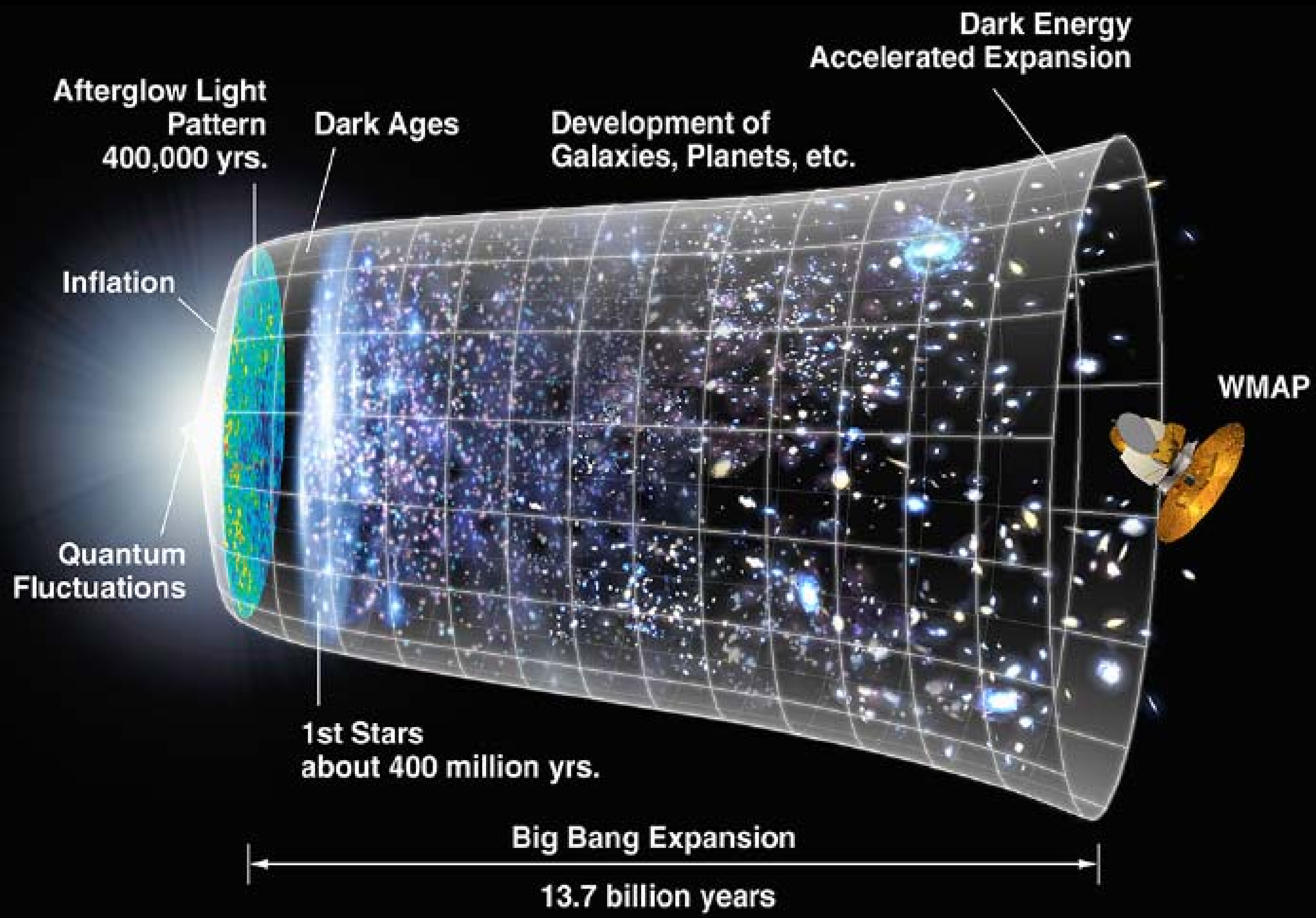
Introduction to Cosmology

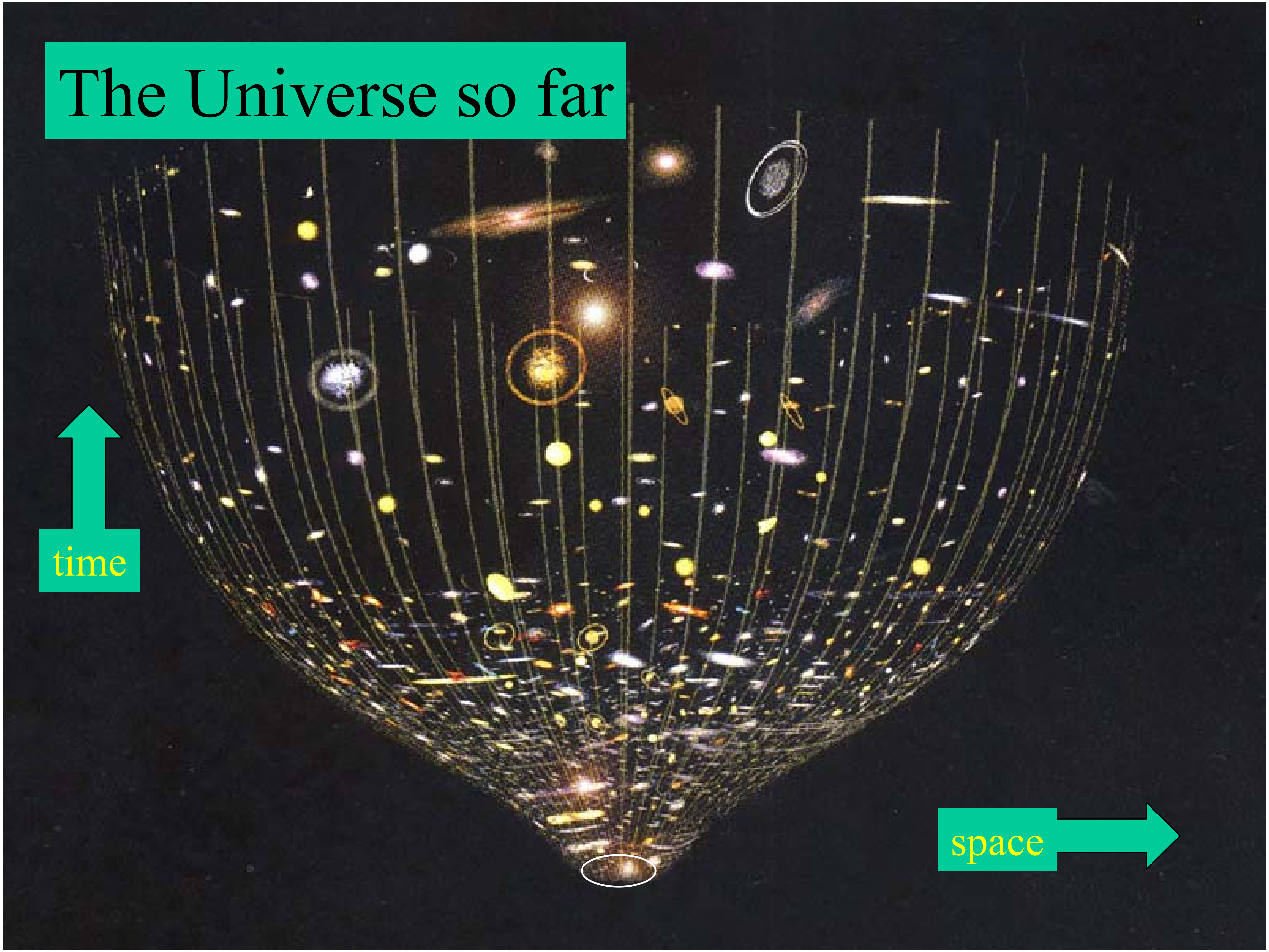


CERN, July 2006
John Ellis

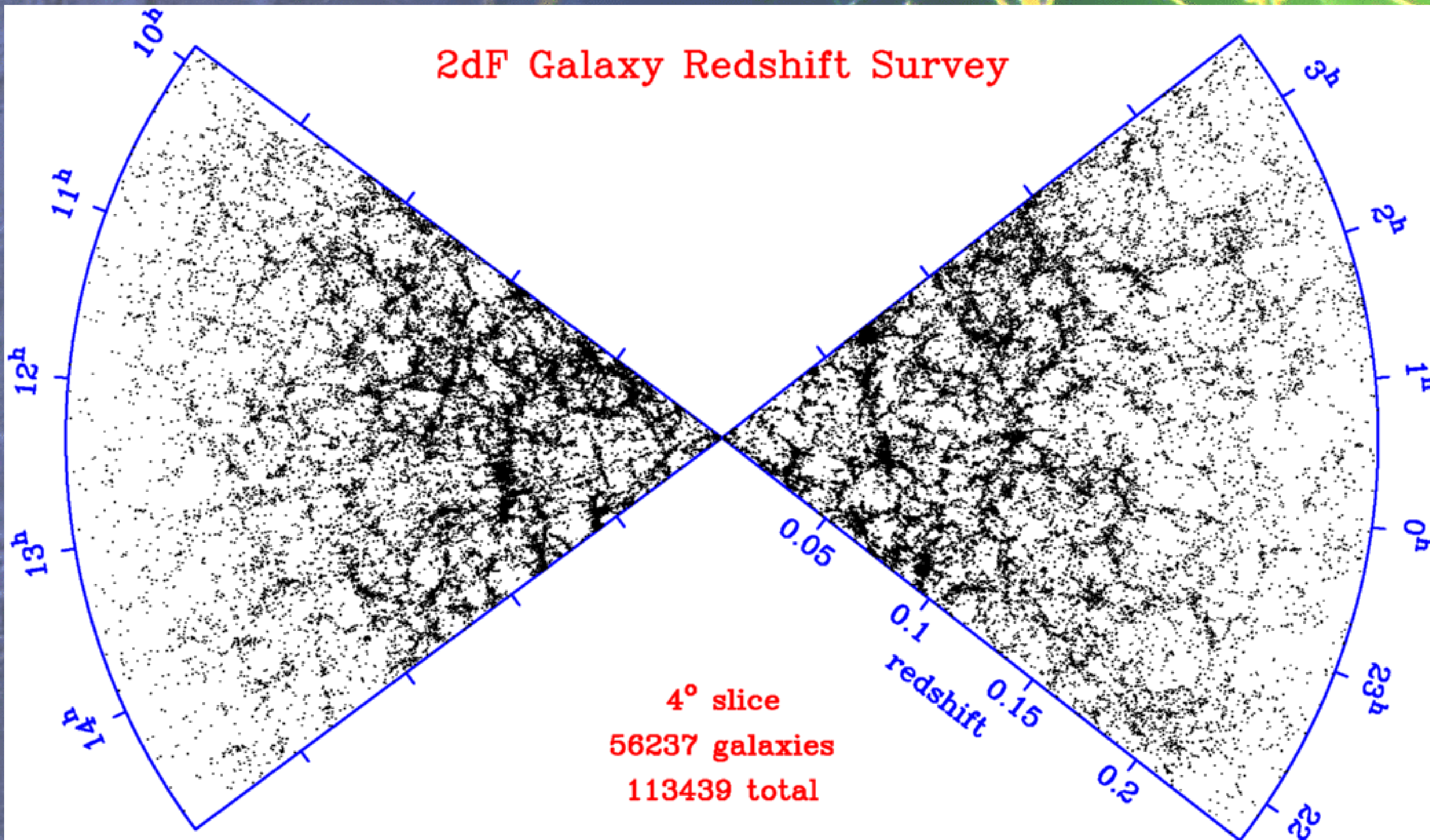
Links with particle physics

Outline

- The expansion of the Universe:
  - Olbers' paradox, Hubble expansion, Cosmic microwave background radiation, Light elements
  - Importance of particle physics in early Universe
- The matter/energy content of the Universe
  - Few % ordinary matter, 25 % dark matter, 70 % dark energy
  - Possible information from the LHC
- Speculations
  - Very early Universe:
    - Creating matter, cosmological inflation
  - Ultra-high-energy cosmic rays:
    - Astrophysical sources or decaying particles?


The Universe so far
time
space

What we see in the Universe

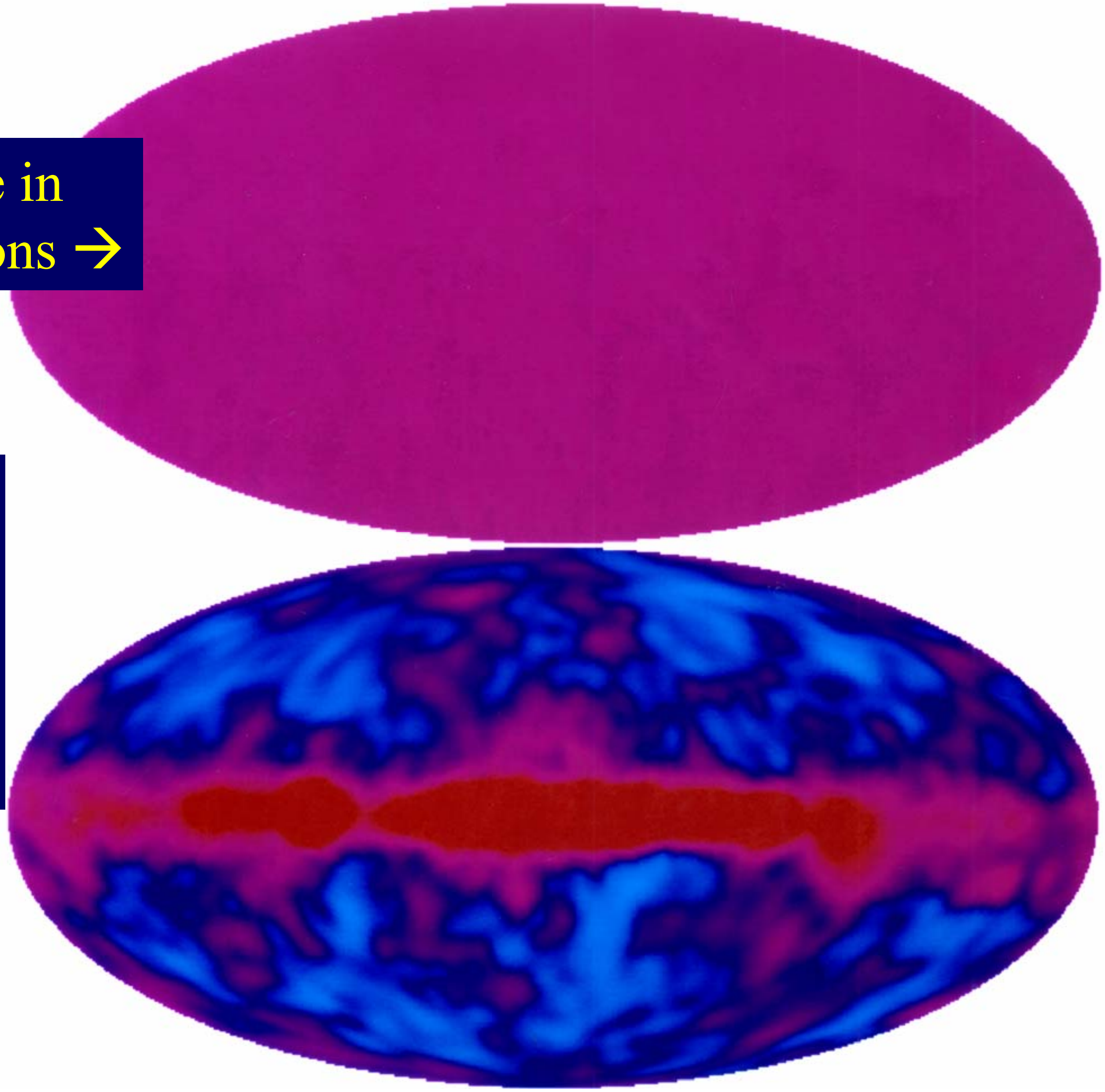


Small-scale structures → homogeneous and isotropic at large scales

Cosmic Microwave Background

Almost the same in different directions →

Small variations discovered by COBE satellite →



Cosmological 'Principle'

- 'Universe looks the same from any point'

  isotropic and homogeneous
- To be interpreted in average sense
- Perfect Cosmological Principle?
- 'Universe looks same at all times and all places'
- Not correct: the Universe is expanding

Olbers' Paradox

- Why is the night sky not as bright as the surface of the Sun?
- In an infinite, static Universe, every line of sight would end at the surface of a star
- Absorption does not help (Herschel)
- Finite spherical Universe no help either
- Universe must be finite in time and/or space

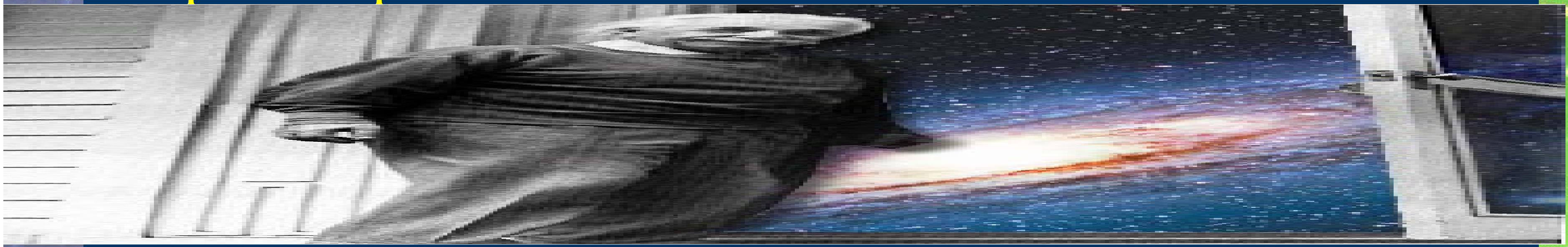
The Universe is expanding

- Galaxies are receding from us

  Hubble expansion law: galactic redshifts

The Hubble Expansion

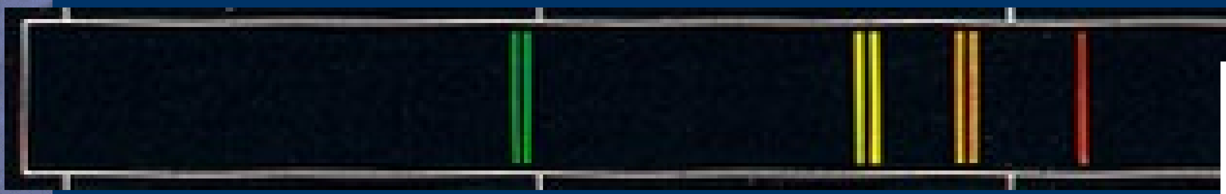
- Light arriving from distant galaxies is redshifted
- The effect increases with distance
- The effect is due to the expansion of light wave as space expands



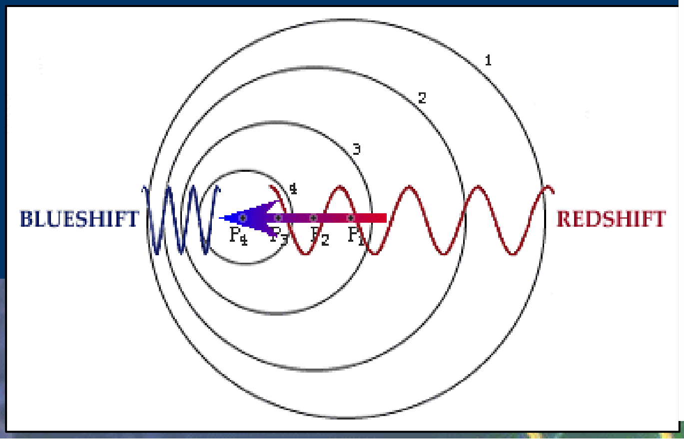
- The most distant objects ~ 10,000,000,000 light years
- **The same physics as in the laboratory!**

Cosmological Redshifts

- Detectable effect on spectrum ‘barcodes’ for different elements, e.g., Sodium:



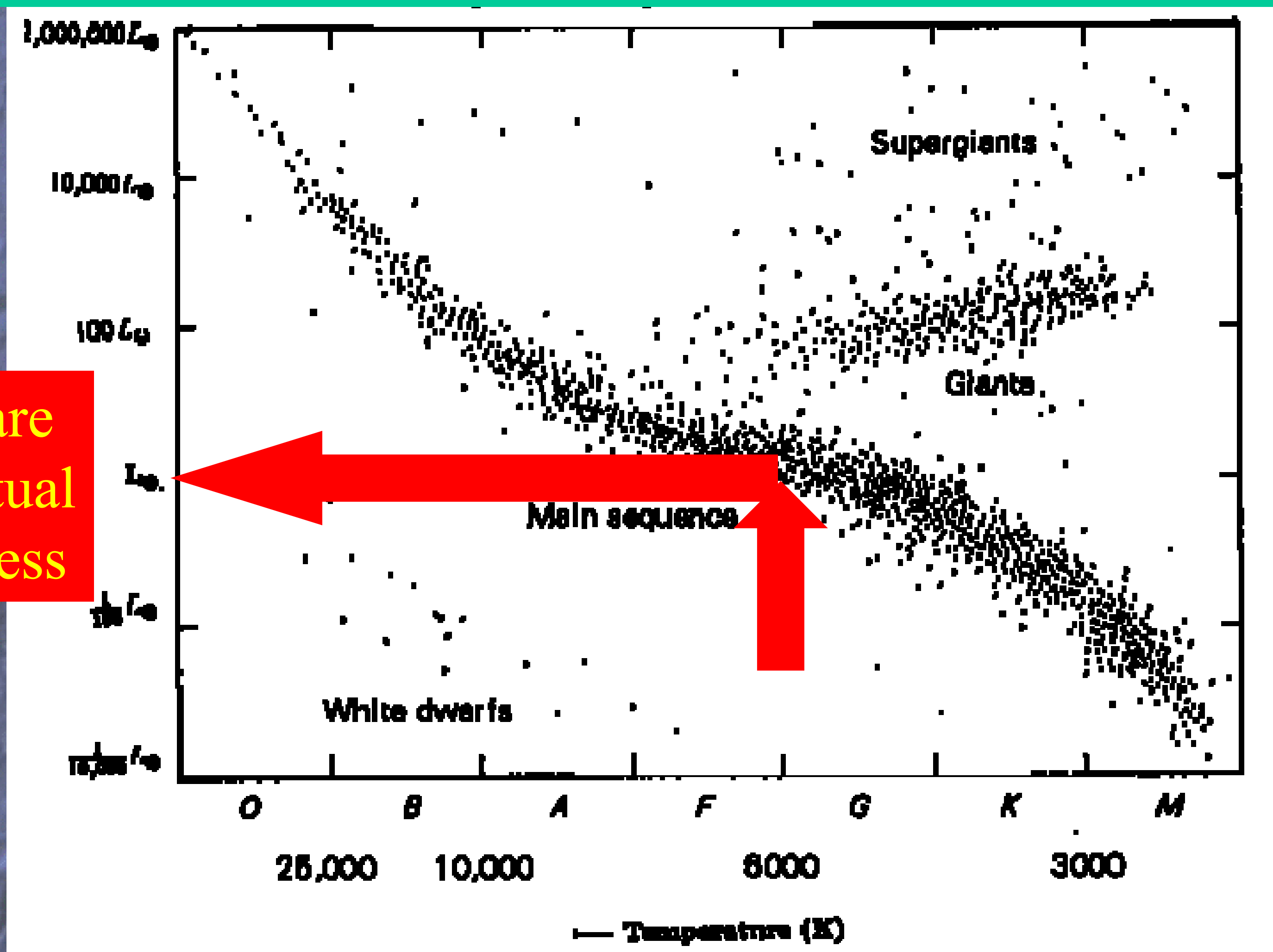
- Döppler effect: $\lambda = \lambda/(1+z)$



