# Dark Matter

**ASTR 333/433**
**Spring 2024**
**TR 11:30am–12:45pm**
**Sears 552**

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


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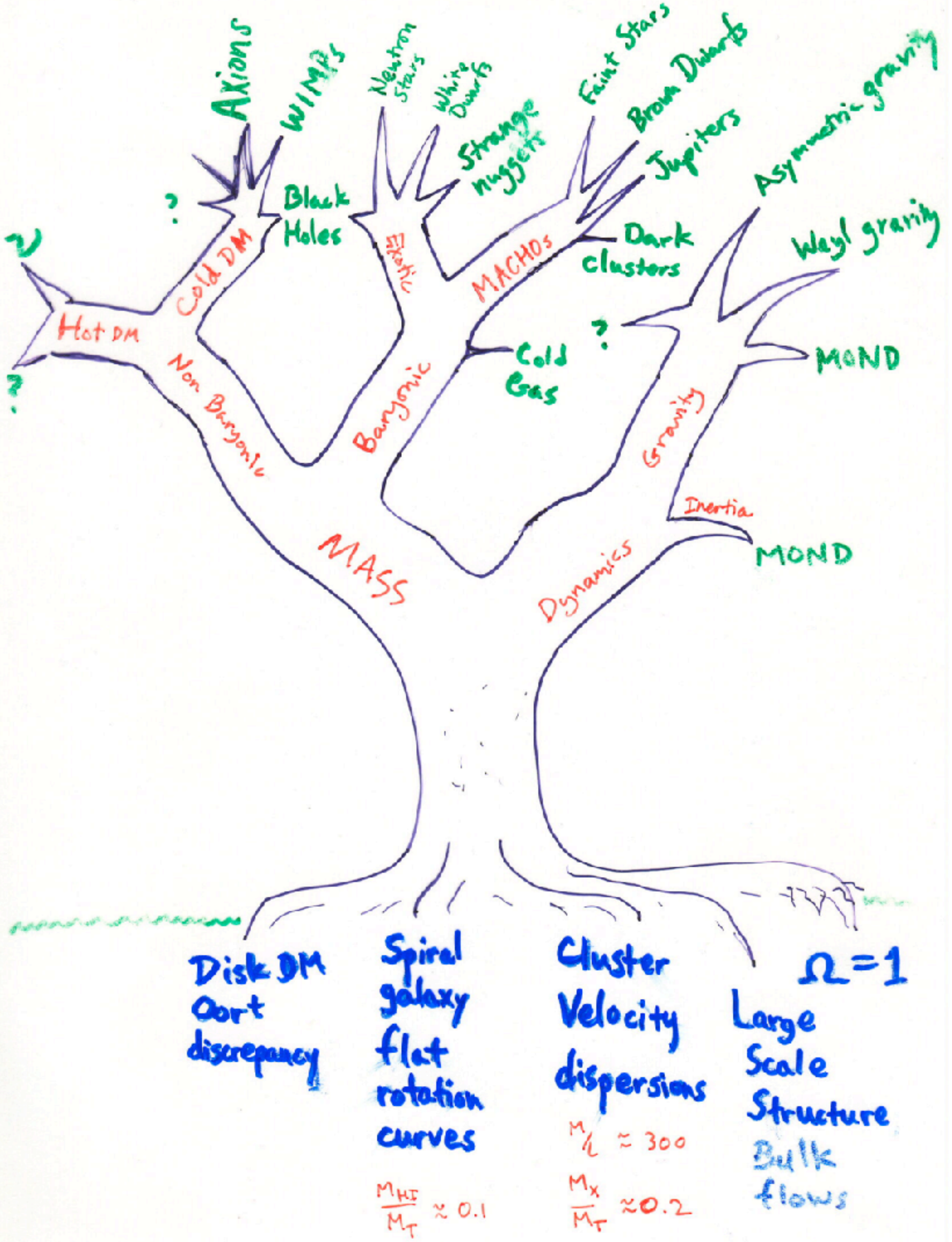


This course will address

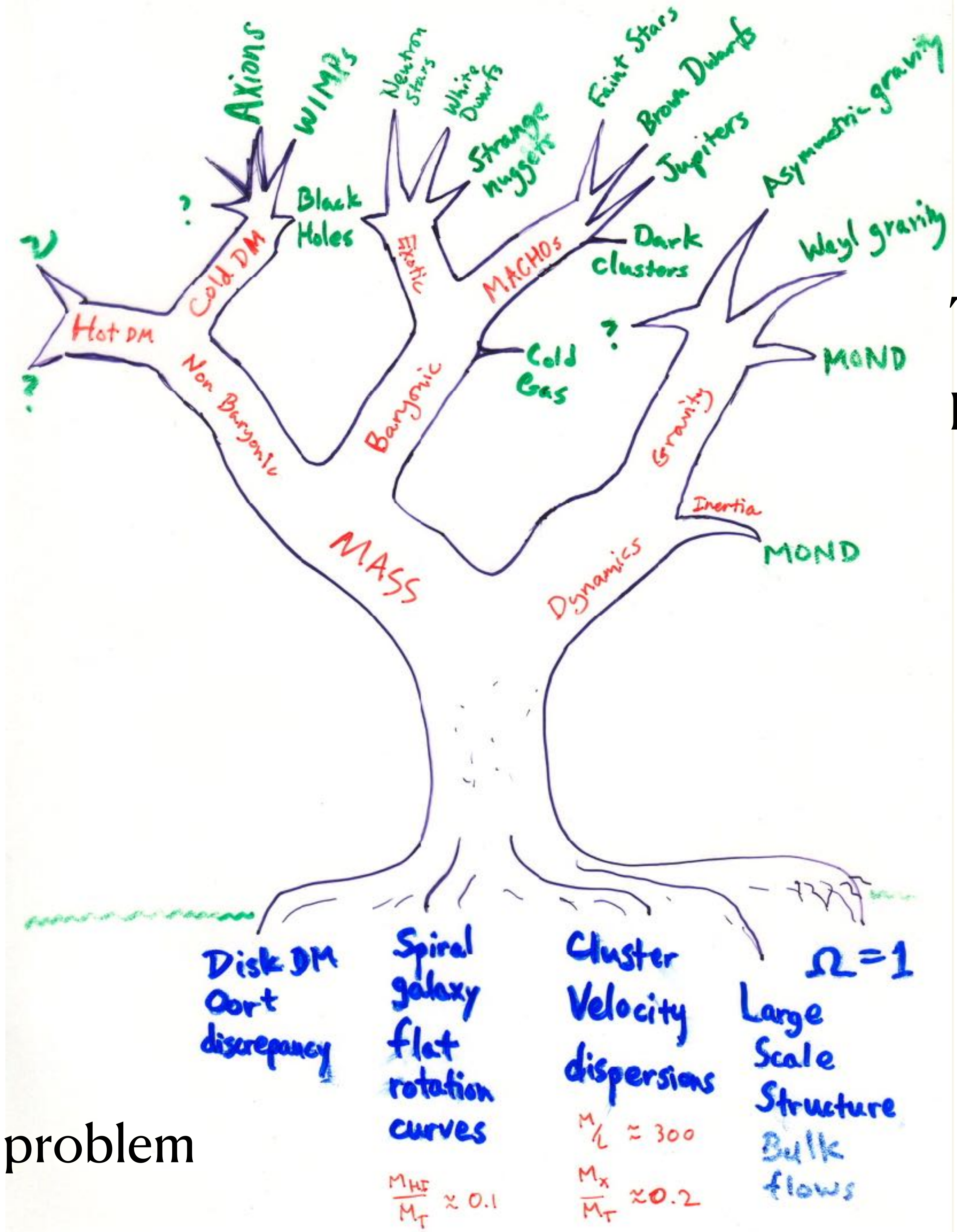
# Some Great Questions

## 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




Theoretical fruit:

