Dark Matter

ASTR 333/433
Spring 2026
TR 11:30am-12:45pm
Sears 552

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

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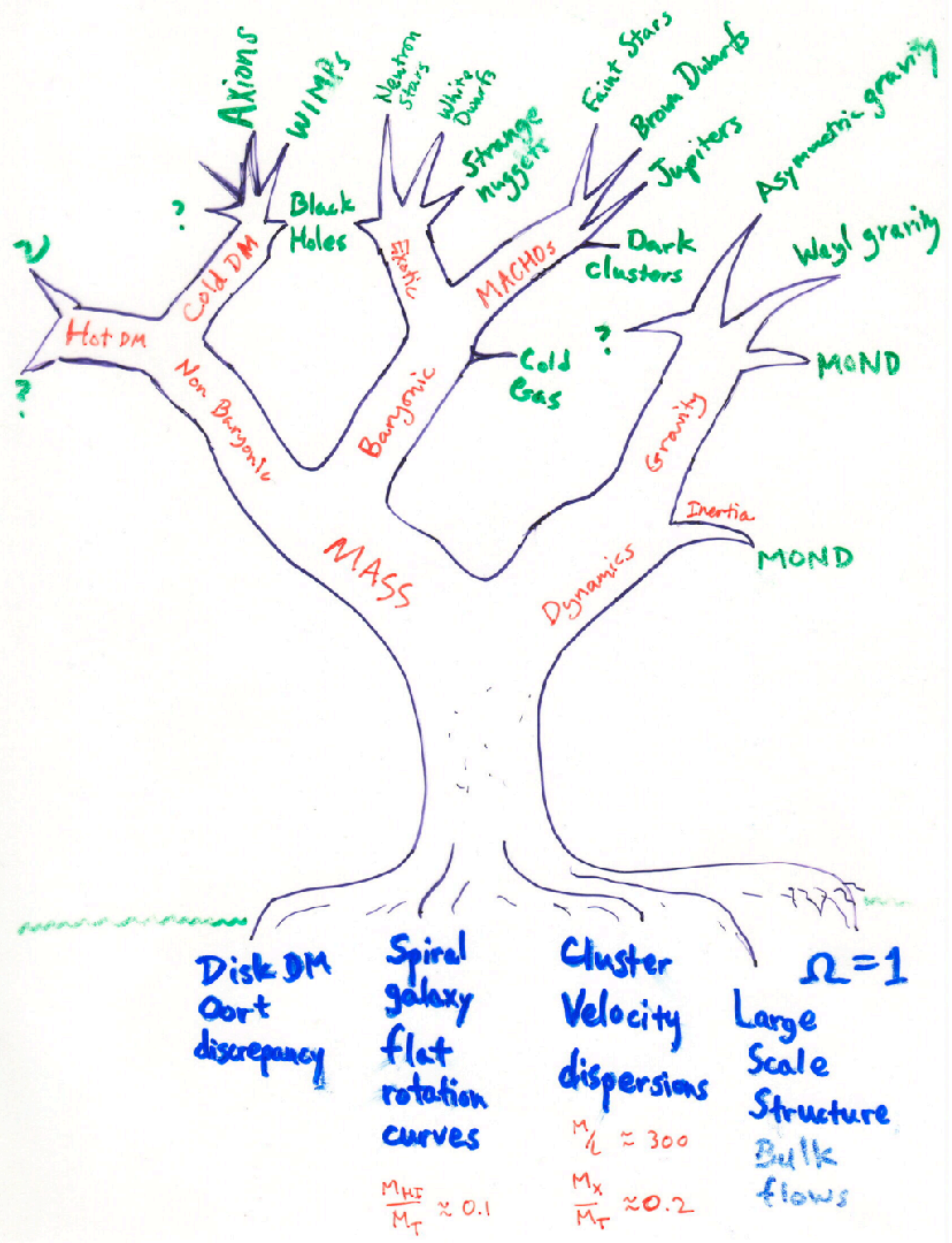

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This is the primary website for the course (not Canvas)
look here for homework assignments, etc.

DARK MATTER

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ASTR 433

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Office Hours
TBD

?

Textbook
Dark Matter:
Evidence, Theory, and Constraints
Marsh, Ellis, & Mehta

Related texts
Galaxy Formation & Evolution
Mo, van den Bosch & White
Mo et al. errata | rogue internet version

Galactic Dynamics
Binney & Tremaine
B&T errata

Introduction to Cosmology
Ryden

Course Links

Course Schedule & Lectures

HTML Syllabus
- Course Description
- Course Outline
- Course Work and Grades
- Learning Outcomes

PDF Syllabus

Course Work Schedule

Homework assignments will appear here

This course will address

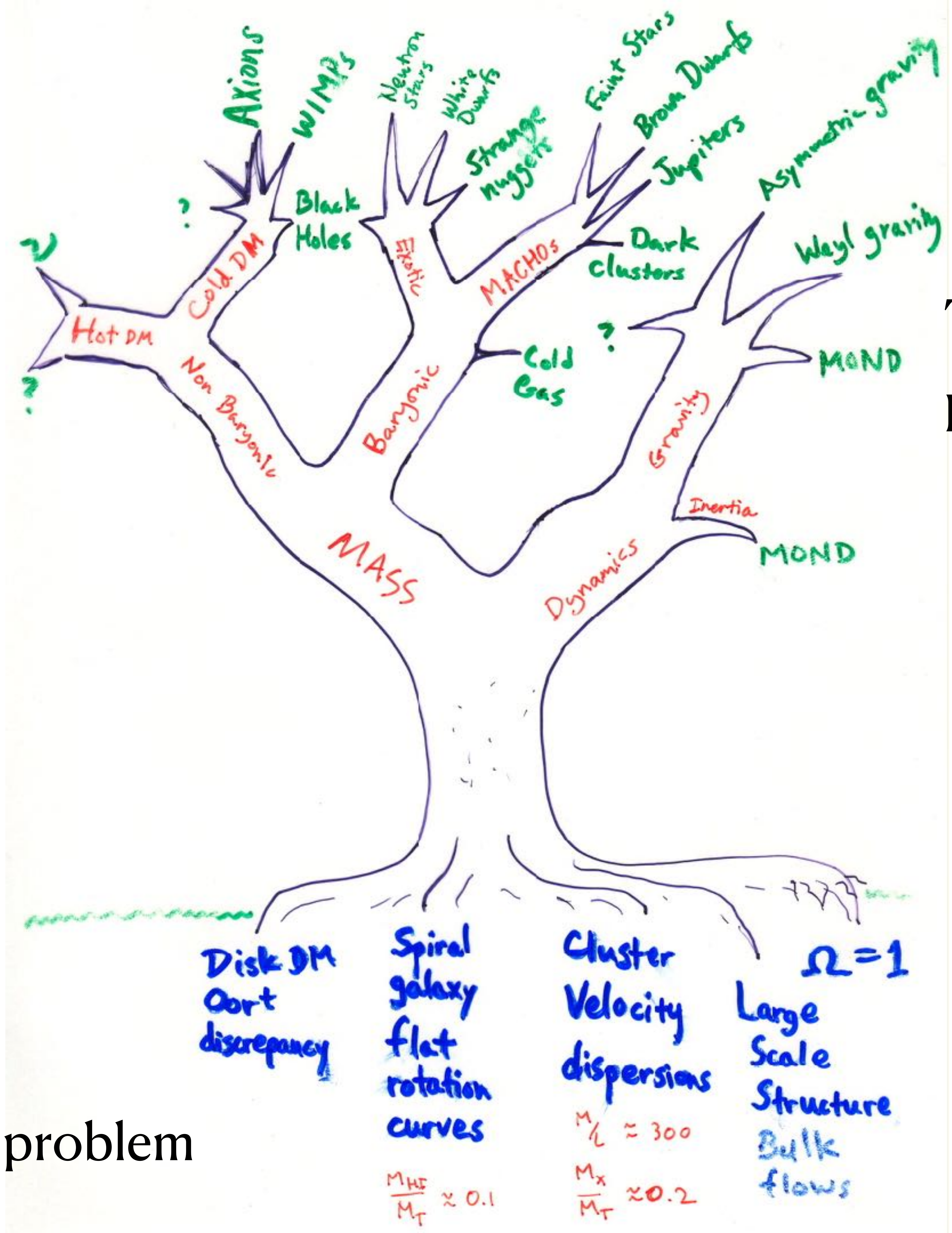
Some Great Questions

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:

