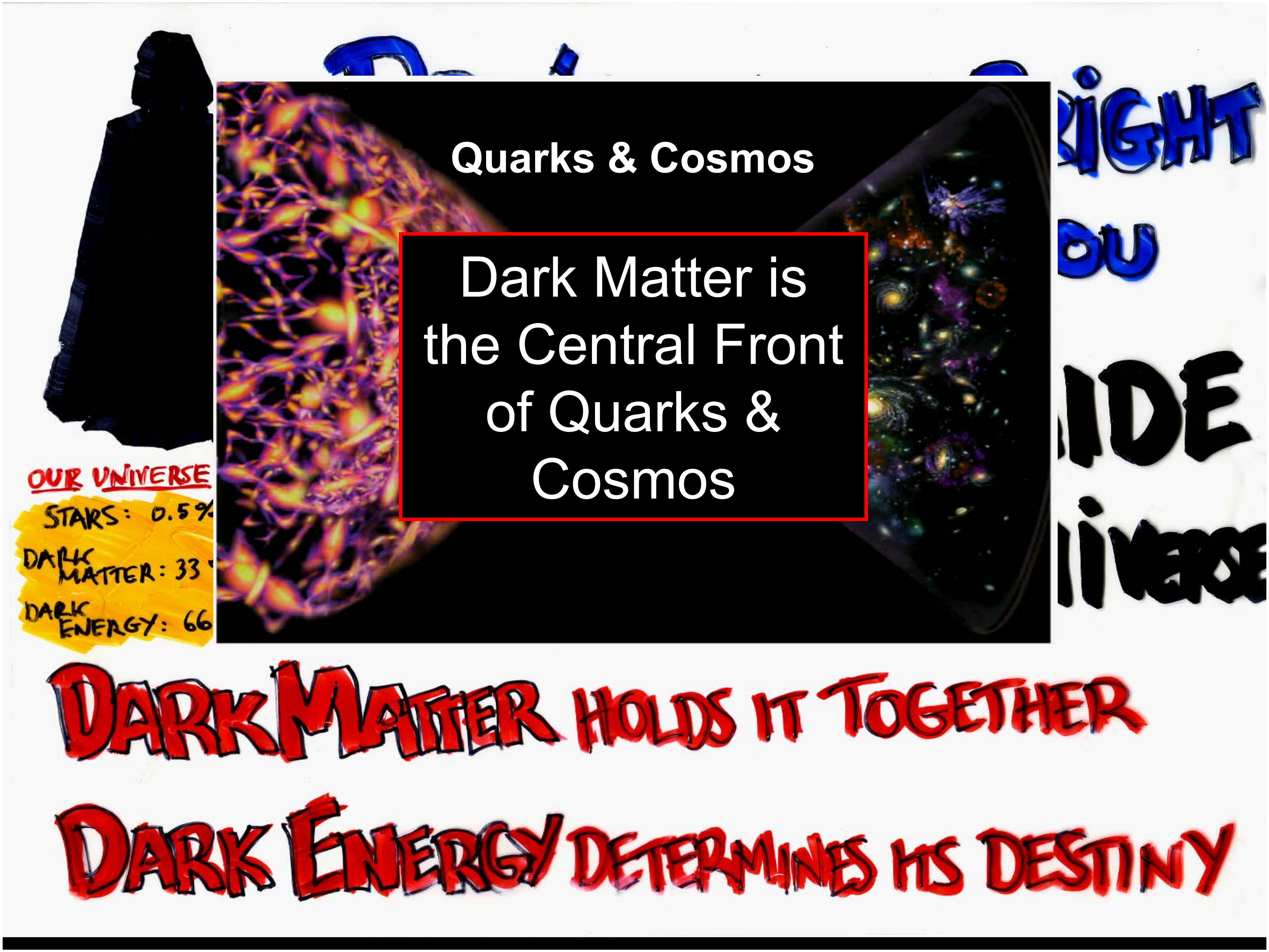
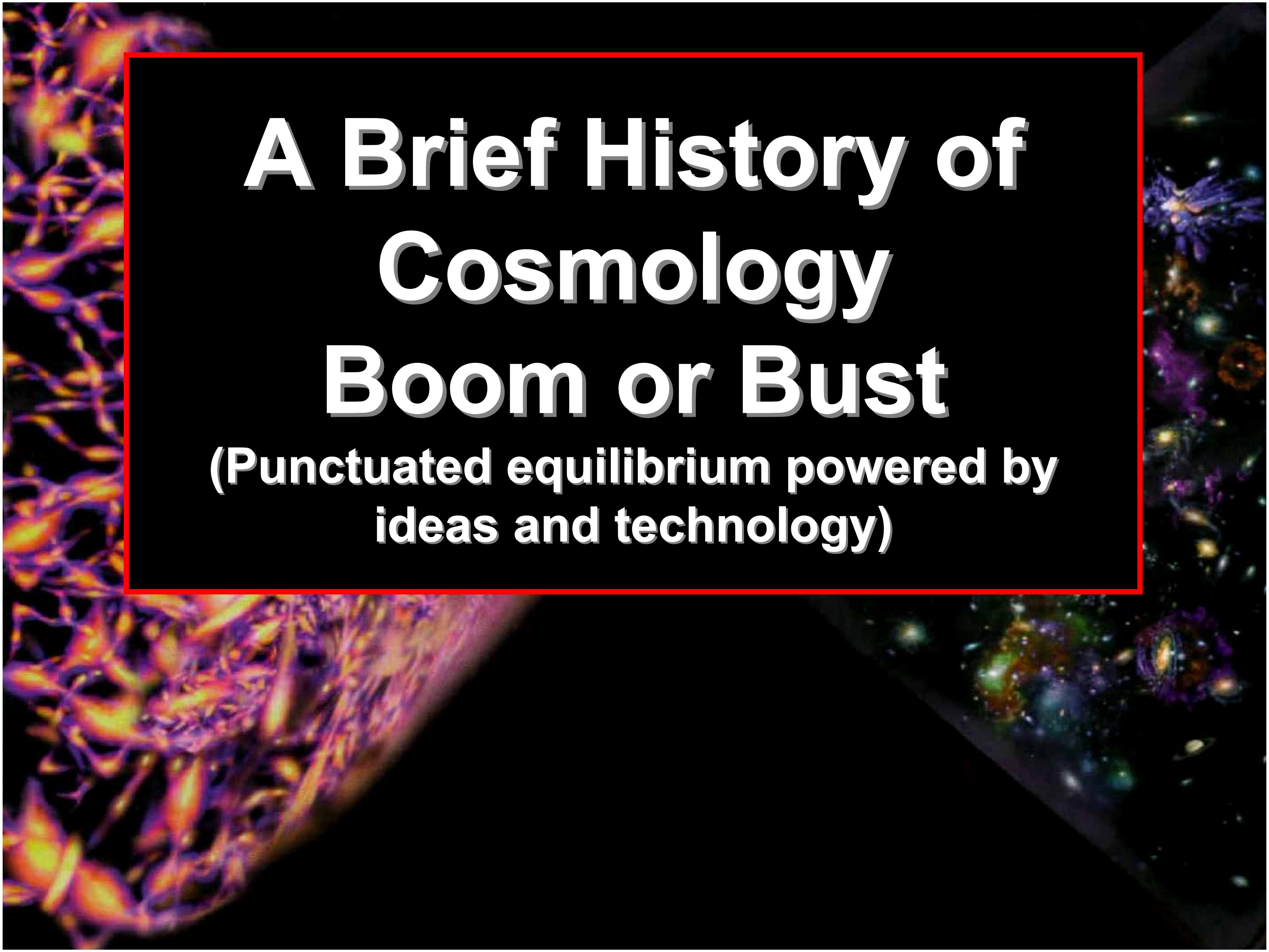
The Dark Matter Puzzle: On the Home Stretch

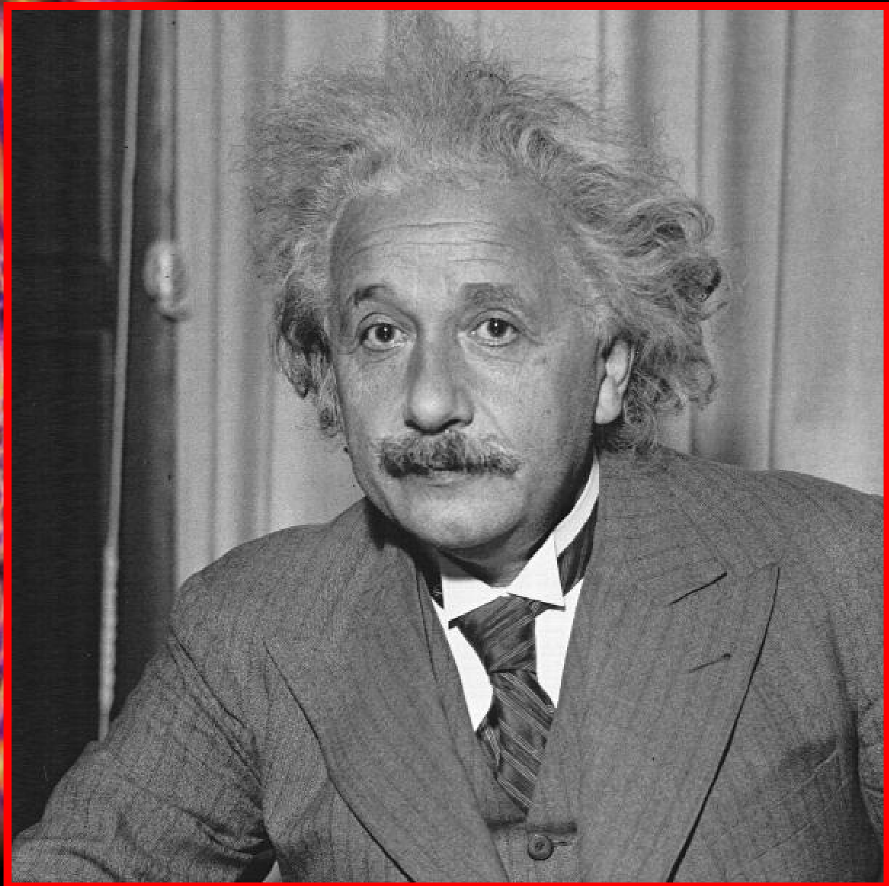
10 August 2007

Michael S. Turner
Kavli Institute for Cosmological Physics
The University of Chicago


Quarks & Cosmos
Dark Matter is the Central Front of Quarks & Cosmos
OUR UNIVERSE
STARS: 0.5%
DARK MATTER: 33
DARK ENERGY: 66
DARK MATTER HOLDS IT TOGETHER
DARK ENERGY DETERMINES ITS DESTINY


A Brief History of
Cosmology
Boom or Bust
(Punctuated equilibrium powered by
ideas and technology)

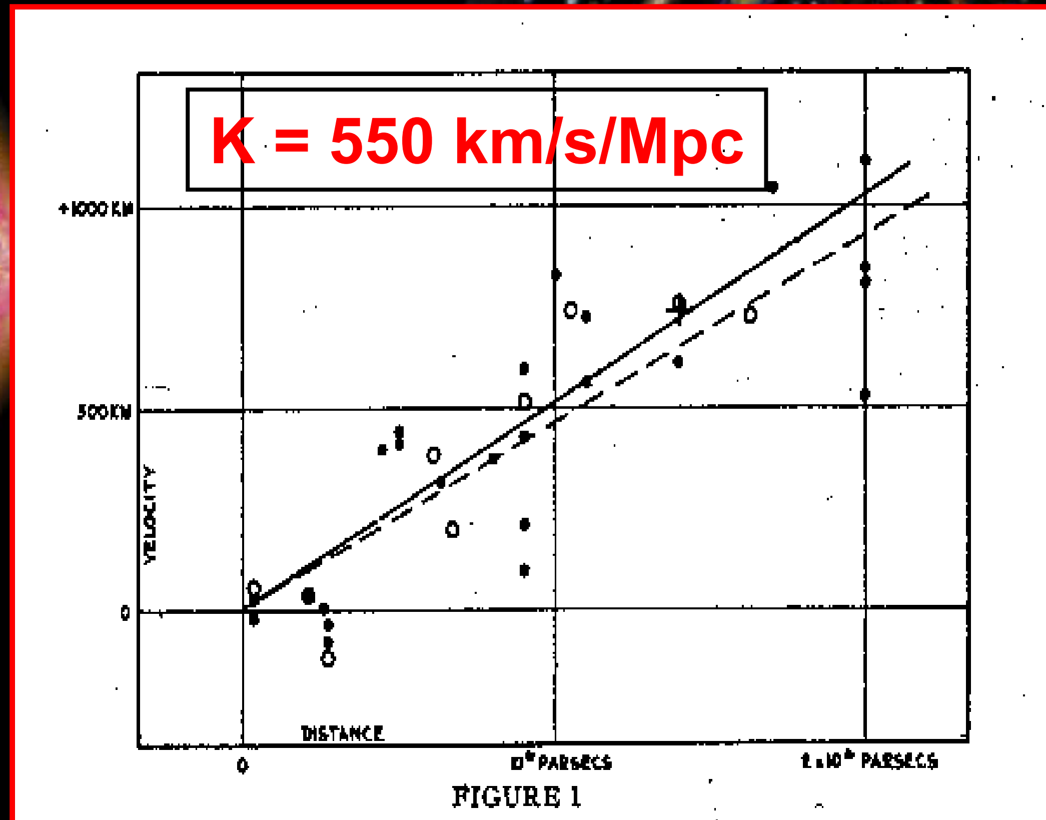
1916-1918: General Relativity & Λ



PS: Never mind on Λ

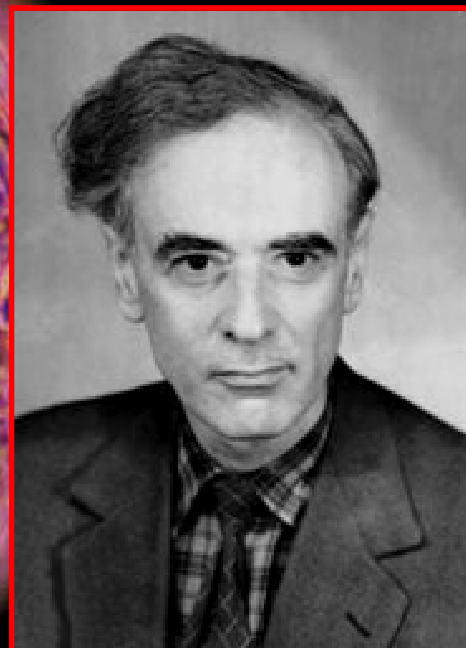
Just One Number K (H_0)

(error bars not needed, velocity in km)



Hubble & Humanson: few 100 galaxies, z < 0.1

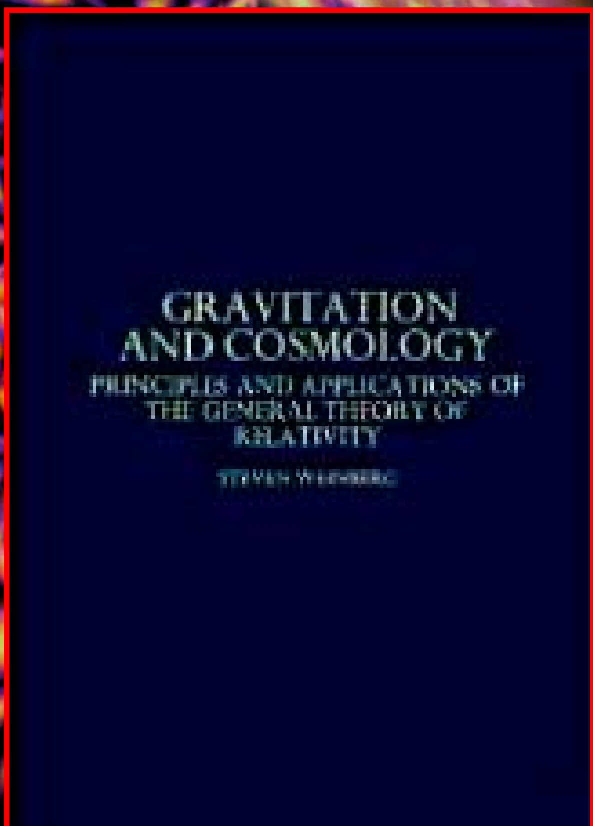
Landau on Cosmologists



Often in Error, Never in Doubt!

Cosmology: The Search for Two Numbers … Sandage 1970

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



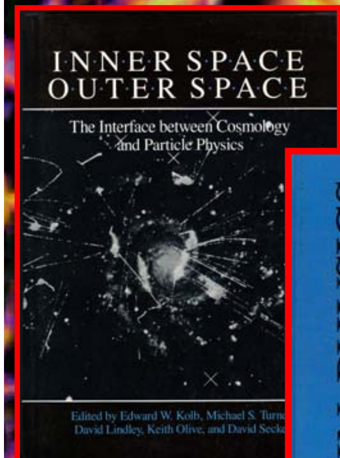
"Reality (physics) Based"

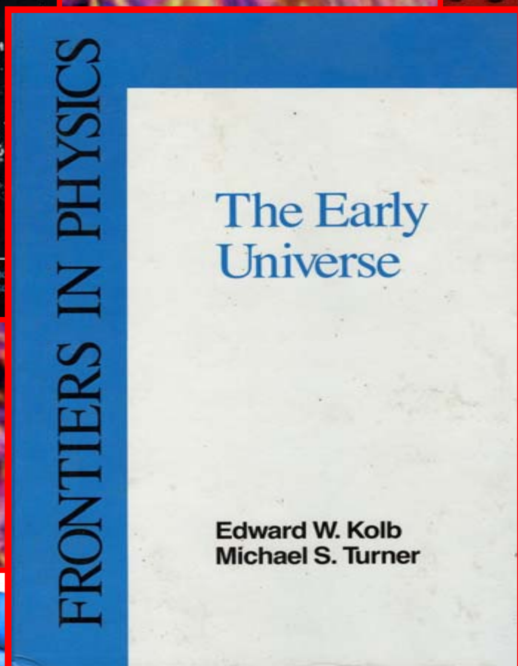
- BBN (nuclear physics)
- CMB (atomic physics)
- Structure Formation (grav. physics)
- Begins at 0.01 sec
- $\Omega_0 \sim 0.1$ (baryons)

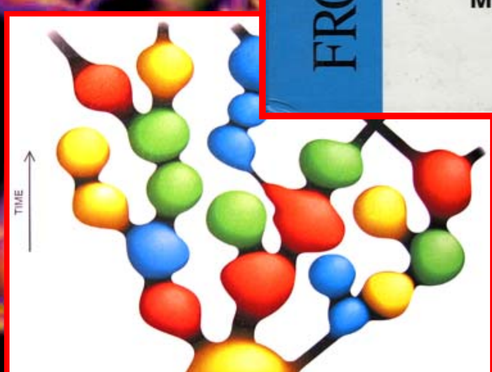
Big Questions

- "The naughts"
- Large entropy per baryon
- Flatness, Oldness
- Origin of density perturbations
- Λ problem

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



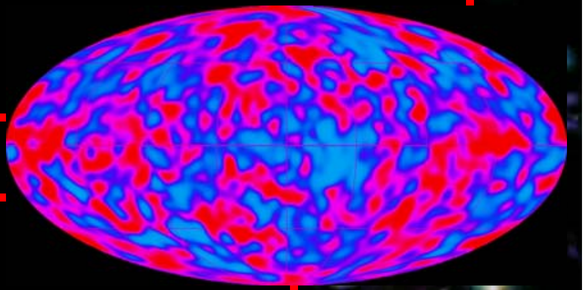




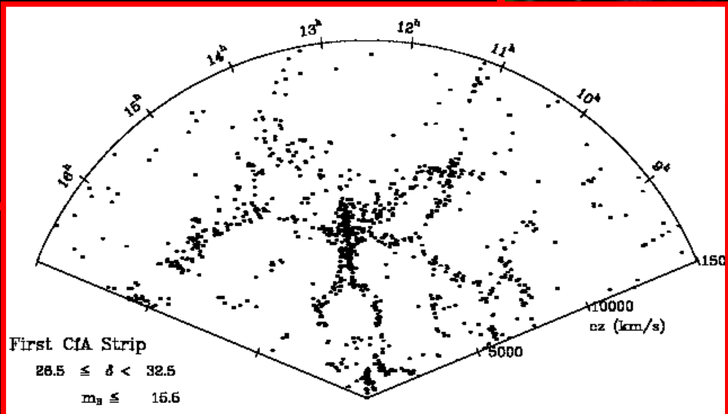
"Creativity Based"

