The Big Picture

The Dark Universe, 2010

26 September 2010

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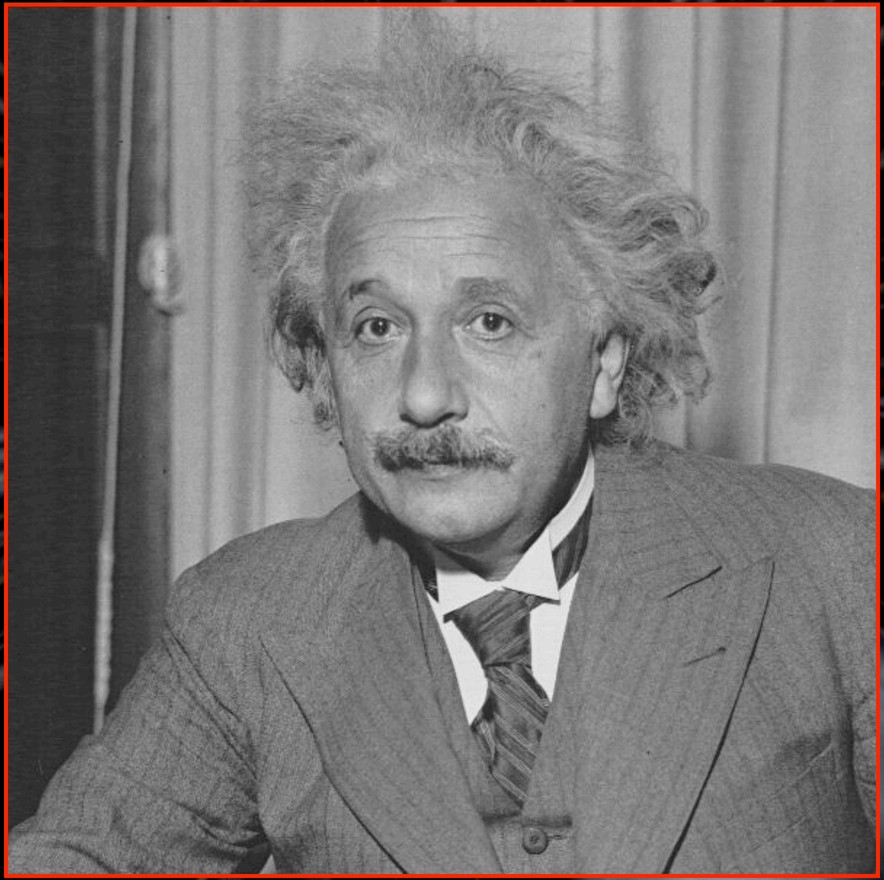
Cosmology
is a young science

its story only begins 90 years ago, 300+ years after the invention of the telescope

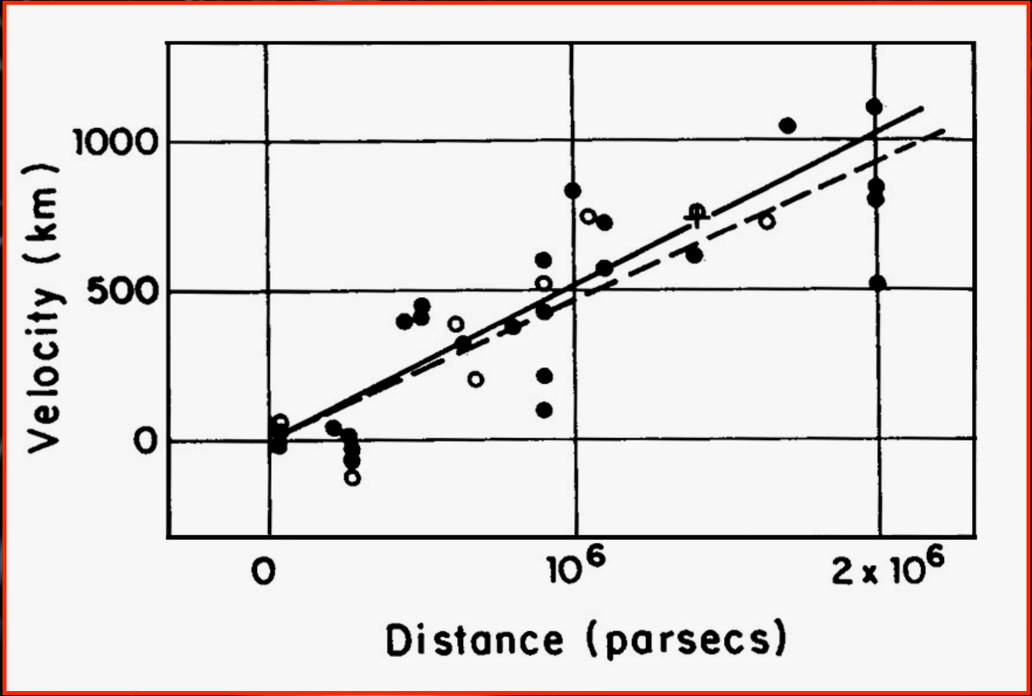
1916-1918: General Relativity & Λ



PS: Flip-flopper on Λ

1929: Just One Number K

(error bars not needed, velocity in km)



Hubble & Humanson: few 100 galaxies, z < 0.1

1929: Just One Number K

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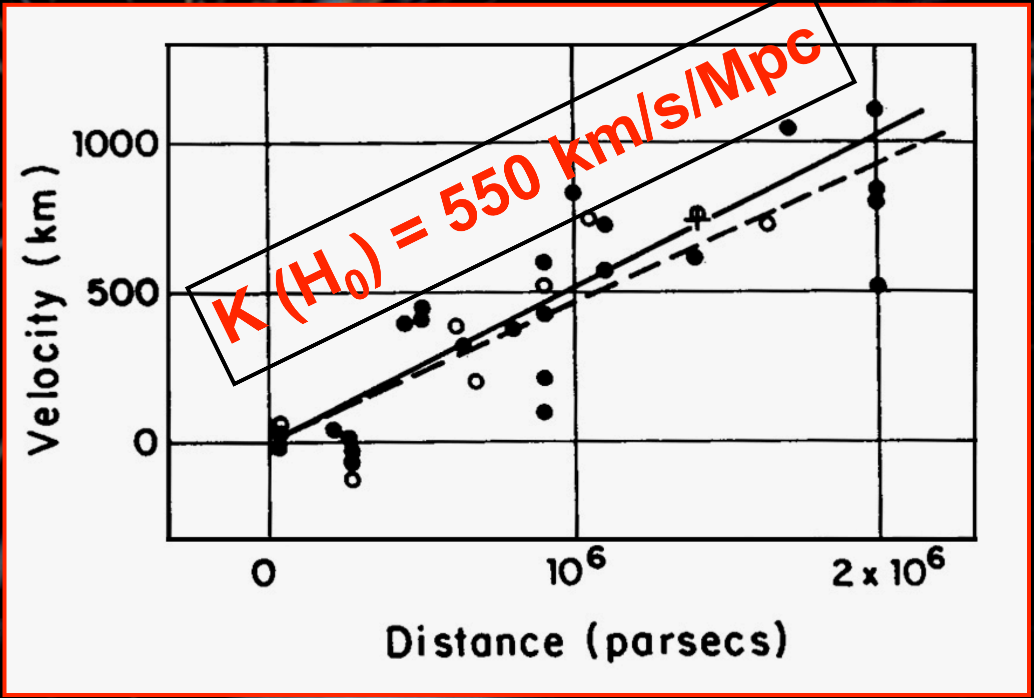
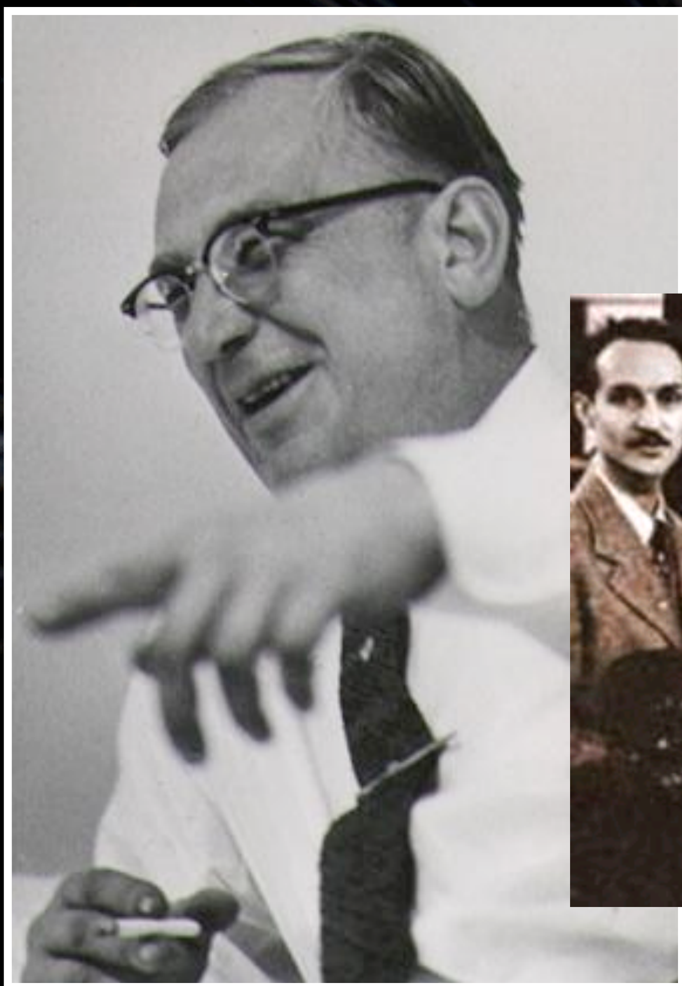
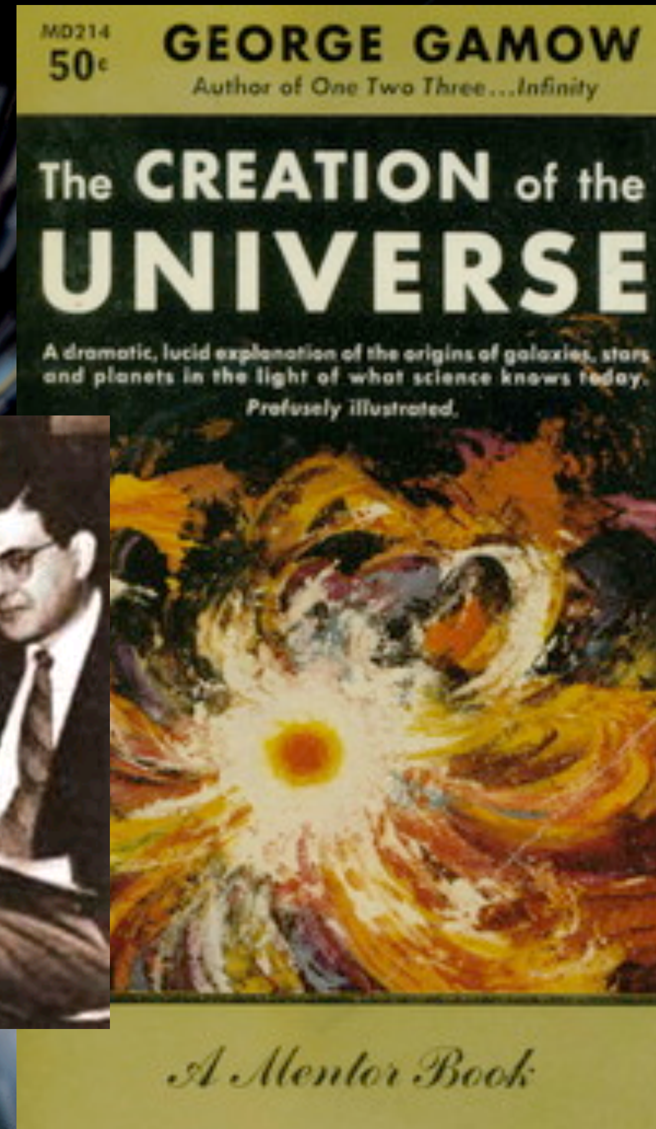


Hubble & Humanson: few 100 galaxies, z < 0.1

Gamow’s Hot Big Bang

“alpher, bethe, gamow,” 1948





1948: Steady State Theory

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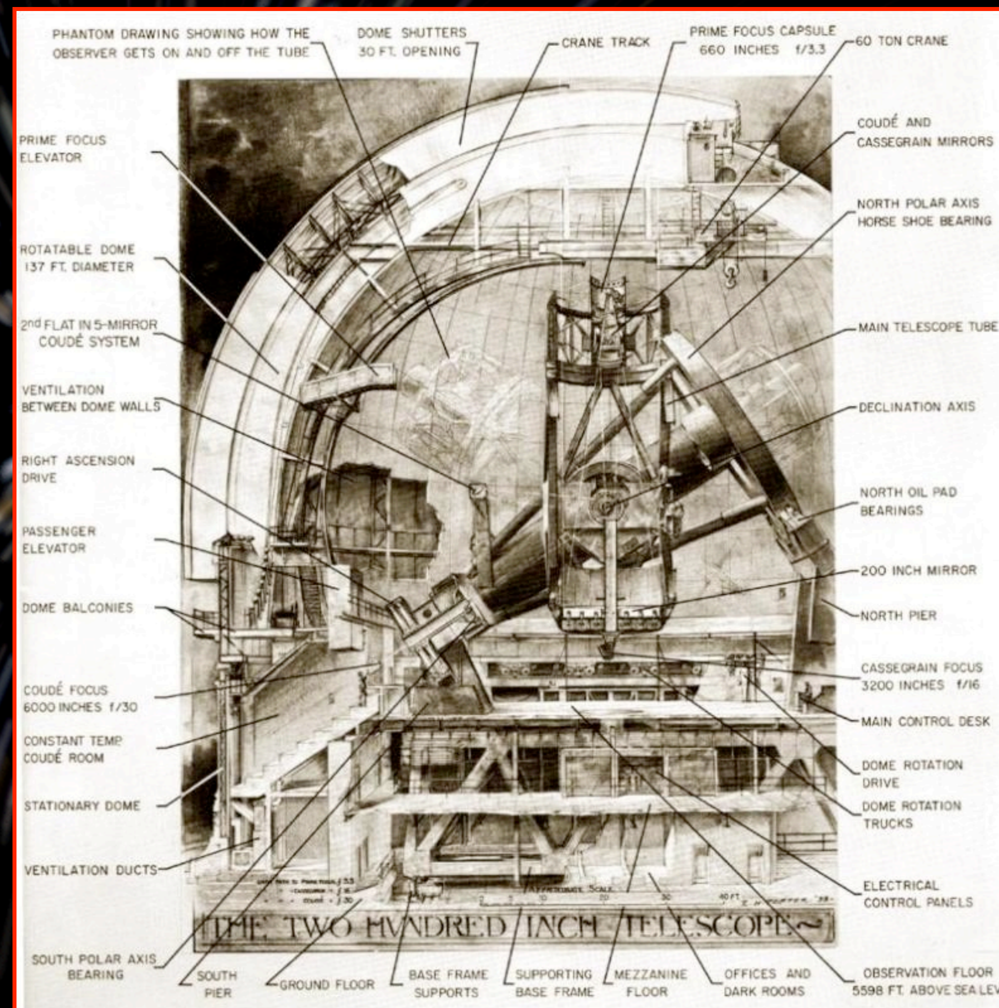
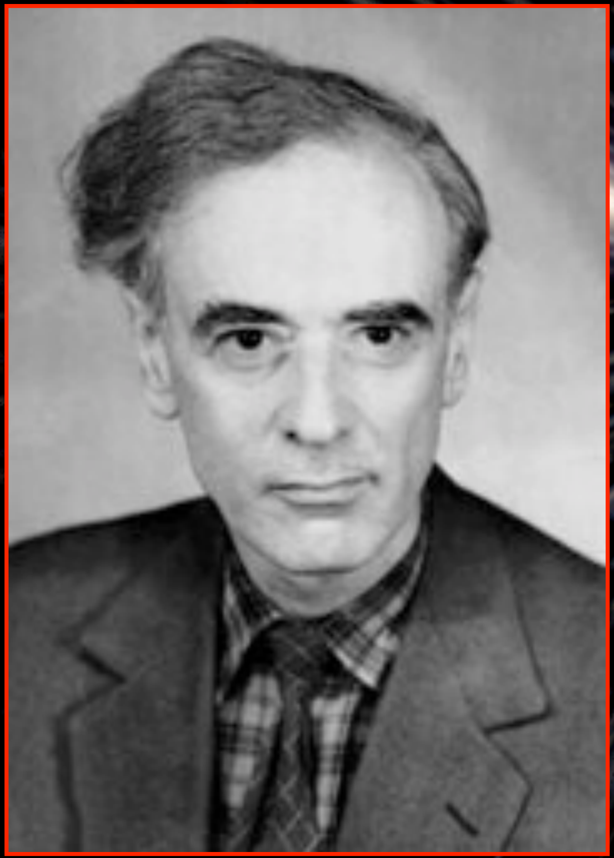
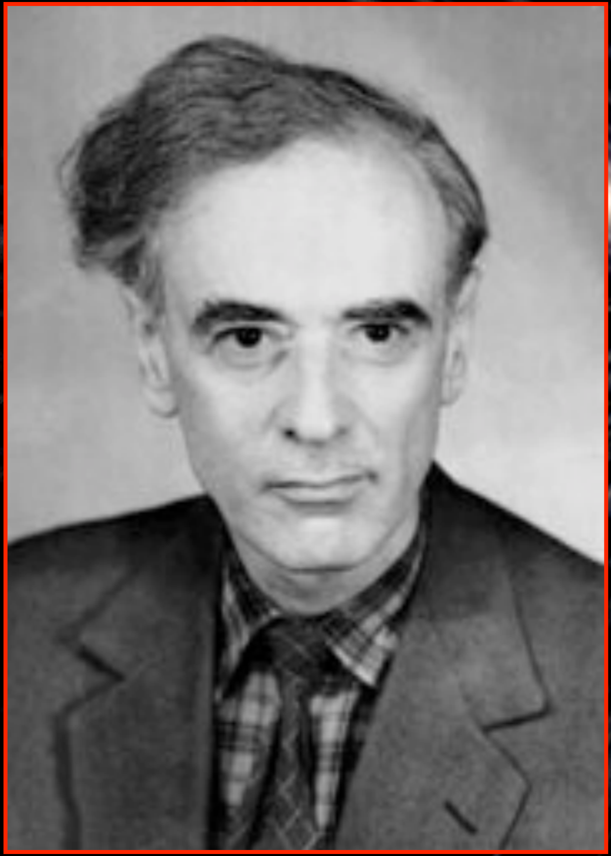
Cosmology: The Search for Two Numbers … H_0 and q_0 (Sandage 1970)



Landau on Cosmologists



Landau on Cosmologists



Often in Error, Never in Doubt!

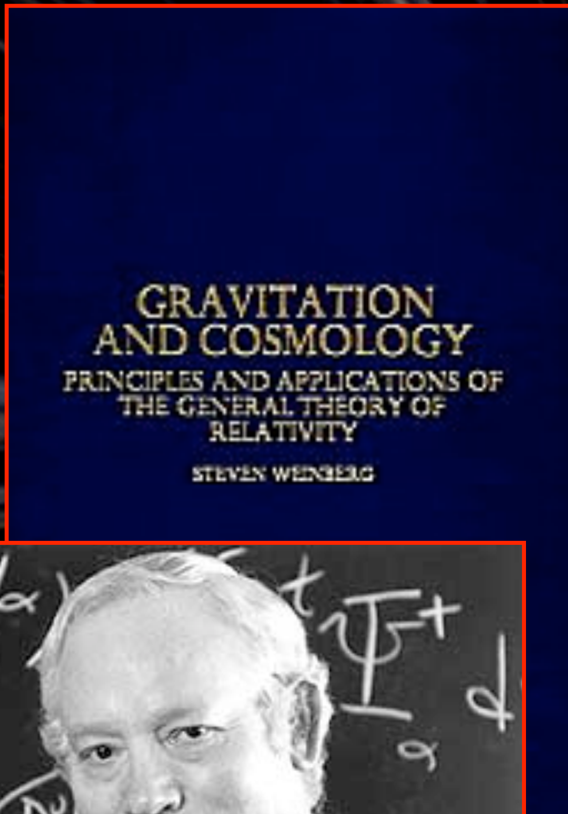
and at U Mass

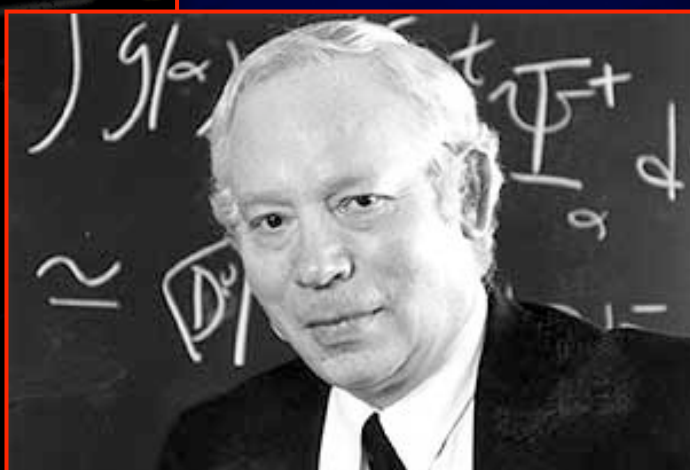
The Redbook, a manual for faculty members that explained what a university was, and what it wasn't. It cited two courses one wouldn't find in a curriculum of higher education: witchcraft and cosmology.

Discovery of Cosmic Microwave Background, 1964

ORDINARY MATTER: FROM QUARKS TO US

"The Standard Model" Hot Big Bang (circa 1972)





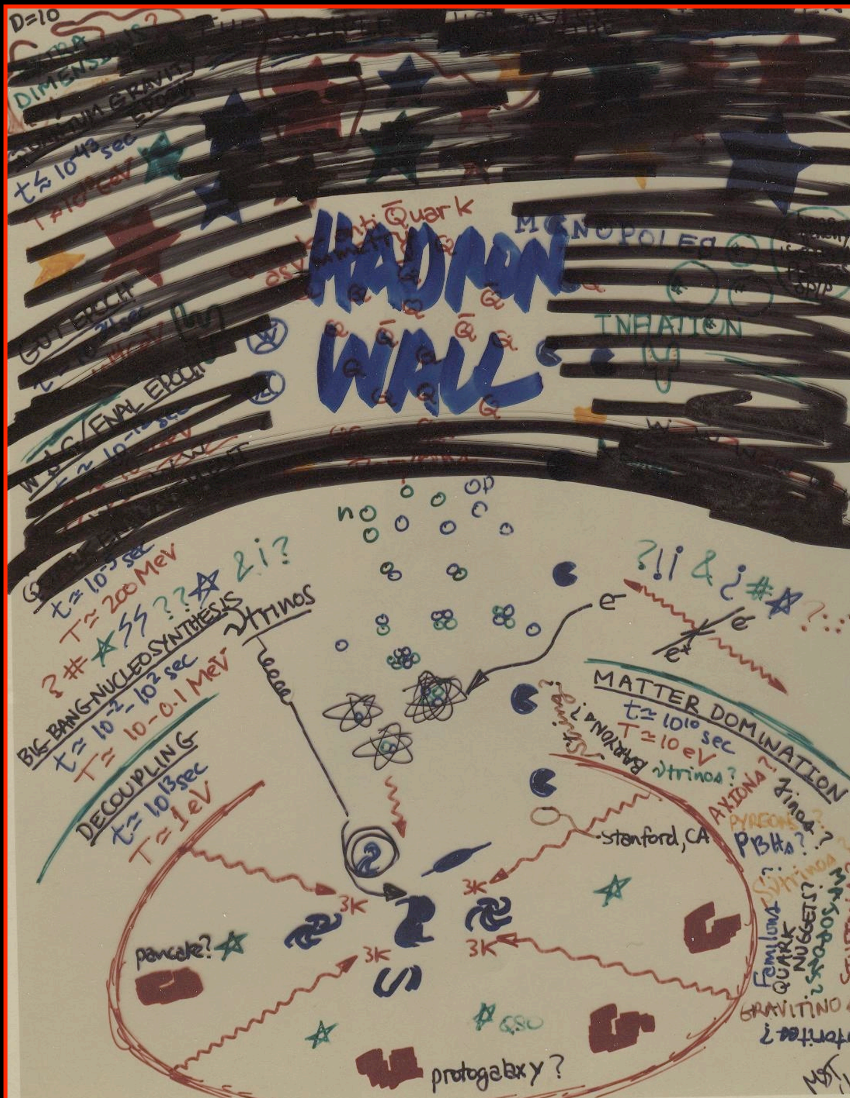
"Reality (physics) Based"

- BBN (nuclear physics)
- CMB (atomic physics)
- Structure Formation (grav. physics)
- Begins at 0.01 sec
- $\Omega_0 \sim 0.1$ (baryons)

Big Questions

- "The naughts": H_0, t_0, Ω_0
- Large entropy per baryon
- Hadron Wall
- Origin of density perturbations

The Hadron Wall



S. Weinberg in *Gravitation & Cosmology*

11 The Very Early Universe

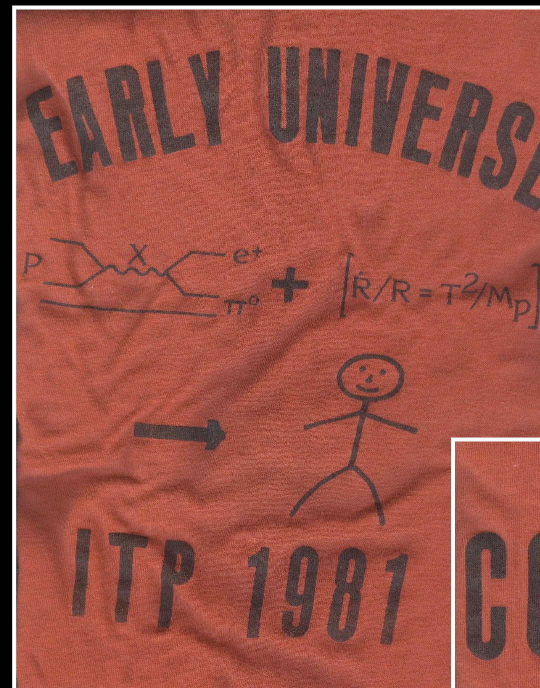
The thermal history of the universe was traced in Section 15.6 back to an era when the temperature was about 10^{12}°K. At this early time, the universe was filled with particles—photons, leptons, and antileptons—whose interactions are hopefully weak enough to allow this medium to be treated as a more or less ideal gas. However, if we look back a little further, into the first 0.0001 sec of cosmic history when the temperature was above 10^{12}°K, we encounter theoretical problems of a difficulty beyond the range of modern statistical mechanics. At such temperatures, there will be present in thermal equilibrium copious numbers of strongly interacting particles—mesons, baryons, and antibaryons—with a mean interparticle distance less than a typical Compton wavelength. These particles will be in a state of continual mutual interaction, and cannot reasonably be expected to obey any simple equation of state.

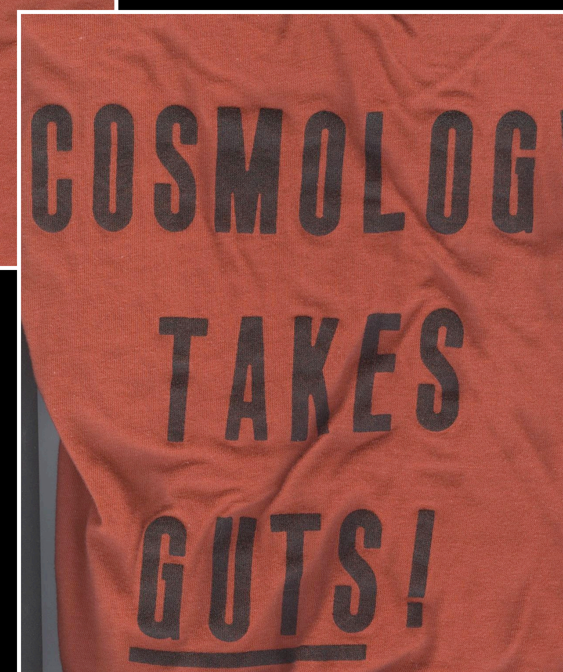
However, the temptation to try to construct some sort of model of the very early universe is irresistible. There are in fact two extremely different simple models that have been widely considered in recent years, and that reflect two divergent views of the nature of the strongly interacting particles. Although neither model can be taken seriously in detail, the hope is that one or the other of these models may come close enough to reality to lead to useful insights about the very early universe.

The first of these two pictures may be called the *elementary particle model*. It is supposed that all particles are made up of a small number of elementary

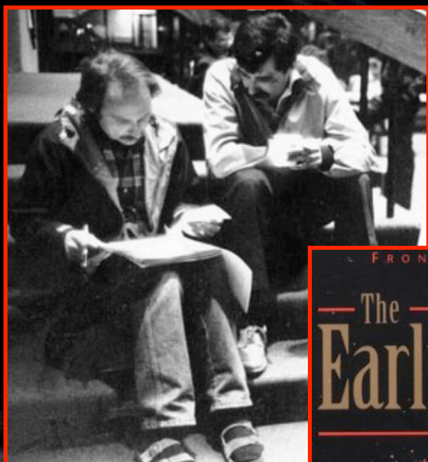
The Fall of “The Hadron Wall”

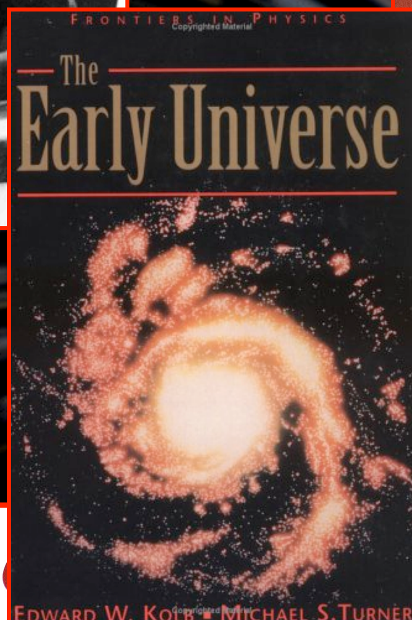
The Fall of “The Hadron Wall”

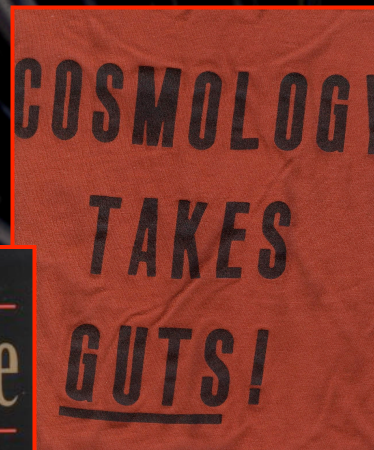


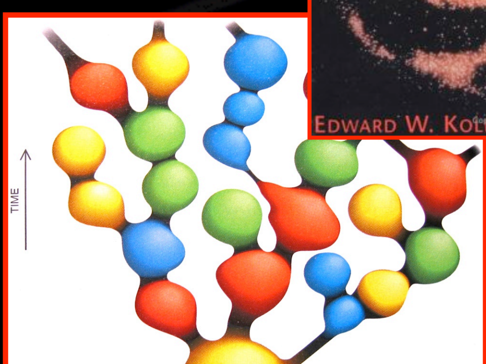


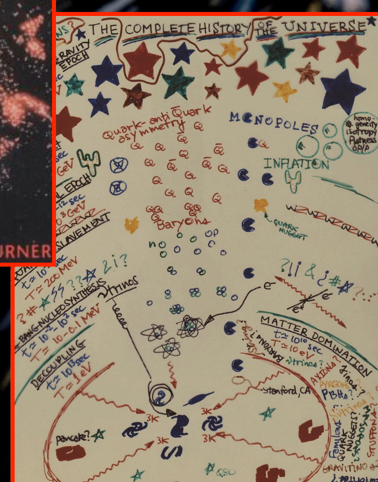
1980s: The Go Go Junk Bond Days of Early Universe Cosmology









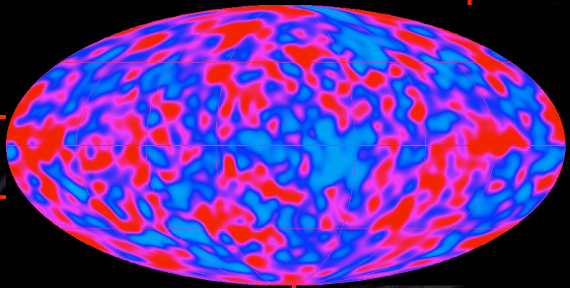


"Creativity Based"

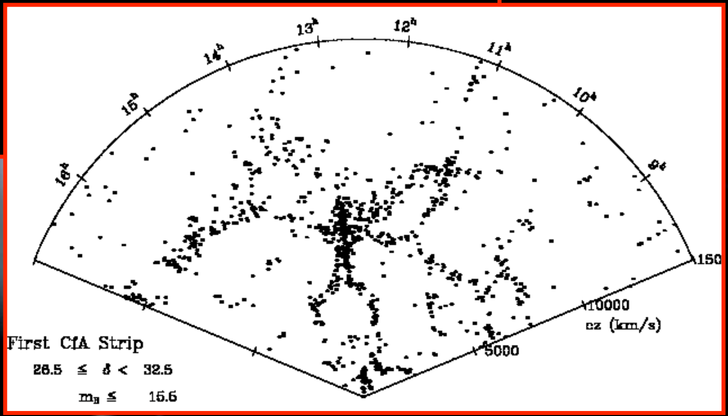
- Inflation
- Cosmic Strings
- Baryogenesis
- Magnetic Monopoles
- Phase Transitions
- Hot and Cold Dark Matter
- Decaying Particles
- Kaluza-Klein

1990s: Beginning of Data-driven Cosmology

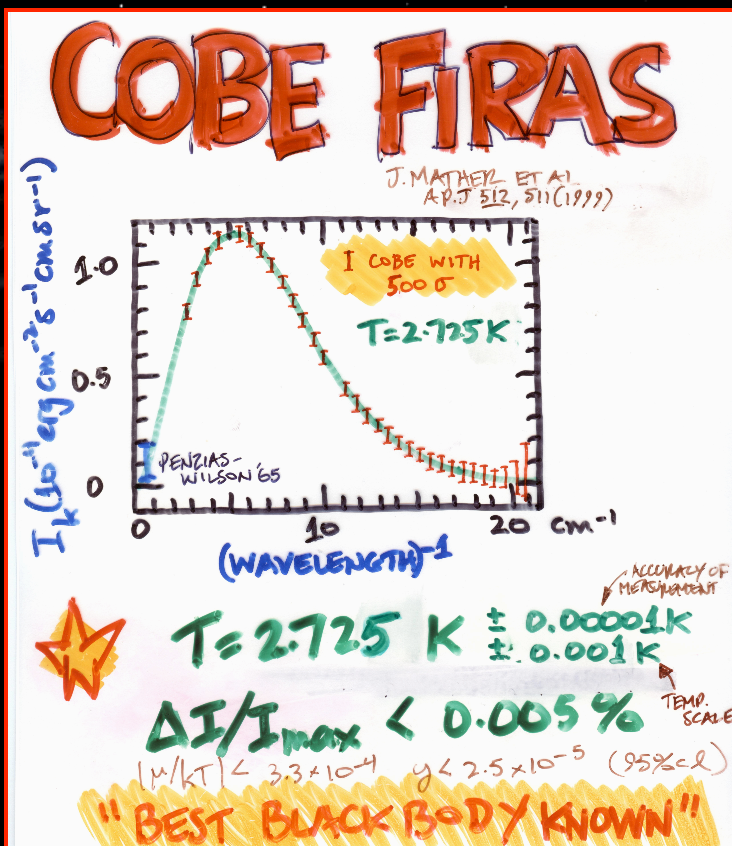
- COBE! and CMB experiments
- Redshift surveys (CfA, IRAS, 2dF, SDSS)
- Large-scale velocity field measurements
- Gravitational lensing
- Big telescopes (Keck, …) with big CCD cameras
- HST, X-ray, gamma-ray, IR, …

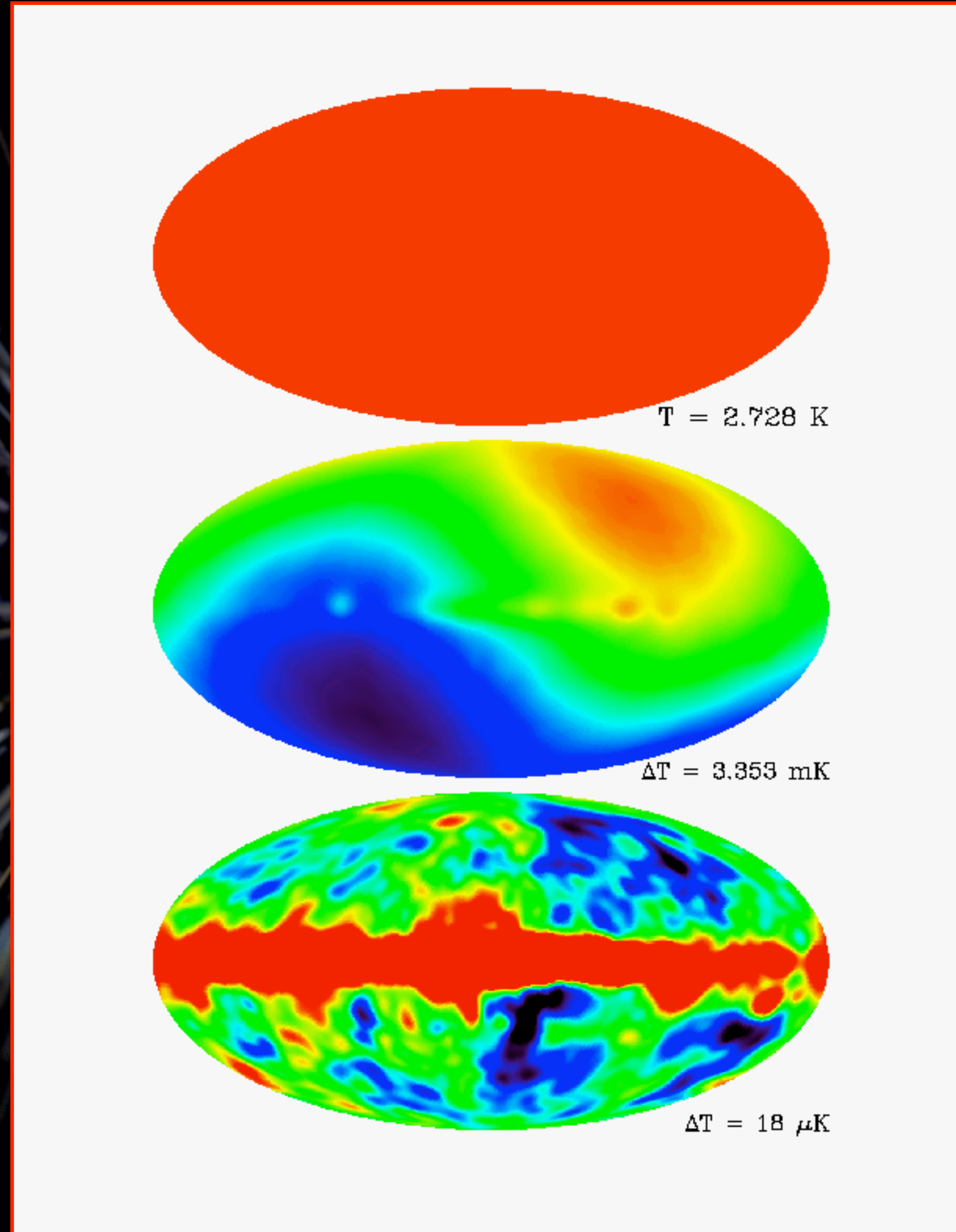


Gravitational Lens HST · WFPC2
Galaxy Cluster 0024+1654
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA

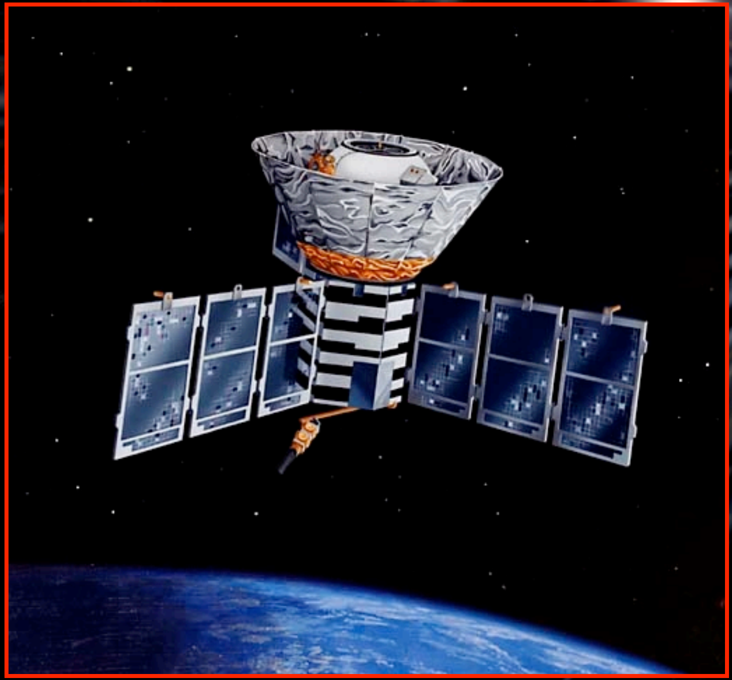


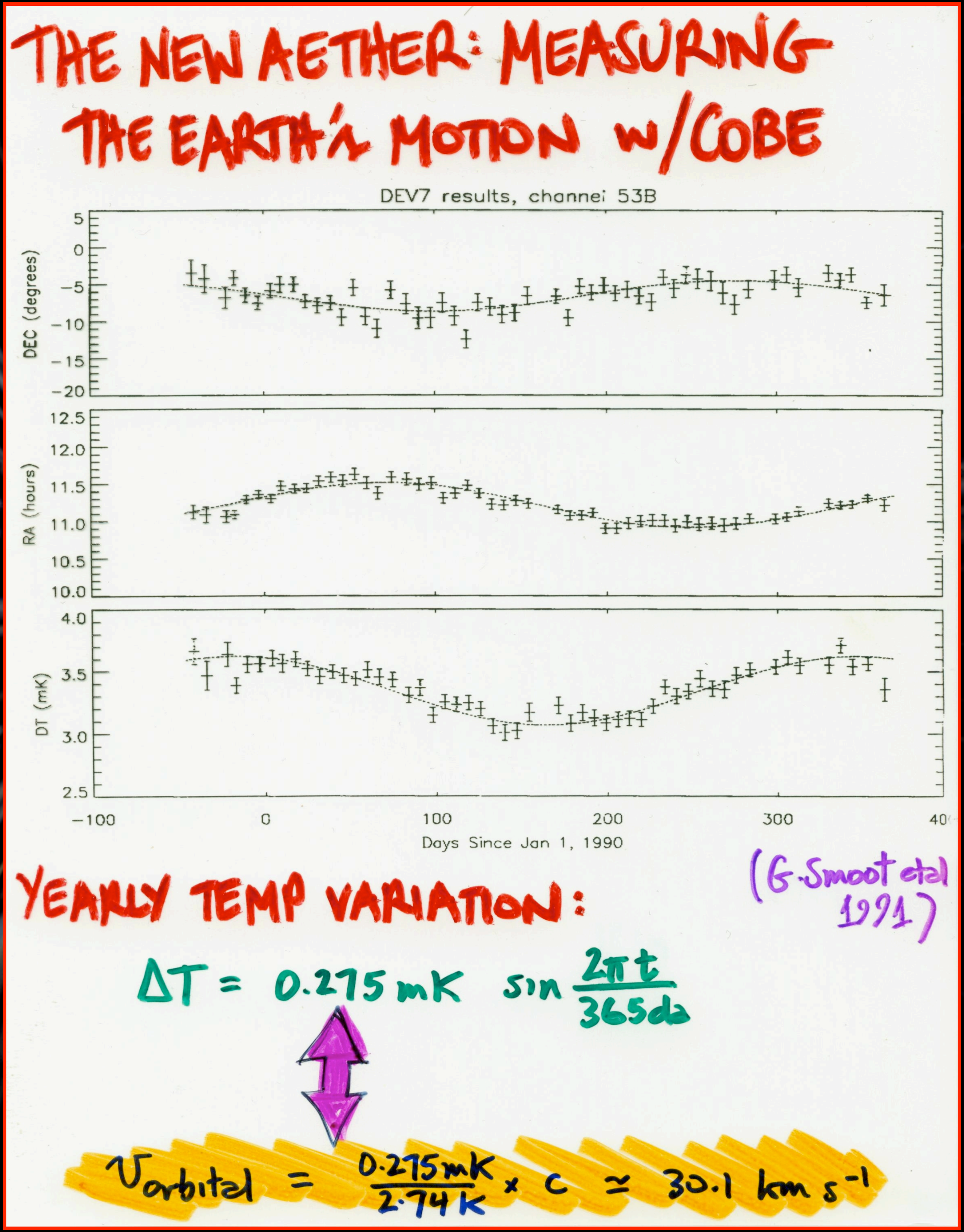
1992: COBE Start of Era of Precision Cosmology





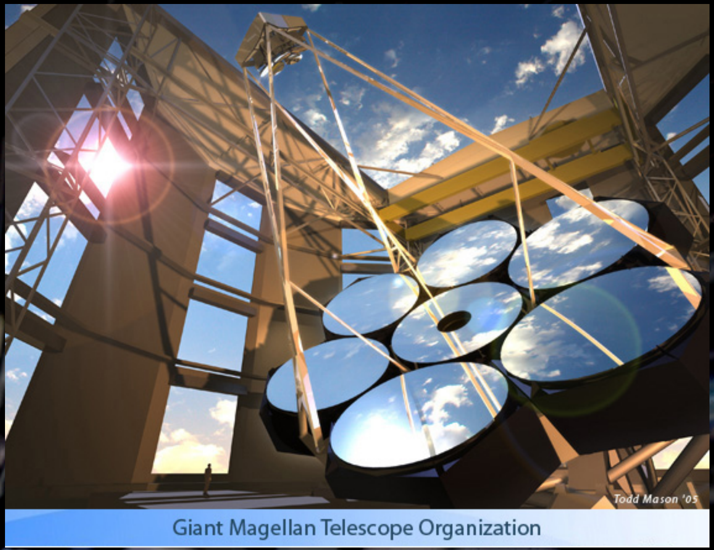
COBE Proves Copernicus Right!

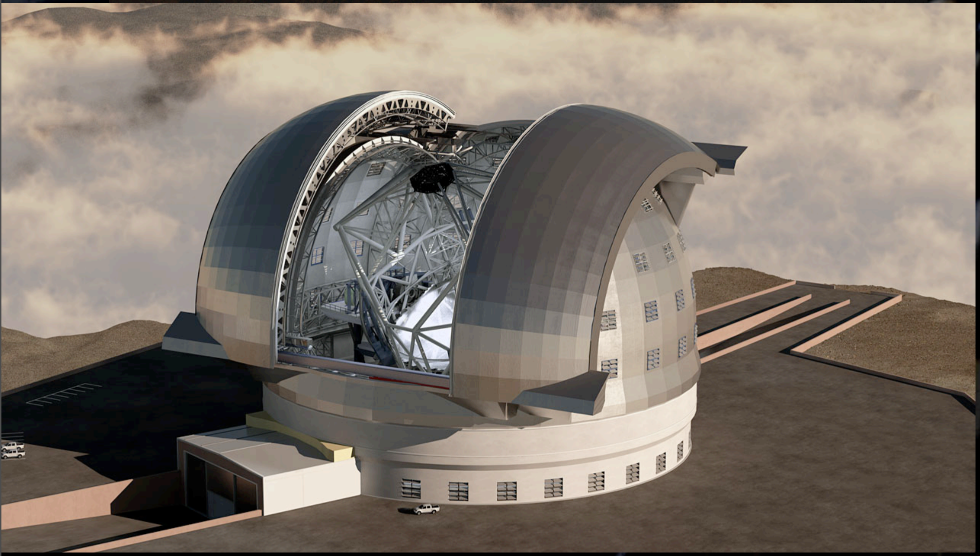


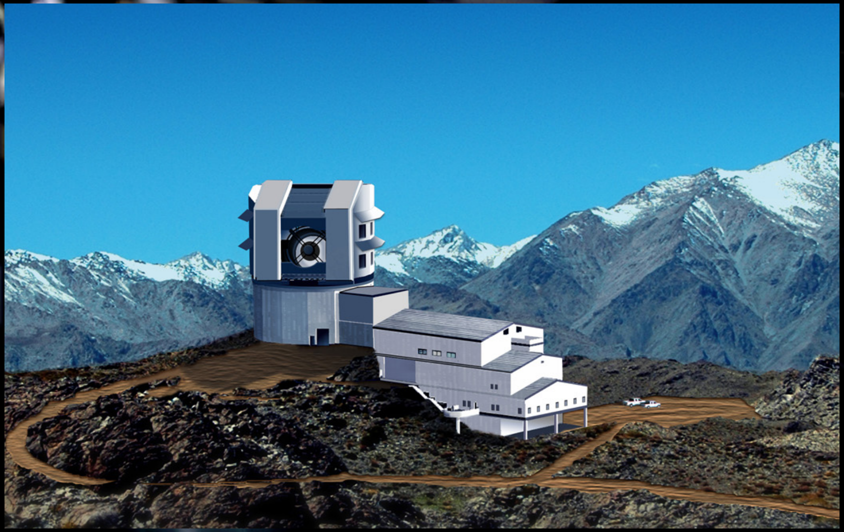


Big Glass on the Ground: 4 VLT, 2 Kecks, 2 Geminis and 2 Magellans

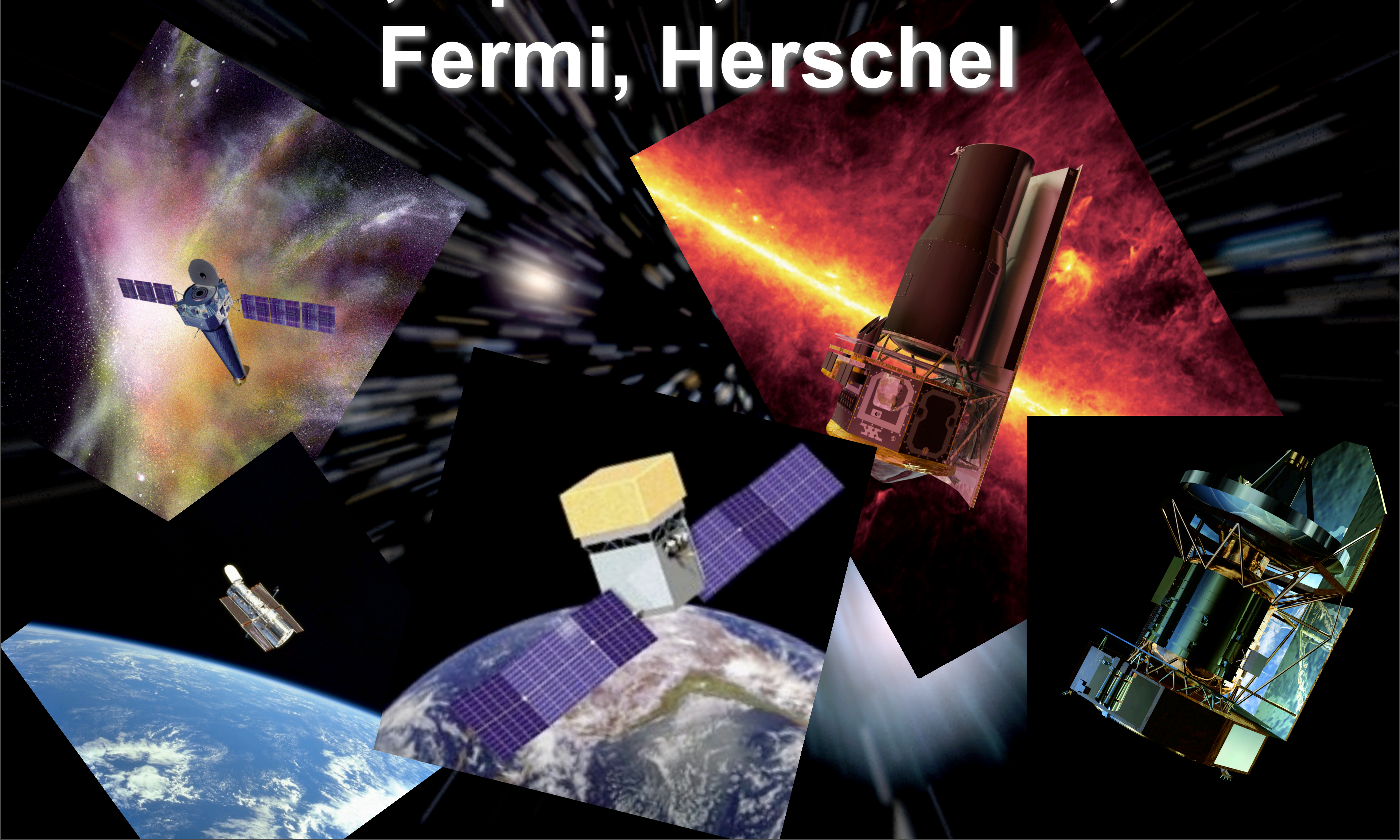
More on the way!





