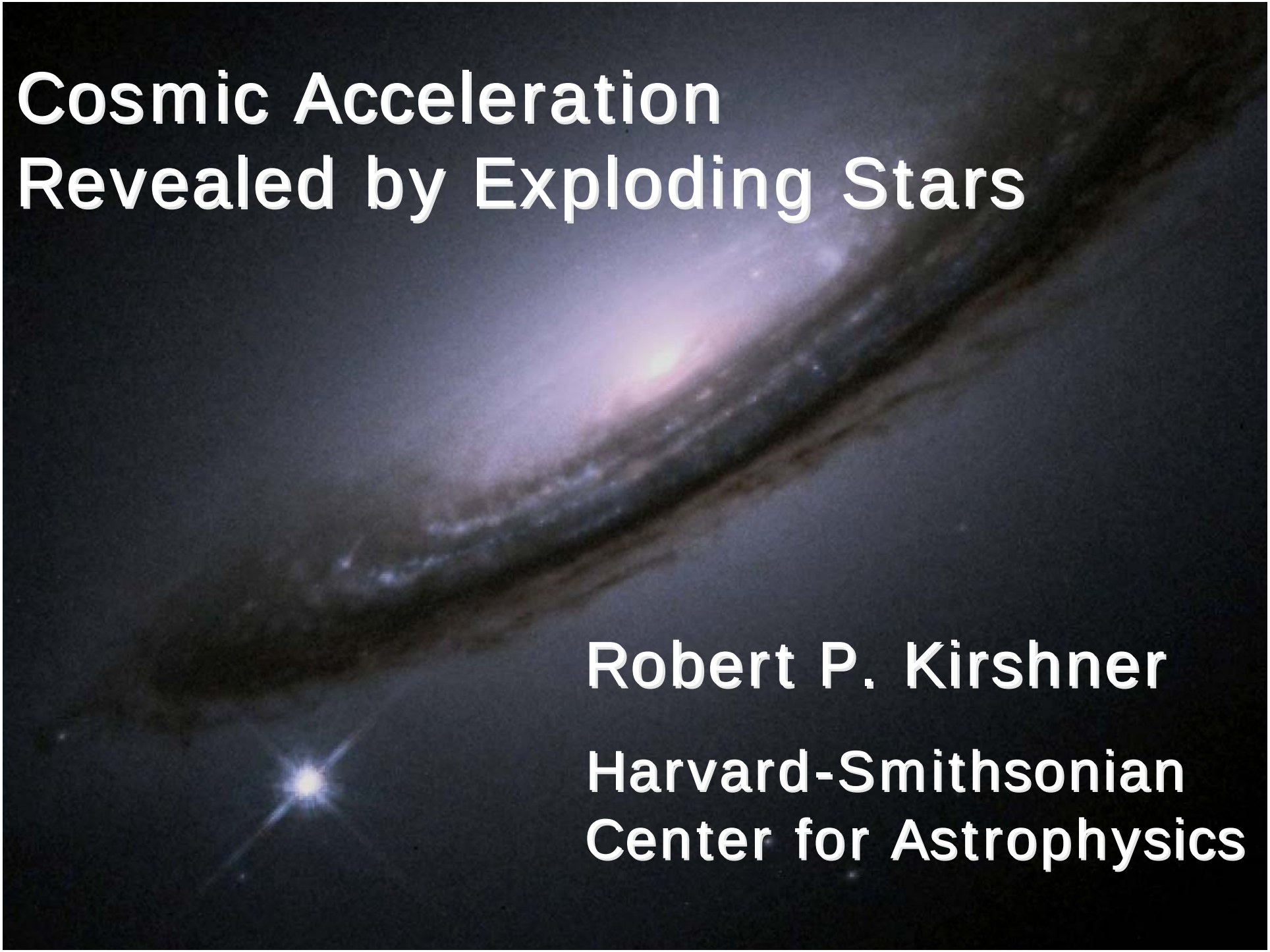
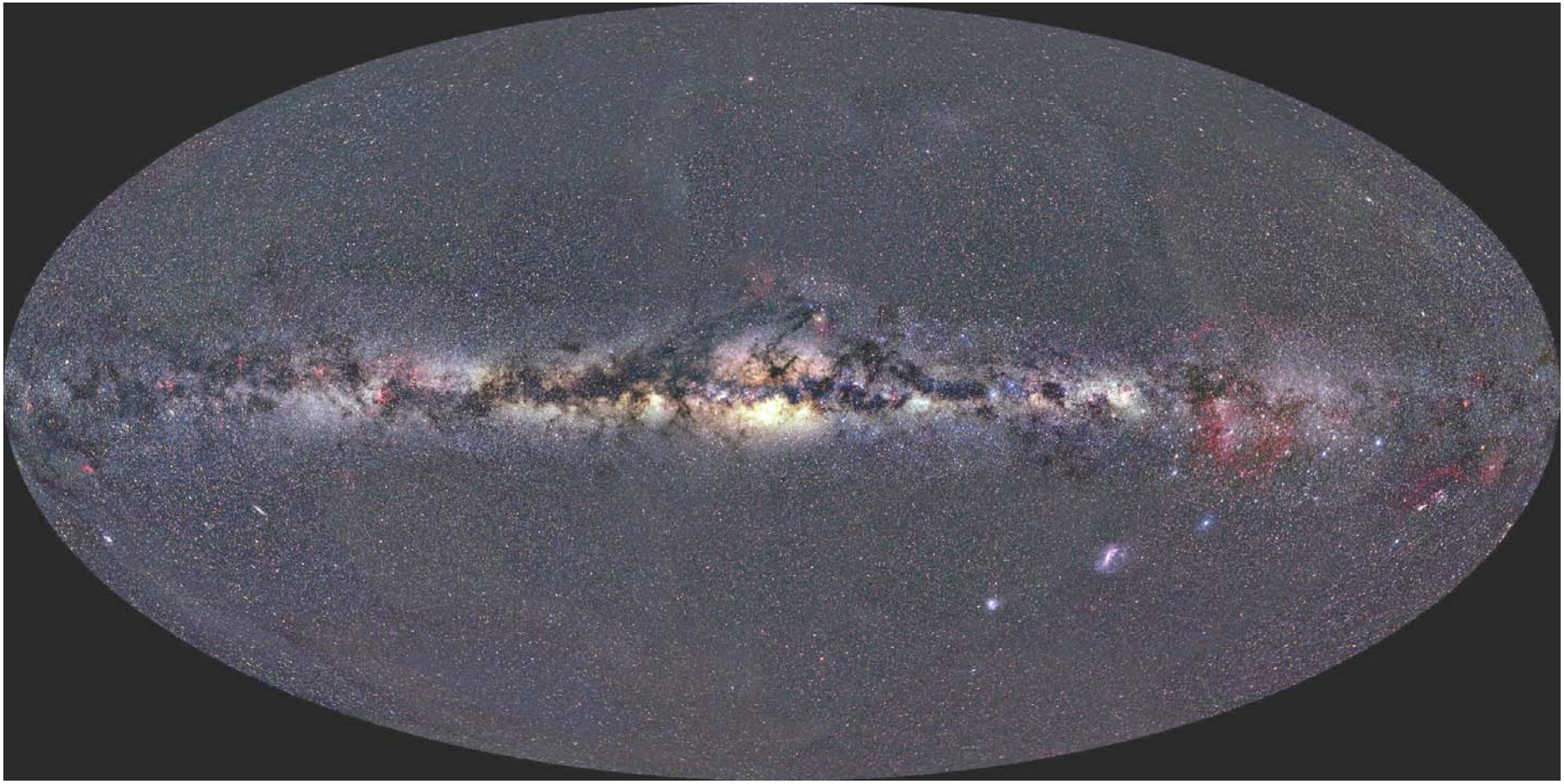
Cosmic Acceleration Revealed by Exploding Stars



Robert P. Kirshner

Harvard-Smithsonian
Center for Astrophysics



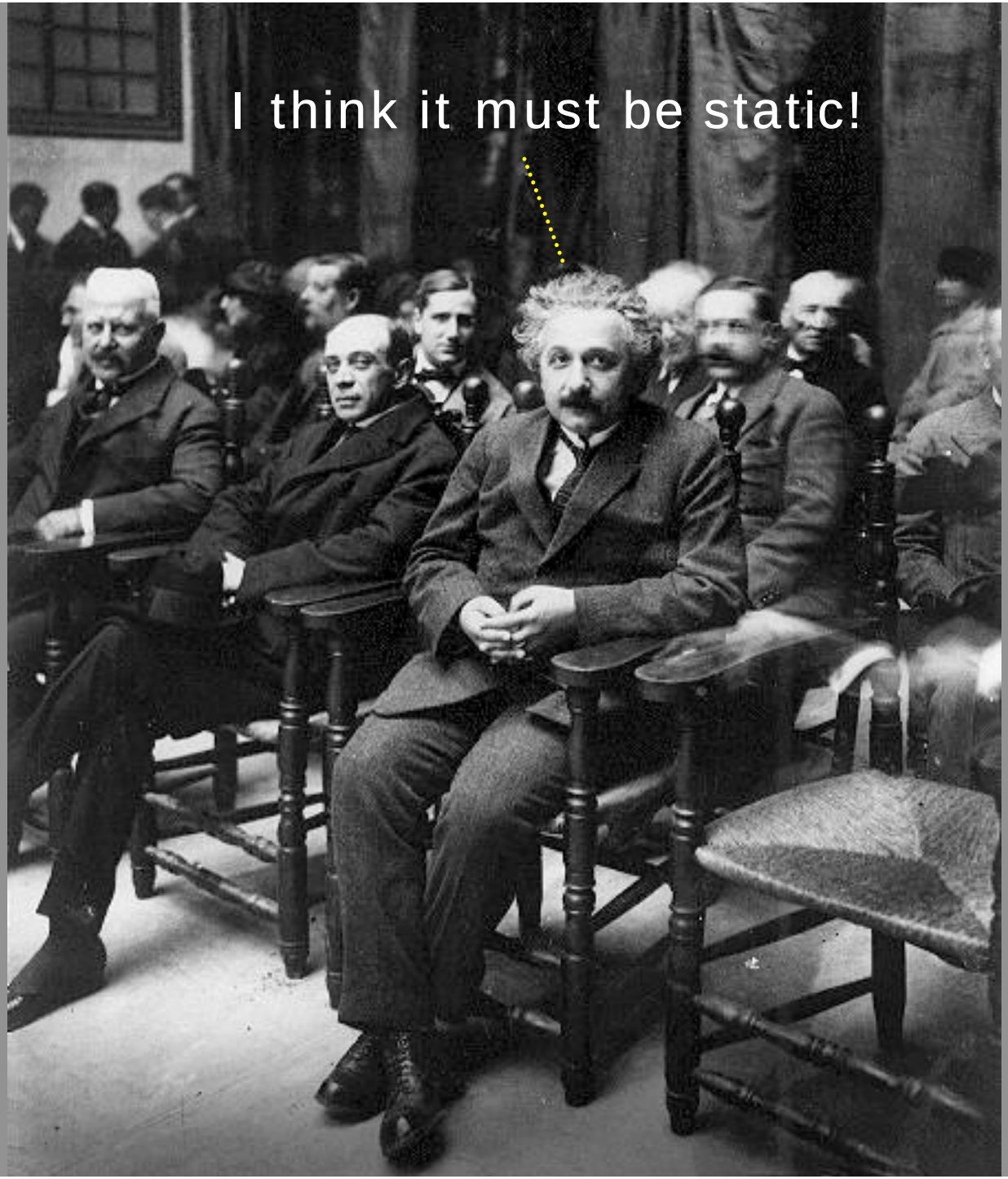
Axel Mellinger

The Milky Way

In 1917 = The Universe

Today = 1 in 10^{11}

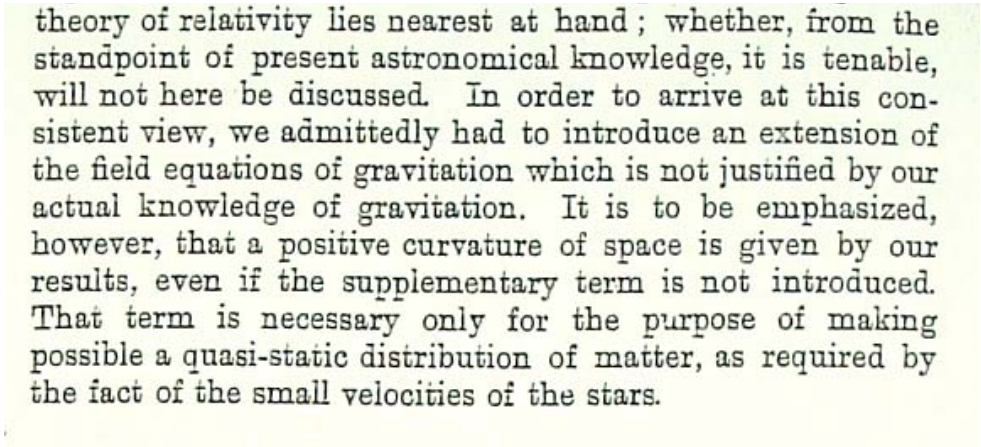
3/19/07



3/19/07

1917:

Einstein stuck in the cosmological constant to make a static Universe.



theory of relativity lies nearest at hand; whether, from the standpoint of present astronomical knowledge, it is tenable, will not here be discussed. In order to arrive at this consistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation. It is to be emphasized, however, that a positive curvature of space is given by our results, even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.

"Universe" = Milky Way Galaxy

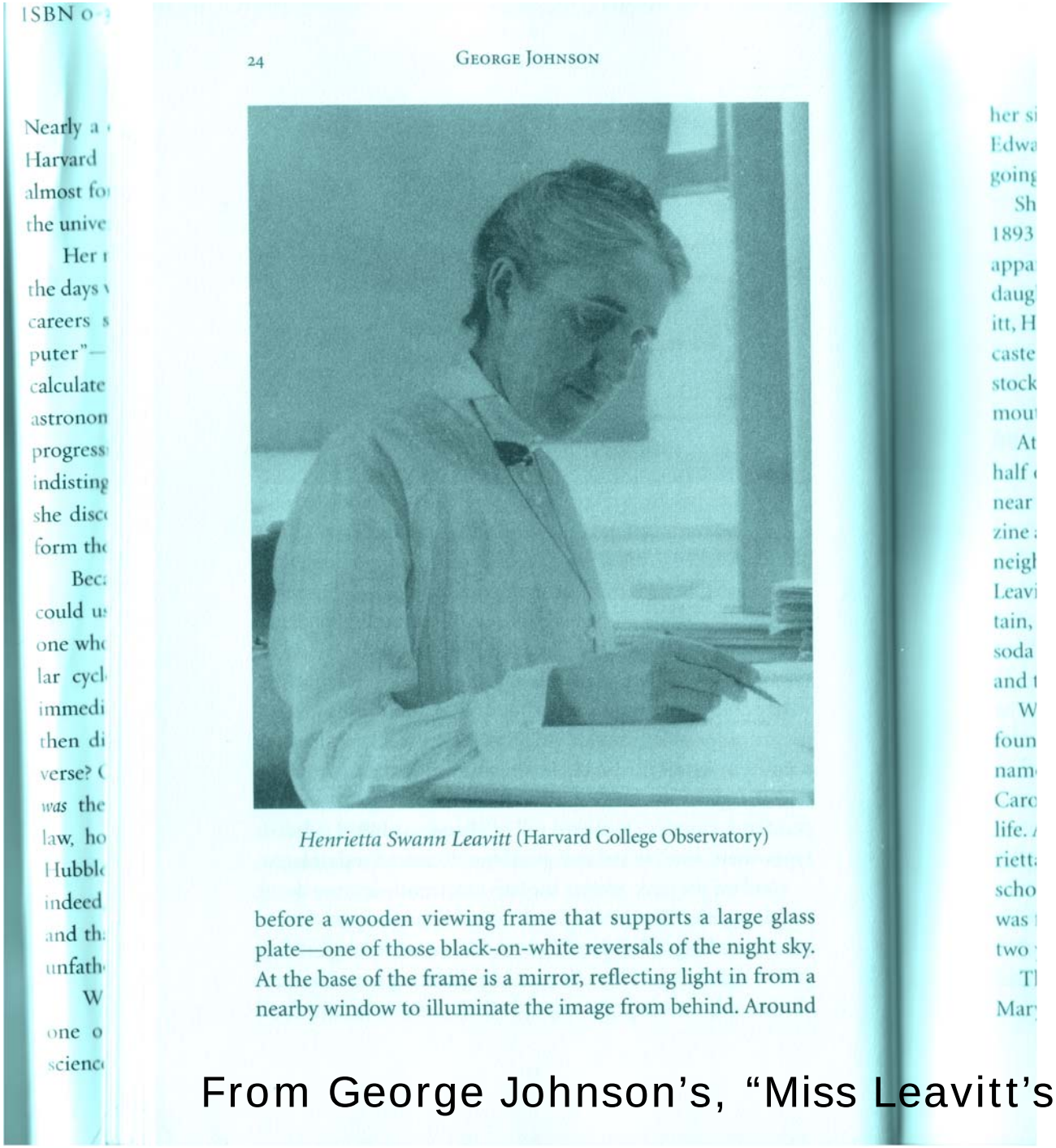

Harvard
“Computers”
~1900

Harvard Observatory Director Pickering:

A great observatory should be as carefully organized and administered as a railroad.

Every expenditure should be watched…and every care taken to secure the greatest possible output for every dollar expenditure.

A great savings may be effectuated by employing unskilled and therefore inexpensive labor, of course under careful supervision.



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24 GEORGE JOHNSON

Henrietta Swann Leavitt (Harvard College Observatory)

before a wooden viewing frame that supports a large glass plate—one of those black-on-white reversals of the night sky. At the base of the frame is a mirror, reflecting light in from a nearby window to illuminate the image from behind. Around

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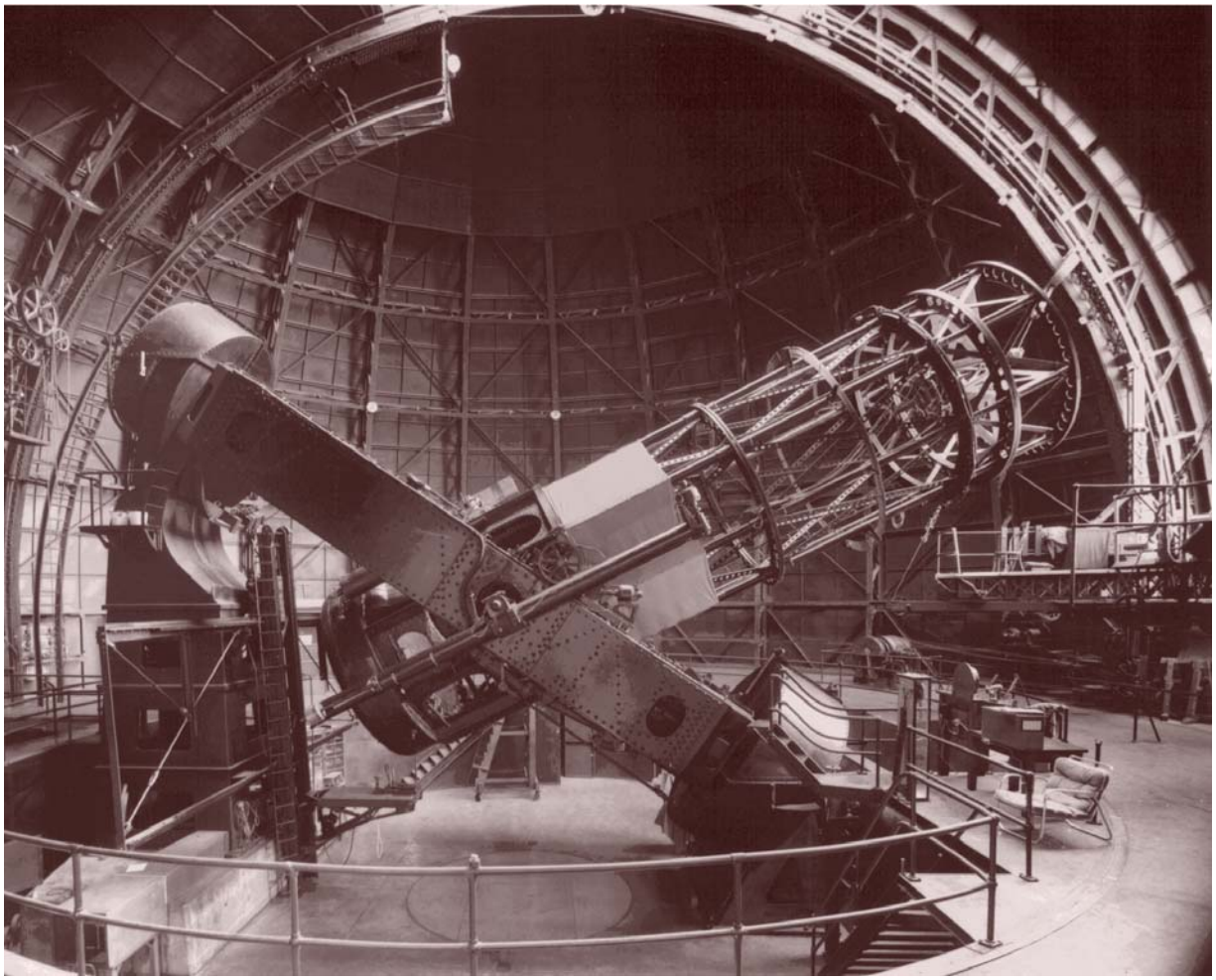
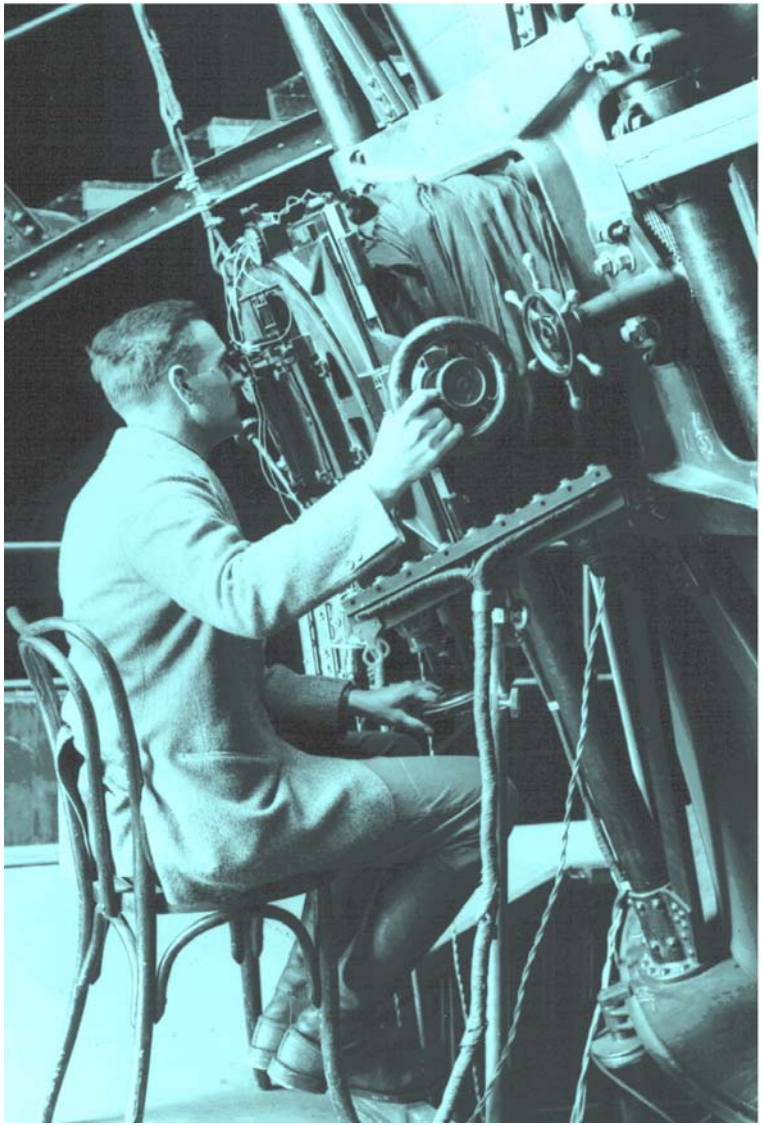
"It is worthy of notice that the brighter variables have the longer periods."

From George Johnson's, "Miss Leavitt's Stars"

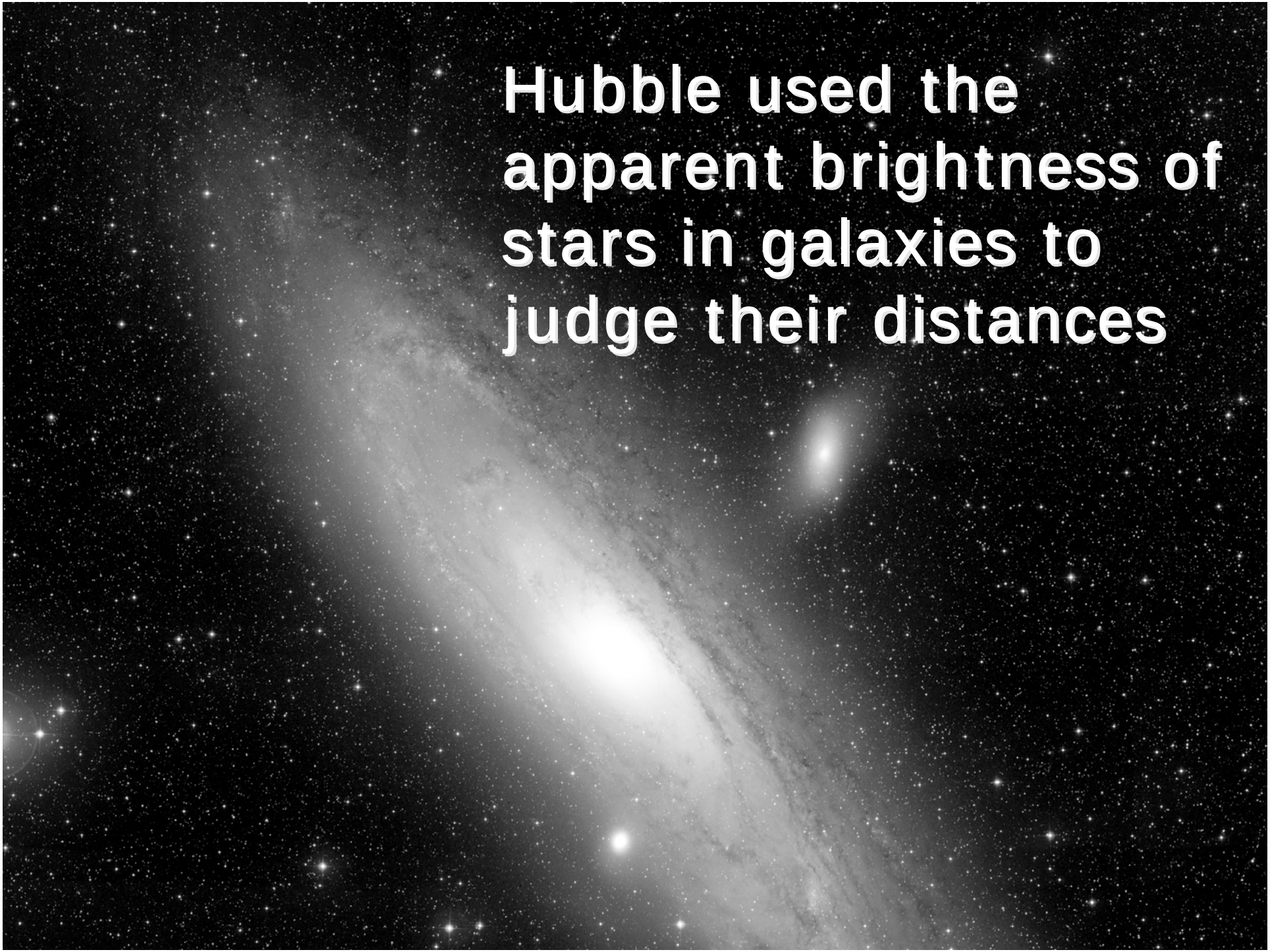
The 100-inch Telescope at Mount Wilson

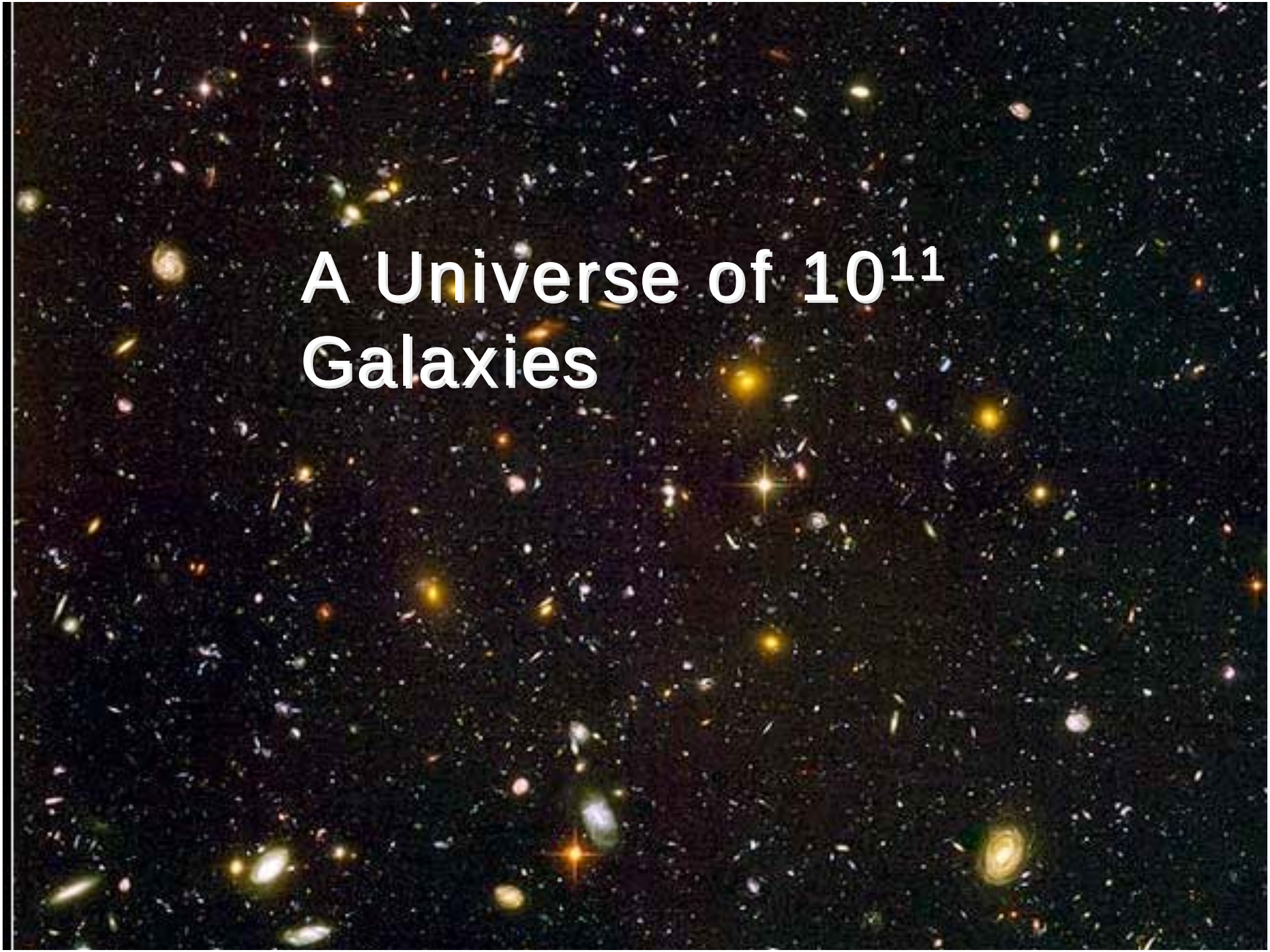




Edwin Hubble showed the Milky Way was **not** the whole Universe.