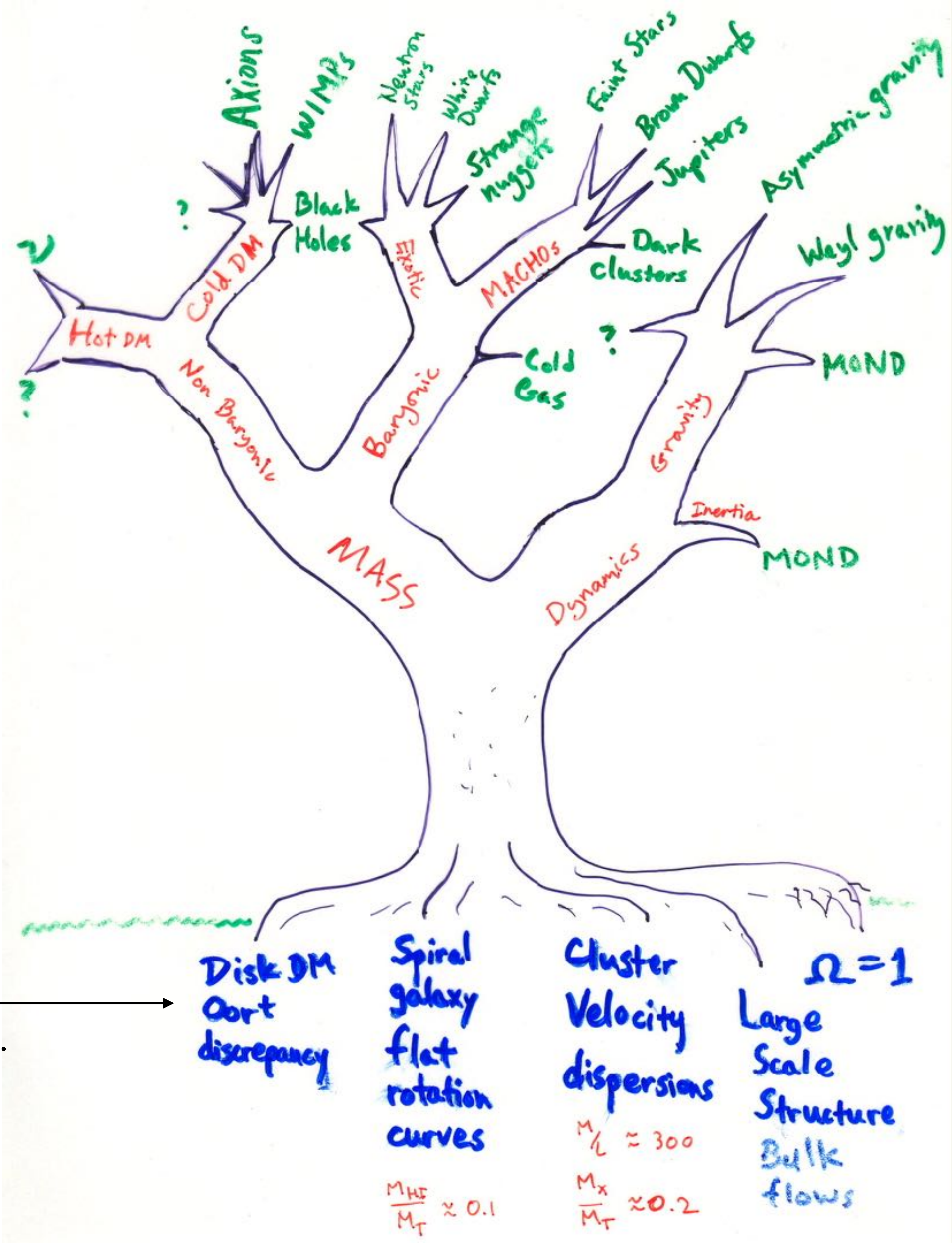
Hypothesized solutions

Empirical roots of the problem

Dark matter tree sketched in 1995

There seems to be more dynamical mass than luminous mass in the plane of the Milky Way (Oort discrepancy; 1932; 1960s).

A factor of ~2 problem



Milky Way

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.*

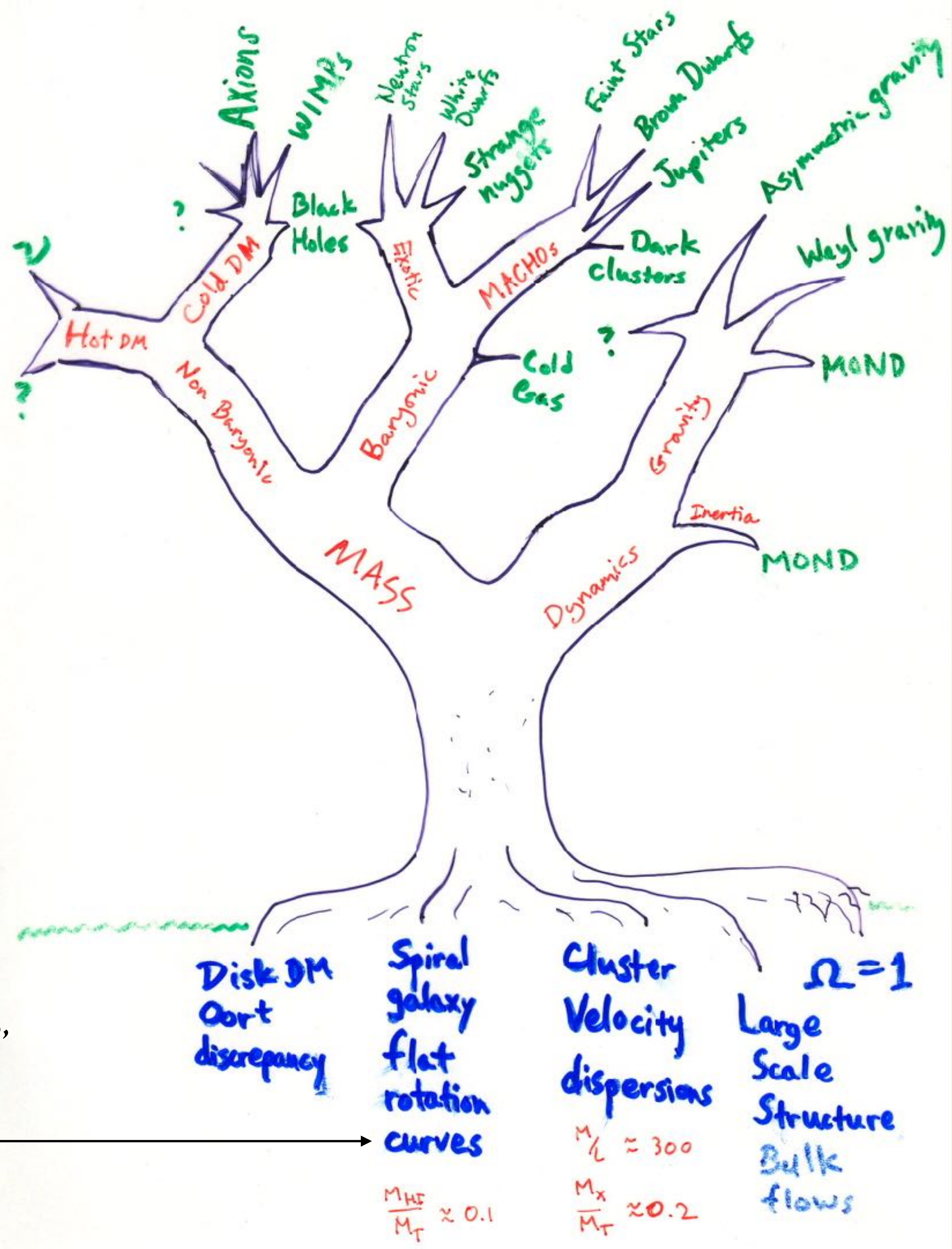
*Notations.*

- $z$ 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 $z$,
- $\Delta$ the star-density,
- $\rho$ 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,
- $\varpi$ distance to the axis of rotation of the galactic system,
- $\delta$ $\partial \log \Delta / \partial \varpi$.

