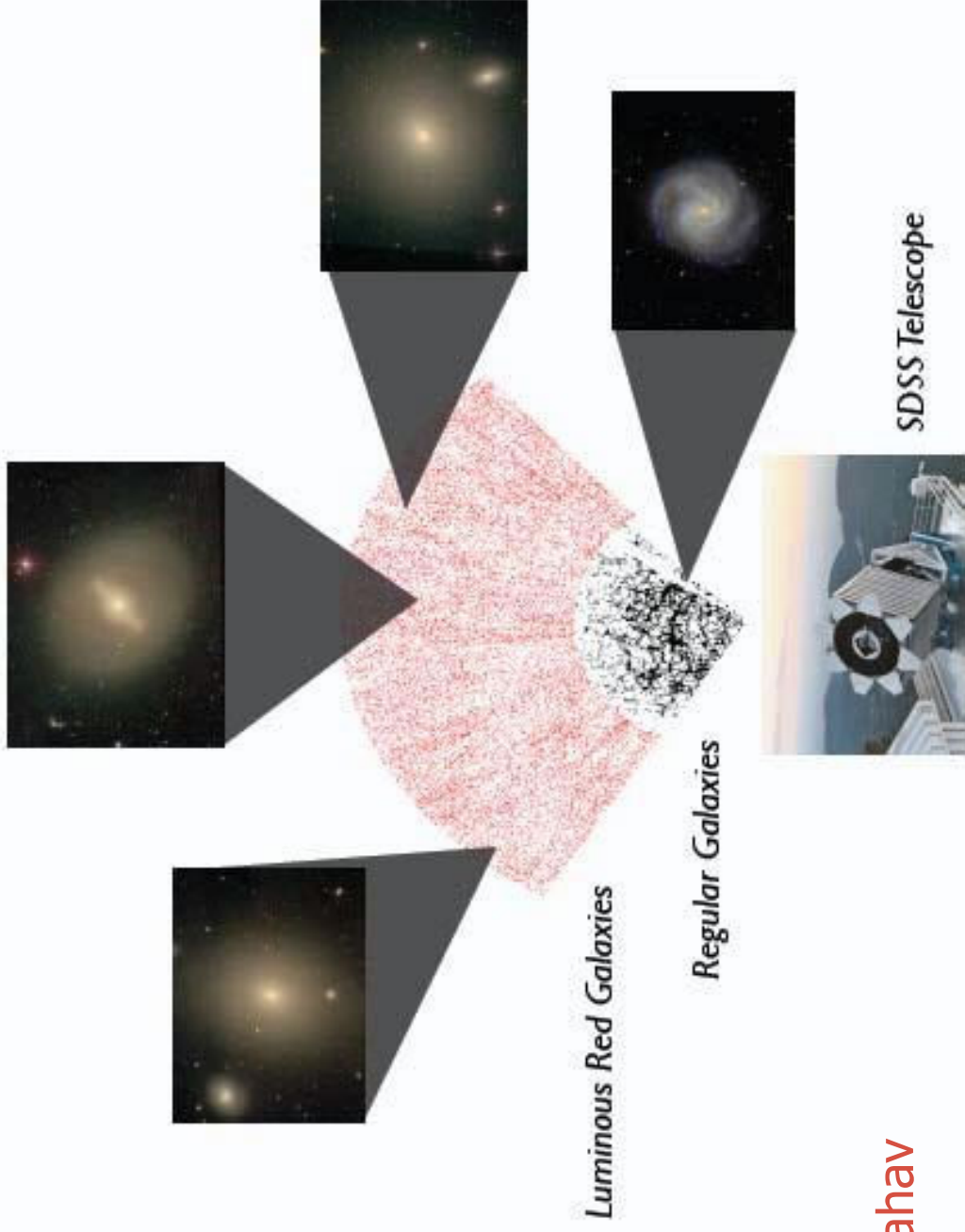


$$\sigma_z = 0.046$$

Collister, Lahav,  
Blake et al.,  
astro-ph/0607630

Edge of the Visible Universe

