

# 25 Years of Quarks and the Cosmos

28 February 2011

Michael S. Turner/Kavli Institute for Cosmological Physics

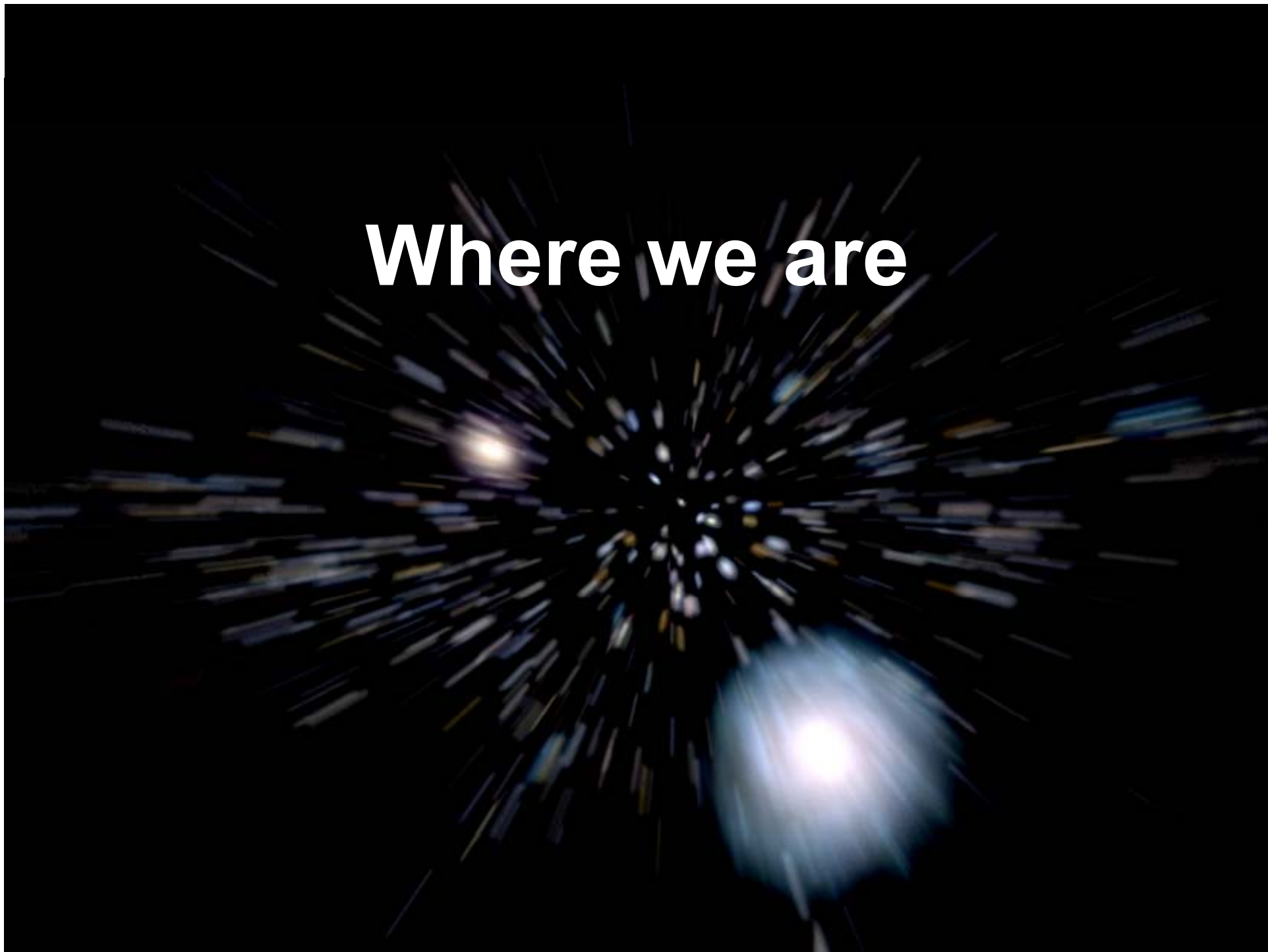
**#25!**



**#70!**

**Les Rencontres de Physique  
de la Vallée d'Aoste**

**Where we are**



# Today's Cosmology

based upon precision measurements

- From lumpy quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- Consistent with inflation
- Precision cosmo parameters
  - $\Omega_0 = 1.005 \pm 0.006$  (uncurved)
  - $\Omega_M = 0.273 \pm 0.014$
  - $\Omega_B = 0.046 \pm 0.0016$
  - $\Omega_{DE} = 0.73 \pm 0.015$
  - $H_0 = 70.4 \pm 1.3$  km/s/Mpc
  - $t_0 = 13.75 \pm 0.11$  Gyr
  - $N_\nu = 4.34 \pm 0.9$

## COSMIC STUFF

0.5% STARS + 30% DARK MATTER + 70% DARK ENERGY

0.01% PHOTONS  
COSMIC MICROWAVE BACKGROUND

4.8% ATOMS

...or

DARK MATTER

TRINOS  
UTRALINOS

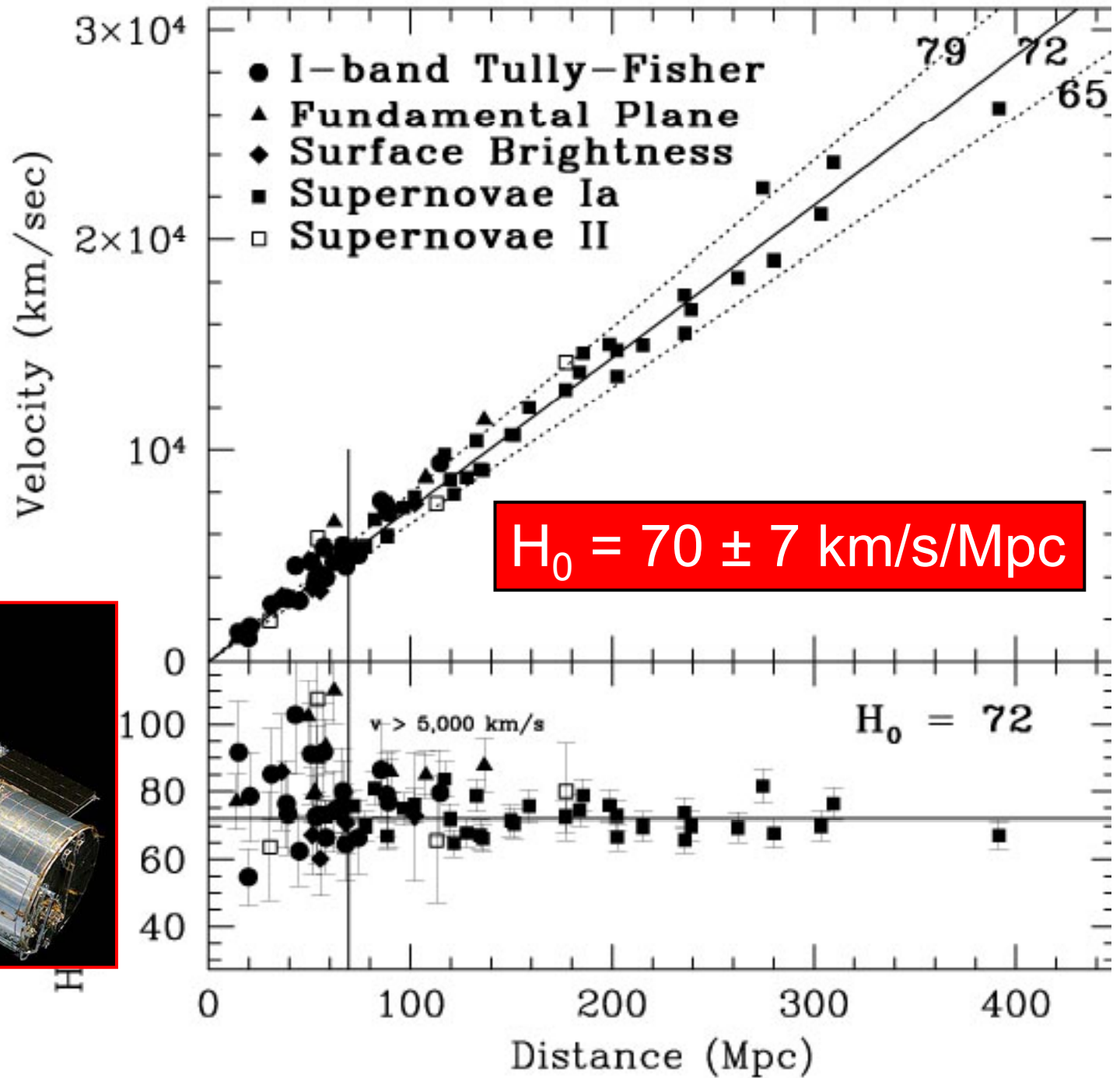
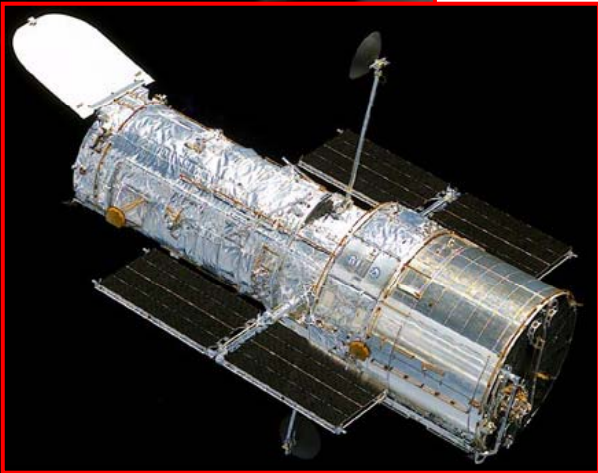
DARK ENERGY

UM ENERGY  
TRESSENCE  
? ?

AS

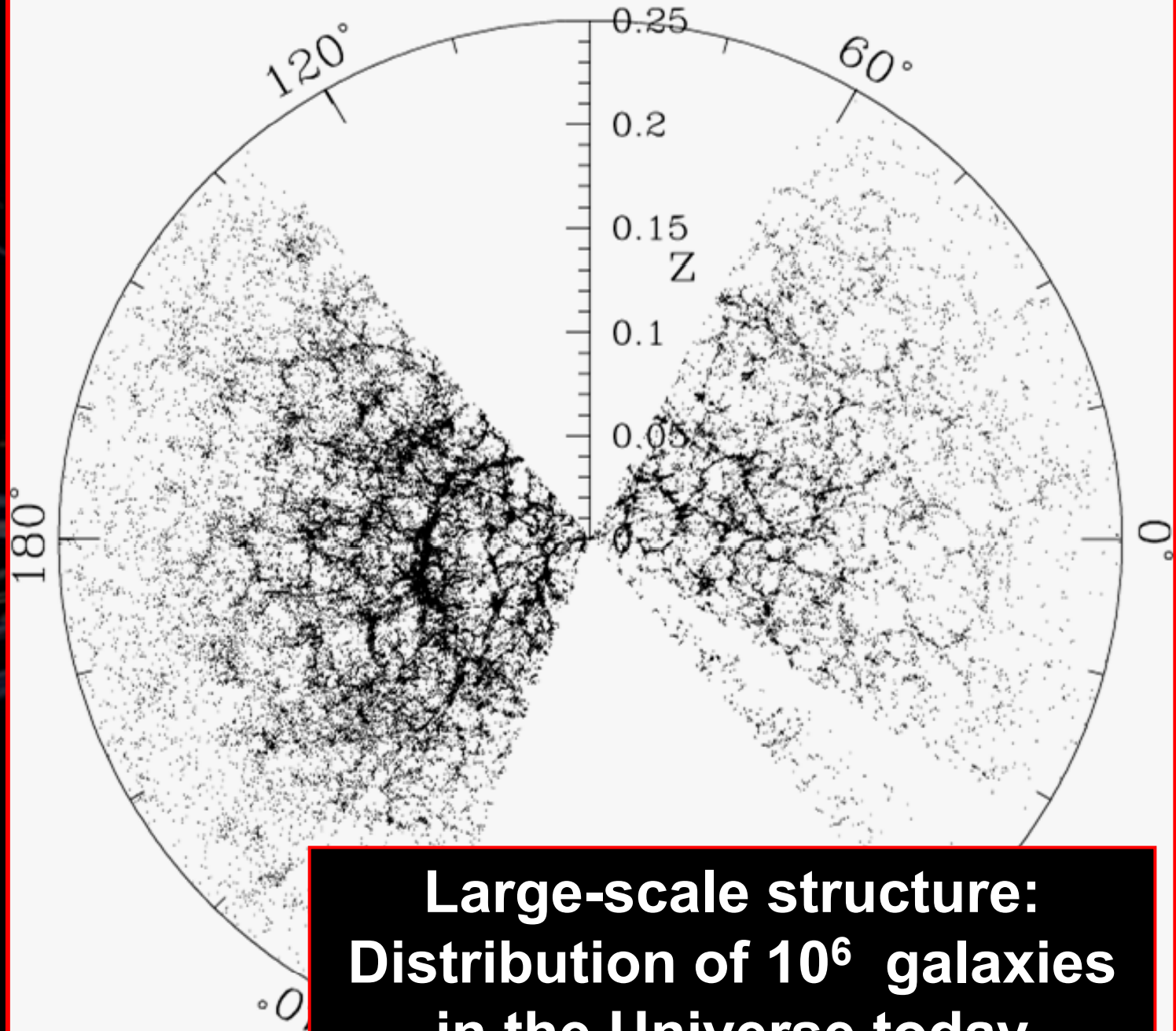
of MATTER & ENERGY

**Consistent with  
all data,  
laboratory and  
cosmological!**



# Sloan Digital Sky Survey

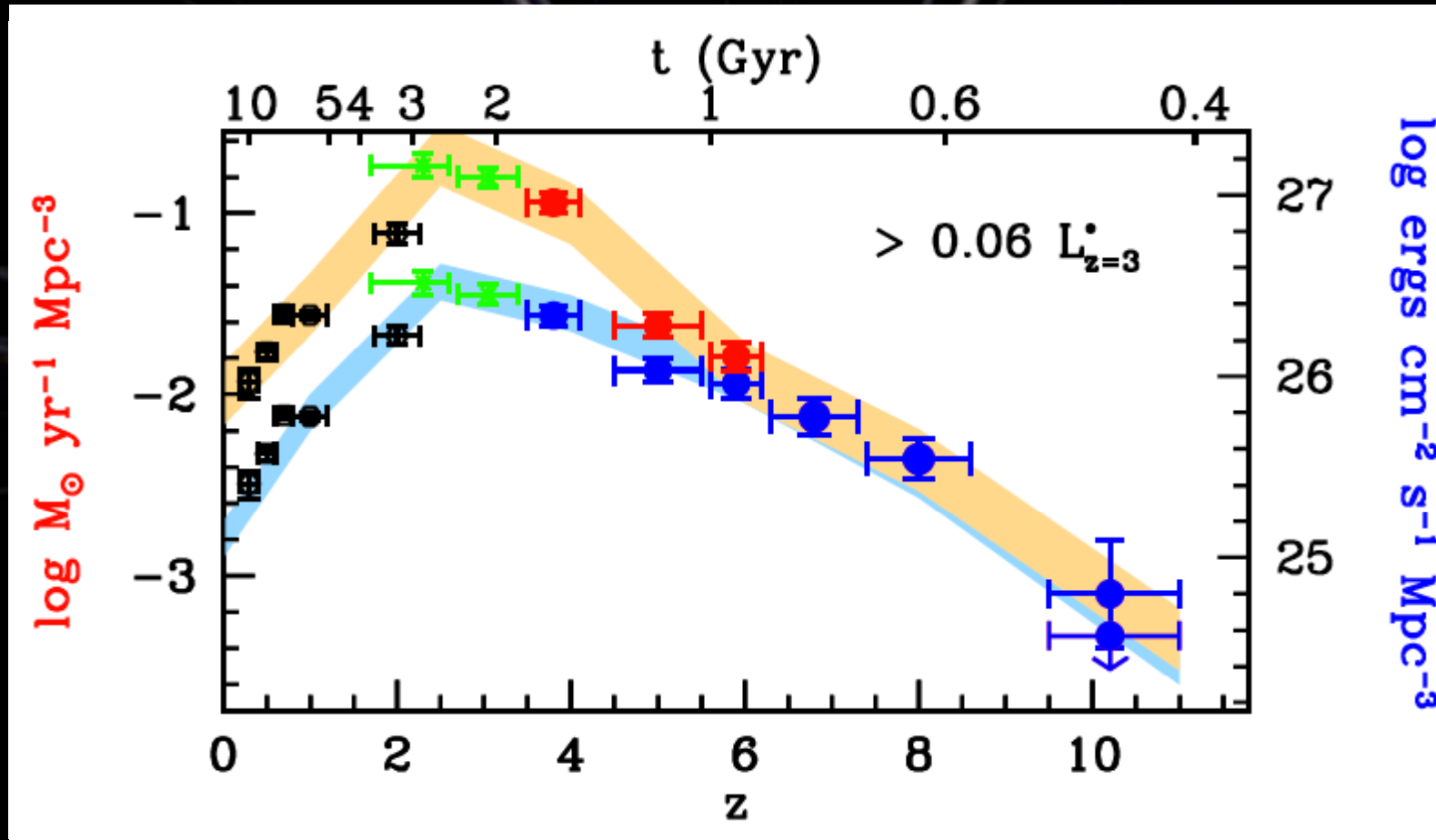
[sdss.org](http://sdss.org)



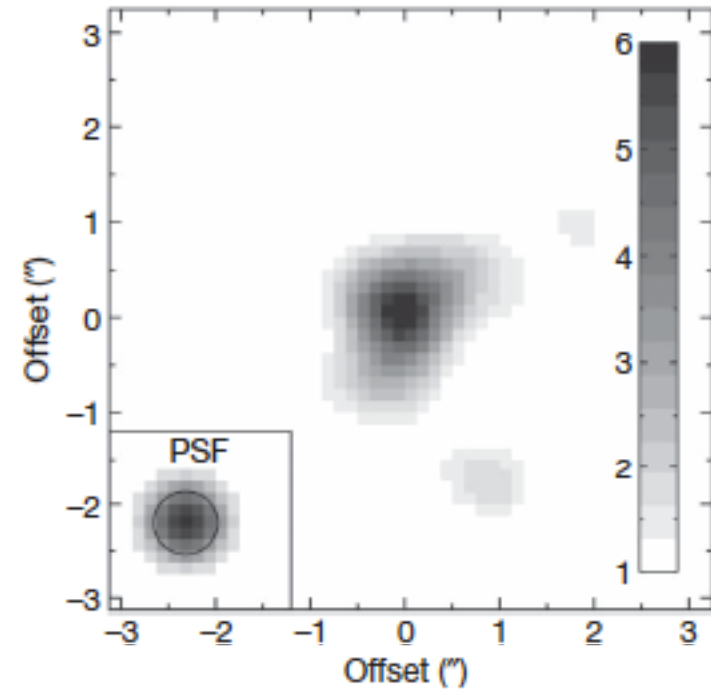
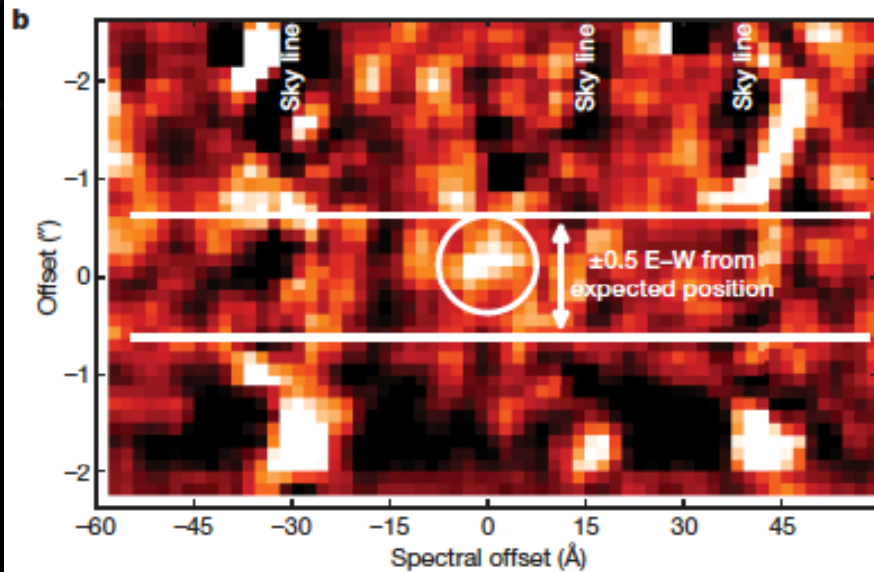
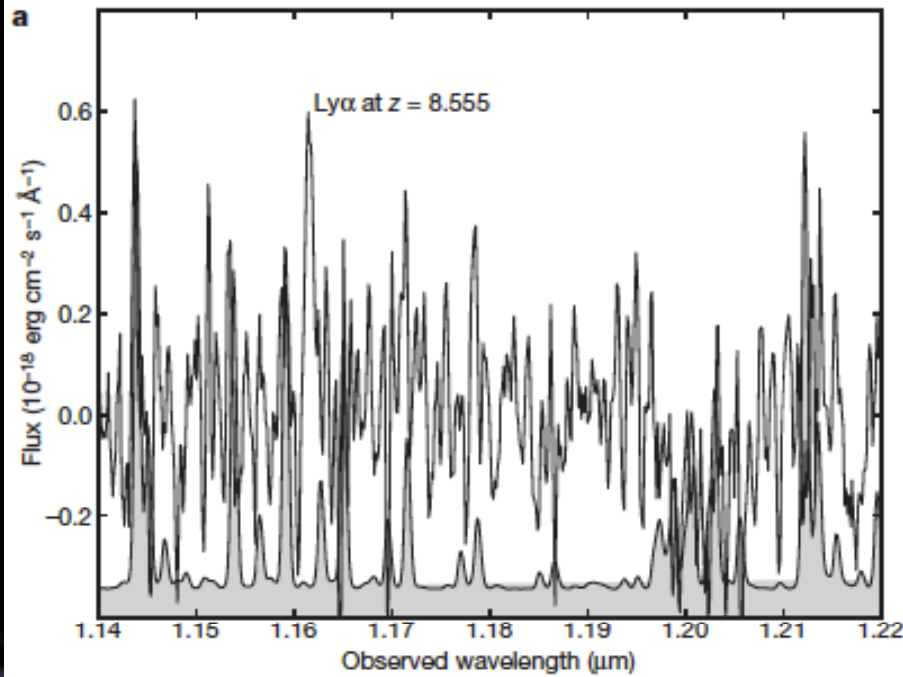
**Large-scale structure:  
Distribution of  $10^6$  galaxies  
in the Universe today**

# Star formation

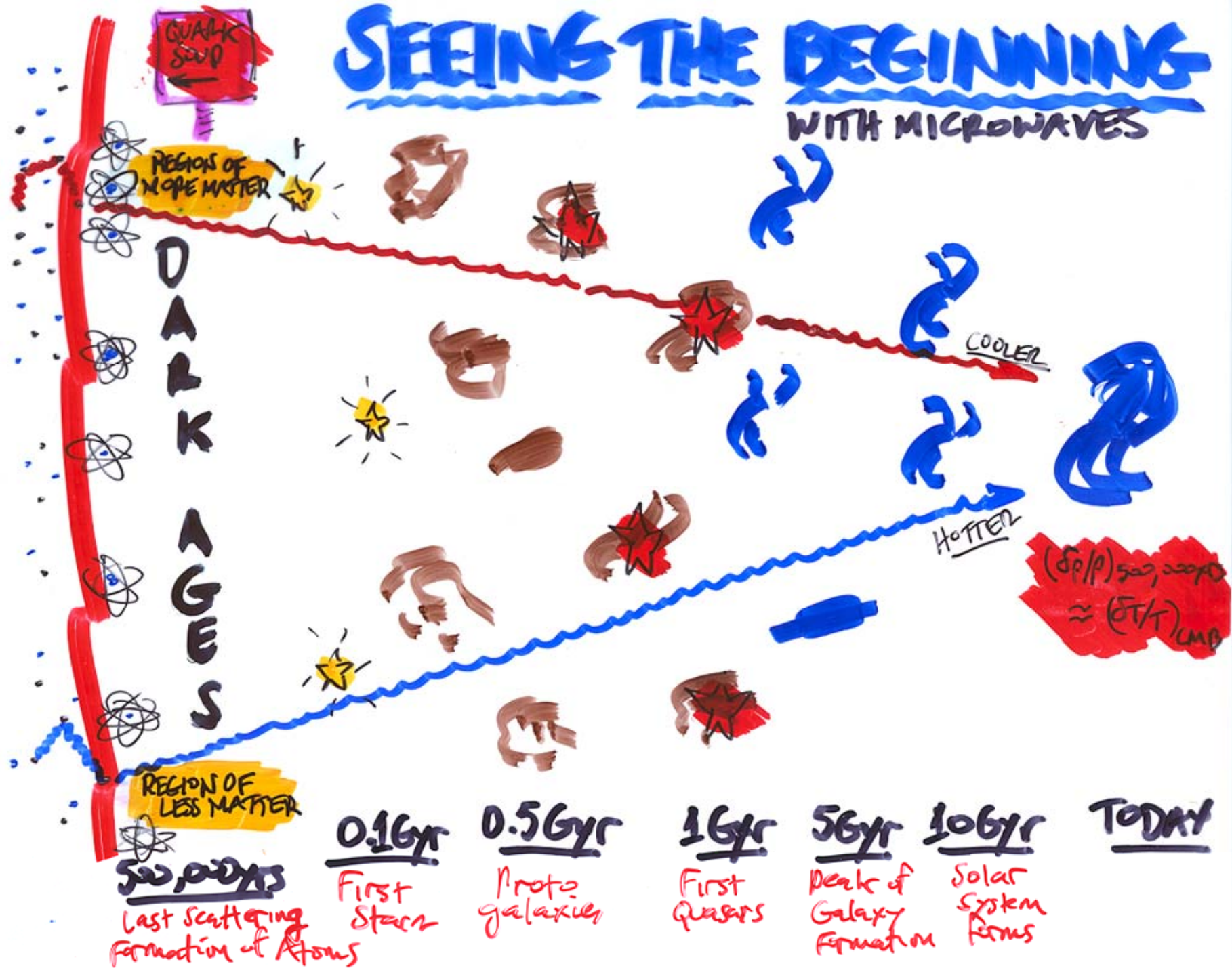
peaked 13 billion years ago, almost done



