Cosmologia e Lentes Gravitacionais



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CBPF

XI ESCOLA DO CBPF

24 a 28 de julho de 2017, Rio de Janeiro

Cosmology and Gravitational Lensing

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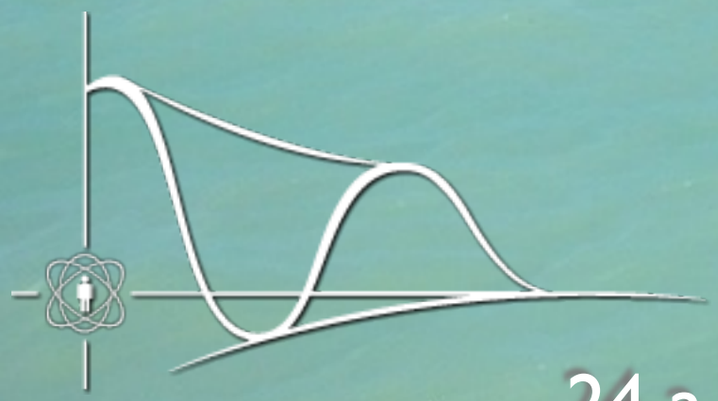

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Cosmology

The study of the structure, evolution and origin of the Universe

Phenomenology

Theoretical cosmologist's Universe

Homogeneous and isotropic

Dominated by Dark Matter and Energy



Astronomer's Universe:

Galaxies, gas, stars, etc.



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Phenomenology

Theoretical cosmologist's Universe
Homogeneous and isotropic
Dominated by Dark Matter and Energy

Astronomer's Universe:
Galaxies, gas, stars, etc.

- Connection between theory and observations
- Statistical analyses
- Modeling, including relevant physical processes (simulations, semi-analytical modeling)
- Observables: where/how can I expect to detect a given phenomenon?
- Interdisciplinary field

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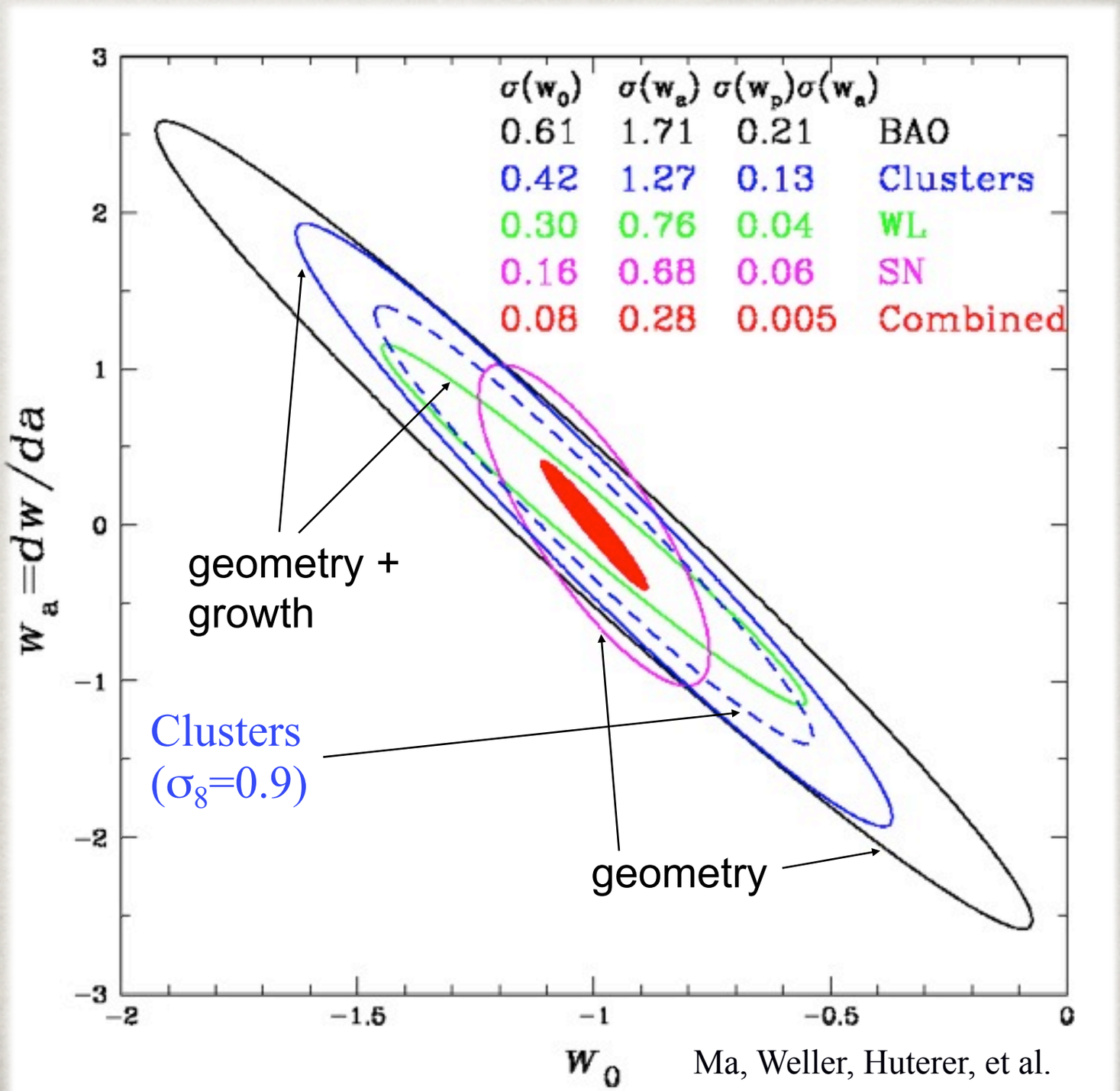
Gravitational Lensing is a Key Cosmological Observavble

- Lensing probes scales from galaxies to the large-scale structure of the Universe
- Is sensitive to all matter ("less astrophysics")
- Is unique to test modified gravity theories and Dark Matter models
- Is somewhat "harder" mathematically/computationally and observationally than other cosmological observables
- Most current and future cosmology projects include lensing

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



Ma, Weller, Huterer, et al.

A plethora of lensing phenomena

Strength

- Strong lensing
  - Strong magnifications
  - Multiple images
  - Distortions
    - Rings
    - Arcs
- Weak Lensing
  - Small twist
  - Small magnification
  - Detected statistically

Angular scale

- Micro-lensing
  - MACHOS
  - Planetary search
- Micro and mili-lensing
  - Quasars
- "Macro-lensing"
  - Galaxies
  - Clusters
  - Large-scale structure

