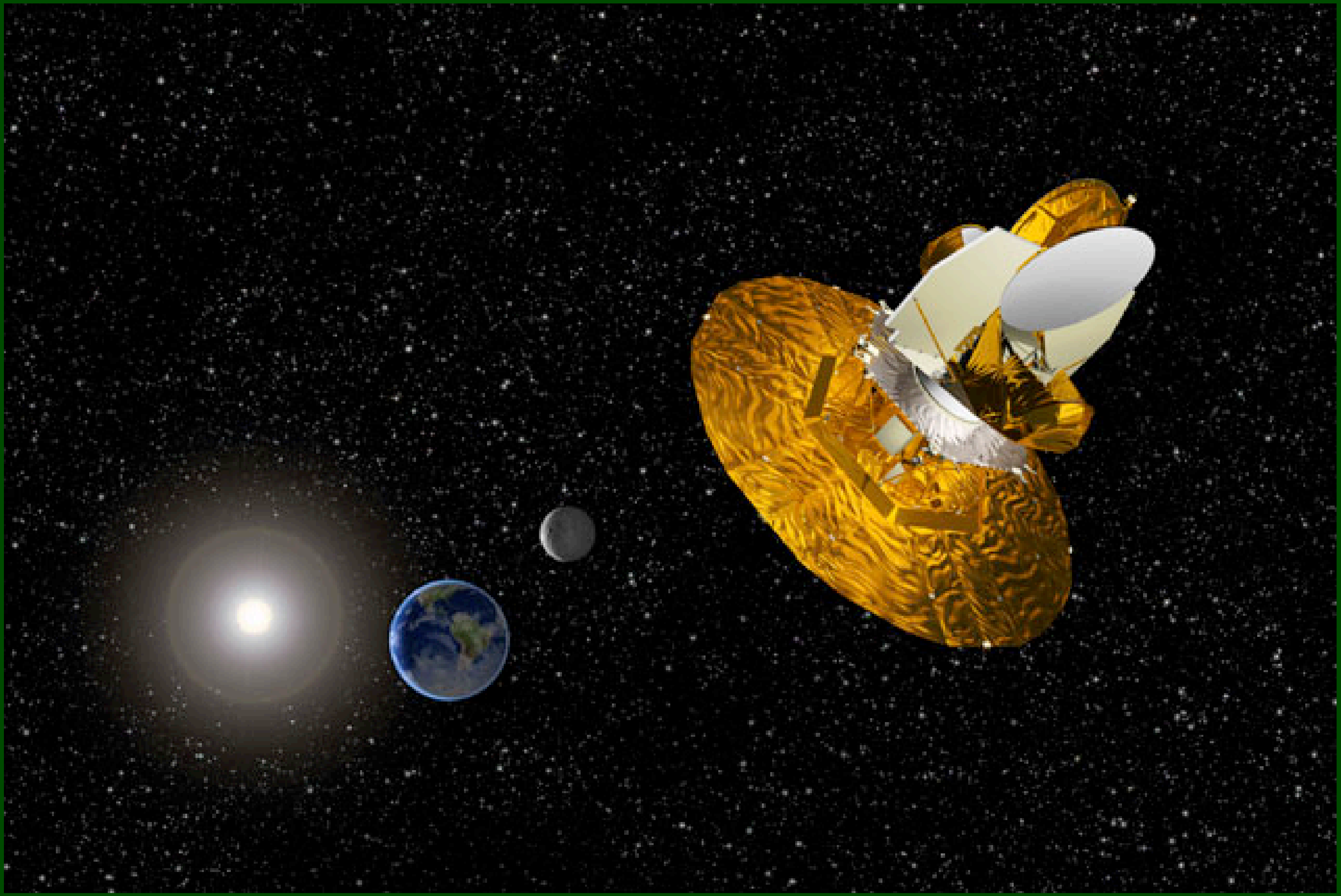
Signatures for Dark Matter in the Universe

Collider and Astroparticle Physics
2006/2007

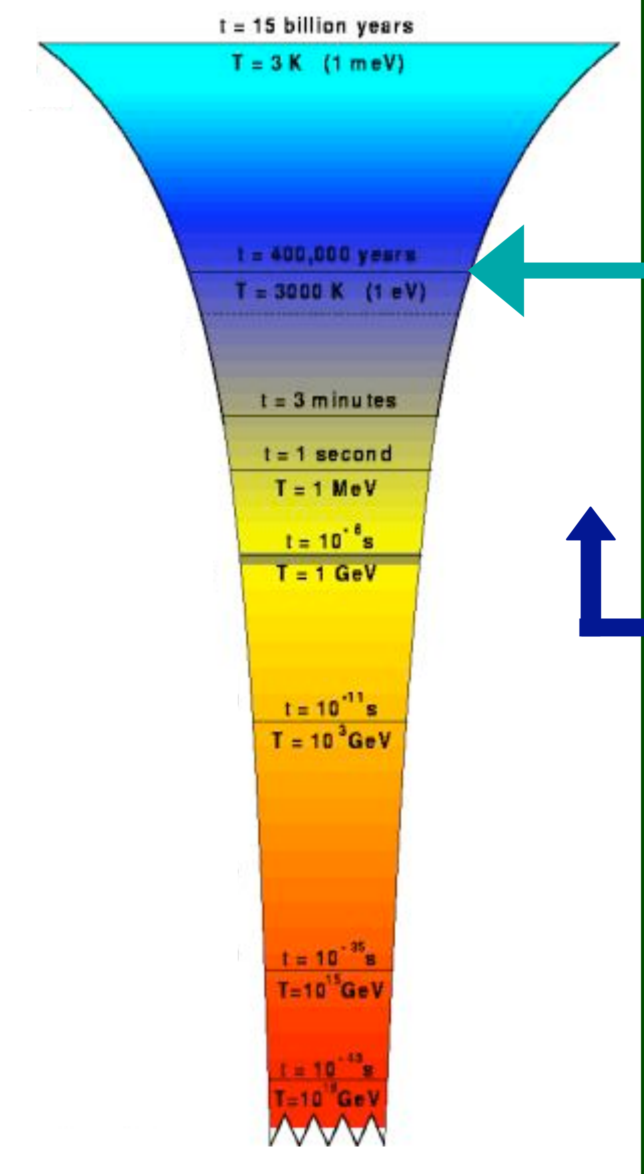
A.F.Żarnecki
25-10-2006

What is WMAP?

- Satellite detecting primordial photons “cosmic microwave background”



The oldest fossil from the early universe



Recombination

CMB

Nucleosynthesis

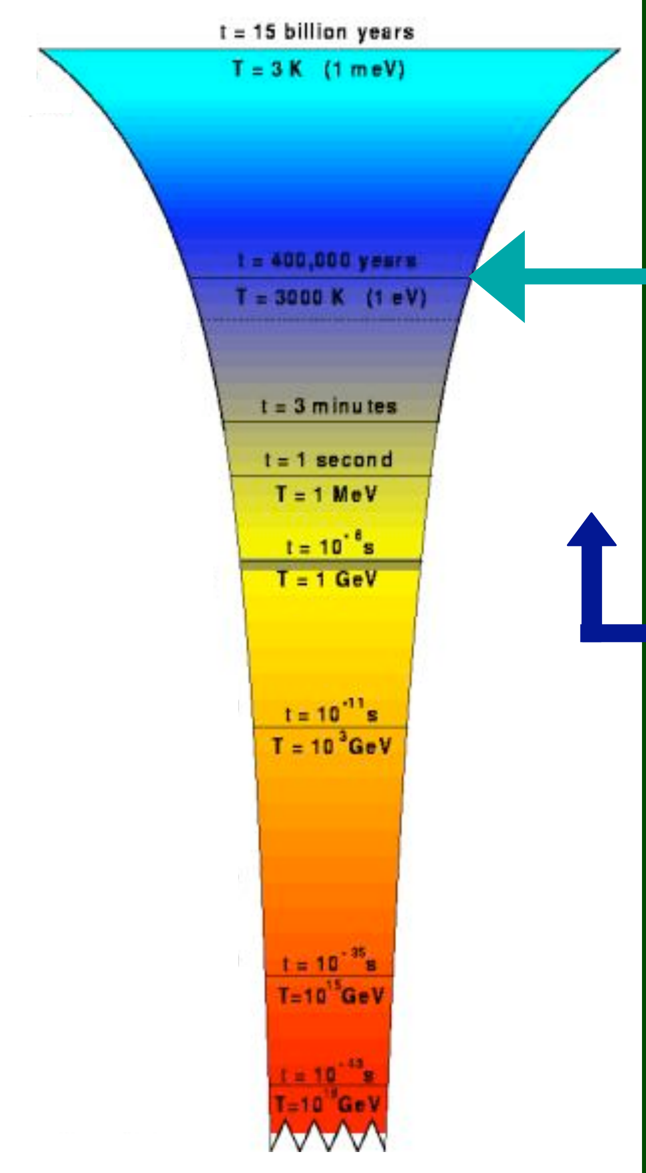
Testable in particle accelerators

Imprint in CMB

Inflation and Grand Unification?

Quantum Gravity/ Trans-Planckian effects….

The cosmic equivalent of tree rings…



Dark Energy domination

Reionization

Galaxy formation

Recombination

Nucleosynthesis

Testable in particle accelerators

Inflation and Grand Unification?

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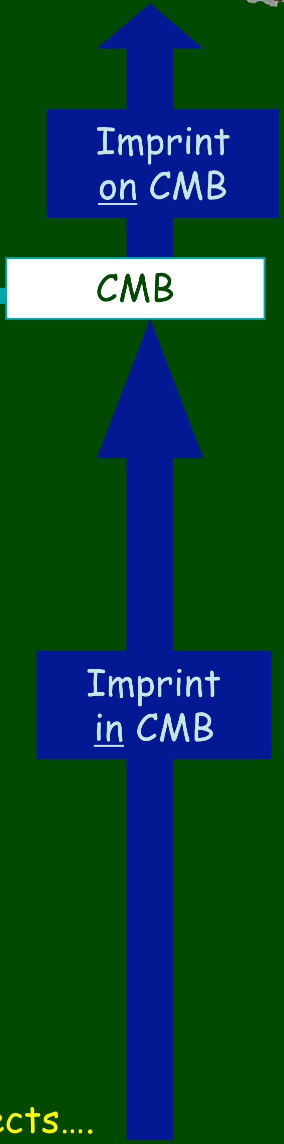


Maps and galactic foregrounds

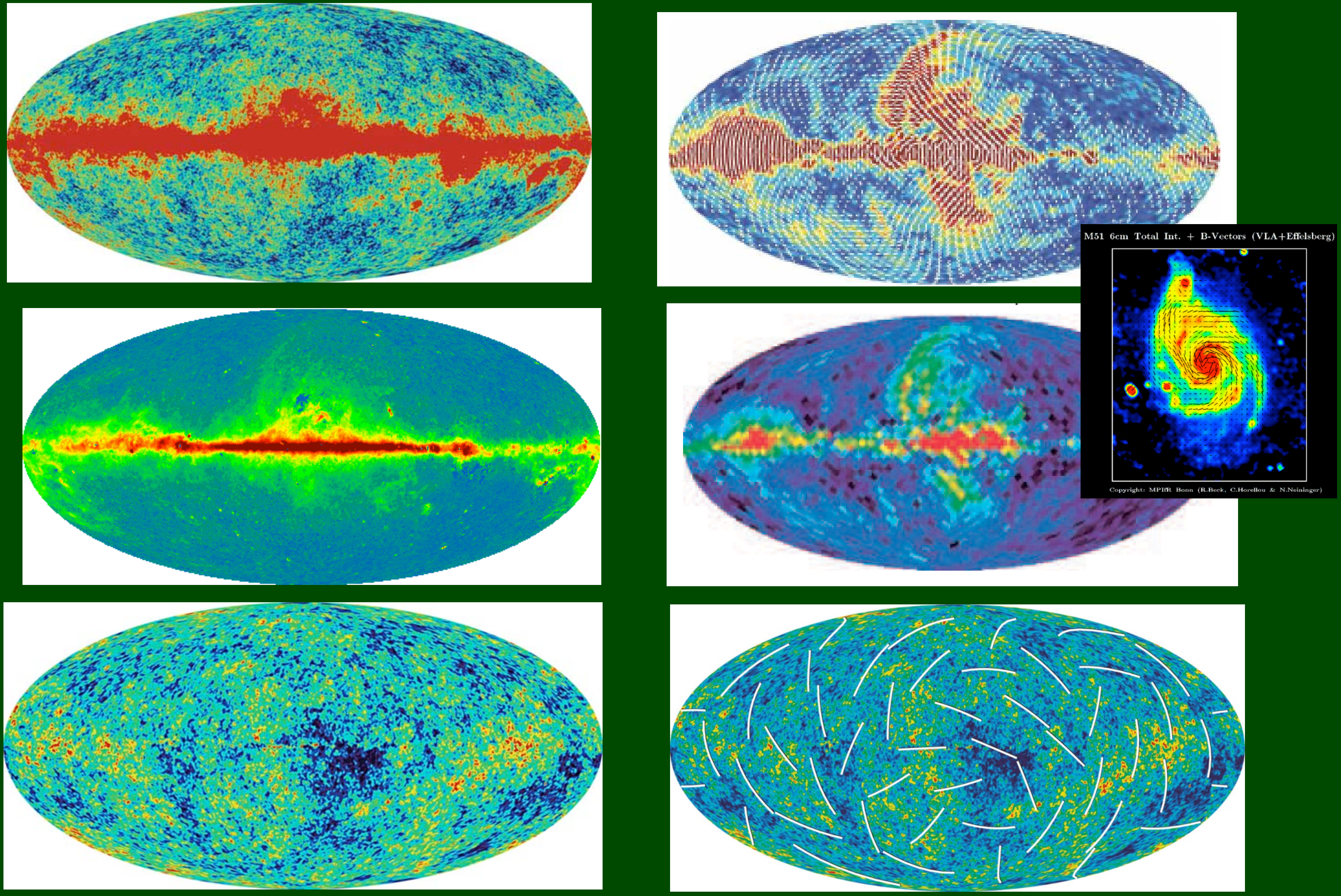
Temperature (~10s uK)

Polarization (~0.1s uK)

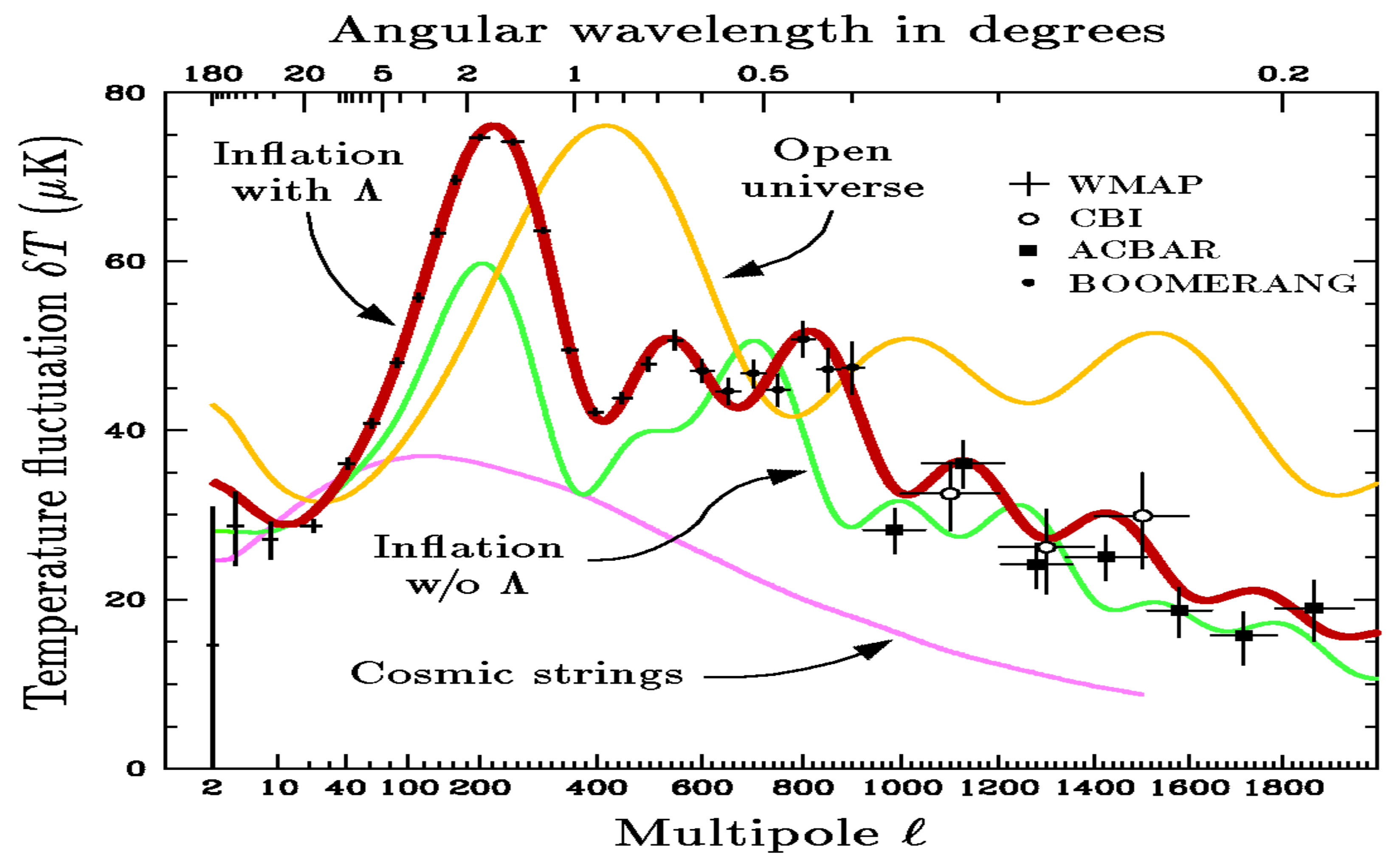
Raw

FG

Cleaned

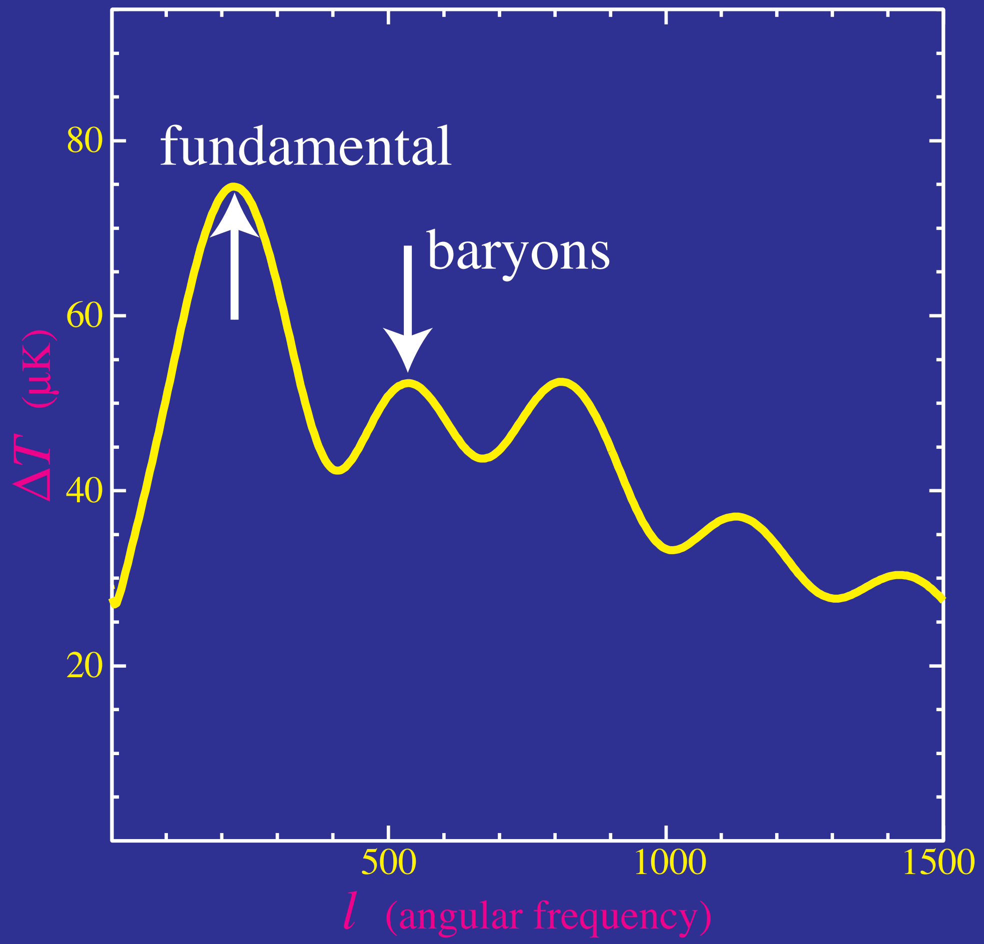


Anisotropy in the CMBR (cont.)



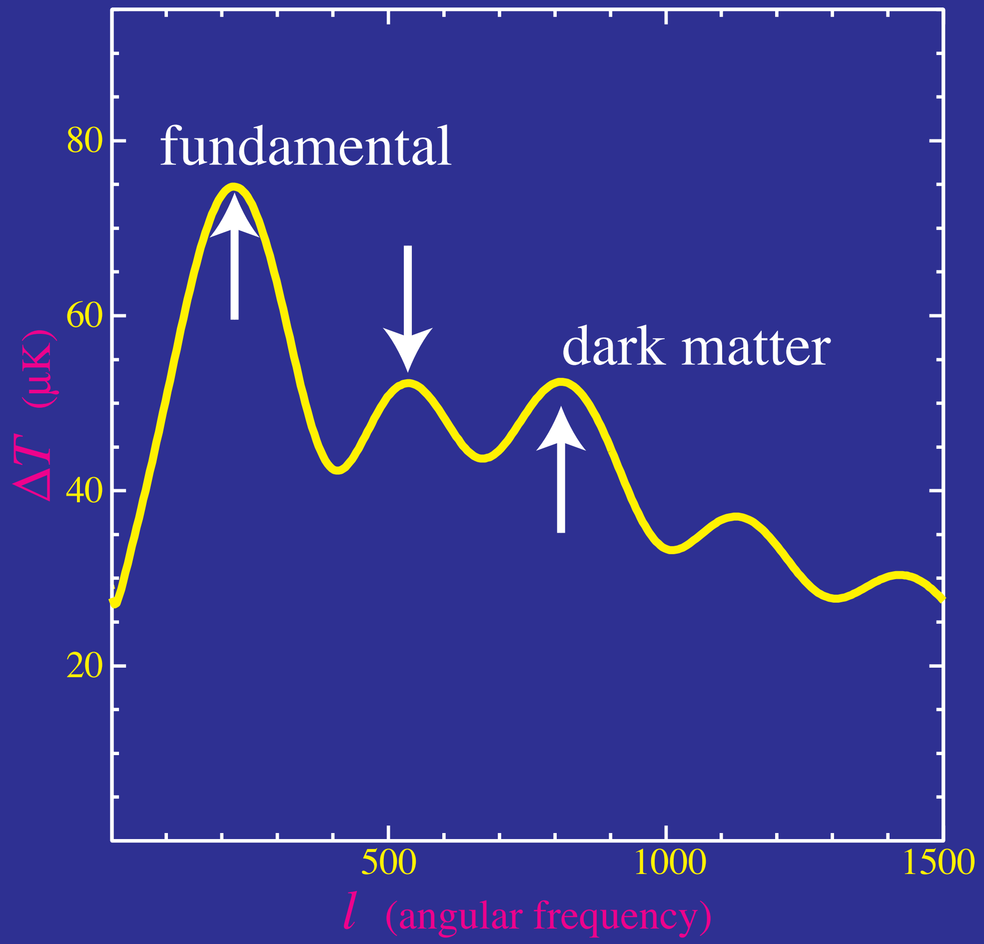
Ordinary Matter

- A low second peak indicates baryon or ordinary matter density comparable to photon density
- Ordinary matter consists of ~5% of the critical density today



Dark Matter

- A third peak comparable to second peak indicates a dark matter density ~5x that of ordinary matter
- Dark matter ~25% of the critical density



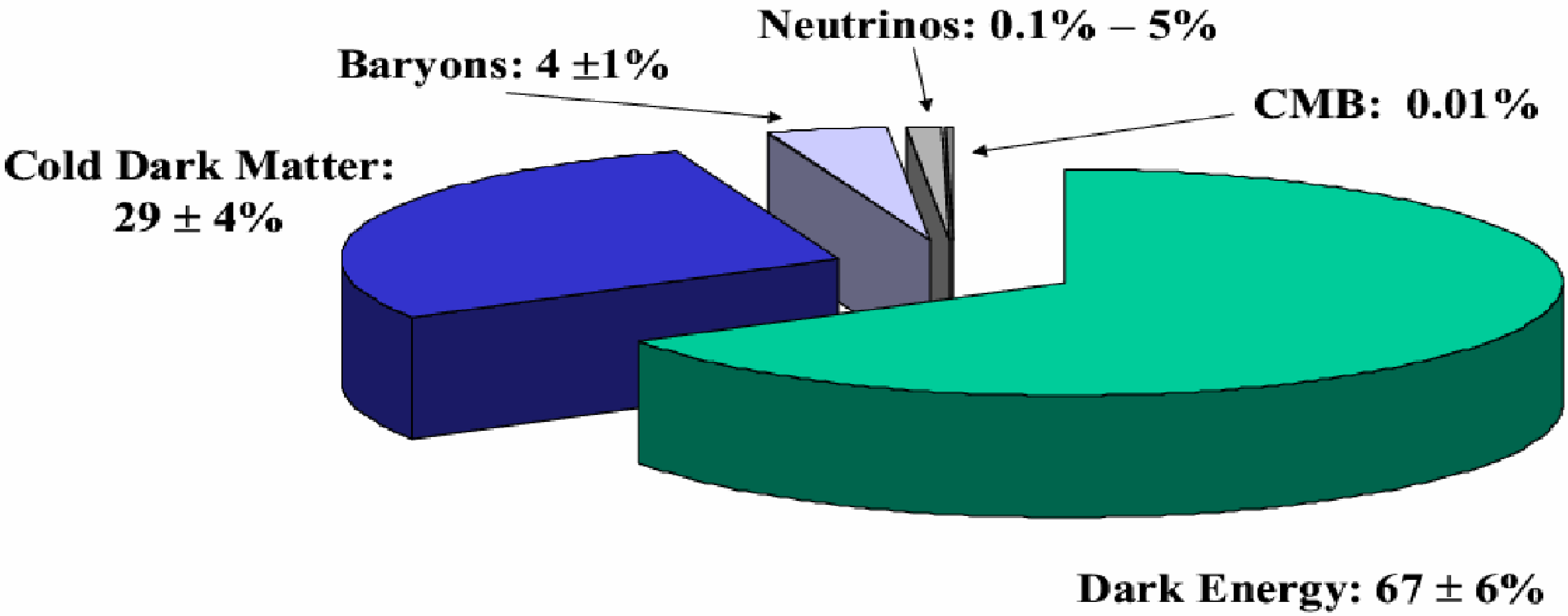
WMASS results

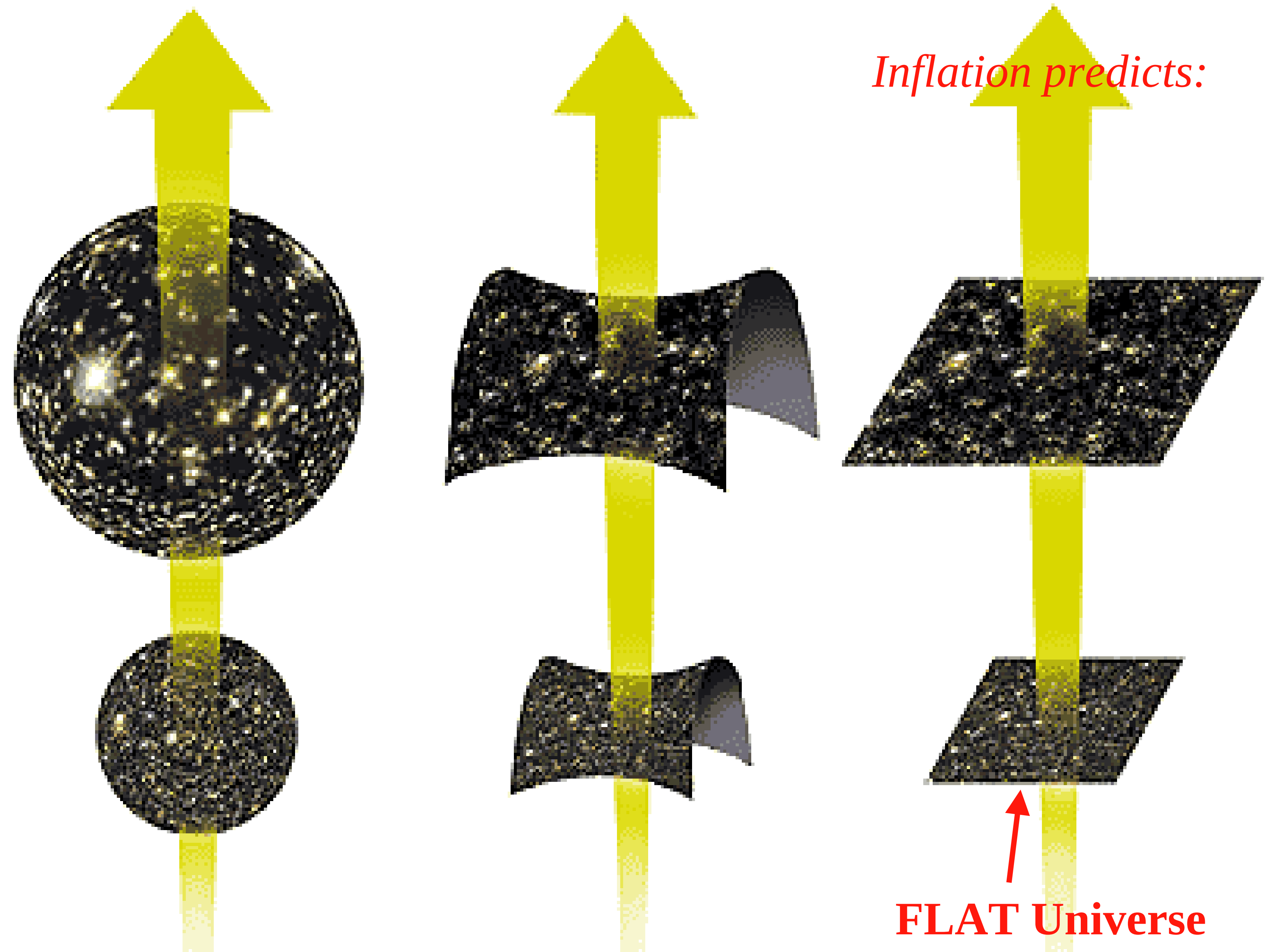
Parameter	Value
Baryon Density	$\Omega_b h^2 = 0.024 \pm 0.001$
Matter Density	$\Omega_m h^2 = 0.14 \pm 0.02$
Hubble Constant	$h = 0.72 \pm 0.05$
Baryon Density/Critical Density	$\Omega_b = 0.044 \pm 0.004$
Matter Density/Critical Density	$\Omega_m = 0.27 \pm 0.04$
Age of the Universe	$t_o = 13.7 \pm 0.2$