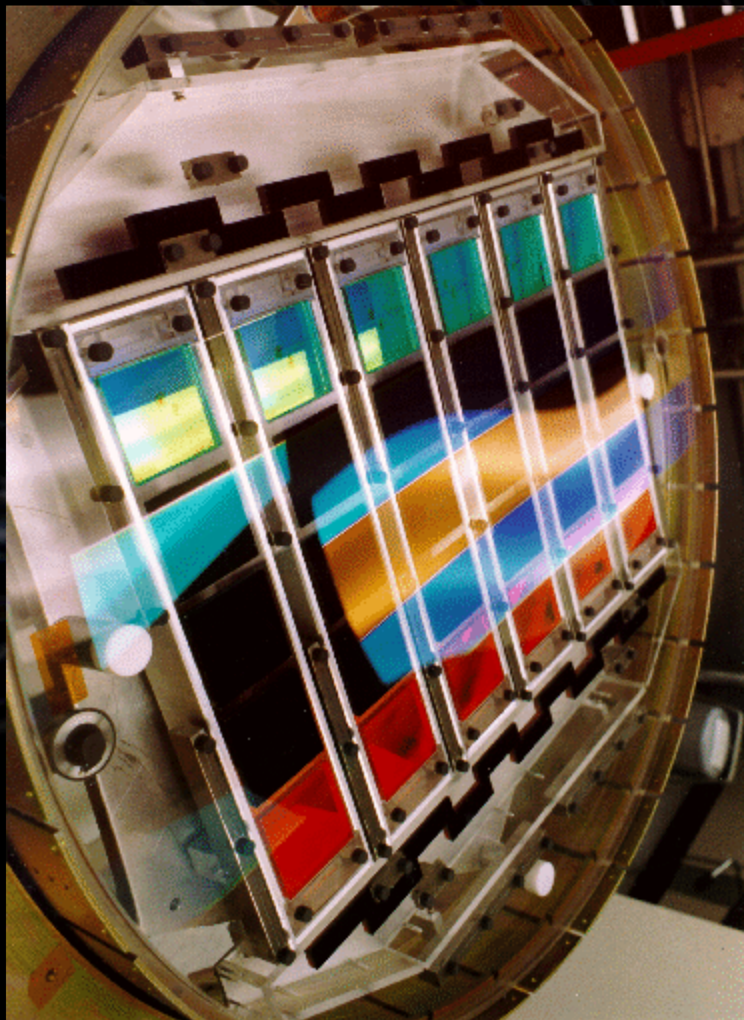


Great Observatories in Space: Hubble, Spitzer, Chandra, and Fermi, Herschel

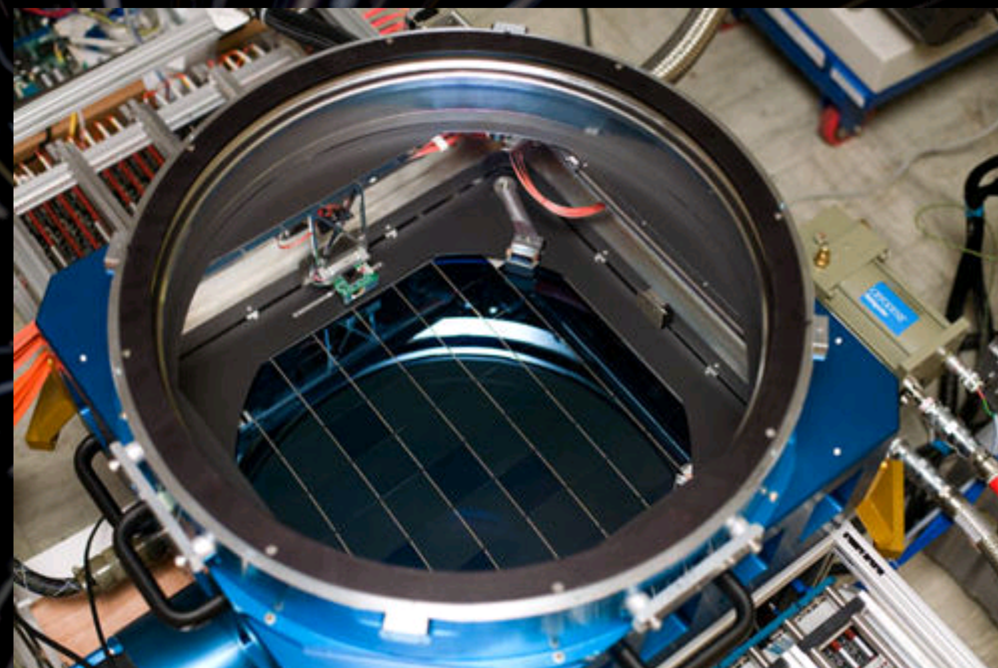


Great Observatories in Space: Soon – JWST

Giant CCD Cameras

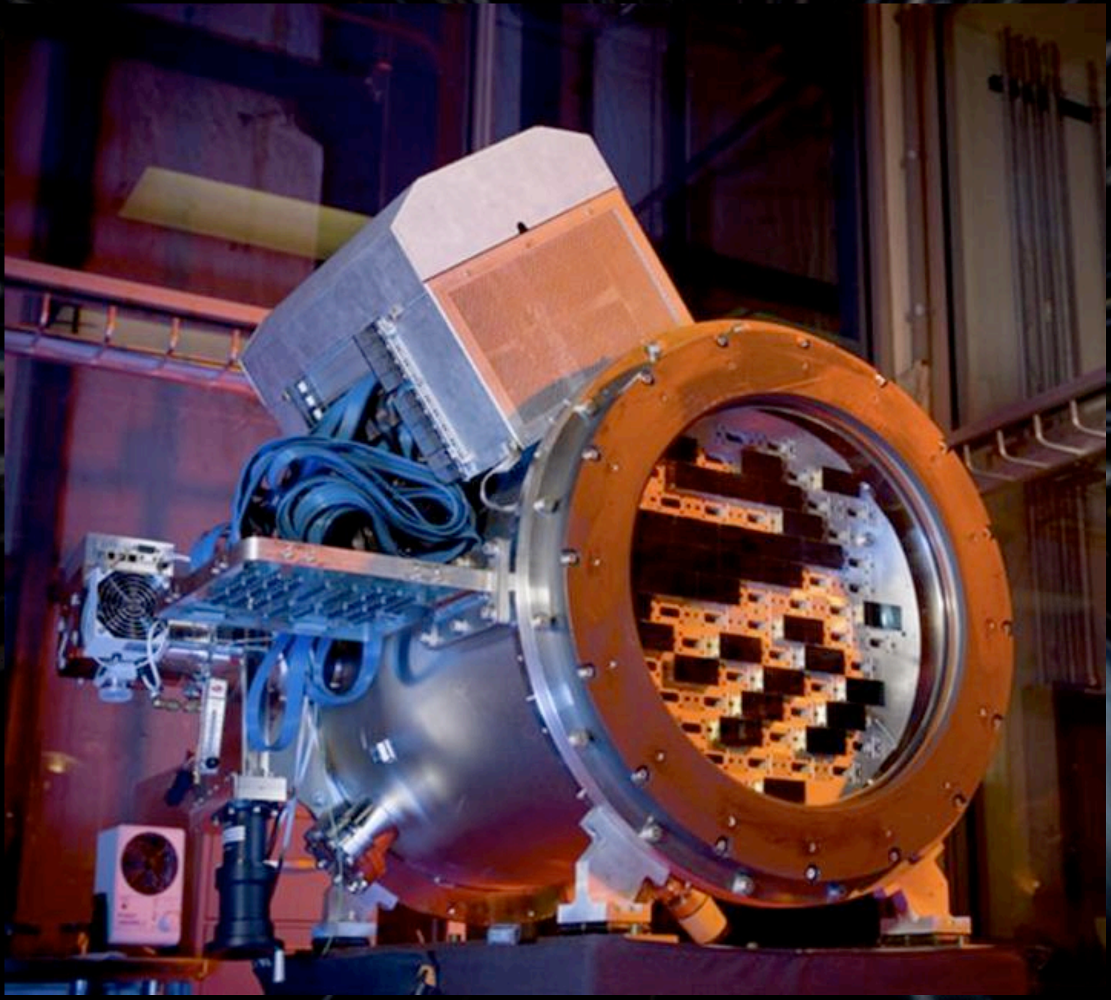


100 Megapixel



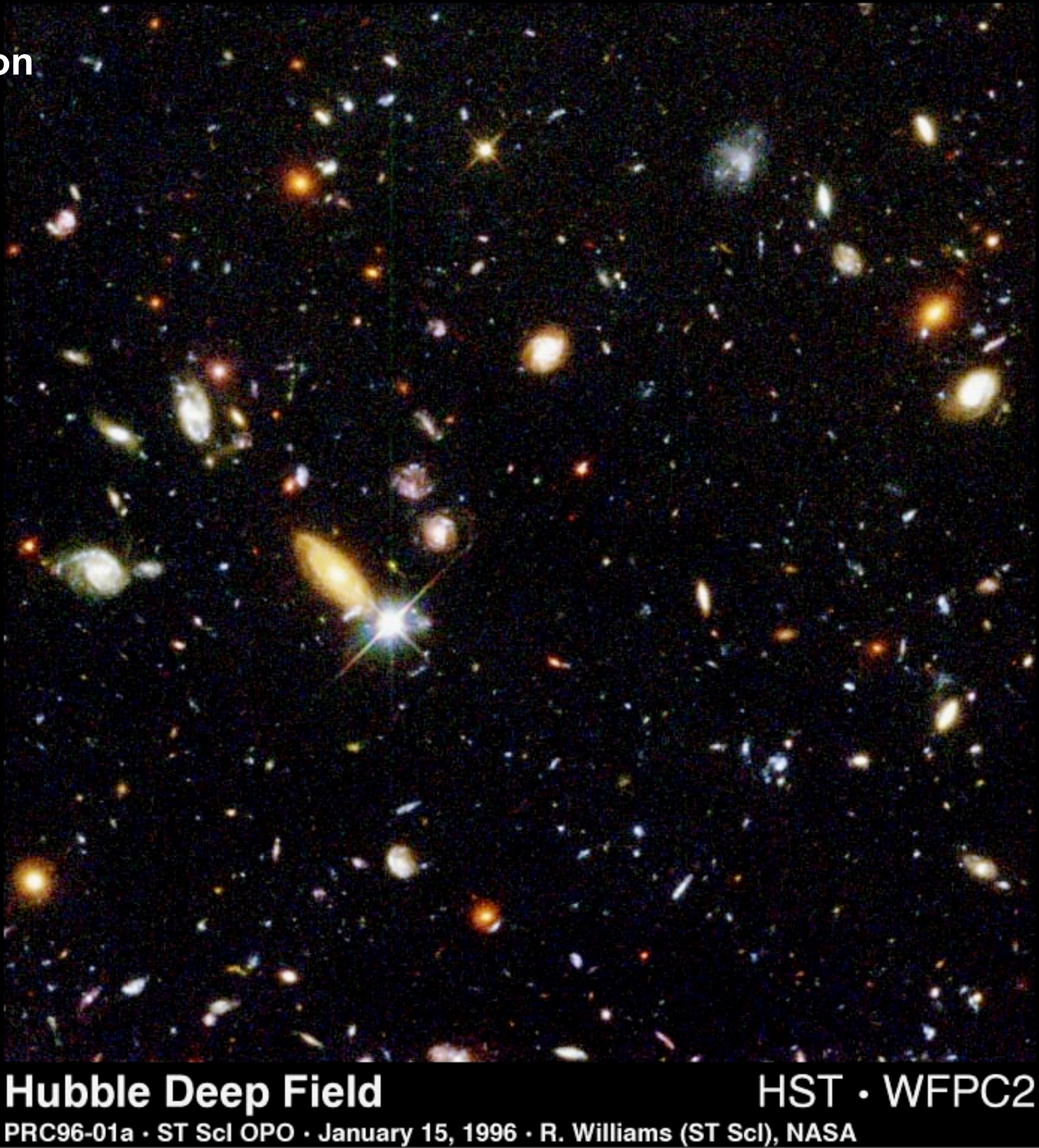
Gigapixel

Giant CCD Cameras: Dark Energy Camera



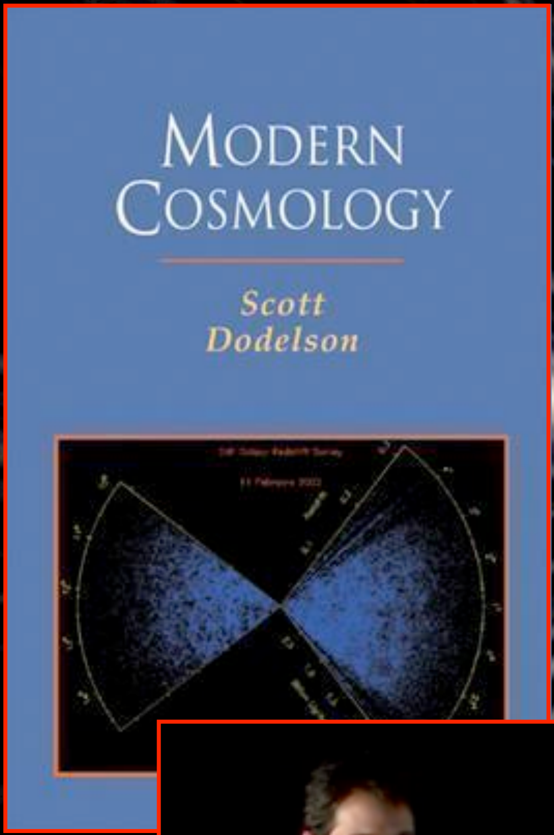
0.5 Gigapixel

How far can you see on a clear day?
Back to the birth of galaxies



How far can you see on a clear day with x-ray eyes?
To supermassive black holes at the edge of the Universe!

2000s: Era of Precision Cosmology



<u>“Fisher Based”</u>

- Cosmological parameters
- Tests of inflation, CDM
- Correlating large, complex data sets
- Cosmological Consistency
- Physical parameters (e.g., neutrino mass)

In the midst of a revolutionary period of discovery -- powerful ideas and instruments

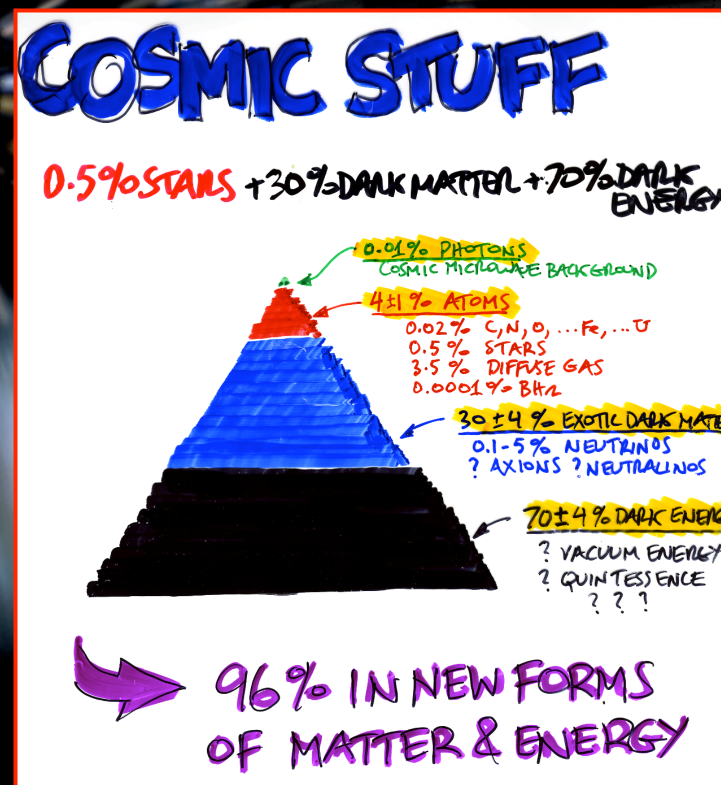
The Consensus Cosmology

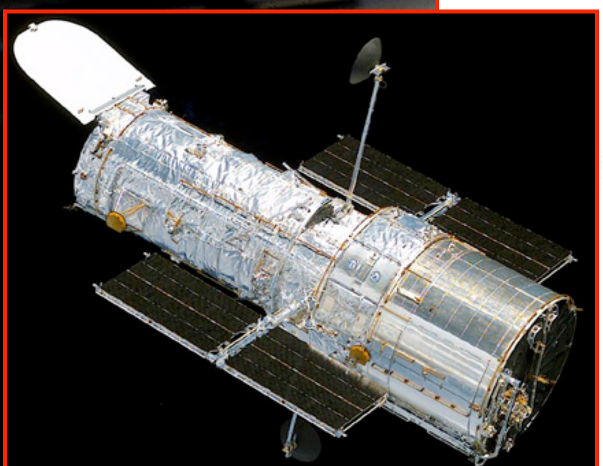
dark matter, dark energy, inflation inspired

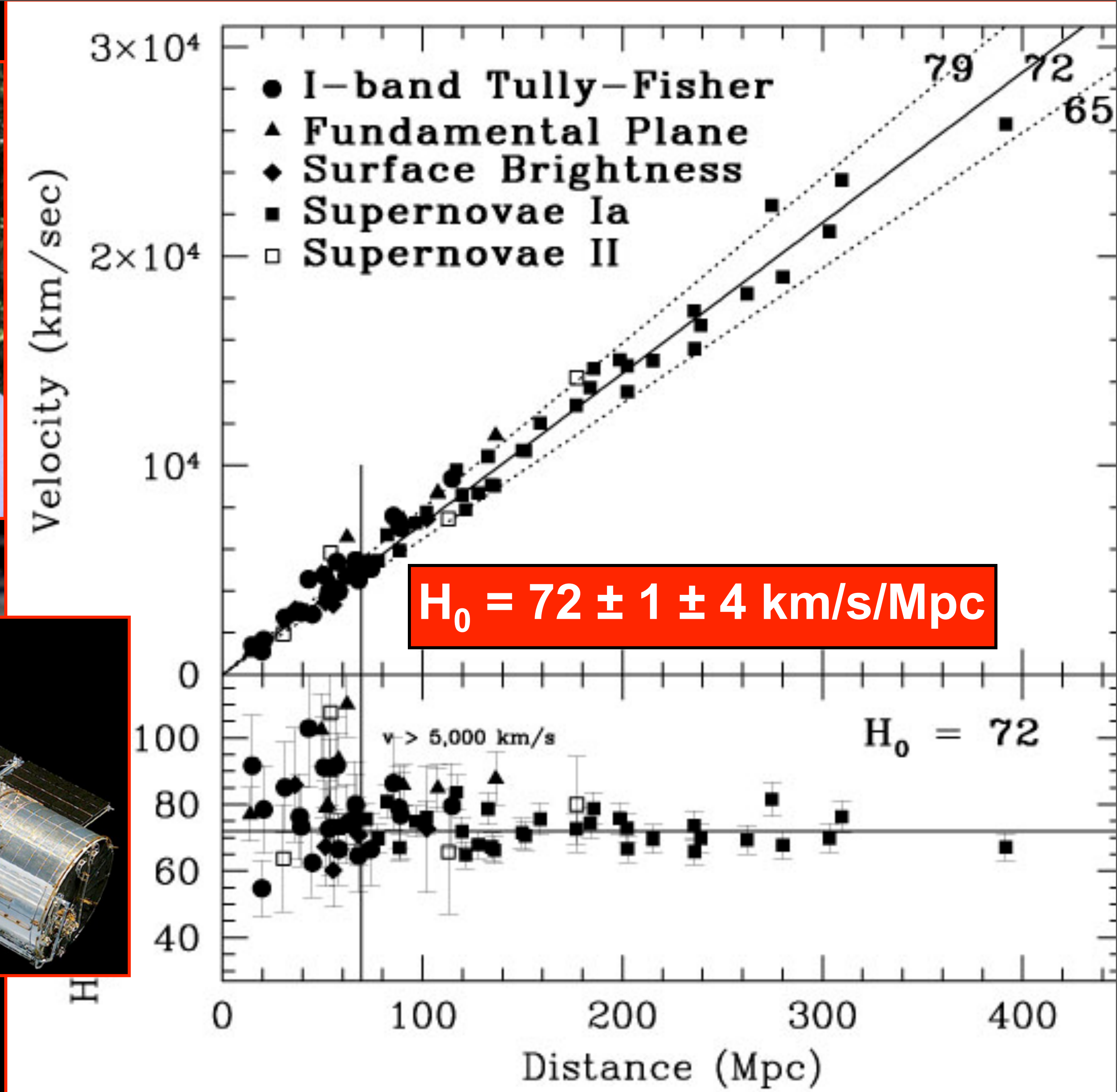
fits a large body of precision data!

The "Consensus Cosmology"

- History from quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- <u>Consistent with inflation</u>
- Precision parameters
  - $\Omega_0 = 1.005 \pm 0.006$ (uncurved)
  - $\Omega_M = 0.280 \pm 0.013$
  - $\Omega_B = 0.045 \pm 0.0015$
  - $\Omega_{DE} = 0.72 \pm 0.015$
  - $H_0 = 70 \pm 1.3$ km/s/Mpc
  - $t_0 = 13.73 \pm 0.12$ Gyr
  - $N_\nu = 4.4 \pm 1.5$

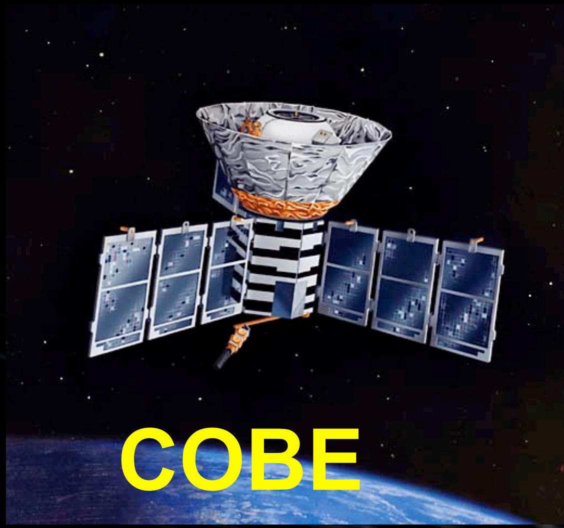


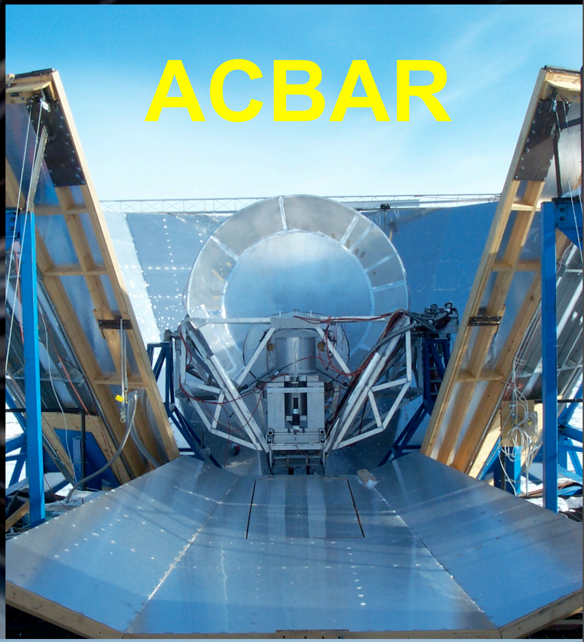


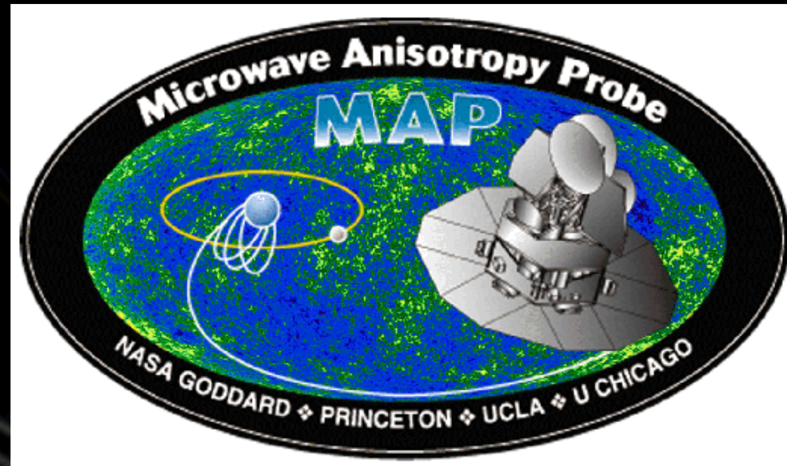

I−band Tully−Fisher
Fundamental Plane
Surface Brightness
Supernovae Ia
Supernovae II
79
72
65
Velocity (km/sec)
3×10⁴
2×10⁴
10⁴
0
H_0 = 72 ± 1 ± 4 km/s/Mpc
v > 5,000 km/s
H_0 = 72
100
80
60
40
0
100
200
300
400
Distance (Mpc)

… and Dr. Sandage, H_0 is now measured and q_0 is negative!

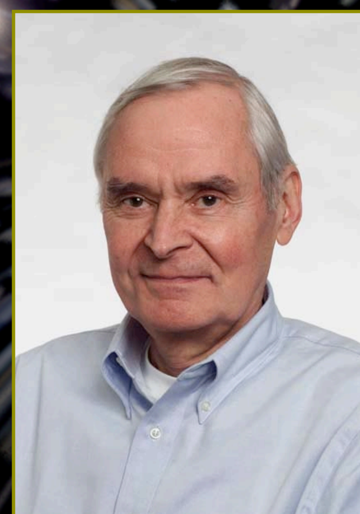
Decoding the Cosmic

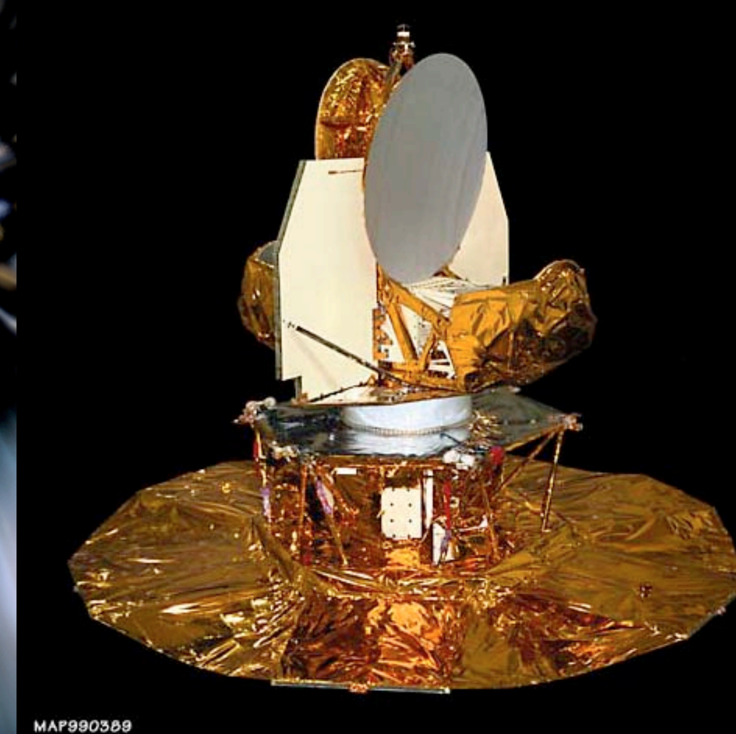





Microwave Anisotropy Probe
MAP
NASA GODDARD ❖ PRINCETON ❖ UCLA ❖ U CHICAGO

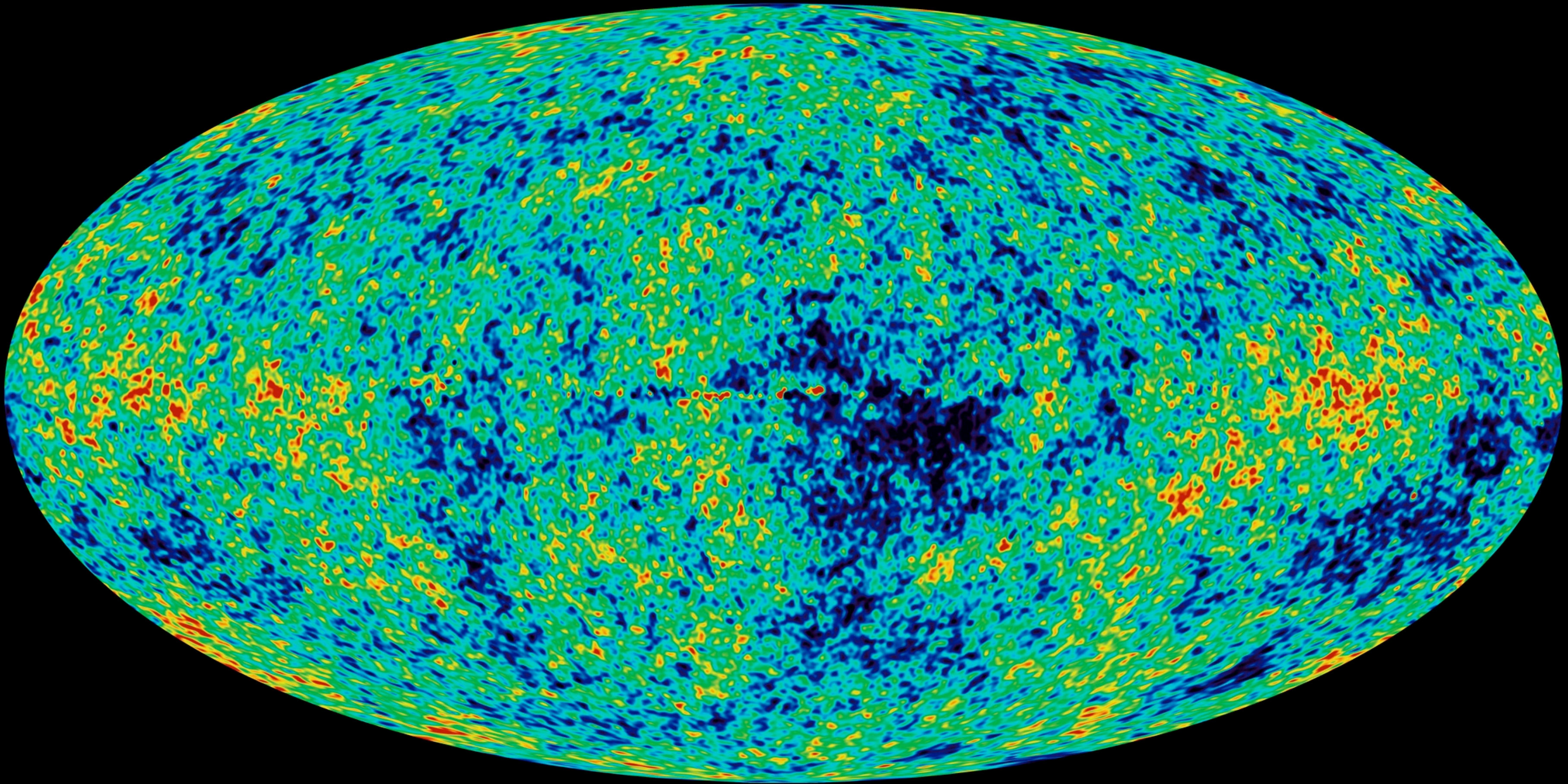

USAF
DELTA
MAP



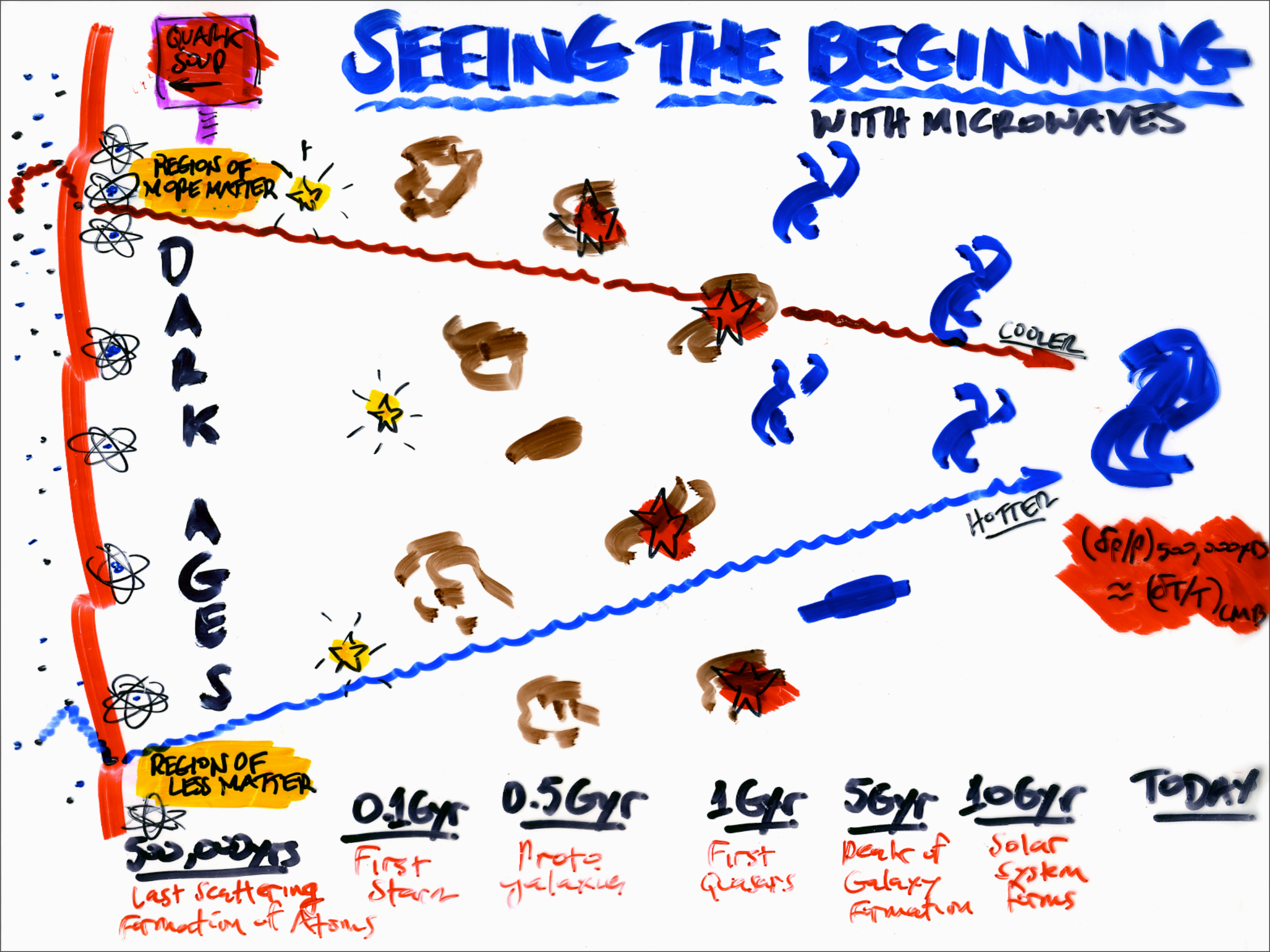

MAP990389

The Universe circa 380,000 yrs

WMAP

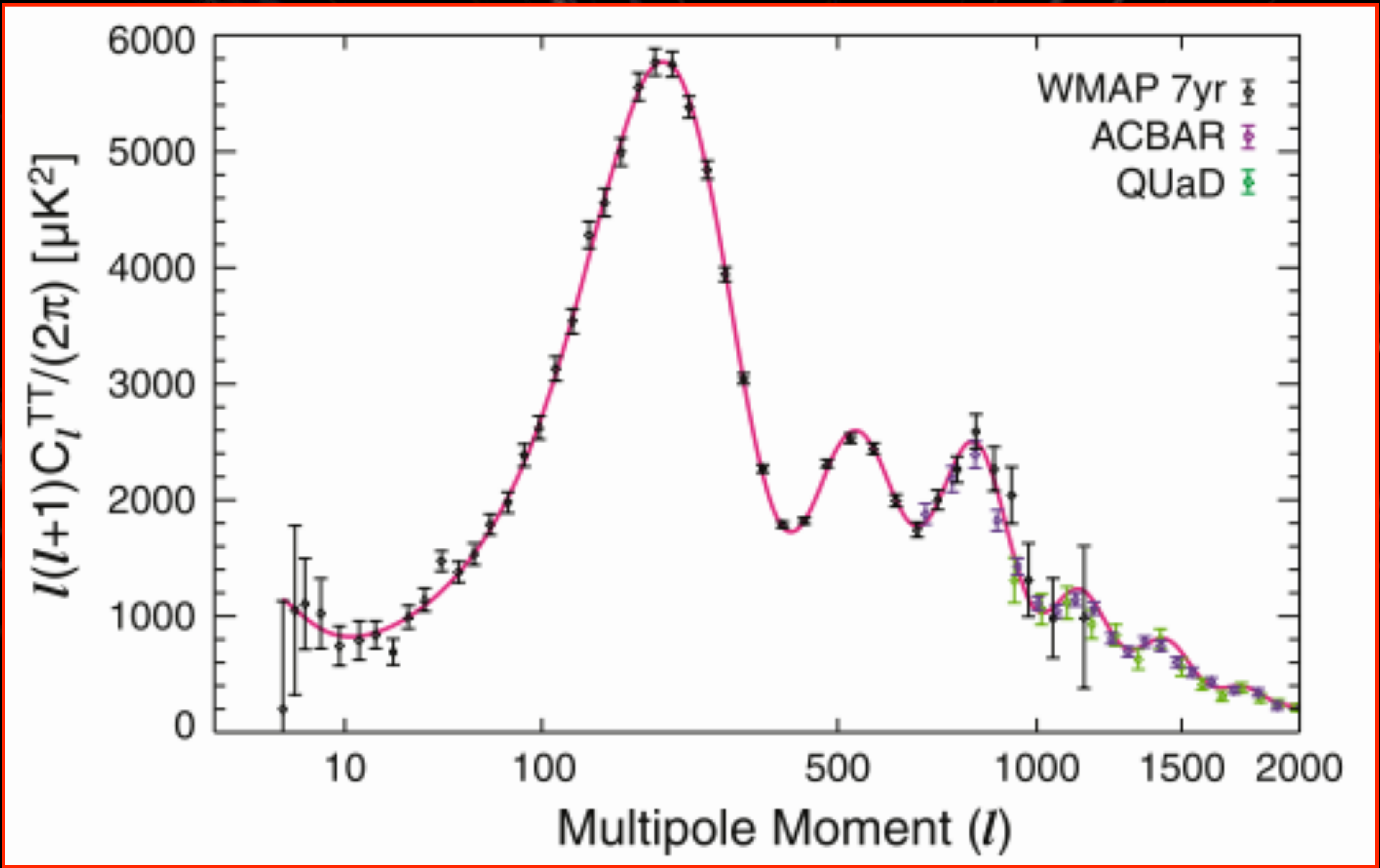


±0.001% Fluctuations

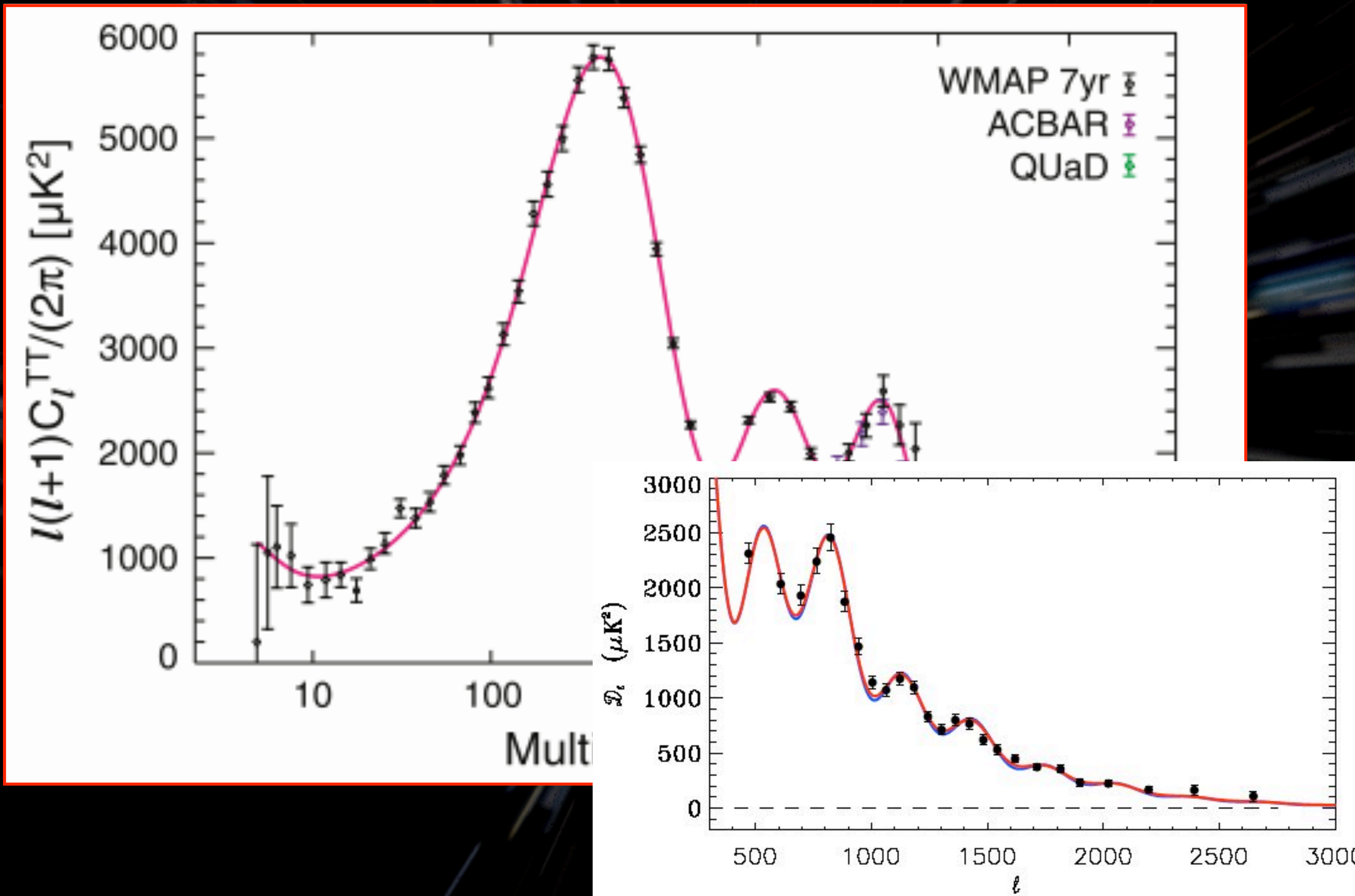


SEEING THE BEGINNING
WITH MICROWAVES
QUARK SOUP
REGION OF MORE MATTER
DARK AGES
COOLER
HOTTER
(δρ/ρ)500,000yrs ≈ (δT/T)CMB
REGION OF LESS MATTER
500,000yrs
Last Scattering
Formation of Atoms
0.1Gyr
First Stars
0.5Gyr
Proto galaxies
1Gyr
First Quasars
5Gyr
Peak of Galaxy Formation
10Gyr
Solar System forms
TODAY

