Observing Dark Matter and Dark Energy

STFC summer school, 1 Sep 2008

Ofer Lahav
University College London

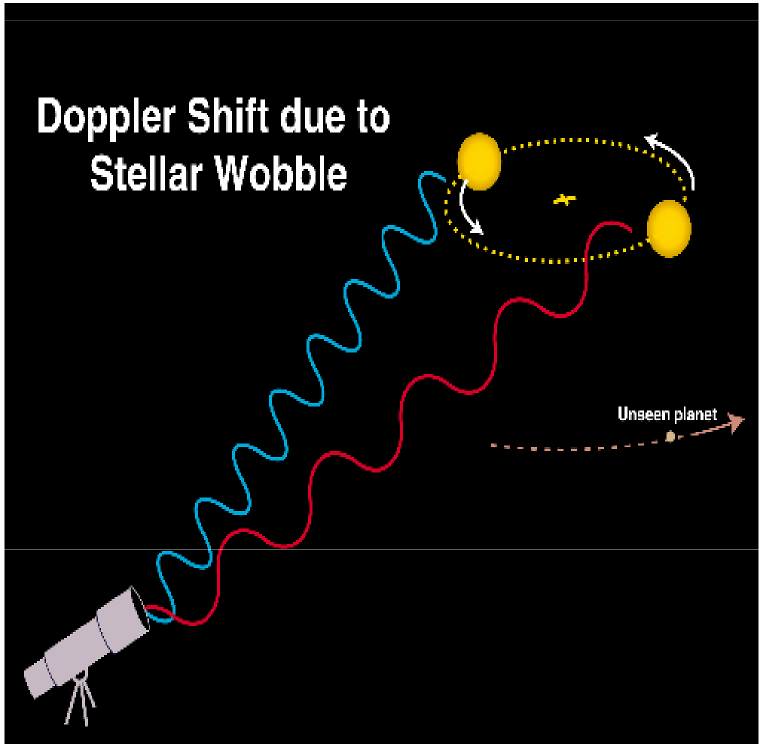
UCL

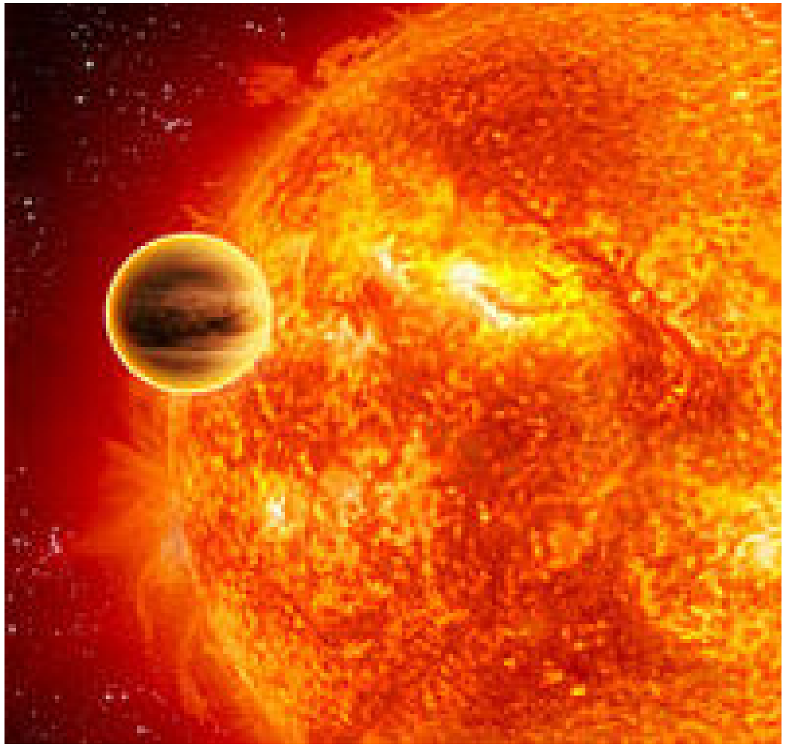
Astrophysics

http://www.star.ucl.ac.uk

University College London

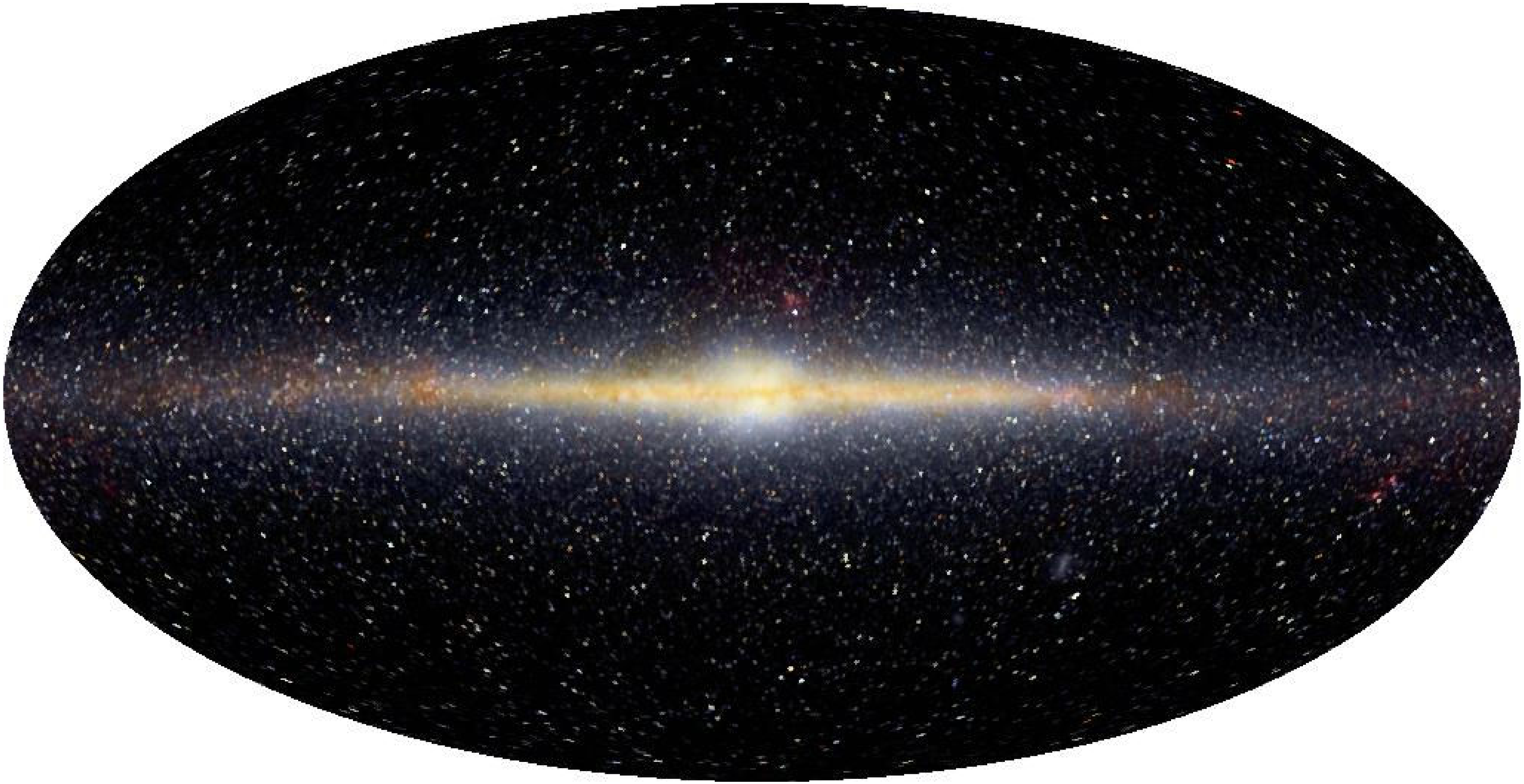
Extra-solar planets



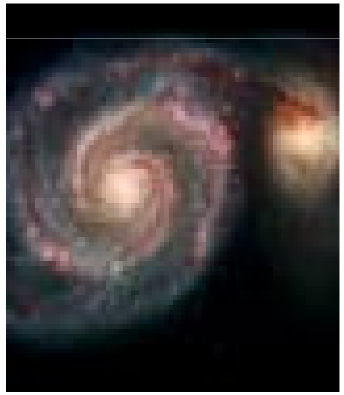


Water on a another planet!