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

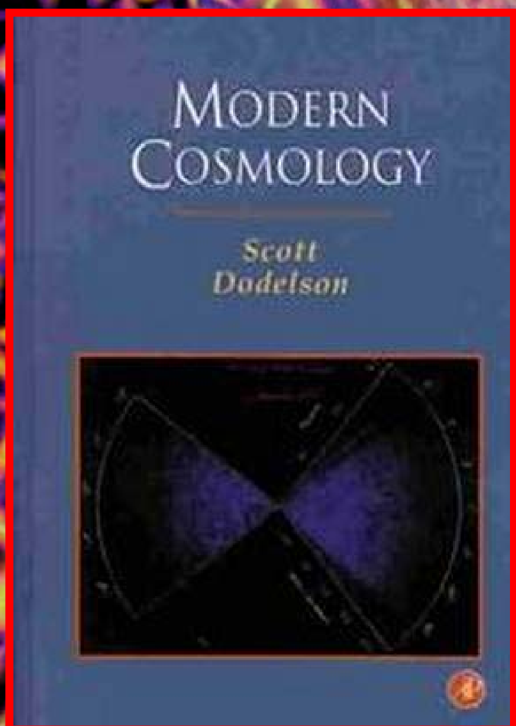
1990s: Beginning of Data-driven Cosmology



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



2000s: Era of Precision Cosmology



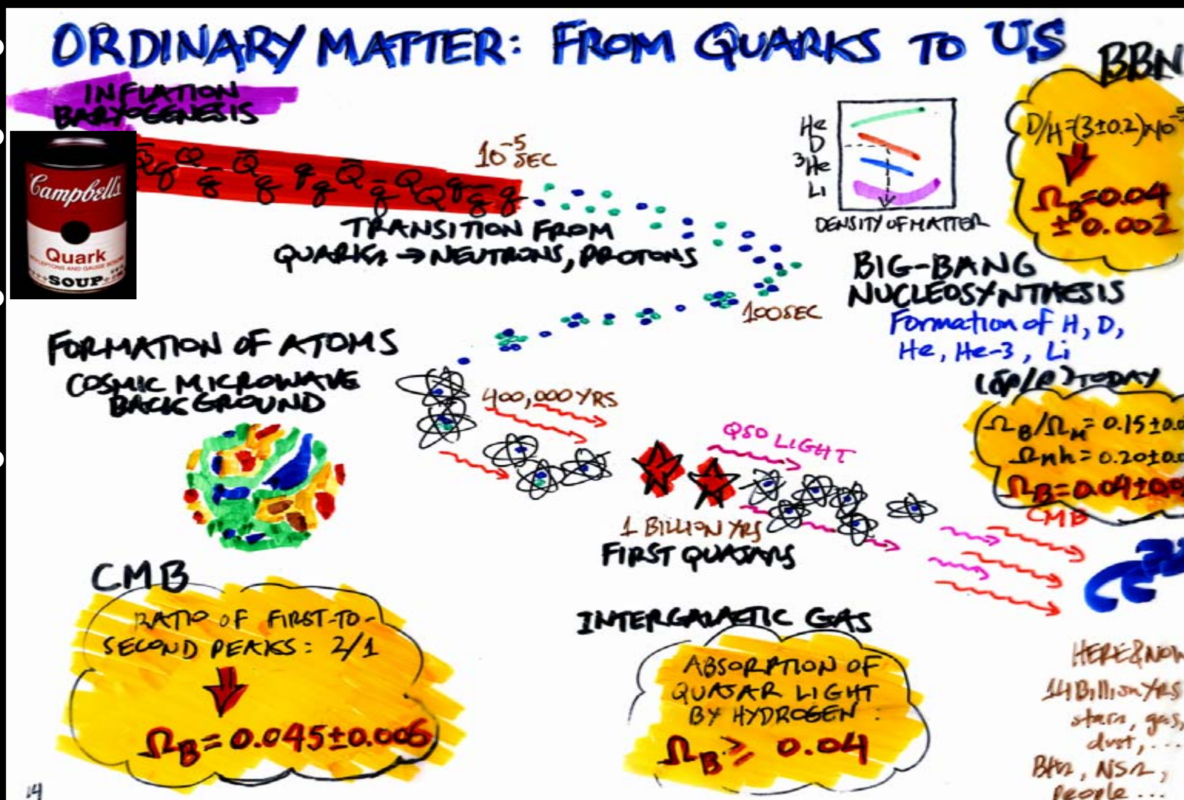
<u>"Fisher Based"</u>

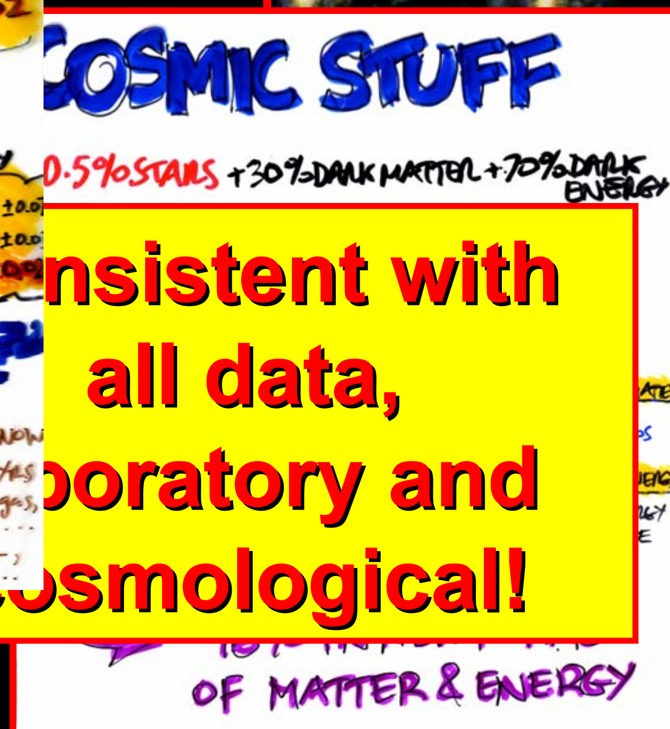
- Cosmological parameters
- Tests of inflation, CDM
- Correlating large, complex data sets
- Cosmological Consistency
- Physical parameters (e.g., neutrino mass)

"The New Cosmology"

(Concordance Cosmology)

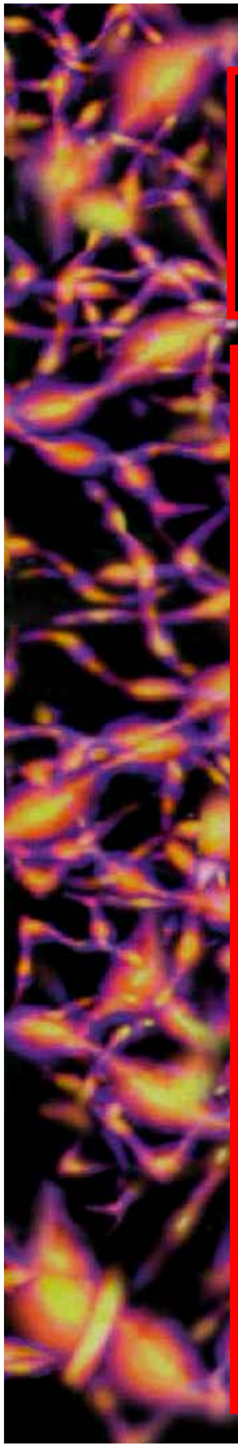
- Standard Hot Big Bang of the 1970s
-
- ...atter,
-
-





...nsistent with all data, ...boratory and ...cosmological!

- $H_0 = 73 \pm 2$ km/s/Mpc
- $t_0 = 13.7 \pm 0.2$ Gyr

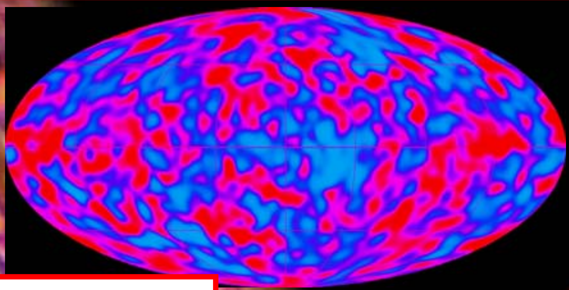


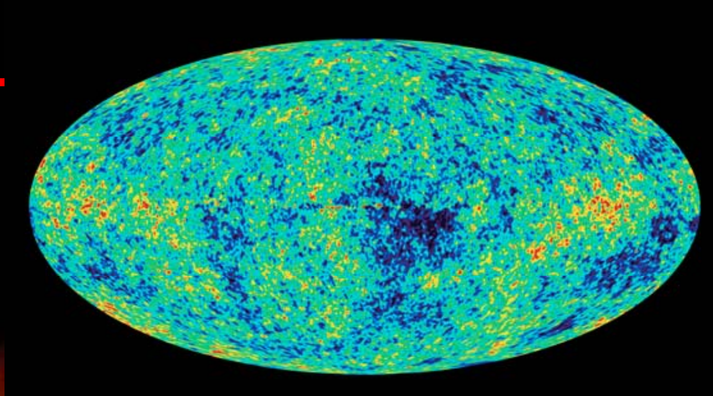
"The New Cosmology"

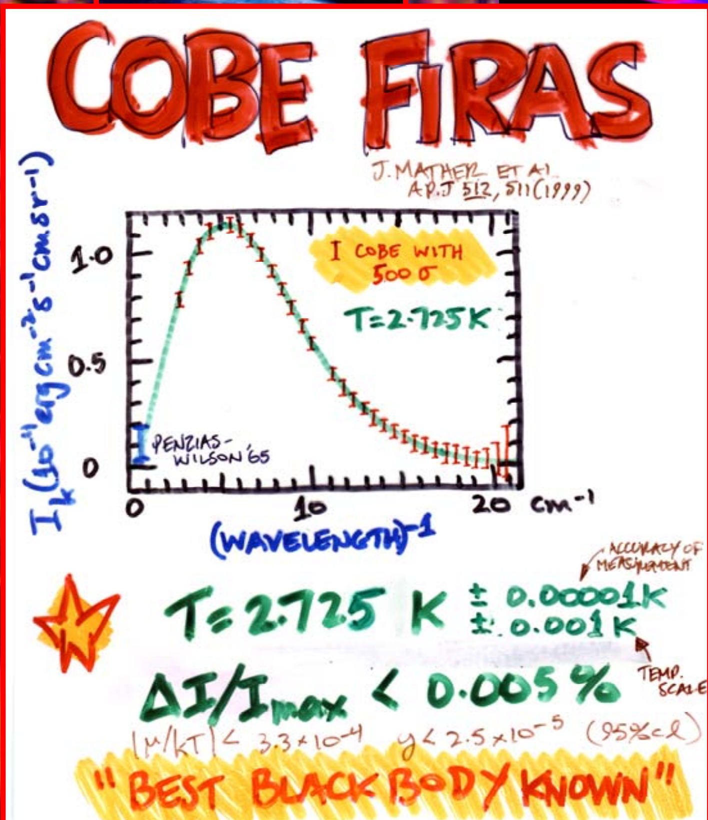
(Concordance Cosmology)

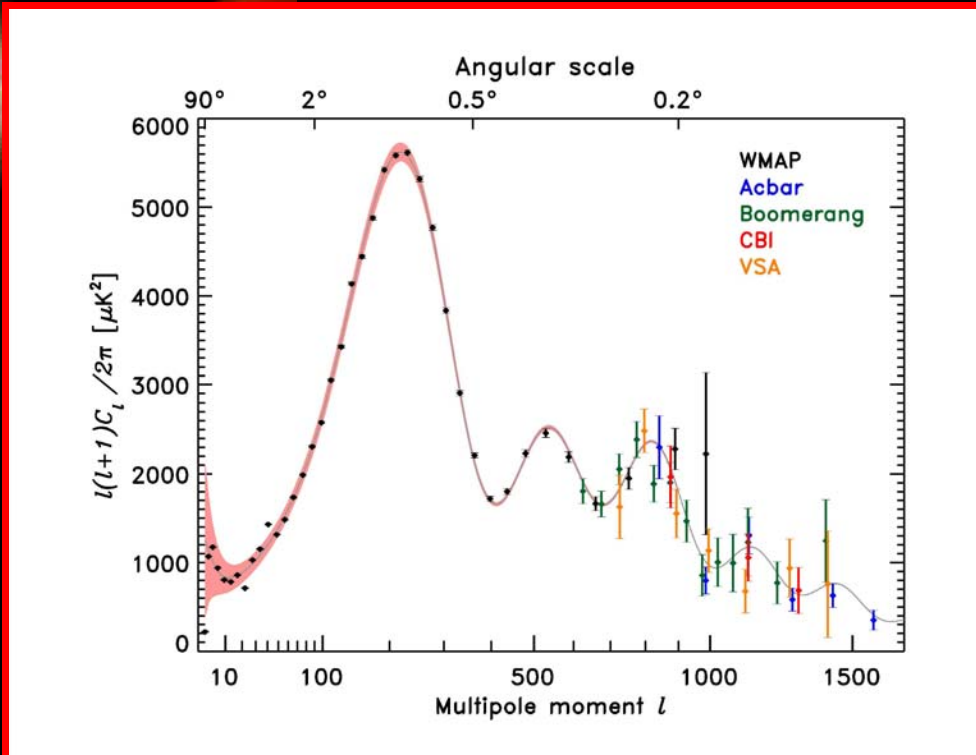
- Standard Hot Big Bang of the 1970s
- Flat, accelerating Universe
- Composed of: atoms, exotic dark matter, and dark energy
- Inflation knocking at the door (first strong evidence: CMB, LSS)
- Precision set of cosmological parameters
  - $\Omega_0 = 1.00 \pm 0.01$
  - $\Omega_M = 0.24 \pm 0.02$
  - $\Omega_B = 0.042 \pm 0.002$
  - $\Omega_\Lambda = 0.76 \pm 0.02$
  - $H_0 = 73 \pm 2$ km/s/Mpc
  - $t_0 = 13.7 \pm 0.2$ Gyr