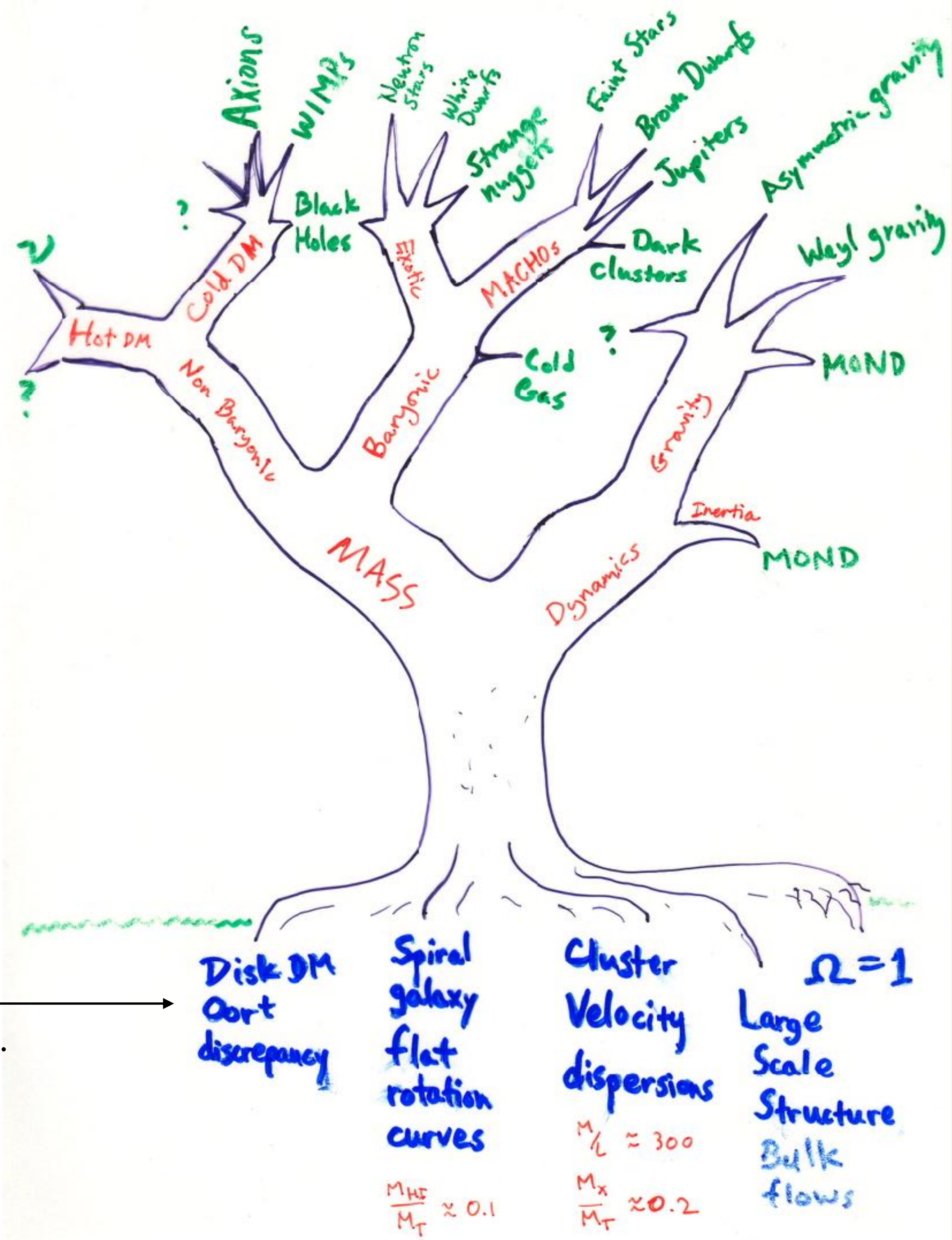
Hypothesized solutions

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,
- 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 $\partial \log \Delta / \partial \varpi$.

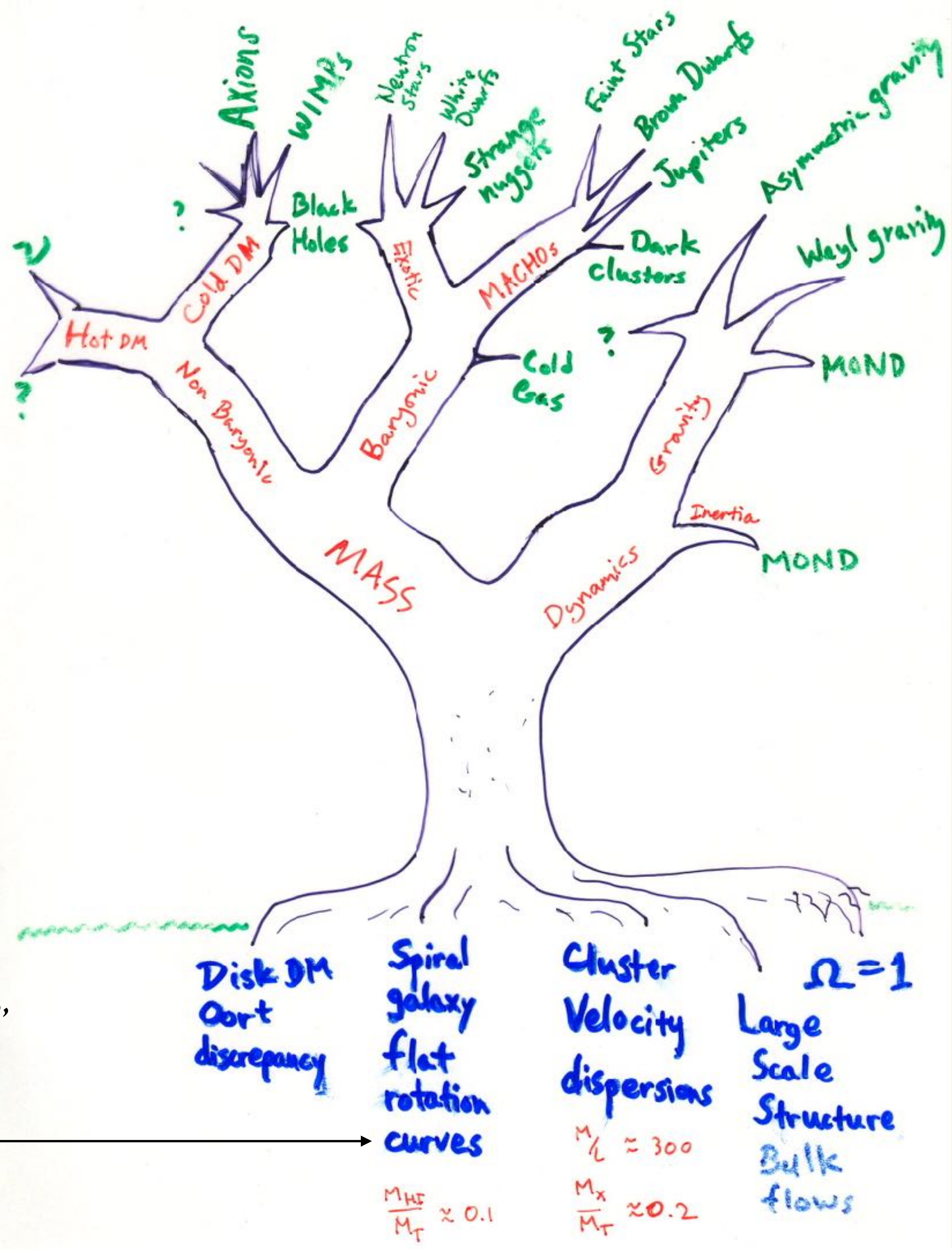
Summary of the different sections.

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.

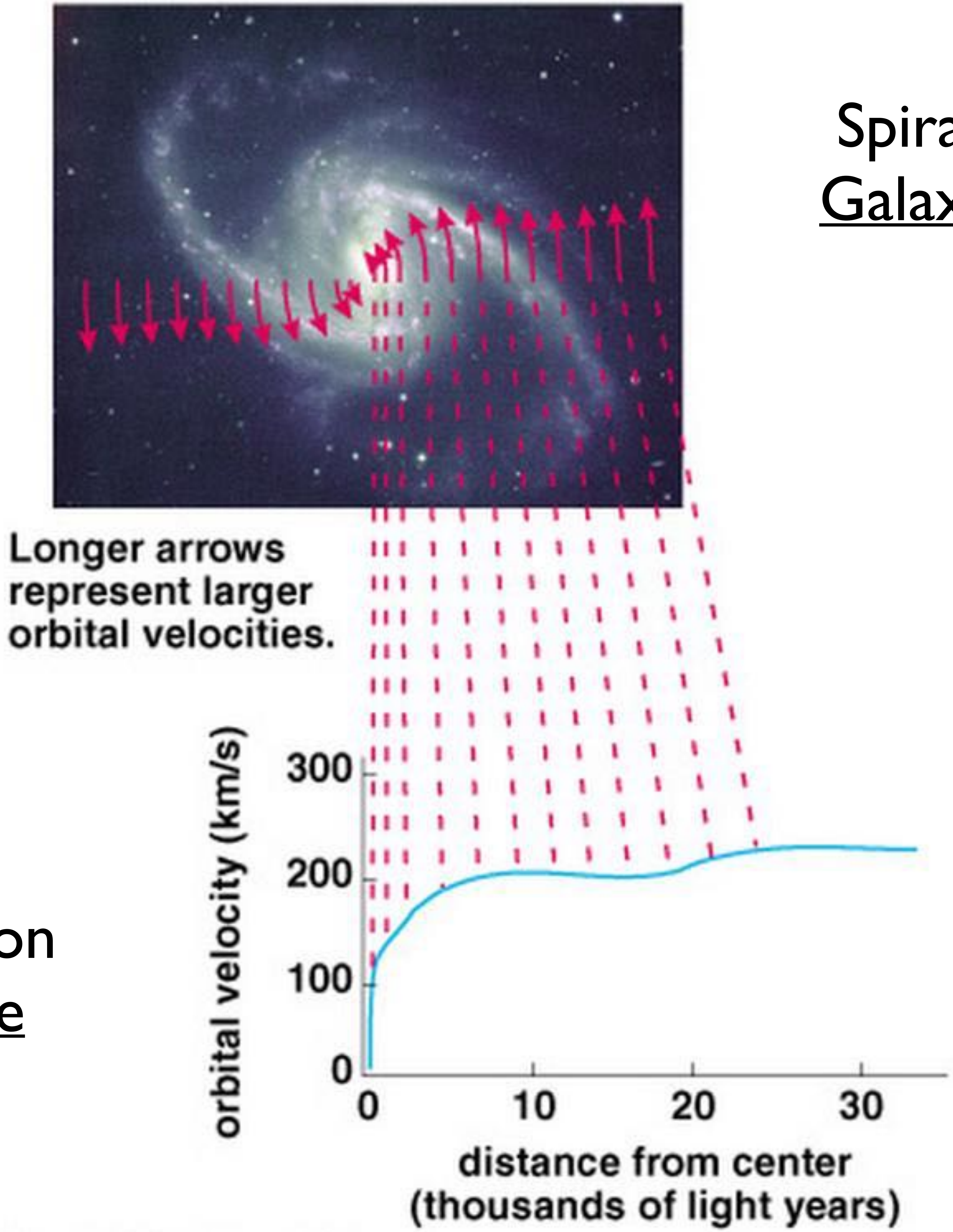
5. With the aid of the data contained in the two preceding sections I have computed the acceleration $K(z)$ between $z = 0$ and $z = 600$. The computations were made by successive approximations; the B stars were eliminated first. The results are in Table 14 and Figure 4, $K'(z)$ giving the values finally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

There seems to be more dynamical mass than luminous mass beyond the edge of spiral galaxies (Opik 1920s? Babcock 1950s, Roberts 1960s, Rubin, Shostak 1970s, Bosma 1980s).

