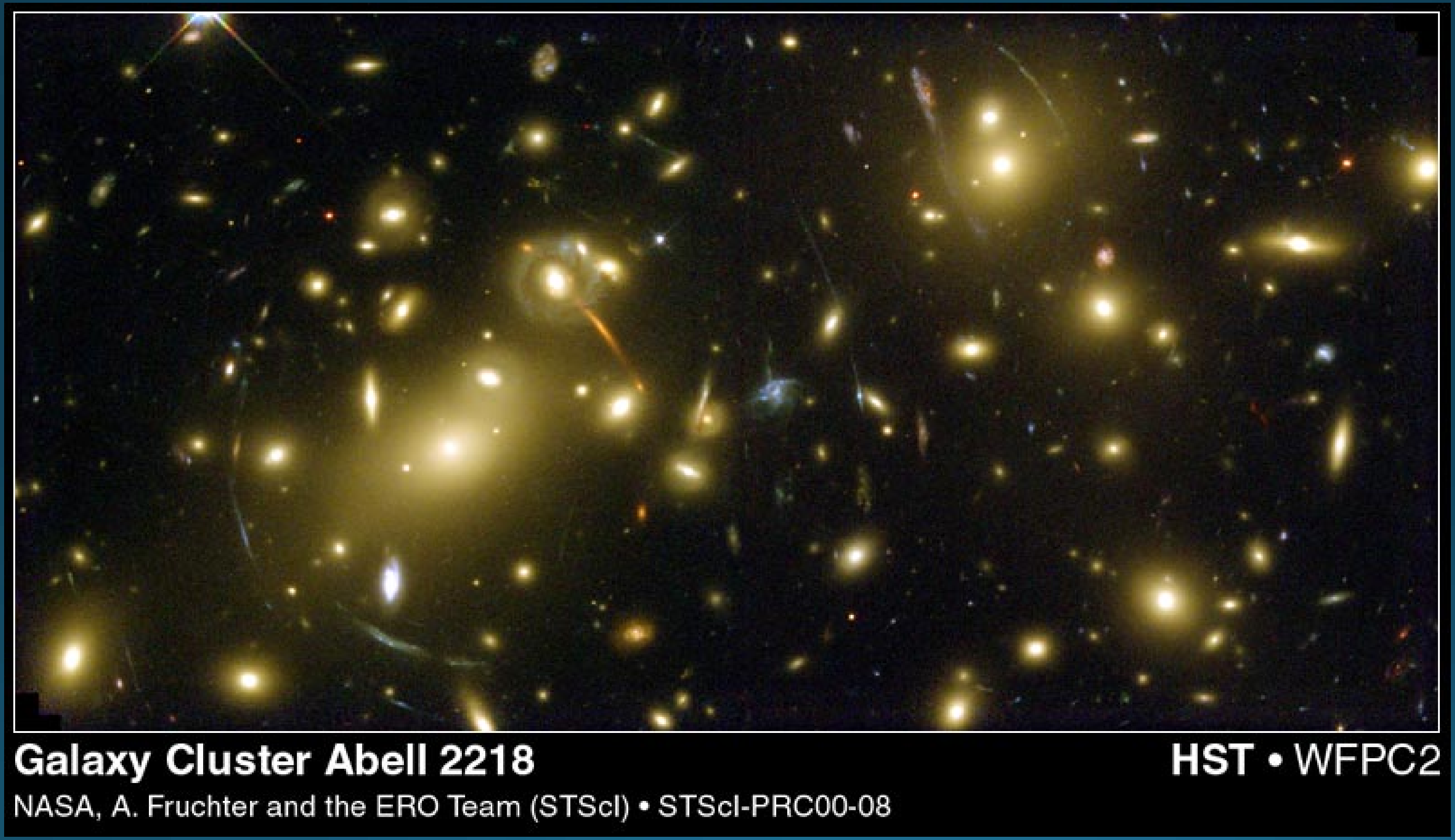
Cosmology 1FA209, 2016
Lecture 6: Dark matter

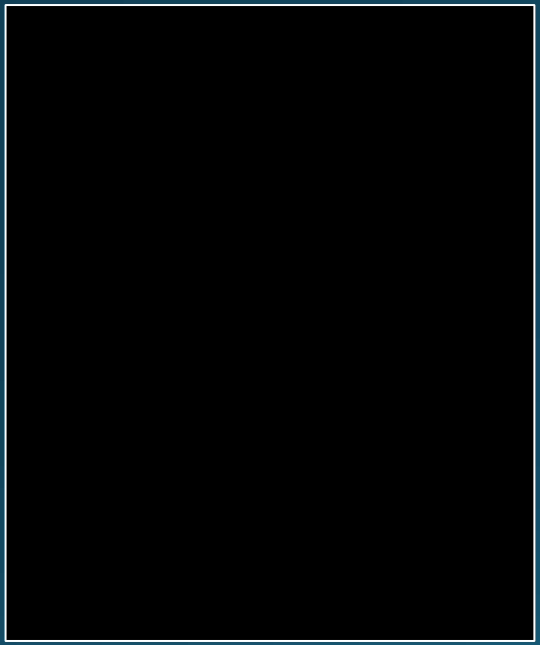


Outline

- What is dark matter?
- How much dark matter is there in the Universe?
- Evidence of dark matter
- Viable dark matter candidates
- Cold dark matter (CDM)
- Problems with CDM
- Search strategies and possible detections
- Alternatives to dark matter

Covers chapter 8 in Ryden + extra stuff

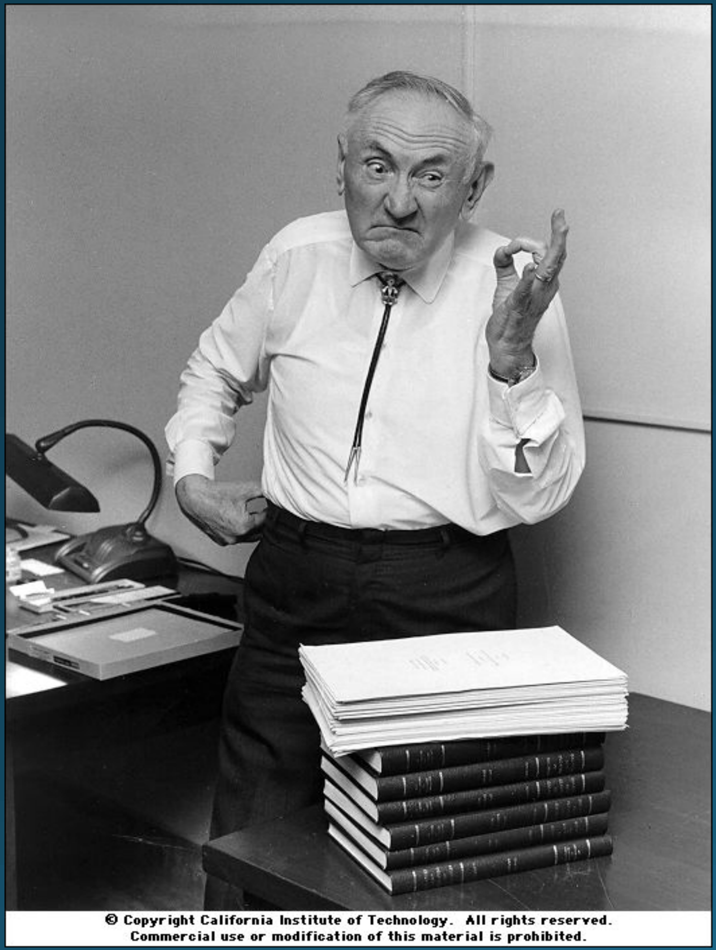
What is Dark Matter?



Dark Matter

Luminous Matter

First detection of dark matter



Fritz Zwicky (1933): Dark matter in the Coma Cluster
Often claimed to be the first detection, but…

First detection of dark matter

Recent (2015) ”rediscovery” of old paper $\Rightarrow$
Knut Lundmark (1930): Dark matter in several galaxies, including the Milky Way and Andromeda

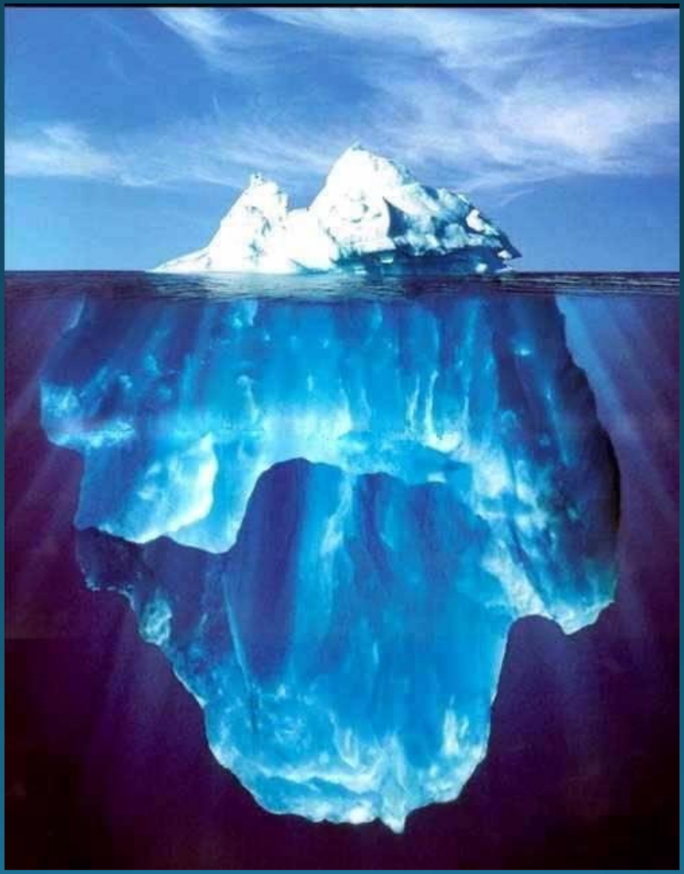
How Much Dark Matter is There in The Universe?

