Every Time We Open A New Window on the Universe, it surprises us!

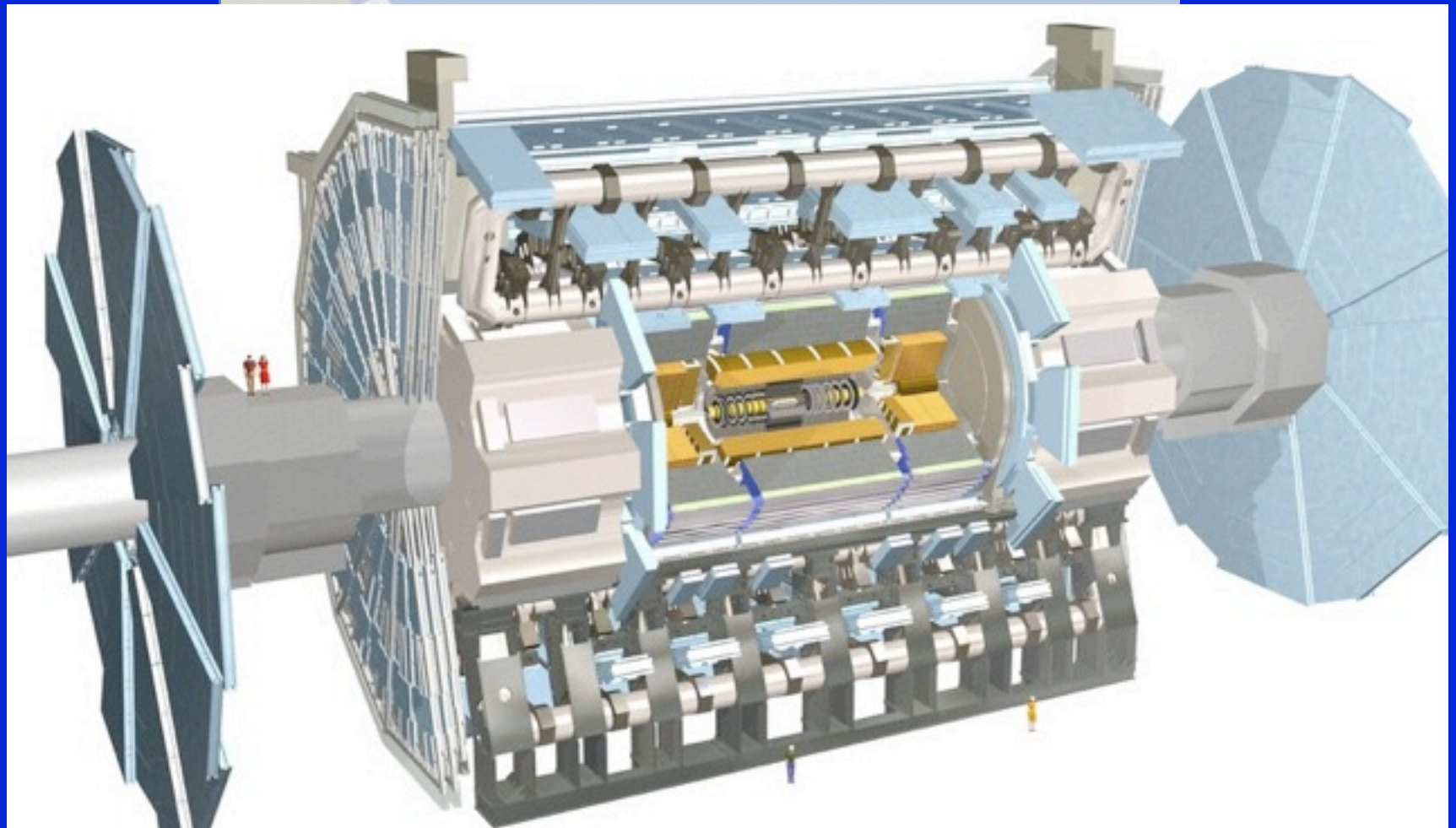
Discovery of Cosmic Rays (1912)

Discovery of Pions (1947)

Discovery of Solar Neutrinos (1965)

Extra Solar Planets

LHC: ????



It was a dark and stormy night…..

Einstein's Equations

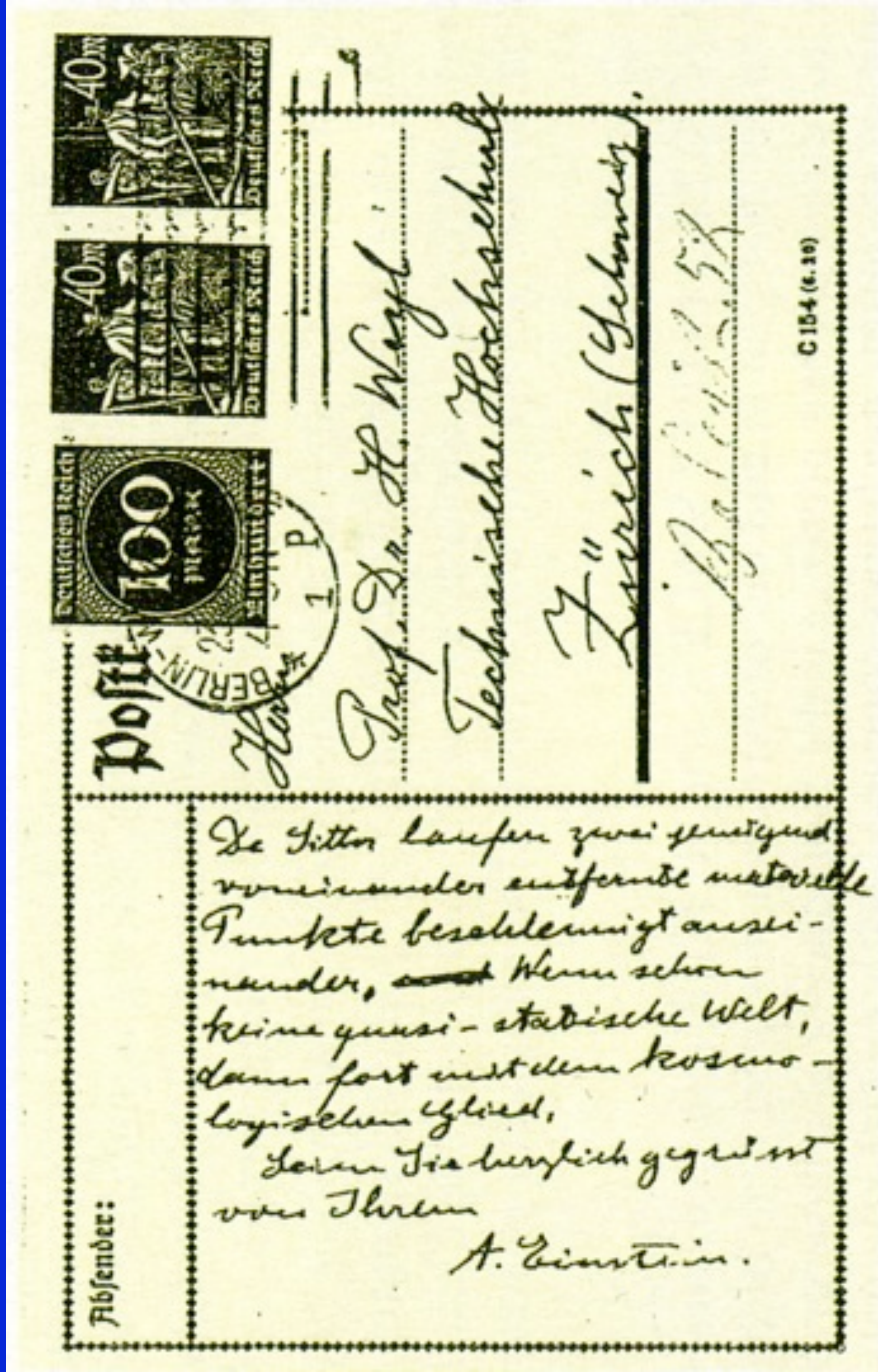
LEFT-HAND SIDE = *RIGHT-HAND SIDE*

CURVATURE = ENERGY-MOMENTUM

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

The Cosmological Term



Postkarte

Prof. Dr. H. Weyl

Technische Hochschule

Zürich (Schweiz)

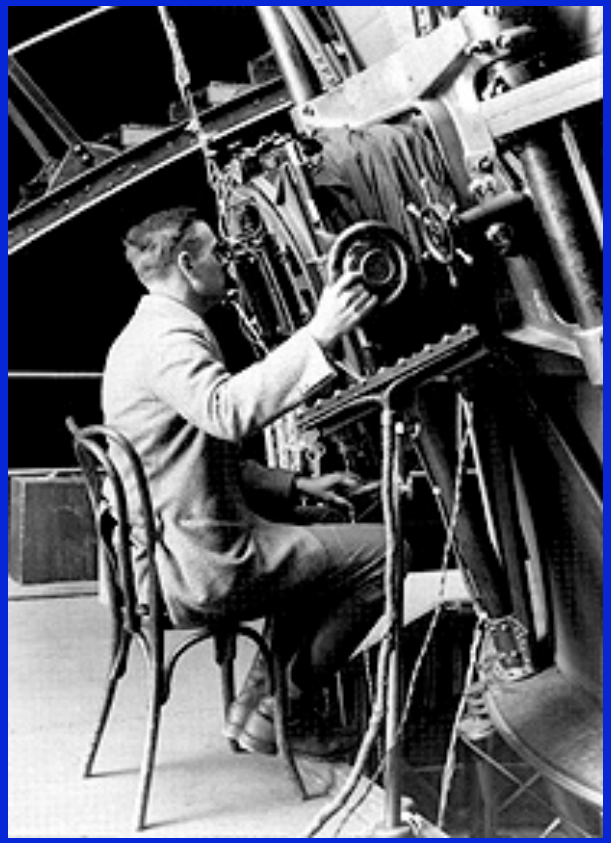
De Sitter laufen zwei genügend voneinander entfernte materielle Punkte beschleunigt auseinander. Wenn schon keine quasi-statische Welt, dann fort mit dem kosmologischen Glied.

Seien Sie herzlich gegrüsst von Ihrem

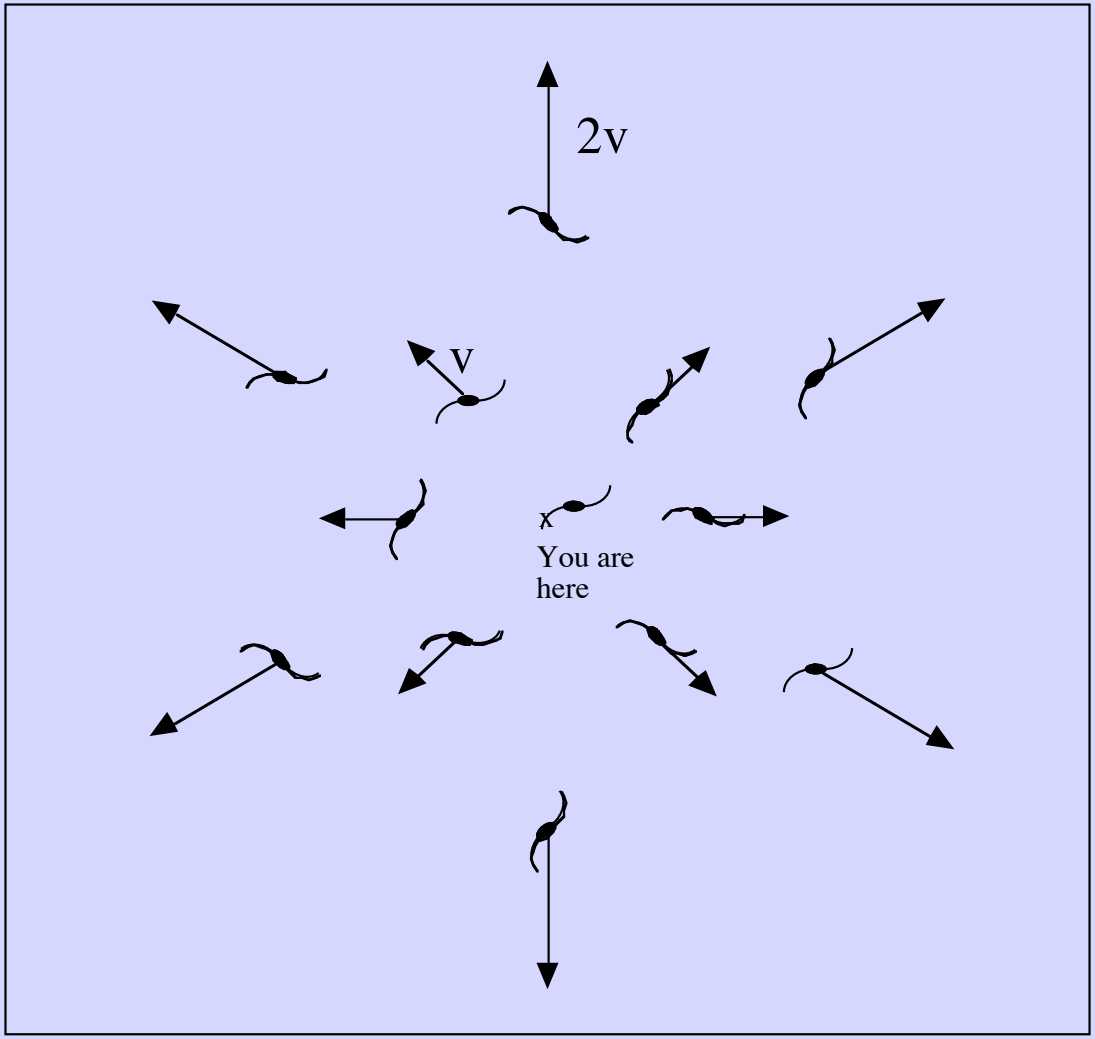
A. Einstein.

