Title: Weighing the Universe

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Abstract: How do we weigh the Universe? Where is the Dark Matter? I will discuss these questions and show that several independent methods, including the observed present-day abundance of rich clusters , the evolution of cluster abundance with redshift, the baryon-fraction in clusters, the observed Mass-to-Light function from galaxies to superclusters, and other large-scale structure observations, all reveal a universe with a low mass density parameter of ~20% of the critical density. The data suggest that the mass in the Universe, including the dark-matter, approximately follows light on large scales and that most of the mass resides in huge dark halos around galaxies. I will review the combined observational evidence for dark-matter and for dark-energy in the universe and their cosmological implications.

WEIGHING THE UNIVERSE

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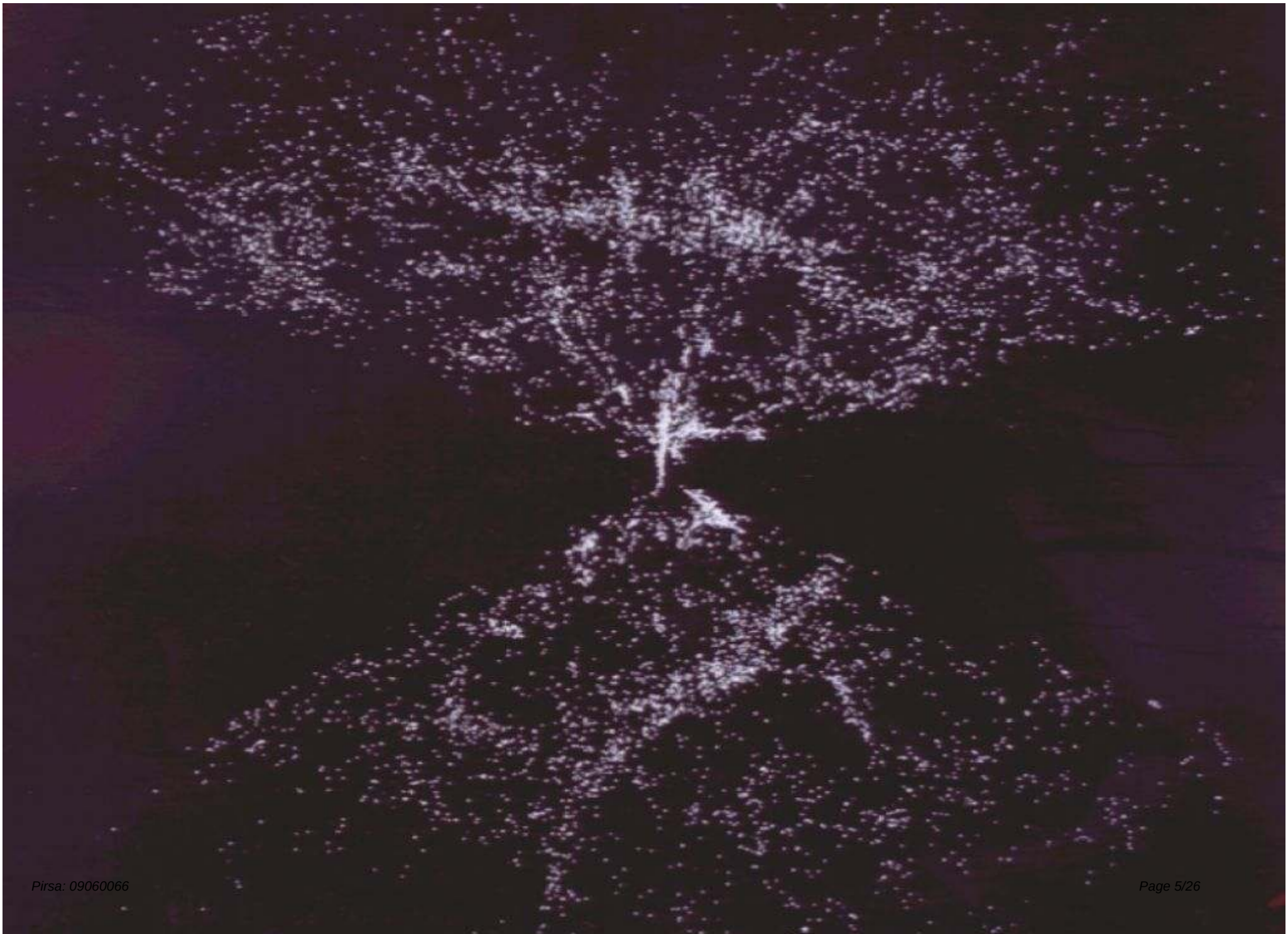
Why Weigh Universe?

- How much matter in Universe?
- Is there Dark-Matter? Where is it located?
- Is there Non-baryonic ('exotic') dark-matter? What is it?

  [Baryon limit is ~4-5% of critical-density.]
- Most fundamental cosmological parameter

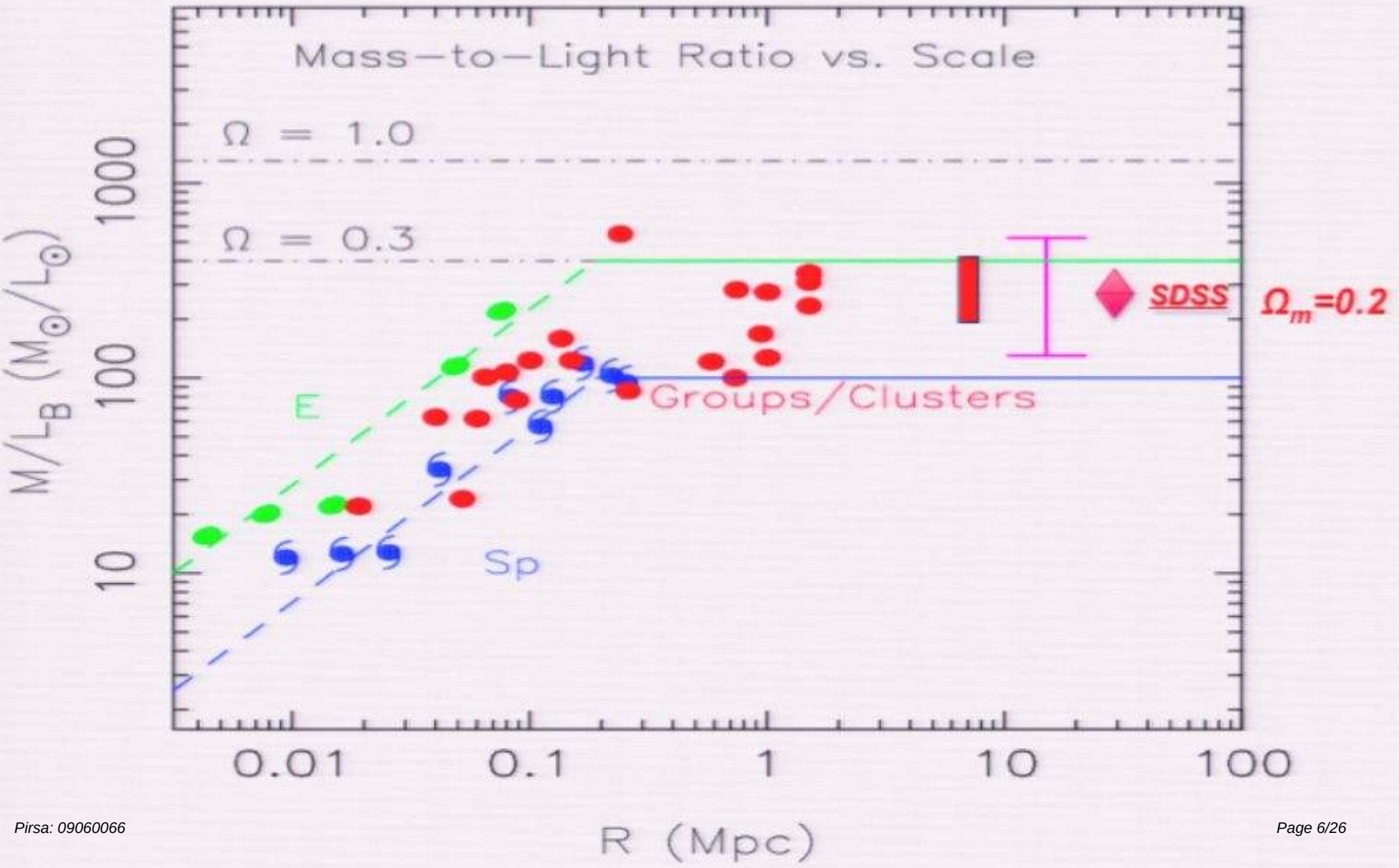
  → Cosmology; Evolution of Universe;

