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

DARK MATTER

ASTR 333
ASTR 433

Spring 2020
TR 11:30AM-12:45PM
Sears 552

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Sears 558
368-1808

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

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Relevant textbooks

Galaxies in the Universe
Sparke & Gallagher

Galactic Dynamics
Binney & Tremaine
B&T errata

Galactic Astronomy
Binney & Merrifield
B&M errata

Cosmological Physics
Peacock

Principles of Physical Cosmology
Peebles

Galaxy Formation & Evolution
Mo, van den Bosch & White
rogue internet version

Introduction To Particle Dark Matter
S. Profumo
related arxiv paper

The Dark Matter Problem
R.H. Sanders

(on reserve)

This course will address

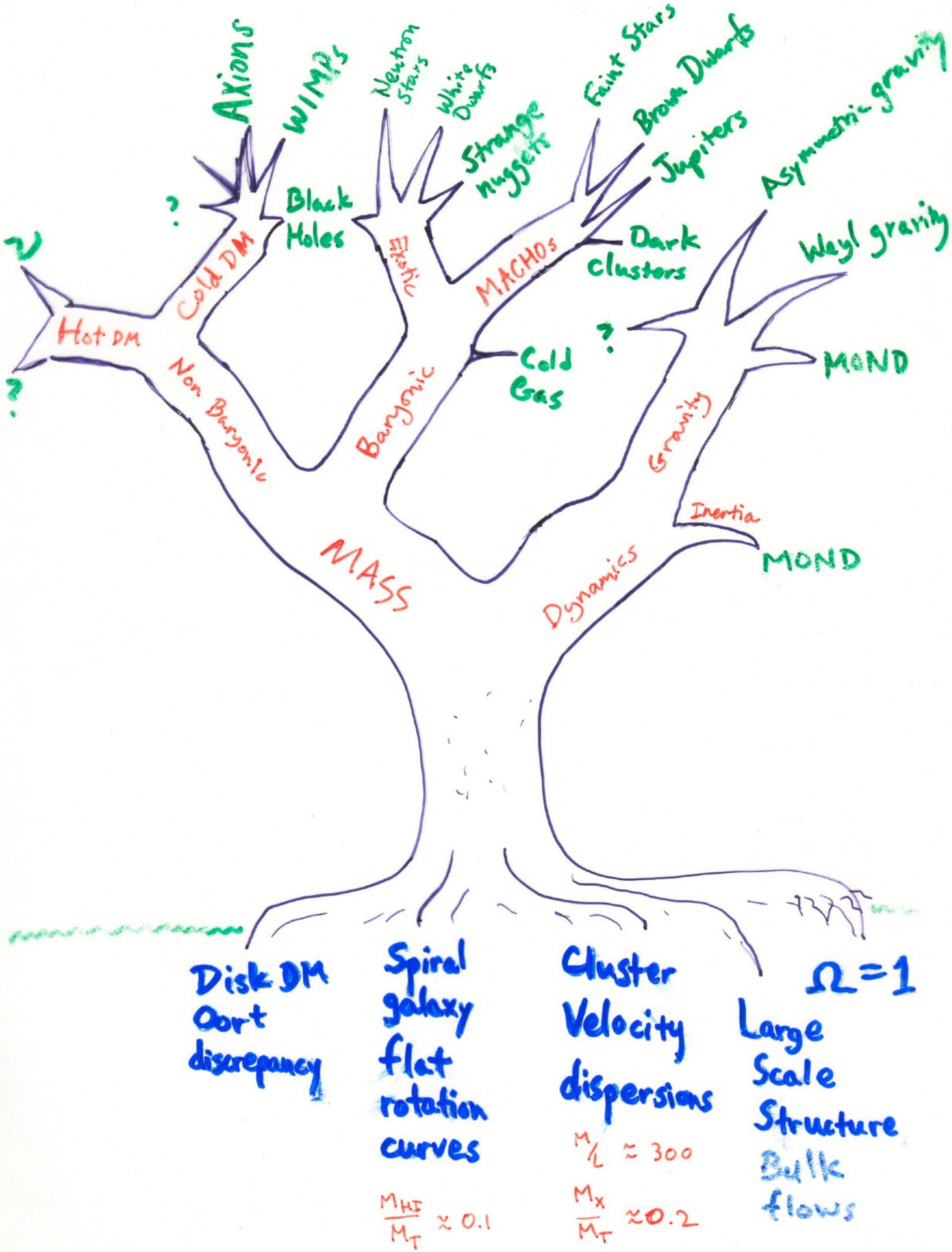
Some Great Questions

of modern physics & astronomy:

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

and offer a multiplicity of answers,
of which at most one can be 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
Cold DM
Exotic
MACHOs
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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.*

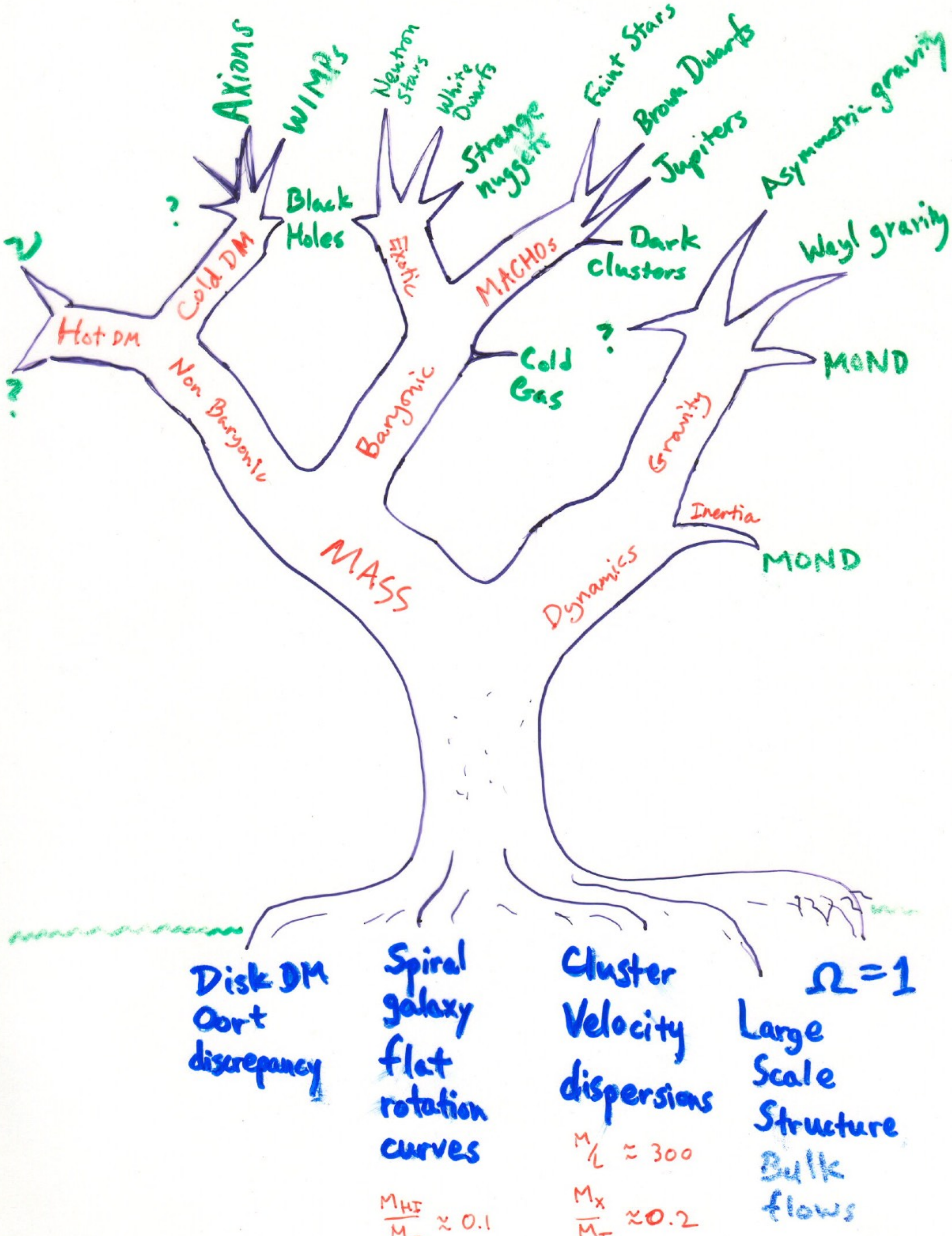
Notations.

