# CMB Observations and the Standard Model of the Universe

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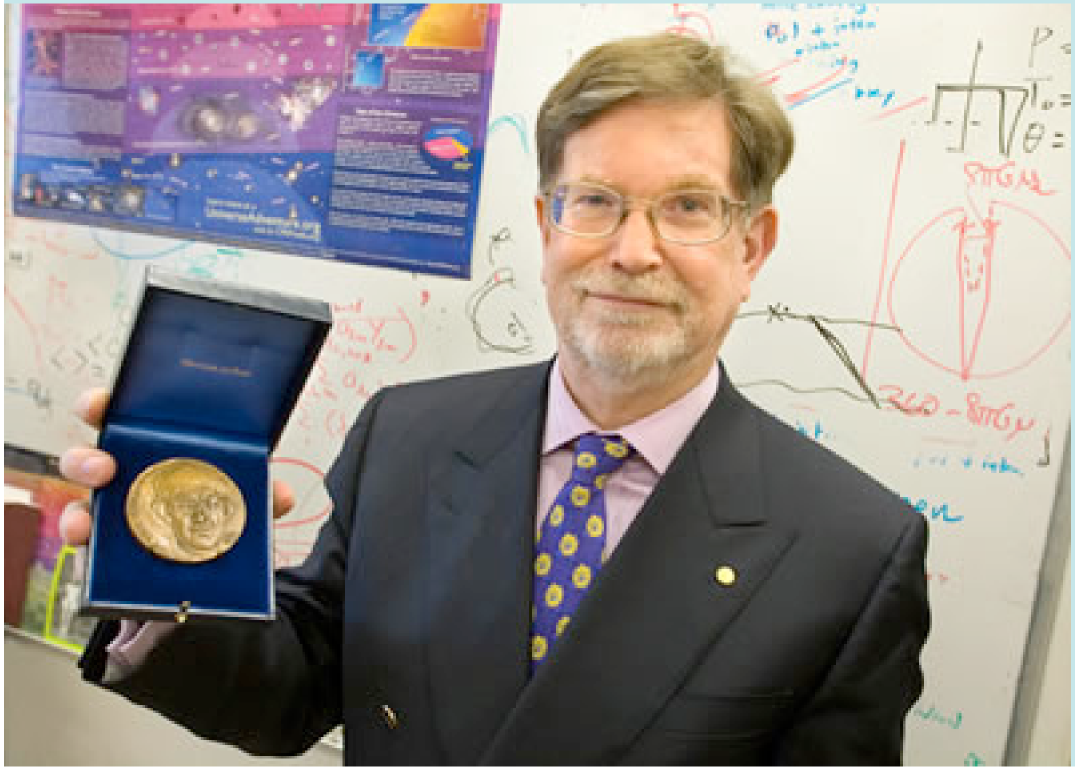
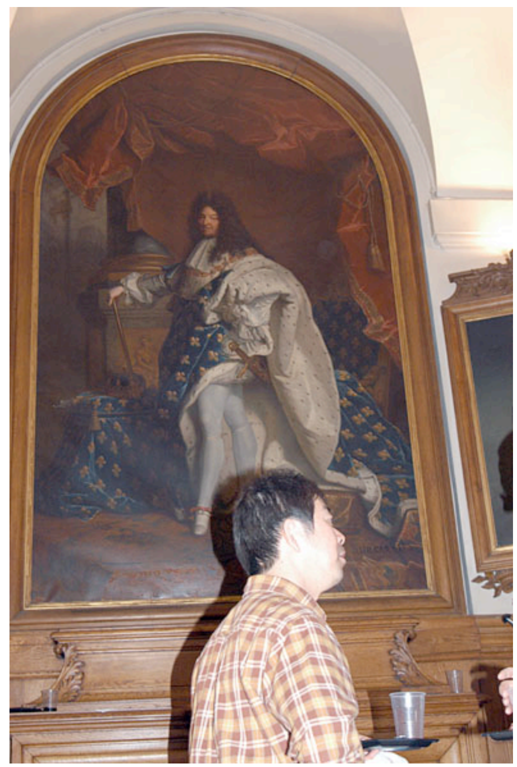
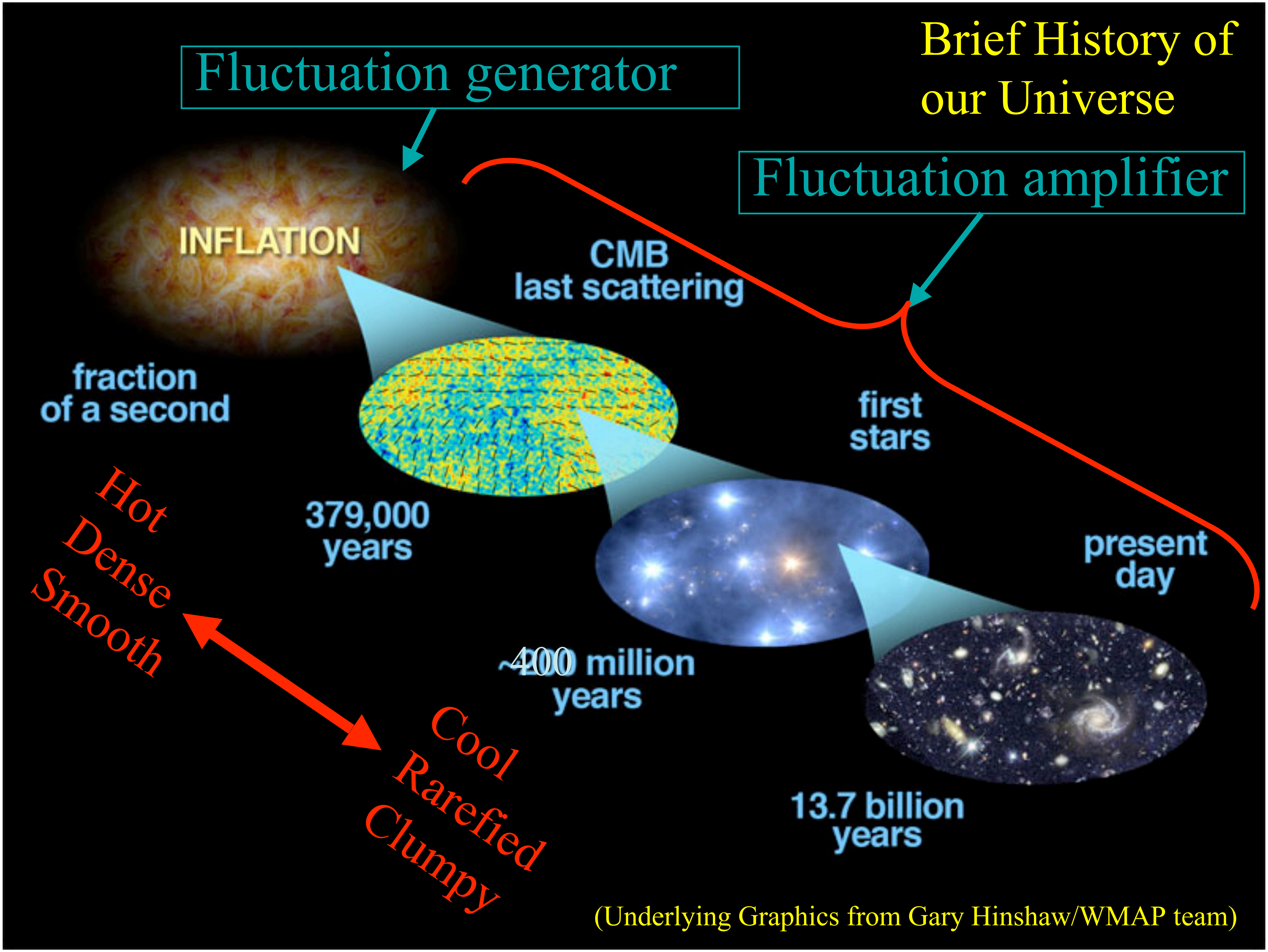
Director Berkeley Center Cosmological Physics

Chalonge Medalist & Nobel Laureate



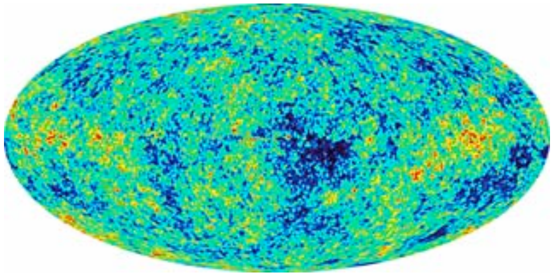

# Simple Beginning
# Complex Present

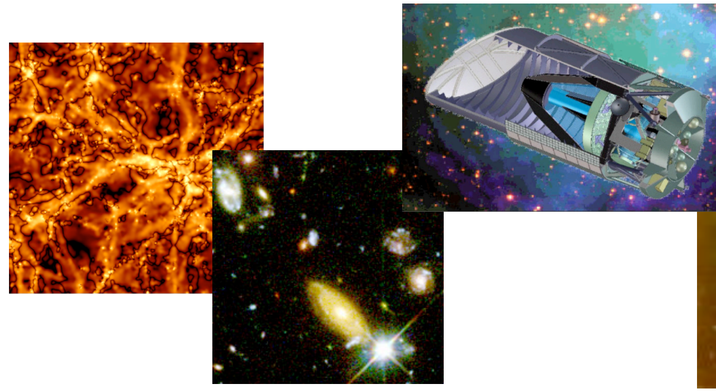


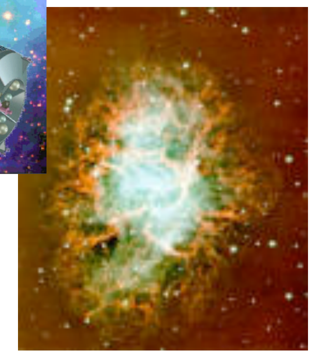


Brief History of our Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
fraction of a second
CMB last scattering
379,000 years
first stars
~400 million years
present day
13.7 billion years
Hot Dense Smooth
Cool Rarefied Clumpy
(Underlying Graphics from Gary Hinshaw/WMAP team)

# Cosmic Archaeology







**CMB: direct probe of quantum fluctuations**

**Time: 0.003% of the present age of the universe.**

**(*When you were 0.003% of your present age, you were 2 cells big*!)**

**Cosmic matter structures: less direct probes of expansion**

**Pattern of ripples, clumping in space, growing in time.**

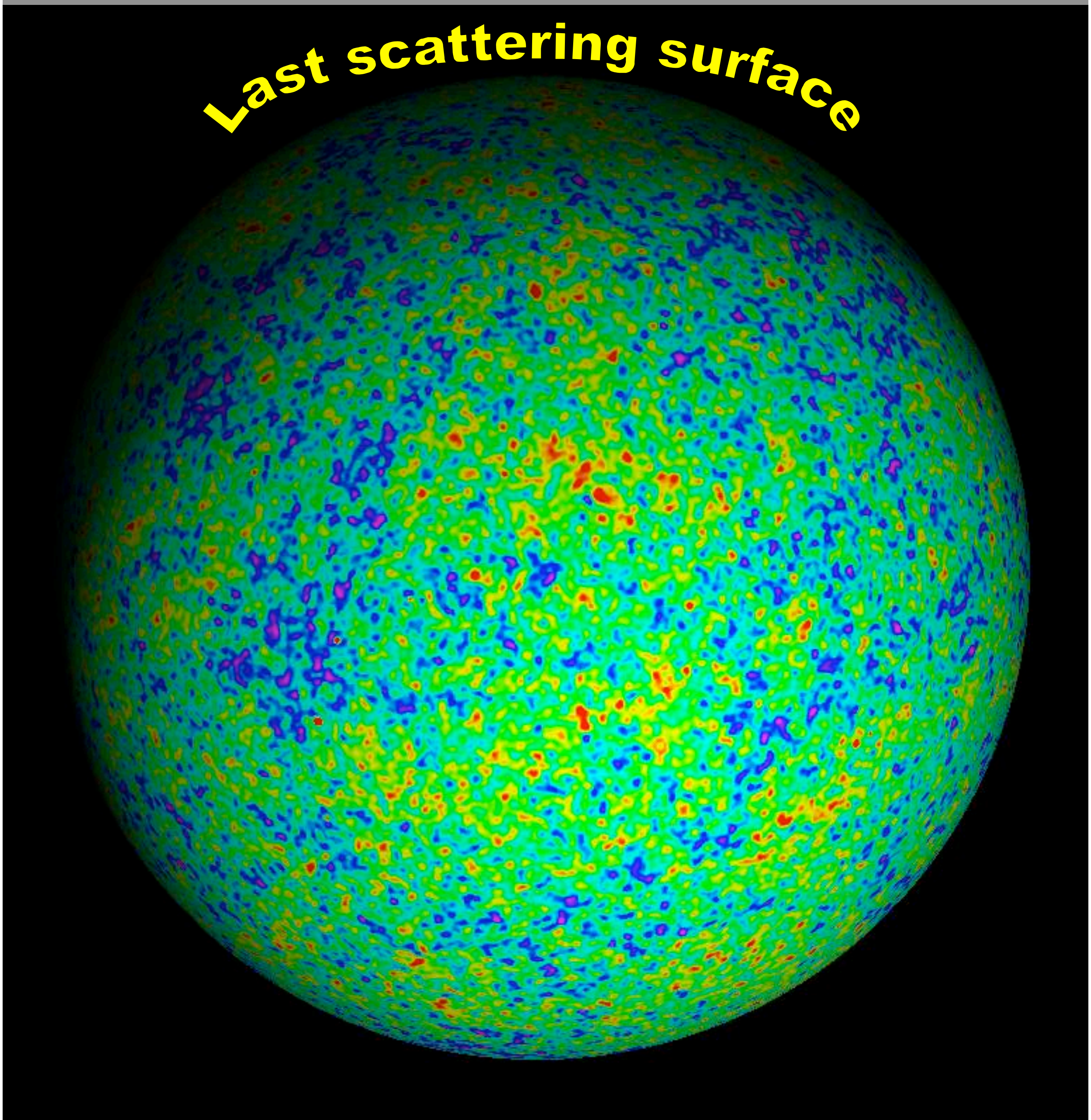
**3D survey of galaxies and clusters - Lensing.**

**Supernovae: direct probe of cosmic expansion**

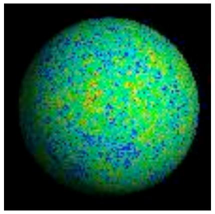
**Time: 30-100% of present age of universe**