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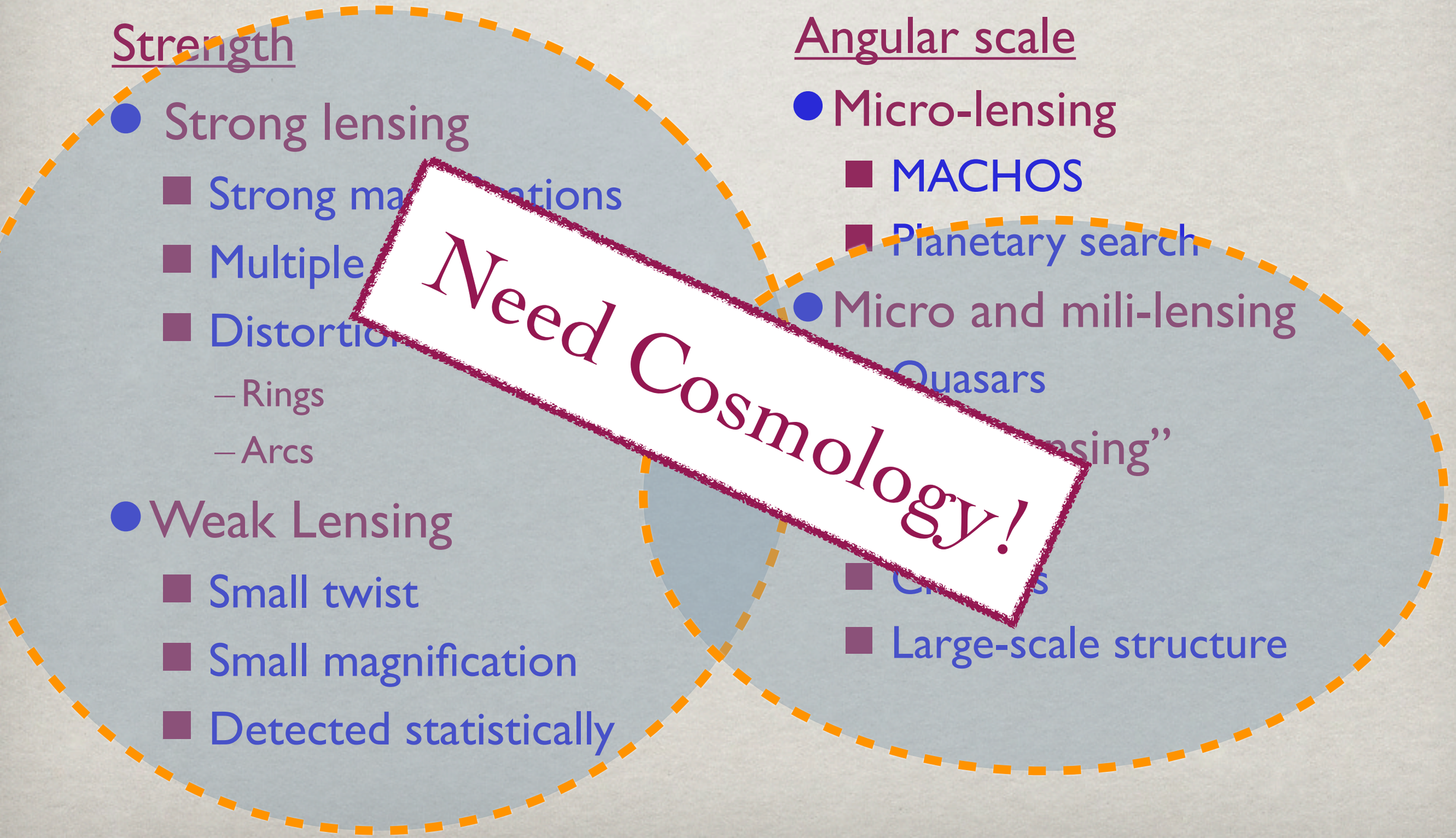
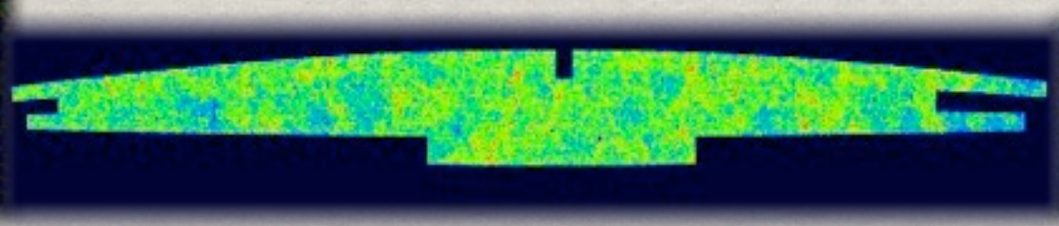
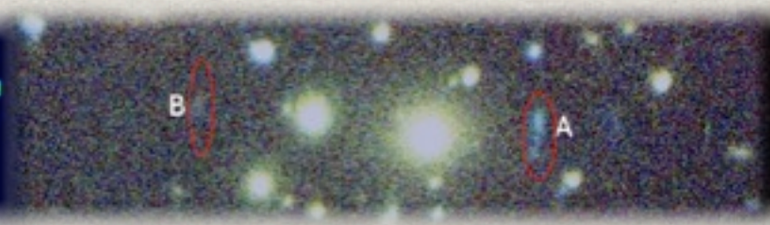
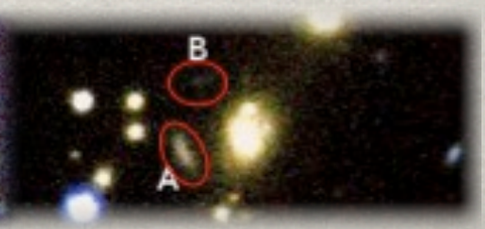


Outline

- Background cosmology and the cosmic pie
- Thermal history and fluctuations (LSS and CMB)
- Introduction to lensing and basics of Strong Lensing
- Weak lensing
- Gravitational lensing and cosmology
- Extra: Dark Matter or Cosmological Observables
- Prize for exercises!







The Dark Side of the Universe

Episode I

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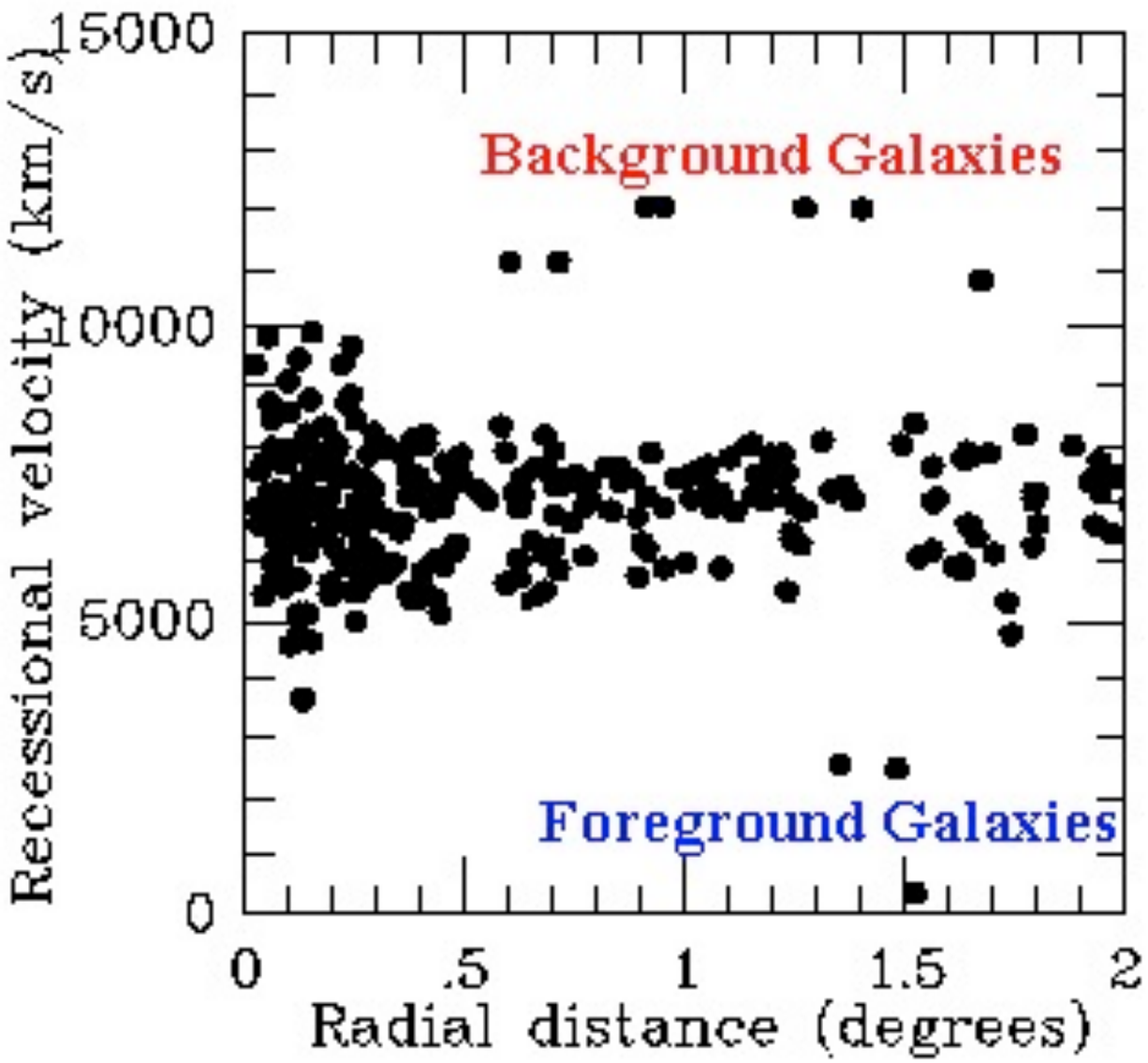
“O único mistério do Universo é o mais e não o menos. [...]
O que existe transcende para mim o que julgo que existe.”
[O Único Mistério Do Universo, Poemas Inconjuntos]



