Benson Memorial Lecture 7 April 2016

MIAMI UNIVERSITY
OXFORD, OH • EST. 1809

Gravity and Cosmology a Century after Einstein

Stacy McGaugh
Professor of Astronomy & Physics
Director, Warner & Swasey Observatory

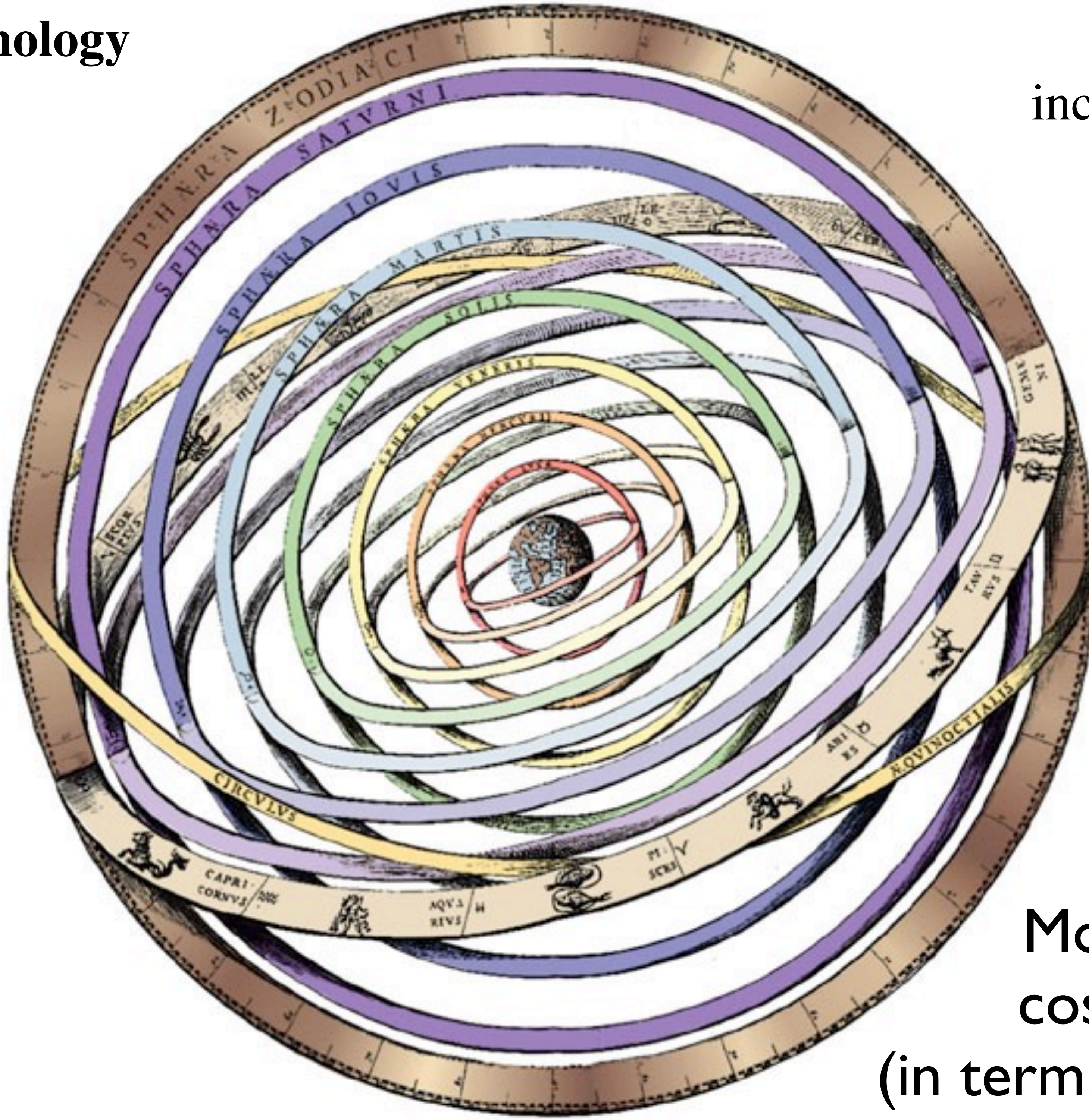
CASE WESTERN RESERVE UNIVERSITY EST. 1826

@DudeDarkmatter

Ptolemaic Cosmology

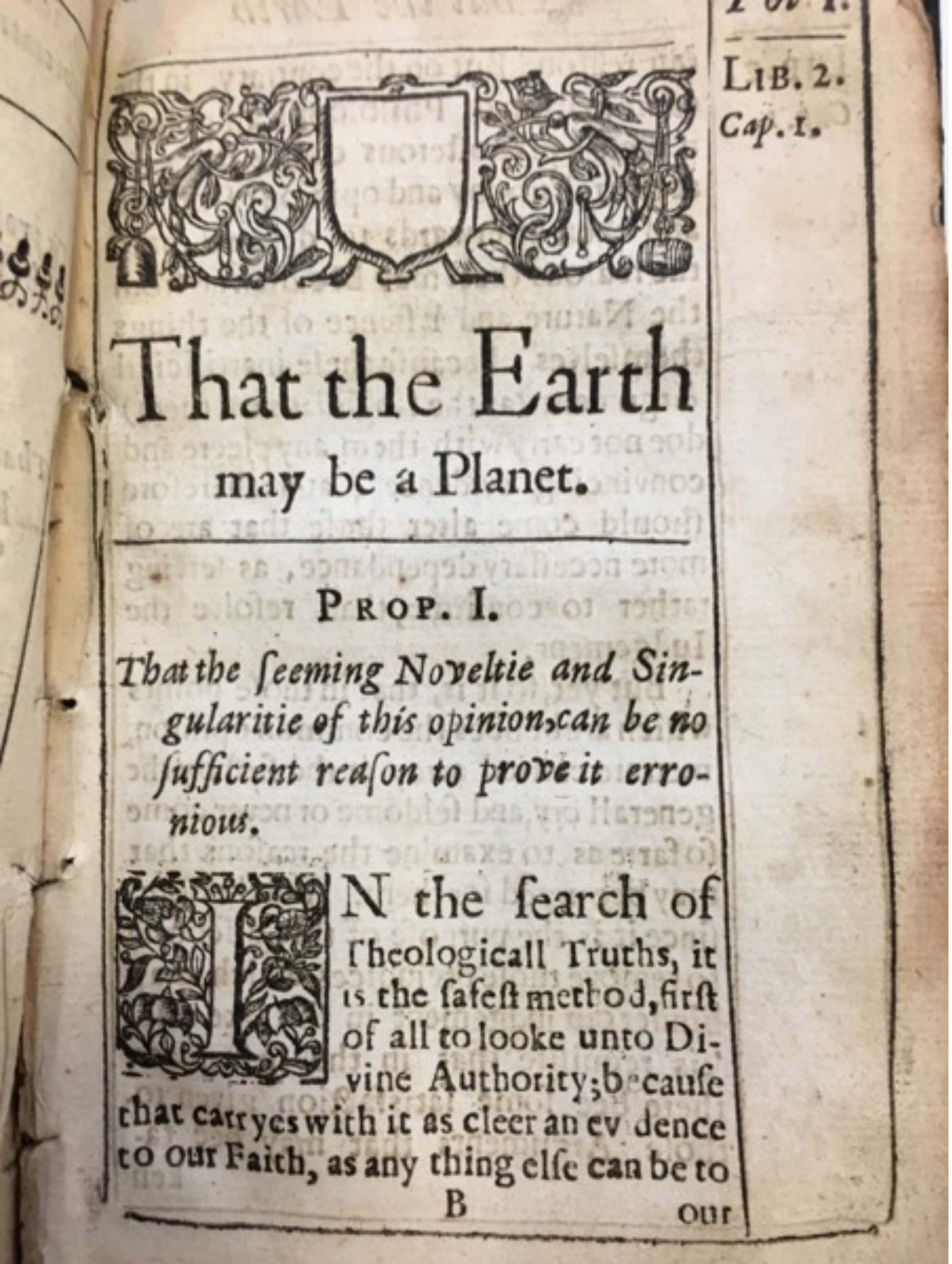
Earth-centered

All planets, including the sun, orbit the Earth



Most successful cosmology ever (in terms of life span)

Page from 1640 text



That the Earth may be a Planet.

Prop. I.

That the ſeeming Noveltie and Singularitie of this opinion, can be no ſufficient reaſon to prove it erronious.

IN the ſearch of Theologicall Truths, it is the ſafeſt method, firſt of all to looke unto Divine Authority; becauſe that carryes with it as cleer an evidence to our Faith, as any thing elſe can be to

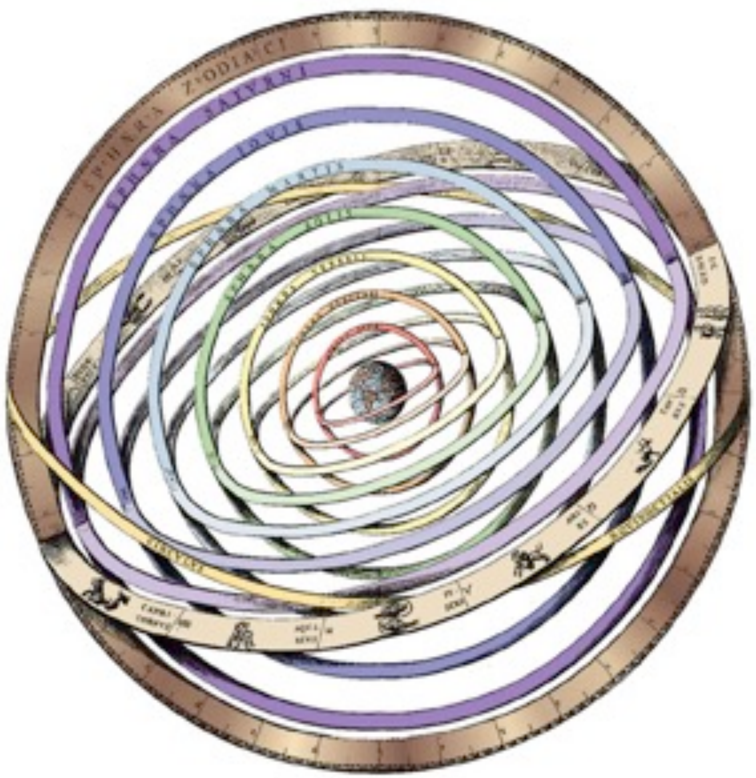
That the Earth
may be a Planet

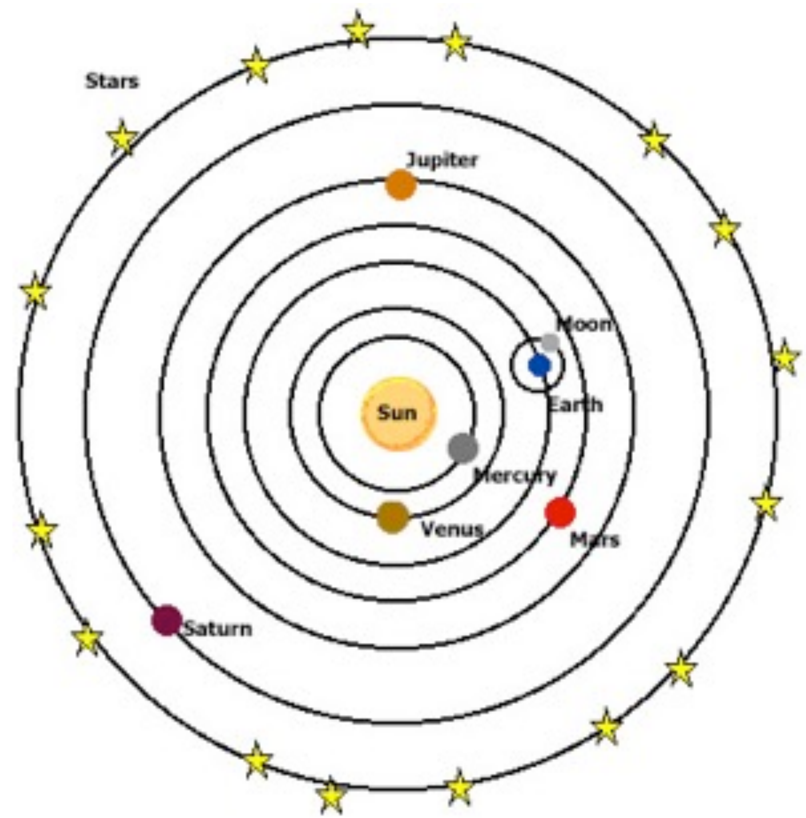
the seeming novelty and singularity of this opinion can be no sufficient reason to prove it erroneous

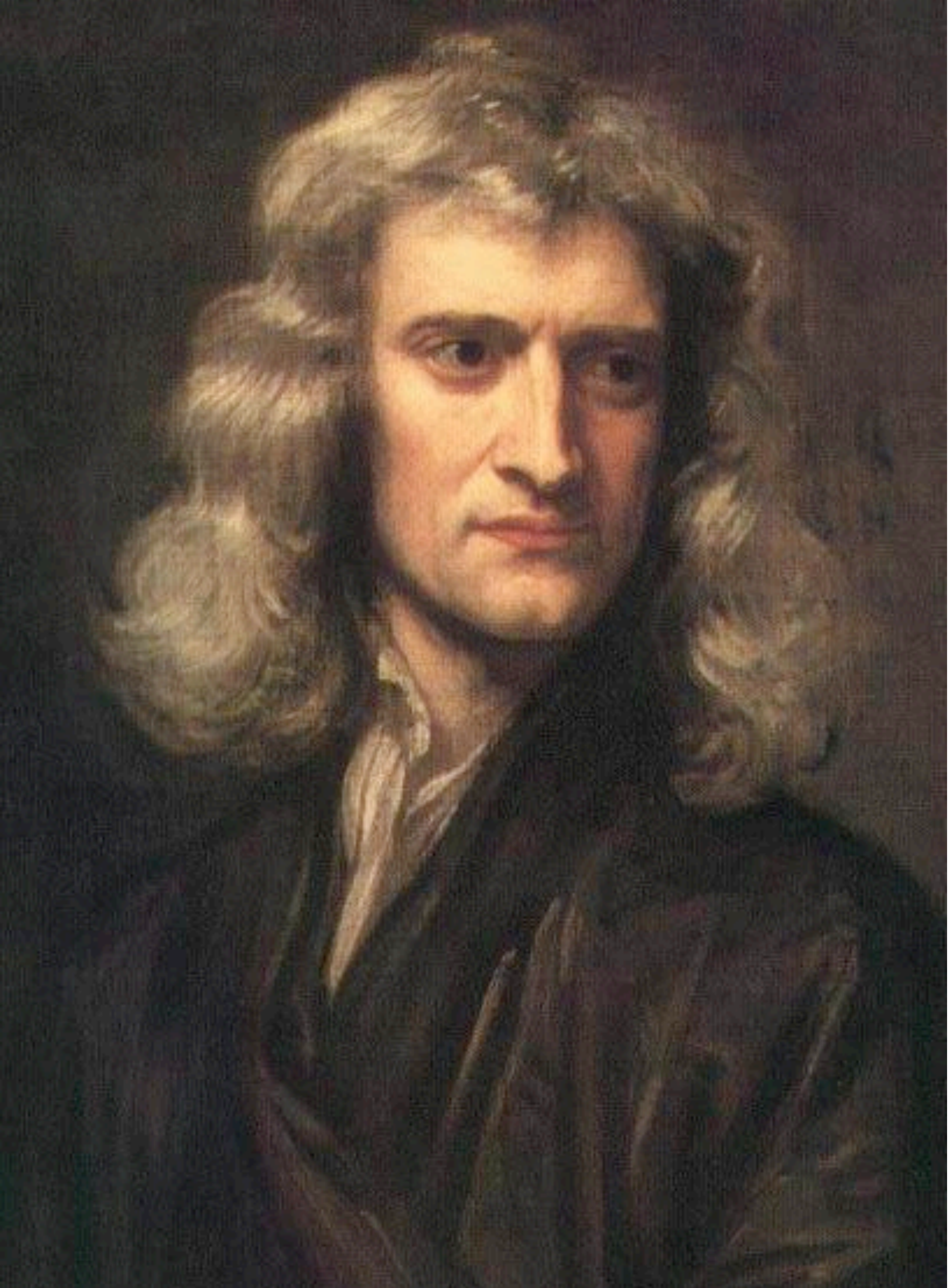
Copernican Revolution placed the Sun at the center

Geocentric
Ptolemaic
Earth at center

Heliocentric
Copernican
Sun at center







Sir Isaac Newton (1642–1727)

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.*

~ 350 years ago ~

Christian Huygens

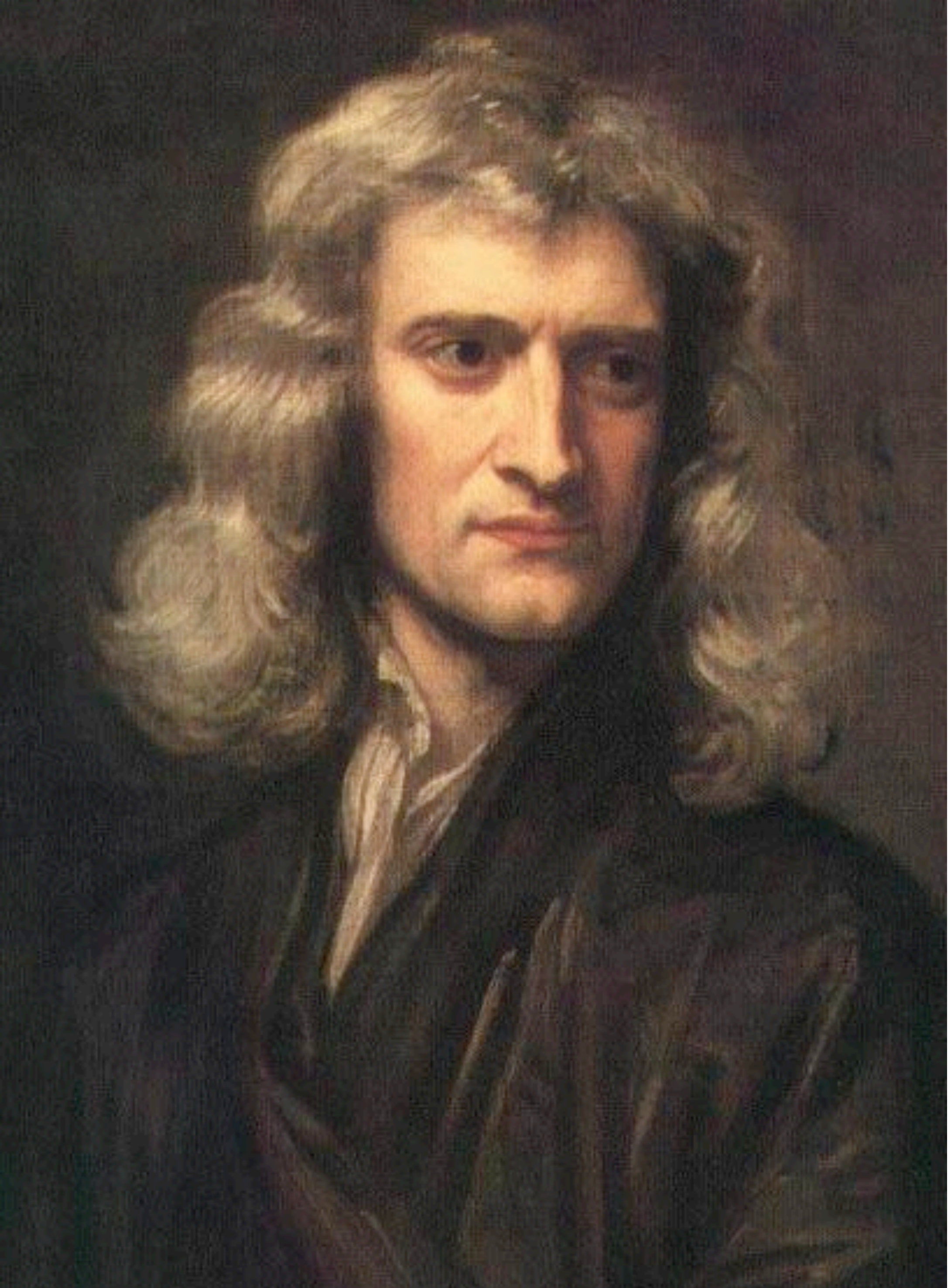
Newton provided the first working, modern, scientific theory of gravity. It still suffices to this day for most practical purposes.

In his own time, Newton did have critics.

Gottfried Leibniz

Huygens questioned how he exaplained **action at a distance**.

Leibniz accused Newton of regarding gravity as a kind of **"occult quality"**, with the quality of bodies somehow hidden within them and beyond the philosopher's understanding, being occult, imperceptible and unintelligible.



Sir Isaac Newton

He said ... *“as if”* ...

Twenty years later, he walked it back:

That gravity should be ... essential to matter, so that one body may act upon another at a distance through a vacuum, without the mediation of anything else, ... is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it.

