Reflections on 50 years of "April Physics"

50 years PRL
moving physics forward

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The University of Chicago

My Approach

- "Game-changing ideas/discoveries"
- Not tied to PRL articles (thanks Jack)
- April Meeting bias (particles, astro, nuclear, … not condensed matter, amo, biological physics, etc)
- NB: I am a theorist! And not without bias and other imperfections

E D I T O R I A L

A Caution to Theorists

We reprint below, by permission, a letter we recently received from one of our referees, unaltered except for the deletion of a name. Written by a prominent theoretical physicist, it was sent as the cover

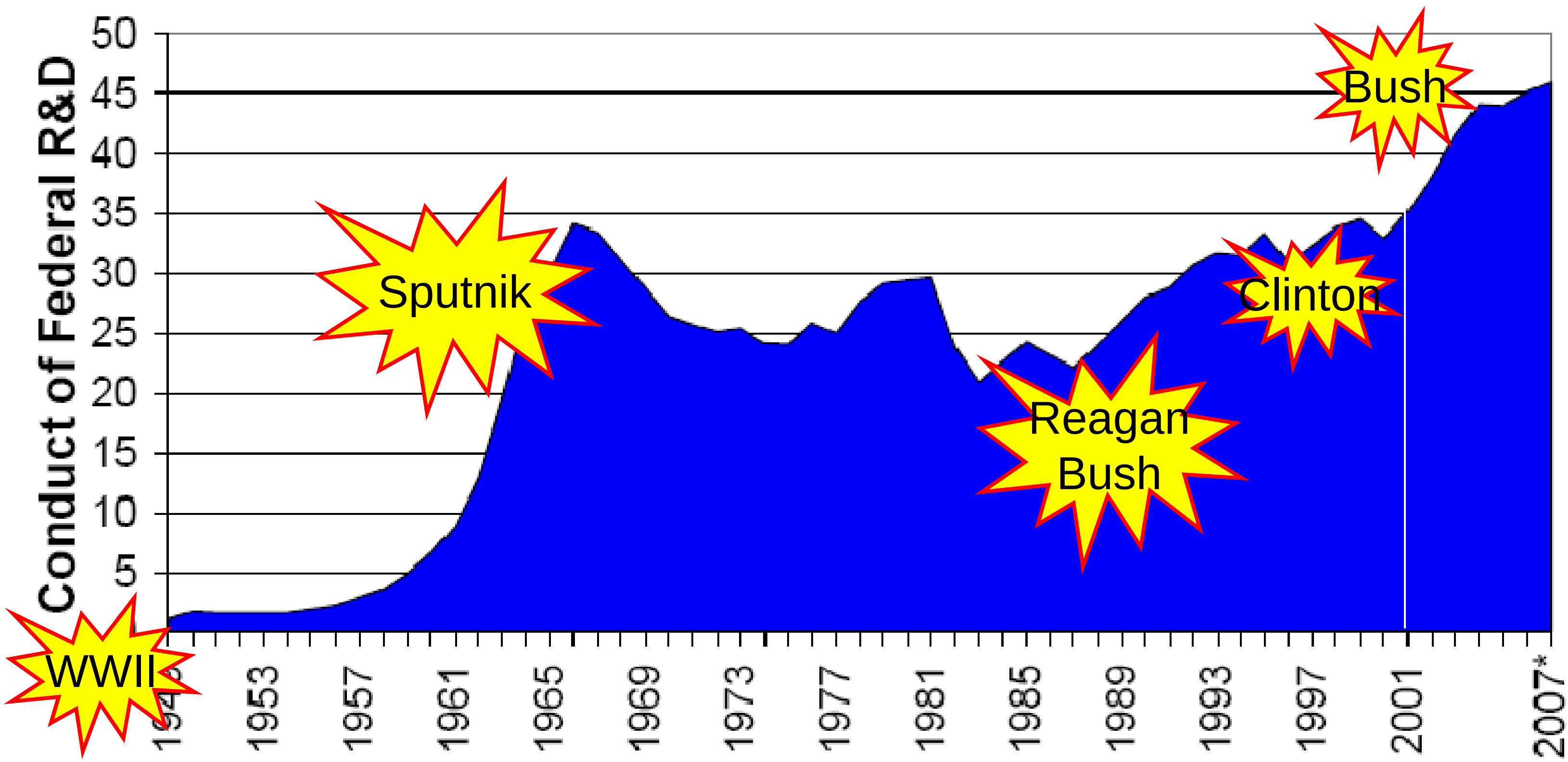
Some Statistics

- Issue 1: 0 errata; 25 articles; 1 editorial
- Issue 2: 1 errata; 17 articles; 1 editorial
- Issue 3: 5 errata; 15 articles; 1 editorial
- Issue 4: 2 errata; 14 articles; 0 editorial
- Issue 5: 2 errata; 11 articles; 1 editorial
- Issue 6: 0 errata; 11 articles; 1 editorial
- Issue 7: 5 errata; 23 articles; 0 editorial

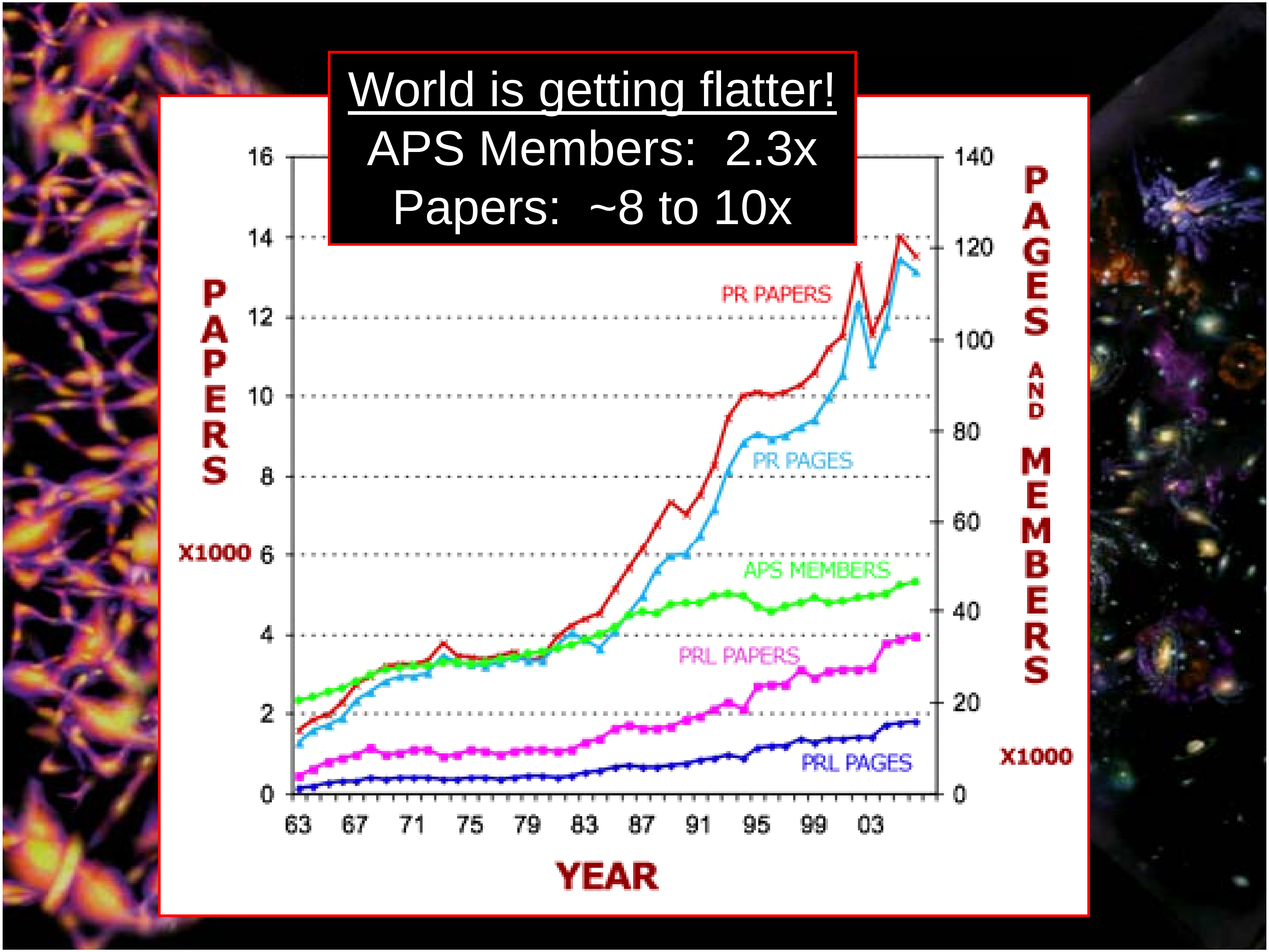
stricting its pages to contributions with solid content. To accept such qualitative contributions would invite a flood of such notes, I believe, for it is obviously an easy thing to write inconclusive or speculative notes of this type about a variety of topics."

George L. Trigg

Federal Non-Defense R&D Spending
(Outlays in billions, constant 2000 dollars)



*President's 2007 Budget



World is getting flatter!
APS Members: 2.3x
Papers: ~8 to 10x
PAPERS
X1000
PAGES AND MEMBERS
X1000
PR PAPERS
PR PAGES
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PRL PAPERS
PRL PAGES
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71
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95
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03

Physics circa 1958

- Astrophysics: 200” telescope with photographic plates (1% efficient); all about stars!; cosmology practiced by a handful of astronomers; H_0 = 550 km/s/Mpc → 280 km/s/Mpc; highest redshift (z ~ 0.1!)
- Particle physics: more particles than understanding
- Nuclear physics: recent divorce from particle physics, two complementary models (shell and liquid drop excitation focused on different dof)
- General relativity: mysterious (and marginal)
- CM/AMO: BCS just published (field theory comes to CM), maser a few years old and laser soon to come (birth of quantum optics)

The four flavors × three colors of "known" quarks.

