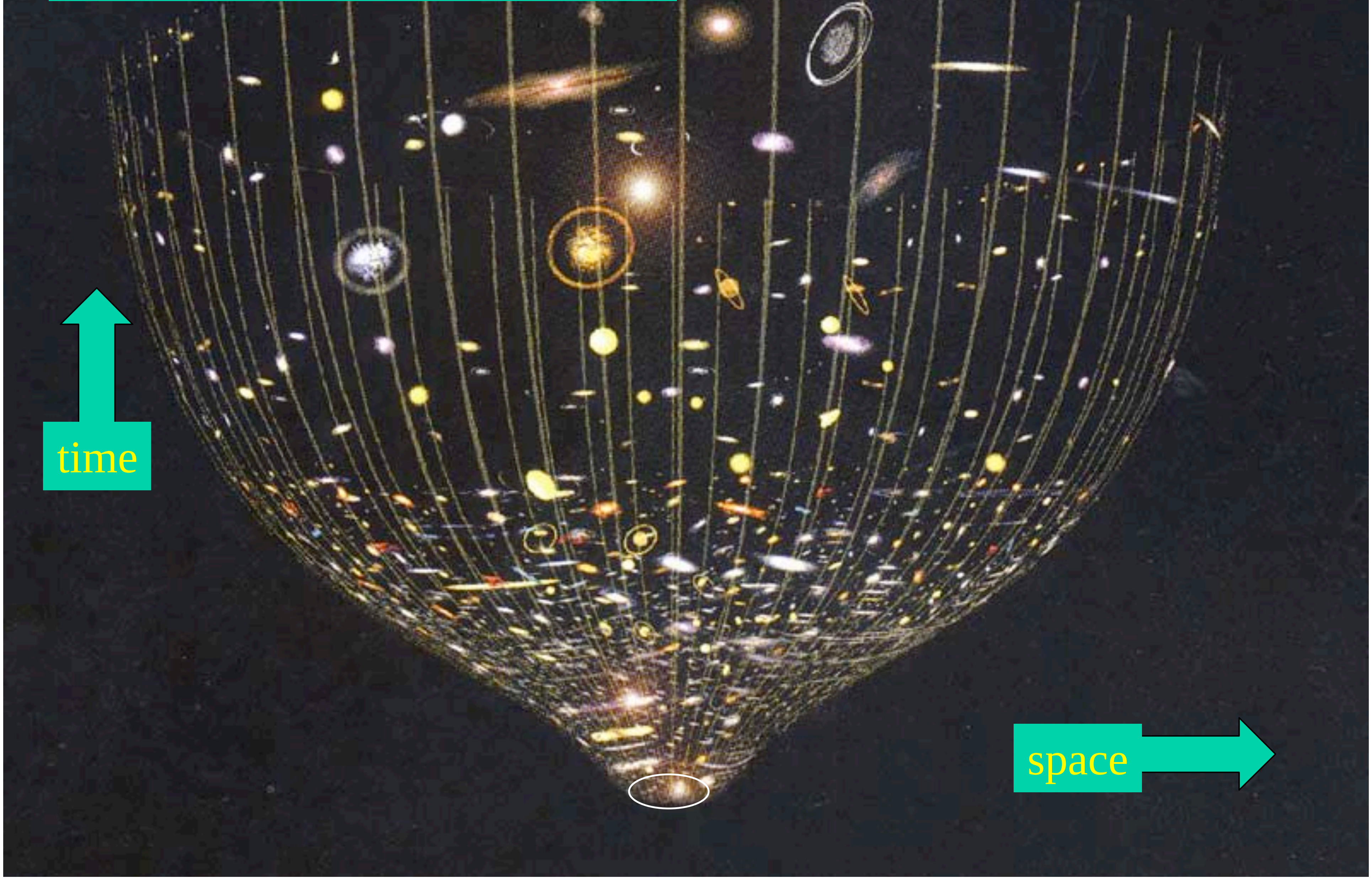
From Little Bangs to the Big Bang

Inauguration of the
Max Planck Research School on Elementary Particle Physics,
October 17th, 2005

John Ellis

The Universe so far



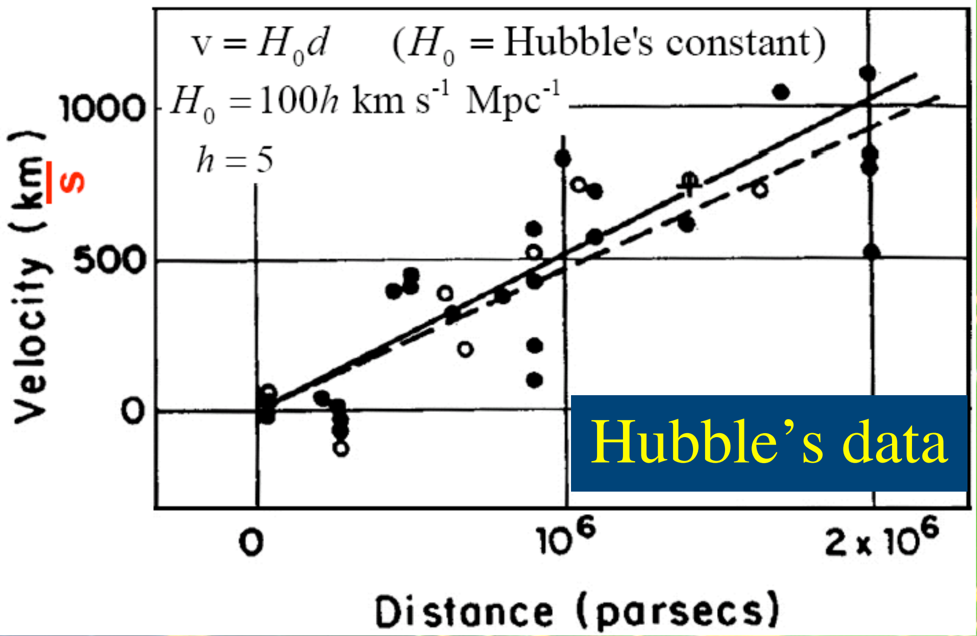
The Universe is expanding

- Galaxies are receding from us

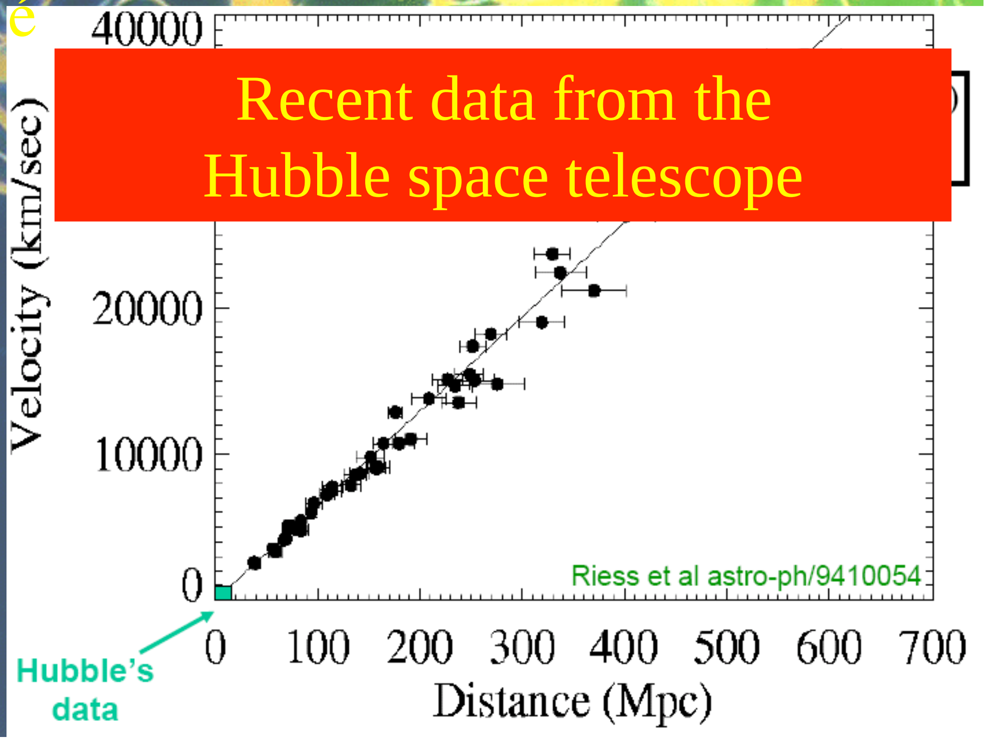
    Hubble expansion law: galactic redshifts