*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.

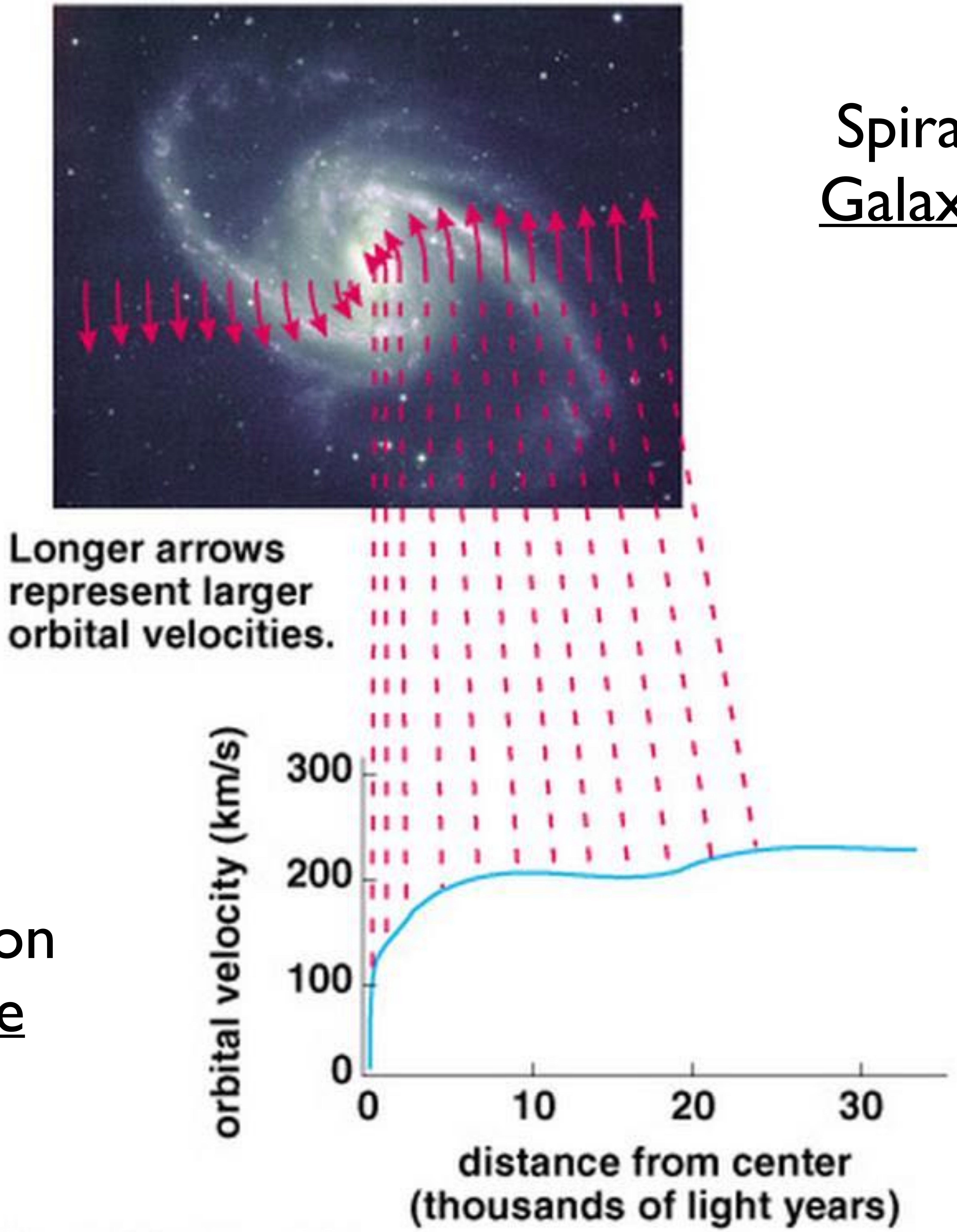
5. With the aid of the data contained in the two preceding sections I have computed the acceleration $K(z)$ between $z = 0$ and $z = 600$. The computations were made by successive approximations; the B stars were eliminated first. The results are in Table 14 and Figure 4, $K'(z)$ giving the values finally 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.