Cosmological Distance Ladder

- Trigonometric parallax:
  motion of Earth around orbit → O(100) pc
- Spectroscopic Parallax:
  based on Hertzsprung-Russell diagram → 50 Kpc
- Cepheid variables: → 4 Mpc
- Other 'Standard Candles':
  clusters, galaxies, radio sources, supernovae …
  weak lensing, microwave background, …
- Hubble constant = 70 km/s/Mpc ± < 10 %

Hertzsprung-Russell Diagram for Stars in our Local Neighbourhood

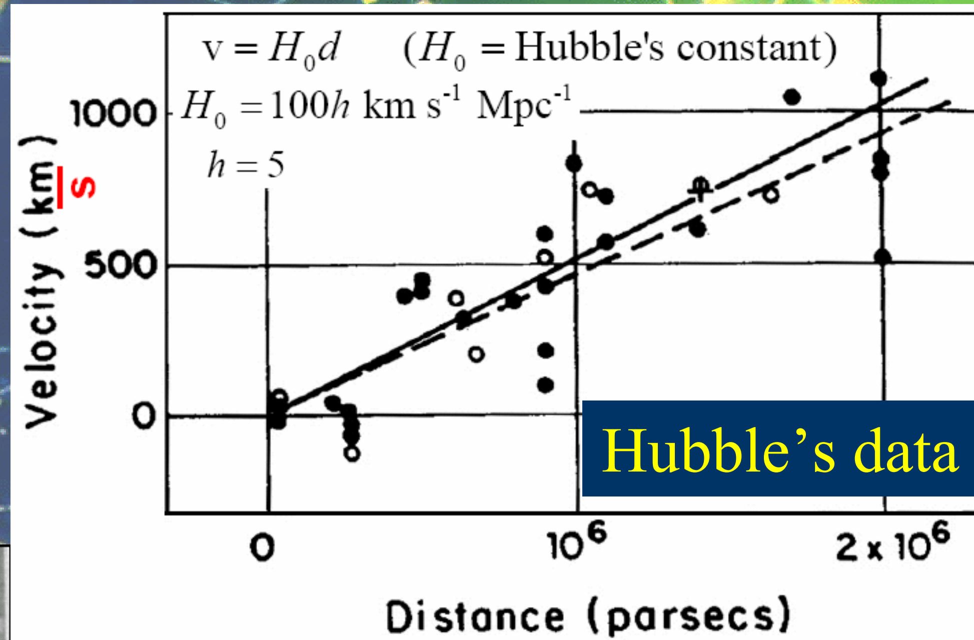


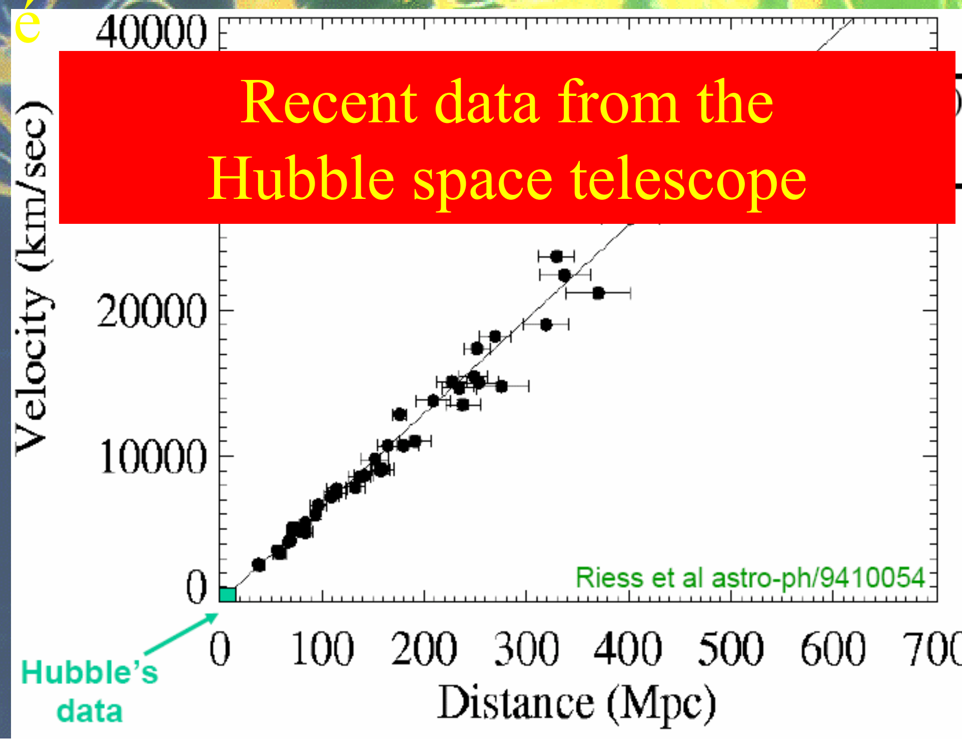
Compare with actual brightness

The expansion of the Universe

Hubble, basketball player

University of Chicago 1909 National Champions





The Universe is expanding

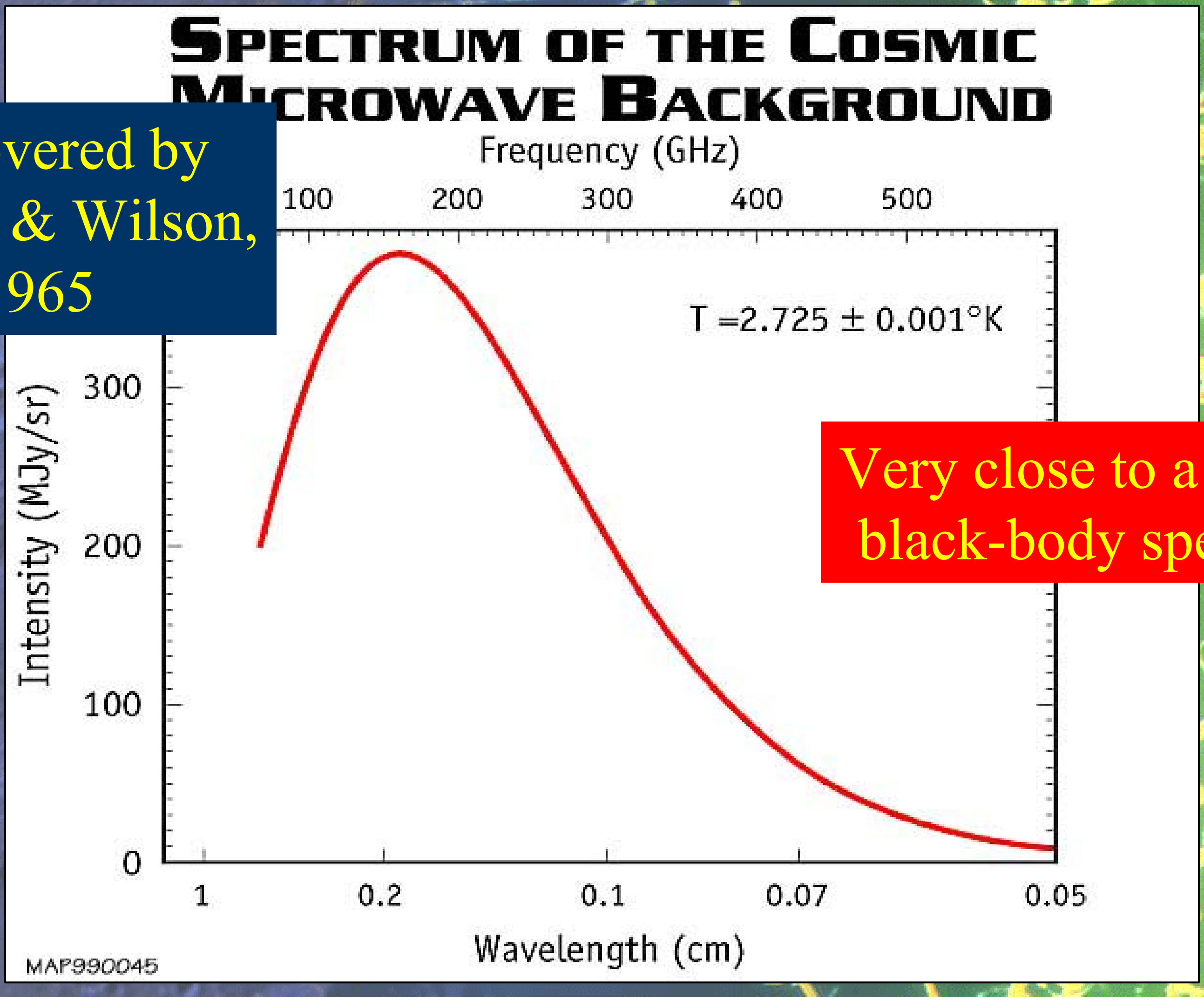
- Galaxies are receding from us

  Hubble expansion law: galactic redshifts

- The Universe was once 3000 smaller, hotter than today

  cosmic microwave background radiation

The Cosmic Microwave Background Radiation



Discovered by Penzias & Wilson, 1965

Very close to a perfect black-body spectrum

Cosmic Microwave Background

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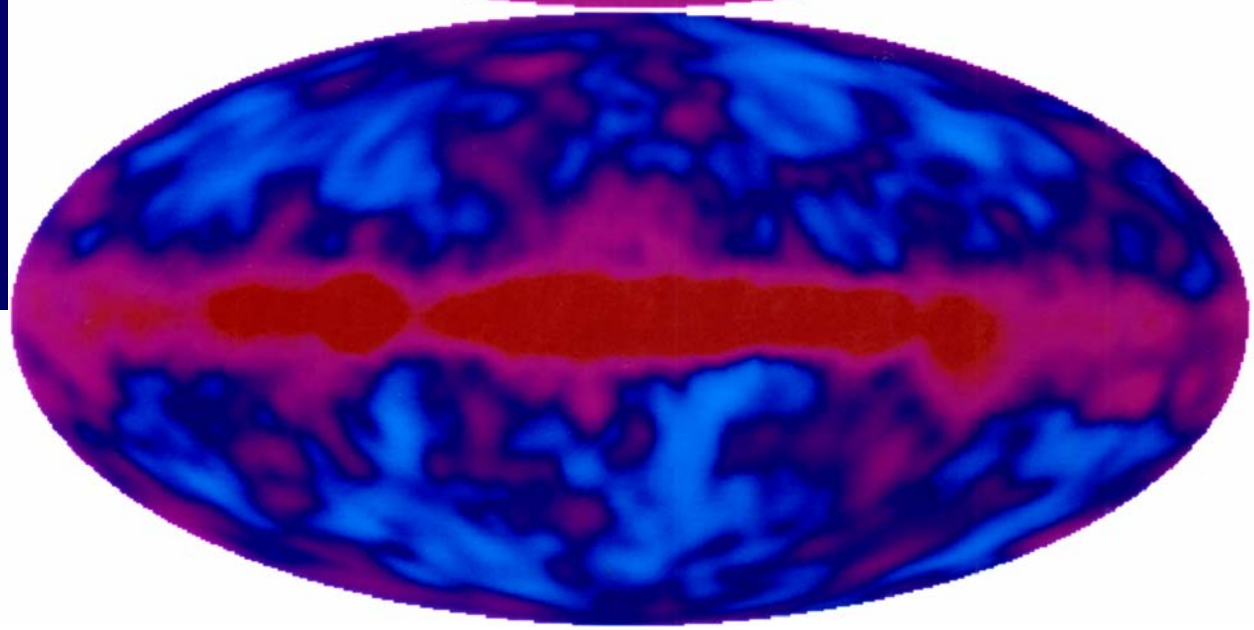
Small variations discovered by COBE satellite →



The Universe is expanding

- Galaxies are receding from us

    Hubble expansion law: galactic redshifts

- The Universe was once 3000 smaller, hotter than today

    cosmic microwave background radiation

- The Universe was once a billion times smaller, hotter than today

    light elements cooked in the Big Bang

Big-Bang Nucleosynthesis

- Universe contains about 24% Helium 4
  - and less Deuterium, Helium 3, Lithium 7
- Could only have been cooked by nuclear reactions in dense early Universe
  - when Universe billion times smaller, hotter than today
- Dependent on amount of matter in Universe
  - not enough to stop expansion, explain galaxies
- Dependent on number of particle types
  - number of different neutrinos measured at accelerators

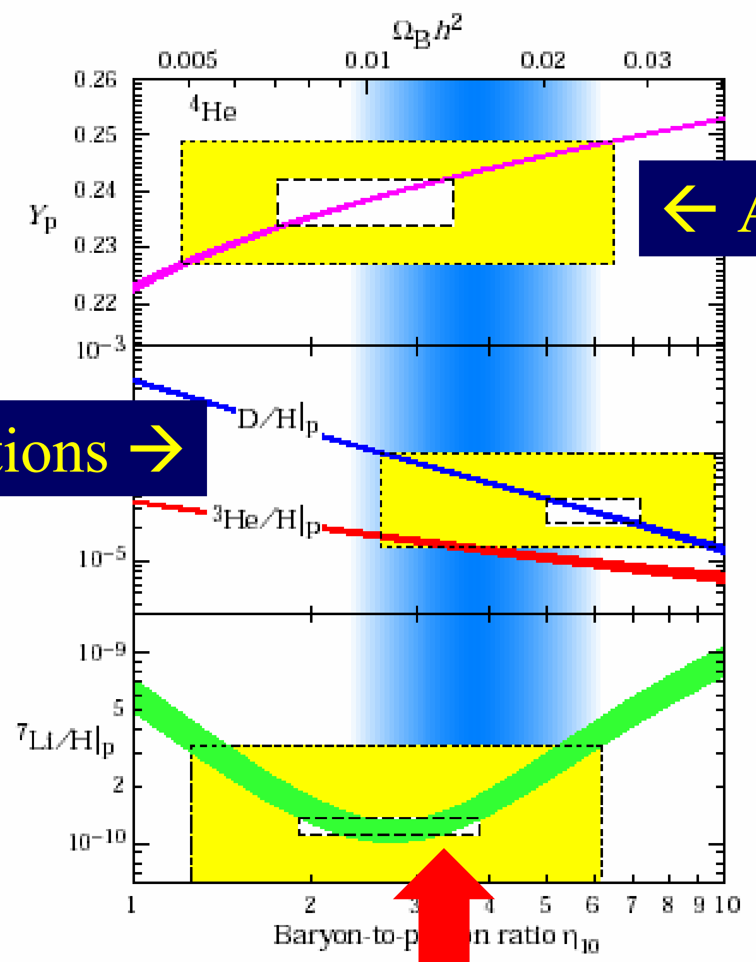
Abundances of light elements in the Universe

Helium

← Agree with data

Theoretical calculations →

Lithium



Not enough ordinary matter for critical density of the Universe

Open Cosmological Questions

- Why is the Universe so big and old?
  ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  almost flat: density nearly critical
- Where did the matter come from?
  1 proton for every 1,000,000,000 photons
- How did structures form?
  ripples + invisible dark matter?
- What is the dark matter?

Need particle physics to answer these questions

The Very Early Universe

- Size: $a \rightarrow$ zero
- Age: $t \rightarrow$ zero
- Temperature: $T \rightarrow$ large

  $T \sim 1/a$, $t \sim 1/T^2$
- Energies: $E \sim T$
- Rough magnitudes:

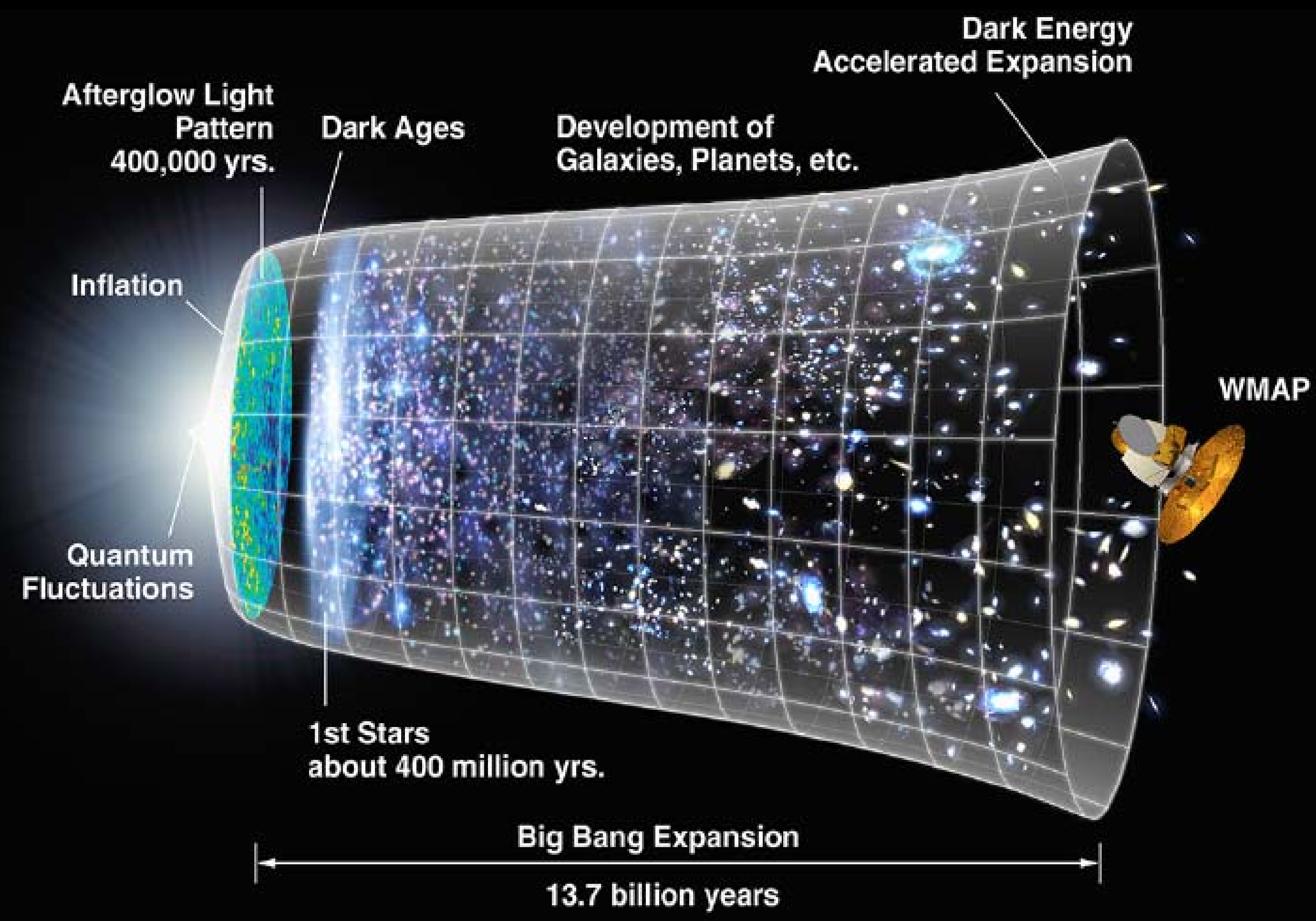
  T ~ 10,000,000,000 degrees

  E ~ 1 MeV ~ mass of electron

  t ~ 1 second

Need particle physics to describe earlier history

Introduction to Cosmology



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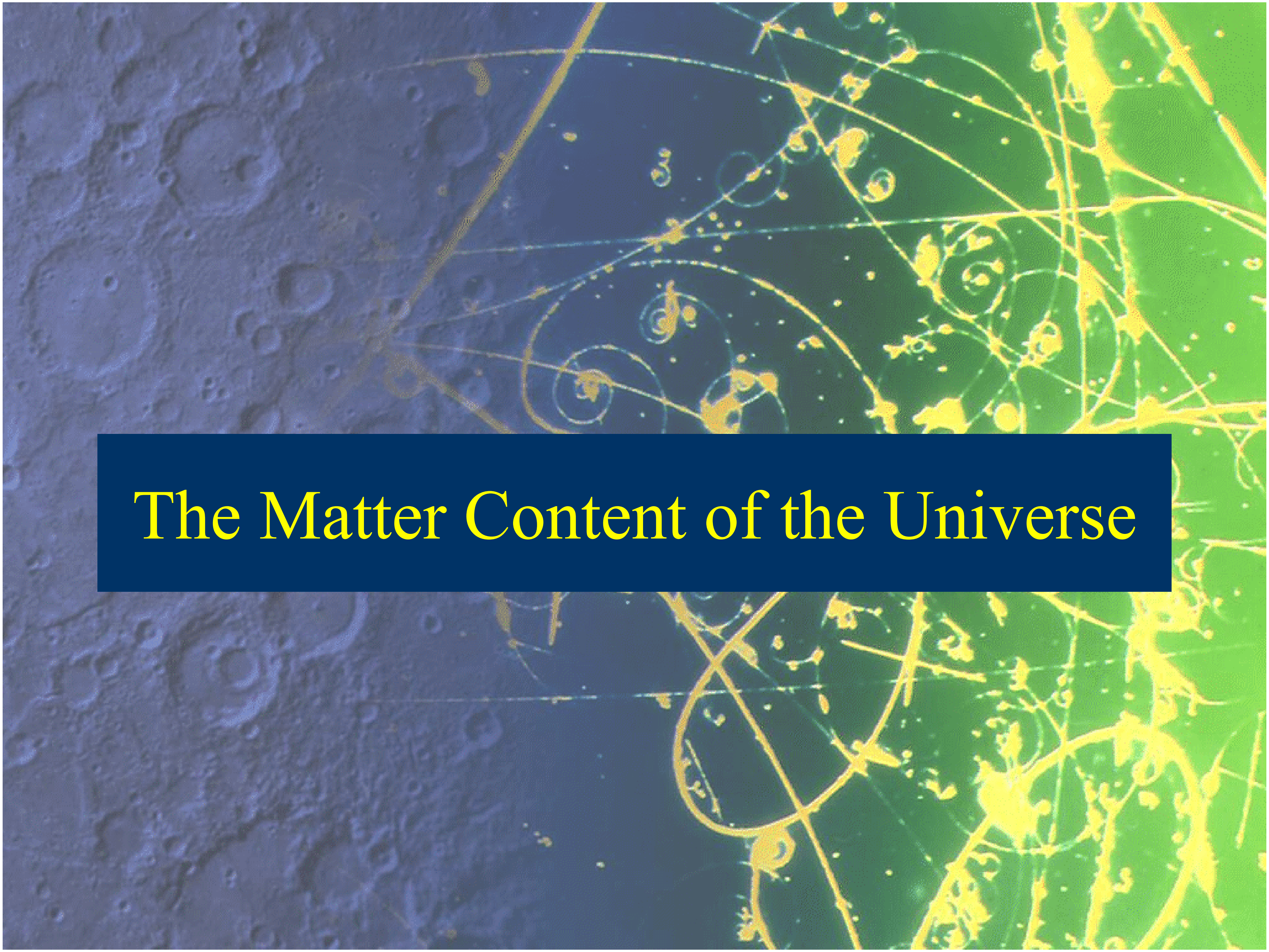