- z distance from the galactic plane,
- Z velocity component perpendicular to the galactic plane,
- Z_o 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/sec^2.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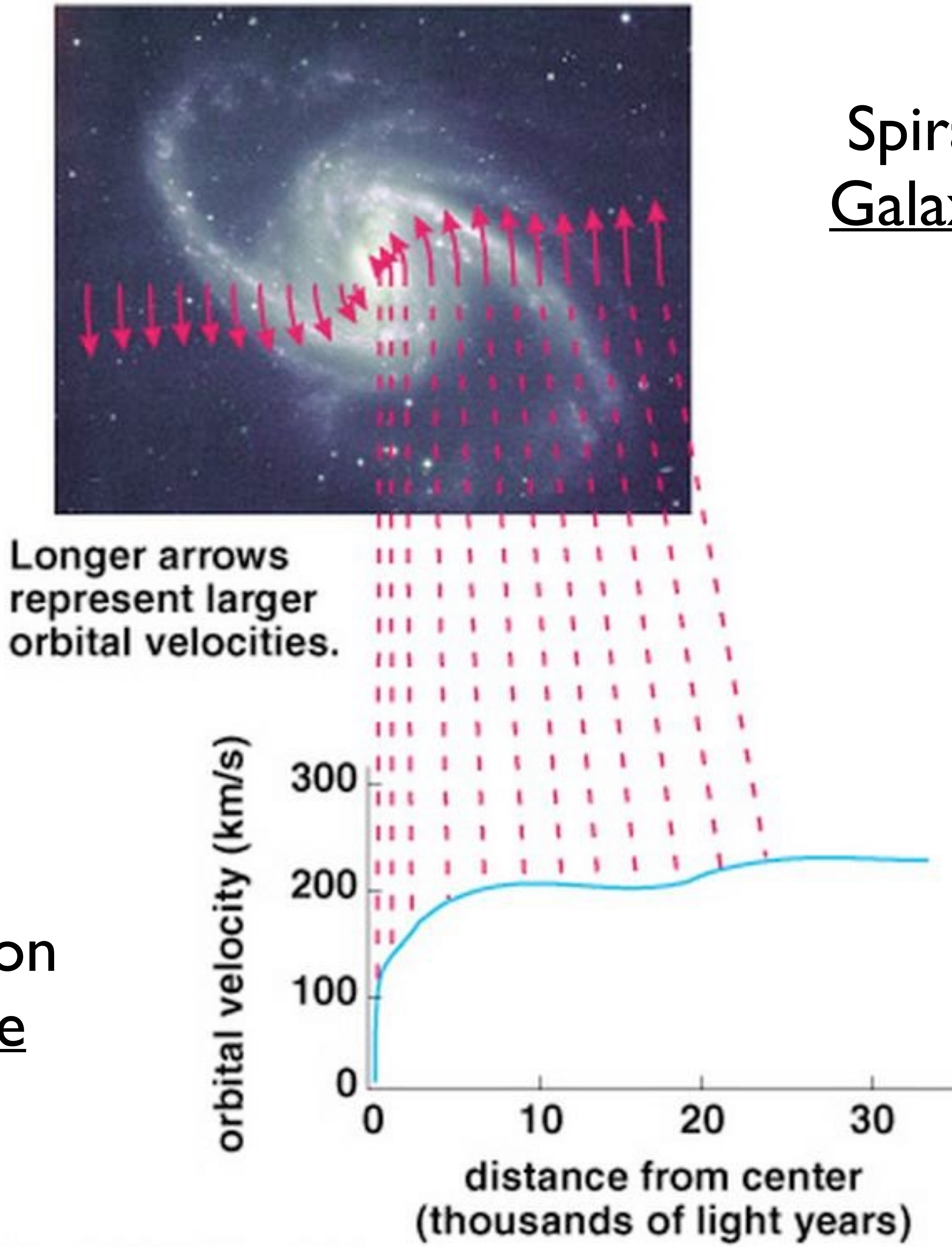
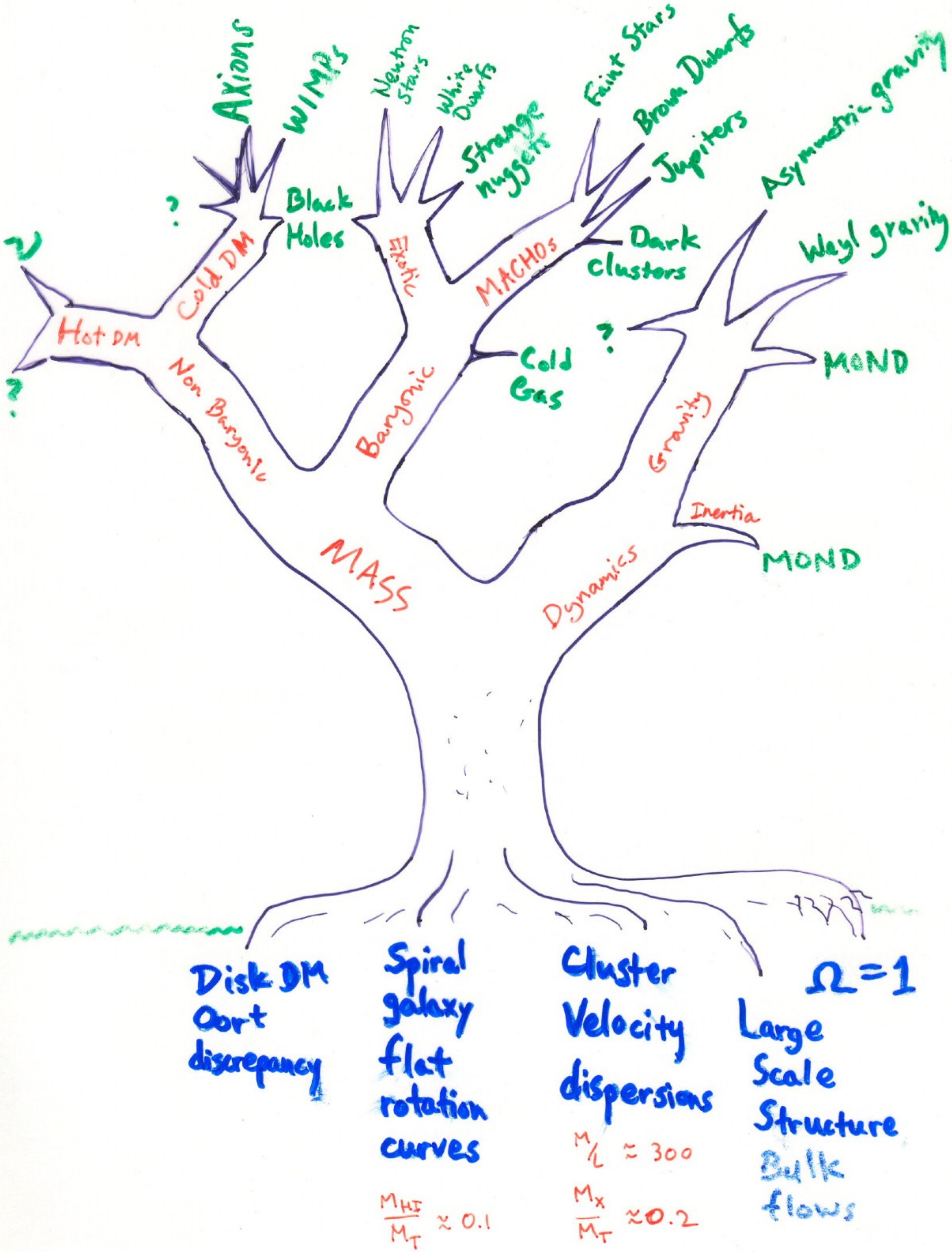
Spiral <u>Galaxy</u>