  Age of Universe; Galaxy Formation; Gravity



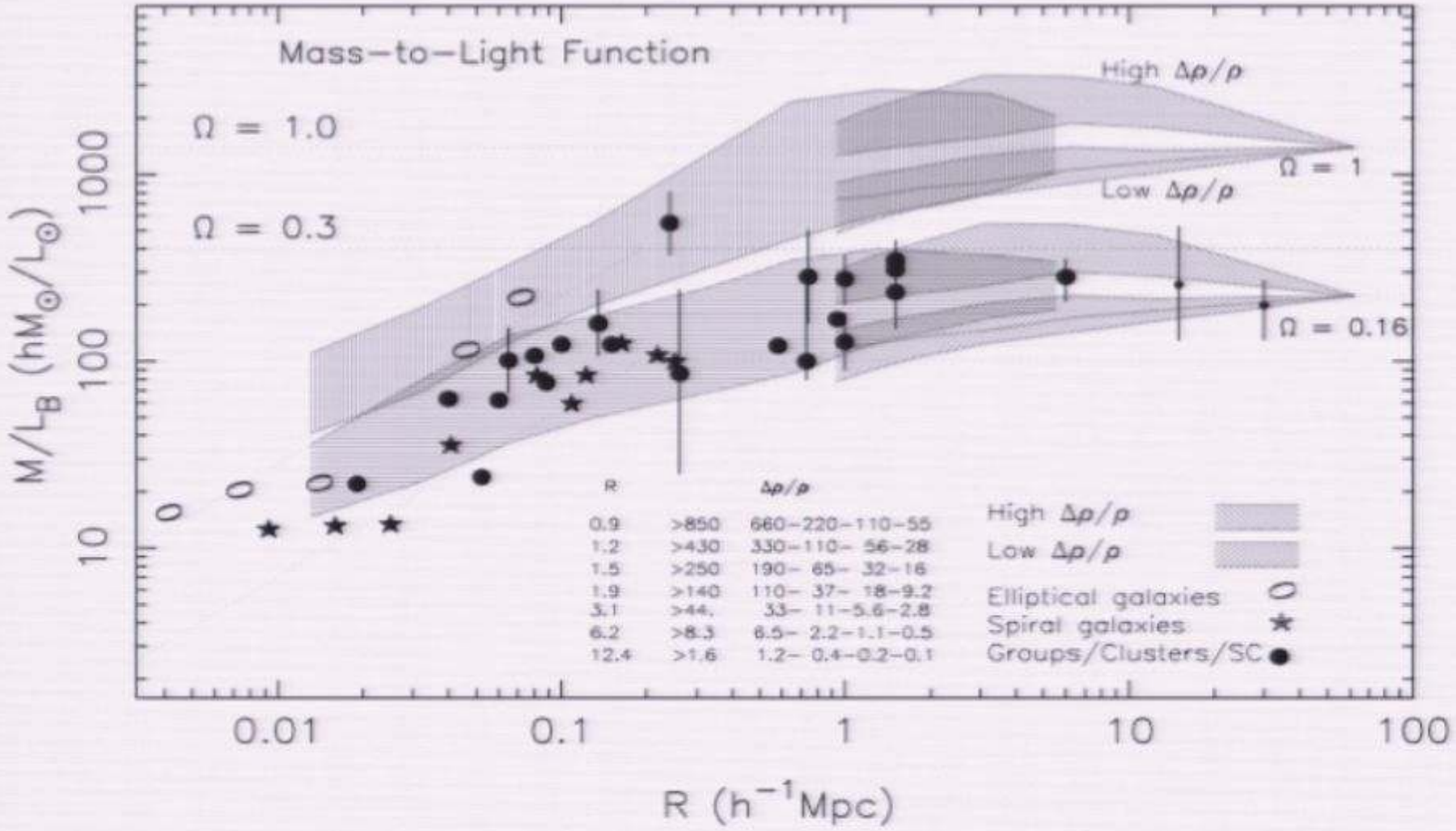
Mass-to-Light Function

(Bahcall, Lubin & Dorman '95; Bahcall and Fan '98)



Theory vs. Observations

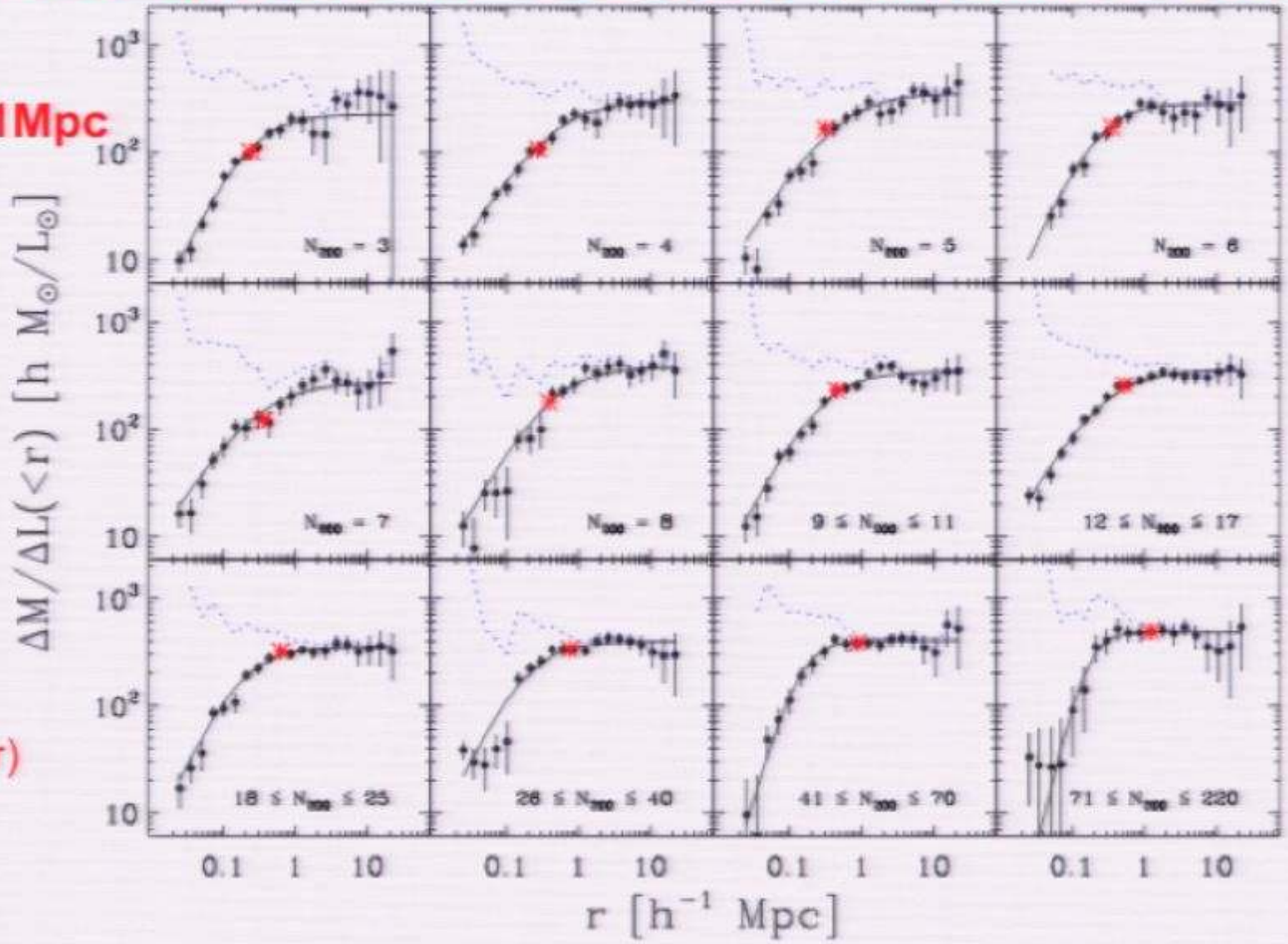
(Bahcall, Yu, et al '01)