Record holder:  
 $z = 8.6!$



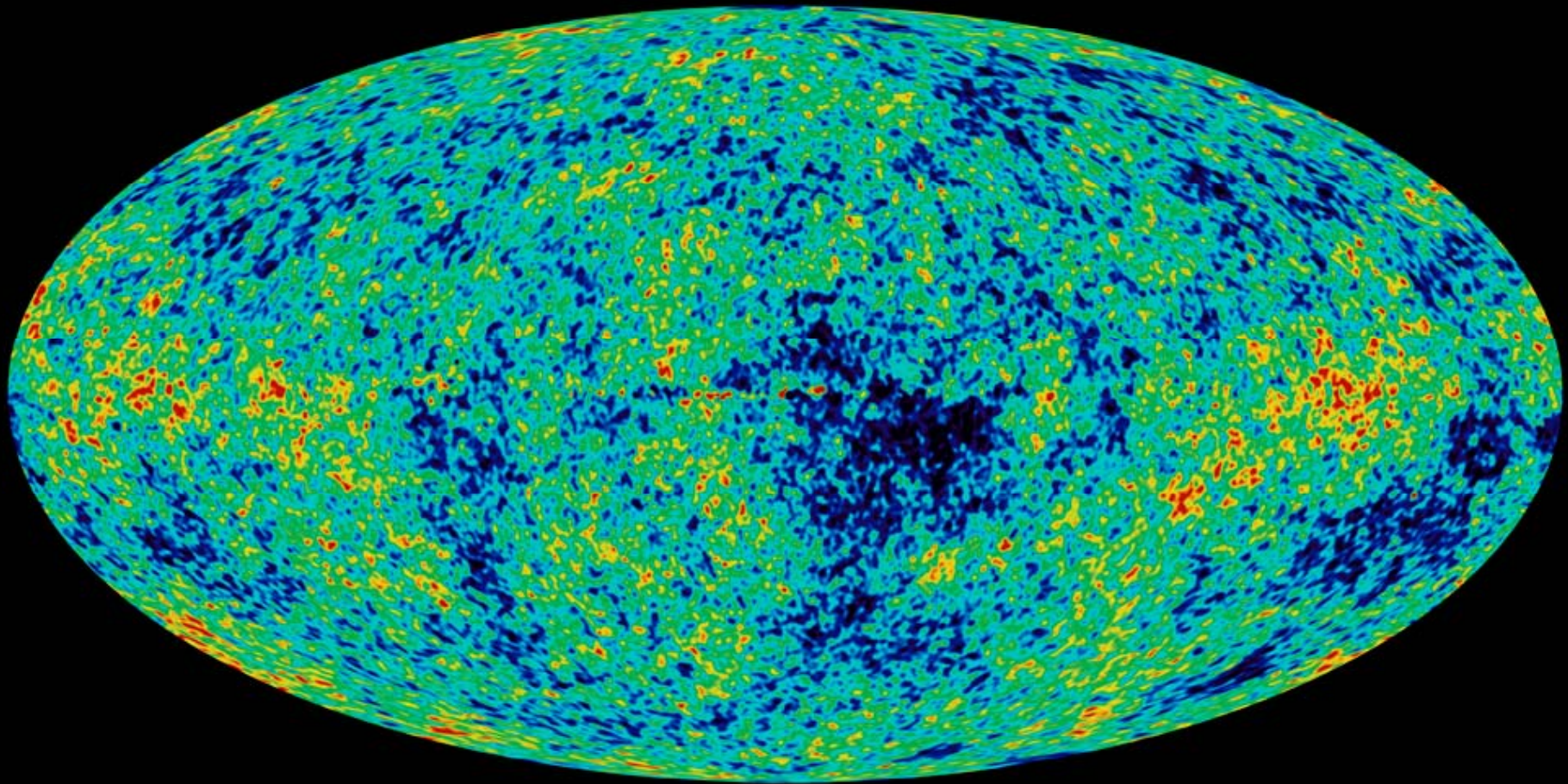
# SEEING THE BEGINNING WITH MICROWAVES





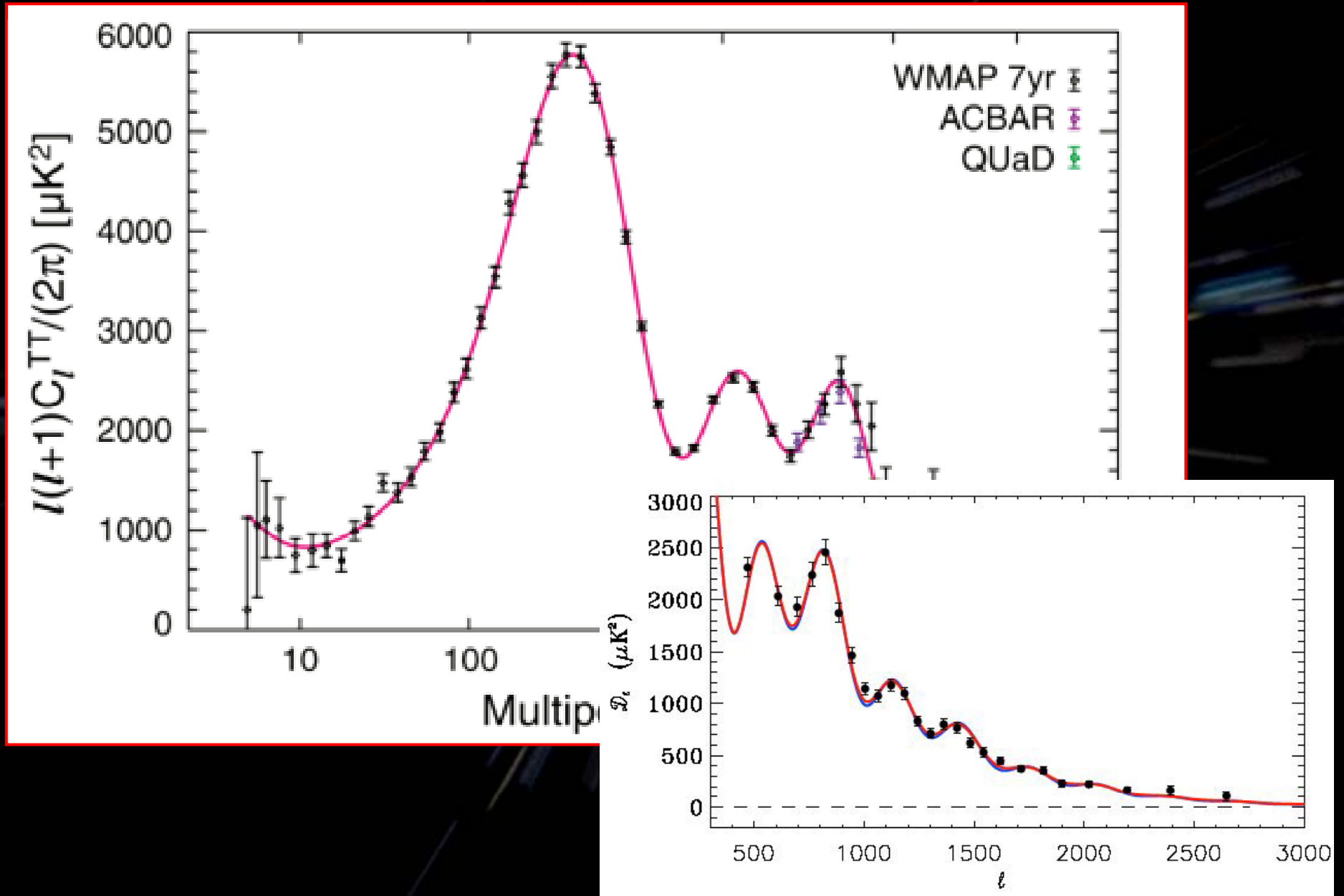
# The Universe circa 380,000 yrs

WMAP



$\pm 0.001\%$  Fluctuations

# Curve = concordance cosmology



Polarization: Where we are today  
 Chiang et al, arXiv: 0906.1181

**r = 0.1**

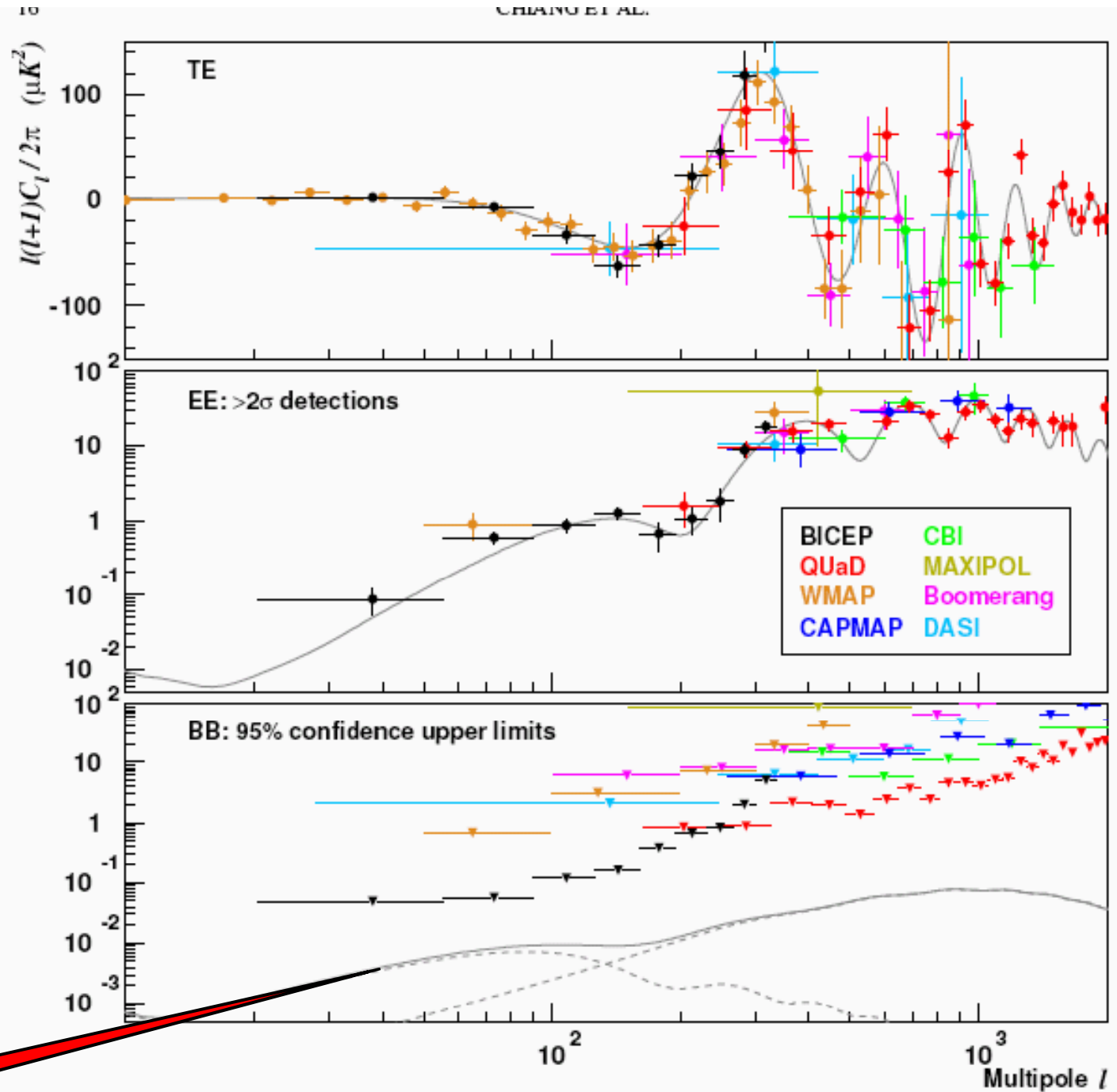
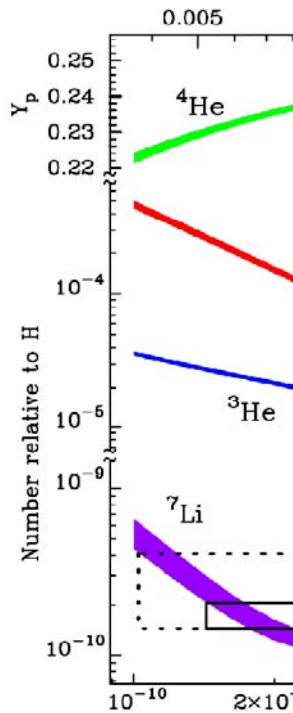


FIG. 13.— BICEP's  $TE$ ,  $EE$ , and  $BB$  power spectra complement existing data from other CMB polarization experiments (Leitch et al. 2005; Montroy et al. 2006; Piacentini et al. 2006; Sievers et al. 2007; Wu et al. 2007; Bischoff et al. 2008; Nolte et al. 2009; Brown et al. 2009). Theoretical spectra from a  $\Lambda$ CDM model with  $r = 0.1$  are shown for comparison. For clarity, only  $EE$  band centers with  $>2\sigma$  significance are plotted. At  $l$  above angular scales, BICEP's constraints

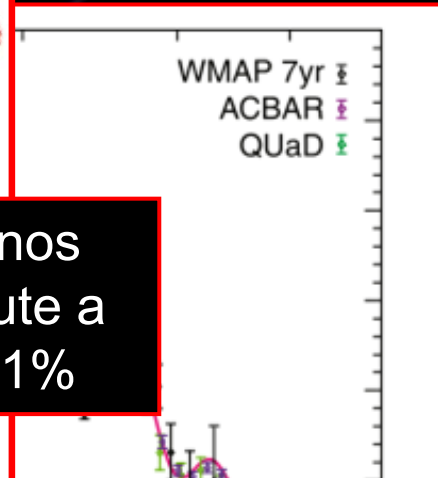
# N<sub>OF</sub> Airtight Evidence for Dark Matter

## MOOSE DIAGRAM DARK MATTER CANDIDATES

MT90



Neutrinos  
contribute a  
few 0.1%



$\Omega_b$  & BBN  
 $0.021 \pm 0.001$   
 vs.  
 $\Omega_b$ /SDSS  
 $0.13 \pm 0.005$   
200% discrepancy

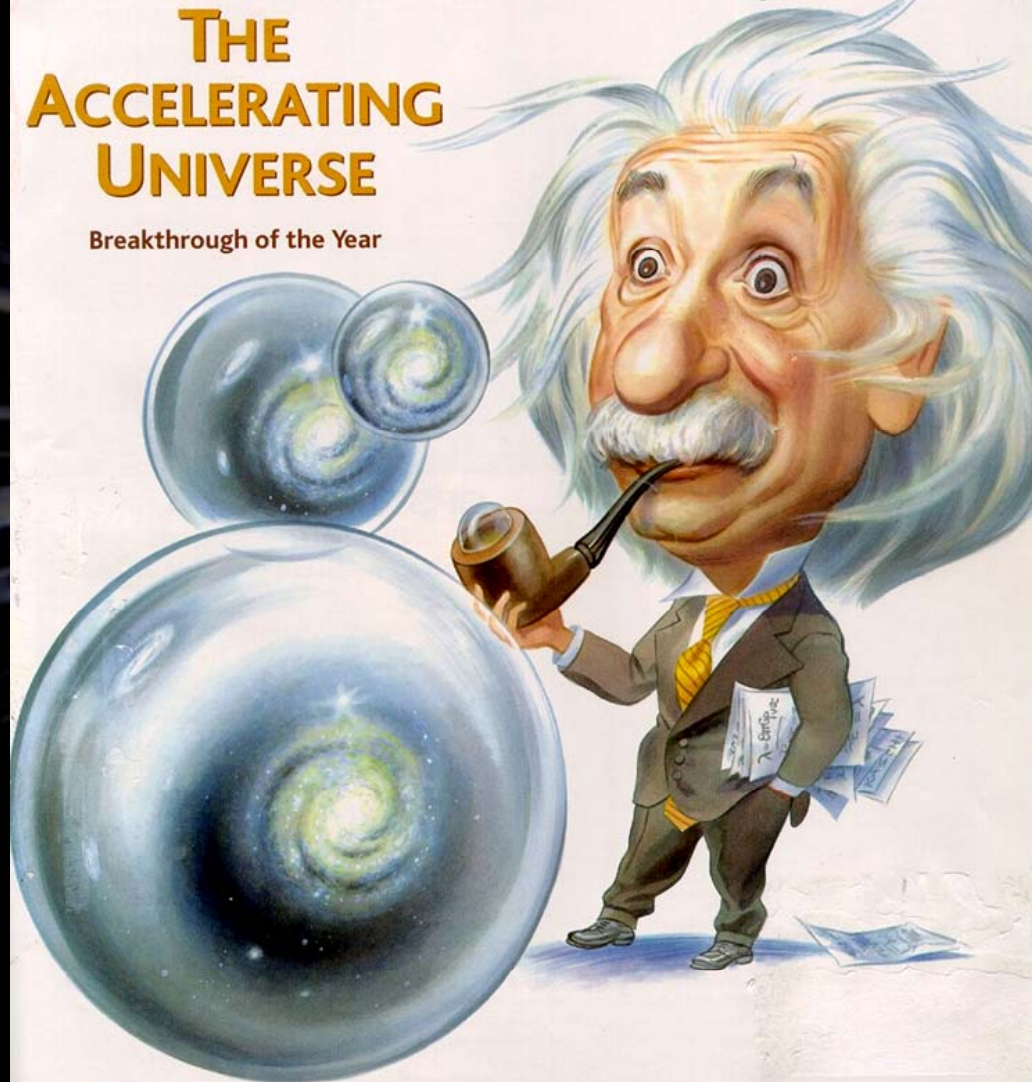
# Science

18 December 1998

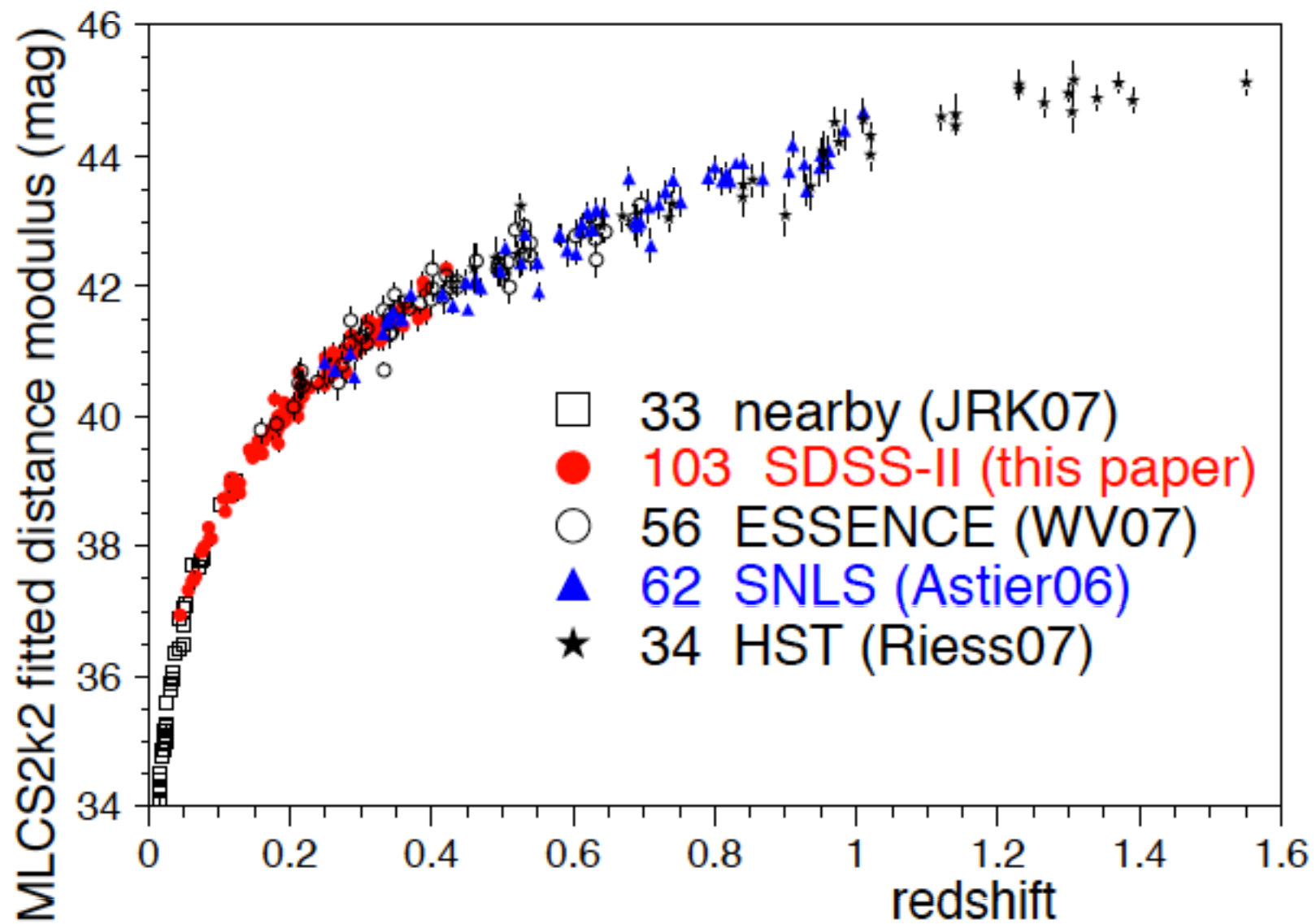
Vol. 282 No. 5397  
Pages 2141-2336 \$7

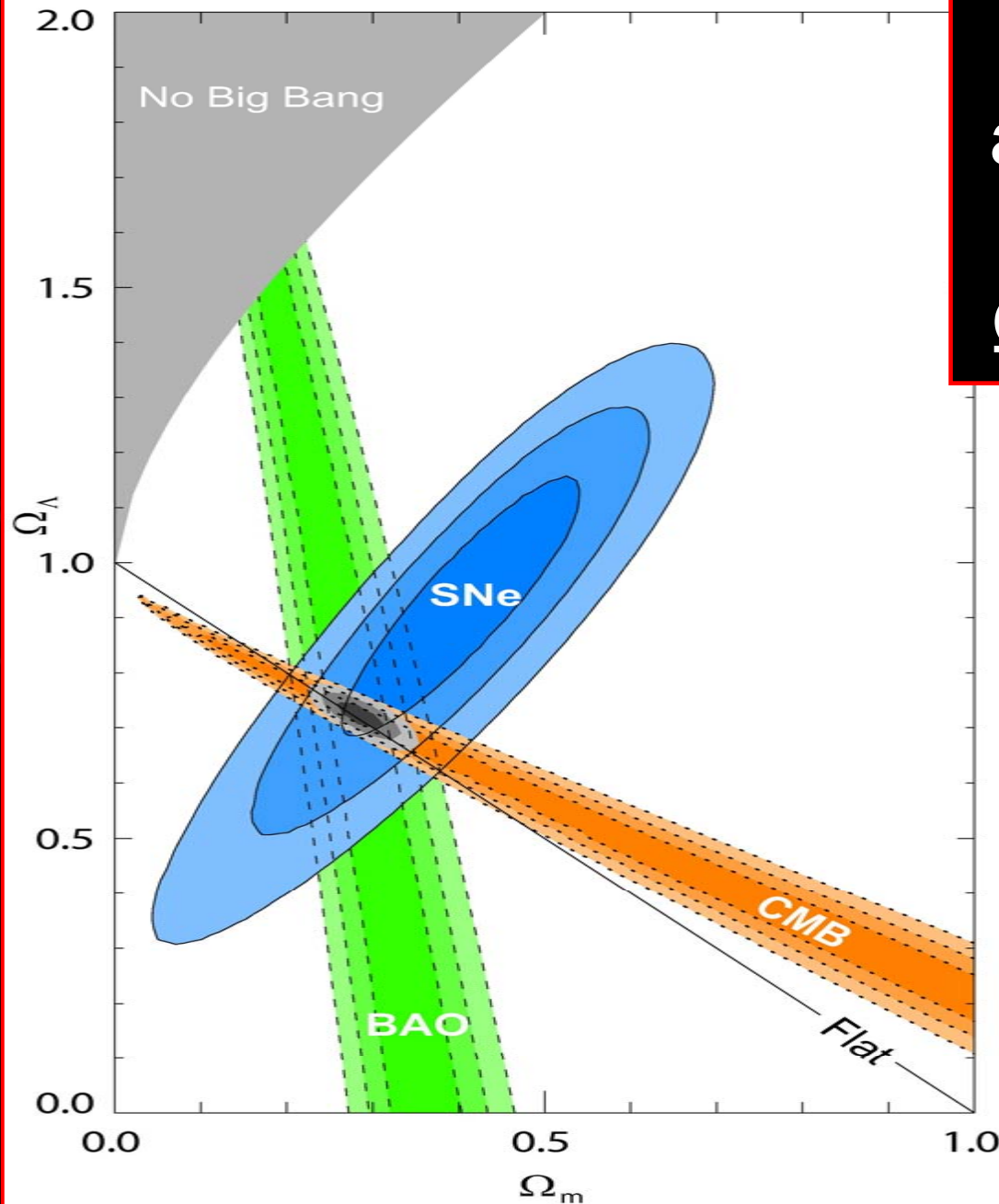
## THE ACCELERATING UNIVERSE

Breakthrough of the Year



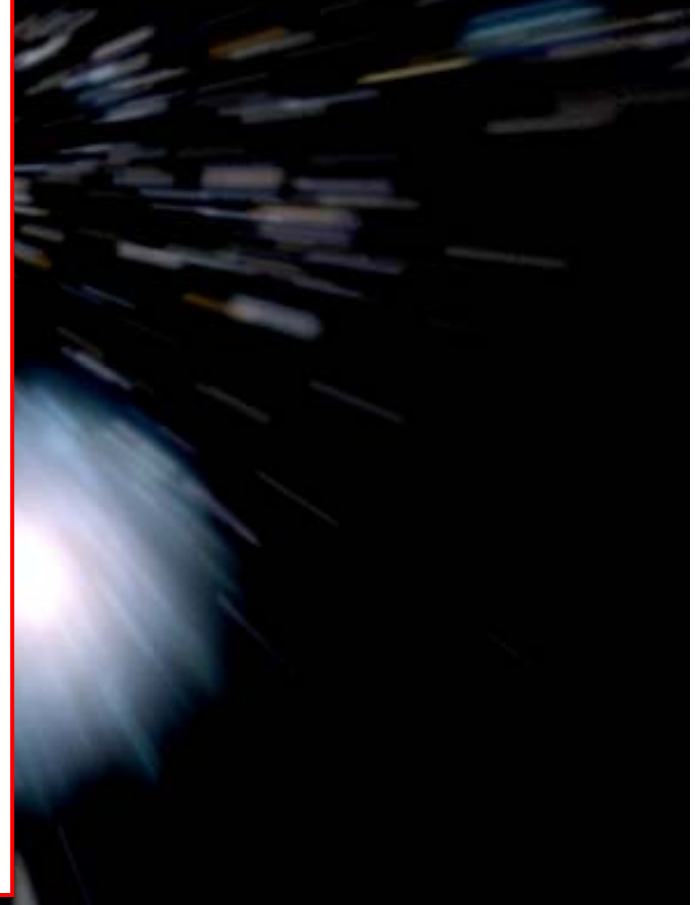
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE





Consistent with  
all observations:

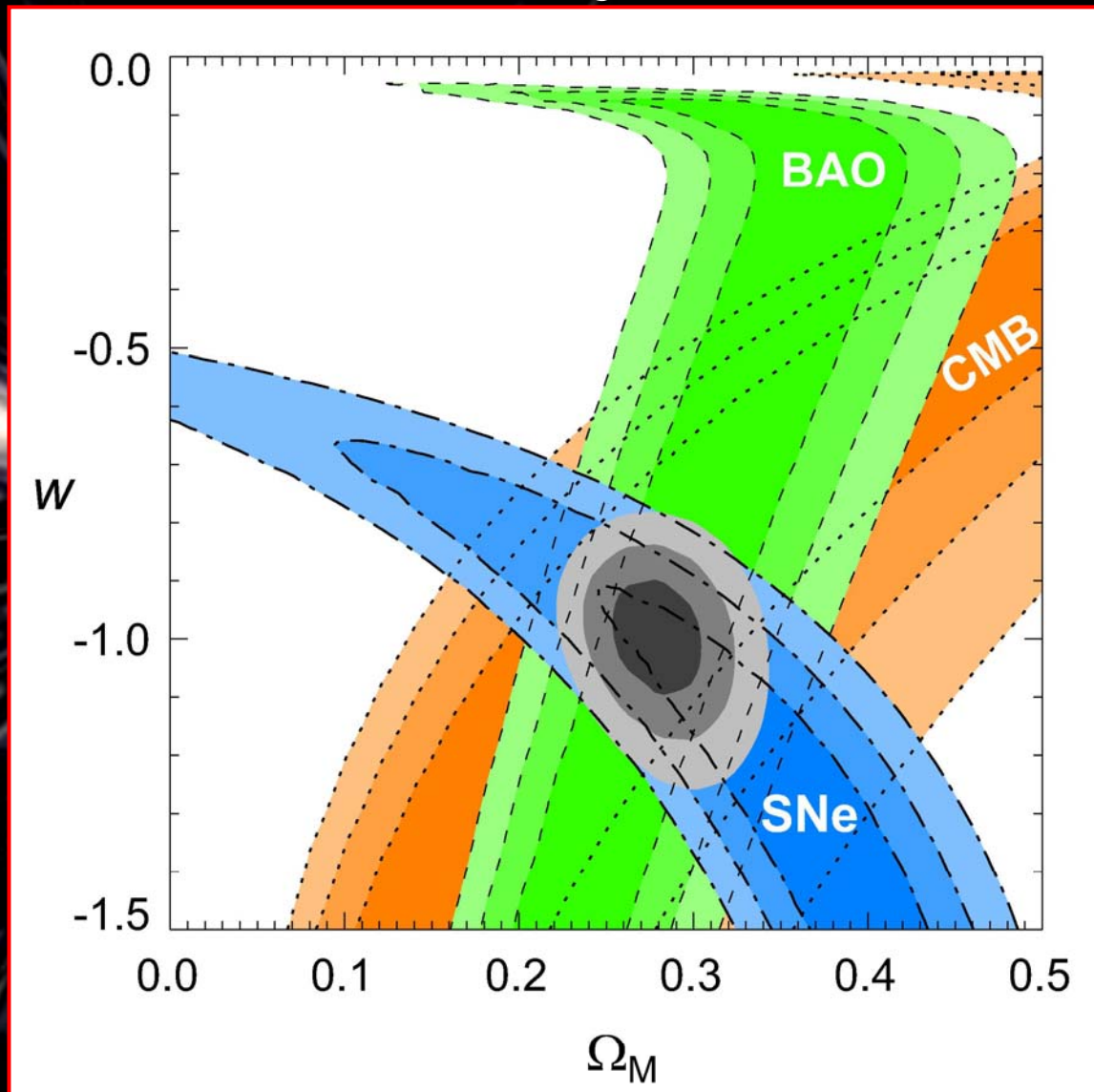
$$\Omega_\Lambda = 0.71 \pm 0.02$$



# Where We Are Today

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

Looks just like  
vacuum energy

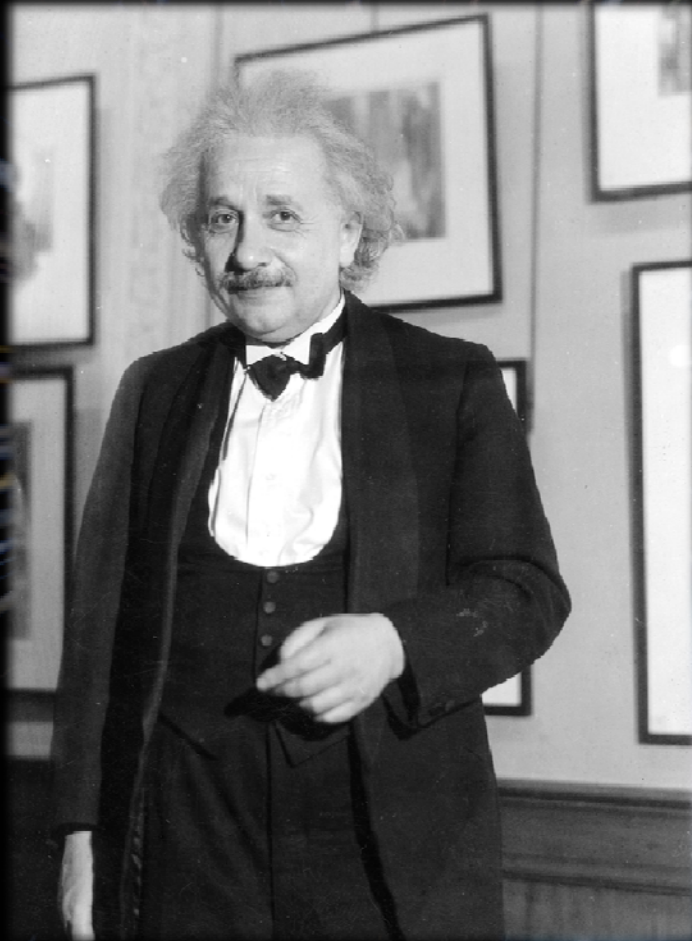




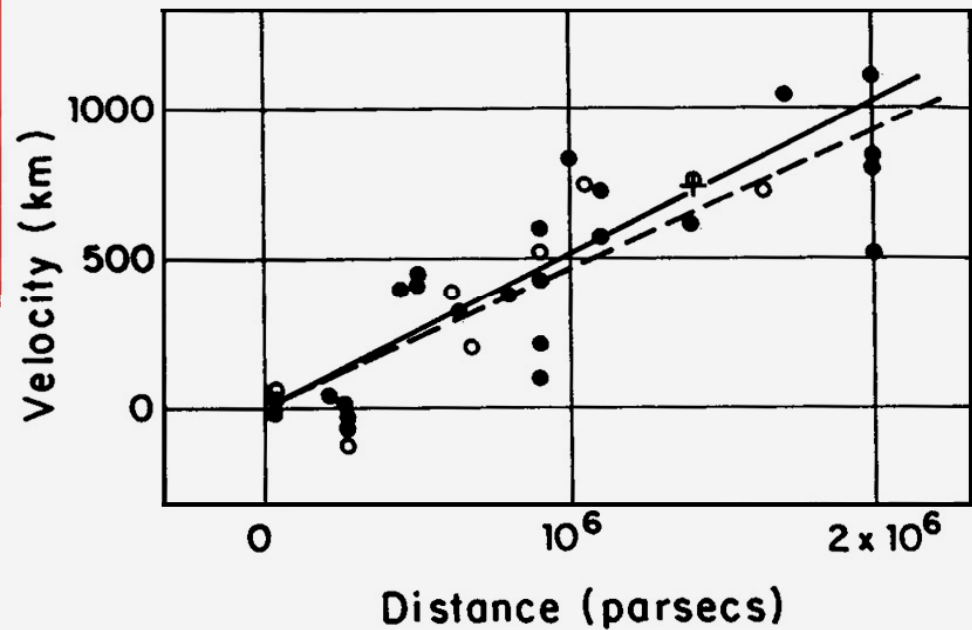
**How we got here**



# 1916-1918: General Relativity & $\Lambda$

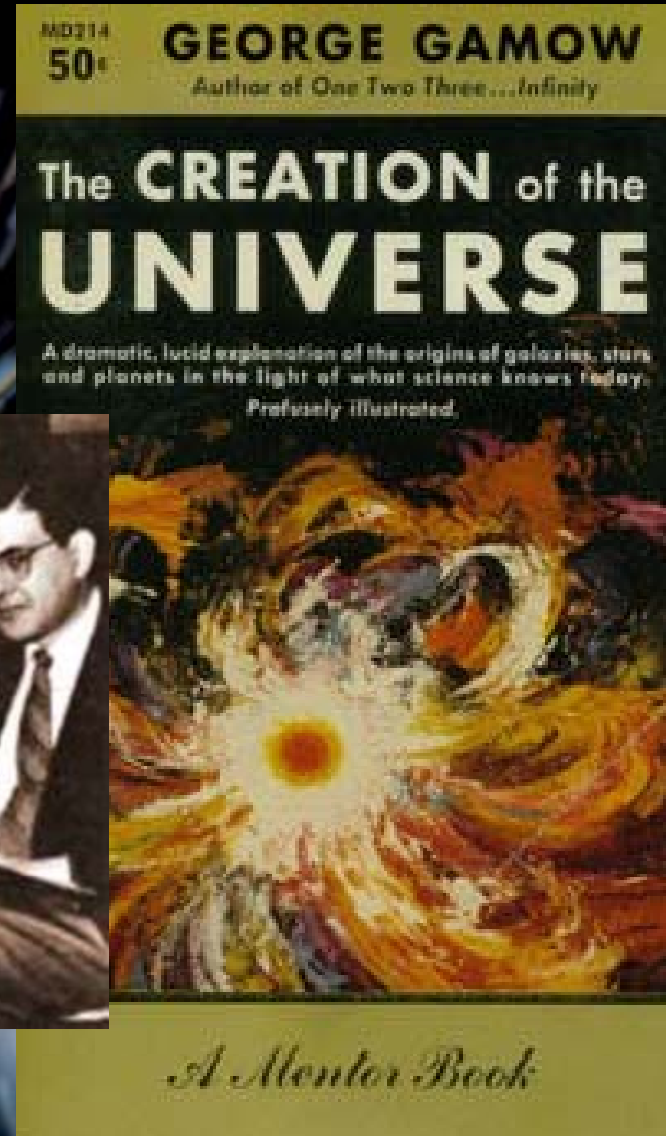
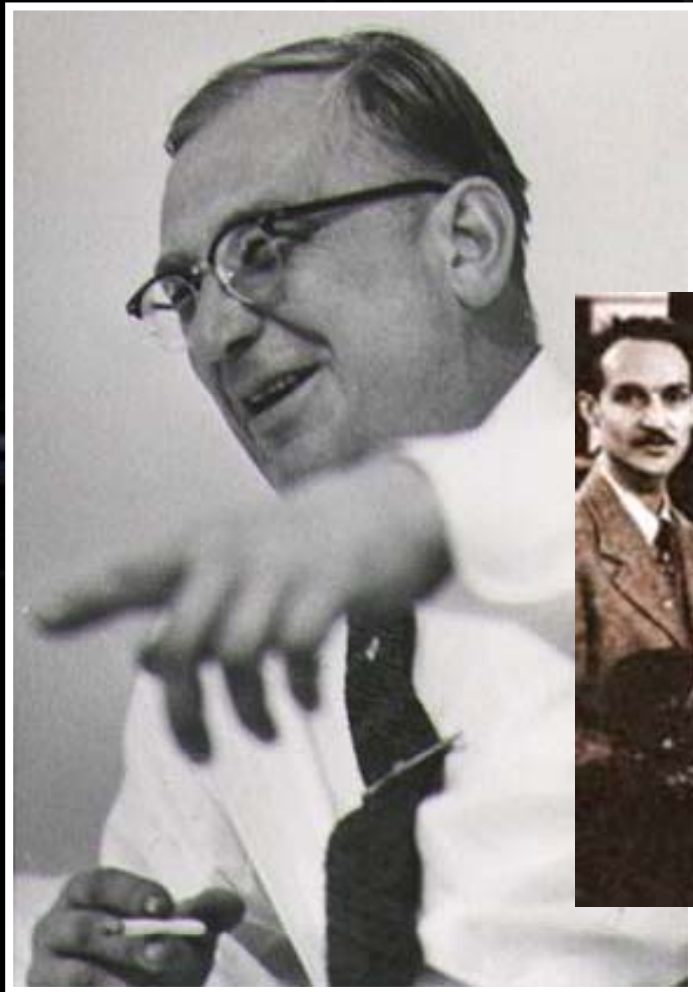


# 1929: Billions of Galaxies and an Expanding Universe

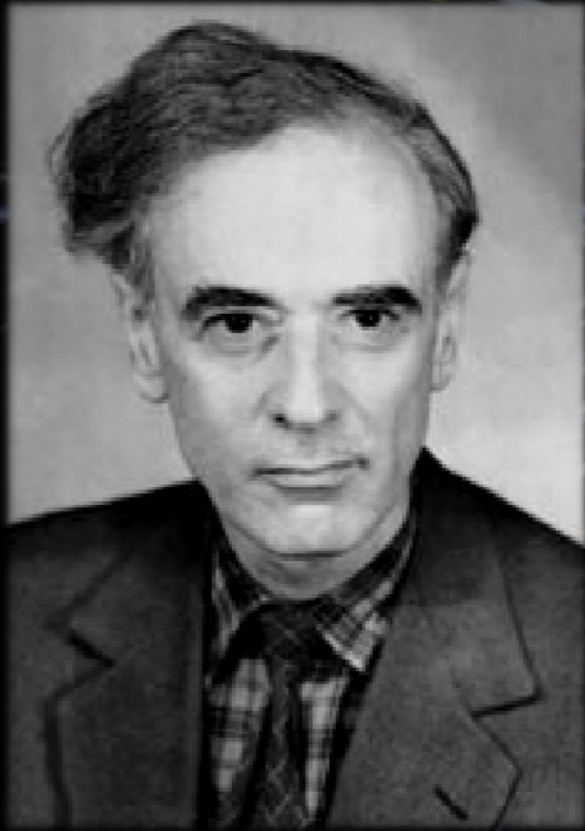


# Gamow's Hot Big Bang

"alpher, bethe, gamow," 1948

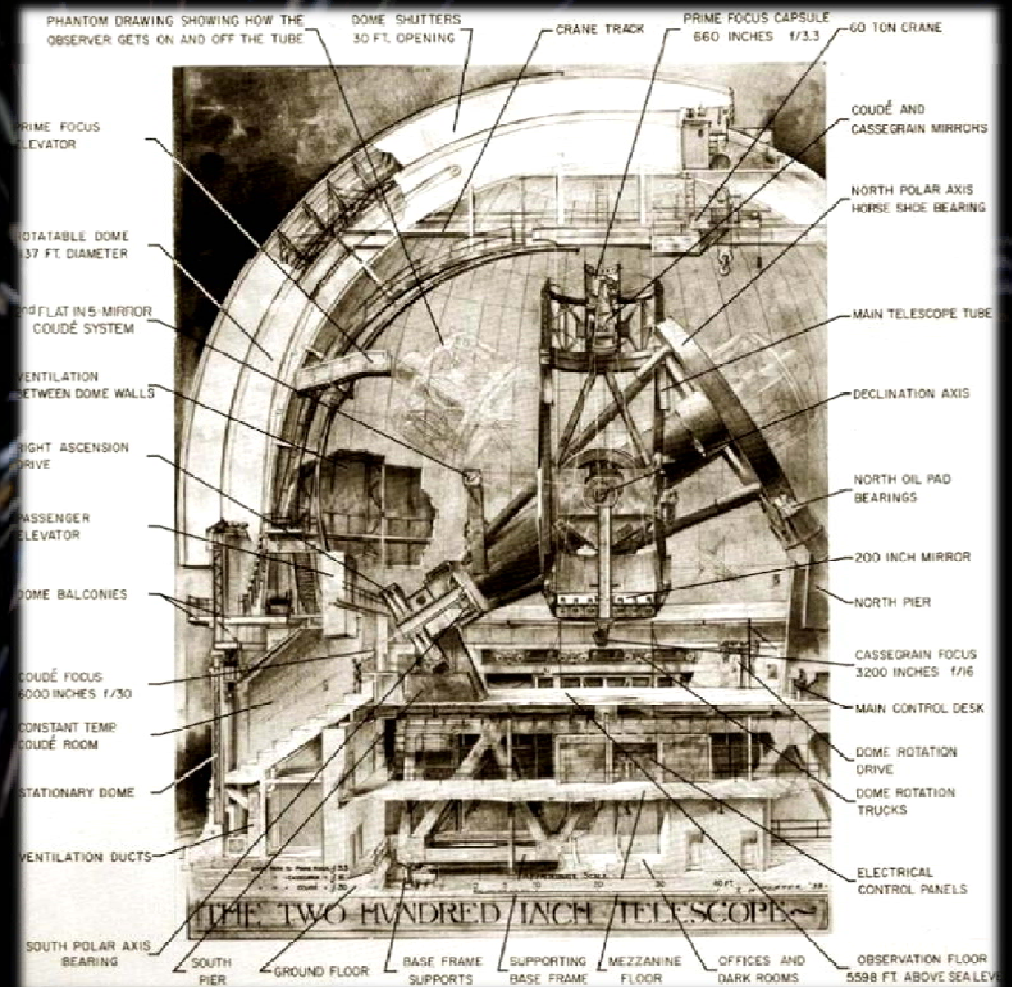


# Landau on Cosmologists



Often in Error,  
Never in Doubt!

# Cosmology: The Search for Two Numbers: $H_0$ & $q_0$





© 2004 Thomson - Brooks/Cole

# Discovery of Cosmic Microwave Background, 1964

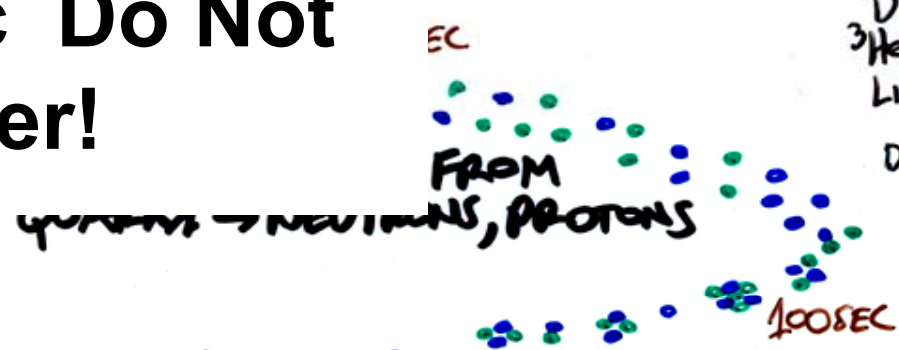
# From the Big Bang to Us

<  $10^{-5}$  sec Do Not Enter!

BBN

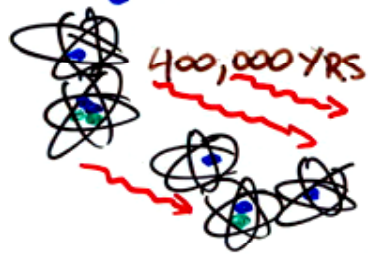
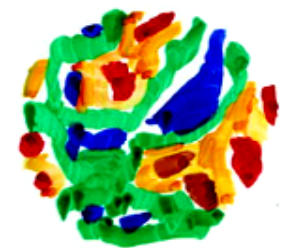


$D/H = (3 \pm 0.2) \times 10^{-5}$   
 $\Omega_B = 0.04 \pm 0.002$



BIG-BANG NUCLEOSYNTHESIS  
 Formation of H, D, He, He-3, Li

FORMATION OF ATOMS  
 COSMIC MICROWAVE BACKGROUND



CMB

RATIO OF FIRST-TO-SECOND PEAKS: 2/1  
 $\Omega_B = 0.045 \pm 0.008$

INTERGALACTIC GAS

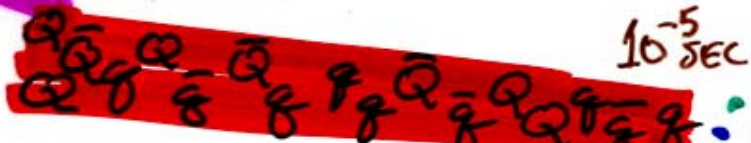
ABSORPTION OF QUASAR LIGHT BY HYDROGEN:  
 $\Omega_B \geq 0.04$

HERE & NOW  
 14 Billion YRS  
 stars, gas, dust, ...



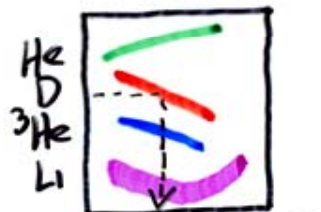
# ORDINARY MATTER: FROM QUARKS TO US

INFLATION  
BARYOGENESIS



$10^{-5}$  SEC

TRANSITION FROM  
QUARKS  $\rightarrow$  NEUTRONS, PROTONS



DENSITY OF MATTER

BIG-BANG  
NUCLEOSYNTHESIS

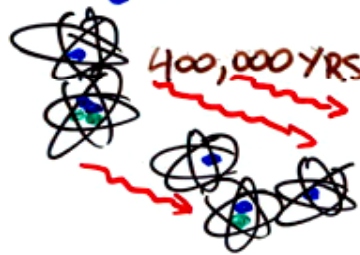
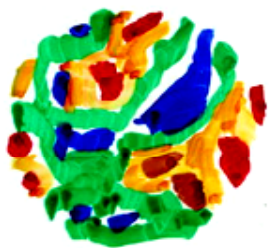
Formation of H, D,  
He, He-3, Li

BBN

$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Omega_B = 0.04 \pm 0.002$

FORMATION OF ATOMS  
COSMIC MICROWAVE  
BACKGROUND

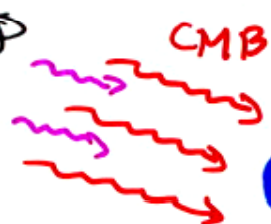


400,000 YRS



1 BILLION YRS  
FIRST QUASARS

QSO LIGHT



CMB

CMB

RATIO OF FIRST-TO-  
SECOND PEAKS: 2/1



$\Omega_B = 0.045 \pm 0.008$

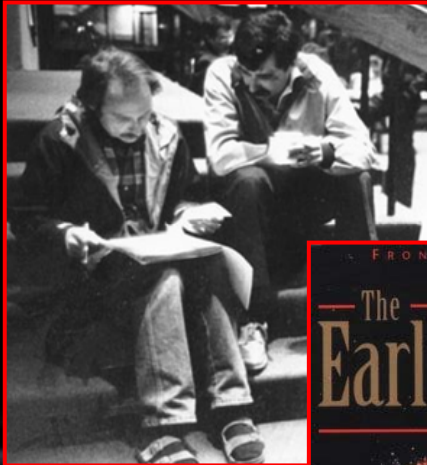
INTERGALACTIC GAS

ABSORPTION OF  
QUASAR LIGHT  
BY HYDROGEN:

$\Omega_B \geq 0.04$

HERE & NOW  
44 Billion YRS  
stars, gas,  
dust, ...

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



## —The Early Universe

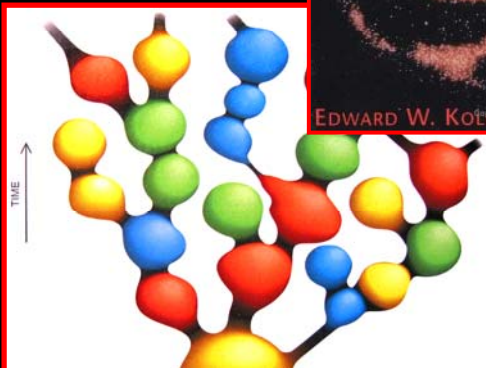


COSMOLOGY  
TAKES  
GUTS!



## “Creativity Based”

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



# Two Really Important Ideas

with de

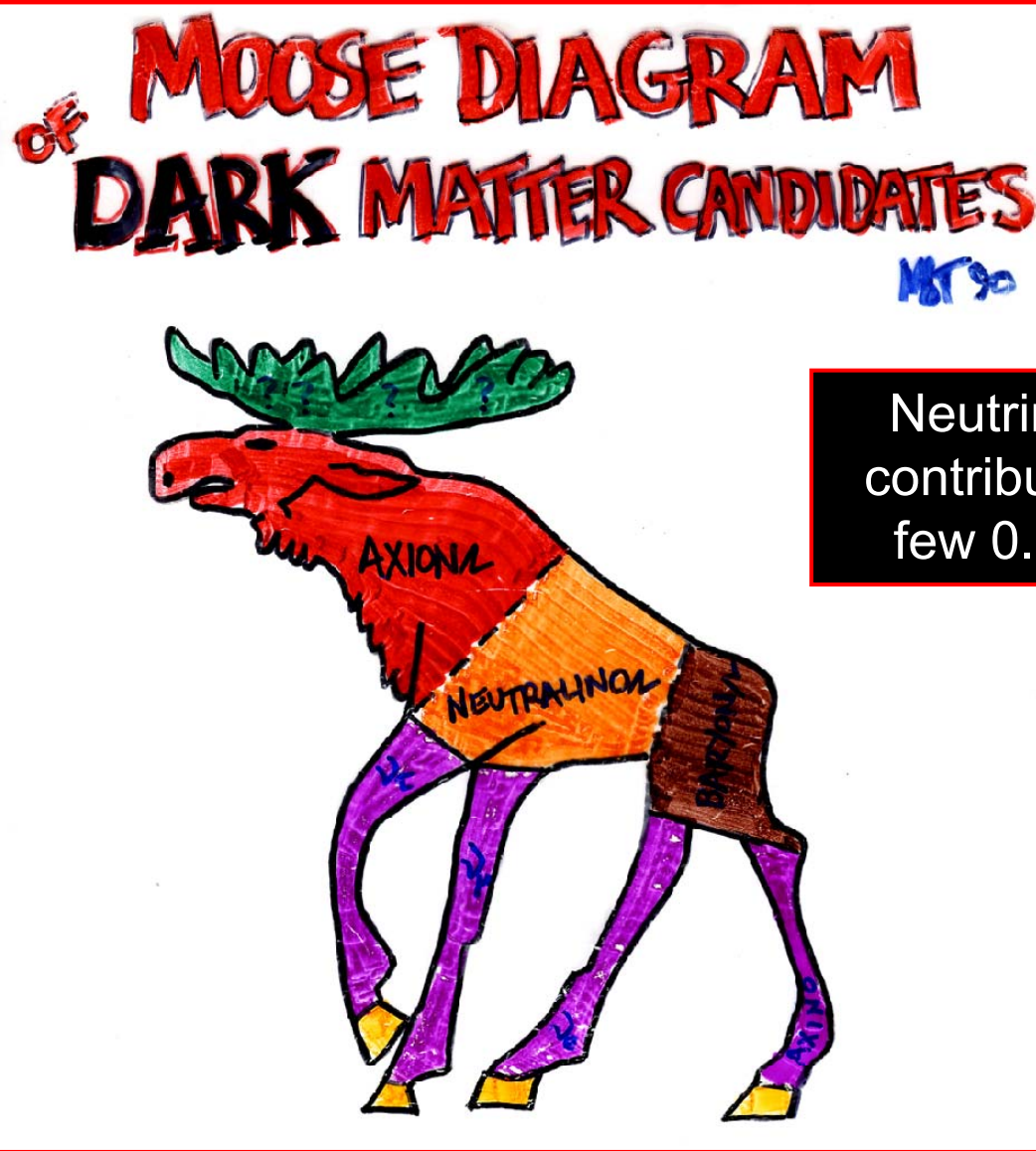
the cosmos

Infla

(ac  
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bar

Parti

ma  
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left



nts for  
ig

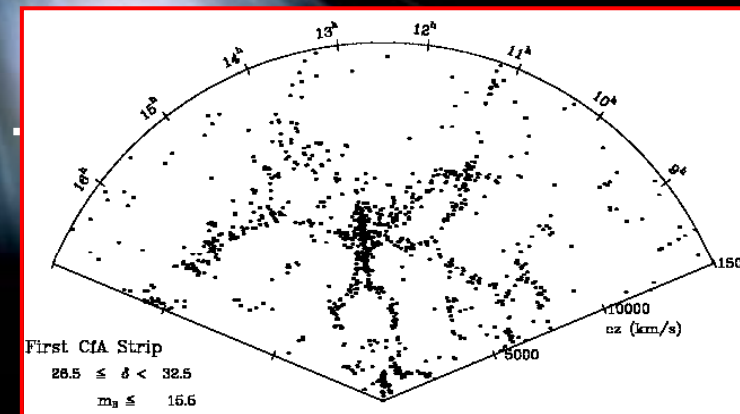
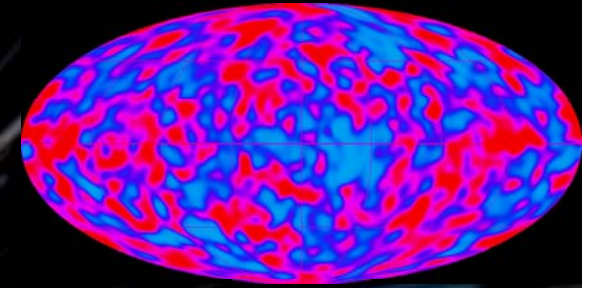
Neutrinos  
contribute a  
few 0.1%

e dark  
together  
particles

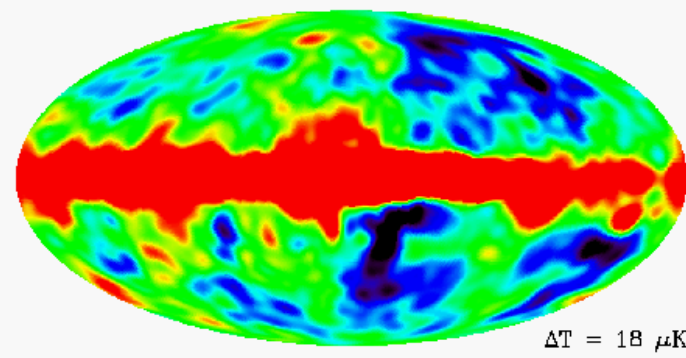
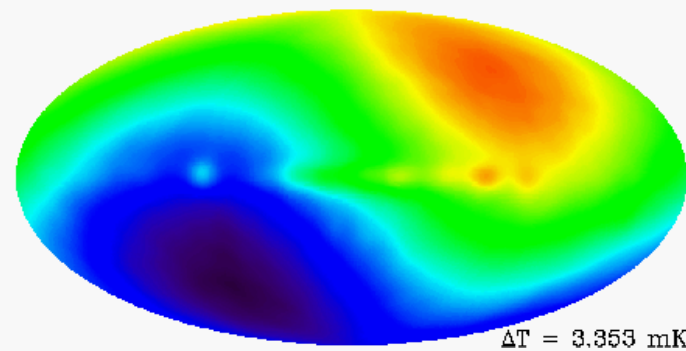
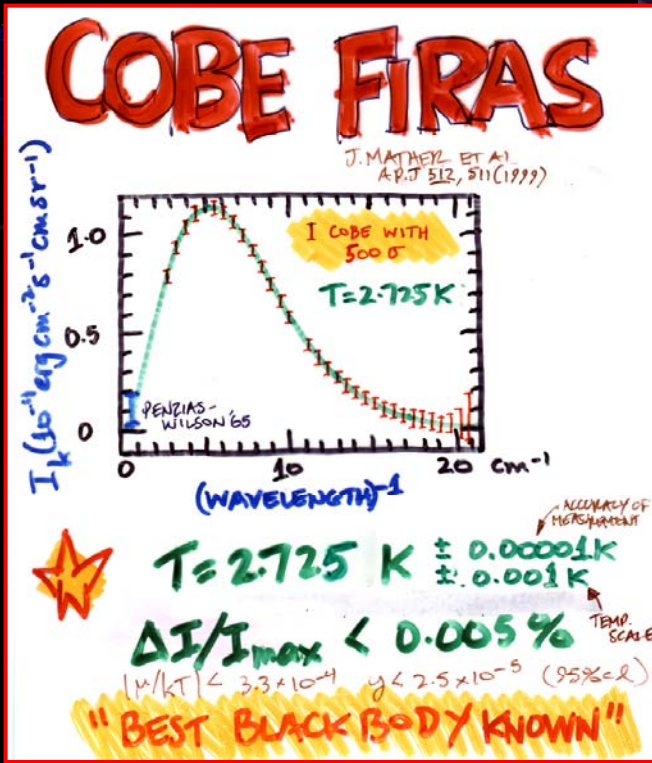
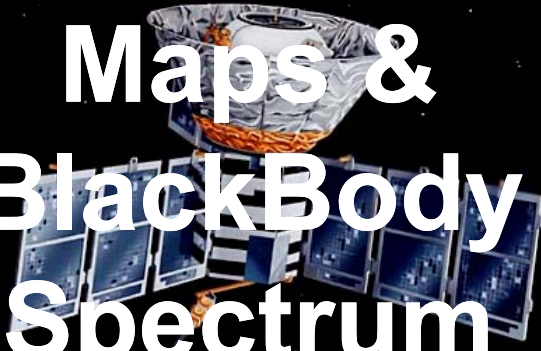
# 1990s: Data-driven Cosmology

## 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, ...



# 1992: COBE Maps & BlackBody Spectrum





## "RIPPLES" IN THE MICROWAVE ECHO

TEMPERATURE VARIATION  $\approx 30\mu\text{K}$



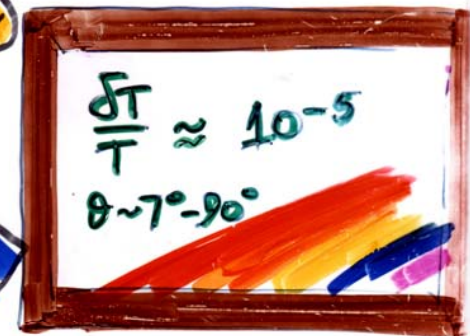
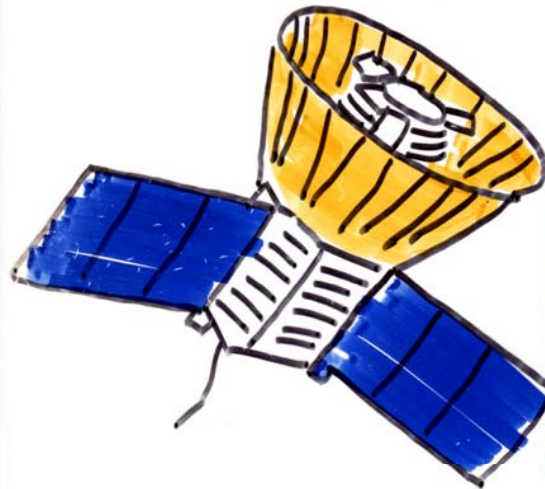
EVIDENCE FOR "PRIMEVAL  
LUMPINESS" THAT SEEDS  
STRUCTURE (STARS,  
GALAXIES, CLUSTERS OF  
GALAXIES, SUPERCLUSTERS  
VOIDS, WALLS, ...)

