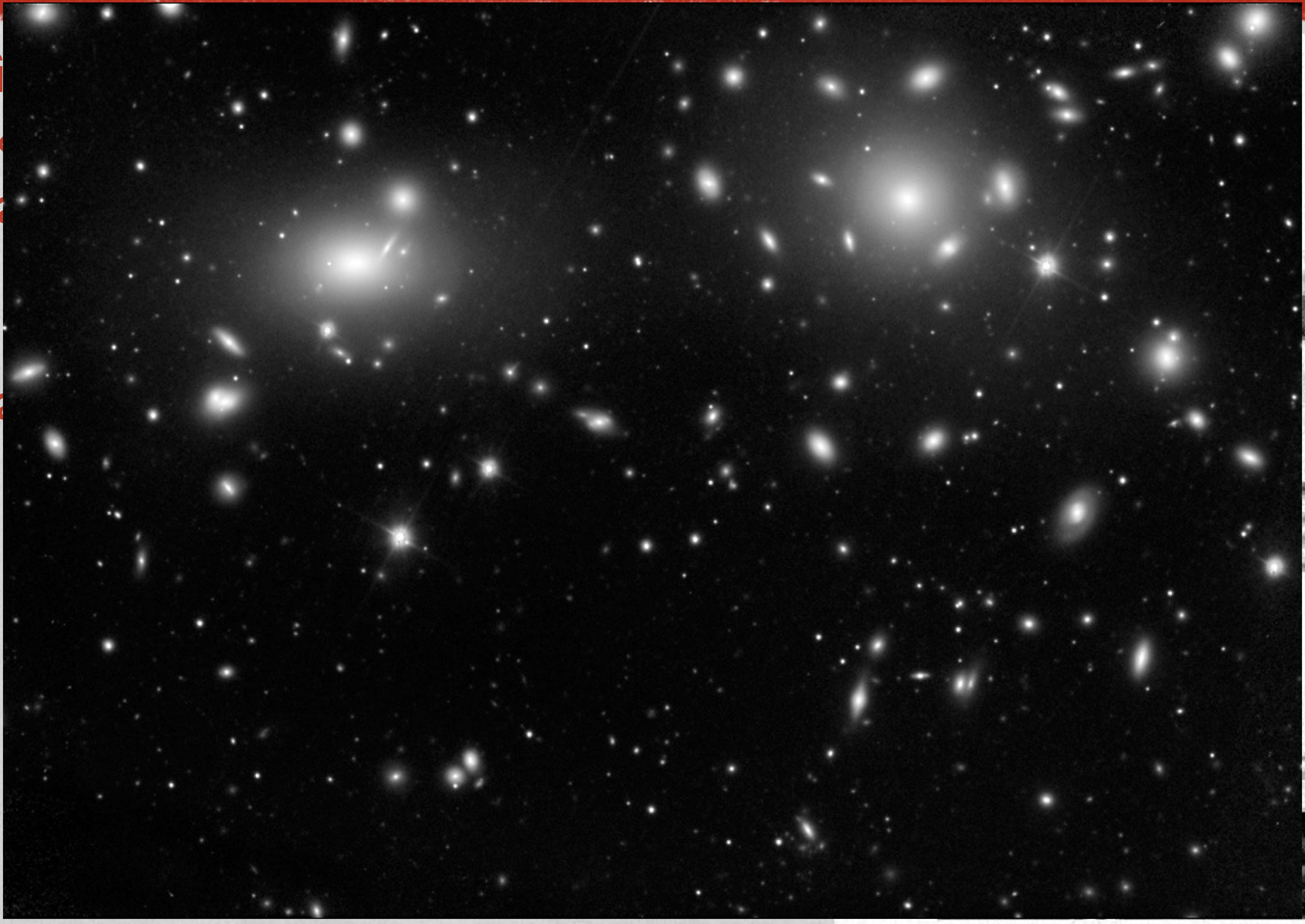
DARK MATTER

Week 4

OUTLINE

- The case for dark matter
- Candidates for dark matter
- Behavior of dark matter
- Problems with the current model

ZWICKY



The fi
Zwick
estima
found
as a d
50 yea

GALAXY CLUSTER

- A galaxy cluster is a region of space with a large over density of galaxies. The density of galaxies is so great they are believed to be gravitationally bound.
- This is strongly supported by measurements of X-ray gas in clusters which have temperatures consistent with being in a potential well large enough to keep the galaxies bound.
- We now also have gravitational lensing maps that verify the masses of these clusters.

OSTRIKER AND PEEBLES

- In 1973, Ostriker and Peebles made an interesting argument for the existence of dark matter.
- The noticed that rotating disk galaxies will naturally form bars and then transfer angular momentum breaking the system into two (or more).
- Since disk galaxies exist, this must not be happening. One way to prevent it would be to have massive spherical halos around galaxies that would stabilize their self gravity.

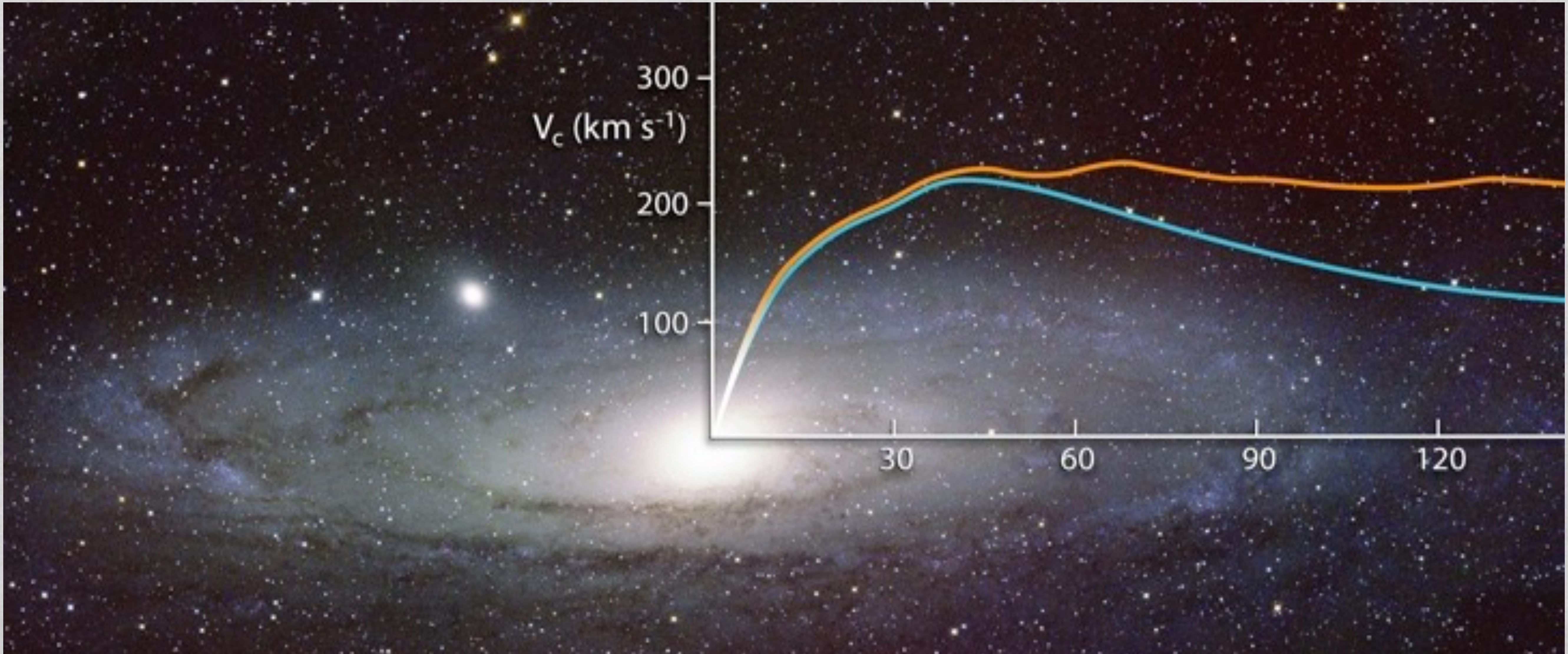
ROTATION CURVES

- Between 1978 and 1983 the first really definitive evidence for dark matter was measured.
- This was done by measuring the rotation rate of gas in the outskirts of galaxies. If the mass was associated with the light, then in these outer regions the rotation velocity should decrease,

$$v = \sqrt{G\frac{M}{R}}$$

- Observations showed that instead the rotation velocity remained flat, implying unseen matter.

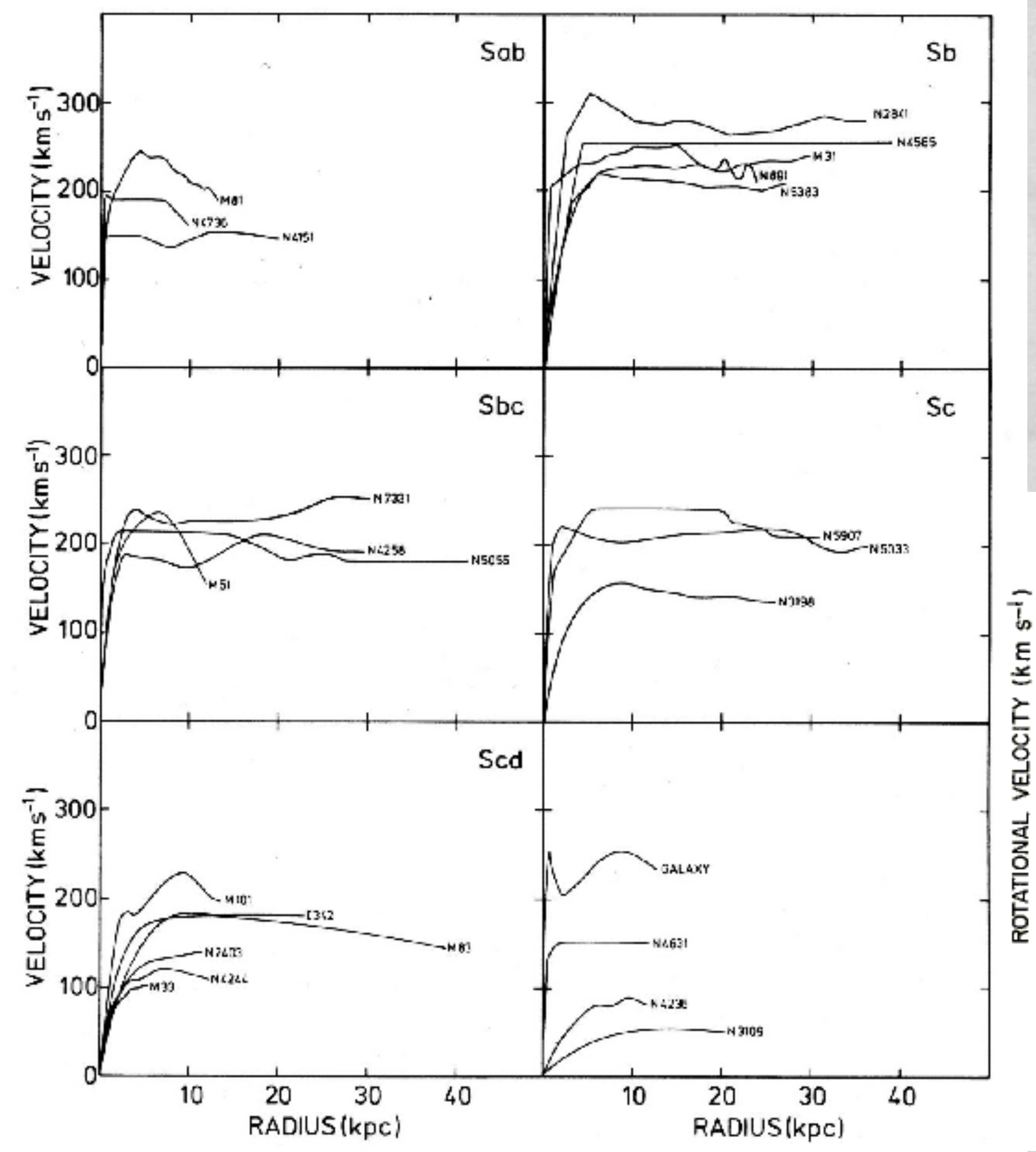
ROTATION CURVES



The turquoise curve shows how the rotation velocity should fall off as you get to the end of the galaxy, the orange curve shows what actually happens.

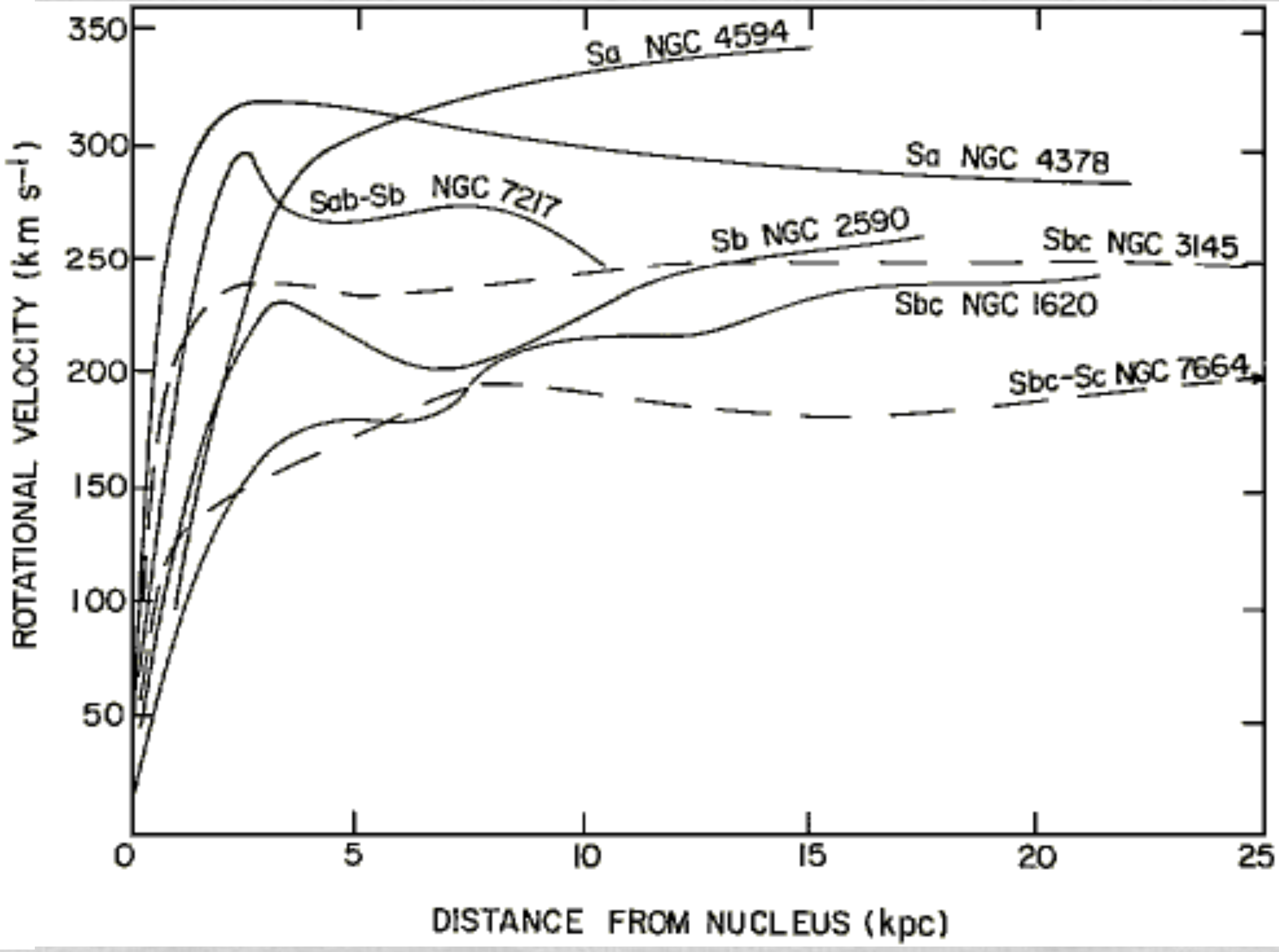
TWO METHODS

- These works at that time (1978 - 1983), were using two different methods to measure the rotation curve.
- HI - observing the 21cm line from neutral hydrogen using radio telescopes.
- L_α - observing the L_α line in the ultraviolet (n=2 to n=1).
- In astronomy speak HI means neutral hydrogen. Ionization states in astronomy are indicated by a number where I is neutral and II is singly ionized, III is doubly ionized, etc.



Bosma using HI radio observations

The combination of different techniques, going farther out in radius and a variety of galaxy types, convinced people that this was real.



Rubin using L_α observations

ALTERNATIVES

- It has been suggested that flat rotation curves can be explained by changing gravity instead of dark matter.
- Newtonian gravity is well studied in the solar system where accelerations are ~0.6 cm/s^2 (centripetal acceleration of Earth around the Sun).
- At the outskirts of galaxies the acceleration is more like 20 nm/s^2, a difference of 7 orders of magnitude.
- Modified Newtonian dynamics (MoND) changes Netwon's 2nd law for a << a_0 to approach

$$F = \frac{ma^2}{a_0}$$

- While such changes to gravity can explain rotation curves, so far they are unable to explain other evidence of dark mater.

OVERWHELMING EVIDENCE

- Now days we have overwhelming evidence for dark matter from many different observations
    - Rotation Curves
    - X-ray Clusters
    - Satellite Galaxies
    - Gravitational Lensing

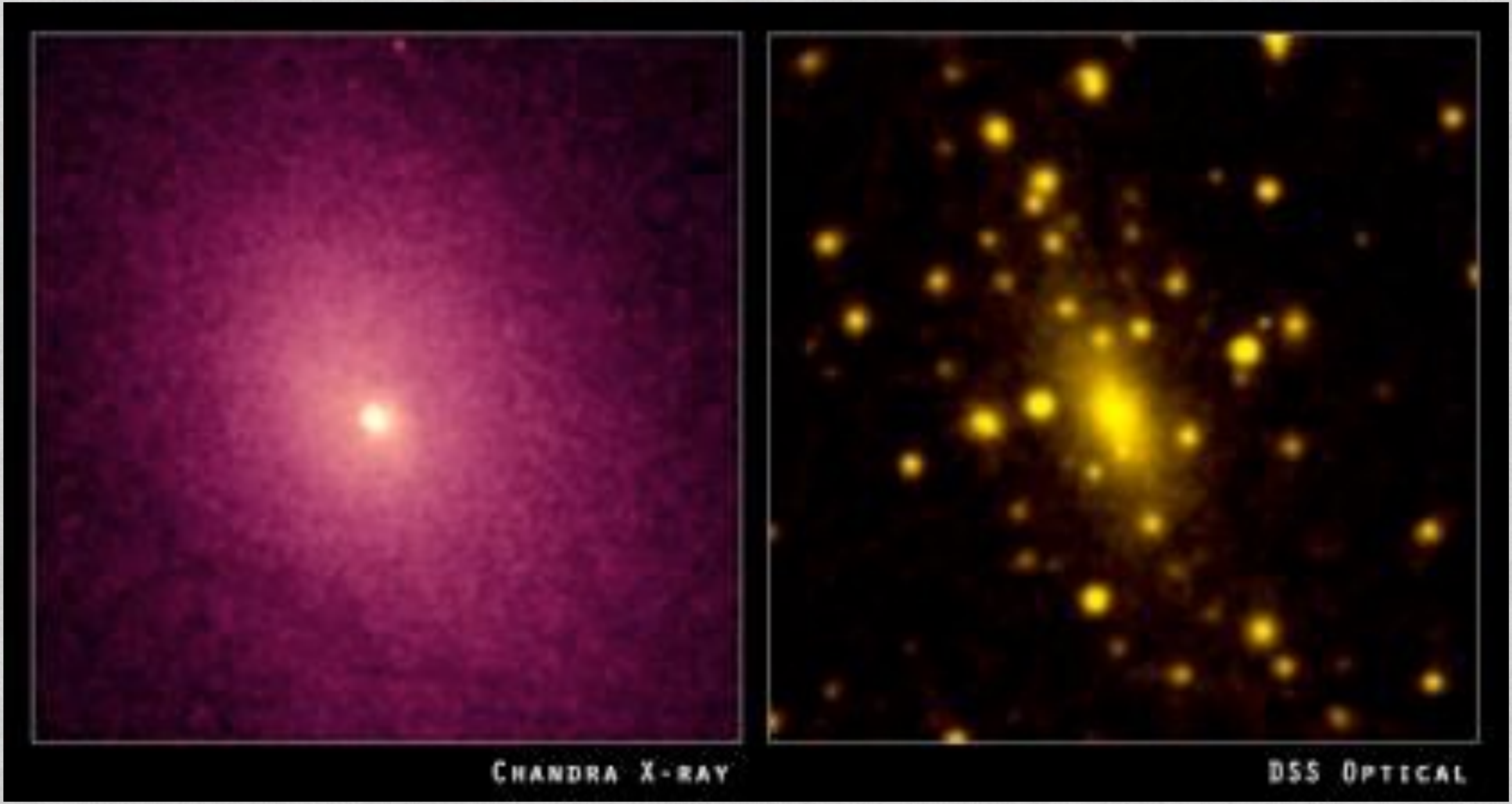
ROTATION CURVES

- We now have rotation curves from hundreds of galaxies that clearly demonstrate the need for dark matter.
- We also have velocity dispersions of spheroidal galaxies that also require dark matter to be explained.
- So the evidence is that all galaxies require unseen mass starting around 5-10 kpc from their centers, but some galaxies seem to require dark matter all the way to their cores.

