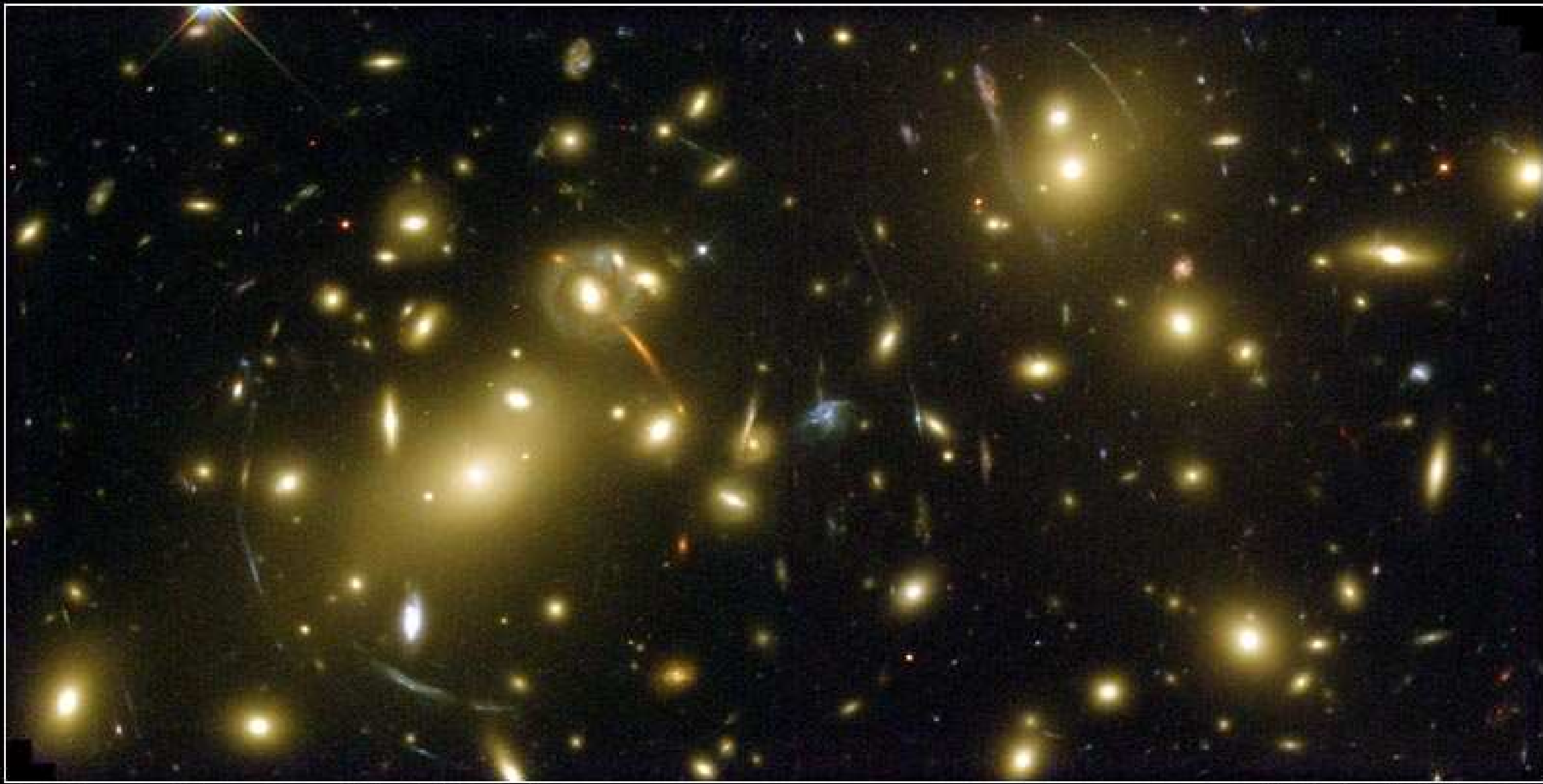
Lecture 4:
Dark Matter in Galaxies



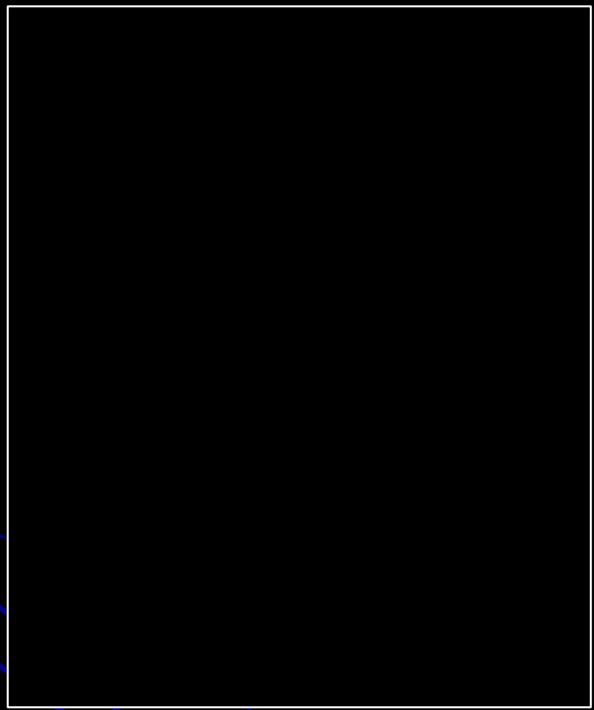
Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Outline

- What is dark matter?
- How much dark matter is there in the Universe?
- Evidence of dark matter
- Viable dark matter candidates
- The cold dark matter (CDM) model
- Problems with CDM on galactic scales
- Alternatives to dark matter

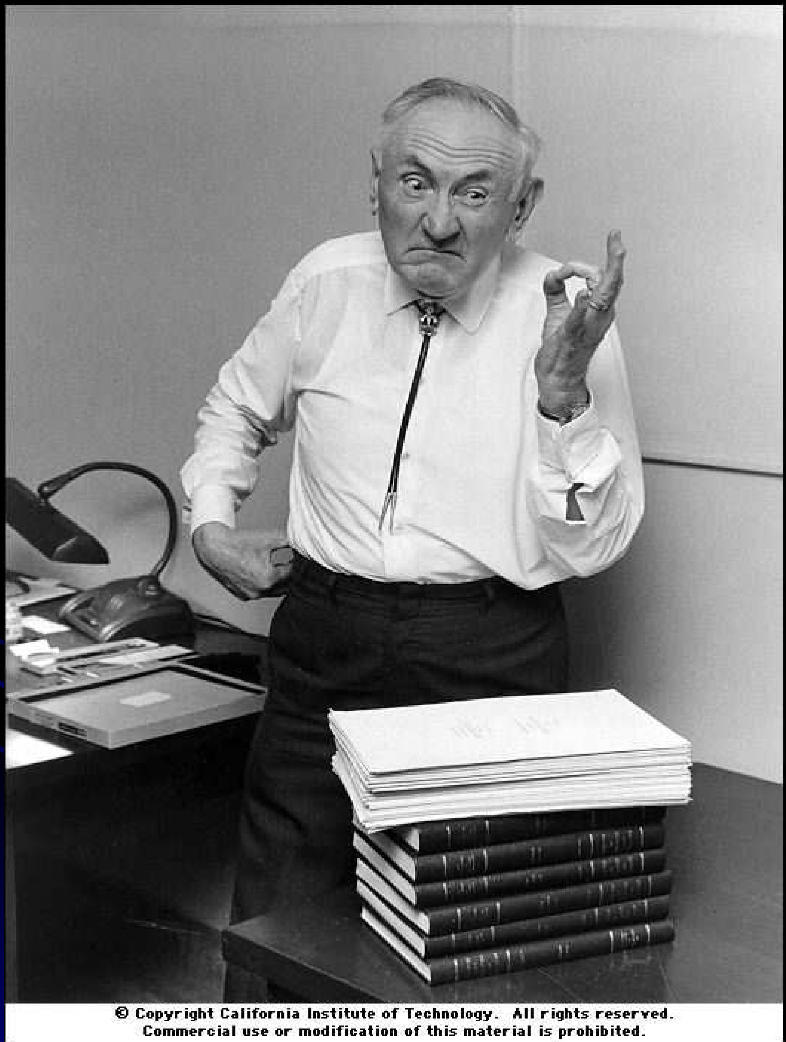
What is Dark Matter?



Dark Matter

Luminous Matter

First detection of dark matter



Fritz Zwicky (1933): Dark matter in the Coma Cluster

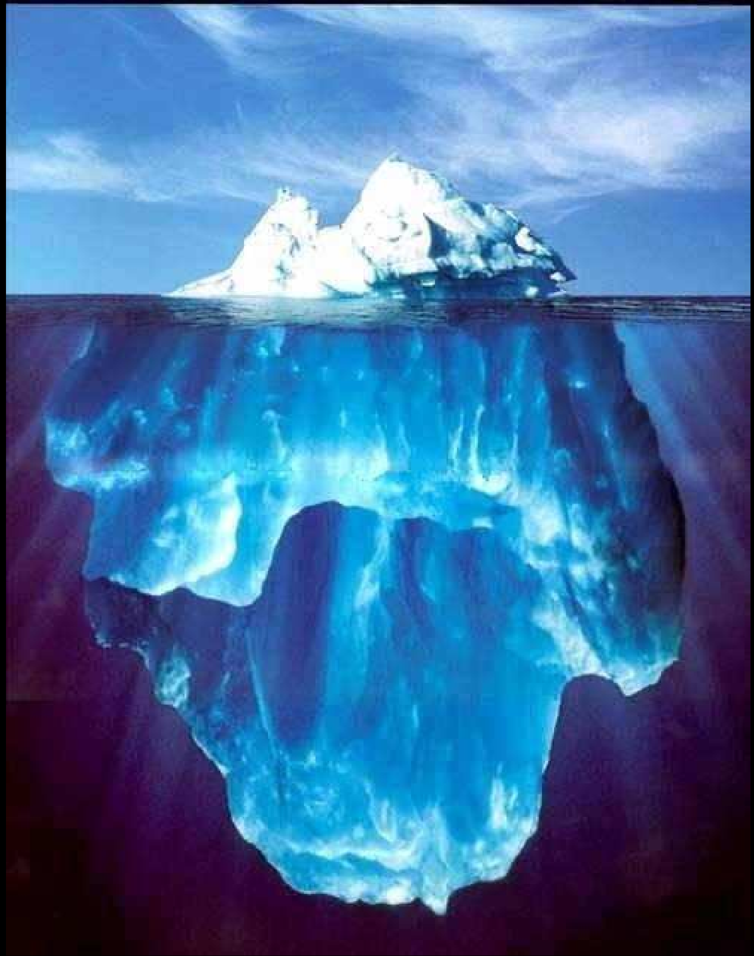
How Much Dark Matter is There in The Universe?