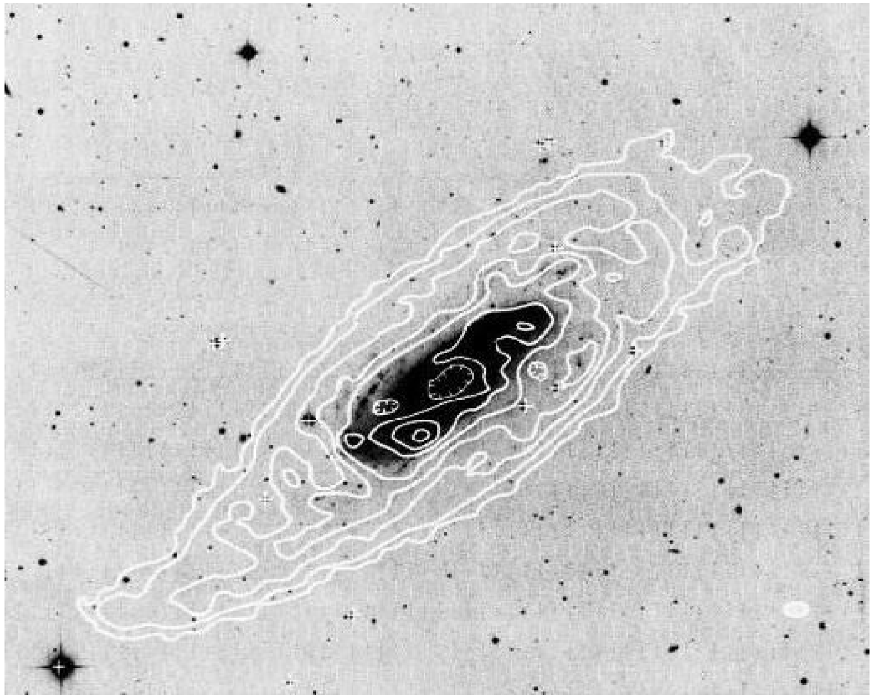
Our Galaxy – The Milky Way

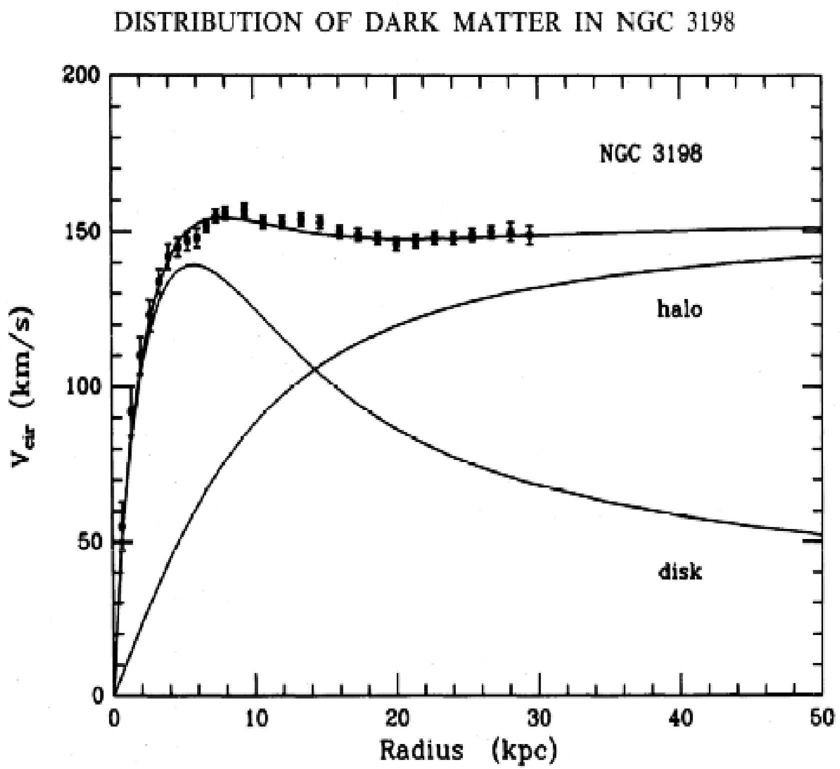


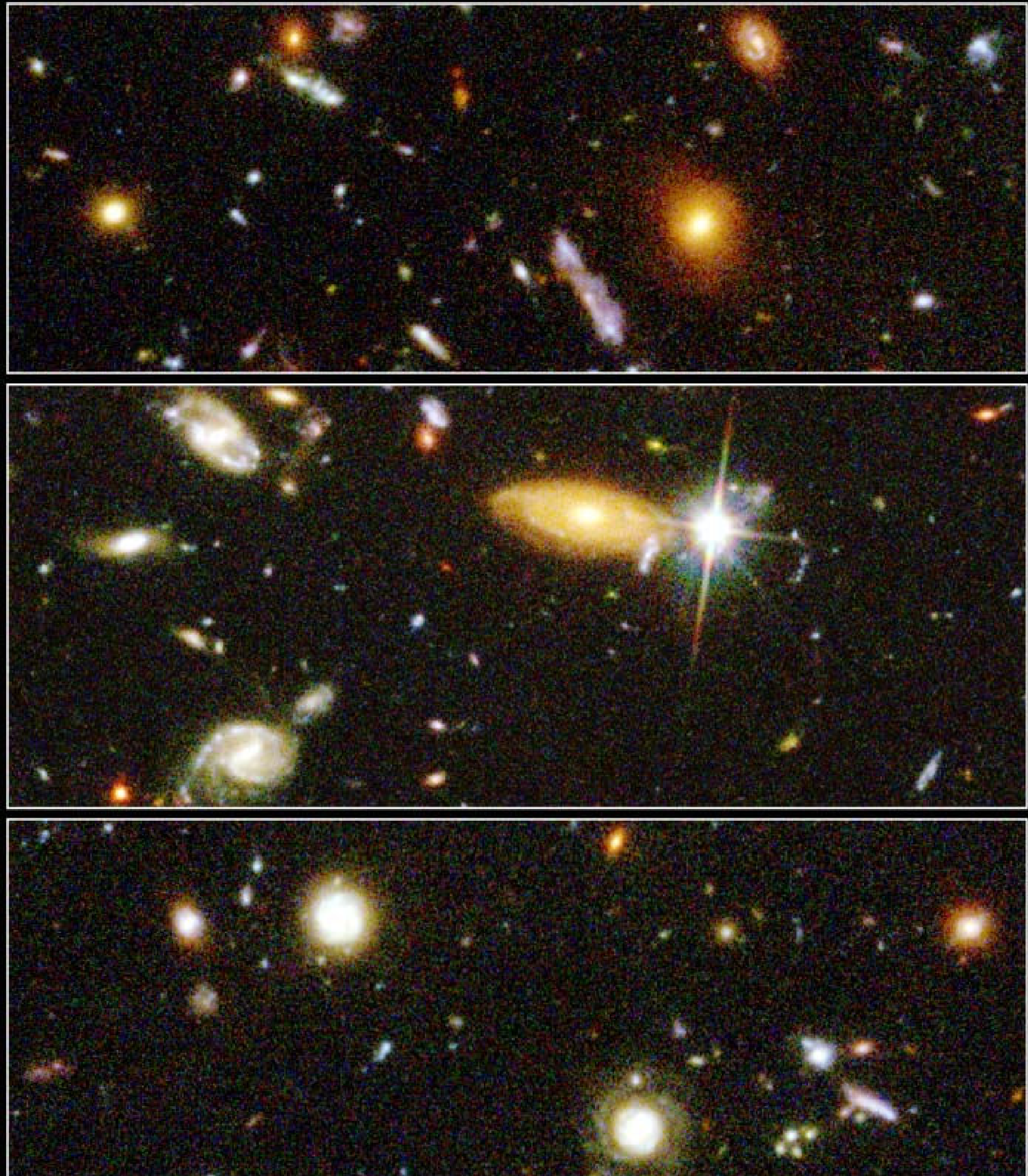
Galaxies



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

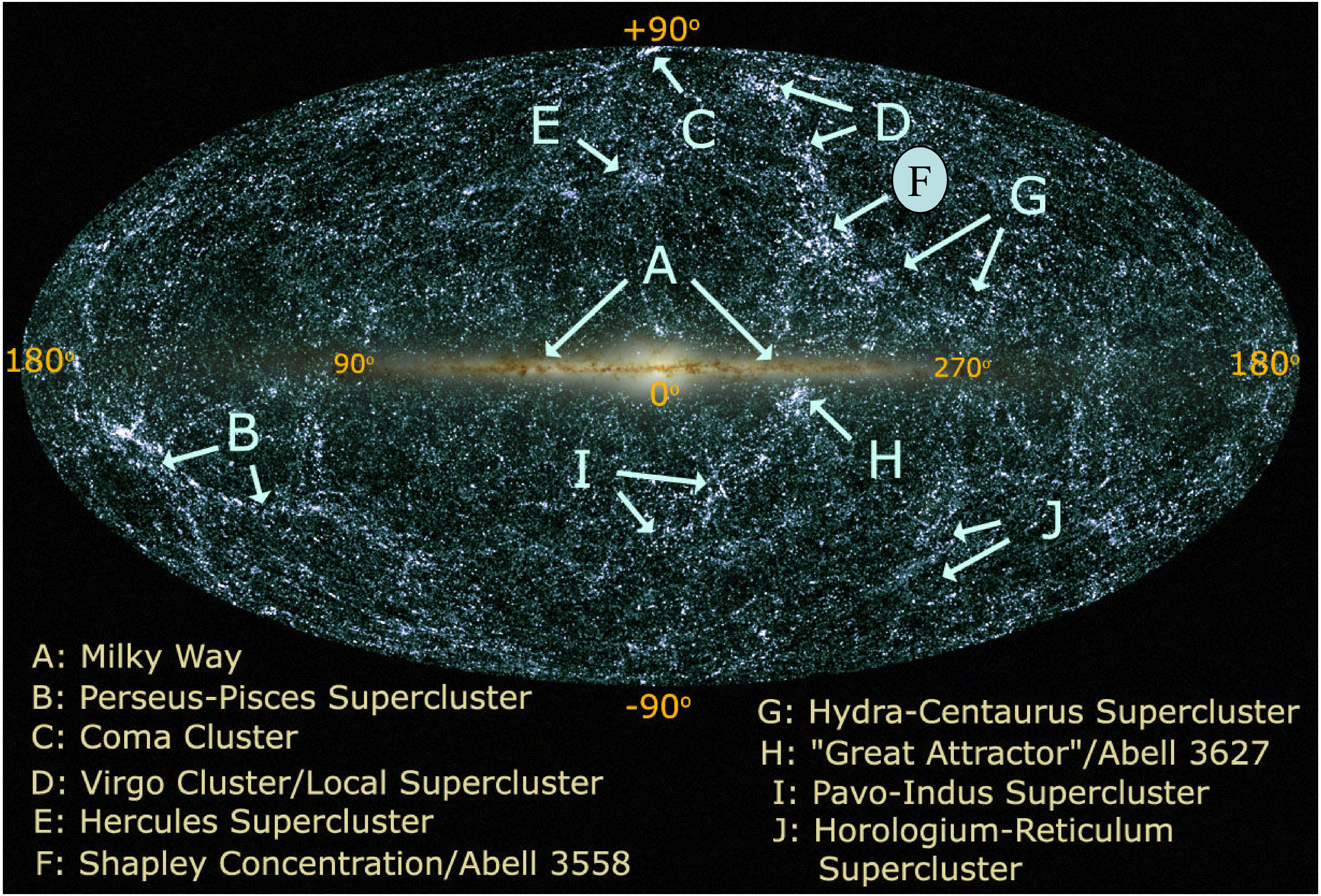






Hubble Deep Field Details HST • WFPC2

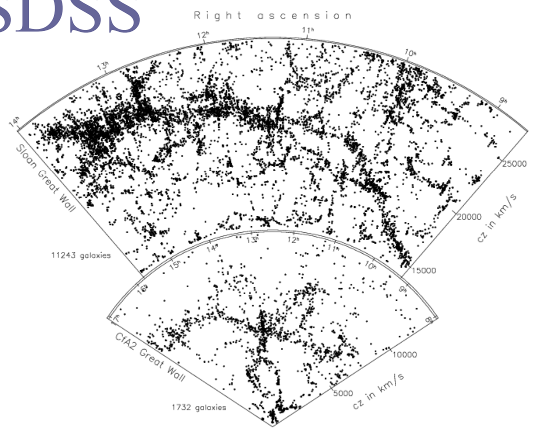
PRC96-01b • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA



