Cosmology: $(13.73 \pm 0.15) \times 10^9$ years* in (60 ± 5) minutes

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NEPPSR, 08/14/2007

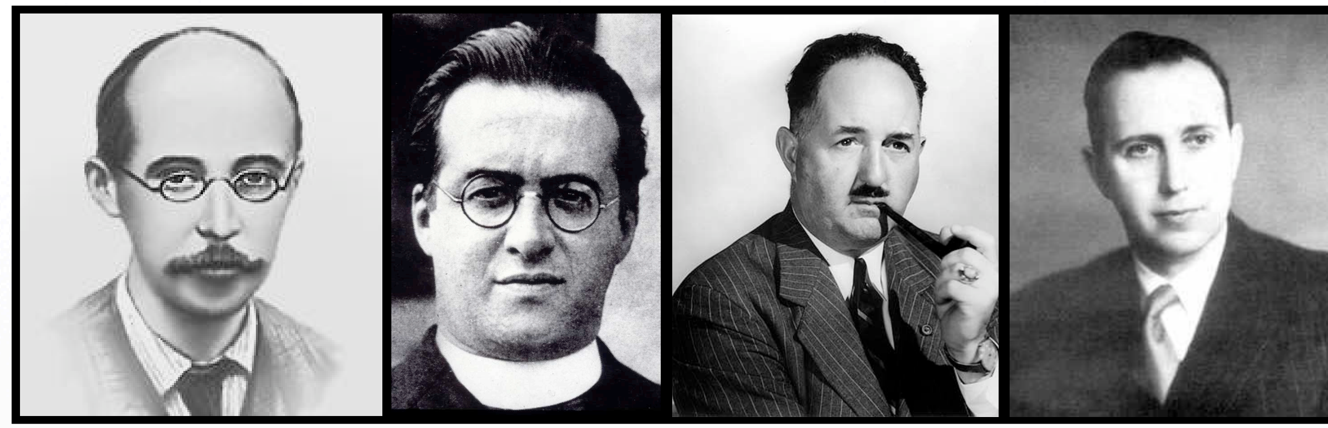
*with priors

Things people have *always* wanted to know about the Universe
- and questions cosmologists claim to address -

- *Did it exist forever or it had a beginning?*
- *Is it finite or infinite?*
- *What is it made of?*
- *How is it going to end?*

Birth of modern (“scientific”) cosmology

-1905-’16: Einstein formulates his theory of <u>General Relativity</u>



-1922-’35: Friedmann, Lemaitre, Robertson, Walker apply General Relativity to the whole Universe:
[Hypothesis: *homogeneity* and *isotropy*]

$$d_{\text{physical}}\left(t\right) = a\left(t\right)\ d_{\text{comoving}}$$

Spatial curvature of the Universe

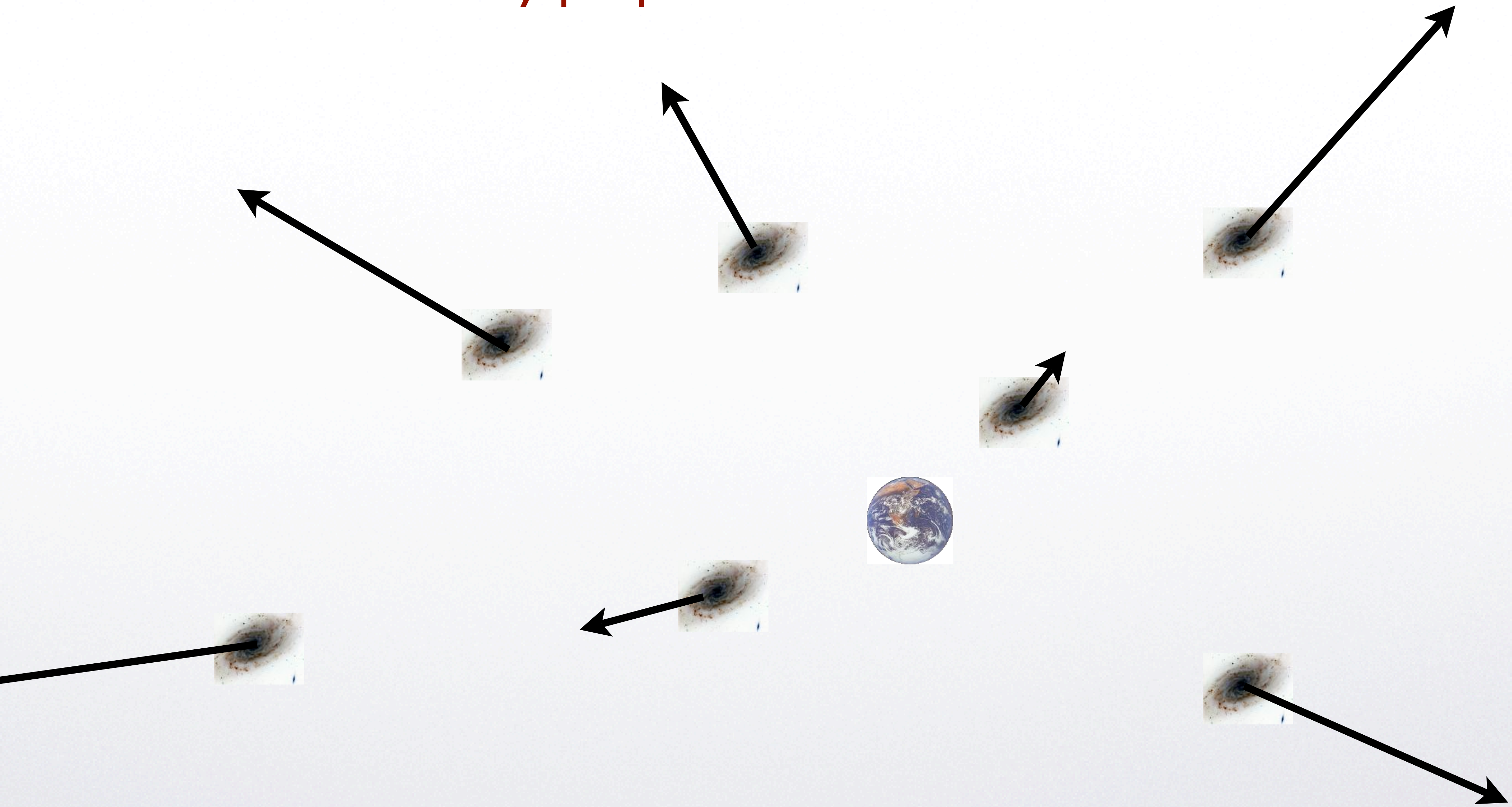
$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

Hubble parameter

Energy density of cosmological matter

$H \neq 0 \Rightarrow$ The Universe is expanding!

Observational support in 1929: Edwin Hubble discovers that galaxies are receding from us with a velocity proportional to their distance!

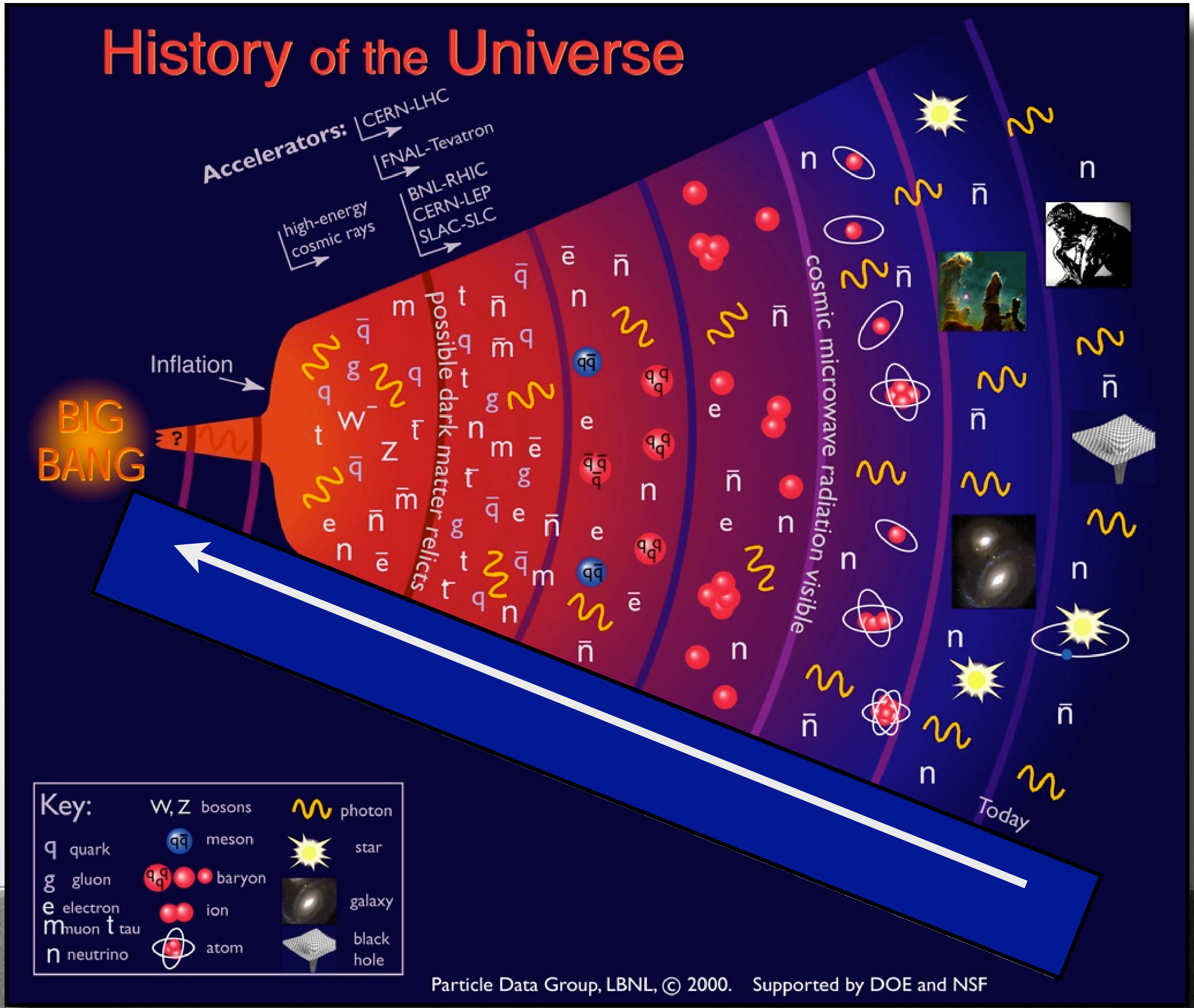


Expansion of the Universe ⇒ Evolution of the Universe

Clock = redshift factor z $\qquad a \equiv a_0/(z+1)$

Today: $z=0$

Before: $z>0$



How do we characterize matter?

Fluids characterized by energy density ρ and pressure *p*

$$dU = T\,\cancel{dS} - p\,dV$$

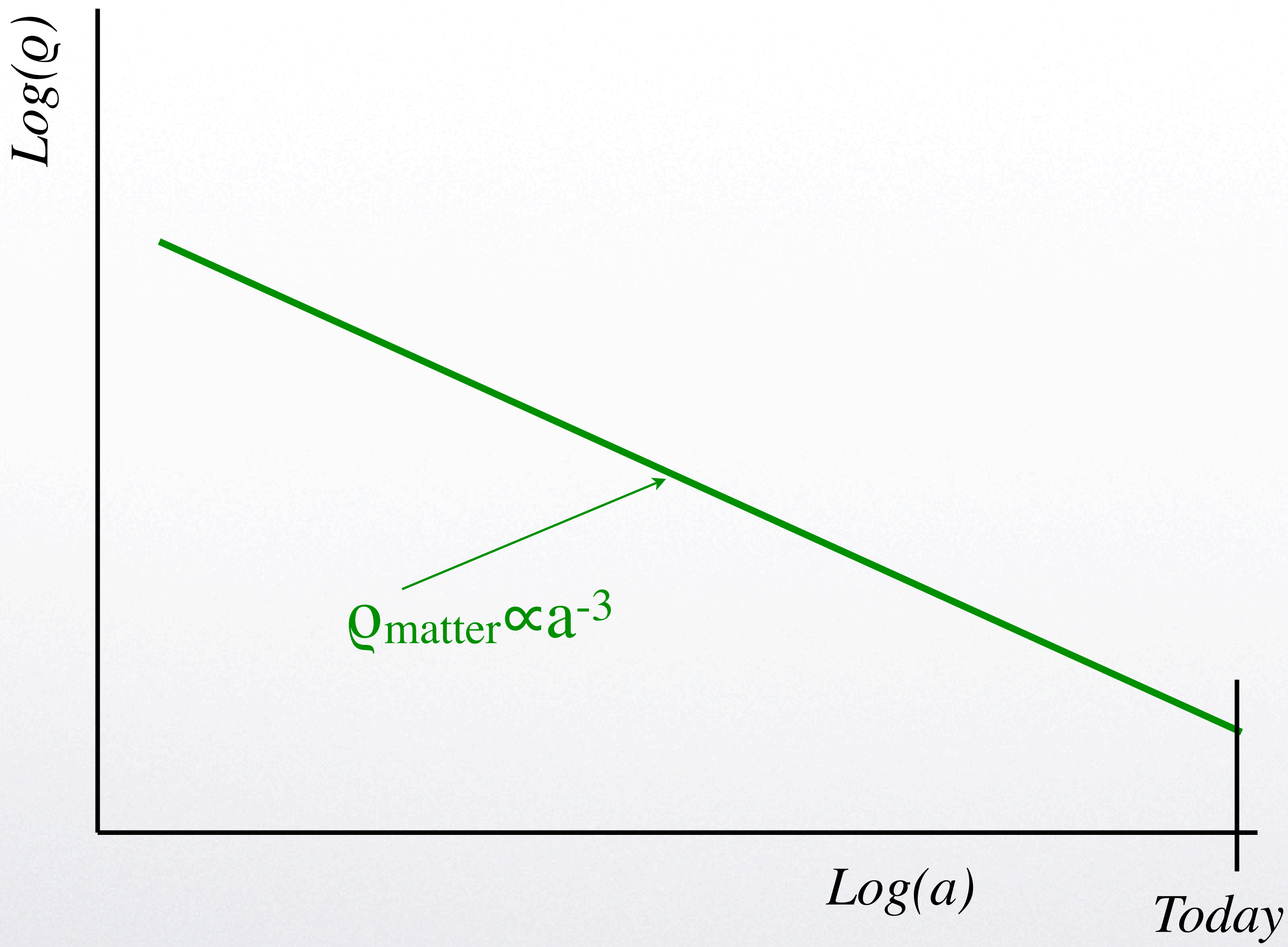
$$\dot{\varrho} + 3\,H\,(\varrho + p) = 0$$