**(*When you were 12-40 years old*)**

Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496



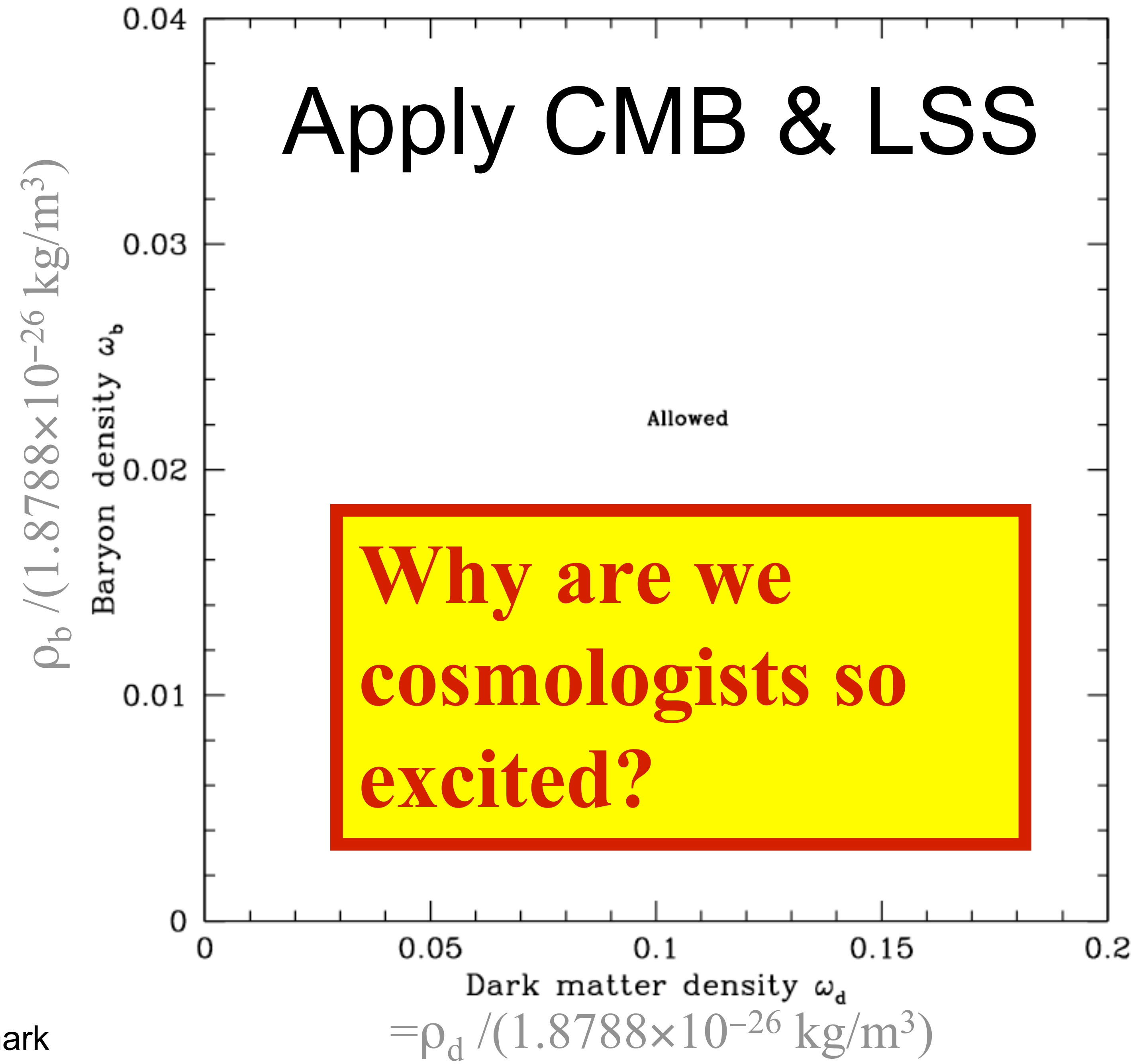
# How much dark matter is there?



CMB

+

P(k)

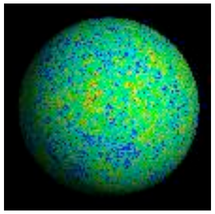



## Apply CMB & LSS

**Why are we cosmologists so excited?**

From Max Tegmark

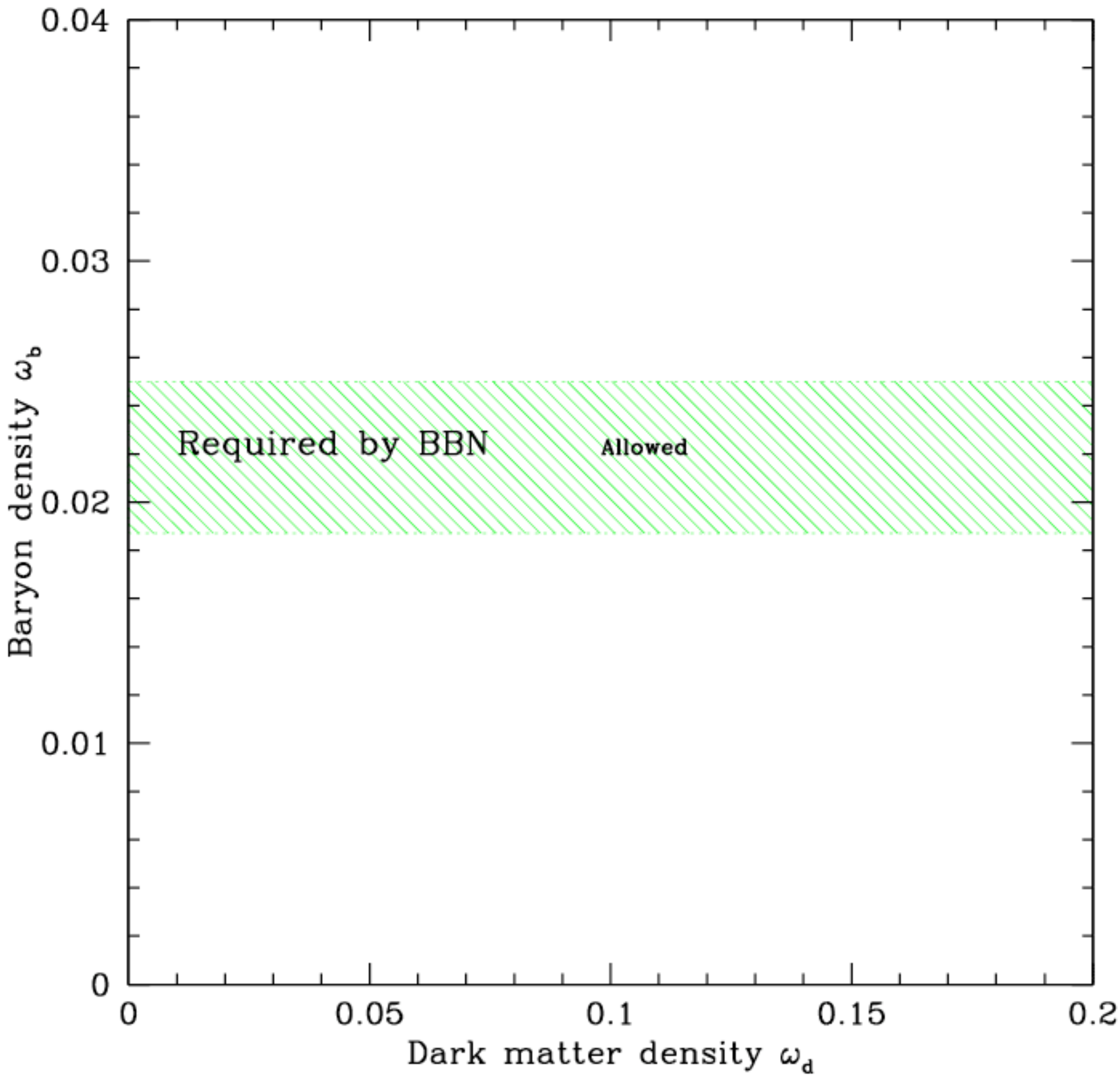
# How much dark matter is there?



**CMB**

**+**

**P(k)**




$\rho_b / (1.8788\times10^{-26}\ \mathrm{kg/m^3})$

$= \rho_d / (1.8788\times10^{-26}\ \mathrm{kg/m^3})$

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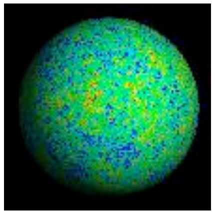
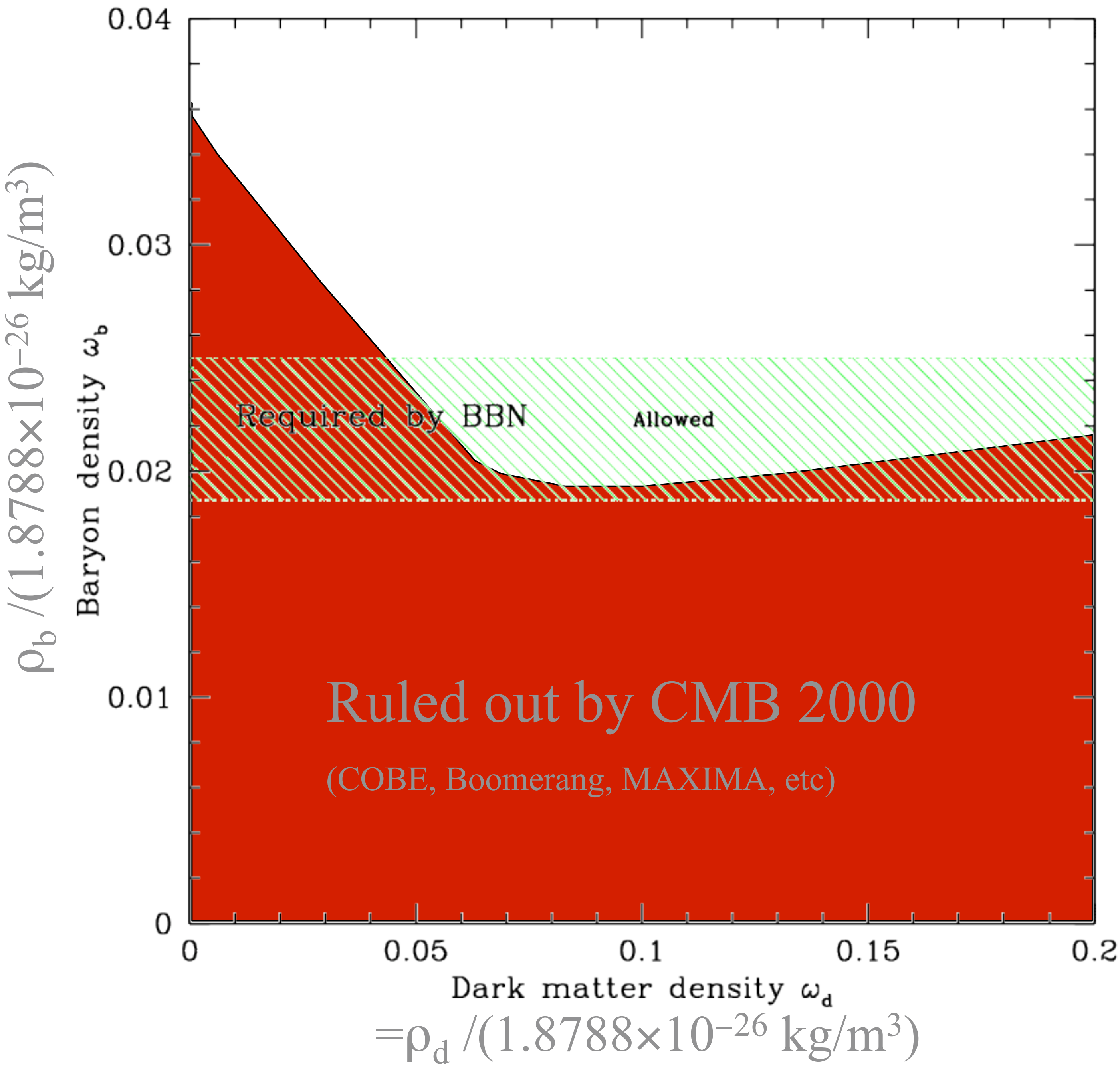


**CMB**

**+**

**P(k)**



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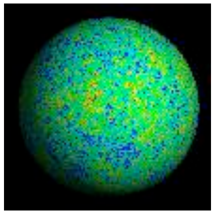
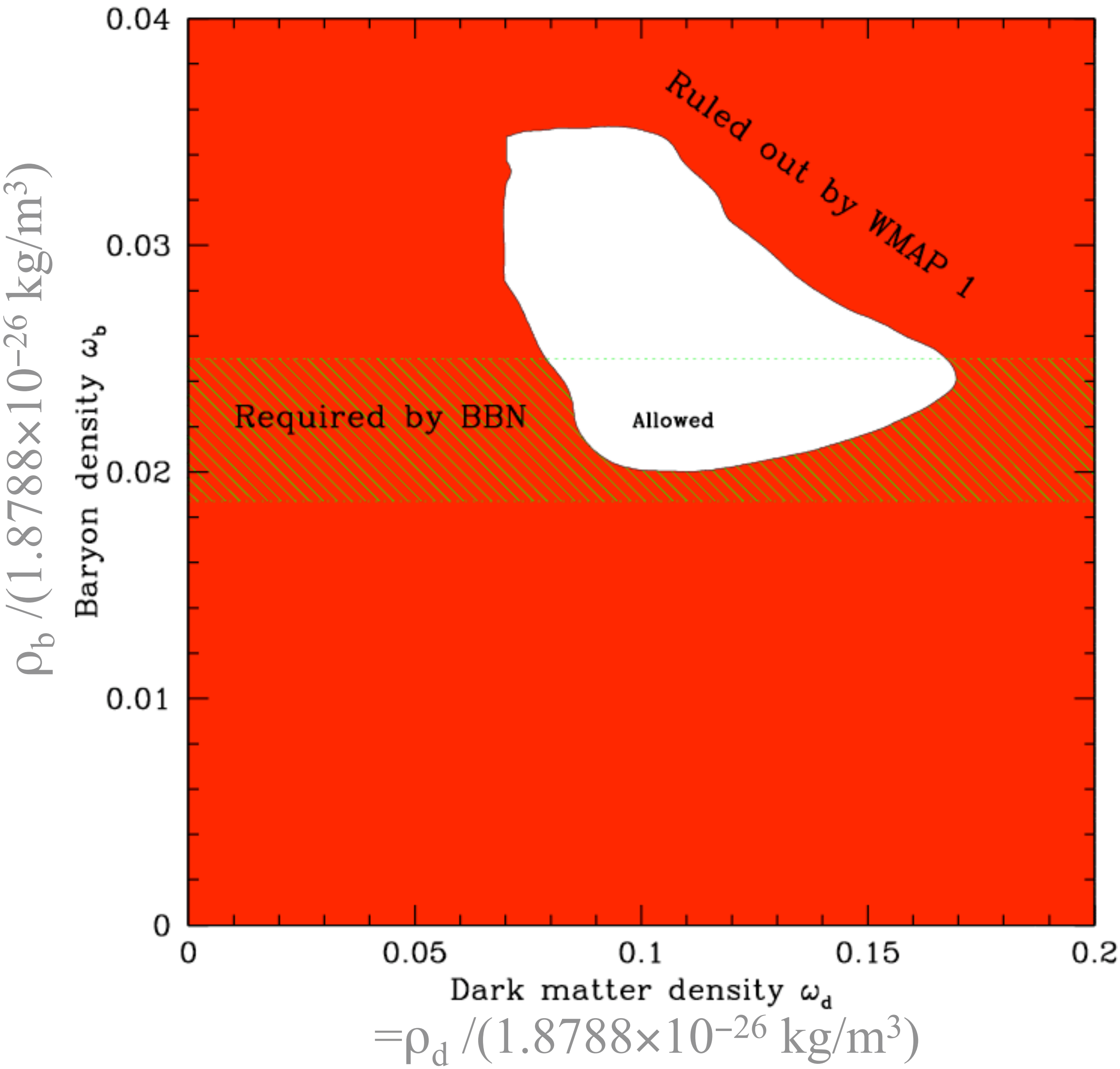
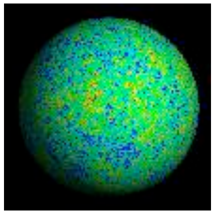