X-RAY HALOS

- An observation that clearly shows the need for dark matter is X-ray halos in clusters.
- This very hot gas ~10^7 K, is basically in hydrostatic equilibrium, but the mass needed for that ~100x the stellar mass of these systems.

The left panel shows the hot gas as measured in X-rays, the right panel the galaxies in the same cluster. The hot gas is about 10x the stellar mass of the cluster, but still a factor of 10 less then what is needed to explain the observed temperature.

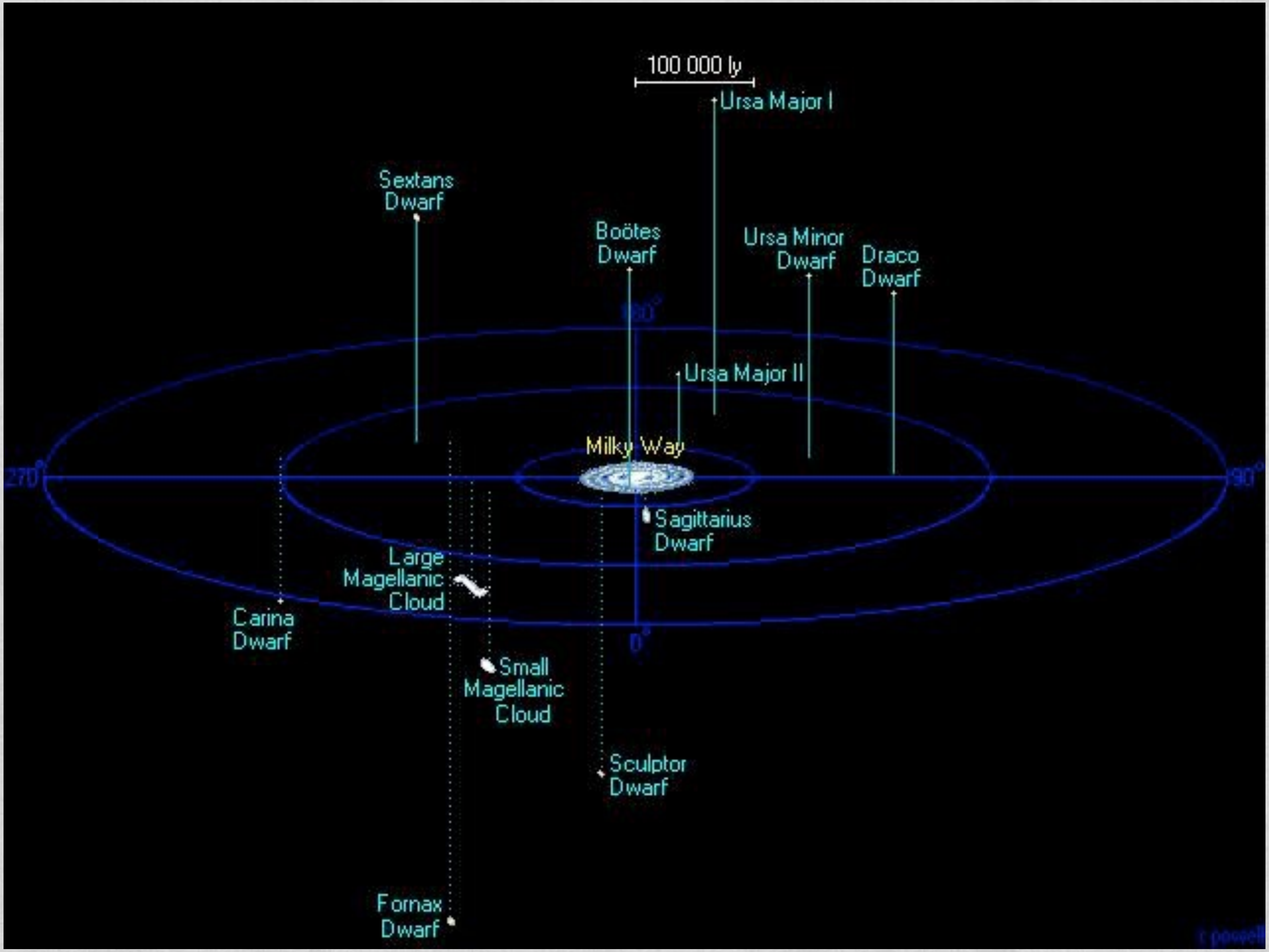


SATELLITE KINEMATICS

Another way to probe gravity around galaxies is to study the motion of satellite galaxies around them.

Of course we don't have time to watch the complete orbit of these satellites (of order Gyr), but we can measure their radial velocities and look at their properties statistically.

The results from such studies is that dark matter continues out to at least ~100 kpc. Which makes the ratio of total dark mass to light mass go from ~2 in the outskirts of galaxies to ~10 at 100kpc.

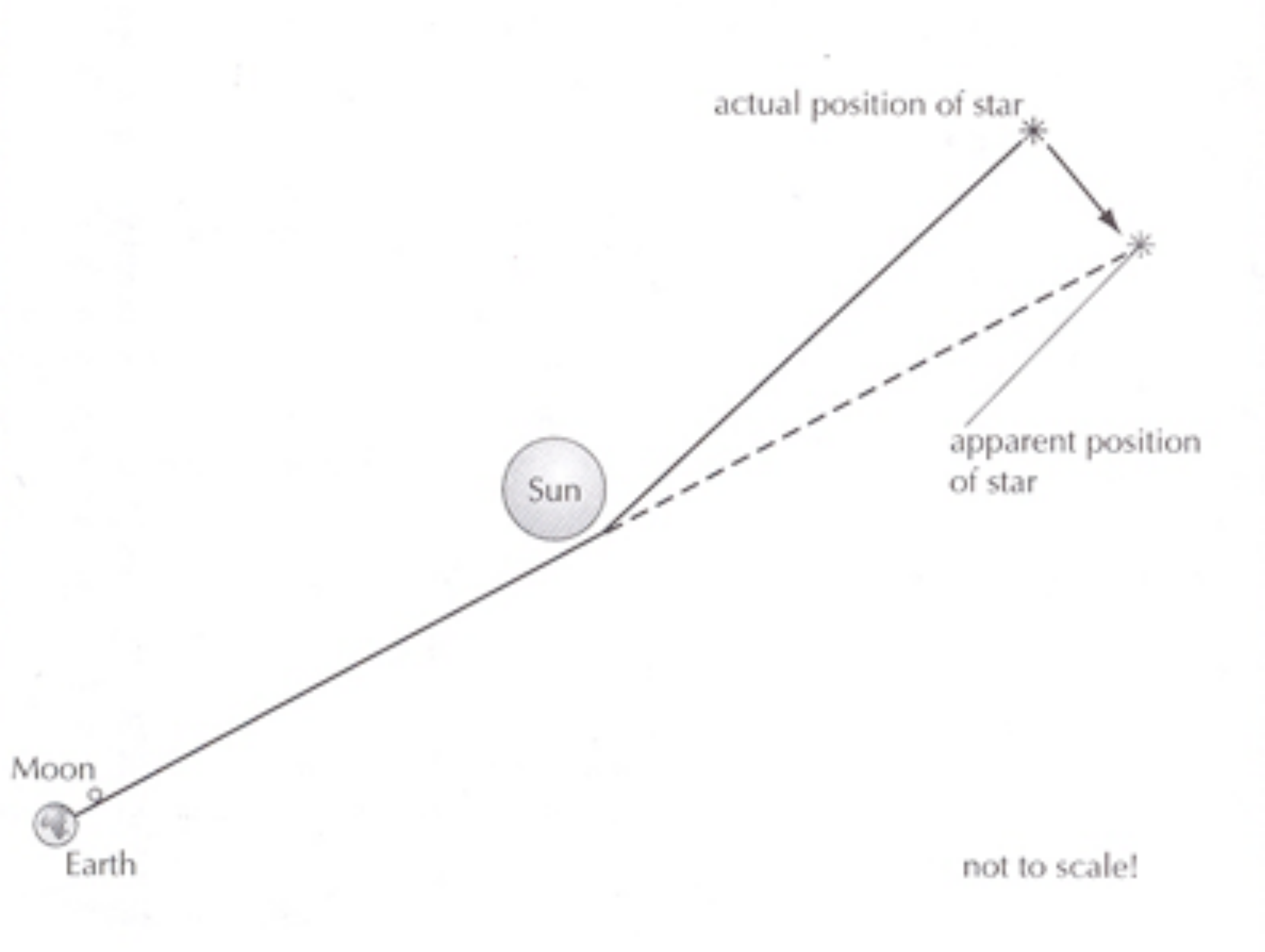


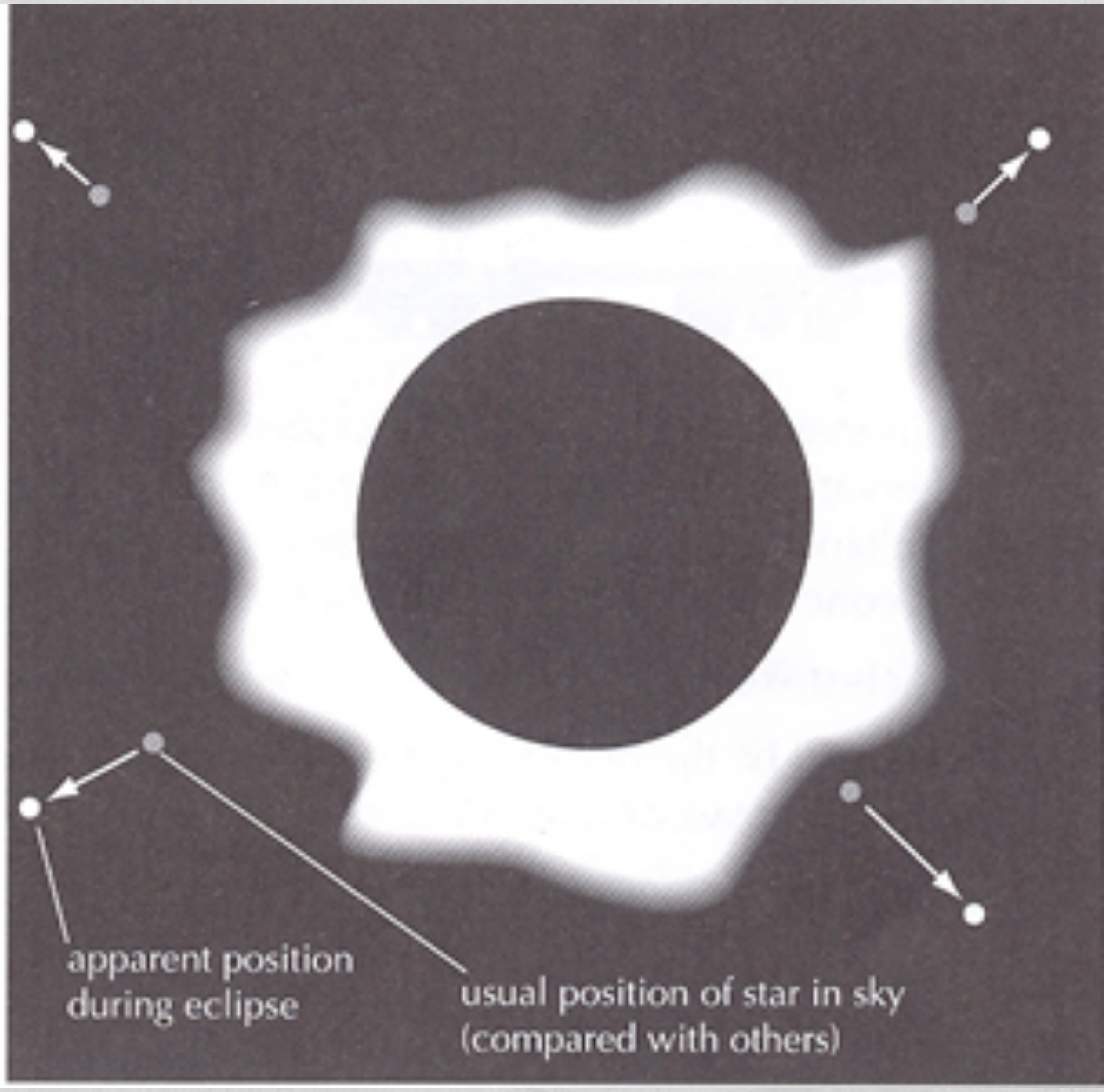
Here you see the more massive satellite galaxies of the Milky Way.
Note these galaxies are very faint and hard to observe.

GRAVITATIONAL LENSING

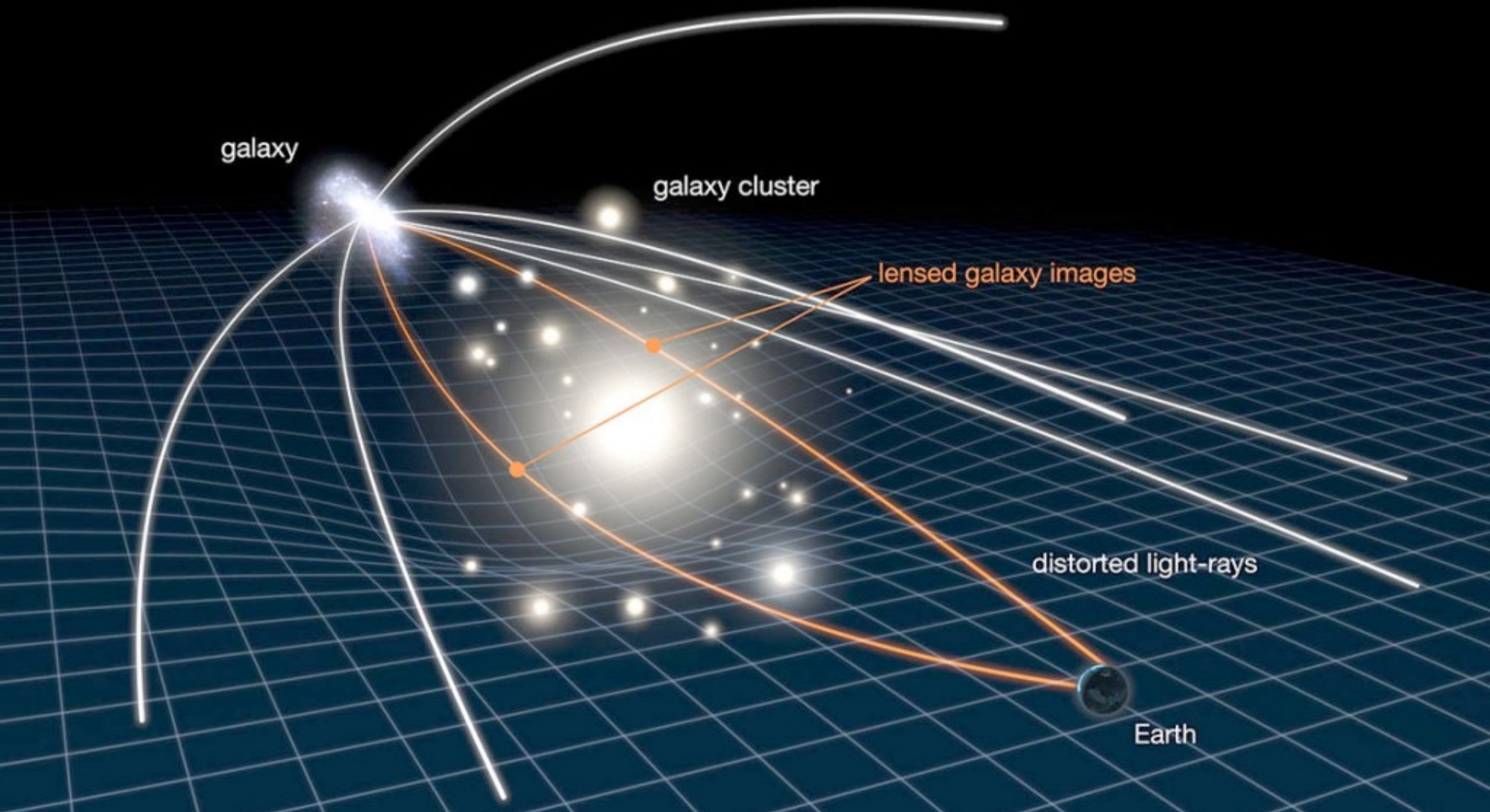
The most direct probe of mass is to use gravitational lensing. Gravitational lensing is a prediction of general relativity that was the first confirmed test.

Gravitational lensing refers to the bending of light by gravity. This was predicting by Einstein and observed by Eddington in May, 1919 being one of the first confirmed predictions of General Relativity. Eddington observed the positions of stars during a solar eclipse. The stars apparent positions had slightly changed compared to their positions in the absence of the Sun.