Equation of state parameter $w \equiv p/\varrho$

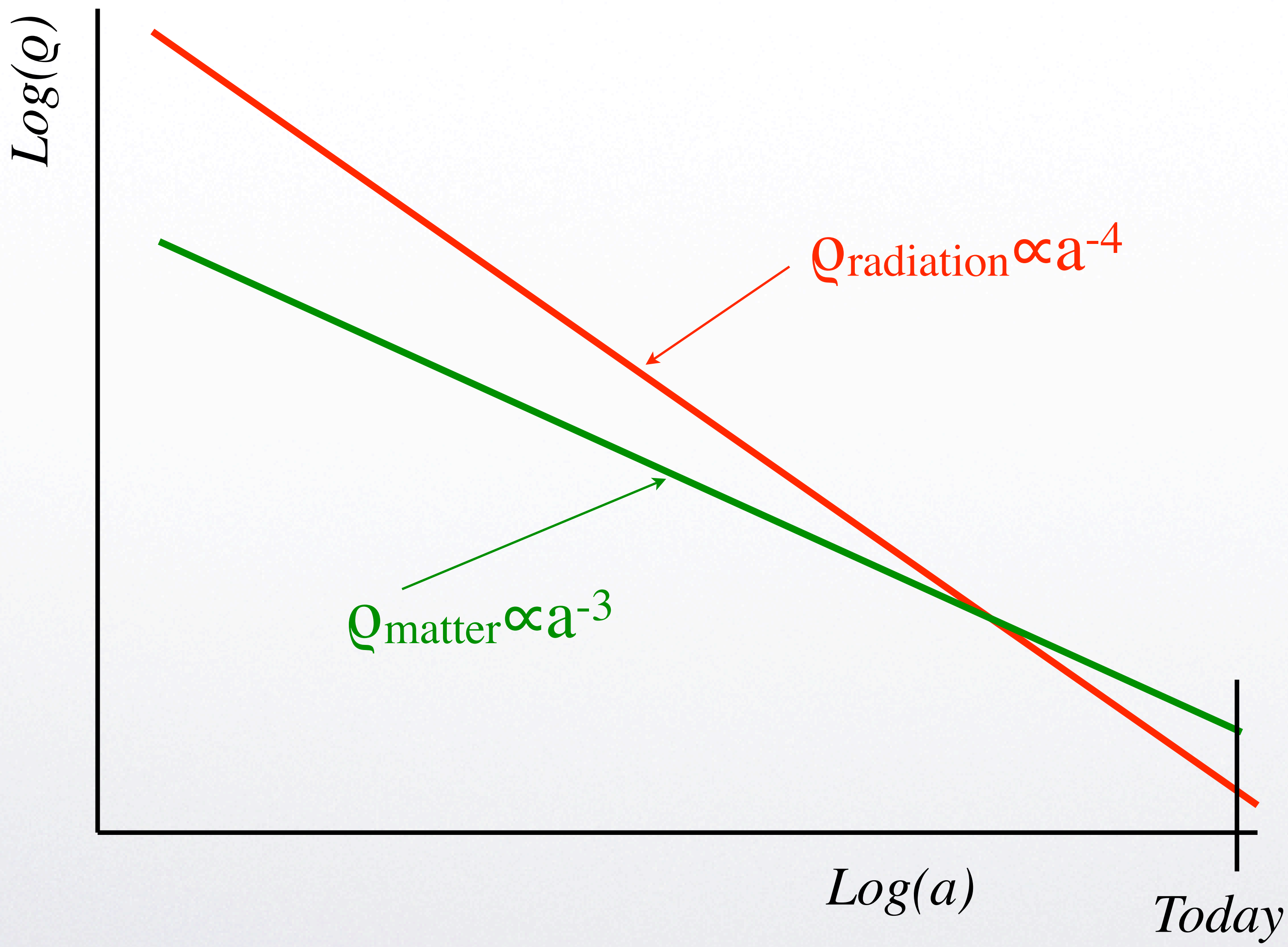
w=0 nonrelativistic stuff
w=1/3 ultrarelativistic stuff

$$\varrho \propto 1/a^{3(1+w)}$$

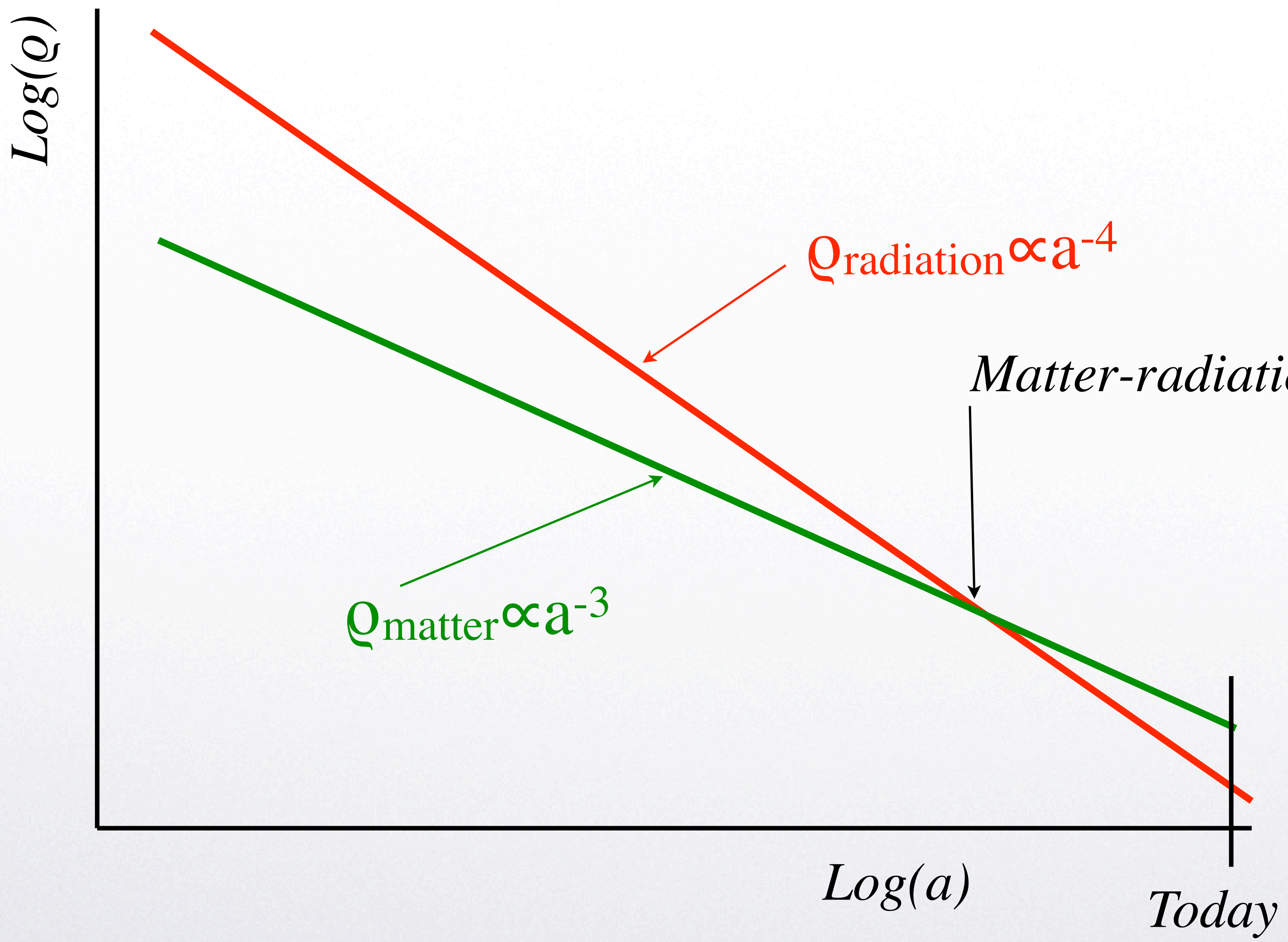
Matter domination *vs* Radiation Domination



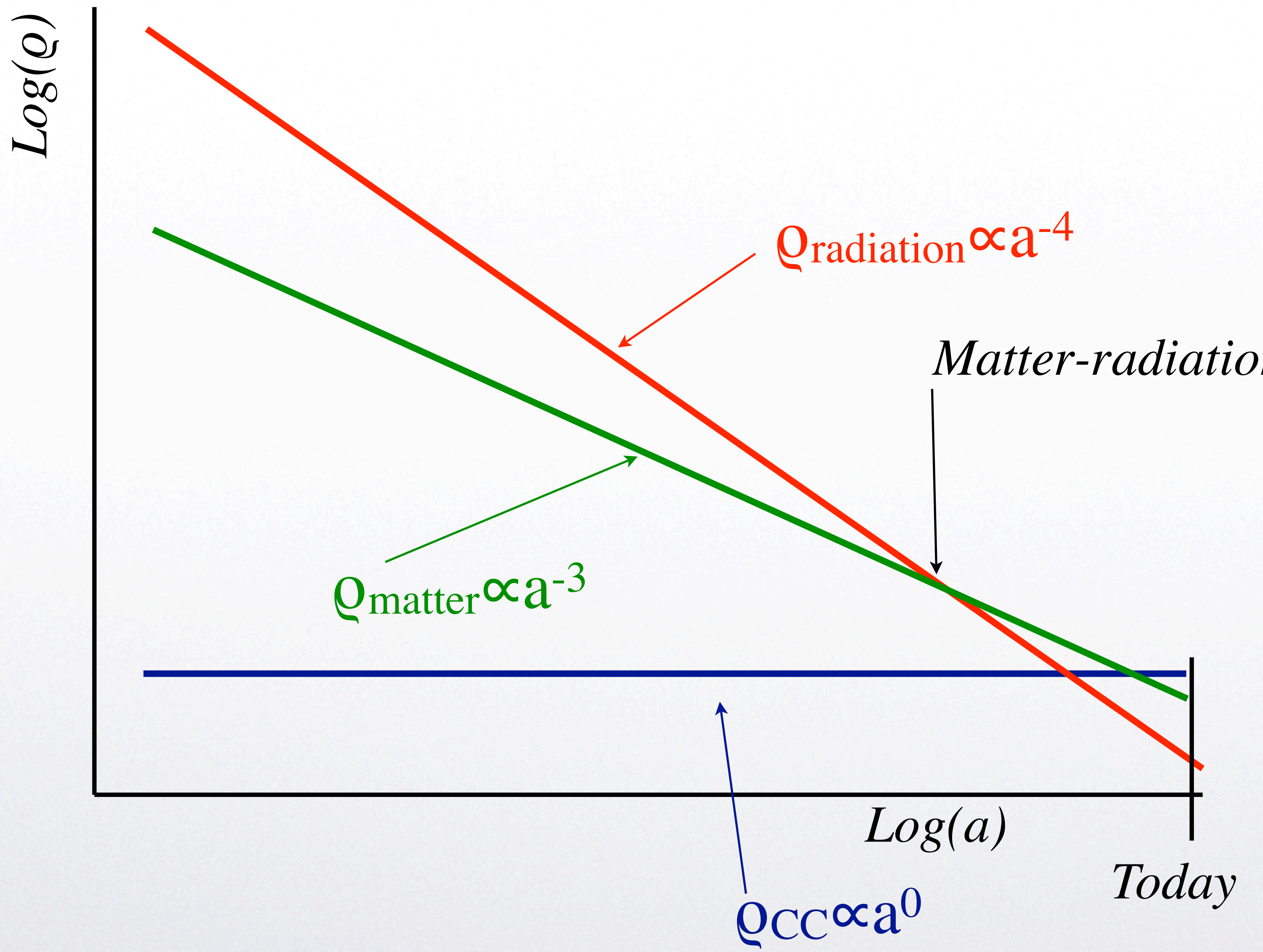
Matter domination *vs* Radiation Domination



Matter domination *vs* Radiation Domination



Matter domination *vs* Radiation Domination *vs* Cosmological Constant (?) Domination [w=-1]



How to measure the amount of energy density in a fluid?

Define critical density:

$$\varrho_c \equiv 3H^2/(8\pi G)$$

For a fluid ψ with energy density ϱ_ψ, define

$$\Omega_\psi = \varrho_\psi / \varrho_c$$

(Def such that $\Omega_{tot}=1$ in a Universe with no curvature)

The matter budget

- Photons
- Baryons
- Neutrinos
- Dark Matter
- Dark Energy

Known knowns

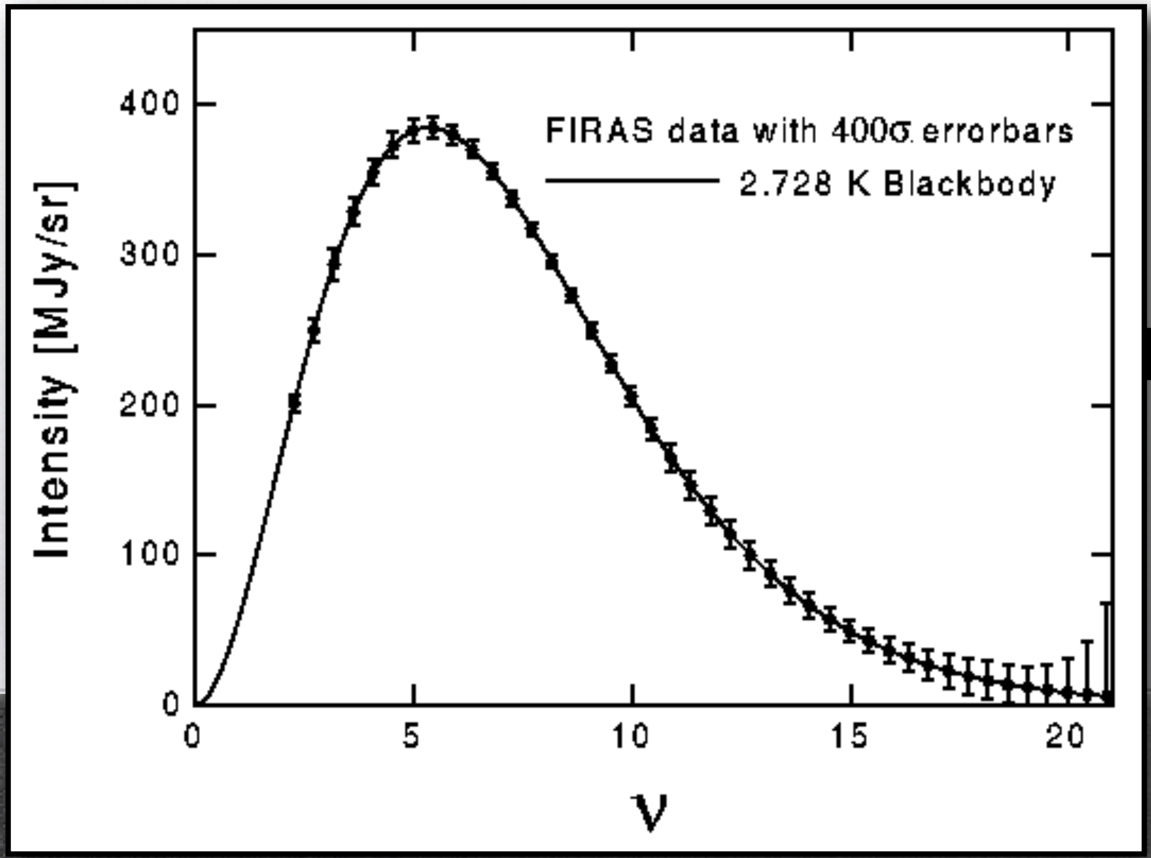
Known unknown

Unknown unknown

Photons

Cosmological photons (homogeneous and isotropic)
first detected by Penzias and Wilson 1965
Cosmic Microwave Background Radiation (**CMB**)

Subsequent measurements⇒CMB spectrum almost perfectly thermal



The Early Universe was
(almost)
perfectly thermalized!