The Matter Content of the Universe

The Density Budget of the Universe

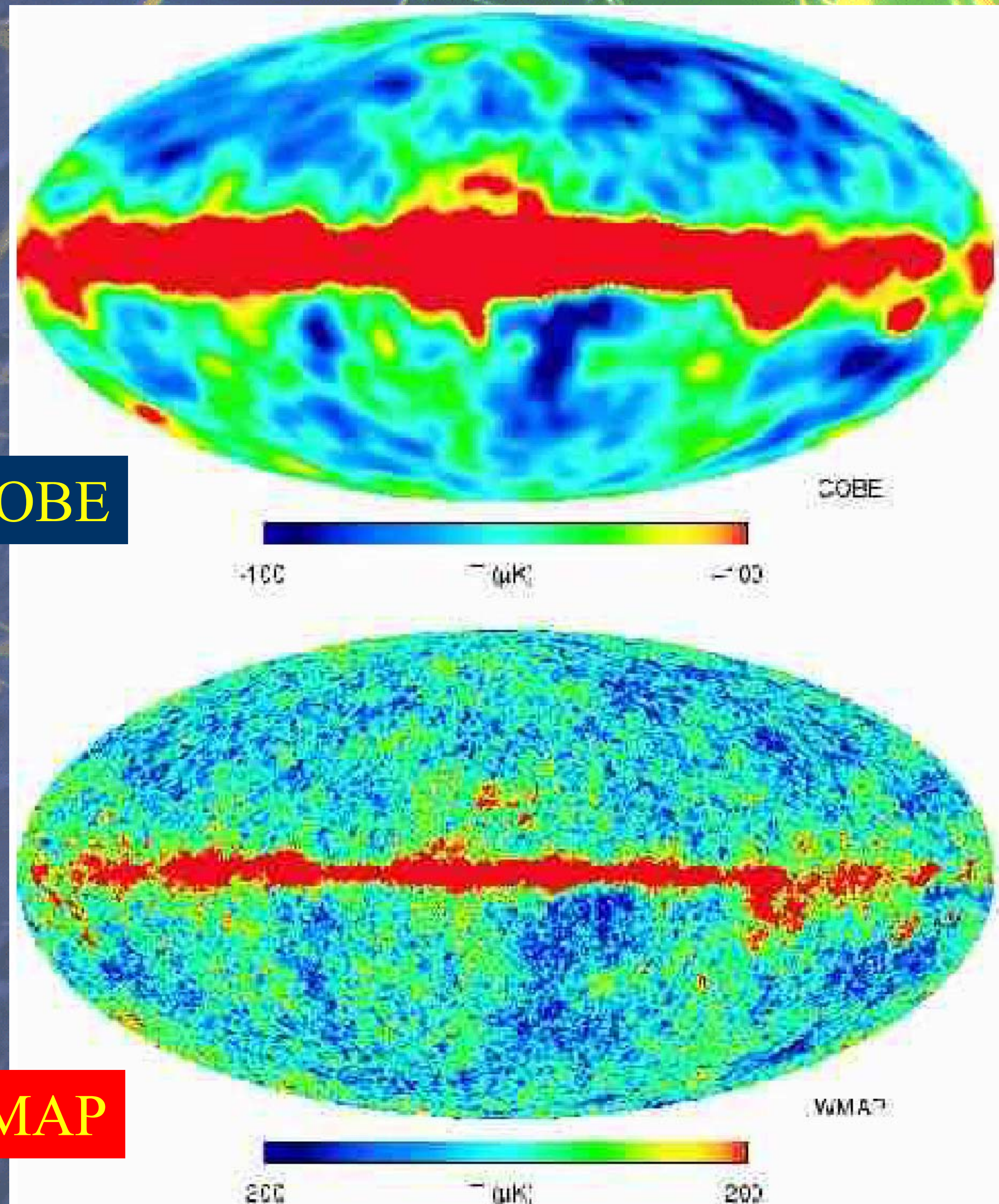
- Total density ~ critical

  Theory of inflation, measurements of microwave background: $\Omega_{Tot} = \sim 1$

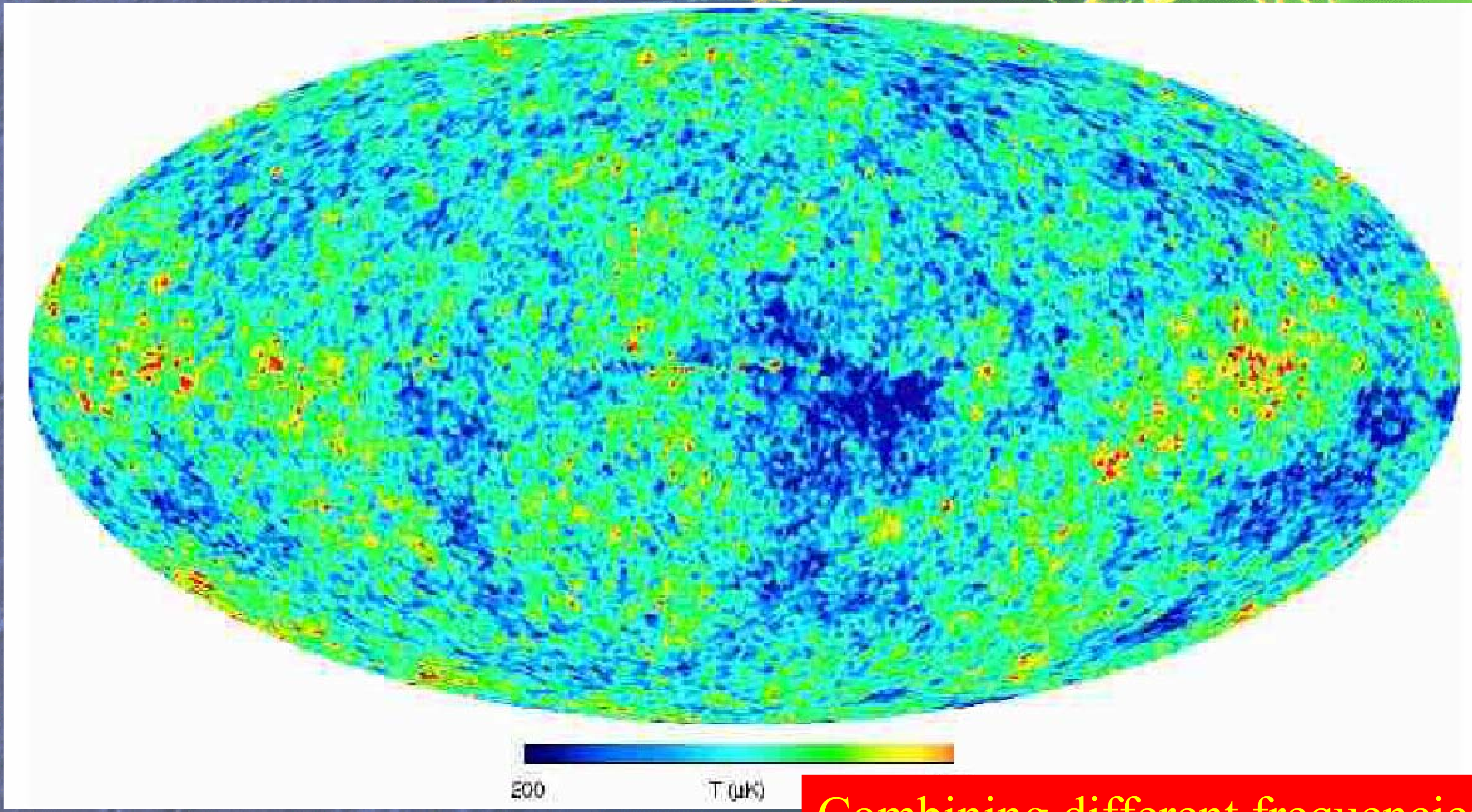
The Cosmic Microwave Background

According to COBE

According to WMAP



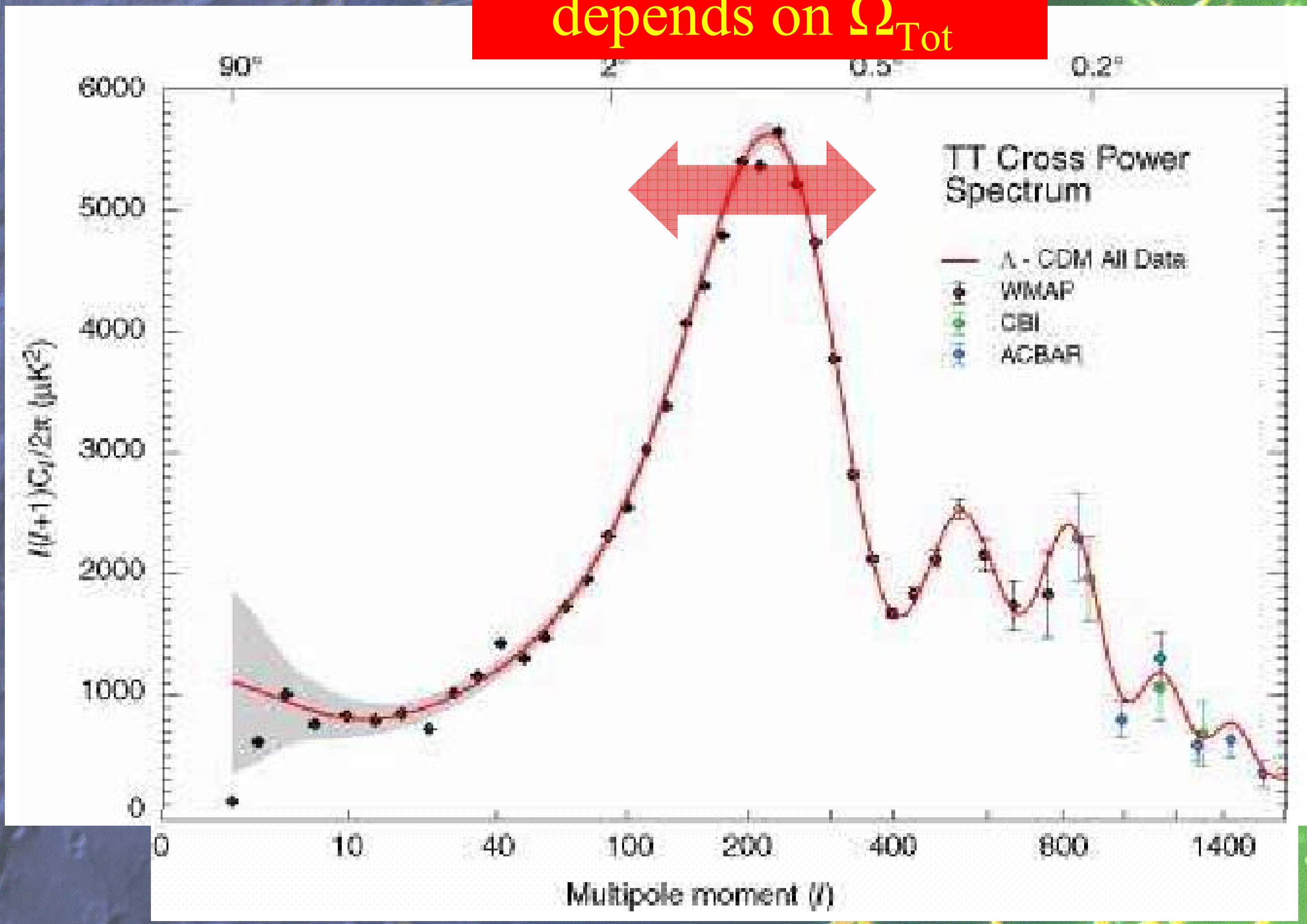
The CMB according to WMAP



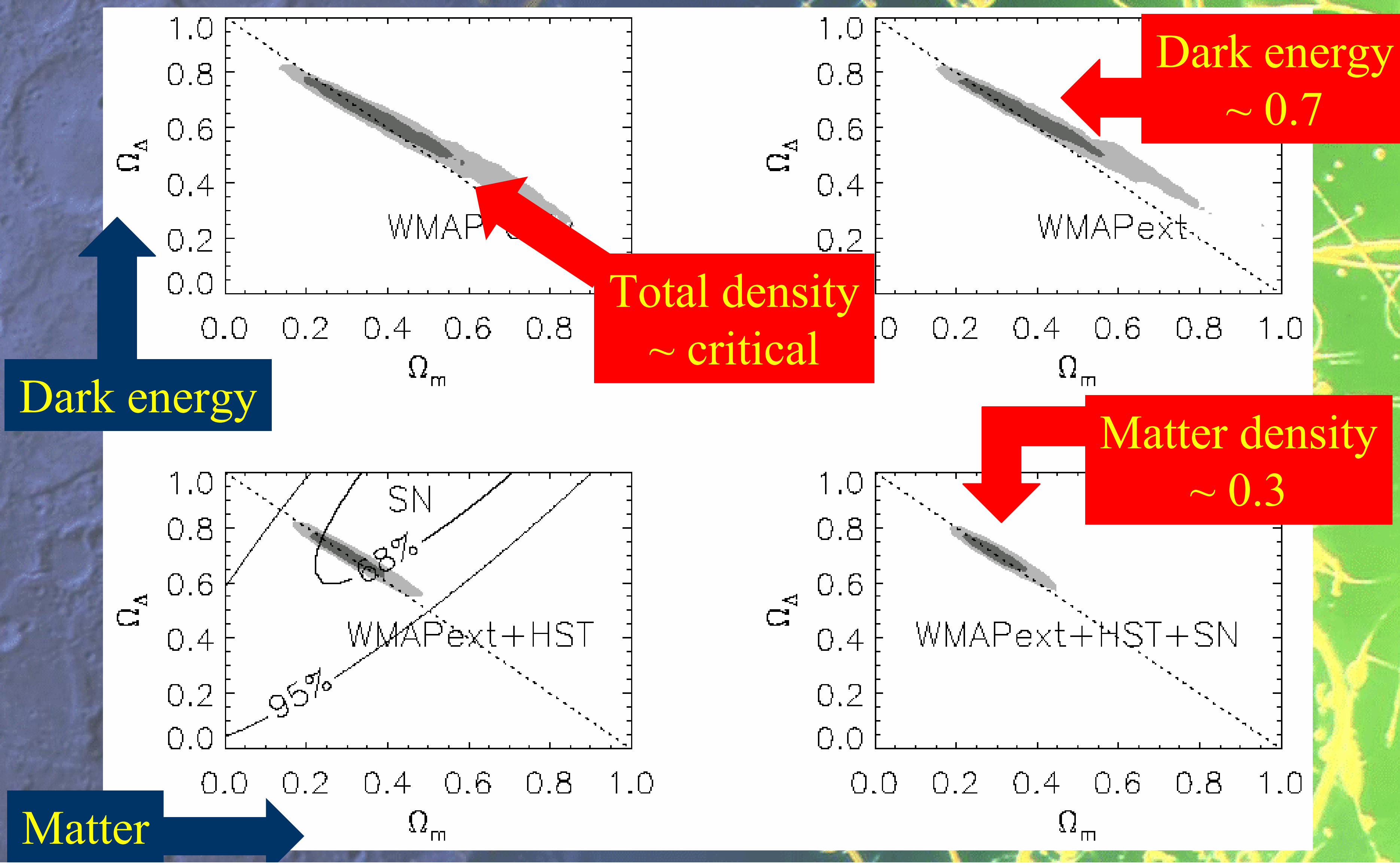
Combining different frequencies

The CMB Power Spectrum

Location of first peak depends on Ω_{Tot}



WMAP Constraints on Density



The Density Budget of the Universe

- Total density ~ critical

  Theory of inflation, measurements of microwave background: $\Omega_{Tot} = \sim 1$

- Baryon density small

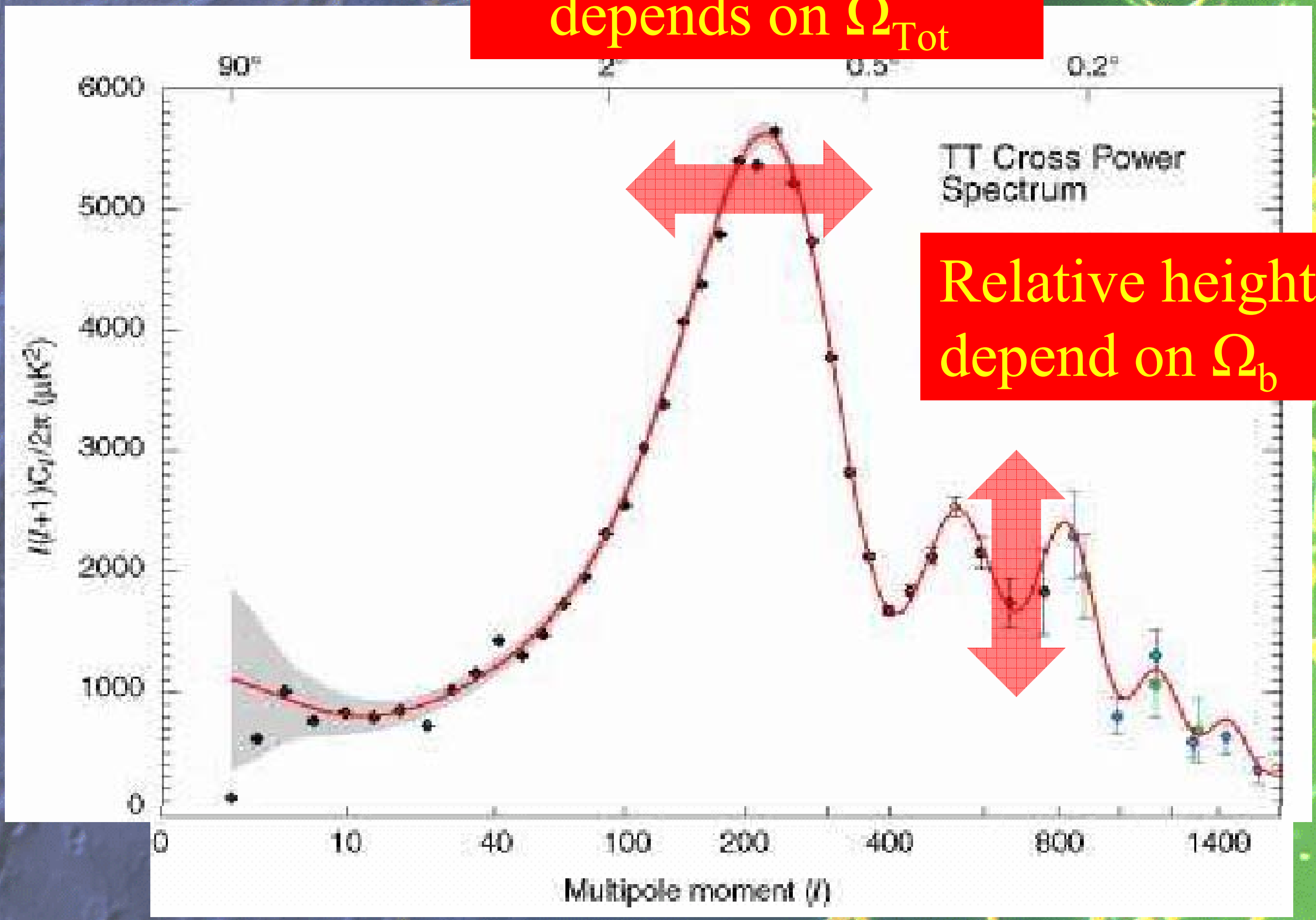
  Big-bang nucleosynthesis, CMB:

  $\Omega_{Baryons} \sim$ few %

The CMB Power Spectrum

Location of first peak depends on Ω_{Tot}

Relative heights depend on Ω_b



Abundances of light elements in the Universe

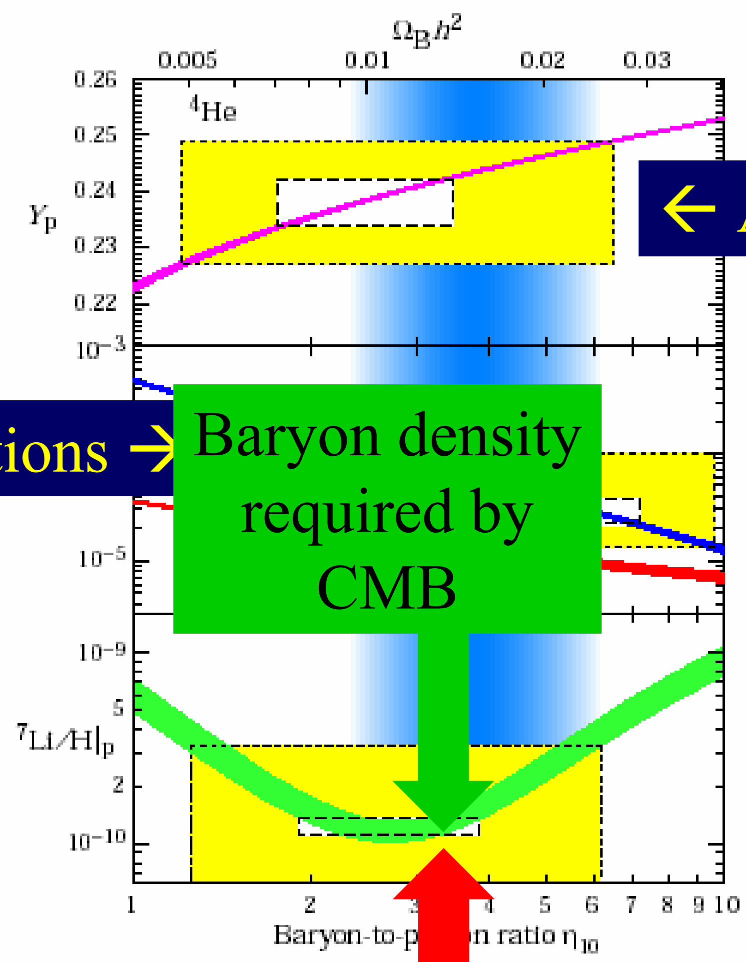
Helium

← Agree with data

Theoretical calculations →

Baryon density required by CMB

Total density required by CMB



Lithium

Not enough ordinary matter for critical density of the Universe

The Density Budget of the Universe

- Total density ~ critical

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  Big-bang nucleosynthesis, CMB:

  $\Omega_{Baryons} \sim$ few %
- Total matter density much larger

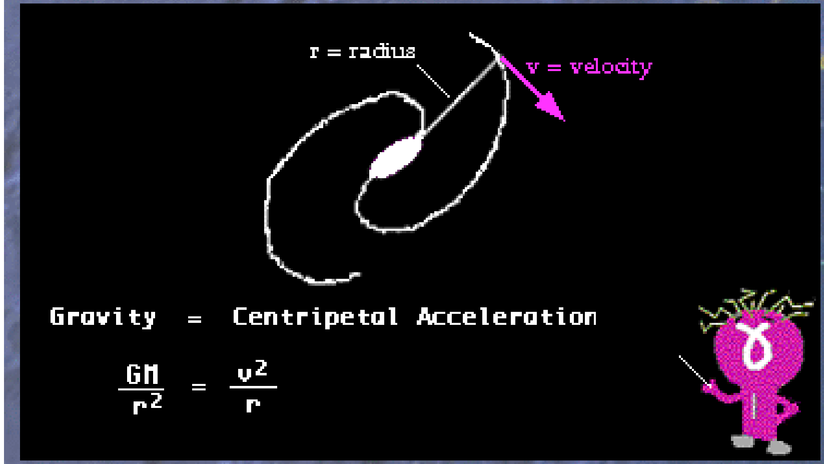
  Clusters of galaxies:

  $\Omega_{Matter} \sim 25$ %
- Mainly cold dark matter

  Enables structure formation

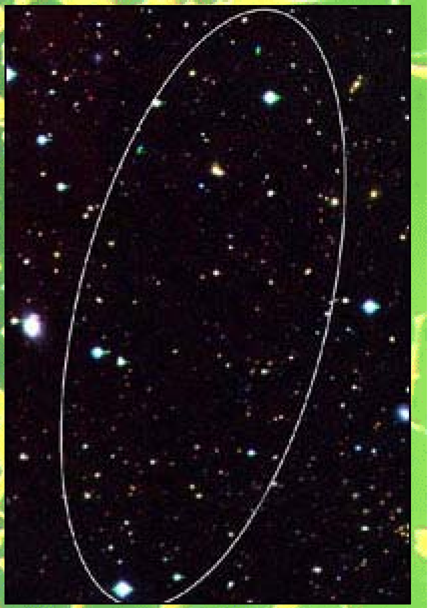
Evidence for Dark Matter

Galaxies rotate more rapidly than allowed by centripetal force due to visible matter



X-ray emitting gas held in place by extra dark matter

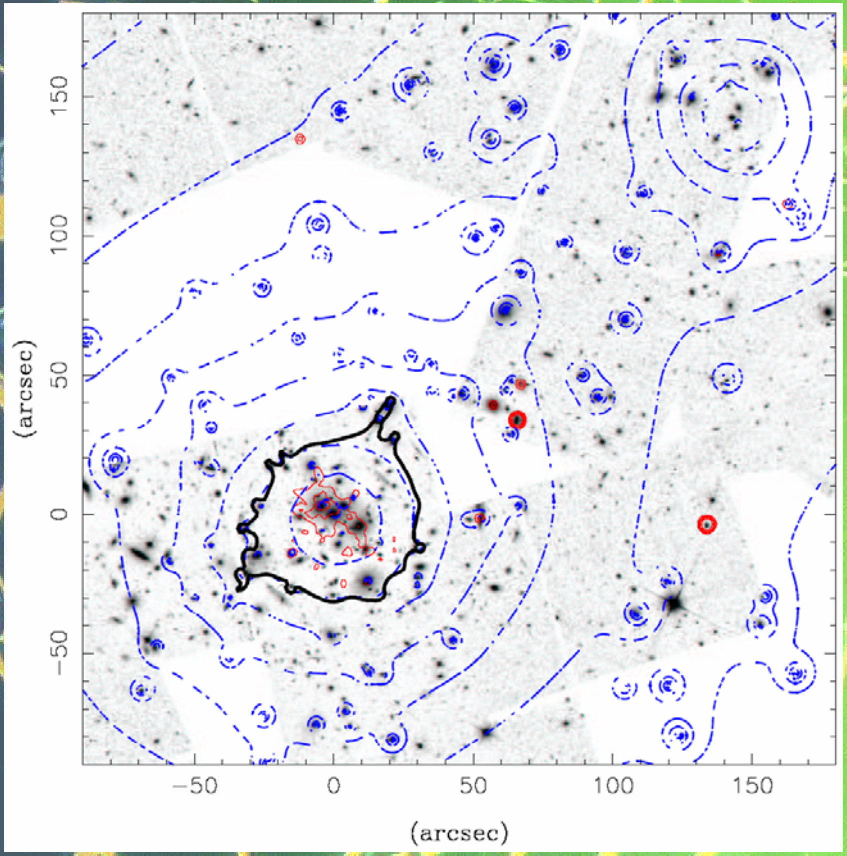
Even a 'dark galaxy' without stars



Evidence for Dark Matter from Gravitational Lensing

Light bent by gravitational field of dark matter

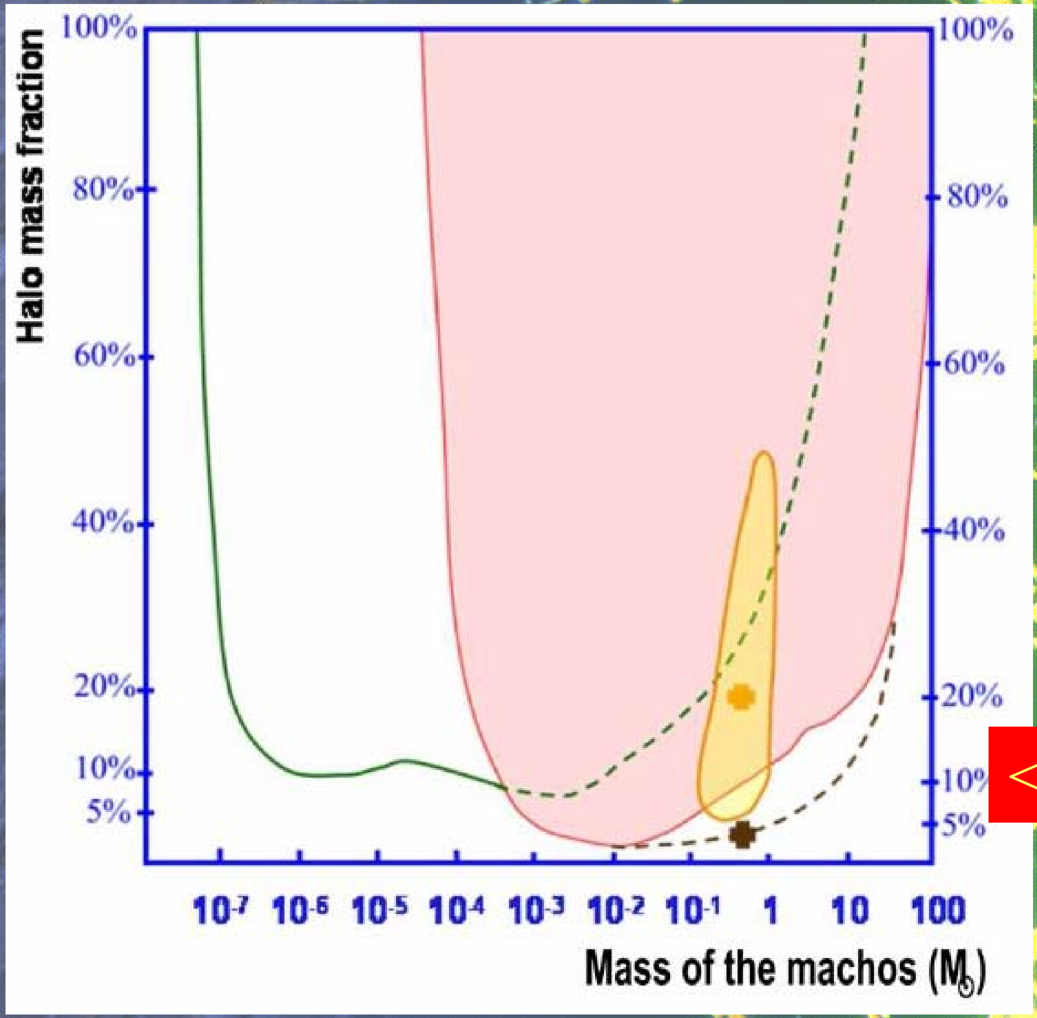
Contours of mass density



Could our galactic halo be ordinary matter?

Our Halo is not made of Machos

= MAssive
Compact
Halo
Objects
= dead stars
or black holes

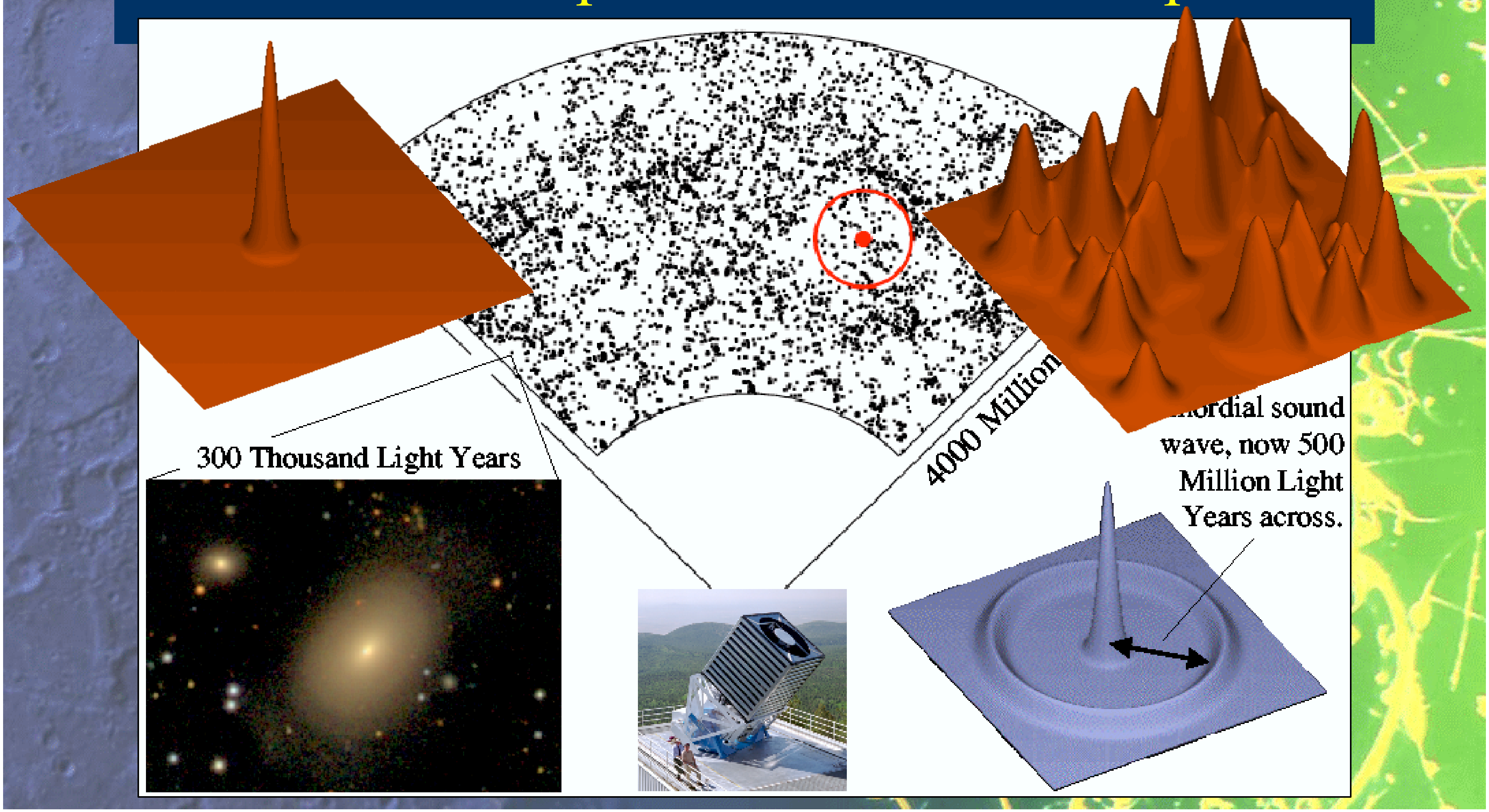


< 10 % of our halo

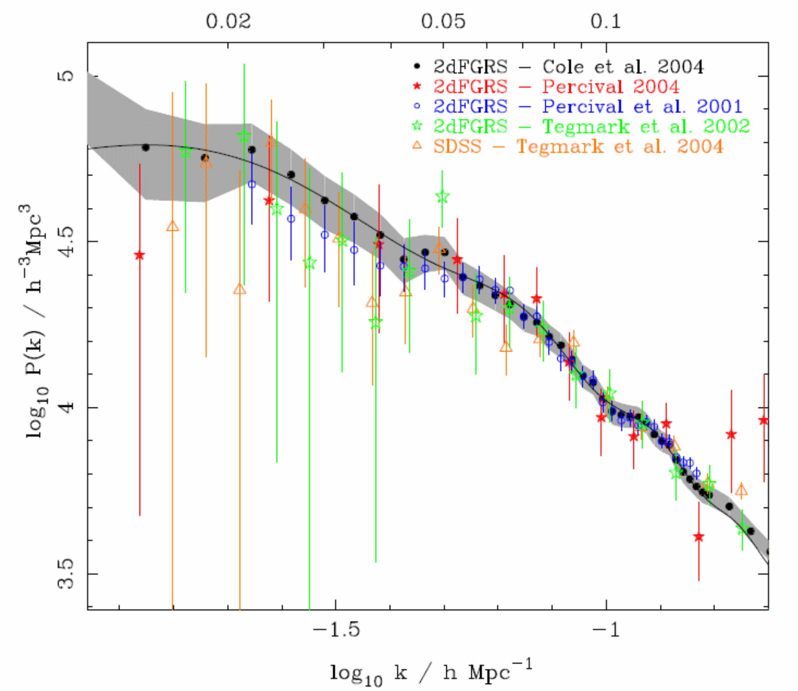
Confirmation

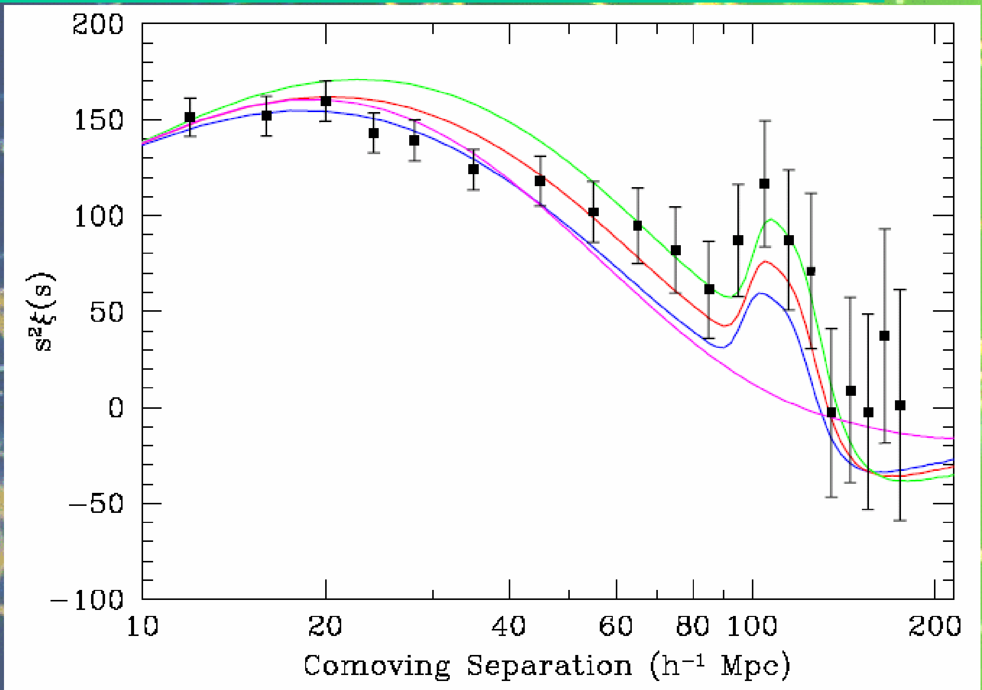
Baryonic Ripples from the Big Bang

- Sound waves spread from CMB bumps:



Observations of Baryonic Ripples





JOINT CONSTRAINTS ON COSMOLOGICAL PARAMETERS INCLUDING CMB DATA

Parameter	Constant w flat WMAP+Main	Constant w flat +LRG	$w=-1$ curved WMAP+Main	$w=-1$ curved +LRG	$w=-1$ flat WMAP+Main	$w=-1$ flat +LRG
w	-0.92 ± 0.30	-0.80 ± 0.18	...	...	...	...
Ω_K	...	...	-0.045 ± 0.032	-0.010 ± 0.009	...	...
$\Omega_m h^2$	0.145 ± 0.014	0.135 ± 0.008	0.134 ± 0.012	0.136 ± 0.008	0.146 ± 0.009	0.142 ± 0.005
Ω_m	0.329 ± 0.074	0.326 ± 0.037	0.431 ± 0.096	0.306 ± 0.027	0.305 ± 0.042	0.298 ± 0.025
h	0.679 ± 0.100	0.648 ± 0.045	0.569 ± 0.082	0.669 ± 0.028	0.696 ± 0.033	0.692 ± 0.021
n	0.984 ± 0.033	0.983 ± 0.035	0.964 ± 0.032	0.973 ± 0.030	0.980 ± 0.031	0.963 ± 0.022

Confirm Cold Dark Matter: constrain parameters

The Density Budget of the Universe

- Total density ~ critical

  Theory of inflation, measurements of CMB:

  $\Omega_{Tot} = \sim 1$
- Baryon density small

  Big-bang nucleosynthesis, CMB:

  $\Omega_{Baryons} \sim$ few %
- Total matter density much larger

  Clusters of galaxies:

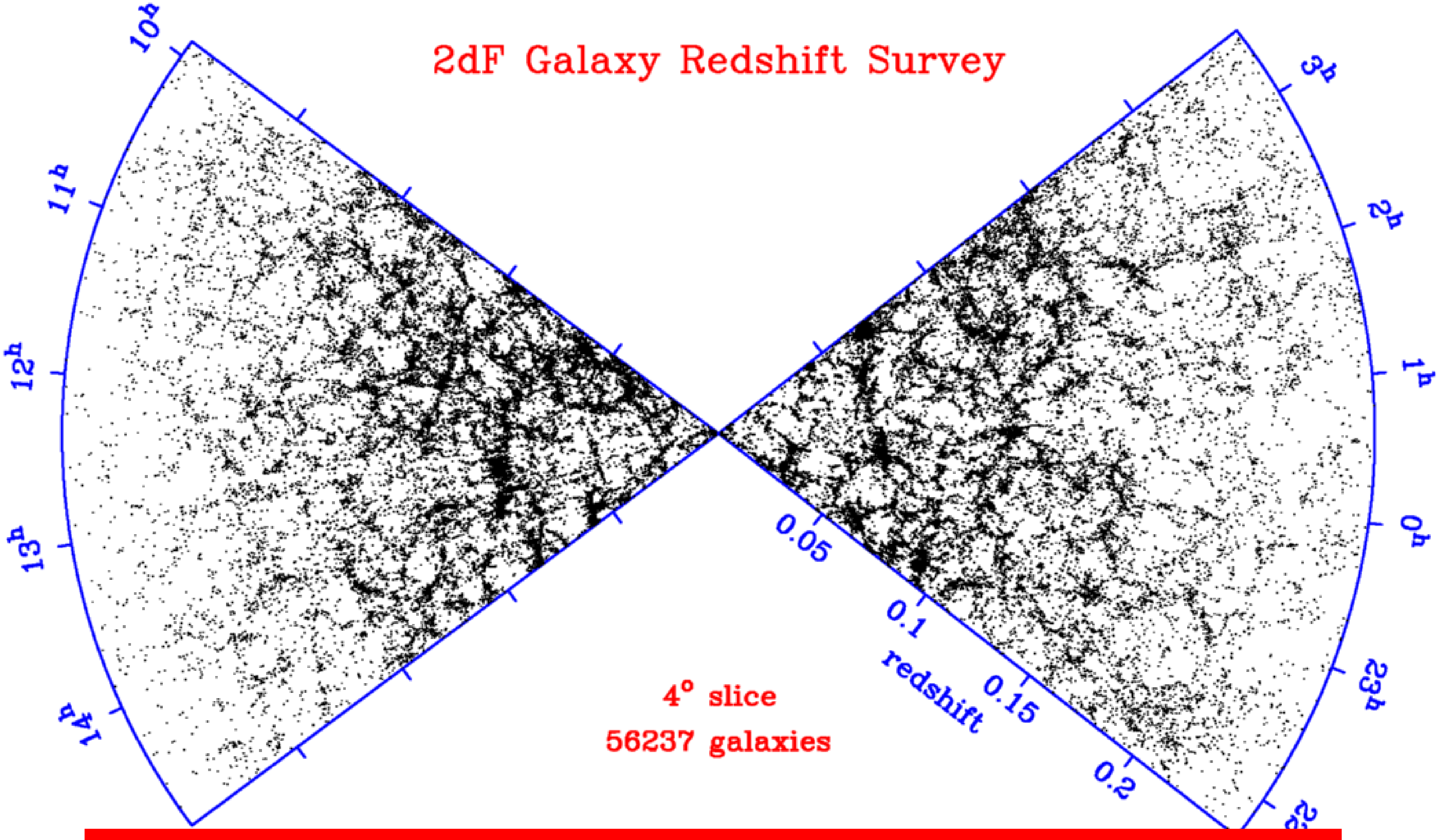
  $\Omega_{Matter} \sim 25$ %
- Mainly cold dark matter

  Enables structure formation

Formation of Structures in Universe

- Develop from CMB fluctuations
- Need amplification
- Possible with massive weakly-interacting particles
- Light neutrinos escape from smaller structures → disfavoured
- Prefer non-relativistic ‘cold dark matter’