J. HAWKING: "GREATEST DISCOVERY  
OF ALL TIME"

$\uparrow$  ONLY A SLIGHT OVERSTATEMENT

# COBE

23 April 1992



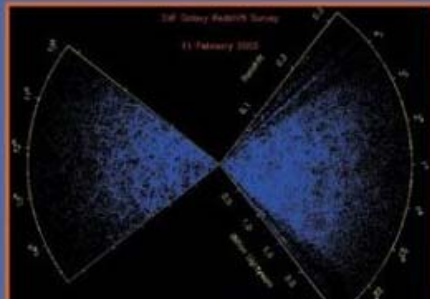
$$\frac{\delta T}{T} \approx 10^{-5}$$
$$\theta \sim 7^\circ - 90^\circ$$

# WOW!

# 2000s: Era of Precision Cosmology

## MODERN COSMOLOGY

*Scott  
Dodelson*



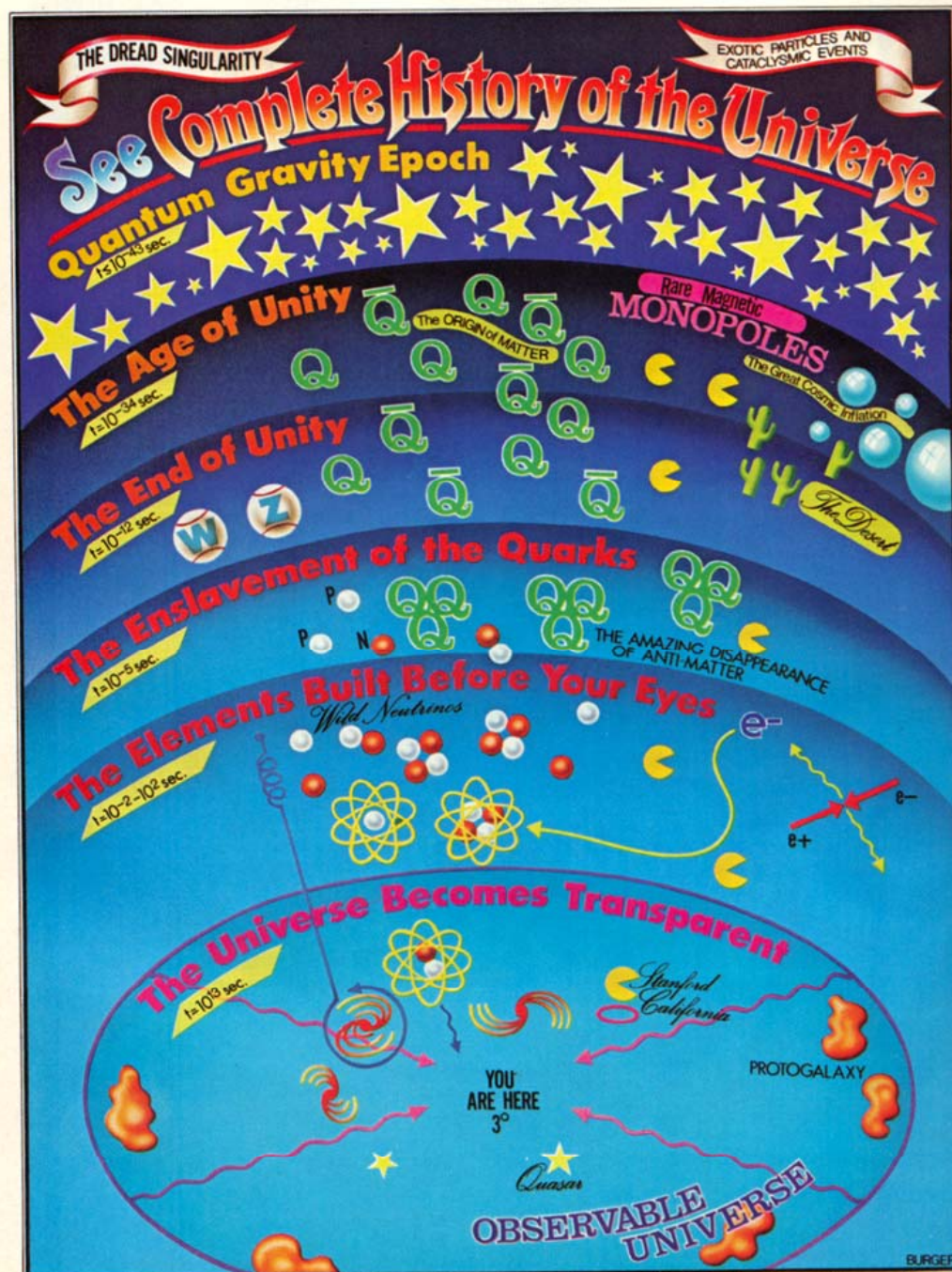
## “Fisher Based”

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



**Our great progress has  
illuminated more clearly  
our ignorance**





A whimsical poster designed by Chicago astrophysicist Michael Turner depicts the evolution of the universe and its contents

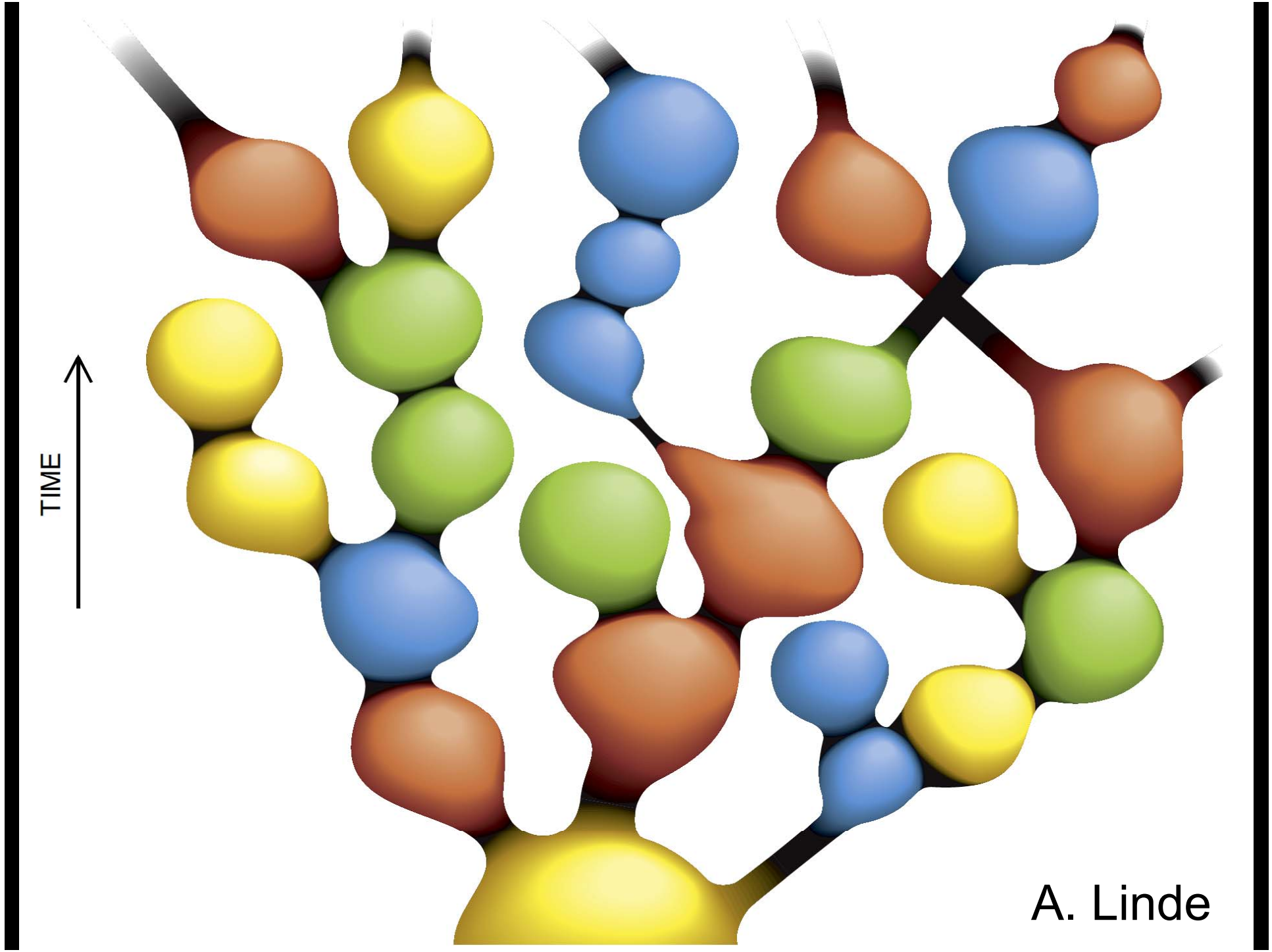
Terra  
Incognita  
exciting ideas  
Inflation,  
multiverse,  
###!

Well understood:  
0.000001 sec to  
400,000 yrs

Story to be  
revealed by  
new  
telescopes

# *Big Questions*

- (“Astrophysical” cosmology – from lumpy atoms to the first stars and galaxies)
- Precision testing of inflation – toward a fundamental model or new paradigm
- Dark Matter: test WIMP™ hypothesis, finish the neutrino story, and don’t forget the axion!
- Baryon asymmetry – related to dark matter?
- Dark energy/cosmic acceleration
  - Vacuum energy? GR correct?
- The mix – photons, neutrinos, atoms, dark matter, dark energy, and more? Who ordered that?
- The Multiverse\$!!# -- the headache and the hope



A. Linde

# The Consensus Cosmology



Rests upon three mysterious pillars  
All implicate new physics!

# The path forward



# The Dark Matter Decade

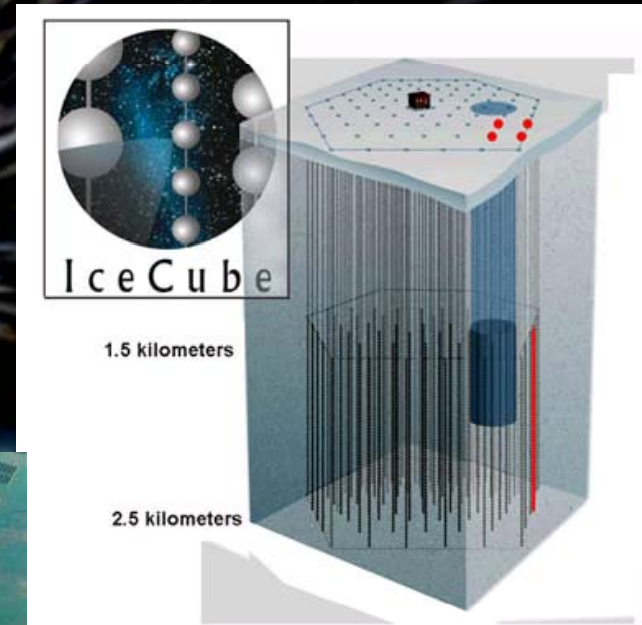
- Hints (and distractions) in the air: Pamela, Fermi-Haze, WMAP Haze, ATIC, CDMSII
- New capabilities: LHC, Xenon100, Fermi, ...
- Prediction: The WIMP/Neutralino hypothesis will be tested this decade!



## Full Court Press!!

- Produce at LHC
- Detect particles in our halo
- Detect annihilation products
- Dark Stars

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





# Serious testing of Inflation has begun

## Key Predictions



Flat Universe



Almost scale-invariant, Gaussian perturbations:

$$|(n-1)| \sim 0.1 \text{ and } |dn/d\ln k| \sim 0.001$$

- Gravity waves: spectrum, but not amplitude



Cold Dark Matter Scenario

## Key Results

- $\Omega_0 = 1.00 \pm 0.006$
- $(n-1) = -0.04 \pm 0.014^*$ ;  $dn/d\ln k = -0.032 \pm 0.02$ ; no robust evidence for nonGaussianity
- $r < 0.2$  (95% cl)\*

\*Depends significantly upon the priors assumed

# GWs: The Smokin' Gun

- Directly reveals epoch of inflation

$$H_I^{-1} = \frac{2 \times 10^{-39} \text{ sec}}{\sqrt{T/S}}$$

$$V^{1/4} = 3 \times 10^{16} \text{ GeV } (T/S)^{1/4}$$

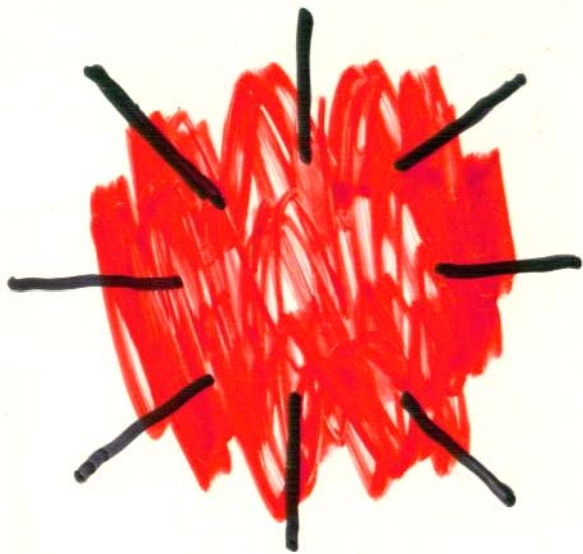
- Reconstruct scalar potential

$$V_{50} = 1.65 T (1 - 1.2n_T);$$

$$V'_{50} = 5.01 \sqrt{-n_T} (V_{50}/m_{\text{Pl}});$$

$$V''_{50} = 4\pi [(n - 1) - 3n_T] (V_{50}/m_{\text{Pl}}^2).$$

- Spectrum provides consistency check:  $T/S = -5n_T$
- Direct detection:
  - LIGO & LISA unlikely; “Big Bang Observer” (a dream)
- B mode of CMB polarization

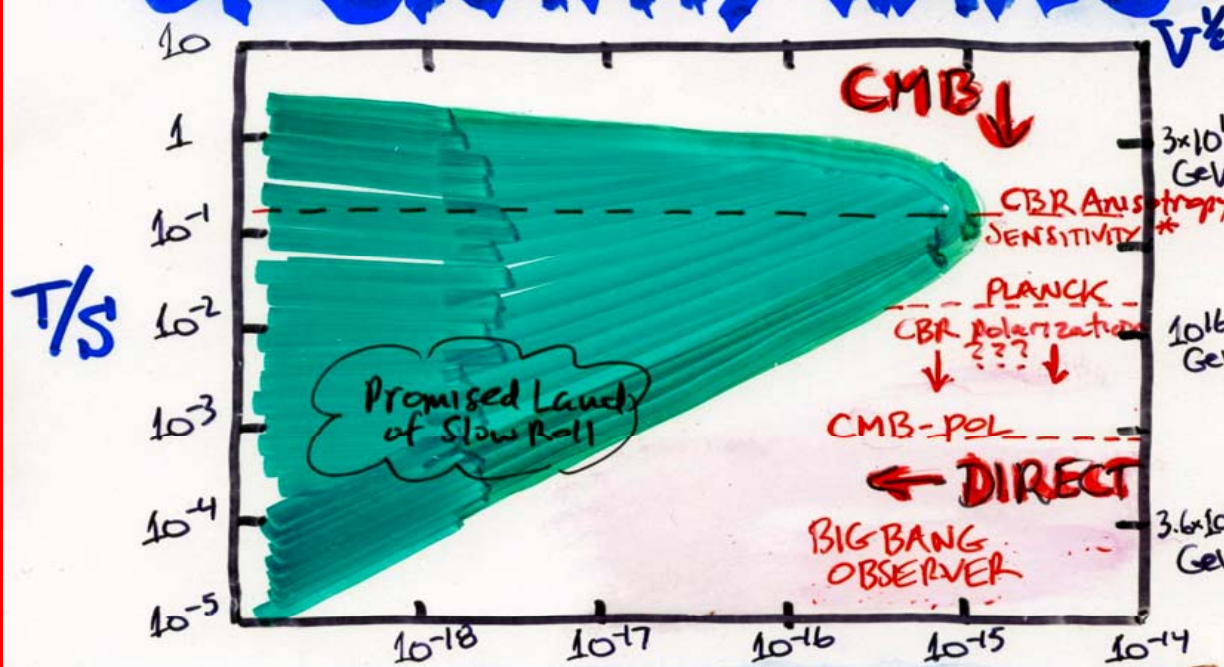


E mode



B mode

# DETECTION OF GRAVITY WAVES



$\Omega_{GW}(Hz)h^2$

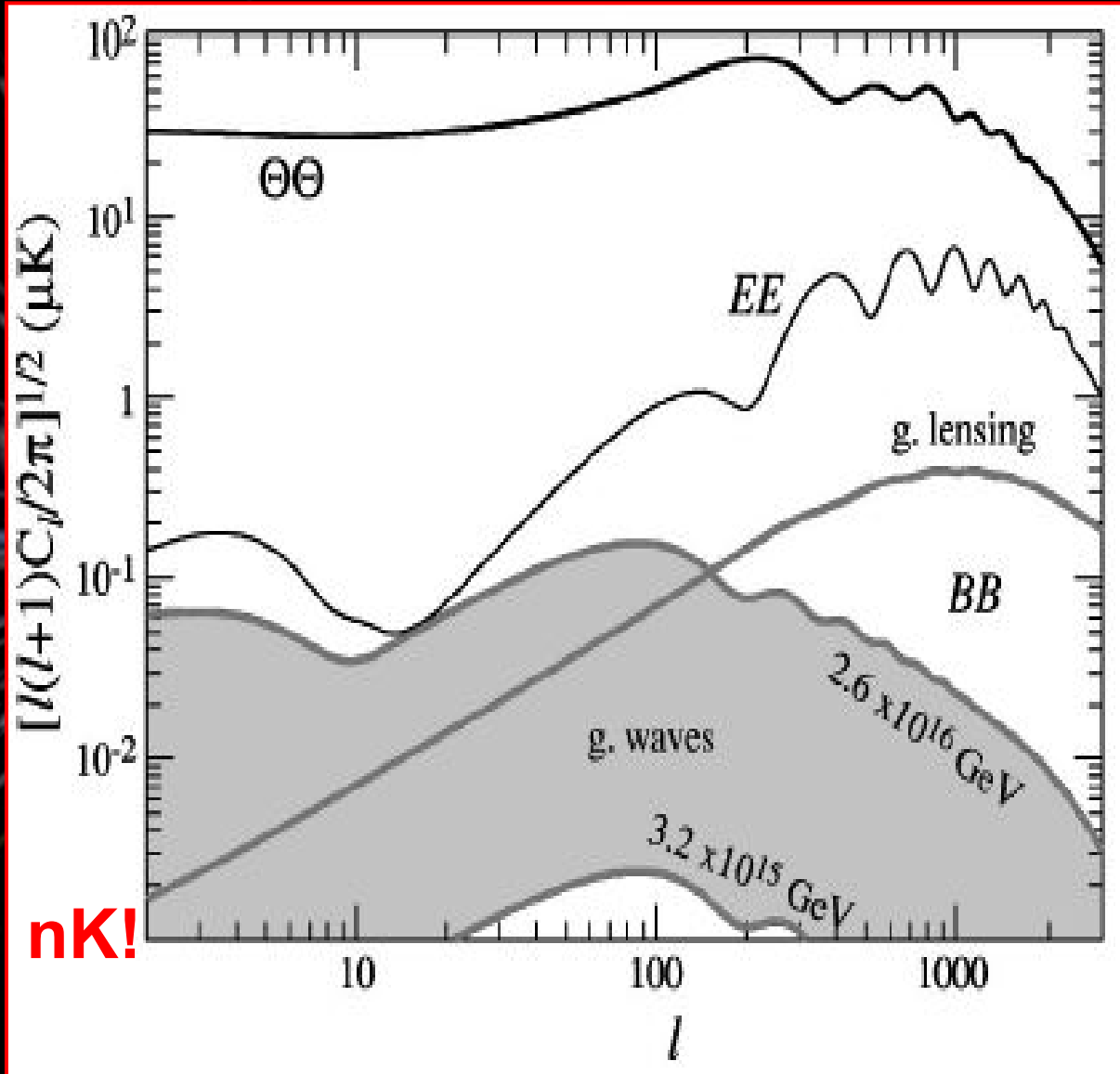
NB:   
 LIGO:  $10^{-8}$    
 LISA:  $10^{-13}$

**VERY CHALLENGING!**

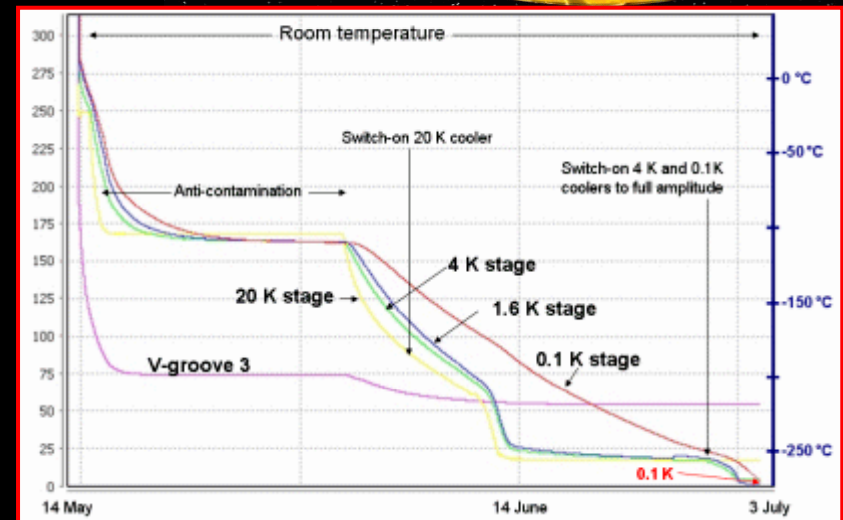
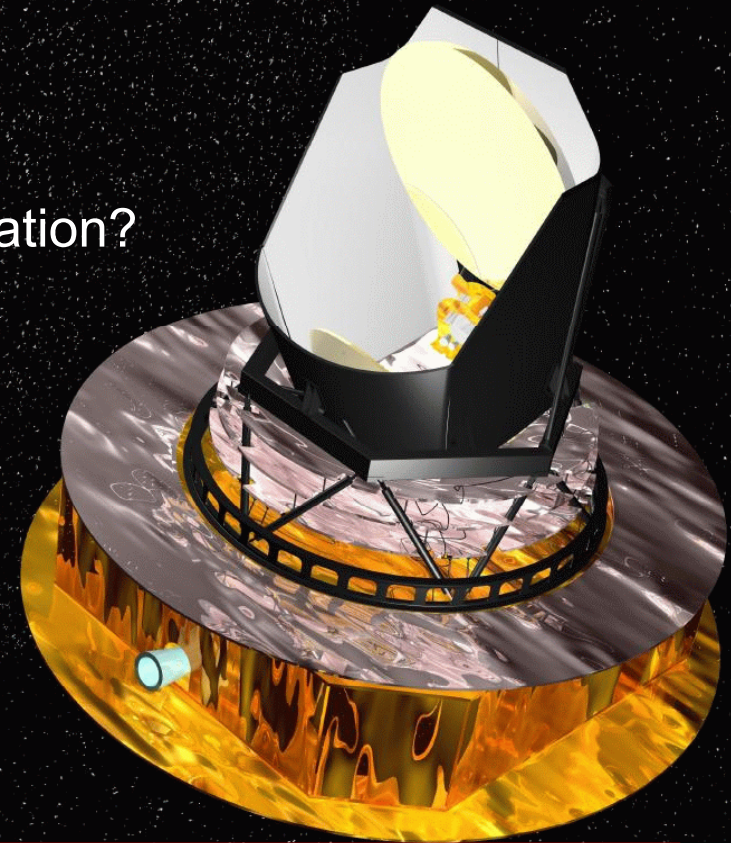
"DOUBLE DETECTION"  $\Rightarrow n_T$  to  $\pm 0.03$

# CMB Anisotropy from Gravity Waves

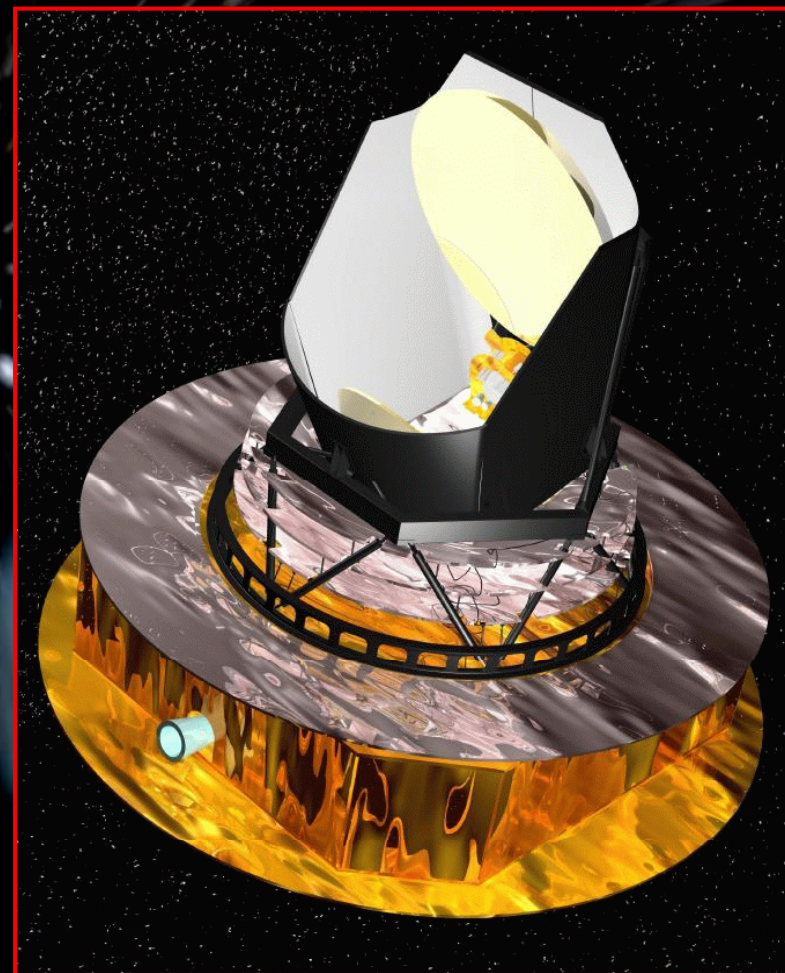
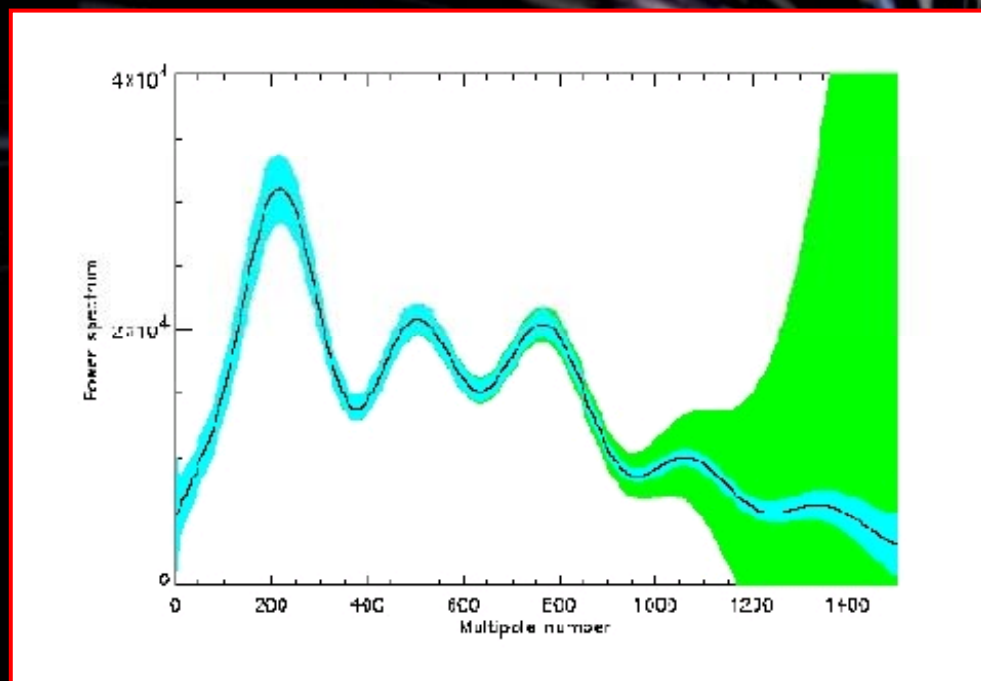
- $\Theta\Theta$  = GW temp
- $EE$  = E mode  
(scalar)
- g lensing: grav  
lensing of  $EE$
- $BB/g$  waves =  
GW B-mode
- Detect  $T/S >$   
0.001?



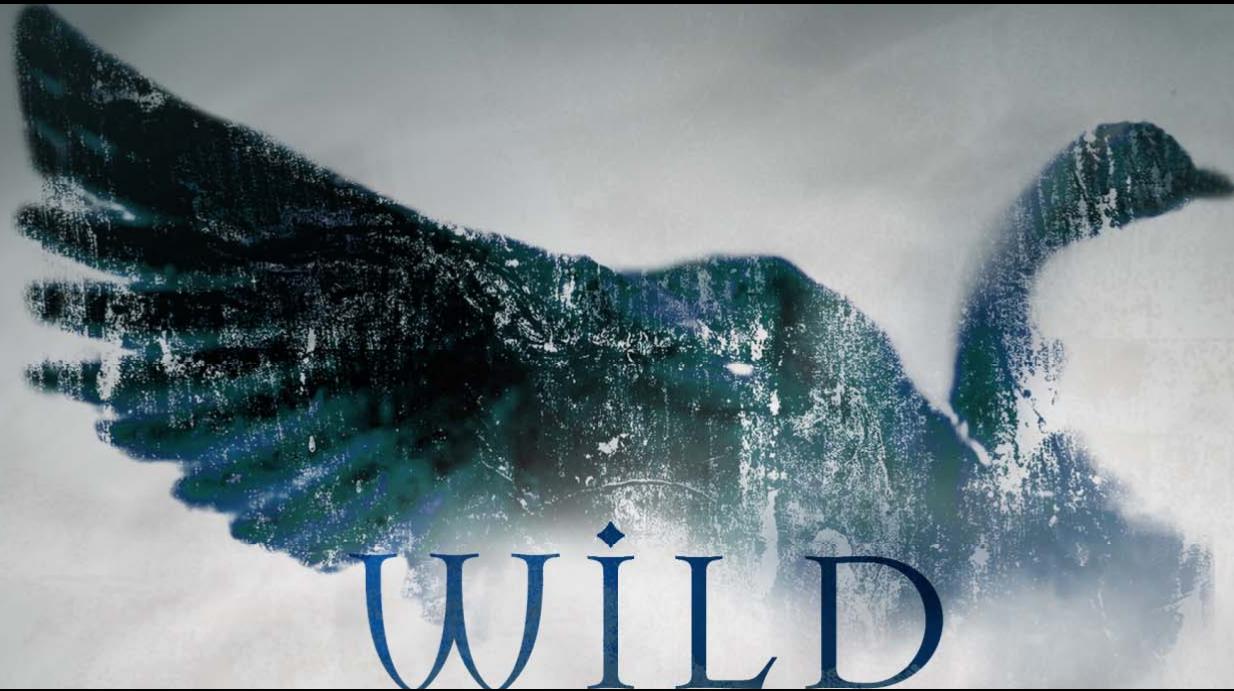
- Successful Launch: 14 May 2009
- Coolest thing in space (93 mK)
- $\Omega_0$ , n-1, dn/dlnk, Gaussianity, B-mode polarization?