Rotation <u>Curve</u>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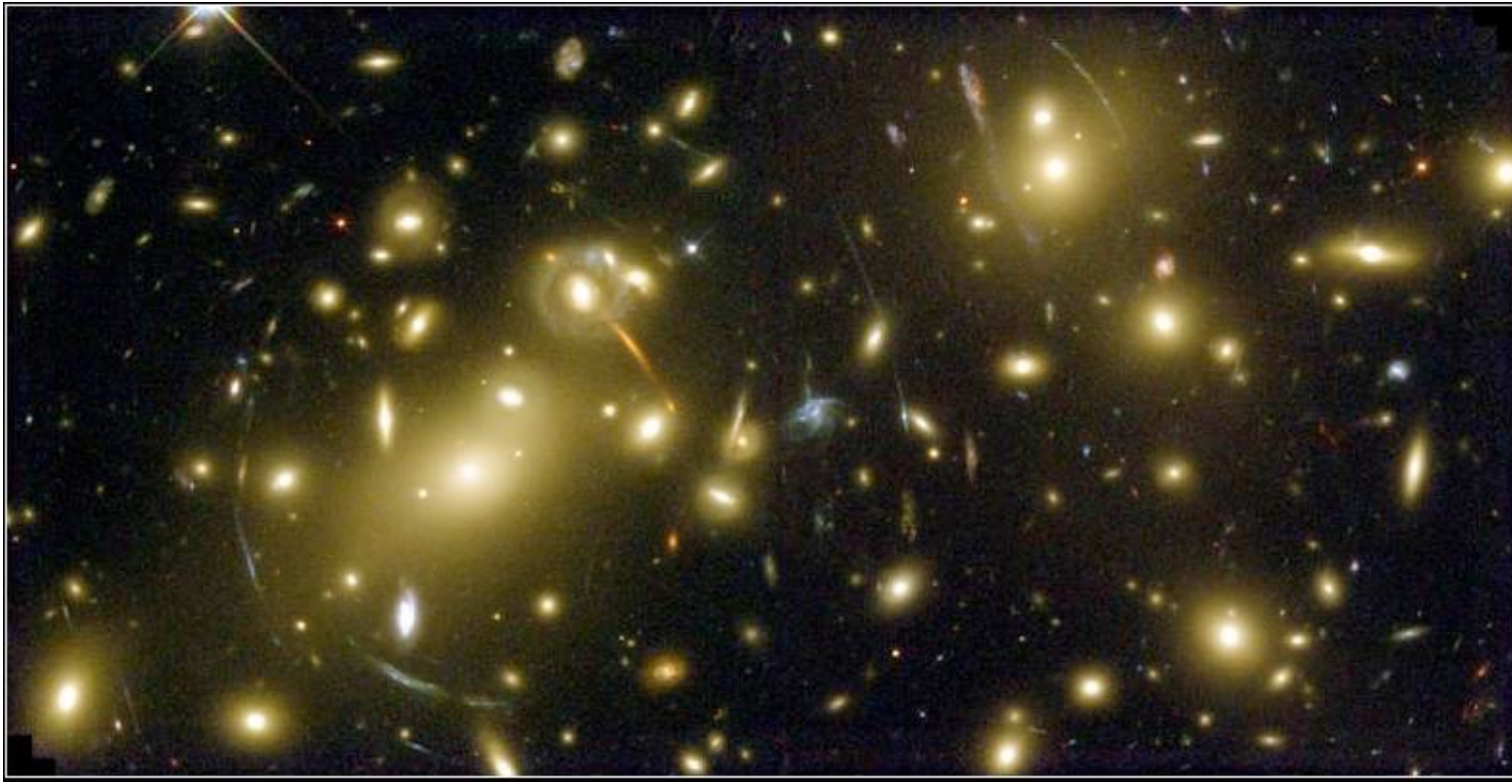
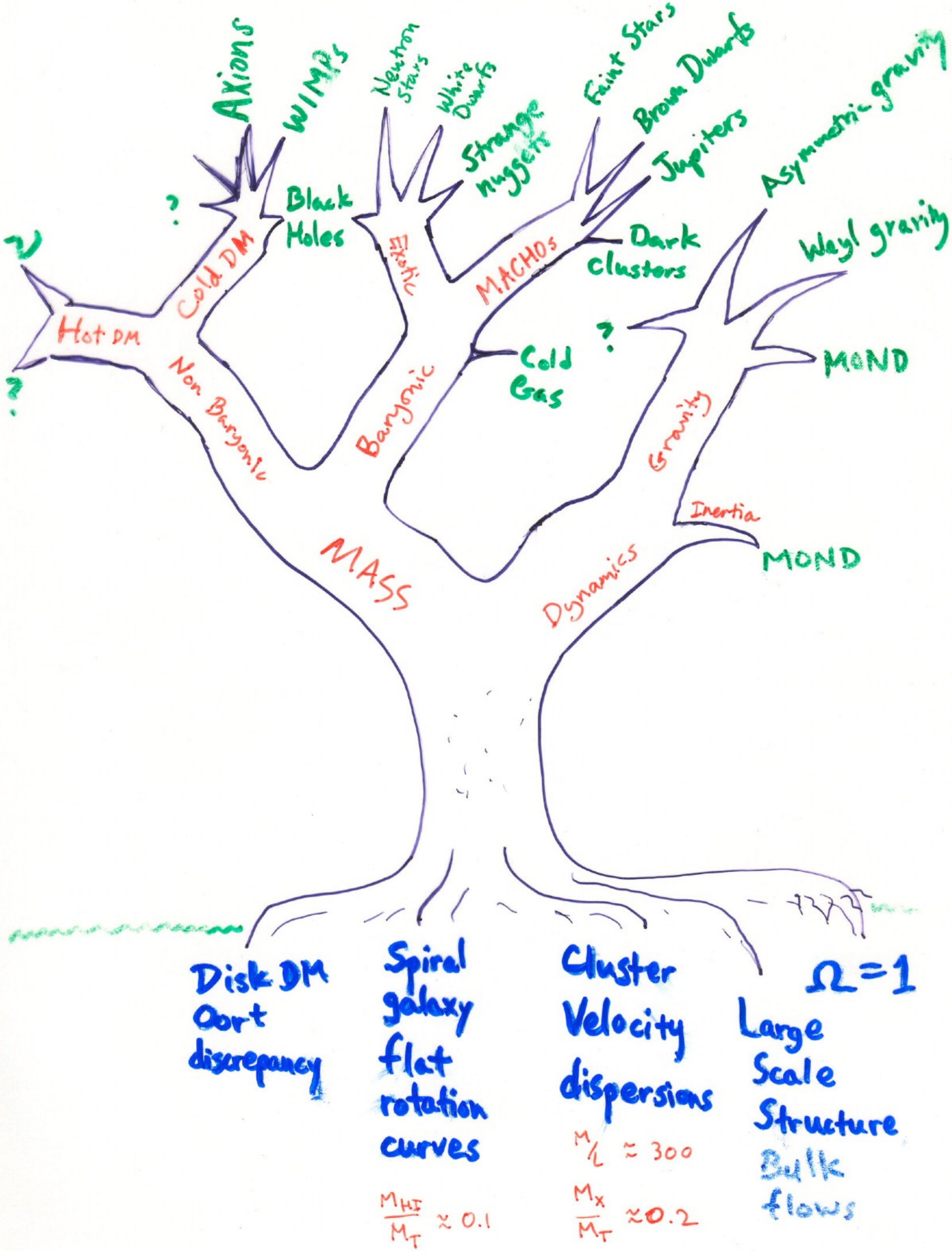
Galaxy Cluster

