Dark Matter

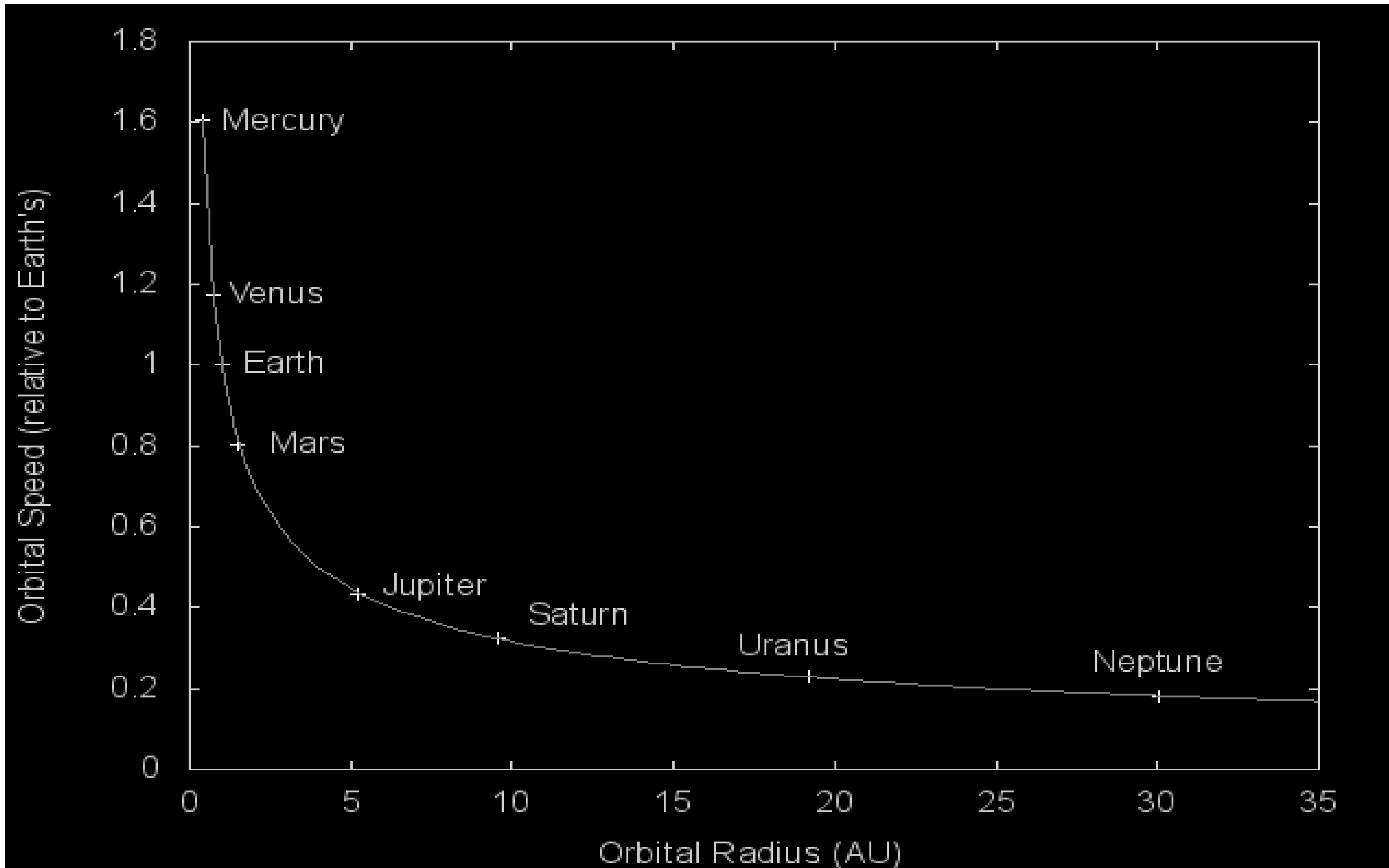
Is that all there is?

We have measured many forms of normal matter from light

- Stars – absorption-line spectra
- Low-density gas – emission-line spectra
- Dust – blocks optical/emits in the far infrared

Is that amount of matter enough to explain the gravitational force pulling on stars in a galaxy or on galaxies in a cluster?

More distant planets move more slowly



From Solar System to Galaxy

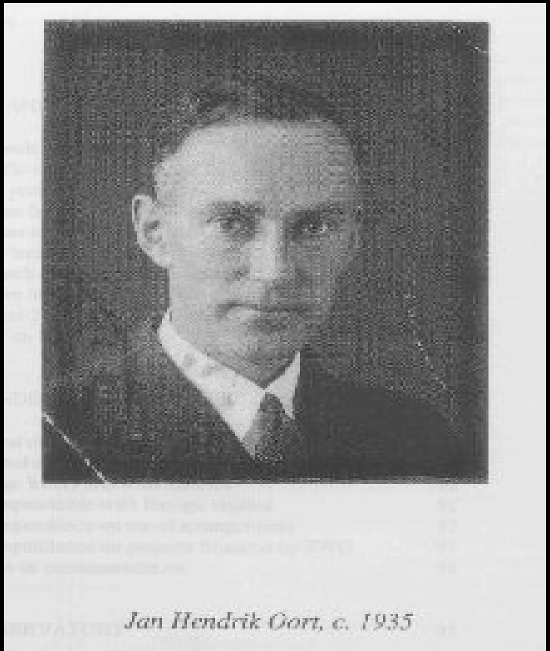
Planets have smaller speeds the further they are from the Sun

- Sun has about 99.8% of the mass in the Solar System
- No substantial contribution from dark matter

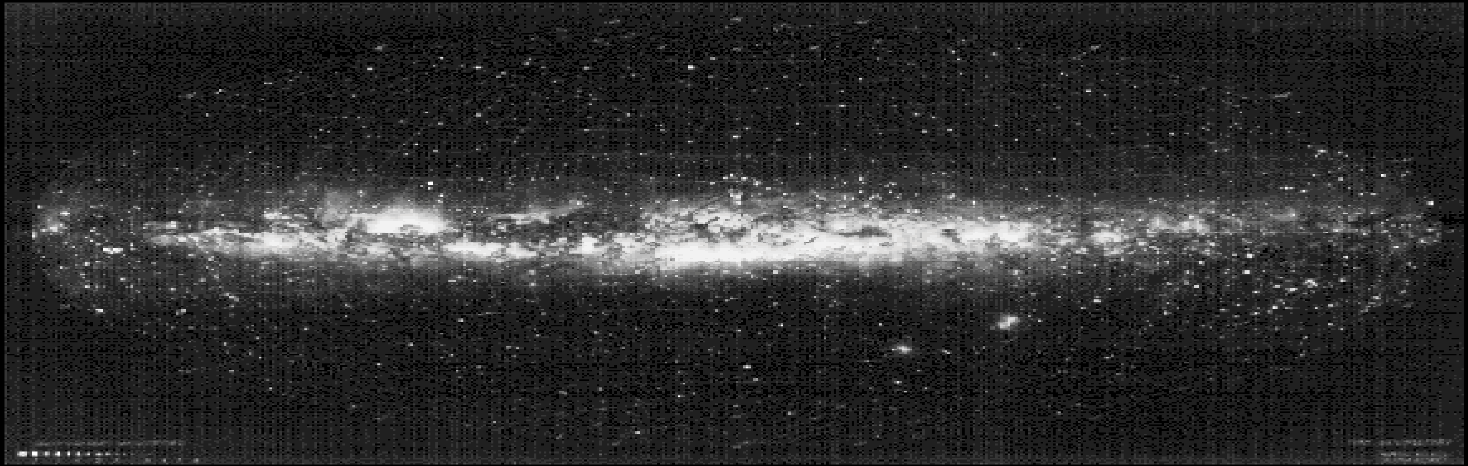
When we look at the same idea in a galaxy it is a little more complicated because the mass isn't essentially concentrated in the center.

- Clearest signal looking relatively far out from center

Dark matter, discovery



Jan Oort 1900-1992



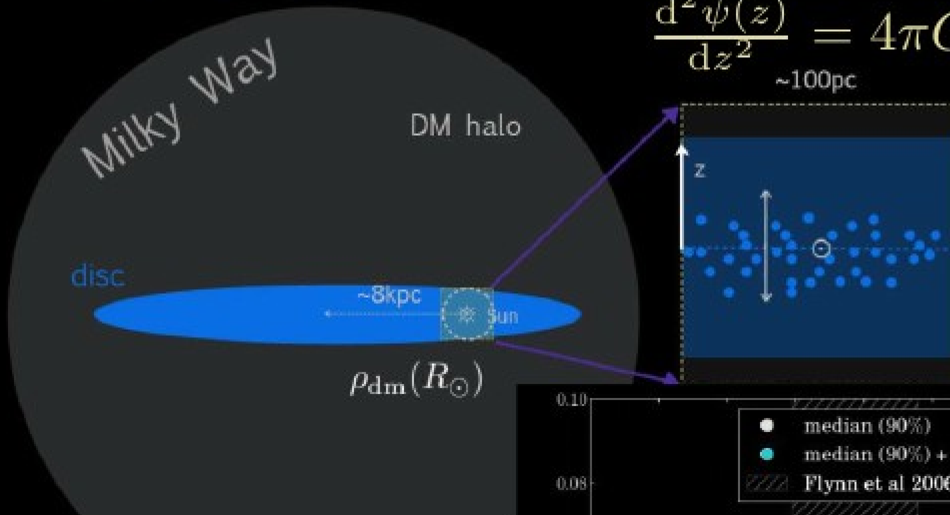
Oort (1932): *Velocity scatter of stars in Galactic Plane* greater than expected from gravitational potential from the stars:

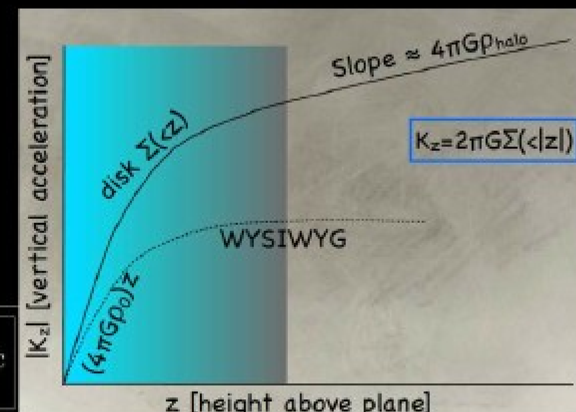
more mass needed!

We can infer the *local* dark matter density by measuring vertical distribution of stars … pioneered by Kapetyn (1922) and Oort (1932)

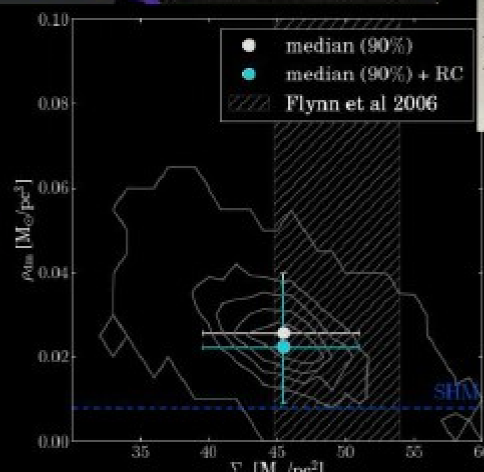
If galaxy is approximated as thin disk, then orthogonal to the Galactic plane:

$$\frac{\mathrm{d}^2\psi(z)}{\mathrm{d}z^2} = 4\pi G_\mathrm{N}\rho_\mathrm{m} \rightarrow \frac{\mathrm{d}\psi(z)}{\mathrm{d}z} = 2\pi G_\mathrm{N}\Sigma_\mathrm{m}$$





Courtesy: Konrad Kuijken



Garbari, Liu, Read & Lake, MNRAS **425**:1445,2012

Using data on K-dwarfs (Kuijken & Gilmore, MNRAS **239**:605,1989) found:

$\rho_\mathrm{DM} = 0.85 \pm 0.6\ \mathrm{GeV/cm^3}$

Bidin *et al* (ApJ **747**:101,2012) claimed $\rho_\mathrm{DM} < 0.04\ \mathrm{GeV/cm^3}$, because of *incorrectly* assuming that the rotational velocity is independent of galactocentric radius at all *z* (Bovy & Tremaine, ApJ **756**:89,2012)

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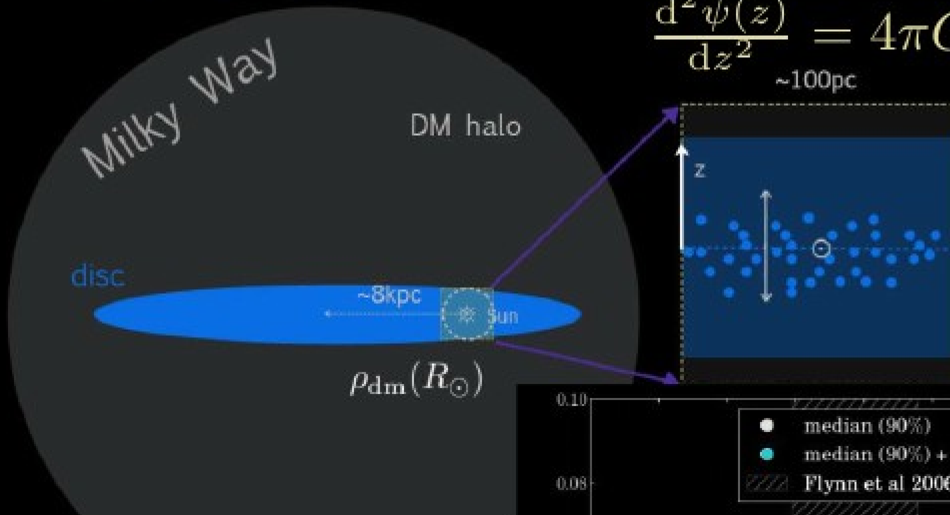