Dark Matter

- Velocity dispersion in galaxy clusters (Zwicky 1934)



Virial theorem

$$2\langle E_K \rangle = -\langle E_G \rangle$$

$$\Downarrow$$

$$\frac{1}{2}\sum_i m_i v_i^2 \sim -\frac{1}{2}\left(-\frac{1}{2}\frac{GM^2}{R}\right)$$

$$\boxed{M \sim \frac{2Rv^2}{G}}$$

Dark Matter

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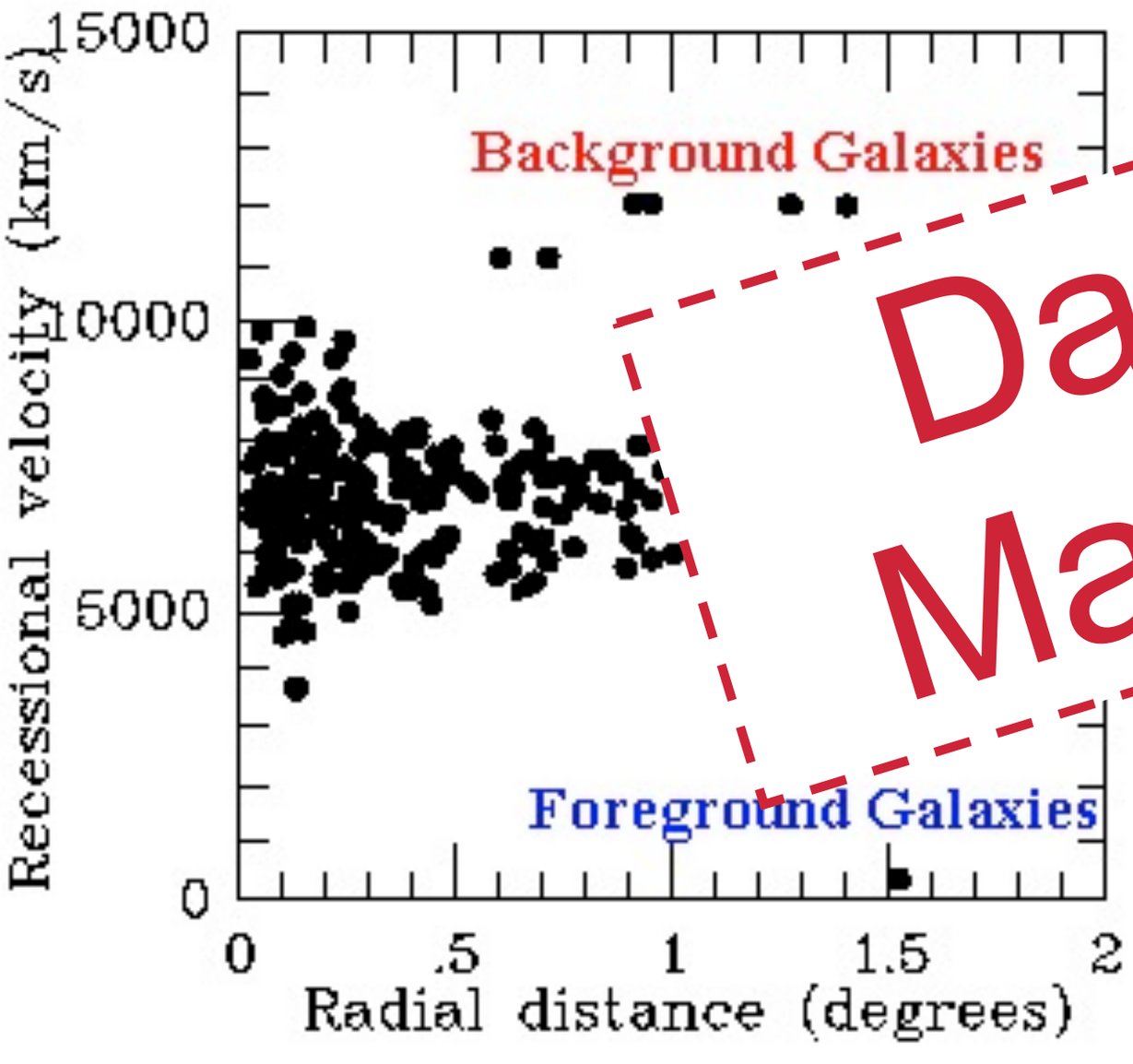

Virial theorem

$$\left\langle T \right\rangle = -\left\langle E_G \right\rangle$$

$$\Downarrow$$

$$\sum_i \frac{1}{2} m_i v_i^2 \sim -\frac{1}{2}\left(-\frac{1}{2}\frac{GM^2}{R}\right)$$

Dark Matter

Clusters need more mass to hold the galaxies!