Photons

$\varrho_\gamma \propto T^4$ and $\varrho_\gamma \propto a^{-4}$

$$T = T_0\, a_0/a$$

Temperature of photons
can be used as a clock

Interaction of different species in the thermal soup described by

Boltzmann Equation

$$E\,\frac{\partial f_\psi}{\partial t} - H\,\vec{p}^{\,2}\,\frac{\partial f_\psi}{\partial E} = \mathcal{C}\,[f_\psi]$$

$f_\psi\,(E,\,t)$ = distribution function of species ψ

Collisional Integral (interactions with other species)

Integral form: (n_ψ=# density of ψs)

$$\boxed{\frac{dn_\psi\,(t)}{dt} + 3Hn_\psi\,(t) = \frac{g}{(2\pi)^3}\int \mathcal{C}\,[f_\psi\,(E,\,t)]\,\frac{d^3p}{E}}$$

$$\boxed{\frac{dn_\psi(t)}{dt} + 3Hn_\psi(t) = \frac{g}{(2\pi)^3}\int \mathcal{C}\left[f_\psi(E,t)\right]\frac{d^3p}{E}}$$

If this term is negligible:

Species in thermal equilibrium

$$f_\psi \propto e^{-E/kT}$$

density of particles with mass>>temperature exponentially suppressed

(unless symmetries imply # conservation)

$$\boxed{\frac{dn_\psi(t)}{dt} + 3Hn_\psi(t) = \frac{g}{(2\pi)^3} \int \mathcal{C}\left[f_\psi(E,\, t)\right] \frac{d^3p}{E}}$$

If this term is negligible:

Species out of equilibrium

$$n_\psi \propto a^{-3}$$

even nonrelativistic particles
can have significant abundance

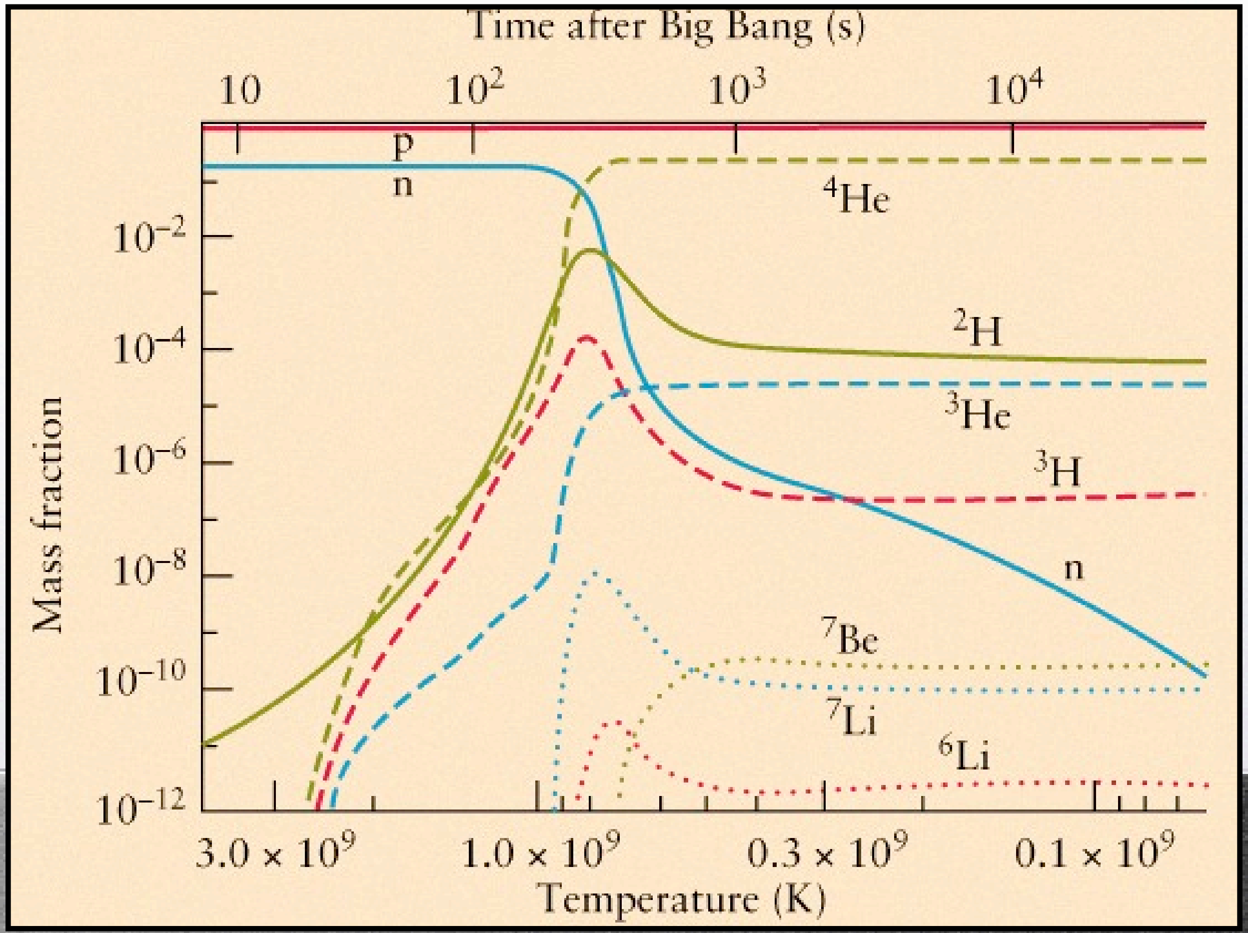
Baryons

Protons and neutrons kept in equilibrium by EW interactions
They get out of equilibrium at $T \cong 1\ MeV$:

Big Bang Nucleosynthesis

Solution of Boltzmann equations

Calculation of primordial abundances
of
H, D,T,^{3}He,^{4}He, ^{7}Li...



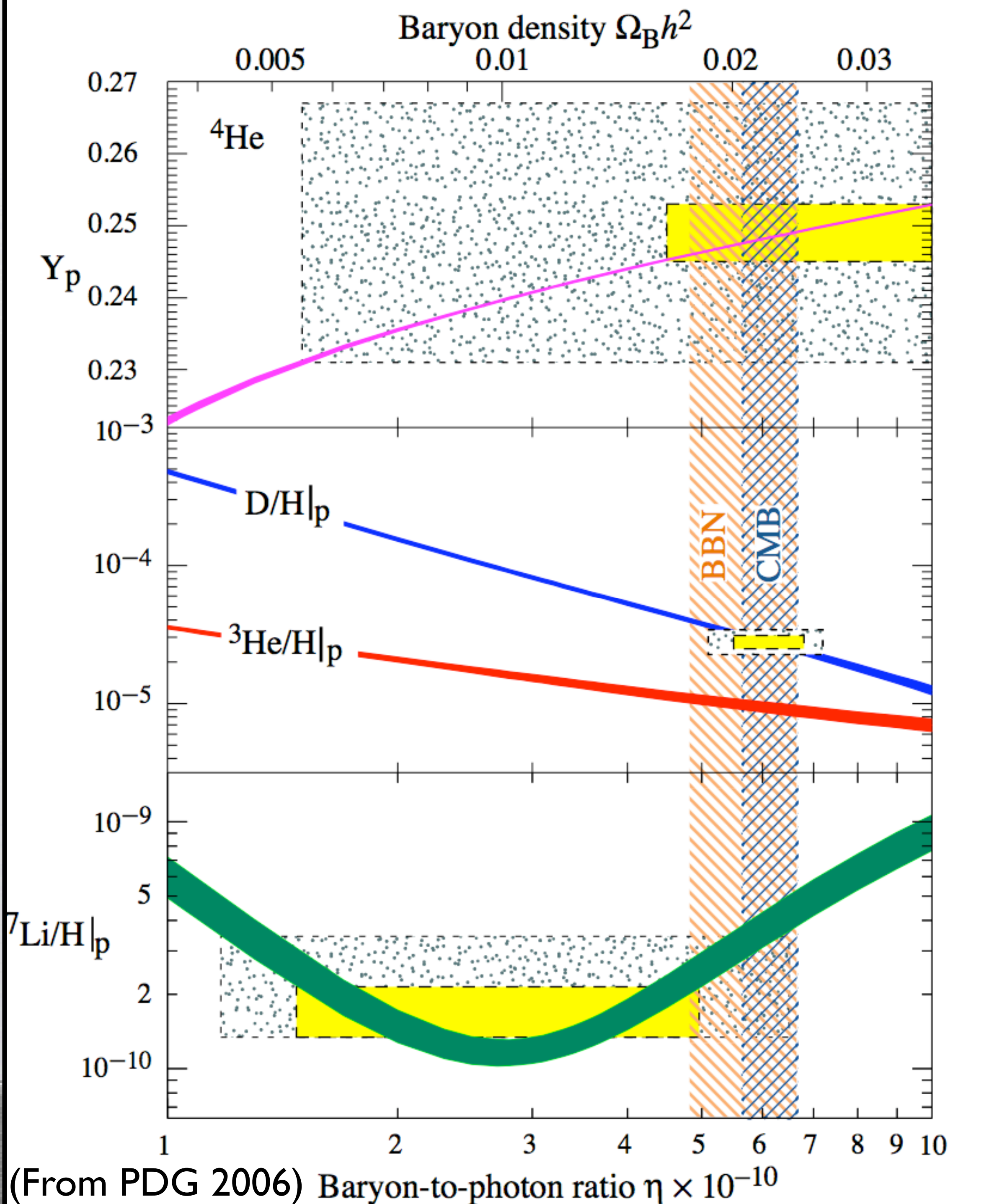
Baryons

Abundance of primordial elements depends only on *one* phenomenological parameter

$$\eta_B \equiv n_{\text{Baryons}}/n_\gamma$$

Observations of abundance of elements agree with each other (!) and give

$$\eta_B \cong 6\times 10^{-10}$$



(From PDG 2006)

Where does η_B come from?

Baryogenesis

Three ingredients needed:

- B violation
- C and CP violation
- Departure from thermal equilibrium

...and plenty of models...

Electrons

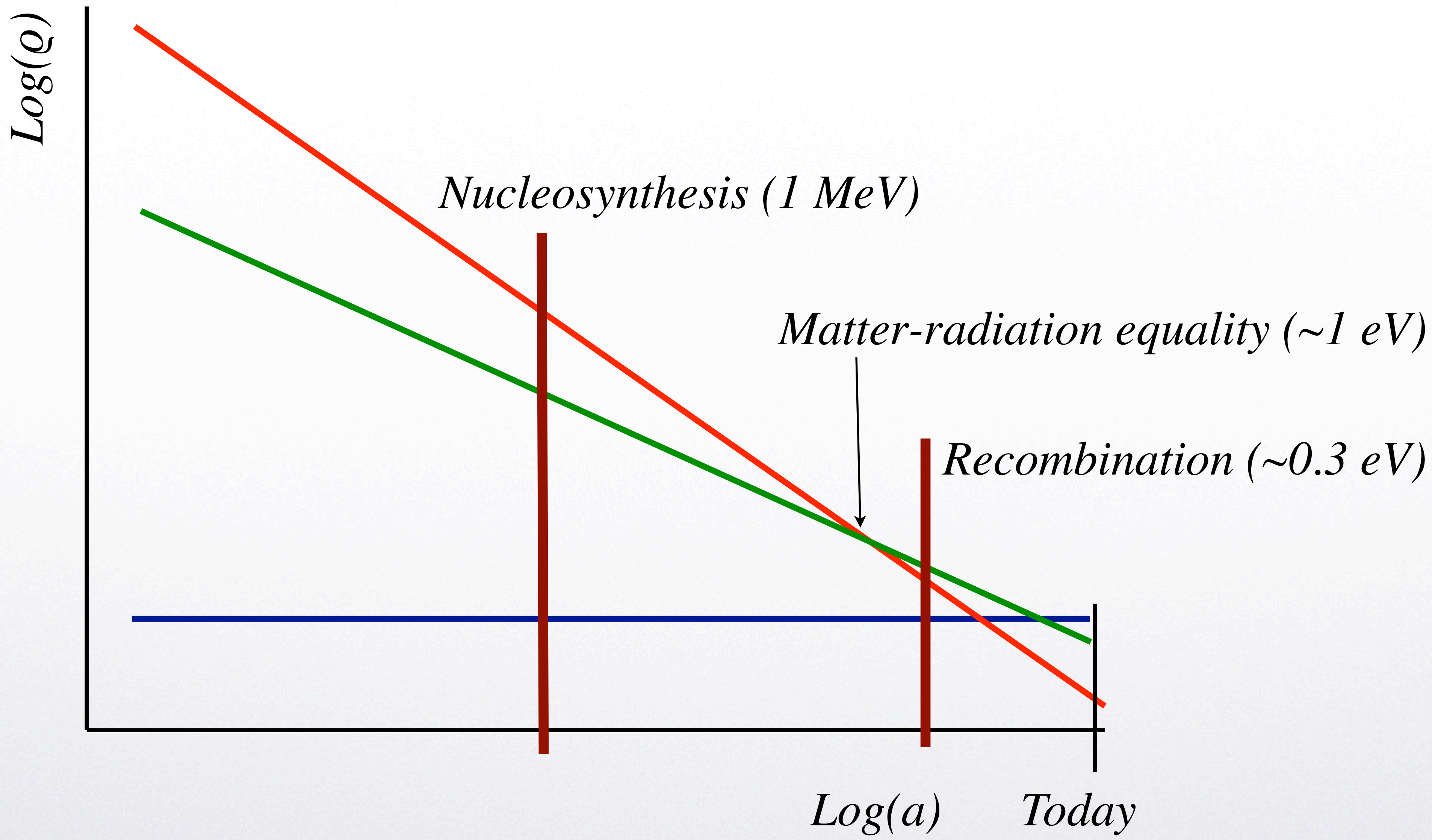
Number density determined by η_B (electric neutrality)

More interesting: $e^{-}p \leftrightarrow H\gamma$ reaction falls out of equilibrium at $T \cong 0.3\ eV$

Recombination

(at z=1088, t=370.000 yers)

After recombination no free ions:
Universe is transparent to radiation (CMB)


Log(ρ)
Nucleosynthesis (1 MeV)
Matter-radiation equality (~1 eV)
Recombination (~0.3 eV)
Log(a)
Today