**CMB**

**+**

**P(k)**





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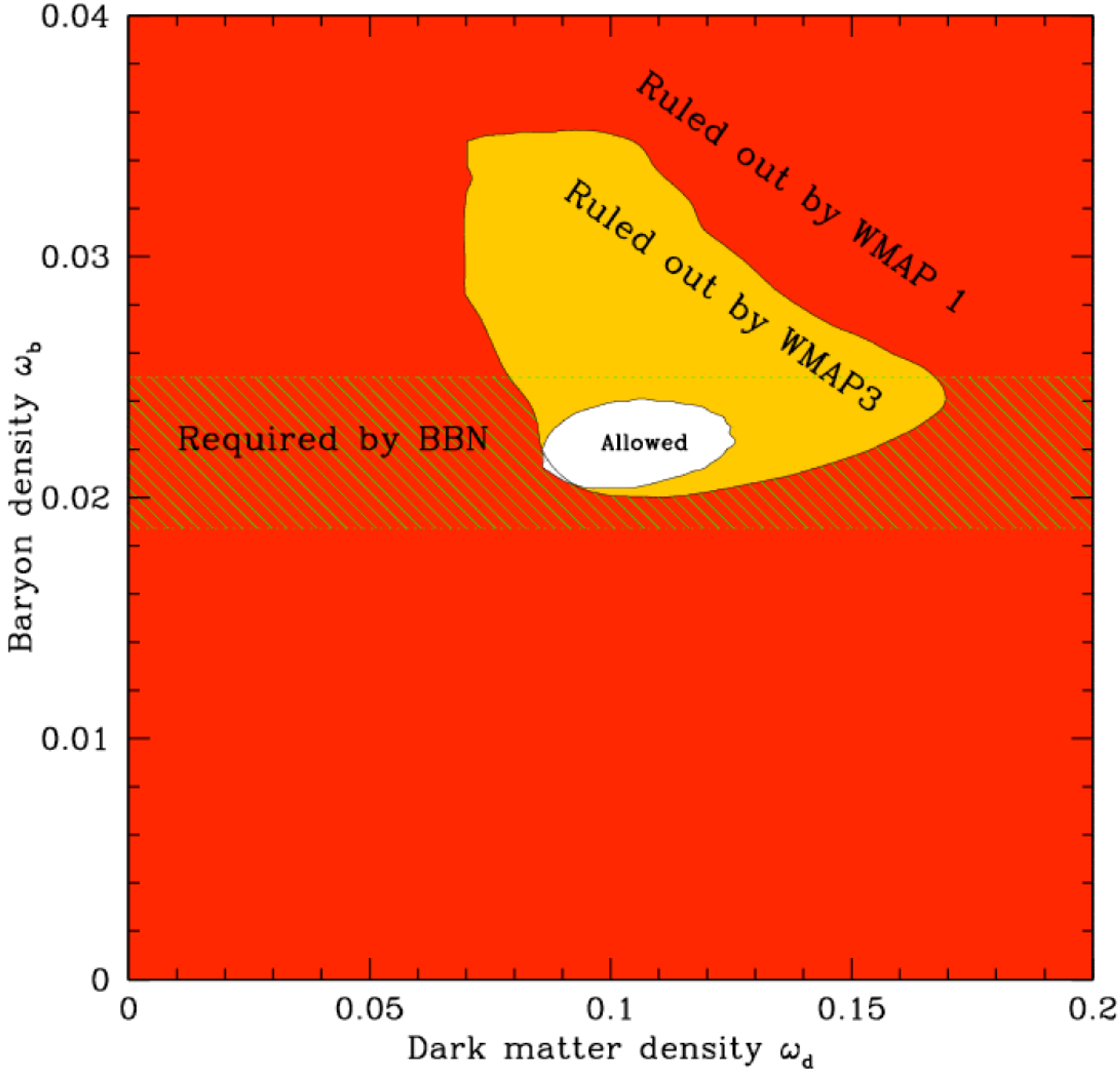
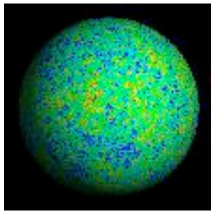



$\rho_b$ /(1.8788×$10^{-26}$ kg/m$^3$)

=$\rho_d$ /(1.8788×$10^{-26}$ kg/m$^3$)



**CMB**

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**P(k)**

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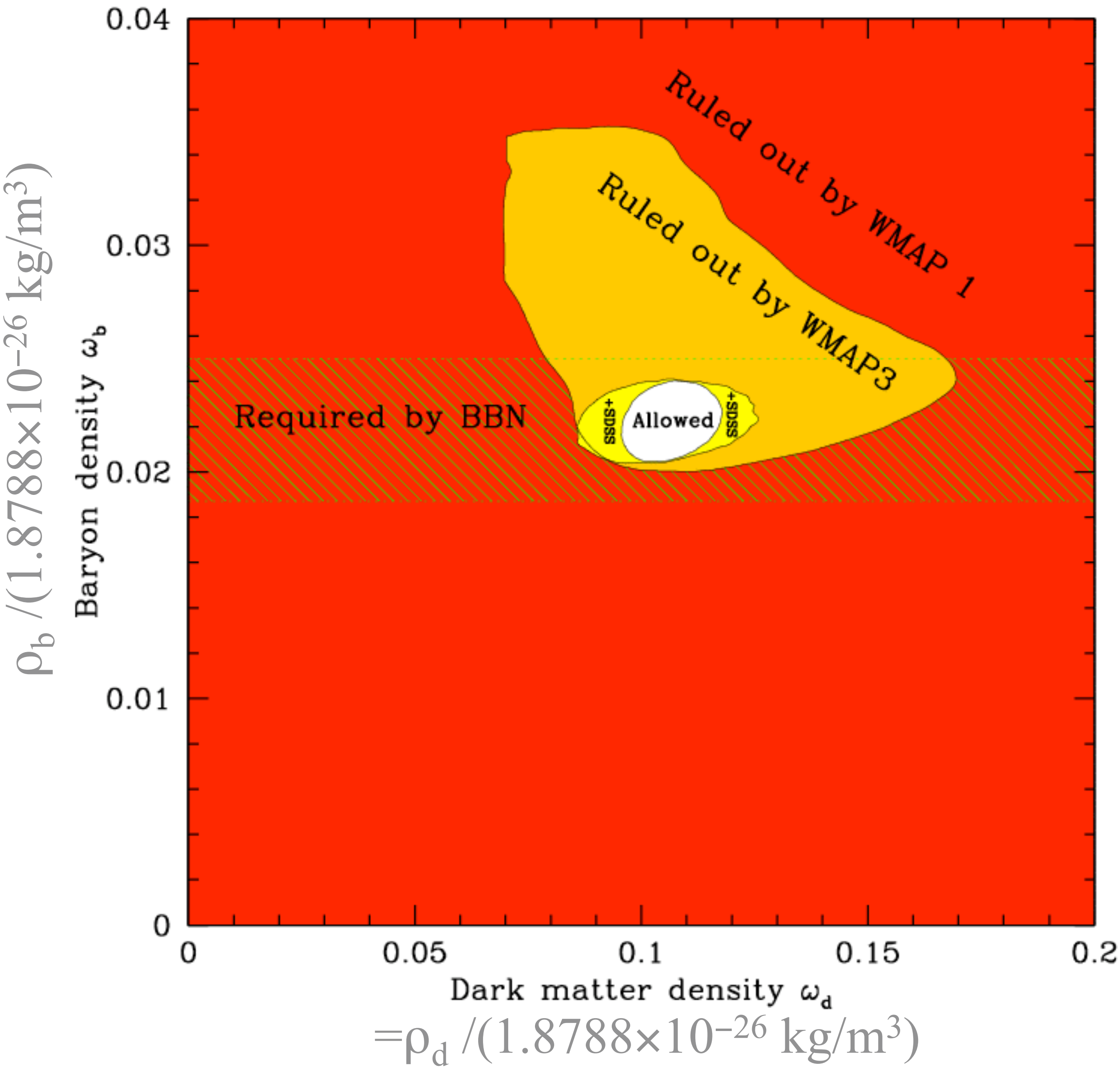
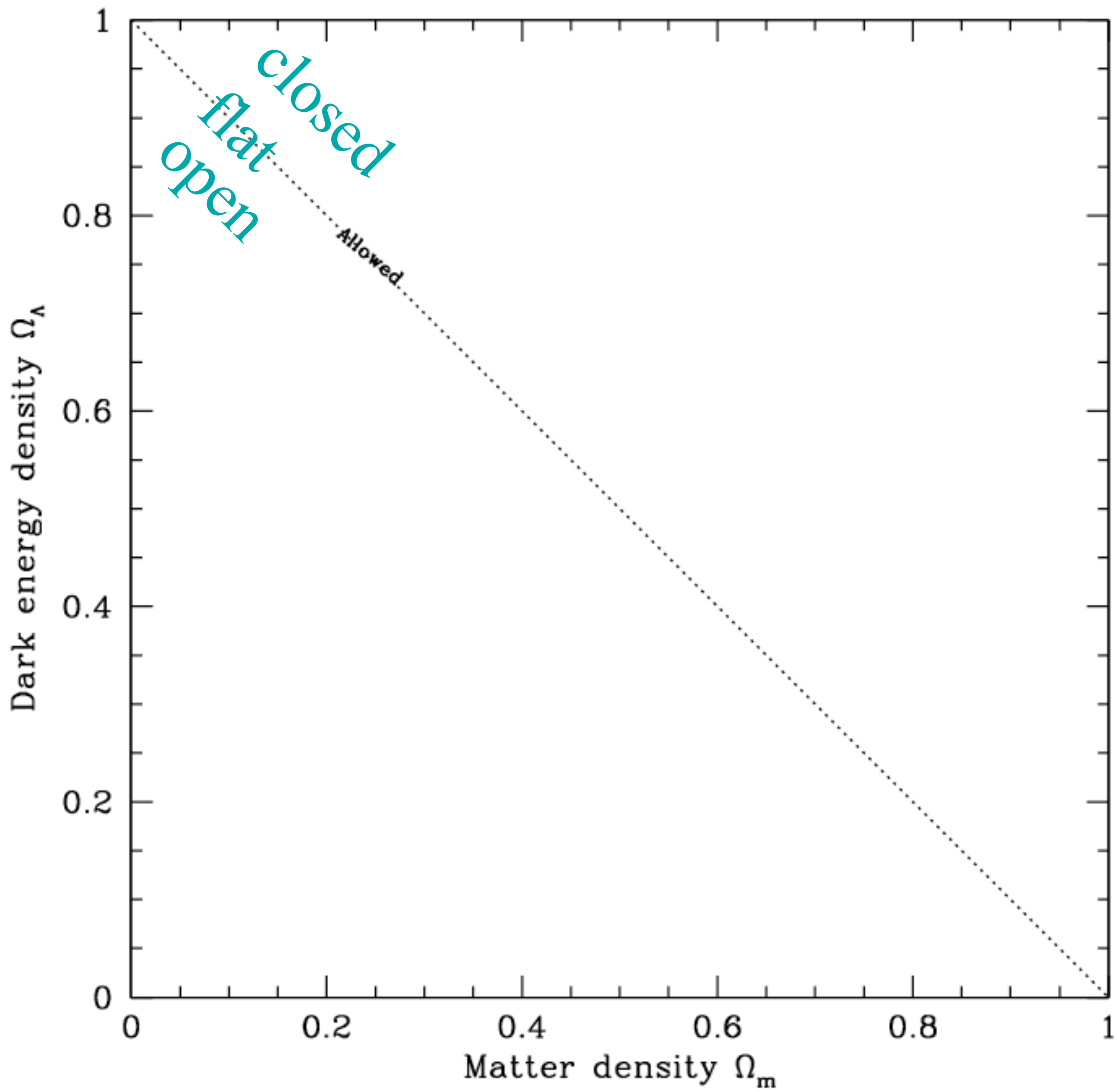


