Detailed energy (mass) budget of the Universe

THE COSMIC ENERGY INVENTORY

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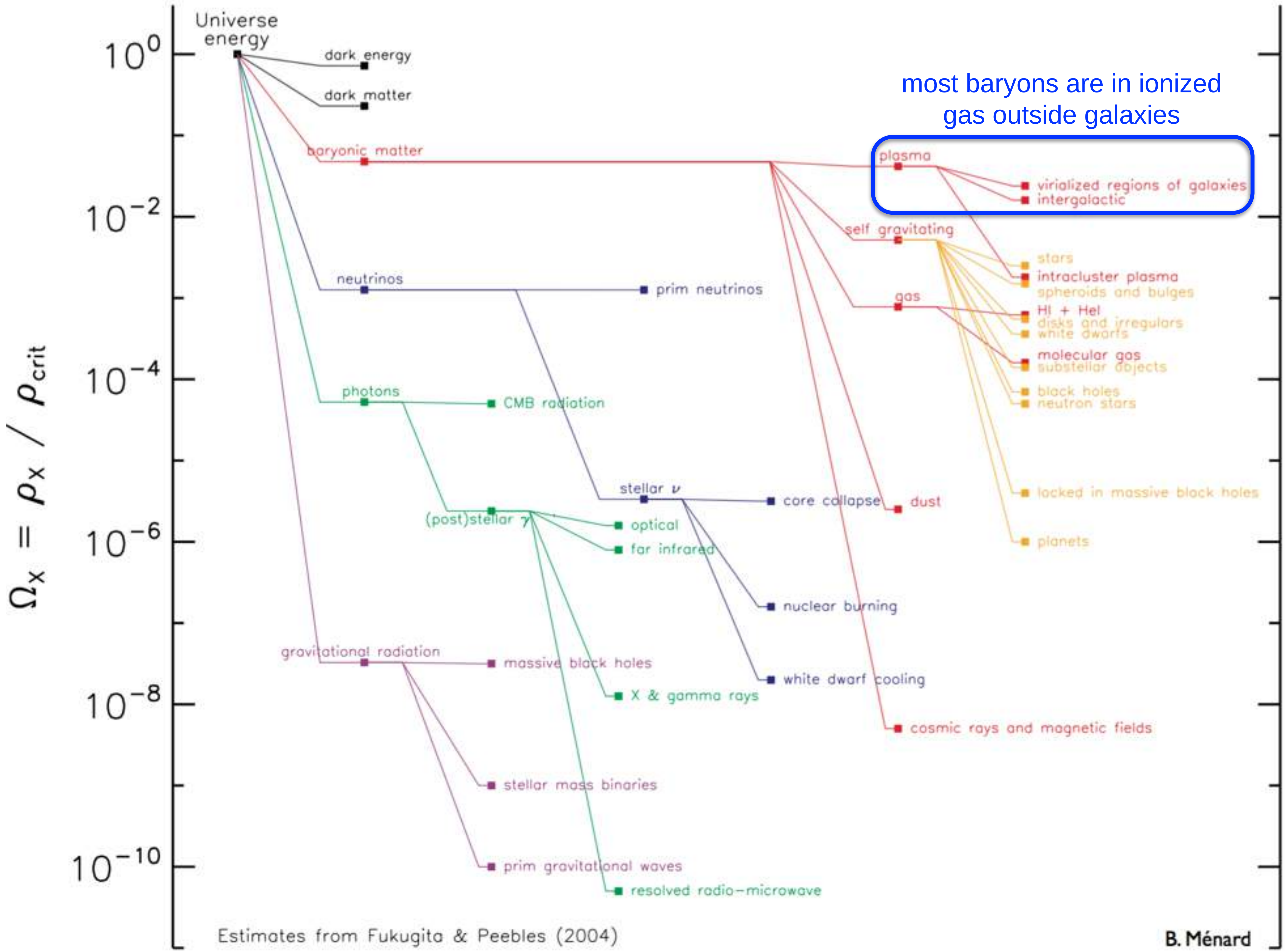
ABSTRACT

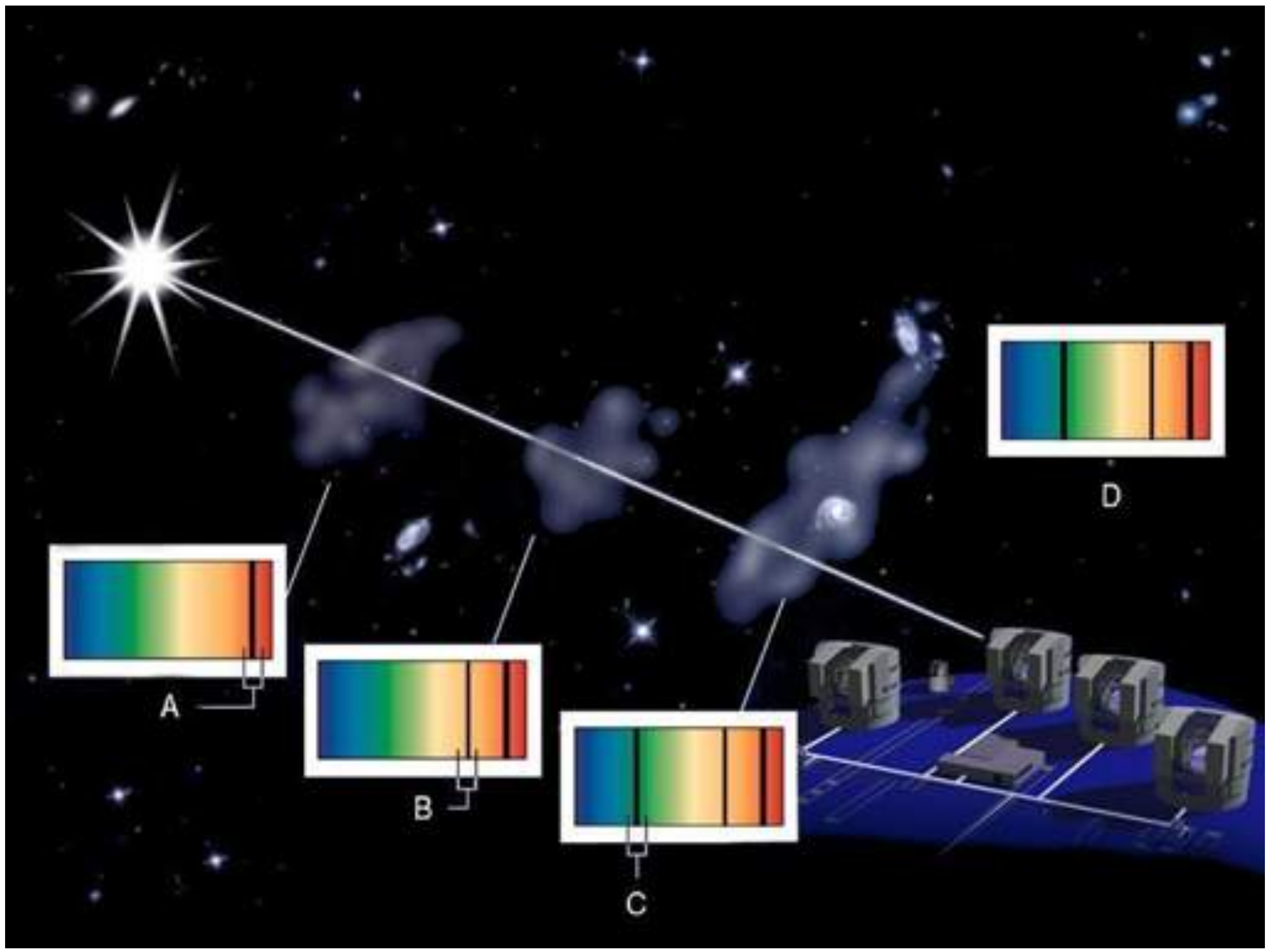
We present an inventory of the cosmic mean densities of energy associated with all the known states of matter and radiation at the present epoch. The observational and theoretical bases for the inventory have become rich enough to allow estimates with observational support for the densities of energy in some 40 forms. The result is a global portrait of the effects of the physical processes of cosmic evolution.