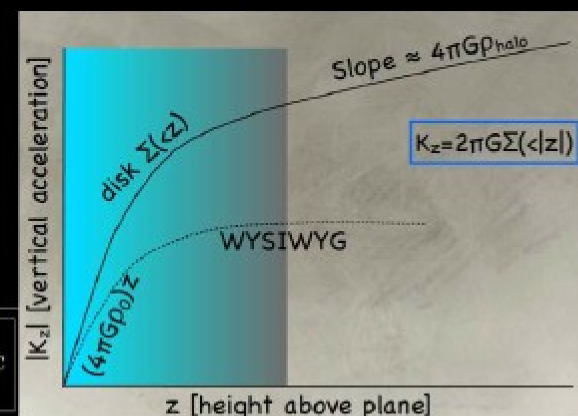

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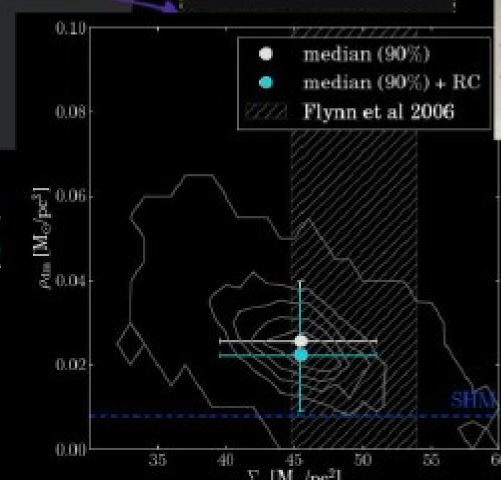

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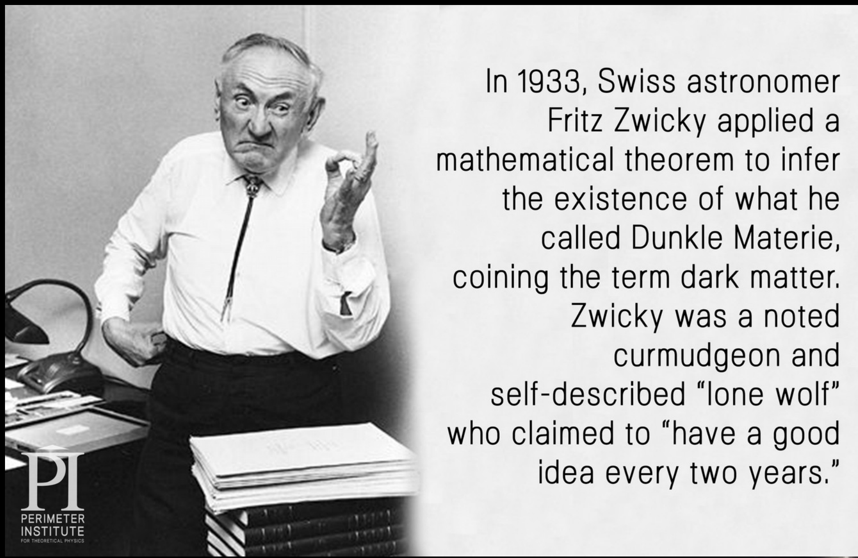
Dark matter, discovery



Fritz Zwicky 1898-1974

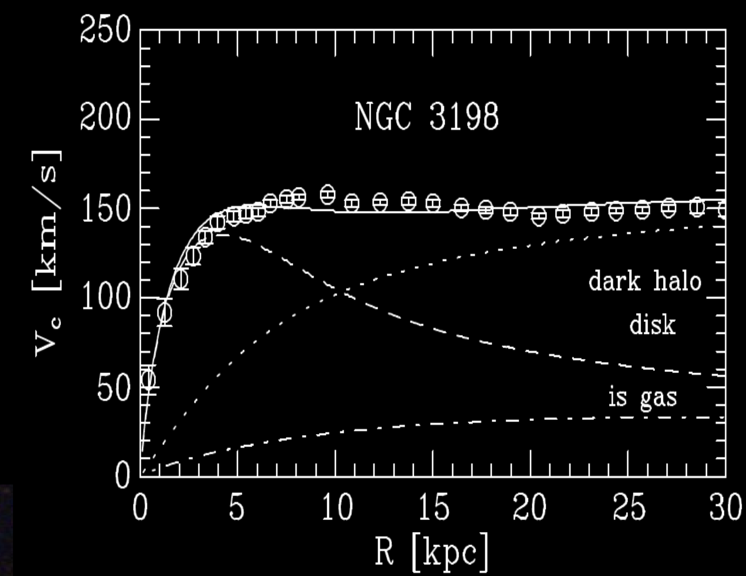
Zwicky (1933): *Velocity scatter among galaxies in Coma Cluster* far greater than gravity from visible matter can balance: ***x 160!***