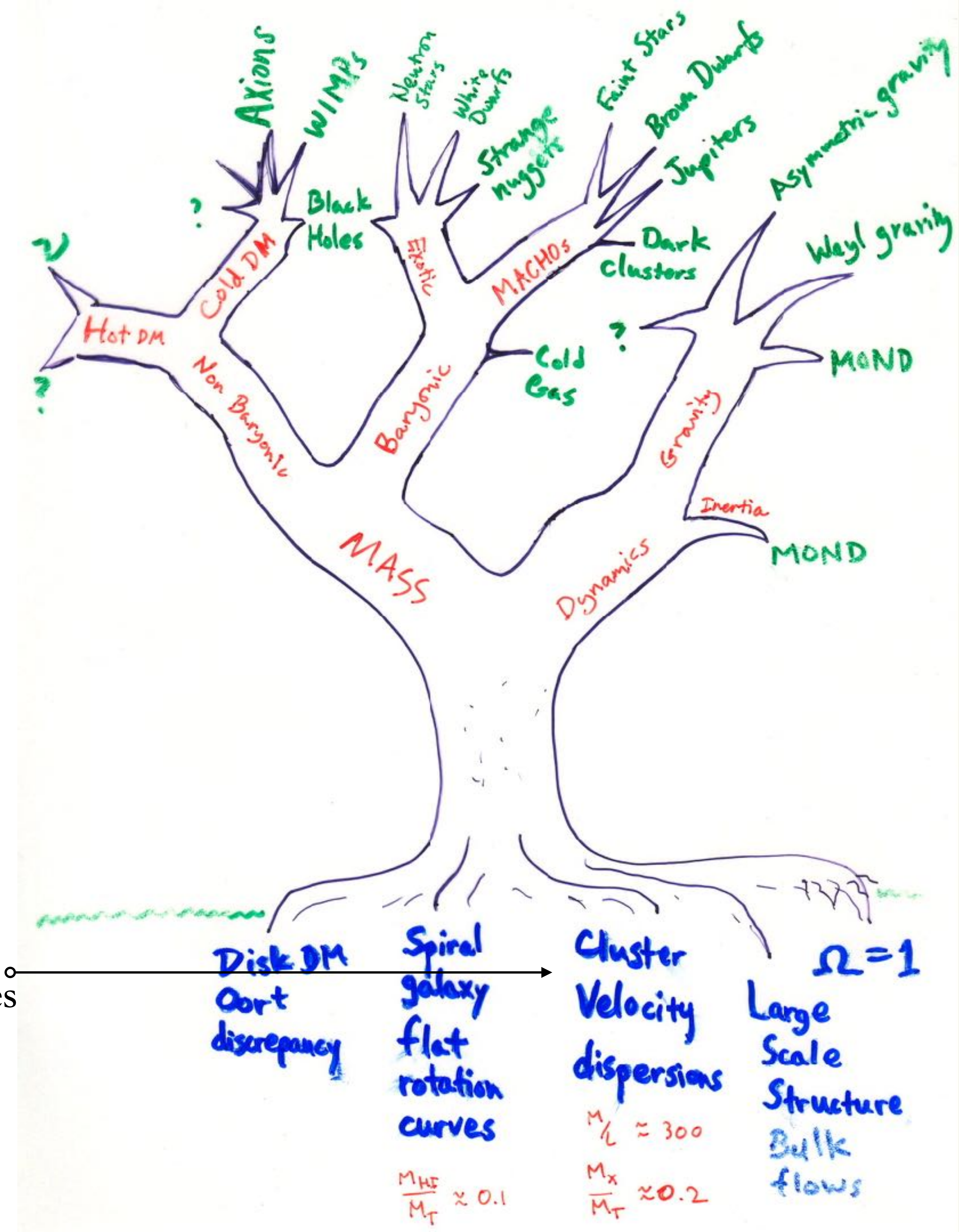
A factor of ~2 - 10 problem



Spiral Galaxy



Rotation Curve

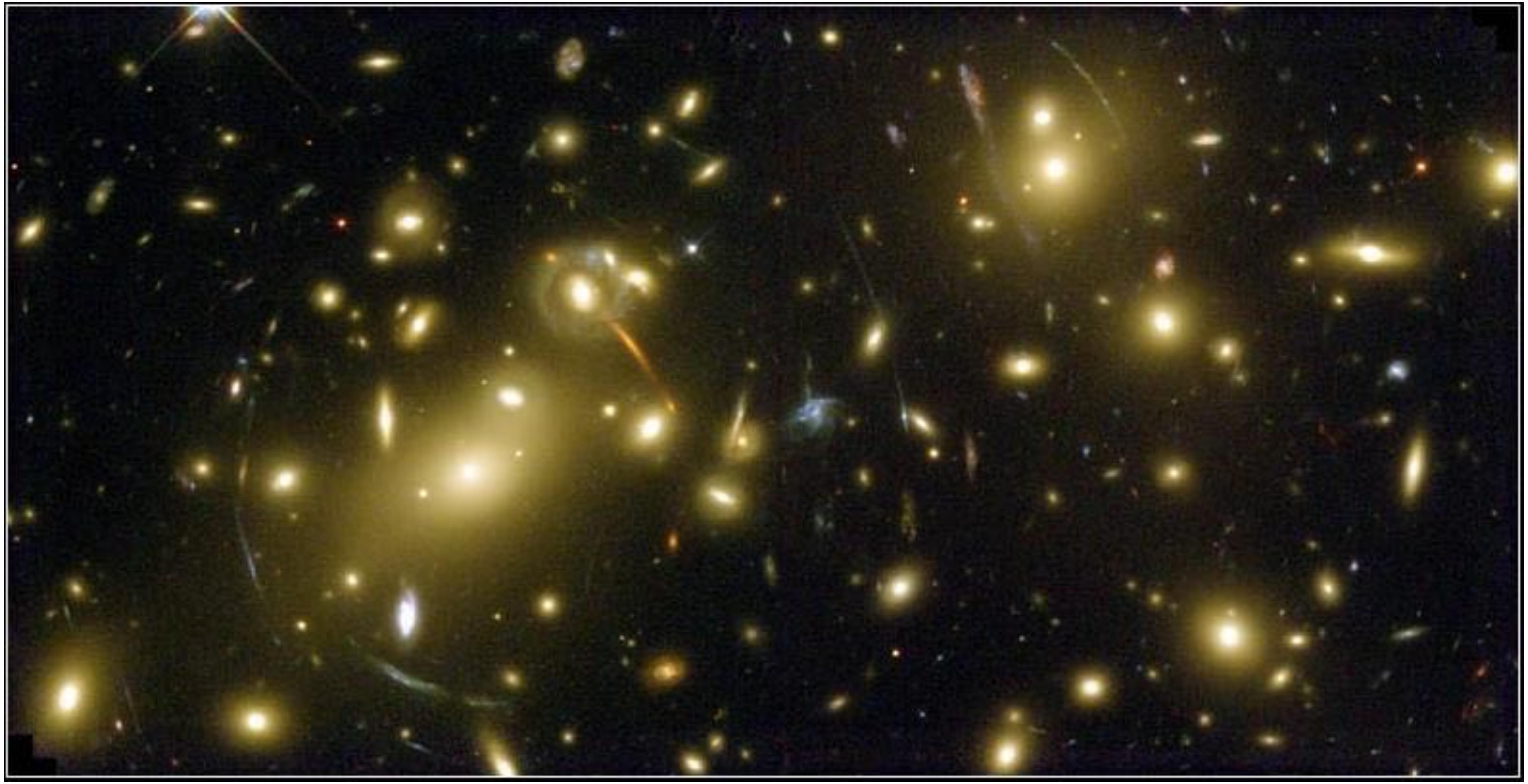


There seems to be more dynamical mass than luminous mass in clusters of galaxies (Zwicky 1933, 1937).