$\Omega_M = \rho_M / \rho_c$

Recent measurements:

$\Omega_M \sim 0.25,\ \Omega_\Lambda \sim 0.75$

$\Omega_{Lum} \sim 0.005$



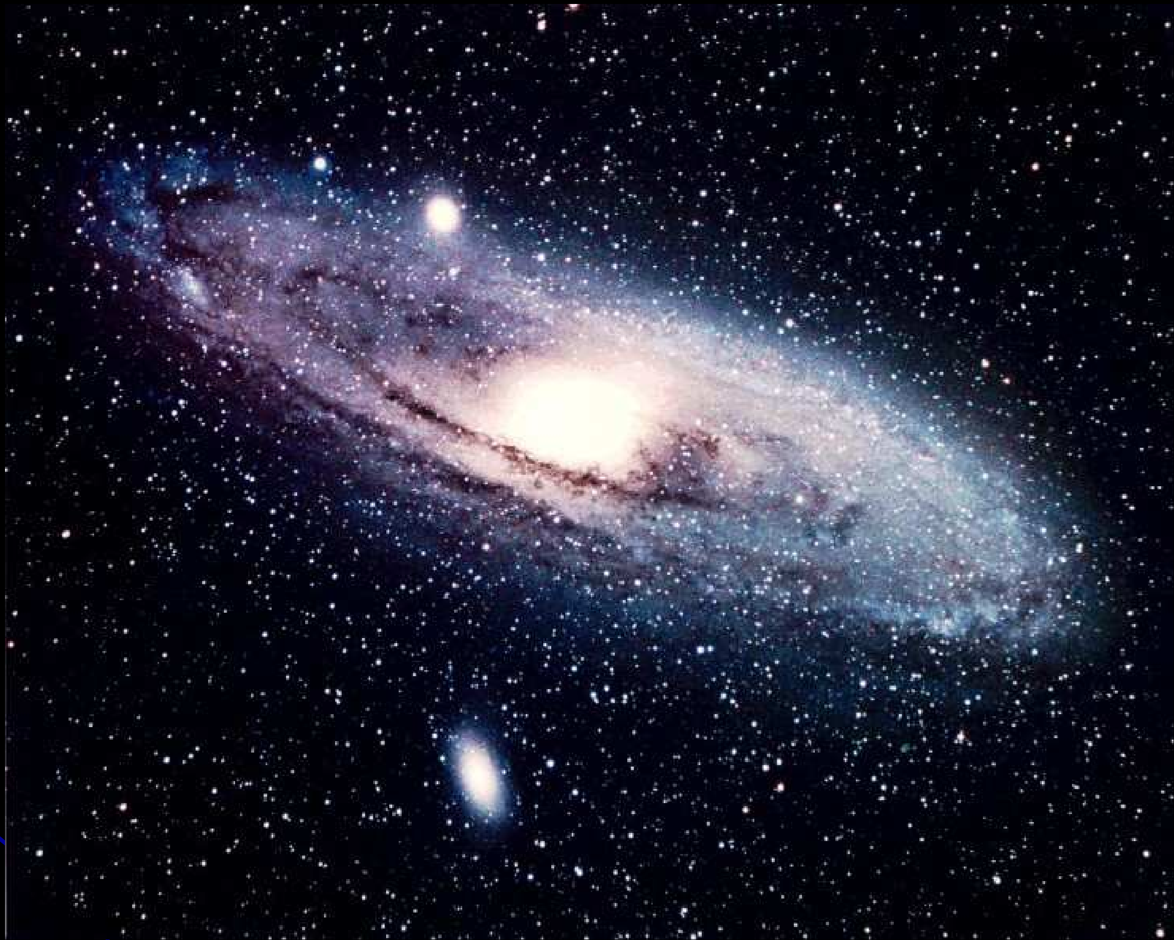
~2%
(Luminous)

~98%
(Dark)

How Do We Know That it Exists?

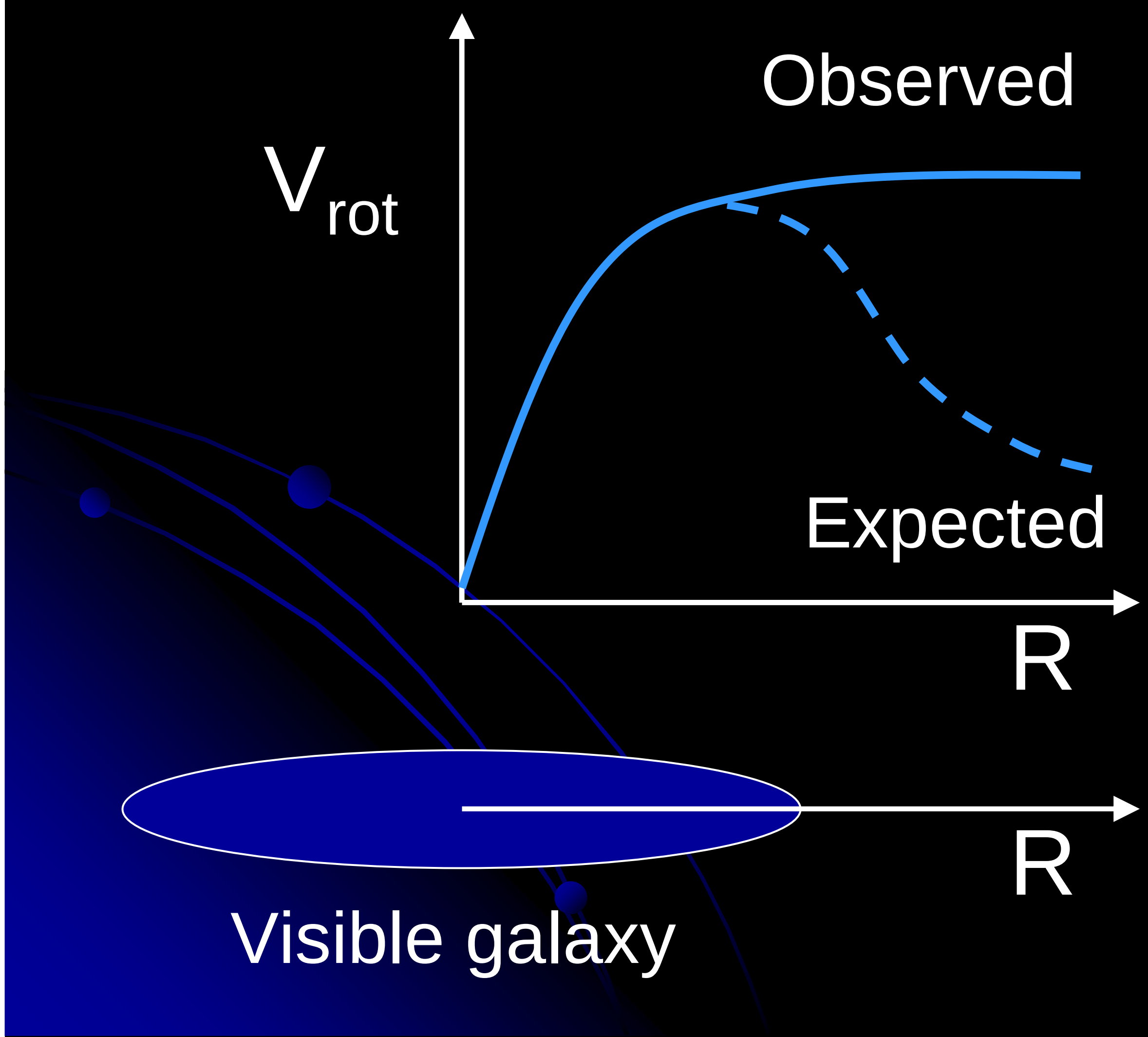
- Cosmological Parameters + Inventory of Luminous material
- Dynamics of galaxies
- Dynamics and gas properties of galaxy clusters
- Gravitational Lensing