Absender:

Expansion of the Universe



1. **Hubble** (1920's-30's): The Universe is Expanding

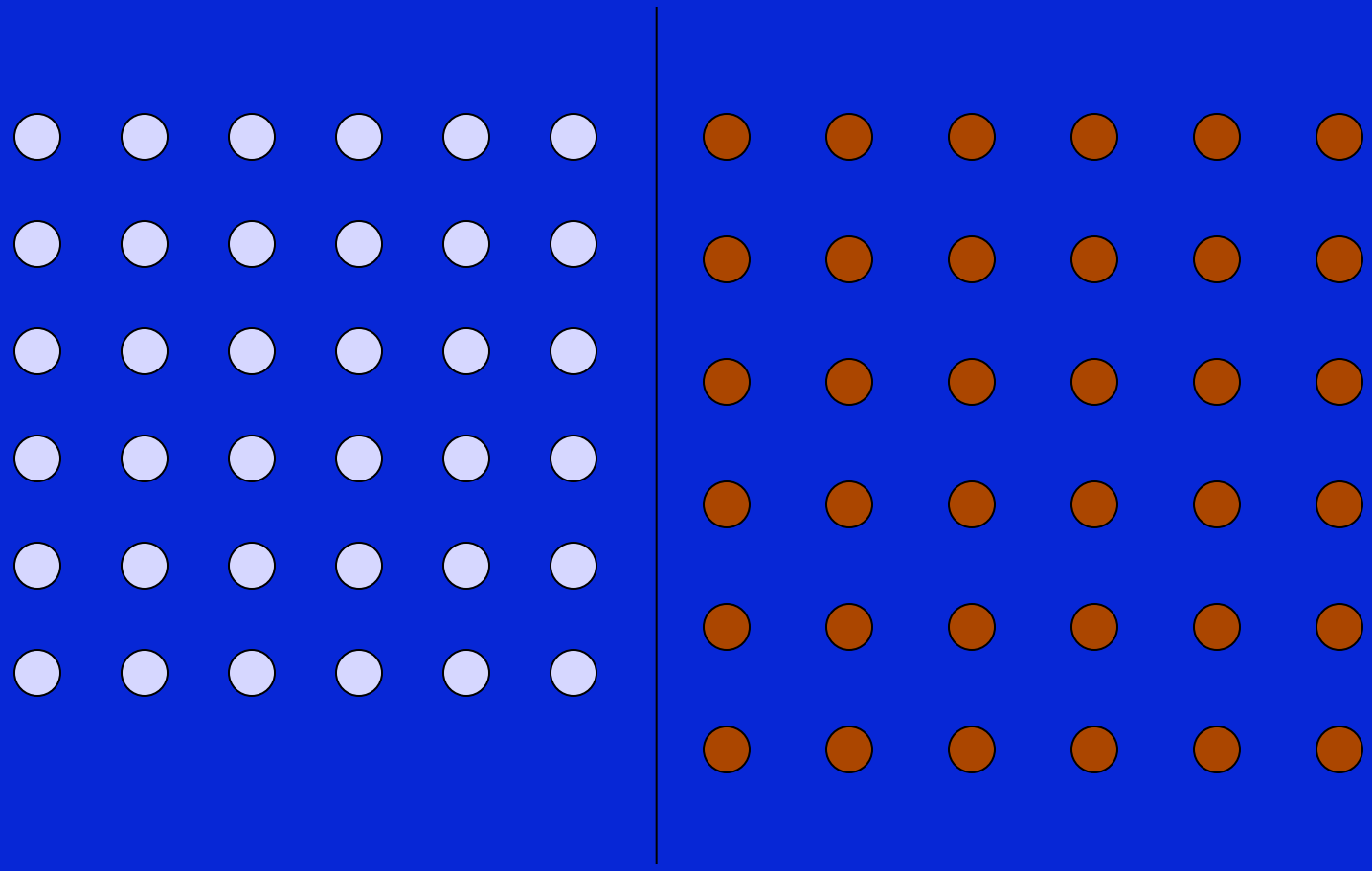


v= H d H= 100*h* km/sec/Mpc

Expansion of the Universe

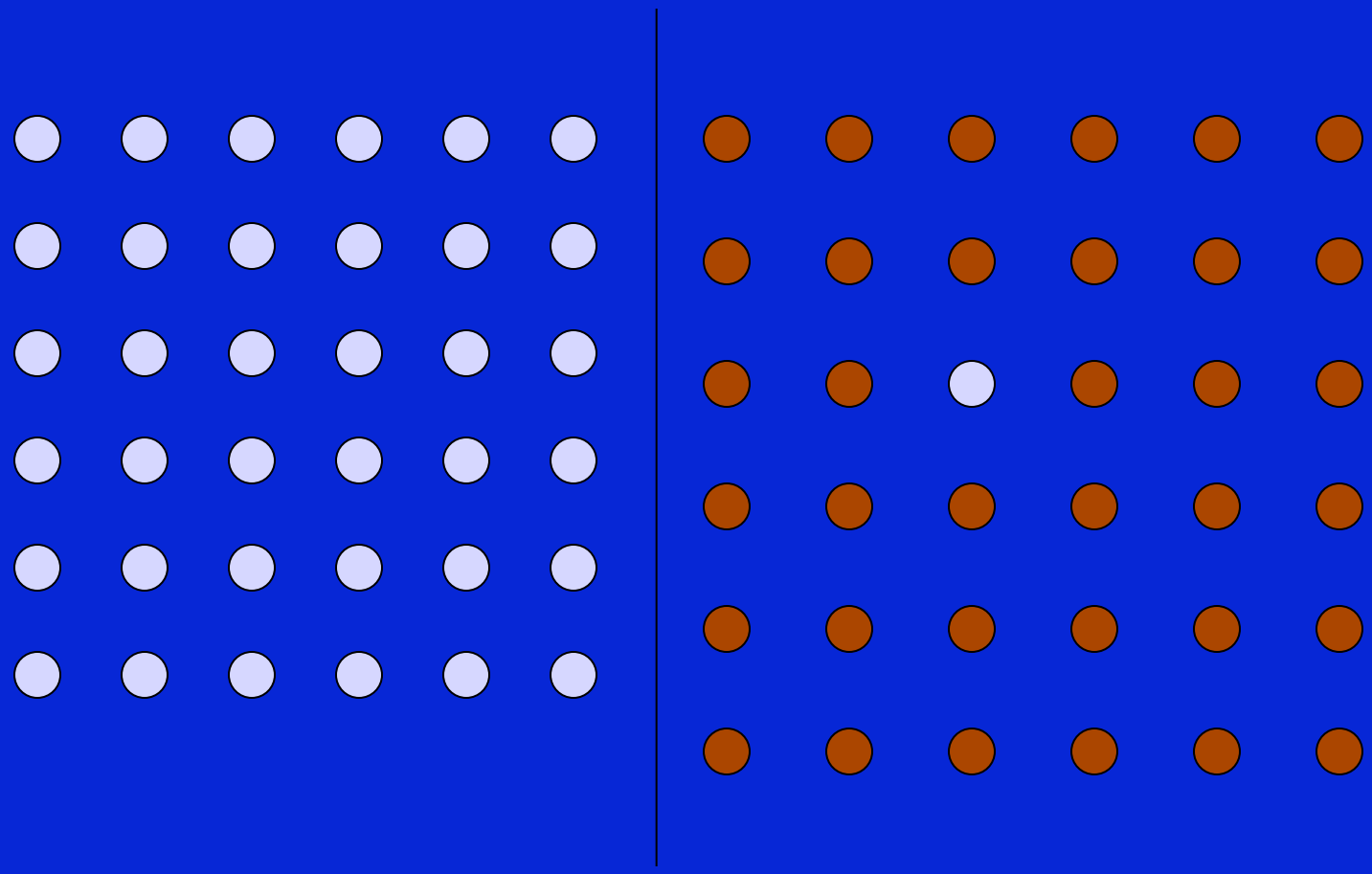
Q: Why is this the signature for an expanding Universe?

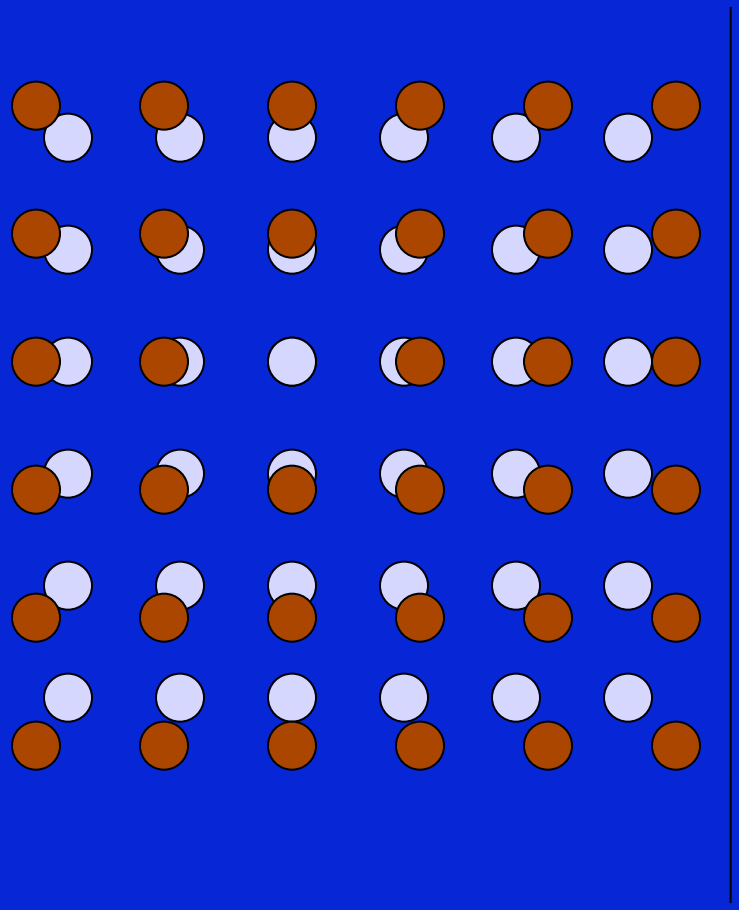
A: Look outside the box….