$\Omega_M = \rho_M / \rho_c$

Recent measurements:

$\Omega_M \sim 0.3$, $\Omega_\Lambda \sim 0.7$

$\Omega_{Lum} \sim 0.005$



~2%
(Luminous)

~98%
(Dark)

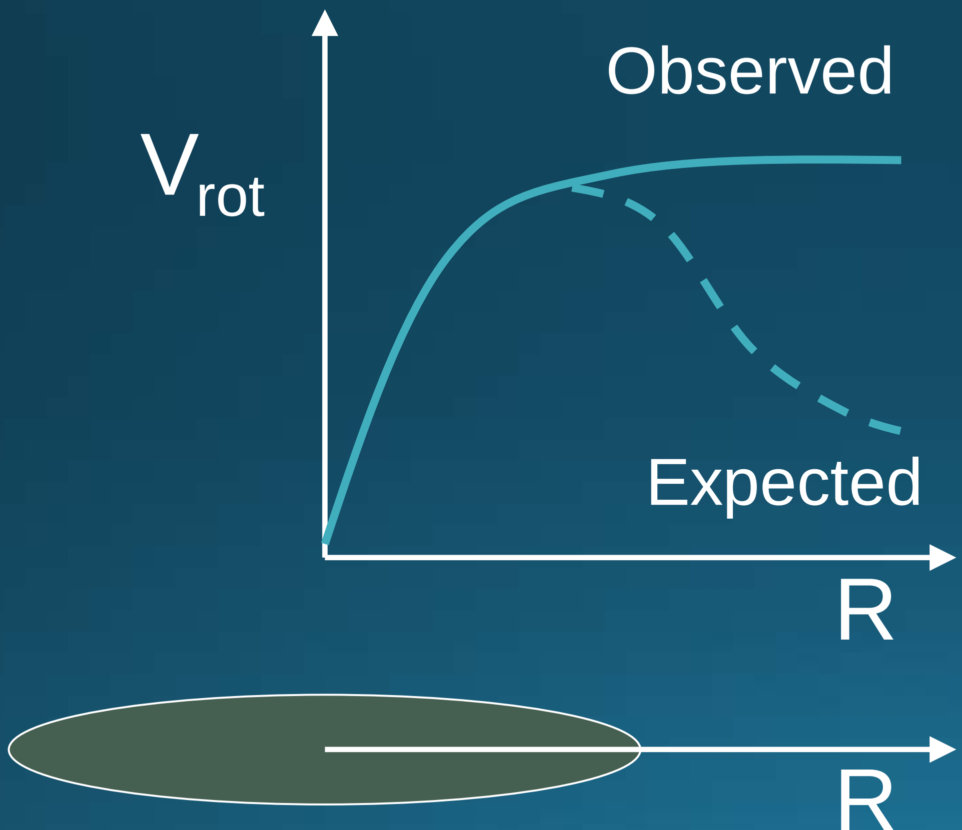
How Do We Know That it Exists?

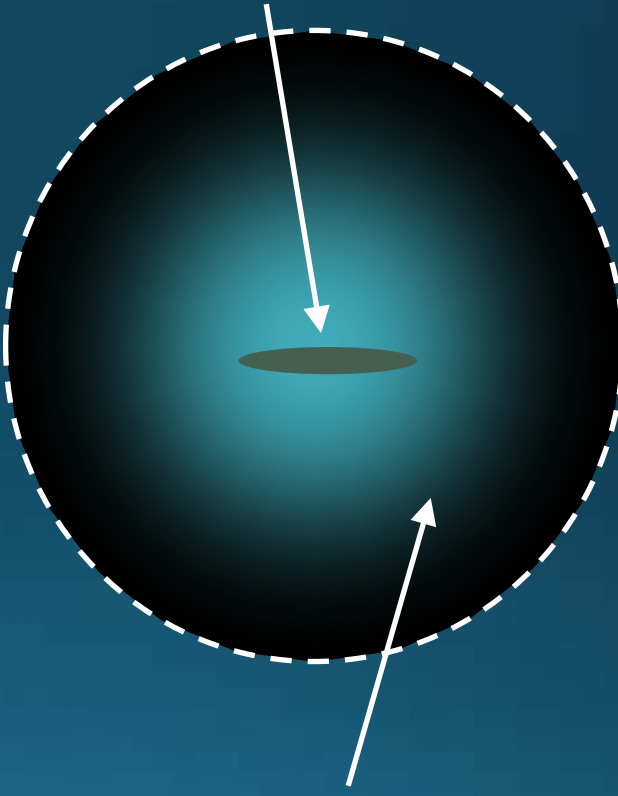
- Cosmological Parameters + Inventory of Luminous material
- Dynamics of galaxies
- Dynamics and gas properties of galaxy clusters
- Gravitational Lensing

Dynamics of Galaxies I

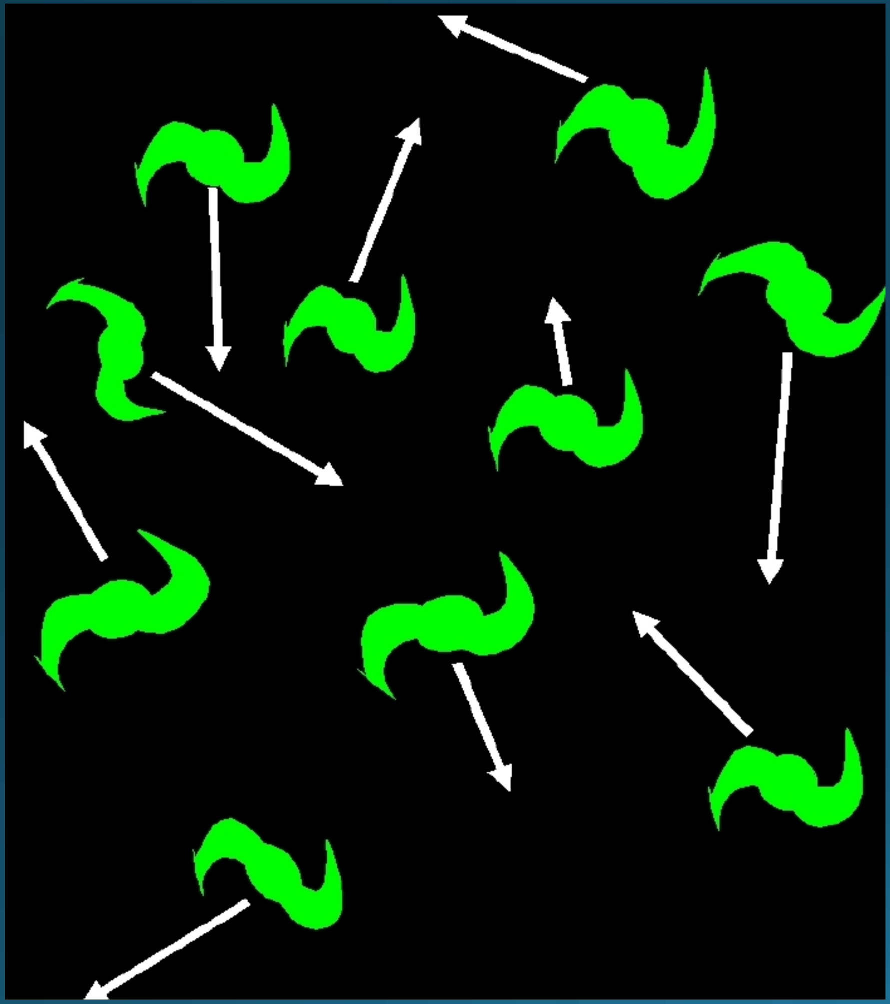
Galaxy ≈ Stars + Gas + Dust + Supermassive Black Hole + Dark Matter