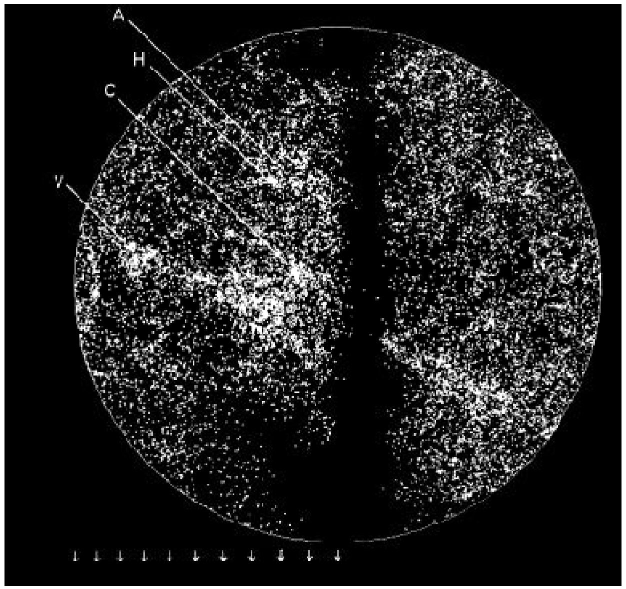
2MASS Galactic chart

The Cosmic Web

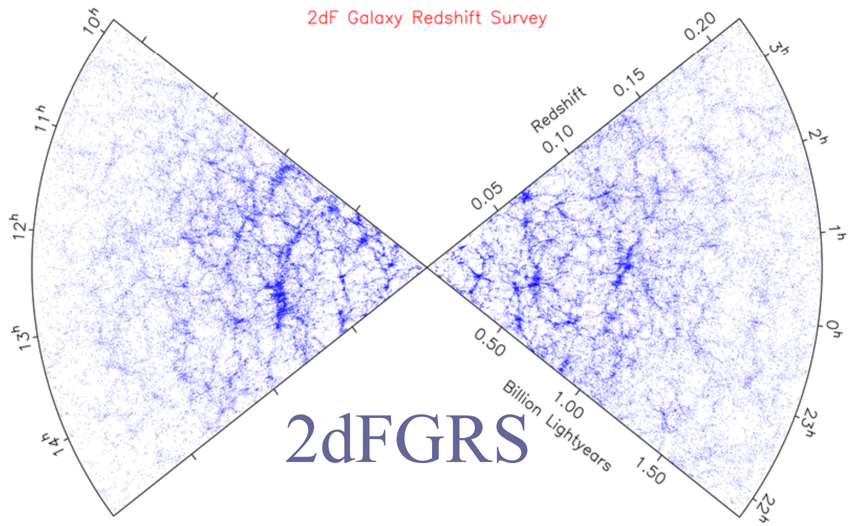
SDSS



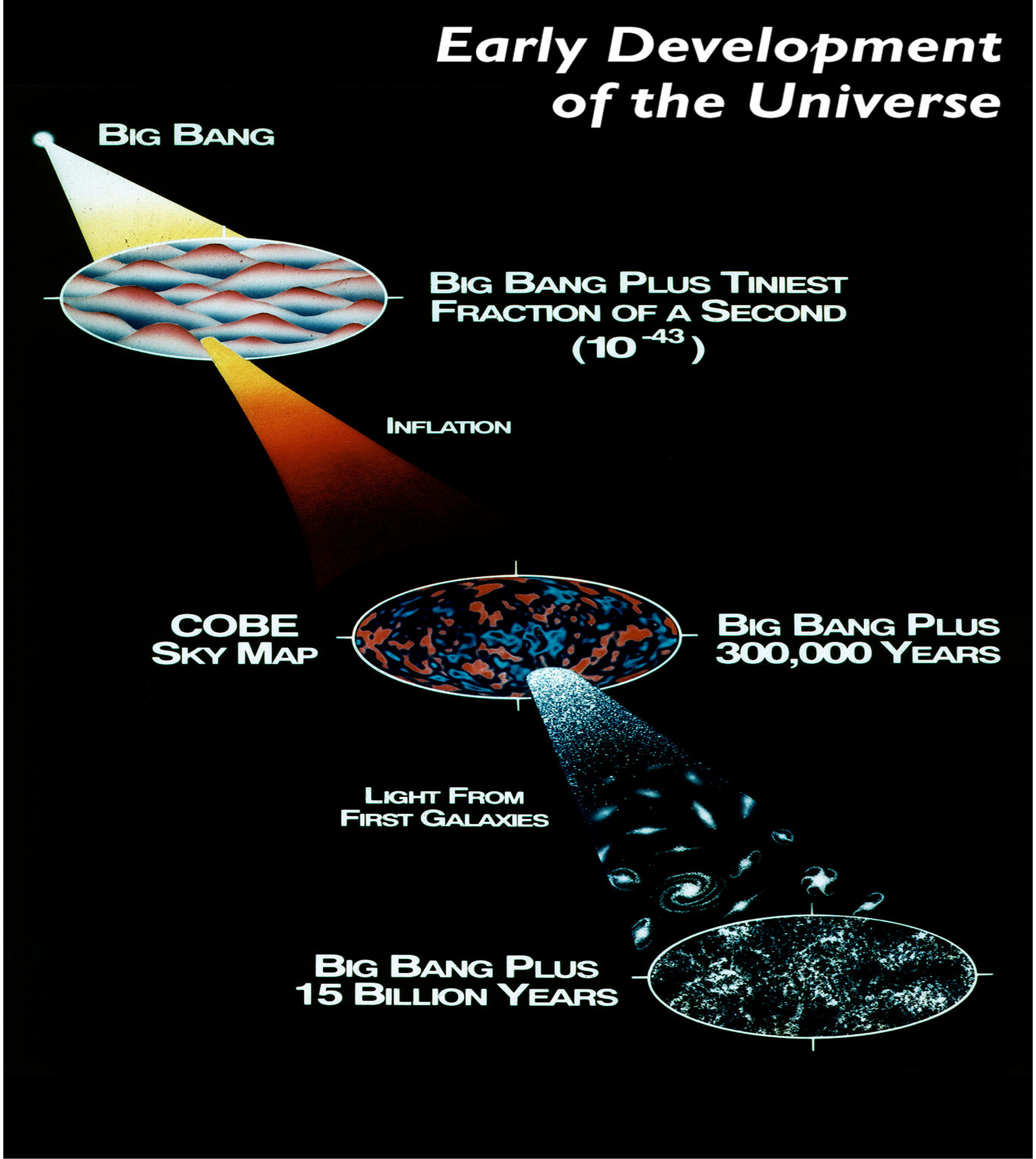
CfA Great Wall



Great Attractor



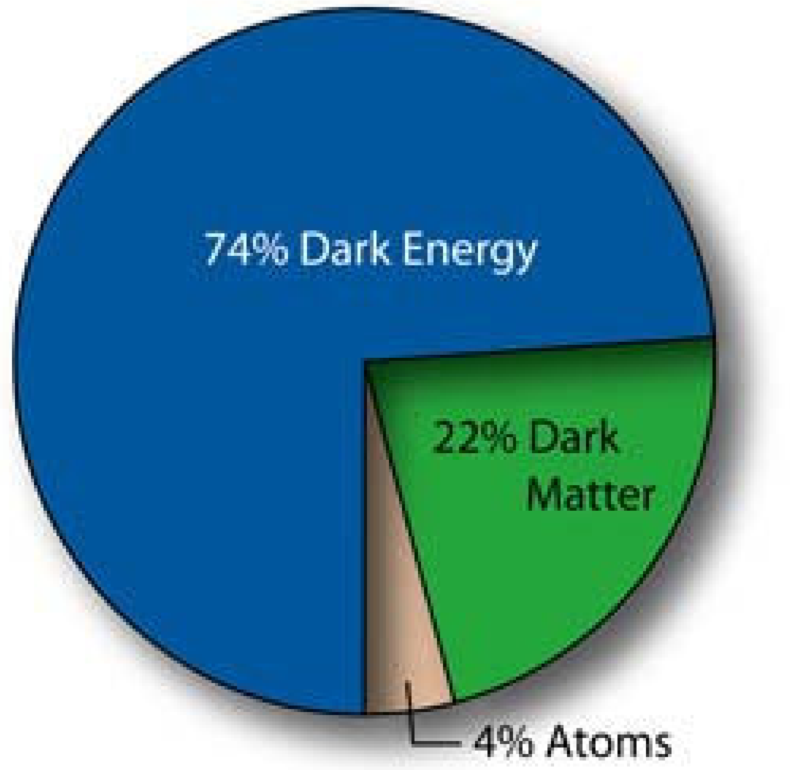
2dFGRS


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:

$$H^2(z) = H^2_0 \; [\Omega_M \,(1+z)^{\,3} + \Omega_{DE}\,(1+z)^{\,3\,(1+w)}] \qquad \text{(flat)}$$

The Chequered History of the Cosmological Constant Λ

The old CC problem:

Theory exceeds observational limits on Λ by 10^{120} !