Charmed Baryon

Both drawings courtesy of A. De Rujula

Re-alignment of Nuclear Physics

- **Hot QCD:** Heavy Ions (quark/hadron transition and phase diagram)
- **Cold QCD:** Nuclear Structure and full extent of chart of nuclides (effective theory of nucleons from QCD) – both nucleonic and shape dof interesting
- ,
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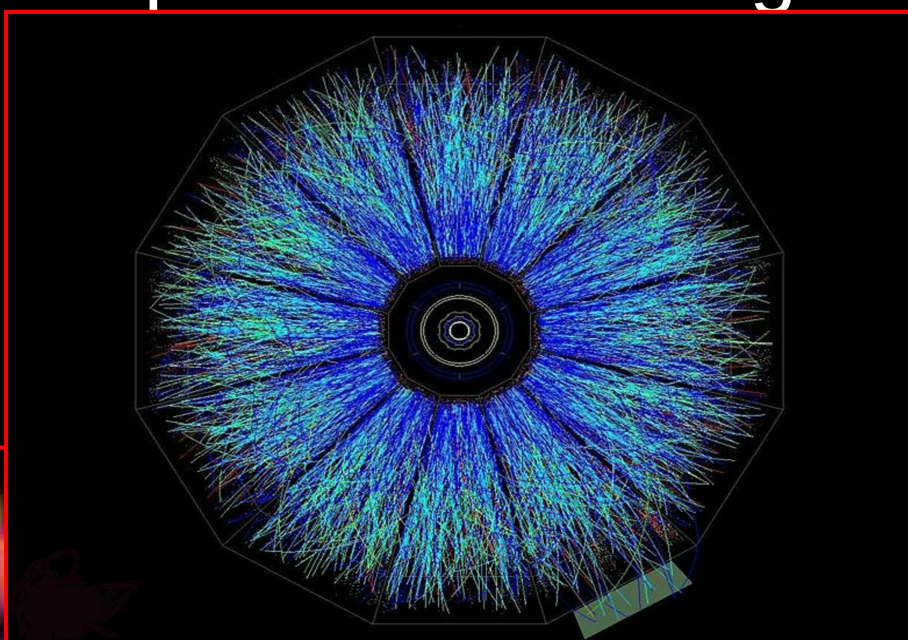

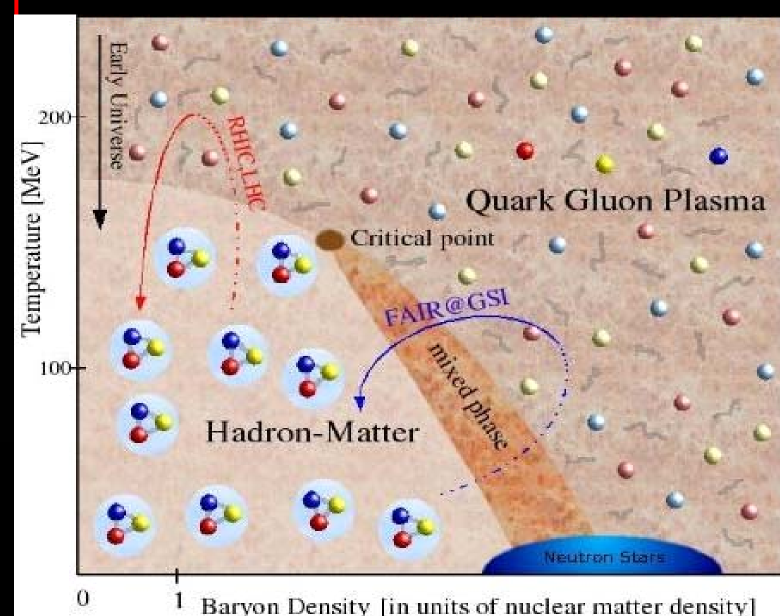

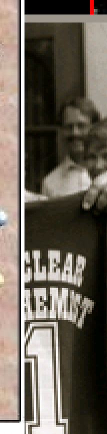

2. Triumph of Field Theory

deeper understanding of Nature: from quarks to the cosmos

- 1954: Yang-Mills: Gauge Theories
- 1957: BCS
- 1961: Nambu, Higgs: Symmetry Breaking
- 1970 ‘t Hooft/Veltman: Renormalizability of Gauge Theories
- Kadanoff, Fisher and Wilson: Renormalization Group
- Standard Model → Grand Unification
- Effective Field Theories (nuclear and particle)
- Opens up early Universe
- Superstring Theory

Quarks + Field Theory: Blossoming of Particle Physics

from the particle zoo and bootstraps to the standard model and beyond

- Yang-Mills: NonAbelian Gauge Theory, PR 96, 191(1954)
- Feynman/Gell-Mann: V-A, PR 109, 193 (1958)
- Symmetry Breaking: e.g., Nambu, PR 122, 345 (1961)
- Electroweak: S. Weinberg, PRL 19, 1264 (1967)
- Asymptotic Freedom: Wilczek, Gross and Politzer, PRL 30, 1343/1346 (1973)
- **Standard Model of Particle Physics: SU(3)xSU(2)xU(1)**
- Grand Unification: Georgi, Quinn and Weinberg, PRL 33, 451 (1974)
- Supersymmetry, String Theory, and the rest is history: e.g., Heterotic String, PRL 54, 502 (1985)

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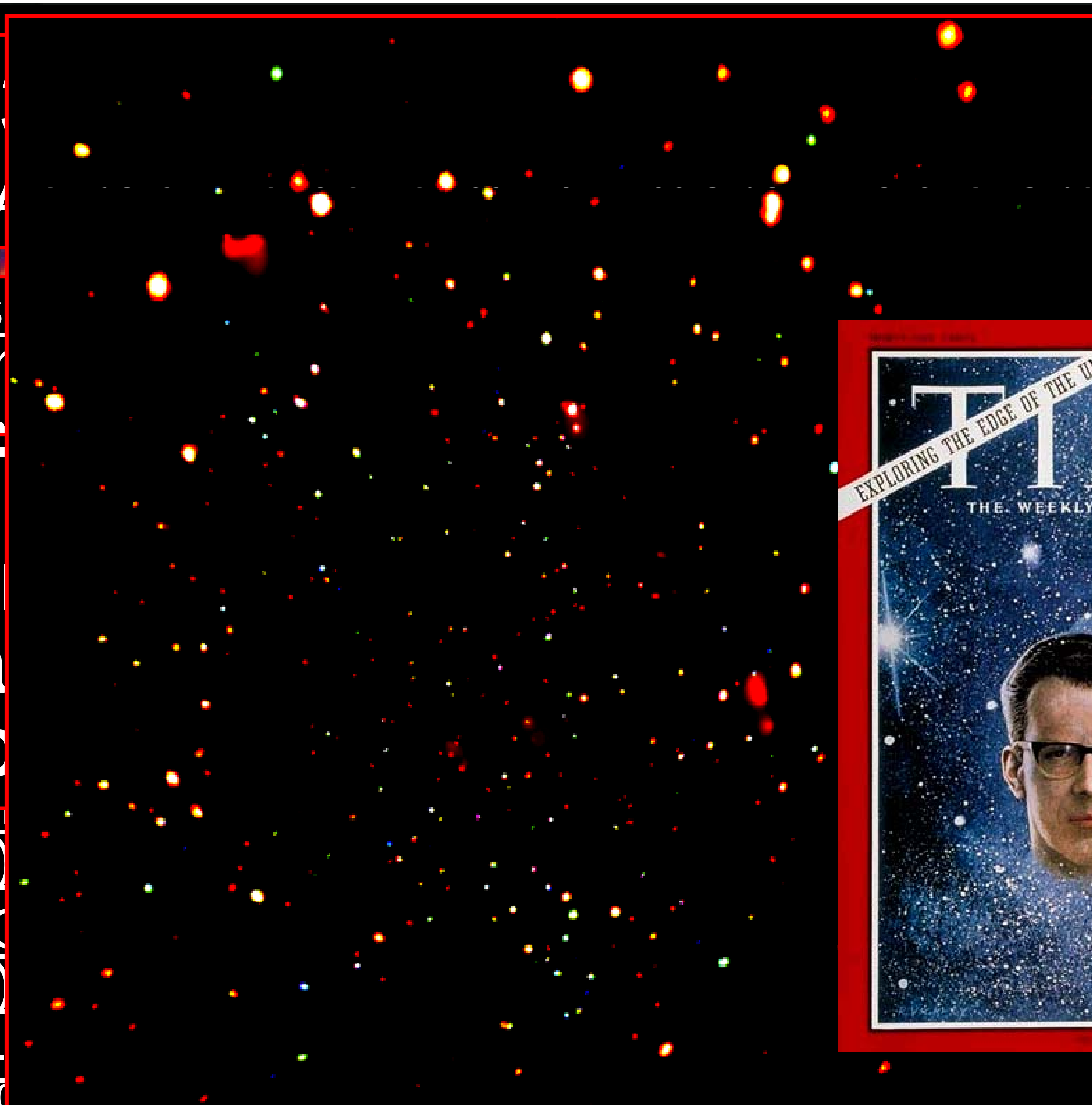
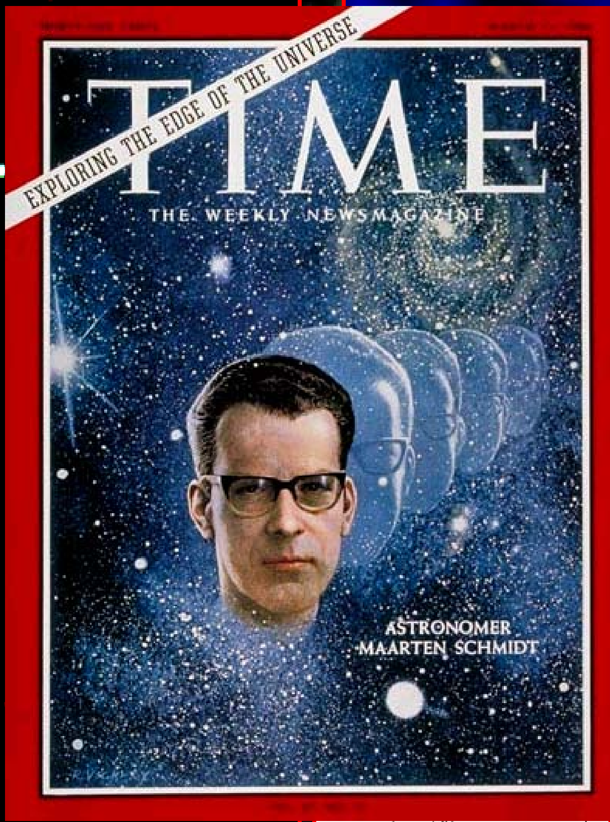
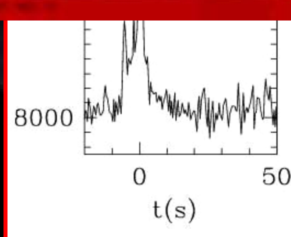
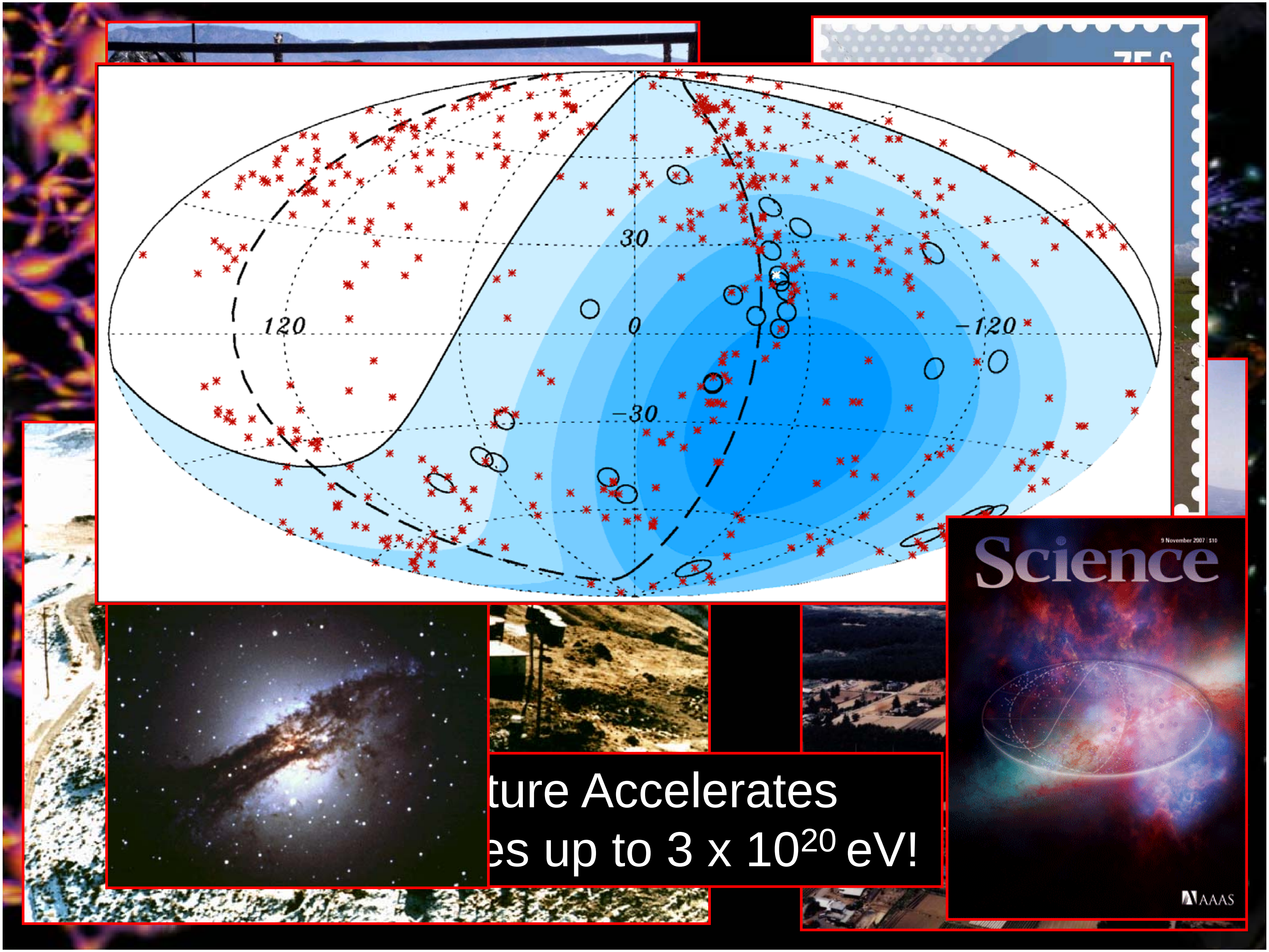