Subject heading: cosmology: miscellaneous

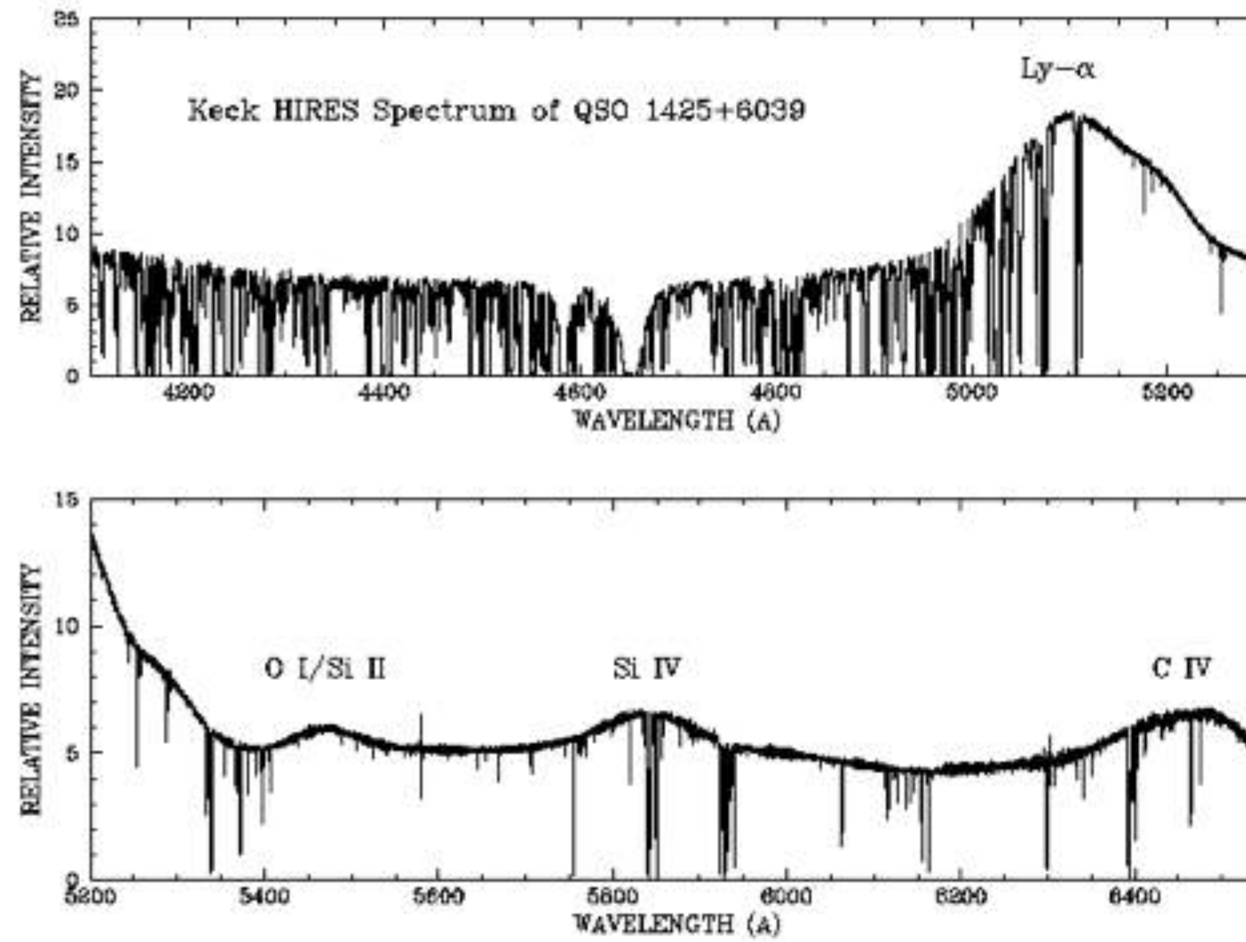

most baryons are in ionized gas outside galaxies
$\Omega_X = \rho_X / \rho_{crit}$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
Universe energy
dark energy
dark matter
baryonic matter
neutrinos
photons
gravitational radiation
prim neutrinos
CMB radiation
(post)stellar γ
optical
far infrared
X & gamma rays
resolved radio-microwave
stellar ν
core collapse
nuclear burning
white dwarf cooling
massive black holes
stellar mass binaries
prim gravitational waves
plasma
virialized regions of galaxies
intergalactic
self gravitating
stars
intracluster plasma
spheroids and bulges
gas
HI + HeI
disks and irregulars
white dwarfs
molecular gas
substellar objects
black holes
neutron stars
locked in massive black holes
planets
dust
cosmic rays and magnetic fields
Estimates from Fukugita & Peebles (2004)
B. Ménard

Intergalactic baryons

Quasar absorption lines

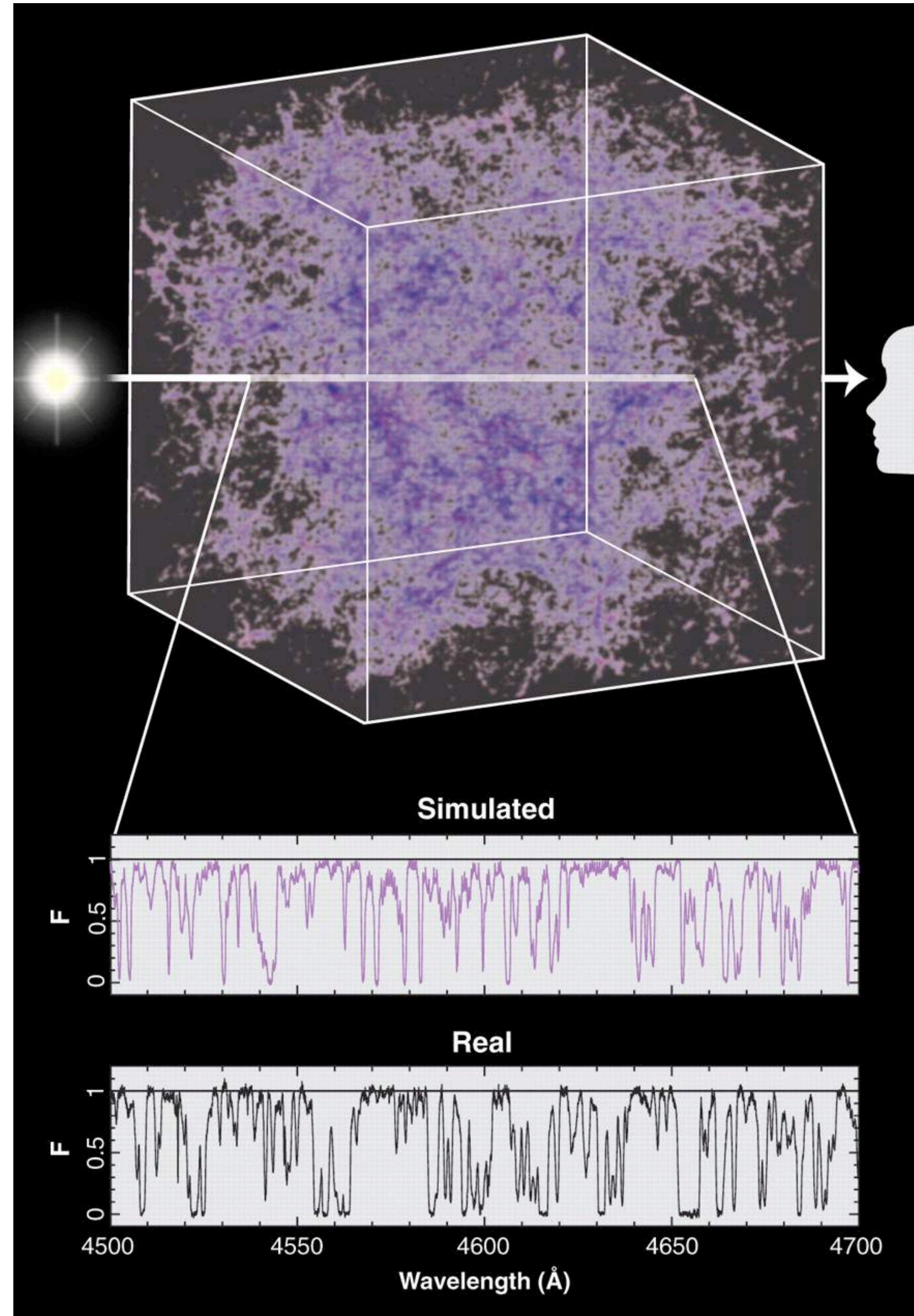


z_{QSO}=3.18



Gas outside galaxies (intergalactic medium)

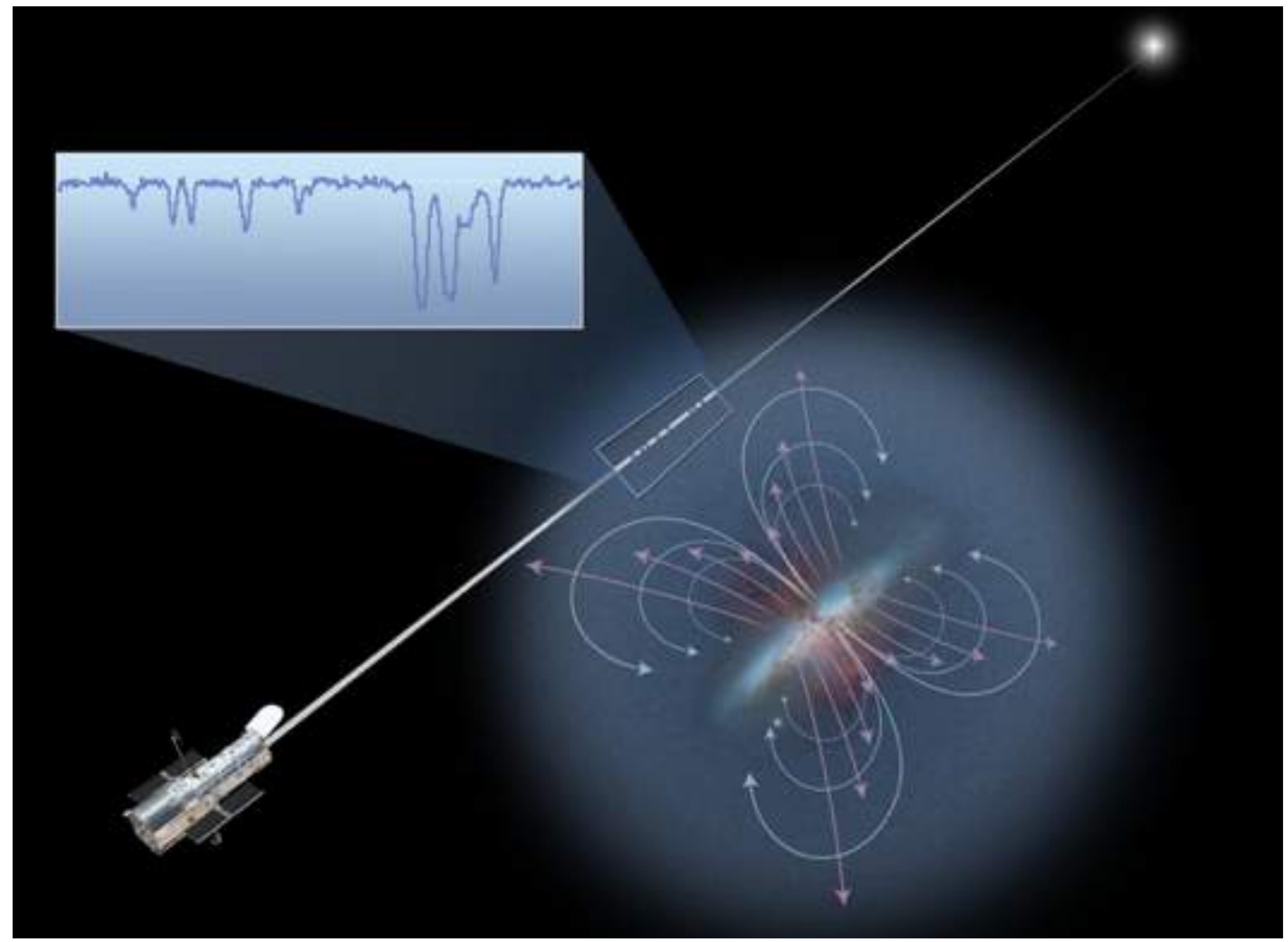
- The space between galaxies is filled with baryons
- See in hydrogen Lyα absorption in spectra of distant quasars — the “Lyα forest”
- High-redshift (z~2-4) Lyα forest observations are consistent with the BBN baryon abundance