Most Distant Object Known ✧



Clustering on  
Gpc scale

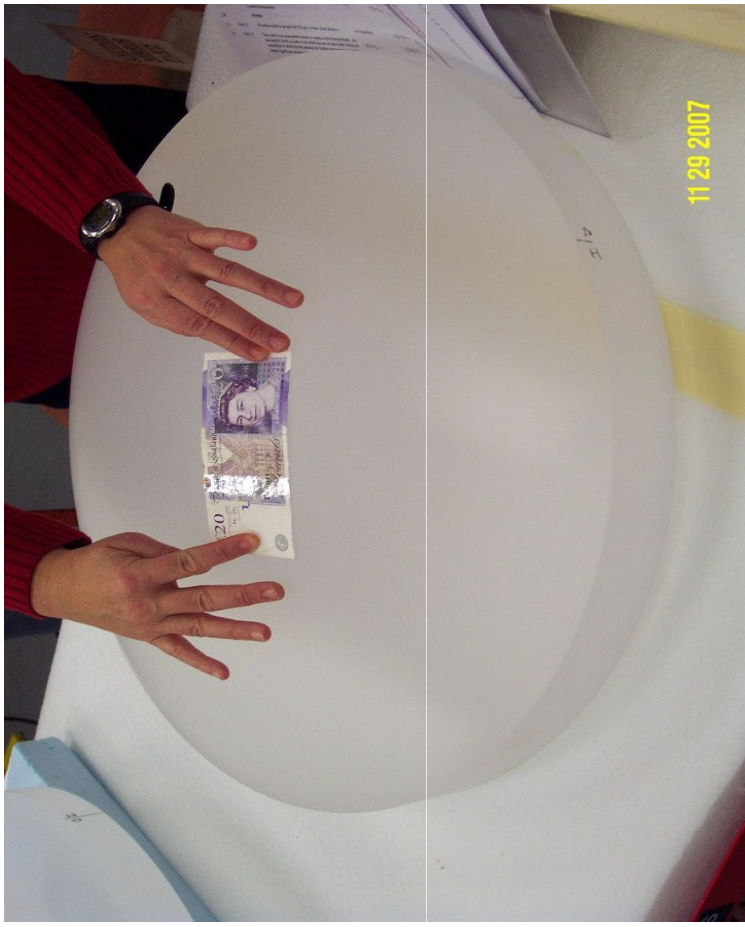
*LRG photo-z*

Padmanabhan et al  