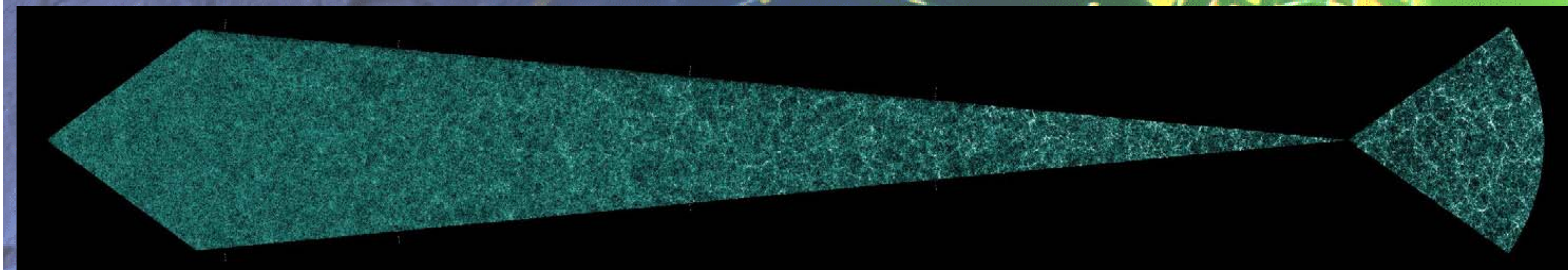
Structures observed in the Universe



Galaxies → Clusters → smooth at largest scales

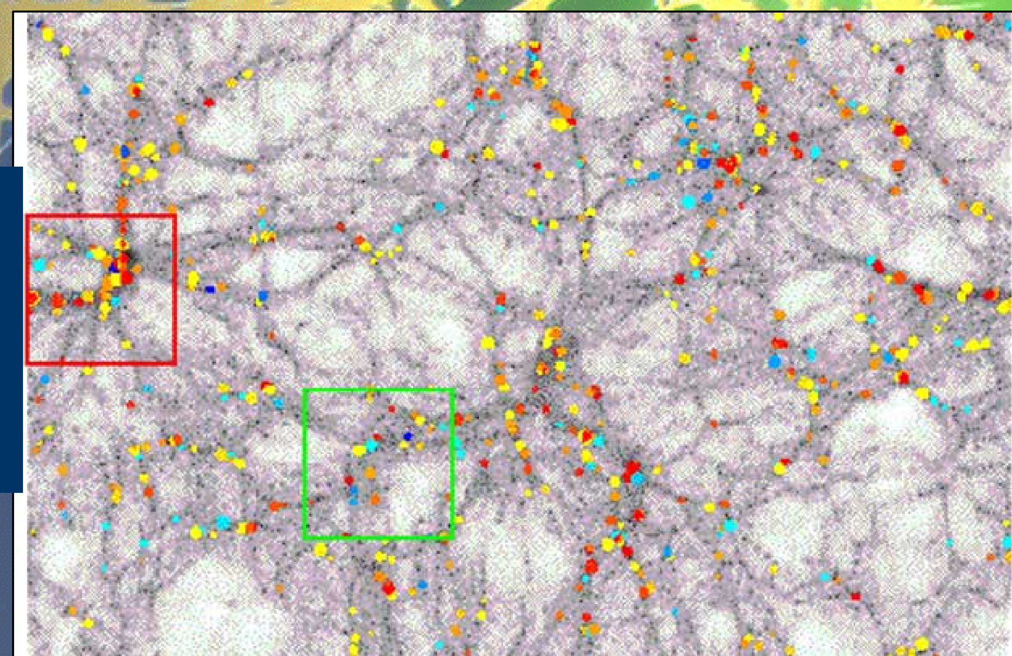
Simulation of Dark Matter

Initially quite homogeneous: gravity → structures form → today



Simulation of present-day Universe:

- Filaments of dark matter,
- Clusters of galaxies at nodes



Structures in Universe vs Concordance Model

Flat Universe:

$\Omega_{Tot} = 1$,

Cold dark matter:

$\Omega_{CDM} \sim 0.25$,

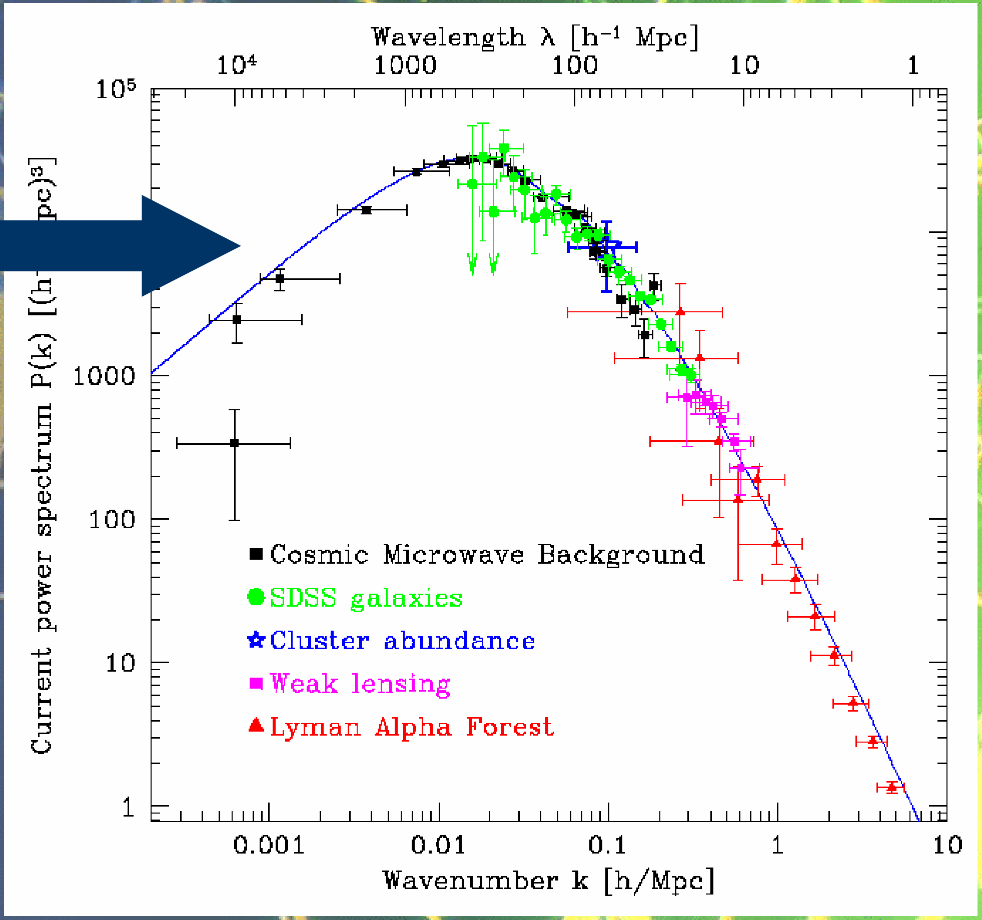
No hot dark matter,

Few baryons:

$\Omega_b \sim 0.05$,

Dark energy:

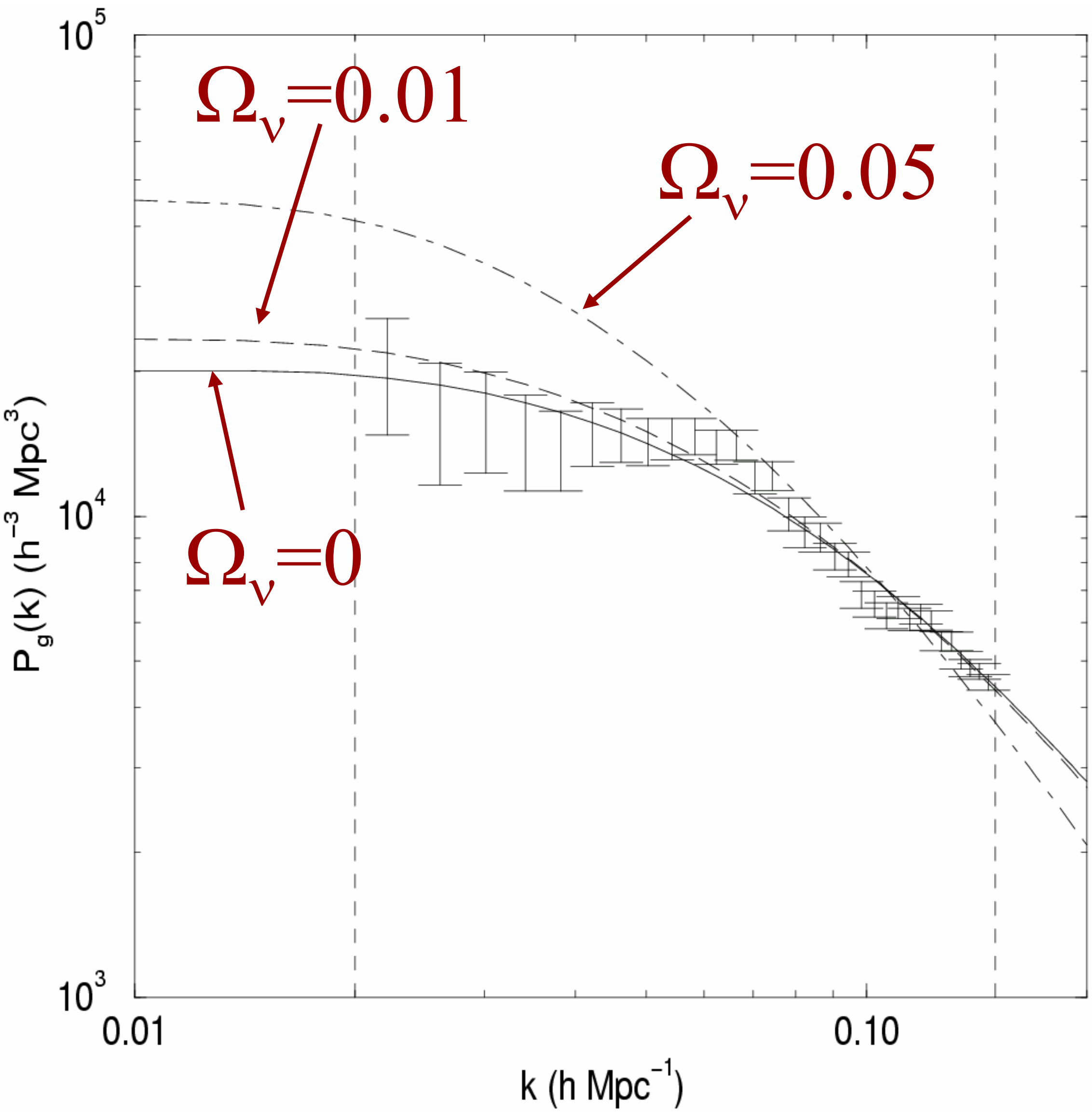
$\Omega_\Lambda \sim 0.7$



Do Neutrinos matter?

- Have very small masses
  - but non-zero – oscillation experiments
- Might make up some of dark matter
  - less than 10%?
- And would escape from galaxies
  - moving relativistically
- Also heavier neutrinos?
  - but unstable: generate matter via Sakharov?
- Need heavier stable dark matter particles
  - supersymmetric particles?

Not much neutrino mass density

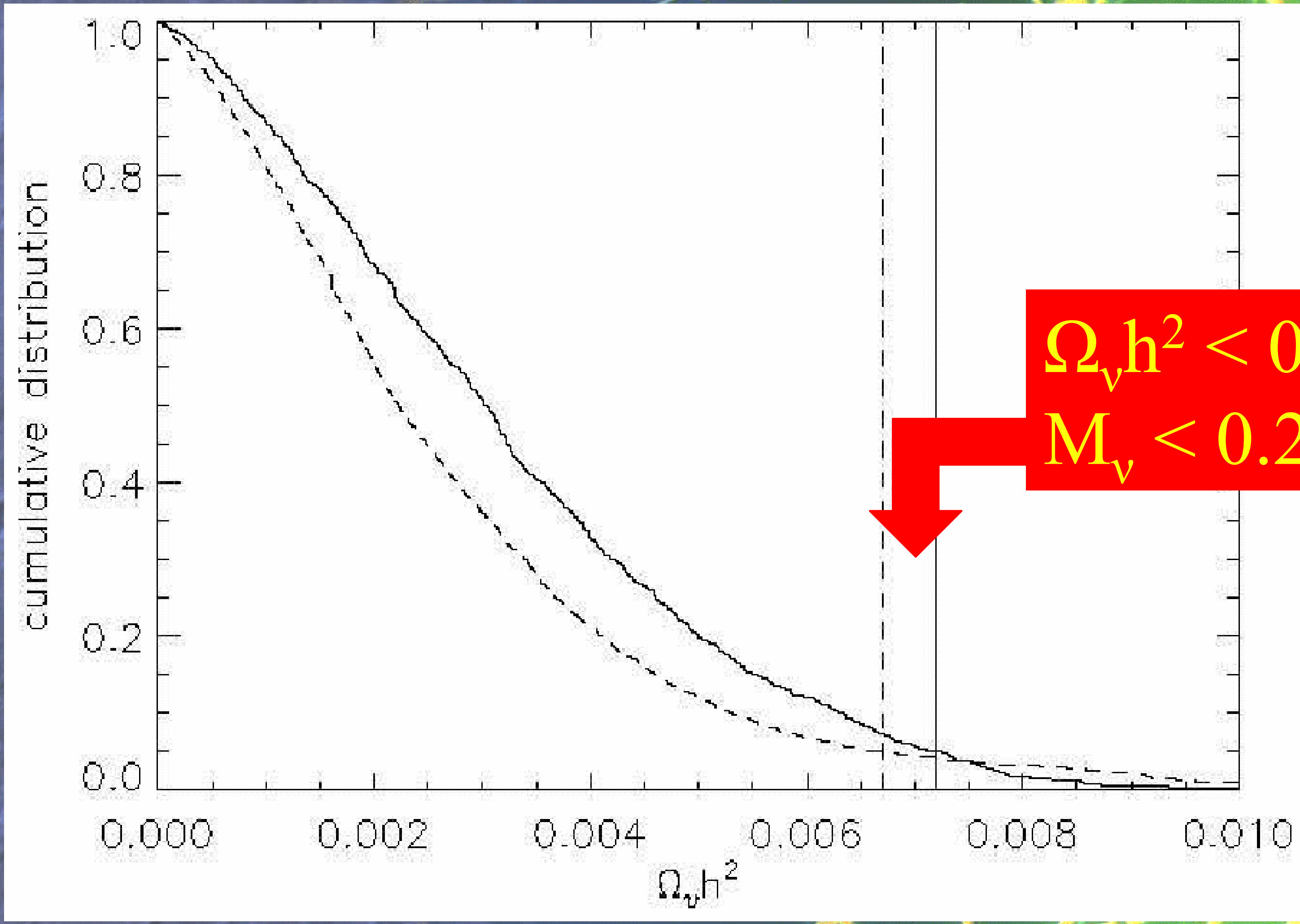


2dF team: astro-ph/0204152

Data on large-scale structures

According to WMAP et al …

Not much Hot (Neutrino) Dark Matter



$\Omega_\nu h^2 < 0.007$

$M_\nu < 0.23$ eV

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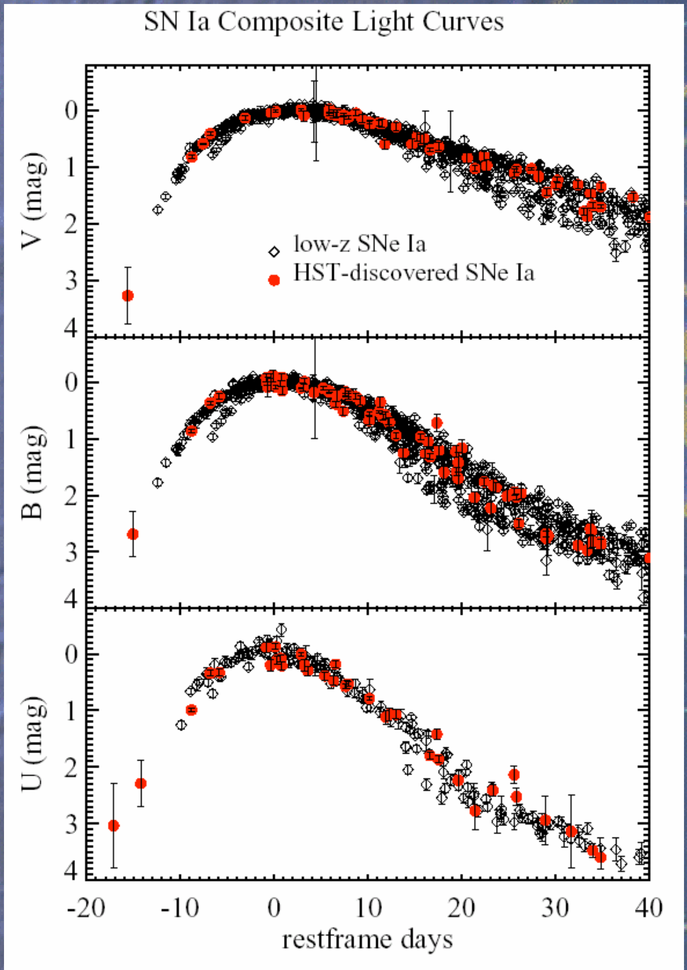
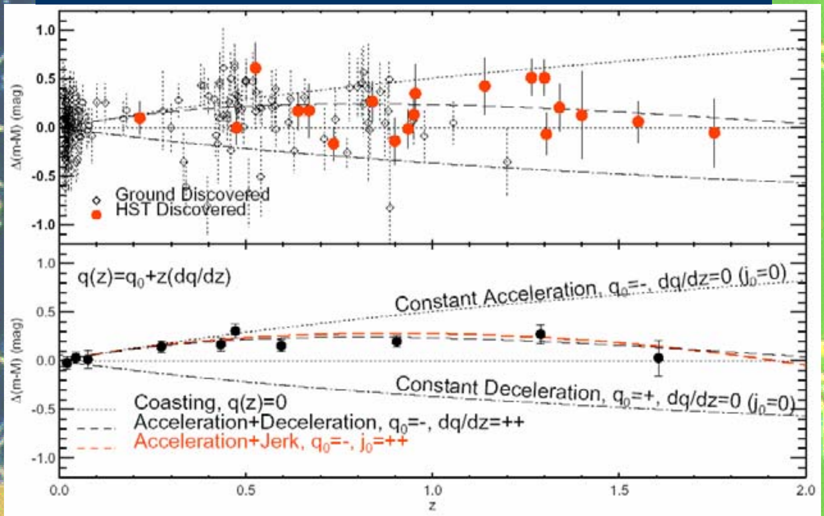
- Baryon density small
  - Big-bang nucleosynthesis, CMB: $\Omega_{Baryons} \sim$ few %
- Total matter density much larger
  - Clusters of galaxies: $\Omega_{Matter} \sim 25\ \%$
- Mainly cold dark matter
  - Enable structure formation
- Most of density is dark energy

Direct evidence for dark energy

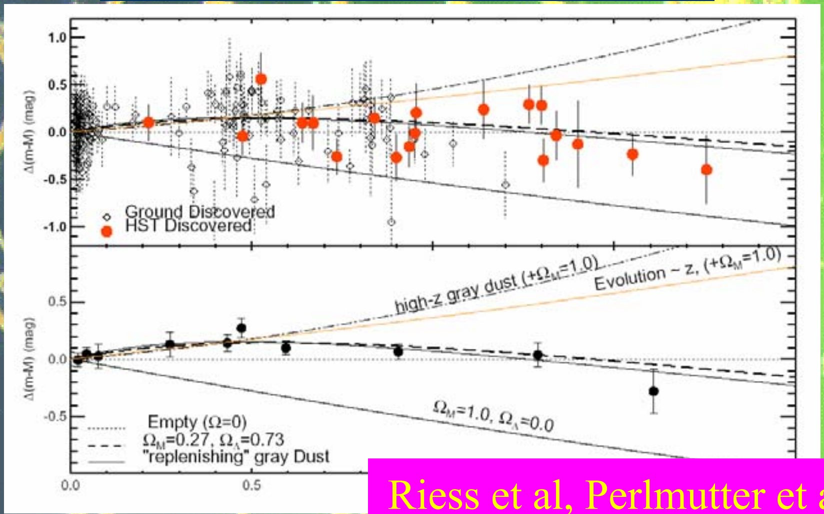
High-redshift supernovae are standard candles