CAFG+08, *Science*

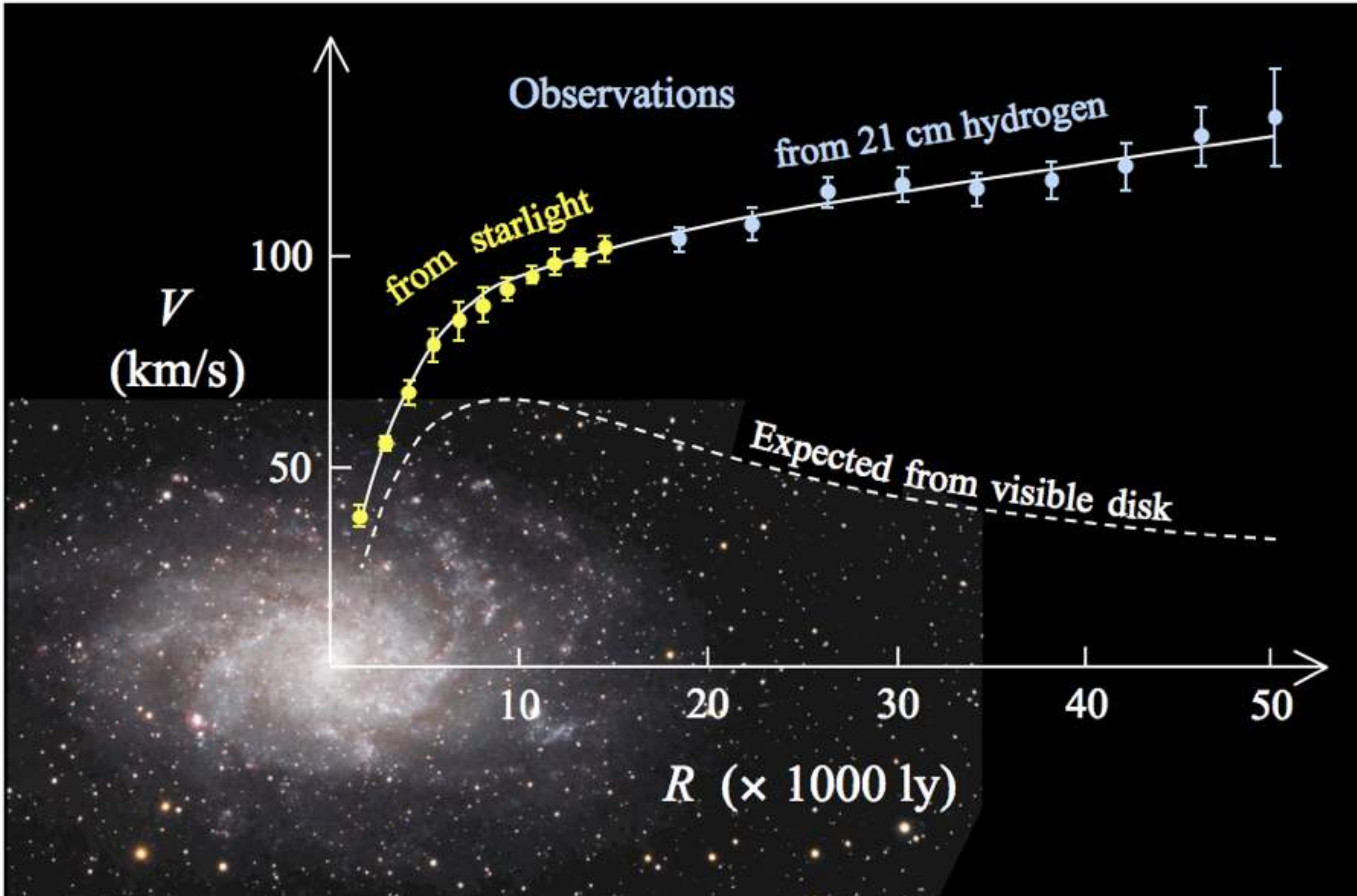
Gas in halos of galaxies (circum-galactic medium)

- Galaxy growth is regulated by mass exchanges with the intergalactic medium
  - inflows fuel star formation & black hole growth
  - feedback from stars and black holes drive powerful outflows
- These baryons are faint: absorption spectroscopy currently gives best constraints

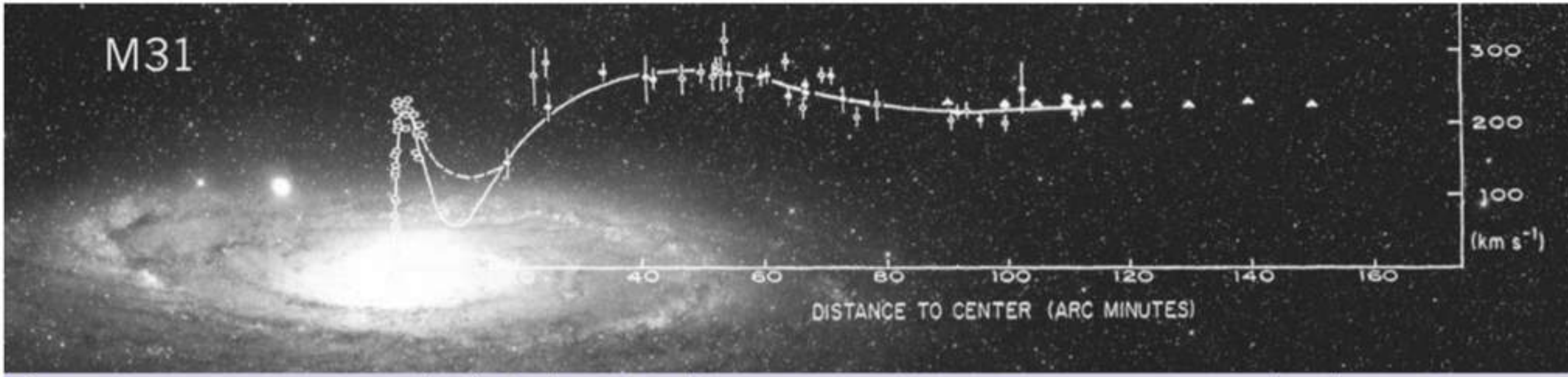


Galaxy rotation curves

Galaxy rotation curves: evidence for dark matter



M33 rotation curve from http://en.wikipedia.org/wiki/Galaxy_rotation_curve



The M31 major axis mean optical radial velocities and the rotation curve,[4] $r < 120$ arcmin, superposed on the M31 image from the Palomar Sky Survey. Velocities from radio observations[5] are indicated by triangles, $90 < r < 150$ arcmin. Rotation velocities remain flat well beyond the optical galaxy, implying that the M31 cumulative mass rises linearly with radius. (Image by Rubin and Janice Dunlap.)

Vera Rubin pioneered measurements of galaxy rotation curves. Starting with her Rubin & Kent (1970) paper on the rotation curve of M31, her work provided compelling evidence for extended halos of dark matter around galaxies.

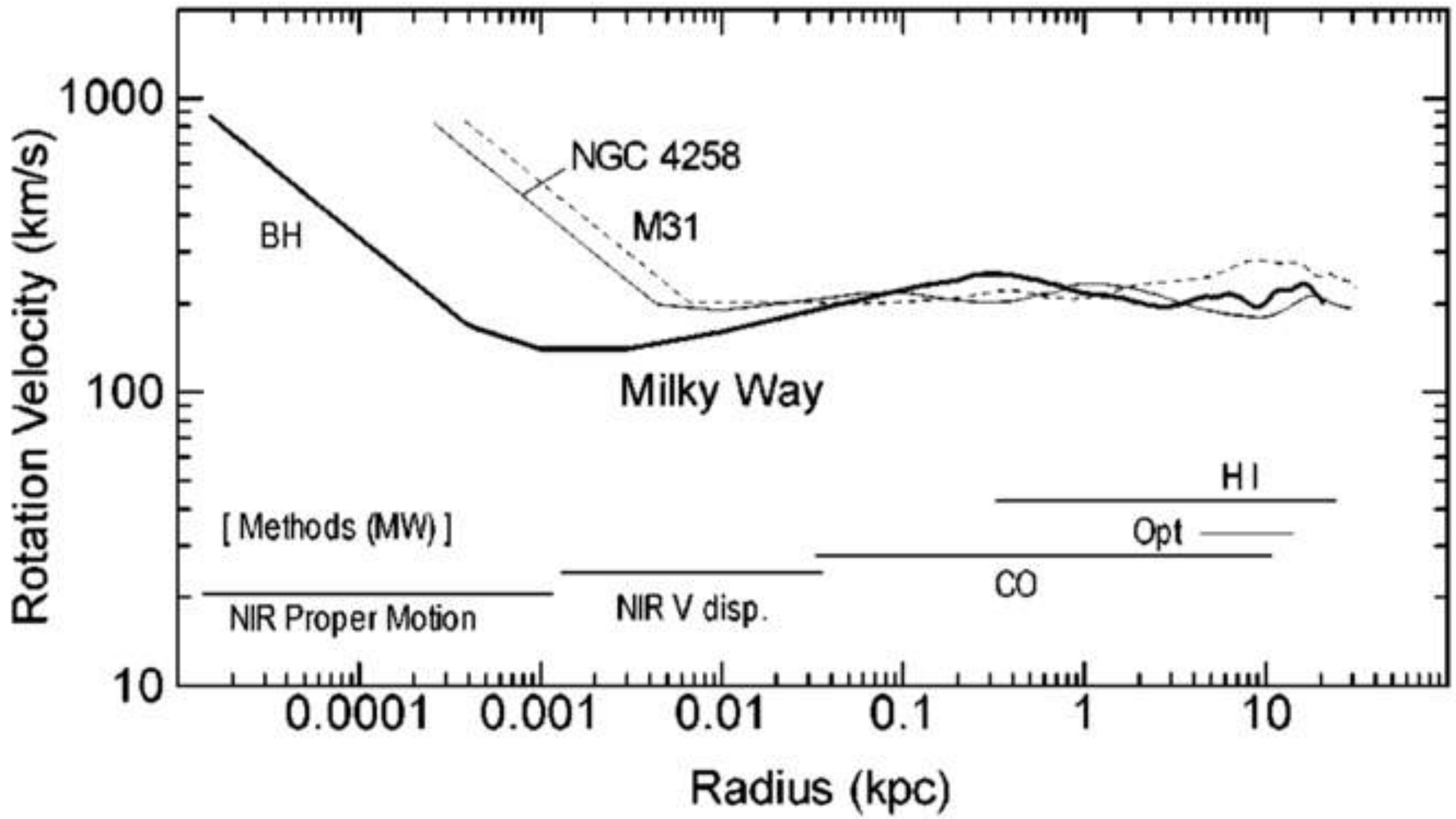


Figure 3 Logarithmic rotation curves of the Milky Way (thick line), NGC 4258 (thin line), and M31 (dashed line). Innermost rotation velocities are Keplerian velocities calculated for massive black holes. Observational methods for the Milky Way (horizontal lines).