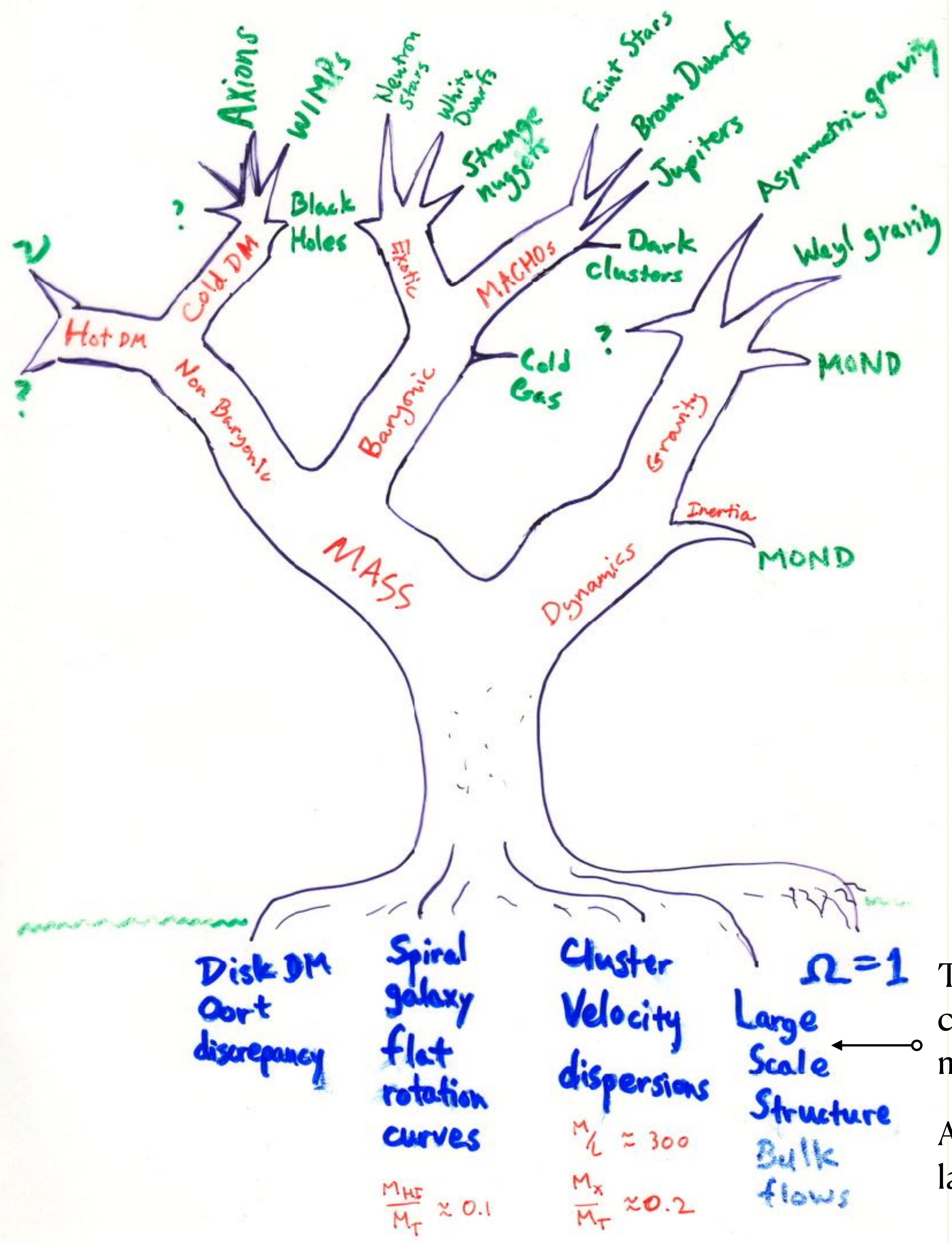
A factor of ~100 - 1000 problem

Galaxy Cluster

Zwicky 1933, 1937



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

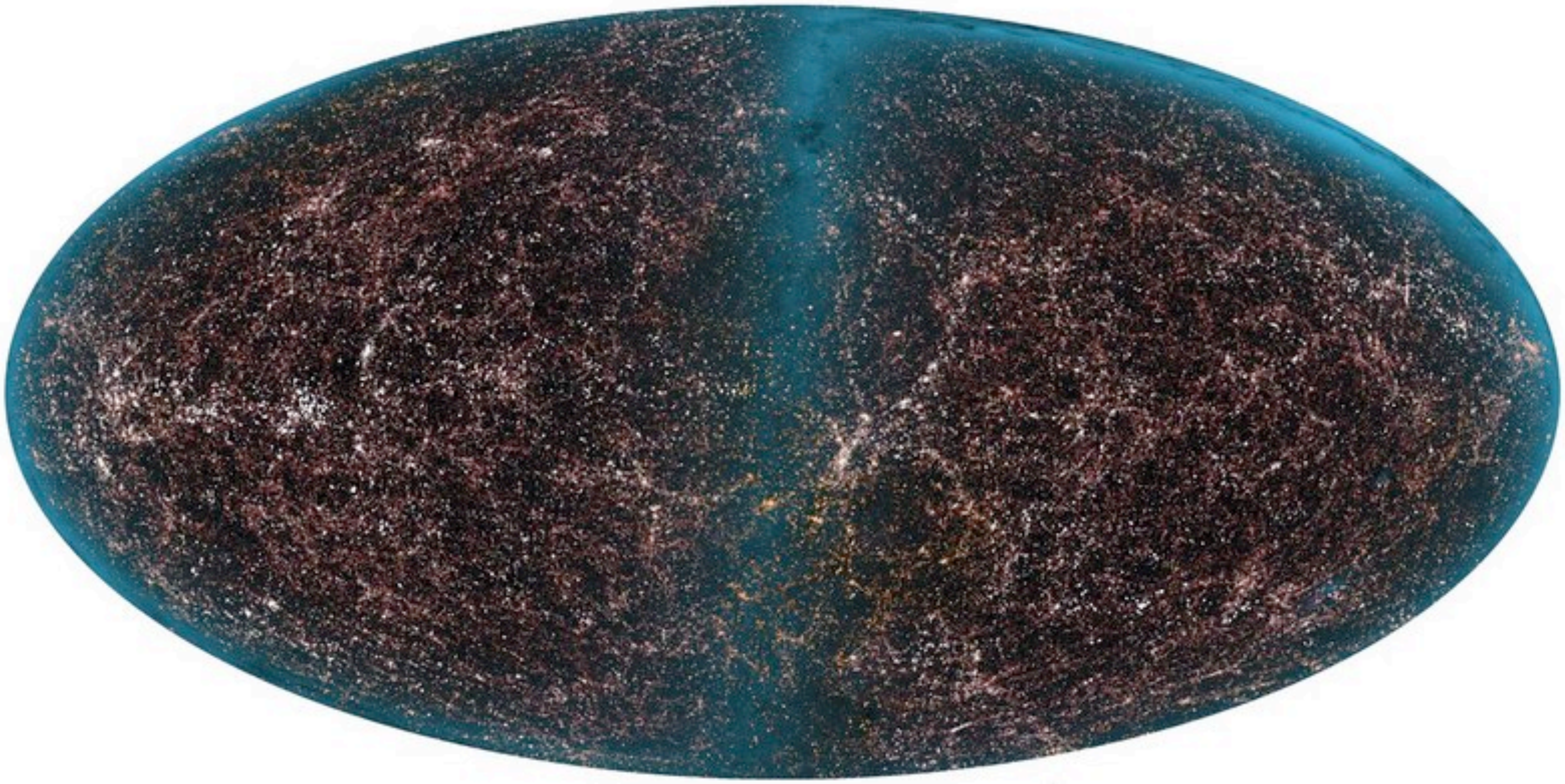


There needs to be more gravitation than can be provided by baryons [normal matter] (Peebles; Silk 1960s).

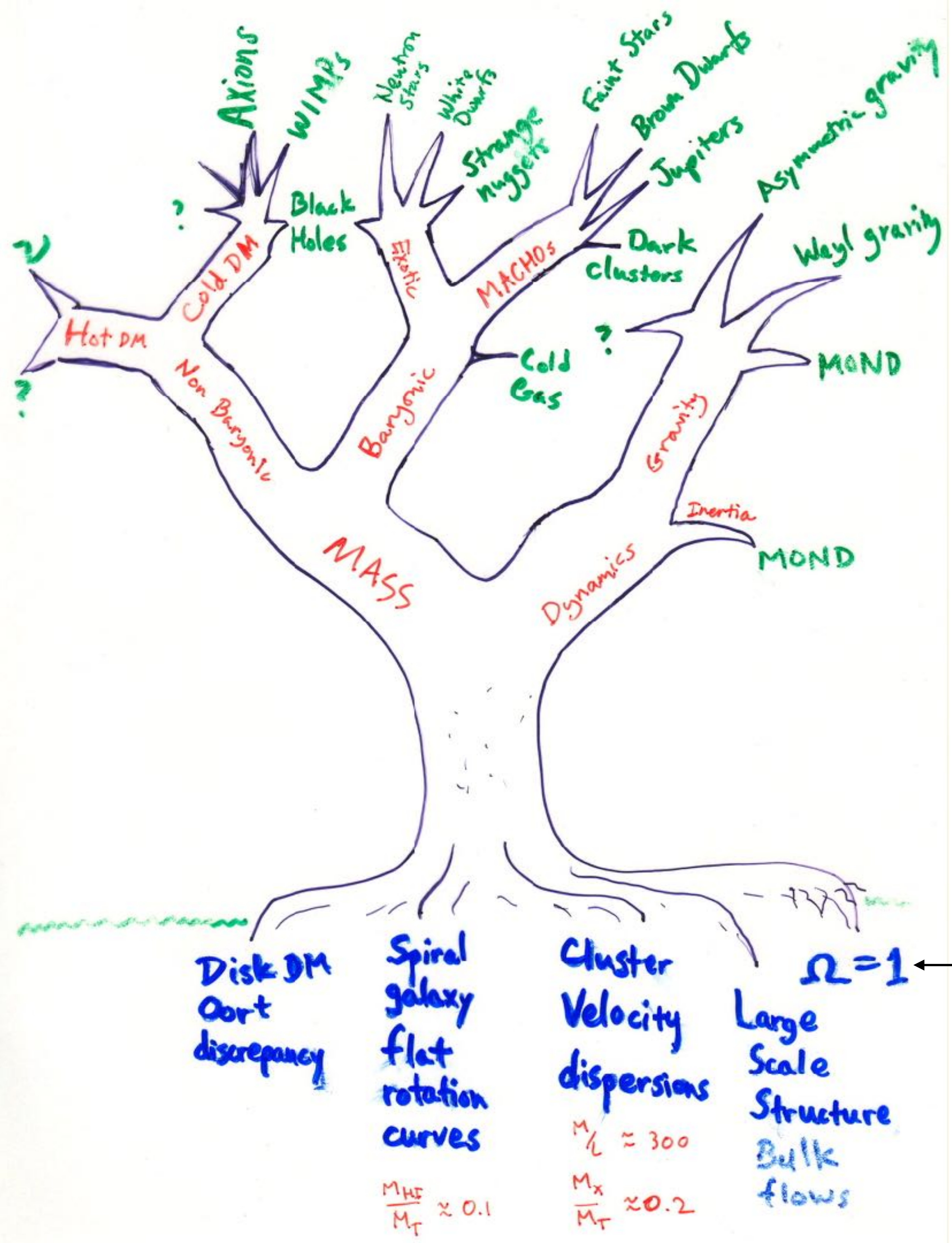
A factor of ~100 problem in the growth of large scale structure

Large Scale Structure

Each dot is an entire galaxy



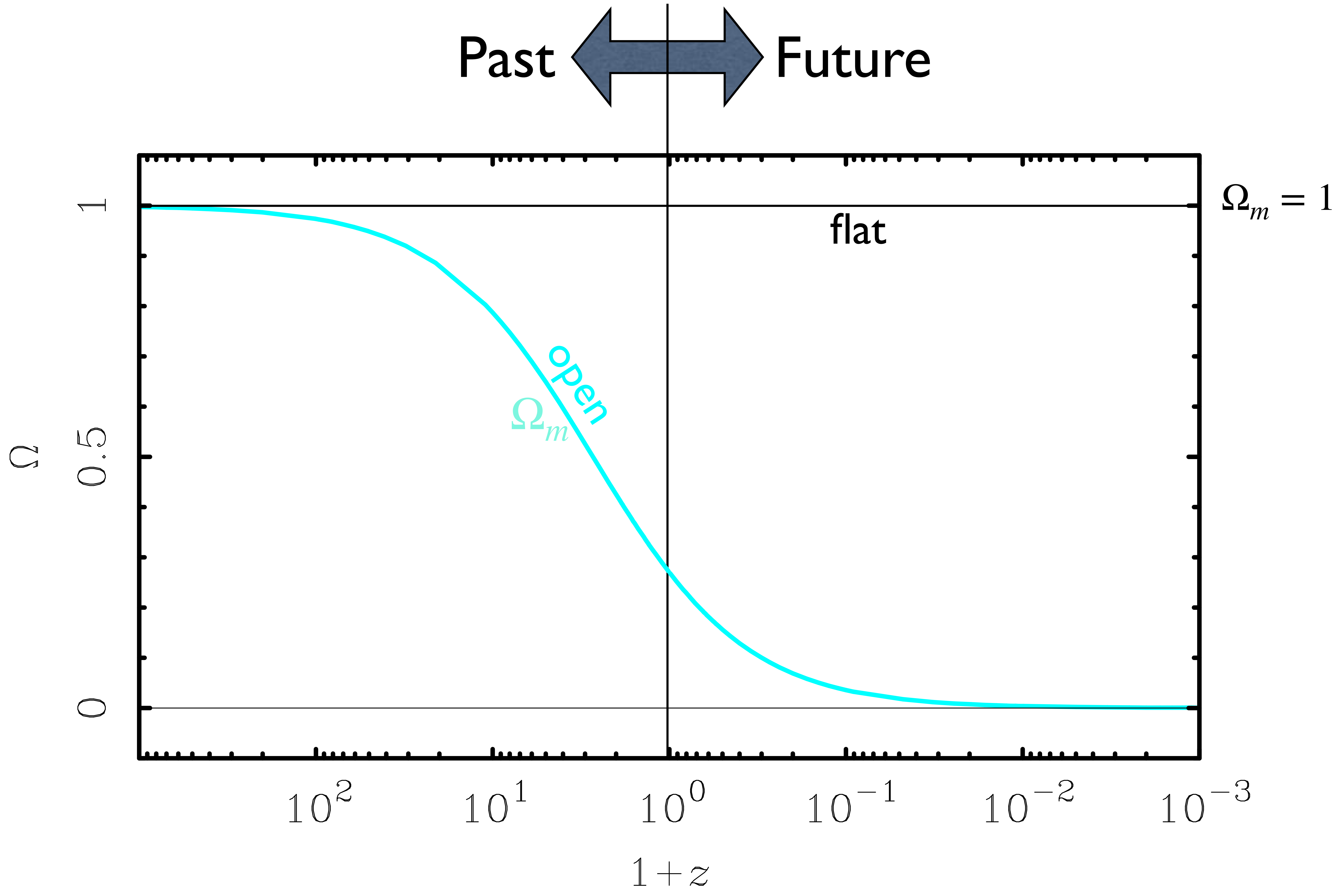
Need something to prompt structure formation - gravity + visible matter don't suffice



