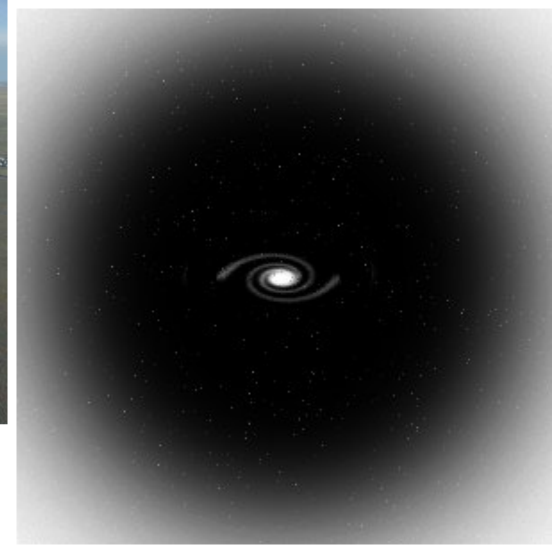
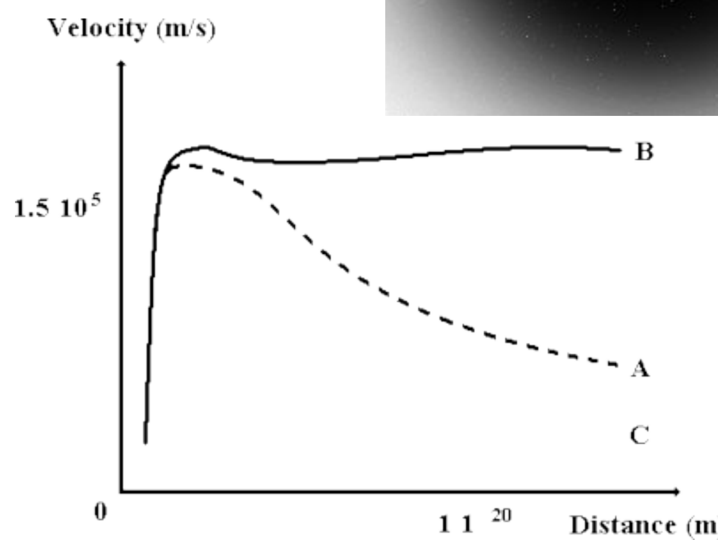
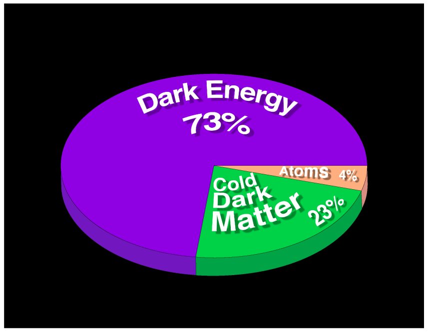
Dark Matter

Readings: HH §15, Shu §12.1, §12.2, Allday §14







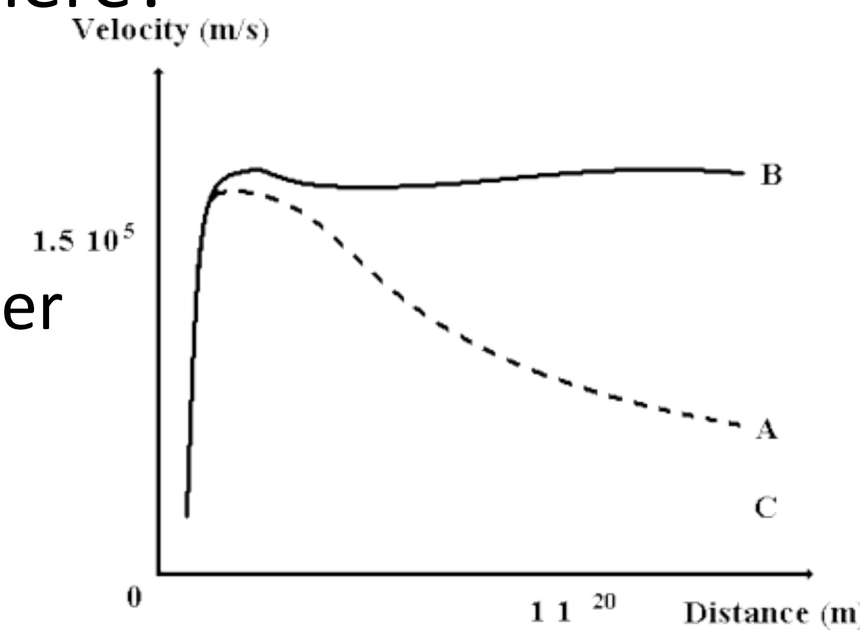
Dark matter ≠ Dark energy

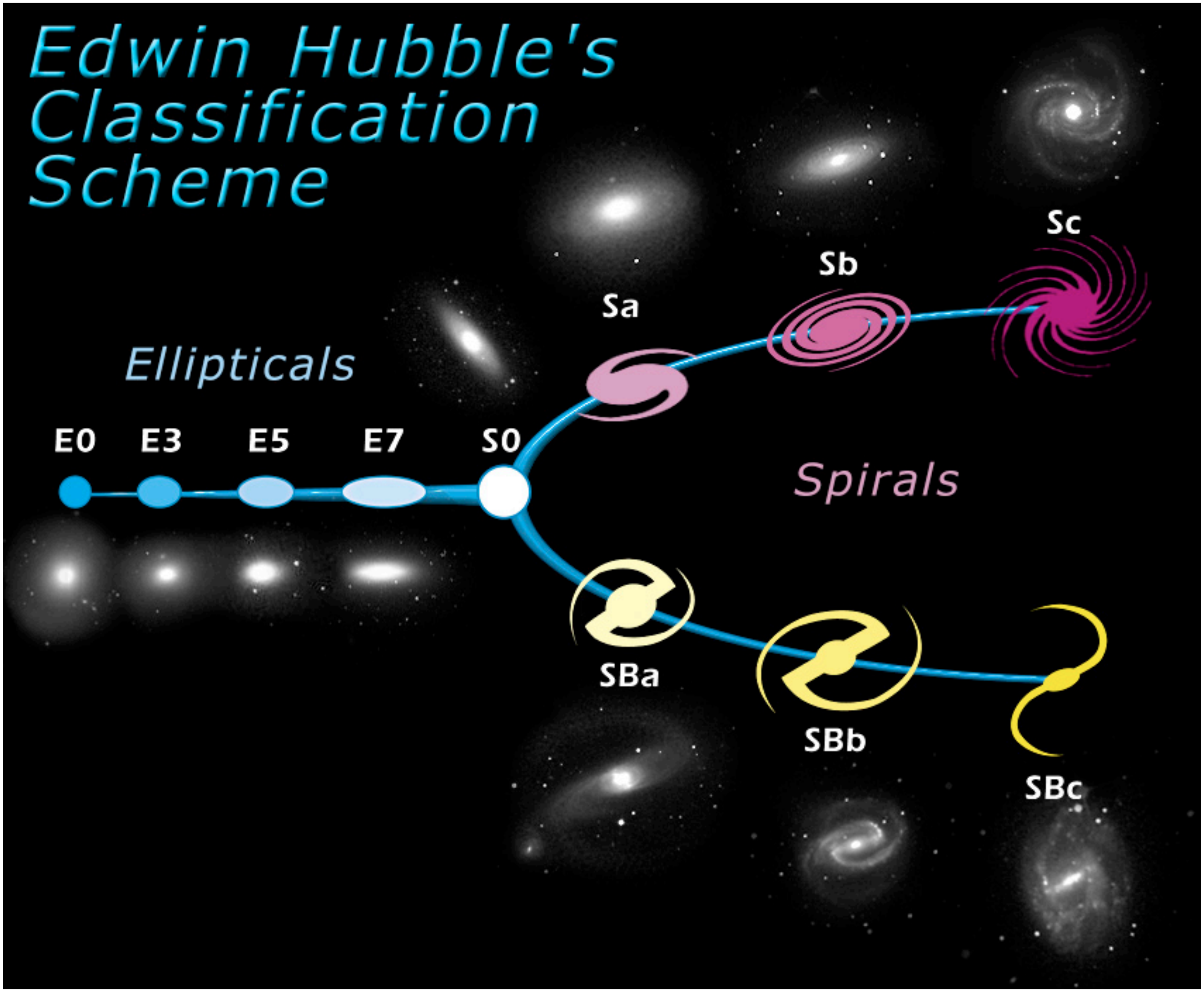
- Dark matter is matter
  - – concentrated around galaxies and clusters
  - – works against the expansion of the Universe
  - – responsible for keeping us together!
- Dark energy is energy
  - – homogeneously distributed in the Universe
  - – helps the expansion of the Universe
  - – responsible for accelerated expansion!