Sofue & Rubin 2001

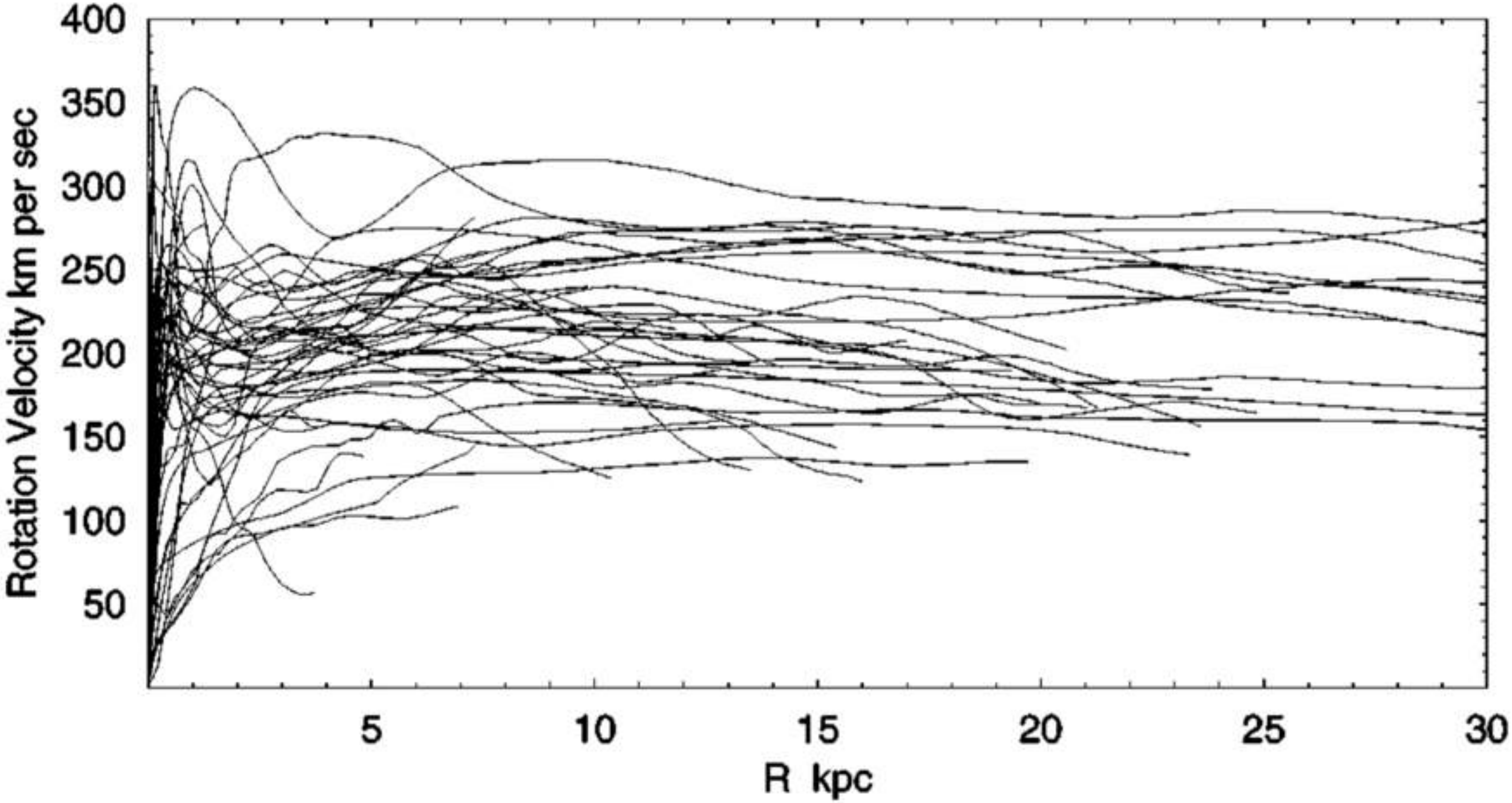


Figure 4 Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999a).

Sofue & Rubin 2001

Rotation curves for disk mass distributions

(rather than spherically-symmetrically distributed — Newton's theorem does *not* apply)

Example for razor-thin exponential disk

Mass distribution: $$\Sigma(R) = \Sigma_0 \mathrm{e}^{-R/R_\mathrm{d}}$$

Potential obtained by solving Poisson's eq:

$$\Phi(R,0) = -4G\Sigma_0 \int_0^R \mathrm{d}a\, \frac{aK_1(a/R_\mathrm{d})}{\sqrt{R^2-a^2}}$$
$$= -\pi G\Sigma_0 R\left[I_0(y)K_1(y) - I_1(y)K_0(y)\right] \qquad y \equiv \frac{R}{2R_\mathrm{d}}$$

modified Bessel functions

Rotation curve:

$$v_\mathrm{c}^2(R) = R\frac{\partial\Phi}{\partial R} = 4\pi G\Sigma_0 R_\mathrm{d} y^2 \left[I_0(y)K_0(y) - I_1(y)K_1(y)\right]$$

Binney & Tremaine 08, ch. 2

Applying Newton's theorem to disk is not strictly correct, but the approximation is good to ~15%

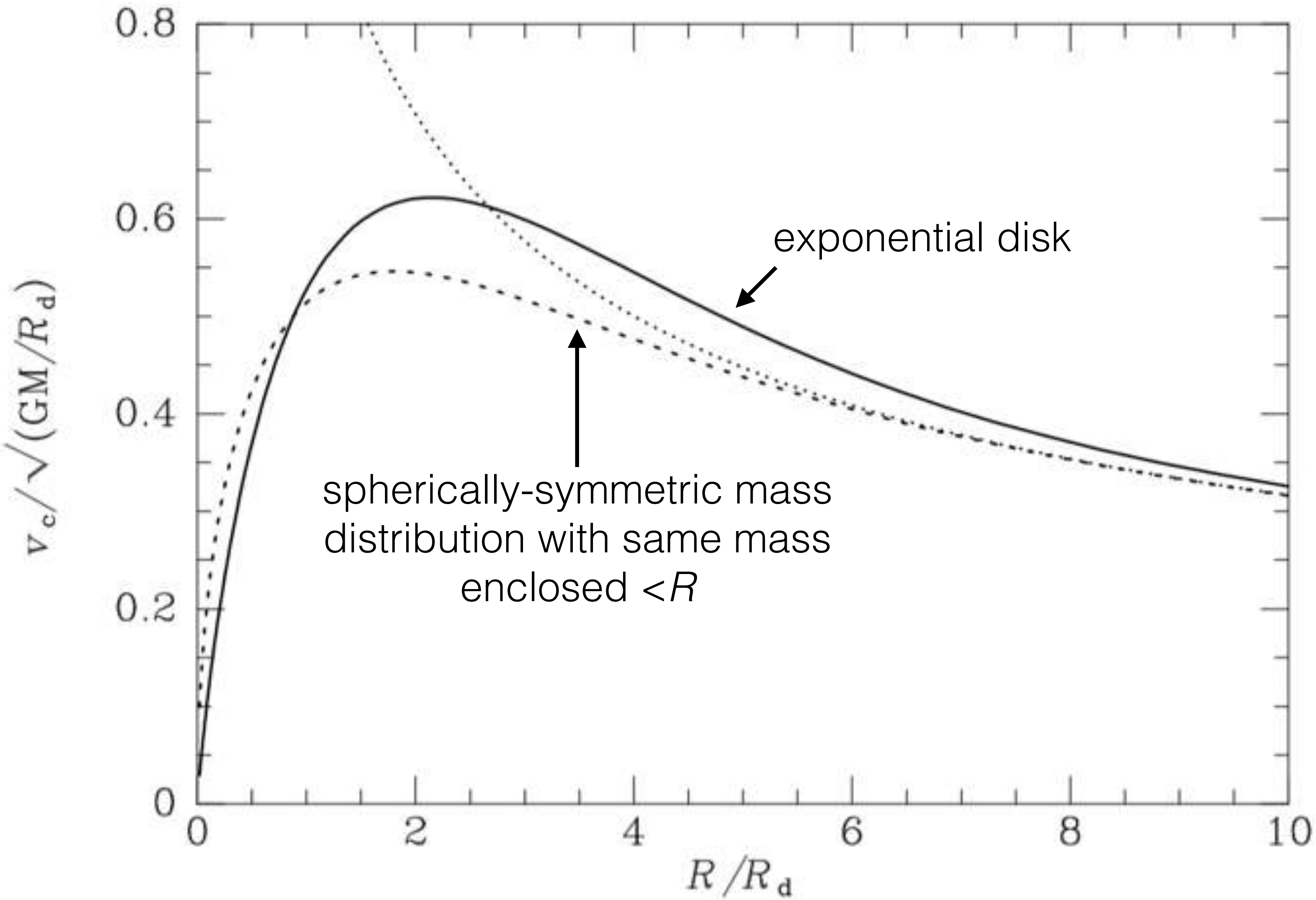
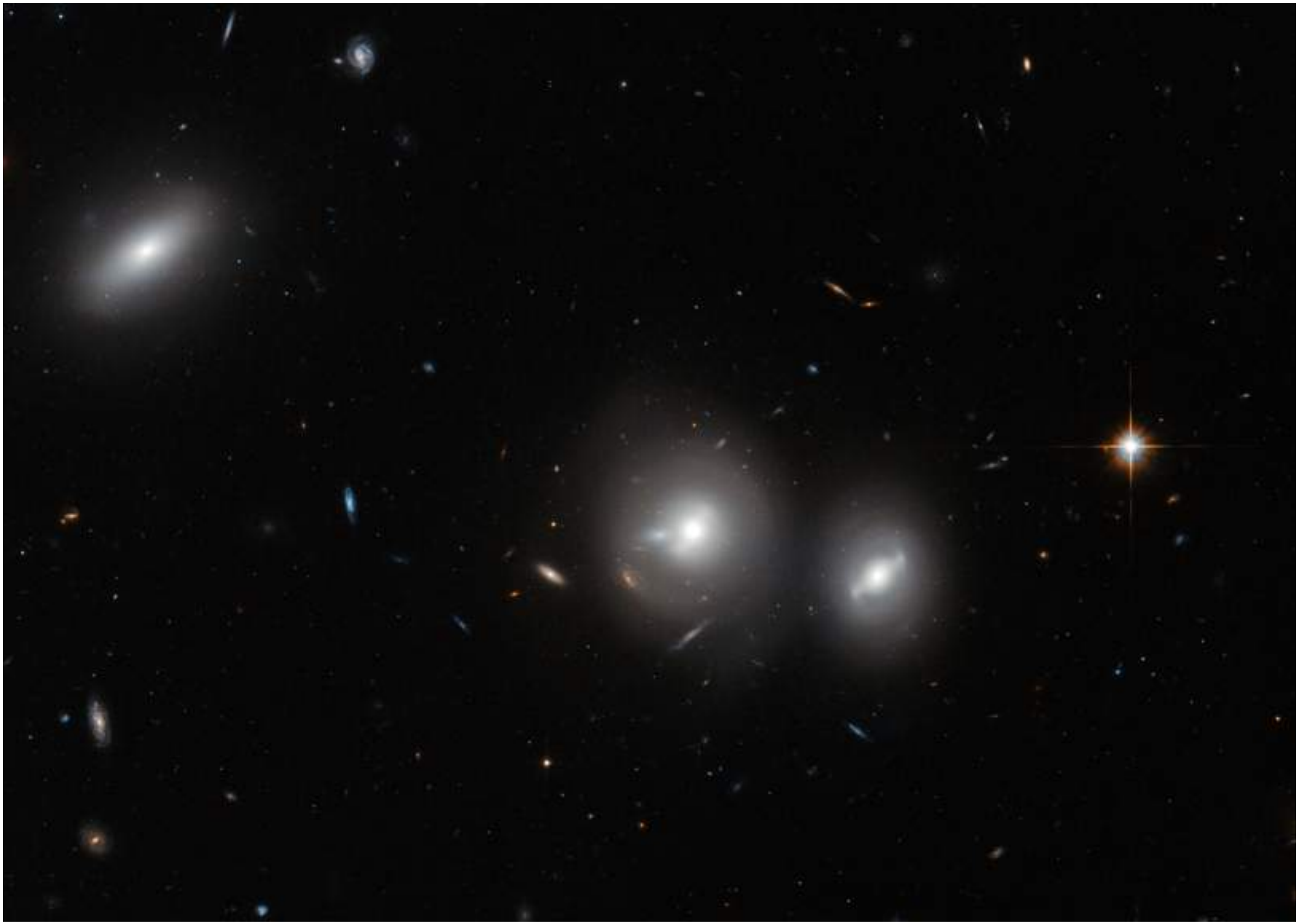