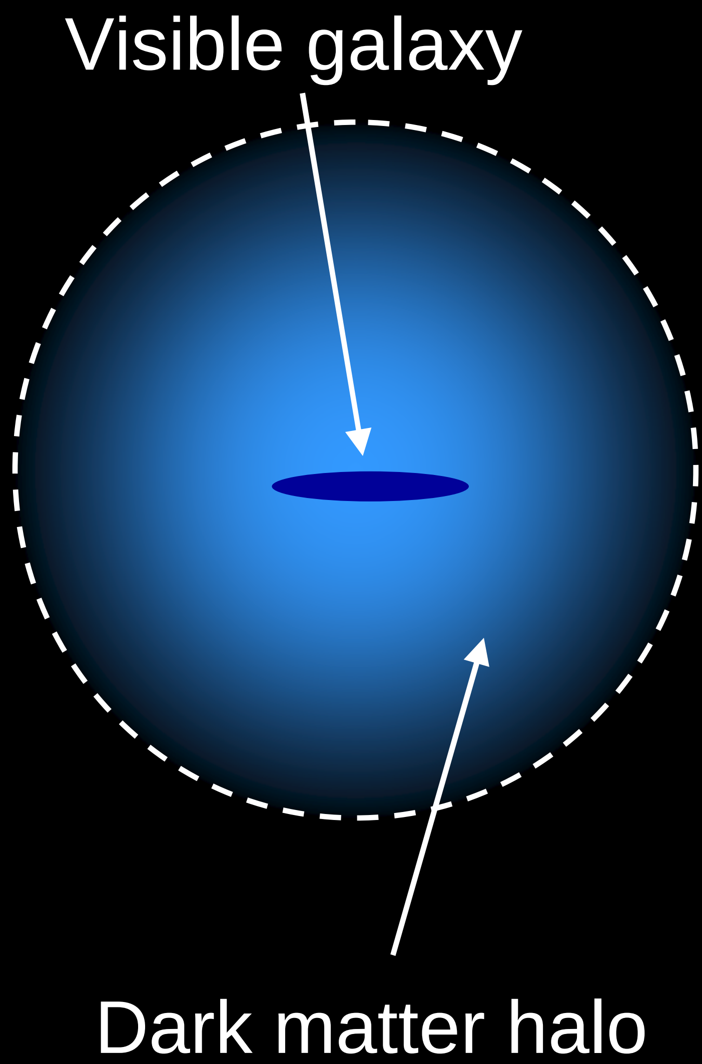
Dynamics of Galaxies I



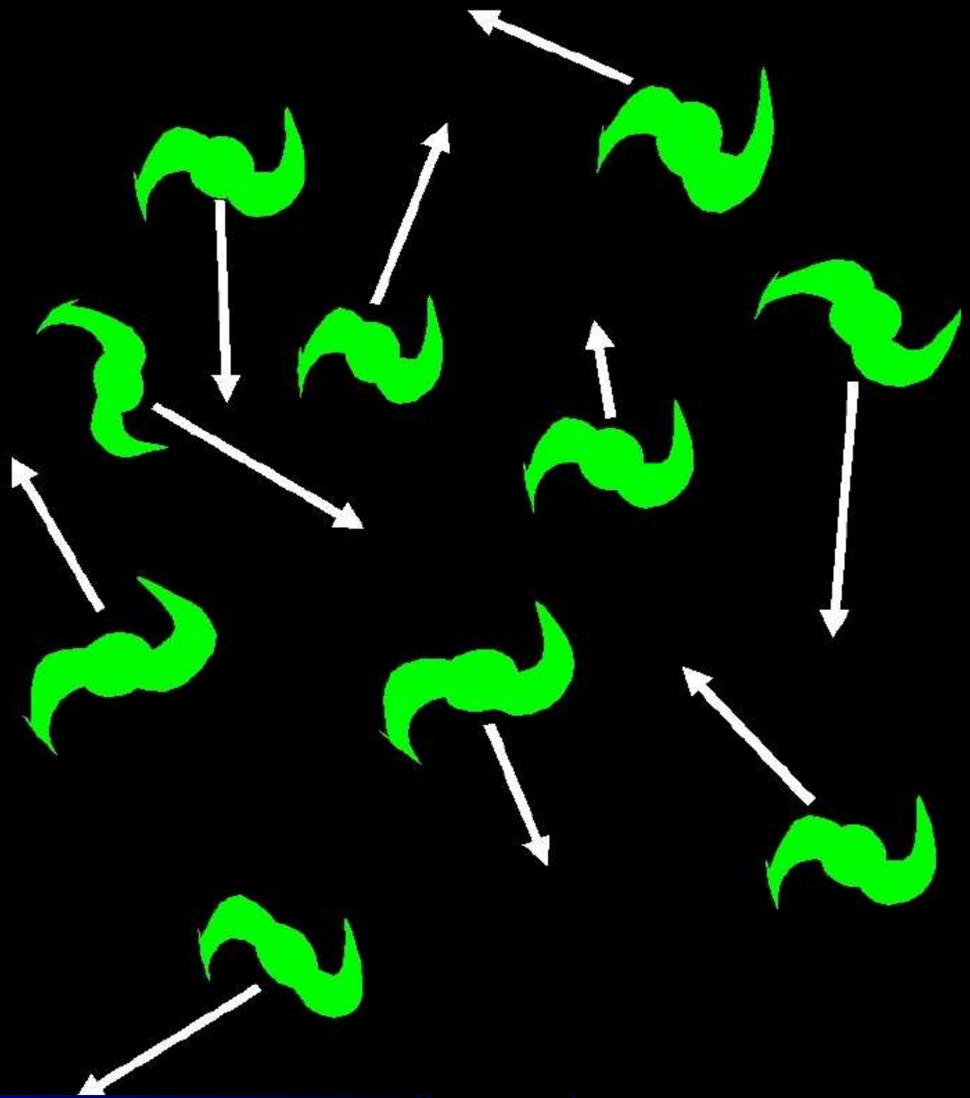
Galaxy ≈ Stars + Gas + Dust + Supermassive Black Hole + Dark Matter

Dynamics of Galaxies II





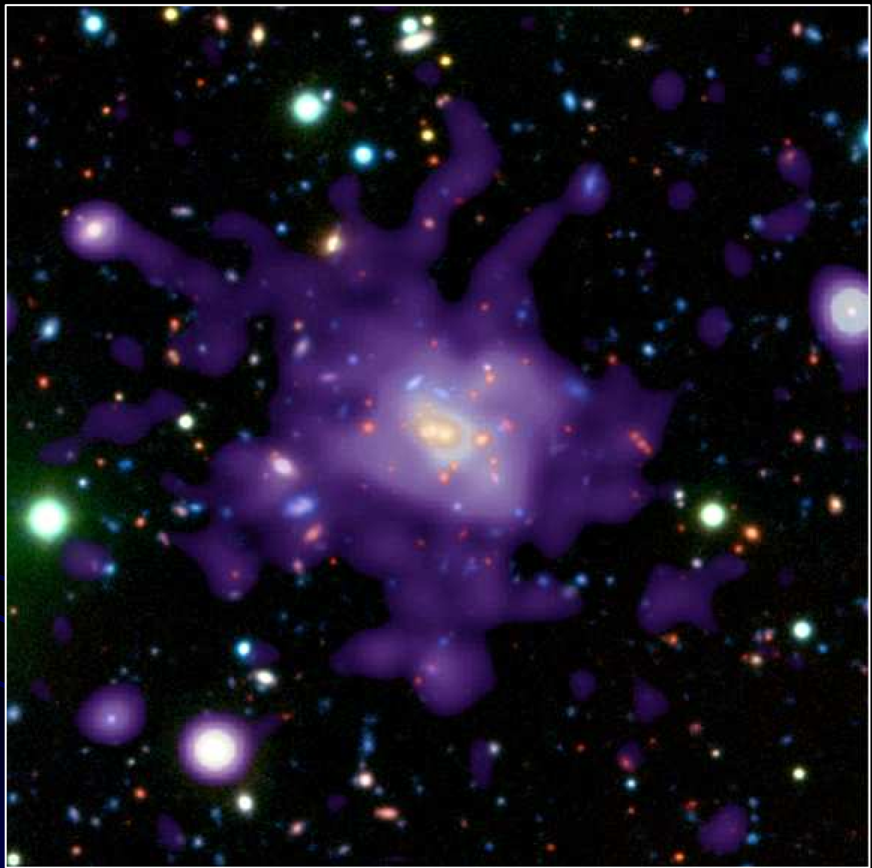
Dynamics of Galaxy Clusters



Balance between kinetic and potential energy →
Virial theorem:

$$M_{\mathrm{vir}} = \frac{\langle v^2 \rangle R}{G}$$

Hot Gas in Galaxy Clusters



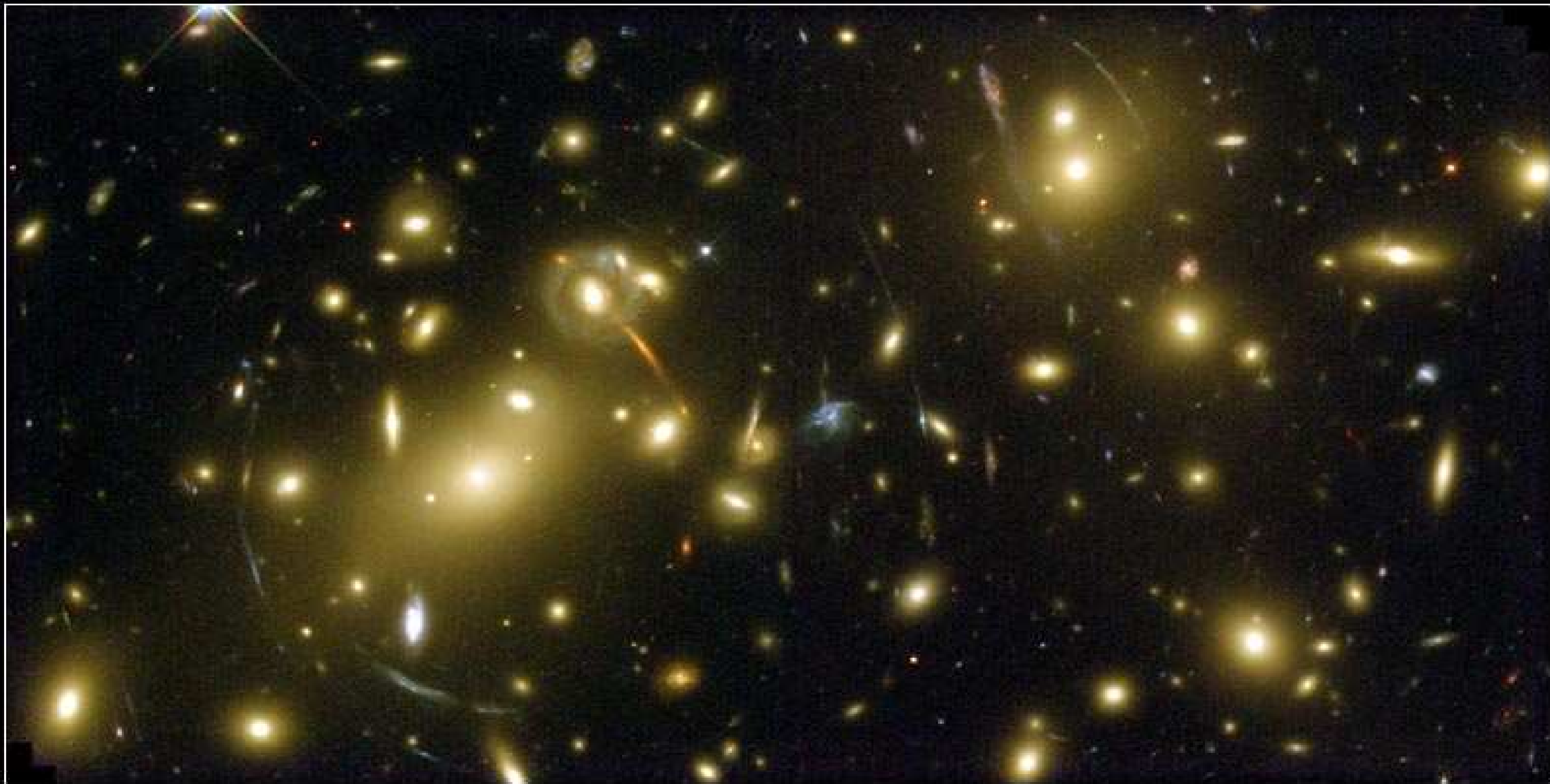
X-ray gas, $T=10^7$—10^8 K

High mass required to keep the hot gas from leaving the cluster!