Astro-ph/0605302

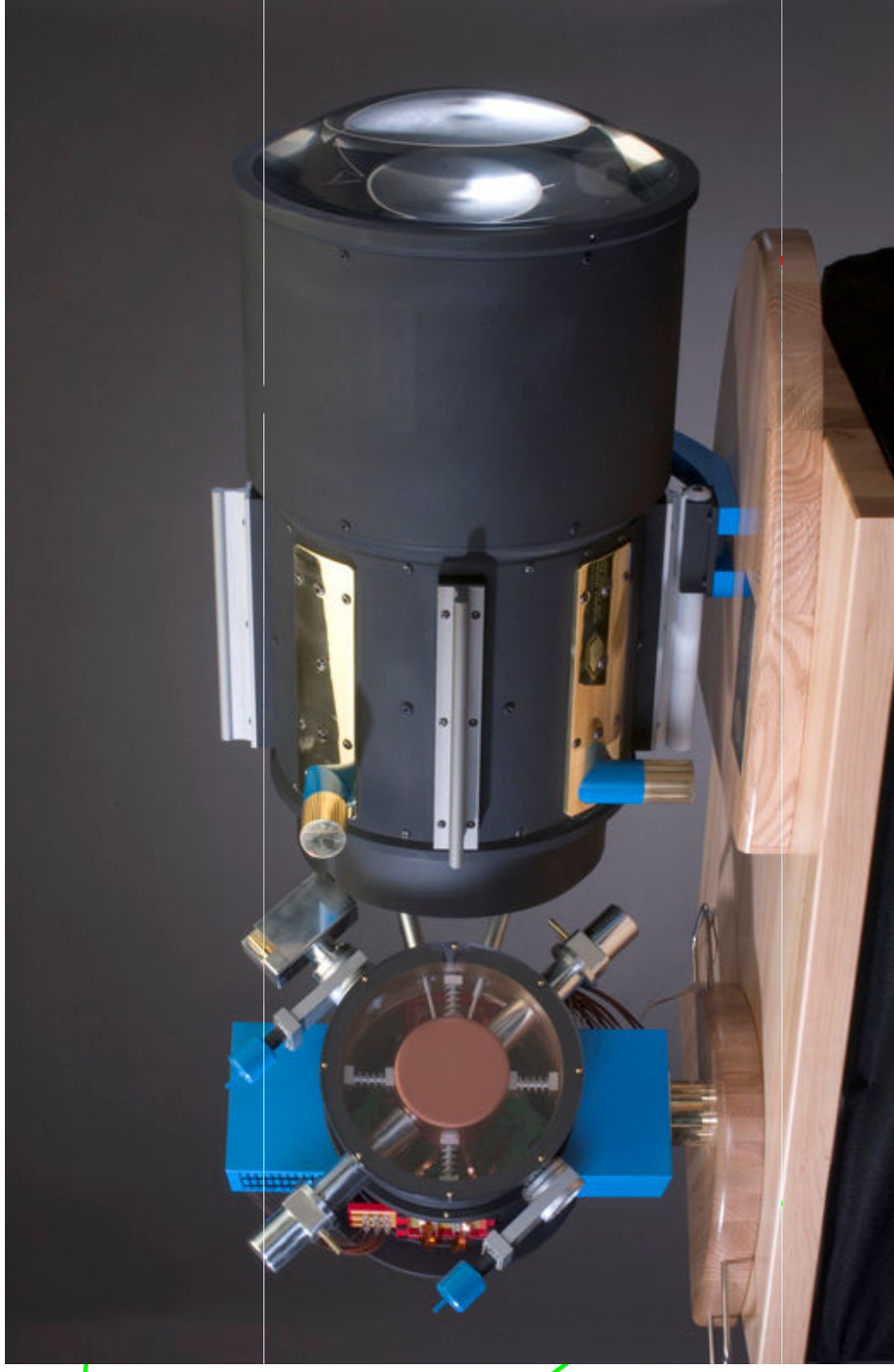
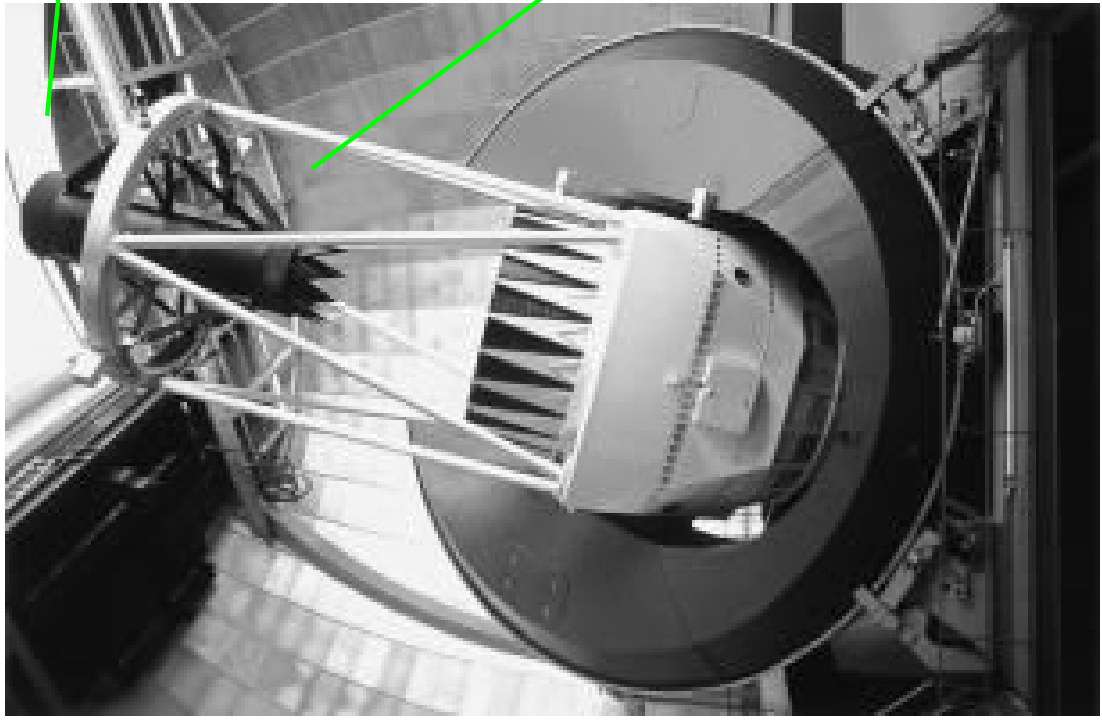
Blake, Collister, Bridle, Lahav  
Astro-ph/0605303