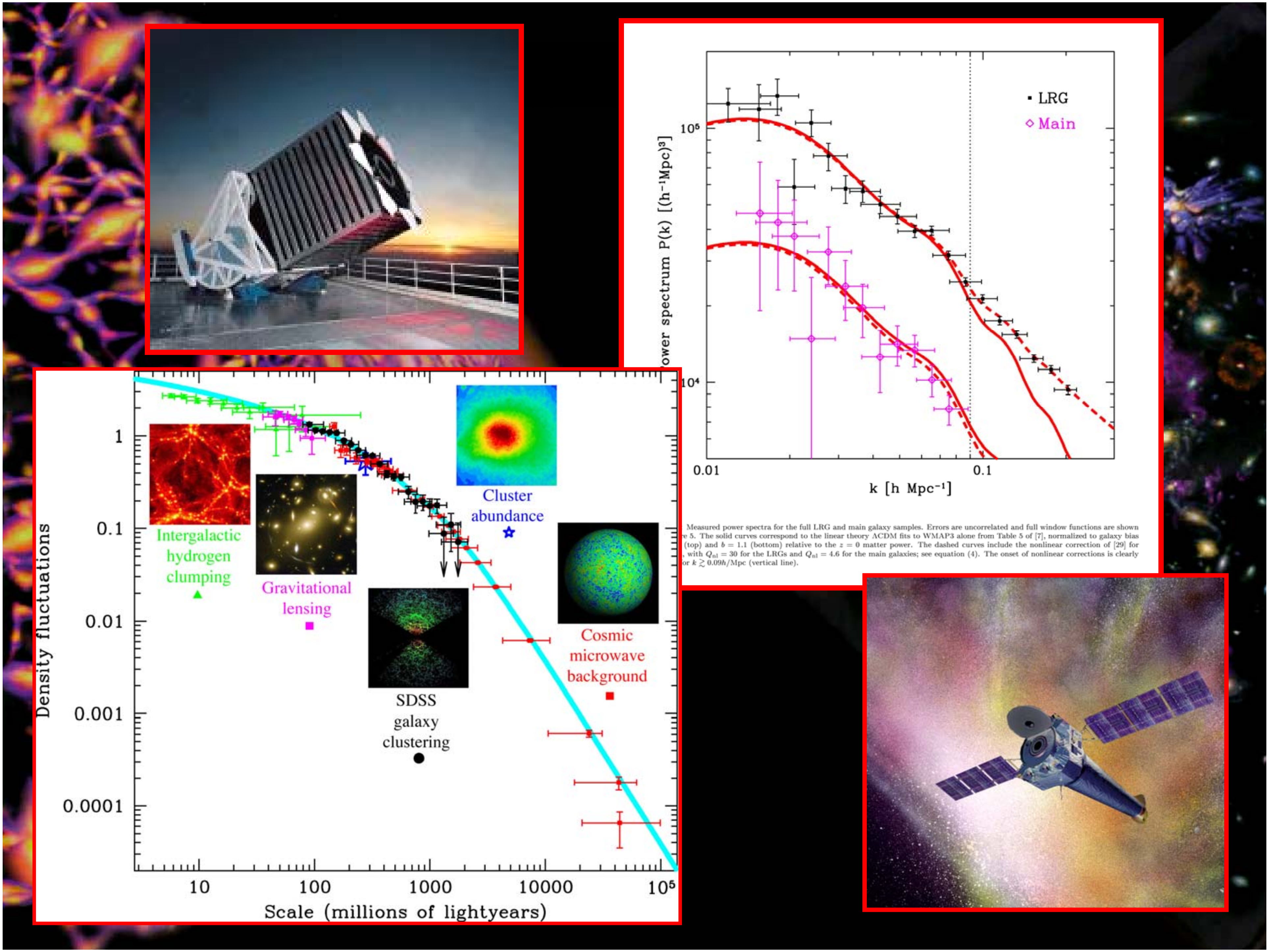
Precision ~~Cosmology~~ Science



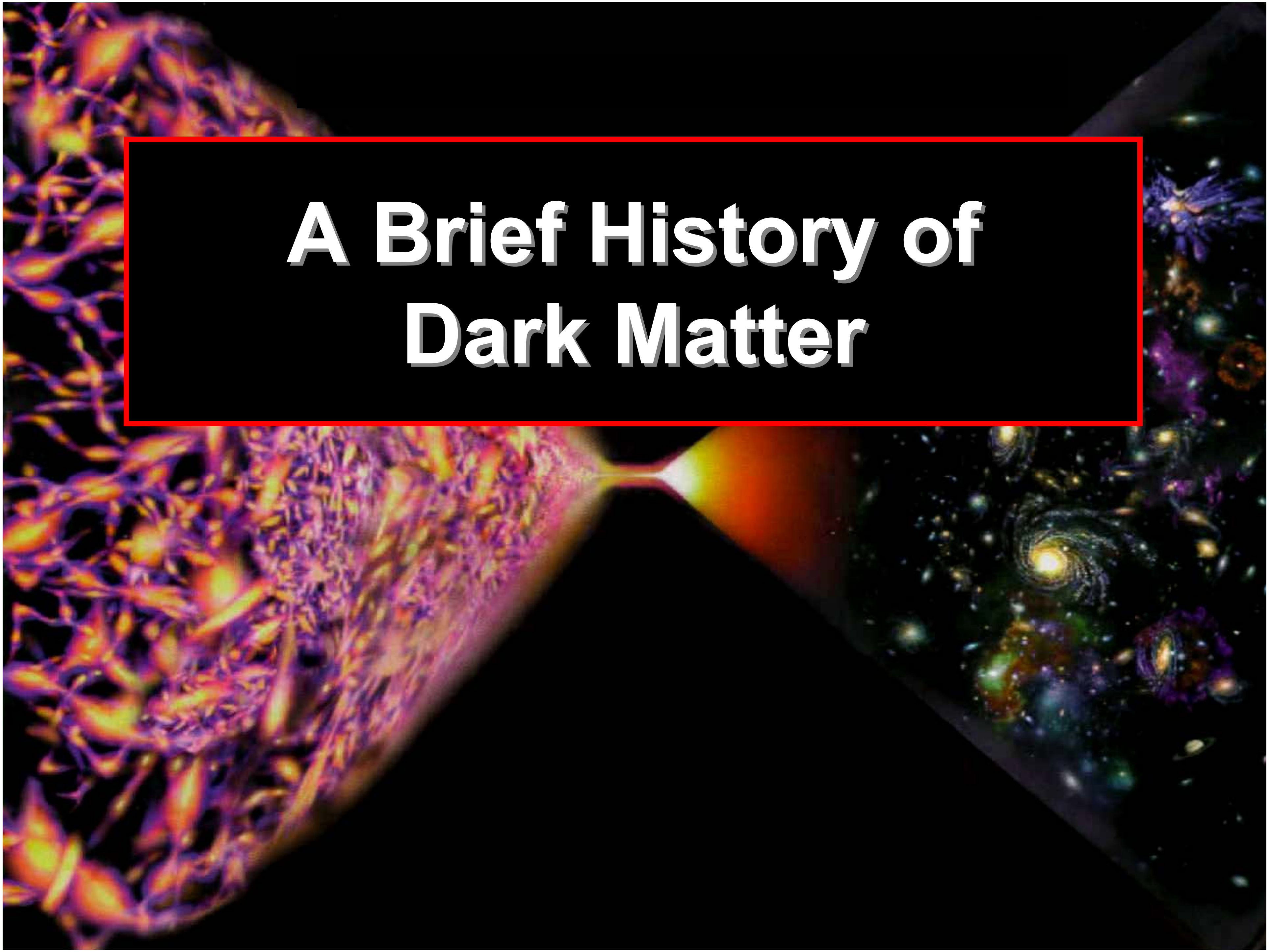




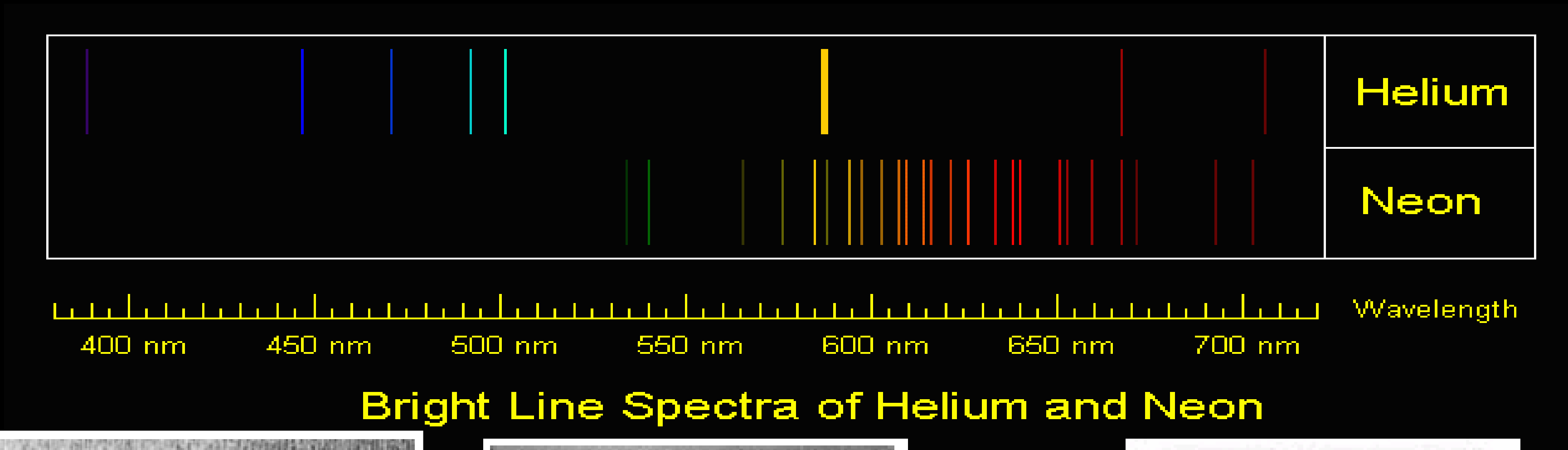


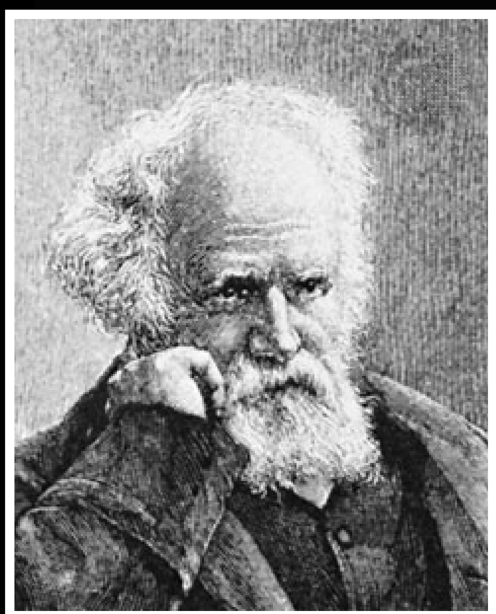


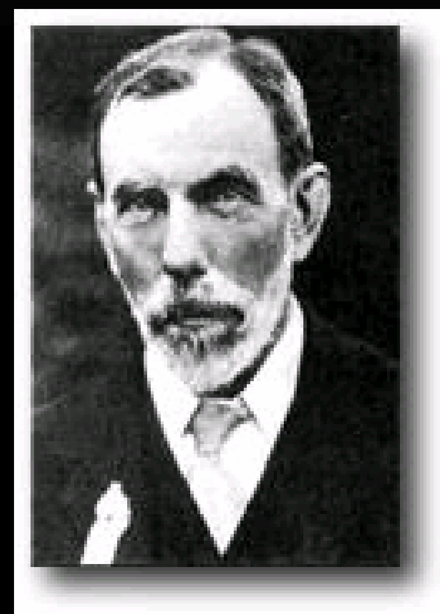
LRG
◇ Main
10⁵
10⁴
ower spectrum P(k) [(h⁻¹Mpc)³]
0.01
0.1
k [h Mpc⁻¹]
Measured power spectra for the full LRG and main galaxy samples. Errors are uncorrelated and full window functions are shown
e 5. The solid curves correspond to the linear theory ΛCDM fits to WMAP3 alone from Table 5 of [7], normalized to galaxy bias
(top) and b = 1.1 (bottom) relative to the z = 0 matter power. The dashed curves include the nonlinear correction of [29] for
, with Q_nl = 30 for the LRGs and Q_nl = 4.6 for the main galaxies; see equation (4). The onset of nonlinear corrections is clearly
or k ≳ 0.09h/Mpc (vertical line).
Density fluctuations
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10⁵
Scale (millions of lightyears)
Intergalactic hydrogen clumping
Gravitational lensing
SDSS galaxy clustering
Cluster abundance
Cosmic microwave background


A Brief History of
Dark Matter

The First Missing Matter Puzzle: Helium



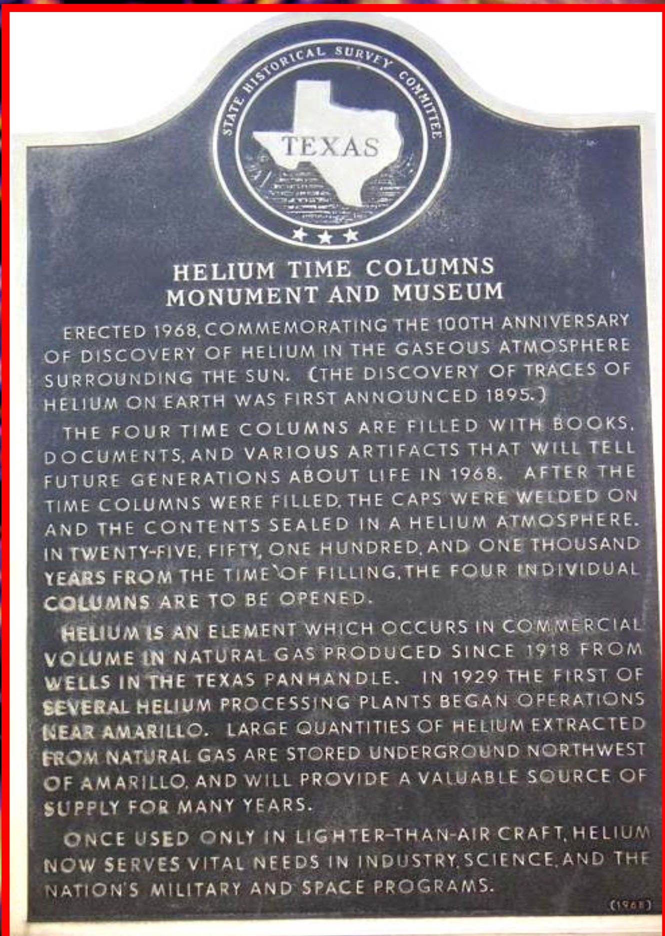




1868: Janssens and Lockyer find evidence for new element, the D3 line

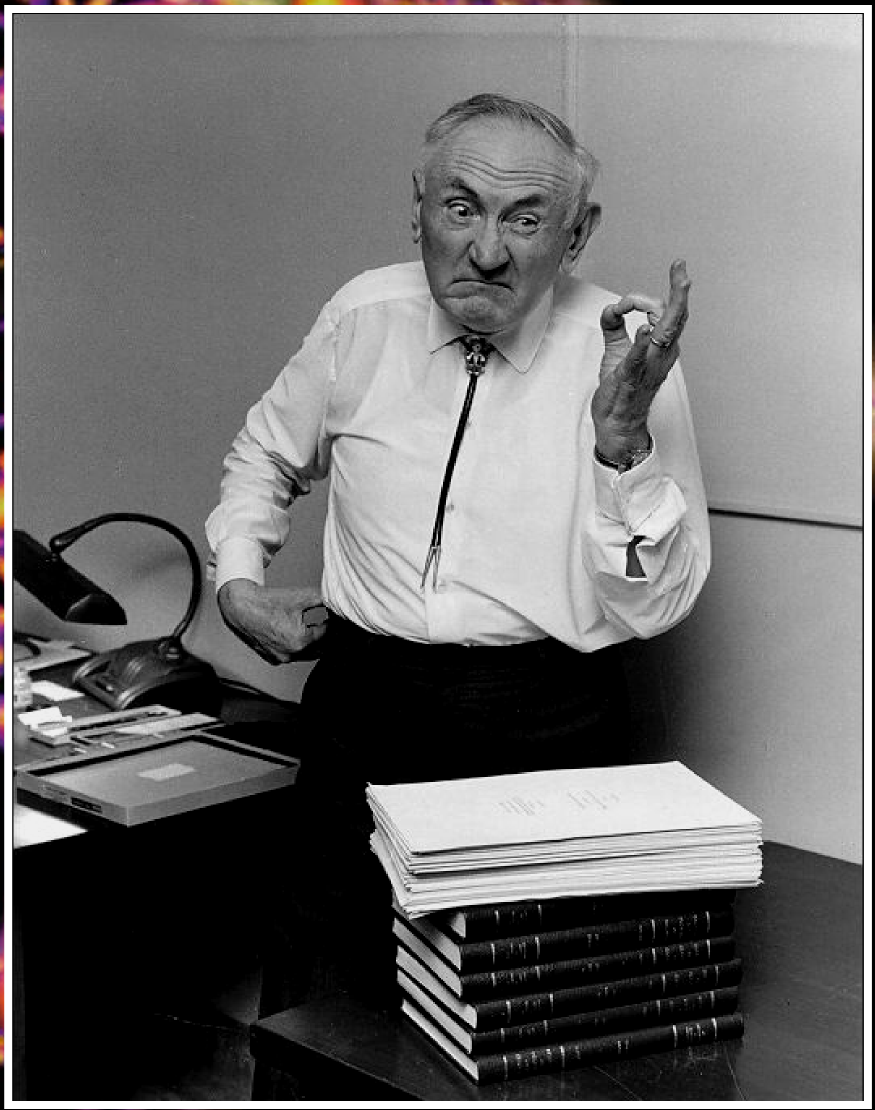
1895: Ramsay solves puzzle by isolating He gas produced by cleveite

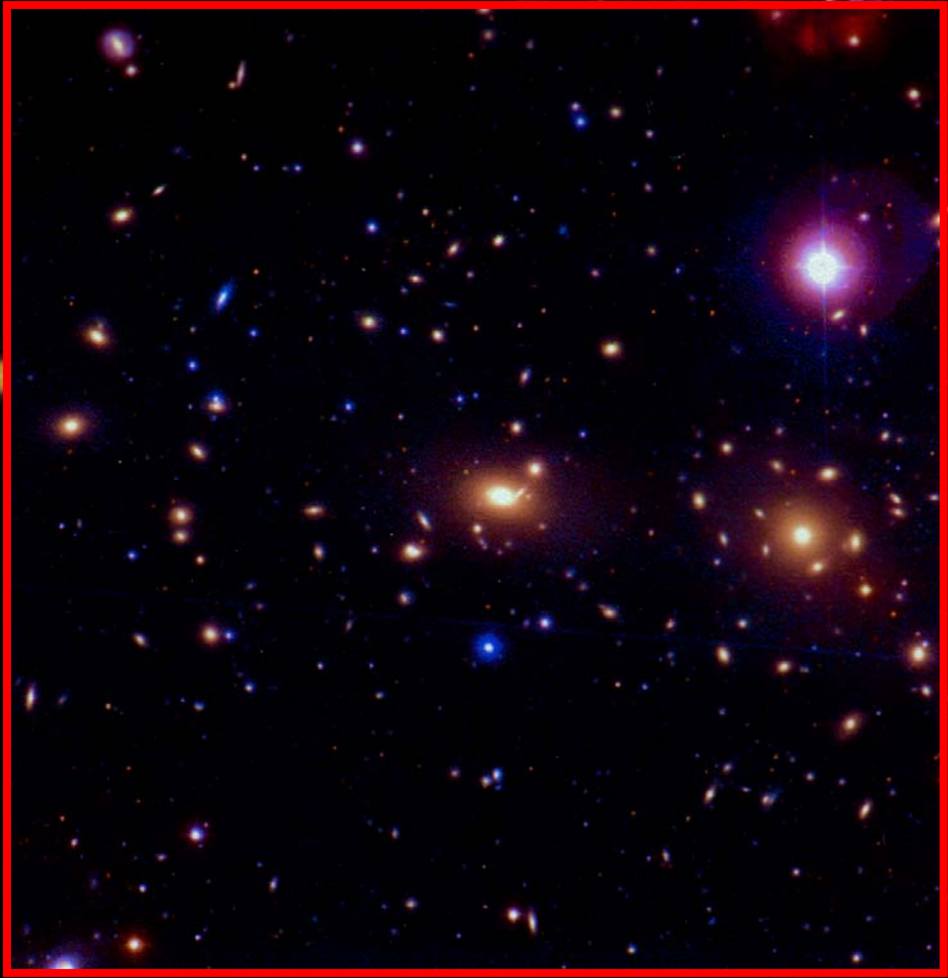
Which City Will Be Know As The City Of Dark Matter?



National Helium Monument
Celebrating 100th Anniversary of Discovery

1935: Zwicky, Coma and Dark Matter



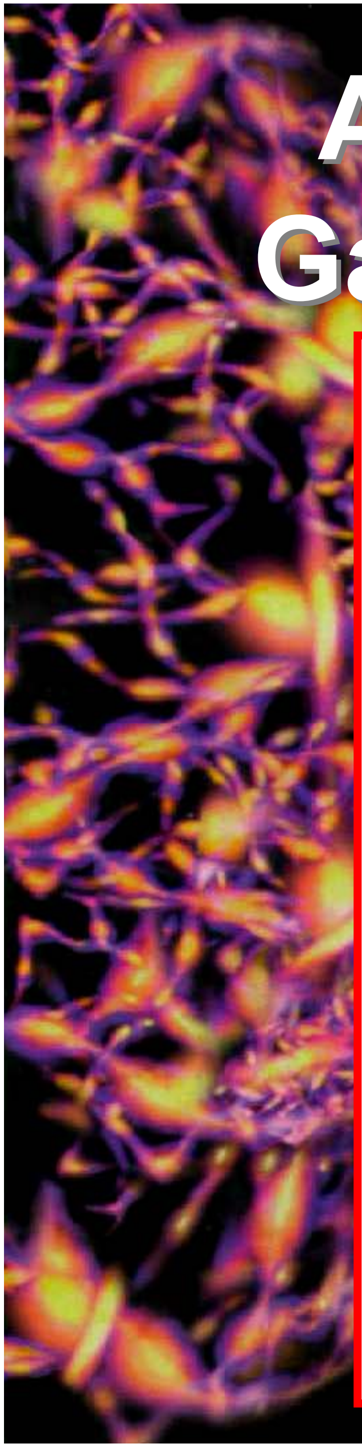


The Gravity of the Stars is not Enough to Hold Clusters Together

Clusters Must be Held Together by the Gravity of Unseen "Dark Matter"

Cosmology was very young, clusters were new, and astronomy was not ready for dark matter (or most of Zwicky's ideas)

Astrophysical Hints for Galactic Dark Matter Halo



THE ASTROPHYSICAL JOURNAL, 186:467–480, 1973 December 1

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

J. P. OSTRIKER
Princeton University Observatory
AND
P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

Received 1973 May 29

ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Subject headings: galactic structure — stellar dynamics

AN UNBOUND UNIVERSE?*

J. RICHARD GOTT III
California Institute of Technology
JAMES E. GUNN†
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington
DAVID N. SCHRAMM
The University of Texas at Austin
AND
BEATRICE M. TINSLEY
The University of Texas at Austin and at Dallas
Received 1974 June 28

ABSTRACT

...gly suggest that the density of the universe is no more than a tenth of the value ...s in this reasoning may exist, but if so, they are primordial and invisible, or

Deuterium Used as Baryometer to constrain baryon density

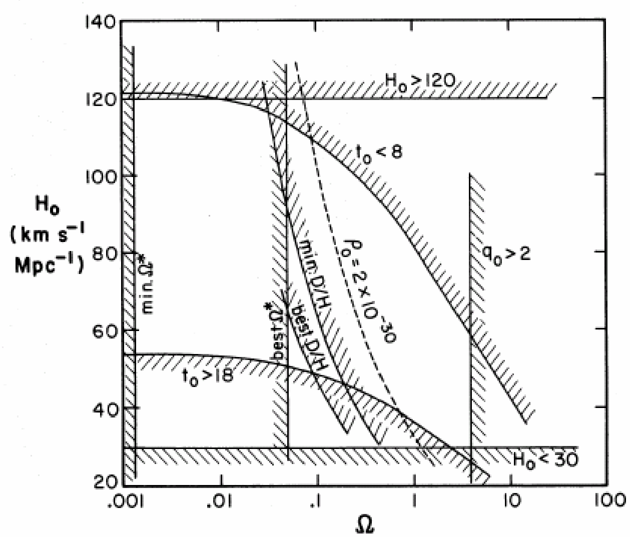


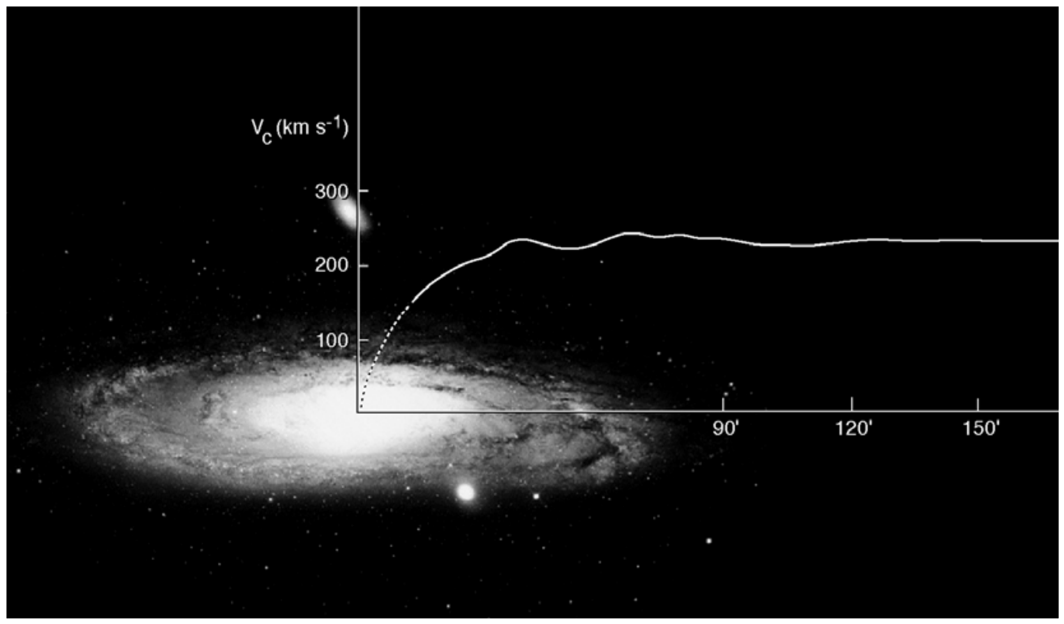
FIG. 1.—Constraints on the Hubble constant (H_0) and density parameter (Ω) that determine the Friedmann model if $\Lambda = 0$, explained in the following sections: the distance scale H_0 (§ II*a*); the age of the universe, t_0, shown in 10^9 yr (§ II*b*); the deceleration parameter q_0 (§ III*a*); minimal estimate of Ω^*, the contribution of galaxies to Ω (§ IV*a*); best estimate of Ω^* (§ IV*b*); upper limit to the present density ρ_0, from minimal estimate of the deuterium abundance and assuming standard big bang nucleosynthesis (§ V*a*); best upper limit to ρ_0 assuming standard big-bang synthesis of deuterium (§ V*a*); upper limit to ρ_0 (*dashed line*, in g cm^{-3}) from deuterium synthesis if the leptonic number may be nonzero.