Slicing the Pie of the Cosmos

WMAP3: Ω_{CDM} =0.24±0.02, Ω_{Λ} =0.72±0.04 , Ω_b =0.042±0.003

Confirming earlier data (Supernovae, WMAP1 etc):

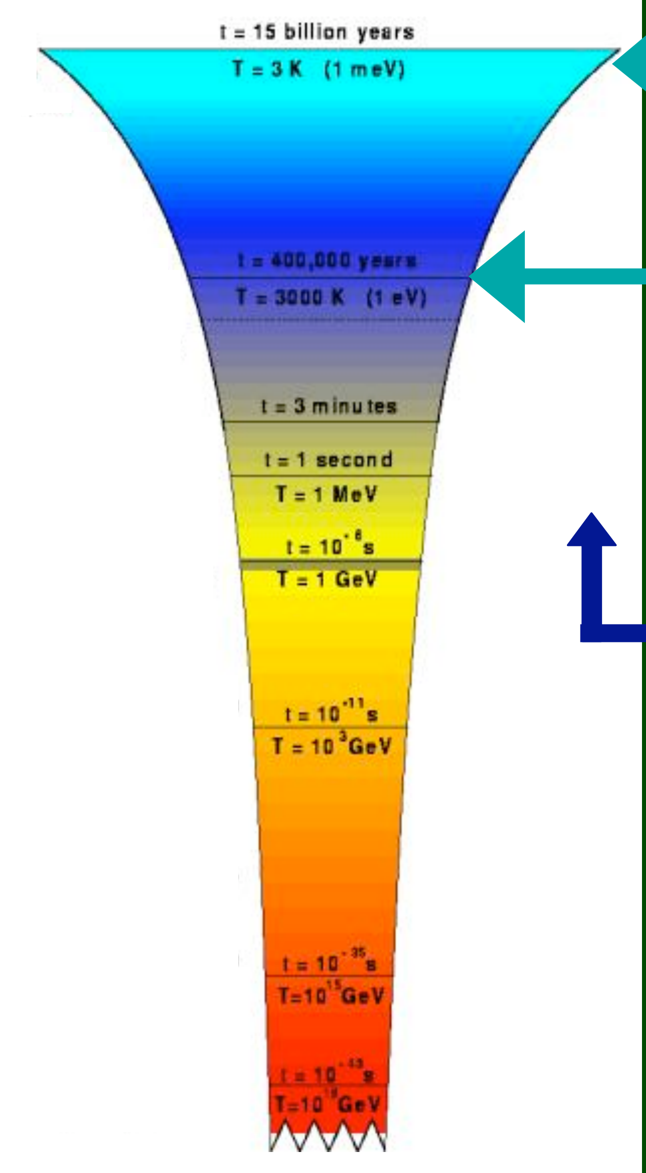




Inflation predicts:

FLAT Universe

Important comparisons with later observations



Supernovae
Weak lensing
LSS surveys

Dark Energy domination

Reionization

Galaxy formation

Imprint
on CMB

Recombination

CMB

Nucleosynthesis

Testable in particle accelerators

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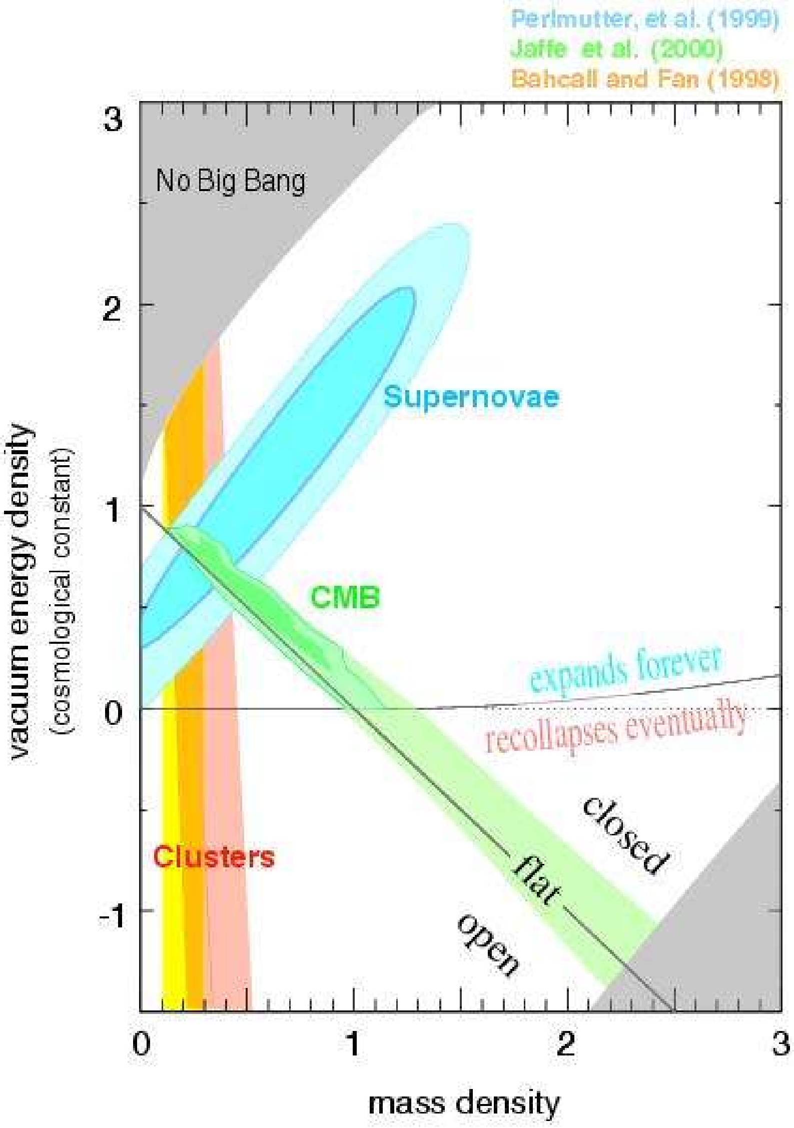
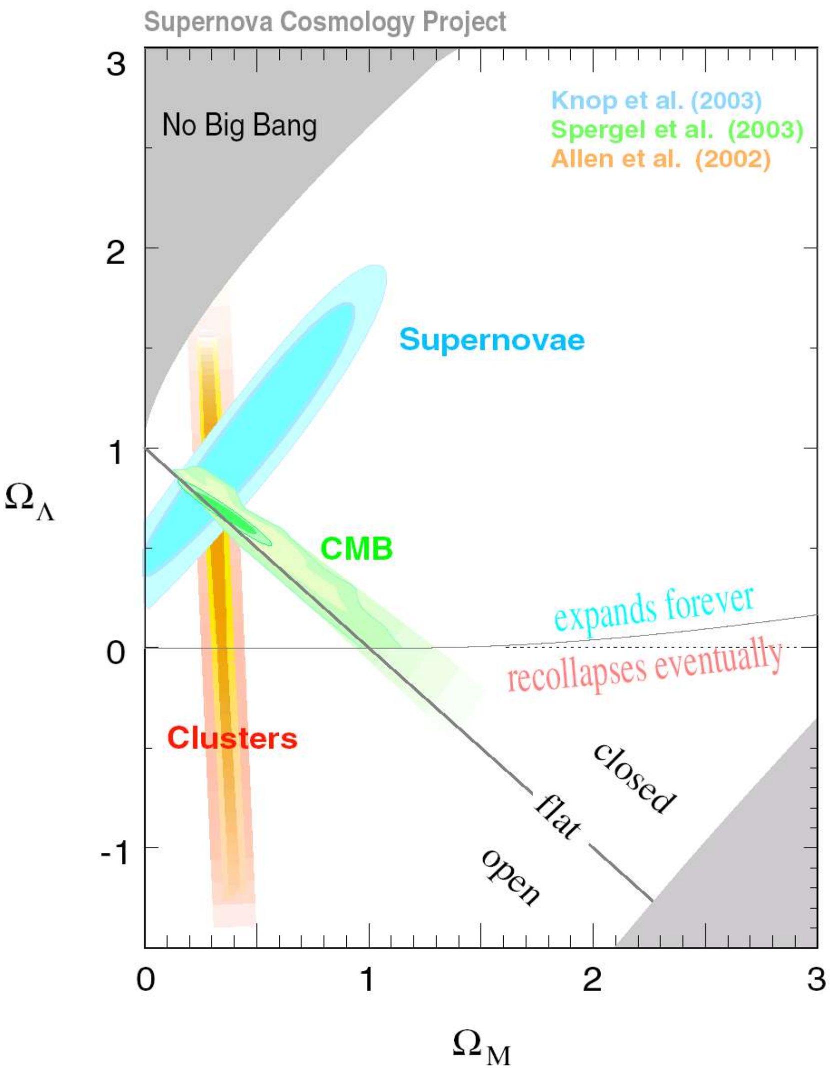
Inflation and Grand Unification?

Quantum Gravity/ Trans-Planckian effects….

1999-2003


Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall and Fan (1998)
No Big Bang
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3


Supernova Cosmology Project
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Ω_Λ
Ω_M
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0
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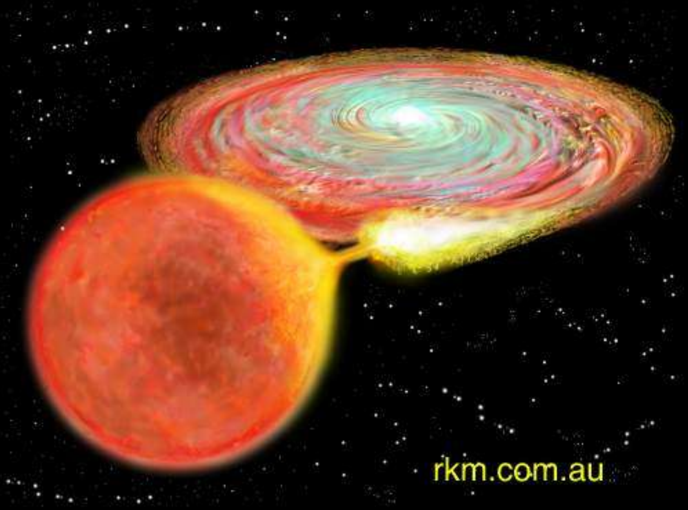
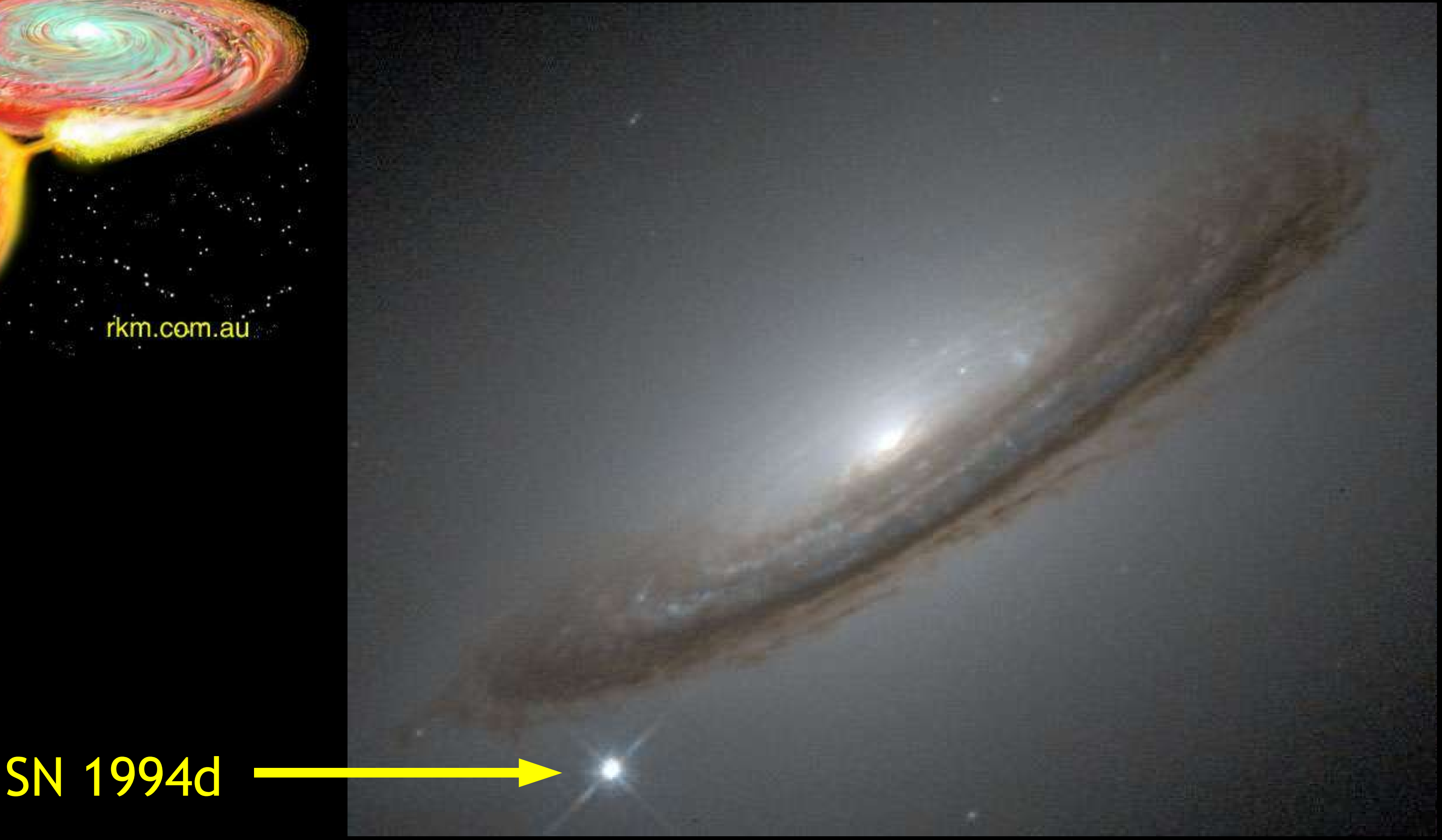
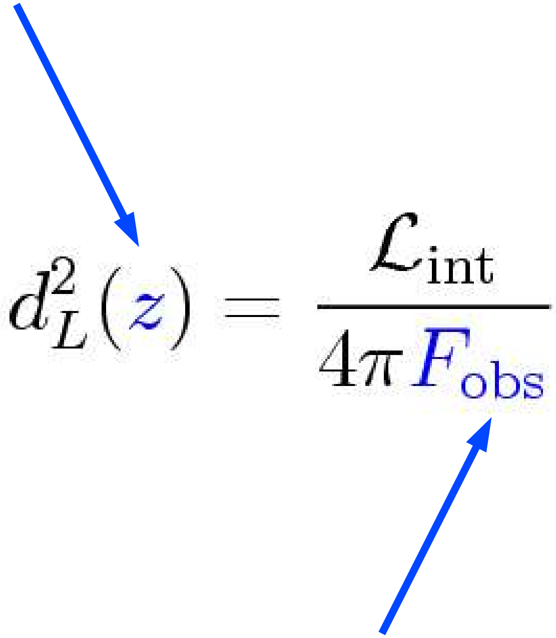
To track the expansion rate, use Supernovae (exploding white dwarf stars) as standard candles.





Luminosity Distance



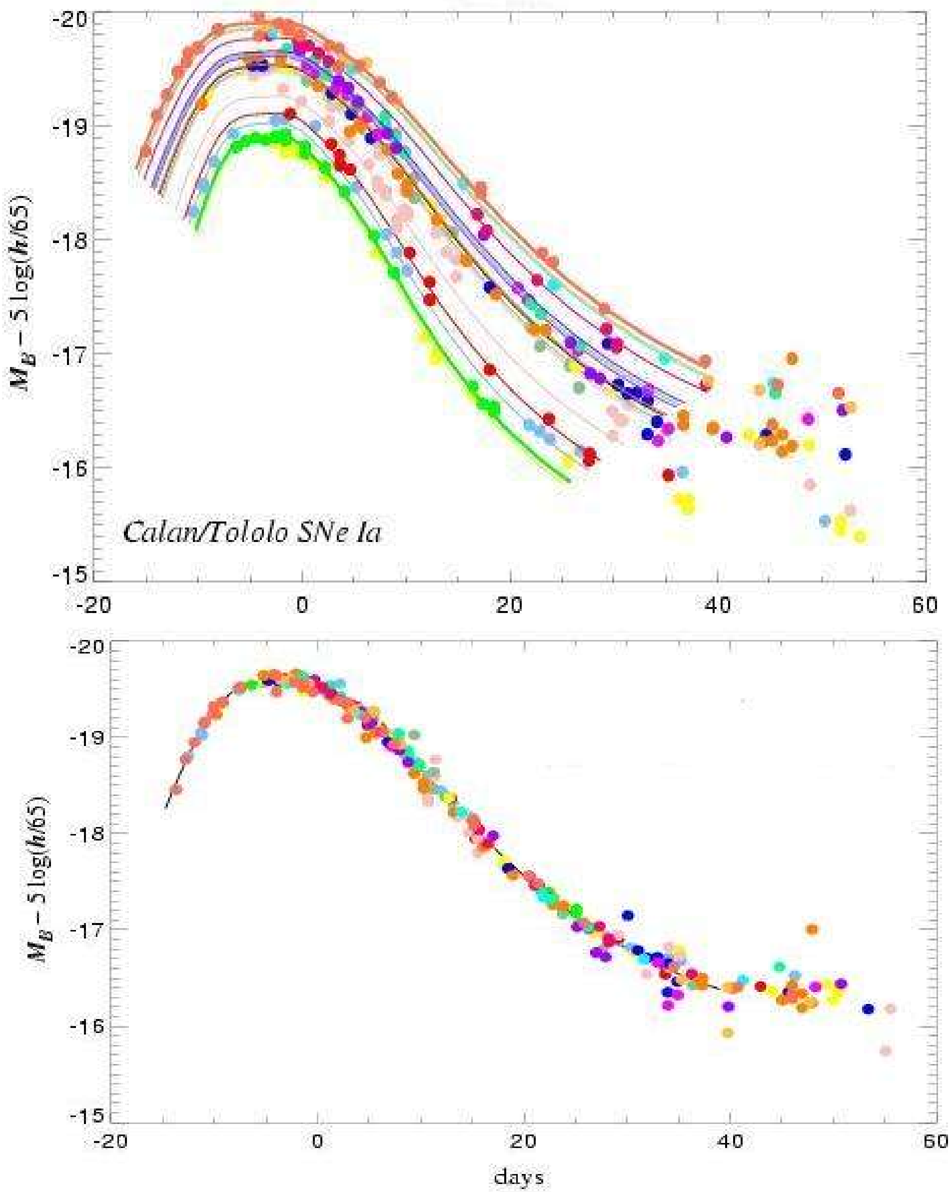
Spectroscopy

$$d_L^2(z) = \frac{\mathcal{L}_{\mathrm{int}}}{4\pi F_{\mathrm{obs}}}$$

Photometry

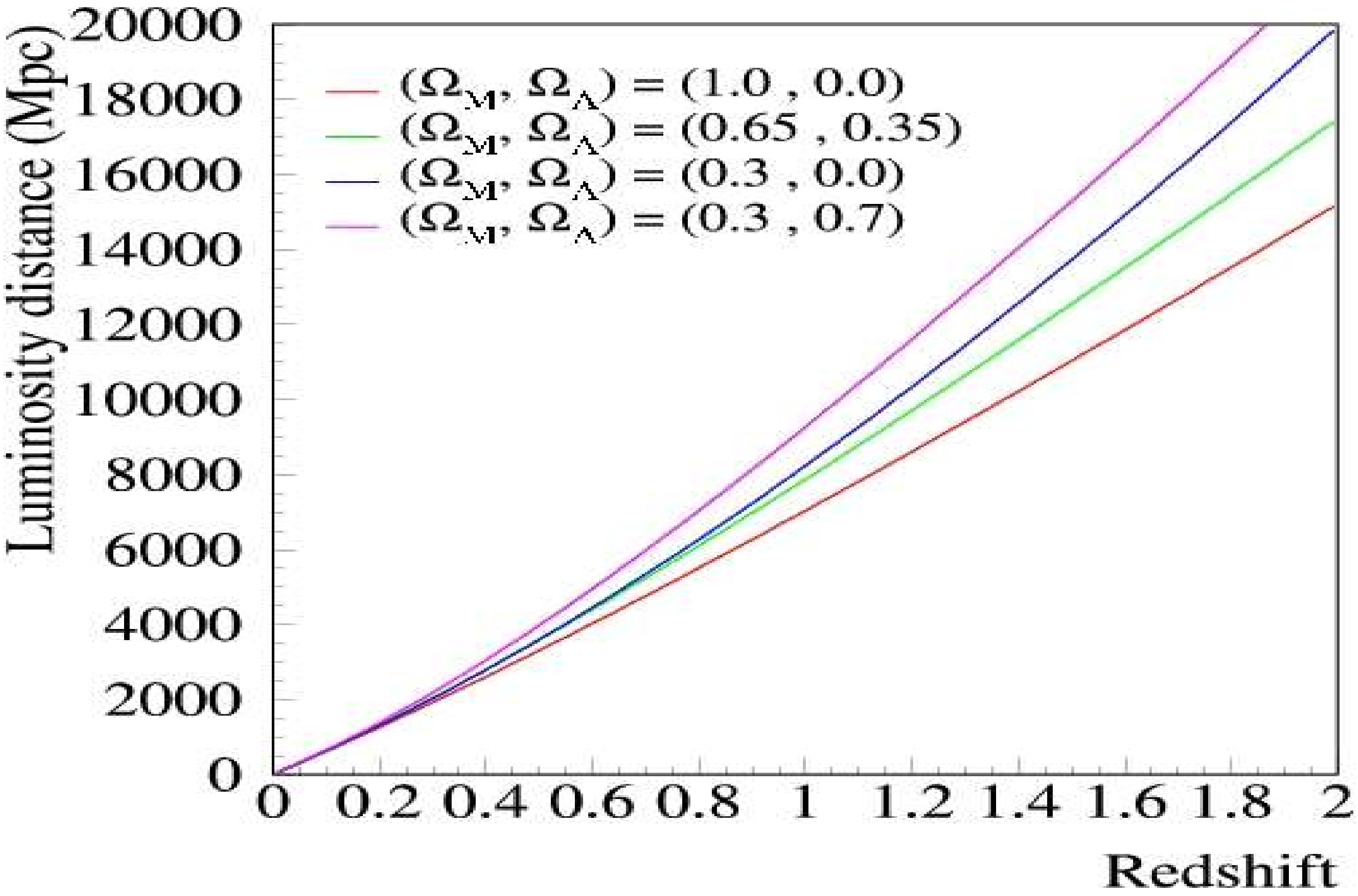
SNe Ia

Bright

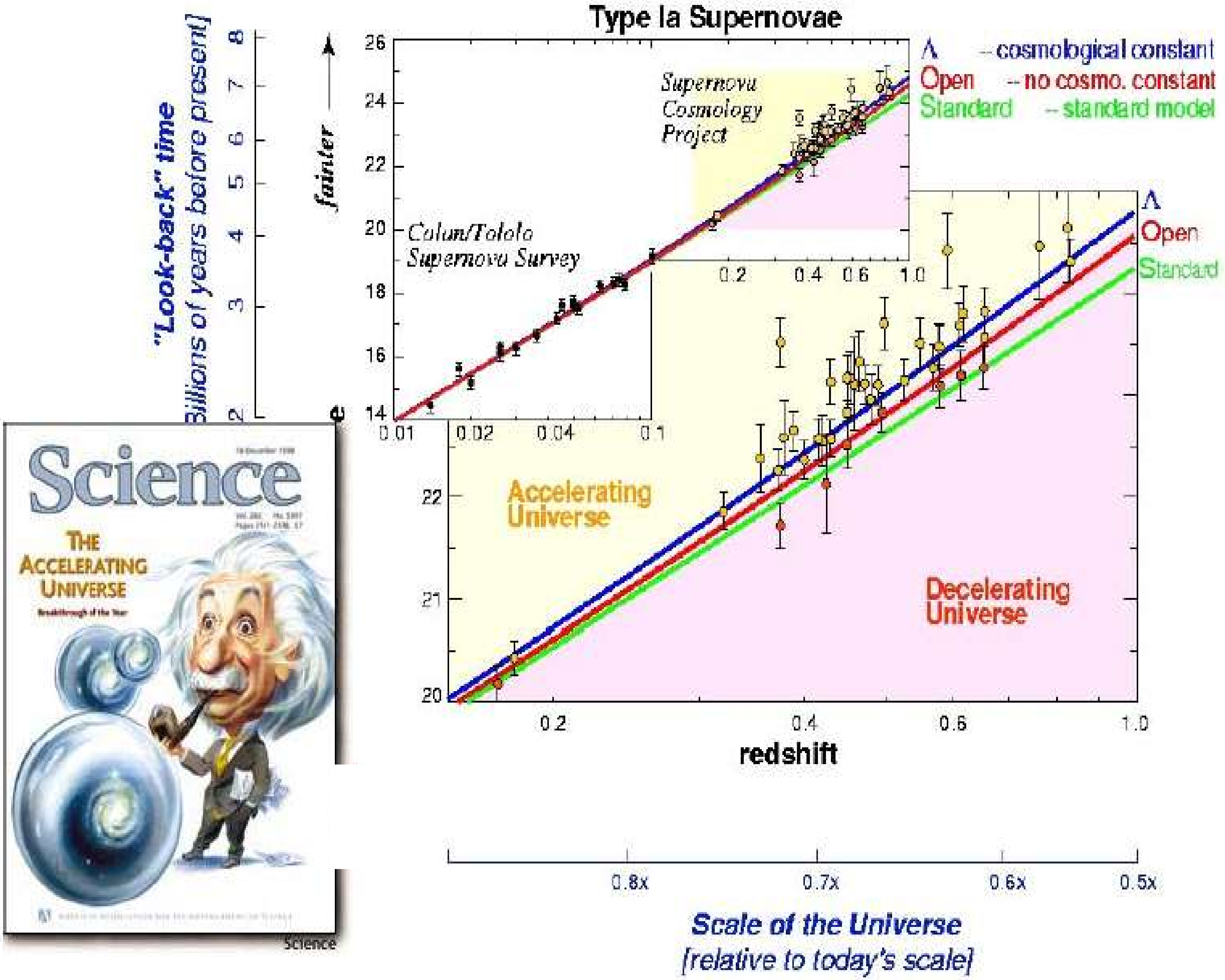


Light curve similarities

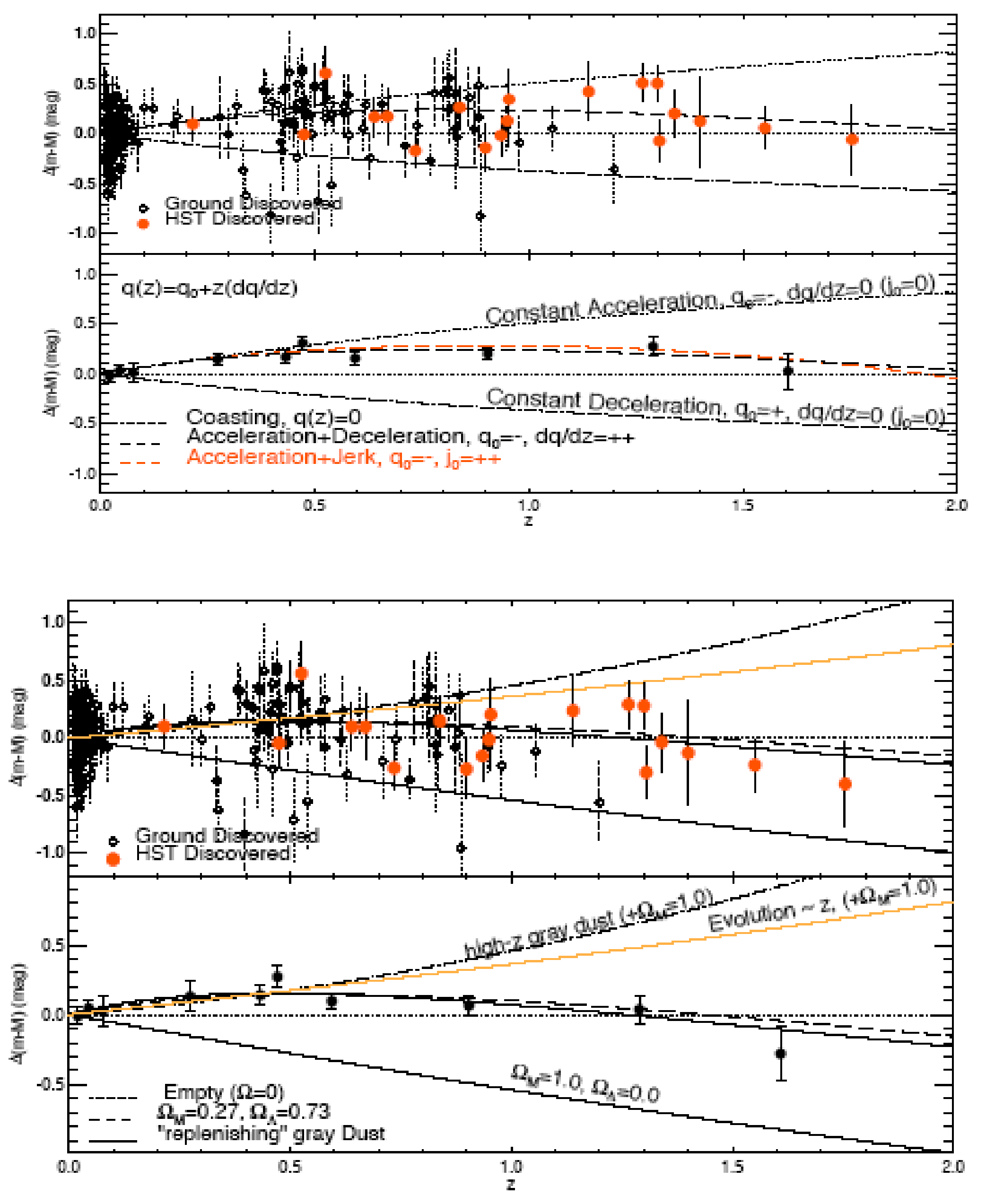
SNe Ia Distances in FLRW

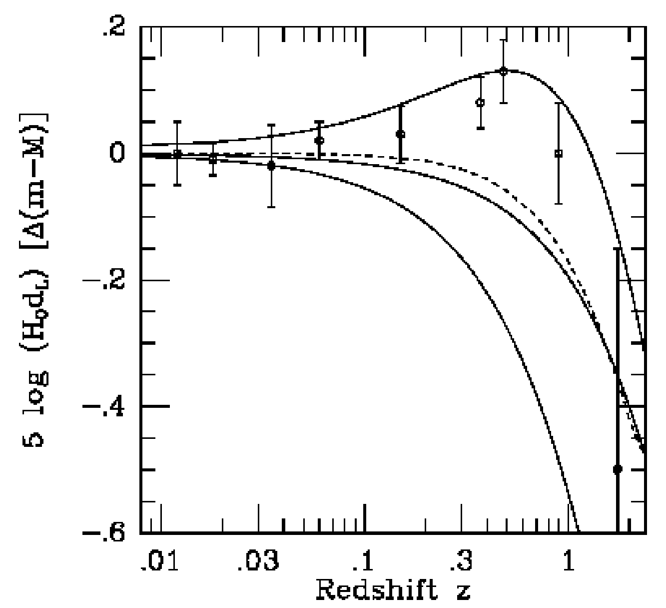


$$d_L(z) = f(z; \Omega_M, \Omega_\Lambda)$$


Type Ia Supernovae
Λ -- cosmological constant
Open -- no cosmo. constant
Standard -- standard model
Supernova Cosmology Project
Calan/Tololo Supernova Survey
fainter
"Look-back" time
[Billions of years before present]
2
3
4
5
6
7
8
14
16
18
20
22
24
26
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1.0
Λ
Open
Standard
Accelerating Universe
Decelerating Universe
20
21
22
redshift
0.8x
0.7x
0.6x
0.5x
Scale of the Universe
[relative to today's scale]
Science
The Accelerating Universe
Breakthrough of the Year
Science