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)

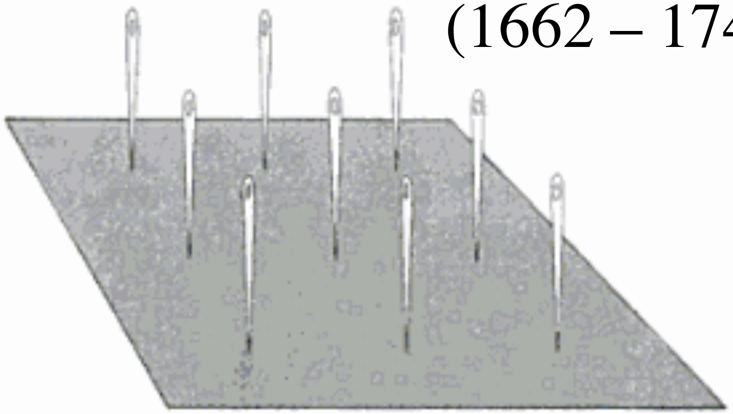


Figure 3.12. Newton agreed with Bentley that stars cannot form a finite and bounded system (as in the Stoic cosmos), for they would fall into the middle of such a system by reason of their gravitational attraction. They agreed that matter was uniformly distributed throughout infinite space, and realized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

~ 100 years ago ~

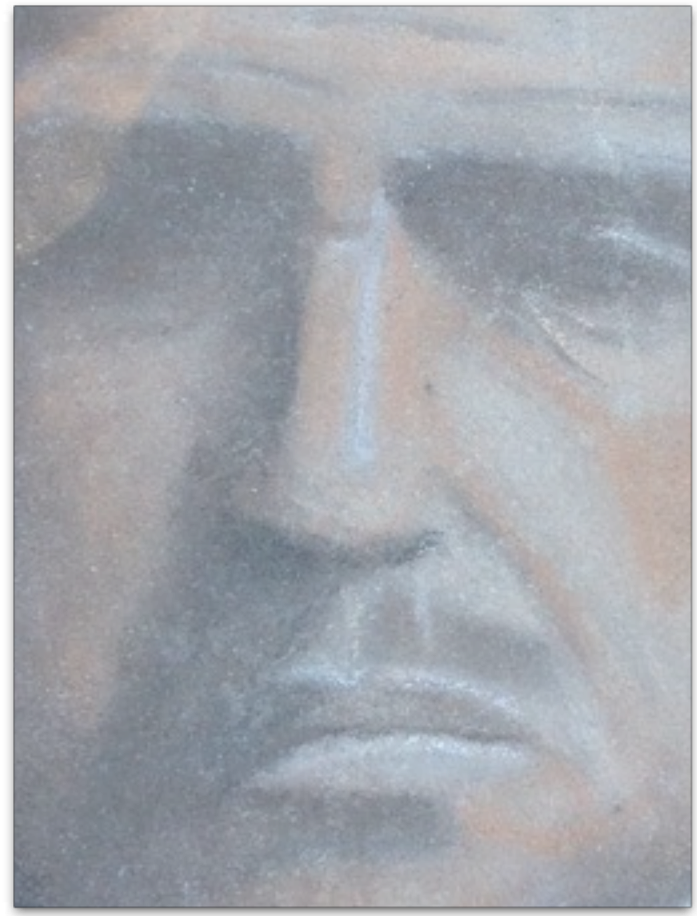
General Relativity

Geometric theory of space-time

Encompassed Newton's Universal Law of Gravitation and predicts new phenomena

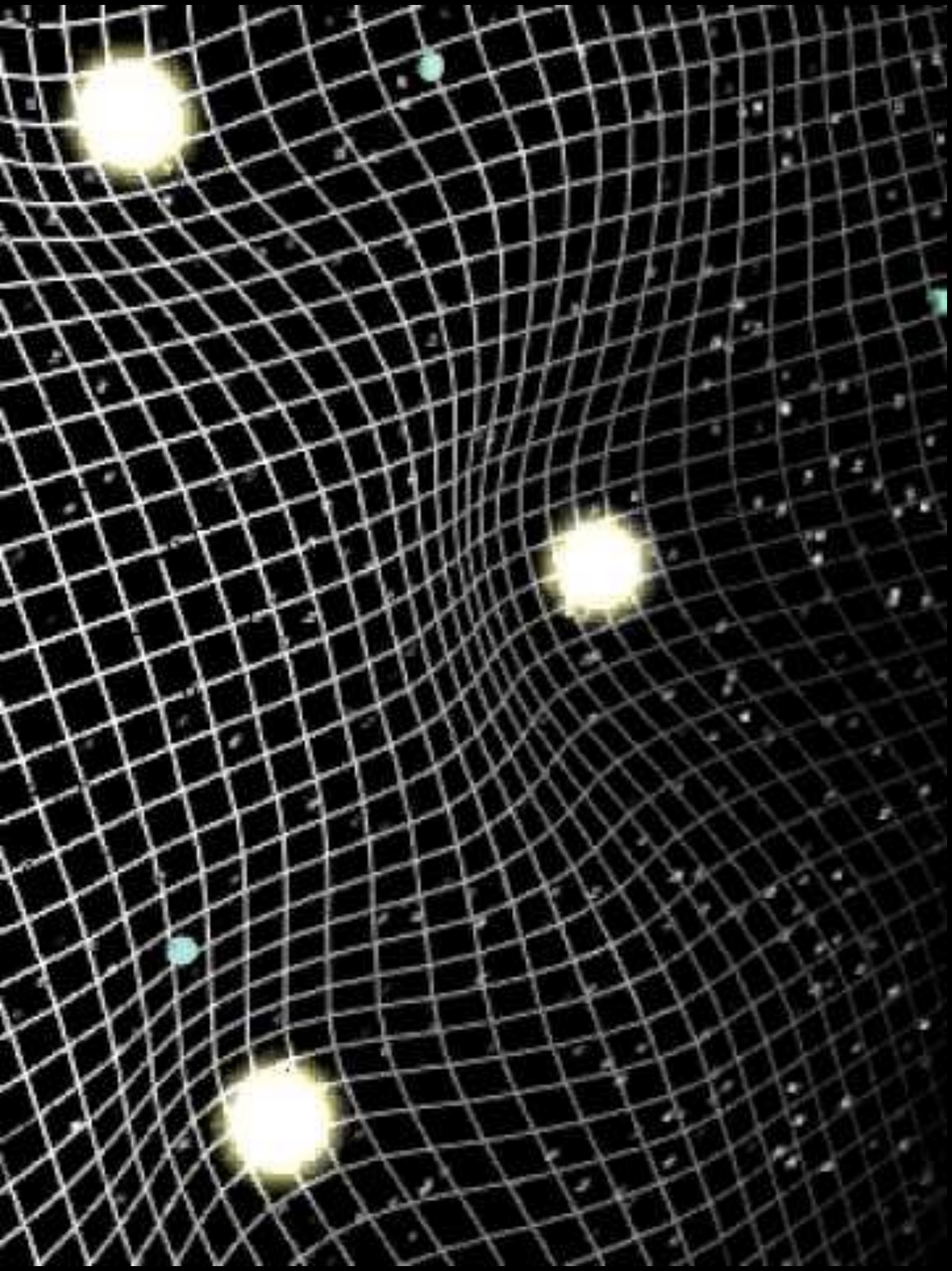
General Relativity

Newton's Law of Gravity



Albert Einstein (1879–1955)

Einstein's explanation of action at a distance



Matter tells spacetime how to curve; curved spacetime tells matter how to move.

Newton's action at a distance problem is solved by geometry: what we perceive as a gravitational force is the result of trying to move in a straight line through curved space.

Phenomena of General Relativity

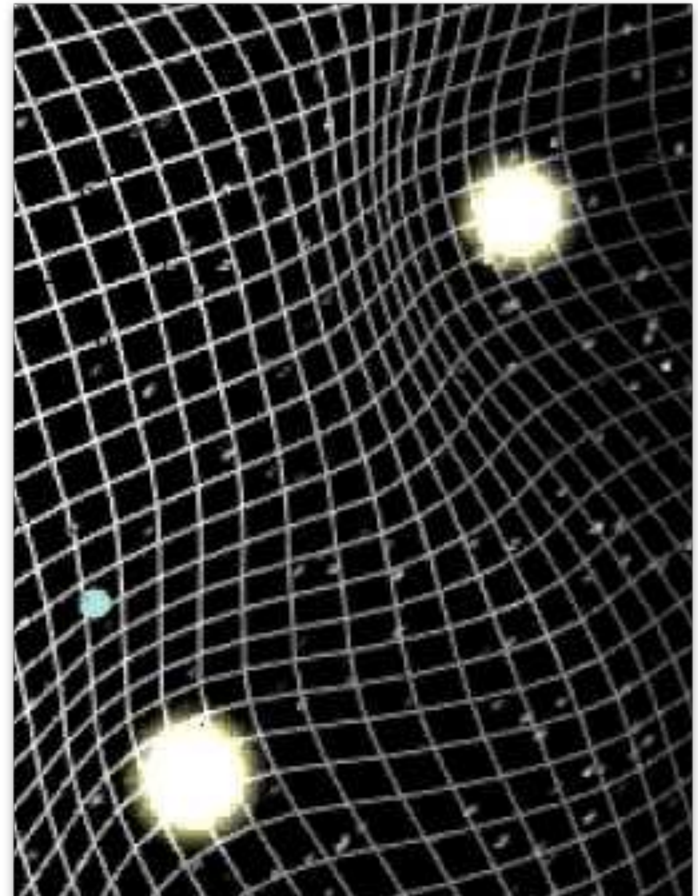
Curved Space-Time

Time Dilation

Gravitational Lensing

Gravitational Waves

The Expanding Universe



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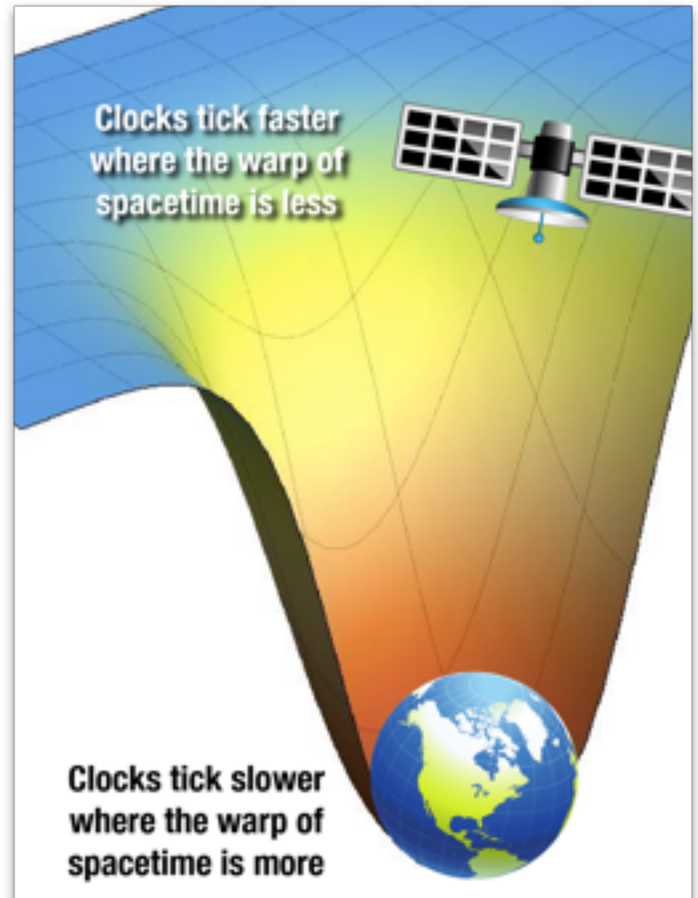

Time passes slightly faster for Global Positioning Satellites - a General Relativistic effect that must be included for GPS to work.

Phenomena of General Relativity

Curved Space-Time
Time Dilation
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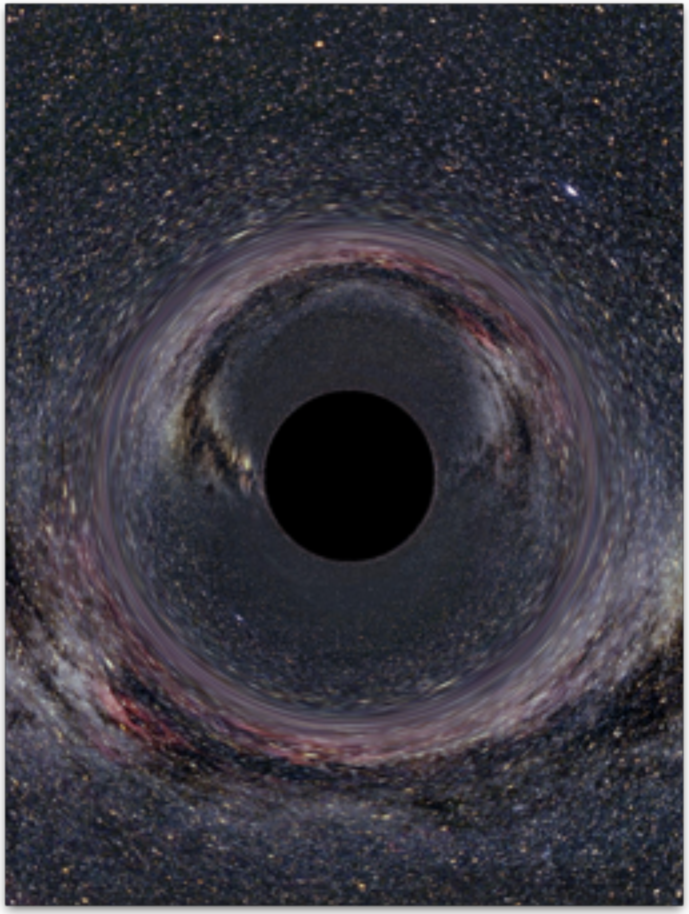

Curved space bends light; can act like a magnifying glass

Phenomena of General Relativity

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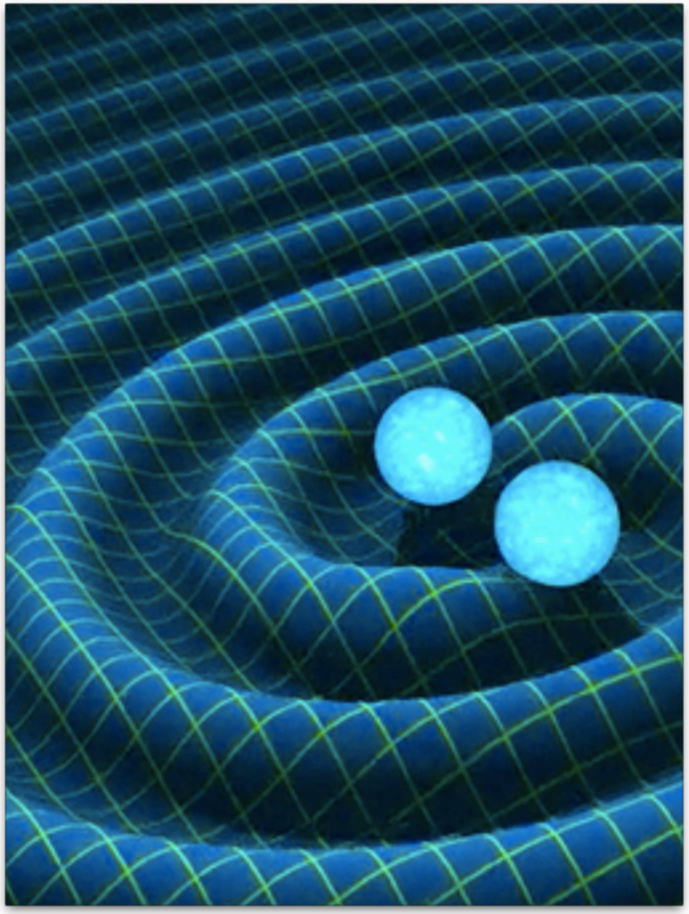
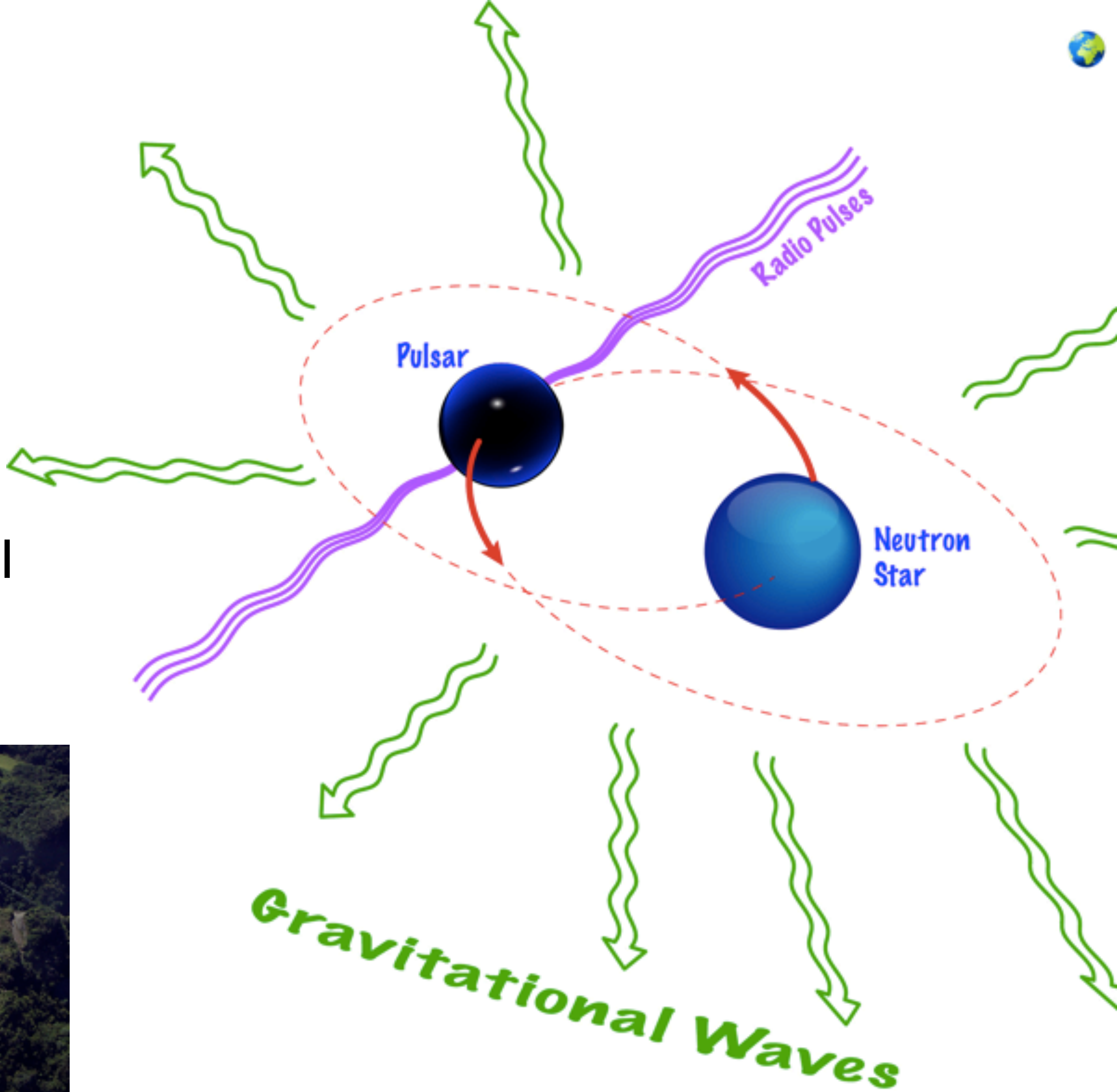


Ripples in the fabric of space-time

Gravitational waves wer inferred from the orbit of a binary pulsar -

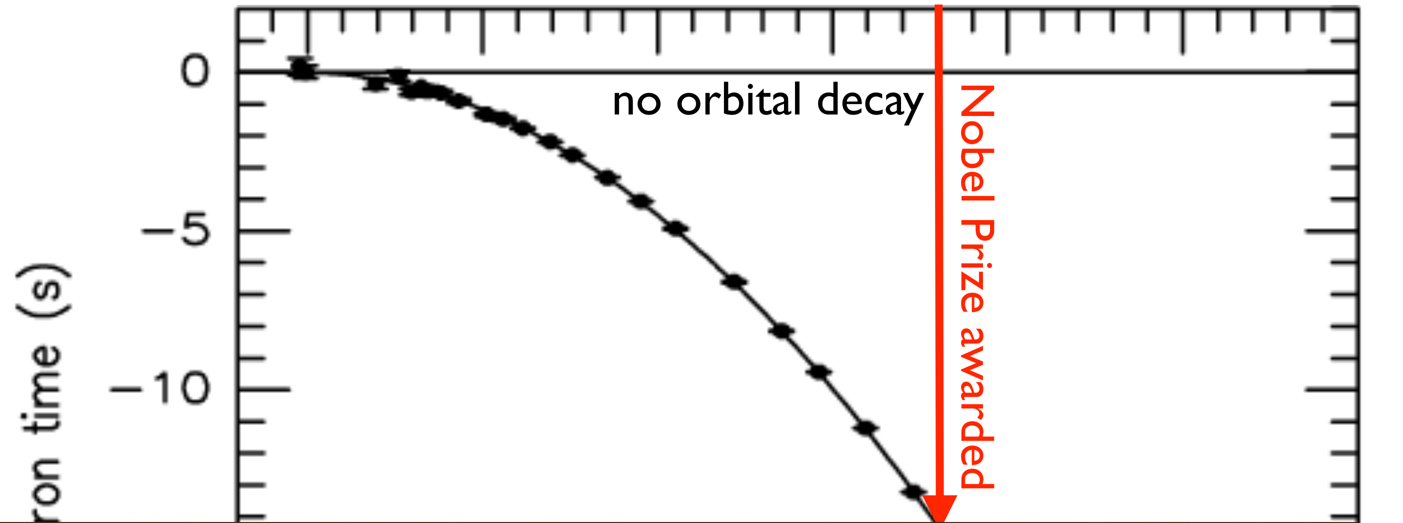
Hulse & Taylor awarded Nobel Prize in 1993.



INDIRECT GRAVITY WAVE DETECTION

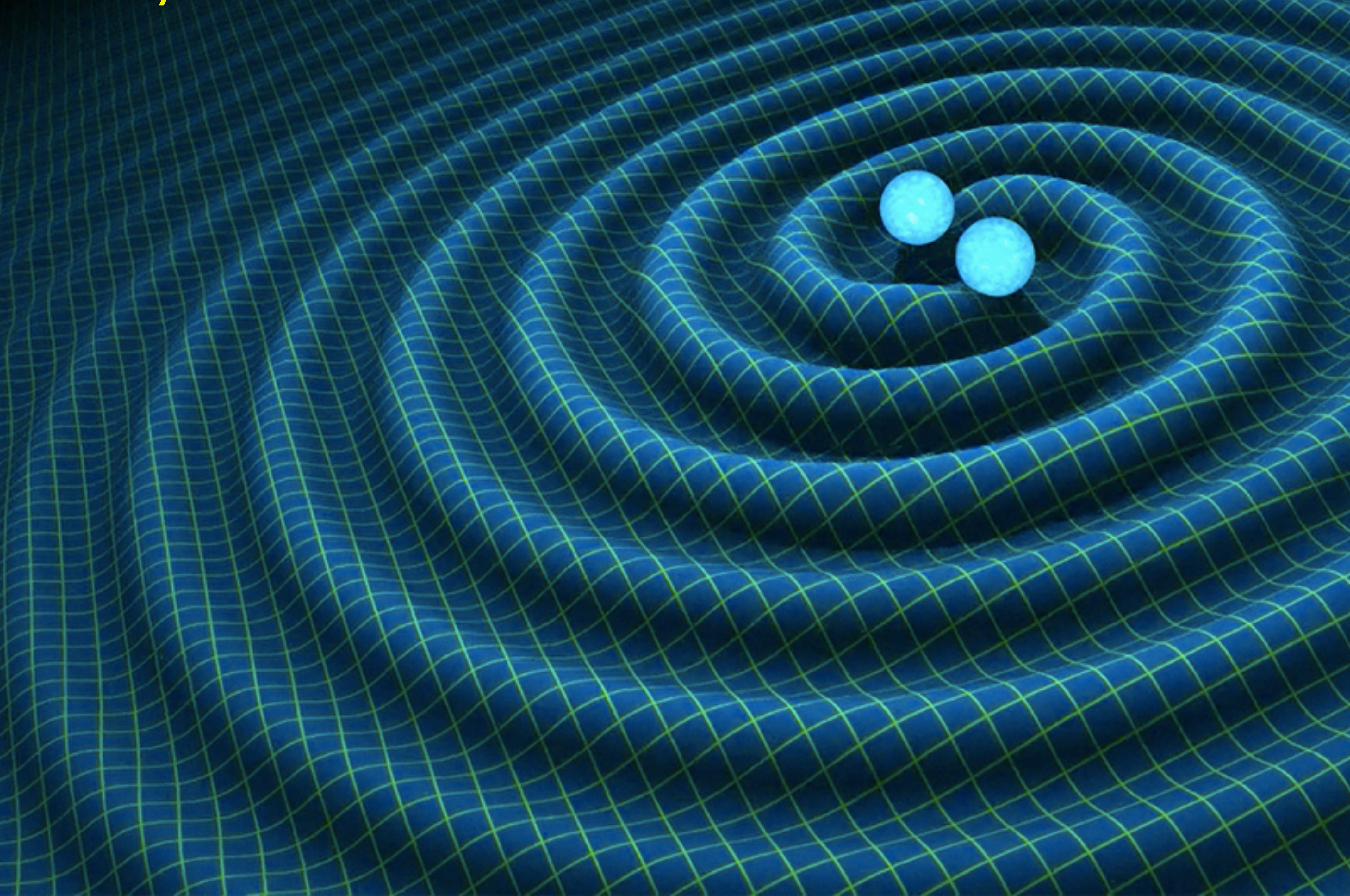
Gravitational waves wer inferred from the orbit of a binary pulsar -

Hulse & Taylor awarded Nobel Prize in 1993.