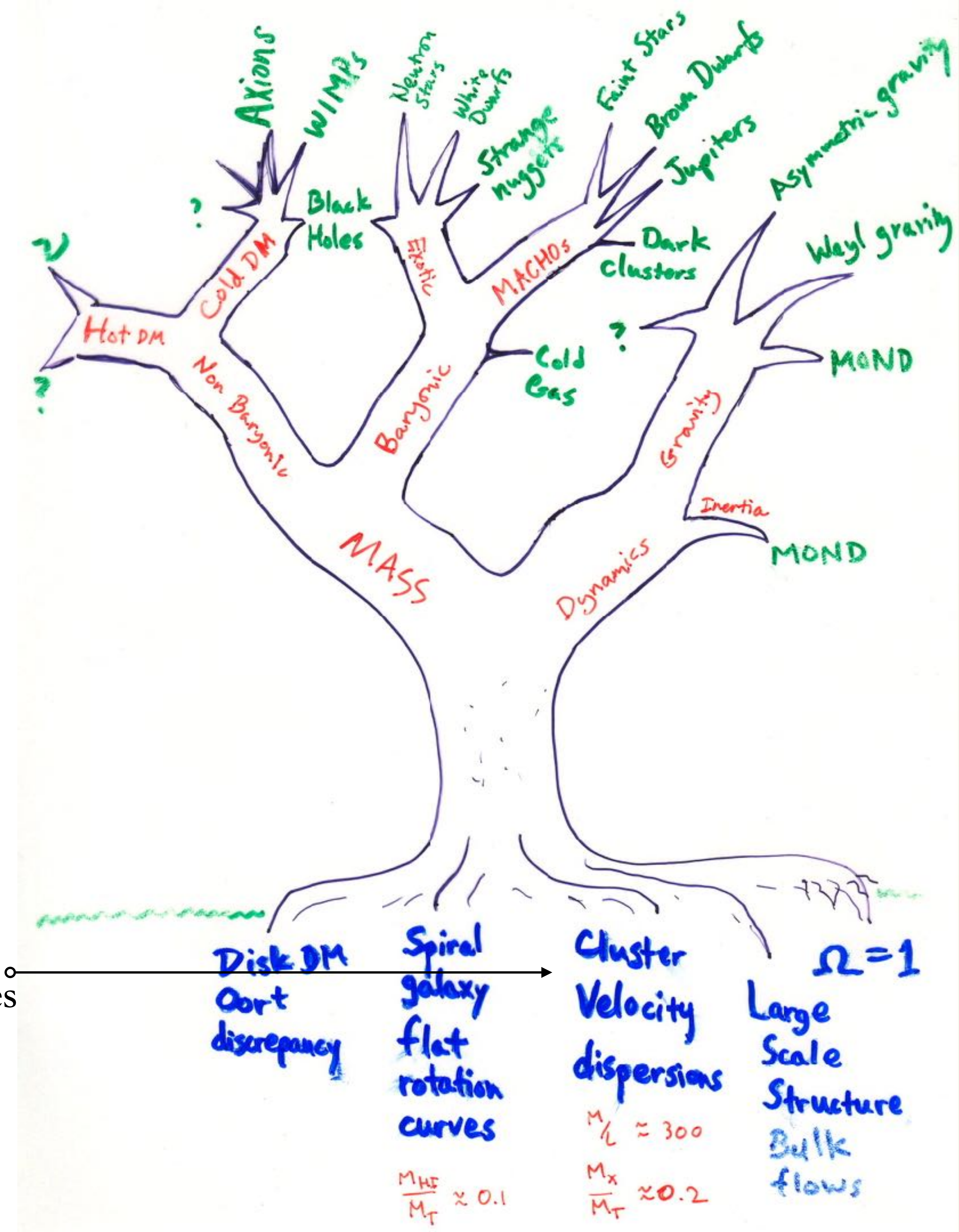

There seems to be more dynamical mass than luminous mass beyond the edge of spiral galaxies (Opik 1920s? Babcock 1950s, Rubin 1970s, Bosma 1980s).

A factor of ~2 - 10 problem

Spiral Galaxy




Rotation Curve

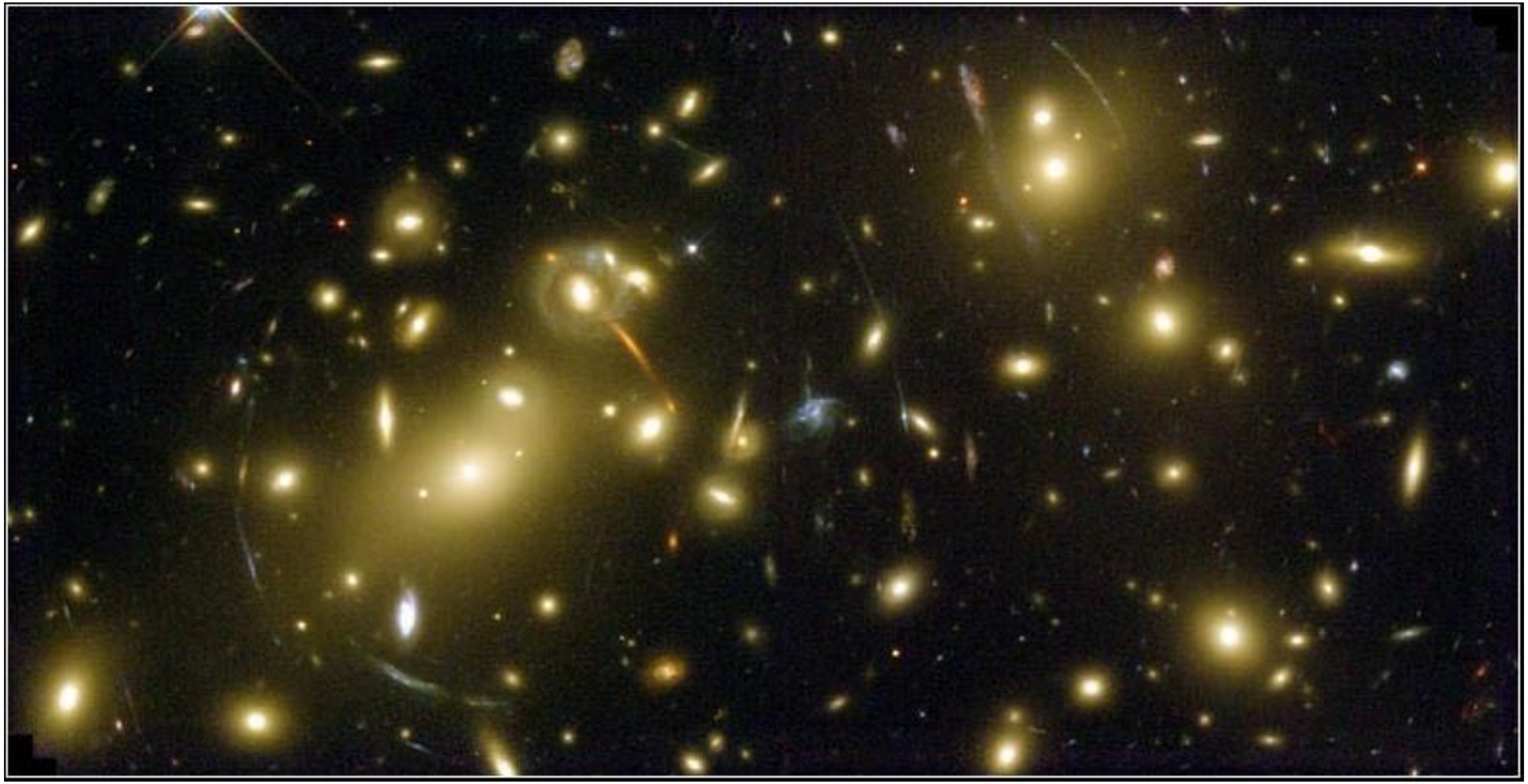



There seems to be more dynamical mass than luminous mass in clusters of galaxies (Zwicky 1933, 1937).

