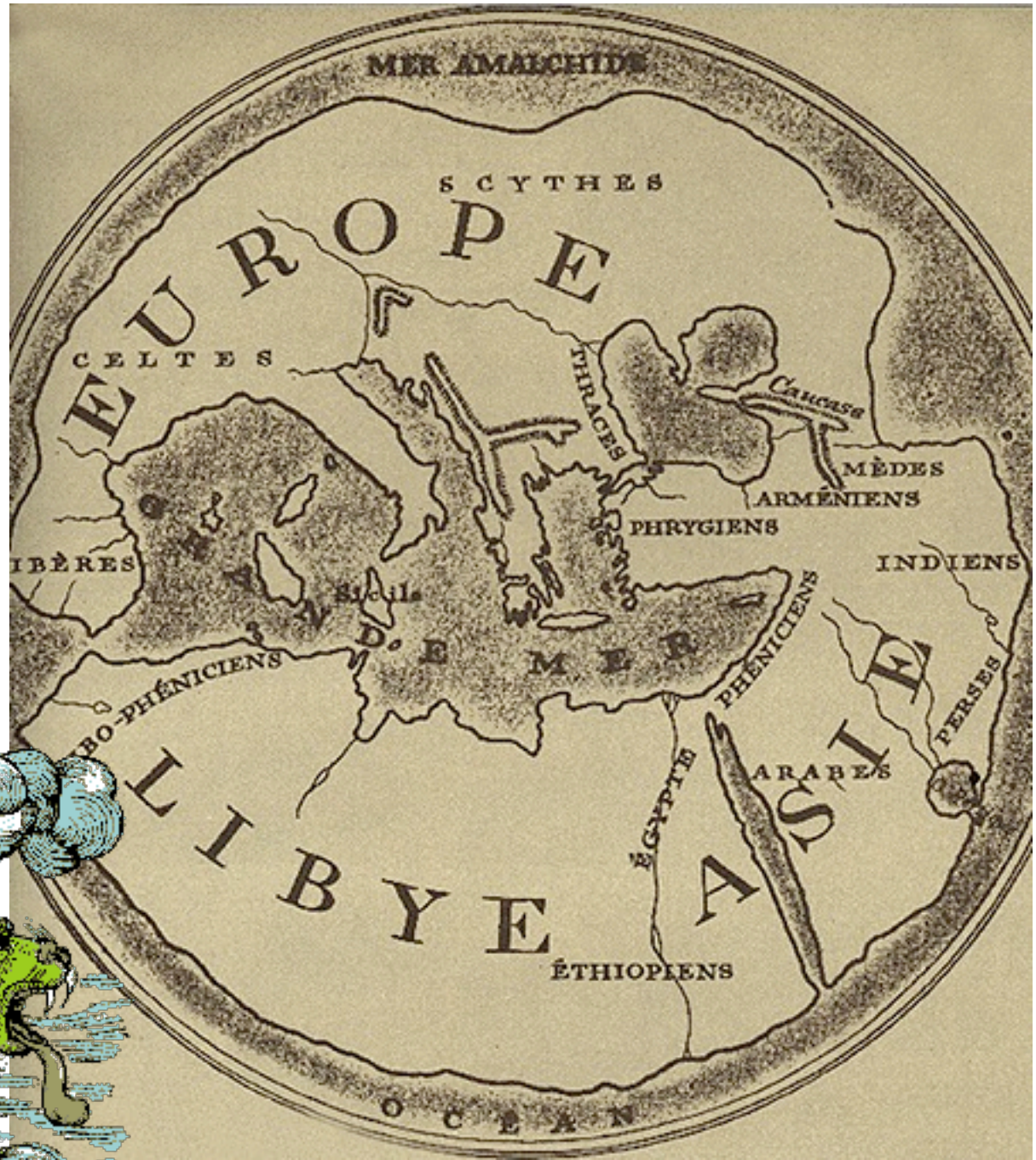
MICHIGAN ASTRONOMY

Cracking the Cosmic Code

Stacy McGaugh
Case Western Reserve University

Ancient Cosmology: A Flat Earth

Here there be dragons!

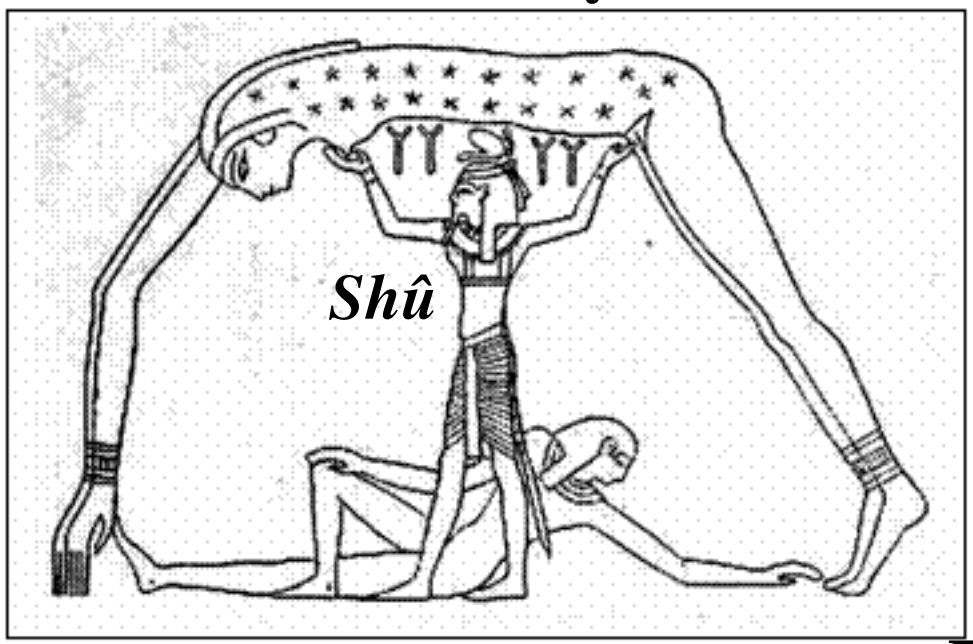


d Map of Hecataeus of Miletus (c. 500 BC)

Nuit, the goddess of the night, was in a tight embrace with her husband *Sibû*, the earth god. Then one day, the god *Shû* grabed her and elevated her to [*become*] the sky despite the protests and painful squirming of Sibû. But Shû has no sympathy for him and freezes Sibû even as he is thrashing about. And so he remains to this day, his twisted pose generating the irregularities we see on the Earth's surface. Nuit is supported by her arms and legs which become the columns holding the sky.

Ancient Egyptian Creation Myth

Nuit - the sky



Sibû - the earth

UP

DOWN

The ancient Egyptians conceived the sky as a roof placed over the world supported by columns placed at the four cardinal points. The Earth was a flat rectangle, longer from north to south, whose surface bulges slightly and having the Nile as its center. On the south there was a river in the sky supported by mountains and on this river the sun god made his daily trip (this river was wide enough to allow the sun to vary its path as it is seen to do). The stars were suspended from the heavens by strong cables, but no apparent explanation was given for their movements.

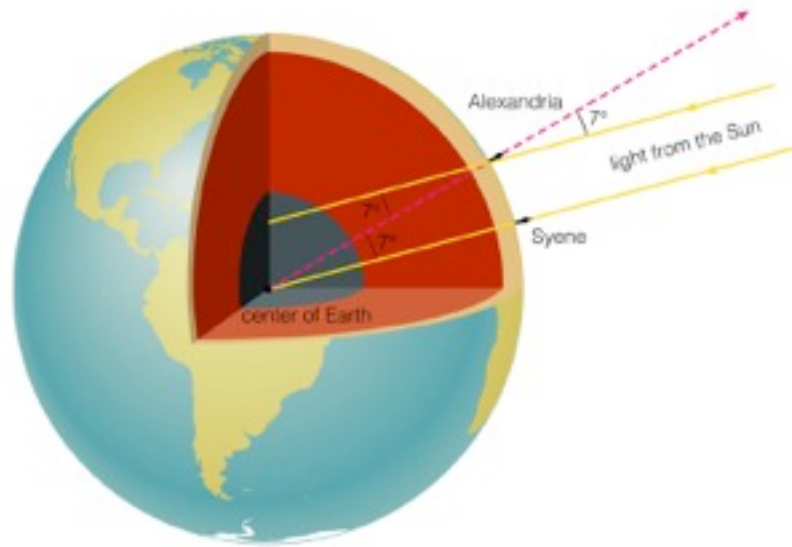
THE ANCIENT HEBREW CONCEPTION
OF THE UNIVERSE

TO ILLUSTRATE THE ACCOUNT OF CREATION AND THE FLOOD

Incan Cosmology

The Ancient Greeks recognized that the earth is round

Eratosthenes measures the Earth (c. 240 B.C.)



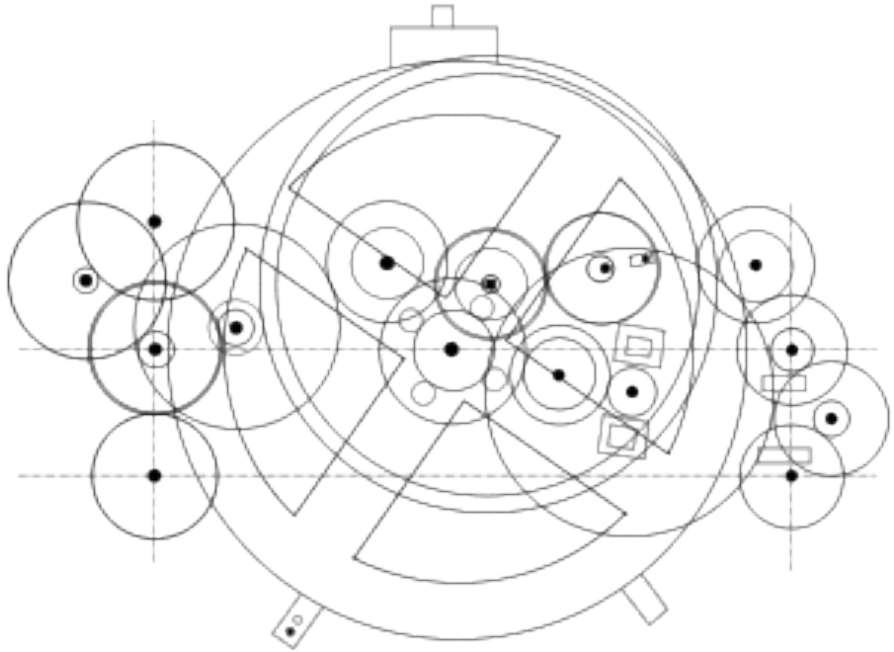
<u>Measurements:</u>

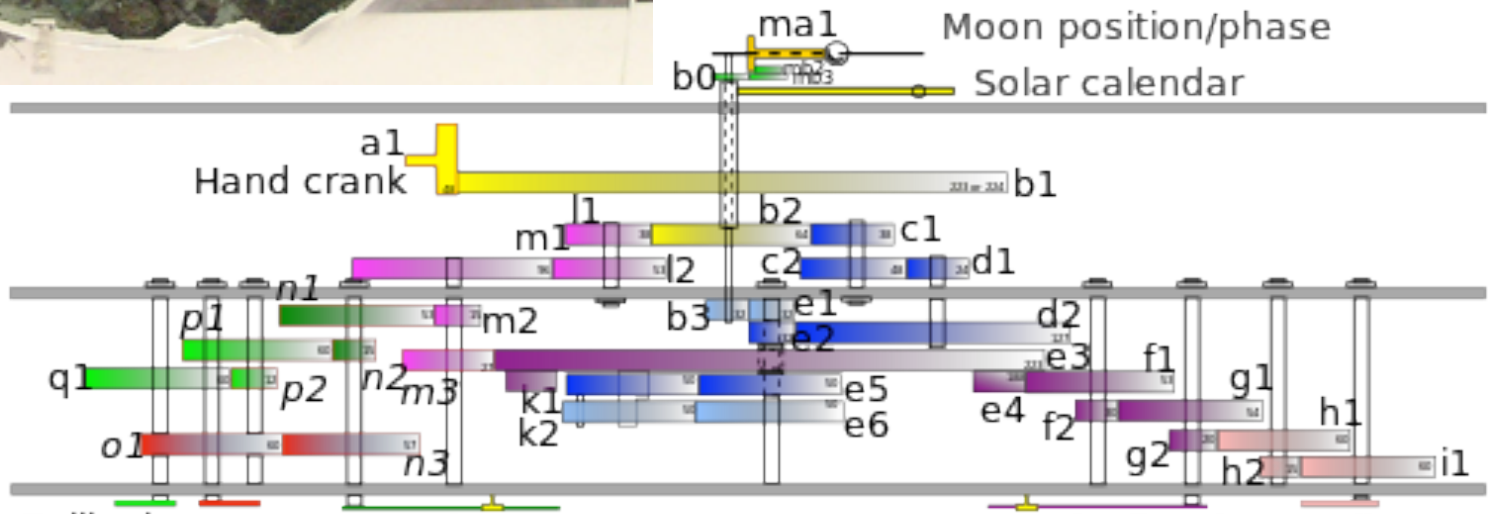
Syene to Alexandria

- distance ≈ 500 miles
- angle = 7°
- i.e, 7/360 of the circumference
- circumference of the Earth: ≈ 25,000 miles

It was known long before Columbus that the Earth is not flat!

Antikythera mechanism (c. 90 BC)





(improved lunar cycle)

Olympiad

(months/year)

(improved eclipse with location info)

Schools of thought

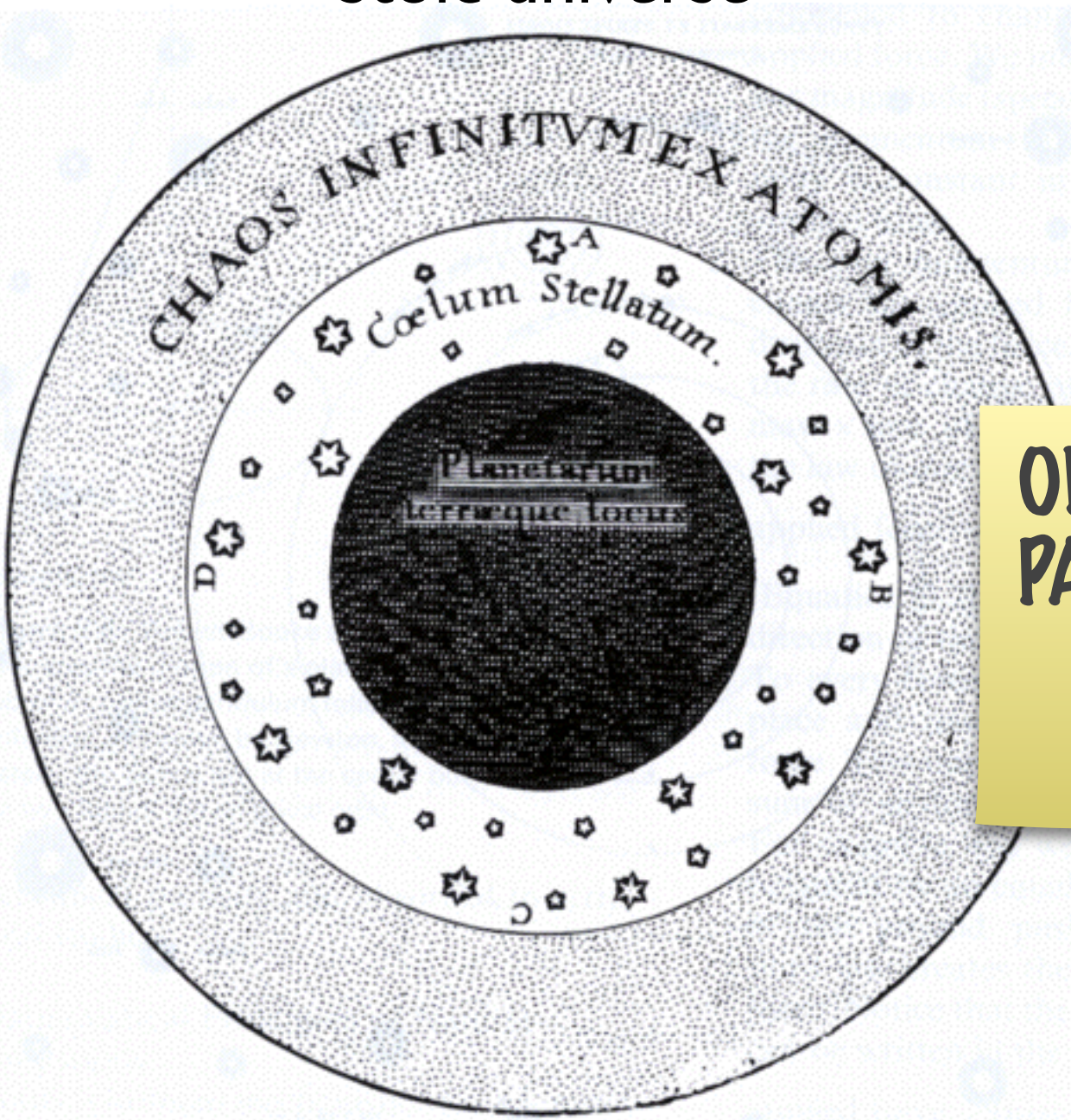
Aristotle: Earth at the center of a finite universe

Stoics: Earth at the center of an indefinite universe

Epicurus: Earth just one of many planets in an infinite universe

Aristarchus: recognized that the sun was larger than the earth, and that the earth orbited the sun.
His original work does not survive and is only known from the criticism of others.

