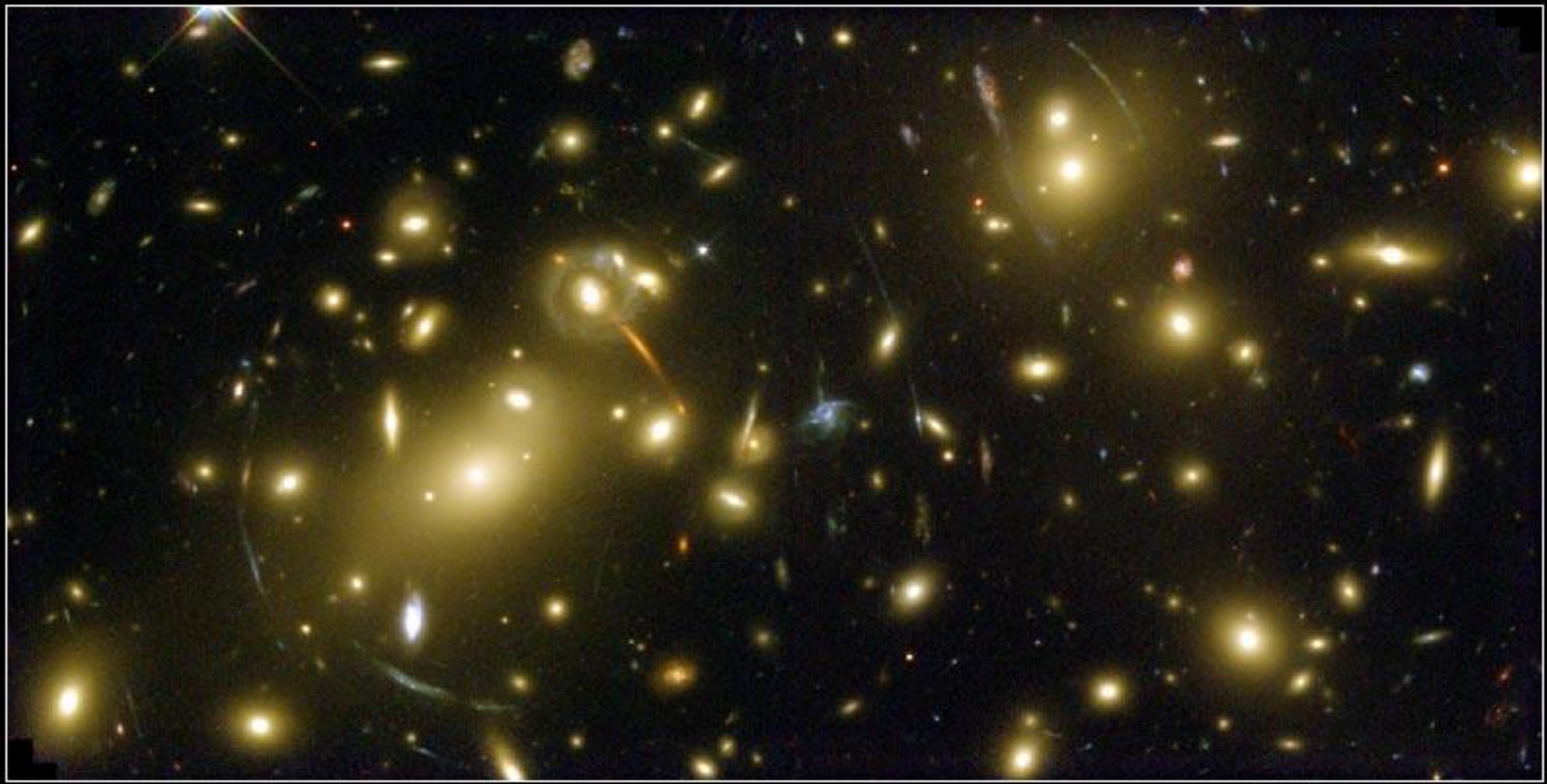
# Physics of Galaxies 2020
# Lecture 3: Dark matter in galaxies



**Galaxy Cluster Abell 2218** **HST • WFPC2**

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

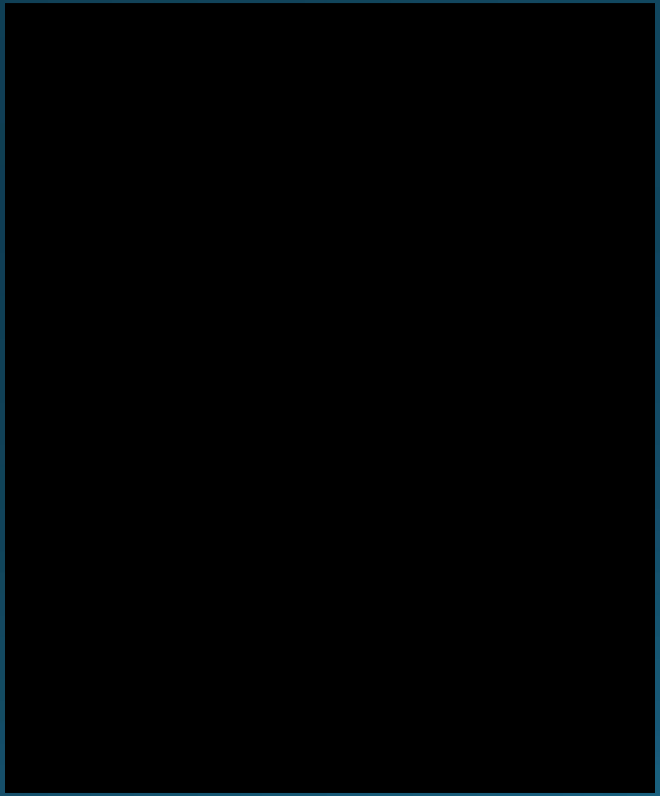
# Outline I

- What is dark matter?
- How much dark matter is there?
- How do we know it exists?
- Dark matter candidates
- The Cold Dark Matter (CDM) model

# Outline II

- Dark halos and subhalos
- Problems with CDM
- Dark matter annihilation

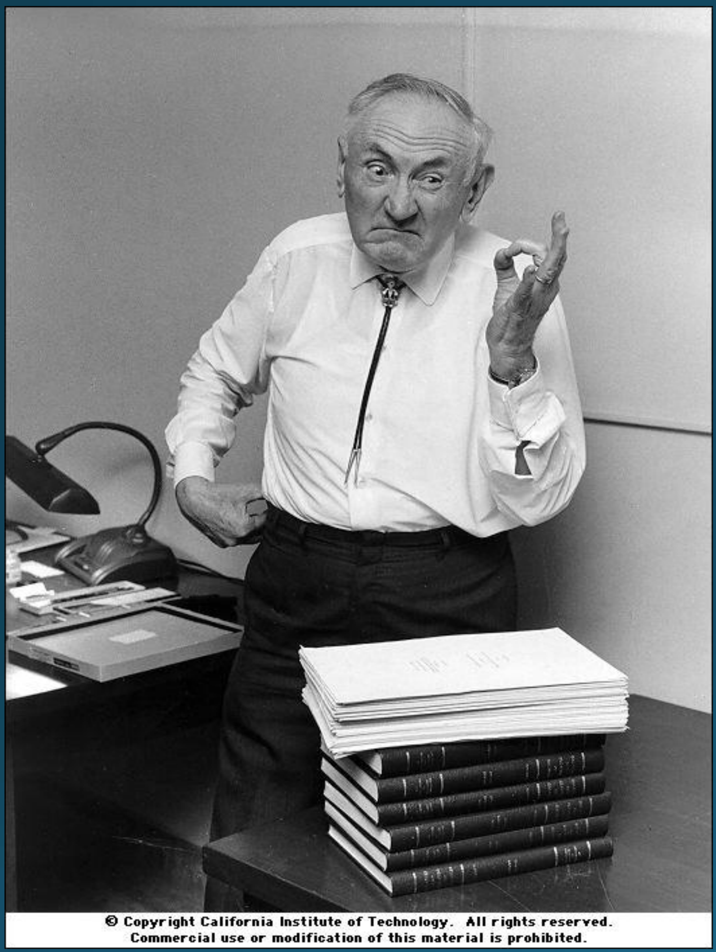
# What is Dark Matter?



Dark Matter


Luminous Matter

# First detection of dark matter




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

# First detection of dark matter

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

# How Much Dark Matter is There?

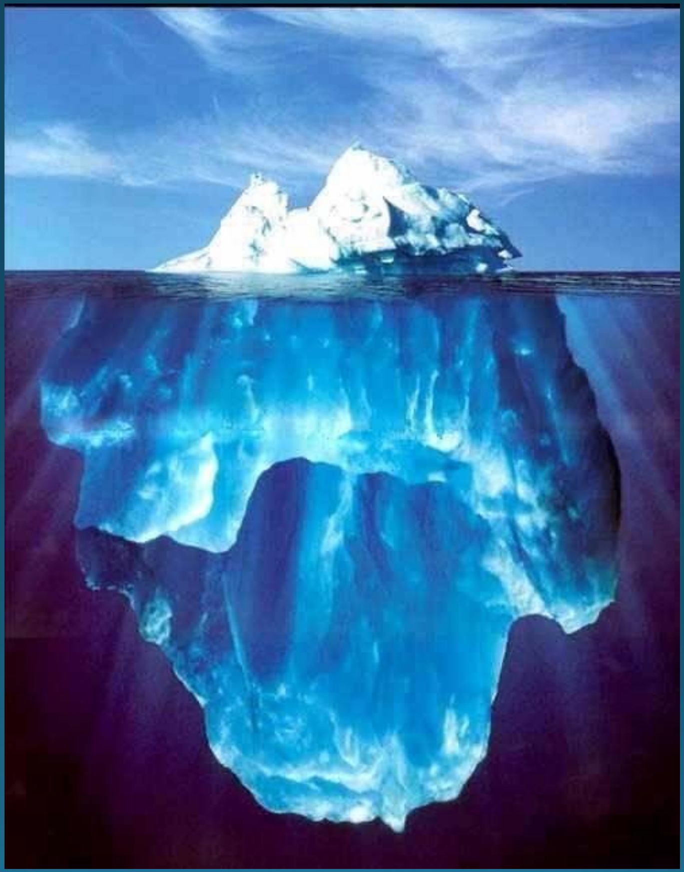
$\Omega_M = \rho_M / \rho_c$

Recent measurements:

$\Omega_M \sim 0.27$

$\Omega_\Lambda \sim 0.73$

$\Omega_{Lum} \sim 0.005$



~2%
(Luminous)

~98%
(Dark)