Zwicky 1933, 1937



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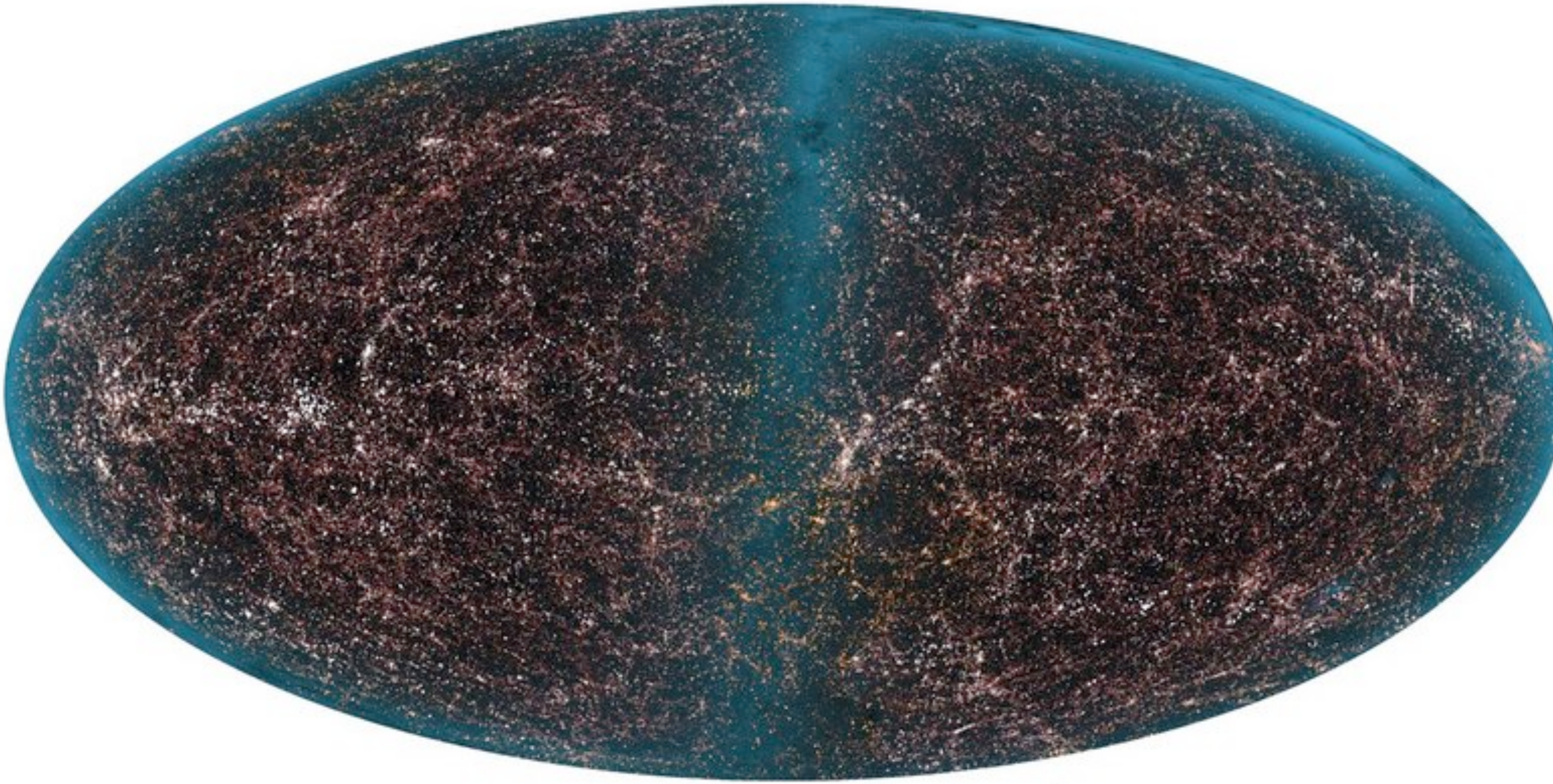