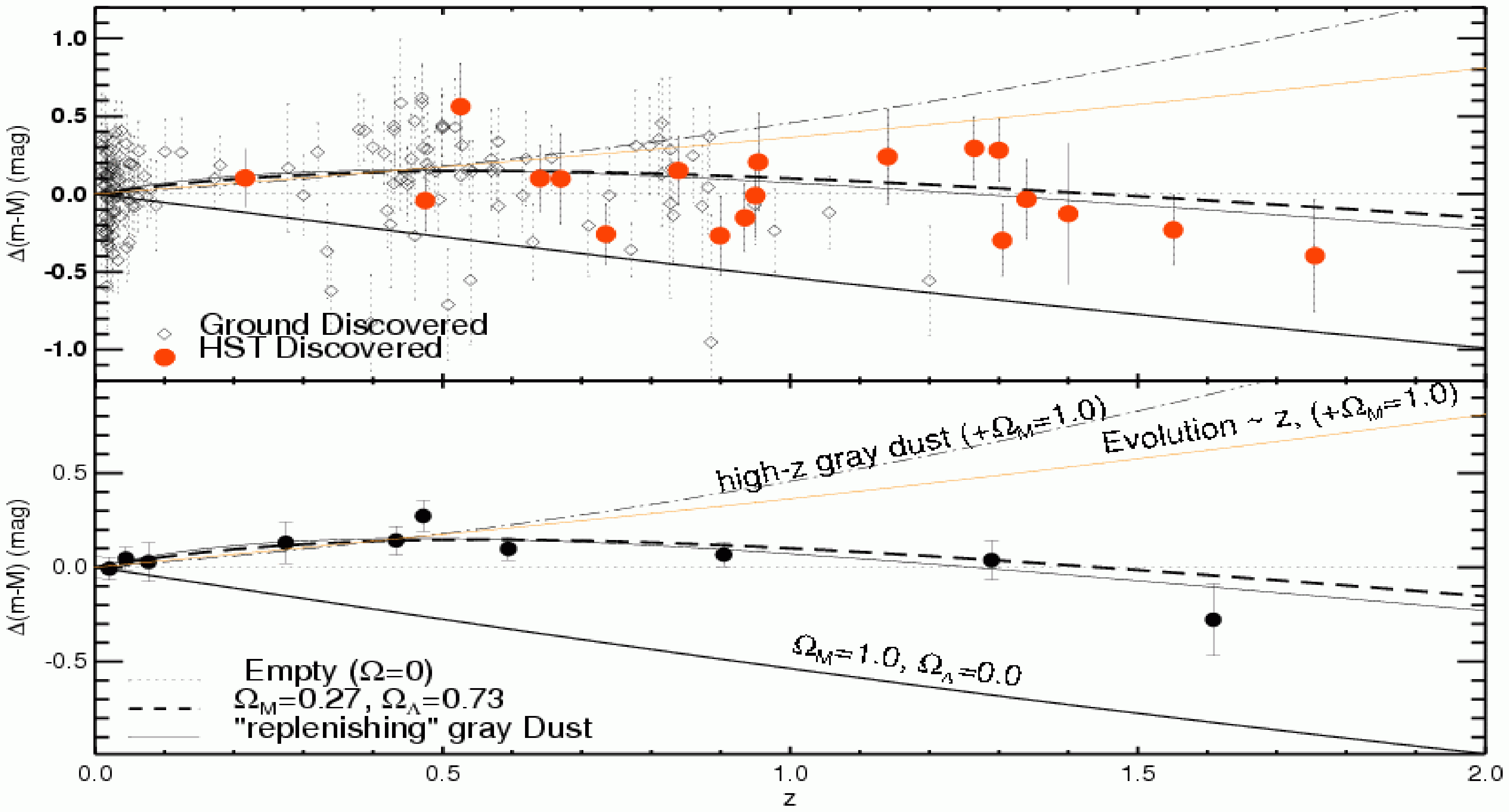
Expect dq/dz





Riess et al. ApJLett 04,
HST 16 SNIa

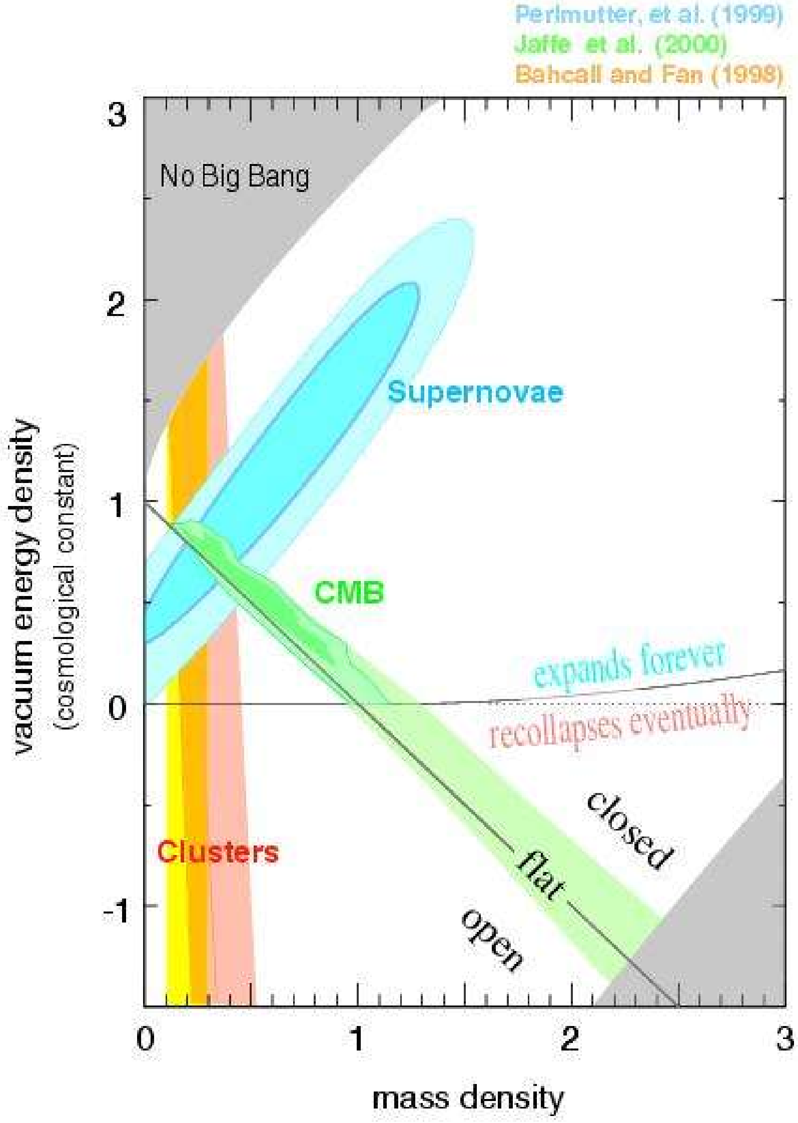
PANS/GOODS - Results



- Exclude "standard gray dust"
- Deceleration in the past

Riess 2004

1999-2003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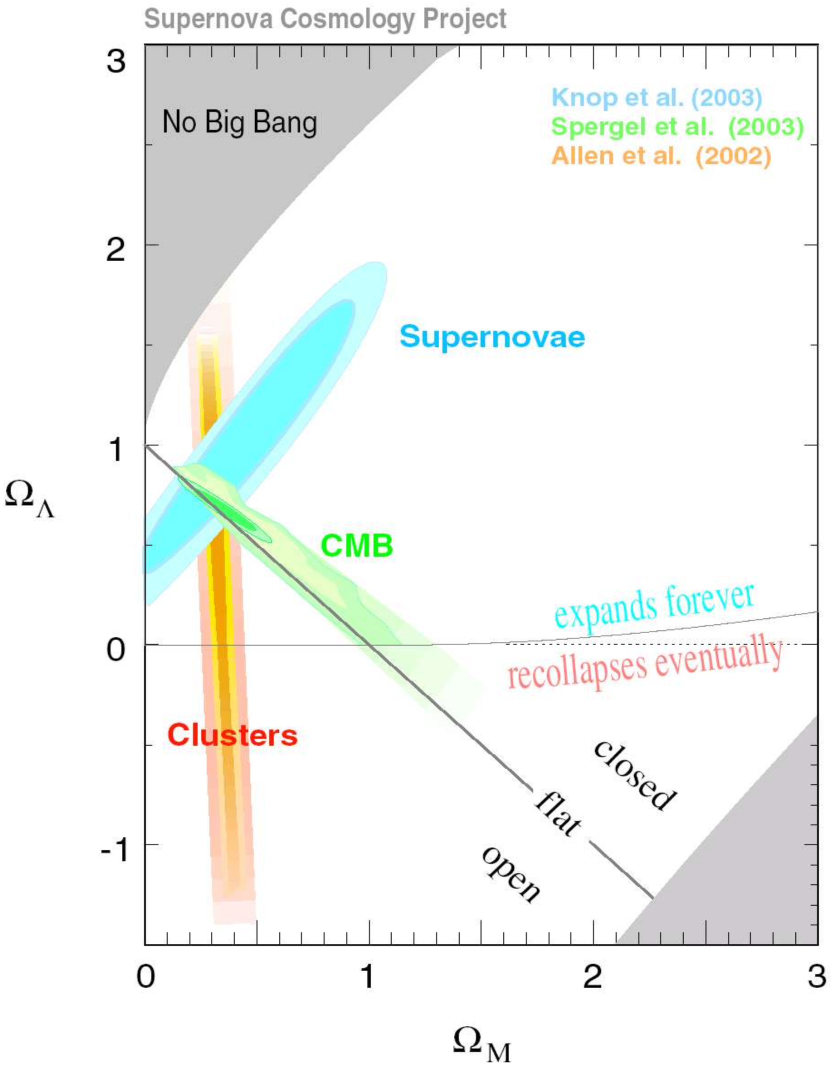
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Ω_Λ
Ω_M
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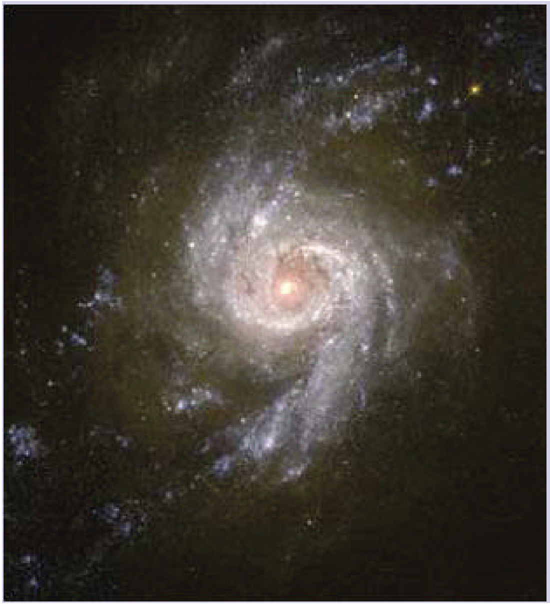
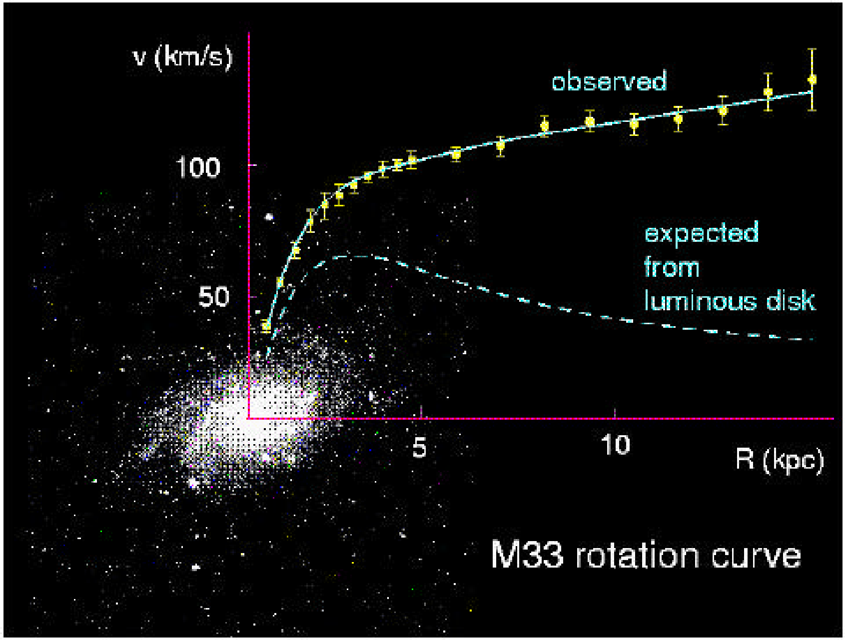
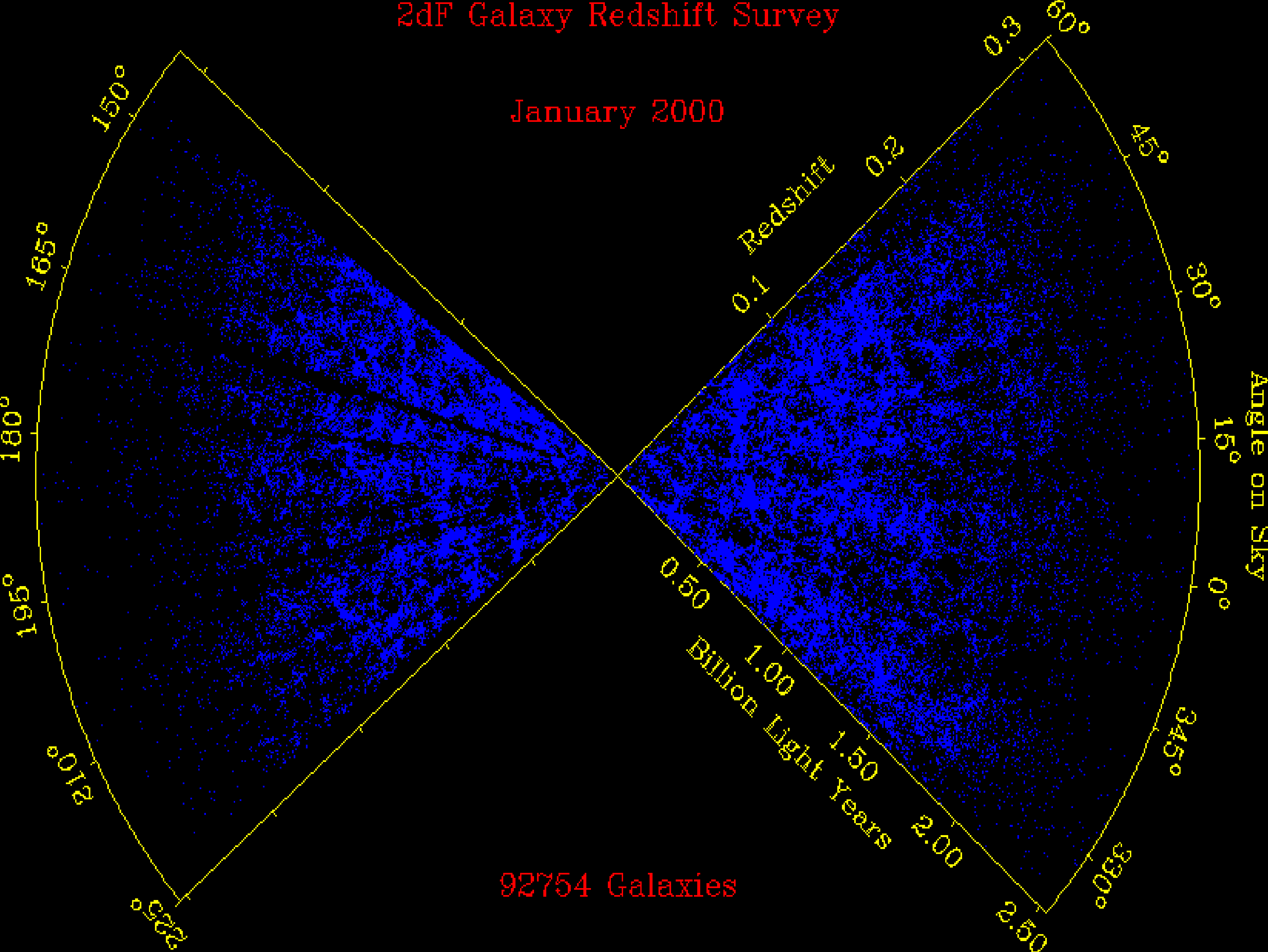
2
1
0
-1
0
1
2
3

Galactic rotation curves

- Doppler measurements in spiral galaxies.
  - Observe: v(r)
  - if v is constant, then: M ~ r
  - Needs “dark matter”






2dF Galaxy Redshift Survey
January 2000
92754 Galaxies
150°
165°
180°
195°
210°
225°
60°
45°
30°
15°
0°
345°
330°
Redshift
0.1
0.2
0.3
Billion Light Years
0.50
1.00
1.50
2.00
2.50
Angle on Sky

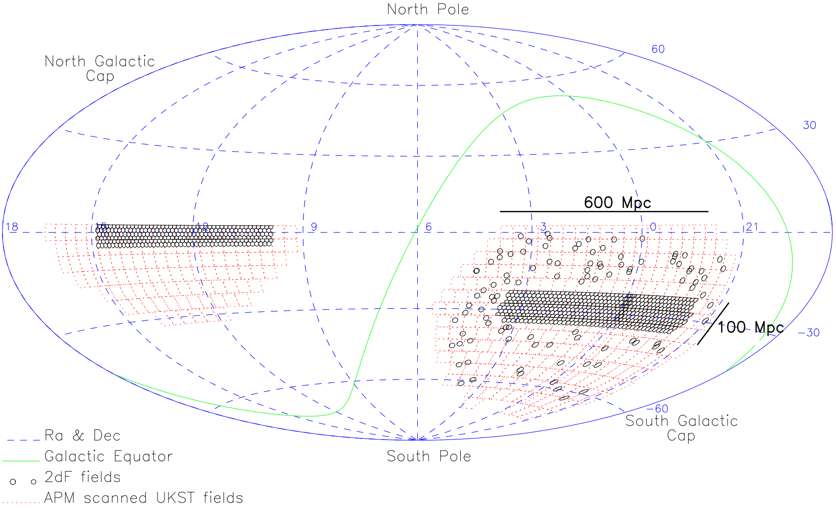


Fig. 1.1. A map of the sky showing the locations of the two 2dFGRS survey strips (NGP strip at left, SGP strip at right) and the random fields. Each 2dF field in the survey is shown as a small circle; the sky survey plates from which the source catalogue was constructed are shown as dotted squares. The scale of the strips at the mean redshift of the survey is indicated.

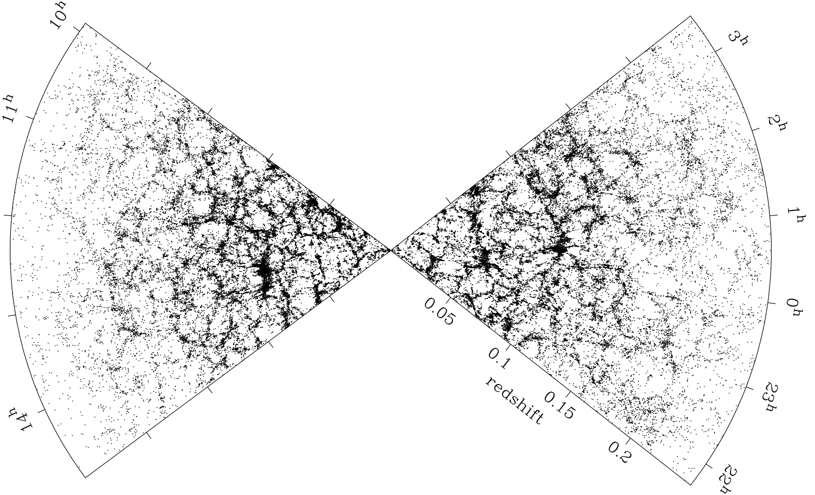


Fig. 1.2. The large-scale structures in the galaxy distribution are shown in this 3°-thick slice through the 2dF Galaxy Redshift Survey map. The slice cuts through the NGP strip (at left) and the SGP strip (at right), and contains 63000 galaxies.

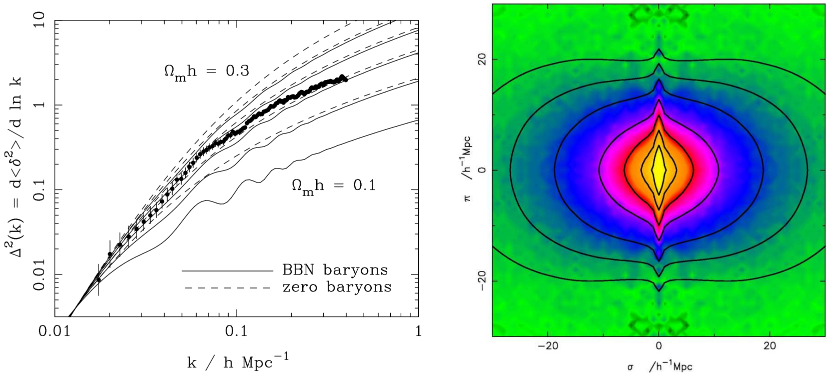
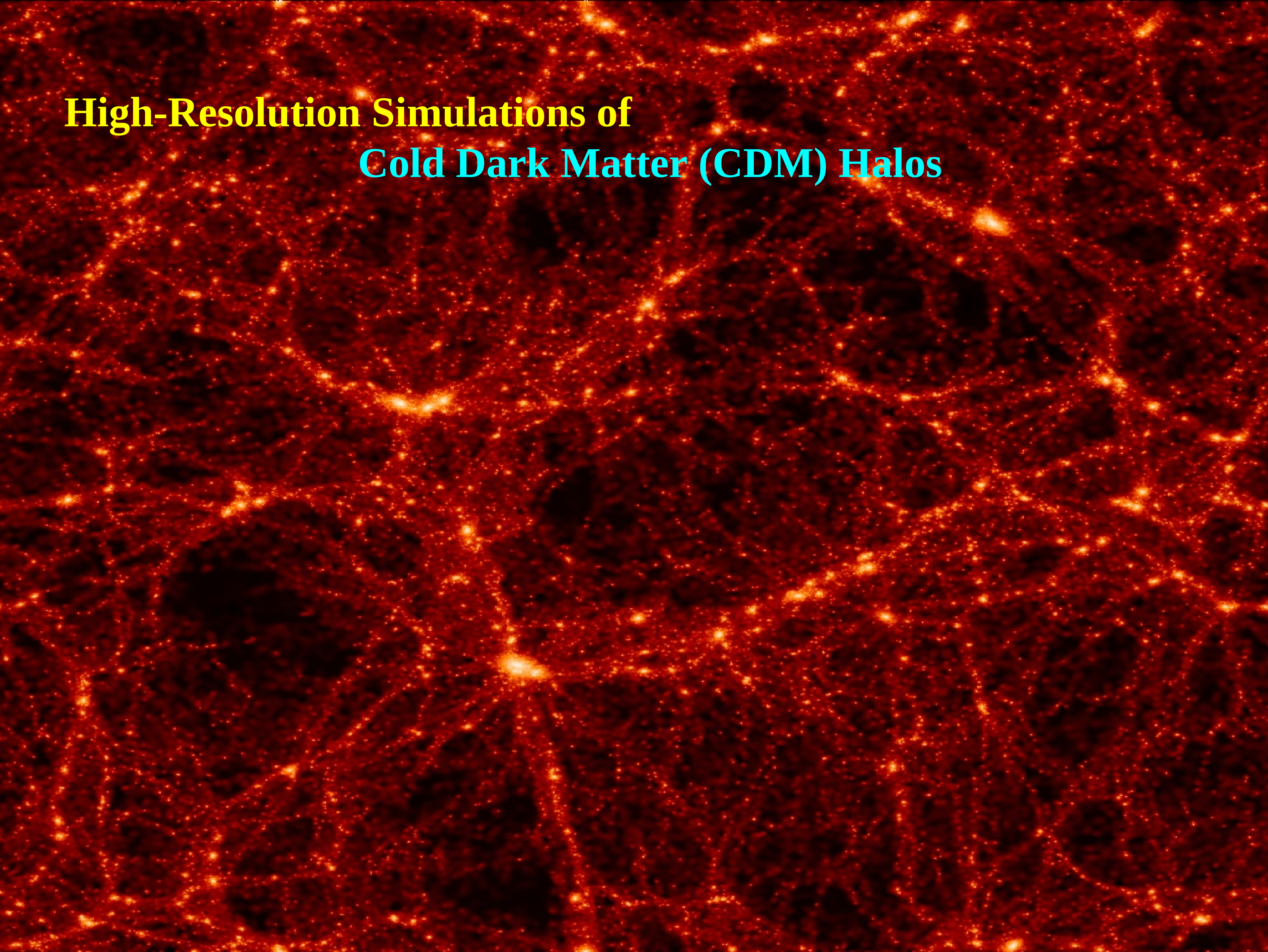
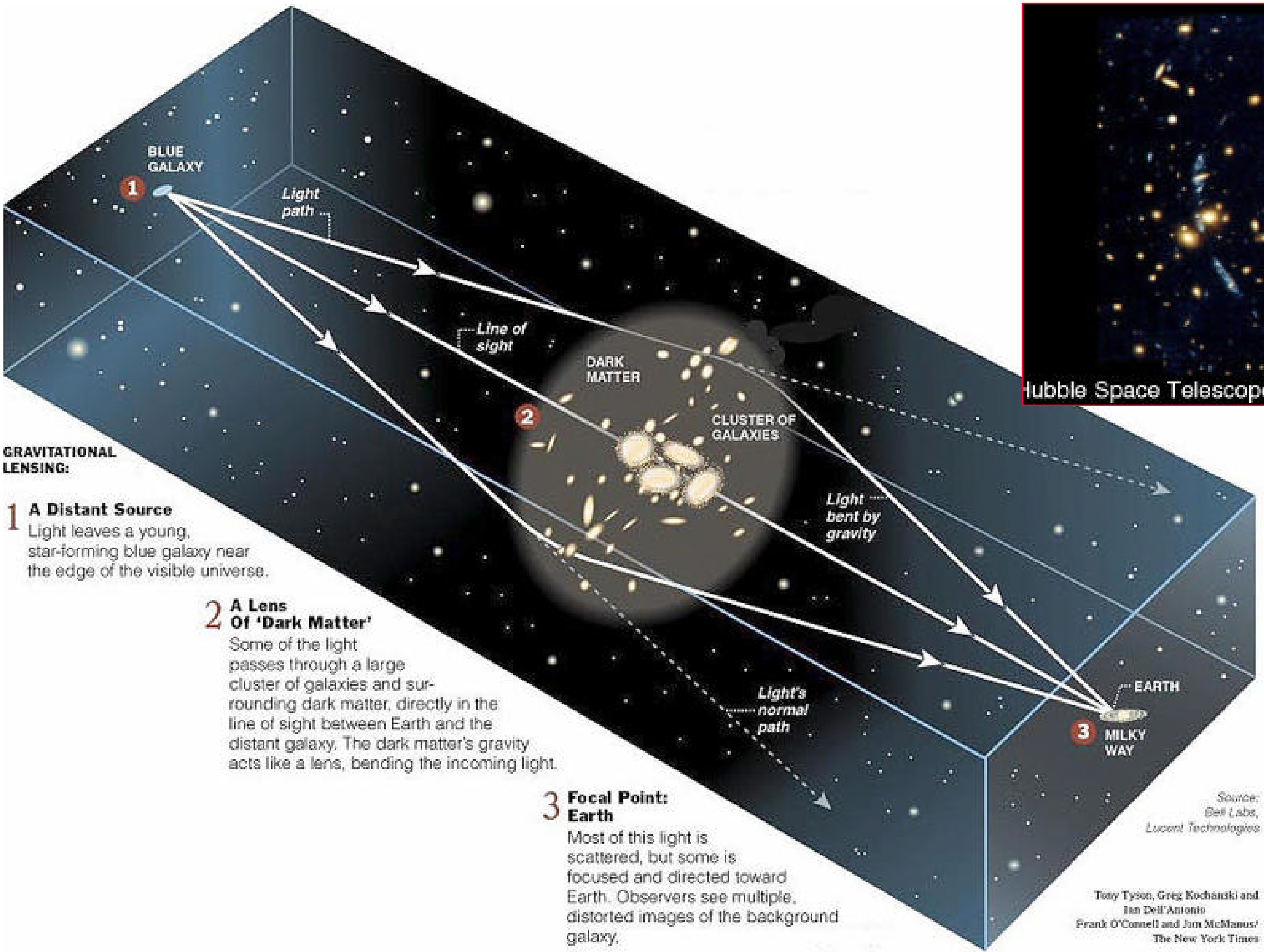


Fig. 1.3. Large scale-structure statistics from the 2dFGRS. The left panel shows the dimensionless power spectrum $\Delta^2(k)$ (Percival et al. 2001, Peacock et al. 2003). Overlaid are the predicted linear-theory CDM power spectra with shape parameters $\Omega h = 0.1, 0.15, 0.2, 0.25, 0.3$ with the baryon fraction predicted by Big Bang nucleosynthesis (solid curves) and with zero baryons (dashed curves). The right panel shows the two-dimensional galaxy correlation function, $\xi(\sigma, \pi)$, where σ is the separation across the line of sight and π is the separation along the line of sight (Hawkins et al. 2003). The grayscale image is the observed $\xi(\sigma, \pi)$ and the contours show the best-fitting model.