Cluster $M/L_i(R)$ Profile (SDSS, weak lensing

$2x10^4$ clusters N= 3 to 220 (Sheldon etal 2008)

Flat >~ 1Mpc
M ~ L



X=R(vir)

FIG. 8.— Excess mass to excess light ratio profiles for each of the N_{200} bins. Light is measured in the $^{0.25}i$ bandpass. These curves are the ratio of the curves shown in Figures 6 and 7. The points with error bars include the mean BCG luminosity, while the dotted curves exclude the luminosity of the BCG. The asterisk marks r_{200}^{mean}. The curve through the data is a simple descriptive model as discussed in §8.6

M/L_i(r=22Mpc) vs. M_{cl} (SDSS; Sheldon etal '08)

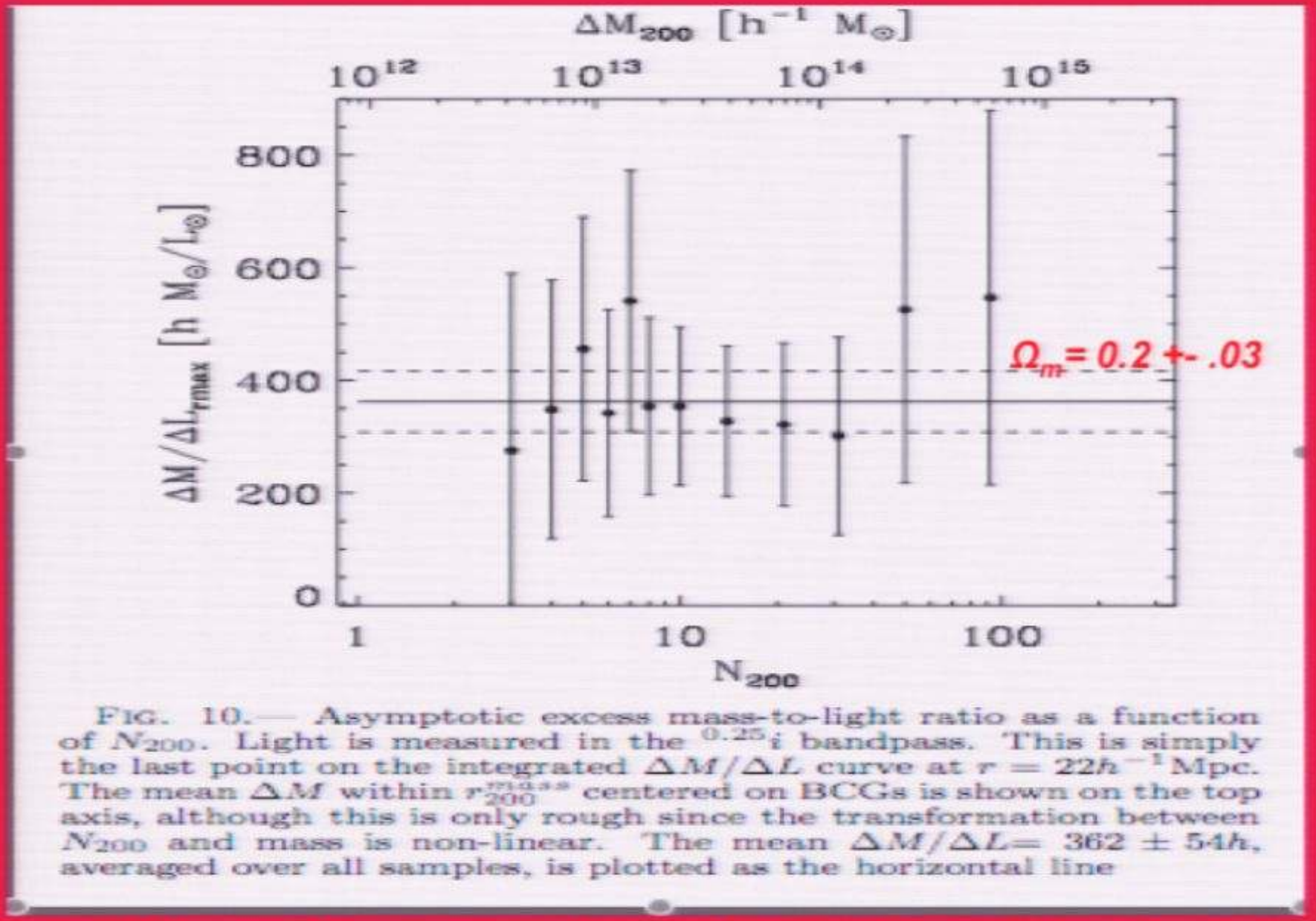


FIG. 10.— Asymptotic excess mass-to-light ratio as a function of N_{200}. Light is measured in the $^{0.25}i$ bandpass. This is simply the last point on the integrated $\Delta M/\Delta L$ curve at $r = 22h^{-1}$ Mpc. The mean ΔM within r_{200}^{mass} centered on BCGs is shown on the top axis, although this is only rough since the transformation between N_{200} and mass is non-linear. The mean $\Delta M/\Delta L = 362 \pm 54h$, averaged over all samples, is plotted as the horizontal line

Flat M/L on large scales; SAME for ALL clusters!

M/L Function: Conclusions

- **M/L Function Flattens on Large Scales:**

  → $M \sim L$ (on large scales)

  reaching the end of Dark-Matter

- **Total Mass-Density of Universe:**

  → $\Omega_m = 0.2 +- 0.05$

Baryons in Clusters
[Stars and Gas]

- $\Omega_b/\Omega_m(cl) \cong M_b/M_{tot}(cl) =$
  0.13 (gas) $+ 0.03$ (stars) $= 0.16$ $(h=0.7)$

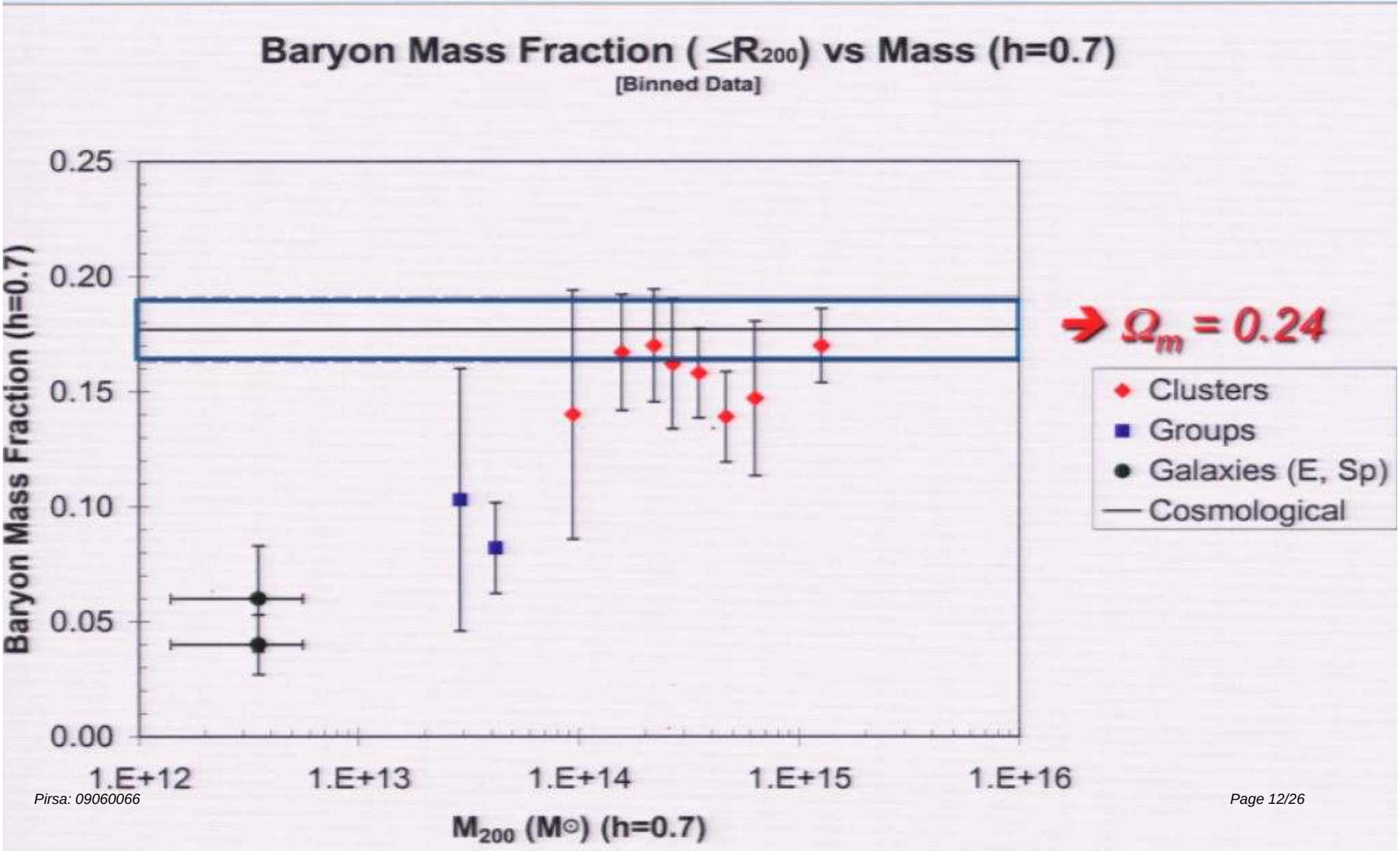
- $\Omega_b(BBN;\ CMB) = 0.042$ $(h=0.7)$