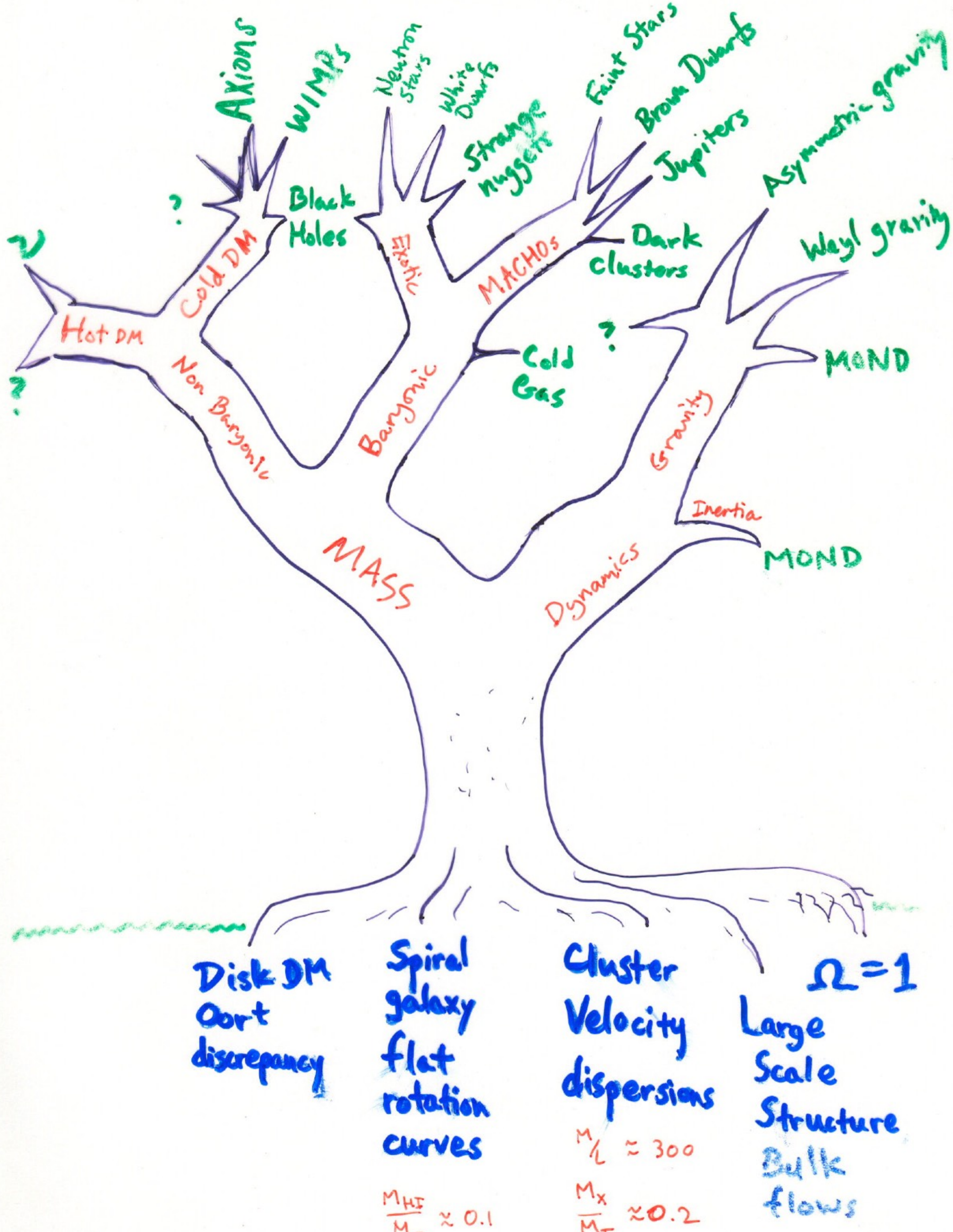

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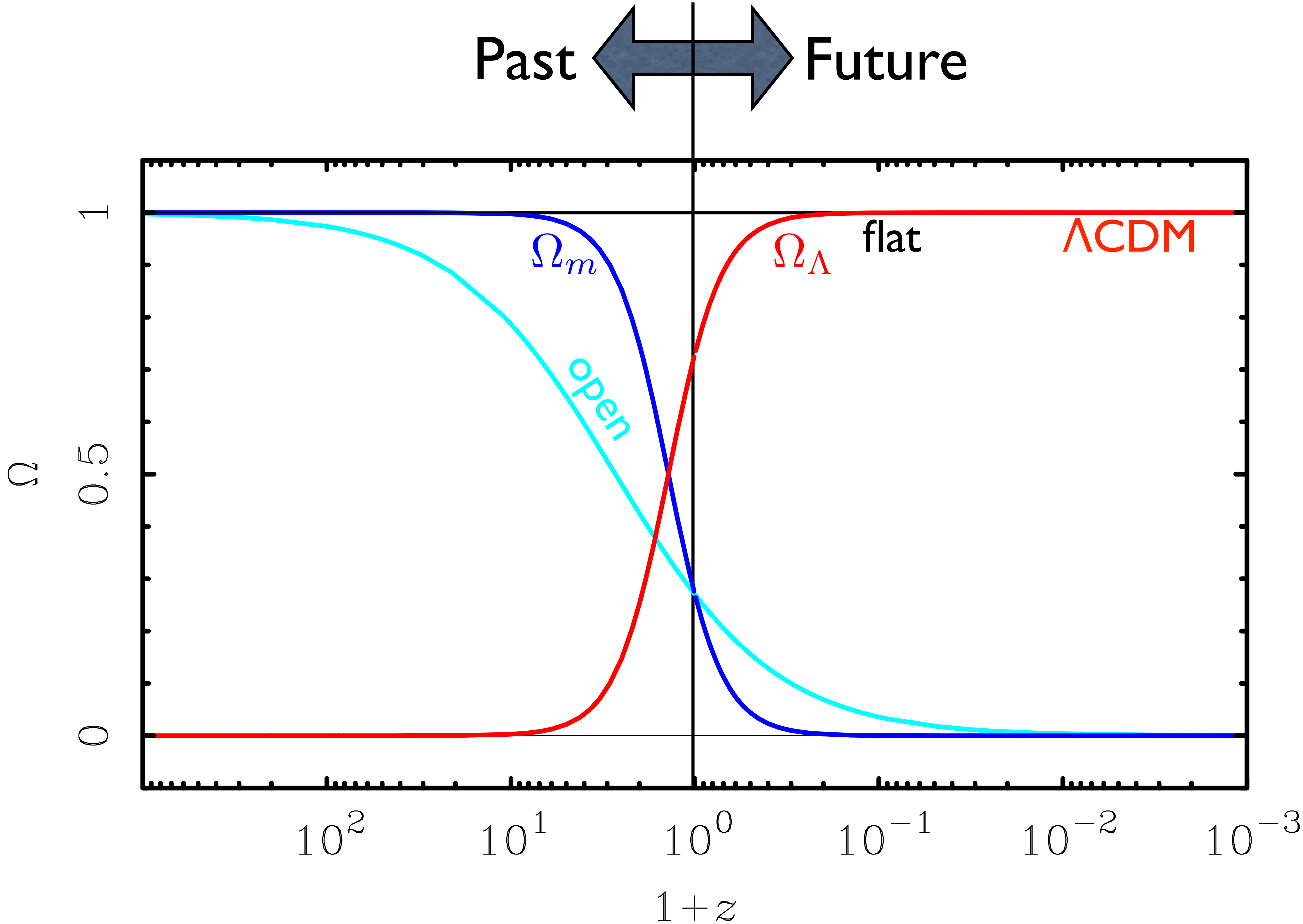
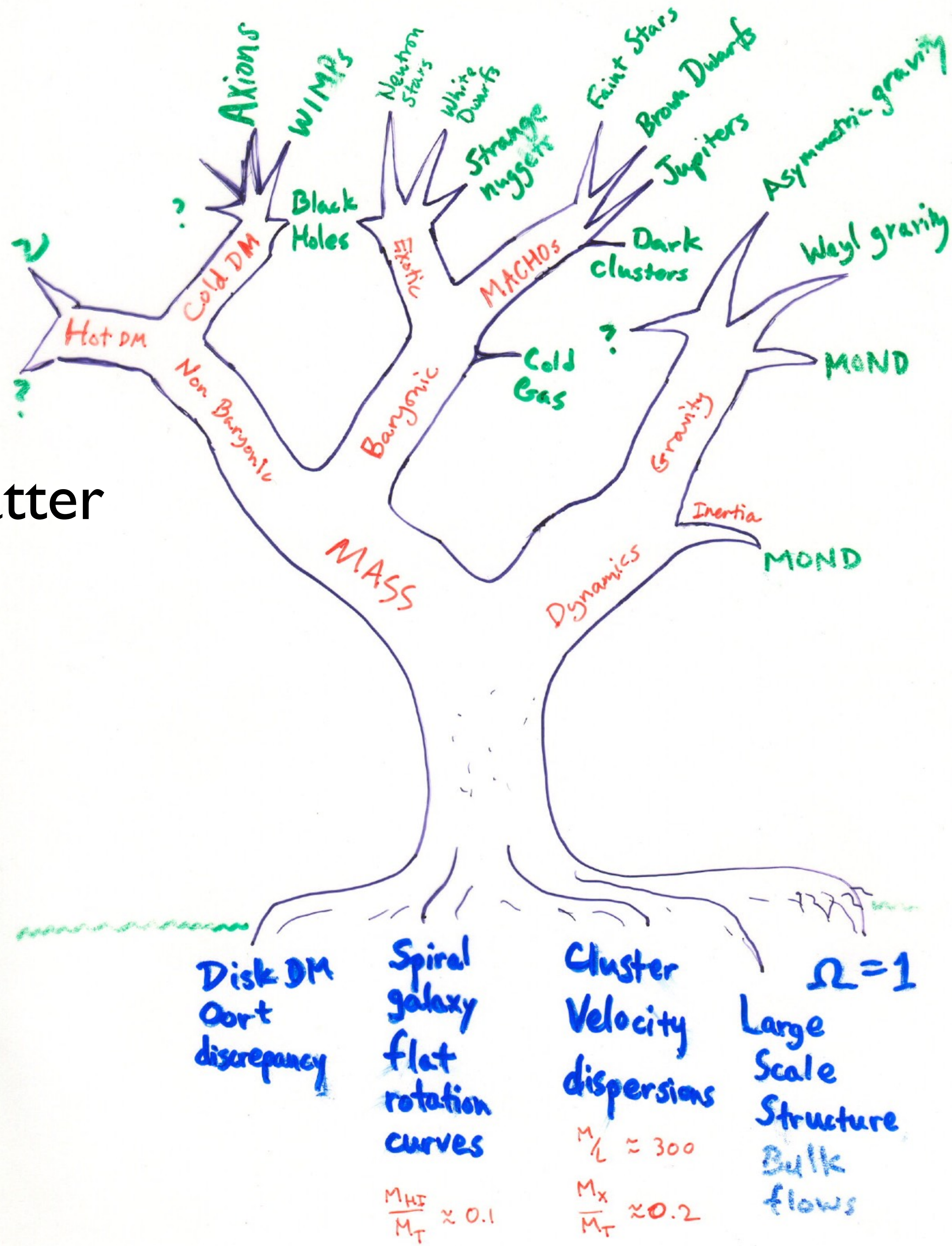