Dynamics of Galaxies II





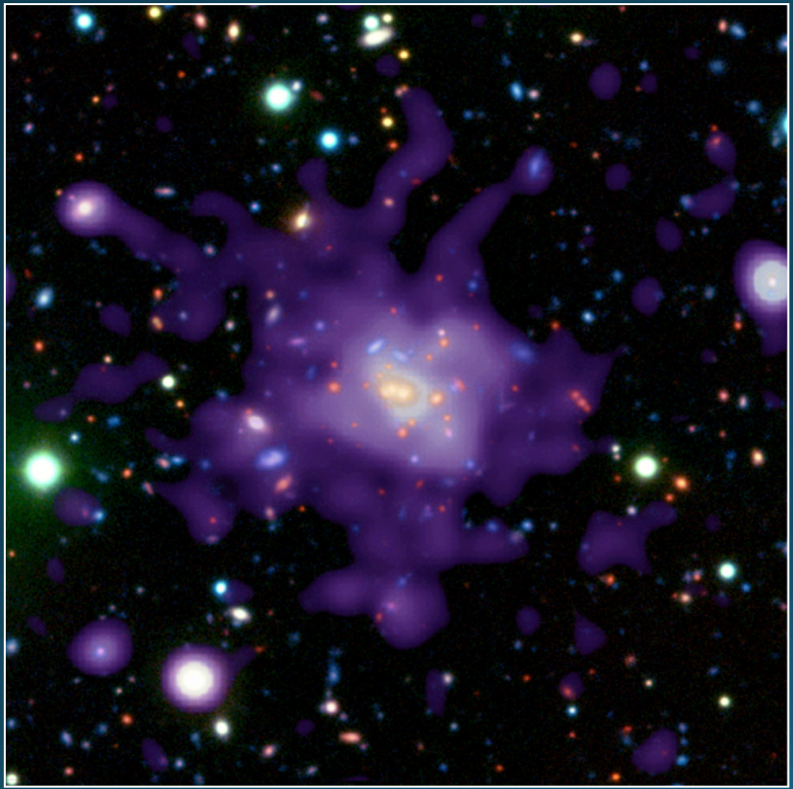
Dynamics of Galaxy Clusters



Balance between kinetic and potential energy →
Virial theorem:

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

Hot Gas in Galaxy Clusters



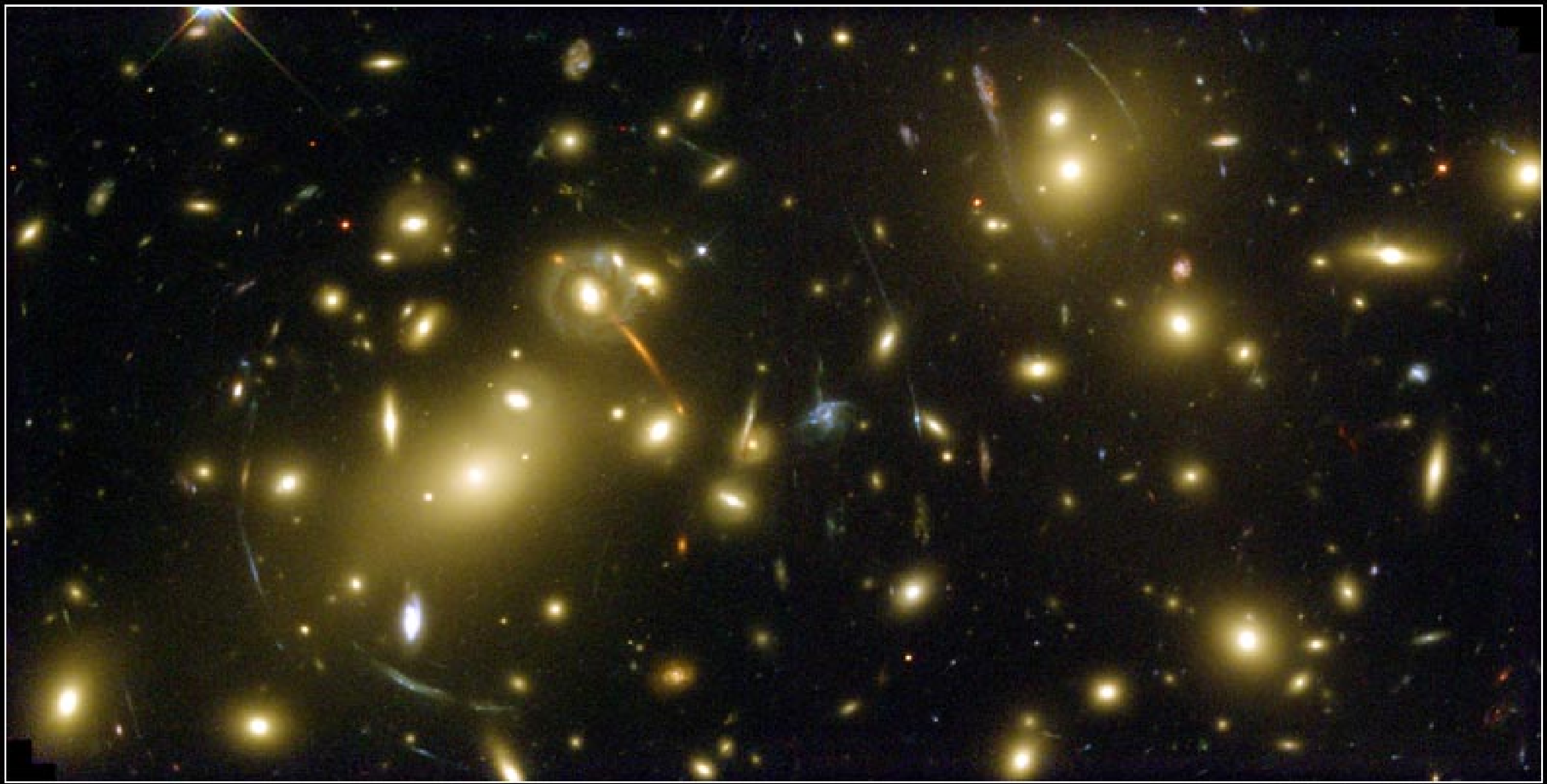
X-ray gas, $T=10^7$—10^8 K

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

If gas in hydrostatic equilibrium → Luminosity and temperature profile → mass profile

Gravitational Lensing

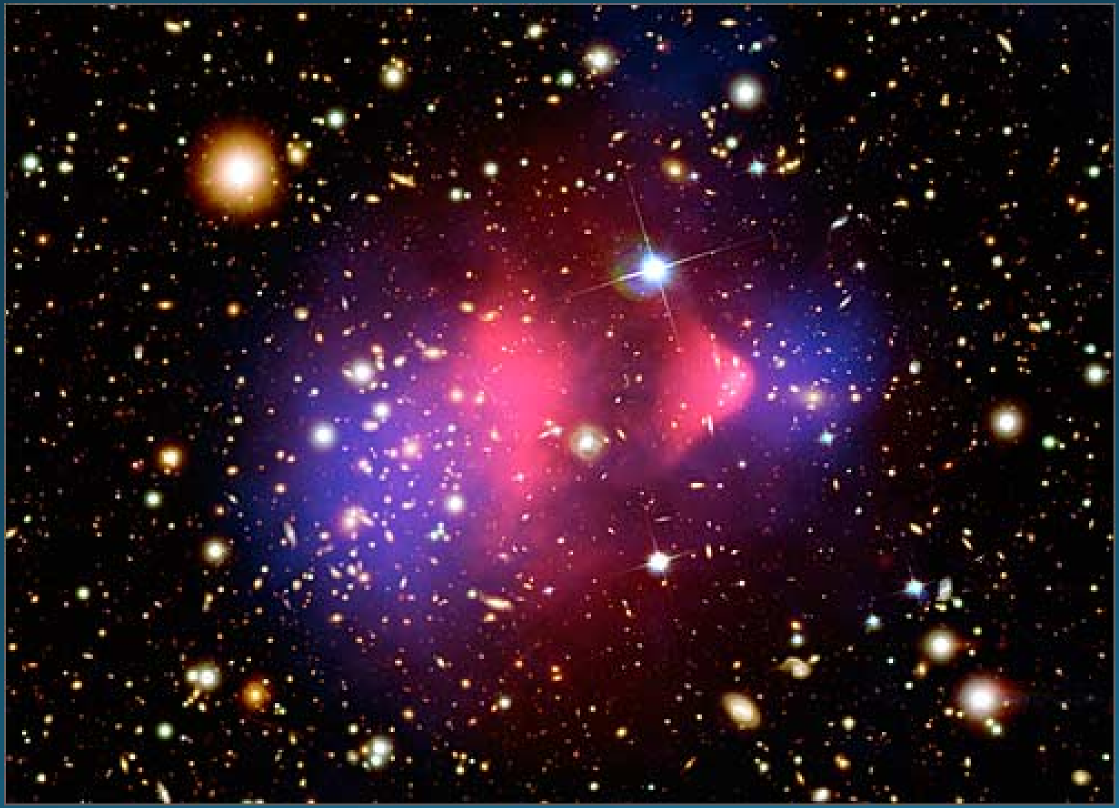
Gravitational Lensing II



Galaxy Cluster Abell 2218 **HST • WFPC2**

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

Suggestion for Literature Exercise: The Bullet Cluster as a proof* of the existence of dark matter



* Note: Not everybody agrees that this is a proof!