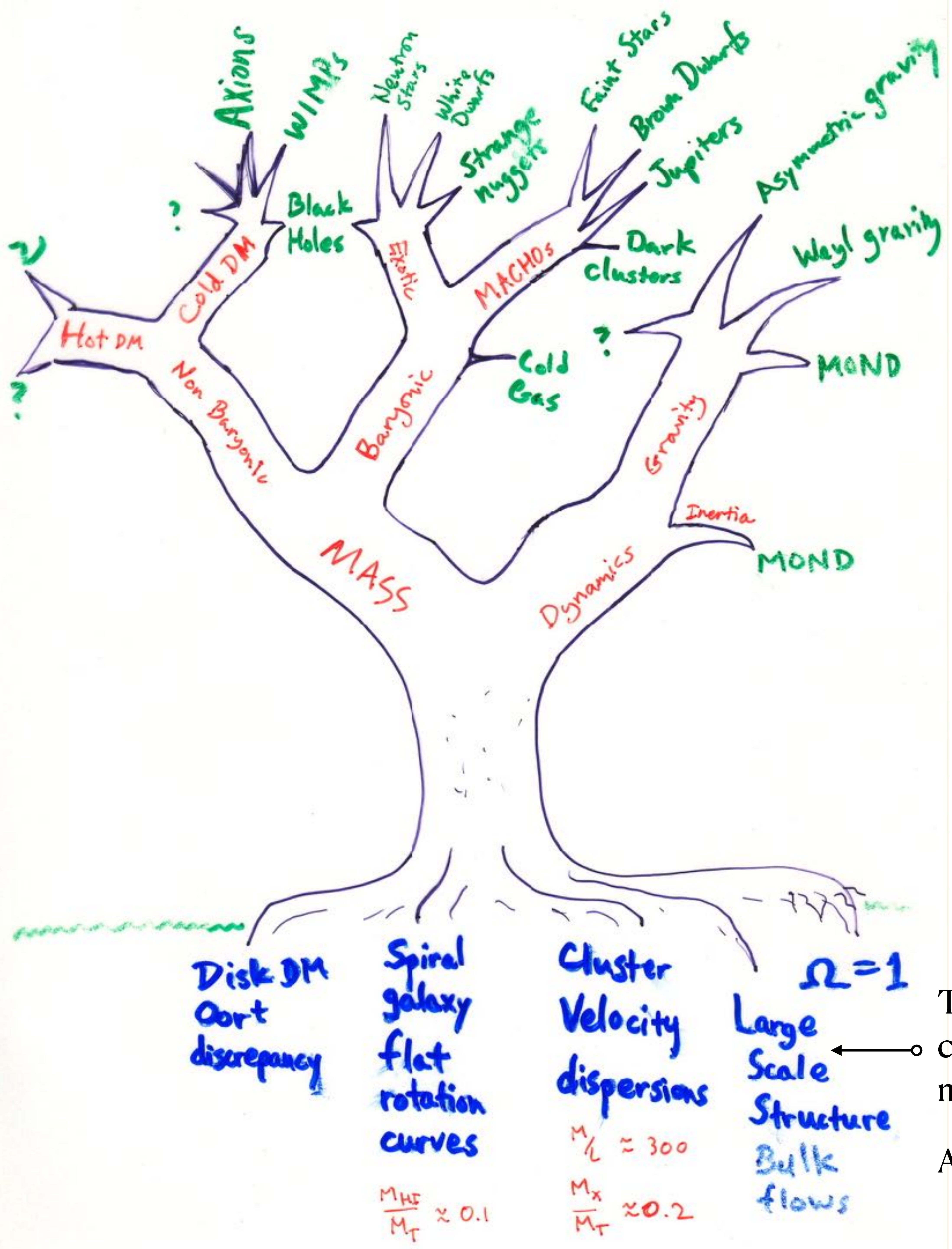
A factor of ~100 - 1000 problem

# Galaxy Cluster

Zwicky 1933, 1937



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

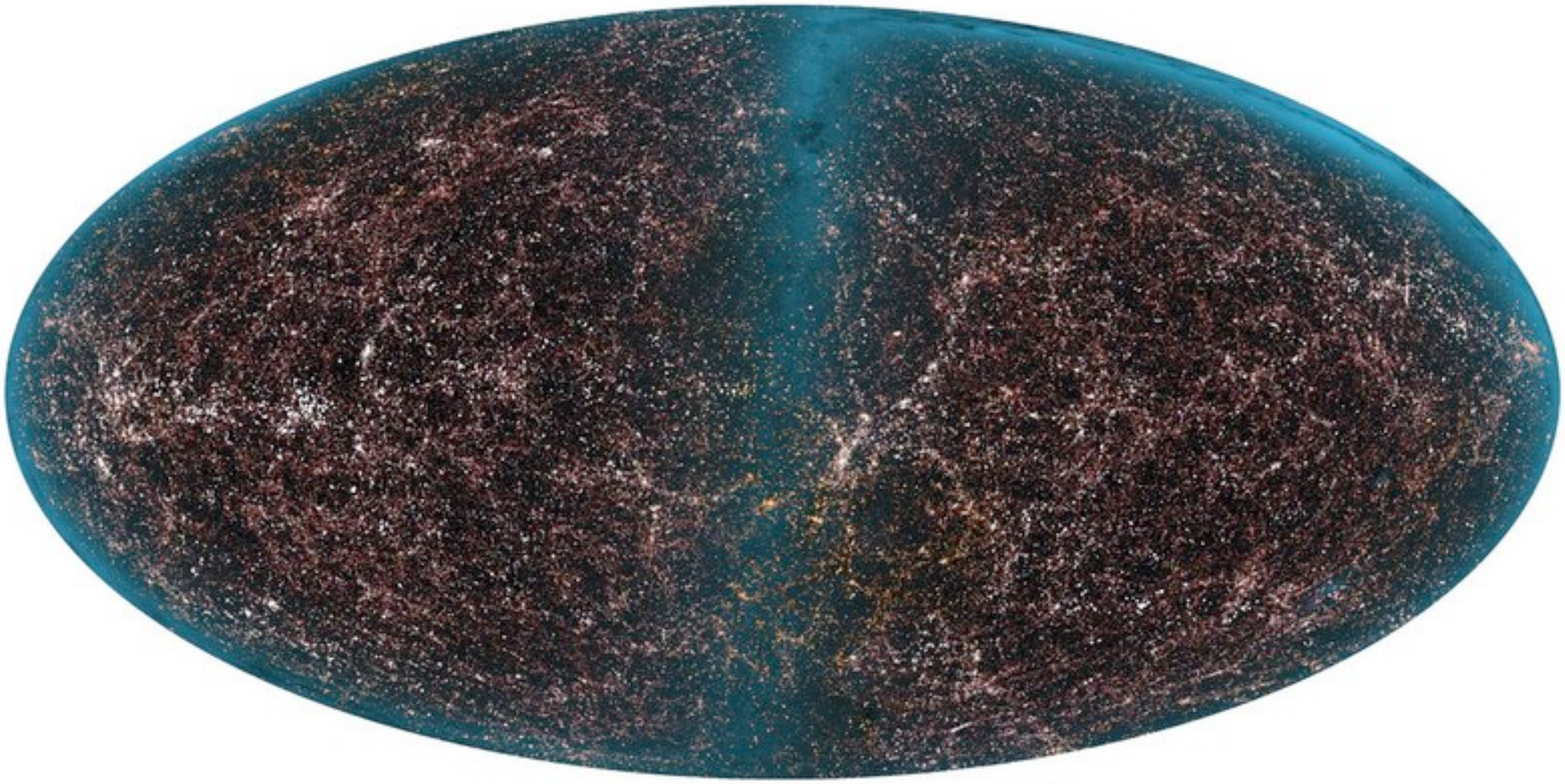



There needs to be more gravitation than can be provided by baryons [normal matter] (Peebles; Silk 1960s).