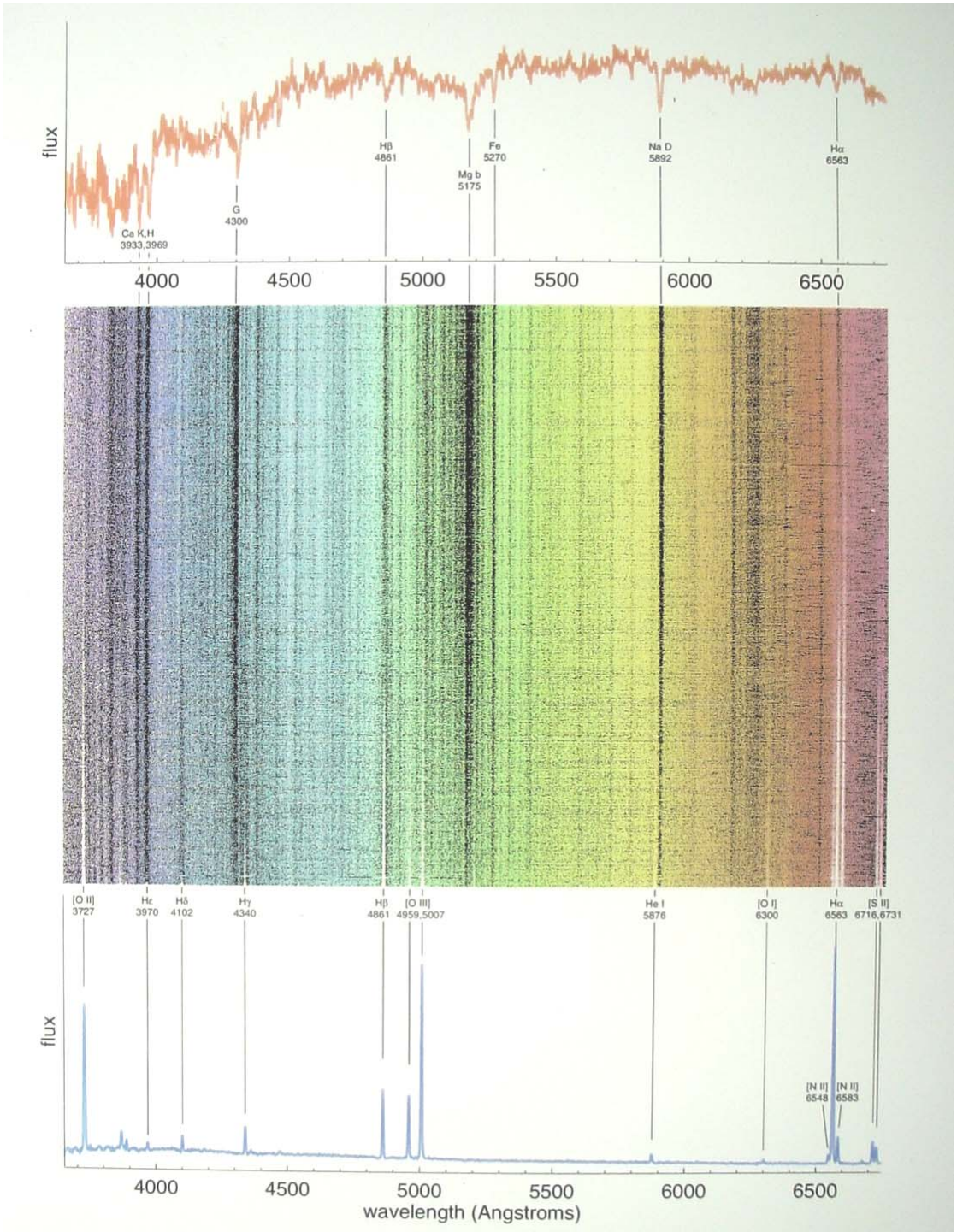
We live in a Universe of galaxies, each equivalent to the Milky Way.


Hubble used the apparent brightness of stars in galaxies to judge their distances

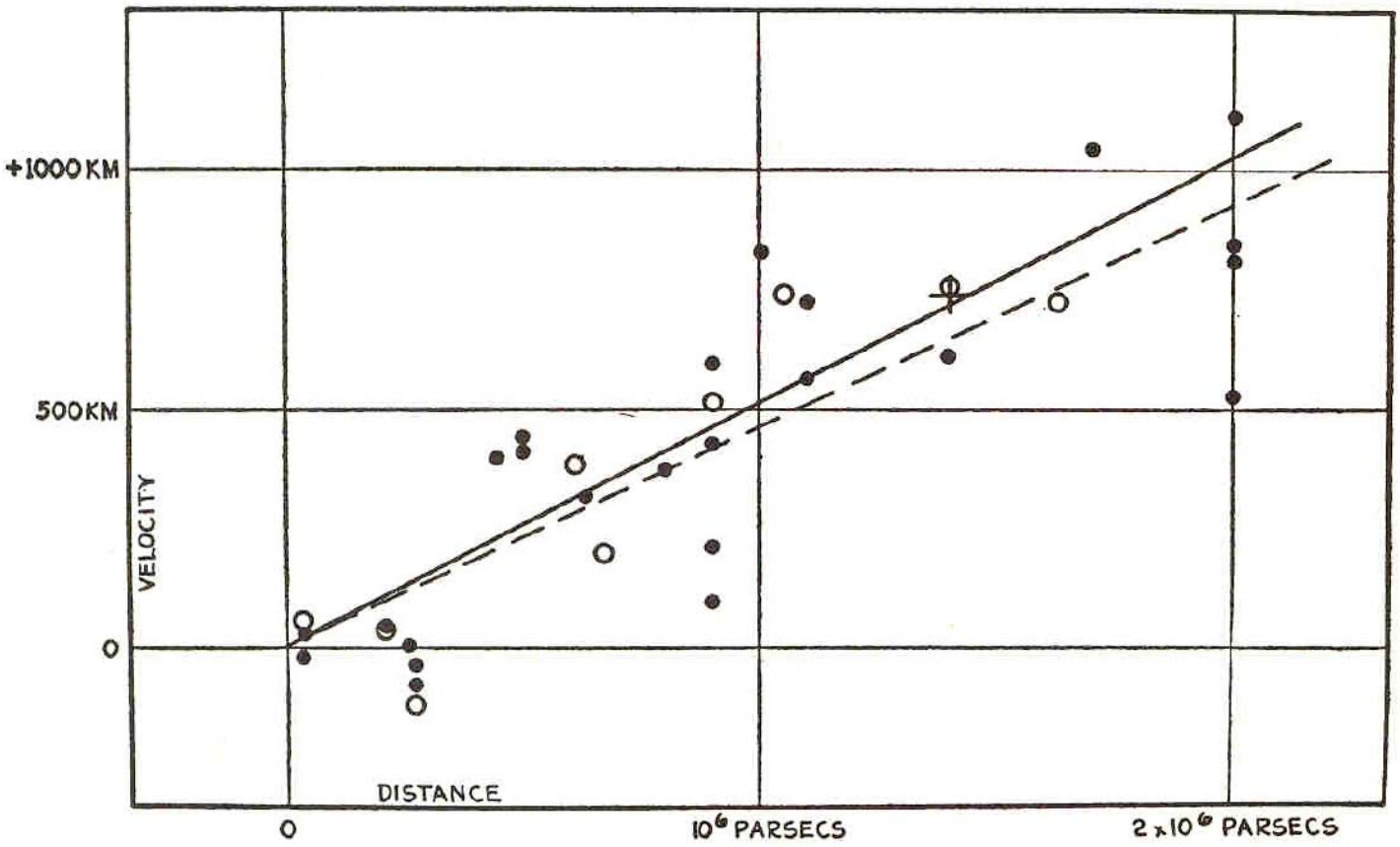

A Universe of 10^{11} Galaxies

Measure Motion from the spectrum:

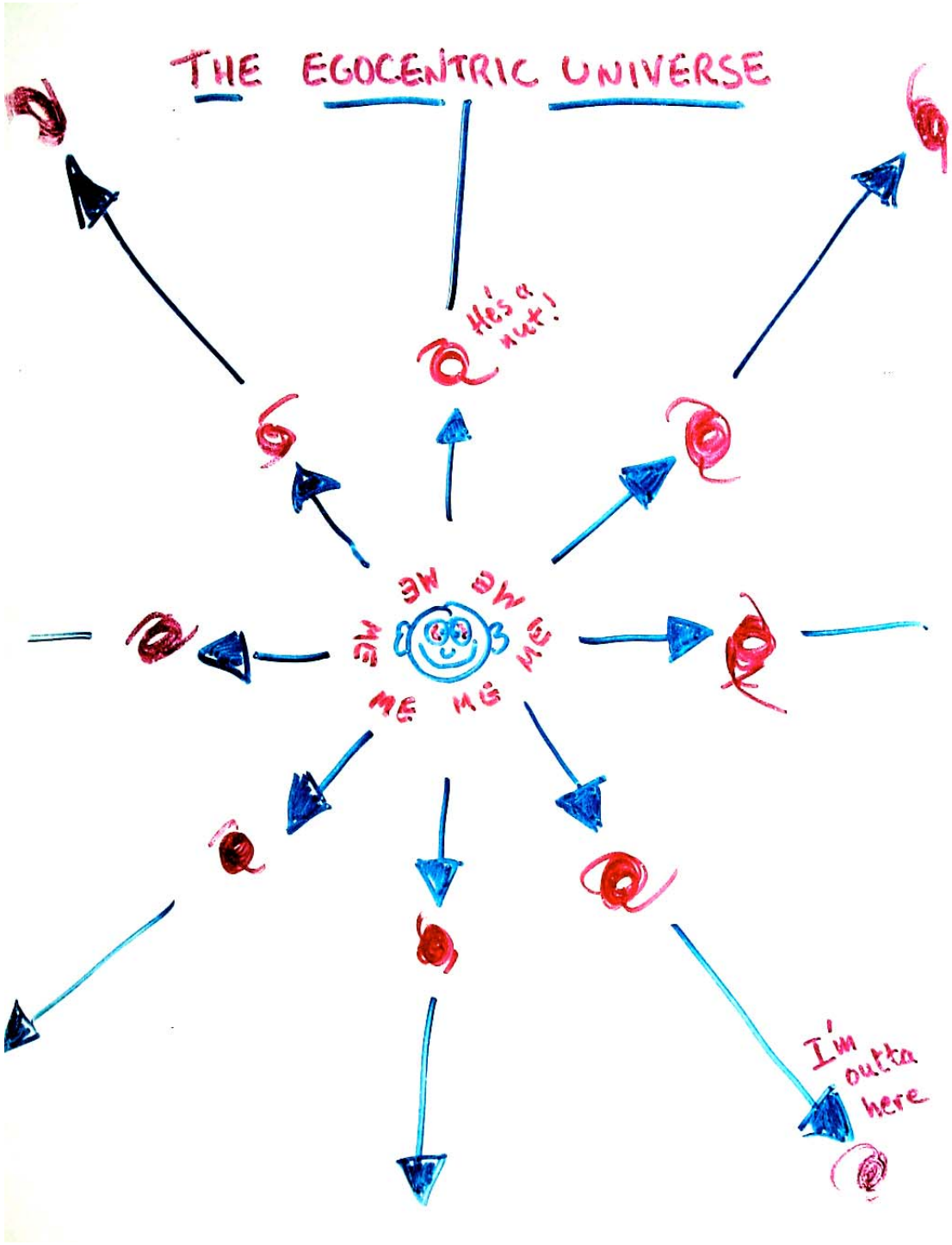
The Redshift



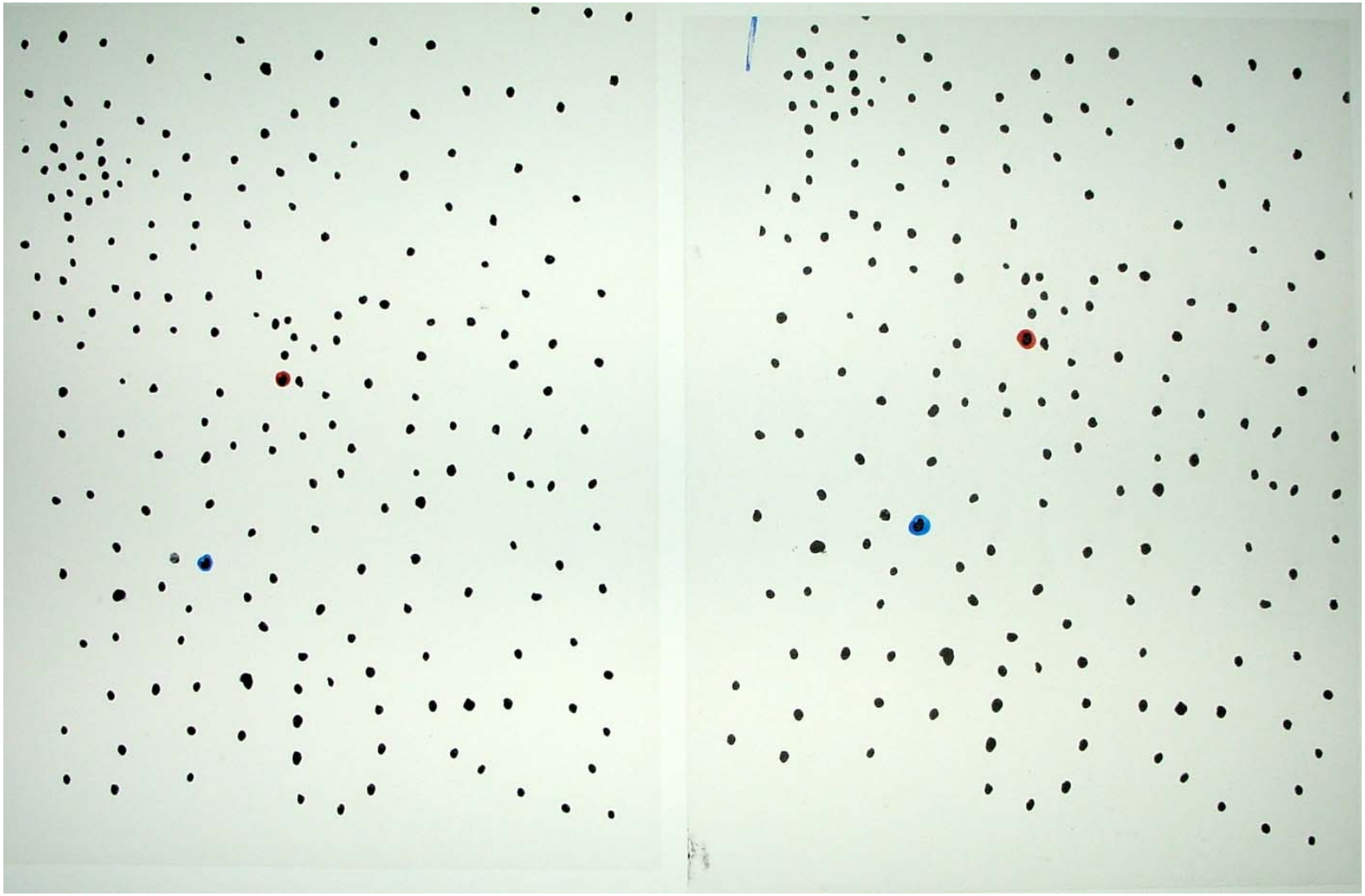
Hubble's Own 1929 Hubble Diagram



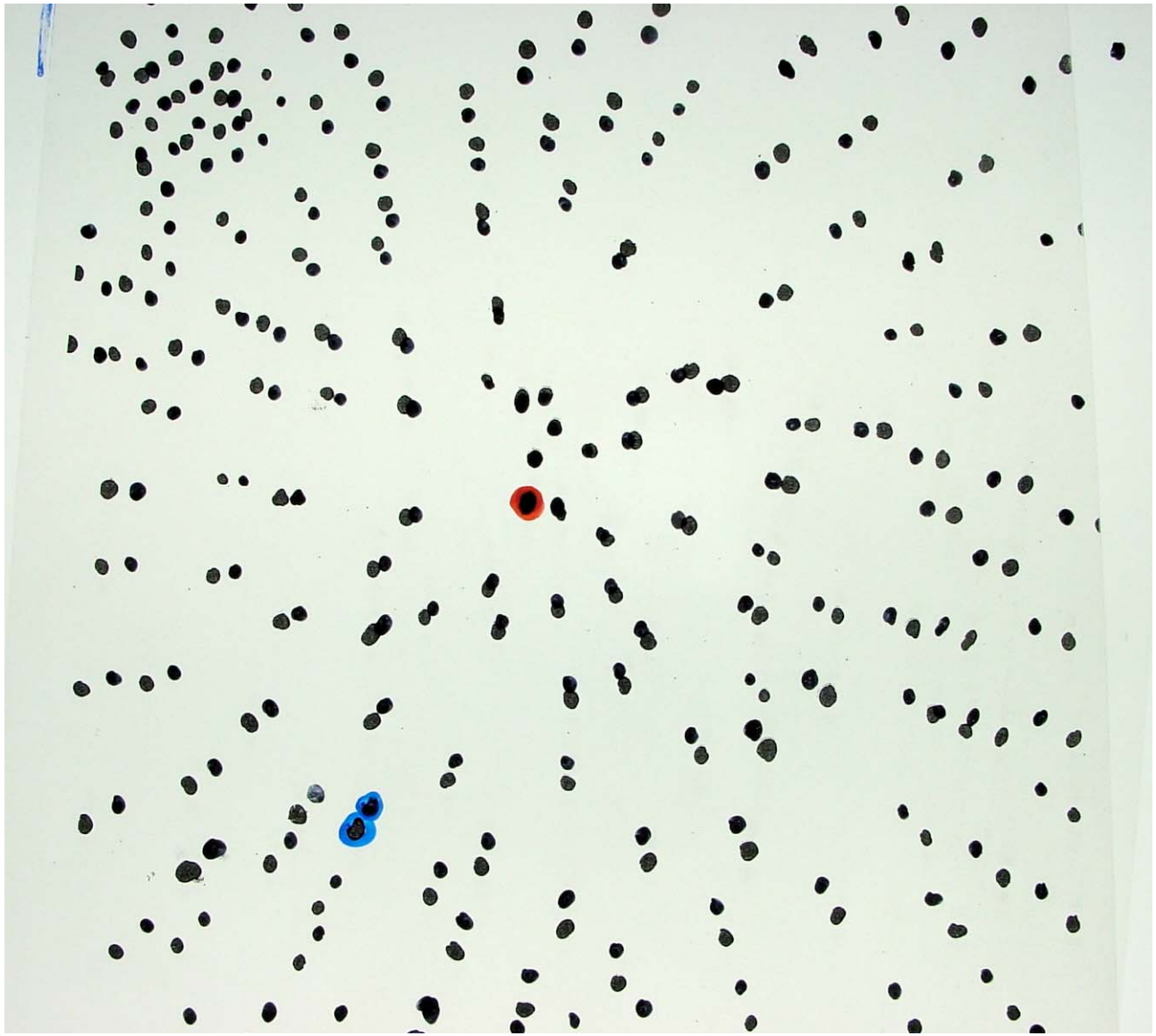
Redshift proportional to distance


THE EGOCENTRIC UNIVERSE
He's a nut!
ME
ME
ME
ME
ME
ME
I'm outta here

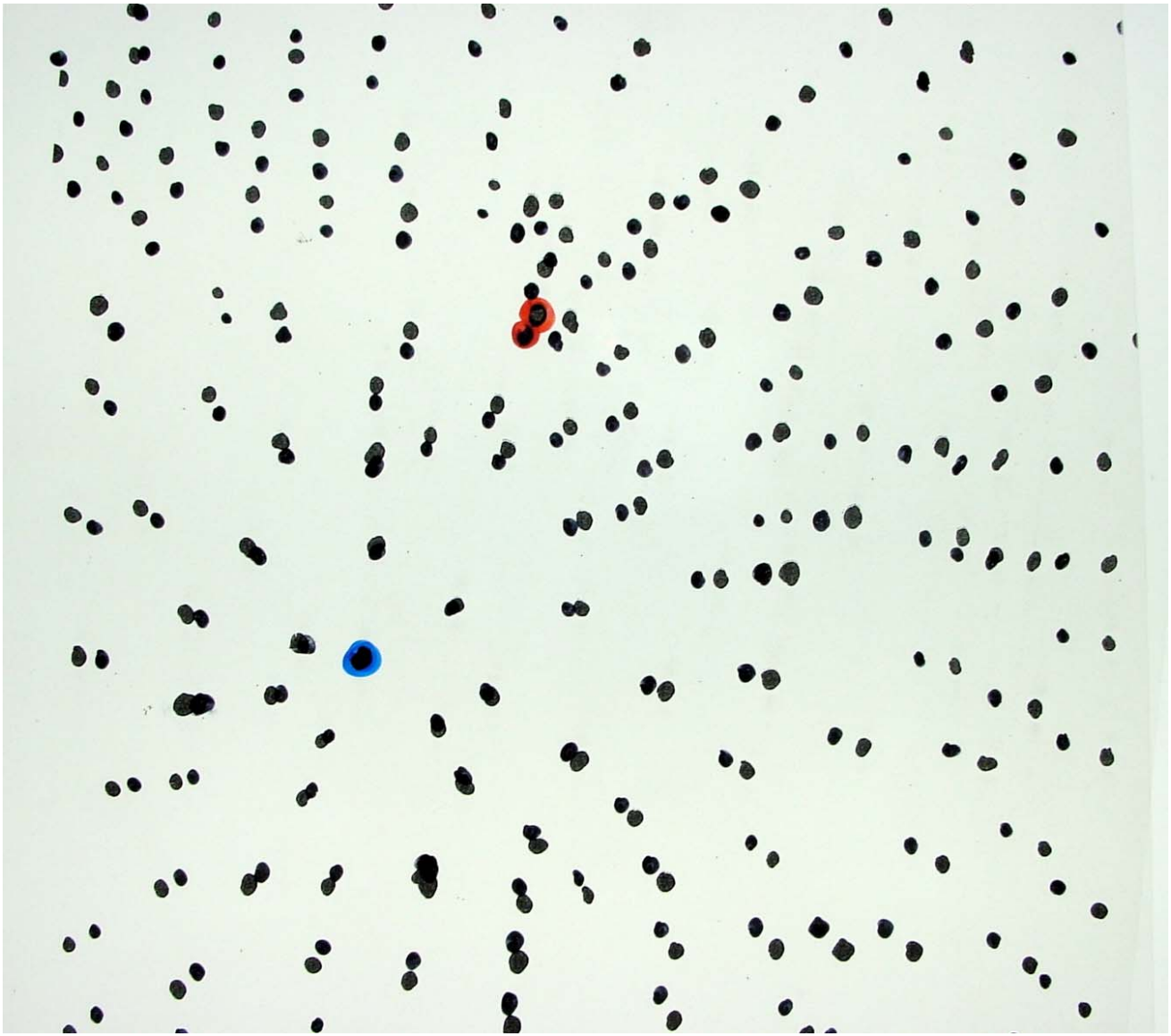
3/19/07



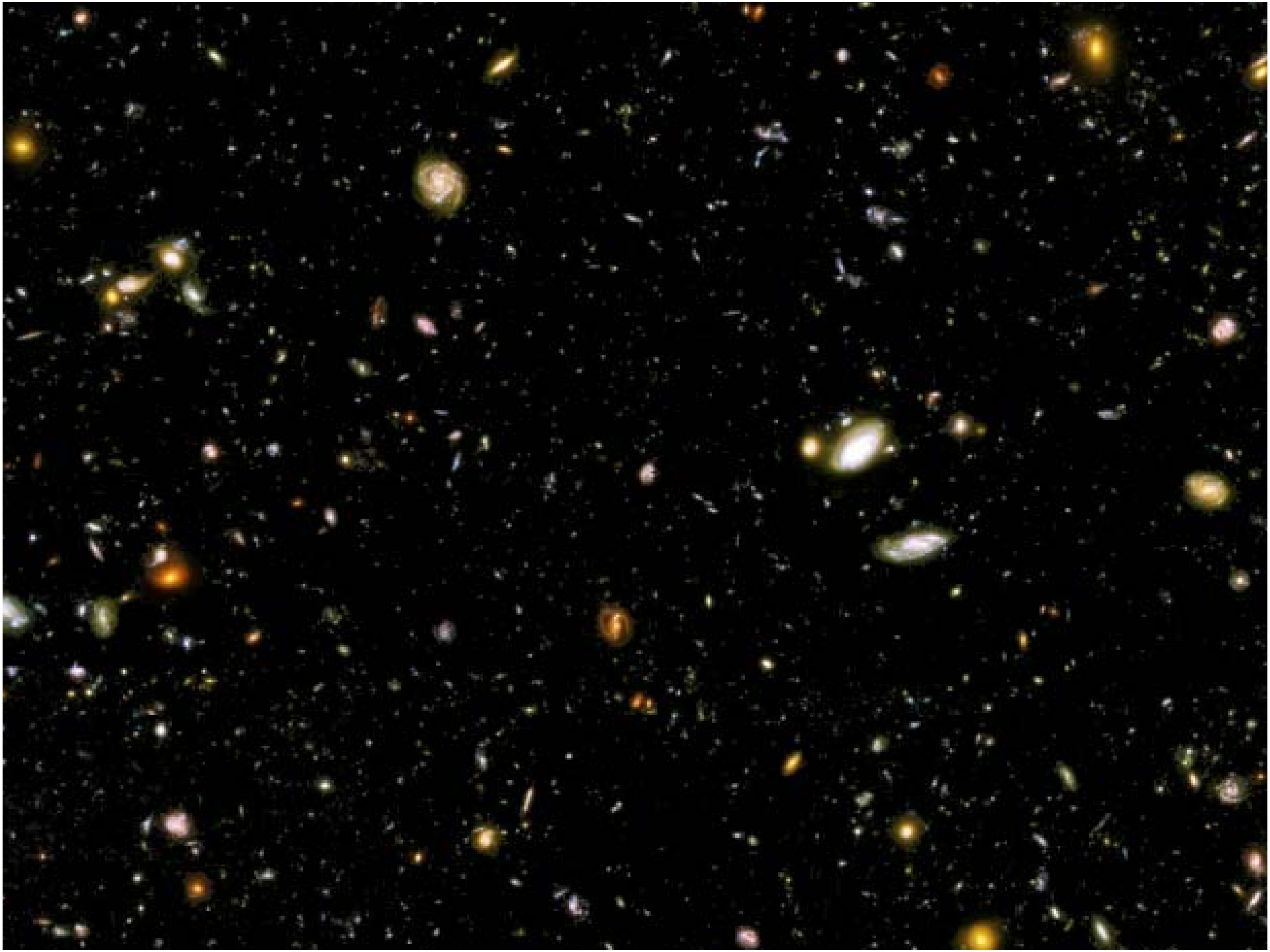
3/19/07 SB Teachers

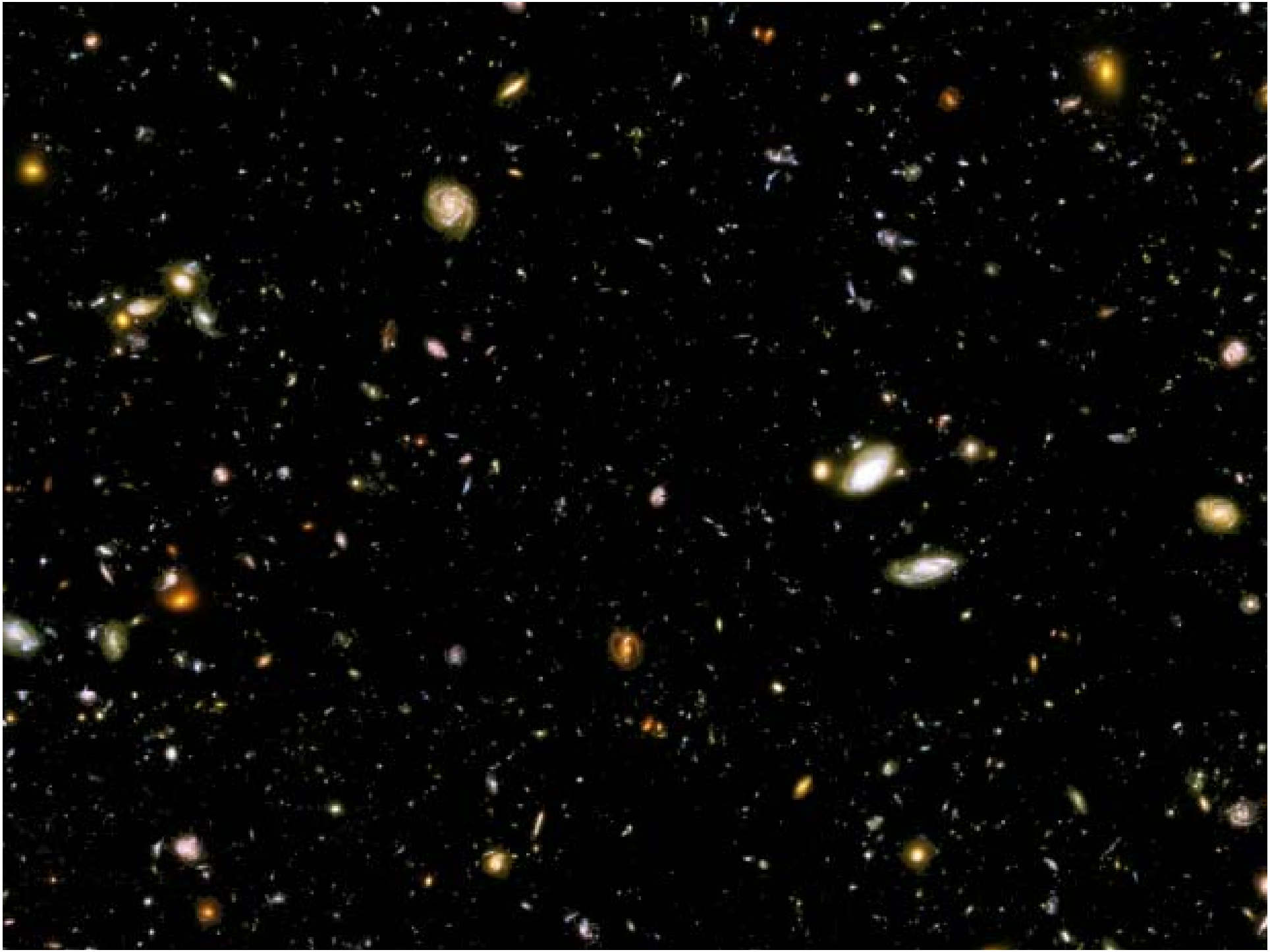


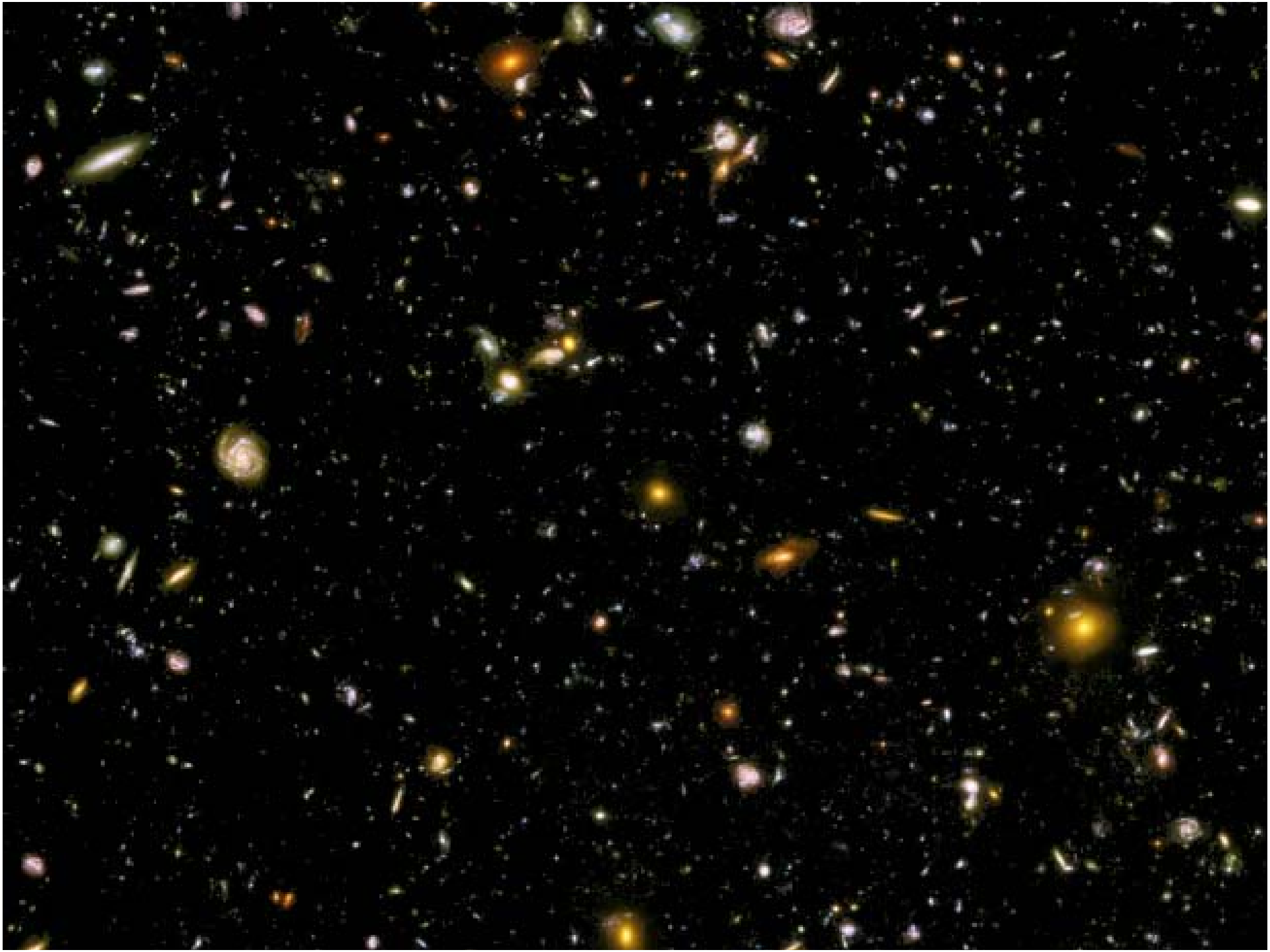
3/19/07 SB Teachers

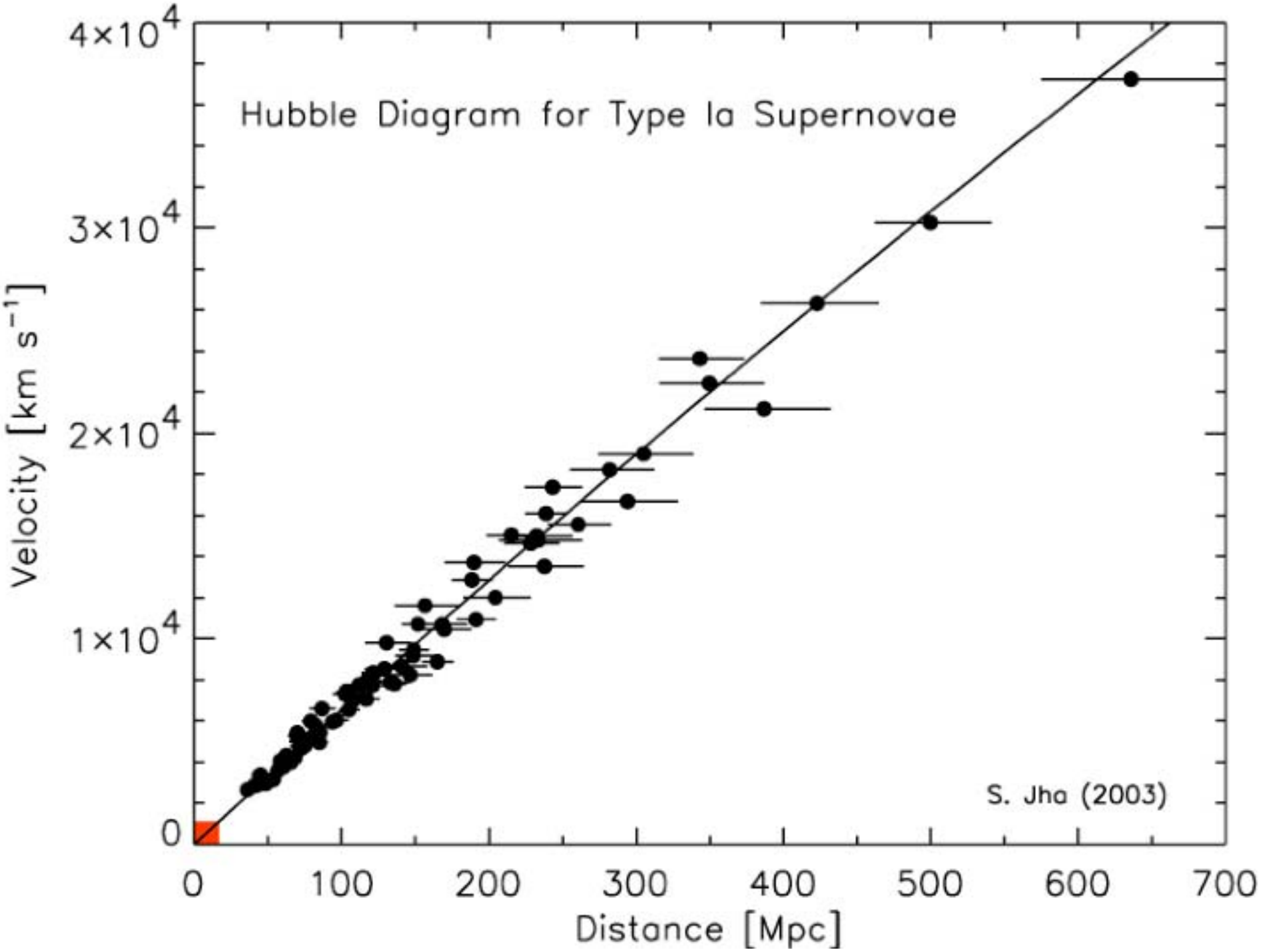


3/19/07 SB Teachers

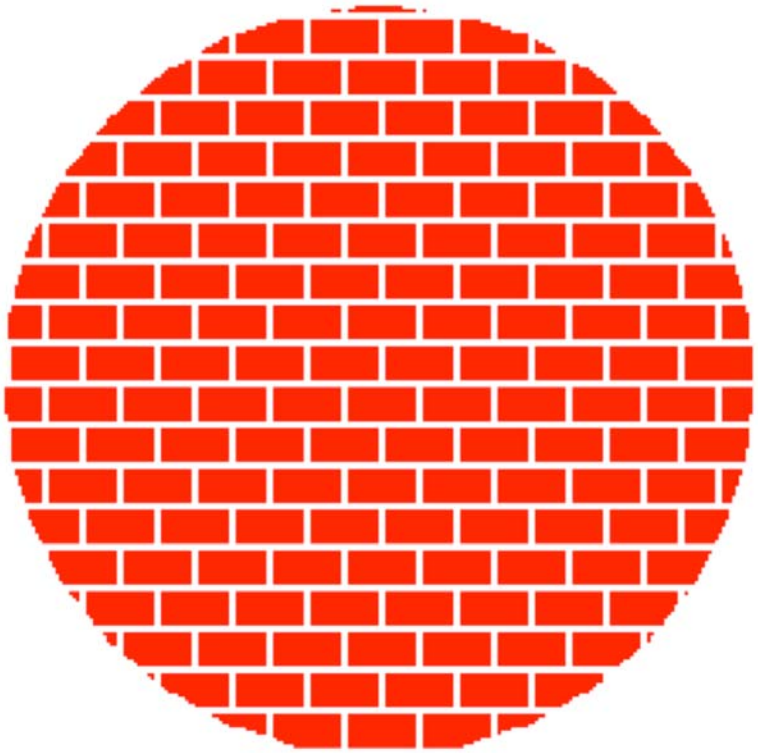




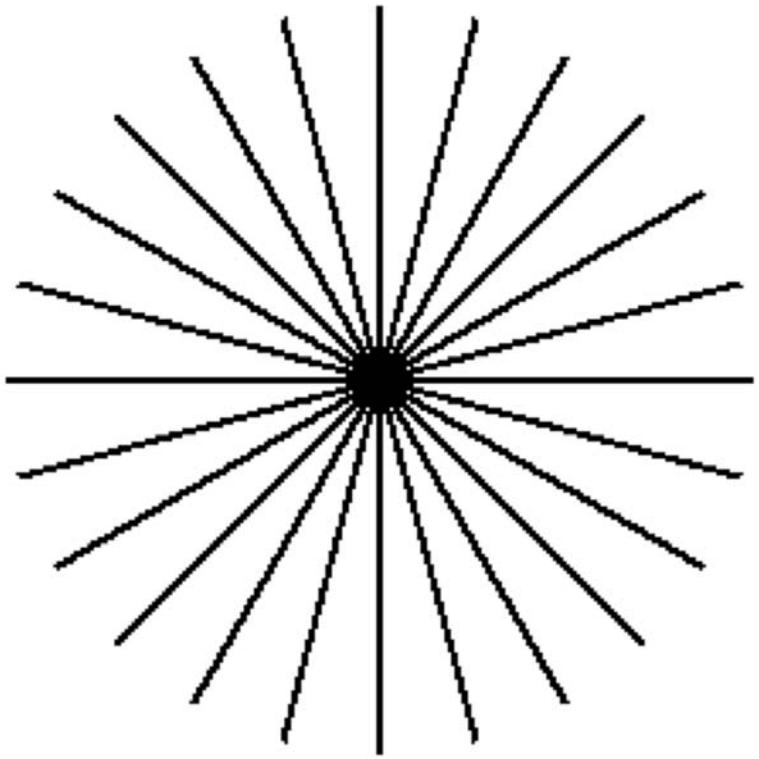


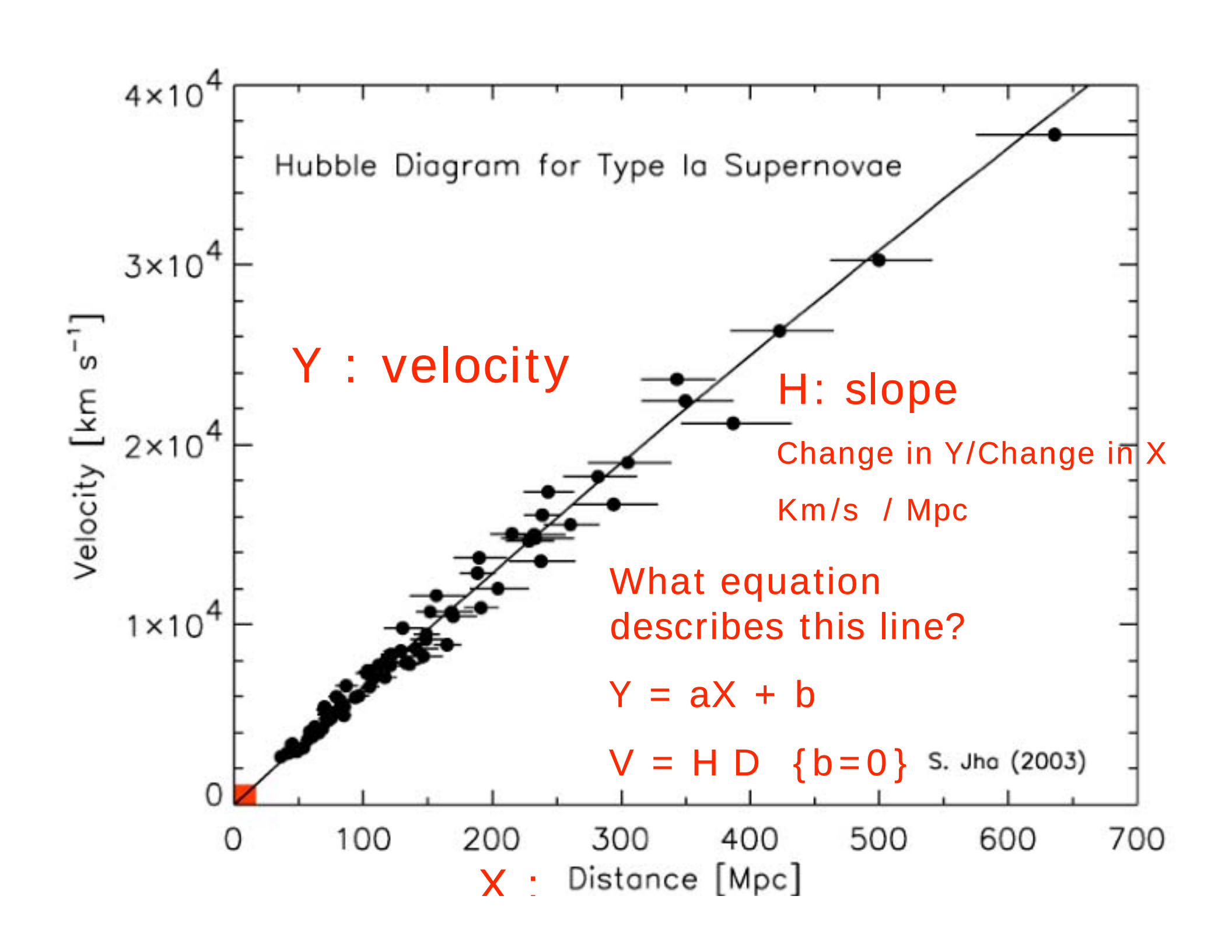

Hubble Diagram for Type Ia Supernovae
S. Jha (2003)
Velocity [km s^{-1}]
Distance [Mpc]
0
1×10^4
2×10^4
3×10^4
4×10^4
0
100
200
300
400
500
600
700

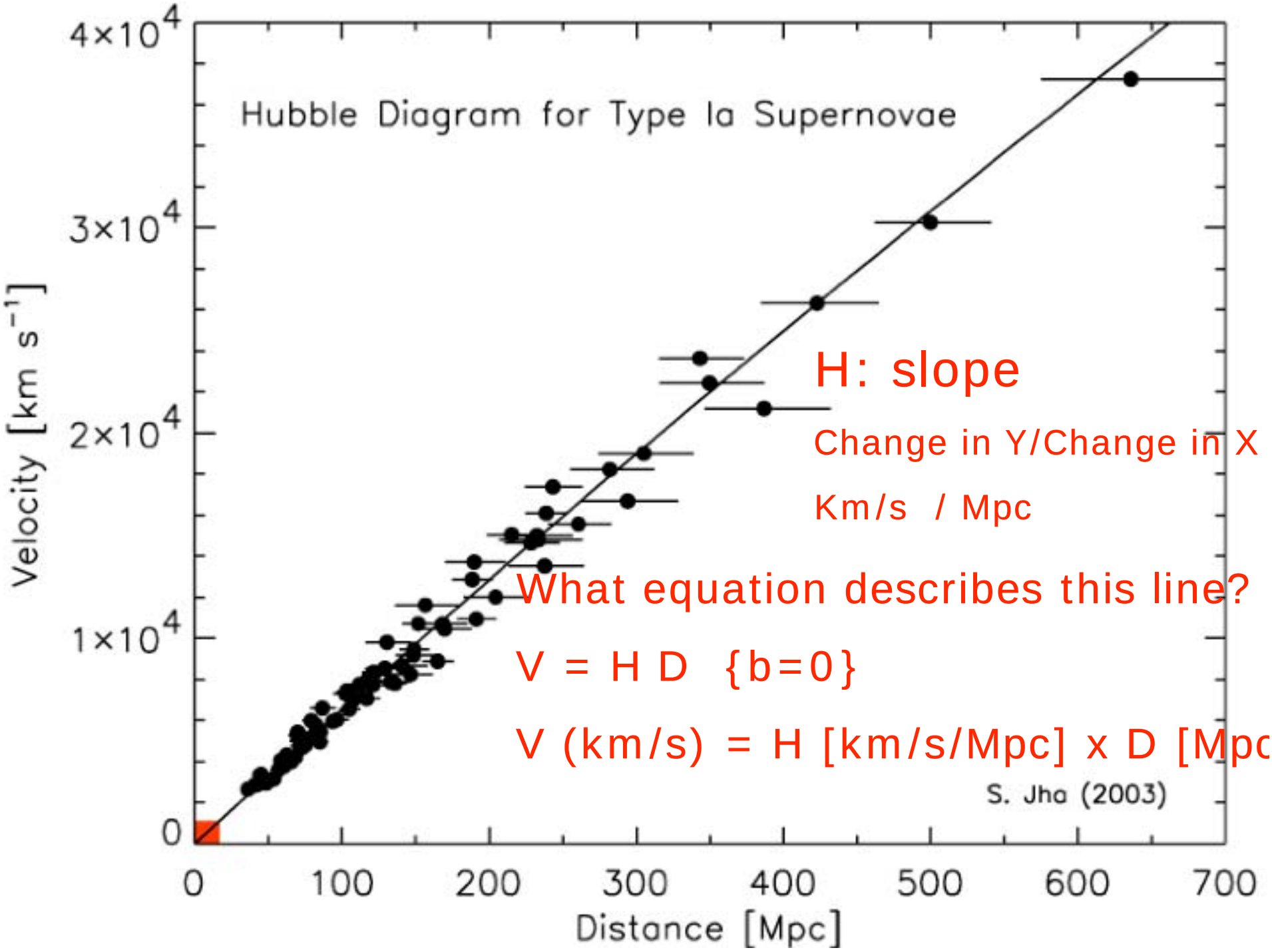
Homogenous, but not isotropic



Isotropic, but not homogeneous




Hubble Diagram for Type Ia Supernovae
Y : velocity
H: slope
Change in Y/Change in X
Km/s / Mpc
What equation describes this line?
Y = aX + b
V = H D {b=0}
S. Jha (2003)
X : Distance [Mpc]
Velocity [km s⁻¹]
4×10⁴
3×10⁴
2×10⁴
1×10⁴
0
0
100
200
300
400
500
600
700


Hubble Diagram for Type Ia Supernovae
Velocity [km s^{-1}]
4×10^4
3×10^4
2×10^4
1×10^4
0
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100
200
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500
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700
Distance [Mpc]
S. Jha (2003)
H: slope
Change in Y/Change in X
Km/s / Mpc
What equation describes this line?
V = H D {b=0}
V (km/s) = H [km/s/Mpc] x D [Mpc

Computing the Cosmic Age

V = H x D

t = Distance/Speed = D/(H x D)

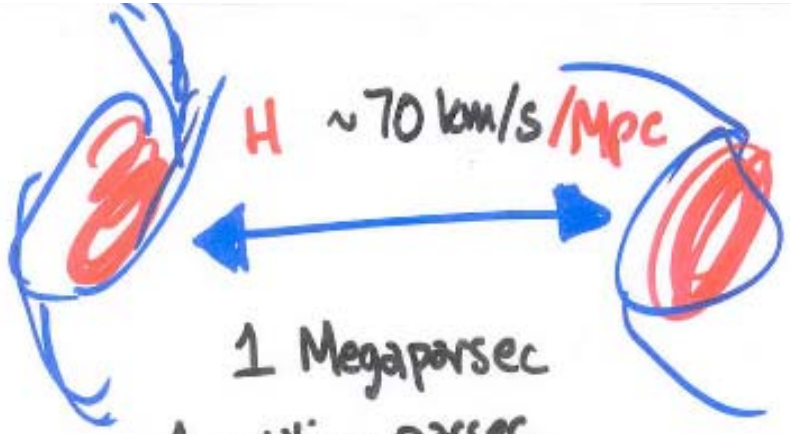
t = 1/H

Need to get the units right
(km/sec/Mpc) => 1/sec

t in seconds

Insert Hubble's Law:

V= D x H for "speed"



1 Megaparsec

1 million parsec

10^6 parsec

1 parsec = 3.08×10^{16} meters

30 Petameters!

HOW LONG TO GET TO THEIR CURRENT SEPARATION?

$$\text{TIME} = \frac{\text{DISTANCE}}{\text{SPEED}}$$

[s] [m] [miles]

[hours] [m/s] [miles/hour]

$$\text{TIME} = \frac{\text{DISTANCE}}{\text{DISTANCE} \times H} = \frac{1}{H} = \frac{1}{70 \frac{km}{s} / Mpc}$$

SPEED

3/19/07

When did cosmic expansion start?

$$t_{[s]} = \frac{1}{H\left[\frac{km/s}{Mpc}\right]} = \frac{1[Mpc]}{1[Mpc] \times H\left[\frac{km/s}{Mpc}\right]} = \frac{1\ Mpc}{70\ km/s}$$

$$t_{[s]} = \frac{1[Mpc] \times 10^{6}\left[\frac{pc}{Mpc}\right] \times 3\times10^{16}\left[\frac{m}{parsec}\right]}{70\left[\frac{km}{sec}\right] \times 10^{3}\left[\frac{m}{km}\right]}$$

$$t_{[s]} = \frac{3\times10^{6+16}\ [m]}{7\times10^{1+3}\left[\frac{m}{s}\right]} = \frac{3}{7}\times10^{22-4}\ [s]$$

$$t \approx \frac{3}{7}\times10^{18}\ [s]$$ ← "Age of Universe"

$0.43\times10^{18} \sim 1.3\times10^{17}$ sec

1 year $\approx 3\times10^{7}$ sec

$$t = \frac{3\times10^{18}\ [sec]}{7\times3\times10^{7}\left[\frac{sec}{year}\right]} = \frac{1}{7}\times10^{18-7} \approx 0.14\times10^{11}$$

1.4×10^{10} (year)

14×10^{9} years = 14 BILLION YEARS

Cosmic Age

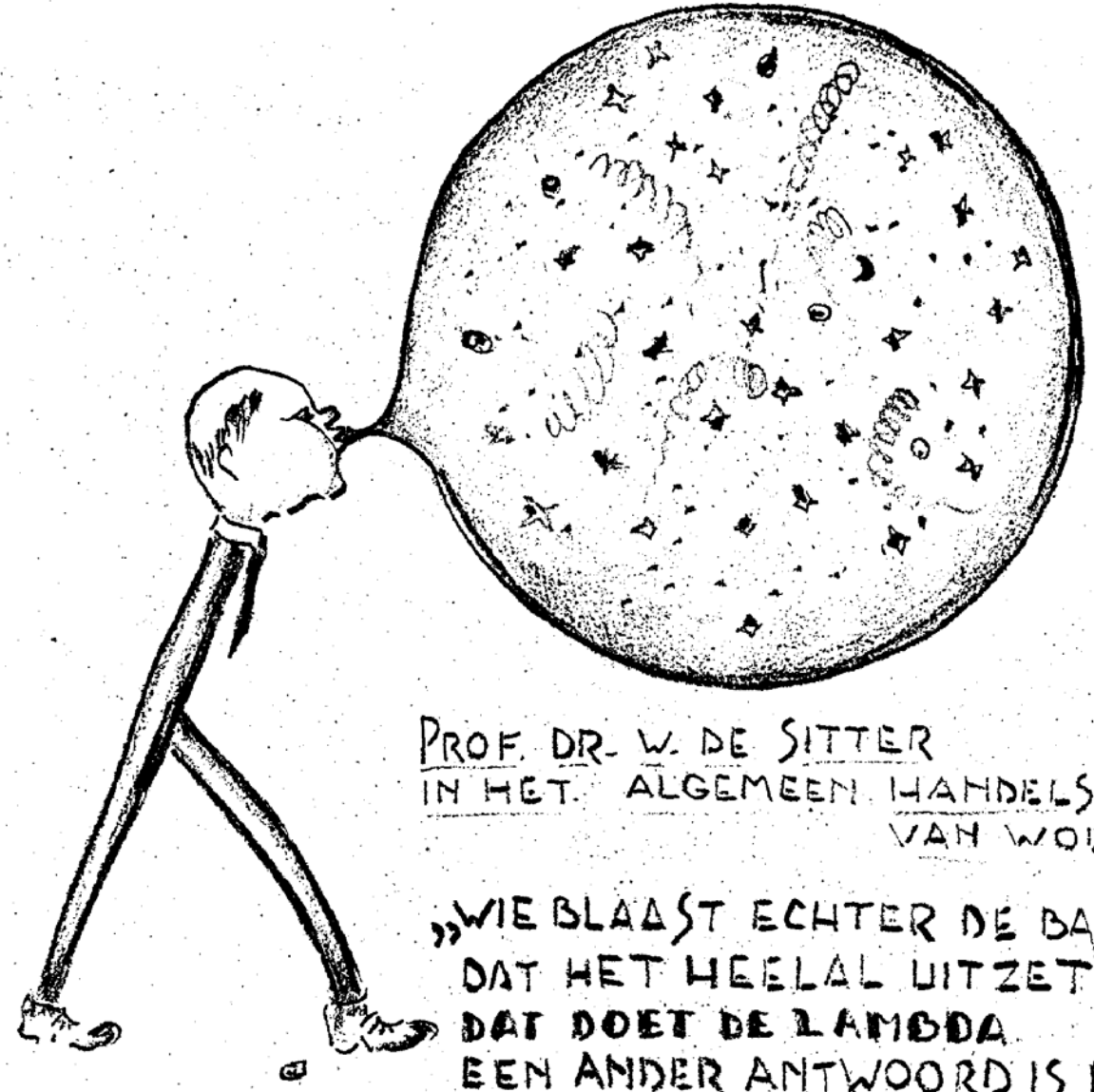
From expansion:
T = 14 Gyr (H/70)

Other ages--
Radioactivities-- solar system ~5 Gyr
Ages of globular cluster stars ~12 Gyr

A real history of the physical world!