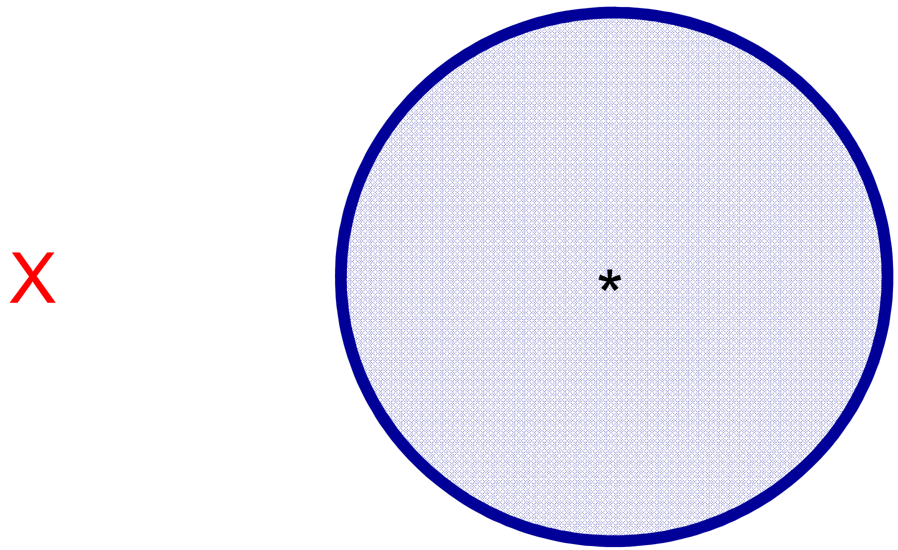
The new CC problem:

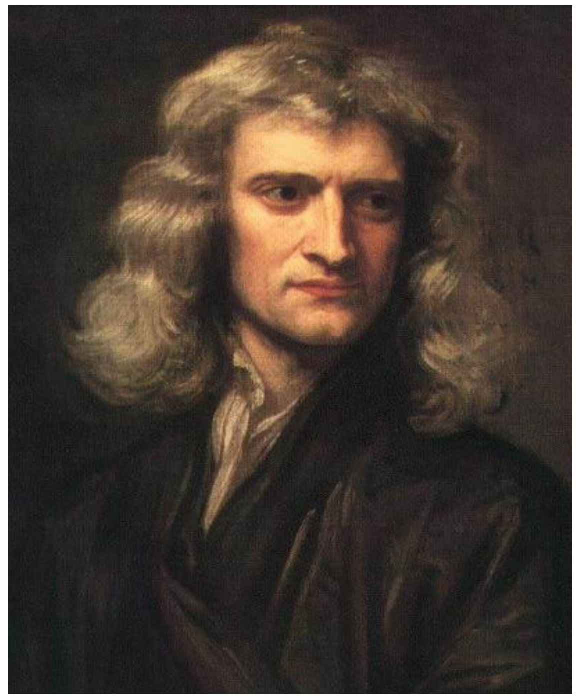
Why are the amounts of Dark Matter and Dark Energy so similar?

Back to Newton's Principia?

Weak field limit of GR:

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





Lucy Calder & OL
A&G Feb 08 issue
http://www.star.ucl.ac.uk/~lahav/CLrev.pdf
(revised)

Newton, Principa (1687, Book I, Proposition 77, Theorem 37)

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

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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.

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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:

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

Curvature *Matter* *Dark (Vacuum) Energy*

OR modified curvature

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

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 Ω_b
- Matter Ω_m
- Dark Energy (Cosmological Constant) Ω_Λ
- Hubble parameter H_0
- Amplitude A
- Initial shape of perturbations n

Probing Dark Matter & Dark Energy

- Through the history of the expansion rate:

$$H^2(z) = H^2_0 \; [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}] \qquad \text{(flat Universe)}$$

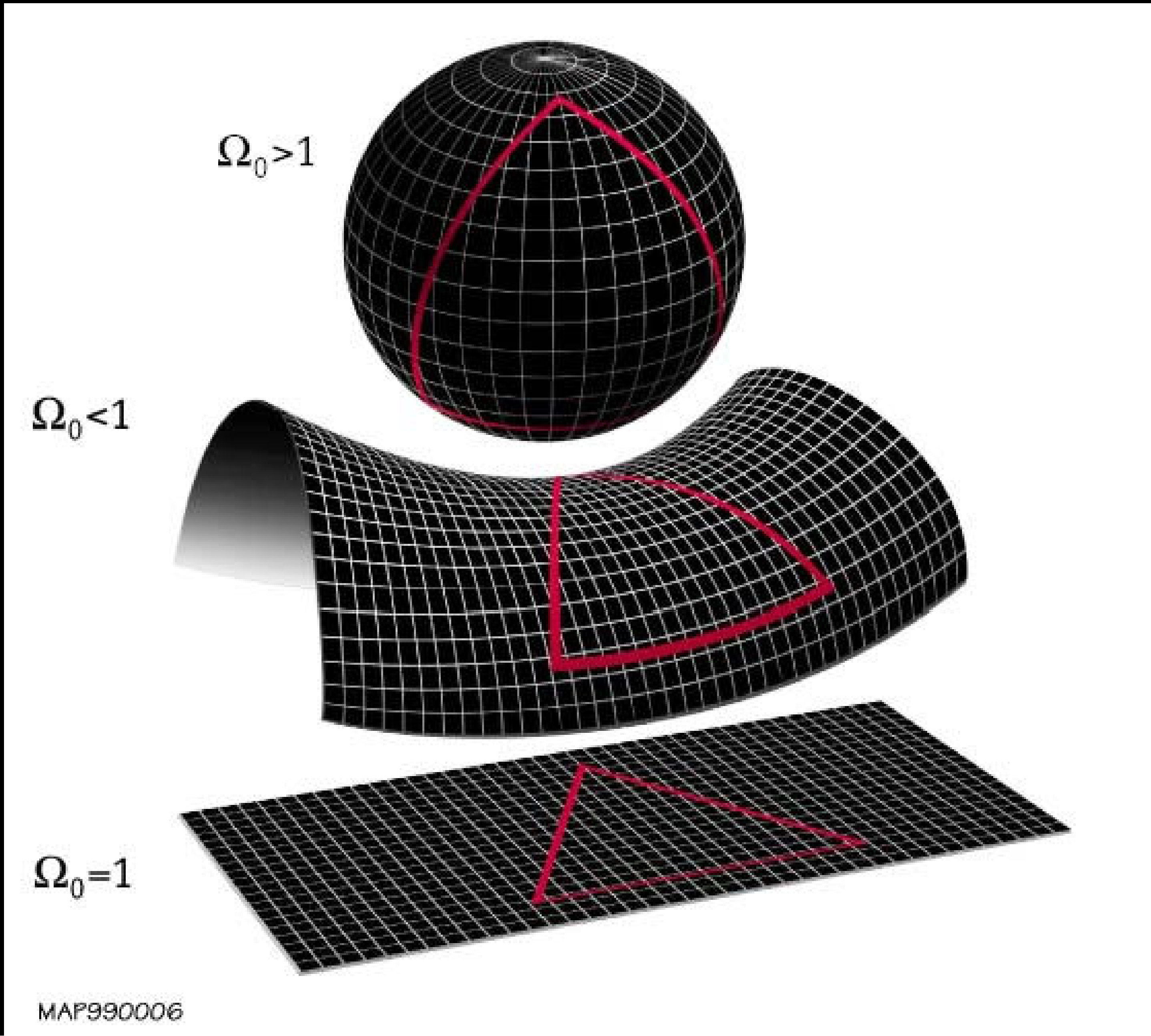
matter — dark energy (constant w)

$P = w \rho$

- Comoving distance: $r(z) = \int dz/H(z)$
- Standard Candles: $d_L(z) = (1+z)\, r(z)$
- Standard Rulers: $d_A(z) = (1+z)^{-1}\, r(z)$

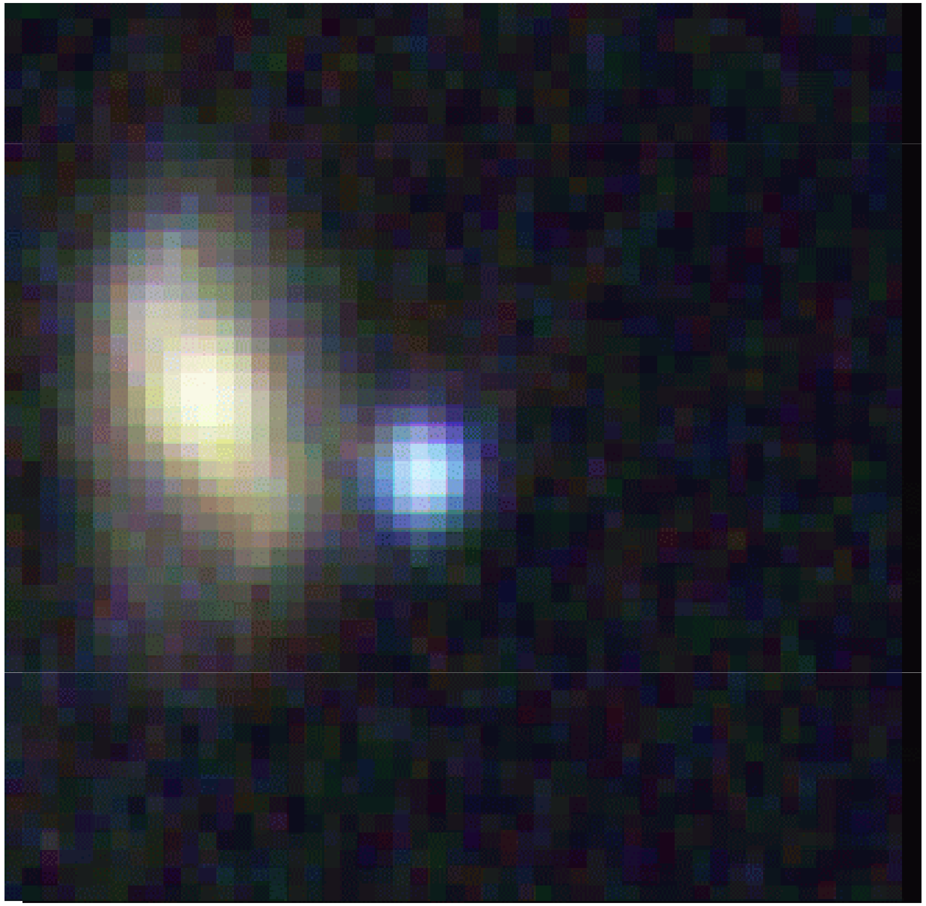
- The rate of growth of structure also determined by H(z) and by any modifications of gravity on large scales