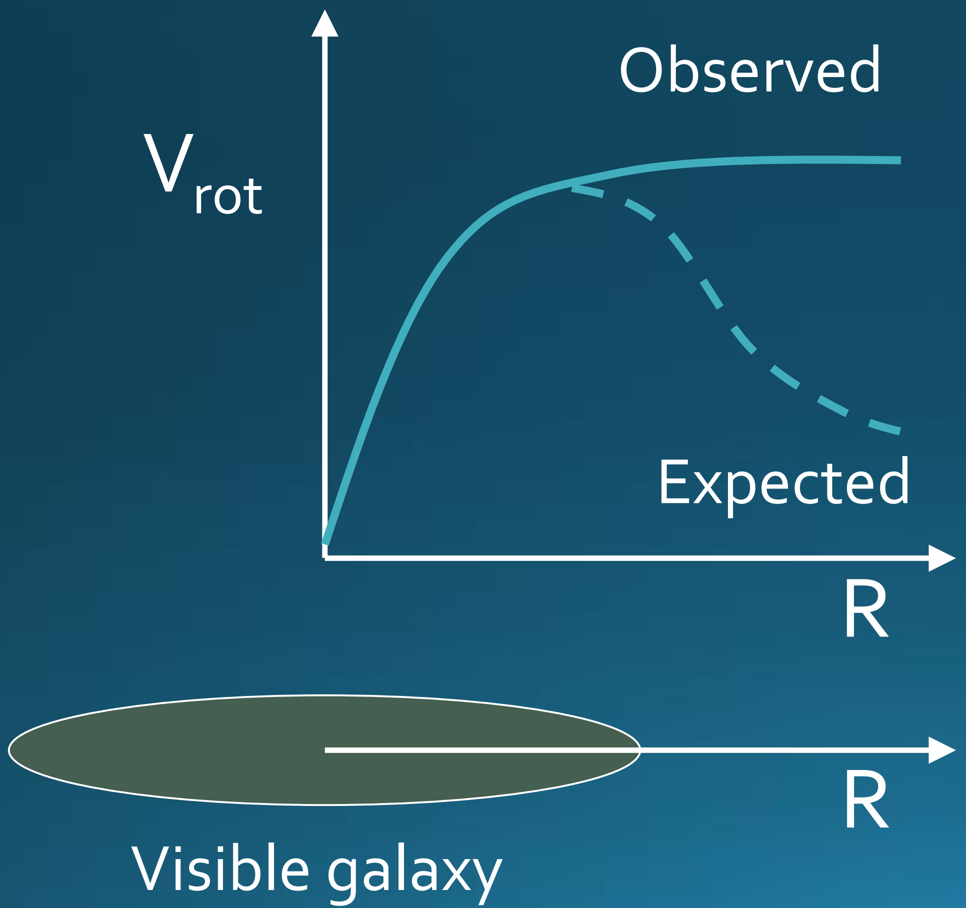
# How do we know that it exists?

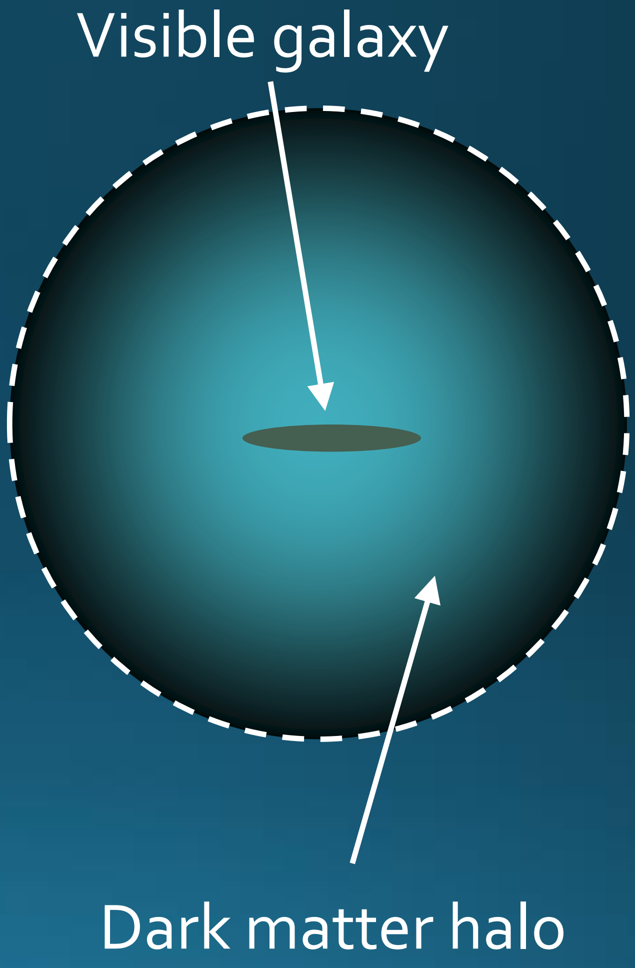
- Dynamics of galaxies
- Dynamics and gas properties of galaxy clusters
- Gravitational Lensing
- Cosmological Parameters + Inventory of luminous material

# Dynamics of Galaxies I

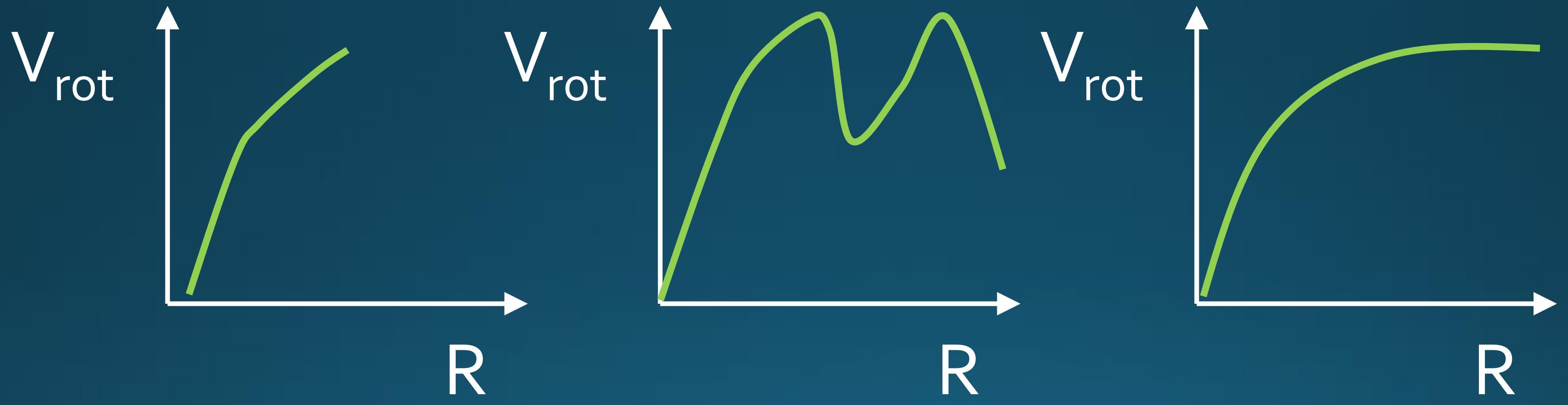
Galaxy ≈ Stars + Gas + Dust + Supermassive Black Hole + Dark Matter

# Dynamics of Galaxies II

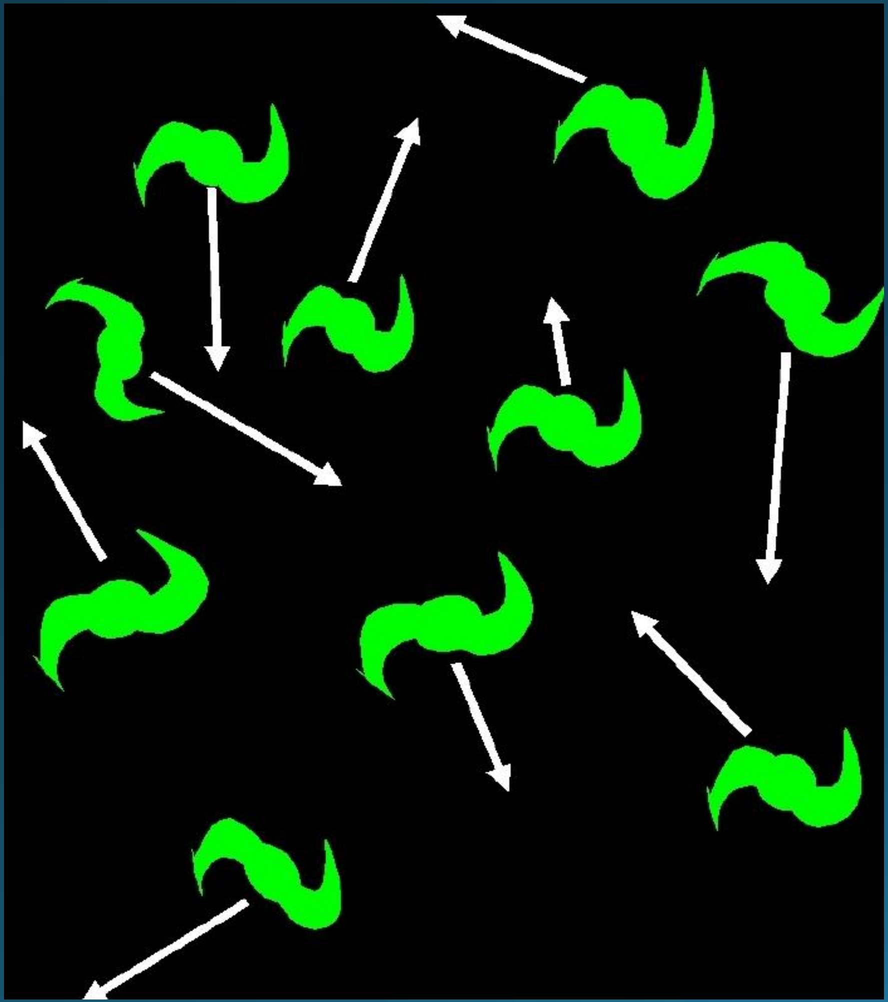


# Intermission: What do these rotation curves tell you?



# Dynamics of Galaxy Clusters

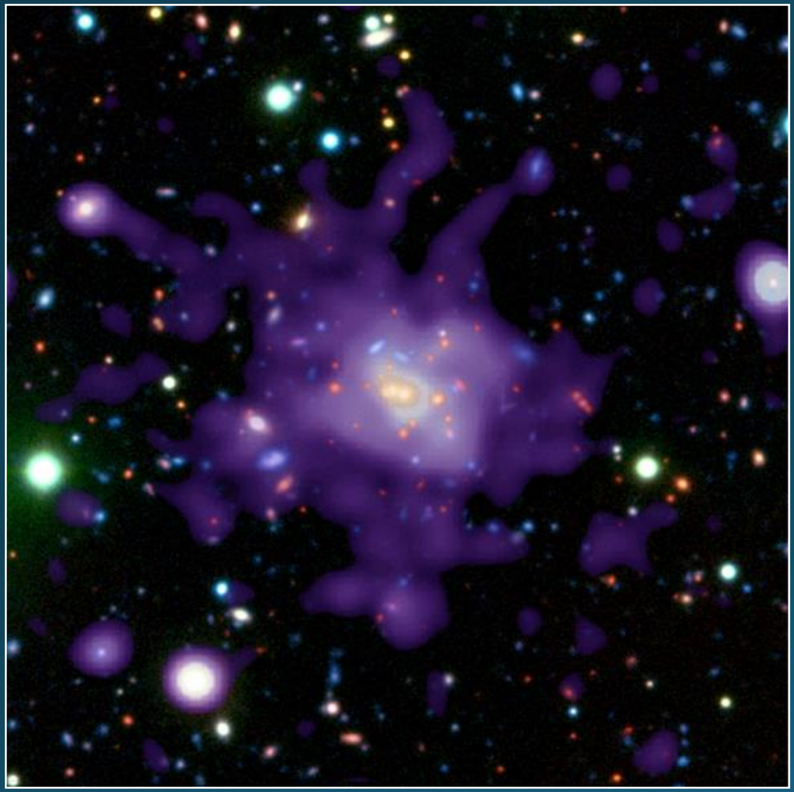


Balance between kinetic and potential energy →
Virial theorem:

$$M_{\rm vir} = \frac{\langle v^2 \rangle R_{\rm G}}{G}$$

Check out Sect. 6.3.2 in Schneider's book for details

# Hot Gas in Galaxy Clusters



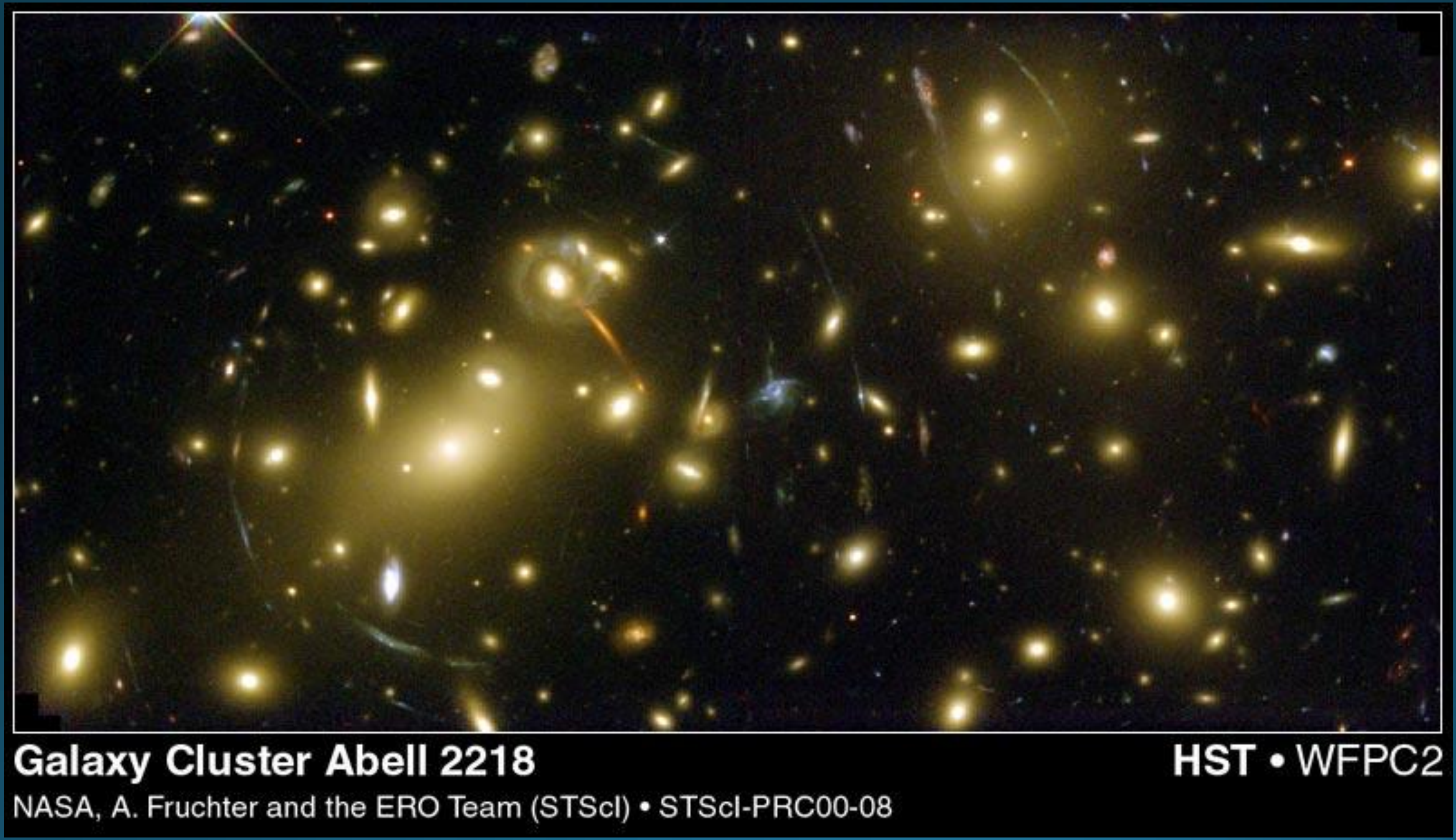
High mass required to keep the hot gas from leaving the cluster!

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

X-ray gas, $T=10^7$—$10^8$ K

# Gravitational Lensing

# Gravitational Lensing II



# Intermission: One of these is not a lensed system – which one?



# Baryonic and non-baryonic matter

$$\Omega_M \sim 0.27$$

$$\Omega_{baryons} \sim 0.04$$

Most of the matter (85%) in the Universe shares no resemblance to the matter we know from everyday life!

Particles with 3 quarks, like the proton and neutron

# A few non-baryonic* dark matter candidates

Popular!

- 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

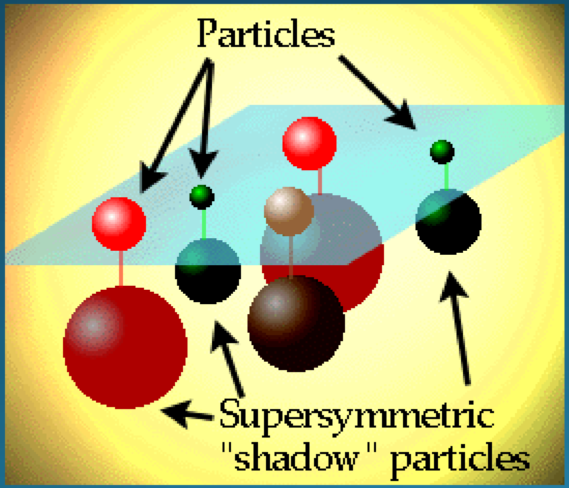
# What is supersymmetry (SUSY)?

- A high-energy extension of the standard model
- SUSY predicts a symmetry between bosons and fermions:

Standard particle ↔ SUSY partner

fermion (e.g. quark) ↔ boson (e.g. squark)
boson (e.g. photon) ↔ fermion (e.g. photino)

→ Zoo of new particles: selektrons, sneutrinos, gluinos, Higgsinos, gravitinos, axinos…



# Weakly Interacting Massive Particles (WIMPs)

- Interactions through weak force and gravity only $\rightarrow$ dark matter transparent
- Weak-scale interactions $\rightarrow$ right cosmological density to be dark matter ("The WIMP miracle")
- Massive (GeV to TeV scale)
- No WIMP candidate in standard model of particle physics
- The canonical WIMP is a SUSY particle (often a neutralino), but not all WIMP candidates are SUSYs

# WIMPs in your morning coffee

Generic assumptions (~100 GeV WIMPs) $\rightarrow$
Handful of WIMPs in an average-sized coffee cup

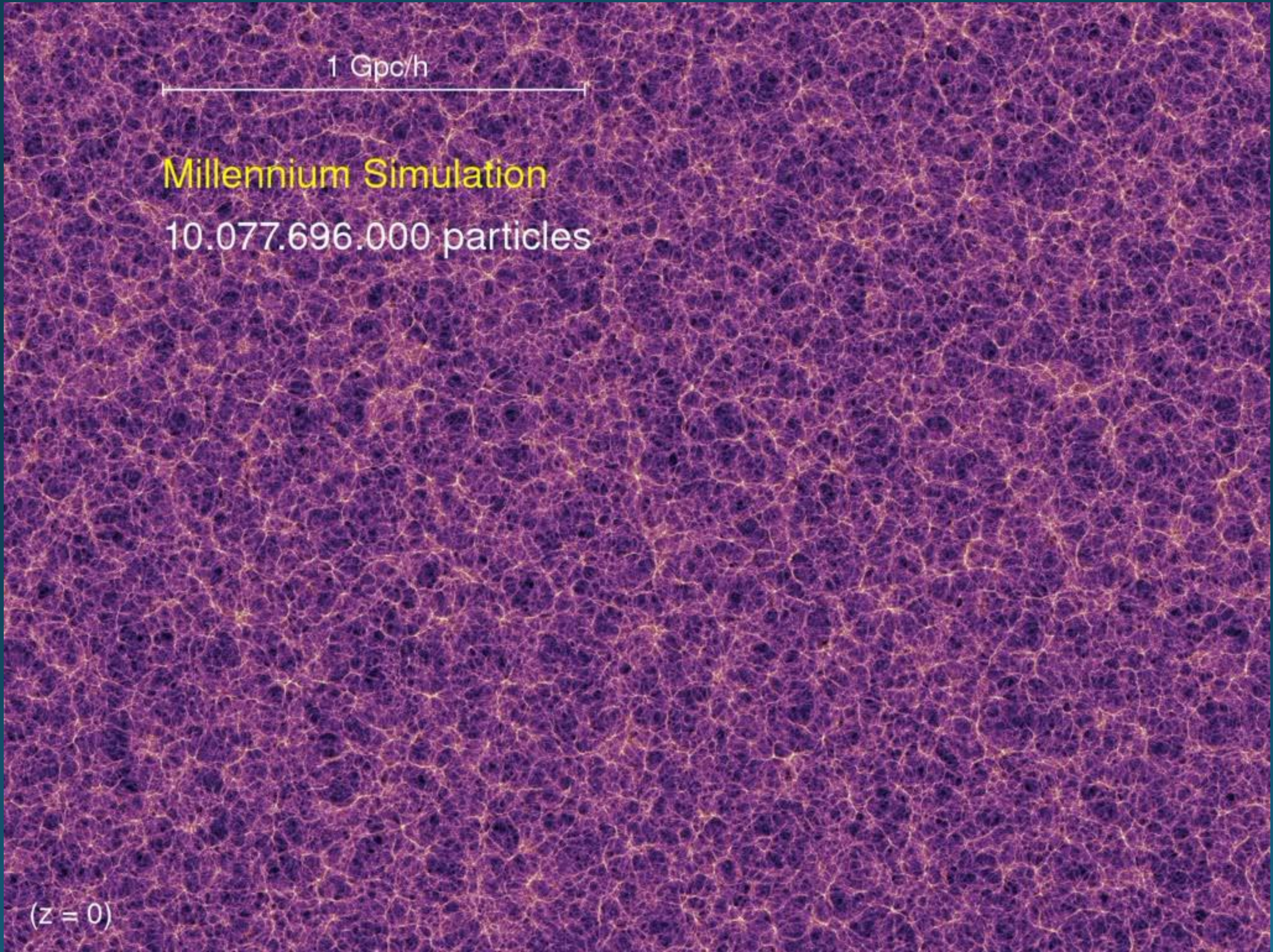
# Hot and Cold Dark Matter

- Hot Dark Matter (HDM)
  - Relativistic early on (at decoupling)
  - Ruled out by observations
- 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 (galaxies, galaxy clusters, voids and filaments)