Hot Gas in Clusters

Intra-cluster gas

$T \sim 10.000.000\ ^oC$

➔ x-ray emission

Hydrostatic equilibrium

$$\nabla\phi = -\frac{1}{\rho}\nabla p$$

➔ temperature depends on mass

Example $$\rho(r) = \frac{kT_e}{2\pi G m_e r^2}$$



Hydra in the optical

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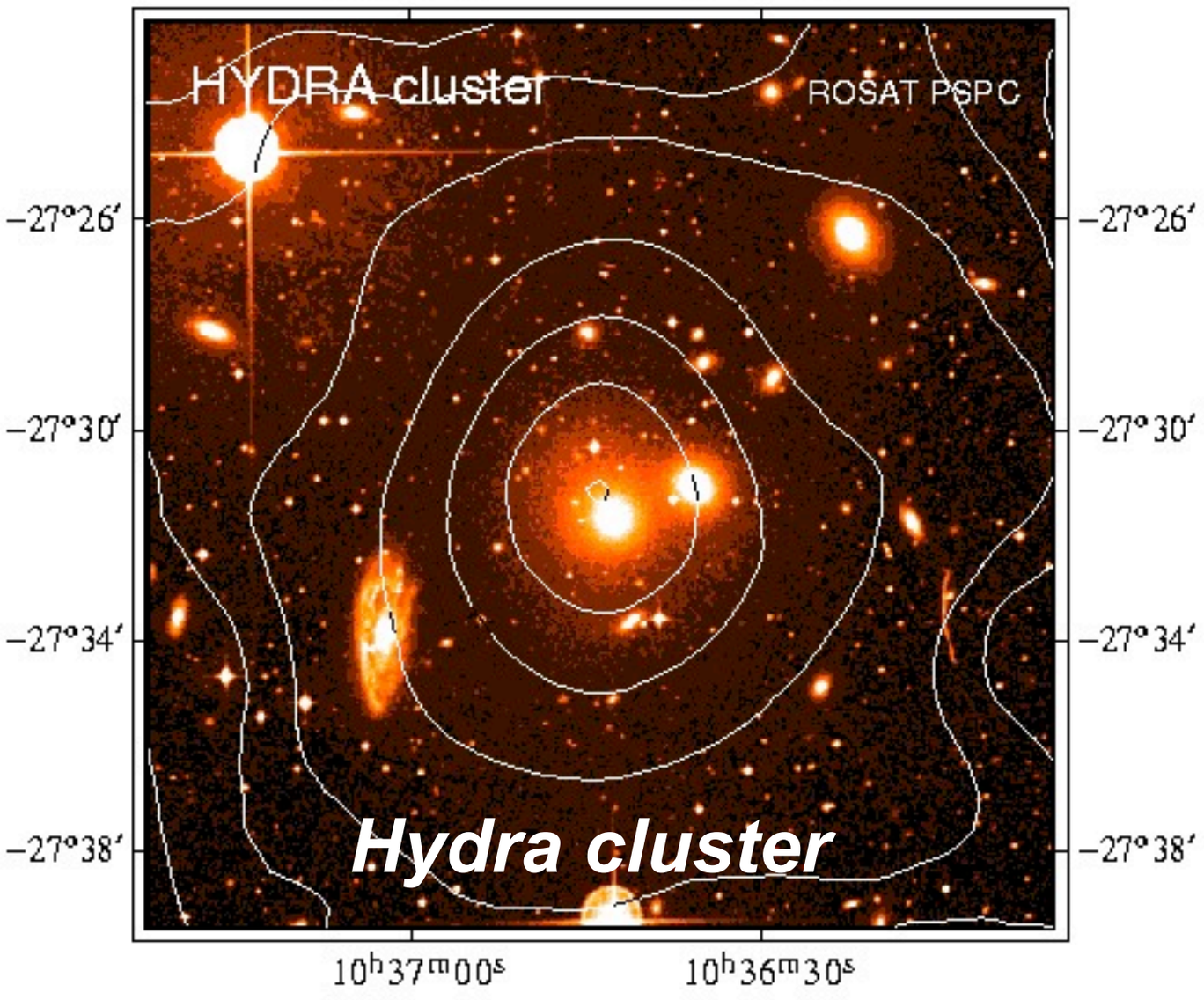
X-ray Clusters

