Title: The Dark Side of the Universe

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Abstract: What is the Universe made of? Recent observations suggest surprising results: not only most of the matter in the Universe is dark and unconventional but, more surprisingly, the major component of the Universe may be in the form of 'dark energy' -- a form of energy that opposes the pull of gravity and causes the expansion of the universe to accelerate. By combining recent observations of clusters of galaxies, distant supernovae, and the cosmic microwave background, we find evidence for a Universe that has only 5% 'normal' baryonic matter, 20% non-baryonic dark matter, and 75% 'dark energy'. The observations suggest a Universe that is lightweight, with only 25% of the critical mass-density needed to halt the Universal expansion, and a geometry that is flat with no space curvature. The observations of the dark side of the Universe and their implications will be discussed.

The Dark Side of the Universe

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What is the Universe Made of?

- Luminous matter: Stars, Galaxies, Gas
- Dark stuff:
  - Dark Matter: How know? How much? Where? What is it?
  - Dark Energy: How know? How much? Where? What is it?

Whirlpool Galaxy - M51
NASA, ESA, S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA) - Hubble Space Telescope ACS - STScI-PRC05-12a

Weighing Galaxies

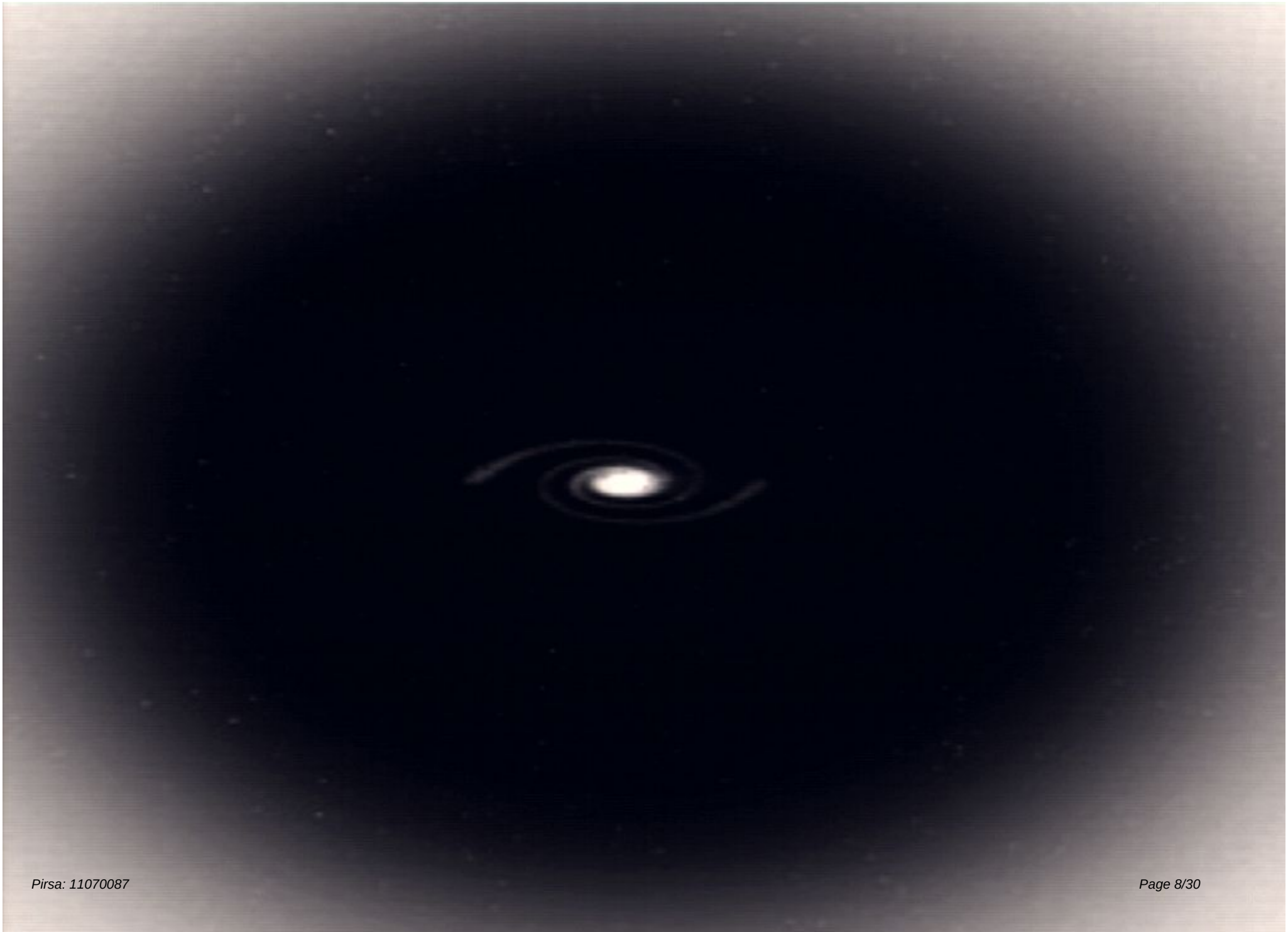
- Motion (v) of Stars and Gas: $v^2 = GM(<r)/r$