WHO'S PERFECT?
EXPANDING UNIVERSE =>
"AWAY WITH THE COSMOLOGICAL CONSTANT!"

Λ as the source of cosmic expansion: DeSitter in 1930



PROF. DR. W. DE SITTER
IN HET ALGEMEEN HANDELSBLAD*
VAN WOENSDAG 9 JULI 1930

„WIE BLAAST ECHTER DE BAL OP? WAT MAAKT
DAT HET HEELAL UITZET, OF OPZWELT?
DAT DOET DE LAMBDA
EEN ANDER ANTWOORD IS NIET TE GEVEN"

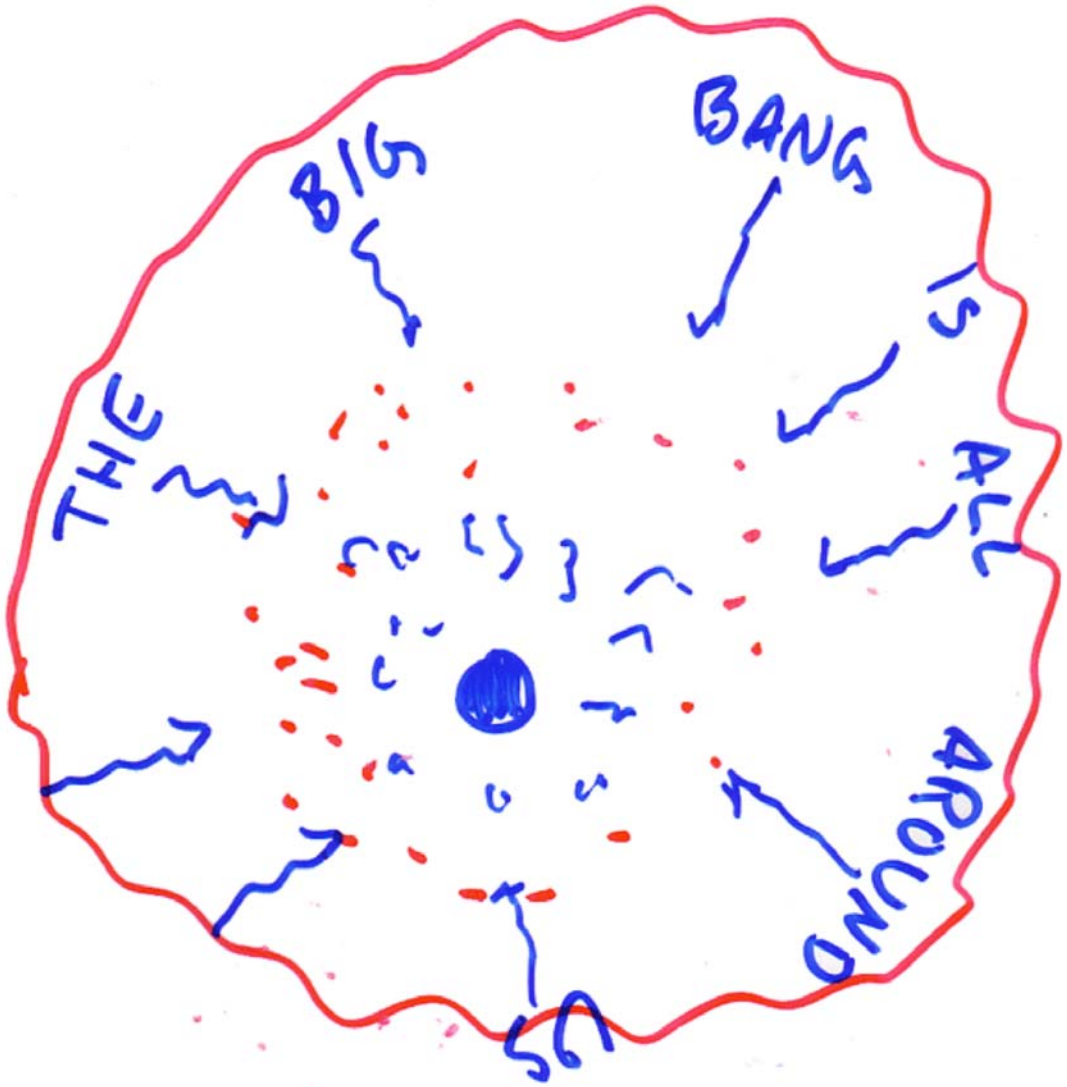
"Who however blows up the ball? What makes the Universe expand: or swell up?
That is done by the Lambda.
An other answer cannot be given."

* A well known dutch newspaper

Thanks to Jim Peebles

Einstein's View on Λ

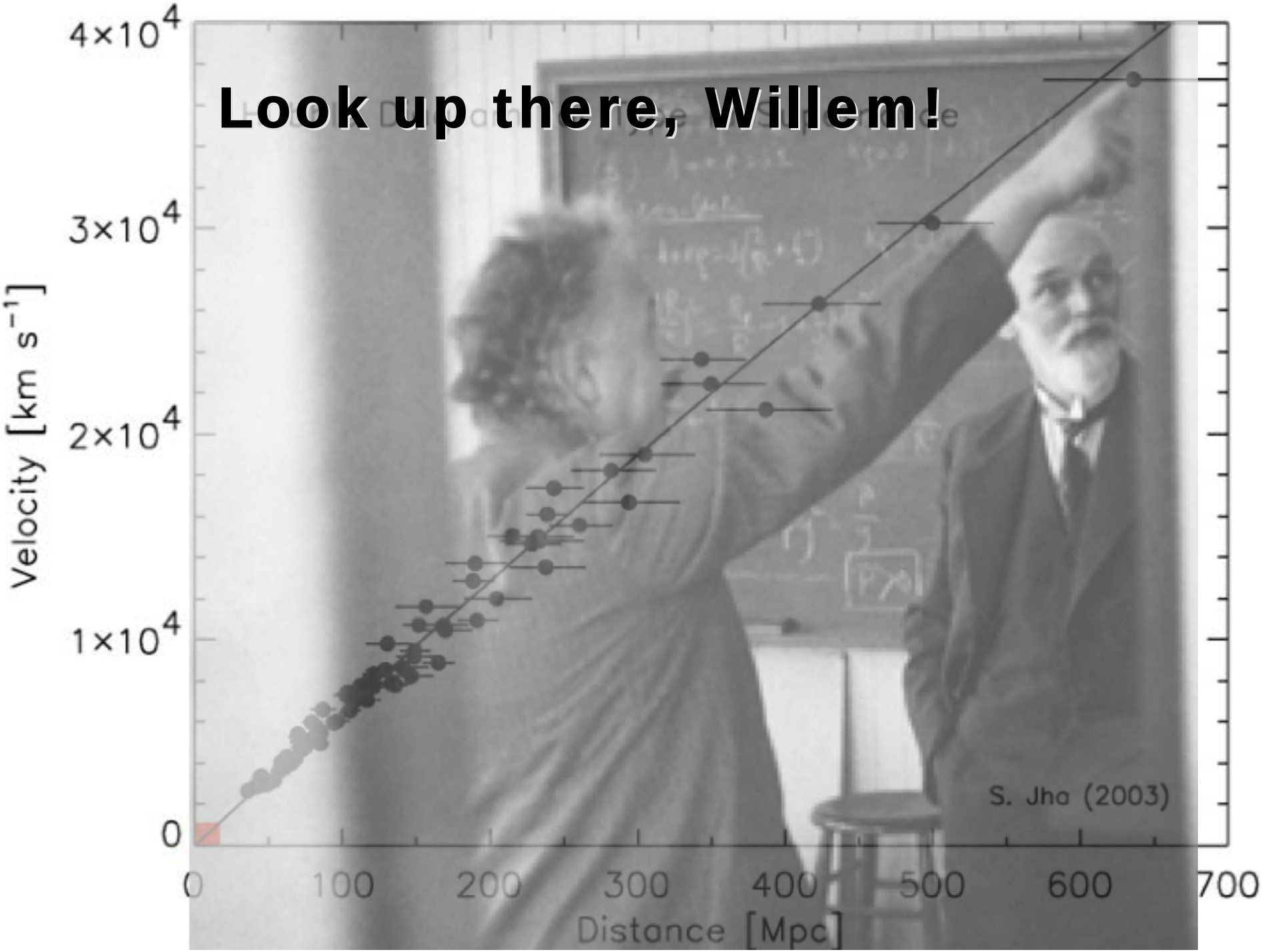
"An increase in the precision of data ...will enable us in the future to fix its sign and determine its value." 1932

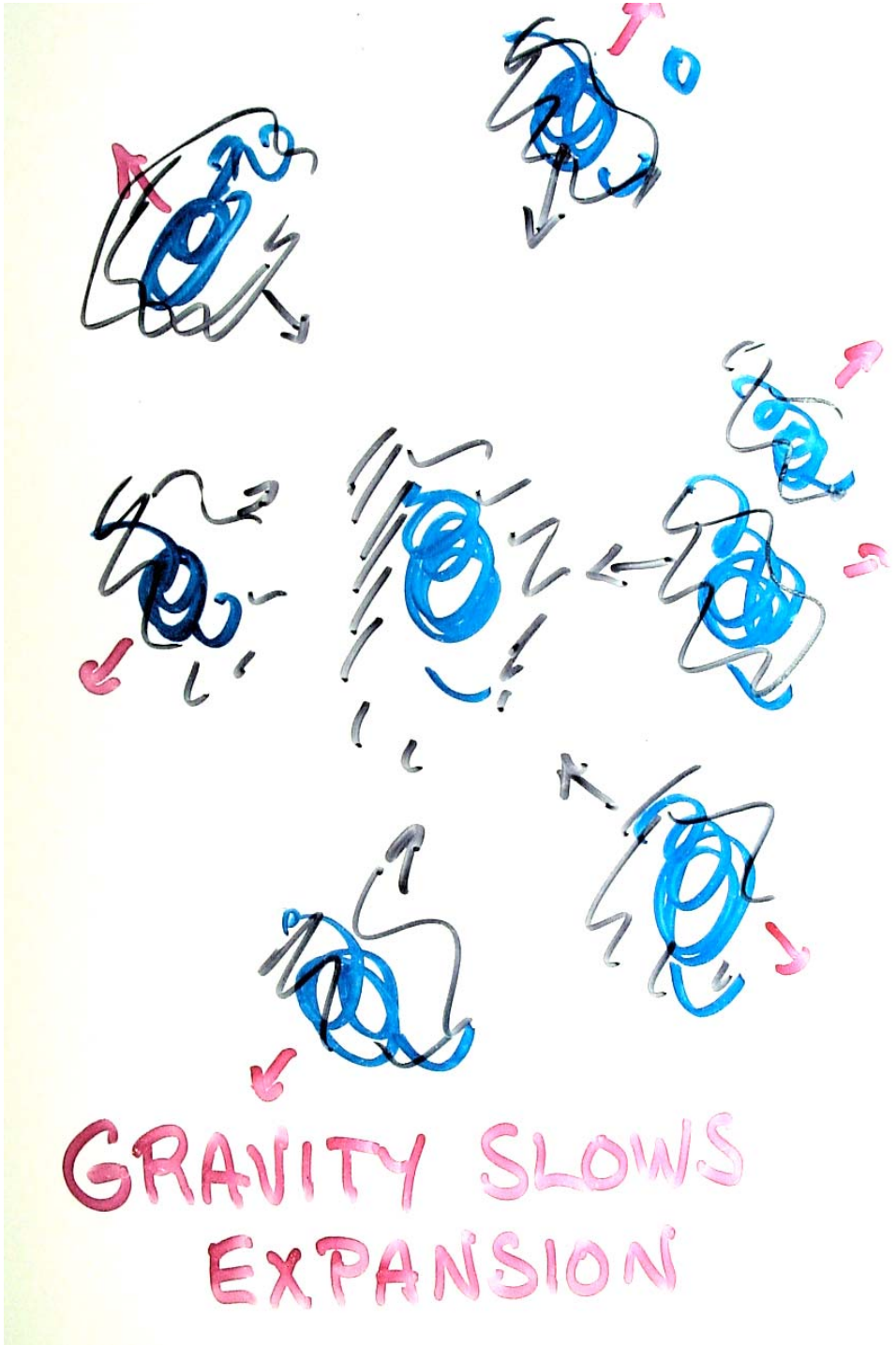


BIG BANG WAS HERE

14 BILLION YEARS AGO

3/19/07

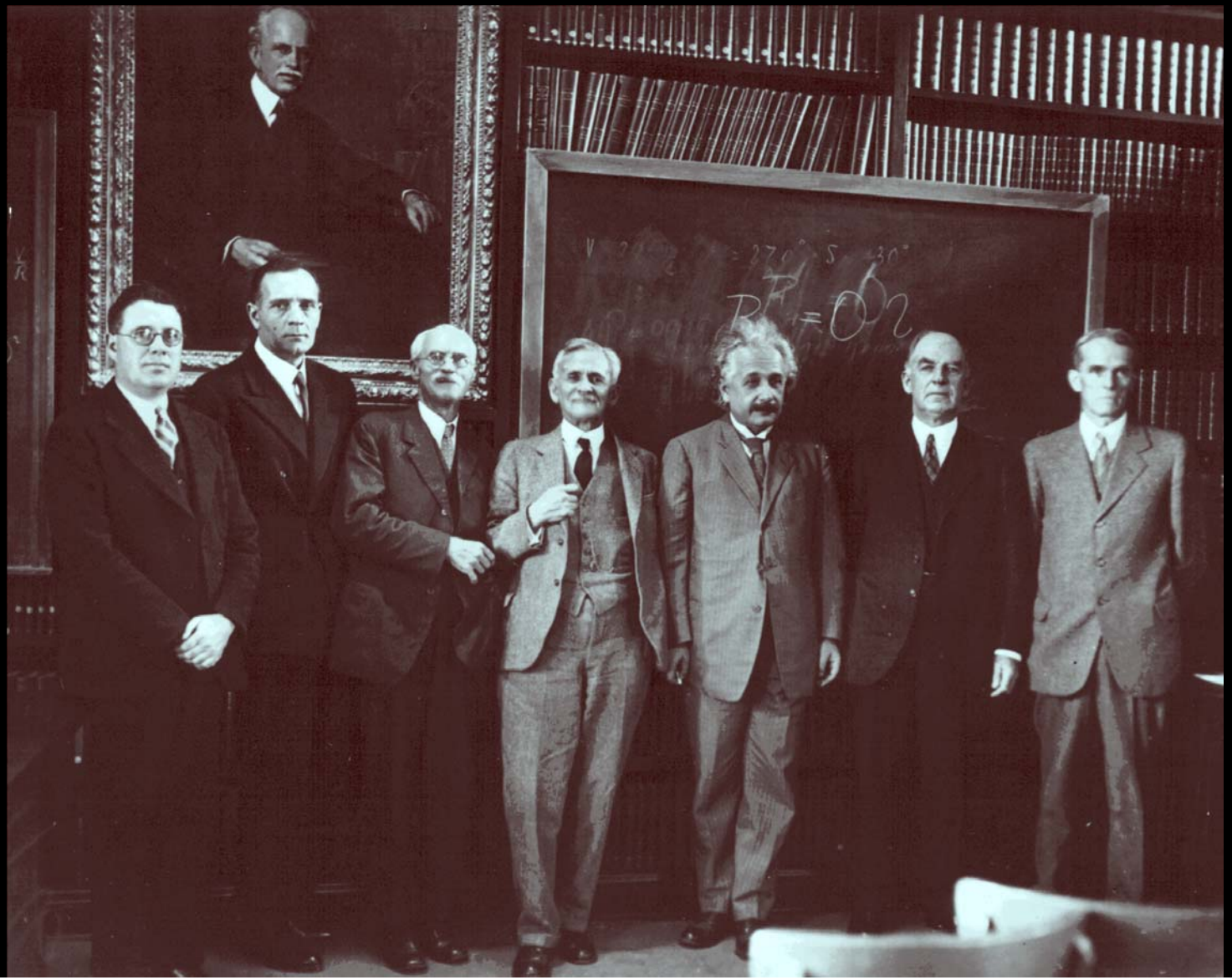

Look up there, Willem!
Velocity [km s^{-1}]
4×10^4
3×10^4
2×10^4
1×10^4
0
0
100
200
300
400
500
600
700
Distance [Mpc]
S. Jha (2003)



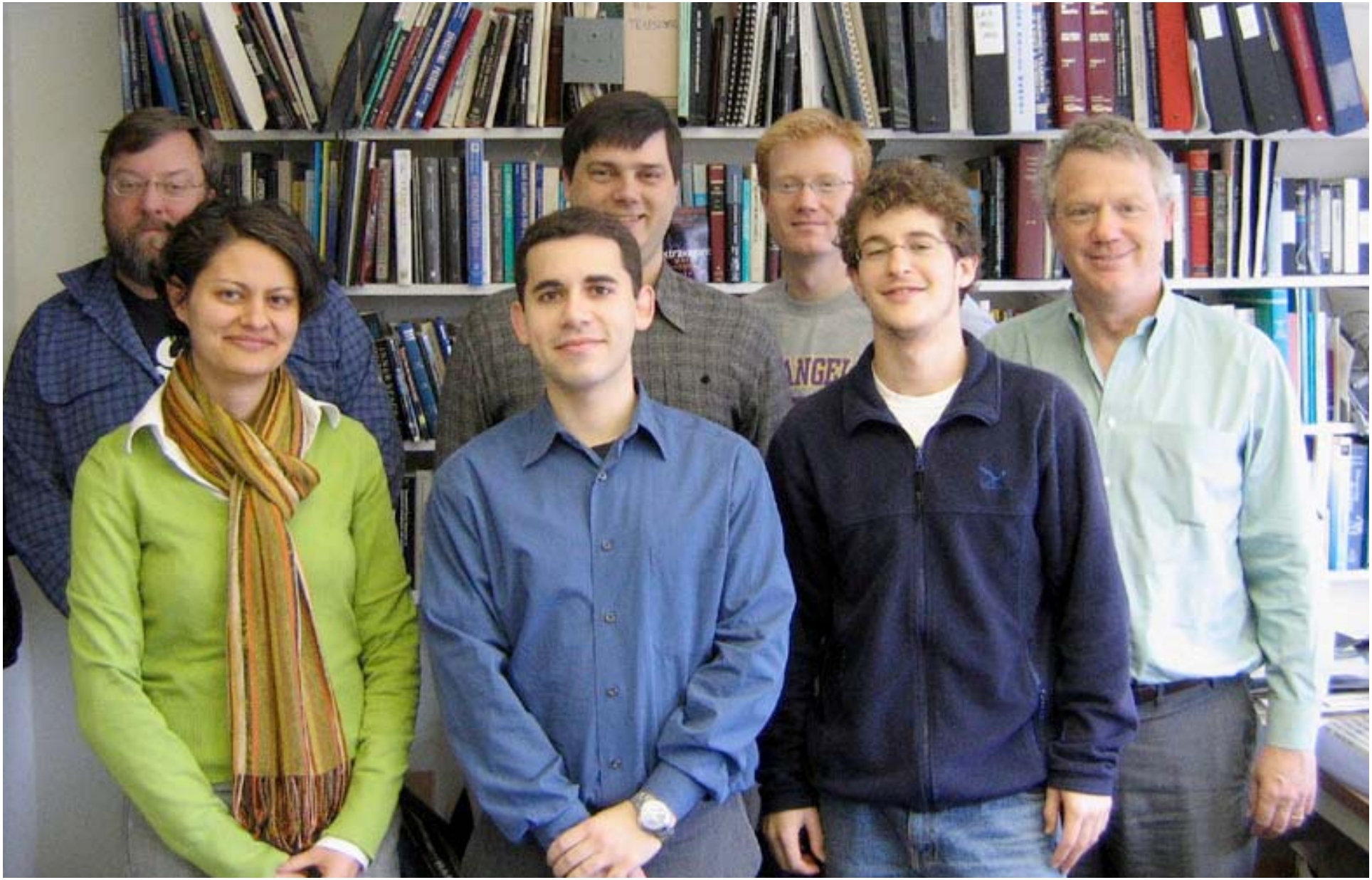
Expected to measure slowing down of cosmic expansion due to gravity.