Neutrinos

Cosmological neutrinos not observed

Their abundance inferred indirectly from BBN *($1.4<N_\nu<4.9$)*

---

e^+e^- annihilation occurs after ν decoupling

⇓

\# density of a ν family < # density of photons

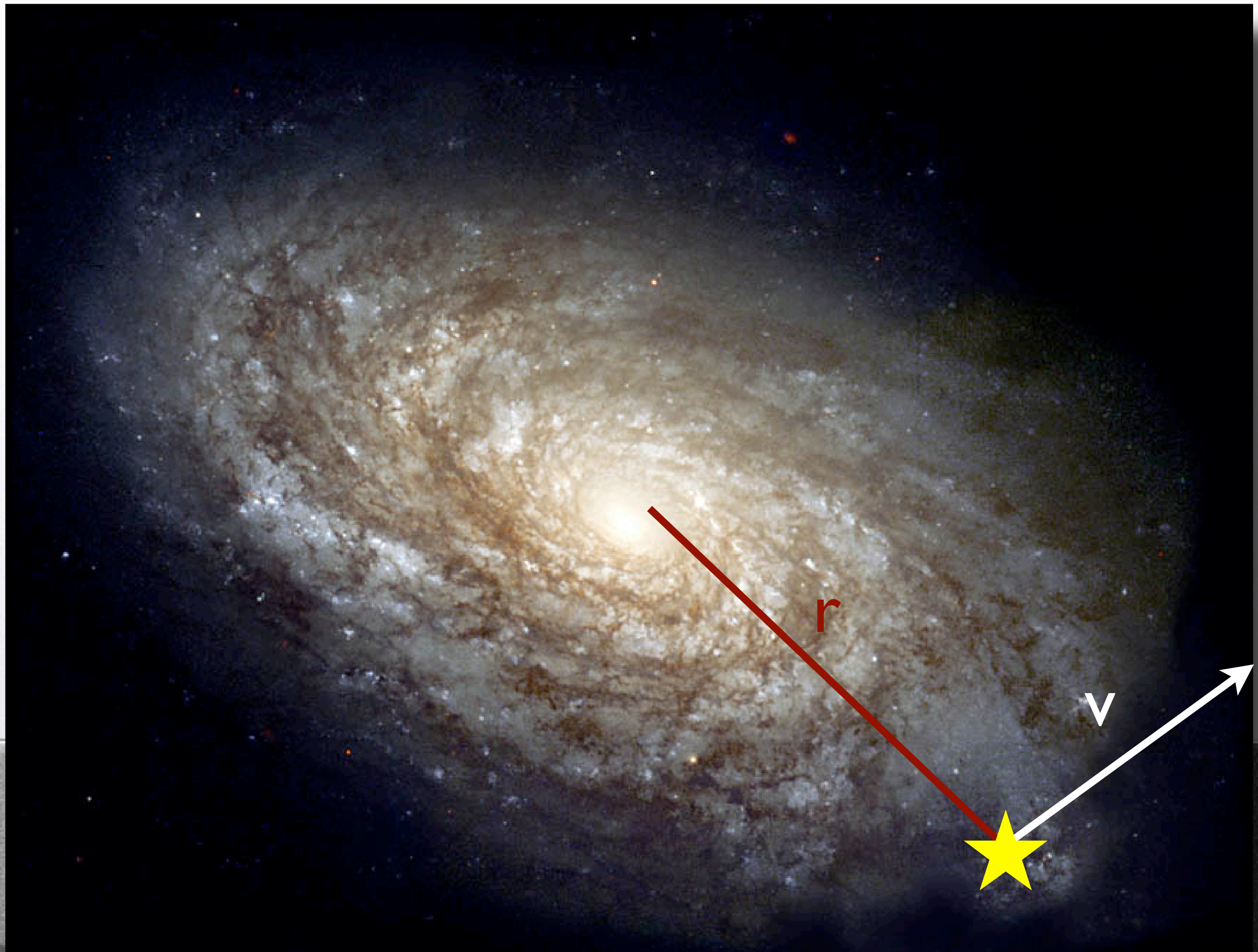
Summary of known knowns

- Photons ➻ $\Omega_\gamma \cong 5\times10^{-5}$
- Atoms ➻ $\Omega_B \cong 0.04$
- Neutrinos ➻ $\Omega_\nu \cong 5\times10^{-4}$-0.01

Dark Matter

First suggested by Zwicky (1933)
to explain motion of galaxies in clusters

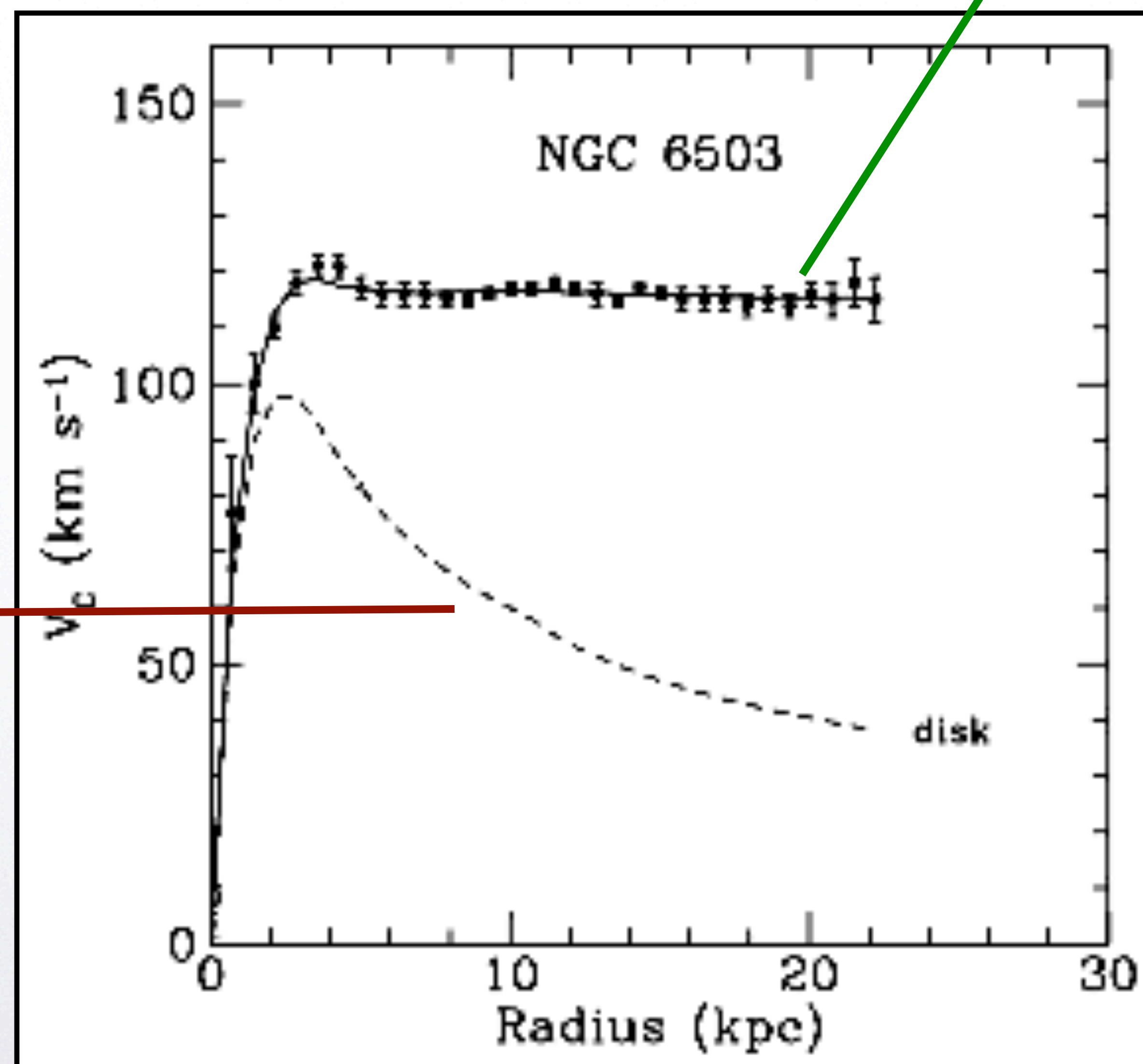
Strong observational support from study of galaxy rotation curves



Dark Matter

Results of measurements:

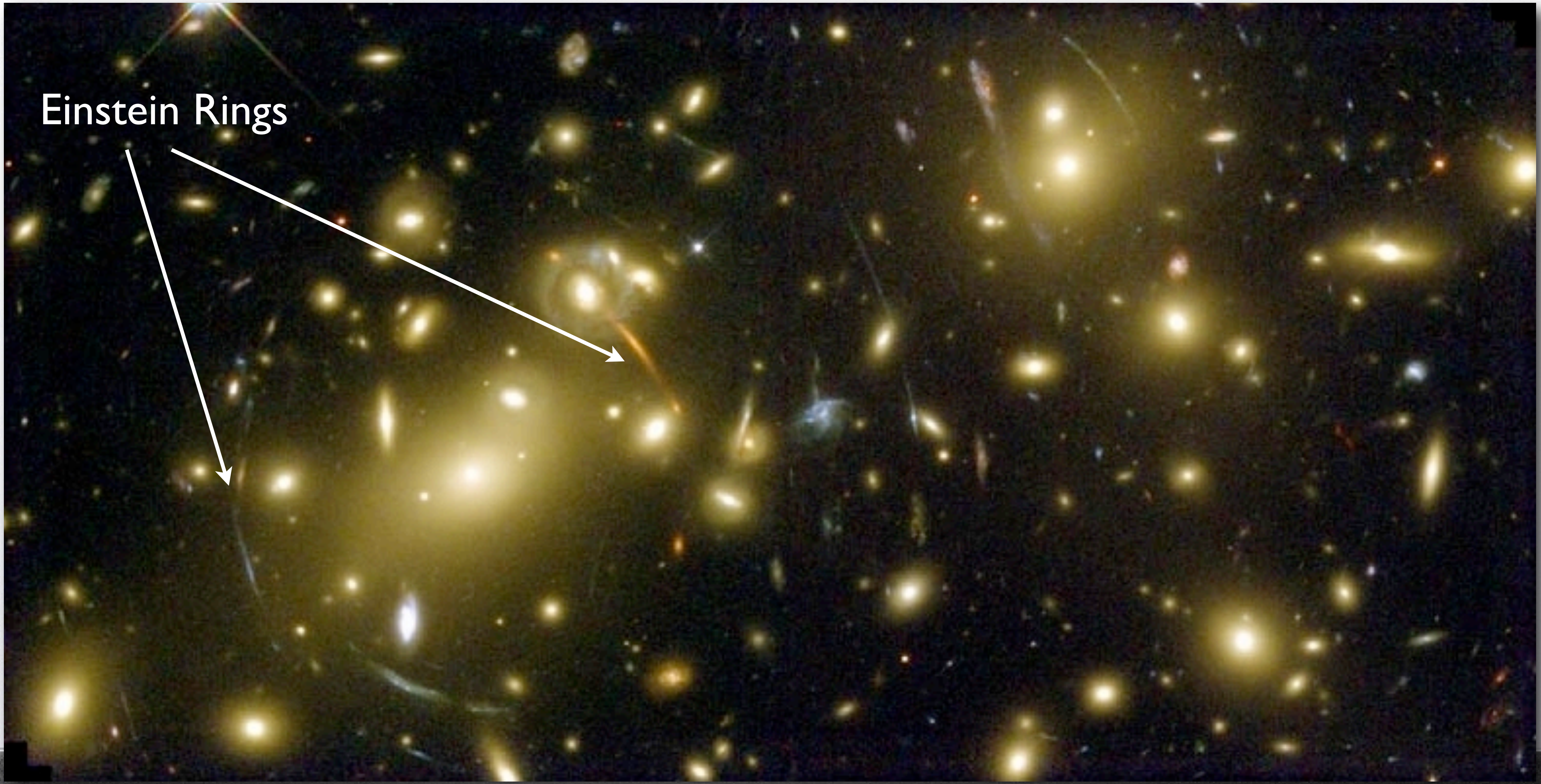
measured v(r)



v(r) if there was only luminous matter in the galaxy

Dark Matter

More evidence: gravitational lensing (see Dell’Antonio tomorrow!)



Dark Matter

More evidence: X rays

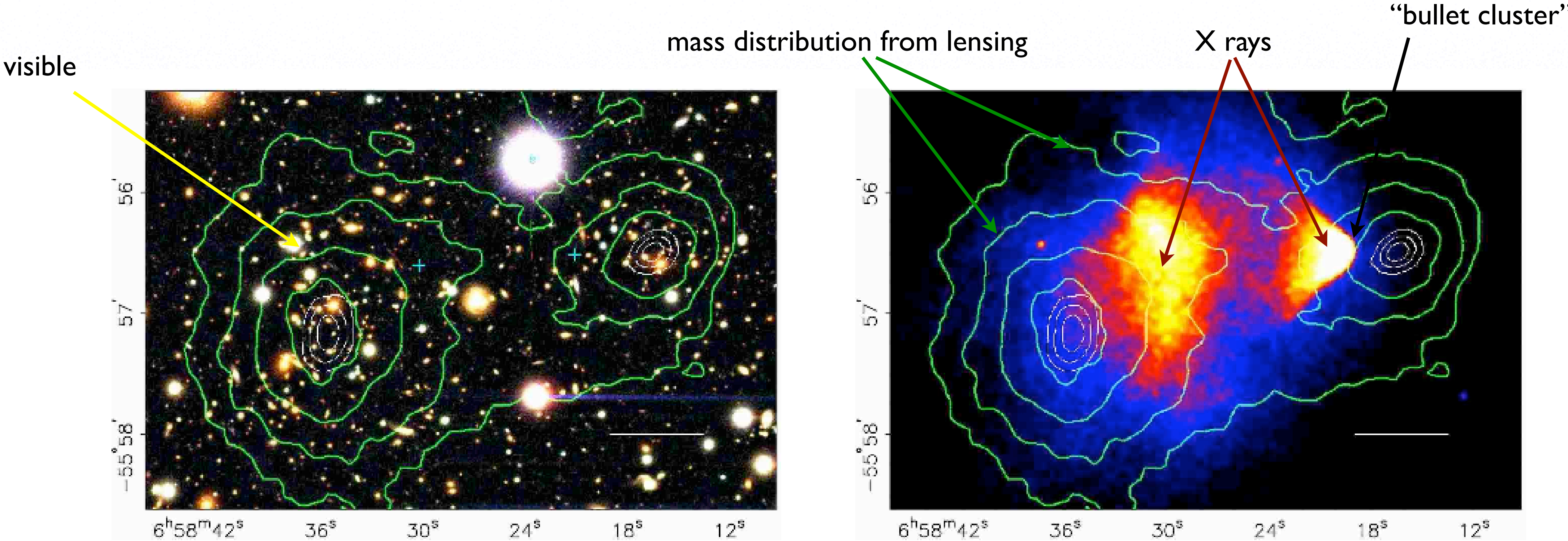


FIG. 1.— Shown above in the top panel is a color image from the Magellan images of the merging cluster 1E0657−558, with the white bar indicating 200 kpc at the distance of the cluster. In the bottom panel is a 500 ks Chandra image of the cluster. Shown in green contours in both panels are the weak lensing κ reconstruction with the outer contour level at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue +s show the location of the centers used to measure the masses of the plasma clouds in Table 2.