Figure 2.17 The circular-speed curves of: an exponential disk (full curve); a point with the same total mass (dotted curve); the spherical body for which $M(r)$ is given by equation (2.166) (dashed curve).

Dark matter in galaxy clusters

Coma galaxy cluster in optical



~2,000 galaxies total

Coma cluster in x-rays

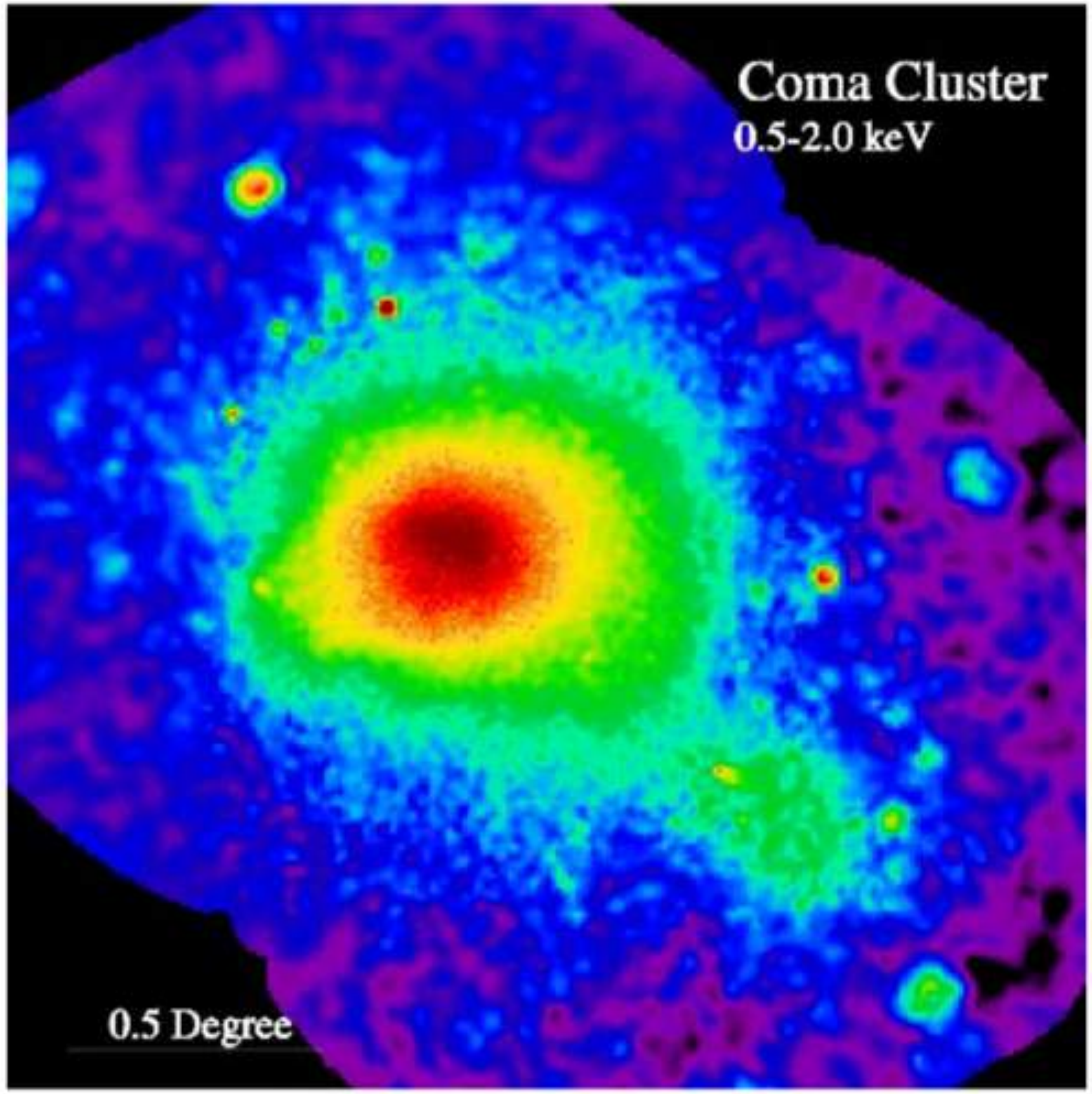
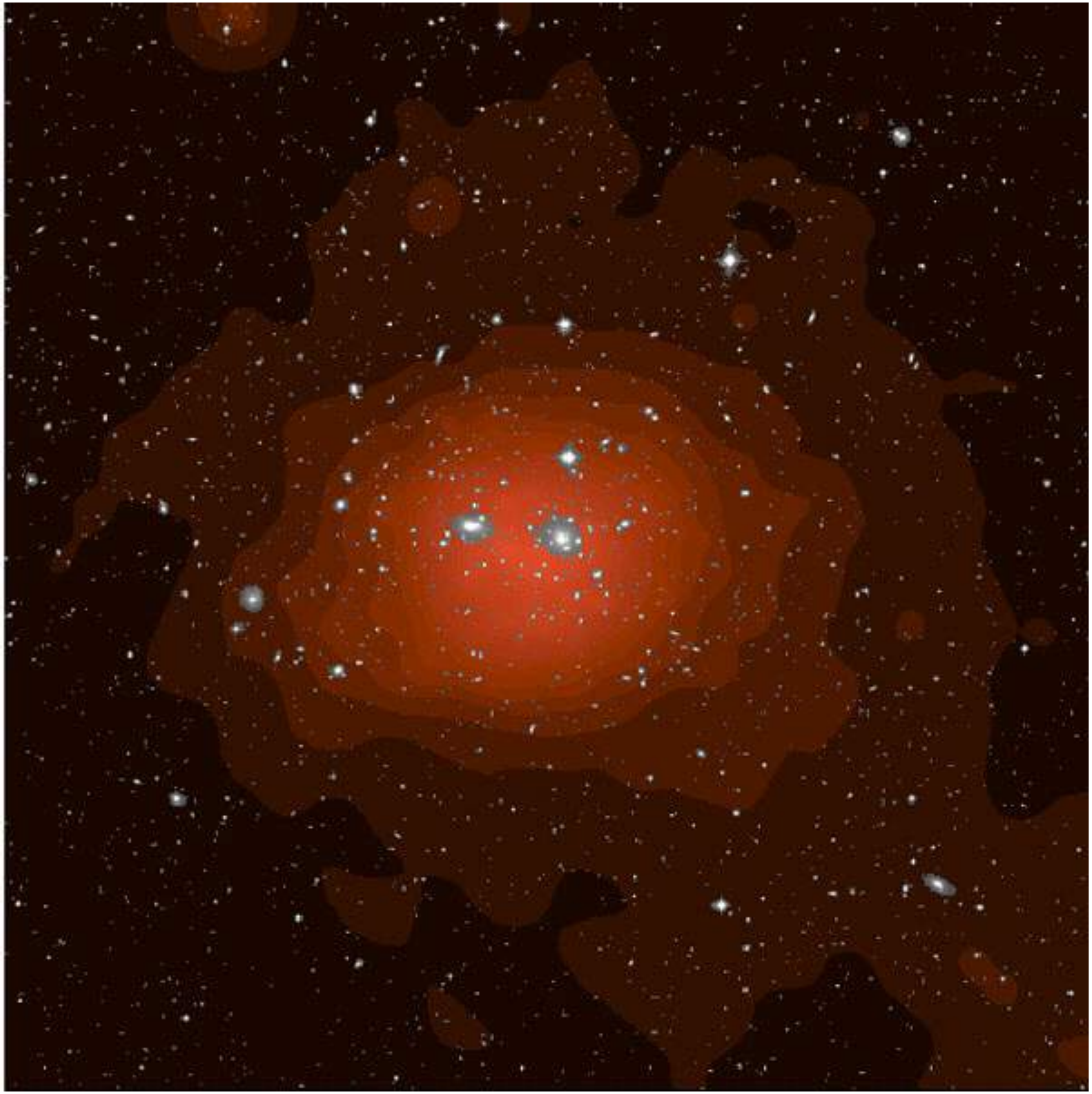


