Dark Matter

ASTR 333/433
Fall 2021
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

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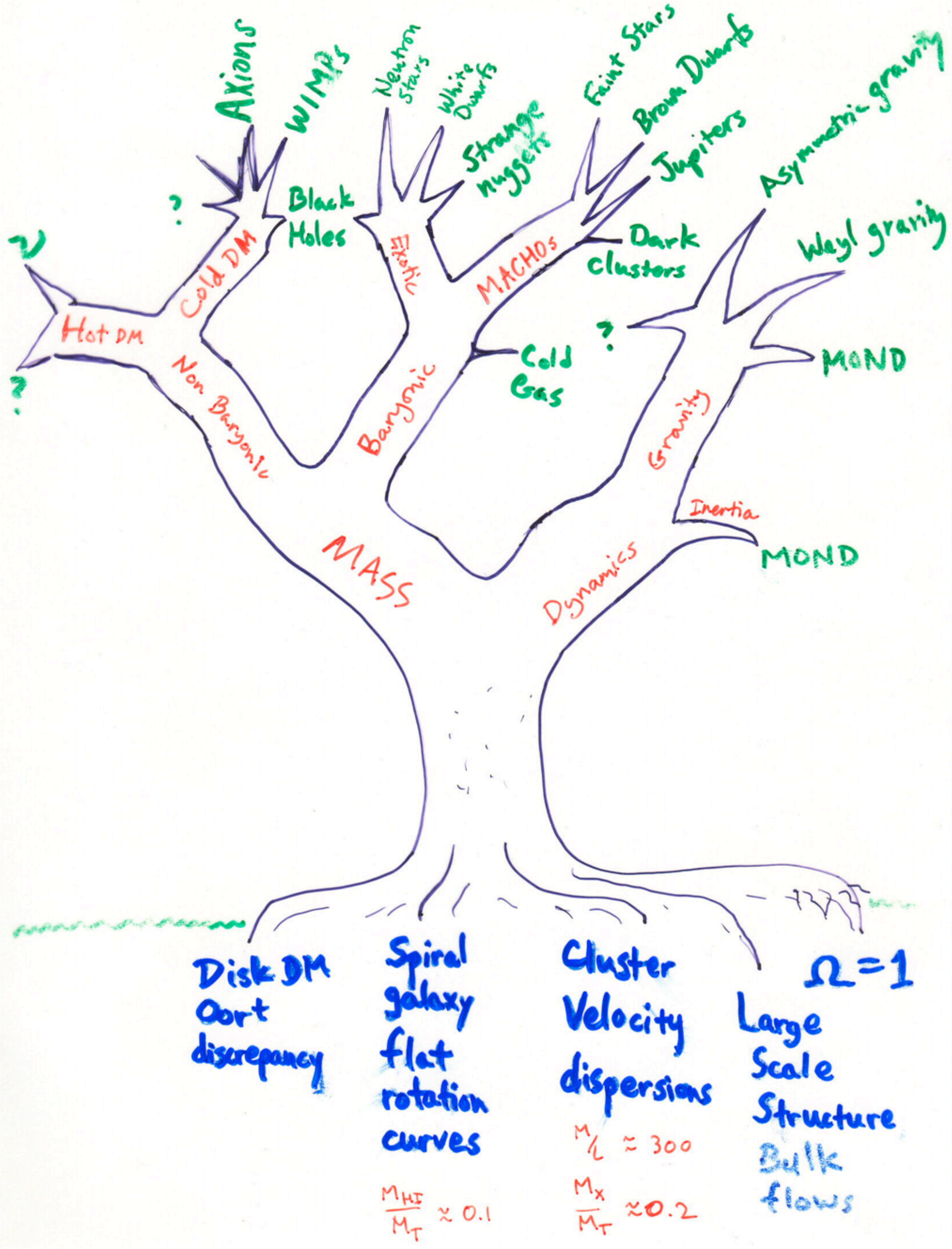

http://astroweb.case.edu/ssm/ASTR333/

This is the primary website for the course (not Canvas)
look here for homework assignments, etc.

DARK MATTER

ASTR 333
ASTR 433

Fall 2021
MW 3:20-4:35PM
Sears 552

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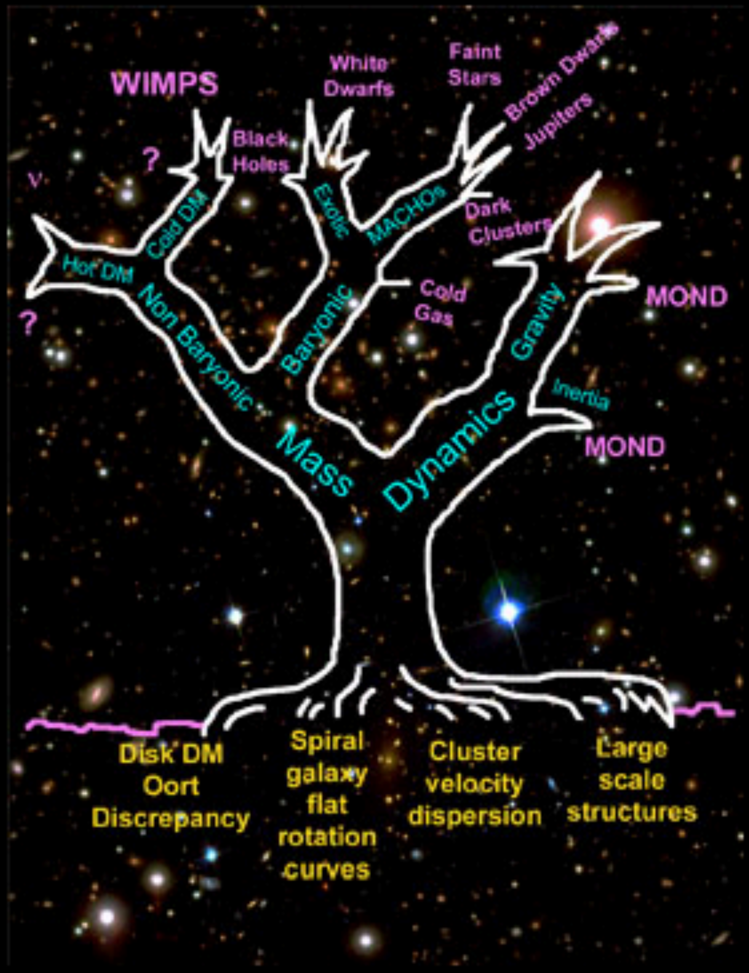
Office Hours
T 3-4PM
F 2-3PM



?