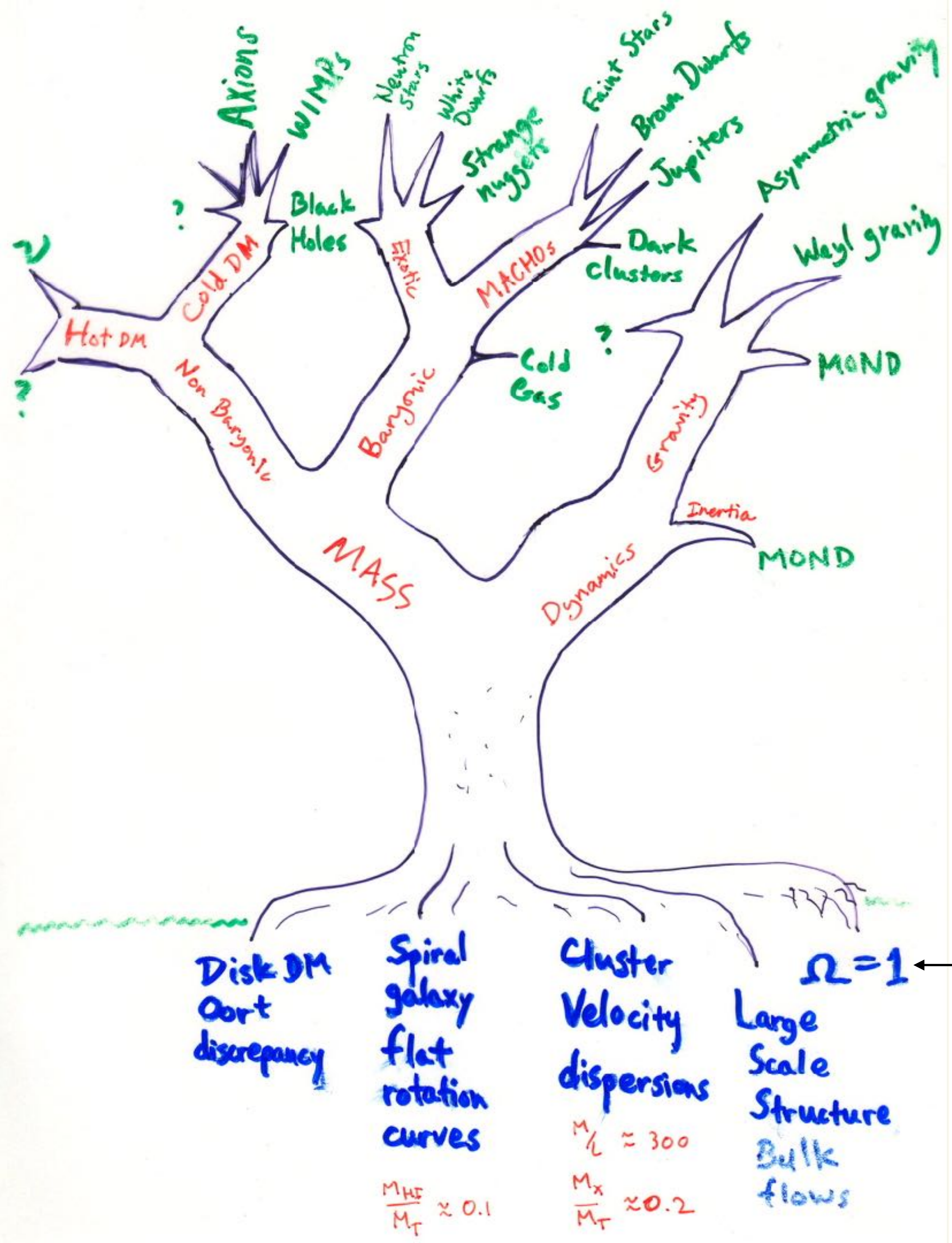
A factor of ~100 problem

# Large Scale Structure

Each dot is an entire galaxy



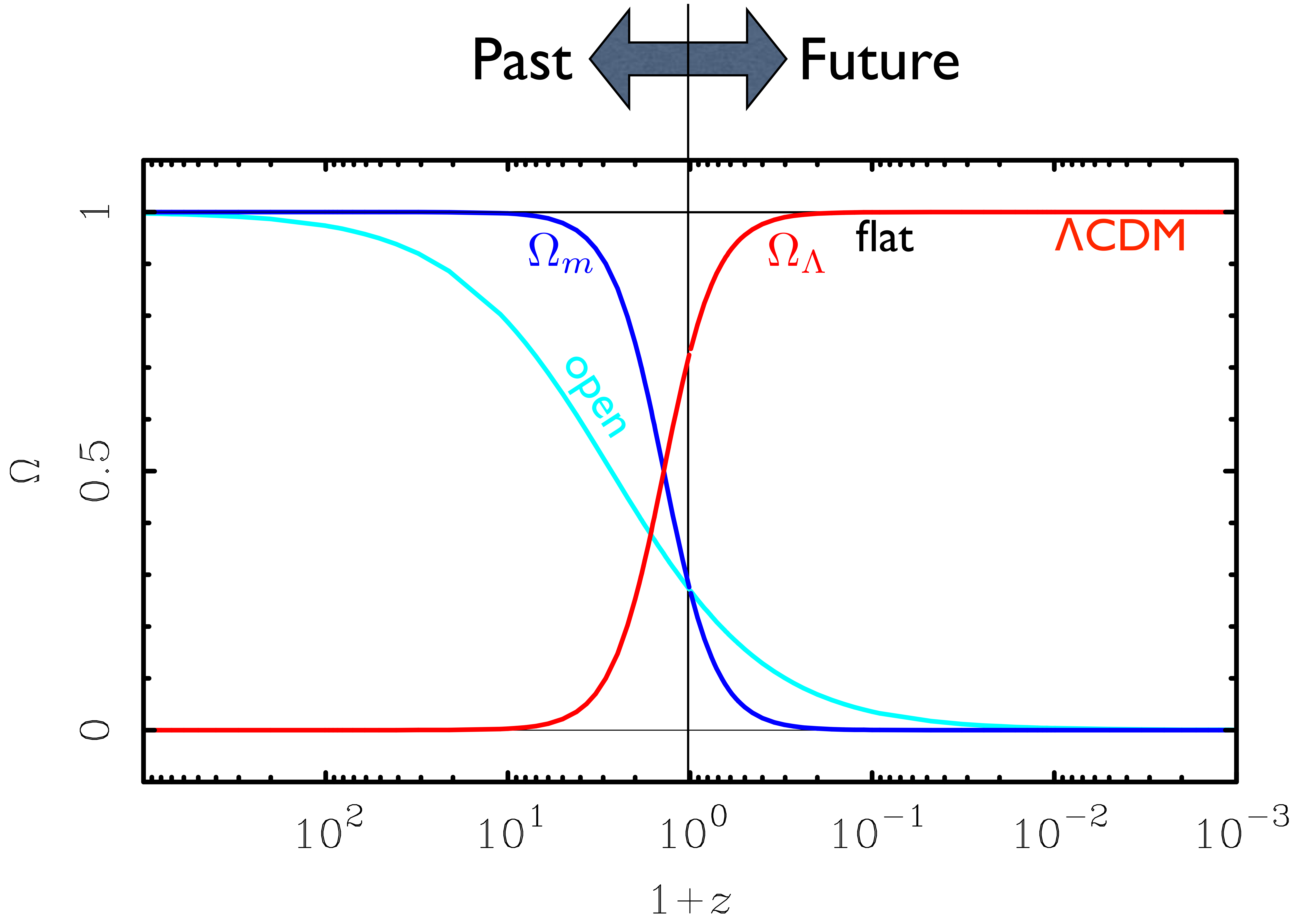
Need something to prompt structure formation - gravity + visible matter don't suffice