Coming Soon: Planck Surveyor Launch 2008  
Cosmic Variance Limited to  $l \sim 2500$  (vs  
WMAP to  $l \sim 1000$ ) + polarization



Many, many more experiments on the ground and in balloons chasing “the wild goose” of B-modes:  
SPT-pol, QUIET, SPIDER, BICEP2, KECK Array, PolarBear, ACTpol, CMB-Pol,



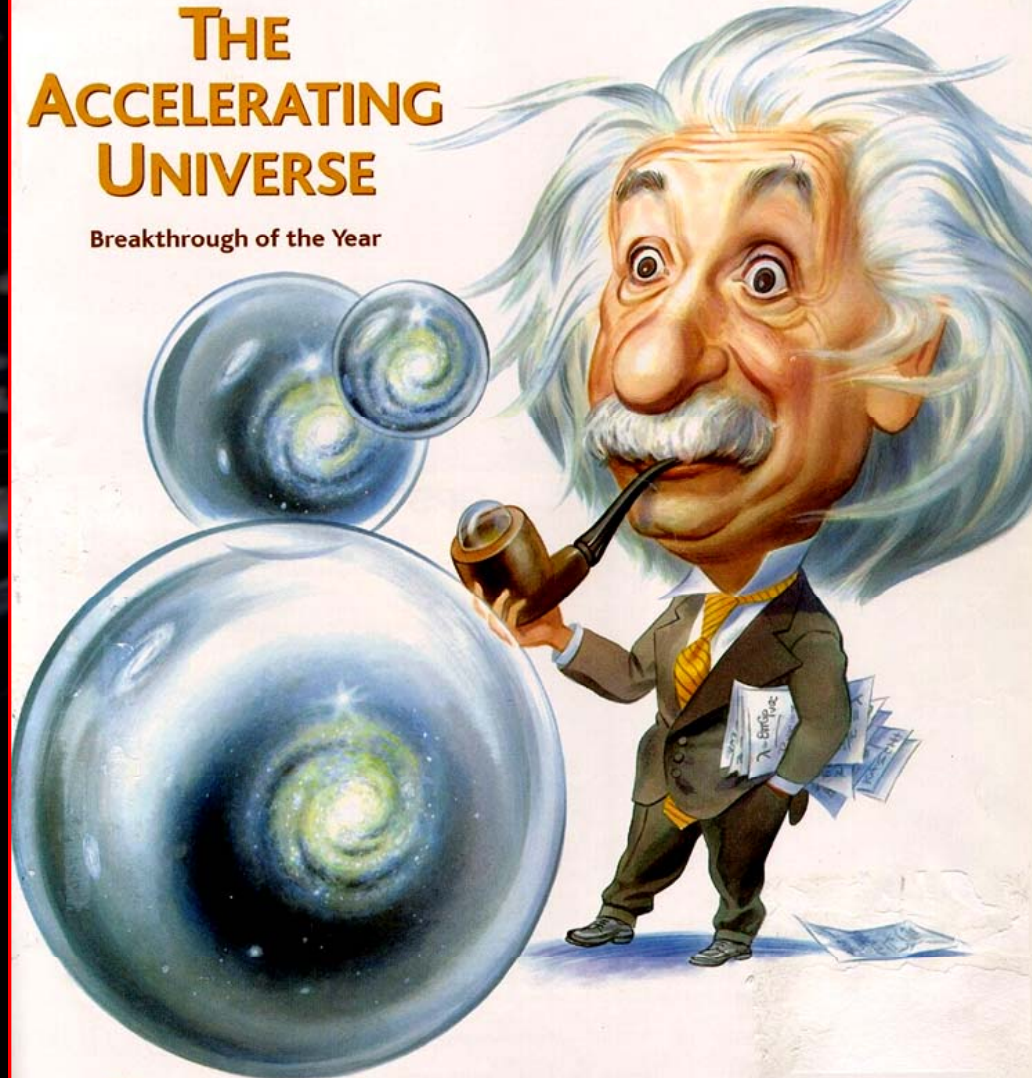
18 December 1998

# Science

Vol. 282 No. 5397  
Pages 2141-2336 \$7

## THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE



**DARK ENERGY**

**MAY BE THE MOST**

**PROFOUND PROBLEM**

**IN ALL OF SCIENCE TODAY**



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

# Drill for Dark Energy!

# Two Big Dark Questions

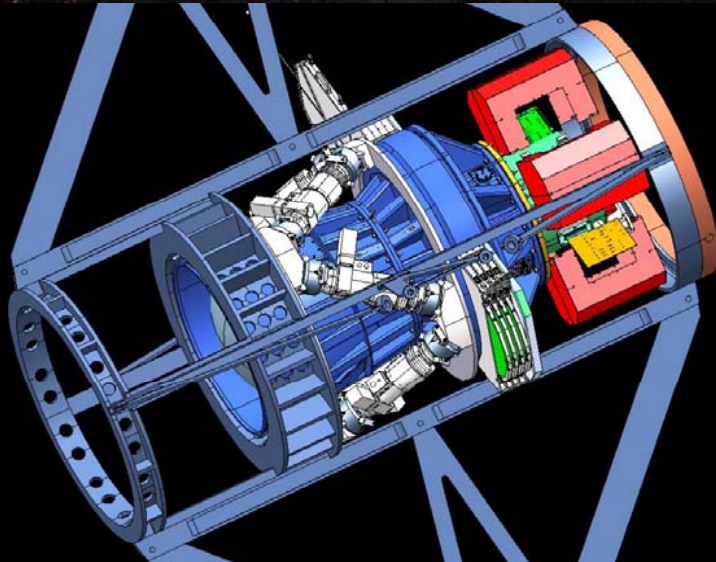
**Does Dark Energy change with time (i.e., is dark energy vacuum energy)?**

**No, at the 10 to 20% level**

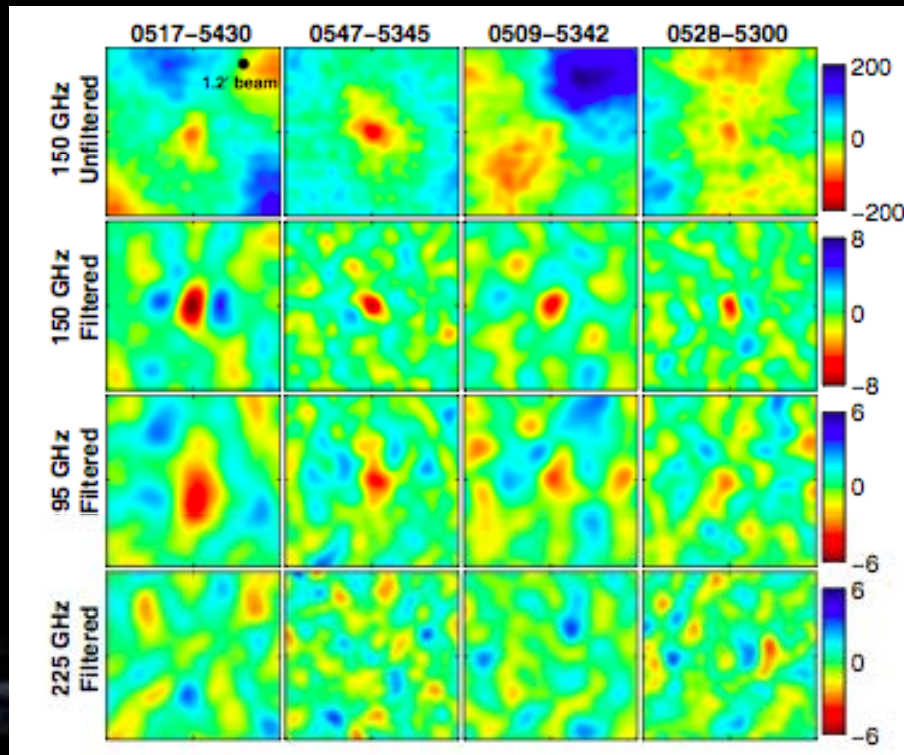
**Does Cosmic Acceleration require going beyond General Relativity?**

**Not well tested**

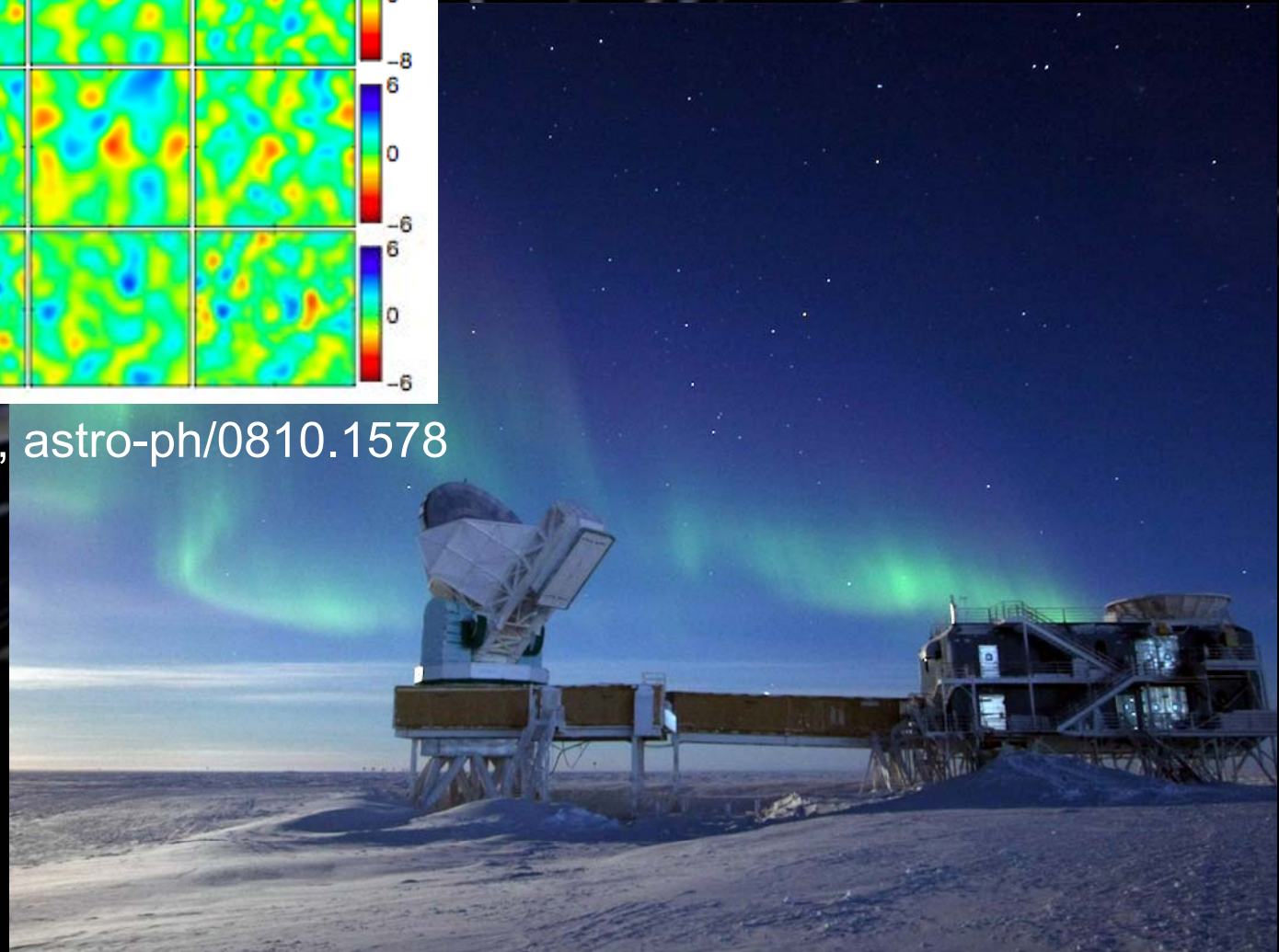
# Dark Energy Survey



# First Results from the South Pole Telescope



Staniszewski et al, astro-ph/0810.1578

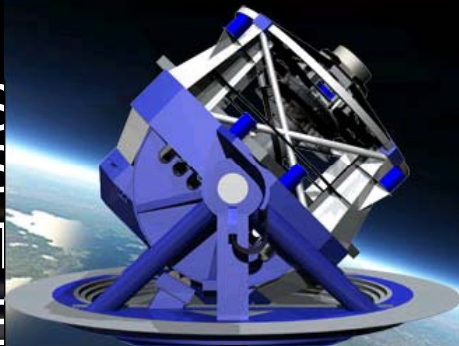


Impre  
P



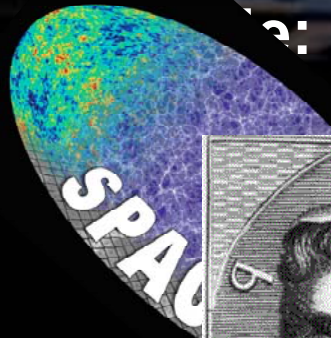
nergy  
n

- BAO: S
- WFMO
- CL: SPT
- e: DE



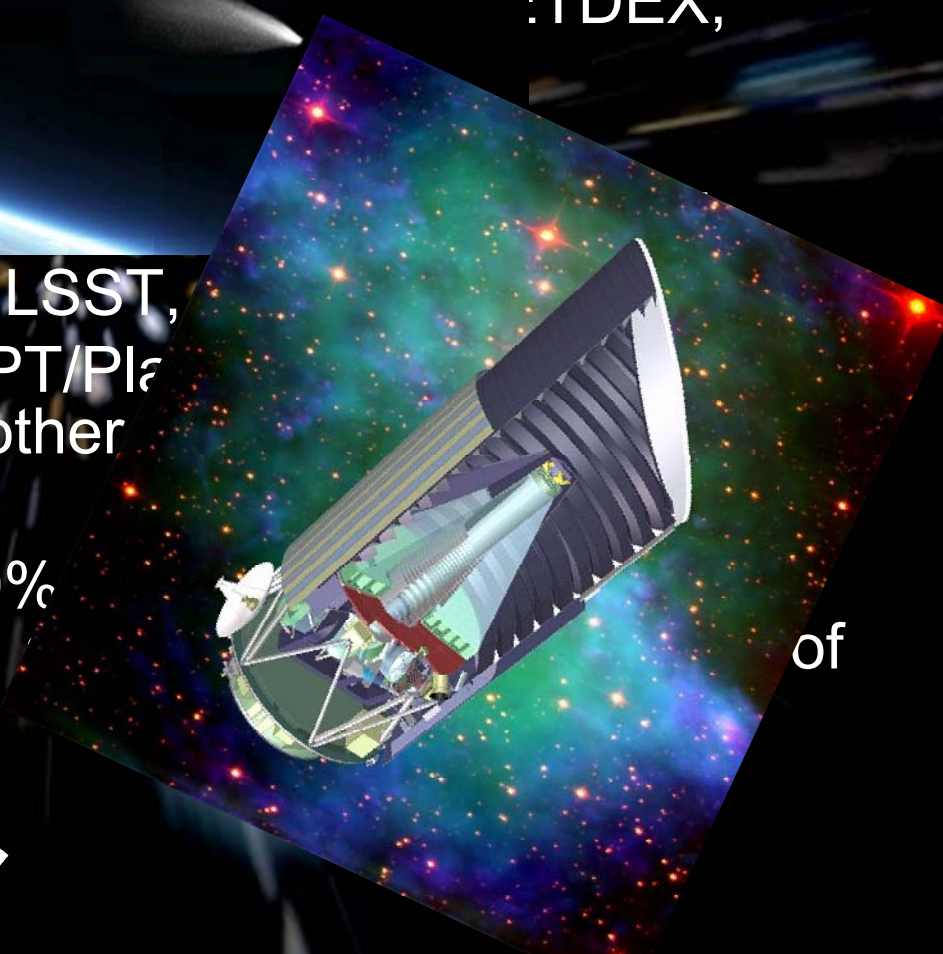
TDEX,

ES, PanSTARRS → LSST,  
AP/ACT/SPT/Pl  
ke many other



On  
u  
d

% in  $w_0$ , 10%  
theory ...



of

na

# The stakes are very high

Goal: Understand matter, energy,  
space and time and the complete  
history of the Universe

# The pieces on the table

- Dark matter
- Inflation
- Dark Energy
- Baryon asymmetry
- Eternal inflation/multiverse
- The mix

- Standard model, gravity
- Unified gauge theory
- “Stringy ideas”\*
- Holography
- Duality, extra dims
- Landscape, multiverse
- Emergence

\* The collection of powerful ideas formerly known as String Theory



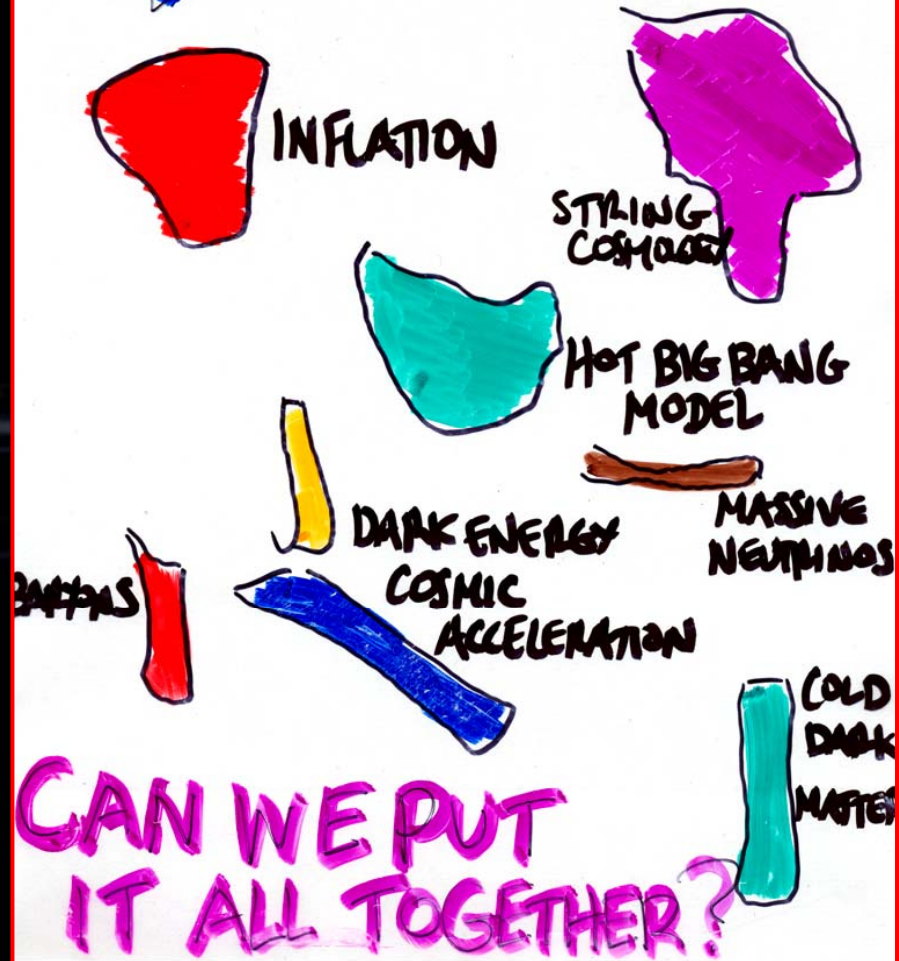
# Lots of data ahead



# Missing pieces/surprises

- Gravity waves (CMB, LIGO/VIRGO, LISA)
  - Non-flat Universe (probe to 0.1%)
  - $w \neq -1$ , const (probe to few%)
  - varying constants
  - tilted universe
  - No dark matter
  - No dark energy
- ... almost certainly a surprise ahead

# WE KNOW MUCH



# THE BIG PICTURE



# OUR UNIVERSE

# *the Birthers*



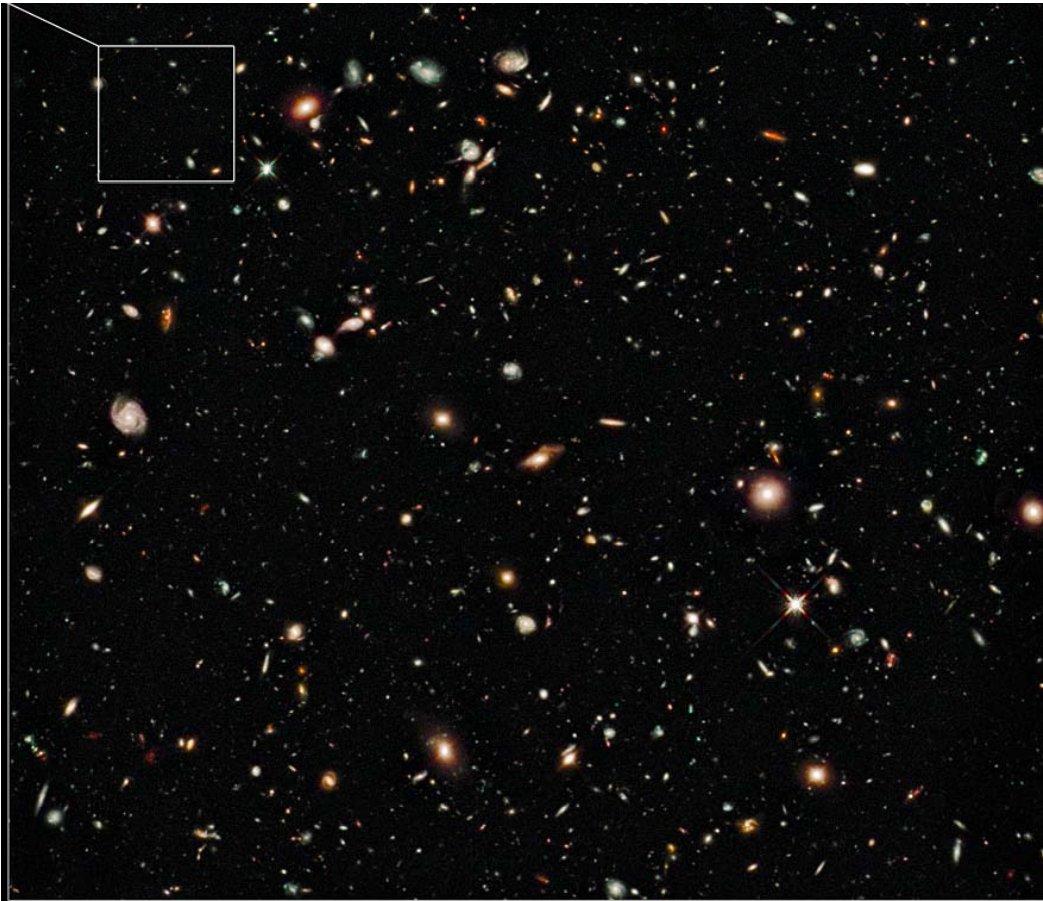
Dedicated to the rebirth of our Constitutional Republic



*Birther: A conspiracy theorist who believes that Barack Obama is ineligible for the Presidency of the United States, based on any number of claims related to his place of birth, birth certificate, favorite birthday, or whether or not he has heard the song Africa by Toto. Birthers also believe cosmic acceleration is part of the very same conspiracy.*

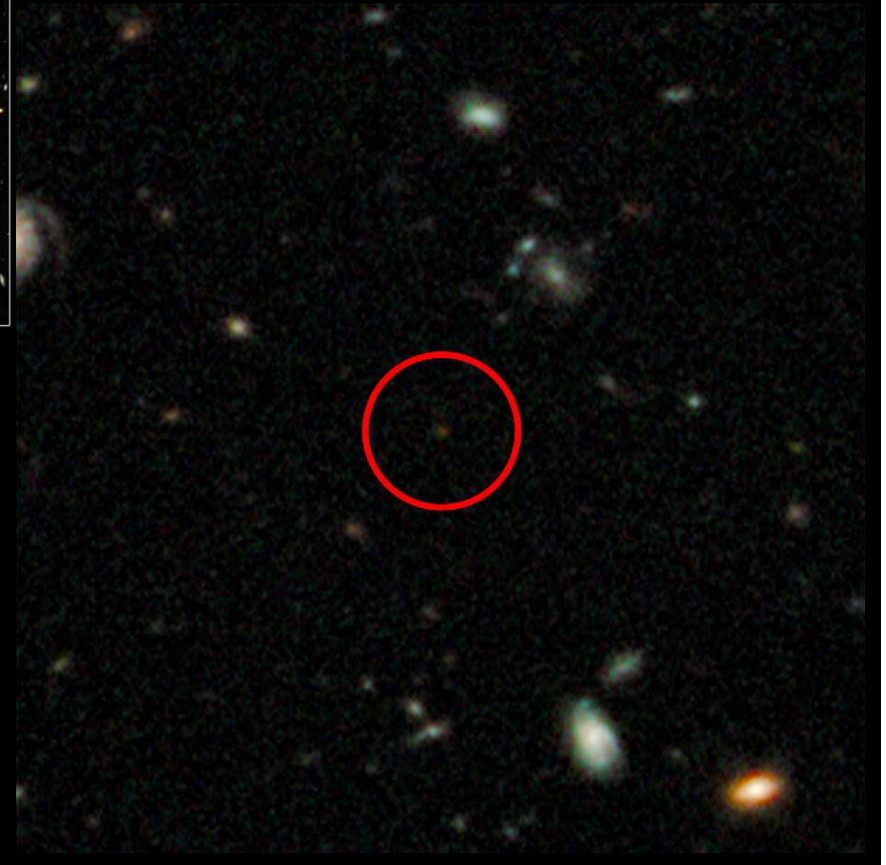
# Beyond 2030: A Dark Future?

No surprises, no answers, ...  
The Universe is a very, very big,  
often beyond the reach of our  
ideas and instruments.



Most Distant Galaxy:  
UDFy-38135539  
Redshift 8.6  
Universe 9.6x smaller  
and only 600 Myr old

0.5 photons per sec!



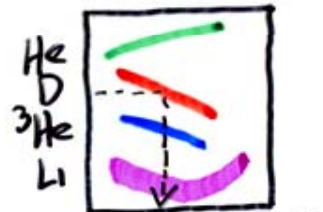
# ORDINARY MATTER: FROM QUARKS TO US

INFLATION  
BARYOGENESIS



$10^{-5}$  SEC

TRANSITION FROM  
QUARKS  $\rightarrow$  NEUTRONS, PROTONS



DENSITY OF MATTER

BIG-BANG  
NUCLEOSYNTHESIS

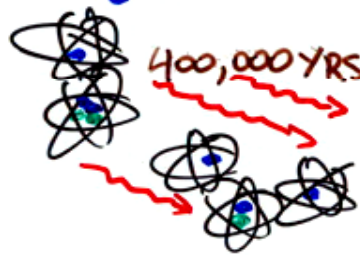
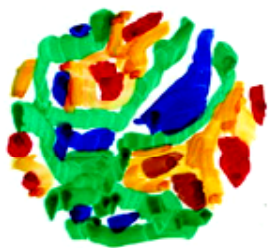
Formation of H, D,  
He, He-3, Li

BBN

$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Omega_B = 0.04 \pm 0.002$

FORMATION OF ATOMS  
COSMIC MICROWAVE  
BACKGROUND

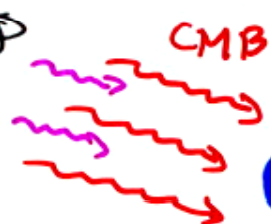


400,000 YRS



1 BILLION YRS  
FIRST QUASARS

QSO LIGHT



CMB

CMB

RATIO OF FIRST-TO-  
SECOND PEAKS:  $2/1$



$\Omega_B = 0.045 \pm 0.008$

INTERGALACTIC GAS

ABSORPTION OF  
QUASAR LIGHT  
BY HYDROGEN

$\Omega_B \geq 0.04$

HERE & NOW  
44 Billion YRS  
stars, gas,  
dust, ...