Textbooks
There are no textbooks.
There are many *related* texts.
(none are required)

Galaxies in the Universe
Sparke & Gallagher

Galactic Dynamics
Binney & Tremaine
B&T errata

Galactic Astronomy
Binney & Merrifield
B&M errata

Introduction to Cosmology
Ryden

This course will address

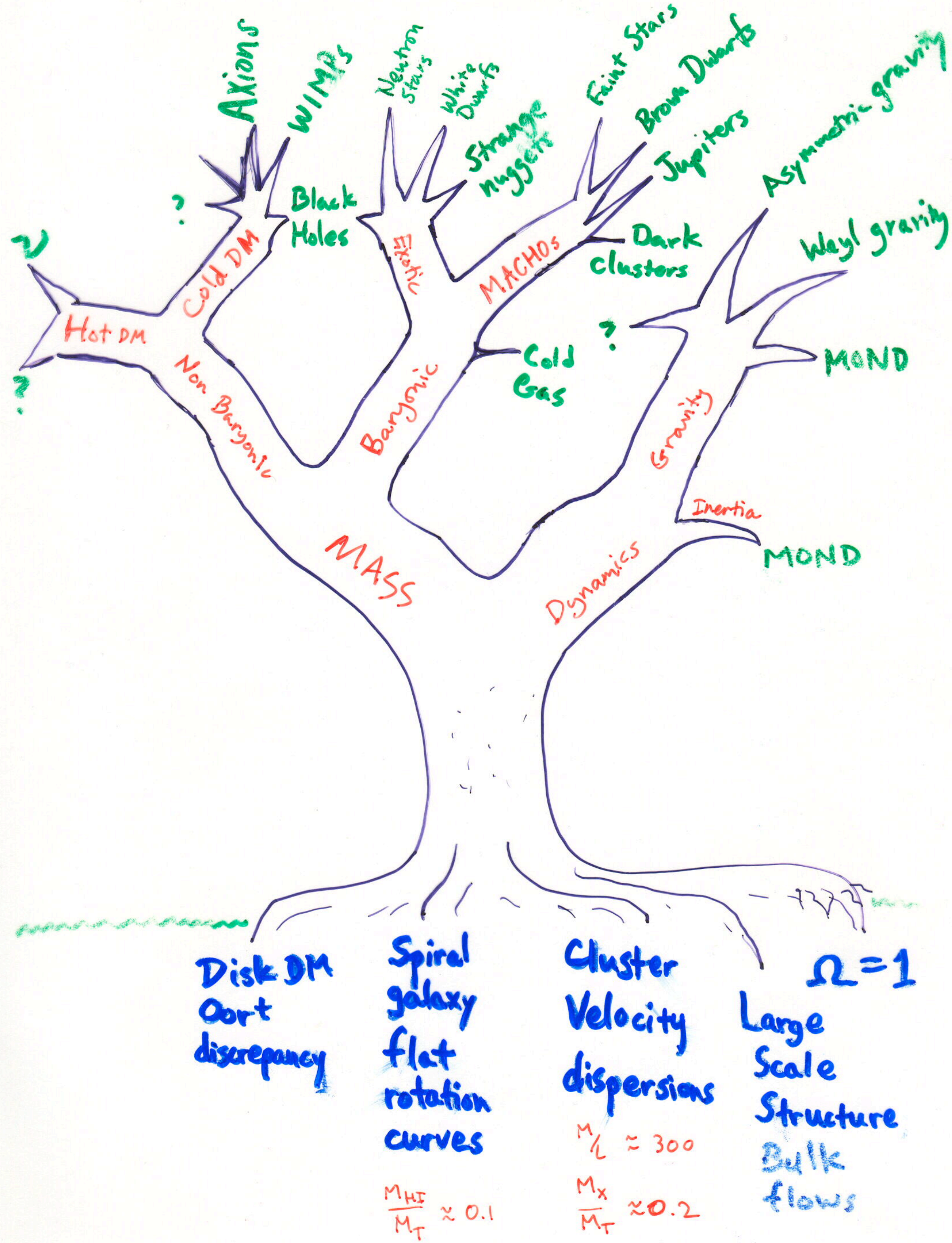
Some Great Questions

of modern physics & astronomy:

What is the missing mass problem?
What is the dark matter?
Is it necessary to modify the law of gravity?

a multiplicity of answers have been hypothesized, of which at most one can be essentially correct.

First we will cover the empirical evidence that indicates the existence of mass discrepancies



Axions
WIMPs
Neutron Stars
White Dwarfs
Faint Stars
Brown Dwarfs
Asymmetric gravity
Strange nuggets
Jupiters
Black Holes
Dark clusters
Weyl gravity
Cold DM
Exotic
MACHOs
Hot DM
Cold Gas
MOND
Non Baryonic
Baryonic
Gravity
Inertia
MOND
MASS
Dynamics
Disk DM
Oort discrepancy
Spiral galaxy flat rotation curves
$M_{HI}/M_T \approx 0.1$
Cluster Velocity dispersions
$M/L \approx 300$
$M_X/M_T \approx 0.2$
$\Omega = 1$
Large Scale Structure
Bulk flows

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 | Volume VI. | No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

Notations.