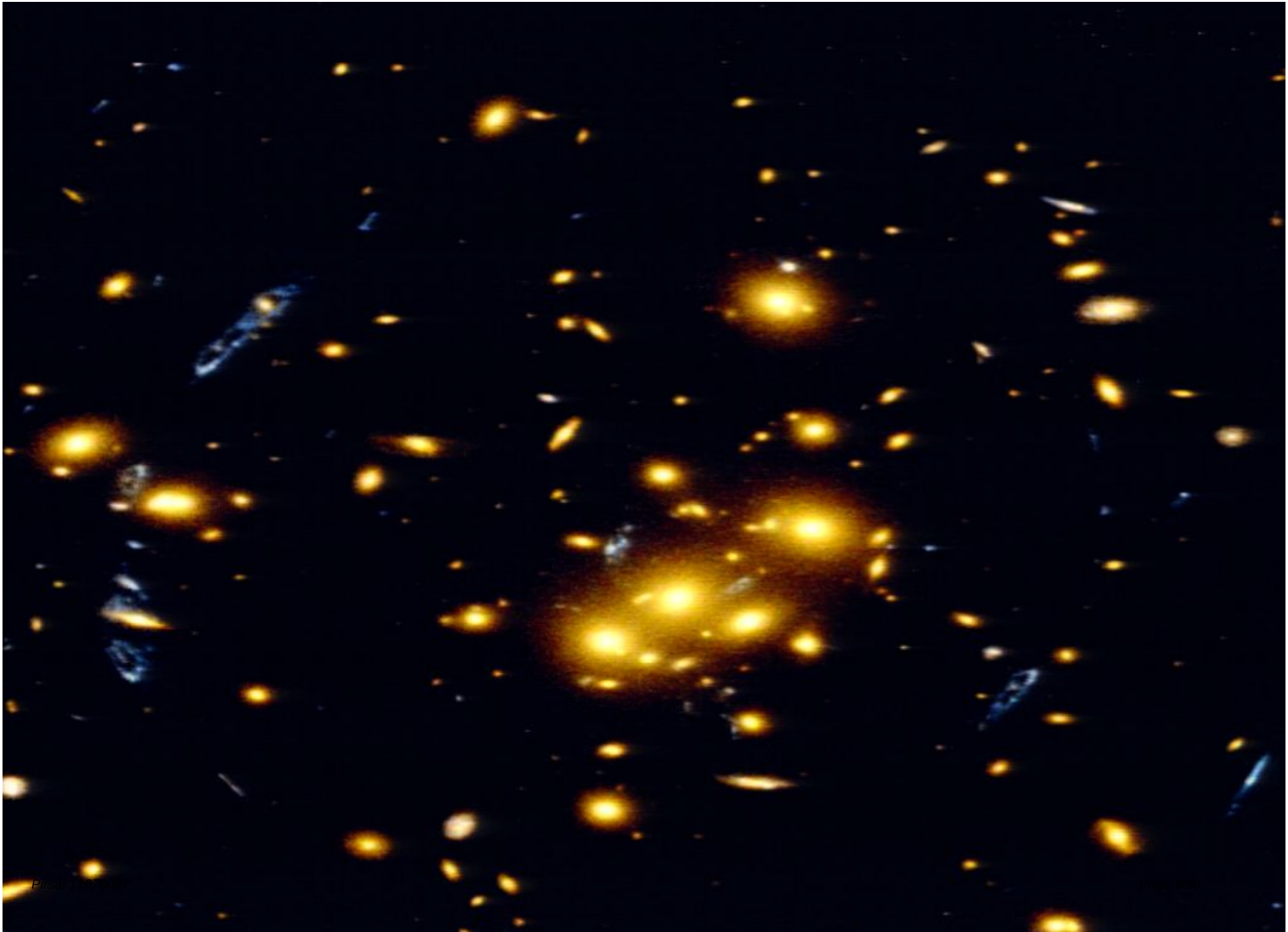
  [Virial Theorem: $GM(<r)m/r^2 \sim mv^2/r$]

- Gravitational Lensing: $M(<r)$

- Data show **velocity** and **mass** in large halos around luminous galaxies

➔ Implies: Dark Matter in Galactic Halos!





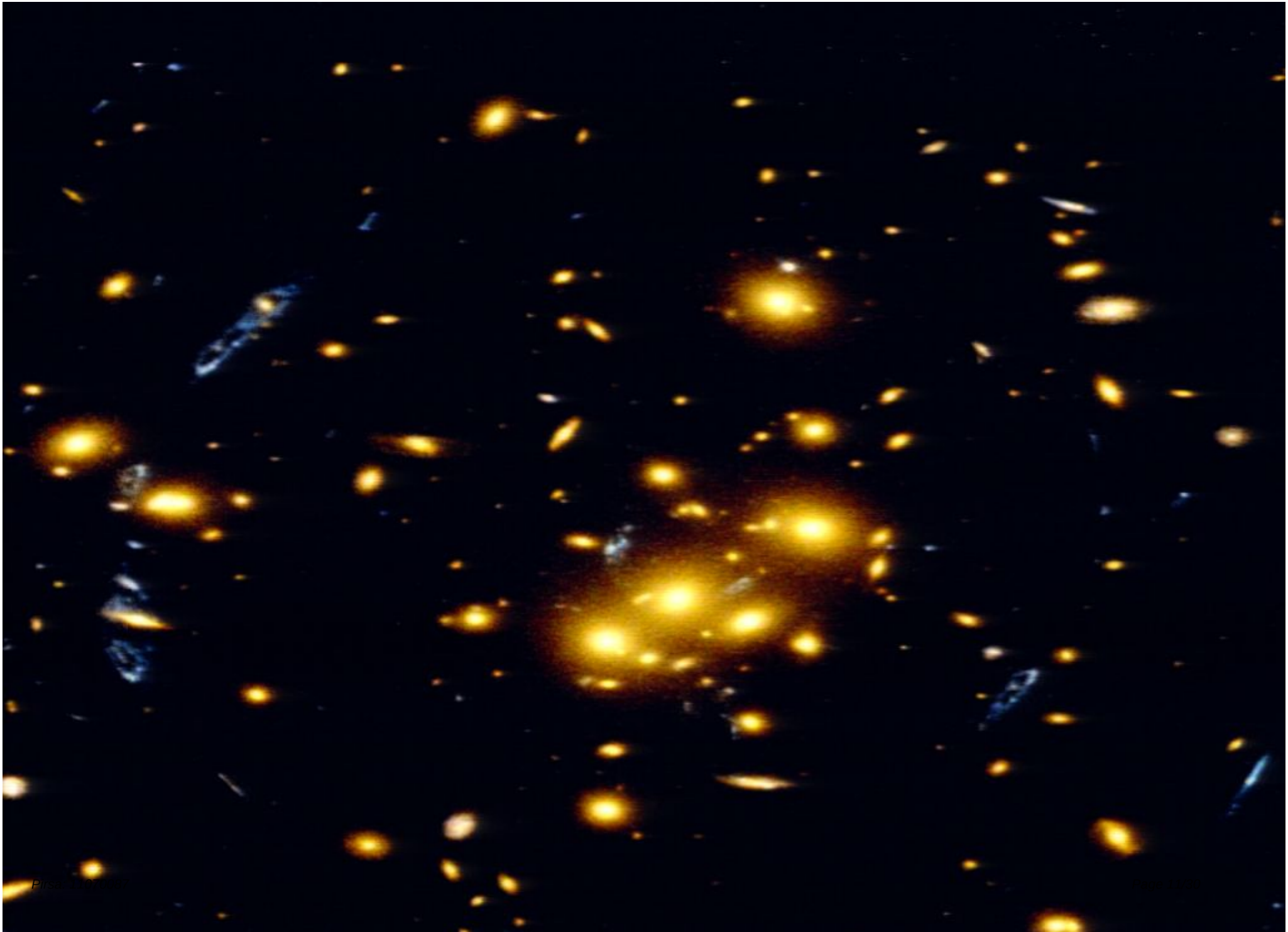
Mass-Density of Universe: How Much? Where?