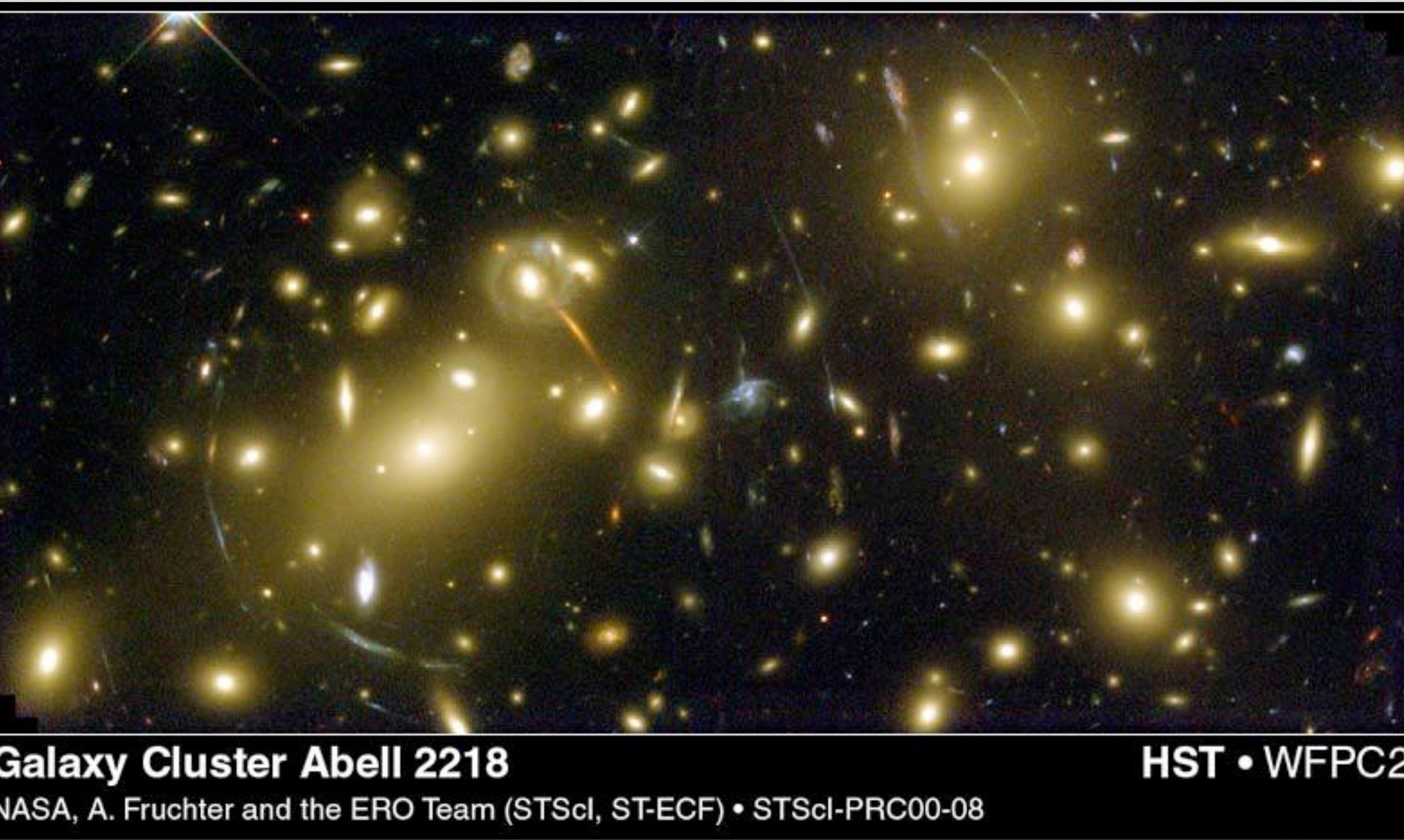




Gravitational lensing alters the apparent position of objects because light instead of traveling on a Euclidean straight line, travels along a null geodesic in curved space. Usually this is impossible to detect, because we have no way of knowing where the object would appear in the absence of the lensing. Gravitational lensing by the Sun is a rare exception to this.



Usually we can only detect gravitational lensing when its effects are more obvious by distorting images or creating multiple images of the same object.

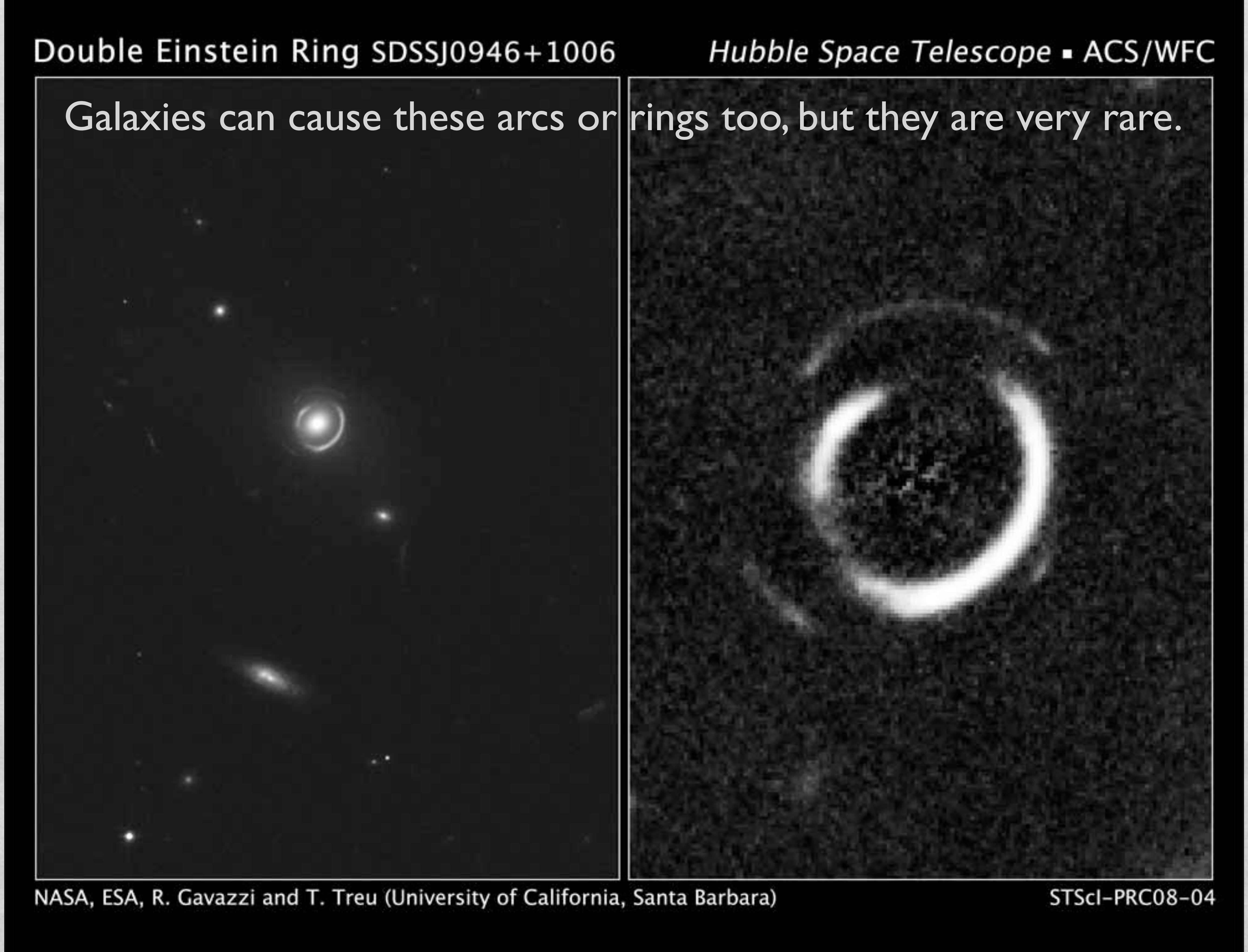


Galaxy Cluster Abell 2218 **HST** • WFPC2

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

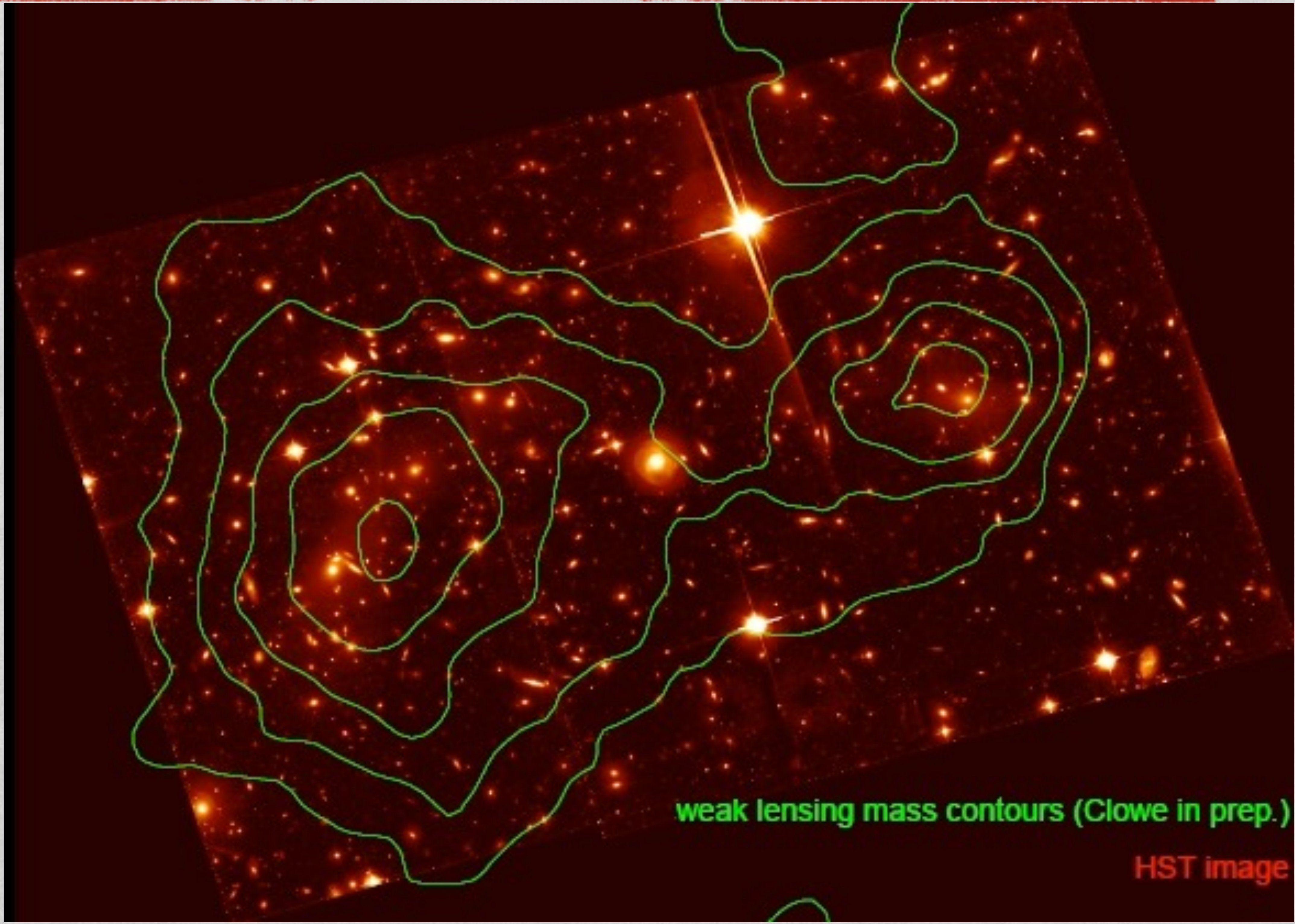
Notice the stretched galaxies called arcs. This is an example of strong lensing where you can obviously see the effects.

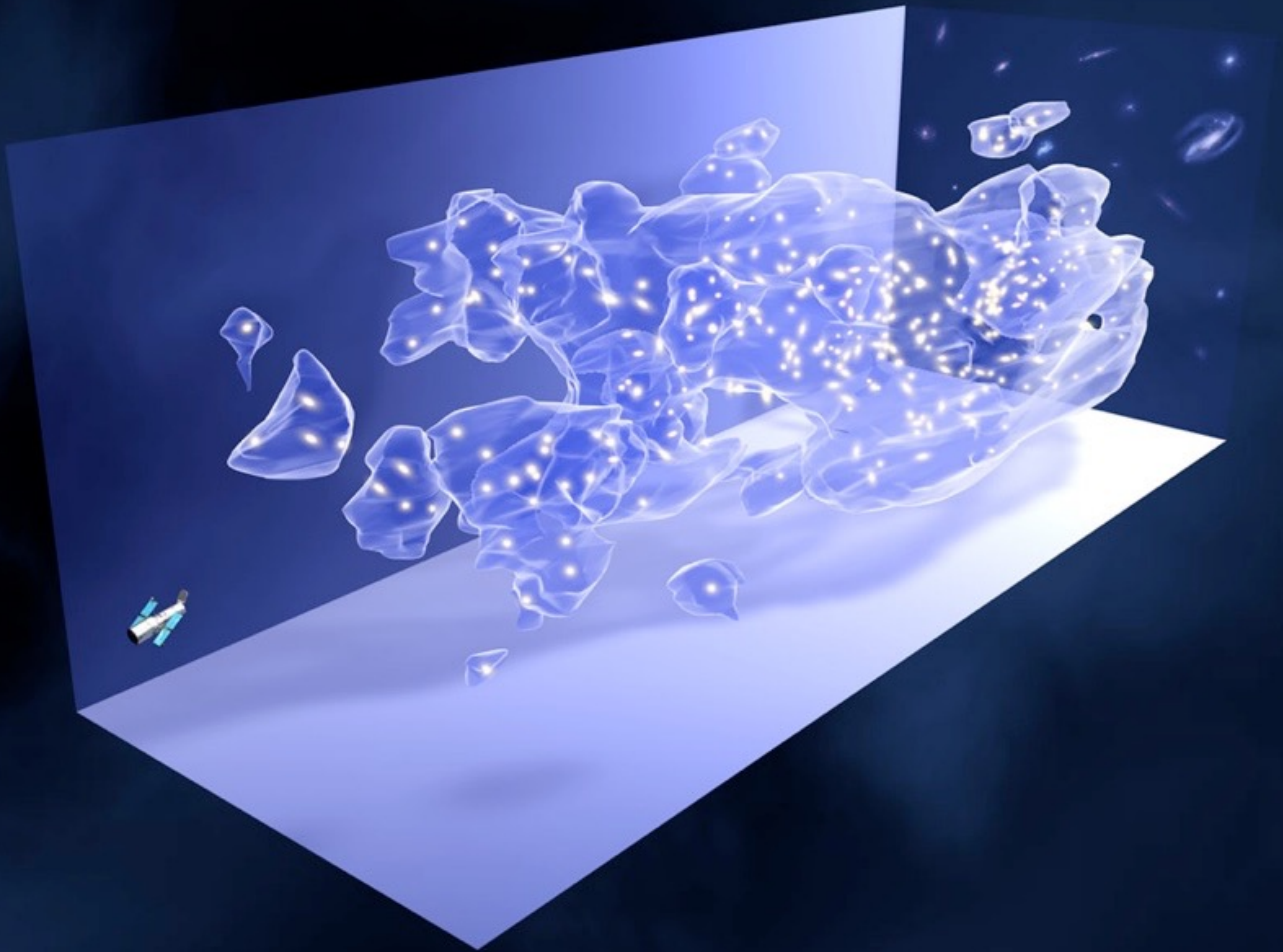
Galaxies can cause these arcs or rings too, but they are very rare.



WEAK GRAVITATIONAL LENSING

Most mass measurements are done by weak gravitational lensing which is not obviously seen by eye. In weak lensing one statistically looks at the small changes to galaxies ellipticities and uses that to infer the projected mass distribution.





DARK MATTER CANDIDATES

DARK MATTER SOLUTIONS

There have been many proposed solutions to this dark matter problem. In general they fall into three categories:

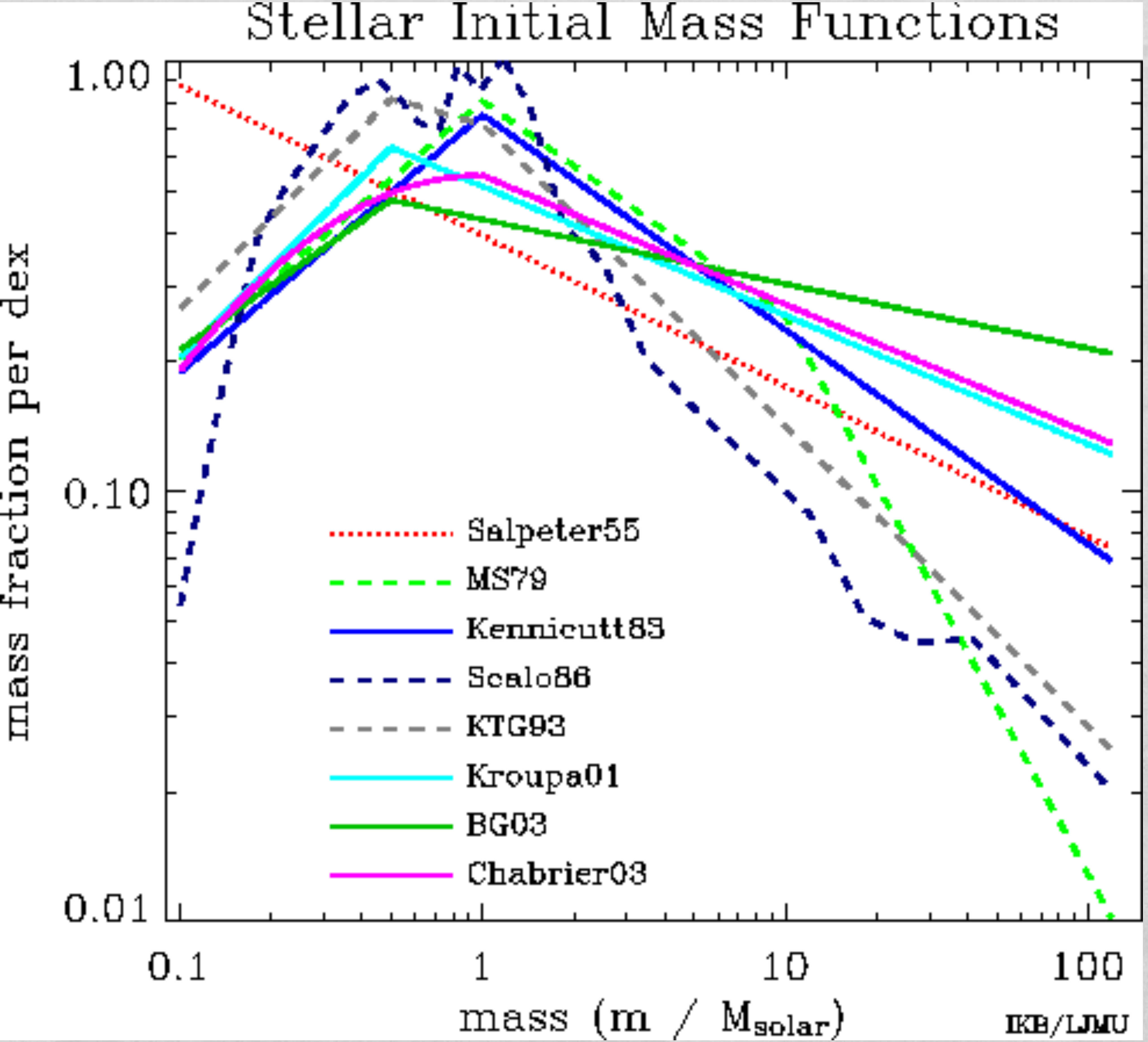
1. Baryonic - normal atoms that simply are not shining like stars
    1.1. Brown Dwarfs - very little emission
    1.2. compact objects - white dwarfs, neutron stars, black holes
    1.3. Cold Gas - emits in radio waves (unless it is molecular, H_2)
    1.4. Hot Gas - emits in X-rays
2. Nonbaryonic - dark matter is a particle that doesn't interact with the electro-magnetic force.
    2.1. neutrinos - no charge so no electro-magnetic force
    2.2. A new particle - often called a WIMP (Weakly Interacting Massive Particle)
3. Modified Gravity - there is no new matter, we just don't know the laws of gravity.

BARYONIC MASS

- In astronomy speak baryon is used to mean atoms or plasmas.
- The discovery of dark matter originally did not suggest anything highly unusual, it is quite reasonable to assume many atoms in the universe are not emitting visible light.
- Stars emit light, but planets, brown dwarfs, compact objects, cold gas and hot gas do not.
- So the first place to look for dark matter is in ordinary protons, neutrons and electrons.