# How flat is space?



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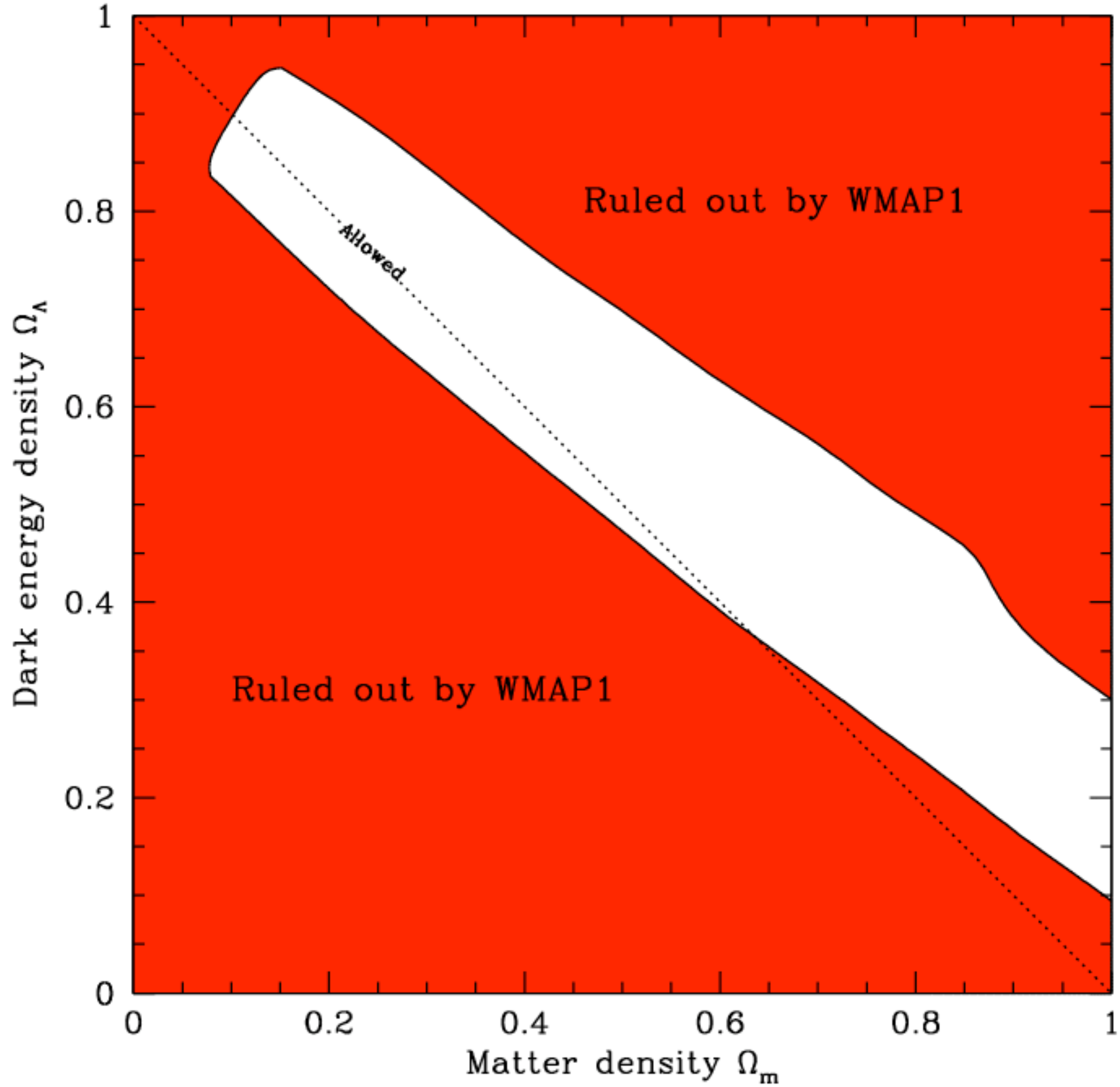
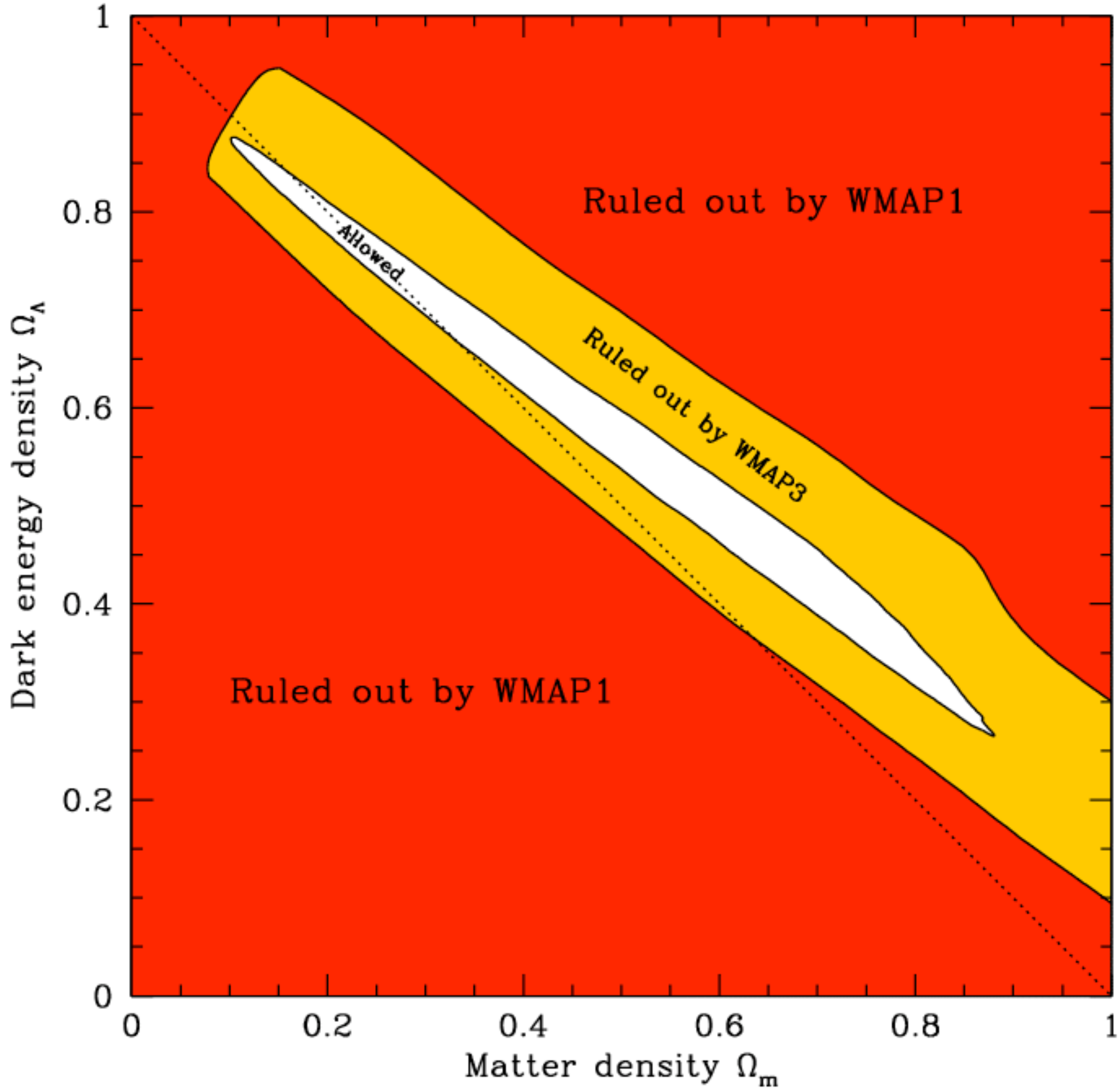
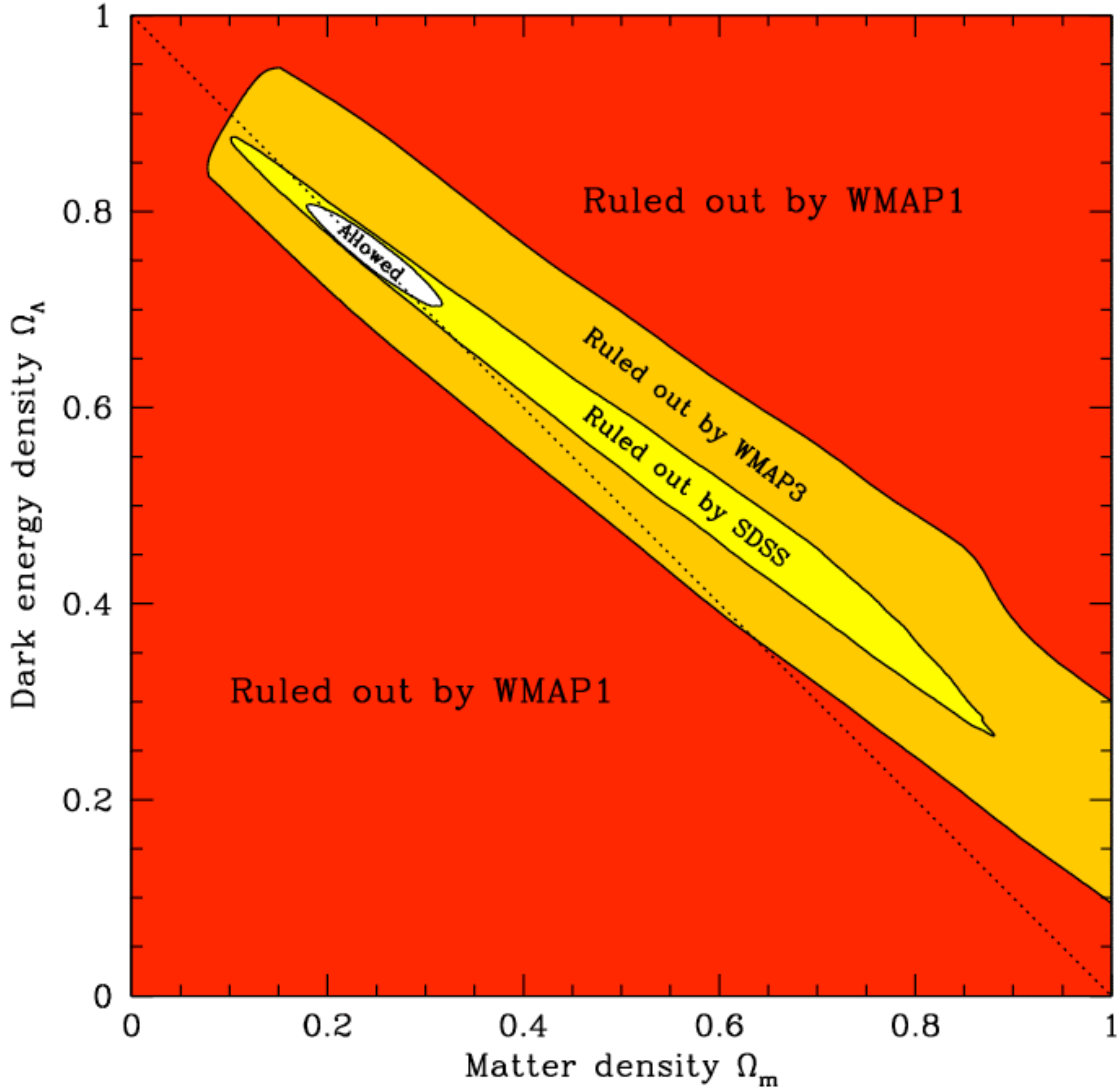
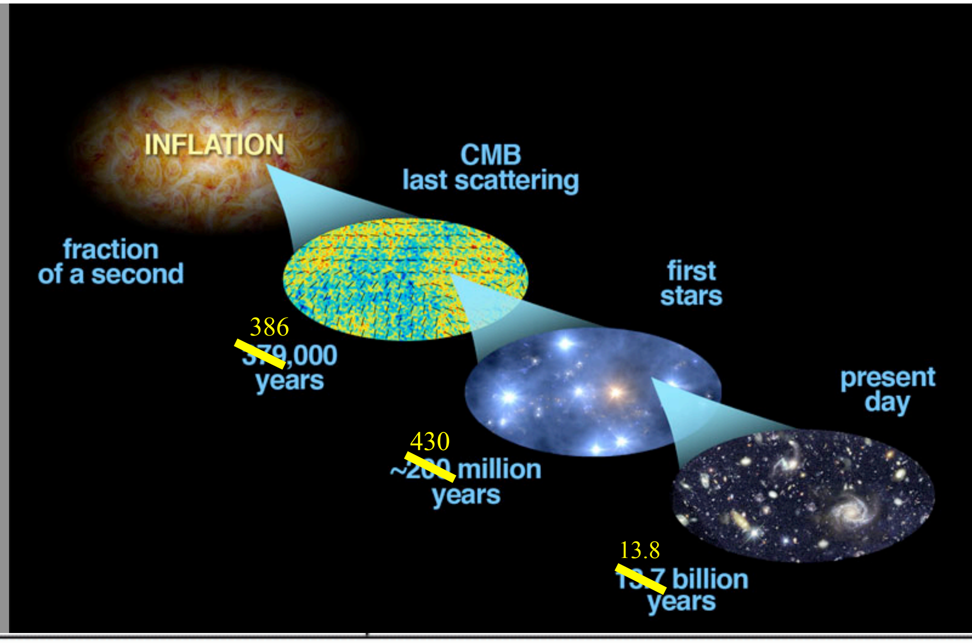


# How flat is space? Somewhat.



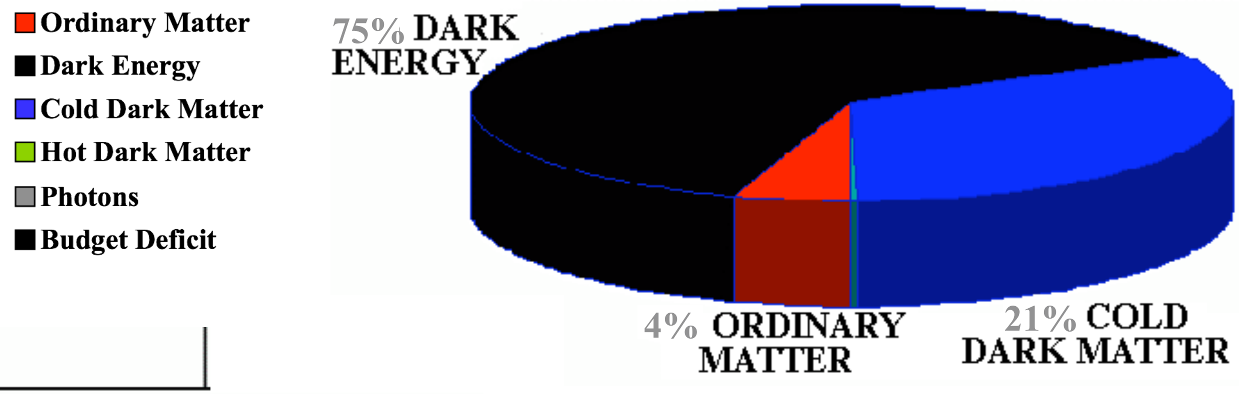
# How flat is space? $\Omega_{tot}=1.003\pm0.010$