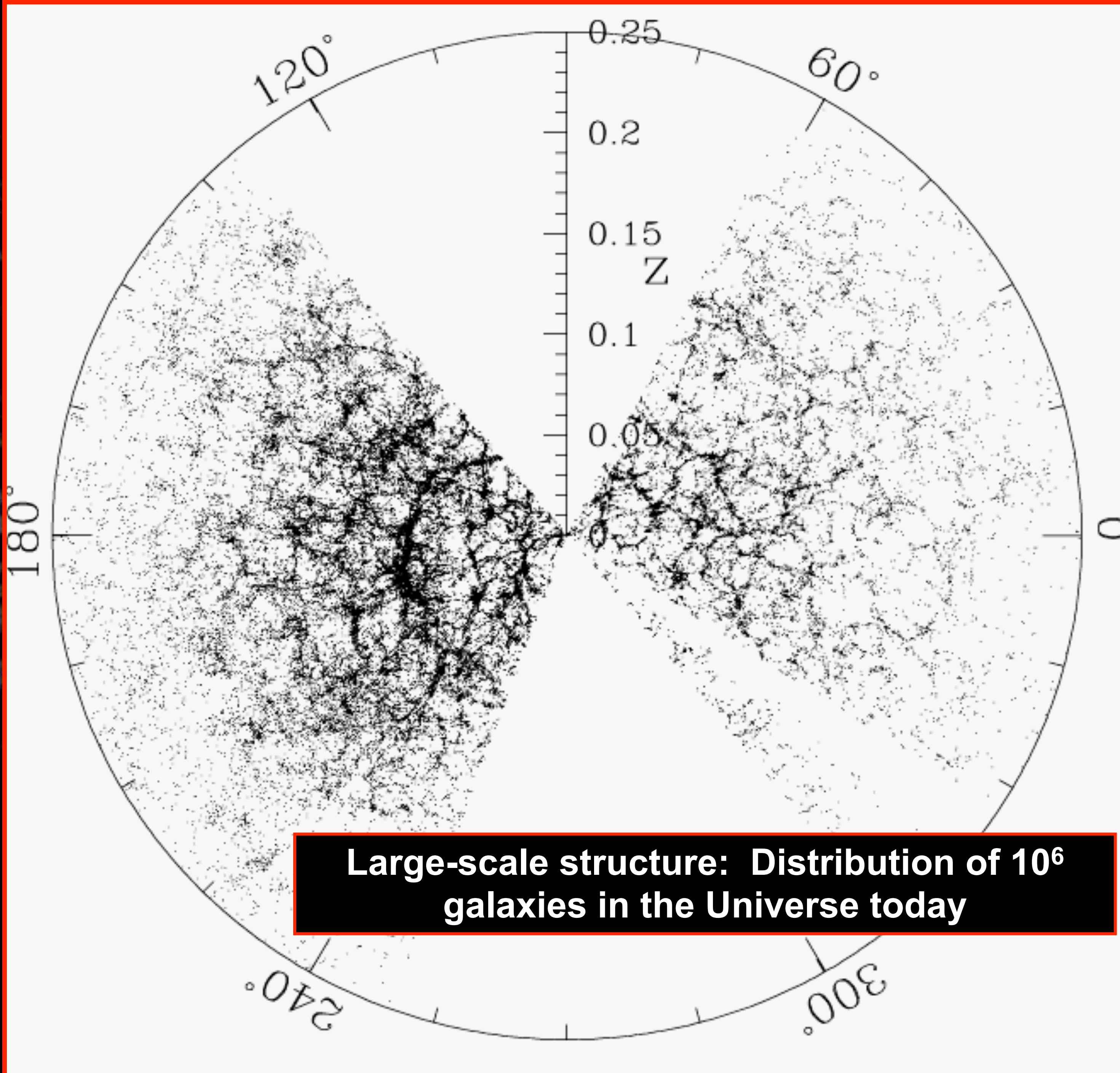
Curve = concordance cosmology



Curve = concordance cosmology

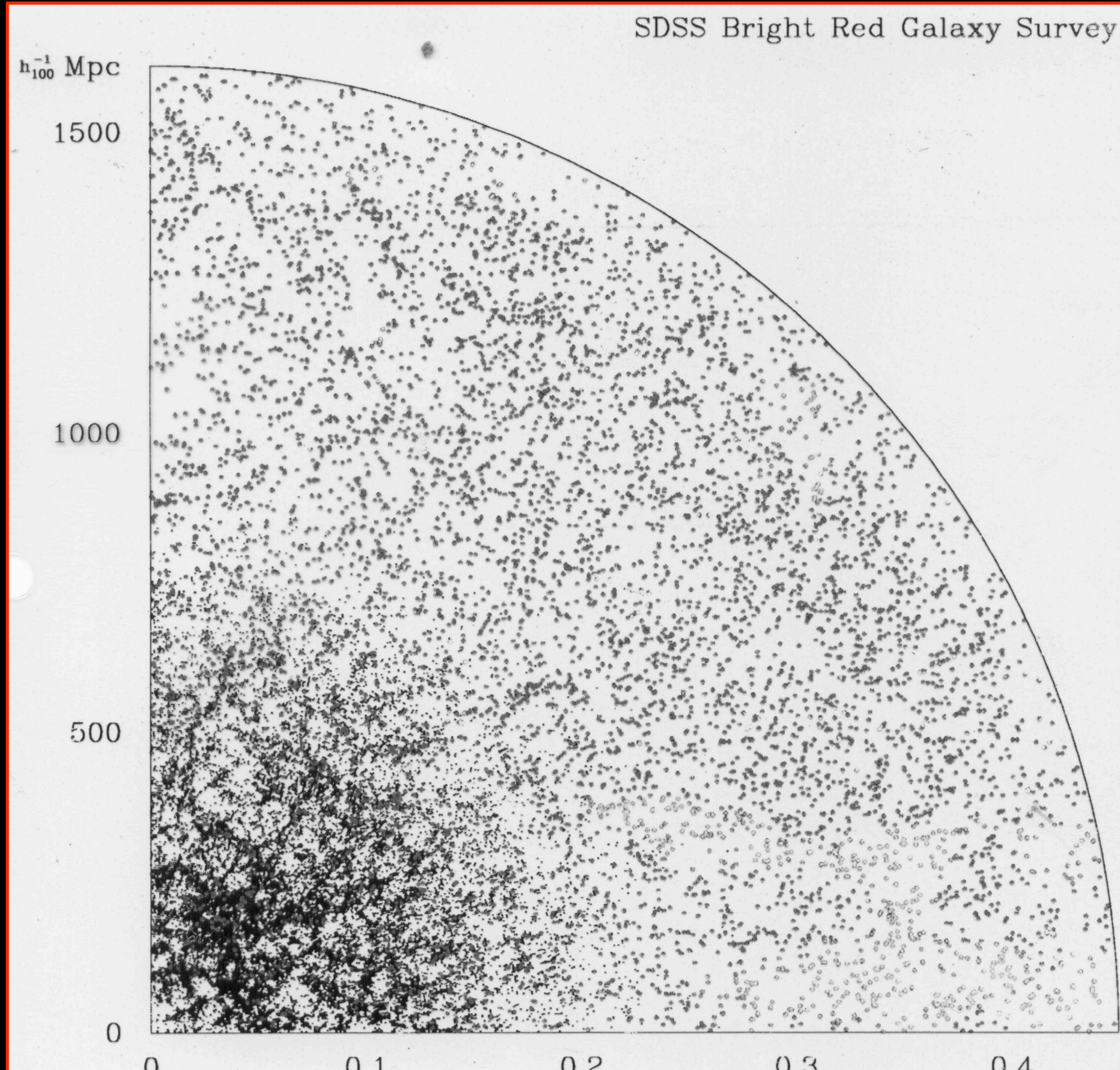


Sloan Digital Sky Survey
sdss.org

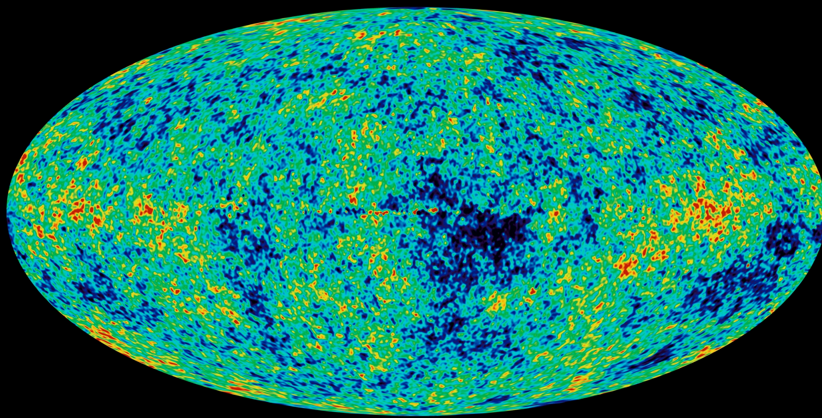


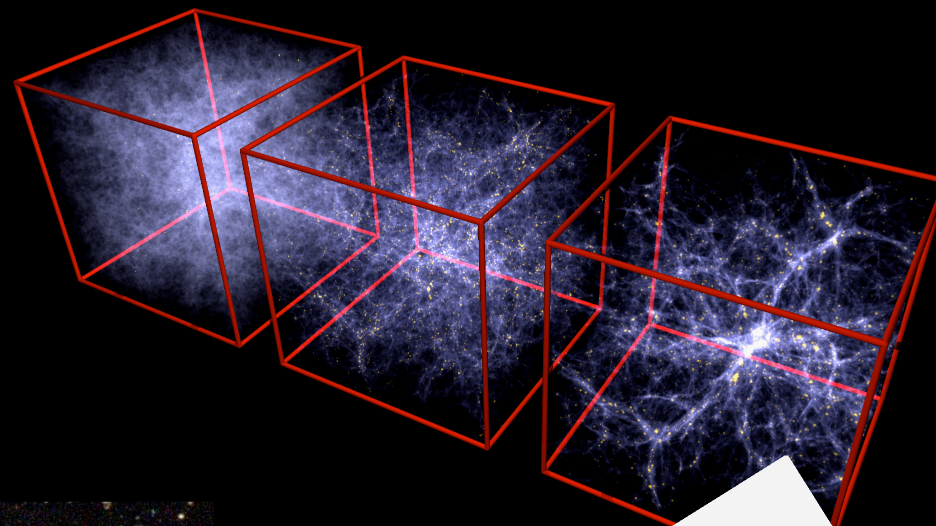
Large-scale structure: Distribution of 10^6 galaxies in the Universe today

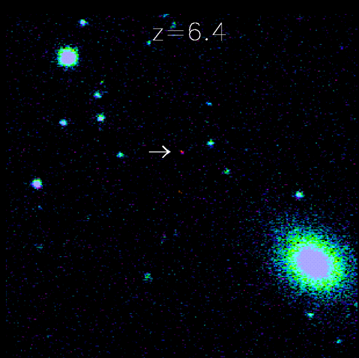
Sloan Digital Sky Survey
sdss.org

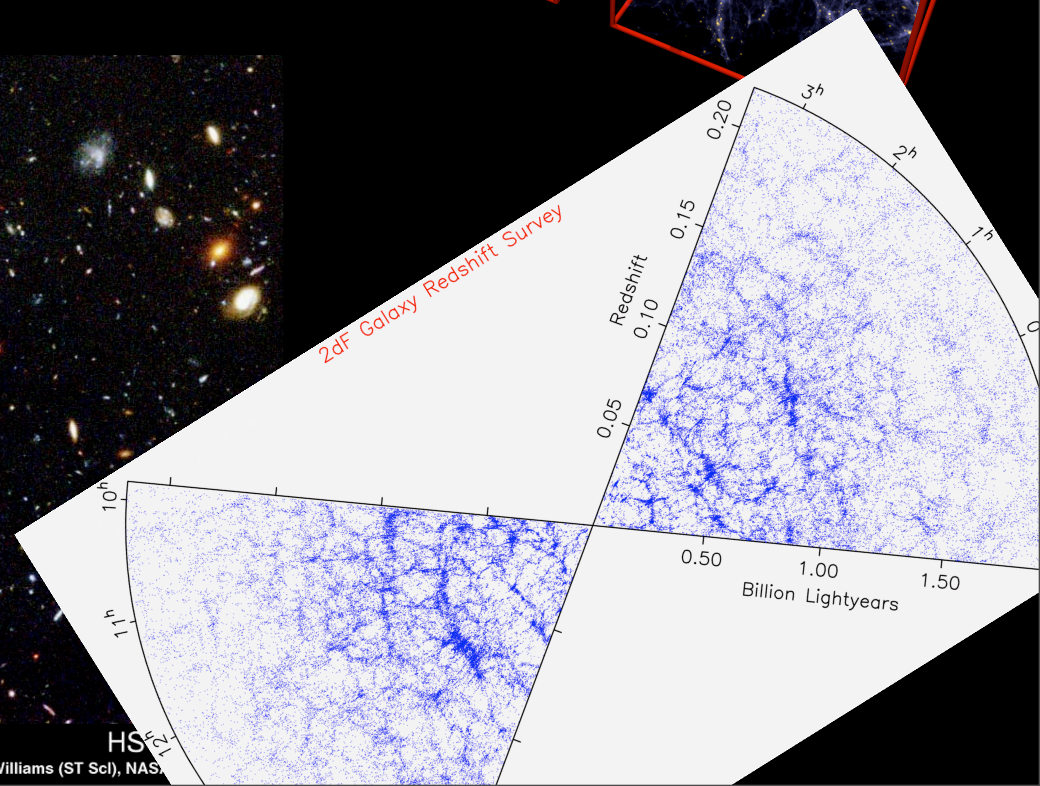


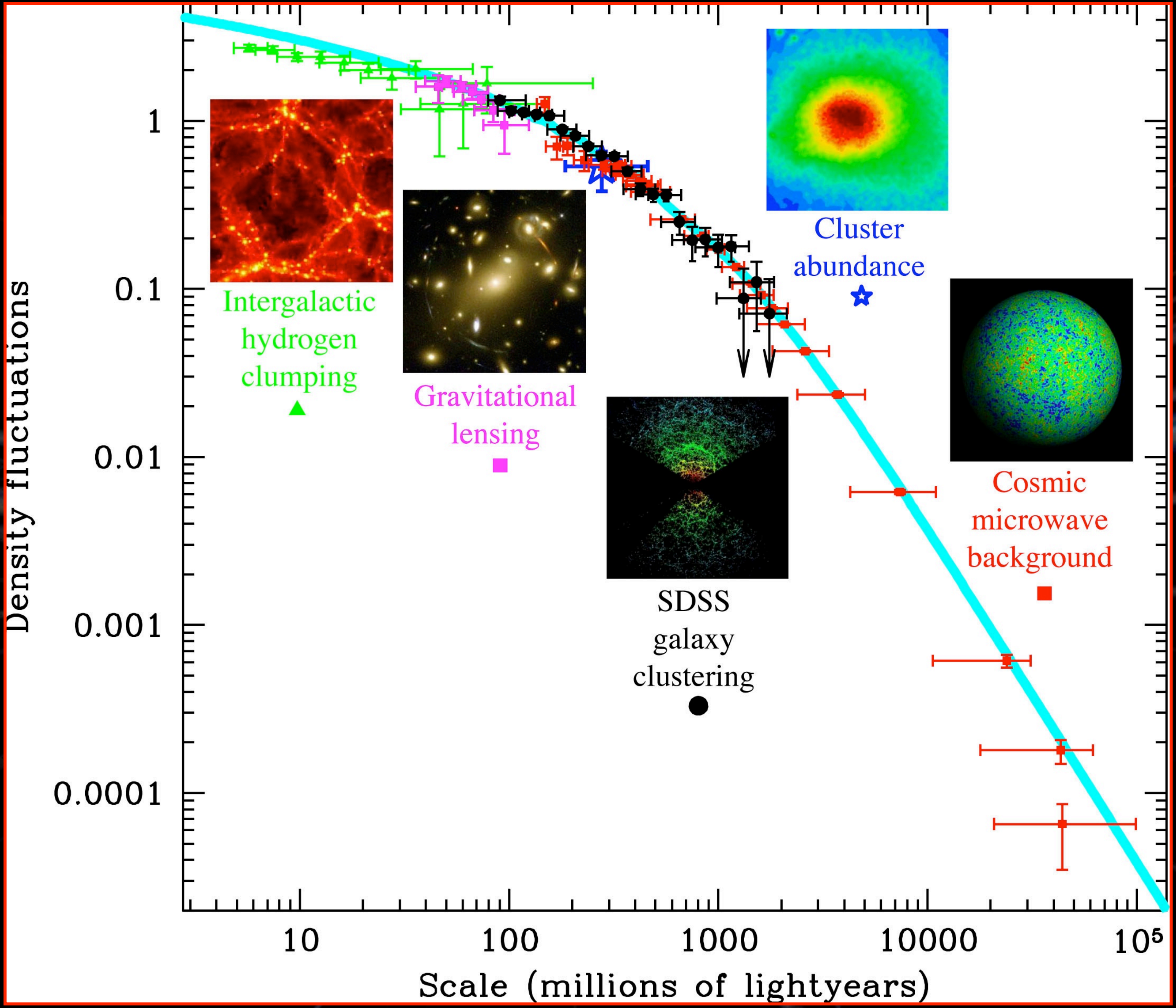
Tracing the history from a slightly lumpy Universe to galaxies ablaze











Density fluctuations
Scale (millions of lightyears)
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10^5
Intergalactic hydrogen clumping
Gravitational lensing
SDSS galaxy clustering
Cluster abundance
Cosmic microwave background

The Consensus Cosmology

consistent with an impressive body of data

describes Universe from a burst of inflation through the formation of structure shaped by dark matter to today when dark energy controls the fate of the Universe

but …

The Consensus Cosmology

Rests upon three mysterious pillars

All implicate new physics!

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

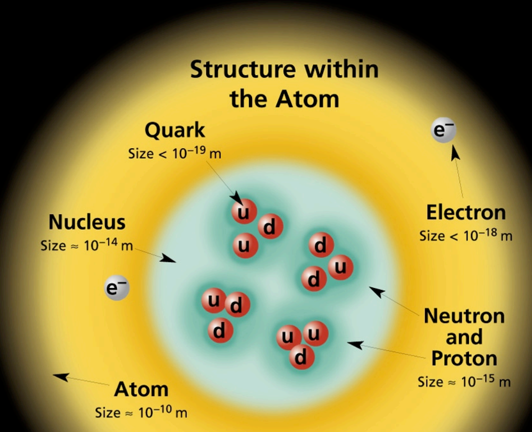
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

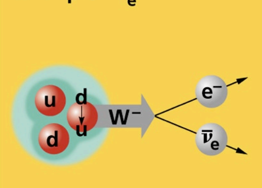
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

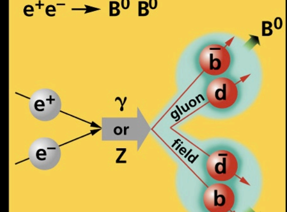
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



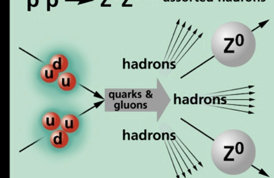
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

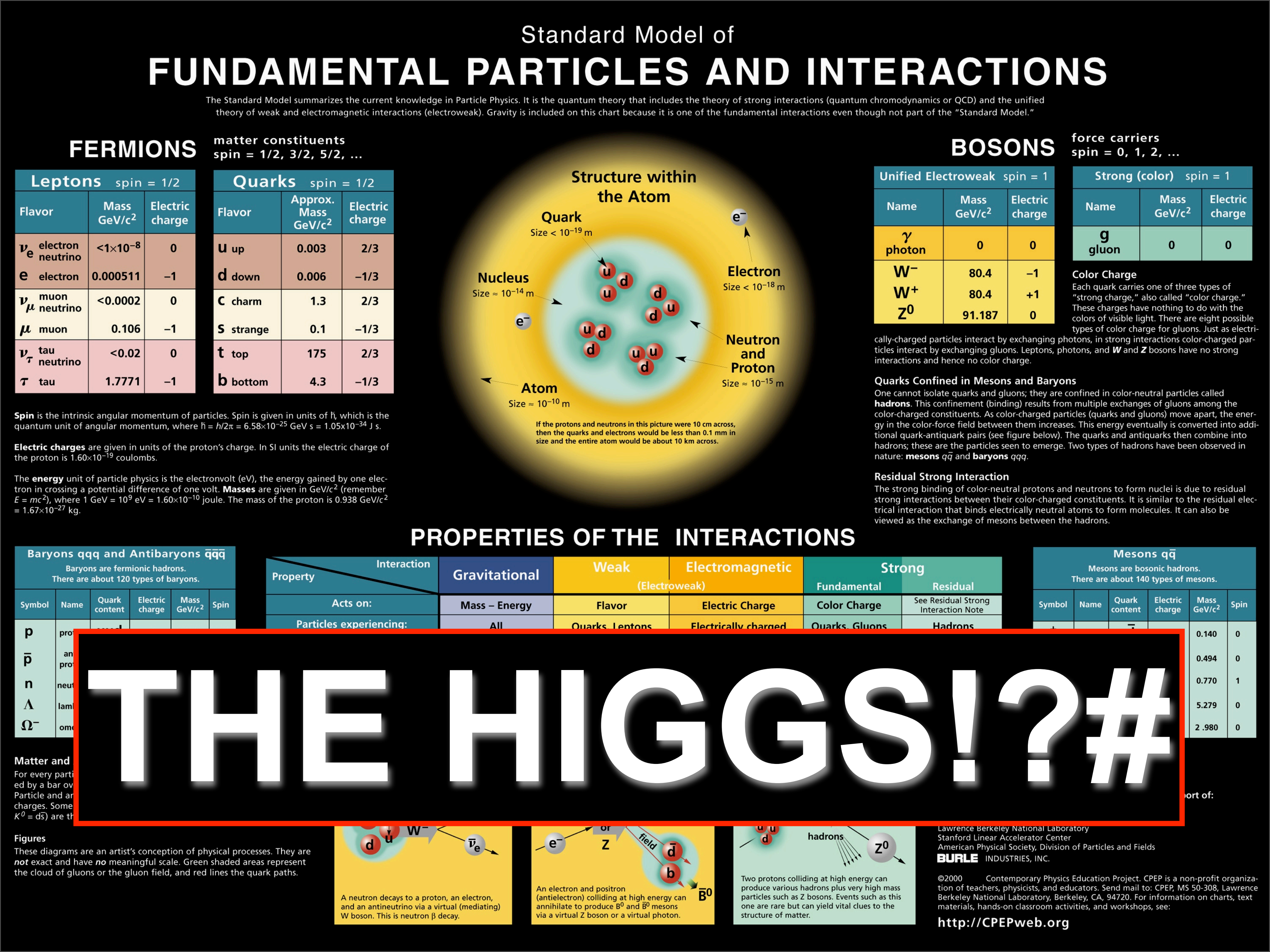
The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:

U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."
FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...
Leptons spin = 1/2
Flavor
Mass GeV/c²
Electric charge
νe electron neutrino <1×10⁻⁸ 0
e electron 0.000511 –1
νμ muon neutrino <0.0002 0
μ muon 0.106 –1
ντ tau neutrino <0.02 0
τ tau 1.7771 –1
Quarks spin = 1/2
Flavor
Approx. Mass GeV/c²
Electric charge
u up 0.003 2/3
d down 0.006 –1/3
c charm 1.3 2/3
s strange 0.1 –1/3
t top 175 2/3
b bottom 4.3 –1/3
Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where ħ = h/2π = 6.58×10⁻²⁵ GeV s = 1.05x10⁻³⁴ J s.
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Structure within the Atom
Quark
Size < 10⁻¹⁹ m
Nucleus
Size ≈ 10⁻¹⁴ m
Electron
Size < 10⁻¹⁸ m
Neutron and Proton
Size ≈ 10⁻¹⁵ m
Atom
Size ≈ 10⁻¹⁰ m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
BOSONS
force carriers
spin = 0, 1, 2, ...
Unified Electroweak spin = 1
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Mass GeV/c²
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γ photon 0 0
W⁻ 80.4 –1
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Baryons qqq and Antibaryons q̄q̄q̄
Baryons are fermionic hadrons.
There are about 120 types of baryons.
Symbol Name Quark content Electric charge Mass GeV/c² Spin
Interaction
Property
Gravitational
Weak
Electromagnetic
(Electroweak)
Strong
Fundamental
Residual
Acts on: Mass – Energy Flavor Electric Charge Color Charge
See Residual Strong Interaction Note
Mesons qq̄
Mesons are bosonic hadrons.
There are about 140 types of mesons.
Symbol Name Quark content Electric charge Mass GeV/c² Spin
0.140 0
0.494 0
0.770 1
5.279 0
2 .980 0
THE HIGGS!?#
Matter and
Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.
An electron and positron (antielectron) colliding at high energy can annihilate to produce B⁰ and B̄⁰ mesons via a virtual Z boson or a virtual photon.
Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.
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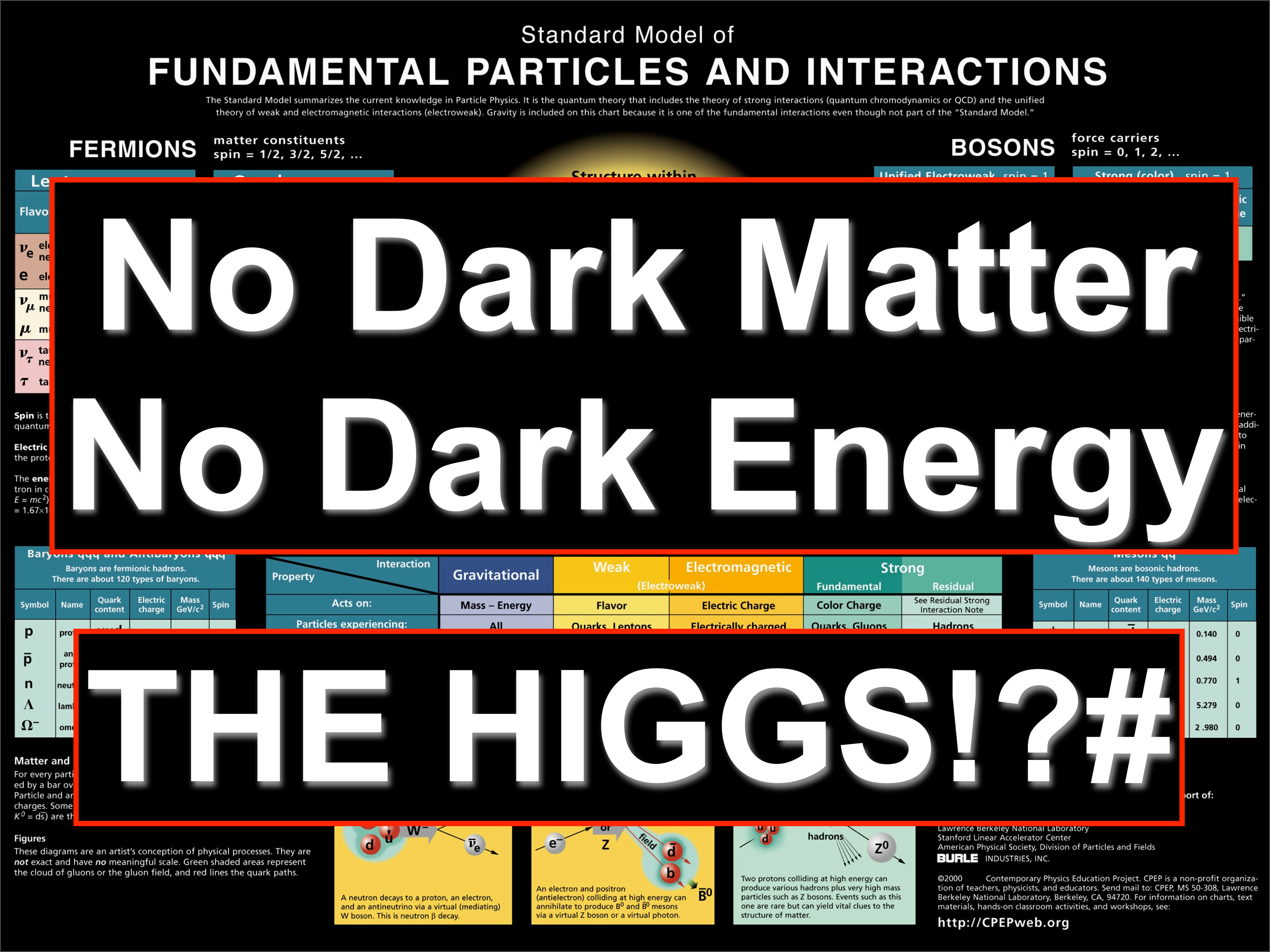

No Dark Matter
No Dark Energy
THE HIGGS!?#
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http://CPEPweb.org

Dark Matter/Dark Energy: The Scientific Approach

- Evidence
  - Meets the Sagan Standard
- Ideas
  - Rooted in exciting ideas about extending the standard model of particle physics
- Probes
  - Full court press – answers will come soon!

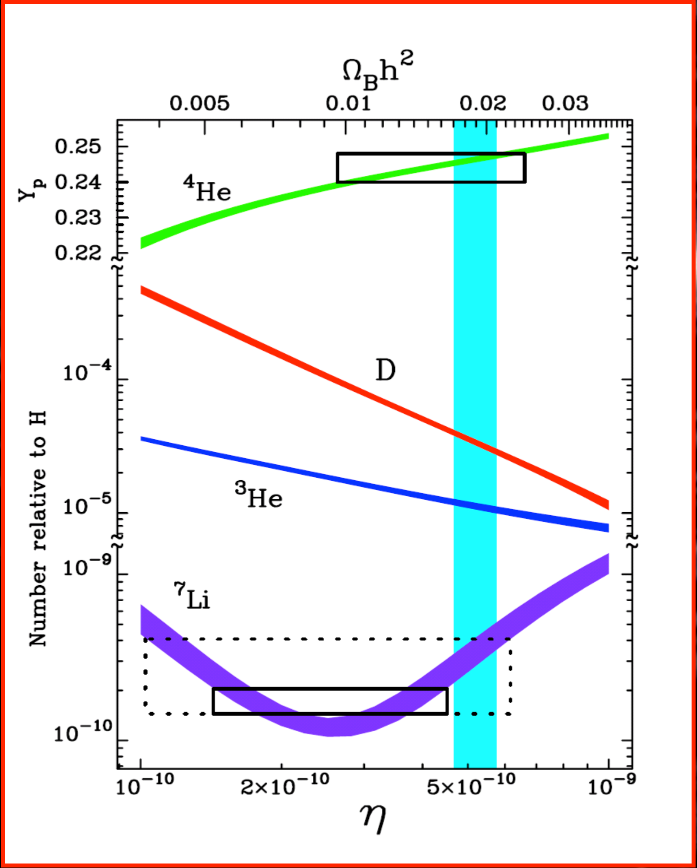
Carl Sagan:

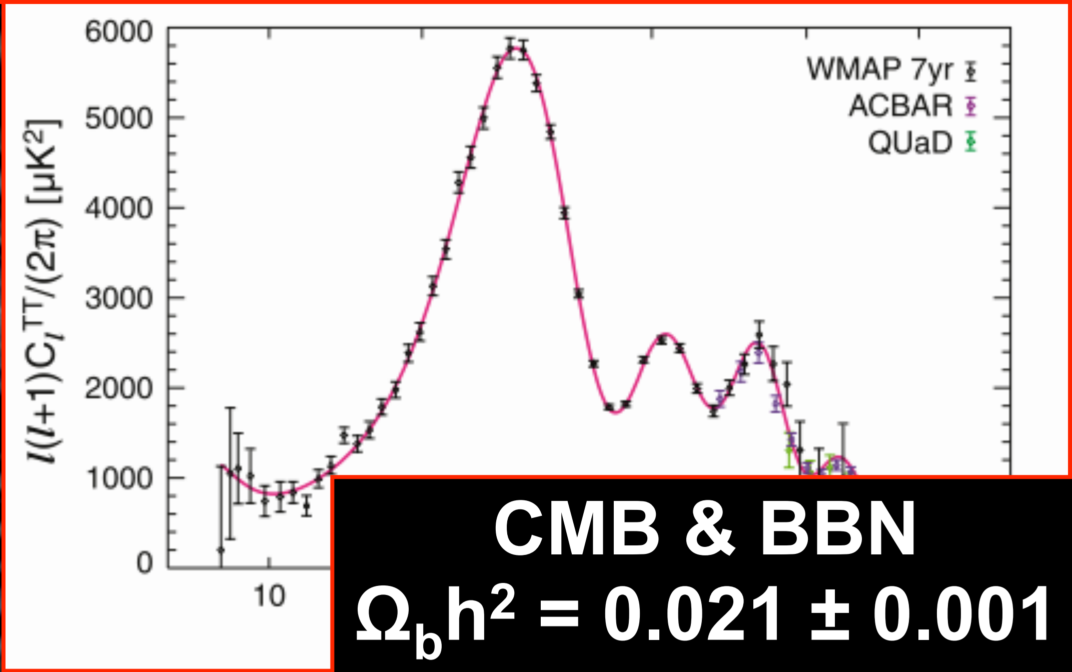
Extraordinary Claims Require Extraordinary Evidence

Evidence for Dark Matter

- Flat rotation curves of galaxies (galaxies have large, dark halos)
- Clusters are held together by dark matter (galaxy motions, gravitational lensing)
- Without the gravity of exotic dark matter cannot make observed structure
- Airtight evidence for non baryonic nature
  - BBN/CMB census of stuff in the Universe

Airtight Evidence for Nonbaryonic Dark Matter





CMB & BBN

$\Omega_b h^2 = 0.021 \pm 0.001$

vs.

CMB/SDSS

$\Omega_M h^2 = 0.13 \pm 0.005$

<u>20σ discrepancy</u>

BIG Gap Between Matter and Baryons

Baryons: 21 ± 1

Matter: 130 ± 5

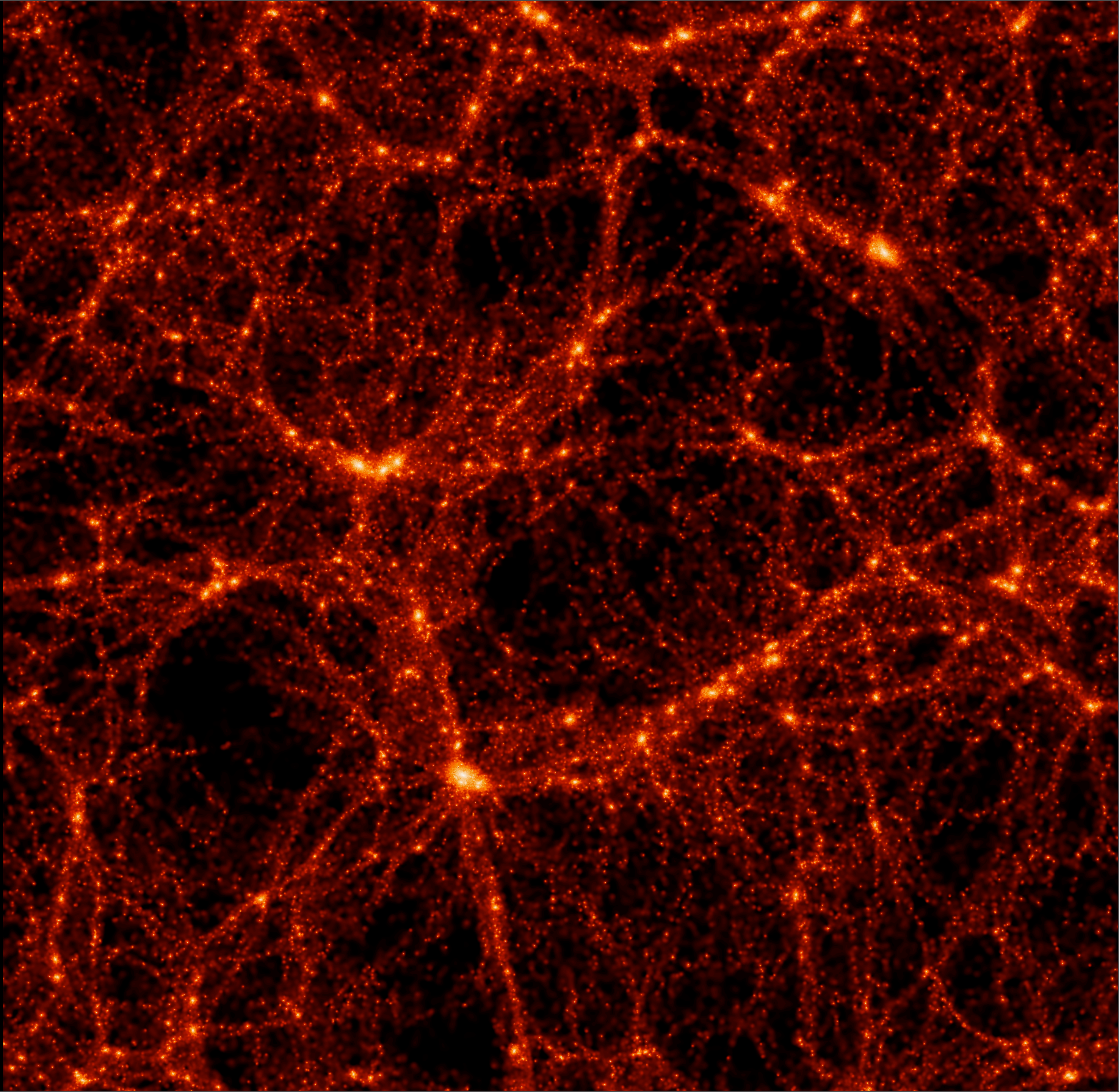
→ **Most of the matter is not baryons**

Dark Numbers

- Stars: 0.5% of critical density
- Atoms: 4.5% of critical density
- Matter total: about 28% of critical density
- Dark Atoms: 4% of critical density

Bottom Line: Atoms can only explain 4% of the Dark Matter, the other 24% must be a new form of matter ("exotic dark matter")

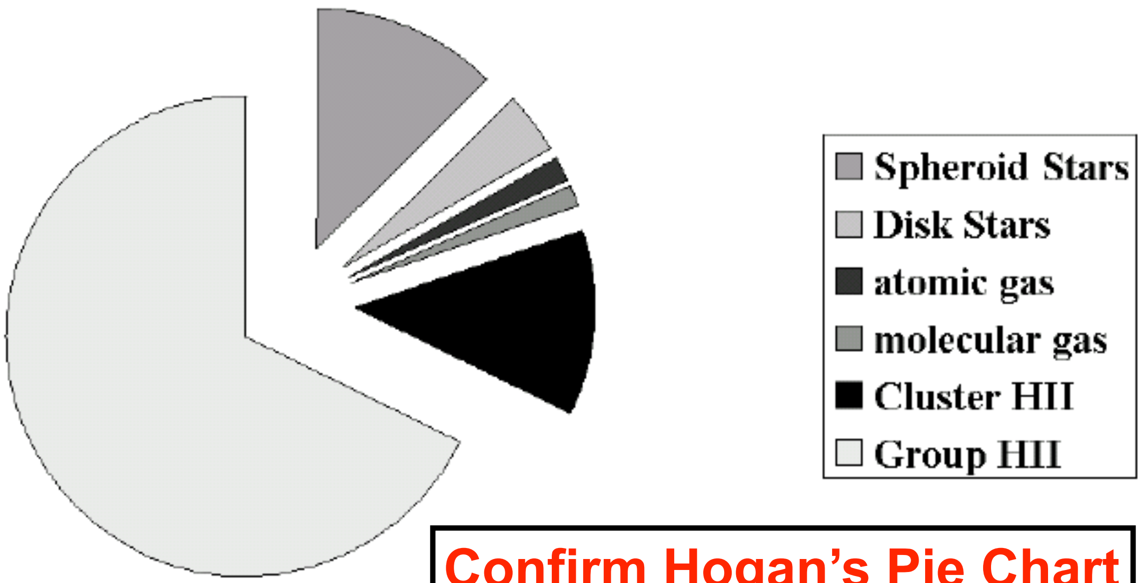
Cosmic Web of Dark Matter Decorated by Stars



Big Dark Questions

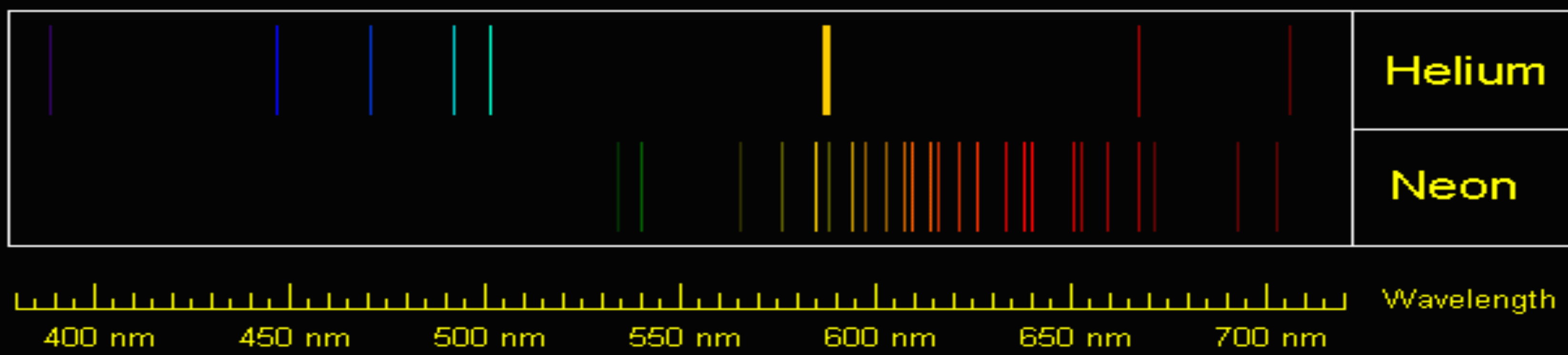
- Where are the dark atoms (atoms: 4.5% total vs. in stars: 0.5%)?
  – Probably hot gas; seen in clusters
- Neutrinos: how much of the dark matter is neutrinos?
  – Between 0.2% and 2% (comparable to what exists in stars!)
- What is the Rest of the Dark Matter?
  – Neutralino: Accelerators, Specialized detectors and space
  – Axions: Specialized detectors

Finish the Baryon Story

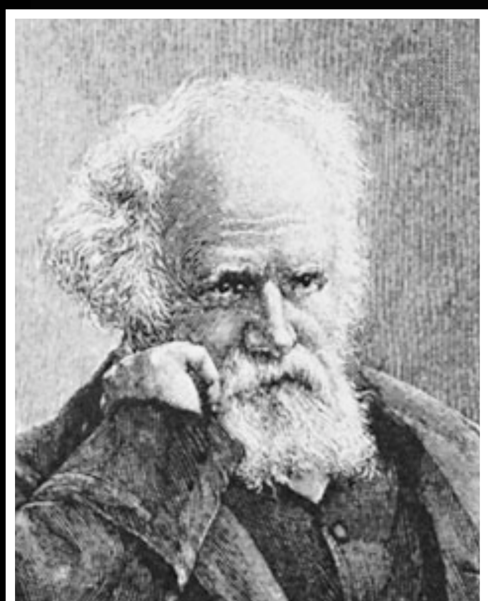


Confirm Hogan's Pie Chart

The First Missing Matter Puzzle: Helium

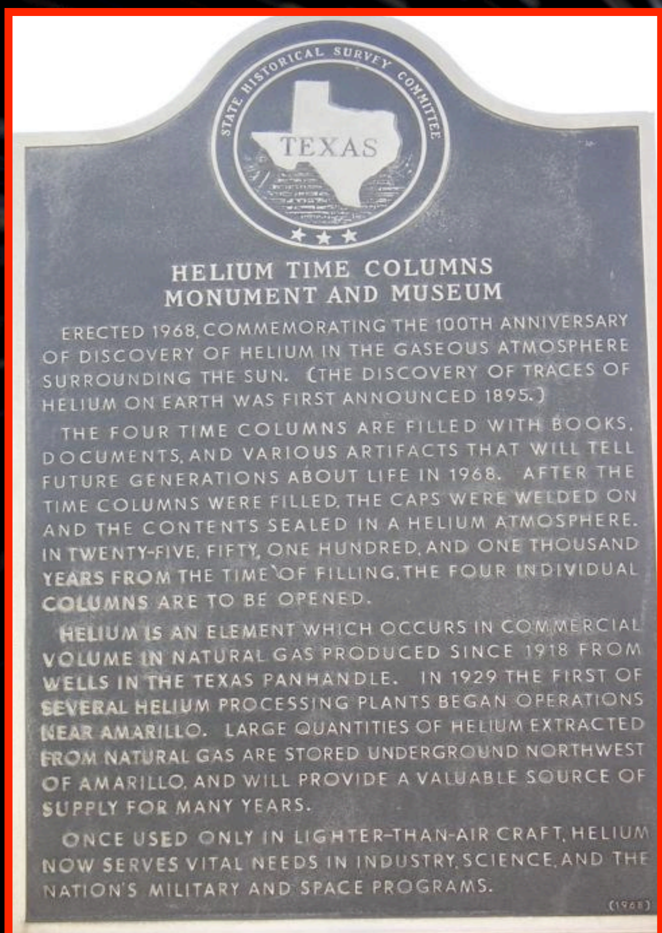


Bright Line Spectra of Helium and Neon



1868: Janssens and Lockyer find evidence for new element, the D3 line

1895: Ramsay solves puzzle by isolating He gas produced by cleveite


HELIUM TIME COLUMNS
MONUMENT AND MUSEUM

ERECTED 1968, COMMEMORATING THE 100TH ANNIVERSARY OF DISCOVERY OF HELIUM IN THE GASEOUS ATMOSPHERE SURROUNDING THE SUN. (THE DISCOVERY OF TRACES OF HELIUM ON EARTH WAS FIRST ANNOUNCED 1895.)

THE FOUR TIME COLUMNS ARE FILLED WITH BOOKS, DOCUMENTS, AND VARIOUS ARTIFACTS THAT WILL TELL FUTURE GENERATIONS ABOUT LIFE IN 1968. AFTER THE TIME COLUMNS WERE FILLED, THE CAPS WERE WELDED ON AND THE CONTENTS SEALED IN A HELIUM ATMOSPHERE. IN TWENTY-FIVE, FIFTY, ONE HUNDRED, AND ONE THOUSAND YEARS FROM THE TIME OF FILLING, THE FOUR INDIVIDUAL COLUMNS ARE TO BE OPENED.

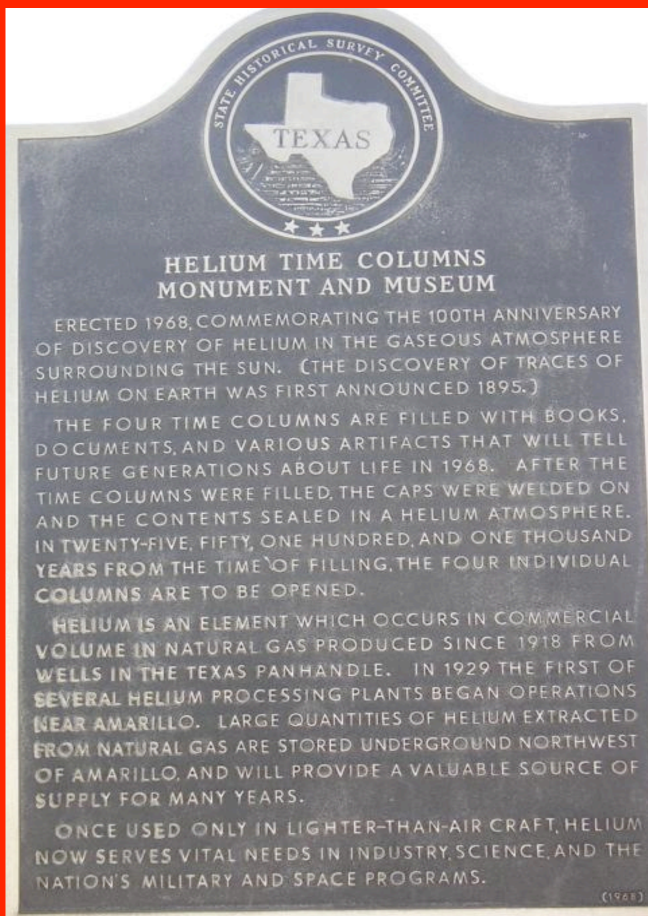
HELIUM IS AN ELEMENT WHICH OCCURS IN COMMERCIAL VOLUME IN NATURAL GAS PRODUCED SINCE 1918 FROM WELLS IN THE TEXAS PANHANDLE. IN 1929 THE FIRST OF SEVERAL HELIUM PROCESSING PLANTS BEGAN OPERATIONS NEAR AMARILLO. LARGE QUANTITIES OF HELIUM EXTRACTED FROM NATURAL GAS ARE STORED UNDERGROUND NORTHWEST OF AMARILLO, AND WILL PROVIDE A VALUABLE SOURCE OF SUPPLY FOR MANY YEARS.

ONCE USED ONLY IN LIGHTER-THAN-AIR CRAFT, HELIUM NOW SERVES VITAL NEEDS IN INDUSTRY, SCIENCE, AND THE NATION'S MILITARY AND SPACE PROGRAMS.

(1968)

National Helium Monument
Celebrating 100th Anniversary of Discovery

Which City Will Be Know As The City Of Dark Matter?



National Helium Monument
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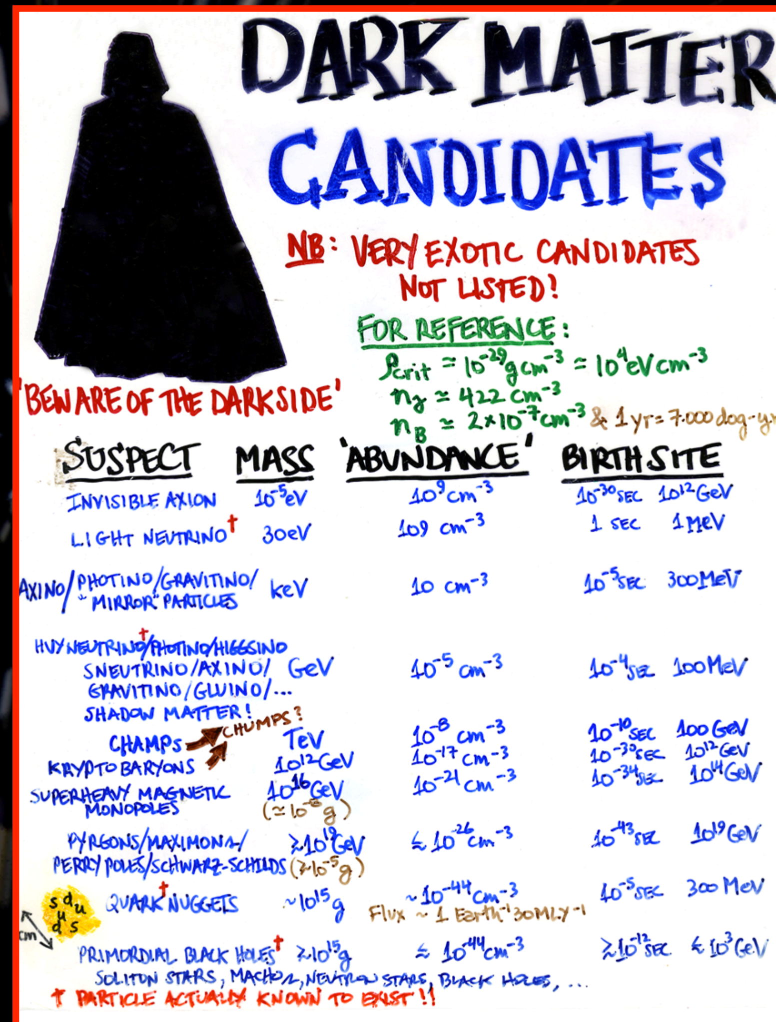
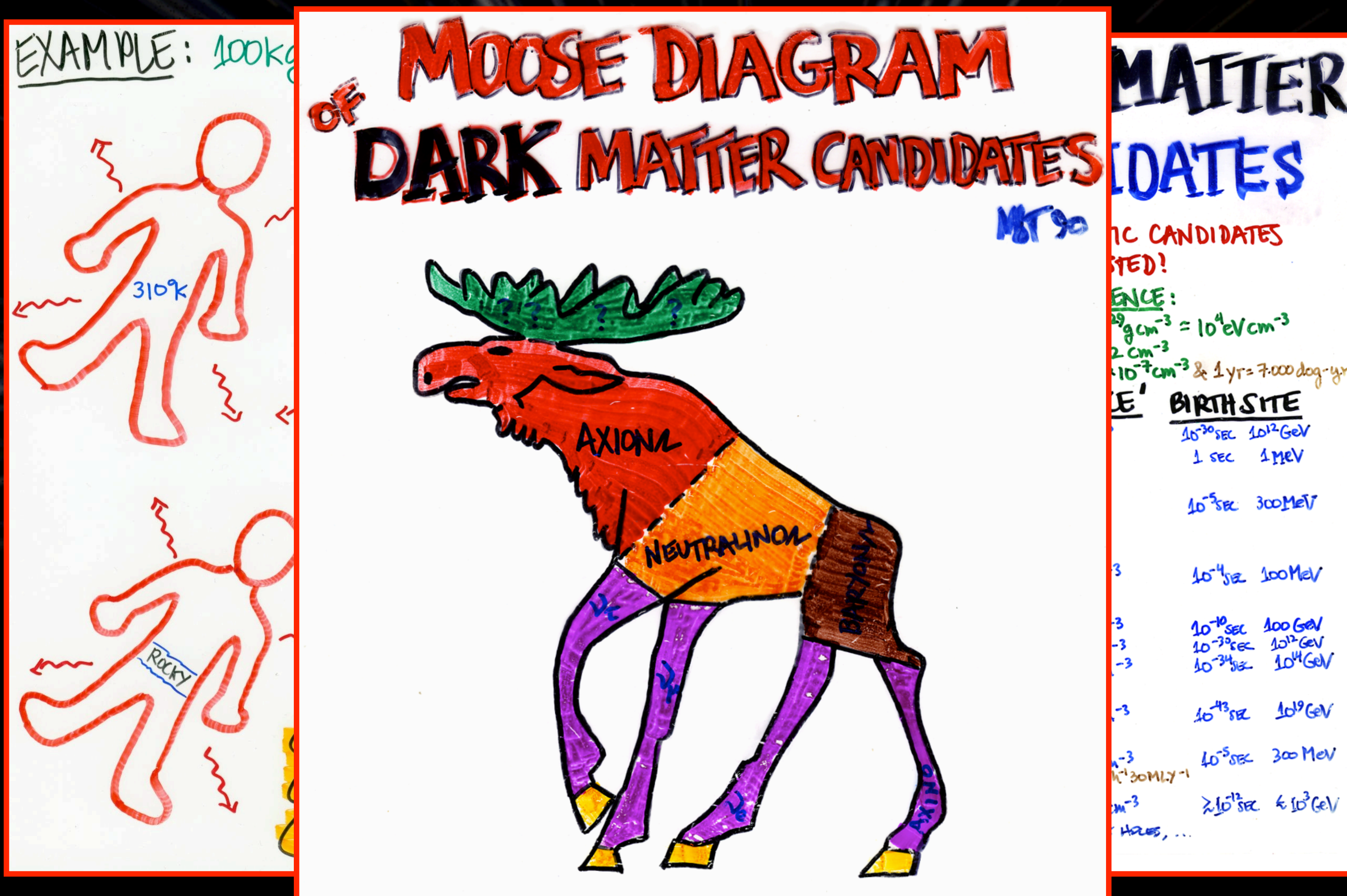
Dark Matter Candidates



Dark Matter Candidates



MOOSE DIAGRAM of DARK MATTER CANDIDATES

MST 90

Full Court Press!!