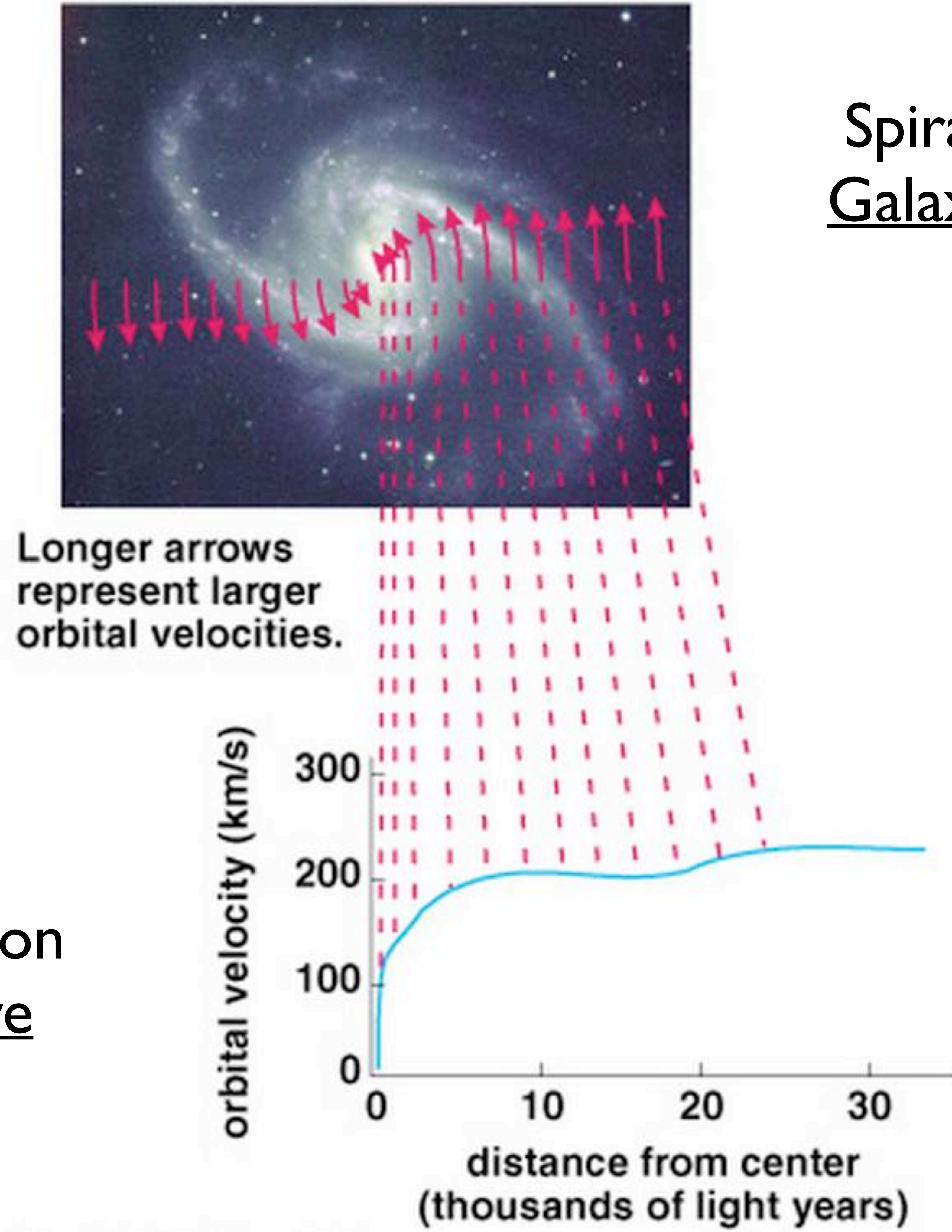
- z distance from the galactic plane,
- Z velocity component perpendicular to the galactic plane,
- Z_0 the value of Z for $z = 0$,
- l modulus of a Gaussian component of the distribution of Z (formula (5), p. 253),
- $K(z)$ the acceleration in the direction of z,
- Δ the star-density,
- ρ the distance of a star from the sun,
- $\Phi(M)$ the number of stars per cubic parsec between $M - \frac{1}{2}$ and $M + \frac{1}{2}$,
- $A(m)$ the number of stars per square degree between $m - \frac{1}{2}$ and $m + \frac{1}{2}$,
- b galactic latitude,
- ϖ distance to the axis of rotation of the galactic system,
- δ $\partial \log \Delta / \partial \varpi$.

Summary of the different sections.

4. From VAN RHIJN's tables in *Groningen Publication* No. 38 the density distribution $\Delta(z)$ has been computed for four intervals of visual absolute magnitude (Table 13 and Figure 1). Figures 2 and 3 show $\log \Delta(z)$ for A stars and yellow giants, as derived by LINDBLAD and PETERSSON.

5. With the aid of the data contained in the two preceding sections I have computed the acceleration $K(z)$ between $z = 0$ and $z = 600$. The computations were made by successive approximations; the B stars were eliminated first. The results are in Table 14 and Figure 4, $K'(z)$ giving the values finally adopted. The good agreement between the practically independent values of $K(z)$ derived from the separate absolute magnitude groups is a strong argument in favour of the approximate correctness of the data up to $z = 400$. The result may be summarized by stating that the absolute value of $K(z)$ increases proportionally with z from $z = 0$ to $z = 200$; between $z = 200$ and $z = 500$ it remains practically constant and equal to $3{\cdot}8.10^{-9}$ cm/sec².

