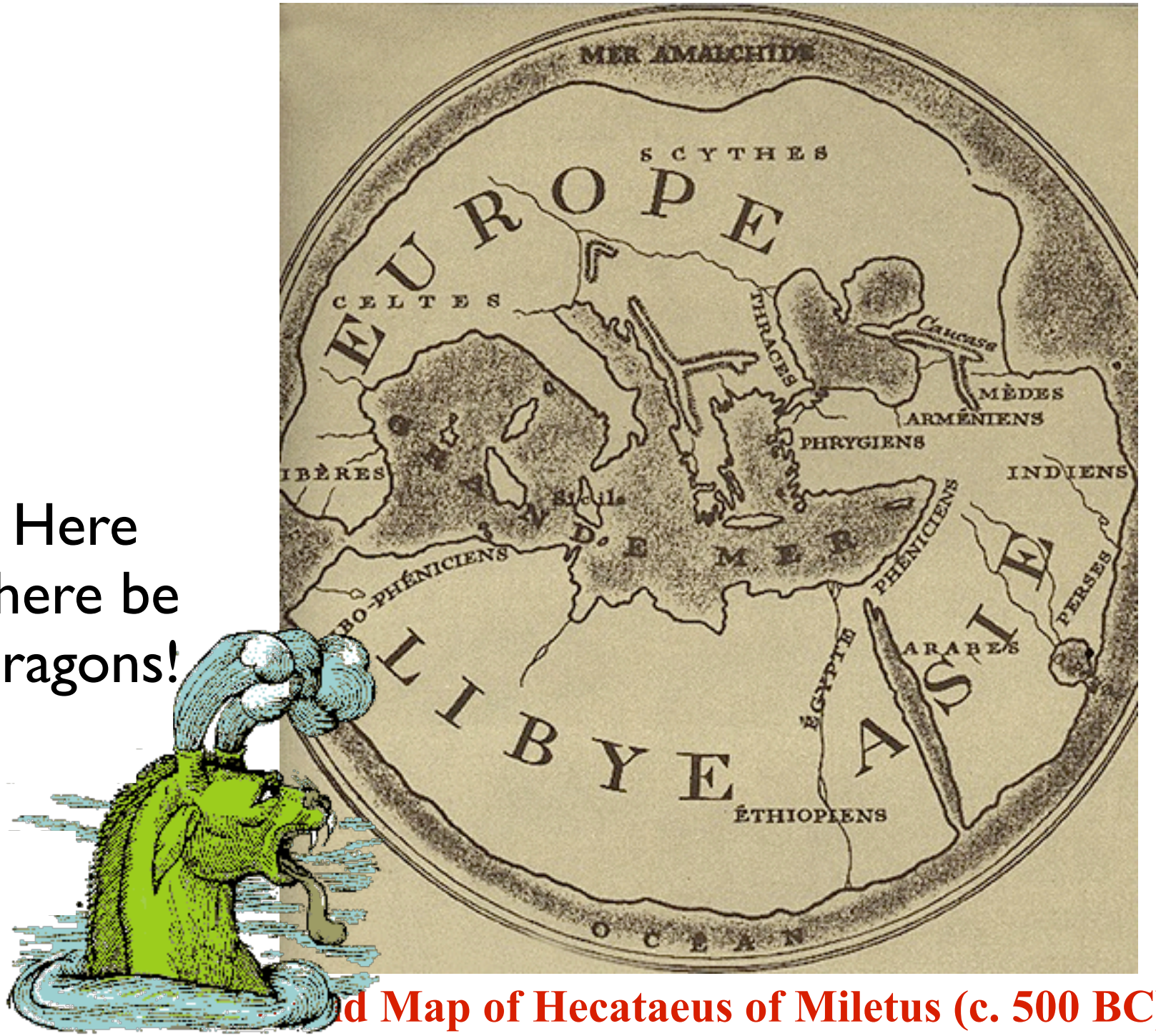
Cleveland Museum of Natural History, 9 December 2010

The Driving Role of Gravity in Cosmology

Stacy McGaugh
University of Maryland

Ancient Cosmology: A Flat Earth

Here there be dragons!

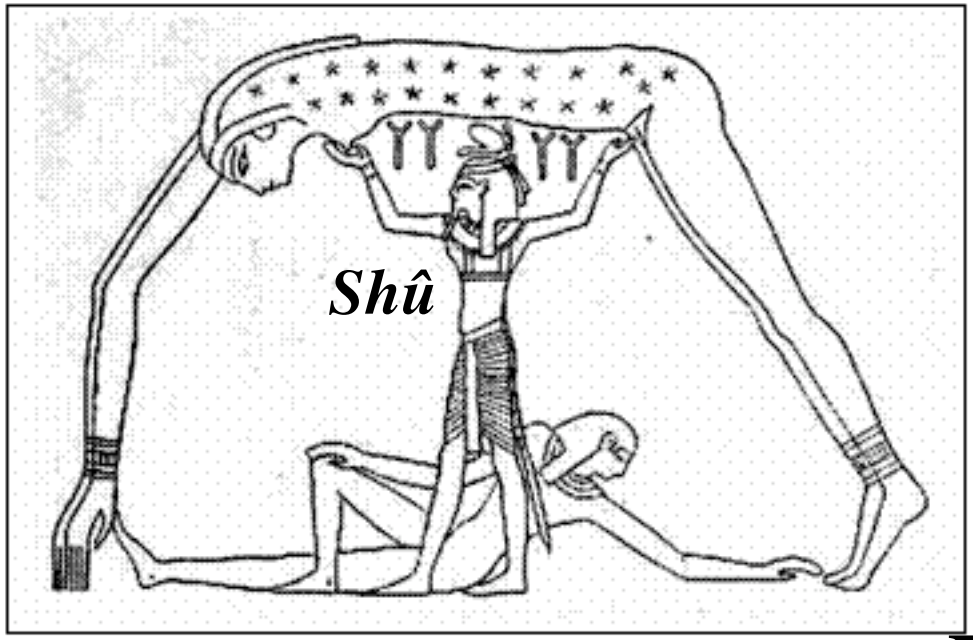


d Map of Hecataeus of Miletus (c. 500 BC)

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.

UP

DOWN

Greek Map in 3D

Incan Cosmology

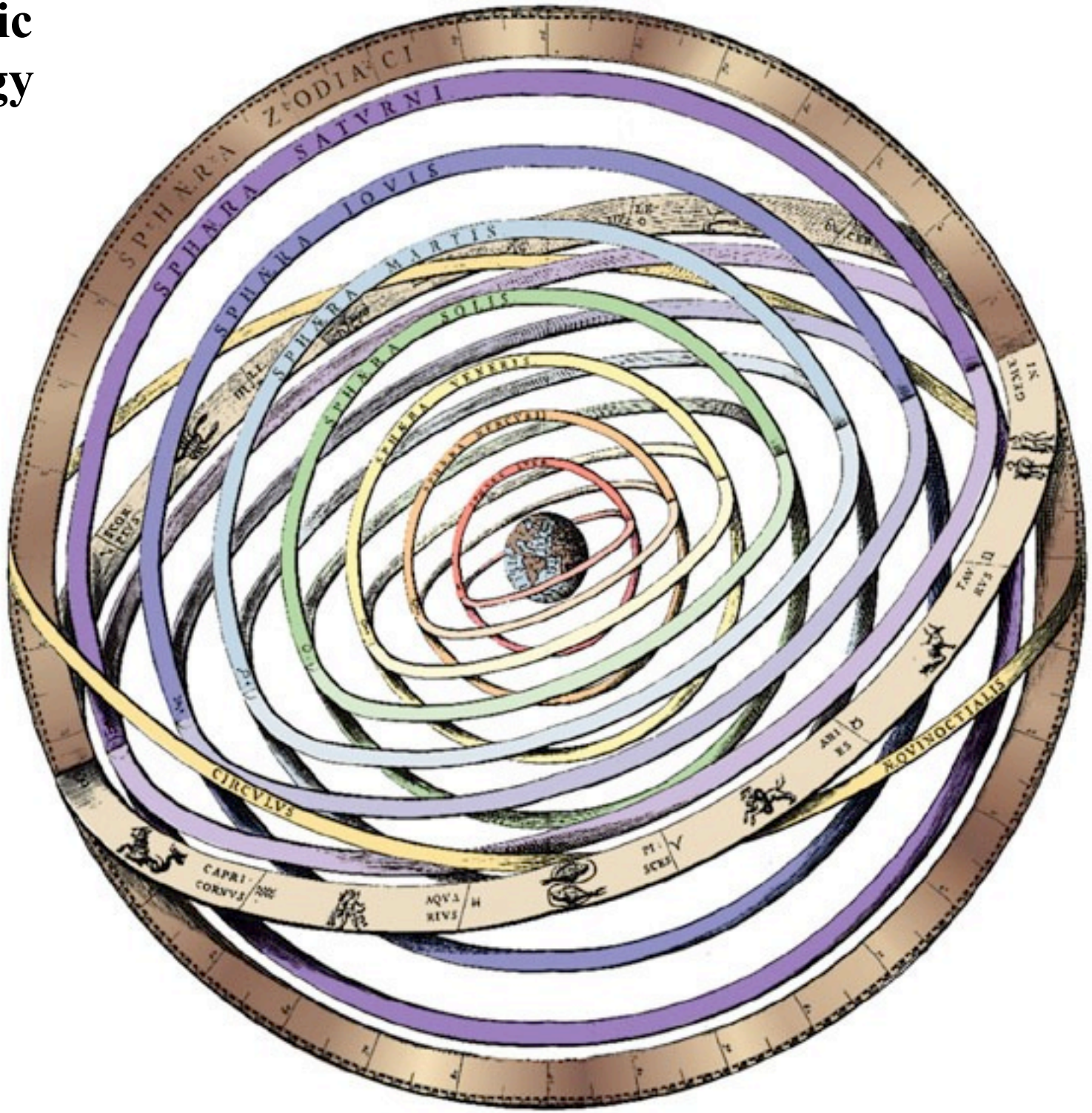
THE ANCIENT HEBREW CONCEPTION OF THE UNIVERSE

TO ILLUSTRATE THE ACCOUNT OF CREATION AND THE FLOOD

well, maybe the earth is round

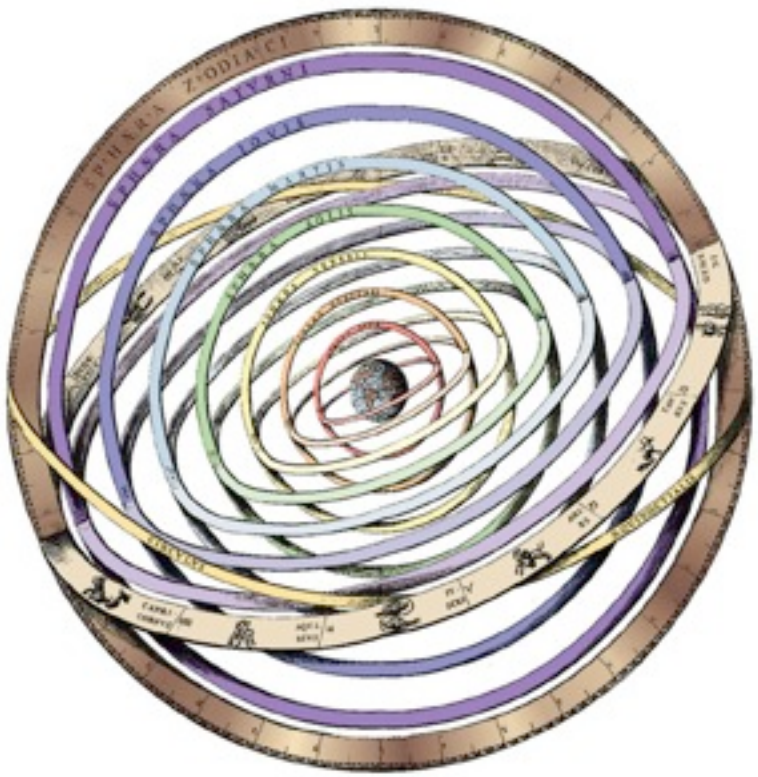
and the center of creation.