Mass-to-Light Ratios

Mass-to-light: $\dfrac{M}{L} \quad \left[\dfrac{M_{solar}}{L_{solar}}\right]$

Observed luminosity

Different choices for M:

M_{tot} = Total mass $\rightarrow$

Dynamical mass-to-light ratio

M_{stars} = Mass of stars & stellar remnants

$\rightarrow$ Stellar mass-to-light ratio

Mass-to-Light Ratios II

What are M/L-ratios good for?

The mass-to-light ratio indicates how dark matter-dominated a certain object is.

Higher M/L $\rightarrow$ More dark-matter dominated

Typically: $(M/L)_{stars} < 10$ (from models)

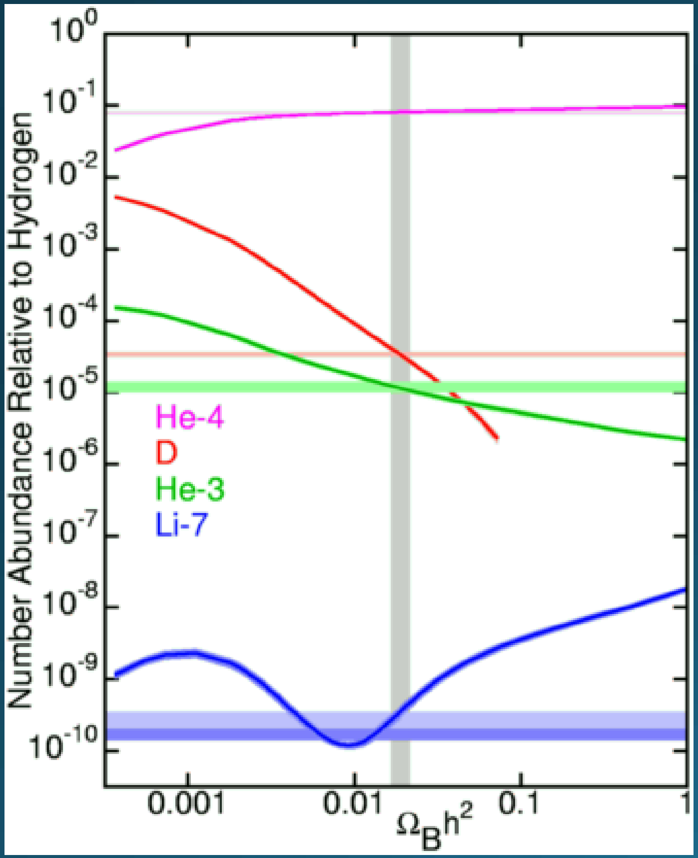
But: $(M/L)_{tot} \sim 100$ for galaxies

$(M/L)_{tot} \sim 500$ for galaxy clusters

$(M/L)_{tot} > (M/L)_{stars} \rightarrow$ Dark matter!

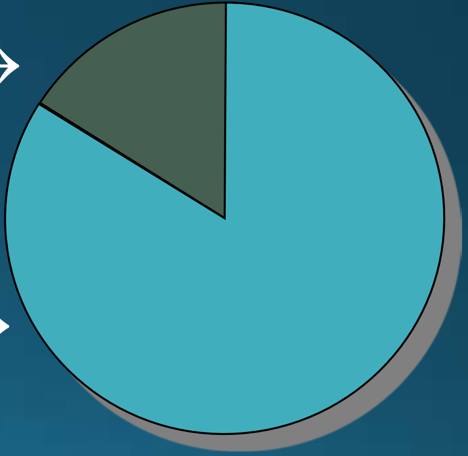
Baryonic and Non-Baryonic Dark Matter I

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



BBNS modelling + measurements
of primordial abundances
or CMBR analysis $\rightarrow$ $\Omega_{\text{baryons}} \approx 0.045$

$\Omega_{\text{Baryonic}} \approx 0.045 \rightarrow$



$\Omega_{\text{Non-baryonic}} \approx 0.25 \rightarrow$

$$\Omega_M = \Omega_{\text{Baryonic}} + \Omega_{\text{Non-baryonic}} \approx 0.3$$

MACHOs and WIMPs

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

But beware of misconceptions!

A Few Viable Dark Matter Candidates

Very Popular!

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

Hot and Cold Dark Matter

- Hot Dark Matter (HDM)
  - Relativistic early on (at decoupling)

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

Additional Assumed CDM Properties

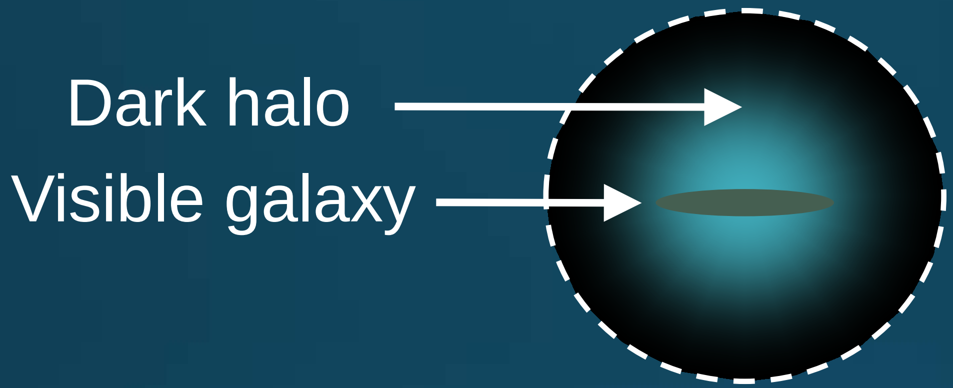
- Collisionless – interacts mainly through gravity
- Dissipationless – cannot cool by radiating photons
- Long-lived particles
- Behaves as perfect fluid on large scales
- Adiabatic primordial density perturbations, following a scale-invariant power spectrum

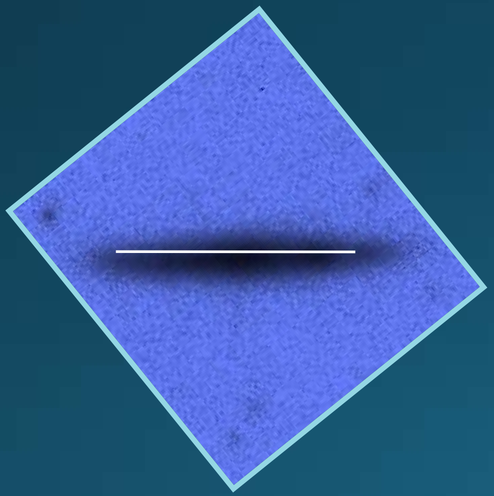
More in structure formation lecture!

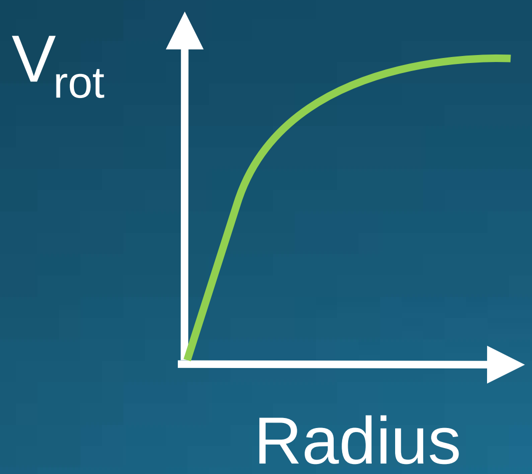
Problems with CDM

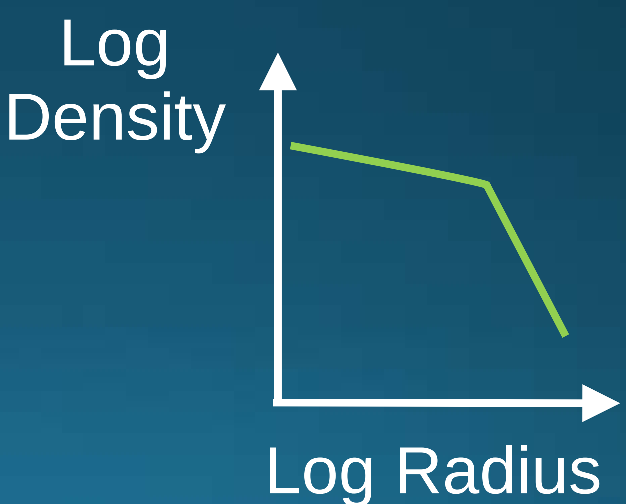
- Dark halo density profiles
- Dark halo substructure
- Dark halo shapes
- The angular momentum problem