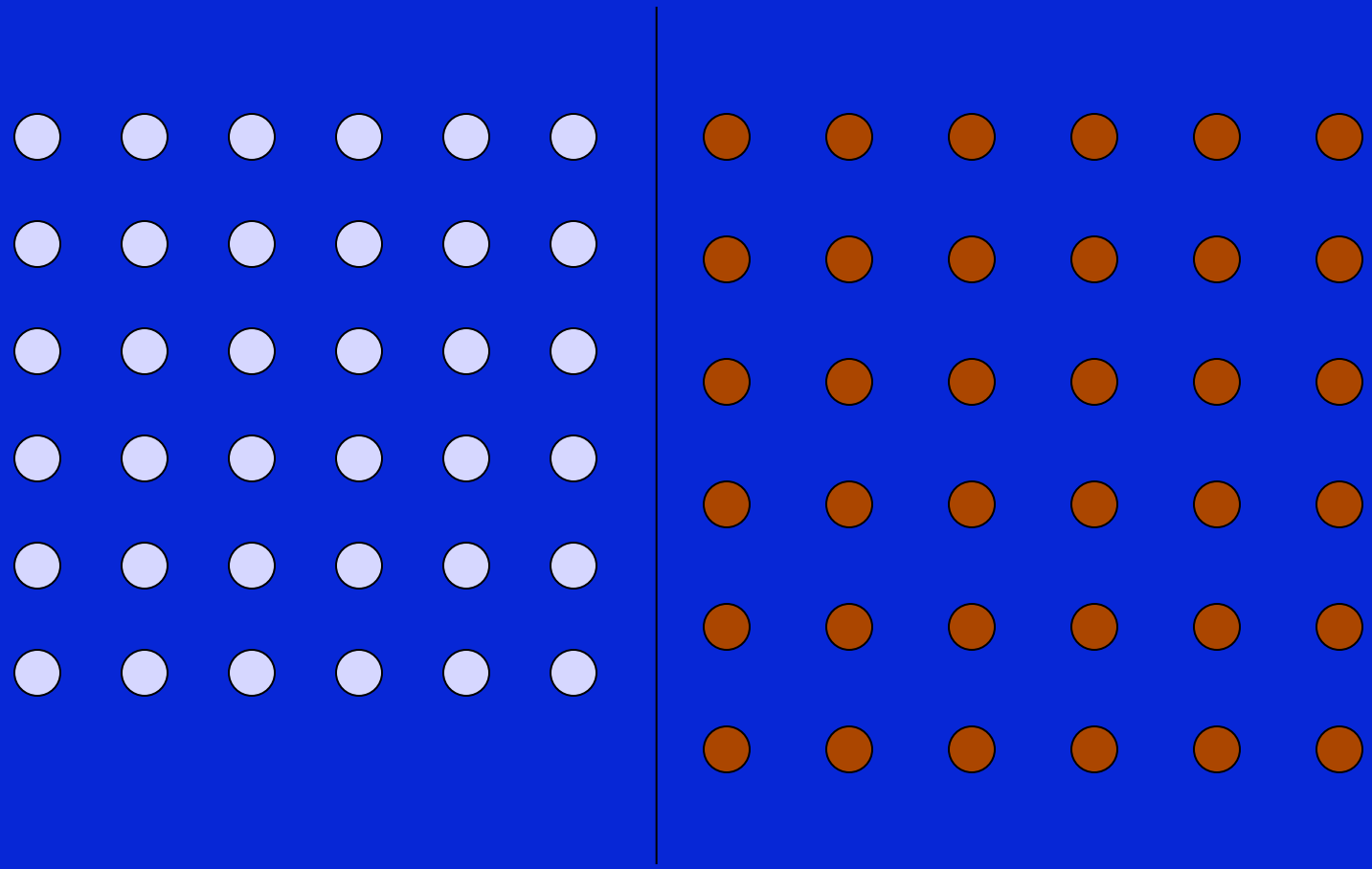


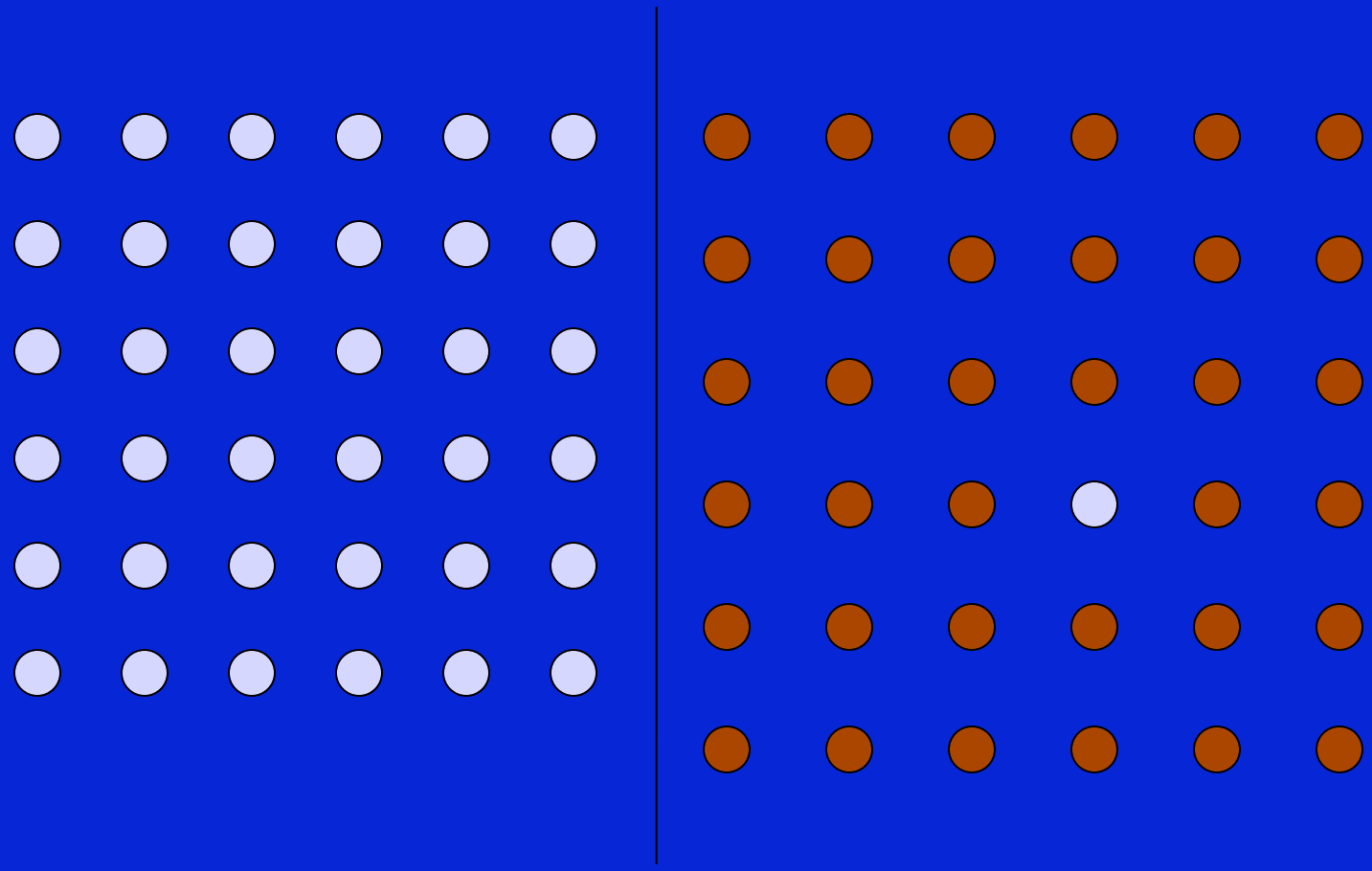
"Galaxies" at t_1

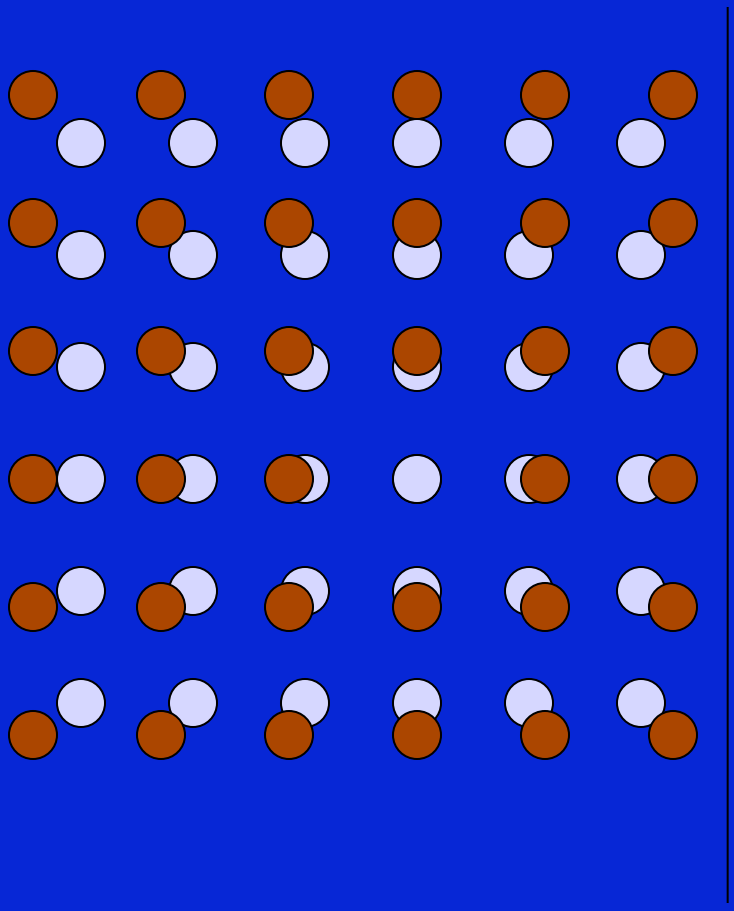
"Galaxies" at t_2











Hubble's Data!

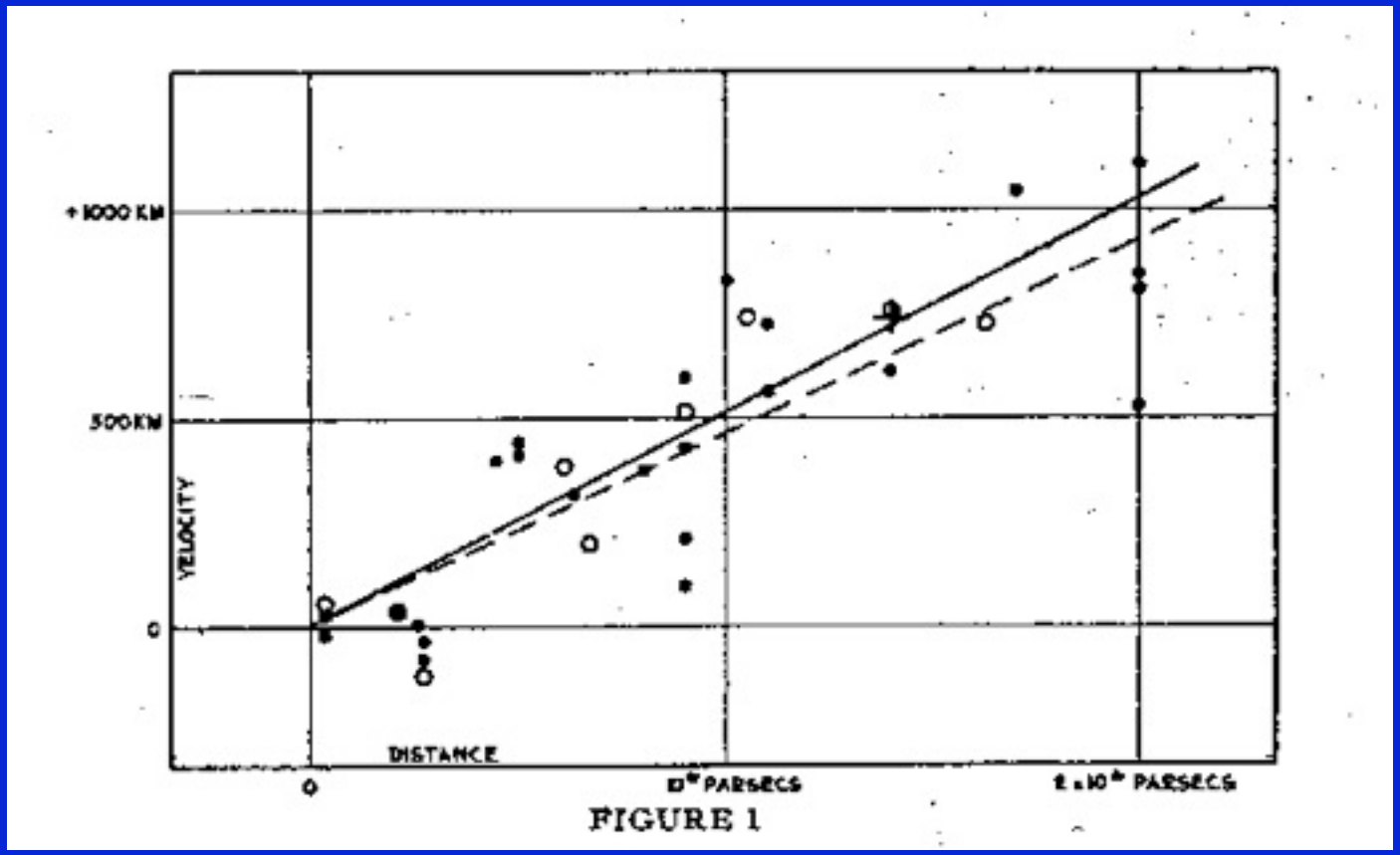
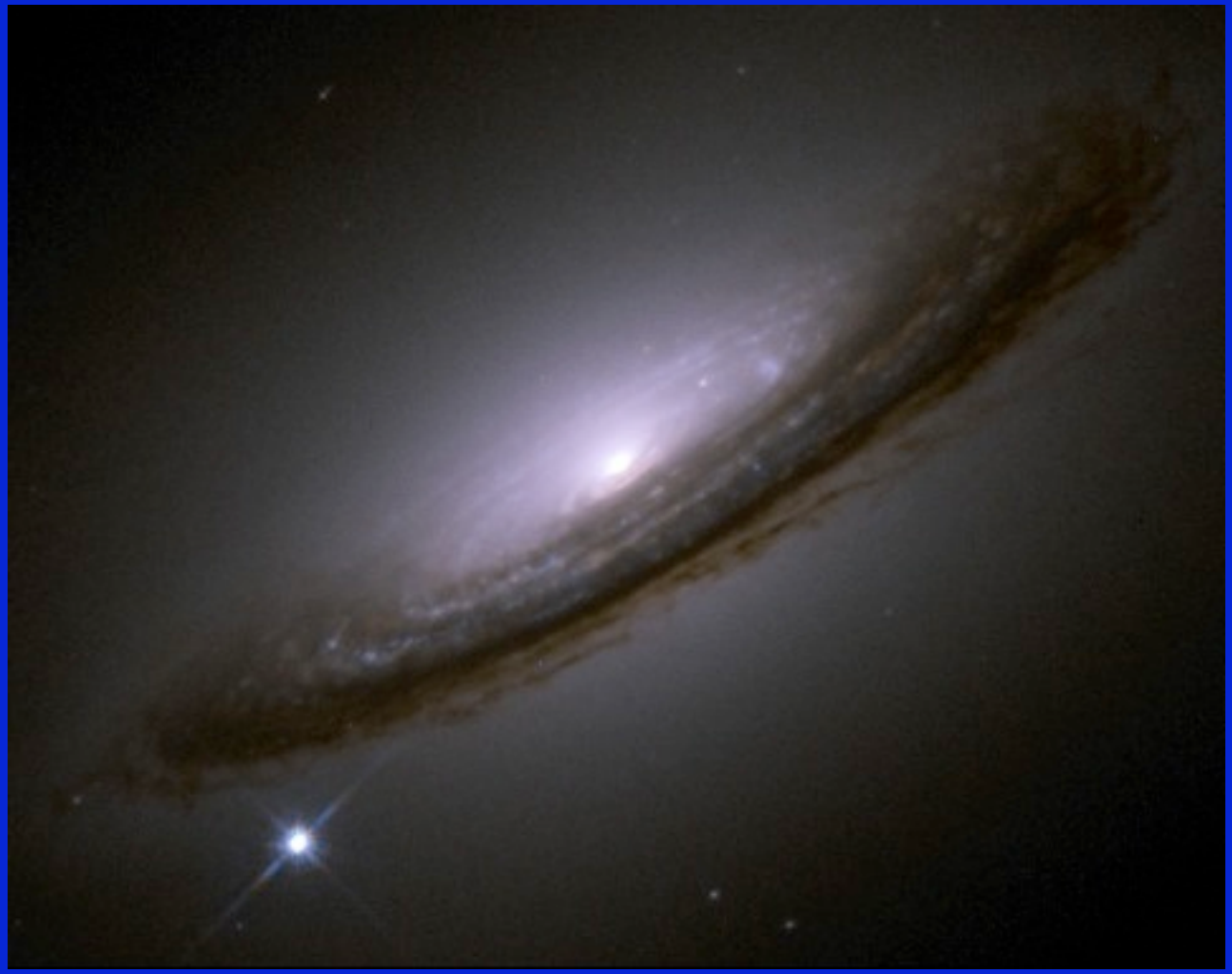
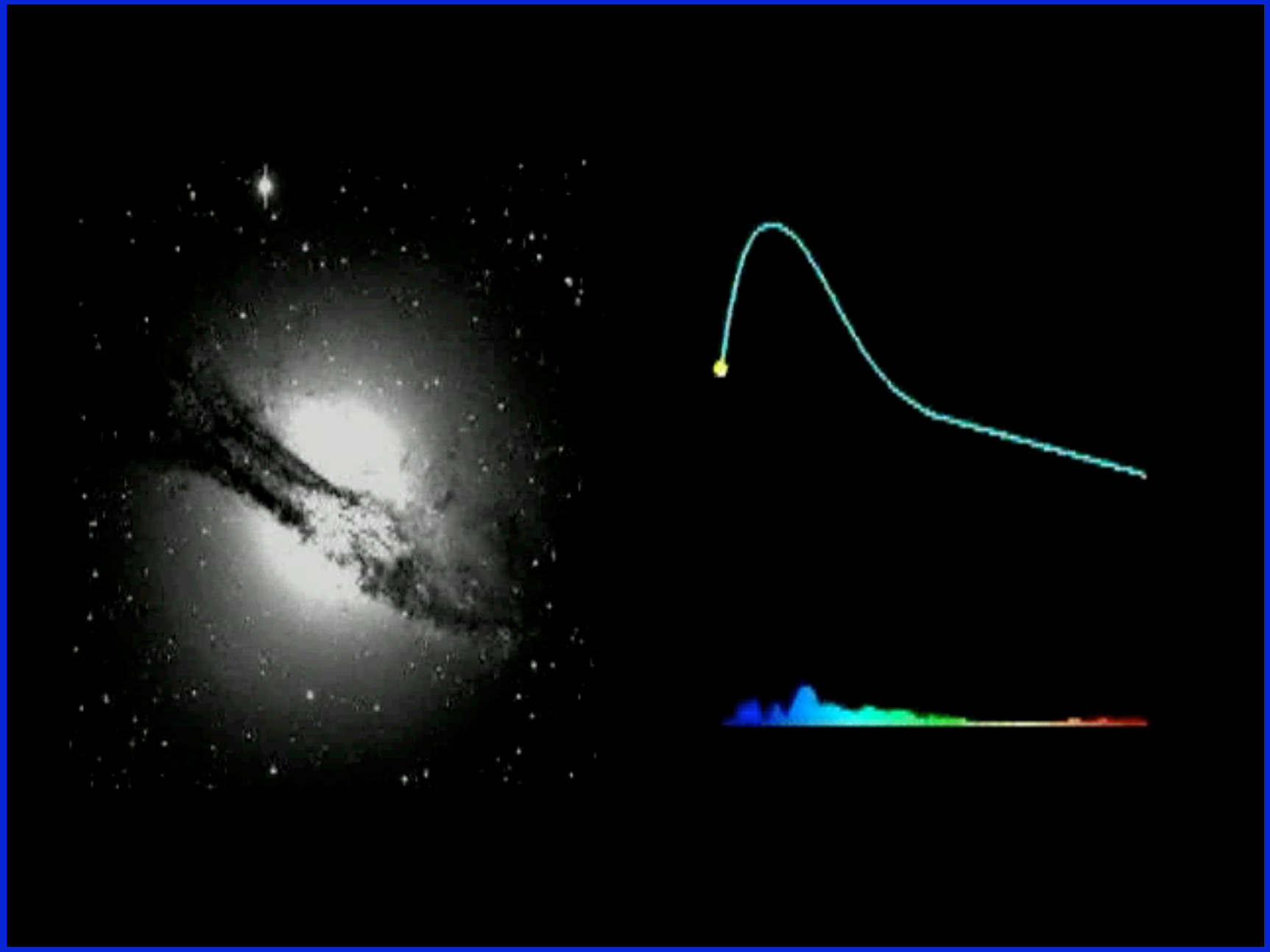
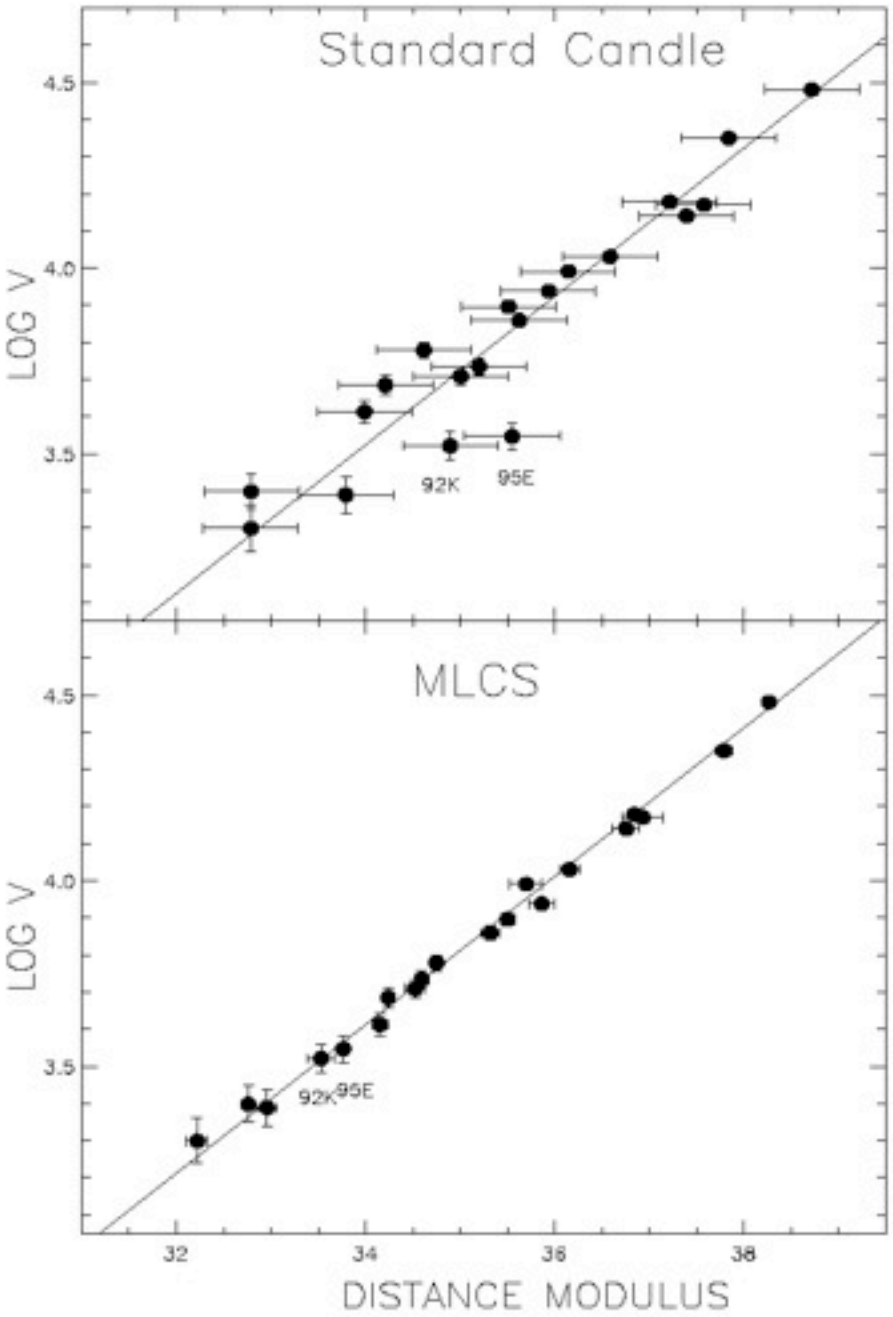