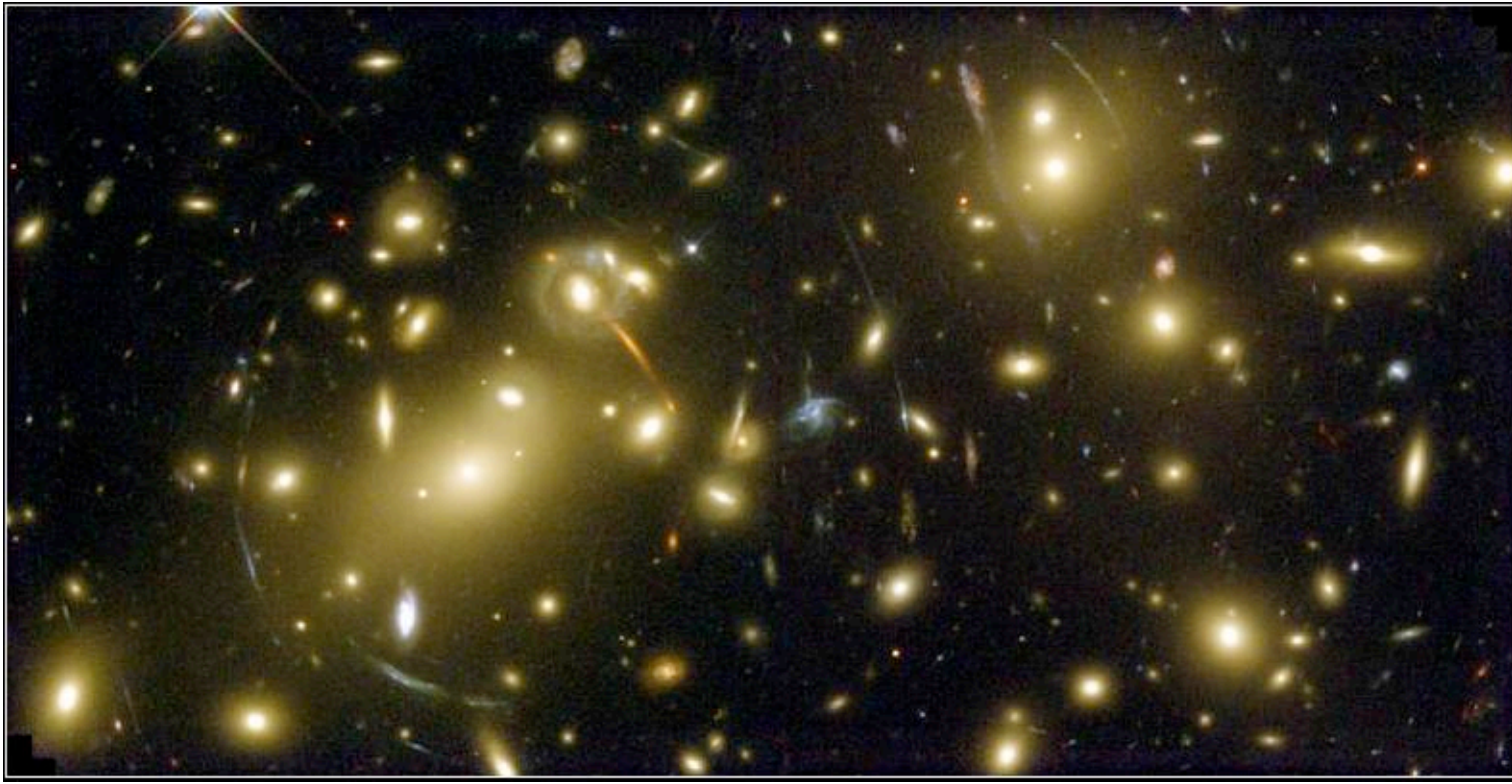
Spiral Galaxy



Rotation Curve

Galaxy Cluster

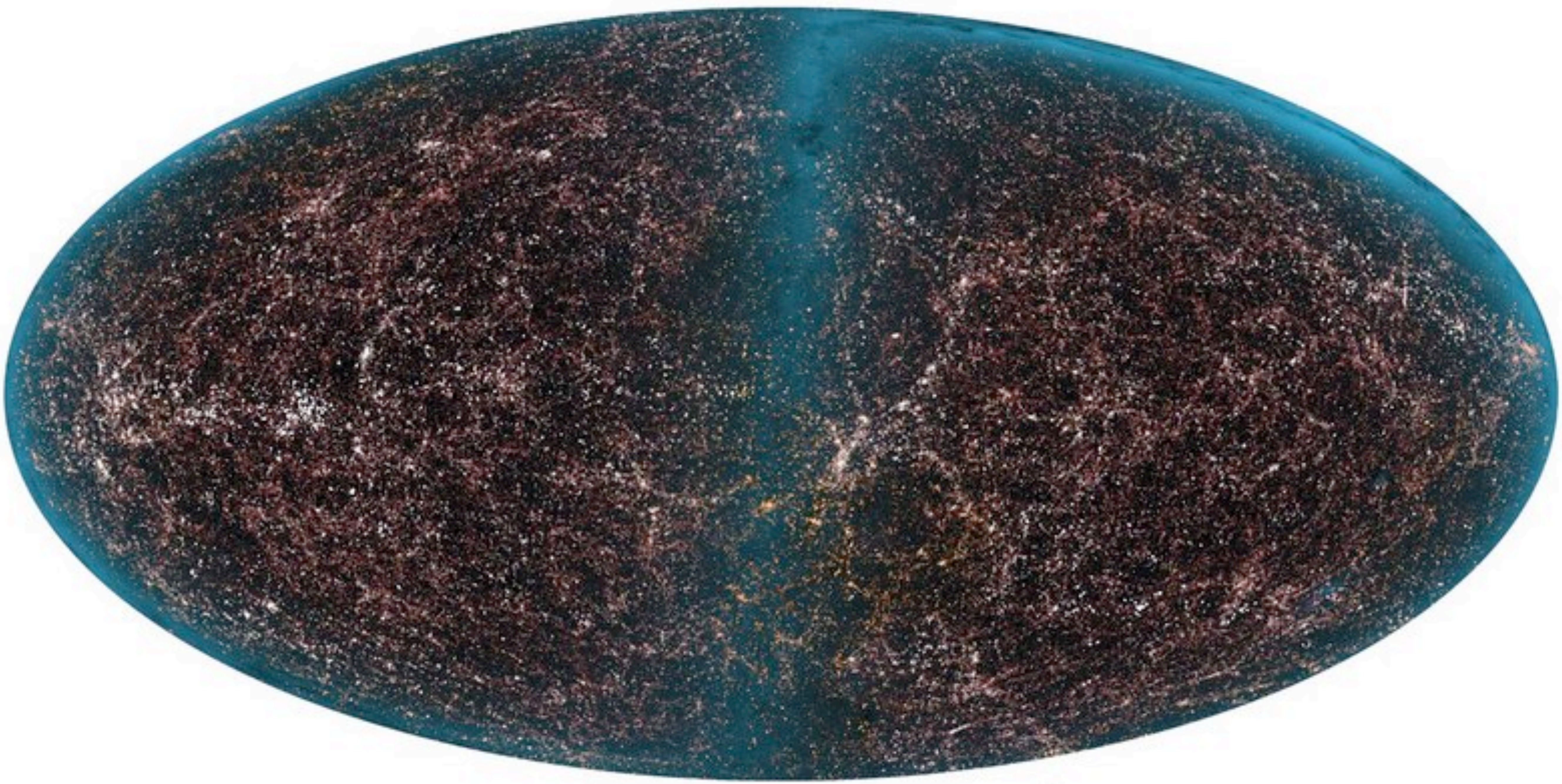
Zwicky 1933, 1937



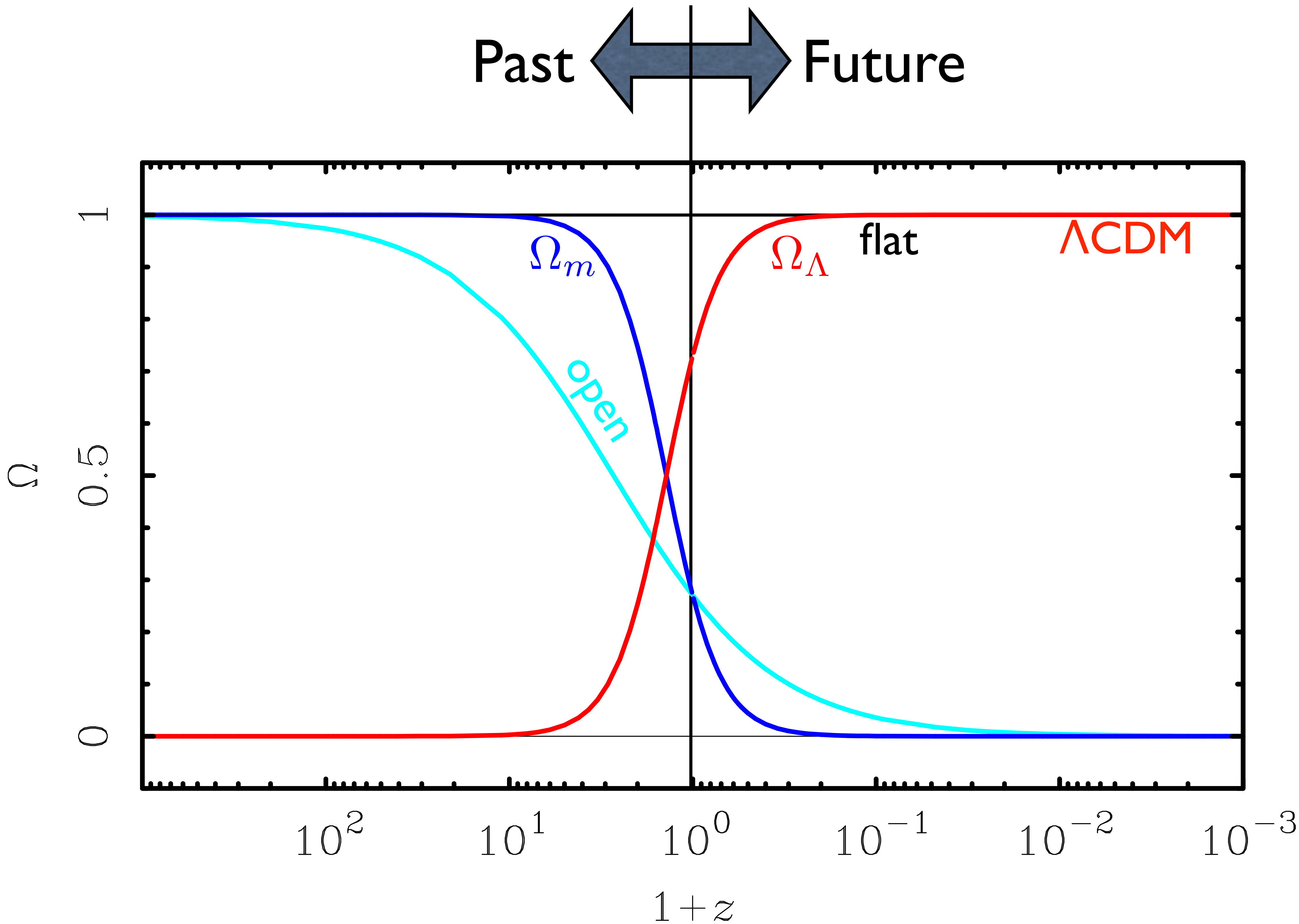
3 distinct measures: velocity dispersion, gravitational lensing, and hydrostatic equilibrium of X-ray gas

Large Scale Structure

Each dot is an entire galaxy



Need something to prompt structure formation - gravity + visible matter don’t suffice



Coincidence/flatness problem:
why is the density parameter of order unity?

Pruning the tree

Baryonic Dark Matter

Many candidates:
- brown dwarfs