Geocentric Cosmology

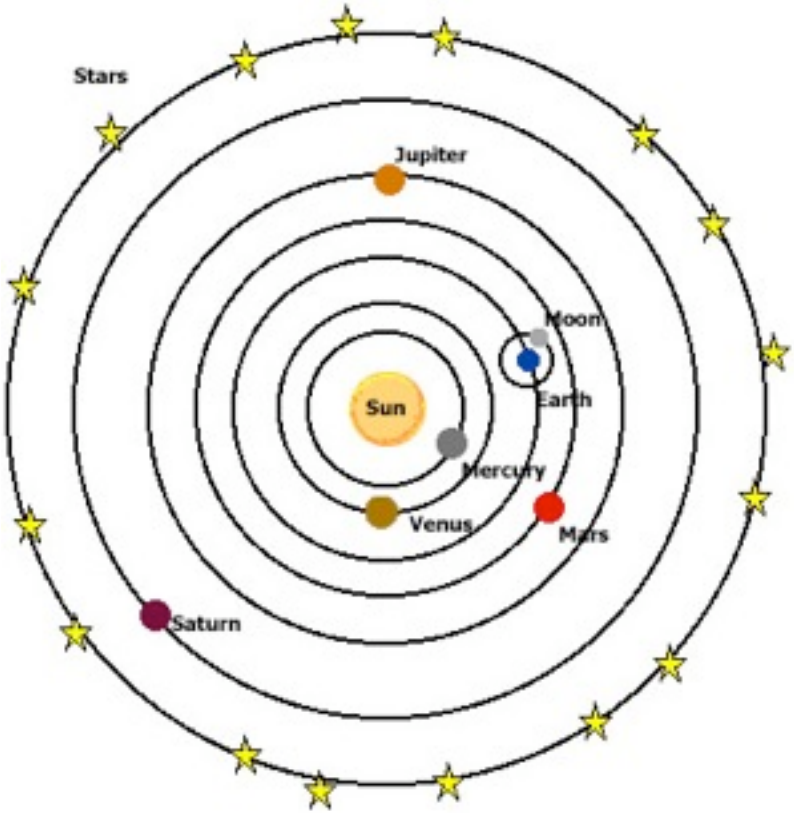


Competing Cosmologies

Geocentric
Ptolemaic
Earth at center



Heliocentric
Copernican
Sun at center



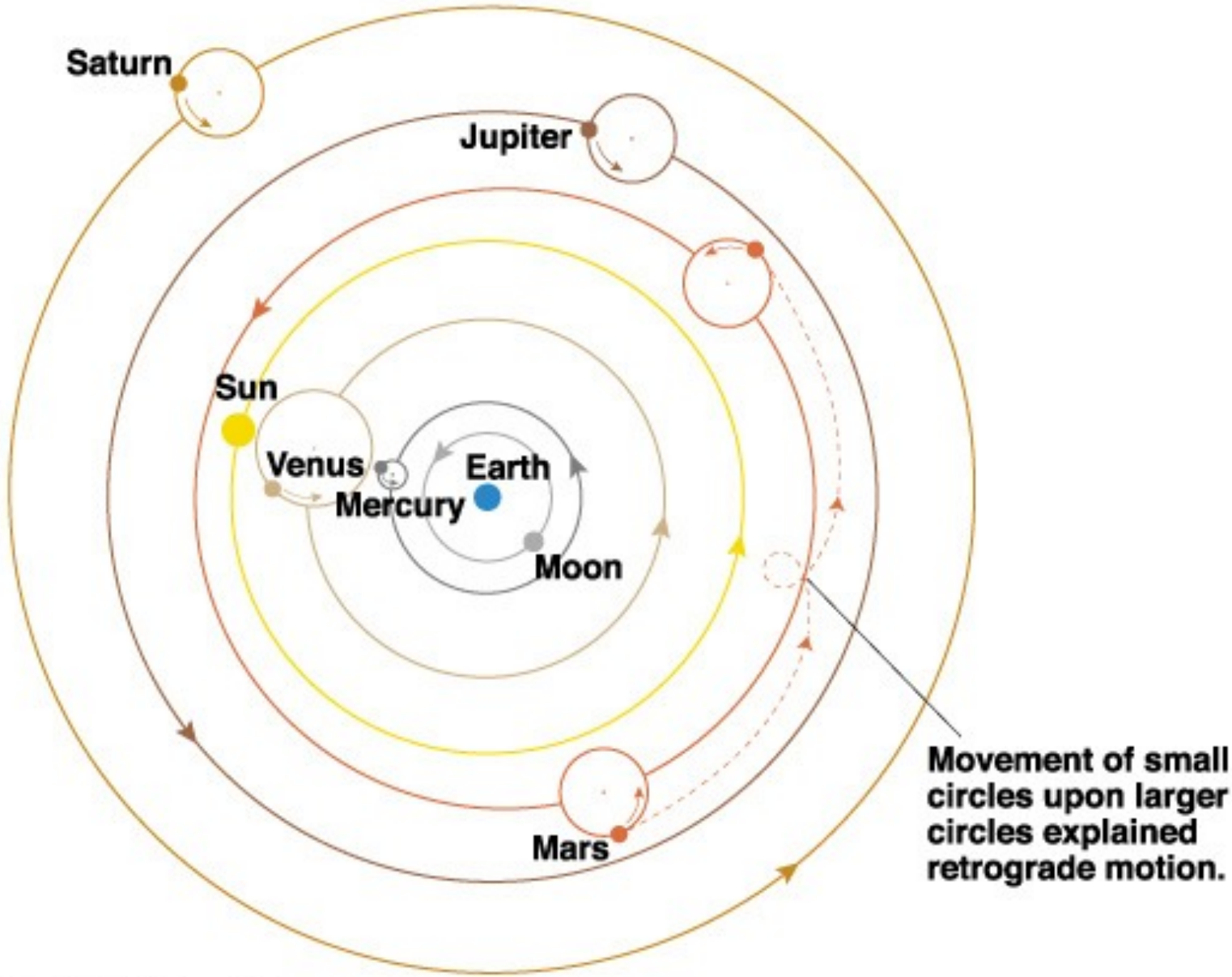
Geocentric Cosmology

Ptolemy

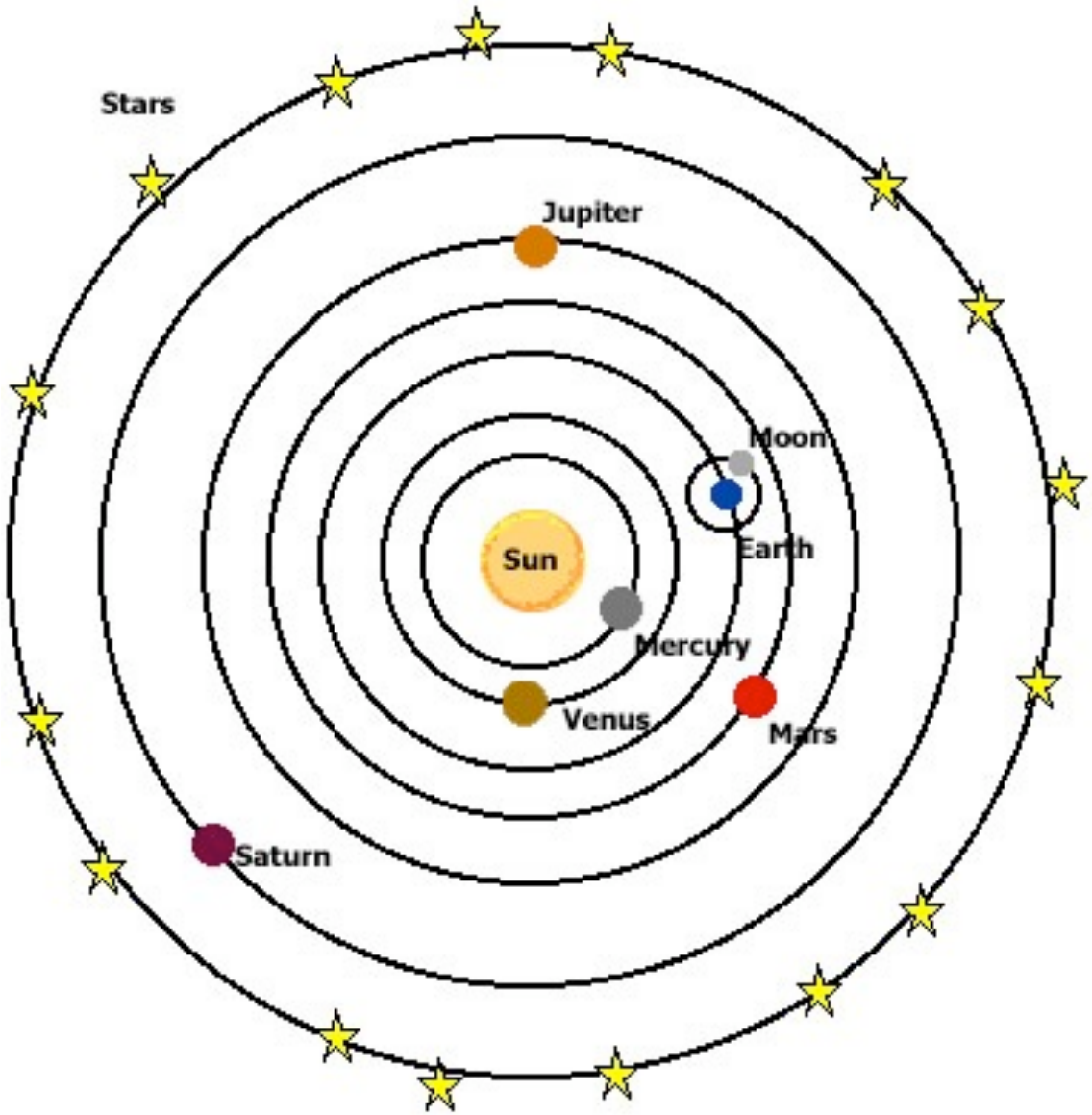
The most sophisticated geocentric model was that of Ptolemy (A.D. 100–170) — the **Ptolemaic model:**

- Sufficiently accurate to remain in use for 1,500 years
  - i.e., predicted correct positions of planets for many centuries
- Arabic translation of Ptolemy's work named *Almagest* ("the greatest compilation")

Geocentric Cosmology



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

Retrograde Motion

Needs epicycles	Consequence of Lapping

Inferiority of Mercury & Venus

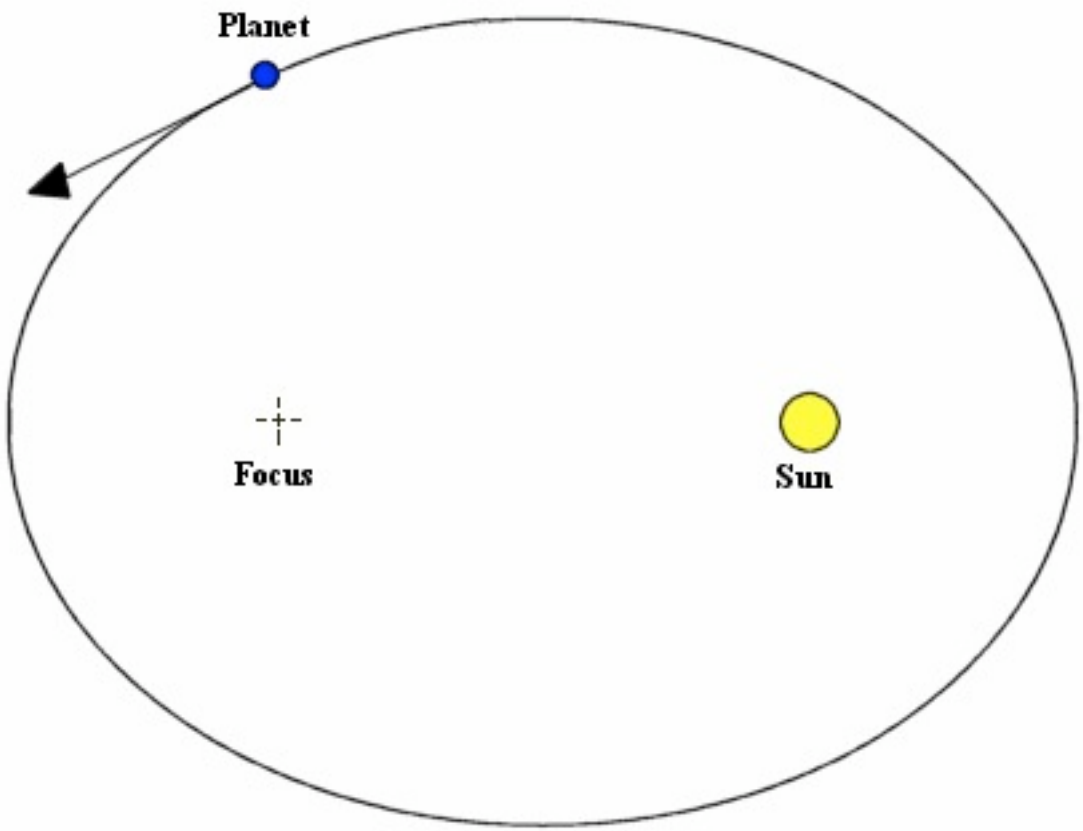
Must tie to sun	Interior to Earth's Orbit

Predicts

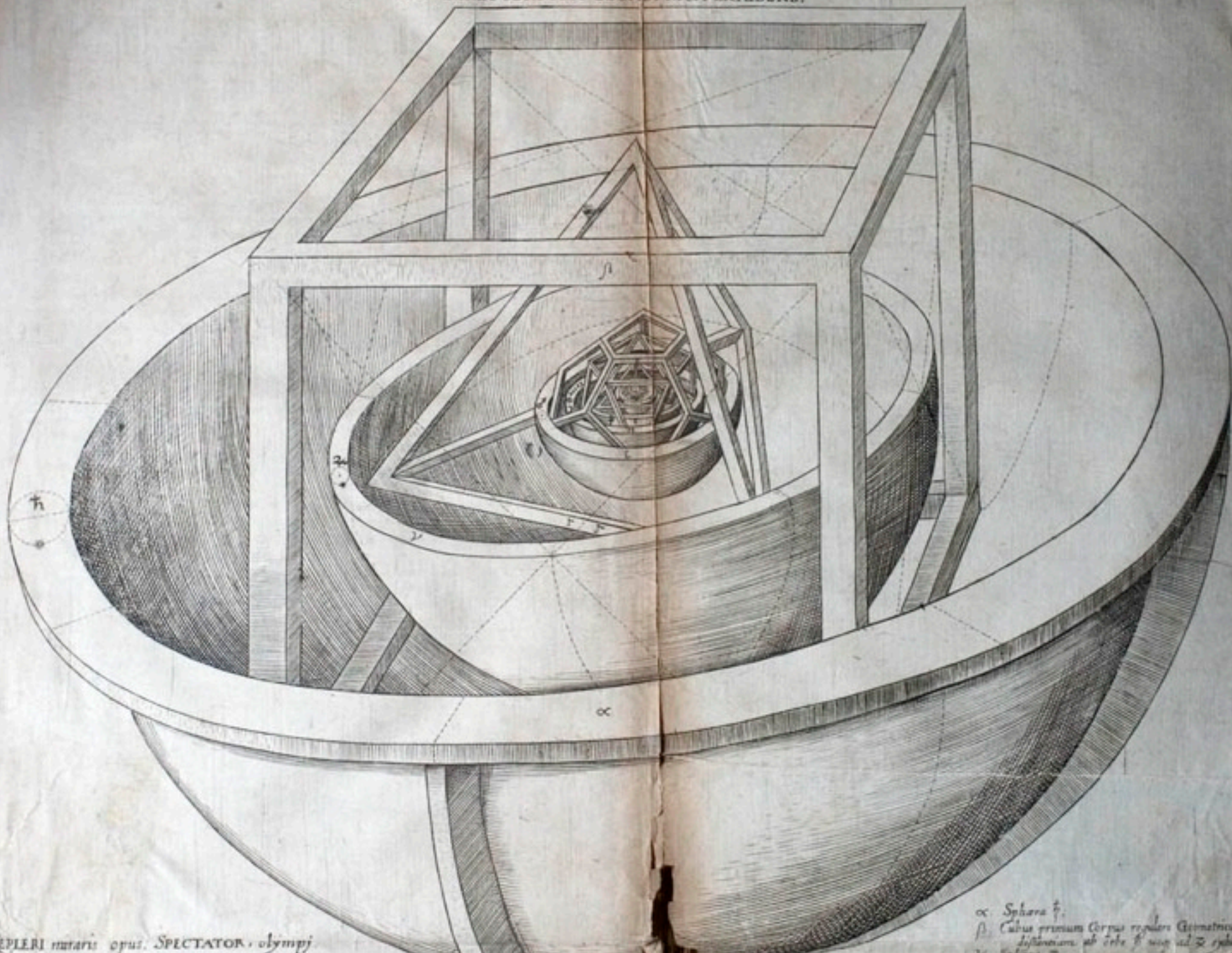
- No parallax	- Parallax
- Venus: crescent phase only	- Venus: all phases

Johannes Kepler
(1571–1630)

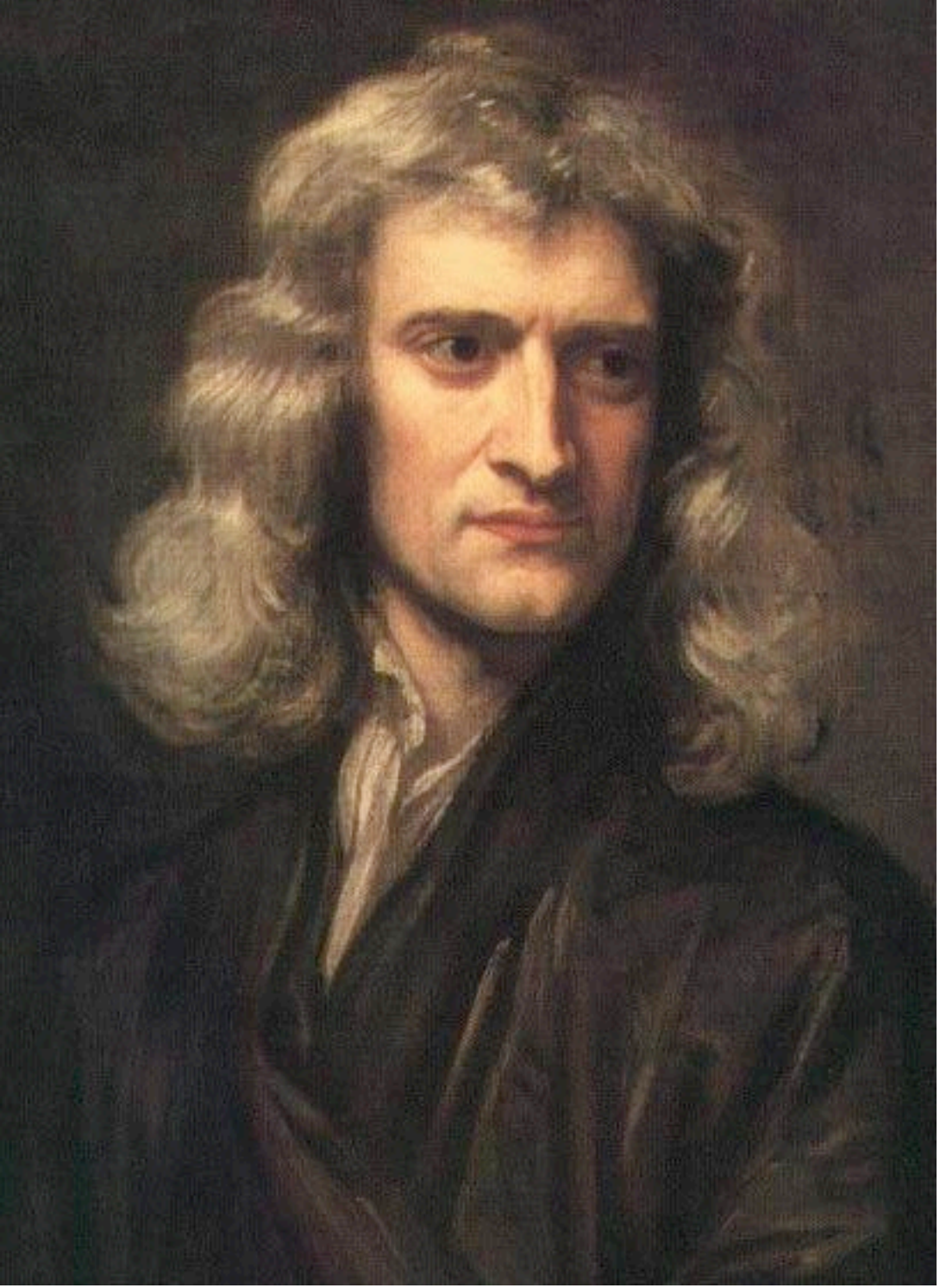
"If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy."



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



KEPLERI mirabilis opus. SPECTATOR, olympij
Antes quæ monumentum. Ibis figura tibi



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)

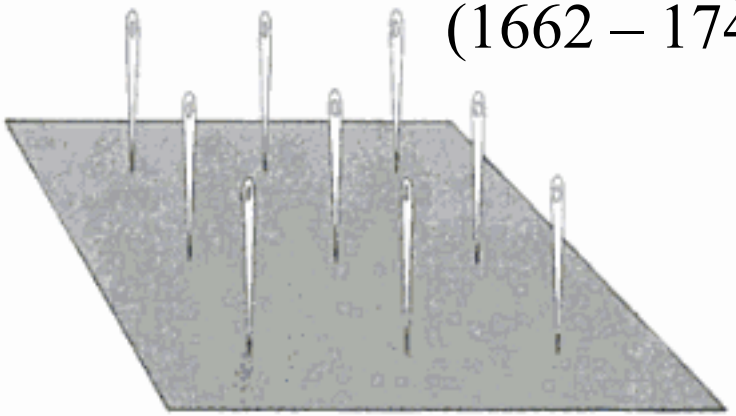
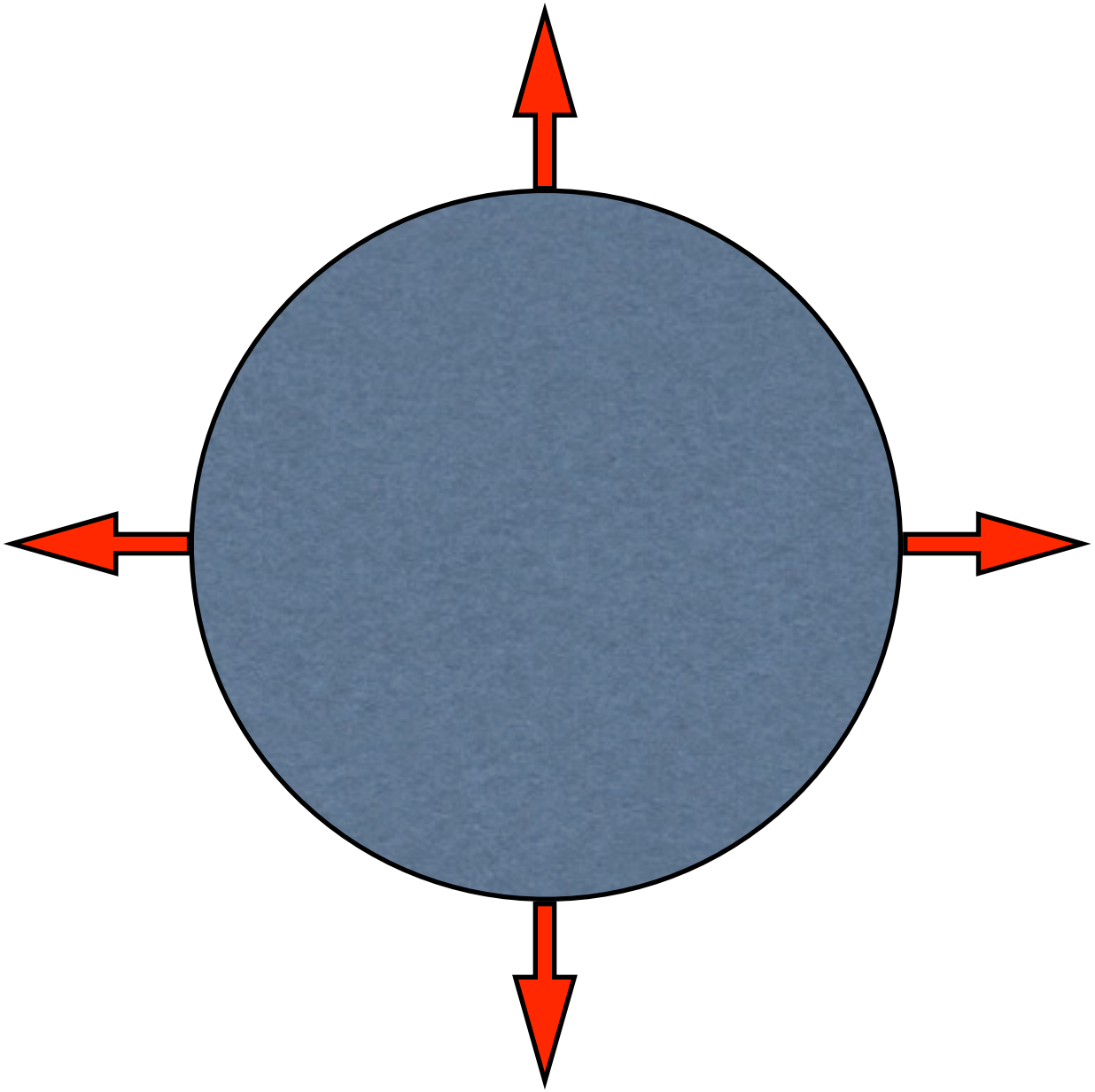


Figure 3.12. Newton agreed with Bentley that stars cannot form a finite and bounded system (as in the Stoic cosmos), for they would fall into the middle of such a system by reason of their gravitational attraction. They agreed that matter was uniformly distributed throughout infinite space, and realized 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."