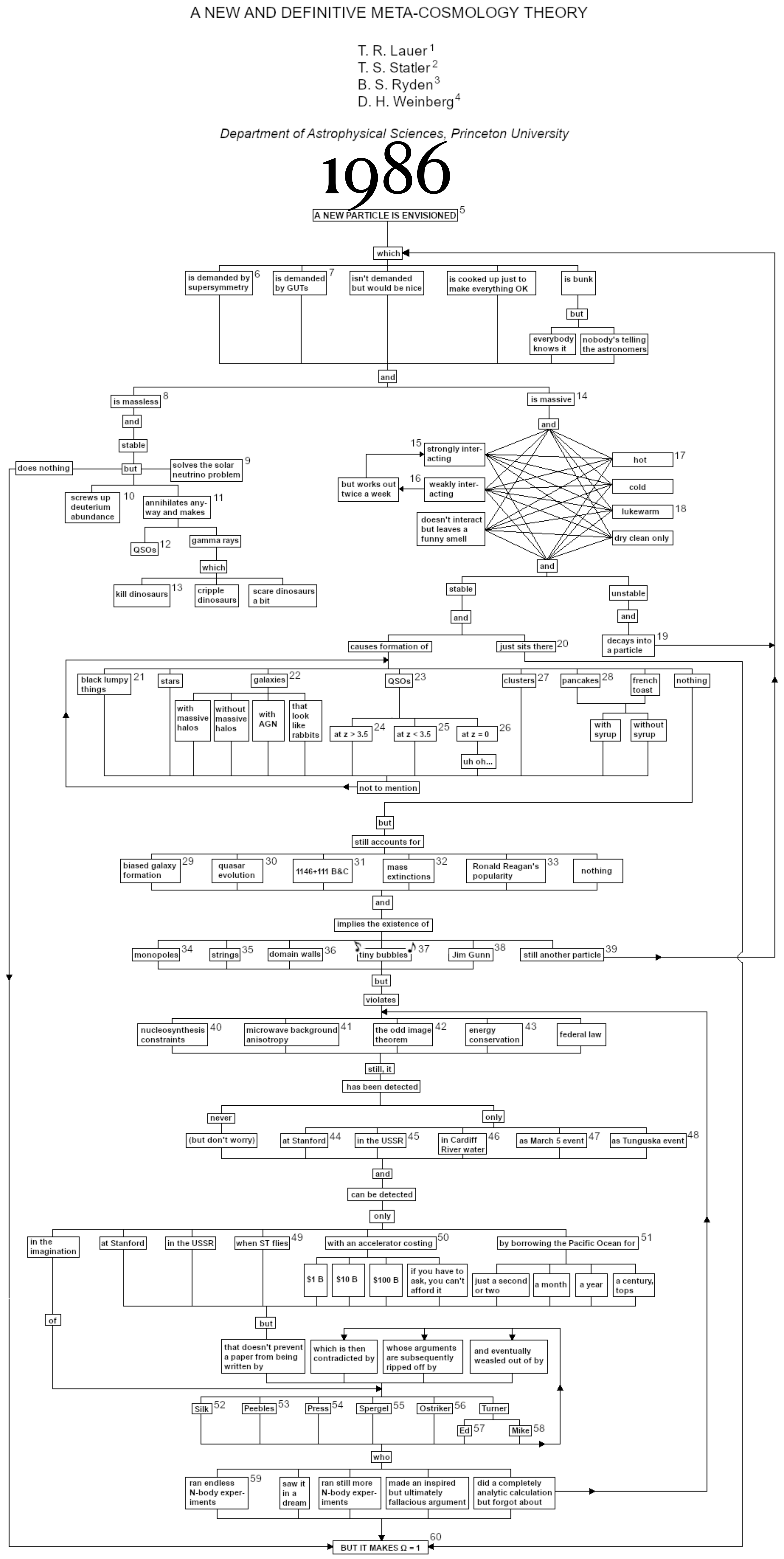
Theoretical desire for $\Omega_m = 1$

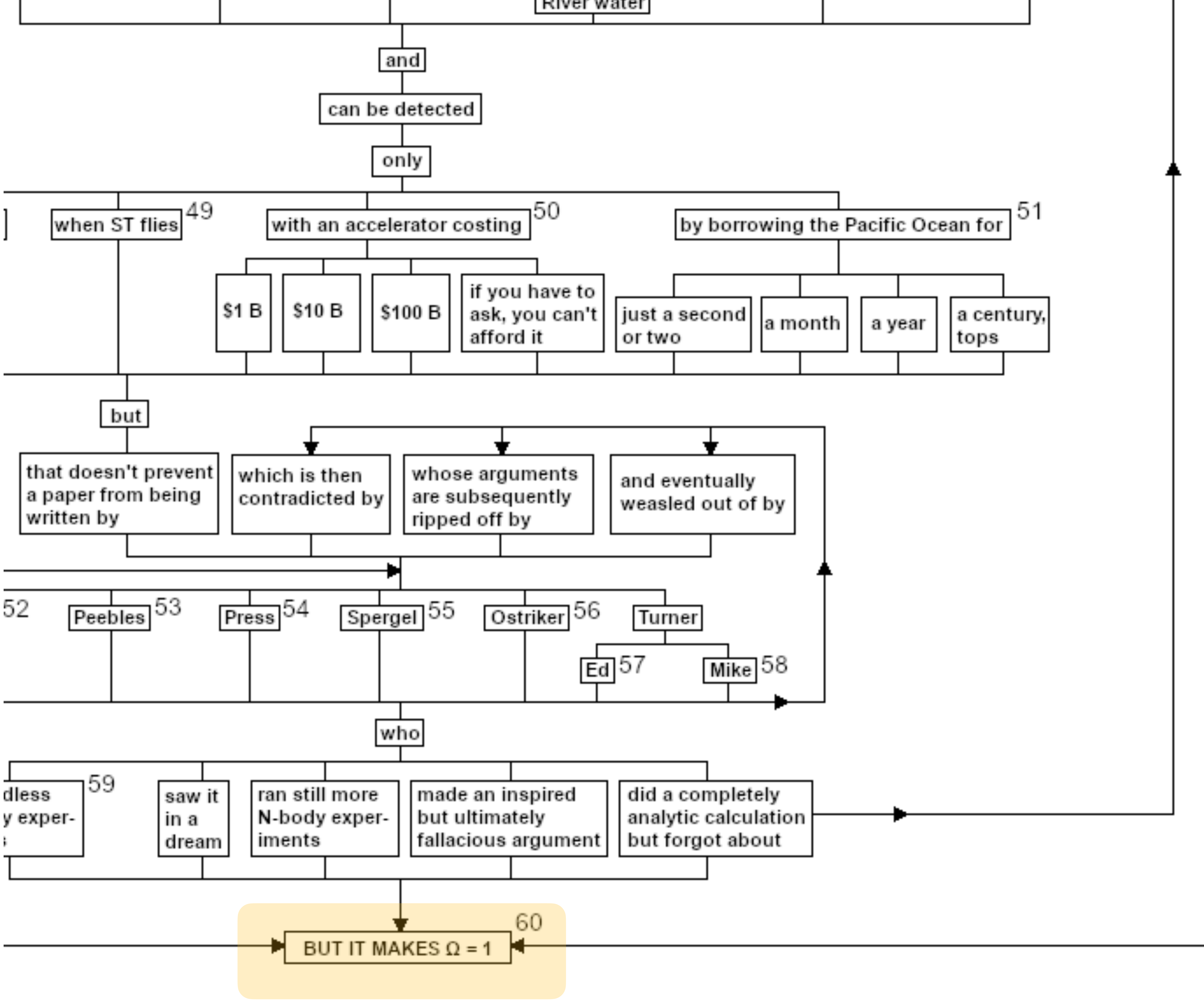
(Guth; Linde 1980 [Inflation]).

A factor of ~a few issue



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


A NEW AND DEFINITIVE META-COSMOLOGY THEORY
T. R. Lauer 1
T. S. Statler 2
B. S. Ryden 3
D. H. Weinberg 4
Department of Astrophysical Sciences, Princeton University
1986
A NEW PARTICLE IS ENVISIONED 5
which
is demanded by supersymmetry 6
is demanded by GUTs 7
isn't demanded but would be nice
is cooked up just to make everything OK
is bunk
but
everybody knows it
nobody's telling the astronomers
and
is massless 8
is massive 14
and
stable
does nothing
but
solves the solar neutrino problem 9
screws up deuterium abundance 10
annihilates anyway and makes 11
QSOs 12
gamma rays
which
kill dinosaurs 13
cripple dinosaurs
scare dinosaurs a bit
strongly interacting 15
but works out twice a week
weakly interacting 16
doesn't interact but leaves a funny smell
hot 17
cold
lukewarm 18
dry clean only
and
stable
unstable
and
and
causes formation of
just sits there 20
decays into a particle 19
black lumpy things 21
stars
galaxies 22
QSOs 23
clusters 27
pancakes 28
french toast
nothing
with massive halos
without massive halos
with AGN
that look like rabbits
at z > 3.5 24
at z < 3.5 25
at z = 0 26
uh oh...
with syrup
without syrup
not to mention
but
still accounts for
biased galaxy formation 29
quasar evolution 30
1146+111 B&C 31
mass extinctions 32
Ronald Reagan's popularity 33
nothing
and
implies the existence of
monopoles 34
strings 35
domain walls 36
tiny bubbles 37
Jim Gunn 38
still another particle 39
but
violates
nucleosynthesis constraints 40
microwave background anisotropy 41
the odd image theorem 42
energy conservation 43
federal law
still, it
has been detected
never
(but don't worry)
only
at Stanford 44
in the USSR 45
in Cardiff River water 46
as March 5 event 47
as Tunguska event 48
and
can be detected
only
in the imagination
of
at Stanford
in the USSR
when ST flies 49
with an accelerator costing 50
$1 B
$10 B
$100 B
if you have to ask, you can't afford it
by borrowing the Pacific Ocean for 51
just a second or two
a month
a year
a century, tops
but
that doesn't prevent a paper from being written by
which is then contradicted by
whose arguments are subsequently ripped off by
and eventually weasled out of by
Silk 52
Peebles 53
Press 54
Spergel 55
Ostriker 56
Turner
Ed 57
Mike 58
who
ran endless N-body experiments 59
saw it in a dream
ran still more N-body experiments
made an inspired but ultimately fallacious argument
did a completely analytic calculation but forgot about
BUT IT MAKES Ω = 1 60