Mass-to-Light Method

(Tracing the Dark Matter)

- $\langle M/L \rangle_{cl} L_{univ} (L_o/Vol) = \rho_m (M_o/Vol)$
- *Weigh cluster mass,* M_{cl} *(<R~1Mpc)*
- $\langle M/L \rangle_{cl} = 300h \langle M/L \rangle_o$
- $\Omega_m = \rho_m / \rho_{critical}$

➔ $\Omega_m \sim 0.2 \pm 0.1$



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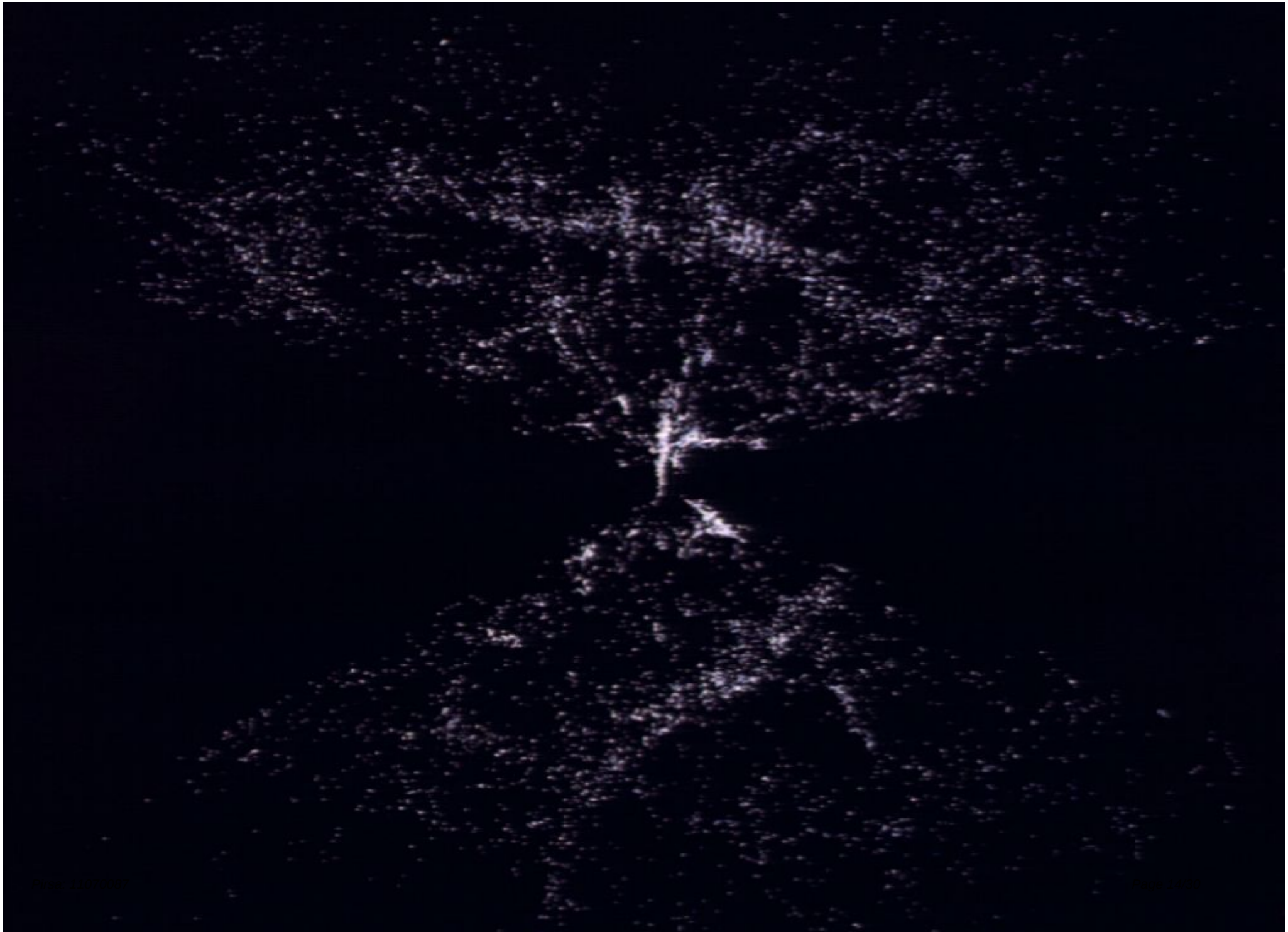
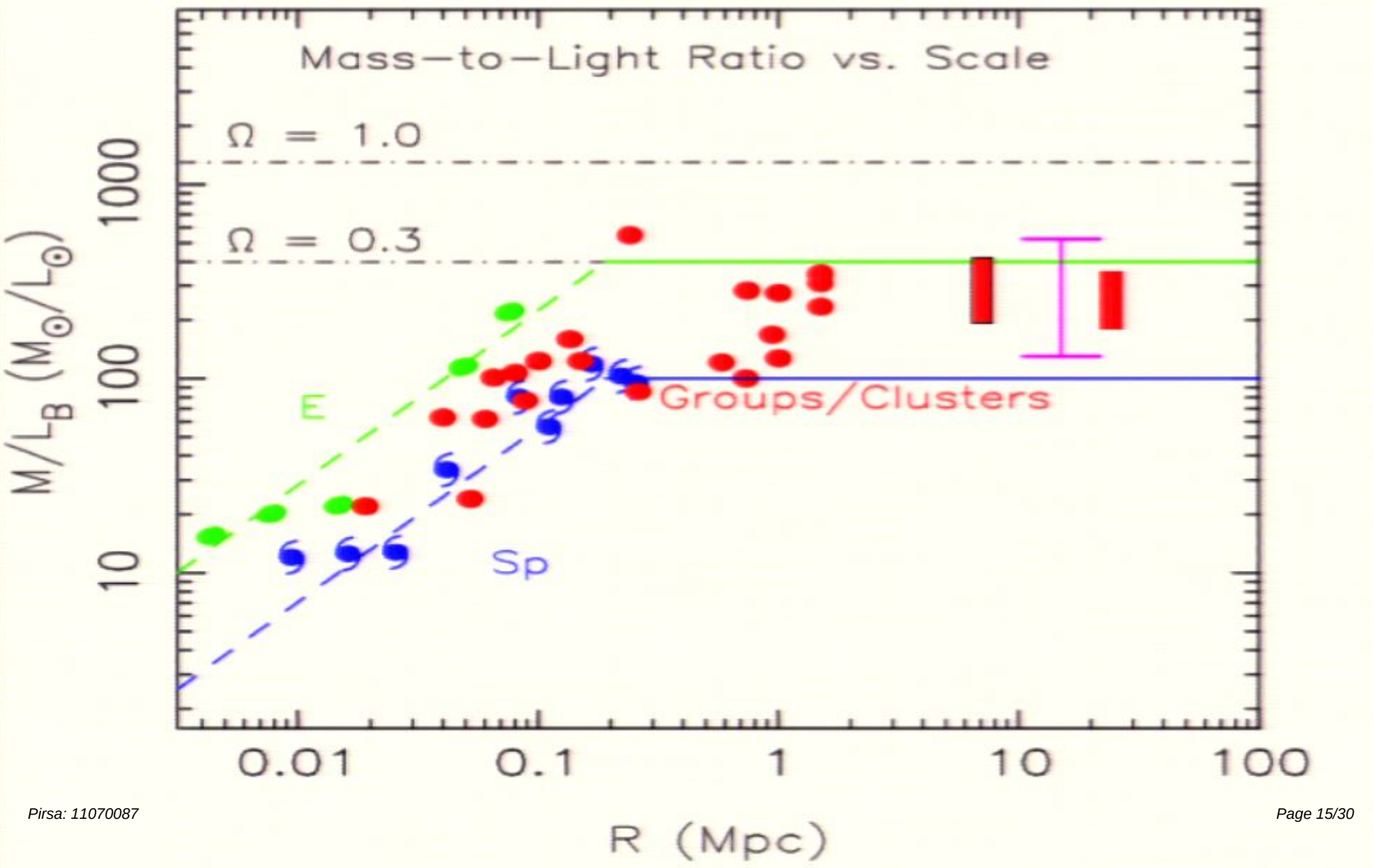
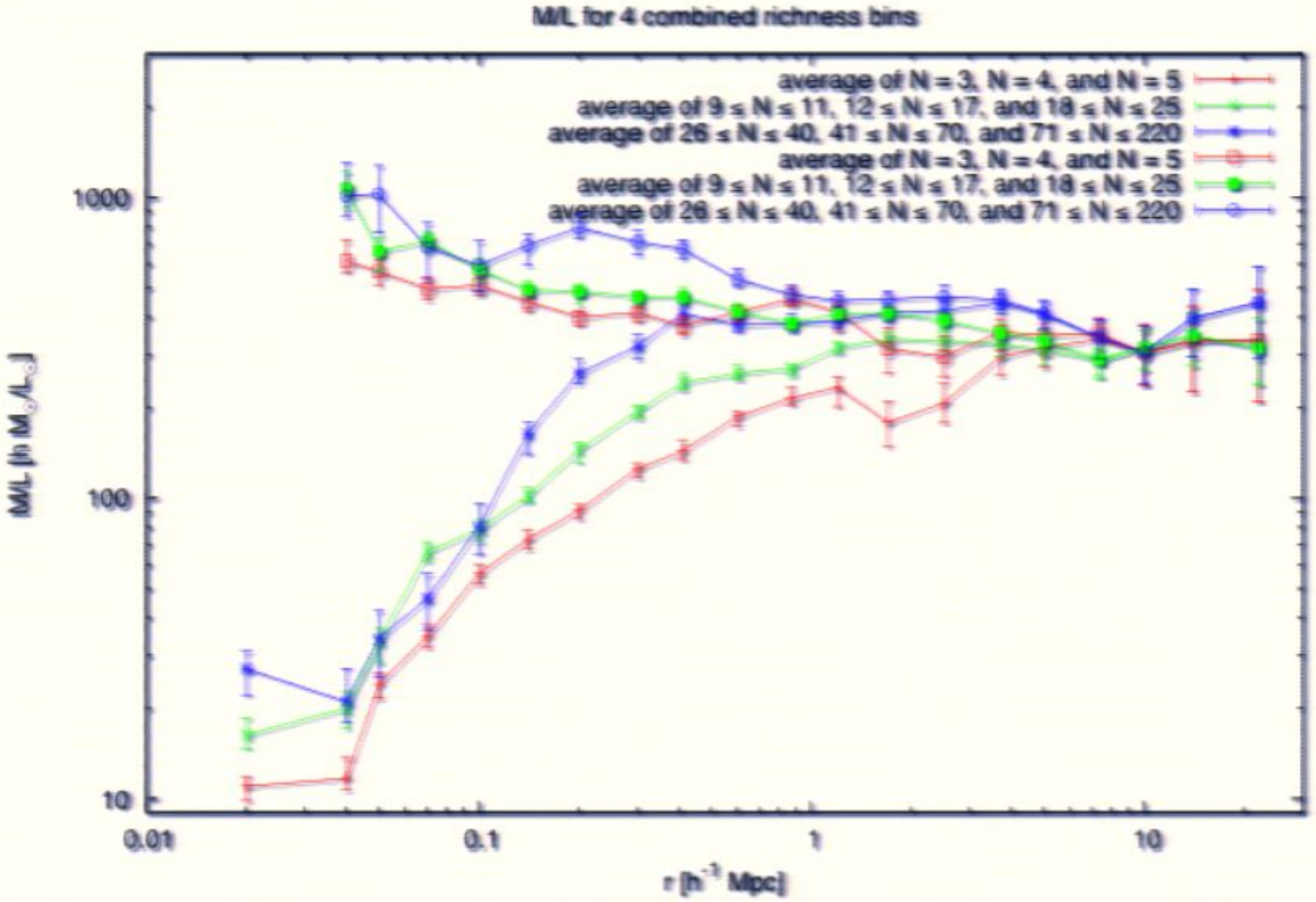