# 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

# The Universe according to CDM



# The dark matter halo

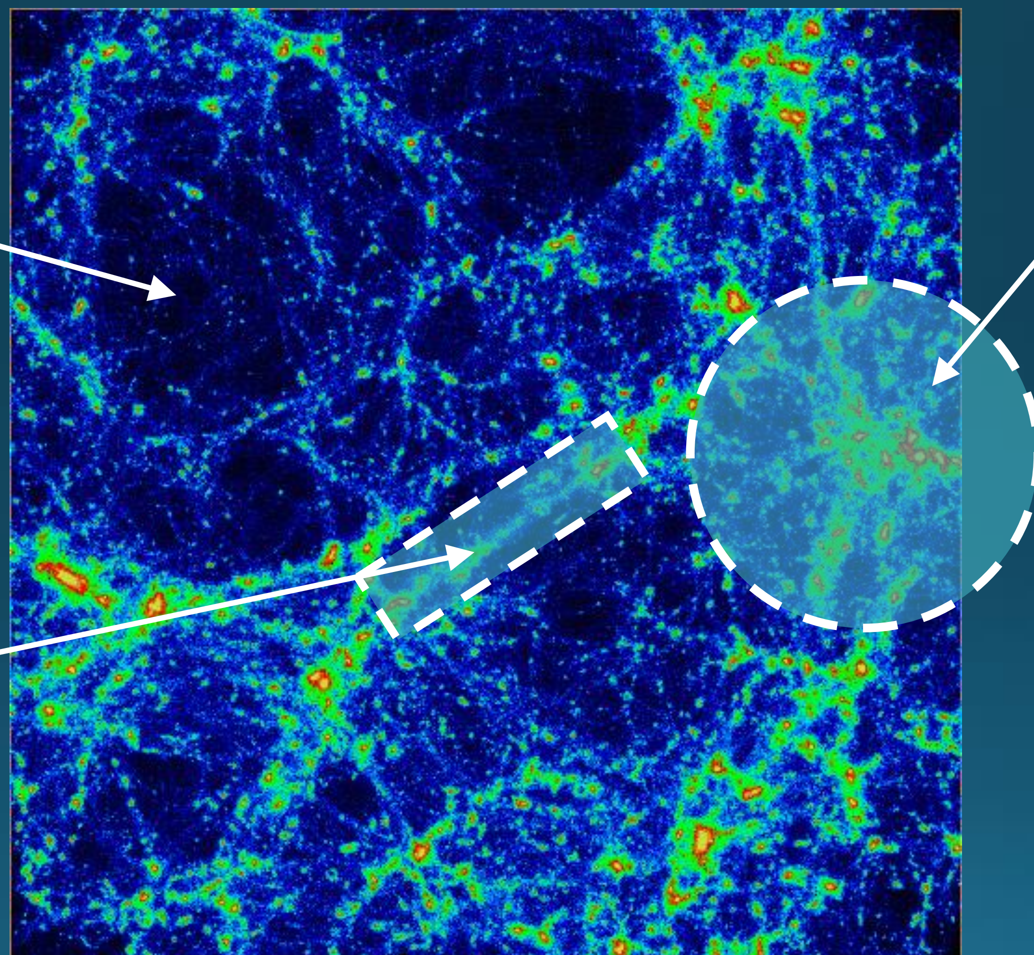
Schematic illustration

What it looks like in actual N-body simulations

# Voids, halos and filaments

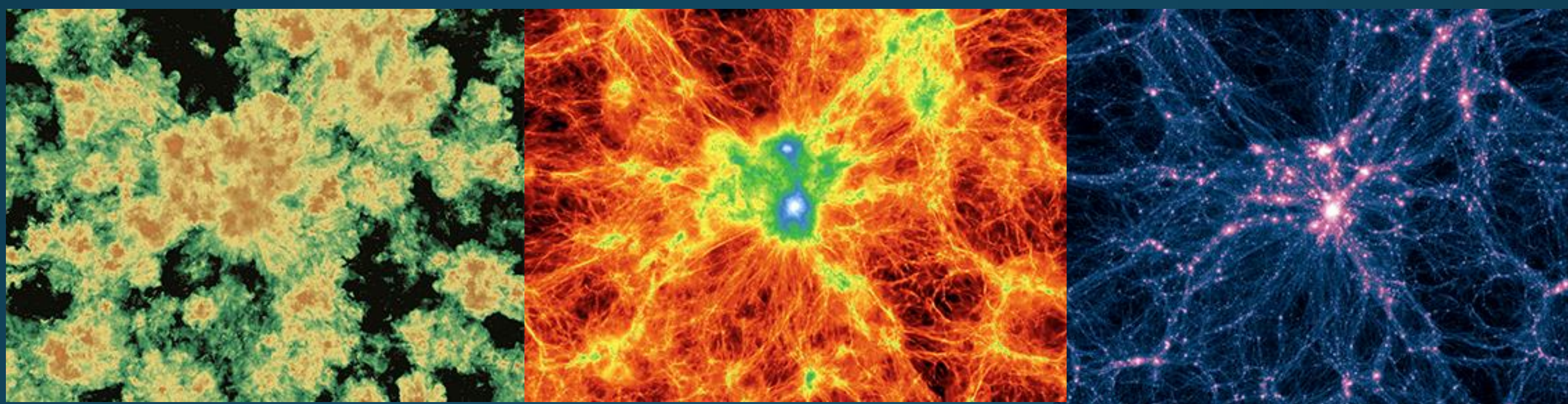
Void: low-density region

Halo: high-density region



Filament: connects the halos

# Intermission:
# What are you looking at?



Credit: Illustris Collaboration

These are frames from the Illustris simulation –
showing dark matter density, gas density and gas metallicity within a cube of side ≈100 Mpc – but which frame shows what?

# A hierarchy of dark matter halos

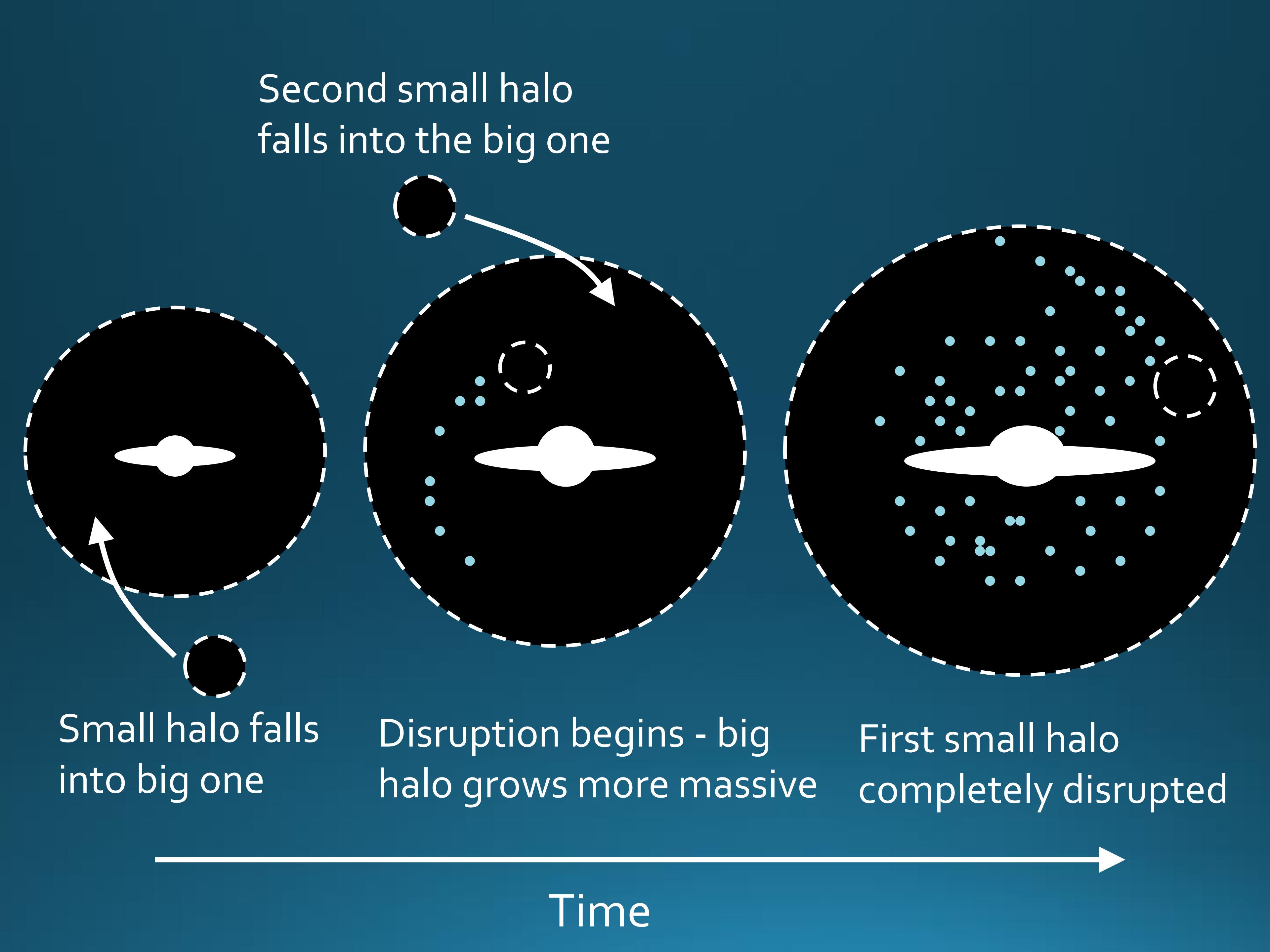
- All galaxy clusters and *almost* all galaxies form at the centre of dark matter halos

- Halo mass range: ~$10^{-6}$ – $10^{15}$ Msolar
  - $M_{halo} > 10^{13}$ Msolar: Galaxy groups and clusters
  - $M_{halo} \sim 10^{11}$–$10^{13}$ Msolar: Large galaxies
  - $M_{halo} \sim 10^{8}$–$10^{11}$ Msolar: Dwarf galaxies
  - $M_{halo} < 10^{8}$ Msolar: ???