Best Fit Universe

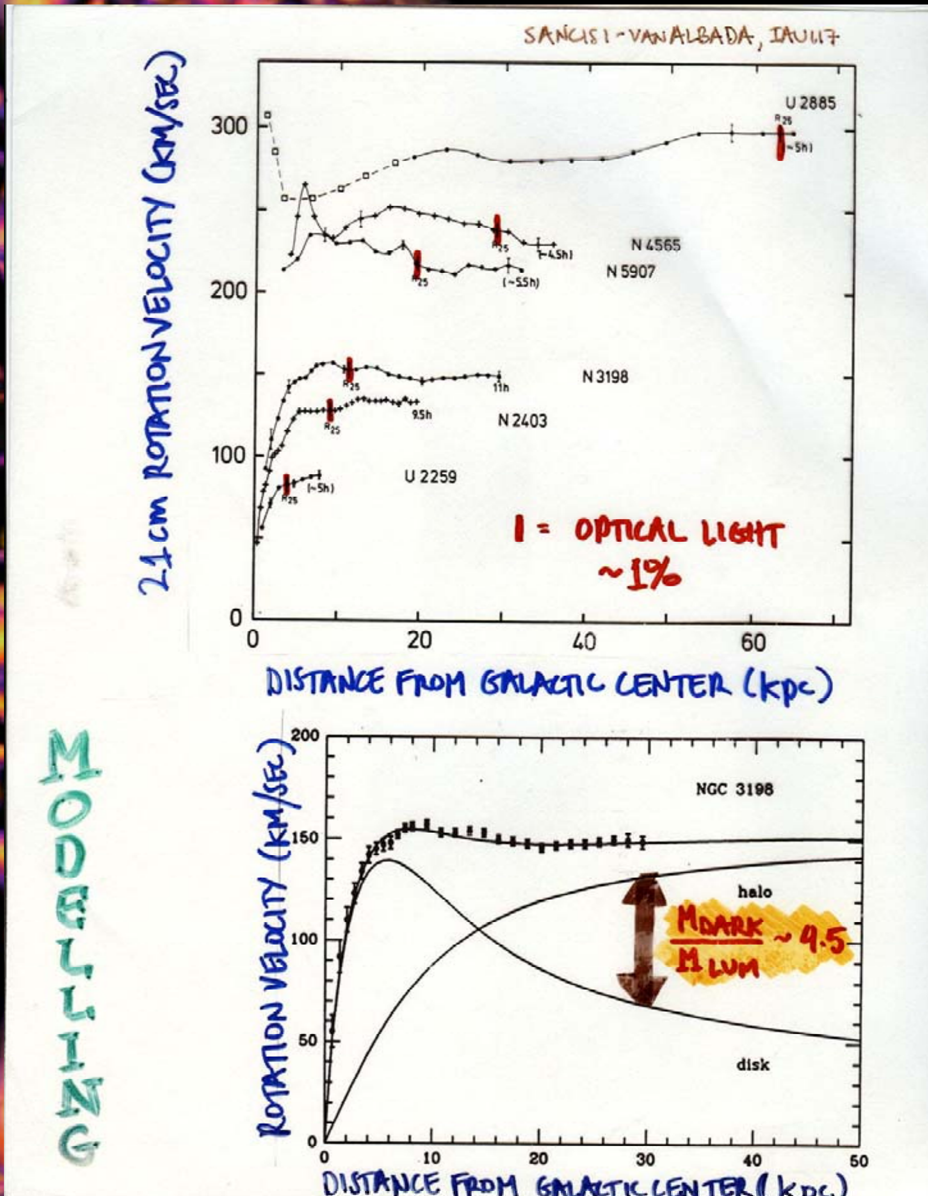
- H_0 ~ 60 km/s/Mpc
- $\Omega_0 \sim \Omega_B \sim 0.1$
- t_0 ~ 14 to 18 Gyr

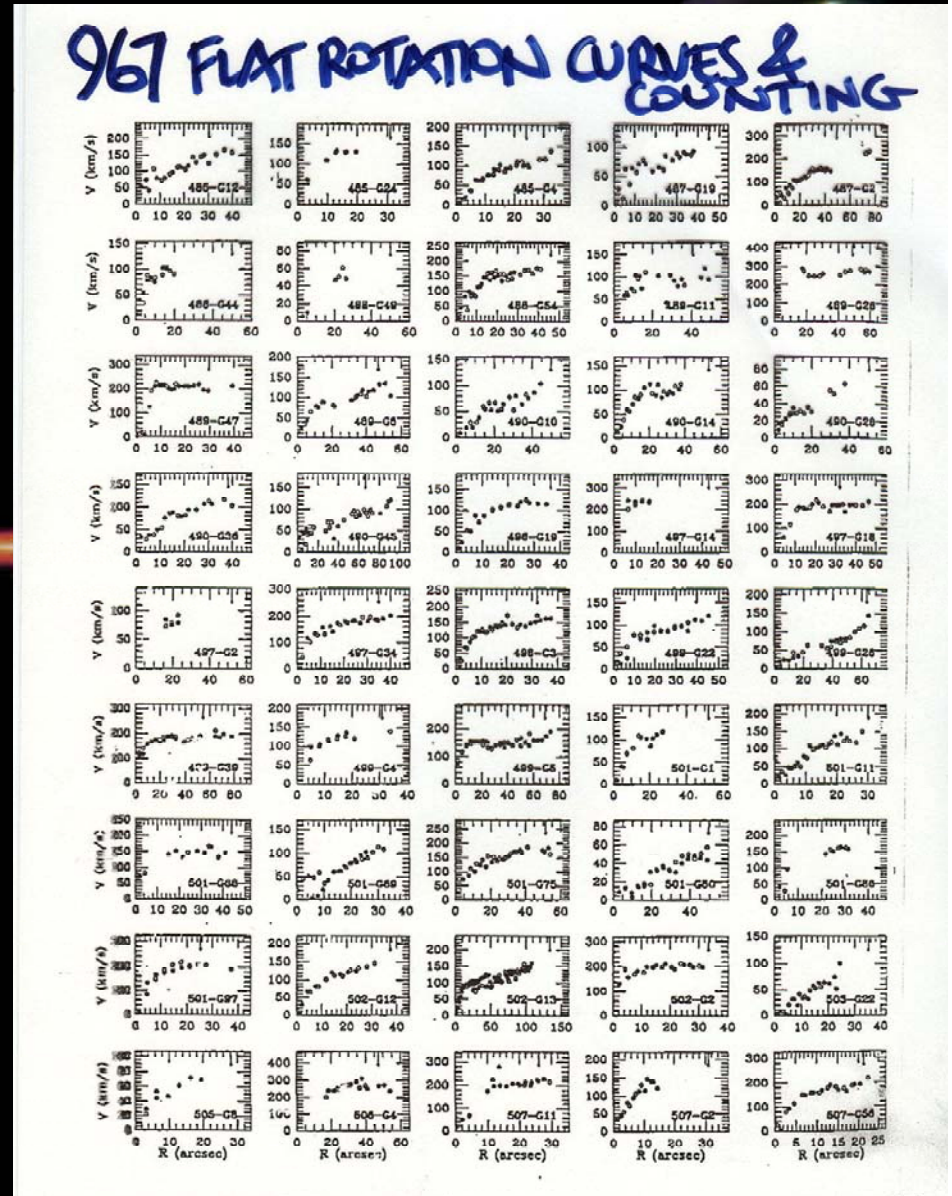
1970s: Vera Rubin and Flat Rotation Curves

Dark Matter Close to Home

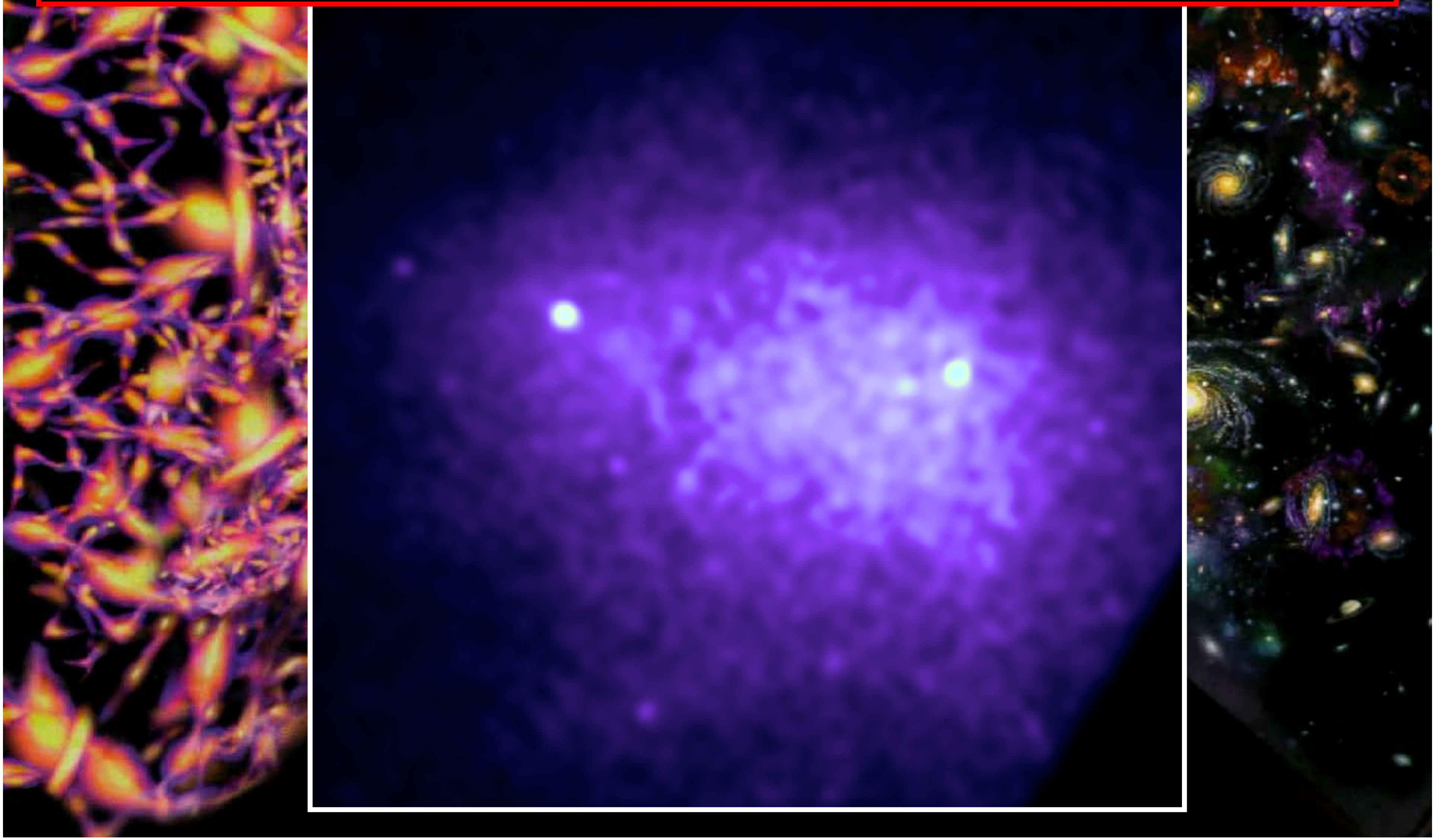


1000s of Rotation Curves





1980: X-Rays Reveal that Some of the Cluster "Dark" Matter is Hot Gas



1980: Particle Dark Matter!?

Volume 94B, number 2 PHYSICS LETTERS

AN ESTIMATE OF THE υ_e MASS FROM THE β-SPECTRUM OF TRITIUM IN THE VALINE MOLECULE

V.A. LUBIMOV, E.G. NOVIKOV, V.Z. NOZIK, E.F. TRETYAKOV and V.S. KOSIK
Institute of Theoretical and Experimental Physics, Moscow, USSR

Received 4 June 1980

The high energy part of the β-spectrum of tritium in the valine molecule ($C_5H_{11}NO_2$) was meas by a toroidal β-spectrometer. The results give evidence for a non-zero electron antineutrino mass.

thus have

$$14 \leqslant M_\nu \leqslant 46 \text{ eV} \quad (99\% \text{ C.L.}) .$$

We consider this as an indication that the electron antineutrino has a non-zero mass. For the time being we do not see any effects which could have shifted essenti ... tinue the ex ... tium.

$\Omega_\nu = m_\nu/91h^2\text{eV}$

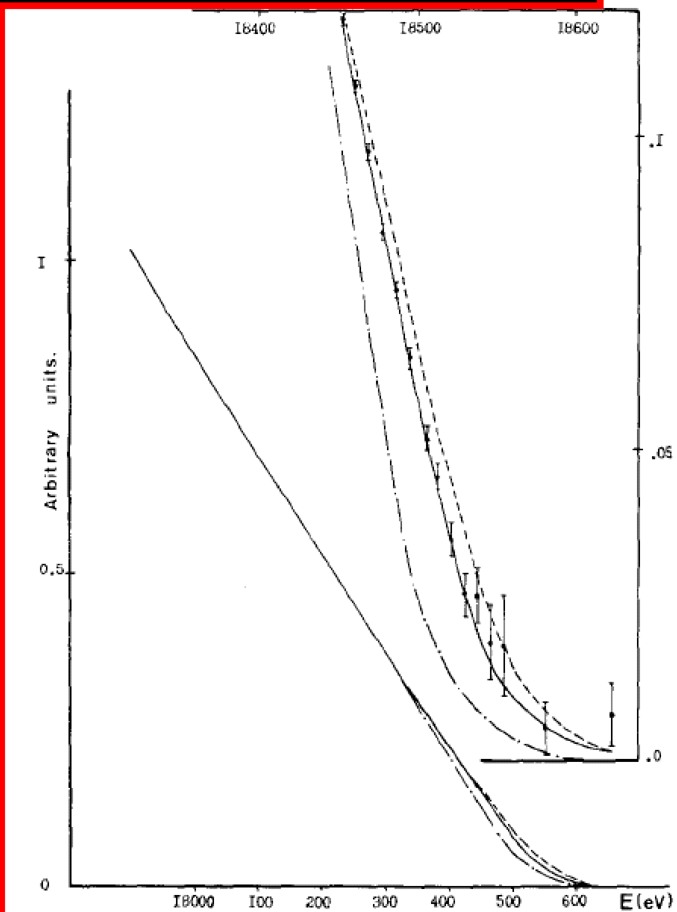


Fig. 1. The measured β-spectrum of tritium (Kurie plot). The results of the χ^2 fit (see text) for different values of M_ν for half of the statistics are shown (solid line 37 eV, E_0 = 18 578 eV; dashed line 0 eV, E_0 = 18 574 eV; dash–dotted line 80 eV, E_0 = 18 586 eV).

Neutrinos and Cosmology

General Relativity and Gravitation, Vol. 13, No. 2, 1981

A Neutrino-Dominated Universe[1]

DAVID N. SCHRAMM

Enrico Fermi Institute, University of Chicago

GARY STEIGMAN

Bartol Research Foundation of The Franklin Institute

Abstract

Relic neutrinos produced during the early evolution of the universe will be abundant ($n_\nu \approx n_\gamma$) and, if they have a small mass ($3 \lesssim m_\nu \lesssim 10$ eV), may supply the dominant contribution to the total mass density. We review the data on the mass on various scales galaxies, binaries, small groups, large clusters) and conclude that ordinary matter (nucleons) is capable of accounting for the inferred mass on all scales except that of clusters of galaxies. Were the mass in clusters mainly in nucleons, too much helium and too little deuterium would have been produced during primordial nucleosynthesis. Relic neutrinos with $m_\nu \gtrsim 3$ eV are heavy enough to collapse into clusters of galaxies; for $m_\nu \lesssim 10$ eV they are too light to collapse along with binaries and small groups. Such neutrinos would supply the dominant contribution to the mass in the universe.

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland

Department of Physics, University of California, Berkeley, California 94720

(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

Astron. & Astrophys. 49, 437—441 (1976)

Neutrino Rest Mass from Cosmology

A. S. Szalay and G. Marx

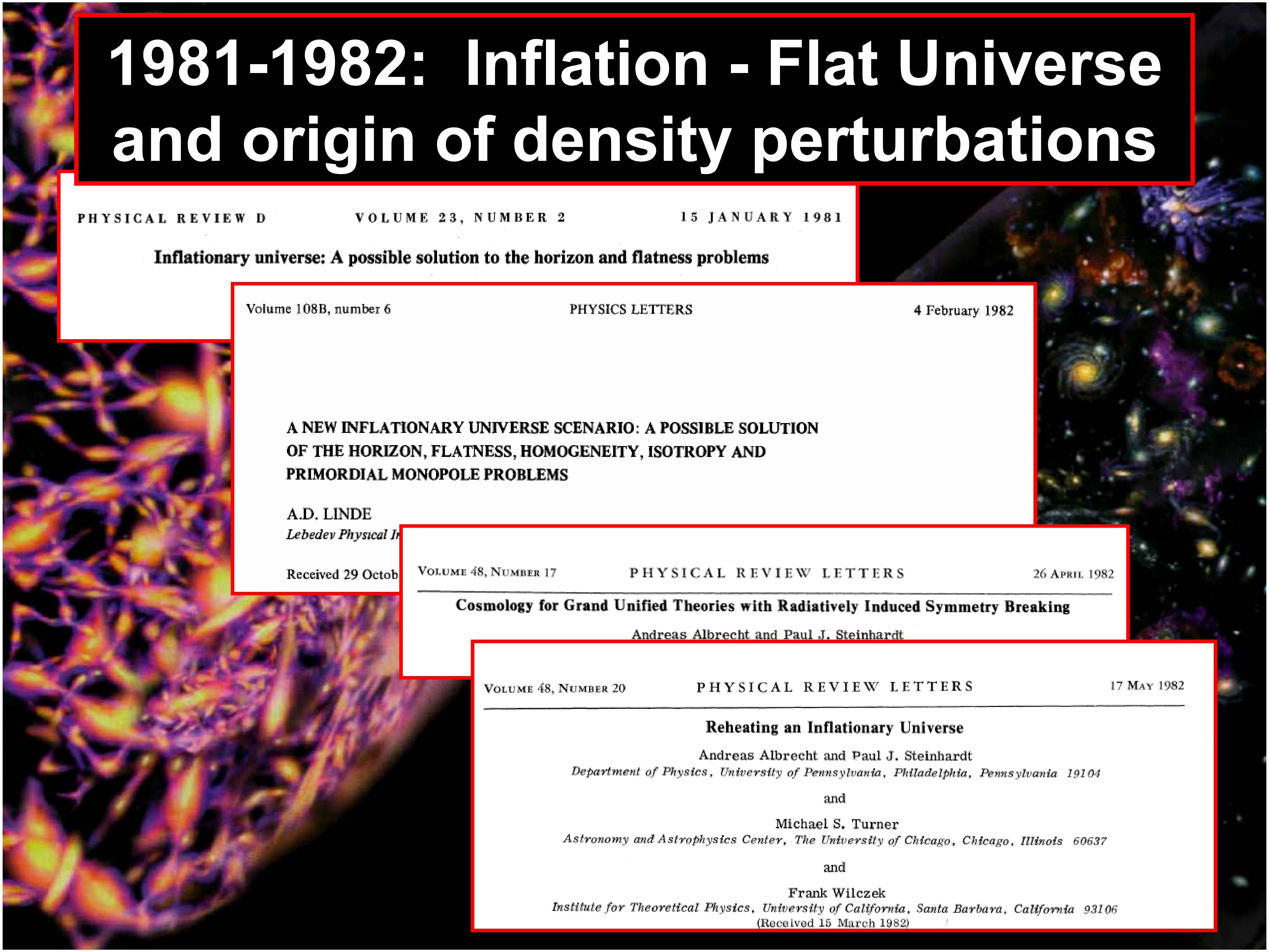
Department of Atomic Physics, Roland Eötvös University, Budapest

Received January 27, 1975

Summary. In standard cosmological models, the overall mass density of the Universe can be calculated from the observed value of the Hubble constant H_0 and the deceleration parameter q_0. Their most recent values suggest a density considerably higher than the estimated density of the known matter in the Universe. The "missing mass" phenomenon is also known in clusters of galaxies. The missing mass may be explained by the relict cosmological neutrinos, produced in the hot era following the Big Bang, if we assume nonvanishing neutrino and neutretto rest masses. The cosmological evolution of the Universe has been calculated in this model. The observed values of H_0, q_0 and t_0 (age of the Universe) agree with the cosmological model, if one chooses an appropriate value for the neutrino mass m. The upper limit on the neutrino and neutretto rest mass obtained in this way is $m = 13.5$ eV. Density fluctuations in the primordial neutrino gas at the temperature $kT = mc^2$ may initiate the formation of clusters of galaxies. The 13.5 eV mass value leads to a separation of clusters at the present time in good agreement with observation. The relict neutrinos with a rest mass could form a halo around clusters of galaxies: this halo would influence the density profile of the cluster in the outer region. Our final conclusion is that a neutrino or neutretto rest mass larger than 15 eV would contradict the astrophysical evidence.