If gas in hydrostatic equilibrium $\rightarrow$ Luminosity and temperature profile $\rightarrow$ mass profile

Gravitational Lensing

Gravitational Lensing II



Galaxy Cluster Abell 2218 **HST • WFPC2**

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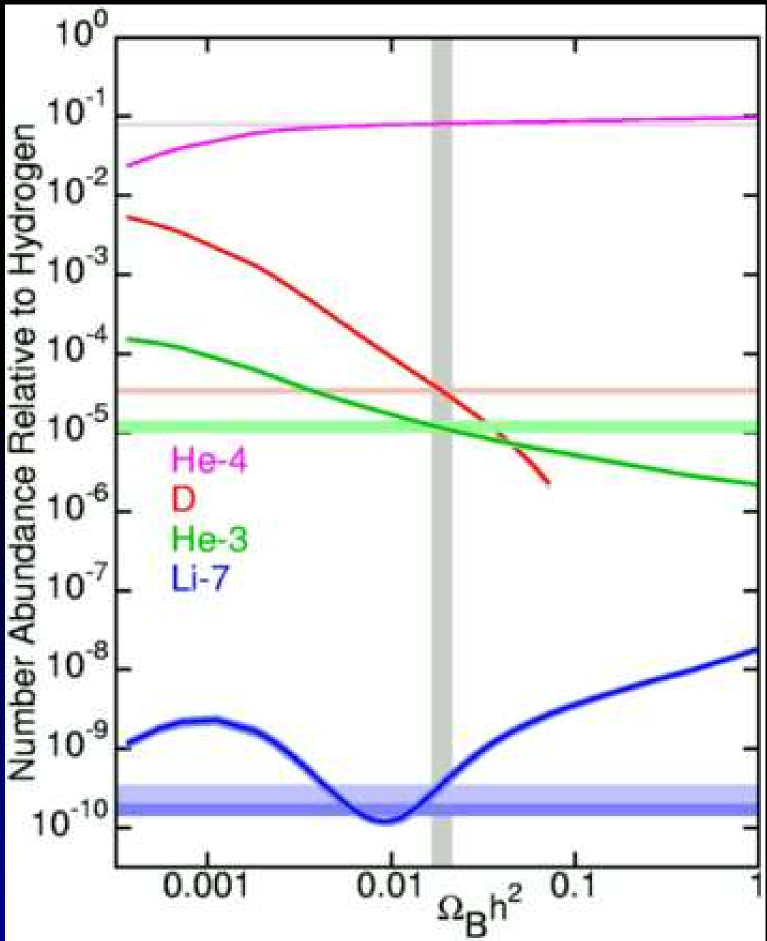
Baryonic and Non-Baryonic Dark Matter I

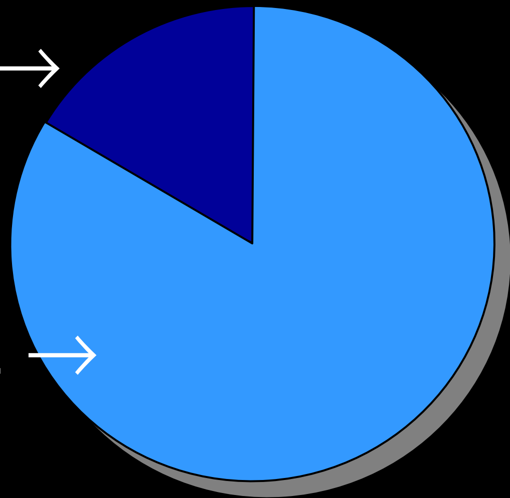
Baryons: Ordinary matter made out of three quarks, like protons and neutrons



BBNS modelling + measurements of primordial abundances *or* CMBR analysis $\rightarrow$ $\Omega_{\text{baryons}} \approx 0.04$

$\Omega_{\text{Baryonic}} \approx 0.04 \rightarrow$

$\Omega_{\text{Non-baryonic}} \approx 0.21 \rightarrow$



$$\Omega_M = \Omega_{\text{Baryonic}} + \Omega_{\text{Non-baryonic}} \approx 0.25$$

Baryonic and Non-Baryonic Dark Matter II

Still missing in the local Universe:

- About 1/3 of the baryons $\rightarrow$

  $\Omega_{\text{DM, baryonic}} \sim 0.015$

  But note: The missing baryons *may* have been detected at high redshift

- Essentially all of the non-baryons $\rightarrow$

  $\Omega_{\text{DM, non-baryonic}} \sim 0.21$ (assuming $\Omega_M = 0.25$)

MACHOs and WIMPs

- MACHO = MAssive Compact Halo Object
- WIMP = Weakly Interacting Massive Particle

But beware of misconceptions!

A Few Viable Dark Matter Candidates

<u>Baryonic</u>

- Faint stars
- Fractal H_2
- Warm/hot intergalactic gas
- Hot gas around galaxies
- Rydberg matter

<u>Non-baryonic</u>*

- Supersymmetric particles
- Axions
- Sterile neutrinos
- Primordial black holes
- Preon stars
- Quark nuggets
- Mirror matter
- Matter in parallel branes
- Kaluza-Klein particles

* or evading current constraints on the cosmic baryon density

Hot and Cold Dark Matter

- Hot Dark Matter (HDM)
  - Relativistic at decoupling

- Cold Dark Matter (CDM)
  - Non-relativistic at decoupling
  - The standard model for the non-baryonic dark matter
  - Successful in explaining the formation of large scale structure

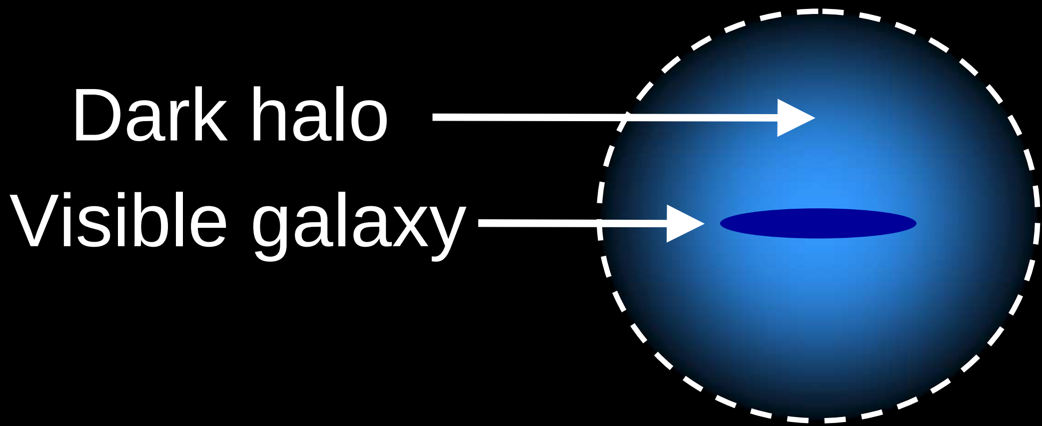
Additional Assumed CDM Properties

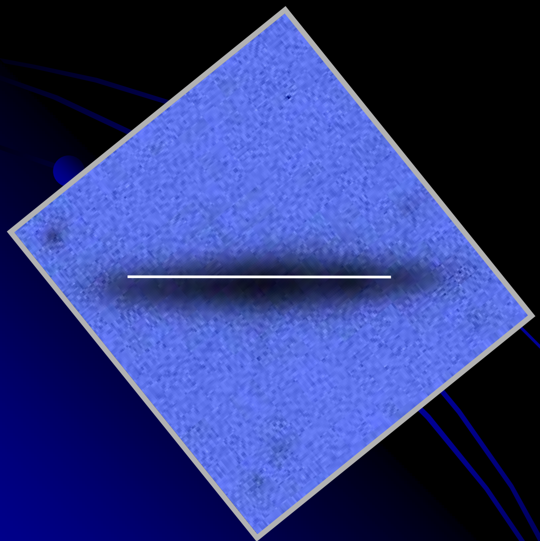
- Collisionless – interacts mainly through gravity
- Dissipationless – cannot cool by radiating photons
- Long-lived particles
- Behaves as perfect fluid on large scales
- Adiabatic primordial density perturbations, following a scale-invariant power spectrum

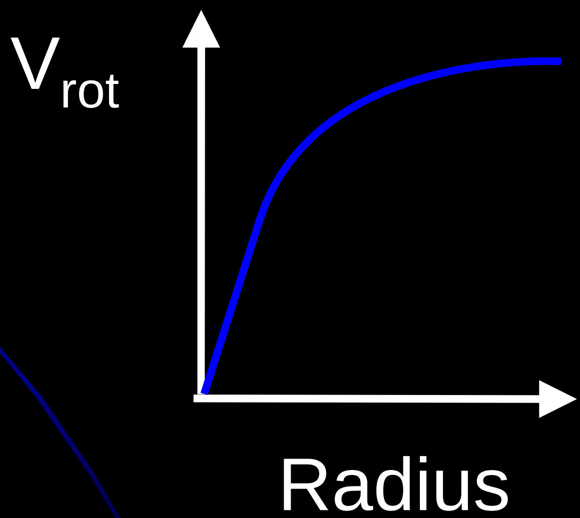
Problems with CDM

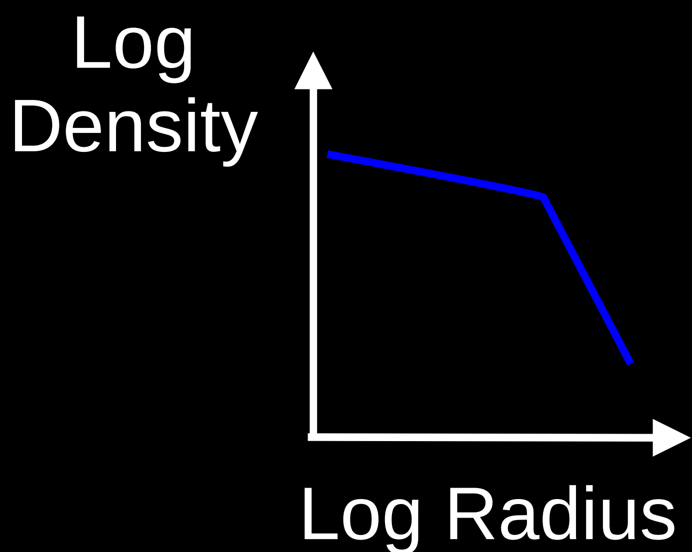
- Dark halo density profiles
- Dark halo substructure
- Dark halo mass function in the field
- Dark halo shapes
- The angular momentum problem