High-Resolution Simulations of Cold Dark Matter (CDM) Halos



Gravitational Lensing



GRAVITATIONAL LENSING:

1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

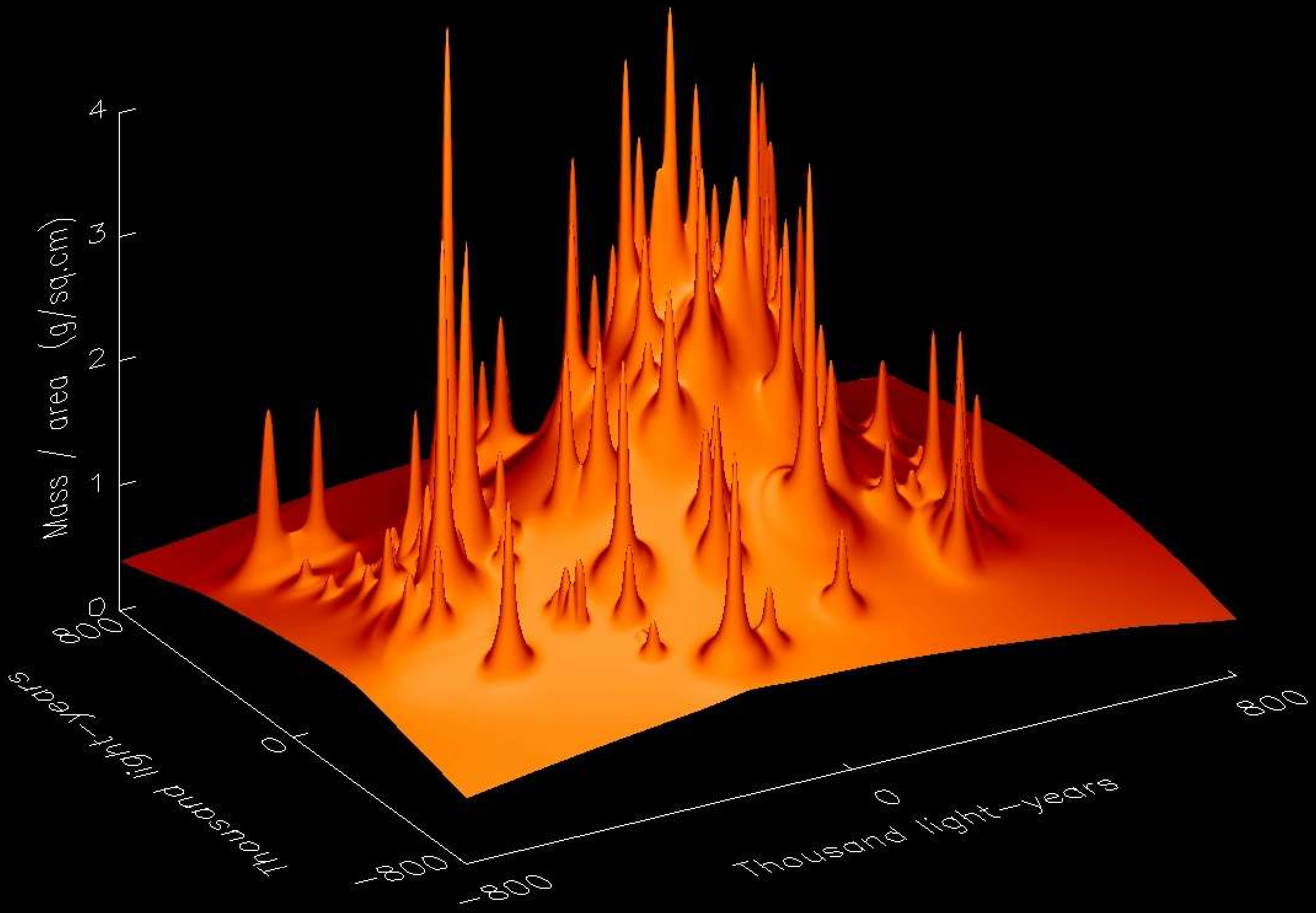
3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

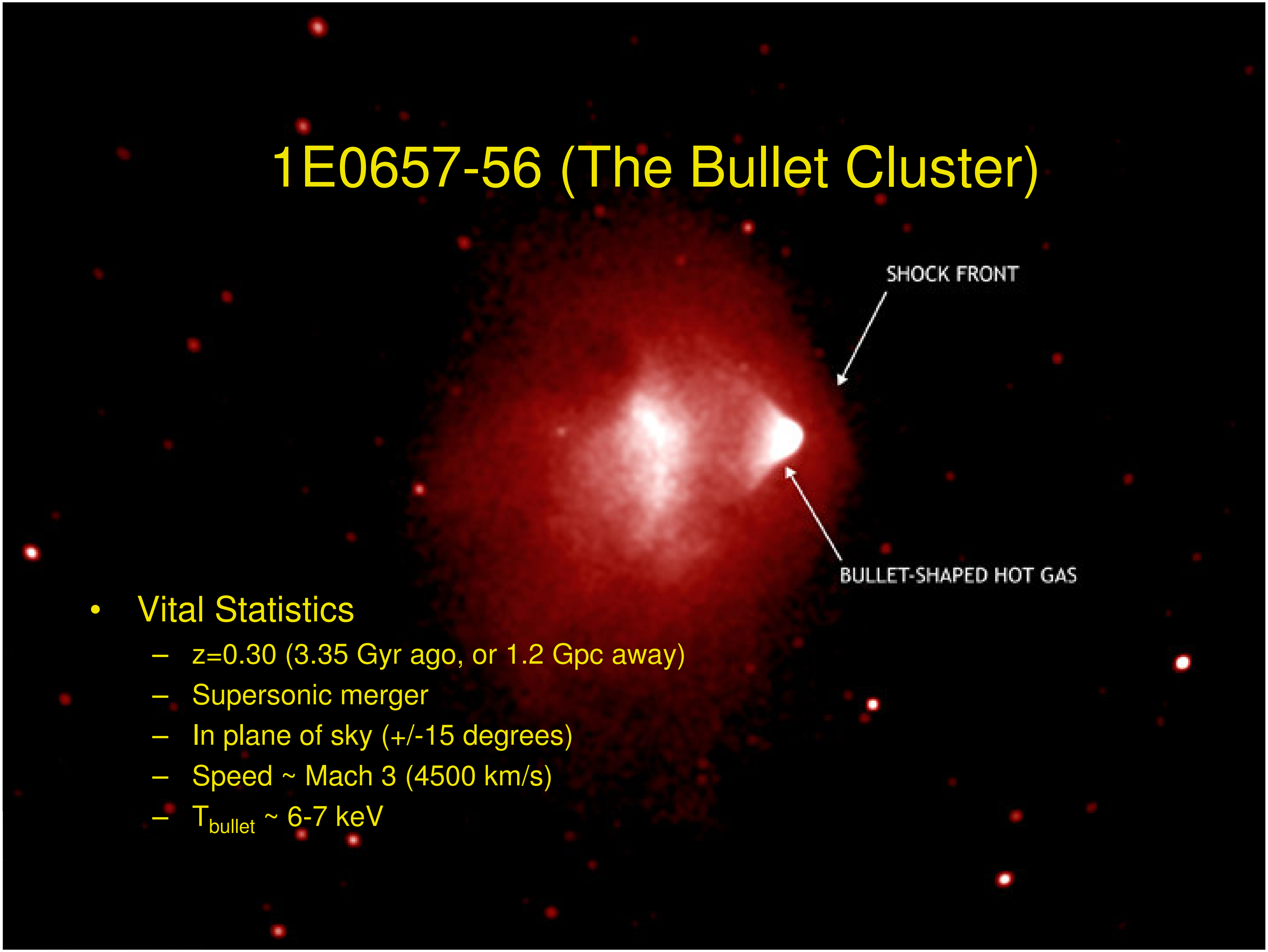

Hubble Space Telescope image of a cluster of galaxies.

Hubble Space Telescope image of a cluster of galaxies.
An irregular blue galaxy in the background is multiply-imaged.

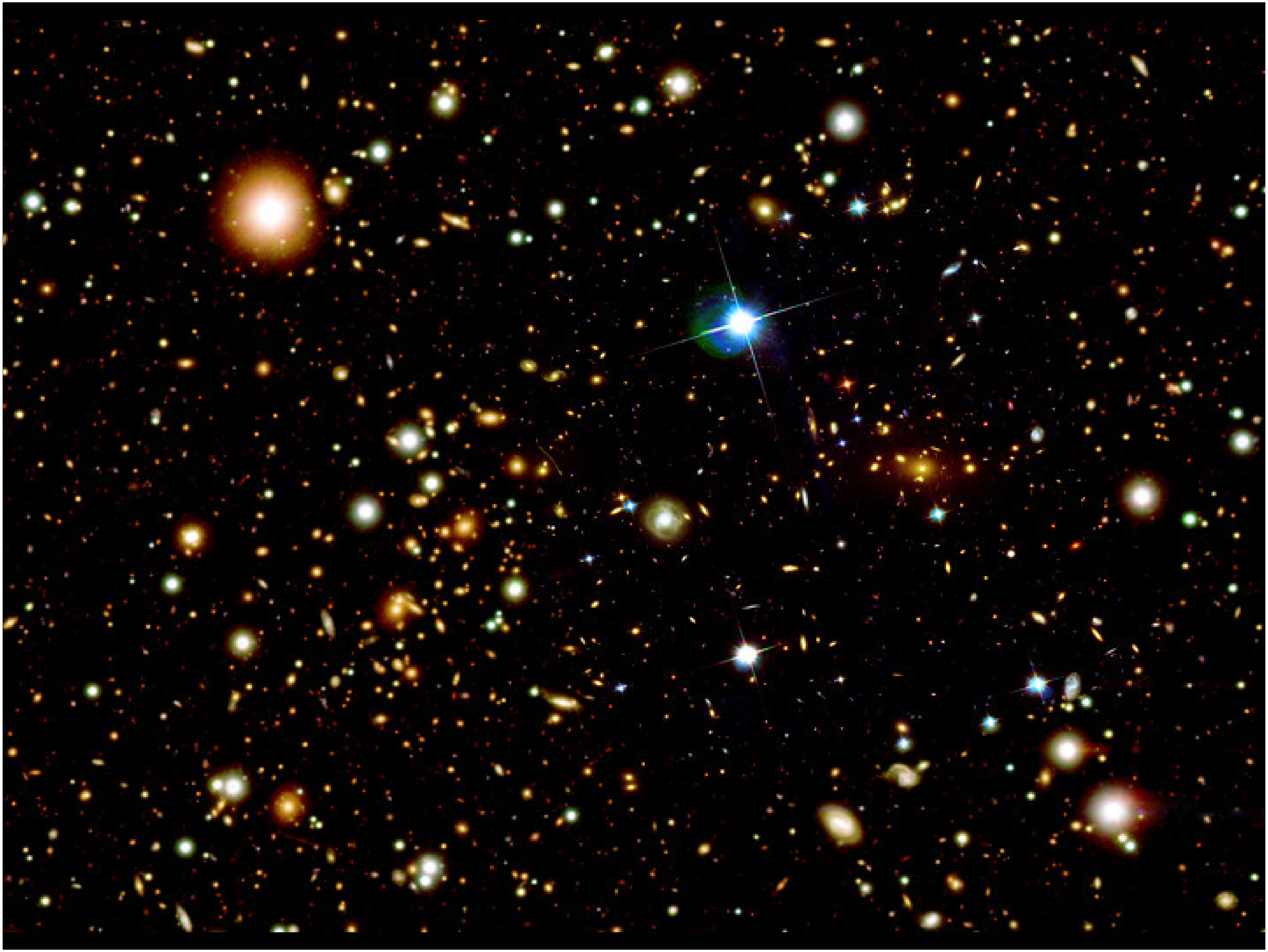


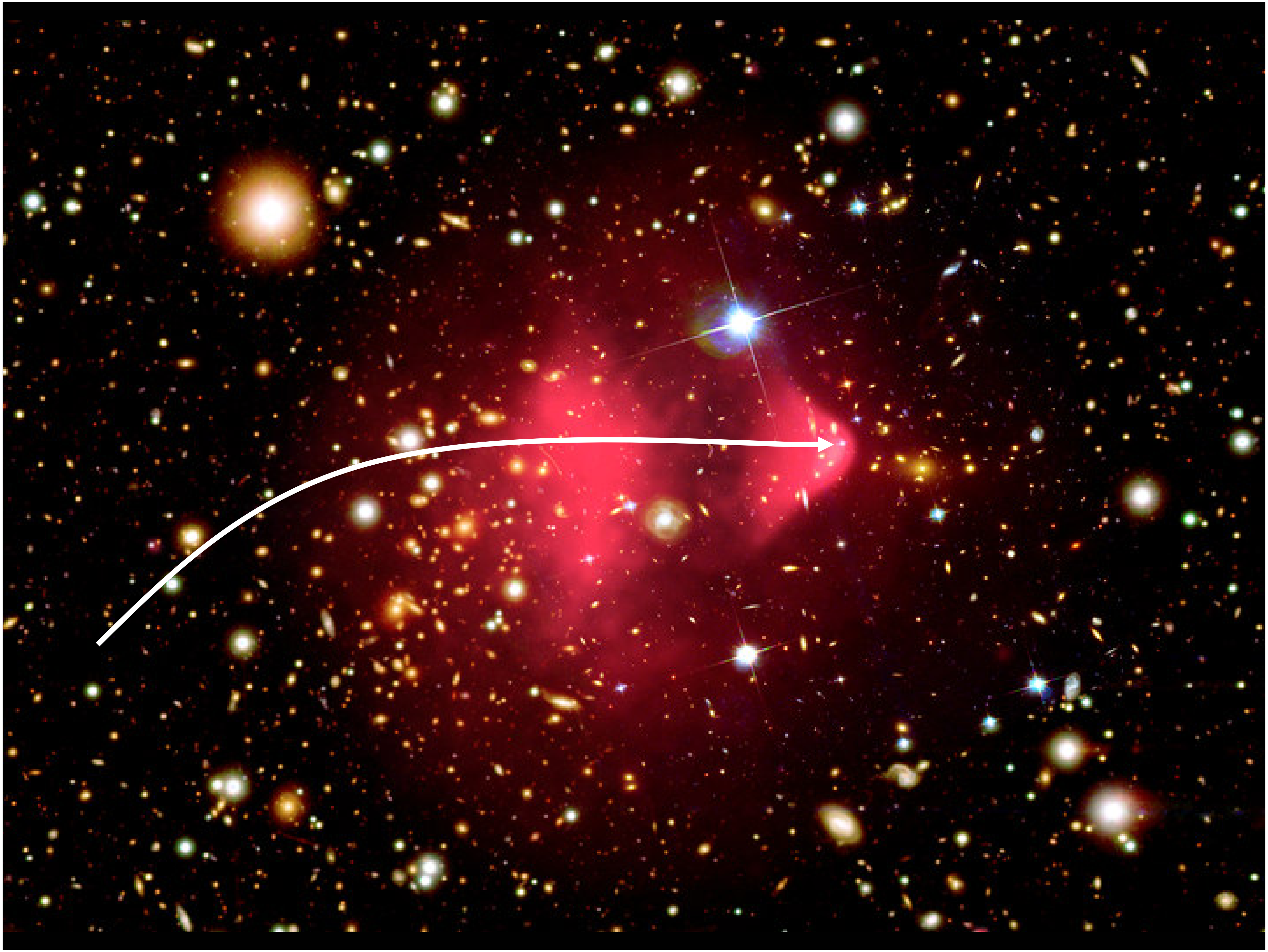
Mass reconstruction of the cluster. Note the large, smooth distribution of (apparently invisible) matter.

1E0657-56 (The Bullet Cluster)



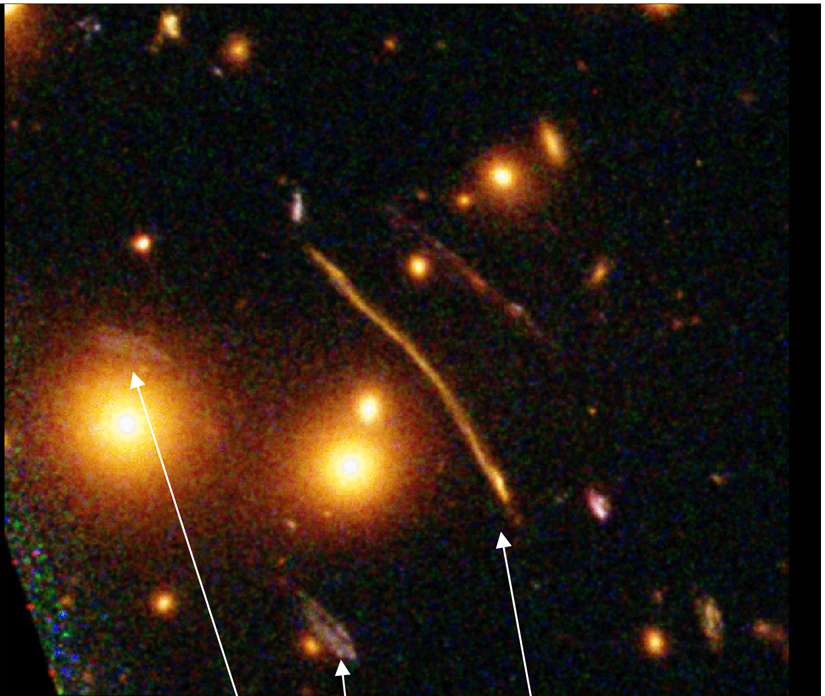
- Vital Statistics
  - z=0.30 (3.35 Gyr ago, or 1.2 Gpc away)
  - Supersonic merger
  - In plane of sky (+/-15 degrees)
  - Speed ~ Mach 3 (4500 km/s)
  - T_{bullet} ~ 6-7 keV

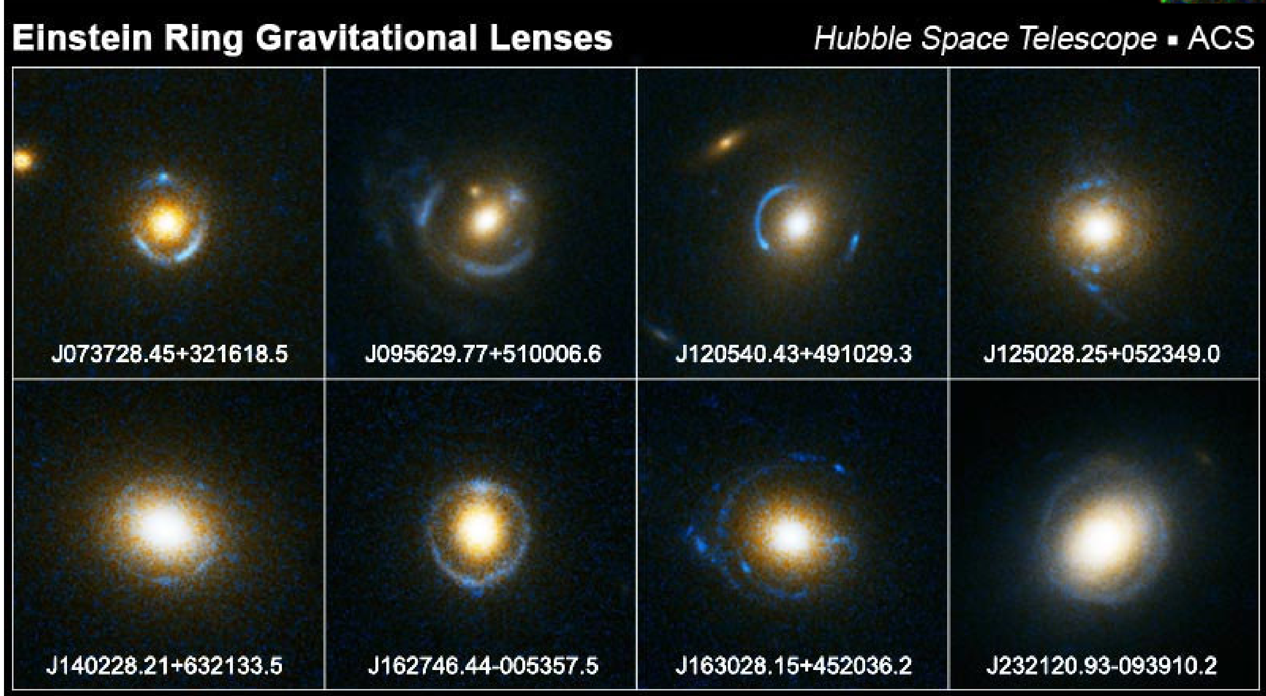




Strong Gravitational Lensing

- Einstein ring
  - Symmetric lens with source directly behind lens
- Strong arcs and multiply lensed sources in clusters
  - More complicated potential
  - Arc geometries probe shear field in cluster core

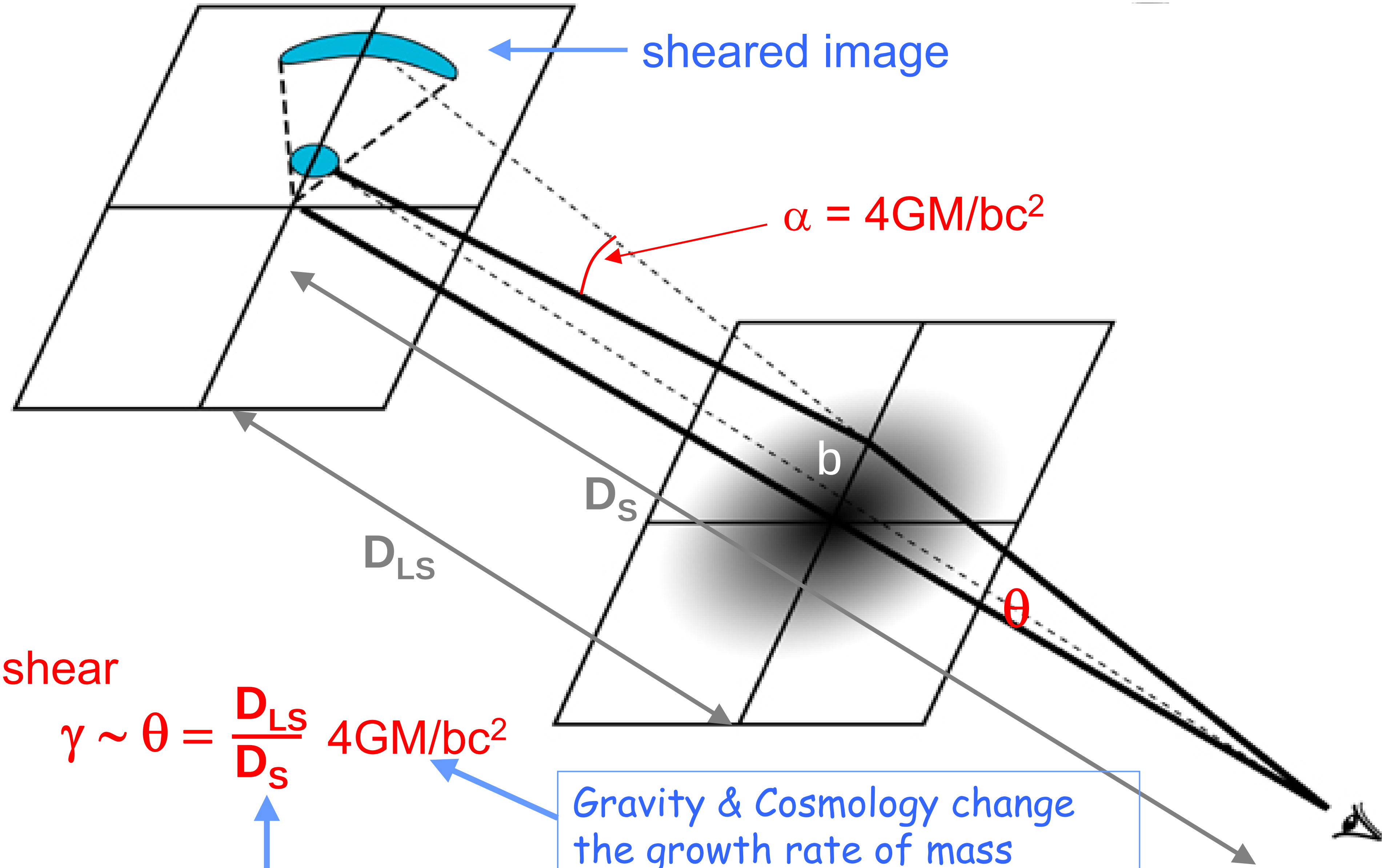



Einstein Ring Gravitational Lenses

Hubble Space Telescope ▪ ACS

NASA, ESA, A. Bolton (Harvard University), and the SLACS Team

STScI-PRC05-32



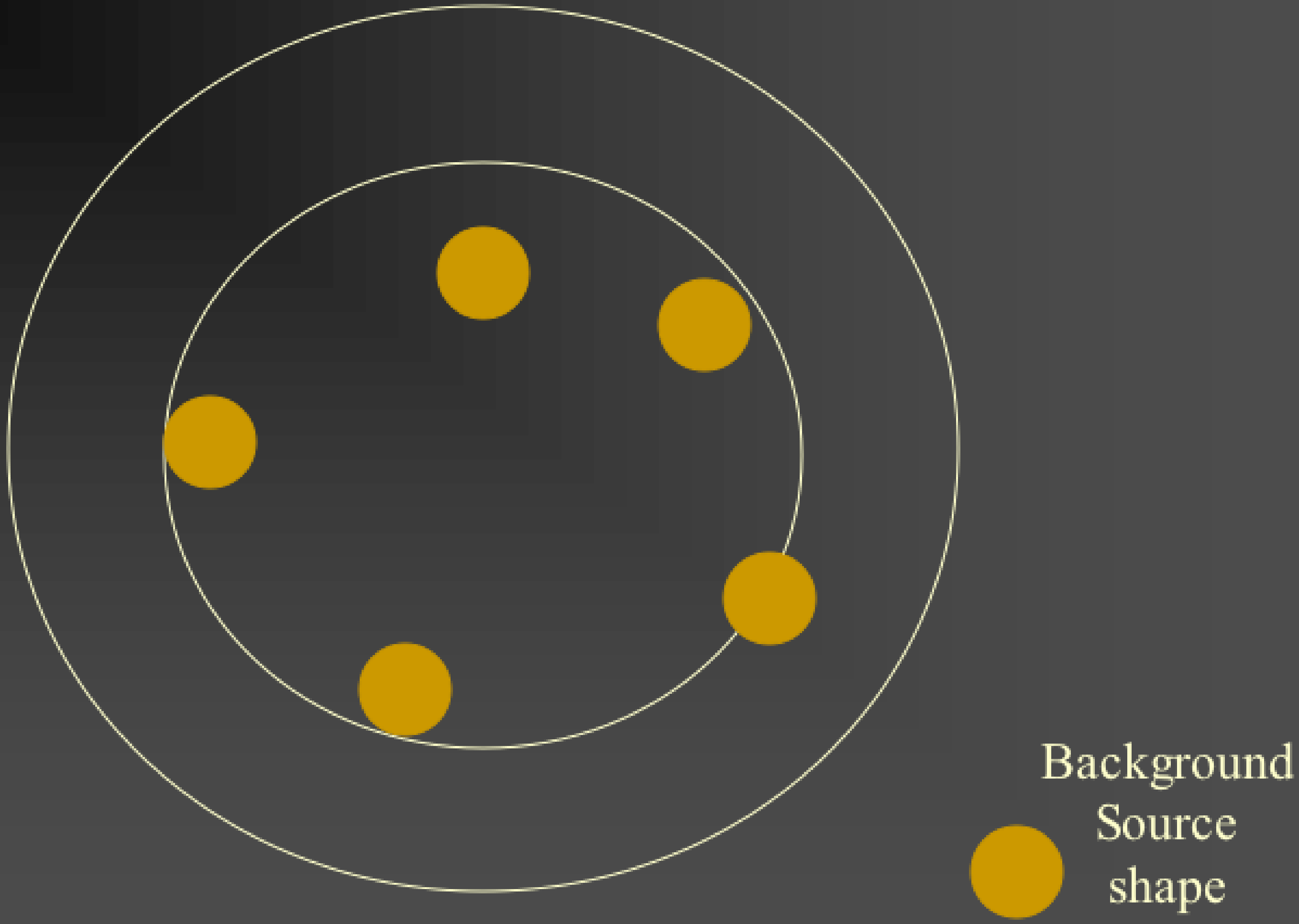
shear

$$\gamma \sim \theta = \frac{D_{LS}}{D_S}\, 4GM/bc^2$$

Gravity & Cosmology change the growth rate of mass structure

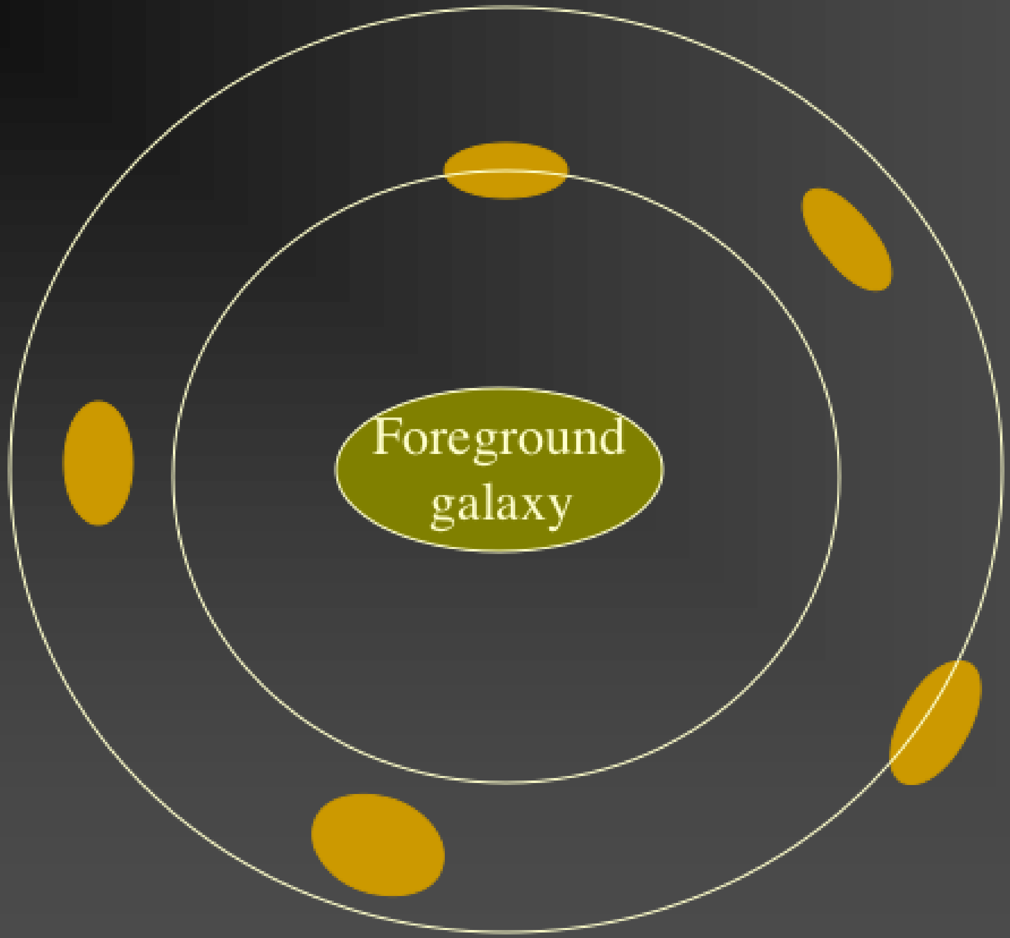
Cosmology changes geometric distance factors