Clowe *et al* (2006)

How much dark matter?

Different measurements in clusters give

$$\rho_{DM} \cong 5 \times \rho_{Baryon}$$

$$\boxed{\text{Ordinary matter+Dark matter} \Rightarrow \; \Omega \cong 0.3}$$

What are the properties of DARK MATTER?

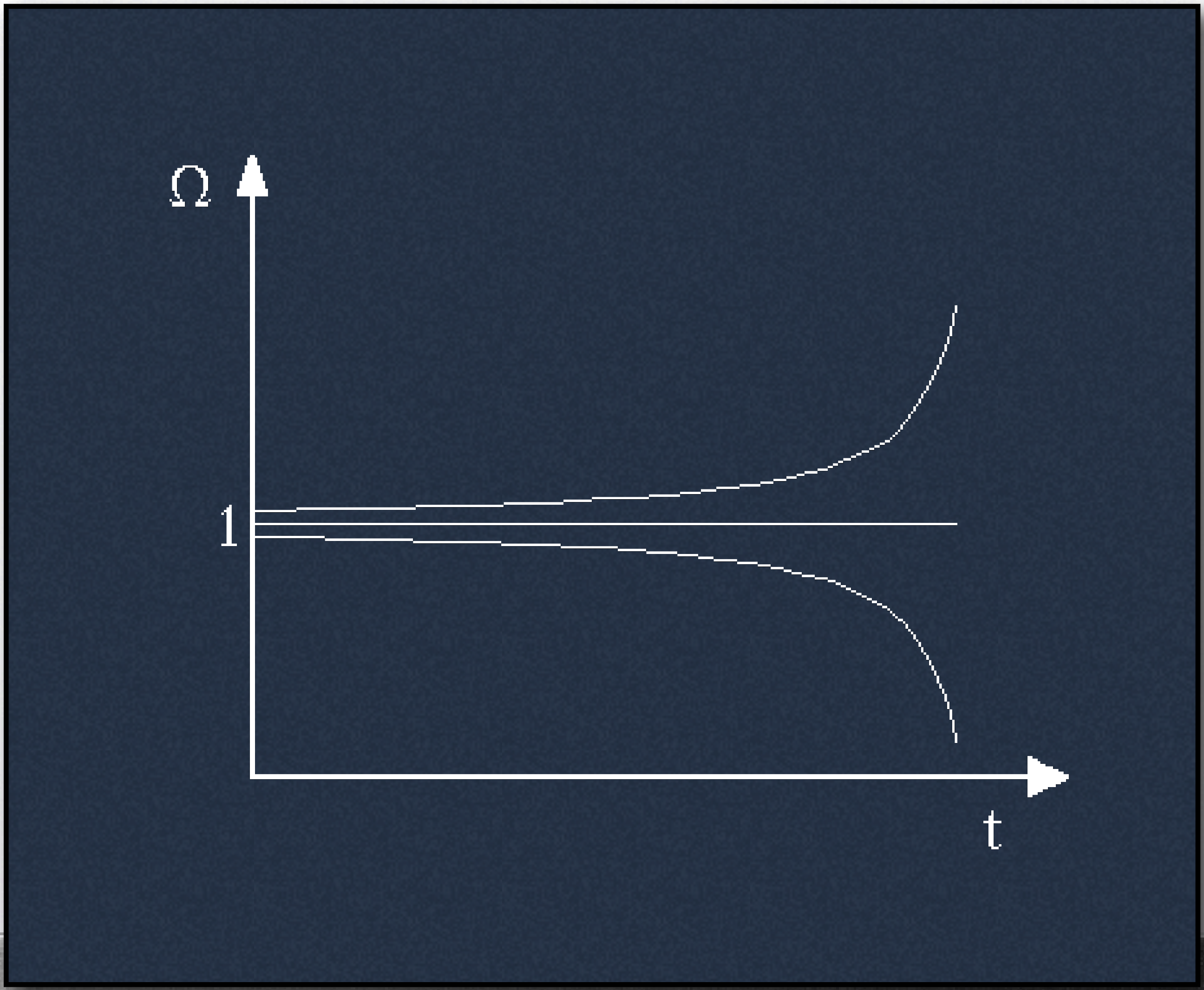
- It clumps, like dust
- It interacts very weakly with ordinary matter (weak scale interactions favored)
- It represents ~ the 80% of the matter content in structures
- Susy neutralino an excellent candidate - see Mc Kinsey on Friday (but also axions, gravitinos, primordial black holes...)

Why do we care about Ω?

Ω=1 is an *unstable* equilibrium point:

evolution of the Universe brings Ω away from 1

If Ω is close to 1 today, it should have been **VERY** close to 1 in the past!



If Ω=0.3 today, then Ω should have been equal to
0.9999999999999999993
at the time of nucleosynthesis

Much more elegant to assume
Ω=1, always

moreover, we have a *mechanism* to generate Ω=1:
Inflation

...but where is the remaining matter that
allows us to go from Ω=0.3 to Ω=1?

Using Friedmann's law to determine the content of the Universe

Derive $\varrho(t)$, $p(t)$ from

$$H^2 = \frac{8\pi G}{3}\varrho - \frac{k}{a^2} \qquad \dot{\varrho} + 3H(\varrho + p) = 0$$

and measures of $H(t)$

$$d_{\text{physical}}(t) = a(t)\, d_{\text{comoving}} \Longrightarrow \dot{d}_{\text{physical}}(t) = \dot{a}(t)\, d_{\text{comoving}}$$

Easy to measure (redshift)

Difficult to measure

UNKNOWN!

Measuring distances from us...

Standard candle: object whose absolute luminosity is known

Absolute luminosity $\mathcal{L}$

Incoming flux on Earth $\mathcal{F}$

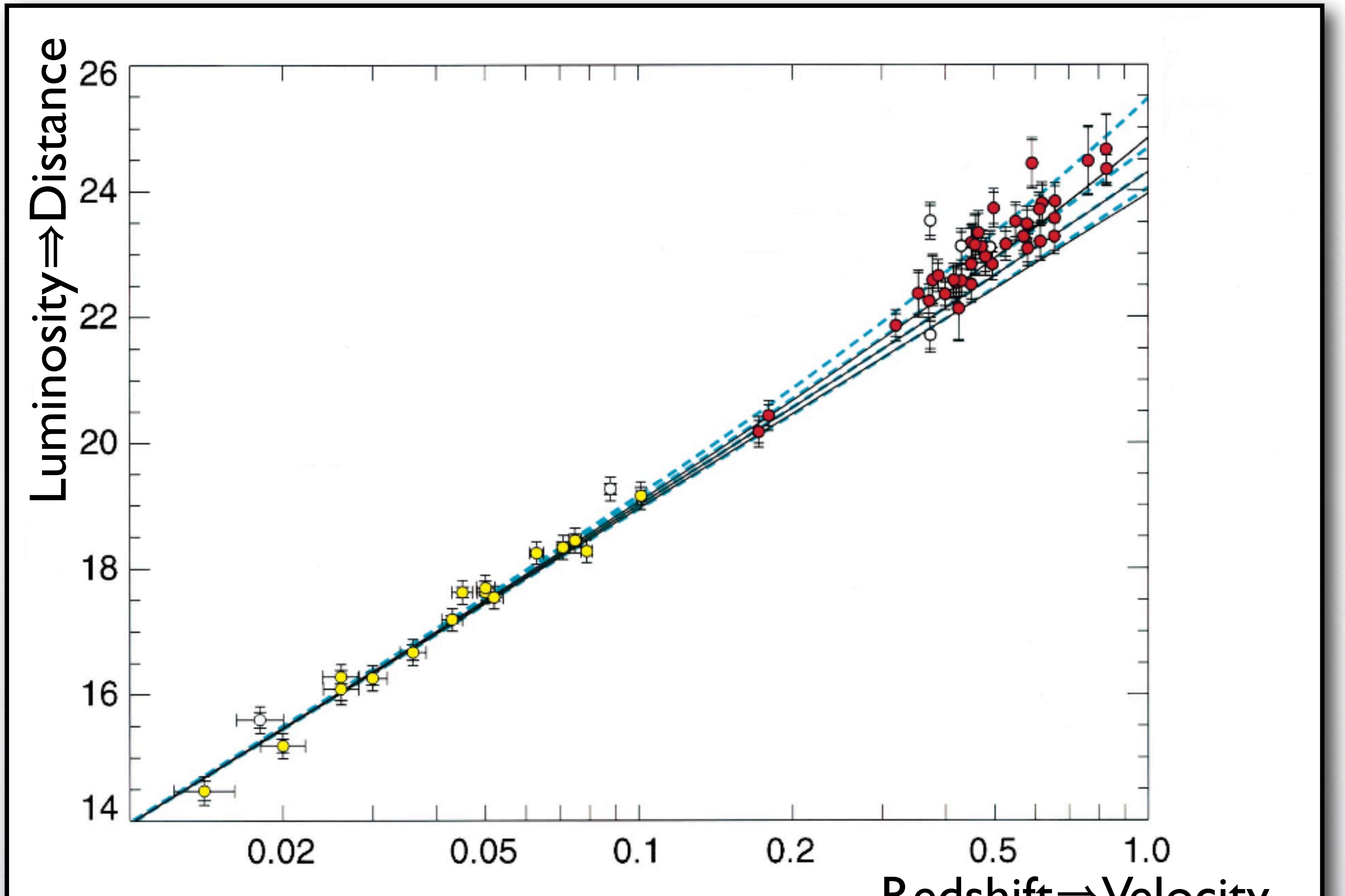
Distance $d=\sqrt{\mathcal{L}/4\pi\mathcal{F}}$

Of course, very difficult to find standard candles!

Today, the most important are

Type Ia Supernovae

Hubble diagram (i.e. $d(z)$)



[from Perlmutter *et al* (1998)]

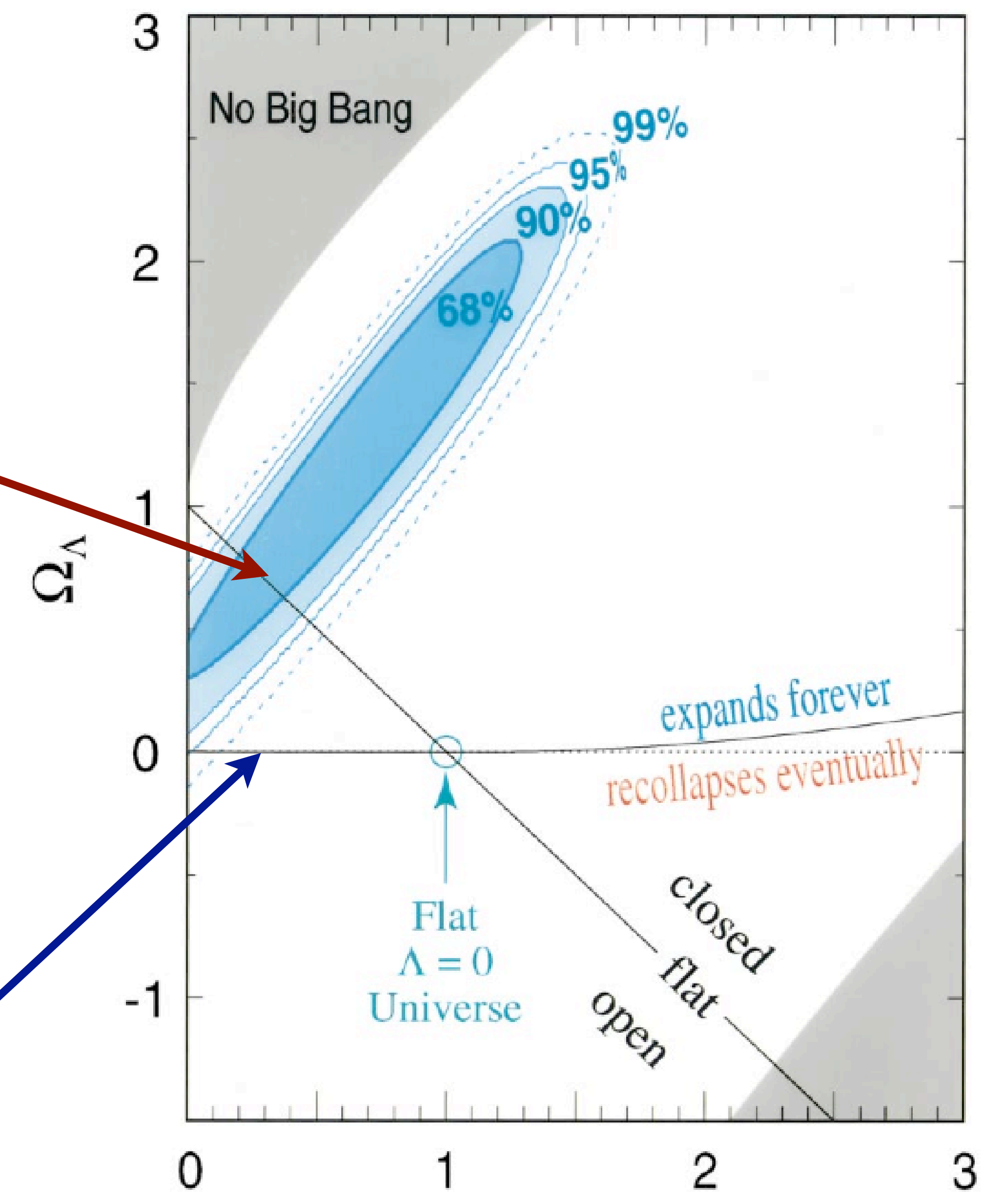
$\varrho(t),\ p(t)$

Besides ordinary matter and dark matter, the Universe contains <u>*extra stuff*</u> that behaves like a fluid *with negative pressure*

DARK ENERGY!