# The Dark Energy Survey

to map 300,000,000 galaxies,  
starting 2011

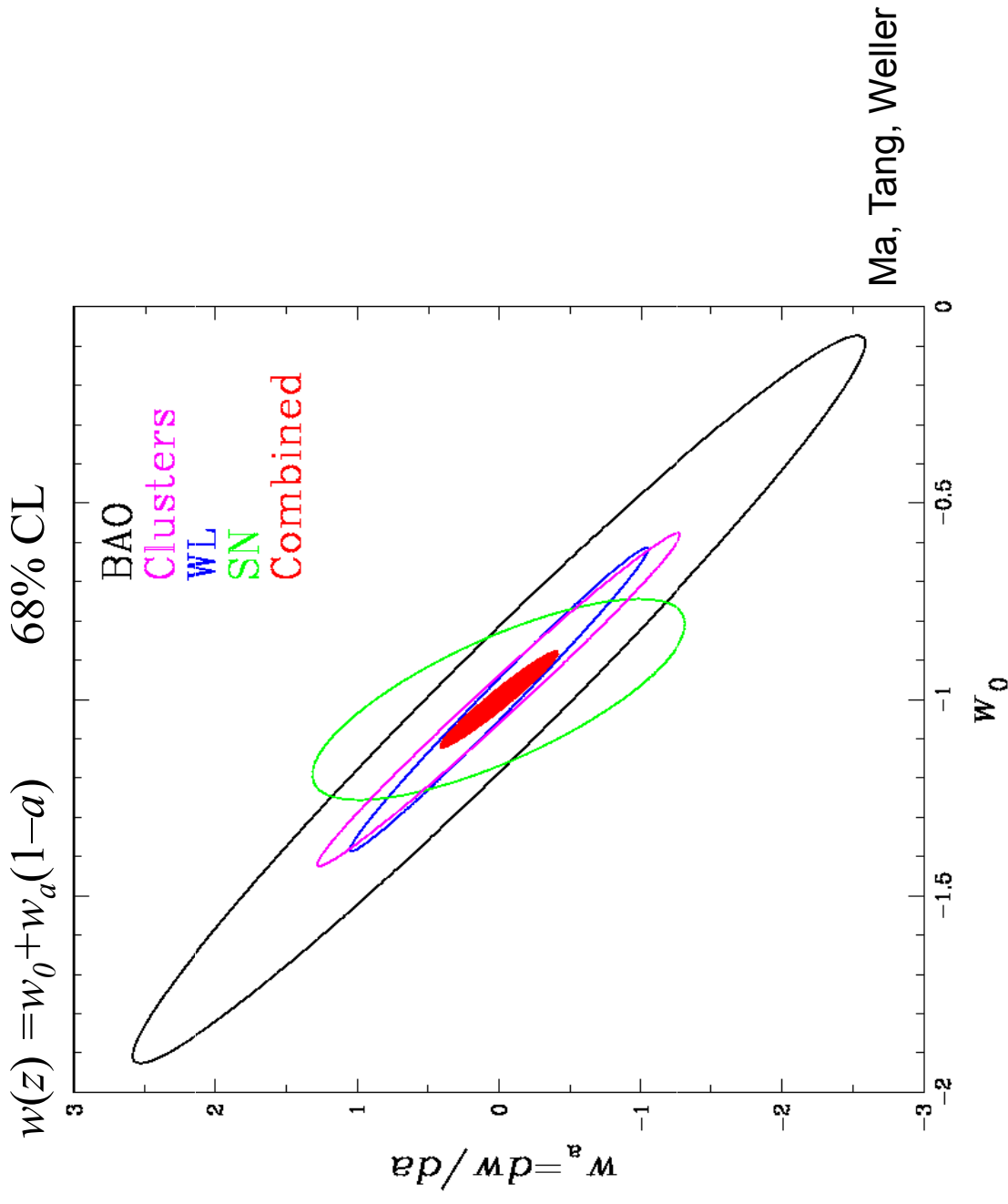


# Dark Energy Survey Instrument



New Prime Focus Cage, Camera, and  
Corrector for the Blanco 4m Telescope  
500 Megapixels, 0.27"/pixel  
Project cost: ~40M\$ (incl. labor)

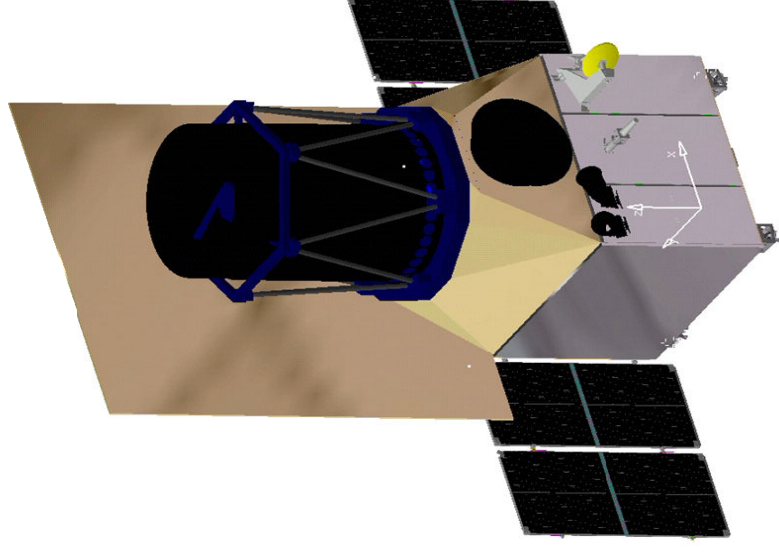
# DES Forecasts: Power of Multiple Techniques