The gas is more uniformly distributed



Hydra in x-ray

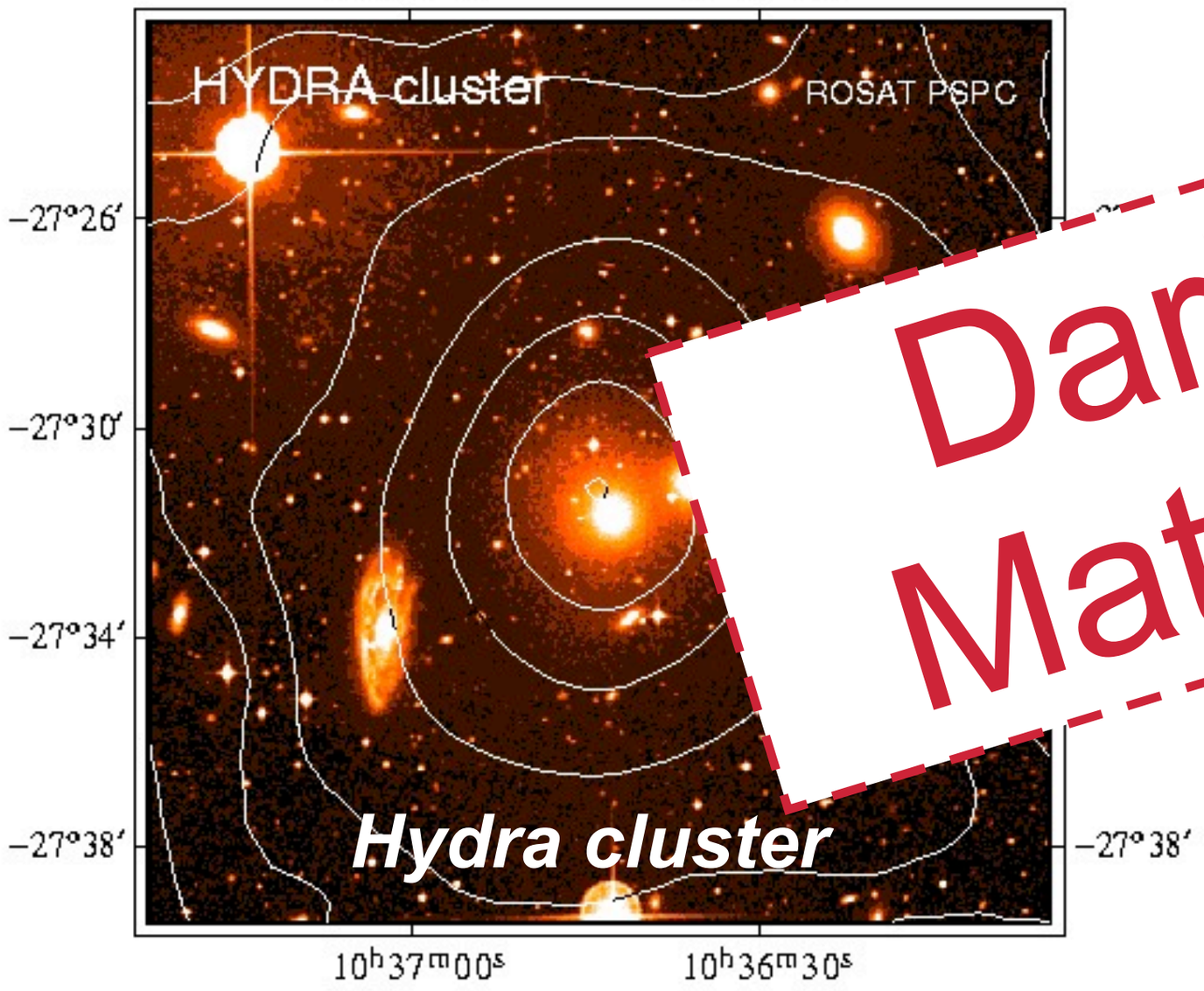


M_{gas} ~ 20 x M_{stars}

Dark matter is still 80%

X-ray Clusters

The gas is more uniformly distributed



Hydra in x-ray



Dark Matter

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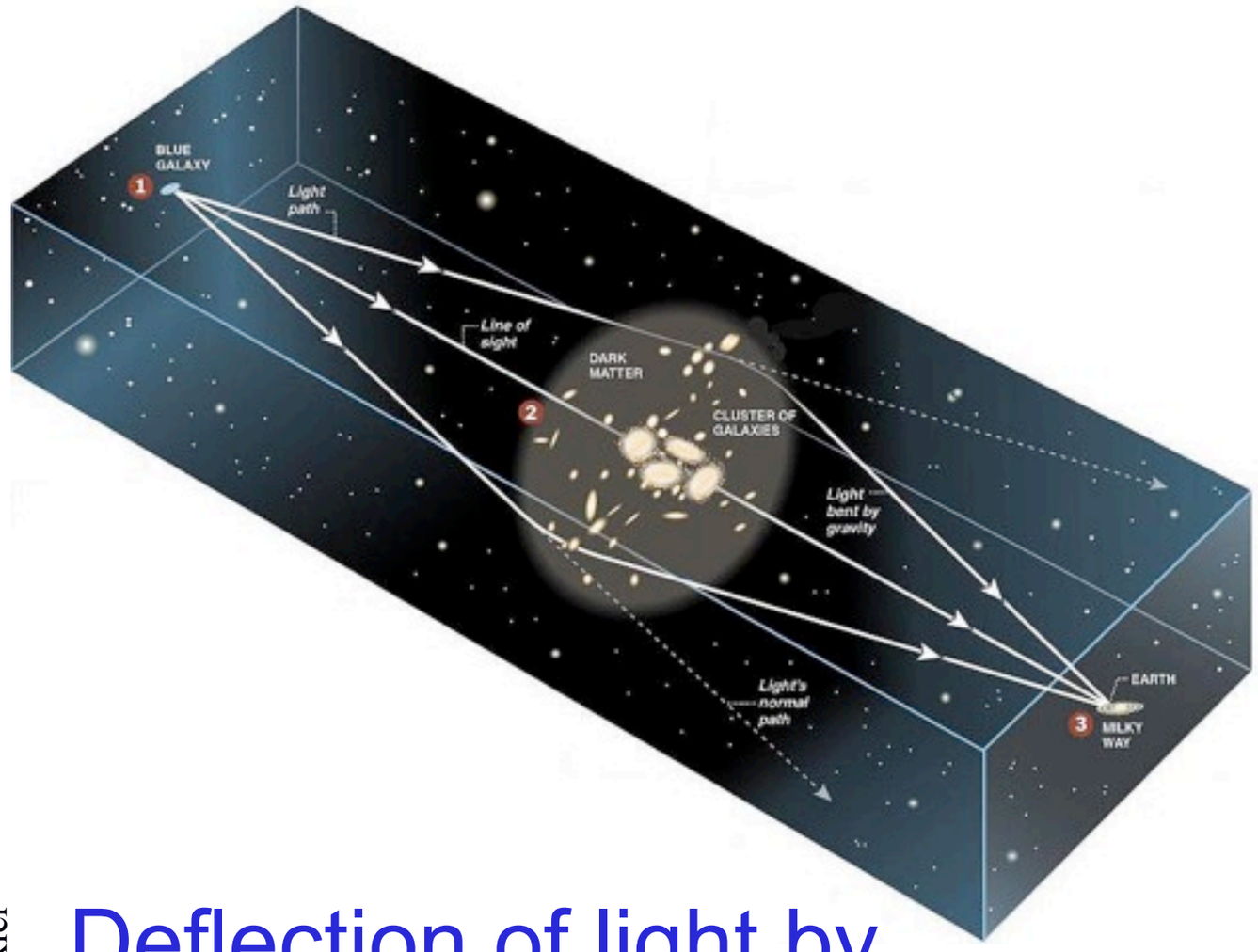
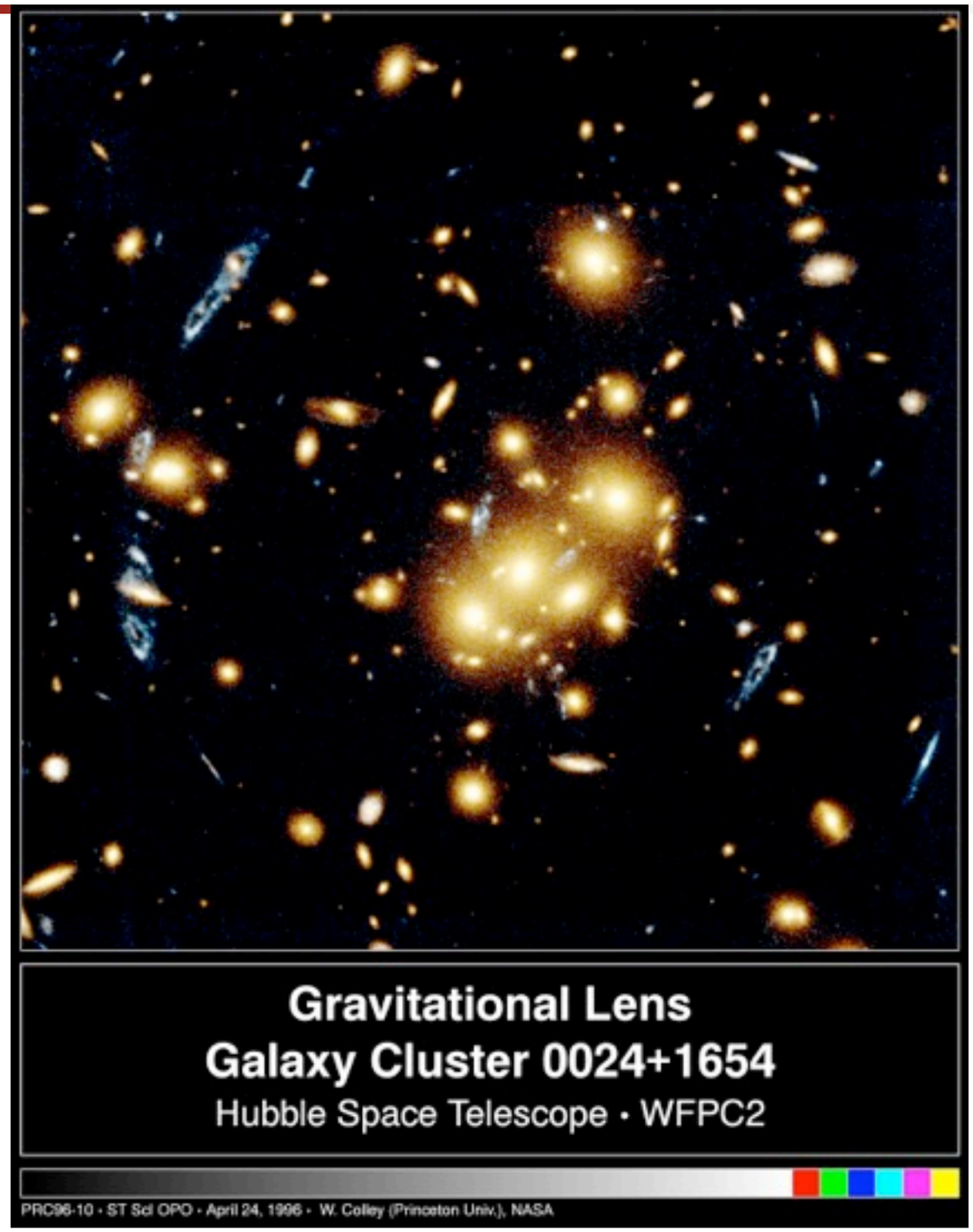
Gravitational Lensing