- Jupiters
- very faint stars
- very cold molecular gas
- warm (~10^5 K) ionized gas

Can usually figure out a way to detect them: most have been ruled out.

Pruning the tree

Hot Dark Matter (HDM)

Obvious candidate:
neutrinos

neutrinos got mass!...
...but not enough.

Also
- neutrinos suppress structure formation
- can't crowd together closely enough
(phase space constraint)

Pruning the tree

Cold Dark Matter (CDM)

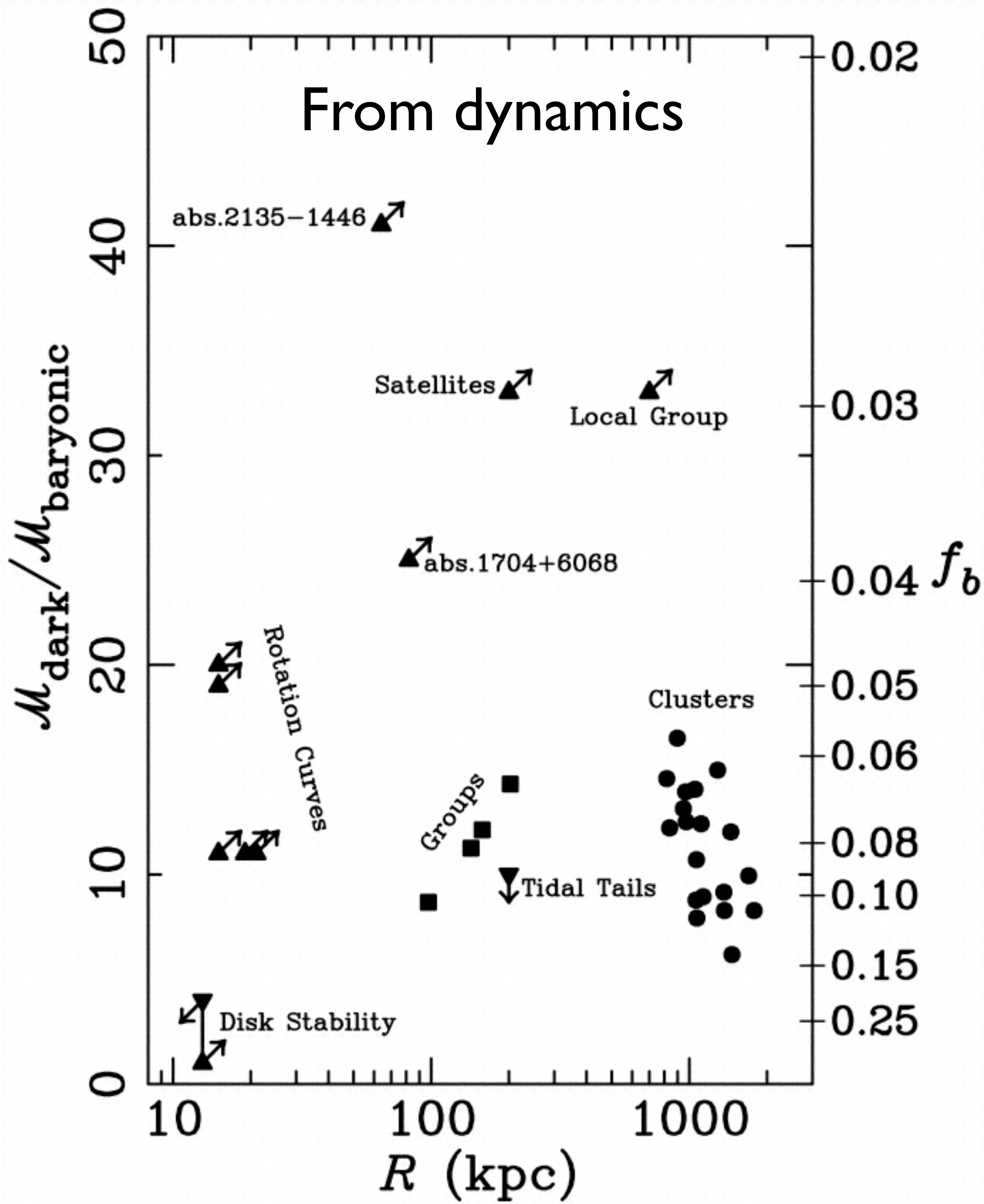
Some new particle, usually assumed to be
WIMPs (Weakly Interacting Massive Particle)
don’t interact electromagnetically, so very dark.