Dark Halo Density Profiles I







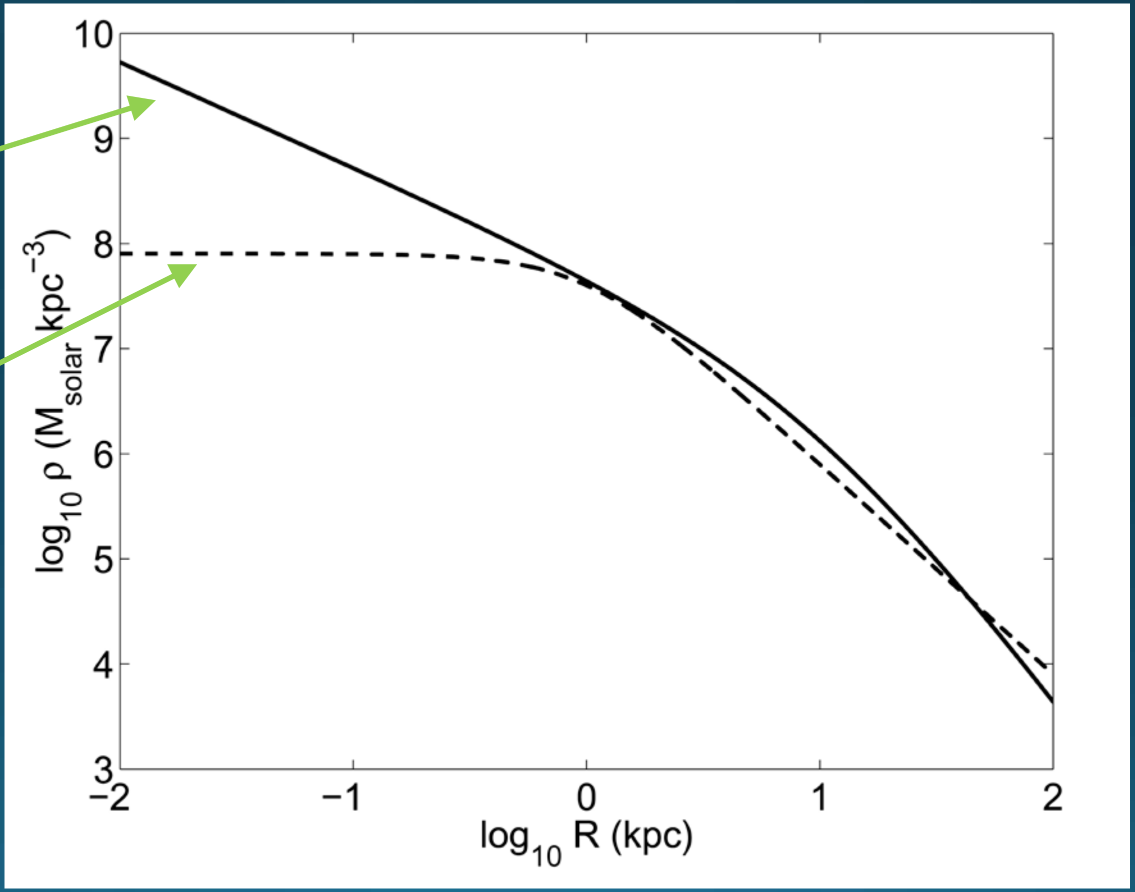


Spectroscopy → Rotation Curve → Halo Density Profile

Dark Halo Density Profiles II

Predicted by the Cold Dark Matter Scenario (density cusp)

Favoured by observations (density core)



Dark Halo Density Profiles III

Currently the favoured solution

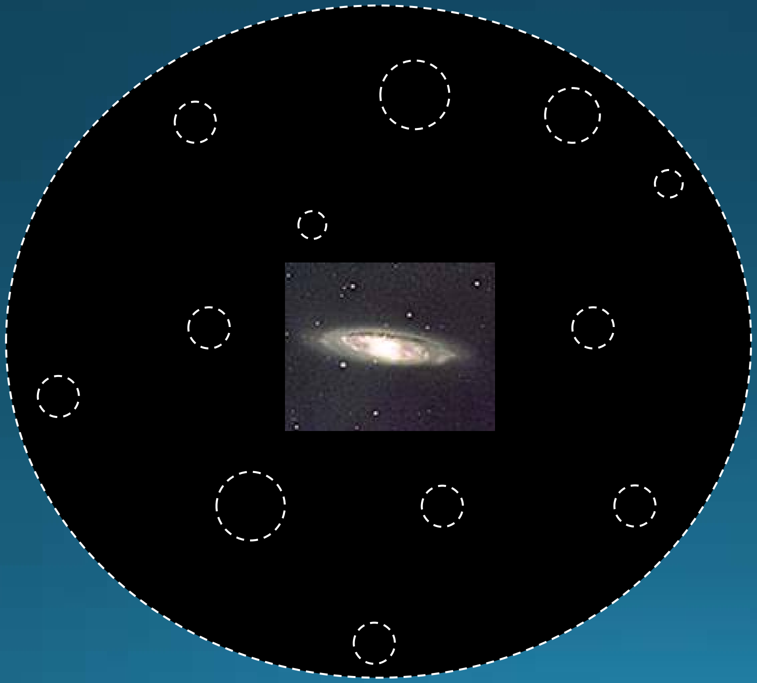
But there are plenty of complications…

- Baryonic processes alter density profile?
- Non-spherical dark matter halos?
- 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

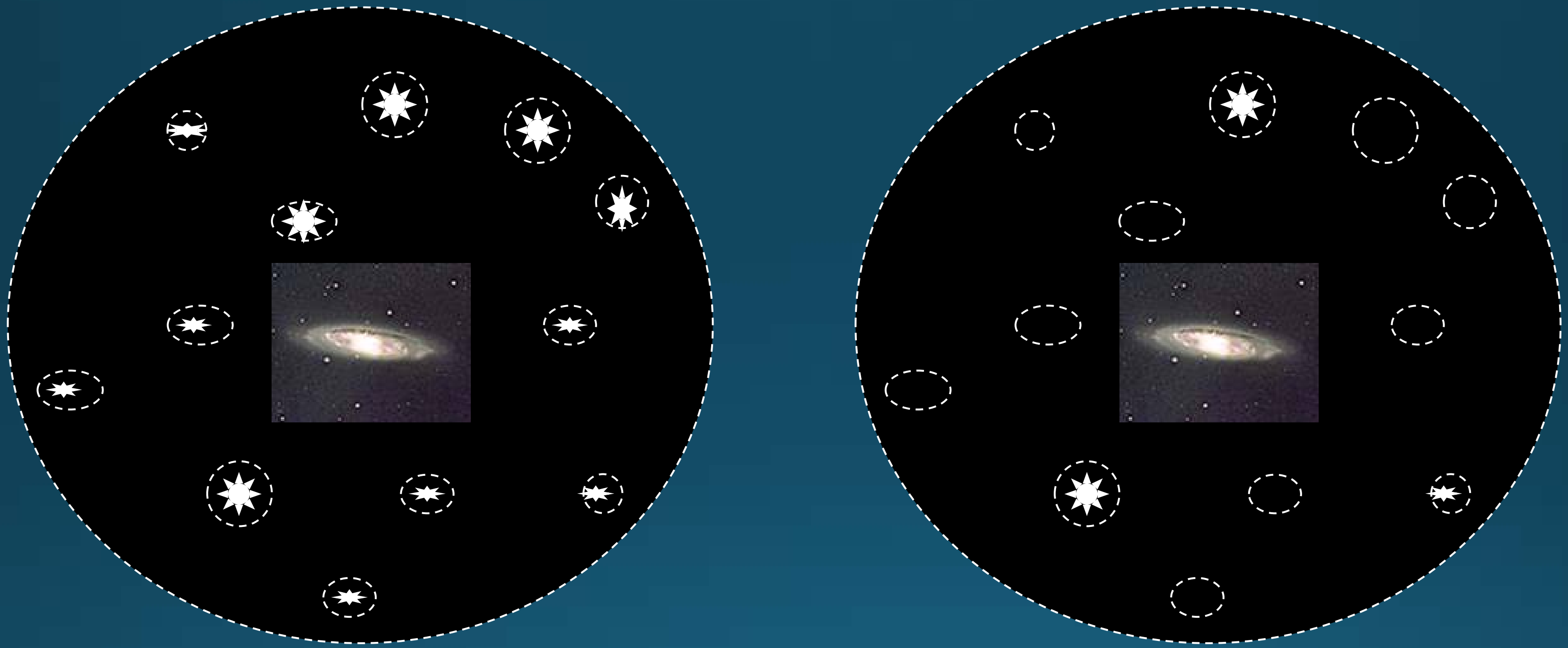
The dark halos around galaxies form the merger of smaller halos, but many remnants of the smaller halos survive → The dark halos of galaxies are not perfectly smooth!