What they have in common is that we don't know what they are, and therefore both are called 'dark'

Dark matter

- How do we know it is there?
  - gravity: what makes stuff move around
  - galaxy rotation curves
  - evidence from galaxy clusters
- Are we really sure it is there?
  - Bullet cluster
  - large scale structure
  - alternatives to dark matter
- Do we know what it is?

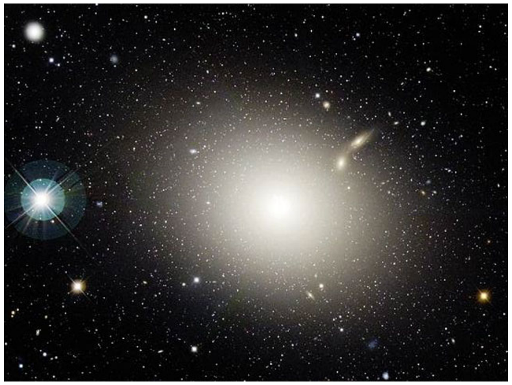



Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

Spiral vs Elliptical Galaxies

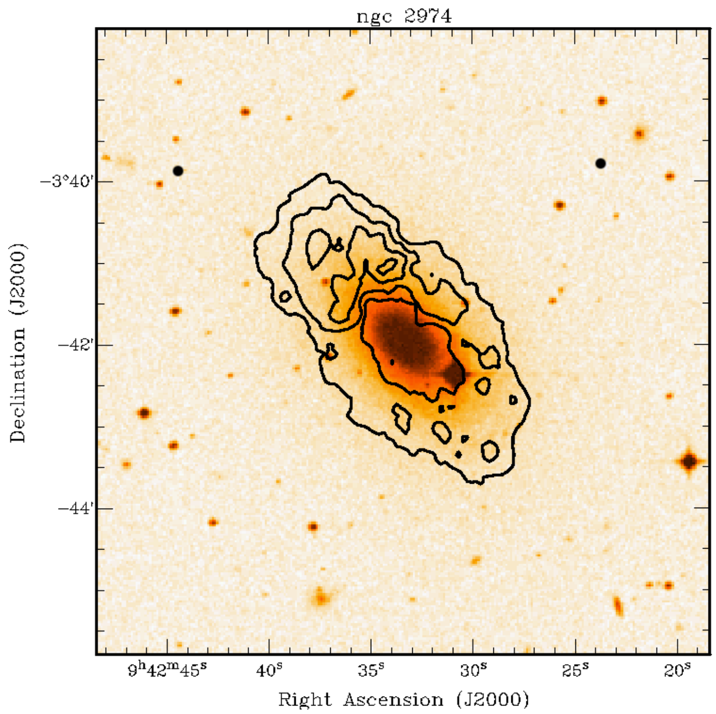
- Spiral Galaxies
  - disc galaxies with extended spiral arms
  - ongoing star formation
    - young stellar populations
    - blue colours
  - contain large discs of cold gas
- Use gas disc for dark matter studies

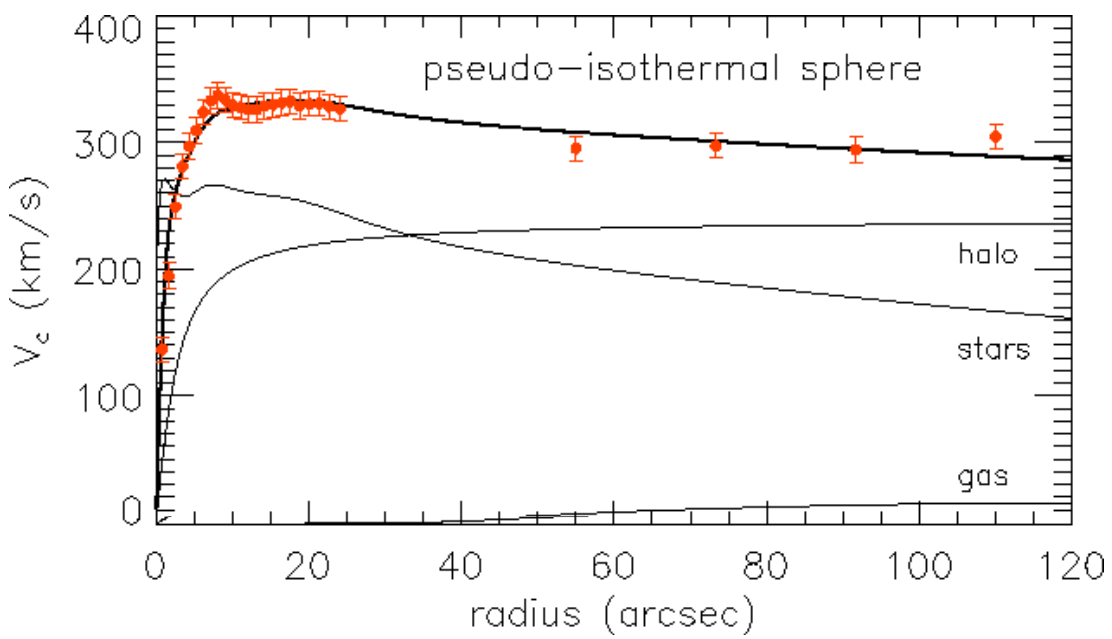
- Elliptical galaxies
  - homogeneous structure, no spiral arms
  - dominated by ‘random motions’ of stars instead of rotation
  - little or no star formation
    - old stellar population
    - red colour
  - little or no gas
- How do we look for dark matter?