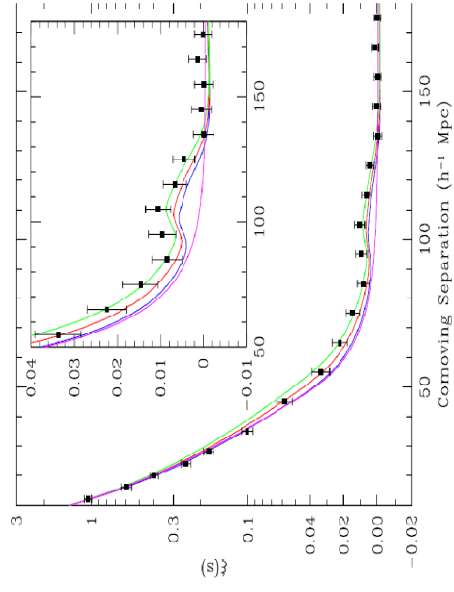
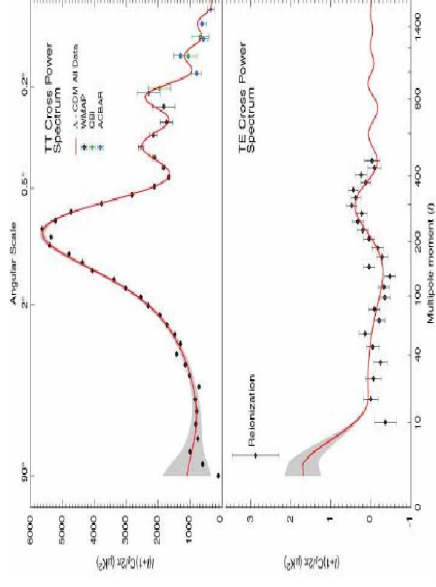
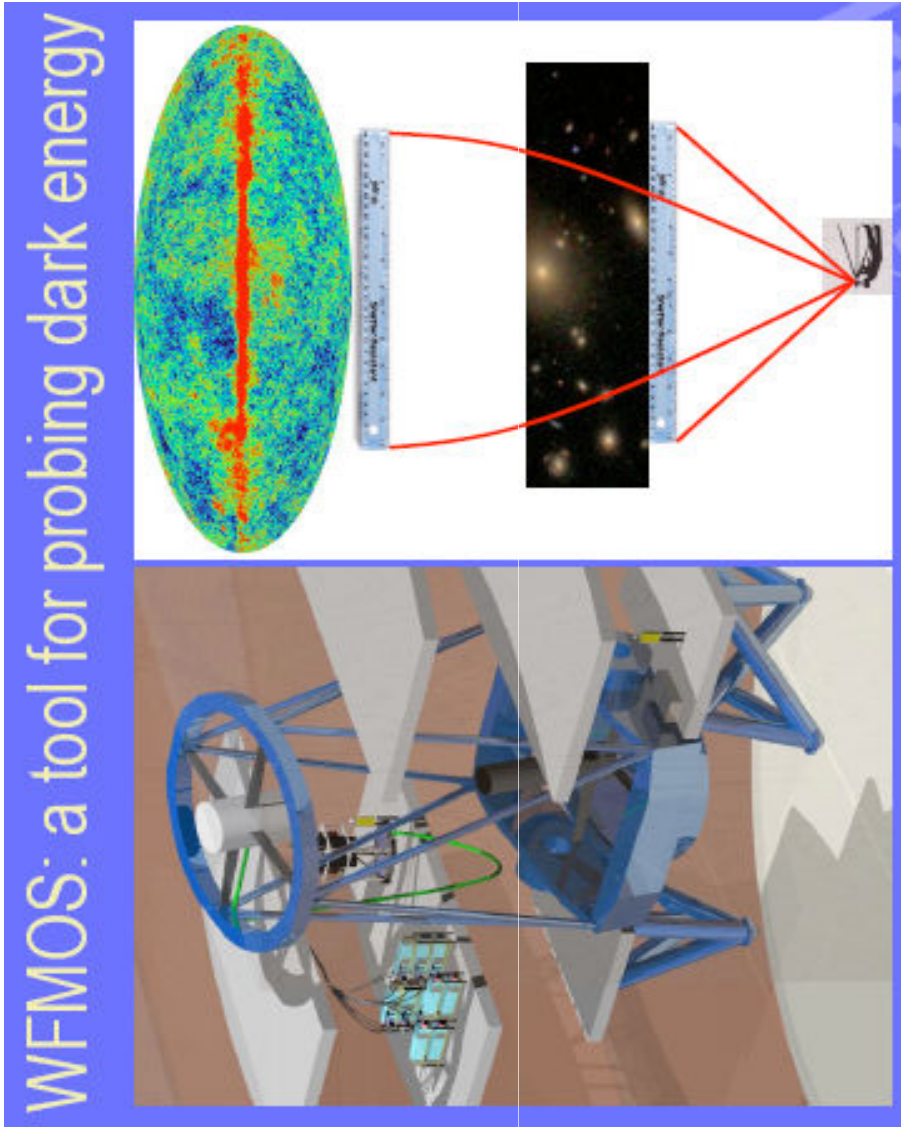
FoM factor **4.6** tighter compared to near term projects

**EUCLID: Obeserving the  
dark universe from space**

**ESA Cosmic Vision  
(2017)**



# Baryon Wiggles as Standard Rulers





# Some Outstanding Questions:

- \* Vacuum energy  
(cosmological constant,  $w = -1.000$  after all ?)
- \* Dynamical scalar field ?
- \* Modified gravity ?
- \* Why  $\Omega_\Lambda / \Omega_m = 3$  ?
- \* Non-zero Neutrino mass  $< 1\text{eV}$  ?
- \* The exact value of the spectral index:  $n < 1$  ?
- \* Excess power on large scales ?
- \* Is the curvature zero exactly ?