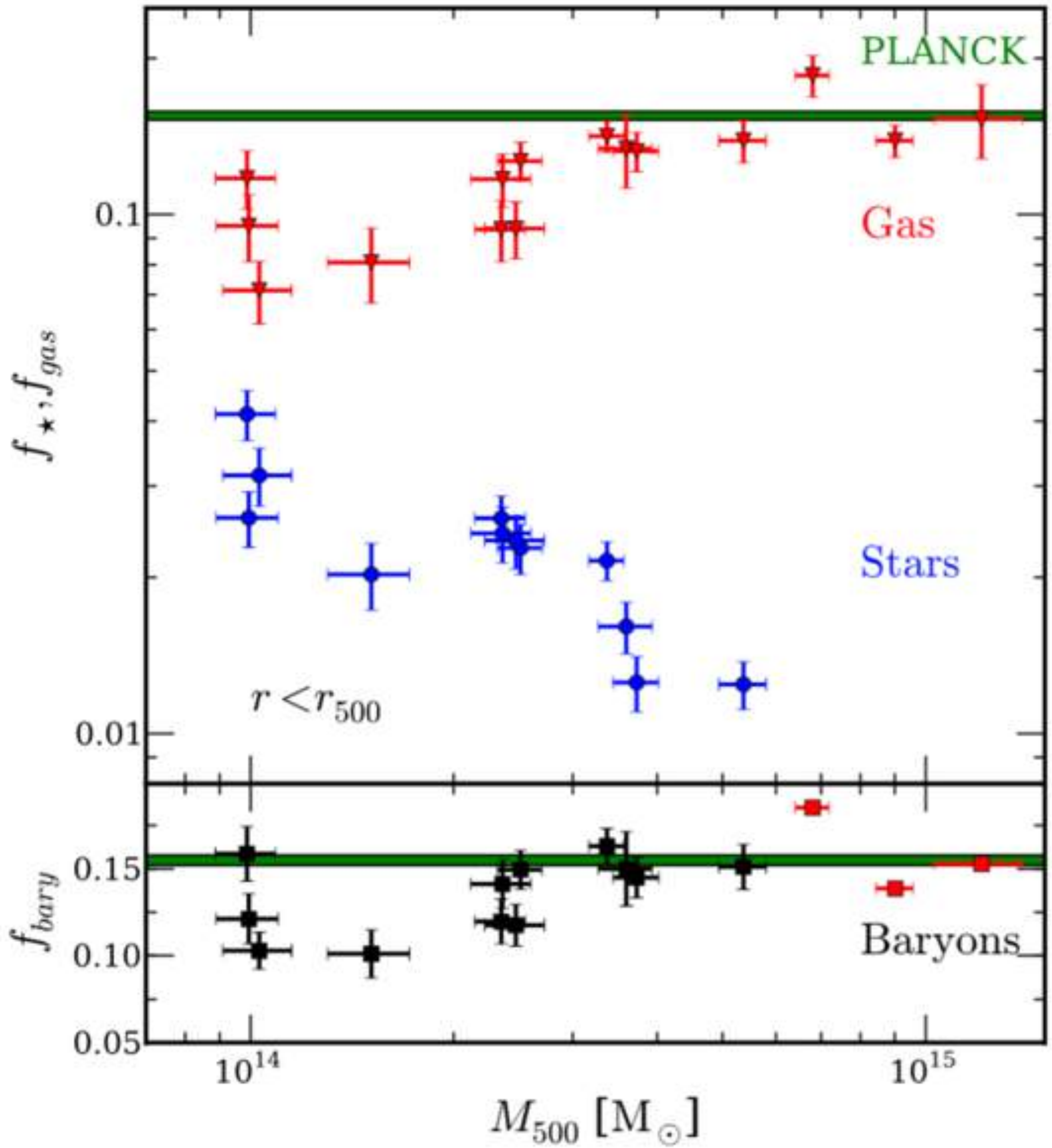
Figure 2. An x-ray image of the Coma cluster obtained with the ROSAT satellite, showing both the main cluster and the NGC4839 group to the south-west. (Credit: S L Snowden, High Energy Astrophysics Science Archive Research Center, NASA.)

Coma cluster: x-rays on top of optical



Most baryons in galaxy clusters are in hot gas, not stars — but not enough gas to account for all mass

mass fractions in stars and gas



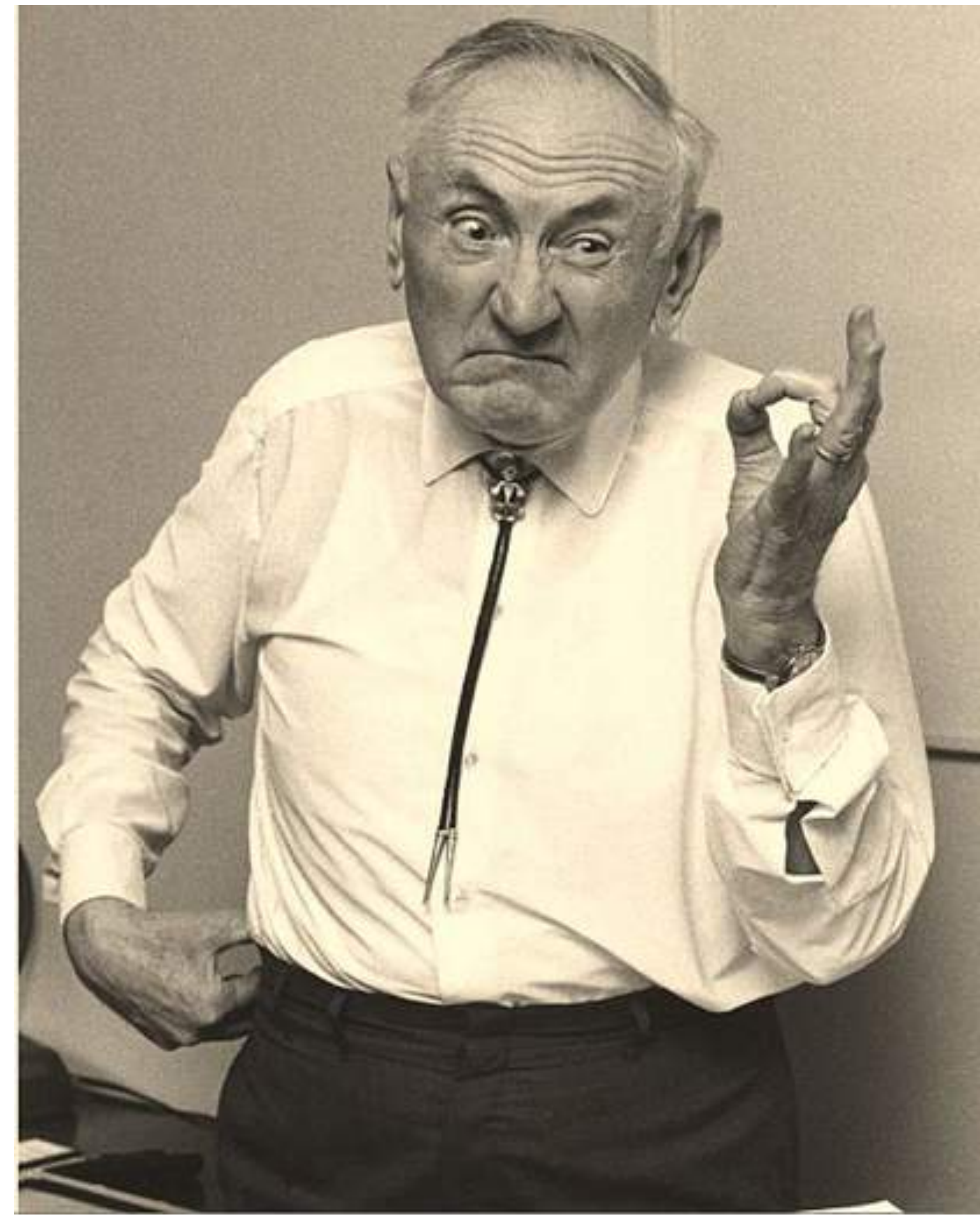
Ω_b/Ω_m

mass enclosed within $500\rho_{crit}$

Gonzalez+13

Fritz Zwicky (1898-1974)

- First observational evidence for dark matter by applying viral theorem to galaxy clusters (1933)
- Coined term 'supernovae' and predicted that they produce neutron stars and cosmic rays (1933)
- Posited in 1937 that galaxy clusters could act as gravitational lenses (first observed in 1979)
- Produced many catalogs of observed galaxies and galaxy clusters (1961-1971)
- Developed some of the earliest jet engines and holds over 50 patents
- …



CATALOGUE OF SELECTED COMPACT GALAXIES AND OF POST-ERUPTIVE GALAXIES

F. Zwicky (1971)

INTRODUCTION

…The naivety of some of the theoreticians, at all times, is really appalling. As a shining example of a most deluded individual we need only quote the high pope of American Astronomy, one Henry Norris Russell, …

…the most renowned observational astronomers in the 1930's also made claims that now have been proved to be completely erroneous…

… E. P. Hubble, W. Baade and the sycophants among their young assistants were thus in a position to doctor their observational data, to hide their shortcomings and to make the majority of the astronomers accept and believe in some of their most prejudicial and erroneous presentations and interpretations of facts.