Mass-to-Light Function

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



M/L (R) SDSS (Bahcall & Kulier 2010)



M/L Function: Conclusions

- M/L(r) Function Flattens on Large Scales:

  → ***M ~ L*** (on large scales)

  reaching the end of growth of Dark-Matter

- Most of the Dark Matter in large Dark Halos

- Total Mass-Density of Universe:

  → $\Omega_m = 0.2 +- 0.05$

Weighing the Universe

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

→ $\Omega_m \cong 0.25$

- 4-5% Baryons + ~20% Dark Matter
- Mass ~ Light

→ Universe Expands Forever!

Ω_m from Baryon-Fraction

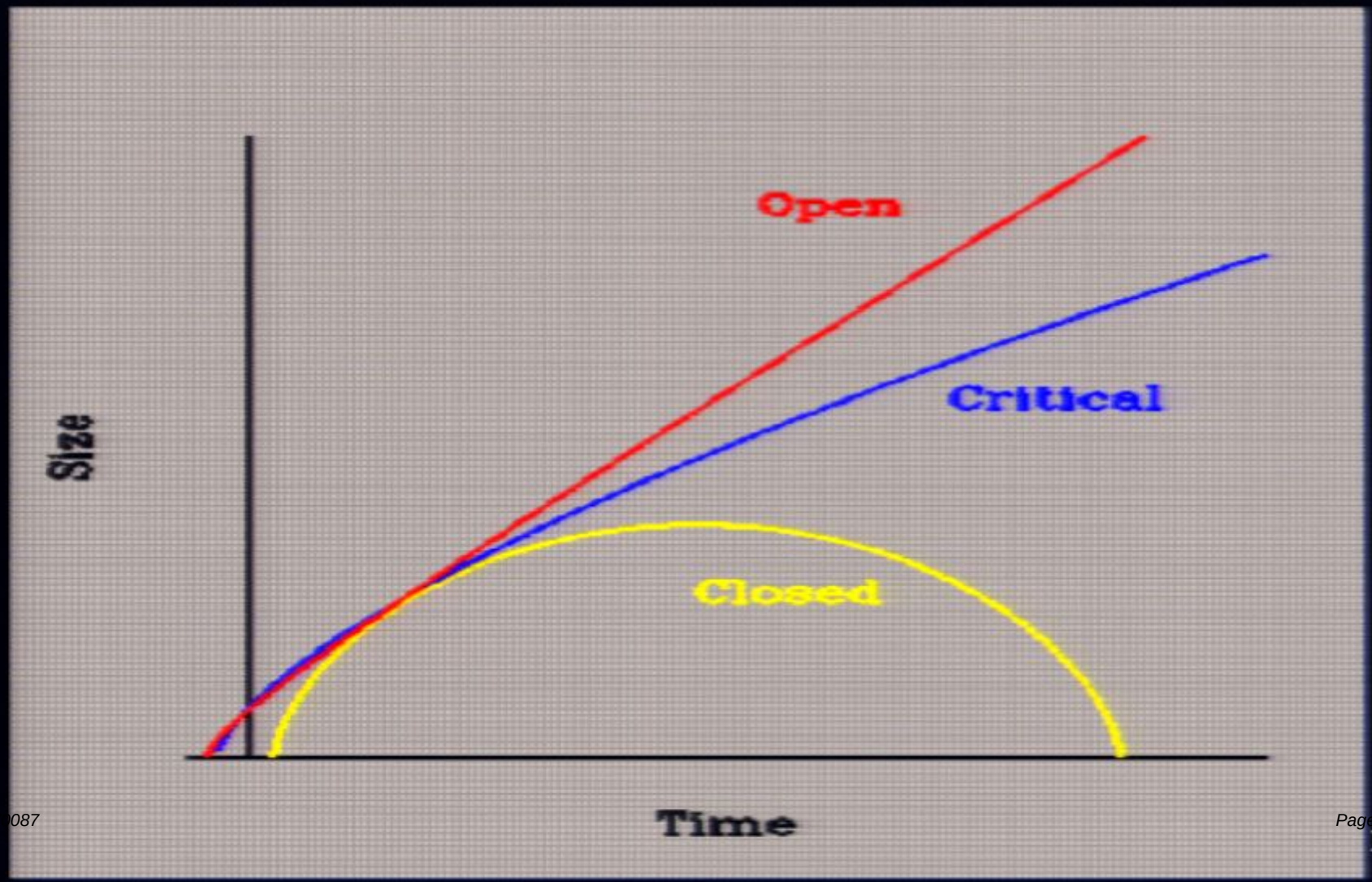
- $\Omega_b/\Omega_m = 0.17 +- 0.02$ $h=0.7$ (Clusters; CMB)
- $\Omega_b = 0.042 +- 0.004$ (BBN; CMB)