Coincidence/flatness problem:
why is the density parameter of order unity?

Dark Matter

Modified Gravity



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.

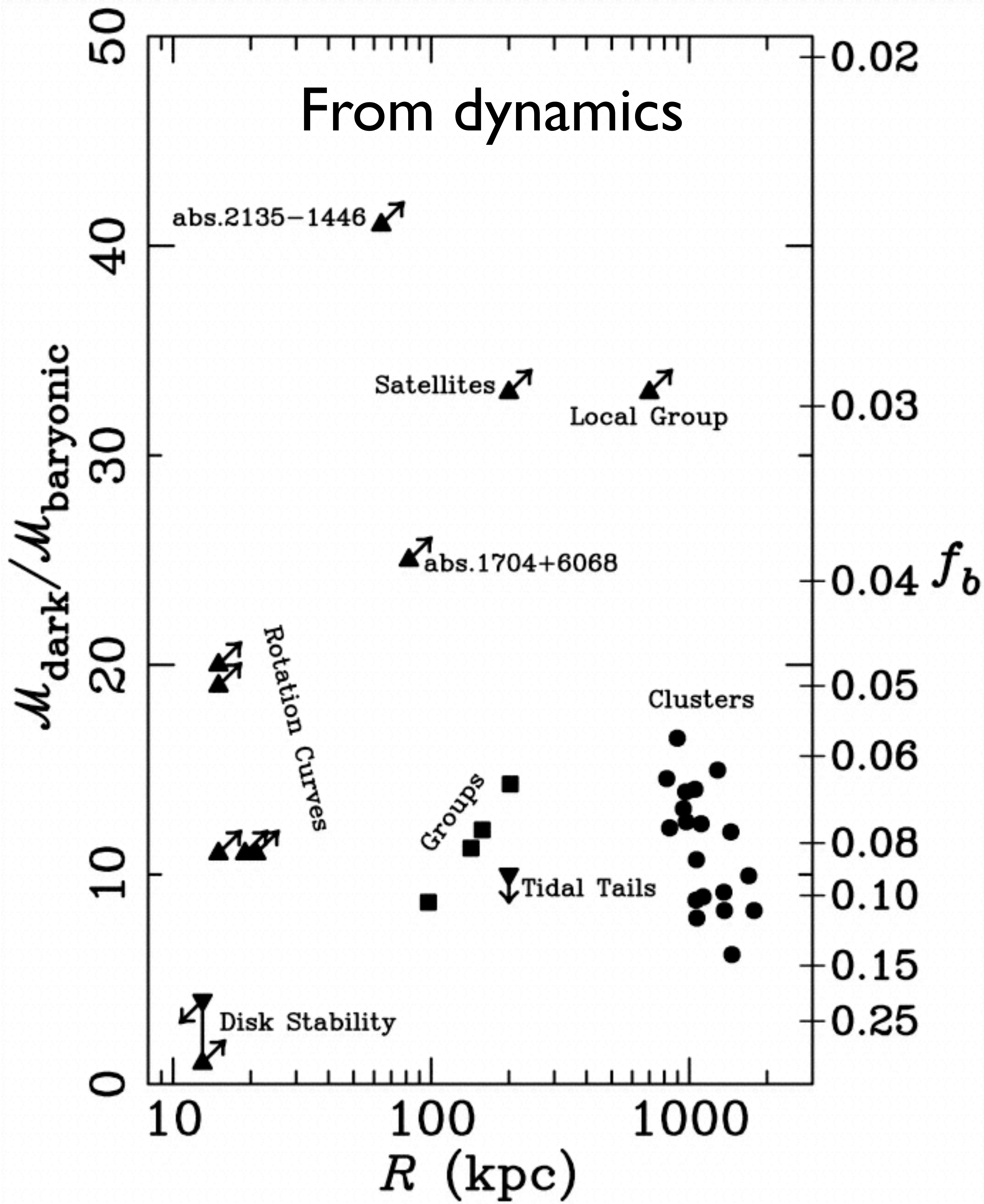
From cosmology

$$\Omega_m \approx 6\Omega_b$$

or equivalently, the baryon fraction

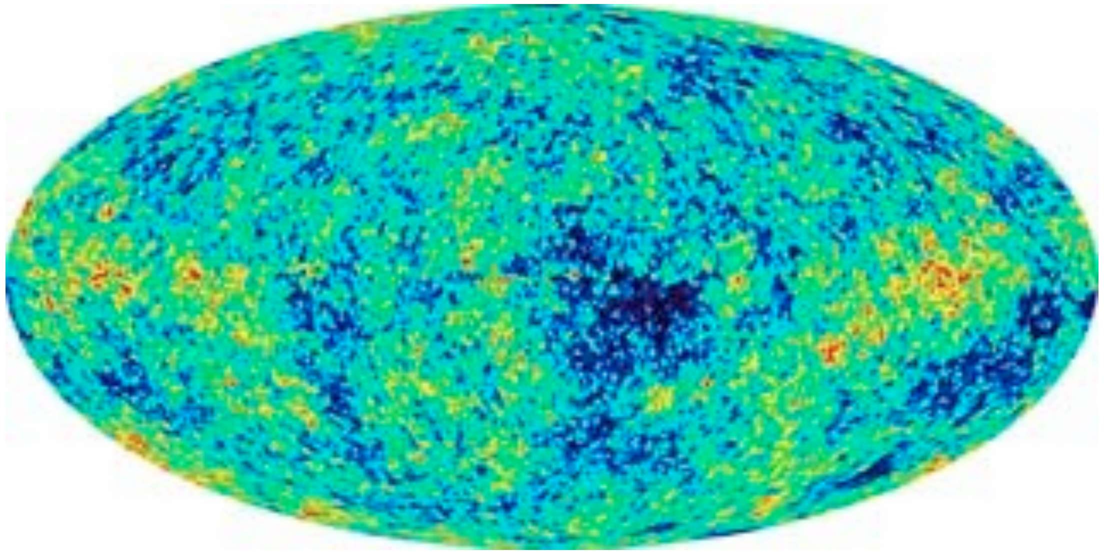
$$f_b = 0.17$$

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



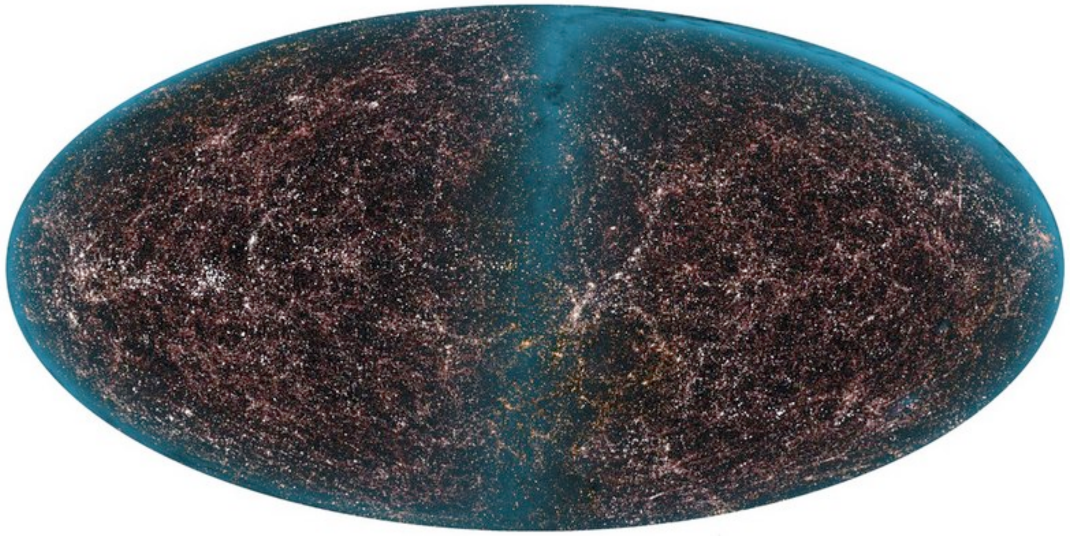
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