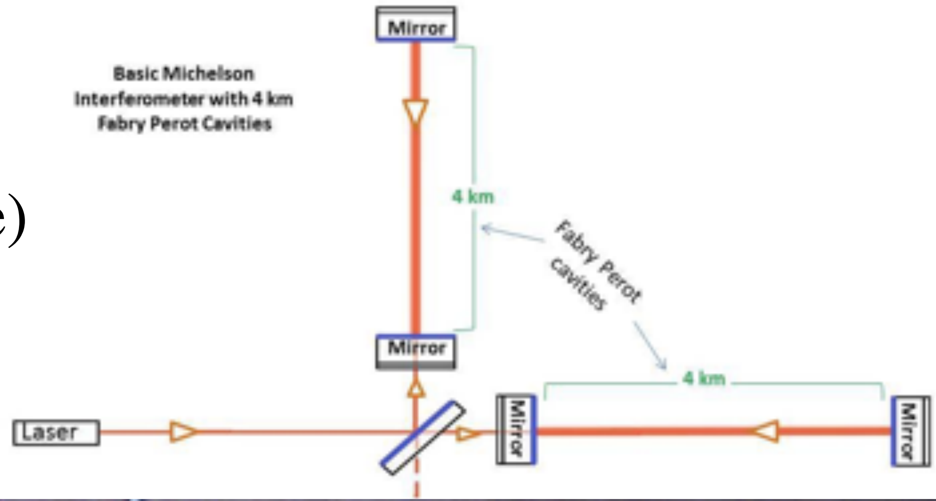
The binary pulsar showed indirect evidence for gravitational waves.

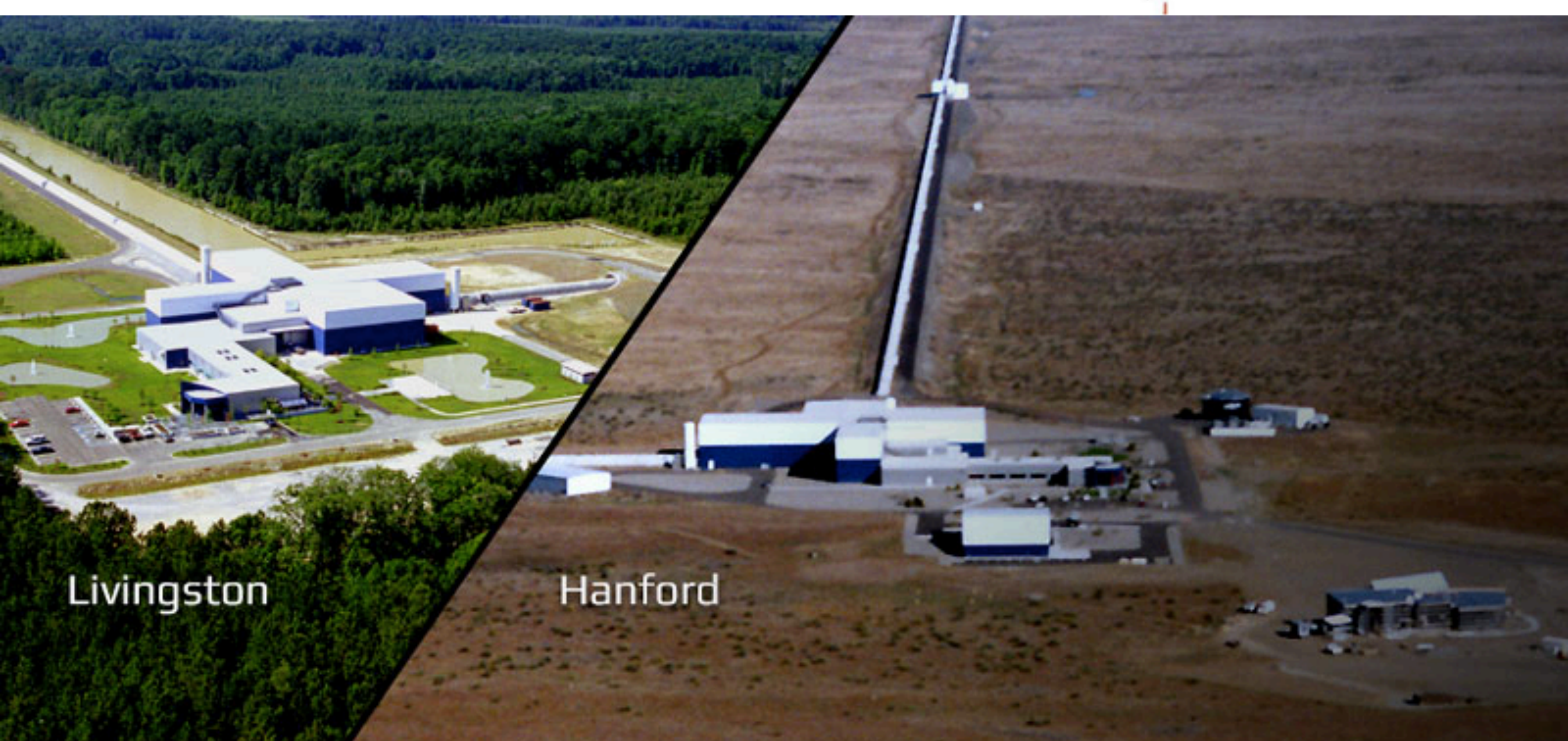
A binary black hole could show direct evidence...



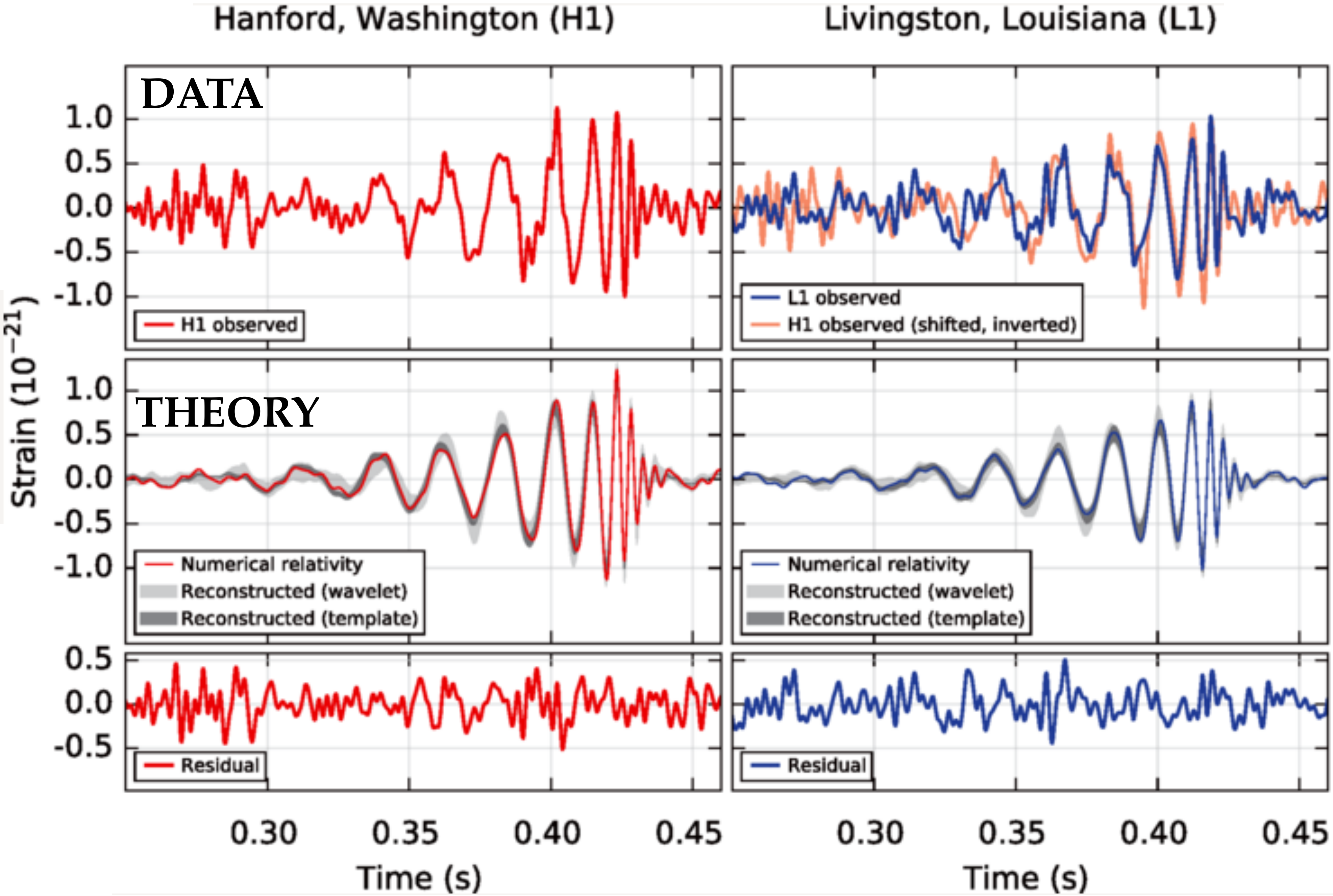
LIGO gravitational wave observatories in Livingston, LA & Hanford, WA

Laser interferrometers with 4km (2.5 mile) long arms in perfect vacuum

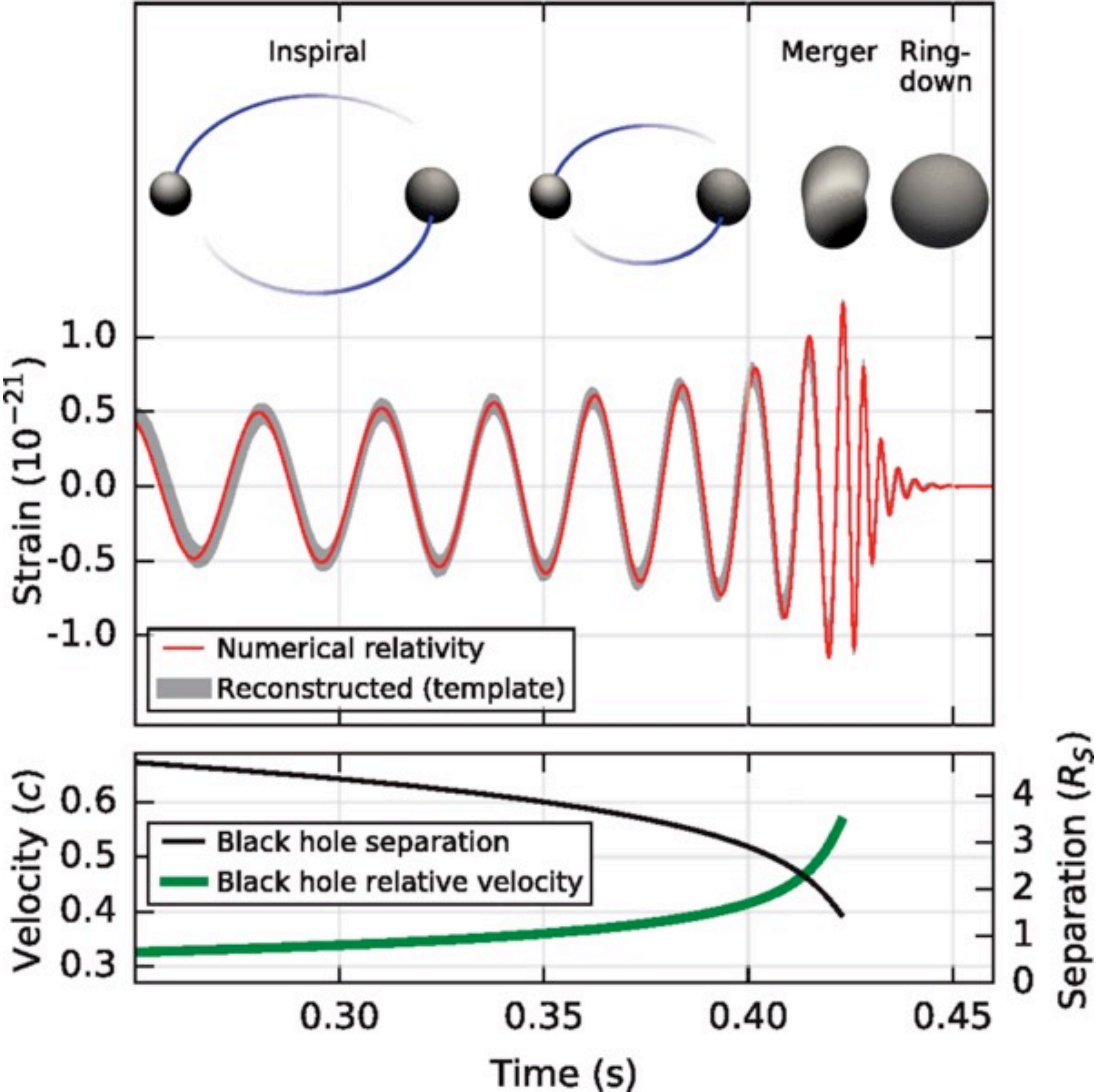




LIGO FIRST DIRECT GRAVITATIONAL WAVE DETECTION



Observed 14 September 2015; announced 11 February 2016



Inspiral
Merger
Ring-
down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

A few numbers

- Bigger Black Hole mass $M_{\bullet,1} = 36\ \mathrm{M}_{\odot}$
- Smaller Black Hole mass $M_{\bullet,2} = 29\ \mathrm{M}_{\odot}$
- Separation at contact (event horizons "touch") $350\ \mathrm{km}$ (I drove 430 km to get here)
- Speed at contact $\frac{1}{2}c$ (half light speed)
- Time to merge $< 0.05\ \mathrm{seconds}$
- Energy radiated (in gravitational waves) $3\ \mathrm{M}_{\odot} c^2$

Nobel Prizes all around!

Expect

Ray Weiss

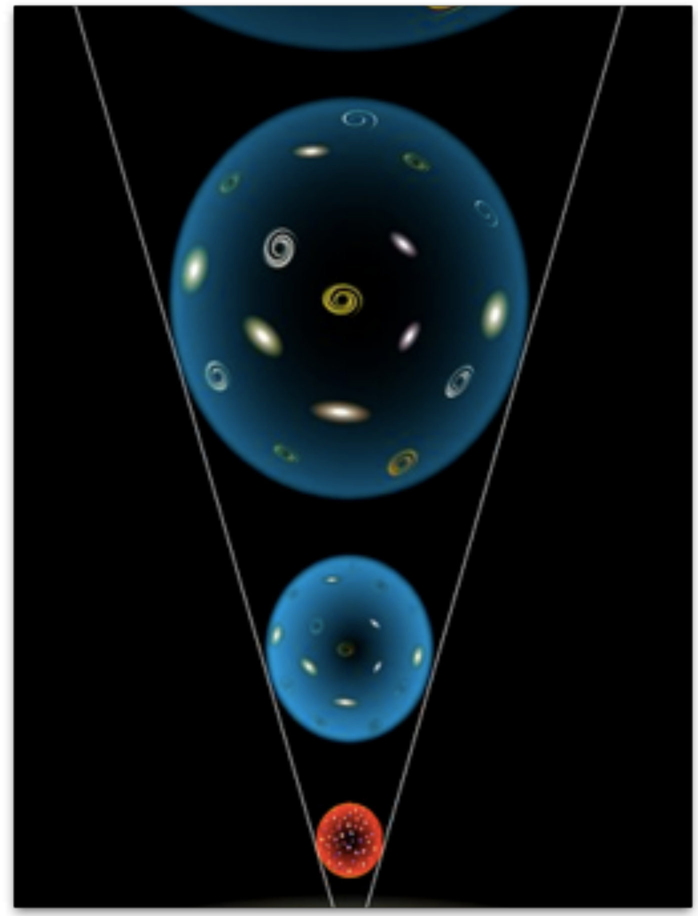
Kip Thorne

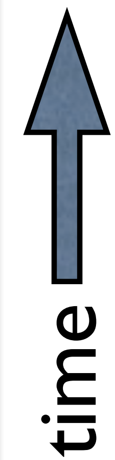
Ronald Drever

to win in September

Phenomena of General Relativity

Curved Space-Time
Time Dilation
Gravitational Lensing
Gravity Waves
The Expanding Universe





The universe itself is dynamic in General Relativity.
It must either expand or contract.

An Expanding Universe?

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

c universe
nstein's
er expand
e static.

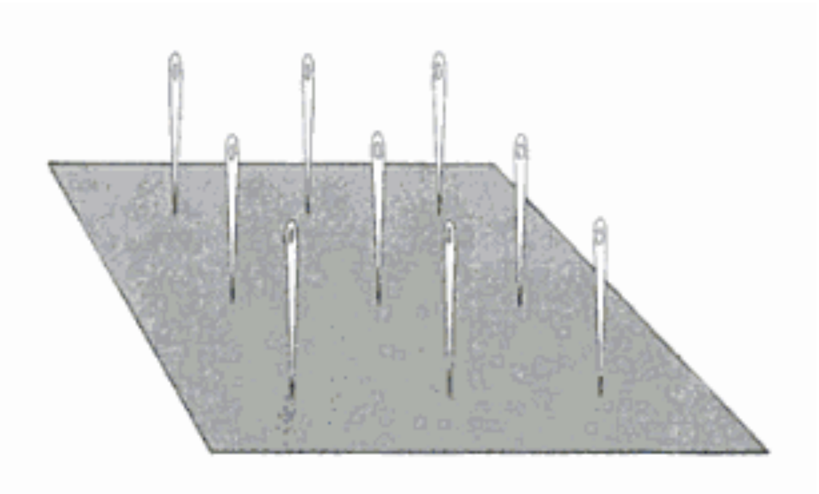
In 1915, an expanding universe was inconceivable. Surely the universe had been around forever!

Or a static one?

Einstein's greatest blunder?

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

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

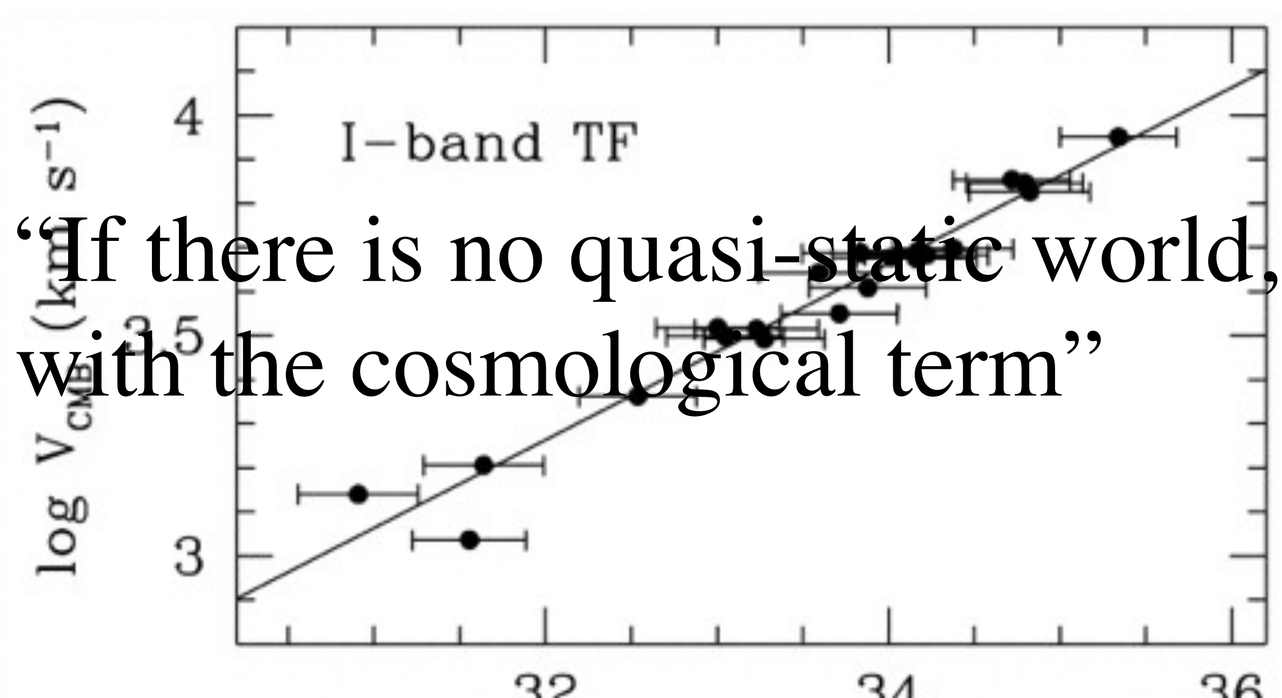


Or a static one?

Einstein's greatest blunder?