~10 % of the dark matter is in clumps (a.k.a. subhalos or halo substructure)



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!

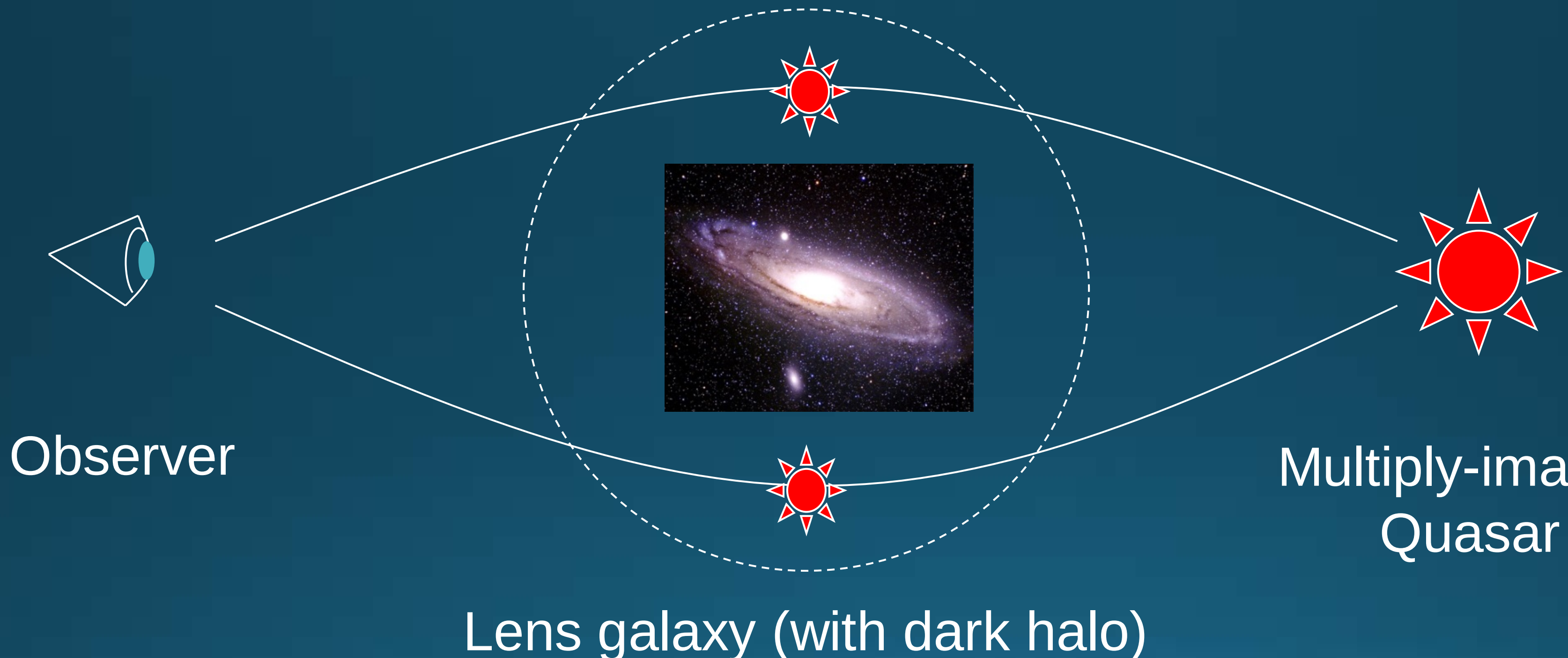
Dark Halo Substructure III

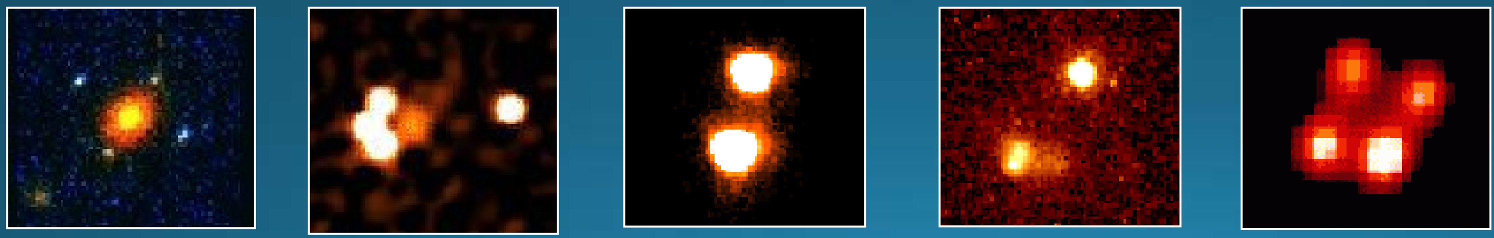
The solution: Dark galaxies?

- Dark galaxy: A dark subhalo which either lacks baryons, or inside which the baryons form very few stars
- Possible detections exist of galaxies with very high mass-to-light ratios ($M/L \geq 1000$), but not yet in sufficient numbers to solve the problem

How to detect halo substructure

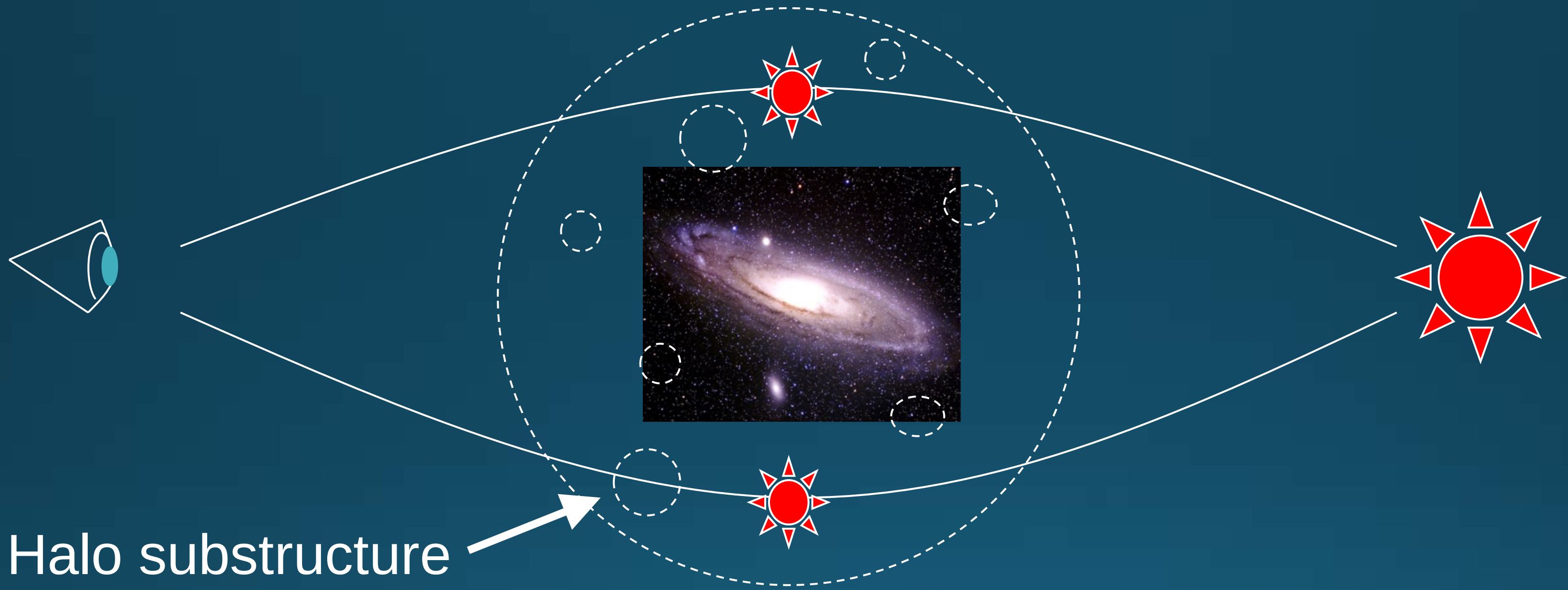
Dark halos can cause image splitting in quasars on angular scales of ~ 1 arcsecond (macrolensing)



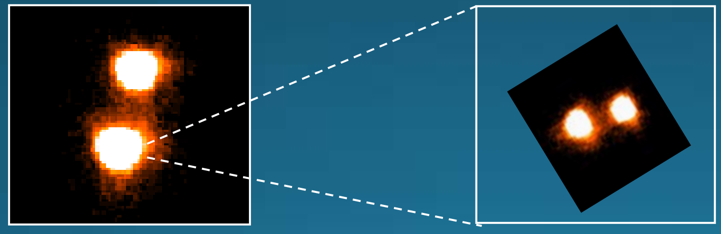


How to detect halo substructure II

Halo substructure can cause additional splitting of each image on angular scales of ~0.001 arcseconds (millilensing)