Thus it was the fate of astronomy … to be again and again thrown for a loop by some moguls of the respective hierarchies. To this the useless trash in the bulging astronomical journals furnishes vivid testimony.

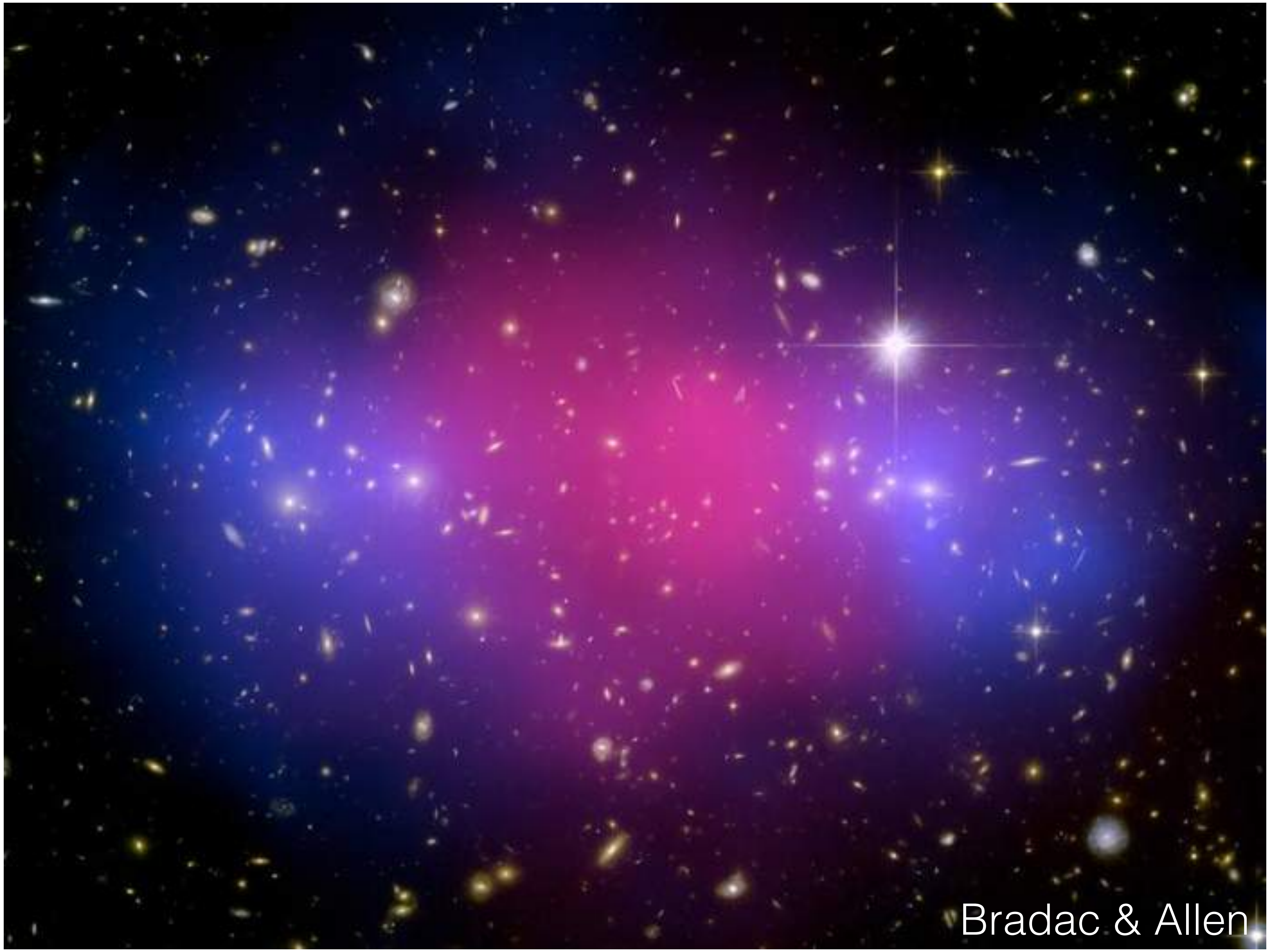
…useful to recall some of the major absurdities that were promulgated about galaxies, clusters of galaxies and other cosmic objects by the high priests of astronomy during the past few decades.

It must be emphasized right at the outset that no one, with the exception of the author has ever clearly stated what a galaxy is, an omission that no doubt will not only baffle every thinking layman but will in particular be judged ludicrous by any true methodologist or professional in morphological research…

As a consequence some of the most absurd and untenable definitions of quasars, quasistellar objects, "interlopers" have been introduced by A. Sandage, M. Schmidt and others to which we shall return later on.

Some of the most glaringly incorrect conclusions drawn by E. P. Hubble and W. Baade that stubbornly persisted in the minds of most astronomers for decades are the following…

Bullet cluster: more evidence for dark matter



- two clusters that recently collided
- gravitational mass traced by weak lensing (blue)
- gas (pink) stuck in middle

Simulation of merging galaxy clusters matches Bullet cluster properties reasonably well

Observed Bullet cluster x-rays | Simulated Bullet cluster x-rays

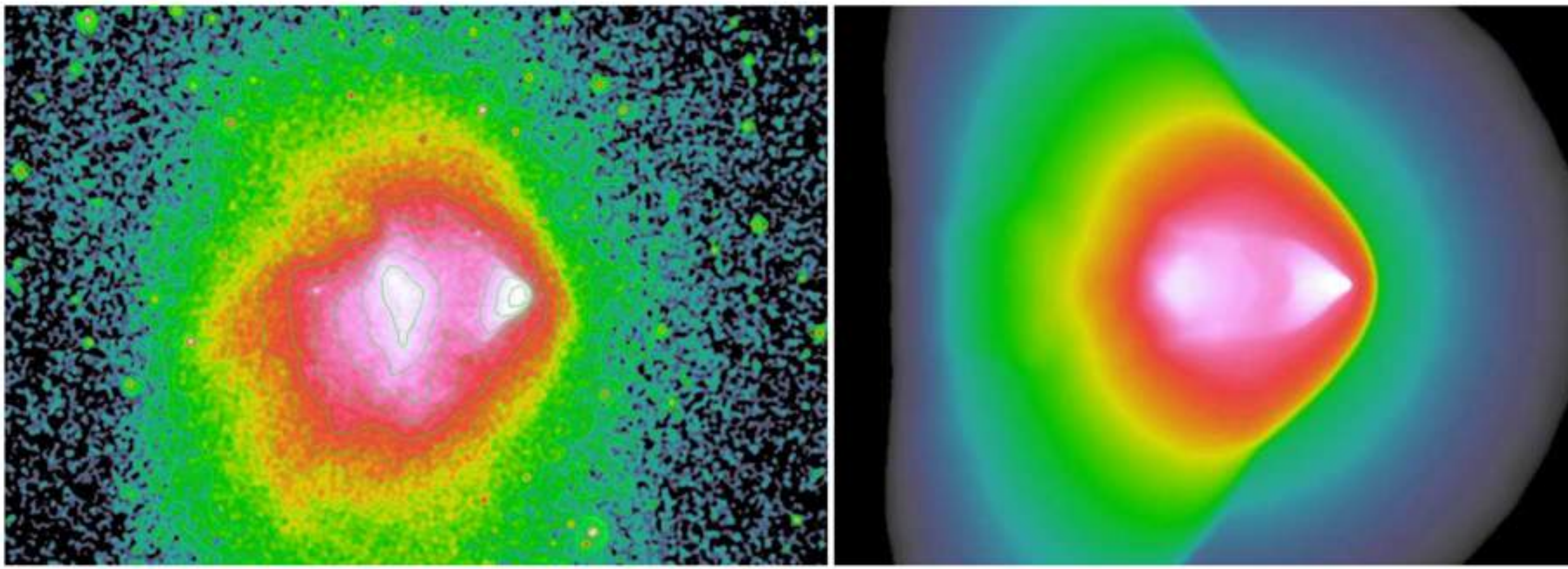
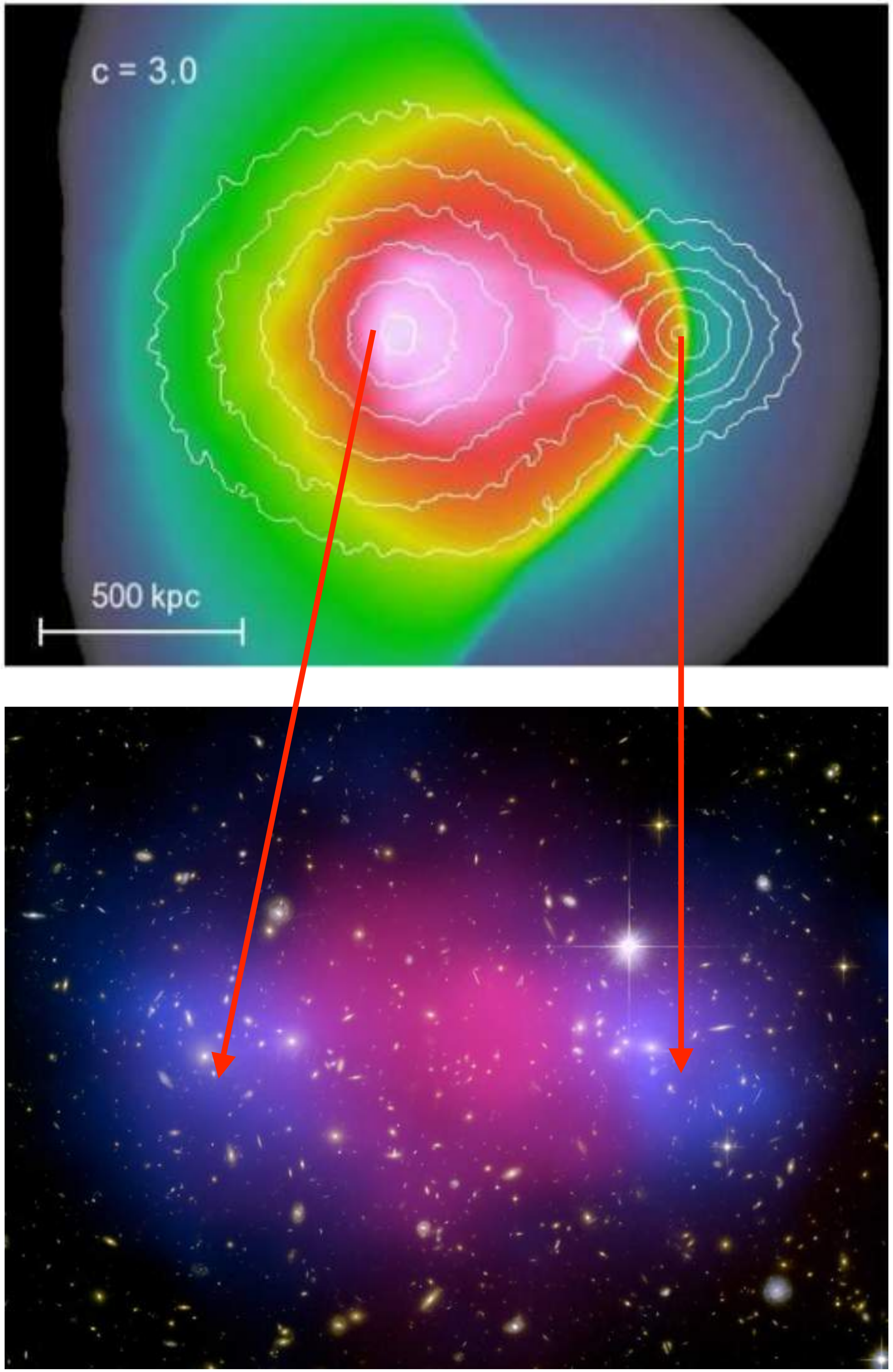