But what if the universe isn't **static**?

If the universe is **expanding**, Newton's gravity gives the right equation of motion just by considering a point on the surface of a sphere that feels the gravity of a uniform density within that sphere (Milne & McCrea).



The Cosmological Principle

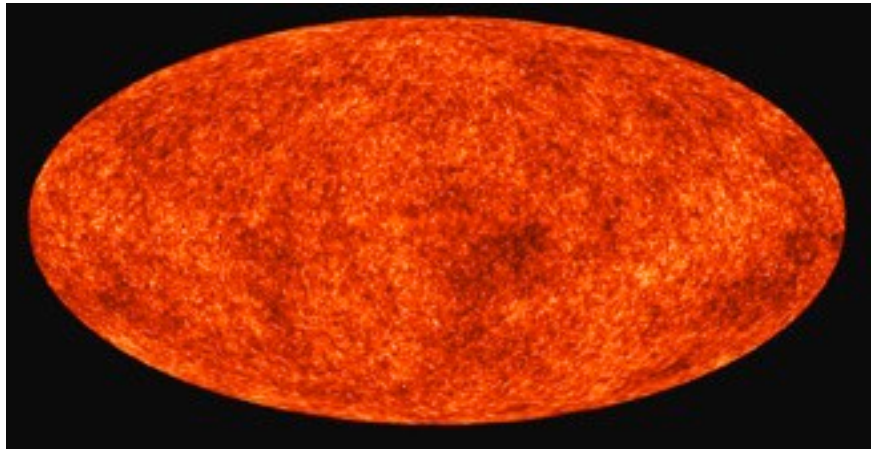
- The Universe is
  - Homogeneous
  - Isotropic

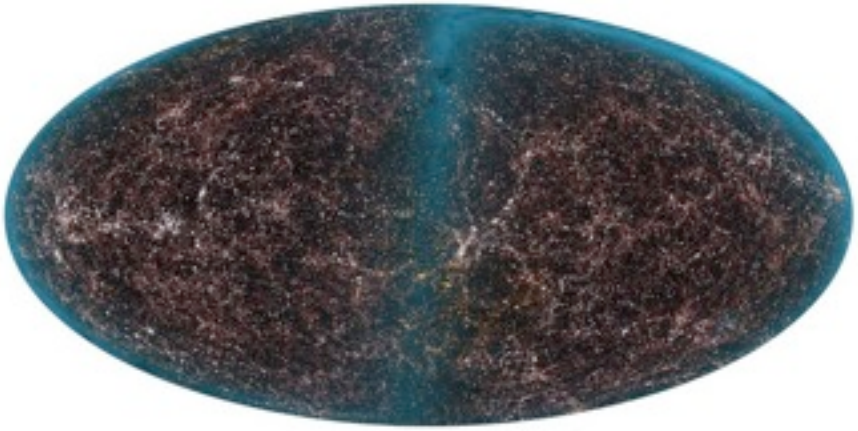
A philosophical assertion that there should be nothing special about where we are, so the universe should look much the same to an distant alien observer as to us.

The Perfect Cosmological Principle

- The universe looks the same from everywhere at all times.

This is a logical extension of the Cosmological Principle in time as well as space. Trouble is, it is **not true**.





An Expanding Universe?

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

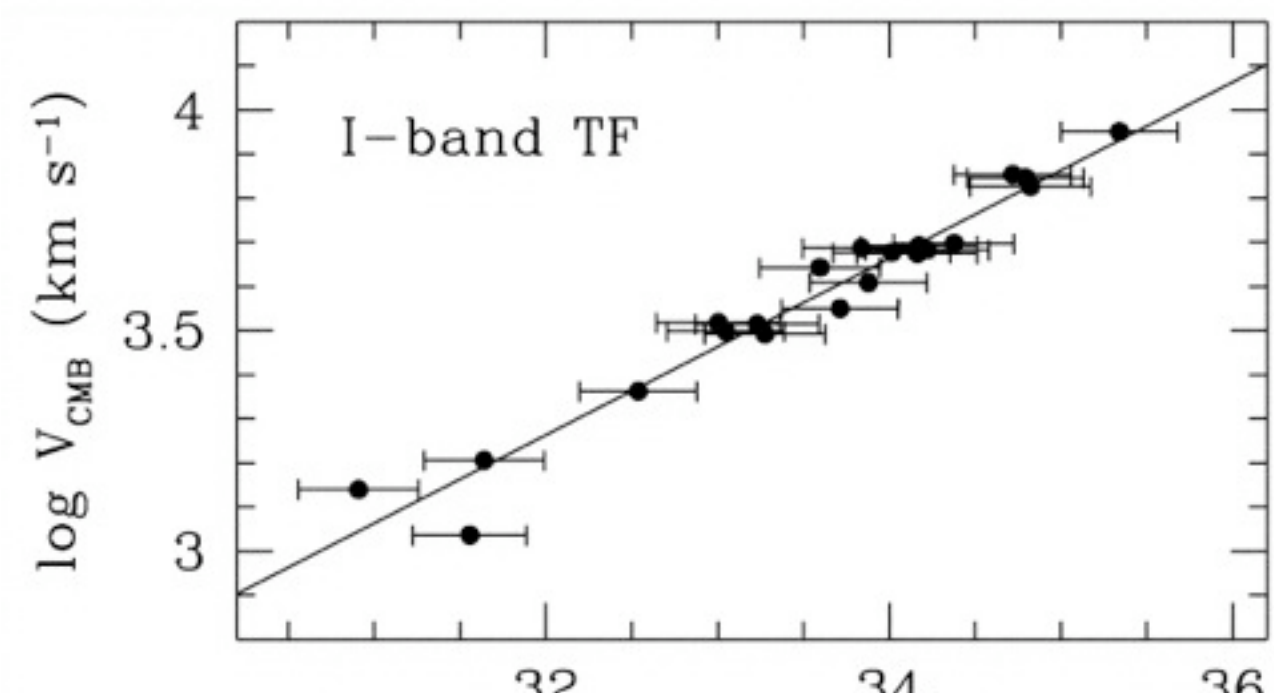
A homogenous, isotropic universe evolving according to Einstein's field equation must either expand or contract. It can not be static.

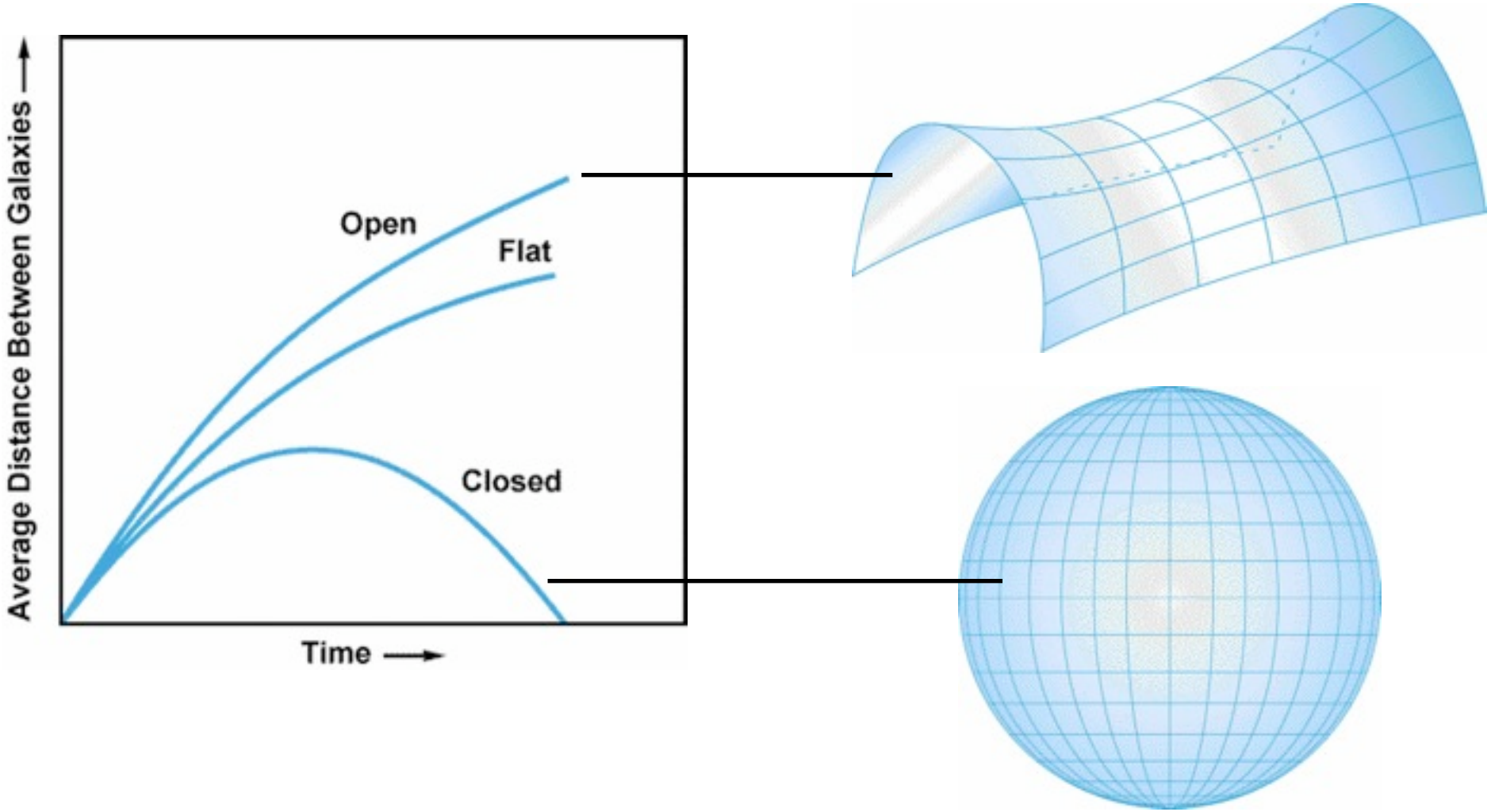
Or a static one?

Einstein's greatest blunder?

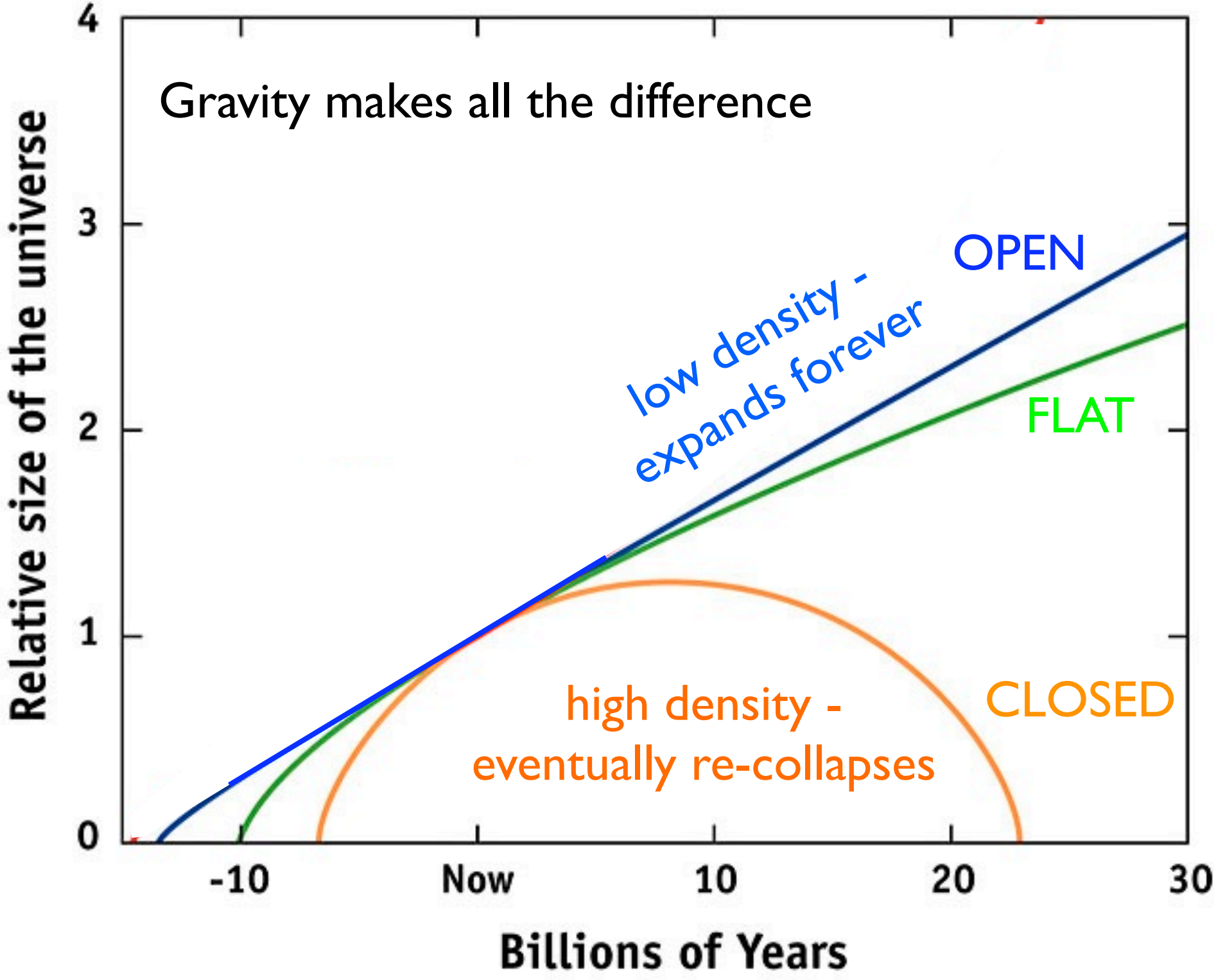
$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu} = 8\pi G T_{\mu\nu} + \cancel{\Lambda} g_{\mu\nu}$$

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

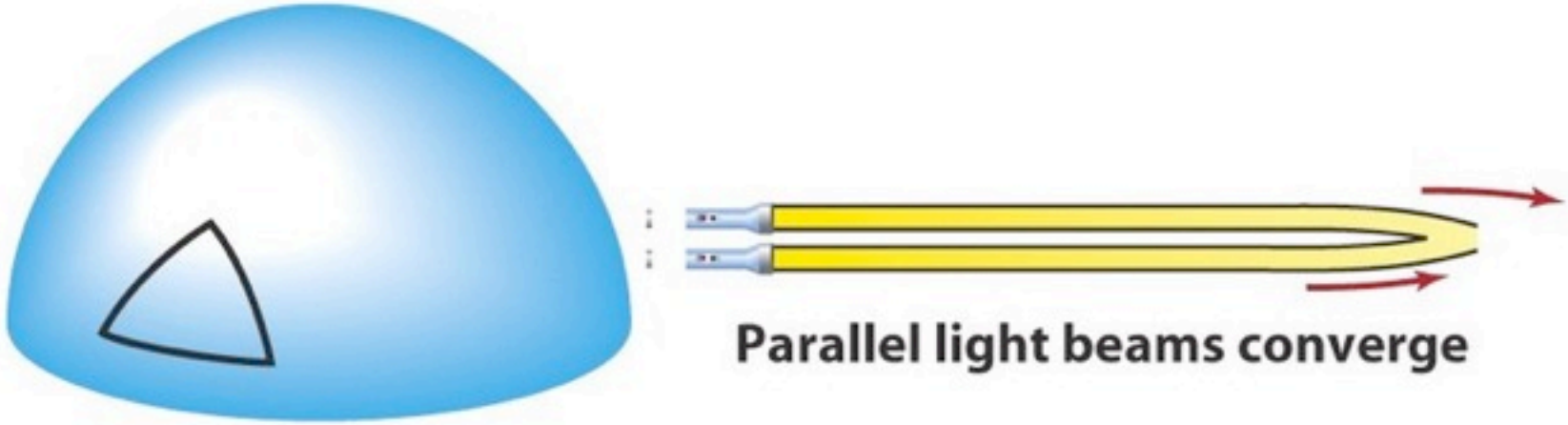




Einstein's geometrical theory of gravity forms the basis of modern cosmology. The expansion history and the geometry of the universe depend on its mass density.