**$M_{halo} < 10^{8}$ Msolar is a largely untested part of the CDM paradigm… The very first stars are predicted to form in these halos at z>15, but where are these halos now?**

# A hierarchy of dark matter halos II

- Halo mass range: ~$10^{-6}$ – $10^{15}$ Msolar
  - Lower cutoff depends on detailed properties of the dark matter particles, could be $10^{-12}$ to $10^{7}$ Msolar, depending on the model
  - Mass function shape: Always far more low-mass halos than high-mass ones
  - Low-mass halos assemble first, then merge to form high-mass ones


Second small halo
falls into the big one
Small halo falls
into big one
Disruption begins - big
halo grows more massive
First small halo
completely disrupted
Time

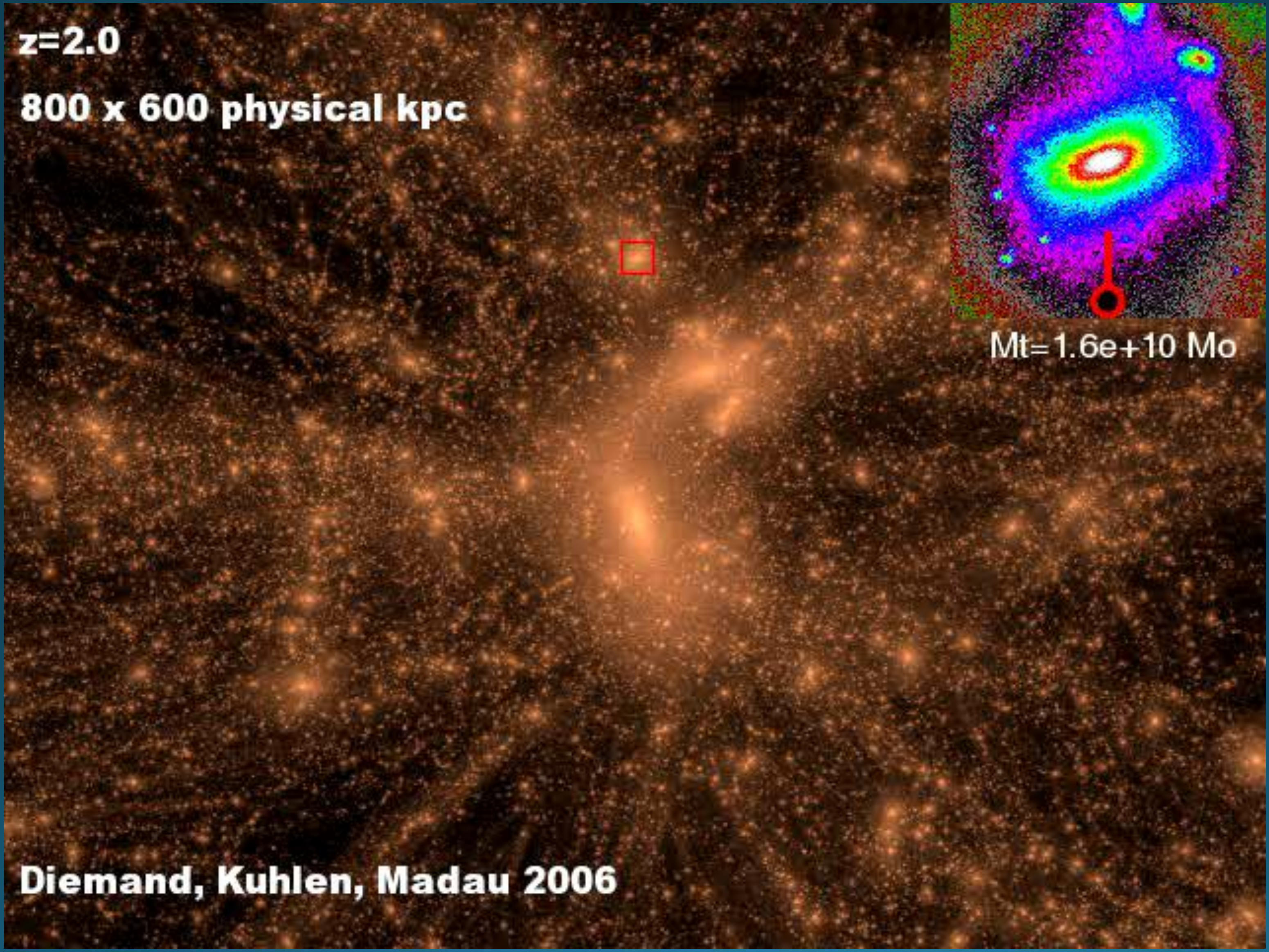
# The formation of a halo

**The Aquarius simulation (Springel et al. 2008)**

# Subhalos

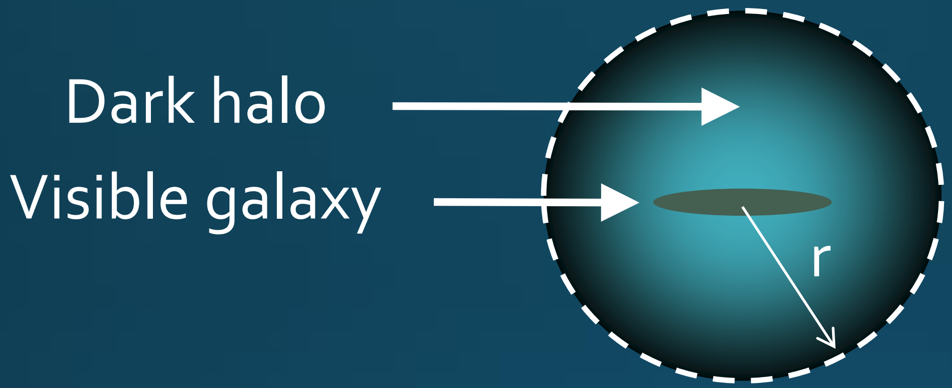
- Massive halos are assembled by the accretion of halos of lower mass
- Many accreted halos get disrupted in the tidal field of the halo they fell into, but some temporarily survive in the form of subhalos
- On average ~10% of the mass of a halo is in the form of subhalos at the current time

# The tumultuous life of a subhalo



# Intermission: What does this picture have to do with subhalos?

# Dark halo density profiles I




Famous dark matter-only, N-body simulations by Navarro, Frenk & White (1996, 1997)→

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_{\mathrm{s}}}{(r/r_{\mathrm{s}})\left(1 + r/r_{\mathrm{s}}\right)^2}$$

$\rho \propto r^{-1}$ at small r

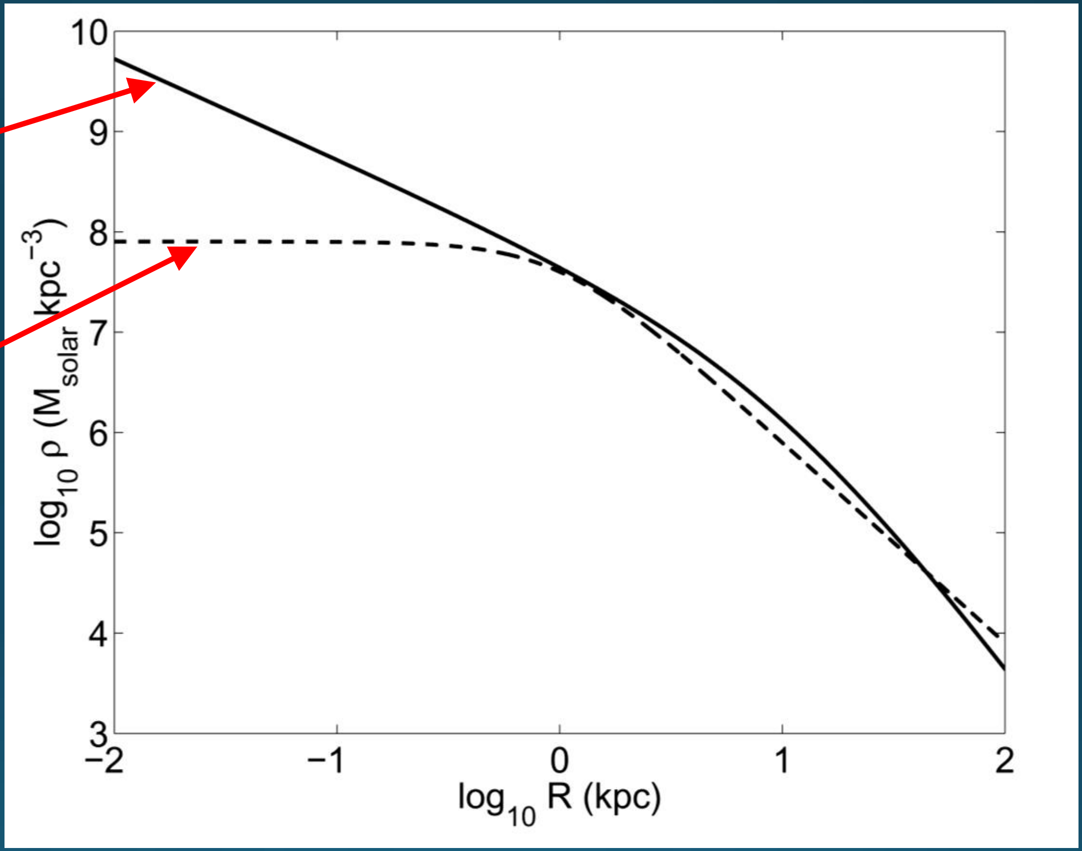
$\rho \propto r^{-3}$ at large r

NFW profile now slightly outdated, but still in active use

# CDM problem I : The core/cusp issue

Predicted by dark matter-only simulations based on CDM (density cusp)

Favoured by observations of dark matter-dominated galaxies (density core)




Possible solution:

Baryonic processes (supernova explosions, "feedback") may have altered the CDM density profile (Governato et al. 2010, Nature)

# Density profiles of real galaxies I

- Singular Isothermal sphere

$$\rho_{\text{SIS}}(r) = \frac{\rho(r_0)}{(r/r_0)^2}$$

$\sigma(r)$ = constant

$\rho(r) \rightarrow \infty$ when $r \rightarrow 0$

$M(<r) \rightarrow \infty$ when $r \rightarrow \infty$

Outer truncation required!