The expansion of the Universe

Hubble, basketball player



Hubble's data



Recent data from the Hubble space telescope

The Universe is expanding

- Galaxies are receding from us

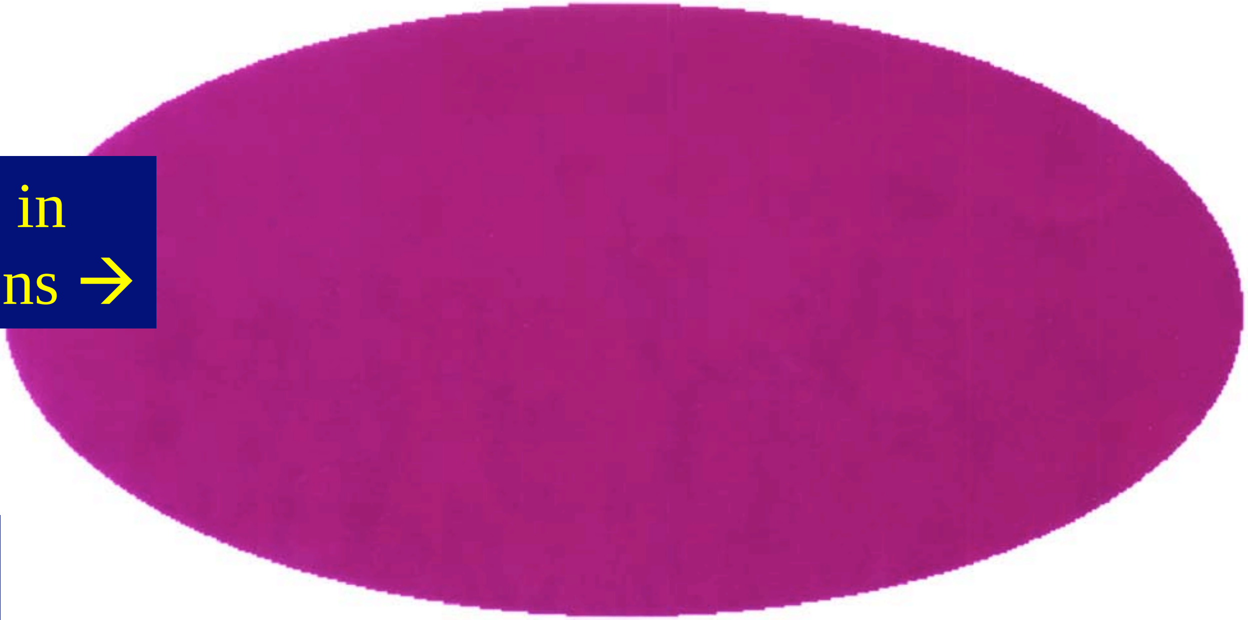
  Hubble expansion law: galactic redshifts

- The Universe was once 3000 smaller, hotter than today

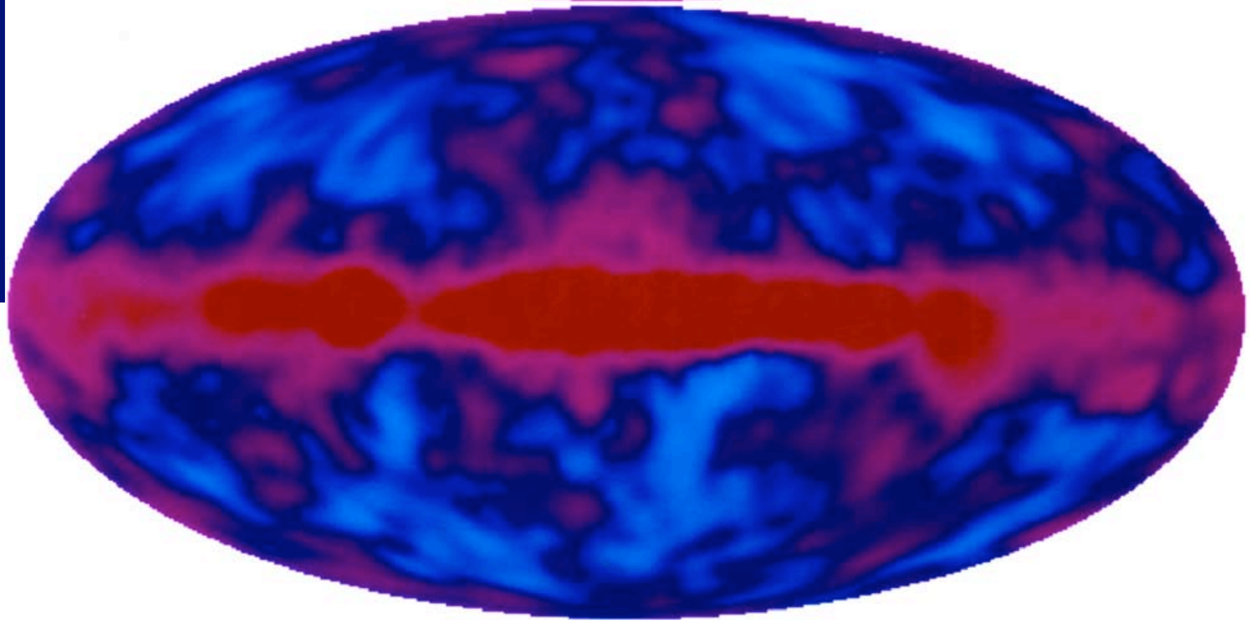
  cosmic microwave background radiation

Cosmic Microwave Background

Almost the same in different directions →



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

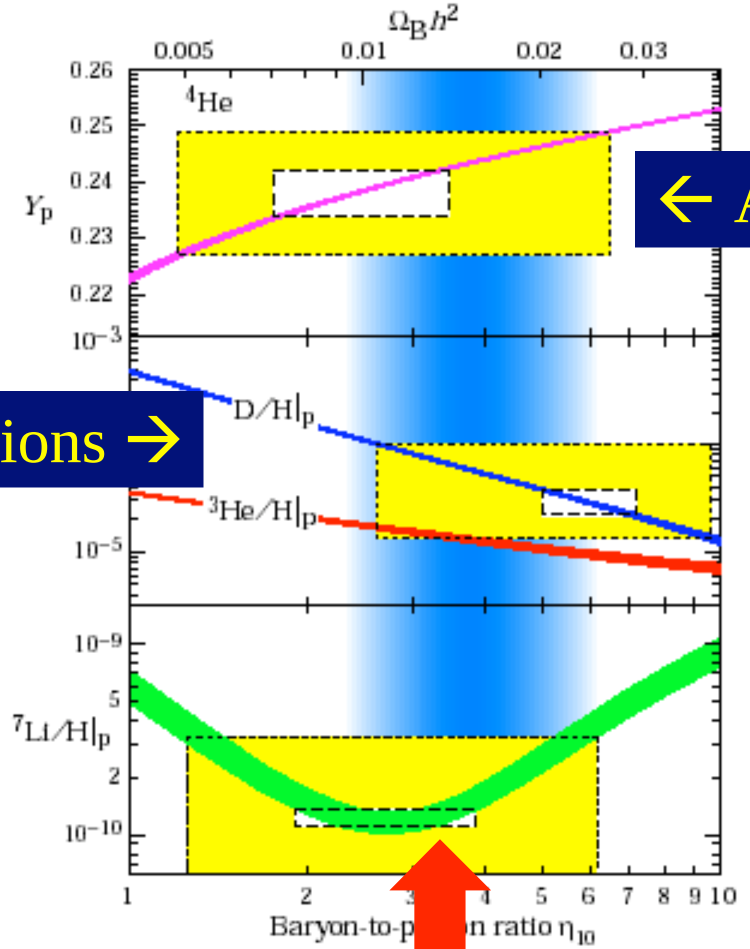
  number of different neutrinos measured at accelerators