's

Einstein visits Mt Wilson 1931



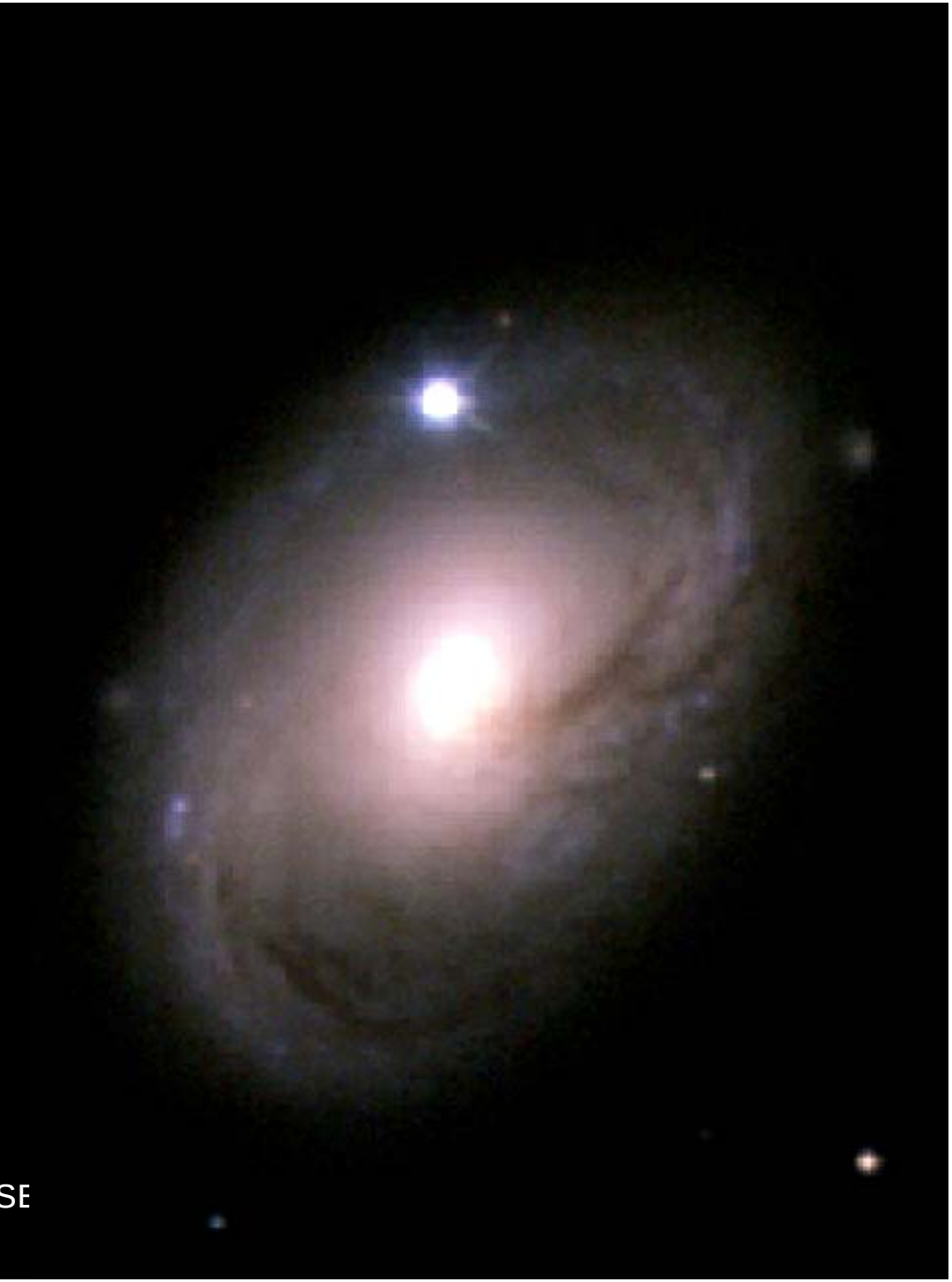
CfA Supernova Group
2006

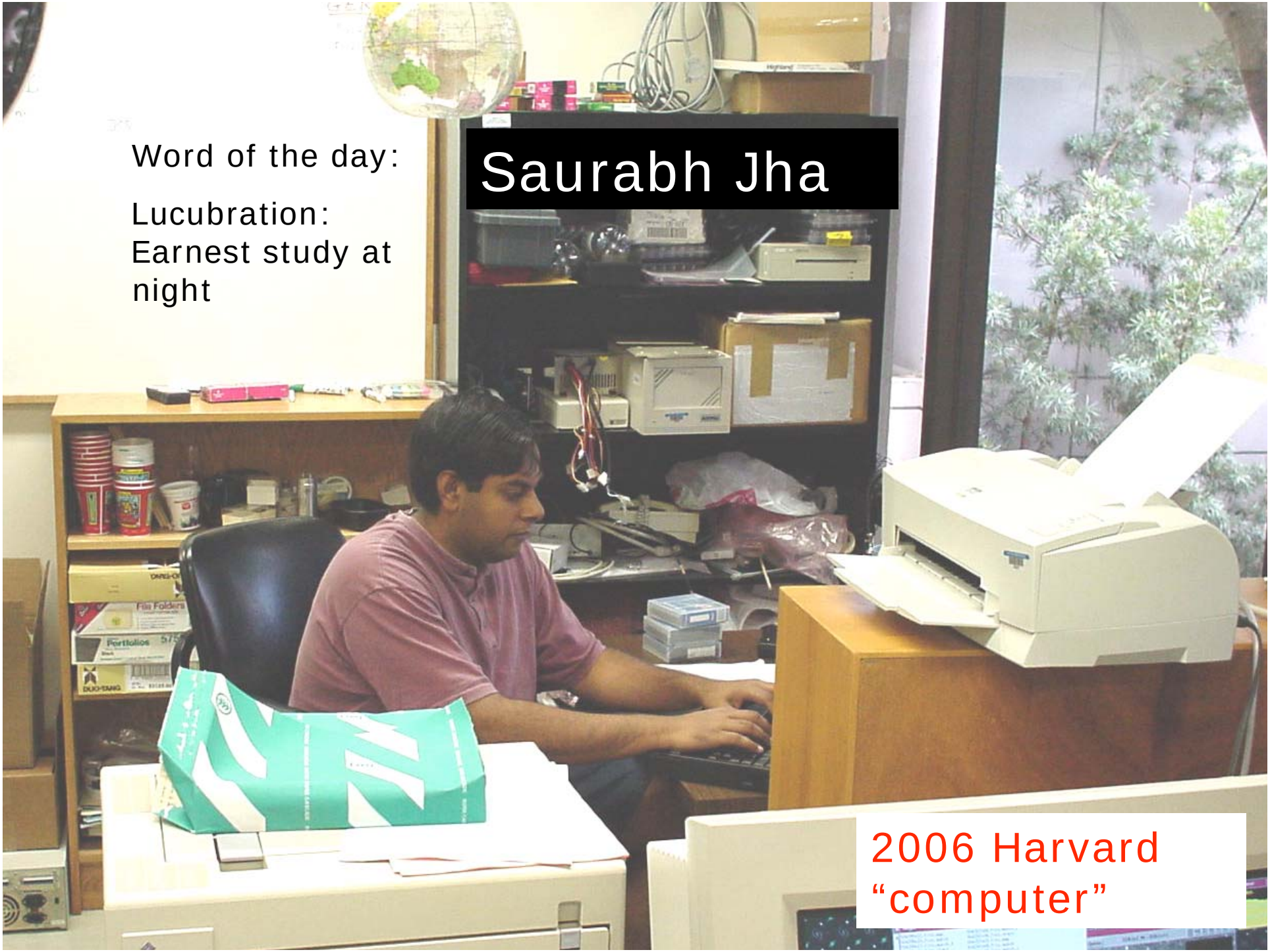


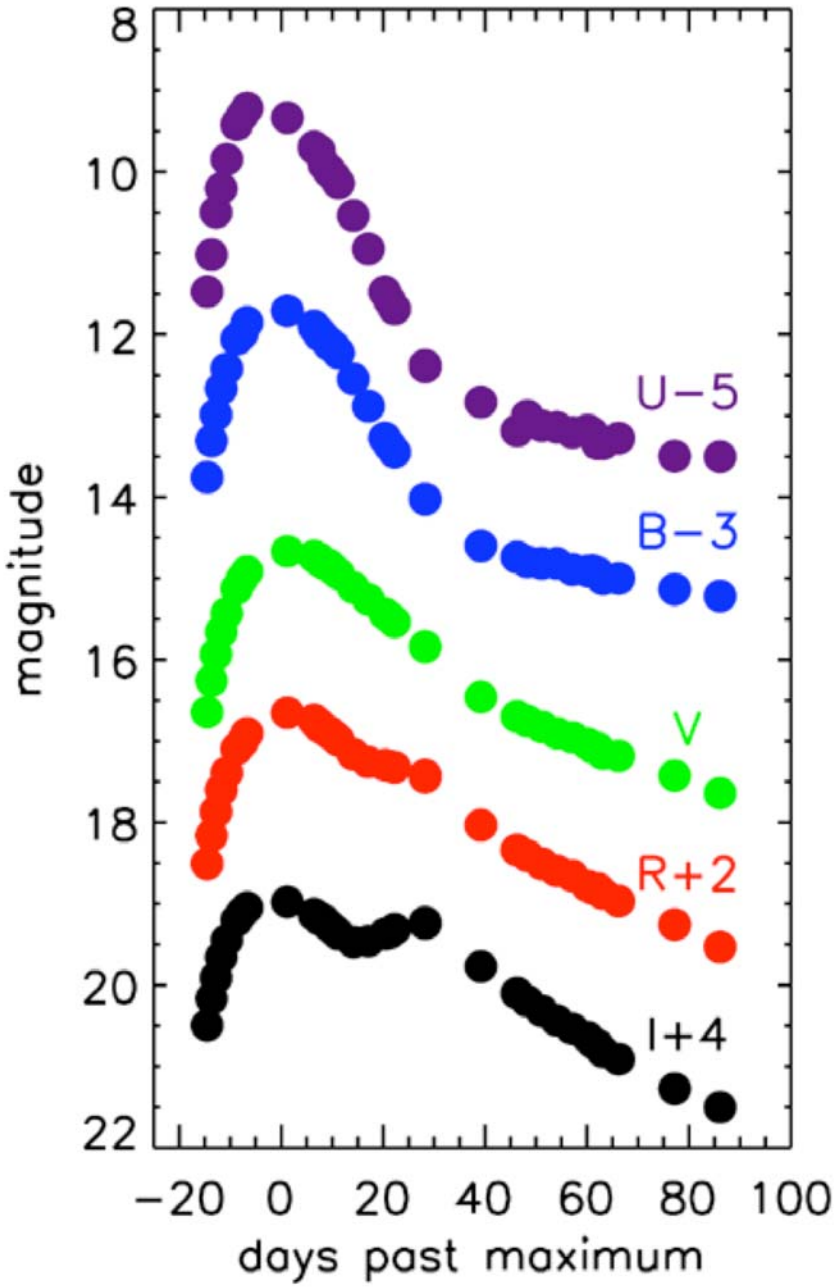
Exploding stars
~ 4 x 10^9 Suns

~1 SNIa /century in a galaxy

~1 per second in the Universe!




Word of the day:
Lucubration:
Earnest study at night
Saurabh Jha
2006 Harvard
“computer”

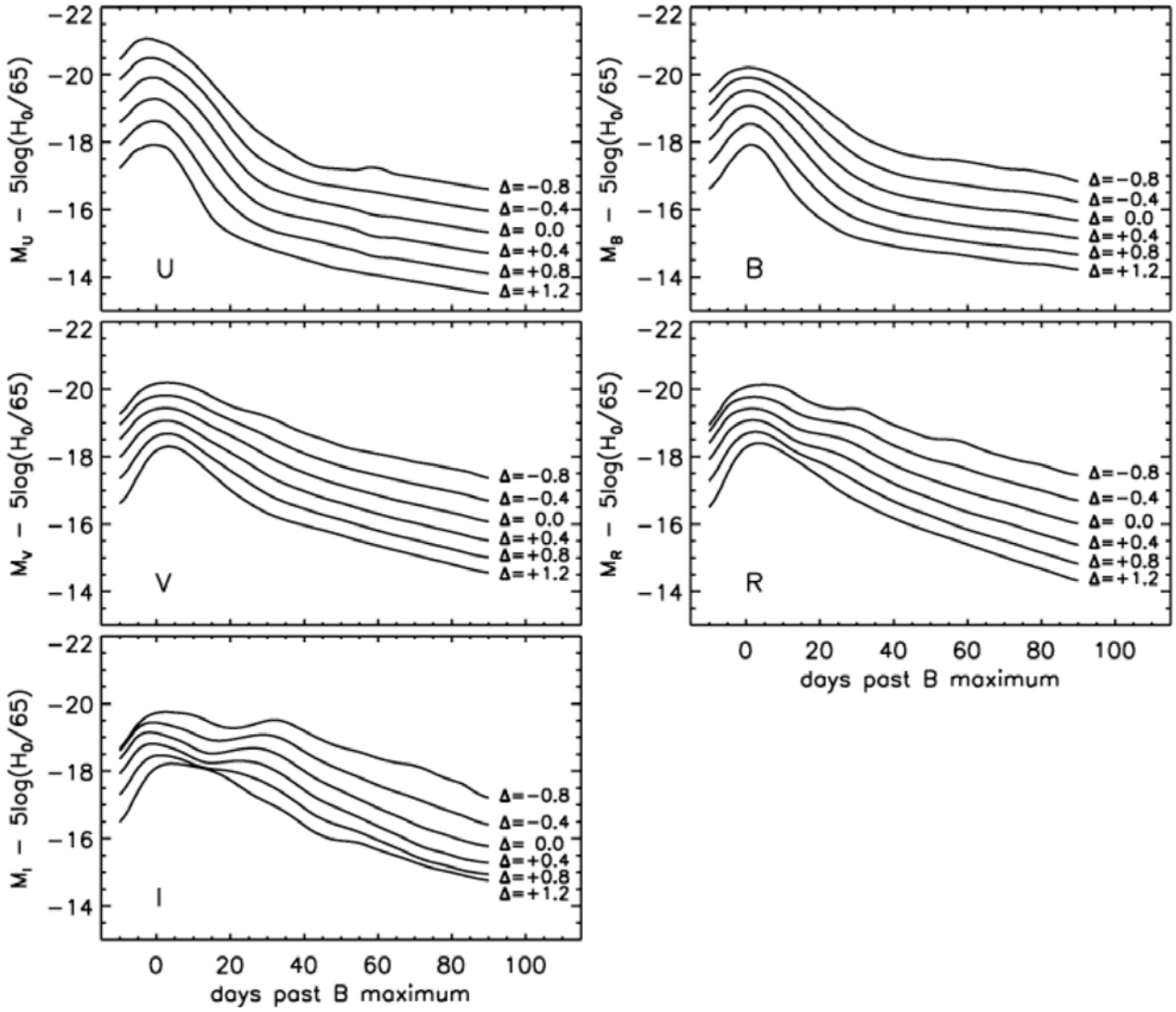


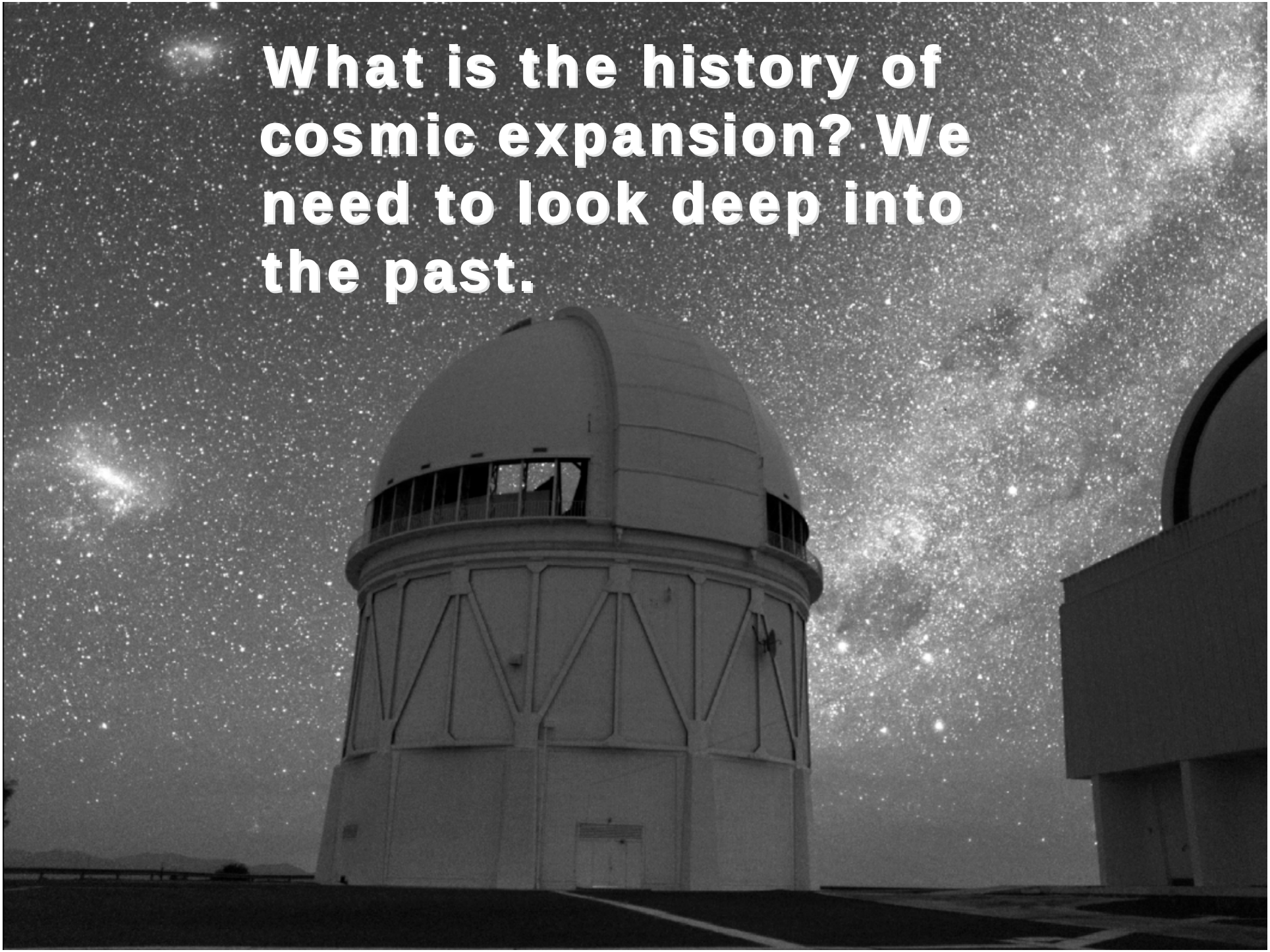
Light Curves: Clues to Luminosity

It is worth noting that the brightest supernovae have the slowest declines

:hers

Light Curve Shapes allow us to separate the bright ones from the dim bulbs

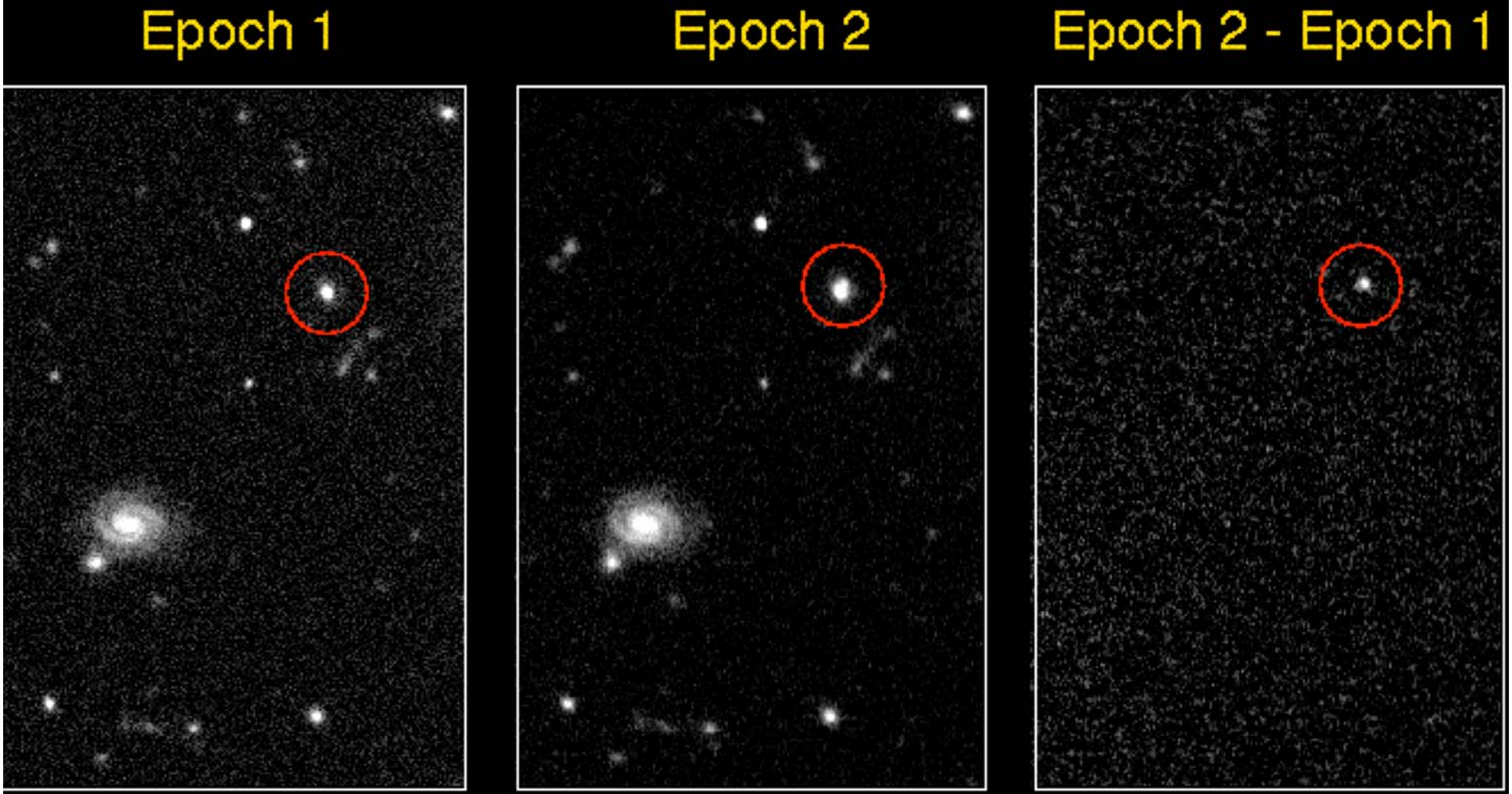



What is the history of cosmic expansion? We need to look deep into the past.

Brian Schmidt explains how easy this will be

Searching by Subtraction

unskilled and therefore inexpensive labor
under careful supervision--computers!



ESSENCE Results

An accelerating universe!

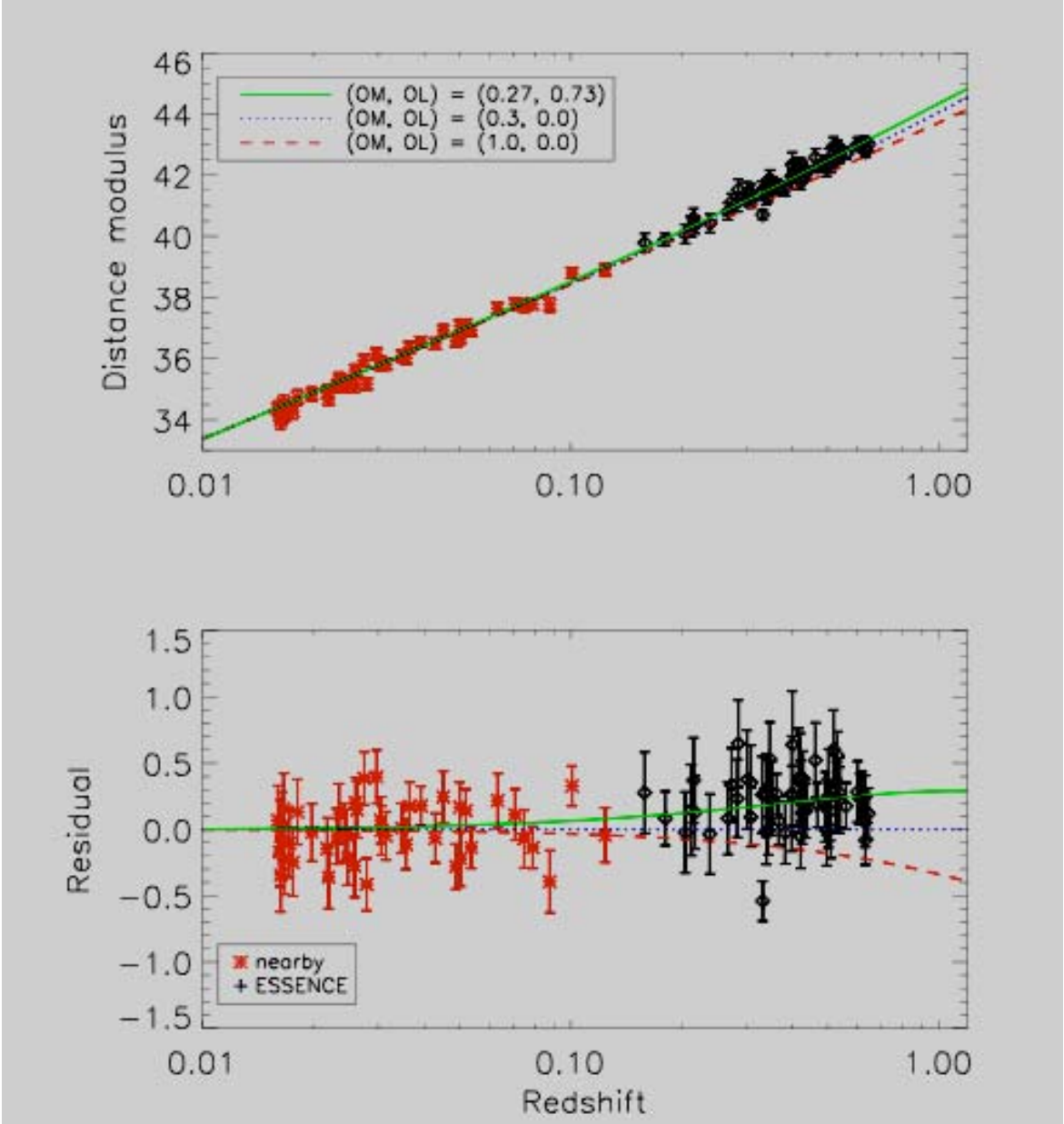


Fig. 8.— Luminosity distance modulus versus redshift for the ESSENCE and nearby SNe Ia for MLCS2k2 with the "glosz" A_V prior. For comparison the overplotted solid line and residuals are for a $(w, \Omega_M, \Omega_\Lambda) = (-1, 0.27, 0.73)$ Universe.

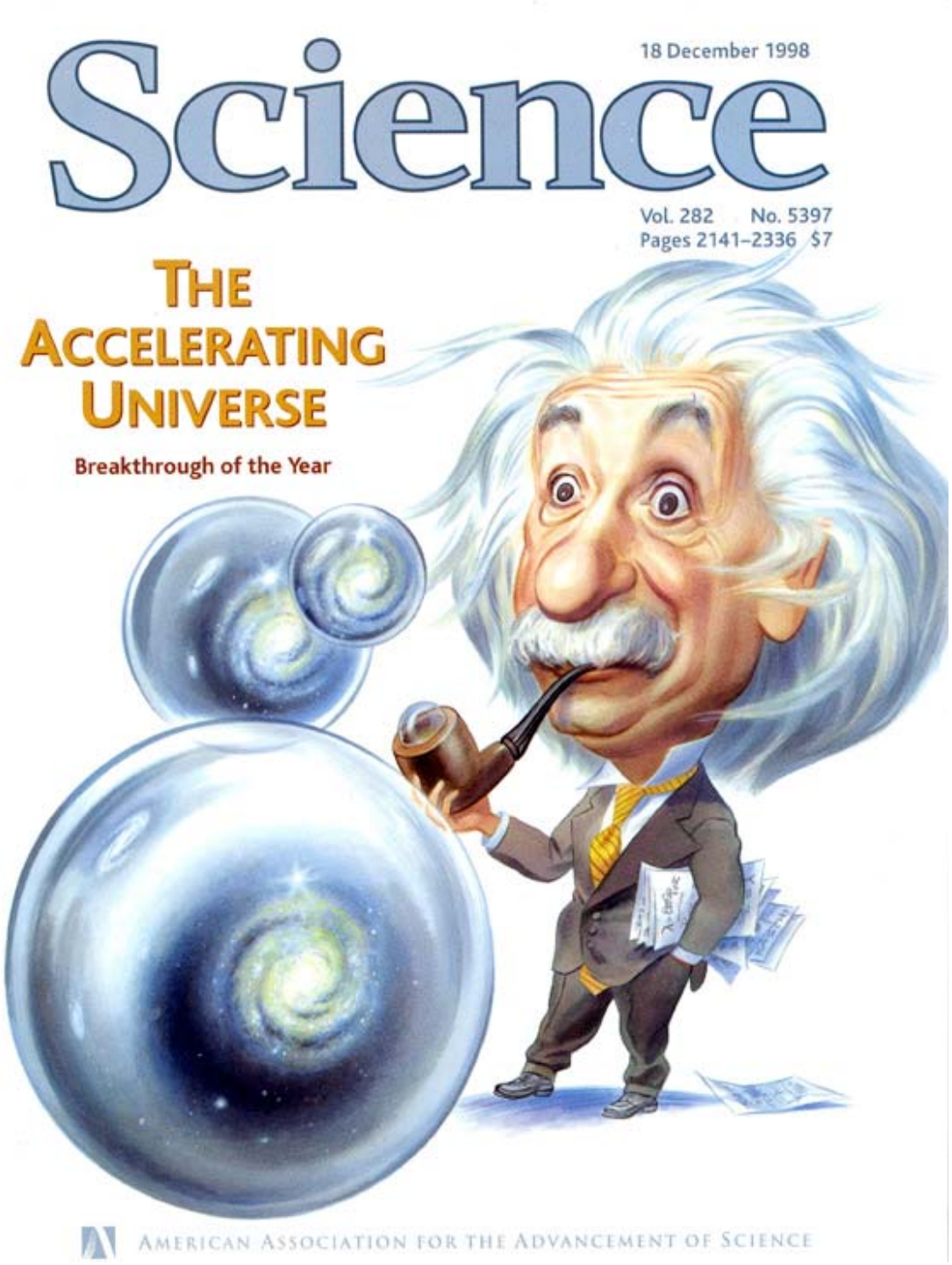
Big News in 1998!

High-Z Team

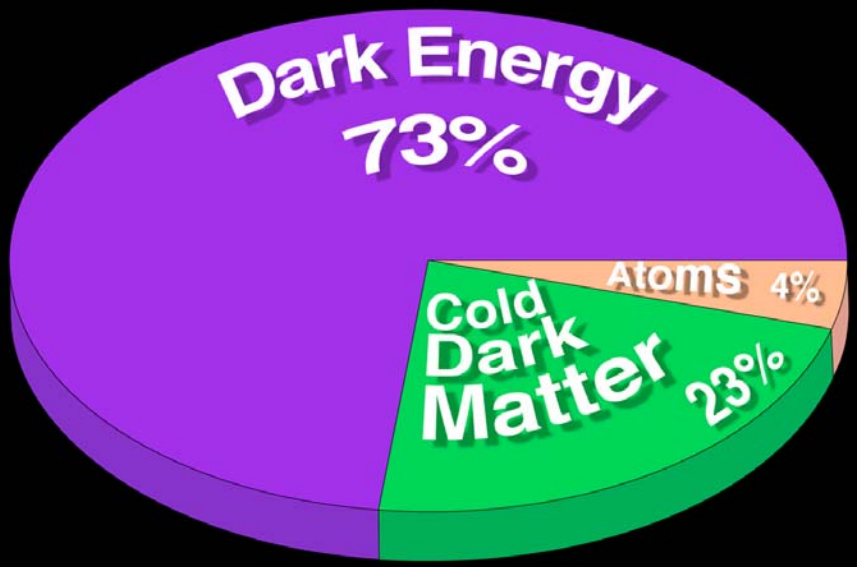
Riess et al. (1998)

Supernova Cosmology Project

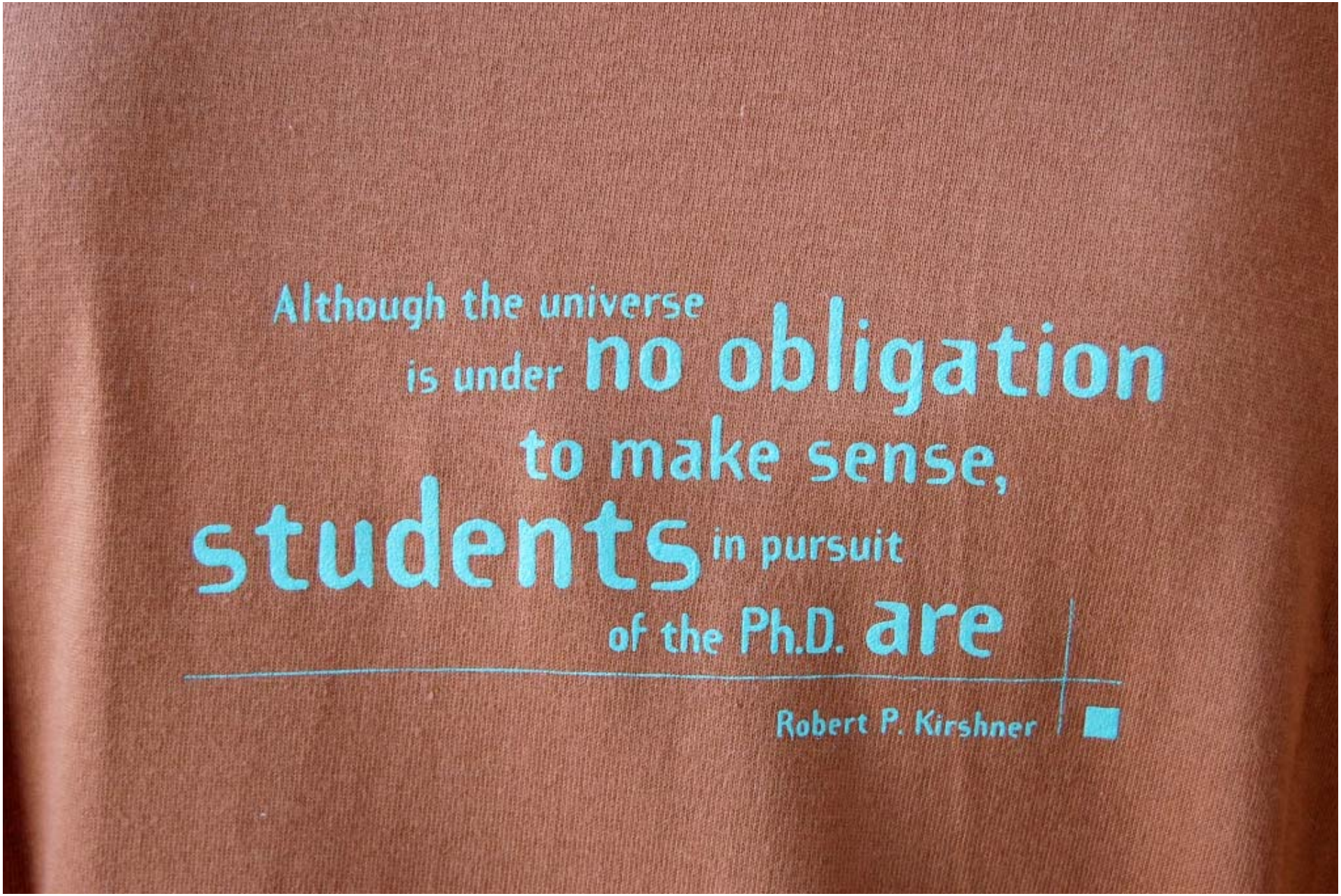
Perlmutter et al. (1999)



Not Your Father's Universe!