Gravity makes all the difference
OPEN
low density -
expands forever
FLAT
high density -
eventually re-collapses
CLOSED
Relative size of the universe
4
3
2
1
0
-10
Now
10
20
30
Billions of Years

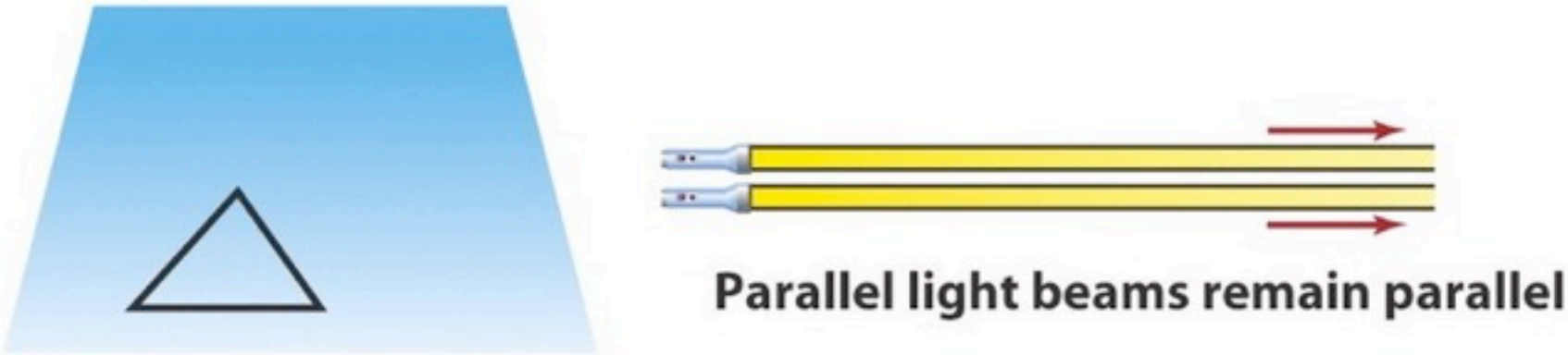
CLOSED



(a) Spherical space

$\rho_0 > \rho_c$, $\Omega_0 > 1$

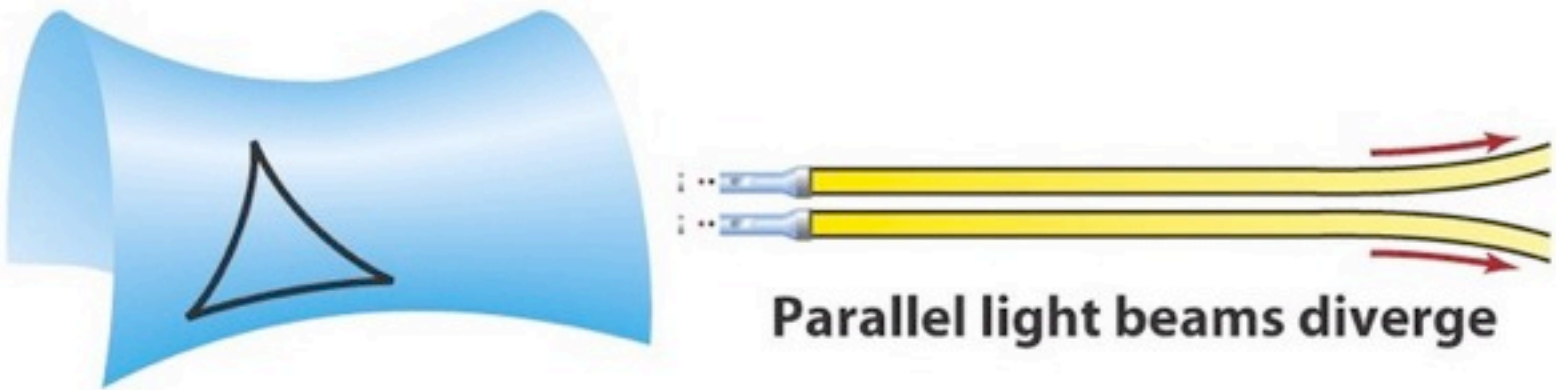
FLAT

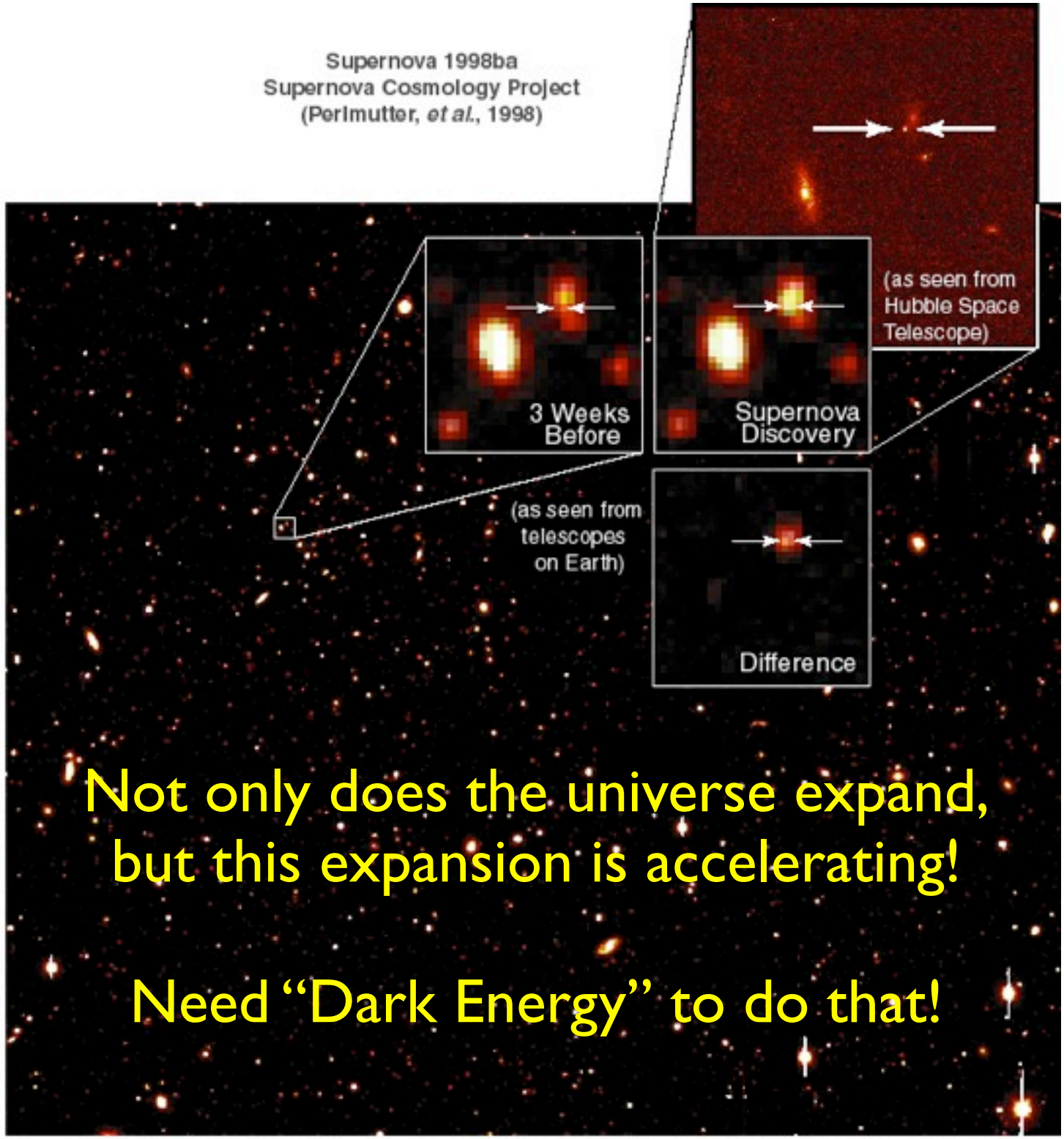


(b) Flat space

$\rho_0 = \rho_c$, $\Omega_0 = 1$

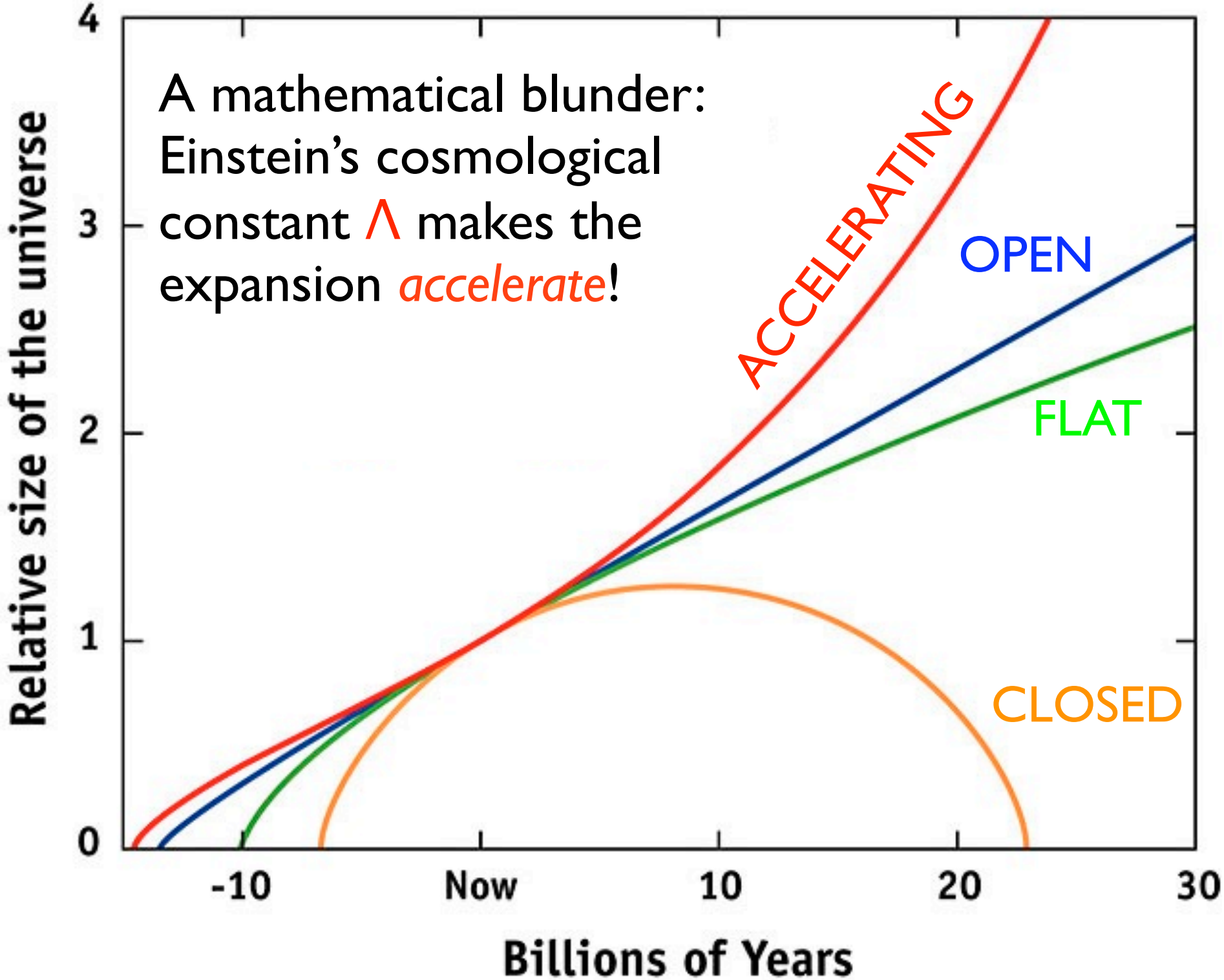
OPEN

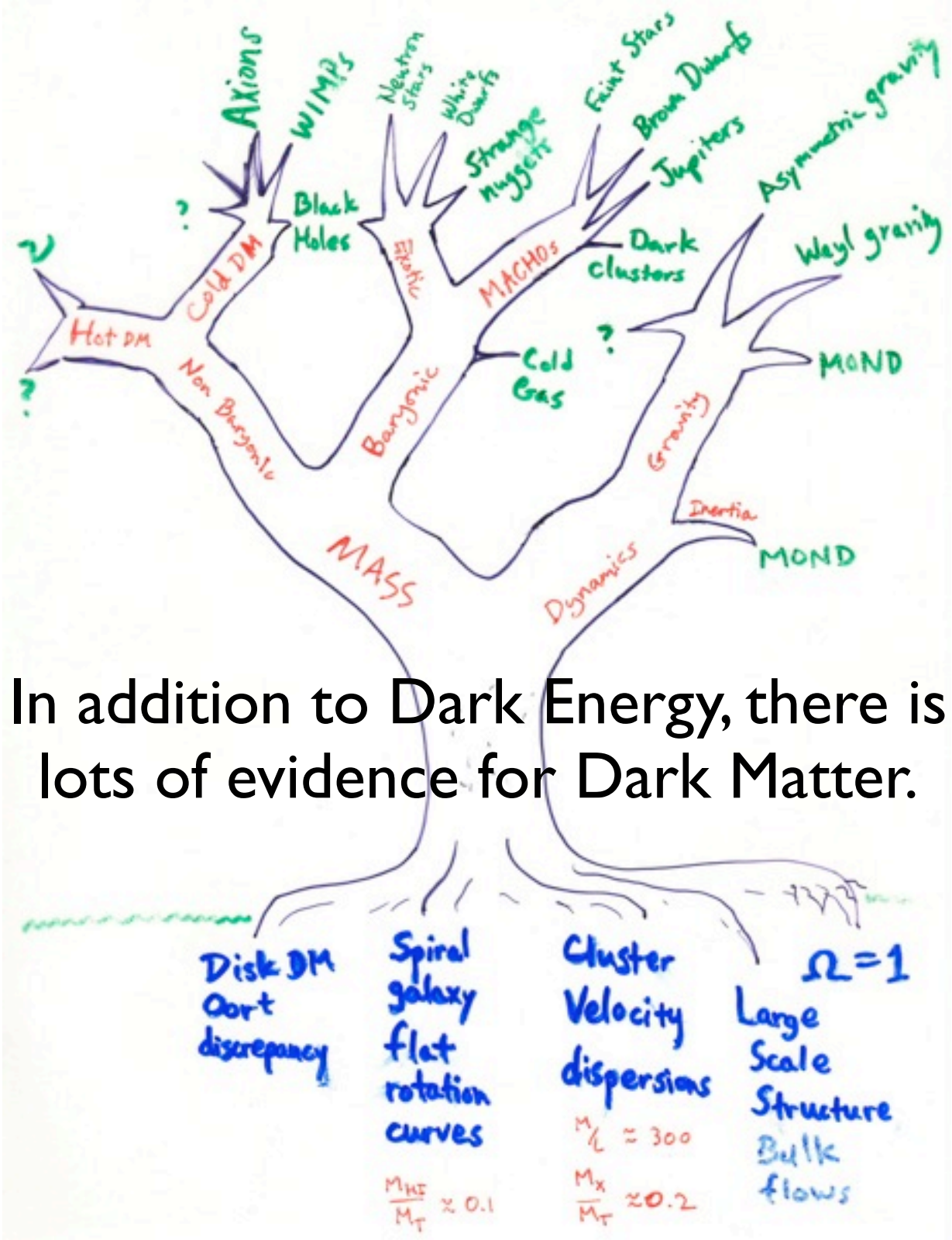




Not only does the universe expand, but this expansion is accelerating!

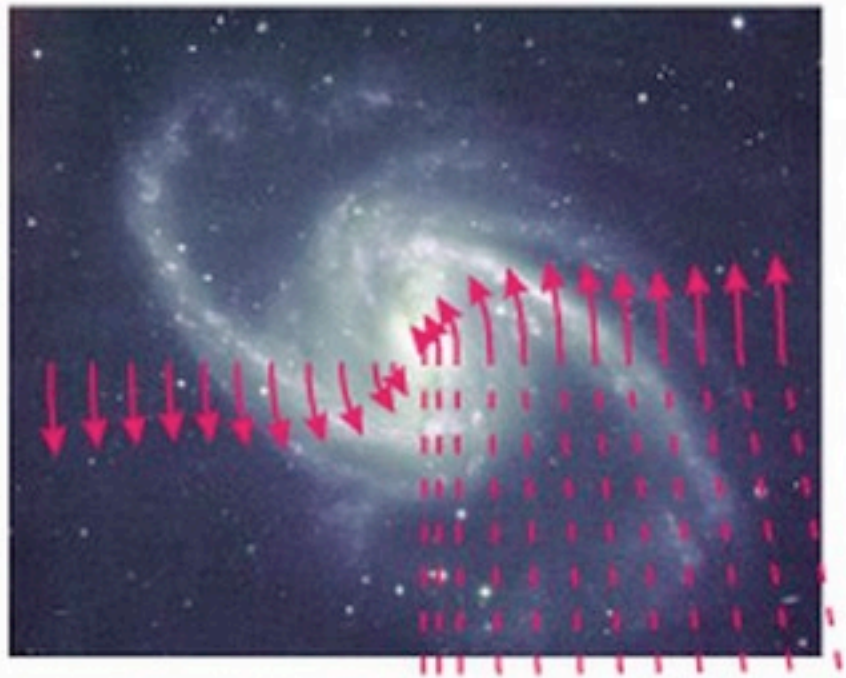
Need "Dark Energy" to do that!


A mathematical blunder:
Einstein's cosmological
constant Λ makes the
expansion *accelerate*!
ACCELERATING
OPEN
FLAT
CLOSED
Relative size of the universe
4
3
2
1
0
-10
Now
10
20
30
Billions of Years



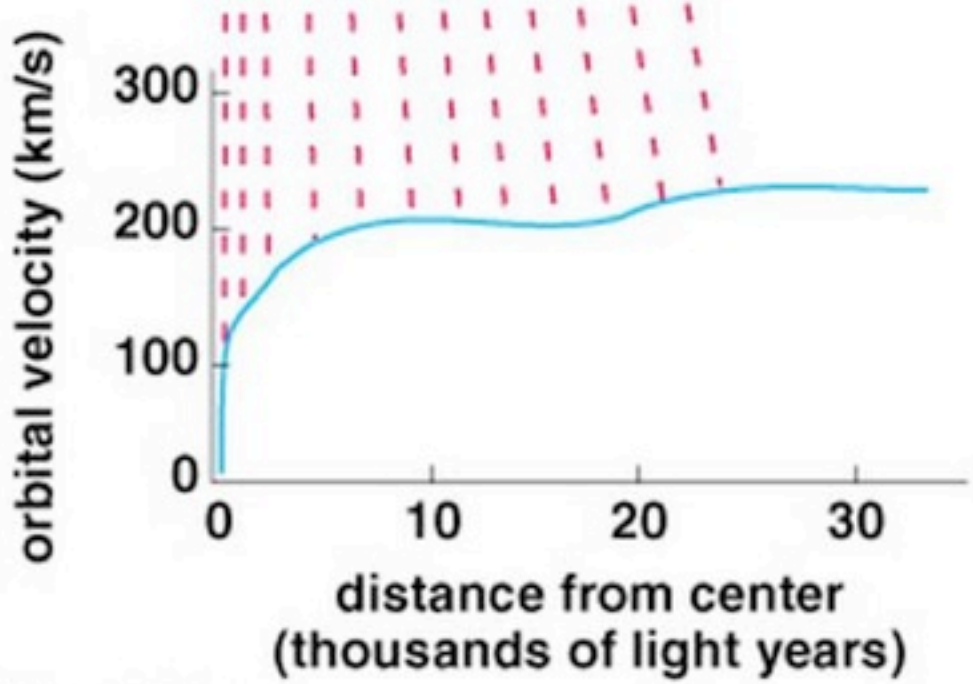
In addition to Dark Energy, there is lots of evidence for Dark Matter.