Abundances of light elements in the Universe

Helium

Theoretical calculations →

Lithium



← Agree with data

Not enough ordinary matter to make the Universe recollapse

The Very Early Universe

- Size: a → zero
- Age: t → zero
- Temperature: T → large

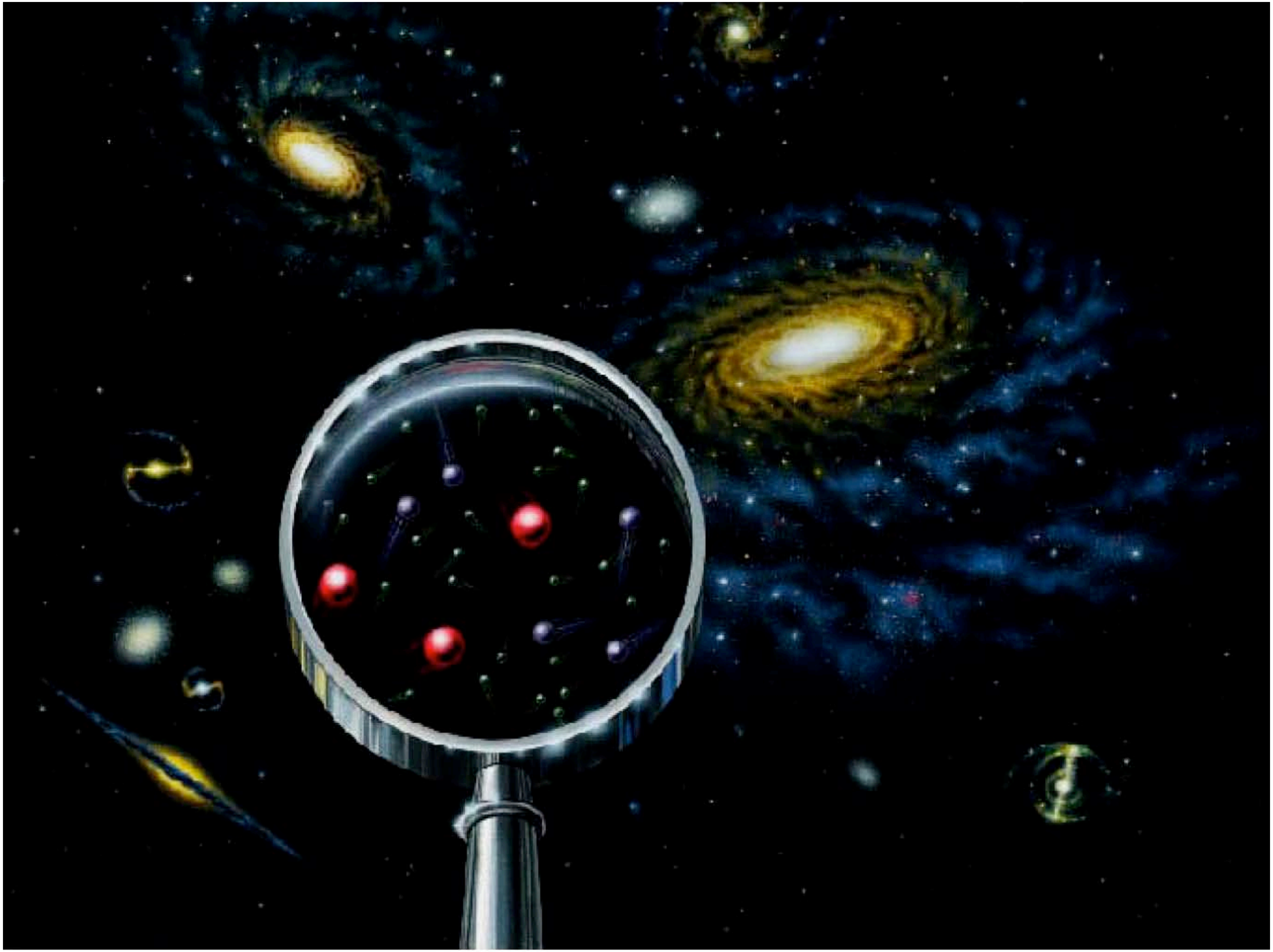
  $T \sim 1/a,\ t \sim 1/T^2$
- Energies: $E \sim T$
- Rough magnitudes:

  T ~ 10,000,000,000 degrees

  E ~ 1 MeV ~ mass of electron

  t ~ 1 second

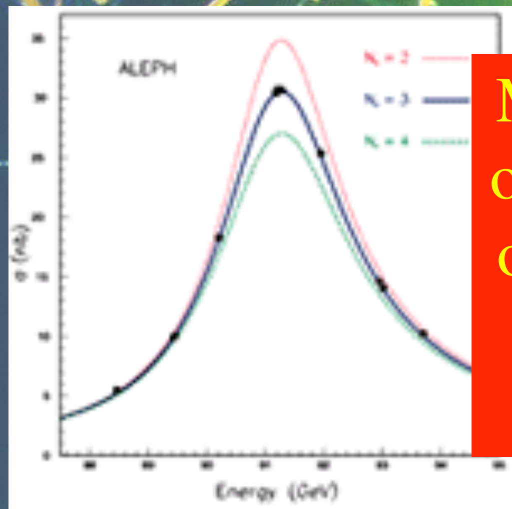
Need particle physics to describe earlier history



The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow & Weinberg

Crucial tests in experiments at CERN



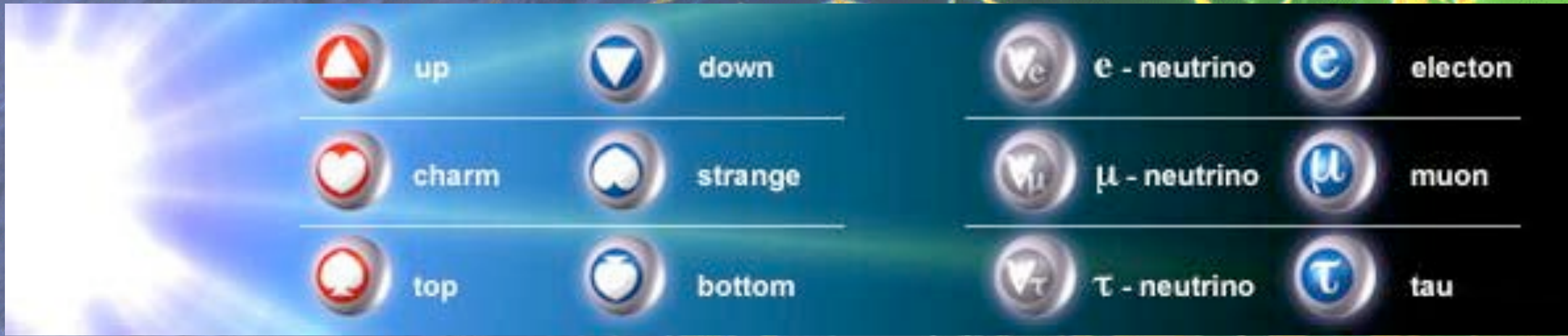
Measurement of the number of families of elementary particles: 3!

In agreement with all confirmed laboratory experiments

The‘Standard Model’