Macrolensing (1”)



Millilensing (≤0.001”)

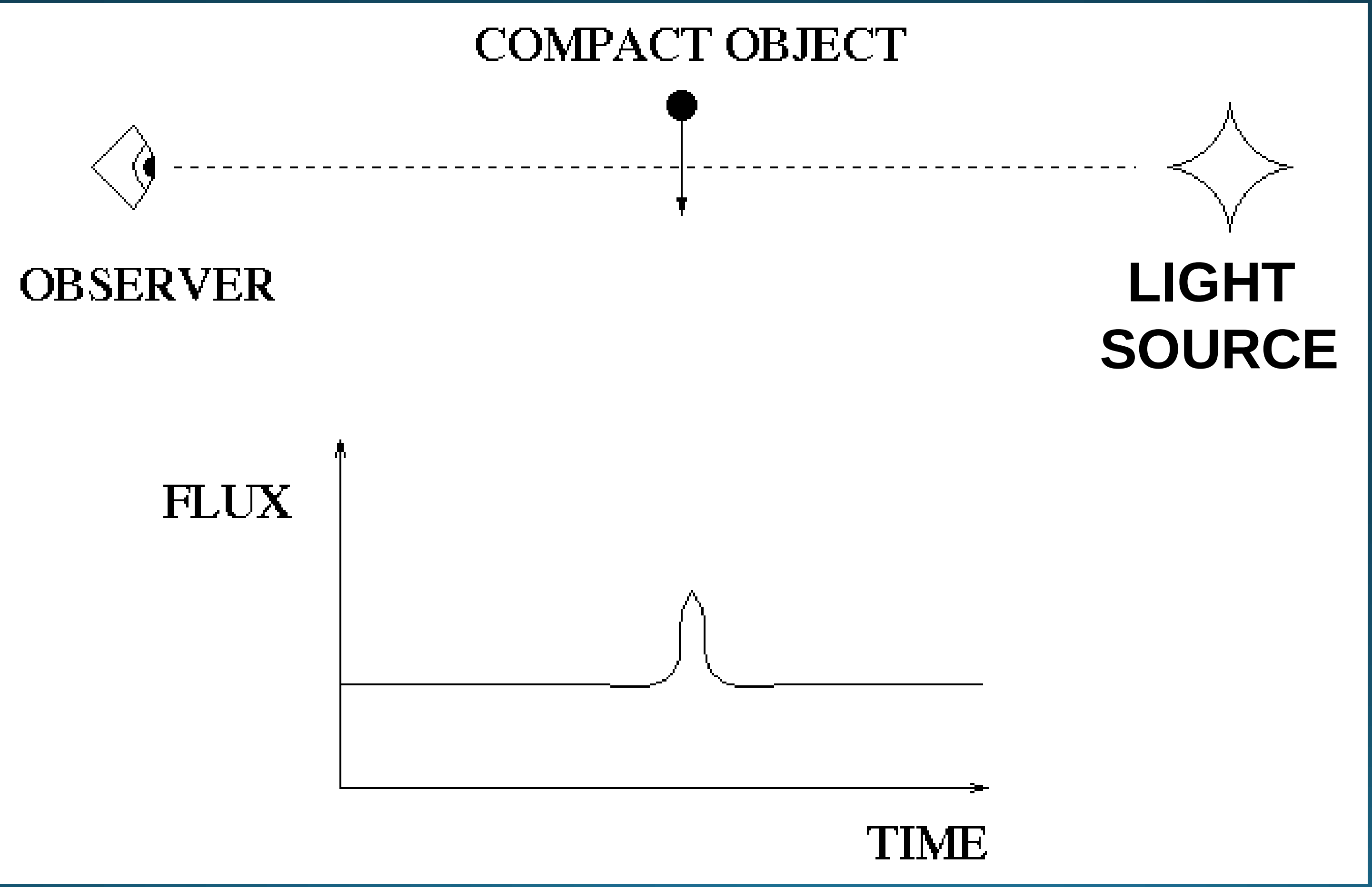
Alternatives to CDM

- Warm dark matter
- Mixed dark matter (cold + hot)
- Self-interacting dark matter
- Decaying dark matter
- Alternative theories of gravity

How to Search for Dark Matter Particles

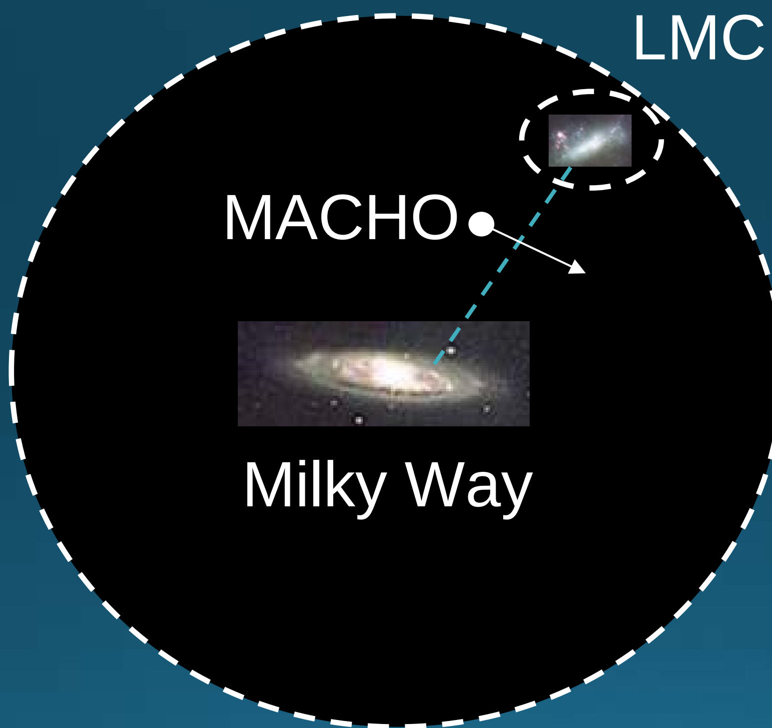
- Gravitational microlensing by MACHOs
- WIMP direct detection
  - Recoil in detector
  - Annular modulation
- WIMP indirect detection
  - Cosmic rays from annihilating WIMPs
  - Neutrinos from WIMP annihilation in Sun/Earth
  - Photons (gamma, radio) from WIMP annihilation in the Galactic Centre

Gravitational Microlensing by MACHOs



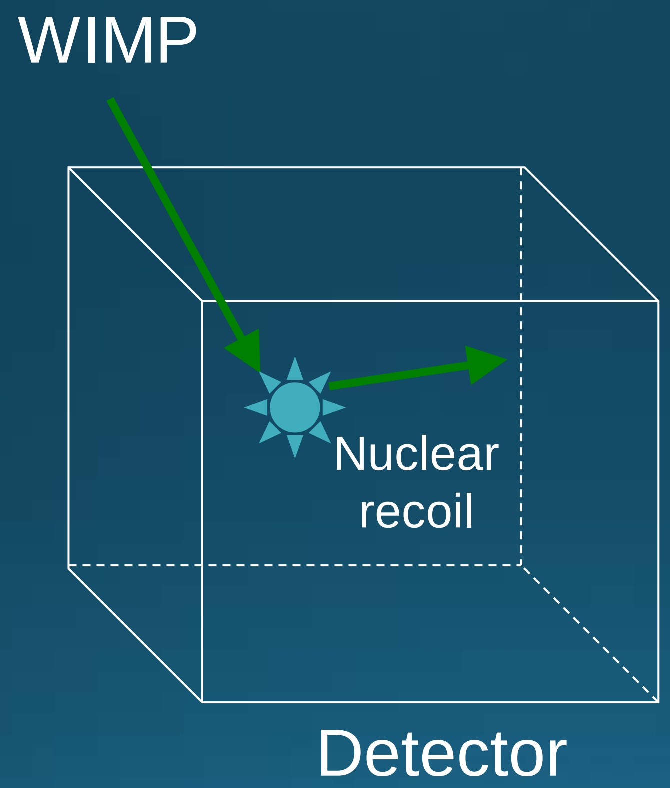
Possible detections I

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



Very controversial detection of $M_{compact}$~10^{-1} M_{solar}, constituting ≈20% of the dark halo