Dark Halo Density Profiles I







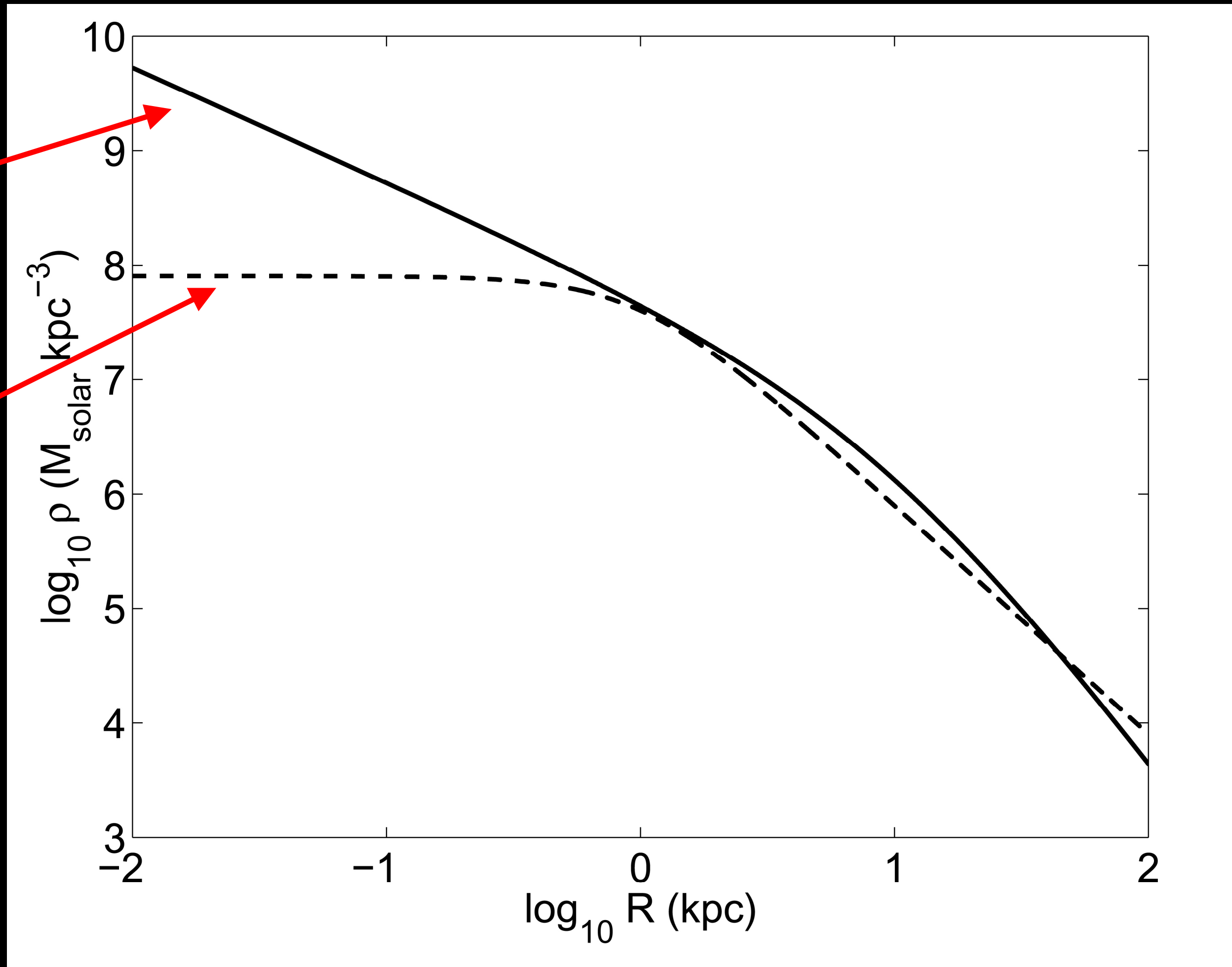


Spectroscopy → Rotation Curve → Halo Density Profile

Dark Halo Density Profiles II

Predicted by the Cold Dark Matter Scenario (density cusp)

Favoured by observations (density core)



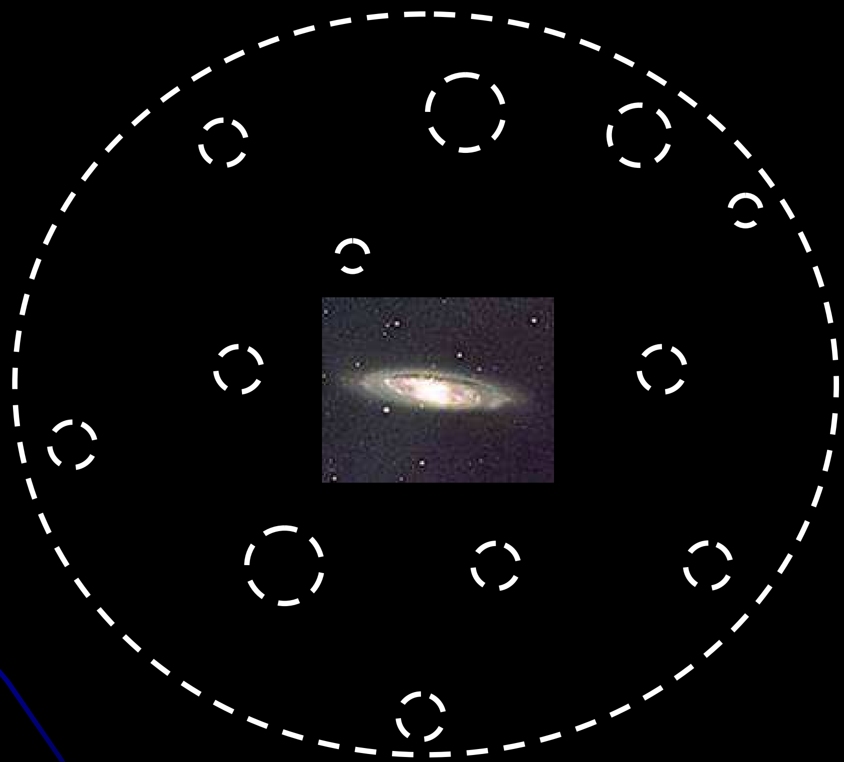
Dark Halo Density Profiles III

But there are plenty of complications…

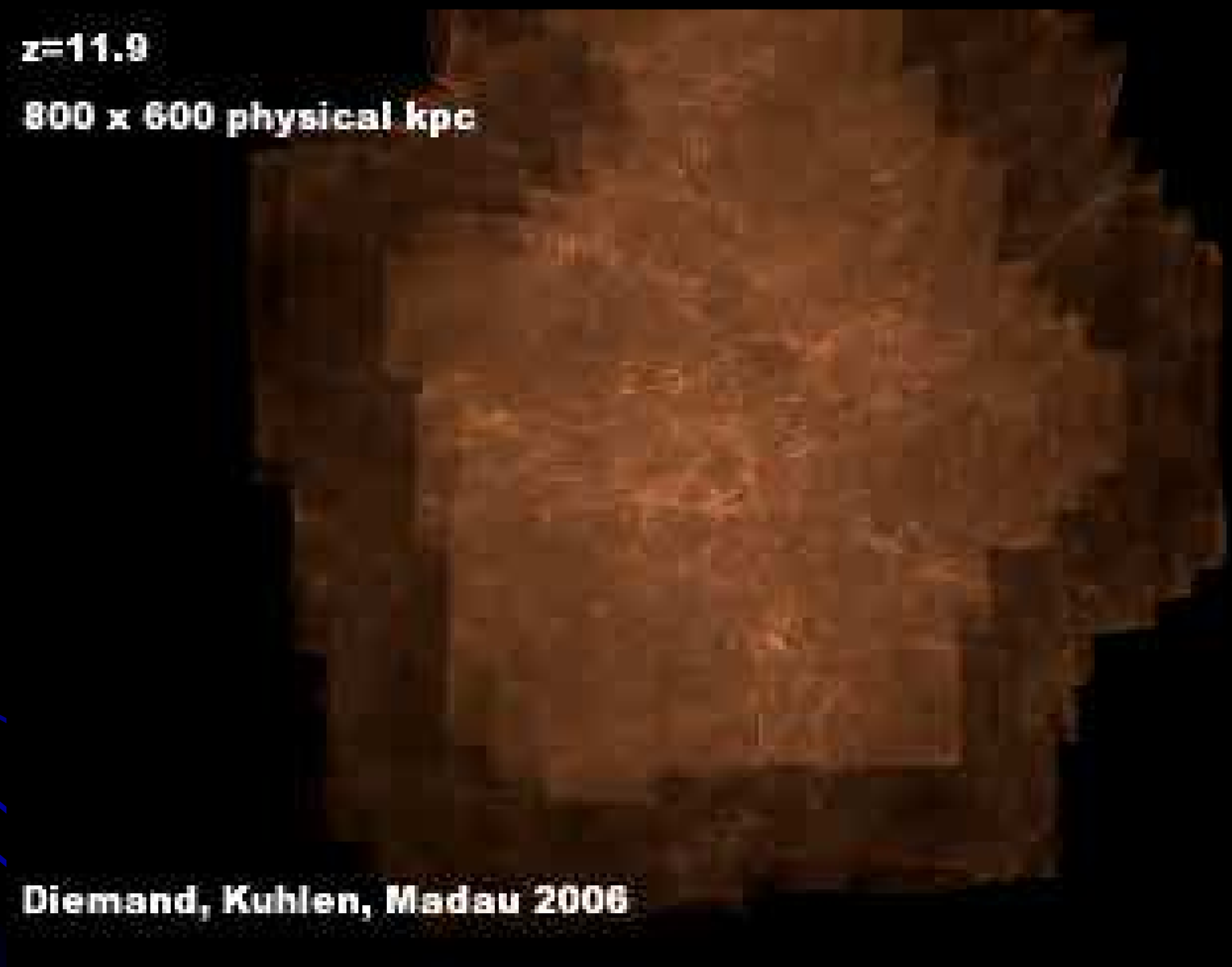
- Non-spherical dark matter halos?
- Central part dominated by dark baryons instead of CDM?
- Best target galaxies do not sit in typical dark halos?
- N-body simulations responsible for the predicted CDM halo profile prediction not reliable?