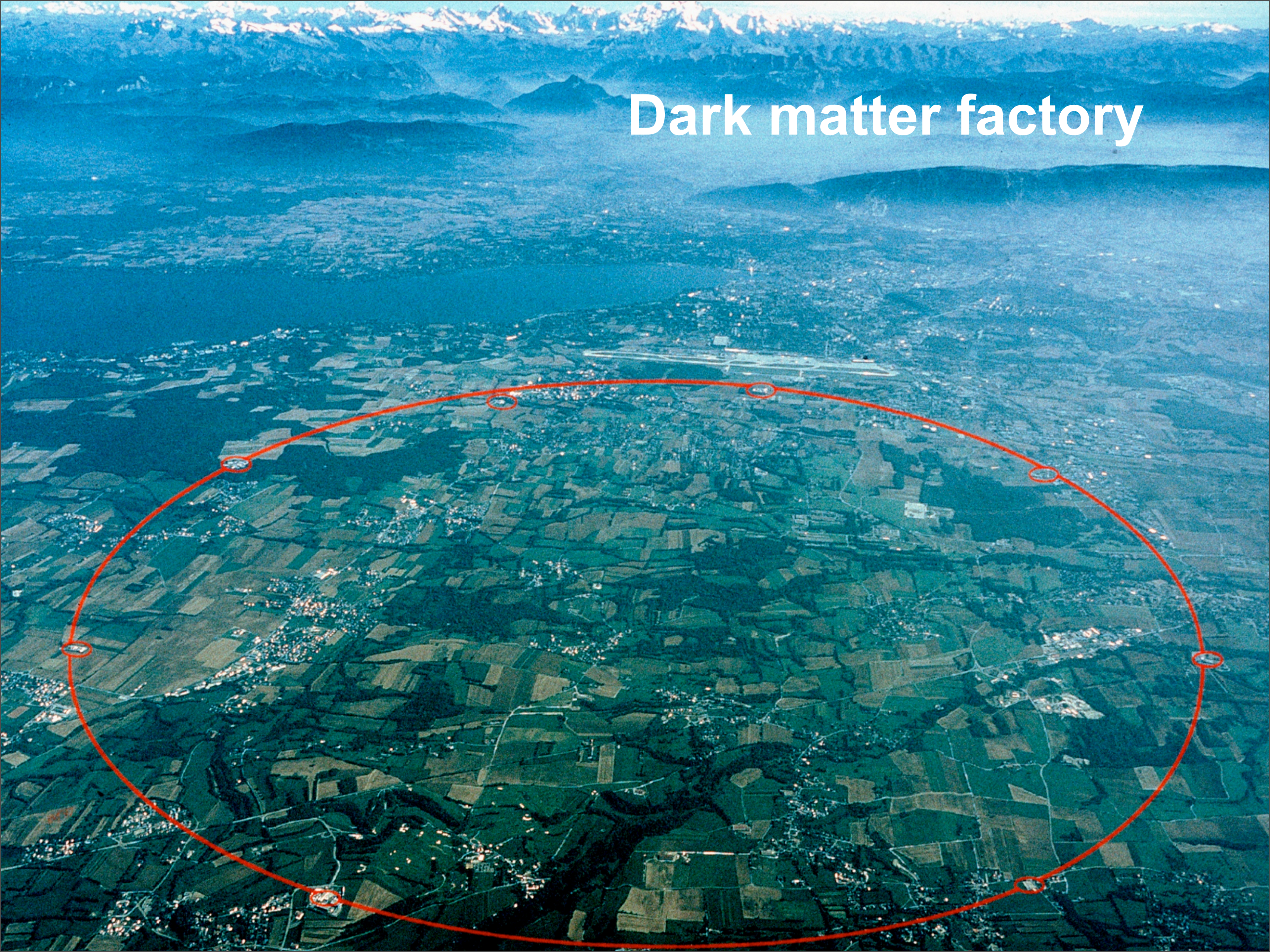
Produce at an accelerator

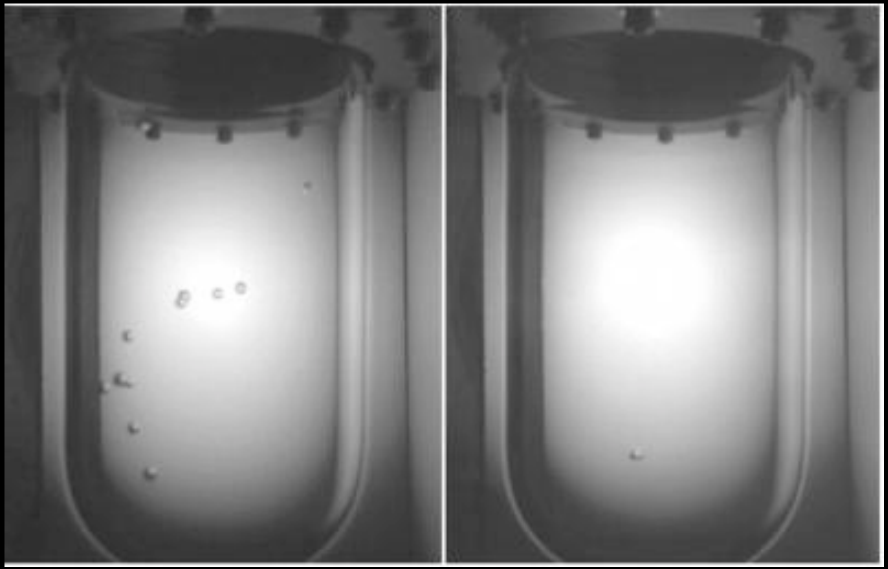
Detect them in our halo

Detect annihilation products


Dark matter factory

Dark matter factory

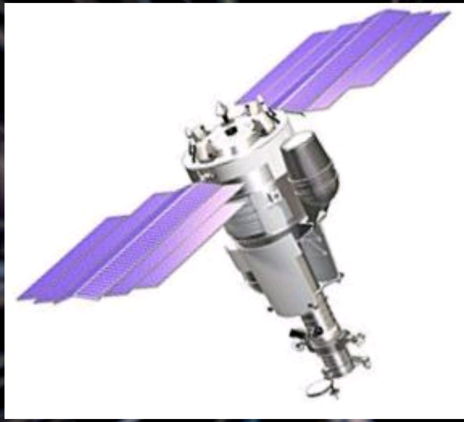


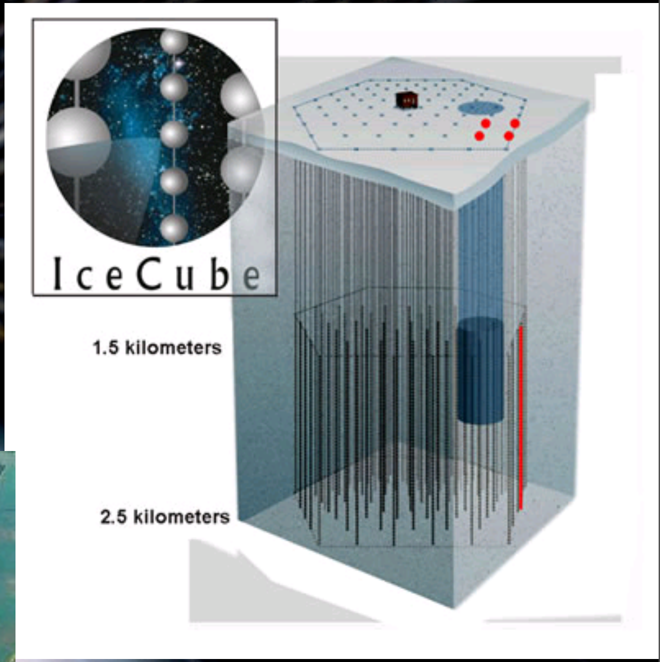


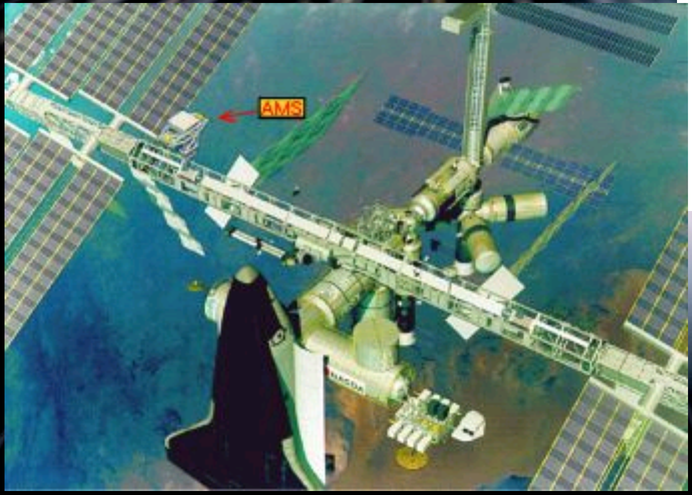
COUPP
Juan Collar

Soudan Mine
Dark Matter Search

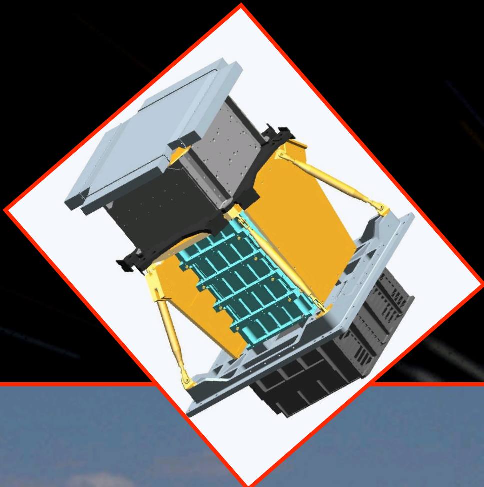
Dark Matter annihilating in our halo produces positrons, neutrinos and gamma rays



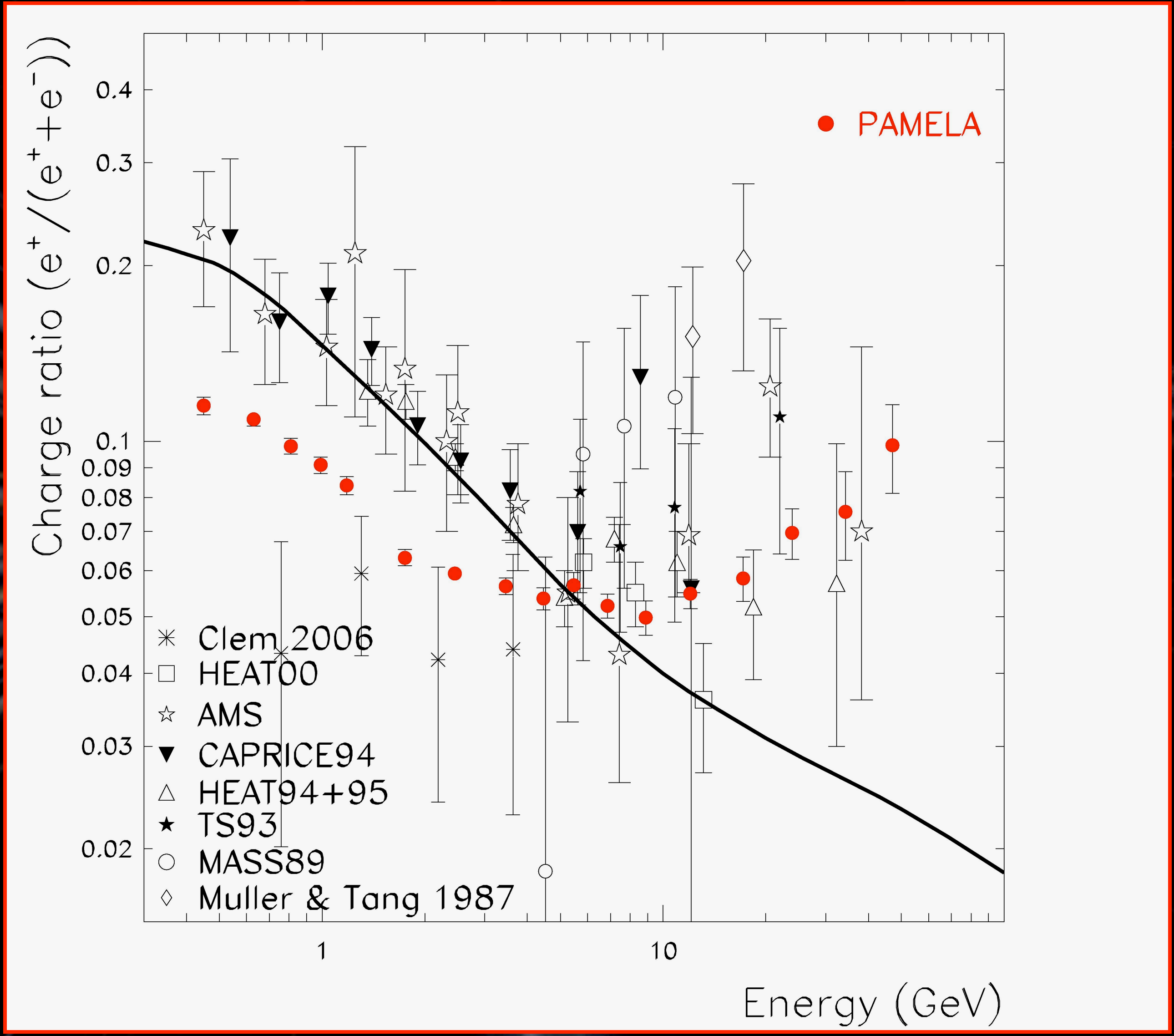




Recent Pamela Positron Data



Confirmed by FGST



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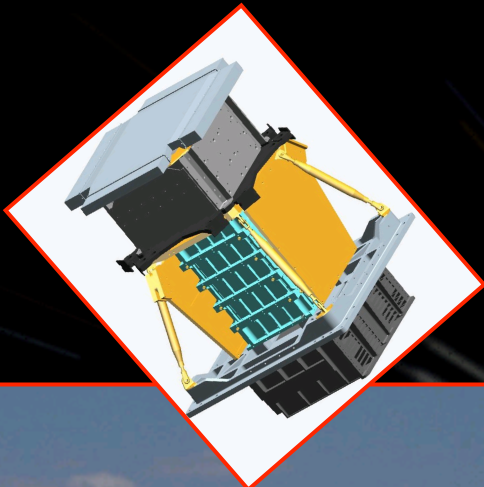

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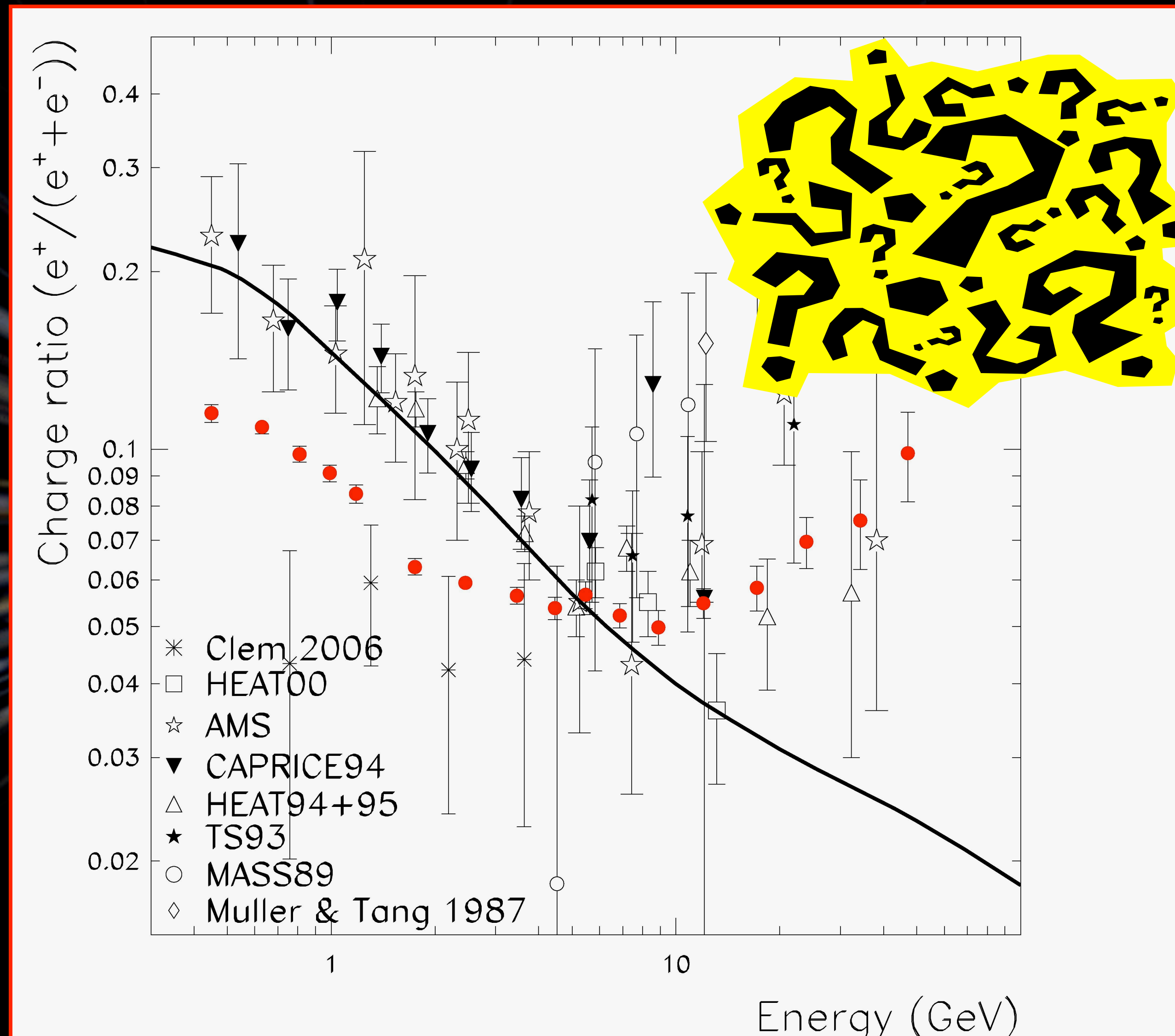
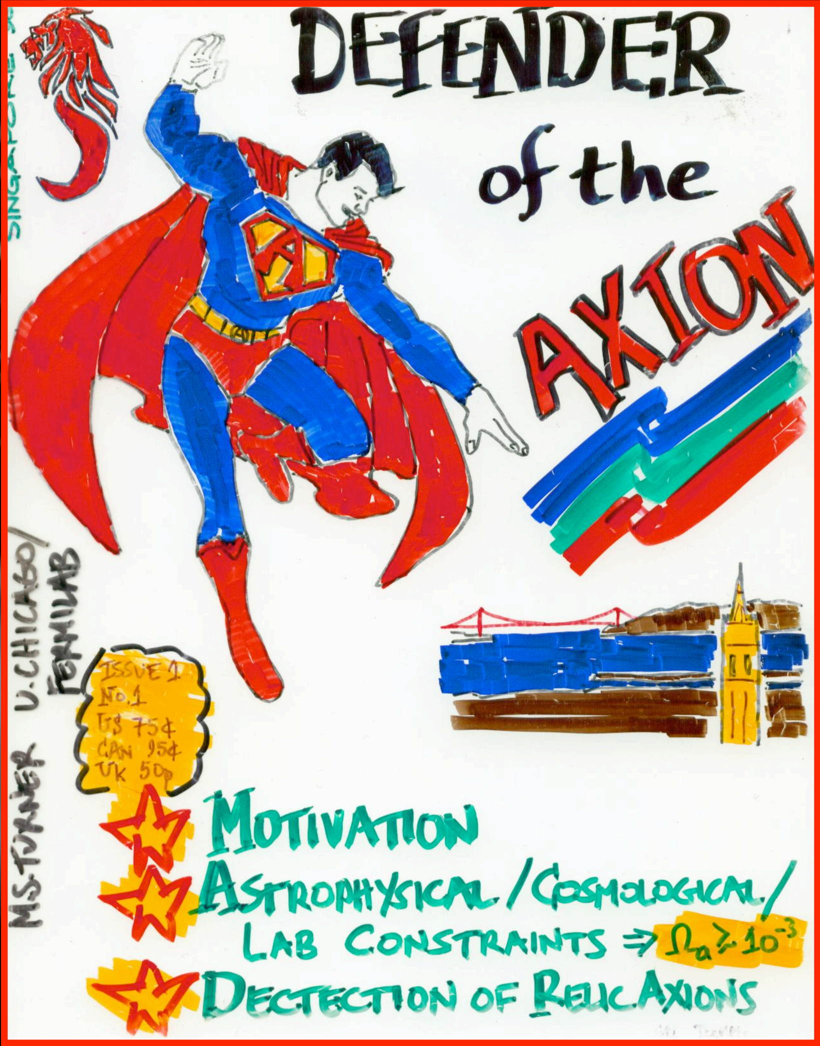


The neutralino is very attractive, but don't forget the axion

- Prediction of the most attractive solution to strong CP problem (Peccei-Quinn symmetry)
- Produced coherently in early Universe, with $\Omega \sim 1$ for $m \sim 10^{-6}$ to 10^{-5} eV
- Dectectable!



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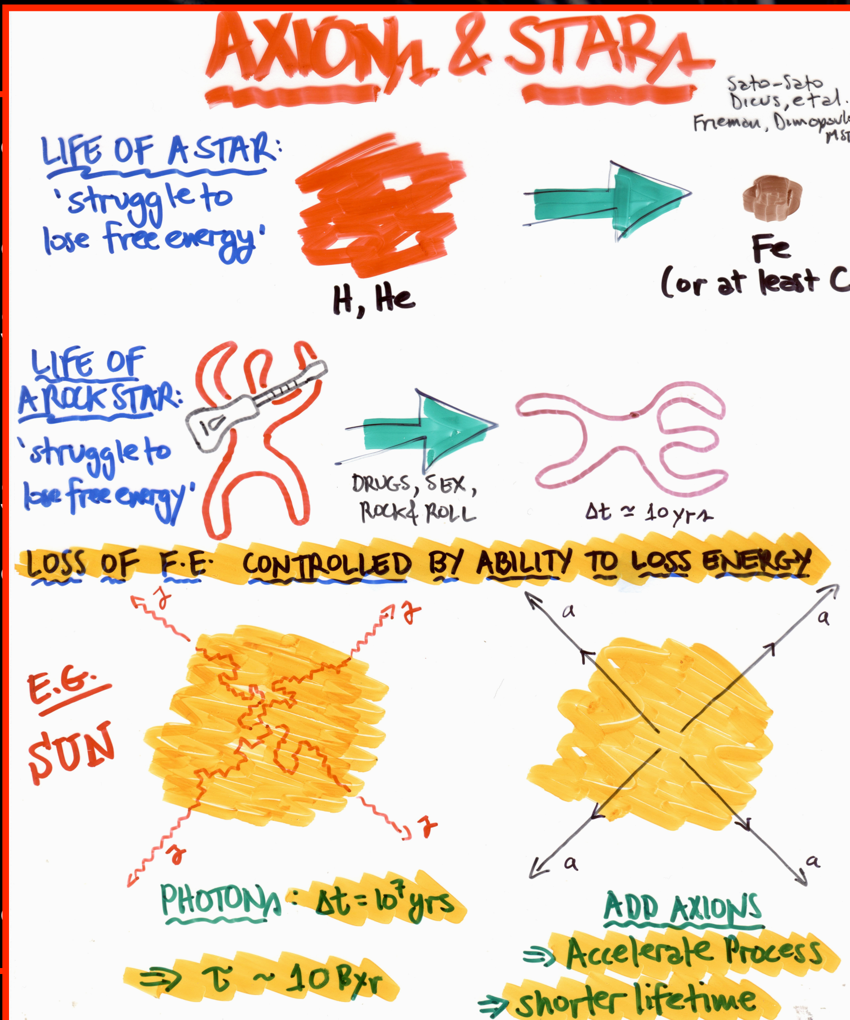
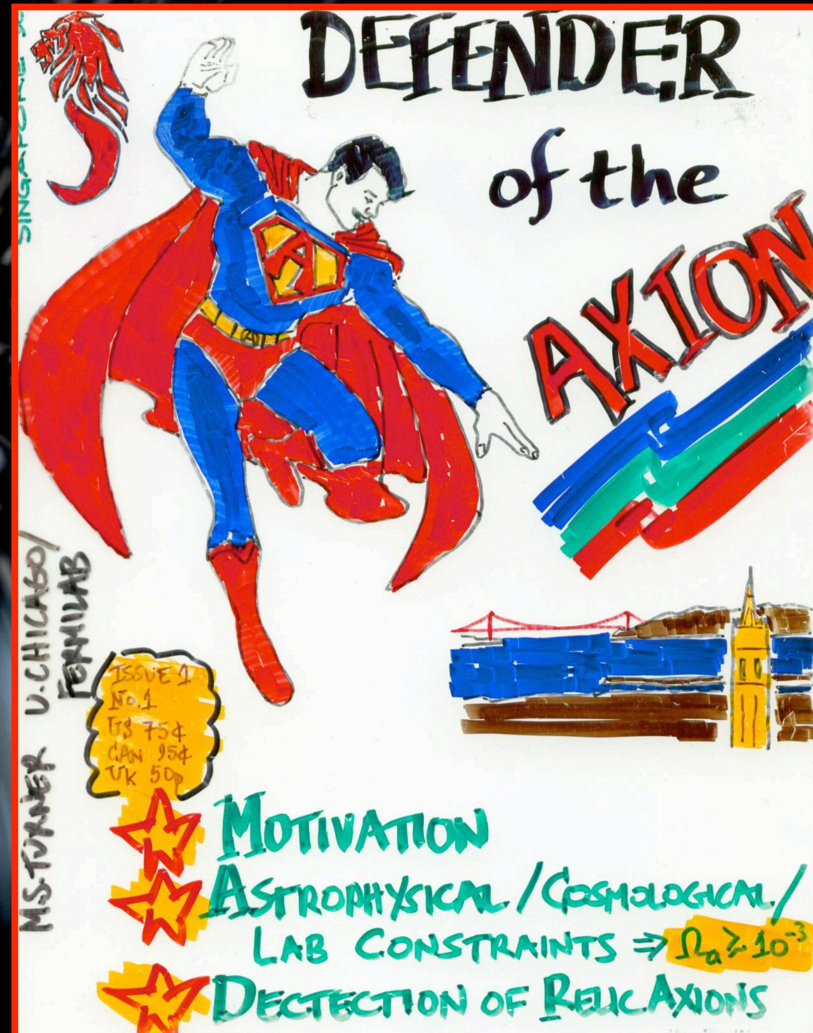
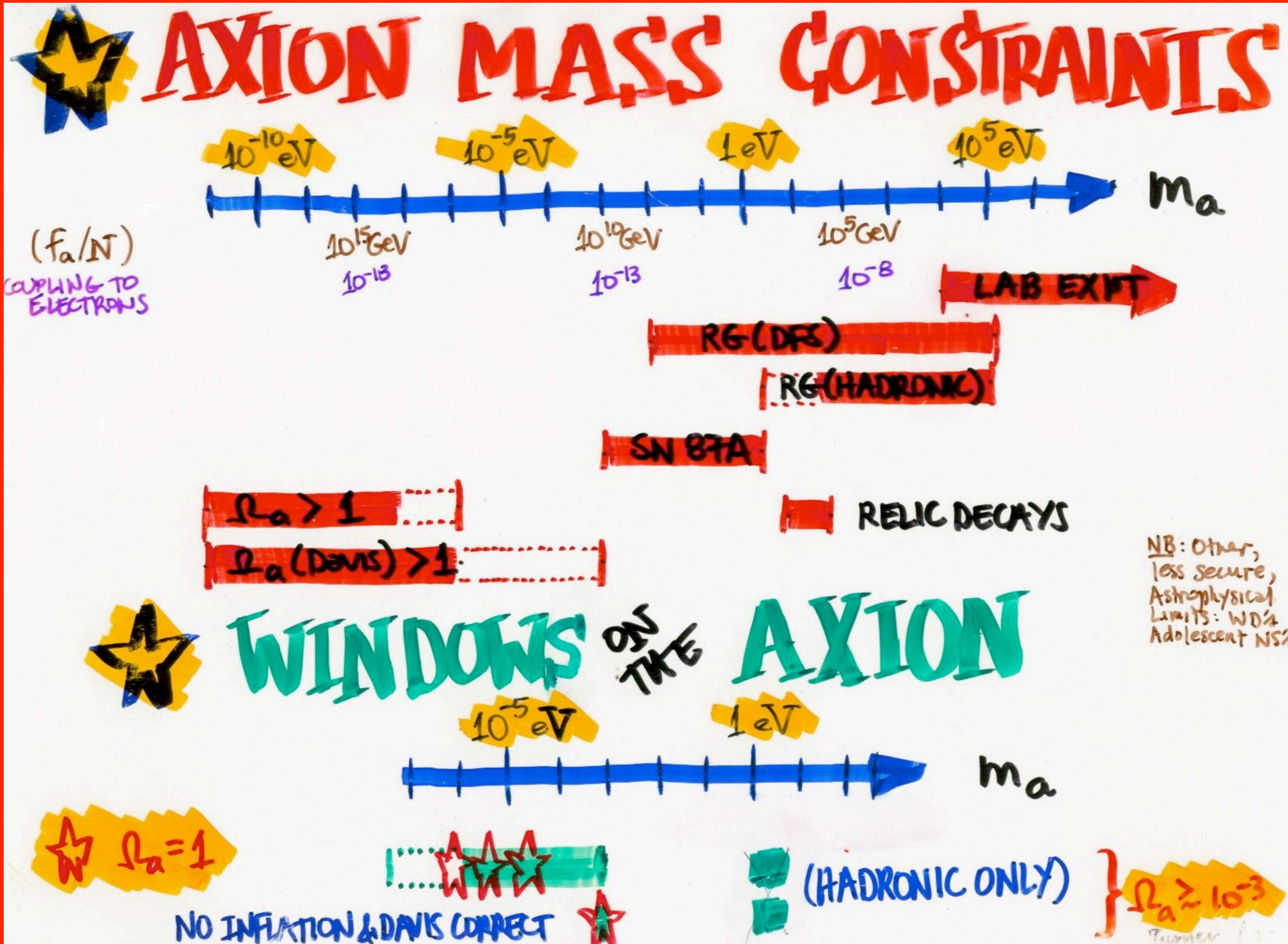
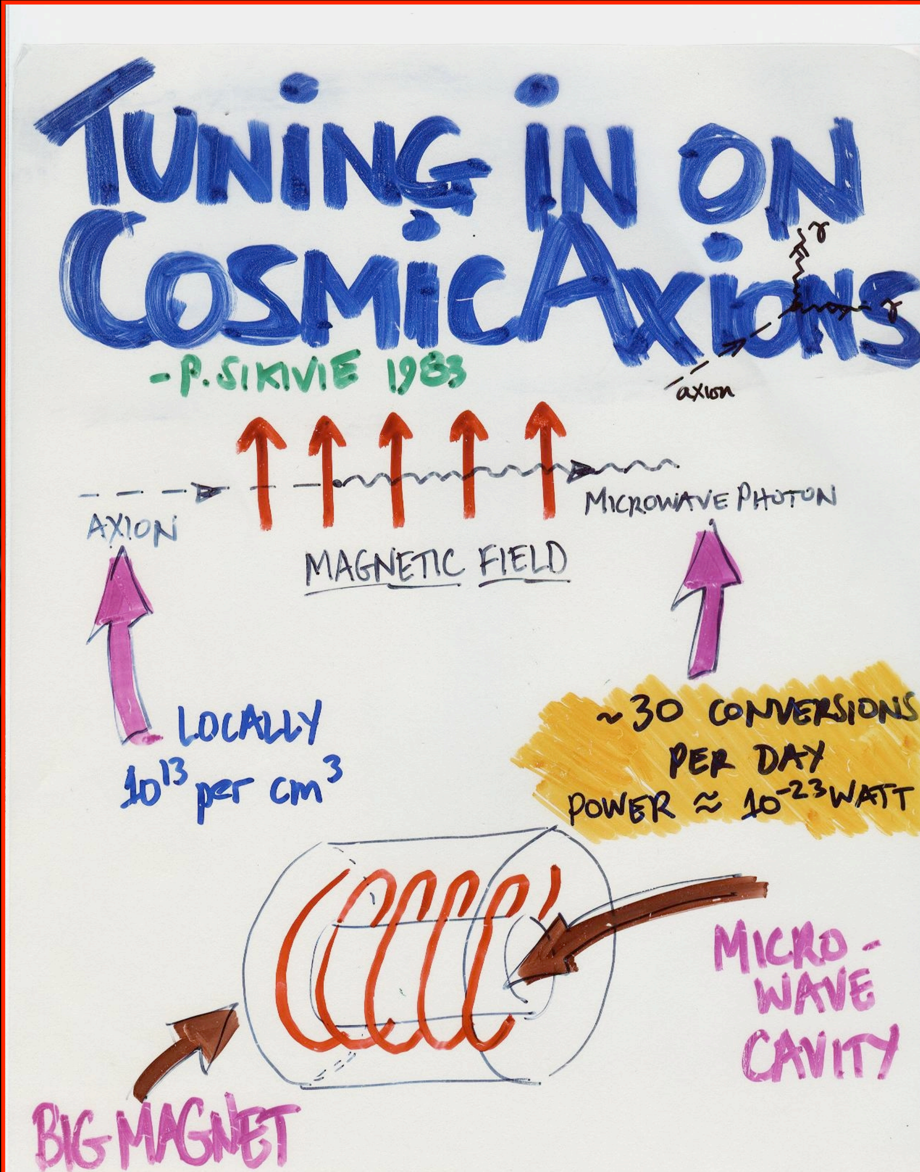
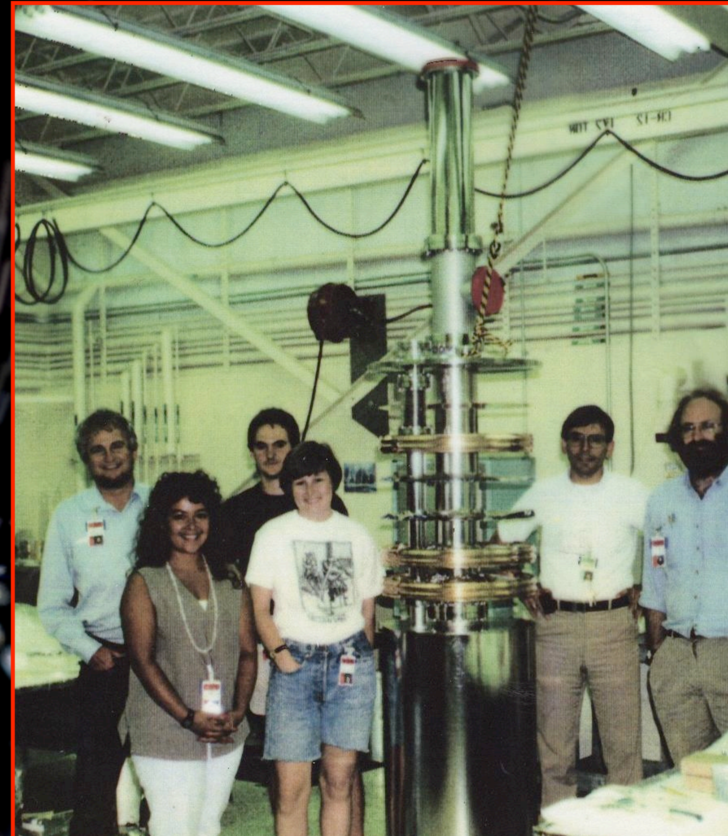


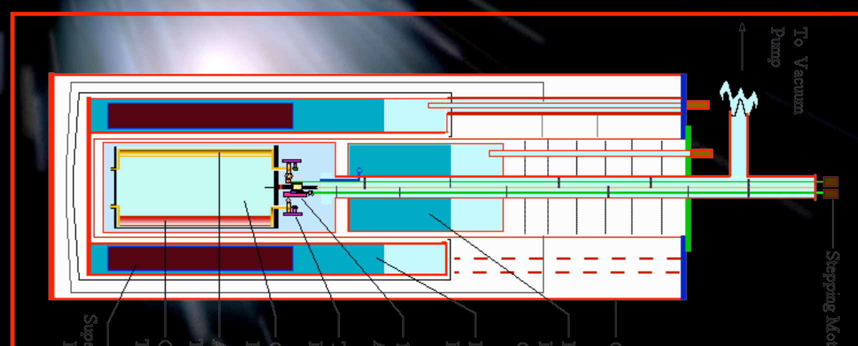



AXION MASS CONSTRAINTS
10^{-10} eV
10^{-5} eV
1 eV
10^{5} eV
m_a
(f_a/N)
10^{15} GeV
10^{10} GeV
10^{5} GeV
COUPLING TO ELECTRONS
10^{-18}
10^{-13}
10^{-8}
LAB EXPT
RG (DFS)
RG (HADRONIC)
SN 87A
$\Omega_a > 1$
Ω_a (Davis) > 1
RELIC DECAYS
NB: Other, less secure, Astrophysical Limits: WD's Adolescent NS's
WINDOWS ON THE AXION
10^{-5} eV
1 eV
m_a
$\Omega_a = 1$
(HADRONIC ONLY)
$\Omega_a \gtrsim 10^{-3}$
NO INFLATION & DAVIS CORRECT

Detecting Cosmic Axions







The Dark Matter Decade

- Hints (and distractions) in the air: Pamela, Fermi-Haze, WMAP Haze, ATIC, CDMSII
- New capabilities: LHC, Xenon100, Fermi, …
- Prediction: The WIMP/Neutralino hypothesis will be tested this decade!

Big Surprise? – No Dark Matter

ASTRONOMY

Seeing Through Dark Matter

Stacy McGaugh

Dark matter was proposed to explain galaxy dynamics. A modification of Newton's law of gravitational force may offer a better explanation.

The universe appears to be dominated by invisible components that astronomers call dark matter and dark energy. The astronomical evidence implicating dark matter has been apparent for a generation (*1*): The rotational speeds of objects in extragalactic systems exceed what can be explained by the visible mass of stars and gas. This discrepancy has led to the inference that there is more mass than meets the eye. However, this inference requires that Newton's law of gravitational force be extrapolated well beyond where it was established. In addition, laboratory searches for dark matter have yet to bear fruit. This lack of corroboration, combined with the increasing complexity and "preposterous" nature of a once simple and elegant cosmology, leads one to wonder if perhaps instead gravity is to blame.

Simply changing the force law on some large length scale does not work (*2*). One idea that has proven surprisingly resilient is the modified Newtonian dynamics (MOND) hypothesized by Milgrom (*3*) in 1983. Rather than change the force law at some large length scale, MOND subtly alters it at a tiny acceleration scale, around 10^{-10} m s^{-2}. In systems with gravitational accelerations above this scale (e.g., Earth, the solar system), everything behaves in a Newtonian sense. It is only when accelerations become tiny, as in the outskirts of galaxies, that the modification becomes apparent.

MOND has successfully described the rotation curves of spiral galaxies (see the figure) (*4*). In case after case, MOND correctly maps the observed mass to the observed dynamics. Why would such a direct mapping exist between visible and total mass if in fact dark matter dominates? Moreover, MOND's explicit predictions for low surface brightness galaxies have been realized (*5*). In contrast, the dark matter par-

Big Surprise? – No Dark Matter

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MOND h[illegible] ssfully described the rotation [illegible] spiral galaxies (see the [illegible] case after case, MOND [illegible] maps the observed mass to the observed dynamics. Why would such a direct mapping exist between visible and total mass if in fact dark matter dominates? Moreover, MOND's explicit predictions for low surface brightness galaxies have been

Big Surprise? – No Dark Matter

ASTRONOMY

Seeing Through Dark Matter

gravity is to blame.

Simply changing the force law on some large length scale does not work (*2*). One

total mass if in fact dark matter dominates? Moreover, MOND's explicit predictions for low surface brightness galaxies have been

If MOND is Right I'll Eat My Powerpoint (laptop included)!

DON'T LET THE BRIGHT LIGHTS FOOL YOU

THE DARK SIDE CONTROLS THE UNIVERSE

OUR UNIVERSE

STARS: 0.5%
DARK MATTER: 33%
DARK ENERGY: 66%

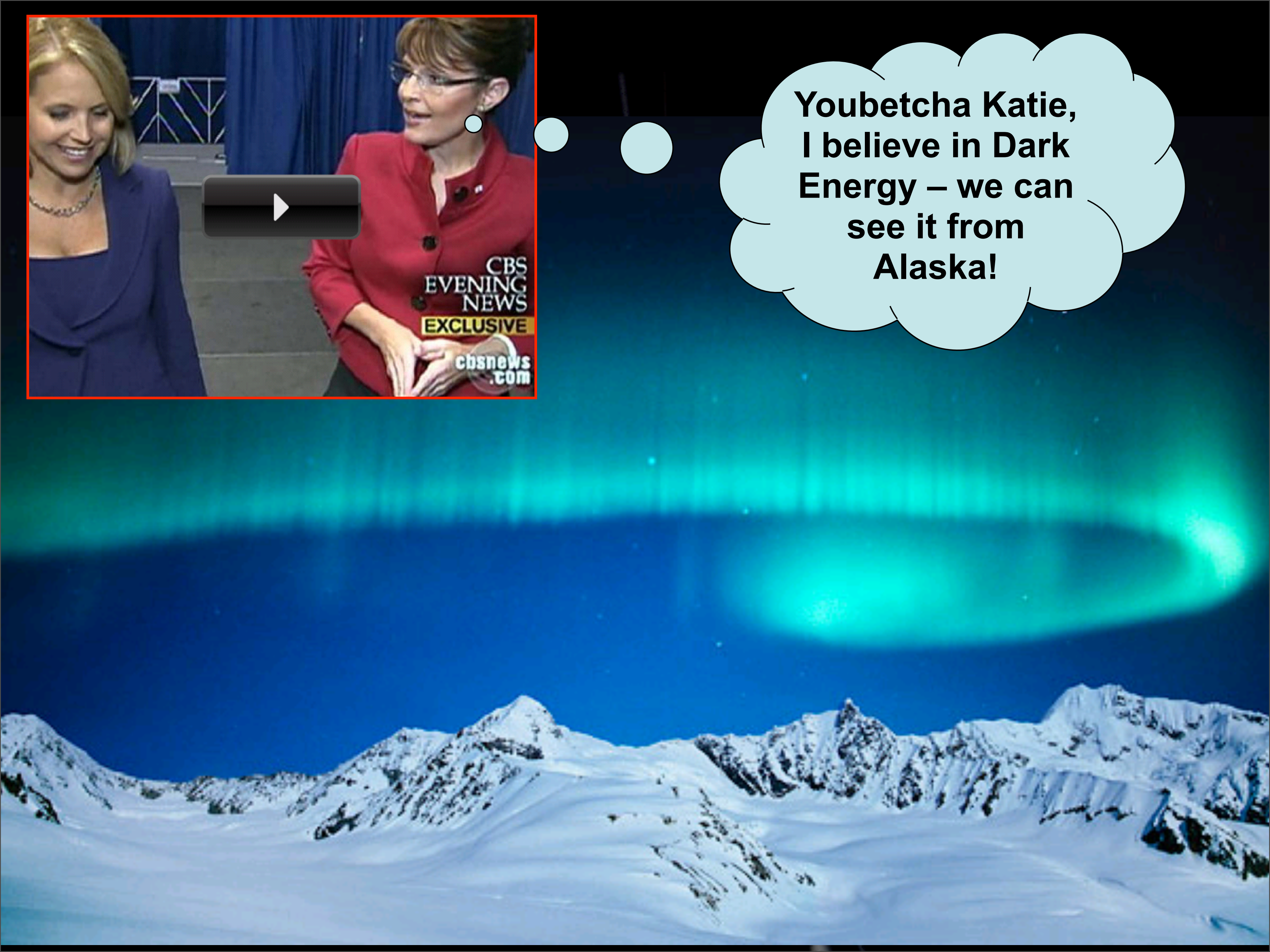
DARK MATTER HOLDS IT TOGETHER

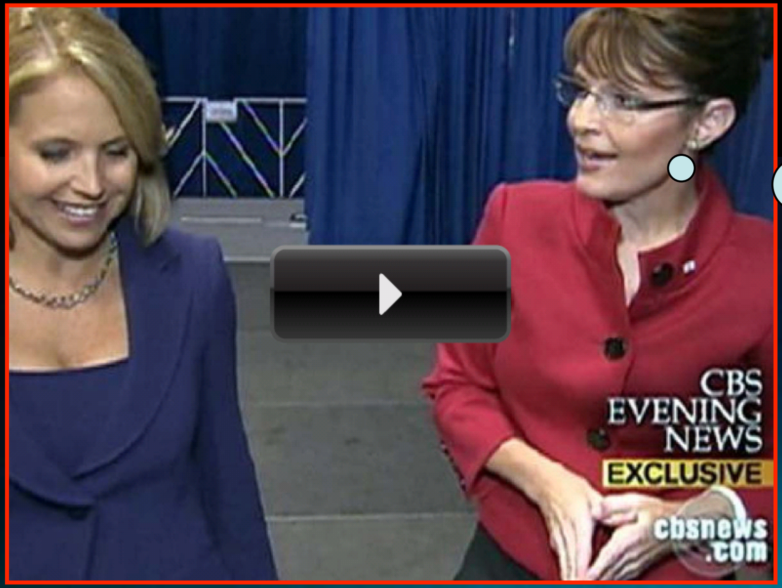
DARK ENERGY DETERMINES ITS DESTINY

DARK ENERGY

MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY

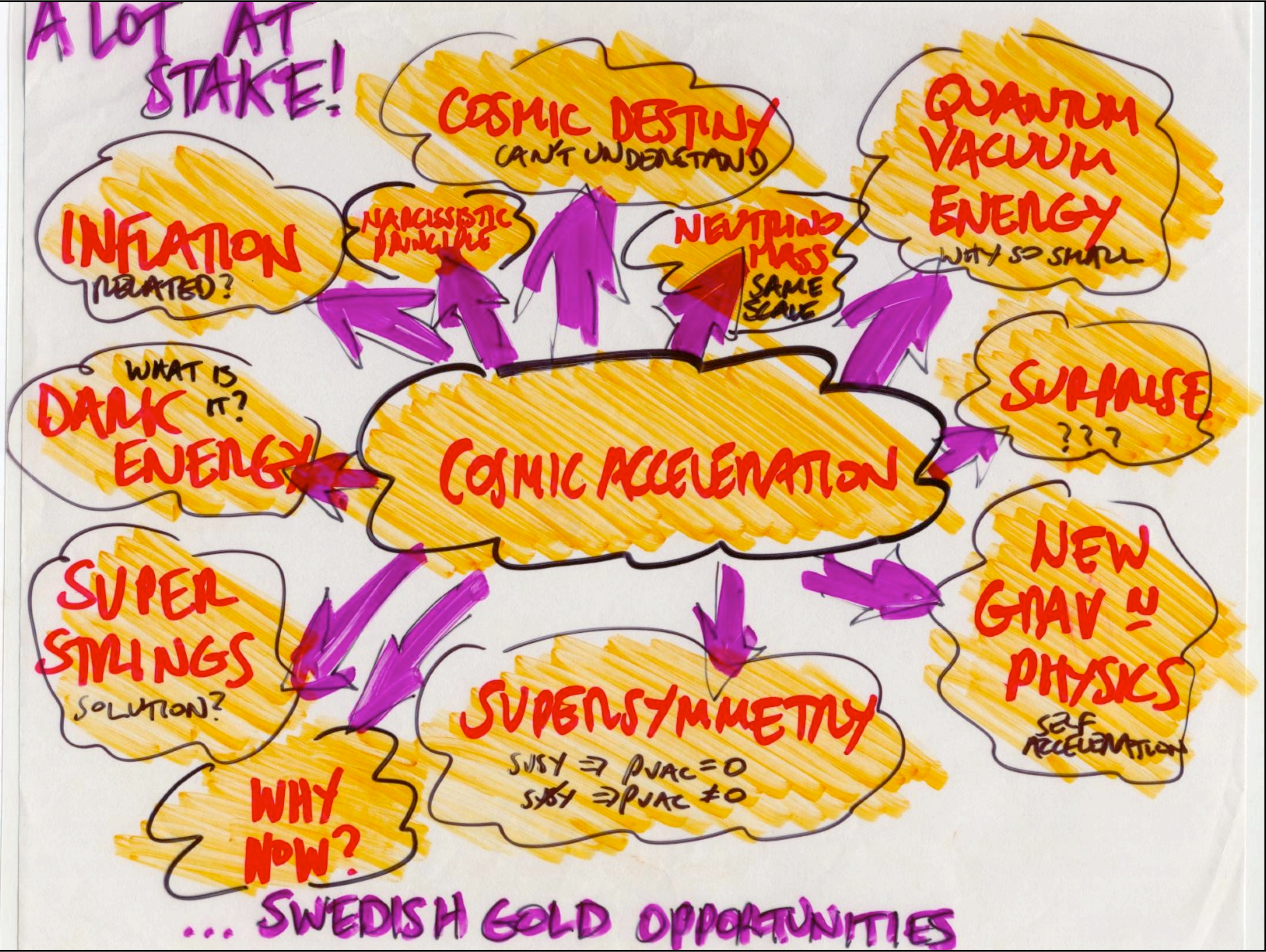

CBS
EVENING
NEWS
EXCLUSIVE
cbsnews.com

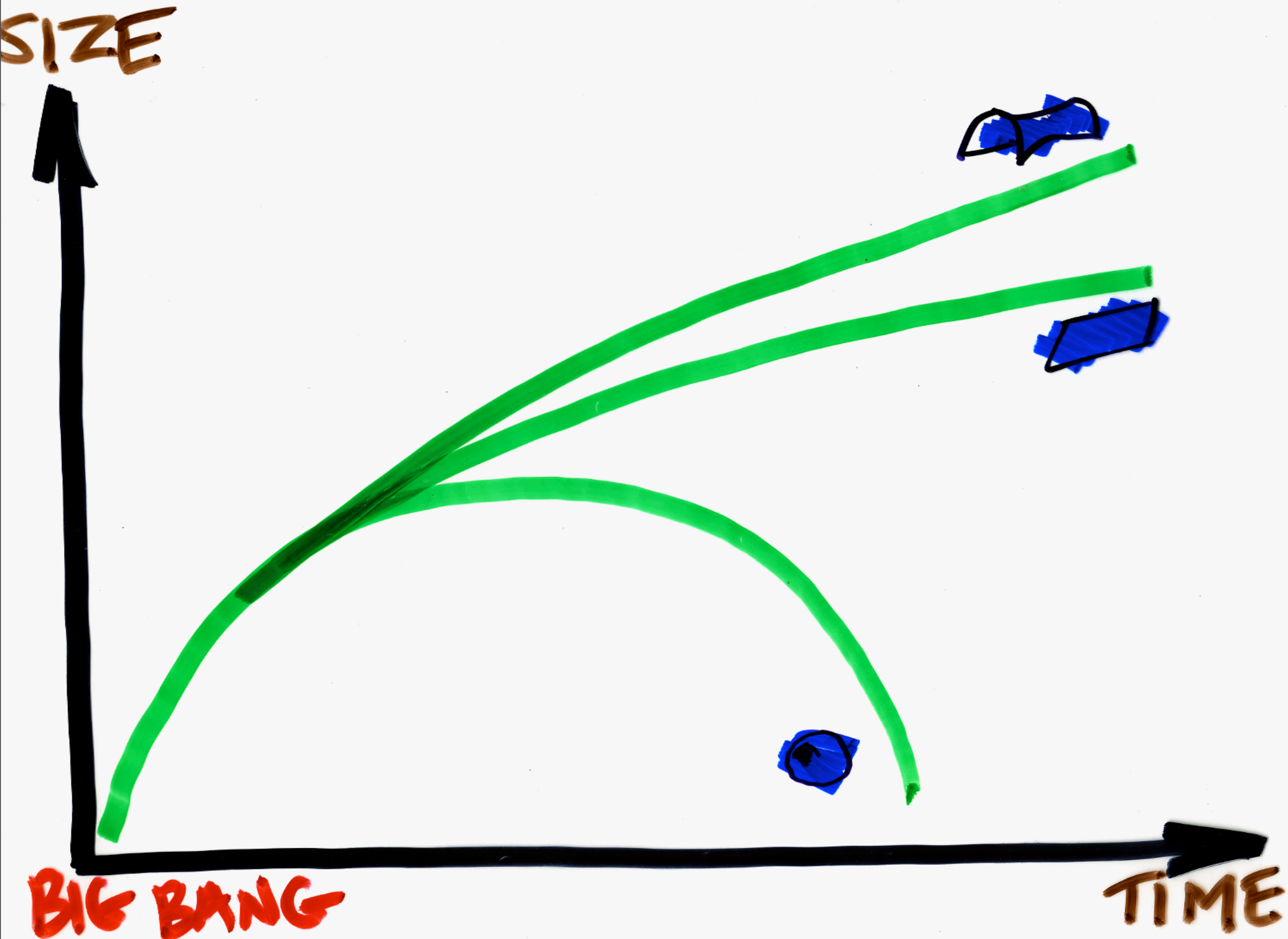

CBS
EVENING
NEWS
EXCLUSIVE
cbsnews.com
Youbetcha Katie, I believe in Dark Energy – we can see it from Alaska!