Virial theorem: $E_{kin} = -U/2$

$E_{kin} \sim 1/2\ N m v^2$

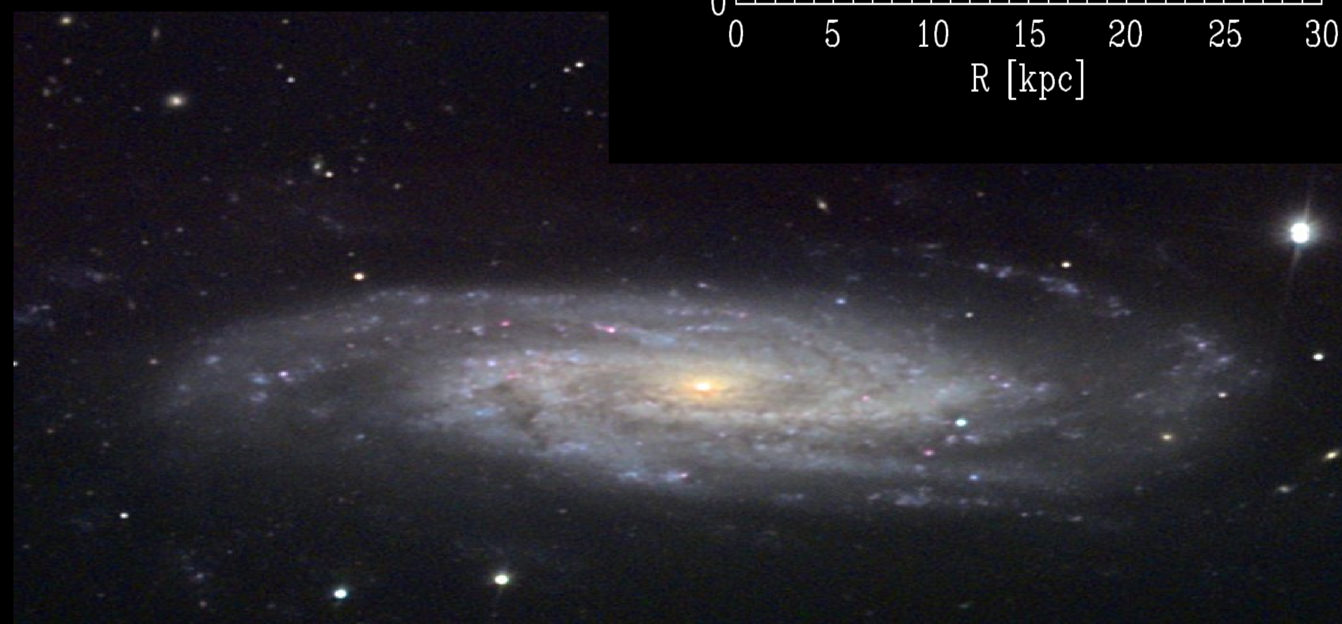
$U = 1/2\ N(N-1)\ G m^2/r$

Rotation curves for galaxies

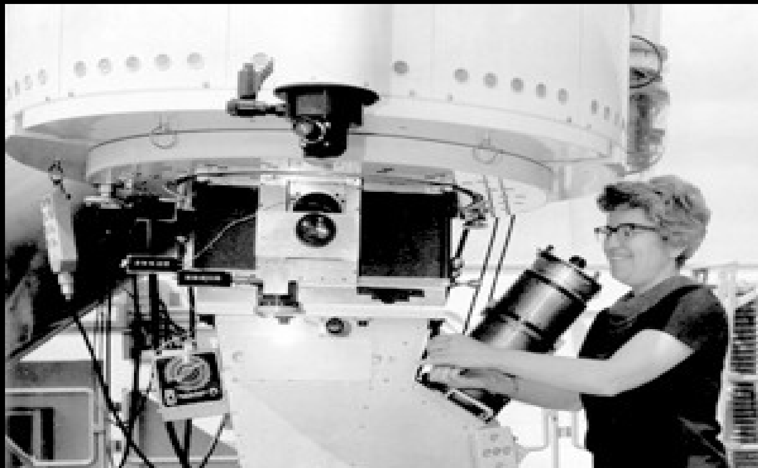


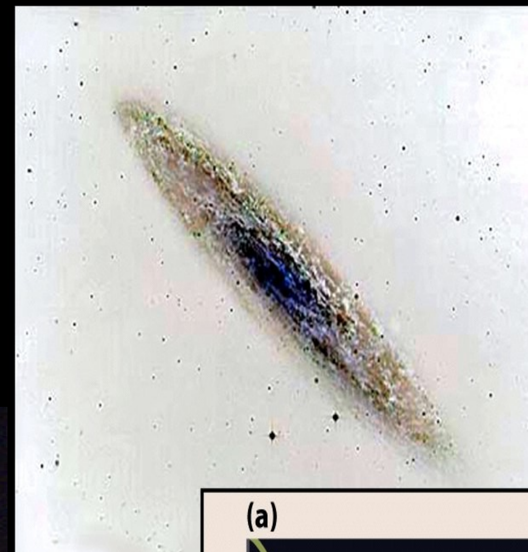
$$v/r \approx G\,M(r) / r^2$$

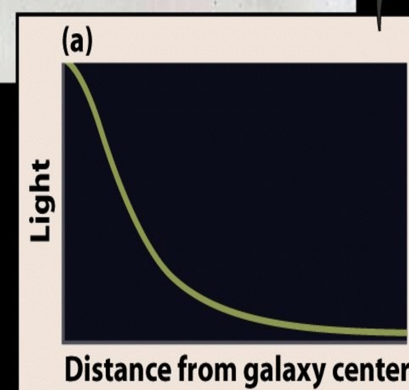
$$v \approx \sqrt{G\,M(r) / r}$$

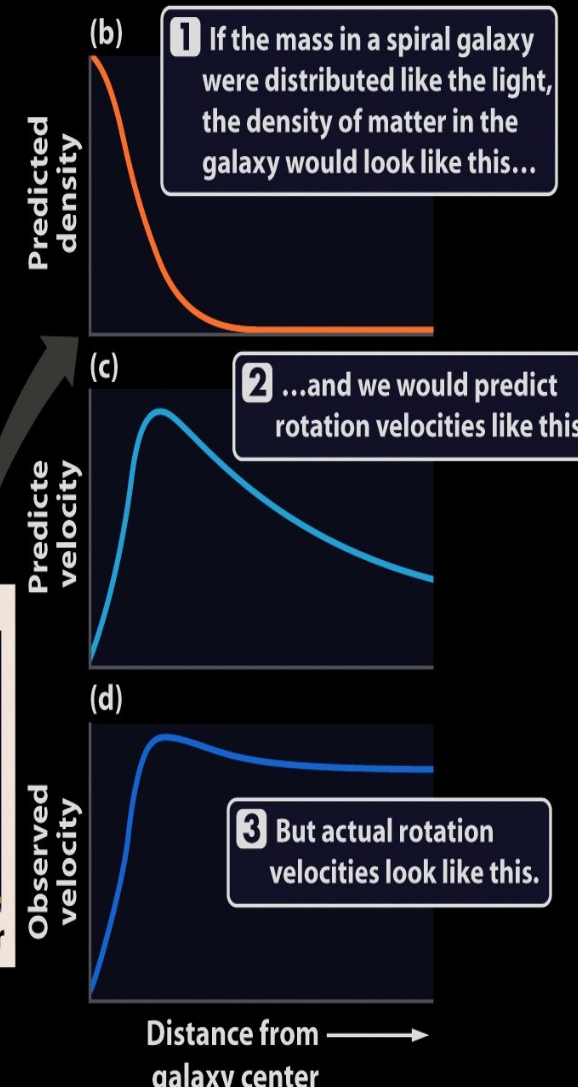


Rotation curves for galaxies









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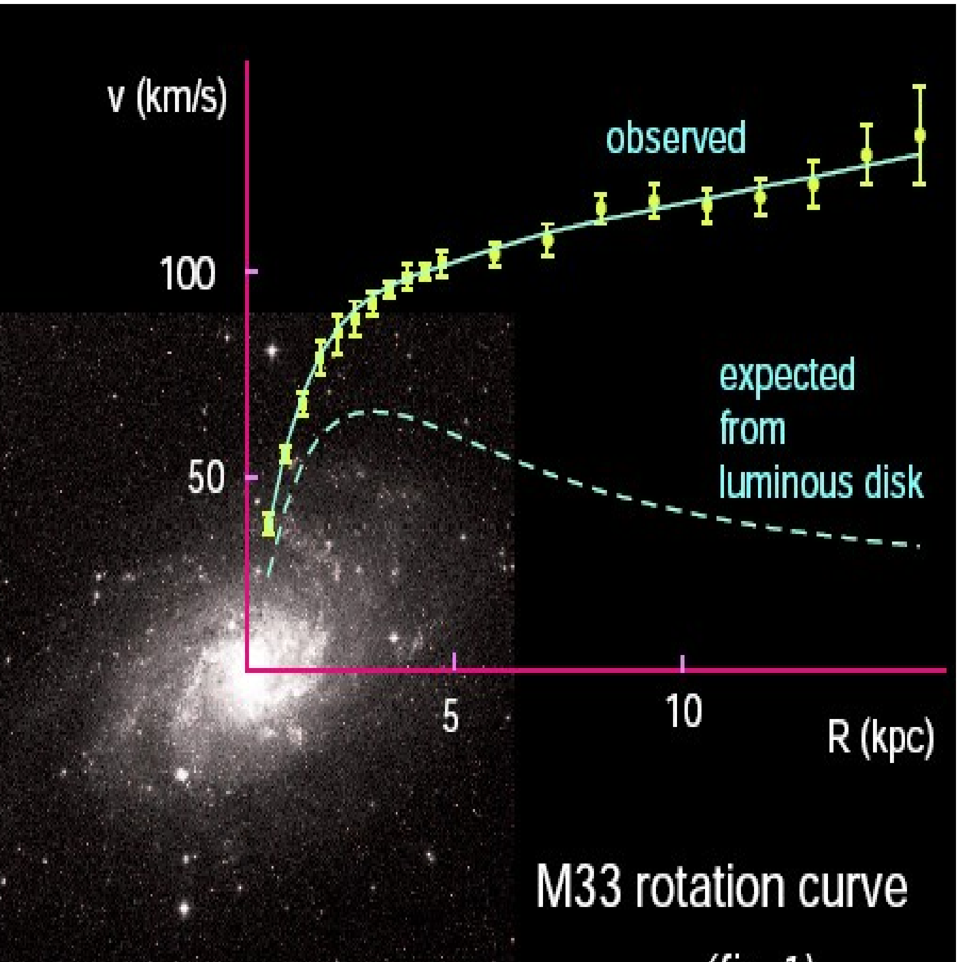
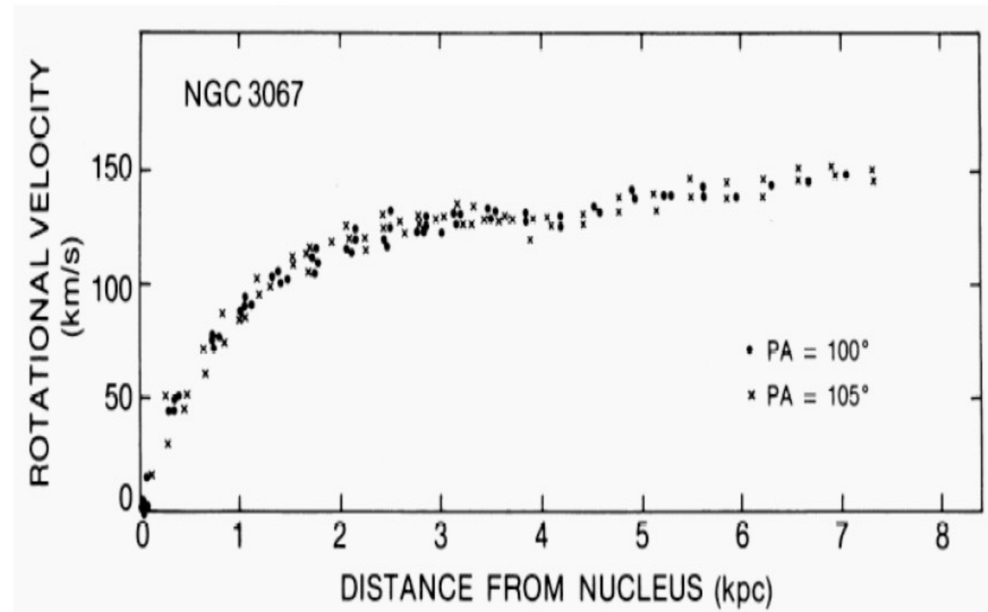
What Actually Happens





To understand this, there must be mass that we don’t see

Ex: Local Group

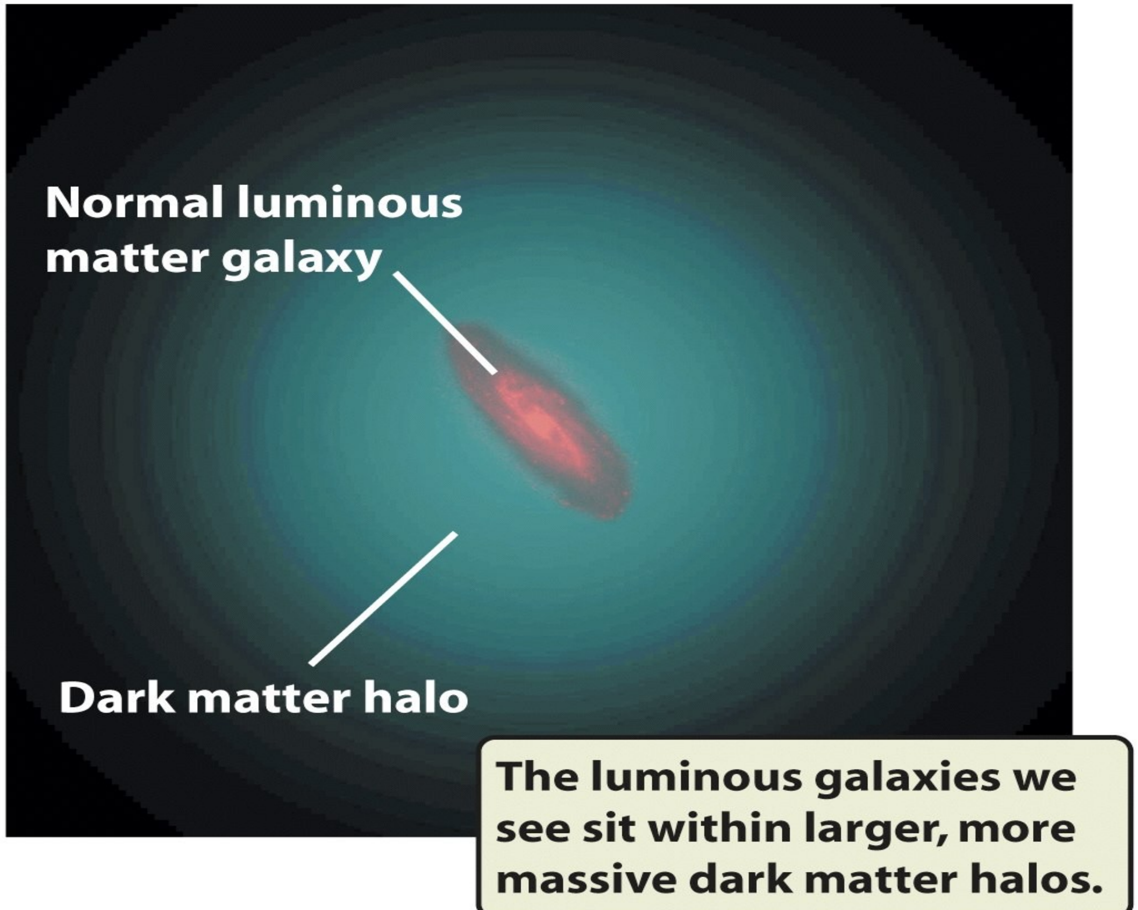
M31, M33, Milky Way, + …

Dynamical mass: 3.2-3.7 10^{12} M_{sun}
Total visible mass 3 10^{11} M_{sun}

Dark energy correction to potential energy: 30%! (Chernin et al. 2009)