Chandra Deep Field:
SMBHs at the Edge of the Universe







30
120
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Science
9 November 2007 | $10
AAAS
ture Accelerates
es up to 3 x 10^{20} eV!

4. General Relativity Comes of Age

- Mossbauer detection of grav redshift (5×10^{-15}): PRL 4, 163 & 337 (1960)
- Kerr BH: PRL 11, 237 (1963)
- Shapiro Time Delay: I.I. Shapiro, PRL 13, 789 (1964); 20, 1265 (1969)
- Joe Weber and GW detectors, PR 117, 306 (1960); PRL 22, 1320 (1969)
- Maximum mass of a neutron star: PRL 32, 324 (1974)
- Hulse/Taylor binary pulsar
- GP-B (2007)
- Gravitational lensing (1979): 0957+961
- 201x: LIGO/LISA open the Gravitational
- Wave Window!

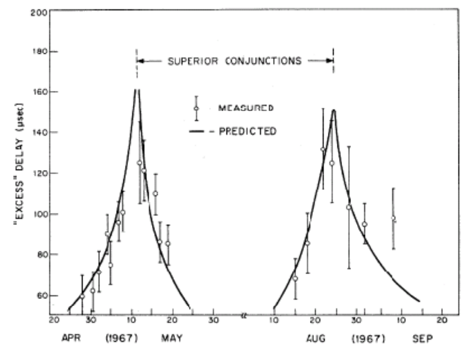
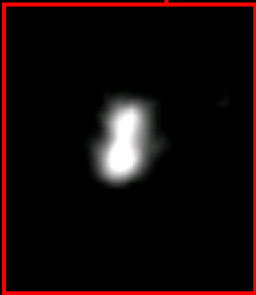
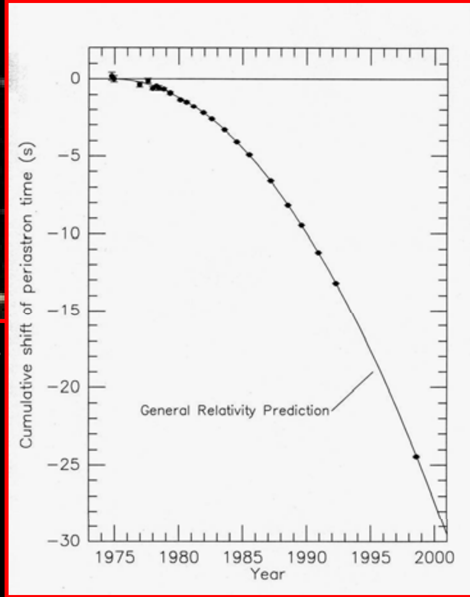
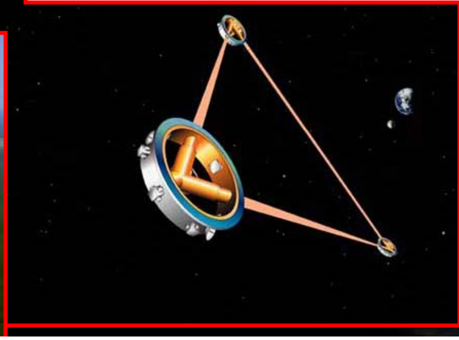


FIG. 3. Comparison of measured and predicted effects of general relativity on Earth-Mercury time delays. Predictions are based on orbits determined from other data.