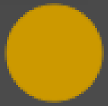
Weak Lensing of Faint Galaxies: distortion of shapes



● Background Source shape

Weak Lensing of Faint Galaxies: distortion of shapes

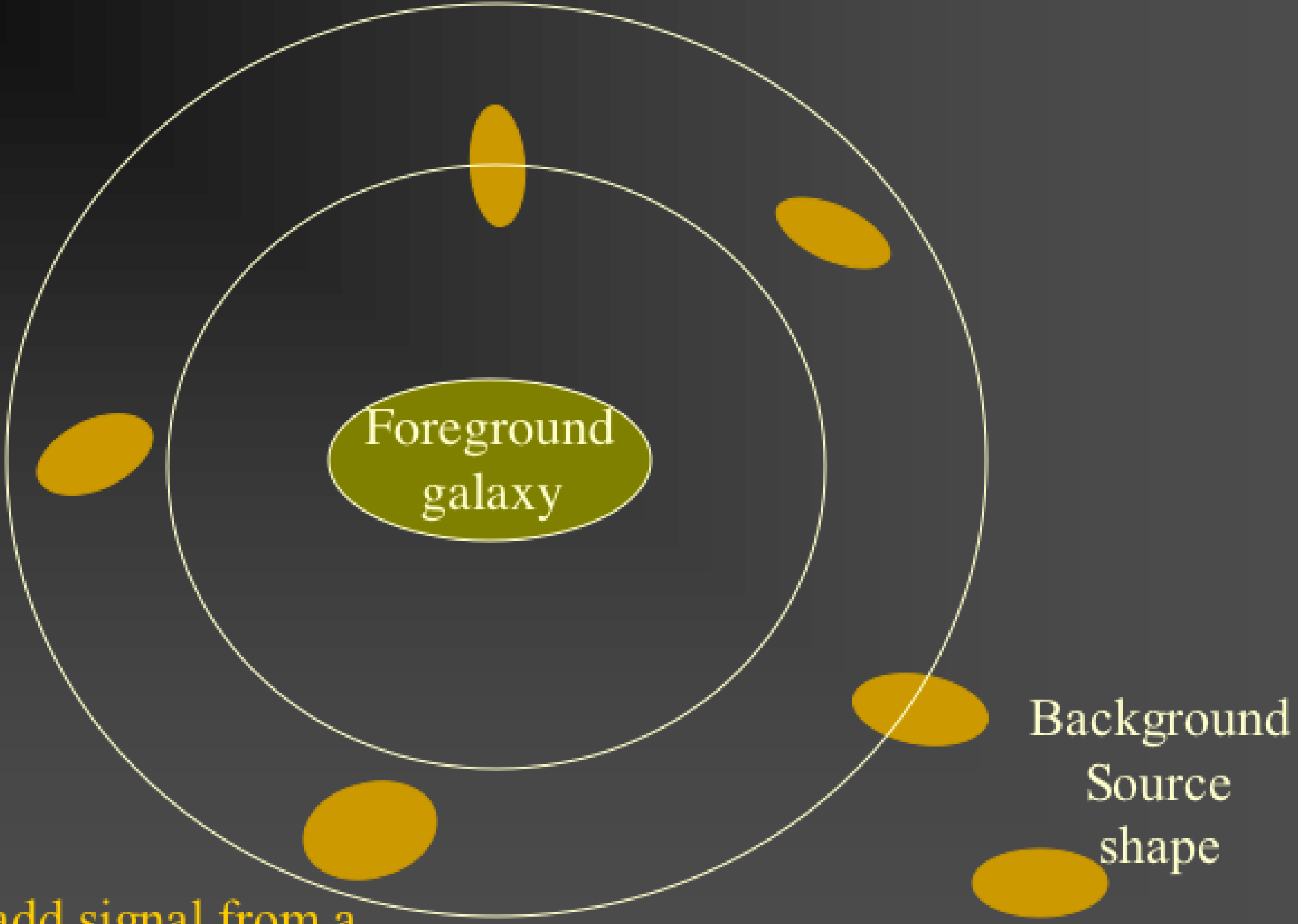




Background
Source
shape

Note: the effect has been greatly exaggerated here

Lensing of real (elliptically shaped) galaxies

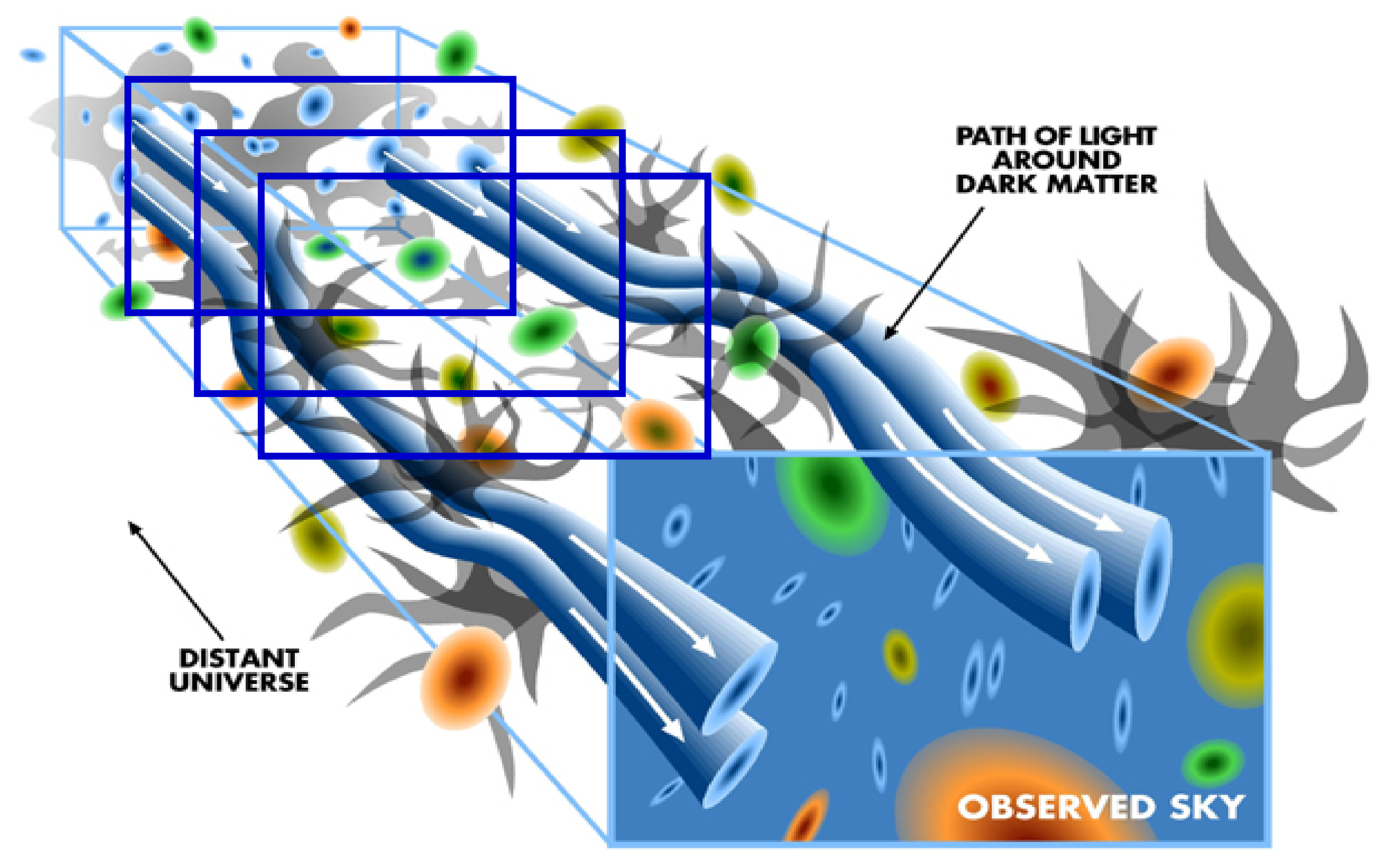


Foreground galaxy

Background Source shape

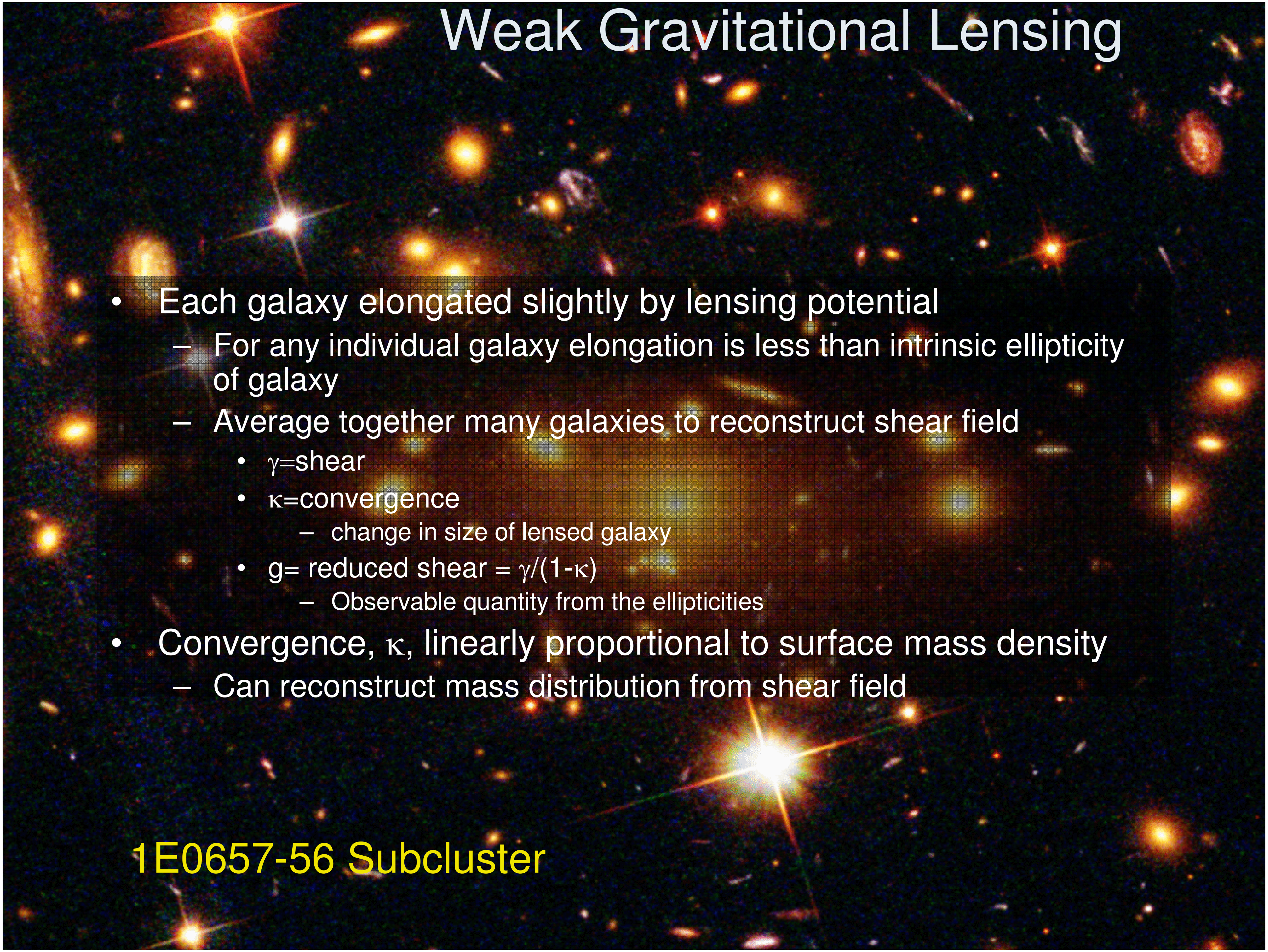
Must co-add signal from a large number of foreground galaxies

Cosmic shear vs redshift



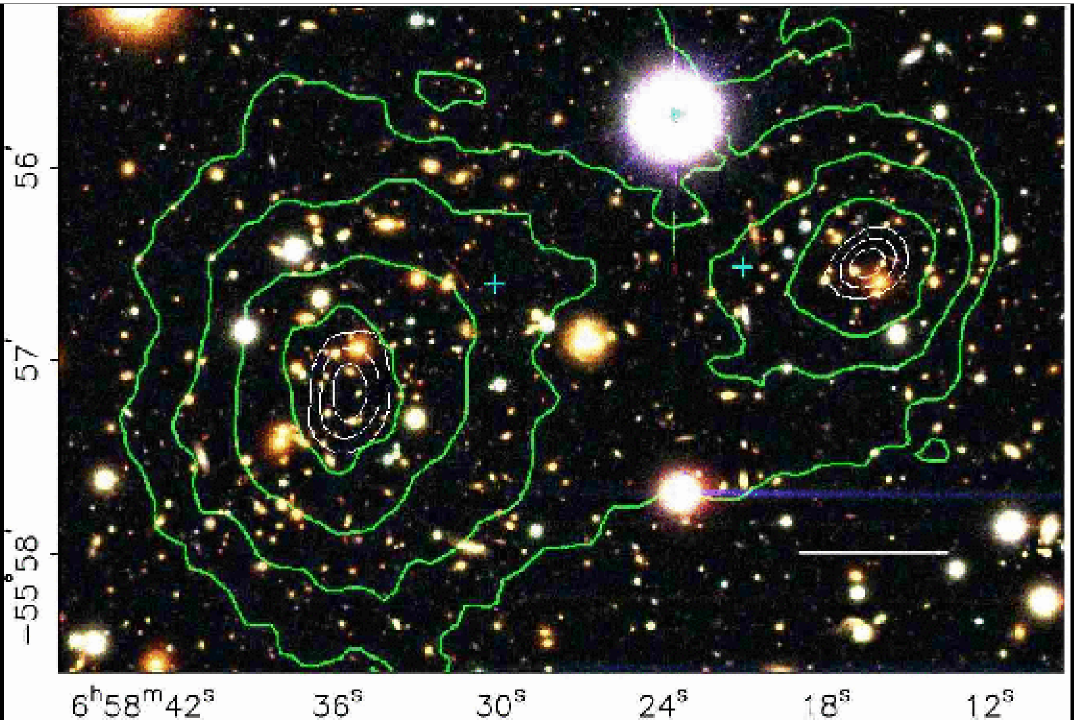
Weak Gravitational Lensing

- Each galaxy elongated slightly by lensing potential
  - For any individual galaxy elongation is less than intrinsic ellipticity of galaxy
  - Average together many galaxies to reconstruct shear field
    - γ=shear
    - κ=convergence
      - change in size of lensed galaxy
    - g= reduced shear = $\gamma/(1-\kappa)$
      - Observable quantity from the ellipticities
- Convergence, κ, linearly proportional to surface mass density
  - Can reconstruct mass distribution from shear field



1E0657-56 Subcluster

2006 Results



Clowe et al. (2006)

Data:

500 ks Chandra

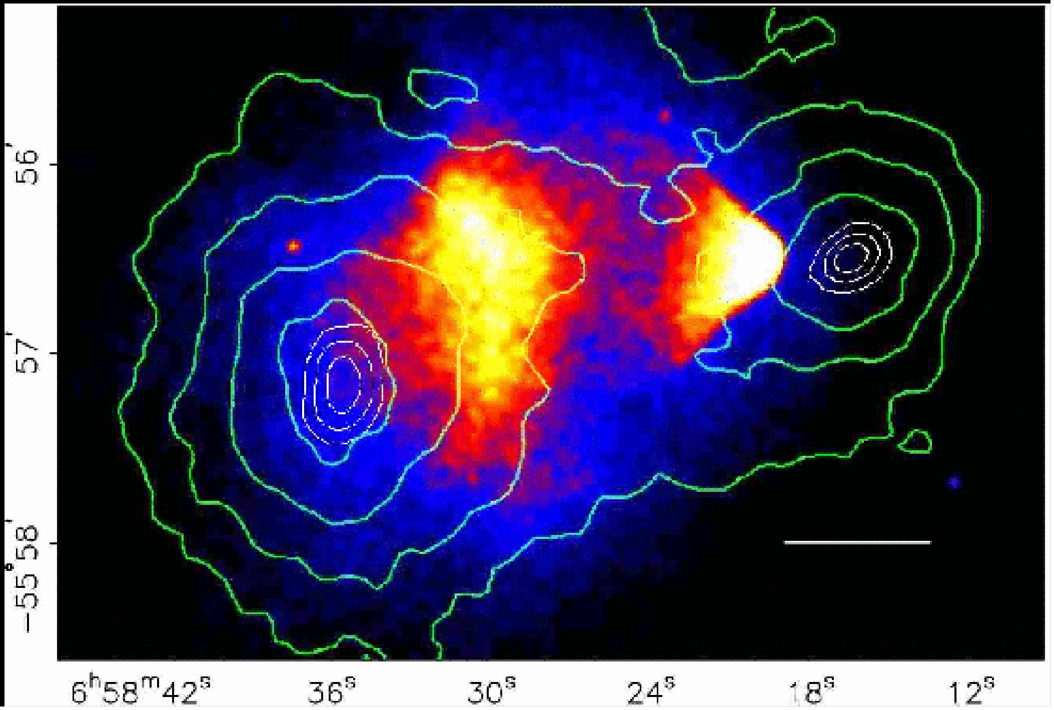
Deep Magellan + HST imaging

Results:

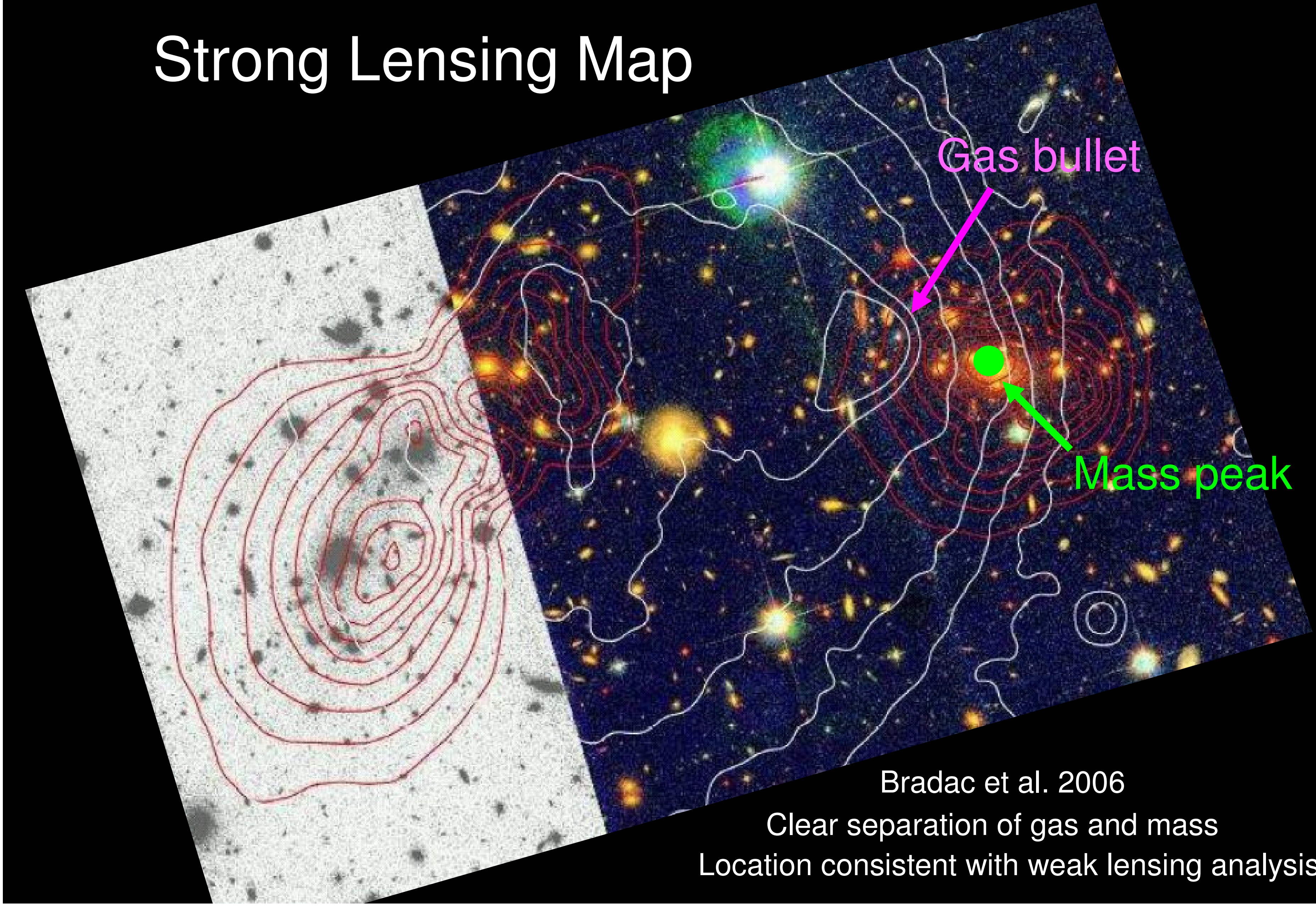
8 σ offset between gas and DM peak

for both main and subcluster

No offset between galaxies and DM



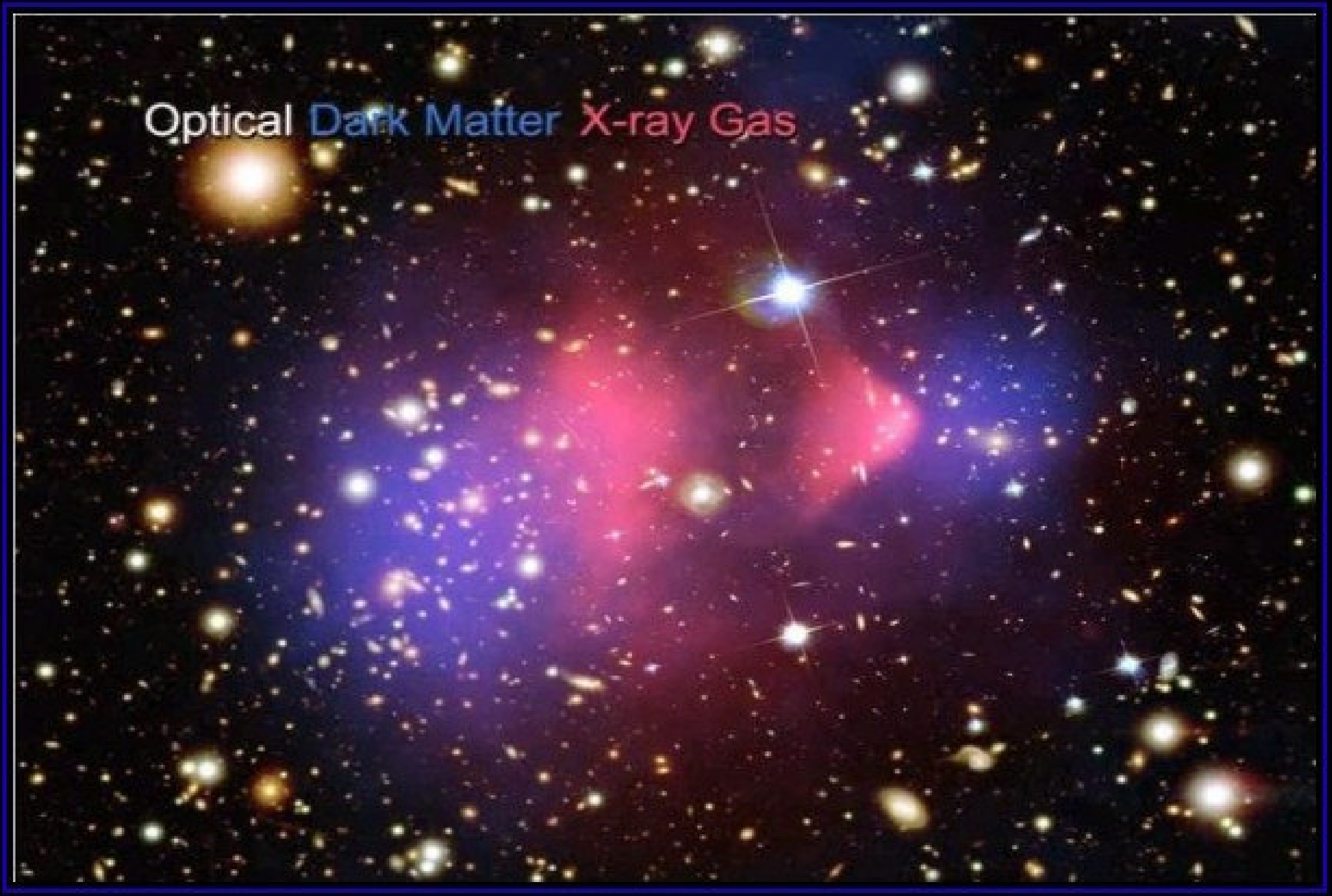
Strong Lensing Map



Bradac et al. 2006

Clear separation of gas and mass

Location consistent with weak lensing analysis

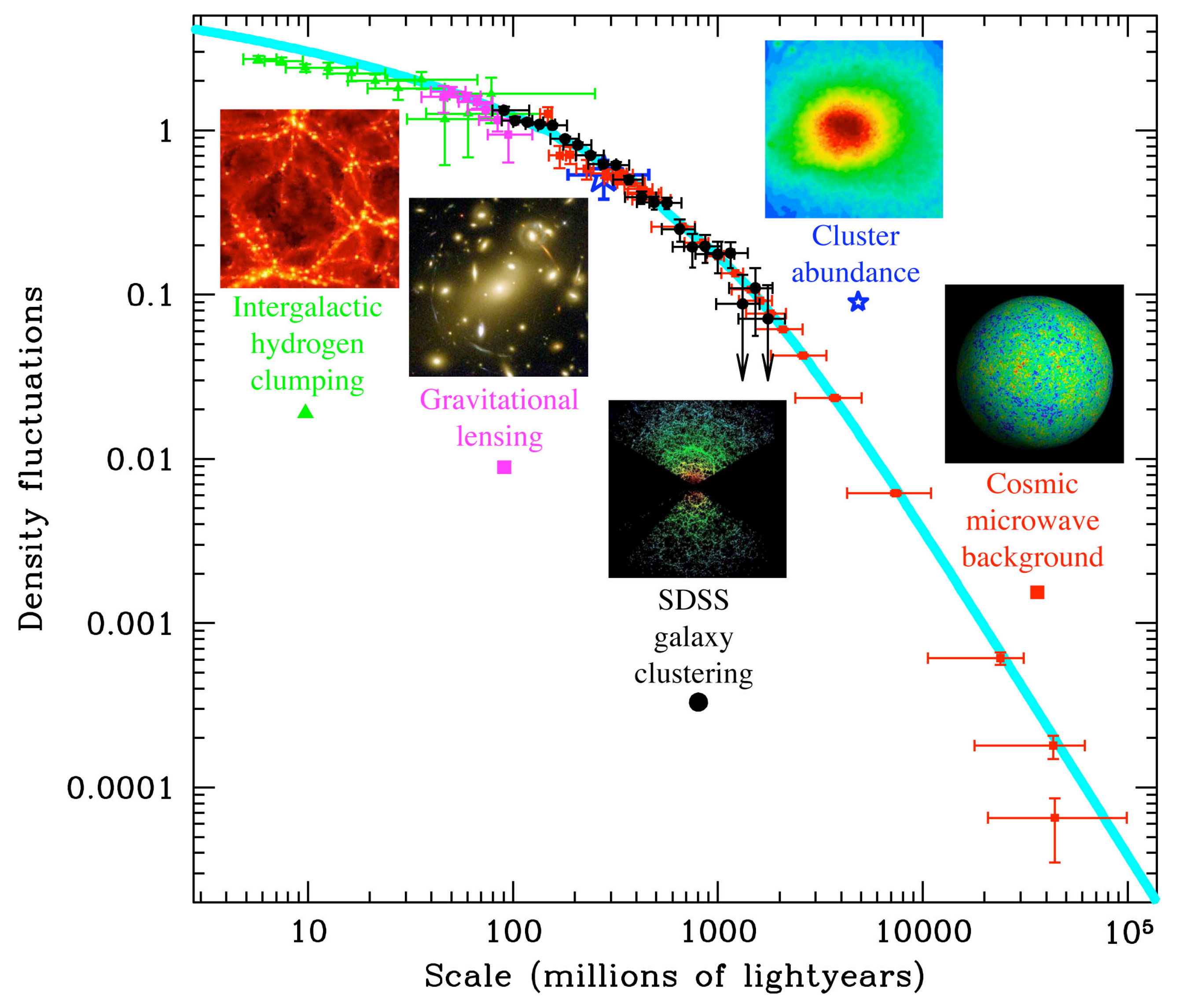


DARK MATTER

Most of the universe can't even be bothered to interact with you.