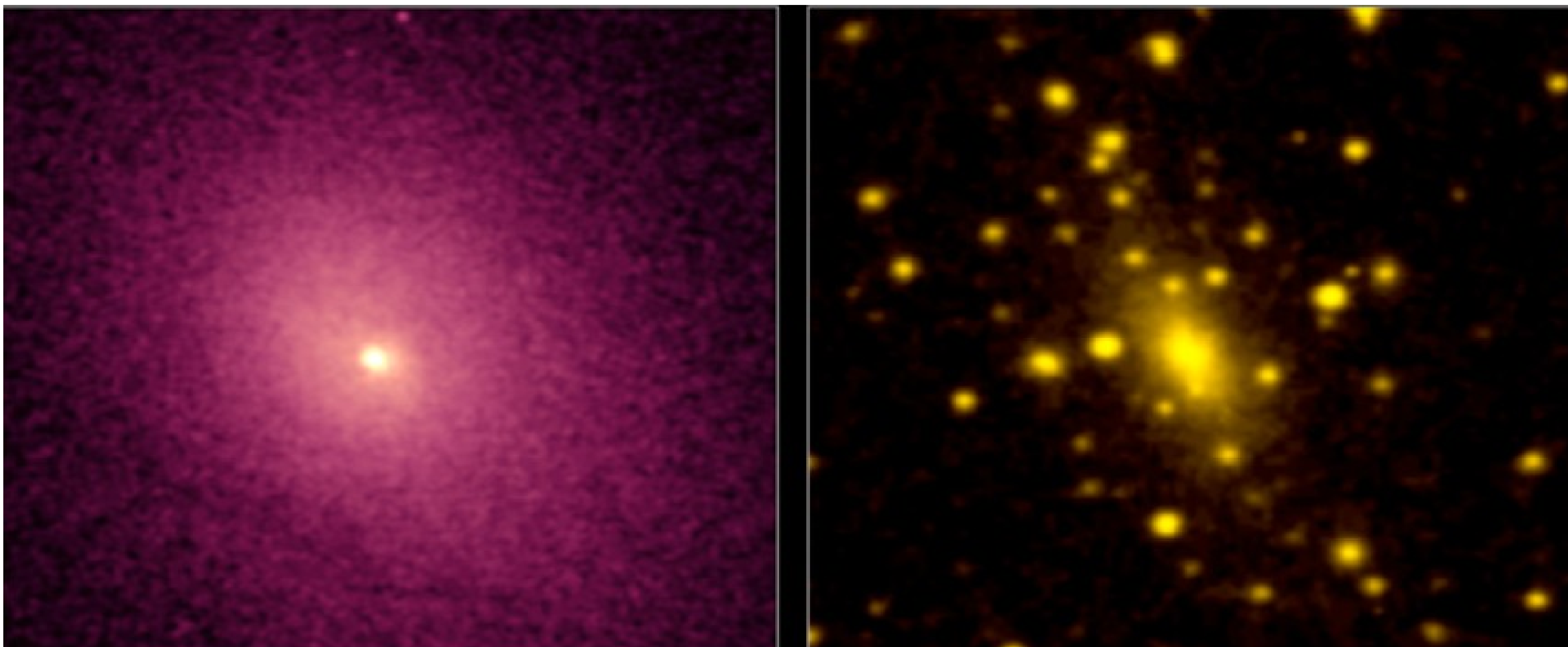



Galaxies are surrounded by dark matter halos



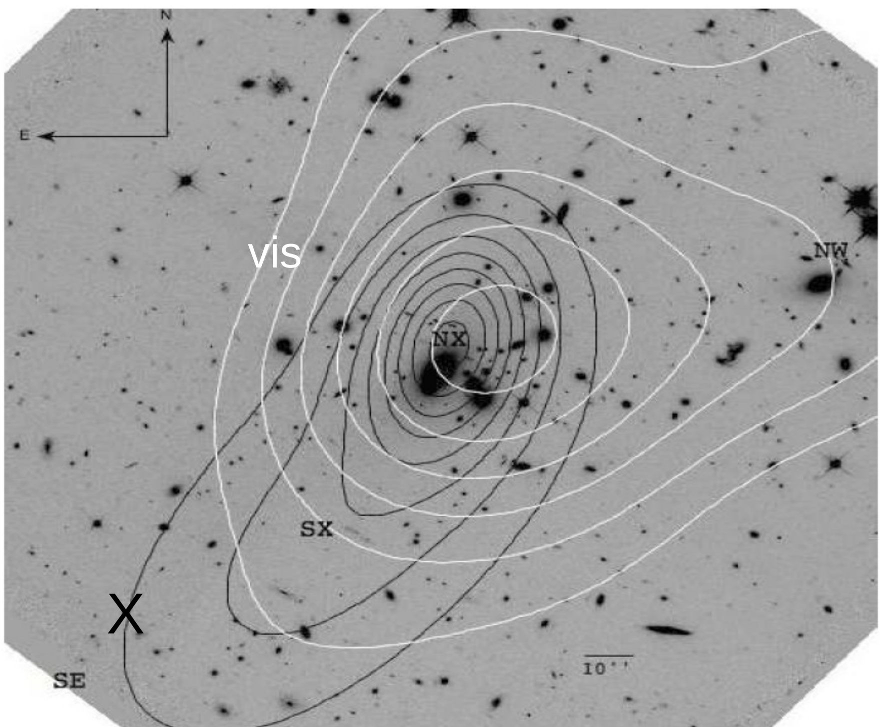
Much of this mass is hot gas

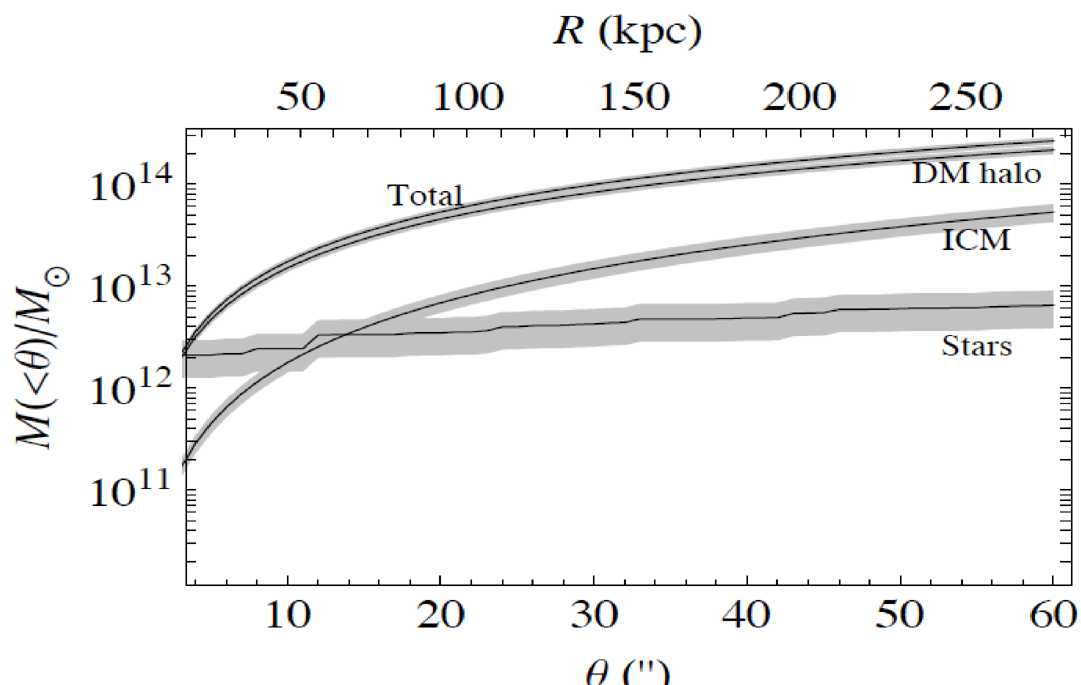
- Hot gas radiates X-rays



Other clusters and galaxy groups

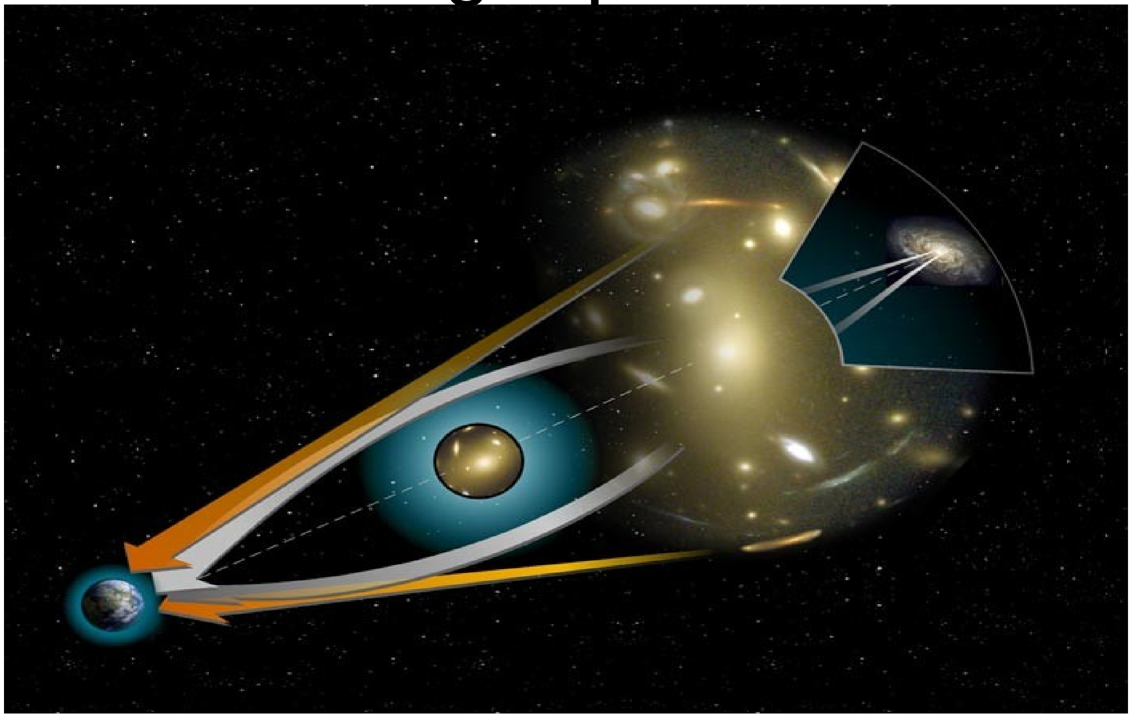
Ex: Sereno et al. (2010)
AC 114





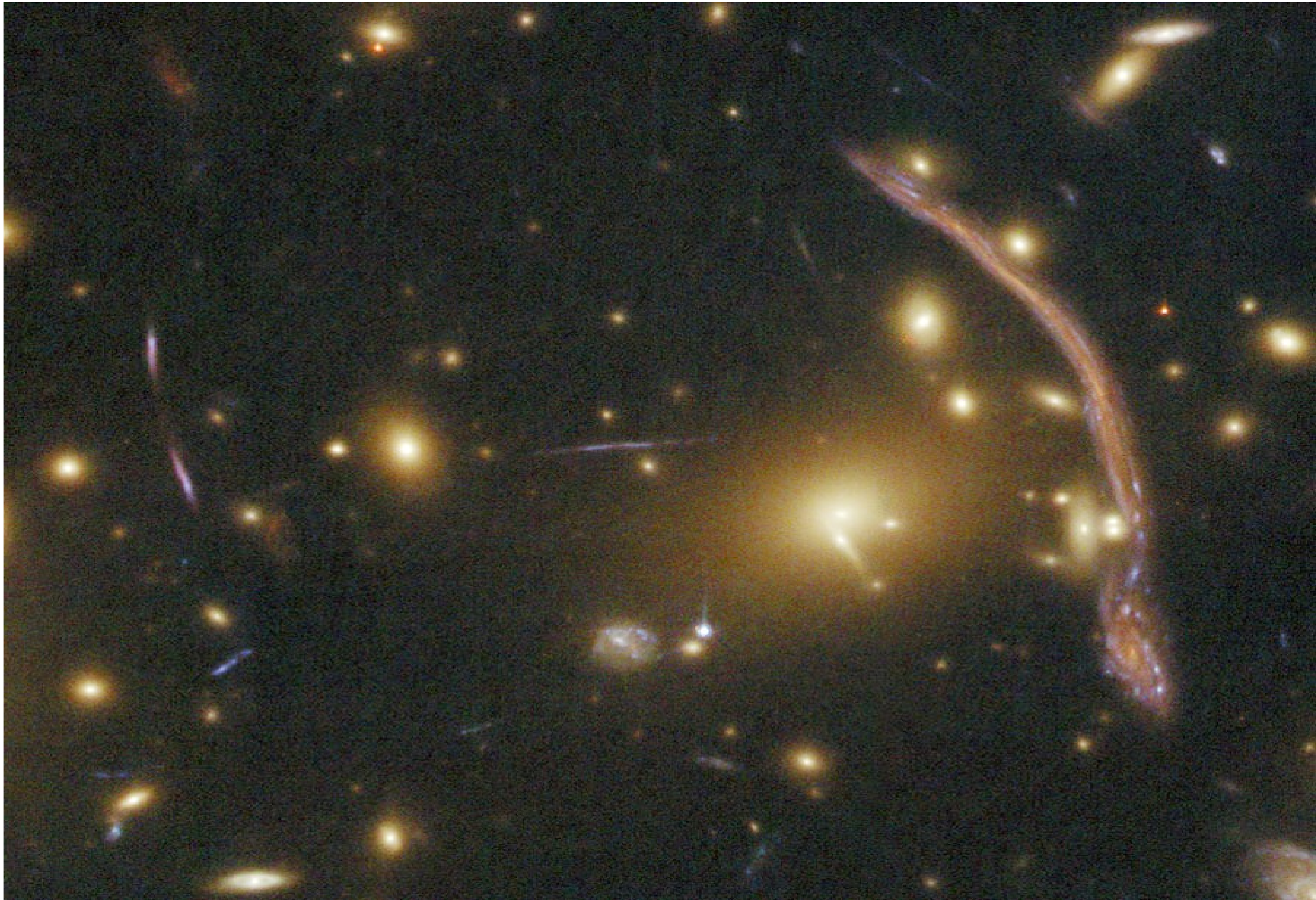
Gravitational Lens

- Orange lines show apparent source of light
- White line is actual light path



Gravitational lensing

- Strong
- Weak
- Micro-lensing



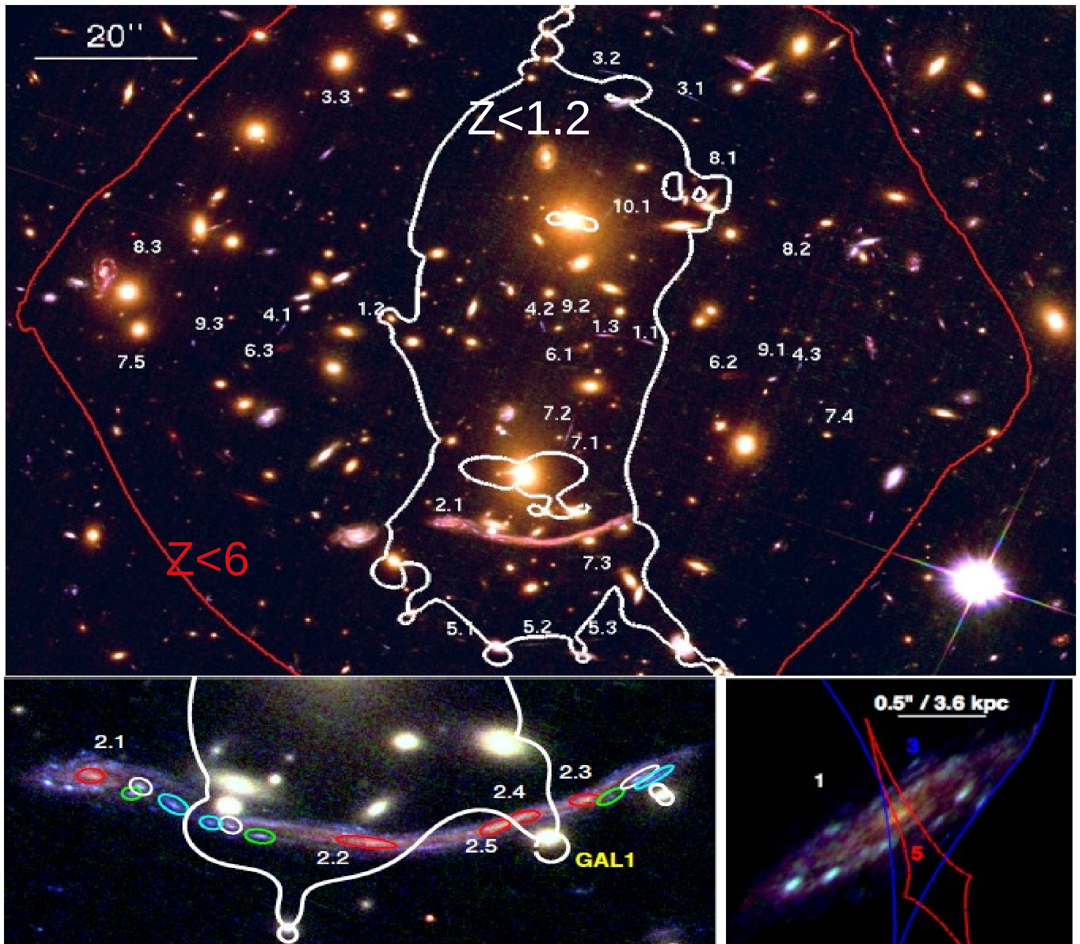
Abell 370

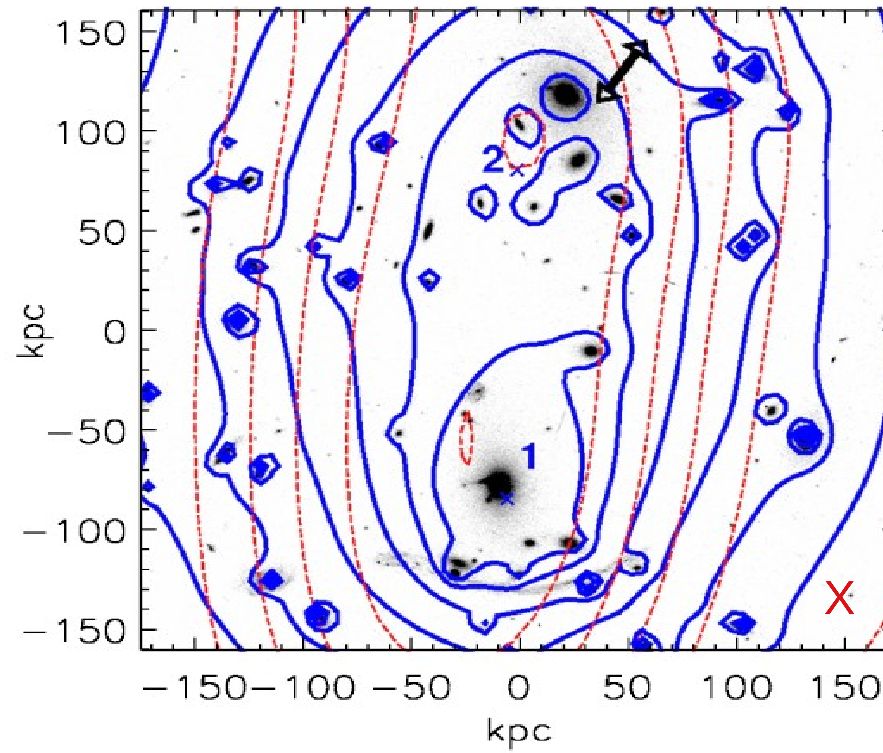
distance 6 10^9 ly

Space Telescope Image

Where the mass is

Richard et al. (2010): Abell 370 revisited



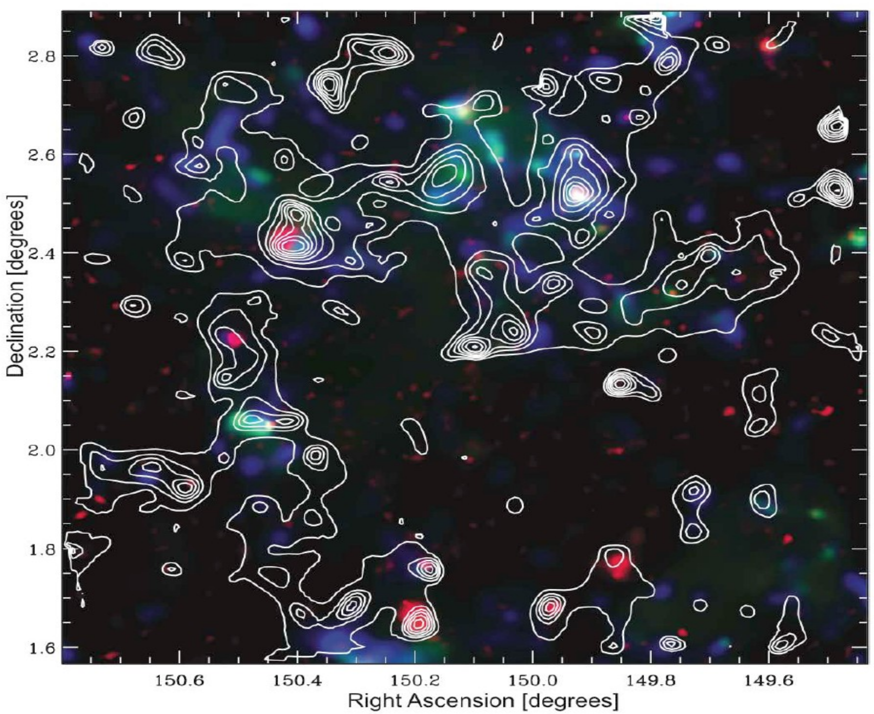


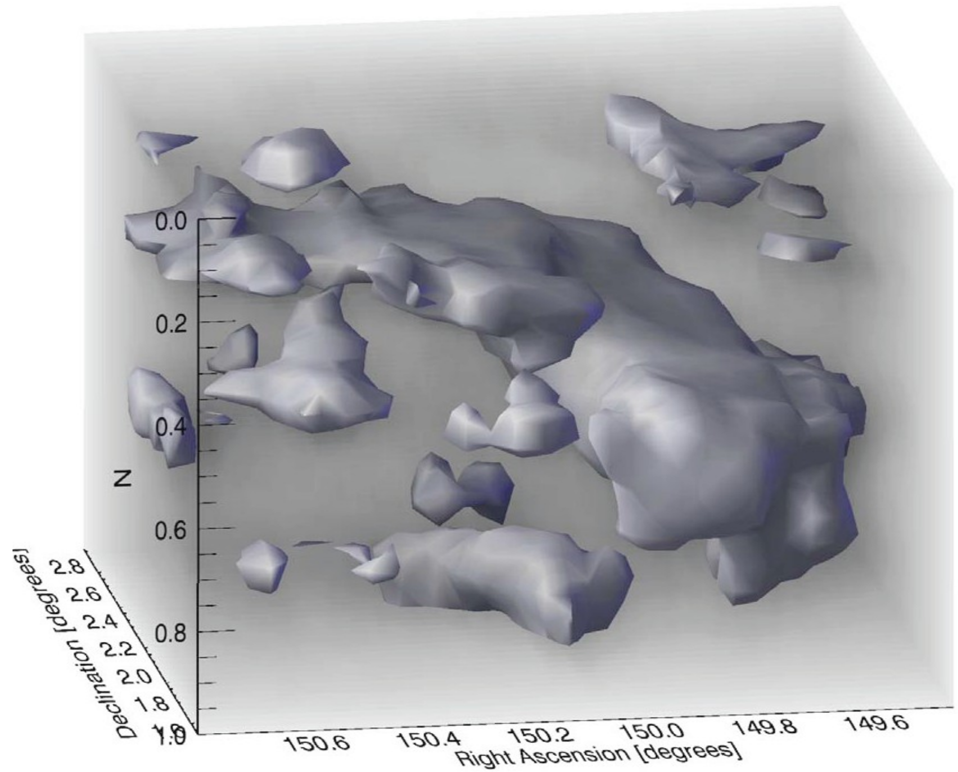
10 background galaxies with multiple images

$M_x = 5\ 10^{13}\ M_{sun}$; $M = 3.8\ 10^{14}\ M_{sun}$