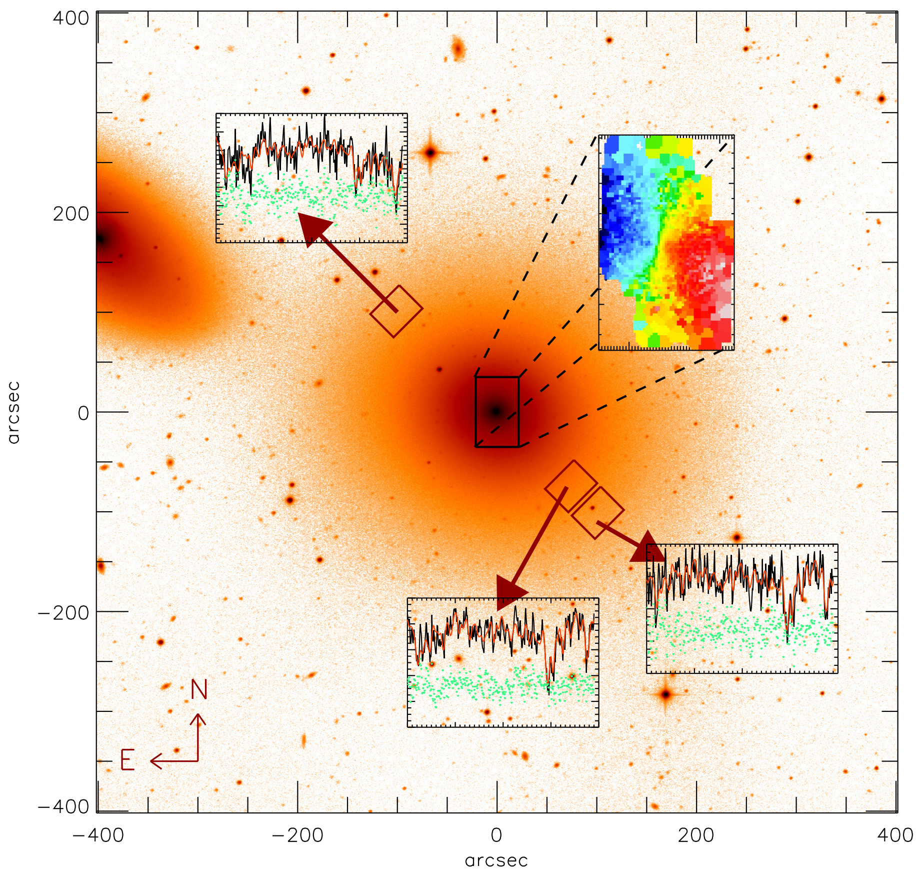
Some elliptical galaxies have gas!

- Use gas discs or rings for rotation curves
  - see problem set





Use the stars instead of the gas



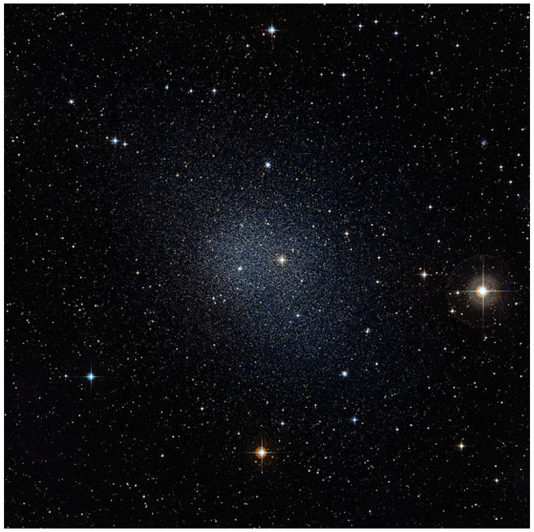
Weijmans et al. 2009

- Problem: stellar light very faint in outskirts of galaxy
- Use 'integral-field spectrograph' to get velocity field in centre
- In outskirts, sum all spectra together
  - one measure point on rotation curve
- Combine stellar kinematics of centre and outskirts to model dark halo

Dwarf galaxies

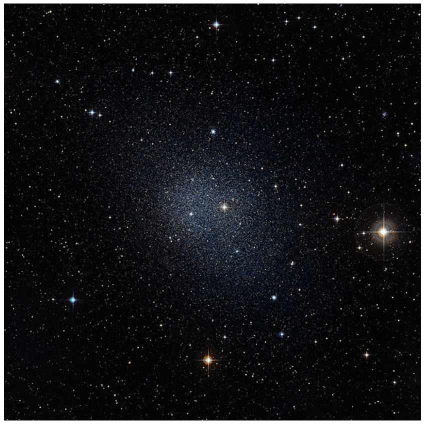
- Small, often irregularly shaped galaxies
  - they contain at most a few million stars
  - our Milky Way has billions of stars!
- Large and Small Magellan clouds visible with naked eye from southern hemisphere



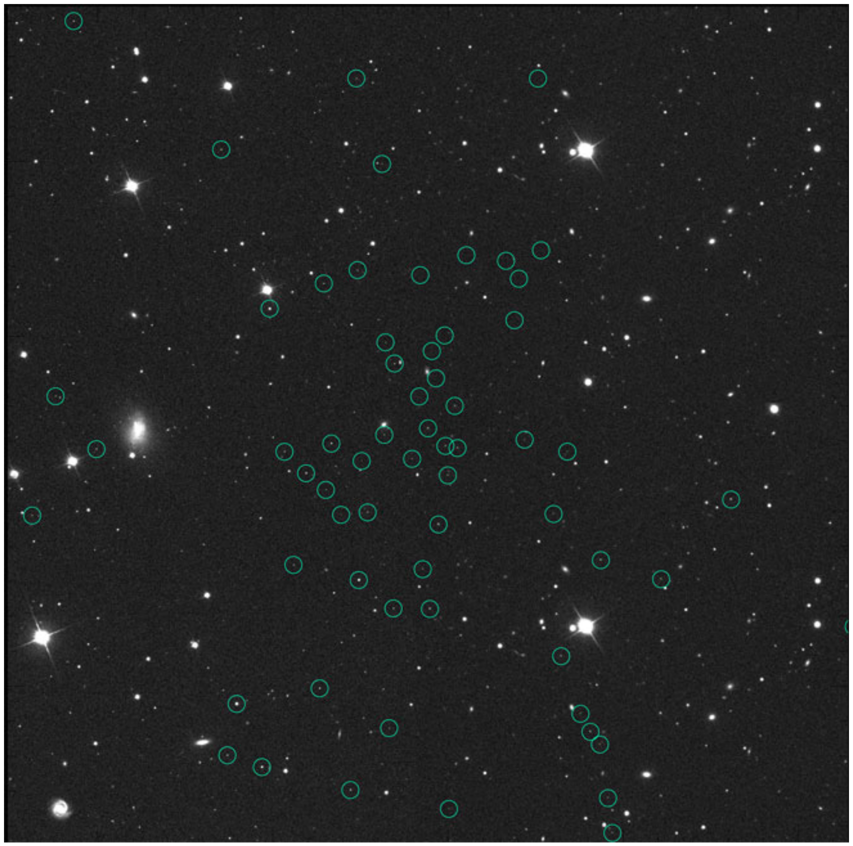


Dark matter in dwarfs

- Determine dark matter content, use same methods as for spiral and elliptical galaxies
  - very near-by systems, can even determine velocities of individual stars!
- Dwarf galaxies are the most dark matter dominated galaxies in the Universe!
  - note: this is relative to their stellar mass
  - low total mass causes them to loose gas easily, which then cannot become stars?
  - do completely dark galaxies exist???