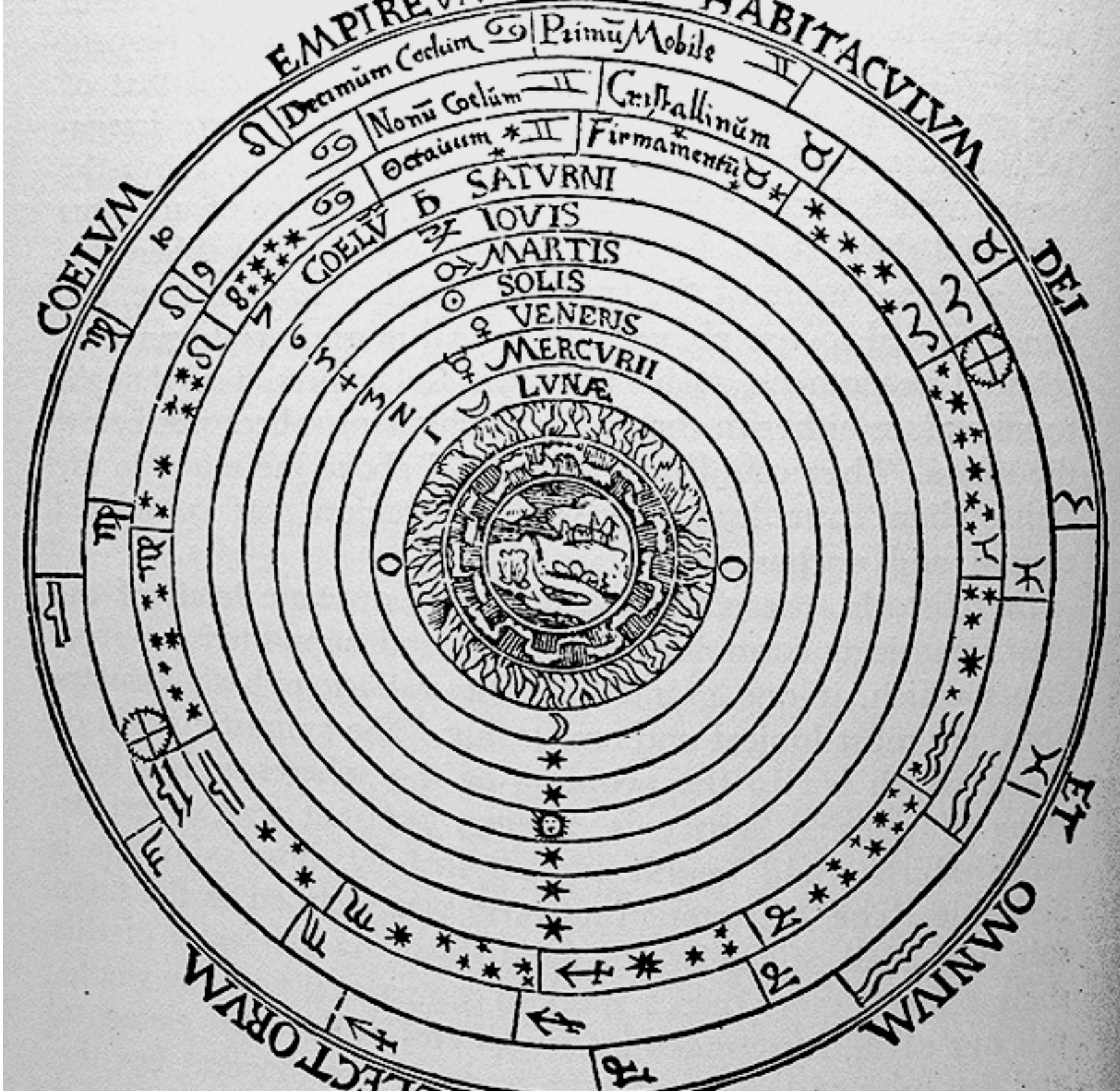
Stoic universe



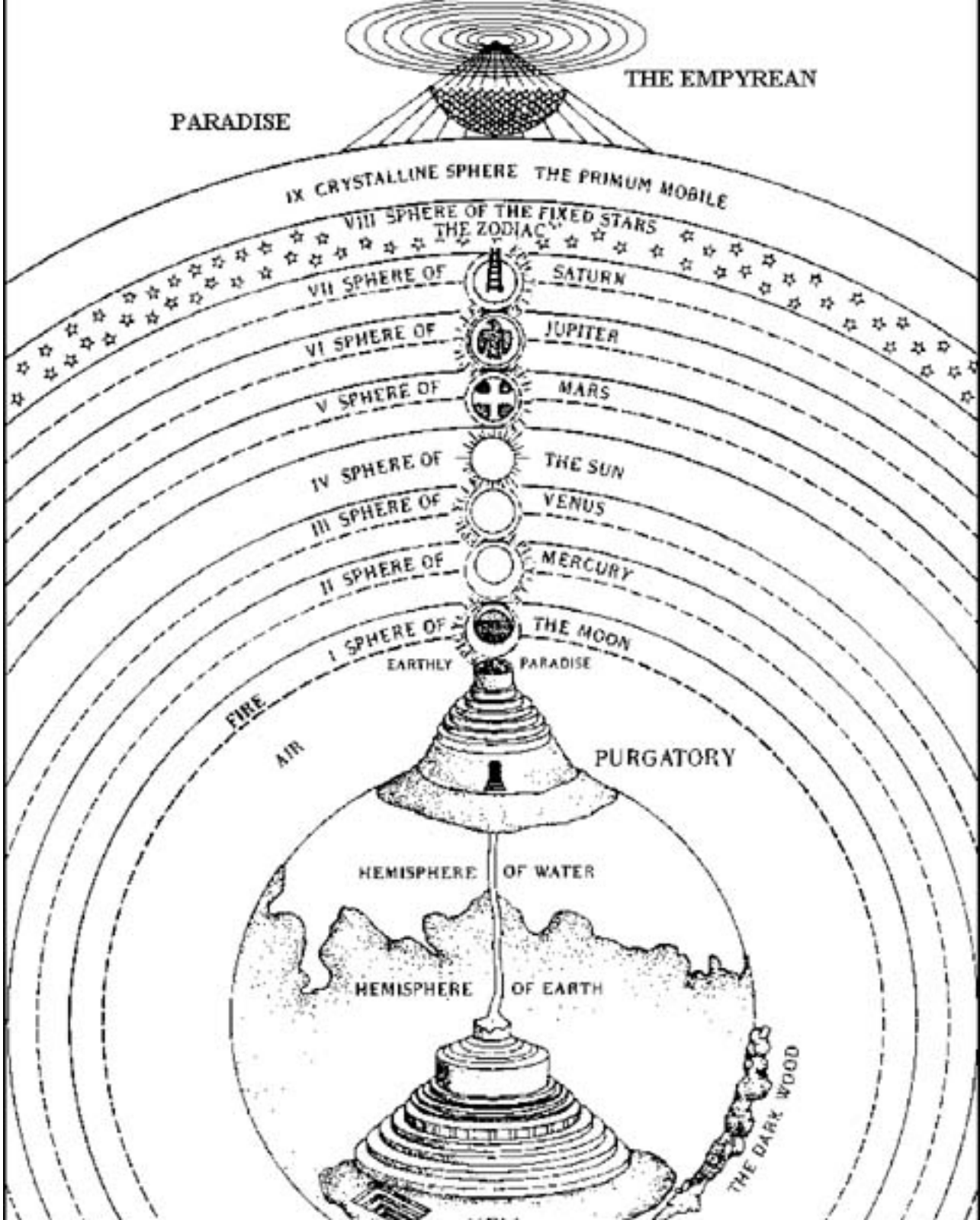
OLBER's PARADOX

Earth at the center surrounded by a finite volume of stars that trails off into an indefinite void.

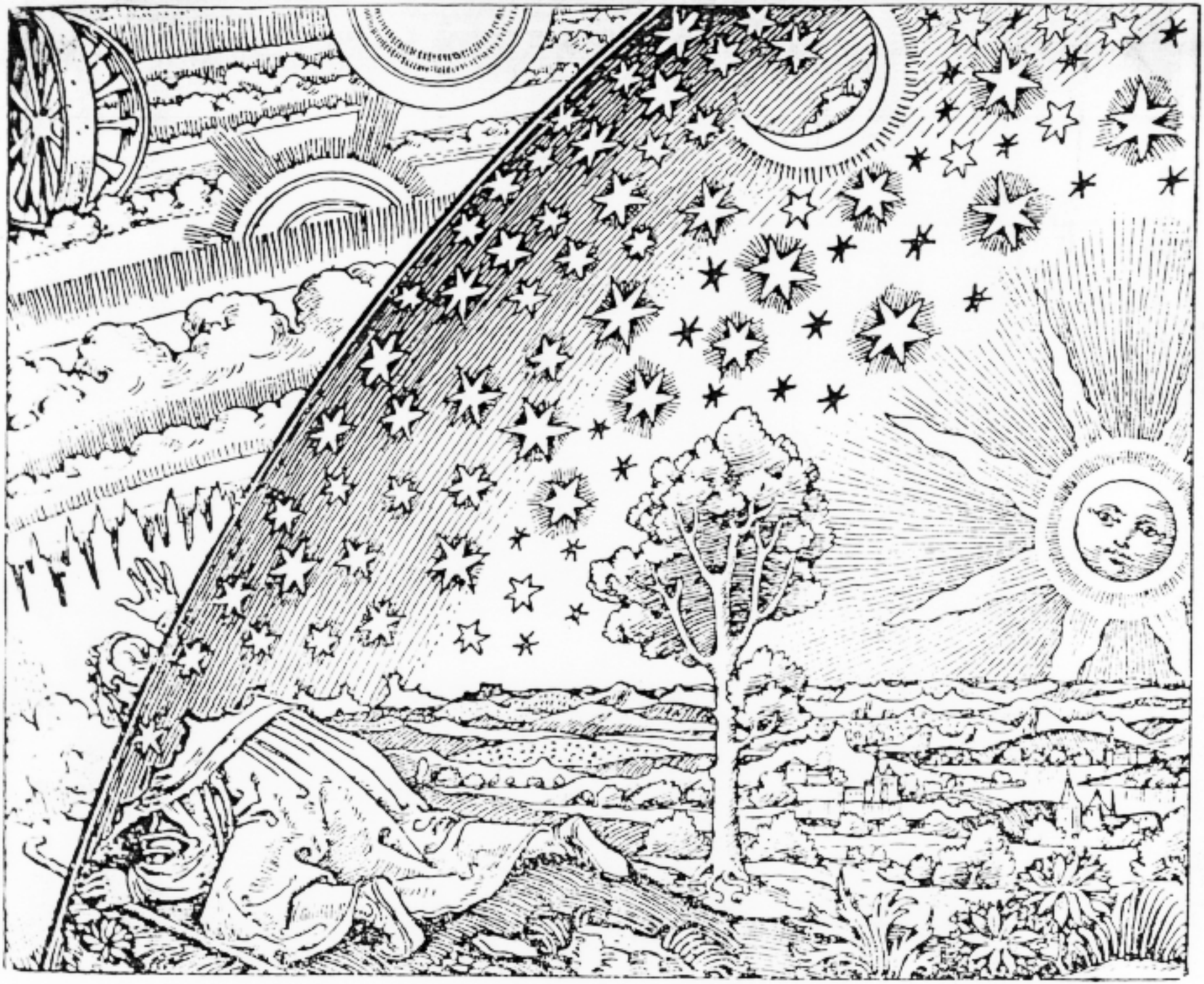
Aristotle argued that the universe had to be finite so that the dome of the sky could rise and set every day - it couldn't go infinitely fast around the fixed earth.



Aristotle's picture of a central earth surrounded by a finite heavenly sphere was adapted by medieval theology

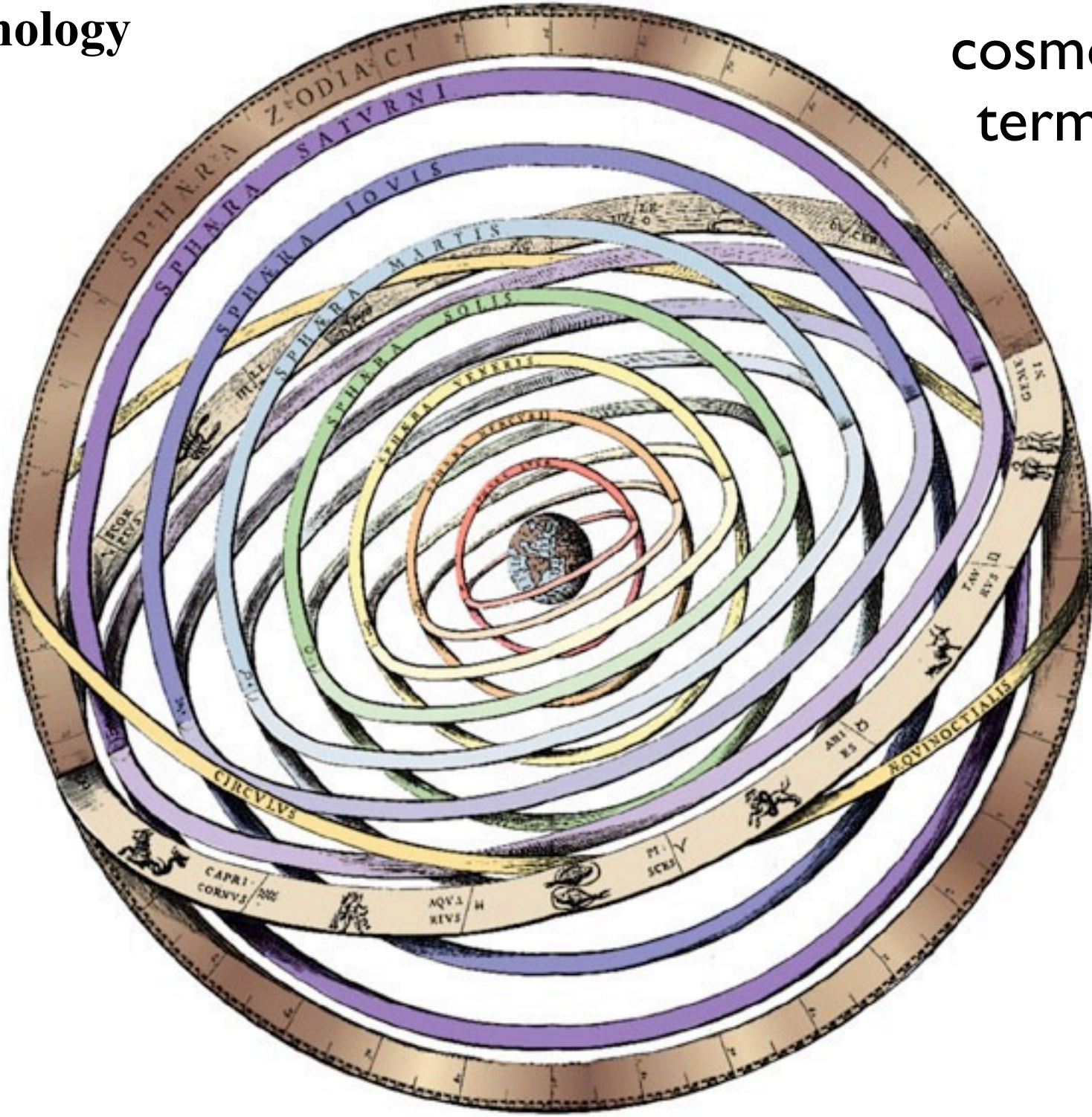


From Dante's *Divine Comedy*



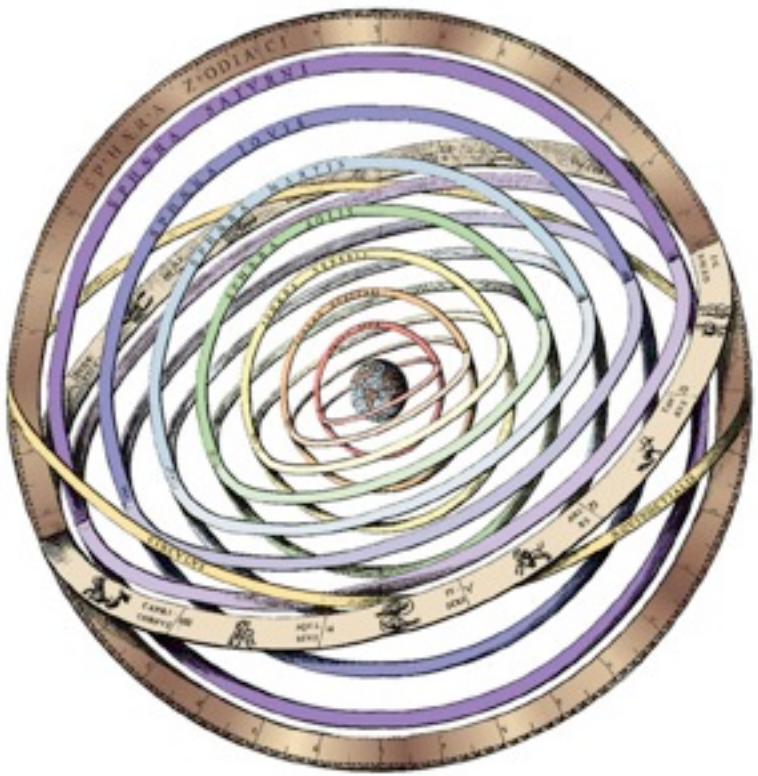
Geocentric Cosmology

The most successful cosmology ever in terms of life span

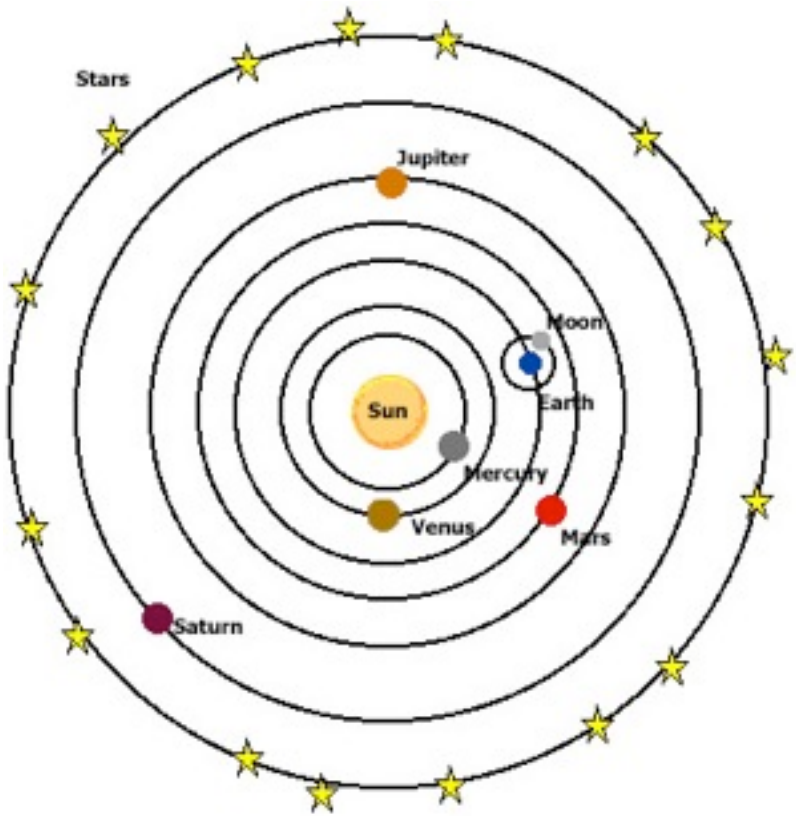


Competing Cosmologies - the Copernican Revolution

Geocentric
Ptolemaic
Earth at center



Heliocentric
Copernican
Sun at center



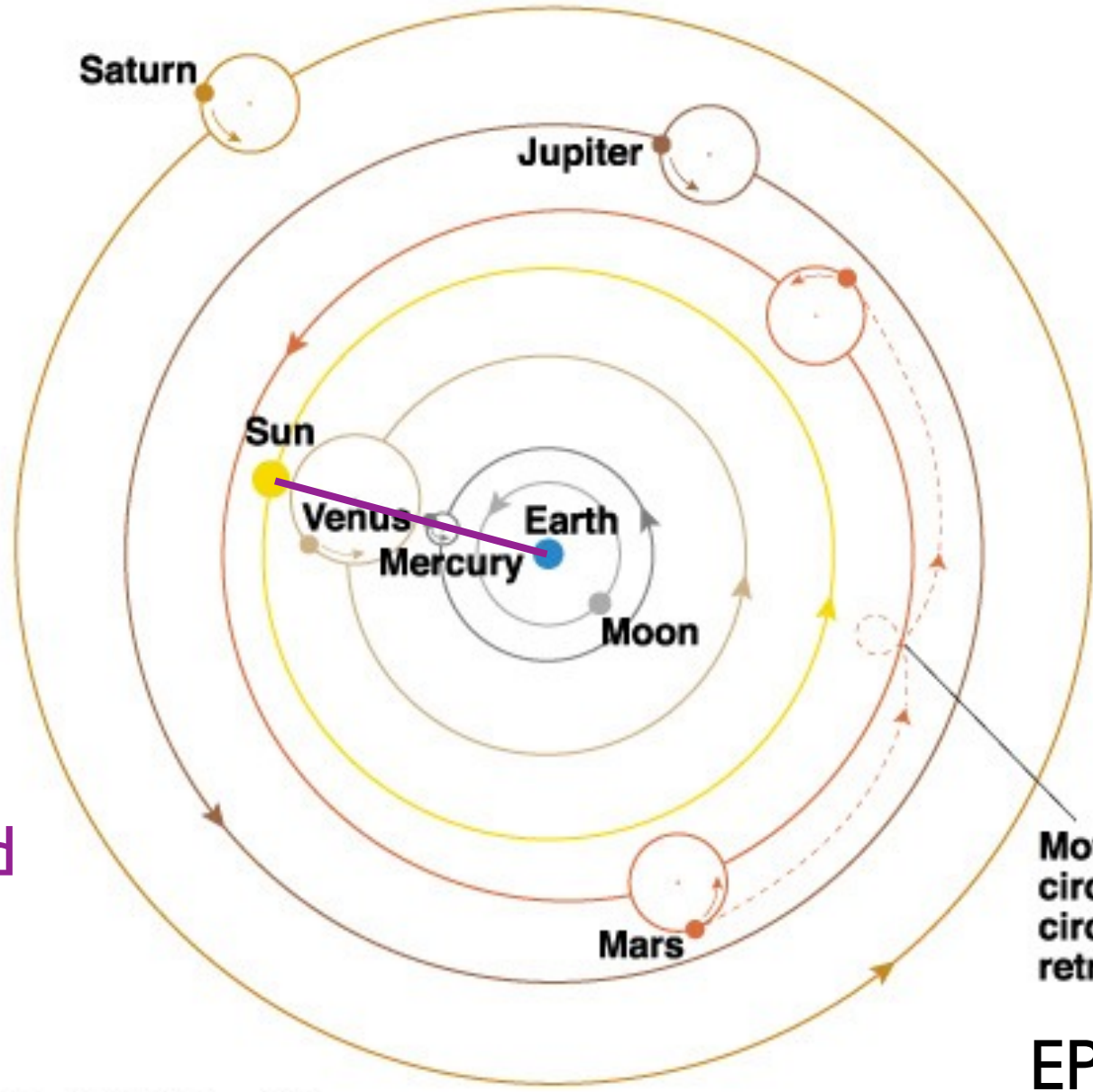
Geocentric Cosmology

Ptolemy

The most sophisticated geocentric model was that of Ptolemy (A.D. 100–170) — the **Ptolemaic model:**

- Sufficiently accurate to remain in use for 1,500 years
  - i.e., predicted correct positions of planets for many centuries
- Ptolemy sought but did not observe parallax, reasonably concluding that the earth did not move

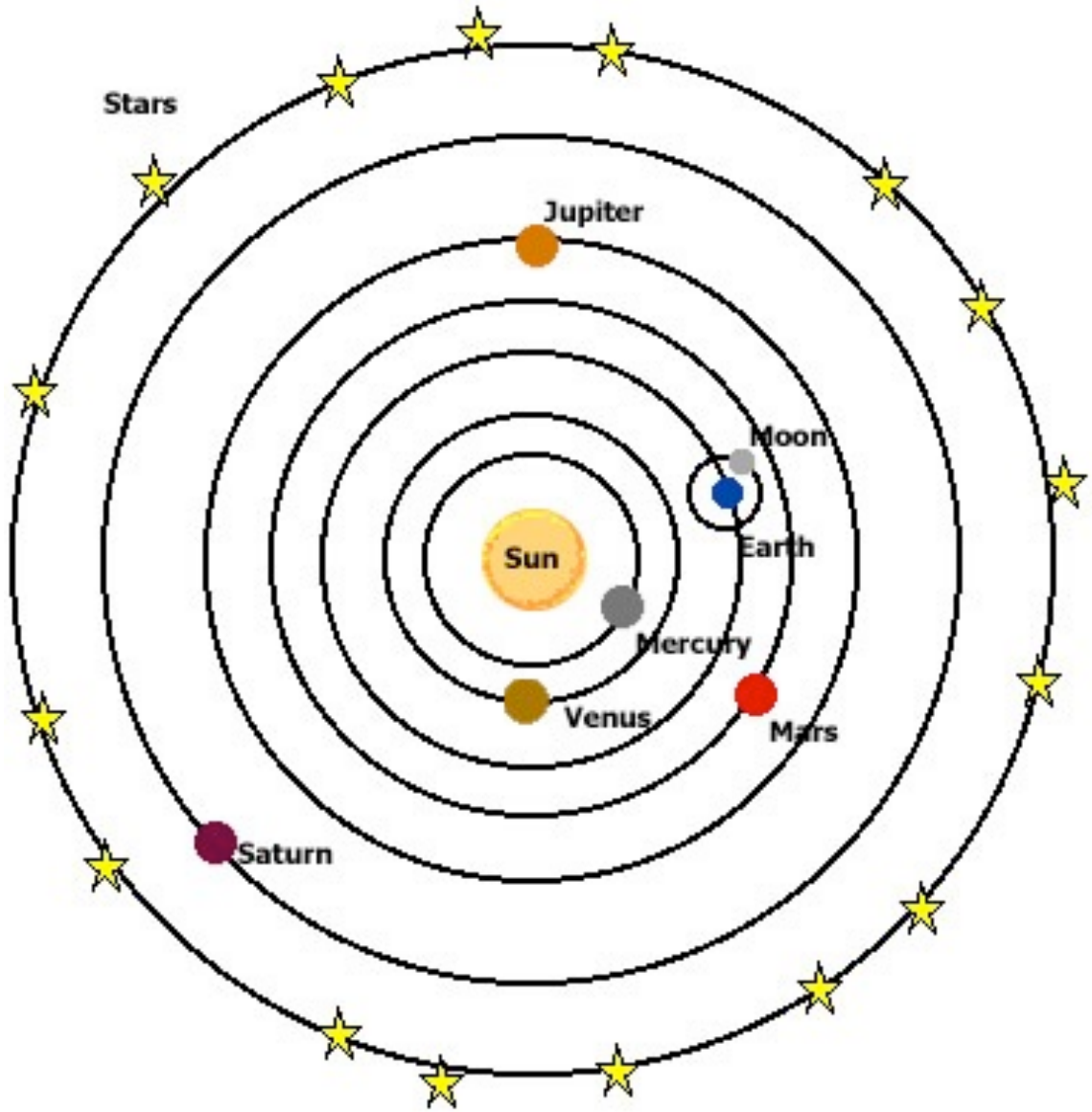
Geocentric Cosmology



Inferior planets arbitrarily tied to earth-sun line

EPICYCLES

Heliocentric Cosmology



Heliocentric Cosmology

Copernicus (1473–1543):

- He proposed the Sun-centered model (published 1543).
- He used the model to determine the layout of the solar system (planetary distances in AU).