Spiral Galaxy

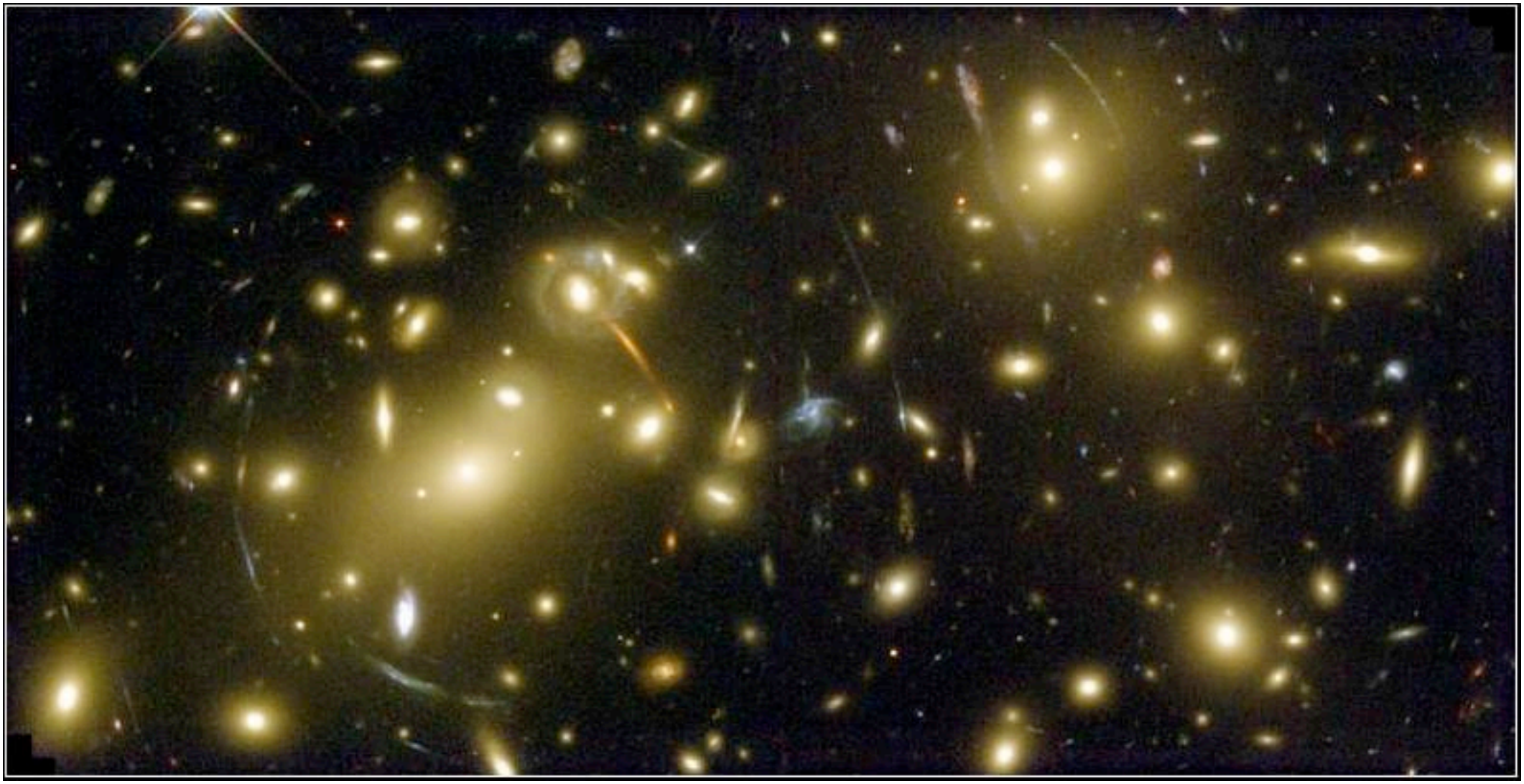


Longer arrows represent larger orbital velocities.

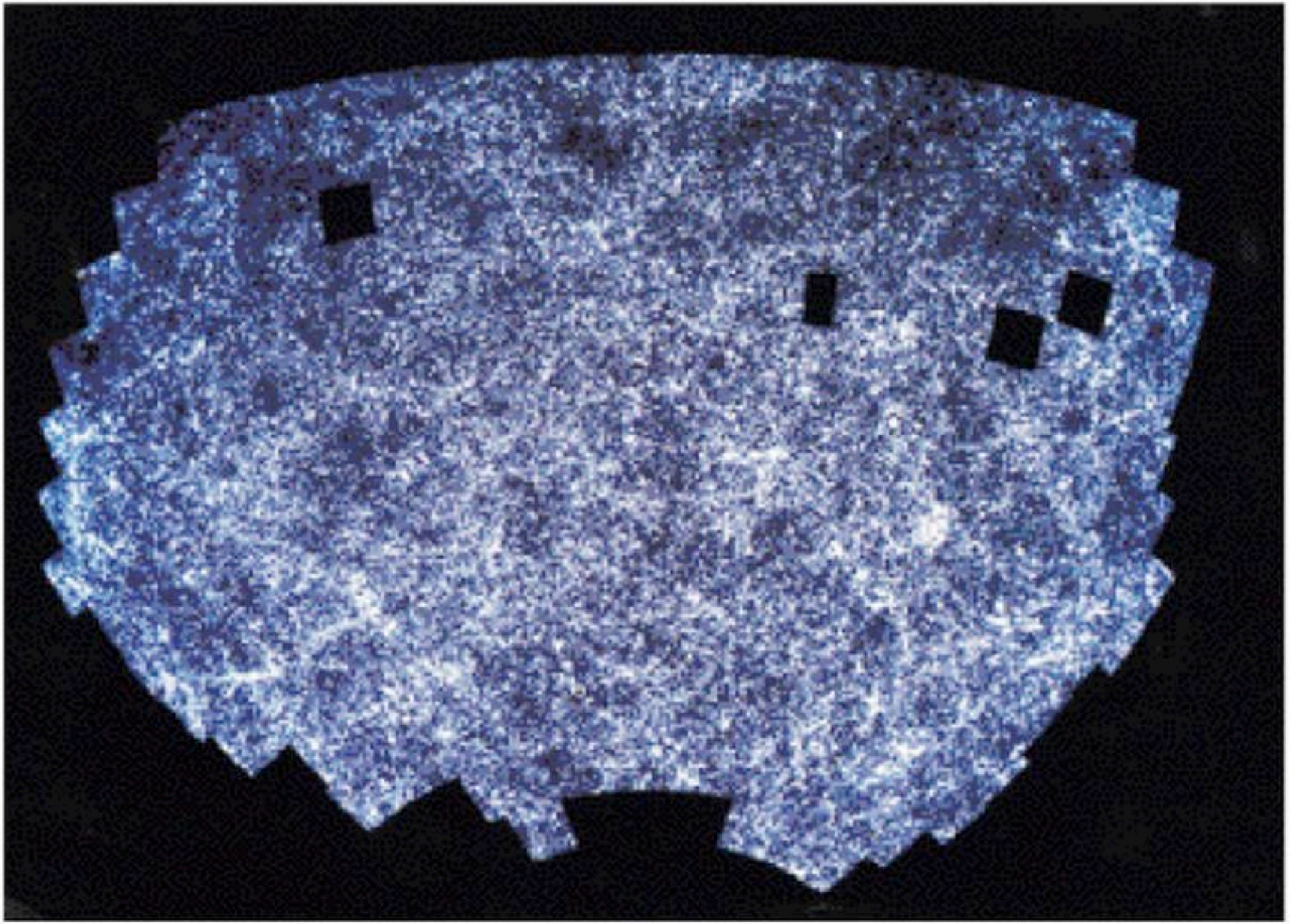
Rotation Curve



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 = 4% of total

from Primordial Nucleosynthesis

Total mass density = 27% of total

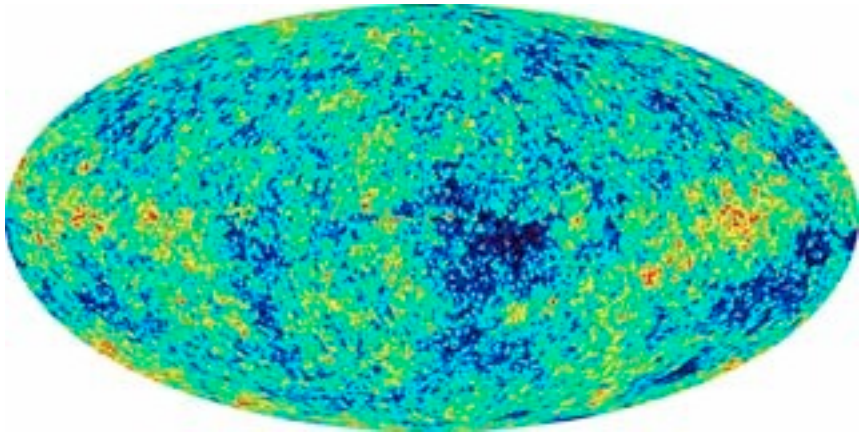
from gravity

gravitating mass >> normal mass

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

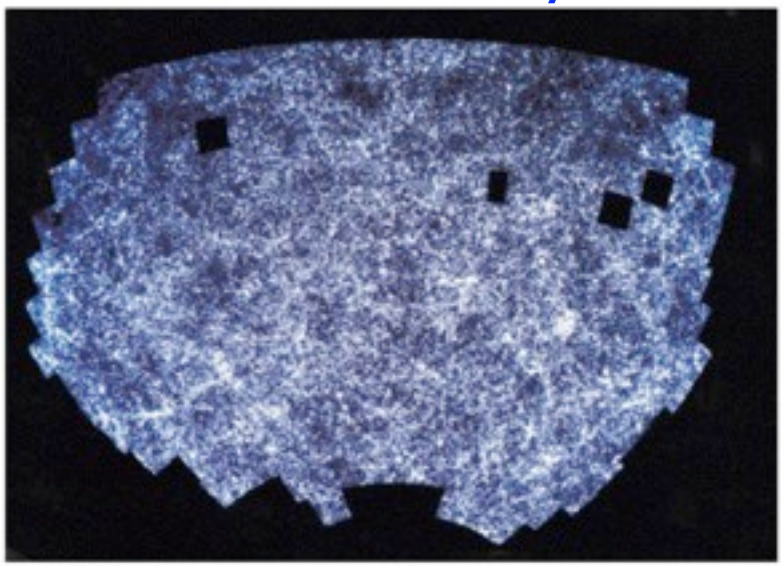
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr



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

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

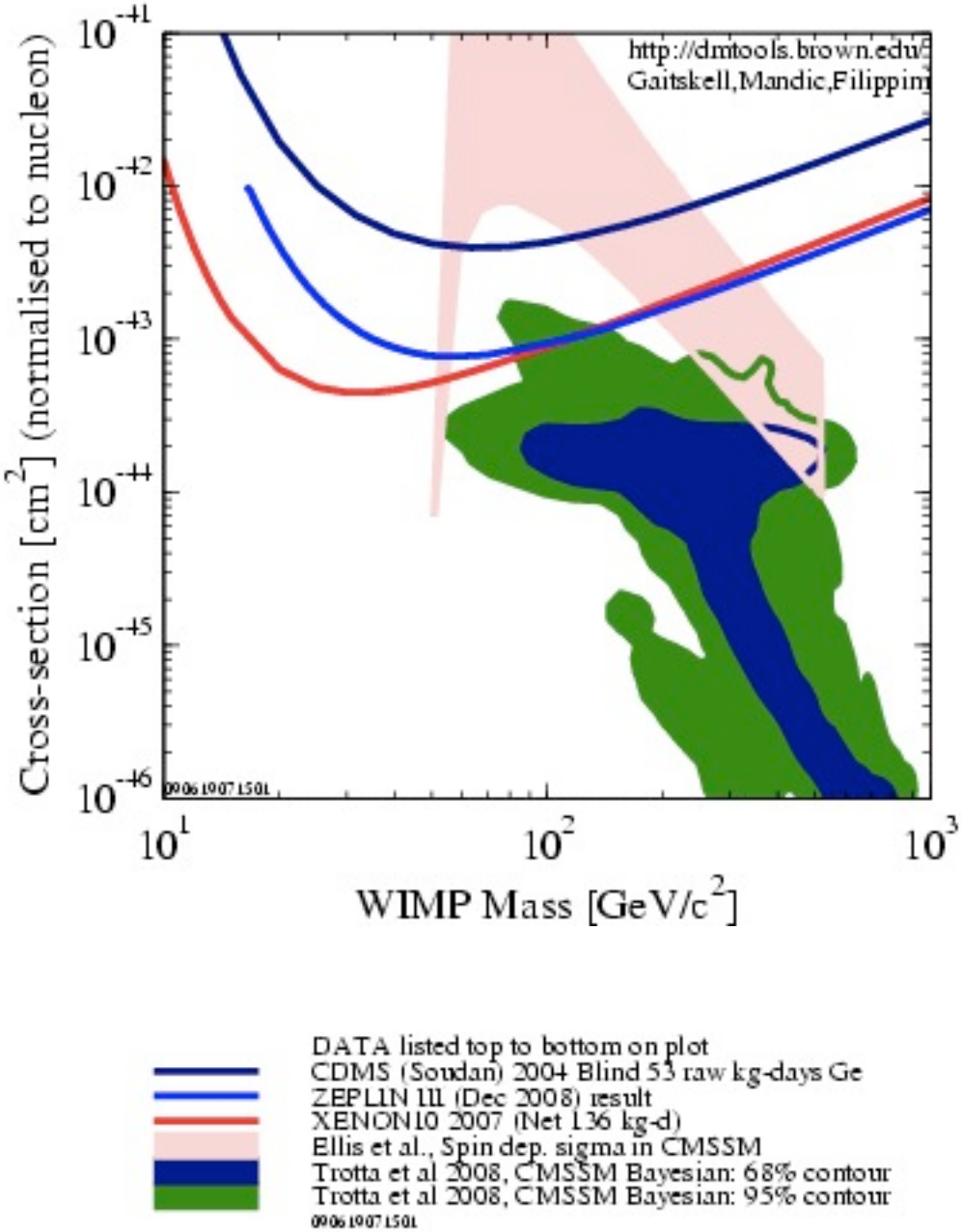


Copyright © Addison Wesley.

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

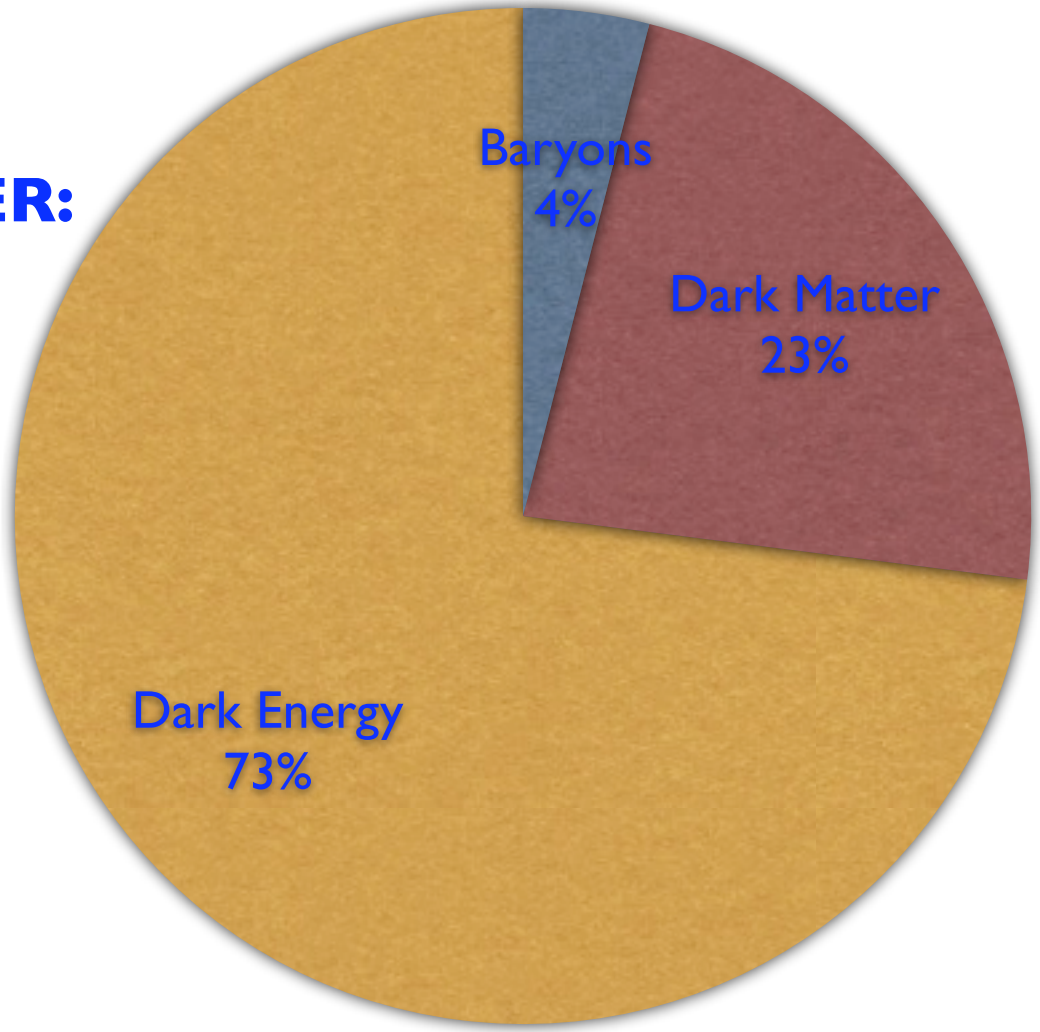
$$\delta\rho/\rho \propto t^{2/3}$$

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.