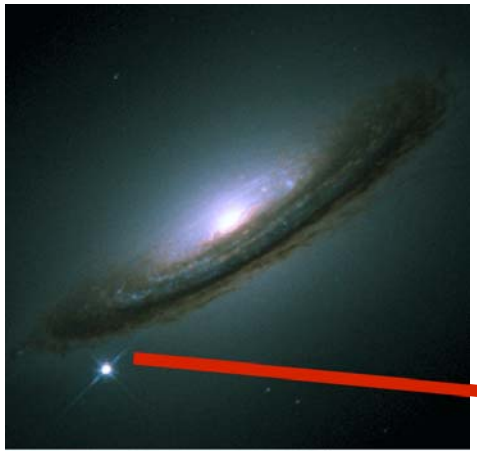


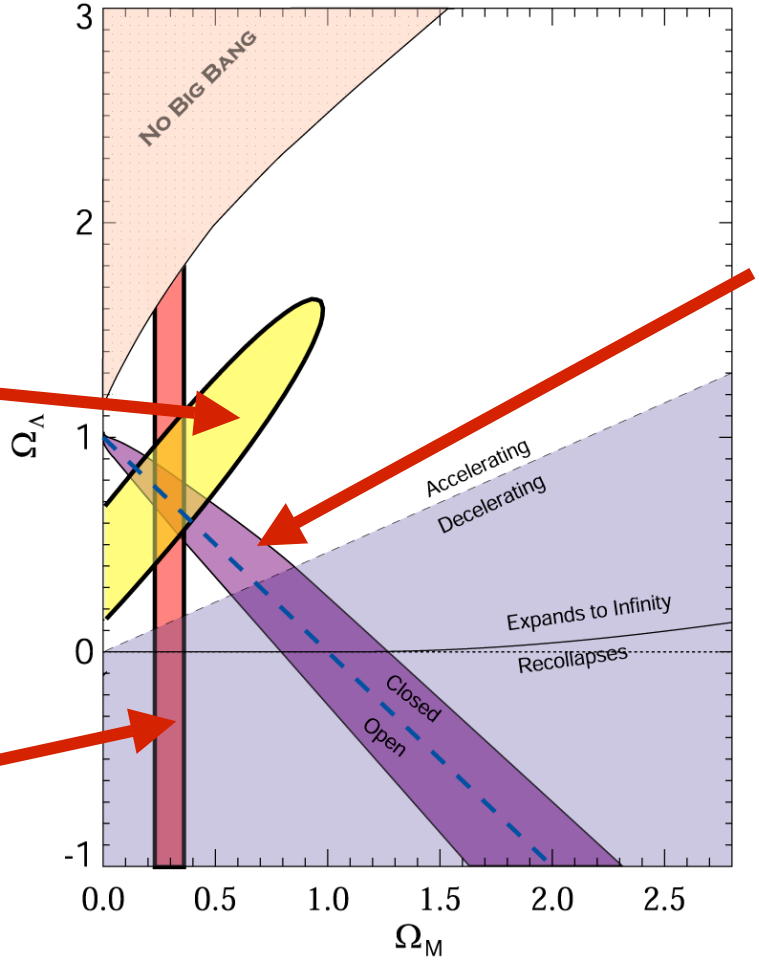
3/19/07 SB Teachers


Although the universe
is under no obligation
to make sense,
students in pursuit
of the Ph.D. are
Robert P. Kirshner

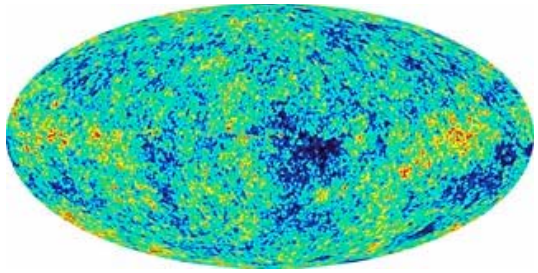
Dark Energy is Real...

SNe Ia



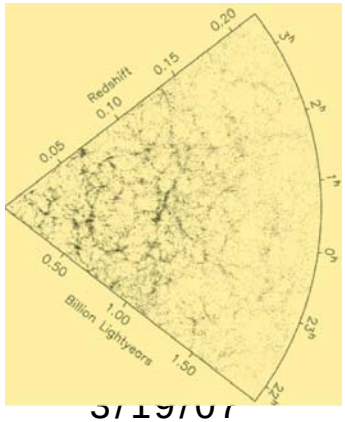


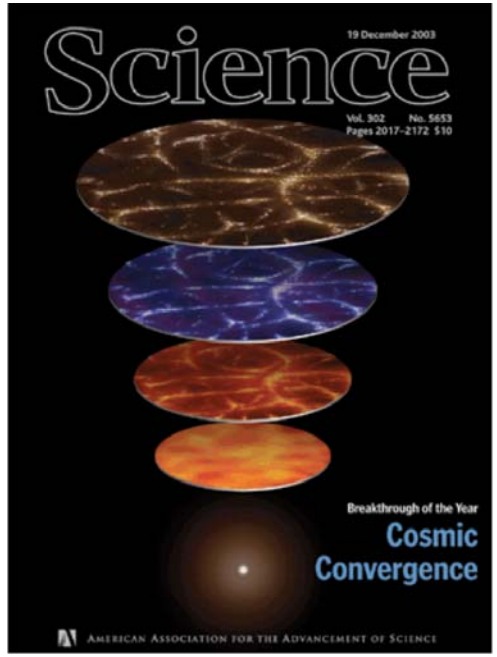
CMB(WMAP)



+ ISW, X-ray Clusters

LSS



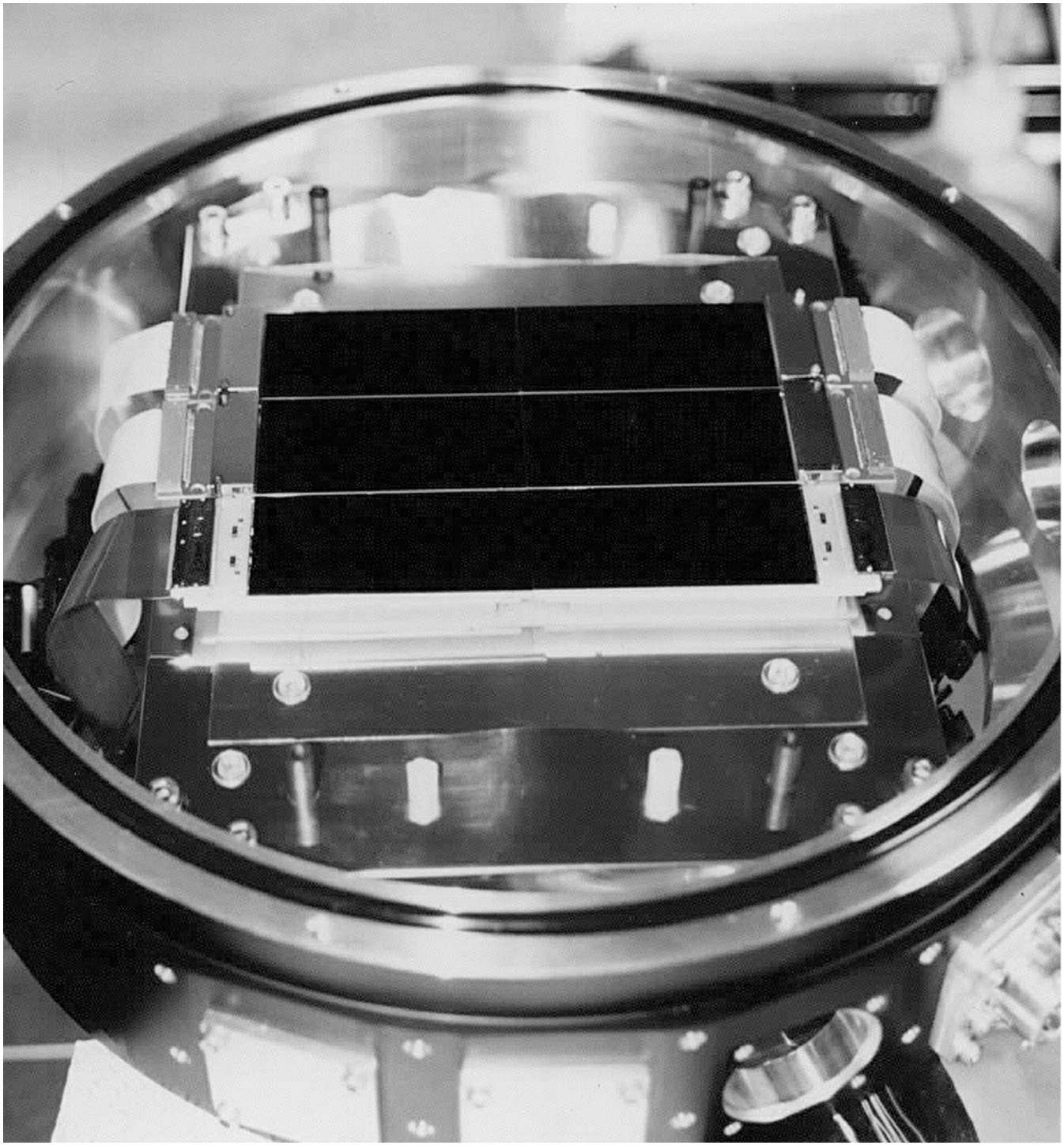


But what is it?

SB Teachers

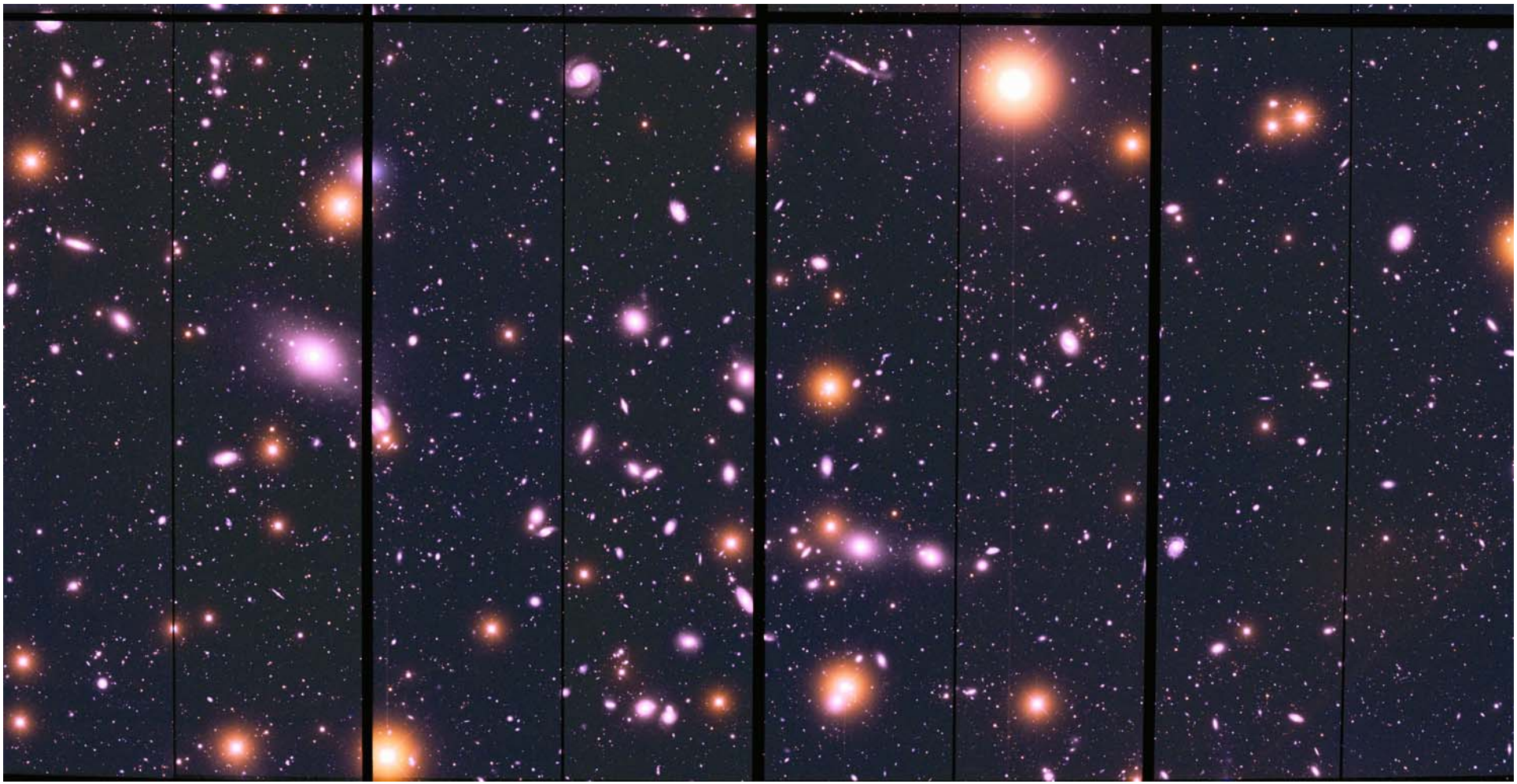
Google ‘Dark Energy’!

“These specialized processes are also responsible for the very distinct odor of Dark Energy!”



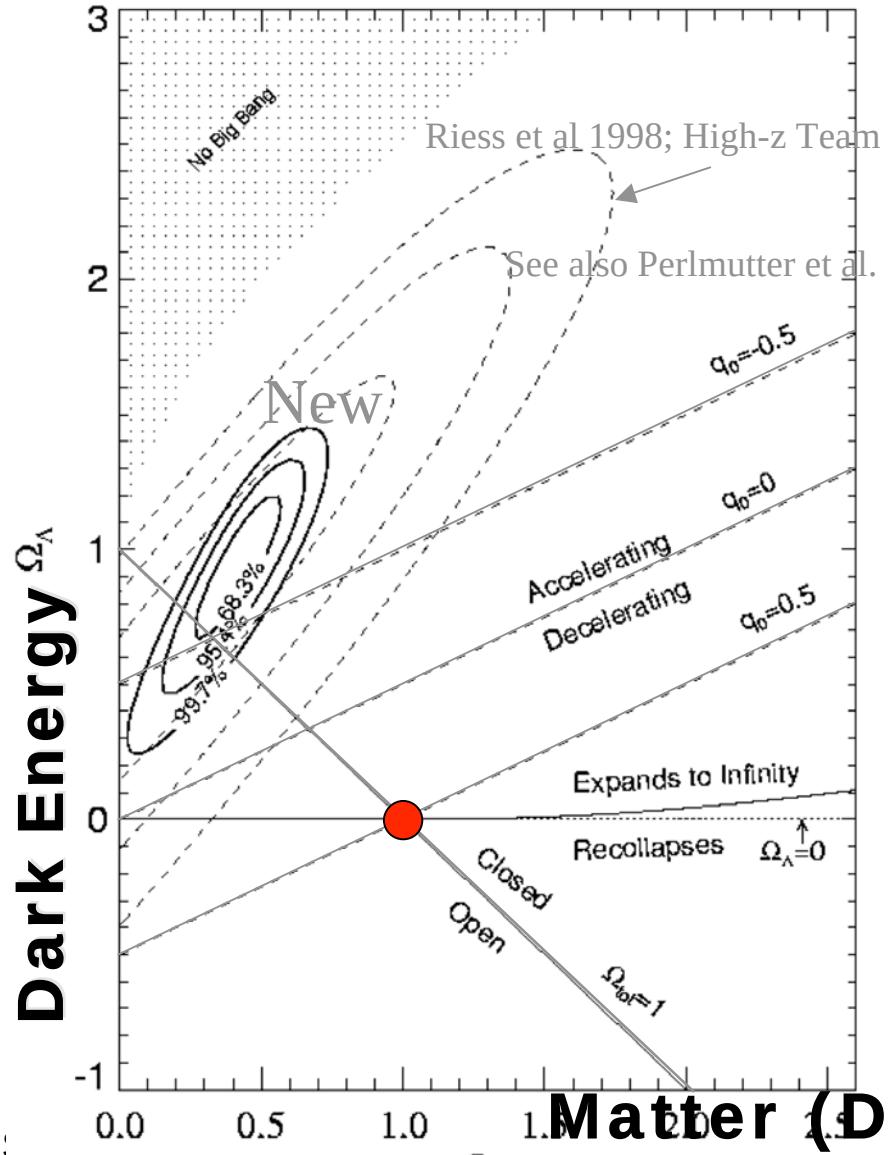
Giant Electronic Cameras Improve Searches

1/100 years ~ 1/5000 weeks => 5000 galaxies



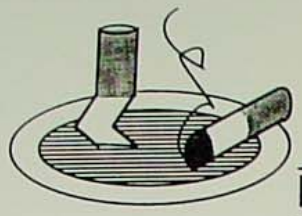
Updated Constraints

Factor of 7 improvement from 1998 by building up the samples and extending the redshift range



Dark Energy

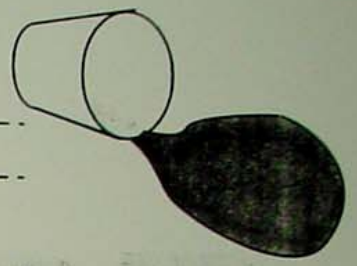
Matter (Dark & Shining)



INTERNATIONAL BROTHERHOOD OF THEORISTS

LOCAL 016

cogito ergo sum



UNICARD

Robert Kirshner

member in good standing

David Gross
president

David Gross

Adam Burrows
shop steward

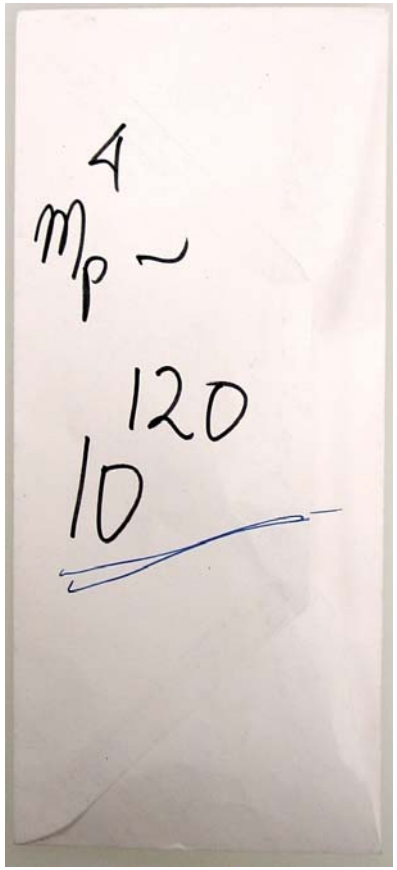
Adam Burrows

Real theorist!

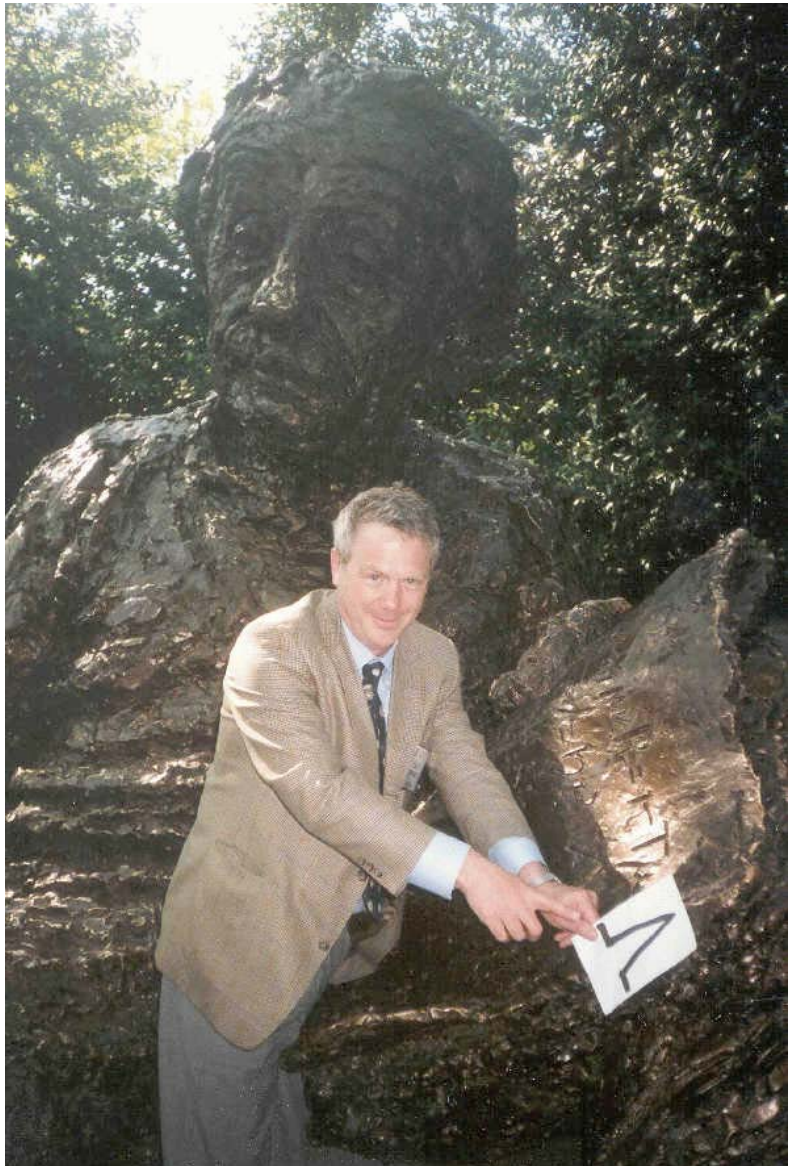
Is the Dark Energy the Cosmological Constant?

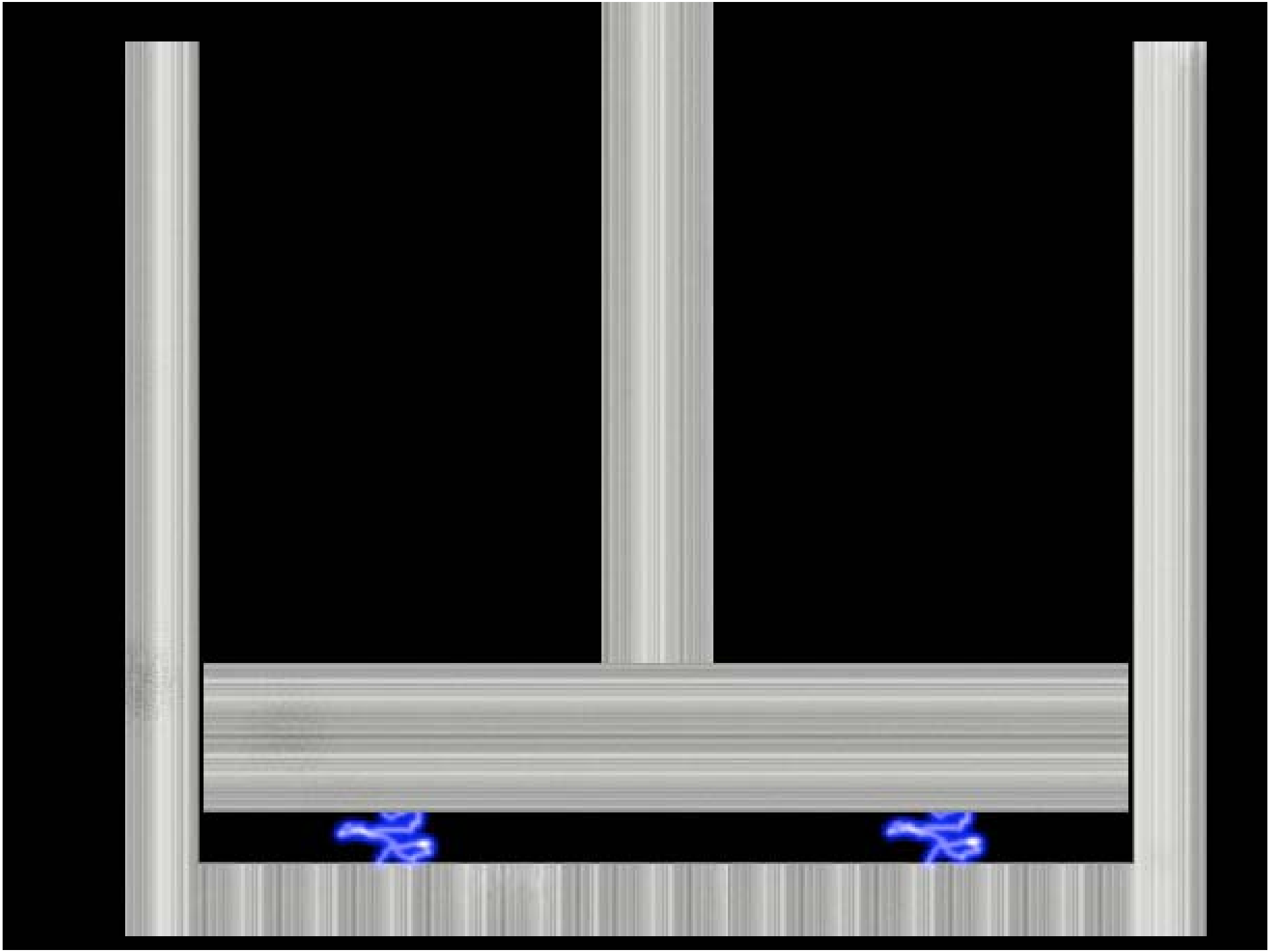
Not good quantitative agreement!