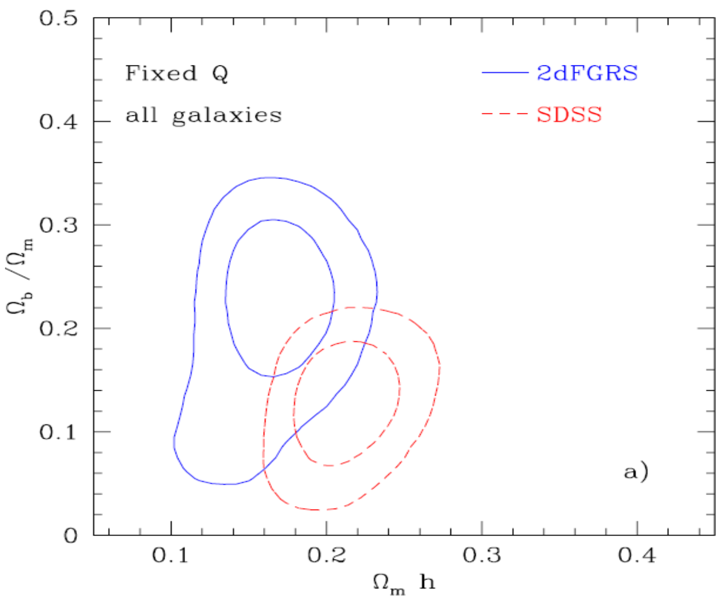
- Statistical lensing, distortion studies

Massey et al. (2007) ~ 500,000 galaxies



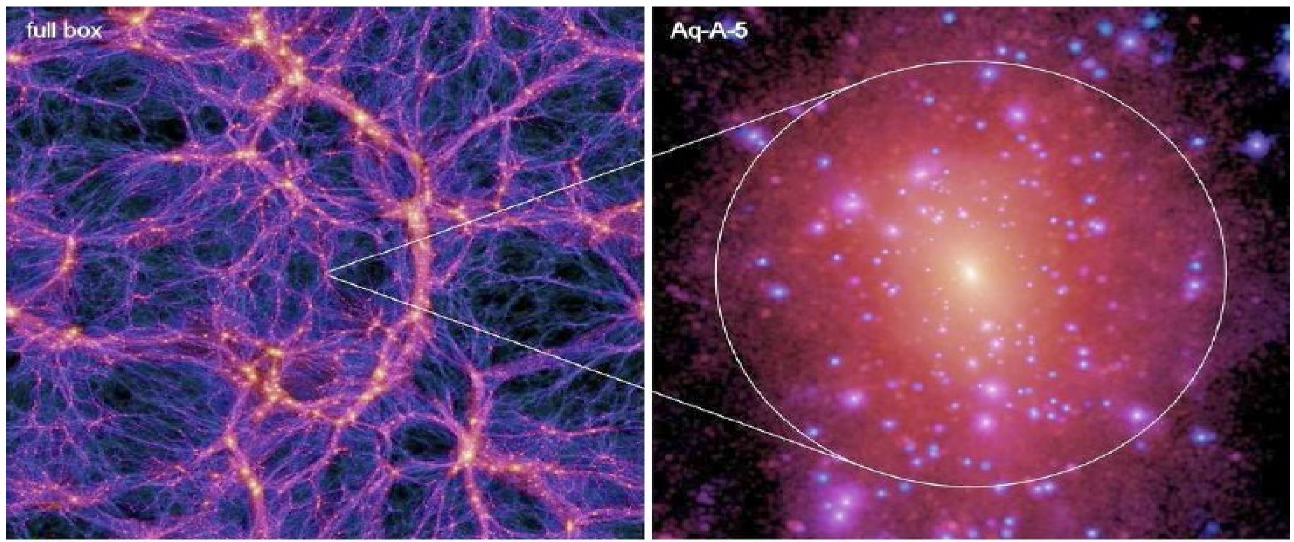


Galaxy formation, large-scale structure



Sanchez & Cole (2008)

Springel et al. (2008)
”Aquarius project”
ΛCDM simulation
300,000 gravitationally bound sub-haloes

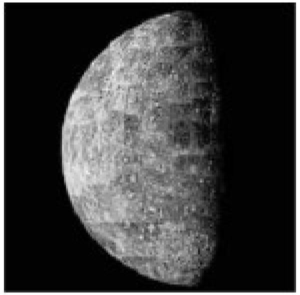


General fit, but too many small dark halos (dwarf galaxies) produced

Inferences of dark matter are not always right ... it may instead be a change in the dynamics

2nd January 1860: "*Gentlemen, I Give You the Planet Vulcan*" French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris (following up on his earlier prediction of Neptune in 1856).

Some astronomers even see Vulcan in the evening sky!



But the precession of Mercury is not due to a dark planet **… but because Newton is superseded by Einstein**

Modified Newtonian Dynamics ("MOND")?