Works reasonably well for massive galaxies acting as strong gravitational lenses, probably due to baryon-domination in the centre

# Density profiles of real galaxies II

- Pseudo-isothermal sphere (cored)

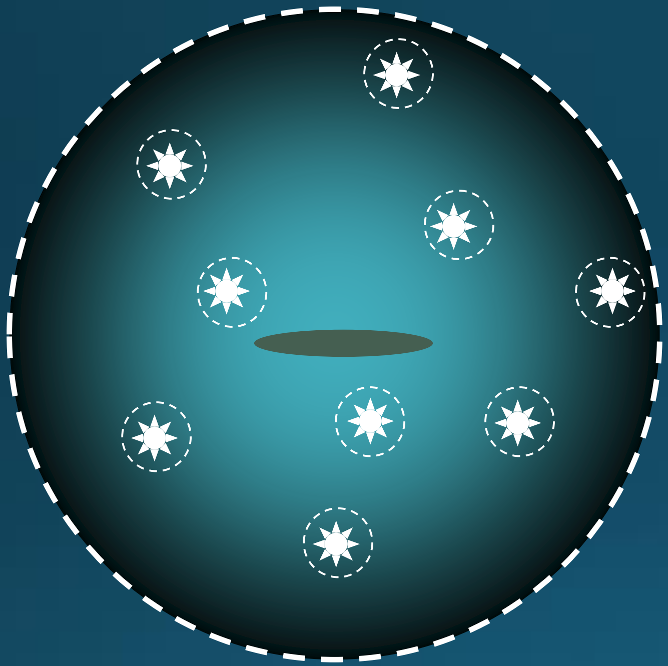
$$\rho_{\mathrm{PIS}}(r) = \frac{\rho_0}{1+(r/r_{\mathrm{c}})^2}$$

$\rho(r) \rightarrow \rho_0$ when $r \rightarrow 0$
$M(<r) \rightarrow \infty$ when $r \rightarrow \infty$
Outer truncation necessary!

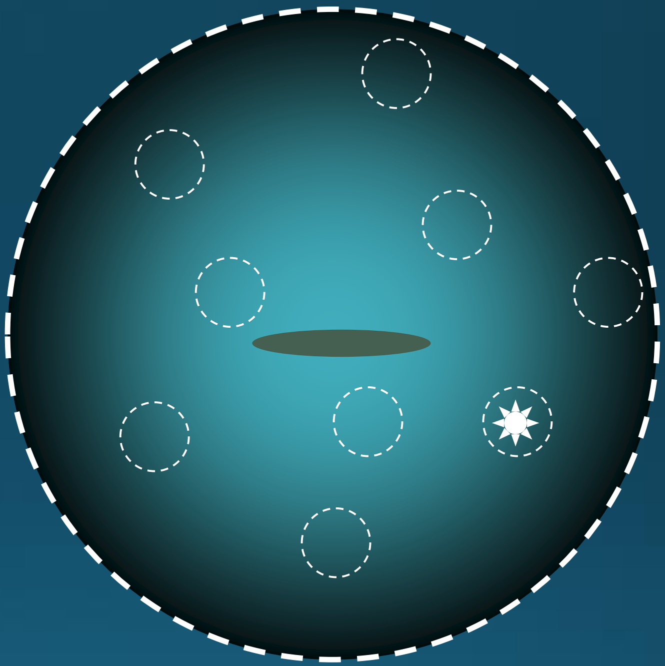
Works reasonably well for dark matter-dominated galaxies (dwarfs and low surface brightness galaxies)

# CDM problem II: Missing satellites

Should not dwarf galaxies form inside the subhalos?



Naïve expectation



Observed

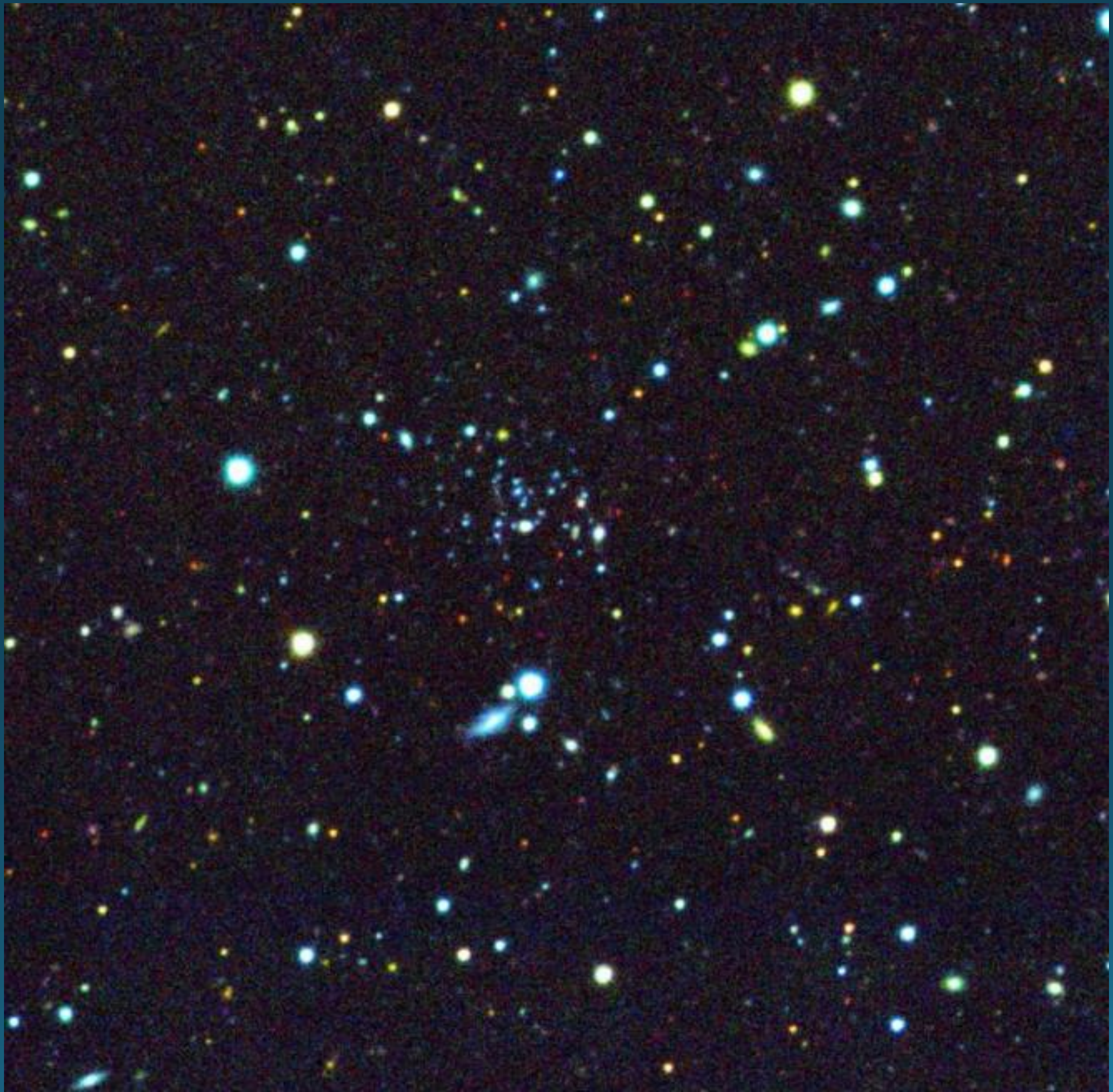
A factor of 10—100 too few satellite galaxies around the Milky Way!

# CDM problem II: Missing satellites

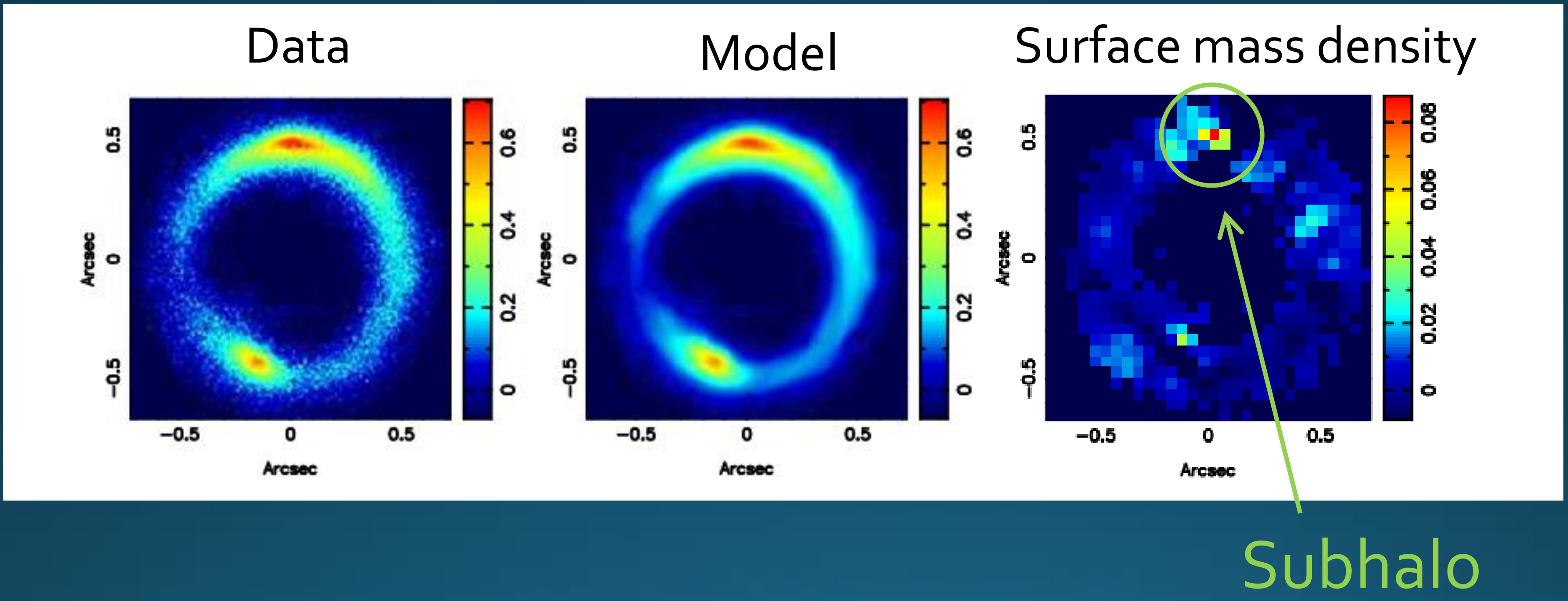
Possible solutions:

- Vanilla CDM incorrect – alternative models (e.g. warm dark matter) produce fewer subhalos
- Star formation in low-mass subhalos inefficient → lots of ultrafaint or completely dark subhalos awaiting detection around the Milky Way

# Intermission: What is this?

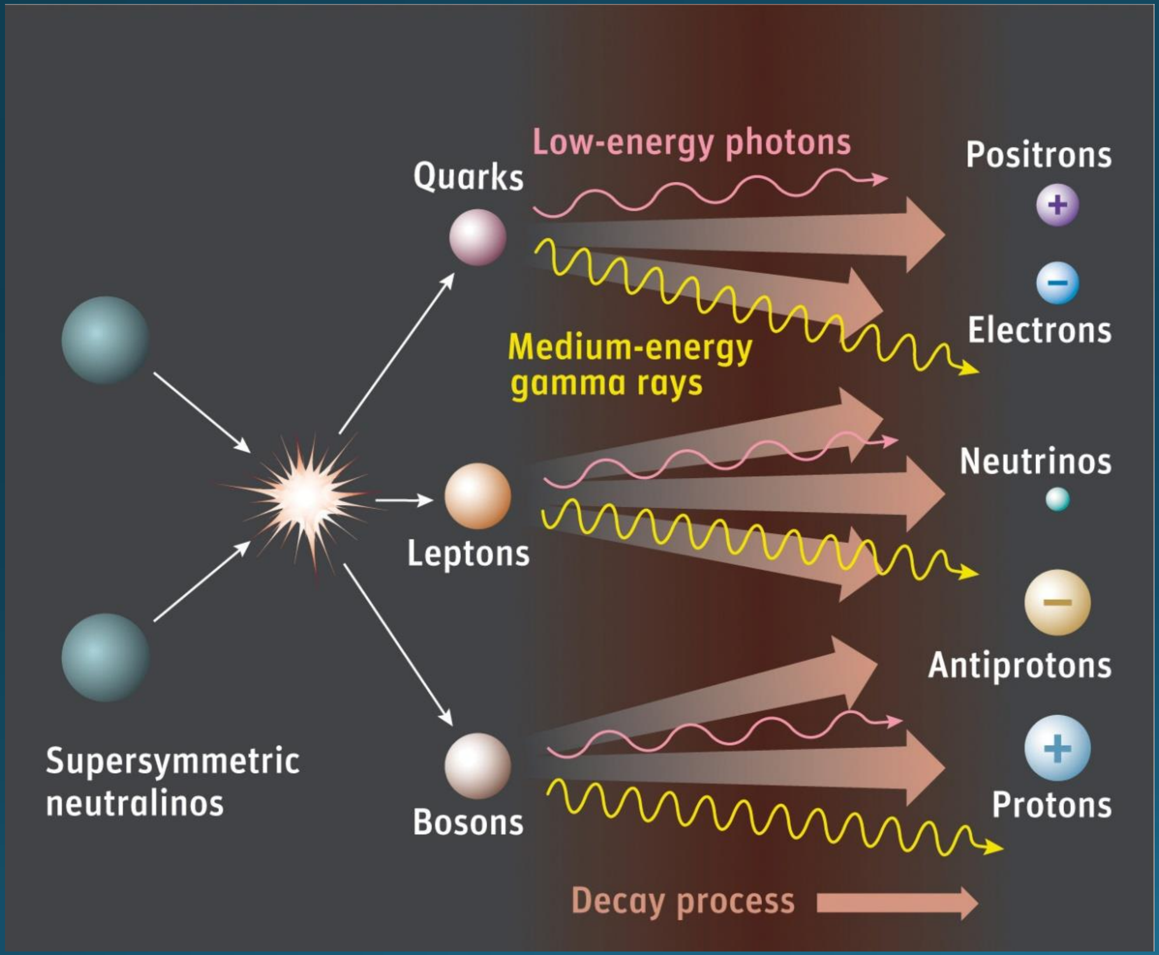


# Lensing detection of subhalos



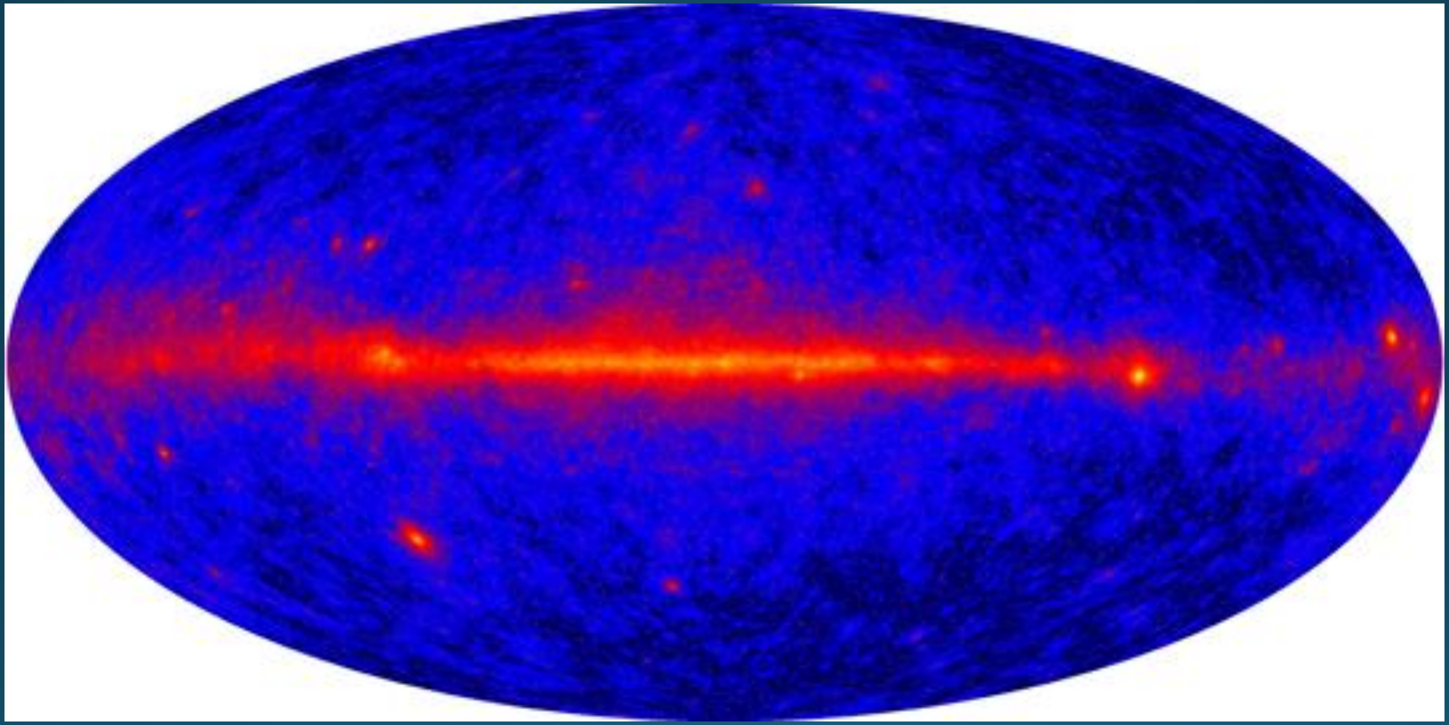

Gravitational lensing allows the detection of subhalos, even if they are completely dark – and one such object has already been detected (Vegetti et al. 2012, Nature)

# WIMP annihilation




WIMPs predicted to annihilate in regions where the CDM density is high
→ Subhalos should glow in gamma-rays

# Fermi Gamma-ray Telescope



Launched in 2008, but still no clear-cut signatures of WIMP annihilation in subhalos

# Mass-to-Light Ratios

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

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 → More dark-matter dominated