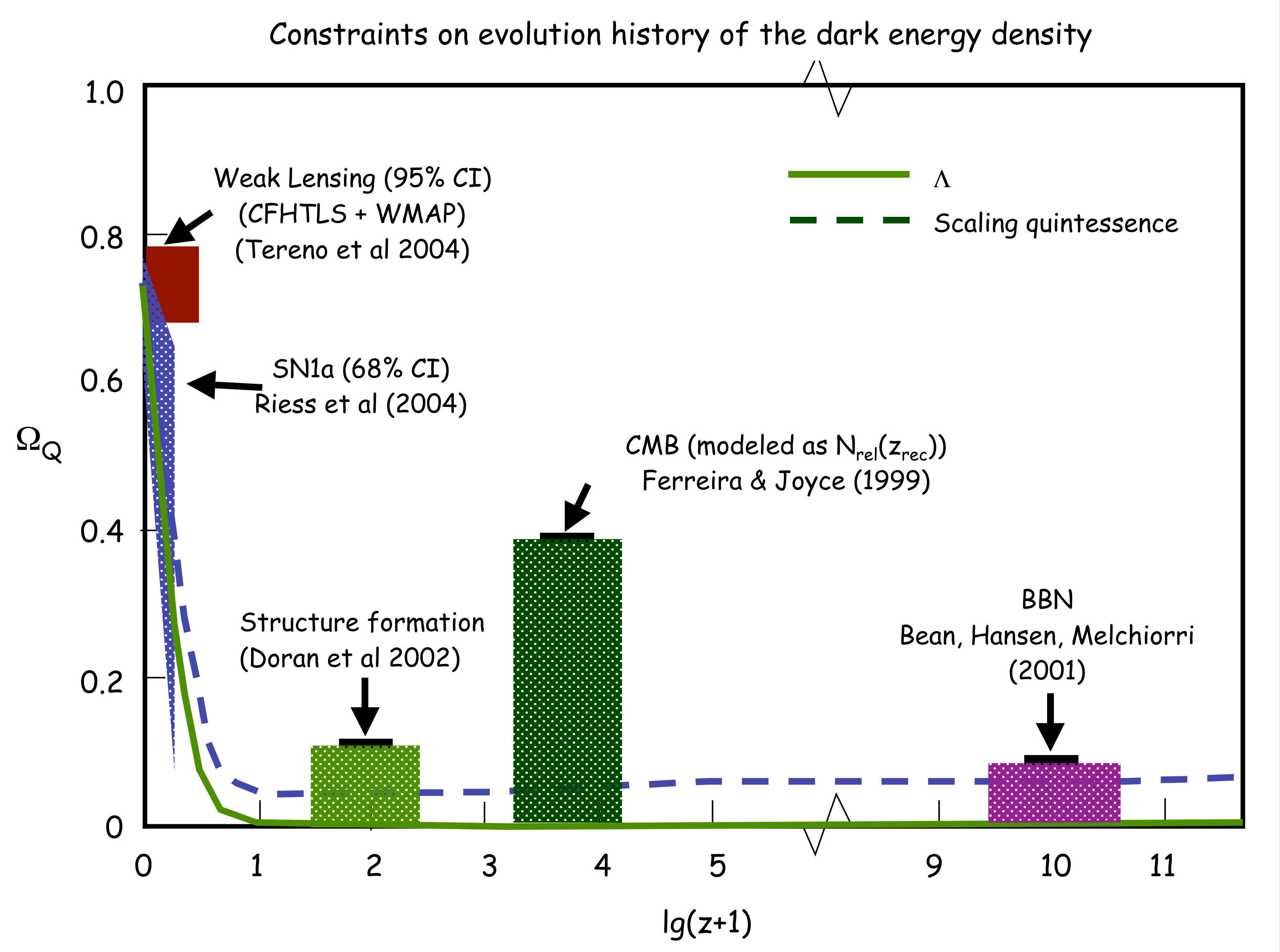
Courtesy Sean Carroll (cosmicvariance.com)

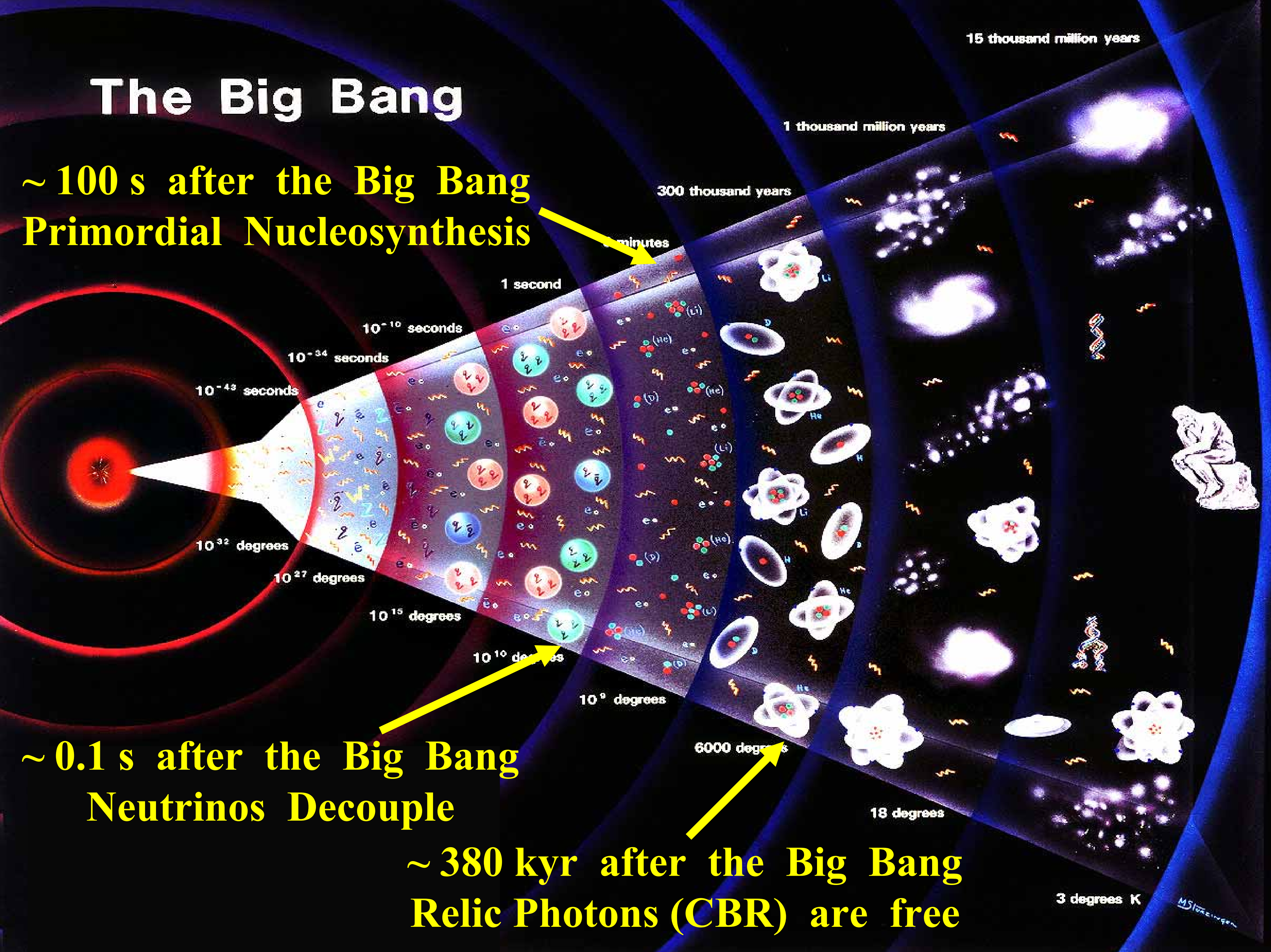
… leveraging evolution on different spatial scales



From Max Tegmark for SDSS

Sensitive to different epochs of evolution history



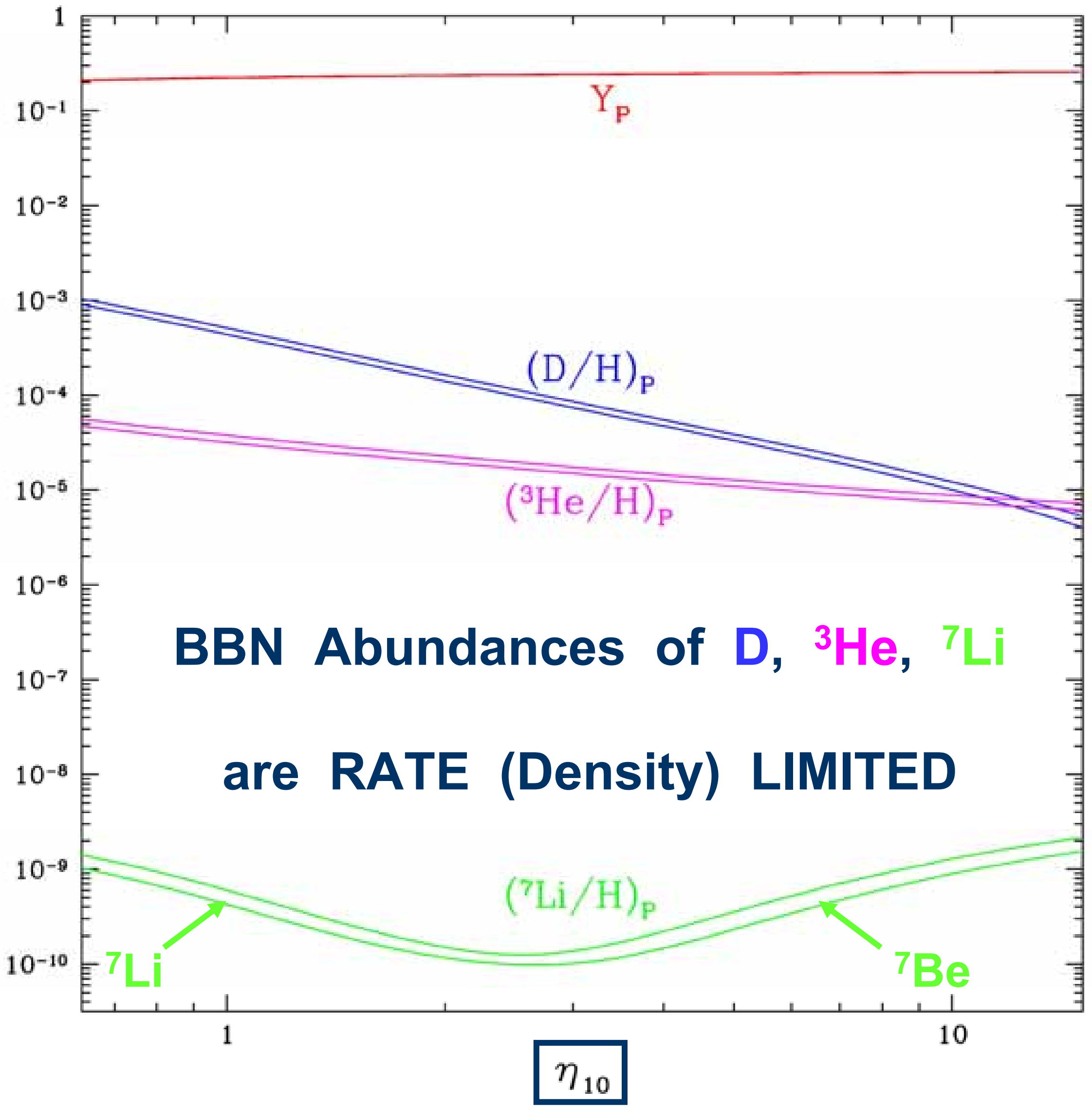


~ 100 s after the Big Bang
Primordial Nucleosynthesis

~ 0.1 s after the Big Bang
Neutrinos Decouple

~ 380 kyr after the Big Bang
Relic Photons (CBR) are free

BBN – Predicted Primordial Abundances

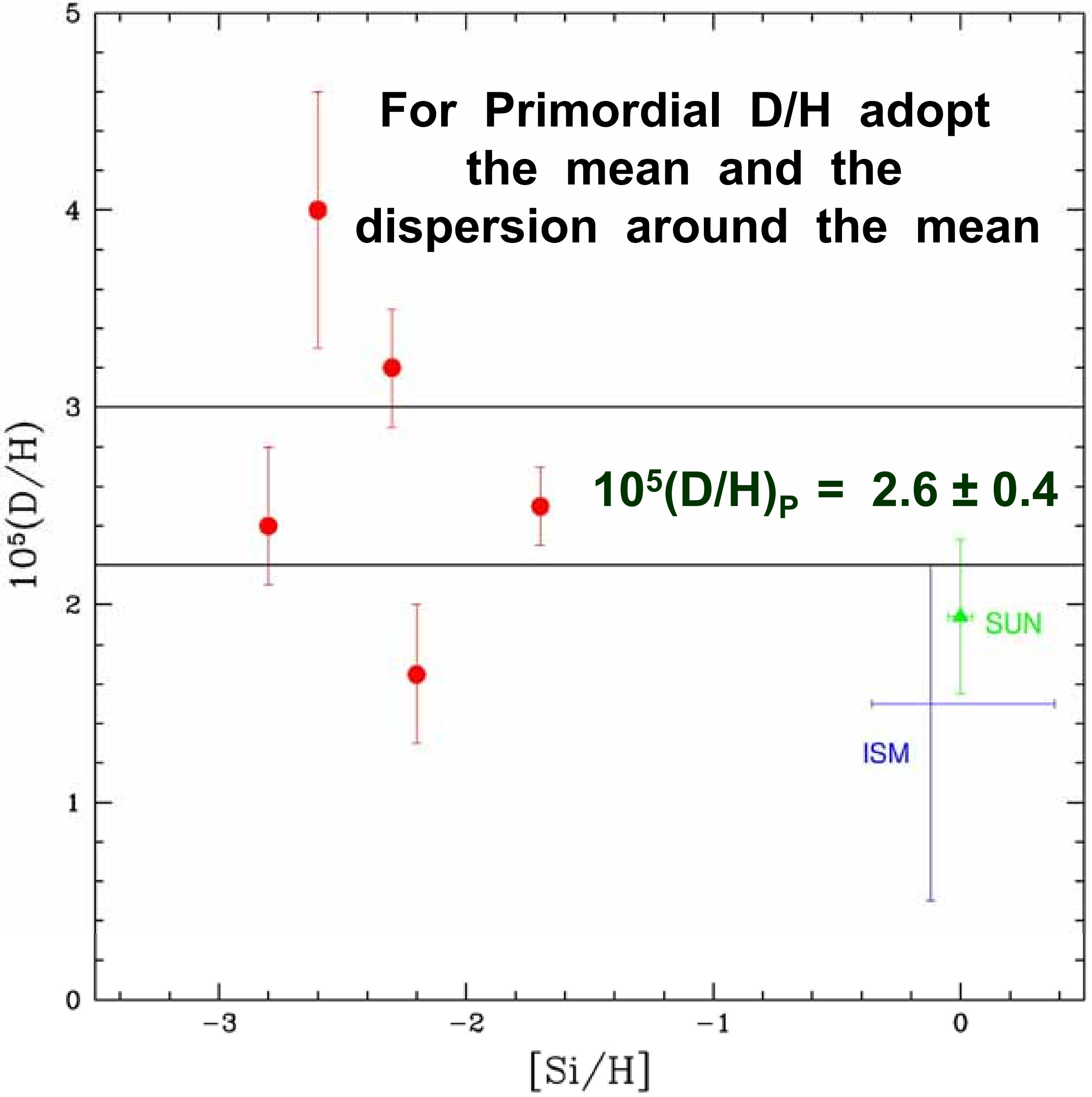


BBN Abundances of D, ^{3}He, ^{7}Li

are RATE (Density) LIMITED

D, ^{3}He, ^{7}Li are potential BARYOMETERS

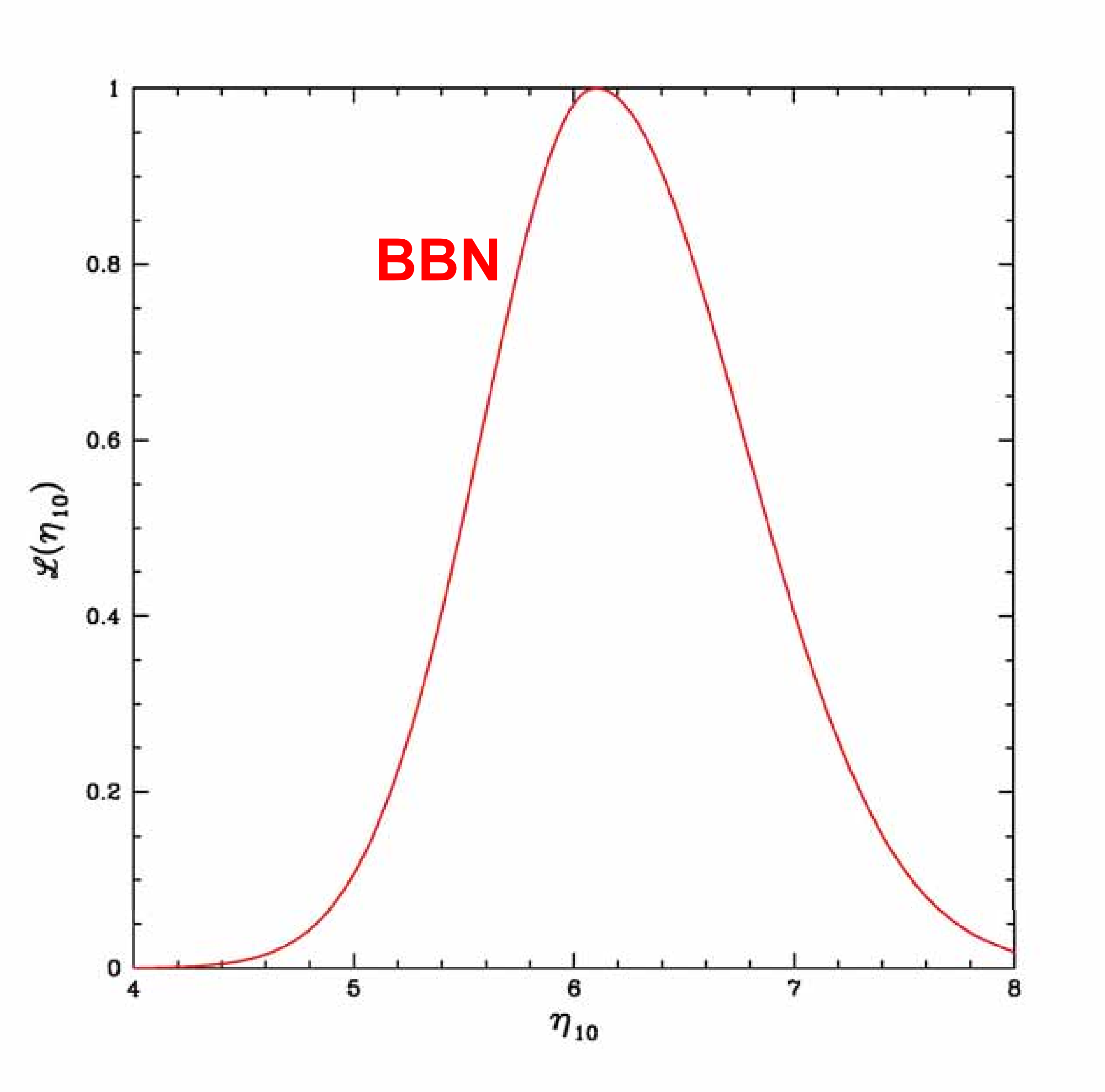
D/H vs. Metallicity



For Primordial D/H adopt the mean and the dispersion around the mean

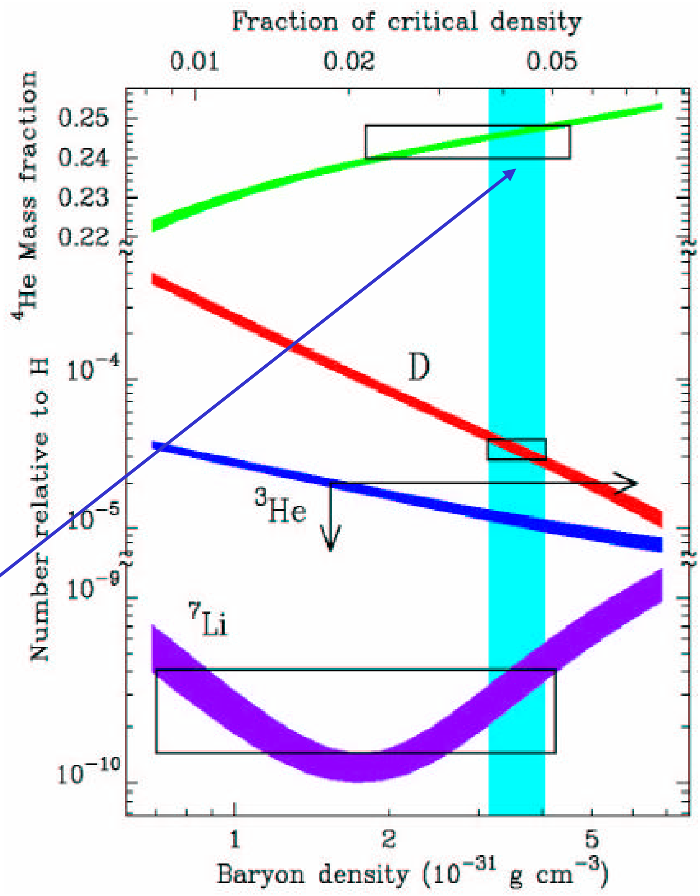
$10^5(D/H)_P = 2.6 \pm 0.4$

$(D/H)_P = 2.6 \pm 0.4 \times 10^{-5}$ + SBBN $\Rightarrow$ $\eta_{10} = 6.1 \pm 0.6$



Ordinary matter from BB Nucleo-Synthesis (baryons)

- Big-Bang Nucleosynthesis depends sensitively on the baryon/photon ratio,
- Since we know how many photons there are, we can constrain the baryon density.
- [Burles, Nollett & Turner]

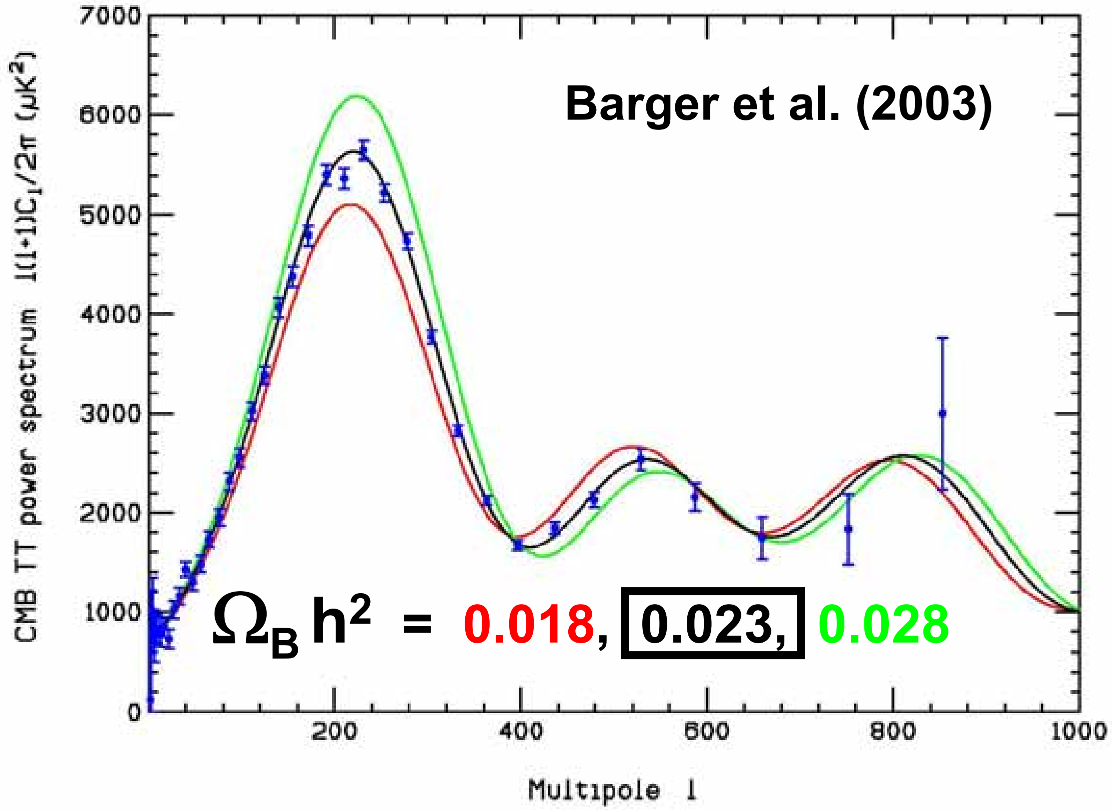


Ω_{BBN} = 0.044 ± 0.004

CBR Temperature Anisotropy Spectrum (2003)

(ΔT^2 vs. θ) Depends On The Baryon Density

$\leftarrow \theta$



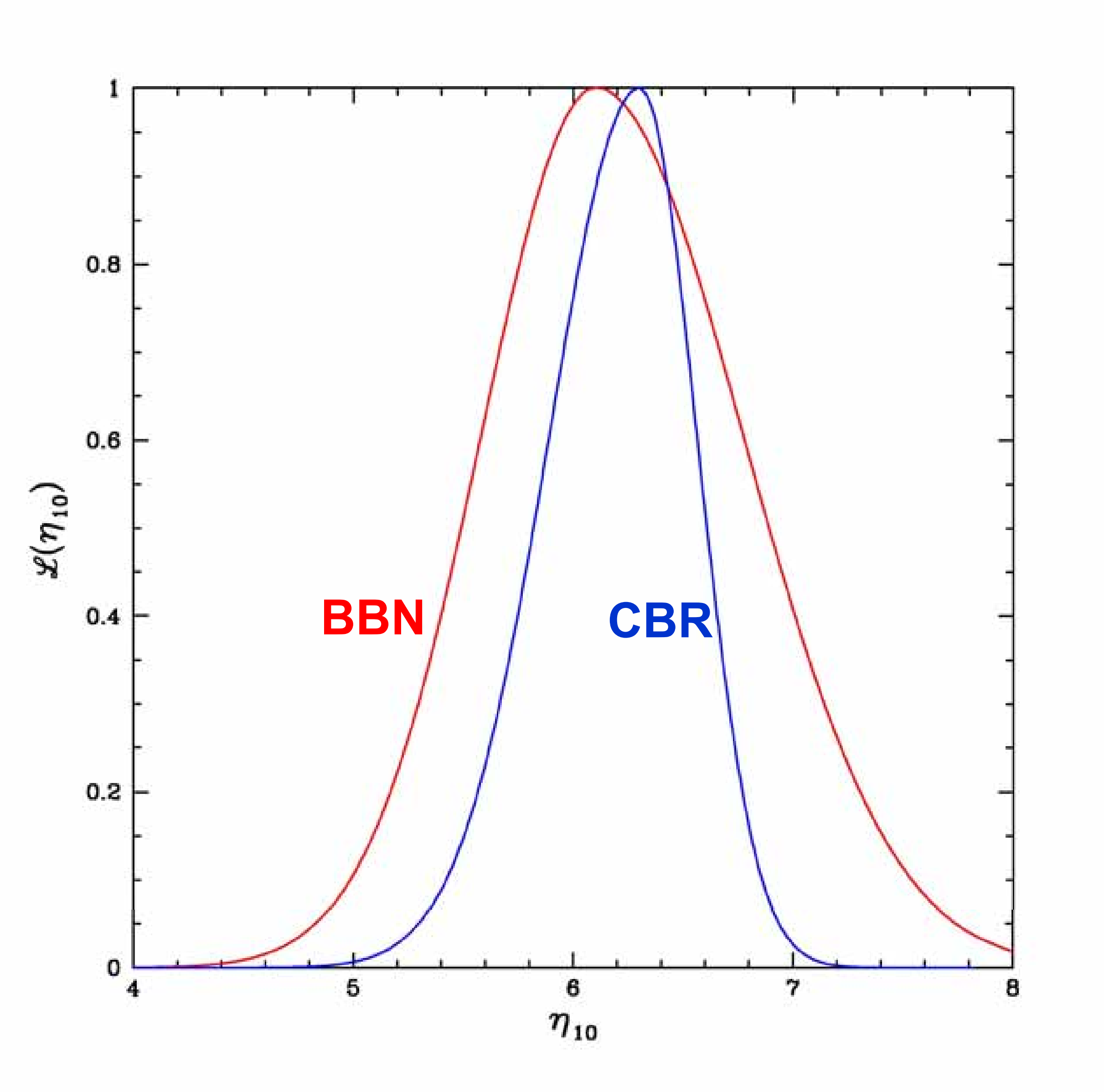
Barger et al. (2003)

$\Omega_B h^2$ = 0.018, $\boxed{0.023,}$ 0.028

CBR (**WMAP**) constrains $\Omega_B h^2$

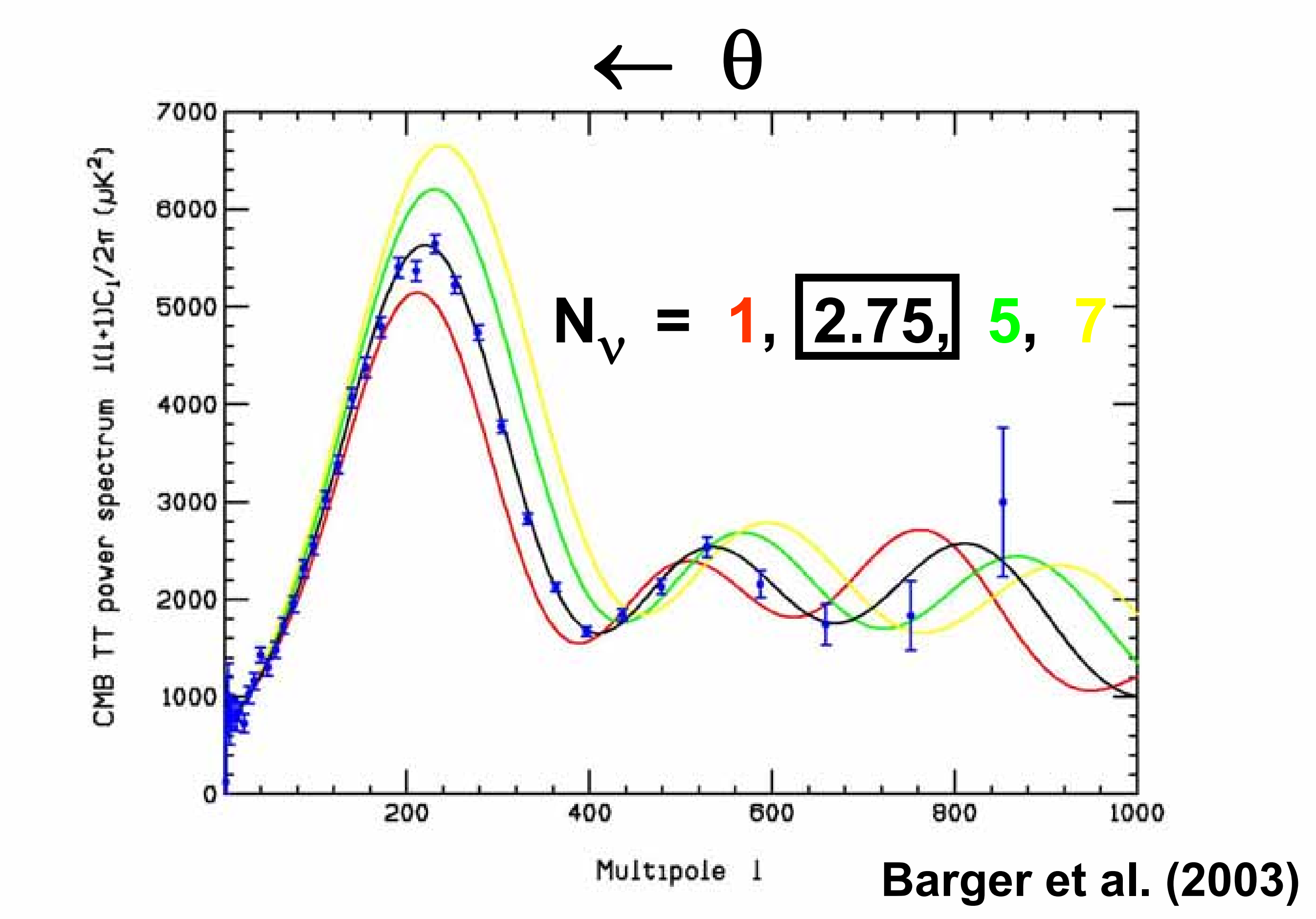
The CBR is an early - Universe Baryometer

BBN (20 min) & CBR (380 kyr) AGREE !