Universe now accelerating, previously decelerating



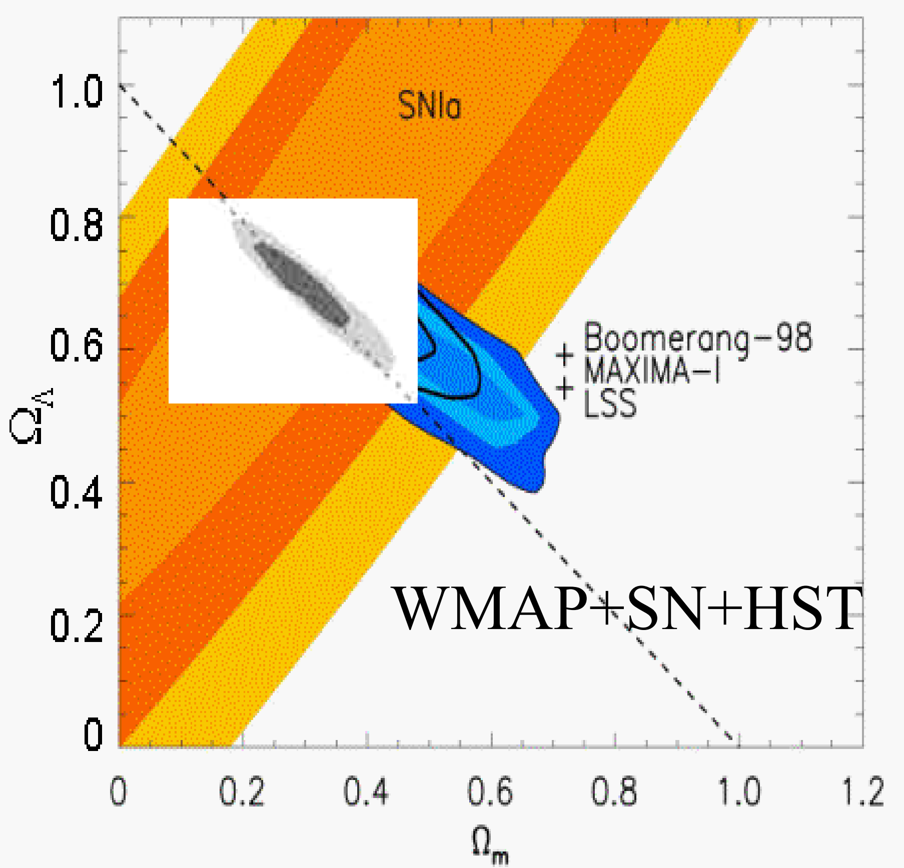
not dust, not evolution



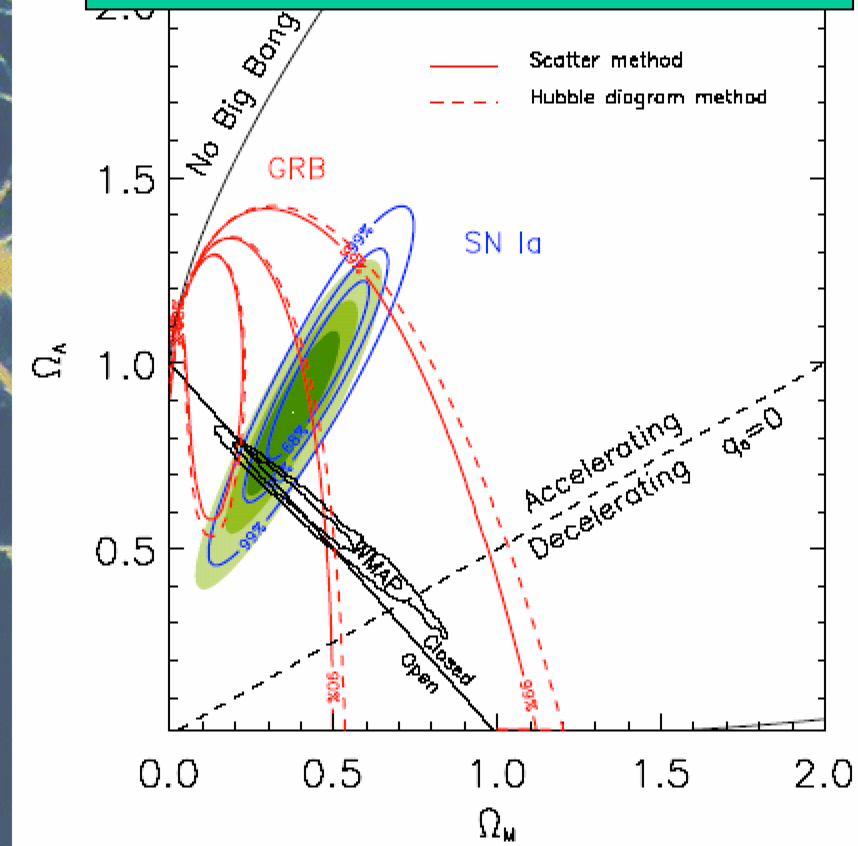
Riess et al, Perlmutter et al

Concordance Cosmological Model

WMAP, Supernovae, Large-scale structures …

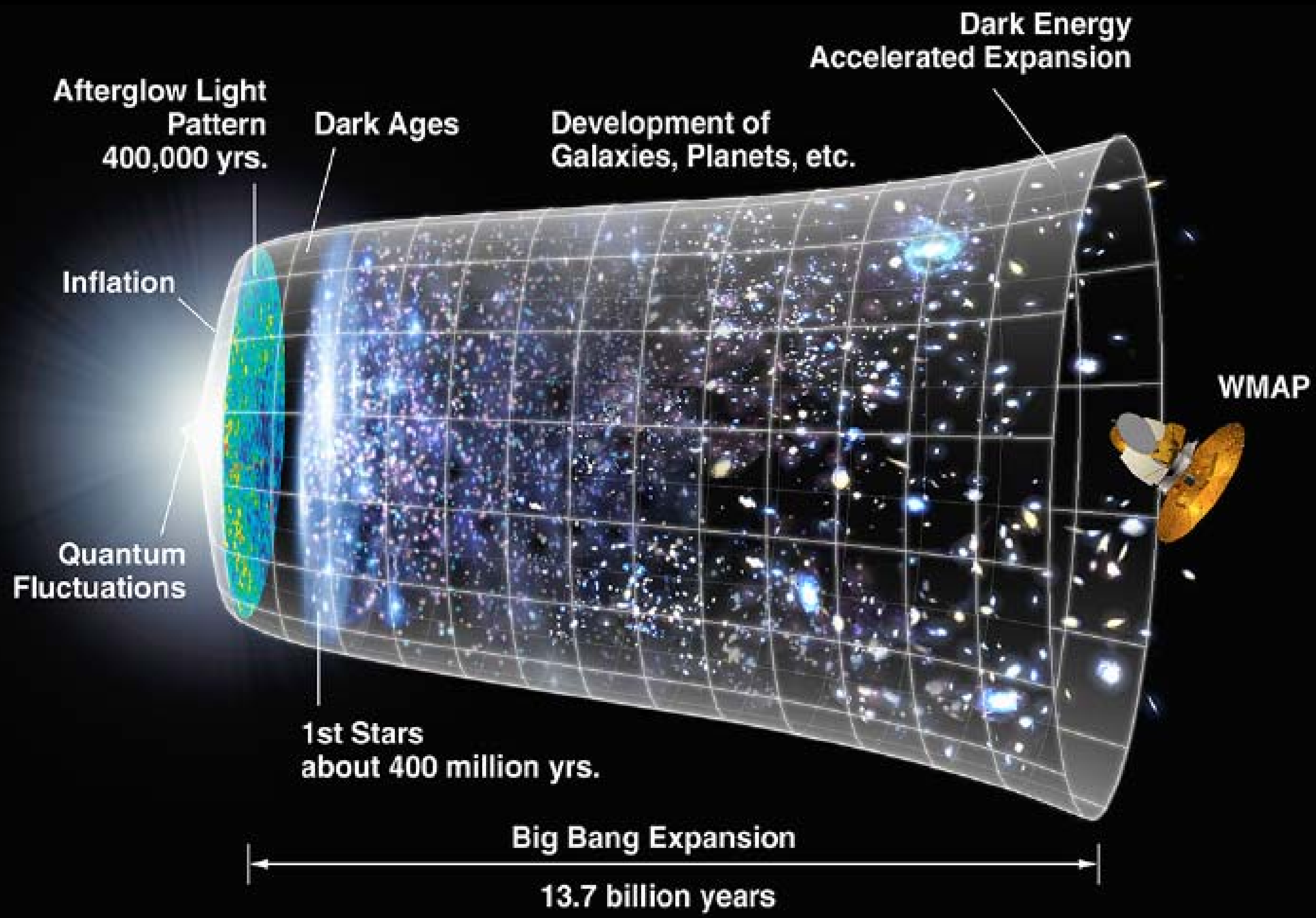


… and gamma-ray bursters?



Barbiellini //, Ghirlanda et al

Introduction to Cosmology



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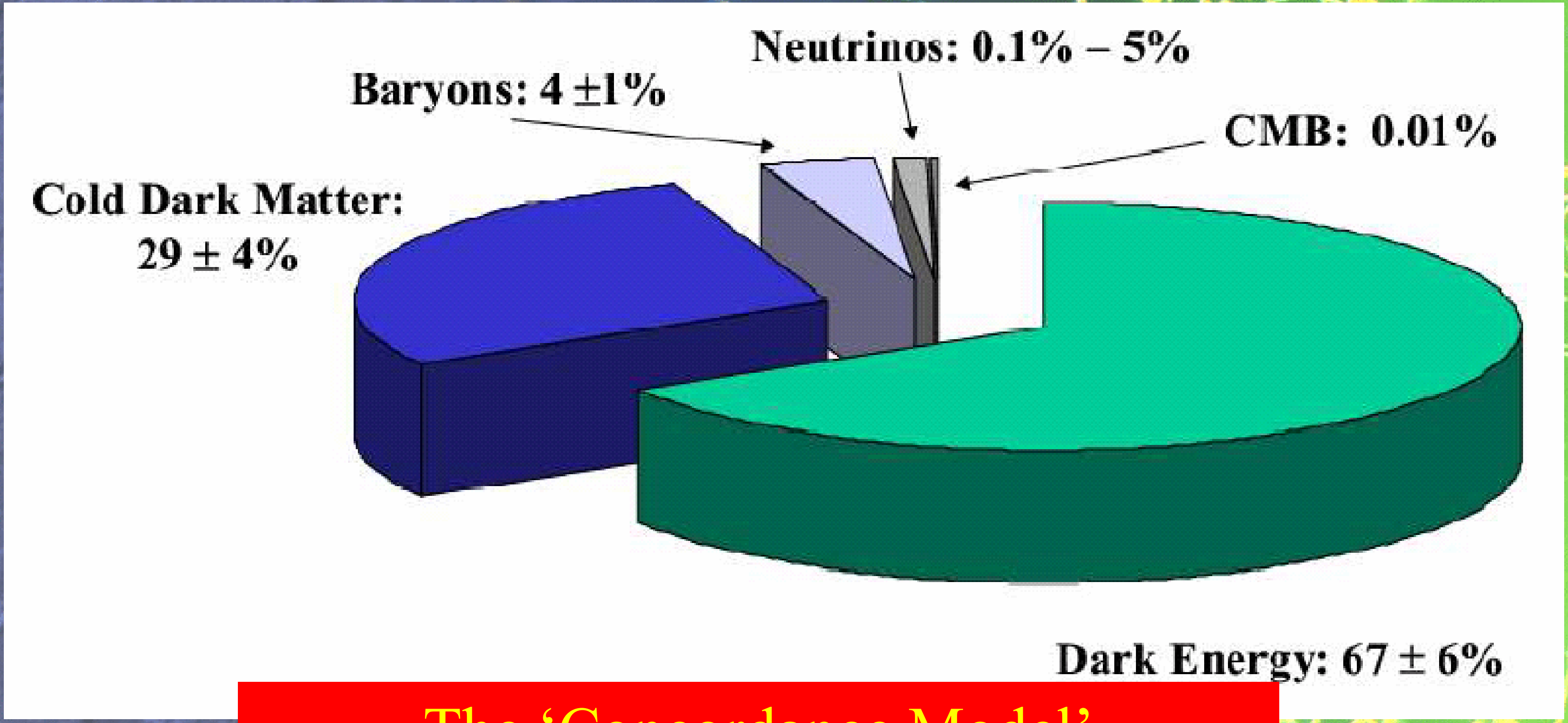
John Ellis

Links with particle physics

A Strange Recipe for a Universe



The 'Concordance Model'
prompted by astrophysics & cosmology

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  - Olbers' paradox, Hubble expansion, Cosmic microwave background radiation, Light elements
  - Importance of particle physics in early Universe
- The matter/energy content of the Universe
  - Few % ordinary matter, 25 % dark matter, 70 % dark energy
- Speculations
  - Possible information from the LHC
  - Very early Universe:
    - Dark matter, creating matter, cosmological inflation

Open Cosmological Questions

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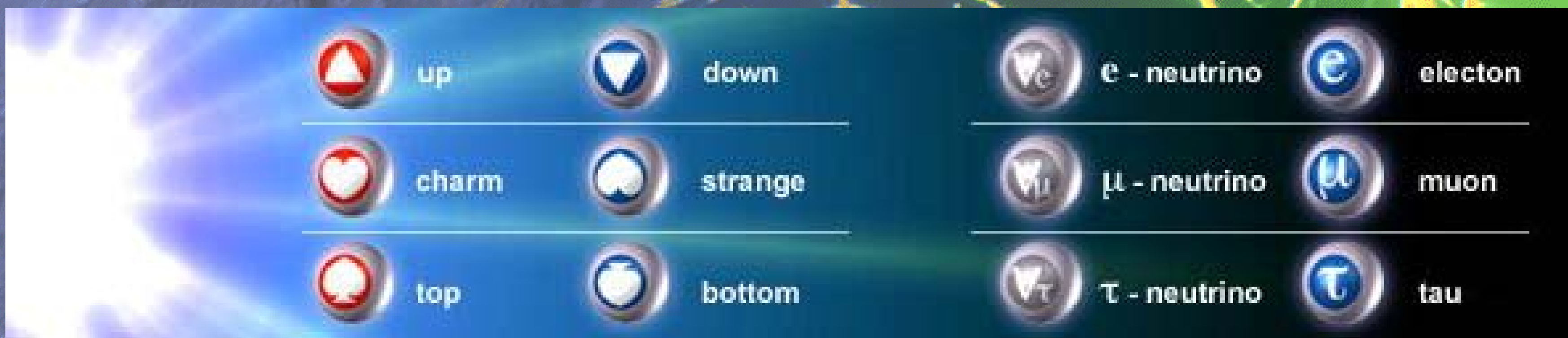
  - ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  - almost flat: density nearly critical
- Where did the matter come from?
  - 1 proton for every 1,000,000,000 photons
- How did structures form?
  - ripples + invisible dark matter?
- What is the dark matter?
- What is the dark energy?

Need particle physics to answer these questions

The'Standard Model'

= Cosmic DNA

The matter particles



The fundamental interactions

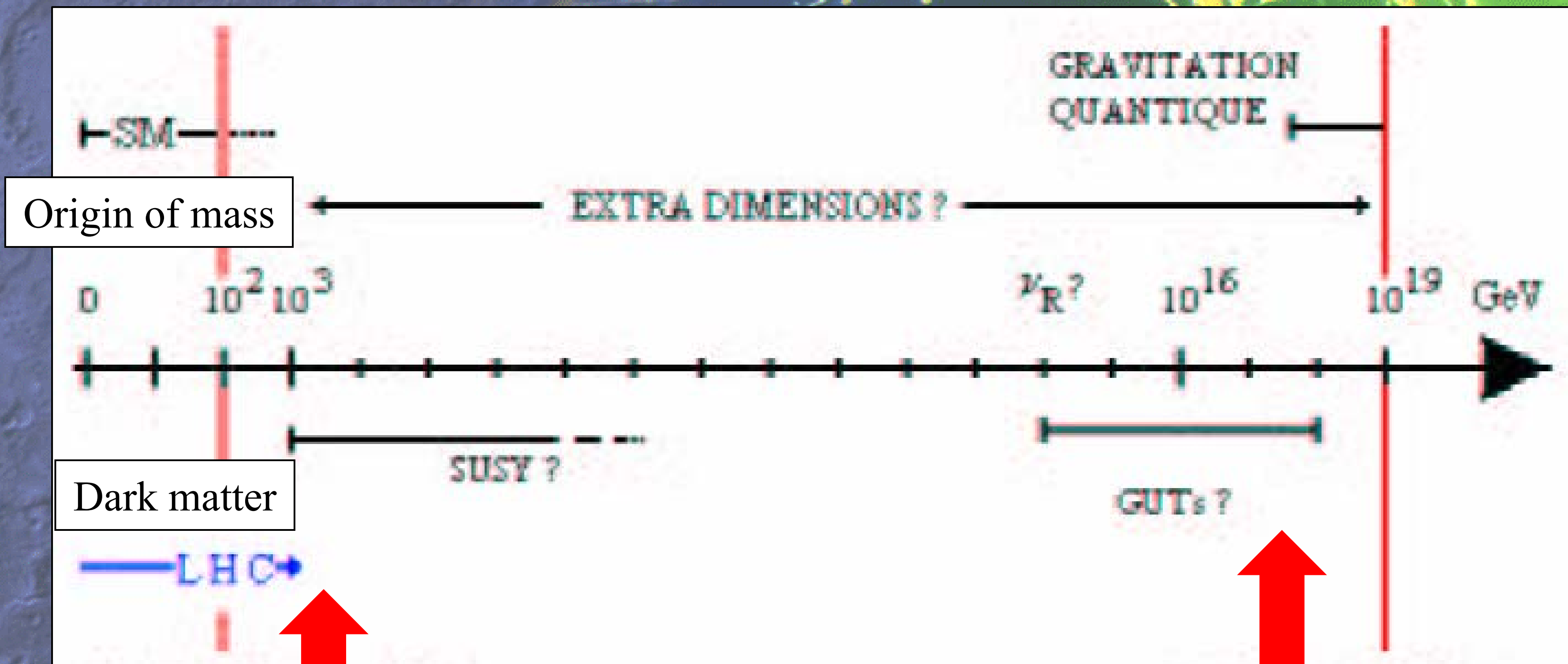
Gravitation electromagnetism weak nuclear force strong nuclear force

Open Questions beyond the Standard Model

- Why do particles have mass?
- Why so many types of matter particles?
- Are the fundamental forces unified?
- Quantum theory of gravity?

LHC

At what Energy is the New Physics?



A lot accessible directly to the LHC

Some accessible only indirectly: via cosmology?

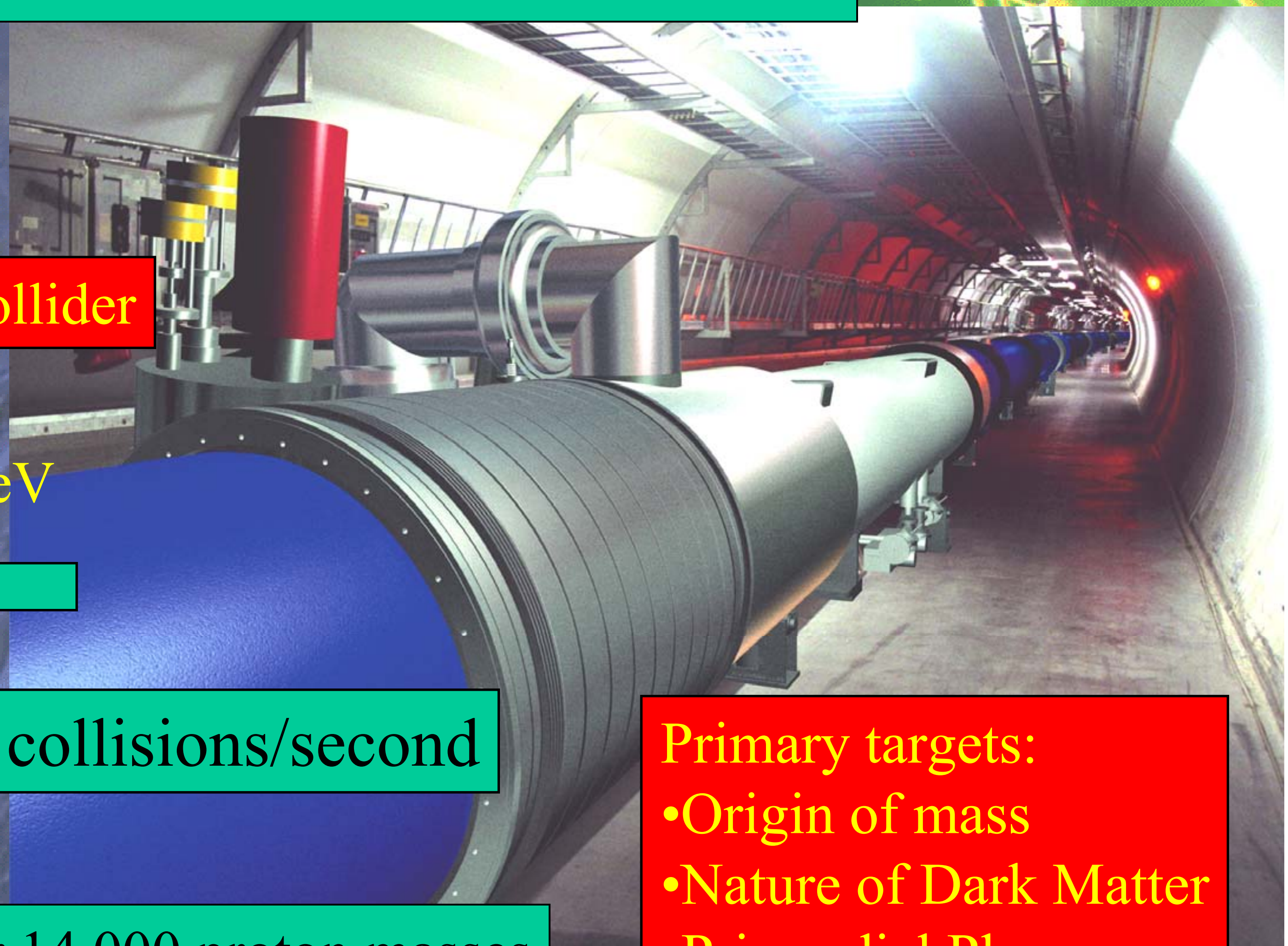
The Large Hadron Collider (LHC)

Proton- Proton Collider

7 TeV + 7 TeV

1,000,000,000 collisions/second

Total energy over 14,000 proton masses

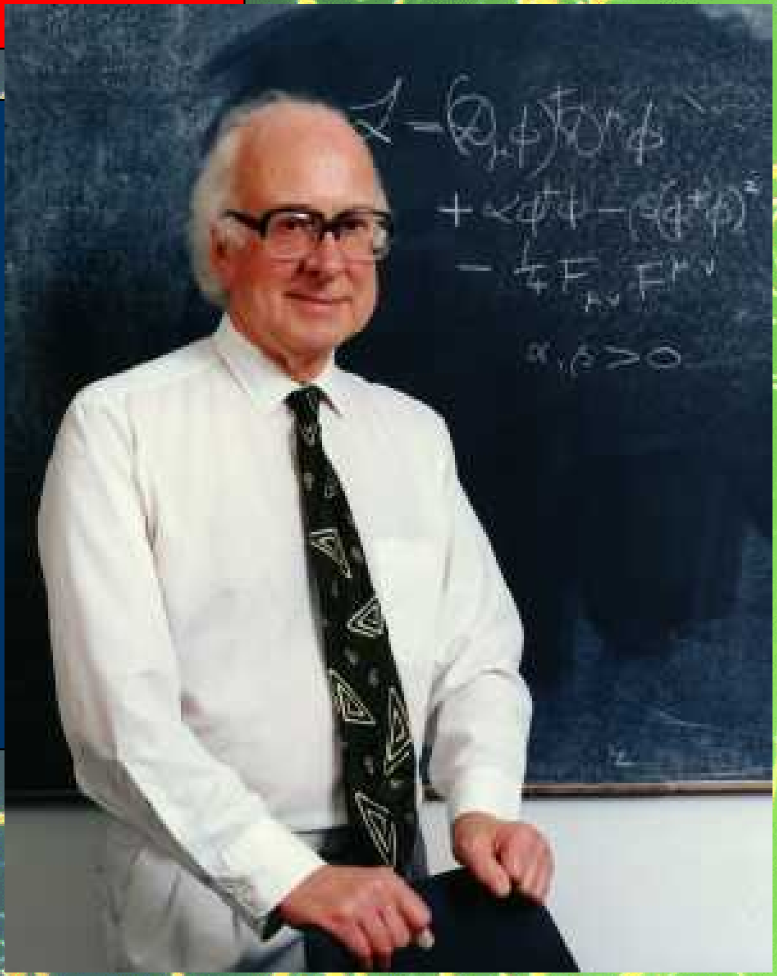


Primary targets:

- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

Some particles have mass, some do not

Where do the masses come from?