But . . .

- The model was no more accurate than Ptolemaic model in predicting planetary positions, because it still used perfect circles.

Competing Cosmologies

Geocentric	**Heliocentric**
Ptolemaic	Copernican
Earth at center	Sun at center

The sun is the source of light in both models

Explains	**Explains**
• **Motion of Sun** • **Motion of Moon** • **Solar and Lunar Eclipses** • **Phases of Moon**	• **Motion of Sun** • **Motion of Moon** • **Solar and Lunar Eclipses** • **Phases of Moon**

Retrograde Motion

Needs epicycles	Consequence of Lapping

Inferiority of Mercury & Venus

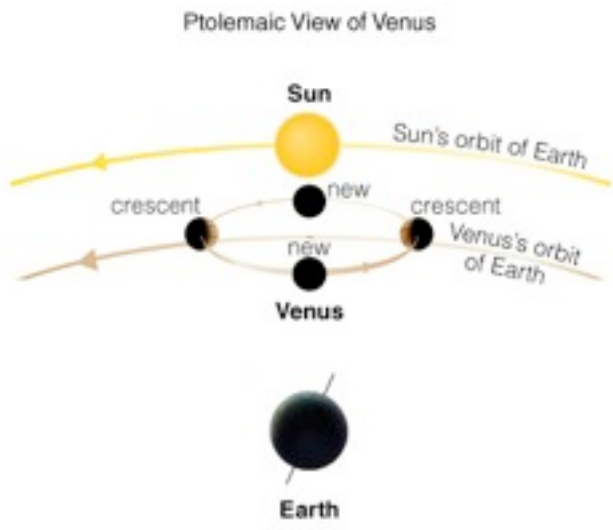
Must tie to sun	Interior to Earth's Orbit

Predicts

- No parallax - Venus: crescent phase only	- Parallax - Venus: all phases

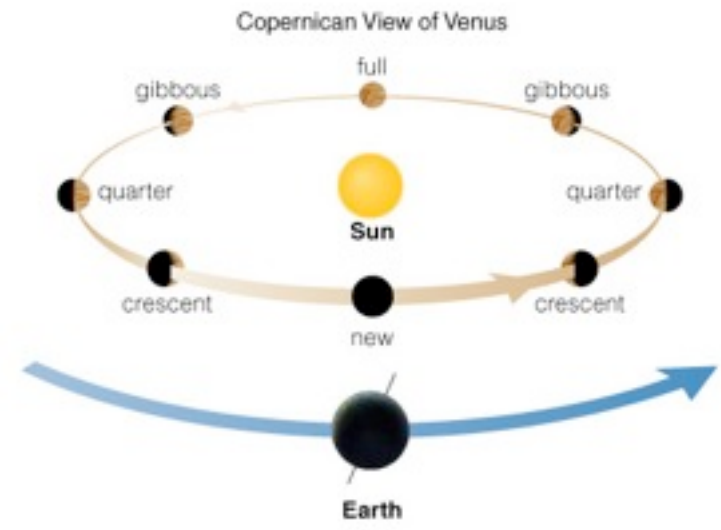
Phases of Venus

Geocentric



Only crescent phase
Size roughly constant

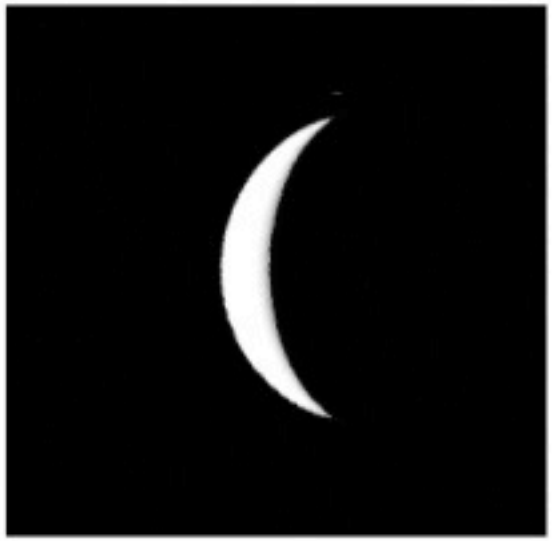
Heliocentric



All phases
Size varies

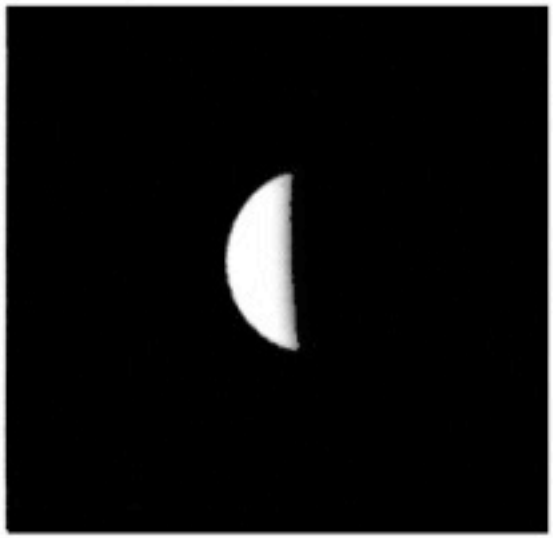
Phases of Venus first observed by Galileo

$\alpha = 58^\circ$

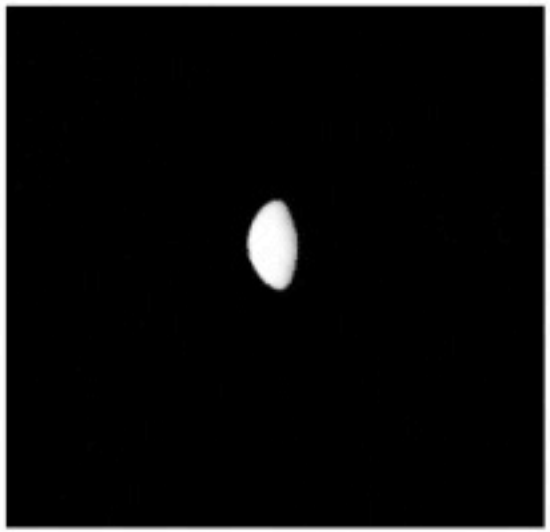


$\alpha = 42^\circ$

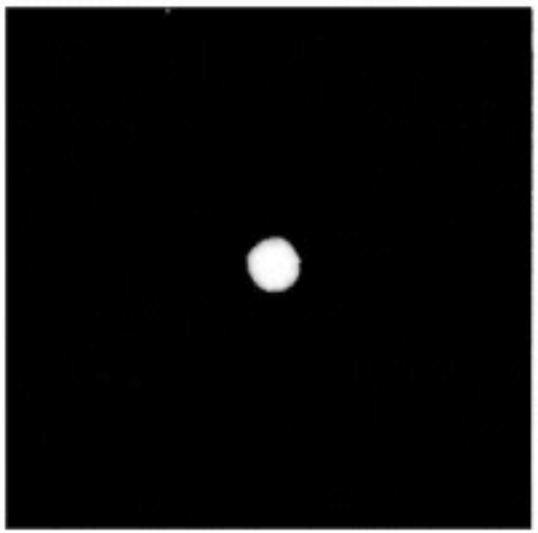
Phase and angular size of Venus depend on viewing angle as expected in the heliocentric cosmology



$\alpha = 24^\circ$



$\alpha = 15^\circ$

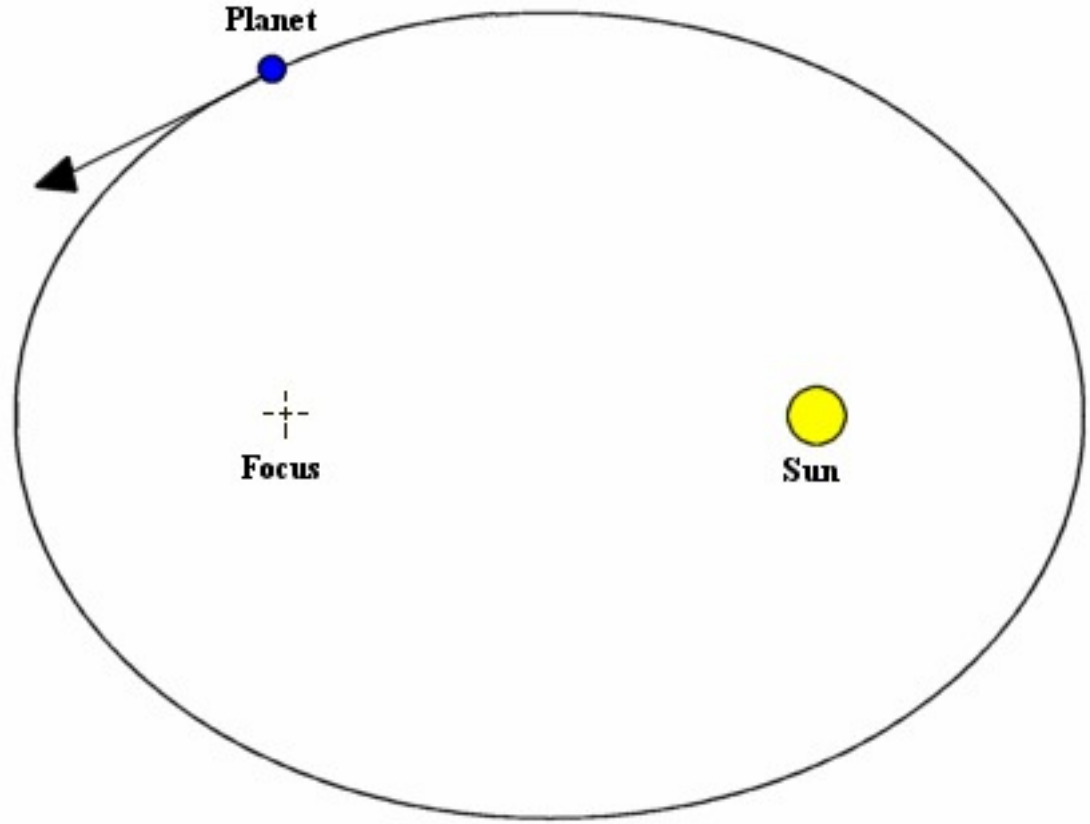


$\alpha = 10^\circ$

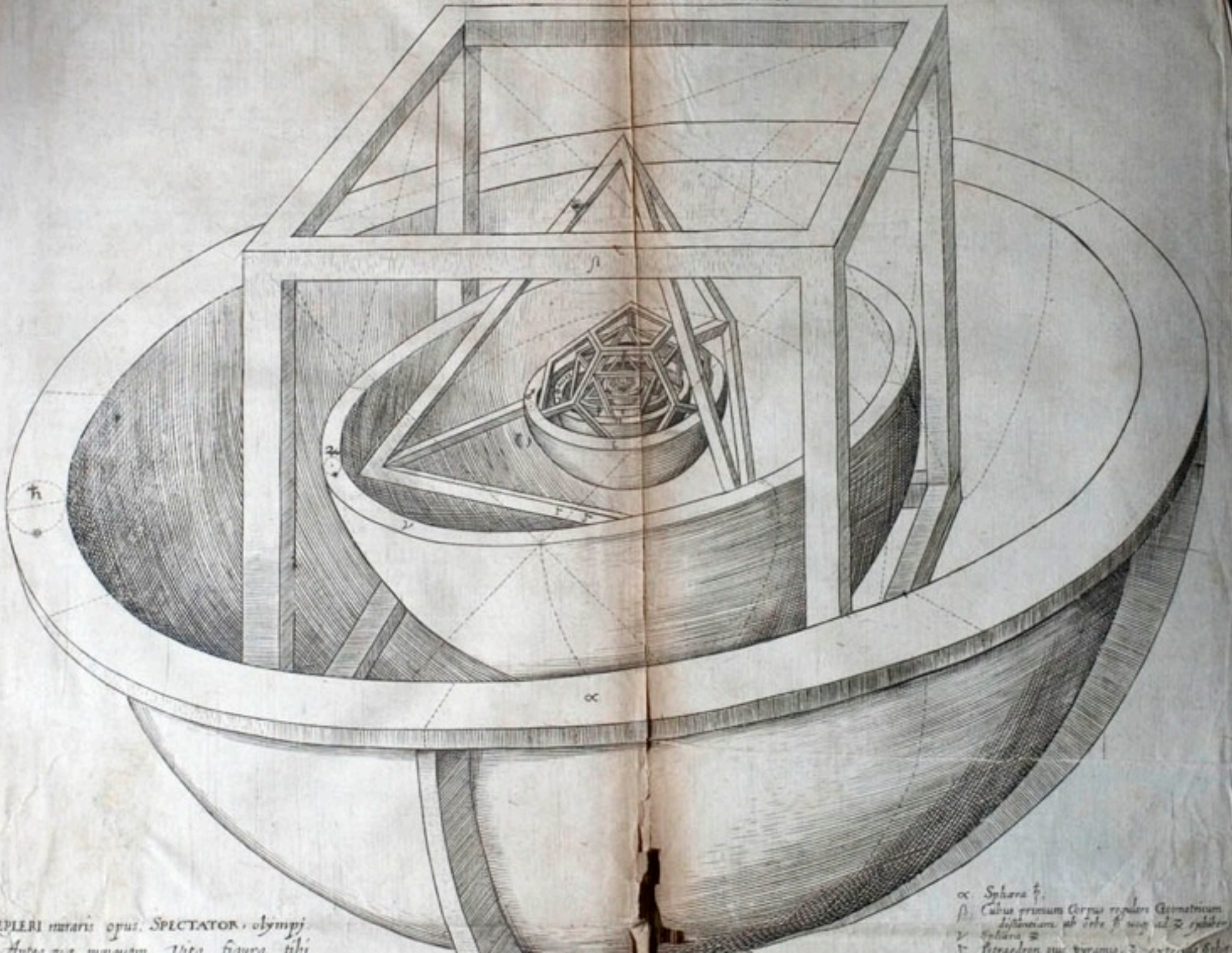
Kepler abandons purely circular orbits

Johannes Kepler
(1571–1630)

"If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy."

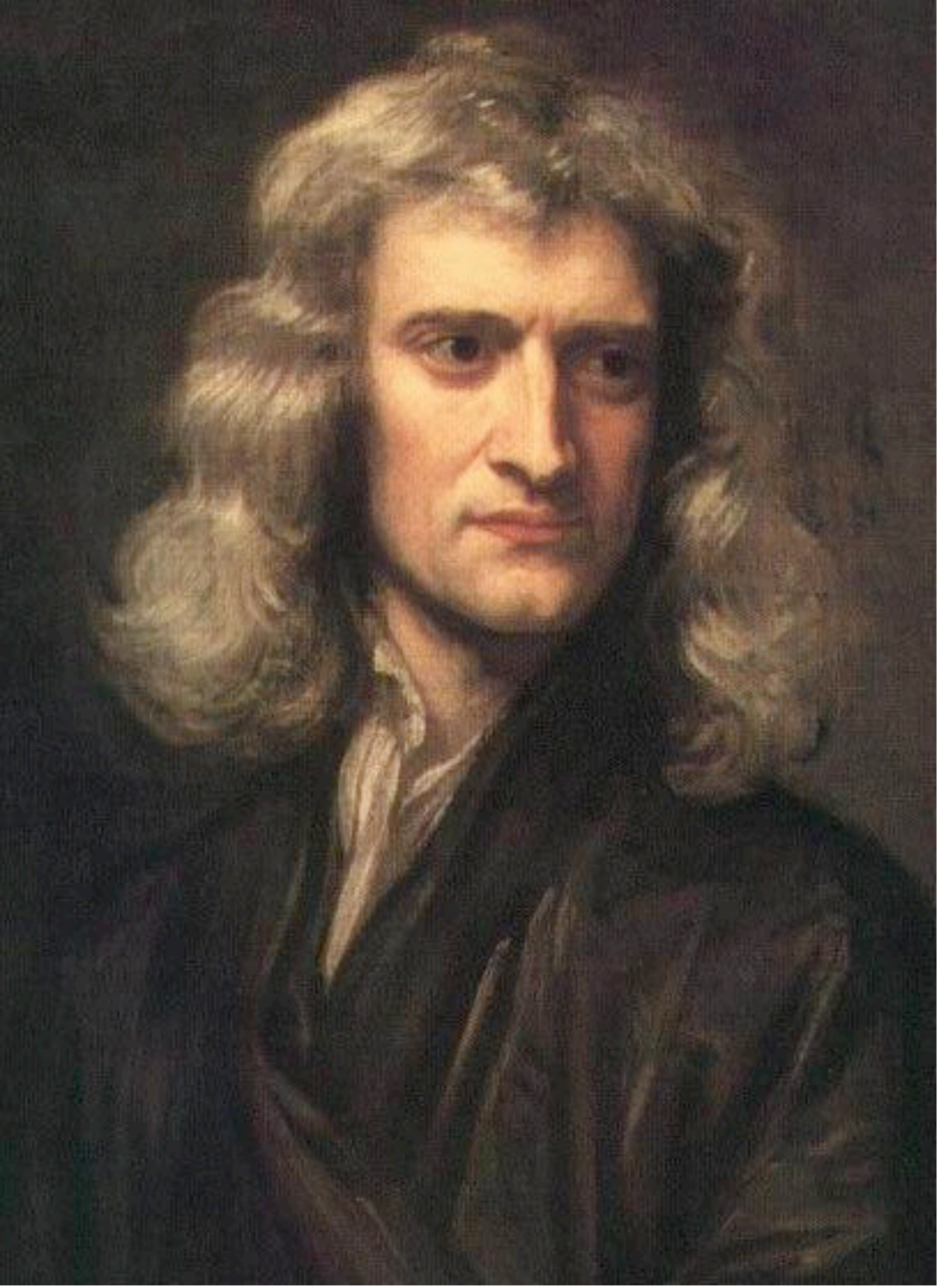


TABVLA MORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA GEOMETRICA EXHIBENS.



KEPLERI naturalis opus. SPECTATOR, olympi

α Sphæra ♄.
β Cubus primum Corpus regulare Geometricum.
γ Sphæra ♃.



Sir Isaac Newton (1642–1727)

Formulated the Universal Law of Gravity

Everything happens ... as if the force between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

Bentley-Newton correspondence

Bentley: would not a finite assemblage of stars collapse from their mutual gravity?

Newton: if the matter was evenly diffused through an infinite space, it would never convene into one mass.

Bentley: can such a system remain stable?

Newton: such an assemblage, even if infinite, is like an array of needles standing upright on their points, ready to fall one way or another.

Newton: this frame of things could not always subsist without divine power to conserve it.

God actively intervenes to keep things in order.