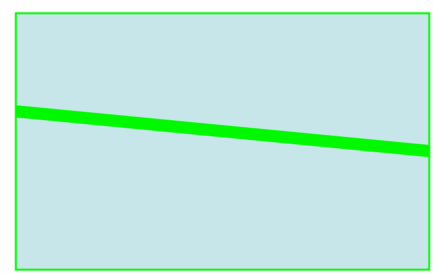



| Cosmic history parameters: | | |
|---|---|---|
| $z_{eq}$ | $3057^{+105}_{-102}$ | Matter-radiation Equality redshift |
| $z_{rec}$ | $1090.25^{+0.93}_{-0.91}$ | Recombination redshift |
| $z_{ion}$ | $11.1^{+2.2}_{-2.7}$ | Reionization redshift (abrupt) |
| $z_{acc}$ | $0.855^{+0.059}_{-0.059}$ | Acceleration redshift |
| $t_{eq}$ | $0.0634^{+0.0045}_{-0.0041}$ Myr | Matter-radiation Equality time |
| $t_{rec}$ | $0.3856^{+0.0040}_{-0.0040}$ Myr | Recombination time |
| $t_{ion}$ | $0.43^{+0.20}_{-0.10}$ Gyr | Reionization time |
| $t_{acc}$ | $6.74^{+0.25}_{-0.24}$ Gyr | Acceleration time |
| $t_{now}$ | $13.76^{+0.15}_{-0.15}$ Gyr | Age of Universe now |

# Using WMAP3 + SDSS LRGs:




| Parameter | Value | |
|---|---|---|
| Matter budget parameters: | | |
| $\Omega_{tot}$ | $1.003^{+0.010}_{-0.009}$ | Total density/critical density |
| $\Omega_\Lambda$ | $0.761^{+0.017}_{-0.018}$ | Dark energy density parameter |
| $\omega_b$ | $0.0222^{+0.0007}_{-0.0007}$ | Baryon density |
| $\omega_c$ | $0.1050^{+0.0041}_{-0.0040}$ | Cold dark matter density |
| $\omega_\nu$ | $< 0.010$ (95%) | Massive neutrino density |
| $w$ | $-0.941^{+0.087}_{-0.101}$ | Dark energy equation of state |
| Seed fluctuation parameters: | | |
| $A_s$ | $0.690^{+0.045}_{-0.044}$ | Scalar fluctuation amplitude |
| $r$ | $< 0.30$ (95%) | Tensor-to-scalar ratio |
| $n_s$ | $0.953^{+0.016}_{-0.016}$ | Scalar spectral index |
| $n_t + 1$ | $0.9861^{+0.0096}_{-0.0142}$ | Tensor spectral index |
| $\alpha$ | $-0.040^{+0.027}_{-0.027}$ | Running of spectral index |



# Where are we Really?

- With Very Simple Assumptions
- And Physics Rules
- We can predict the history and evolution of the Universe to the per cent level of agreement with observations
- This is a great stochastic agreement. Great similarity to Thermodynamics in late 19$^{th}$ century.

# Thermo - Stat Mech Analogy

- With the development of atomic and molecular theories in the late 19th century, thermodynamics was given a molecular interpretation. This field is called **statistical thermodynamics**, which can be thought of as a bridge between macroscopic and microscopic properties of systems.
- Statistical thermodynamics is an approach to thermodynamics based upon statistical mechanics, which focuses on the derivation of macroscopic results from first principles.*

* In physics, a calculation is said to be *from first principles*, or ab initio, if it starts directly at the level of established lawss of physics and does not make assumptions such as model and fitting parameters.

# Ideal Gas Law

- $PV = n R T$ ($= N k_B T$) Equation of State involving only macroscopic quantities: P, V, n, T
- Molecular Model - The ideal gas law can also be derived from first principles using the kinetic theory of gases, in which several simplifying assumptions are made, chief among which are that the molecules, or atoms, of the gas are monatomic point masses, possessing mass but no significant volume, and undergo only elastic collisions with each other and the sides of the container in which both linear momentum and kinetic energy are conserved.
- $PV = N k_B T = N KE_{DOF} = N m \langle v^2 \rangle / 2$

# Our Macroscopic Cosmology

**Standard Microphysics & Content plus**

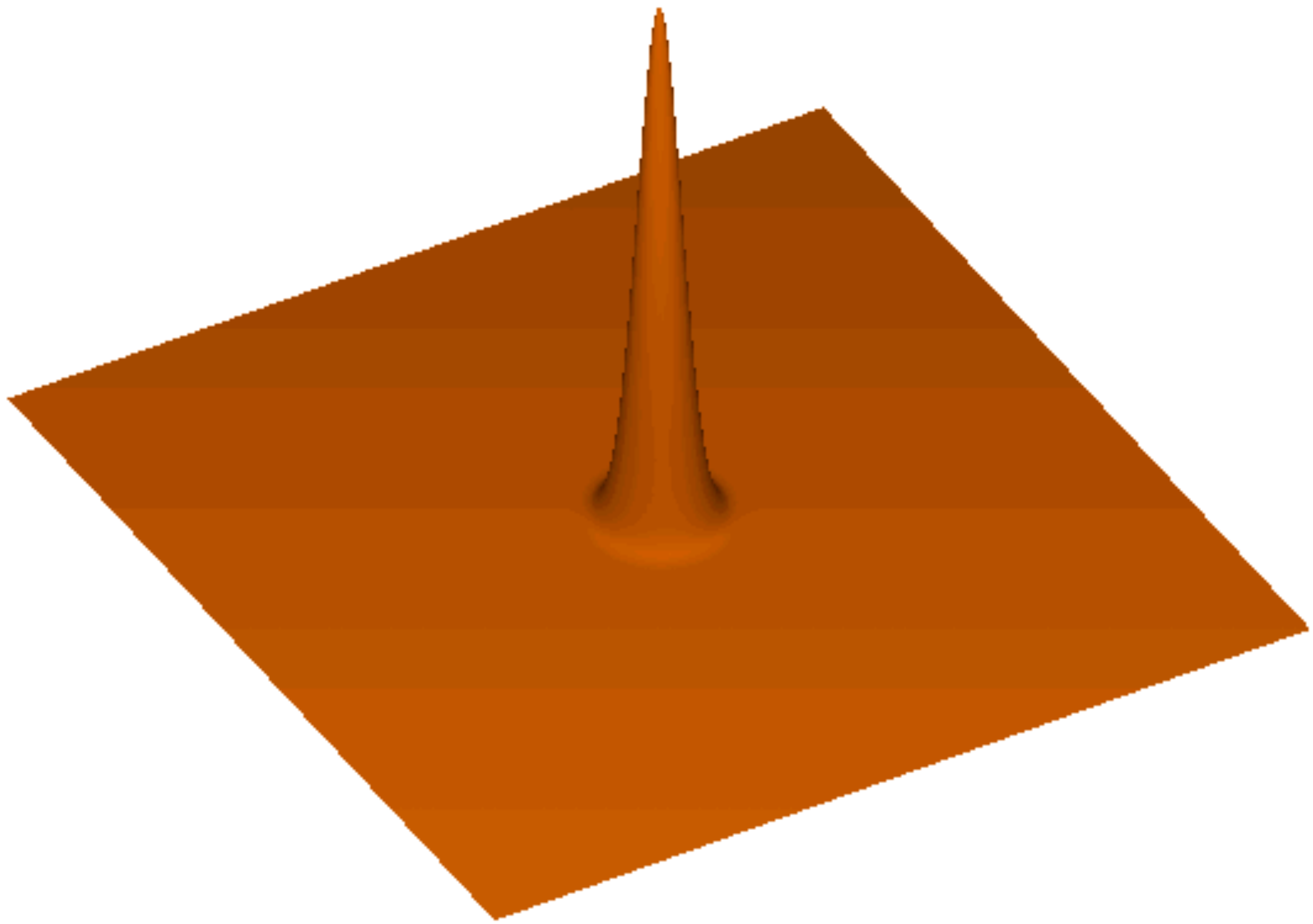
1) Inflation = simple scalar field
2) Dark Matter = CDM
3) Dark Energy = $\Lambda$ or SSF
4) Matter-antimatter asymmetry = yes

**And the nots:**

5) No significant other relics to be found (e.g. cosmic strings)
6) No extra dimensions significant
7) Fundamental constants don't vary
8) Other exotic forces in play?

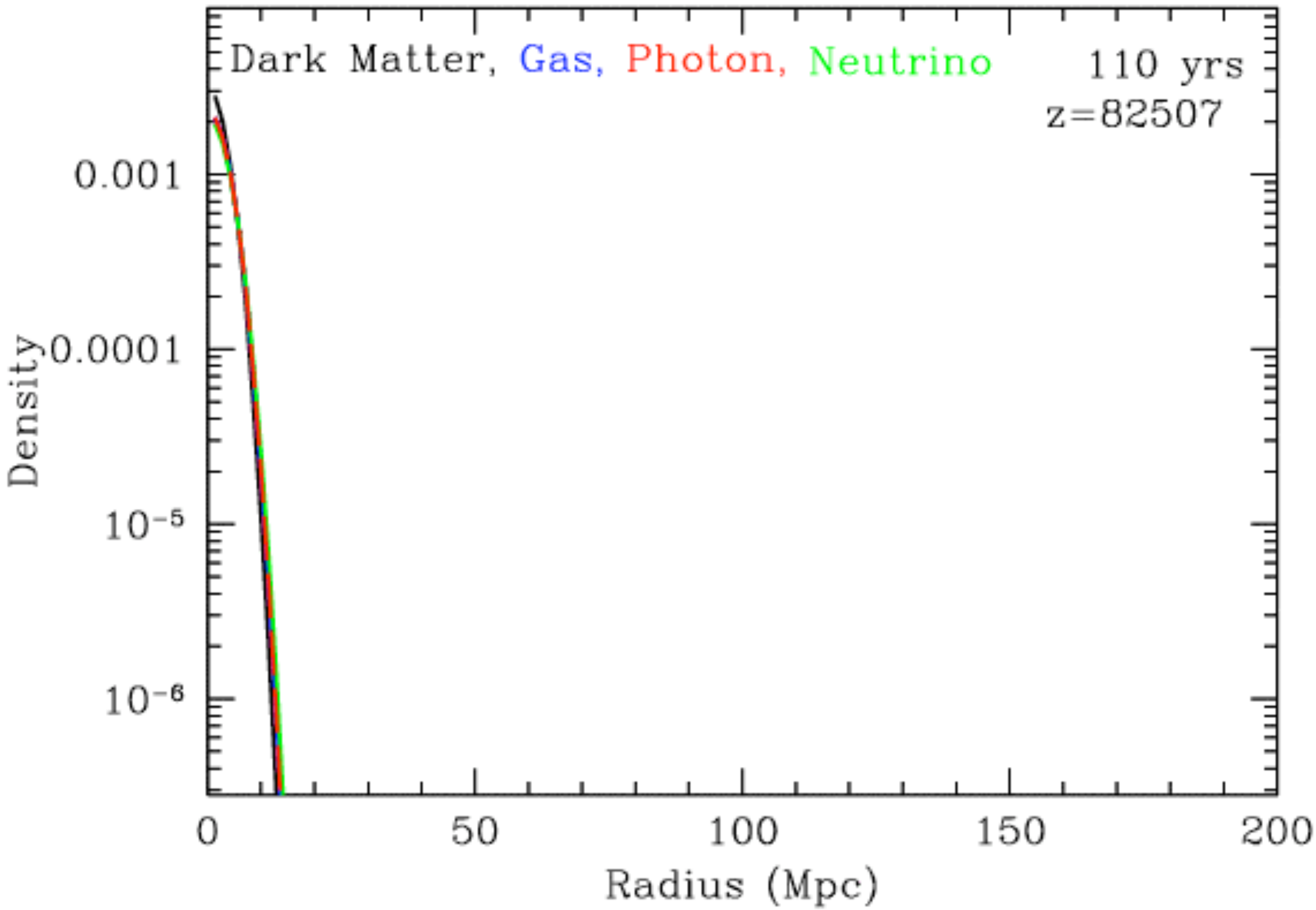
# Evolution of single over dense lump

comoving coordinates



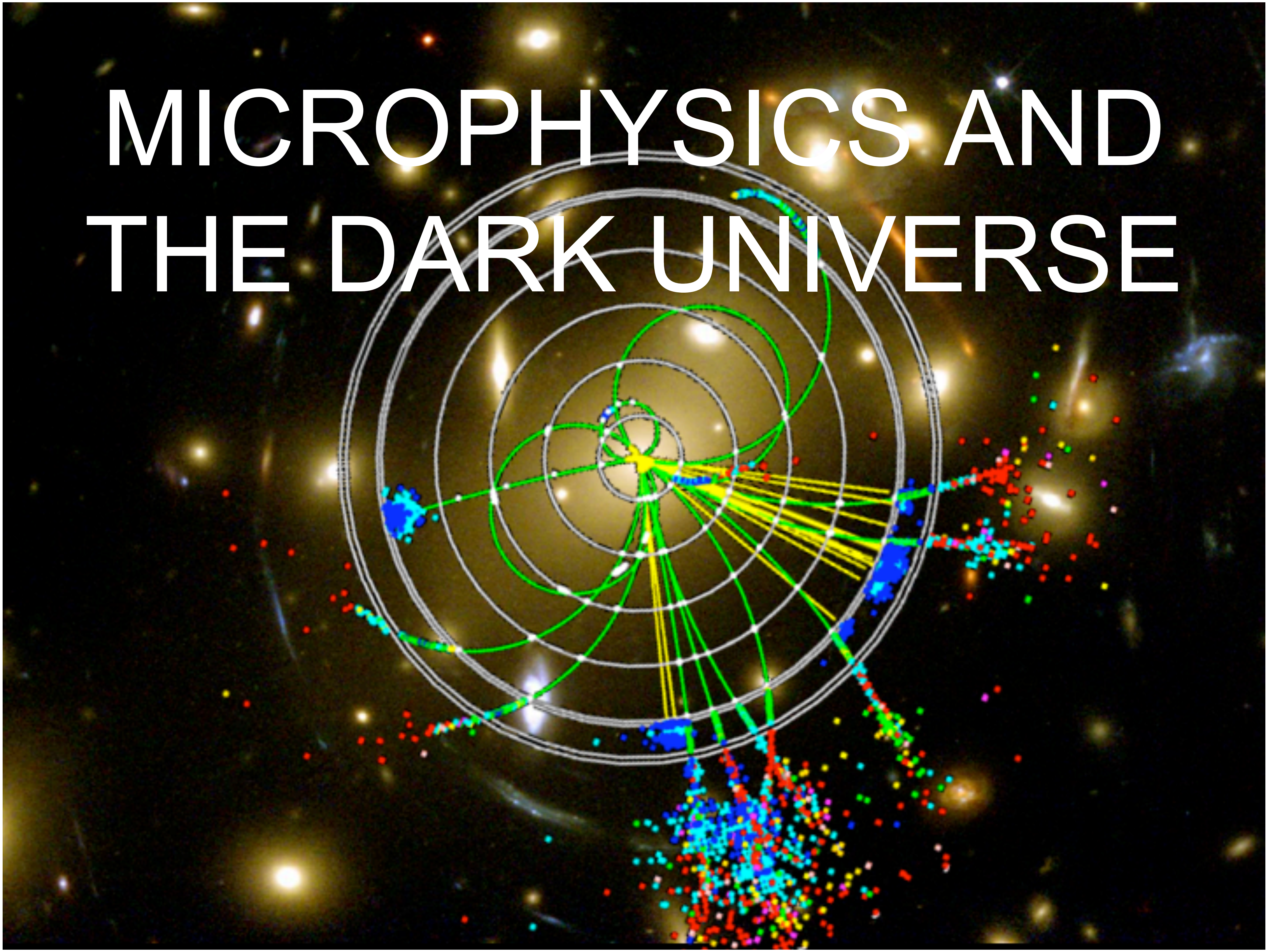
Daniel Eisenstein 2006

# Evolution of Lumps Components




Urbi et Orbi

# MICROPHYSICS AND THE DARK UNIVERSE



# THE DARK UNIVERSE

The problems appear to be completely different

## DARK MATTER

- No known particles contribute
- Probably tied to $M_{weak} \sim 100$ GeV
- Several compelling solutions

## DARK ENERGY

- All known particles contribute
- Probably tied to $M_{Planck} \sim 10^{19}$ GeV
- No compelling solutions

# NEW QUESTIONS

## DARK MATTER

- What is its mass?
- What are its spin and other quantum numbers?
- Is it absolutely stable?
- What is the symmetry origin of the dark matter particle?
- Is dark matter composed of one particle species or many?
- How and when was it produced?
- Why does $\Omega_{DM}$ have the observed value?
- What was its role in structure formation?
- How is dark matter distributed now?