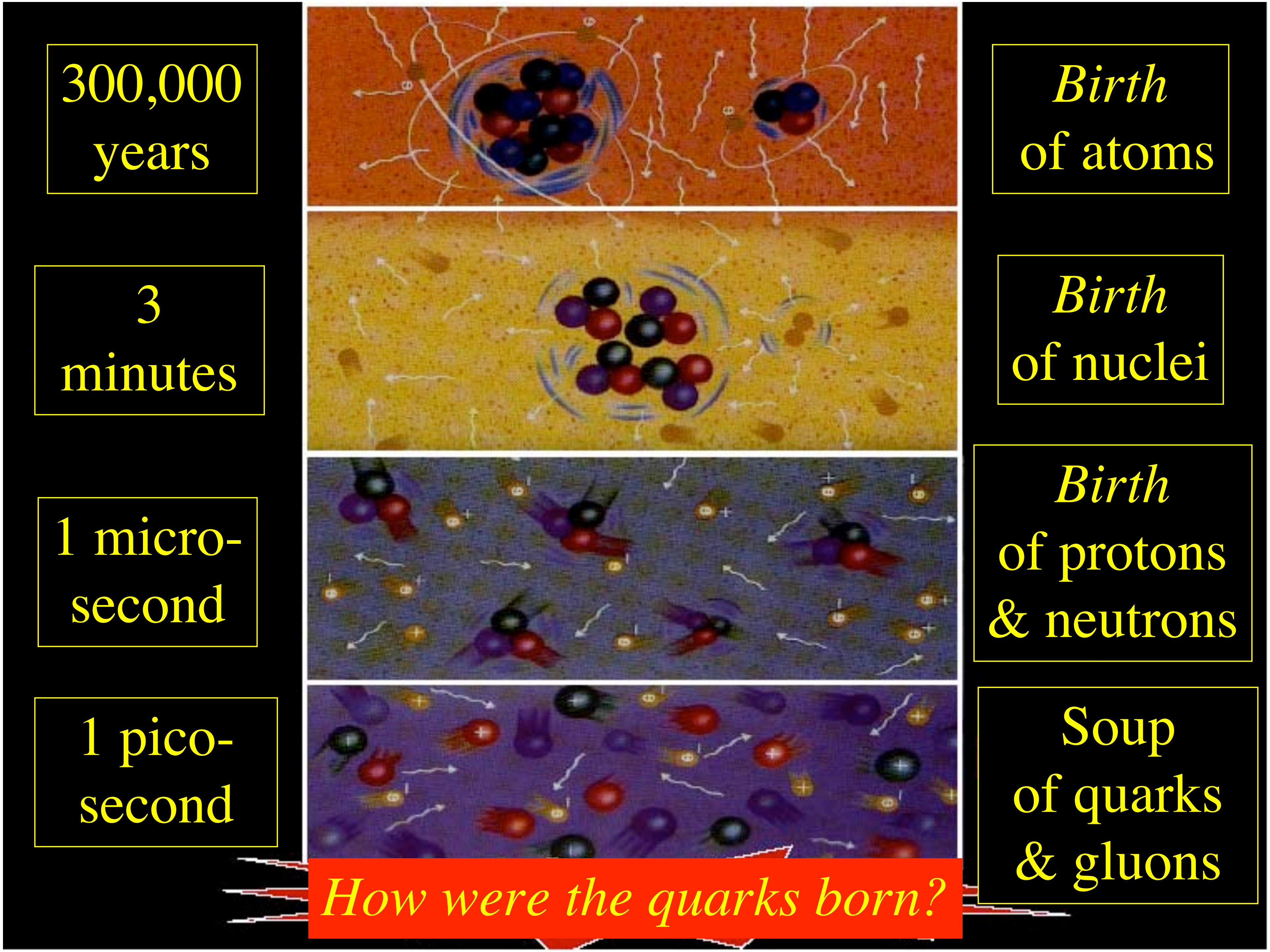
= Cosmic DNA

The matter particles



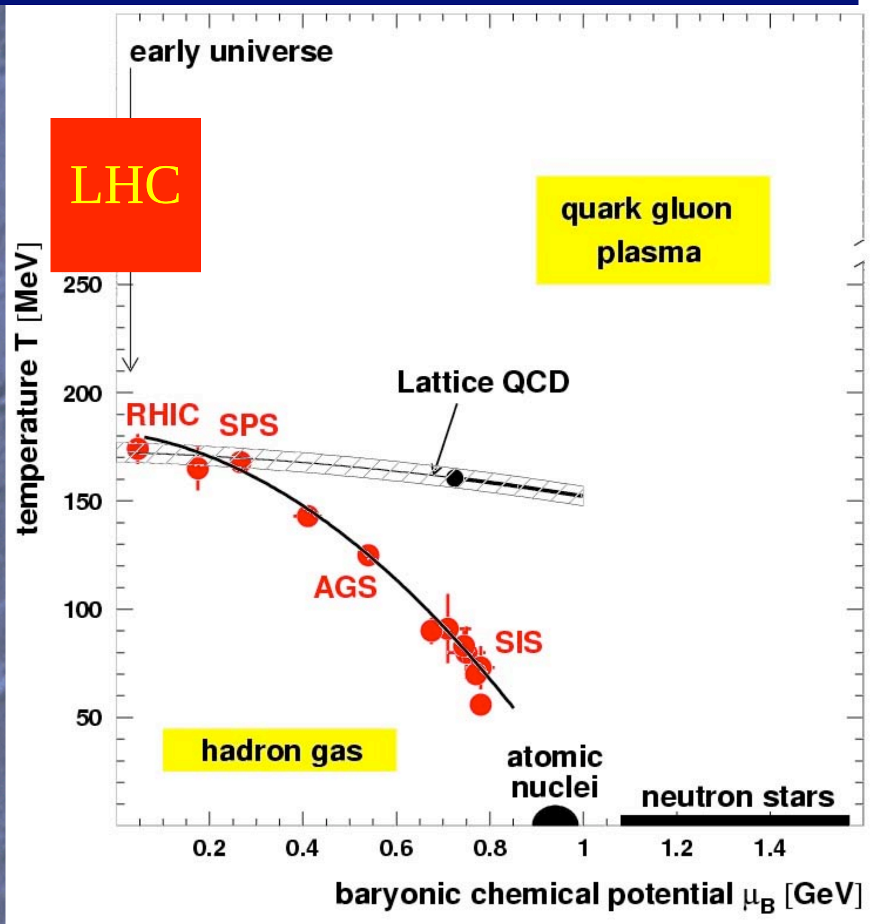
The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

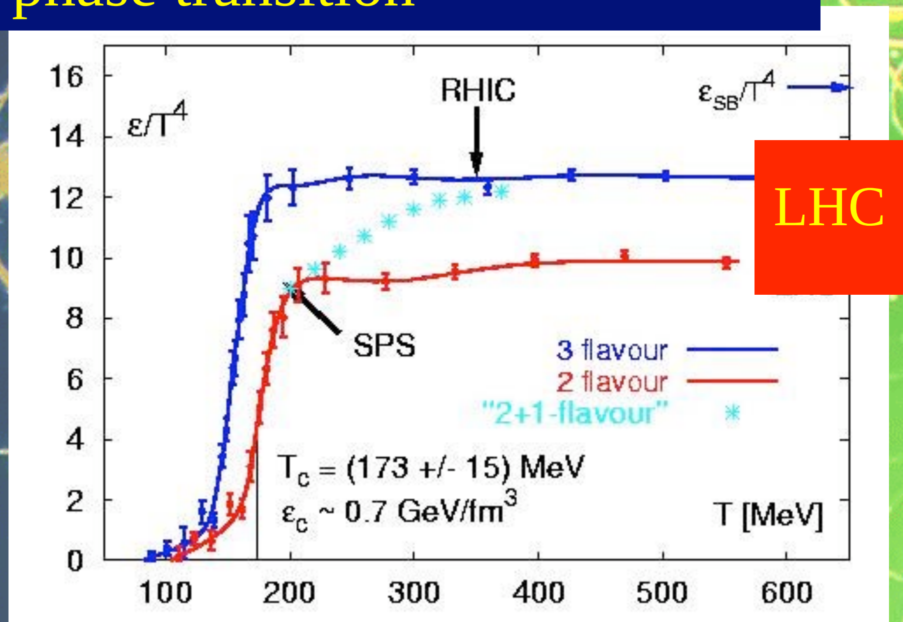

300,000 years
Birth of atoms
3 minutes
Birth of nuclei
1 micro-second
Birth of protons & neutrons
1 pico-second
Soup of quarks & gluons
How were the quarks born?

Relativistic Heavy-Ion Collisions

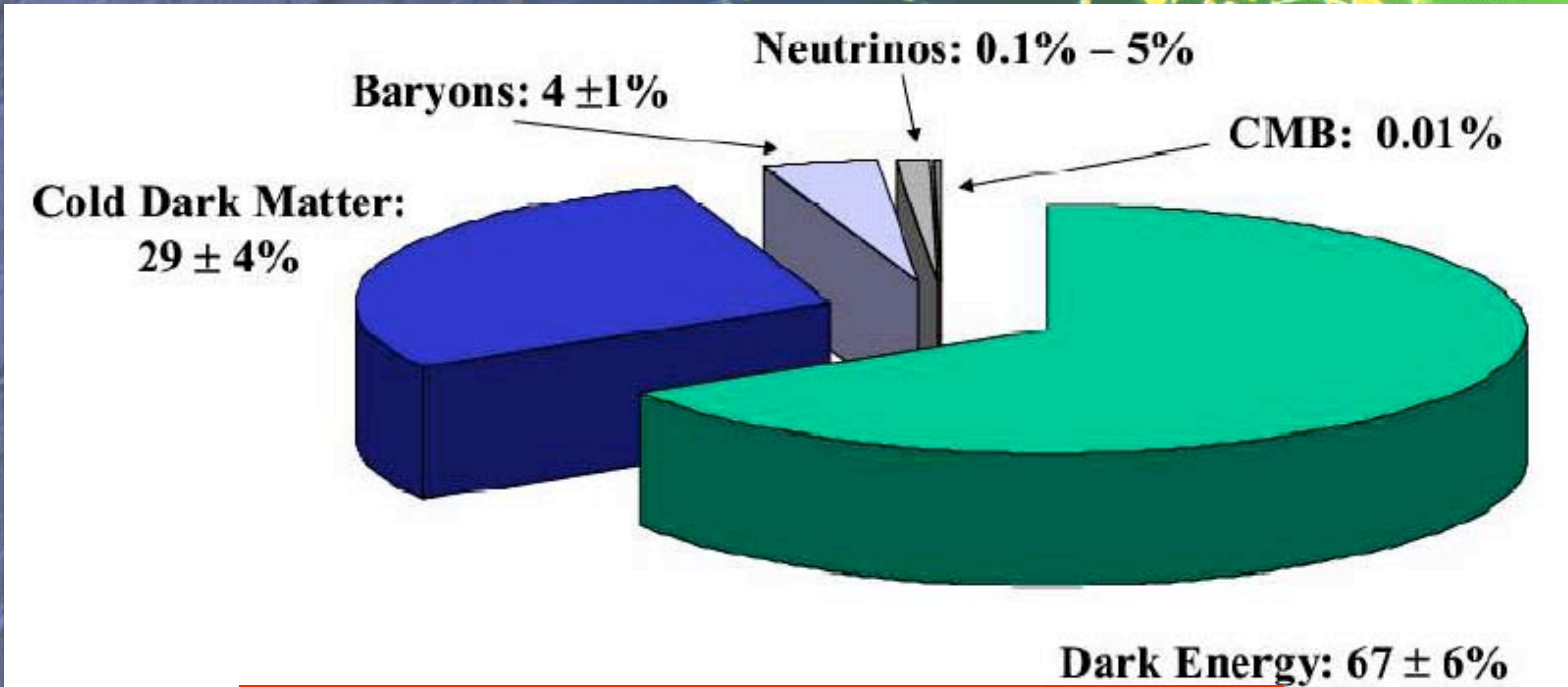
Recreate the first 10^{-6} seconds …



… and probe the quark-hadron phase transition



A Strange Recipe for a Universe



The 'Concordance Model'
prompted by astrophysics & cosmology

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:

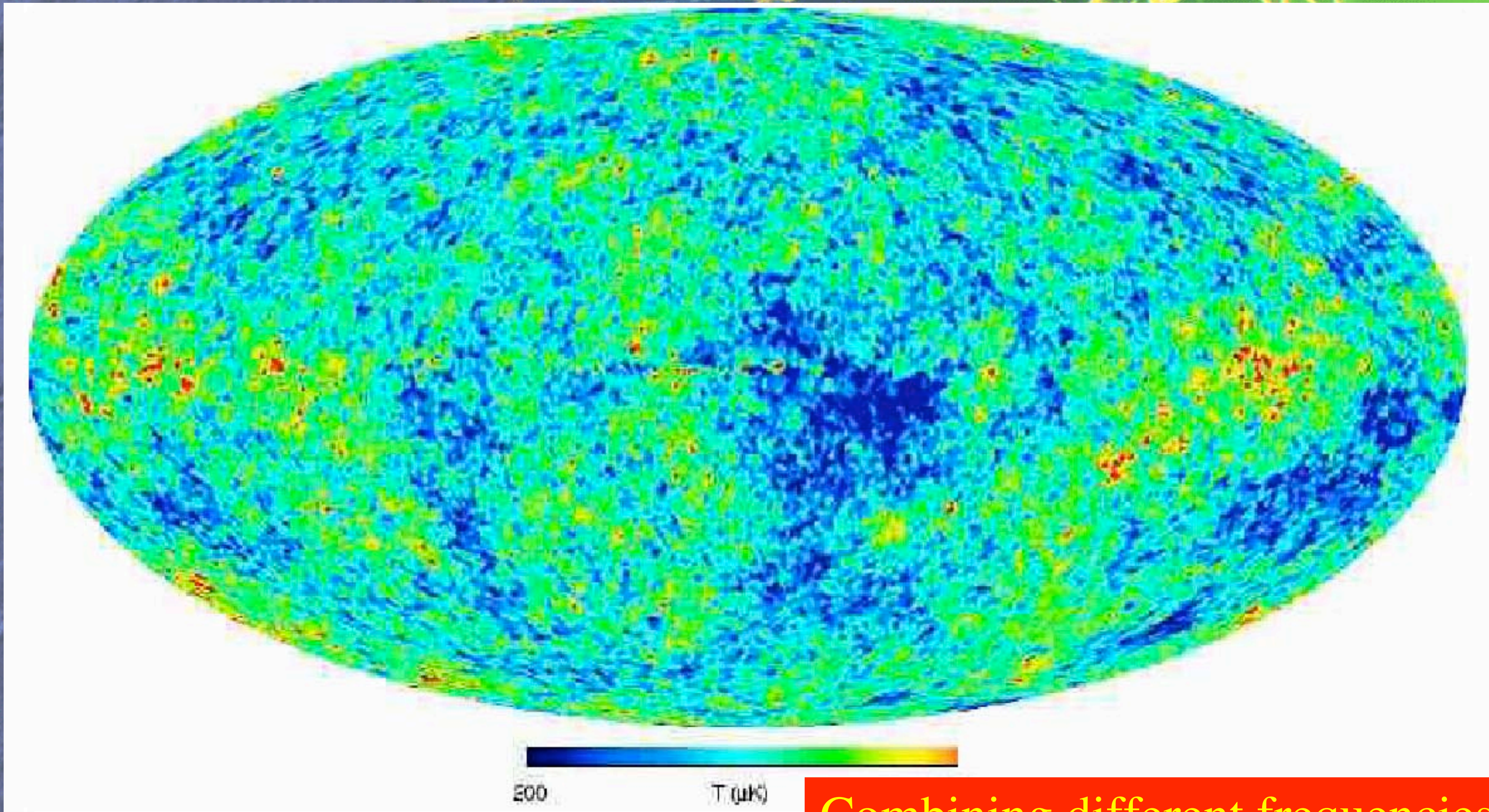
  $\Omega_{Baryons} \sim$ few %

  Total matter density much larger

  Clusters of galaxies:

  $\Omega_{Matter} \sim 25$ %

The CMB according to WMAP

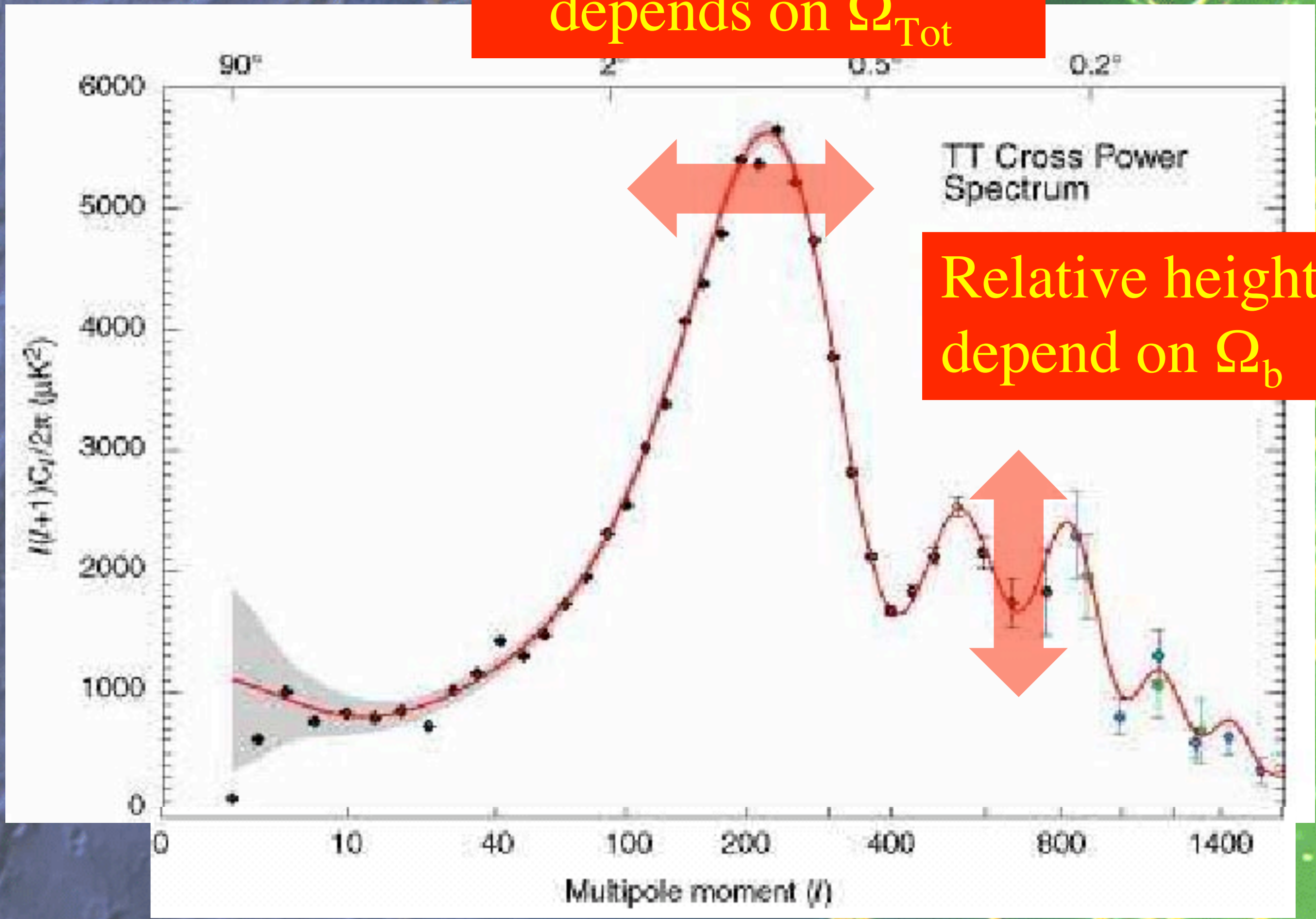


Combining different frequencies

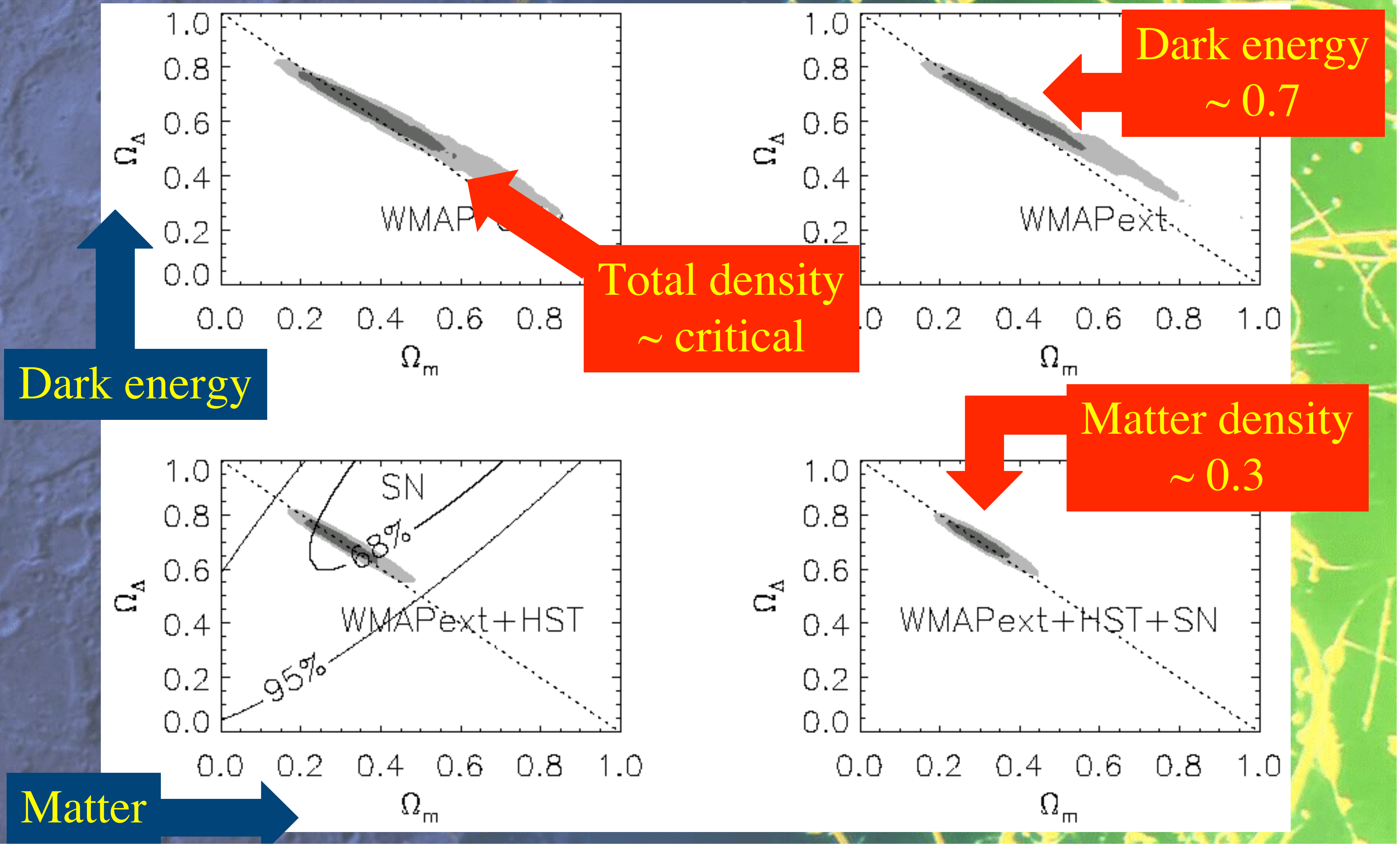
The CMB Power Spectrum

Location of first peak depends on Ω_{Tot}

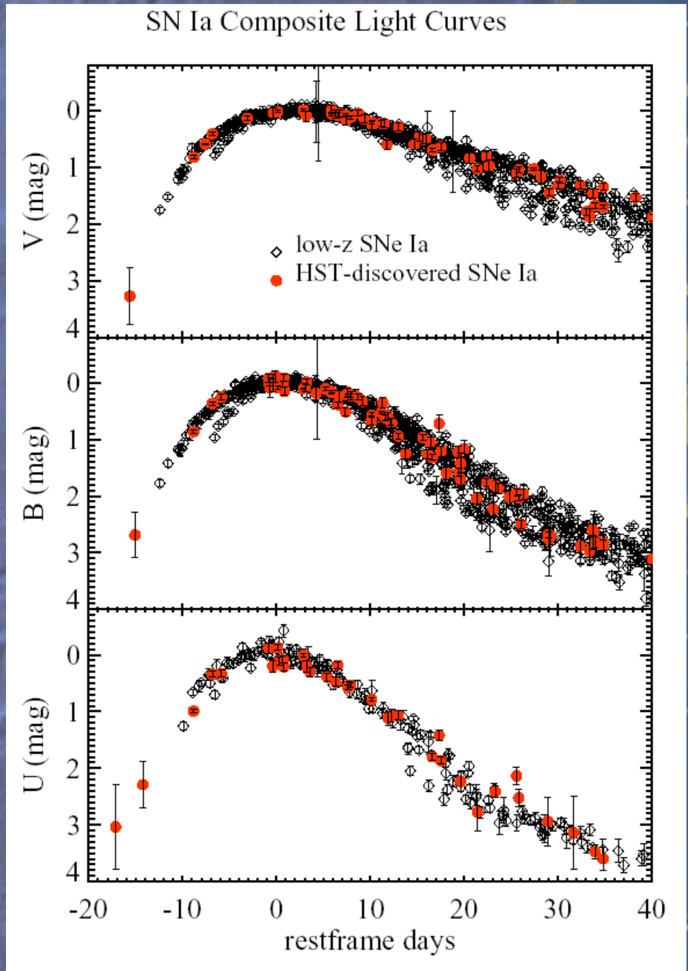
Relative heights depend on Ω_b



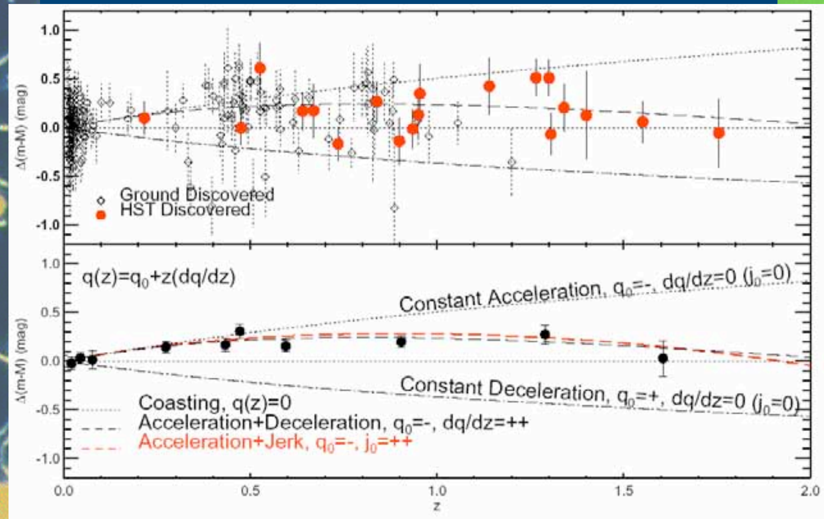
WMAP Constraints on Density



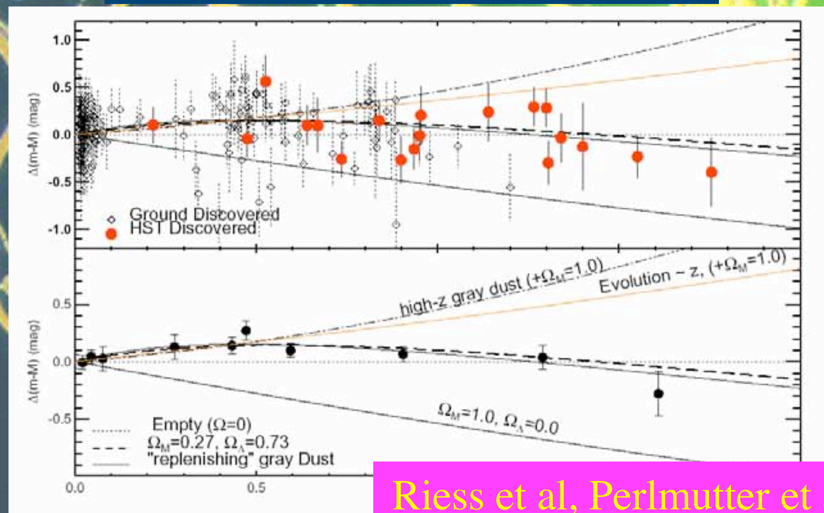
High-redshift supernovae are standard candles