# Boom or bust science

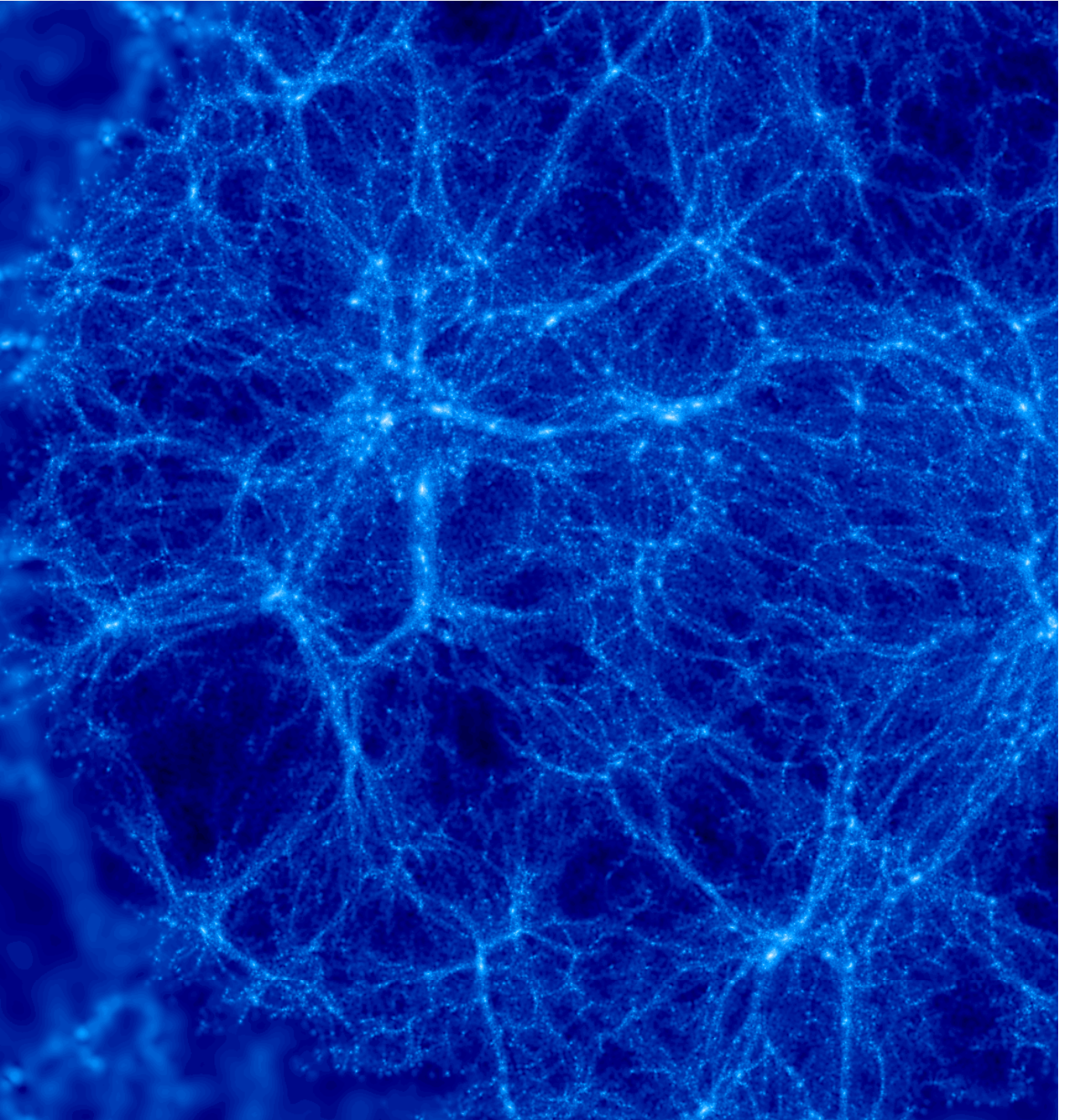
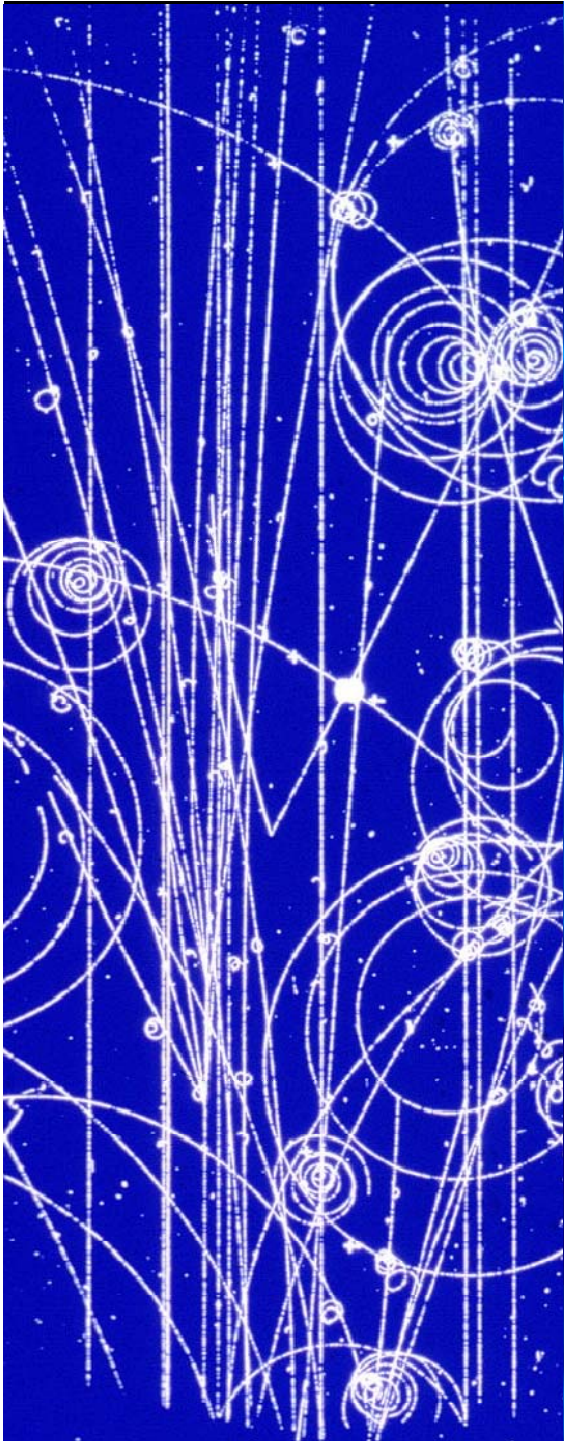
- Circa 1920s
- Circa 1960s
- Circa 1980s
- Circa 2000s

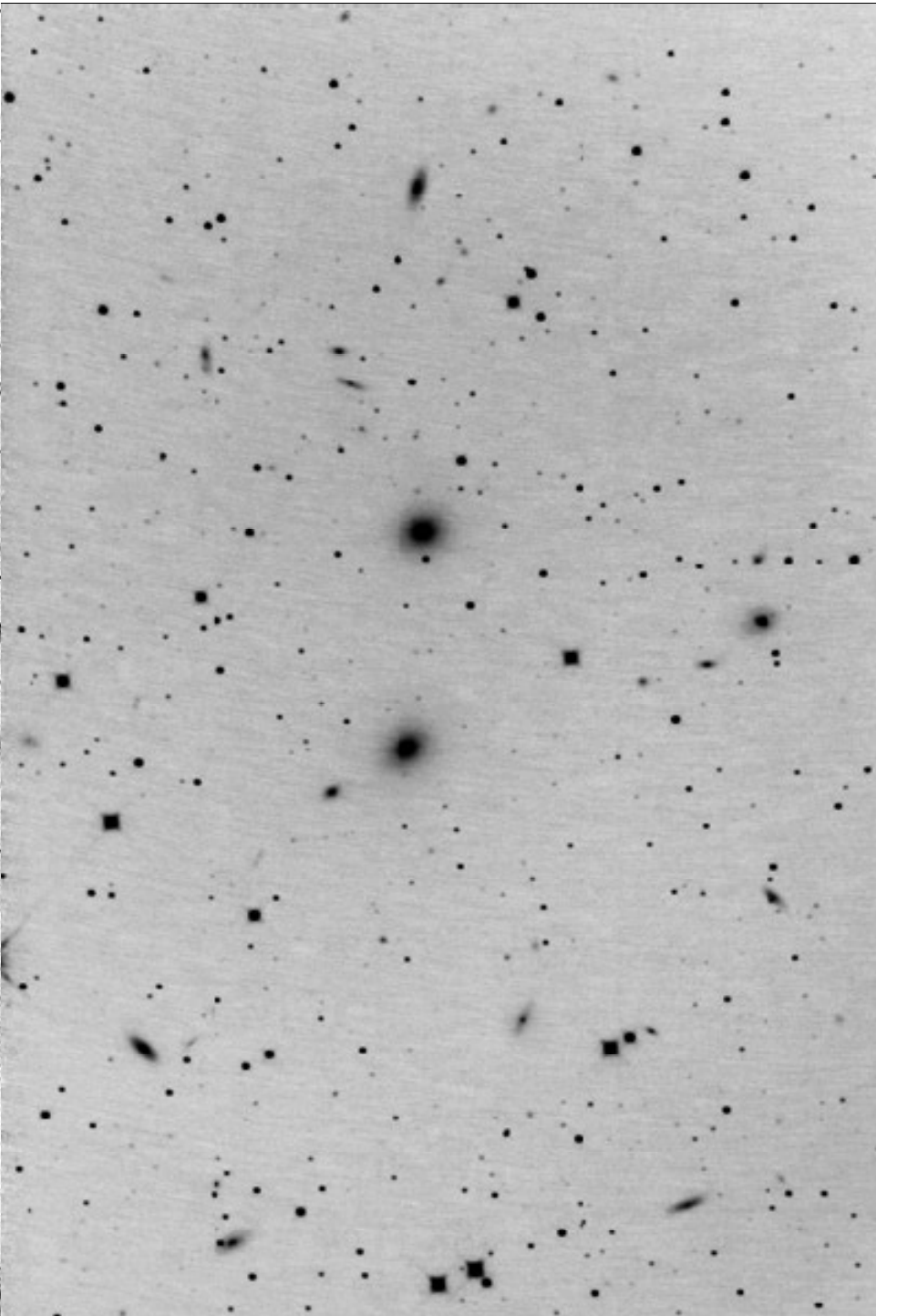
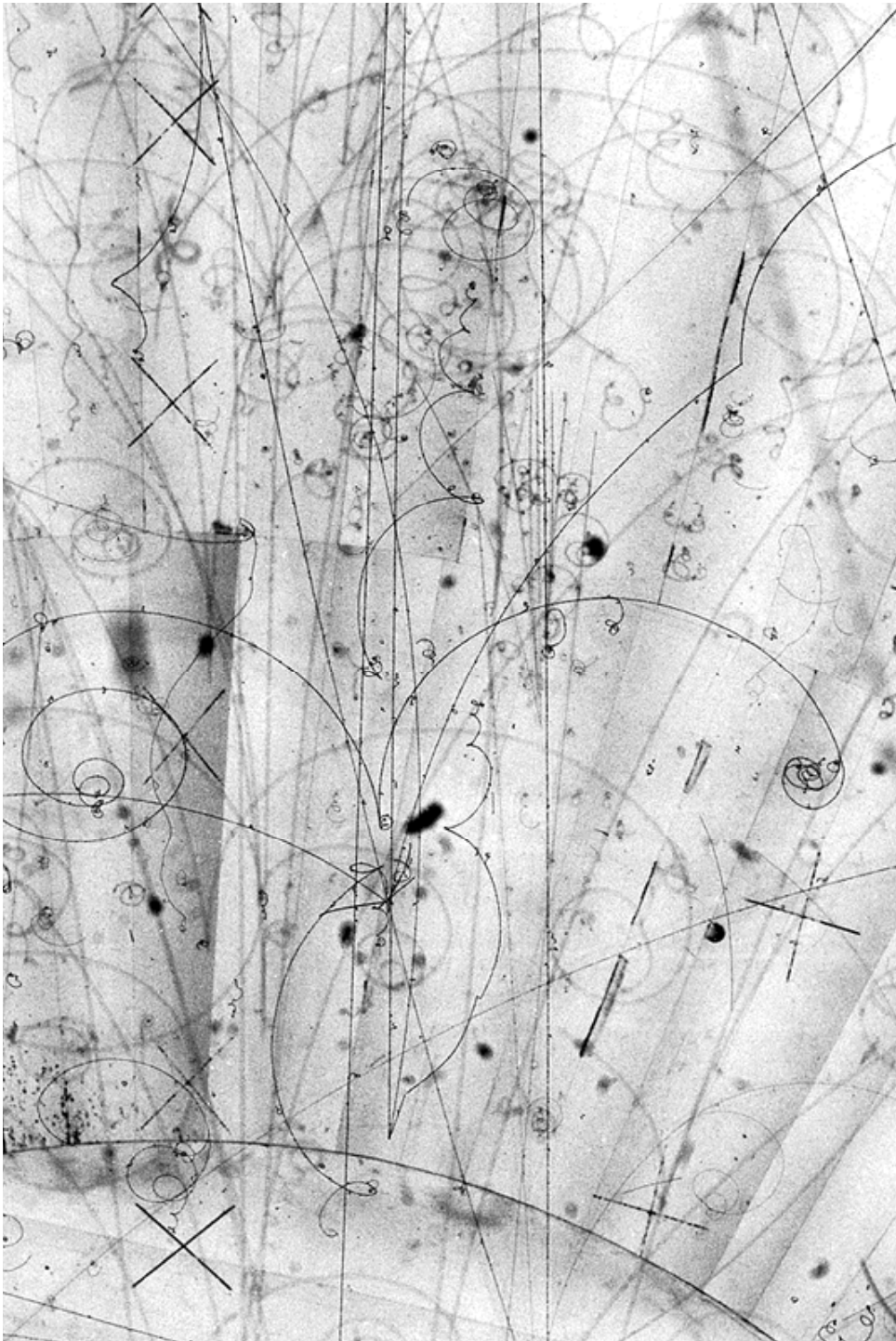
**BOOM**

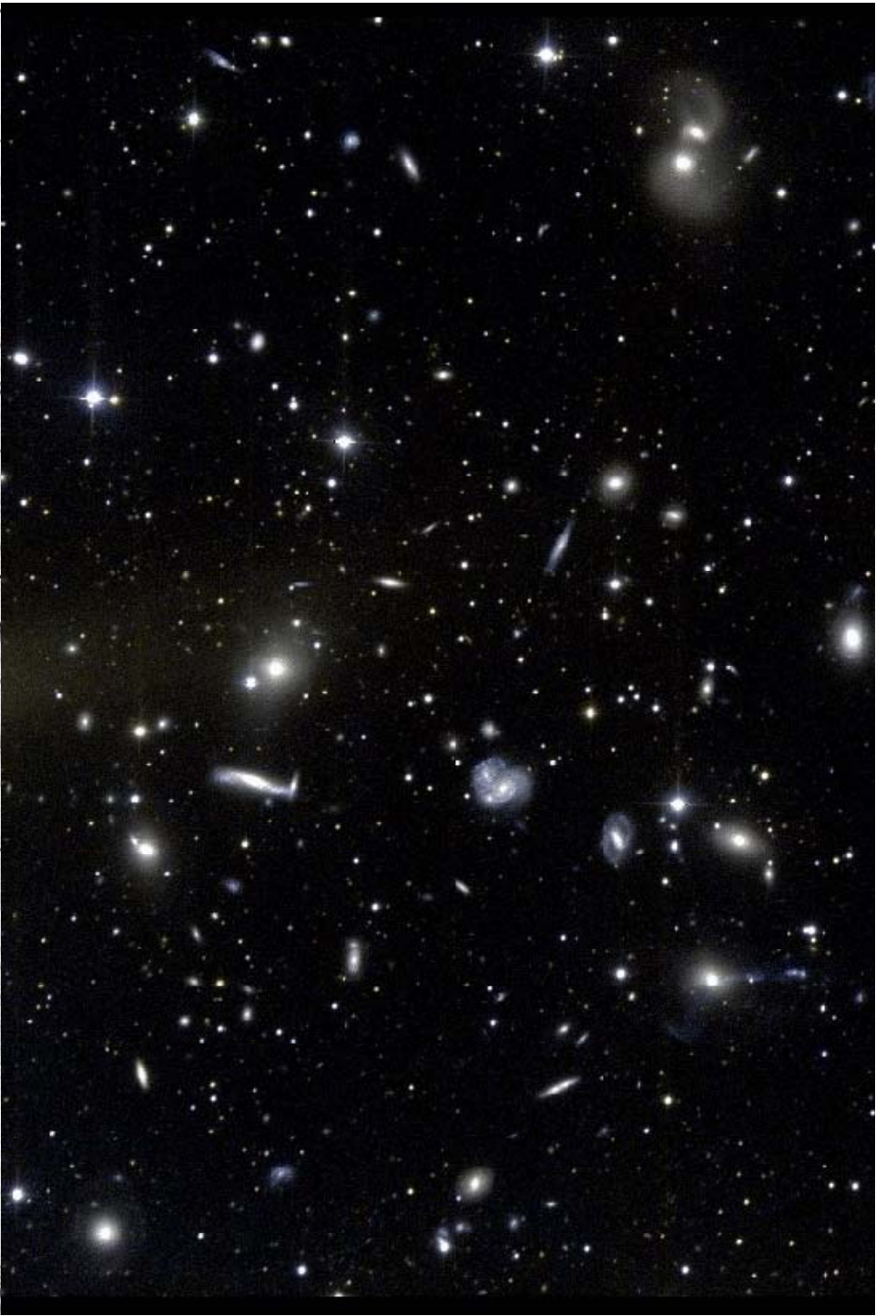
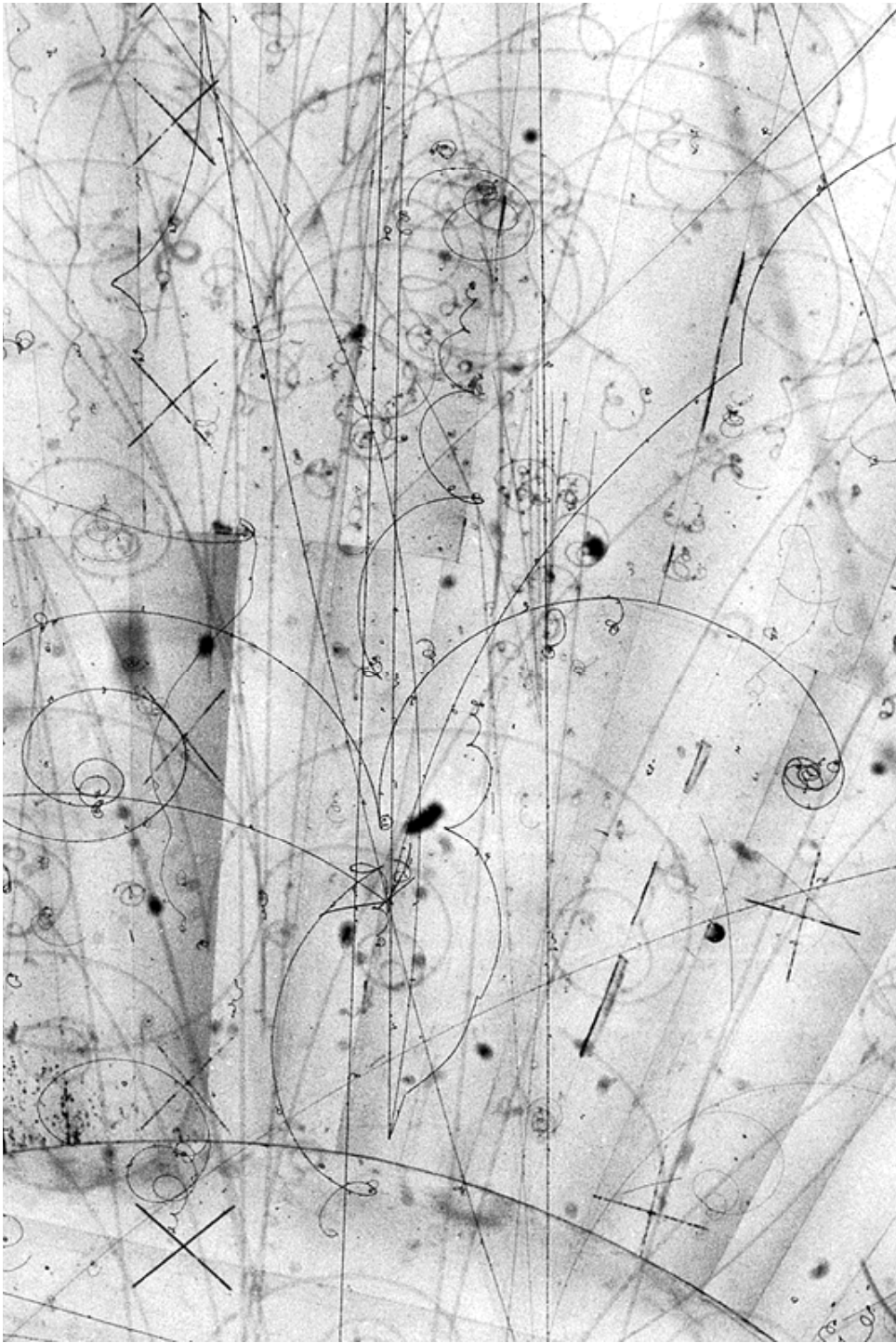
- Pre-1910
- Circa 1930 to 1960
- Circa 1970s
- Circa 1990s  
(recession)

**BUST**









# Dark matter factory





Now we have two puzzles:

Why does nothing weighs so little?

&

What is dark energy?

Puzzles could be related or unrelated!

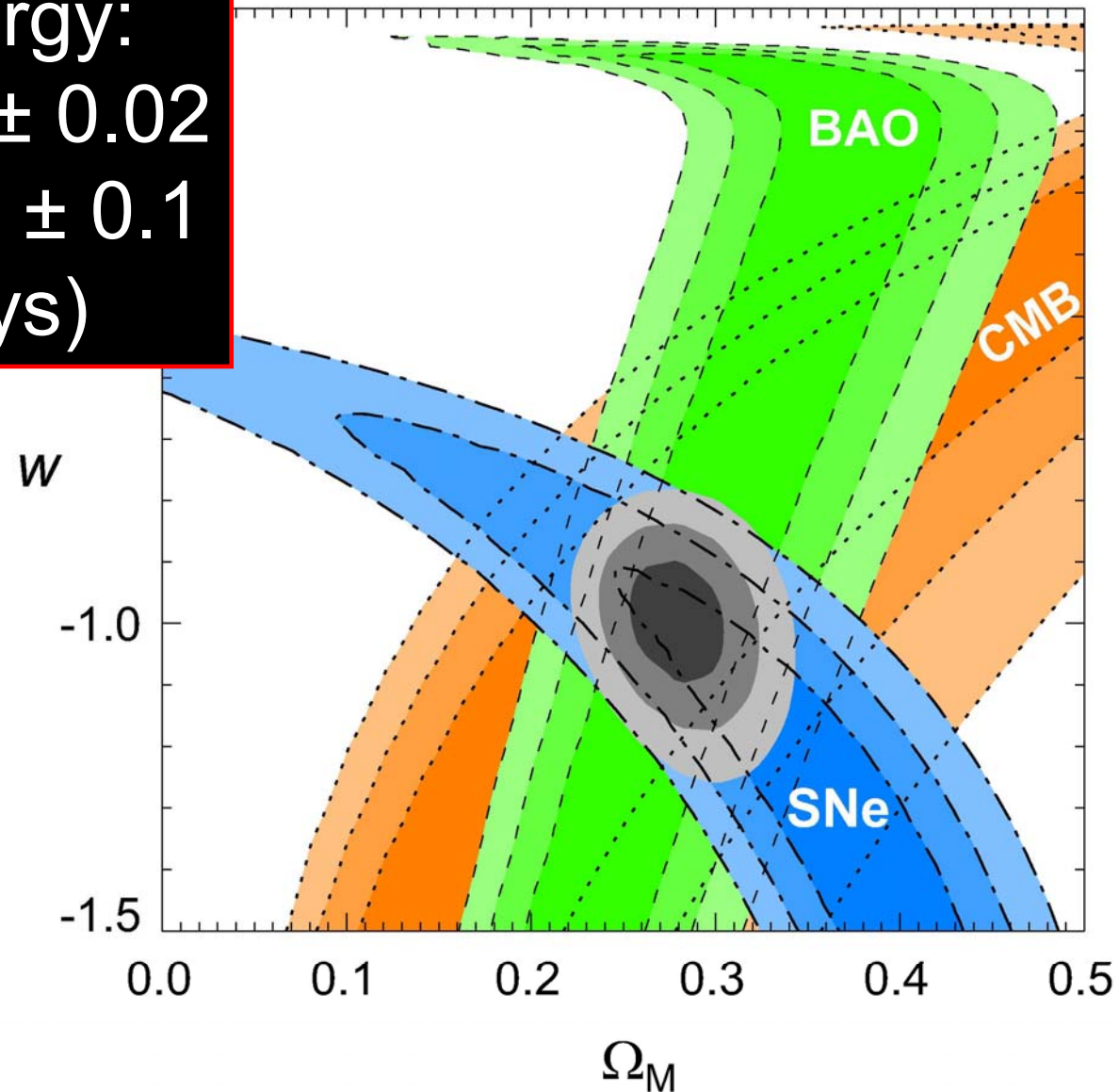
# Where We Are Today

Dark Energy:

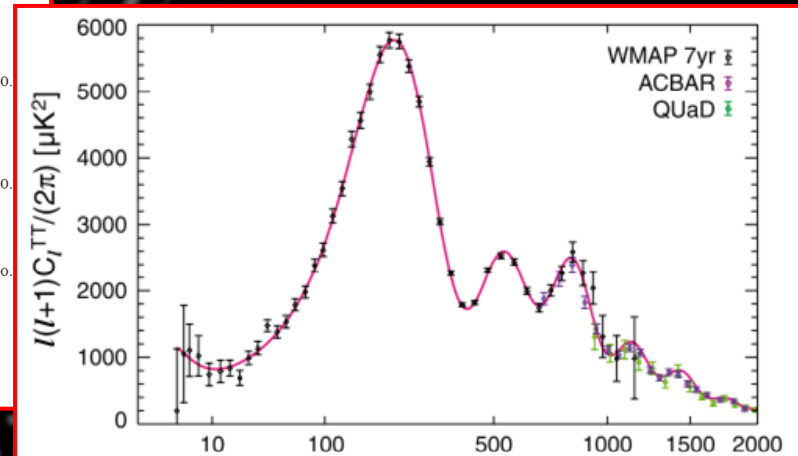
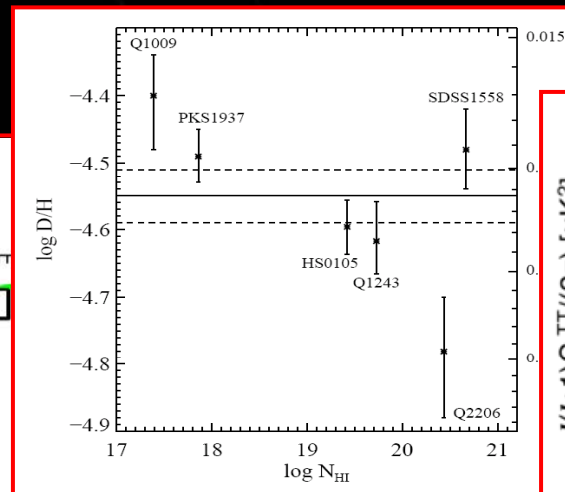
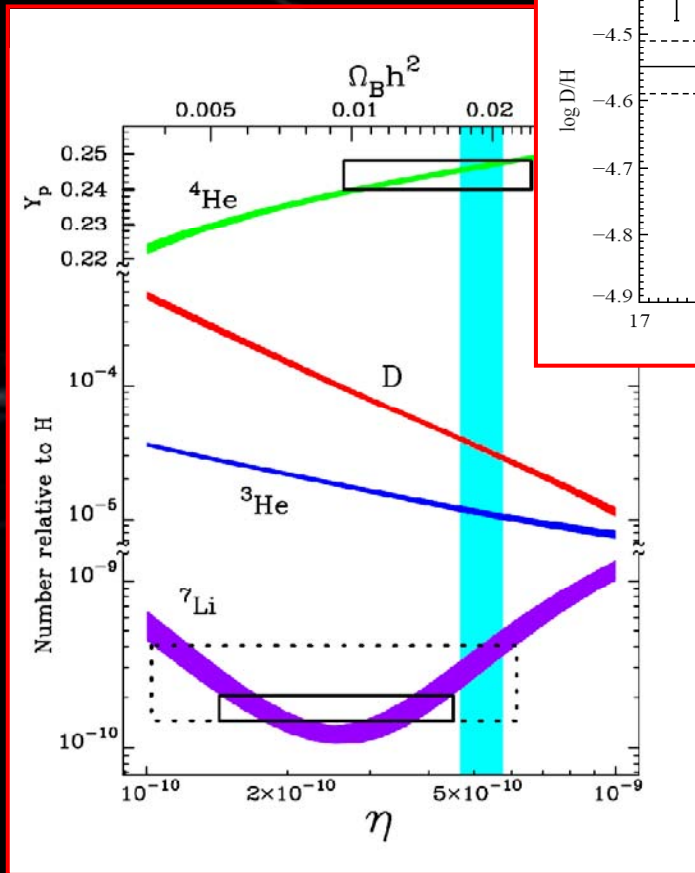
$$\Omega_{\text{DE}} = 0.76 \pm 0.02$$

$$w = -0.94 \pm 0.1$$

( $\pm 0.1$  sys)



# Precision Cosmology Indeed!



CMB (first to second peak)

$$\Omega_b h^2 = 0.0225 \pm 0.0006$$

vs.