River water
and
can be detected
only
when ST flies 49
with an accelerator costing 50
by borrowing the Pacific Ocean for 51
$1 B
$10 B
$100 B
if you have to ask, you can't afford it
just a second or two
a month
a year
a century, tops
but
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which is then contradicted by
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52
Peebles 53
Press 54
Spergel 55
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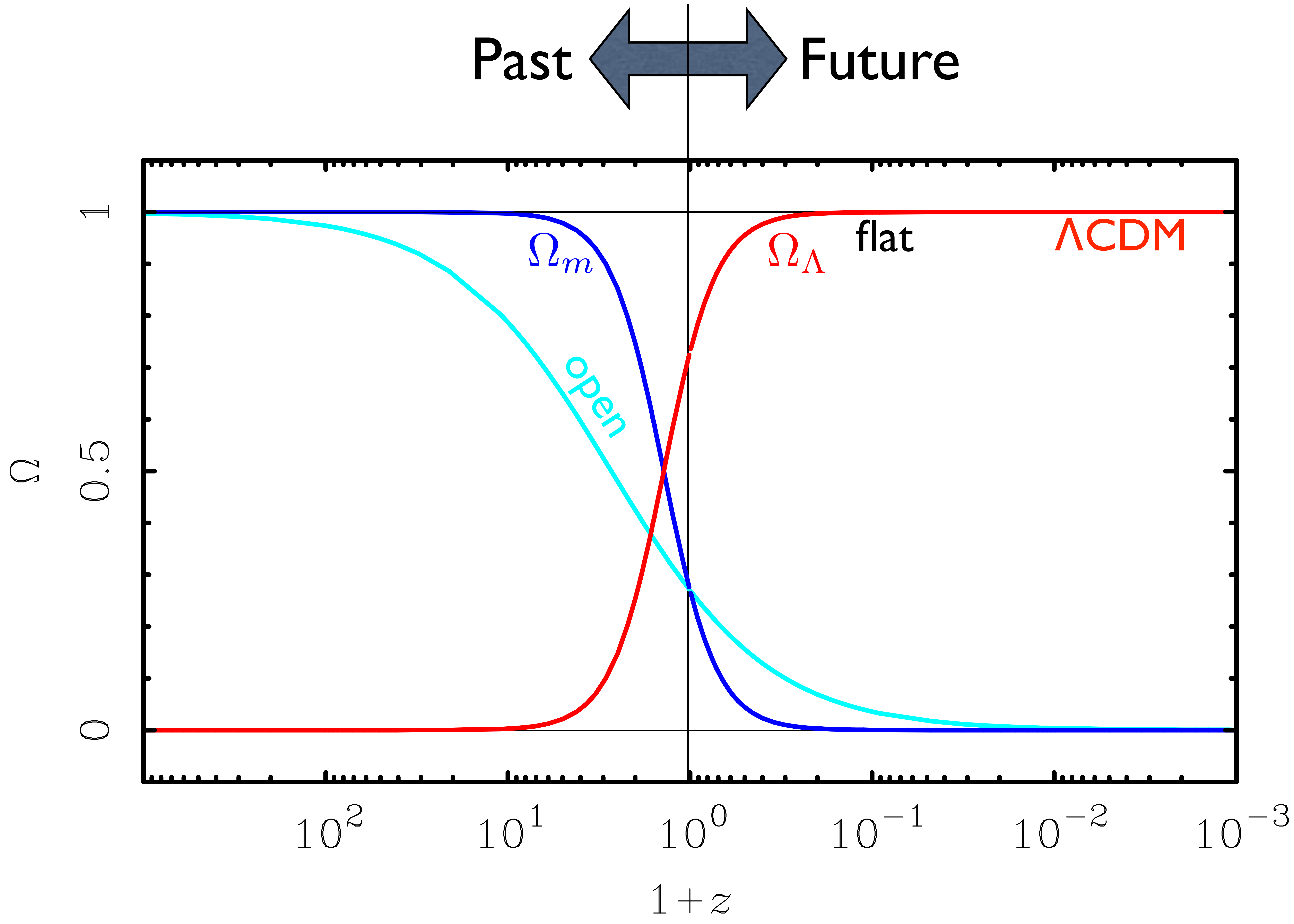

Coincidence/flatness problem:
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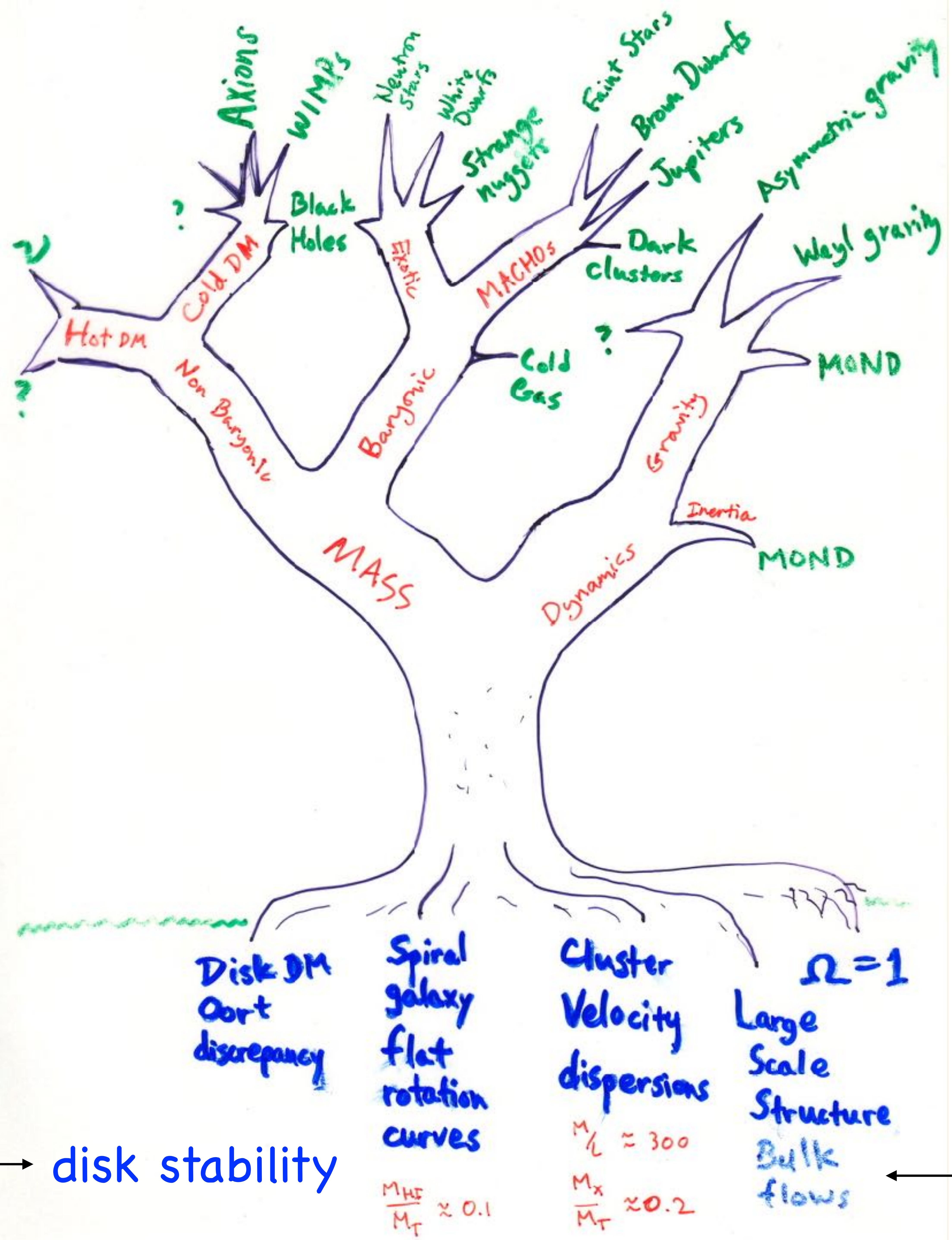
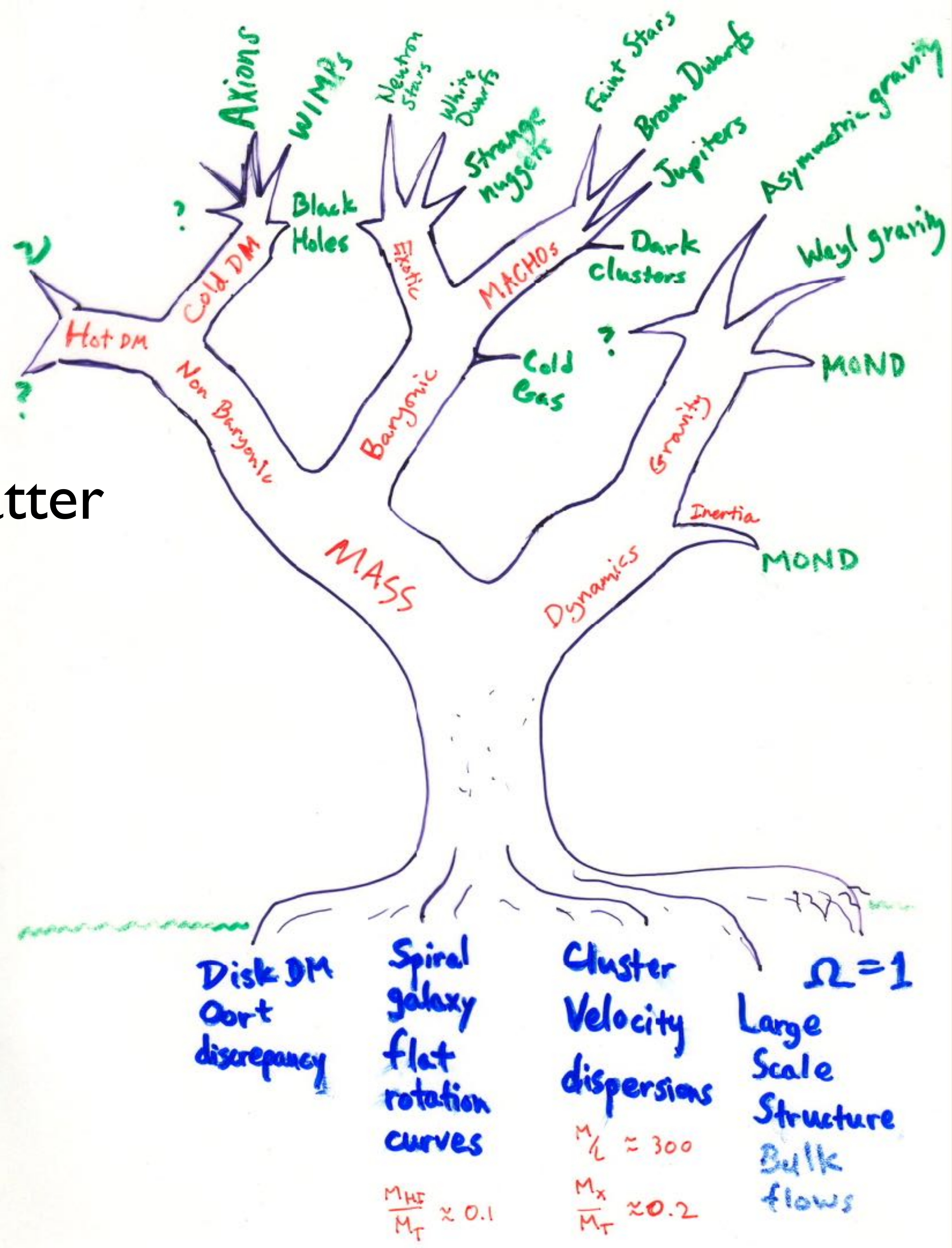