FIGURE 1

H = 500 km/s/Mpc Only a factor of 10 wrong!






Standard Candle
LOG V
4.5
4.0
3.5
92K
95E
MLCS
LOG V
4.5
4.0
3.5
92K
95E
32
34
36
38
DISTANCE MODULUS

Einstein's Equations

LEFT-HAND SIDE = *RIGHT-HAND SIDE*

CURVATURE = ENERGY-MOMENTUM

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

The Cosmological Term

Einstein's Equations

LEFT-HAND SIDE = *RIGHT-HAND SIDE*

CURVATURE = ENERGY-MOMENTUM

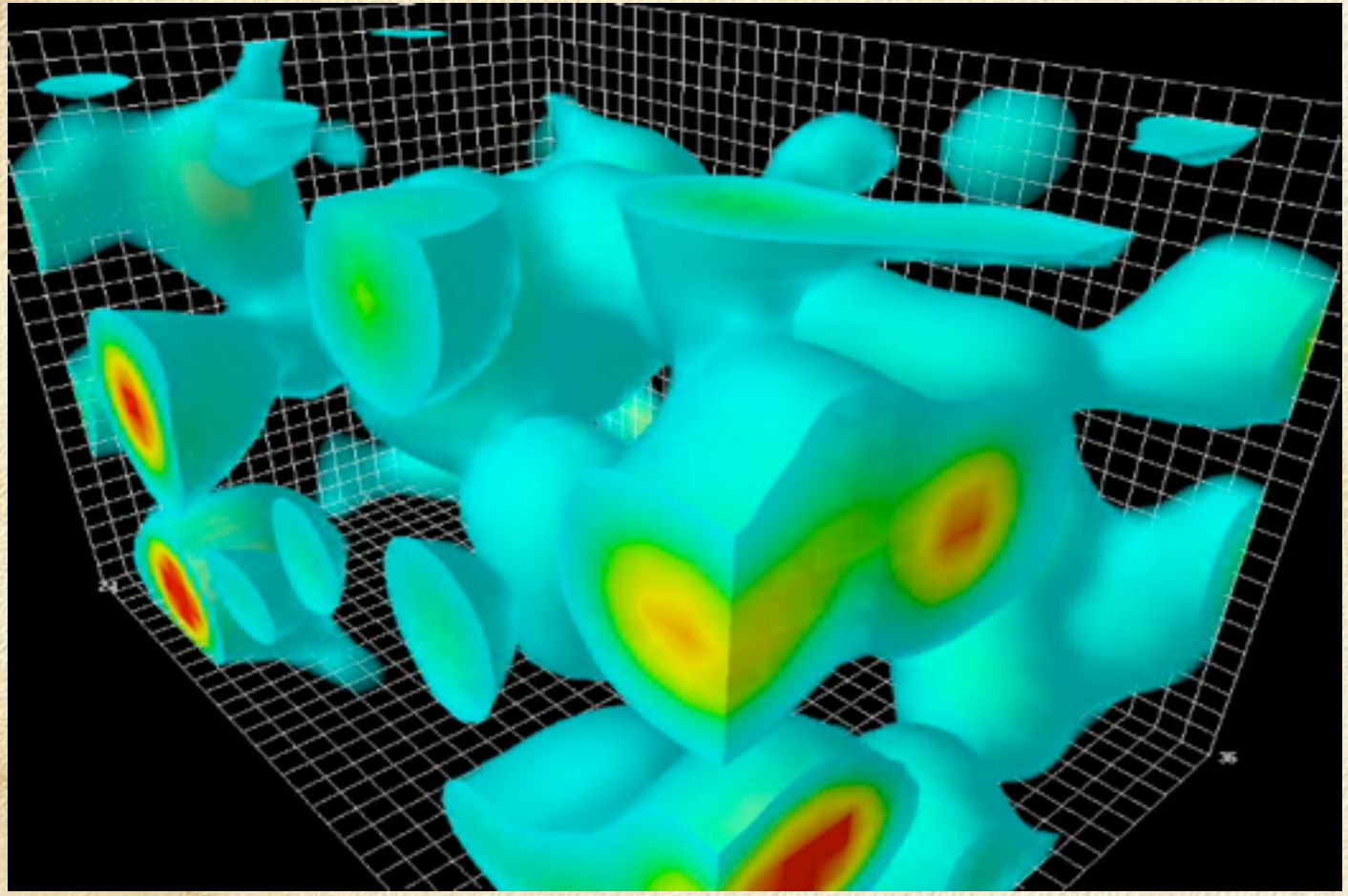
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

→ *The Energy of Nothing?*

Empty Space not Empty!



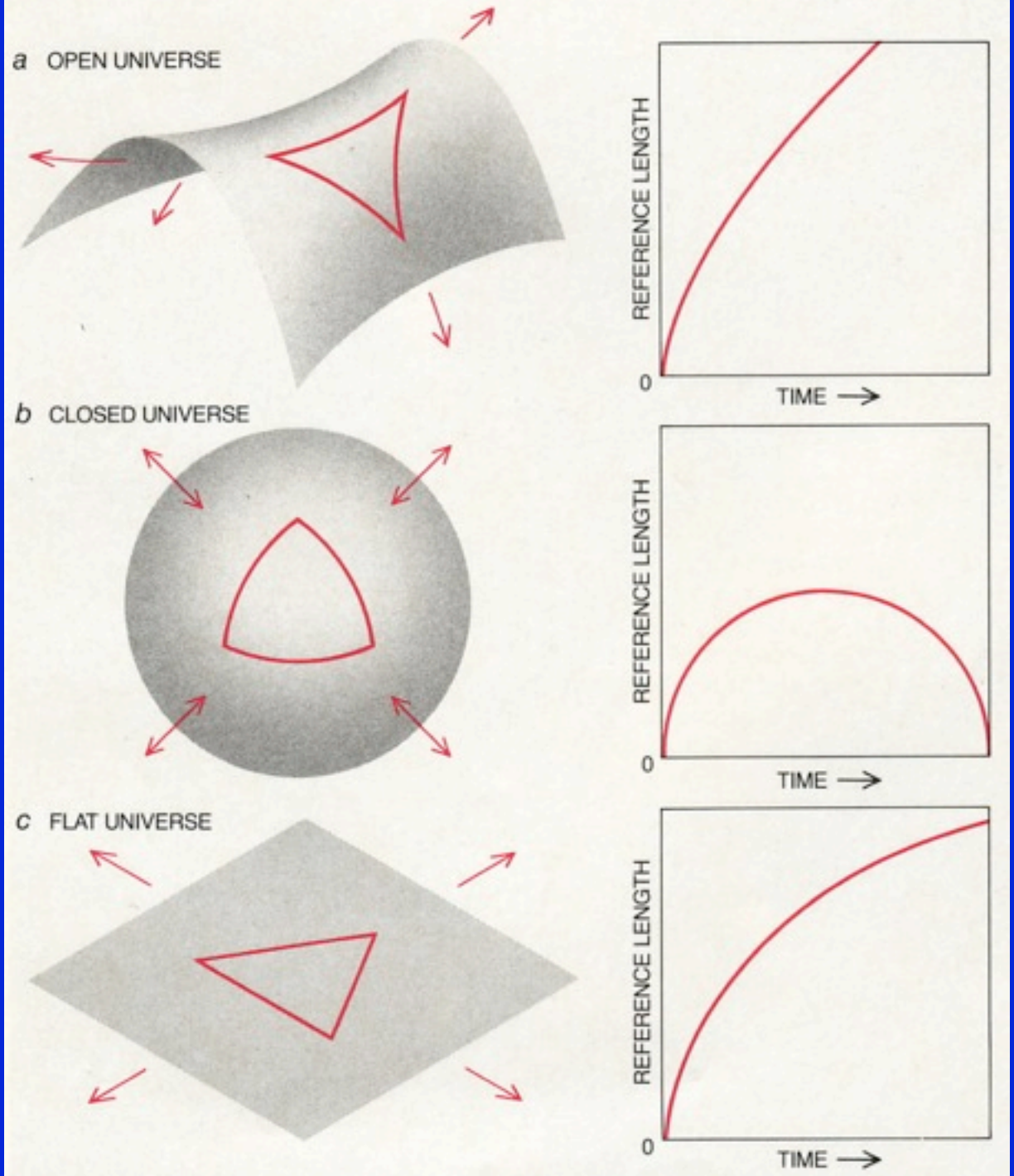
Vacuum Energy =

1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000

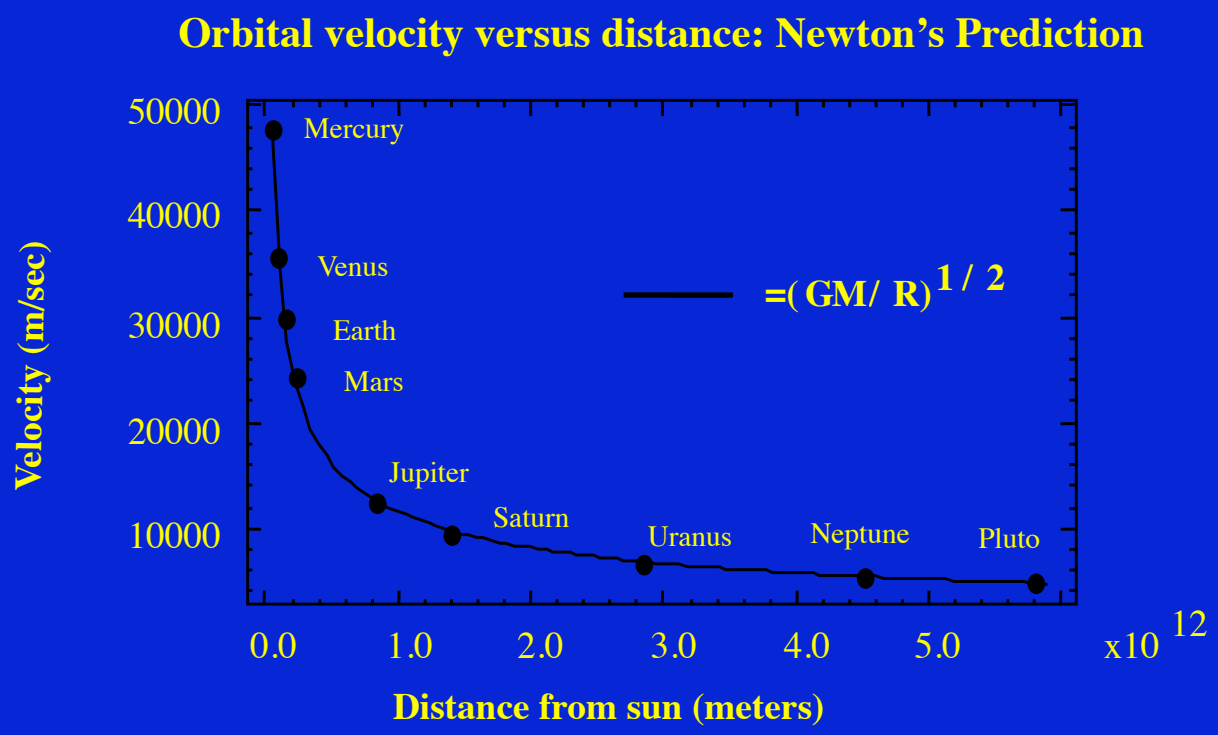
x ***Energy of All Matter in the Universe***

THE WORST PREDICTION IN ALL OF PHYSICS!!