STELLAR MASS

- When stars are born there is some distribution of their masses called the initial mass function of IMF.
- People have taken the IMF to be universal, to have the same functional form in all galaxies and at all times.
- This is based on local observations that showed universality, but mostly because it makes things much simpler. Even locally the functional form is a matter of debate.

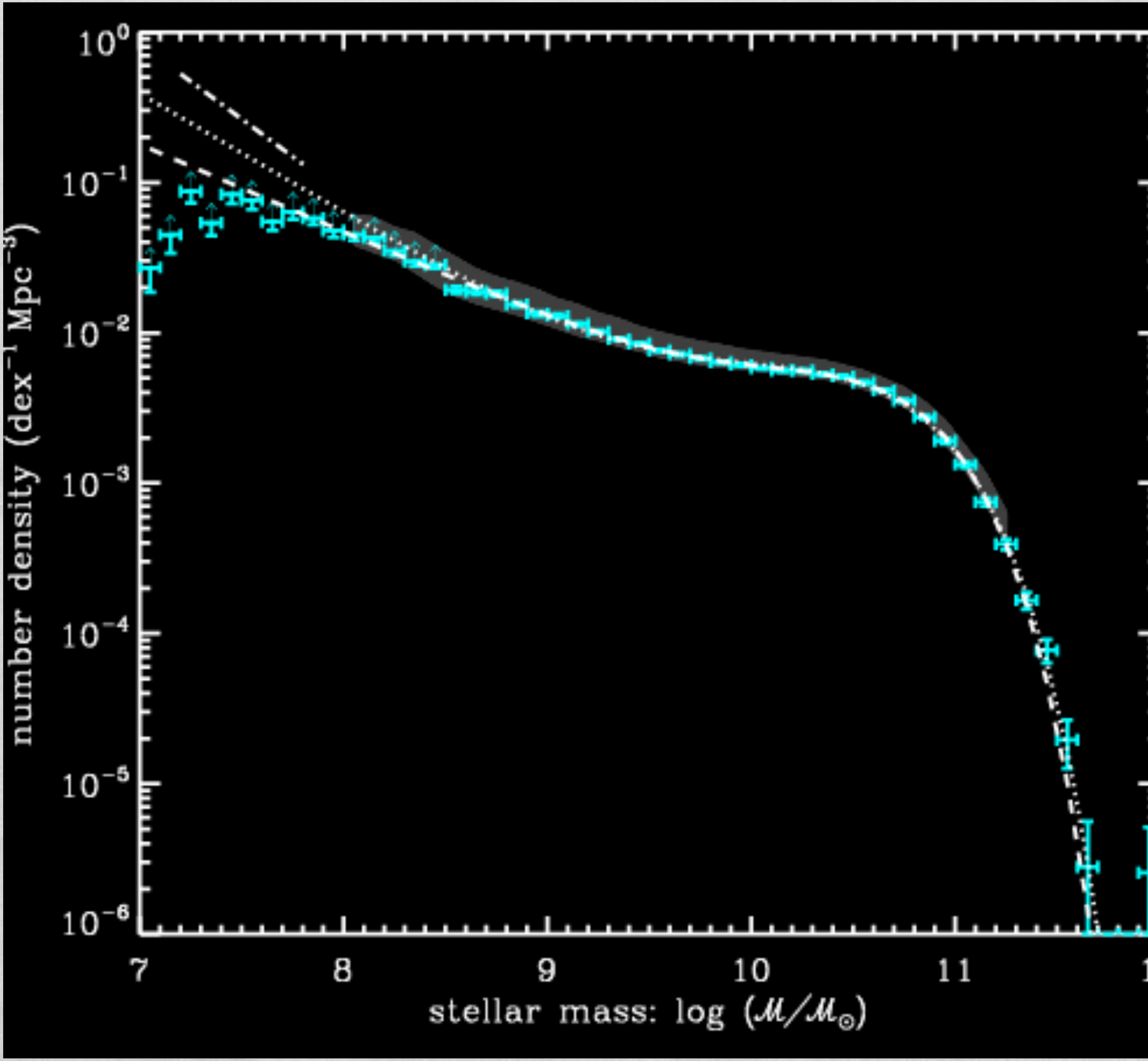


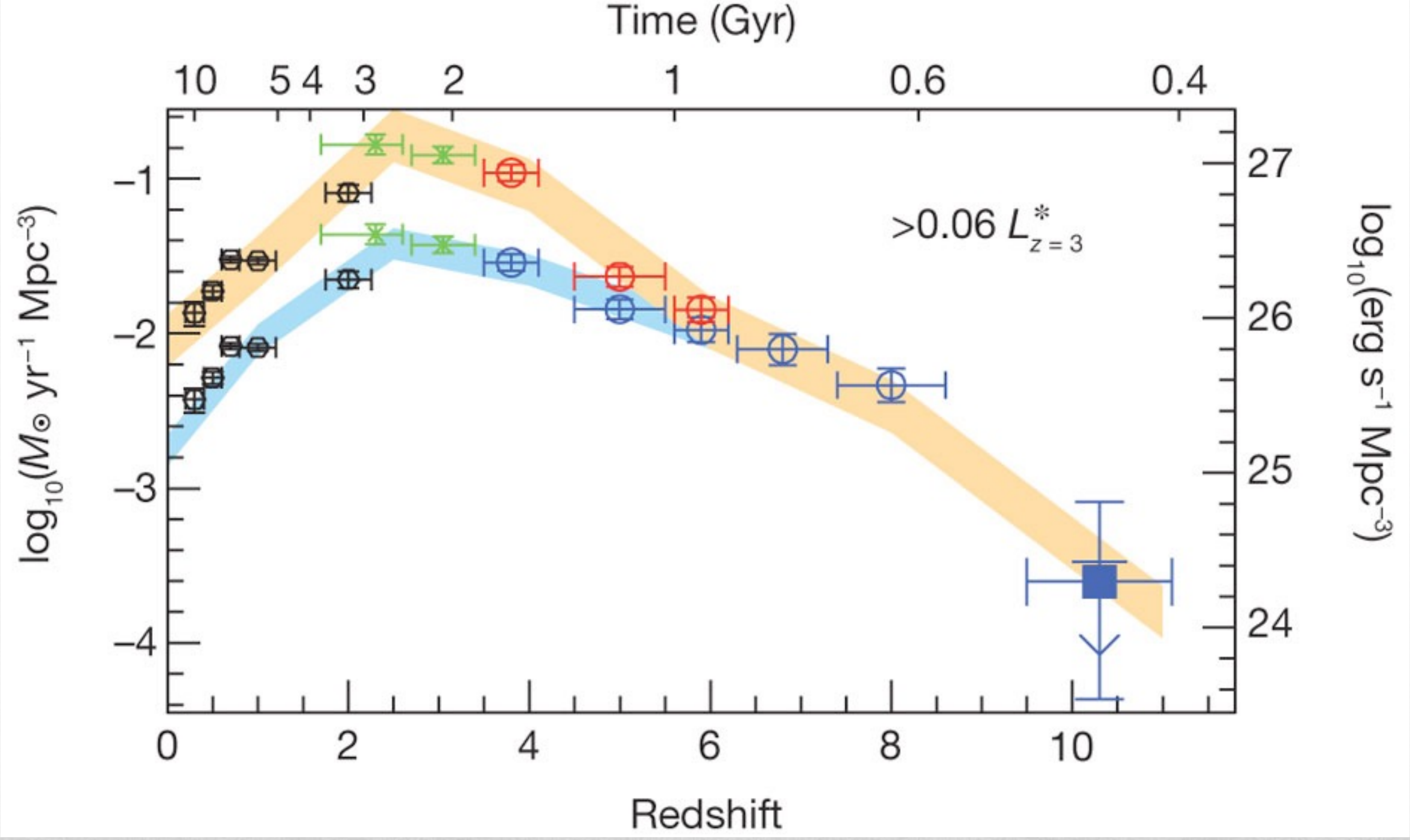
One can see there is a wide range of functions that have been fit to the IMF. The agreement is pretty good for 0.5 > M > 10 where there is plenty of data, but the discrepancies can be large when extrapolated to higher and lower masses.

GALAXY MASS FUNCTION

- Starting with an IMF and adding models of stellar evolution and stellar atmospheres one can evolve what a population of stars should look like at any time.
- If this is then compared with a model for the star formation history of say a galaxy and combined with a model for dust this gives a spectral energy distribution (SED) for a galaxy.
- Thus observing the colors of galaxies one can infer a total stellar mass of the galaxy by using these models.
- From this one can build a model of the galaxy stellar mass function (GSMF).

A measurement of the galaxy stellar mass function. Integrating under the curve gives the stellar mass density of the Universe. Note this quantity tends to grow with cosmic time as more stars are created. While stars also die only the most massive ones have so far and they are a small fraction of the mass.





This figure shows a star formation history of the universe which peaks at about z~2.5 or 10Gyr ago and then falls off after that.

This mass density of stars today is about $5\times10^8\ M_\odot/\mathrm{Mpc}^{-3}$ which gives $\Omega_* = 0.004$.

BROWN DWARFS

- What about stars that don't shine? If a ball of hydrogen and helium is not massive enough to ignite hydrogen fusion it is called a brown dwarf.
- These are obviously much harder to see, so they could be some (or all) of the dark matter.
- These objects are brightest in the infrared and advances in infrared astronomy have greatly improved our knowledge of them.
- They do not contribute a significant mass to the IMF, but that doesn't rule out a different IMF at different locations or times.

COMPACT OBJECTS

- Another possible dark matter candidate are compact objects; white dwarfs, neutron stars and black holes.
- White dwarfs shine while they are young, but neutron stars and black holes are dark. They are only observed indirectly as pulsars and X-ray bursters.
- We can calculate how many of these objects there should be based on the IMF, but if the IMF was very different at some point it is possible to create many more stellar remnants.

COMPACT OBJECTS

- We would expect heavy elements to be produced by these massive stars before they formed compact objects and that constraint seems hard to get around.
- Also they could be observed as super nova which also places constraints. Basically it is hard to make as many stellar remnants as one would need unless things just collapsed directly to black holes.
- Black holes can also be formed 'primordially' which means at some point early in the universe probably when the Universe was a quark-gluon plasma.

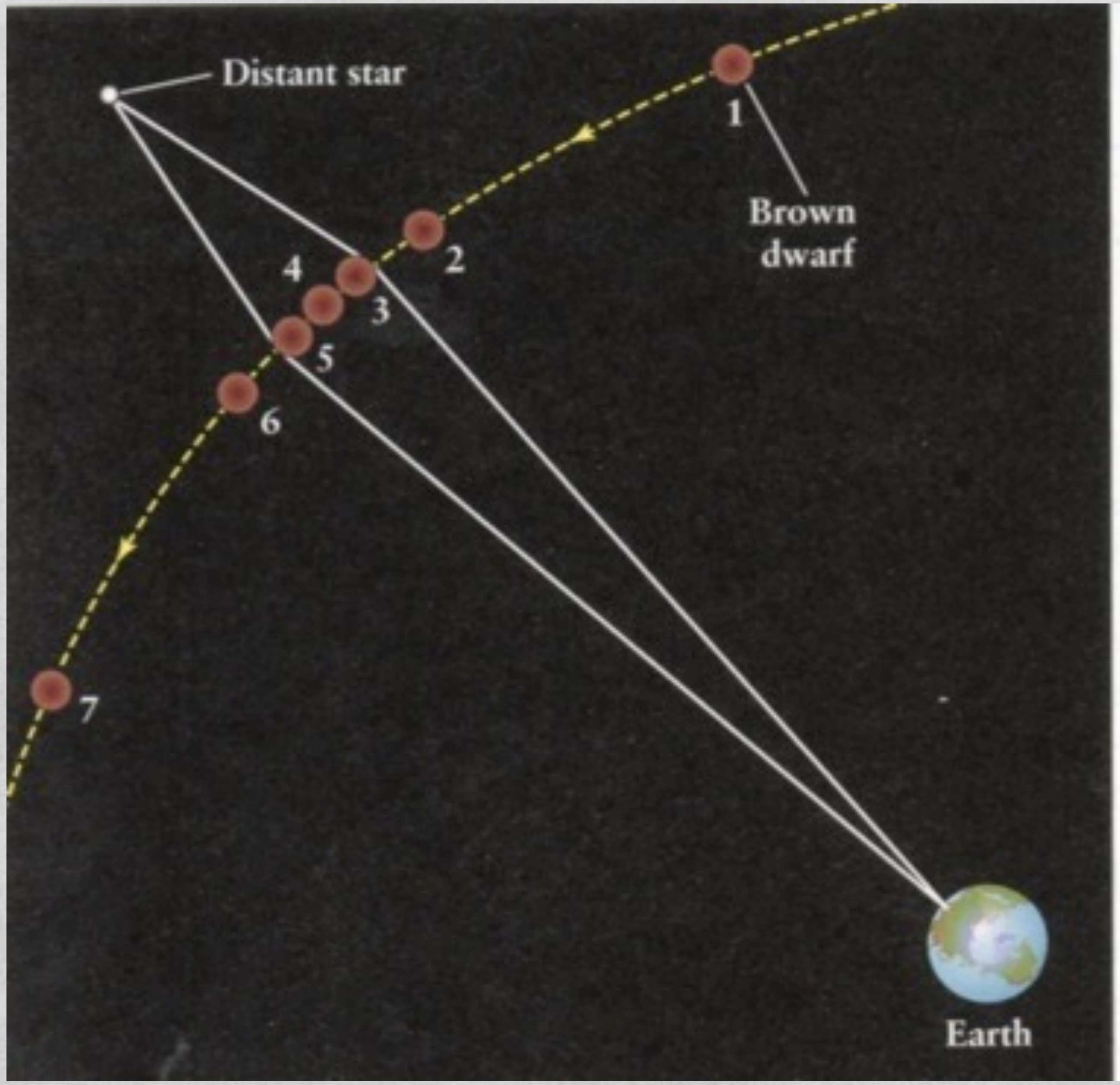
MACHOS

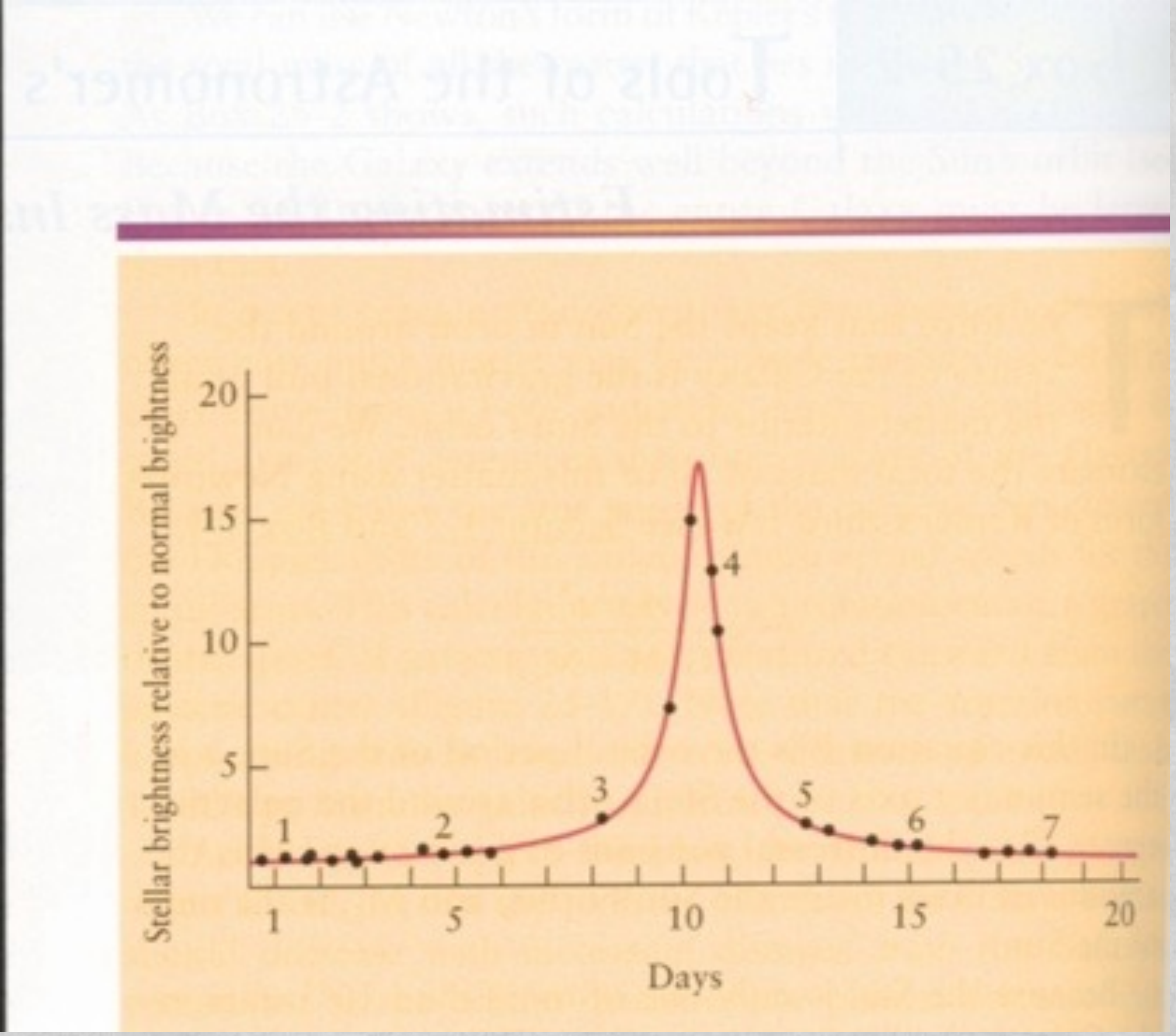
- Compact objects and brown dwarfs can both be considered examples of MACHOS (Massive Compact Halo Objects).
- Massive compared to the proton mass and compact unlike gas which is many of billions times more diffuse.
- MACHOS have been ruled out as significant contributors to dark matter by micro-lensing studies.

MICRO-LENSING

- Micro-lensing refers to gravitational lensing where the distortions can not be seen, but instead the overall change in flux can be measured.
- Micro-lensing thus generally refers to point sources or very small sources.
- If MACHOS pass between us and stars outside of our galaxy we would expect to see a micro-lensing signal.

Micro-lensing studies towards the Magellanic Clouds constrain the contribution of MACHOS to dark matter as less than ~10%. While this experiment basically gave a null result the experience with micro-lensing has pushed other experiments that are now searching for planets and other compact hard to find objects.