Richard Bentley (1662 – 1742)

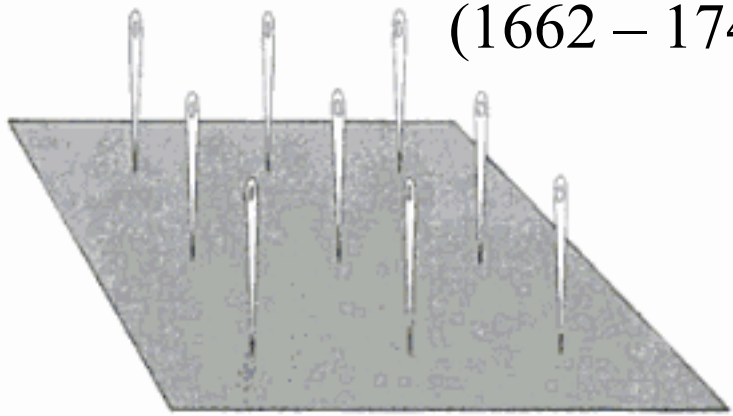
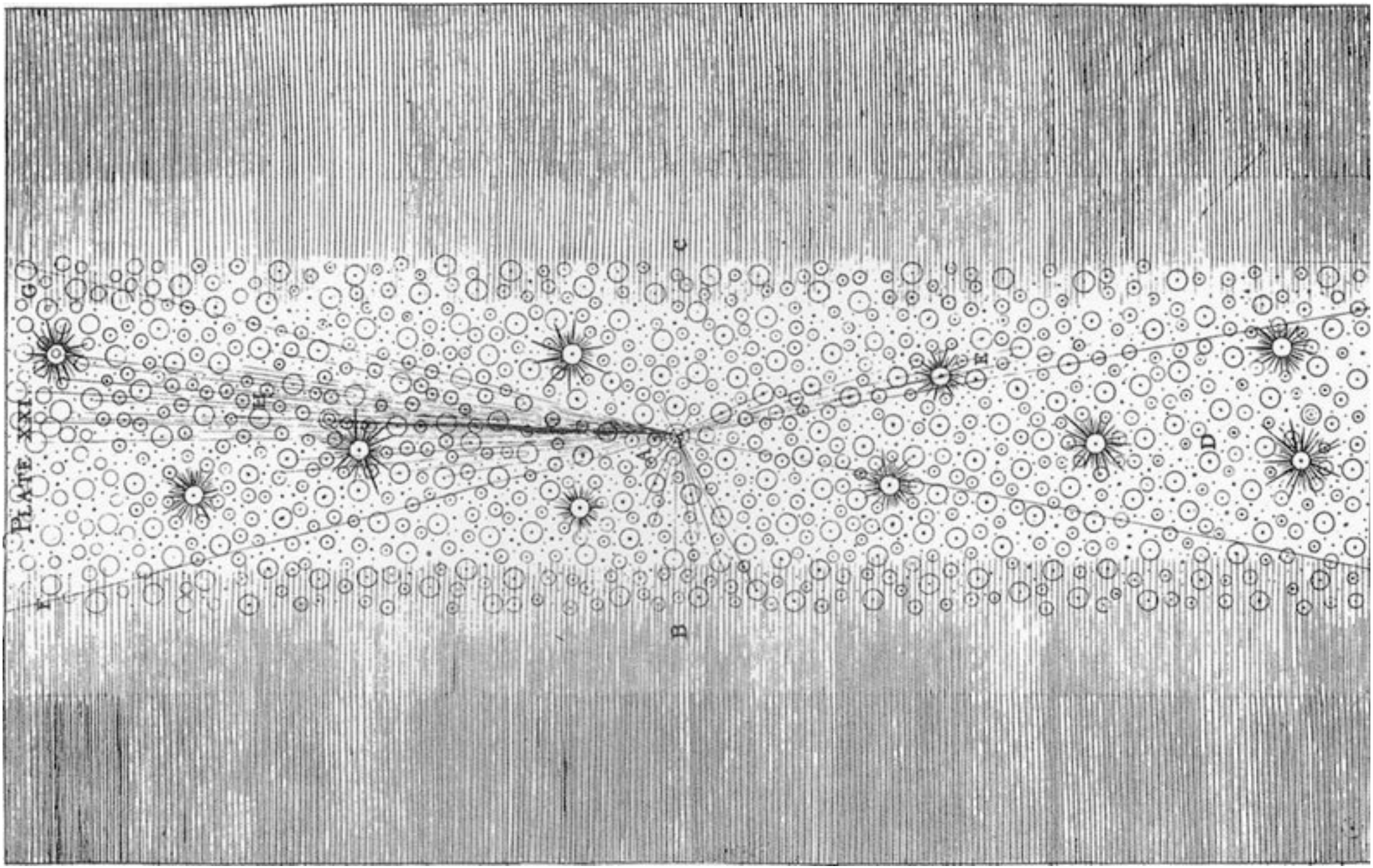
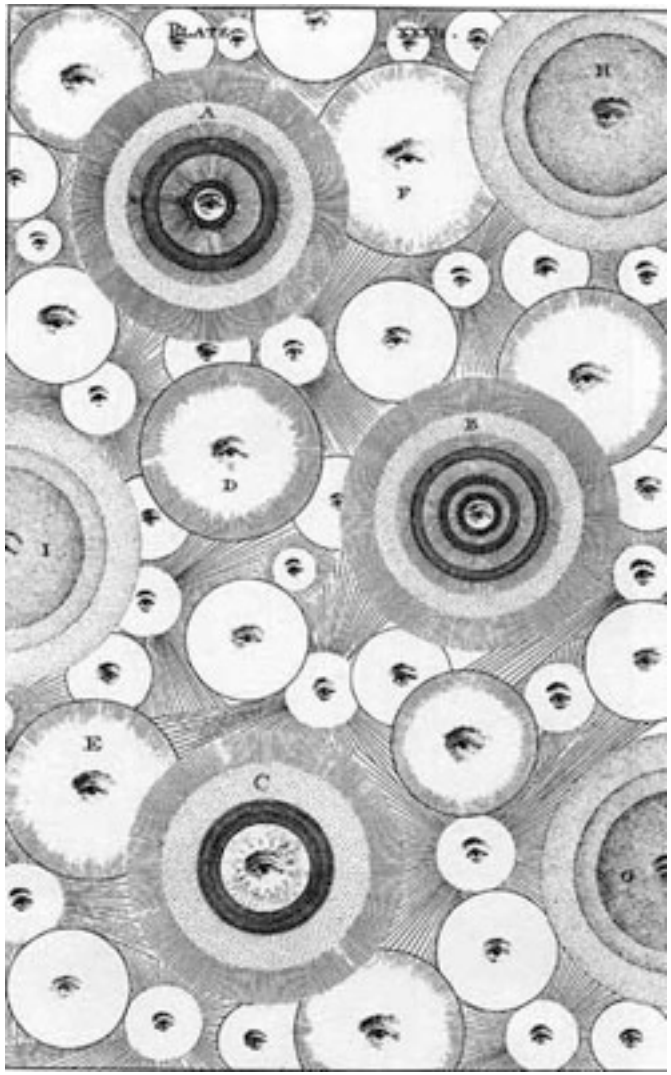


Figure 3.12. Newton agreed with Bentley that stars cannot form a finite and bounded system (as in the Stoic cosmos), for they would fall into the middle of such a system by reason of their gravitational attraction. They agreed that matter was uniformly distributed throughout infinite space, and realized that this was an unstable distribution. The particles of matter, wrote Newton, are like an array of needles standing upright on their points ready to fall one way or another, and "thus might the Sun and fixed stars be formed."

Victorian Universe

Stoic-like with a vast Milky Way embedded in an indefinite void





"No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of coordinate rank with the Milky Way. A practical certainty has been attained that the entire contents, stellar and nebular, of the sphere belong to one mighty aggregation..."

- Agnes Clerke (1890)

i.e., a Stoic picture:
the universe might extend indefinitely to infinity,
but the contents (though enormous) were finite.

Curtis-Shapley Debate
(the "Great Debate" - 1920)

Shapley

Curtis

Michigan Man

The Milky Way is big; we are not near the center

The Milky Way is small; we happen to be near the center

Other nebulae are clouds of gas within the Milky Way

The spiral nebulae are "island universes" comparable to the Milky Way

An Expanding Universe?

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

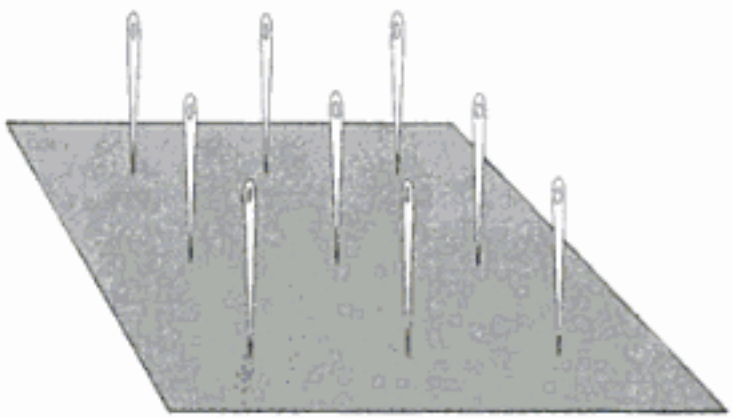
A homogenous, isotropic universe evolving according to Einstein's field equation must either expand or contract. It can not be static.

Or a static one?

Einstein's greatest blunder?

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Einstein's intention was to keep the universe static. But it this solution is unstable!

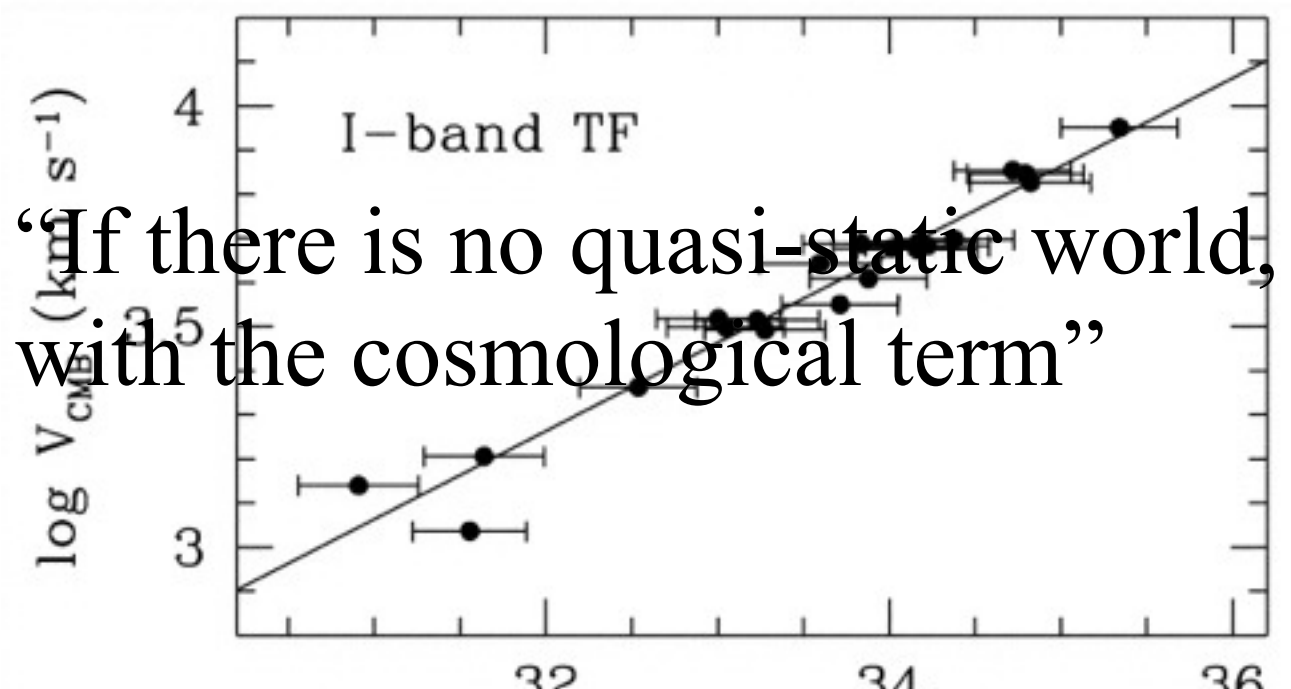


Or a static one?

Einstein's greatest blunder?

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu} = 8\pi G T_{\mu\nu} + \cancel{\Lambda} g_{\mu\nu}$$

Einstein's intention was to keep the universe static. But it does expand!



"If there is no quasi-static world, then *away* with the cosmological term"

- Einstein

Now we believe in an expanding universe

governed by

Einstein field equation

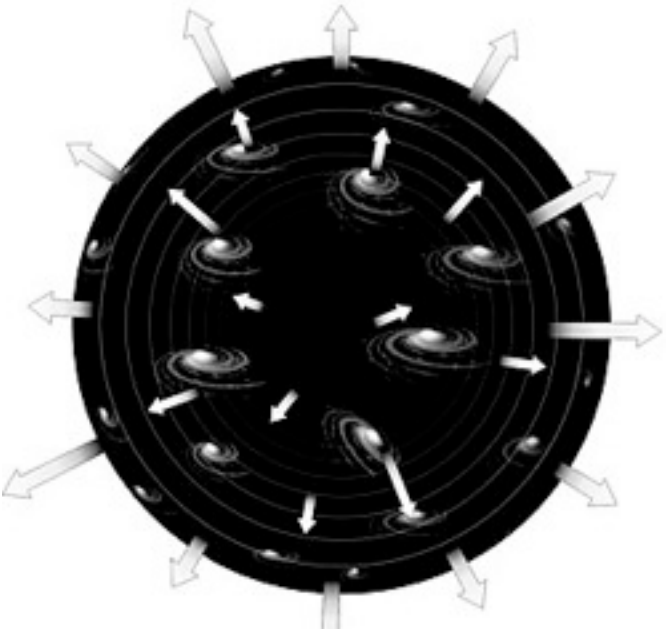
$$\mathbf{R}_{\mu\nu} - \frac{1}{2}\mathbf{g}_{\mu\nu} = \frac{8\pi G}{c^4}\mathbf{T}_{\mu\nu} + \Lambda \mathbf{g}_{\mu\nu}$$

Roberston-Walker metric

$$c^2 ds^2 = -c^2 dt^2 + R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\psi^2\right)$$

Friedmann equation

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda c^2}{3}$$



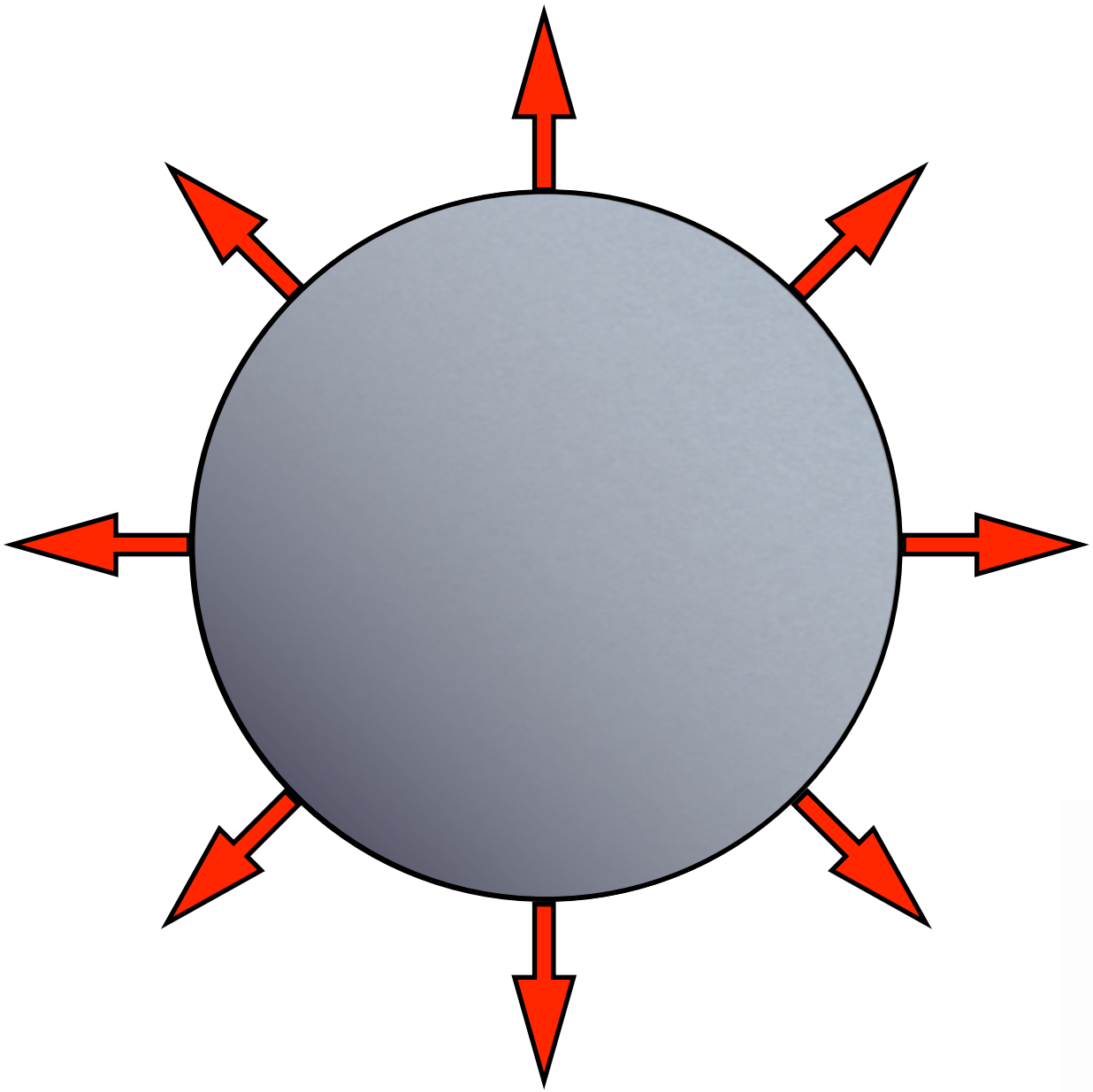
expansion rate

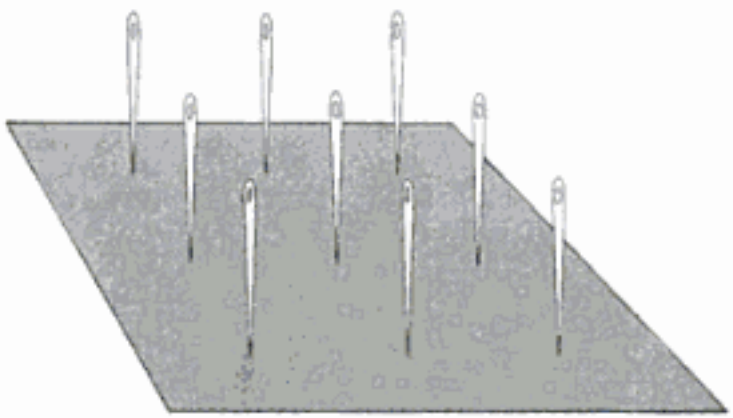
gravitating mass

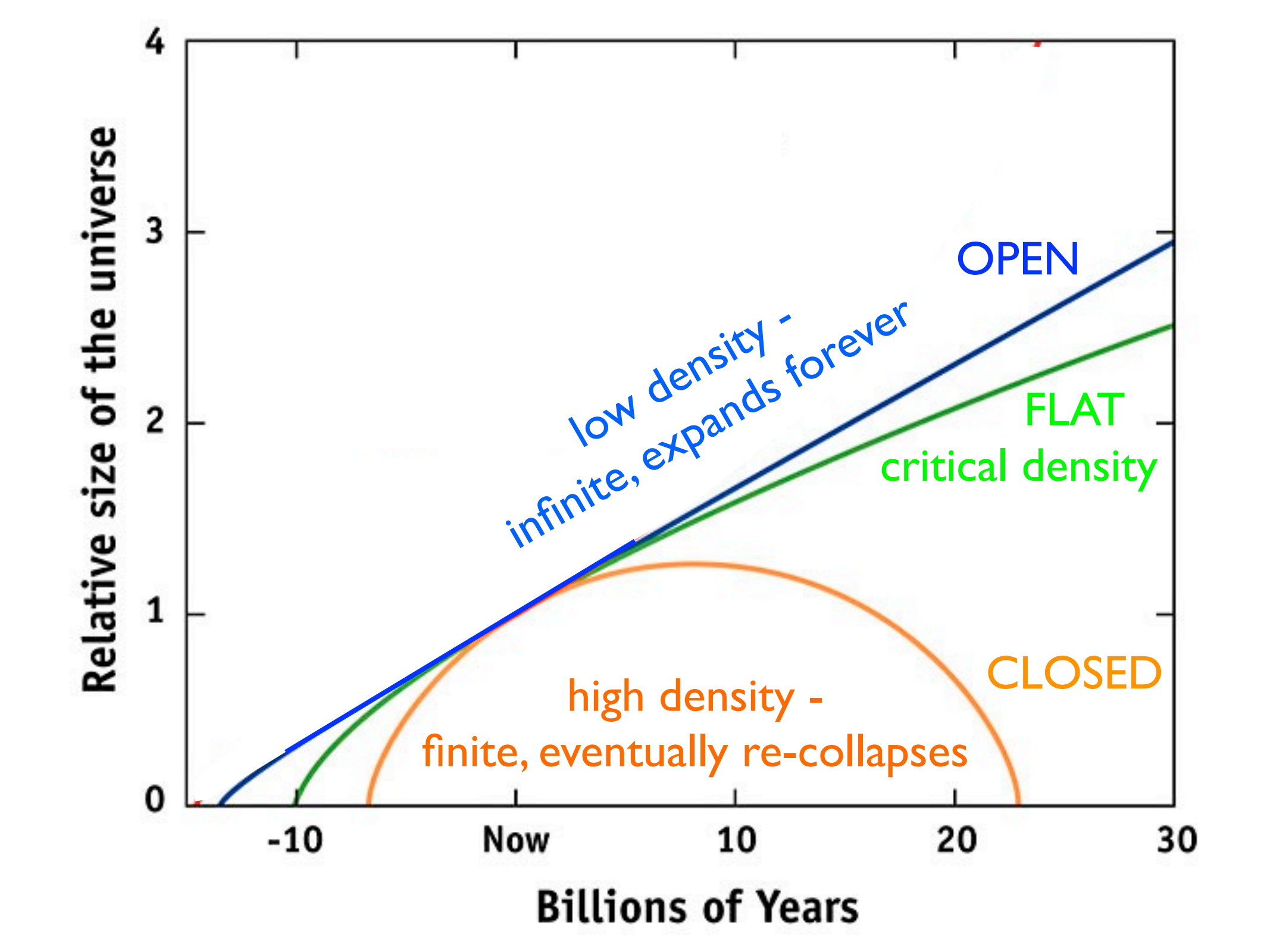
geometry

anti-gravity/
dark energy

An expanding universe solves the stability problem that Newton & Bentley corresponded about.