Weighing the Universe


a OPEN UNIVERSE
REFERENCE LENGTH
0
TIME
b CLOSED UNIVERSE
REFERENCE LENGTH
0
TIME
c FLAT UNIVERSE
REFERENCE LENGTH
0
TIME

Kepler's Discovery



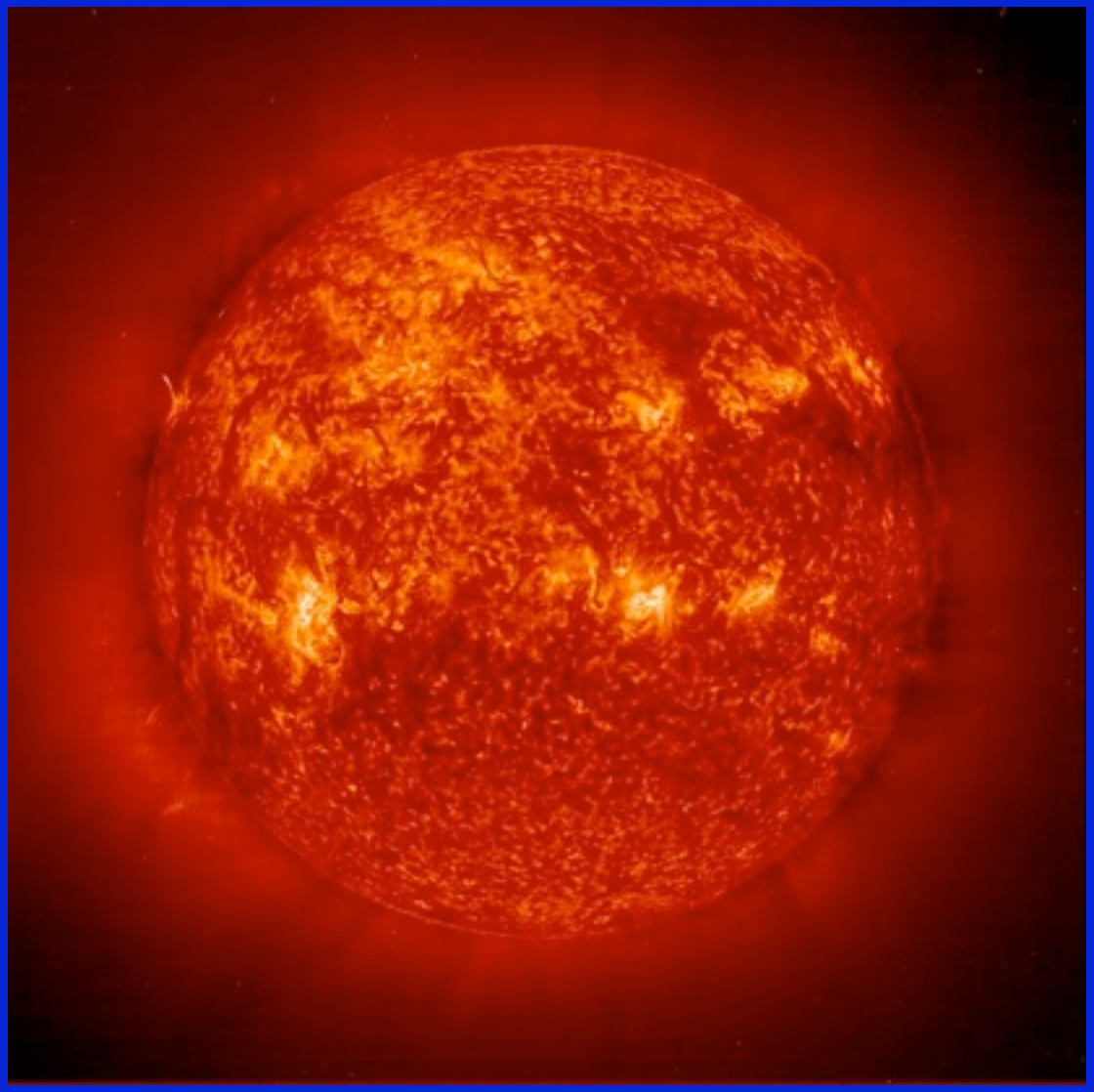
$$v^2 \approx \frac{1}{r}$$

Newton's Law of Gravity

- Brahe
- Kepler..
- Newton:

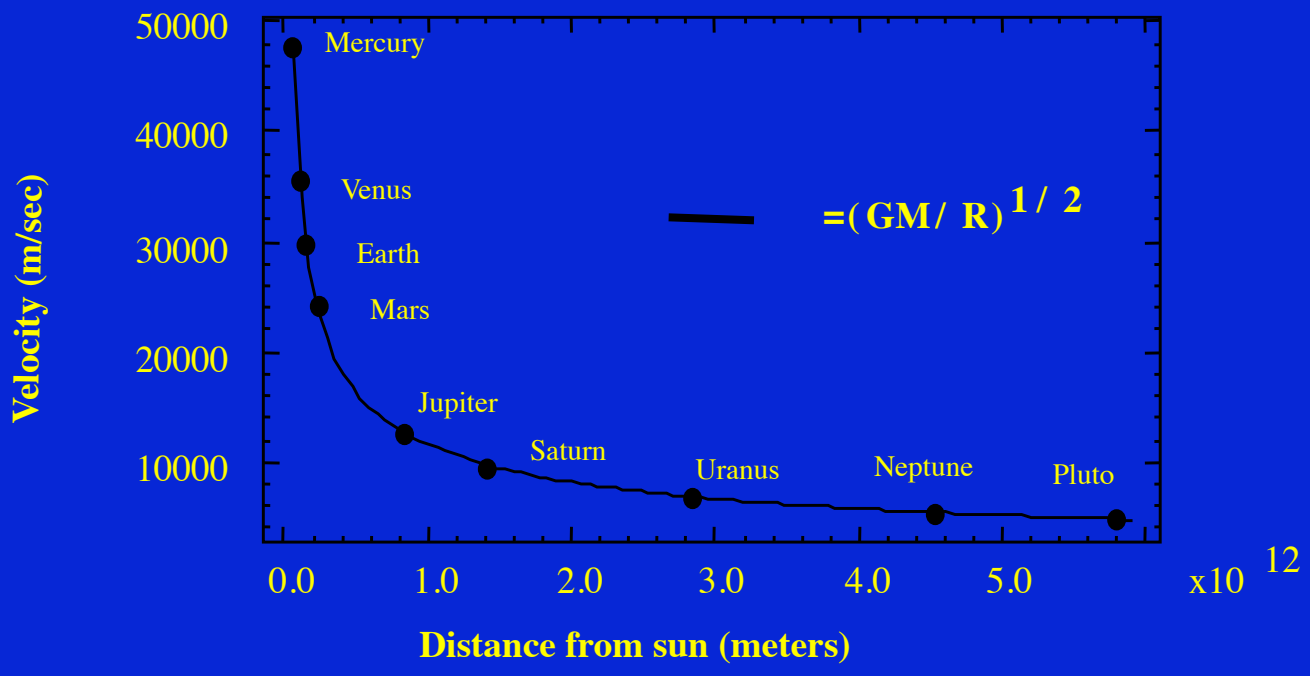
$$F = \frac{GM_1M_2}{r^2}$$

$$v^2 = \frac{GM}{r}$$



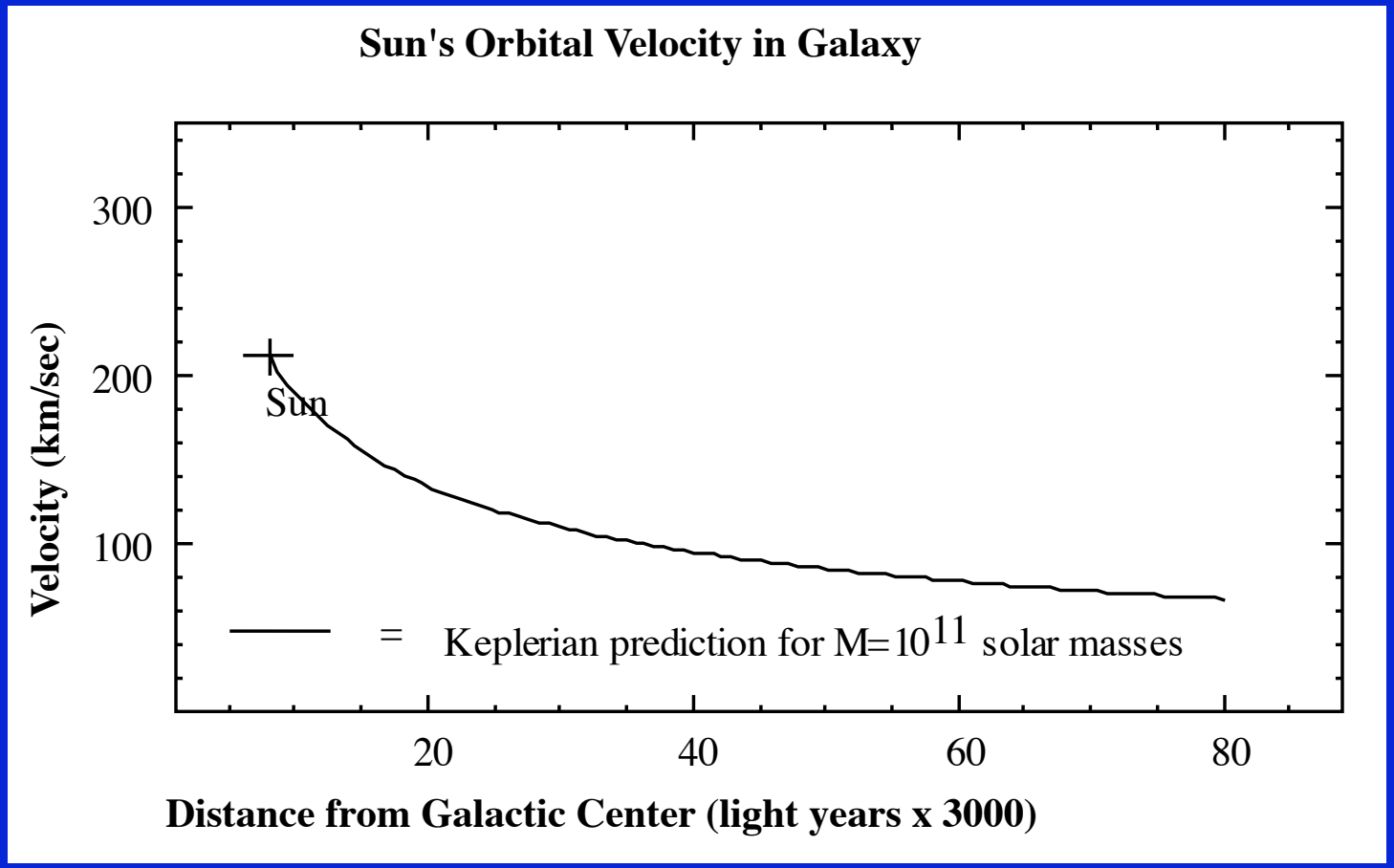
Weighing the Sun!!!

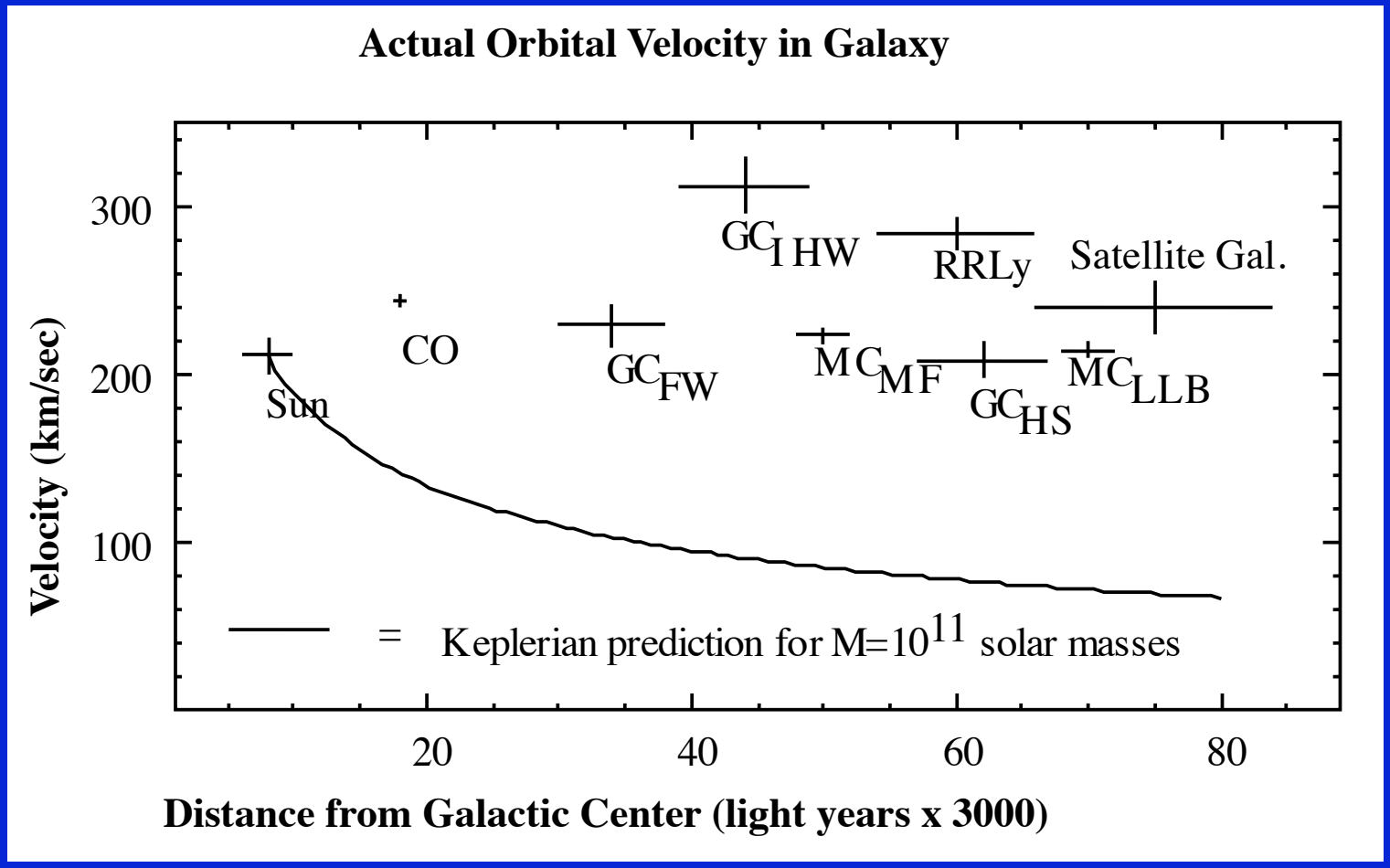
Orbital velocity versus distance: Newton's Prediction