Theoretical desire for $\Omega_m = 1$

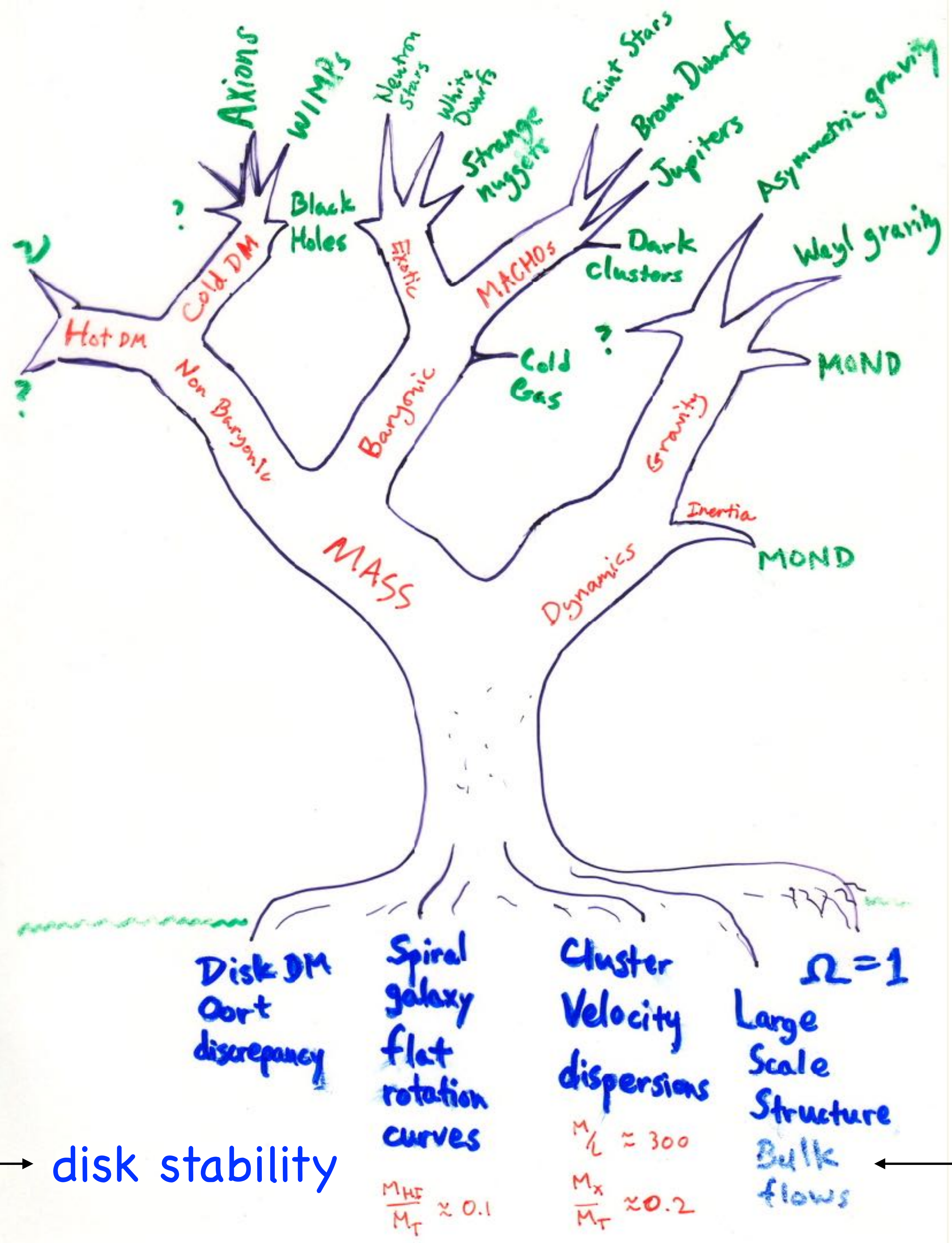
(Guth; Linde 1980 [Inflation]).

A factor of ~20 issue




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

Need something to stabilize spiral galaxies (Ostriker & Peebles 1973) → disk stability




Bulk flows: galaxies move faster than expected relative to Hubble flow.

# Pruning the tree

## Baryonic Dark Matter

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

**Baryons**: 3-quark particles like protons and neutrons. These provide the bulk of the mass of **normal matter**.

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

# Pruning the tree

## **Hot Dark Matter (HDM)**

Obvious candidate:
neutrinos

**HDM** moves relativistically (near speed of light: $V \sim c$).

neutrinos got mass!...

...but not enough.

Also

- neutrinos suppress small scale structure formation
- can't crowd together closely enough
  (phase space constraint from Fermi exclusion principle)

# Pruning the tree

## Cold Dark Matter (CDM)

Some new particle, usually assumed to be a
**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

**CDM** moves non-relativistically ($V \ll c$). Usually assumed to be non-baryonic, e.g., some new particle outside the Standard Model of particle physics.