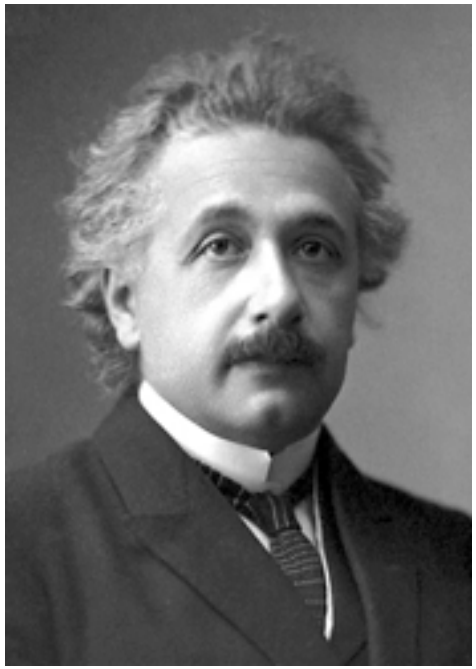




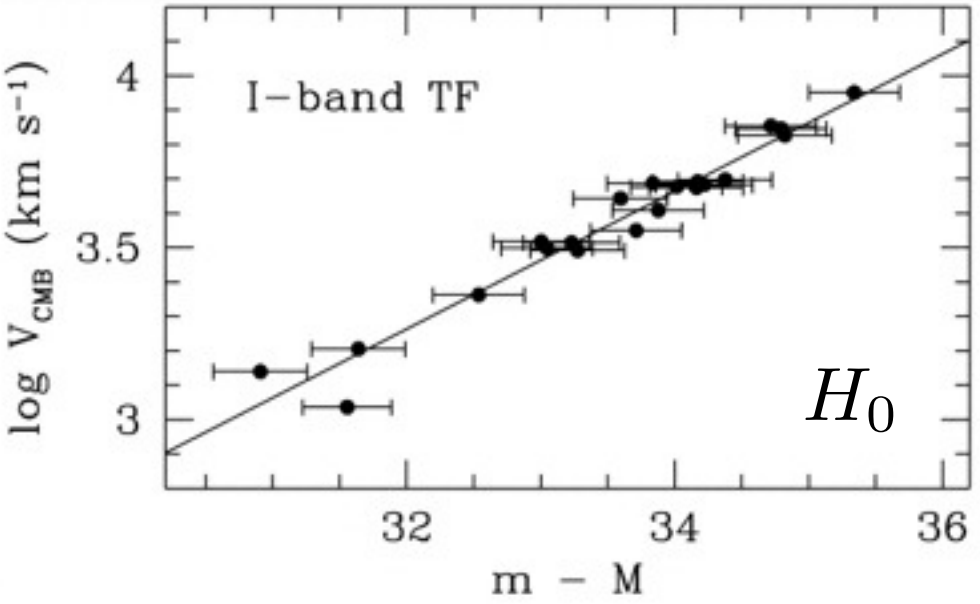

Relative size of the universe
4
3
2
1
0
-10
Now
10
20
30
Billions of Years
OPEN
low density -
infinite, expands forever
FLAT
critical density
CLOSED
high density -
finite, eventually re-collapses

Einstein's General Relativity provides an elegant cosmology

that naturally explains many observations

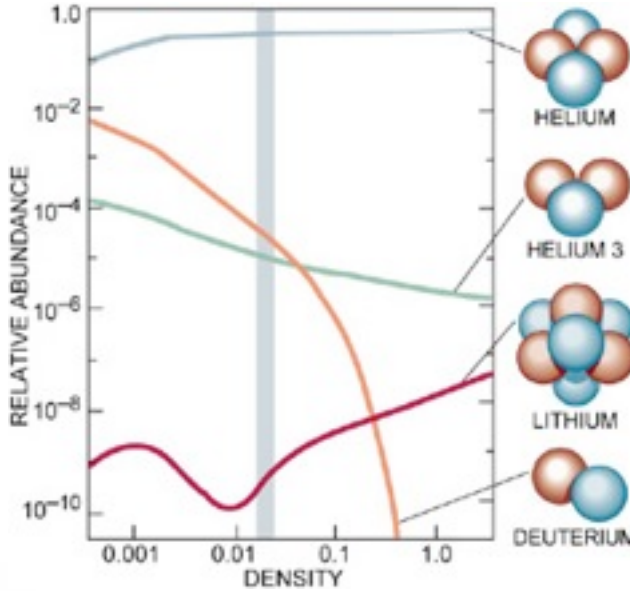


- Expanding Universe
- Finite Age (~ 14 Billion years)
- Early hot phase (Big Bang)
  - Nucleosynthesis of the light elements (H, He, Li)
  - Cosmic Microwave Background



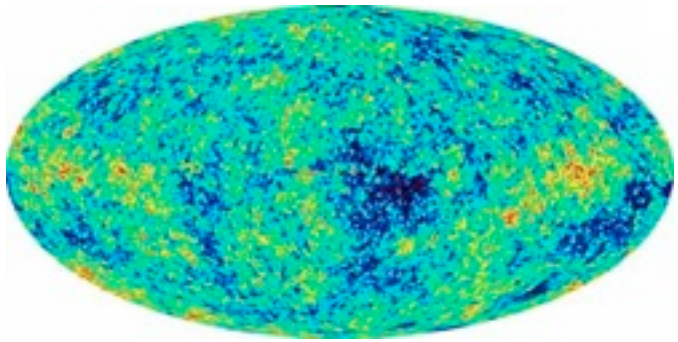
Hubble Expansion

The Good



Big Bang Nucleosynthesis

Origin of the light elements in the first few minutes



Cosmic Microwave Background (~ 380,000 years)

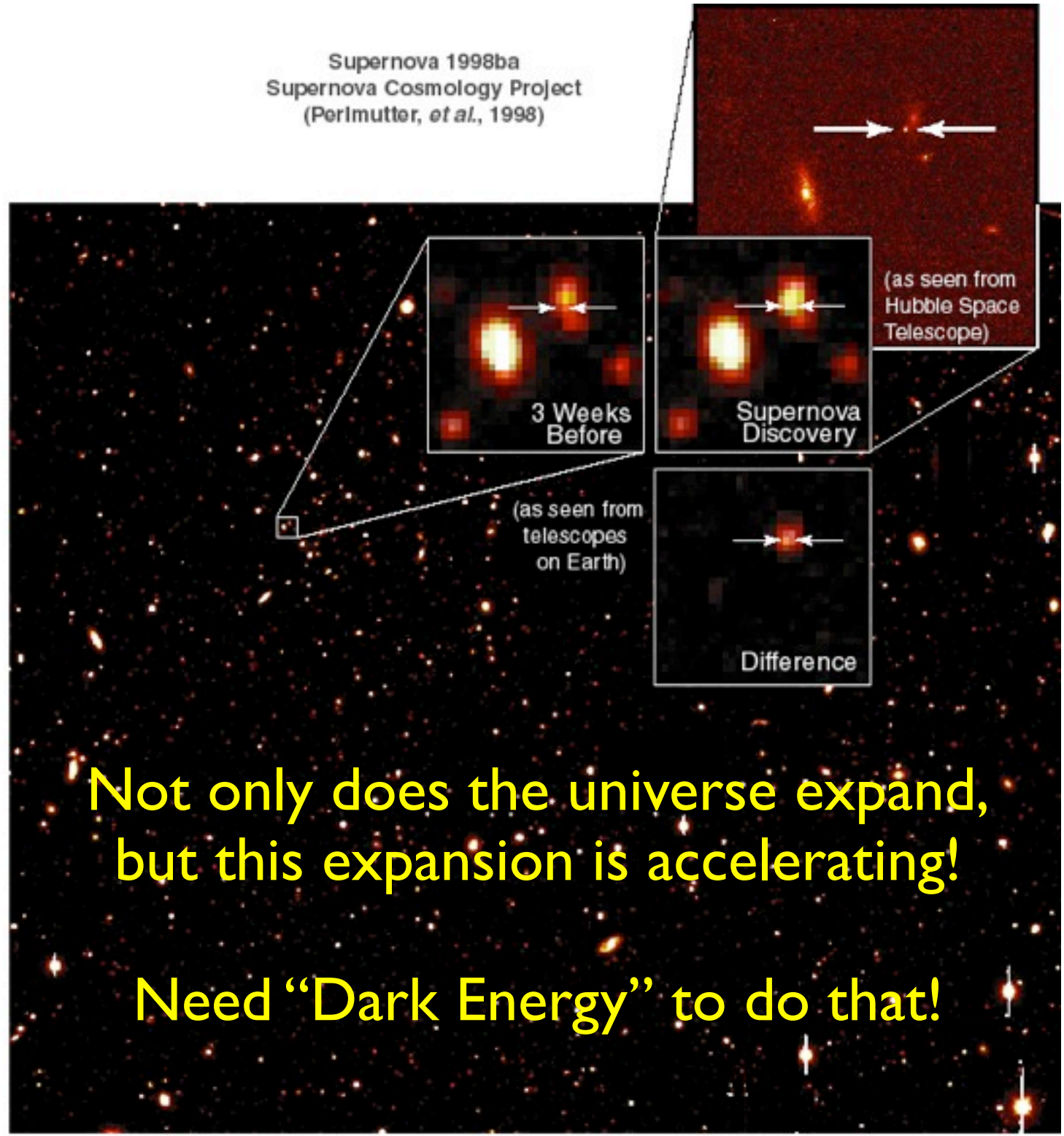
There is also a dark side

The Bad

Modern cosmology only works with

- dark matter → Unseen mass that provides more gravity
- dark energy → Something that acts like antigravity

We don't know what dark matter is and we don't understand what dark energy means


Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, et al., 1998)
(as seen from Hubble Space Telescope)
3 Weeks Before
Supernova Discovery
(as seen from telescopes on Earth)
Difference
Not only does the universe expand, but this expansion is accelerating!
Need "Dark Energy" to do that!

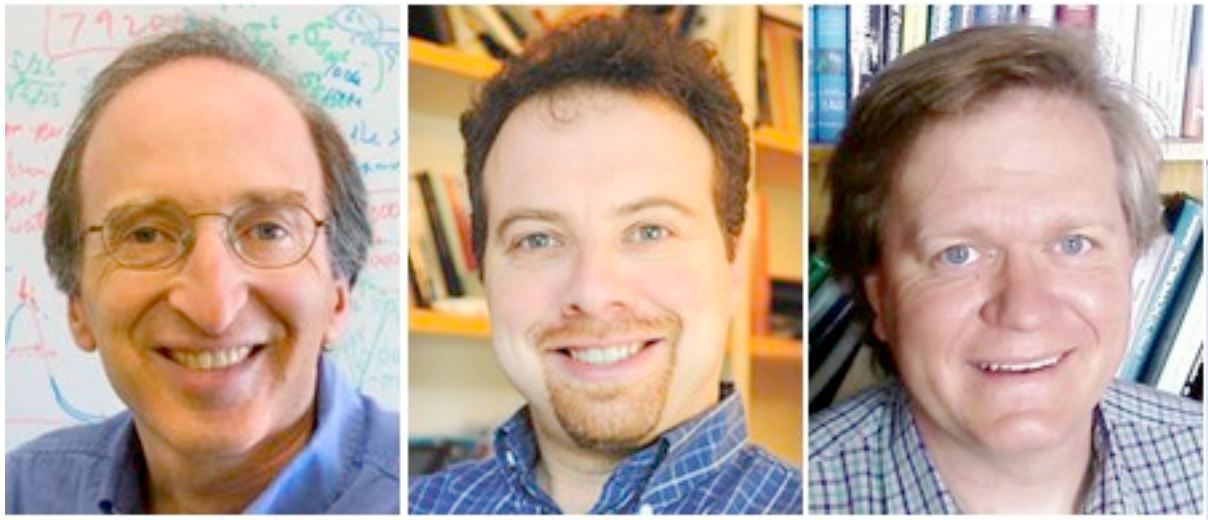
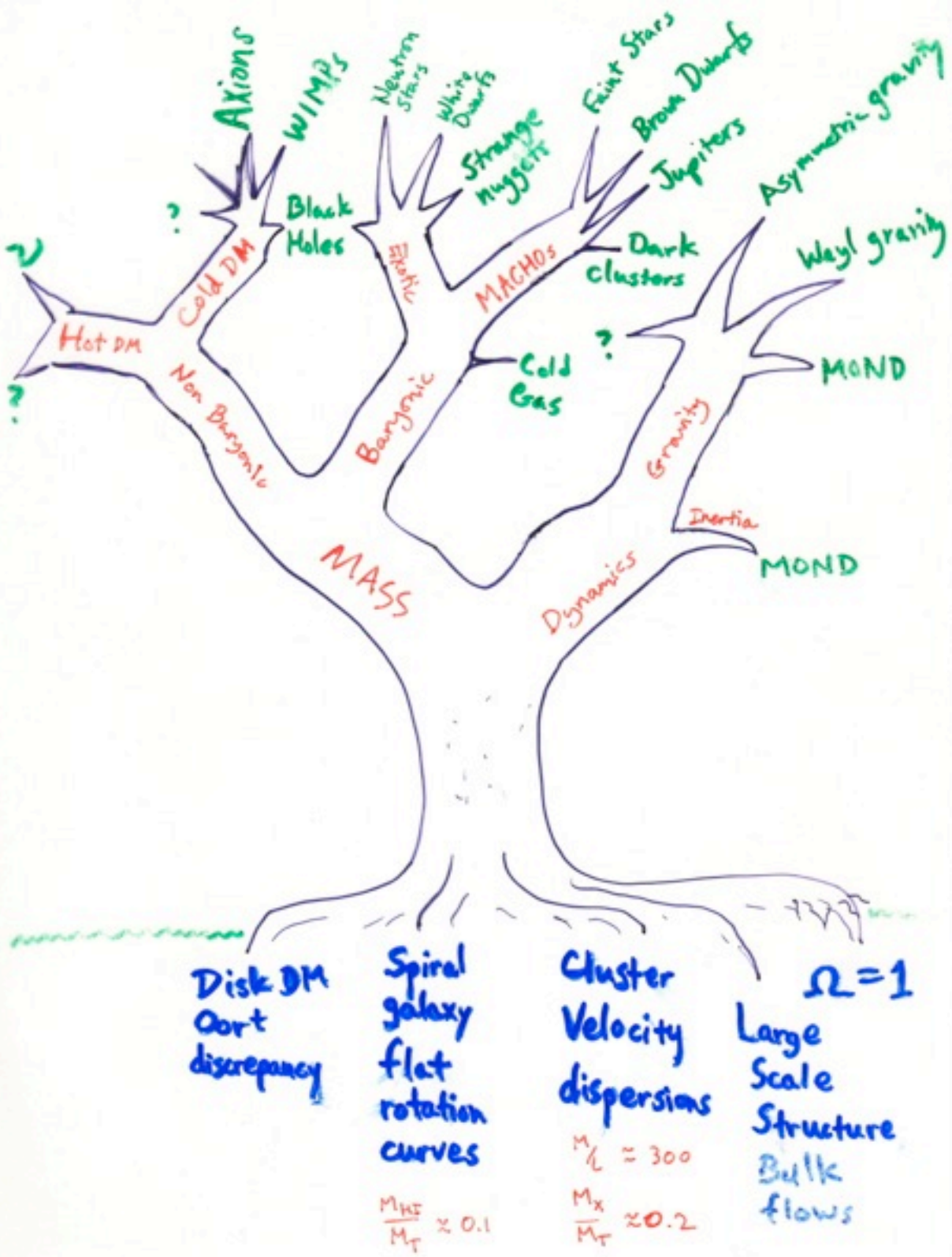
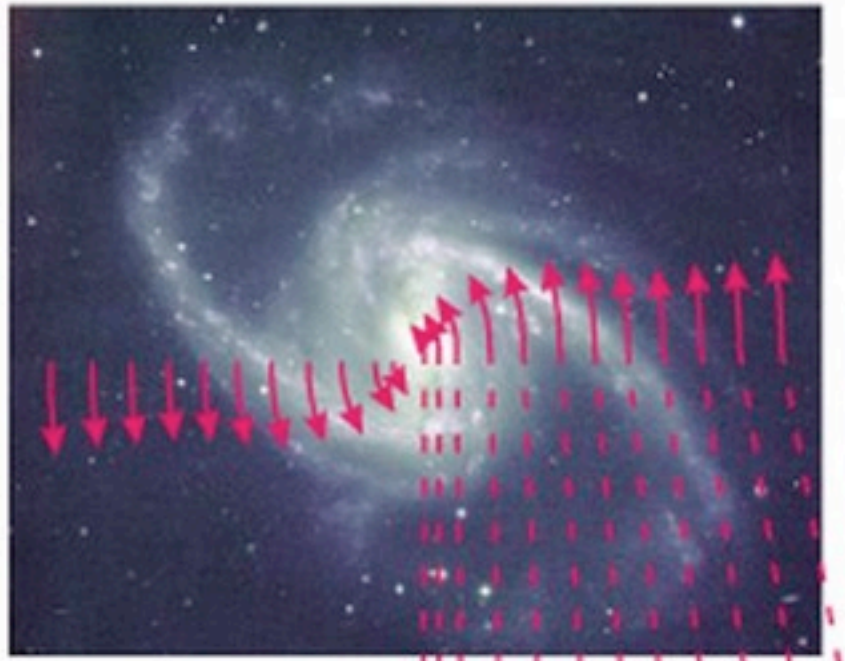


Image Credits (left to right): Roy Kaltschmidt, LBNL; Homewood Photography; Research School of Astronomy and Astrophysics, Australian National University

2011 Nobel Prize in Physics

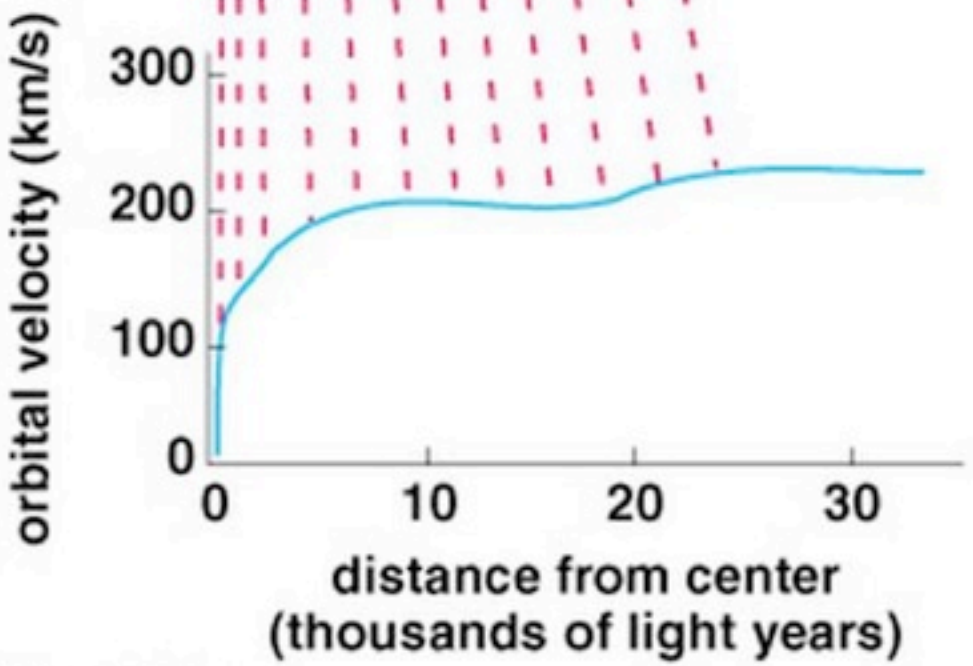

Axions
WIMPs
Neutron stars
White Dwarfs
Strange nuggets
Faint Stars
Brown Dwarfs
Jupiters
Asymmetric gravity
Weyl gravity
MOND
MOND
Black Holes
Cold DM
Hot DM
Baryonic
Non Baryonic
MACHOs
Dark clusters
Cold Gas
Gravity
Inertia
Dynamics
MASS
Disk DM
Oort discrepancy
Spiral galaxy flat rotation curves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

Spiral
Galaxy

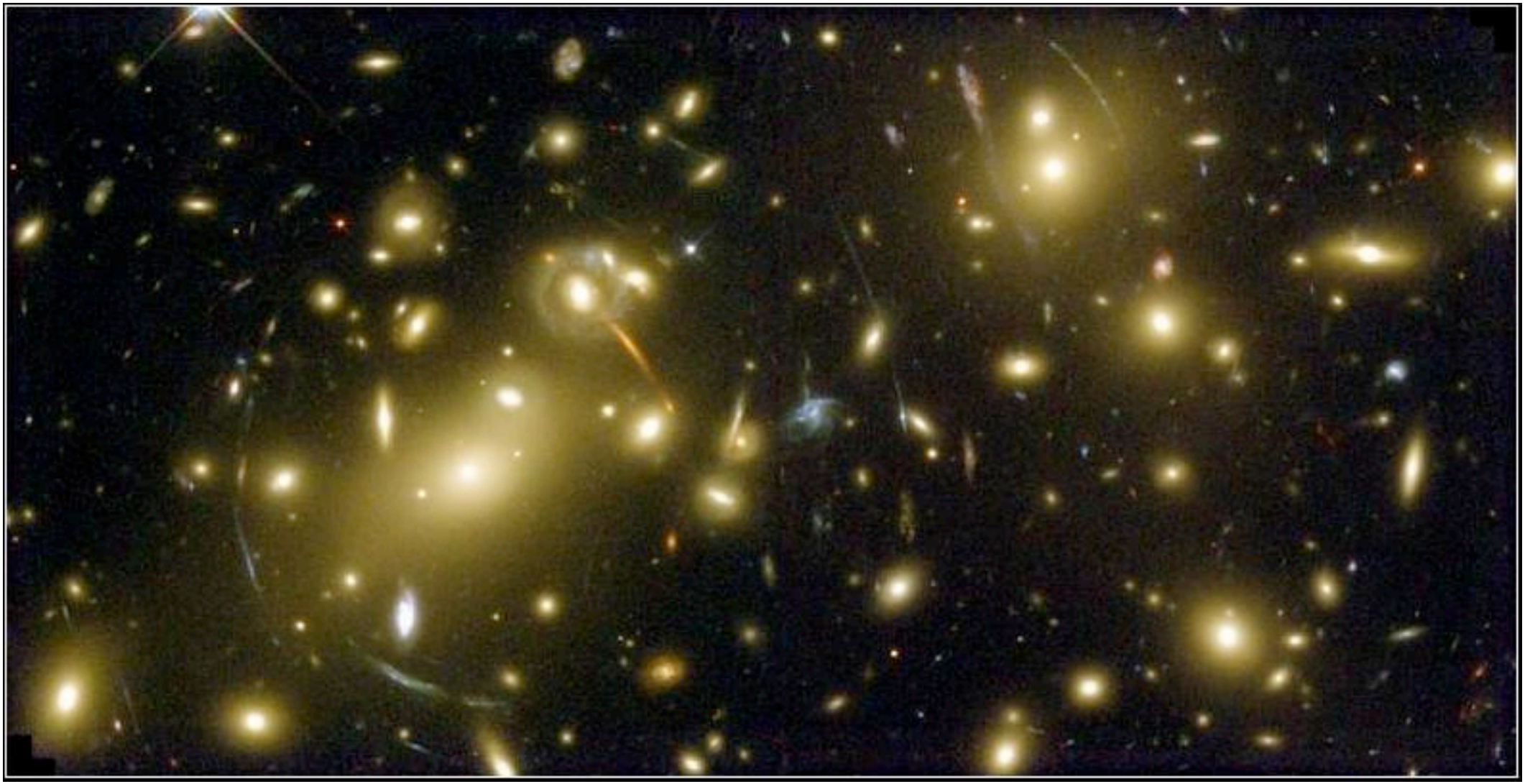


Longer arrows represent larger orbital velocities.