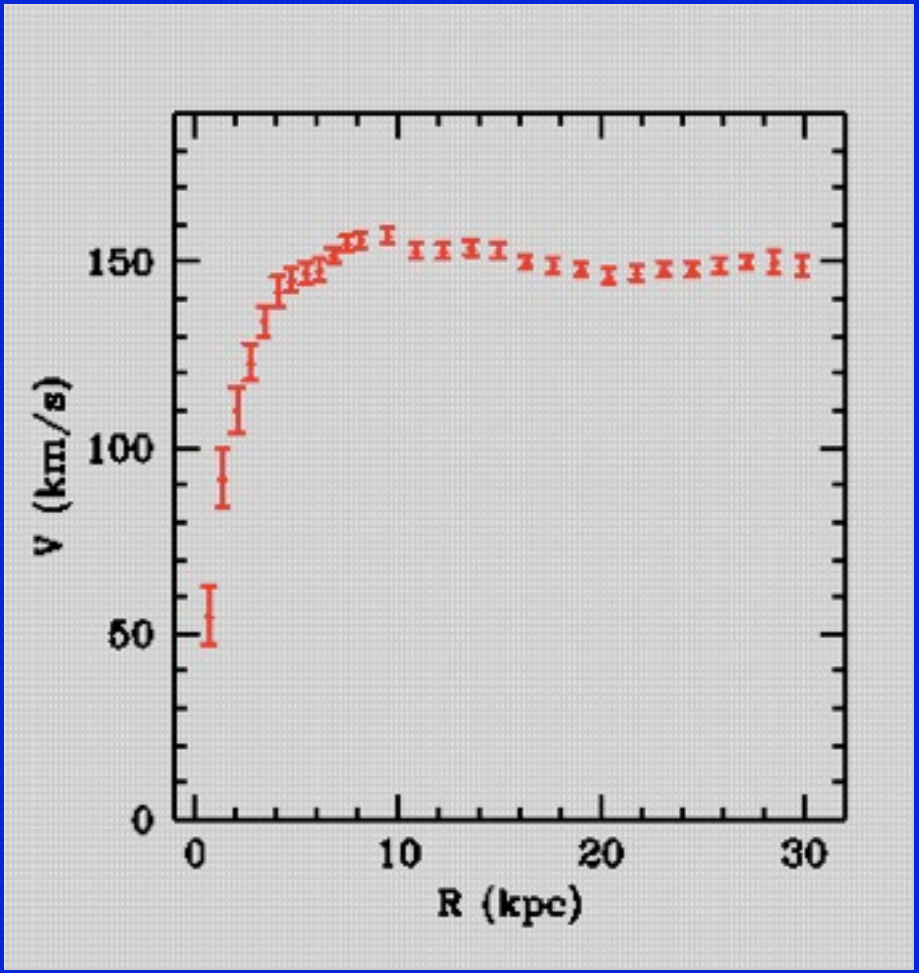
$$M = 2 \times 10^{30} \text{ kg}$$

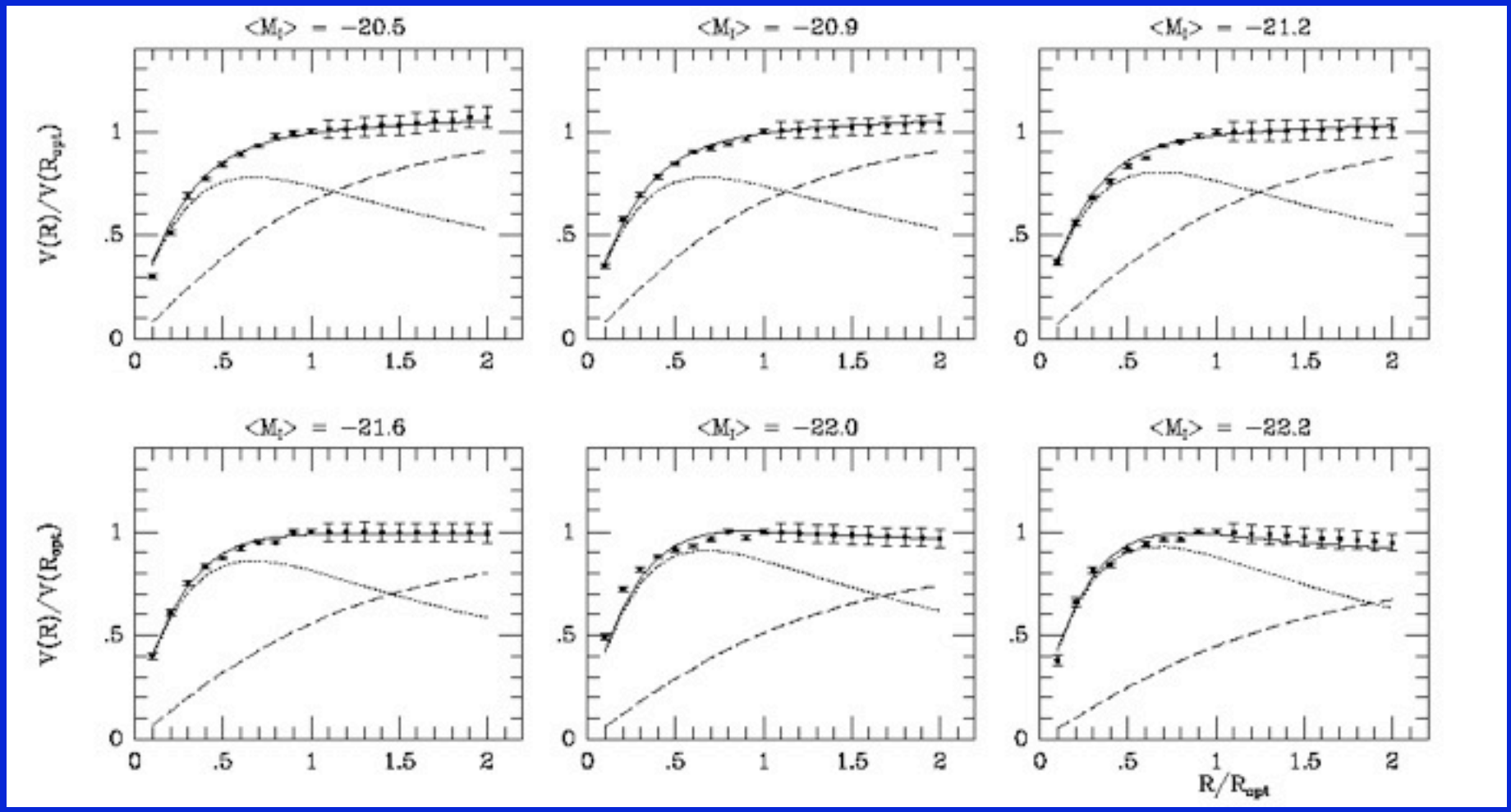
If it works…. Copy it!

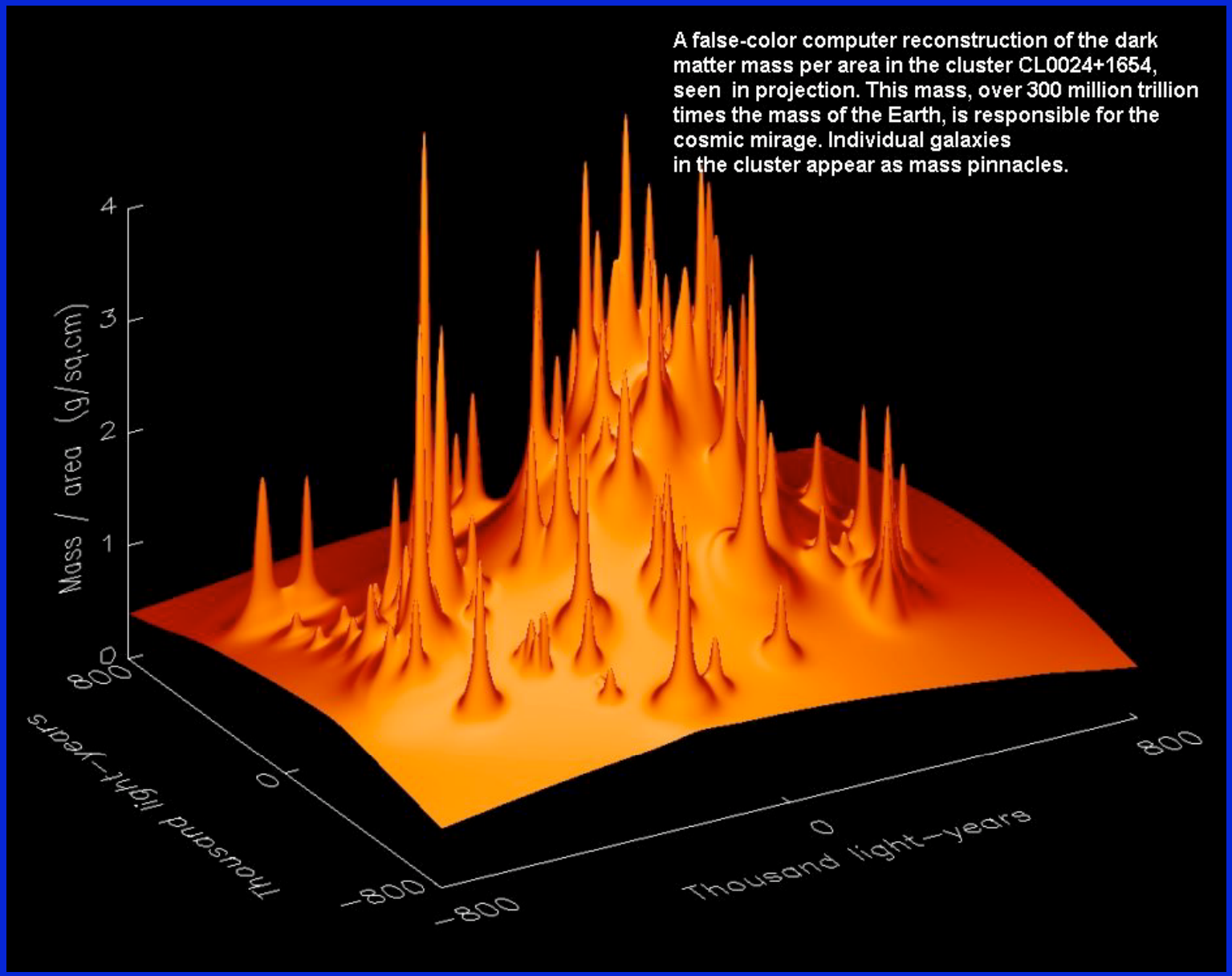

Sun's Orbital Velocity in Galaxy
Velocity (km/sec)
300
200
100
Sun
= Keplerian prediction for M=10^11 solar masses
20
40
60
80
Distance from Galactic Center (light years x 3000)


Actual Orbital Velocity in Galaxy
300
200
100
Velocity (km/sec)
GC I HW
RRLy
Satellite Gal.
CO
Sun
GC FW
MC MF
GC HS
MC LLB
= Keplerian prediction for M=10^11 solar masses
20
40
60
80
Distance from Galactic Center (light years x 3000)

Every Galaxy!!!

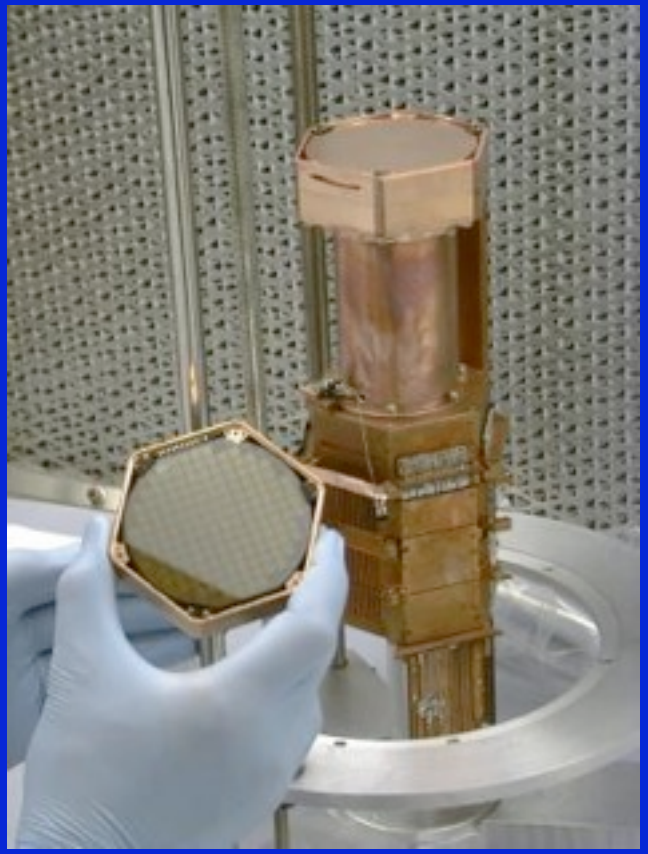



<M_I> = −20.5
<M_I> = −20.9
<M_I> = −21.2
<M_I> = −21.6
<M_I> = −22.0
<M_I> = −22.2
V(R)/V(R_opt)
R/R_opt
0
.5
1
1.5
2

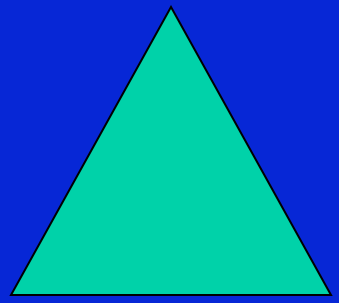


$\Omega_m = 0.30 \pm 0.1$ (95%)

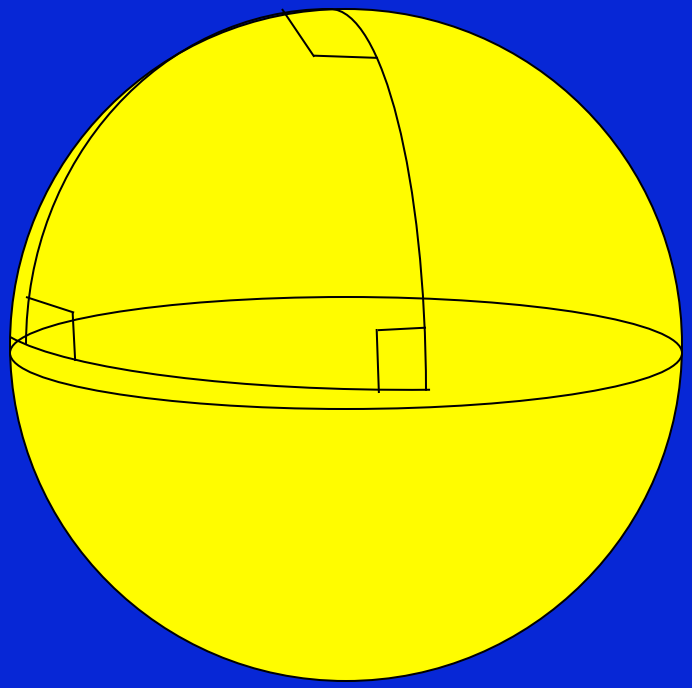
DETECTING IT HERE!