Cosmological Mass-Energy Budget

THE ANSWER:



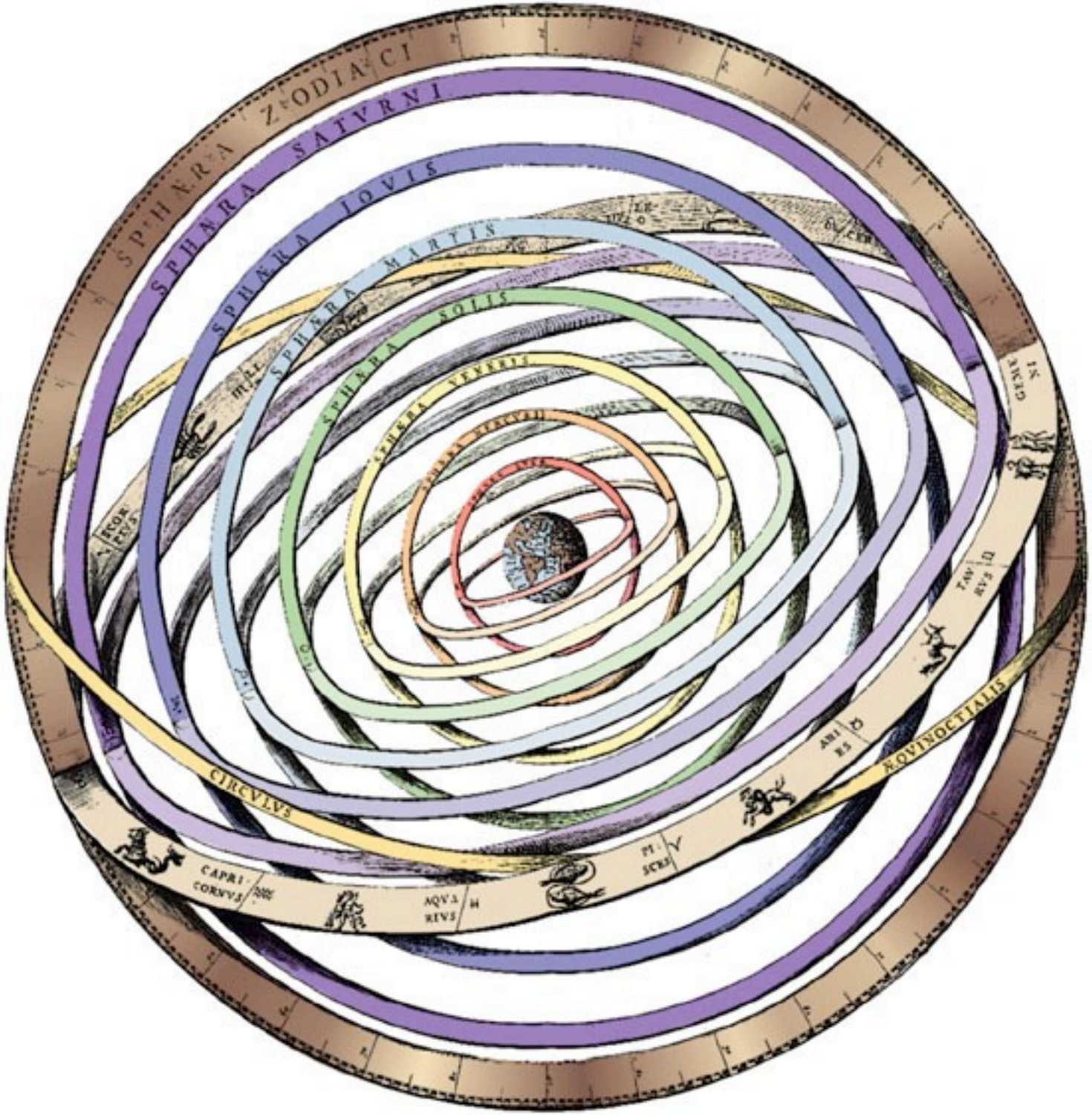
Hot Big Bang
+
Dark Energy
+
Dark Matter

is now called

"ΛCDM"

"Cosmologists are often wrong, but never in doubt"

- Lev Landau



"Cosmologists are often wrong, but never in doubt"

- Lev Laundau

Things we know for sure in cosmology:

1990:

$$\Omega_m = 1.00$$

$$\Omega_\Lambda = 0.00$$

$$\Omega_b h^2 = 0.0125$$

$$H_o = 50 \text{ km/s/Mpc}$$

Dark Matter = Cold Dark Matter

"Cosmologists are often wrong, but never in doubt"

- Lev Laundau

Things we know for sure in cosmology:

2010:

$$\Omega_m = 0.27$$

$$\Omega_\Lambda = 0.73$$

$$\Omega_b h^2 = 0.0224$$

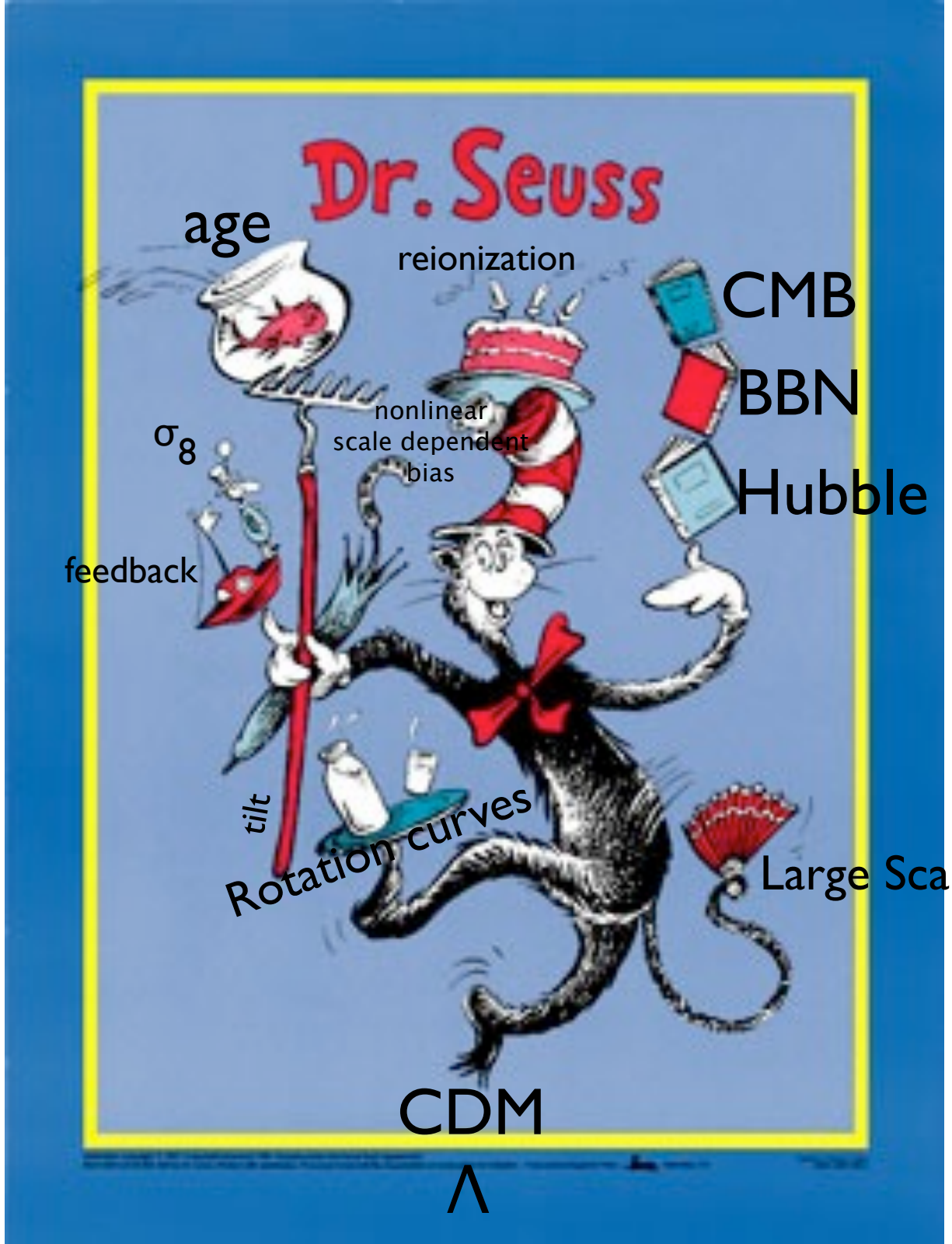
$$H_o = 72 \text{ km/s/Mpc}$$

Dark Matter = Cold Dark Matter

... or maybe Warm Dark Matter

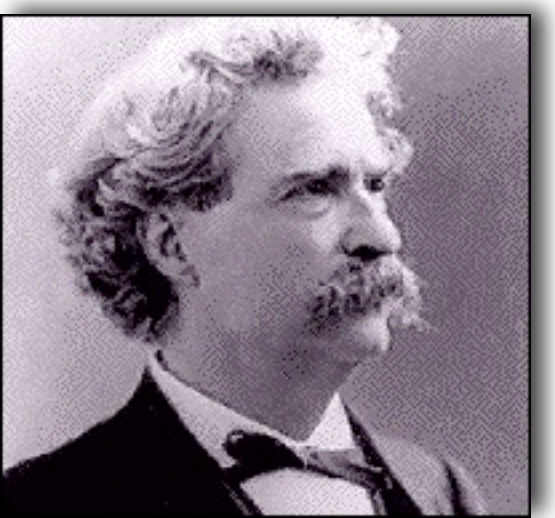
or Self-Interacting Dark Matter

Things are getting a bit complicated!



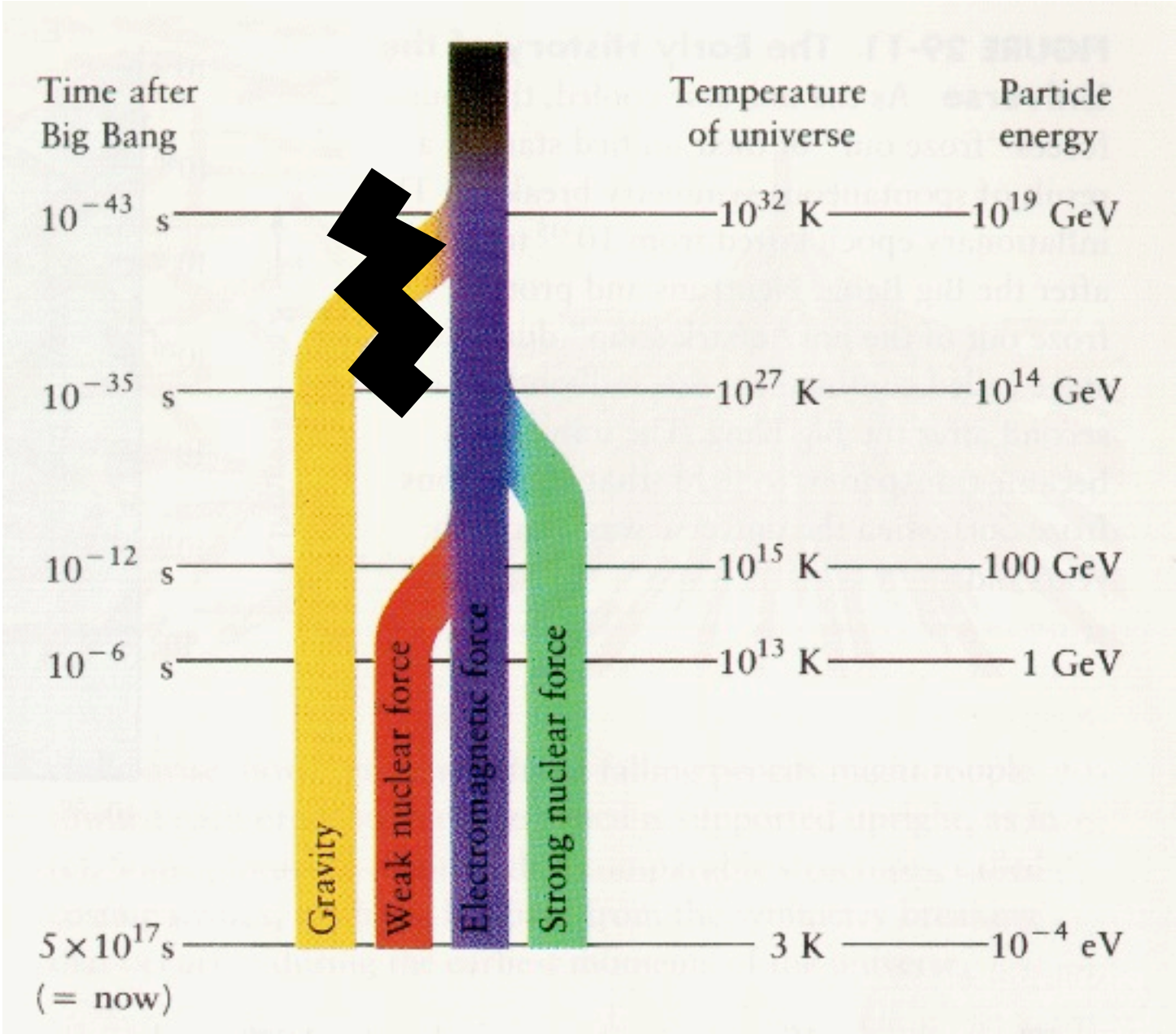
What gets us into trouble is not what we don't know.

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



- Mark Twain

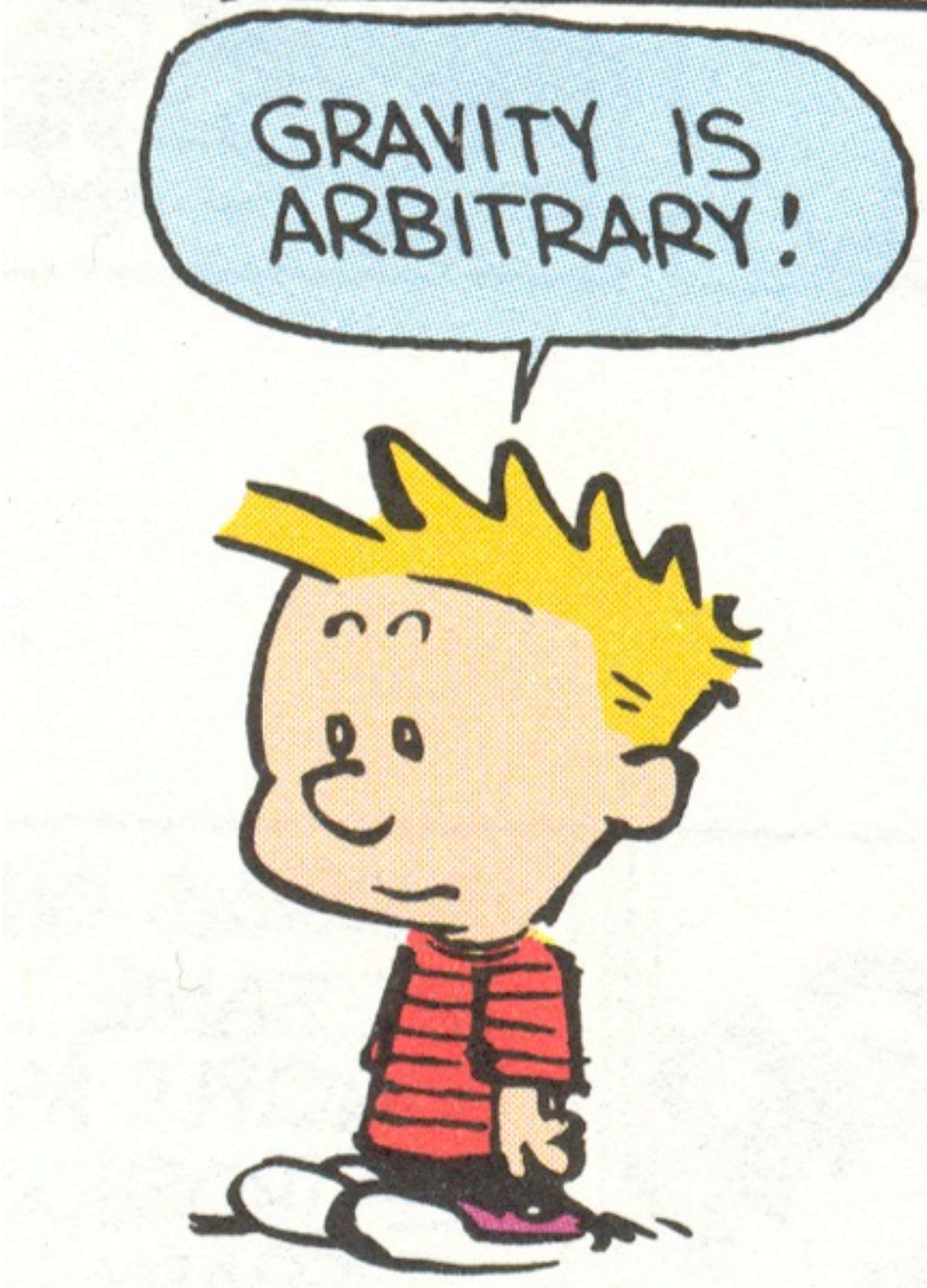
Grand Unified Theories (GUTs)



Can gravity be unified with the other fundamental forces?

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?



Extended gravity theories

- DGP gravity
- MoG
- Weyl gravity
- MOND

- DGP gravity
  - Dvali, Gabadadze, Porrati
  - introduced to provide for an accelerating expansion without dark energy
  - adds a 5th dimension - the usual 4D GR holds at short distances, with 5D dominating at large distances.