Newton:

Weight proportional to Mass

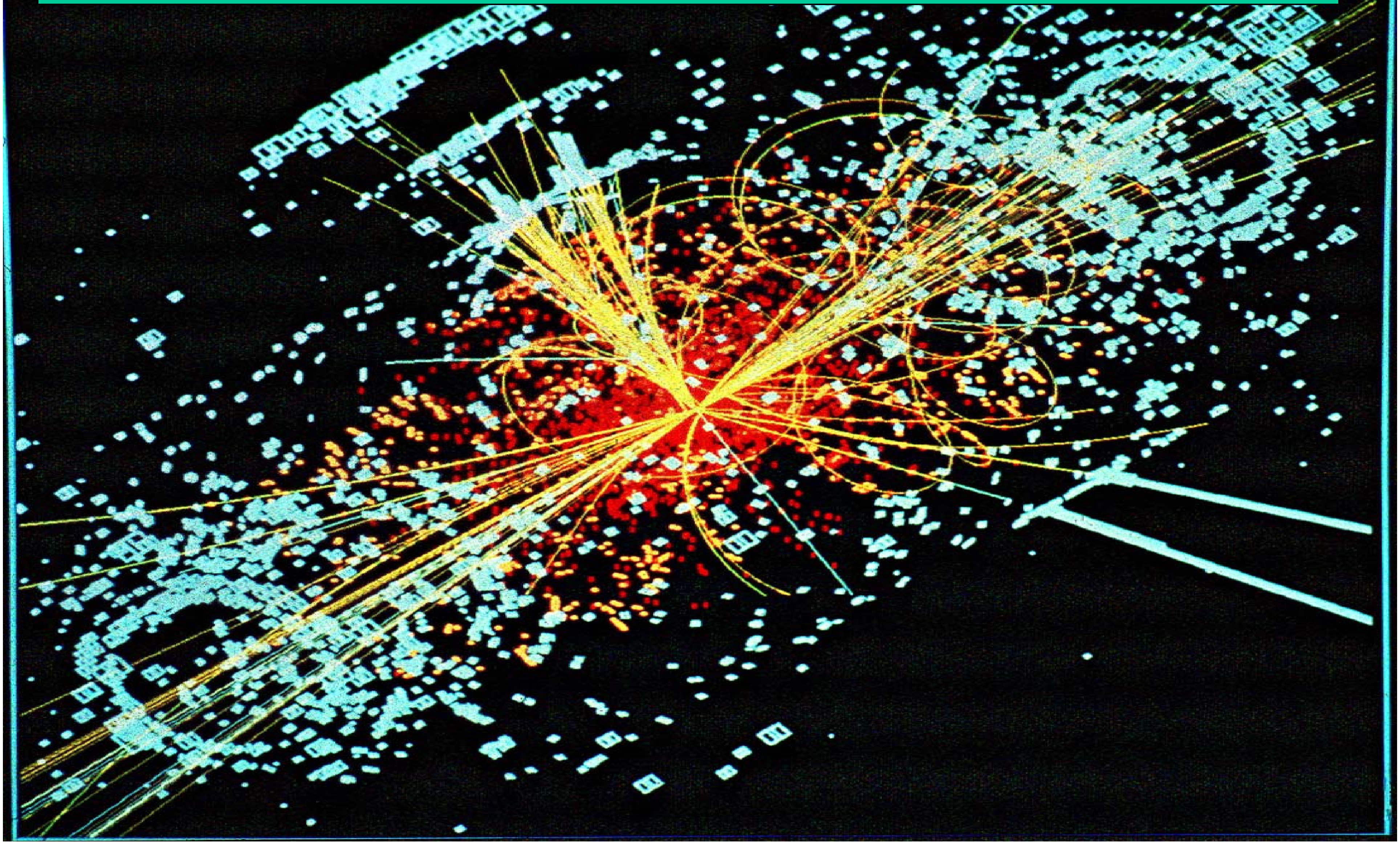
Einstein:

Energy related to Mass

Neither explained origin of Mass

Are masses due to Higgs boson?
(yet another particle)

A Simulated Higgs Event in CMS



The Higgs Boson and Cosmology

- Changed the state of the Universe when it was about 10^{-12} seconds old
- May have generated then the matter in the Universe: electroweak baryogenesis
- Contributes to today's dark energy
- A related inflaton might have expanded the Universe when it was about 10^{-35} seconds old

Open Cosmological Questions

- Why is the Universe so big and old?
  ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  almost flat: density nearly critical
- Where did the matter come from?
  1 proton for every 1,000,000,000 photons
- How did structures form?
  ripples + invisible dark matter?
- What is the dark matter?
- What is the dark energy?

Need particle physics to answer these questions

Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible

Dark Matter

‘Supersymmetric’ particles ?

We shall look for them with the LHC

‘Supersymmetric’ Dark Matter?

- Supersymmetry would relate

  fermionic ‘matter’ particles →

  bosonic ‘force’ particles
- Might help explain mass scale of particles
- Lightest supersymmetric particle stable?

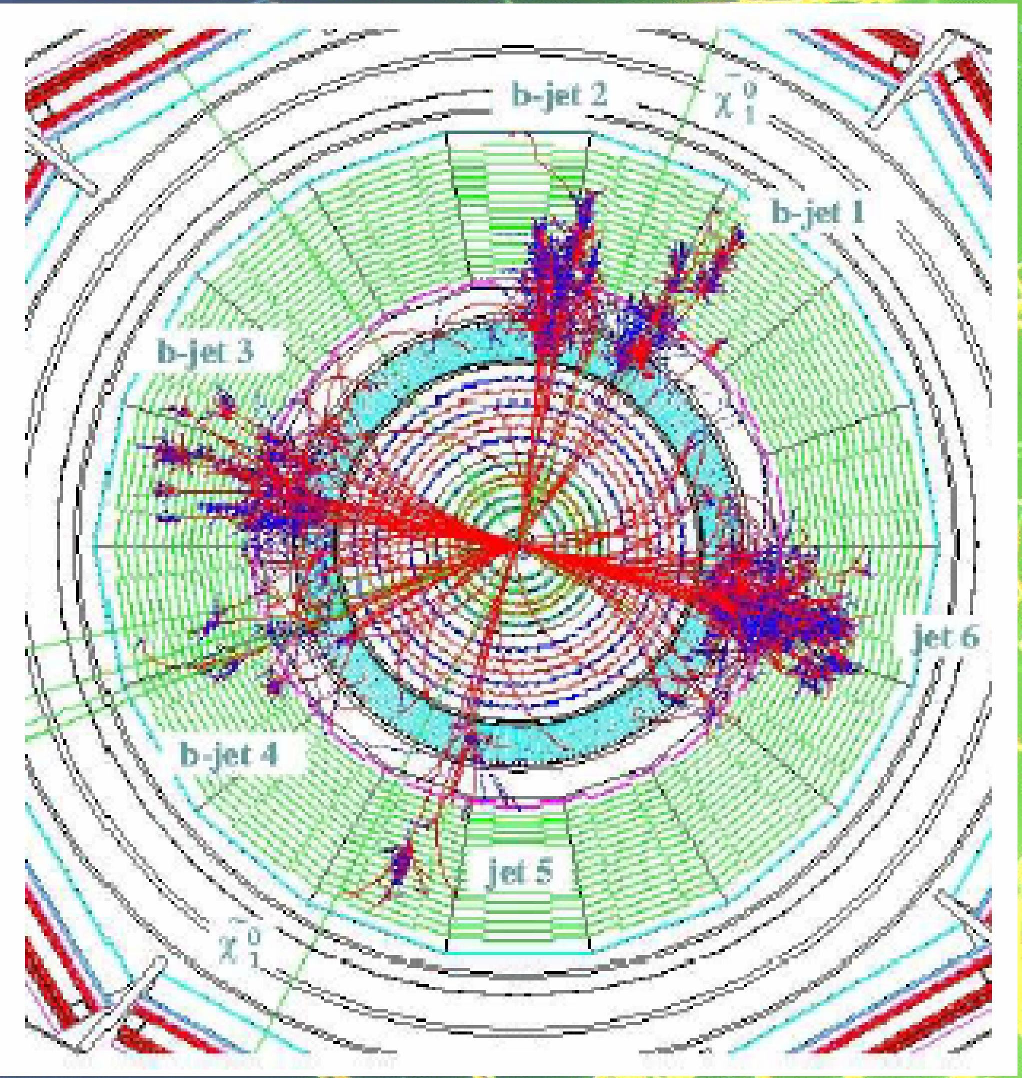
  should weigh below 1000 GeV
- Density similar to required cold dark matter

Directly laboratory searches, indirect astrophysical searches

Supersymmetry at the LHC

`Typical' supersymmetric Event at the LHC

Multiple jets, Electrons



Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?
- Annihilation in galactic centre

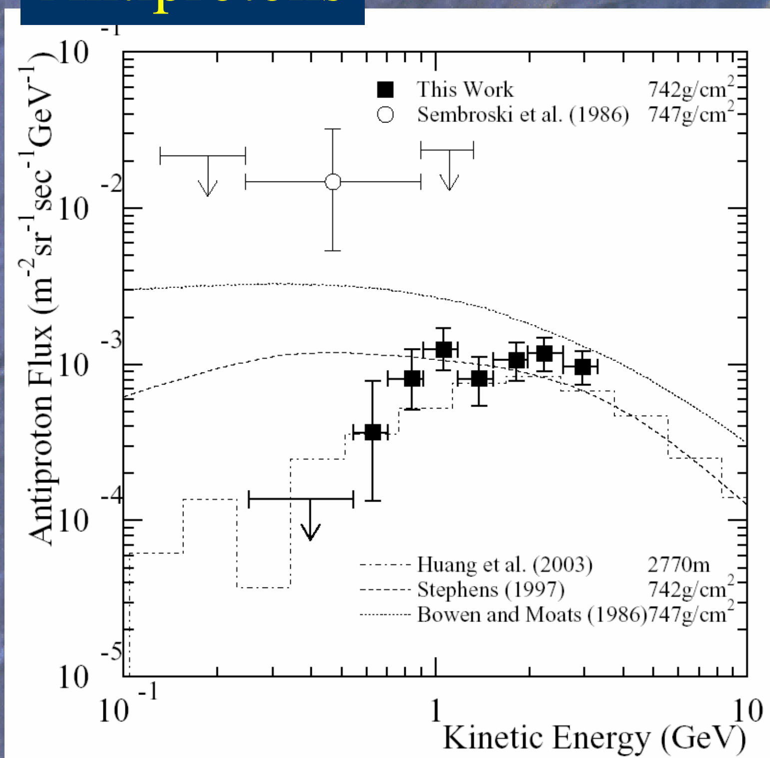
  $\chi - \chi \rightarrow \gamma + \ldots ?$
- Annihilation in core of Sun or Earth

  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$
- Scattering on nucleus in laboratory

  $\chi + A \rightarrow \chi + A$

Annihilation in Galactic Halo

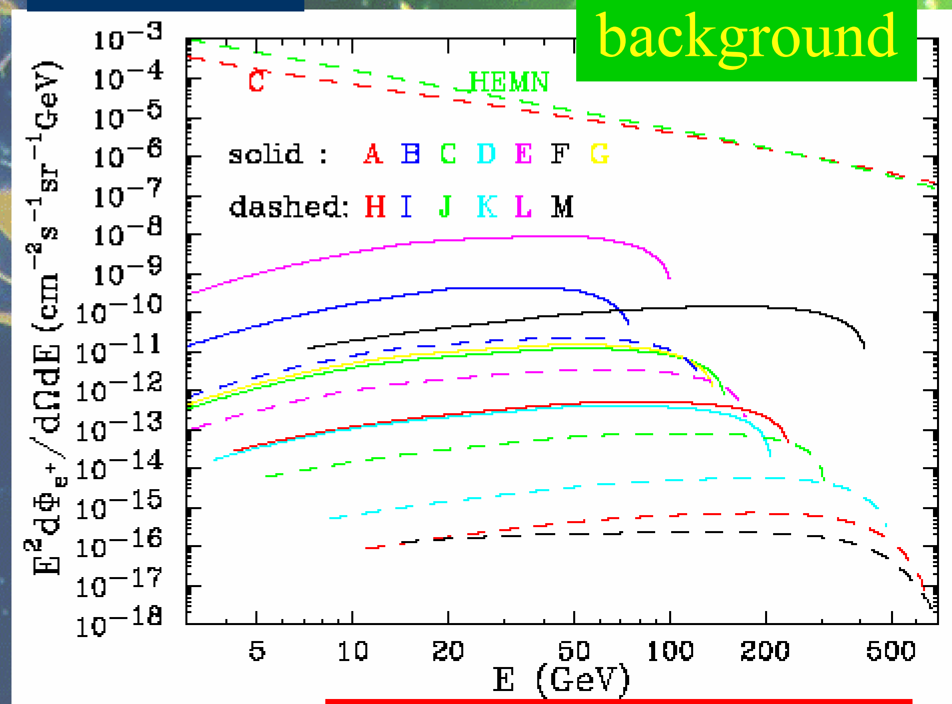
Antiprotons



Consistent with production by primary matter cosmic rays

Positrons

Cosmic-ray background

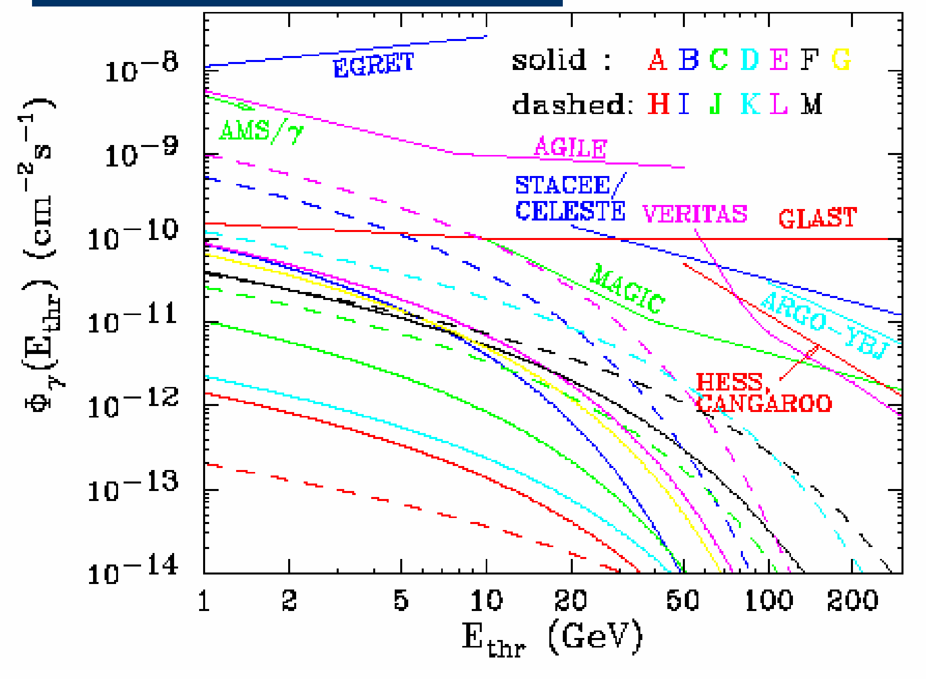


Benchmark scenarios

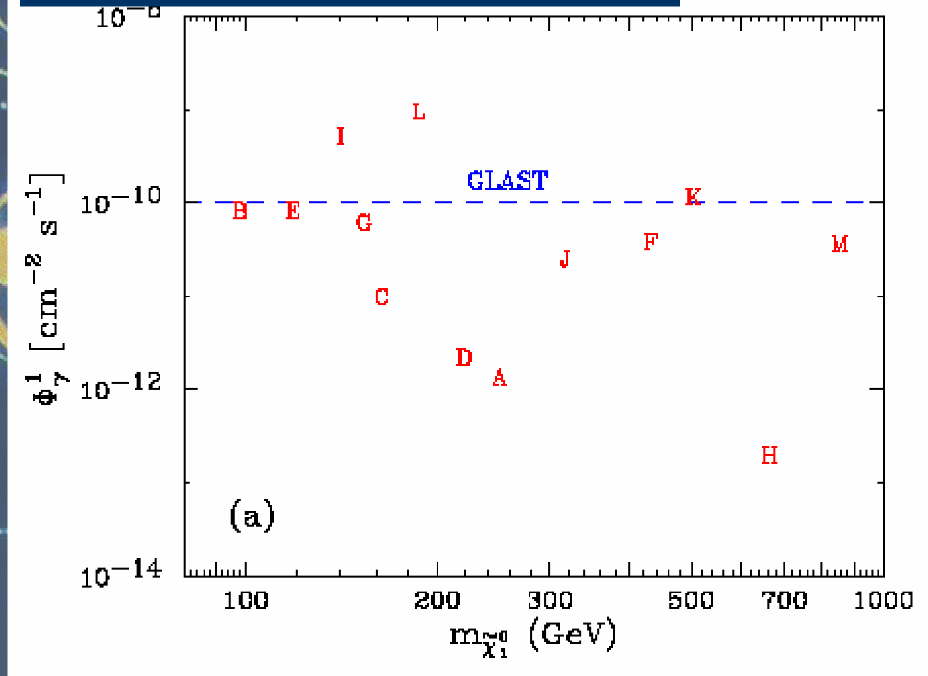
JE + Feng + Ferstl + Matchev + Olive

Annihilations in Galactic Centre

Benchmark spectra



Benchmarks → GLAST

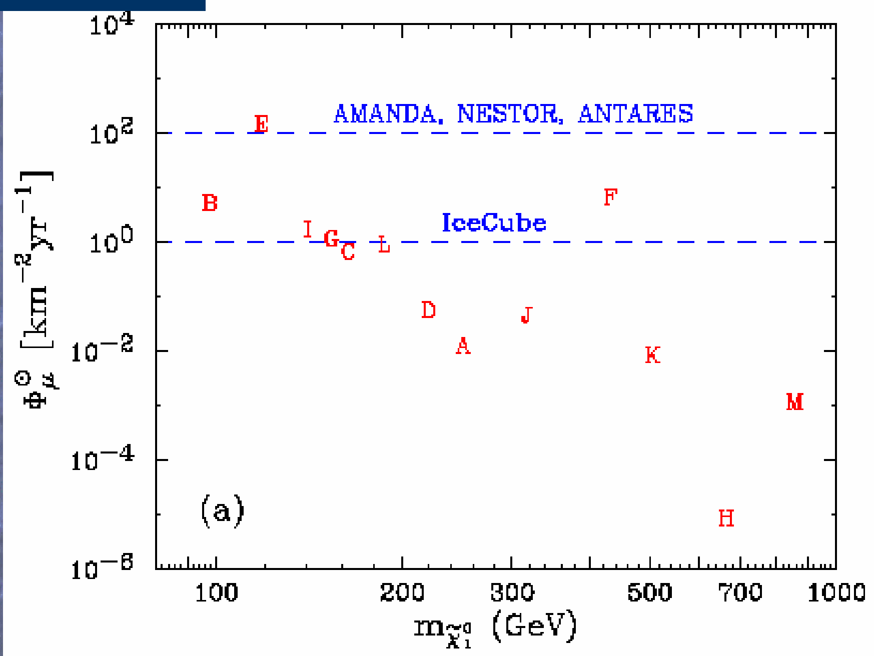


Enhancement of rate uncertain by factor > 100!