BBN (Deuterium)

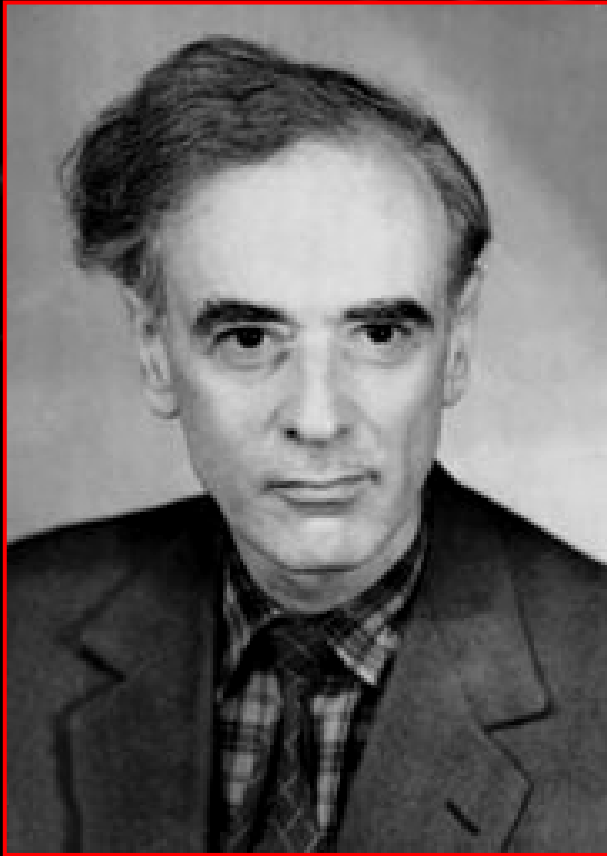
$$\Omega_b h^2 = 0.021 \pm 0.001$$

*~5% agreement*

$$\Omega_b = 0.044 \pm 0.002$$

$$h = H_0/100 \text{ km/s/Mpc} \sim 0.7$$

# Circa 2008



~~Often in Error,  
Never in Doubt!~~





**Impressive achievement.  
Golden Age?  
If we can answer the big  
questions**

- Dark Matter: what is it?
- Dark Energy: ##??!
- Origin of ordinary matter (baryons)?
- Inflation: how did the Universe begin?



# **Back to 1980s & Motivations for Inflation**

# Successes of Standard Hot Big Bang Cosmology

- Big-bang nucleosynthesis
- Expansion of the Universe
- Cosmic Microwave Background (CMB)
- Structure formation by gravity
- Tested account from Quark Soup ( $10^{-5}$  sec) on to the present

# Big Unanswered Questions circa 1980

- Origin of baryons
- Dark Matter
- Cosmological constant
- Before the big bang/initial singularity
- Dynamite behind the big bang
- Heat of the big bang
- Isotropy, homogeneity and flatness (not generic initial conditions)
- Origin of seed inhomogeneity

**Addressed by Inflation**

# SPACE-TIME GEOMETRY

our initial geometry



smooth, small ripples



15 Gyr



generic initial geometry



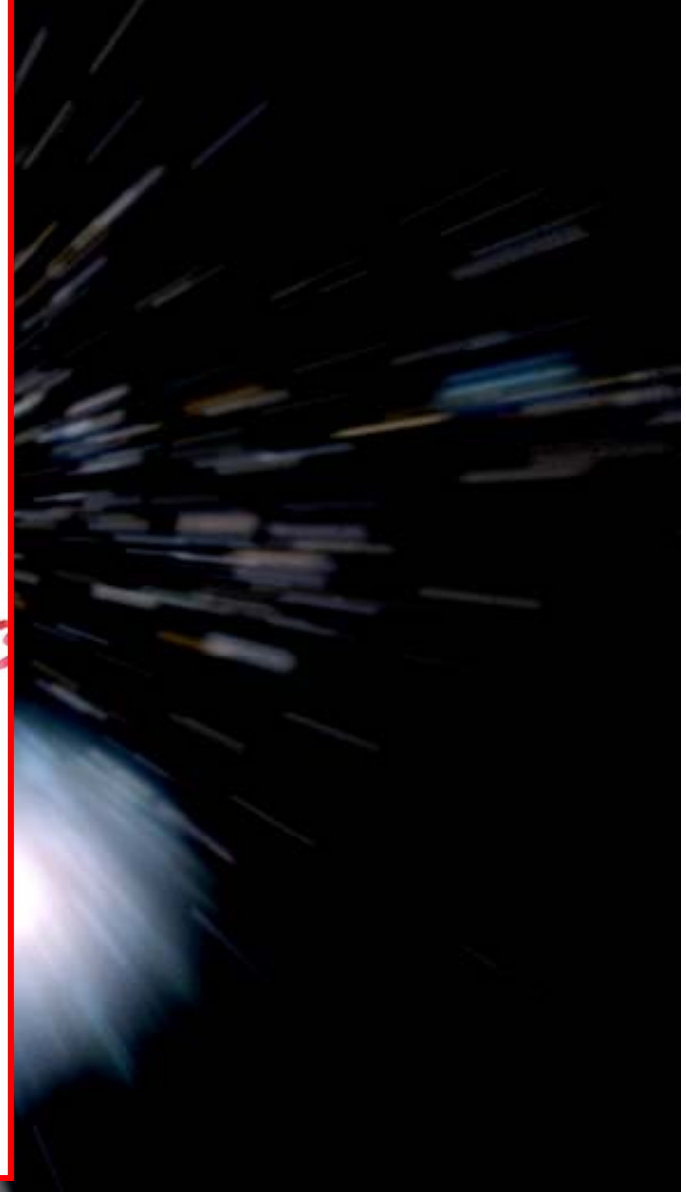
$10^{-43}$  sec

Black holes, anisotropy, ...  
"A MESS"

Collins & Hawking '73

★ NOT LOGICAL INCONSISTENCY!

★ DILEMMA OF INITIAL DATA  
(WHY SO SPECIAL?)

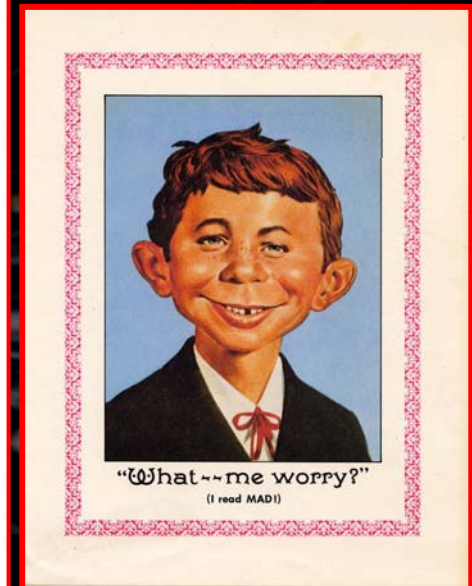
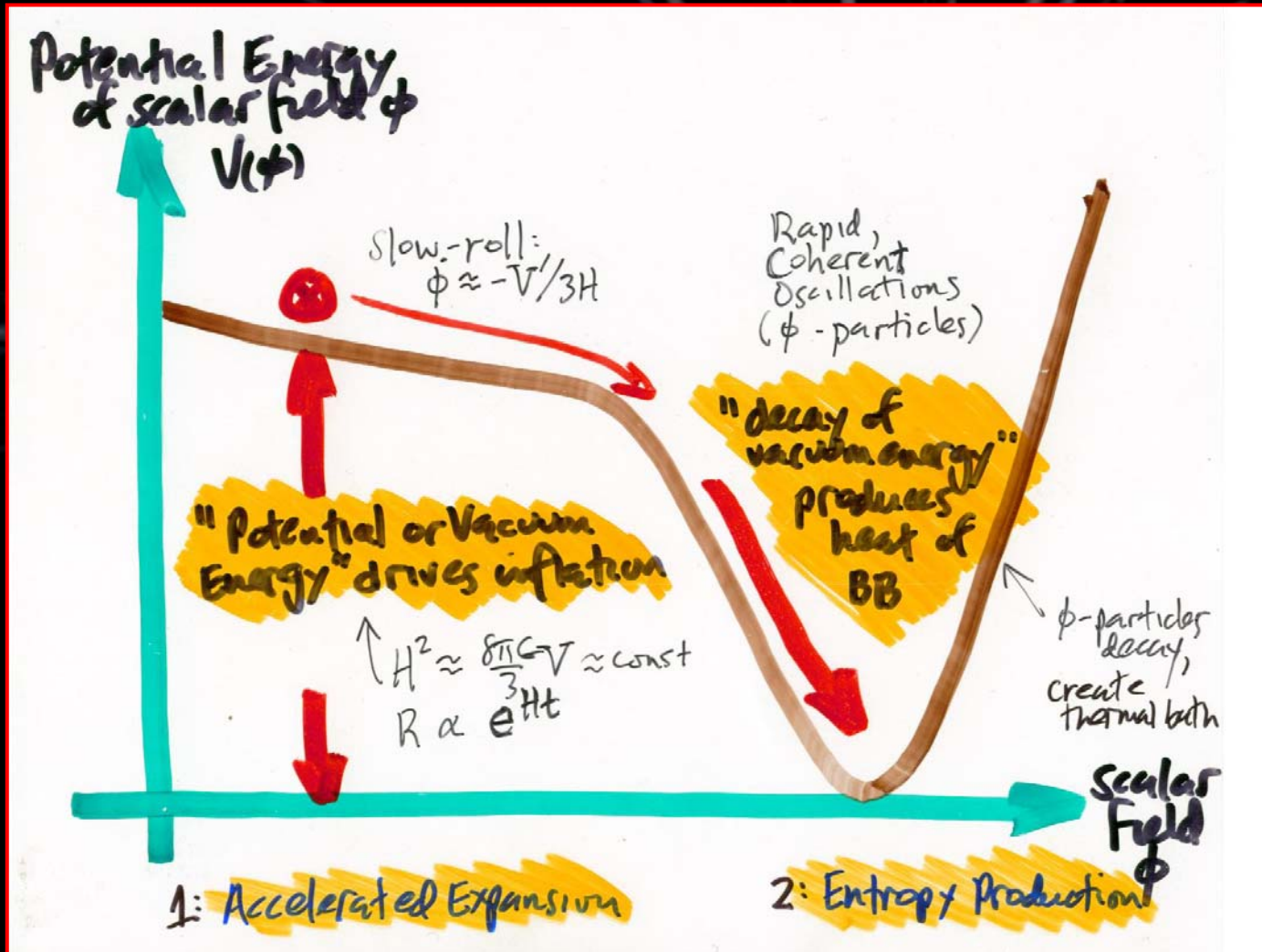


# Key Elements of Inflation

- Period of exponential expansion (constant Hubble Constant and horizon size)
- Tremendous entropy production (called reheating)

→ Greatly reduce dependence upon initial data

# Inflation Implemented as Scalar-field Dynamics



Theorists:  
When in  
doubt, just  
add a  
scalar field



TINY ( $\lll 1\text{cm}$ ) BIT  
OF UNIVERSE IS FLAT  
& SMOOTH (but too  
small to contain all we  
see today)

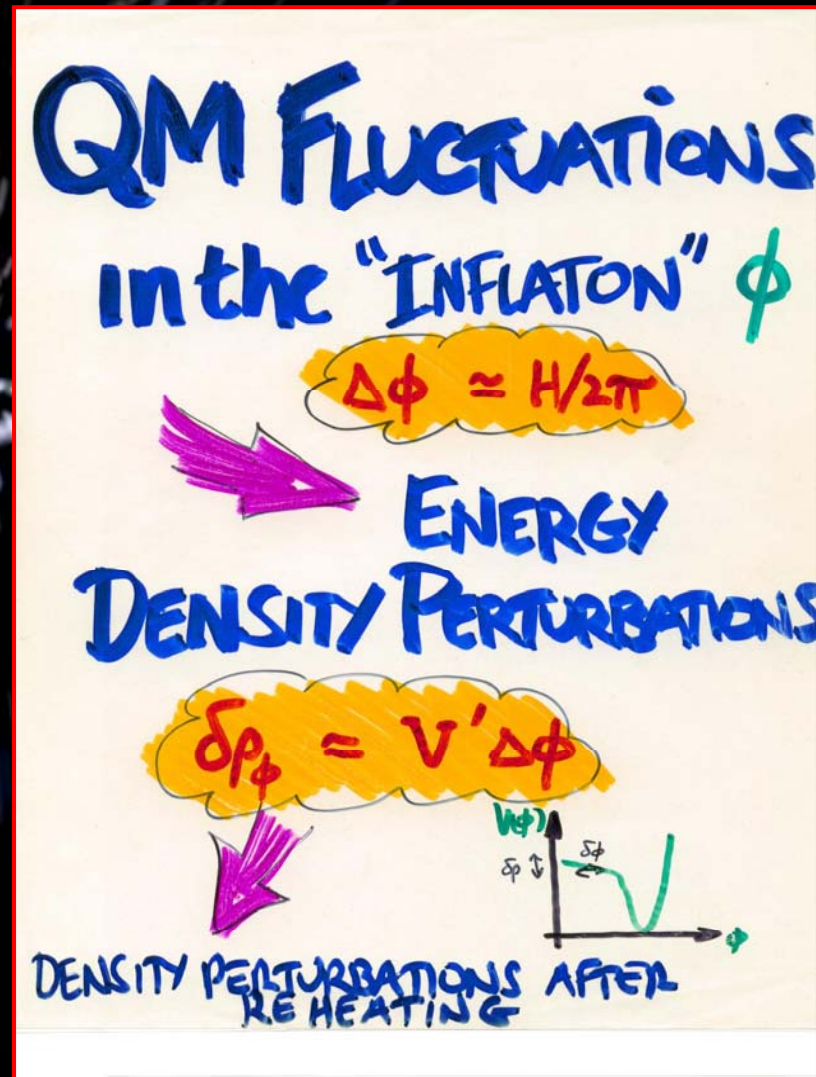
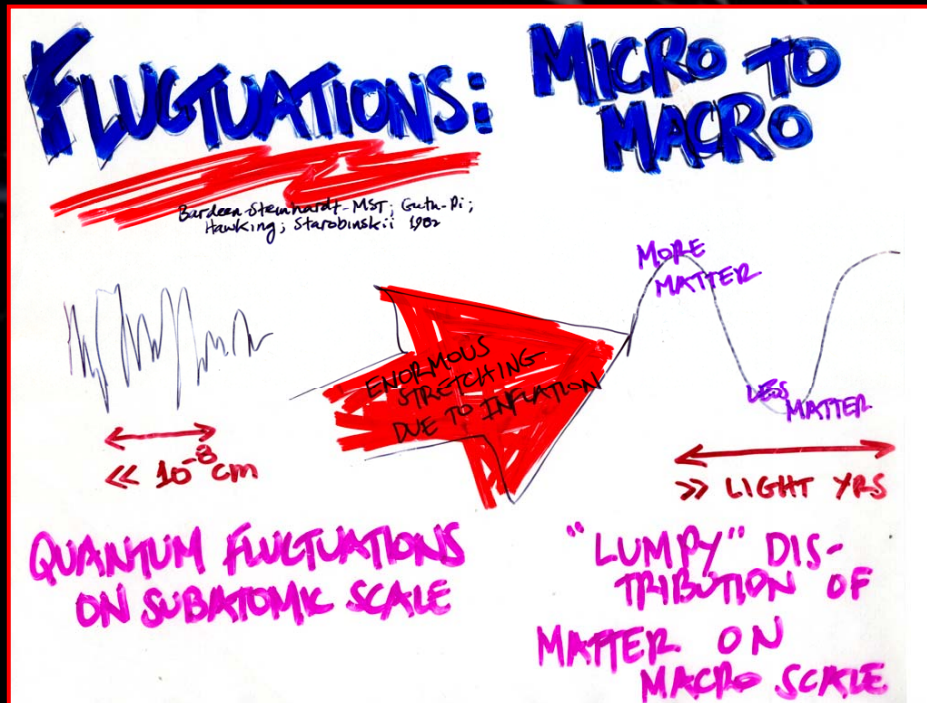


ALL THAT  
WE CAN  
SEE TODAY  
(STILL SMOOTH  
& FLAT)

Solving the Flatness,  
Horizon Problems



# Quantum Fluctuations Seed Density Perturbations



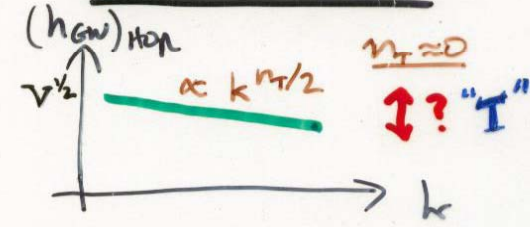
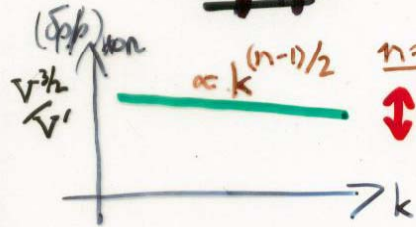
Given scalar potential  $V(\phi)$ , can compute all observables in terms of  $V$ ,  $V'$  and  $V''$

# INFLATIONARY QUANTUM FLUC.

DEFINITE POTENTIAL MAKES DEFINITE PREDICTION

$\delta\rho/\rho$

Grav Wave



NEARLY SCALE-INVARIANT, MODEL-DEPENDENT AMPLITUDE

AMPLITUDES (measure by contribution to variance of CBR quadrupole)

$$S \equiv \frac{5 \langle |a_{2m}^S|^2 \rangle}{4\pi}$$

$$T \equiv \frac{5 \langle |a_{2m}^T|^2 \rangle}{4\pi}$$

$$S \approx \frac{2.2 V/m_{pl}^4}{(m_{pl} V'/V)^2} + \dots$$

$$T \approx 0.61 V/m_{pl}^4 + \dots$$

would like  $\approx$  few  $\times 10^{-11}$  to

would like to measure!

SPECTRAL INDICES (scale invariant + small correction)

$$n = 1 - \frac{1}{8\pi} \left( \frac{m_{pl} V'}{V} \right)^2 + \frac{m_{pl}}{4\pi} \left( \frac{m_{pl} V''}{V} \right) + \dots$$

Small correction  $\sim (0.03-0.2)$

$$n_T = 0 - \frac{1}{8\pi} \left( \frac{m_{pl} V'}{V} \right)^2 + \dots$$

Small correction

$$\frac{dn}{dn_k} = \frac{1}{8\pi} \left( \frac{m_{pl} V''}{V} \right) \left( \frac{m_{pl} V'}{V} \right) + \frac{1}{8\pi} \left( \frac{m_{pl} V'''}{V} \right) \left( \frac{m_{pl} V'}{V} \right) - \frac{3}{8\pi} \left( \frac{m_{pl} V''}{V} \right)^2$$

NB:  $n_T = -\frac{1}{5} \frac{T}{S}$      $n_T < 0$      $n_T \neq n-1$

# What we know about inflation

1. Paradigm, no standard model, many viable models (new, chaotic, ...)
2. Three key predictions
  - Flat Universe:  $\Omega_0 = 1.0000$
  - Almost scale-invariant adiabatic, almost power-law, Gaussian adiabatic fluctuations
    - $|n-1| \sim 0.1$ ,  $|dn/d\ln k| \sim 10^{-3}$
  - Almost scale-invariant spectrum of gravitational waves
    - $n_T \sim 0$  to  $-0.1$  (i.e., negative)
3. Consistency relation:  $T/S = -5n_T$ 
  - Unfortunately,  $T/S$  not related to  $n$

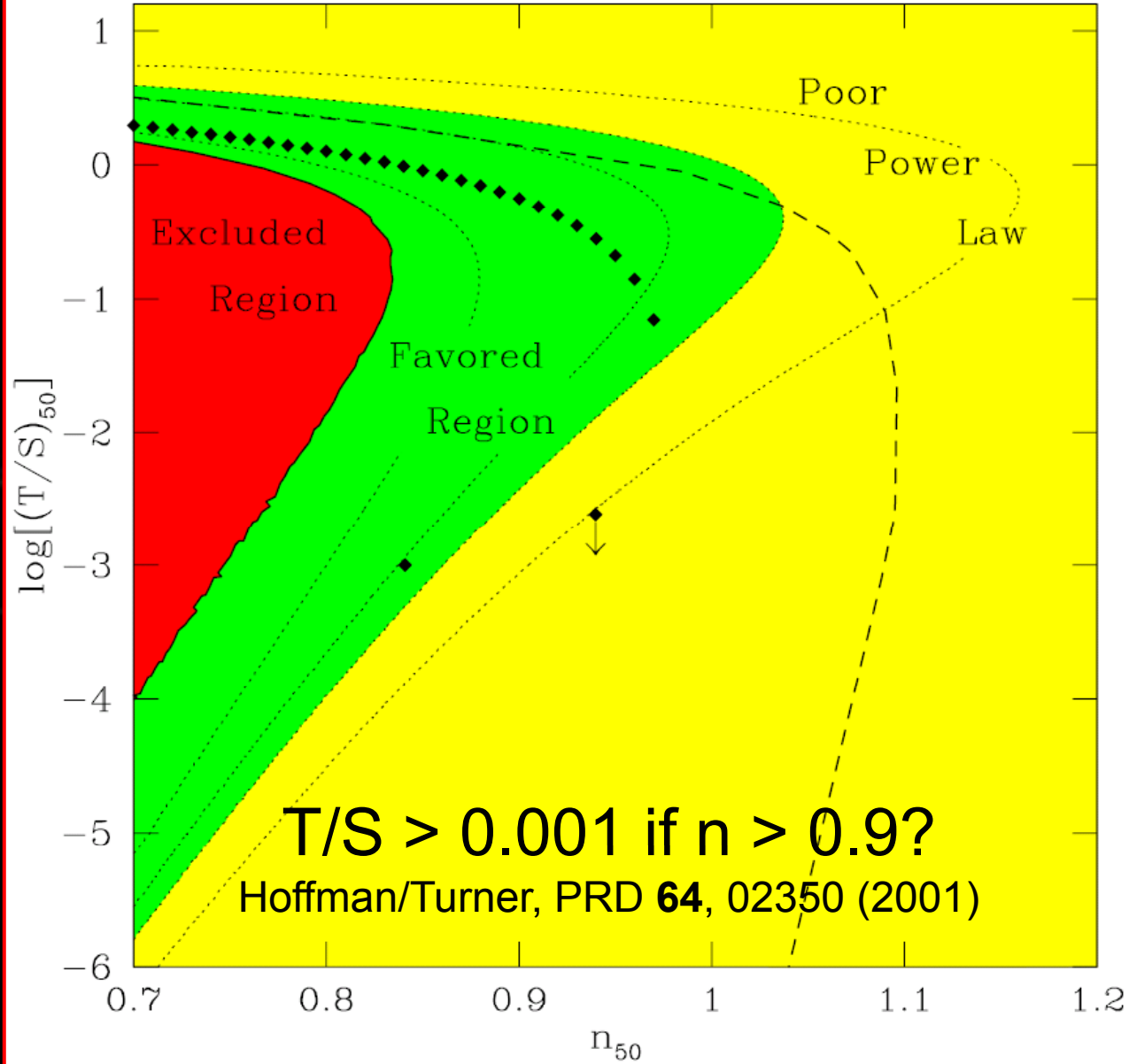
# Important Facts About Inflation, cont'd

4. Measuring GWs immediately gives scale of inflation!

$$H_I^{-1} = \frac{2 \times 10^{-39} \text{ sec}}{\sqrt{T/S}}$$

$$V^{1/4} = 3 \times 10^{16} \text{ GeV } (T/S)^{1/4}$$

5. But, no robust prediction for  $T/S$  ( $=r$ )
6. Most important idea in cosmology since hot big bang



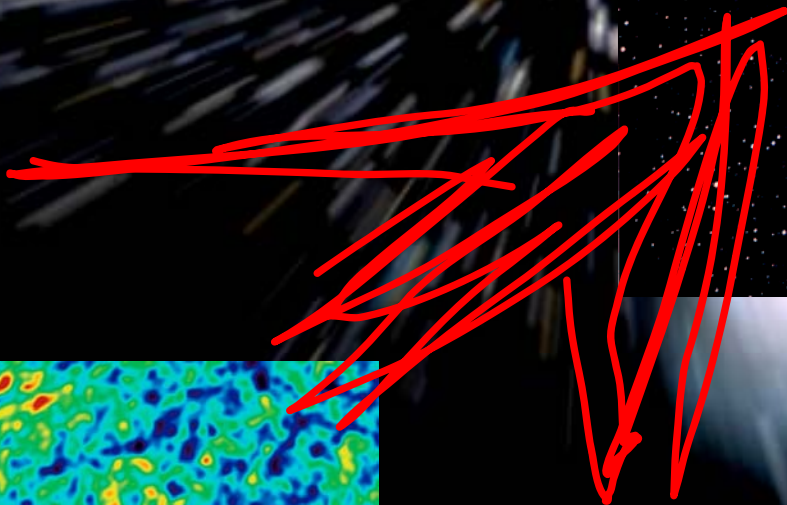
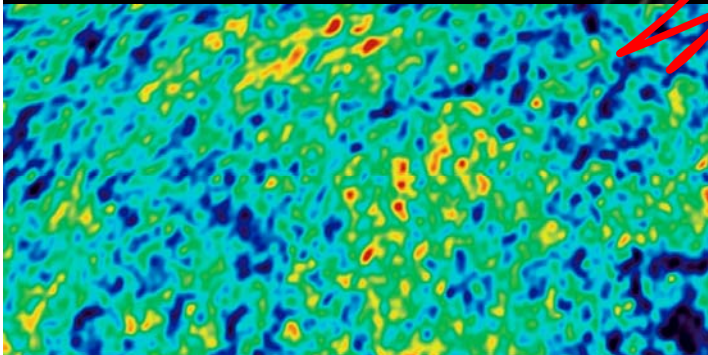
STATUS OF  
INFLATION:

EXCELLENT!

M.S. Turner / U. Chicago &  
Feminists

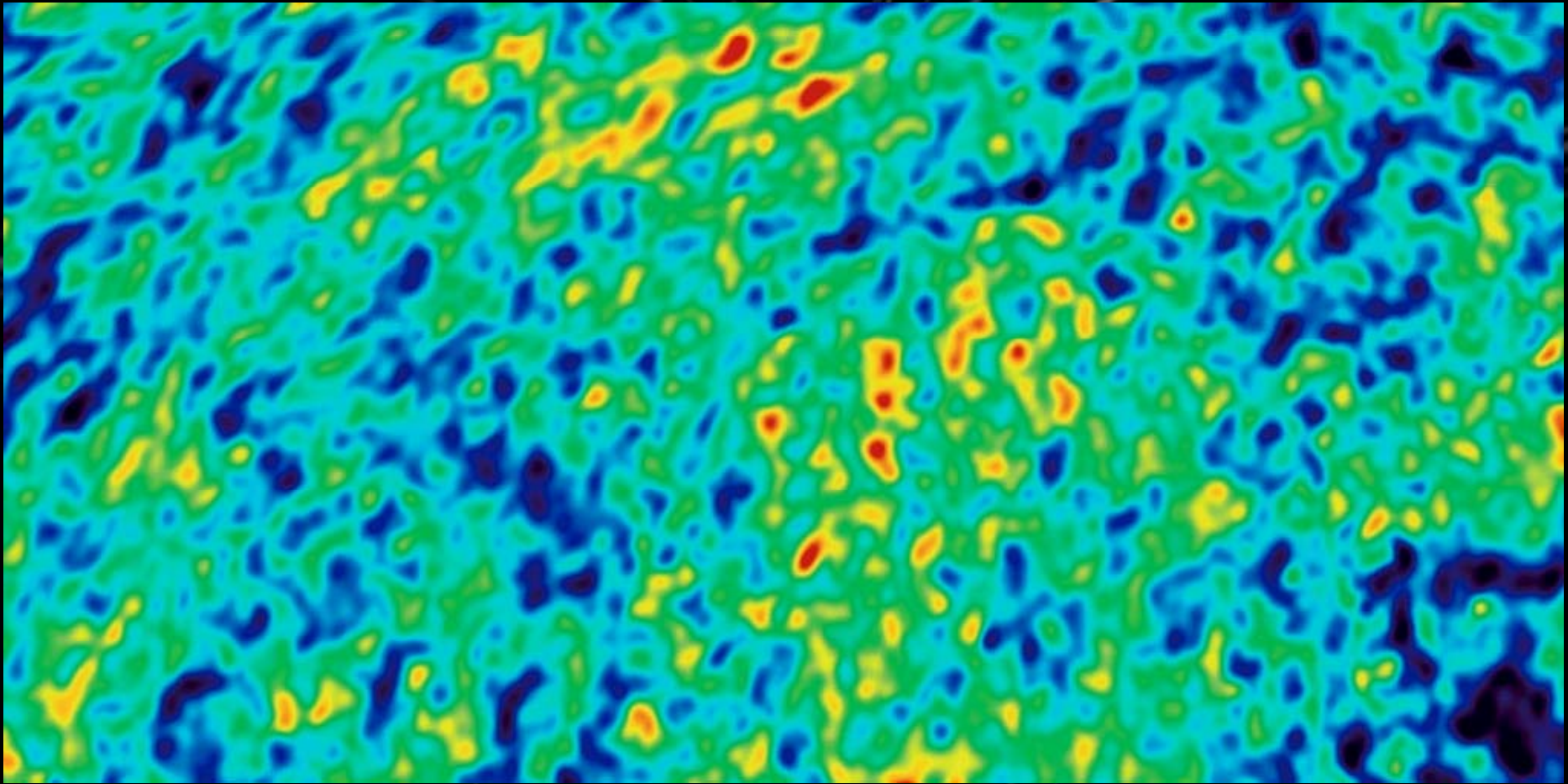


**The Largest Things in the Universe  
Began from Subatomic Quantum  
Fluctuations!**



**WOW!**

# Quantum World Projected Across the Sky by the Expansion of the Universe



← one billionth the size of a proton →



# **Inflation: The Challenges Ahead**

**I. Observational – precision testing: plenty  
of room to falsify!**

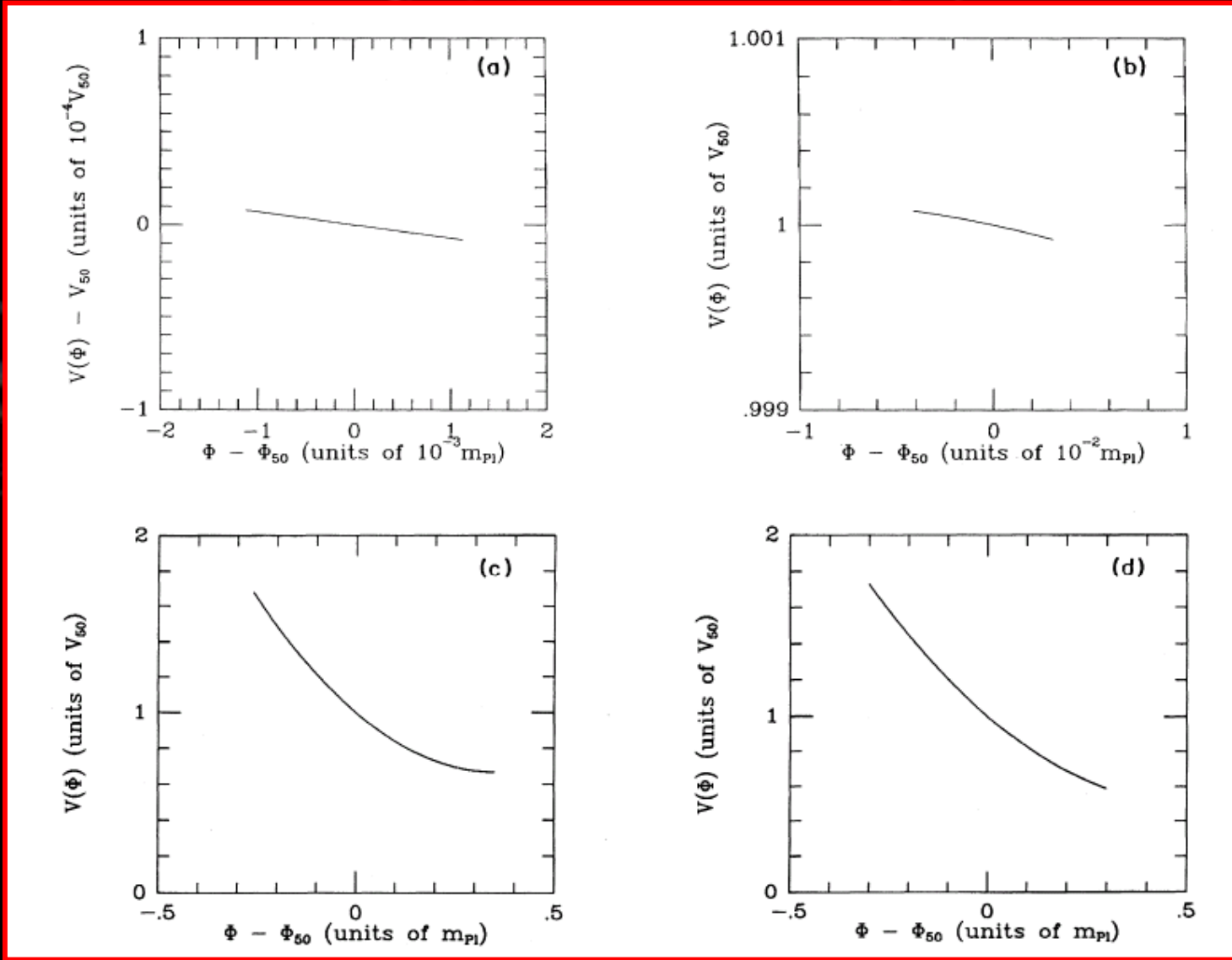
**II. Foundational – conceptual + laboratory  
evidence**

# Precision Testing of Inflation

- Measure  $\Omega_0$  to  $\pm 0.001$
  - Measure  $n-1$  to  $\pm 0.001$
  - Detect  $dn/d\ln k$
  - Gaussianity to  $O(1)$
  - Detection of GW: 0.001
    - CMB B mode polarization
    - direct detection
  - Measure  $n_T$ 
    - CMB B-mode or CMB + direct detection
- Prediction:
- $= 1.0000$
- $= \pm O(0.1)$
- $\pm O(0.001)$
- $f_{NL} \sim O(0.1)$
- T/S = ?
- T/S =  $-5n_T$ ?