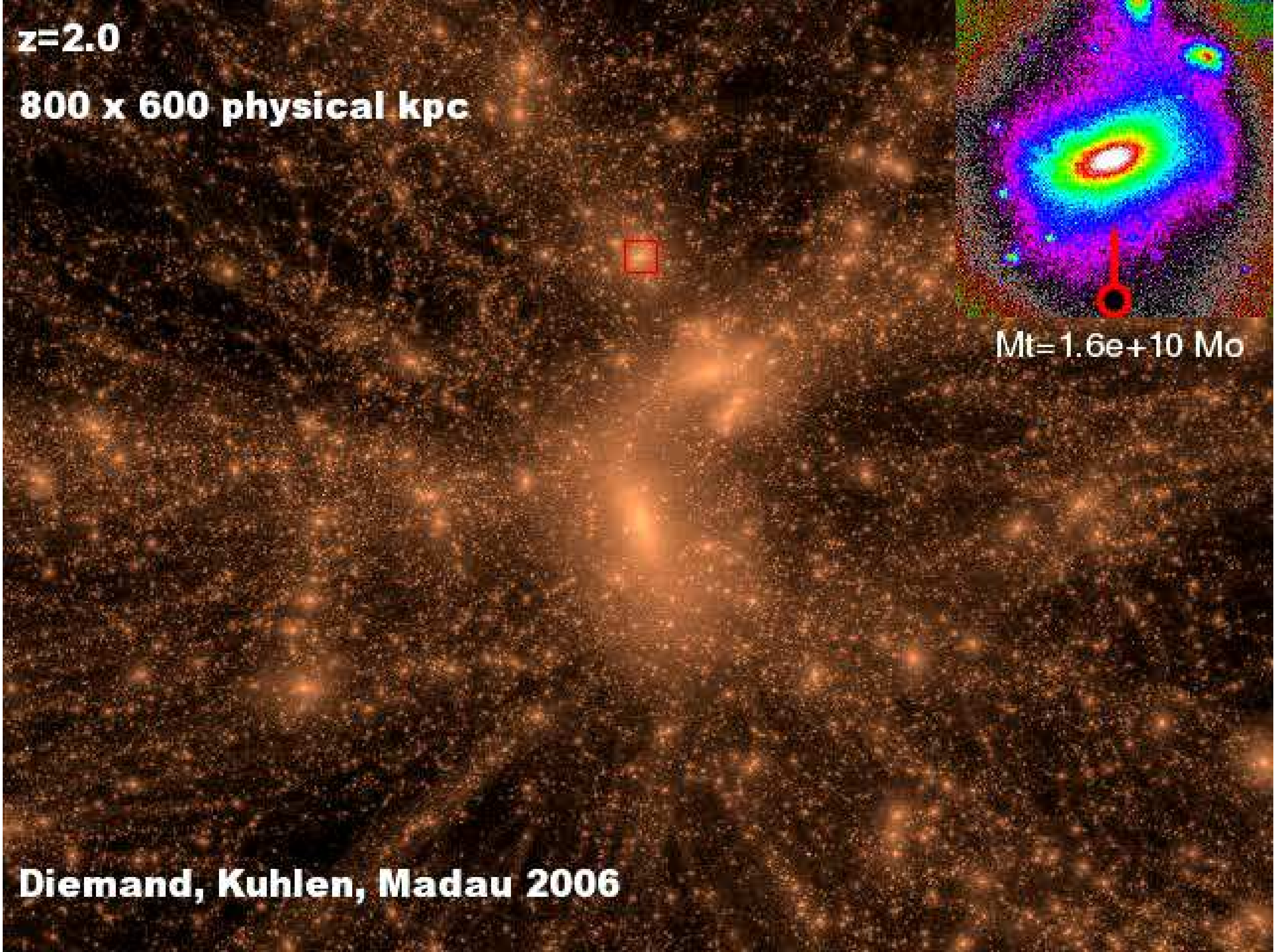
Dark Halo Substructure I

The dark halos around galaxies form the merger of smaller halos, but many remnants of the smaller halos survive $\rightarrow$ The dark halos of galaxies are not perfectly smooth!



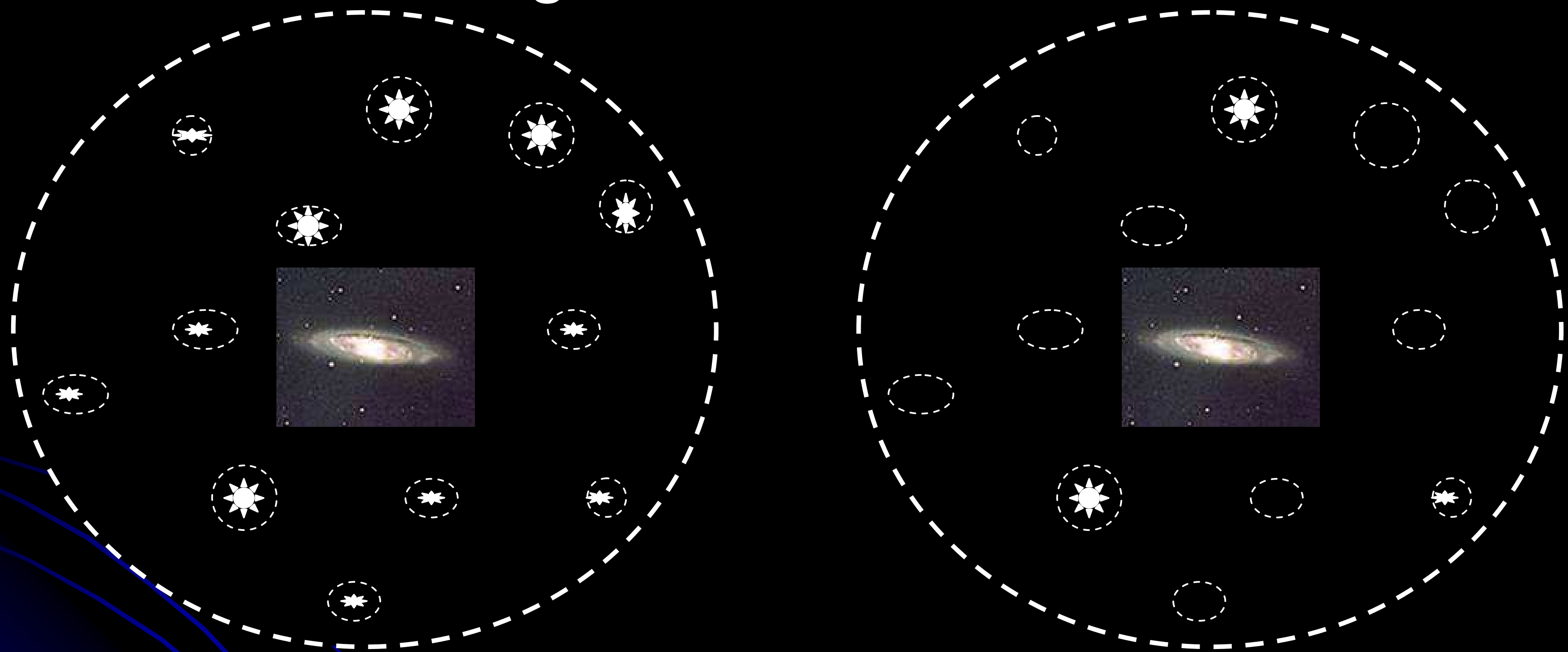
$$M_{subhalos} \leq 0.1 \times M_{halo}$$


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006


z=2.0
800 x 600 physical kpc
Mt=1.6e+10 Mo
Diemand, Kuhlen, Madau 2006

Dark Halo Substructure II

Should not dwarf galaxies form inside the subhalos?



Naïve expectation | Observed

A factor of 10—100 too few satellite galaxies around the Milky Way!