Curvature of the Universe bends light



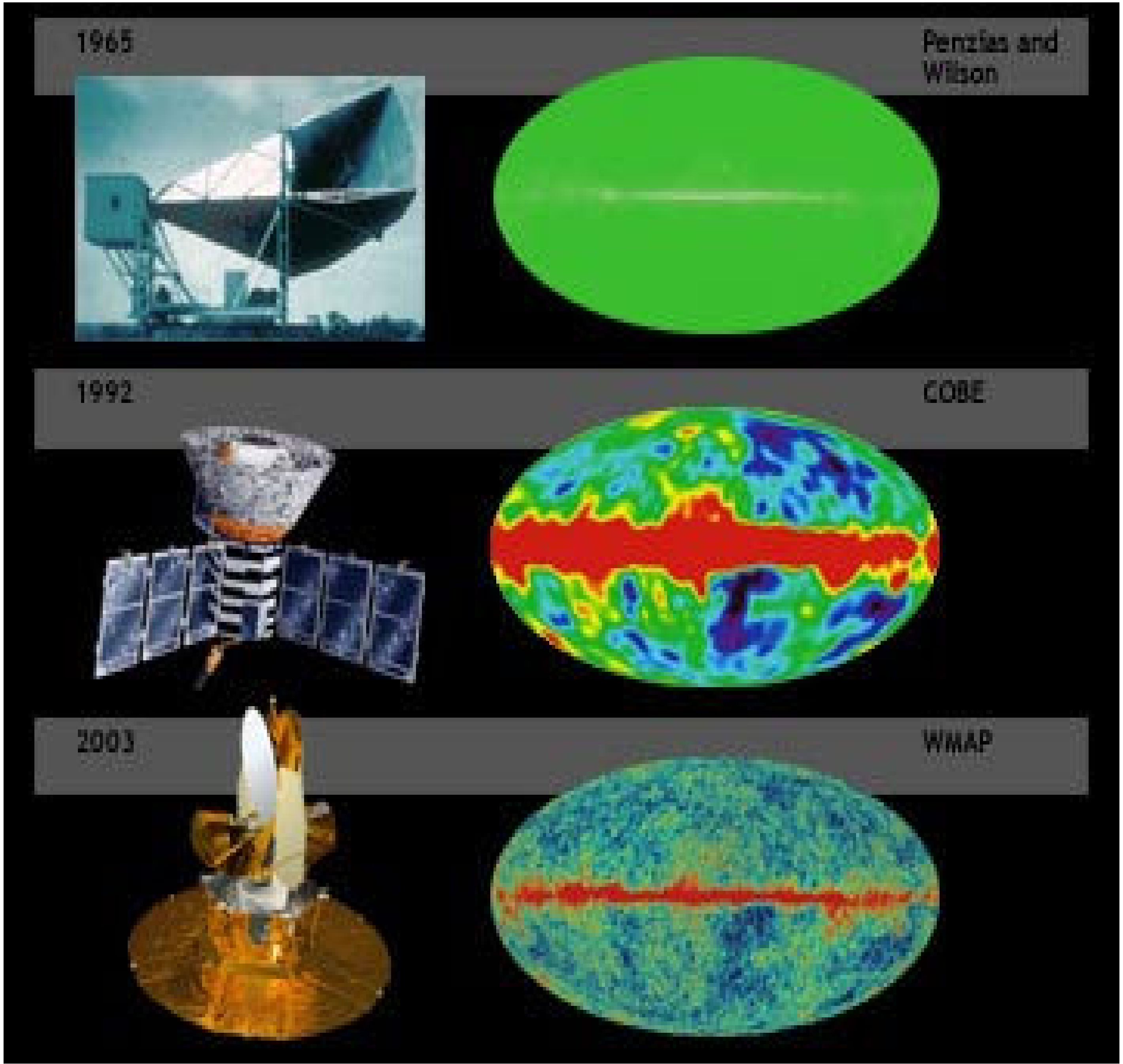
Supernovae

- Geometric Probe of Dark Energy



SDSS

The History of CMB observations

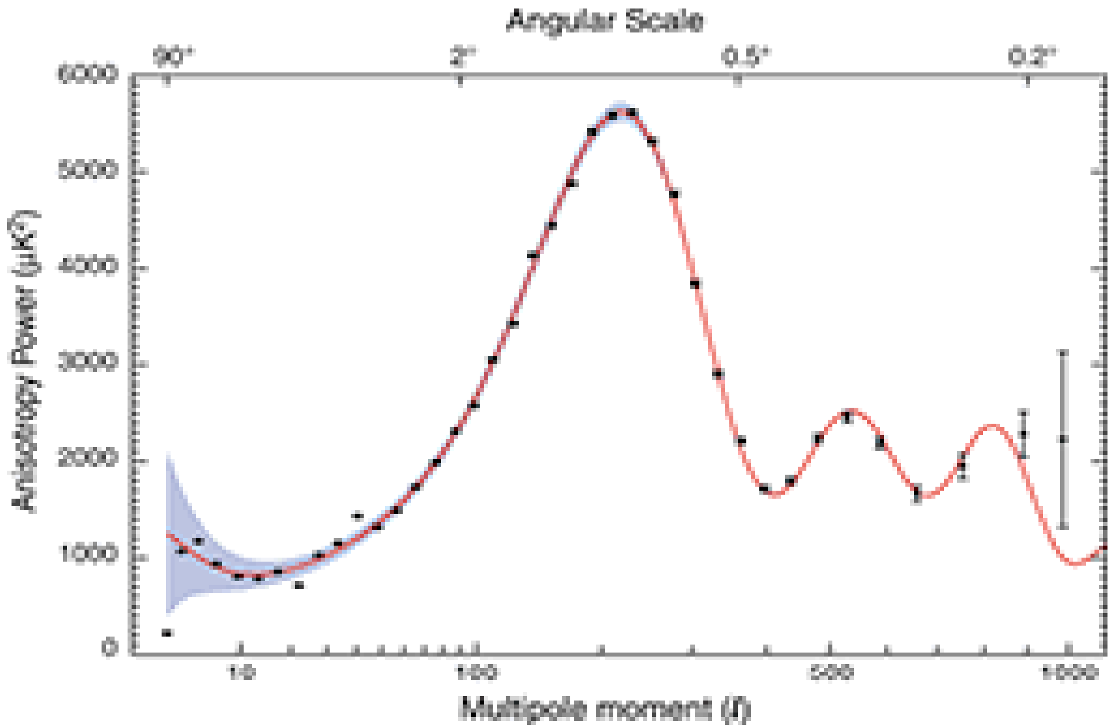


1965 — Discovery

1992 — COBE

2003 — WMAP

WMAP3



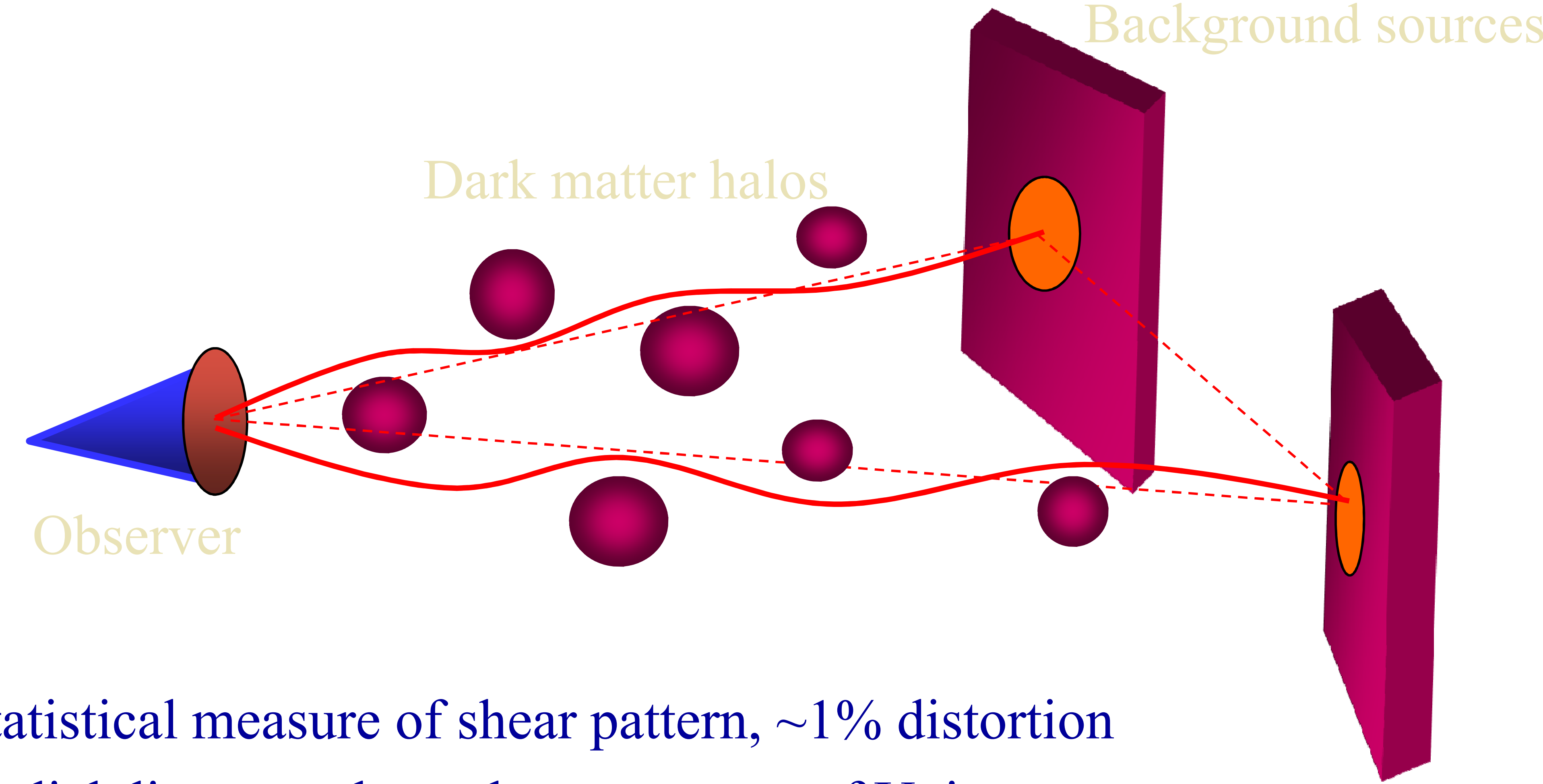
$\Omega_m = 0.24 \pm 0.04$

$\sigma_8 = 0.74 \pm 0.06$

$n = 0.95 \pm 0.02$

$\tau = 0.09 \pm 0.03$

Weak Lensing: Cosmic Shear

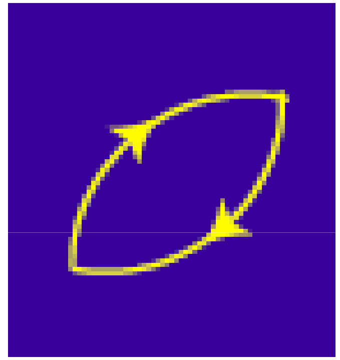


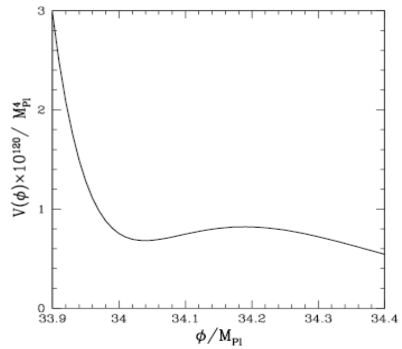
- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

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?