Can We Measure the Geometry of the Universe Directly?



180 degrees

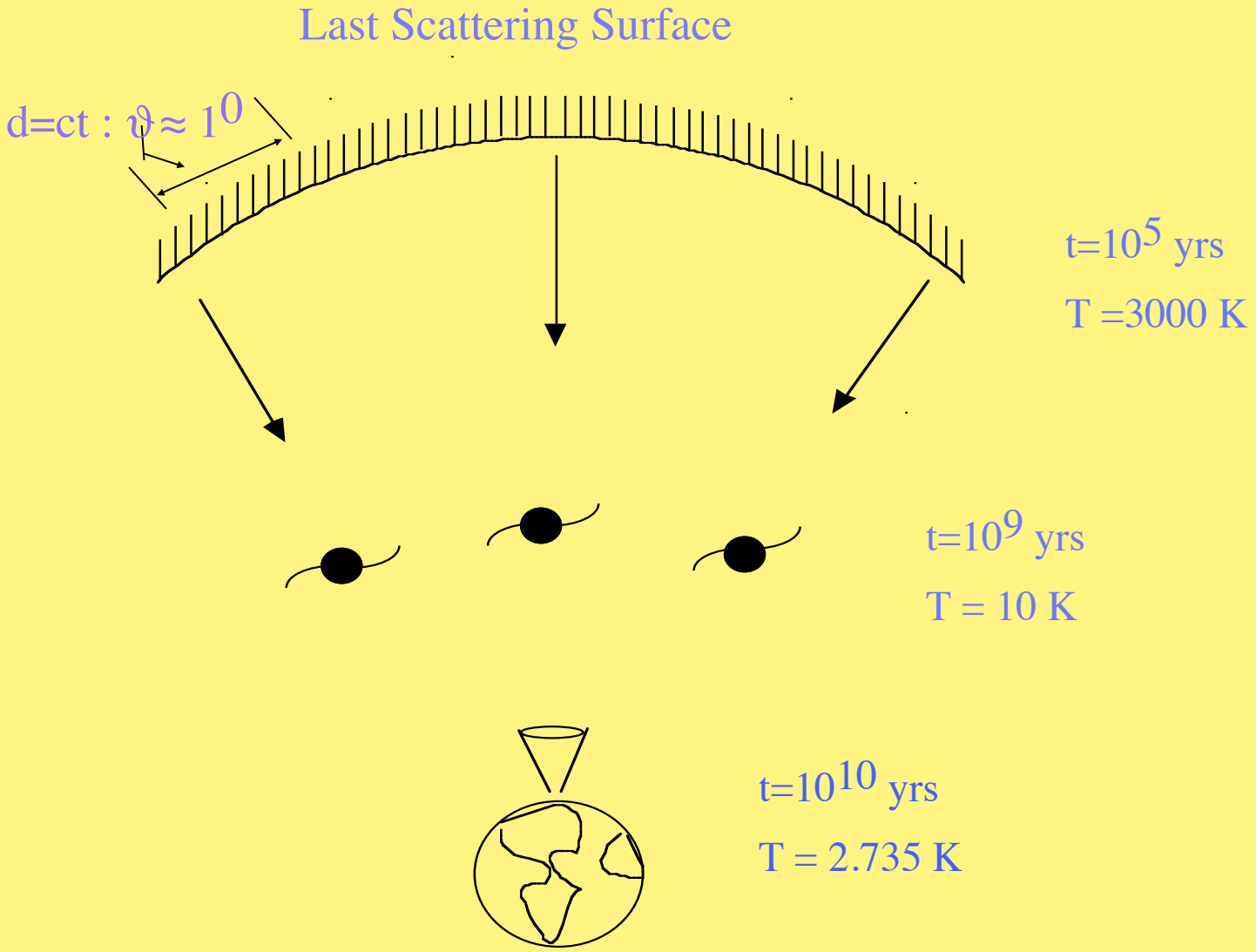


Q: How could you measure curvature of the Earth if:

(a) no recourse to outside space?

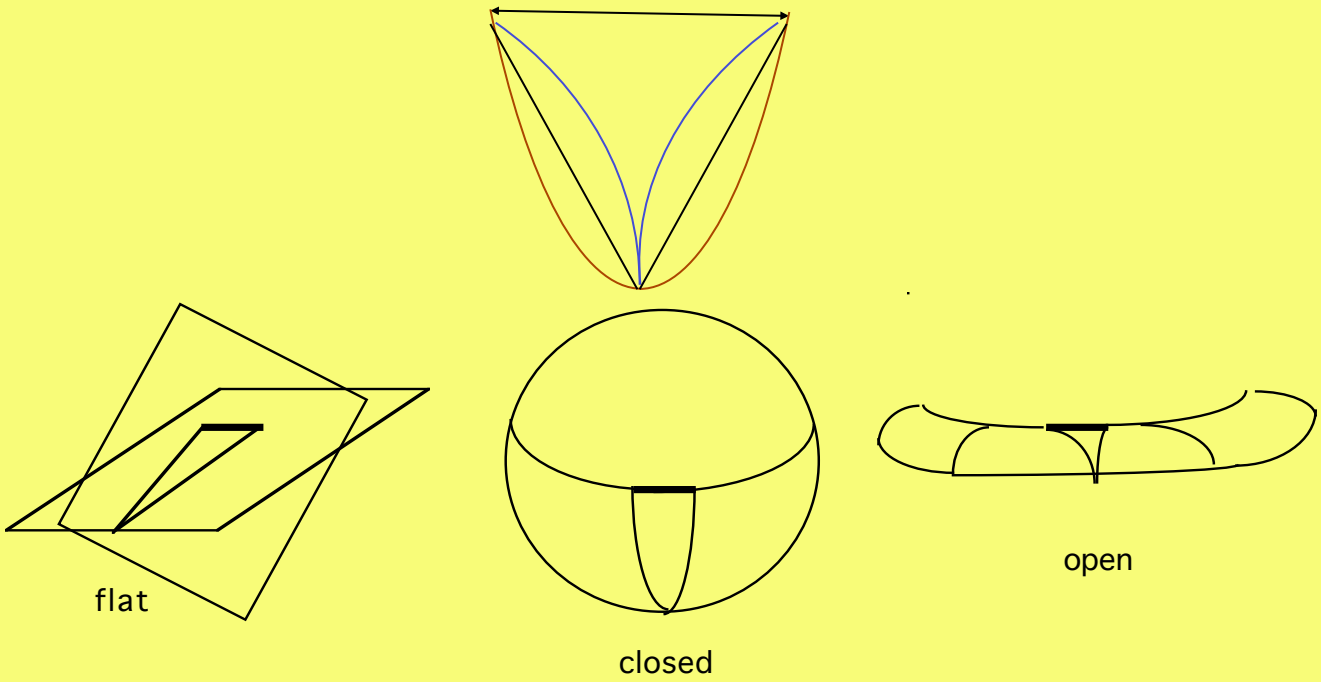
(b) not able to go around it?

COSMIC MICROWAVE BACKGROUND



Angular Size of a Fixed Scale in Open, Closed, and Flat Universes:

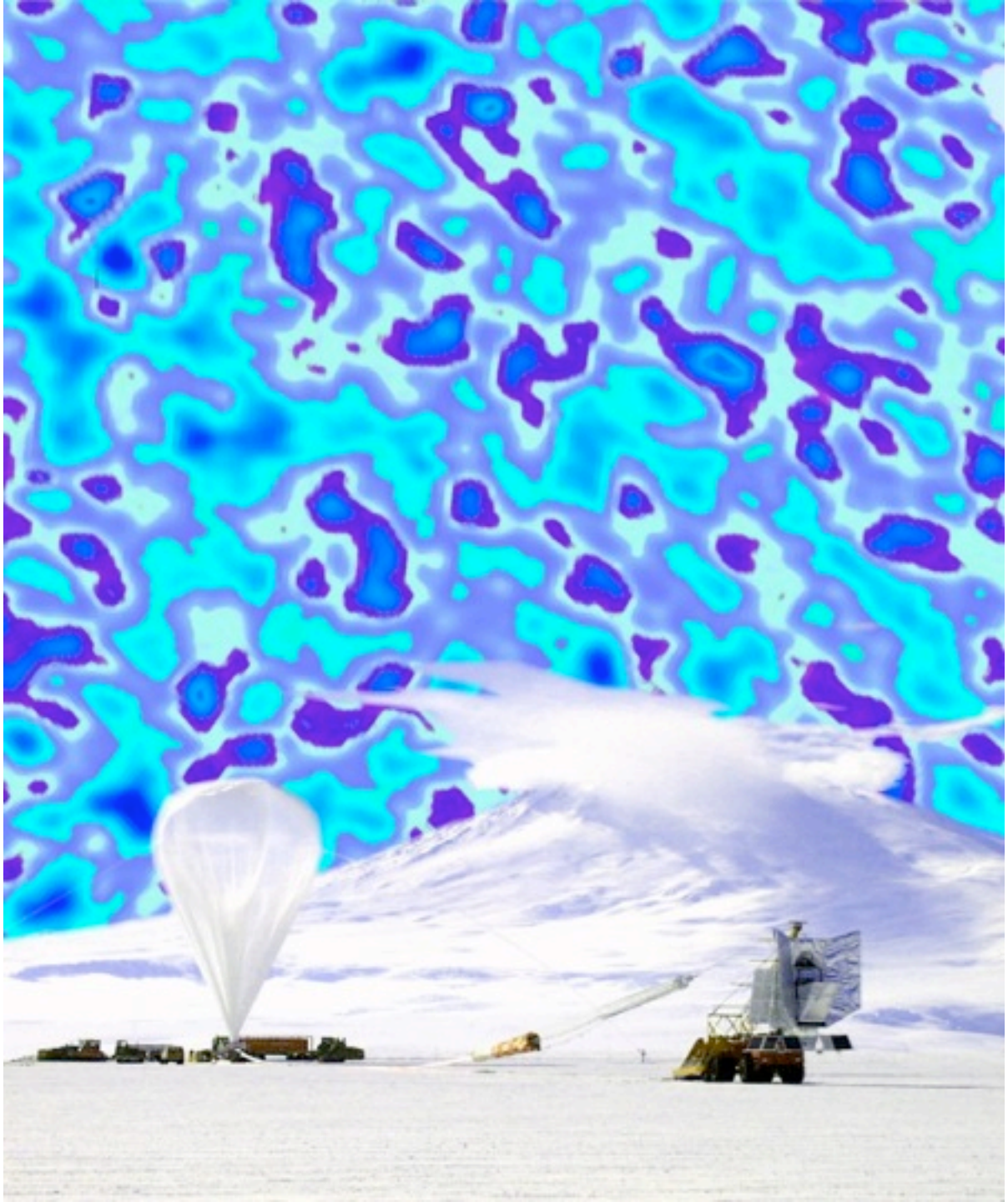
First Scale to Collapse after Recombination
(≈distance spanned by light ray =horizon size)