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

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

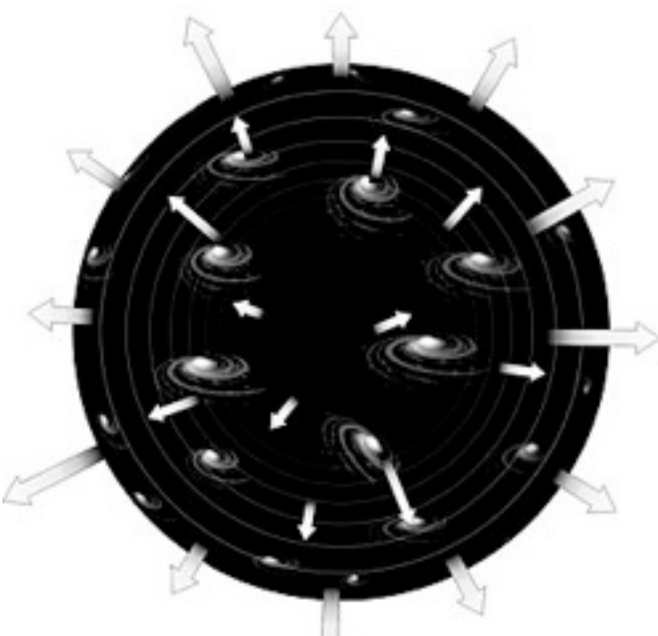
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda c^2}{3}$$

expansion rate

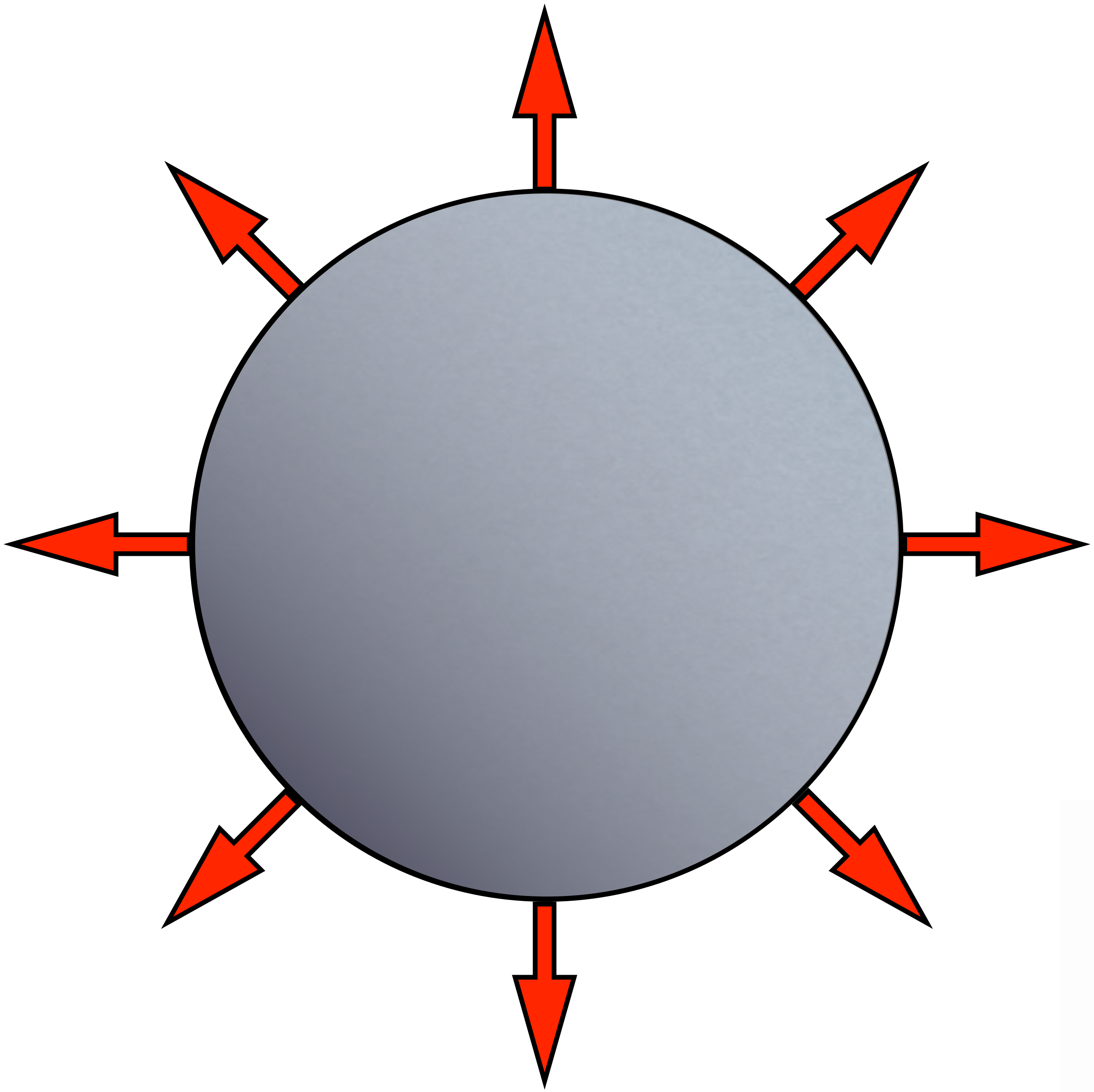
gravitating mass

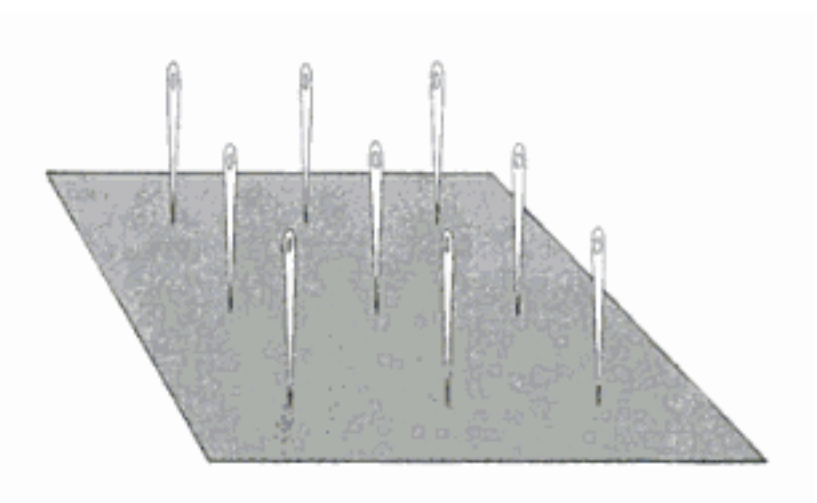
geometry

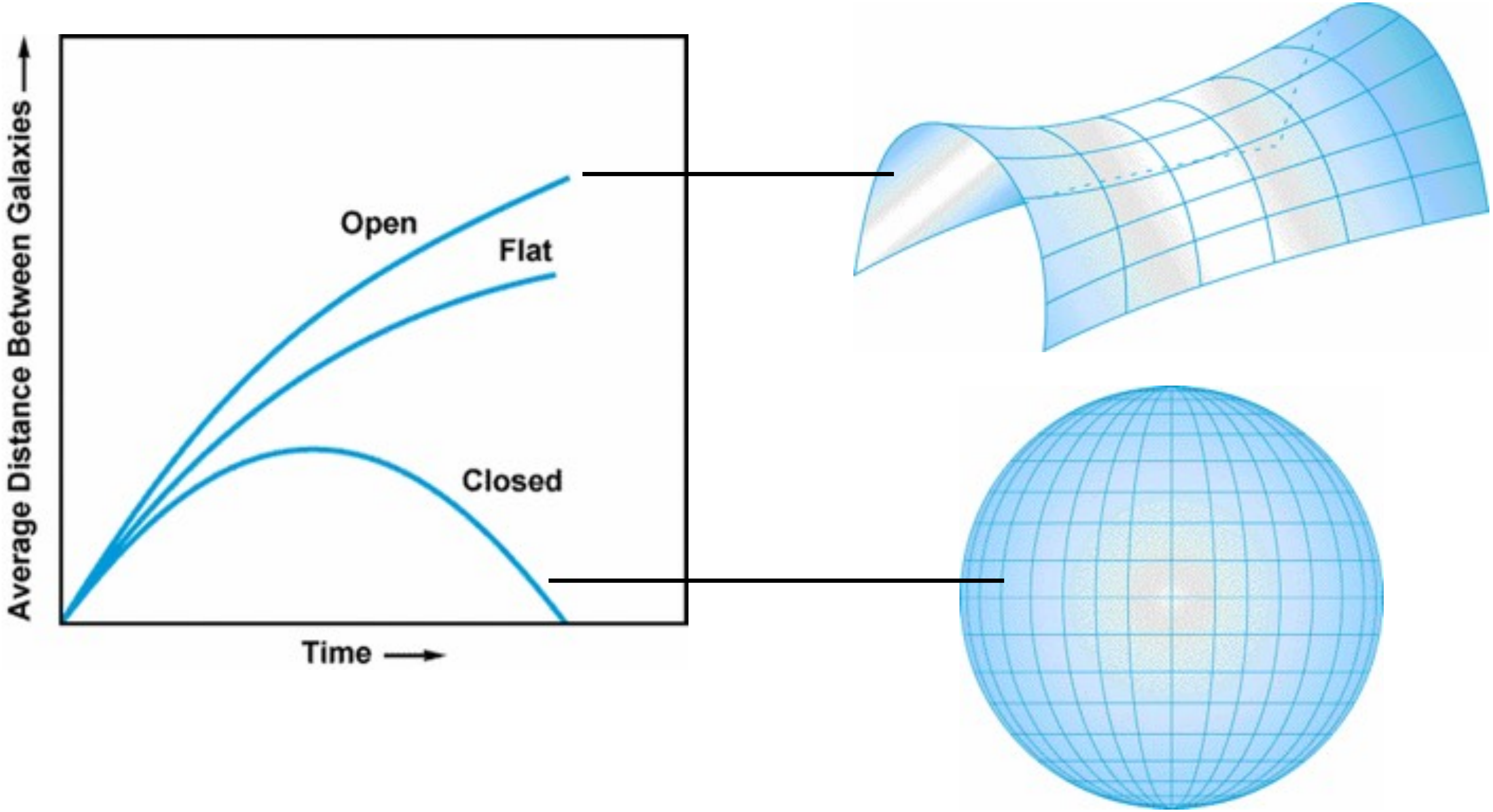
anti-gravity/
dark energy



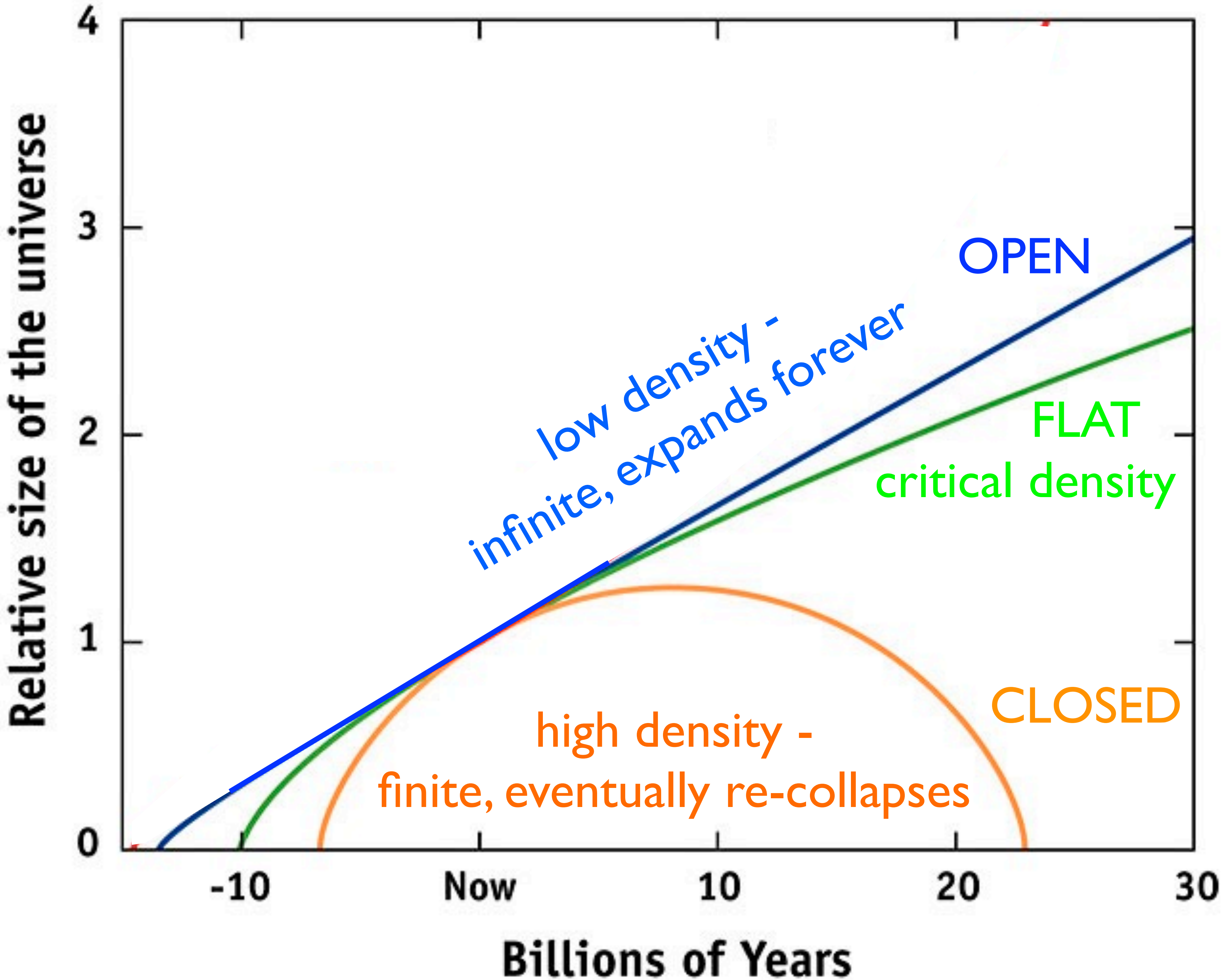
An expanding universe solves the stability problem that Newton & Bentley corresponded about.







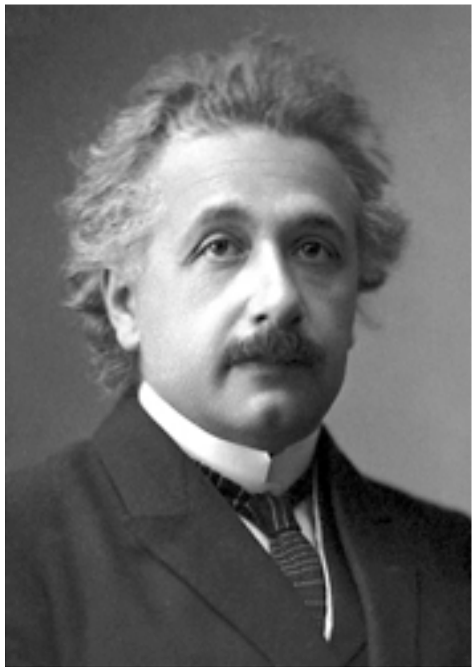
Einstein’s geometrical theory of gravity forms the basis of modern cosmology. The expansion history and the geometry of the universe depend on its mass density.



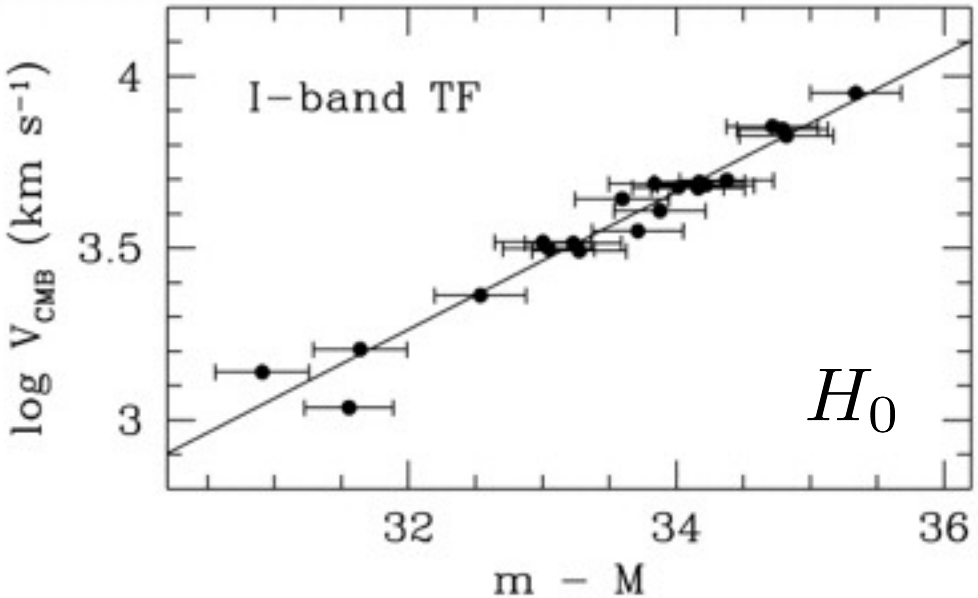
Relative size of the universe
0
1
2
3
4
-10
Now
10
20
30
Billions of Years
OPEN
low density -
infinite, expands forever
FLAT
critical density
CLOSED
high density -
finite, eventually re-collapses

Einstein's General Relativity provides an elegant cosmology

that naturally explains many observations



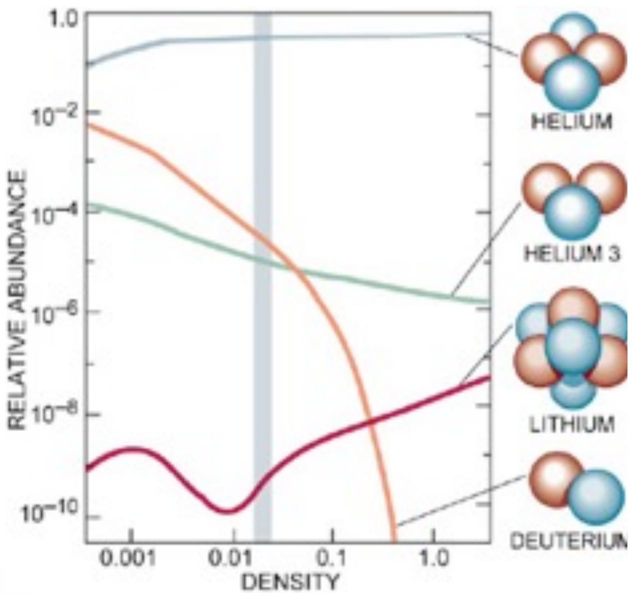
- Expanding Universe
  - redshift-distance relation
  - geometry of space-time
- Finite Age (~ 14 Billion years)
- Early hot phase (Big Bang)
  - Nucleosynthesis of the light elements (H, He, Li)
  - Cosmic Microwave Background



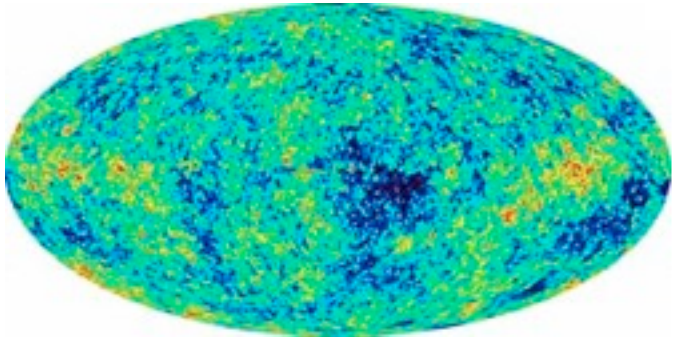
Hubble Expansion

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

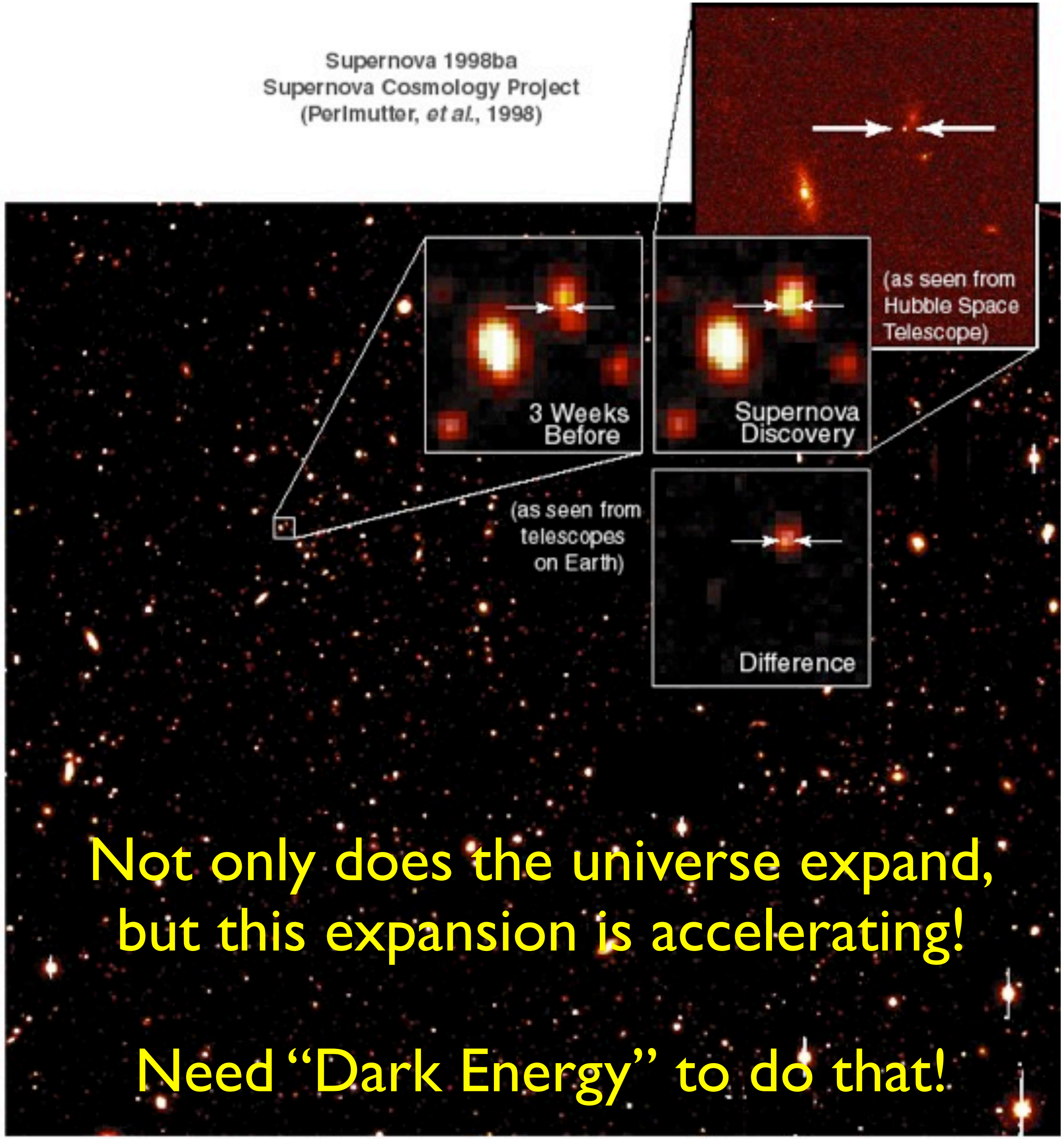
Modern cosmology only works with

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

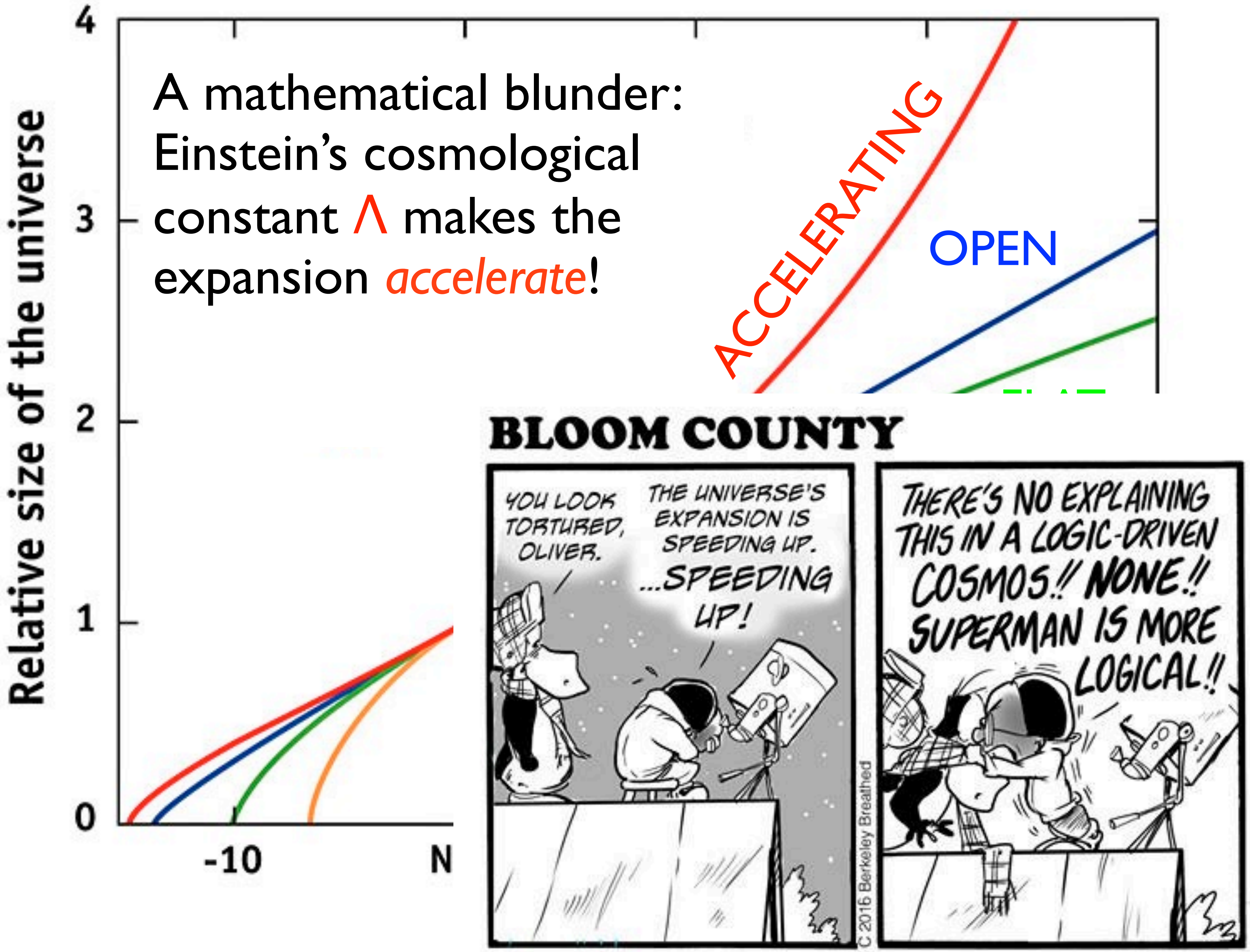
We don't know what dark matter is and we don't understand what dark energy means