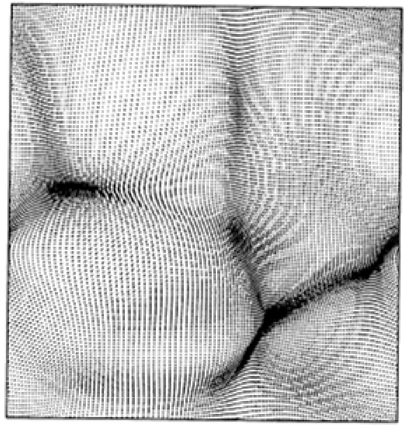
Brief History of 'Hot Dark Matter'

* 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%):

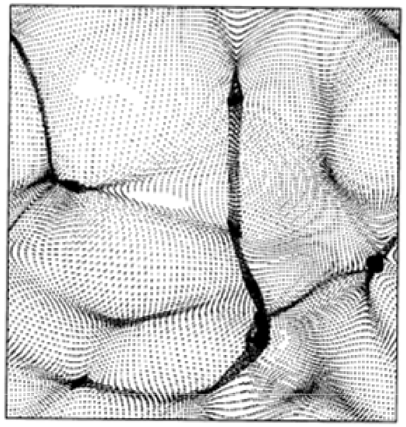
  But now we know HDM exists!
  How much?

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

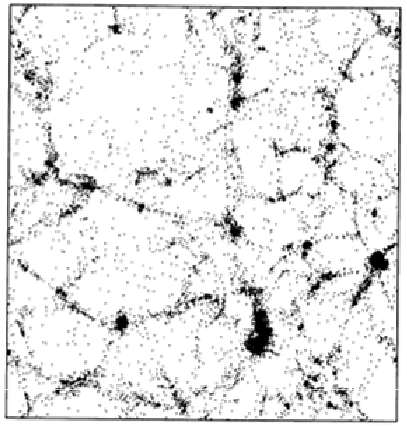
112 neutrinos per cm^3



CDM+HDM



WDM



CDM

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

From Ly-a+SDSS +CMB $M_\nu < 0.17\ eV$ *(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(model | data)=
  P(data | model) P (model) / P(data)

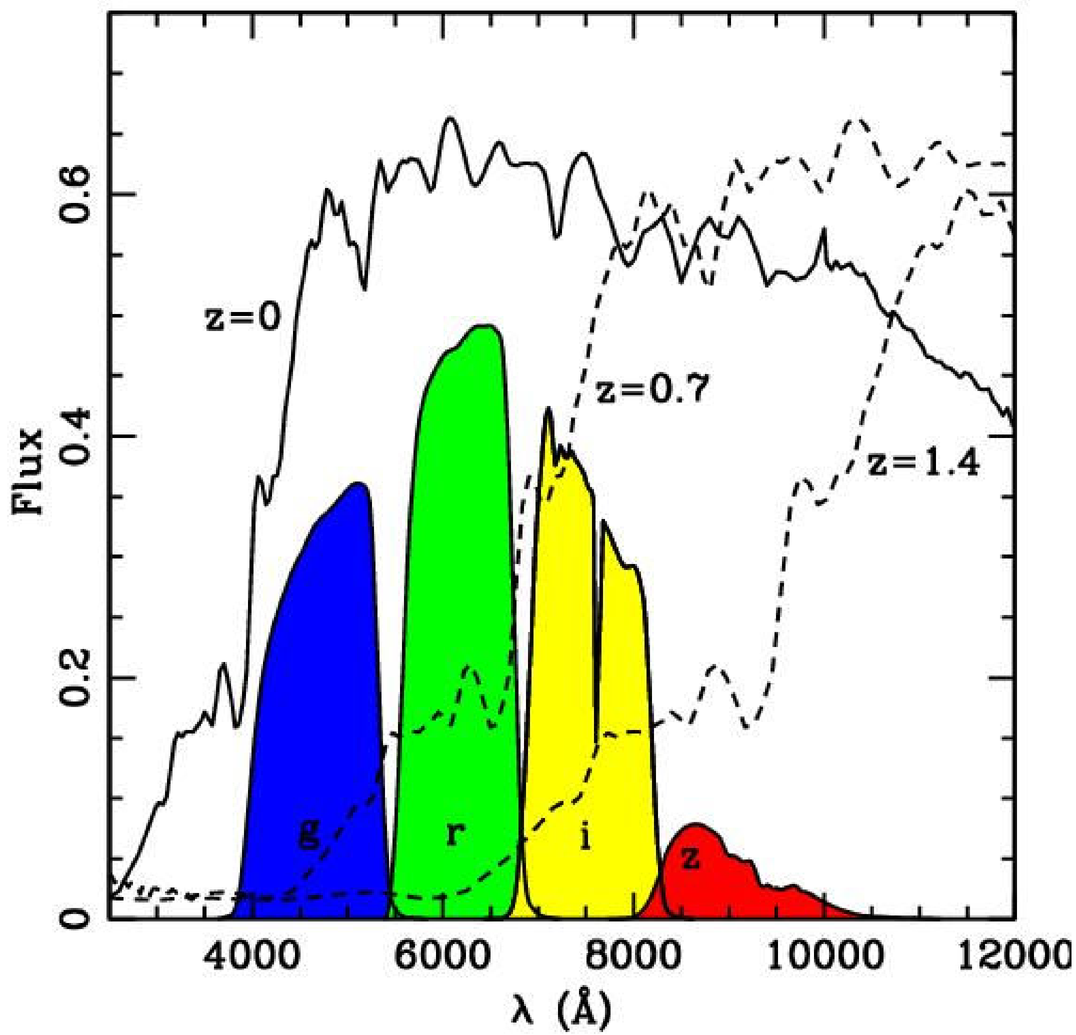
↑	↑	↑
Likelihood	*Prior*	*Evidence*
$exp\,(-\chi^2/2)$		

1702-1761
(paper only published in 1764)

Photometric redshift

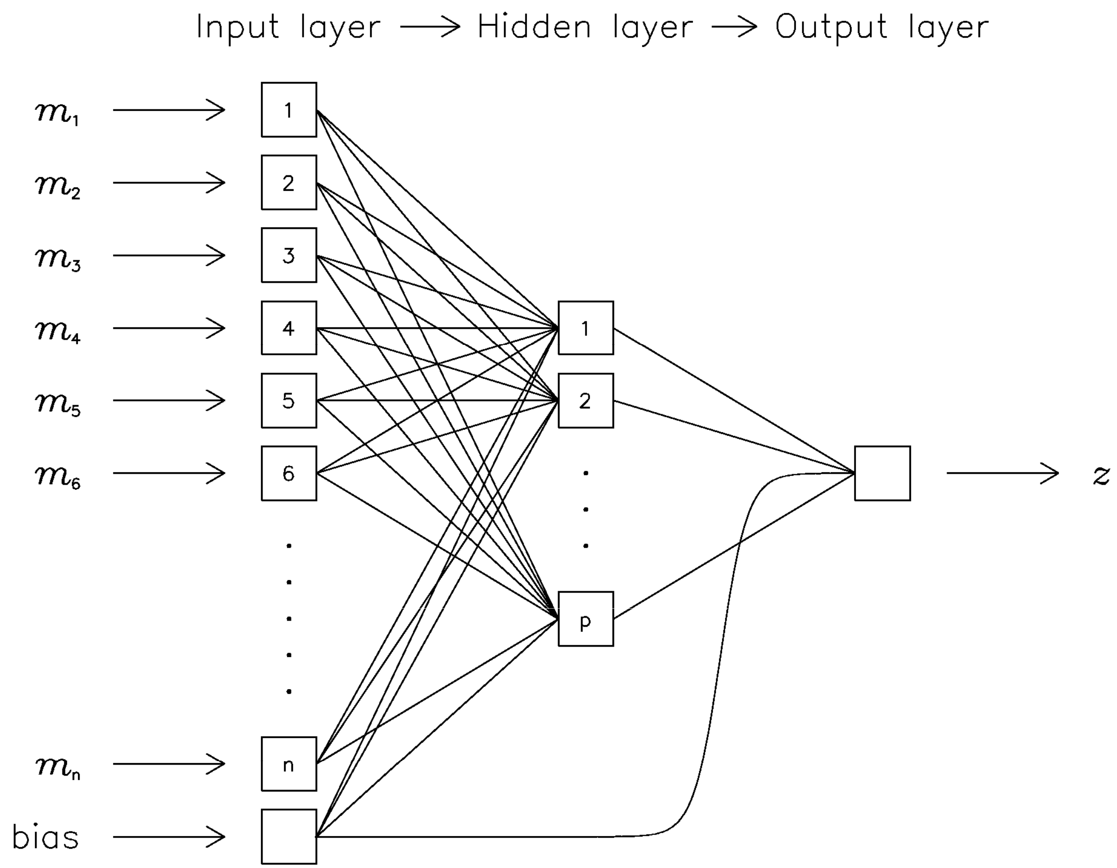
- Probe strong spectral features (4000 break)

- Difference in flux through filters as the galaxy is redshifted.