Key words: neutrinos-rest mass — cosmology — clusters of galaxies

1981-1982: Inflation - Flat Universe and origin of density perturbations



PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 1981

Inflationary universe: A possible solution to the horizon and flatness problems

Volume 108B, number 6 PHYSICS LETTERS 4 February 1982

A NEW INFLATIONARY UNIVERSE SCENARIO: A POSSIBLE SOLUTION OF THE HORIZON, FLATNESS, HOMOGENEITY, ISOTROPY AND PRIMORDIAL MONOPOLE PROBLEMS

A.D. LINDE

Lebedev Physical In

Received 29 Octob

VOLUME 48, NUMBER 17 PHYSICAL REVIEW LETTERS 26 APRIL 1982

Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking

Andreas Albrecht and Paul J. Steinhardt

VOLUME 48, NUMBER 20 PHYSICAL REVIEW LETTERS 17 MAY 1982

Reheating an Inflationary Universe

Andreas Albrecht and Paul J. Steinhardt

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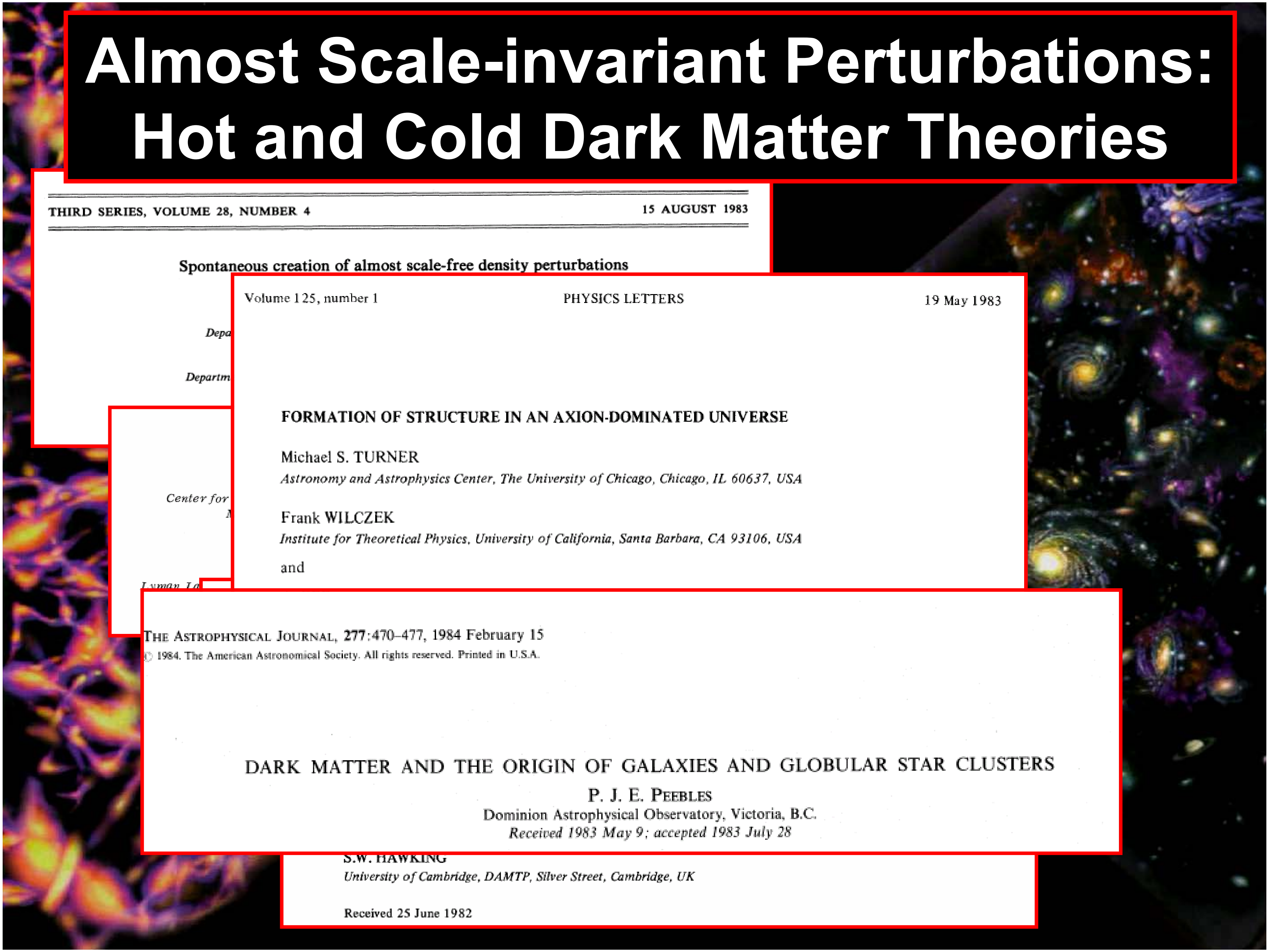
(Received 15 March 1982)

Almost Scale-invariant Perturbations: Hot and Cold Dark Matter Theories



THIRD SERIES, VOLUME 28, NUMBER 4 15 AUGUST 1983

Spontaneous creation of almost scale-free density perturbations

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Lyman La

Volume 125, number 1 PHYSICS LETTERS 19 May 1983

FORMATION OF STRUCTURE IN AN AXION-DOMINATED UNIVERSE

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Received 25 June 1982

THE ASTROPHYSICAL JOURNAL, 277:470–477, 1984 February 15

DARK MATTER AND THE ORIGIN OF GALAXIES AND GLOBULAR STAR CLUSTERS

P. J. E. PEEBLES
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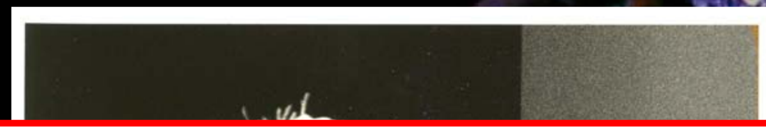
Received 1983 May 9; accepted 1983 July 28

1984: Inner Space/Outer Space

the Woodstock of Quarks & the Cosmos

I·N·N·E·R S·P·A·C·E



NATURE VOL. 311 11 OCTOBER 1984 REVIEW ARTICLE 517

Formation of galaxies and large-scale structure with cold dark matter

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Joel R. Primack†§ & Martin J. Rees‡§

† Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA
‡ Institute of Theoretical Physics, University of California, Santa Barbara, California 93106, USA

The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) spectrum of primordial fluctuations.

The Rise of CDM as the Theory to Knock Off

1985: Official Birth of WIMPs

Nuclear Physics B253 (1985) 375-386

COSMOLOGICAL CONSTRAINTS ON THE PROPERTIES OF WEAKLY INTERACTING MASSIVE PARTICLES

Gary STEIGMAN

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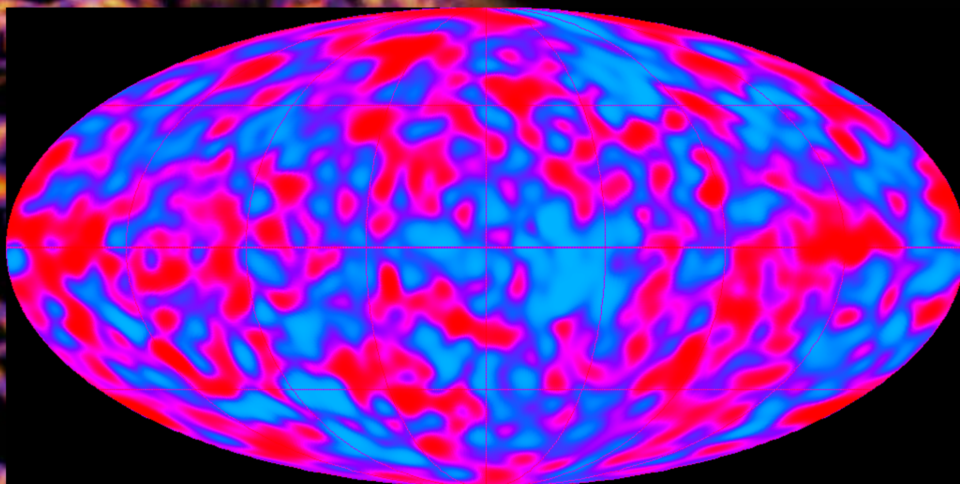
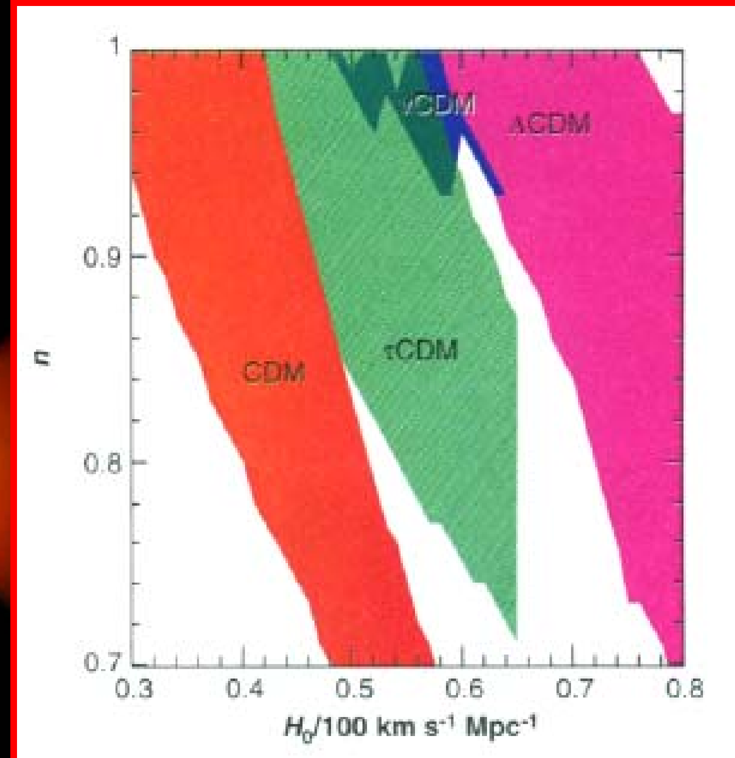
Received 9 October 1984

Considerations of the age and density of, as well as the evolution of structure in, the universe lead to constraints on the masses and lifetimes of weakly interacting massive particles (WIMPs). The requirement that the observed large-scale structure of the universe be permitted to develop, leads to much more restrictive bounds on the properties of WIMPs than those which follow from considerations of the age and density of the universe alone.

1992: COBE Changed it all by providing, accurate large-scale normalization: Flavors of CDM





ARTICLE

Cold Dark Matter

Scott Dodelson, Evalyn I. Gates, Michael S. Turner

Motivated by inflation, the theory of big-bang nucleosynthesis, and the quest for a deeper understanding of fundamental forces and particles, a paradigm for the development of structure in the universe has evolved. It holds that most of the matter exists in the form of slowly moving elementary particles left over from the earliest moments—cold dark matter—and that the small density inhomogeneities that seed structure formation arose from quantum fluctuations around 10^{-34} seconds after the big bang. A flood of observations, from determinations of the Hubble constant to measurements of the anisotropy of cosmic background radiation, are now testing the cold dark matter paradigm.

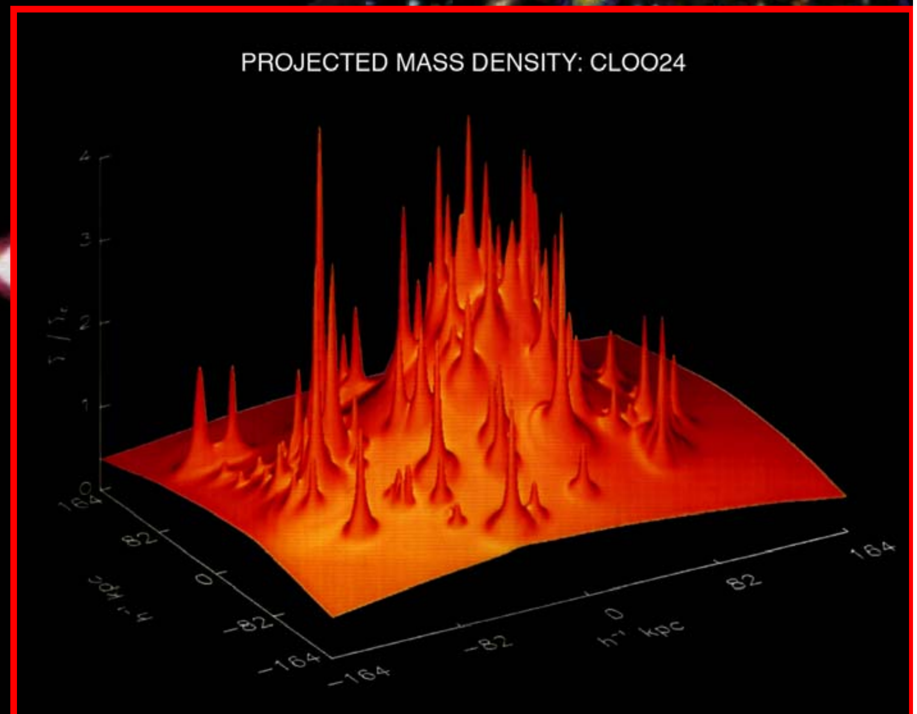
Science **274**, 69 (1996)

CDM: The Theory with 9 Lives

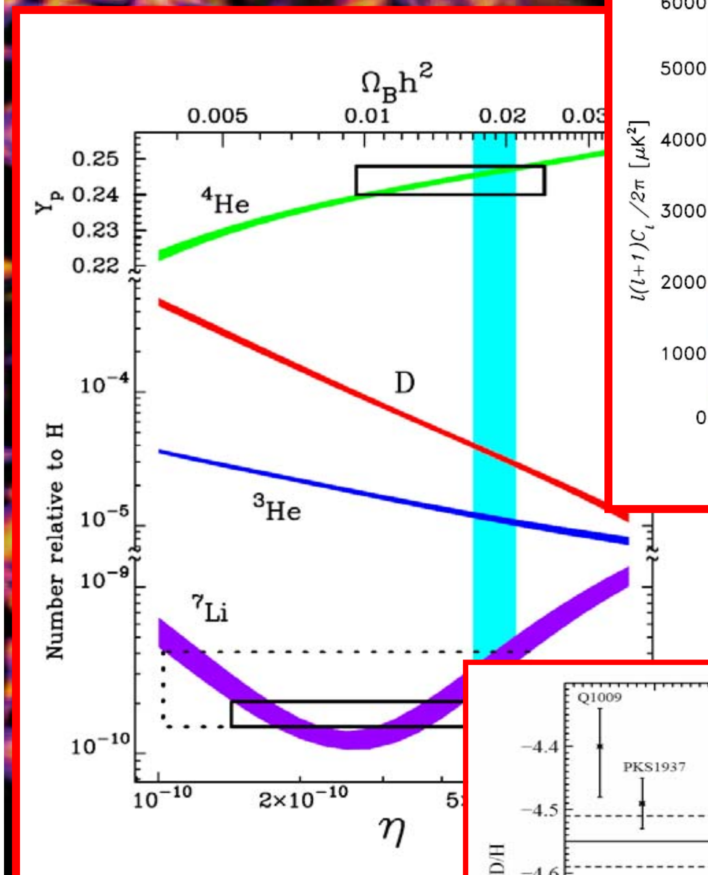
Mapping Dark Matter

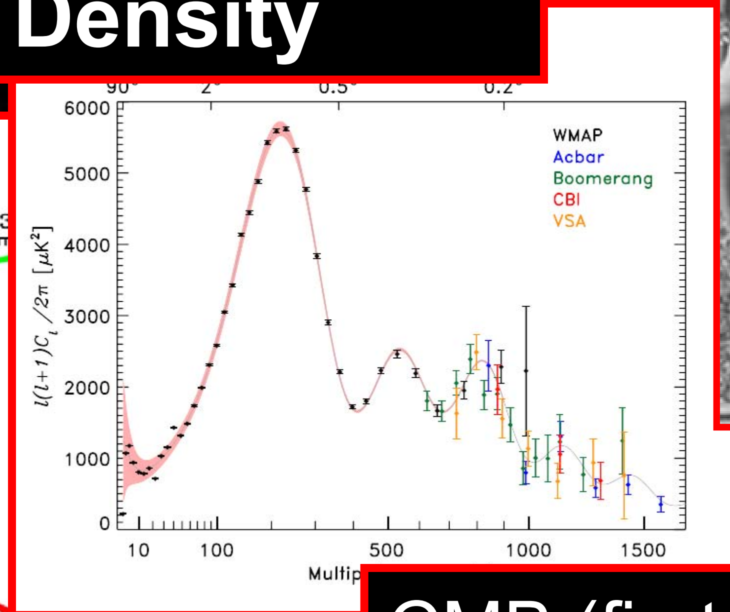
Gravitational Lens
Galaxy Cluster 0024+1654
HST • WFPC2

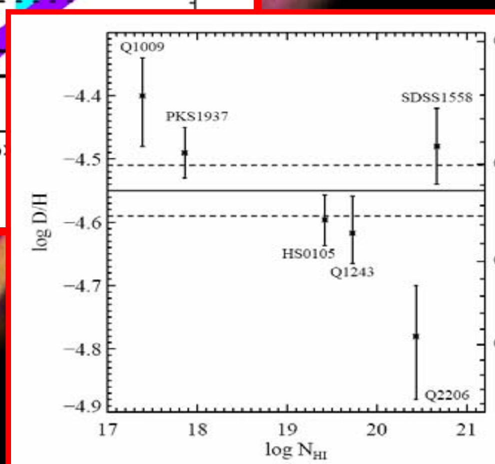
PRC96-10 • ST ScI OPO • April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA



2001: Nailing Down the Baryon Density







CMB (first to second peak)

$\Omega_b h^2 = 0.022 \pm 0.0007$

vs.

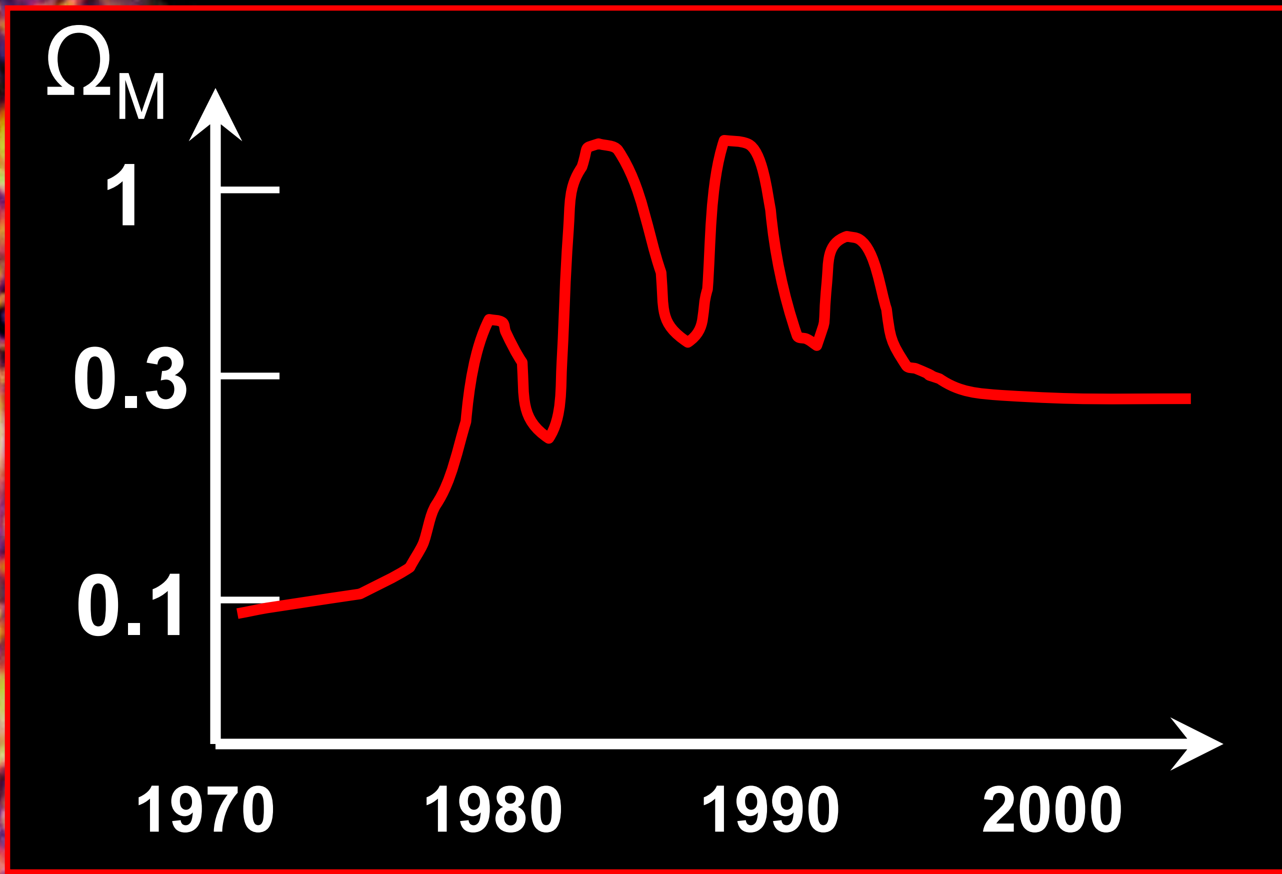
BBN (Deuterium)