The darkest galaxy ever observed!



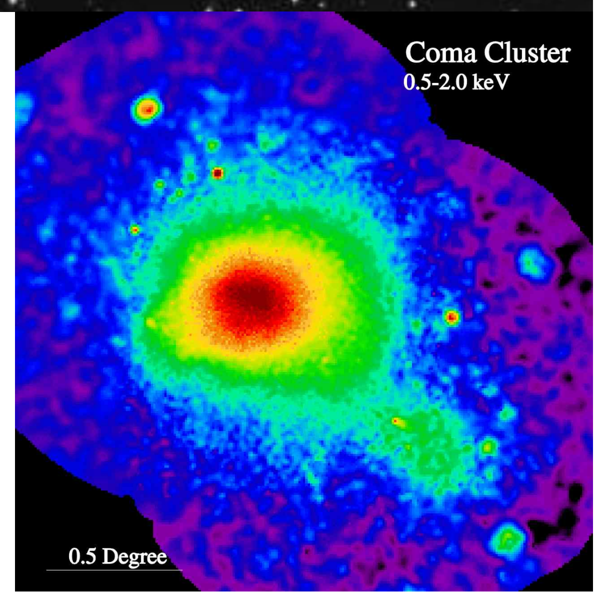
- Segue 1: satellite galaxy of Milky Way
- ~ 1000 very old stars
- $M_{dark} = 3400 M_{stars}$

Picture credit: M. Geha

Press release: http://keckobservatory.org/news/found_heart_of_darkness/
Journal Article: J. Simon et al., 2011, ApJ, 733, 46

Fritz Zwicky and the Coma Cluster

Fritz Zwicky
1898 - 1974



Escaping from the Coma Cluster

- Calculate velocity required to escape from the cluster, based on luminous matter distribution
  - escape velocity $V^2_{esc} = 2GM/R$
- Measure velocities of the galaxies in cluster
- Measured velocities exceed V_{esc}

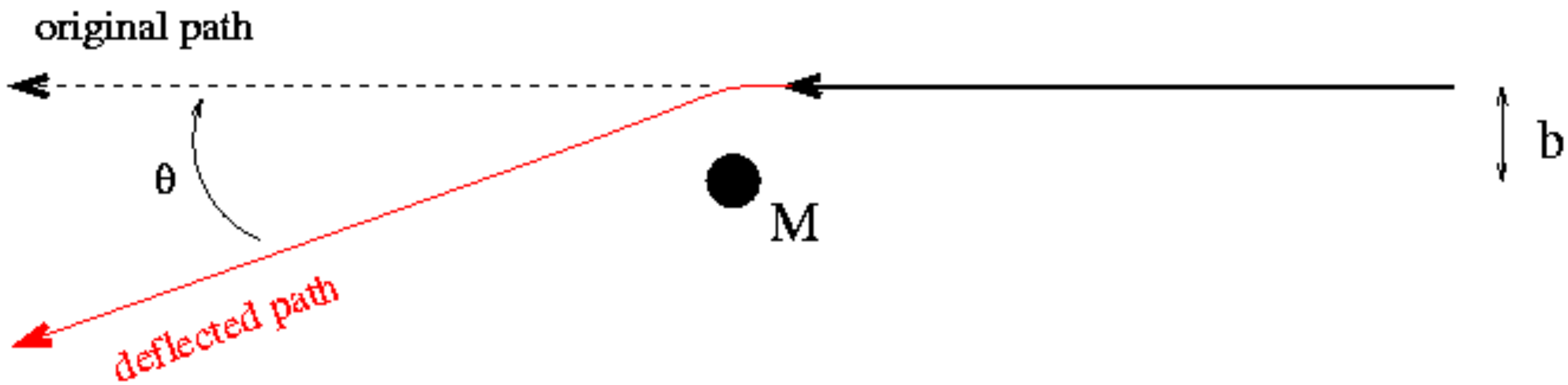
Dark mater needed to keep the cluster gravitationally bound

Gravitational lensing

Galaxy Cluster Abell 2218 **HST** • WFPC2

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

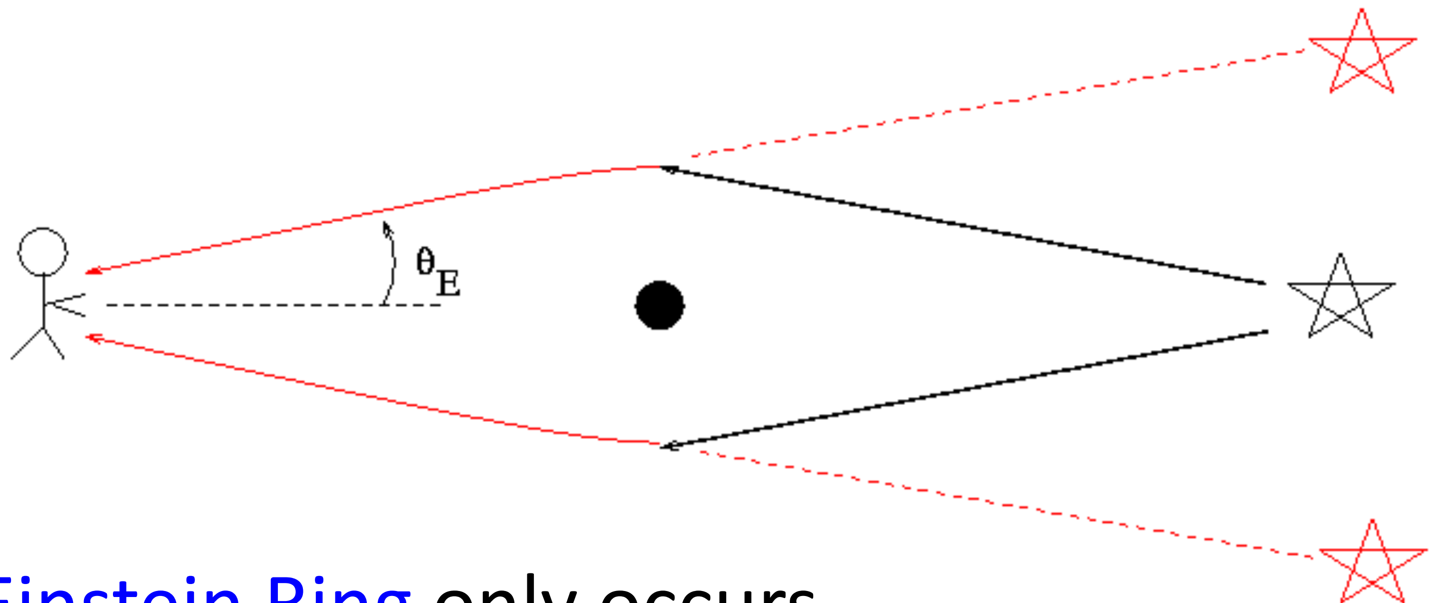
What is happening?