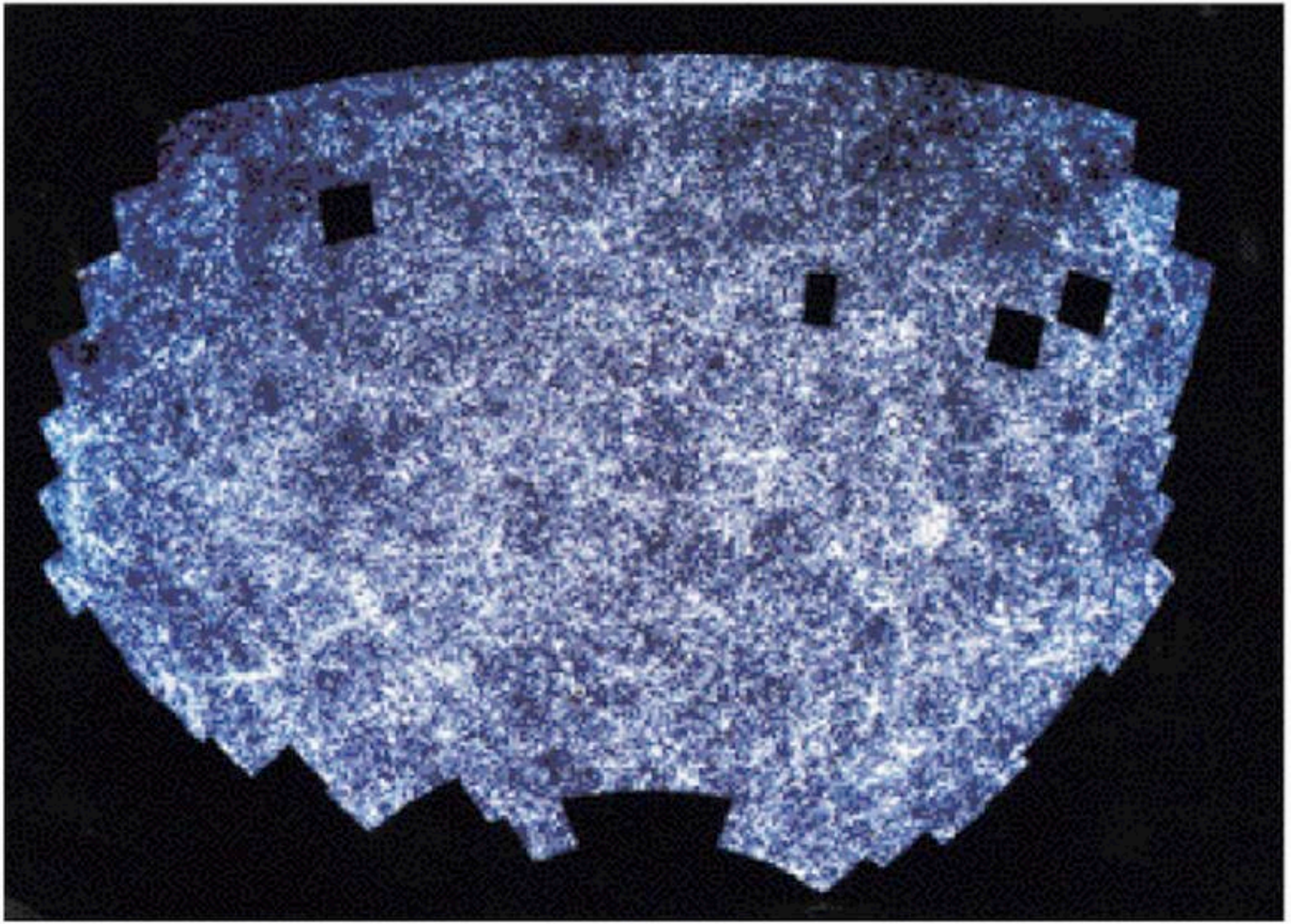
Rotation
Curve



Galaxy Cluster



Large Scale Structure



What is the Dark Matter?

Baryonic Dark Matter

Normal things:

very faint stars, brown dwarfs

other hard-to-see objects (planets, gas)

Hot Dark Matter

neutrinos - got mass, but not enough

✔ **Cold Dark Matter**

Some new fundamental particle

doesn't interact with light, so quite invisible.

Two big motivations:

1) total mass outweighs normal mass from BBN

2) needed to grow cosmic structure

(1)

Normal baryonic mass = 5% of critical density

from Primordial Nucleosynthesis

Total mass density = 30% of critical density

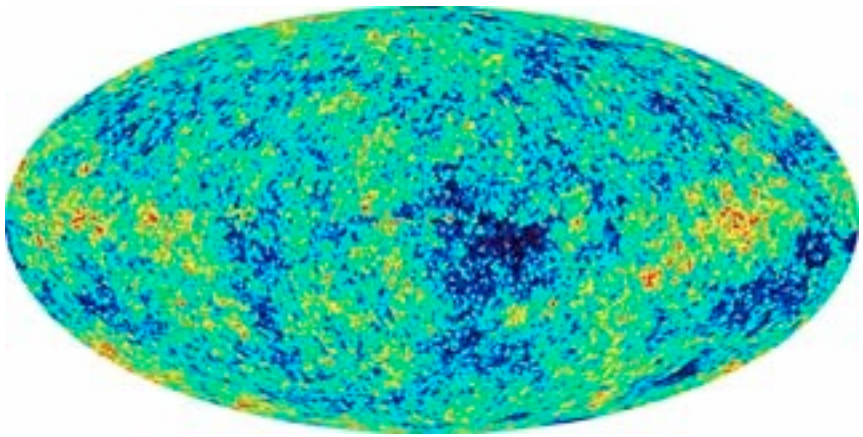
from gravity

gravitating mass >> normal mass

Most of the mass needs to be
in some brand new form!

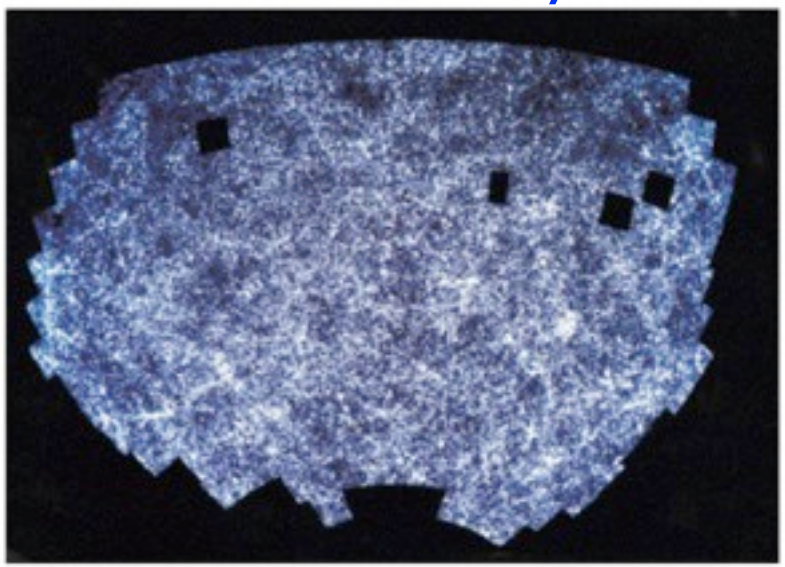
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr



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

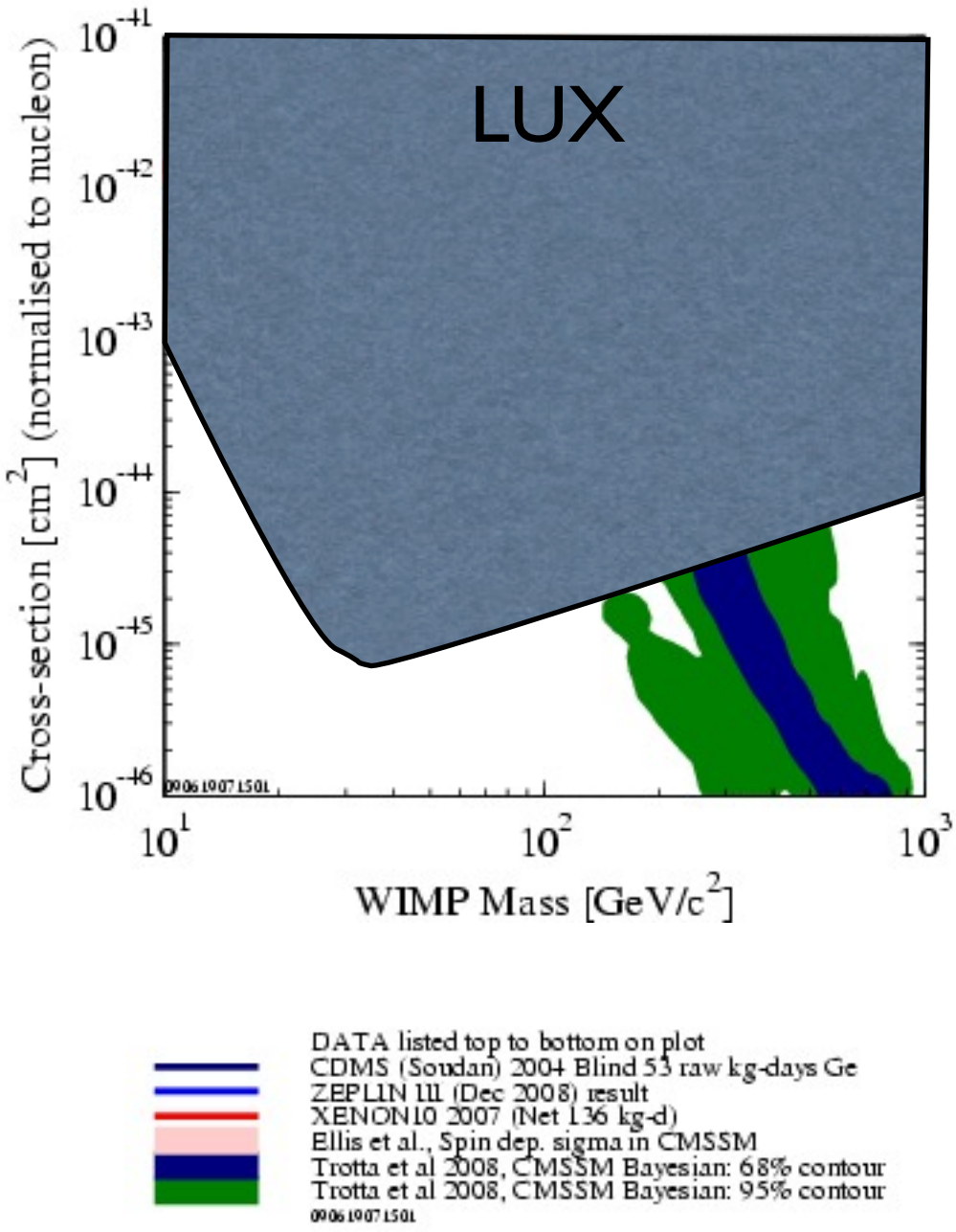
$t = 1.4 \times 10^{10}$ yr



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

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

Particle physicists' best guess is that the **Cold Dark Matter** needed in cosmology is a new form of fundamental particle called the **WIMP** (Weakly Interacting Massive Particle). There are ambitious projects to detect WIMPS in underground laboratories.

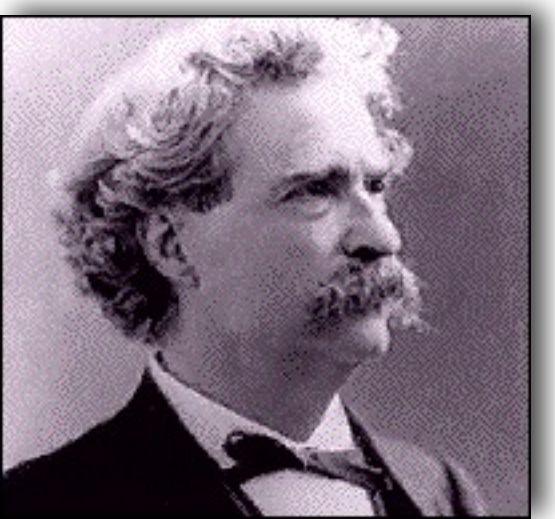


"Cosmologists are often wrong, but never in doubt"

- Lev Landau

What gets us into trouble is not what we don't know.

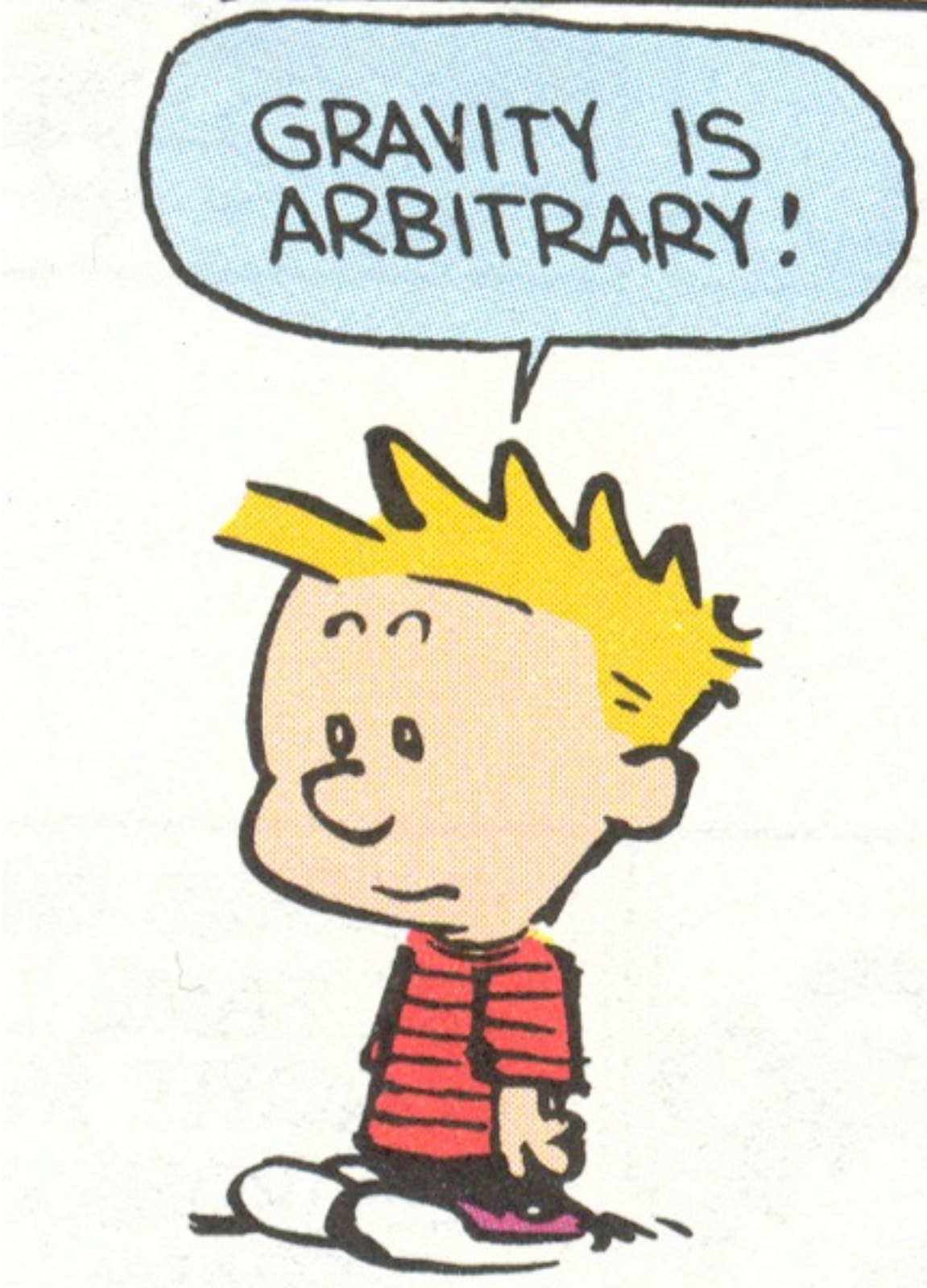
It's what we know for sure that just aint so.



- Mark Twain

As yet, we have no quantum theory of gravity. We do not understand it at a fundamental level.

Might that matter to cosmology?
Could dark matter and/or dark energy really be a sign of new gravitational phenomena?



MOND

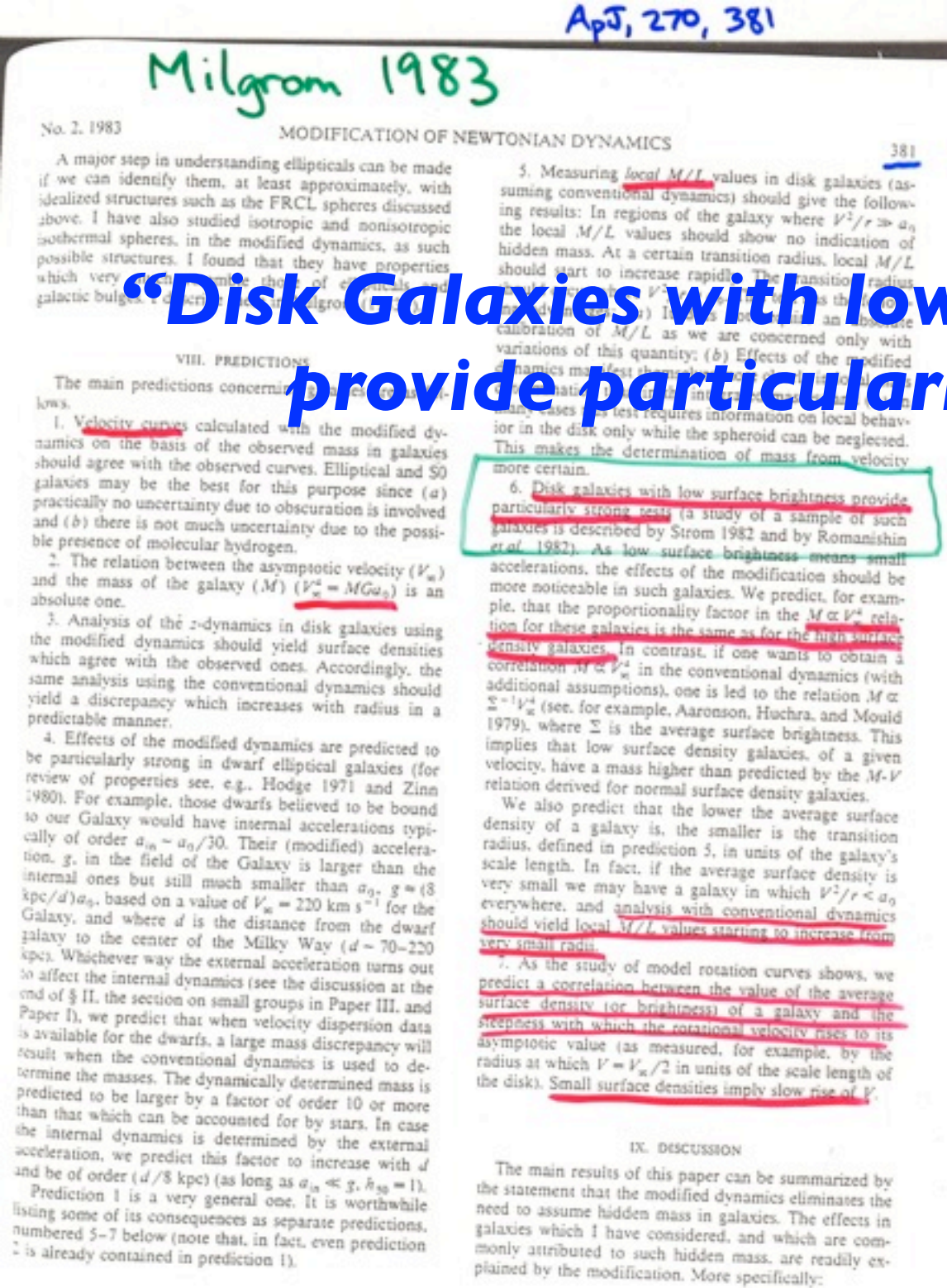
The Ugly

Modify gravity at an acceleration scale

$$a_0 \approx 10^{-10}\ \mathrm{m\,s^{-2}} \sim cH_0 \sim c\Lambda^{1/2}$$

$$a \gg a_0 \qquad a \to g_N$$

$$a \ll a_0 \qquad a \to \sqrt{g_N a_o}$$



ApJ, 270, 381

Milgrom 1983

No. 2, 1983 MODIFICATION OF NEWTONIAN DYNAMICS 381

A major step in understanding ellipticals can be made if we can identify them, at least approximately, with idealized structures such as the FRCL spheres discussed above. I have also studied isotropic and nonisotropic isothermal spheres, in the modified dynamics, as such possible structures. I found that they have properties which very [illegible] of elliptical and galactic bulges [illegible]

VIII. PREDICTIONS

The main predictions concerning [illegible] follows.