Two big motivations:

1) total mass outweighs normal mass from BBN

2) needed to grow cosmic structure

(1) There's more dark mass than baryons.



From cosmology

$$\Omega_m \approx 6\Omega_b$$

or equivalently, the baryon fraction

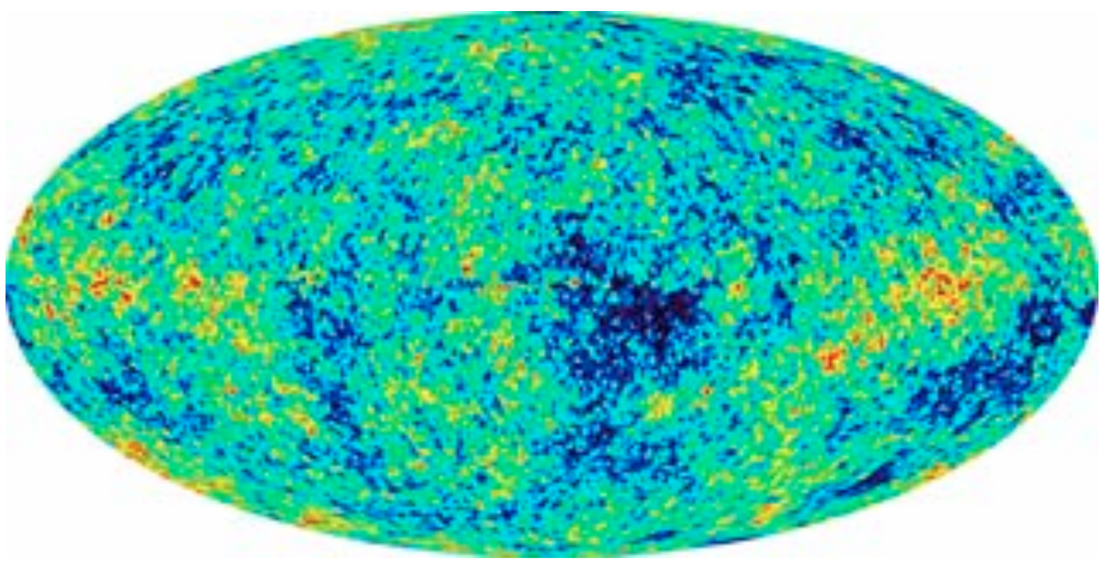
$$f_b = 0.17$$

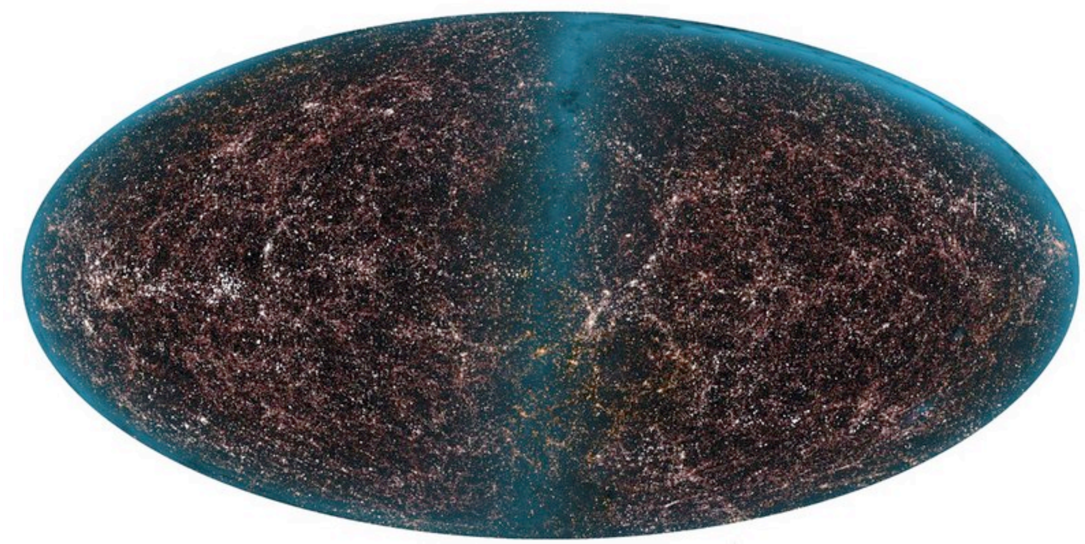
The gravitating mass density exceeds the baryon density from Big Bang Nucleosynthesis (BBN)