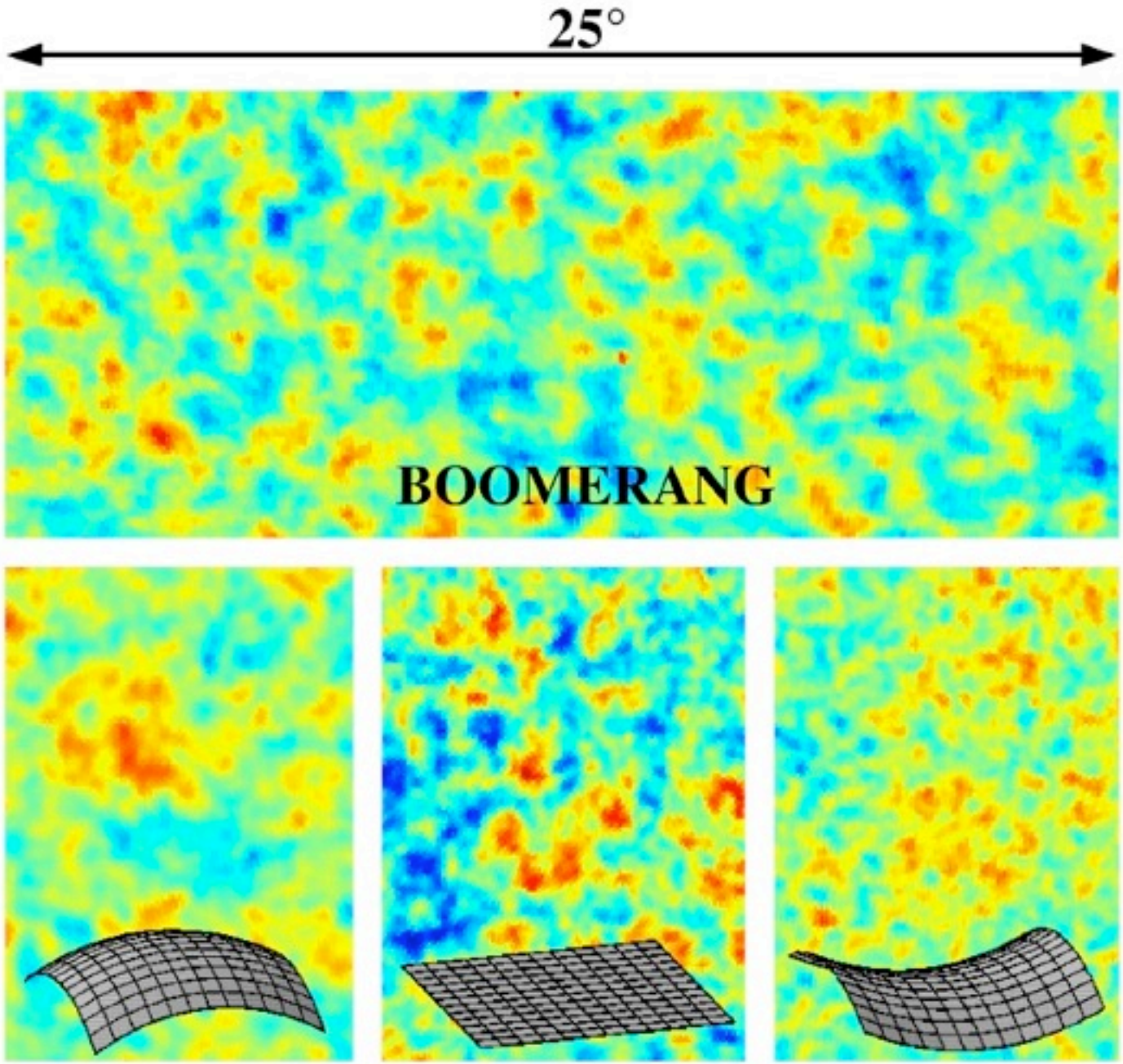


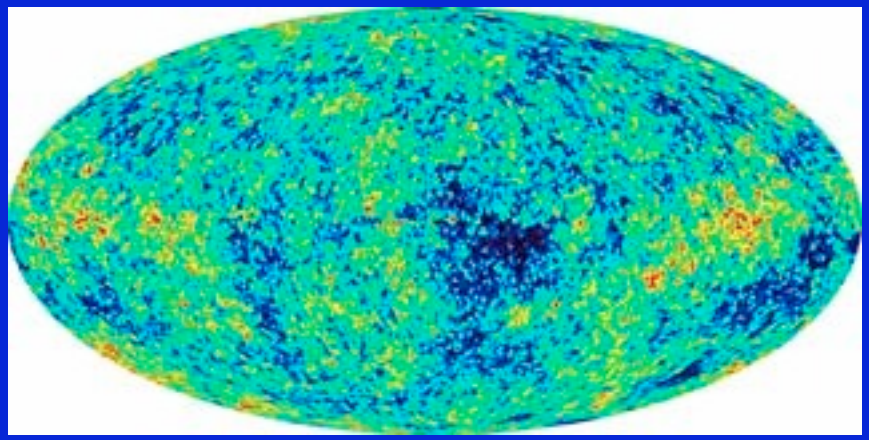
OPEN

CLOSED

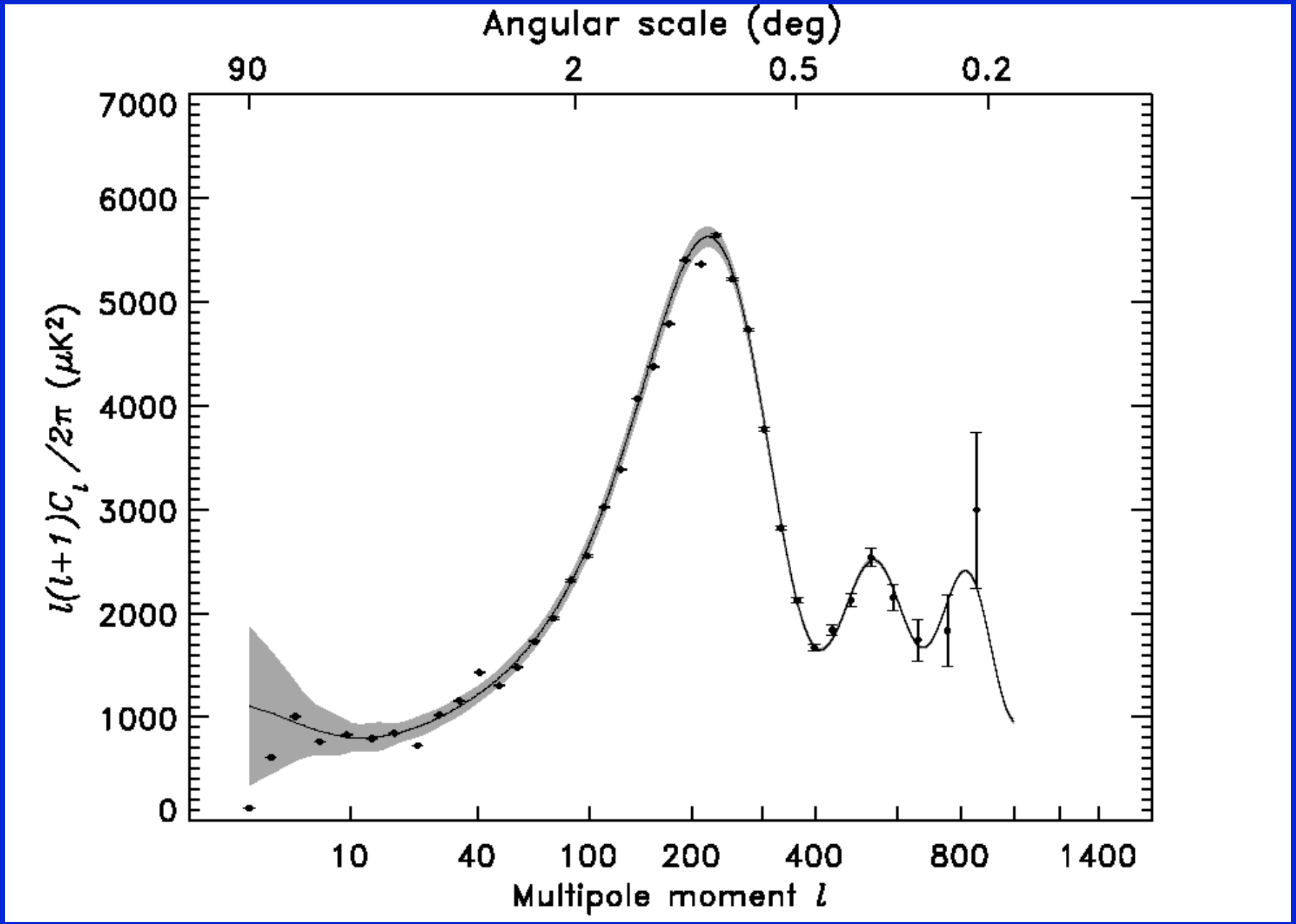
FLAT

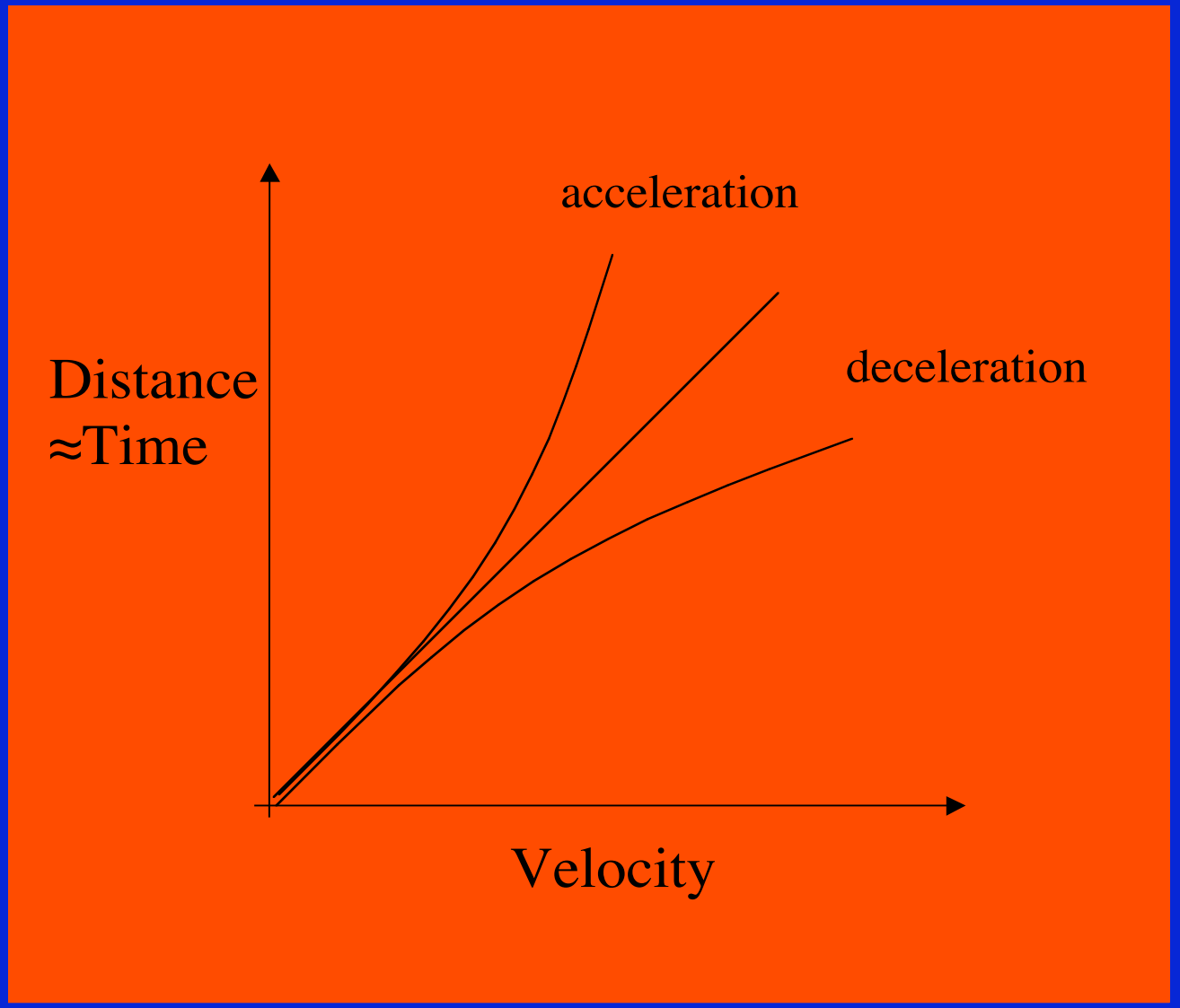


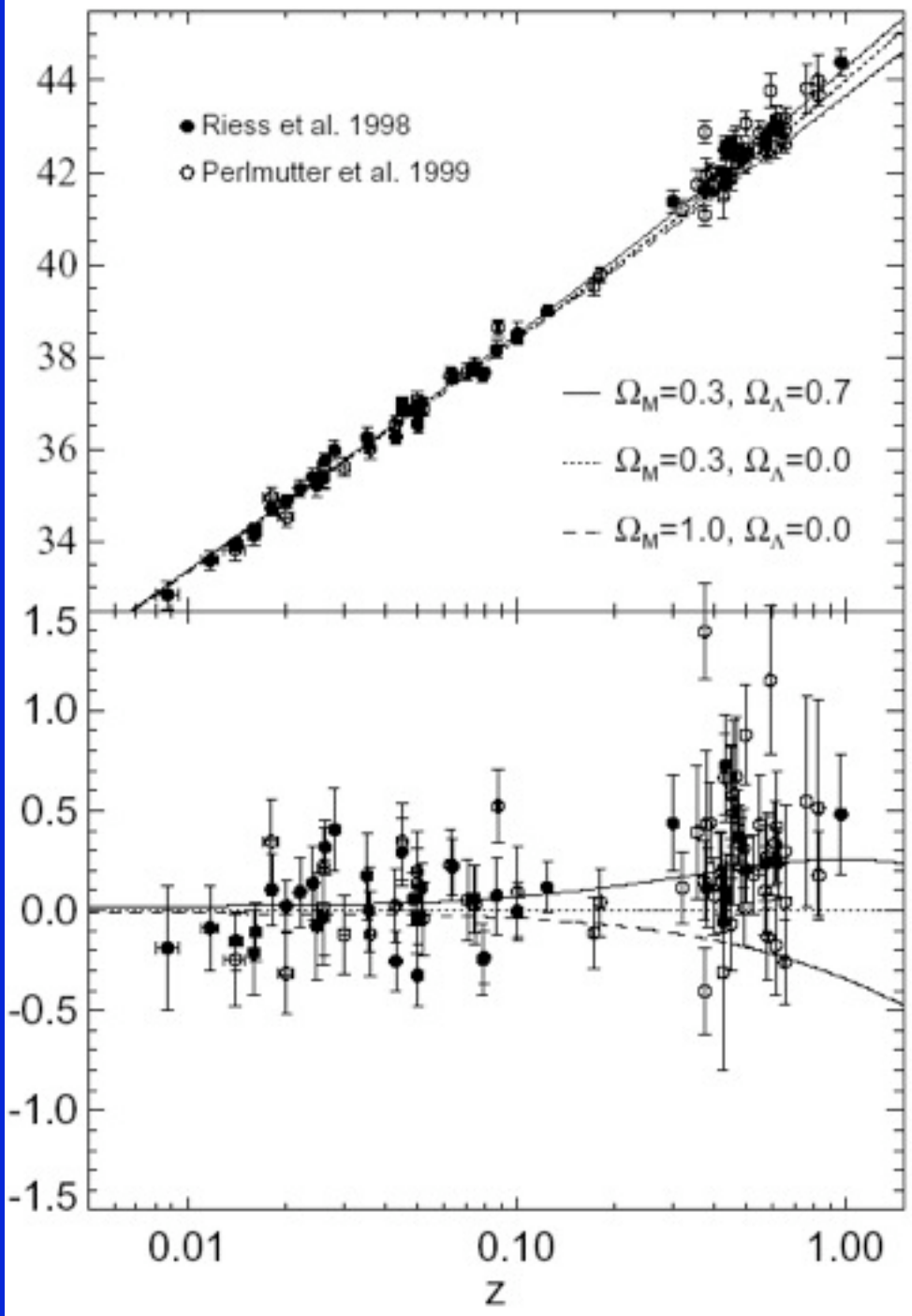

25°
BOOMERANG



Wilkinson Microwave
Anisotropy Probe (WMAP)


Angular scale (deg)
90
2
0.5
0.2
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
10
40
100
200
400
800
1400
Multipole moment l


acceleration
deceleration
Distance
≈Time
Velocity


Riess et al. 1998
Perlmutter et al. 1999
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
44
42
40
38
36
34
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.01
0.10
1.00
z

MUCH ADO ABOUT NOTHING!

- THE DOMINANT ENERGY IN THE UNIVERSE RESIDES IN EMPTY SPACE
- WE HAVE NO IDEA WHY IT IS THERE
- ITS EXISTENCE IS PROBABLY TIED TO THE VERY NATURE OF SPACE AND TIME AND TO THE ORIGIN OF OUR UNIVERSE.
- IT WILL DETERMINE OUR FUTURE!