"A bone in the throat."--
S. Weinberg



Putting Λ on the Right Hand Side





Essence results: dark energy could be Λ

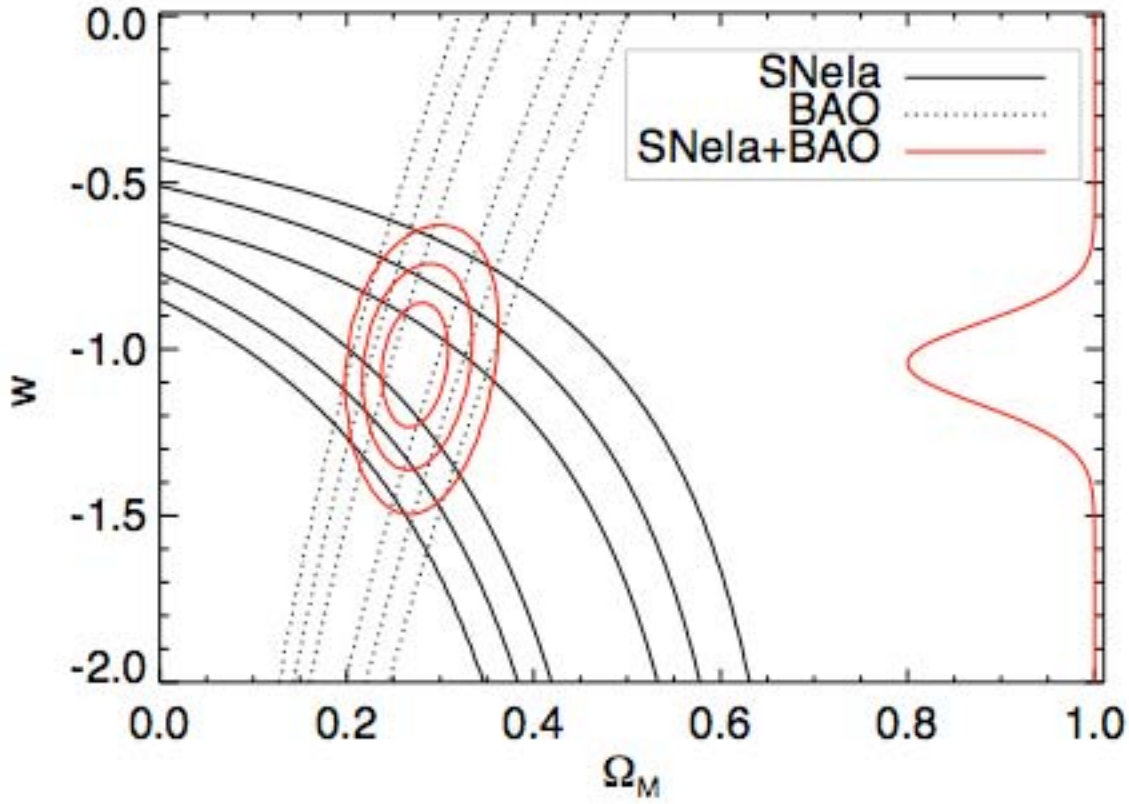
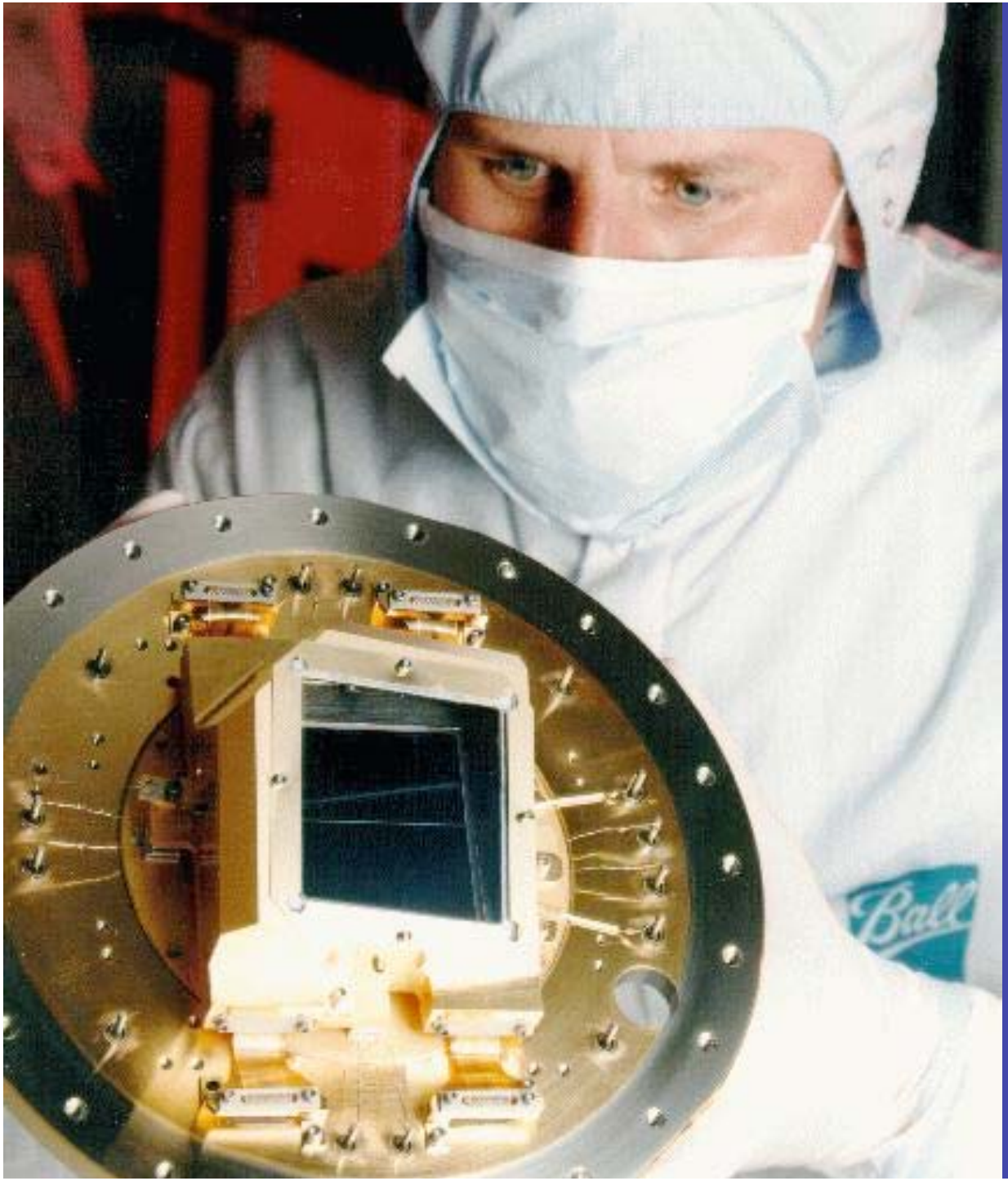


Fig. 9.— The Ω_M-w contours from the ESSENCE + nearby sample for MLCS2k2 with the "glosz" A_V prior.

Searching for Supernovae with HST

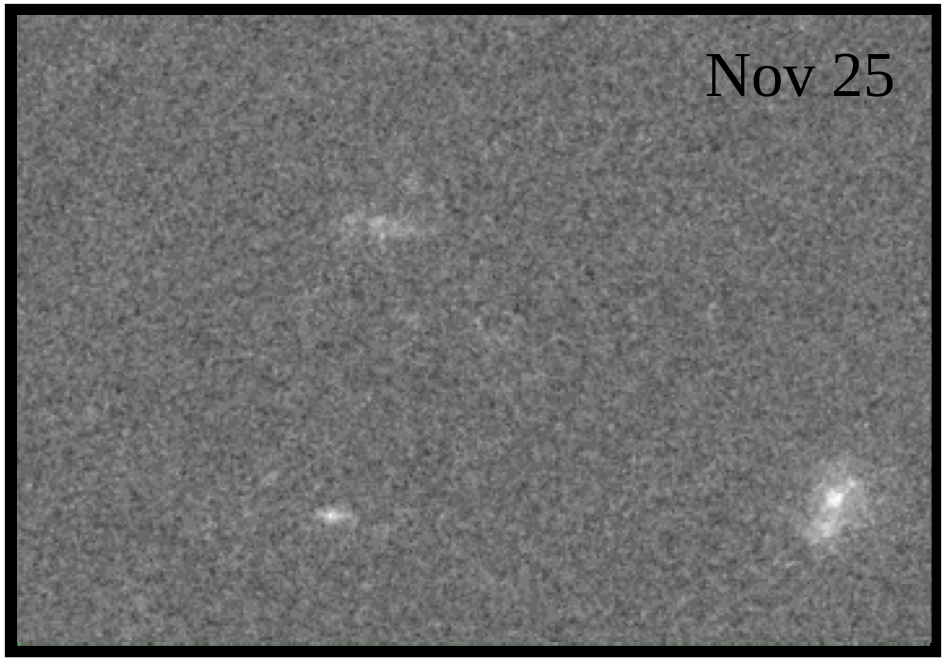
Back to the age of ***de***celeration

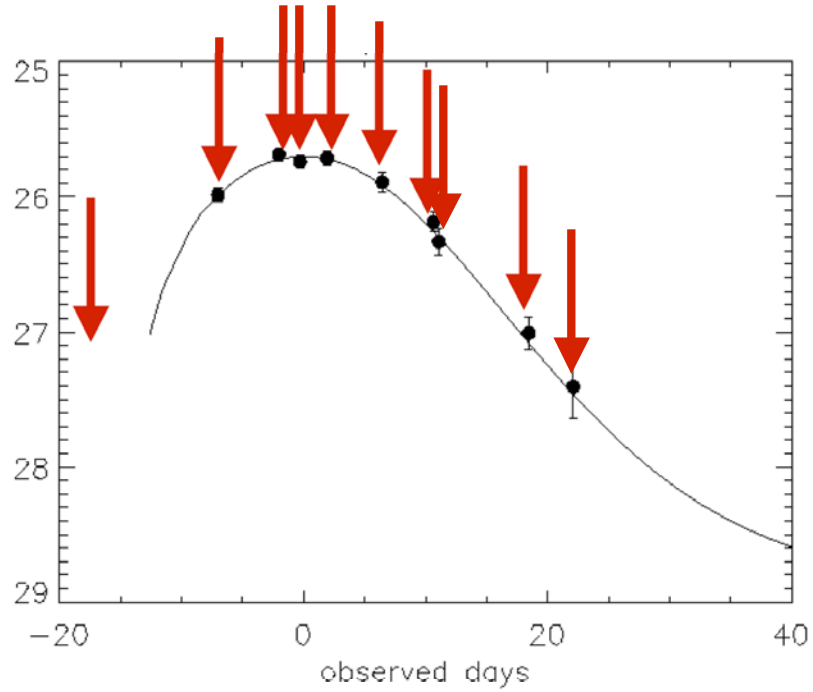
HST Refurbishing



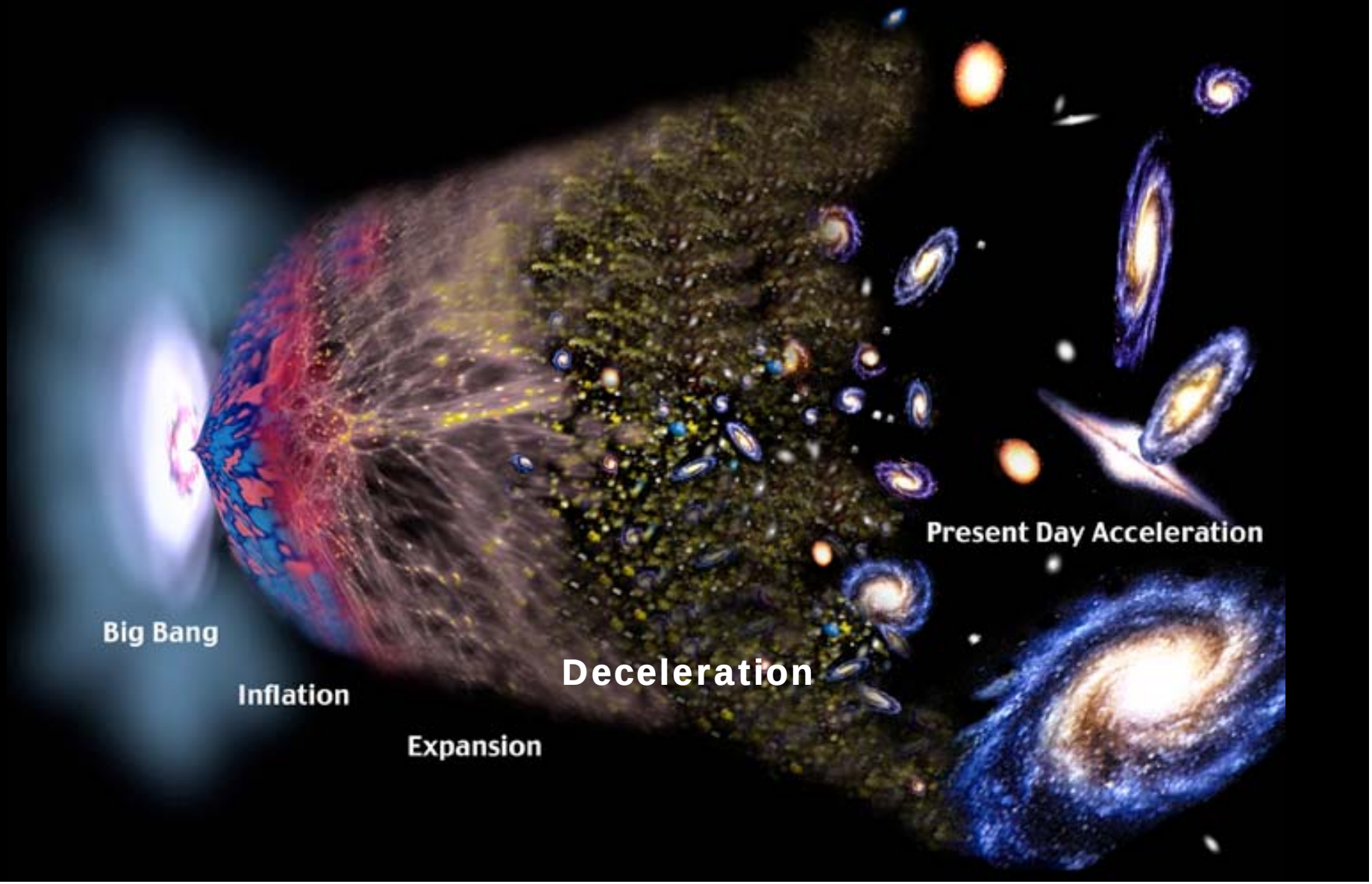
A New Camera on HST

The Rise and Fall of a Distant Supernova





Cosmic Deceleration from Dark Matter, then Acceleration from Dark Energy!



A 'Cosmic Jerk' That Reversed the Universe

By DENNIS OVERBYE

CLEVELAND, Oct. 10 — Astronomers said on Friday that they had determined the time in cosmic history when a mysterious force, "dark energy," began to wrench the universe apart.

Five billion years ago, said Dr. Adam Riess, an astronomer at the Space Telescope Science Institute in Baltimore, the universe experienced a "cosmic jerk." Before then, Dr. Riess said, the combined gravity of the galaxies and everything else in the cosmos was resisting the expansion, slowing it down. Since the jerk, though, the universe has been speeding up.

The results were based on observations by a multinational team of astronomers who used the Hubble Space Telescope to search exploding stars known as Type 1a supernovas, reaching back in time three-quarters of the way to the Big Bang, in which the universe was born. The results should help quell remaining doubts that the expansion of the universe is really accelerating, a strange-sounding notion that has become a pillar of a new and widely accepted model of the universe as being full of mysterious dark matter and even more mysterious dark energy.

"This gives great confidence that we've been on the right track," said Dr. Riess, who announced his results at a meeting here on the Future of Cosmology sponsored by the Center for Education and Research in Cosmology and Astrophysics at Case Western Reserve University and the Kavli Institute.

Dr. Lawrence M. Krauss, an astrophysicist at Case Western, called the turnaround from slowing down to speeding up important confirmation.

"The big surprise," Dr. Krauss said, "would have been if it hadn't happened."

Dr. Joseph Lykken, a physicist at the Fermi National Accelerator Laboratory, known as Fermilab, in Batavia, Ill., said, "I could go home now and be happy."

Knowing how and when the jerk occurred, astronomers said, was an important step in figuring out just what the dark energy is.

"He gave us information about when the universe hit the gas pedal," said Dr. Michael S. Turner, a cosmologist at the University of Chicago who is director of mathematics and

Marty Katz for The New York Times

Dr. Adam Riess, who reported yesterday on the speeding and expanding universe, at the Space Telescope Science Institute in Baltimore.

The goal was to measure how much the universe was being slowed by the collective gravity of the cosmos and determine whether the universe would go on forever or recollapse in a "Big Crunch" on one distant day.

The groups found, though, that nearby supernovas looked dimmer than they should, implying that the universe was growing faster than expected, speeding up, under the influence of some form of antigravity — perhaps embedded in the fabric of spacetime itself.

The results were buttressed by studies of radiation left over from the Big Bang that suggested that two-thirds of the mass-energy of the universe resided in this dark energy.

"But there was always a nagging doubt," Dr. Riess told his colleagues.

'Dark energy' made the universe speed up 5 billion years ago.

If that was the case, supernovas even

collaborators found Hubble observations of a supernova 10 billion years in the past. It proved to be anomalously bright, lending credence to the idea that a dark energy had taken over some time in between.

"But a single object is just not robust enough," he said. For the last year, he and his colleagues have used the Hubble in collaboration with a large galaxy survey known as Goods to find distant supernovae.

"We found lots of weapons of mass destruction," he said, showing Hubble pictures of some exploding with the brilliance of small galaxies 8 billion to 10 billion light-years away.

More important, they were brighter than expected. When he plotted their velocities against distance, or time in the past, Dr. Riess found that the universe had to have changed direction, from slowing to speeding up, over a period of time five billion years ago, the so-called cosmic jerk, using the technical term for a change in acceleration.

"It's great to see it," Dr. Riess said.

In Dr. Lykken's words, and as borne out by discussions at the meeting here, "theorists don't have a clue" about the identity of the dark energy that is so important.

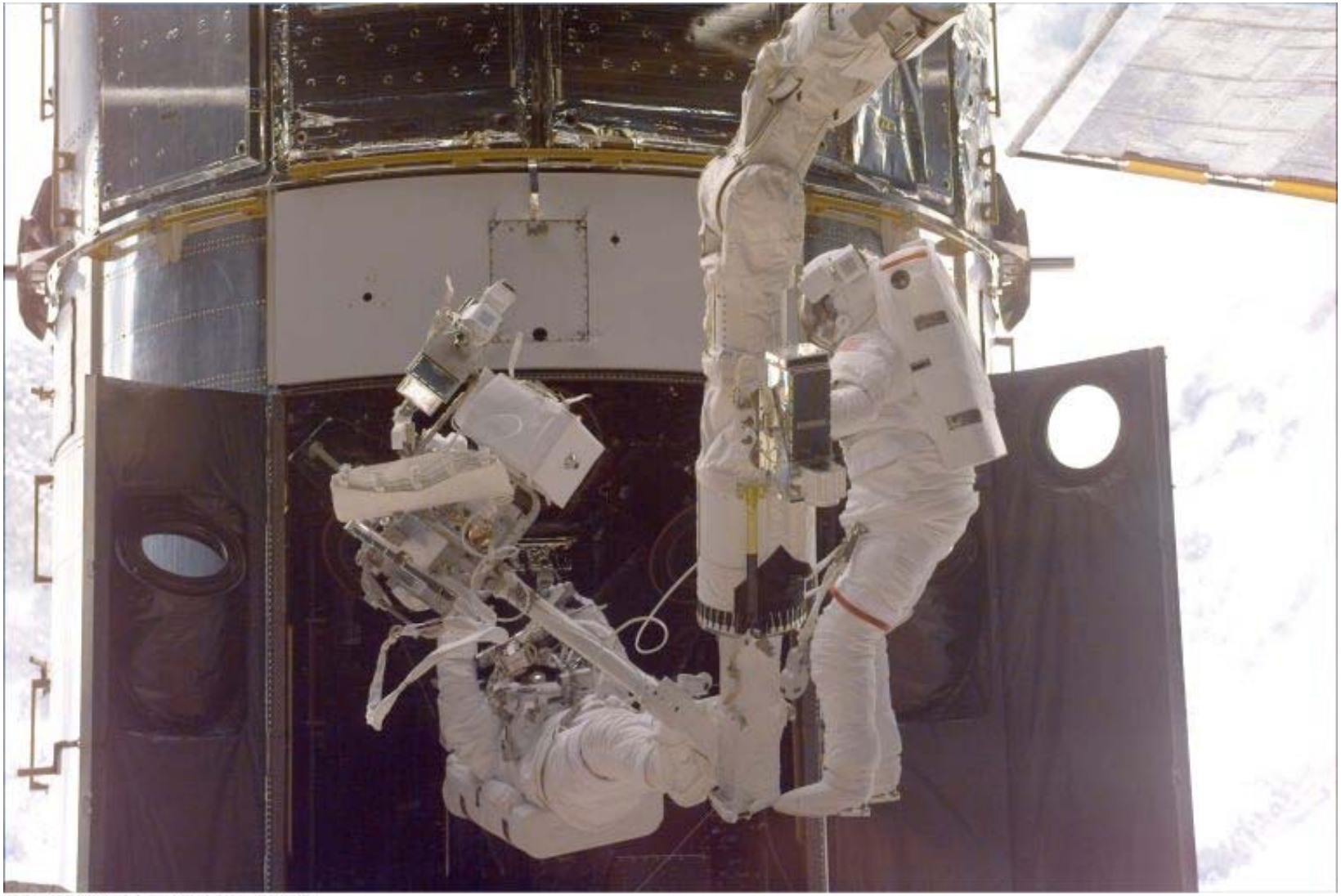
Evidence for a change in cosmic acceleration: '**cosmic jerk**'

Future:

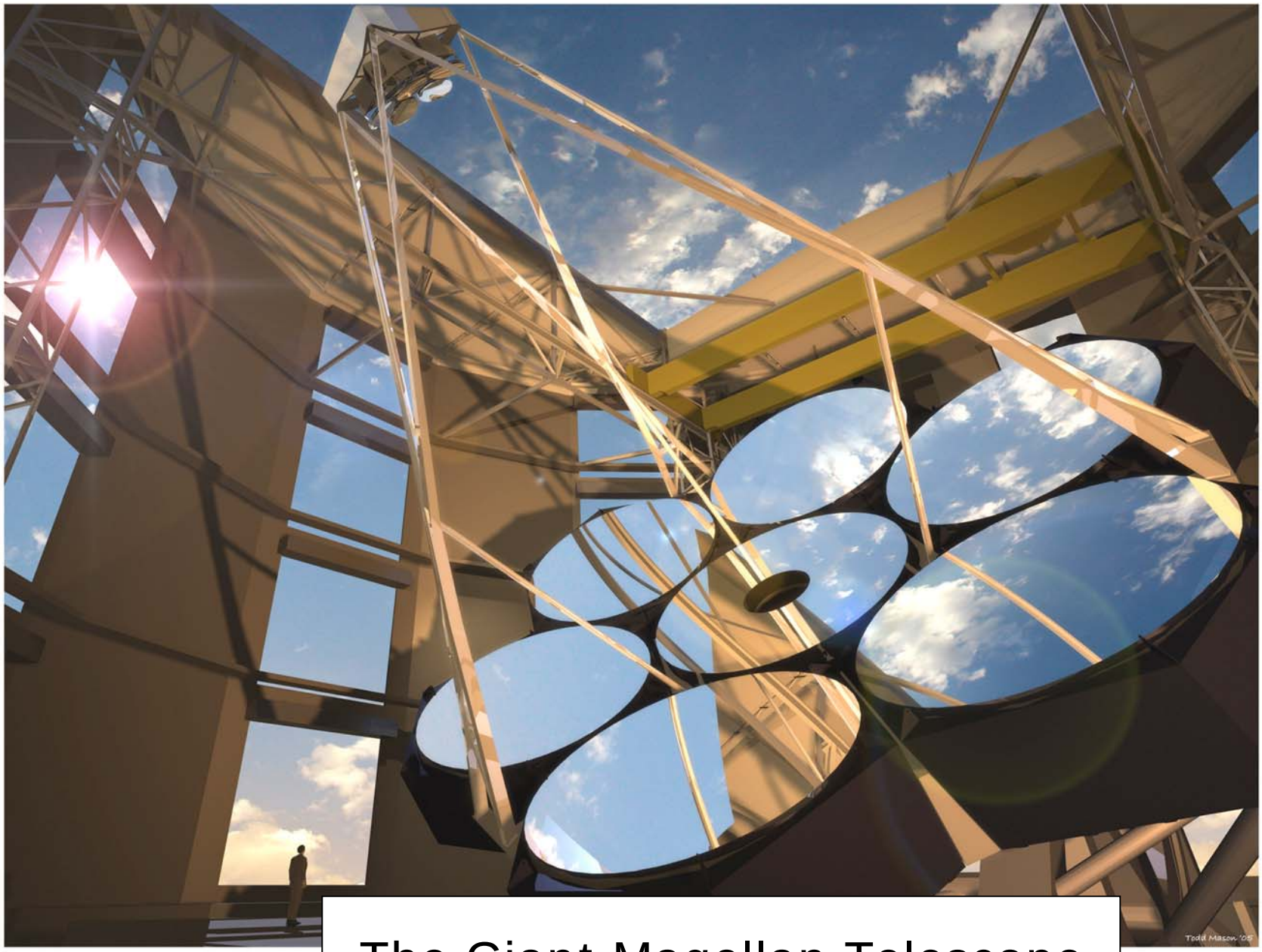
Acceleration without end?

Big rip?

What next for HST?



S103E5204 1999:12:22 16:32:29



The Giant Magellan Telescope


The first mirror has already been cast!

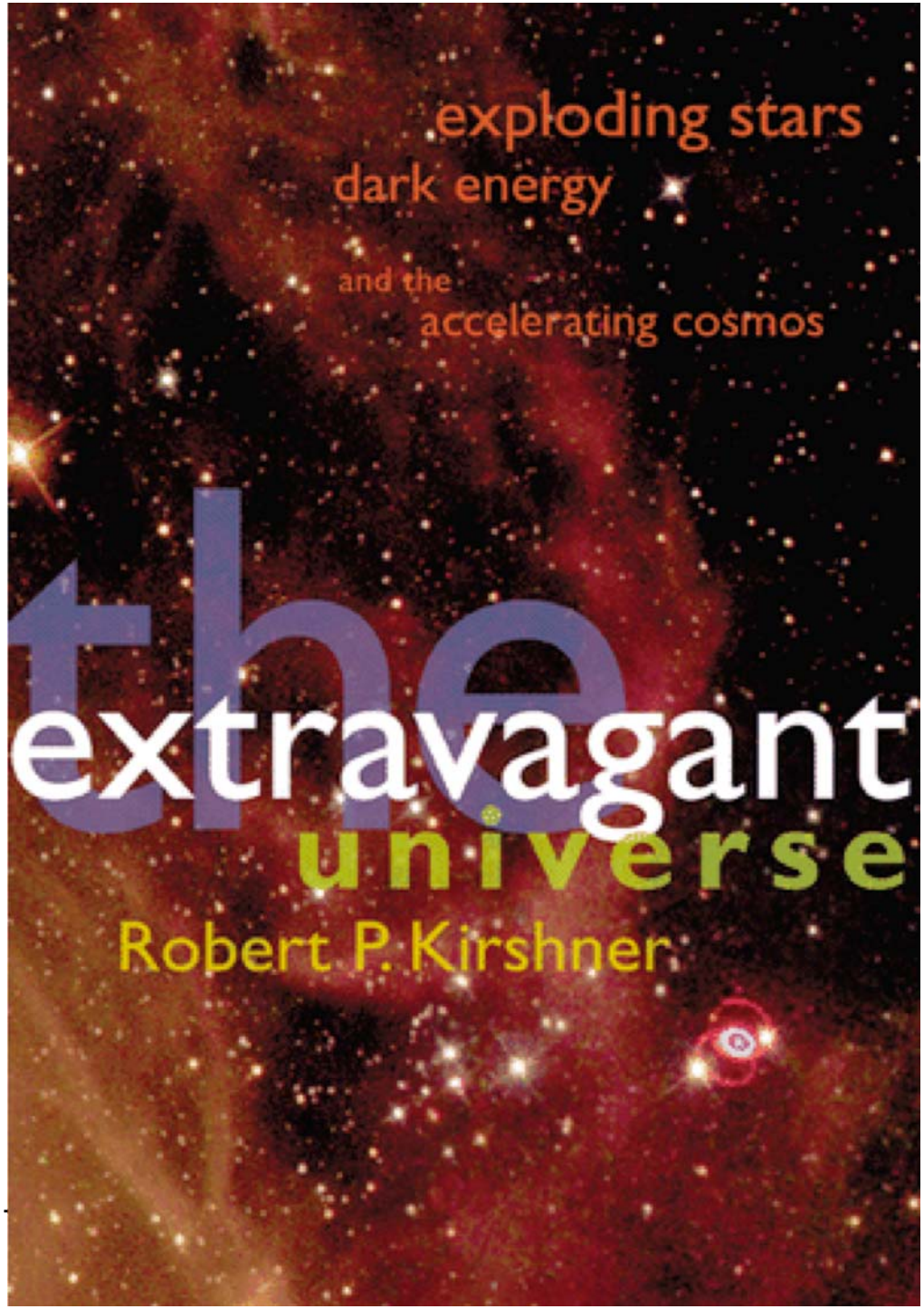
DESTINY

Dark Energy Space Telescope

Dark Energy puzzles-- a sign that we do not know how to combine gravity with quantum physics!

Modifications to General Relativity?

Effect of Extra Dimensions?