(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr

$t = 1.4 \times 10^{10}$ yr





very smooth: $\delta\rho/\rho \sim 10^{-5}$

very lumpy: $\delta\rho/\rho \sim 1$

$$\delta\rho/\rho \propto t^{2/3}$$

These considerations made CDM the dominant paradgim

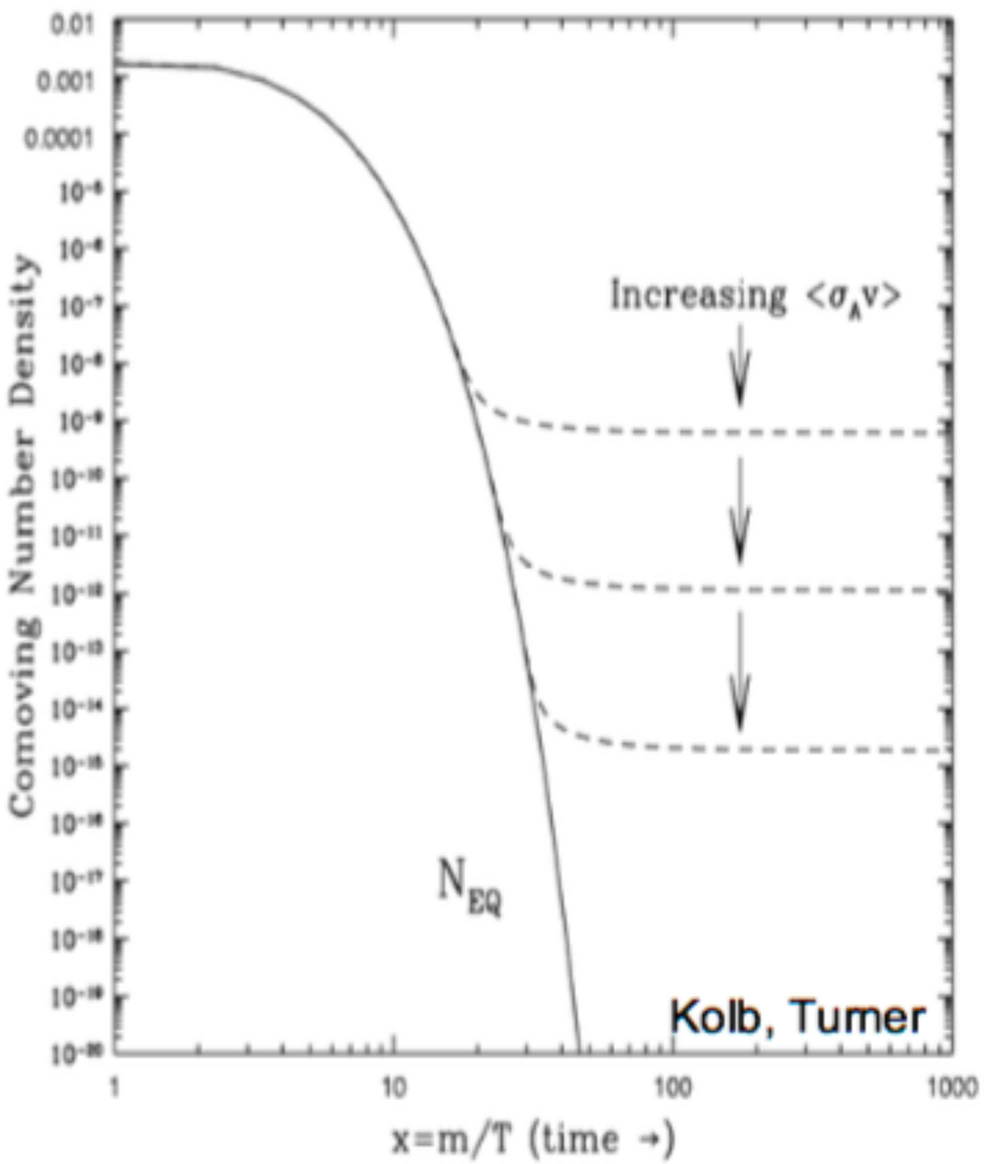
Only requirement to be CDM is

- dynamically cold (slow moving)
- non-baryonic (no E&M interactions)

could be
WIMPS
(or some other particle)
or
Black Holes
(masses of ~ 10^5 $M_\odot$ conceivable)

WIMPs are considered the odds-on favorite CDM candidate because of the so-called `WIMP miracle': the relic density of a new weakly interacting particle is about right to explain the mass density.

THE WIMP MIRACLE

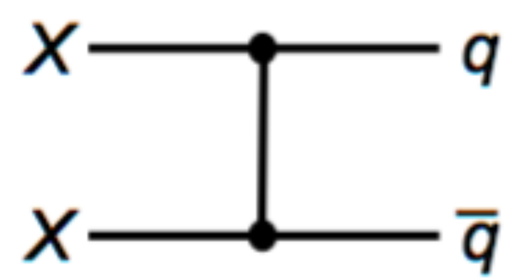


In the very early universe

- Assume a new (heavy) particle *X* is initially in thermal equilibrium

- Its relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

Lots of particle candidates for CDM:

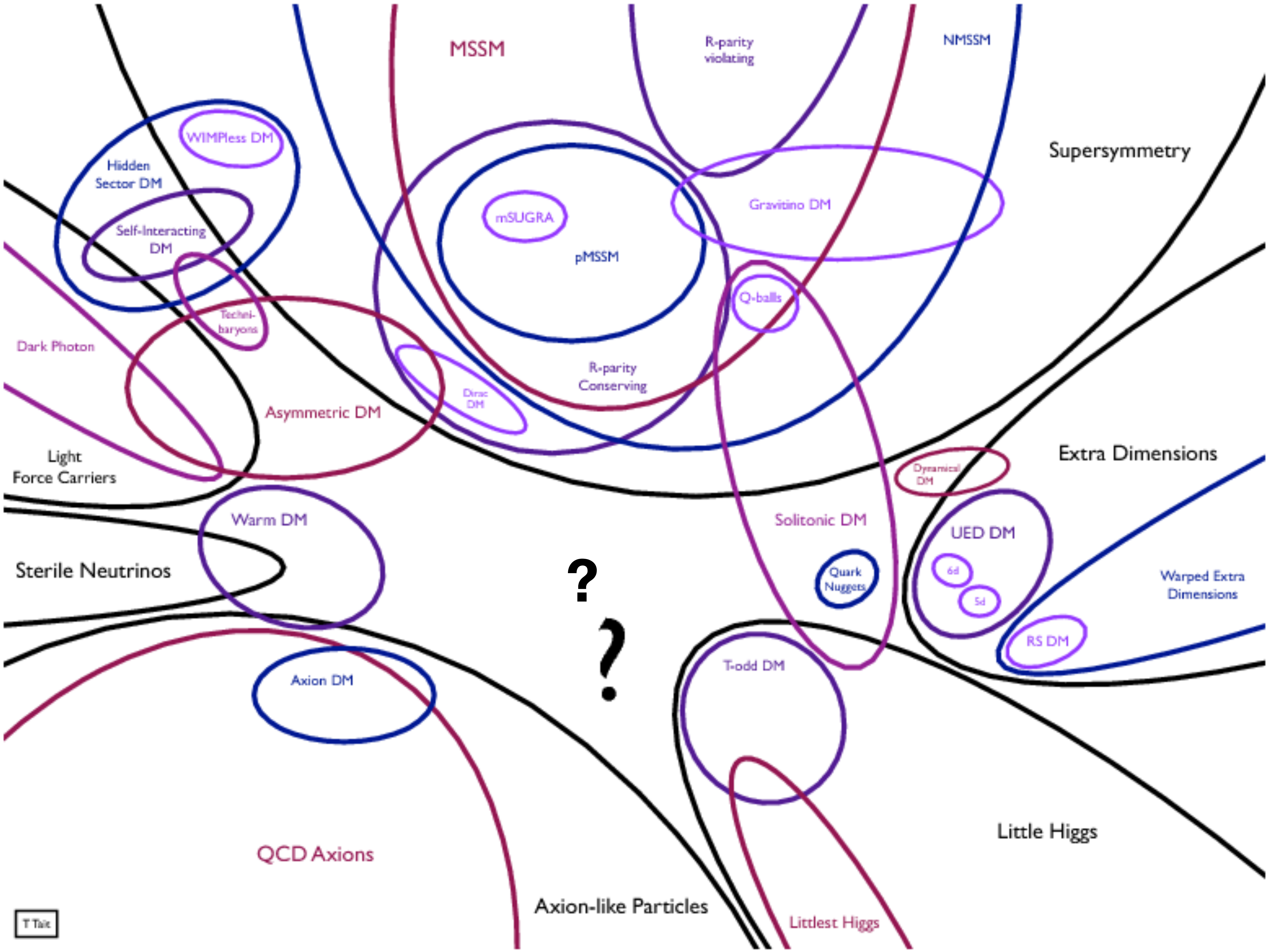
WIMPs
Axions
Light dark matter
wimpzillas
etc.