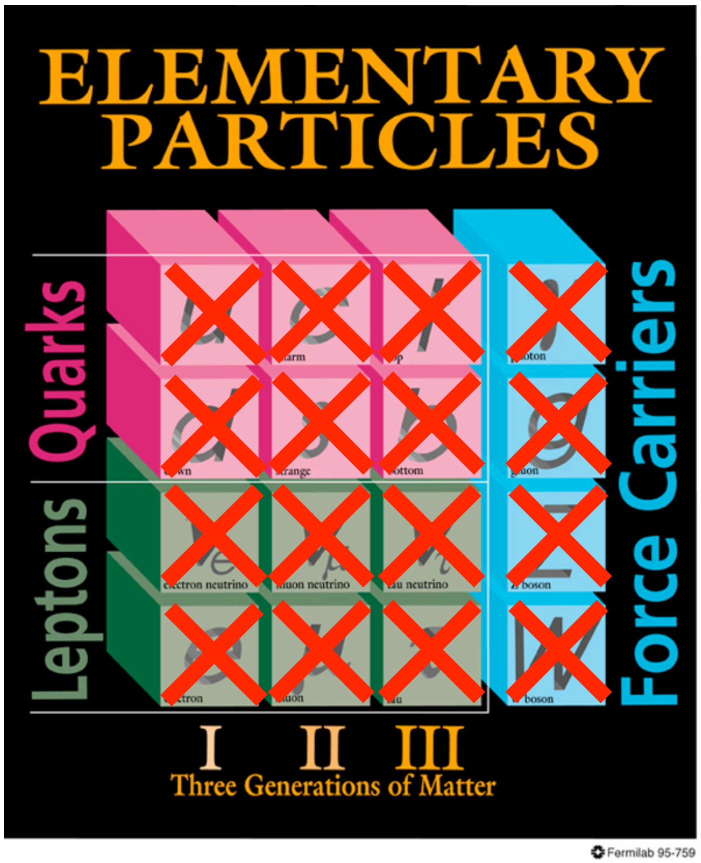
## DARK ENERGY

- What is it?
- Why not $\Omega_\Lambda \sim 10^{120}$?
- Why not $\Omega_\Lambda = 0$?
- Does it evolve?

## BARYONS

- Why not $\Omega_B \approx 0$?
- Related to neutrinos, leptonic CP violation?
- Where are all the baryons?

# DARK MATTER

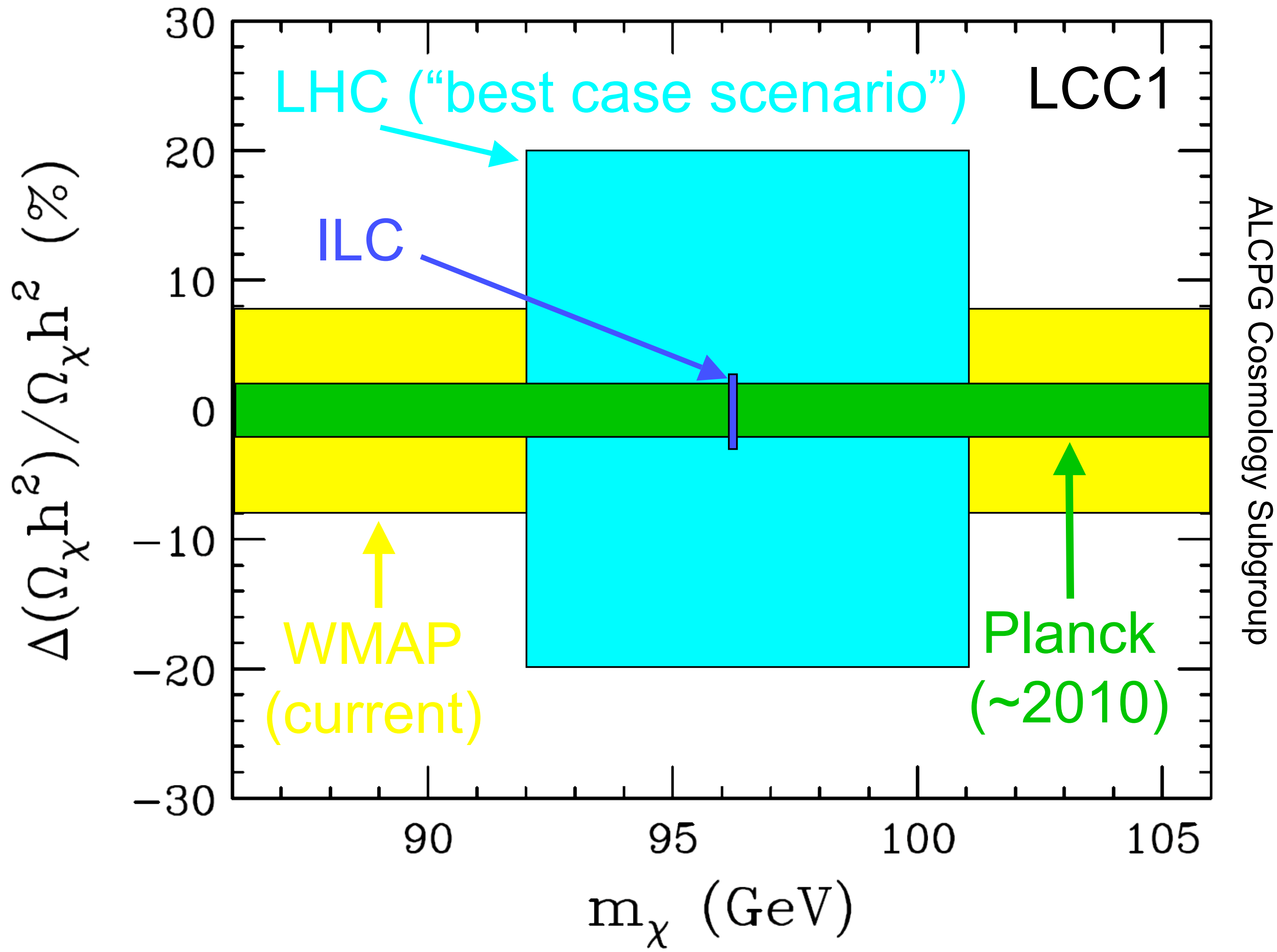



Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

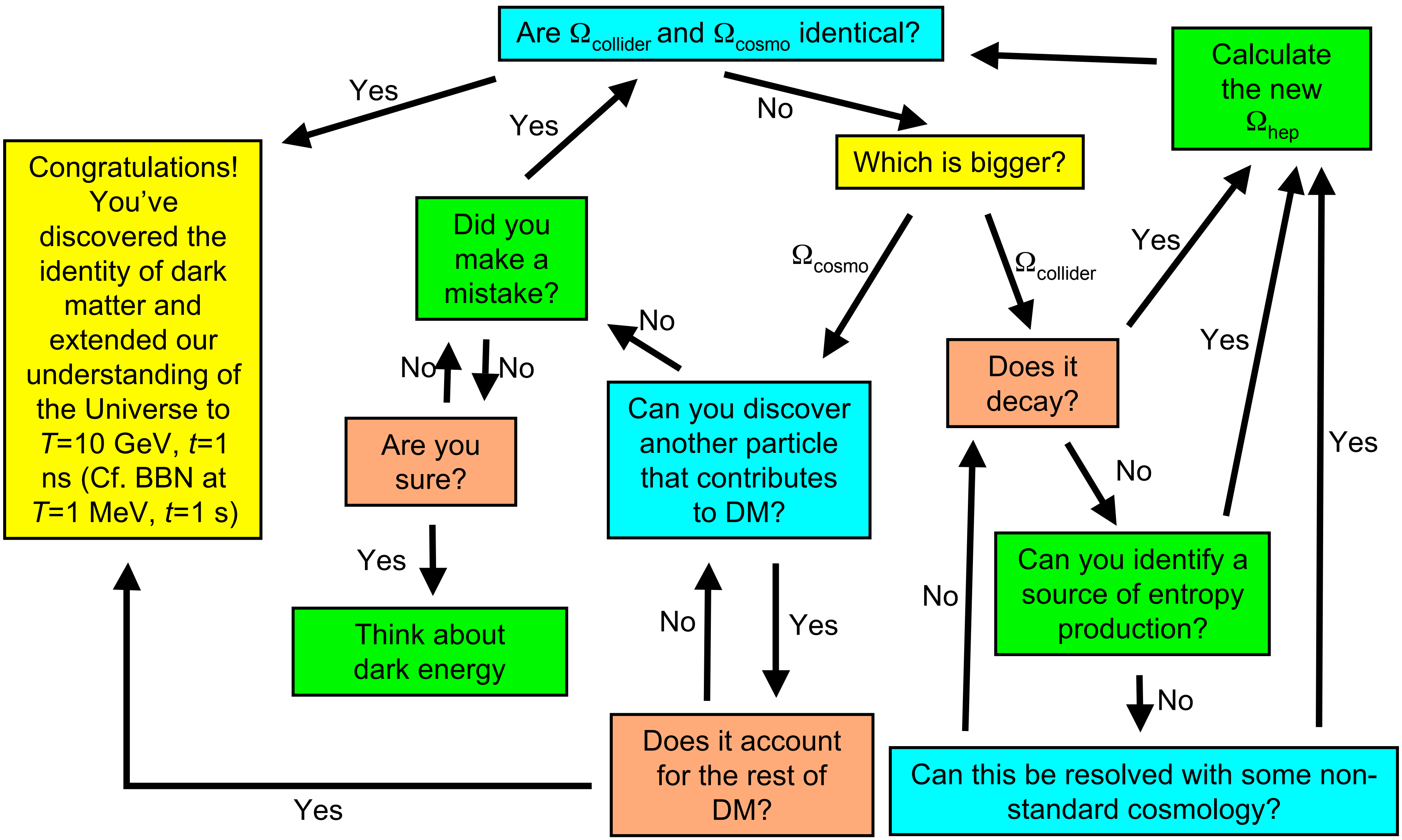
Unambiguous evidence for new physics

# RELIC DENSITY DETERMINATIONS



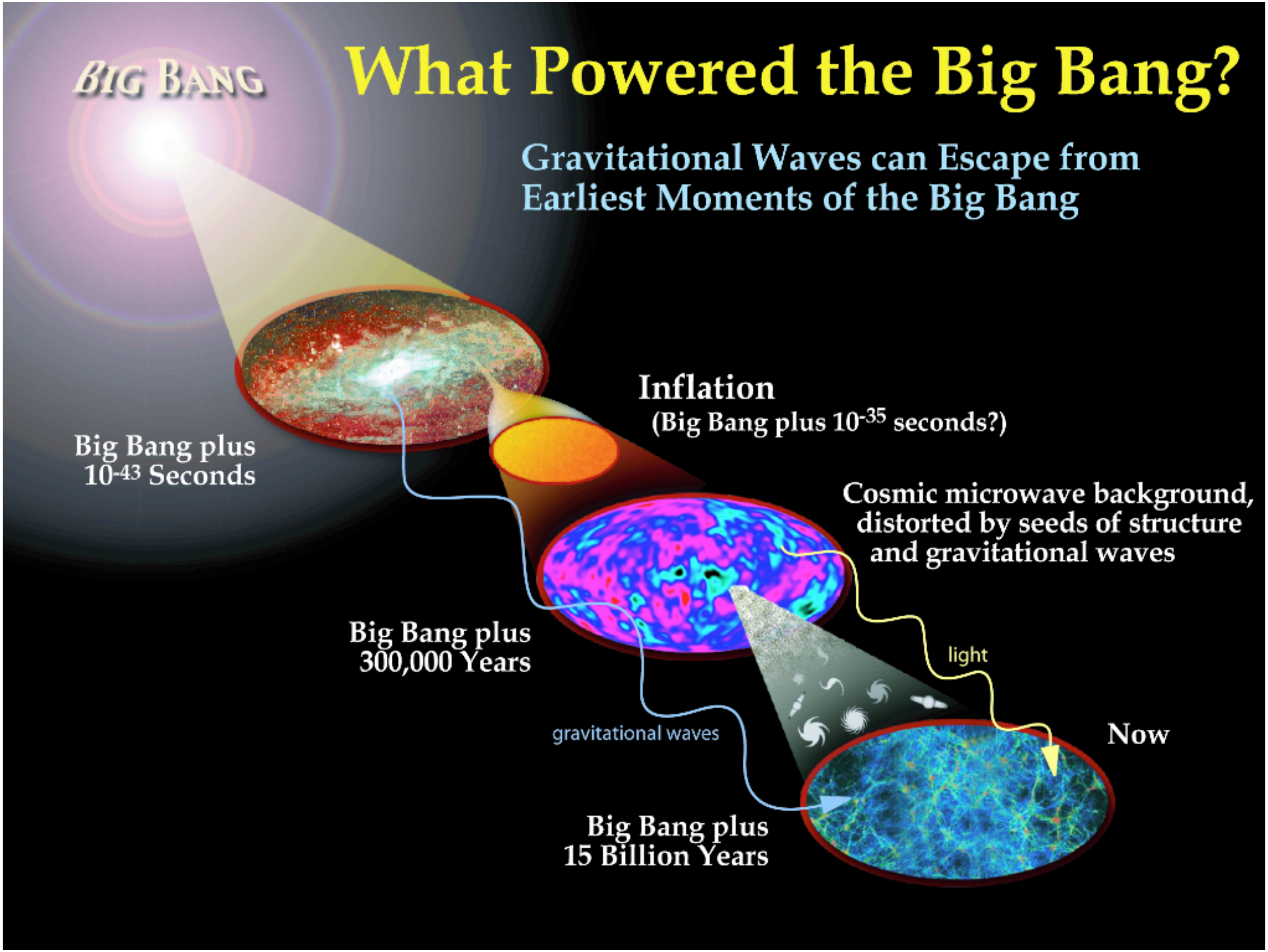

% level comparison of predicted $\Omega_{collider}$ with observed $\Omega_{cosmo}$