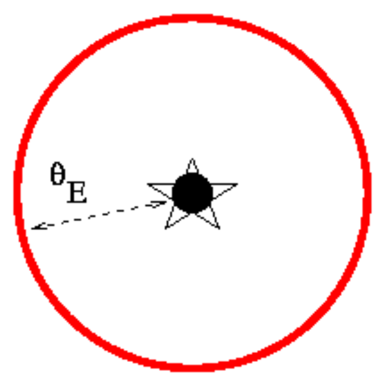
- Mass deflects light
- We see a deformed, magnified image

→ gravitational lens

Resulting image

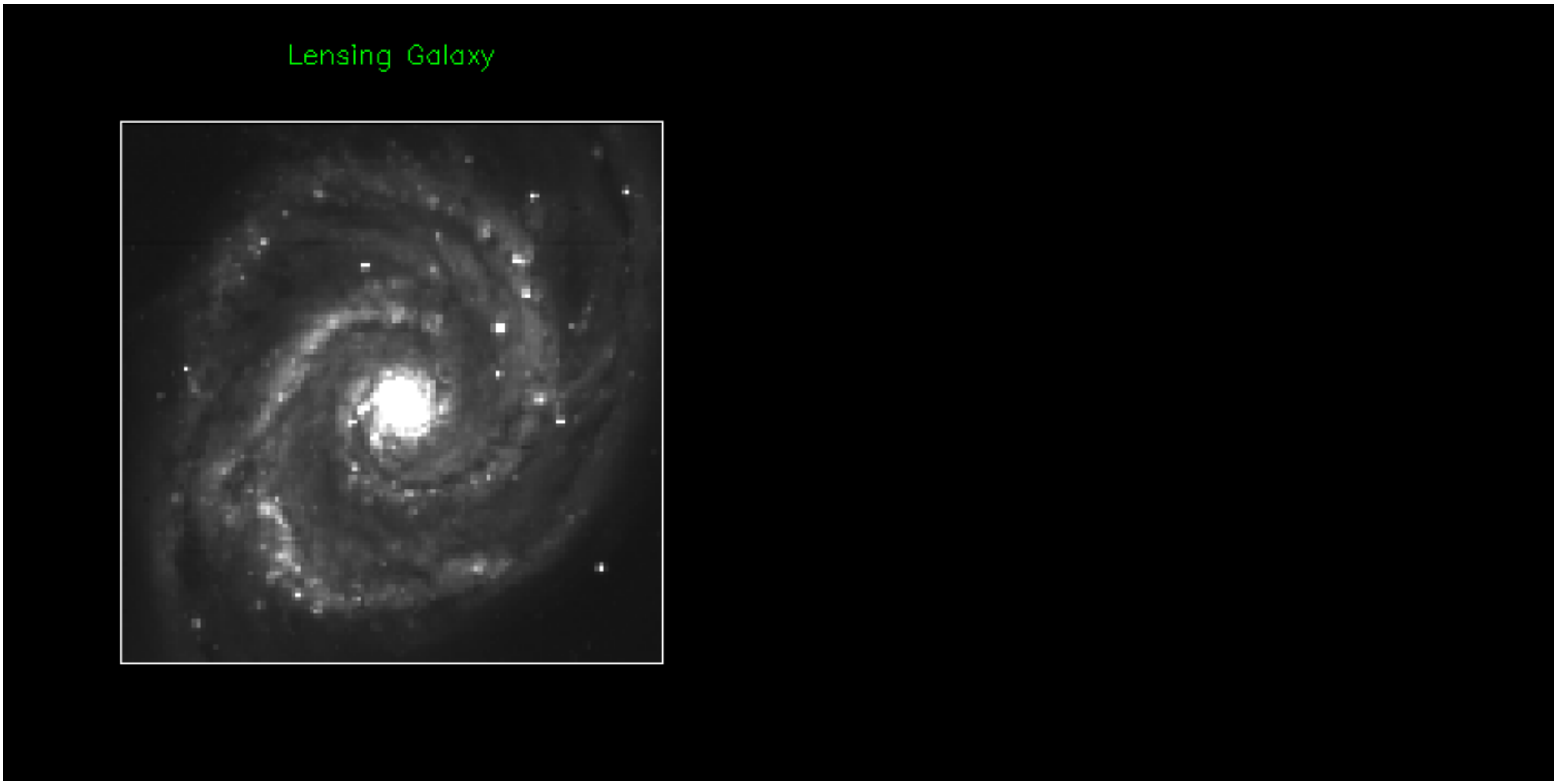


- Einstein Ring only occurs if source, lens and observer are aligned
- No alignment, then 'arced' galaxy images