Deflection of light by space-time curvature



Multiple images

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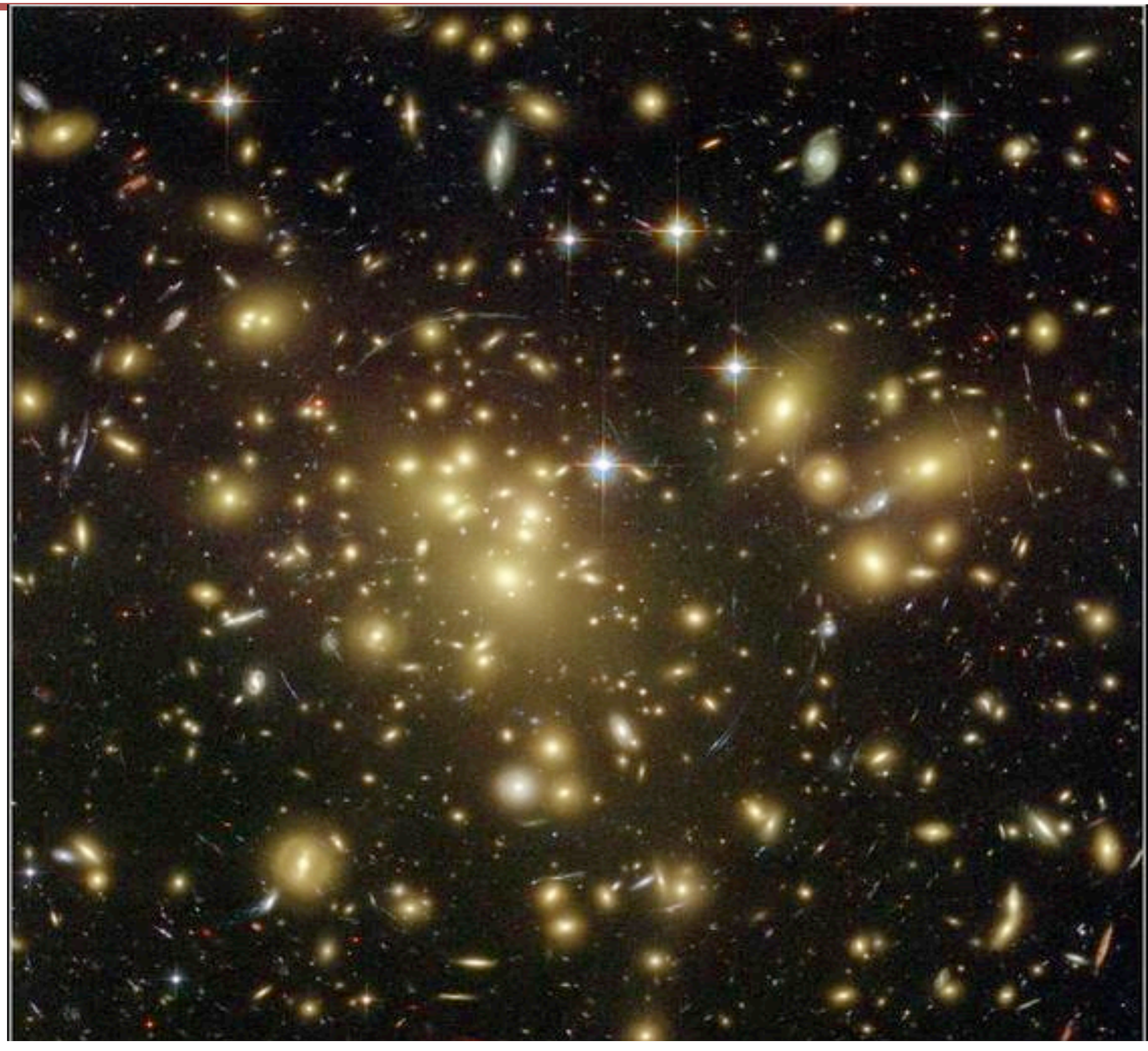
Gravitational Lensing Effects

- Deformation (and magnification) of background galaxies
- Orientation in the tangential direction
- Statistical measurement
- Dark Matter is less concentrated



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Gravitational Lensing Effects

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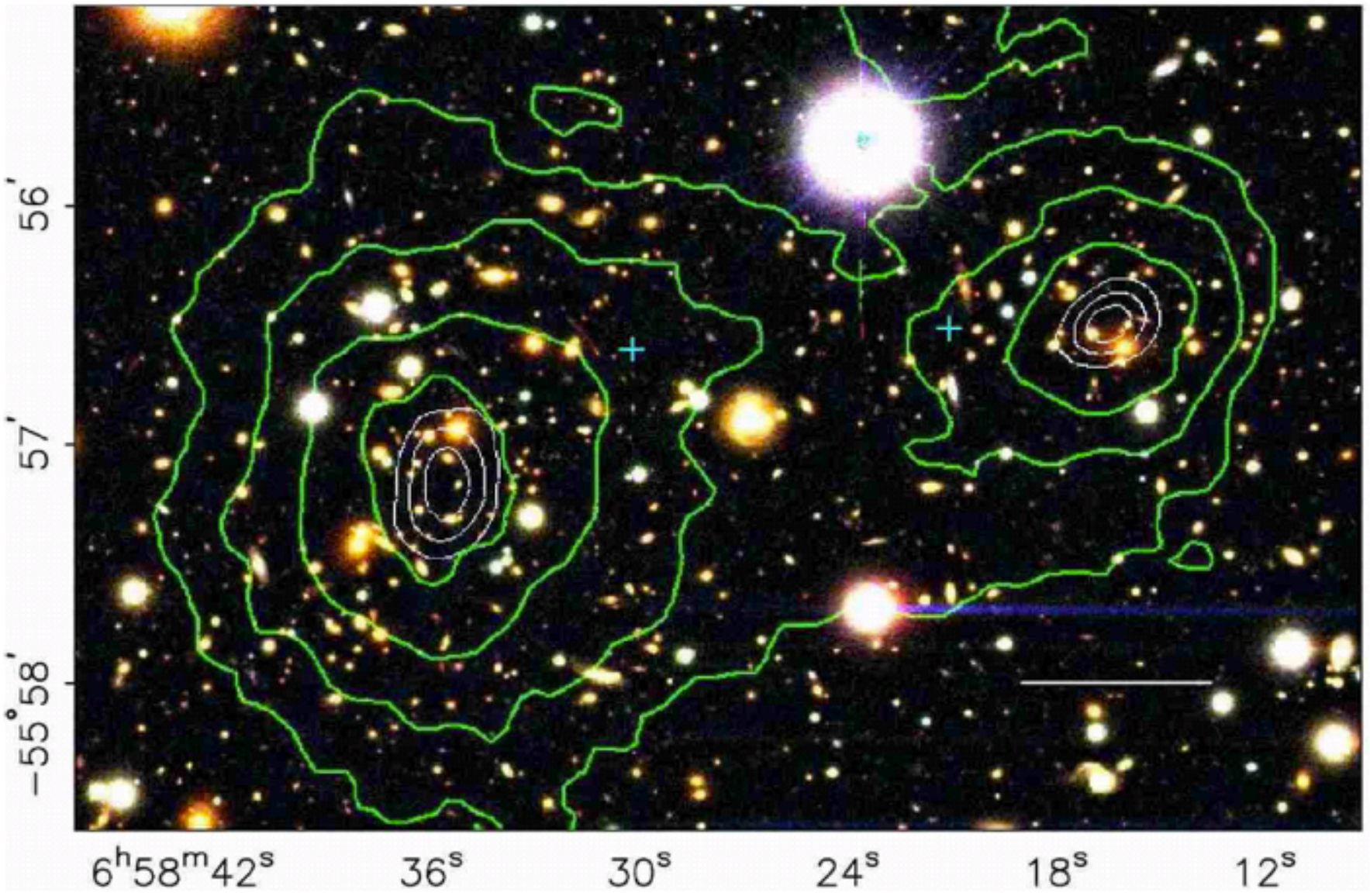
The Bullet Cluster