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

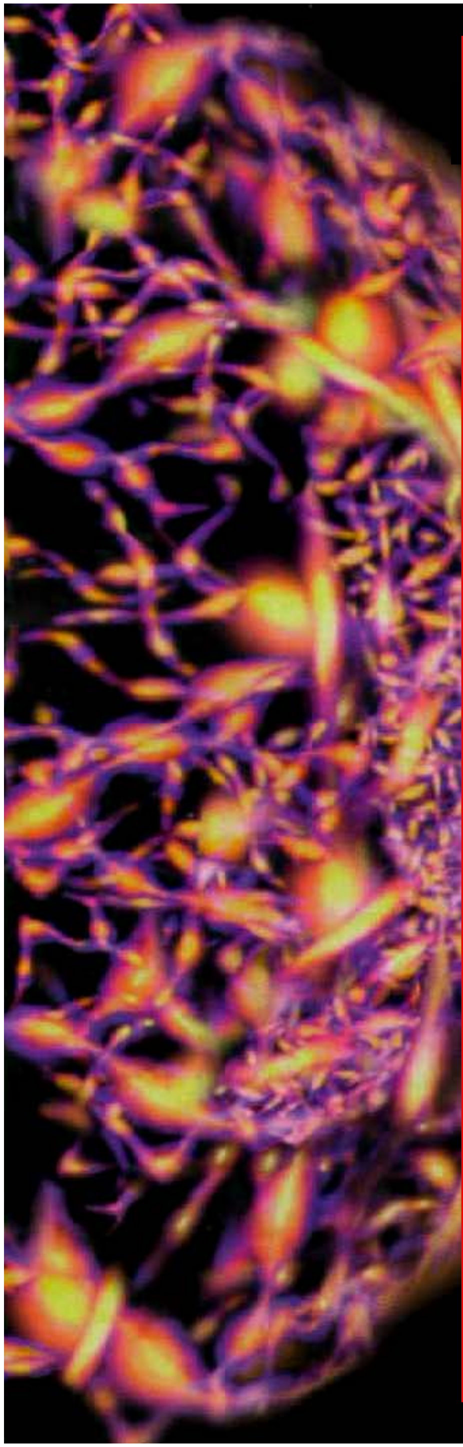
5% agreement

$\Omega_b = 0.042 \pm 0.002$

The Rise and Fall of Omega

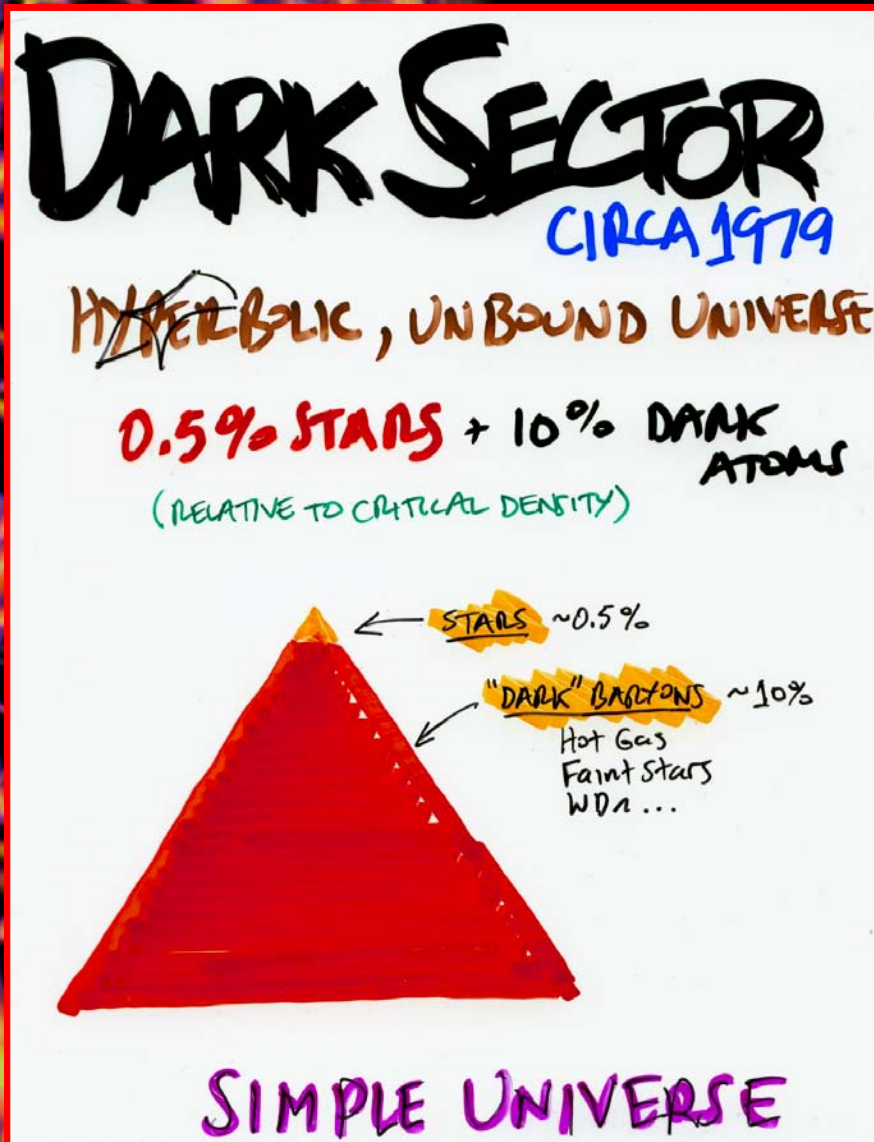


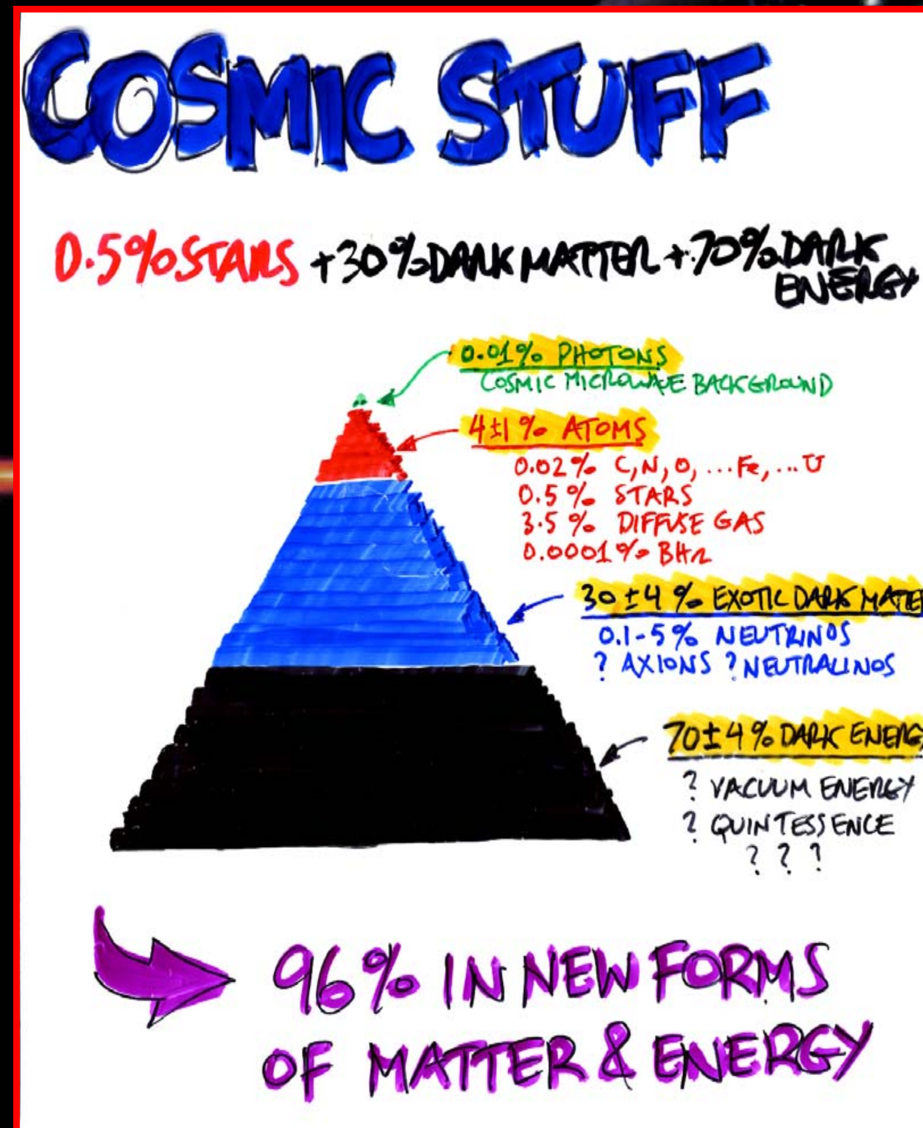
- 1970s: Mass-to-light ratios on limited parts of the galaxy
- 1980s: Peculiar velocity measurements probe larger regions
- 1990s: Cluster fair sample, LSS, peculiar flows
- 2000s: CMB, LSS, BAO, clusters



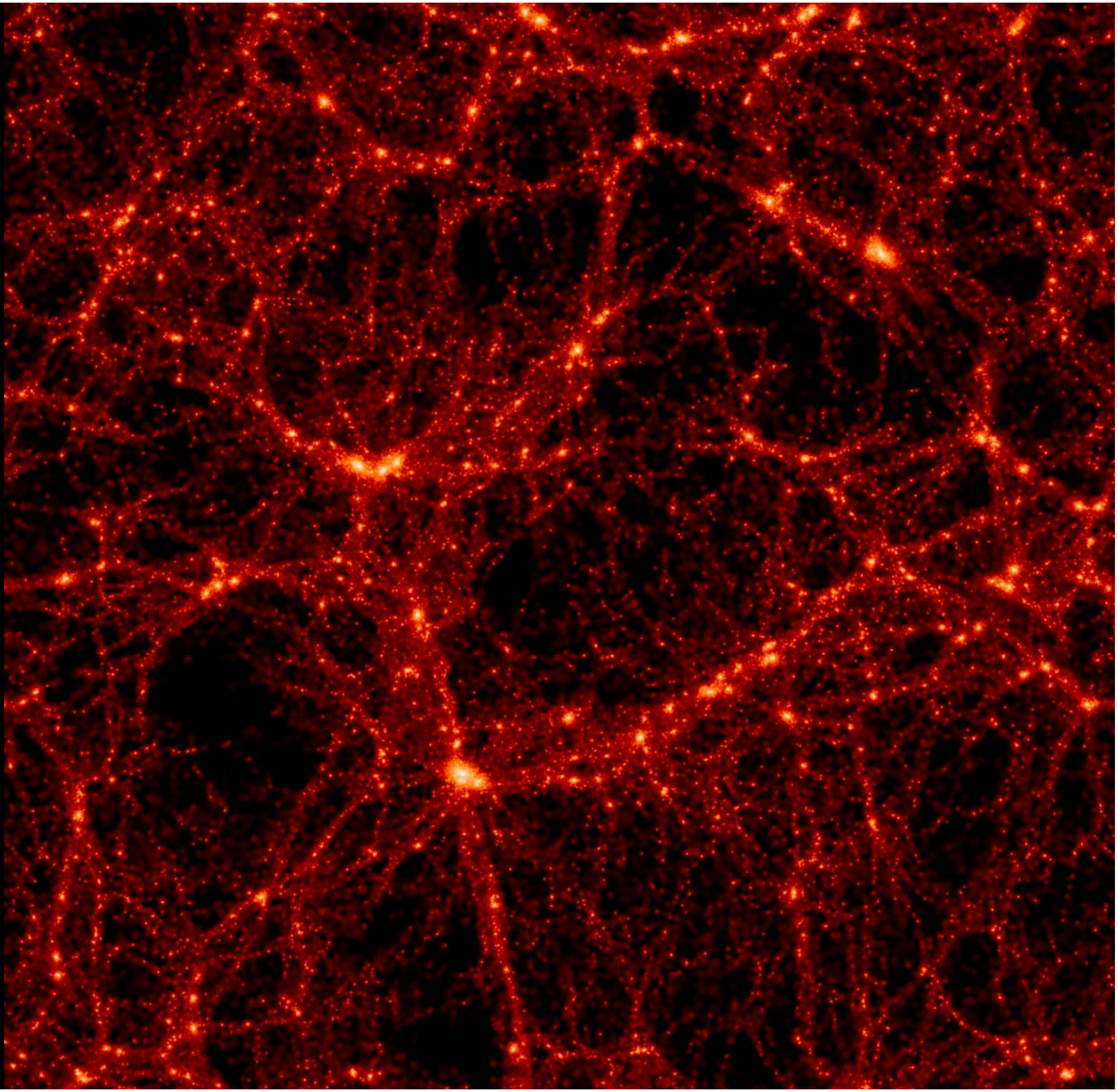
... and the winner is ΛCDM

1979 vs. 2007


DARK SECTOR
CIRCA 1979
HYPERBOLIC, UNBOUND UNIVERSE
0.5% STARS + 10% DARK ATOMS
(RELATIVE TO CRITICAL DENSITY)
STARS ~0.5%
"DARK" BARYONS ~10%
Hot Gas
Faint Stars
WDs ...
SIMPLE UNIVERSE


COSMIC STUFF
0.5% STARS + 30% DARK MATTER + 70% DARK ENERGY
0.01% PHOTONS
COSMIC MICROWAVE BACKGROUND
4±1% ATOMS
0.02% C, N, O, ... Fe, ... U
0.5% STARS
3.5% DIFFUSE GAS
0.0001% BHs
30±4% EXOTIC DARK MATTER
0.1-5% NEUTRINOS
? AXIONS ? NEUTRALINOS
70±4% DARK ENERGY
? VACUUM ENERGY
? QUINTESSENCE
? ? ?
96% IN NEW FORMS OF MATTER & ENERGY

Cosmic Web of Dark Matter



Dark Matter:
Where We Are Today
10 Things to Take Home

1. Overwhelming Evidence for Dark Matter

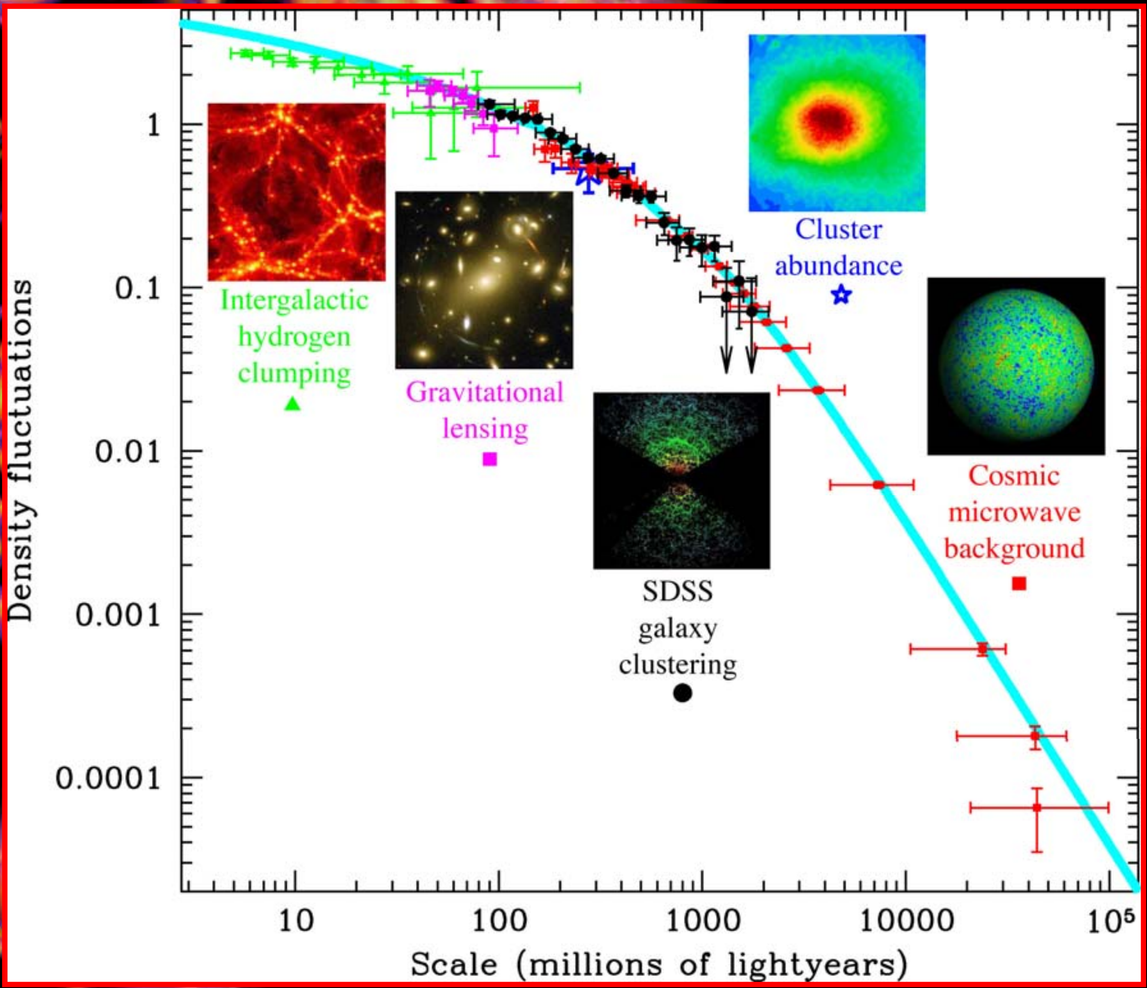
- Flat rotation curves of galaxies (galaxies have large, dark halos)
- Clusters are held together by dark matter (galaxy motions, lensing maps, x-ray gas)
- CMB census of stuff in the Universe
- Without gravity of dark matter cannot make observed structure
- CDM has most of the truth

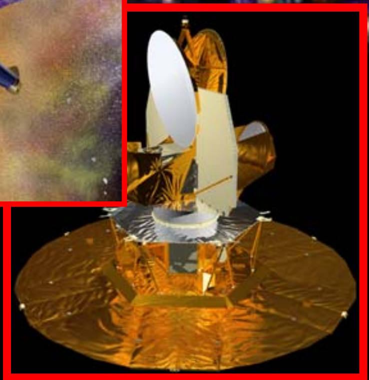
2. Dark Numbers

- Stars: ~0.5% (definition dependent)
- Atoms: 4.2 ± 0.2%
- Dark Atoms: ~3.7% (90% of atoms)
- Exotic Dark Matter: 20 ± 2%
- Neutrinos: 0.02% to 1%

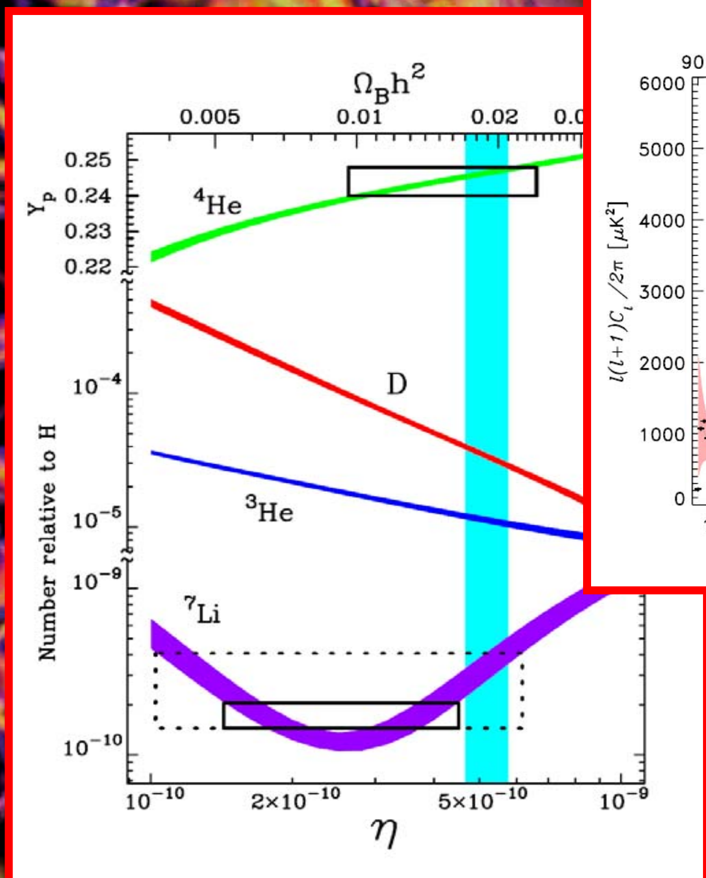
…. the rest is dark energy

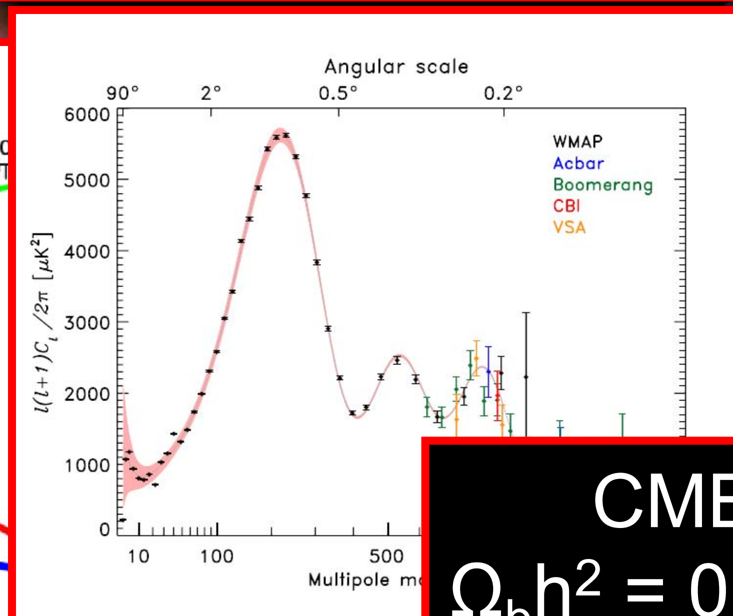
3. Concordance Model Doesn't Exist w/o Particle Dark Matter!