➔ $\Omega_m = 0.24 +- 0.04$

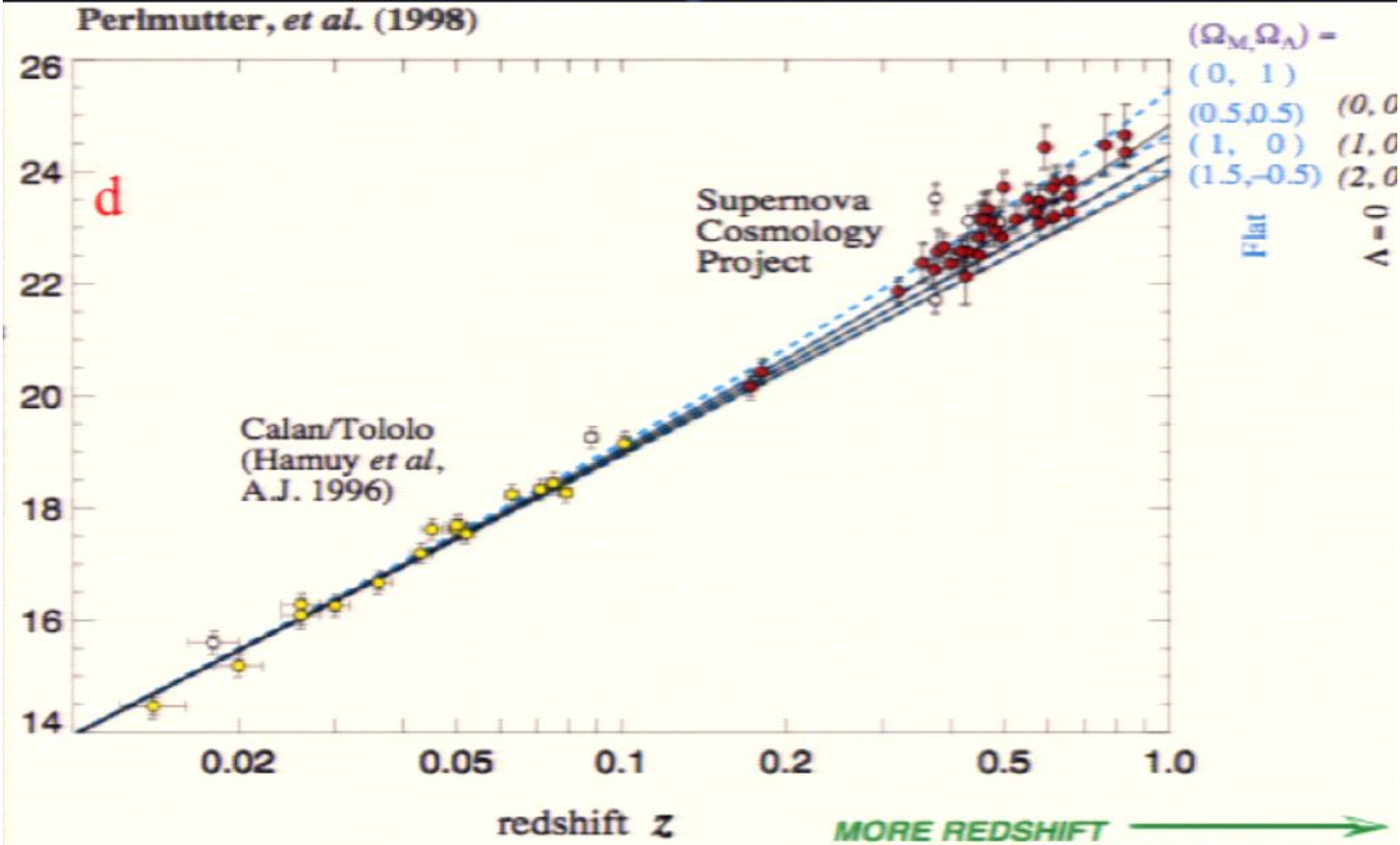
Dark Matter

- How know?
  - ➔ Gravity: Motion, Gravitational Lensing
- Where is it located?
  - ➔ Large Galaxy Halos, Clusters
- How much?
  - ➔ ~20% of Critical Density
    [atoms/luminous: only ~5%]
- What is it?
  - ➔ New particles ???

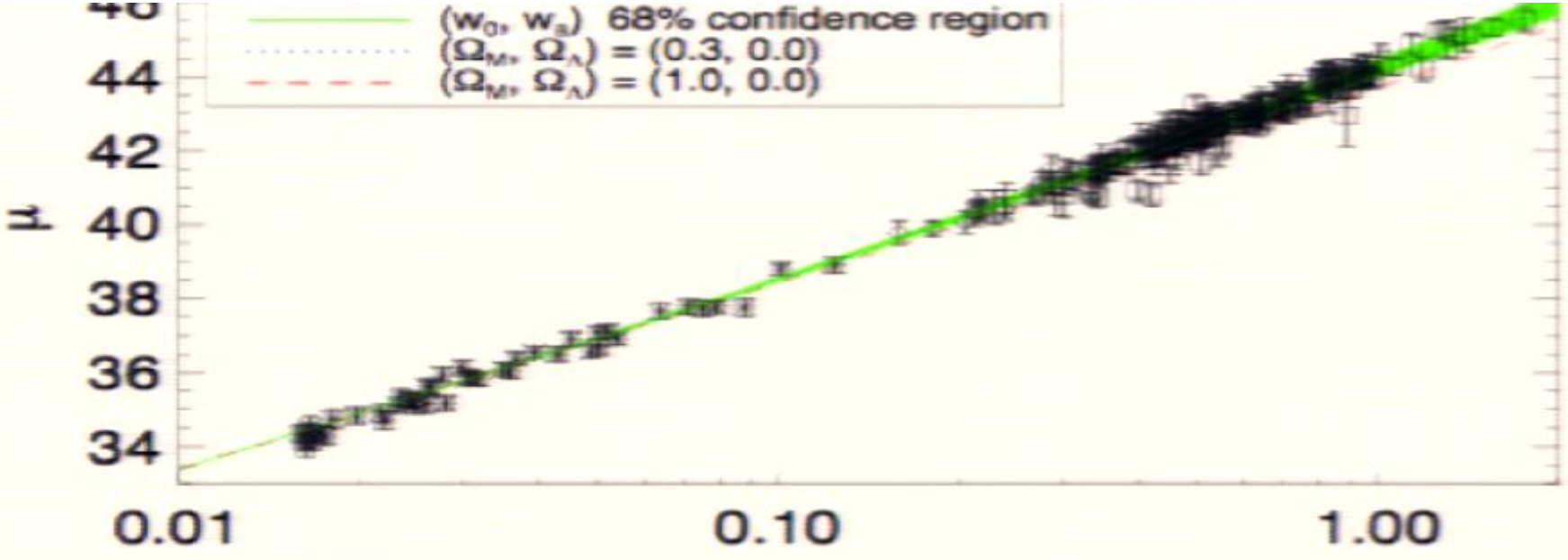
Universe Expansion: Hubble Law



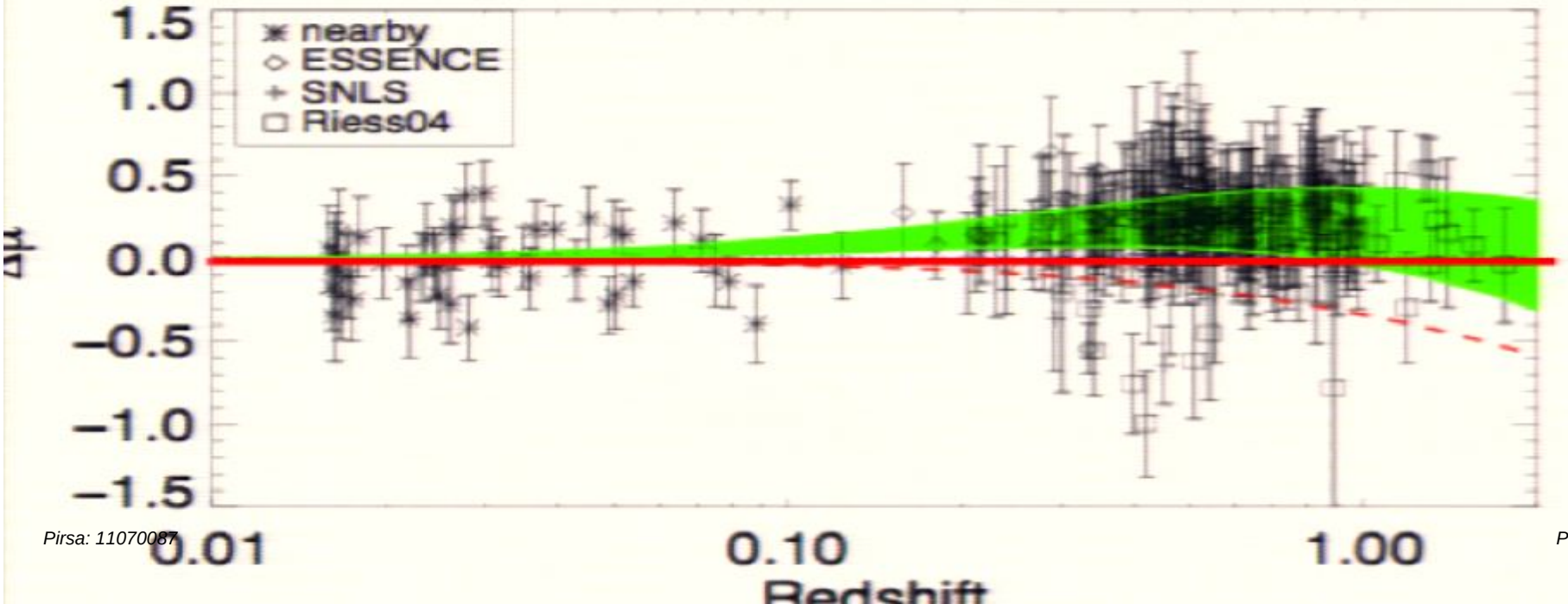
Hubble Expansion of Universe



MORE REDSHIFT →
(More total expansion of universe since the supernova explosion)