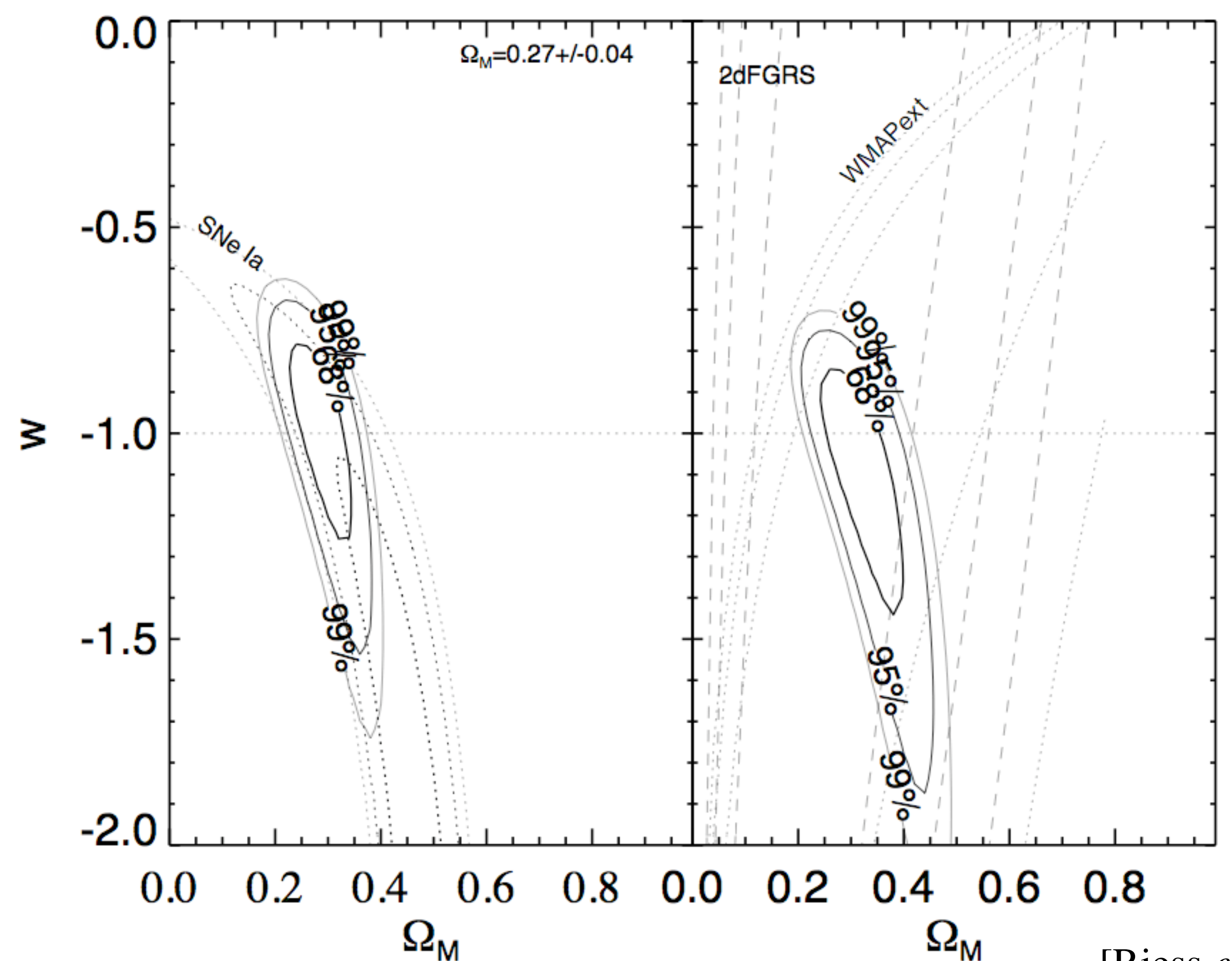
Ω_M=0.3, Ω_{DE}=0.7

Ω_M=0.3, Ω_{DE}=0



[from Perlmutter *et al* (1998)] Ω_M

Constraints on the plane (w_{DE}, Ω_{DE})



[Riess *et al*, 2004]

What are the properties of DARK ENERGY?

- It is smoothly distributed EVERYWHERE
- It looks a lot like a cosmological constant (the energy of vacuum)
- It does not dilute away as the Universe expands
- It represents ~ the 70% of the matter content of the Universe
- We have no idea what it might be (cosmological constant? quintessence? modified gravity?)

The inhomogeneous Universe

Gravity is different from other forces:

equal charges attract each other

Instability!

Inhomogeneites (can) GROW!

Behavior of perturbations in FRW Universe

$\delta\varrho/\varrho$	Radiation domination	Matter domination
Superhorizon $\lambda > H^{-1} \sim t$	Constant	Constant
Subhorizon $\lambda > H^{-1} \sim t$	Constant	**Grow** $\propto a(t)$

← Causality

↑ Pressure

Inhomogeneities were small in the past

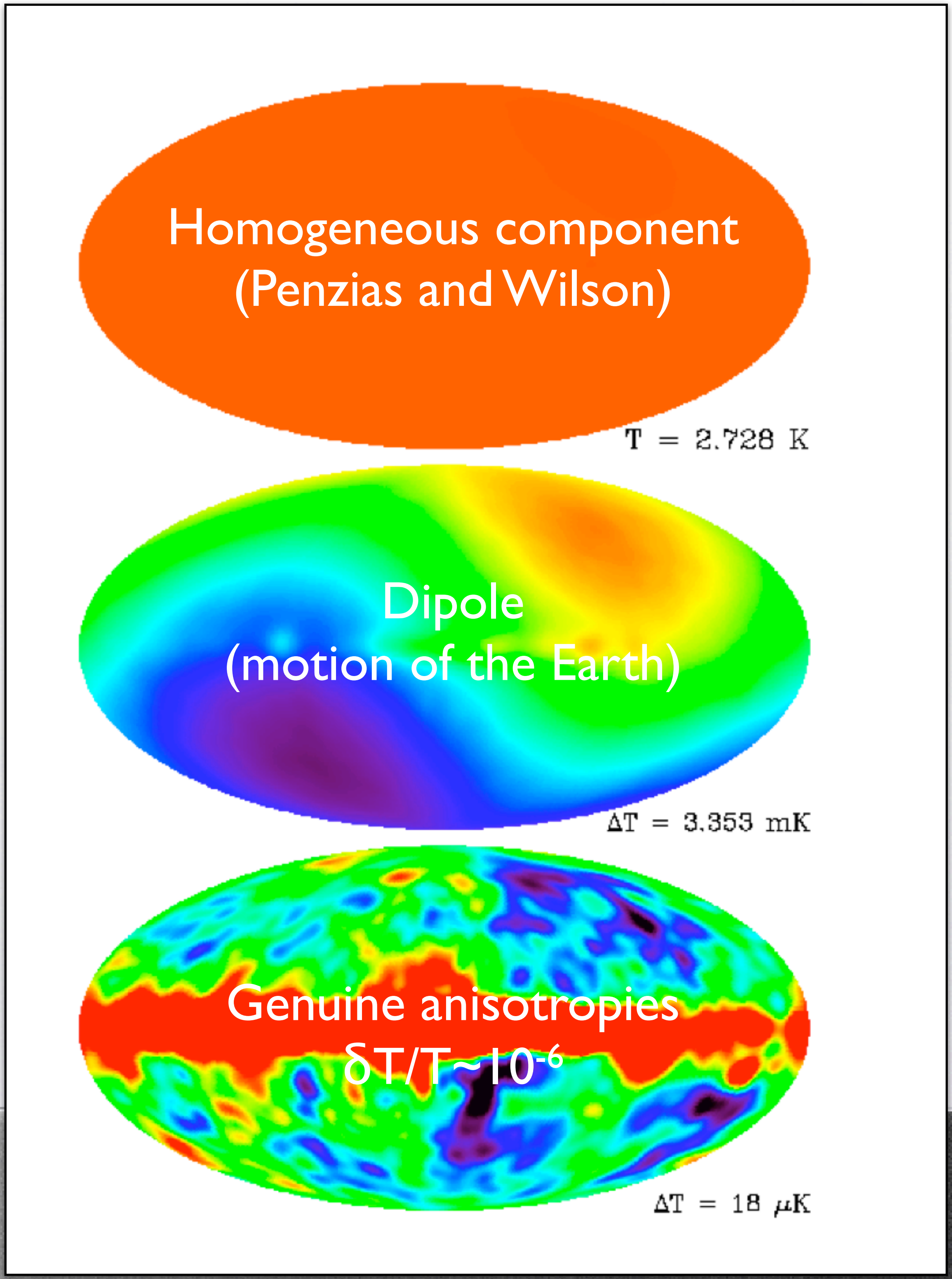
CMB

Last interaction with
matter at recombination.

CMB anisotropies:
a picture of the Universe
at recombination!

Map of the anisotropies:
a wealth of information
about the Universe

COBE (1992)

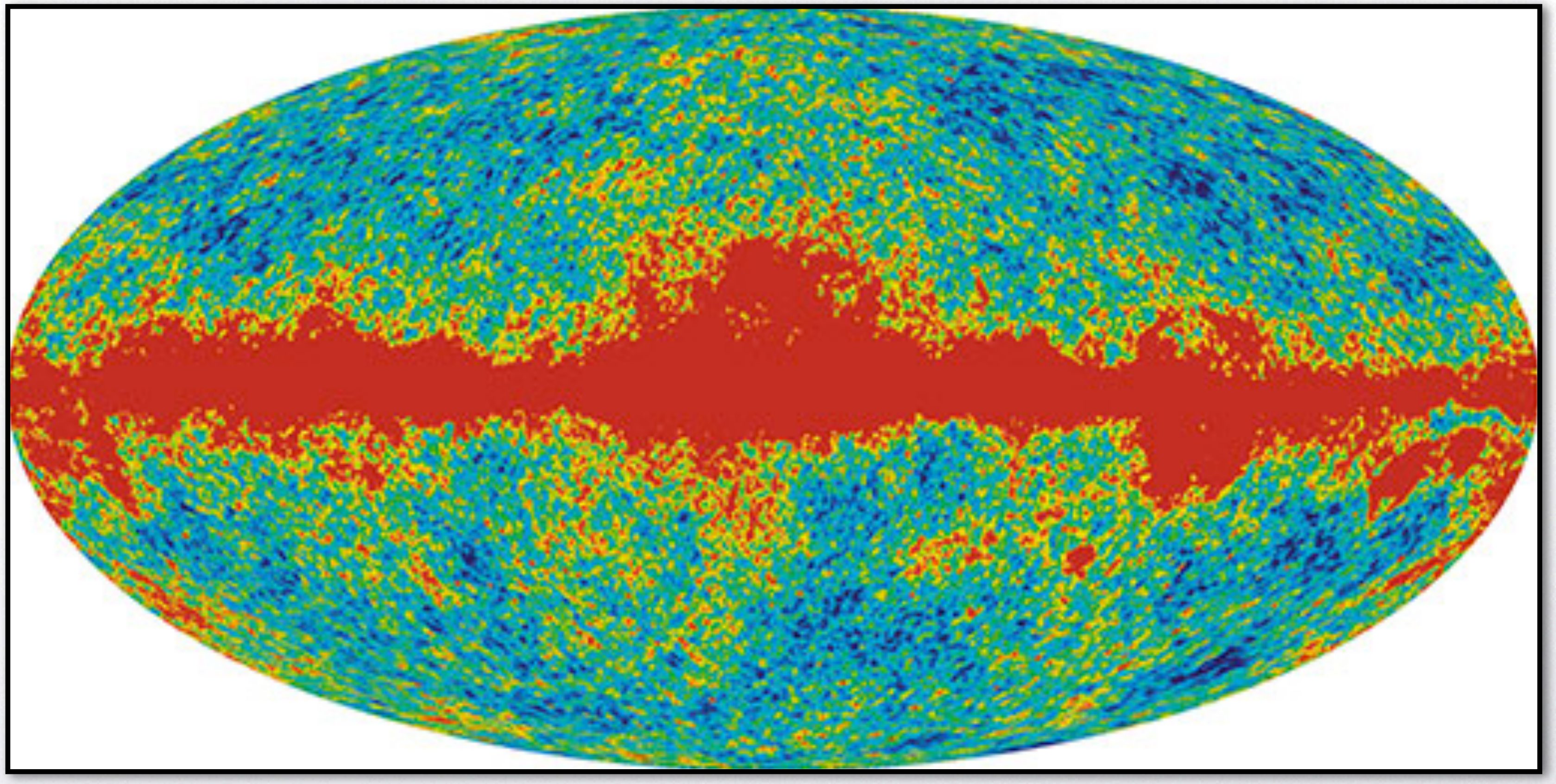


WMAP
(Wilkinson Microwave Anisotropy Probe)

Launched 2001 - still taking data

Better resolution

Polarization!