- MoG $\ddot{r} = \underbrace{-\frac{GM}{r^2}}_{\text{Newton}} + \underbrace{\frac{G - G_N}{r^2}(1 + \frac{r}{r_0})e^{-r/r_0}}_{\text{Yukawa-like}}$
  - Moffat
  - adds massive vector field to the tensor already present in GR
  - net result is a locally repulsive term that makes "normal" gravity weaker than it is at large scales
  - fits all data all the time
- couples with rolling constants (fudge factors?)

$$\Phi(r) = \overset{\text{GR}}{\boxed{1 - \frac{2m}{r}}} + \overset{\text{DM}}{\boxed{ar}} + \overset{\Lambda}{\boxed{br^2}}$$

- Conformal Weyl gravity
  - Mannheim & Kazanas
  - Raises gravity to 4th order conformally invariant theory (Einstein stopped at simplest 2nd order generally covariant theory)
  - Theoretically appealing, but can it fit data?

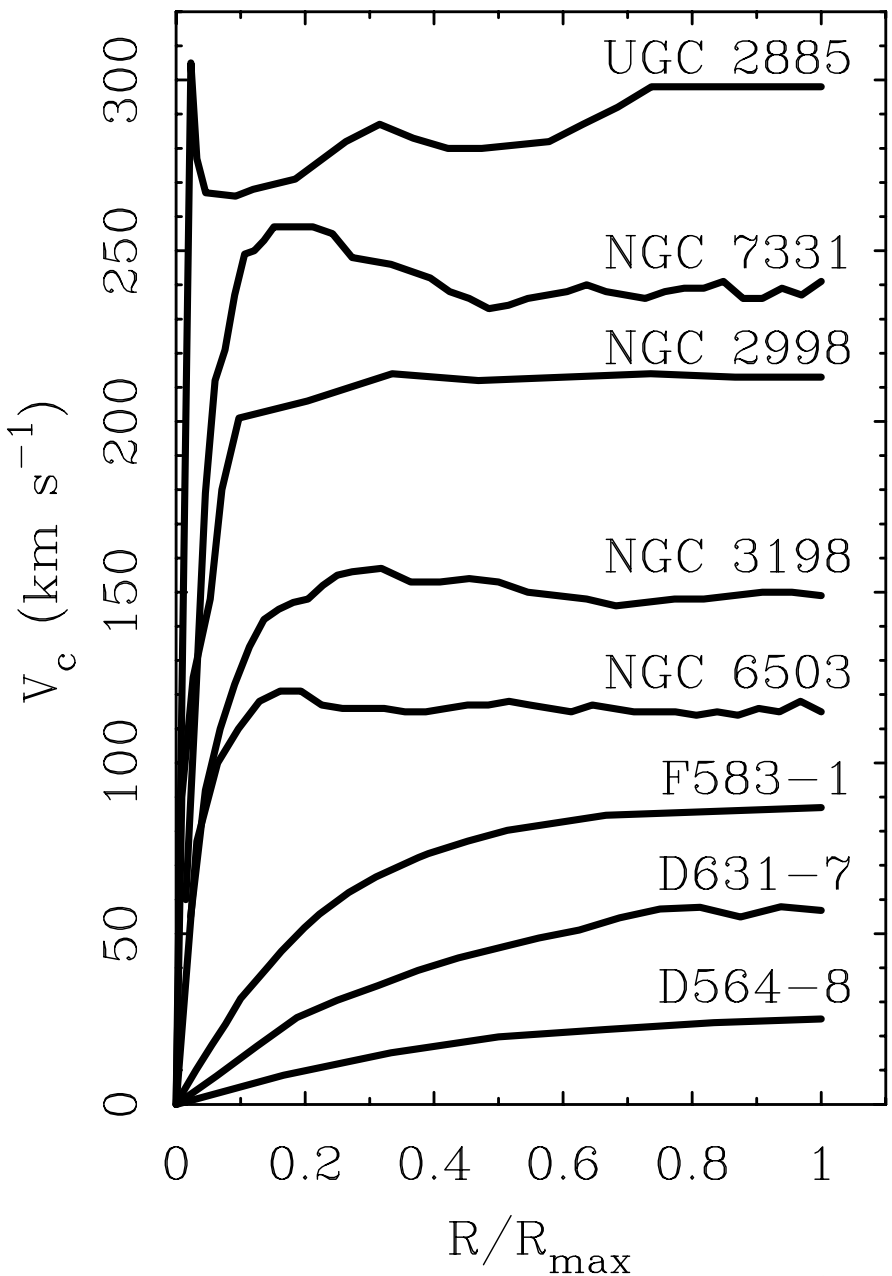
$$\ddot{r} = \sqrt{a_0 \underbrace{\left(\frac{GM}{r^2}\right)}_{\text{Newton}}} \quad \text{for } \ddot{r} \ll a_0$$

- MOND

$$a_0 \approx 1\ \text{Å}\,\text{s}^{-2}$$

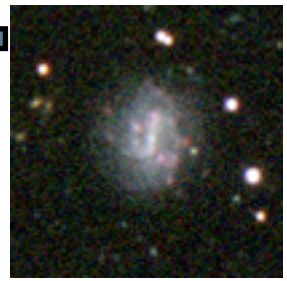
  - Milgrom; Bekenstein
  - Fits data well, but can it be a viable relativistic theory?
    - TeVeS (tensor-vector-scalar)
    - bimetric MOND

Rotation curves



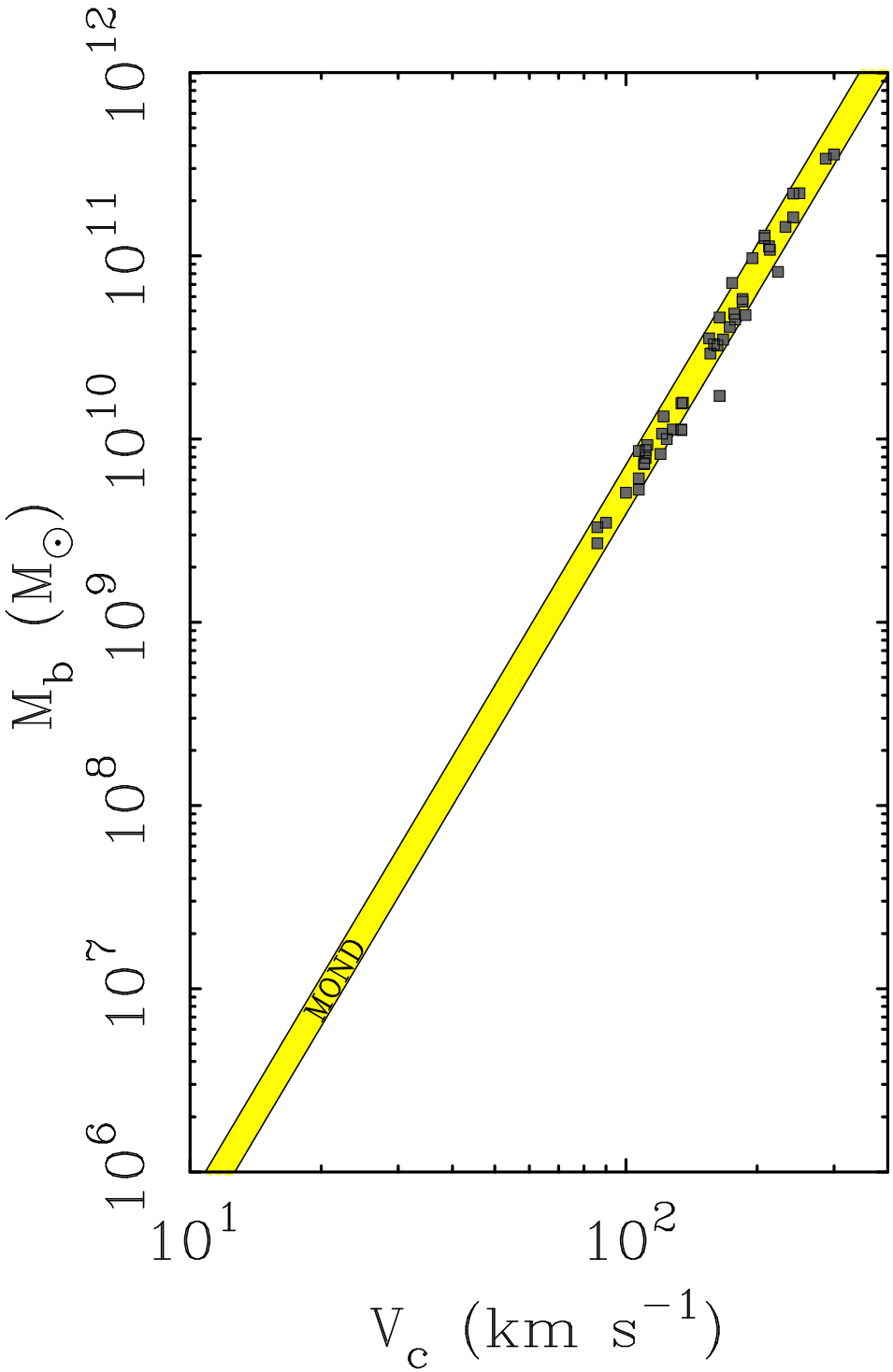
spirals

$M_* > M_g$.

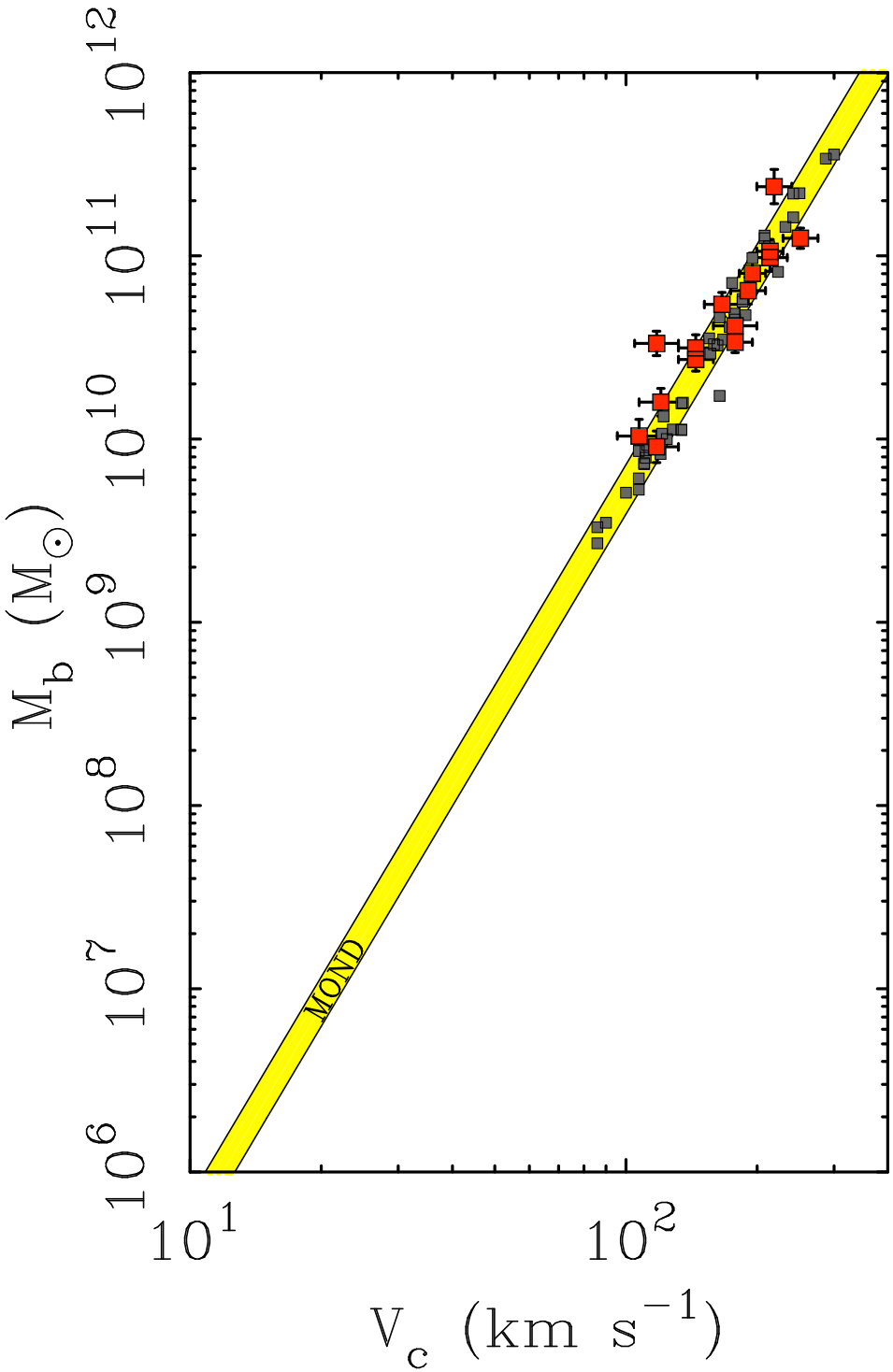


gas disks
with $M_* < M_g$.

MOND predicts $a_0 GM = V^4$



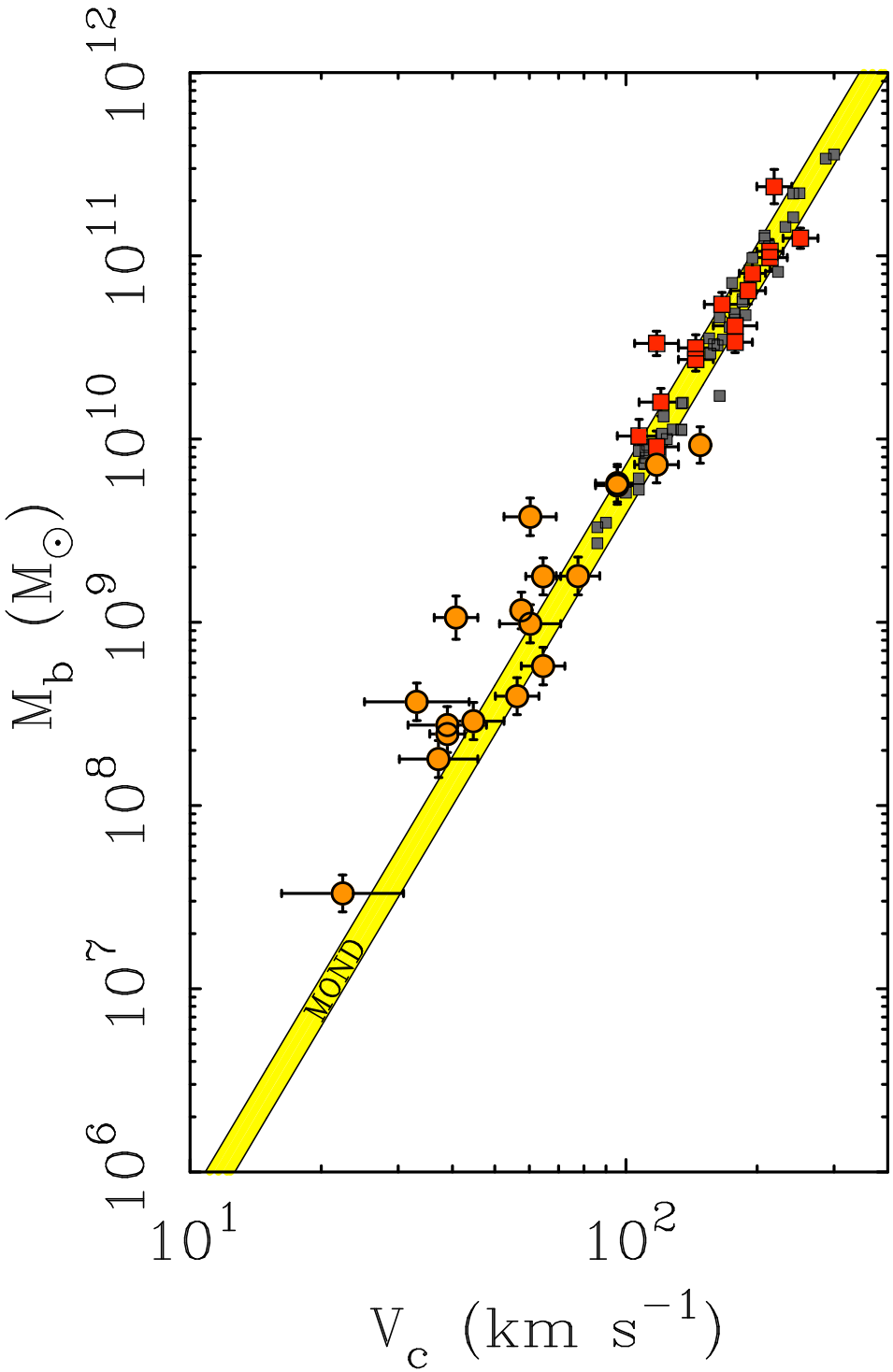
■ $M_* > M_g$ (MOND fits)
McGaugh (2005)



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

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

Stellar M_*/L independent of theory.