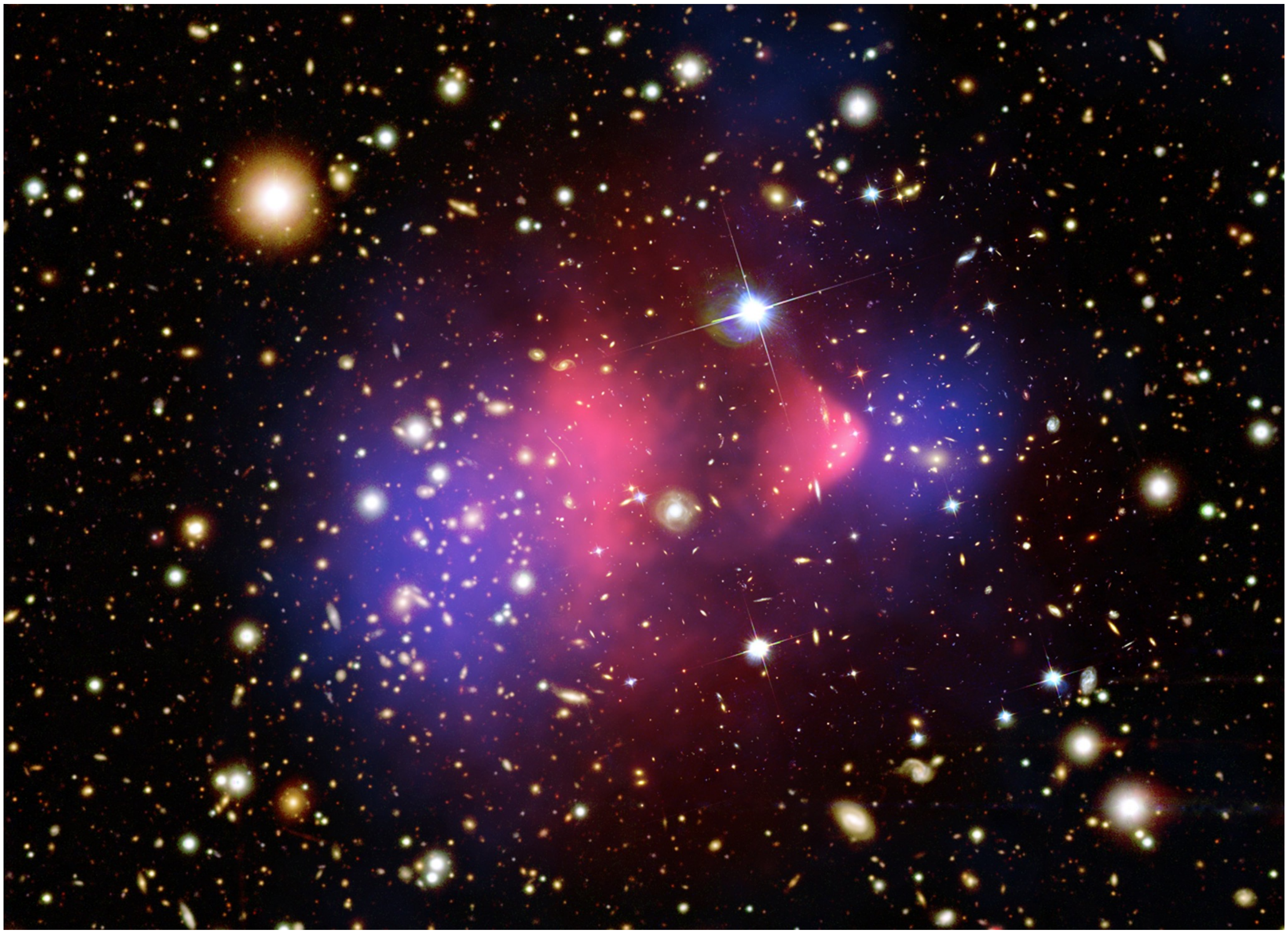


Einstein Rings

Gravitational lens simulation

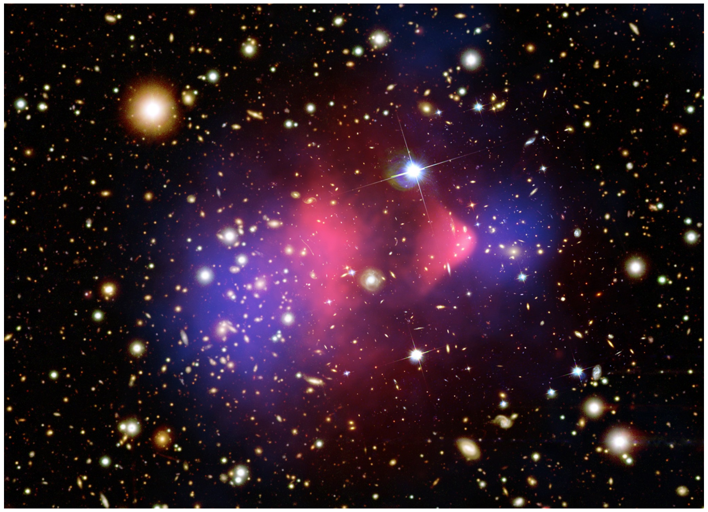


Direct evidence for dark matter
Bullet Cluster



Bullet Cluster

- Two clusters ‘collided’ with each other
  – galaxies: no direct hits, no problem
  – hot gas: direct collision
- Expect most of the mass to be in the hot gas
- X-rays reveal the massive hot gas: red
- Lensing model reveals total mass: blue
- Most of mass concentrated on stars, not on the gas

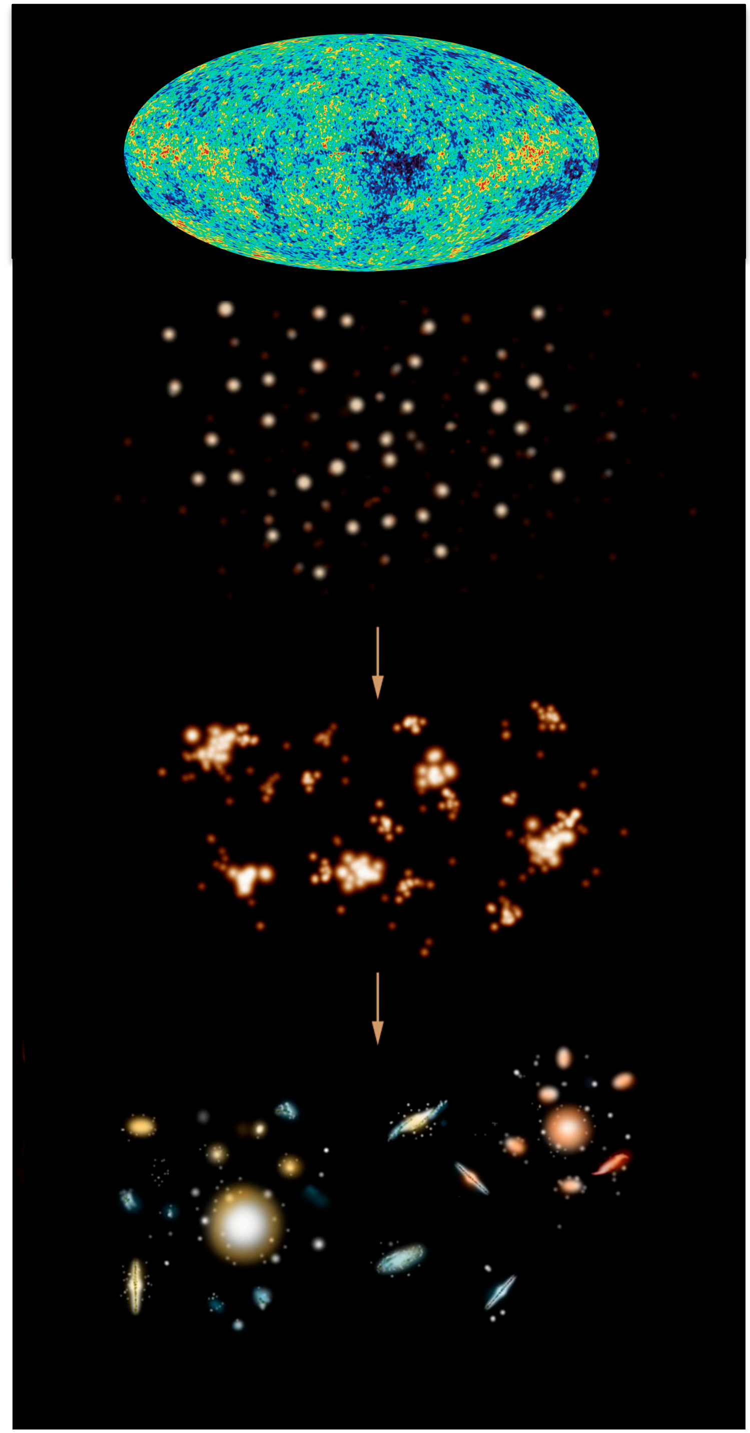


Dark matter is most massive component in the cluster http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Dark matter in the cosmic web