- Modehai Milgrom (1983)

  $F \neq m\,a$ at very small a;

  later modified gravity, and

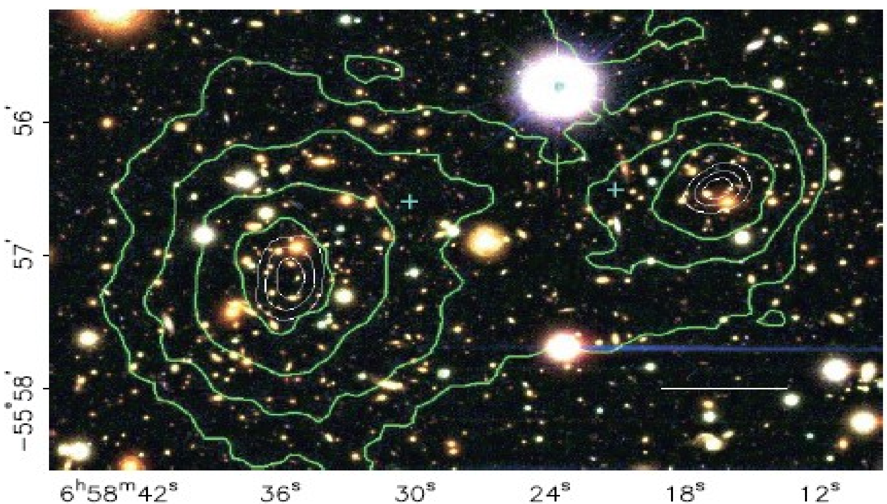
  relativistic gravity (Bekenstein)

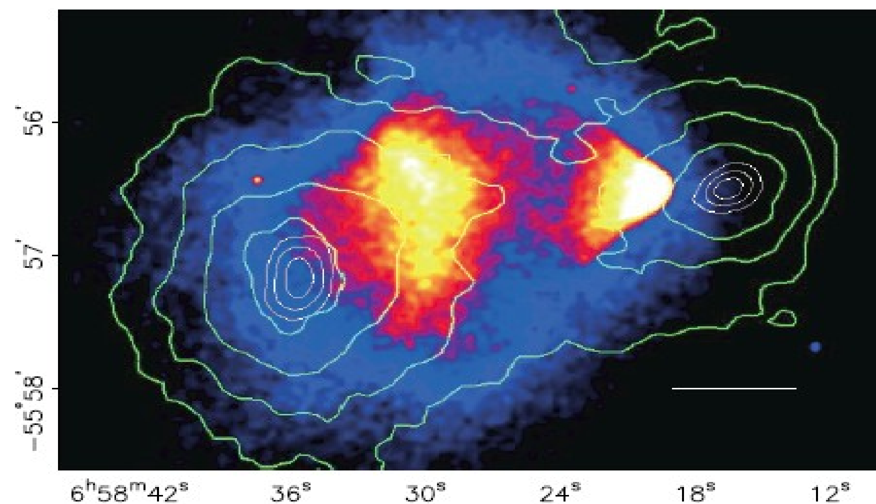
Merging clusters (”The Bullet”)

Clowe (2006), cluster MACS J0025.4.1222

Weak lensing reconstruction

Colours: X-rays (dominating baryonic mass component)





Possible candidates

Stellar remnants

- Black holes
- Neutron stars
- White dwarfs

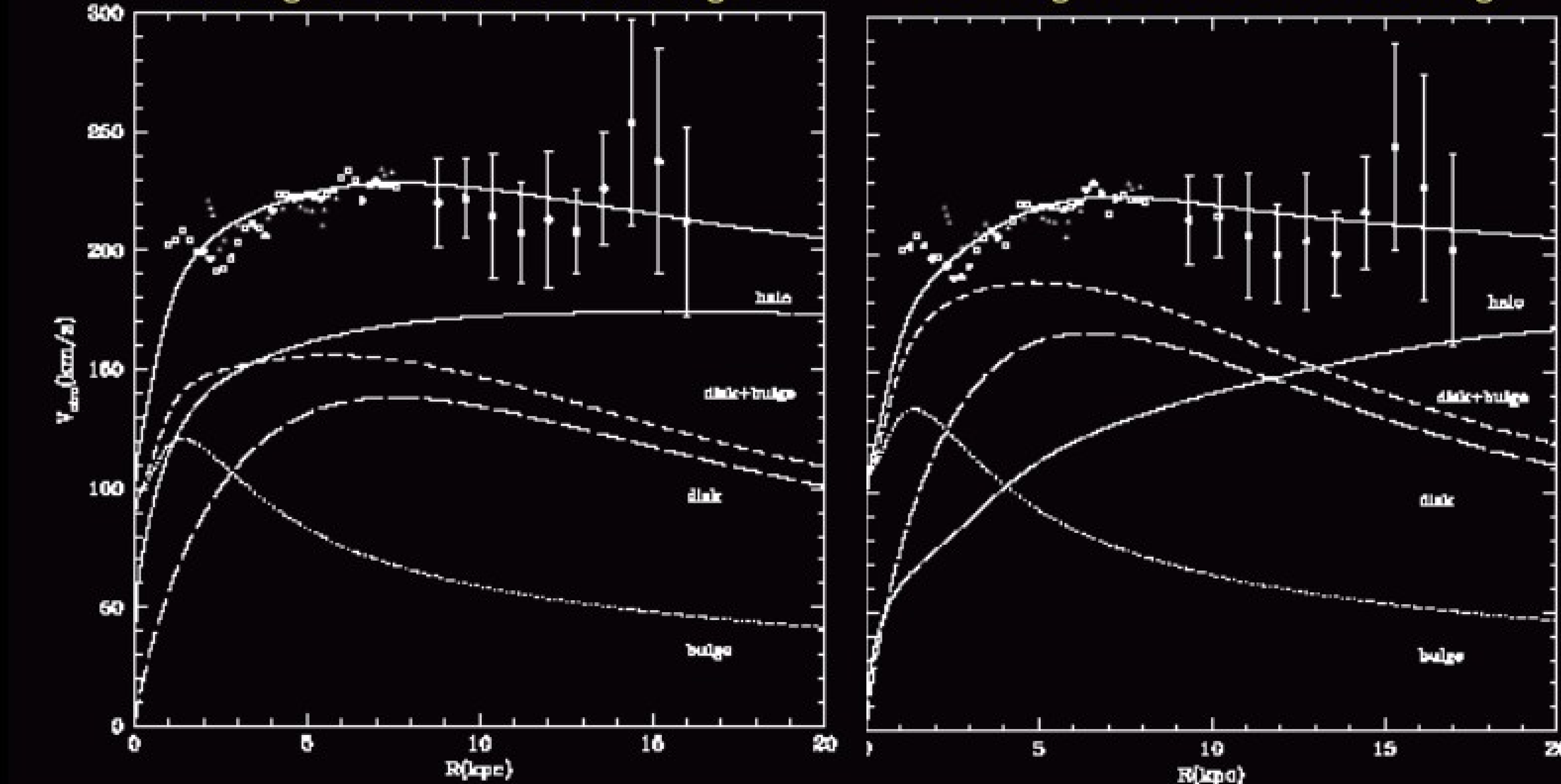
MACHOs -- MAssive COmpact Halo Objects

Brown Dwarfs & Planets

Particle

- Neutrino
- New Particle – Weakly Interacting Massive Particles (WIMPs)

No angular momentum exchange | With angular momentum exchange



Klypin, Zhao & Somerville, ApJ **573**:597,2002

With the $1/r^2$ density profile, the solution of the collisionless Boltzmann equation is the 'Maxwellian distribution':

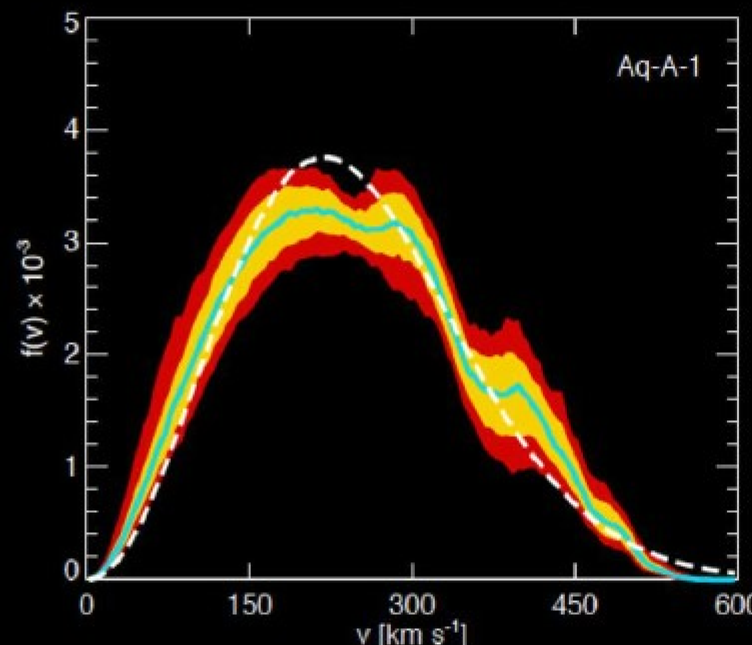
$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{x}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

$$f(\mathbf{v}) = N \exp\left(-\frac{3|\mathbf{v}|^2}{2\sigma^2}\right)$$

$$\sigma = \sqrt{3/2}\, v_c$$

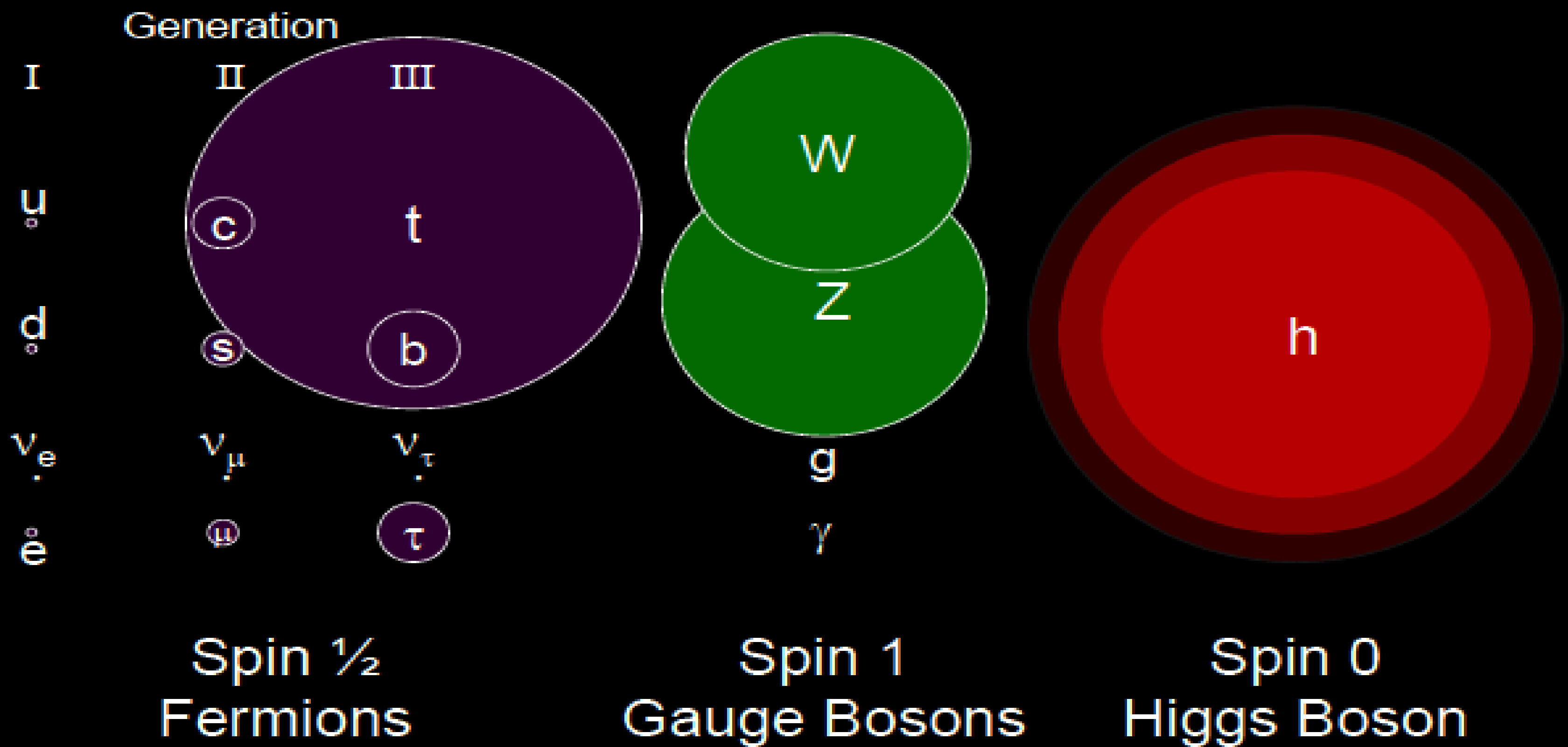
The 'standard halo model' has $v_c = 220$ km/s and is truncated at $v_{esc} = 544$ km/s (both numbers have large observational uncertainties)

High resolution numerical simulations however suggest significant deviations from the Maxwellian distribution, particularly at high velocities (⇒ important implications for direct detection experiments)



Vogelsberger *et al*, MNRAS **395**:797,2009

Particles in the Standard model



SM problems (J. Feng 2010*)

- Gauge Hierarchy Problem
- New Physics Flavour Problem
- Neutrino Mass Problem
- Strong CP Problem
- SM Flavour Problem
- Cosmological Constant Problem

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* arXiv: 1003.0904v2

Gauge Hierachy Problem

- Why is physical Higgs boson mass so small?
  114 GeV < h_H < 186 GeV (LEP)
- Expected: Planck mass $h_{Pl} = \sqrt{hc/G} \approx 10^{19}$ GeV. Why $h_H << h_{Pl}$?
  New physics at the weak scale (10 GeV – TeV).
  New particles at corresponding masses

=> WIMPS or superWIMPS

(Weakly or superweakly interacting massive particles)

WIMPS

- WIMPS freeze out (chemically decoupling):
  - Annihilation vs Expansion

$\Rightarrow \Omega_w \approx$ const $<\sigma_A\, v>^{-1}$

Annihilation cross section $\sigma_A\, v \approx$ const m_w^{-2}

$\Omega_w = \Omega_{DM}$ => 100 GeV < m_w < 1 TeV

Fits what is needed to solve the Gauge Hierarchy Problem: *"The WIMP Miracle"*

Are WIMPS stable?