Cosmic Acceleration



Dark Energy

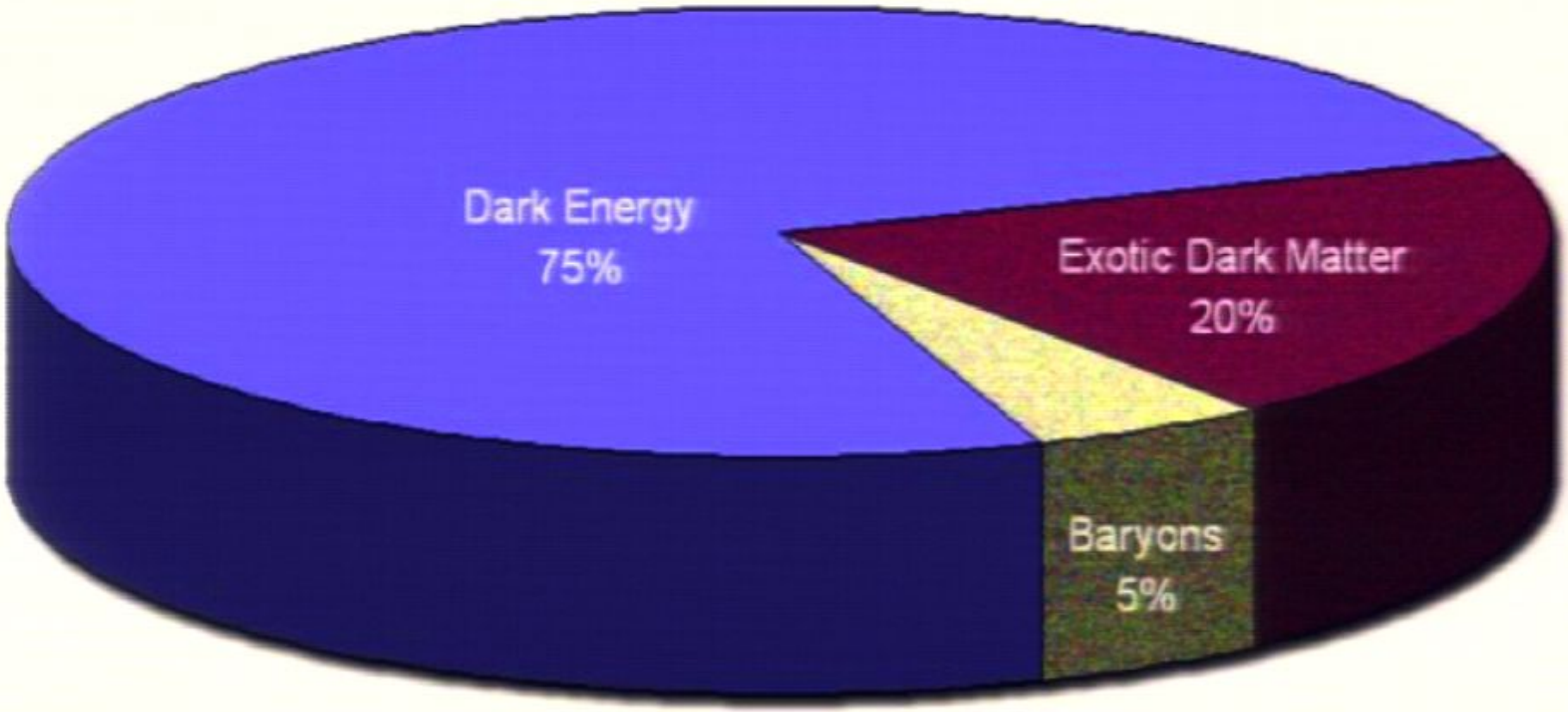
Universe acceleration ➔
Dark-Energy 'Stretch' > Mass-Density 'pull'
(at present time)

- Acceleration: $\Omega_m - \Omega_\Lambda \sim -0.5$
- Mass-Density: $\Omega_m \sim 0.25$