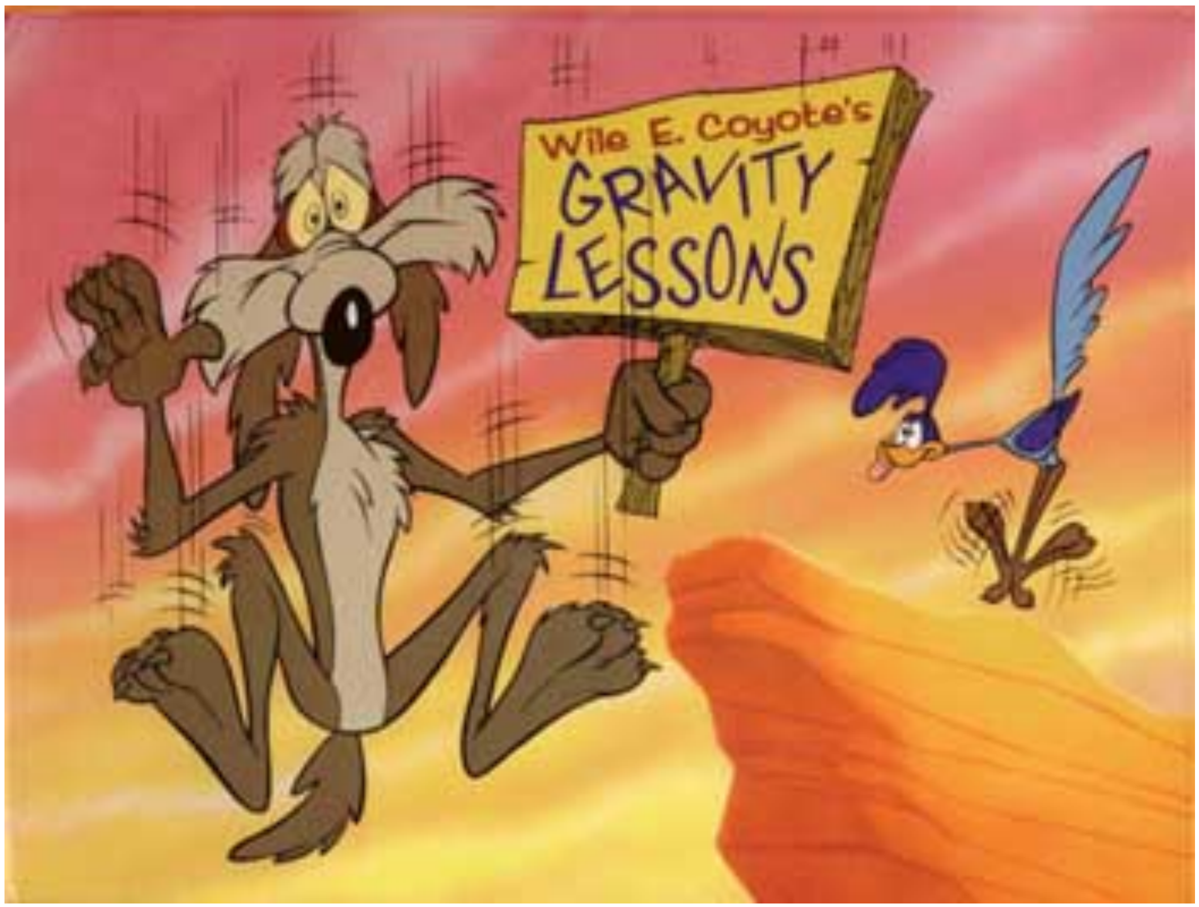
Structure Formation

- Hierarchical formation
  - start with small clumps of dark matter → haloes
  - gas forms stars in these clumps → first galaxies
  - small galaxies merge into bigger ones
- This is on-going process!



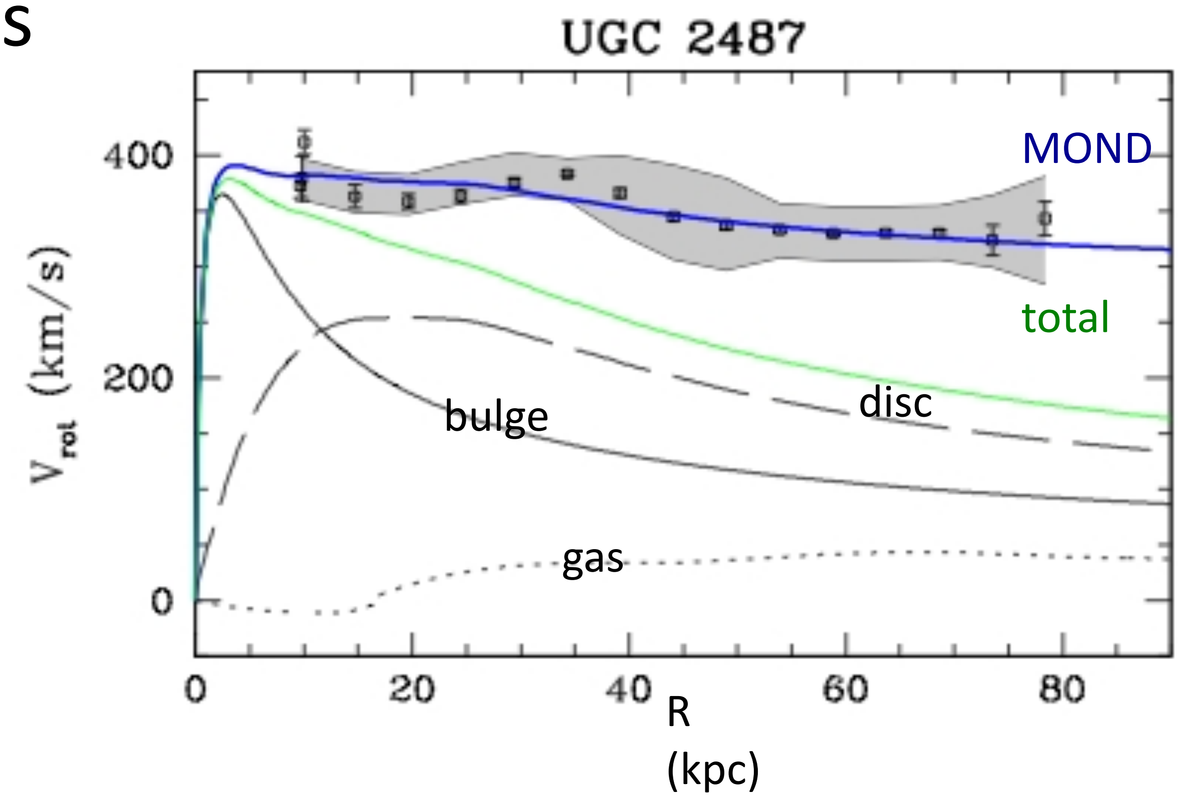
Alternatives to Newtonian gravity?