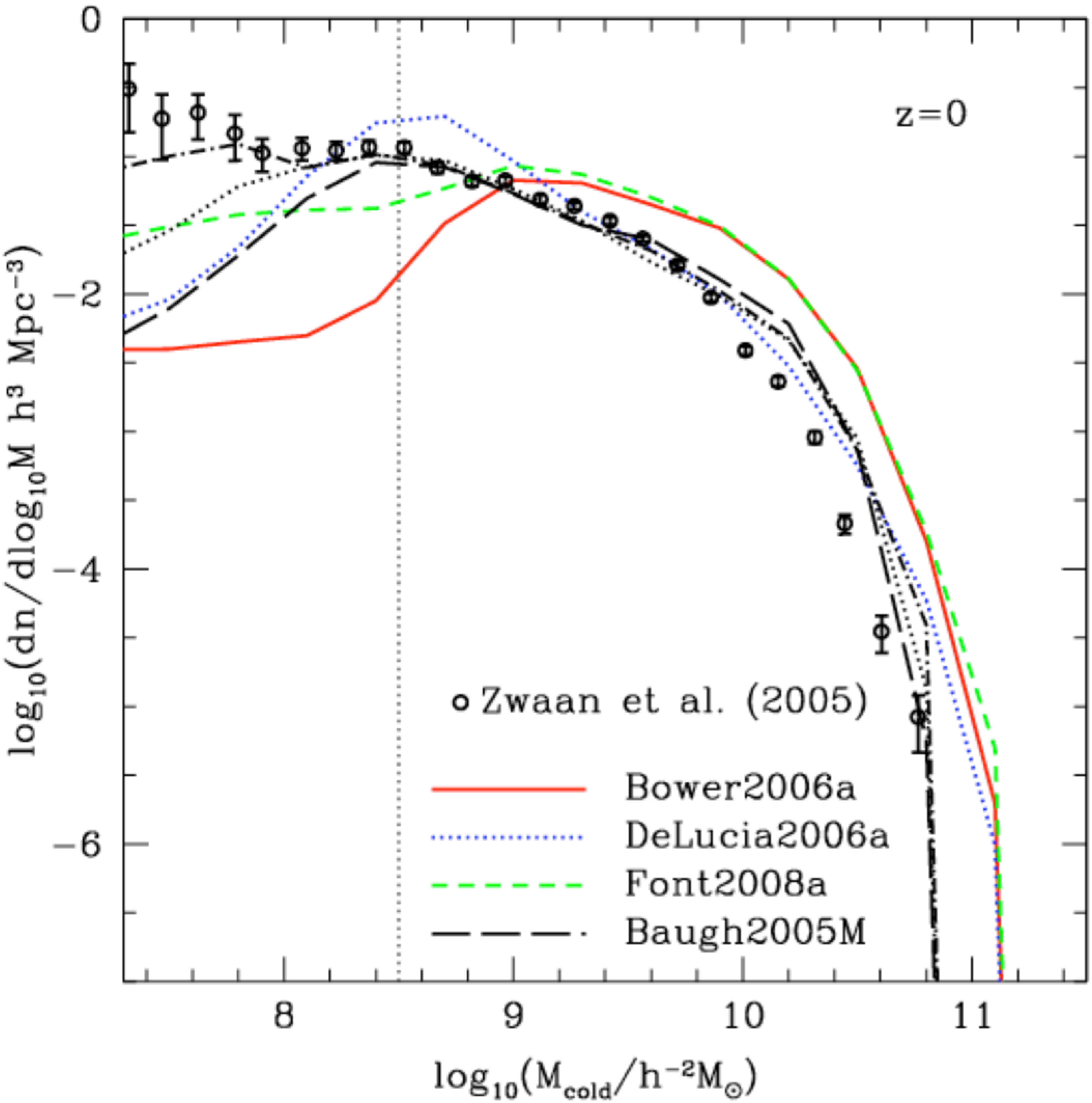




COLD GAS

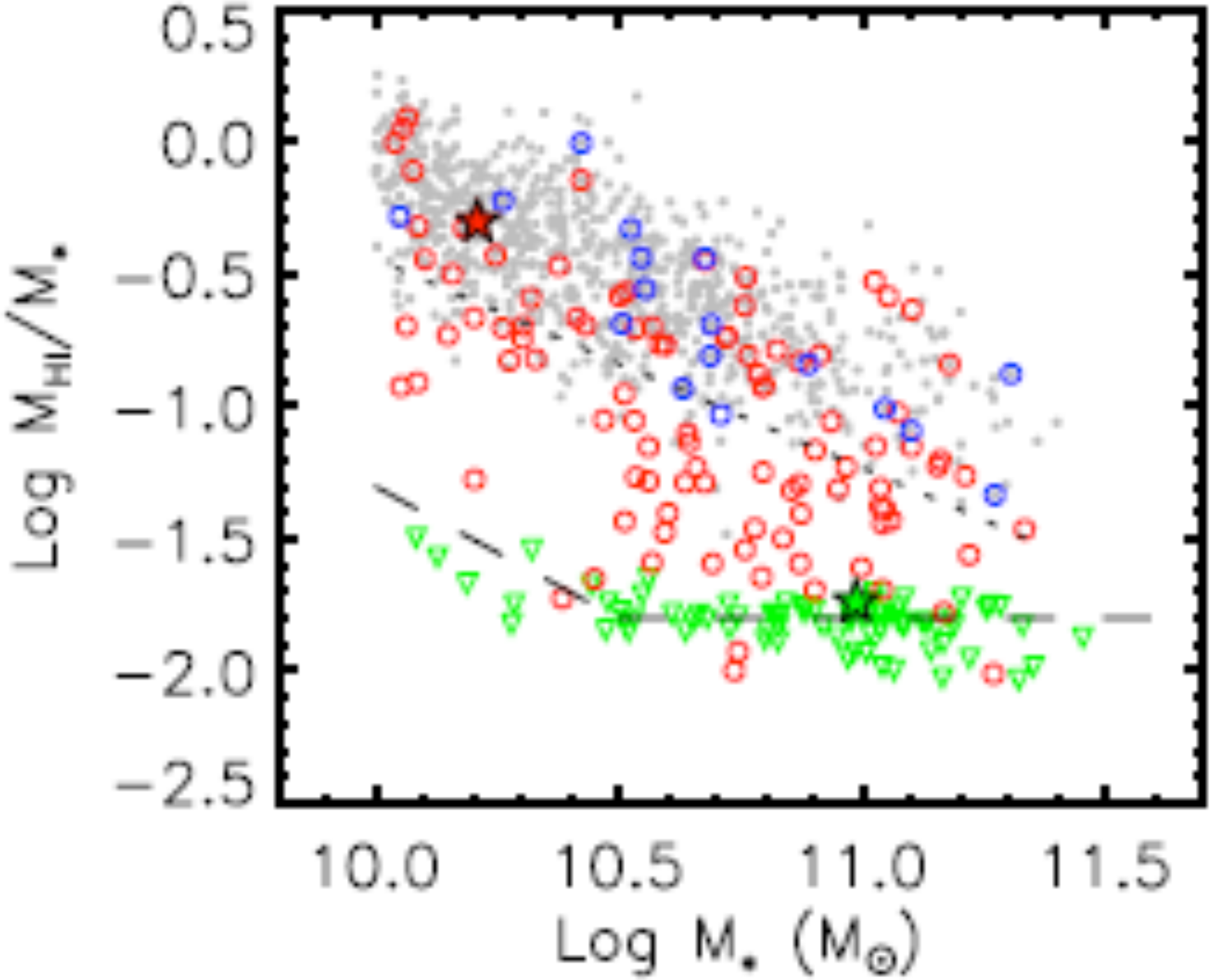
- Cold gas is another state that baryons can be in where they don't radiate visible light.
- However, they emit radio waves at 21cm and they absorb background radiation.
- Molecular hydrogen, H_2, is very hard to detect but it seems to be associated with CO which is detectable as mm radiation (and now easily mapped with ALMA).

Using radio telescopes the neutral hydrogen galaxy mass function can be measured. While in some galaxies neutral gas can be 10x as much as the stellar mass overall this component contributes much less mass to the Universe then stars.



While in massive galaxies neutral hydrogen is only 5-10% the mass of the stars, in low mass galaxies in can be the majority of baryonic mass.

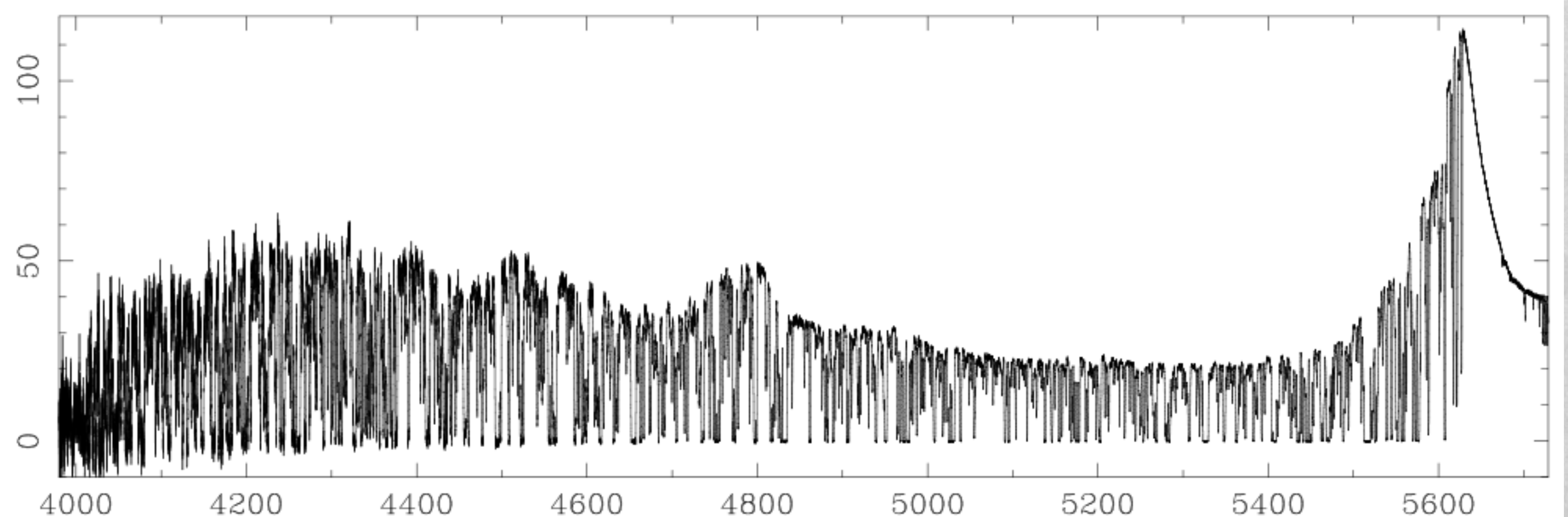
HI mass fraction



The Antennae Galaxies imaged with HST and ALMA. HST shows starlight while ALMA shows molecular hydrogen through CO.

QUASAR ABSORPTION SYSTEMS

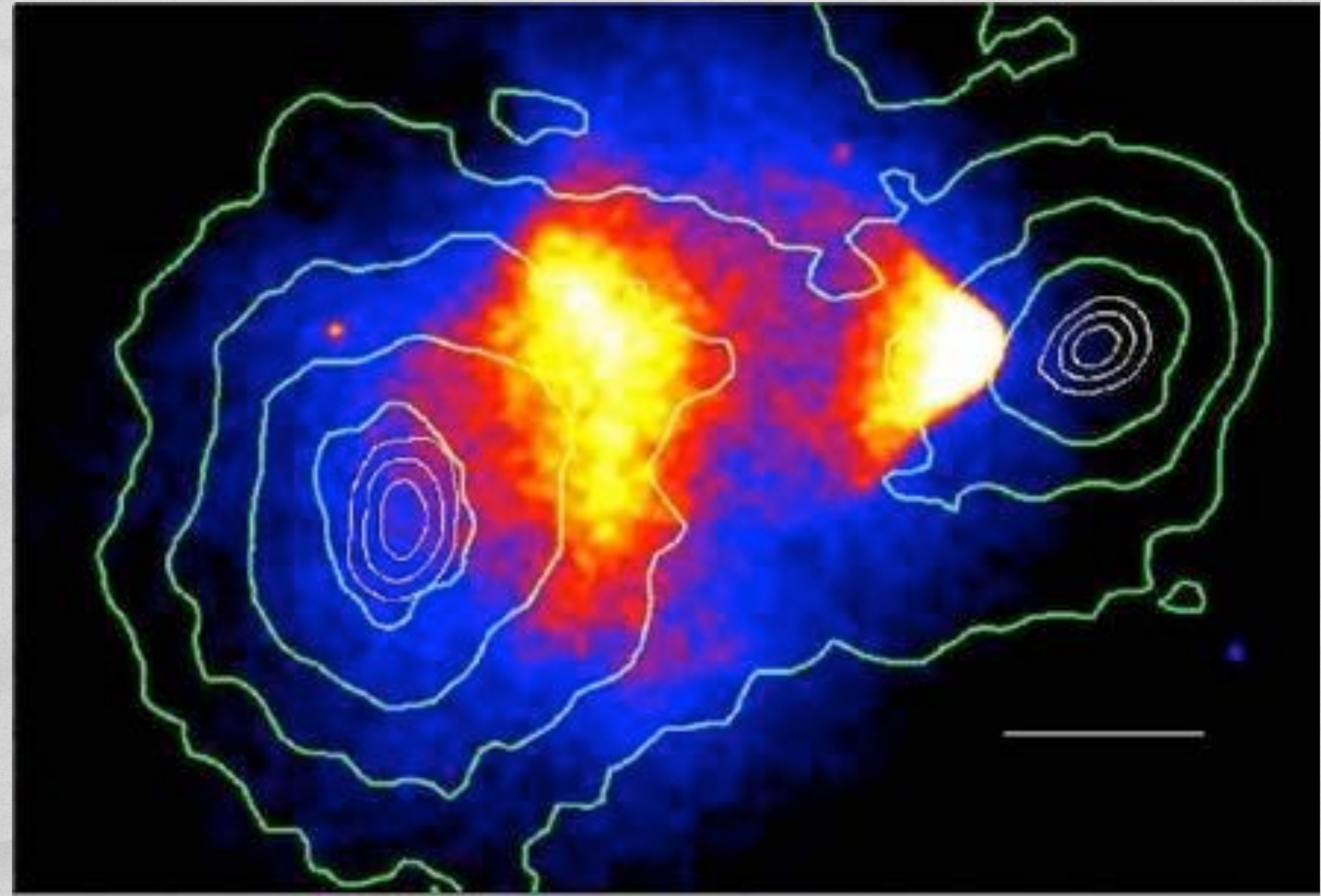
- Gas can also be detected by its absorption of background light sources (mainly quasars).
- For hydrogen these spectral lines are in the UV, so either UV telescopes are needed, or this can be done at higher redshift ($z < 2.5$).
- At high redshift these ubiquitous absorption lines are called the Lyman alpha forest and account for almost 100% of the baryons at $z > 3$.



WARM AND HOT GAS

- Hot gas can be detected with X-ray telescopes if it is hot enough ~10^7K.
- Hot gas halos are easily detected in clusters and some groups where it is called ICM (Inter Cluster Medium). It is also detected around elliptical galaxies.
- Hot gas in clusters is ~10x the mass in stars. In groups it is a factor of a few and for individual galaxies it is of order the mass of the galaxy.
- Detecting hot gas around spiral galaxies has been a challenge as this gas is expected to be cooler ~10^6K and more diffuse.

The bullet cluster is a cluster that has just merged and we can see the hot gas undergoing shocks. Weak lensing shows the mass is not following the gas.



WARM AND HOT GAS

- It is believed that as much as half of all baryons at low redshift ($z<1$) are in the form of warm diffuse gas between galaxies.
- This is just like the Lyman alpha forest, but the densities are lower and temperatures higher because of the expansion of the Universe.
- This gas is often referred to as WHIM (Warm Hot Intergalactic Medium), but people aren't careful distinguishing gas around galaxies and between galaxies.

BARYON SUMMARY

- There are many issues with properly counting baryonic contributions to dark matter.
- However, those uncertainties are at the factor of about 2 level, which falls short of what is needed to explain the missing mass.
- We will see later that the CMB tightly constrains the total baryon content of the Universe, effectively ruling out baryonic dark matter.

NON BARYONIC DARK MATTER

- Once you’ve given up on normal protons and electrons for dark matter you are left with two choices:
  - Neutrinos - a particle we know exists and doesn’t have charge, but we don’t know its mass.
  - WIMPS - Weakly Interacting Massive Particles
  - Axions - proposed particle to explain CP symmetry

NEUTRINOS

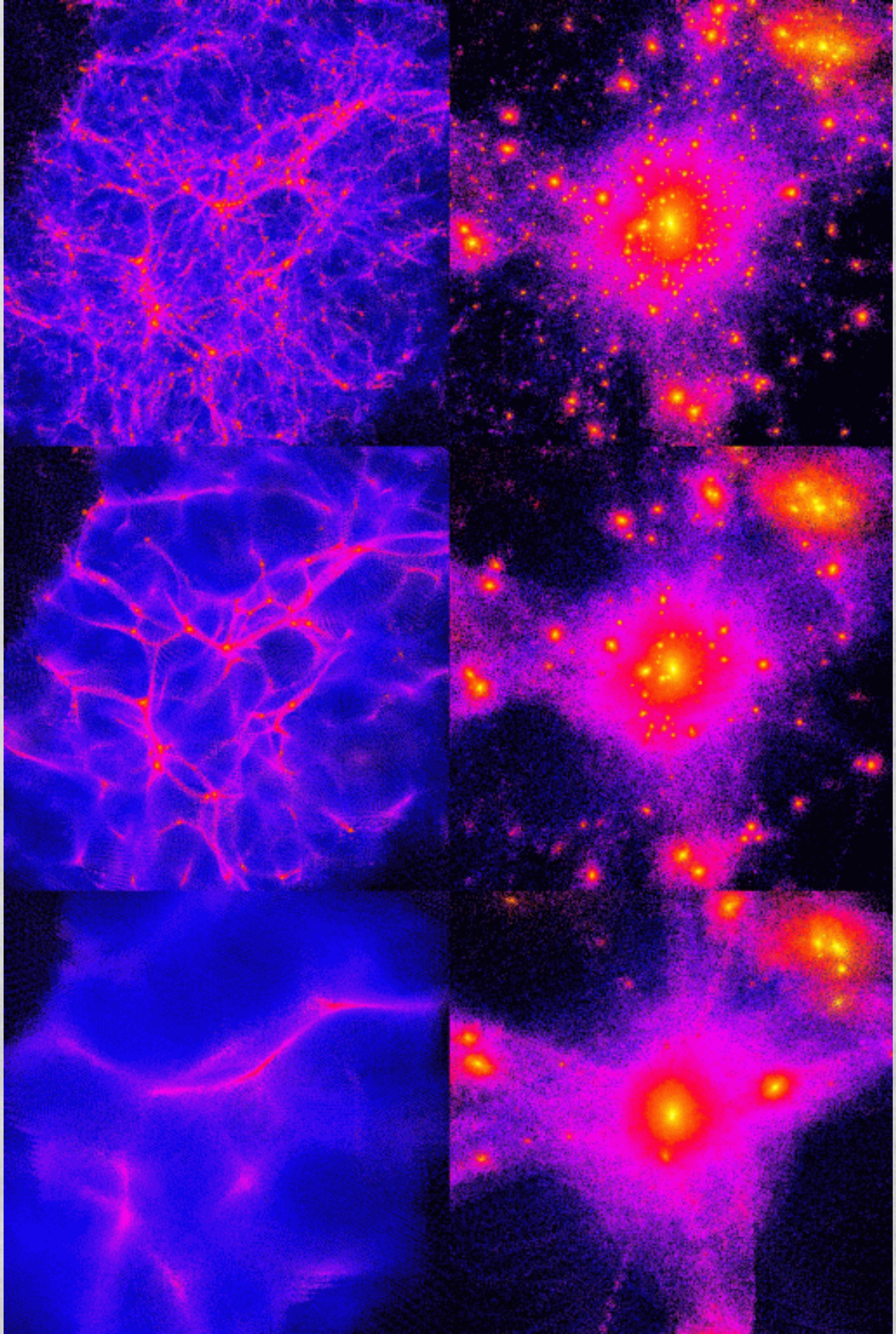
- One of the first guesses for dark matter was neutrinos. We know they exist, we know they don’t participate in electro-magnetic reactions, perfect candidate.

- We now also know they have mass, because we have observed neutrino oscillations both from the Sun and in the atmosphere.

- The problem with neutrinos is that they are ‘hot’ dark matter, which means they are relativistic at least at early times.

- This effects how they form structure and can now be ruled out. Neutrinos can still contribute to the dark matter and constraints can be placed on the neutrino mass by considering their contribution.

Simulations of cold, warm and hot dark matter. One sees that as the temperature of the dark matter rises structures are washed out. Hot dark matter does not produce enough structure to be compatible with our Universe.