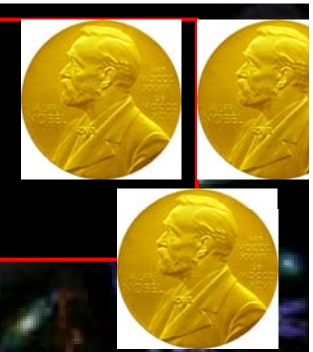




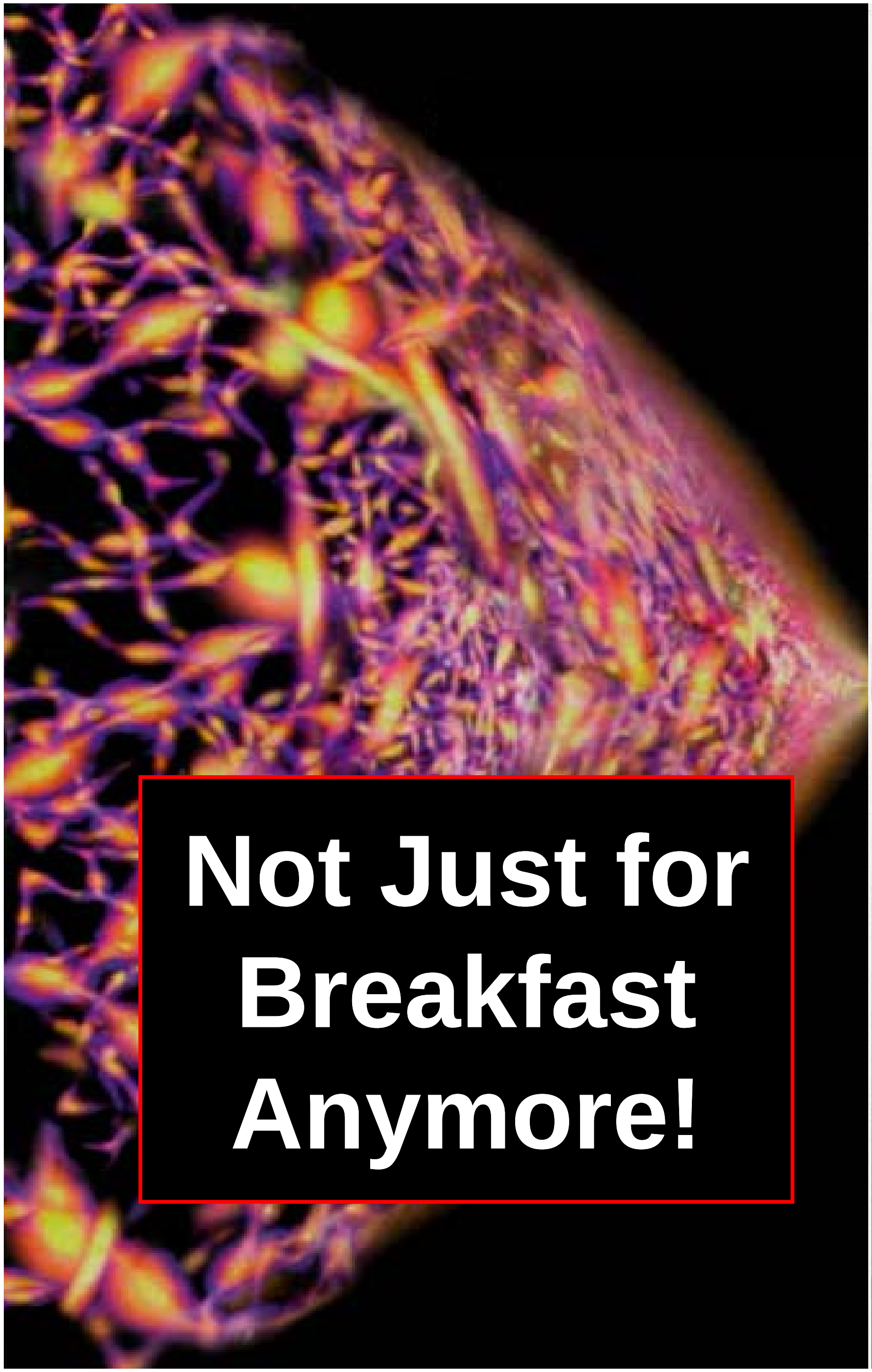


5. Neutrinos Come of Age

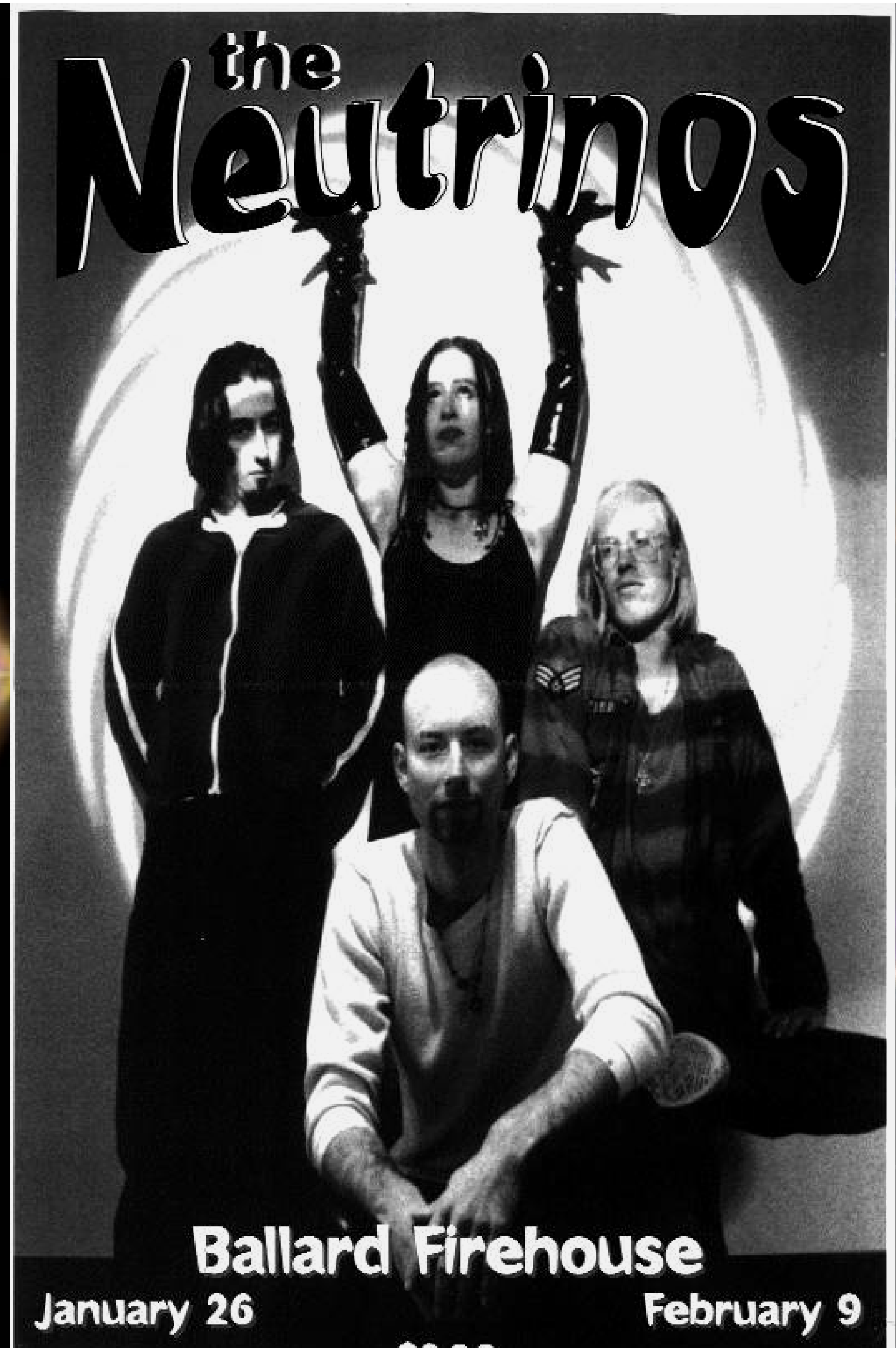
from hypothetical to center stage



- Detection: Reines et al 1960, PR 117, 159 (1960)
- Two kinds of neutrinos!: Danby et al, PRL 9, 36 (1962)
- Three kinds of neutrinos: Perl et al, PRL 22, 1489 (1975)
- Extra-terrestrial neutrinos - solar and SN1987A: PRL 20, 1205 (1968); 58, 1490 (1987); 86, 5651 (2001); 87, 071301 (2001)
- Mass/oscillations → physics beyond the standard model: PRL 81, 1562 (1998)
- Important role in astrophysics: stellar explosions, large-scale structure and nucleosynthesis,

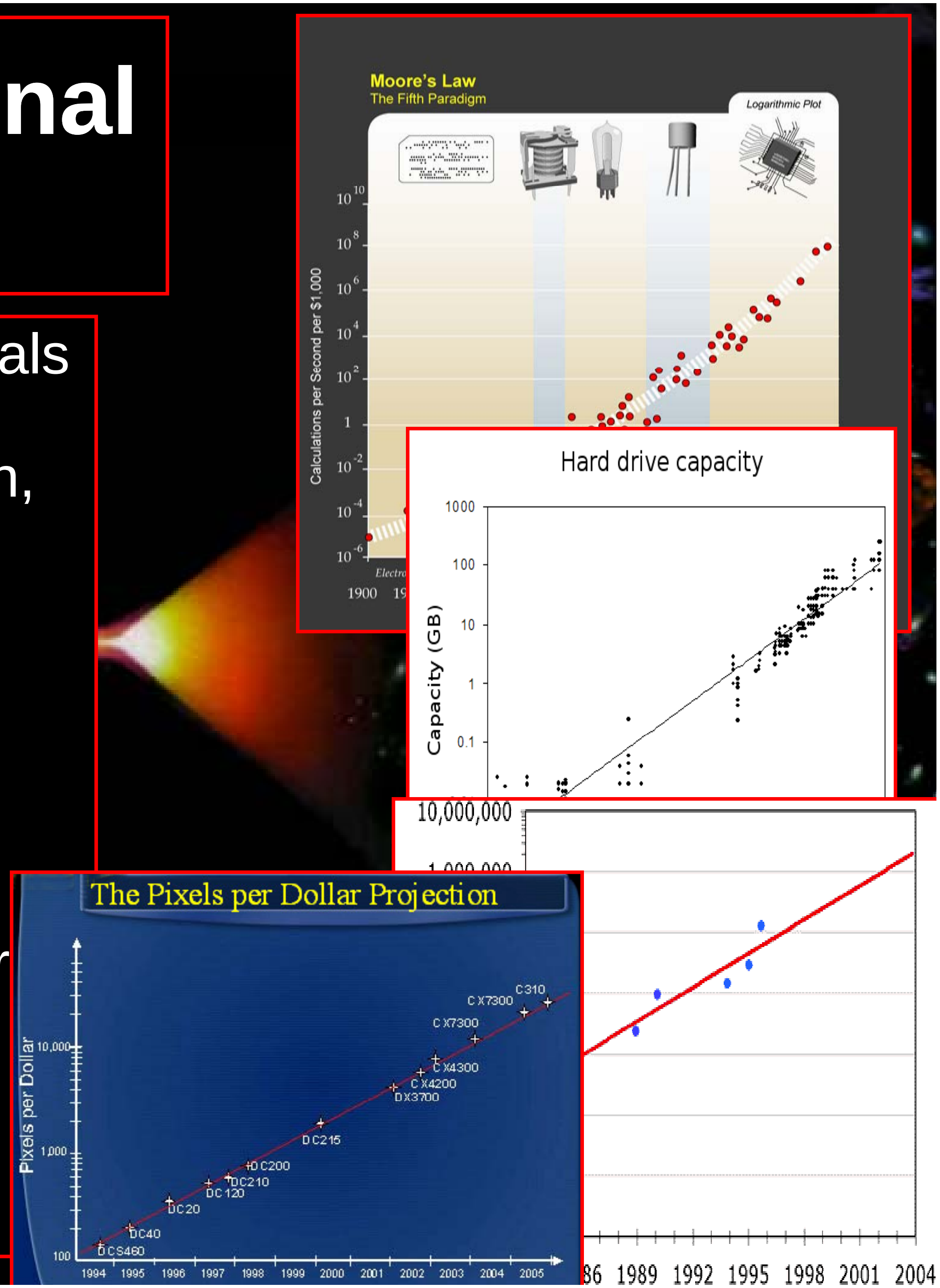


Not Just for Breakfast Anymore!



6. Computational Physics

- Driven by the 4 exponentials of the information age: speed, storage, bandwidth, sensor complexity
- Third branch of science (after experiment and theory)
- Now essential to the other two branches!
  – Top quark
  – Large-scale structure



Top Quark Discovery

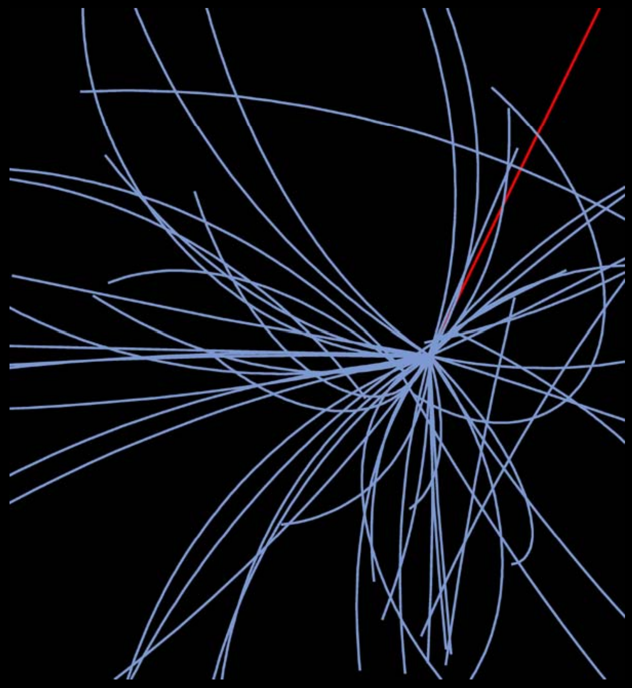
a handful of tops from trillions of events!

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\overline{p}p$ Collisions with the Collider Detector at Fermilab