t = 3.8 x 10^5 yr



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

t = 1.4 x 10^{10} yr



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

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

These considerations made CDM the dominant paradgim

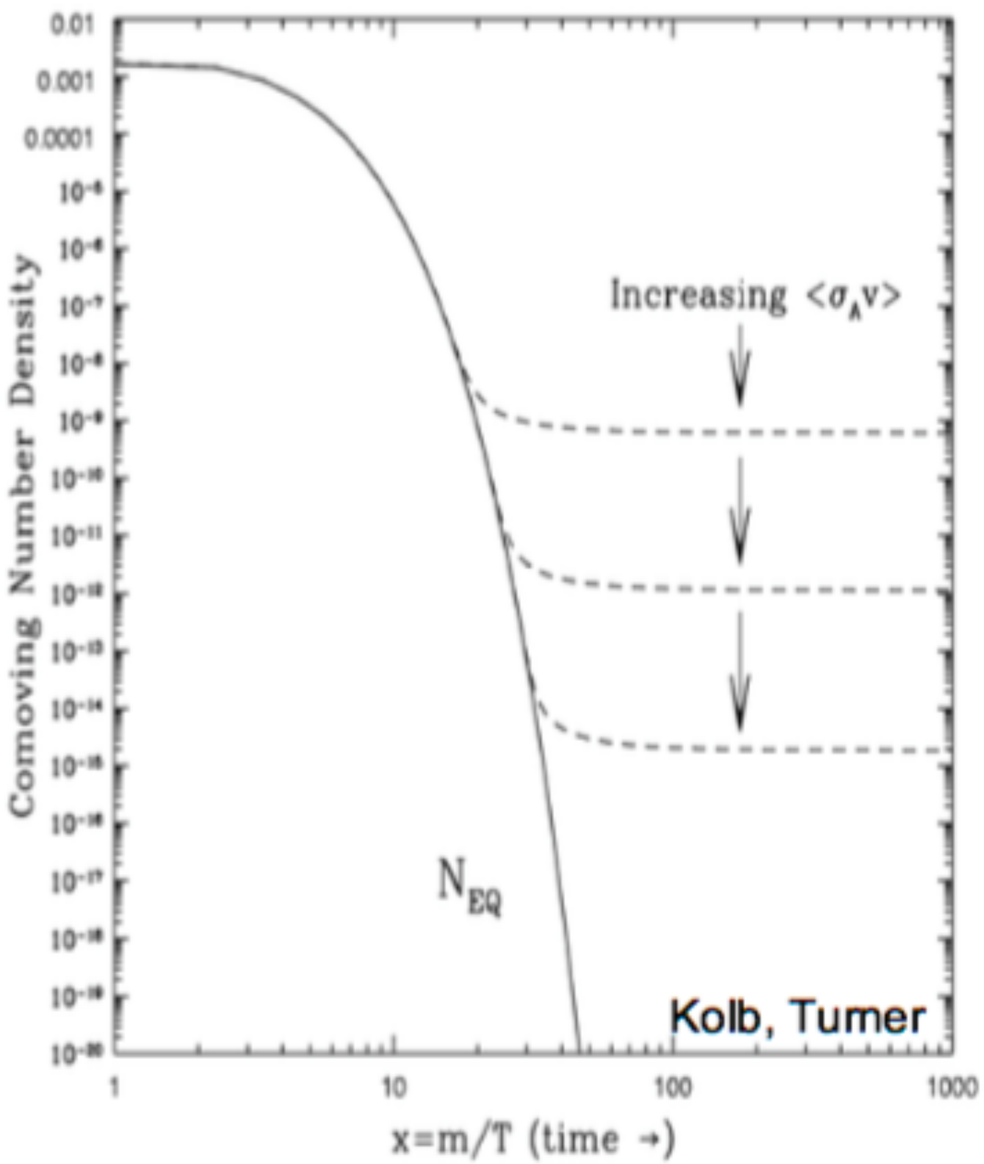
Only requirement to be CDM is

- 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

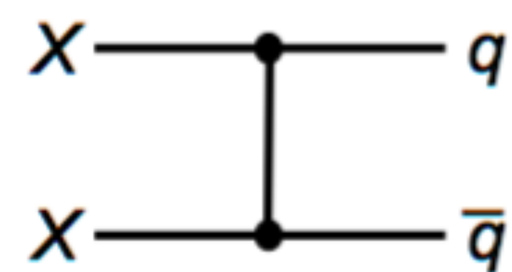


In the very early universe