COLD DARK MATTER

- Thus we are left with the idea of cold dark matter also called WIMPs (Weakly Interacting Massive Particles).
- Cold dark matter seems to form structure like we see in our Universe and could give off no electromagnetic radiation.
- Cold dark matter provides an excellent fit to all data at scales larger than 10s of kpc.

CANDIDATES FOR CDM

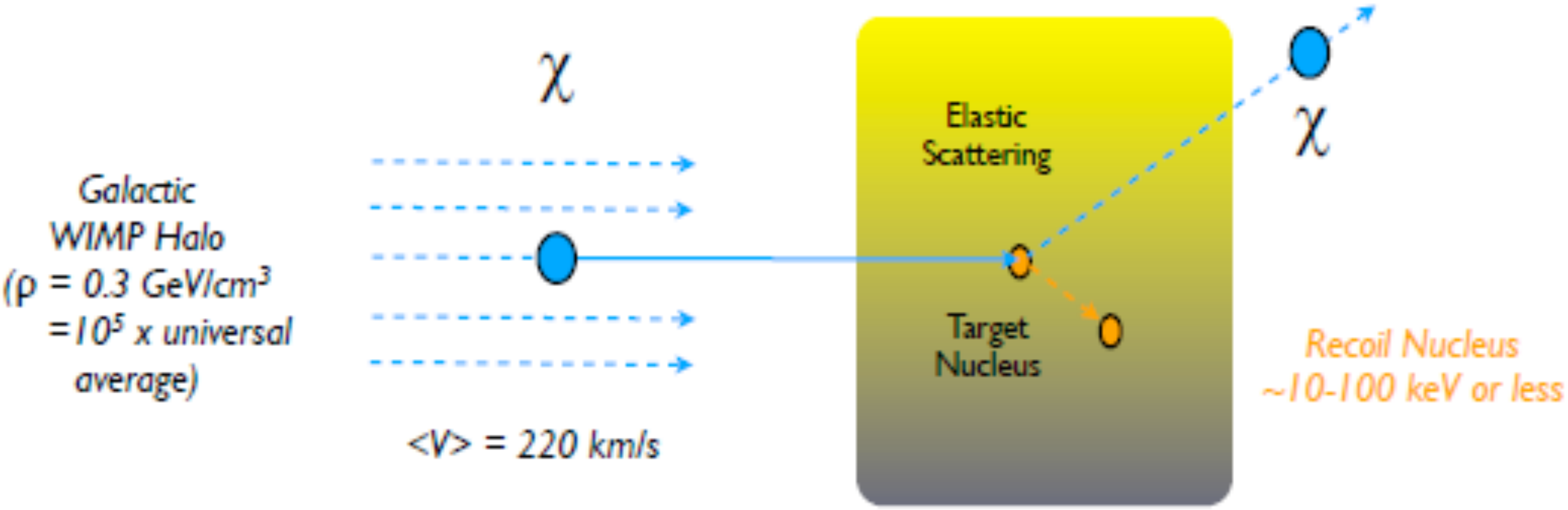
- WIMPS (lightest super symmetric particle)
  - The most promising dark matter candidate comes from super symmetry. In super symmetry every fermion has a boson partner, and every boson has a fermion partner.
  - Since this symmetry is broken, the partner particles will have masses of order the symmetry scale.
  - If there is a conserved quantity then the lightest super symmetric particle may not be able to decay, it would be a cold relic from the big bang.
- Axion - a boson that is created in one solution to the strong CP problem (why there seems to be CP symmetry).

DETECTION

- Both WIMPS and axions do have weak interactions and thus are detectable. In fact any dark matter candidate that is related to particle physics should have some interaction.
- Attempts to detect dark matter are either direct detection of the dark matter particle scattering off normal matter in the laboratory.
- Or indirect detection by the dark matter particle annihilating or decaying and leaving other particles.

Principle of Direct Detection

Goodman and Witten: coherent scattering of WIMPs off nuclei (1985)



χ

Galactic
WIMP Halo
(ρ = 0.3 GeV/cm^3
=10^5 x universal
average)

<V> = 220 km/s

Elastic
Scattering

Target
Nucleus

χ

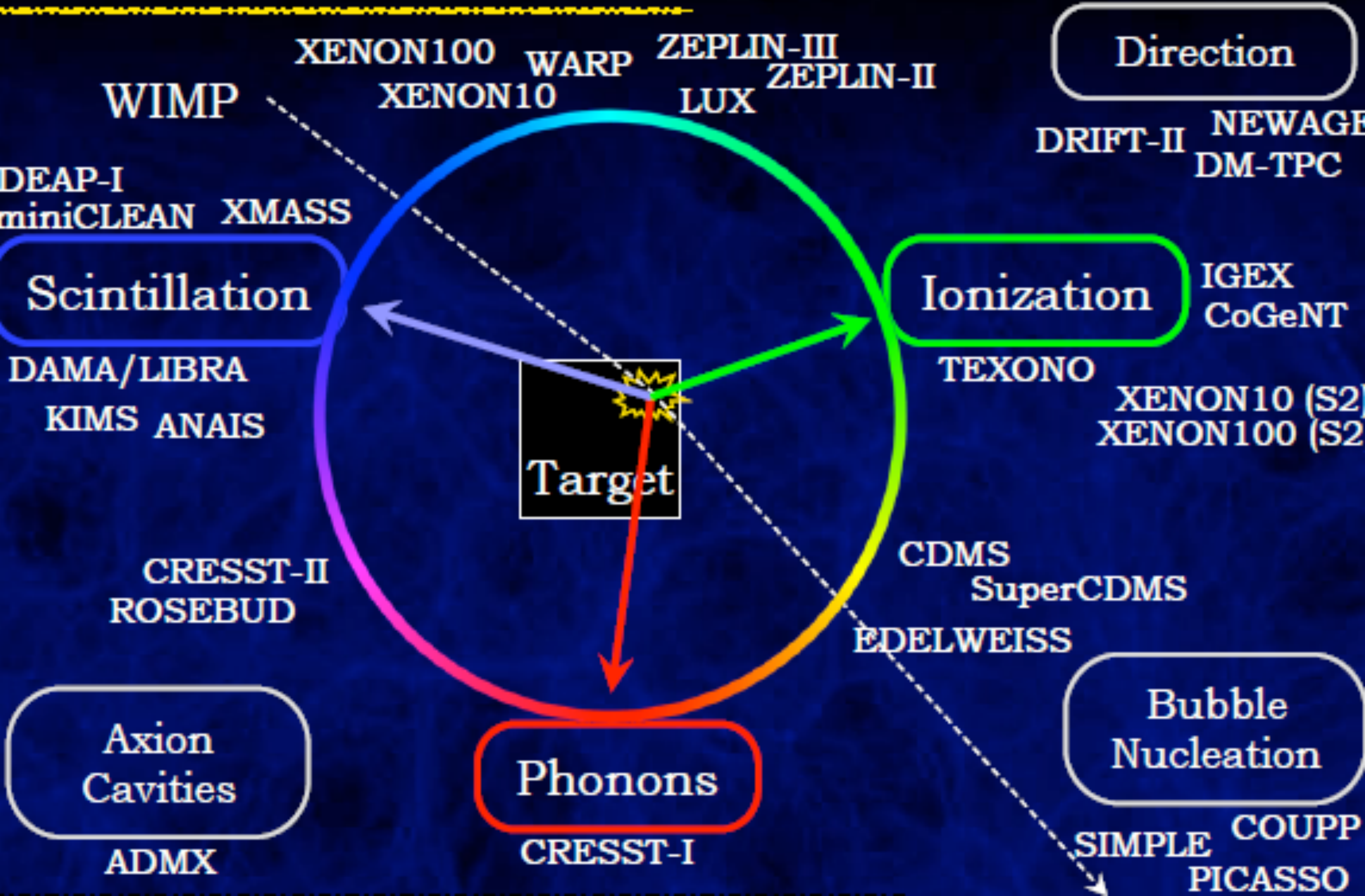
Recoil Nucleus
~10-100 keV or less

$\sigma_{\chi N}$ probed to-date ~ 10^{-44} cm^2

What is measured (with different target nuclei and detectors) : energy of the recoiling nucleus

What are the challenges: very small energy, very large backgrounds and very small rate

Particle Detection Channels



WIMP

Target

XENON100
WARP
ZEPLIN-III
ZEPLIN-II
XENON10
LUX

DEAP-I
miniCLEAN
XMASS

Scintillation

DAMA/LIBRA
KIMS
ANAIS

Ionization

IGEX
CoGeNT
TEXONO
XENON10 (S2)
XENON100 (S2

Direction

DRIFT-II
NEWAGE
DM-TPC

CRESST-II
ROSEBUD

CDMS
SuperCDMS
EDELWEISS

Phonons

CRESST-I

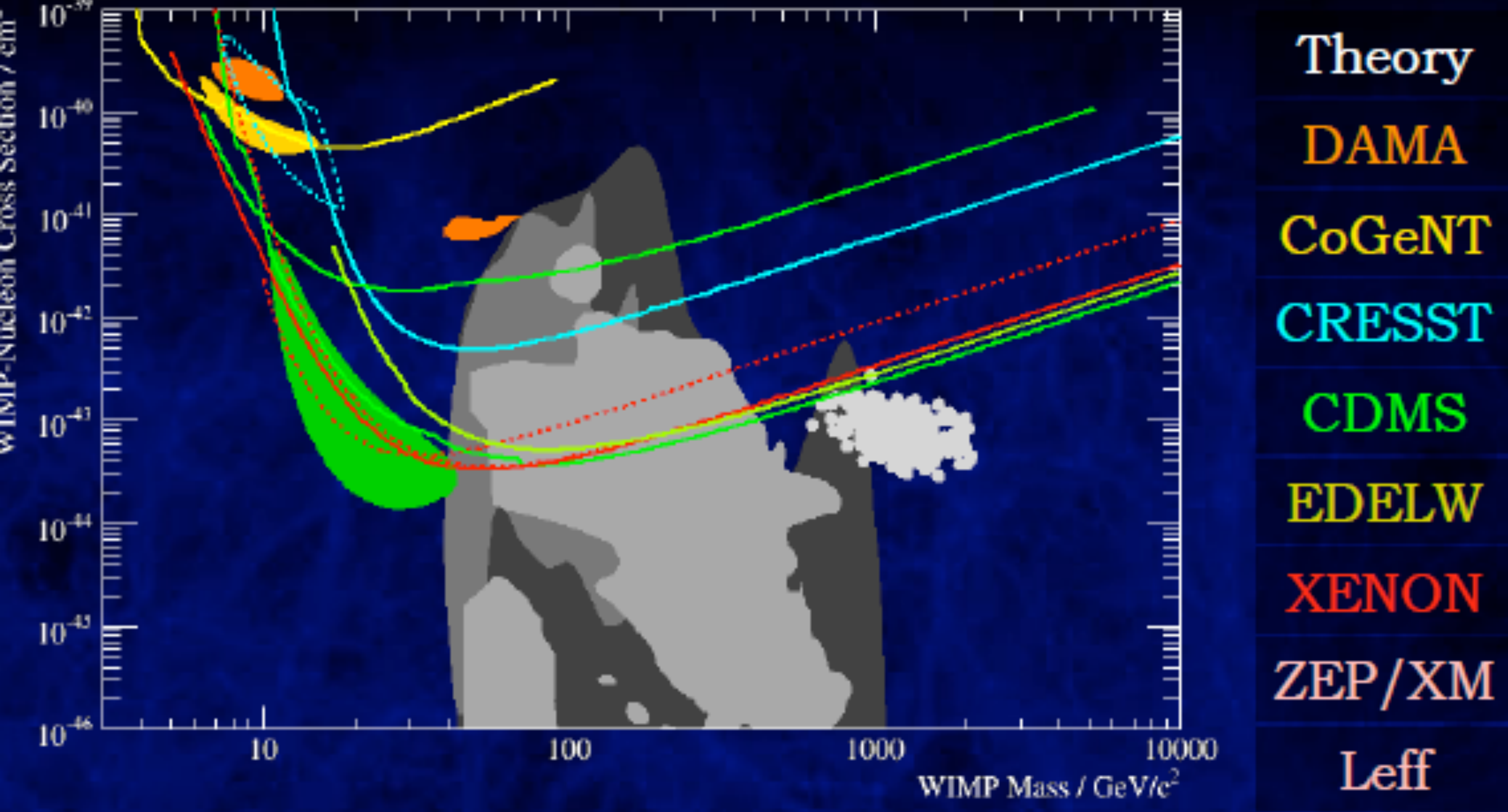
Axion Cavities

ADMX

Bubble Nucleation

SIMPLE
COUPP
PICASSO

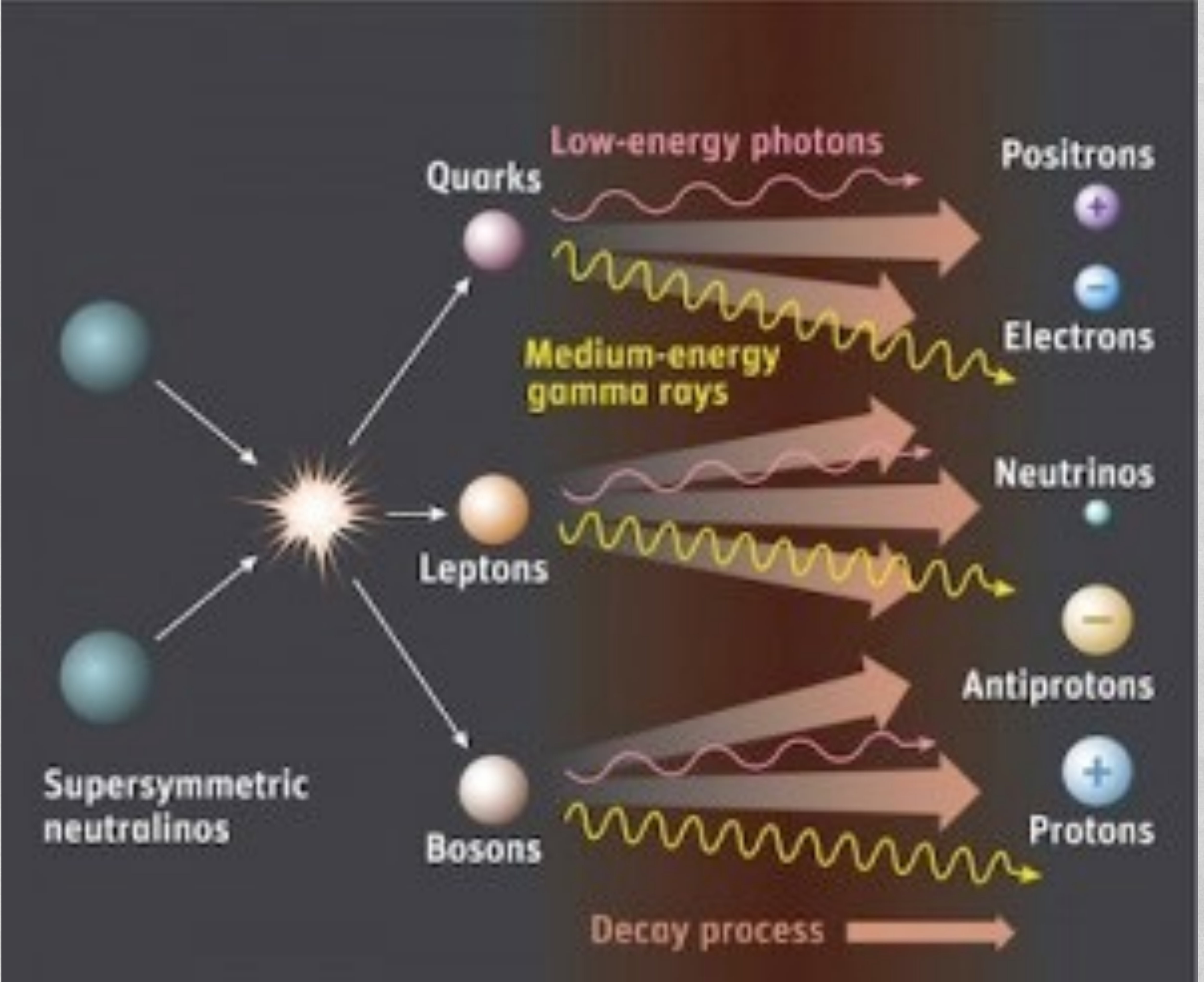
Summary



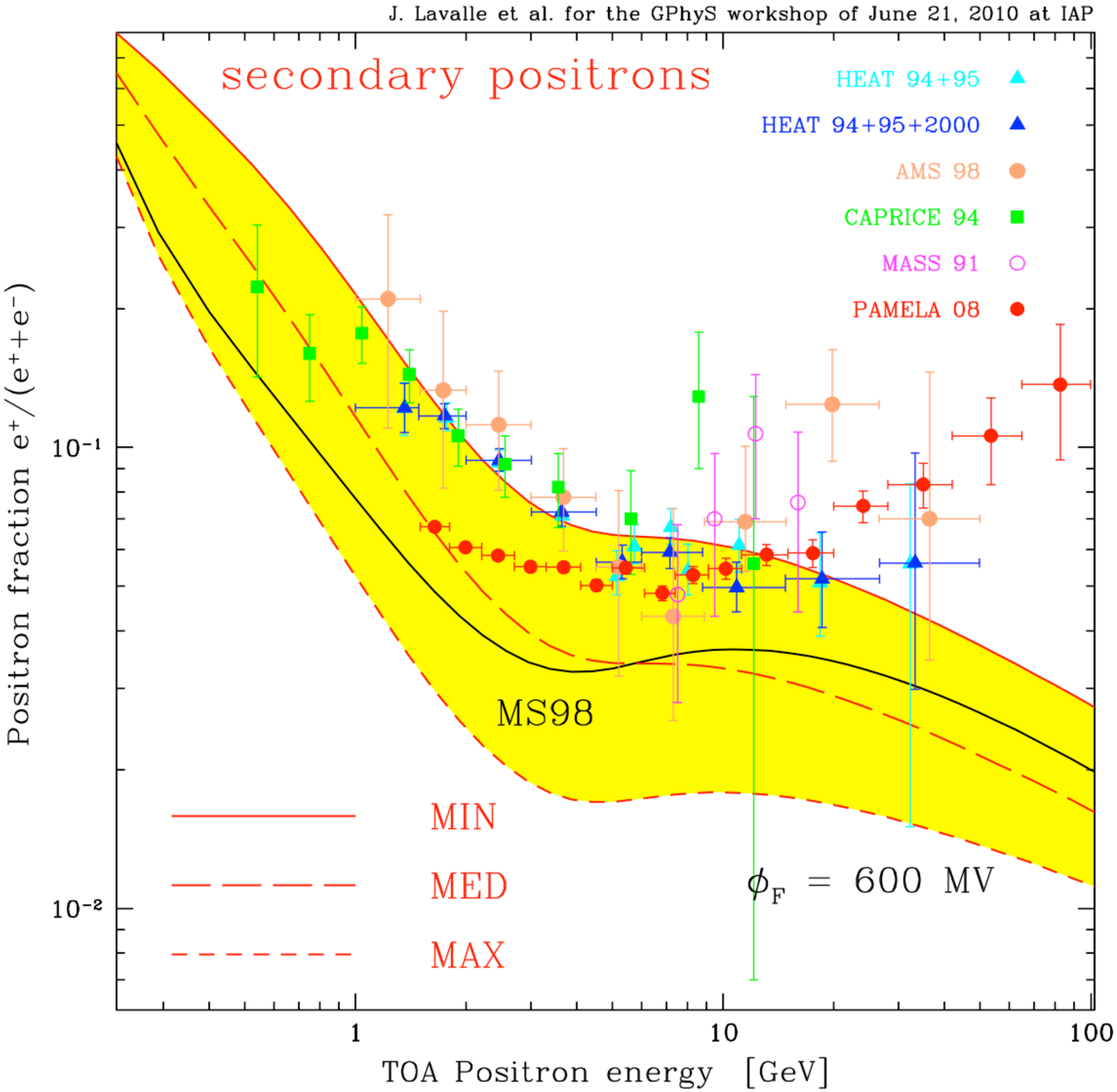
A very active and versatile field of research
many hints to follow up, many promising experiments