ANNz - Artificial Neural Network

Input: magnitudes



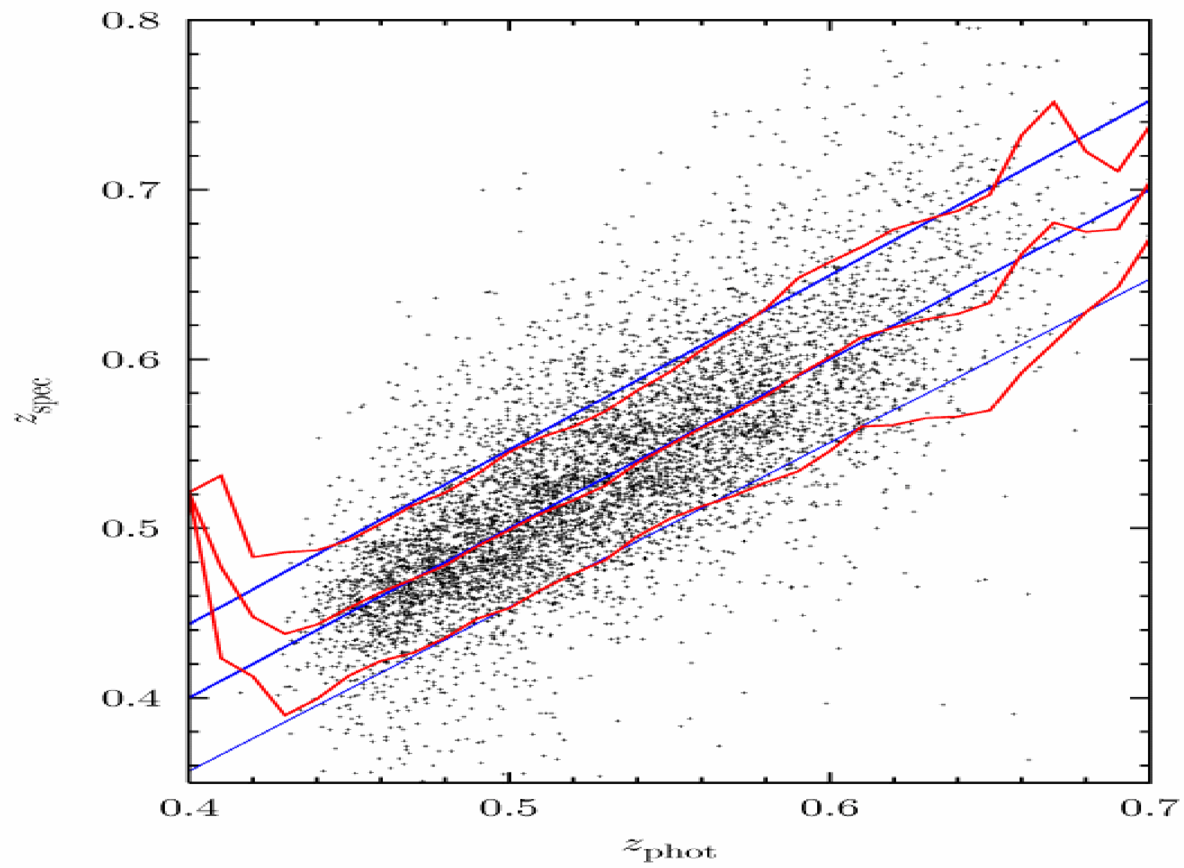
$z = f(\mathbf{m},\mathbf{w})$

Output: redshift

Collister & Lahav 2004

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

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

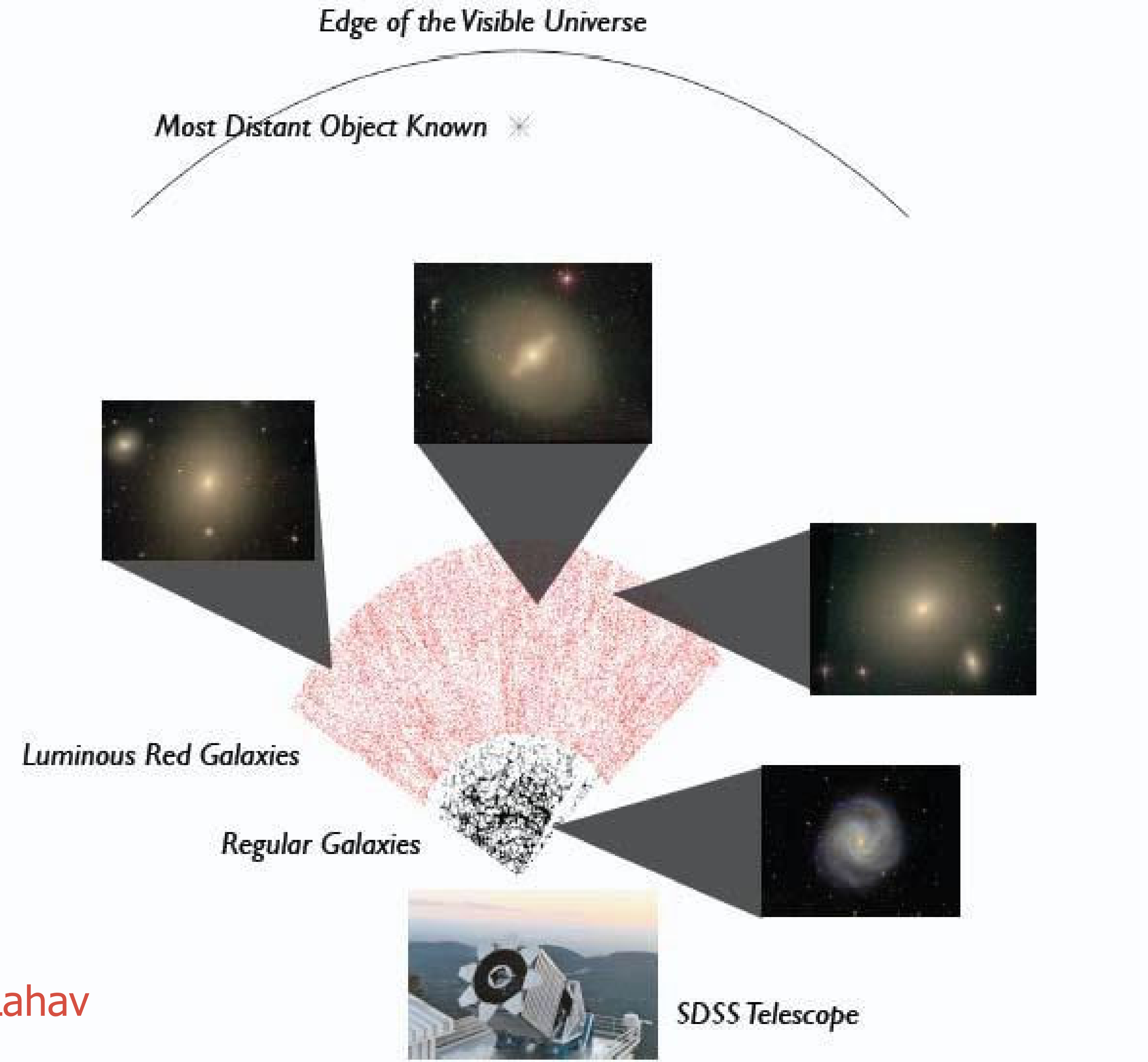


$\sigma_z = 0.046$

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

Clustering on Gpc scale

LRG photo-z



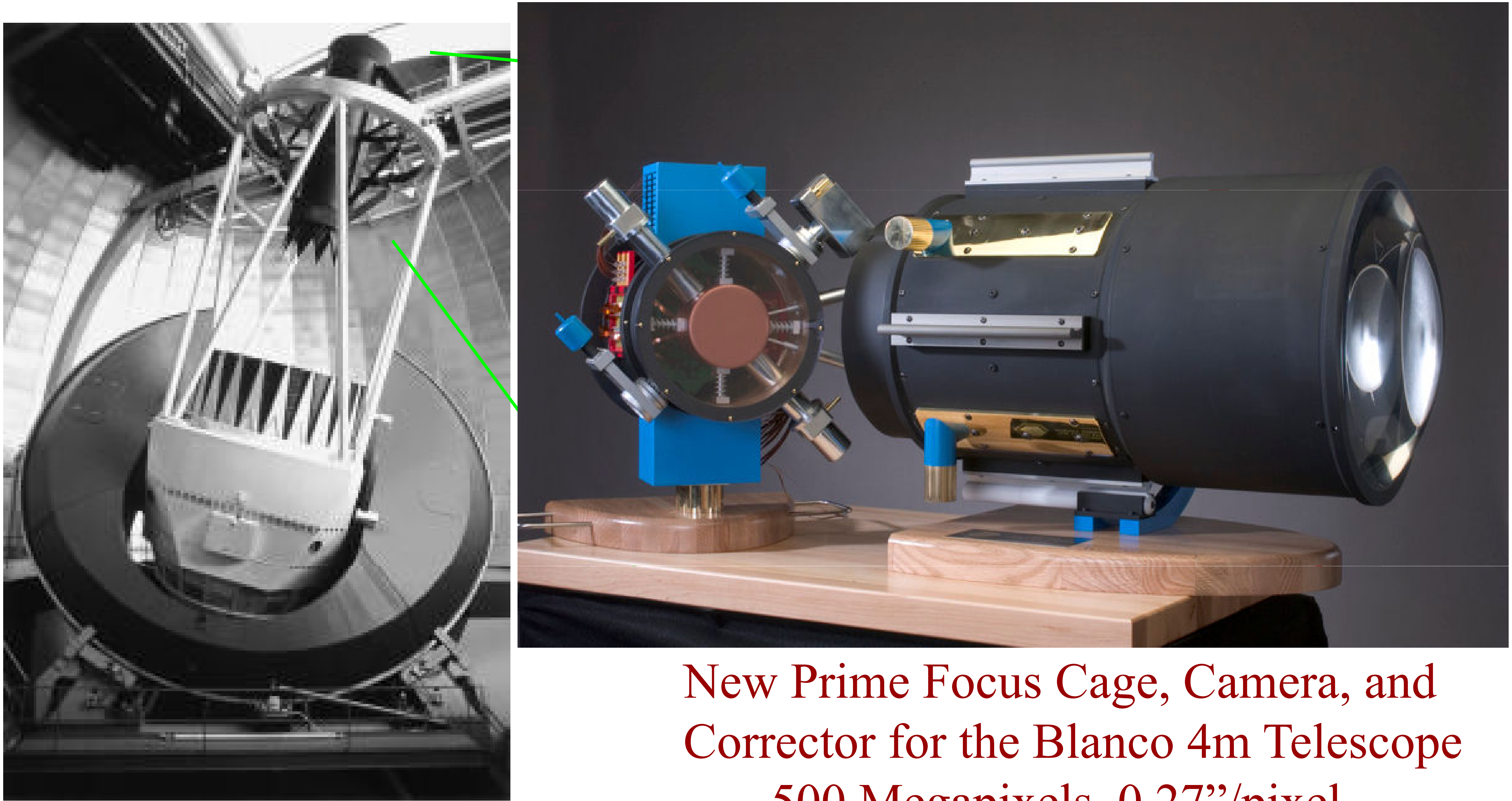
Padmanabhan et al
Astro-ph/0605302

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

The Dark Energy Survey

to map 300,000,000 galaxies, starting 2011

Dark Energy Survey Instrument



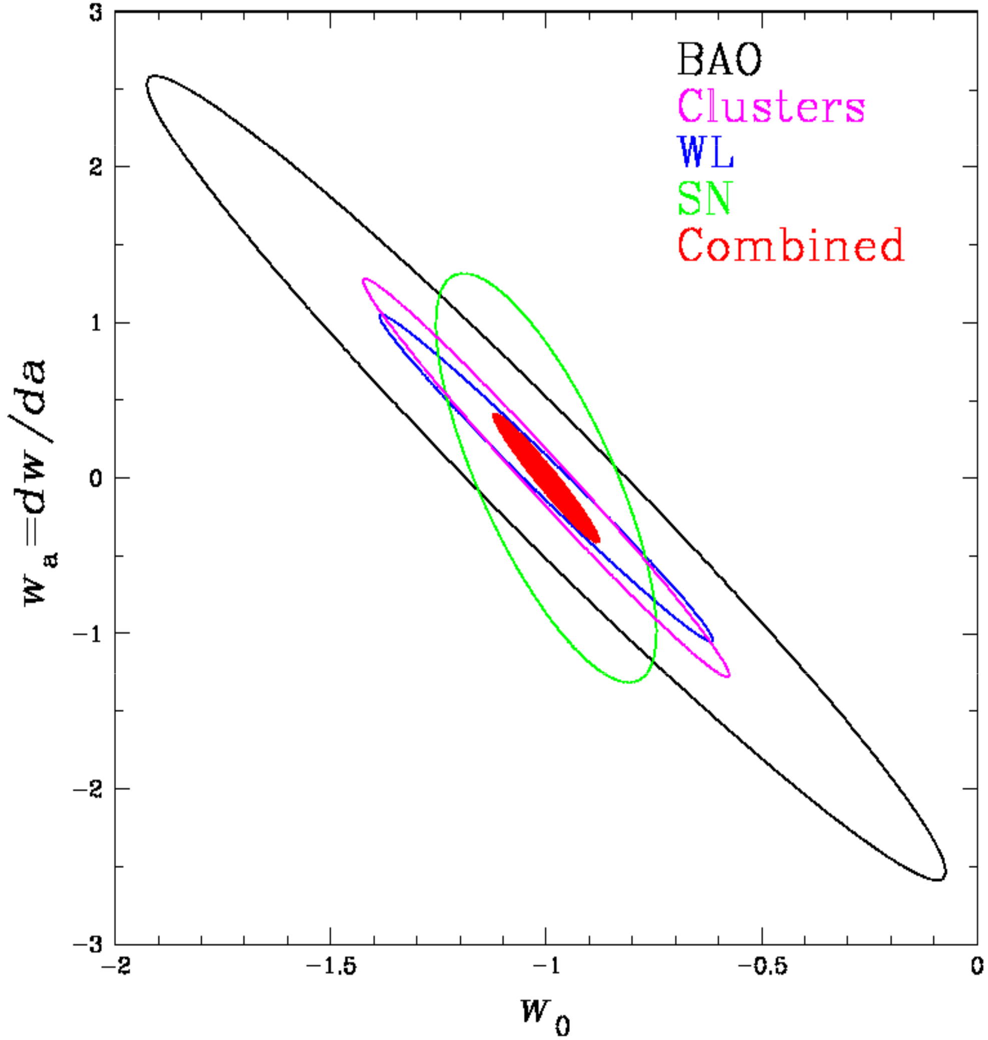