- Optical image + Weak lensing signal



astro-ph/0608407

Mass reconstruction using weak lensing

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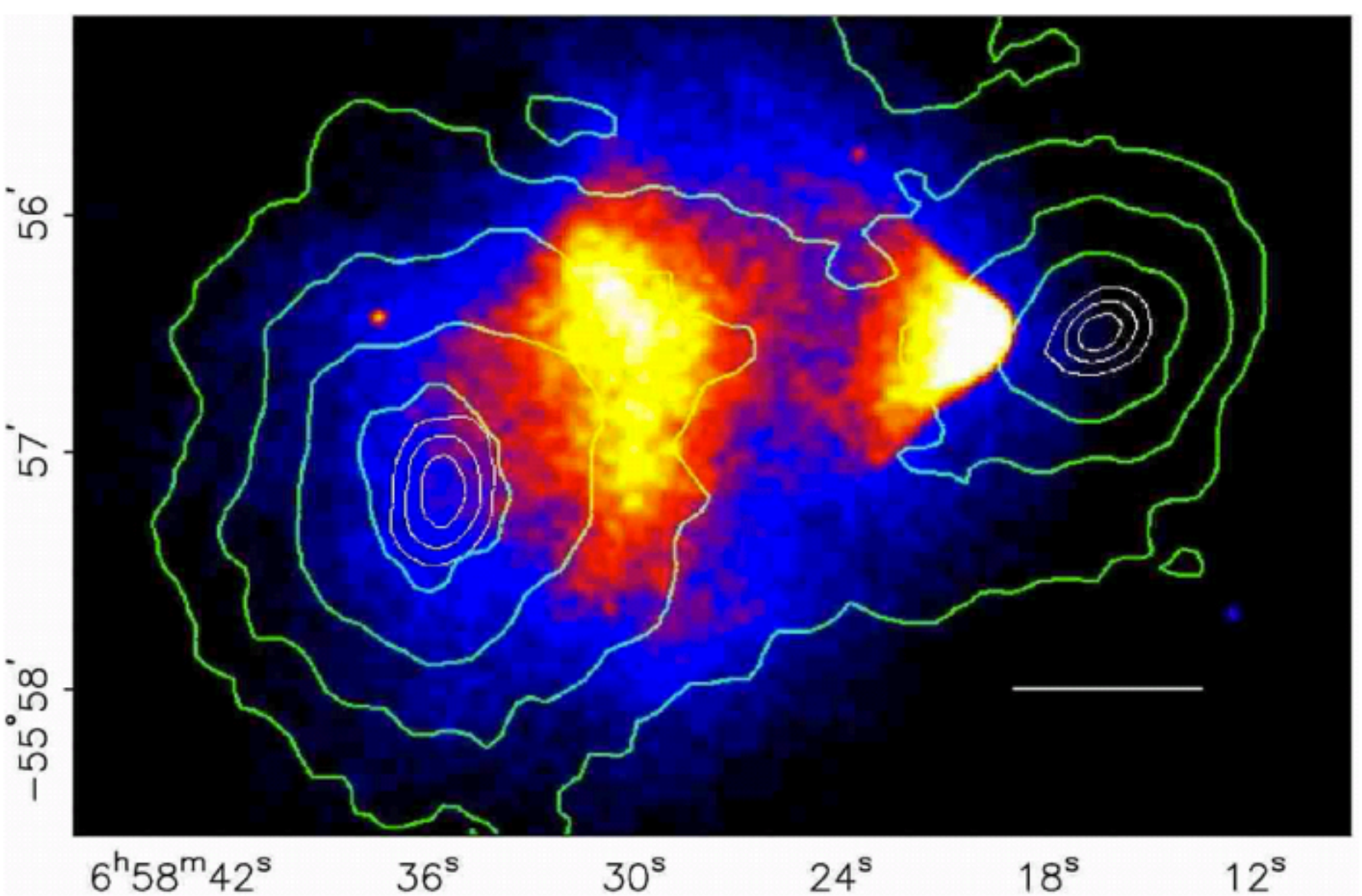
Evidences for Dark Matter

- Gas distribution (most of baryonic matter)



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8σ deviation in the center of the distributions

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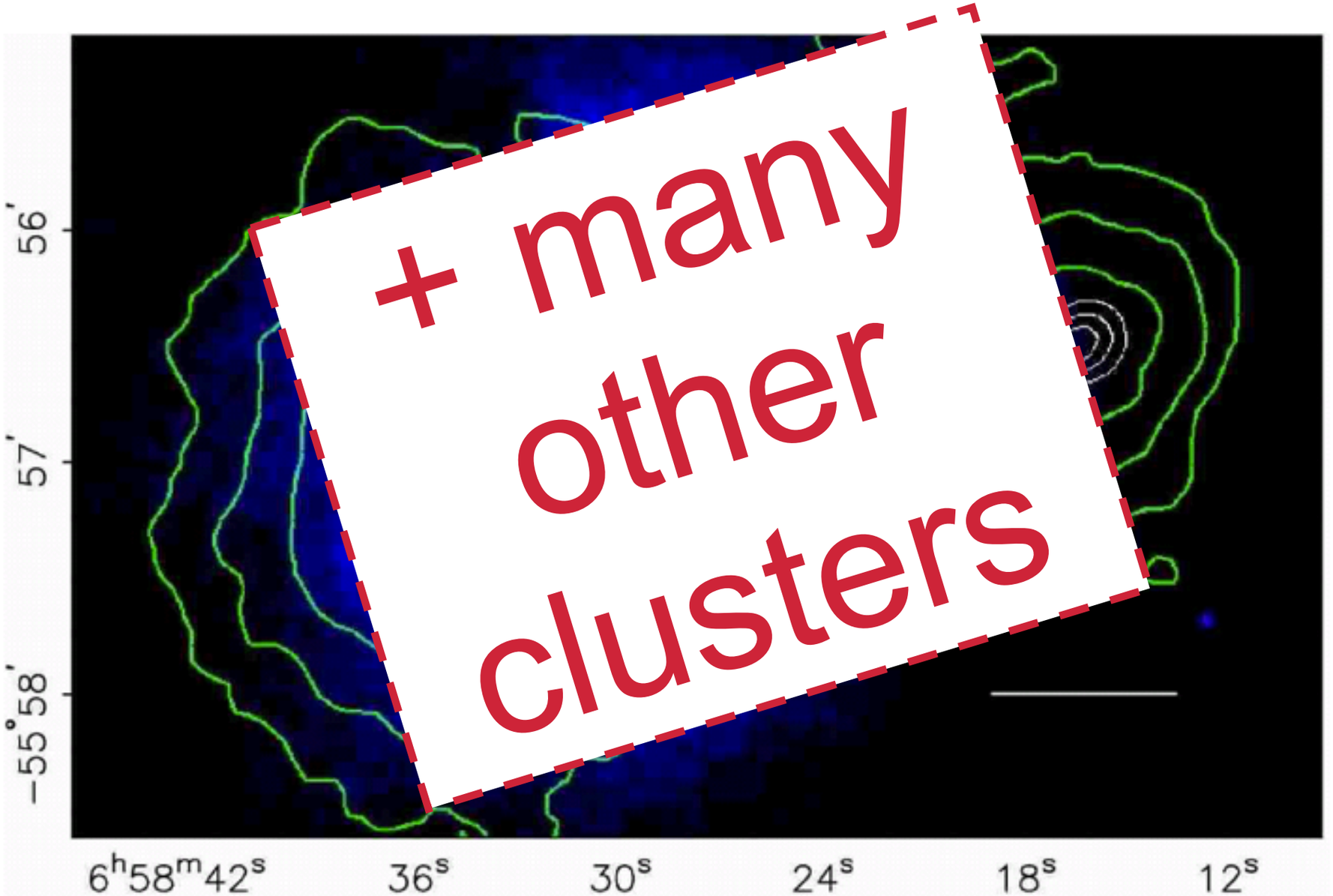