$\rightarrow \Omega_m = \Omega_b/(\Omega_b/\Omega_m) = 0.26 \pm 0.04$

$\rightarrow$ 0.24 +- 0.04 corrected for gas outflow

Baryon Fraction vs. Scale (→ 0.18)

(Bahcall & Martin '07)



Ω_m from Baryon-Fraction

- $\Omega_b/\Omega_m = 0.18 +- 0.02$ $h=0.7$ (Clusters; CMB)
- $\Omega_b = 0.042 +- 0.004$ (BBN; CMB)

→ $\Omega_m = 0.24 +- 0.04$

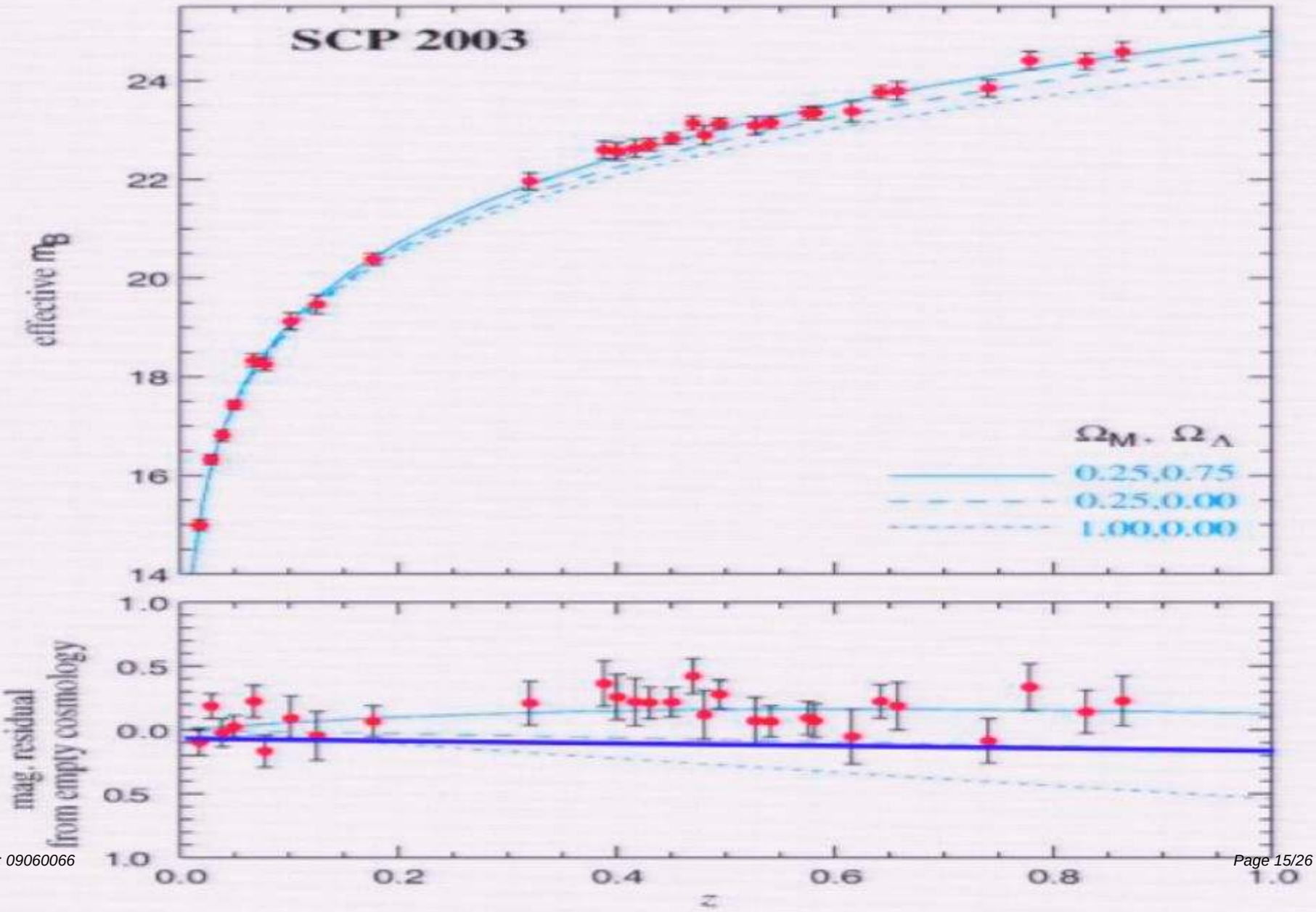
Weighing the Universe

- M/L Function $\Omega_m = 0.2 +- 0.05$
- Baryon Fraction $0.24 +- 0.04$
- Cluster Abundance $0.2 +- 0.05$
  and Evolution $[\sigma_8 = 0.9 +- 0.1]$
- Supernovae Ia + Flat $0.25 +- 0.05$
- CMB + LSS + h + Flat $0.24 +- 0.04$