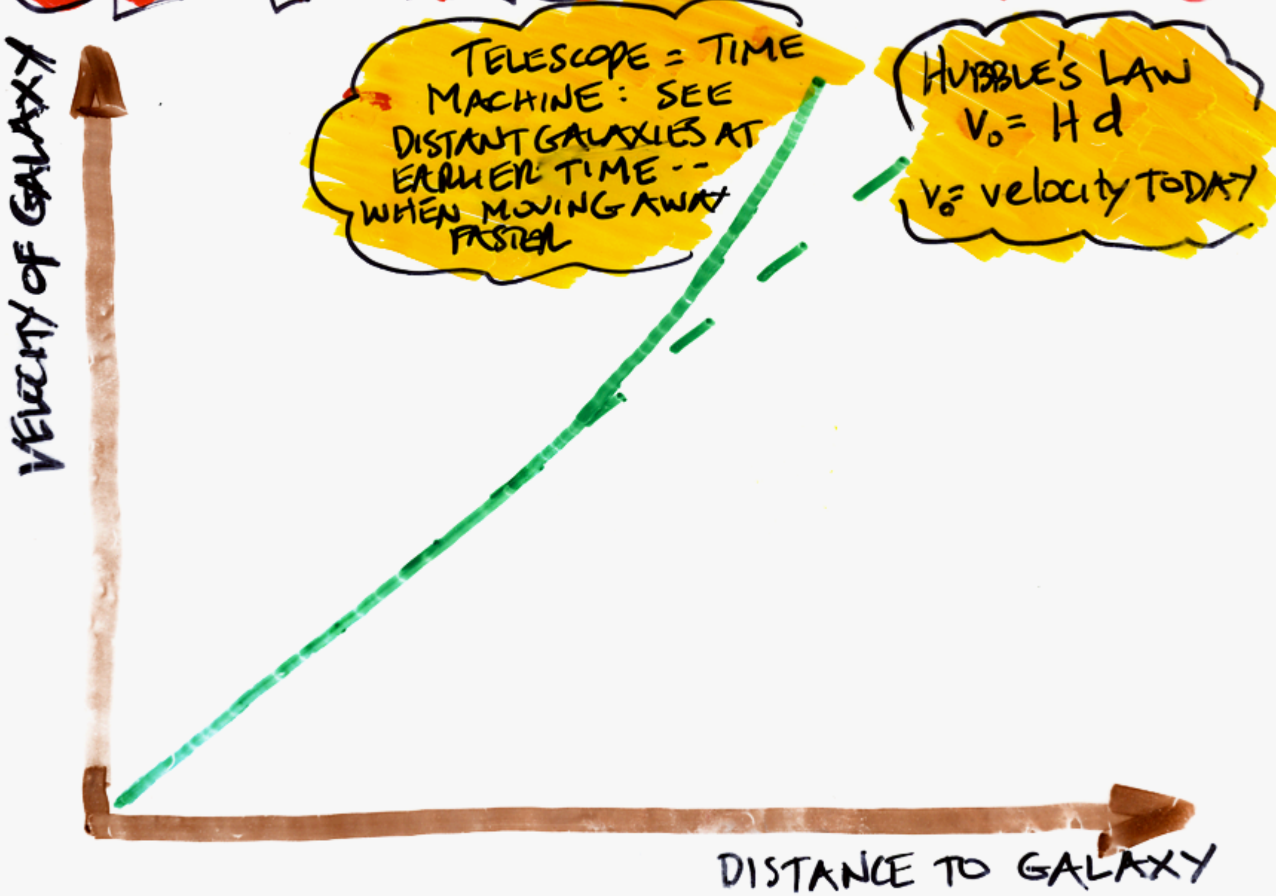
Youbetcha Katie,
I believe in Dark
Energy – we can
see it from
Alaska!

Drill for Dark Energy!

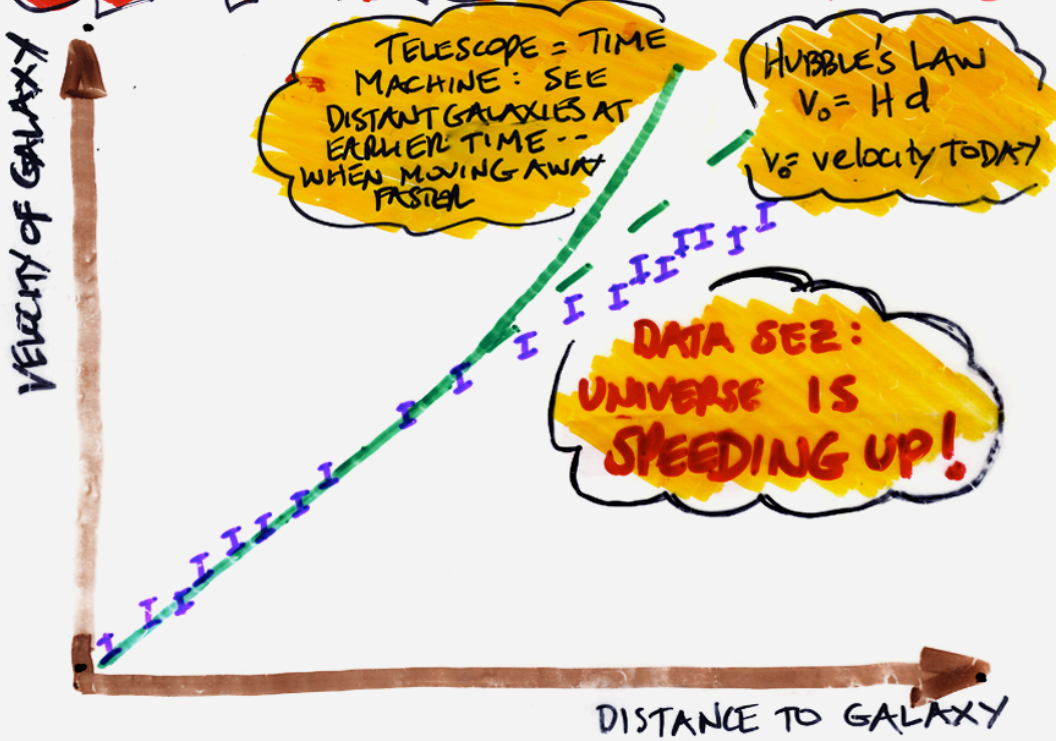

A LOT AT STAKE!
COSMIC DESTINY
(CAN'T UNDERSTAND)
QUANTUM VACUUM ENERGY
WHY SO SMALL
INFLATION
RELATED?
NARCISSISTIC PRINCIPLE
NEUTRINO MASS
SAME SCALE
DARK ENERGY
WHAT IS IT?
COSMIC ACCELERATION
SURPRISE
???
SUPER STRINGS
SOLUTION?
NEW GRAV'N PHYSICS
SELF ACCELERATION
SUPERSYMMETRY
SUSY ⇒ ρVAC=0
~~SUSY~~ ⇒ ρVAC≠0
WHY NOW?
... SWEDISH GOLD OPPORTUNITIES


SIZE
BIG BANG
TIME

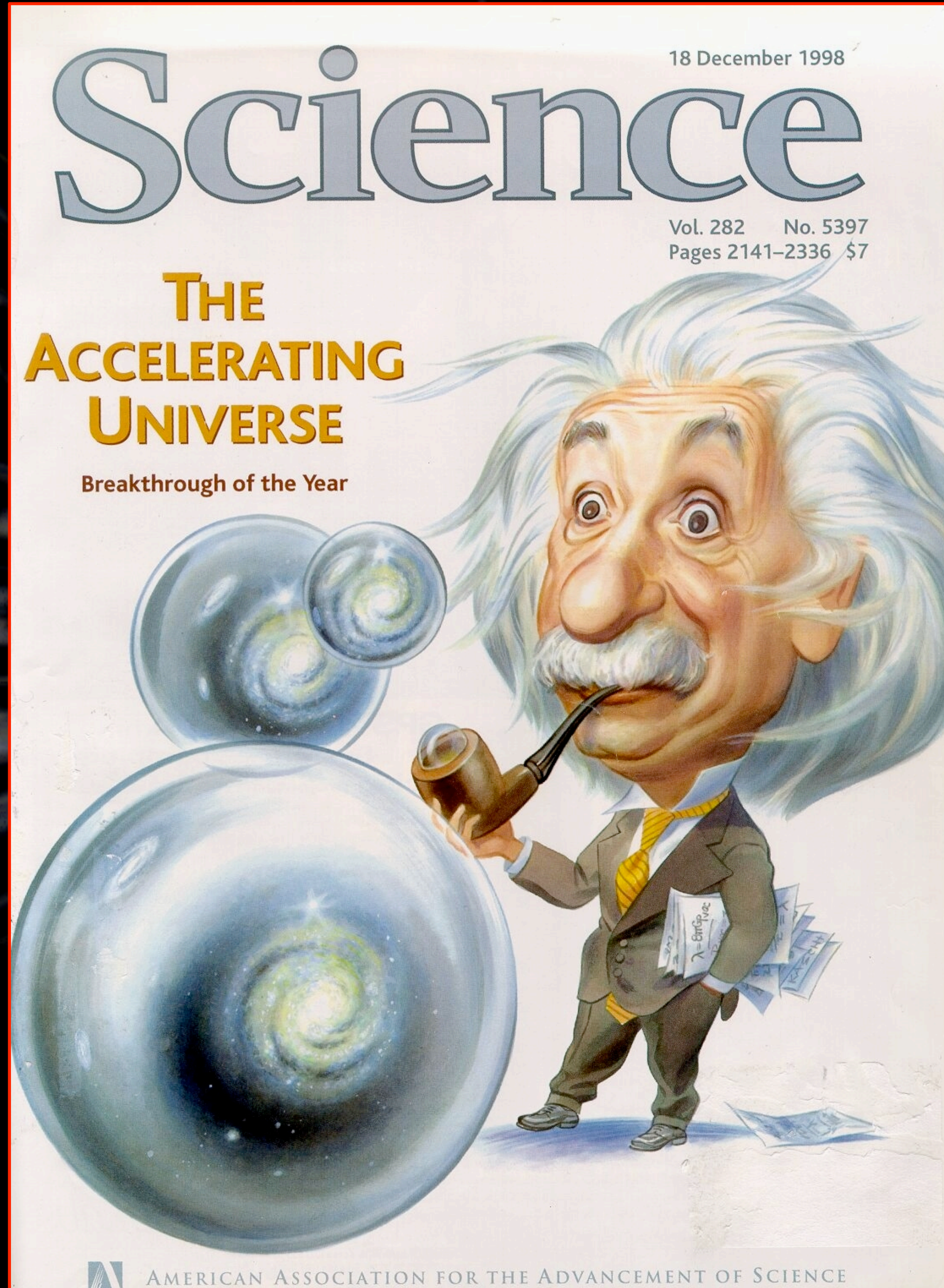
IS THE UNIVERSE SLOWING DOWN?



IS THE UNIVERSE SLOWING DOWN?



UNIVERSE IS SPEEDING UP!?# WHY?


18 December 1998
Science
Vol. 282 No. 5397
Pages 2141–2336 $7
The Accelerating Universe
Breakthrough of the Year
American Association for the Advancement of Science

Discovery! – 1998

Hi z Supernova Team

Supernova Cosmology Project

Discovery! – 1998

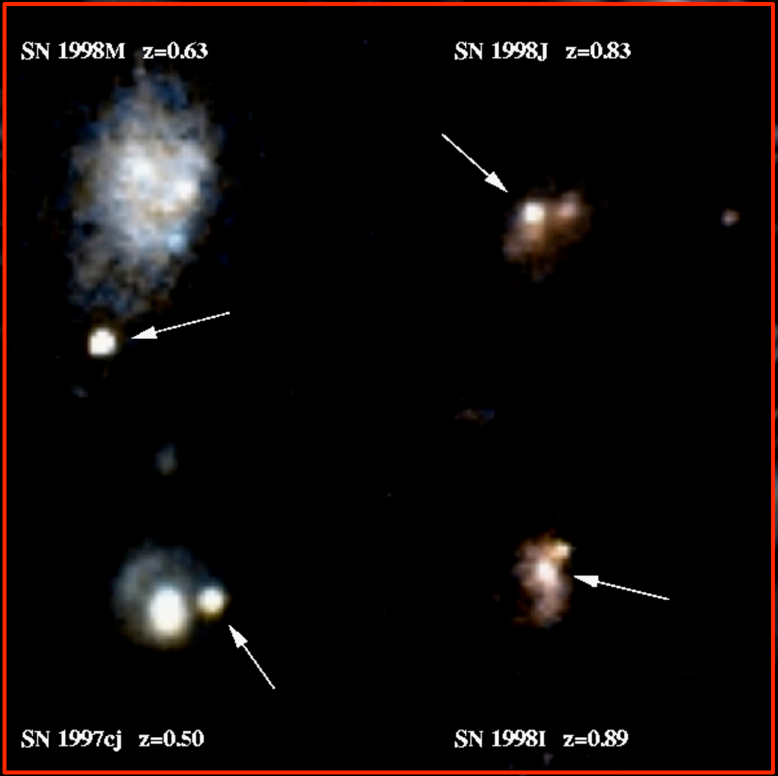
Hi z Supernova Team

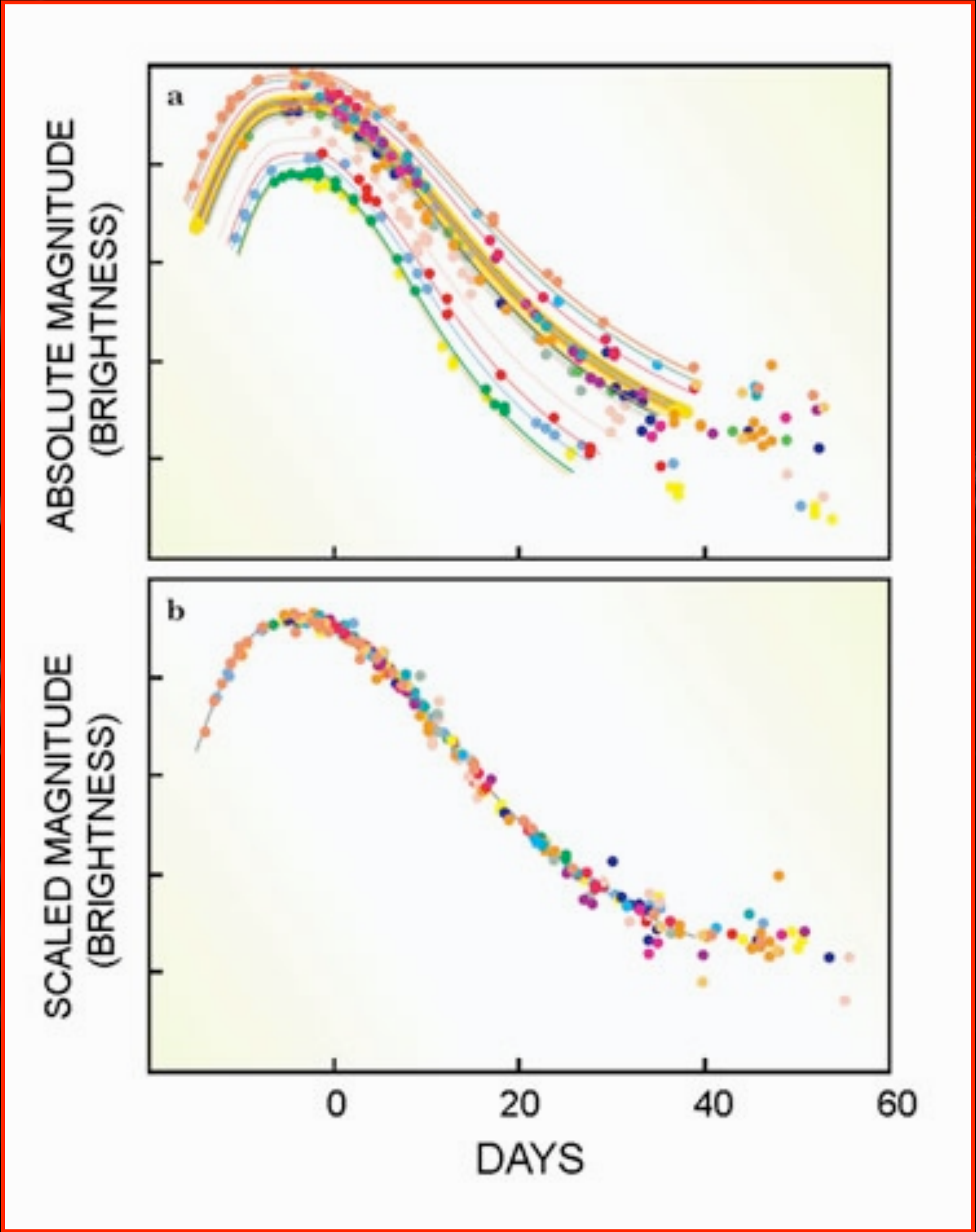
Mark Philips

Supernova Cosmology Project

Two Technological Enablers:

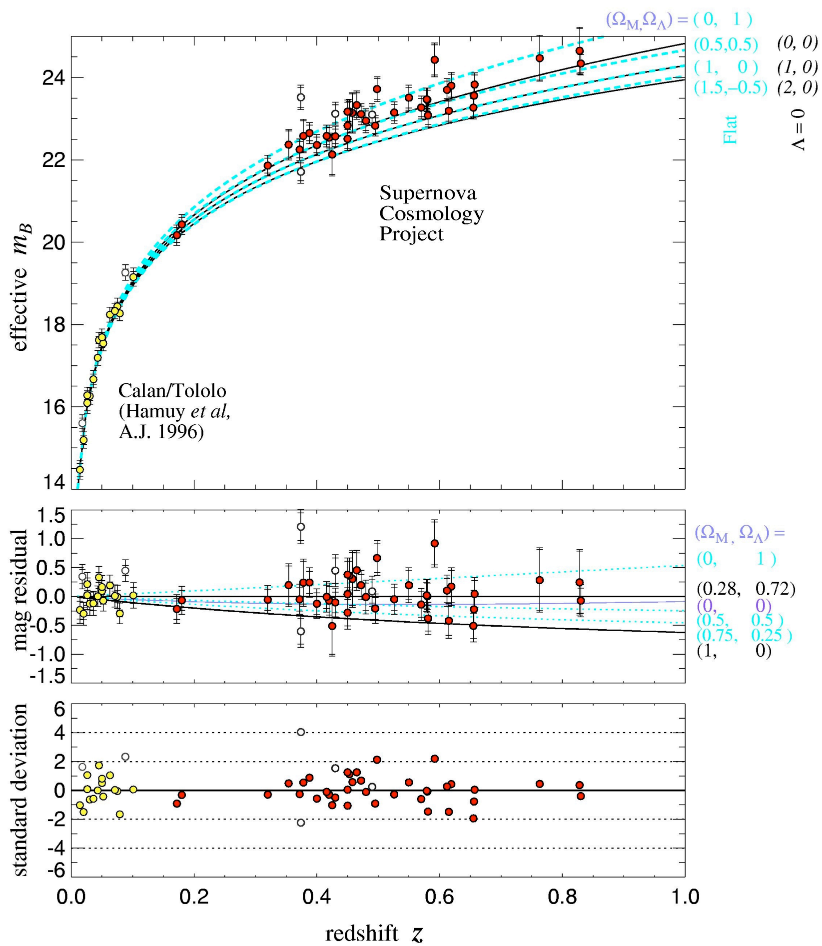
1. Large (100 Mpixel) CCD Cameras
2. SNe Ia: Bright, Standardizable Candles (1.4 solar mass bomb)





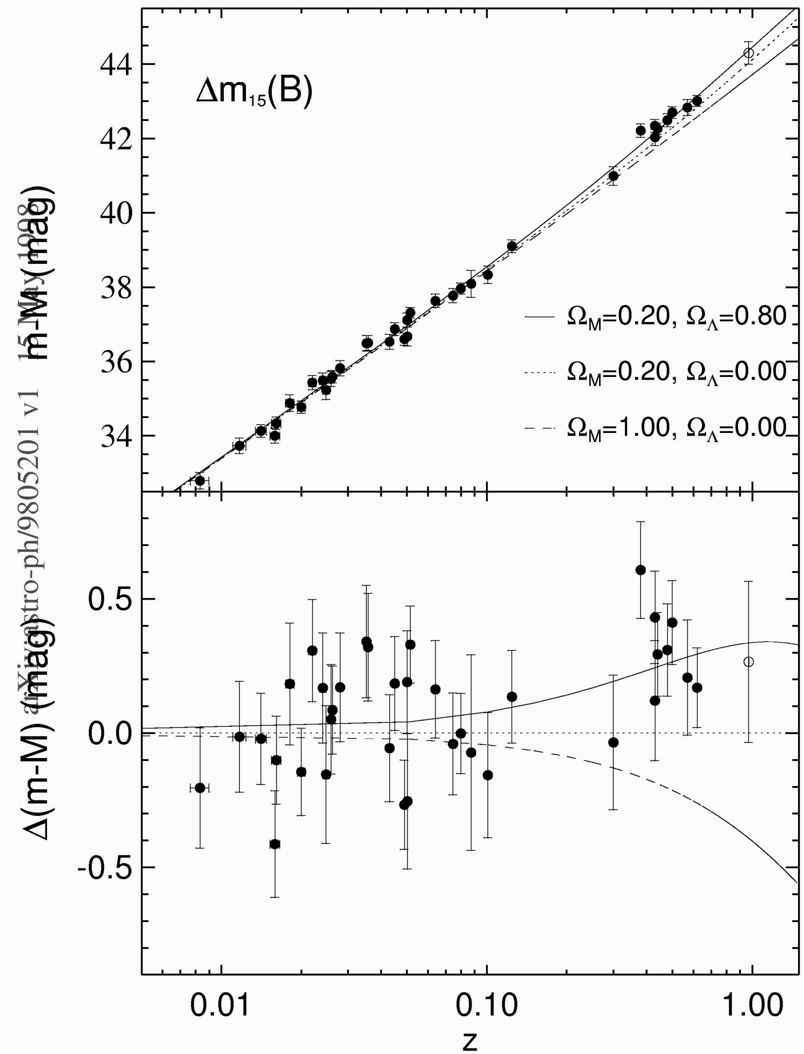
The Discovery Data

Perlmutter et al, 1999



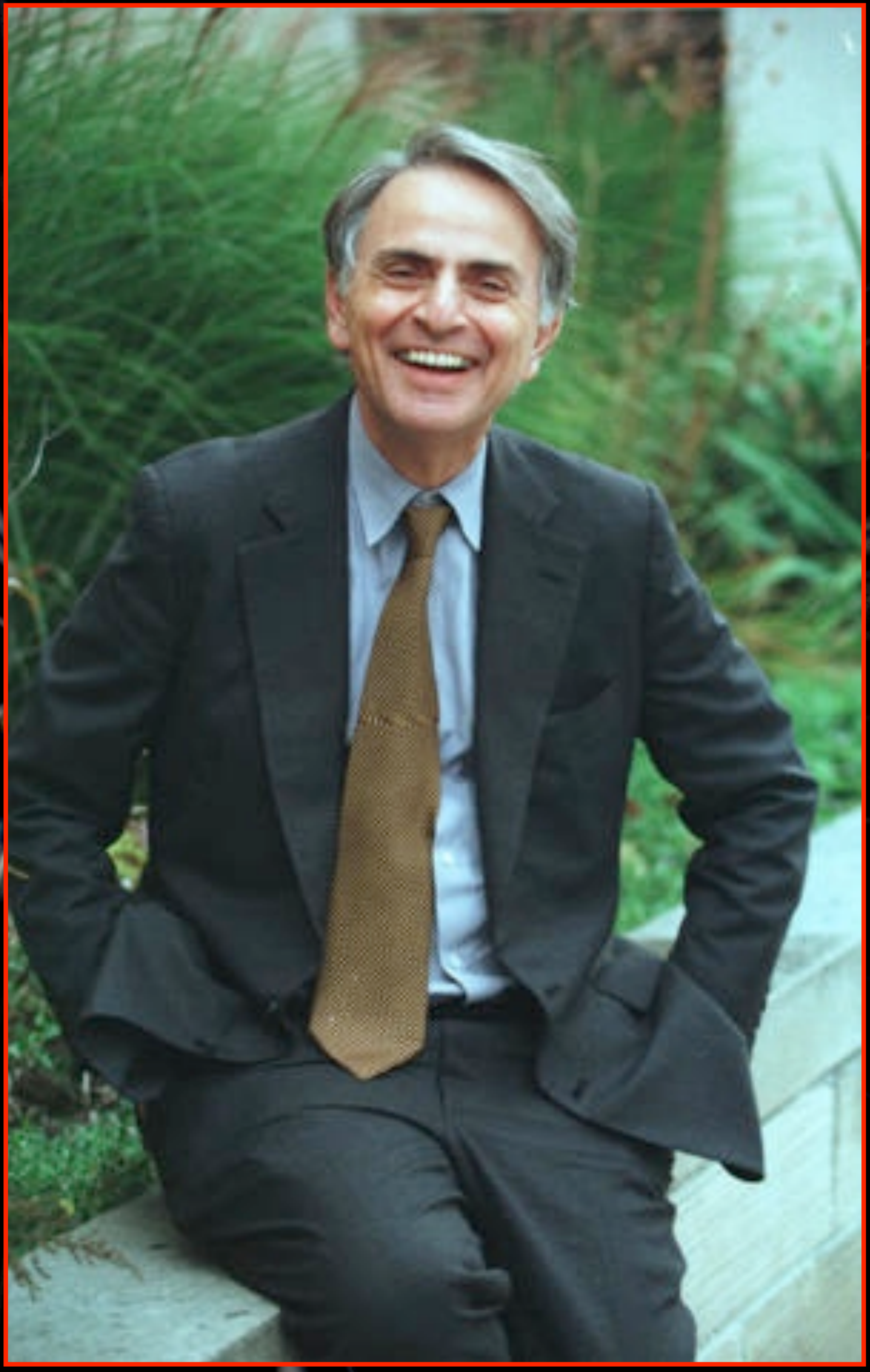
Perlmutter, *et al.* (1998)

Riess et al, 1998



Carl Sagan:

Extraordinary Claims Require Extraordinary Evidence



1000 SNe from:

the original teams +

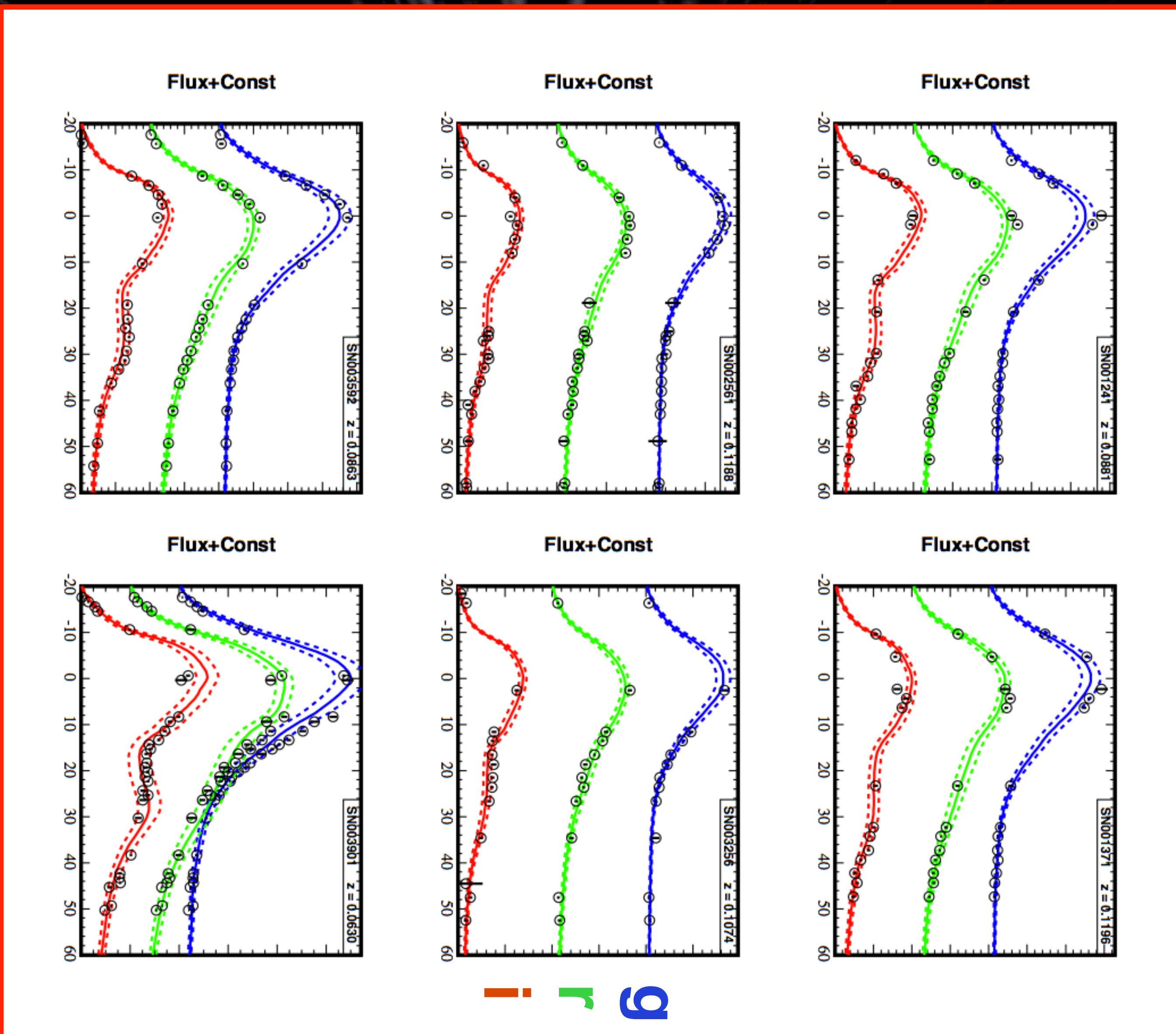
SNLS, ESSENCE, SDSS,
CfA, CSP, …

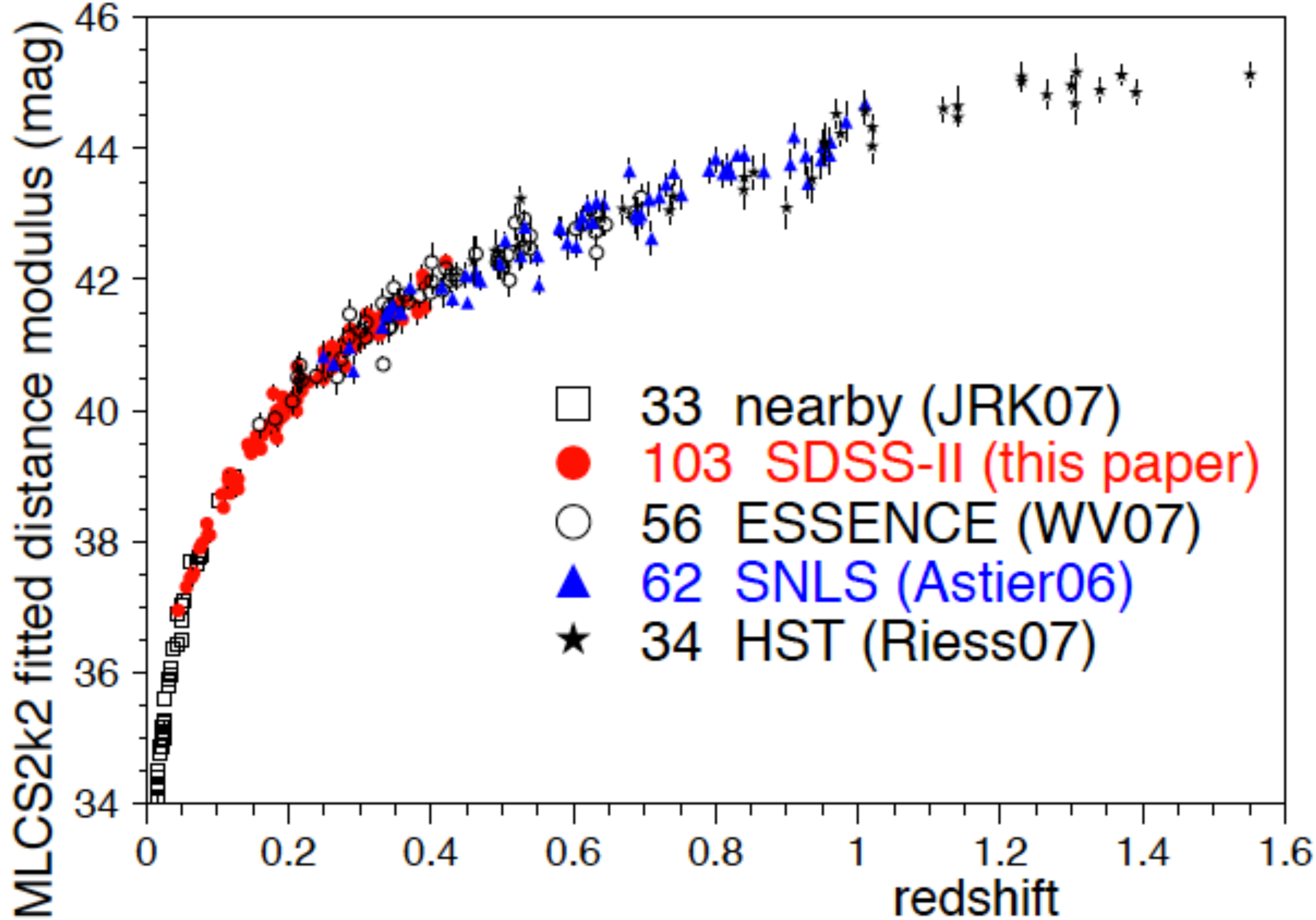
More data stronger signal

SDSS-II Supernova Survey

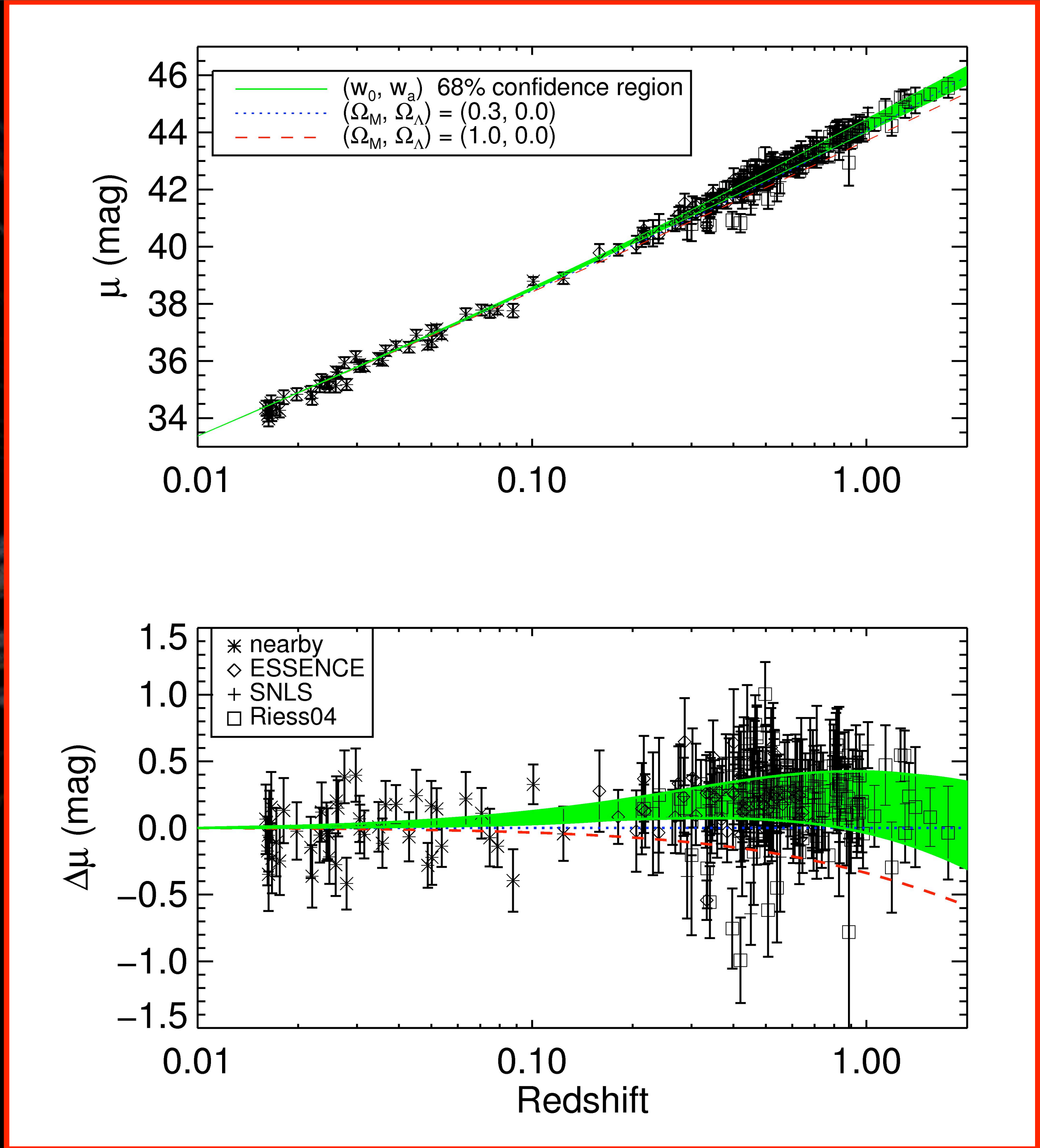
~500 Well studied SNe Ia, suitable for framing

SDSS Low-redshift Light curves will lead to better understanding of Type Ia Supernovae





MLCS2k2 fitted distance modulus (mag)
46
44
42
40
38
36
34
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
redshift
33 nearby (JRK07)
103 SDSS-II (this paper)
56 ESSENCE (WV07)
62 SNLS (Astier06)
34 HST (Riess07)

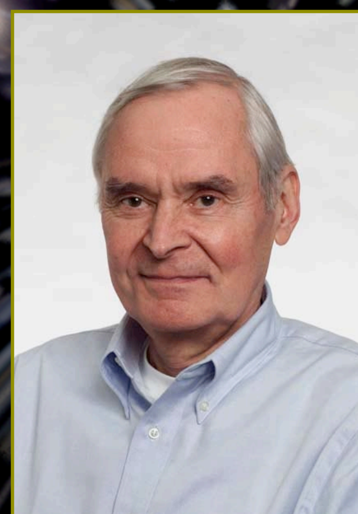


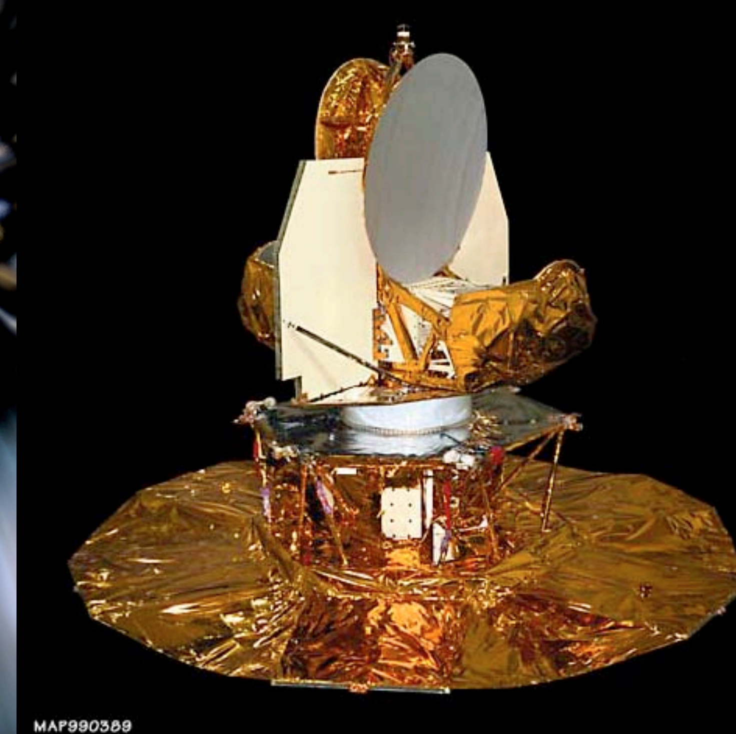
(w0, wa) 68% confidence region
(ΩM, ΩΛ) = (0.3, 0.0)
(ΩM, ΩΛ) = (1.0, 0.0)
μ (mag)
46
44
42
40
38
36
34
0.01
0.10
1.00
nearby
ESSENCE
SNLS
Riess04
Δμ (mag)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.01
0.10
1.00
Redshift

Microwave Anisotropy Probe

MAP

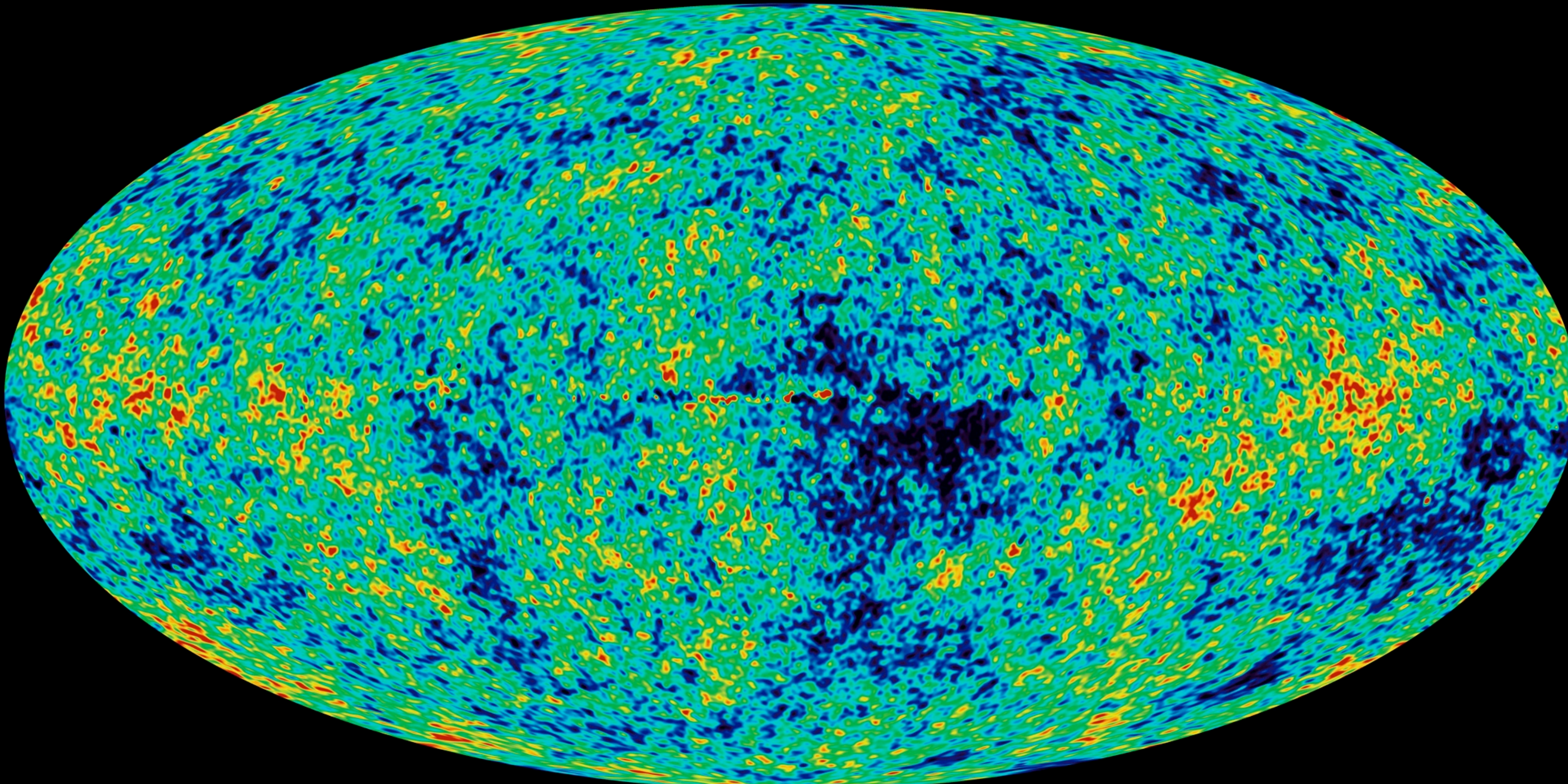
NASA GODDARD ❖ PRINCETON ❖ UCLA ❖ U CHICAGO





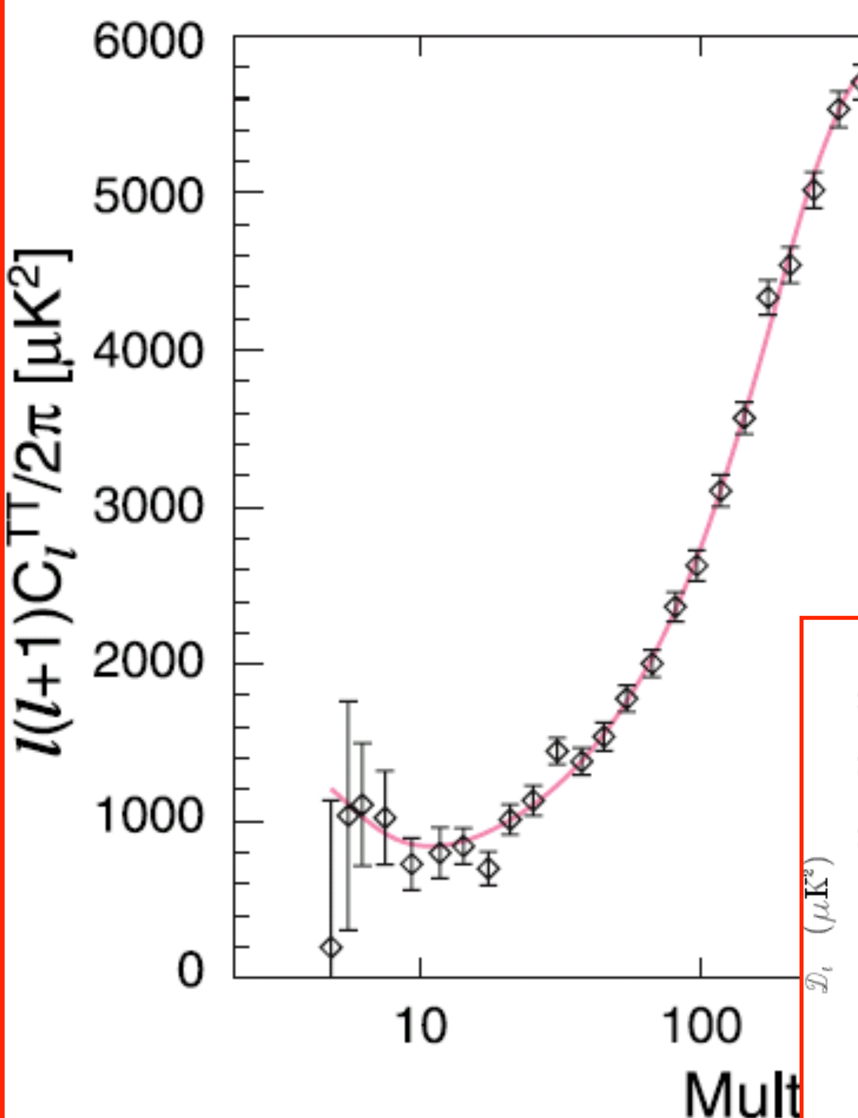
The Universe circa 380,000 yrs

WMAP



±0.001% Fluctuations

Curve = concordance cosmo

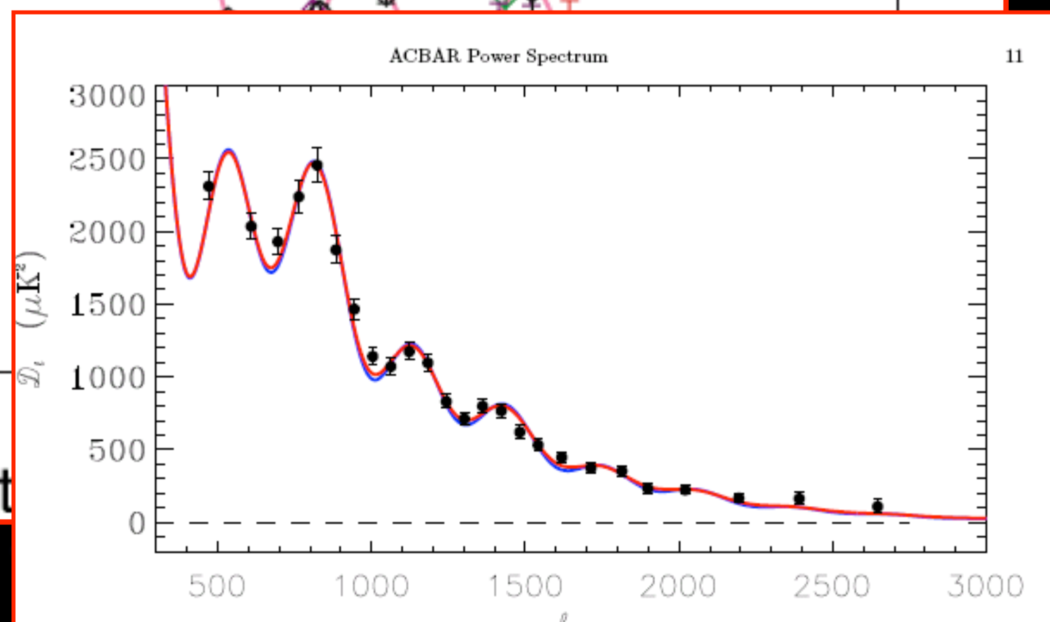


$\Omega_0 = 1.005 \pm 0.006$

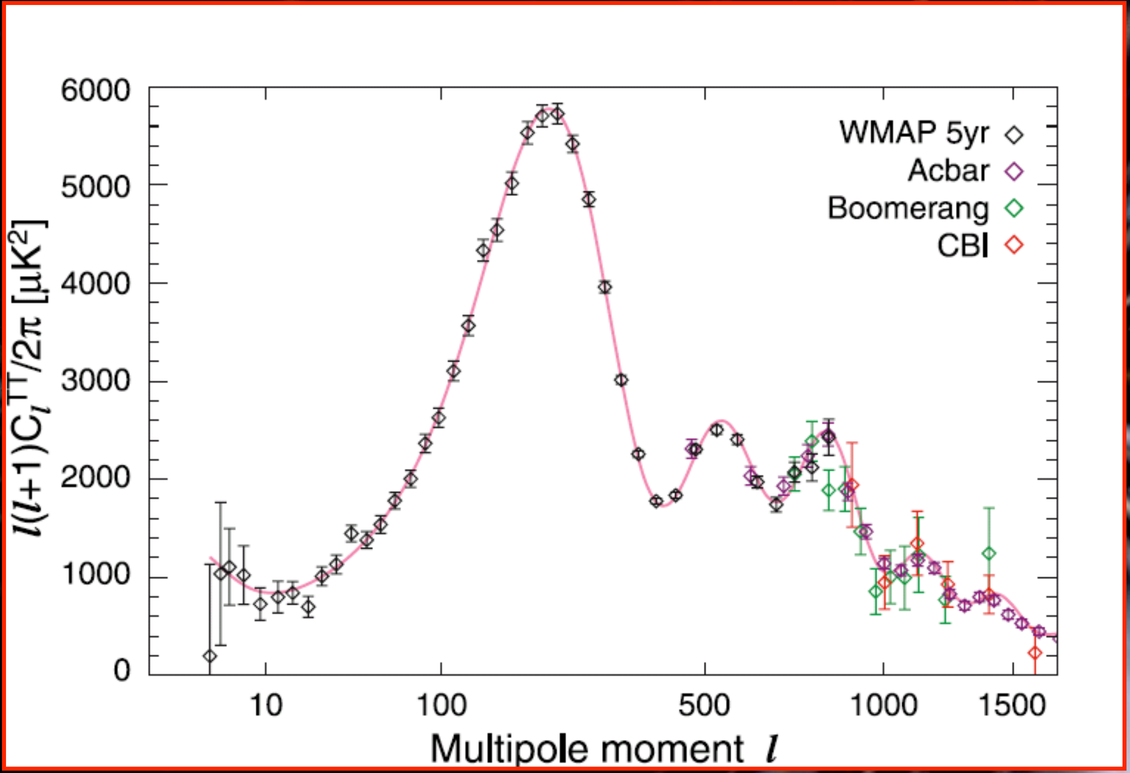
$\Omega_M = 0.28 \pm 0.015$

<u>only consistent if</u>

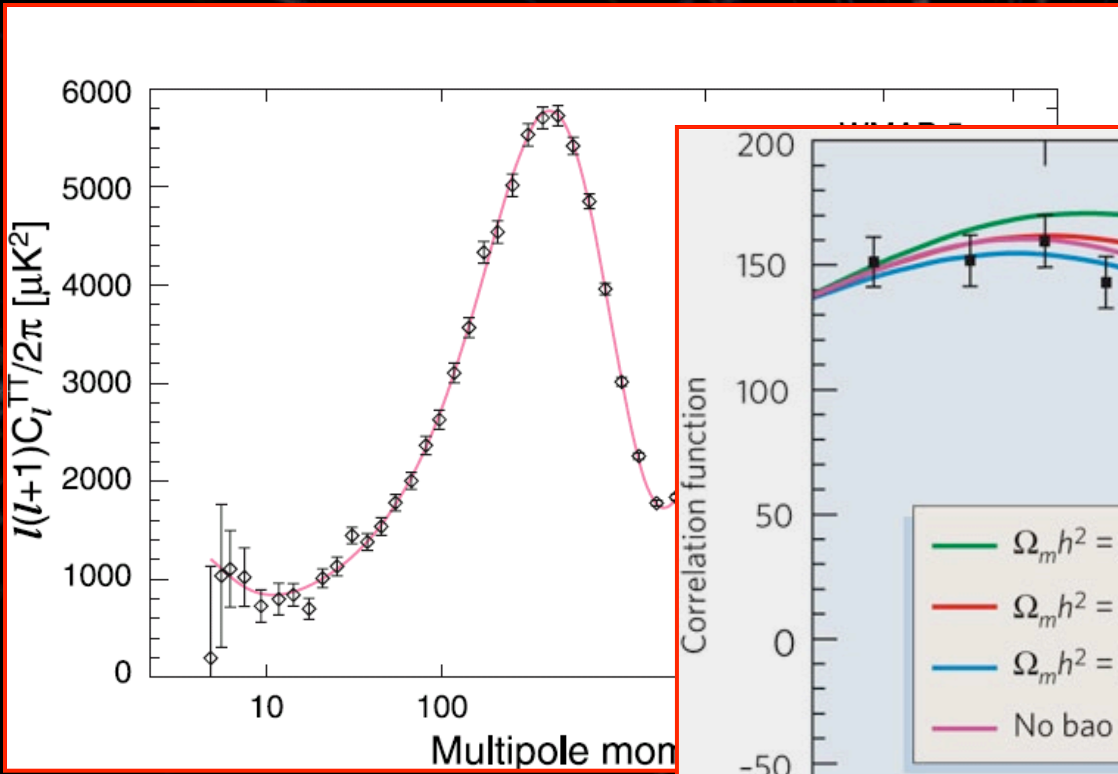
$\Omega_{\Lambda\text{-like}} = 0.72 \pm 0.015$