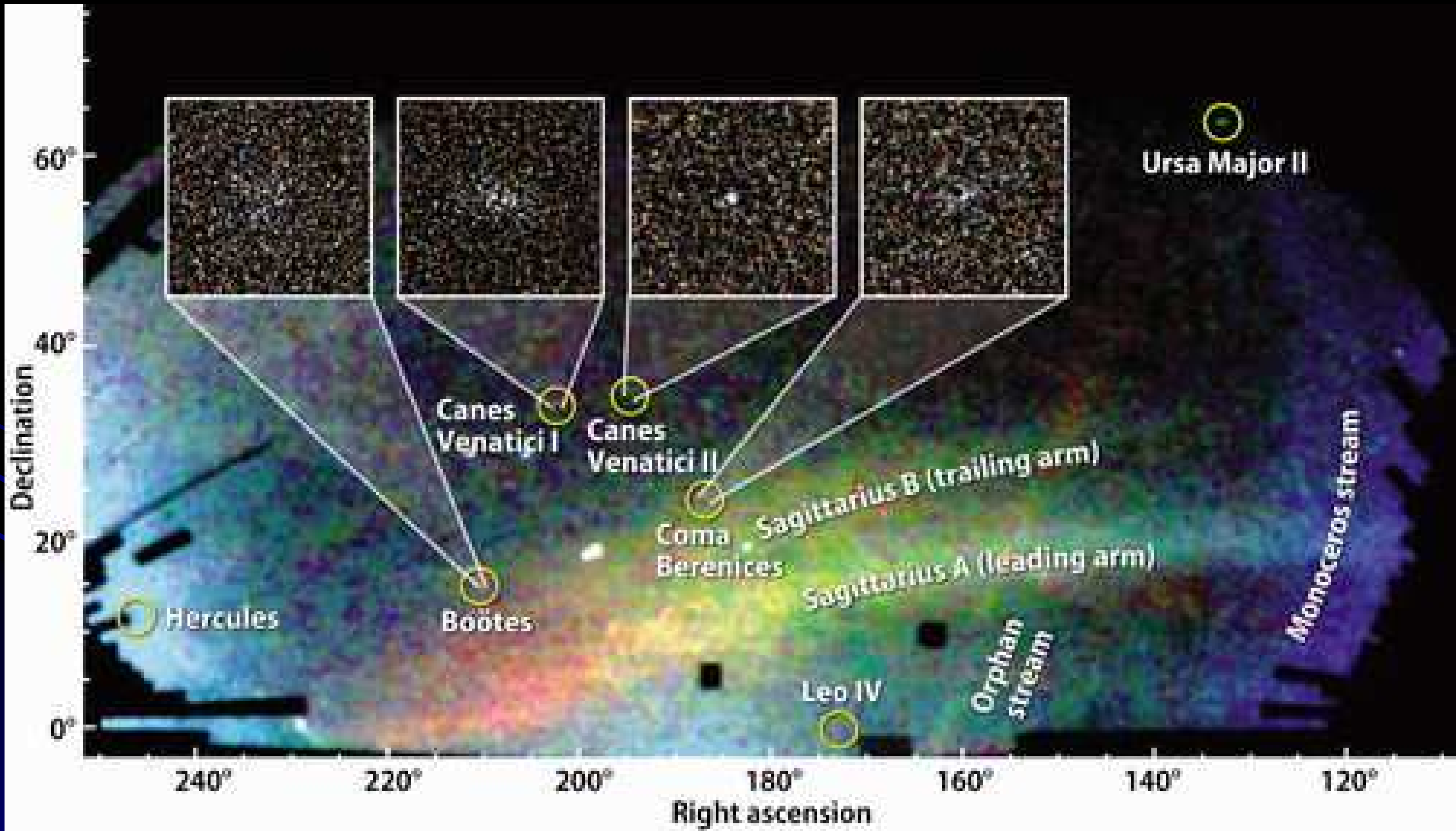
Dark Halo Substructure III

The solution: Dark galaxies?

- Dark galaxy: A dark subhalo which either lacks baryons, or inside which the baryons form very few stars
- Possible detections exist:
  - Galaxies with very high mass-to-light ratios
  - Possible gravitational lensing detections

How to detect halo substructure I

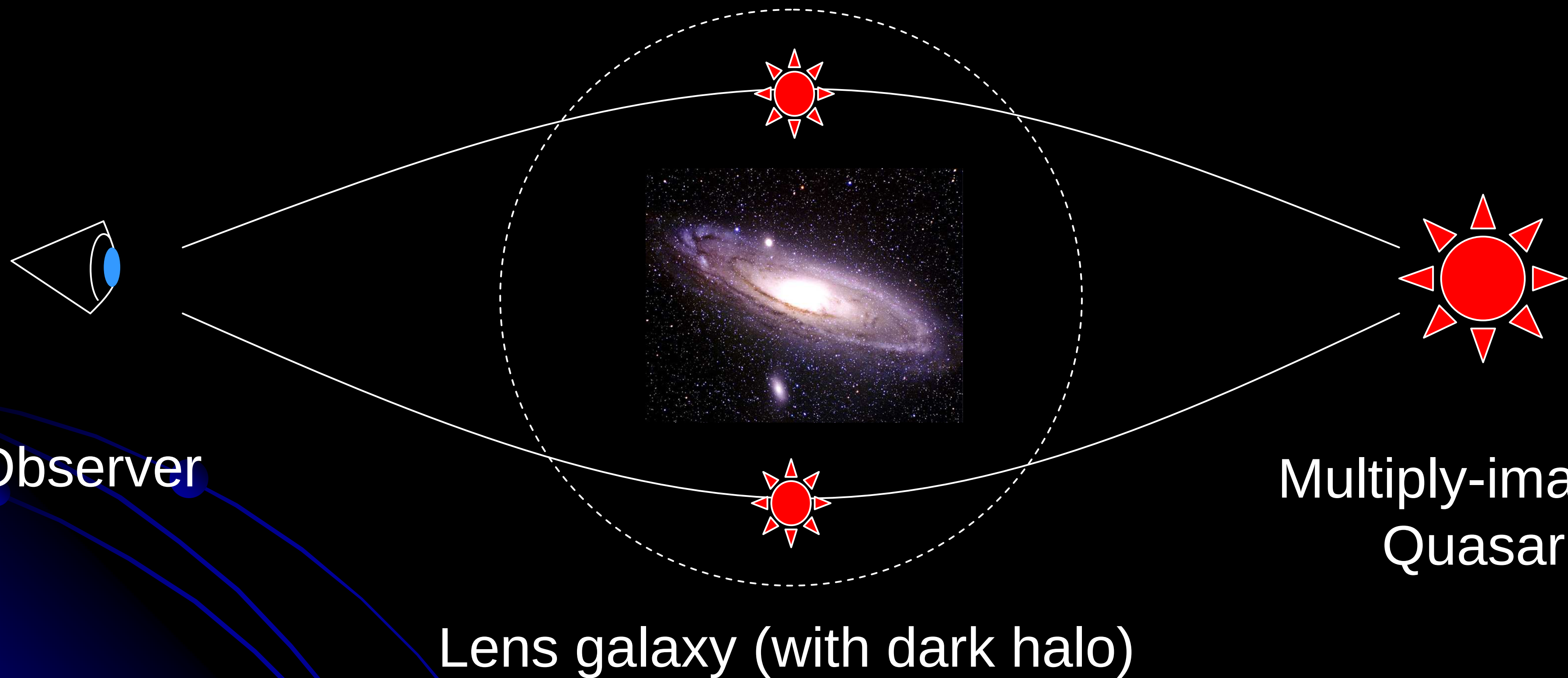
Searching for ultrafaint galaxies
around the Milky Way using the SDSS →
Lots of very faint galaxies found

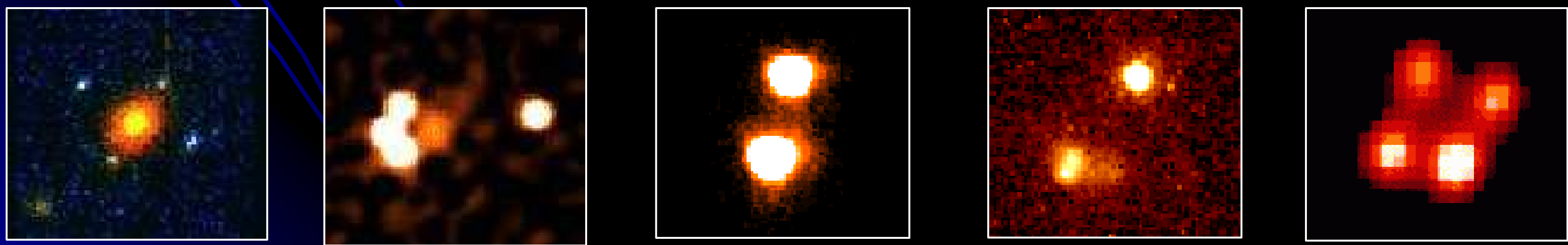


But: Not enough of them to confirm the CDM predictions…

How to detect halo substructure II

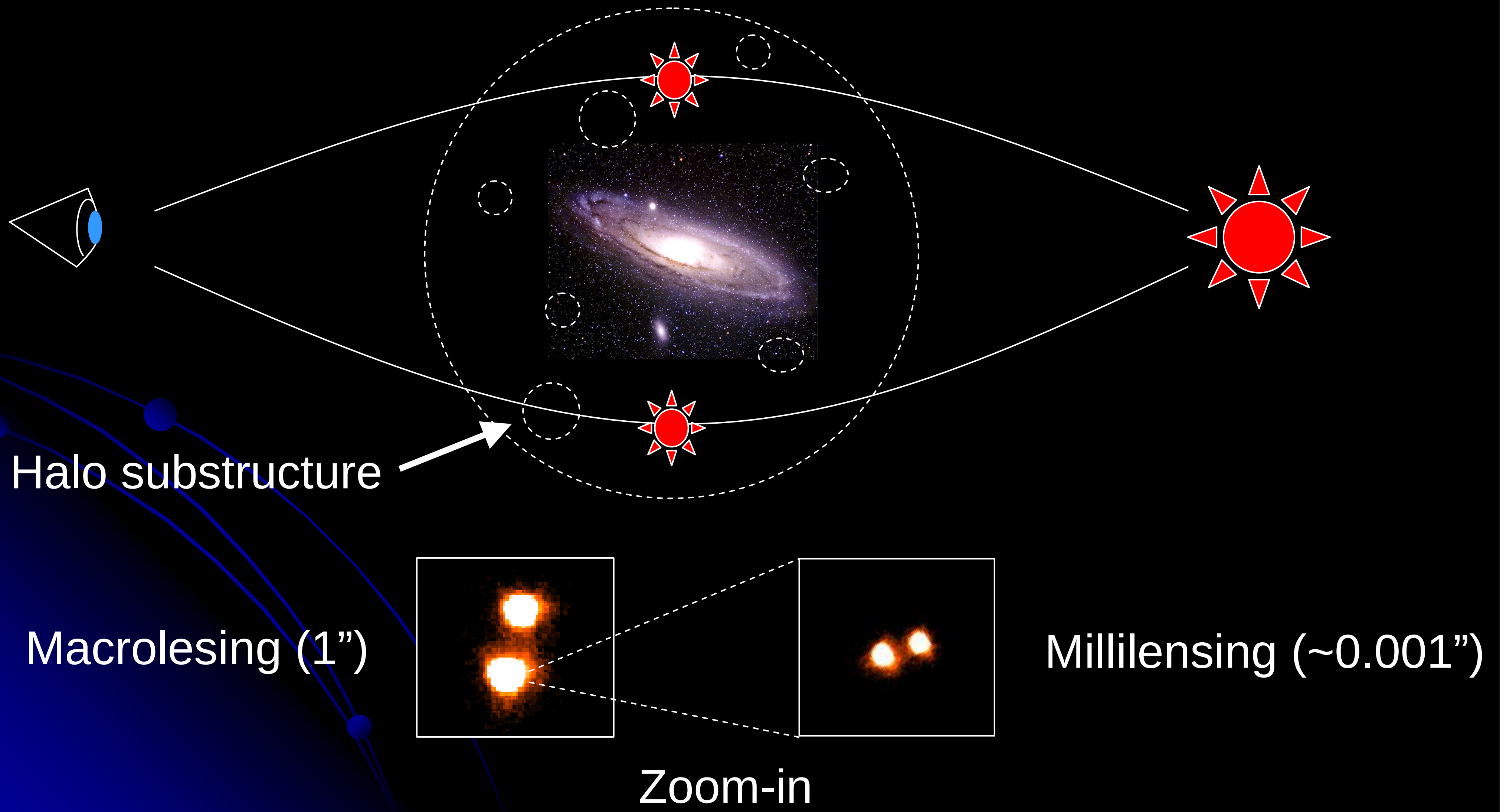
Dark halos can cause image splitting in quasars on angular angular scales of ~1 arcsecond (strong lensing or macrolensing)