CBR Temperature Anisotropy Spectrum (2003)

Depends on the Radiation Density ρ_R (S or N_ν)

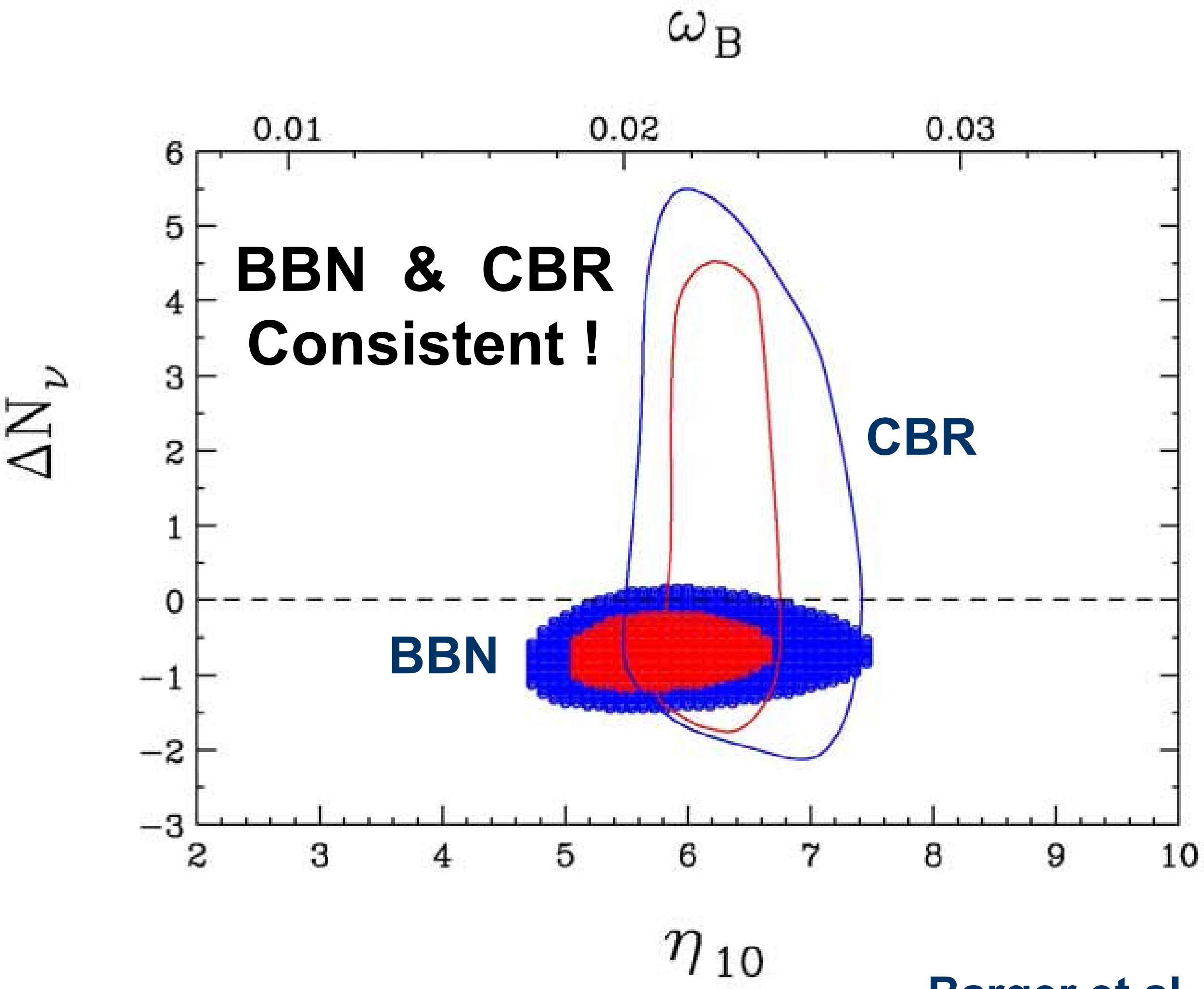


Barger et al. (2003)

CBR (WMAP) constrains N_ν (S)

The CBR is an early - Universe Chronometer

BBN (D & ^{4}He) + CBR (WMAP – 2003)



BBN & CBR Consistent !

Barger et al. (2003)

CONCLUSIONS

(Pre – WMAP 2006)

BBN (~ 20 min.) And The CBR (~ 400 kyr)

Are CONSISTENT !

$1.9 \le N_\nu \le 3.1$ allowed @ ~ 95%

(Also : $\eta_{10} = 6.1 \pm 0.2$)

The second cosmic ruler. The BAO

CMB acoustic oscillations @ z=1089

Single peak in baryon matter correlation function

@≈150h^{-1} Mpc (≈ 200 Mpc)

Observed by SDSS @ z=0.35

2 standard rulers available at 2 epochs

Distance between the two epochs known @ 4%

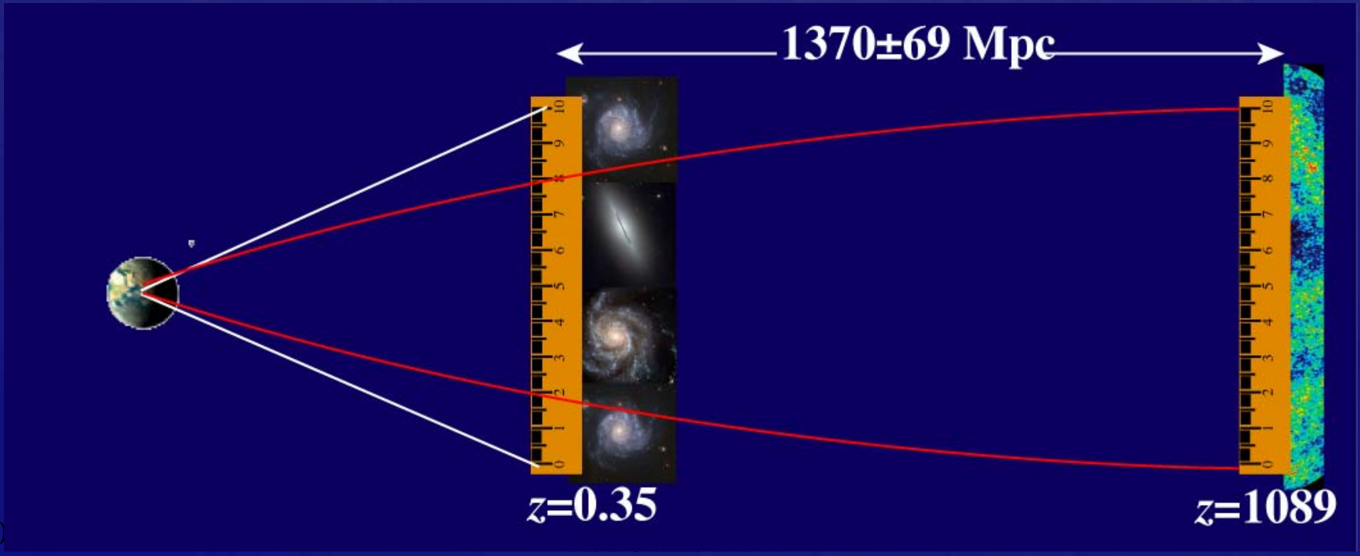
Confirms linear cosmological perturbation theory across an expansion factor = 800

Removes degeneracy between curvature and expansion rate

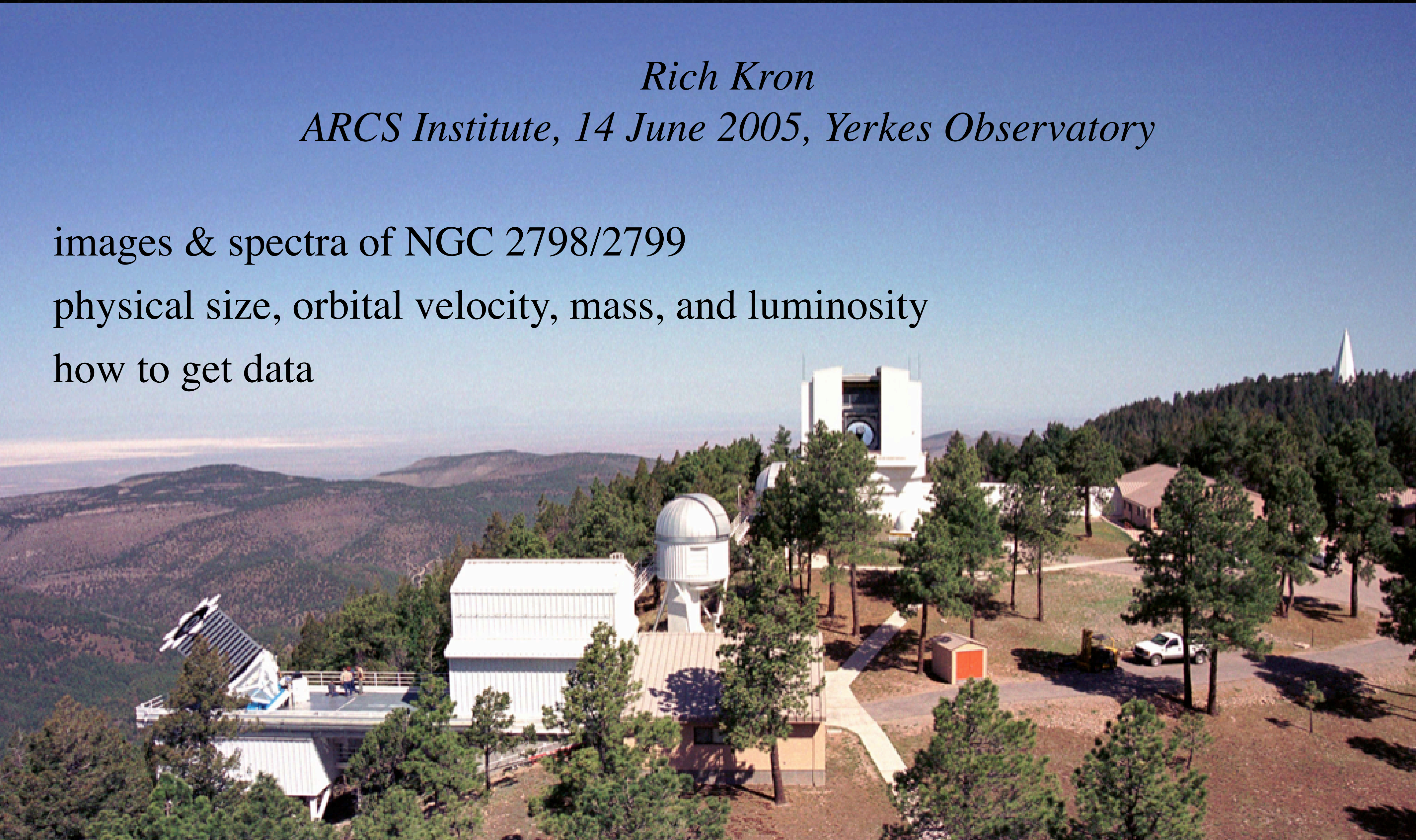
(Distance)^2×correlation function

Curves are for different Ω_m

Astro-ph/0501171



Measuring the Masses of Galaxies in the Sloan Digital Sky Survey



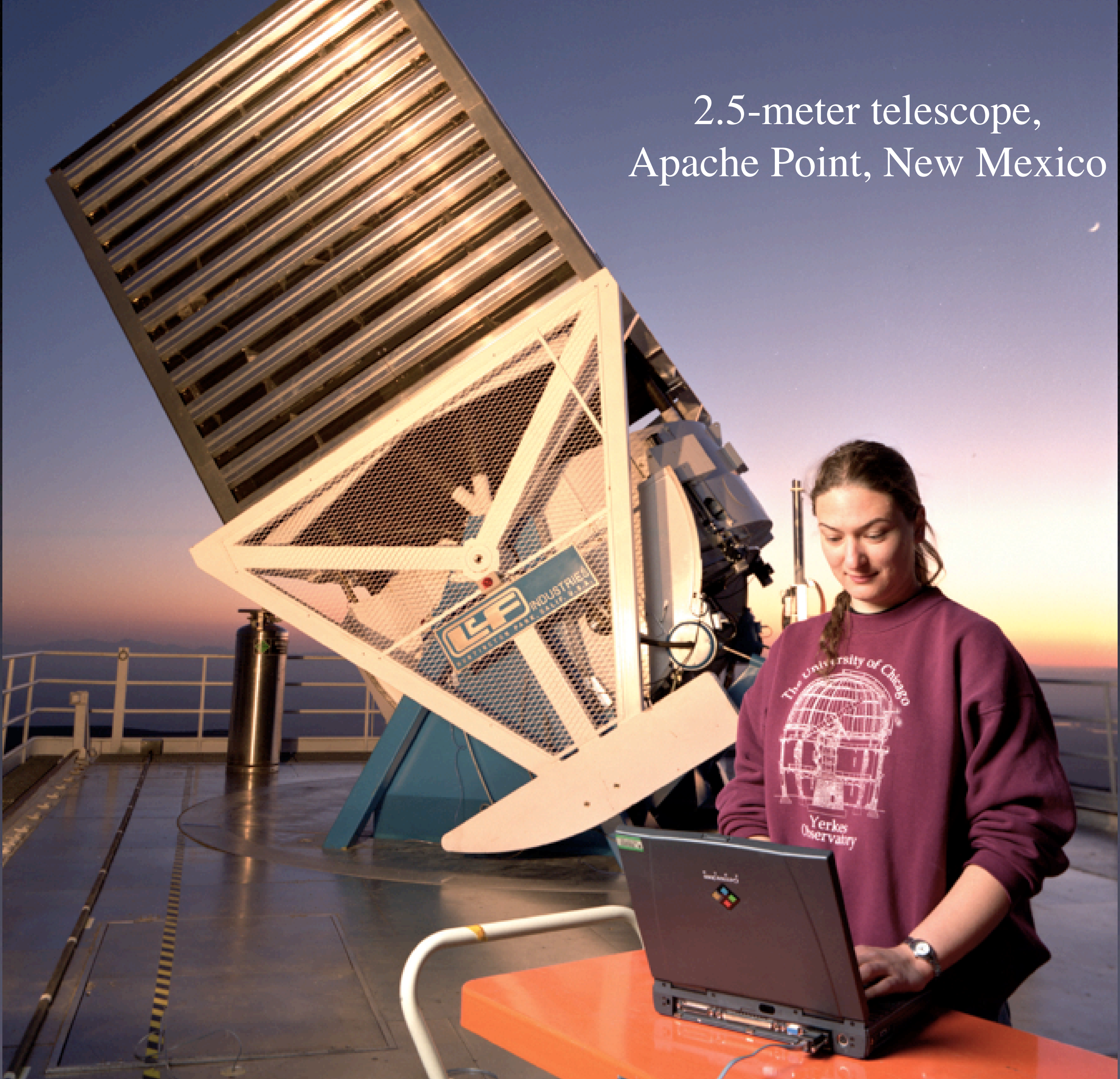
Rich Kron

ARCS Institute, 14 June 2005, Yerkes Observatory

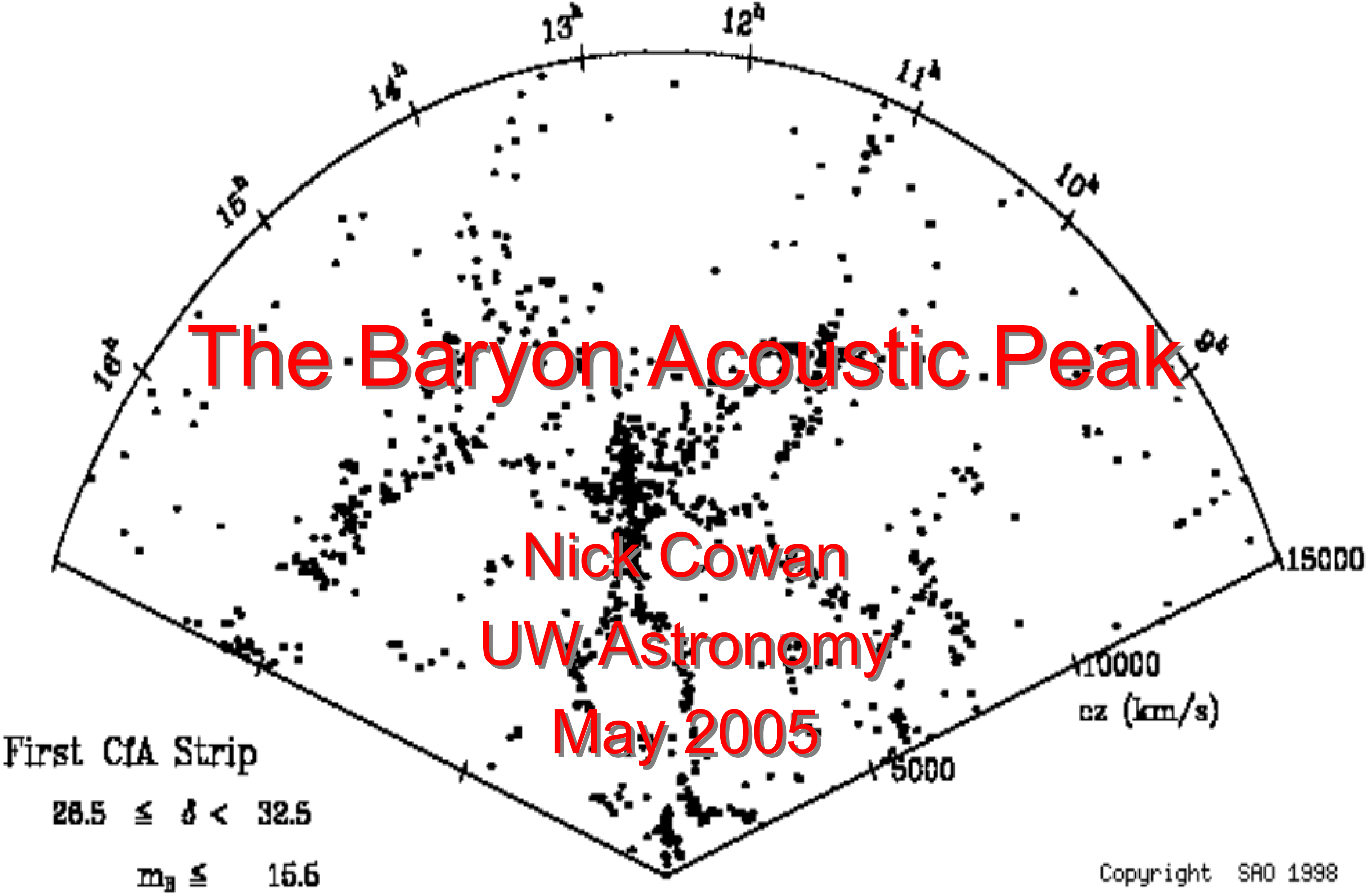
images & spectra of NGC 2798/2799

physical size, orbital velocity, mass, and luminosity

how to get data



2.5-meter telescope,
Apache Point, New Mexico



The Baryon Acoustic Peak

Nick Cowan

UW Astronomy

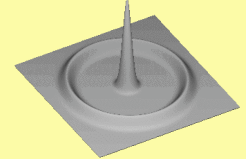
May 2005

An Acoustic Peak

Before recombination at $z\sim1000$, the universe was ionized, and in this plasma the cosmic microwave background photons are well coupled to the baryons and electrons. The photons have such enormous pressure that the sound speed in the plasma is relativistic.

The initial perturbations are equal in the dark matter and baryons. However, an overdensity in the baryons also implies a large overpressure, with the result that a spherical pressure wave is driven into the plasma. By the time of recombination, this wave has reached a comoving radius of 150 Mpc, the sound horizon.

The dark matter overdensity on the other hand remains centrally concentrated. After recombination, perturbations grow gravitationally in response to the sum of the dark matter and baryons. The central concentration dominates, but there is a small (1%) imprint at 150 Mpc scale that generates a single acoustic peak in the matter correlation function.

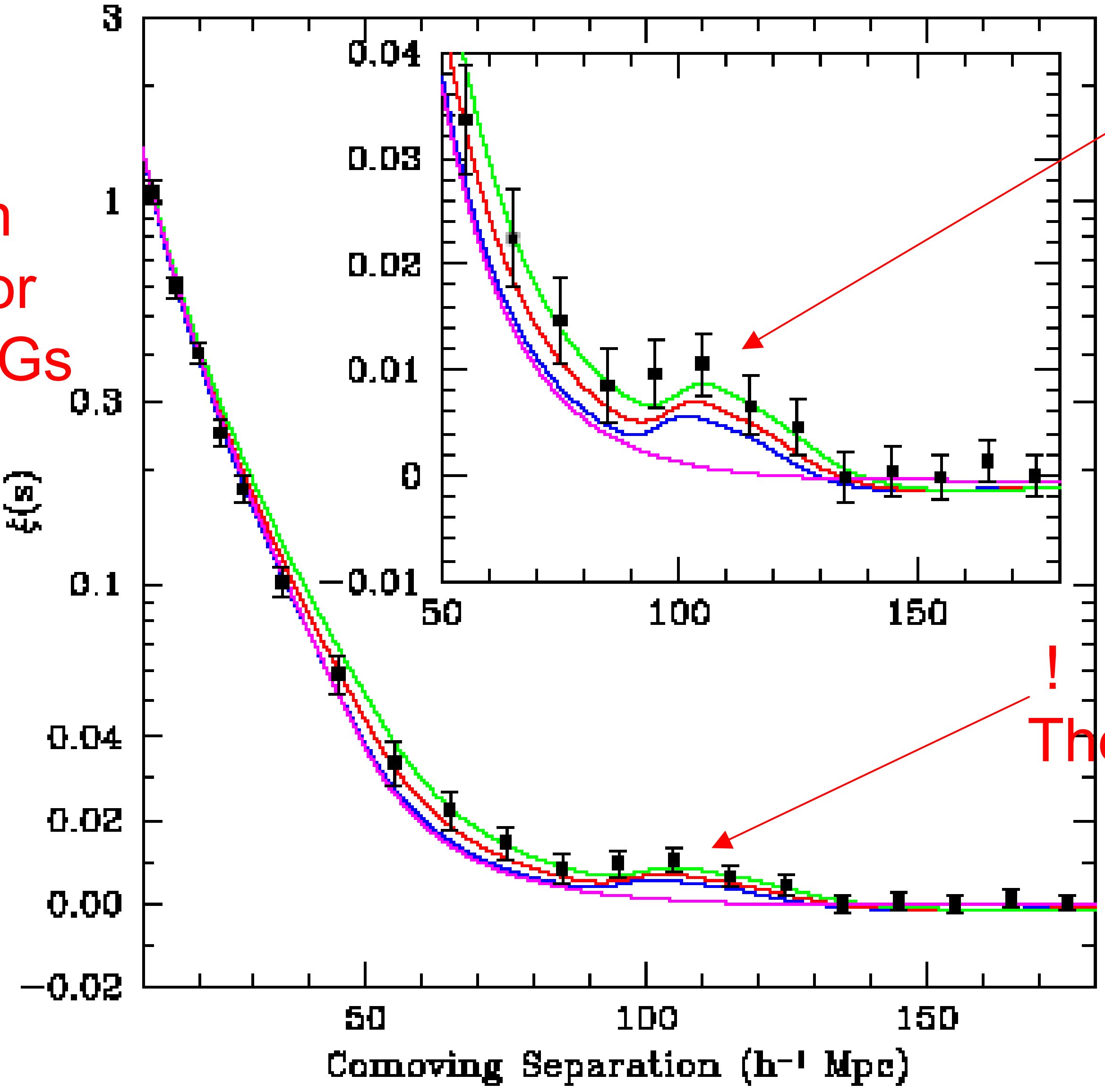


An illustration of the baryonic pressure wave expanding from a central overdensity, where the dark matter perturbation remains. The amplitude of the wave has been exaggerated; it should be only 1% of the central peak. The Universe is a superposition of many such structures.

Importantly, the sound horizon depends only on the baryon-to-photon ratio ($\Omega_b h^2$) to set the sound speed and the matter and radiation densities ($\Omega_m h^2$ and $\Omega_r h^2$) to set the propagation time. Measuring these densities, e.g., from the acoustic peaks of the CMB, allows one to calibrate this standard ruler.

Results from SDSS

Correlation Function for 46,748 LRGs



Points look too high because the covariance is “soft” w.r.t. shifts in ξ.

!

There’s the peak!

We know

Dark matter is ...

cold (non-relativistic)

22 % of the Universe

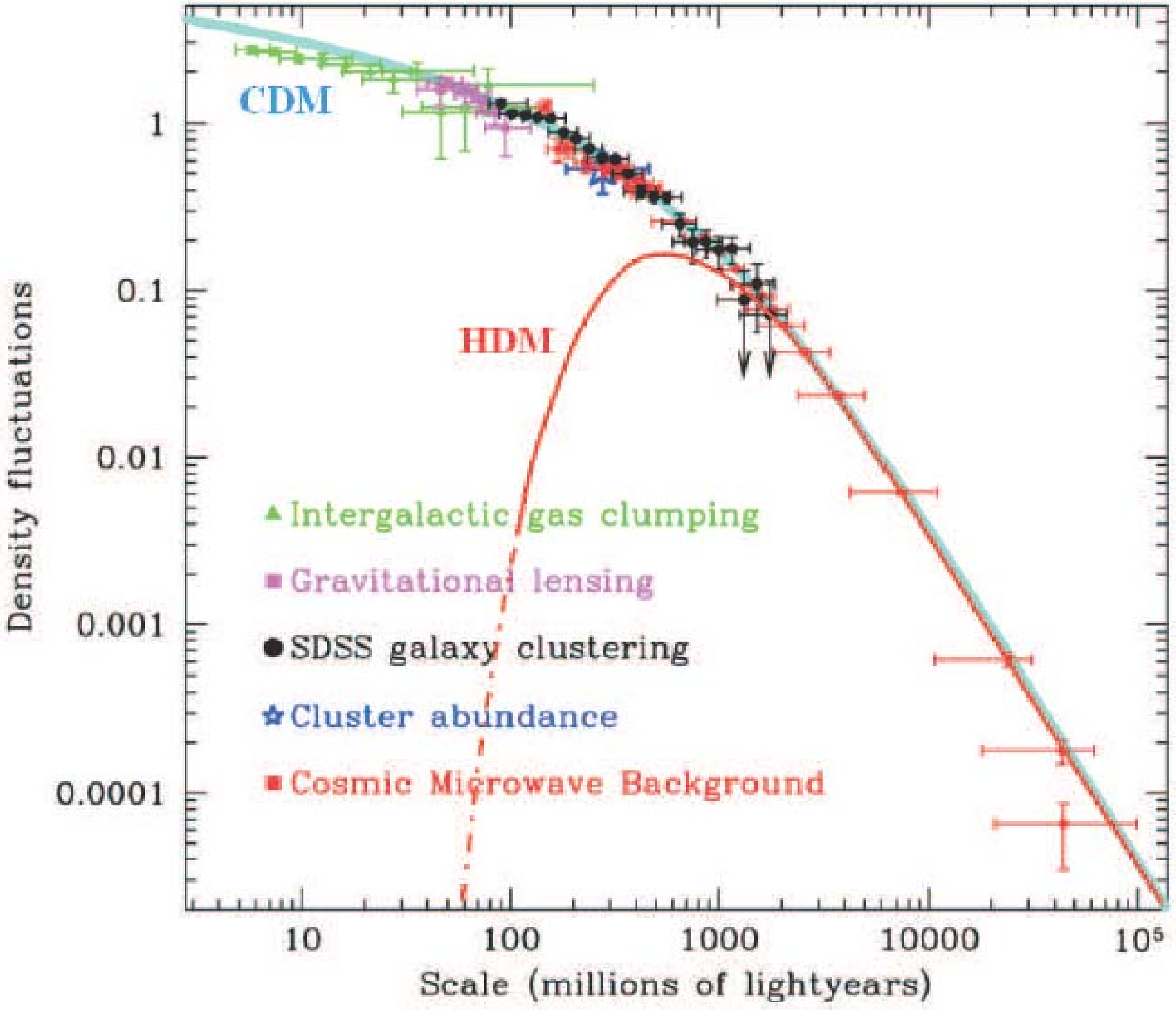
non-baryonic

weakly interacting (collisionless)

Cold

— Galactic structure requires cold dark matter

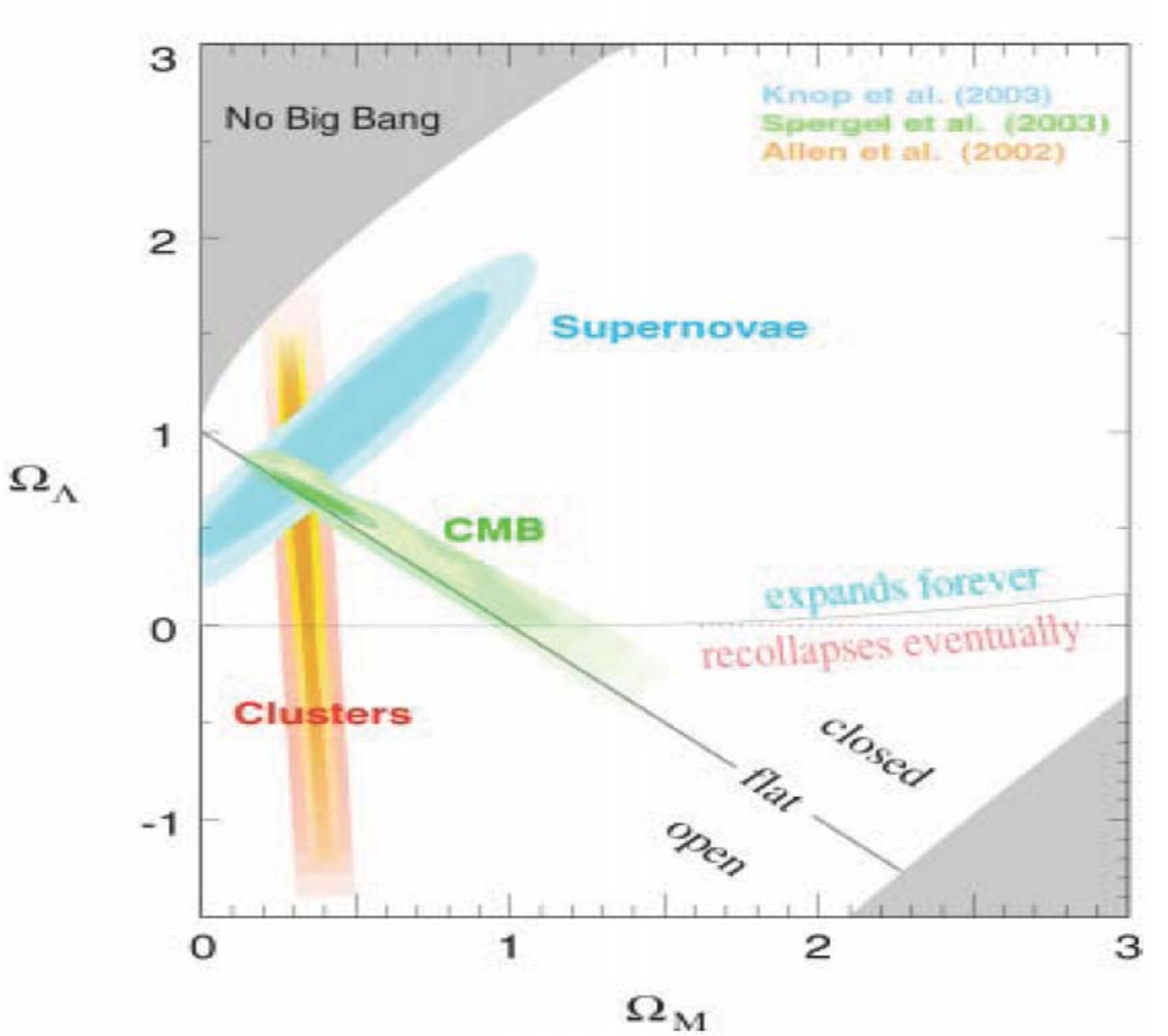
- CDM collapses first, attracting matter later