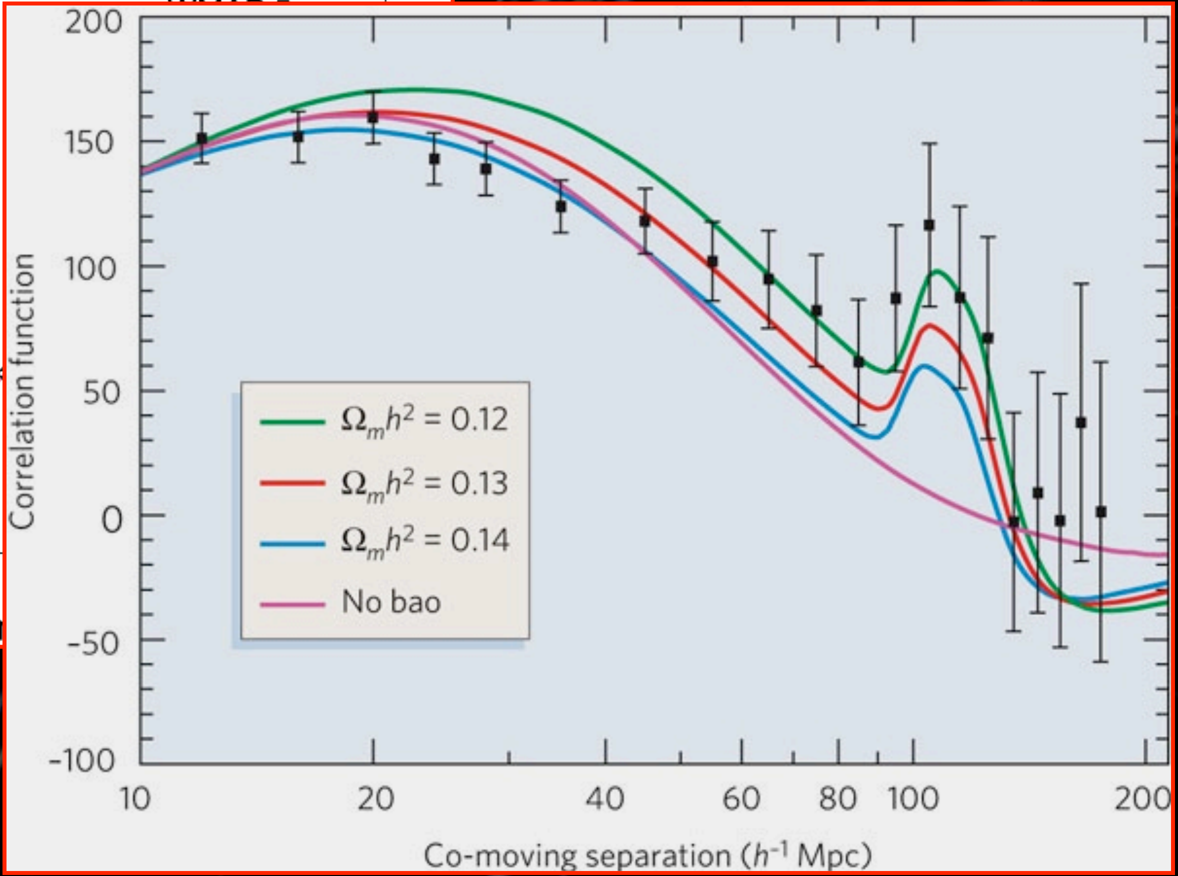


Baryon Acoustic Oscillations (BAO): Zel'dovich's Standard Ruler

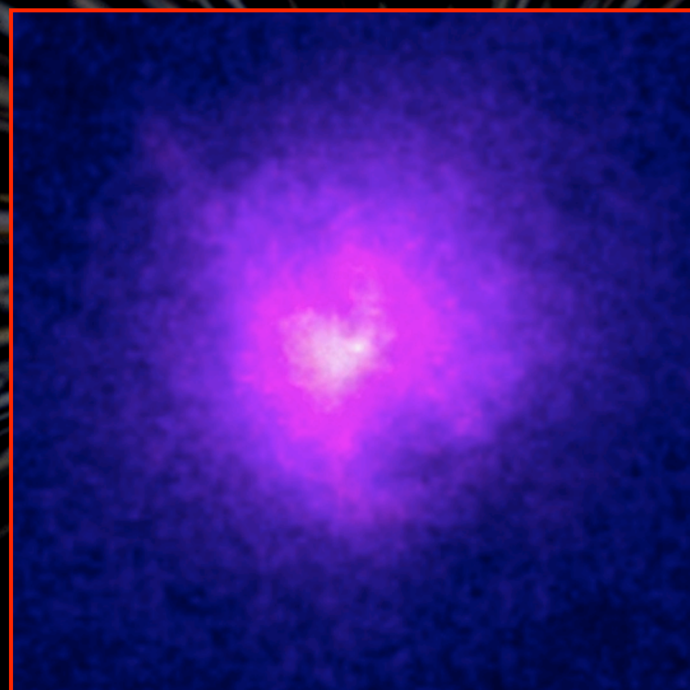


Baryon Acoustic Oscillations (BAO): Zel'dovich's Standard Ruler





New stand alone evidence for cosmic acceleration from clusters observed by Chandra



A.Vikhlinin et al, ApJ 692, 1060 (2009) [arXiv:0812.2720]

36 Clusters w/<z>~0.55 and 49 w/<z>~0.05

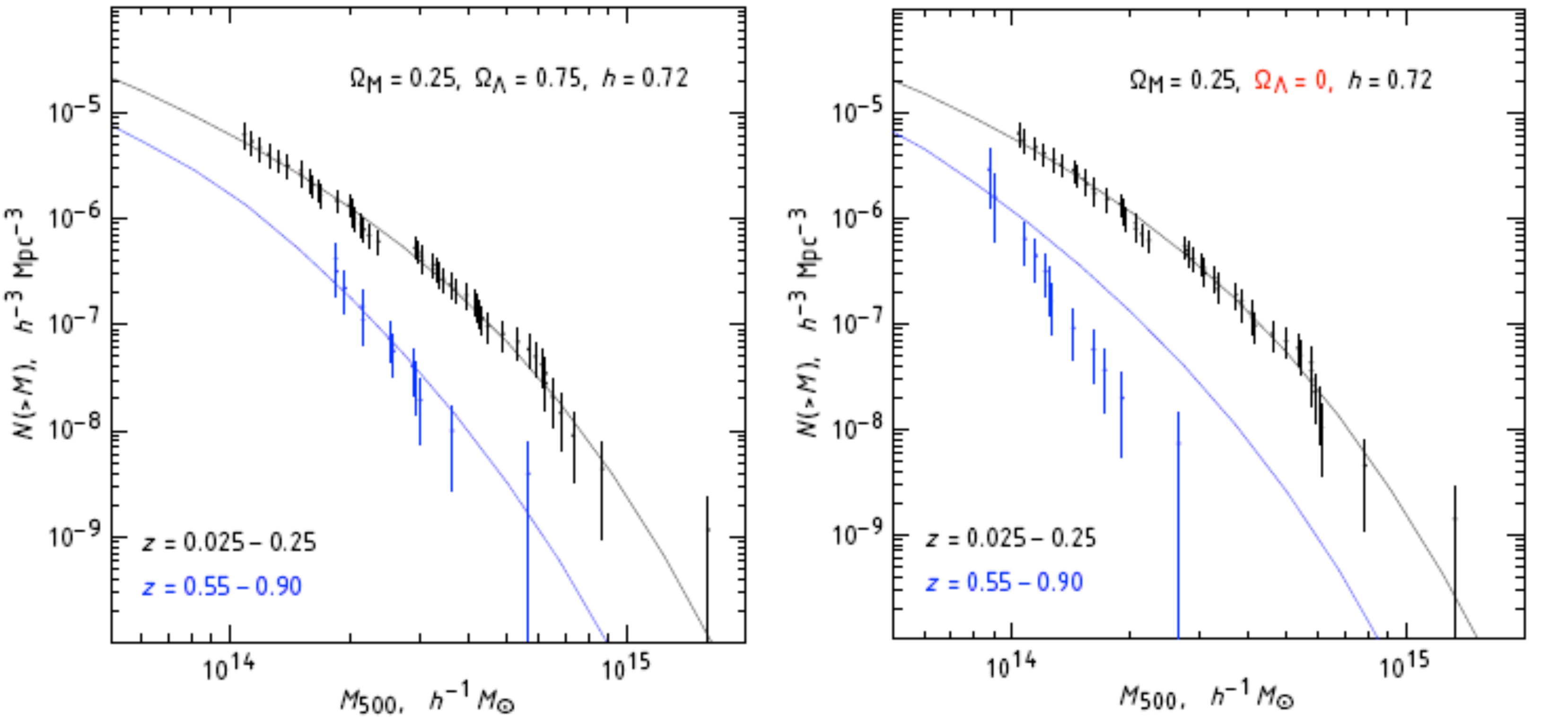
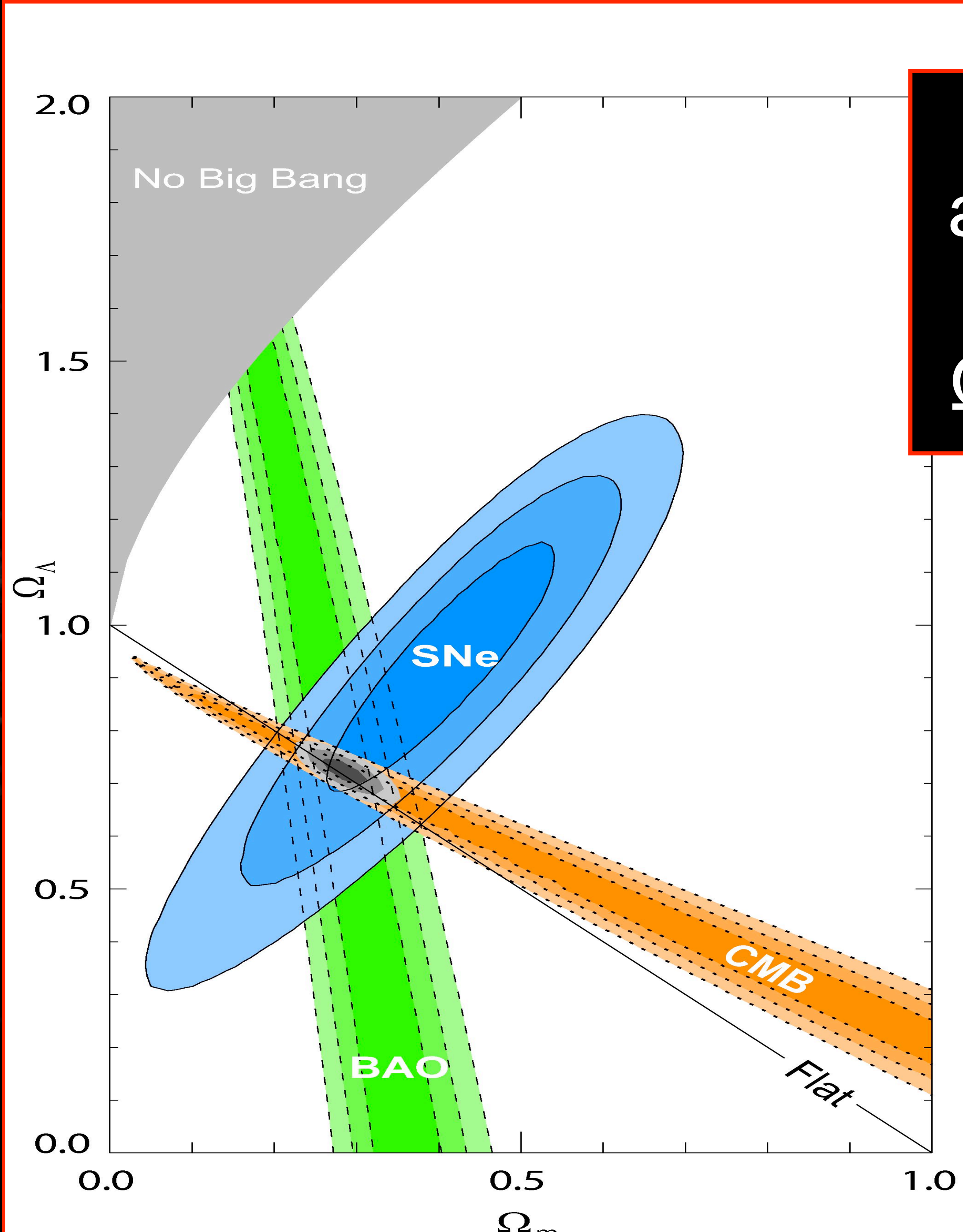


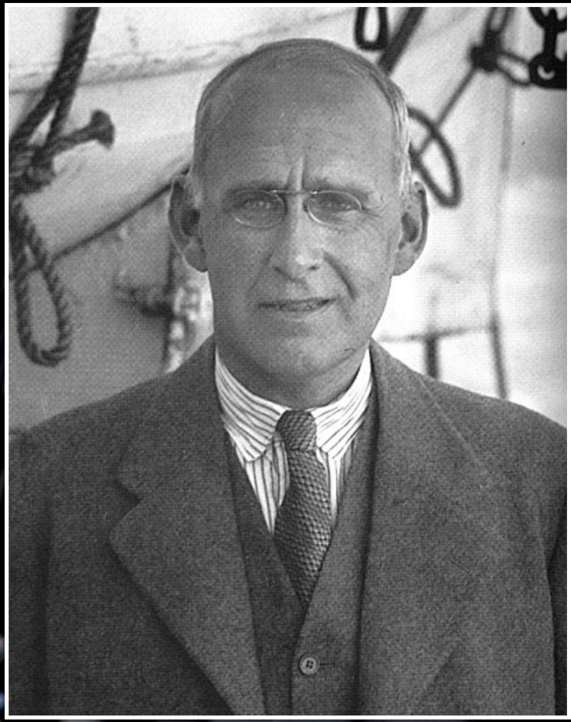
FIG. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at $z = 0$ adjusted) computed for a cosmology which is close to our best-fit model. The low-z mass function is reproduced from Fig. 1, which for the high-z cluster we show only the most distant subsample ($z > 0.55$) to better illustrate the effects. In the right panel, both the data and the models are computed for a cosmology with $\Omega_\Lambda = 0$. Both the model and the data at high redshifts are changed relative to the $\Omega_\Lambda = 0.75$ case. The measured mass function is changed because it is derived for a different distance-redshift relation. The model is changed because the predicted growth of structure and overdensity thresholds corresponding to $\Delta_{\rm crit} = 500$ are different. When the overall model normalization is adjusted to the low-z mass function, the predicted number density of $z > 0.55$ clusters is in strong disagreement with the data, and therefore this combination of Ω_M and Ω_Λ can be rejected.



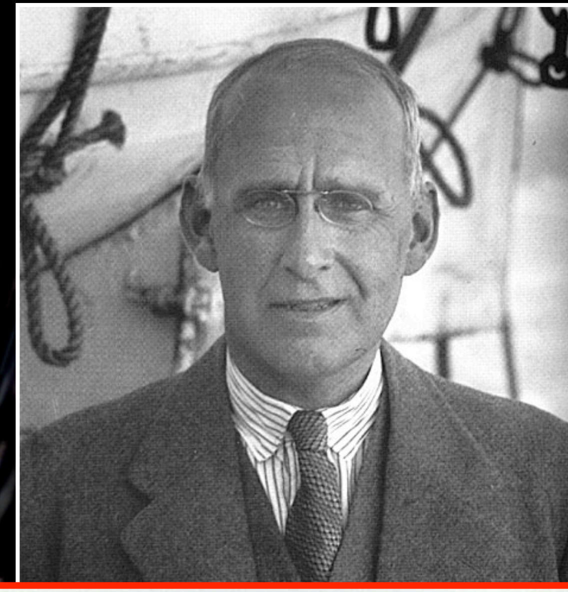
Consistent with all observations:

$\Omega_\Lambda = 0.71 \pm 0.02$

Eddington Criterion



Eddington Criterion



EDDINGTON:

"NO EXPERIMENTAL RESULT SHOULD BE ACCEPTED UNTIL CONFIRMED BY THEORY"

Very elastic stuff ($p < -\rho/3$) with repulsive gravity is called "dark energy"

GR ALLOWS FOR REPULSIVE GRAVITY:

SOURCE OF GRAVITY IN GR:

$$\rho + 3p$$

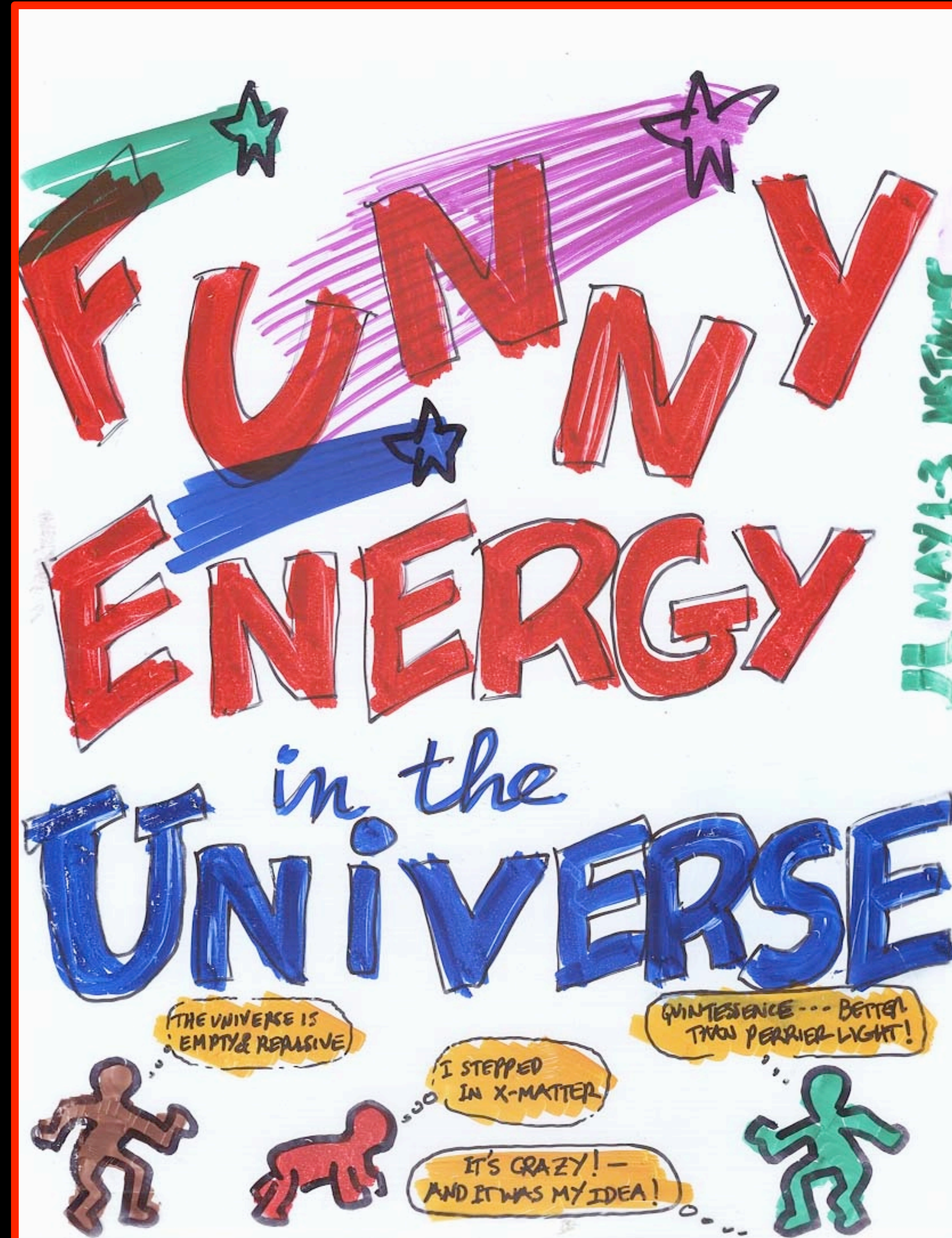
(SPHERICAL SYMMETRY)

FEATURE NOT A BUG!

→ BLACK HOLES WHEN $p \gtrsim \rho/3$

→ REPULSIVE GRAVITY WHEN $p < -\rho/3$

May 1998
Birth of Funny Energy
But, Focus Groups
Didn't Like Name
August 1998
Birth of Dark Energy
Third Stromlo Symposium
astro-ph/9811454



Dark Energy

Defining features:

• Large negative pressure, $p \sim -\rho$, so that $(\rho + 3p) < 0$

• $w = p/\rho$ (equation-of-state parameter) ~ -1

• Smoothly distributed

• Not particulate (dark matter has $p \sim 0$)

Simplest example:

• Energy of the quantum vacuum: $w = -1$

Dark Energy

Defining features:

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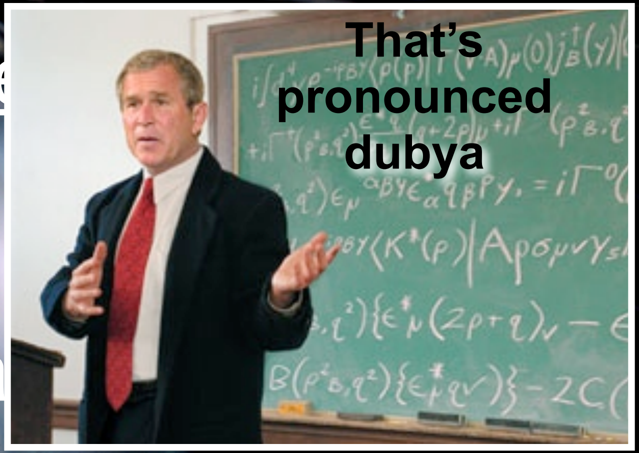
Simplest example:

• Energy of the quantum va



Dark Energy

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- Smoothly distributed
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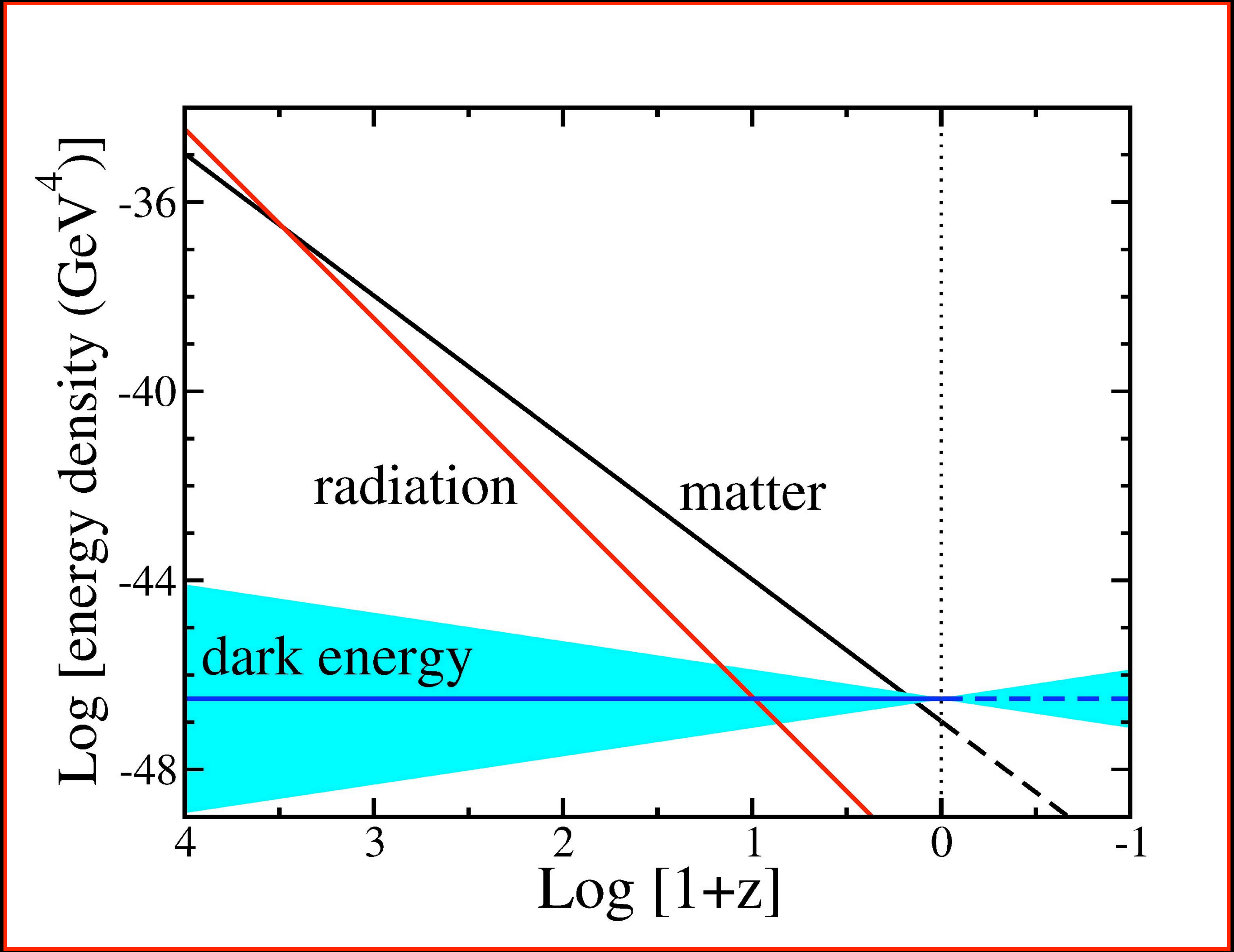
Simplest example:

- Energy of the quantum vacuum: $w = -1$

$$\rho_{DE} \sim (1 + z)^{3(1+w)}$$

w = pressure/energy density



$$\rho_{DE} \sim (1 + z)^{3(1+w)}$$

w = pressure/energy density

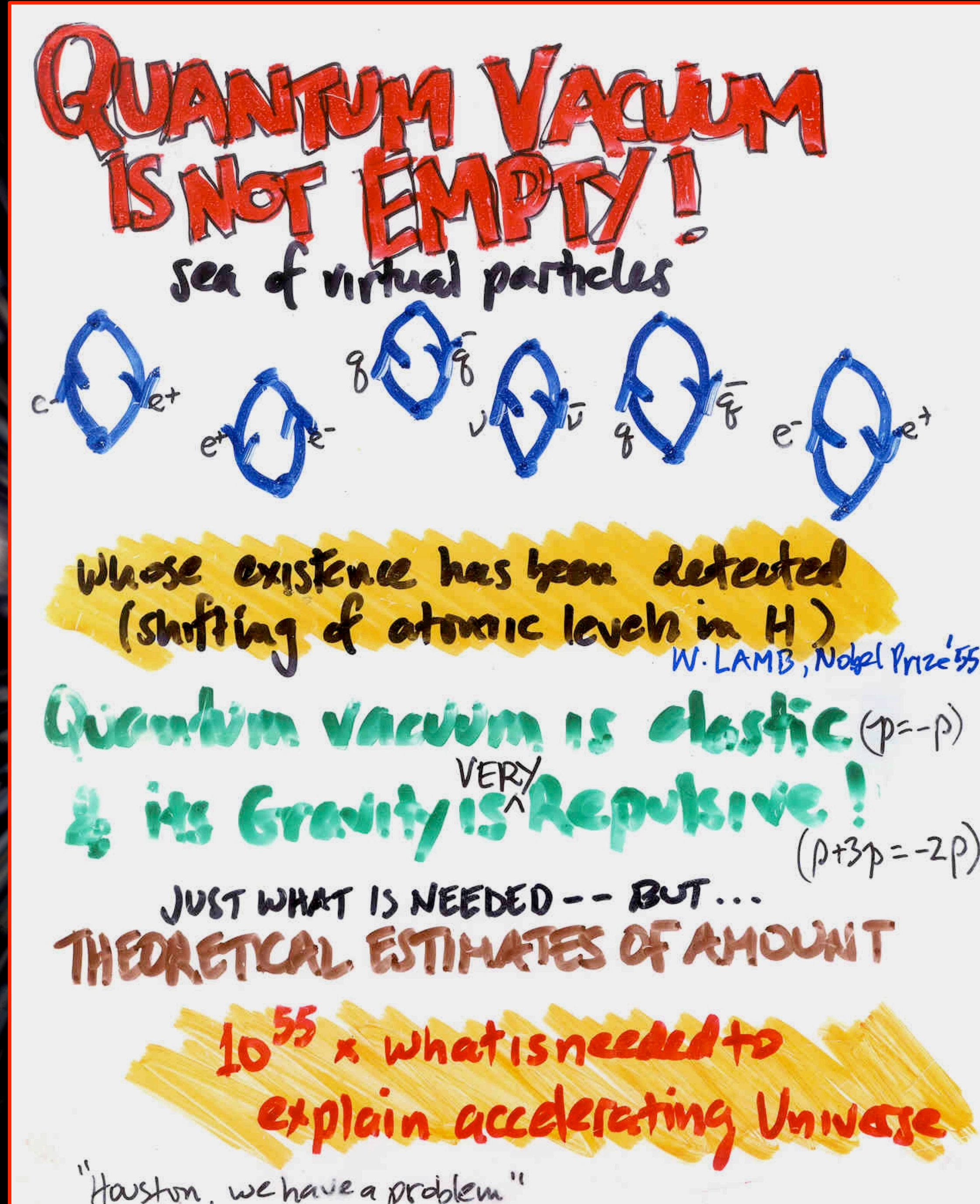
The Gravity of Nothing Is Repulsive

… But How Much Does Nothing Weigh?

Apparently, Way Too Much or Possibly Nothing

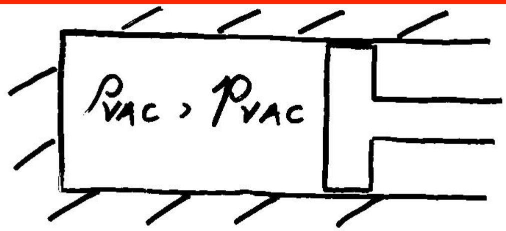
to be more precise, the answer is nonsensical (infinite) – not as bad as a finite answer that is off by orders of magnitude

$$\rho_{vac} \approx 3 \times 10^{-11}\ eV^4$$



The Gravity of Nothing Is Repulsive

… But How Much Does



$$dE = -p\,dV \quad \text{(First Law)}$$

$$\rho_{VAC}\,dV = -p_{VAC}\,dV \Rightarrow \underline{p_{VAC} = -\rho_{VAC}}$$

$$T^{\mu\nu}_{VAC} = \rho_{VAC}\, g^{\mu\nu}$$

(same as Λ)

$\rho_{vac} \approx 3 \times 10^{-11}\ eV^4$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles

e^- e^+ e^+ e^- q $\bar{q}$ ν $\bar{\nu}$ q $\bar{q}$ e^- e^+

whose existence has been detected (shifting of atomic levels in H)

W. LAMB, Nobel Prize '55

Quantum vacuum is elastic $(p = -\rho)$

& its Gravity is VERY Repulsive!

$(\rho + 3p = -2\rho)$

JUST WHAT IS NEEDED -- BUT...

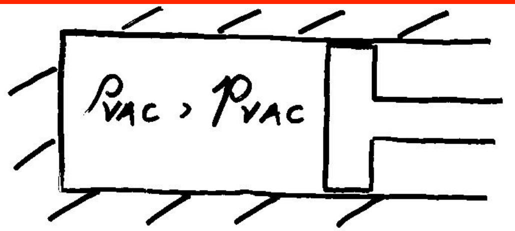
THEORETICAL ESTIMATES OF AMOUNT

10^{55} x what is needed to explain accelerating Universe

"Houston, we have a problem"

The Gravity of Nothing Is Repulsive

… But How Much Does



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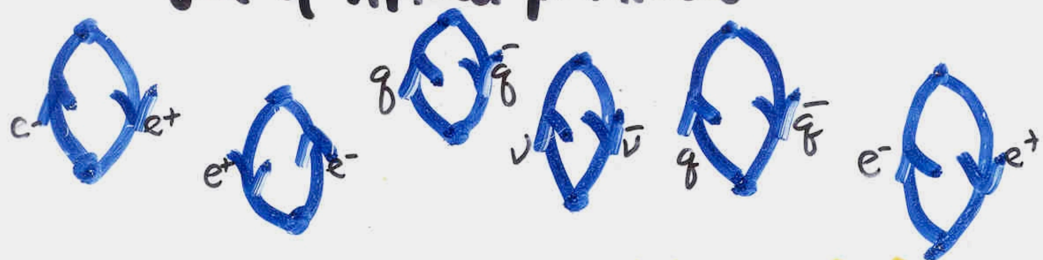
QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



whose existence has been detected (shifting of atomic levels in H)

W. LAMB, Nobel Prize '55

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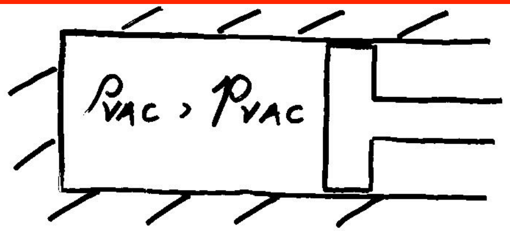


$dE = -p\,dV$ (First Law)

$\rho_{VAC}\,dV = -P_{VAC}\,dV \Rightarrow \underline{P_{VAC} = -\rho_{VAC}}$

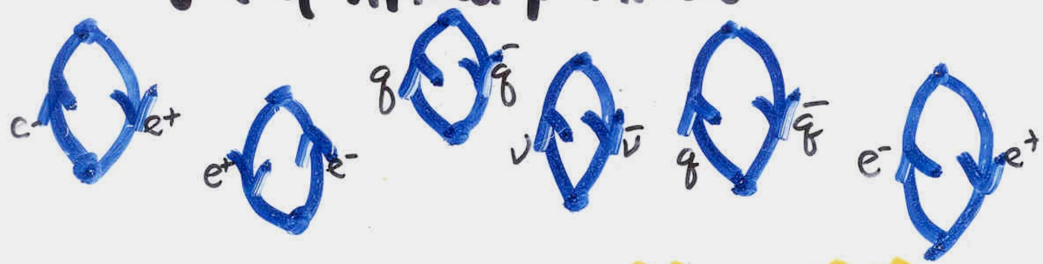
$T^{\mu\nu}_{VAC} = \rho_{VAC}\, g^{\mu\nu}$

(same as Λ)

$\rho_{vac} \approx 3 \times 10^{-11}\ \mathrm{eV}^4$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



whose existence has been detected (shifting of atomic levels in H)

W. LAMB, Nobel Prize '55

Quantum vacuum is elastic ($p = -\rho$)

& its Gravity is VERY Repulsive! ($\rho + 3p = -2\rho$)

JUST WHAT IS NEEDED -- BUT...

THEORETICAL ESTIMATES OF AMOUNT

$$\rho_{\rm zero\,pt} = \frac{1}{2}\int_0^\infty \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} = \frac{1}{16\pi^2}k_{\rm max}^4$$

$$\rho_{\rm zero\,pt} < \rho_{\rm crit} \Rightarrow k_{\rm max} < 0.03\,\mathrm{eV}$$

Now we have two puzzles:

Why does nothing weighs so little?

&

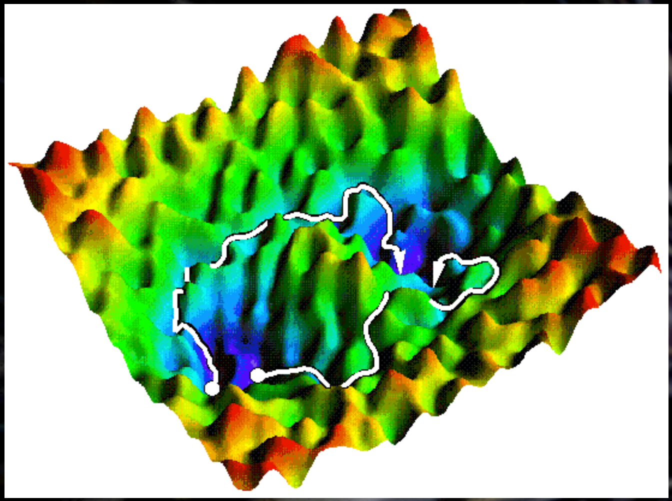
What is dark energy?

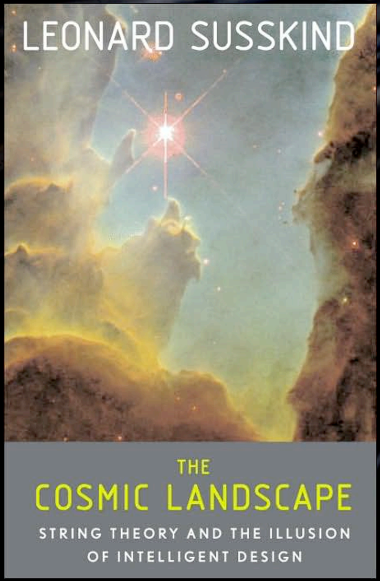
Puzzles could be related or unrelated!

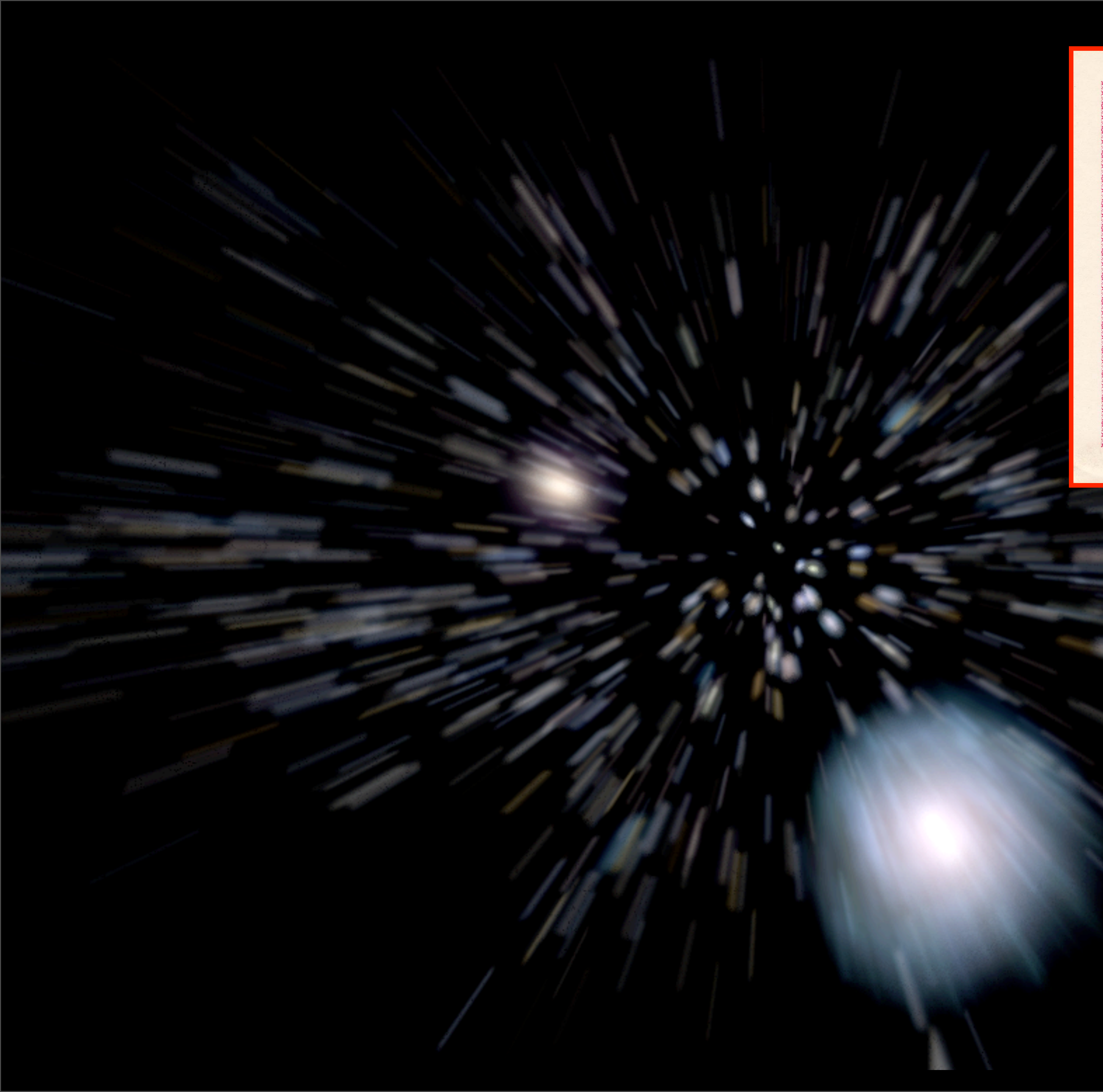
SOLVING THE COSMIC ACCELERATION RIDDLE WILL REQUIRE A CRAZY, NEW IDEA!

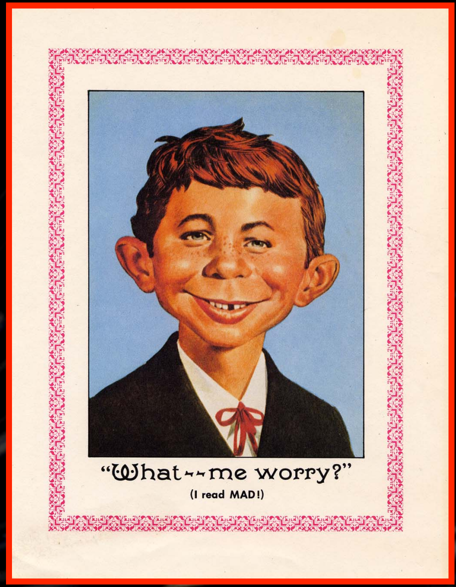
NB: NOT EVERY CRAZY IDEA IS A SOLUTION TO A PROFOUND PROBLEM!

Vacuum Energy Problem Solved by Supersymmetry or ?









Theorists: When in doubt, just add a scalar field

ROLLING SCALAR FIELD

(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)

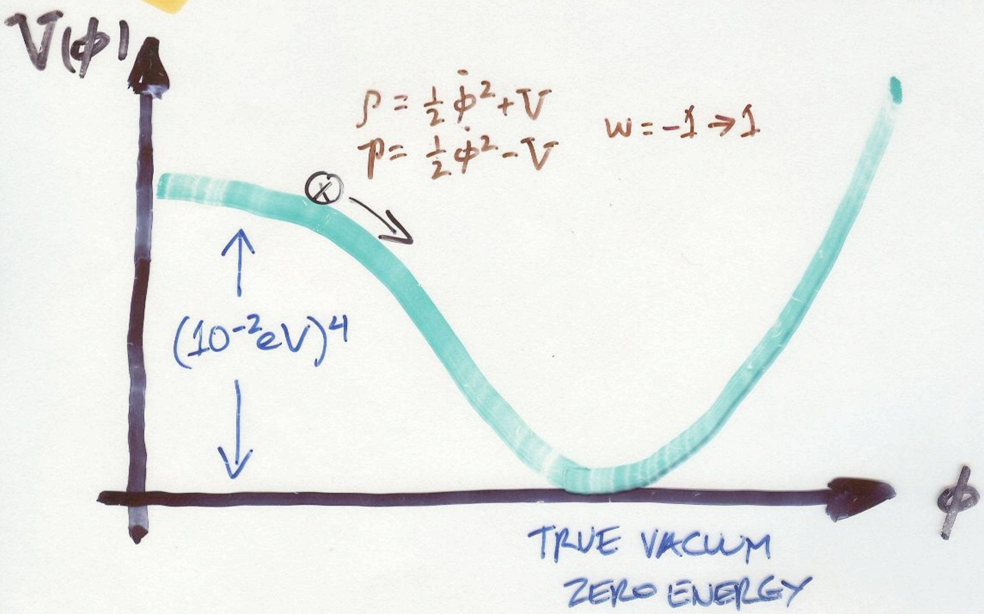
Bronstein 1933 (executed by Stalin 1935)
Hull Schramm Fry 1986
Freese et al 1987
Ratra - Peebles 1988
Frieman et al 1995
Caldwell et al 1998
& others

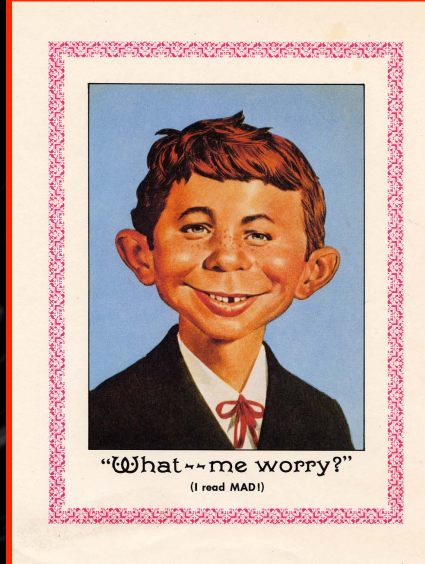
A. GREENSPAN 1998: "... Brief Episodes of Inflation Are Unavoidable."