New Prime Focus Cage, Camera, and Corrector for the Blanco 4m Telescope

500 Megapixels, 0.27”/pixel

Project cost: ~40M$ (incl. labor)

DES Forecasts: Power of Multiple Techniques

$w(z) = w_0 + w_a(1-a)$ 68% CL

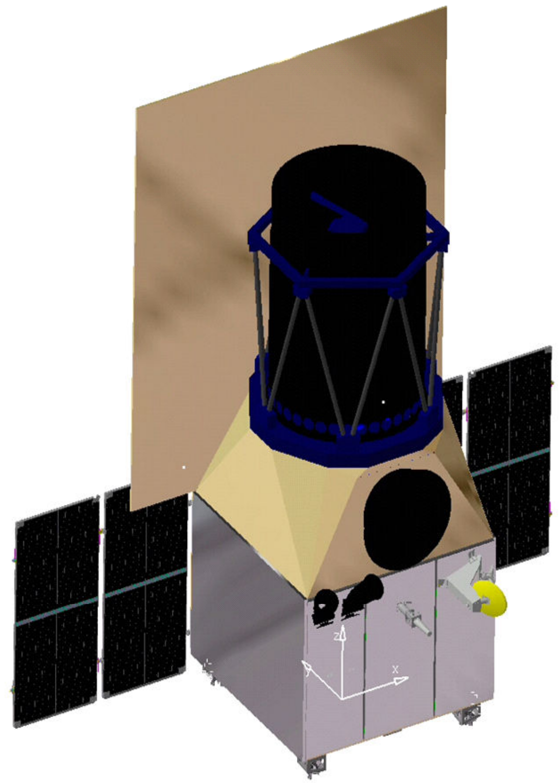


Ma, Tang, Weller

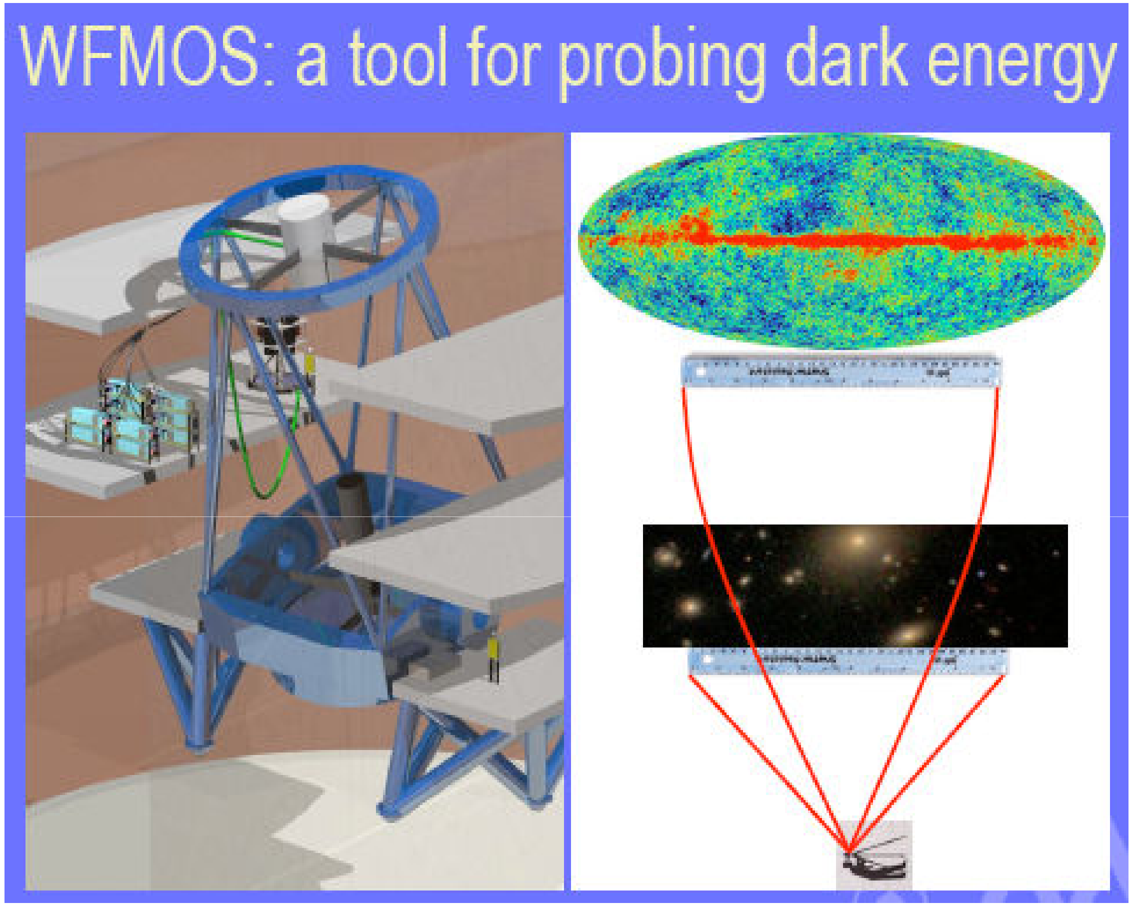
FoM factor 4.6 tigther compared to near term projects

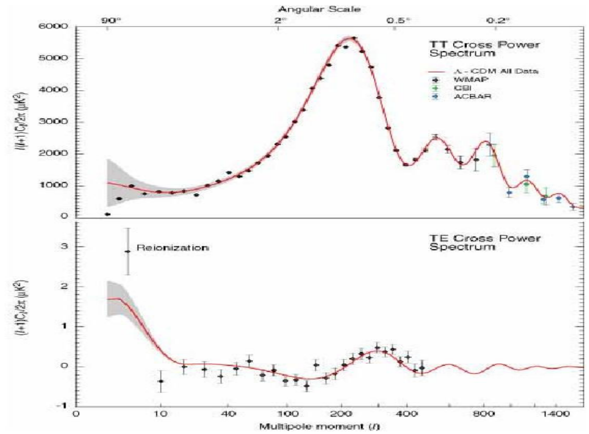
EUCLID: Obeserving the dark universe from space

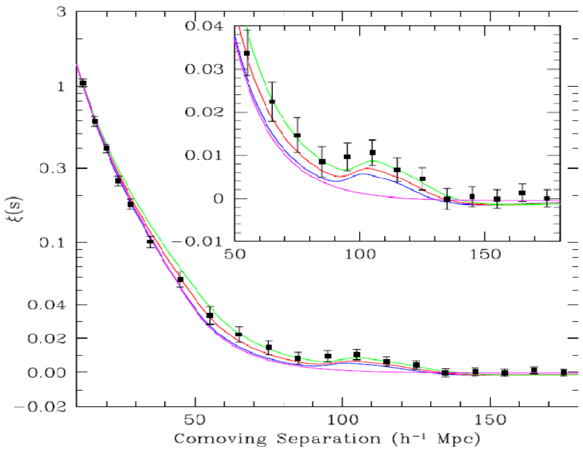
ESA Cosmic Vision
(2017)



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 < 1eV ?

* The exact value of the spectral index: n < 1 ?

* Excess power on large scales ?

* Is the curvature zero exactly ?