4. Airtight Evidence for Nonbaryonic Dark Matter





CMB & BBN

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

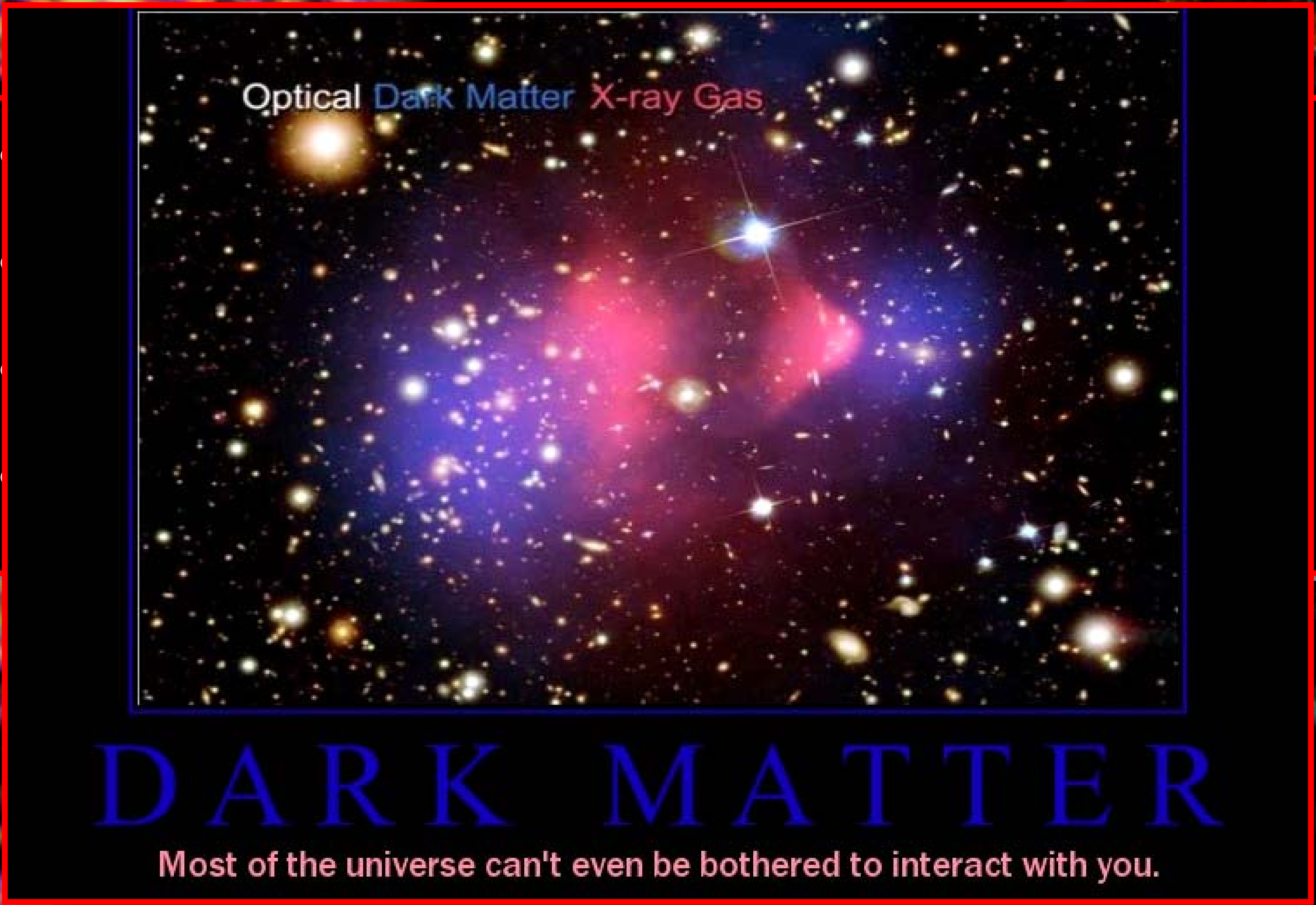
vs.

CMB/SDSS

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

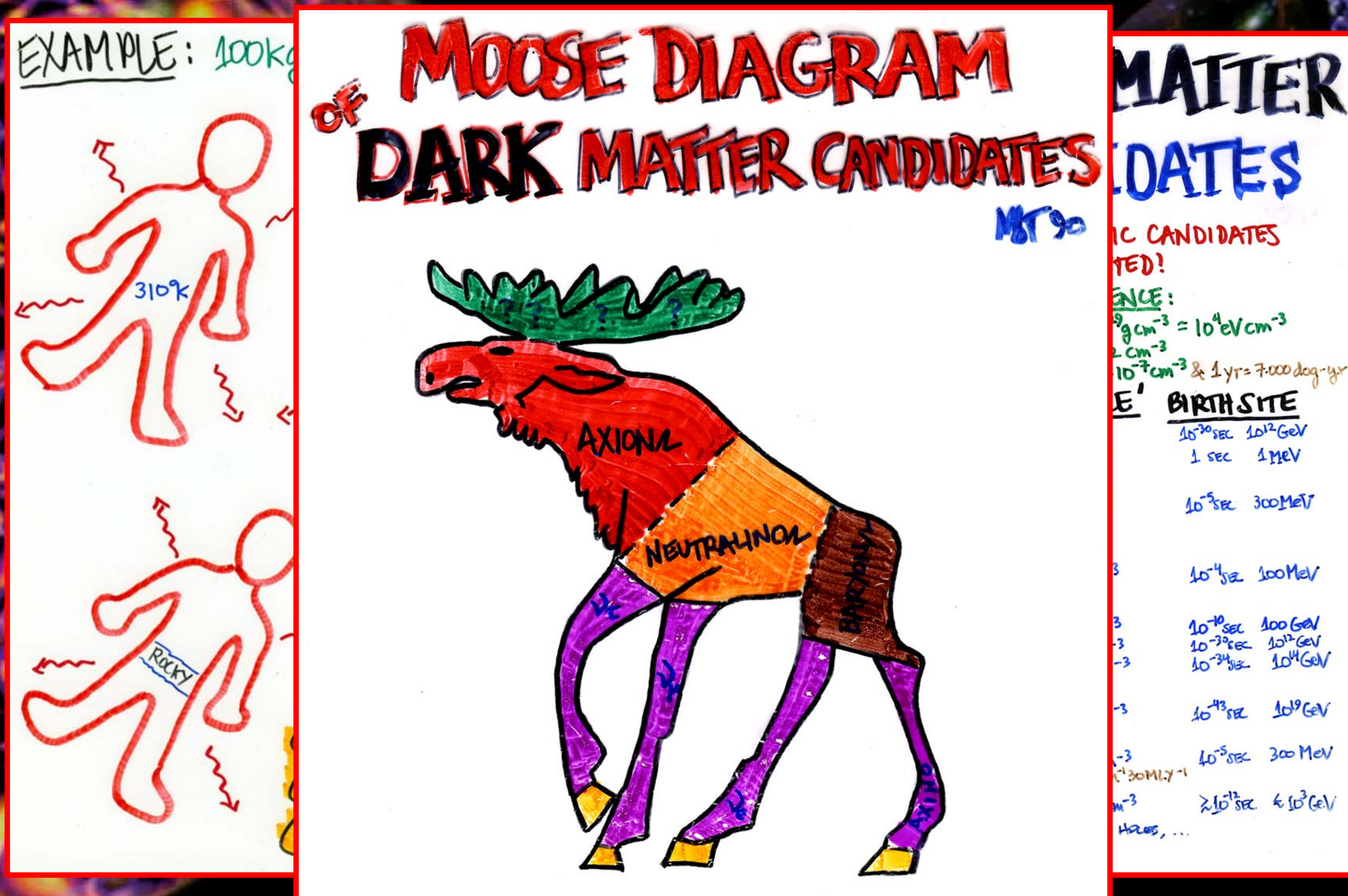
<u>20σ discrepancy</u>

5. Clusters: Nature's Fair Sample of the Cosmos

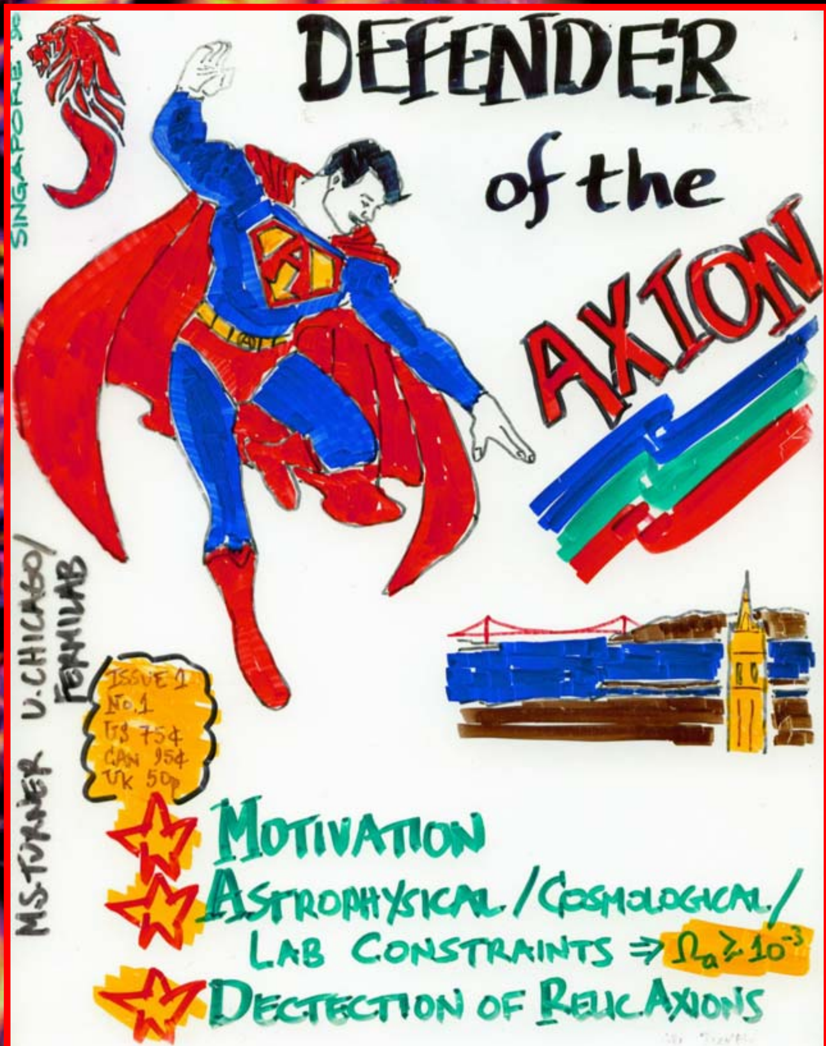


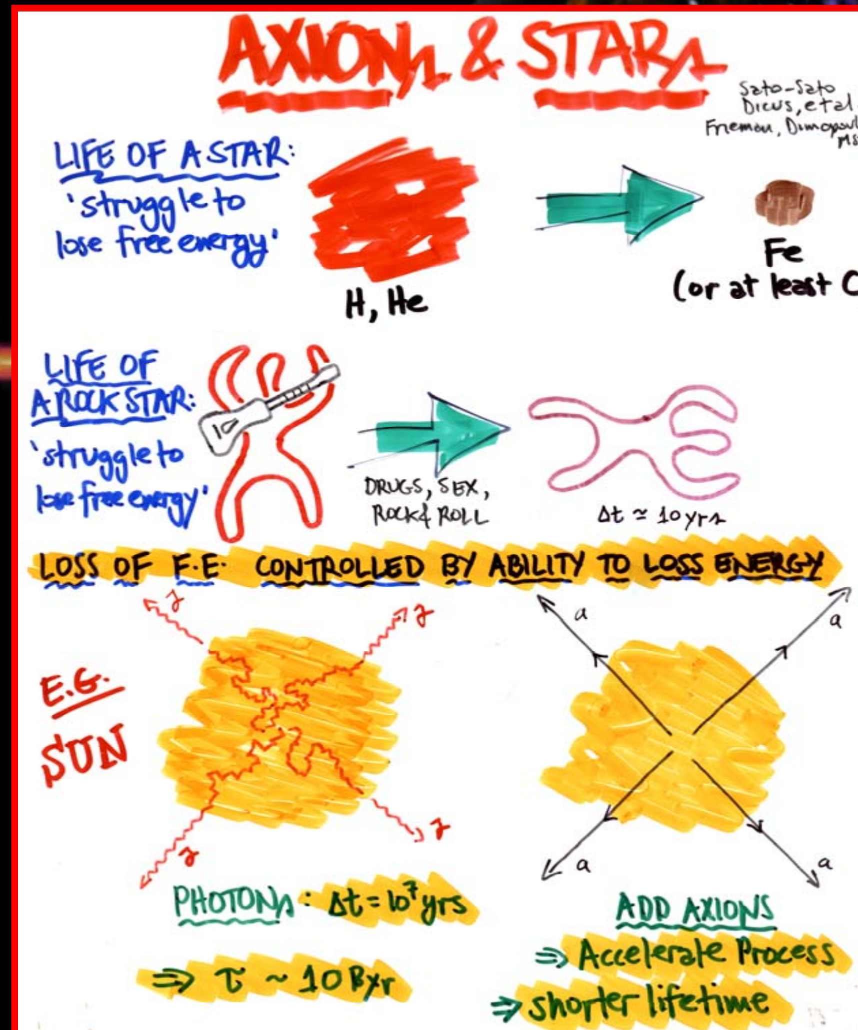
5. Strongest Evidence for Physics Beyond the Standard Model and #8 in Haber's Top Ten List for Believing in SUSY

6. Dark Matter Candidates



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





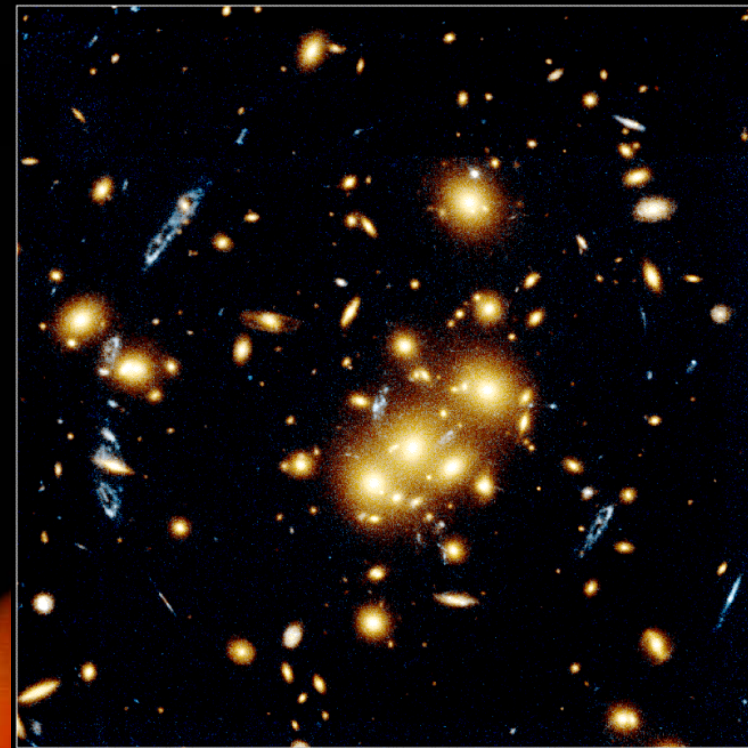
7. Full Court Press on Dark Matter

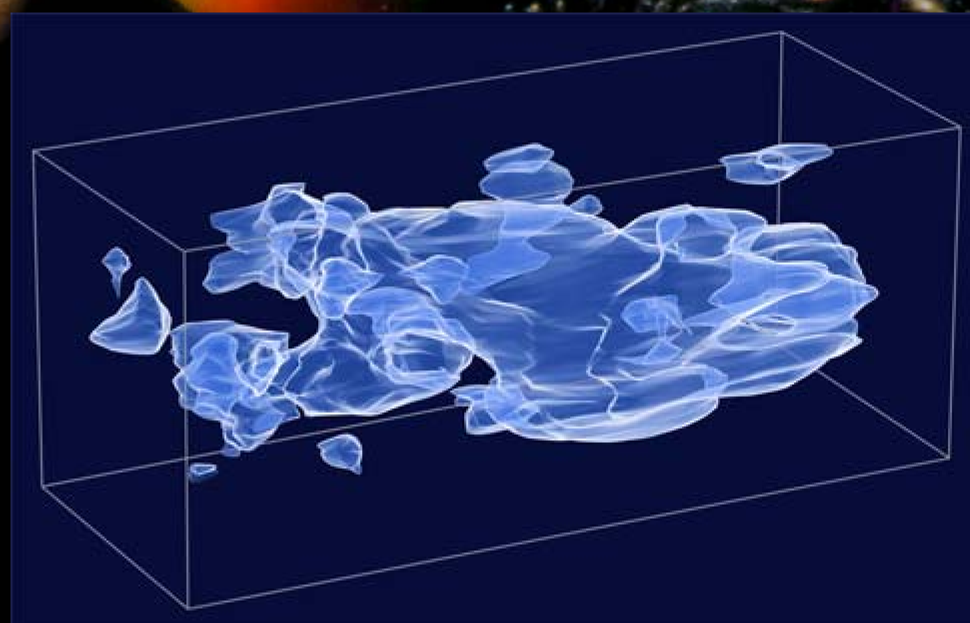
7. Full Court Press on Dark Matter

- Particle accelerators (Tevatron, LHC, ILC)
- Direct searches for halo dark matter
  - Axions and neutralinos (multiple techniques)
  - Within reach of detection!
- Indirect searches
  - Sun/earth annihilation neutrinos
  - Halo annihilation positrons, gammas, antiprotons
- Telescopes mapping dark matter

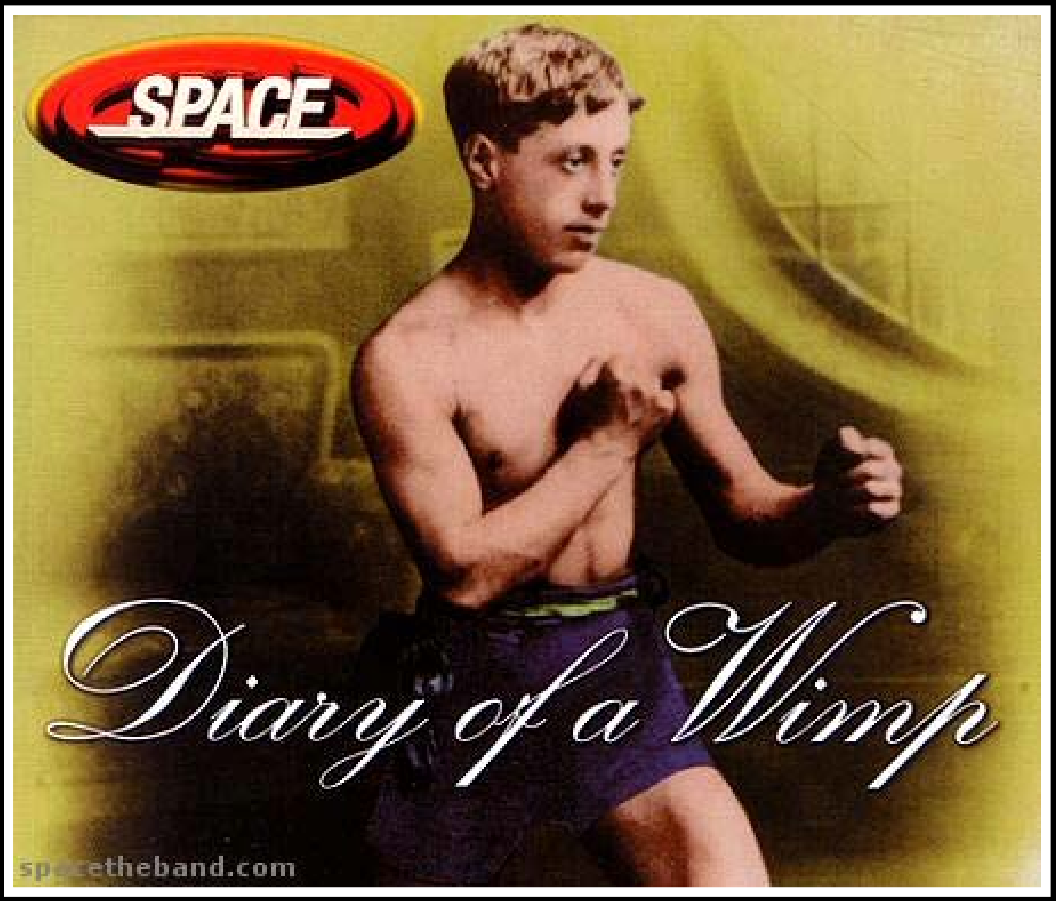
8. Mapping Dark Matter in the Universe

- Halos
- Clusters
- Large-scale Structure
- CMB





9. MACHOs* are NACHOs*: The Triumph of the WIMPs

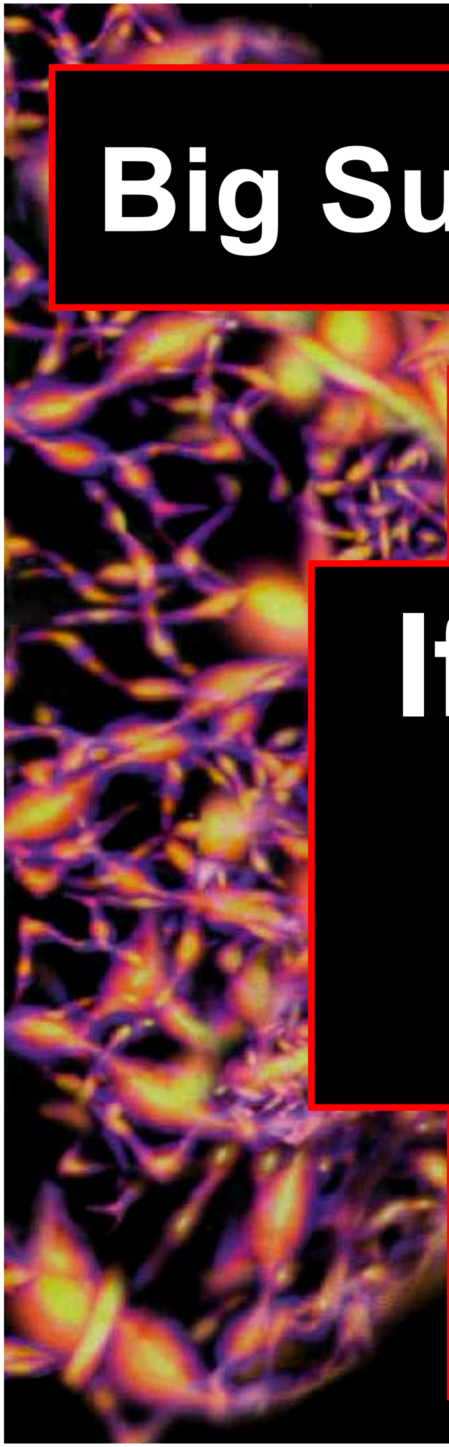


*MACHO = Massive Astrophysical Compact Halo Object
*NACHO = Not an Astrophysical Compact Halo Object

10. Three Big Dark Questions

- Where are the bulk of the baryons?
- How much of a spice are neutrinos?
- What is the cold dark matter particle?