- 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

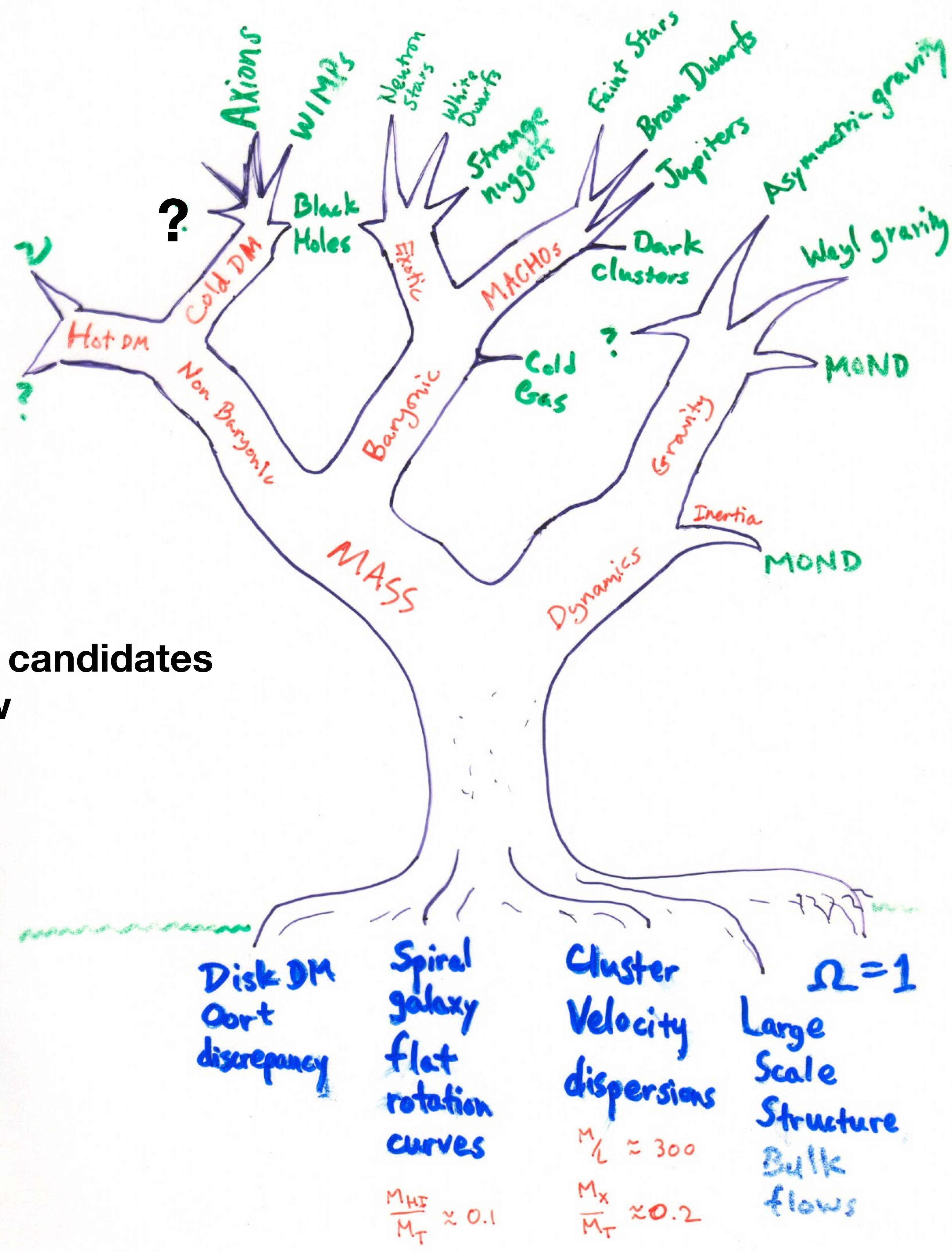
IF **the predicted new particles exist**

Lots of particle candidates for CDM:

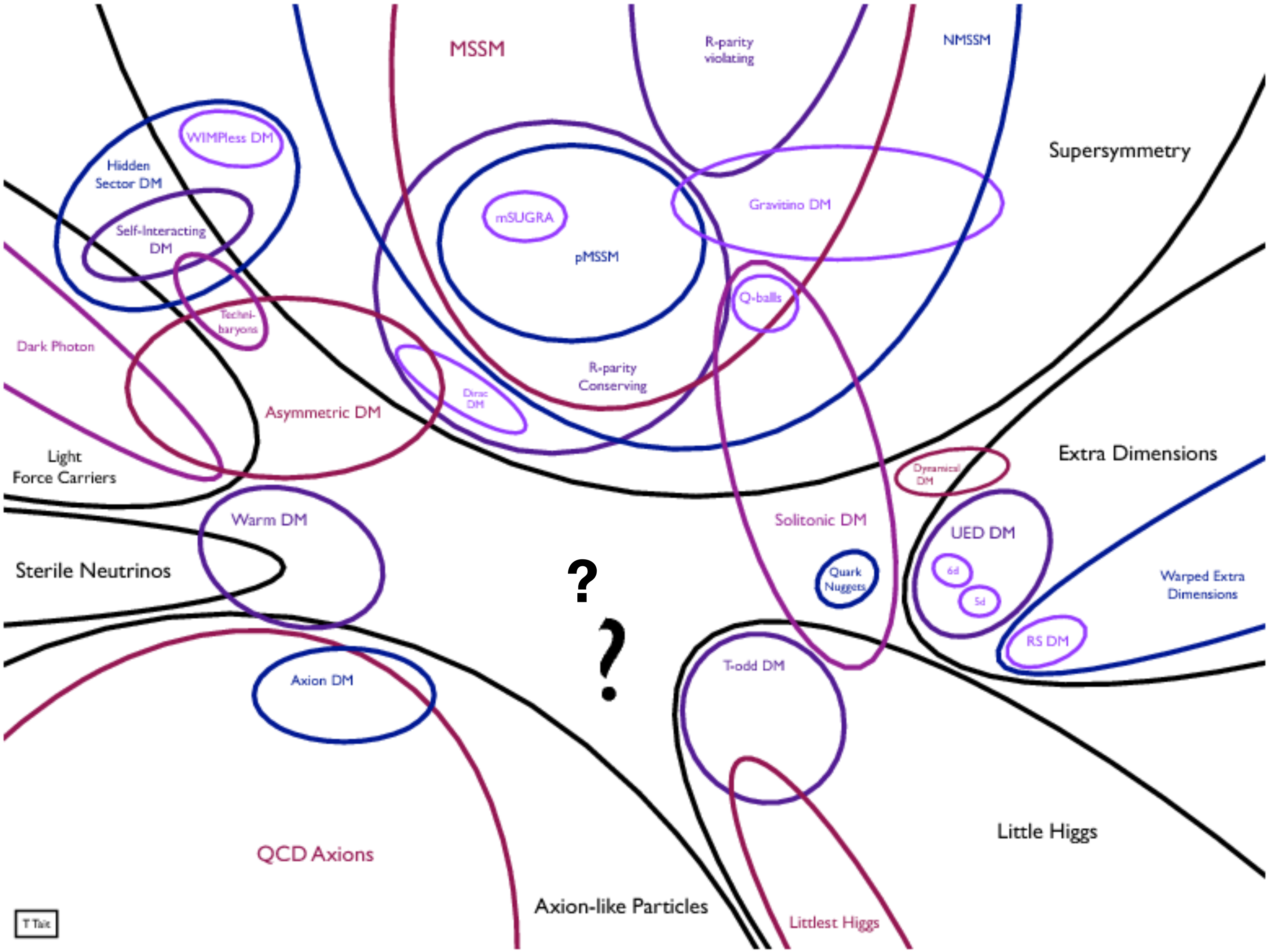
WIMPs
Axions
Light dark matter
wimpzillas
etc.

Can imagine other candidates as well:

Warm DM
Self-interacting DM
etc.



Indeed, the list of candidates continues to grow



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