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

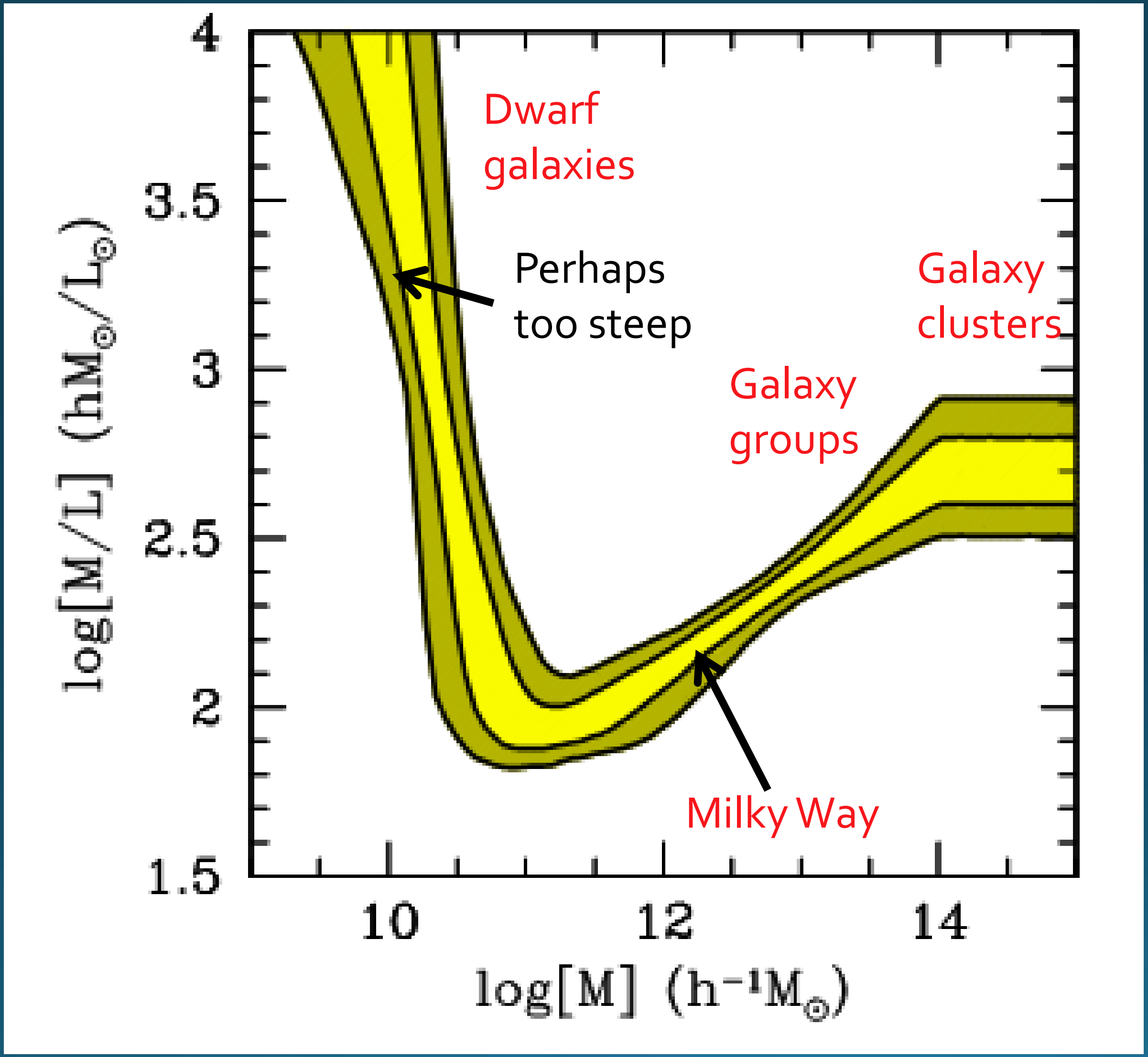
$(M/L)_{tot}$ ~100 for large galaxies

$(M/L)_{tot}$ ~ 300 for galaxy clusters

$(M/L)_{tot}$ ~ 1000 for ultrafaint dwarf galaxies

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

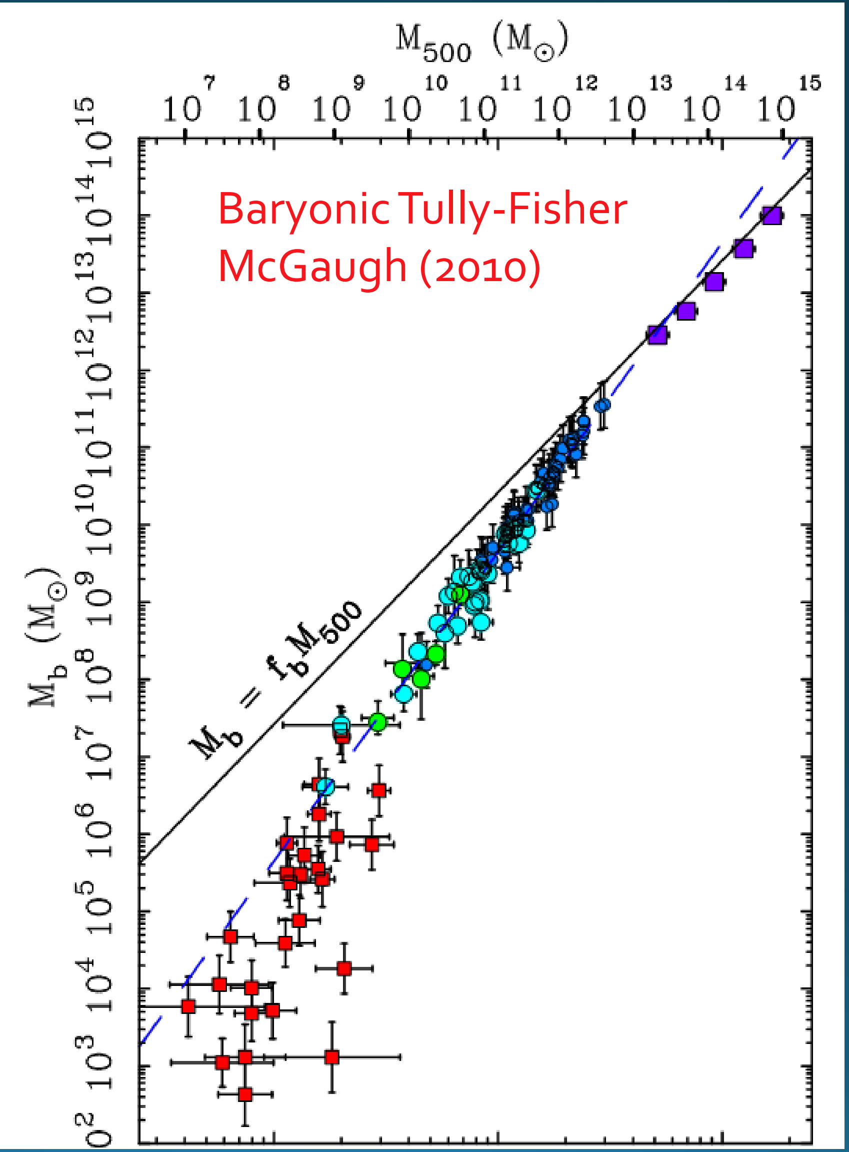
# Mass-to-Light Ratios III




**Model by Van den Bosch et al. (2005)**

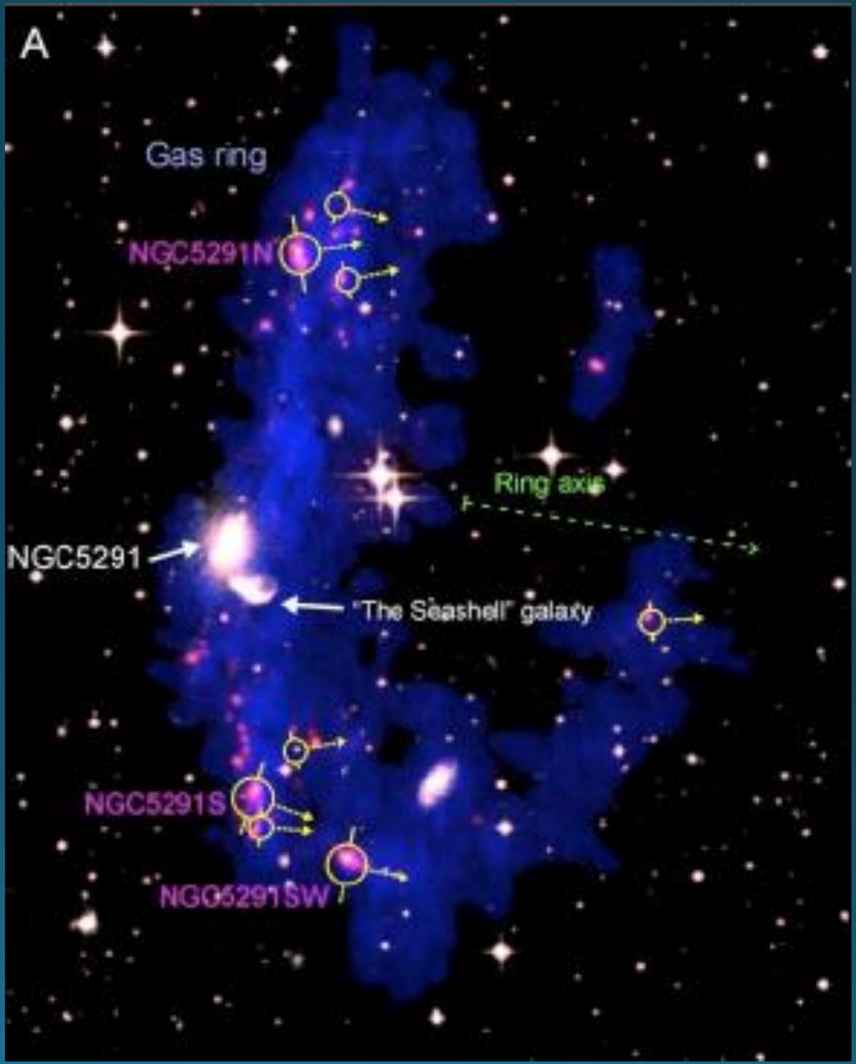
# Baryon fractions

- Baryon fraction $f_b$ below cosmic average in nearly all galaxies
- Long-standing missing-baryon problem: About 1/3 of the cosmic baryons unaccounted for at z=0
- Many of the missing baryons have recently been found in the intergalactic medium (in between halos)



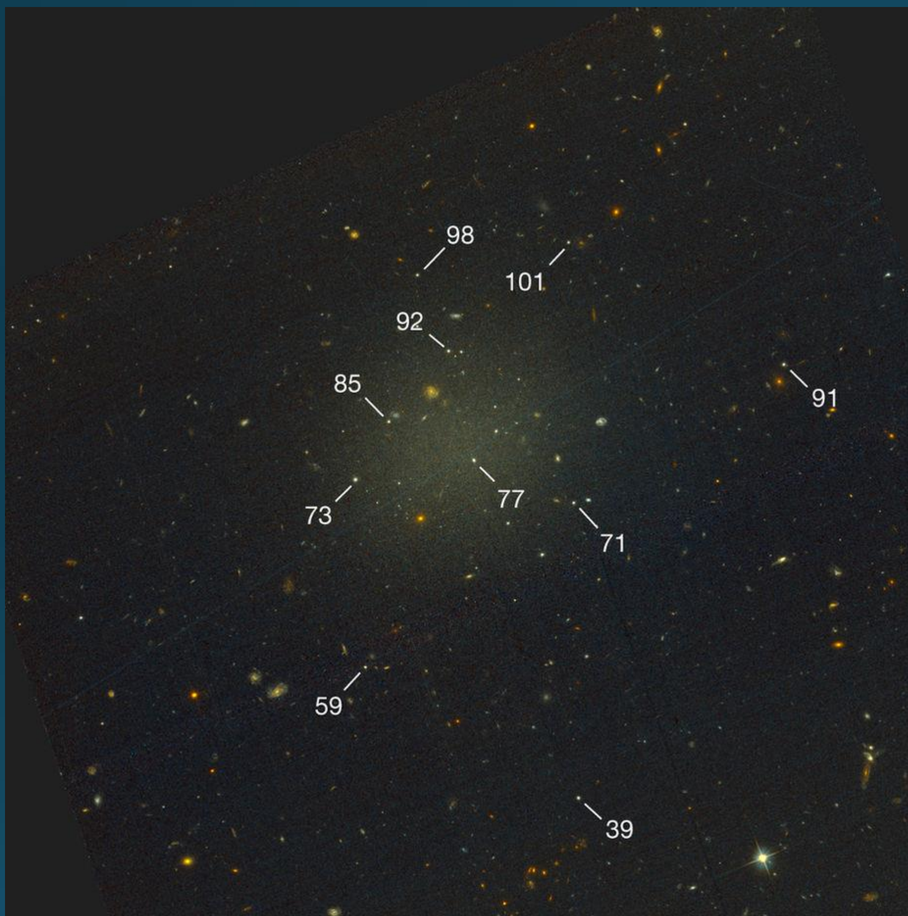
# Tidal dwarf galaxies

- TDGs form out of shredded disk material
- One type of galaxy predicted and observationally confirmed to be nearly CDM-free



Tidal dwarf galaxies observed with the Very Large Telecope, Chile

# Recent stuff: Ultradiffuse galaxies without dark matter




This could be the first evidence of a second mechanism for creating galaxies without dark matter!

First case reported in 2018, second in 2019

Nice topic for literature exercise!

Van Dokkum et al. 2018, *Nature* **555**, 629