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark



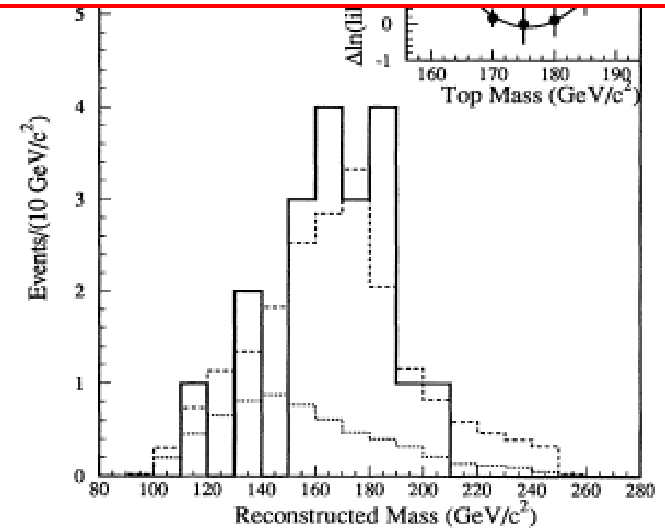
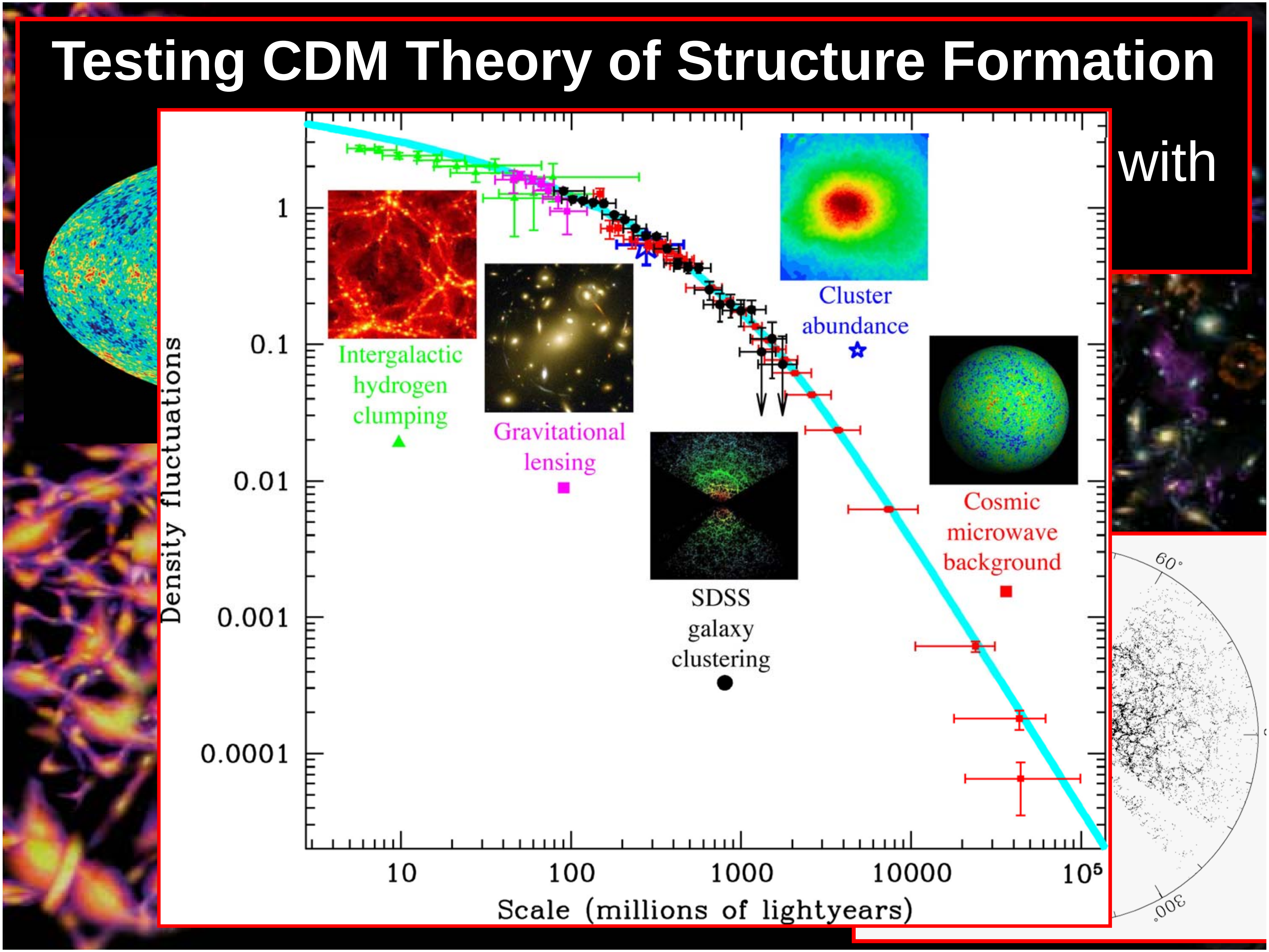
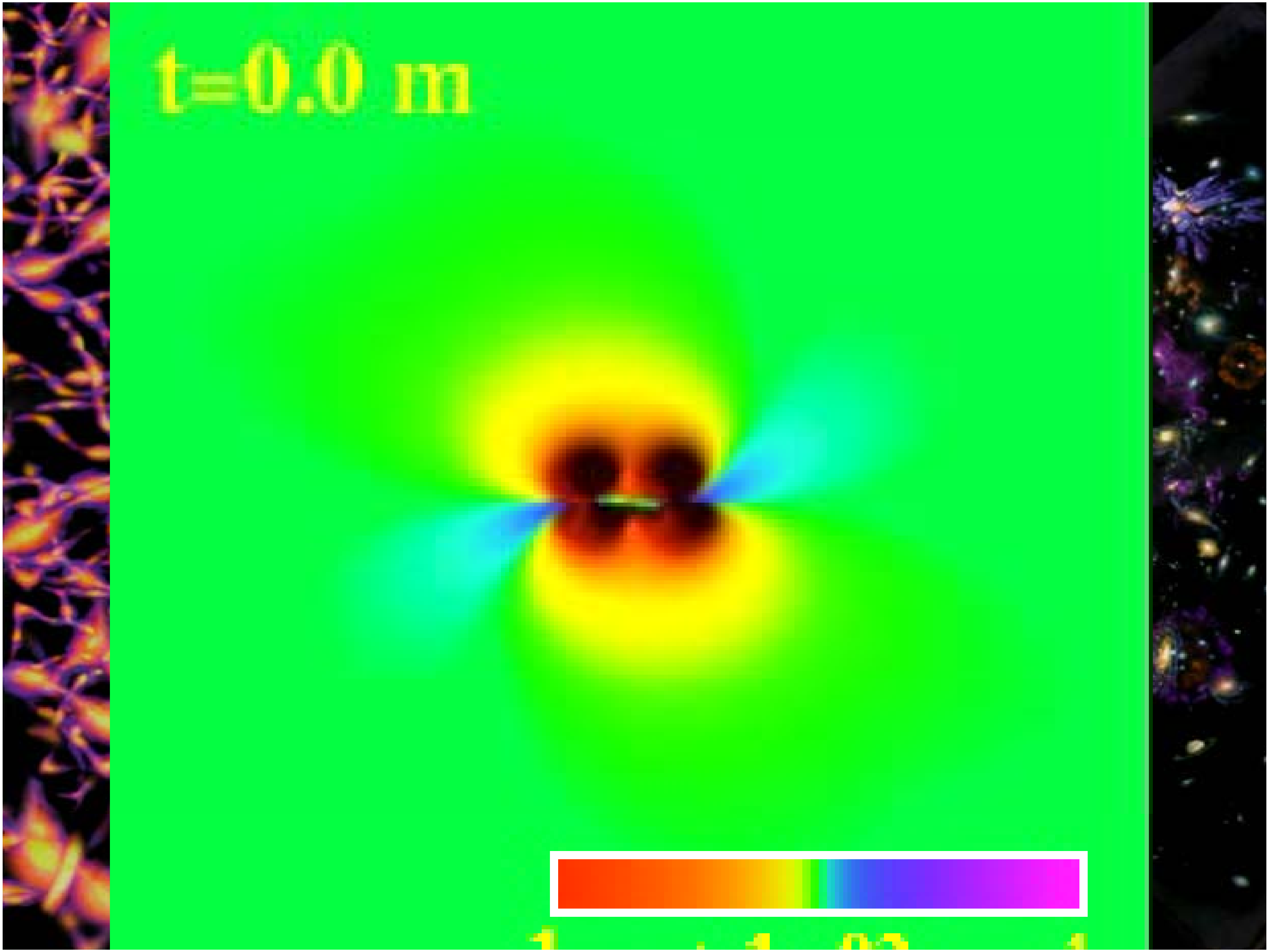


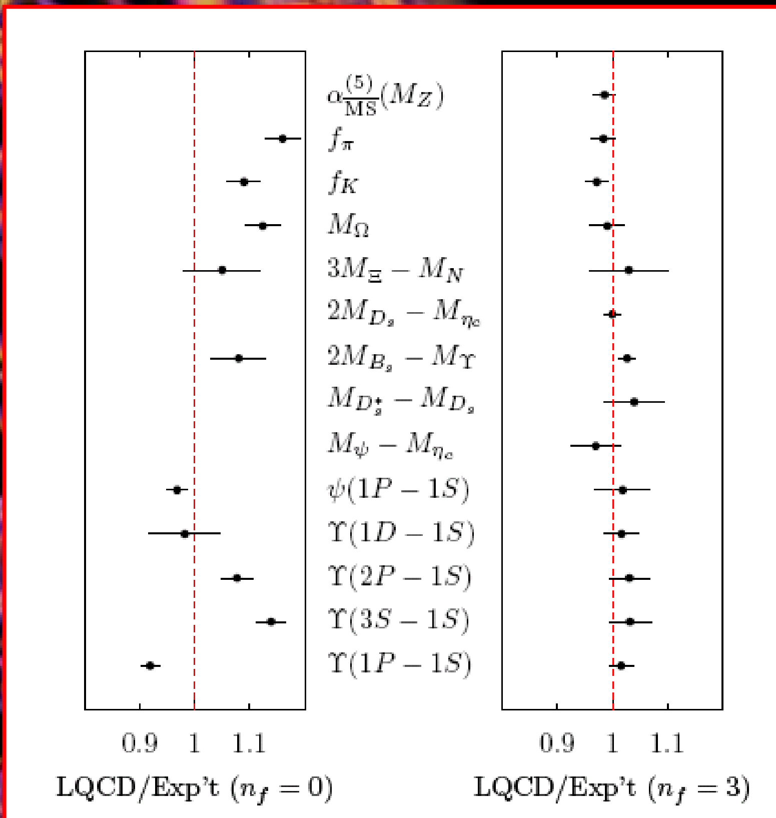
FIG. 3. Reconstructed mass distribution for the b-tagged $W+ \geq 4$-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{top} = 175$ GeV/c^2 (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

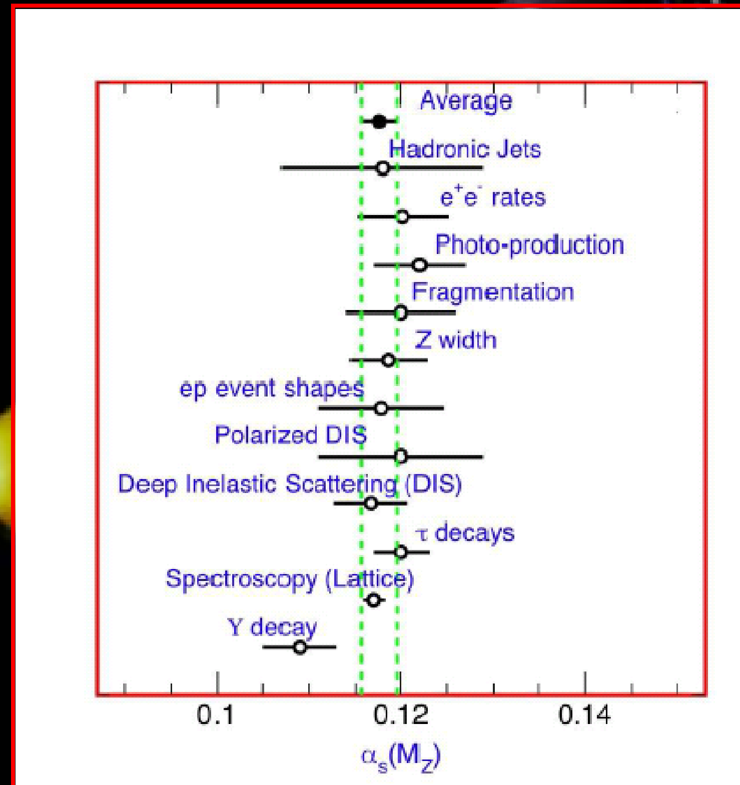
Testing CDM Theory of Structure Formation with




t=0.0 m

Lattice QCD





$$m_s = 88(0)(3)(4)\ \text{MeV}$$

$$\hat{m} = \frac{1}{2}(m_u + m_d) = 3.2(0)(1)(2)\ \text{MeV}$$

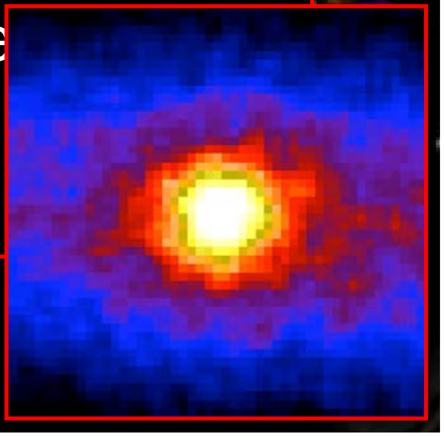
$$m_s/\hat{m} = 27.2(1)(3)(0)$$

Errors are (statistical)(systematic)(perturbative).