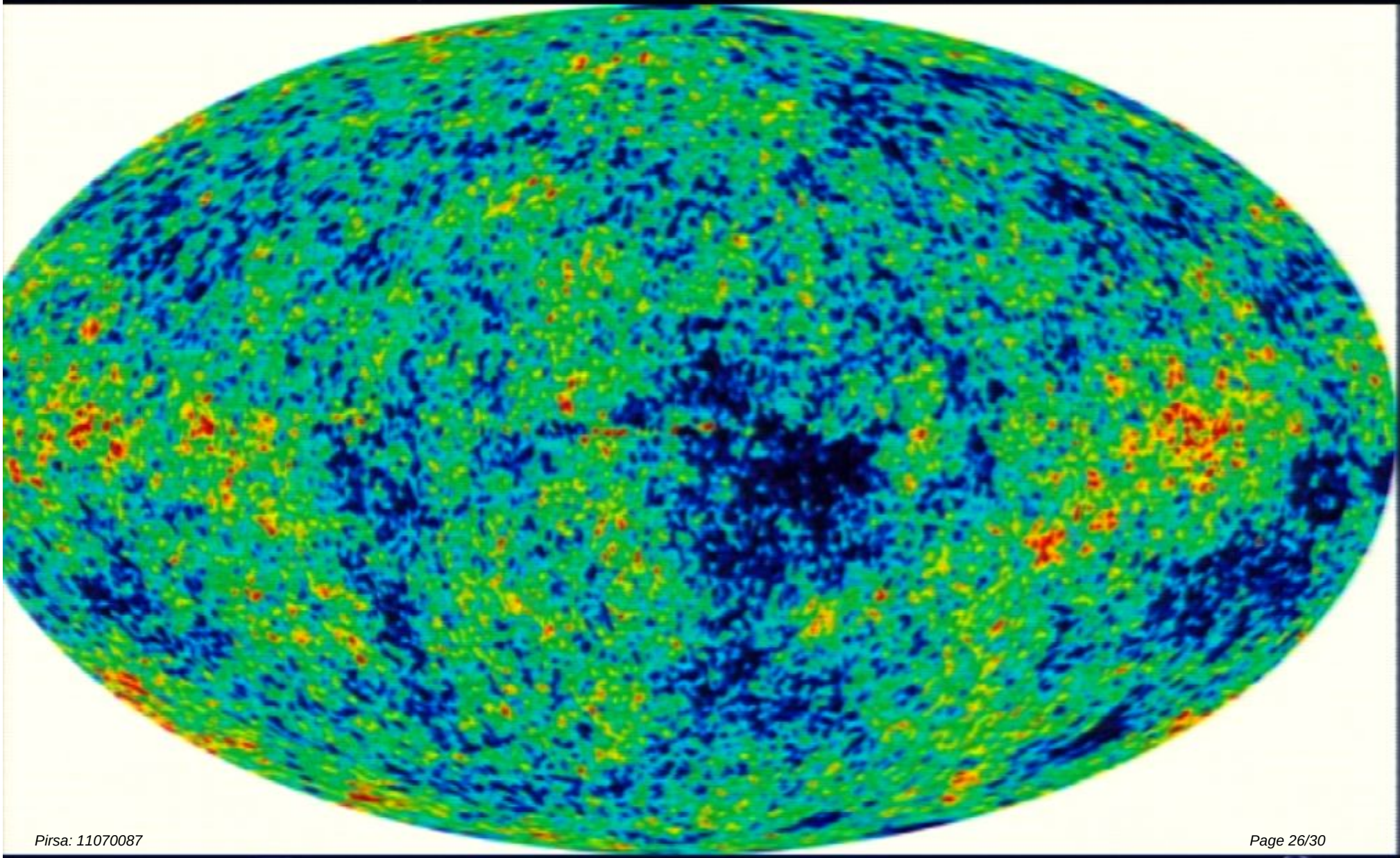
➔ $\Omega_\Lambda \sim 0.75$

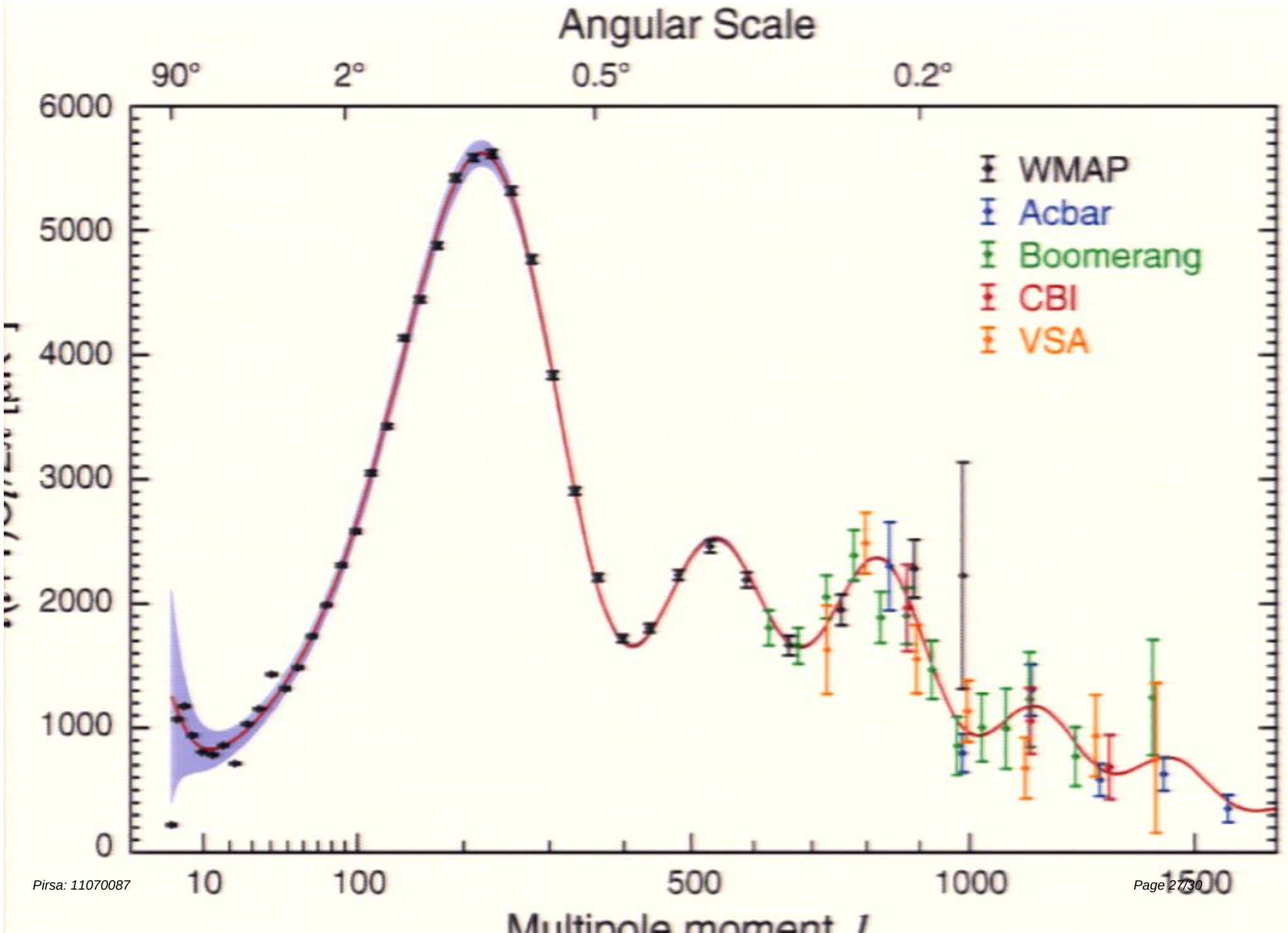
What is it ? ➔ ???

Contents of the Universe



Universe's Baby Pictures (WMAP)




Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
WMAP
Acbar
Boomerang
CBI
VSA
10
100
500
1000
1500
Multipole moment, l

The Content of the Universe

- Baryons (5%): Stars, Galaxies, Gas, ...
- Dark Matter (20%): New particles (?)
- Dark Energy (75%): Cosmological Constant?

[or GR modified? Or else?]

- Flat Universe ($\Omega_{tot} = 1$)

Dark Energy: Determining Properties w, w(z)

Methods -- Plans for near future:

- SN Ia [D(z)]
- Baryon Acoustic Oscillations [BAO; D(z)]
- Cluster Abunance Evolution [D(z) + gravity]
- Weak Lensing Evolution [D(z) + gravity]

Fate of Universe

Universe Will Expand Forever becoming:

- ***Larger and Larger***
- ***Sparser and Sparser***
- ***Darker and Darker***
- ***Colder and Colder***