FIG. 2.— X-ray surface brightness of 1E0657–56 observed with Chandra (left). Clearly visible are two X-ray peaks. The wedge-like structure on the right associated with the 'bullet' is bounded by a sharp contact discontinuity, which is interpreted as a cold front. The prominent bow shock in front demonstrates that the subcluster is moving to the right with high velocity. The panel on the right-hand side shows the X-ray surface brightness in one of our merger simulations, roughly drawn on the same scale and with similar dynamic range in the color table.

1:10 mass ratio collision at ~2,600 km/s

Springel & Farrar 07



Simulated Bullet

Contours: collisionless dark matter-dominated mass

Color map: x-ray gas

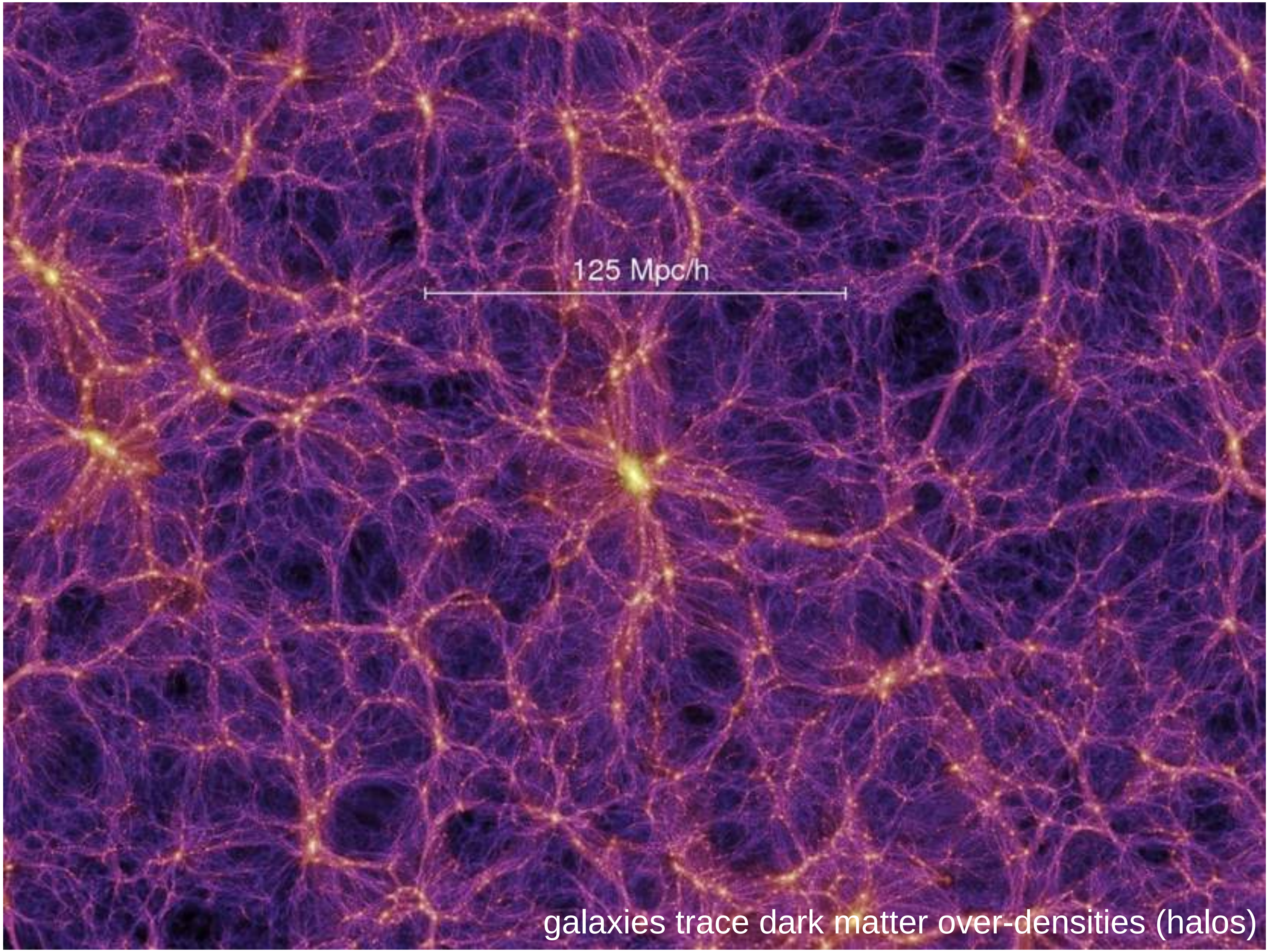
Observed Bullet

Blue: total mass measured using gravitational lensing

Pink: x-ray gas

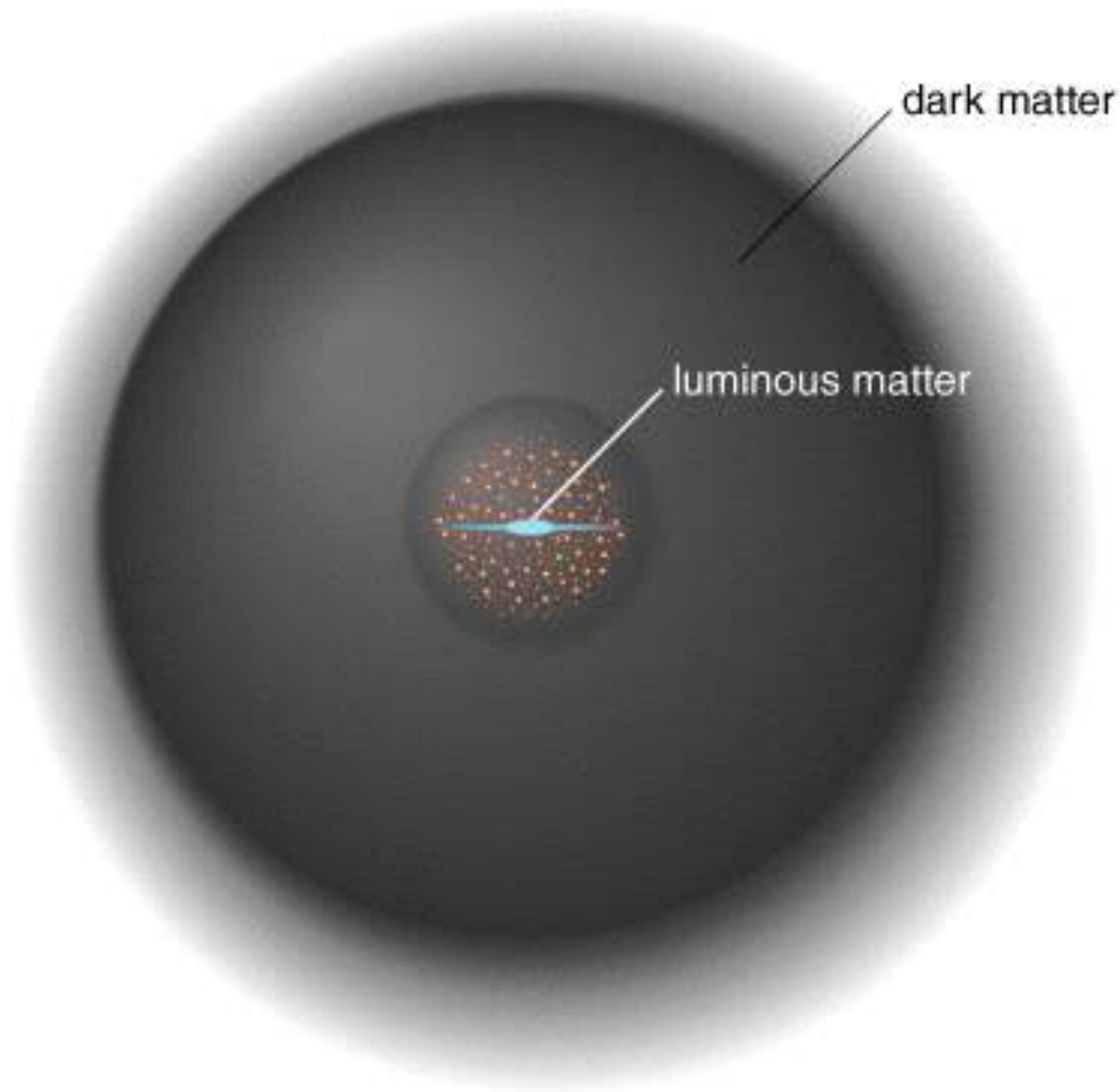
Springel & Farrar 07

Simulated dark matter distribution at z=0 in ΛCDM model



Springel 2005 (Millennium simulation)

Dark halos are usually much larger than galaxies



E.g., <u>Milky Way</u>:

- scale length of stellar disk R_s~5 kpc
- viral radius of halo R_{200c}~200 kpc

because baryons can radiate away their energy and condense but dark matter cannot, so is supported in larger structures by internal kinetic energy