8. New Telescopes

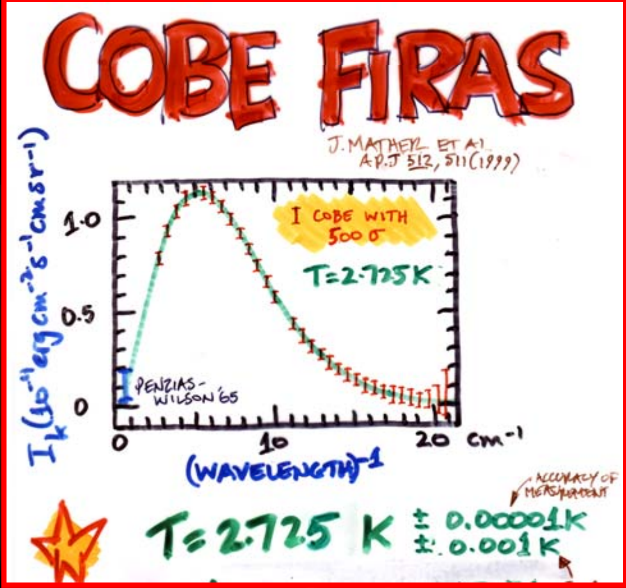
New Eyes on the Universe

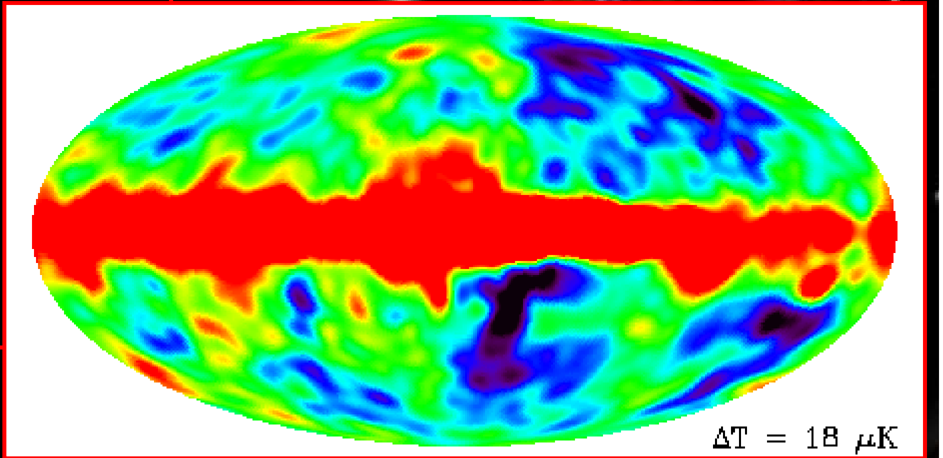
- The Telescope (1609): G. Galileo, PRL,..
- Cosmic rays: directly sample material from around the Universe
- Radio: electrons in magnetic fields, hydrogen, …
- CMB photons: echo of the big bang
- X-rays: black holes and neutron stars at work
- Infra-red: peer into the dusty corners and hi-z Universe
- Gamma rays: neutron stars and black holes
- Neutrinos: look deep inside the sun, supernovae, …
- Coming soon: Gravitational waves, Dark Matte particles, other relics from the early universe



9. Cosmology
"becomes real science"

- 1965: Penzias/Wilson (Roll and Wilkinson, PRL 16, 405 1966 – first confirmation)
- 1967: CP Violation (Cronin & Fitch)
- 1992: COBE Spectrum and anisotropy
- Inflation, dark matter and all that
- Cosmic Acceleration
- 2000s: WMAP, SDSS → precision cosmology





The Establishment of the Hot Big Bang Model (1964 – 1980)

Radiation-dominated era

(10^{-6} sec to 400,000 yrs)

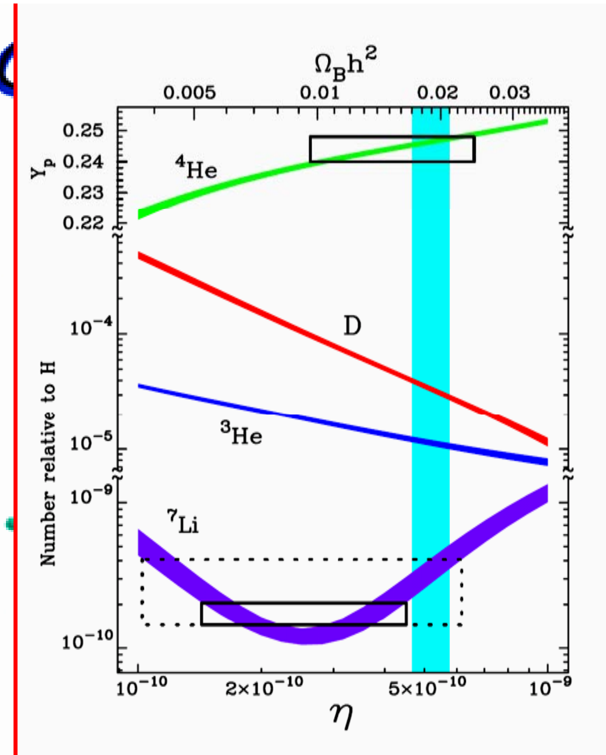
- Thermal bath of particles, trace amount of matter
- Big successes: Cosmic Microwave Background and Big-bang Nucleosynthesis, Quark Soup Beginning
- Missing pieces: cosmological parameters, formation of structure (galaxies, clusters) and initial conditions

ORDINARY MATTER: FROM

INFLATION
BARYOGENESIS

10^{-5} SEC

TRANSITION FROM
QUARKS → NEUTRONS, PROTONS



FORMATION OF ATOMS
COSMIC MICROWAVE BACKGROUND

400,000 YRS

QSO LIGHT

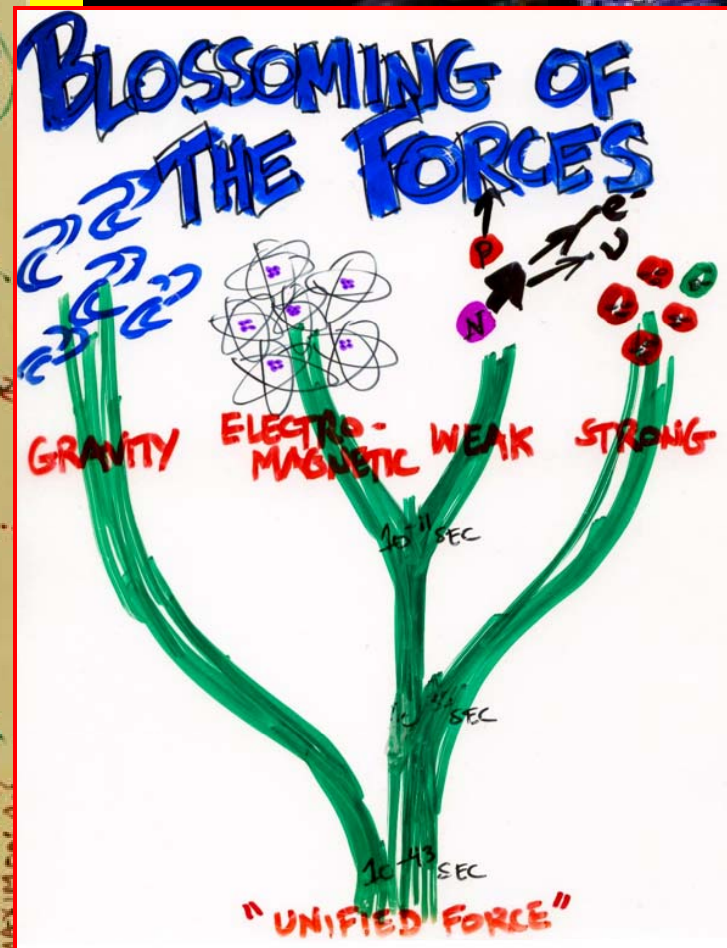
1 BILLION YRS
FIRST QUASARS

INTERGALACTIC GAS

ABSORPTION OF QUASAR LIGHT BY HYDROGEN
$\Omega_B \geq 0.04$

$\Omega_B h = 0.2$
$\Omega_B = 0.04$
CMB

HERE
14 Billion
stars, dust
BHs, NS, people


THE COMPLETE HISTORY OF THE UNIVERSE
D=10
EXTRA DIMENSIONS?
QUANTUM GRAVITY EPOCH
t ≲ 10^-43 sec
T ≳ 10^19 GeV
Quark-anti Quark asymmetry
MONOPOLES
homo-geneity isotropy flatness
INFLATION
GUT EPOCH
t ≈ 10^-34 sec
T ≈ 10^14 GeV
W-S-G/FINAL EPOCH
t ≈ 10^-12 sec
T ≈ 10^3 GeV
QUARK ENSLAVEMENT
t ≈ 10^-5 sec
T ≈ 200 MeV
Baryons
QUARK NUGGET
BIG BANG NUCLEOSYNTHESIS
t ≈ 10^-2 - 10^2 sec
T ≈ 10 - 0.1 MeV
νtrinos
MATTER DOMINATION
t ≈ 10^10 sec
T ≈ 10 eV
DECOUPLING
t ≈ 10^13 sec
T ≈ 1 eV
Stanford, CA
3K
pancake?
protogalaxy?
GRAVITINO?