How to detect halo substructure III

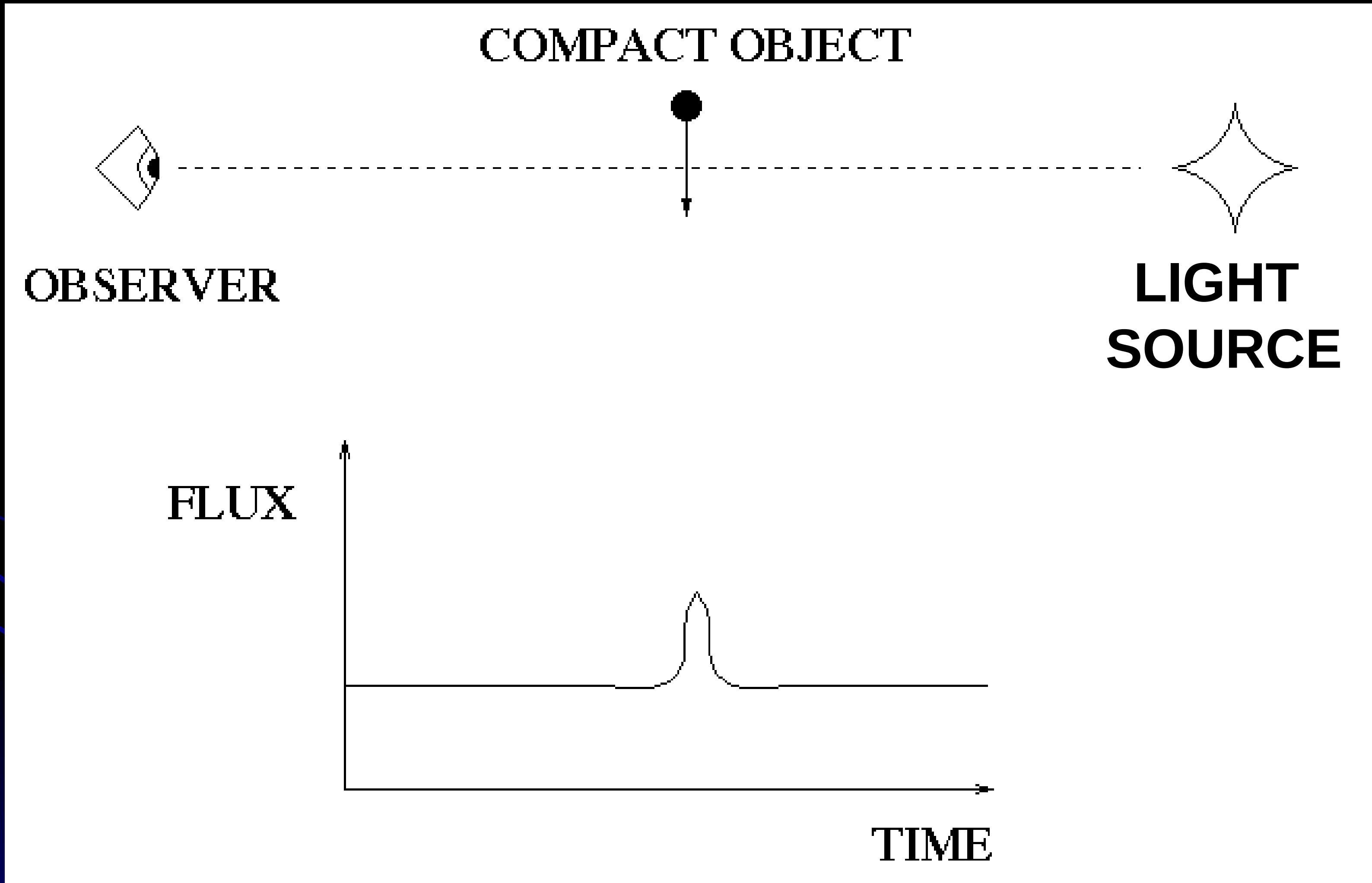
Halo substructure can cause additional magnification and possibly splitting of each image. The splitting is predicted to occur on angular scales of ~0.001 arcseconds (millilensing).



How to Search for the Dark Matter

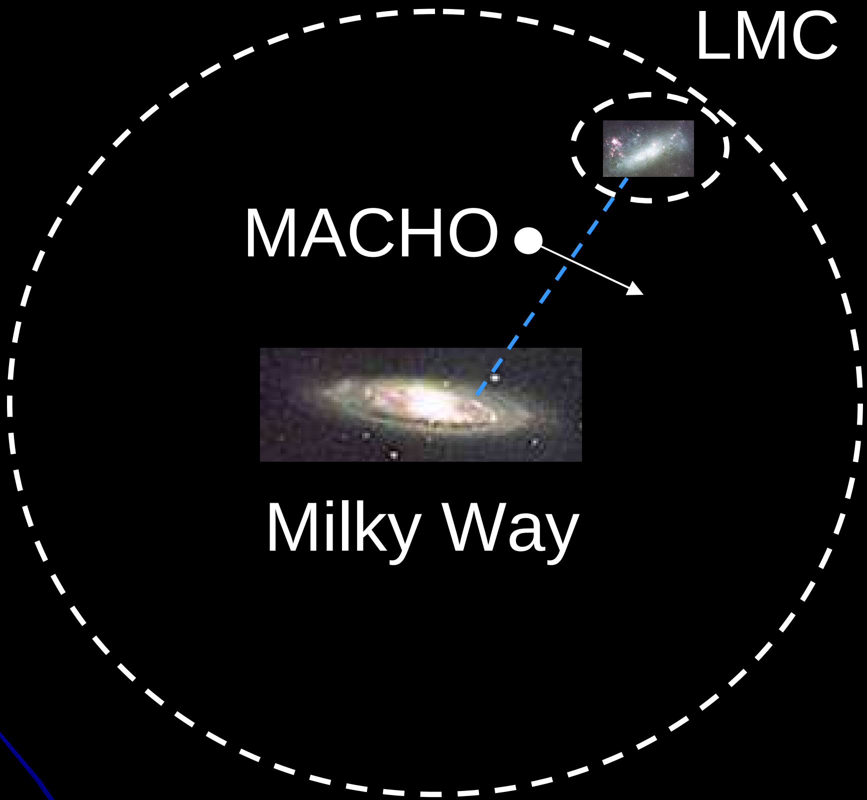
- Gravitational microlensing by MACHOs
- WIMP direct detection
  - Recoil in detector
  - Annular modulation
- WIMP indirect detection
  - Cosmic rays from annihilating WIMPs
  - Neutrinos from WIMP annihilation in Sun/Earth
  - Photons (gamma, radio) from WIMP annihilation in the Galactic Centre

Gravitational Microlensing by MACHOs



Possible detections of MACHOs

MACHO project: monitoring of 12×10^6 stars in the Large Magellanic Cloud



Detection of $M_{compact}\sim10^{-1}\ M_{solar}$, constituting $\approx$20% of the dark halo

Alternatives to CDM

- Warm dark matter
- Mixed dark matter (cold + hot)
- Self-interacting dark matter
- Self-annihilating or decaying dark matter
- Fuzzy dark matter
- Alternative theories of gravity

Do We Have the Correct Theory of Gravity?

”I invite the reader (...) to test whether he/she is not left with some uneasiness as our wonderful 'standard' cosmology seems in fact to be so far essentially based on

a) a *Dark Matter* we do not detect

b) a *Dark Energy* we do not understand

c) a fraction of Baryons we cannot completely find!

Yet everything seems to work;

isn't this reminiscent of epicycles?“

L. Guzzo (2002)

MOND

(MOdified Newtonian Dynamics; Milgrom 1984)

Newtonian dynamics: $a = MG/r^2$

MOND: $a^2/a_0 = MG/r^2$

in the limit of small accelerations

$\rightarrow$ $\mu(a/a_0)a = MG/r^2$

where $\mu(x) \approx 1$ when $x \gg 1$

$\mu(x) \approx x$ when $x \ll 1$

Remarkably successful in explaining the dynamics of galaxies!

MOND II

From Stacy McGaugh's homepage:

"'You do not know the Power of the Dark Side. Join me, and together we can use dark matter to make galaxy rotation curves flat.'
I often hear this sort of paternalistic line from well intentioned senior astronomers. My response is the same as Luke's, with analogous consequences for my career."

Problems with MOND

- Original MOND: Phenomenological extension of Newtonian gravity $\rightarrow$ No predictions for e.g. gravitational lensing or cosmic expansion

  Solved by Bekenstein (2004)!
- Fails to explain the dynamics of galaxy clusters (e.g. the famours "Bullet cluster") – some dark matter is still required
- Fails to explain difference between systems of similar baryonic masses, e.g. globular clusters and dwarf galaxies
- Problems in explaining observed gravitational image splitting

But: Other alternative theories of gravity (e.g. MOG) may do better!

Summary

- The nature of dark matter is one of the great unsolved problems of cosmology
- Astronomical observations can constrain the properties of dark matter
- Observations on galactic scales seem to contradict the CDM model

Identifying the dark matter particle will probably get you the Nobel prize!