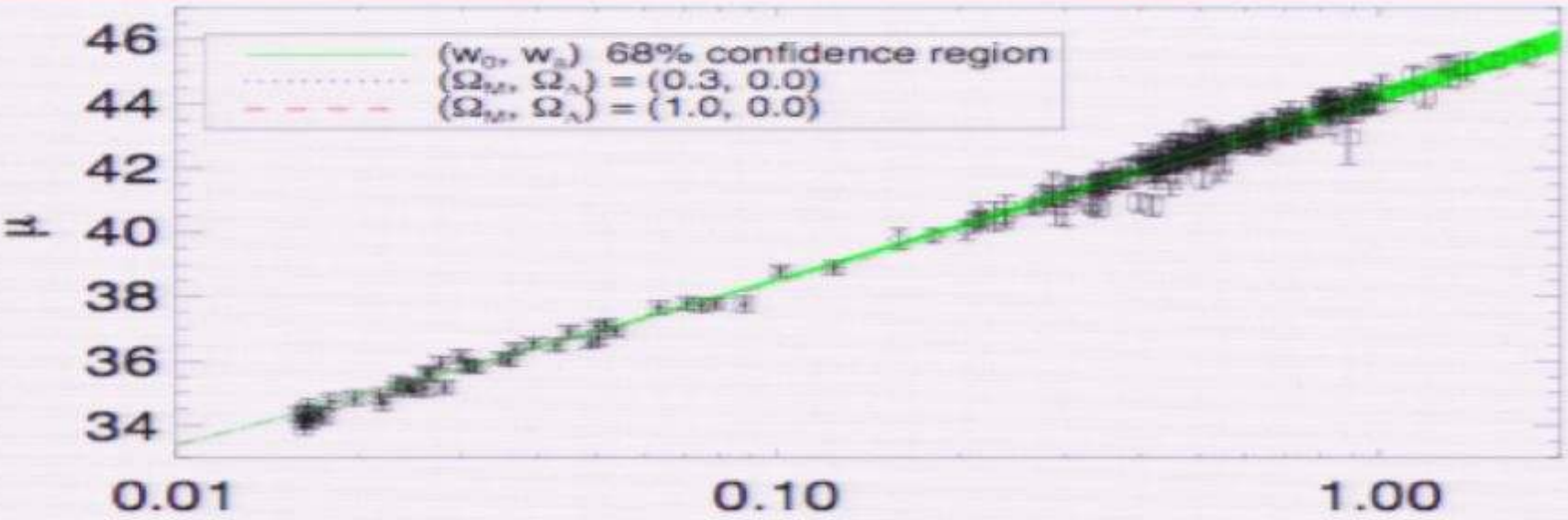
→ $\Omega_m \approx 0.23 +- 0.05$

- **4% Baryons + ~20% Dark Matter**
- **Mass ~ Light** (R >~ 1Mpc)

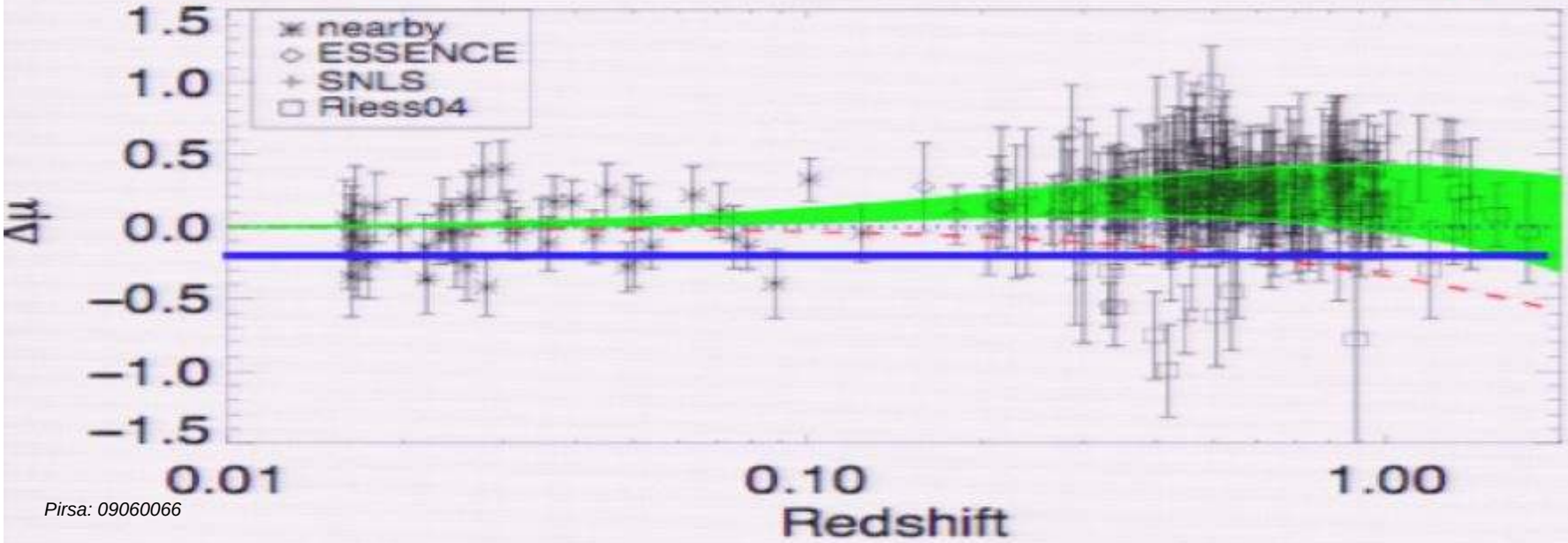
Cosmic Acceleration: Supernovae



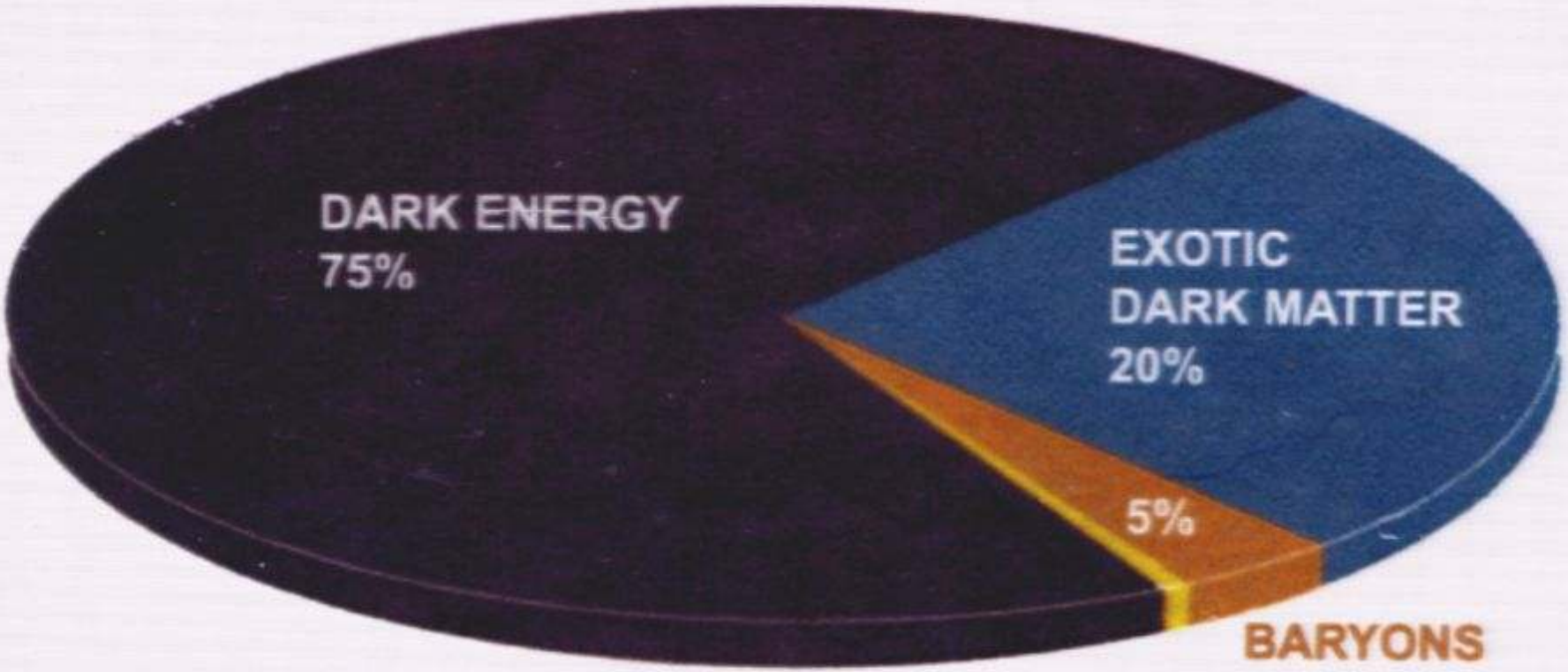
Cosmic Acceleraion: Supernovae ('07)