Direct WIMP detection

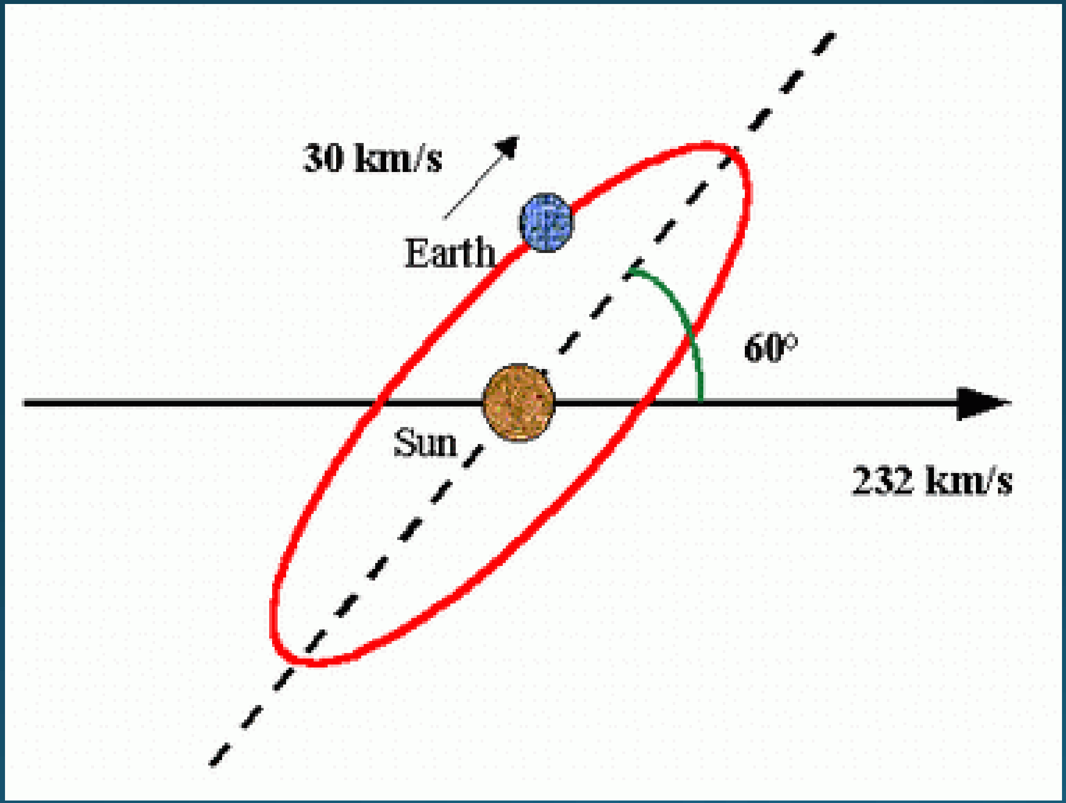


Problem: Background of other rare reactions

Direct WIMP Detection in Ancient Mica

WIMP recoils cause chemical changes in ancient mica
$\rightarrow$ Natural detector with integration time ~ 1 Gyr

Annular Modulation



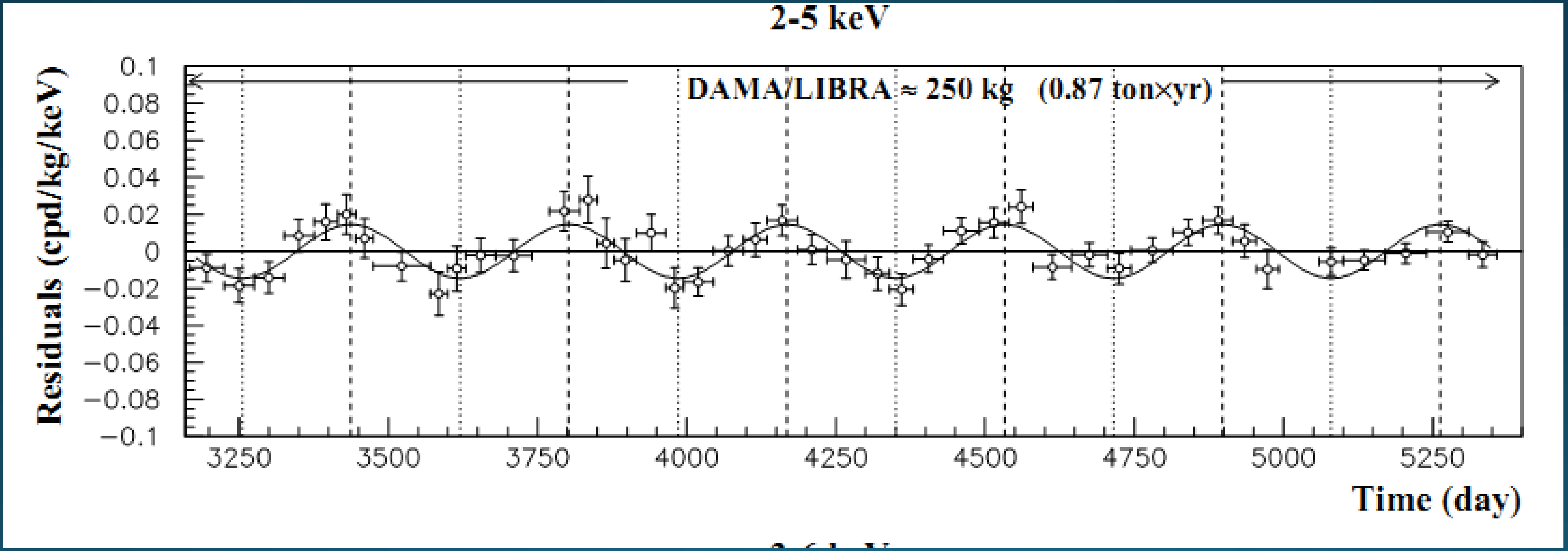
WIMP wind from the dark halo
should show seasonal variations!

Possible detections II

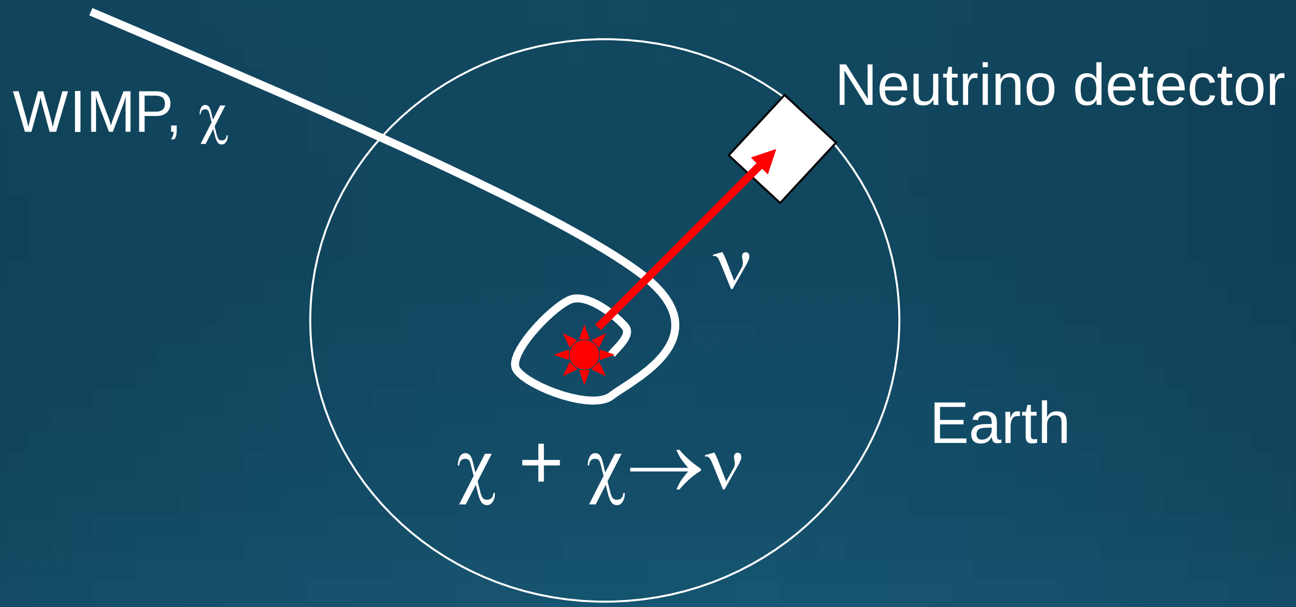
WIMP search by the DAMA experiment

Detected annular modulation signature

$\rightarrow \geq 10^{-3}$ of halo fraction in WIMPs



Indirect WIMP detection by Neutrinos from the Sun/Earth



WIMPs may accumulate in the potential well of the Sun/Earth, and annihilate to produce neutrinos

Is There no Alternative to Dark Matter?

”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

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

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

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

MOND II

From Stacy McGaugh’s old 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.”

Known problems with MOND

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

  Fails to explain the dynamics of galaxy clusters – some dark matter is still required
- Fails to explain difference between systems of similar baryonic masses, e.g. globular clusters and dwarf galaxies

Suggestion for literature Exercises: Alternative theories of gravity vs. Dark matter

- Many examples (pick *one*):
  - MOND – Lots of work done. Fairly easy to understand at an undergraduate level
  - MOdified Gravity (MOG) – Slightly more technical. Requires some understanding of tensors.
- Can GR explain rotation curves without dark matter?