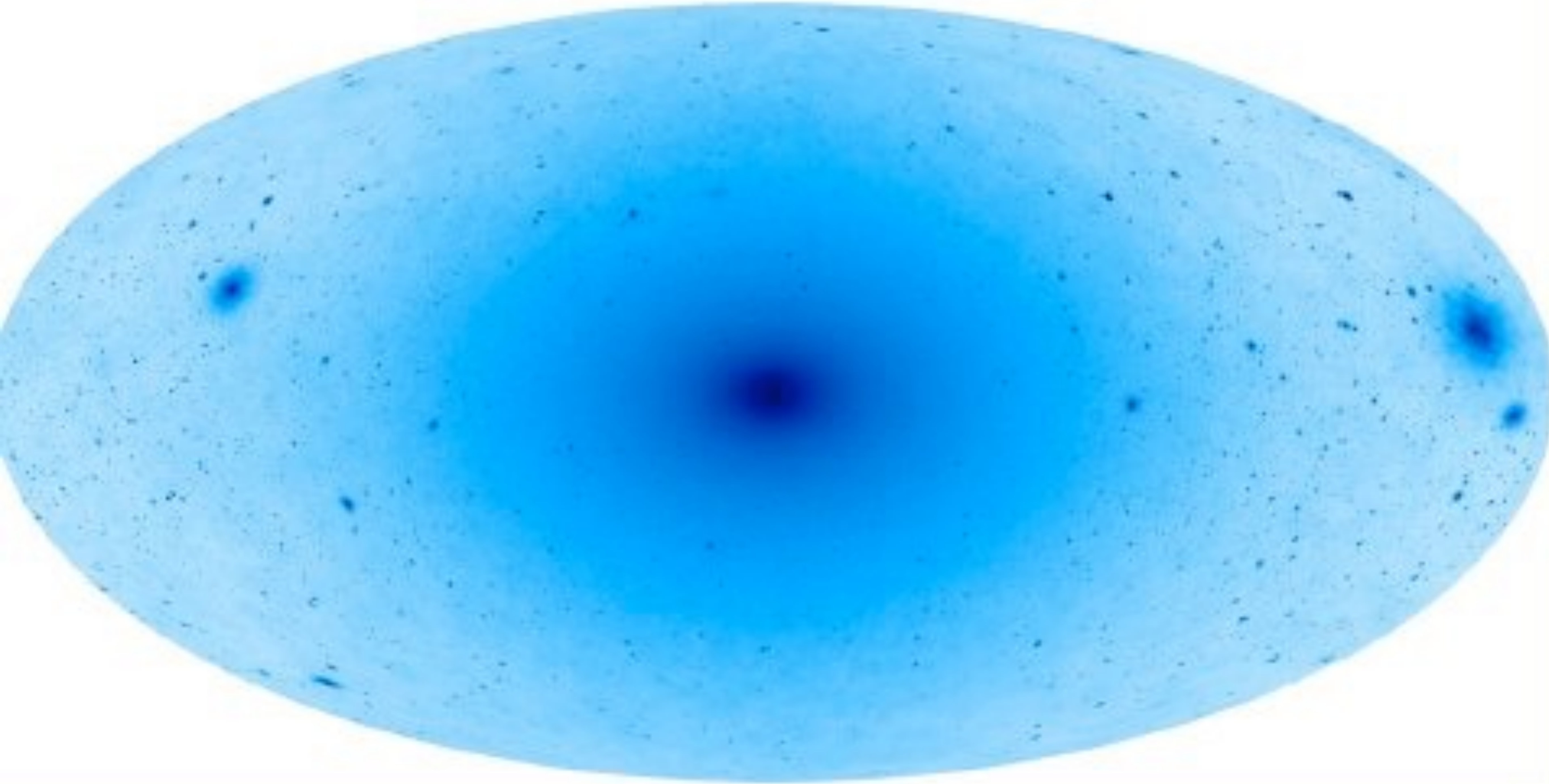
INDIRECT DETECTION

- If there is a dark matter halo around our Galaxy of WIMPS who have some weak interactions we might be able to detect them.
- Interaction among WIMPS would probably lead to photons and/or antimatter being formed (matter too, but no way to notice that).
- Looking for unexplained γ-ray emission or an excess of positrons seems like the best bets.


Low-energy photons
Quarks
Positrons
Medium-energy gamma rays
Electrons
Neutrinos
Leptons
Antiprotons
Supersymmetric neutralinos
Protons
Bosons
Decay process

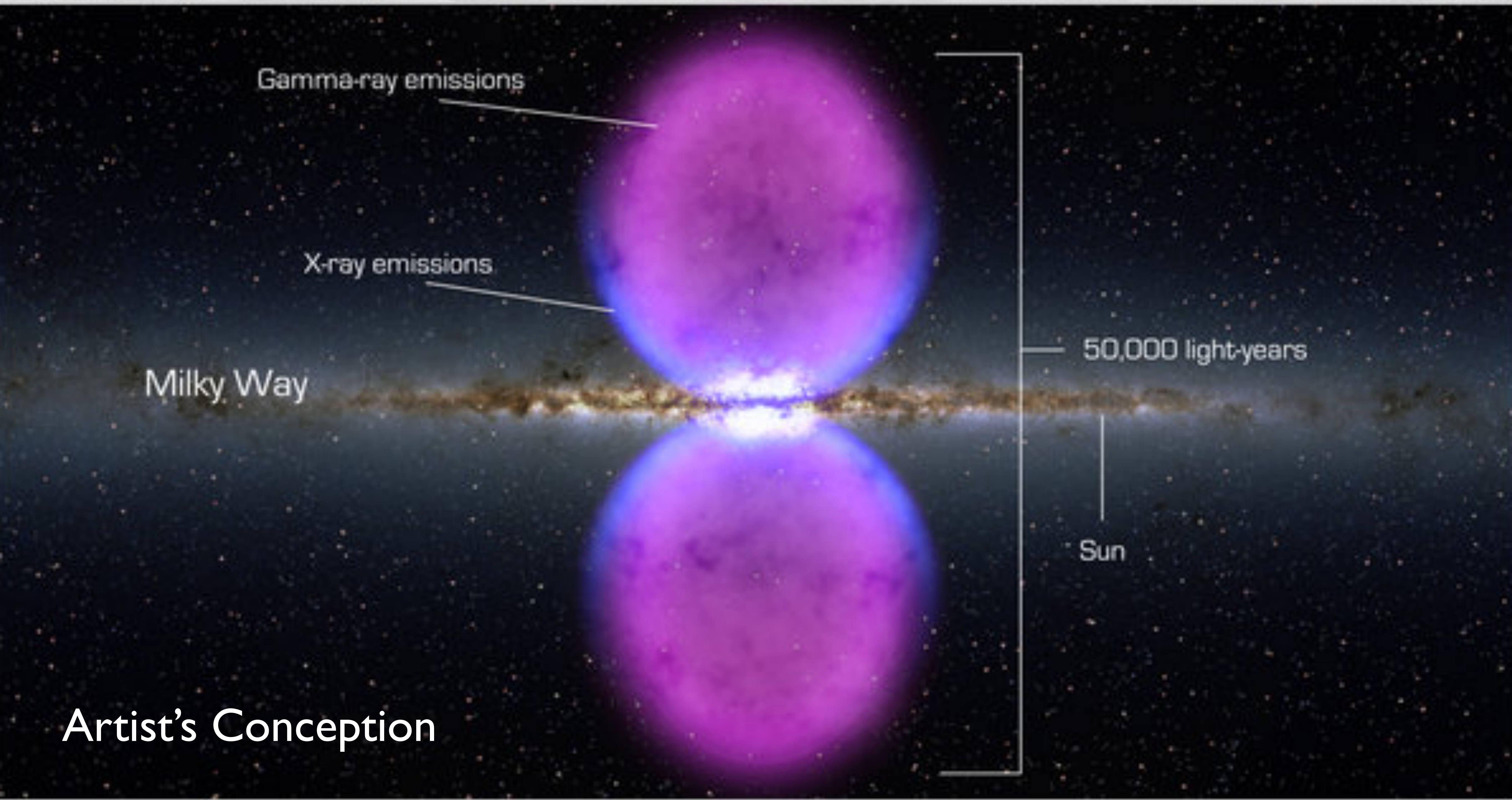
Currently people are very excited about an apparent excess of positrons at high energies. However, the creation of positrons is not simple to model and this may simply be astrophysical (see Piran et al 2009).





People spent a lot of effort trying to predict what the γ-ray signal from annihilation would look like. They found something like this, where the small blobs are caused by small subhalos that are associated with dwarf galaxies. This is important because there are many other sources of γ-rays in the Galaxy's center, emission from dwarf galaxies would be a strong signal.

Unfortunately, Su et al. 2010, found this instead. Two giant bubbles of gamma-ray emission. Whatever these are they are not dark matter annihilation. They are a mystery.



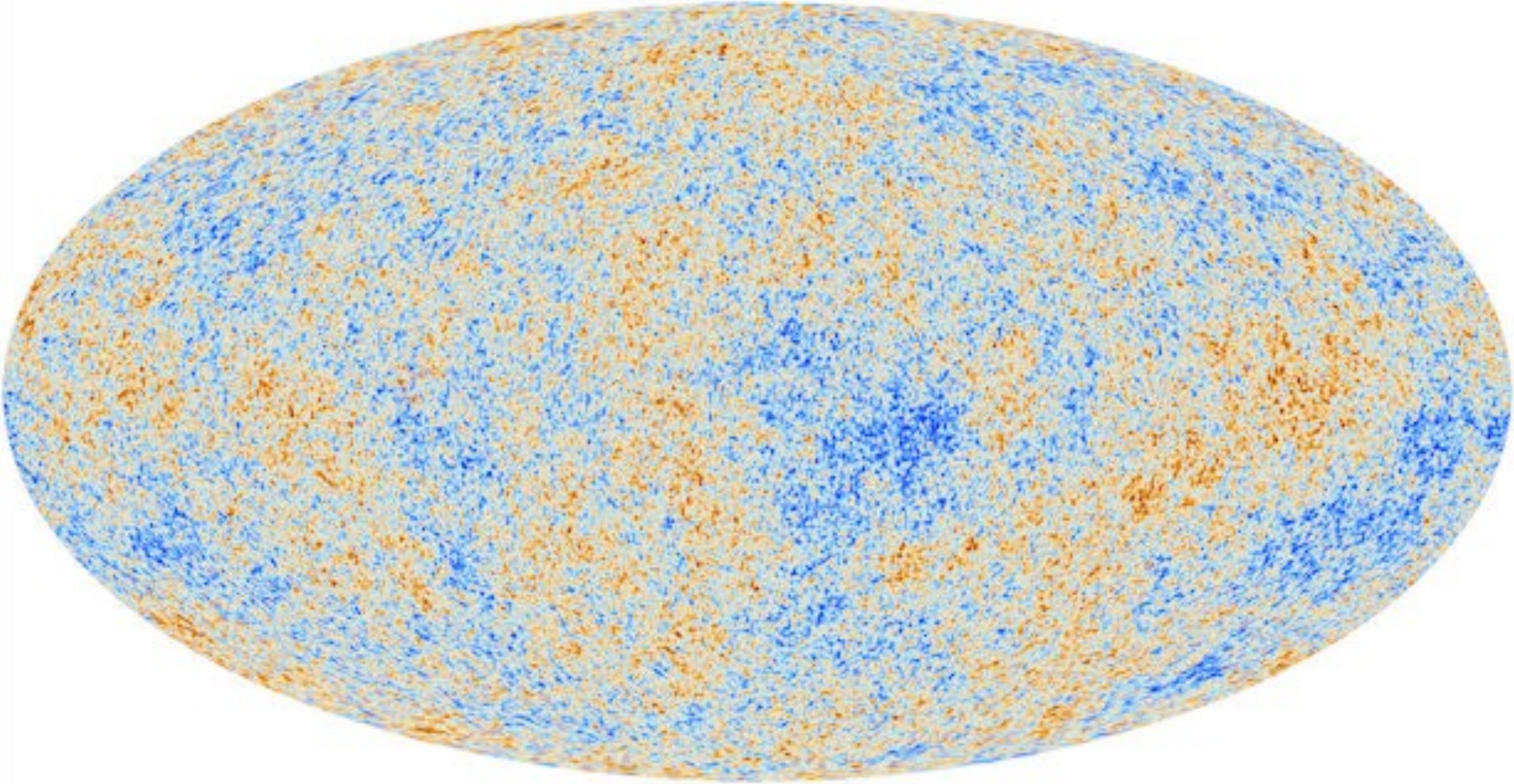
Artist's Conception

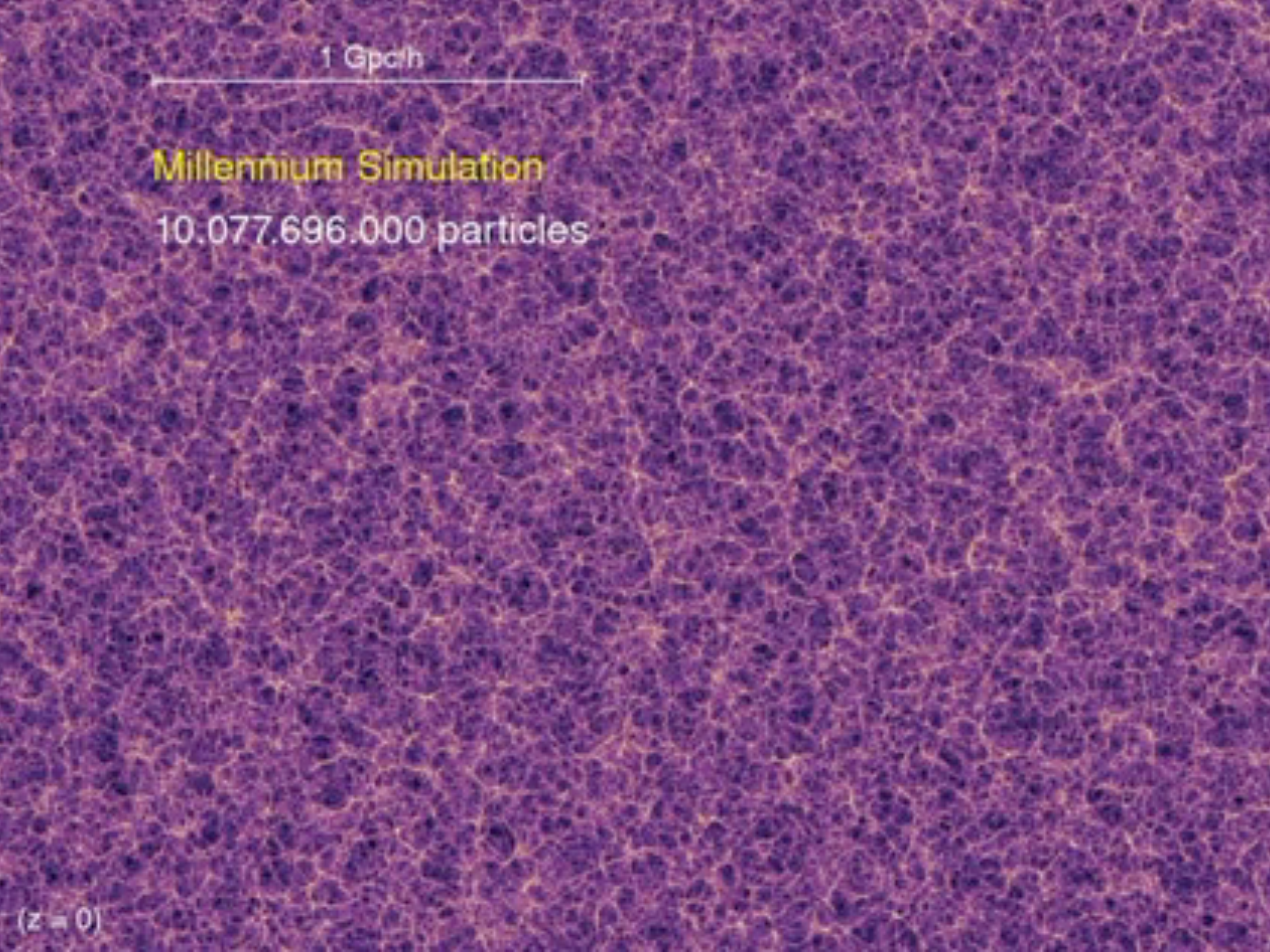
PROPERTIES OF DARK MATTER

N-BODY SIMULATIONS

- Since we expect the CDM particle to have only very weak interactions, we can model its behavior on a computer considering only gravity.
- From a cosmological model ($H_0, \Omega_m, \Omega_\Lambda$) and initial density fluctuations we can follow structure formation on the computer (without baryon physics).
- The density fluctuation can be measured from the Cosmic Microwave Background (CMB).

PLANK CMB temperature measurements





1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

DARK MATTER HALOS

- The N-body simulations create a density field of dark matter. However, we would like to connect the dark matter to galaxies (which are point like on large scales).
- This is done with the idea of dark matter halos (White & Reese 1978), basically we find density maximum and then go out to some density threshold and call this a halo.
- Galaxy formation then is mostly the attempt to connect these halos to galaxies.

DENISTY PROFILE

- Dark matter halos tend to have a universal profile (first noted by Navarro, Frenk & White et al. 1996) which goes as 1/r at small r.
- Further studies show some deviations from this, but always an every increasing density as r goes to 0.
- This universal profile has one parameter, a concentration that measures how dense the core of the halo is compared to the whole object.
- Concentration scales with mass such that lower mass halos are more concentrated.