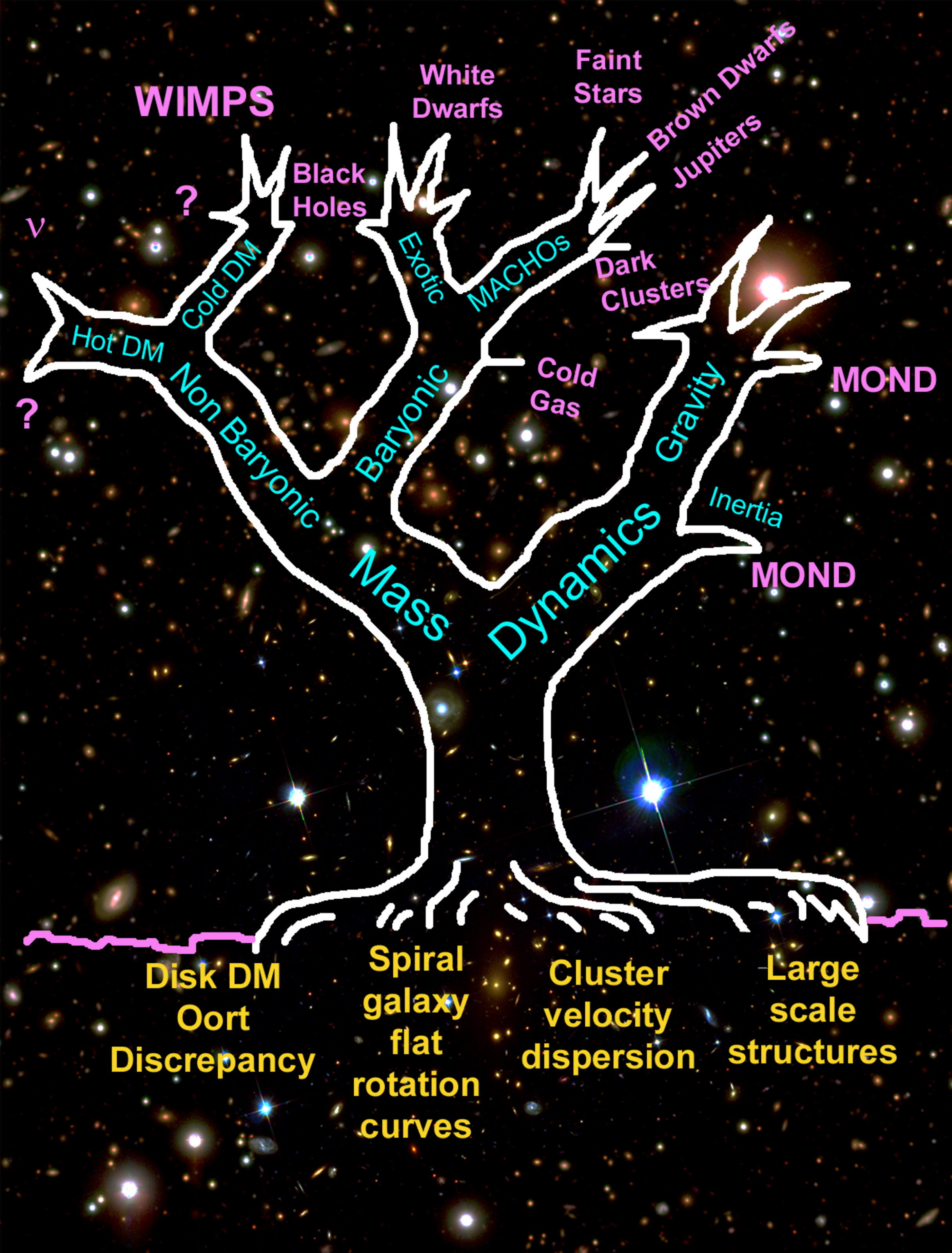
2011 Nobel Prize awarded to

Perlmutter
Riess
Schmidt



A mathematical blunder: Einstein's cosmological constant Λ makes the expansion *accelerate*!



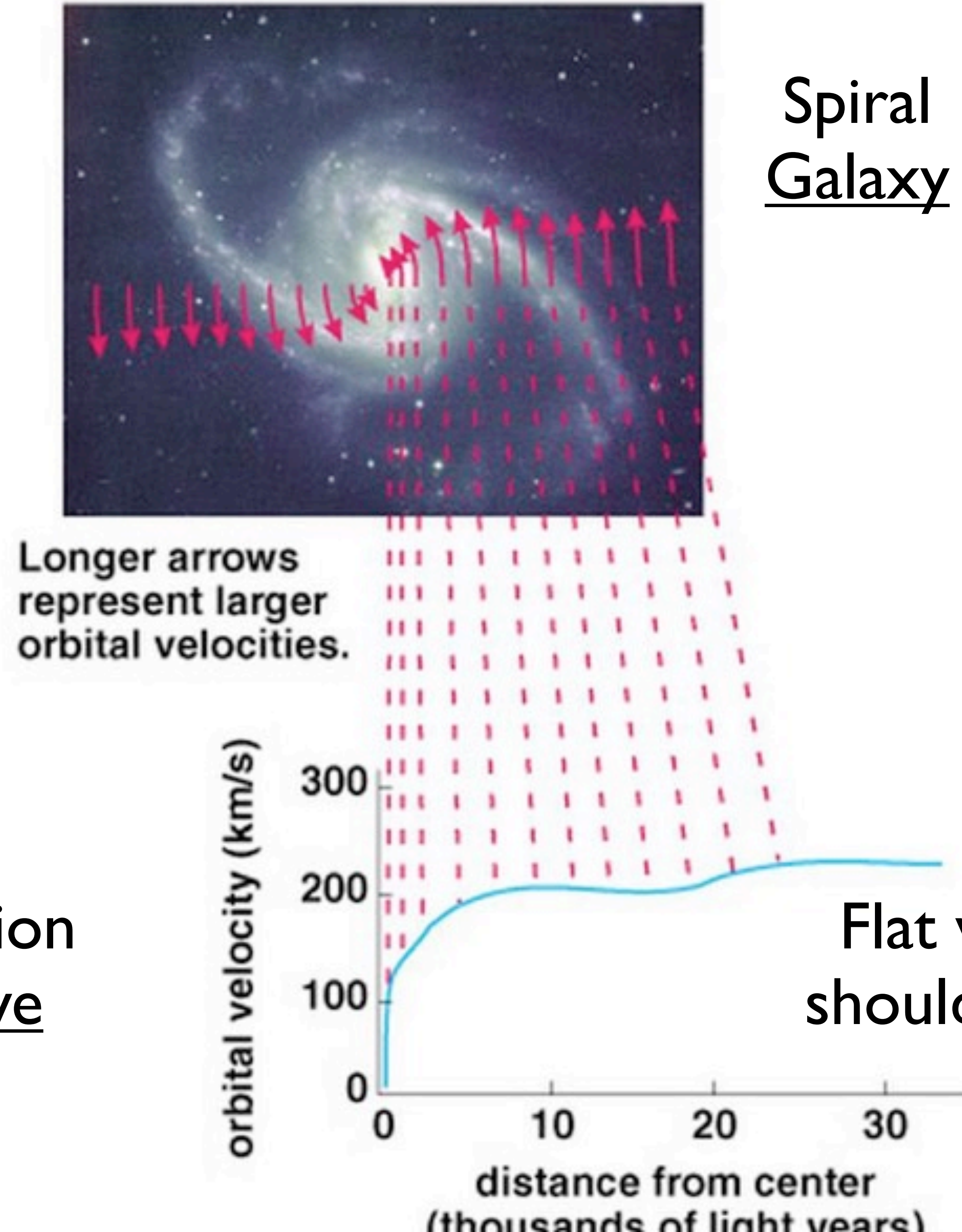


Need

- Dark Energy
  - to make the expansion accelerate
- Dark Matter
  - to gather the galaxies and in the darkness bind them

Ample evidence for dark matter

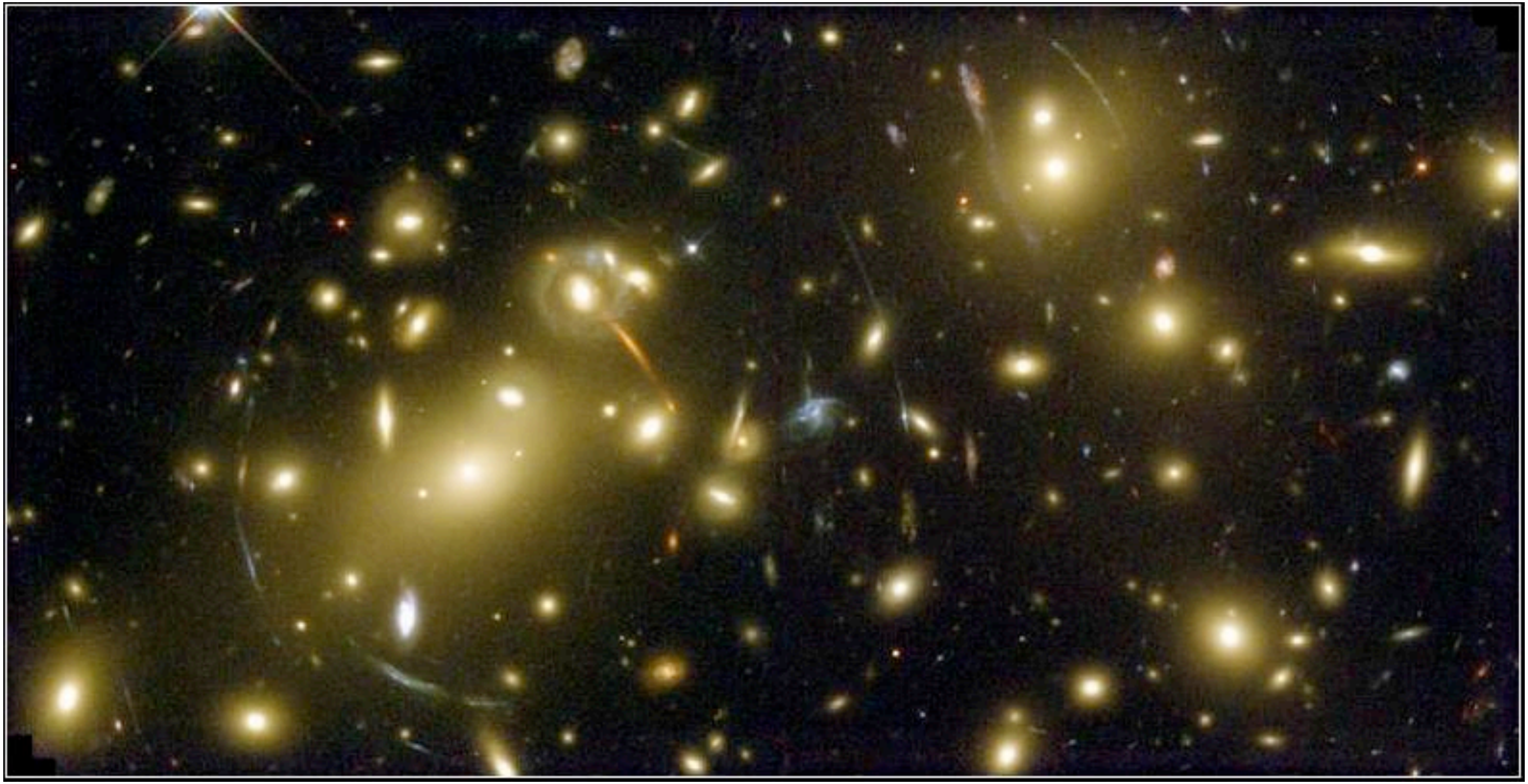
Spiral Galaxy



Rotation Curve

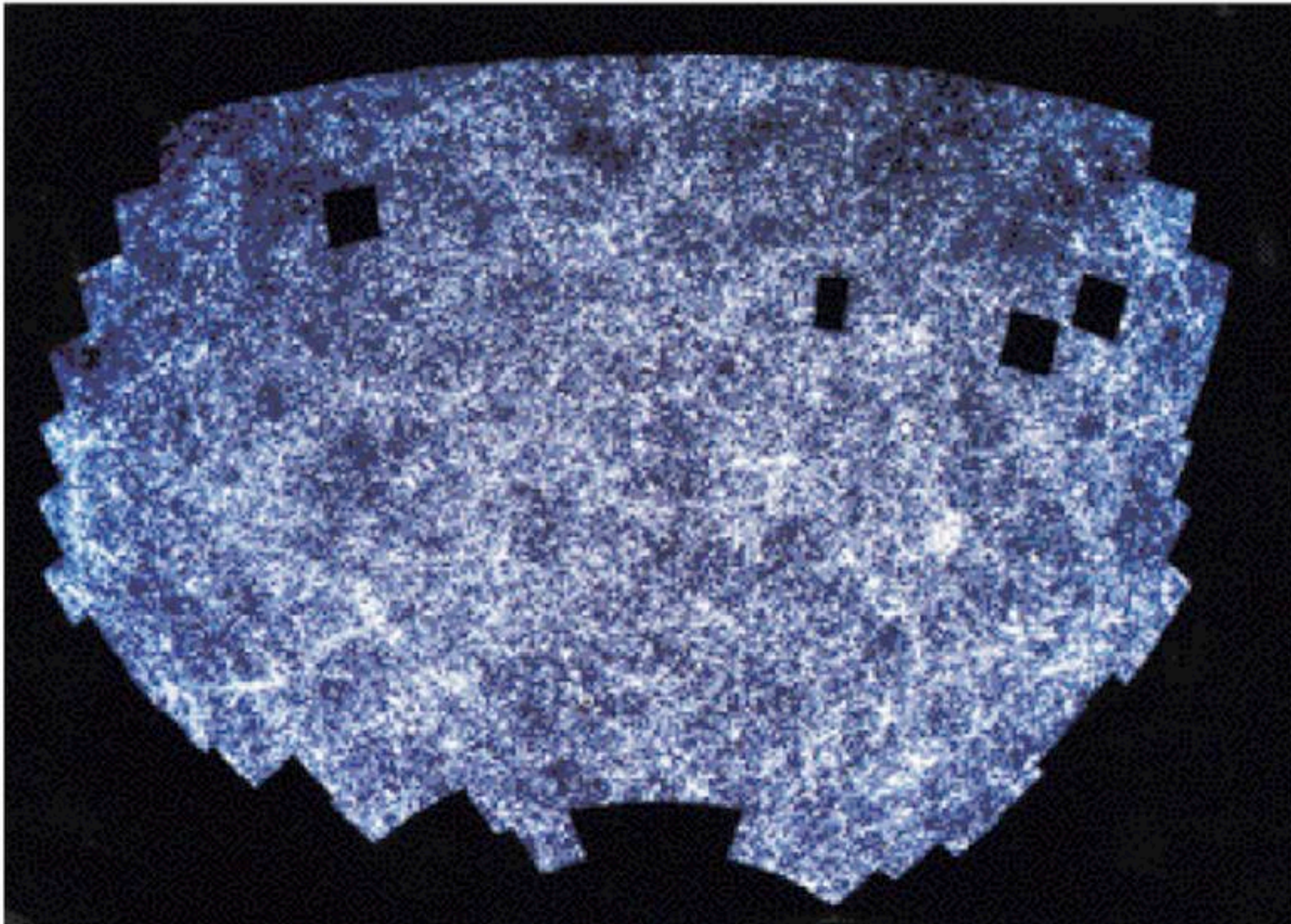
Flat when it should decline

Galaxy Cluster



Velocity dispersions (Zwicky); X-ray gas; gravitaitonal lensing

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

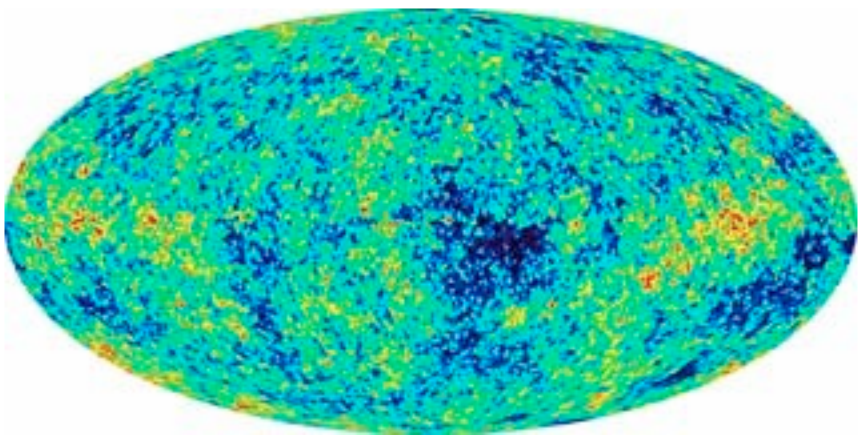
from gravity

gravitating mass >> normal mass

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

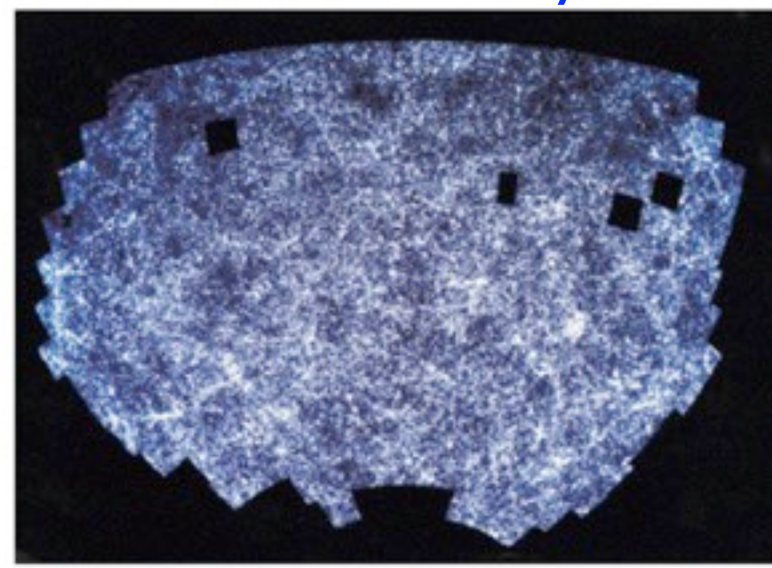
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr



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

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



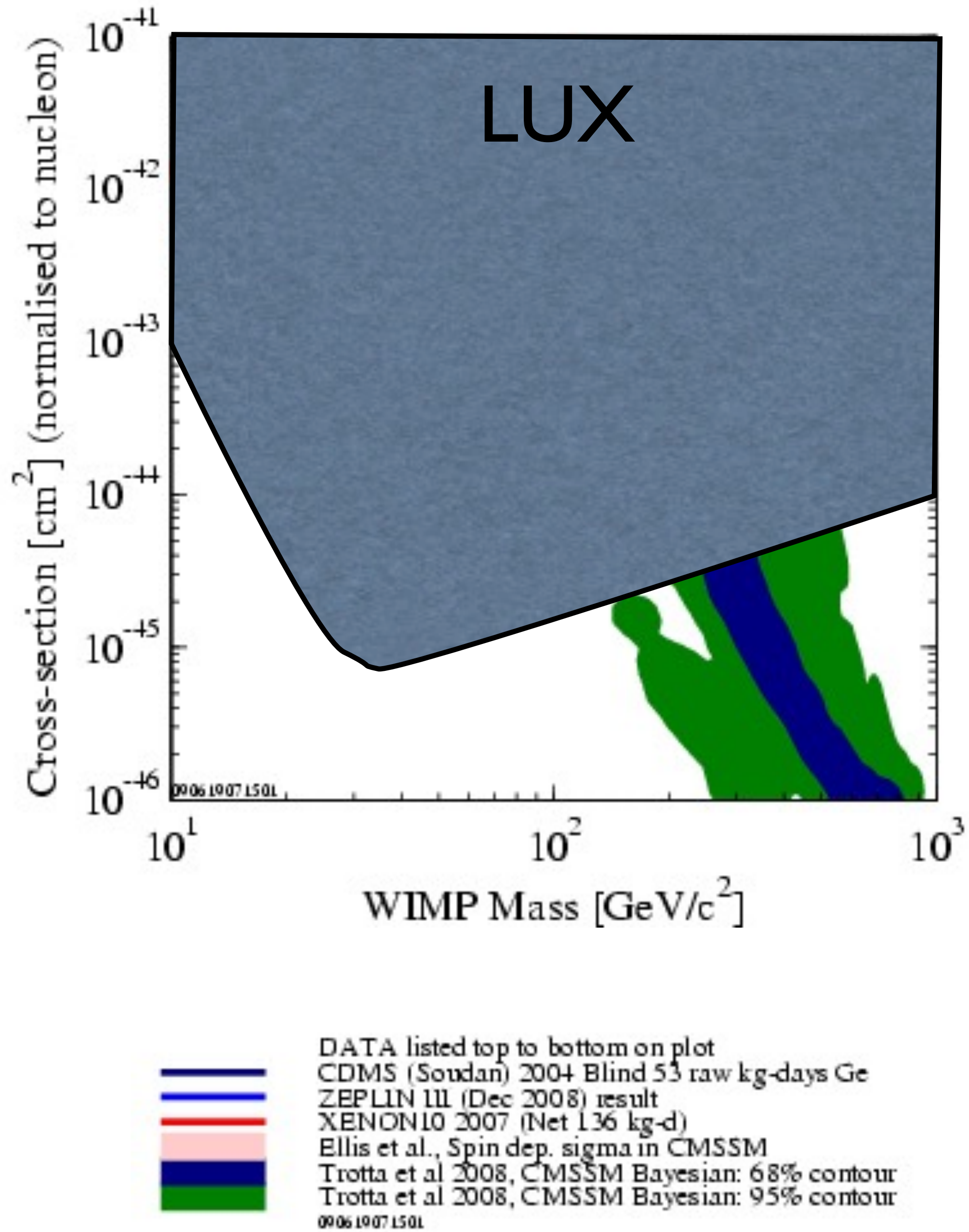
very lumpy: $\delta\rho/\rho \sim 1$

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

Many ongoing experimental searches for
Cold Dark Matter

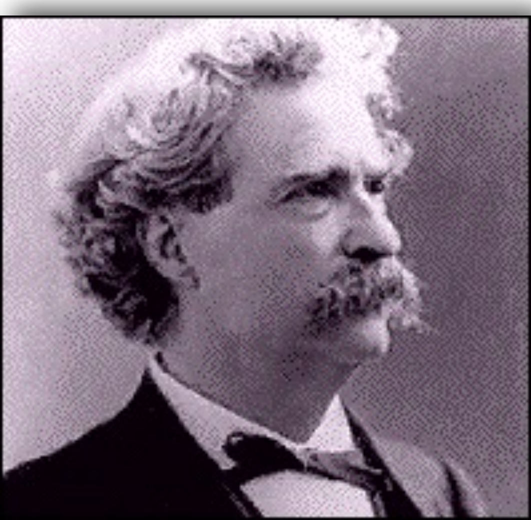
Paging
Cold Dark Matter

Paging
Cold Dark Matter ... hello?