Need something to stabilize spiral galaxies (Ostriker & Peebles 1973) → disk stability

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

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

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)

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

Obvious candidate:
neutrinos

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.

$$\Omega_m > \Omega_b$$

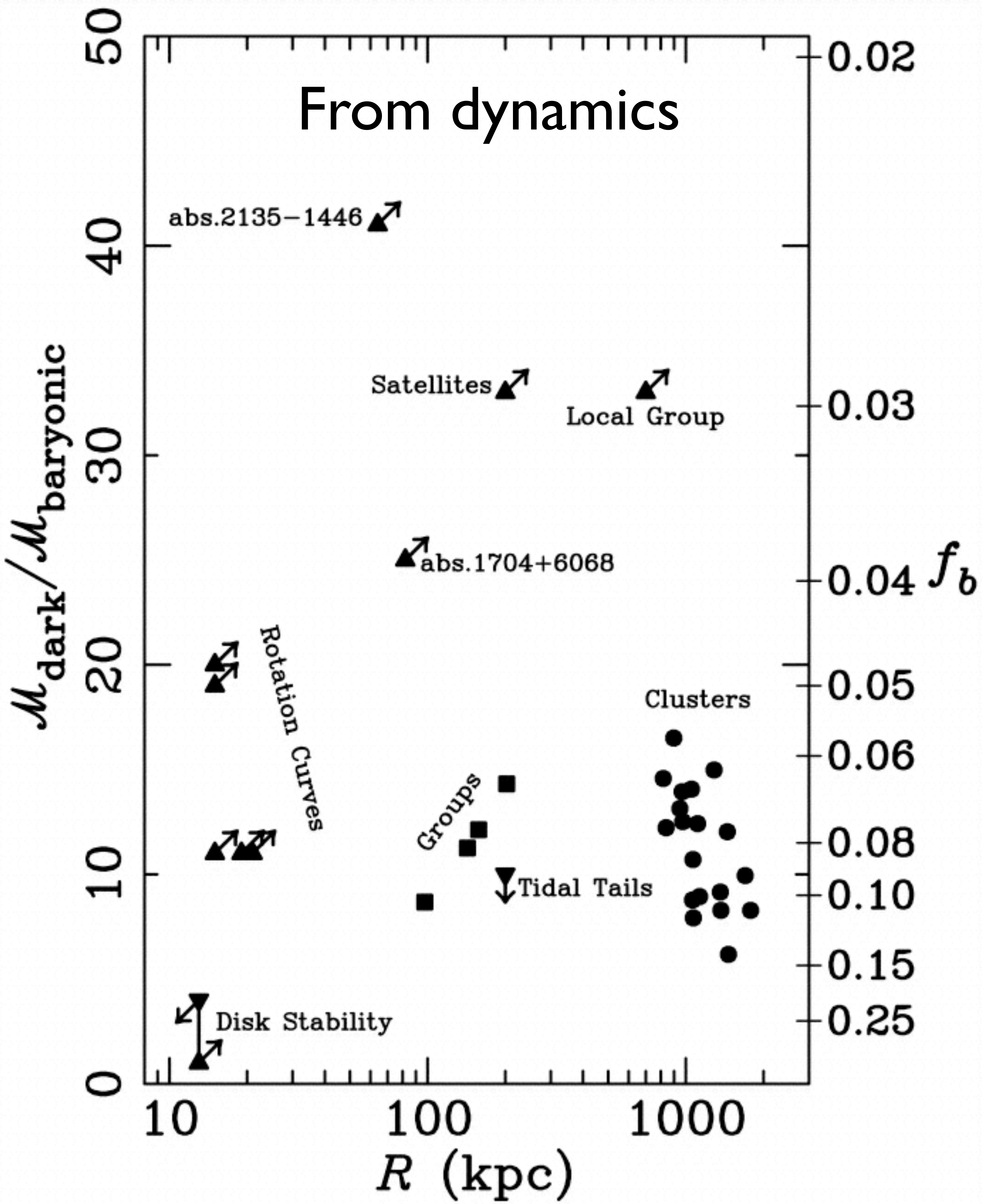
From cosmology

$$\Omega_m \approx 6\Omega_b$$

or equivalently, the baryon fraction

$$f_b = 0.17$$

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

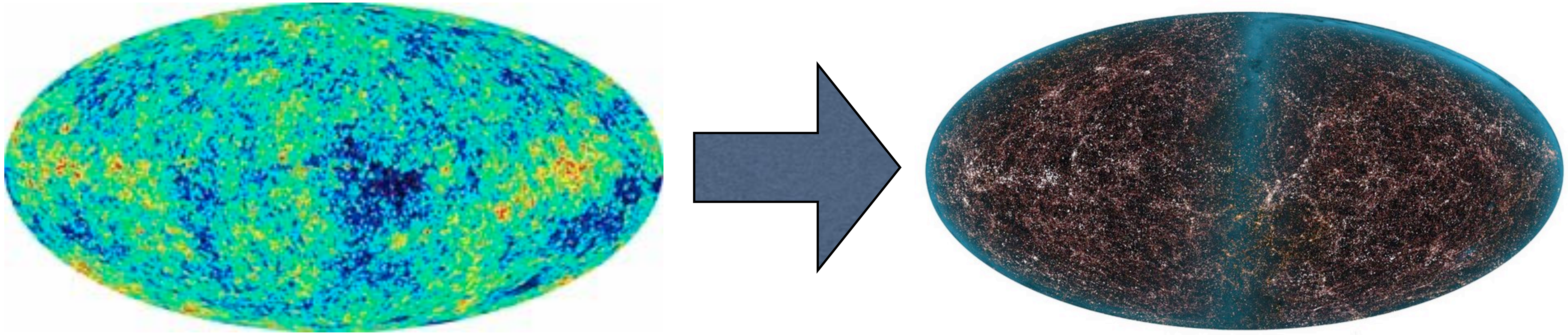


Dynamically cold because

(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

t = 1.4 x 10^{10} yr



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

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

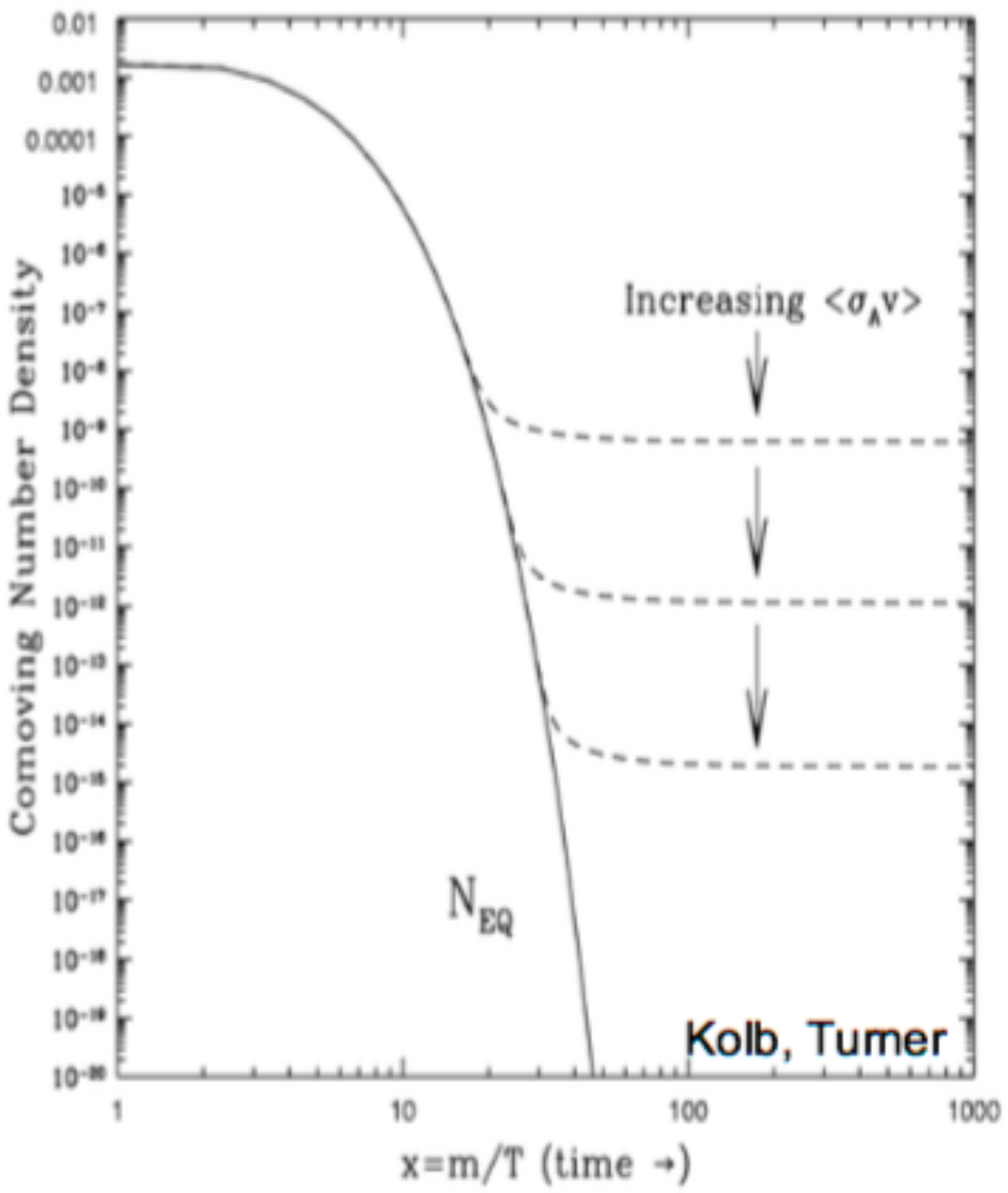
To be CDM

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.