# IDENTIFYING DARK MATTER



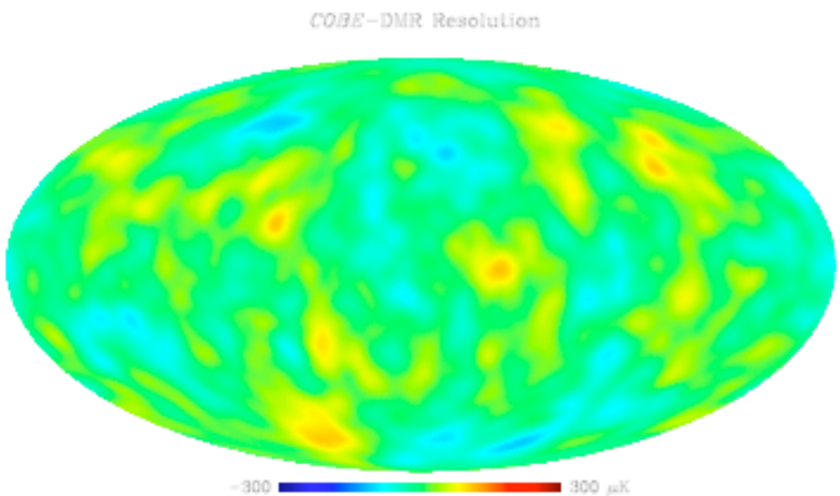
# Microphysics must produce Macro-Universe from first Principles

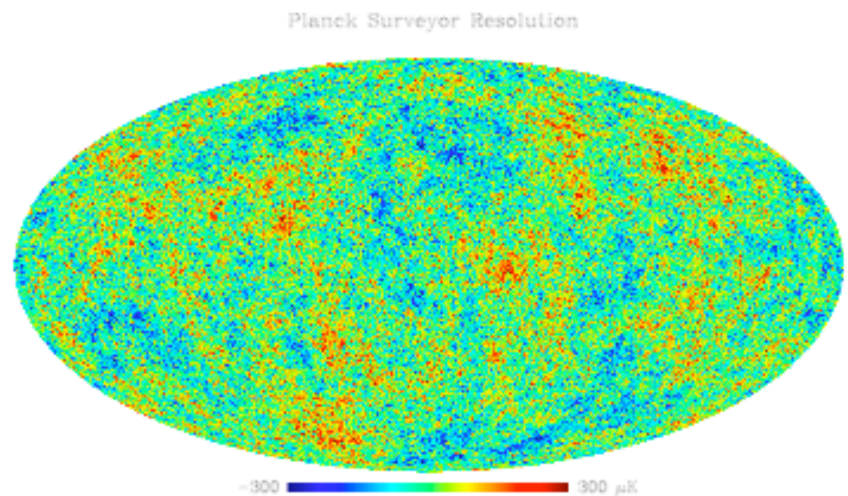
- Extremely well-constrained by observations and macro-Cosmological model
- Guided by symmetry principles and theoretical constructs - e.g. string theory inspired.
- New concepts and questions arise:
  - What was the universe like before the Big Bang?
  - By the anthropic principle we are mostly to be a construct in some one’s simulation.



BIG BANG
What Powered the Big Bang?
Gravitational Waves can Escape from Earliest Moments of the Big Bang
Inflation
(Big Bang plus $10^{-35}$ seconds?)
Big Bang plus $10^{-43}$ Seconds
Cosmic microwave background, distorted by seeds of structure and gravitational waves
Big Bang plus 300,000 Years
light
gravitational waves
Now
Big Bang plus 15 Billion Years

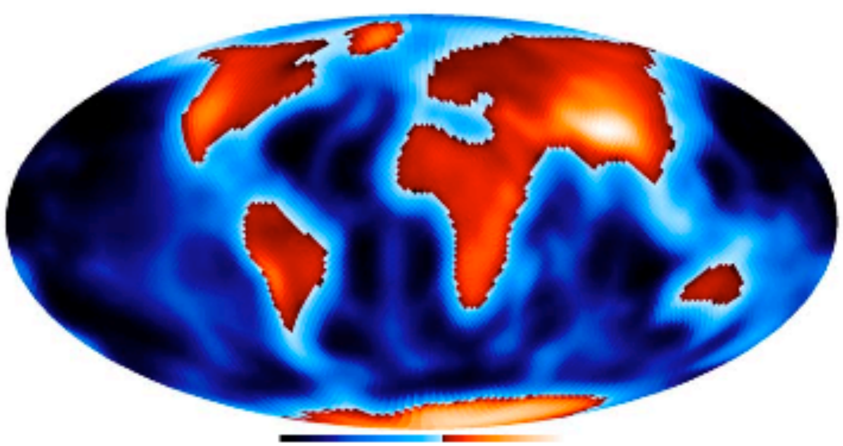
# Great Discovery Era Unfolds …

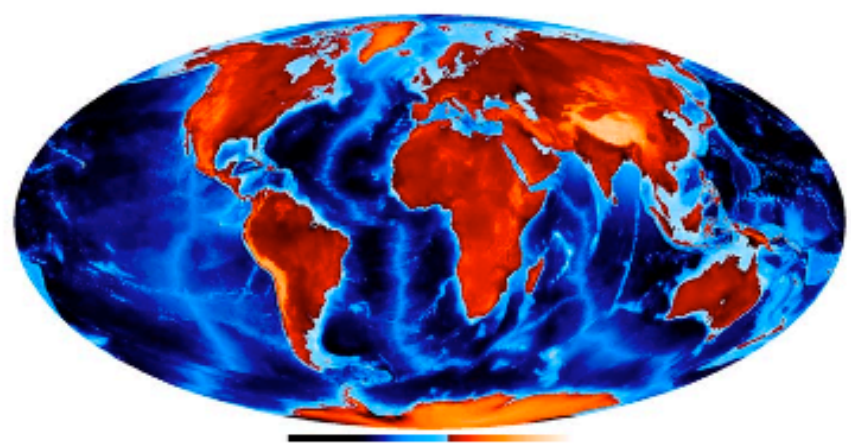


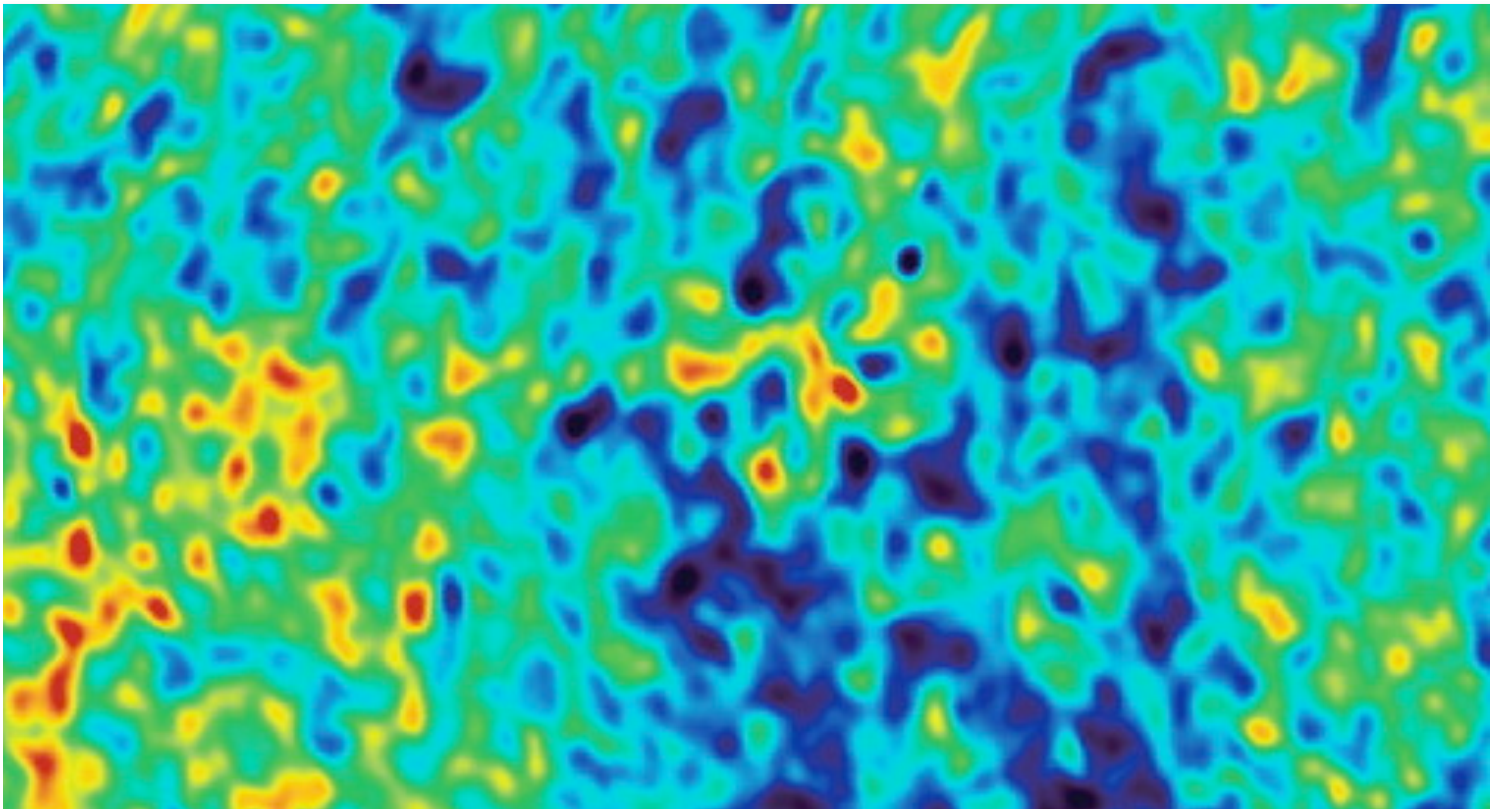

COBE DMR

WMAP & Planck





# An image of quantum fluctuations blown up to the size of the universe.



# Primordial Perturbations

- Originate as quantum fluctuations in Inflationary scenario
- CMB maps on the largest scales are faithful impression of quantum fluctuations
- Each blob is about a single quantum
  - Our own Galaxy (The Milky Way) was a quantum fluctuation  in the early universe
  - So were other galaxies and clusters of galaxies.
- The expanding universe is a better microscope than any laboratory imager

# Cosmological Koans

- The largest and smallest entities in Nature are imaged by the CMB.

- The Universe began with almost no information.

A **kō·an** (公案; Korean: *gong'an*, Japanese: *kōan*, Chinese: *gōng-�*) is a story, dialogue, question, or statement in the history and lore of Ch� (Zen) Buddhism, generally containing aspects that are inaccessible to rational understanding, yet that may be accessible to intuition.
A famous kōan is, "Two hands clap and there is a sound; what is the sound of one hand?'
Kōans originate in the sayings and doings of sages and legendary figures, usually those authorized to teach. Kōans are said to reflect the enlightened or awakened state of such persons, and sometimes said to confound the habit of discursive thought or shock the mind into awareness.

# Cosmological Koans

- CMB anisotropies are simultaneously the largest and smallest entities’ images in Nature.

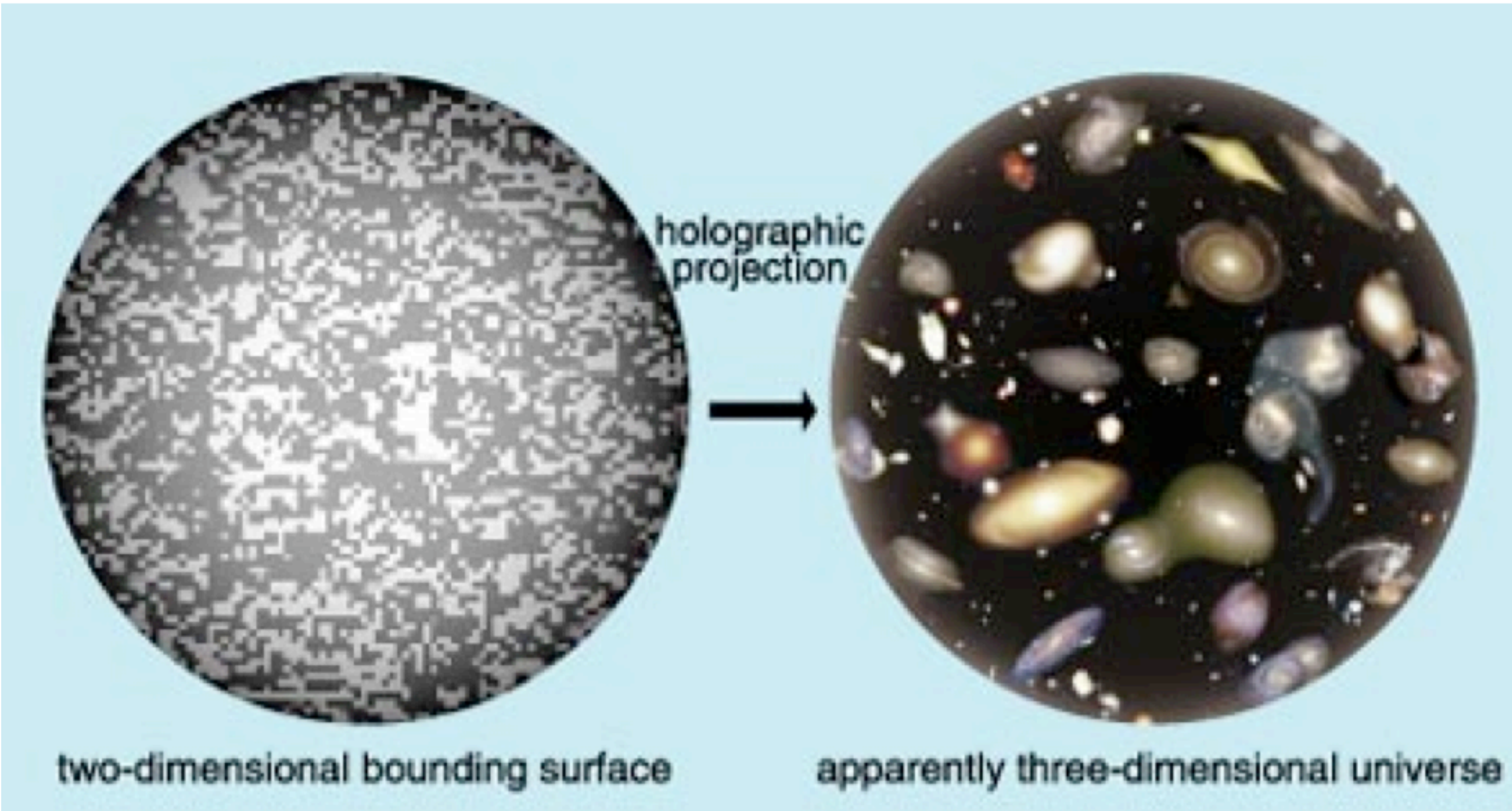
- The Universe began with almost no information.