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

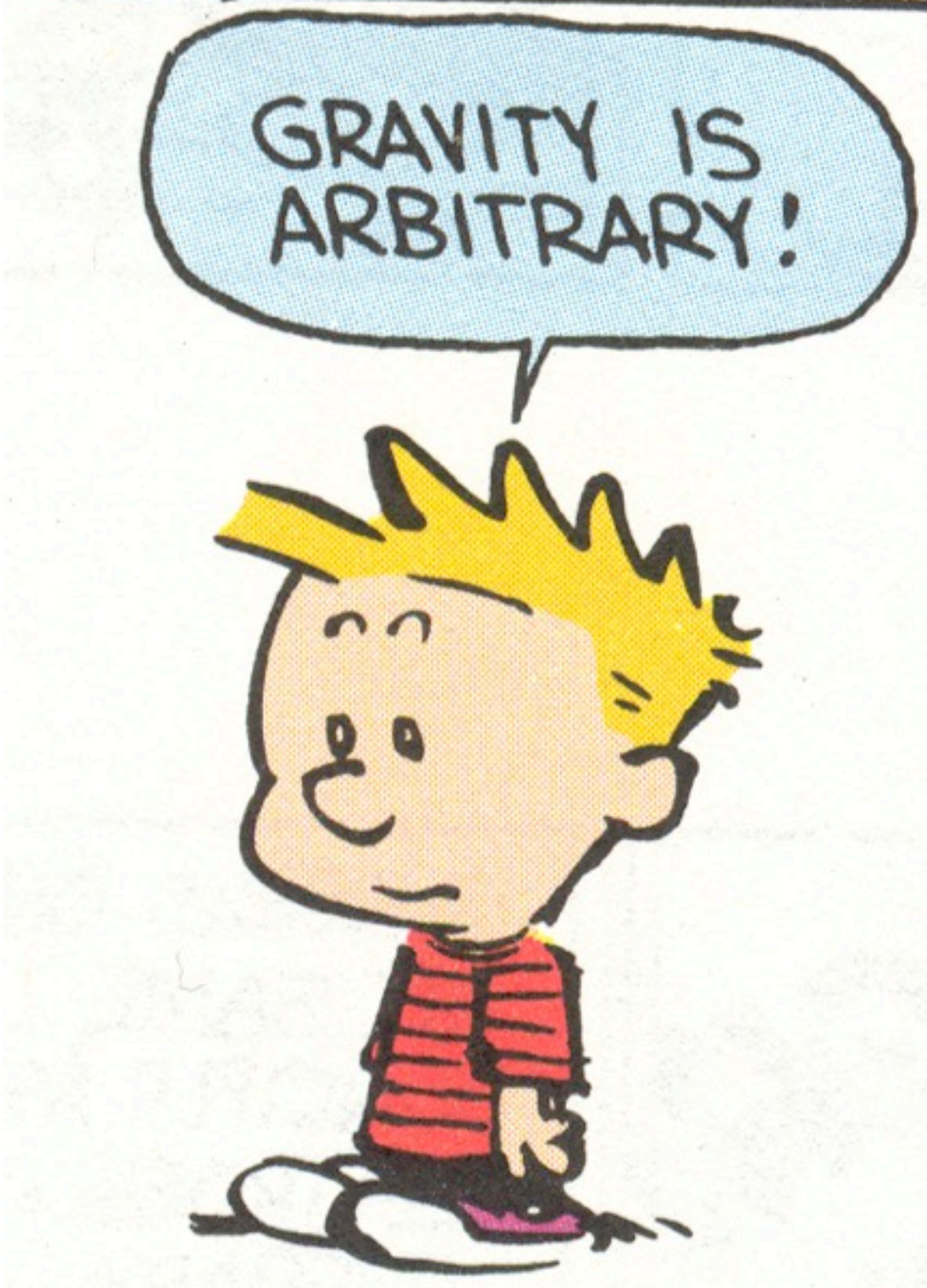
It’s what we know for sure that just aint so.



- 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

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

$$a \gg a_0 \qquad a \rightarrow g_N$$

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

ApJ, 270, 381

Milgrom 1983

MOND predictions

“Disk Galaxies with low surface brightness provide particularly strong tests”

- 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 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] those of [illegible] and galactic bulges. [illegible]

VIII. PREDICTIONS

The main predictions concerning [illegible] lows.

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, $g \approx (8\ \mathrm{kpc}/d)a_0$, based on a value of $V_\infty = 220\ \mathrm{km\ s^{-1}}$ 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 [illegible] many cases [illegible] test requires information on local behavior 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.

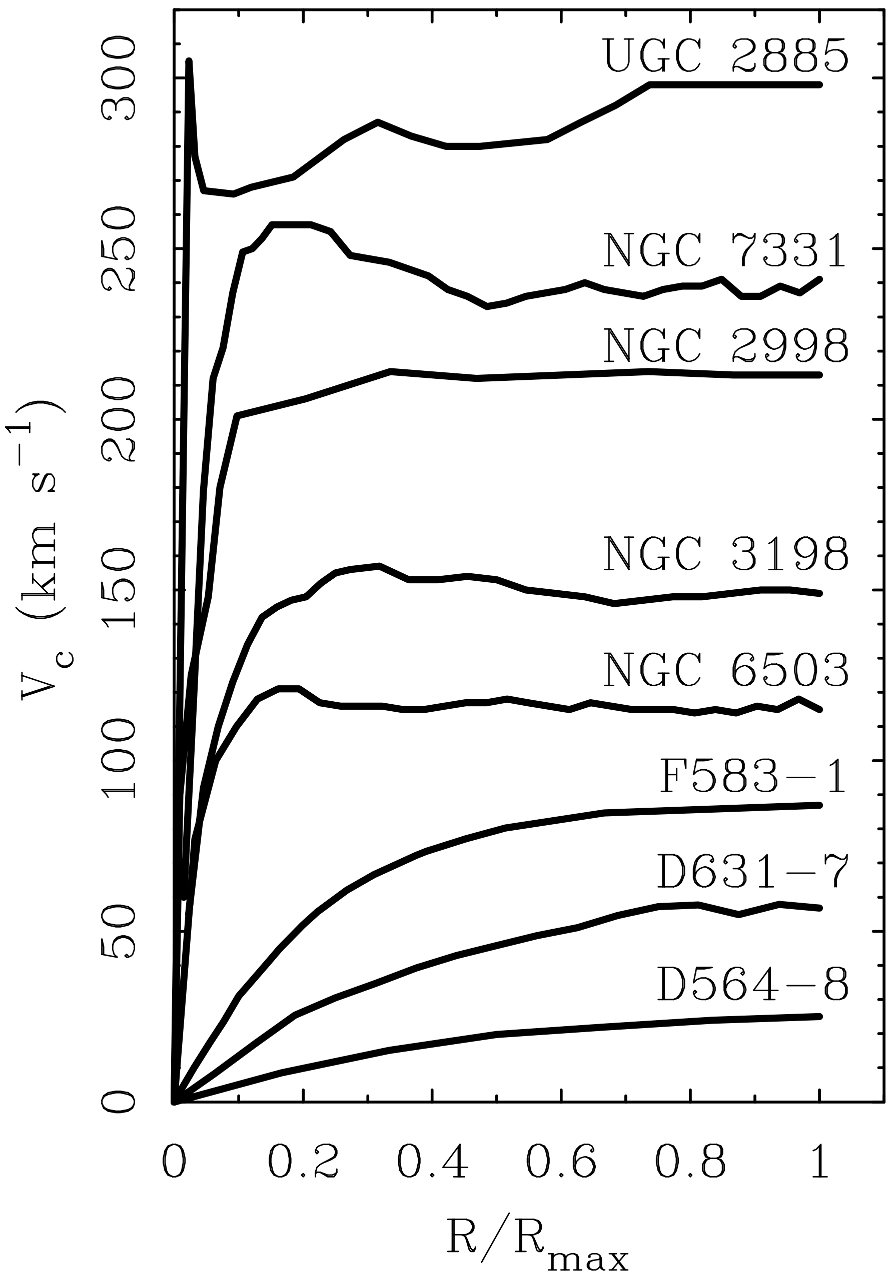
We also predict that the lower the average surface density of a galaxy is, the smaller is the transition radius, defined in prediction 5, in units of the galaxy's scale length. In fact, if the average surface density is very small we may have a galaxy in which $V^2/r < a_0$ everywhere, and analysis with 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

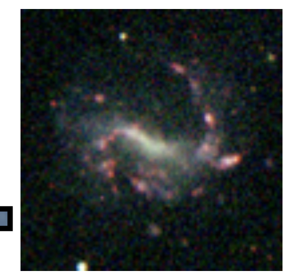
The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

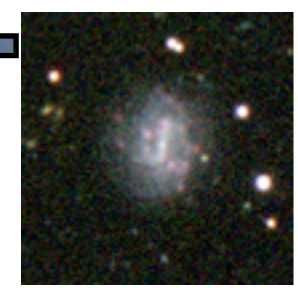
Rotation curves



spirals

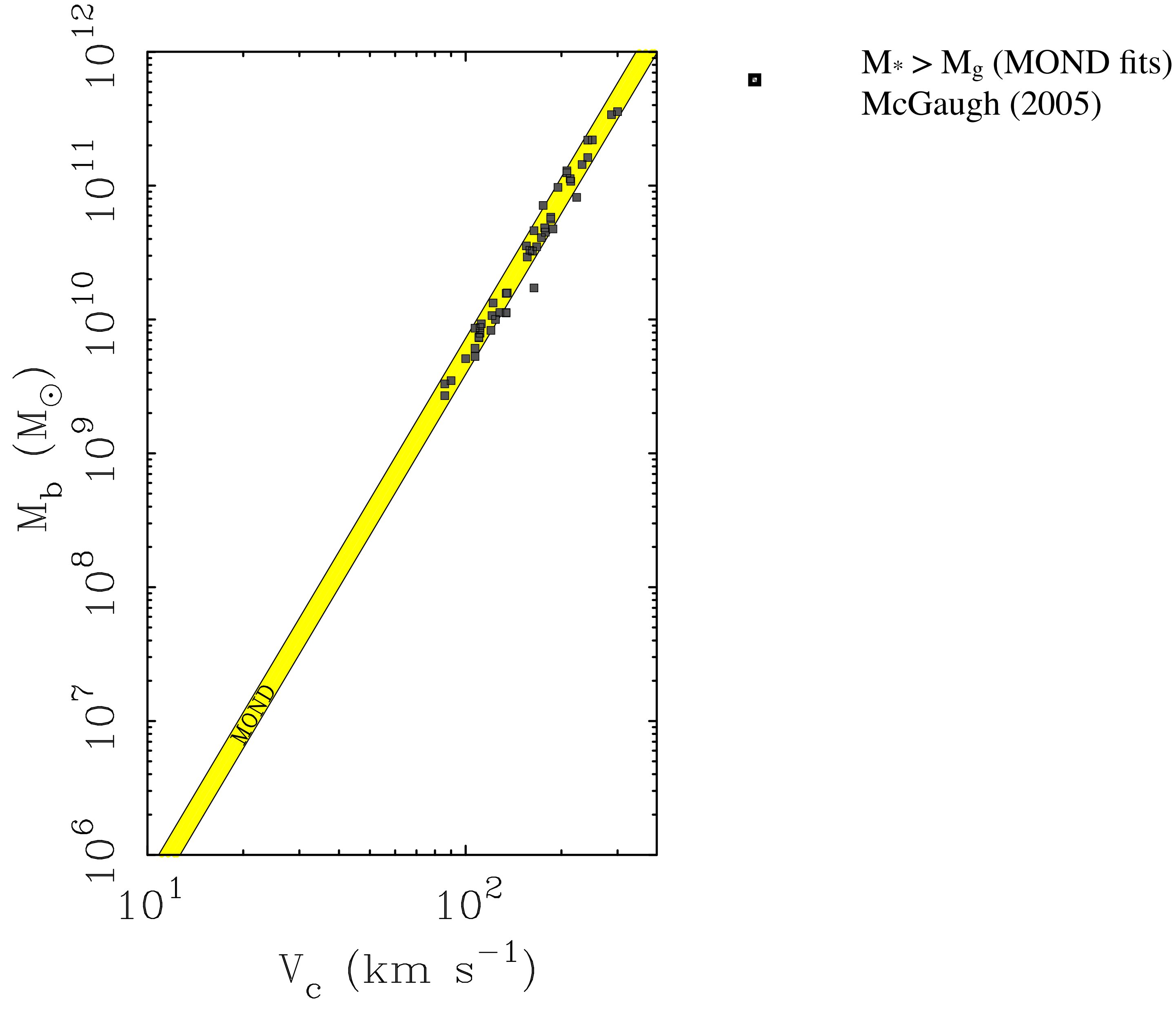
$M_* > M_g$.



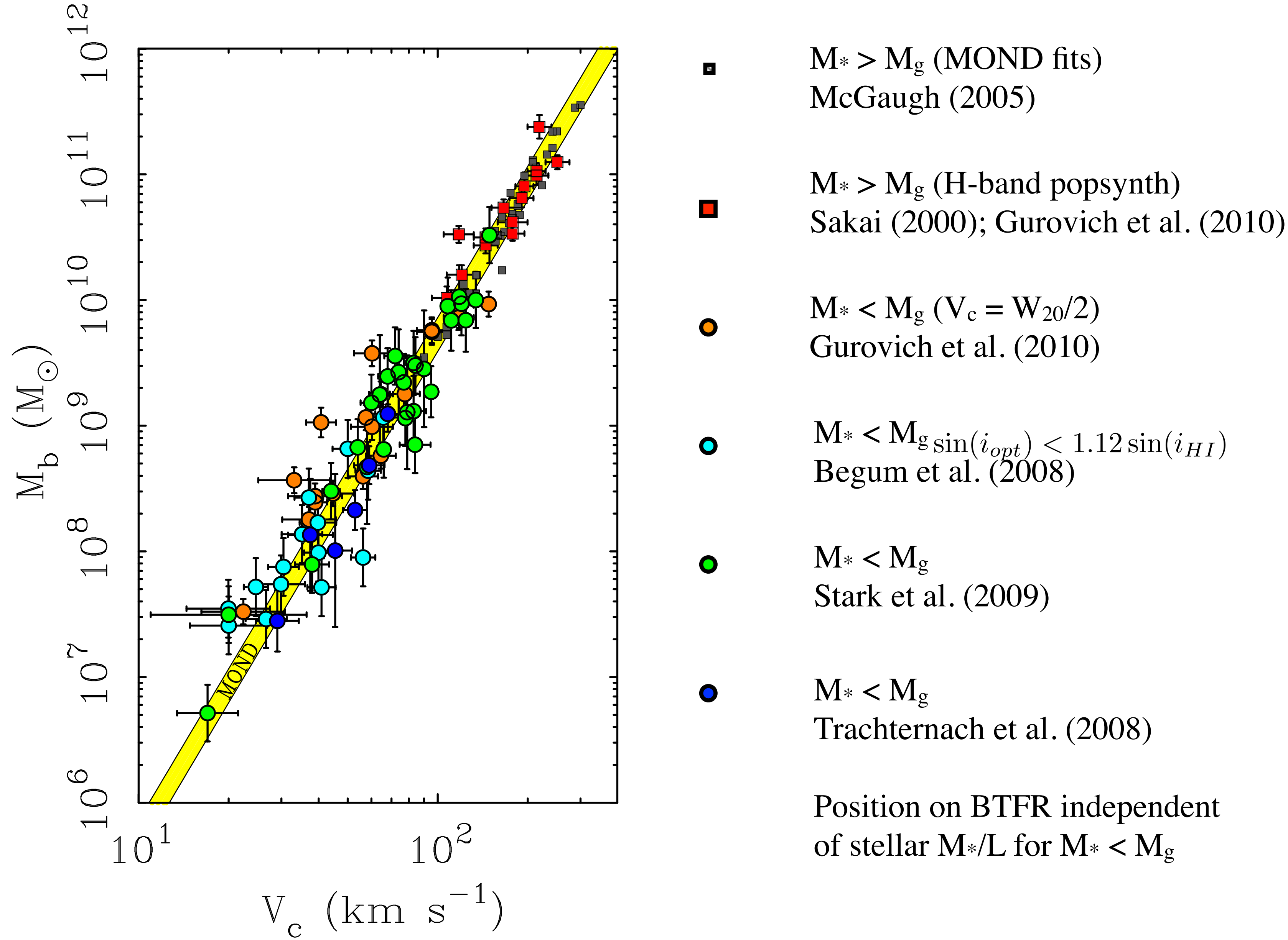


gas disks with $M_* < M_g$.