Any body suspended in space will remain in space until made aware of its situation



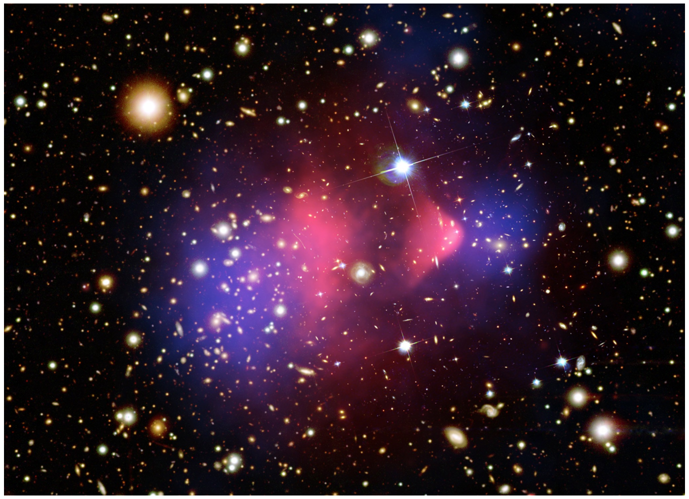
MODified Newtonian Dynamics (MOND)

- Designed to fit flat rotation curves of galaxies
- Idea: gravity behaves differently at low accelerations



So, does MOND replace dark matter?

- MOND provides good fit to rotation curves of disc/spiral galaxies
  - but how exactly do we need to modify gravity?
  - what about elliptical galaxies?
- MOND has problems explaining structure formation and cluster profiles
  - e.g. Bullet Cluster



We still need some form of dark matter!

Requirements for dark matter

- Dark matter does not interact with the electromagnetic force
  - otherwise it would not be ‘dark’
- Dark matter does interact with gravitational force
  - that is how we are able to detect it
- Not known whether dark matter would interact with weak force
- There is a lot of dark matter in the Universe
  - so any dark matter candidate must be sufficiently massive and/or numerous

Outdated candidates

- Massive Compact Halo Objects (MACHOs)
  - faint, ordinary baryonic matter in haloes of galaxies
  - e.g. low-mass dwarf stars, brown dwarfs, planets
  - should be visible by gravitational micro-lensing
  - but: detected MACHO numbers way too low
- Neutrinos
  - only interacts with weak and gravitational force
  - produced in large numbers during Big Bang, but also in stars, supernovae, etc.
  - but: masses too low to account for all dark matter
  - and also: relativistic speed enables them to escape from galaxy (hot dark matter)

Most popular candidate

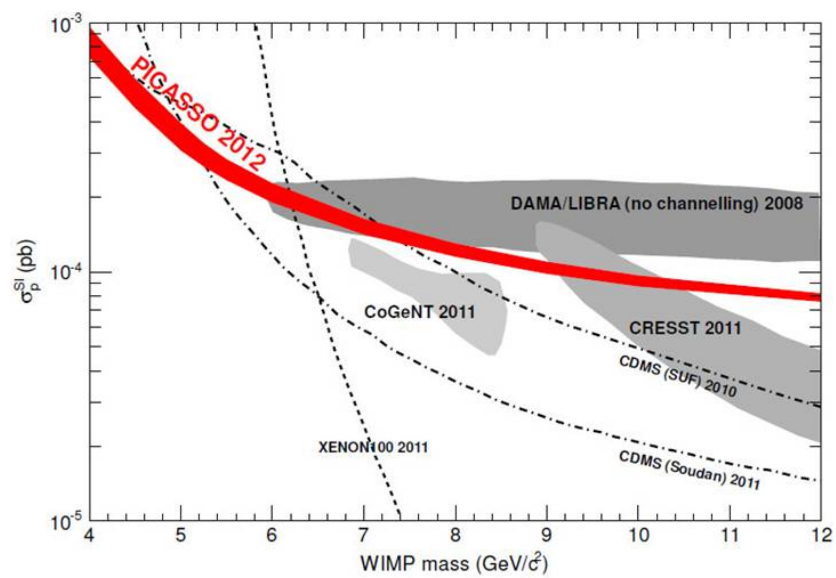
- Weakly Interacting Massive Particle (WIMP)
  - massive enough to account for all dark matter
  - only interacting with gravitational and weak force
  - cold dark matter: not moving at relativistic speeds
  - but: these particles have not been detected (yet)
- SuperWIMP
  - WIMP that only interacts with gravitational force
- These particles would result from supersymmetry
  - each particle has a supersymmetric partner
  - predicted by unification and string theories
  - WIMPs can undergo annihilation

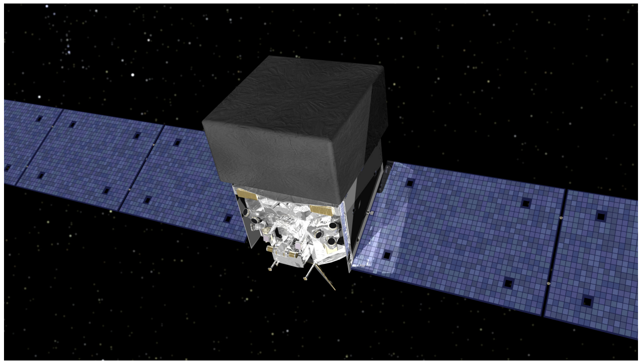
Looking for dark matter

- Large Hadron Collider (LHC) might produce dark matter particles
- Experiments looking for dark matter interactions
  - underground detectors, consisting of large crystals
  - WIMPs striking nuclei in crystal should leave a trace
  - e.g. DArkMAtter (DAMA), Cold Dark Matter Search (CDMS), Xenon100, Project In CAnada to Search for Supersymmetric Objects (PICASSO)
- Look for annihilation signal of WIMPs in centre Milky Way, dwarf galaxies
  - e.g. Fermi, CANGAROO II
- Results so far?

Results from earth

- LHC: testing supersymmetry (SUSY) predictions
  - 3.5σ result in contradiction with some SUSY theories
  - but this does not rule out all SUSY theories
  - upgrade of collider for 2015 (stay tuned!)
  - http://www.newscientist.com/article/dn22492-rare-particles-decay-confounds-hunt-for-new-physics.html
- PICASSO
  - no dark matter found
  - instead: limits on cross-section and mass
  - www.picassoexperiment.ca





Results from space

- Fermi: γ-ray satellite looking for WIMP annihilation signal at Galactic Centre
  - spike in signal! http://www.nature.com/news/2009/091019/full/news.2009.1018.html
  - but is it significant? http://www.nature.com/news/2009/090724/full/news.2009.730.html
- Signal from dwarf galaxies?
  - again: limits on mass and cross-section
  - http://www.nasa.gov/mission_pages/GLAST/news/dark-matter-insights.html

Summary

- Galaxies are dominated by dark matter halo
  - use rotation curves of gas discs (or stars)
  - halo found for spiral, elliptical and dwarf galaxies
- Galaxy clusters are dominated by dark matter
  - use velocities of galaxies and/or lensing to determine dark matter content
- The Universe is dominated by dark matter
- True nature of dark matter still a mystery
  - several candidates known, but till today dark matter particle is not detected

Want to know more?