$\rho = \frac{1}{2}\dot{\phi}^2 + V$

$p = \frac{1}{2}\dot{\phi}^2 - V$

$w = -1 \rightarrow 1$





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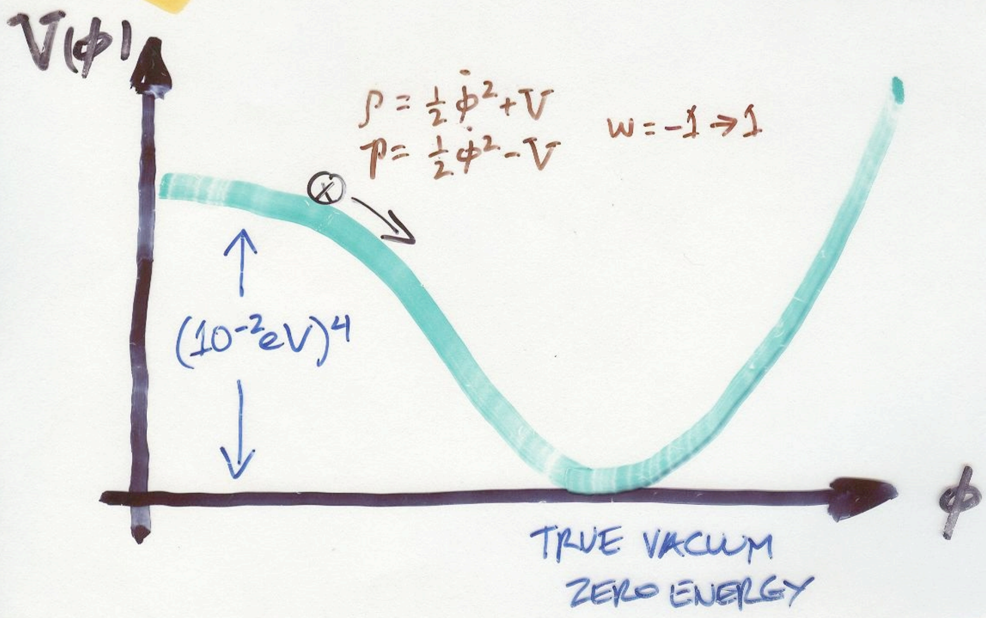

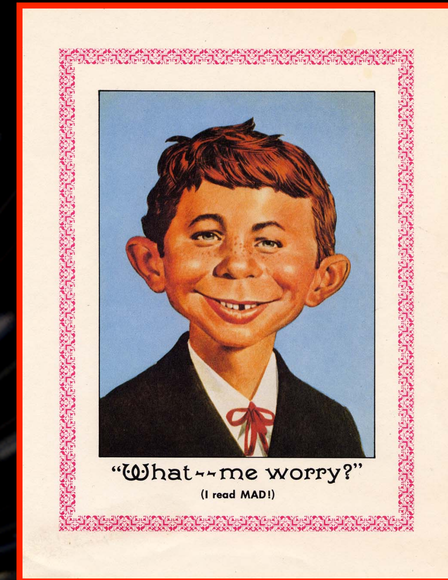

Theorists: When in doubt, just add a scalar field

NB: does not address of the lightness of nothing

NO DARK ENERGY

NEW ASPECT OF GRAVITY

→ "EMPTY" UNIVERSE UNDERGOES ACCELERATED EXPANSION !

AVERAGE MATTER DENSITY TODAY $\approx 10^{-29}$ g/cm^3

$\approx 10^{-100} \times$ DENSITY AFTER INFLATION

Dark Theory Summary

1. GR + repulsive gravity of dark energy (Conservative)
   - Quantum vacuum energy/cosmological constant
   - “Quintessence”
   - ?? Something else with negative pressure
2. No dark energy, new theory of gravity (Progressive)
3. No dark energy, no new theory of gravity (Birther)
   - Non linear gravitational effects
   - Center of the Universe

Two Big Dark Questions

Does Dark Energy change with time (i.e., is dark energy vacuum energy)?

Does Cosmic Acceleration require going beyond General Relativity?

Two Big Dark Questions

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No, at the 10 to 20% level

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Two Big Dark Questions

Does Dark Energy change with time (i.e., is dark energy vacuum energy)?

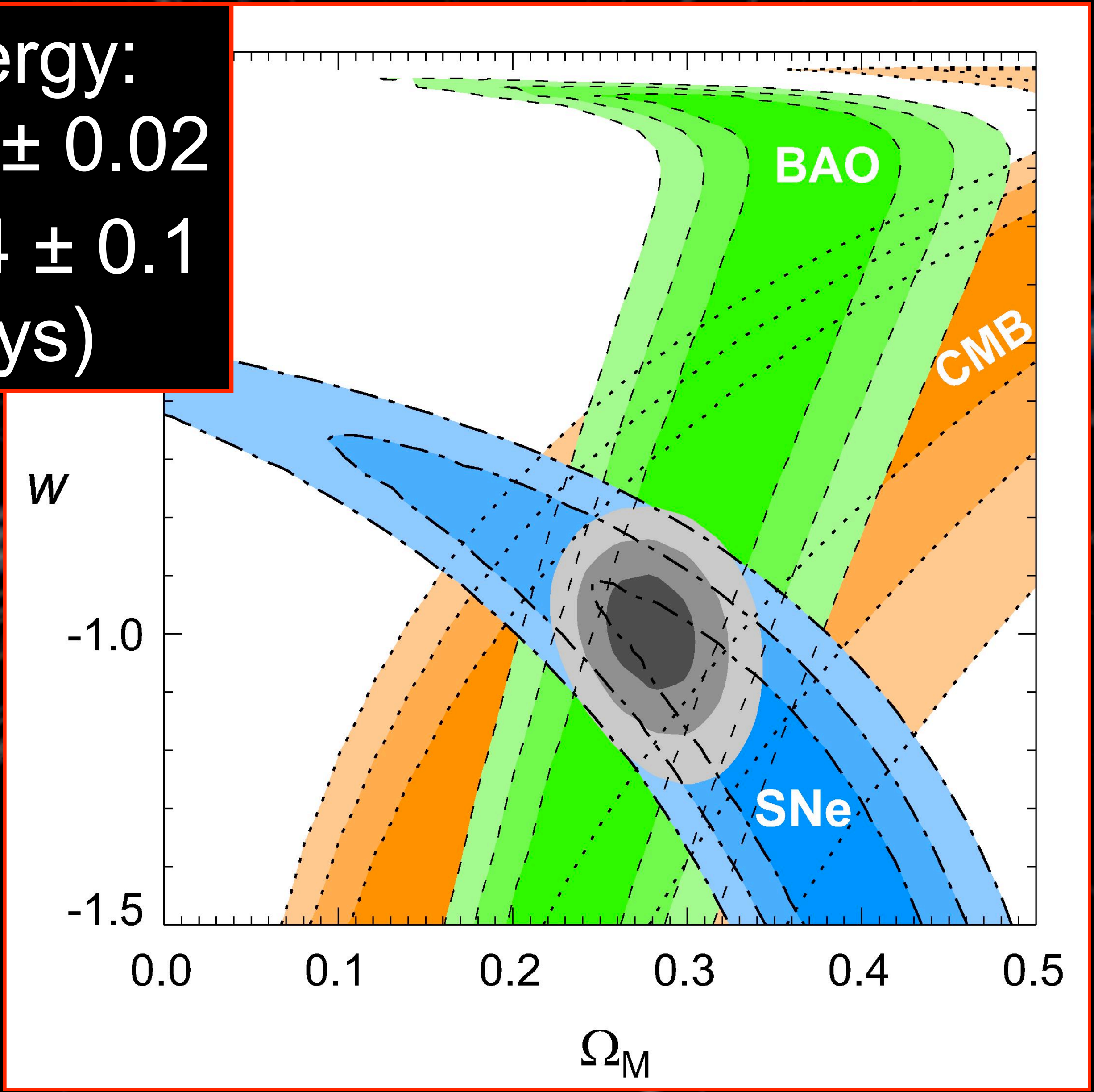
No, at the 10 to 20% level

Does Cosmic Acceleration require going beyond General Relativity?

Not well tested

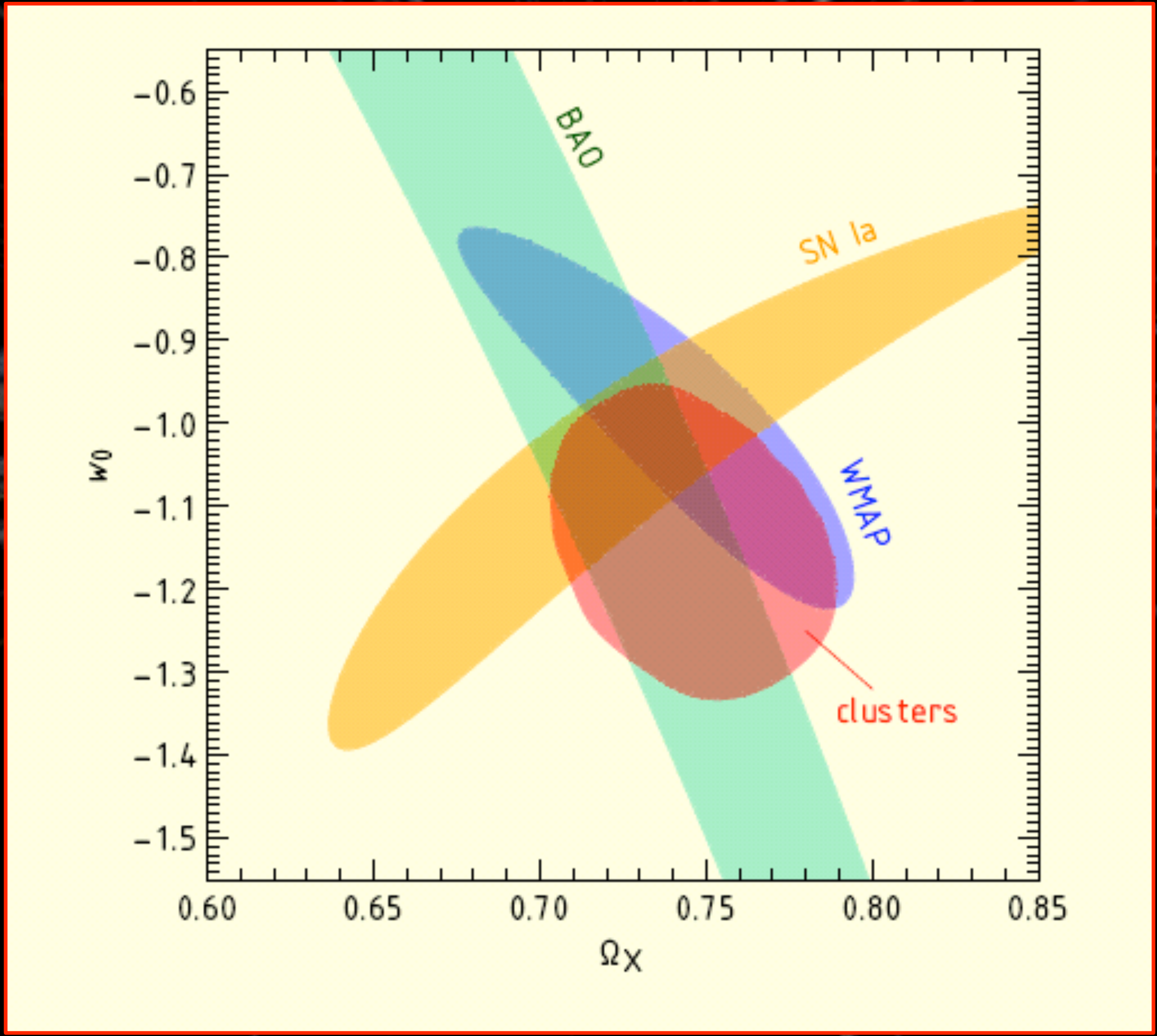
Where We Are Today

Dark Energy:
$\Omega_{DE} = 0.76 \pm 0.02$
$w = -0.94 \pm 0.1$
($\pm$ 0.1 sys)



New Results 400d Survey

Alexey Vikhlinin et al, CCCP

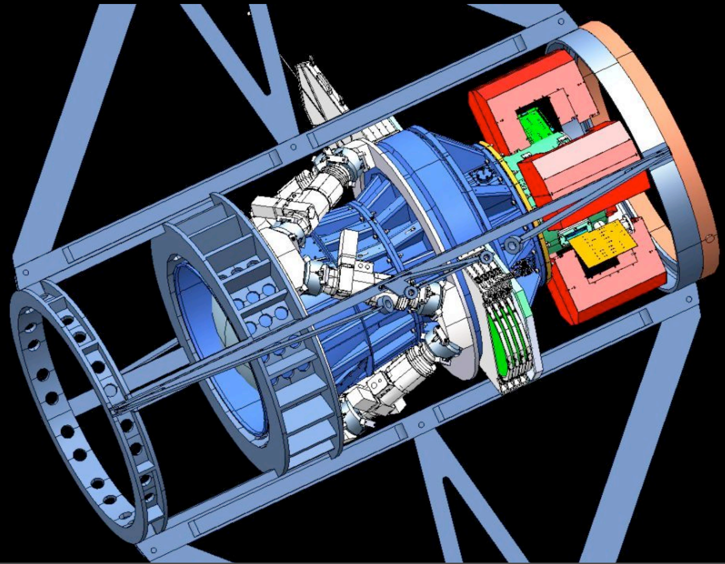


Known Probes of Dark Energy

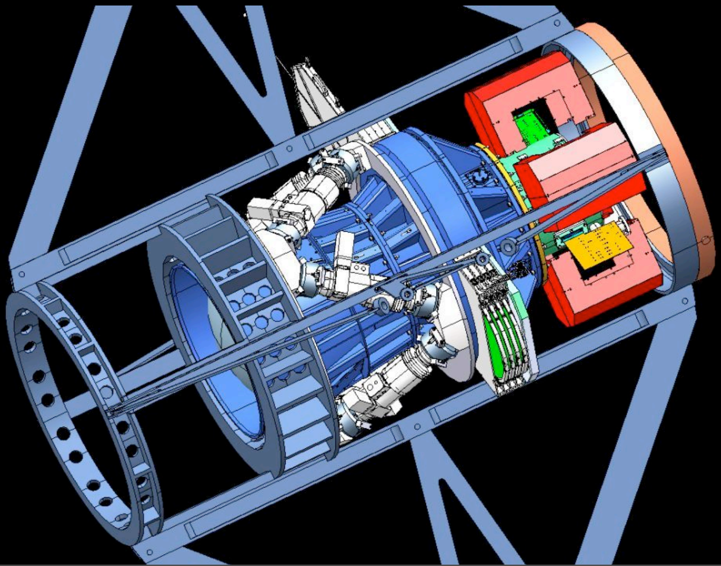
- Supernovae: Geometric
- BAO: Geometric + simple physics
- Weak Lensing: Geometric + dynamic
- Clusters: Dynamics + geometric
- Evolution of large-scale structure (dynamic)
  - Must reproduce LCDM
  - Growth factor/red-shift space distortions
- CMB and other precision data that pin down cosmological parameters (provide priors)

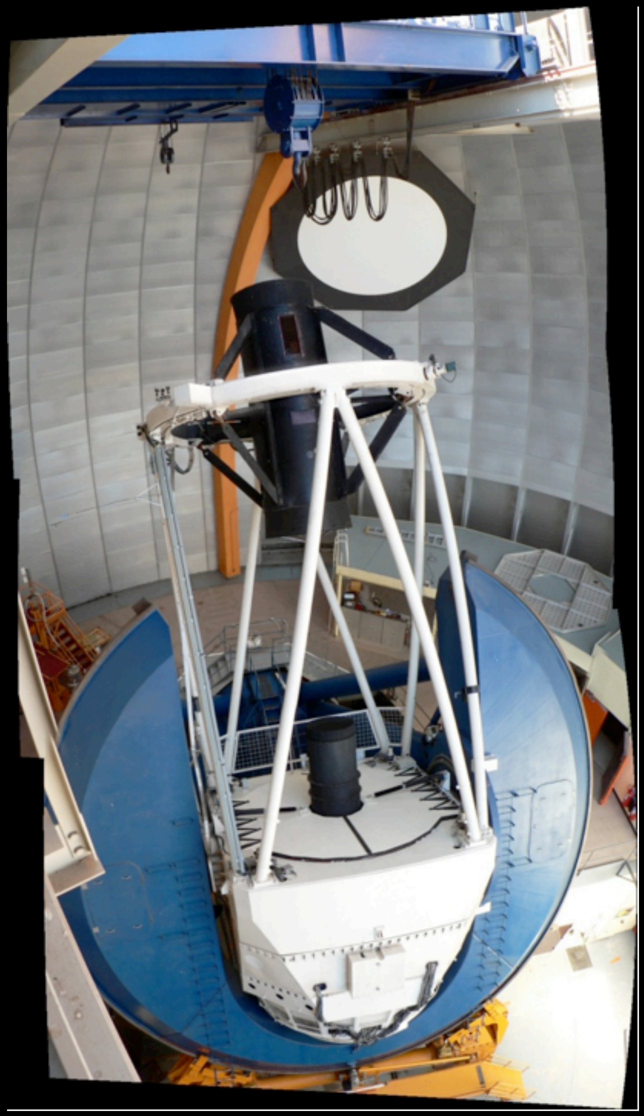
Dark Energy Survey

Dark Energy Survey

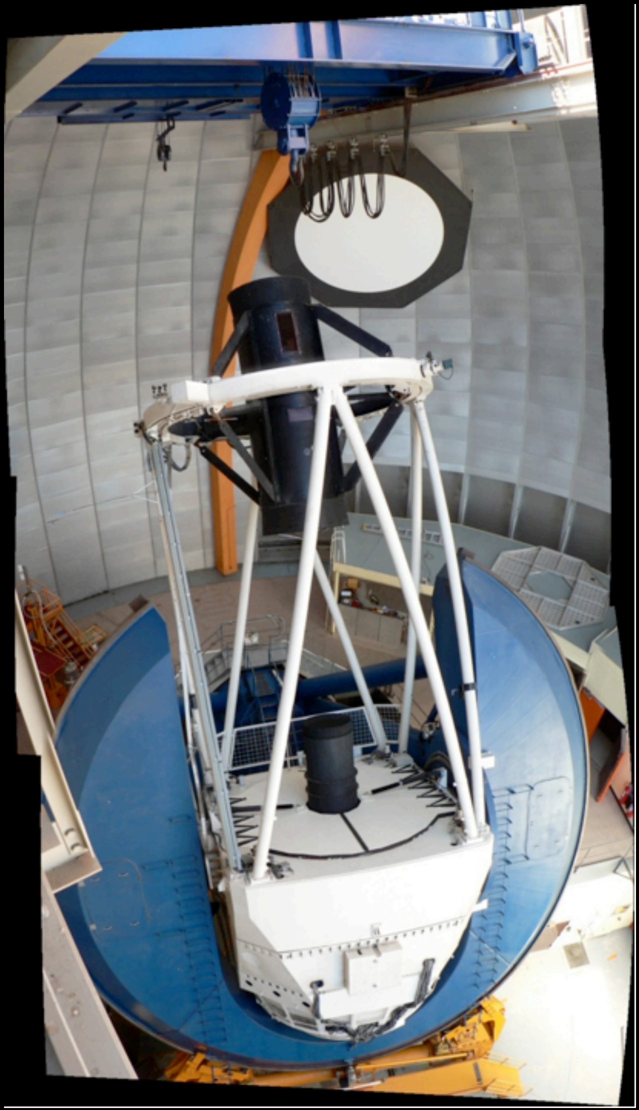


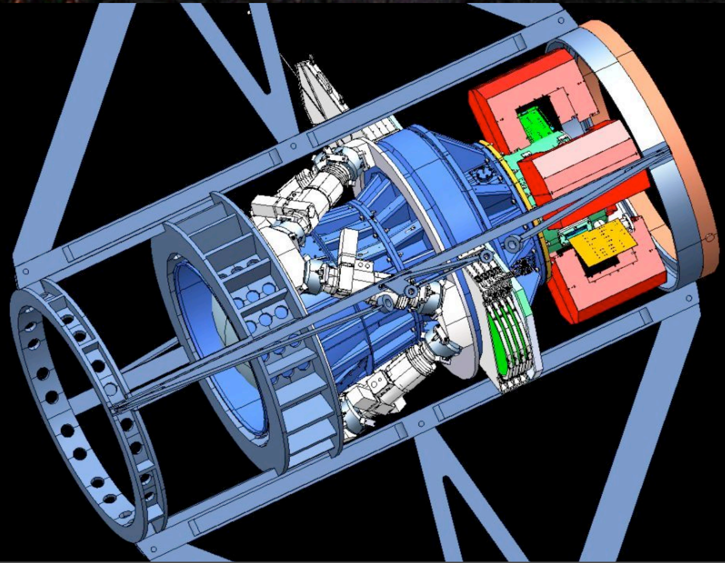
Dark Energy Survey



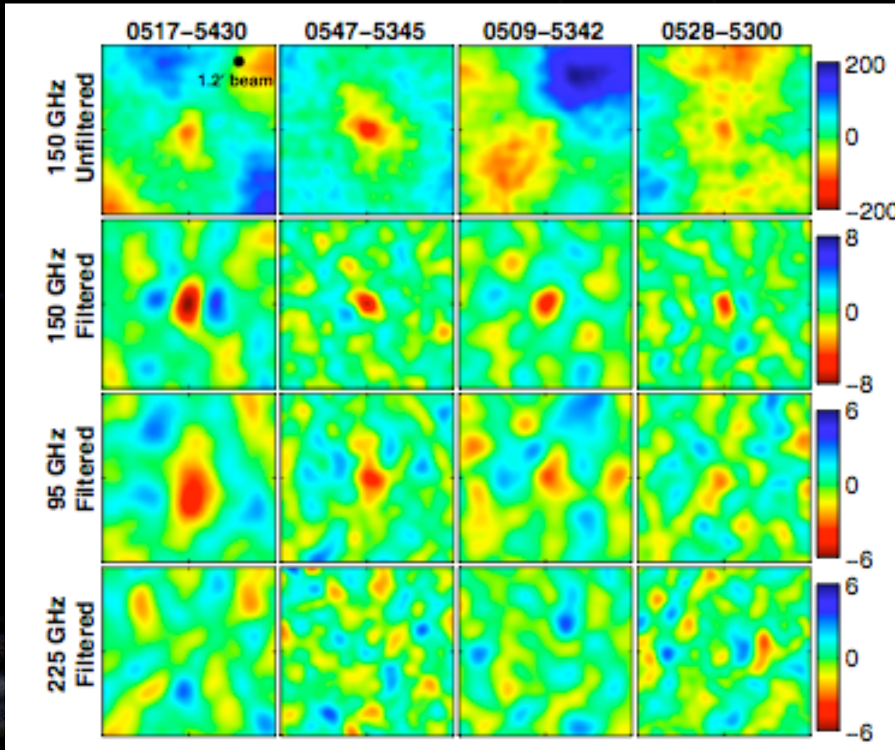


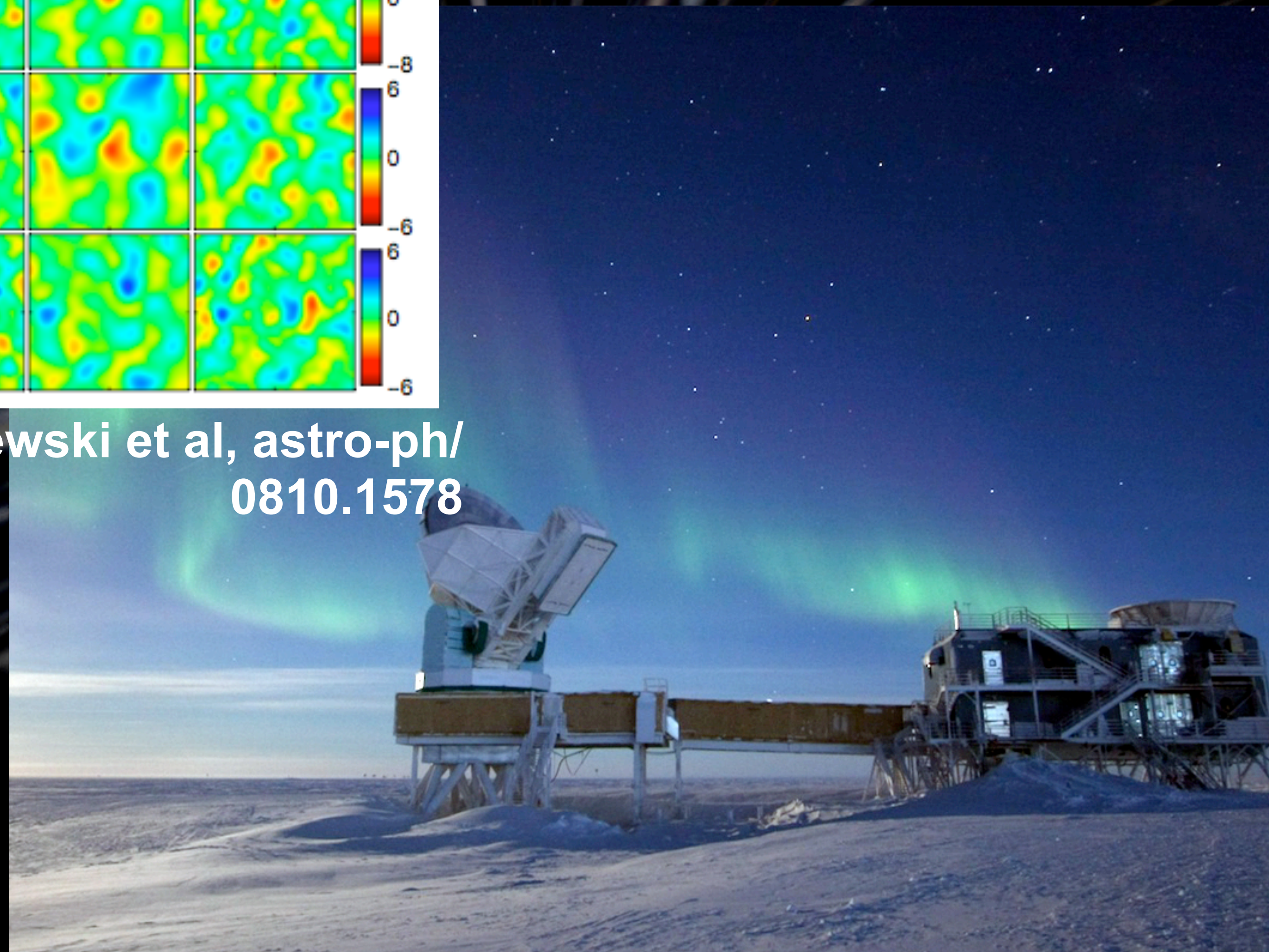
Dark Energy Survey





First Results from the South Pole Telescope





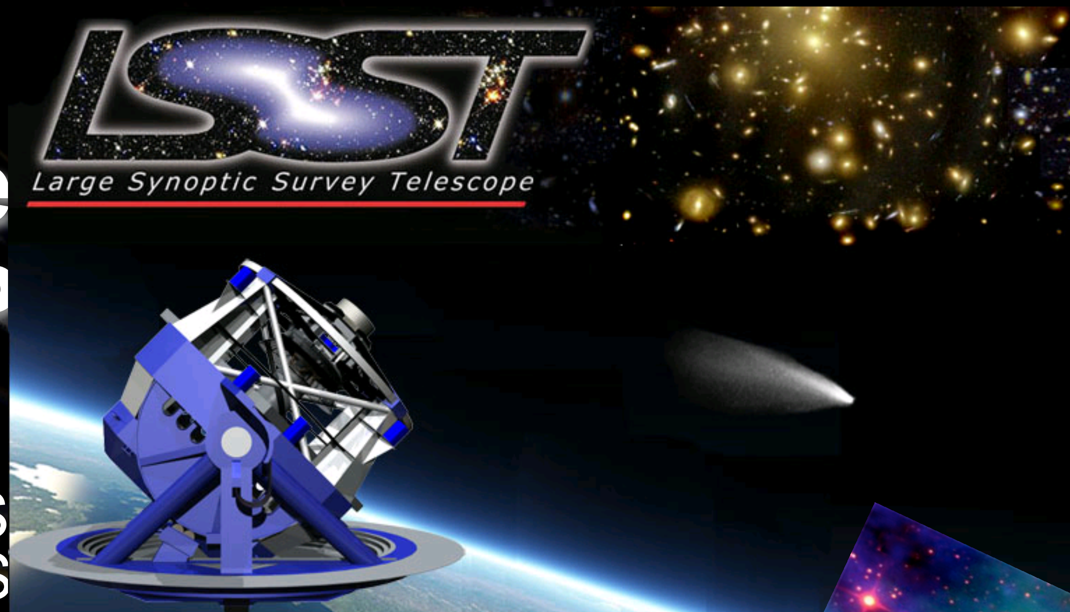
Staniszewski et al, astro-ph/ 0810.1578

Impressive Array of Dark Energy Projects on the Horizon

- **BAO:** SDSS/2dF, WiggleZ, FMOS, BOSS HETDEX, WFMOS, PAU → EUCLID & JDEM
- **CL:** SZA, SPT, DES, ACT, Chandra → eROSITA
- **SNe:** DES, PanSTARRS → LSST, EUCLID & JDEM
- **WL:** DES, PanSTARRS → LSST, EUCLID & JDEM
- **CMB et al:** WMAP/ACT/SPT/Planck – cosmological degeneracies make many other observations valuable

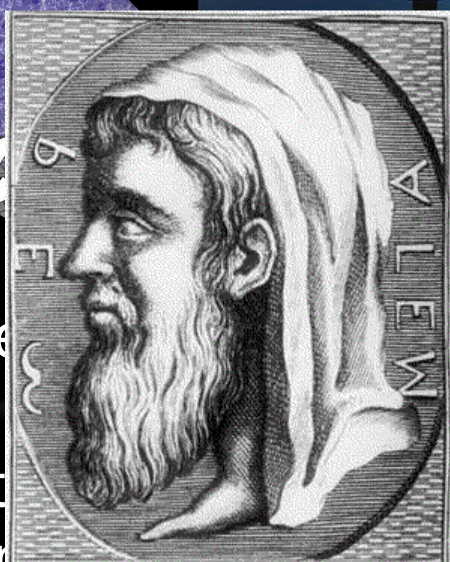
On the way to few % in w_0, 10% in w_a, significant tests of underlying gravity theory … and deeper understanding of dark energy

Impre nergy P n

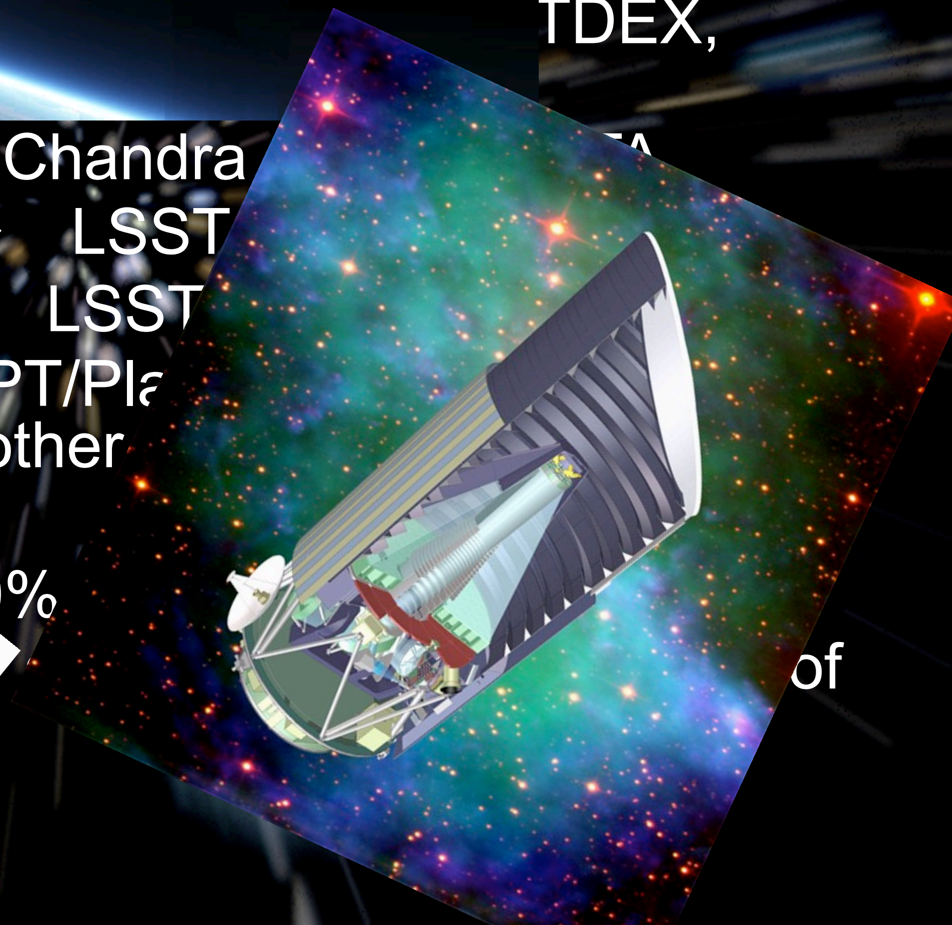


O: S TDEX,
OS

DES, ACT, Chandra A
TARRS → LSST
TARRS → LSST



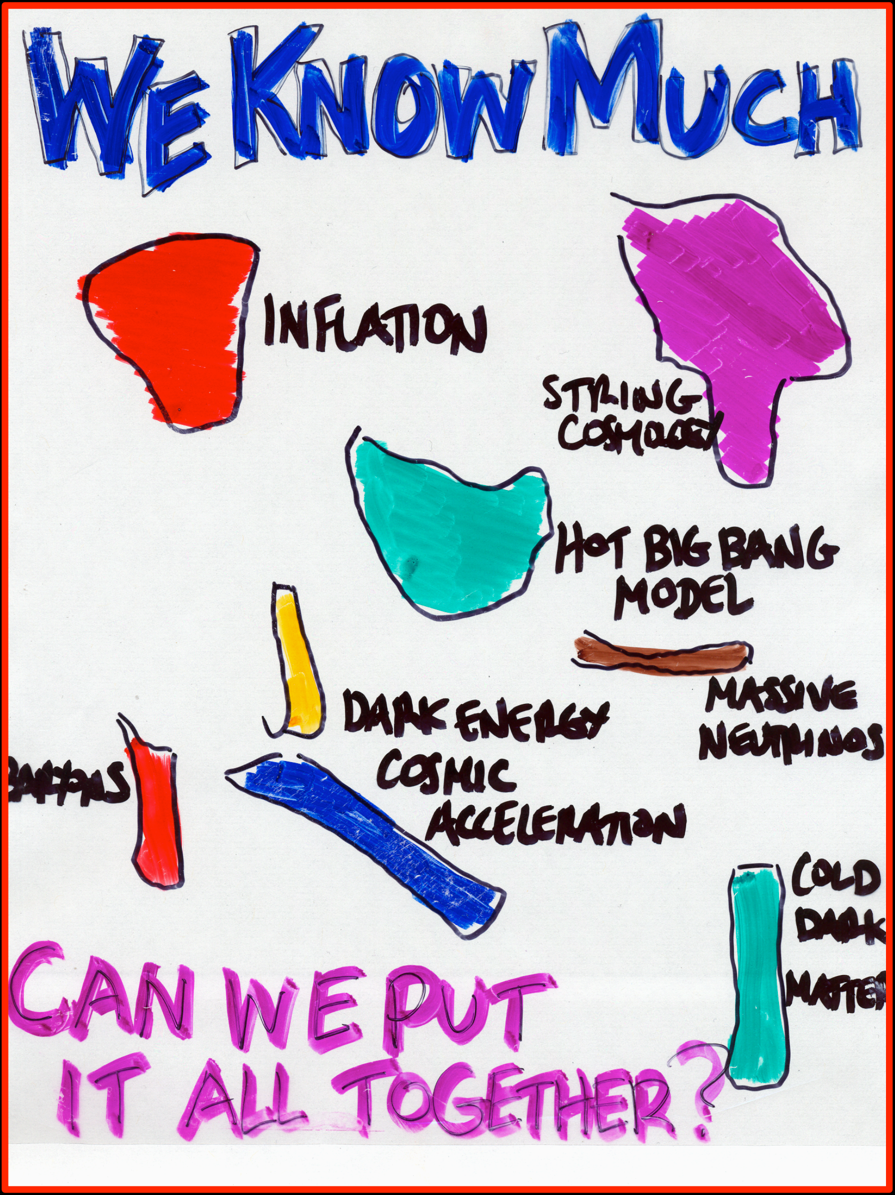
-
- C P/ACT/SPT/Pla
  de e many other

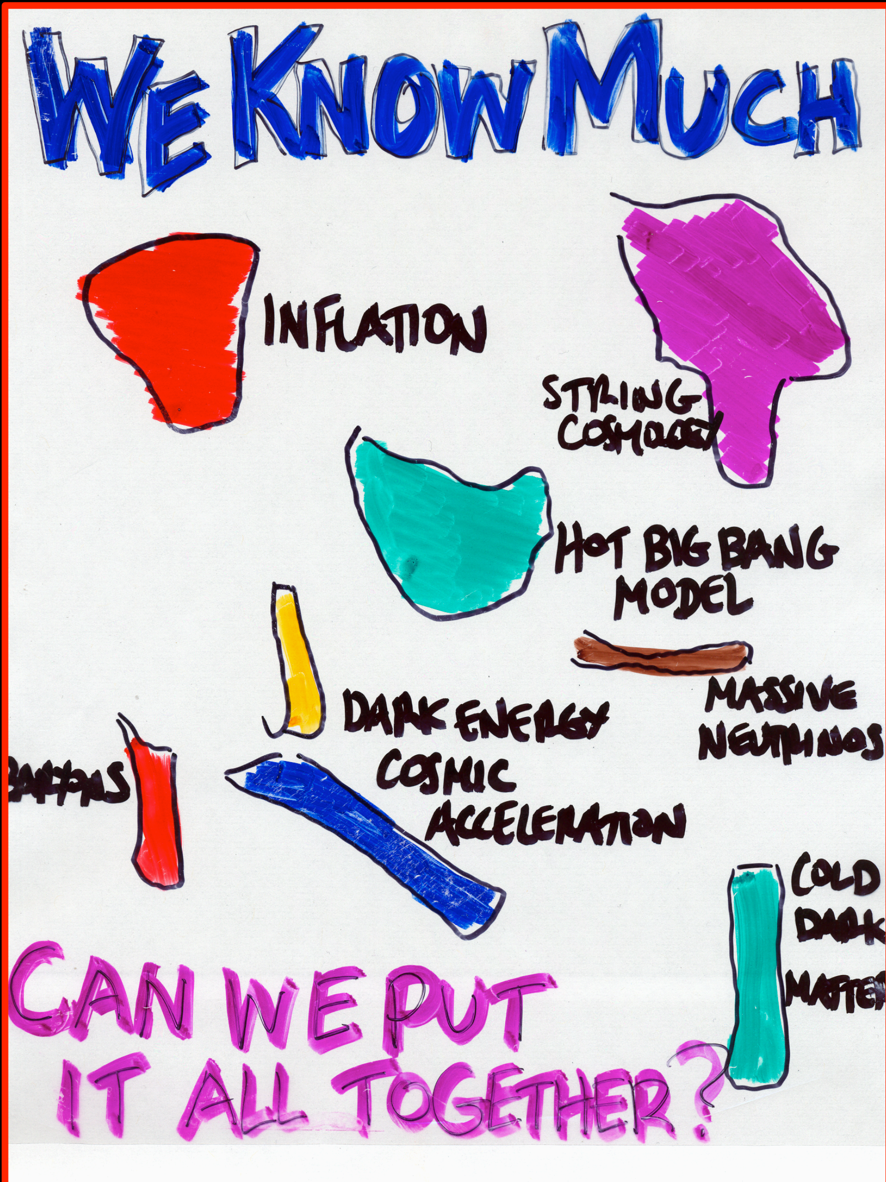


On t 10%
un of
dark energy

The New Cosmology

- What we know for sure
  - Quark Soup to Expanding Galaxies
  - BBN, Gravity the masterbuilder, CMB, the phenomena of Dark Matter and Accelerated Expansion
- Knocking at the Door (ie, testing now)
  - Particle dark matter, inflation, dark energy, (baryogenesis)
- Wild Speculation
  - Before the big bang, multiverse, extra dimensions, emergence of space


WE KNOW MUCH
INFLATION
STRING COSMOLOGY
HOT BIG BANG MODEL
MASSIVE NEUTRINOS
DARK ENERGY
COSMIC ACCELERATION
COLD DARK
CAN WE PUT IT ALL TOGETHER?


WE KNOW MUCH
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COSMIC ACCELERATION
BARYONS
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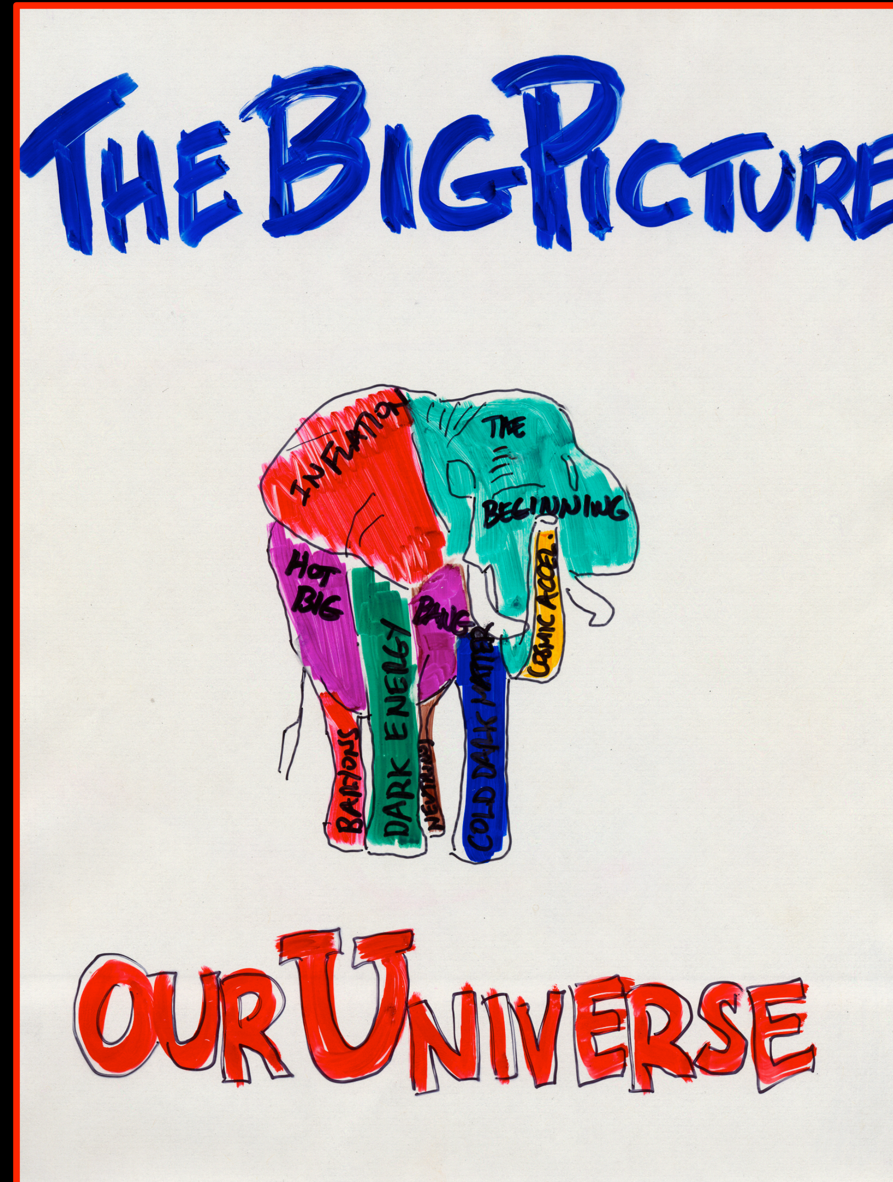
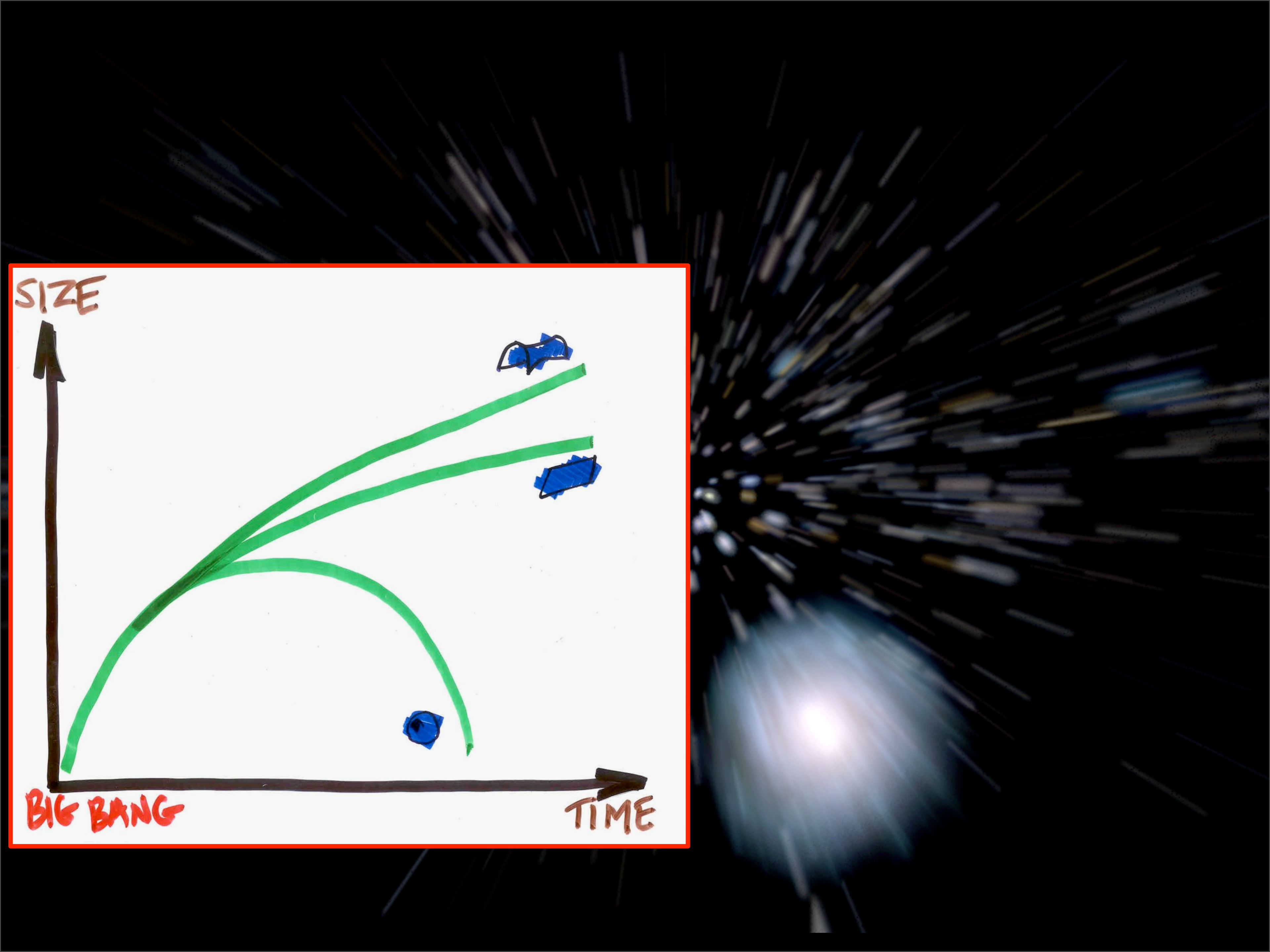
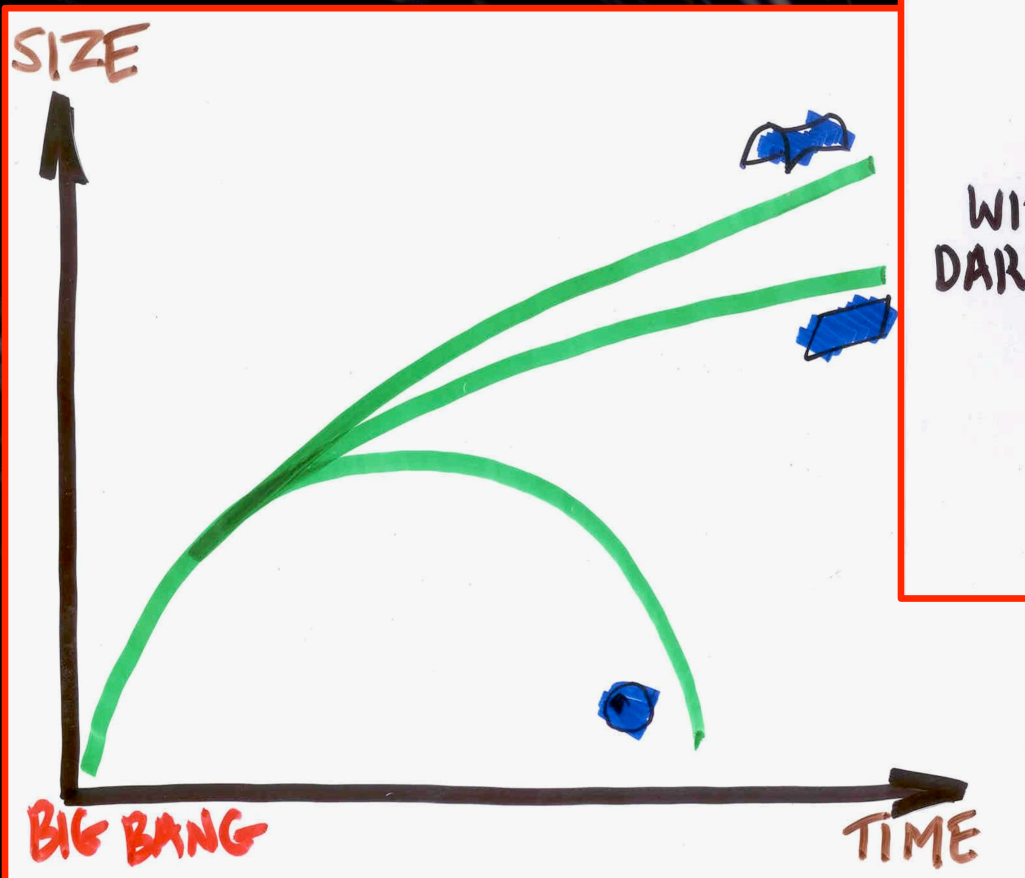
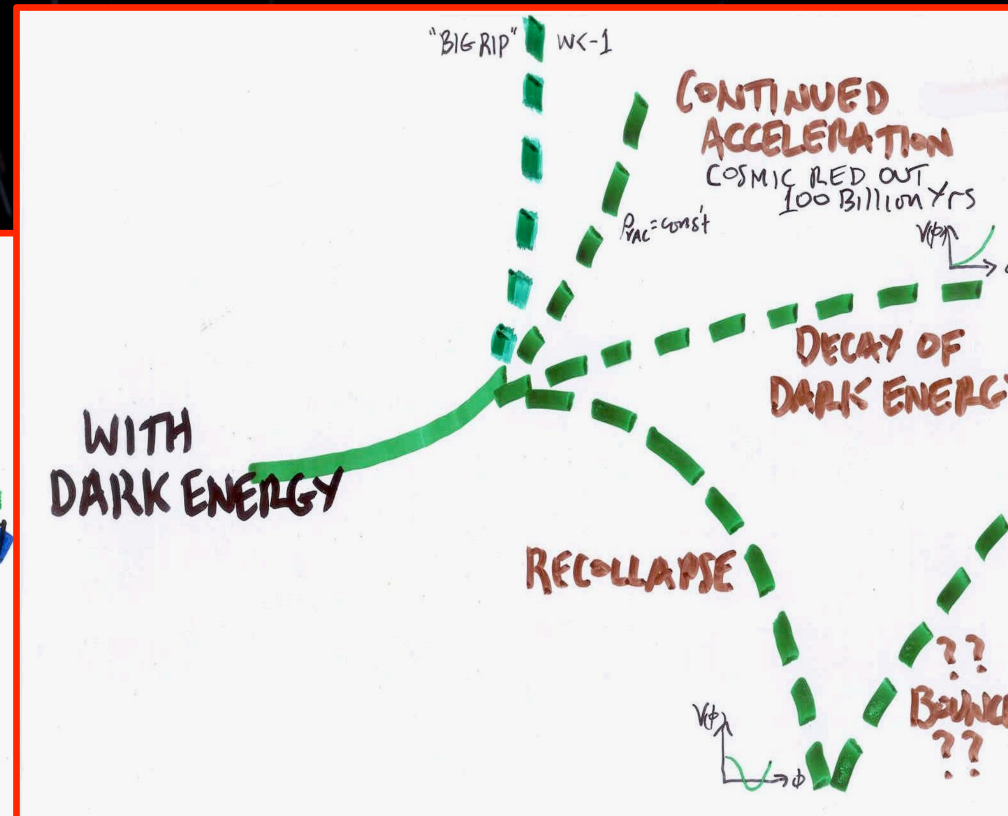