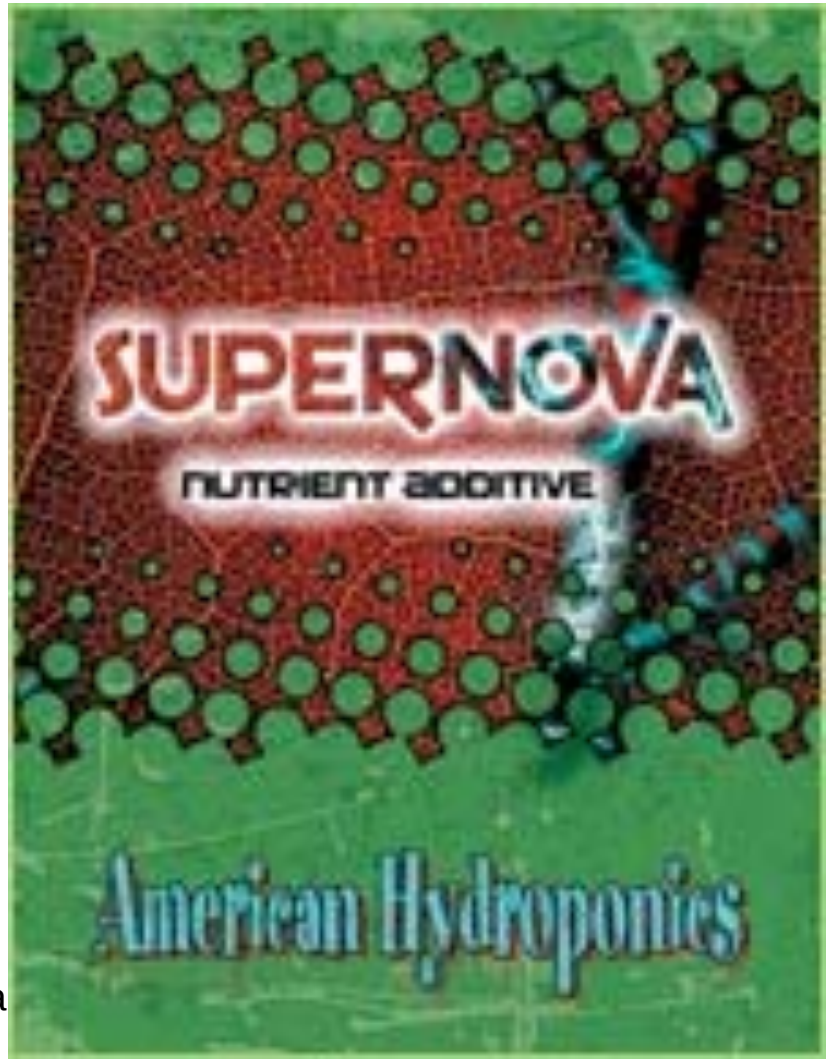

Science for…
Technology
Defense
Medicine


Science for…
Technology => Rich
Defense => Safe
Medicine => Immortal


Science for…
Technology => Rich
Defense => Safe
Medicine => Immortal
& Bored


Science for…
The joy of finding out
how the world works

America: A Land of Scientific Culture



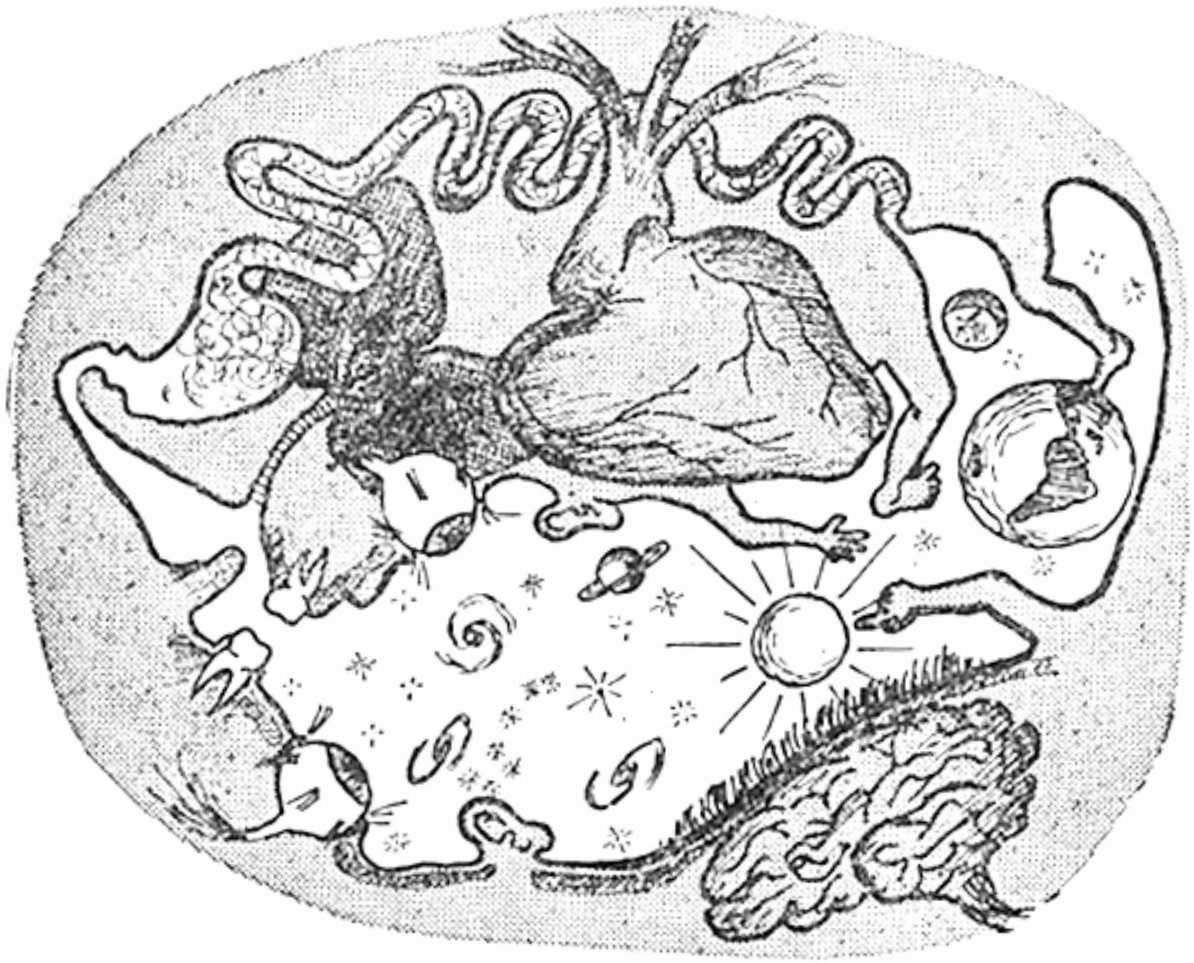


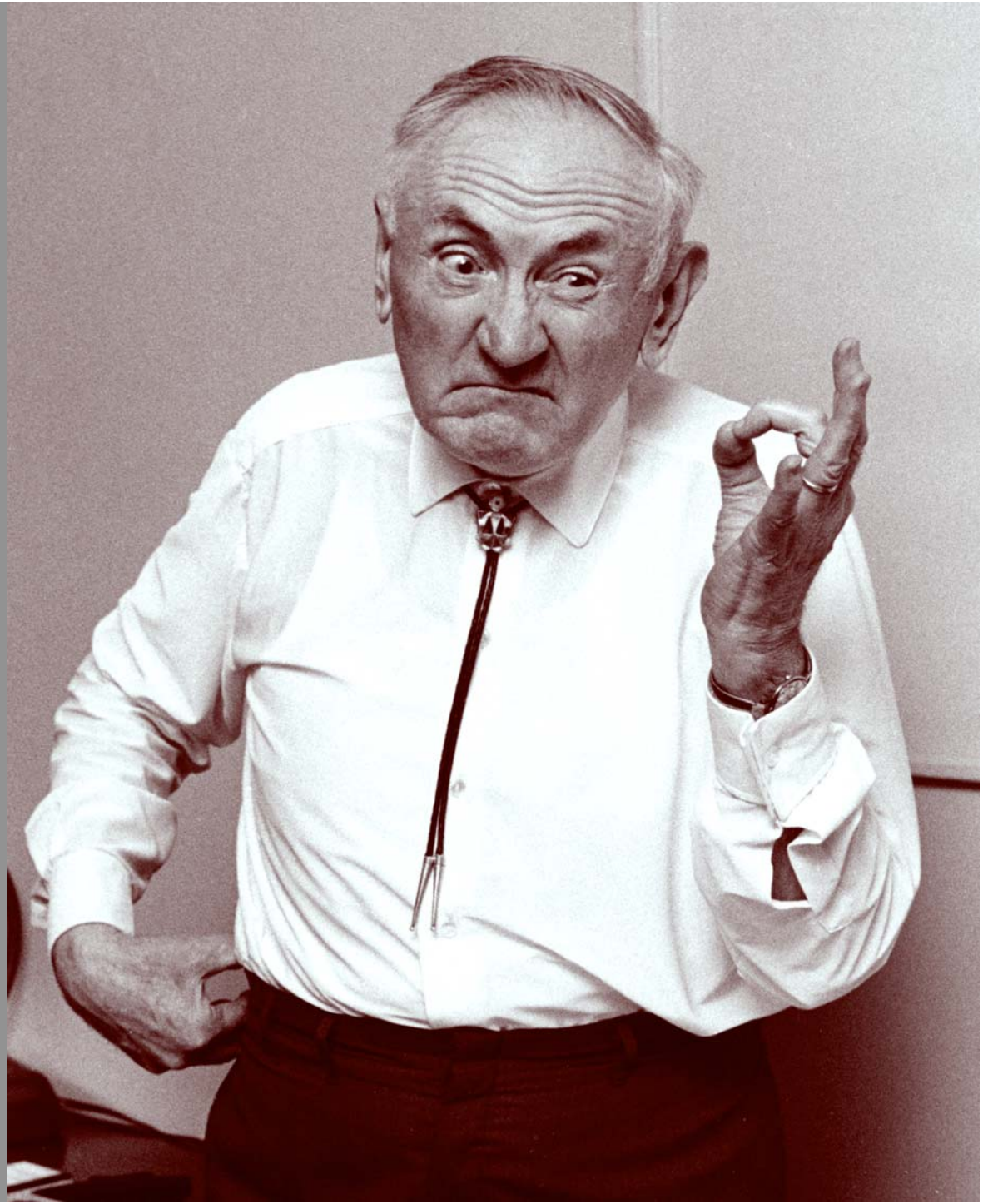
FIGURE 20

Inside-out universe. This surrealistic drawing represents a man walking on the surface of the Earth and looking up at the stars. The picture is transformed topologically according to the method indicated in Figure 19. Thus the Earth, sun, and stars are crowded in a comparatively narrow channel running through the body of the man, and surrounded by his internal organs.

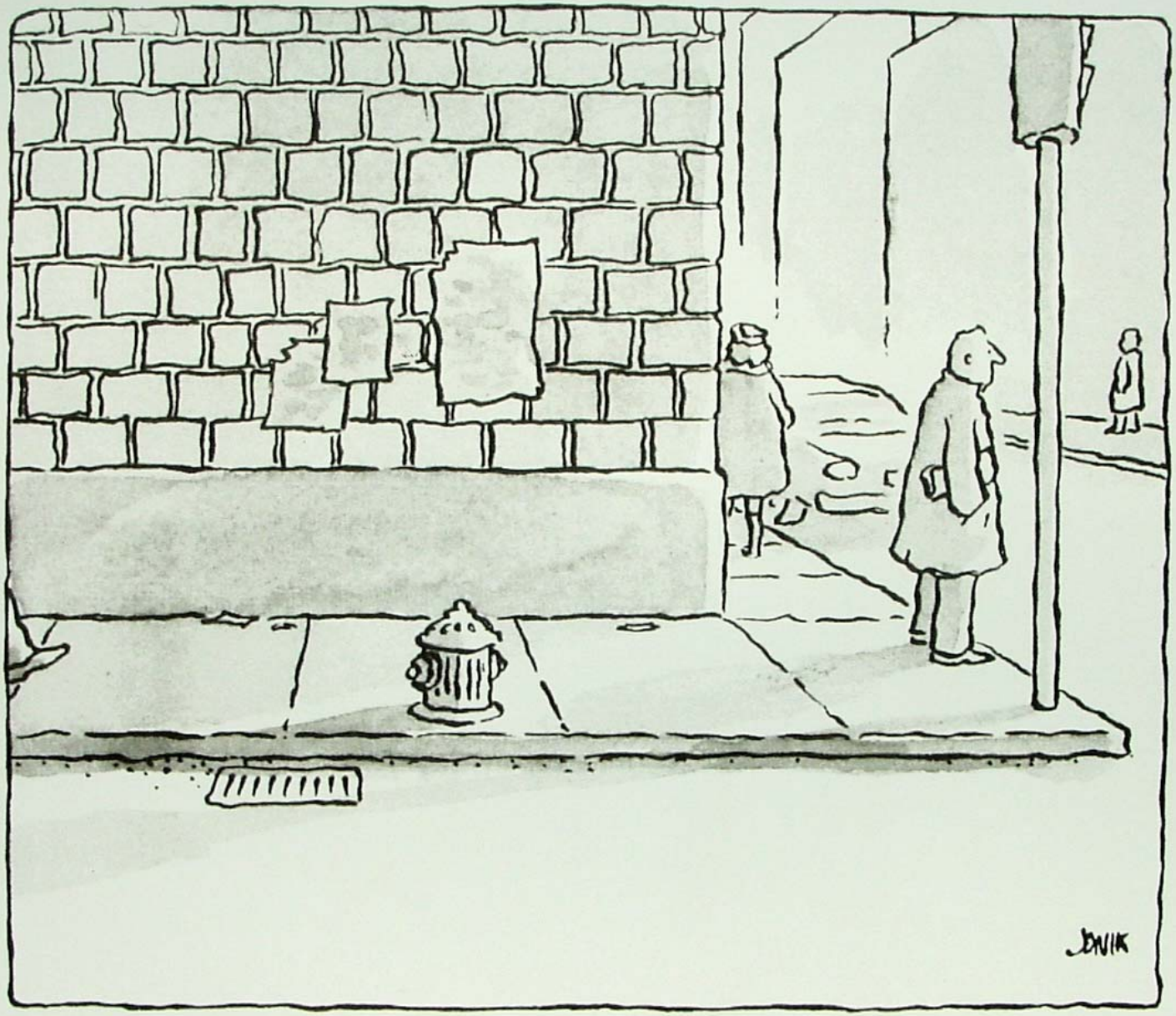
Gamow:

Seriously
Funny
in
1,2,3,
Infinity

Fritz Zwicky--Supernova Visionary!

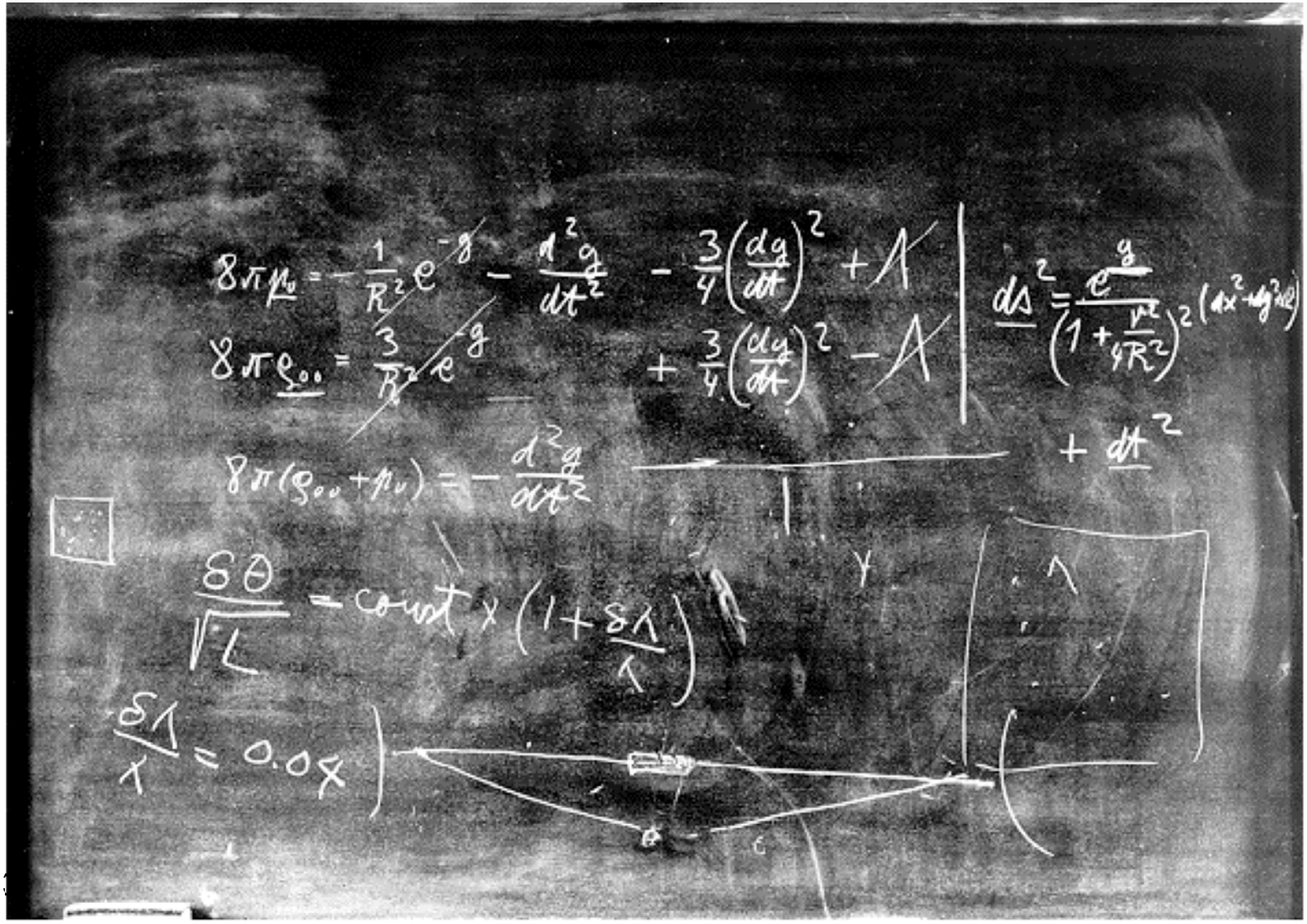


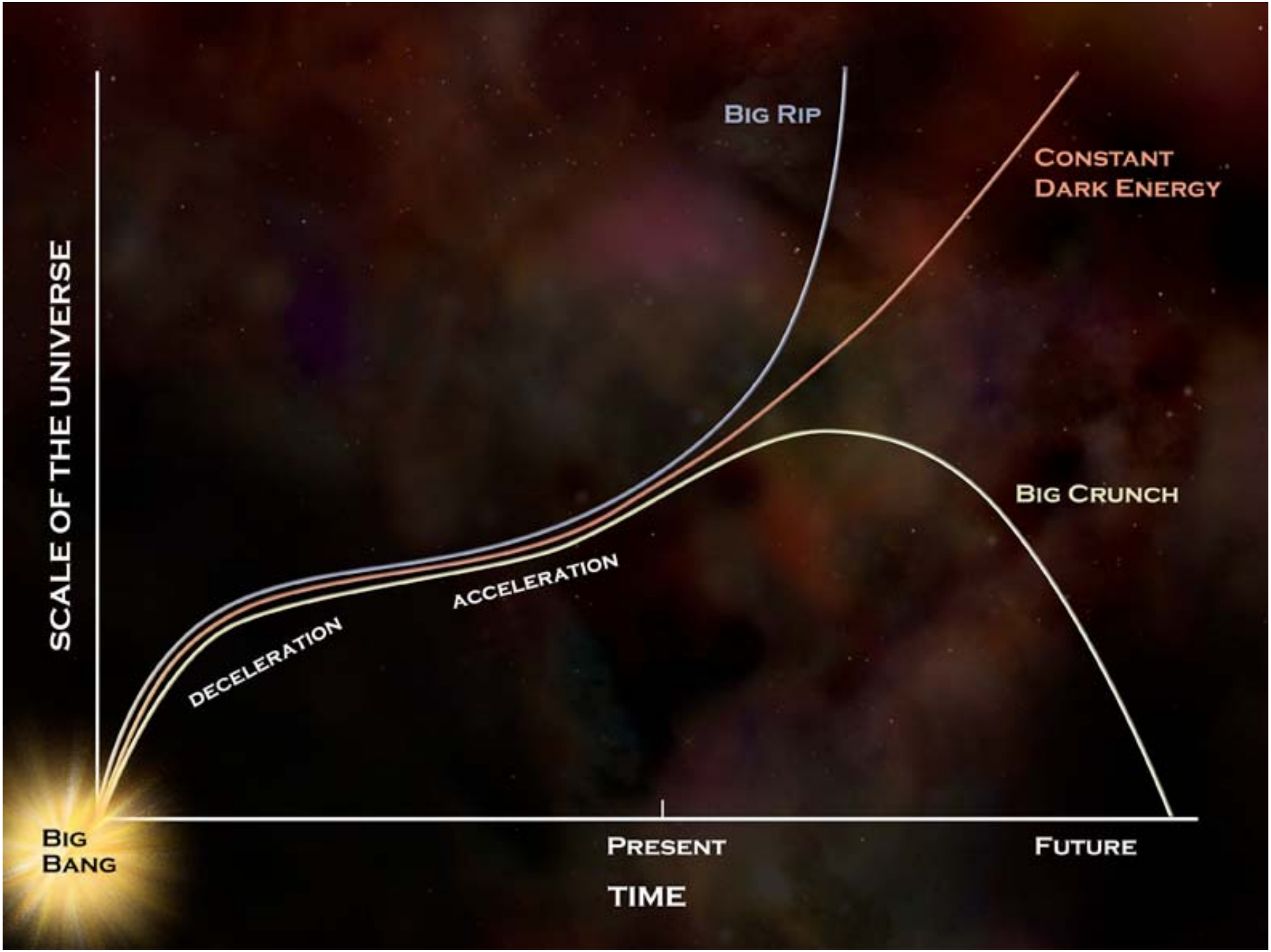
3/19/07



THE MILKY WAY
(Detail)

Einstein's Blackboard 1931

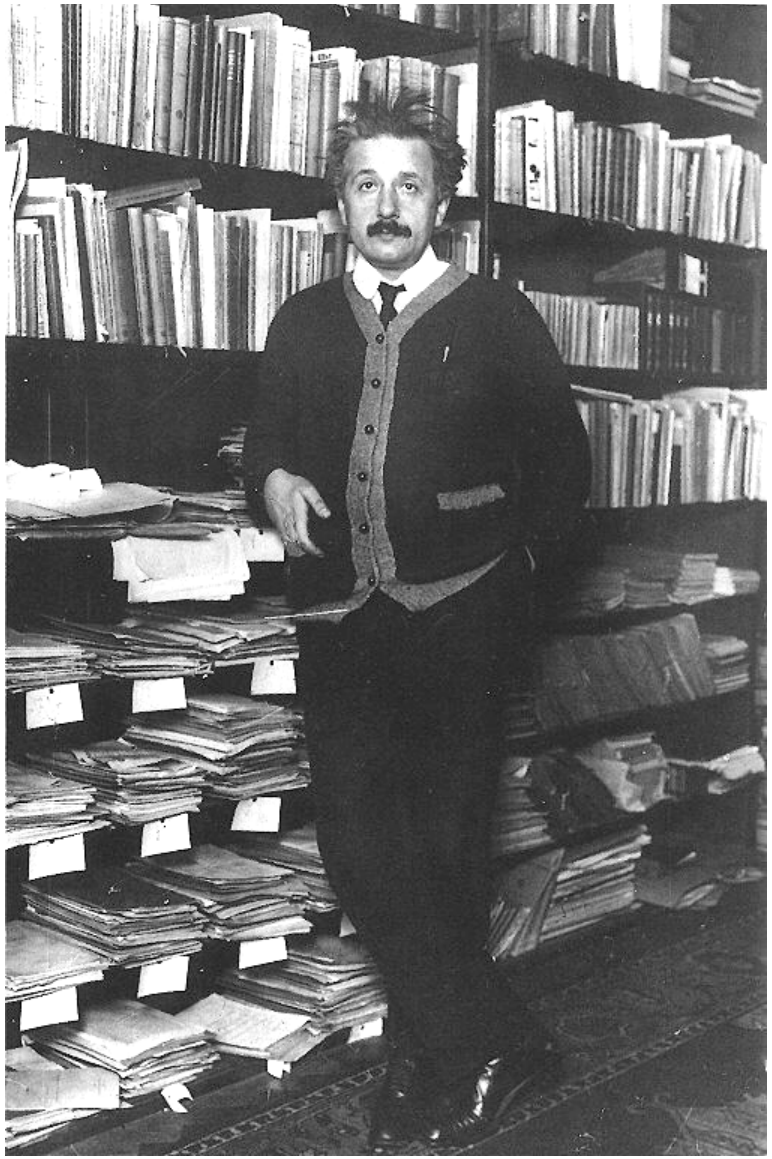



SCALE OF THE UNIVERSE
BIG RIP
CONSTANT
DARK ENERGY
BIG CRUNCH
DECELERATION
ACCELERATION
BIG
BANG
PRESENT
FUTURE
TIME

mann realized that this opened an entire new world of time-dependent universes: expanding, collapsing, and pulsating ones. Thus, Einstein's original gravity equation was correct, and changing it was a mistake. Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder he ever made in his life. But this "blunder," rejected by Einstein, is still sometimes used by cosmologists even today, and the cosmological constant denoted by the Greek letter Λ rears its ugly head again and again and again.

Gamow dubs a blunder

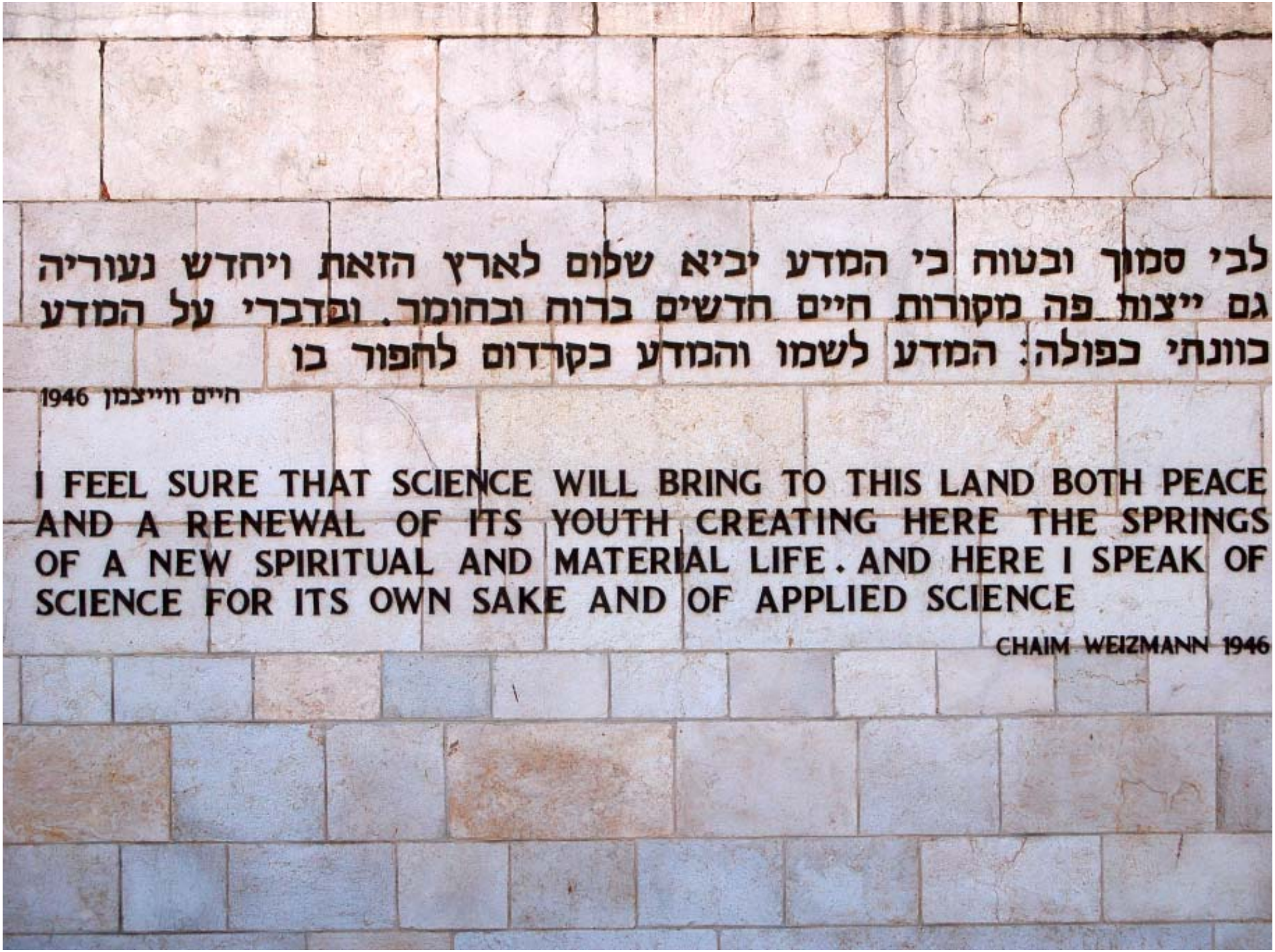
From *My World Line*



Einstein in 1917

Gravitation would make matter clump

Added in a "Cosmological Term" to make a static universe: Λ


לבי סמוך ובטוח כי המדע יביא שלום לארץ הזאת ויחדש נעוריה
גם ייצוא פה מקורות חיים חדשים ברוח ובחומר. ובדברי על המדע
כוונתי כפולה: המדע לשמו והמדע בקרדום לחפור בו
חיים ווייצמן 1946
I FEEL SURE THAT SCIENCE WILL BRING TO THIS LAND BOTH PEACE
AND A RENEWAL OF ITS YOUTH, CREATING HERE THE SPRINGS
OF A NEW SPIRITUAL AND MATERIAL LIFE. AND HERE I SPEAK OF
SCIENCE FOR ITS OWN SAKE AND OF APPLIED SCIENCE
CHAIM WEIZMANN 1946