BLOSSOMING OF THE FORCES
GRAVITY
ELECTRO-MAGNETIC
WEAK
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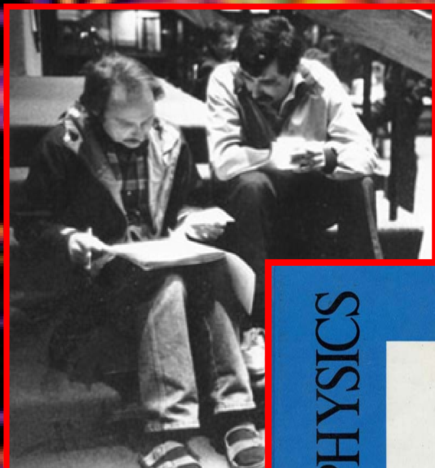
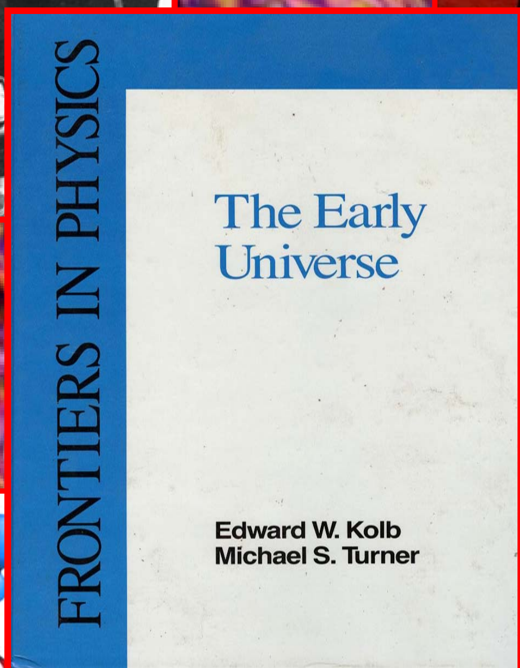
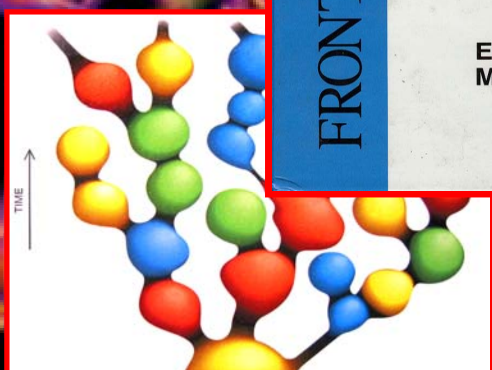
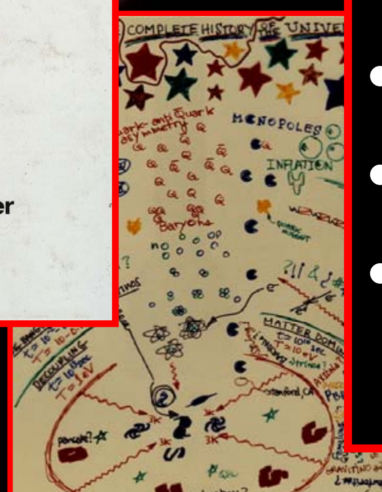
"UNIFIED FORCE"

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









"Creativity Based" driven by ideas from particle physics

- Inflation:
- Cosmic Strings
- Baryogenesis
- Magnetic Monopoles
- Phase Transitions
- Hot and Cold Dark Matter

Two Really Important Ideas

with deep connections between quarks and the cosmos

Inflation: brief period of rapid (accelerated) expansion accounts for smoothness, flatness; heat of the big bang; and seed inhomogeneities

Particle dark matter: bulk of the dark matter that holds the Universe together resides in a sea of elementary particles left over from the big bang

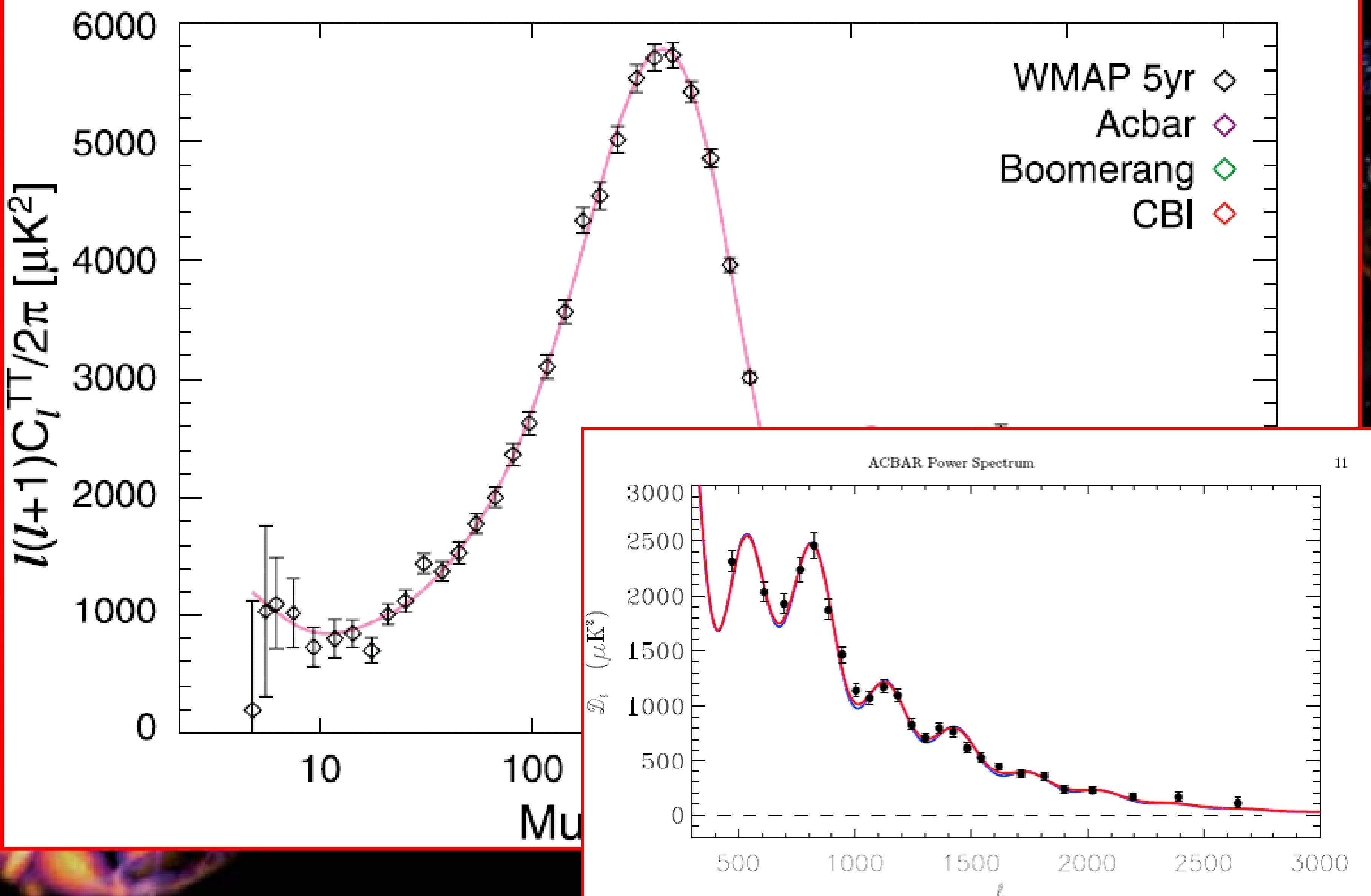
Neutrinos contribute few 0.1%

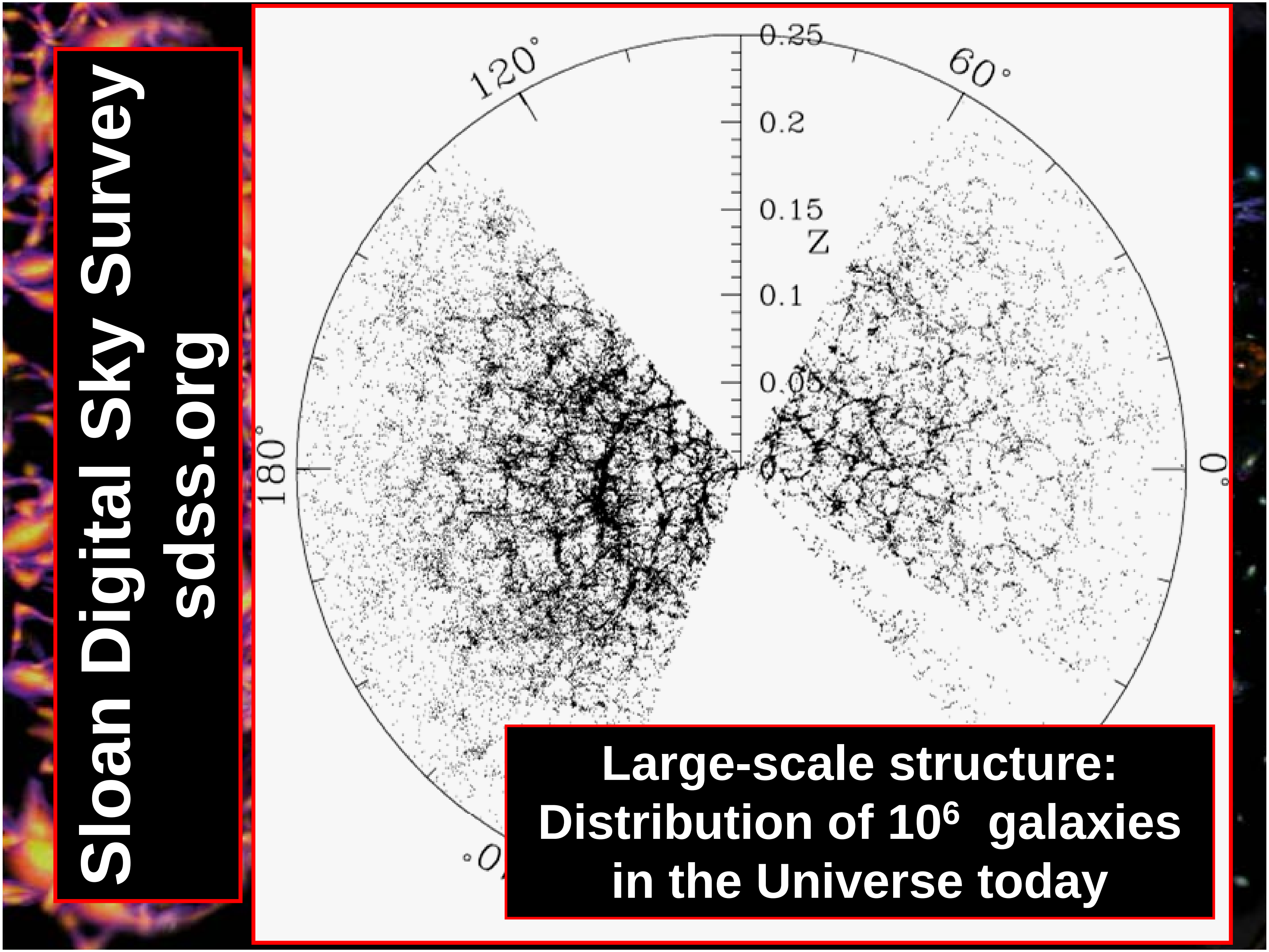
1990s: Data-driven Cosmology
insights on the early and late Universe