1. Velocity curves calculated with the modified dynamics on the basis of the observed mass in galaxies should agree with the observed curves. Elliptical and S0 galaxies may be the best for this purpose since (*a*) practically no uncertainty due to obscuration is involved and (*b*) there is not much uncertainty due to the possible presence of molecular hydrogen.

2. The relation between the asymptotic velocity (V_∞) and the mass of the galaxy (M) ($V_\infty^4 = MGa_0$) is an absolute one.

3. Analysis of the *z*-dynamics in disk galaxies using the modified dynamics should yield surface densities which agree with the observed ones. Accordingly, the same analysis using the conventional dynamics should yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the modified dynamics are predicted to be particularly strong in dwarf elliptical galaxies (for review of properties see, e.g., Hodge 1971 and Zinn 1980). For example, those dwarfs believed to be bound to our Galaxy would have internal accelerations typically of order $a_{in} \sim a_0/30$. Their (modified) acceleration, g, in the field of the Galaxy is larger than the internal ones but still much smaller than a_0, $g \approx (8$ kpc$/d)a_0$, based on a value of $V_\infty = 220$ km s^{-1} for the Galaxy, and where d is the distance from the dwarf galaxy to the center of the Milky Way ($d \sim 70$–220 kpc). Whichever way the external acceleration turns out to affect the internal dynamics (see the discussion at the end of § II, the section on small groups in Paper III, and Paper I), we predict that when velocity dispersion data is available for the dwarfs, a large mass discrepancy will result when the conventional dynamics is used to determine the masses. The dynamically determined mass is predicted to be larger by a factor of order 10 or more than that which can be accounted for by stars. In case the internal dynamics is determined by the external acceleration, we predict this factor to increase with d and be of order (d/8 kpc) (as long as $a_{in} \ll g$, $h_{50} = 1$).

Prediction 1 is a very general one. It is worthwhile listing some of its consequences as separate predictions, numbered 5–7 below (note that, in fact, even prediction 2 is already contained in prediction 1).

5. Measuring *local* M/L values in disk galaxies (assuming conventional dynamics) should give the following results: In regions of the galaxy where $V^2/r \gg a_0$ the local M/L values should show no indication of hidden mass. At a certain transition radius, local M/L should start to increase rapidly. The transition radius [illegible] calibration of M/L as we are concerned only with variations of this quantity; (*b*) Effects of the modified dynamics may [illegible] ior in the disk only while the spheroid can be neglected. This makes the determination of mass from velocity more certain.

6. Disk galaxies with low surface brightness provide particularly strong tests (a study of a sample of such galaxies is described by Strom 1982 and by Romanishin *et al.* 1982). As low surface brightness means small accelerations, the effects of the modification should be more noticeable in such galaxies. We predict, for example, that the proportionality factor in the $M \propto V_\infty^4$ relation for these galaxies is the same as for the high surface density galaxies. In contrast, if one wants to obtain a correlation $M \propto V_\infty^4$ in the conventional dynamics (with additional assumptions), one is led to the relation $M \propto \Sigma^{-1} V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface density galaxies, of a given velocity, have a mass higher than predicted by the M-V relation derived for normal surface density galaxies.

We also predict that the lower the average surface density of a galaxy is, the smaller is the transition radius, defined in prediction 5, in units of the galaxy's scale length. In fact, if the average surface density is very small we may have a galaxy in which $V^2/r < a_0$ everywhere, and analysis with conventional dynamics should yield local M/L values starting to increase from very small radii.

7. As the study of model rotation curves shows, we predict a correlation between the value of the average surface density (or brightness) of a galaxy and the steepness with which the rotational velocity rises to its asymptotic value (as measured, for example, by the radius at which $V = V_\infty/2$ in units of the scale length of the disk). Small surface densities imply slow rise of V.

IX. DISCUSSION

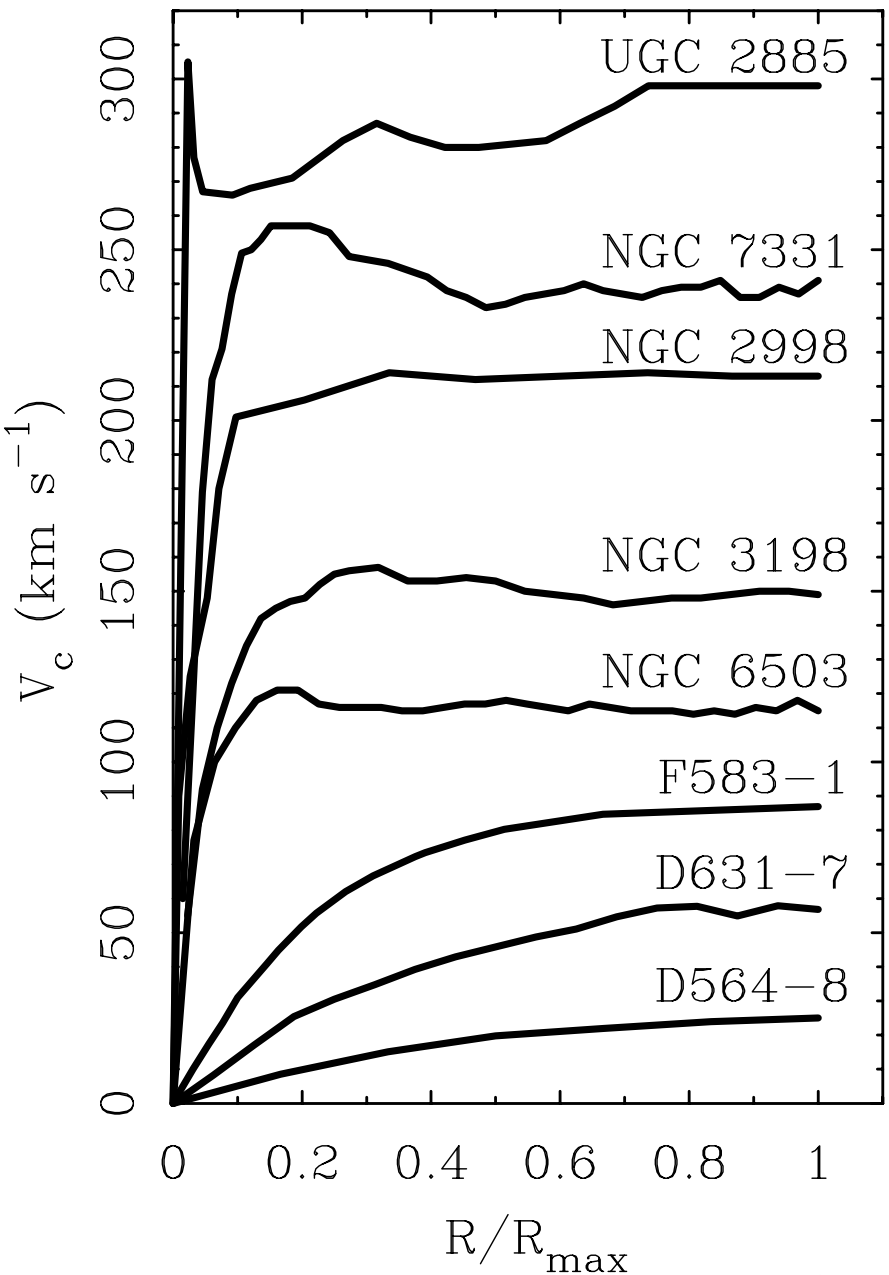
The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

"Disk Galaxies with low surface brightness provide particularly strong tests"

MOND predictions

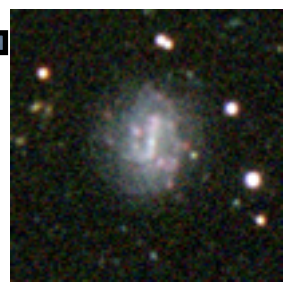
- The Tully-Fisher Relation
  - Slope = 4
  - Normalization = $1/(a_0 G)$
  - Fundamentally a relation between Disk Mass and V_{flat}
  - No Dependence on Surface Brightness
- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Surface Density ~ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios

Rotation curves



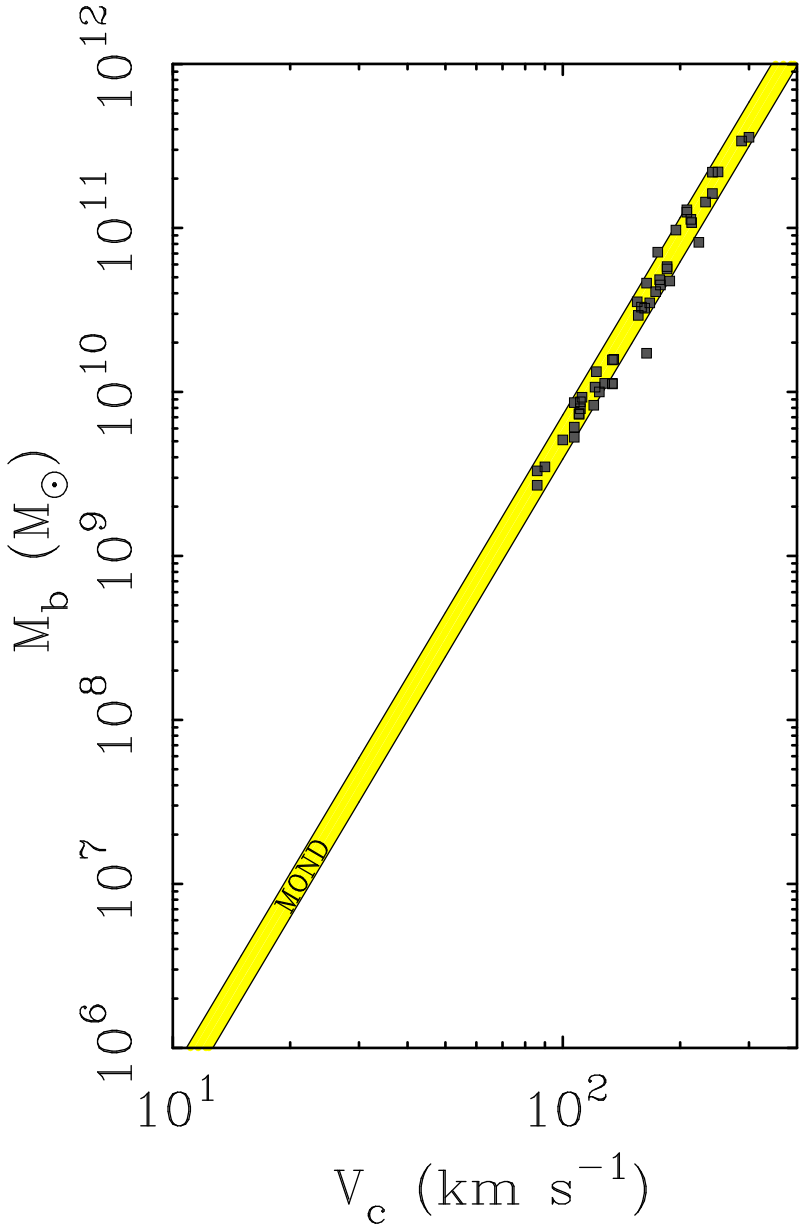
spirals

$M_* > M_g$.

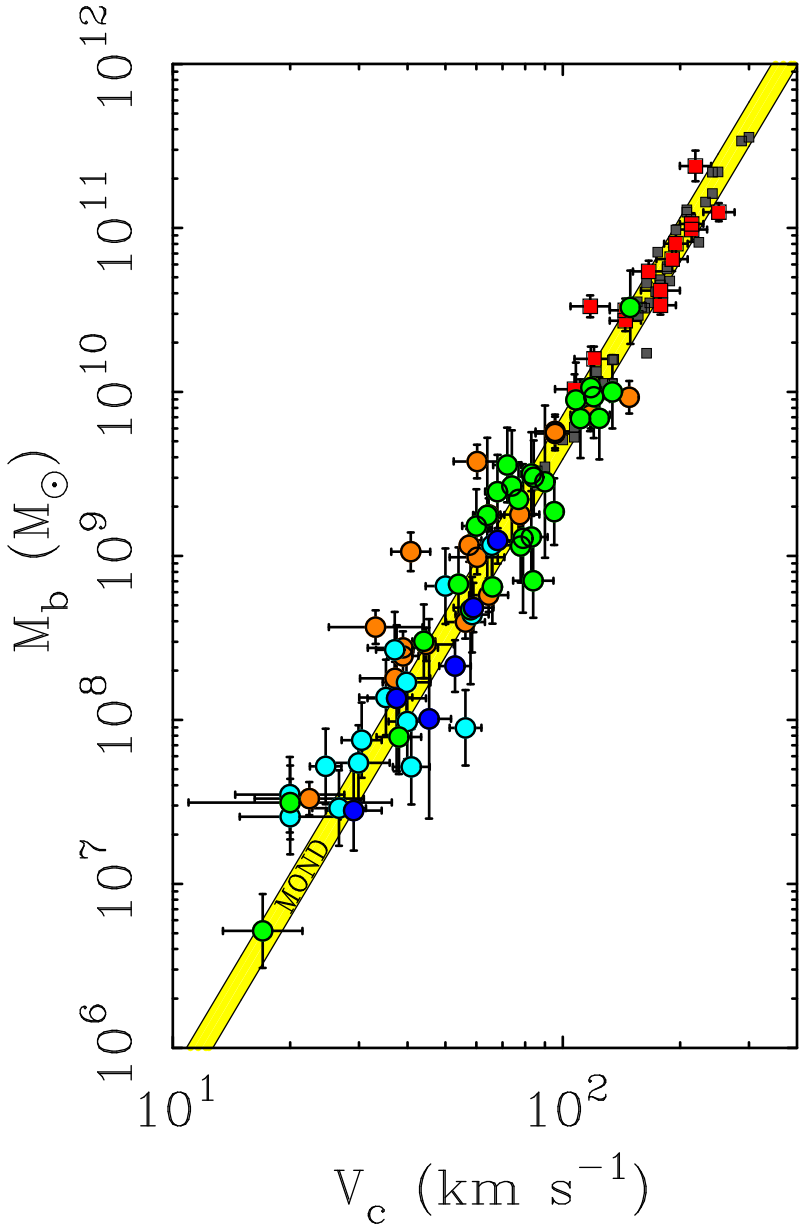


gas disks
with $M_* < M_g$.

MOND predicts $a_0 GM = V^4$



$M_* > M_g$ (MOND fits)
McGaugh (2005)



$M_* > M_g$ (MOND fits)
McGaugh (2005)

$M_* > M_g$ (H-band popsynth)
Sakai (2000); Gurovich et al. (2010)

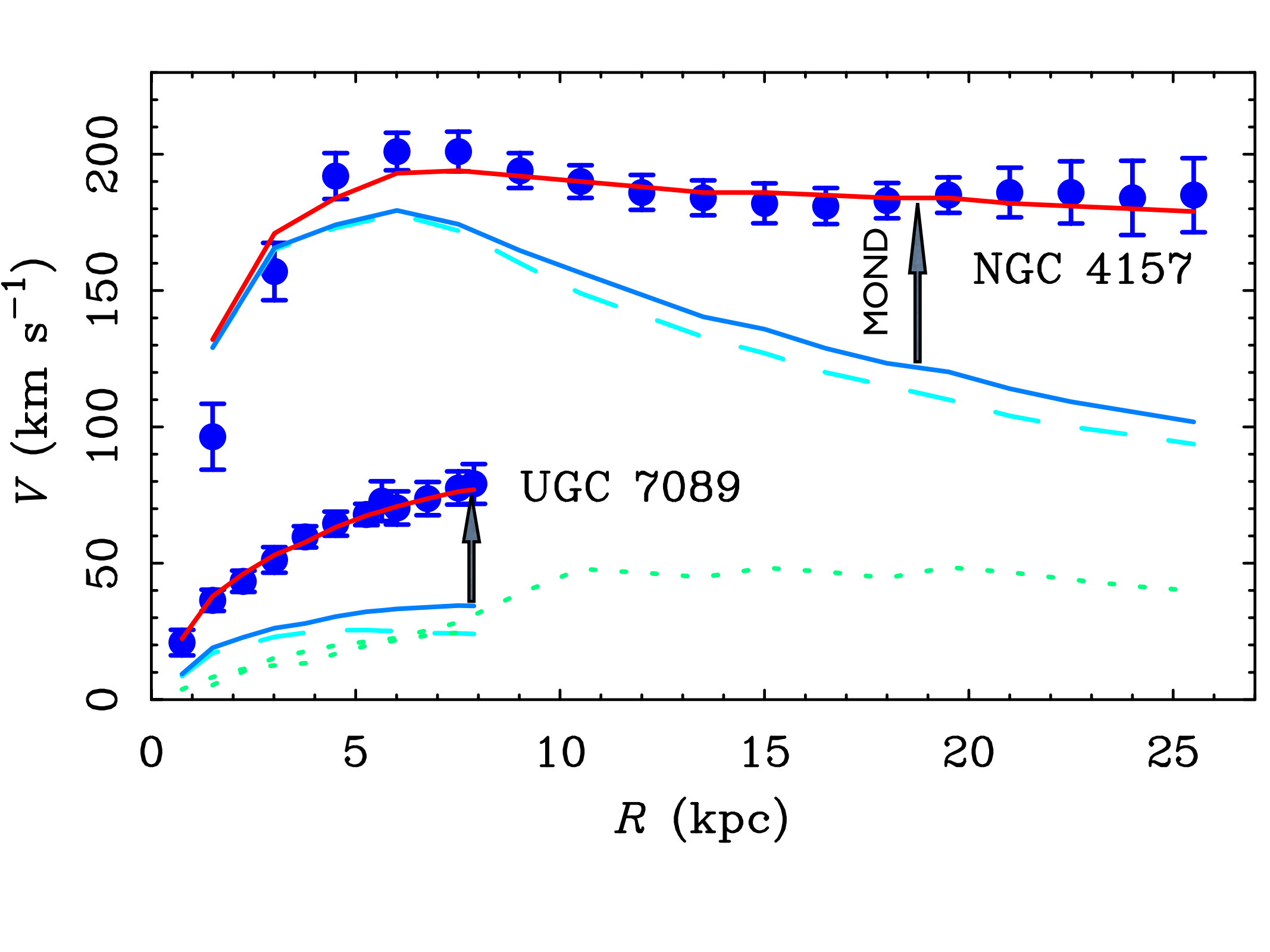
$M_* < M_g$ ($V_c = W_{20}/2$)
Gurovich et al. (2010)

$M_* < M_g \sin(i_{opt}) < 1.12 \sin(i_{HI})$
Begum et al. (2008)

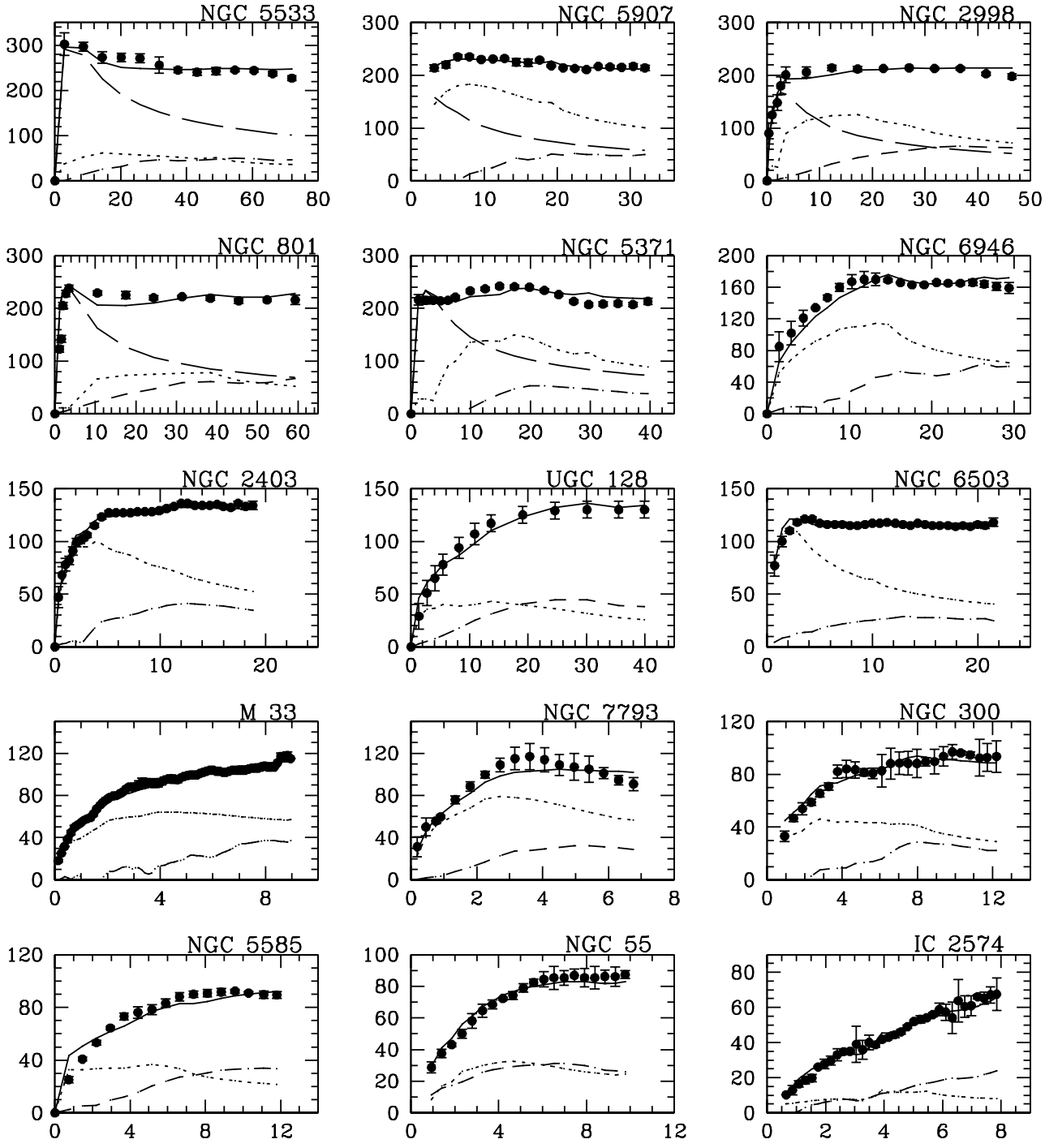
$M_* < M_g$
Stark et al. (2009)