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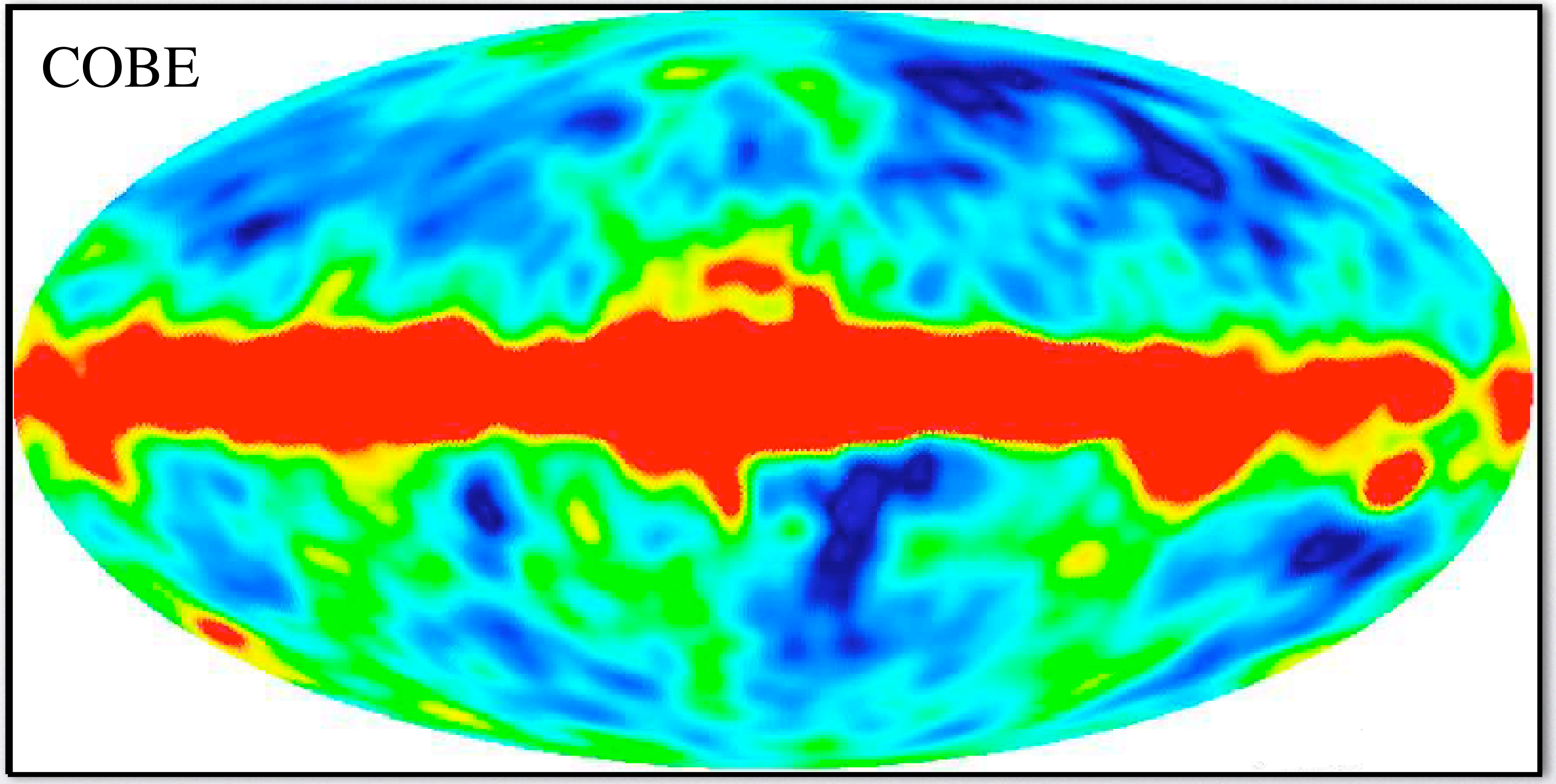
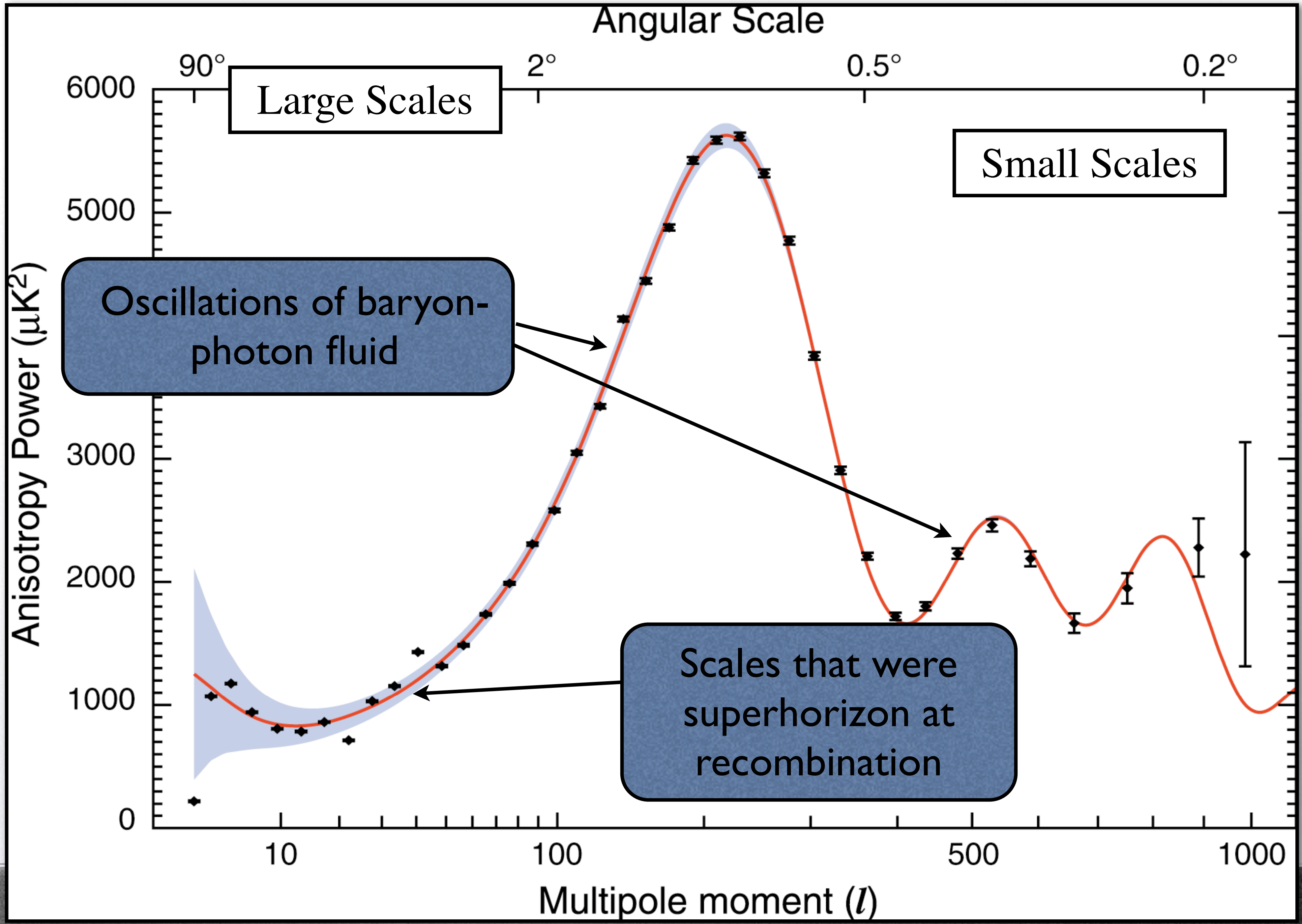
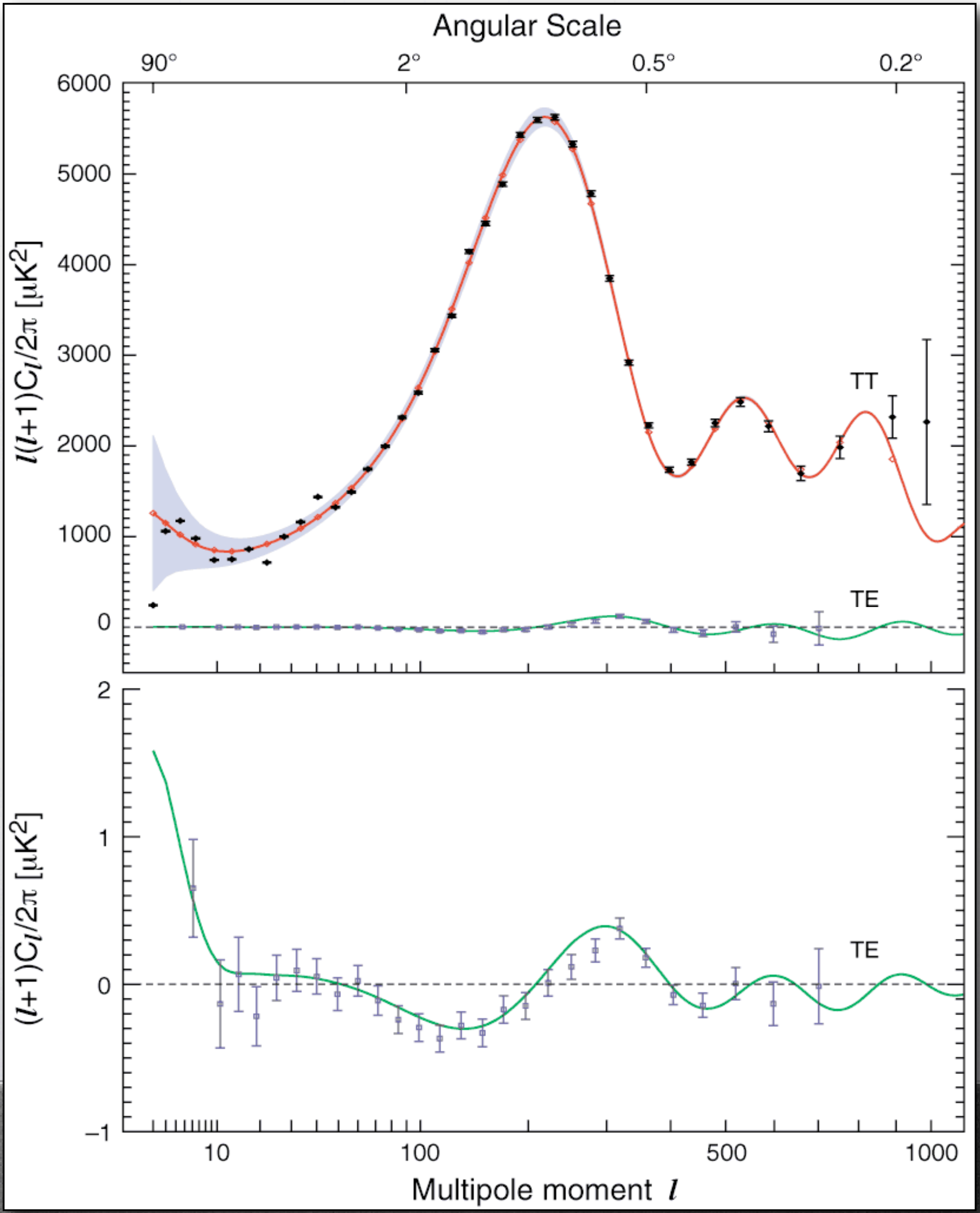


“Fourier transform” of data (C_l)



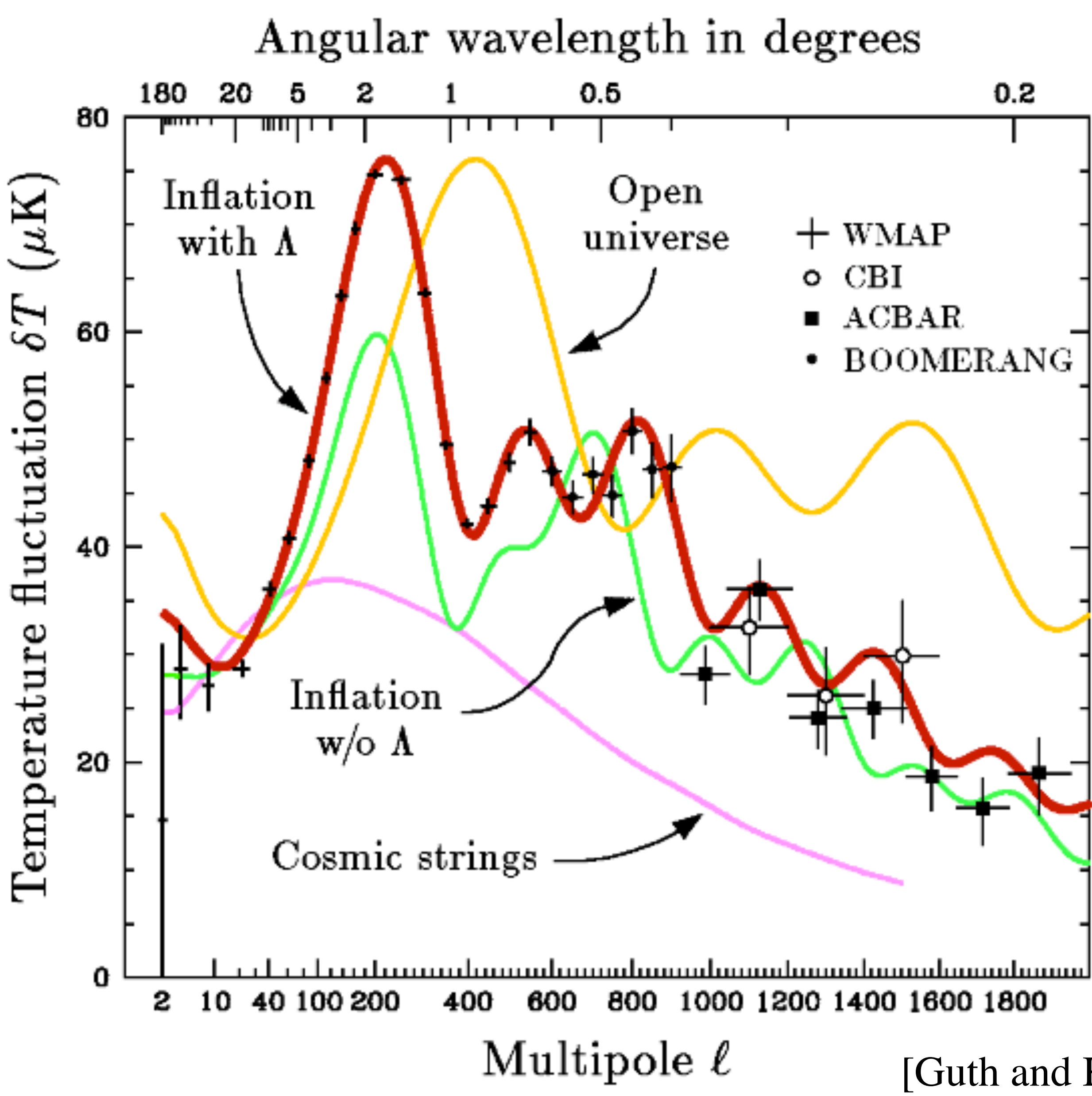
Polarization!



CMB power spectrum depends on and gives info about

- The spectrum of superhorizon perturbations at recombination
- The evolution of perturbations that entered the horizon before recombination
- The evolution of the Universe after recombination

Effects on CMB power spectrum



[Guth and Kaiser 2005]

A lot of information , but **DEGENERACIES**!

CMB and Precision Cosmology

Ω_{Baryon} in fantastic agreement with BBN!

Spectral index of primordial perturbations agrees with expectation from inflation

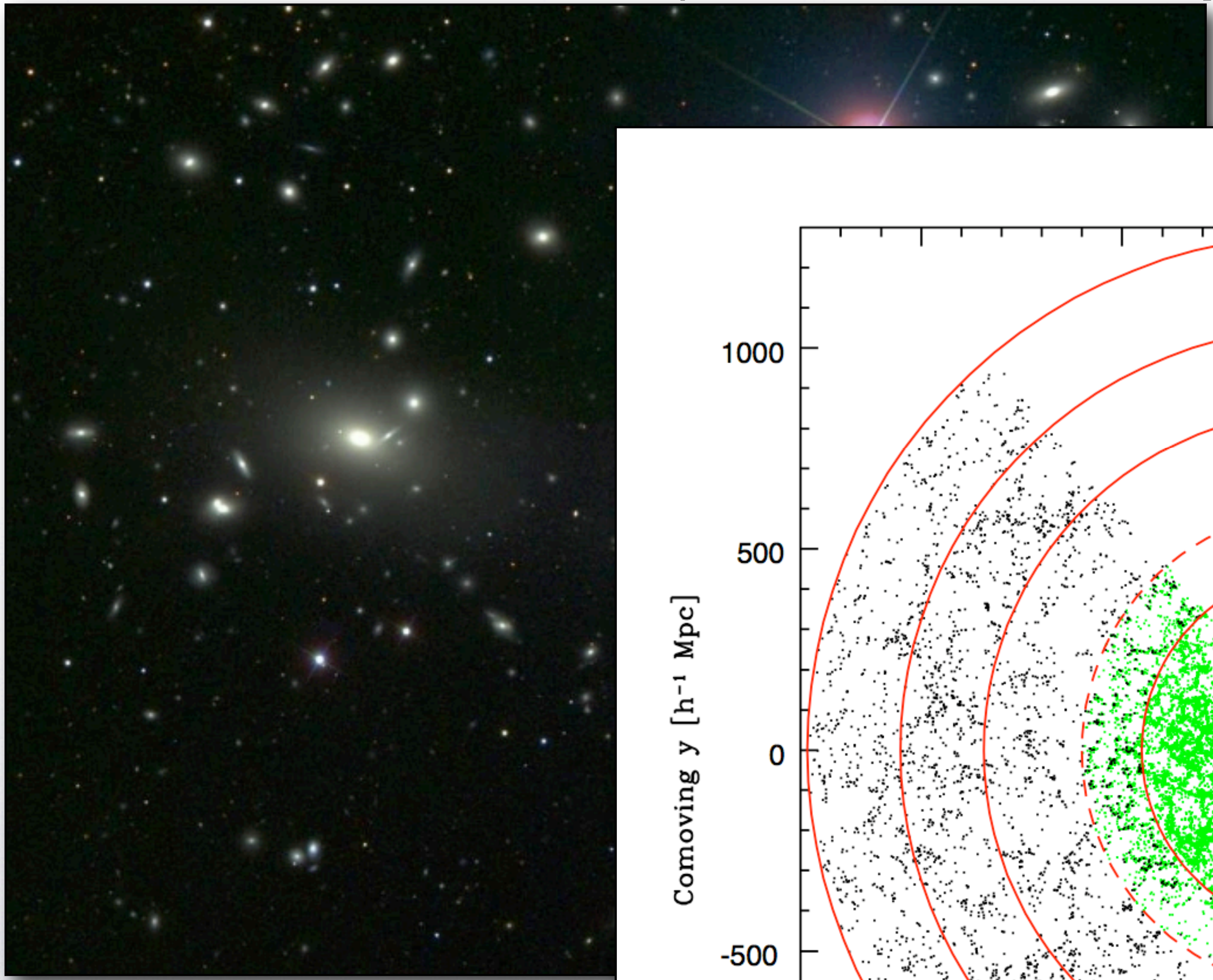
Amount of dark matter same as estimated from clusters