- All particles with mass > 1 GeV in SM decay. Arguments for that the lightest new particle is stable.

  They can still annihilate with identical particles.

The spin ½ SUSYs: *neutralinos*; the lightest should be stable.

SUSY extensions of SM contain many free parameters

-- simplest ”minimal supergravity” (5 parameters)

Other WIMP alternatives:

- *Kaluza-Klein particles* (compact extra dimensions, modern version Universal Extra Dimensions), LKK 600 GeV – 1.4 TeV
- *Branons* (large extra dimensions)
- *Exited states* (warped extra dimensions).

- All produced through thermal freeze out – all are cold and essentially collision less.

superWIMPS
super-weakly interacting …

- Produced by WIMP decay long after WIMP freeze-out

  $\Omega_{sWIMP} = m_{sWIMP}/m_{WIMP} \times \Omega_{WIMP}$

- WIMP miracle => sWIMP miracle if masses are similar
- Ex: *gravitinos, axinos, Kaluza-Klein graviton* and *axion states*, *quintessinos*, …   Several well motivated!

If decaying WIMP was charged, so is sWIMP – interesting detection possibilities

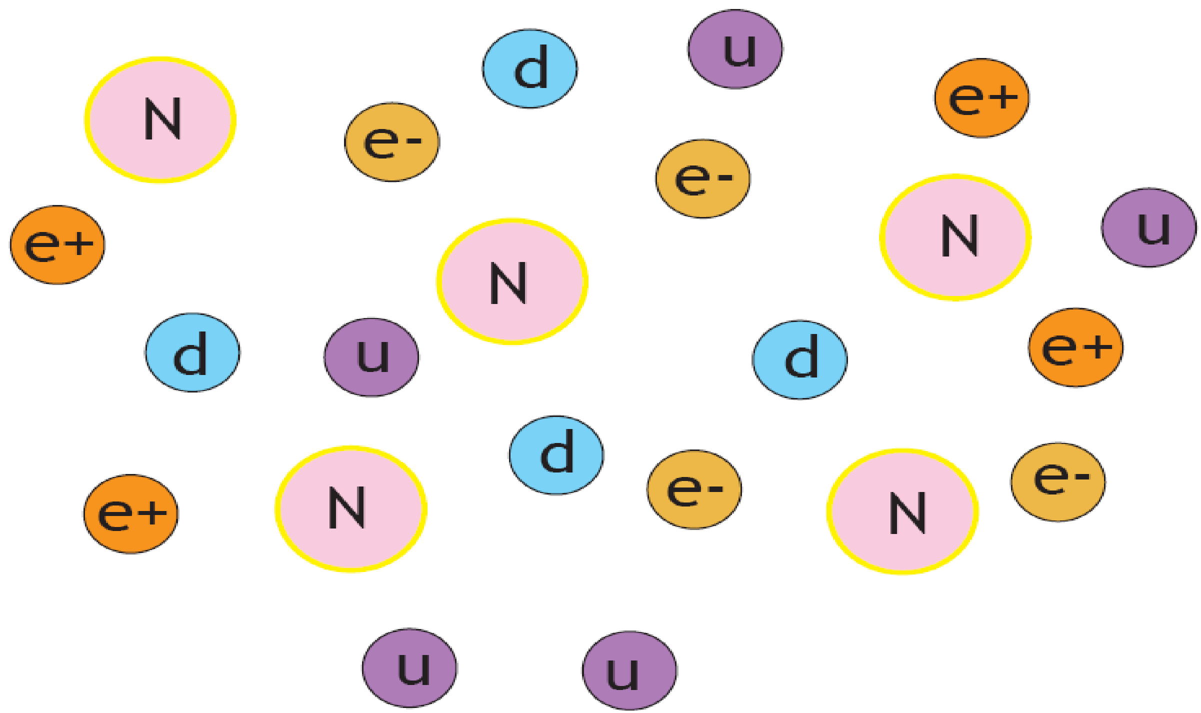
CMB and BB nucleosynthesis may be effected (late appearance)

Produced at high speeds at late times => may affect structure formation and diffuse structures.

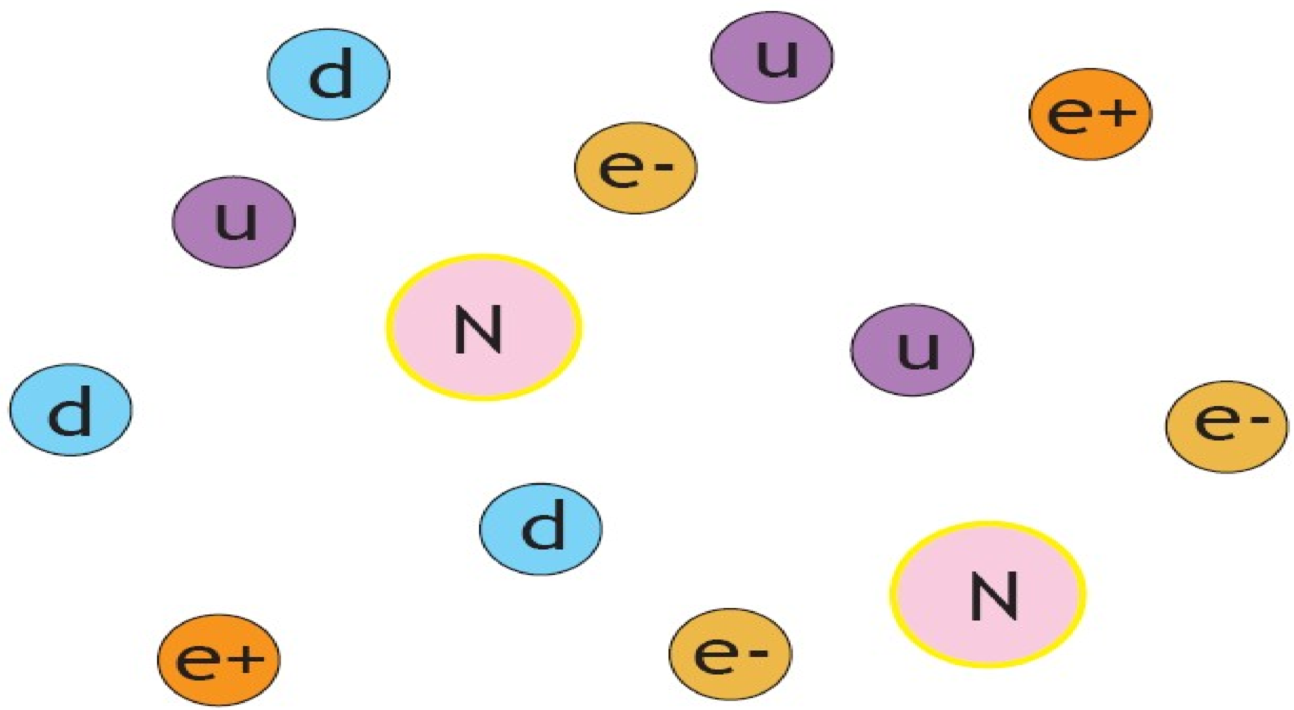
Other possibilities

- *Light gravitinos* (eV-keV)
- *”Hidden dark matter”* – no SM interaction
- *Sterile neutrinos* (righthanded ν:s, warm dark matter; affect structure formation)
- *Axions*. Light (<20 eV, else decay, weakly interacting, production non-thermal, else too hot. Peccei-Quinn phase transition in early Universe). No ”miracle”.

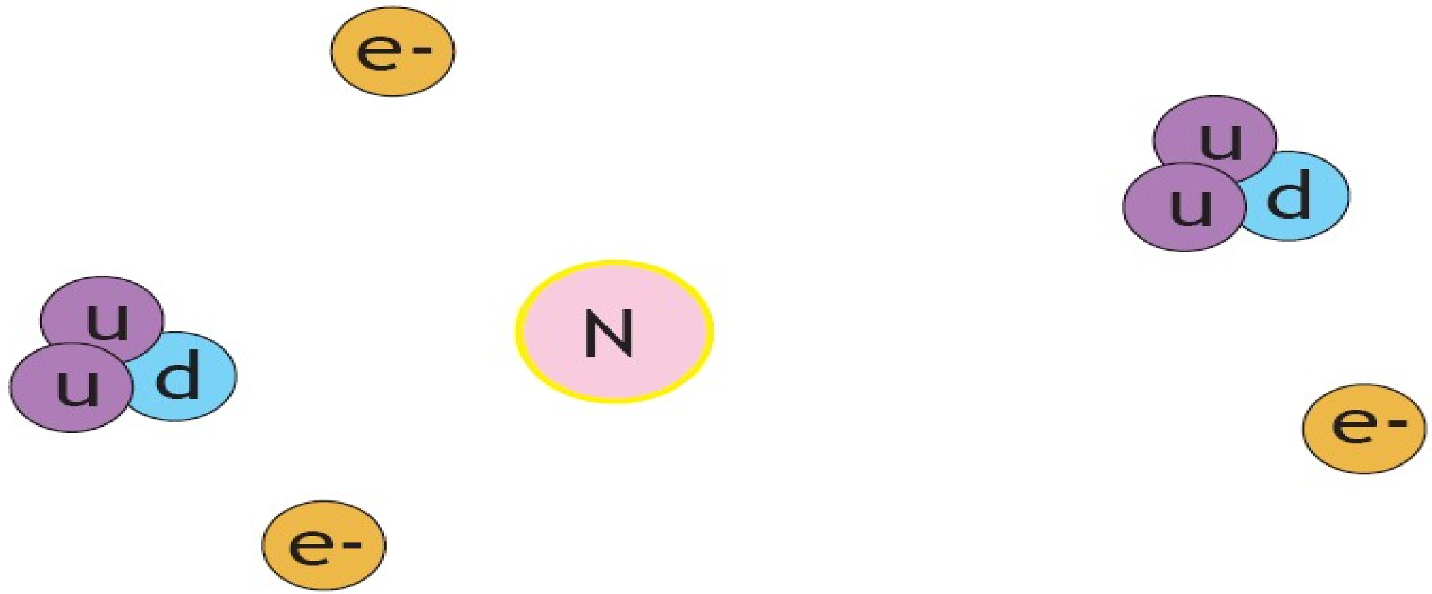
The Early Universe



The Universe Expands and Cools



Today



The left-over density is density $\sim m_N^2$

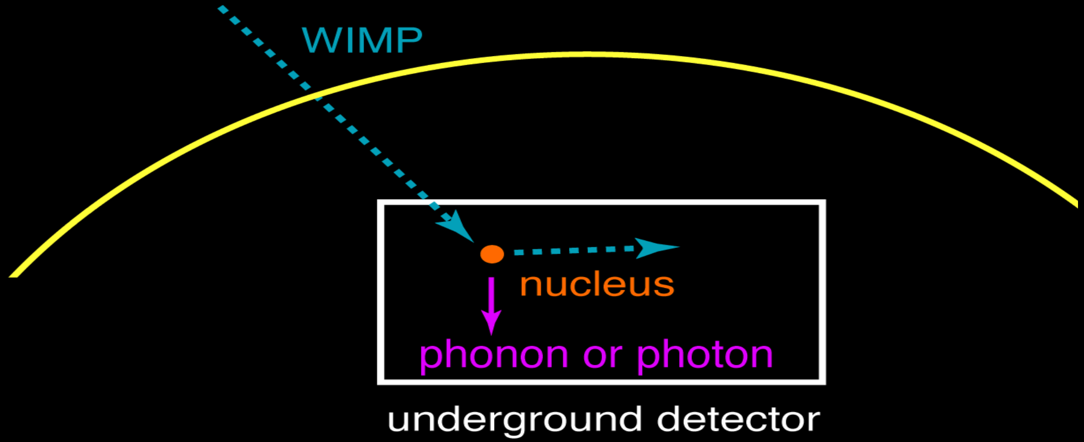
We get the observed density for $m_N^2 \sim 200$ GeV

- The density of WIMPS depends on how quickly they annihilate
- To get the right density today, the effective size is 1/1000 of the atomic nucleus
- WIMPs must be particles with weak interactions and masses 100-1000 times heavier than a proton.

Particle Dark Matter

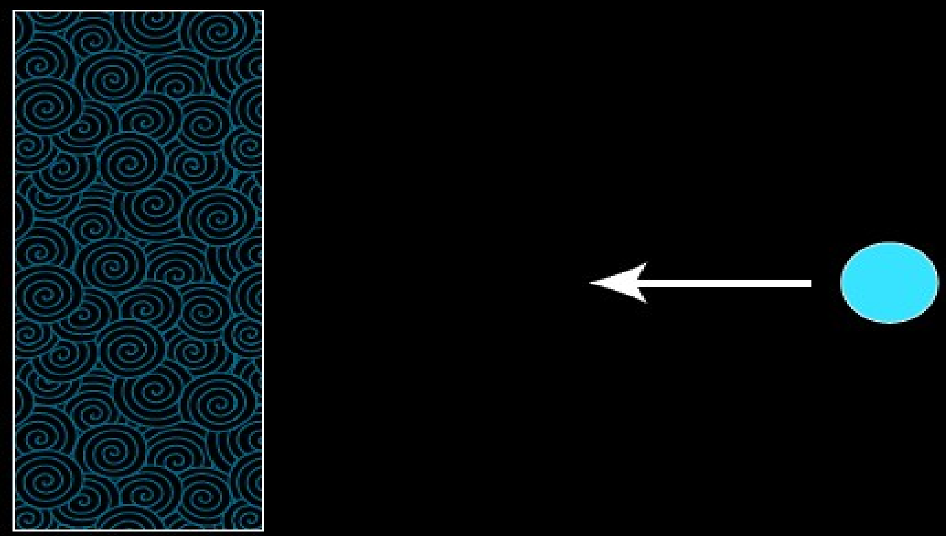
- We'd like to detect dark matter in the lab
  - To show they're in the galactic halo …
- And to produce them at an accelerator
  - To measure their properties …

Why put detector underground?