Universe now accelerating, previously decelerating

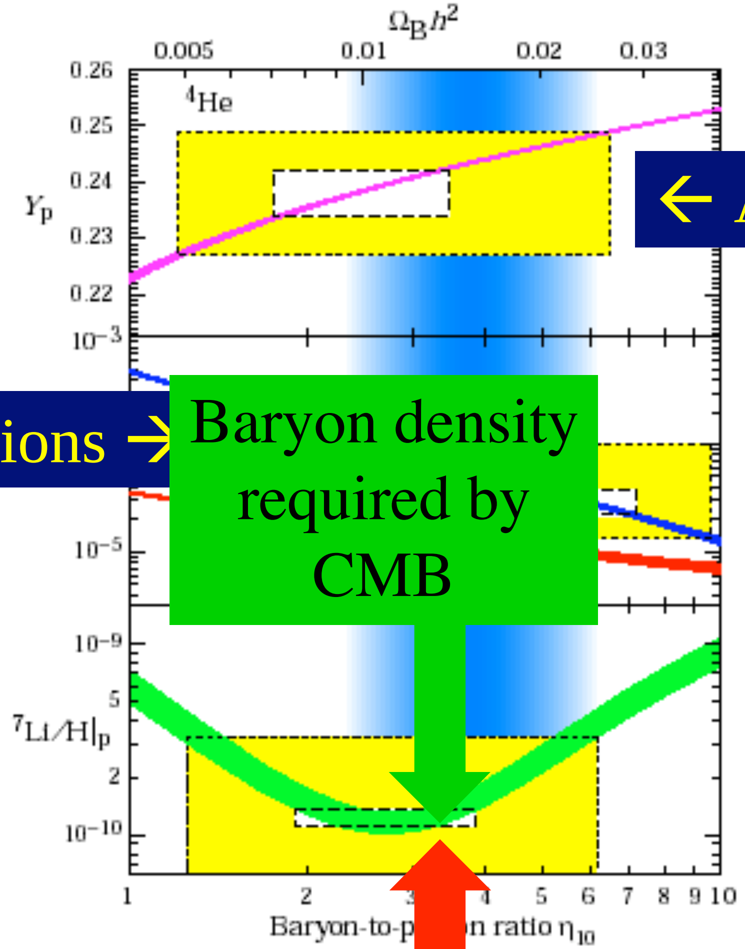


not dust, not evolution



Riess et al, Perlmutter et al

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 to make the Universe recollapse

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?

The Density Budget of the Universe

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  $\Omega_{Baryons} \sim$ few %

- Total matter density much larger

  Clusters of galaxies:

  $\Omega_{Matter} \sim 25$ %

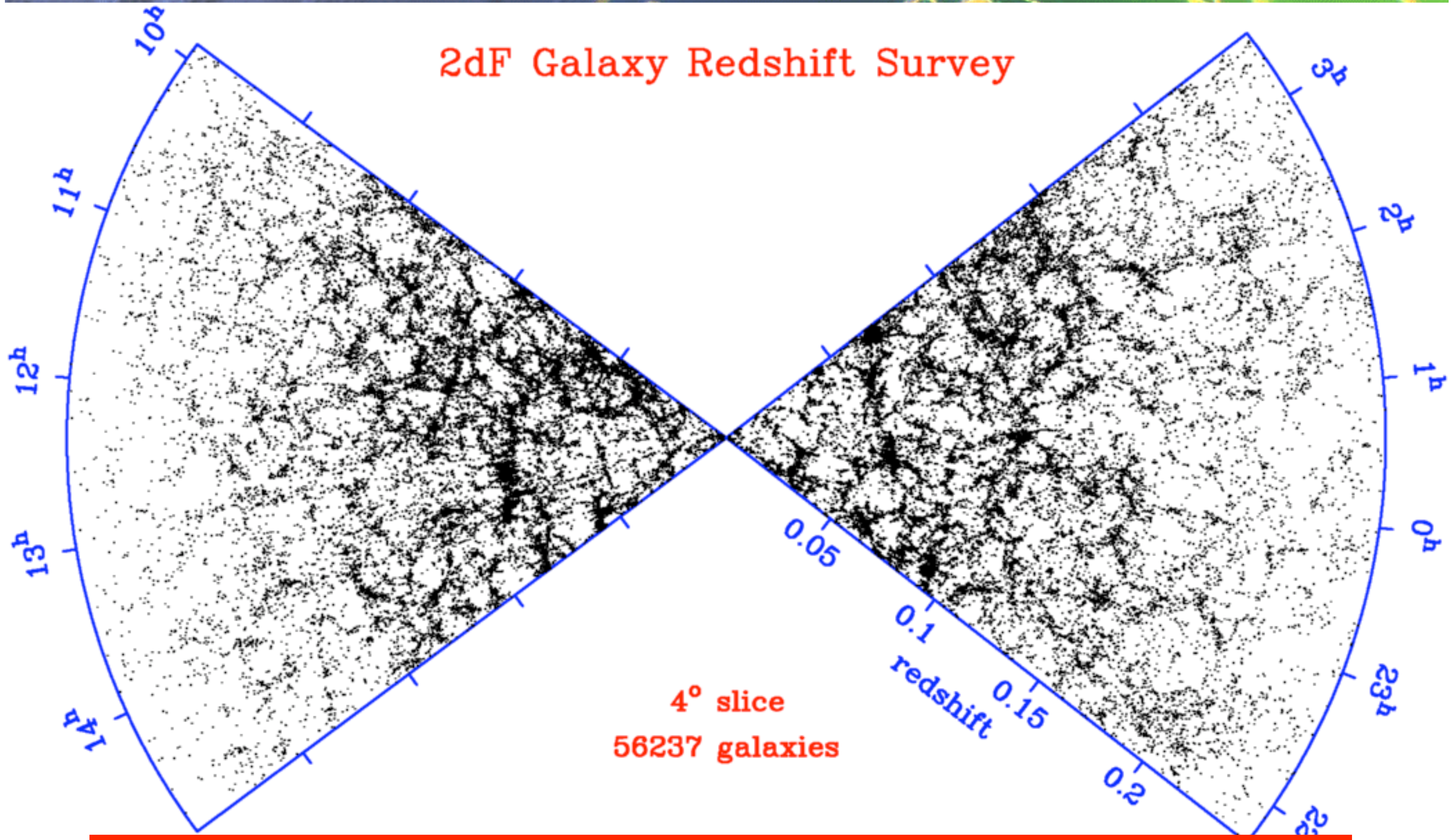
- Mainly cold dark matter

  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



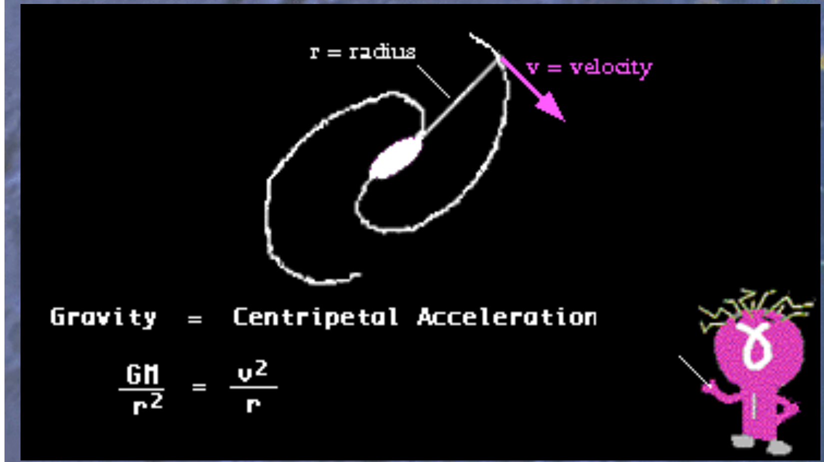
Galaxies → Clusters → smooth at largest scales