Can imagine other candidates as well:

Warm DM
Self-interacting DM
etc.

All of these ideas require a new "dark sector" beyond the known physics of the Standard Model. Some require complex dark sectors, with new forces as well as new particles (i.e., new forces of nature that only interact in the dark sector, e.g., dark E&M mediated by dark photons.)

Indeed, the list of candidates continues to grow



“Graphical representation of the (incomplete) landscape of candidates.” (arXiv:1310.8642)

Two big motivations for CDM:

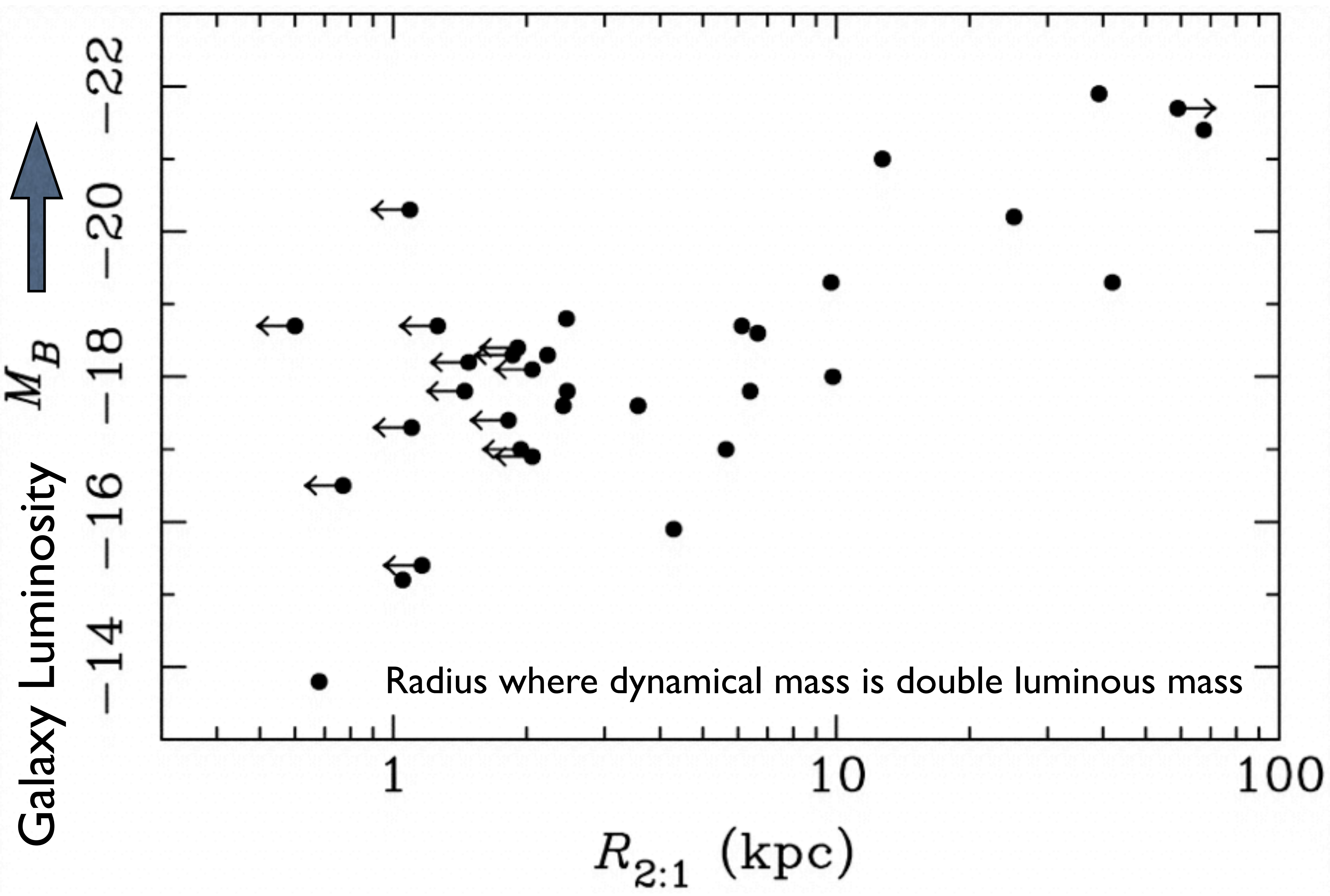
1) total mass outweighs normal mass from BBN

2) needed to grow cosmic structure

Both (1) and (2) hold only when gravity is normal.

Leaves room to consider modifications of dynamical laws (e.g., gravity or inertia) as alternatives to dark matter.

Can exclude length-scale based modifications



Modified dynamical theories

MOND (Modified Newtonian Dynamics) [Milgrom]

can be interpreted as either a modification of gravity or of inertia

modification at a critical acceleration scale

$a_0 \sim 10^{-10}$ m/s/s

MOND has had a surprising amount of predictive success, but there is no clear relativistic extension as yet

Others?

It is not easy to build a theory that is consistent with all known facts. It is also not easy to explain the predictive successes of MOND in terms of dark matter.

An Ancient and Intractable Problem

- The missing mass problem has been with us since at least the work of Oort and Zwicky in the 1930s
- The issue took off in the 1970s; considerable effort has been lavished on it since then
- Despite decades of experimental searches, no clear detections of dark matter have been obtained to date.