- 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, …

WMAP CMB Sky

Curve = concordance cosmology




Sloan Digital Sky Survey
sdss.org
120°
60°
180°
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0.25
0.2
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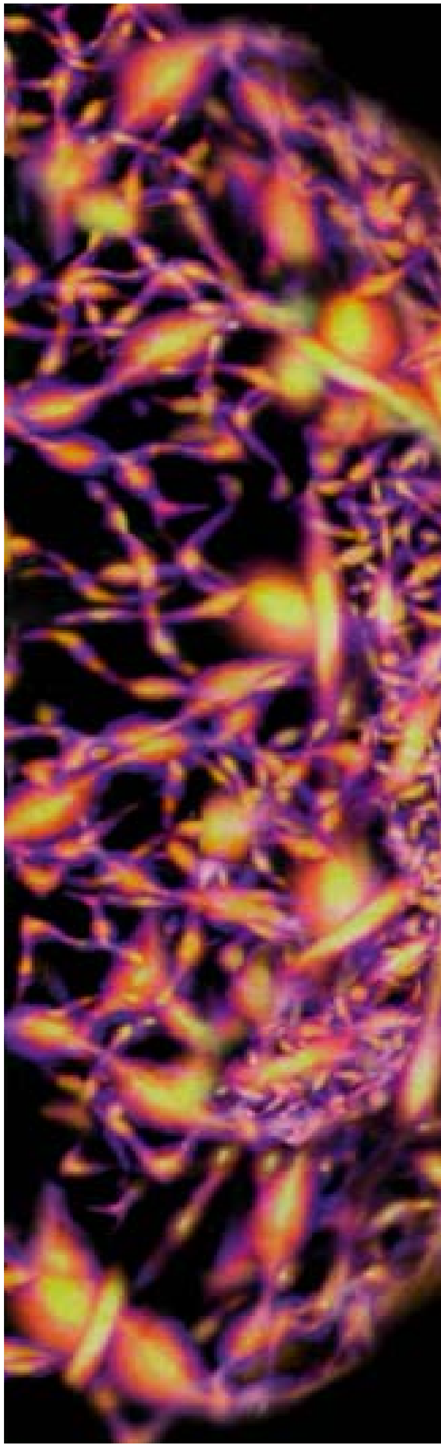
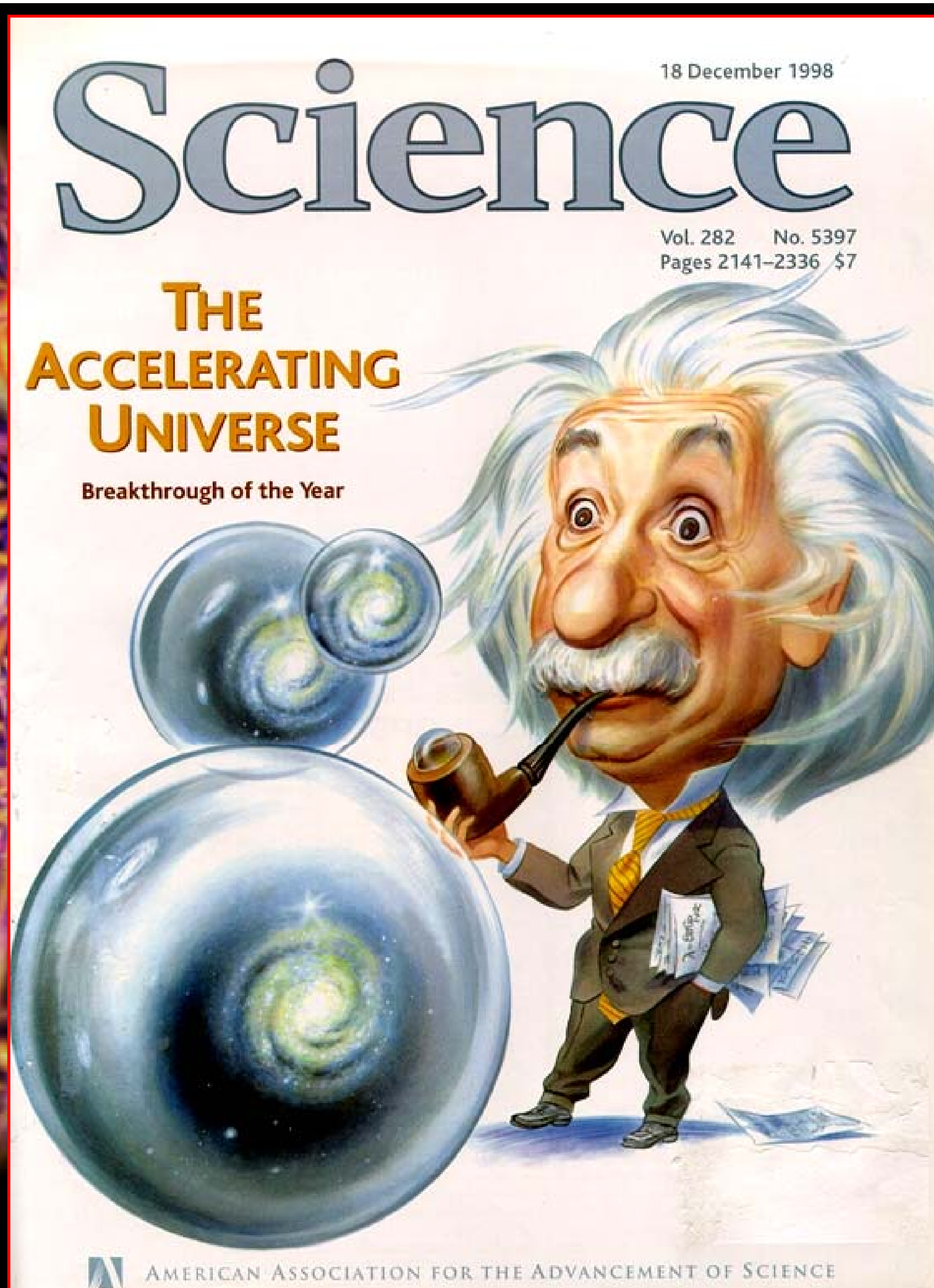
Z
0.1
0.05
0
Large-scale structure:
Distribution of 10^6 galaxies
in the Universe today



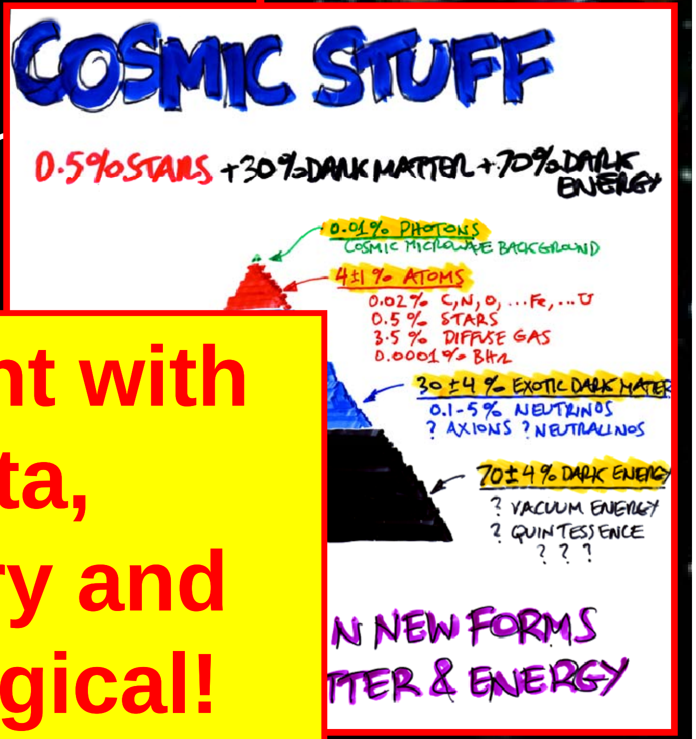


18 December 1998
Science
Vol. 282 No. 5397
Pages 2141–2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

"Precision Cosmology"

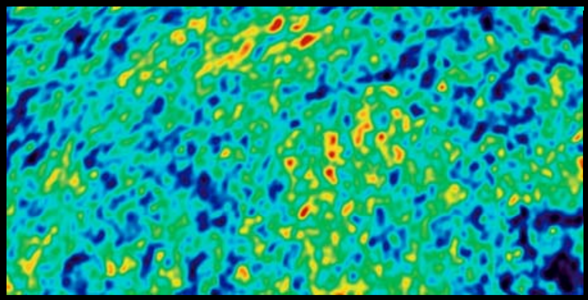
with SDSS + WMAP: concordance model

- Standard Hot Big Bang of the 1970s
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- Consistent with inflation
- Precision set of cosmological para
  - $\Omega_0 = 1.005 \pm 0.006$ (uncurved)
  - $\Omega_M = 0.256 \pm 0.013$
  - $\Omega_B = 0.045 \pm 0.002$
  - $\Omega_\Lambda = 0.72 \pm 0.02$
  - $H_0 = 70 \pm 1.3$ km/s/M
  - $t_0 = 13.73 \pm 0.12$ Gy
  - $N_\nu = 4.4 \pm 1.5$



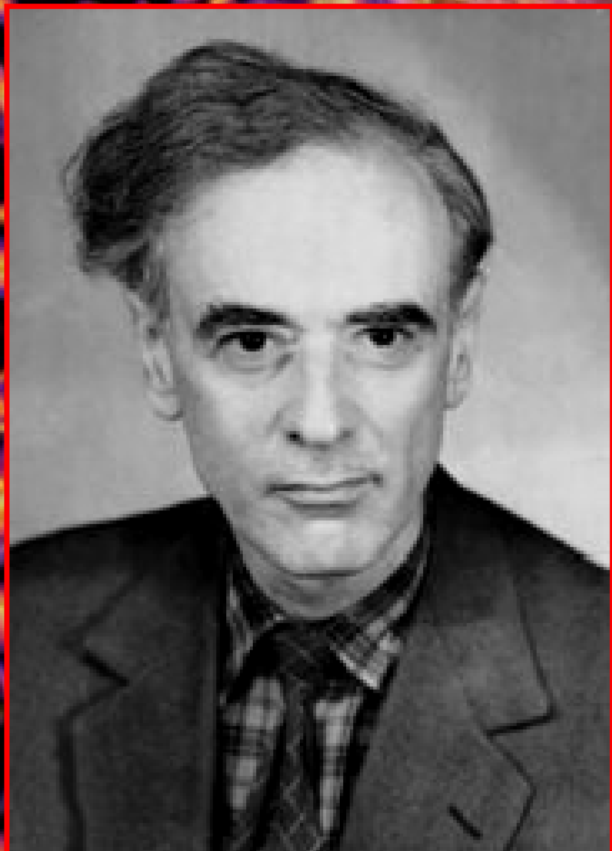
Consistent with all data, laboratory and cosmological!

The Largest Things in the Universe Began from Subatomic Quantum Fluctuations!



WOW!

Landau on Cosmologists



Often in Error, Never in Doubt!

10. Cosmic Convergence: Merging of the Frontiers of Astro, Nuclear and Particle Physics

- What are Dark Matter and Dark Energy?
- How did the Baryon Asymmetry originate?
- How did Neutrinos shape the Universe and what are they telling us about the unification of the forces?
- What is the full extent of the Chart of Nuclides and how did the Chemical Elements Originate?
- How are Nature’s forces and particles Unified?
- What is the origin of Space, Time and the Universe?
- What are the limits of General Relativity?
- What’s at the center of a Black Hole?
- How do Things in the Universe work?

Some General Trends

- Bigger (cost, scope, number of authors)
- Faster (internet, archives, …)
- More Collaborative and Democratic
- More Interdisciplinary
- More International:
  - World is Flat (three equal regions)
  - Dominance no longer an option
  - US (PRL) Leadership is important – principles, values, innovation,

Physics in the 21st Century?

- Defined by its subfields?
- Defined by an approach?
- Defined by what physicists do?

Physical Review Letters will be there!

Looking Forward: Big Questions Ripe to Answer

- What are space and time?
- What is the dark matter?
- How did the Universe begin?
- What is the full extent of the table of nuclides?
- How were the chemical elements made?