$M_* < M_g$
Trachternach et al. (2008)

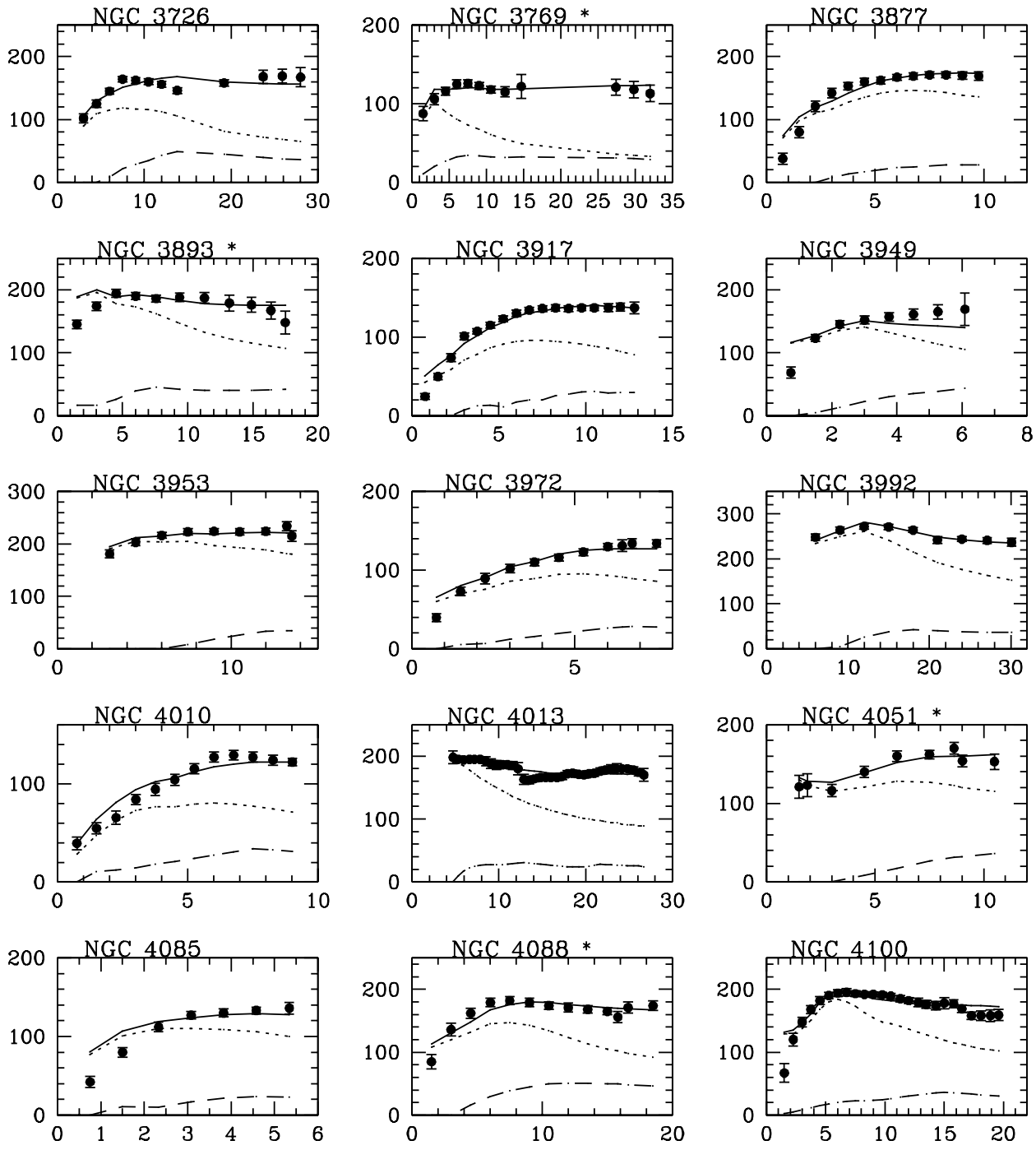
Position on BTFR independent of stellar M_*/L for $M_* < M_g$


NGC 4157
UGC 7089
MOND
V (km s−1)
R (kpc)
0
50
100
150
200
0
5
10
15
20
25

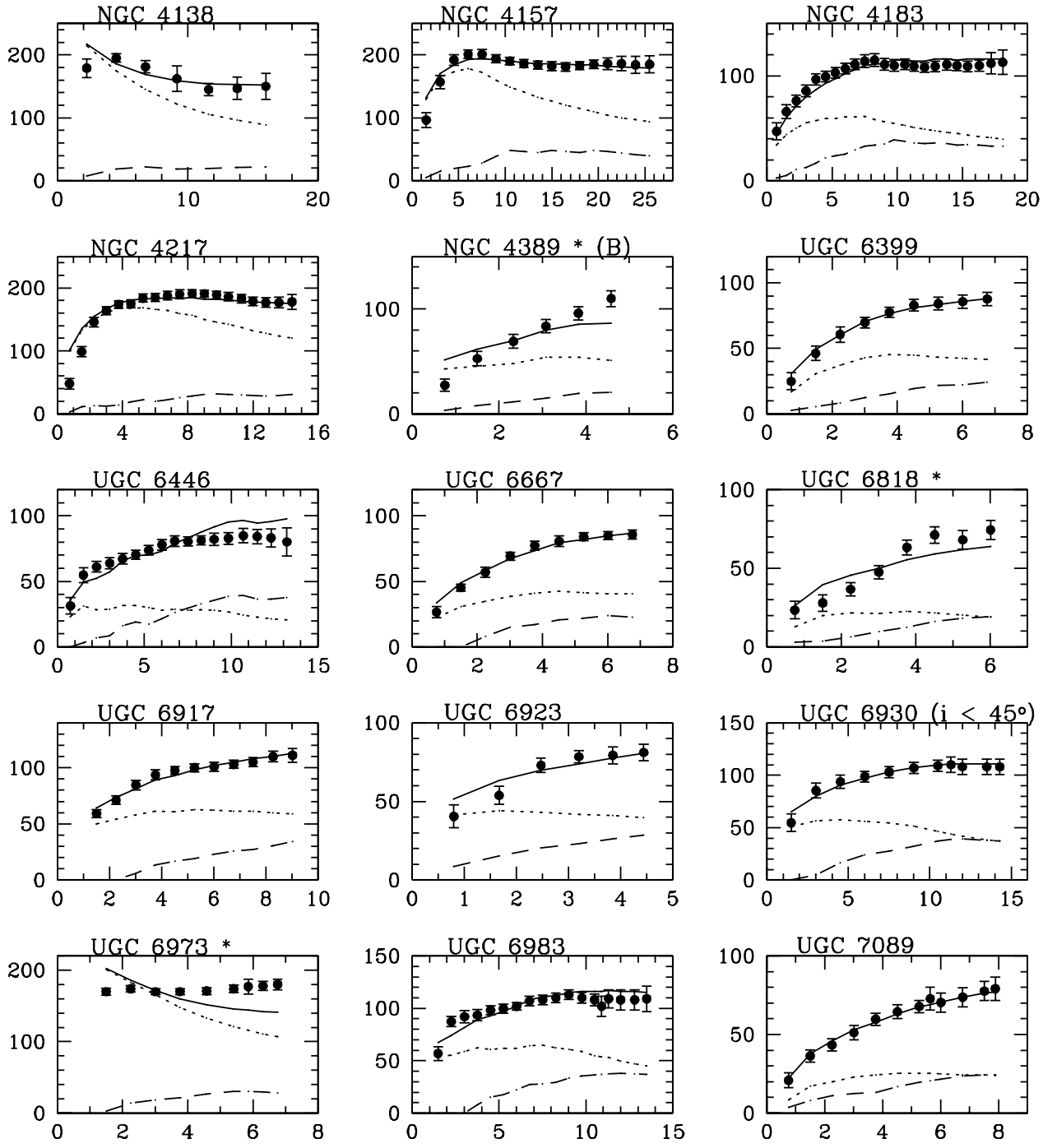
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



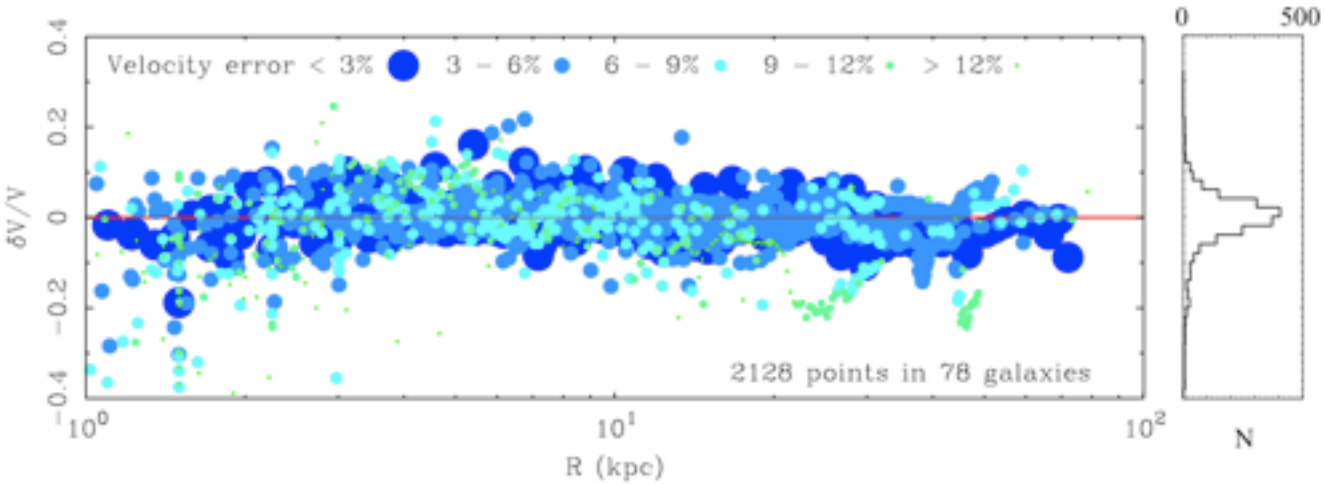
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



Sanders & McGaugh 2002, *ARA&A*, **40**, 263

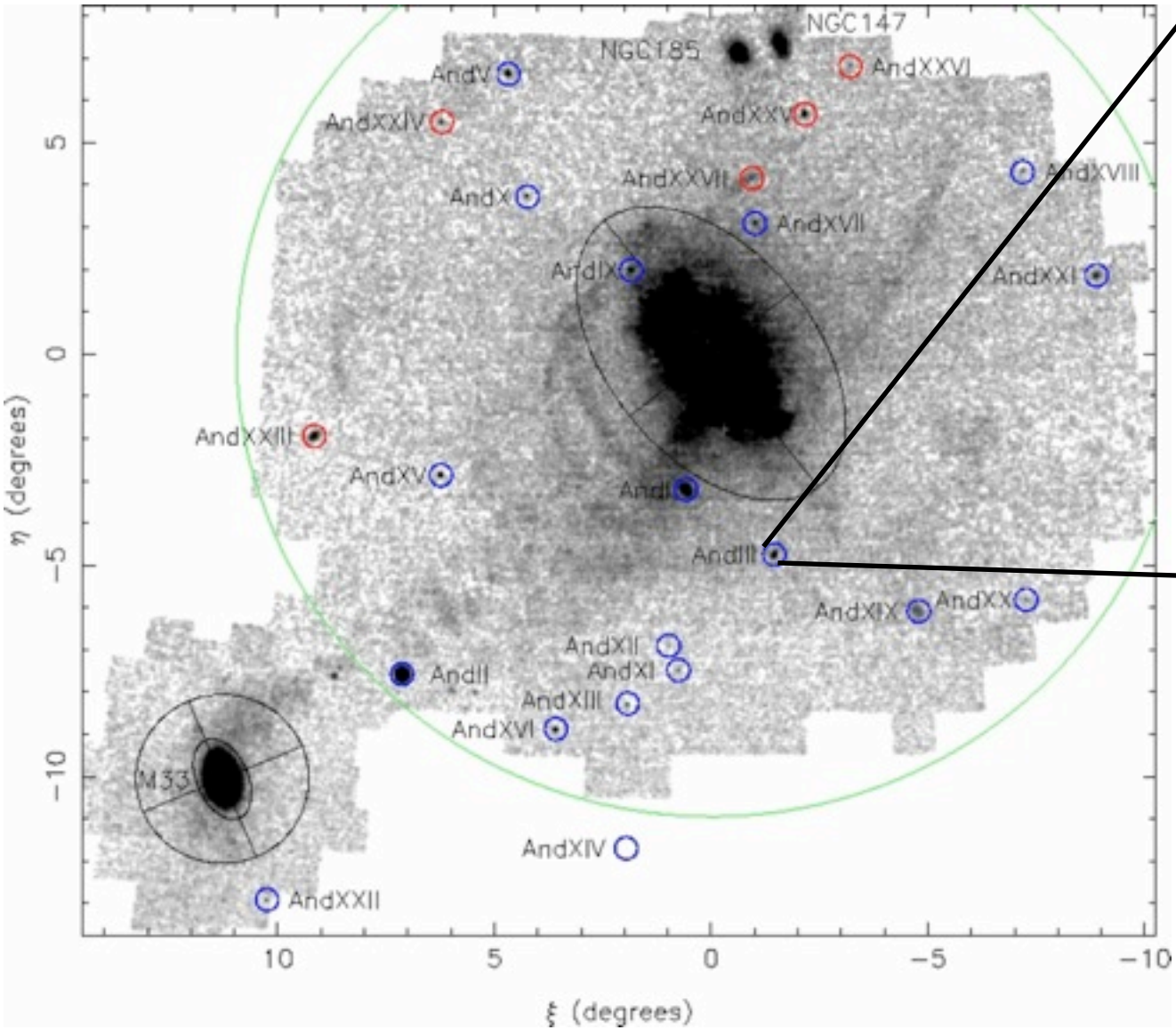


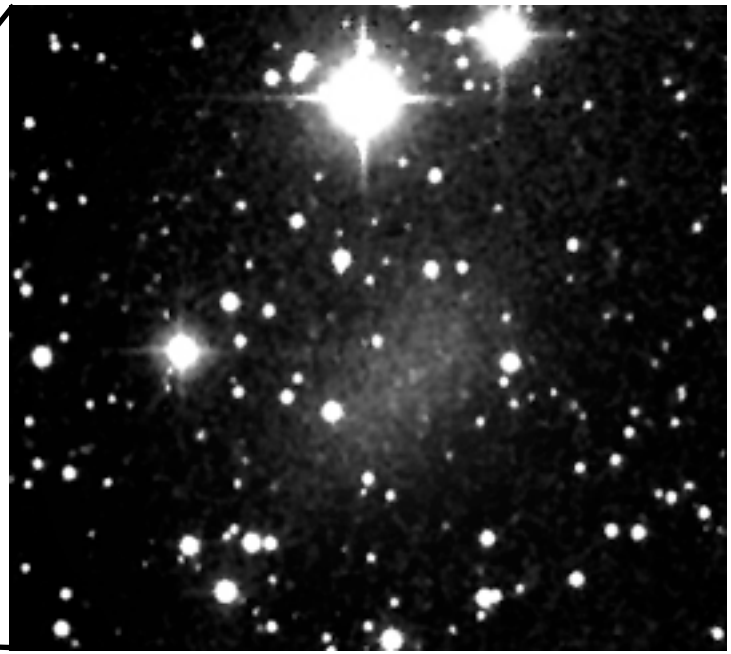
MOND predictions



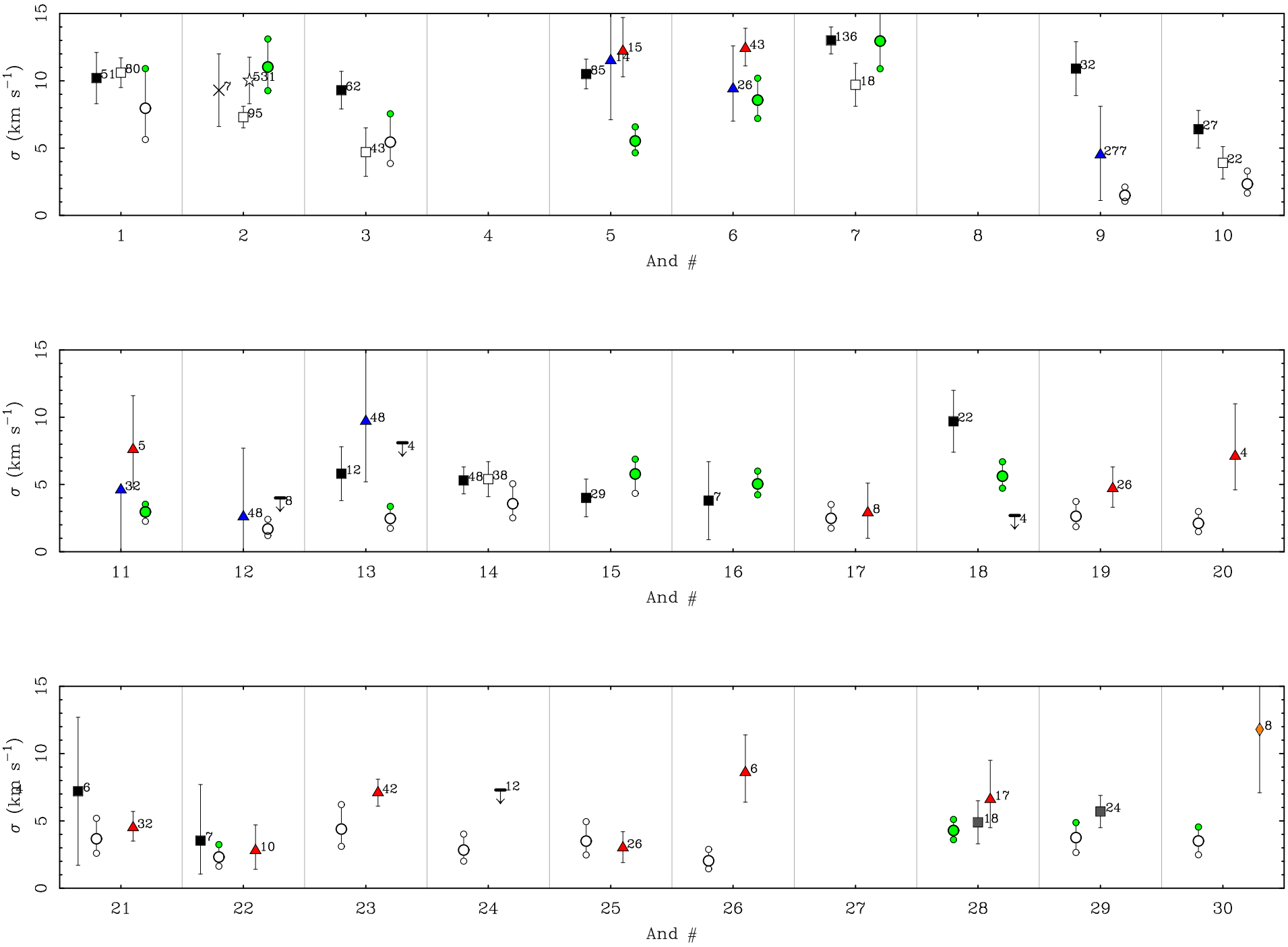
- The Tully-Fisher Relation
  - Slope = 4
  - ✔ Normalization = $1/(a_0 G)$
  - ✔ Fundamentally a relation between Disk Mass and V_{flat}
  - ✔ No Dependence on Surface Brightness
- ✔ Dependence of conventional M/L on radius and surface brightness
- ✔ Rotation Curve Shapes
- ✔ Surface Density ~ Surface Brightness
- ✔ Detailed Rotation Curve Fits
- ✔ Stellar Population Mass-to-Light Ratios

A new test: the dwarf satellites of Andromeda





Use MOND to predict the velocity of stars within each dwarf


σ (km s^{-1})
And #
0
5
10
15
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6
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136
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32
277
27
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5
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8
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6
32
7
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42
12
26
6
17
18
24
8

The Good

Hubble Expansion

Primordial Nucleosynthesis

Cosmic Microwave Background

The Ugly

Dark Matter

Dark Energy

The Bad

MOND

"We find ourselves, in the company of multitudes of others in the past, speaking of the Universe as if it were at last discovered and revealed. Our ancestors made this mistake continually and most likely our descendants will look back and see us repeating the same mistake."

- Edward Harrison, *Cosmology*

We still have a lot to learn.