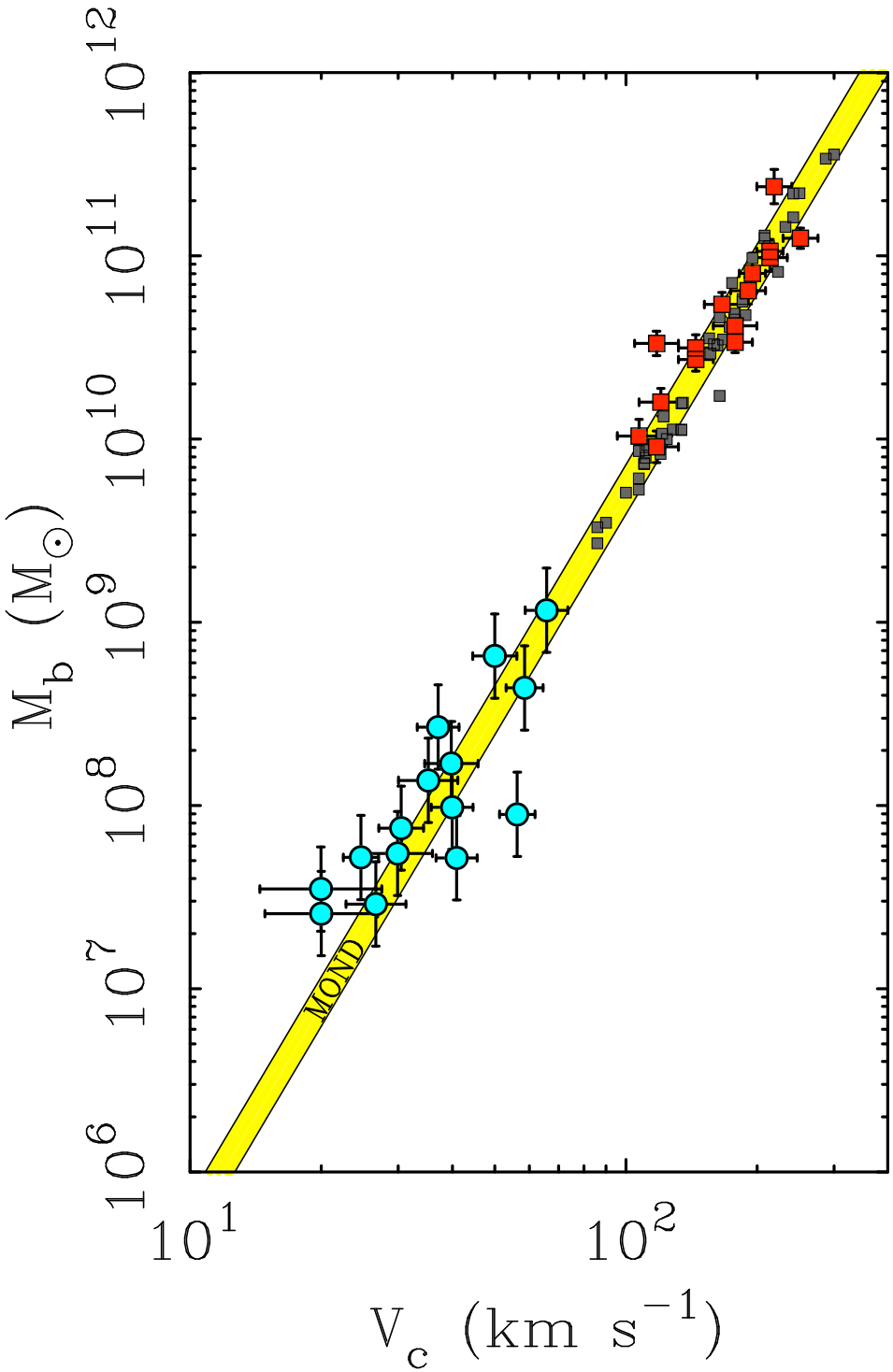


$M_* > M_g$ (MOND fits)
McGaugh (2005)

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

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

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

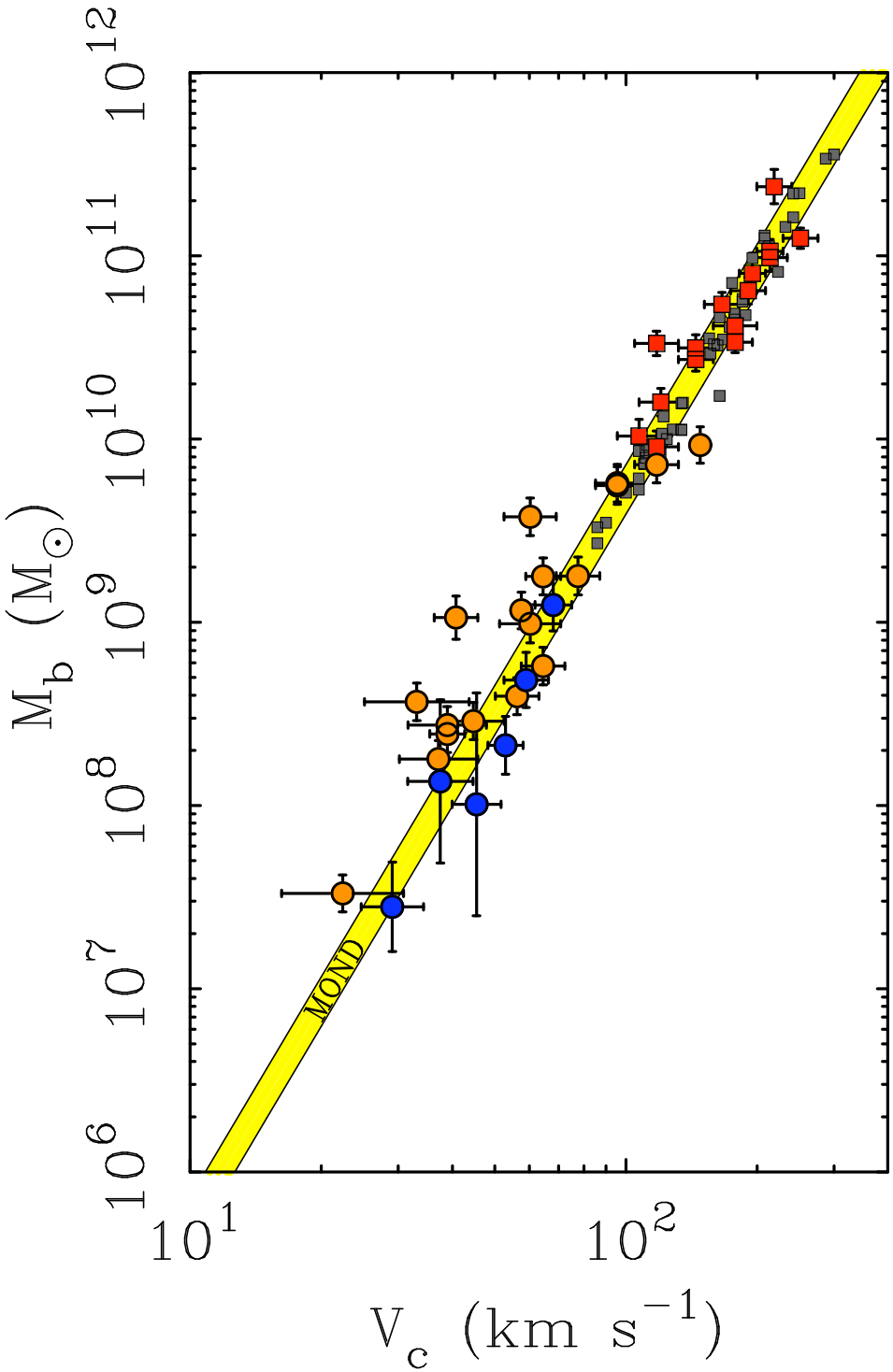


$M_* > M_g$ (MOND fits)
McGaugh (2005)

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

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

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



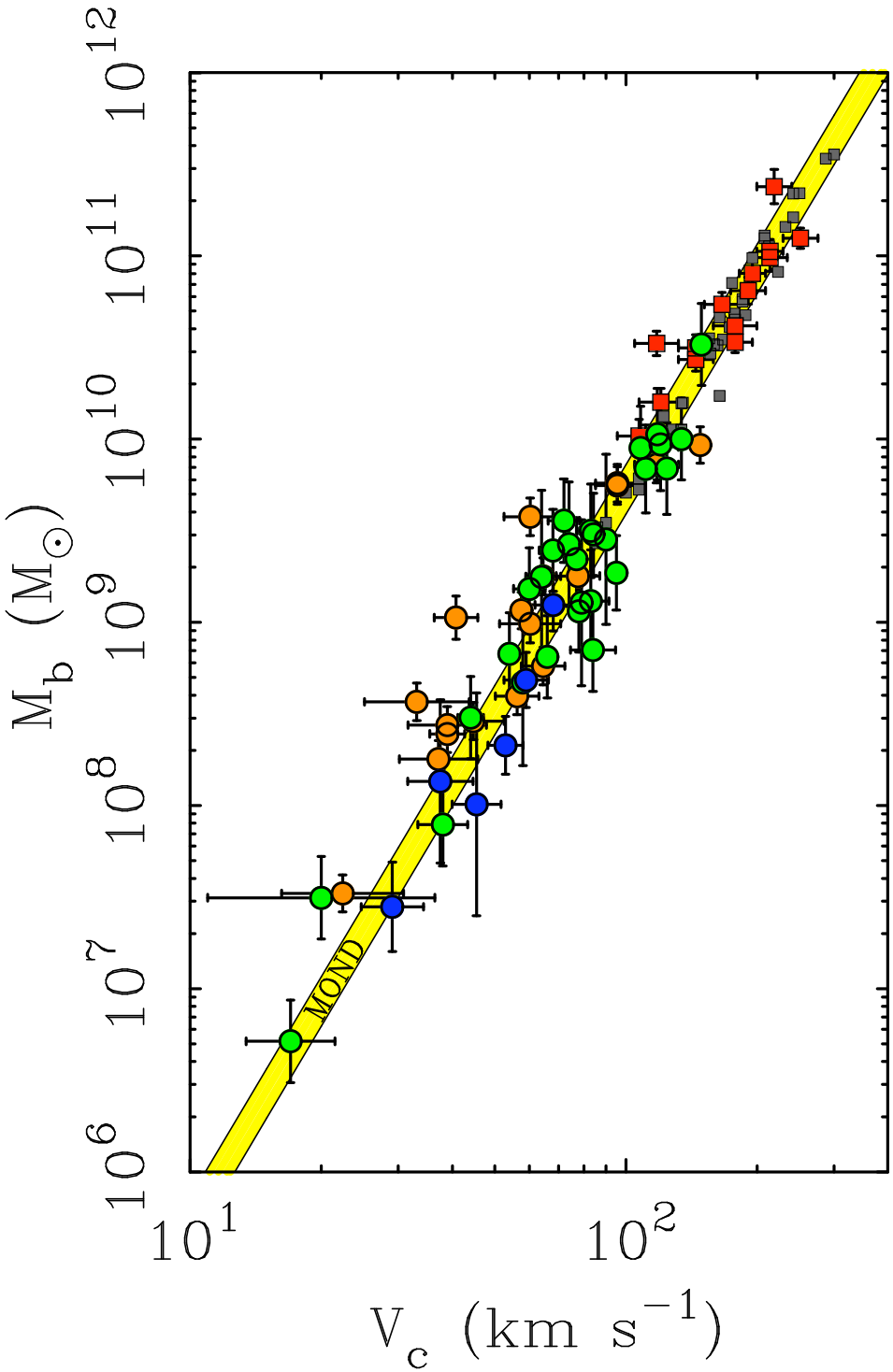
$M_* > M_g$ (MOND fits)
McGaugh (2005)

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

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

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

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



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

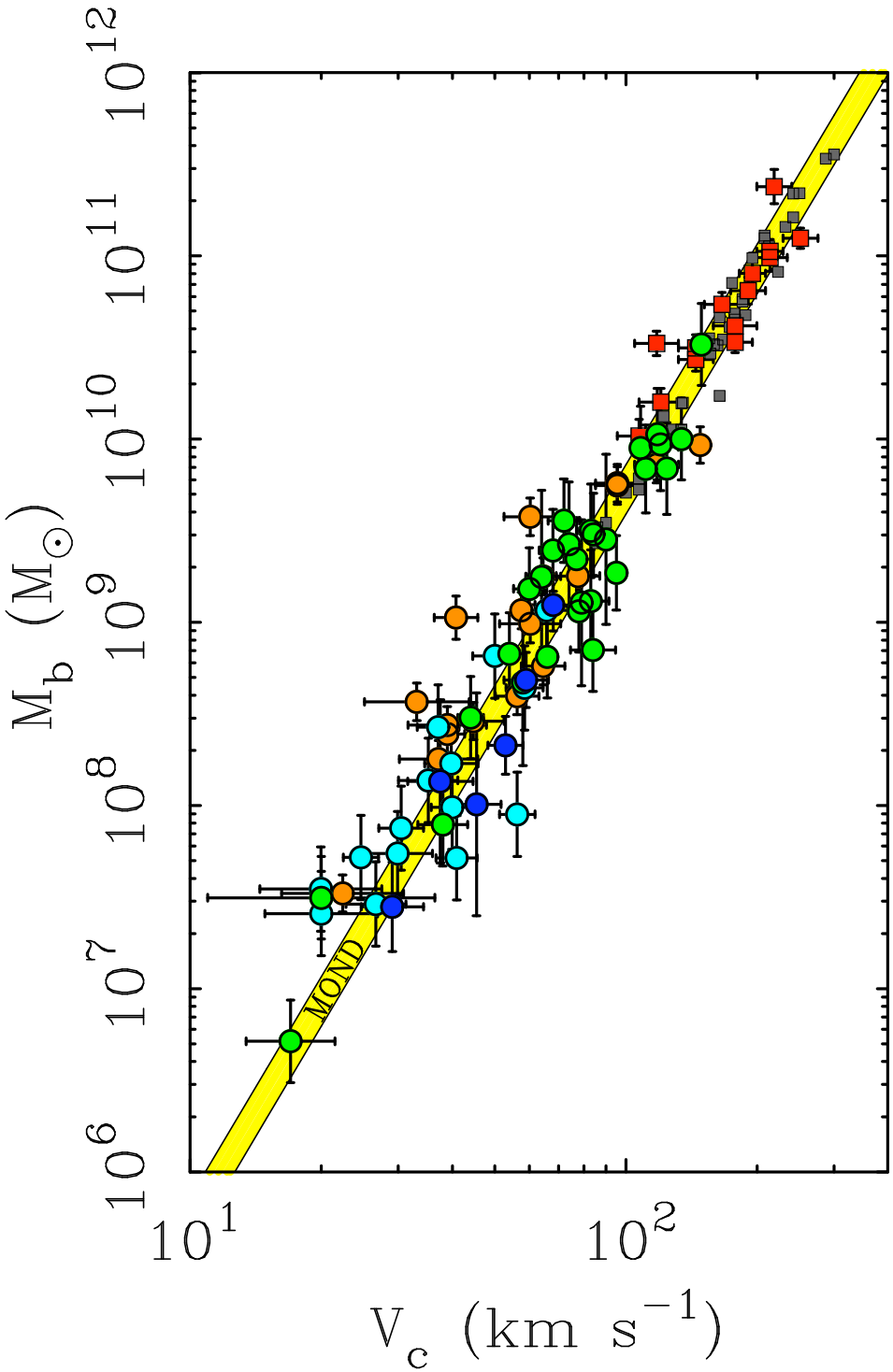
$M_* > M_g$ (H-band popsynth)
Sakai (2000); Gurovich et al. (2010)

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

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

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

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



$M_* > M_g$ (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)

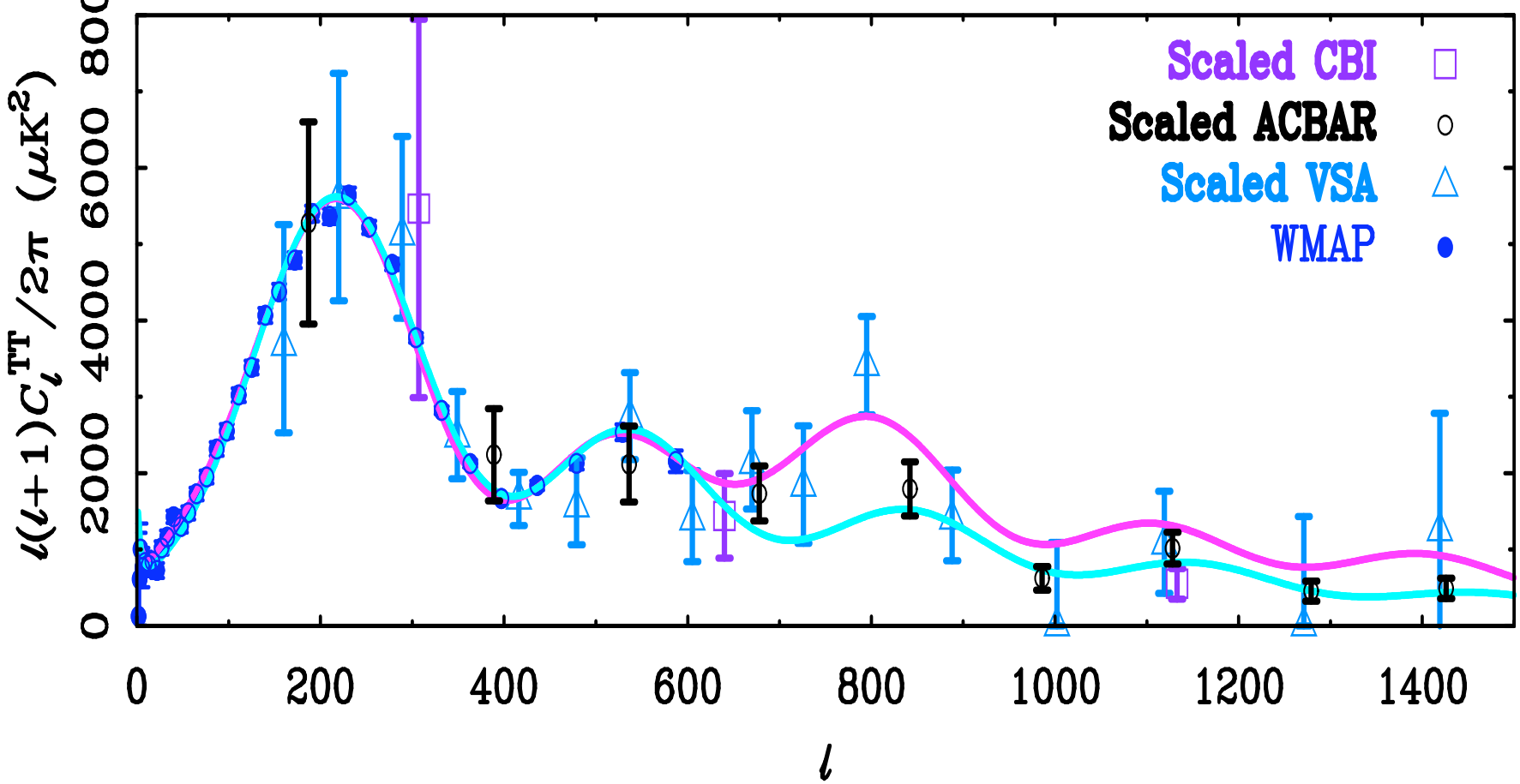
$M_* < M_g$
Stark et al. (2009)

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

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

prediction confirmed

What about cosmology?



Planck mission (ESA)
to report early 2011

We still have a lot to learn.