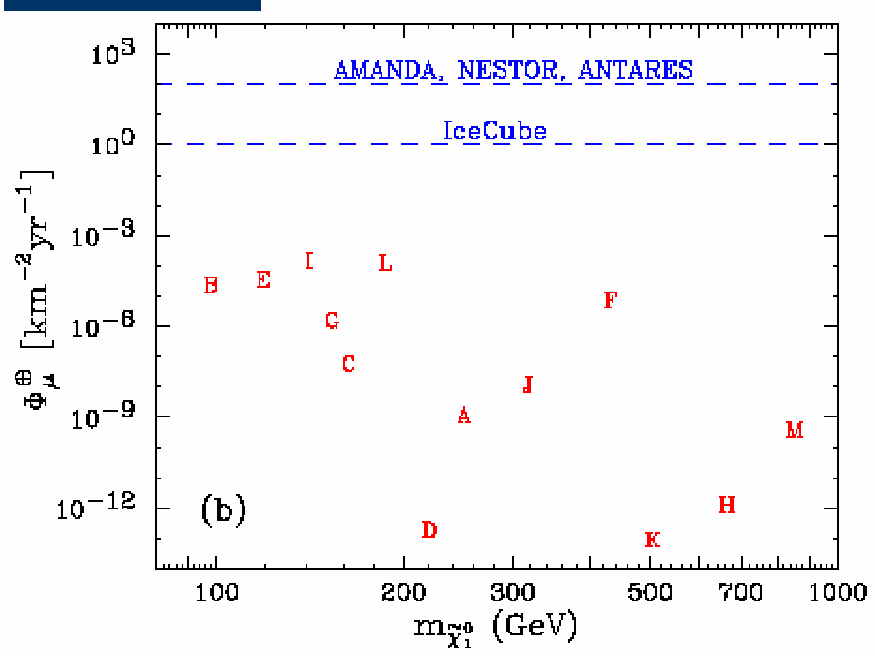
JE + Feng + Ferstl + Matchev + Olive

Annihilations in Solar System …

… Sun



… Earth



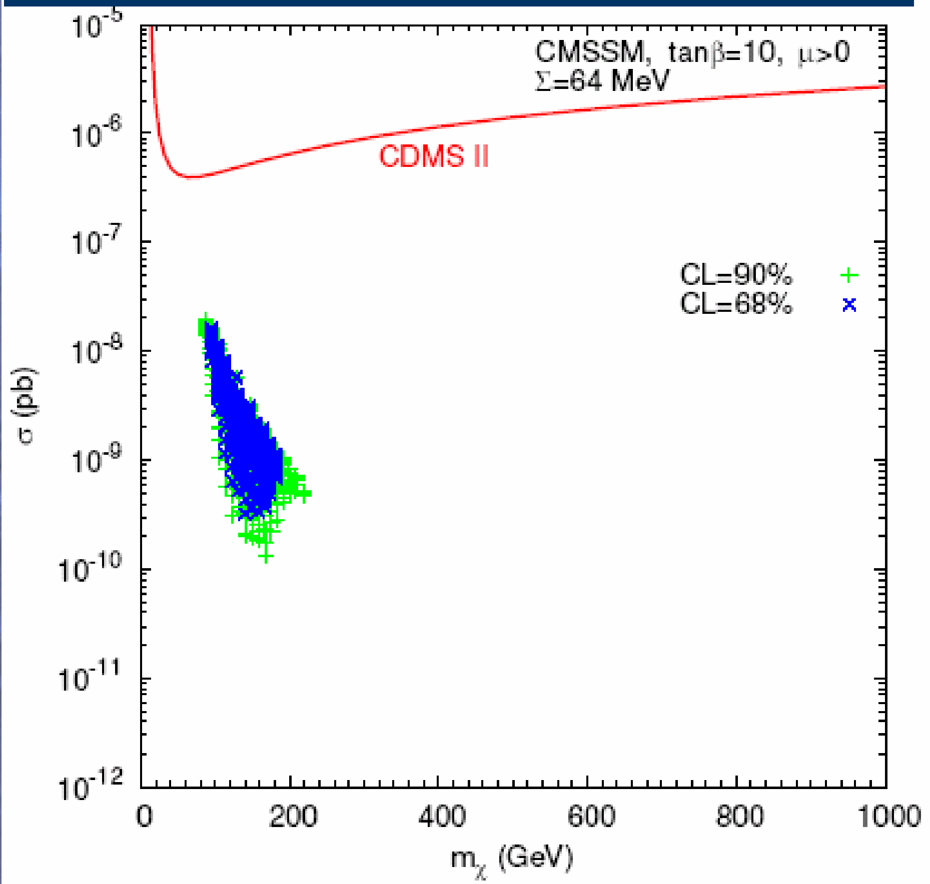
Prospective experimental sensitivities

Benchmark scenarios

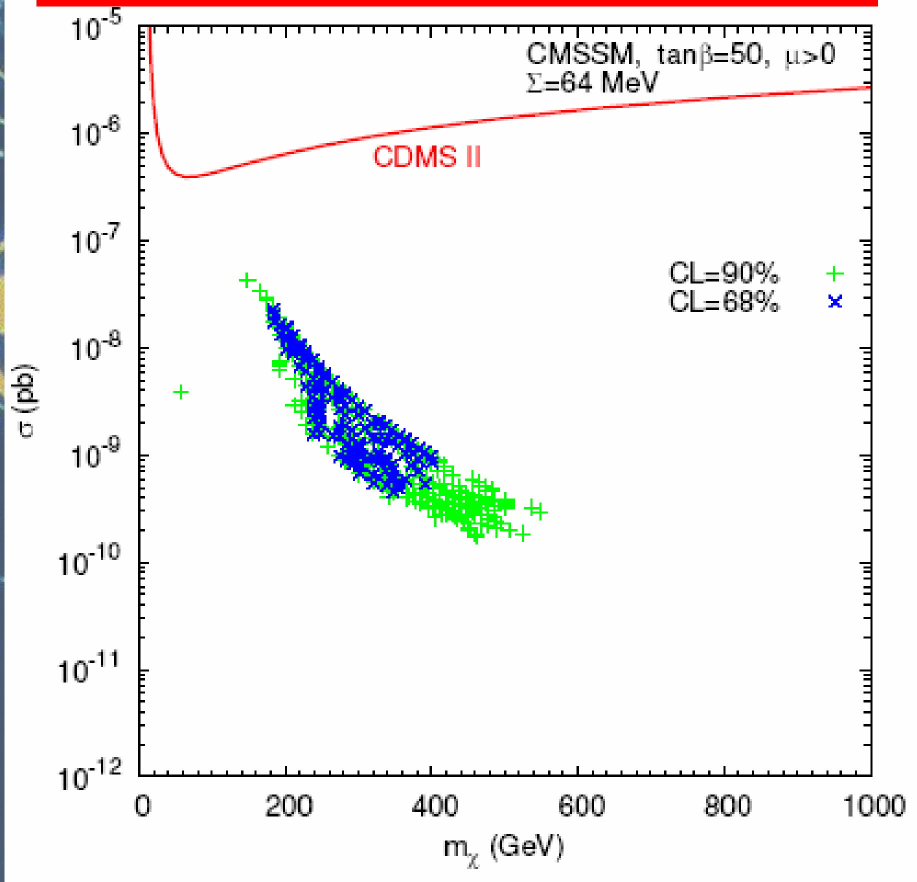
JE + Feng + Ferstl + Matchev + Olive

Elastic Scattering Cross Sections

From global fit to accelerator data



Latest experimental upper limit



JE + Olive + Santoso + Spanos: hep-ph/0502001

Open Cosmological Questions

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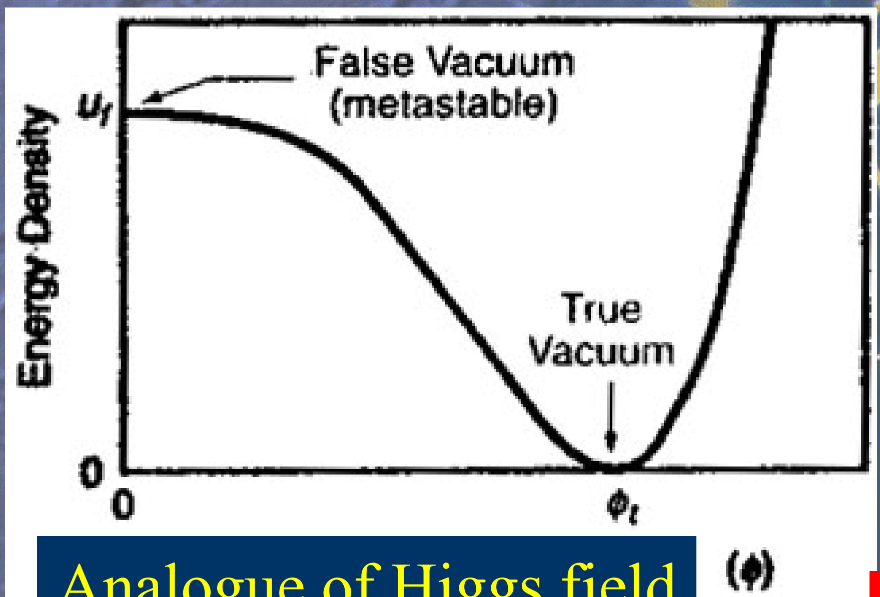
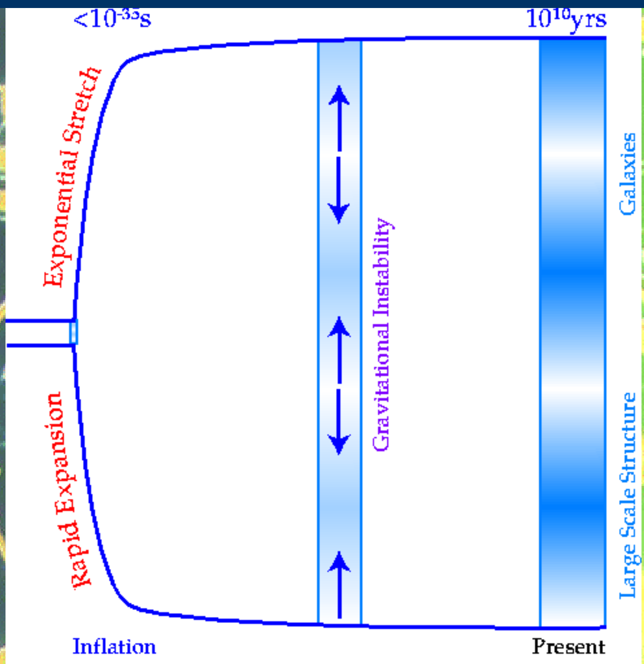
Need particle physics to answer these questions

Cosmological Inflation

Basic idea: very early in the history of the Universe (10^{-35}s?) the energy density was dominated by a ~ constant piece V: would have caused ~ exponential expansion: H ~ √V



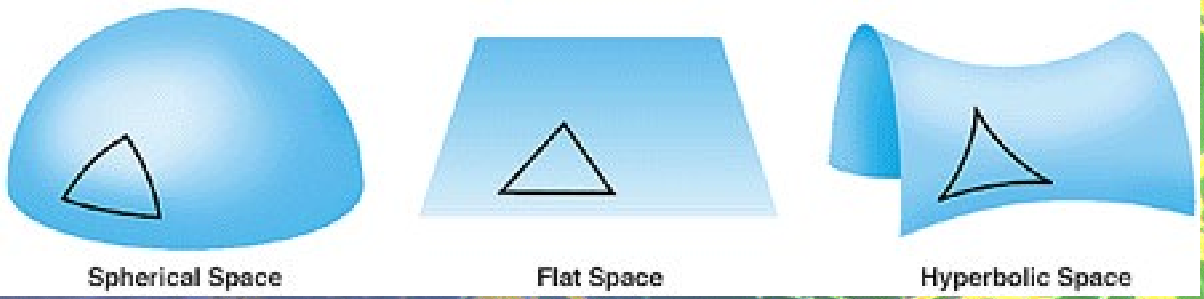
Analogue of Higgs field



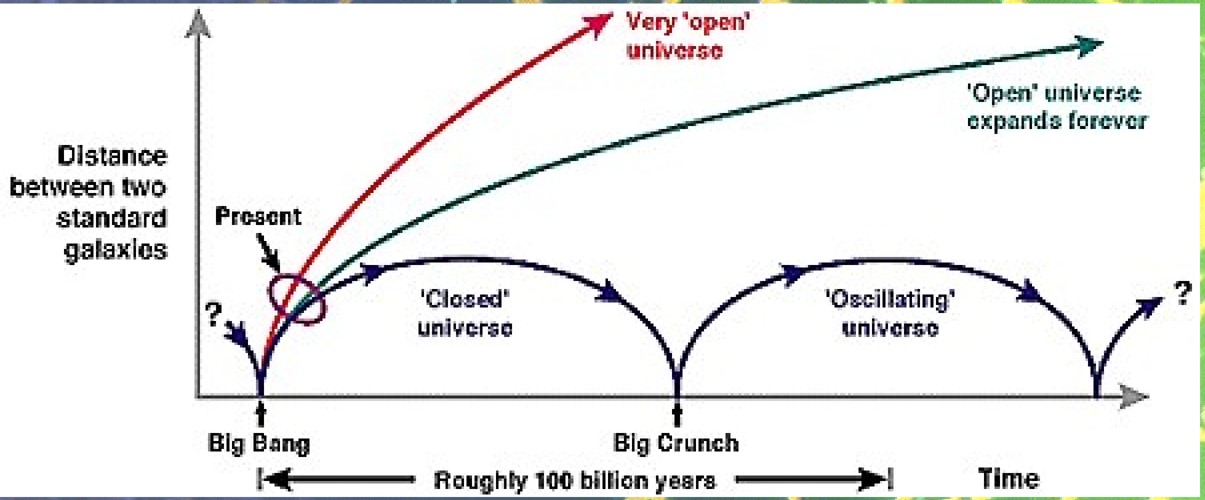
Would have expanded Universe much more than standard Big Bang

Geometry of the Universe?

Closed Universe? Flat Space? Open Universe?

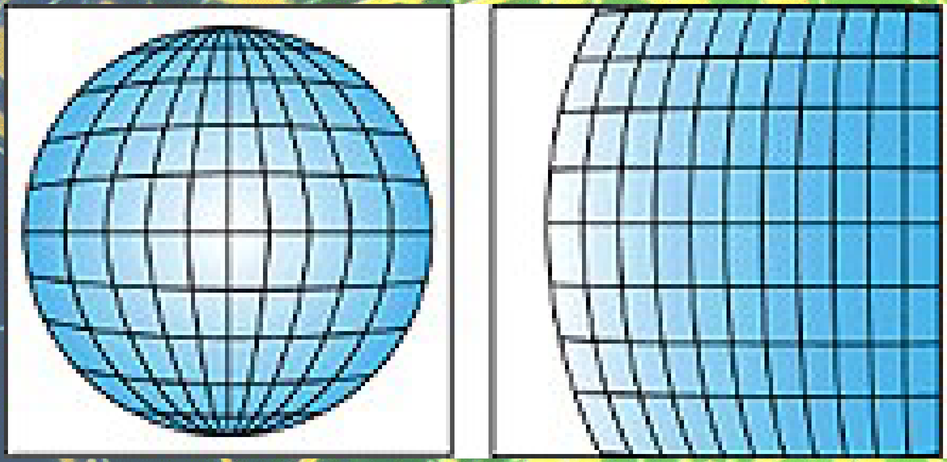


Will the expansion reverse or continue?



Inflation → Flat Universe

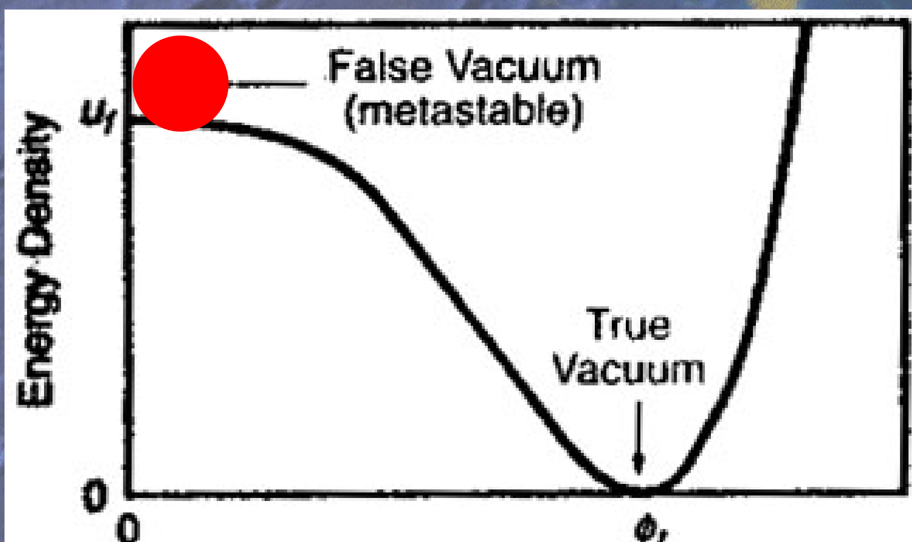
Exponential expansion makes Universe look nearly flat



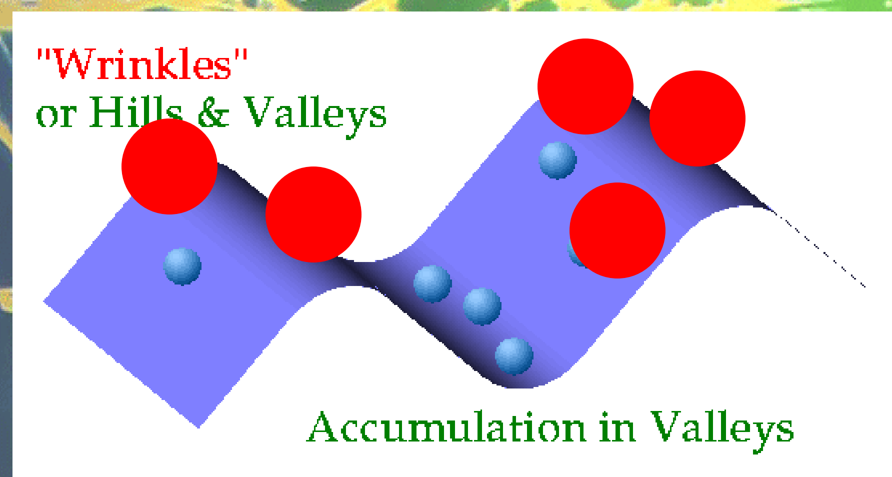
Origin of Structures in Universe

Small quantum fluctuations:
one part in 10^5

Gravitational instability:
Matter falls into
the overdense regions



Analogue of Higgs field converts into matter with varying density



Open Cosmological Questions

- Why is the Universe so big and old?
  ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  almost flat, borderline for eternal expansion
- Where did the matter come from?
  1 proton for every 1,000,000,000 photons
- How did structures form?
  ripples + invisible dark matter?
- What is the dark matter?
- What is the dark energy?

Need particle physics to answer these questions

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:

same mass

opposite internal properties:

electric charge, …

Discovered in cosmic rays

Studied using accelerators

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

Generating the matter in the Universe

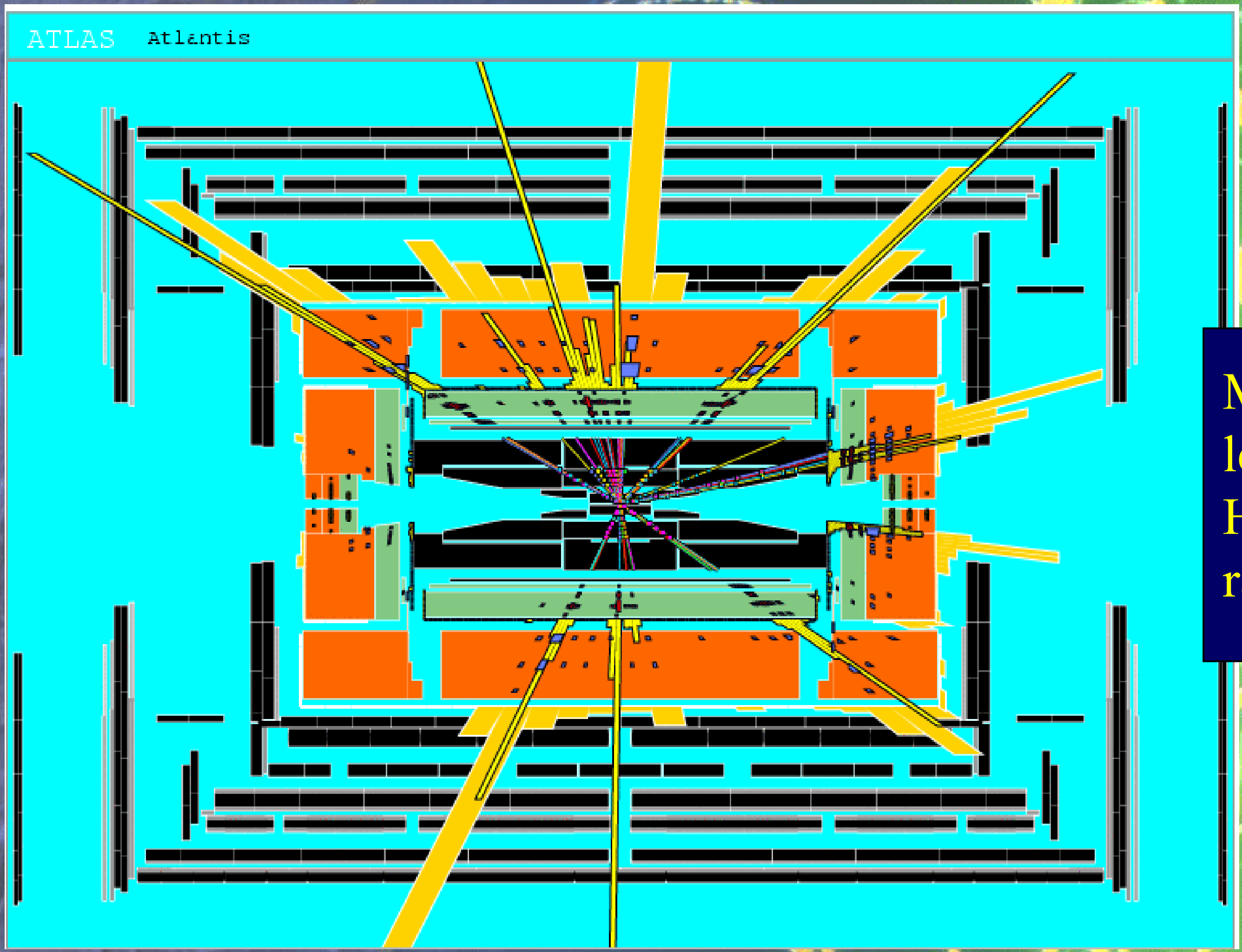
Sakharov

- Need difference between matter, antimatter
  - charge symmetry broken in laboratory
- Need matter-creating interactions
  - present in unified theories – not yet seen
- Need breakdown of thermal equilibrium
  - possible during phase transition (GUT, SM?)
  - in decays of heavy particles (singlet ν_R?)

Can we calculate from laboratory measurements?

And if gravity becomes strong at the TeV scale …

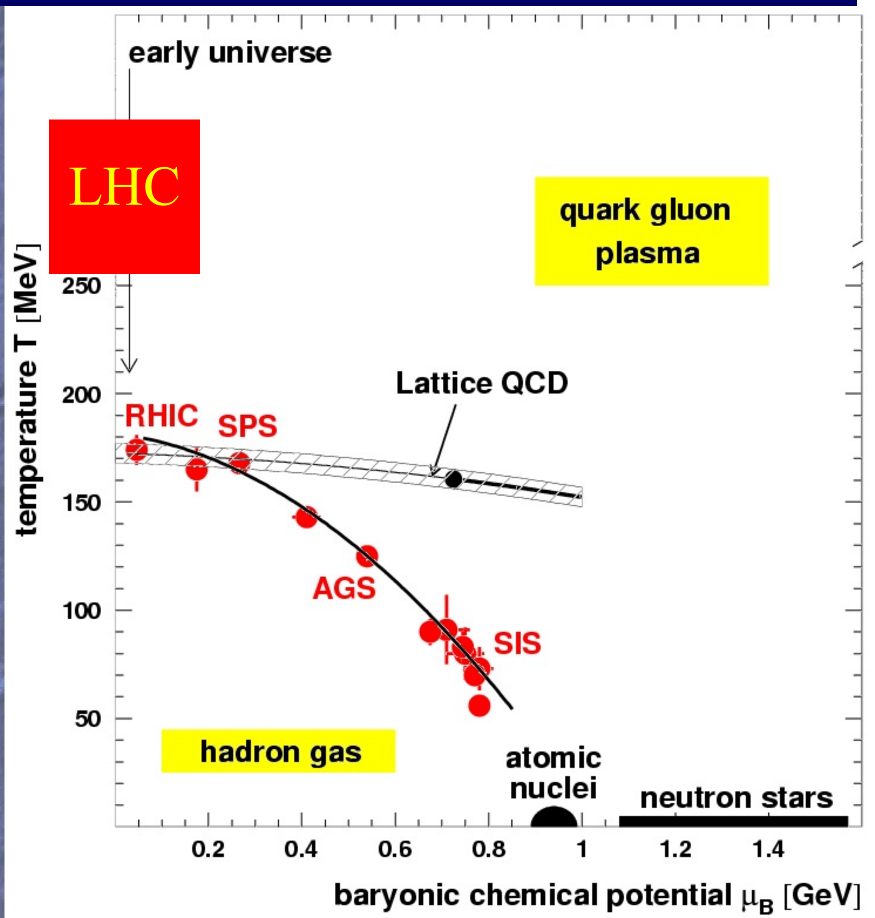
Black Hole Production at LHC?



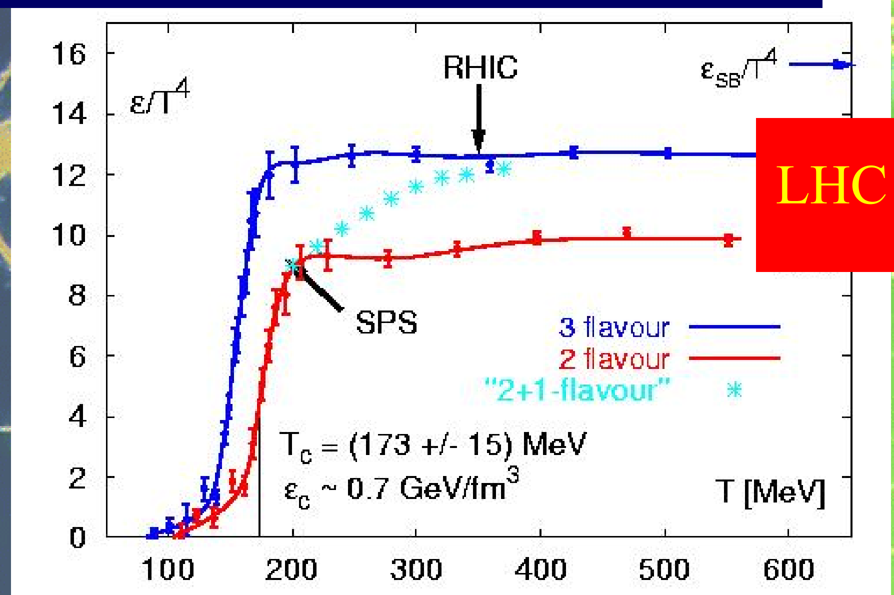
Multiple jets, leptons from Hawking radiation

Hot and Dense Hadronic Matter

Recreate the first 10^{-6} seconds …



… and probe the quark-hadron phase transition



Big Bang ↔ Little Bangs

- The matter content of the Universe
  - Dark matter
  - Dark energy
  - Origin of matter

- Experiments at particle colliders
  - Early Universe
  - Supersymmetry
  - Matter-antimattter asymmetry

Learn particle physics from the Universe
Use particle physics to understand the Universe