Non-baryonic because

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

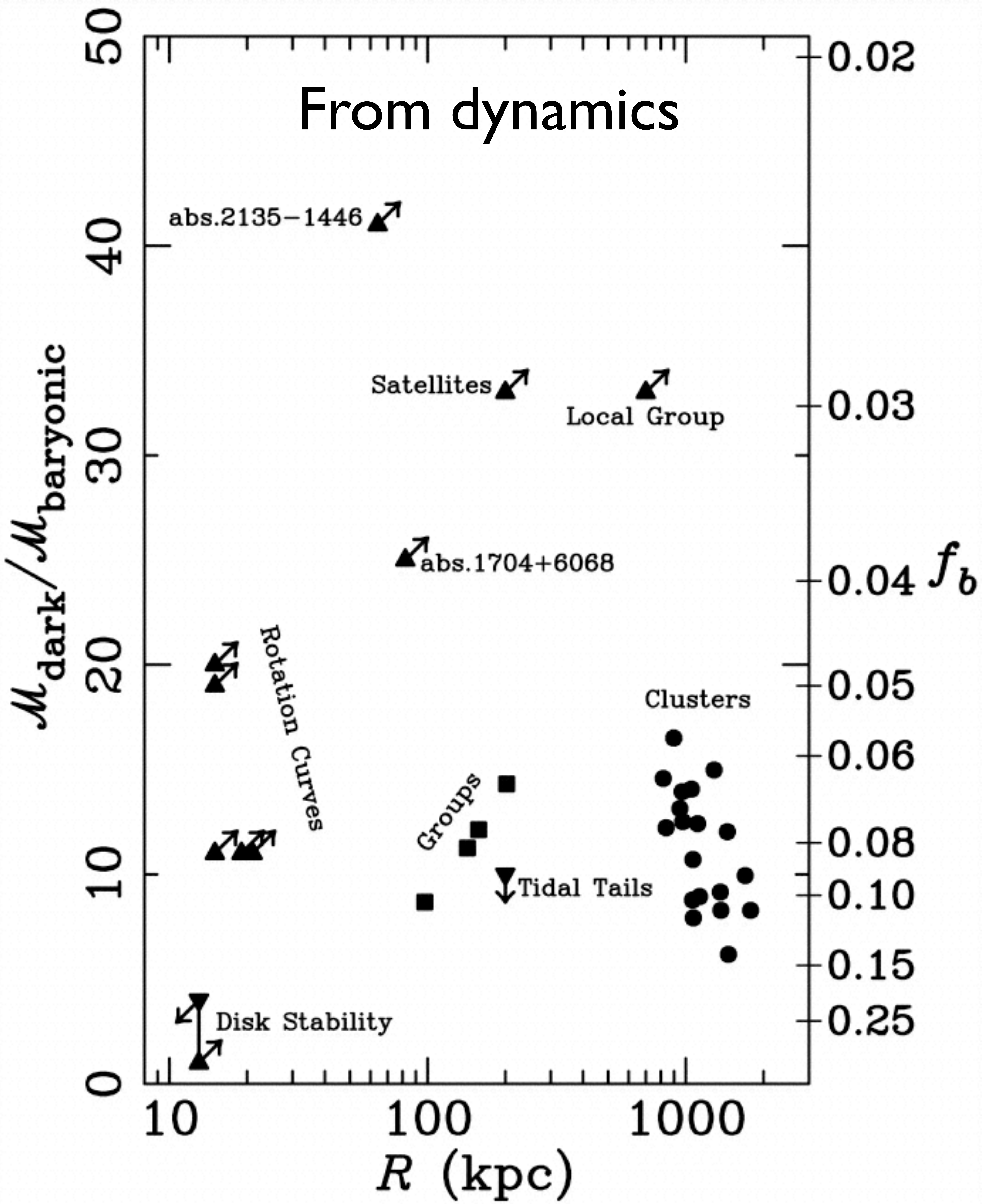
From cosmology

$$\Omega_m \approx 6\Omega_b$$

or equivalently, the baryon fraction

$$f_b = 0.17$$

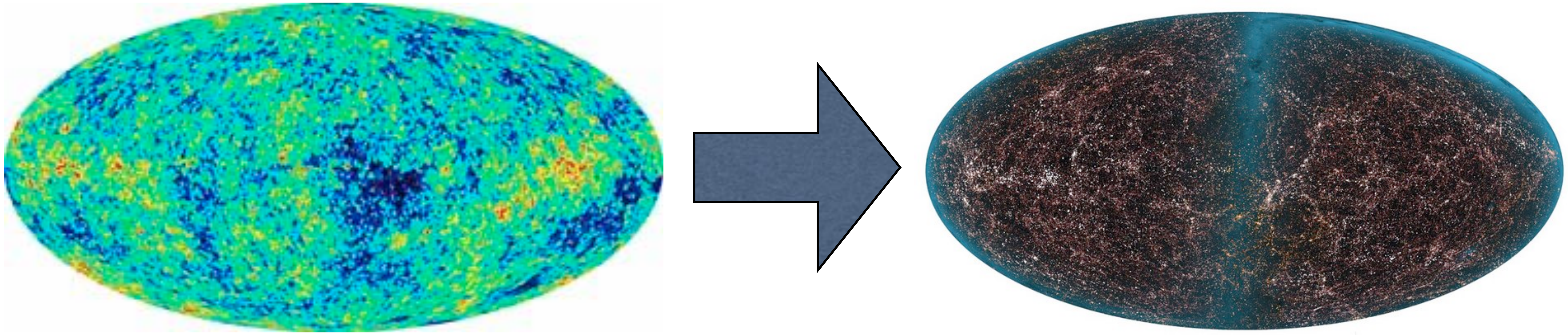
The gravitating mass density exceeds the baryon density from Big Bang Nucleosynthesis (BBN)



Dynamically cold because

(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 $\qquad$ $t$ = 1.4 x $10^{10}$ yr



very smooth: $\delta\rho/\rho \sim 10^{-5}$ $\qquad$ very lumpy: $\delta\rho/\rho \sim 1$

Density fluctuations grow like the expansion factor, $\dfrac{\delta\rho}{\rho} \sim a(t) \sim \dfrac{1}{1+z}$

Need a growth factor of 100,000 but there is only time for a factor of 1,000 for the fluctuations observed in normal matter.

These considerations made CDM the dominant paradgim

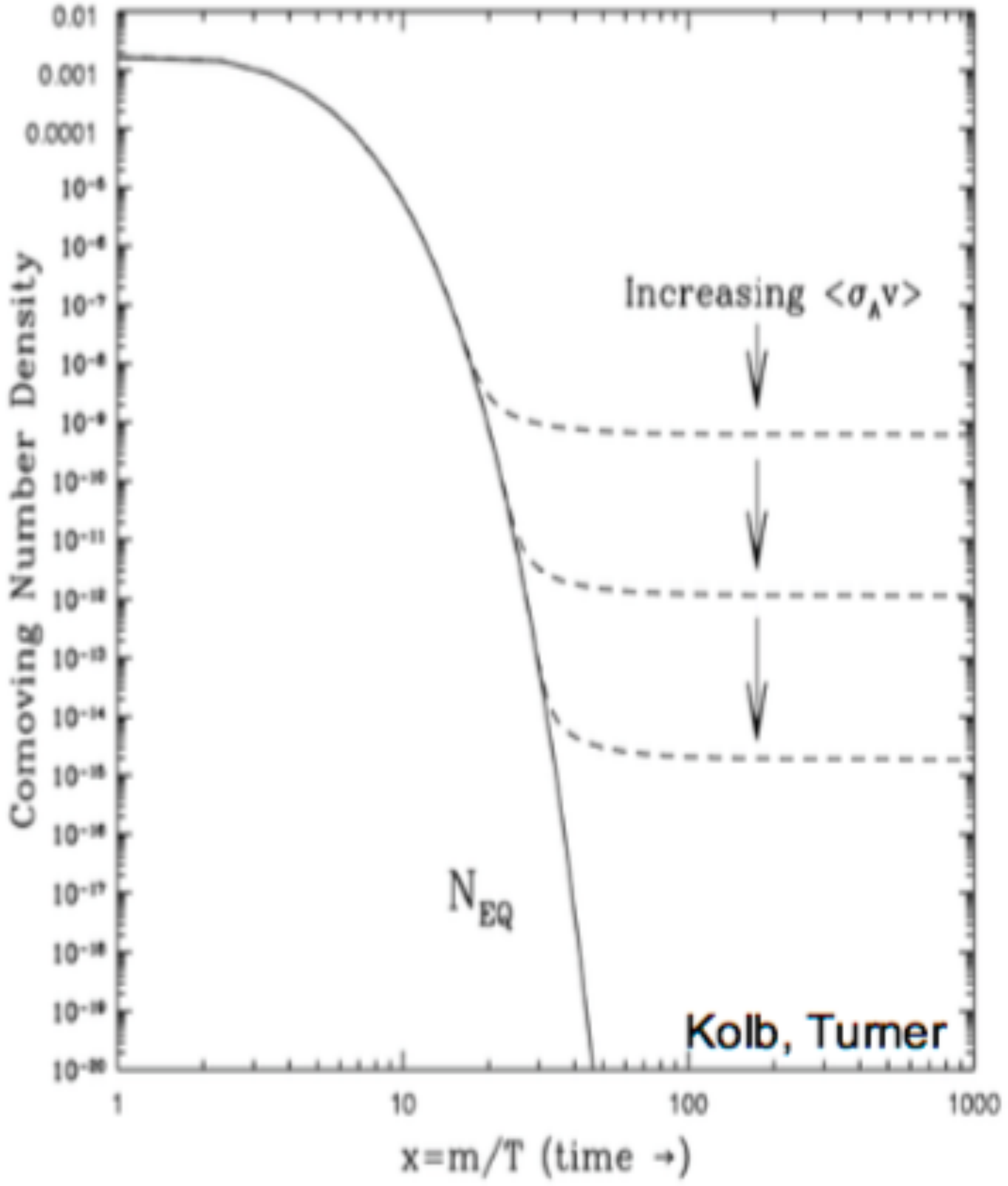
# To be CDM

## only 2 basic requirements

- **Dynamically cold**
  - slow moving particles that can clump gravitationally to form structure
- Effectively **non-baryonic**
  - does not interact with electromagnetic radiation
  - does not participate in Big Bang Nucleosynthesis

WIMPs have been 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.

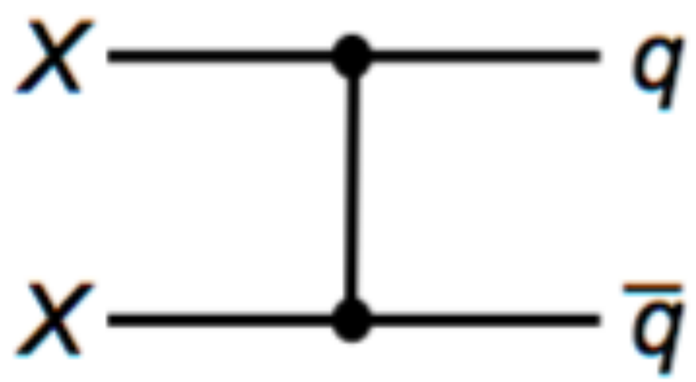
# THE WIMP MIRACLE




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