WMAP Cosmological Parameters Model: lcdm Data: wmap	
$10^2\Omega_b h^2$	2.229 ± 0.073
$\Delta^2_{\mathcal{R}}(k = 0.002/\text{Mpc})$	$(23.5 \pm 1.3) \times 10^{-10}$
h	$0.732^{+0.031}_{-0.032}$
H_0	$73.2^{+3.1}_{-3.2}$ km/s/Mpc
$\log(10^{10} A_s)$	3.156 ± 0.056
$n_s(0.002)$	0.958 ± 0.016
$\Omega_b h^2$	0.02229 ± 0.00073
$\Omega_c h^2$	$0.1054^{+0.0078}_{-0.0077}$
Ω_Λ	0.759 ± 0.034
Ω_m	0.241 ± 0.034
$\Omega_m h^2$	$0.1277^{+0.0080}_{-0.0079}$
σ_8	$0.761^{+0.049}_{-0.048}$
τ	0.089 ± 0.030
θ_A	$0.5952 \pm 0.0021\ ^\circ$
z_r	$11.0^{+2.6}_{-2.5}$

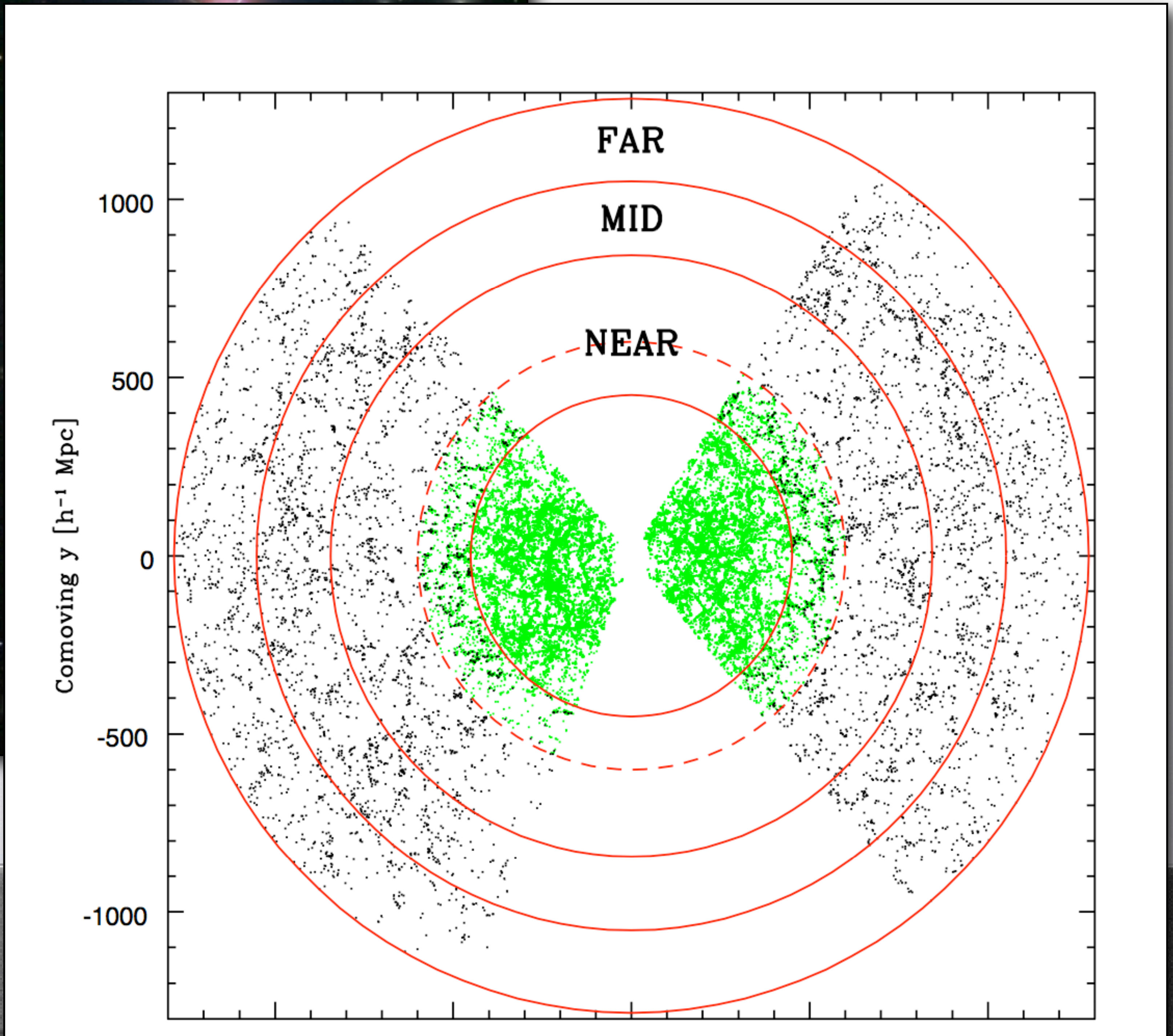
Priors:
$\Omega_{TOT}=1$
dark energy=Cosmological Constant

What we see in the sky

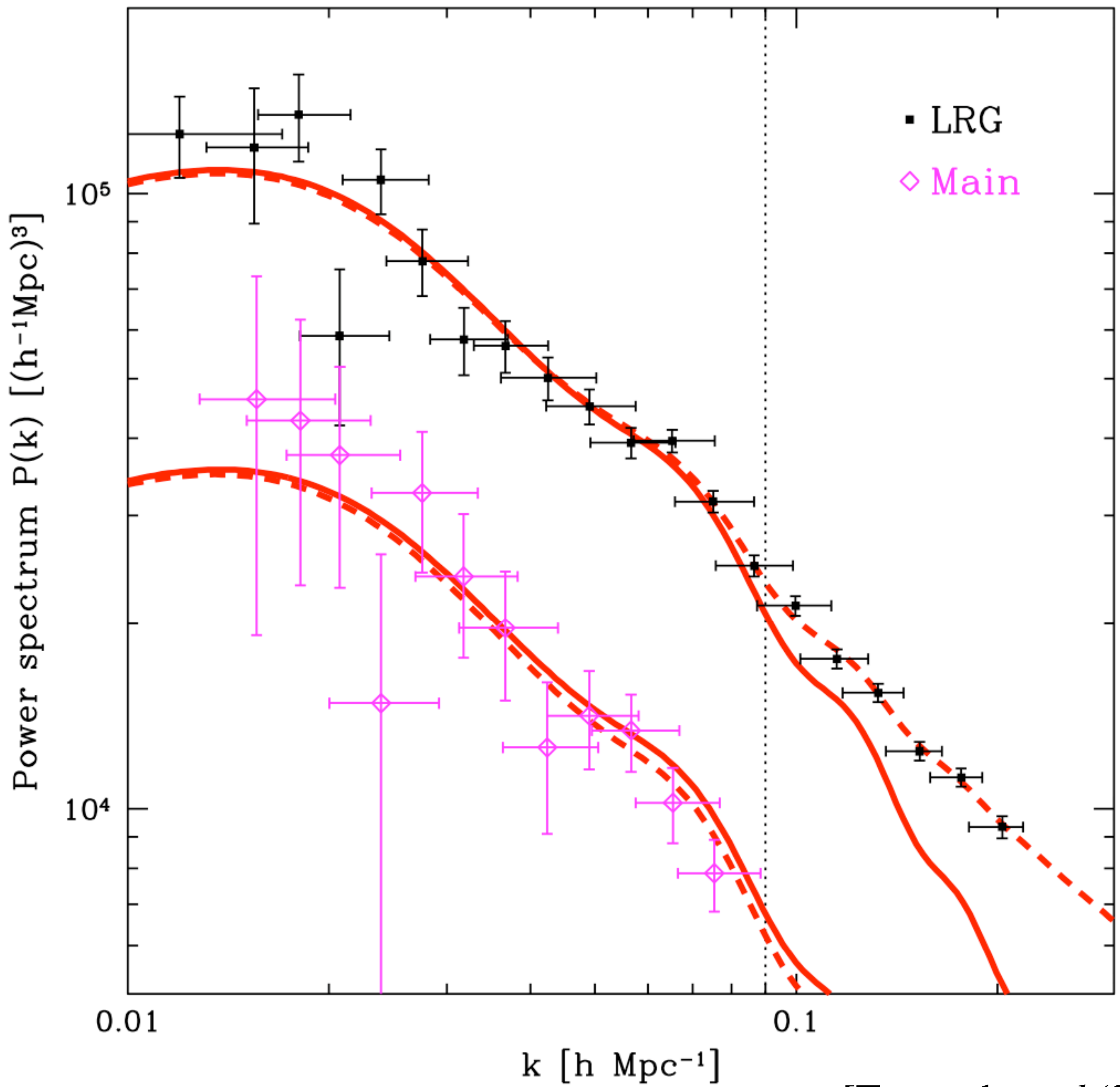
(with galaxy surveys)



[Sloan Digital Sky Survey]



Again, Fourier transforming...

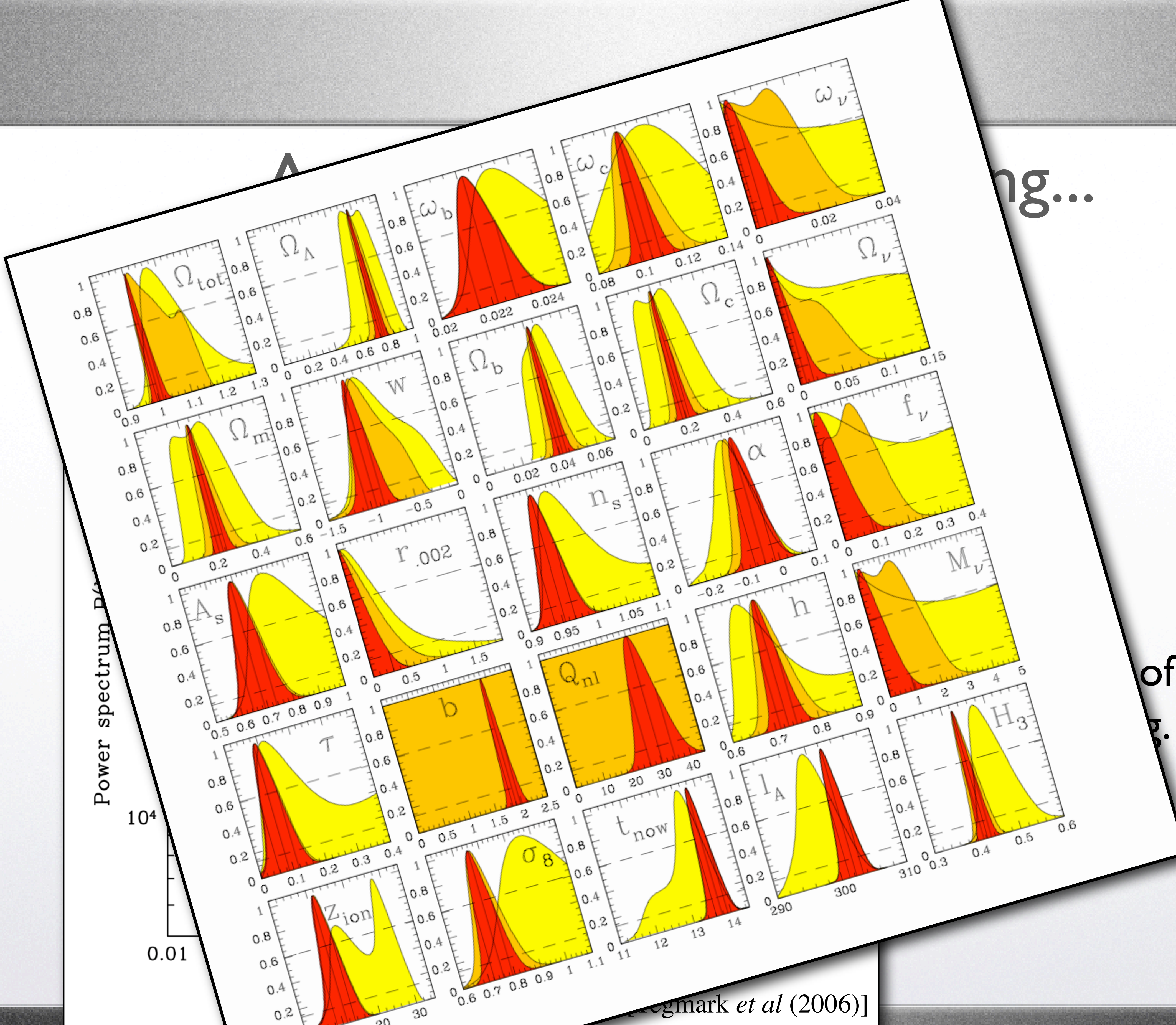


[Tegmark *et al* (2006)]

FIG. 4: Measured power spectra for the full LRG and main galaxy samples. Errors are uncorrelated and full window functions are shown in Figure 5. The solid curves correspond to the linear theory ΛCDM fits to WMAP3 alone from Table 5 of [7], normalized to galaxy bias $b = 1.9$ (top) and $b = 1.1$ (bottom) relative to the $z = 0$ matter power. The dashed curves include the nonlinear correction of [29] for $A = 1.4$, with $Q_{nl} = 30$ for the LRGs and $Q_{nl} = 4.6$ for the main galaxies; see equation (4). The onset of nonlinear corrections is clearly visible for $k \gtrsim 0.09h$/Mpc (vertical line).

A lot of information!
(e.g. ν mass...)

A... ng...



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...of information!

...g. ν mass...)

Conclusions

Cosmology is a powerful instrument - but a dirty one

Very useful in conjunction with a cleaner instrument (accelerators)

By looking at the sky we KNOW that there must be some Physics beyond the Standard Model

Will we be able to uncover it?