➔ $\Omega_m - \Omega_\Lambda \sim -0.5$

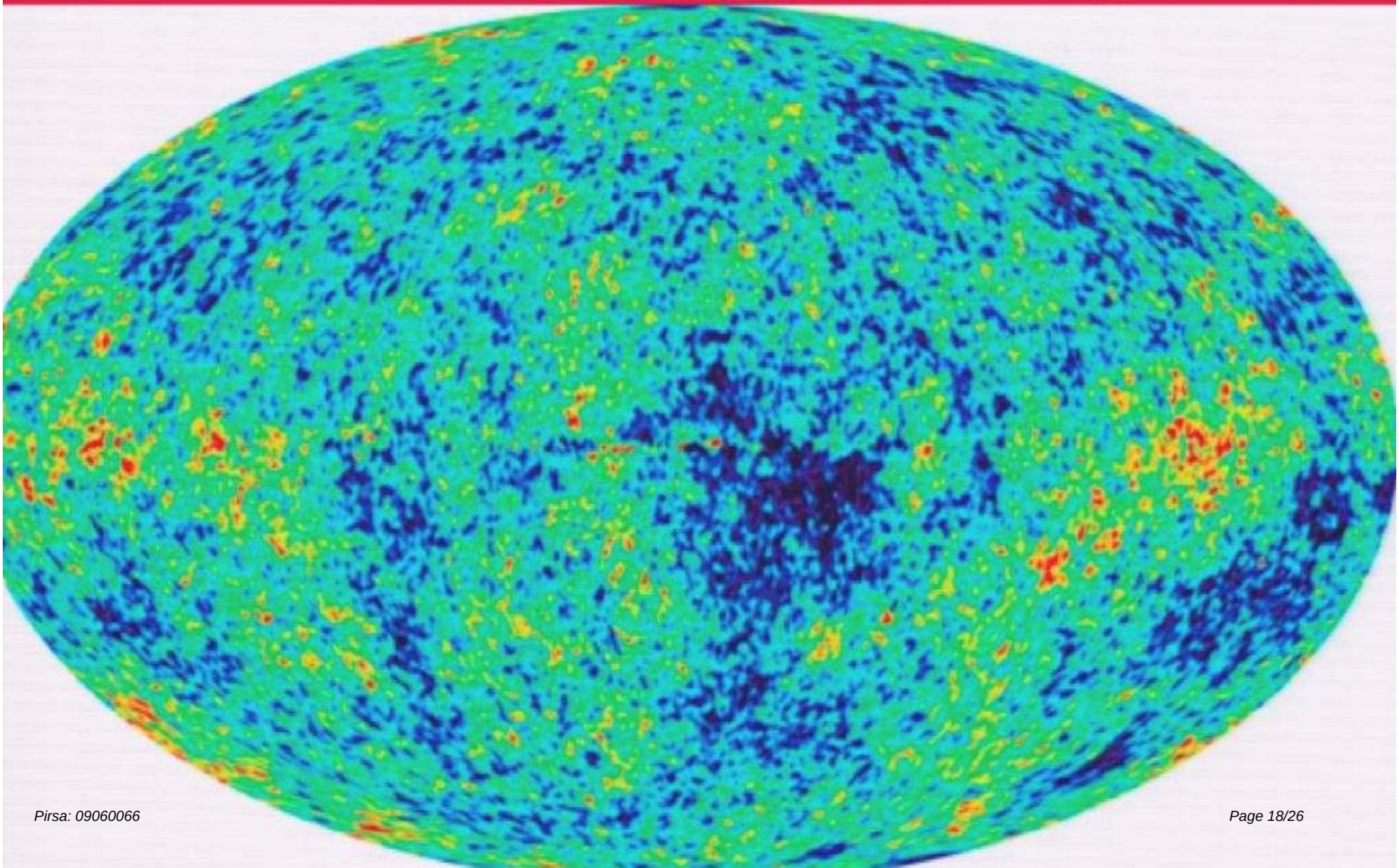


CONTENT OF THE UNIVERSE

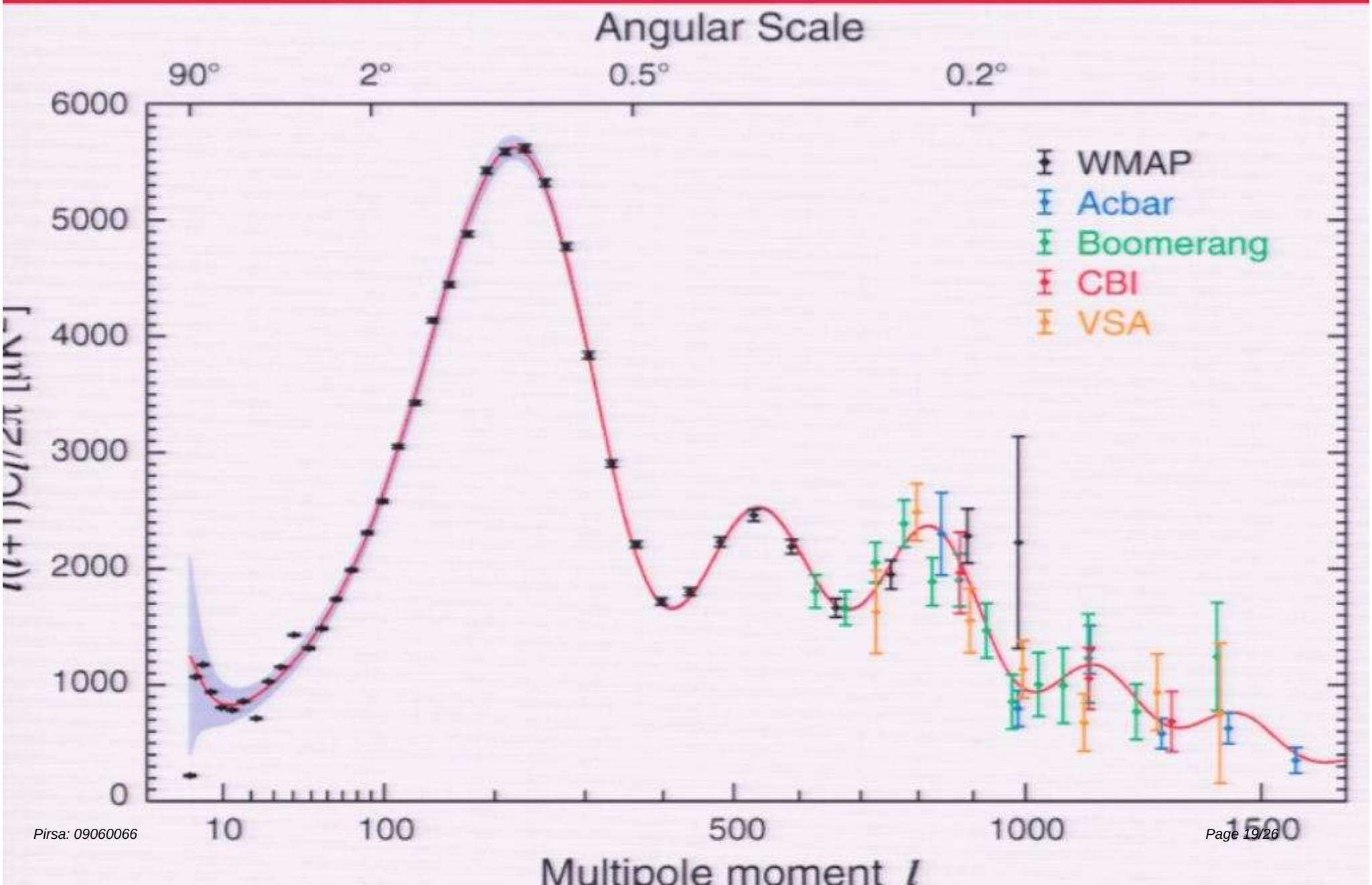


Cosmic Microwave Background

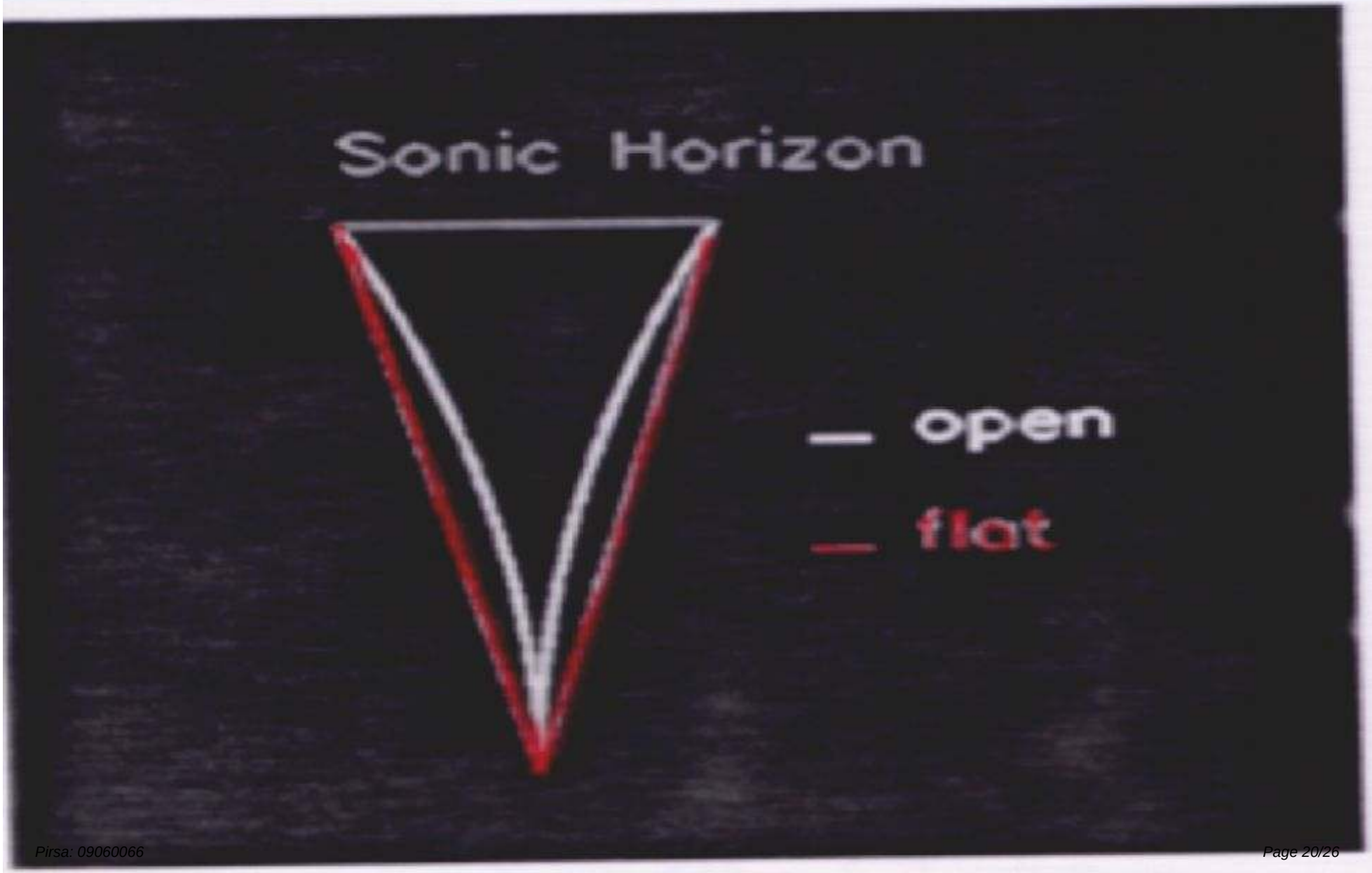
(WMAP)