OTHER PROPERTIES

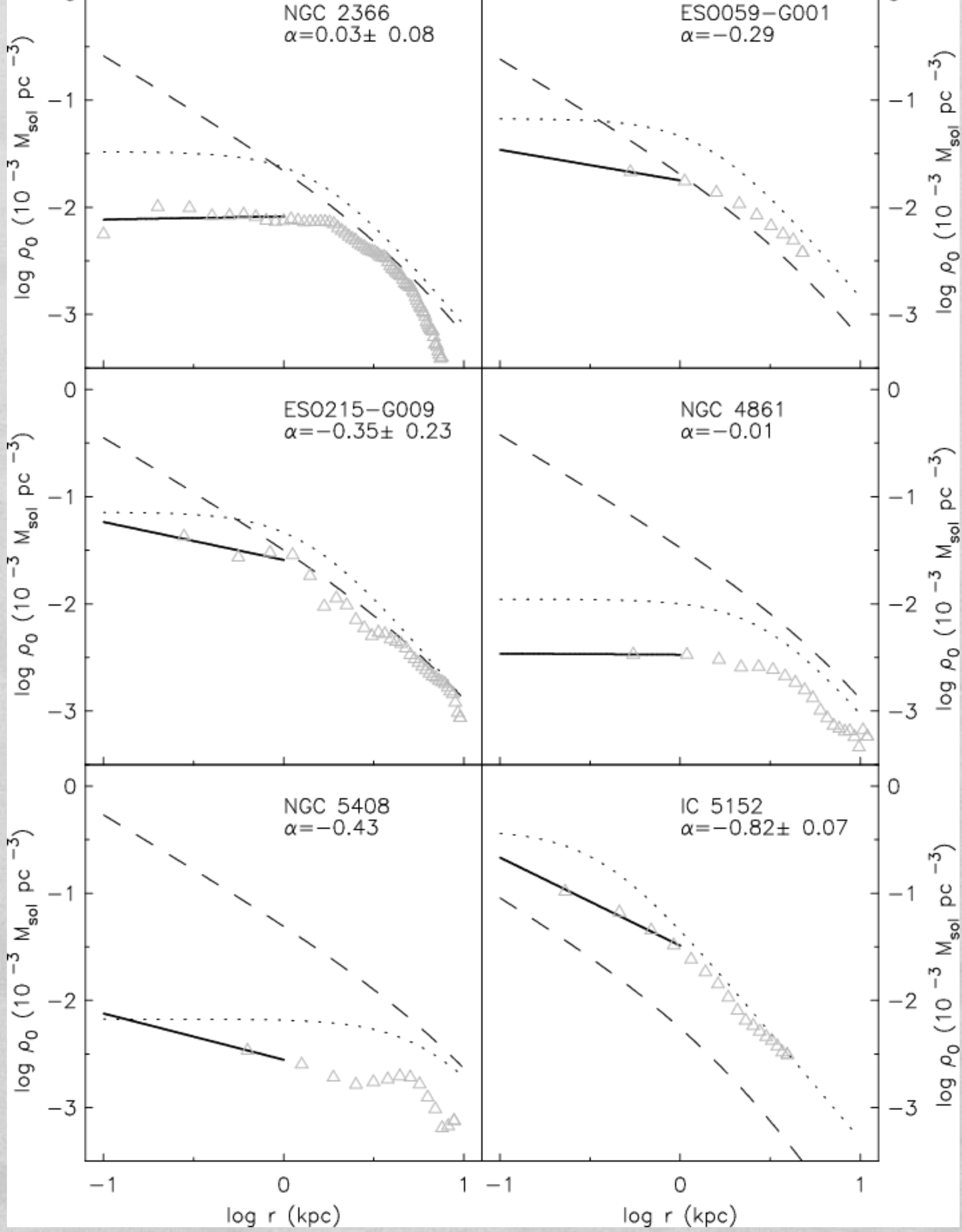
- It has also been noted that dark matter halo have a lognormal distribution of a dimensionless spin parameter, J/(MVR) with a mean of ~ 0.05, independent of mass and redshift.
- The mass growth rate of halos can be characterized by $M(z)=M_0e^{-az}$. Halos can be described by a formation time when some fraction of their mass was in place.
- There is a relationship between formation time and concentration such that halos that form earlier are more concentrated.

CHALLANGES TO CDM ON SMALL SCALES

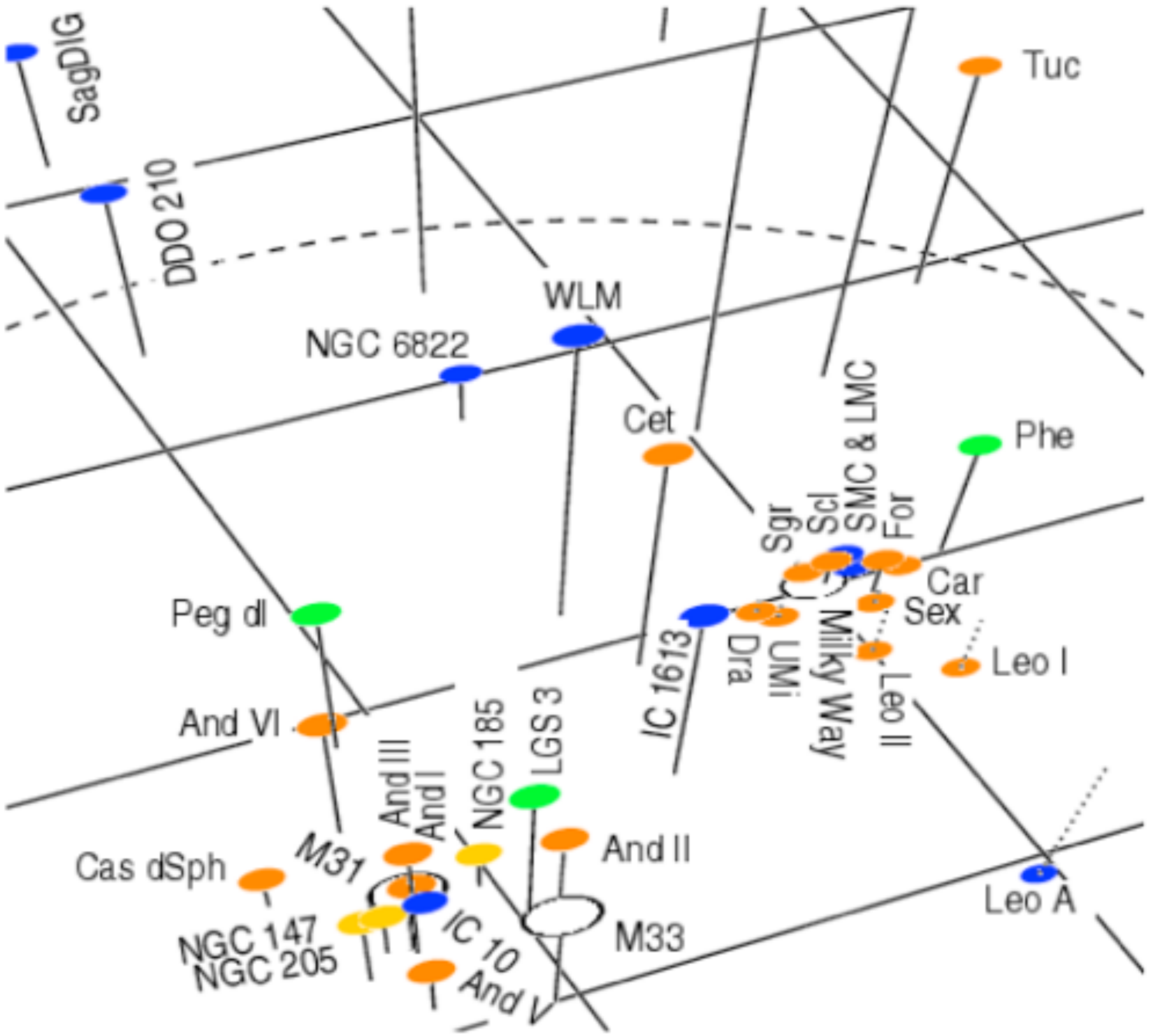
SMALL SCALE PROBLEMS

- While CDM works extremely well on large scales there are a number of small scale problems that may indicate new physics.
  - Cusp/Core problem - While all simulations give density profiles that go ~r^{-1} at small r, observations seem to indicate galaxies have cores (r^0).
  - Missing satellites - Simulations predict thousands of small subhalos in a Milky Way mass halo, but we only have dozens of satellites.
  - Too big to fail - The satellites we do have are not as dense as the densest in simulations, these are missing.

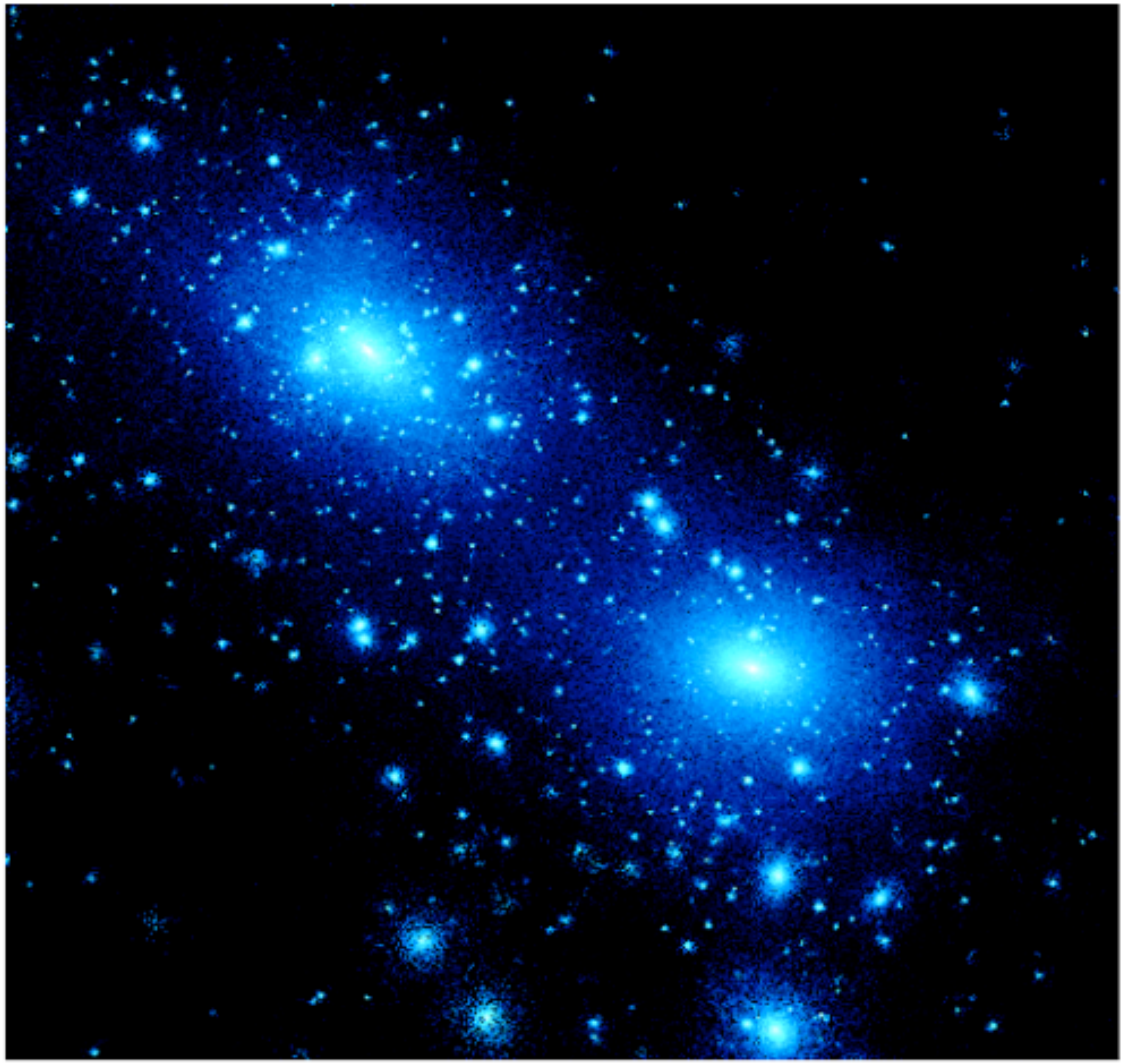
It is hard to disentangle the contribution of stars and dark matter to the mass of most galaxies. Dwarf galaxies have very few stars and thus can be dark matter dominated all the way to their cores. These galaxies to not seen to follow the 1/r profile found in simulations.



The Missing Satellites Problem



The Local Group

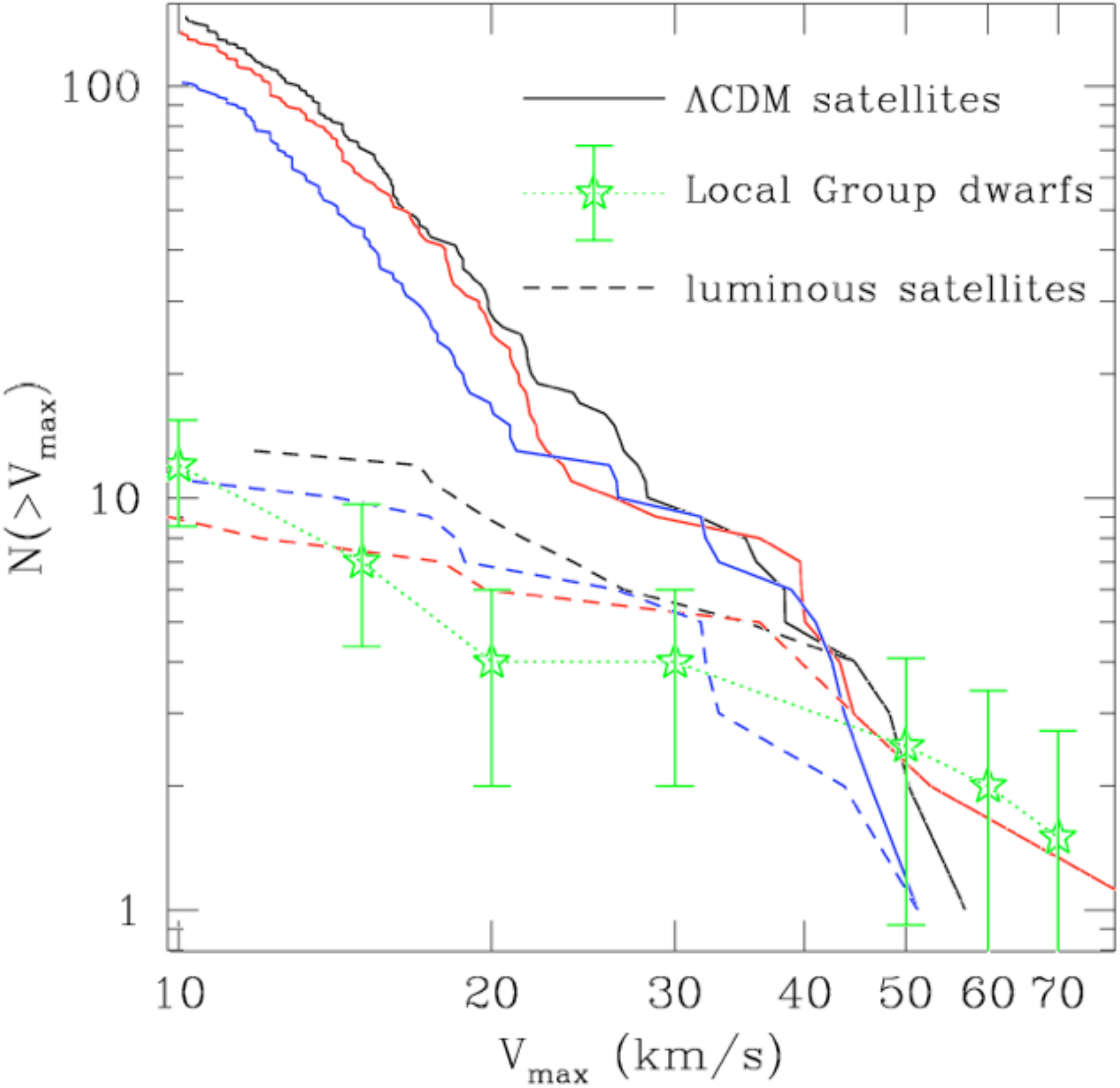


LCDM simulation

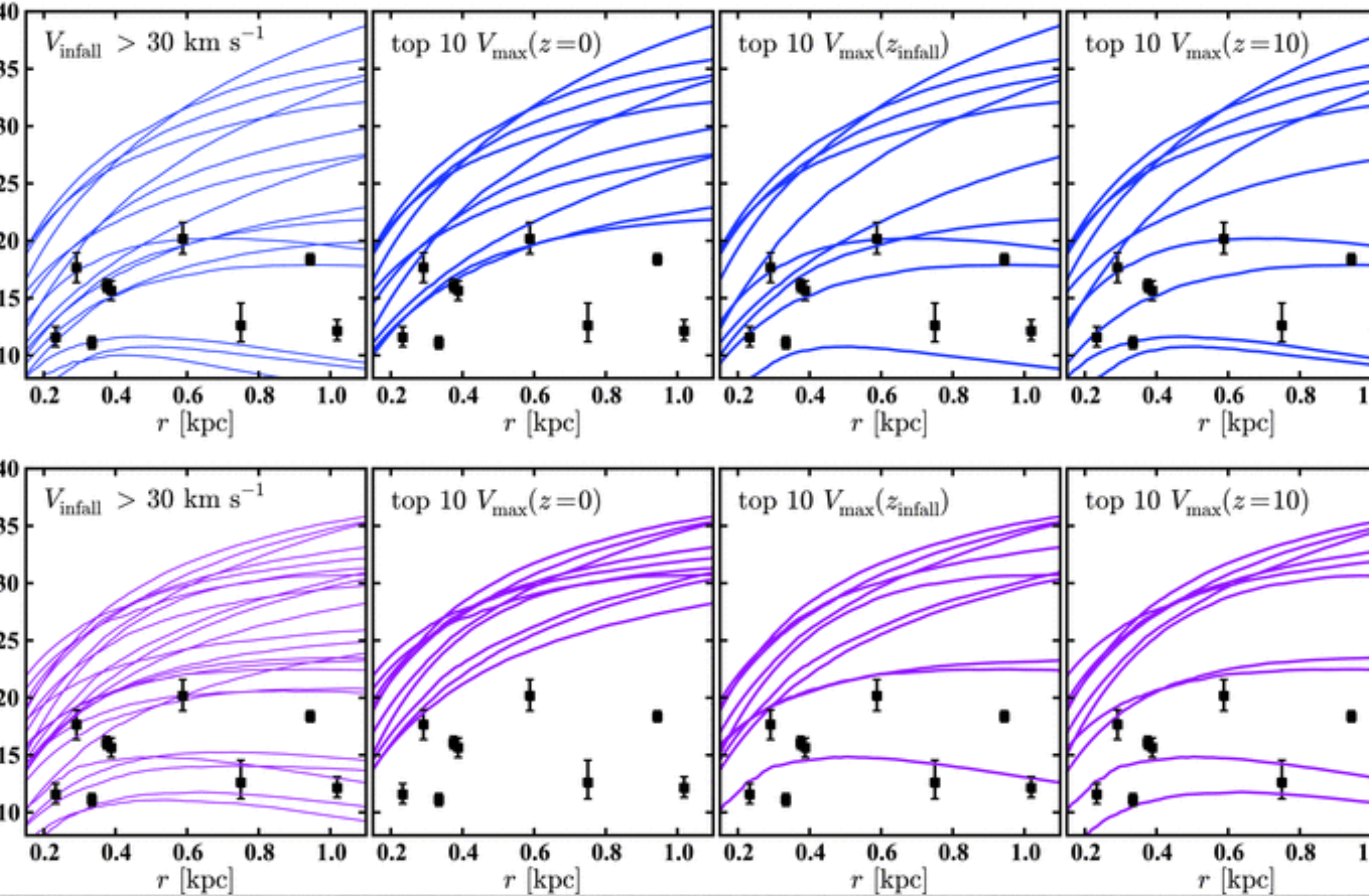
Kauffman, White & Guiderdoni 1993

Klypin, Kravtsov, Valenzuela & Prada 1999; Moore et al. 1999

Velocity function of luminous satellites



Observed MW dwarfs are less dense then simulations



SOLUTIONS

- It should be noted that at small scales ignoring baryons is probably a bad idea. There are ongoing (and largely successful) attempts to solve these problems with baryon physics.

- Alternatives are:
  - Warm DM - adding some warm dark matter will wash out small scale structure possibly creating cores and erasing subhalos.
  - Self Interacting DM - adding a force between dark matter particles can create cores and destroy subhalos.
  - Fuzzy DM - dark matter are bosons with deBroglie wavelengths of around few kpc creating cores.

PROBLEMS

- Suppose the dark matter is $10^{-8}\ M_\odot$ black holes, how far would you expect the nearest black hole to be? Assume dark matter is 10x the mass of the Milky Way, but also extends to 100kpc. How frequently would you expect a black hole to pass with in 1AU of the Sun?
- What angle is a light ray that just grazes the Earth deflected by ($M=5.98\times10^{24}$ kg, $R=6400$ km)? How about a white dwarf ($M=2.0\times10^{30}$ kg, $R=1.5\times10^{7}$ m)? a neutron star ($M=3.0\times10^{30}$ kg, $R=1.2\times10^{4}$ m)?

$$\alpha = \frac{4GM}{c^2 b}$$