Maroto,Ramírez astro-ph/0409280

22 %

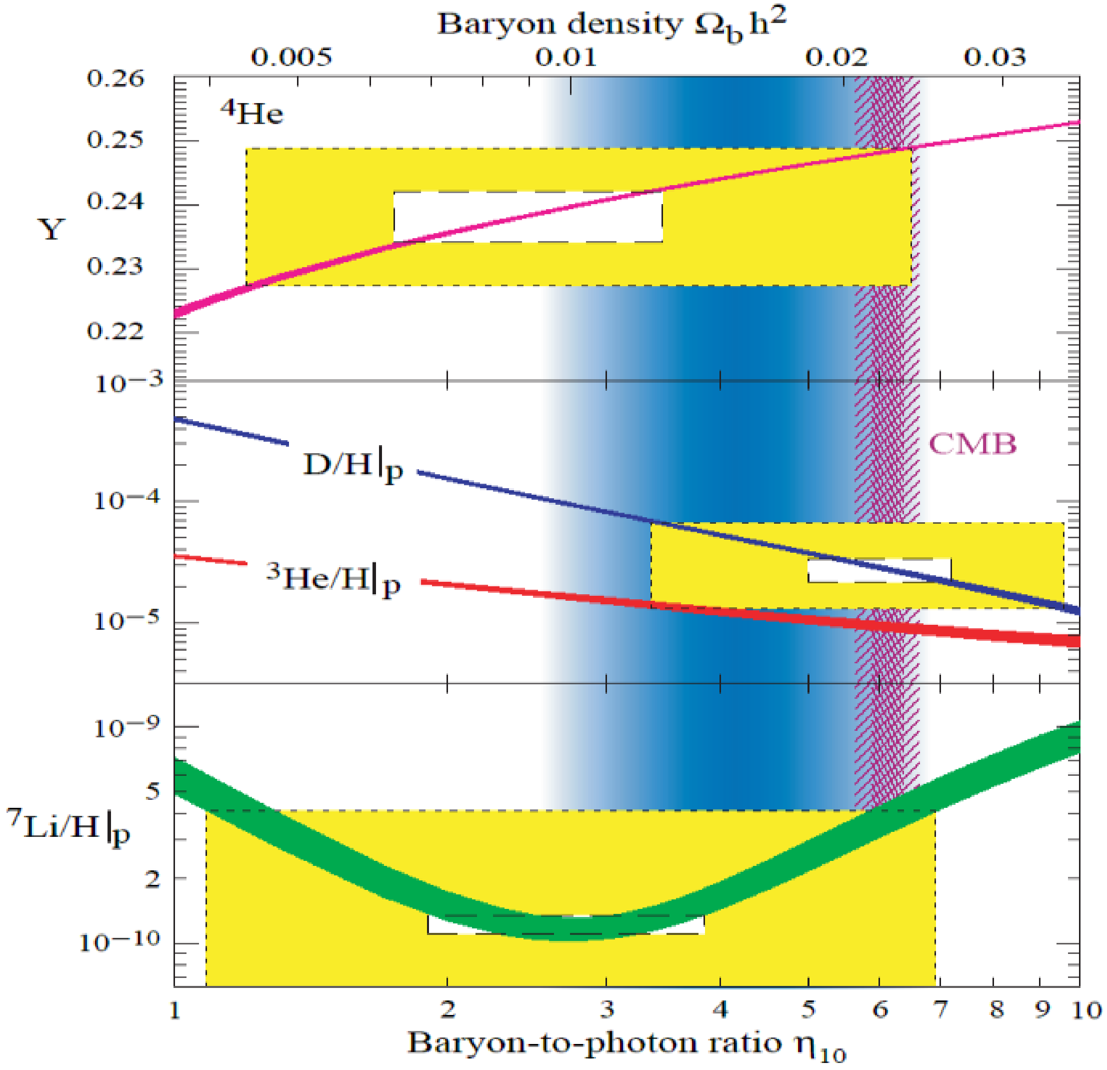
— E balance a 'la FRW: $\frac{\rho}{\rho_c} = \Omega_M + \Omega_\Lambda + \Omega_k$ $\rho_c = 3H_0^2/8\pi G_N$, $H_0 = 71 \pm 4$ km/s/Mpc



- SNe,WMAP,SDSS: $\Omega_M = 0.27 \pm 0.04$ $\Omega_\Lambda = 0.73 \pm 0.04$ $\Omega_{tot} = 1.02 \pm 0.02$
- direct, independent, precise, consistent observations → robust result

Non-baryonic

— Matter content: $\Omega_M = \Omega_{BM} + \Omega_R + \Omega_\nu + \Omega_{DM}$ with $\Omega_\nu, \Omega_r < 0.015$

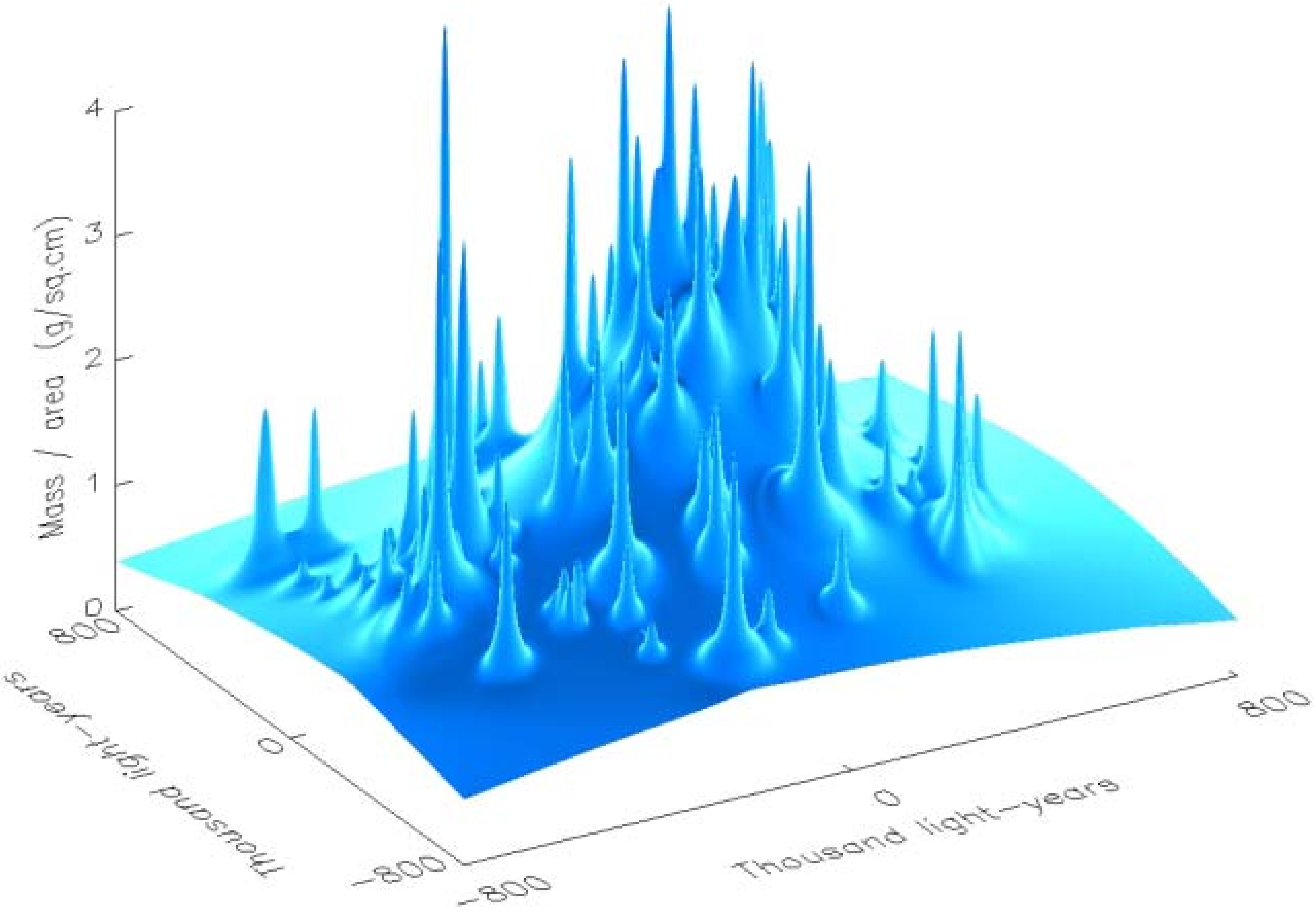


PDB 2005

- BBN&CMB, cosmic concordance: $\Omega_b = 0.044 \pm 0.004 \Rightarrow \Omega_{DM} = 0.22 \pm 0.04$
- new form of matter: non-baryonic, stable

Weakly interacting

– Gravitational lensing → mass dist'n of CL0024+1654 galaxy cluster



http://www.bell-labs.com/news/1997/january/15/1.html

We don't know

Does it exist?

How to directly detect/create it?

Why is it 22 % (now)?

What is it?

...

Open questions

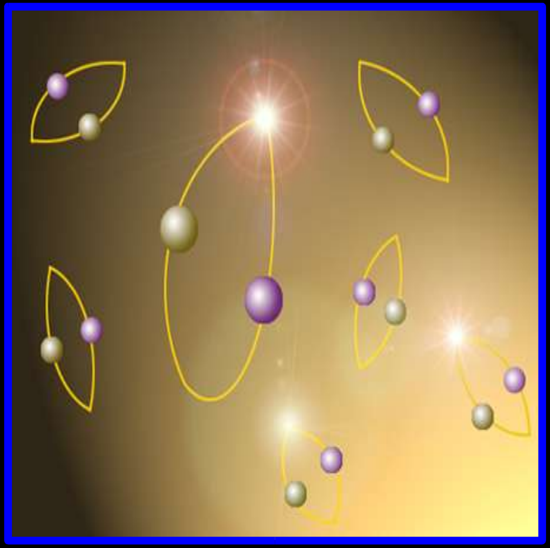
- ↑ Matter: 27%, of which: Baryons: < 5%, Neutrinos: <0.5%
- ↑ Energy: 73%

- ● Dark energy and dark matter have both a common origin or are they two completely unrelated phenomena ?
- ● Is each of them describable as classical (gravitational) or as quantum mechanical phenomenon ?
- ● Cold dark matter is well detected gravitationally: *but does it have other interactions, in particular an electro-weak coupling to ordinary matter?*
- ● If it has electro-weak properties, how can it be so (very) massive and so stable as to have *survived without decay for at least 13.7 billion years* ?

Origin of dark matter

- This has been the Wild, Wild West of particle physics: *axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,...*
- Masses and interaction strengths span many orders of magnitude, but in all cases we expect new particles with electroweak symmetry breaking,
- Particle physics provides an attractive solution to CDM: long lived or stable neutral particles:
  - ↑ Neutrino (but mass ~ 30 eV !)
  - ↑ Axion (mass ~ 10^{-5} eV)
  - ↑ SUSY Neutralino (mass > 50 GeV)
- Axion and SUSY neutralino are the most promising particle dark matter candidates, but they both await to be discovered !

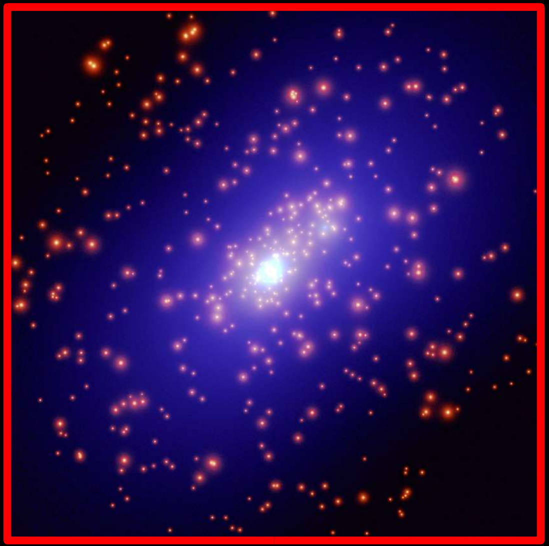
Dark Matter and Dark Energy: Introverted?



dark energy

ordinary matter

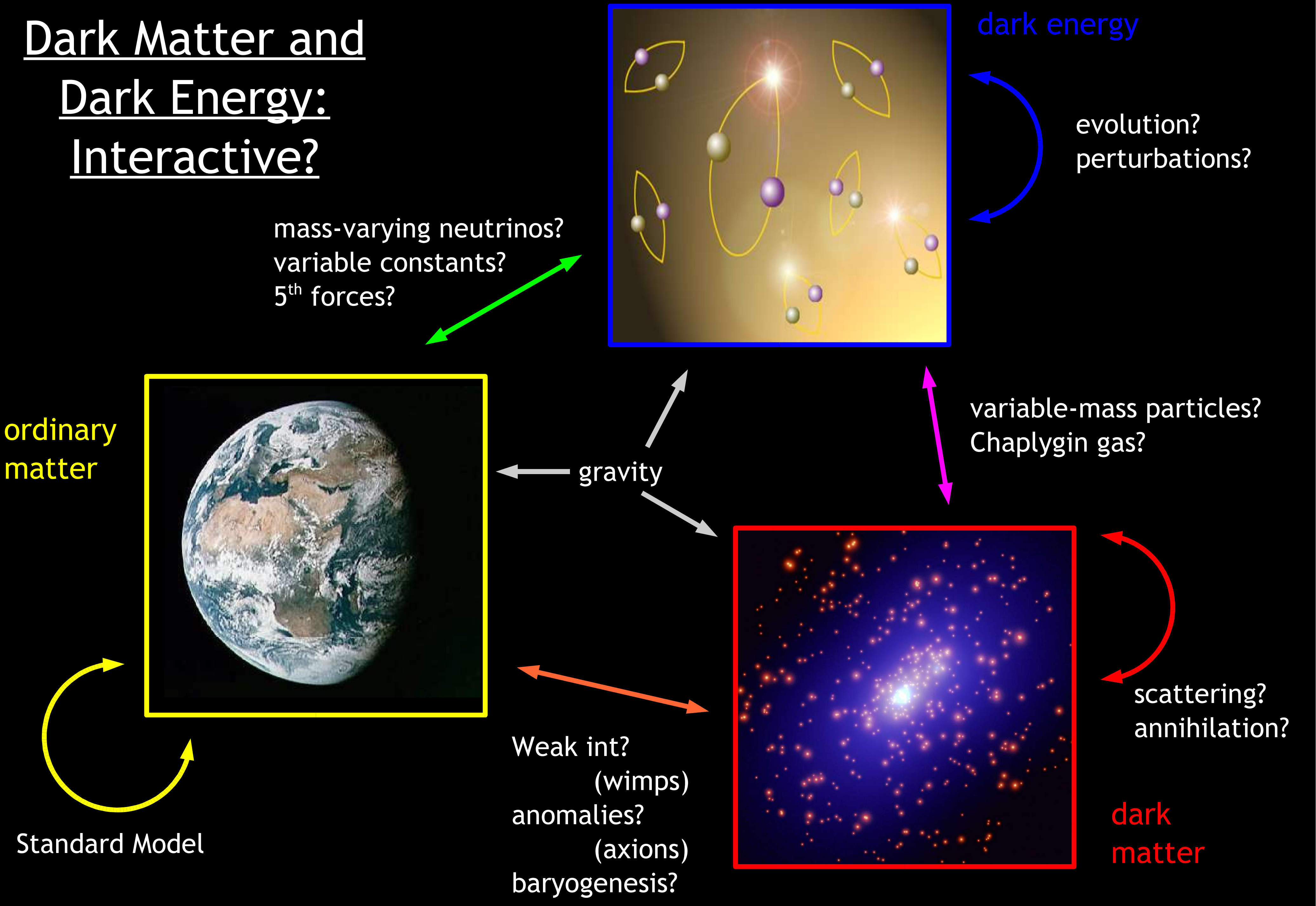
gravity



dark matter

Standard Model

Dark Matter and Dark Energy: Interactive?



dark energy

evolution?
perturbations?

mass-varying neutrinos?
variable constants?
5th forces?

ordinary
matter

gravity

variable-mass particles?
Chaplygin gas?

scattering?
annihilation?

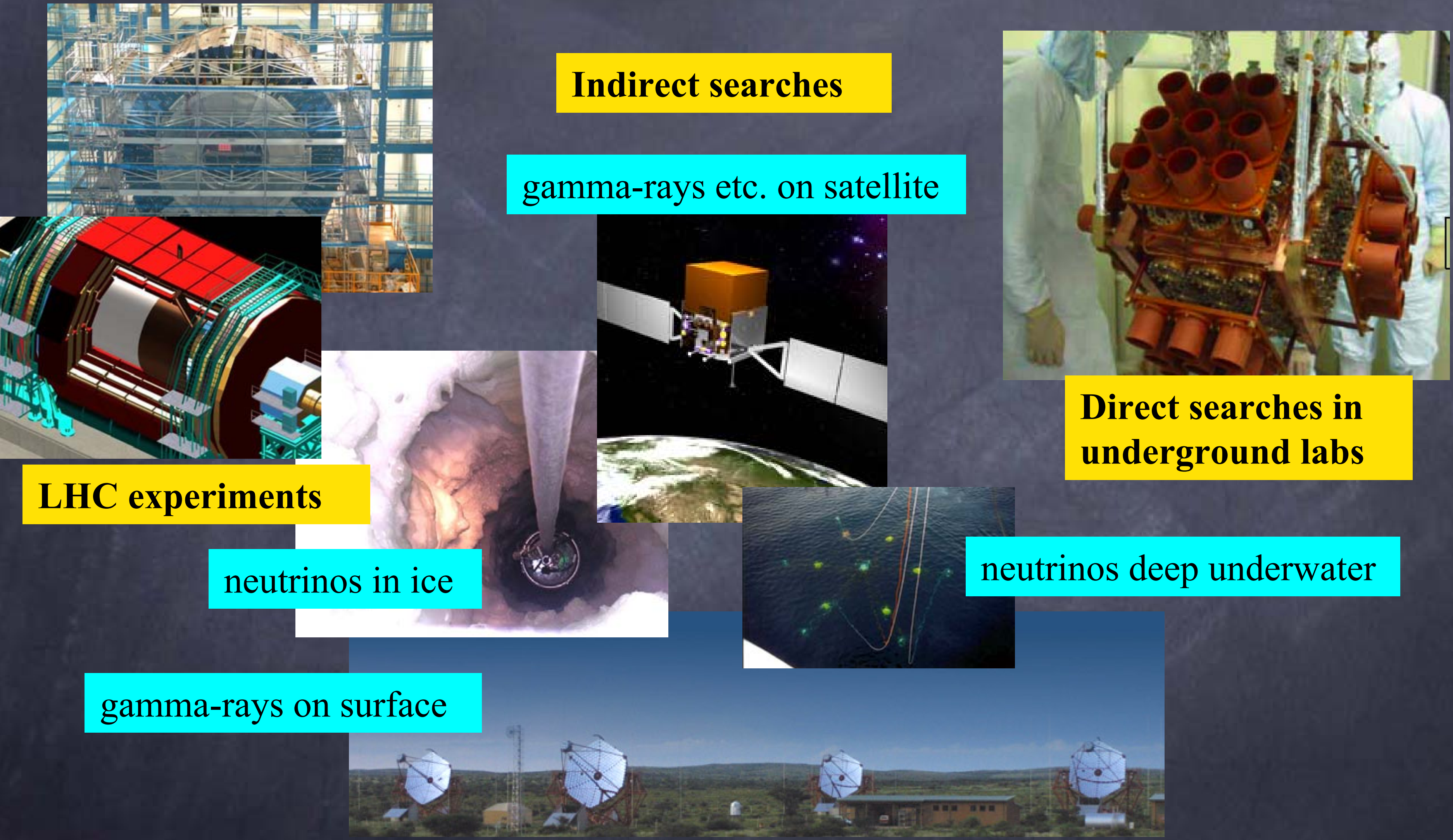
Standard Model

Weak int?
(wimps)
anomalies?
(axions)
baryogenesis?

dark
matter

Complementary search approaches

Hunt for dark matter in the dark needs a set of different weapons, in an integrated way



Indirect searches

gamma-rays etc. on satellite

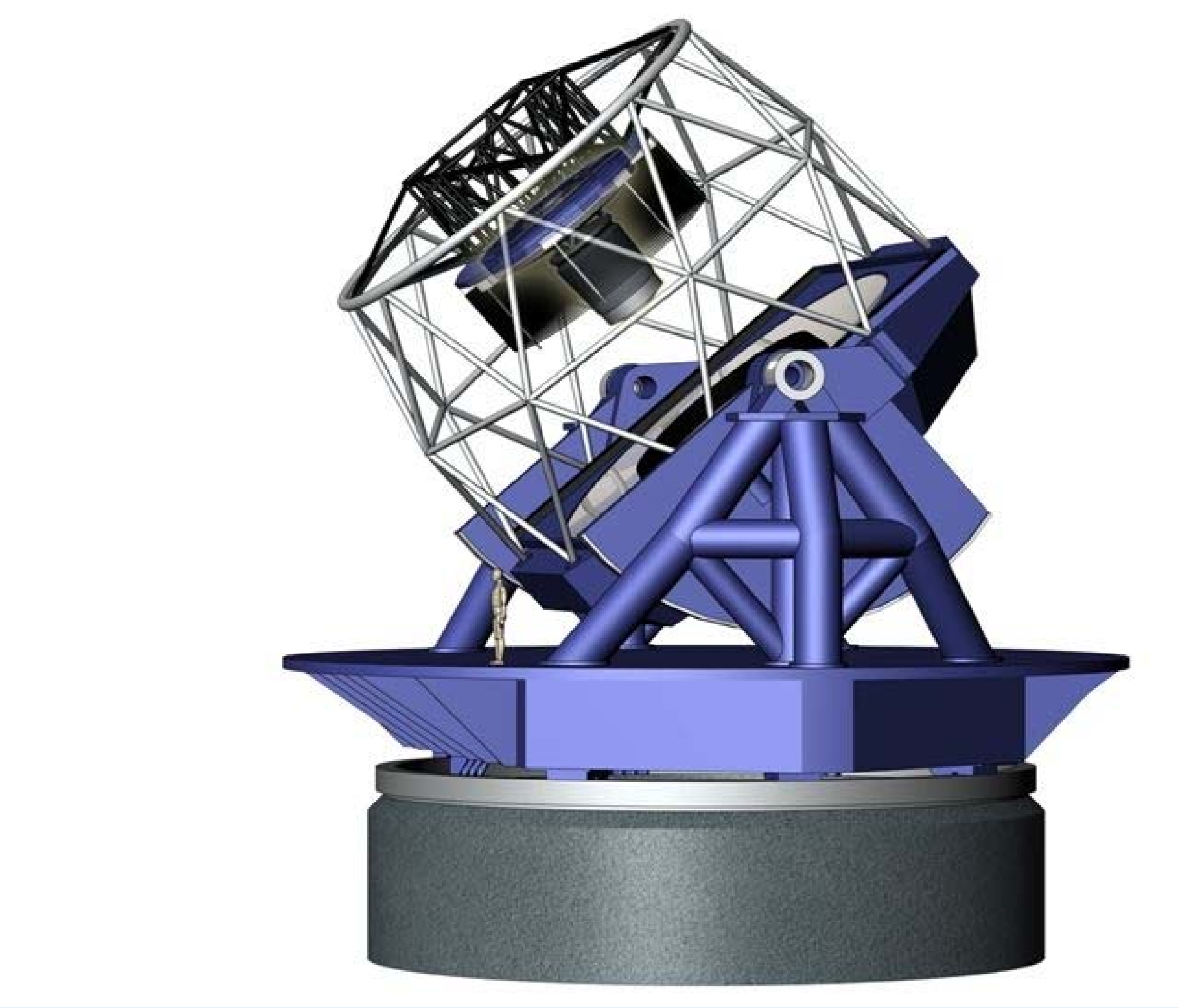
Direct searches in underground labs

LHC experiments

neutrinos in ice

neutrinos deep underwater

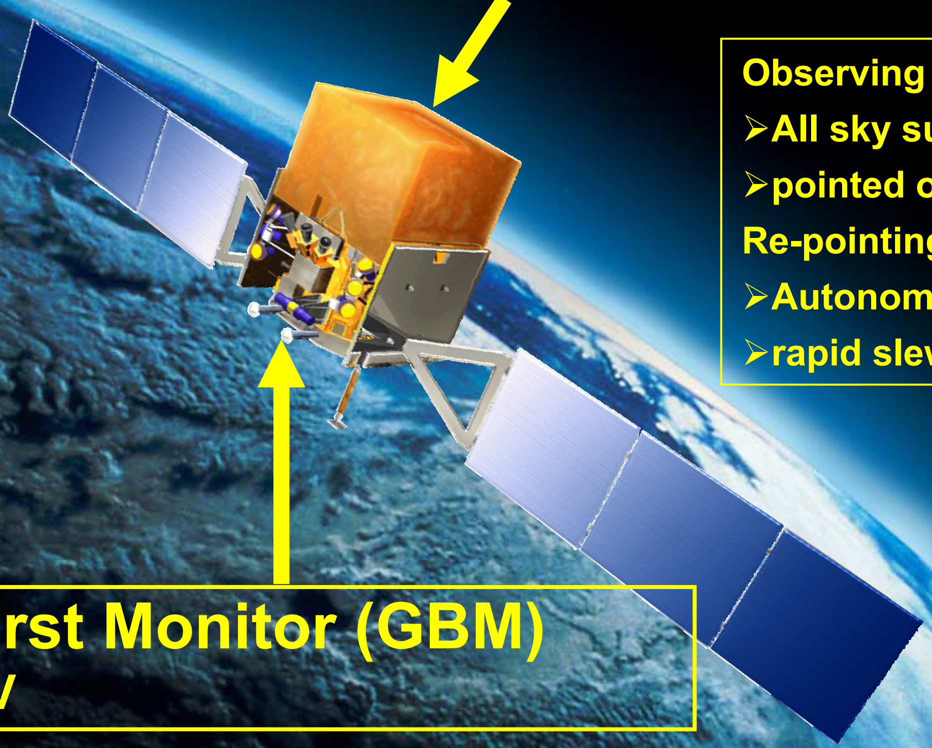
gamma-rays on surface



http://www.lsst.org

GLAST is a NASA Mission

- Launch: September 2007
- Lifetime: 5-years (10-years goal)
- Orbit: 565 km, circular
- Inclination: 28.5°



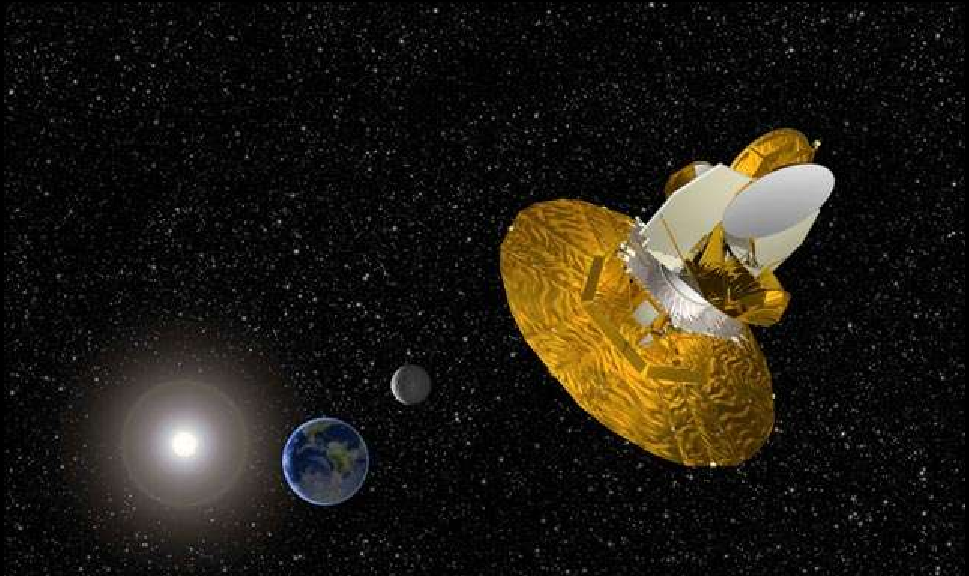
Large Area Telescope (LAT)
20 MeV - 300 GeV

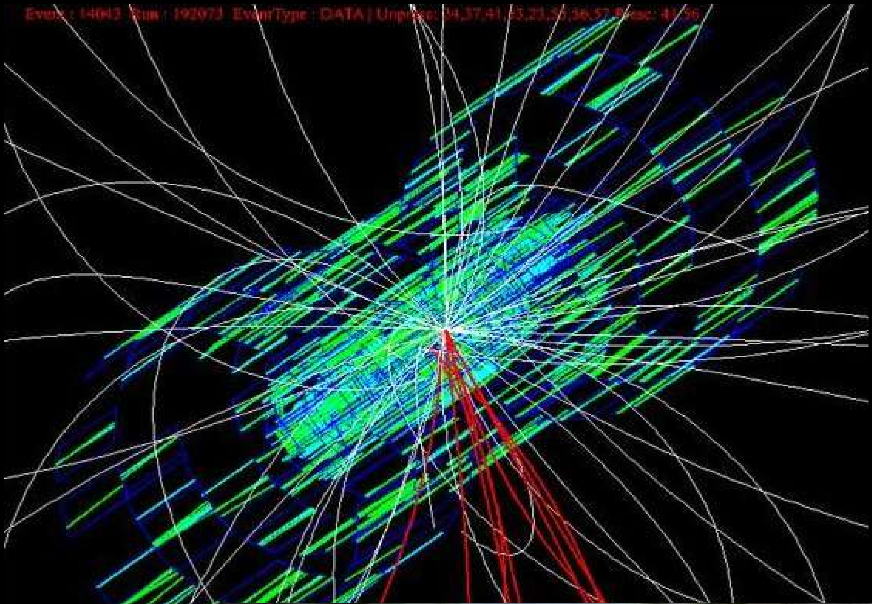
Observing modes:
- All sky survey
- pointed observations

Re-pointing Capabilities:
- Autonomous
- rapid slew speed (75° in < 10 minutes)

GLAST Burst Monitor (GBM)
5 keV - 25 MeV

The Universe and the Laboratory: complementary approaches





Surveillance

Interrogation