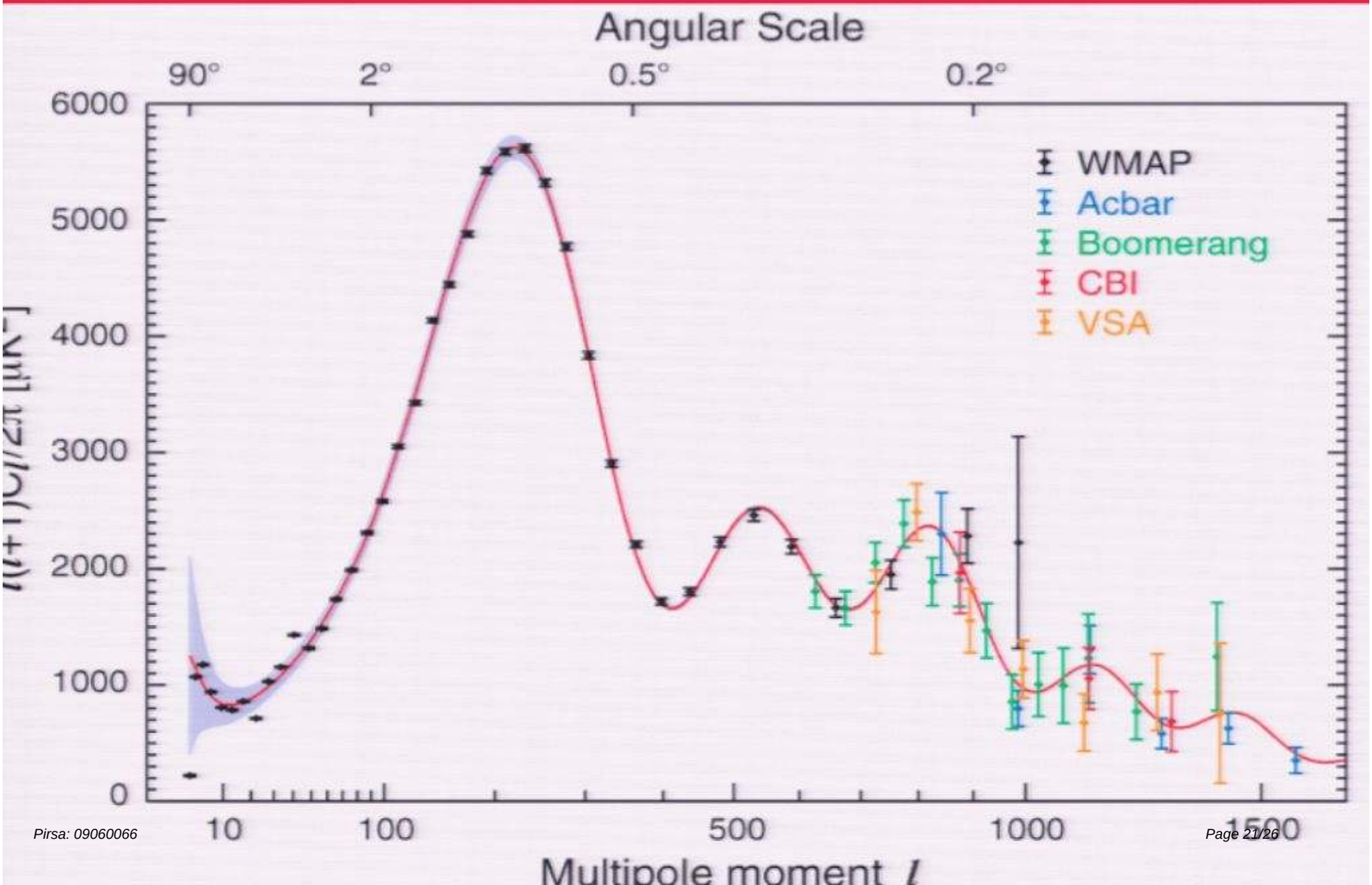
CMB Spectrum



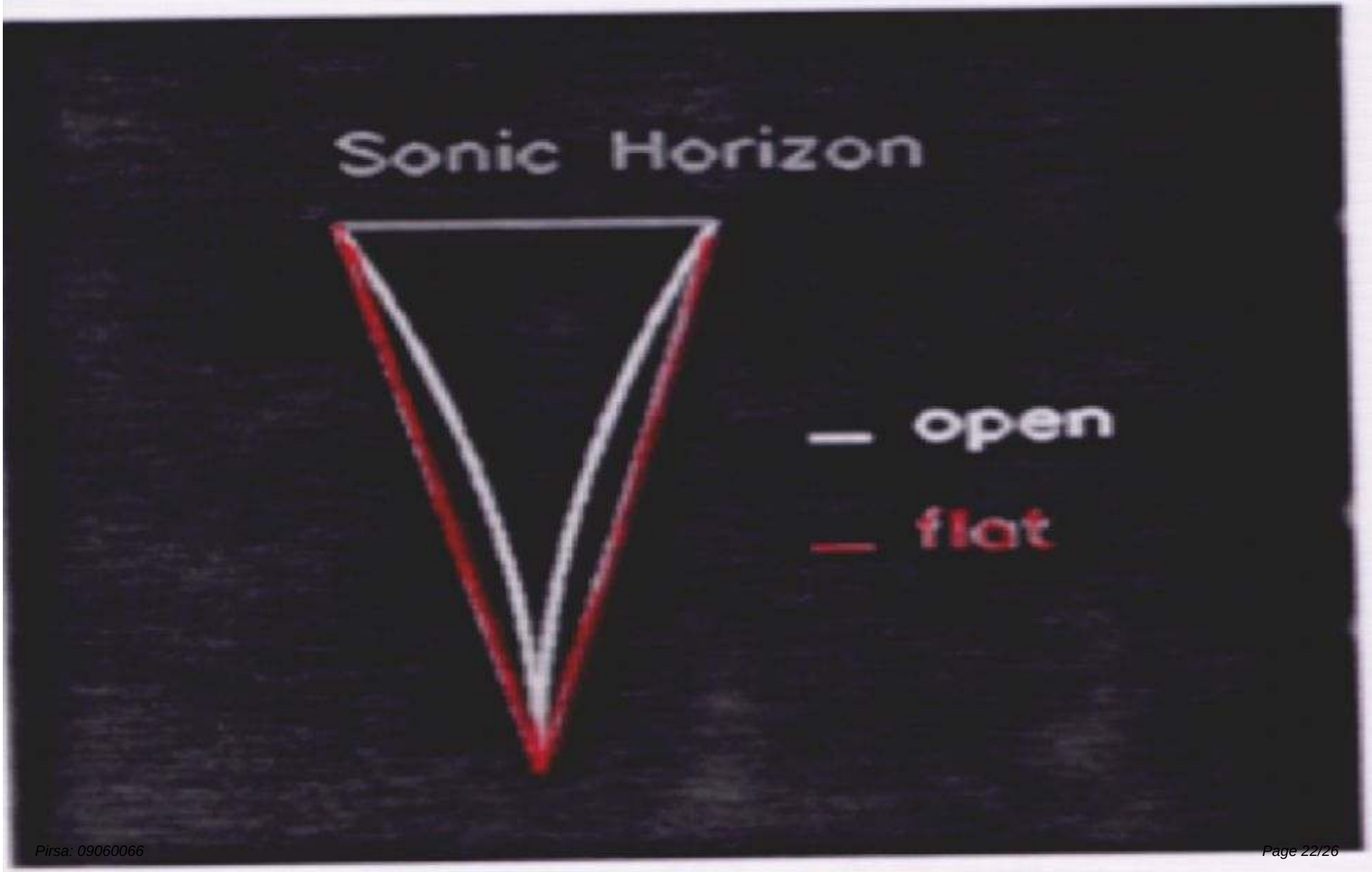
Space Curvature



CMB Spectrum



Space Curvature



The Cosmic Triangle

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

(Friedmann's eq.)

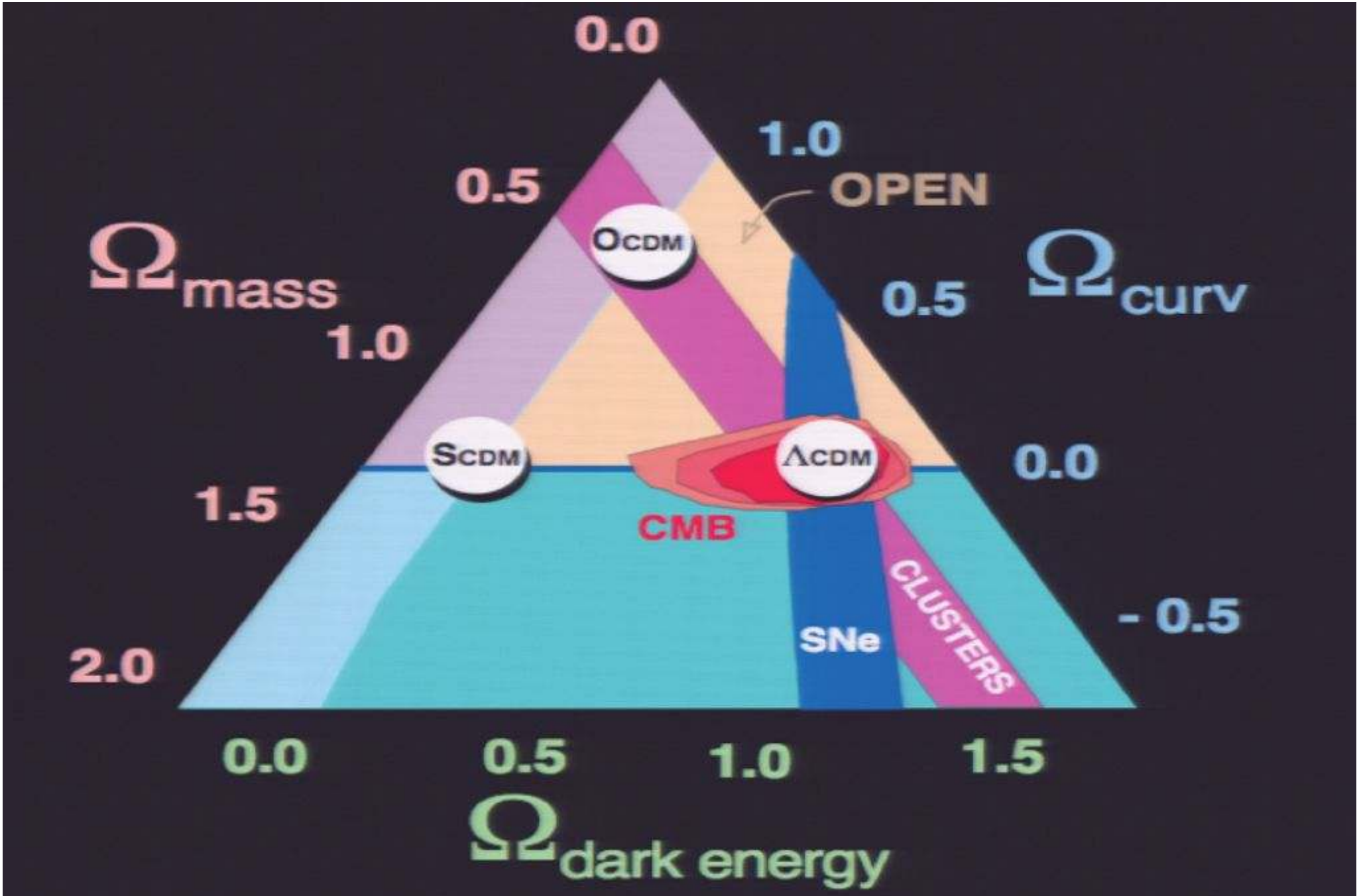
- **Mass Density:** $\Omega_m = 0.25$
- **Dark Energy:** $\Omega_\Lambda = 0.75$
- **Space Curvature:** $\Omega_k = 0$

Mass-density, Curvature, Expansion

- $H^2(t) = 8\pi G(\rho_m + \rho_\Lambda)/3 - k/a^2(t)$
- k = 0 Flat geometry (no curvature)
  1 Closed (positivly curved space)
  -1 Open (negatively curved space)

$/H^2$ → $\Omega_m + \Omega_\Lambda + \Omega_k = 1$ Friedmann Eq.

- $\rho_m \sim a^{-3}$
- $\rho_\Lambda \sim$ **constant** (IF Cosmological Constant)


0.0
1.0
0.5
OPEN
OCDM
Ωmass
Ωcurv
0.5
1.0
SCDM
ΛCDM
0.0
1.5
CMB
CLUSTERS
SNe
- 0.5
2.0
0.0
0.5
1.0
1.5
Ωdark energy

Cosmic Triangle

- Mass Density of Universe: *25% Critical*
  → *Universe will expand forever*
- Dark Energy in Universe: *75%*
  → *Universe expansion accelerates*
- Universe Space Curvature: *0*
  → *Universe 'Flat'*