8σ deviation in the center of the distributions

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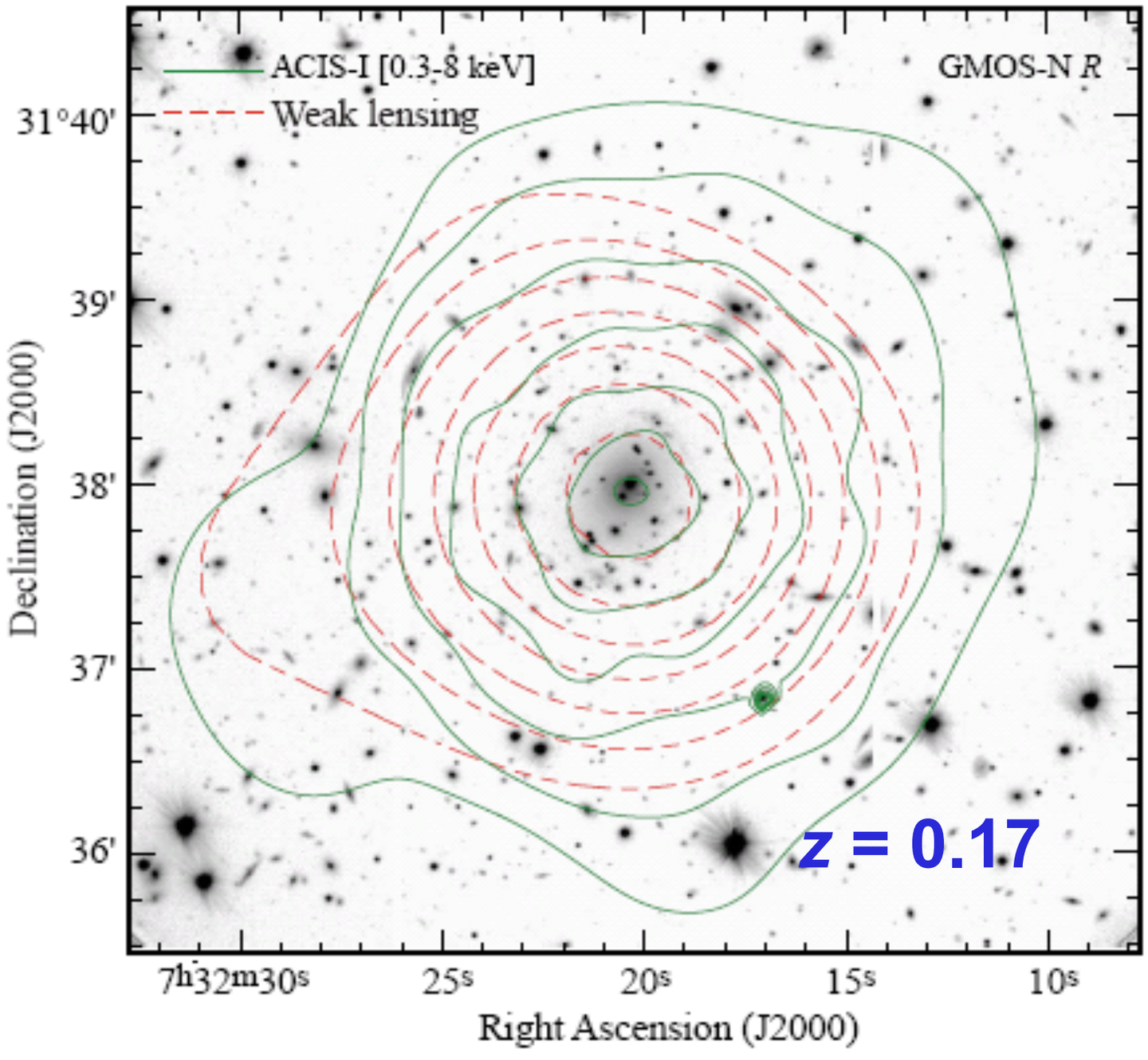
Comparison among Dark Matter measurements in clusters



E. S. Cypriano, et al., astro-ph/0504036

- Weak lensing
- X-ray emission
- Velocity dispersion

➔ agree within ~ 20%
(for relaxed clusters)

Dark Matter is less concentrated

Dark Matter in Galaxies

- Galaxy rotation curves

Back of envelope estimation

$$G\frac{M(r)}{r^2} = \frac{\left[V(r)\right]^2}{r}$$

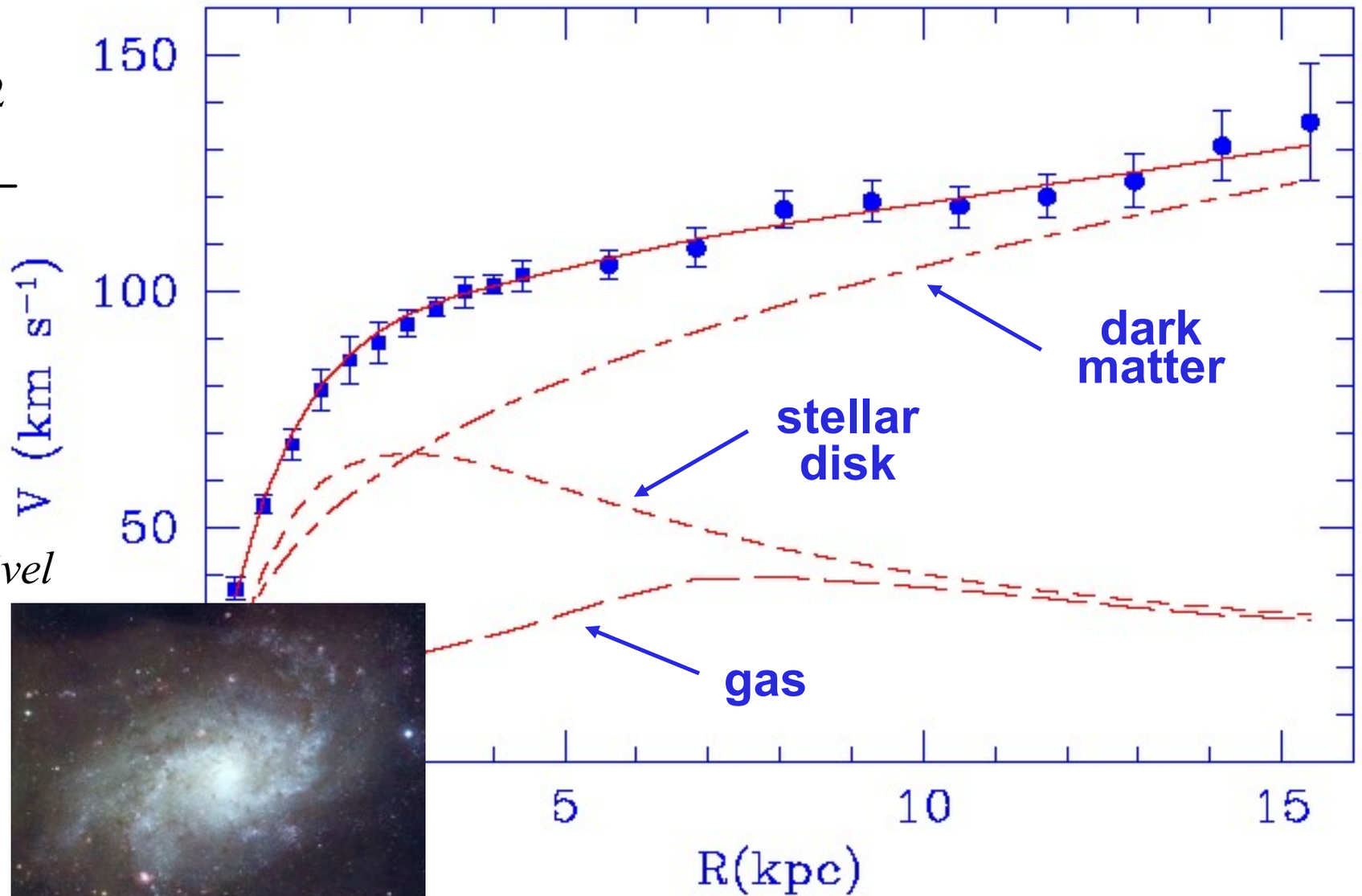
$$\Downarrow$$

$$M_{Halo} \approx 3-10 M_{Visivel}$$

Dark Matter is less concentrated

M33

astro-ph/9909252



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Dark Matter in the Universe

Evidences:

- Galaxy rotation curves
- Motions in galaxies, clusters, and large-scale structure
- X-ray flux in clusters
- Gravitational lensing
- Sunyaev-Zel'dovich effect

There is ~5x more *dark matter* than usual (SM) matter!

Non-baryonic: Does not interact with baryonic matter

(weak/no dissipation, no light emission, no nuclear reactions)

structures, *bullet*, nucleosynthesis...

Where is the "ordinary matter"?

- Visible matter (stars): 10%
- Most part of baryonic matter is "dark" (gas, planets, BH)

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Dark Matter in the Universe

Evidences:

- Galaxy rotation curves
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- X-ray flux i
- C
-

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No

Whe

- Visib
- Most

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Dark Matter is the component - that clusters - that dominates the mass density of the Universe

The Universe is more homogeneous that is seems when looking only at galaxies

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