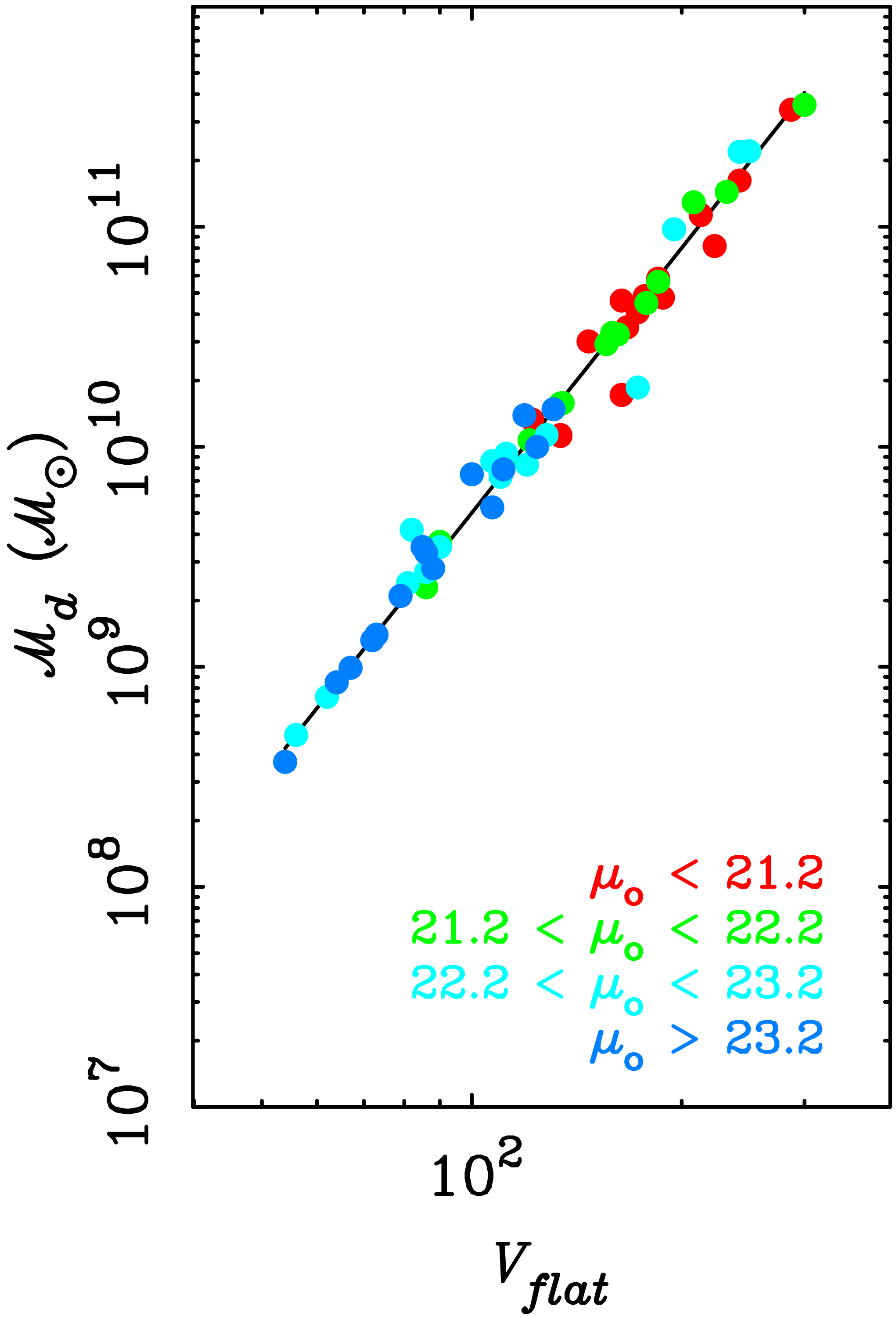
MOND predicts $a_0 GM = V^4$



$M_* > M_g$ (MOND fits)
McGaugh (2005)
MOND
M_b ($M_\odot$)
V_c (km s^{-1})
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^1
10^2

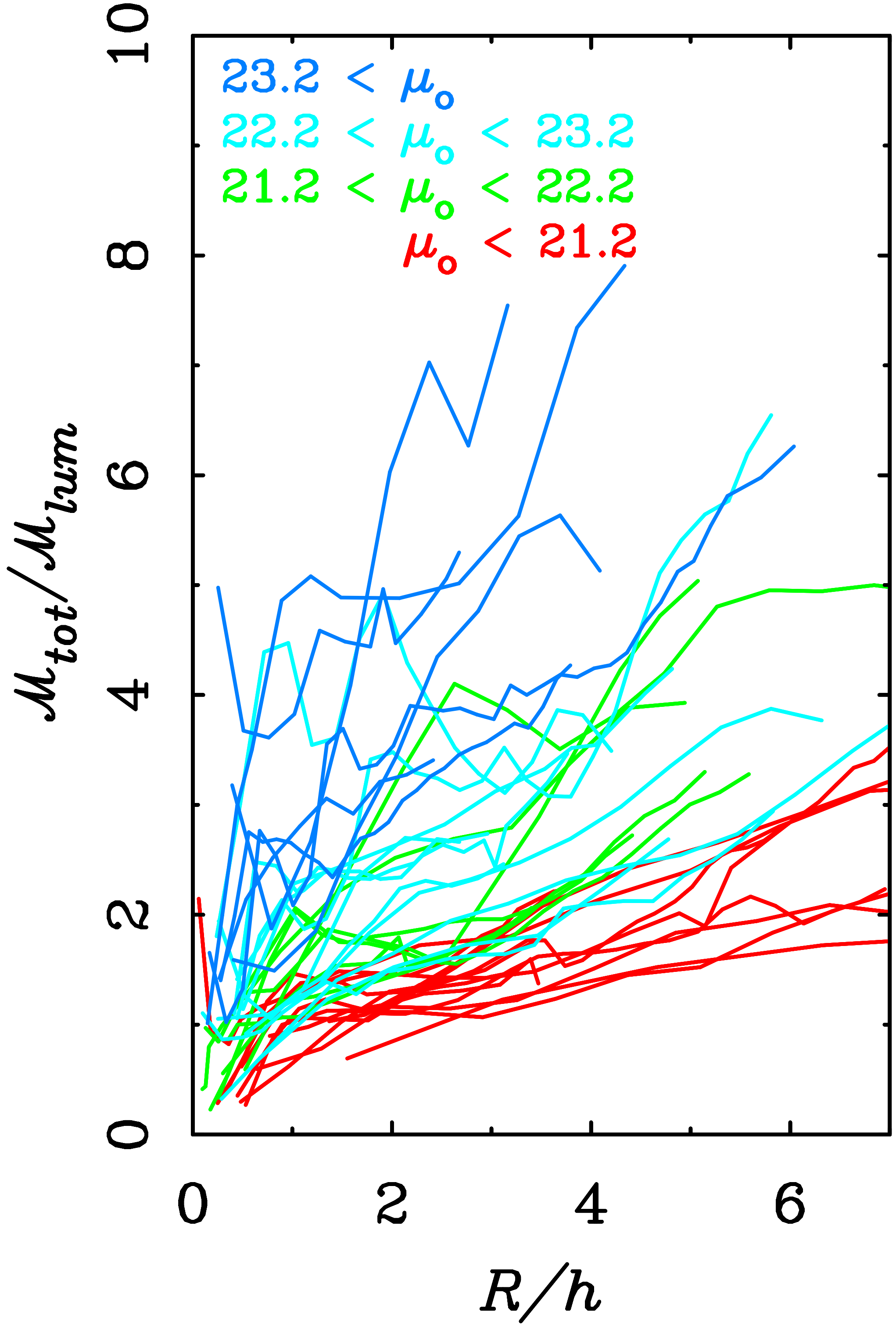


M* > Mg (MOND fits)
McGaugh (2005)
M* > Mg (H-band popsynth)
Sakai (2000); Gurovich et al. (2010)
M* < Mg (Vc = W20/2)
Gurovich et al. (2010)
M* < Mg sin(i_opt) < 1.12 sin(i_HI)
Begum et al. (2008)
M* < Mg
Stark et al. (2009)
M* < Mg
Trachternach et al. (2008)
Position on BTFR independent
of stellar M*/L for M* < Mg
MOND
Mb (M⊙)
Vc (km s−1)



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



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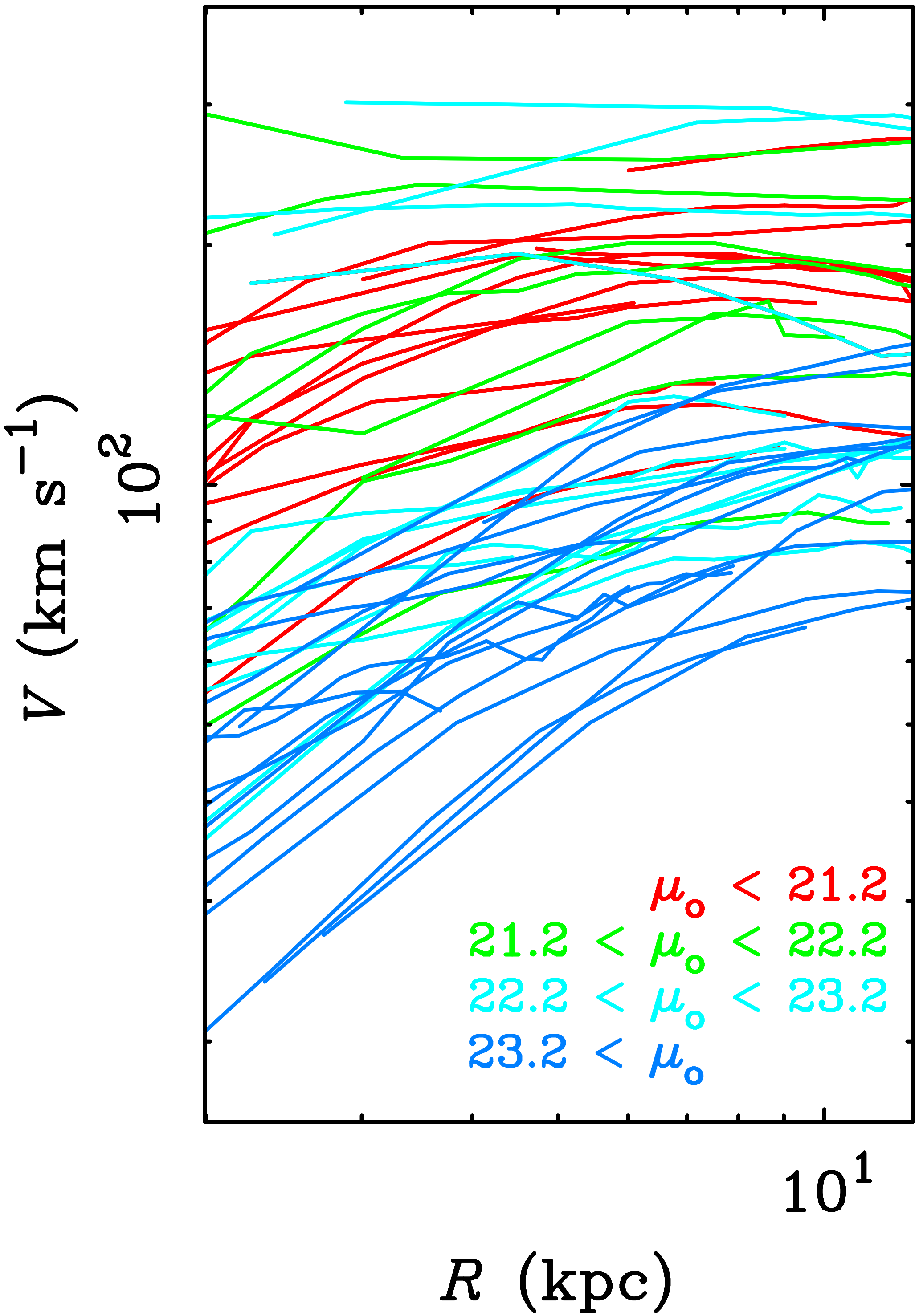

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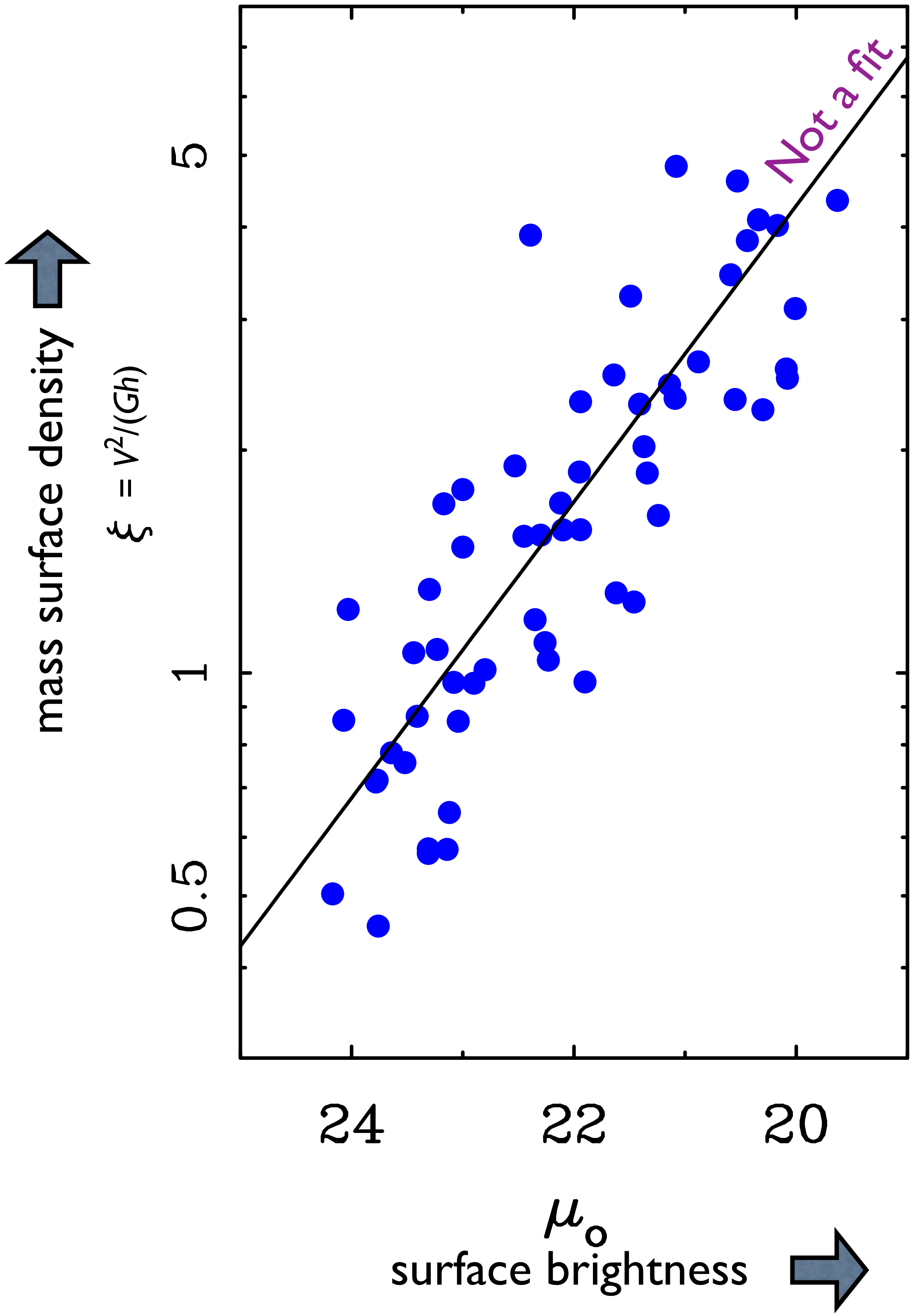

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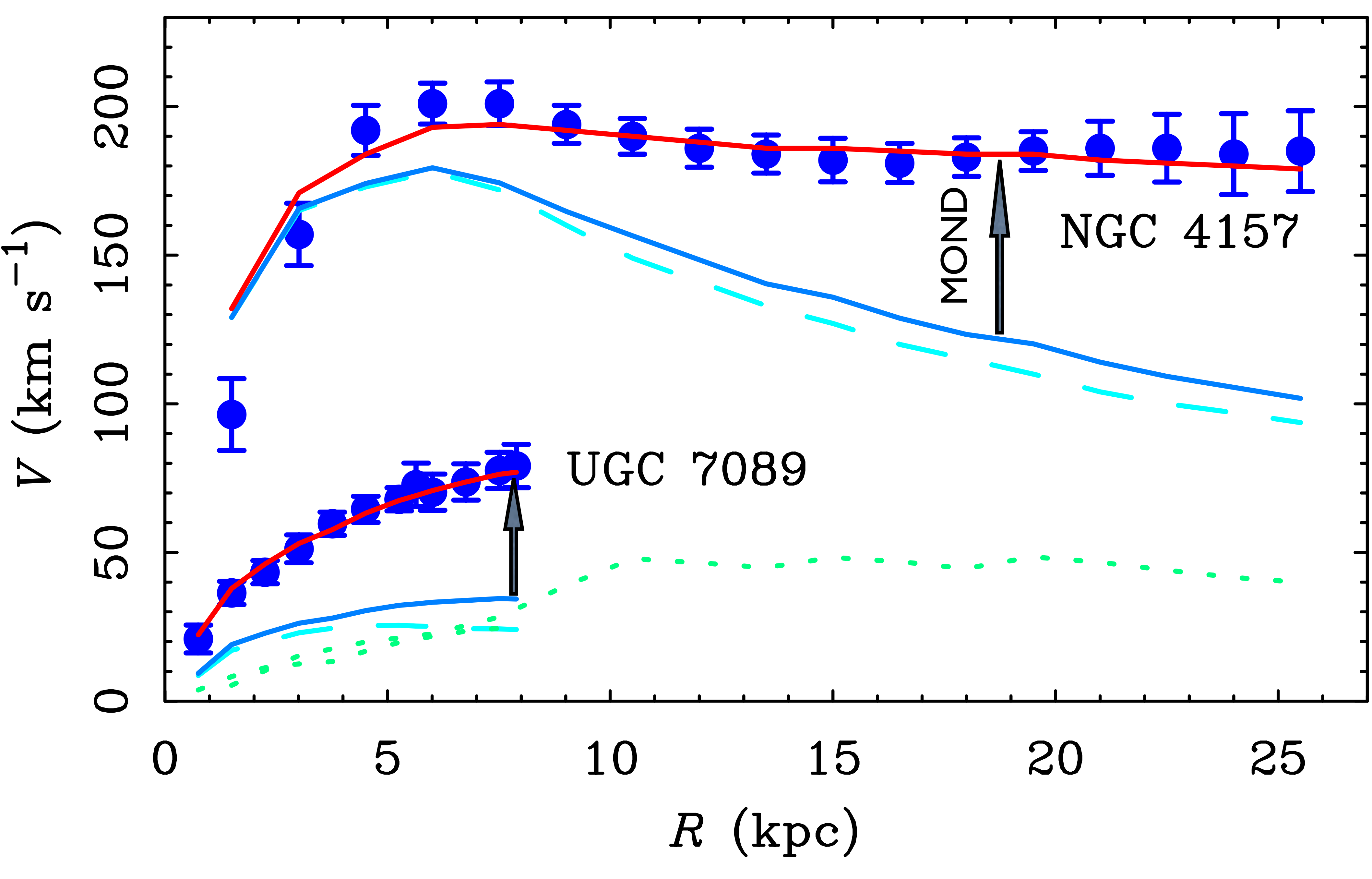
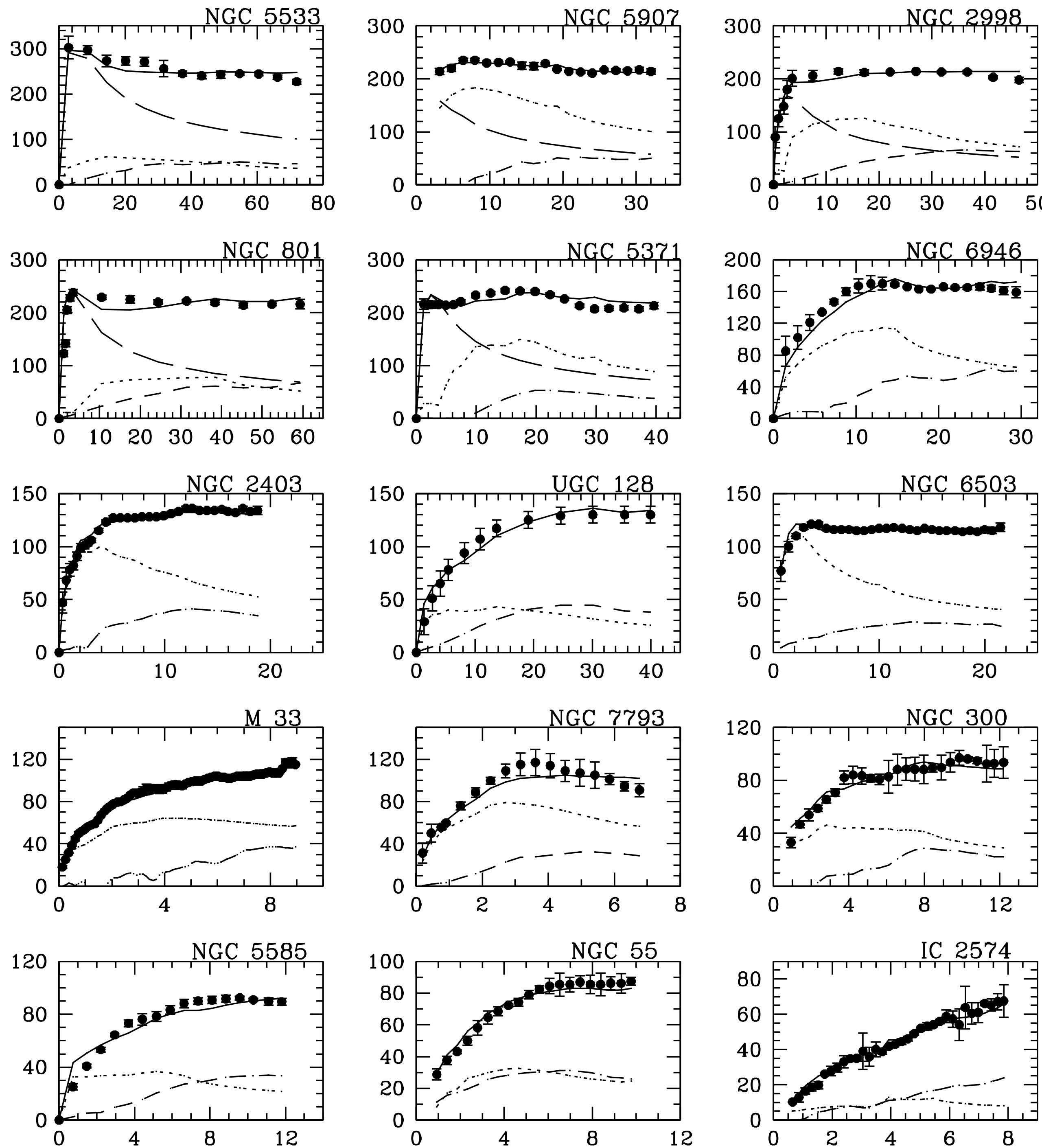
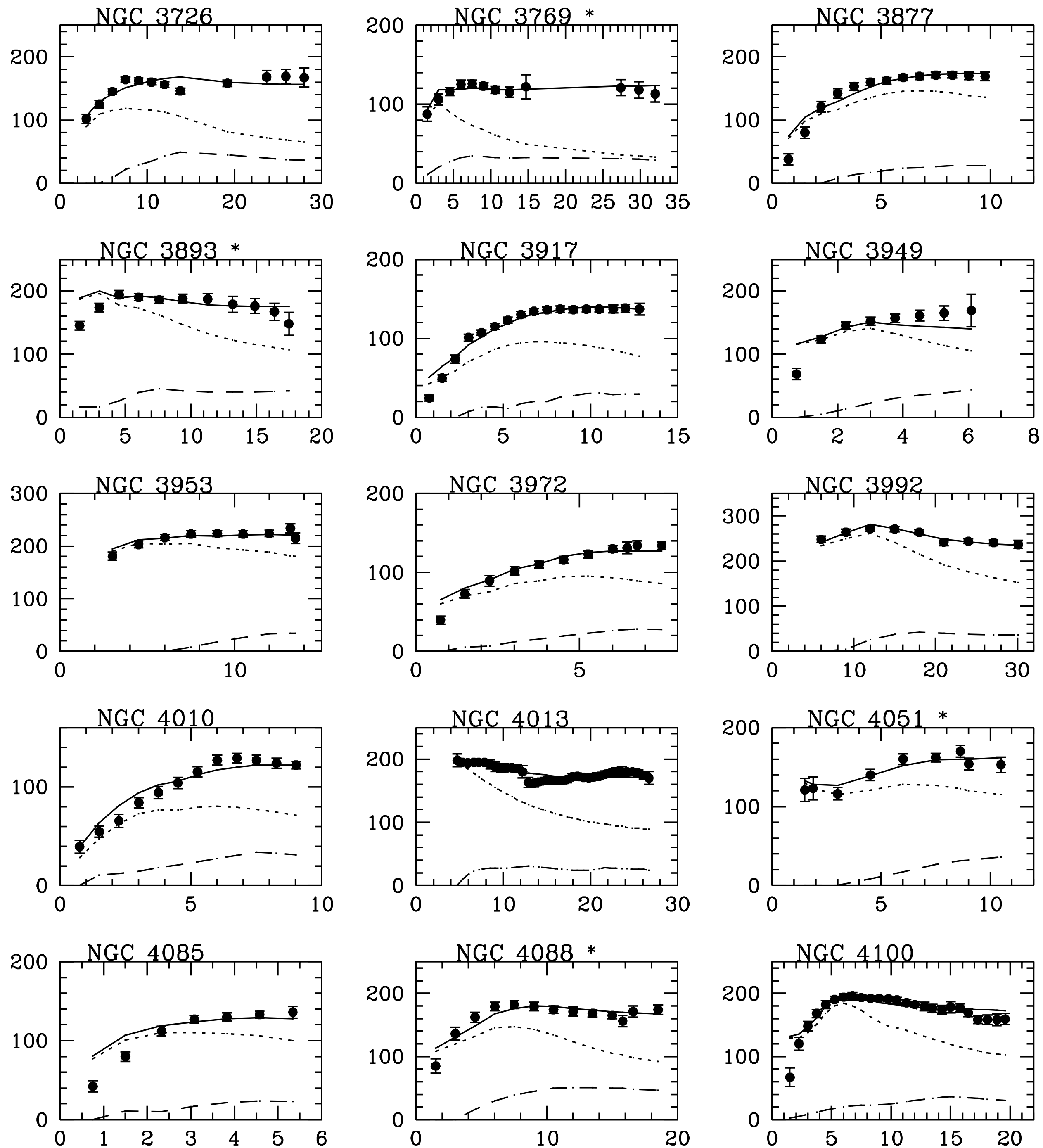