THE BIG PICTURE
INFLATION
THE BEGINNING
HOT BIG
BANG
COSMIC ACCEL.
BARYONS
DARK ENERGY
NEUTRINOS
COLD DARK MATTER
OUR UNIVERSE

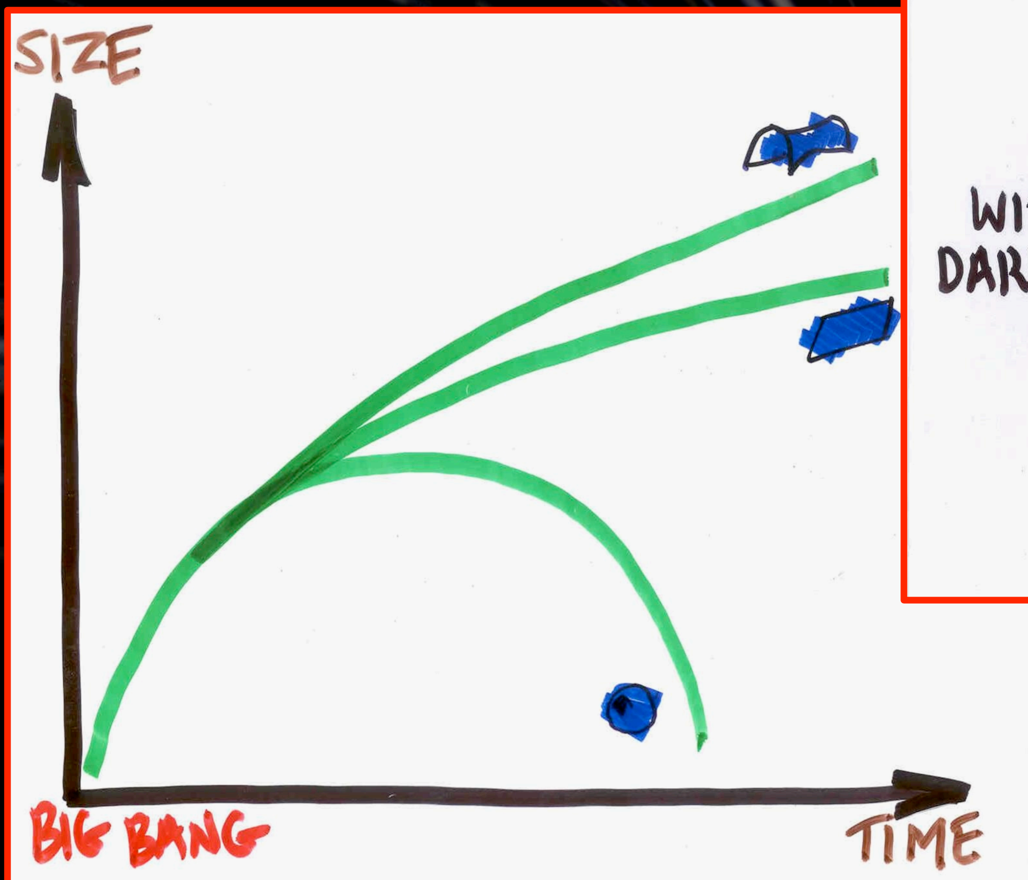

From Here to Eternity

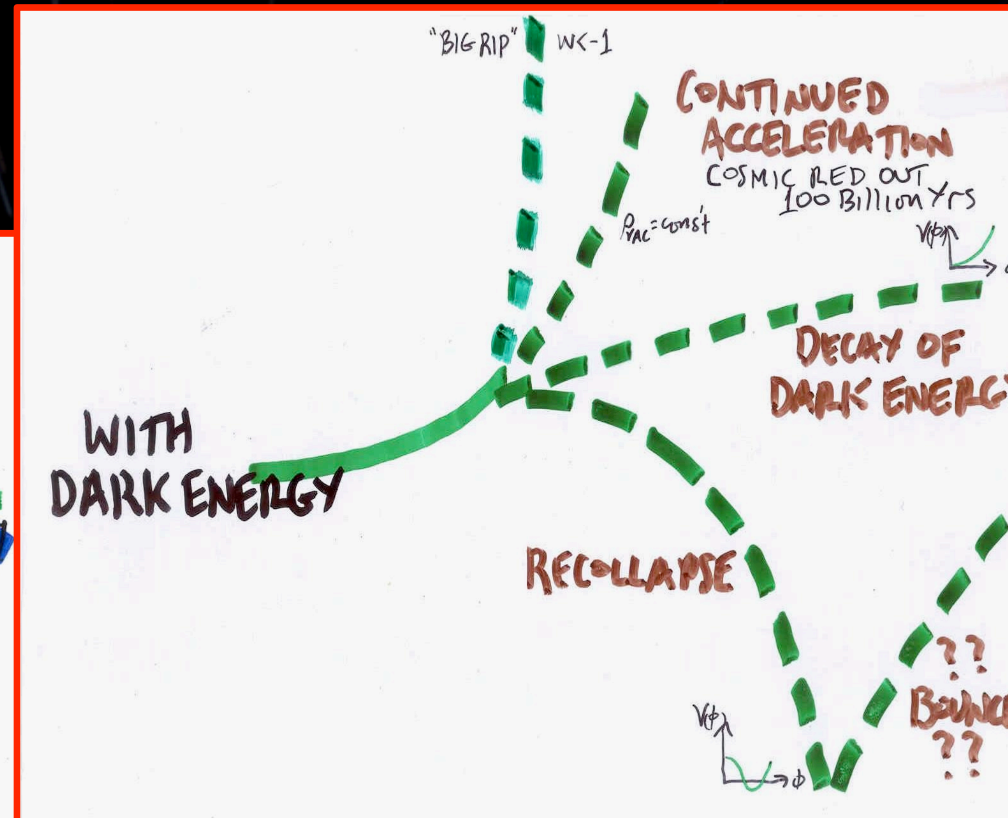

SIZE
BIG BANG
TIME


SIZE
BIG BANG
TIME


"BIG RIP" w<-1
CONTINUED ACCELERATION
COSMIC RED OUT
100 Billion Yrs
WITH DARK ENERGY
DECAY OF DARK ENERGY
RECOLLAPSE
?? BOUNCE ??

In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!





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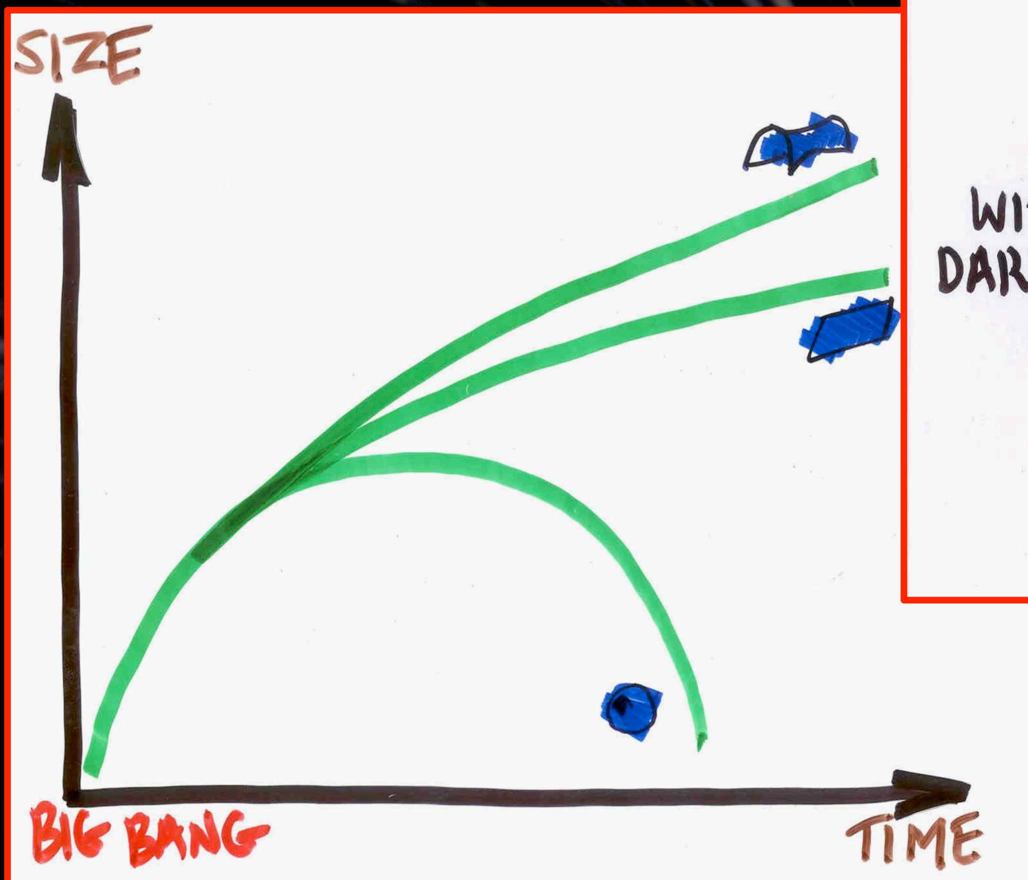
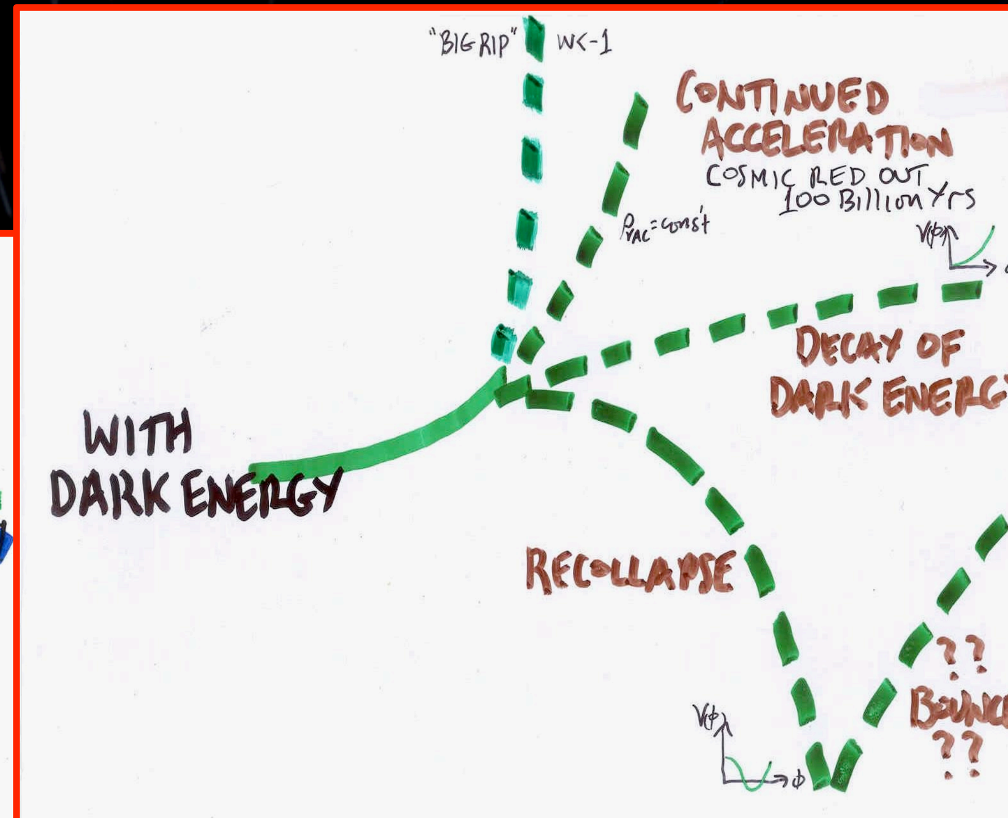
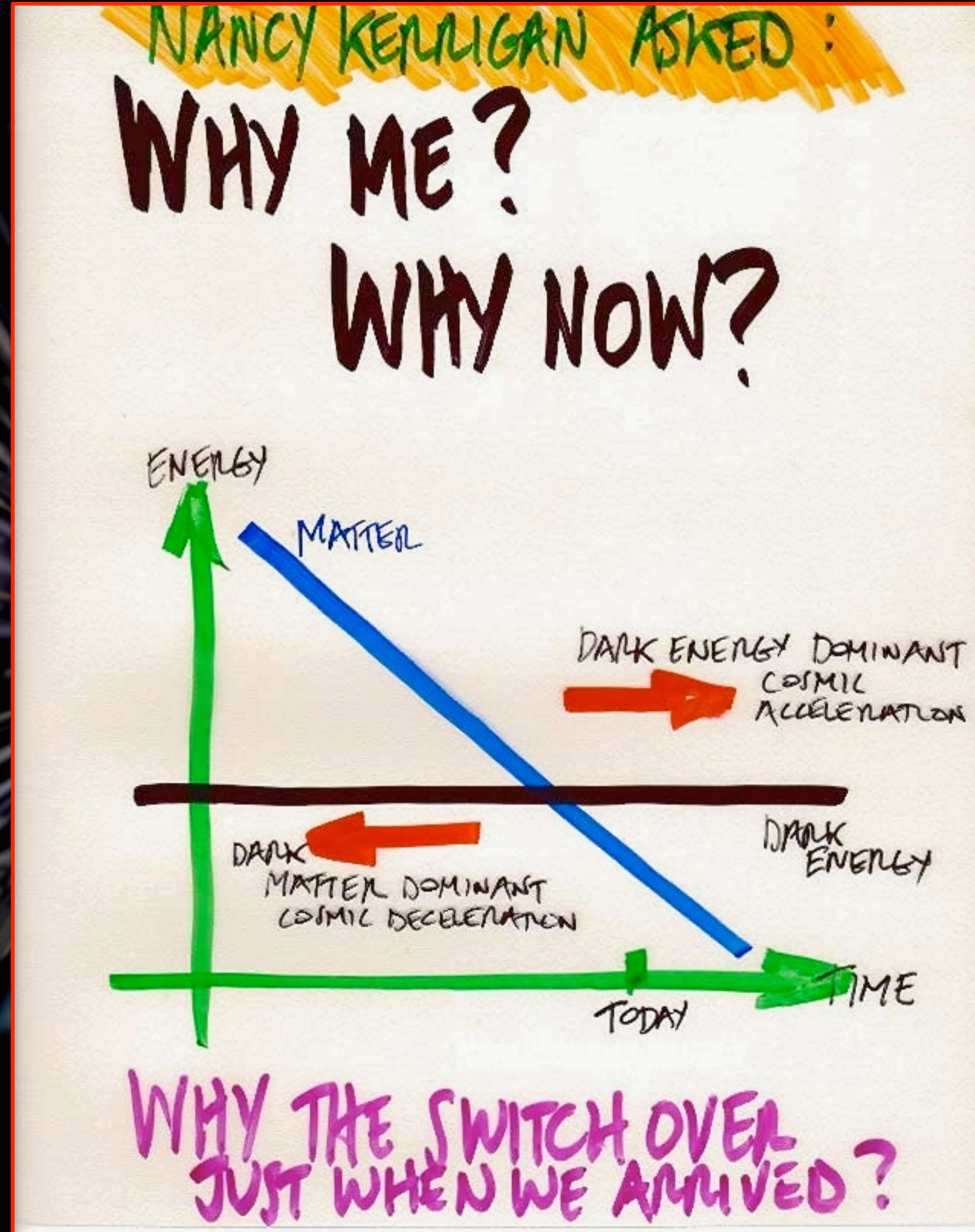
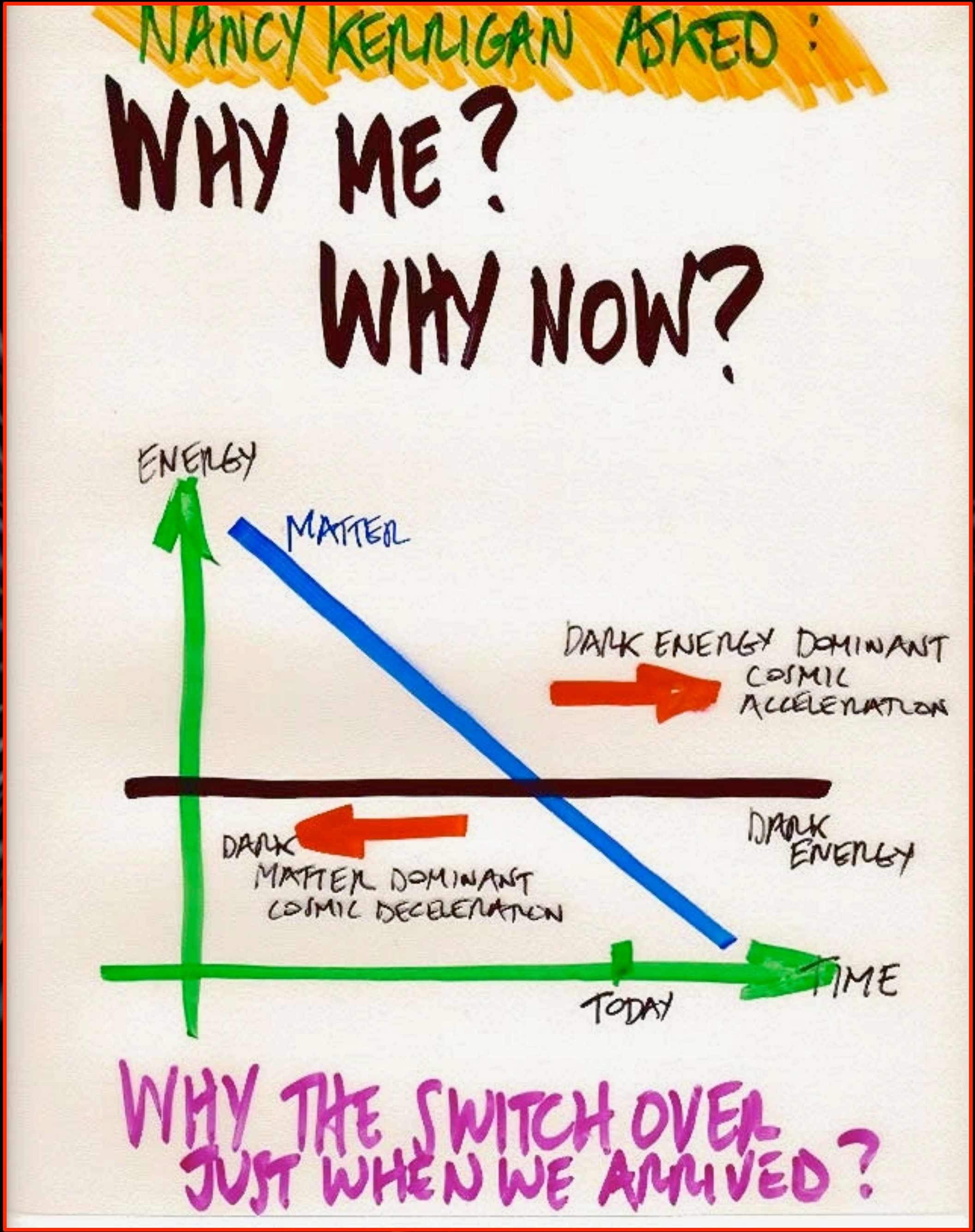




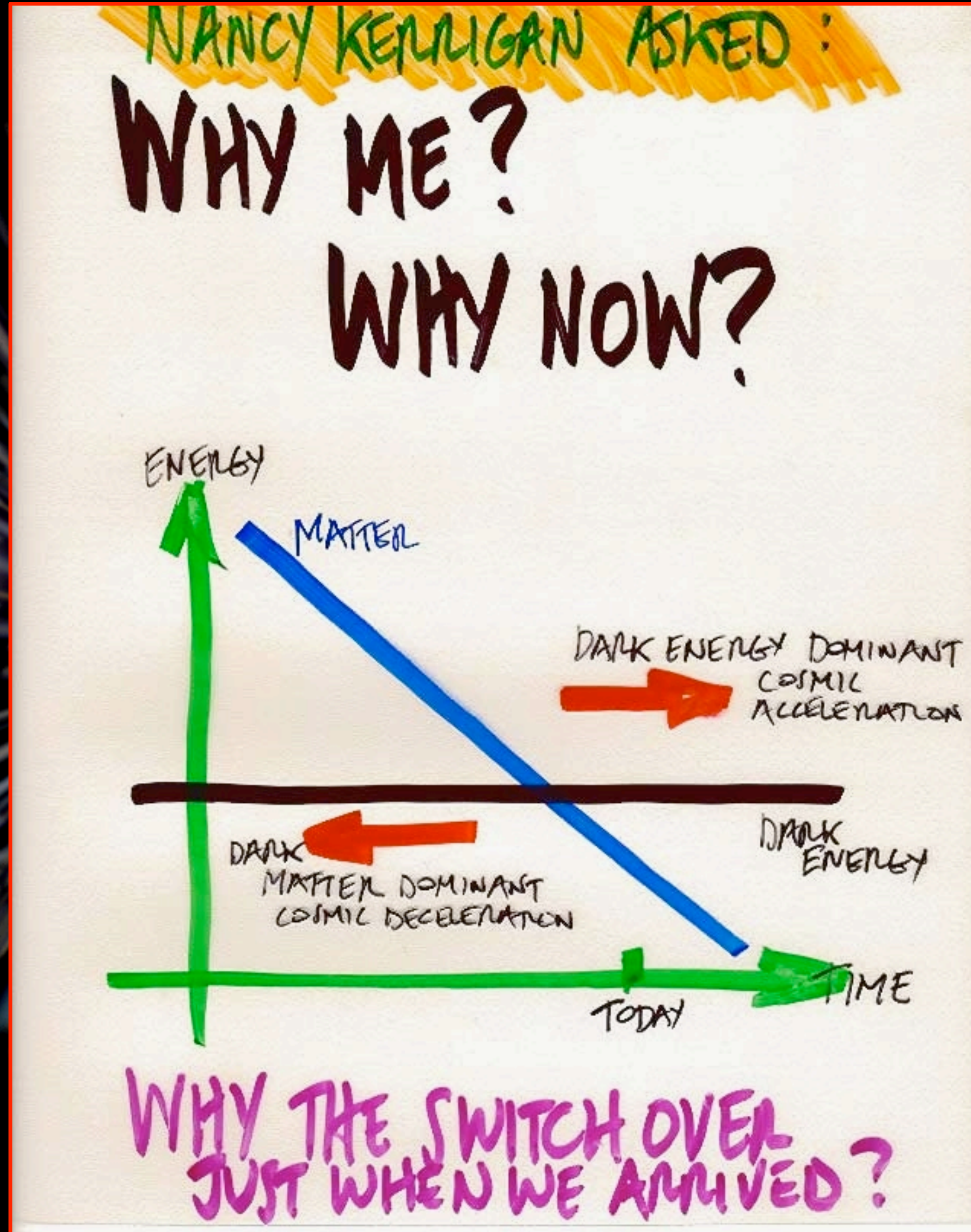
Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!


NANCY KERRIGAN ASKED:
WHY ME?
WHY NOW?
ENERGY
MATTER
DARK ENERGY DOMINANT
COSMIC
ACCELERATION
DARK
ENERGY
DARK
MATTER DOMINANT
COSMIC DECELERATION
TODAY
TIME
WHY THE SWITCH OVER
JUST WHEN WE ARRIVED?

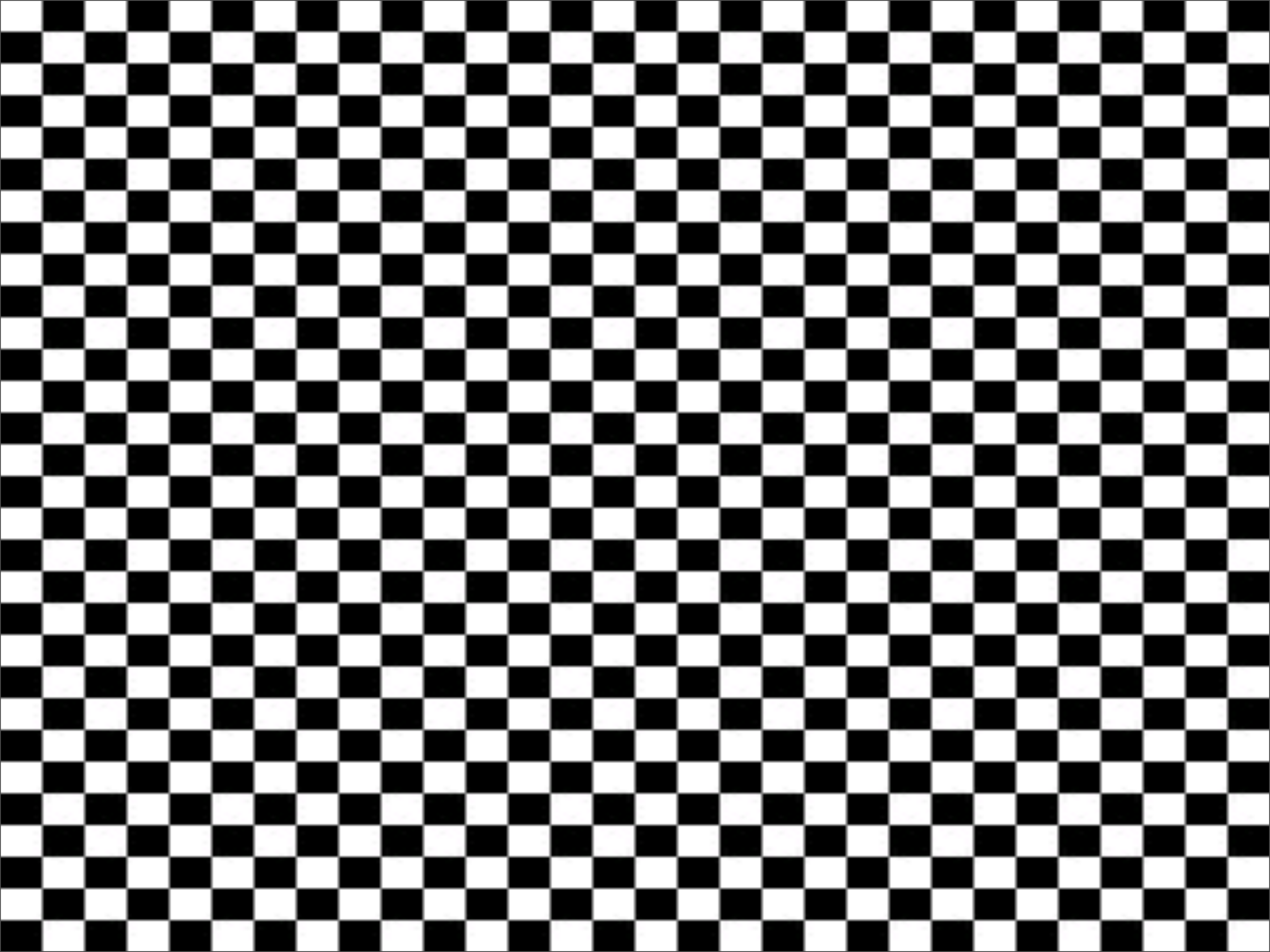
Important clue
or
coincidence?

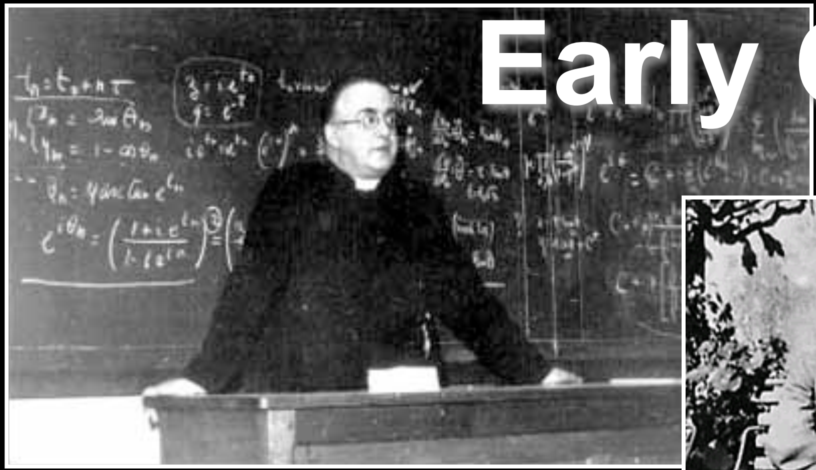


At the very least, we can now say that cosmology is the battle between two dark titans

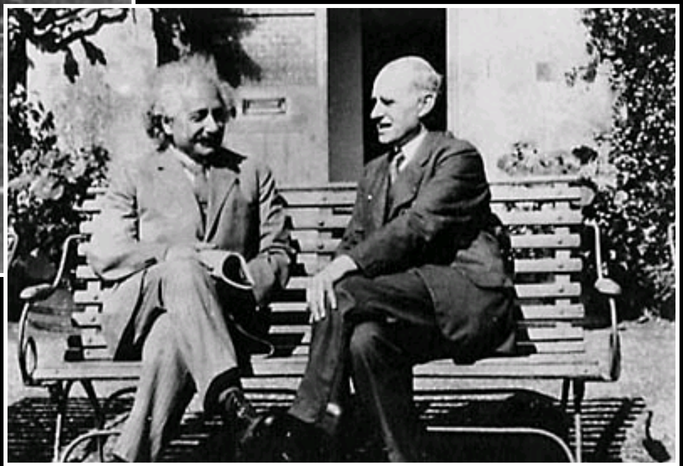


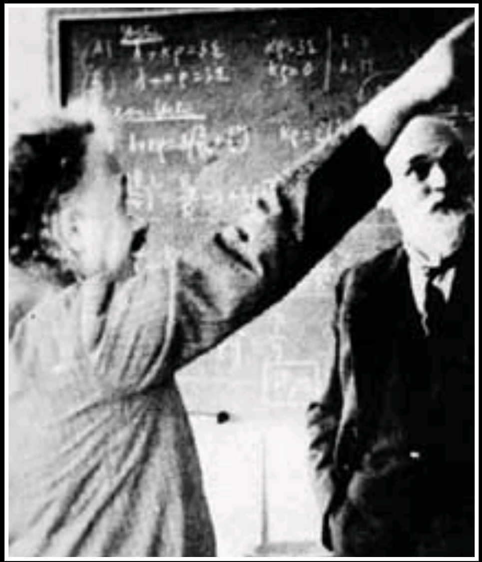
Λ’s Checkered History





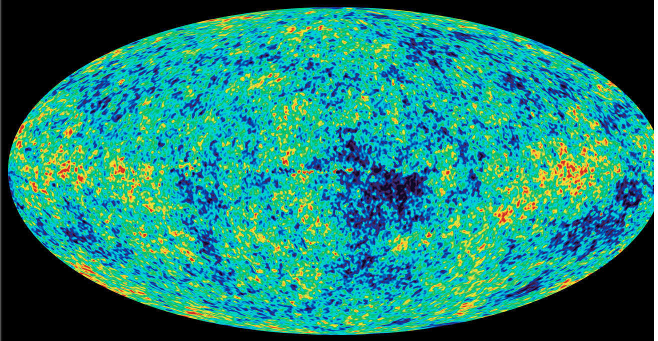
Early Confusion

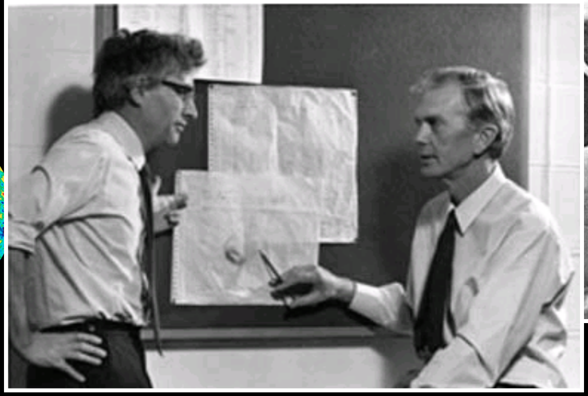




- **1917 – 1929**
  - **Einstein: static, finite, positively curved Universe $\rho_M = 2\rho_\Lambda$, $R = 1/(4\pi G\,\rho_M)^{1/2}$**
  - **de Sitter (1917): vacuum solution, first derivation of Hubble's Law**
  - **Eddington-Lemaitre long lived cosmologies**
  - **Hubble discovers expansion**
  - **Einstein: "my greatest blunder"**
  - **Eddington remains obsessed**

Revivals

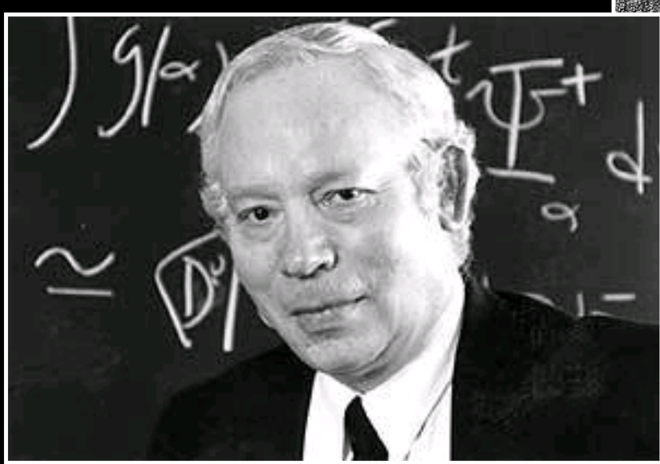


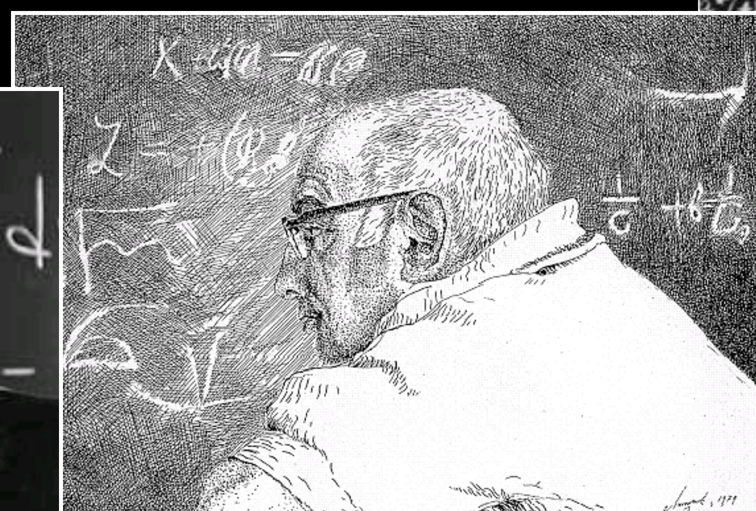


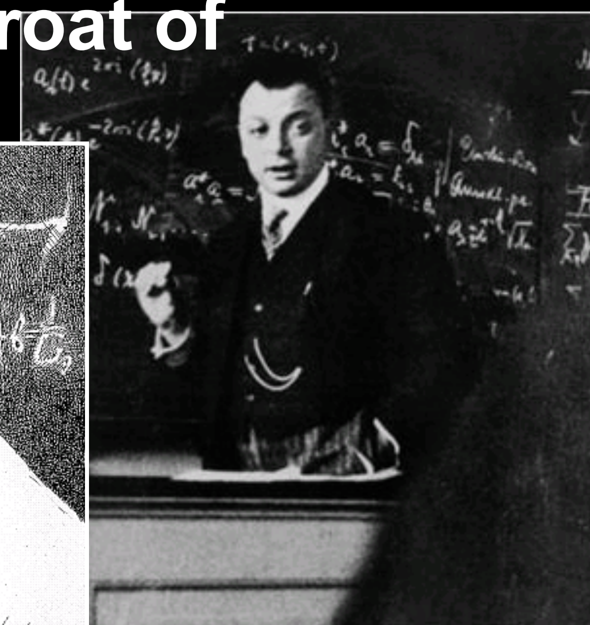
- 1948 – 1970
  - Bondi & Gold, Hoyle: Steady State Cosmology: “perfect cosmology”
  - Strong signs of evolution: quasars, radio sources and CMB kills a beautiful theory
  - Petrosian, Salpeter & Szekeres (abudnace of z ~ 2 QSOs) and Gunn & Tinsley (data)
  - Rise of Standard Cosmology (Hot Big Bang)

Quantum Vacuum Energy: Most Embarrassing Problem in all of Physics

- 1930s: Pauli, “Size of Universe could not reach to the moon”
- 1968: Zel’dovich articulates the problem
- 1989: Weinberg, “Bone in the throat of theorists”







Most Anticipated Surprise Ever

- 1981 – 1984: Inflation & CDM
- 1984 on – "Ω problem"
- 1984 – 1995: Λ solution, best fit Universe, COBE and $\Omega_M \sim 0.3$ & triumph of ΛCDM
- 1998: The Accelerating Universe
- 1998: Cosmology Solved Debate
- 1998: Birth of Dark Energy and a new puzzle

Rapid acceptance
it is the missing piece of the puzzle

EVIDENCE for DARK MATTER

ITS GRAVITY IS:

NEEDED TO HOLD GALAXIES TOGETHER

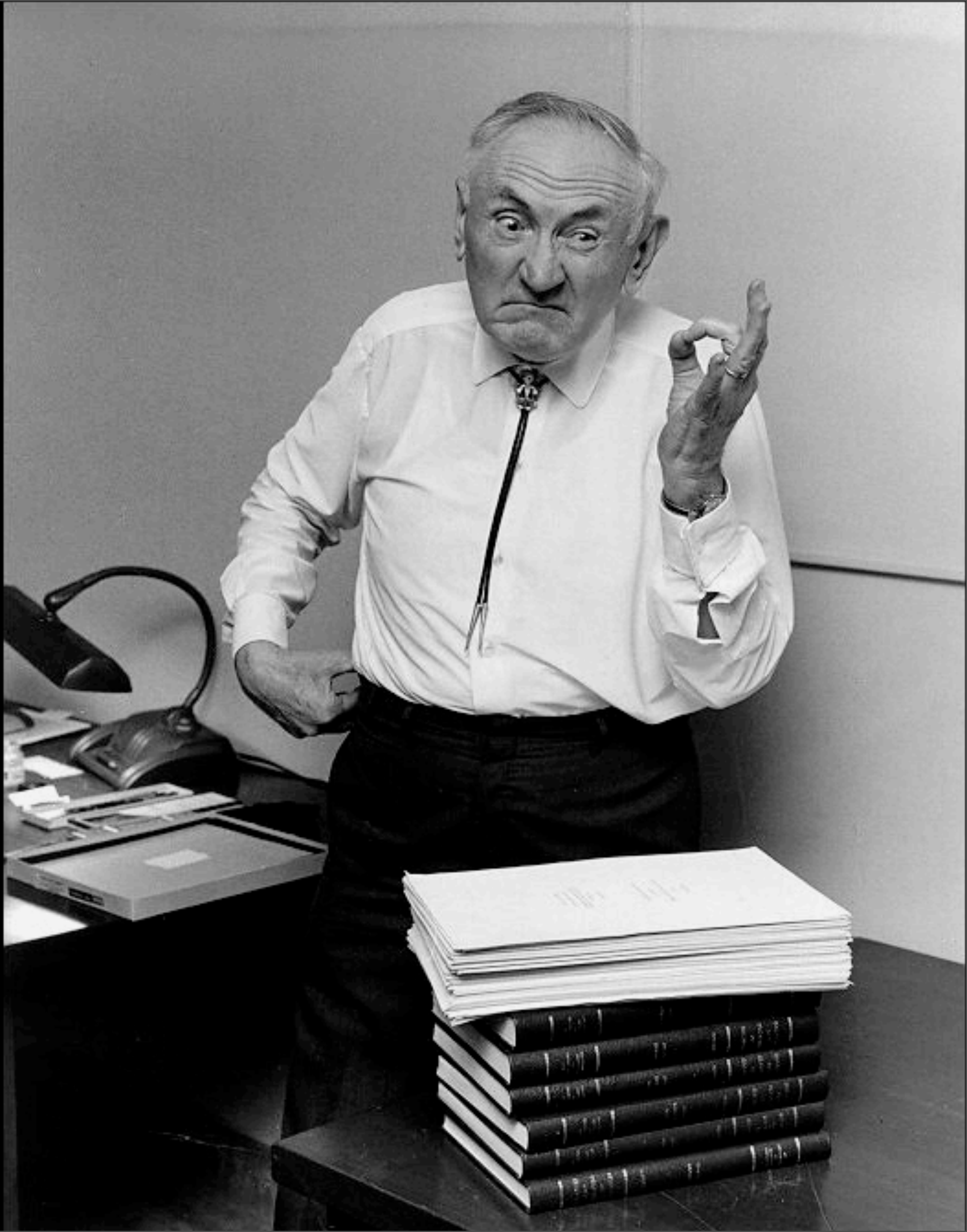
V. RUBIN ET AL '70s.

NEEDED TO HOLD CLUSTERS TOGETHER

ZWICKY '35

Fritz Zwicky

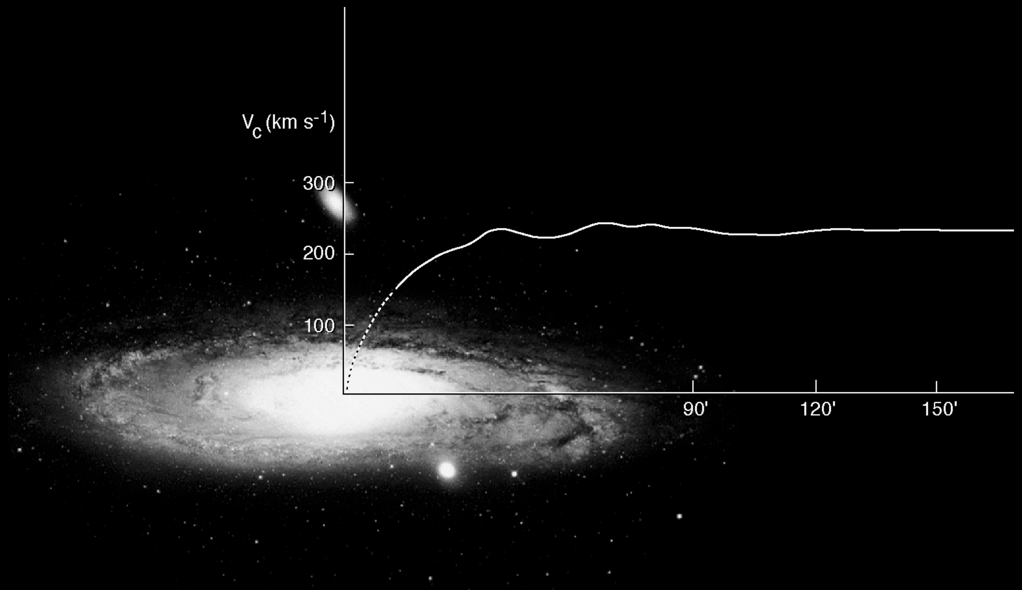
Discoverer of the Dark Side circa 1935



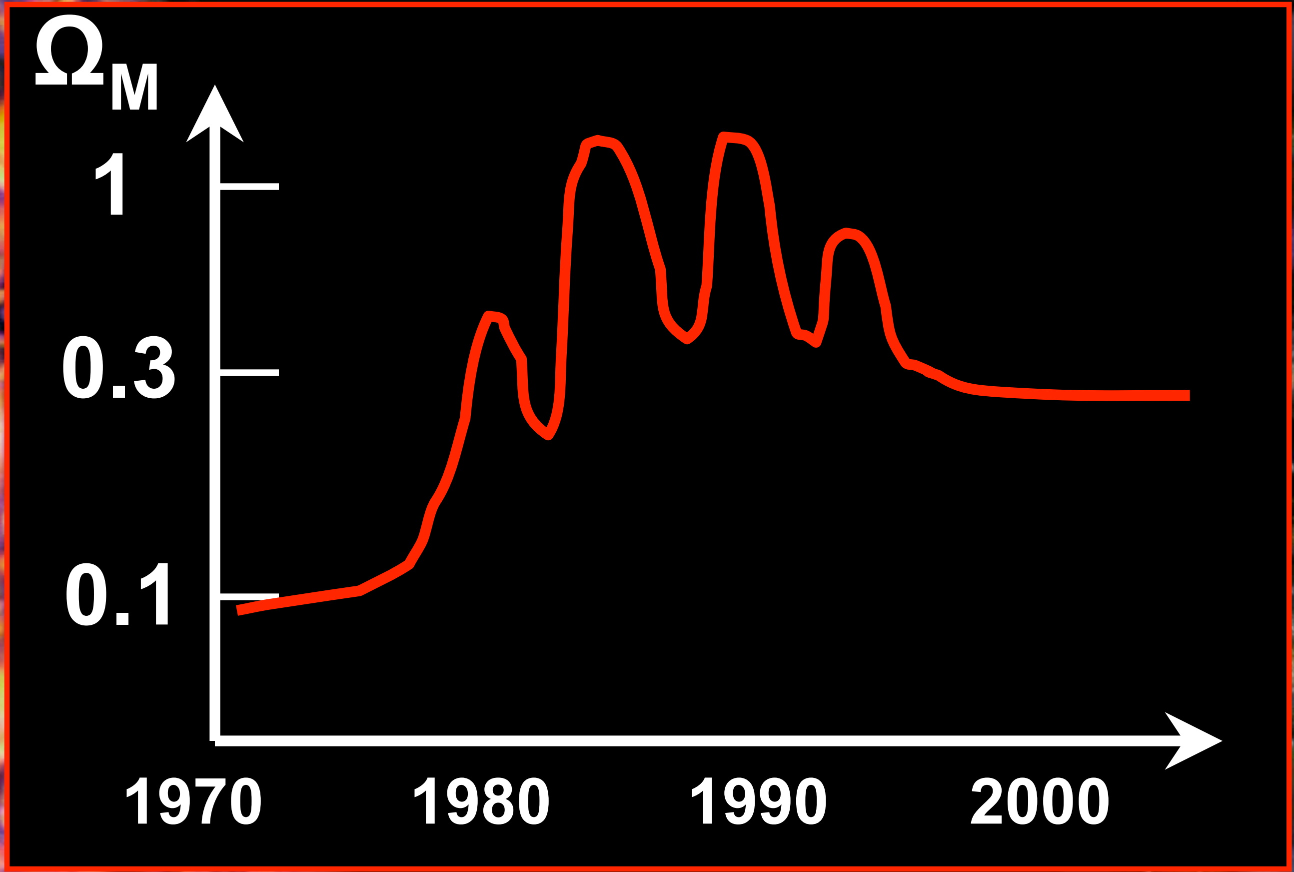
Hercules

Vera Rubin and Flat Rotation Curves

Dark Matter Close to Home



The Rise and Fall of Omega



- 1970s: Mass-to-light ratios on limited parts of the galaxy
- 1980s: Peculiar velocity measurements probe larger regions
- 1990s: Cluster fair sample, LSS, peculiar flows
- 2000s: CMB, LSS, BAO, clusters