# Why is the Information Content of the Observable Universe so very small?

- Physically conceivable: $10^{180}$ bits
- Holographic Principle: $10^{120}$ bits
- Inflationary Universe: $10^{10}$ bits
- Observable Fluctuations: $10^{8}$ - $10^{9}$ bits
- Cosmological Parameters: 20 parameters at about 12 bits plus equations of physics and statistics

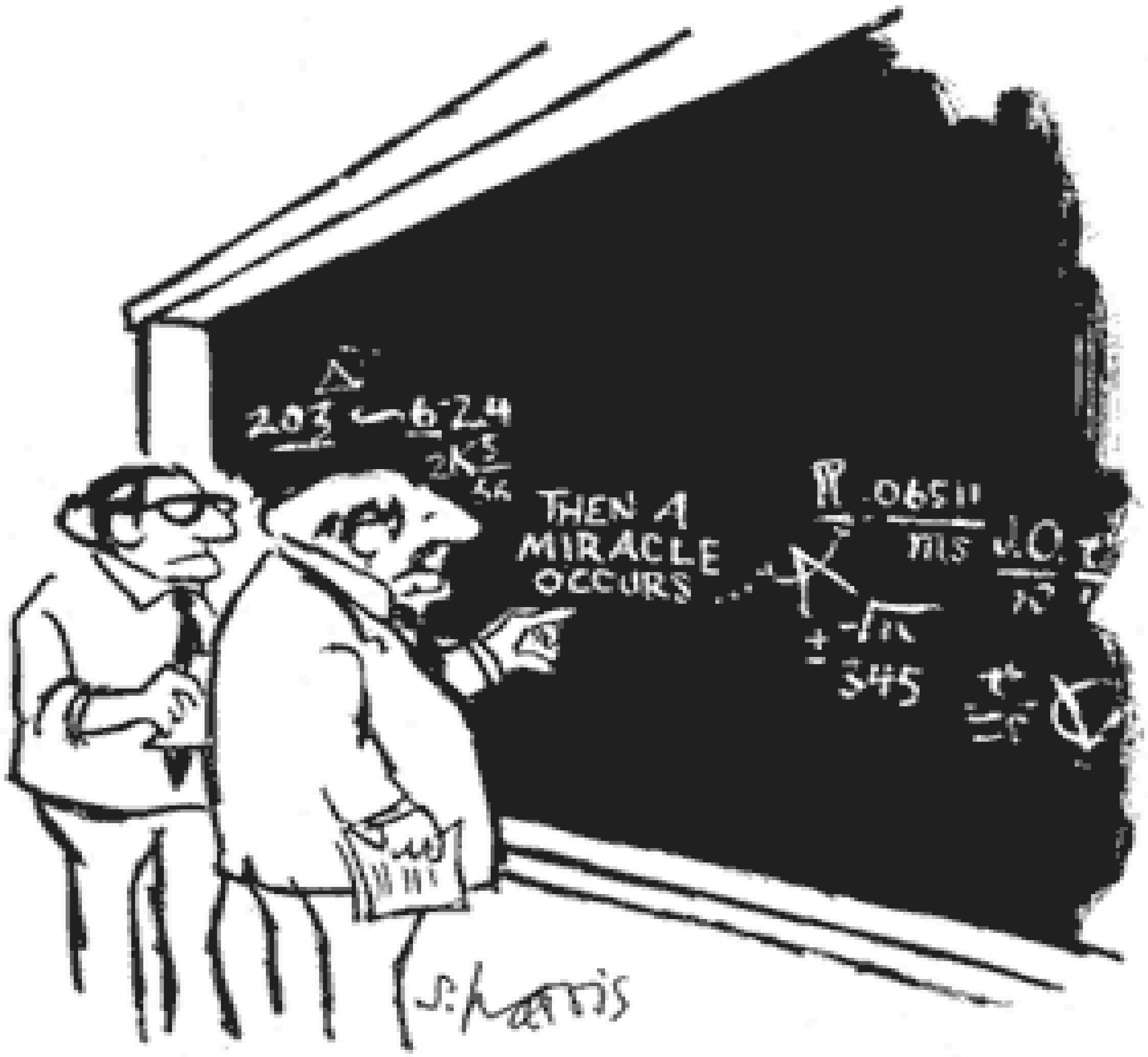
**Data Compression?**

# Holography


holographic
projection
two-dimensional bounding surface
apparently three-dimensional universe

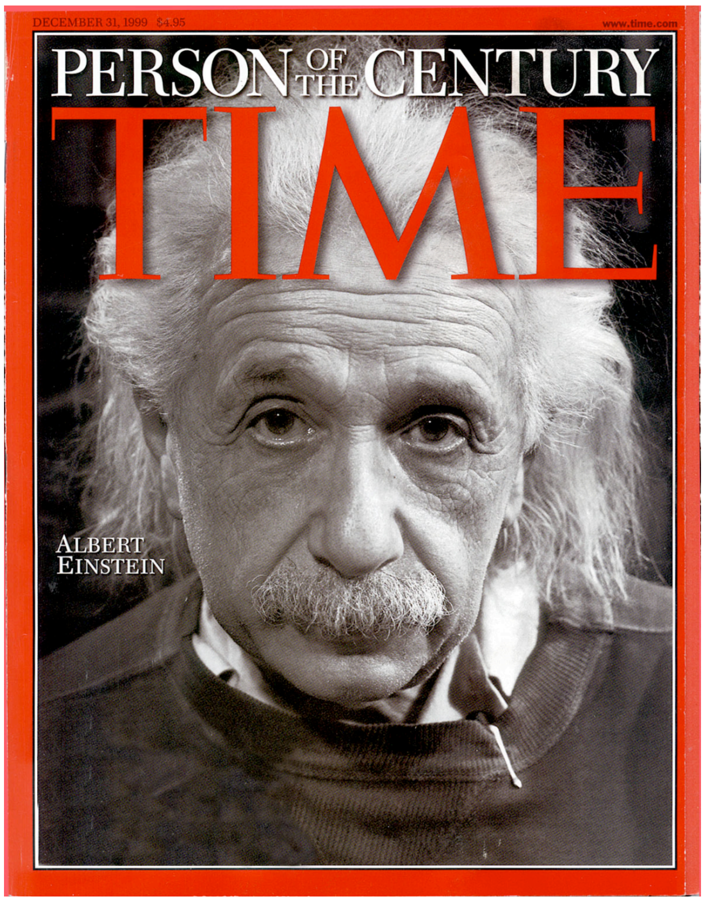

human curiosity

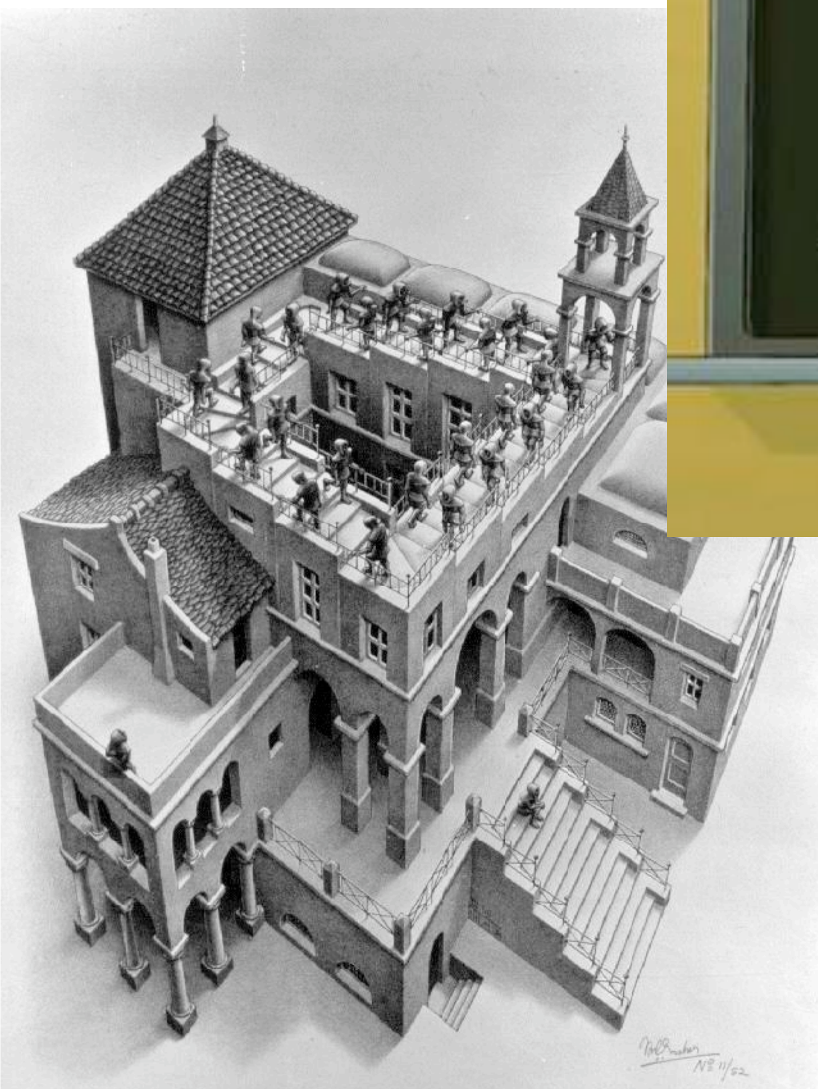
# Sometimes you need a genius or great intuition

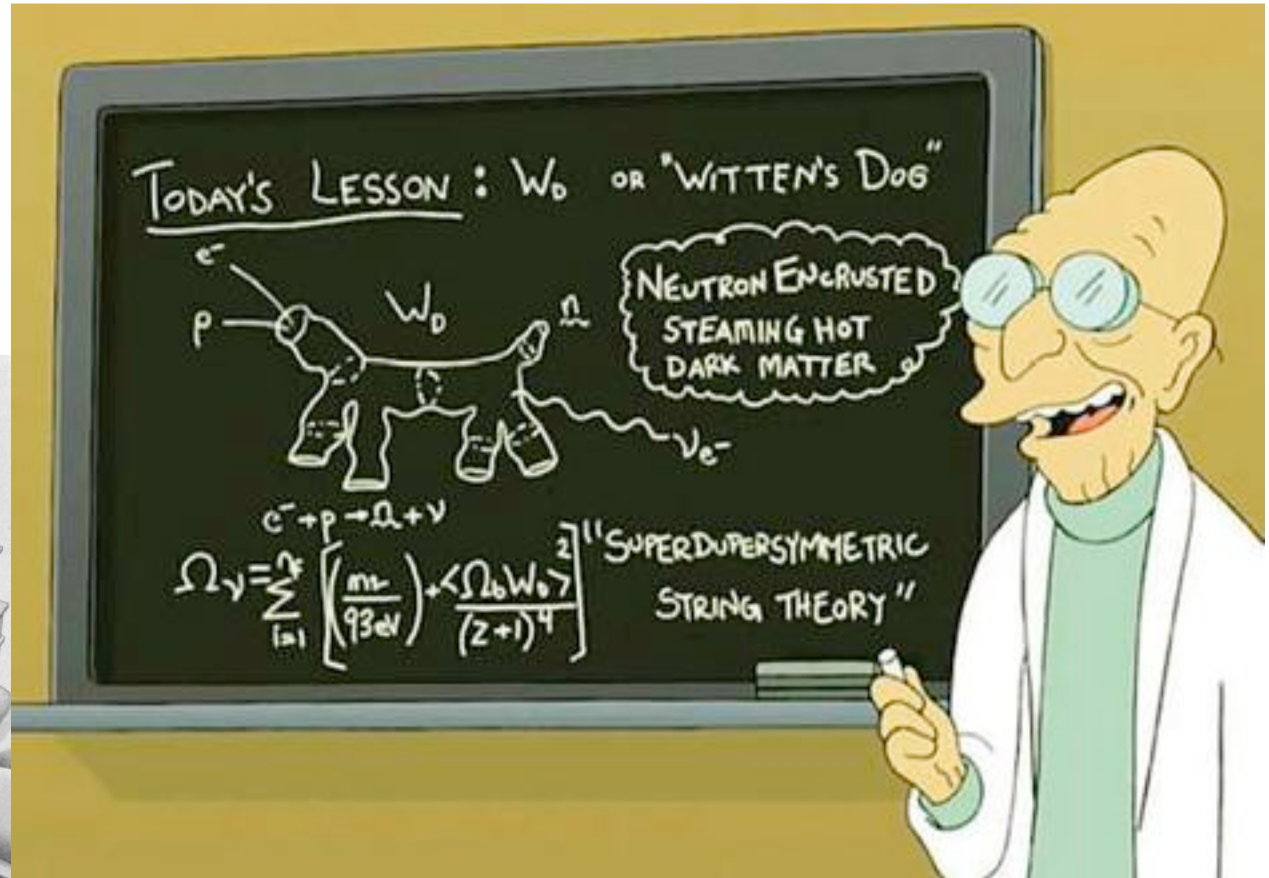



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

# The Future:
# The Person of the 21st Century






TODAY'S LESSON : $W_D$ OR "WITTEN'S DOG"
NEUTRON ENCRUSTED STEAMING HOT DARK MATTER
$W_D$
$e^- + p \rightarrow \Omega + \nu$
"SUPERDUPERSYMMETRIC STRING THEORY"


# CONCLUSIONS

- Cosmology now provides sharp problems that are among the most outstanding in basic science today.
- They require new microphysics, solutions rely on the intimate connection between large and small
- This field may be transformed by the end of this decade