V (km s^{-1})
R (kpc)
MOND
NGC 4157
UGC 7089
0
50
100
150
200
0
5
10
15
20
25

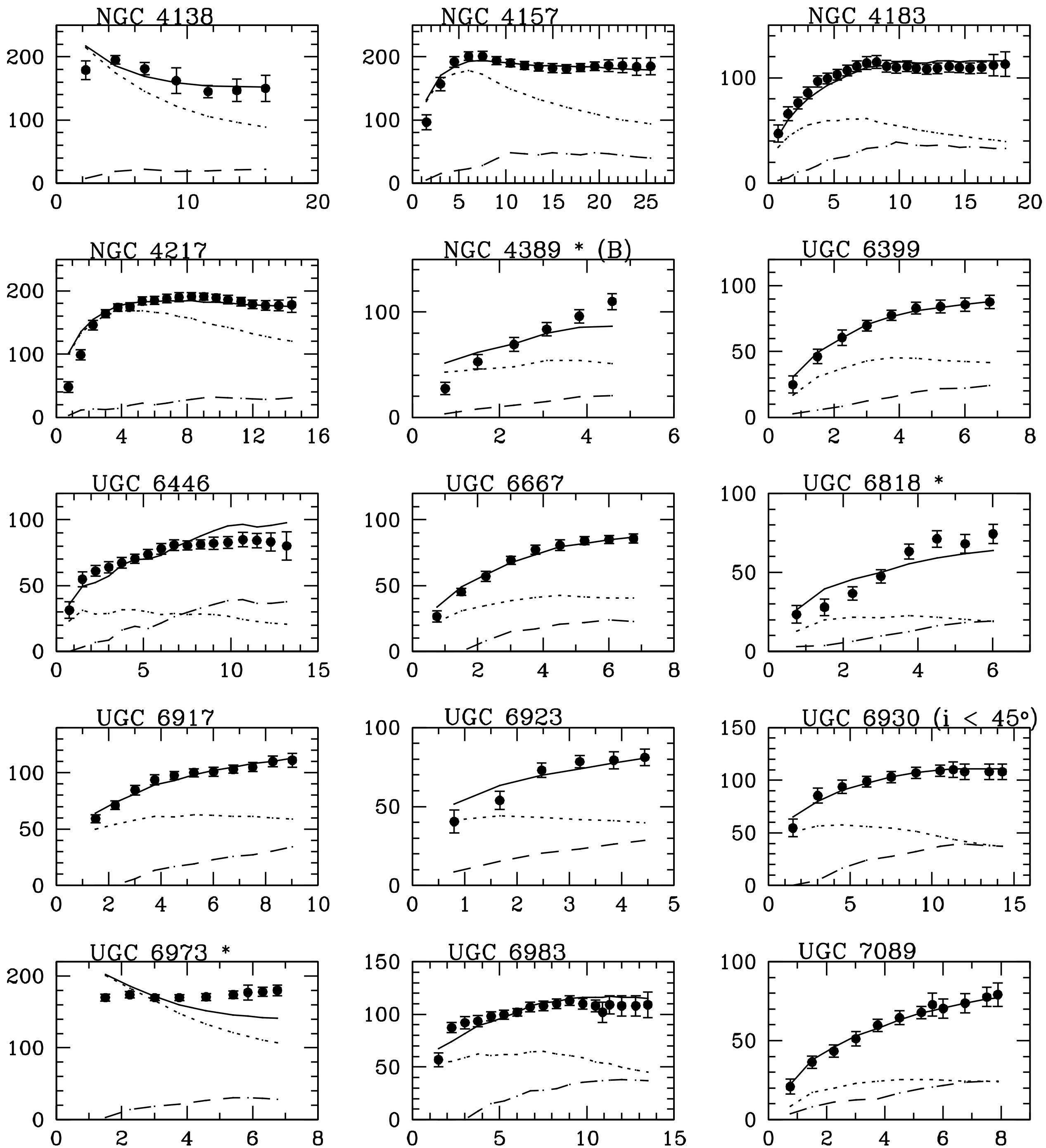
Sanders & McGaugh 2002, *ARA&A*, **40**, 263

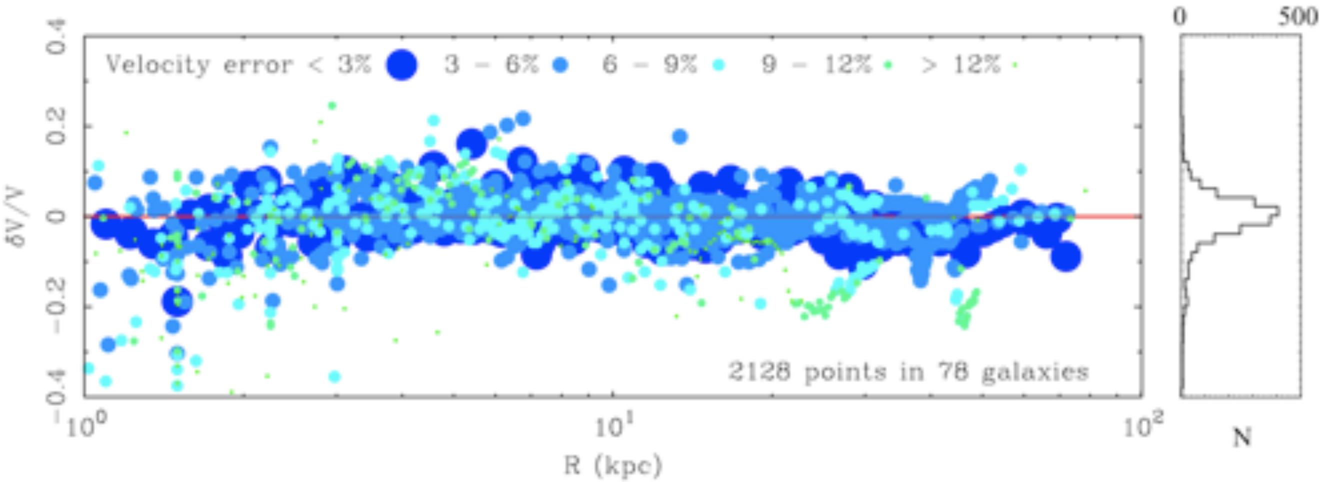


Sanders & McGaugh 2002, *ARA&A*, **40**, 263



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





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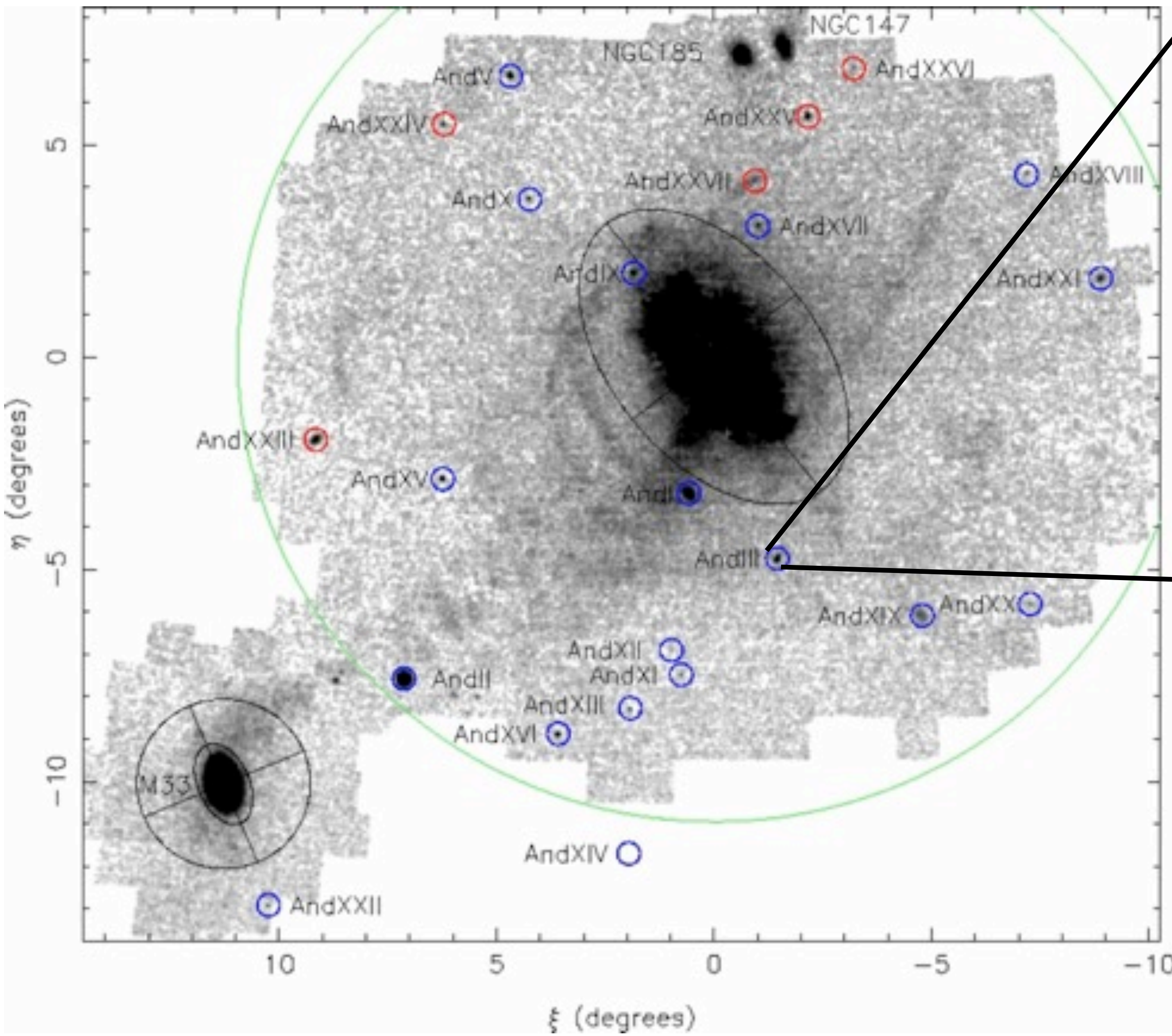
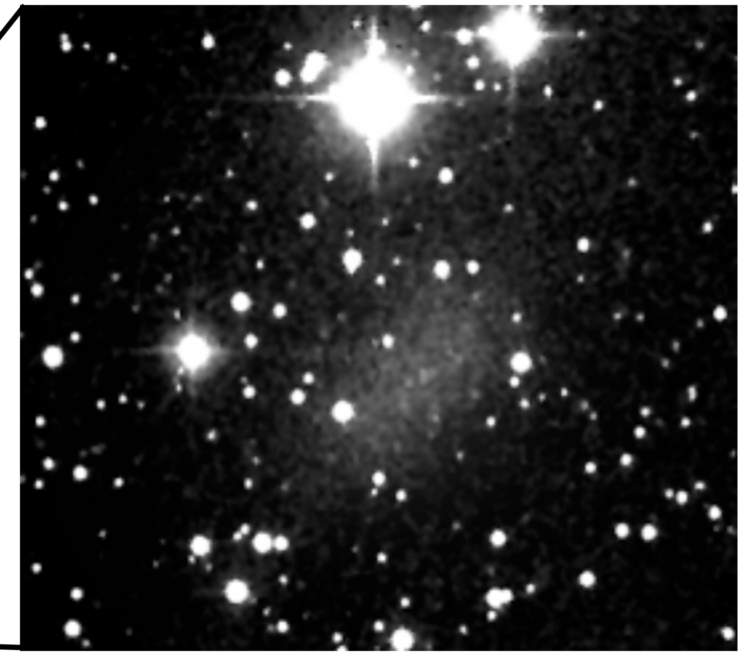
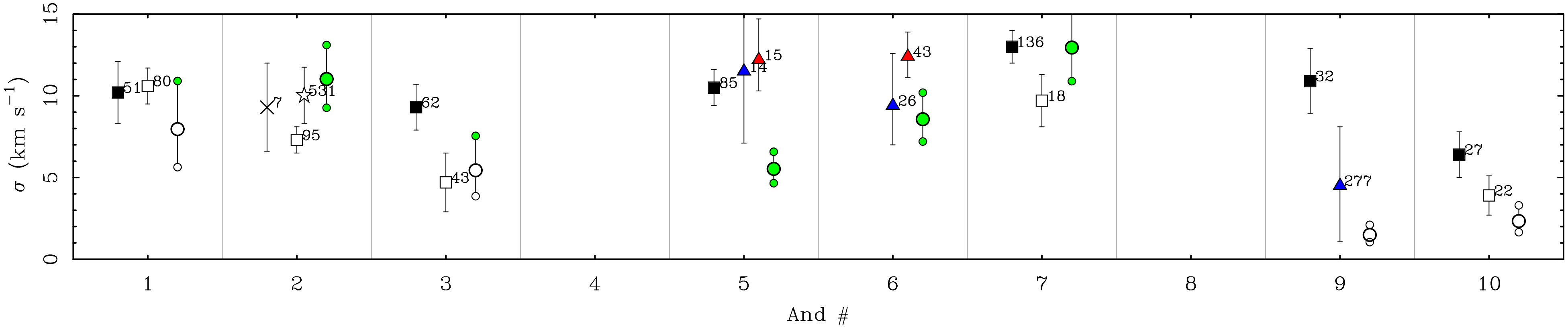
- Rotation Curve Shapes ✔
- Surface Density ~ Surface Brightness ✔
- Detailed Rotation Curve Fits ✔
- Stellar Population Mass-to-Light Ratios ✔

A new test: the dwarf satellites of Andromeda

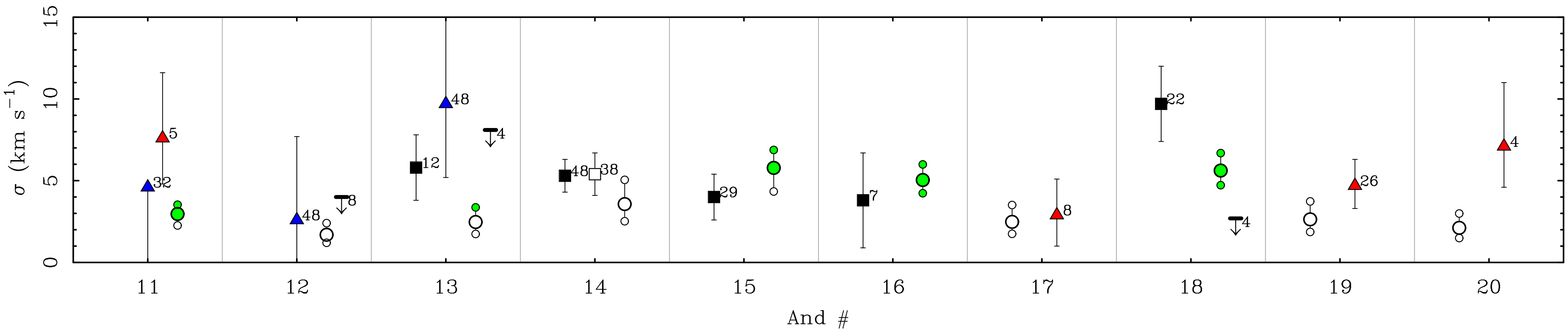


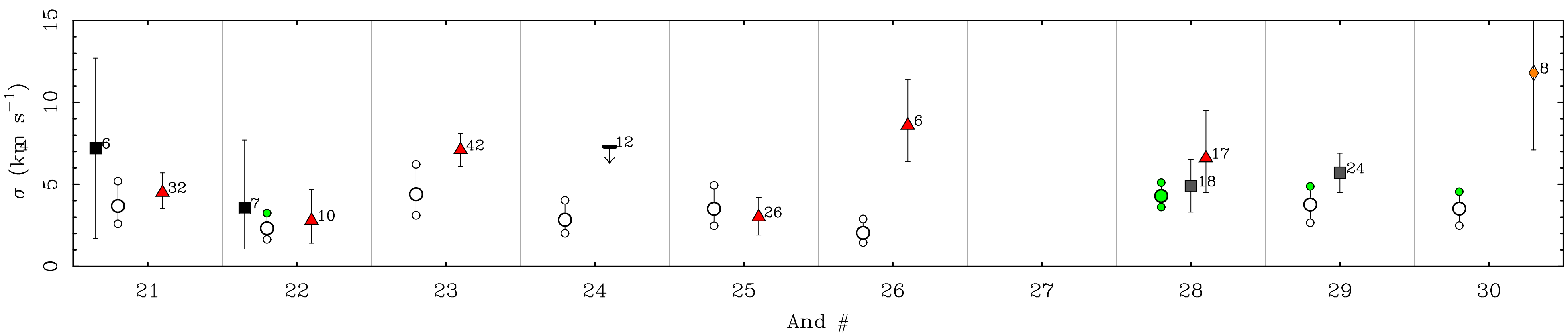


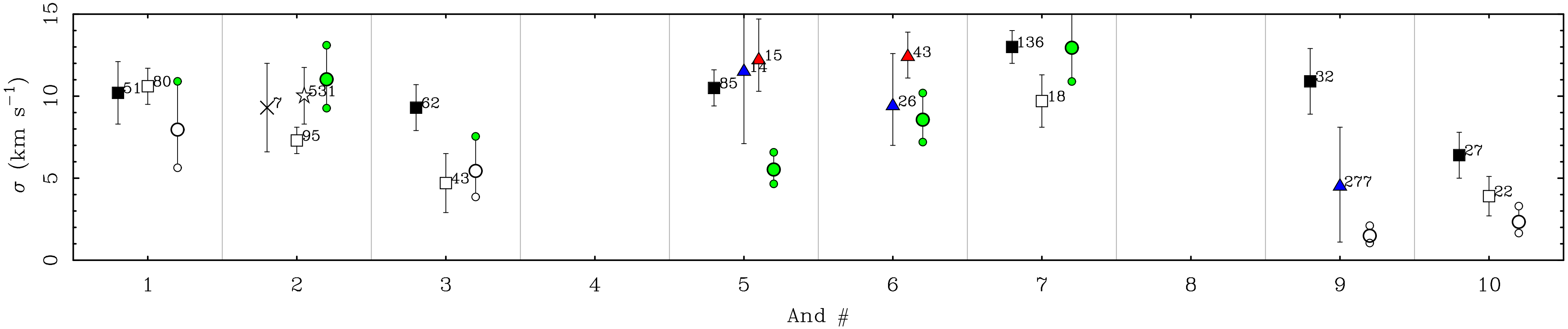
Use MOND to predict the velocity of stars within each dwarf



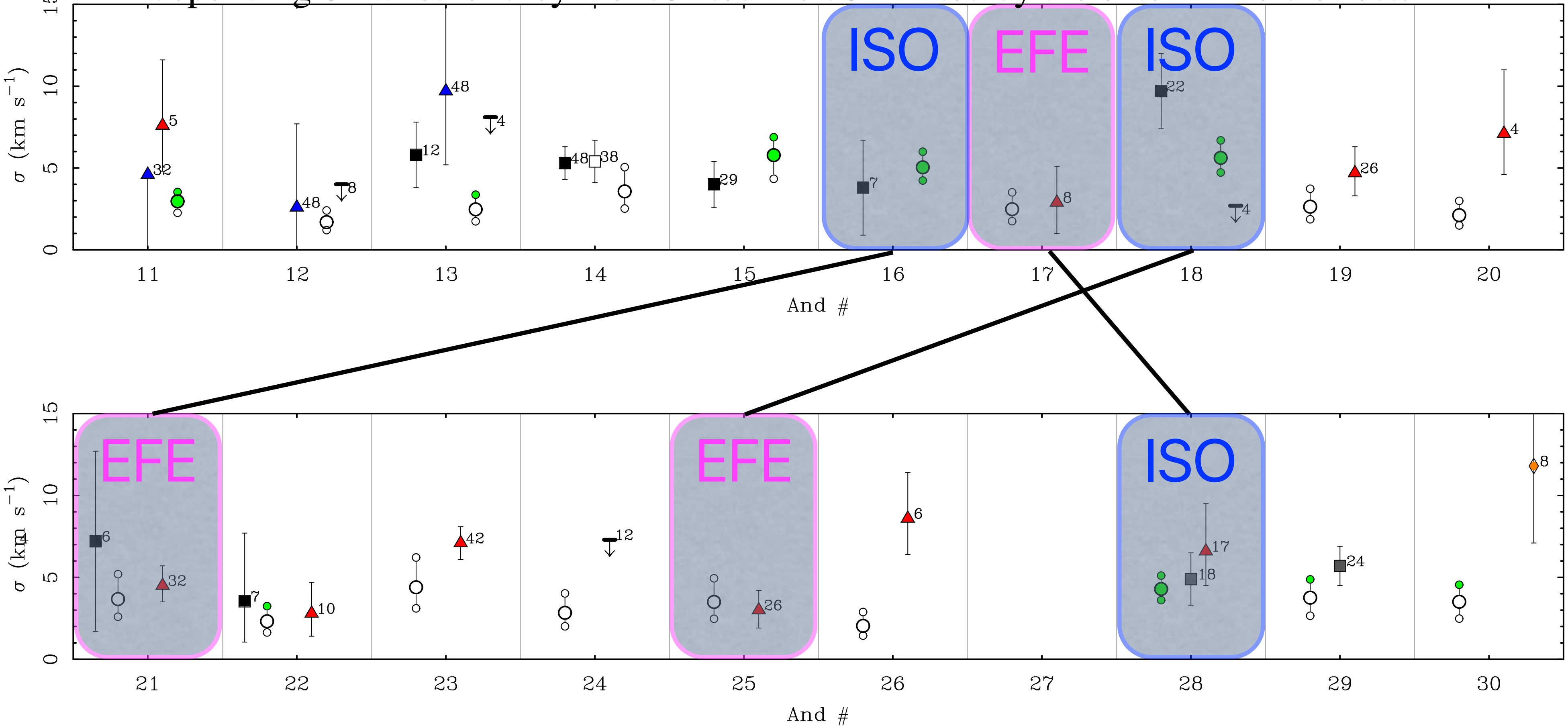
Velocity dispersions of the dwarf satellites of Andromeda







Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.



There is no EFE in dark matter - this is a unique signature of MOND.

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.