# Reconstruction

FIG. 5. The four generic inflationary potentials: (a)  $n-1 = -2 \times 10^{-6}$  and  $T/S = 1.4 \times 10^{-5}$ , with the COBE DMR normalization  $V_{50}^{1/4} = 2.0 \times 10^{15}$  GeV; (b)  $n = 0.85$  and  $T/S = 1.4 \times 10^{-4}$ ,  $V_{50}^{1/4} = 3.6 \times 10^{15}$  GeV; (c)  $n = 1$  and  $T/S = 1$ ,  $V_{50}^{1/4} = 2.9 \times 10^{16}$  GeV; and (d)  $n = 0.85$  and  $T/S = 1$ ,  $V_{50}^{1/4} = 2.9 \times 10^{16}$  GeV. (a)-(d) correspond to cases (1)-(4) in the text.



small  
T/S

large  
T/S

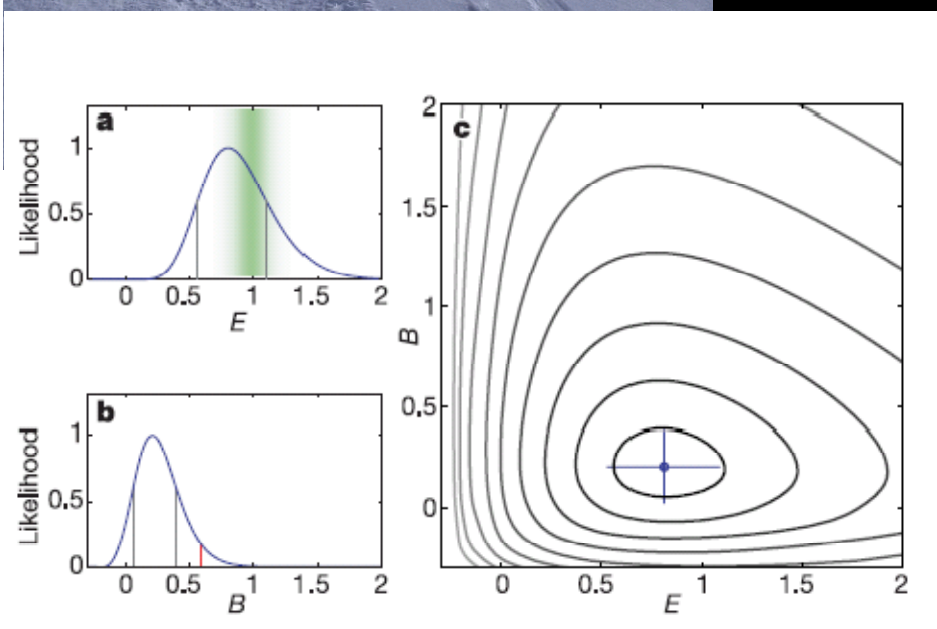
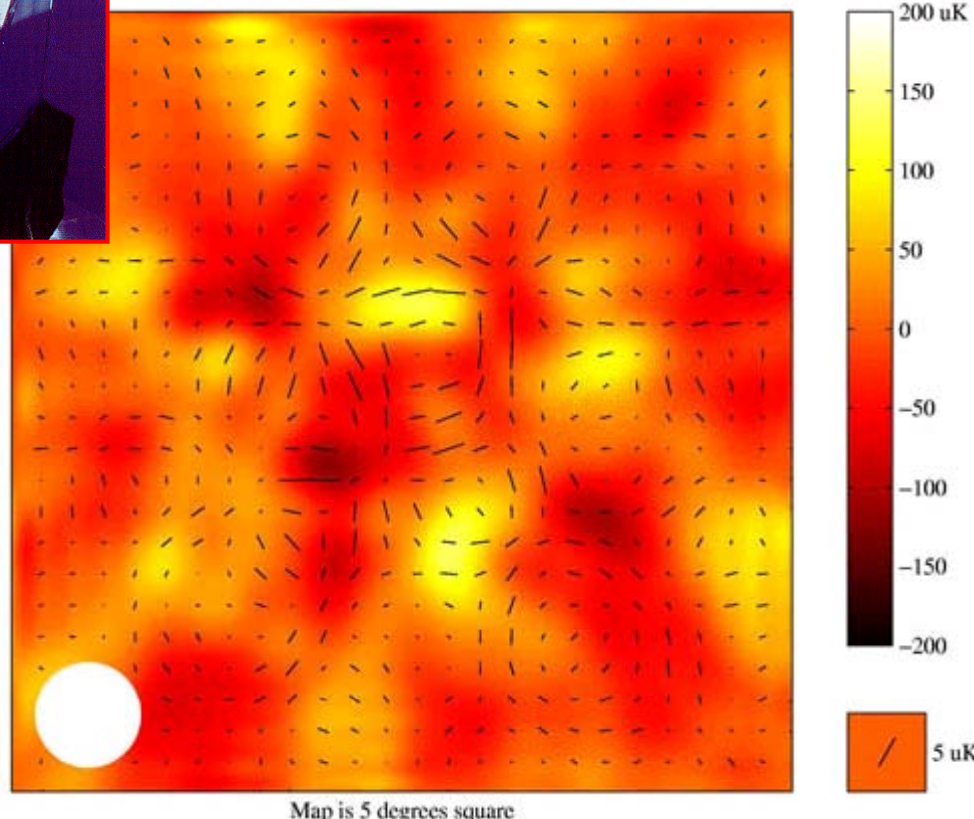
small  $n-1$

large  $n-1$

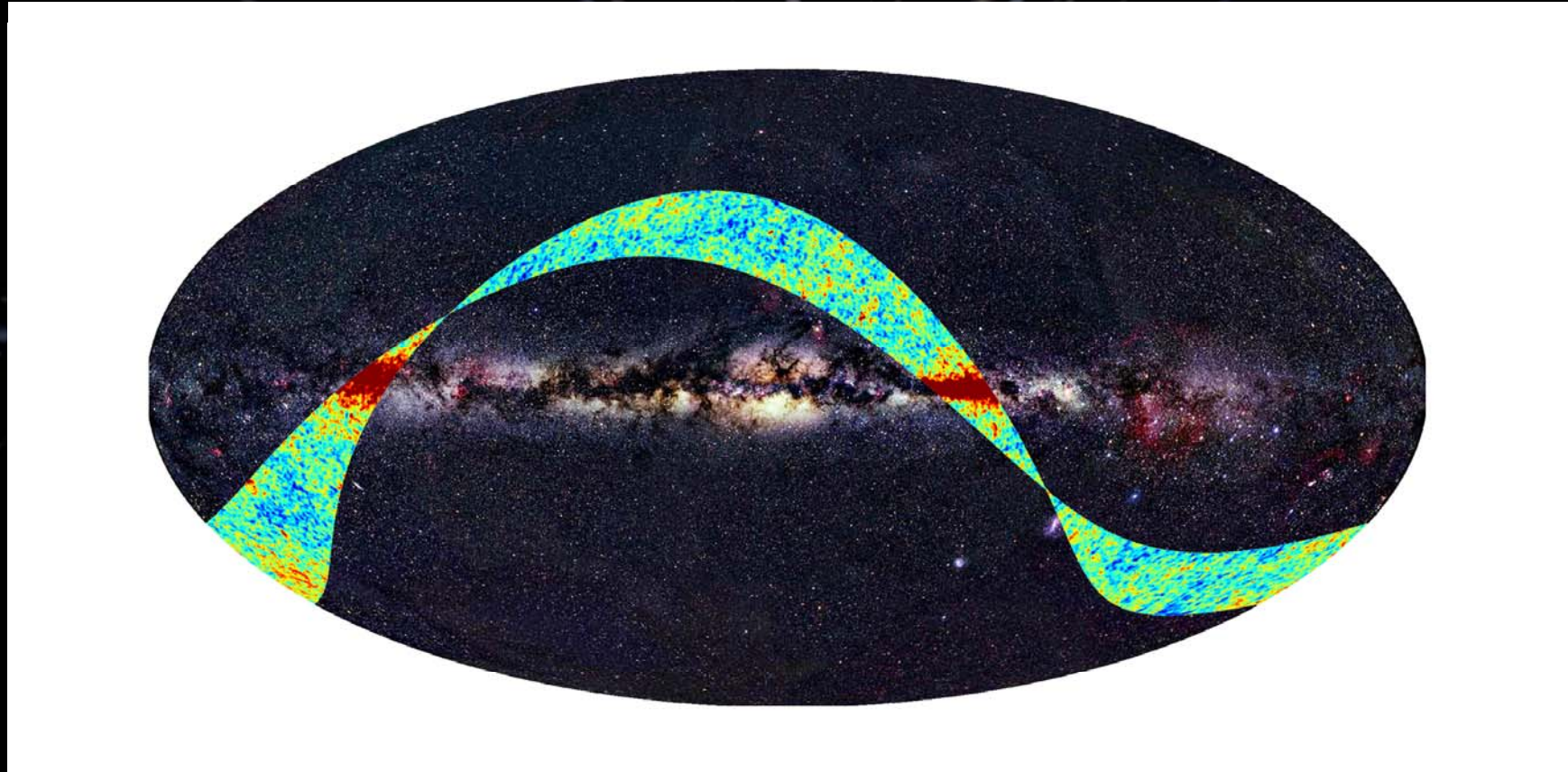


# Discovery of CMB polarization: DASI, 2002

Kovac et al, Nature 420, 772 (2002)



# Planck First Light



Even if  
successful,  
inflation has  
important  
issues



# Game changing idea, but ...

- No fundamental theory
  - “Landau-Ginzburg stage” – is there a BCS theory?
- Does not address initial singularity
  - geodesically incomplete
- Does not address cosmological constant problem
- Like “duct tape”, very useful but ...
  - Only postpones appearance of inhomogeneity
  - not all initial conditions inflate
- Quantum unpredictability & eternal inflation
  - Anything that can happen do so infinitely many times

# SPACE-TIME GEOMETRY

our initial geometry



smooth, small ripples



15 Gyr



generic initial geometry



$10^{-43}$  s



★ NOT LOGICAL INCONSISTENCY!

★ DILEMMA OF INITIAL DATA  
(WHY SO SPECIAL?)

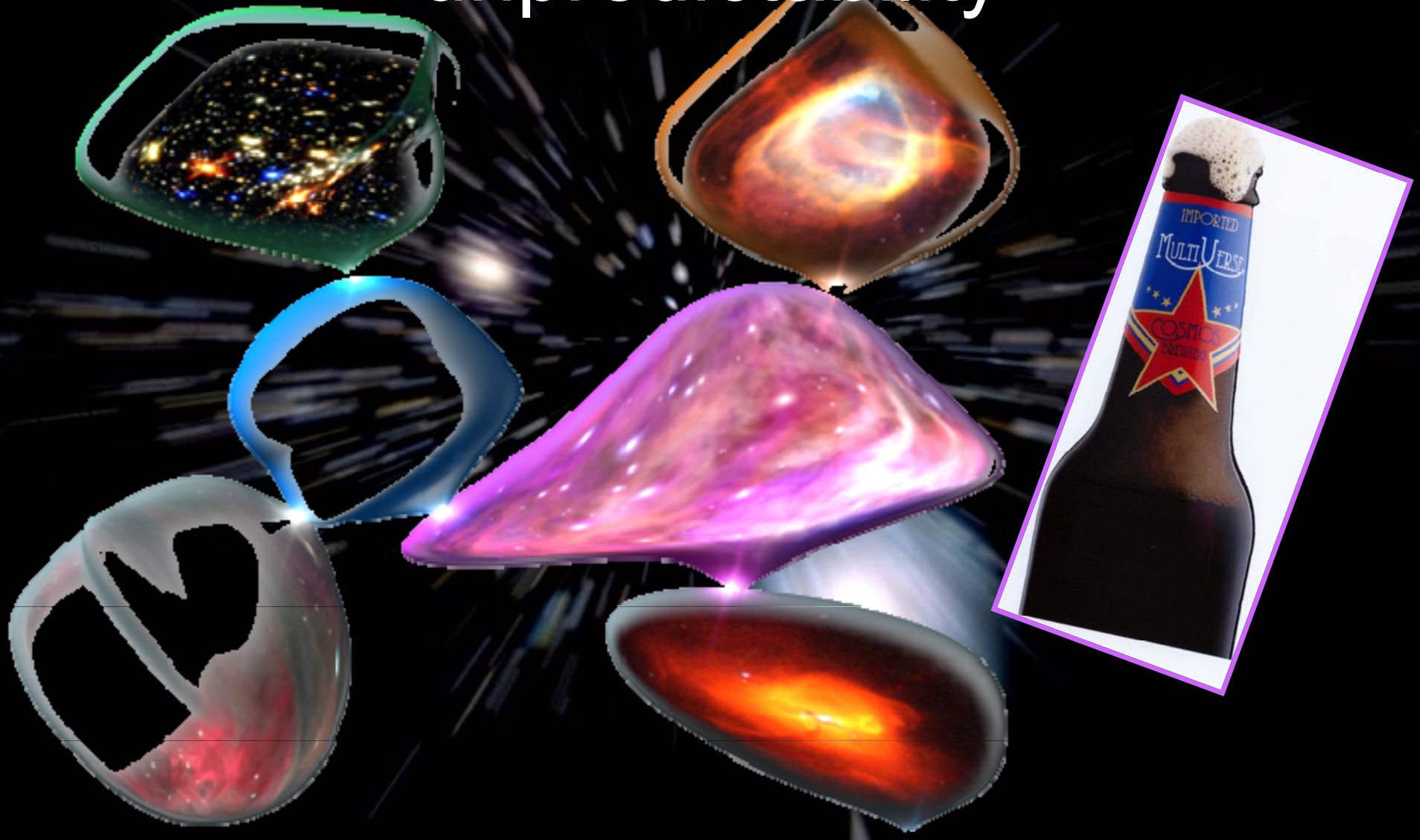




# Game changing idea, but ...

- No fundamental theory
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- Like “duct tape”, very useful but ...
  - Only postpones appearance of inhomogeneity
  - not all initial conditions inflate
- Quantum unpredictability & eternal inflation
  - Anything that can happen do so infinitely many times

# The specter of the multiverse: unpredictability



# “Closing the circle”

- “Believe in BBN (&CMB)” because of laboratory measurements (nuclei, nuclear physics cross sections, etc)
- Close the circle on dark matter: produce at LHC, directly detect halo WIMPs, detect annihilation products
- Inflation: ?? (produce inflaton?)

# Time to be bold again!


## some ideas

- Ekpyrotic (brane-collisions, s l o w c o l l a p s e rather than rapid expansion  
NB: solve horizon problem by  $d^2a/dt^2$  and  $da/dt$  having same sign, positive or negative
- Cyclic (multiple brane collisions)
- Variable speed of light??
- Pre big bang


No well developed competitor for inflation yet  
Potential signatures: nonGaussianity, detection of gravity waves (anti-signature)

HEALTHY  
SCIENCE RELIES  
UPON A  
DYNAMICAL  
BALANCE  
BETWEEN


PASSIONATE  
THEORETICAL  
SPECULATION  
and  
COLD, HARD  
EXPERIMENTAL FACT



DANGEROUS LIMITS



**BOTANY**



PHILOSOPHY

Theorists needed!

# Time to be bold again!

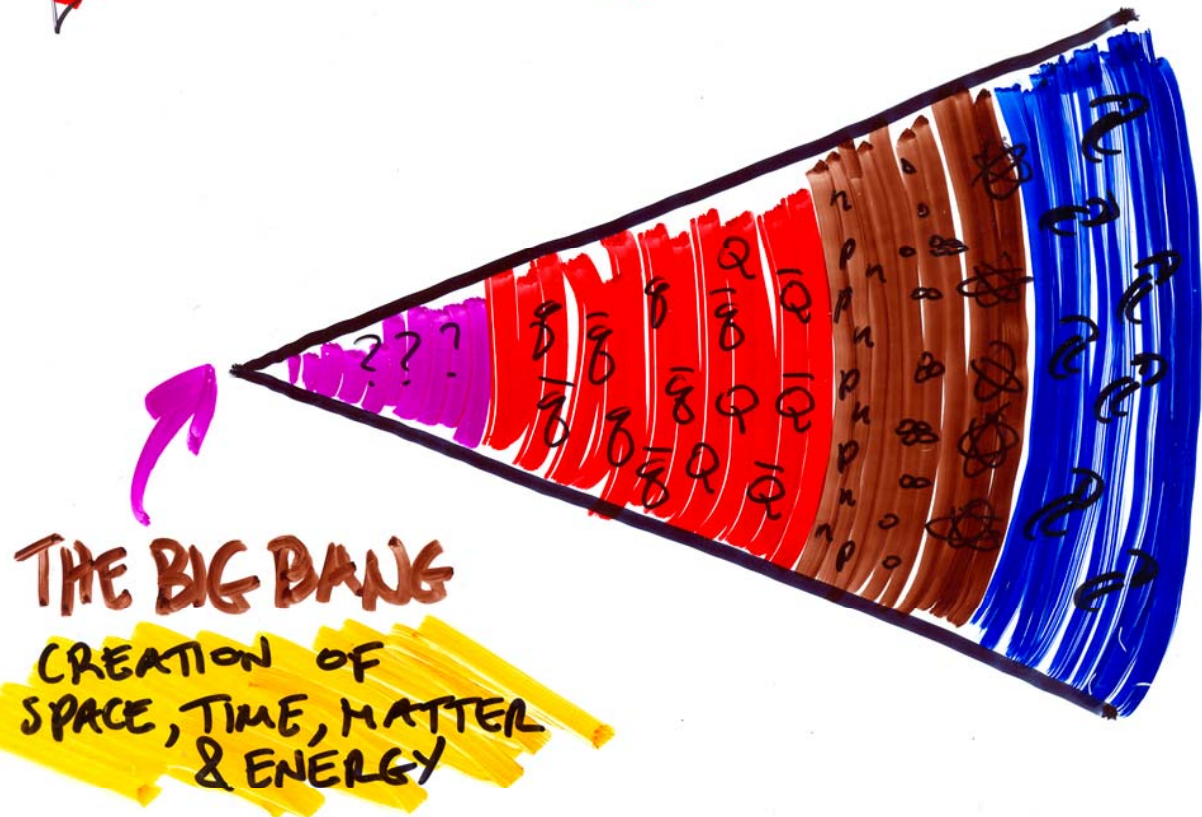
some ideas

- Ekpyrotic (brane-collisions, s l o w c o l l a p s e rather than rapid expansion  
NB: solve horizon problem by  $d^2a/dt^2$  and  $da/dt$  having same sign, positive or negative)
- Cyclic (multiple brane collisions)
- Variable speed of light??
- Pre big bang

No well developed competitor for inflation yet  
Potential signatures: nonGaussianity, detection of gravity waves (anti-signature)

neat & tidy!  
... but Einstein's theory does not incorporate quantum mechanics.  
... and the conditions at the beginning are precisely where quantum effects should be critical!

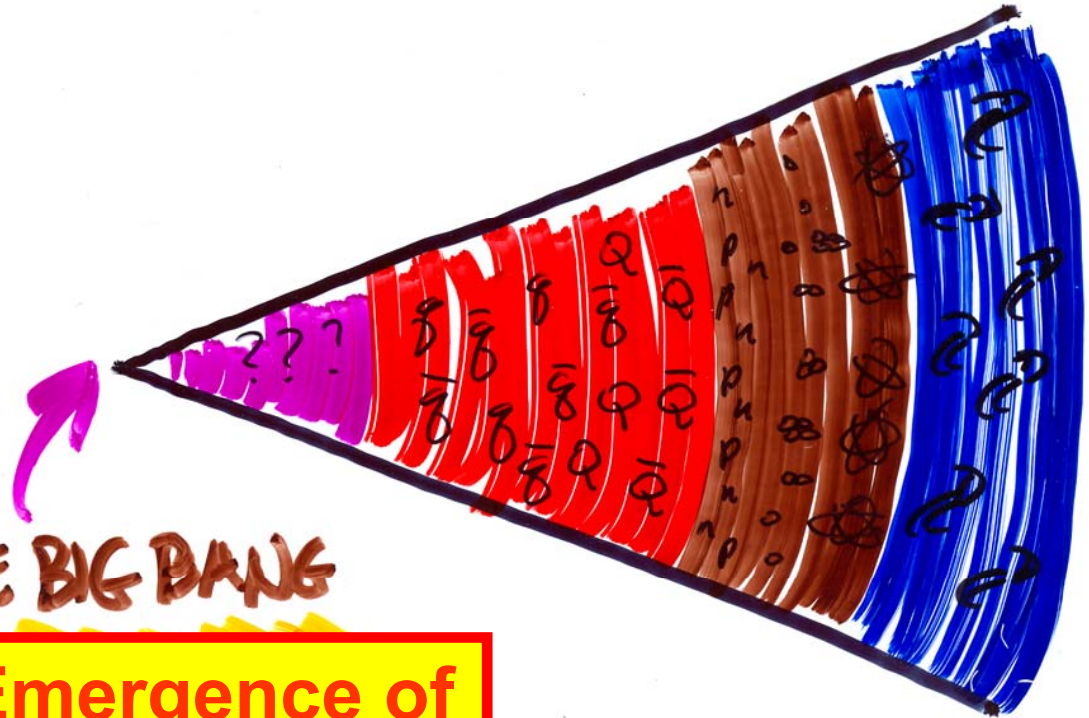
# EINSTEIN'S BIG BANG



• NO BEFORE THE BIG BANG

Einstein got  
the right  
answer for  
the wrong  
reason!

# EINSTEIN'S BIG BANG



THE BIG BANG

= Emergence of  
space and time

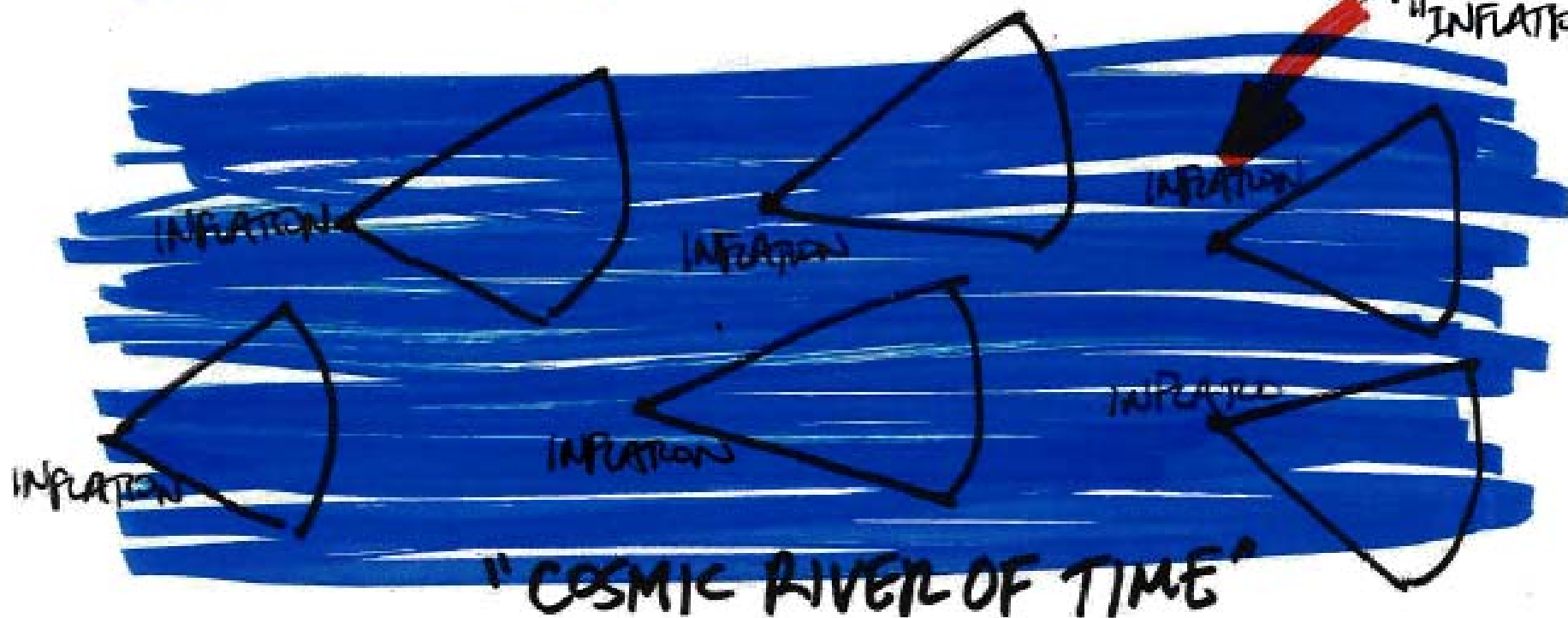
• NO BEFORE THE BIG BANG



# INFLATIONARY MULTIVERSE

INFINITE NUMBER OF BEGINNINGS

TREMENDOUS BURST OF EXPANSION "INFLATION"



# THE INFLATIONARY MULTIVERSE

INFINITE NUMBER OF big bangs

ISSUE of a beginning is made moot

...we are but one of an infinite number of distinct inflationary bubbles!



"RIVER OF COSMIC TIME"



IS IT SCIENCE IF IT IS NOT TESTABLE?

EQ:

$R \sim 3 \times 10^5$   
 $t \sim 100 \text{ yr}$   
 $\rho \sim 10^{-5}$



$R \sim 1/3 - 1/2$   
 $t \sim \text{few Gyr}$   
**GALAXIES FORM**  
Dark halos, baryons  
dissipate



TODAY  
Formation of  
larger structures (superclusters) continues...

# Cold Dark Matter Scenario

Particle DM + Inflation

Structure Forms From the Bottom Up:

First Stars ( $z \sim 10 - 20$ )

Galaxies ( $z \sim 2 - 5$ ), Clusters

( $z \sim 2$ ), and Superclusters ( $z \sim 0$ )