Big Surprise? – No Dark Matter



ASTRONOMY

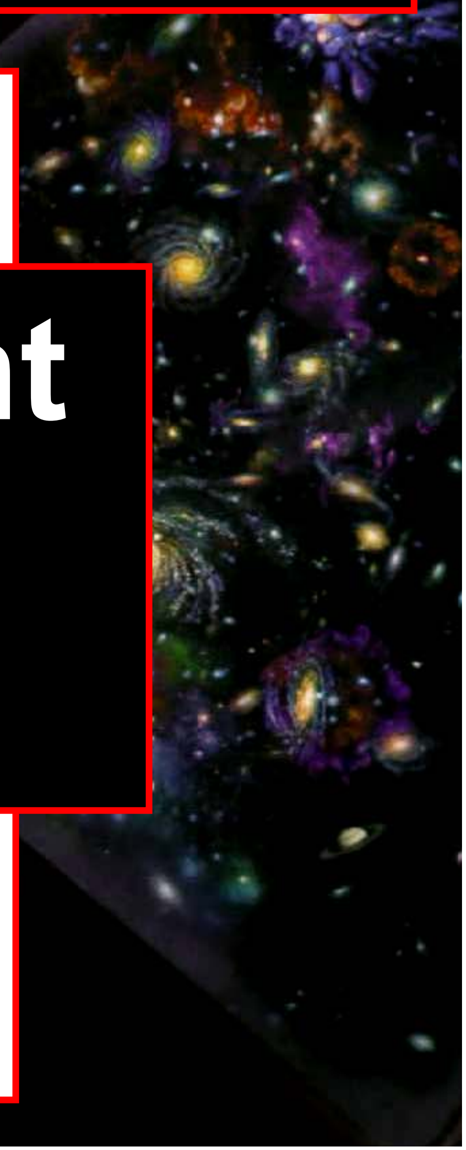
Seeing Through Dark Matter

If MOND is Right I’ll Eat My Powerpoint!

searches for dark matter ha... fruit. This lack of corroboration, co... increasing complexity and “prep... 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

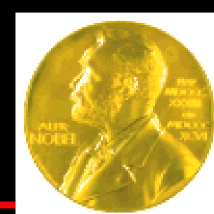
rotation ... spiral galaxies (see the ... case after case, MOND ... maps the observed mass to the observed dynamics. Why would such a direct mapping exist between visible and total mass if in fact dark matter dominates? Moreover, MOND’s explicit predictions for low surface brightness galaxies have been



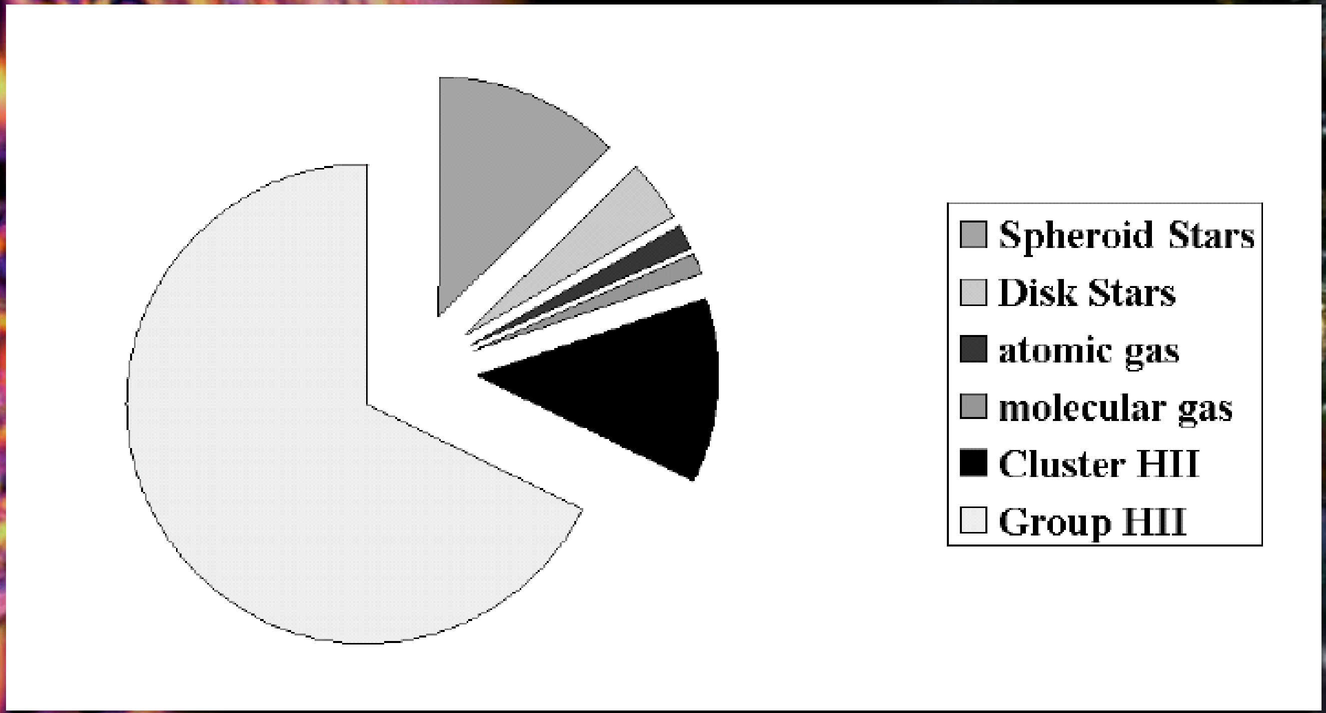

Dark Matter:
10 Challenges Ahead

1. Finish the Neutrino Story

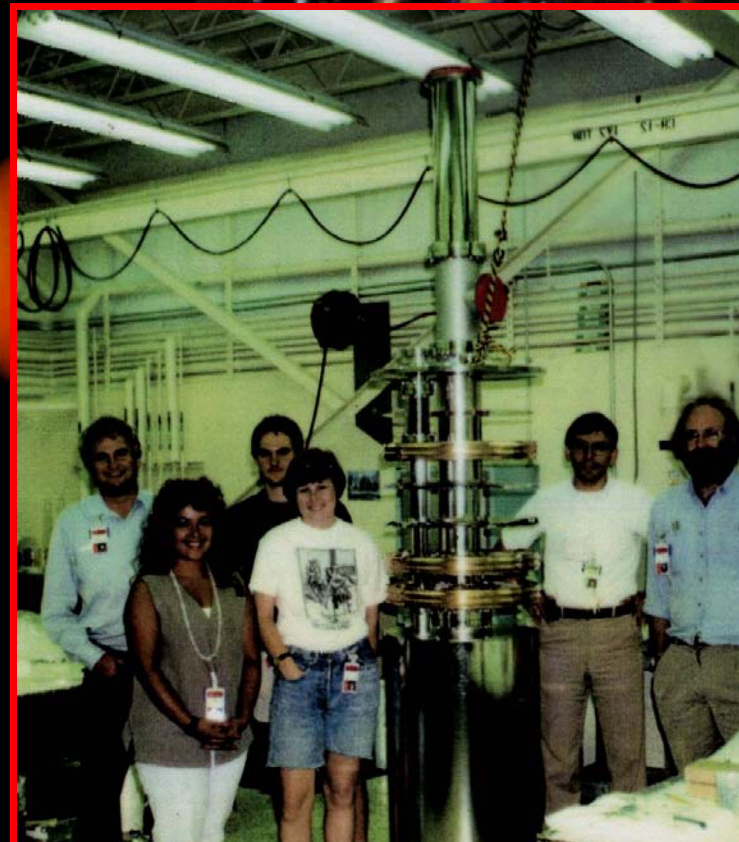
- Three (or more) masses
- Role in large-scale structure
- Other roles in astrophysics
- Detect relic neutrinos



2. Finish the Baryon Story

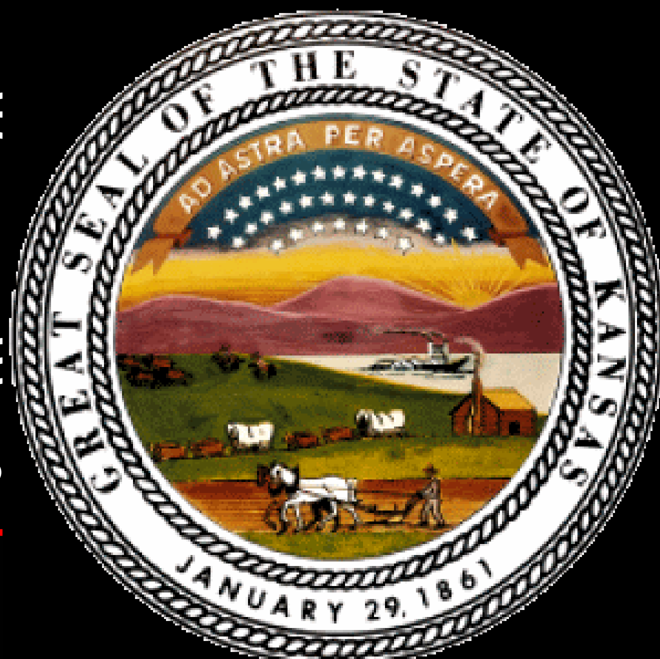


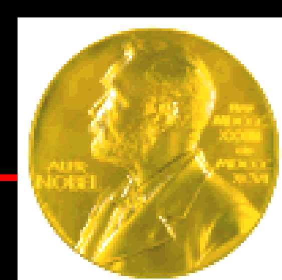
3. Identify the CDM particle



4. The Trifecta: “Closing the DM Circle”

- Directly detect the halo particles
- Produce the … cle
- Detect the a… e halo particles





5. Explain Dark Ratios

- •CDM/Baryon ~ 5
- •Baryon/Neutrino ~ 50
- •Other Ratios?
- •Extra credit:

Dark Energy/Dark Matter

Mod Phys Lett A 2, 1 (1987)

Fermi National Accelerator Laboratory

FERMILAB-Pub-86/66-A
May 1986

Possible Significance of a New Dimensionles Ratio in Cosmology

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Department of Astronomy and Astrophysics, and Physics
Enrico Fermi Institute
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and

Bernard J. Carr
School of Mathematical Sciences
Queen Mary College
Mile End Road
London E1 4NS
England

Observations suggest that the mass density of the Universe is dominated, not by ordinary matter, but by exotic particles which are a relic of the Big Bang. In this case, a new dimensionless cosmological ratio arises, the ratio of the mass density in ordinary matter to that in exotic matter, whose value is about 0.1. *A priori* it might seem remarkable that this ratio should be so close to unity. However, we point out that, for many exotic dark matter candidates, the ratio is related to the fundamental scales of particle physics. A value of order unity arises naturally providing rather simple relationships exist between these scales.

6. Baryogenesis!

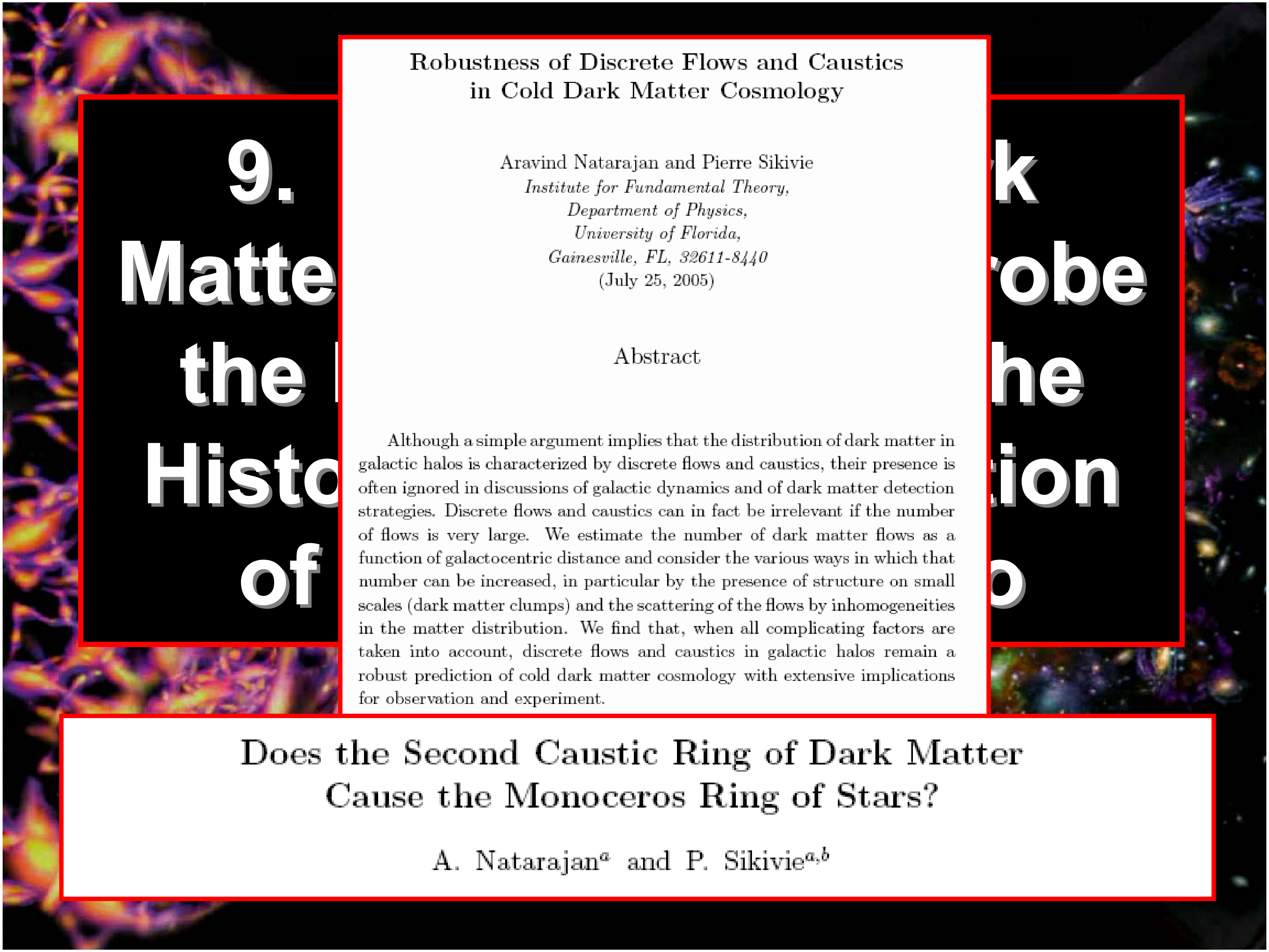
How do massive neutrinos, baryon number violation and CP violation lead to the matter/antimatter symmetry needed to ensure matter in the Universe today

7. Precision Tests of Cosmology/Physics

- $\Omega_{CDM}h^2$: cosmology vs. particle physics
  - Laboratory cross allow prediction of relic abundance (10%)
- $\Omega_B h^2$: BBN vs. CMB
  - Refined measurements of CMB and D/H (few %)
- $\Omega_\nu h^2$: CMB vs. theory (neutrinos slightly heated by $e^\pm$ annihilations); cosmology vs. lab
  - Measure $N_\nu = 3.04$, cross check $\Omega_\nu h^2$ and m_ν

113 – not 112 – relic neutrinos per cm^3

8. Finish CDM Story and convince Jim Peebles, Gary Steigman and Geoffrey Burbidge that ΛCDM is the way it really happened



Robustness of Discrete Flows and Caustics in Cold Dark Matter Cosmology

Aravind Natarajan and Pierre Sikivie
Institute for Fundamental Theory,
Department of Physics,
University of Florida,
Gainesville, FL, 32611-8440
(July 25, 2005)

Abstract

Although a simple argument implies that the distribution of dark matter in galactic halos is characterized by discrete flows and caustics, their presence is often ignored in discussions of galactic dynamics and of dark matter detection strategies. Discrete flows and caustics can in fact be irrelevant if the number of flows is very large. We estimate the number of dark matter flows as a function of galactocentric distance and consider the various ways in which that number can be increased, in particular by the presence of structure on small scales (dark matter clumps) and the scattering of the flows by inhomogeneities in the matter distribution. We find that, when all complicating factors are taken into account, discrete flows and caustics in galactic halos remain a robust prediction of cold dark matter cosmology with extensive implications for observation and experiment.

Does the Second Caustic Ring of Dark Matter Cause the Monoceros Ring of Stars?

A. Natarajan[a] and P. Sikivie[a,b]

10. Discover another "Significant Other Relic"

- Topological debris

- Second kind of CDM

- WIMPzilla

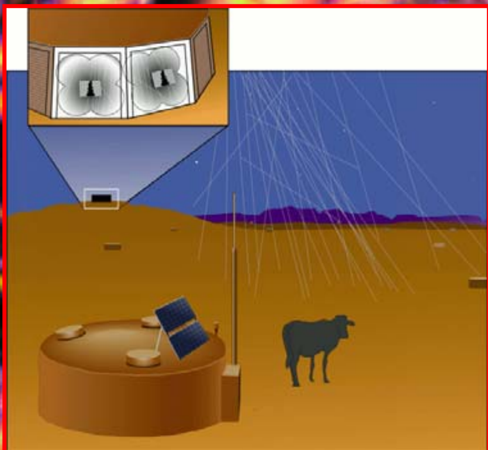
Lessons for Dark Energy

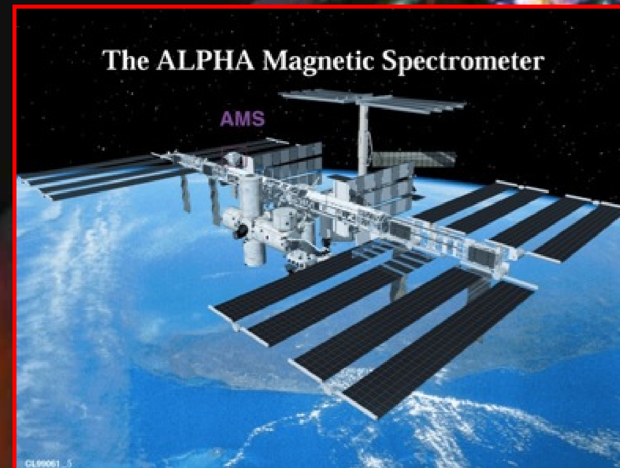
- Twists, Turns and Surprises
  - Particle dark matter not on Zwicky's List
  - At least two kinds of particle dark matter
- It may take a while
  - 32 years & counting (almost there?)
- It takes village
  - Telescopes, accelerators
  - Special detectors, tests of gravity

25+ Years of Boom!

- **1980s:** New ideas from particle physics and convergence of the fields
- **1990s:** Data-driven cosmology
- **2000s:** Precision Cosmology
- **2010s:** **Golden Age with Deepened Understanding of the Universe and the Laws that Govern it**

Some of the Tools in the LHC Era





IceCube

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

DUSEL

- Ton dark-matter search, double beta decay
- CMB polarization
- "Astronomy telescopes"