If we saw something, how would we know what it was?

- We need to know the probability that a dark matter particle will hit another particle and interact



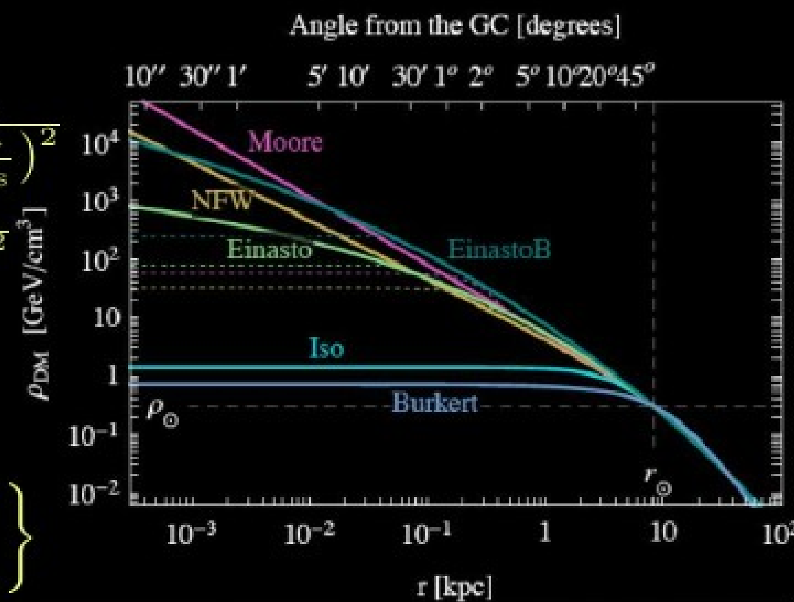
Modelling dark mater halos

Cored isothermal sphere: $\rho_{\rm isothermal} = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)^2}$

Navarro-Frenk-White profile: $\rho_{\rm NFW} = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$
(indicated by CDM simulations)

Burkert profile: $\rho_{\rm Burkert} = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]}$
(fits observations better)

Einasto profile: $\rho_{\rm Einasto} = \rho_s \exp\left\{-d_n\left[\left(\frac{r}{r_s}\right)^{1/n} - 1\right]\right\}$



where d_n is defined such that ρ_s is the density at the radius r_s enclosing half the total mass

… more generally define the **Hernquist profile**: $\rho_{\rm Hernquist} = \rho_s\left(\frac{r}{r_s}\right)^{-\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}$

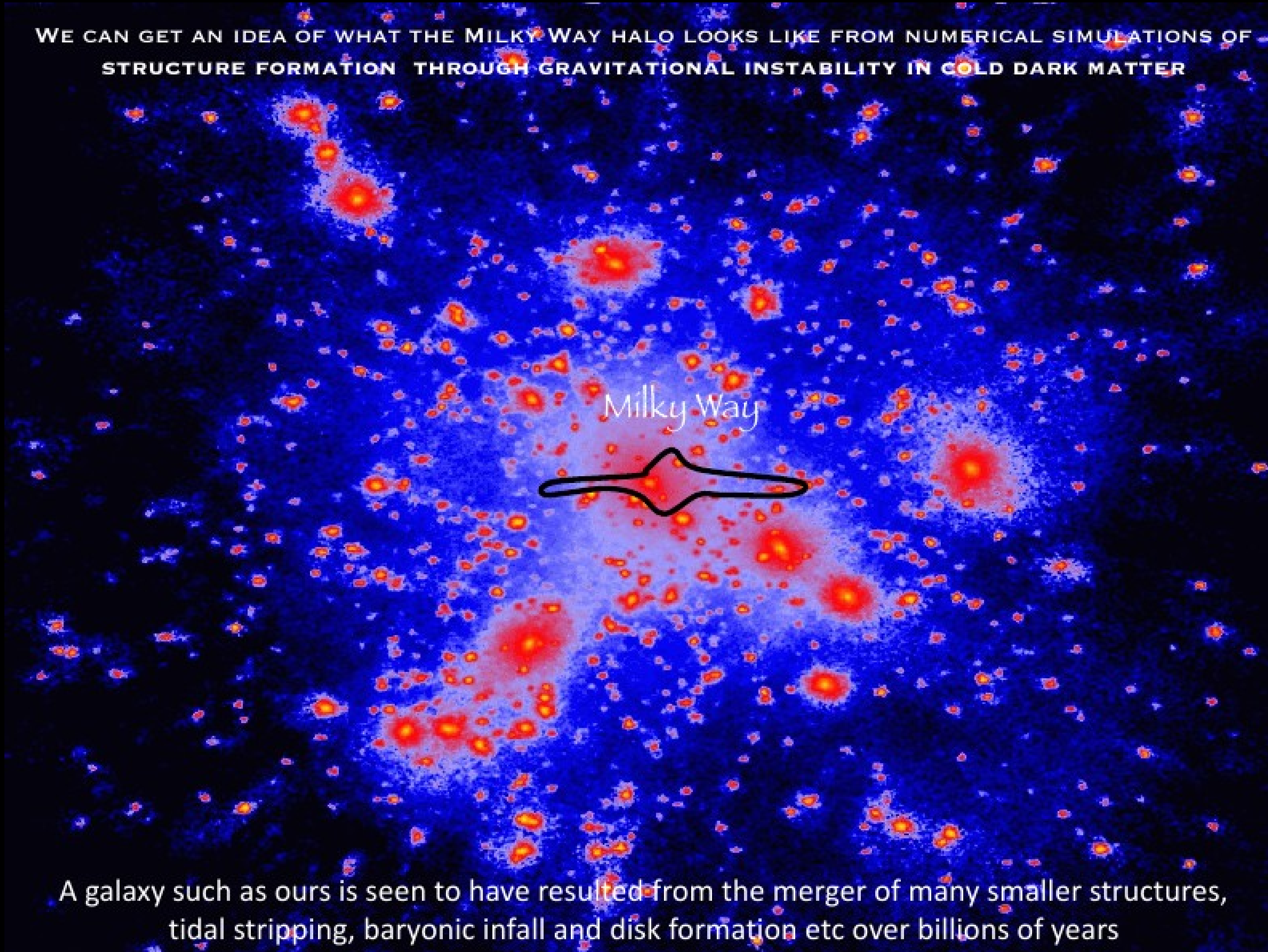
Here r_s is a characteristic scale and α controls the sharpness of the transition from the inner slope $\lim_{r\to 0} {\rm d}\ln(\rho)/{\rm d}\ln(r) = -\gamma$ to the outer slope $\lim_{r\to\infty} {\rm d}\ln(\rho)/{\rm d}\ln(r) = -\beta$

… e.g. the NFW profile corresponds to choosing $\alpha = 1, \beta = 3, \gamma = 1$, whereas a cored isothermal profile corresponds to choosing $\alpha = 1, \beta = 2, \gamma = 0$, and a Moore profile corresponds to $\alpha = 1.5, \beta = 2, \gamma = 1.5$ *etc*

For the Milky Way, the fit parameters are:

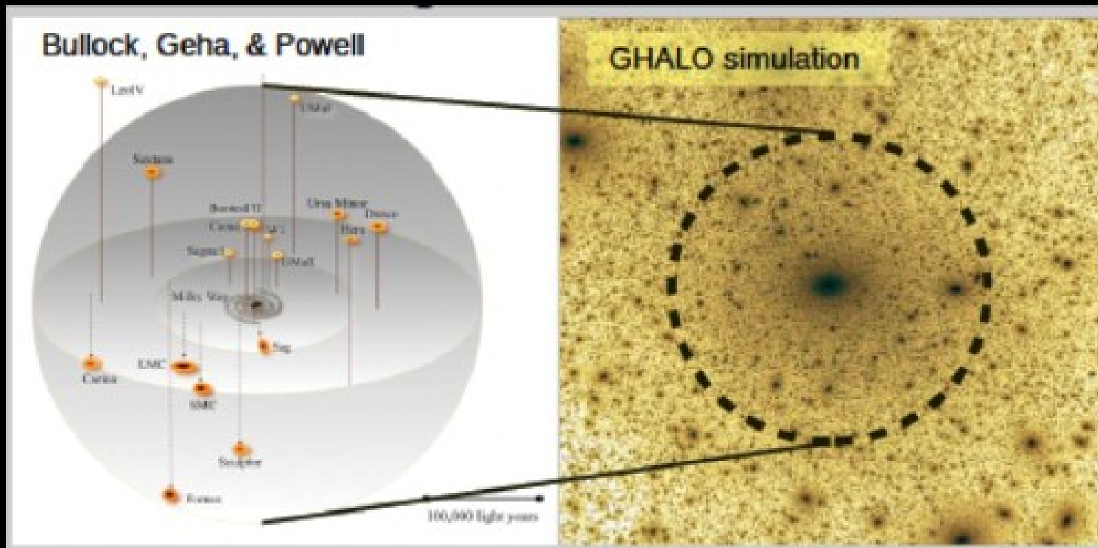
DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

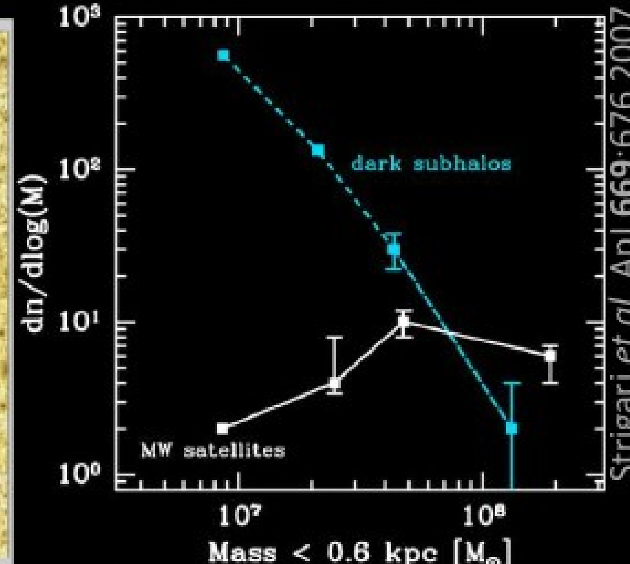
WE CAN GET AN IDEA OF WHAT THE MILKY WAY HALO LOOKS LIKE FROM NUMERICAL SIMULATIONS OF STRUCTURE FORMATION THROUGH GRAVITATIONAL INSTABILITY IN COLD DARK MATTER



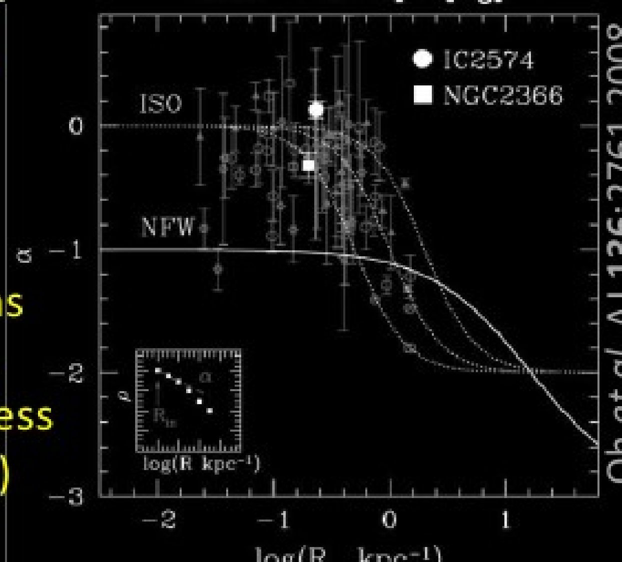
A galaxy such as ours is seen to have resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation etc over billions of years

Moreover whereas the Milky Way does have satellite galaxies and substructure there is a *lot* less than is expected from the numerical simulations





Also, the halo density profile for collisionless dark matter is predicted to be 'cuspy', whereas observations suggest 'cored' isothermal profiles



This *could* be because of the 'feedback effect' of baryons – computer simulations are just beginning to test this – or it could even be because dark matter is *not* collisionless but *self*-interacting (or perhaps `warm' rather than cold)

Discovery possibilities

- Line signals from γ–ray observatories.

  Signals of annihilation neutrinos at IceCube or KM3Net.

- Direct detection (Dama...)

- Producion in particle factories (LHC..)