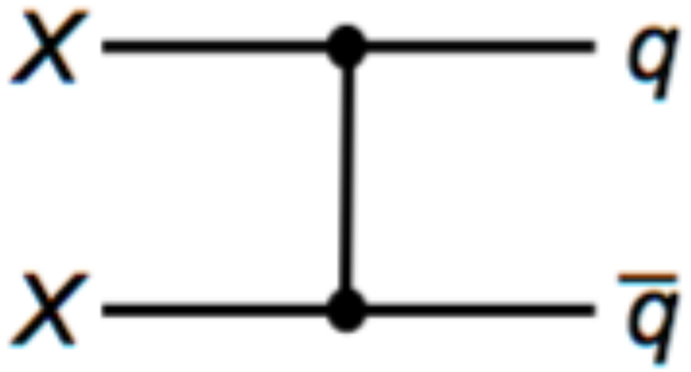
THE WIMP MIRACLE



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

Lots of particle dark matter candidates:

- **WIMPs** — Traditionally preferred candidate for CDM
- **Axions** — Hypothesized for a perceived problem with CP symmetry; not obvious it is related to DM problem
- **Light dark matter** — A low mass WIMP-like entity that violates the Lee-Weinberg limit ($m_X > 2$ GeV)
- **wimpzillas** — A very high mass WIMP-like entity approaching the unitarity limit (1000s of GeV)
- **etc.** — There are limits that exclude many possibilities, yet no limit to stuff we can make up

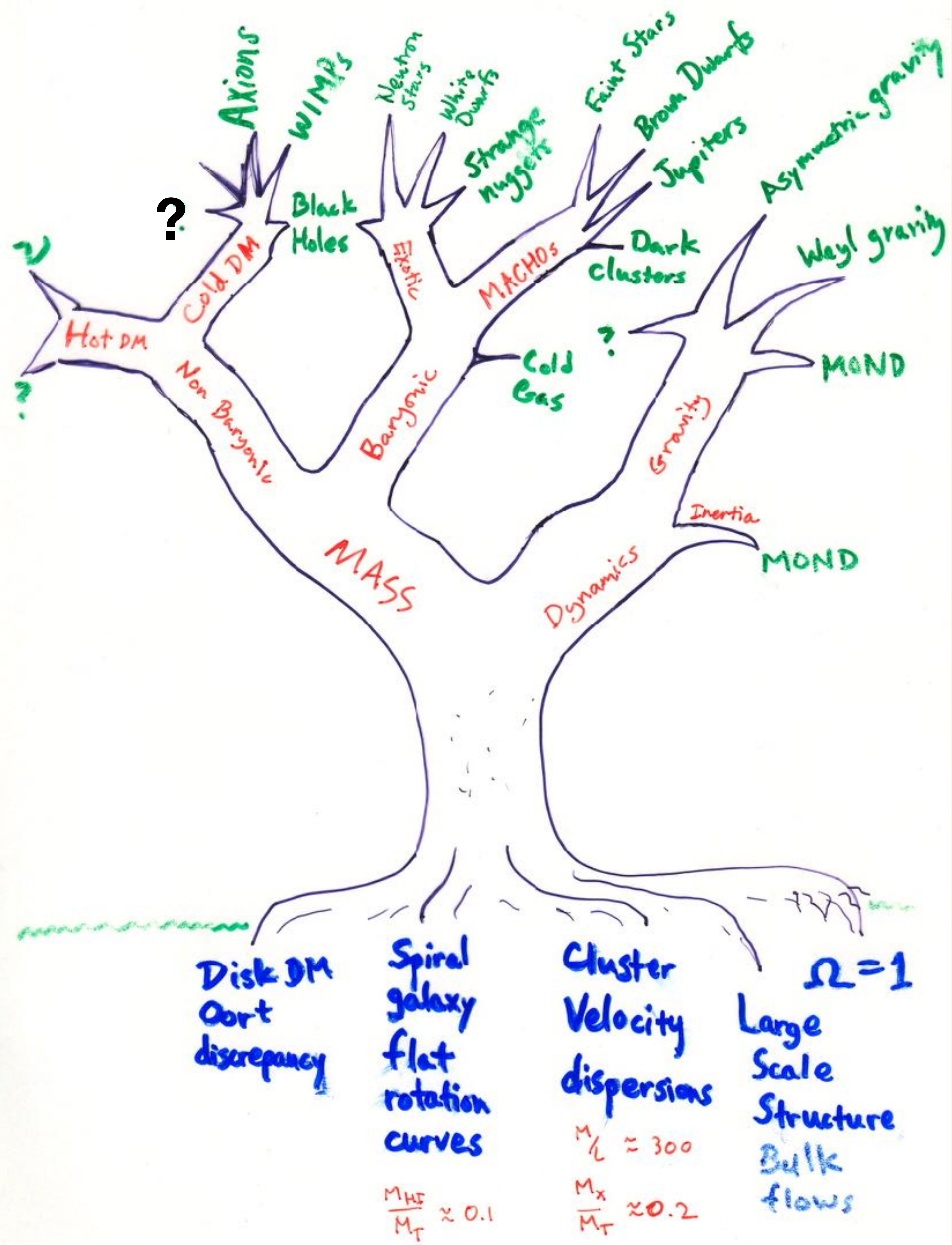
Can imagine other candidates as well:

- **Warm DM** — Low mass (typically keV scale) so not dynamically cold, but not too hot either
- **Self-interacting DM** — These DM particles interact with themselves via some new force that is only active in the dark sector, mediated by dark photons
- **etc.**

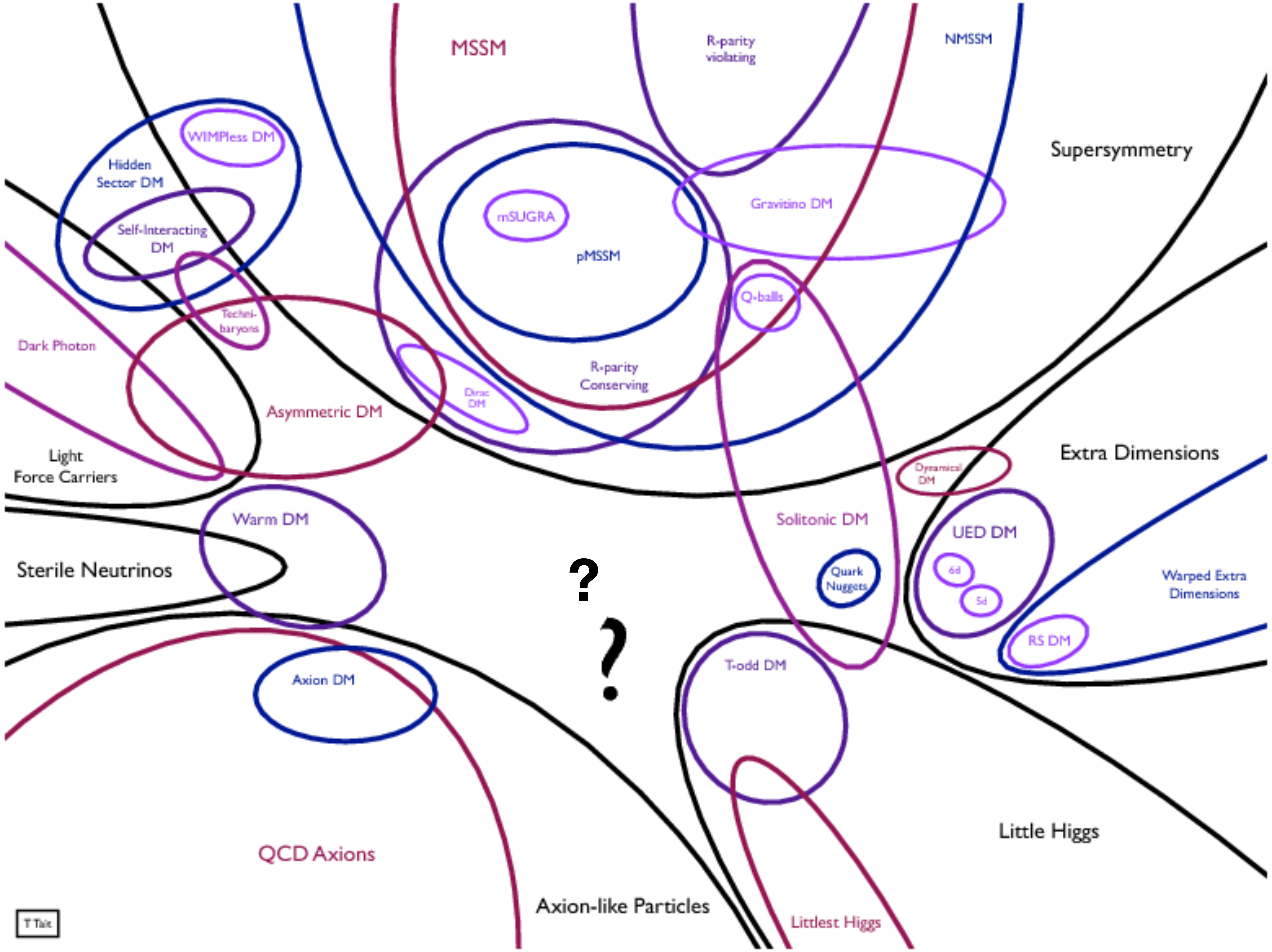
All of these ideas require a new "dark sector" beyond the known physics of the Standard Model. Some require complex dark sectors, with new forces as well as new particles (i.e., new forces of nature that only interact in the dark sector, e.g., dark E&M mediated by dark photons.)

Indeed, the list of dark matter candidates continues to grow

1995



2013



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