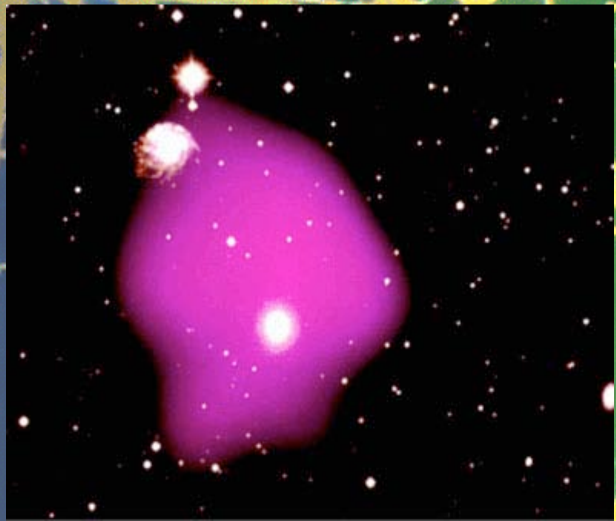
Evidence for Dark Matter

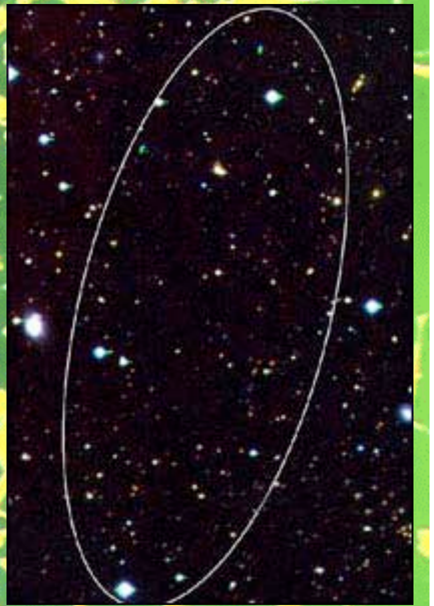
Galaxies rotate more rapidly than allowed by centripetal force due to visible matter

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

Even a ‘dark galaxy’ without stars







Structures in Universe vs Concordance Model

Flat Universe:

$\Omega_{Tot} = 1$,

Cold dark matter:

$\Omega_{CDM} \sim 0.25$,

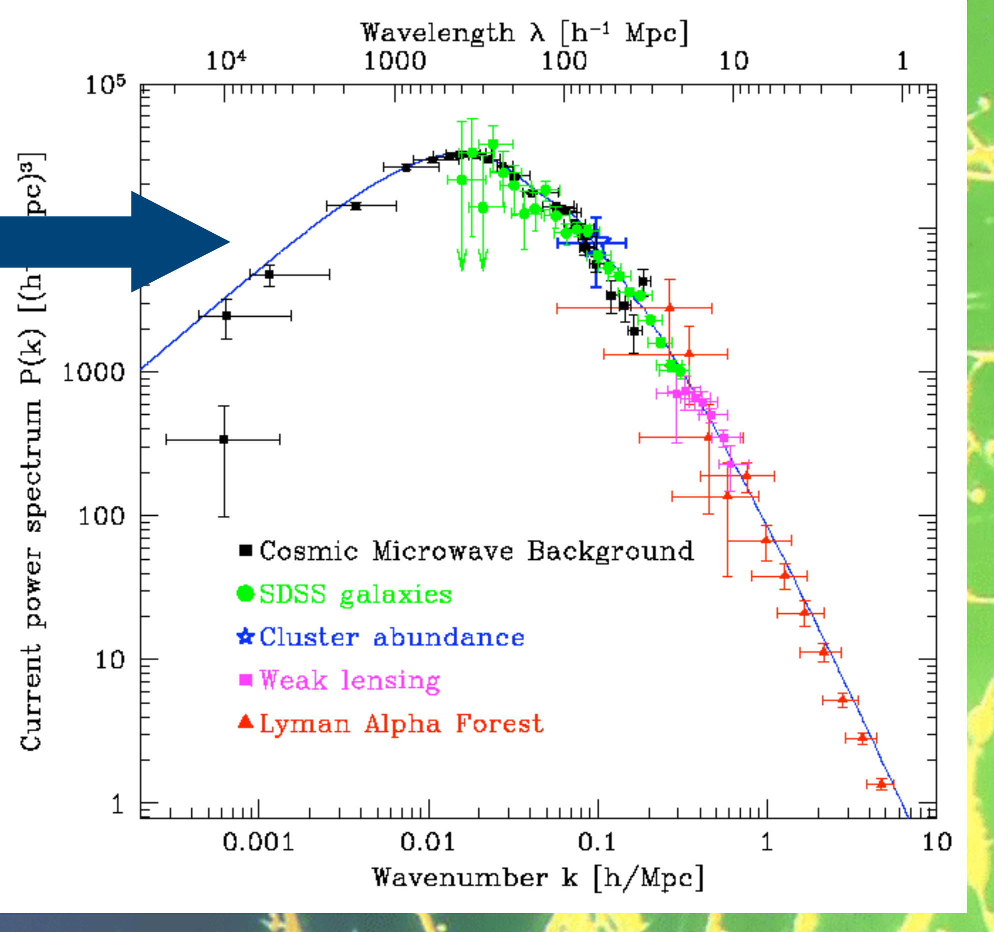
No hot dark matter,

Few baryons:

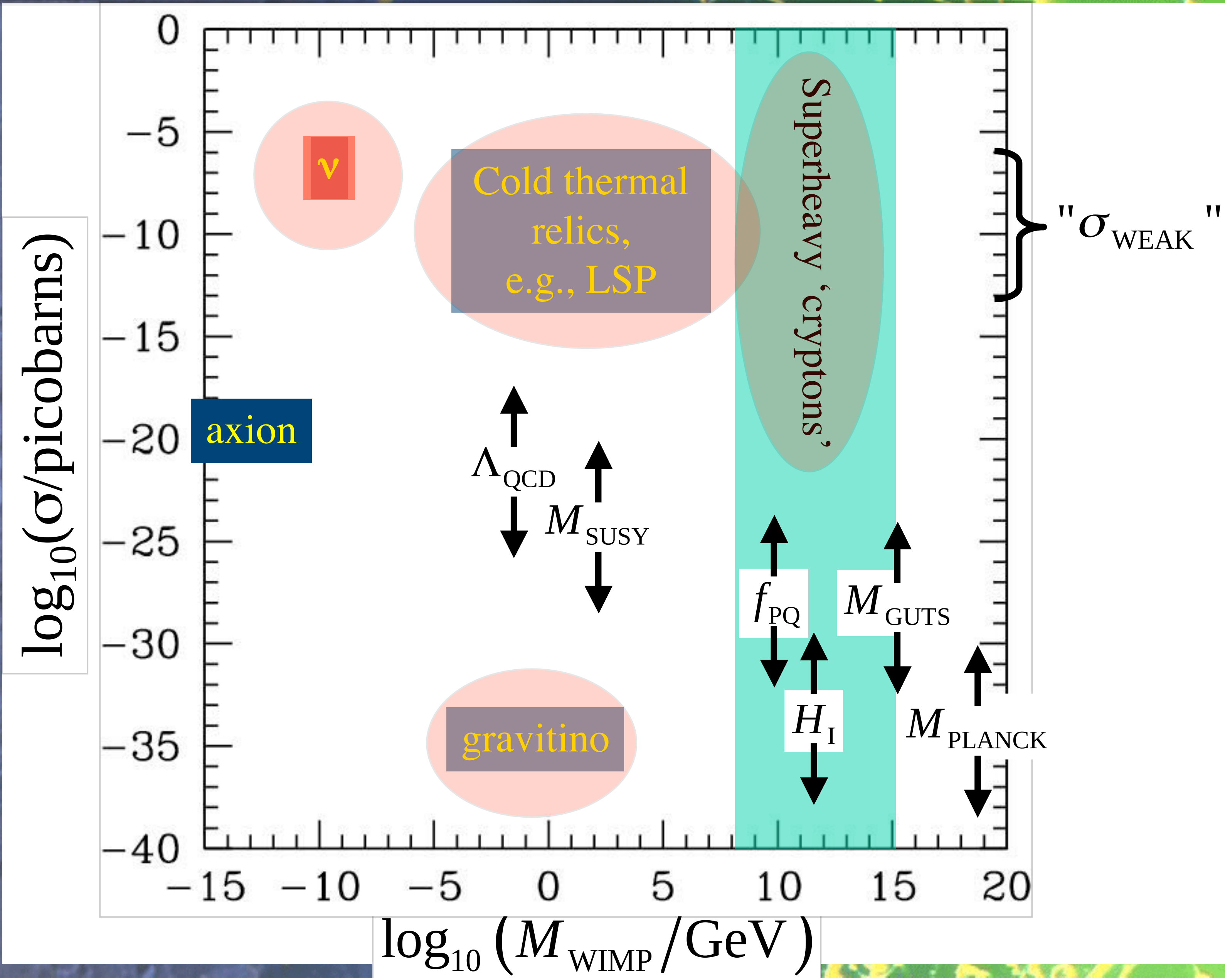
$\Omega_b \sim 0.05$,

Dark energy:

$\Omega_\Lambda \sim 0.7$



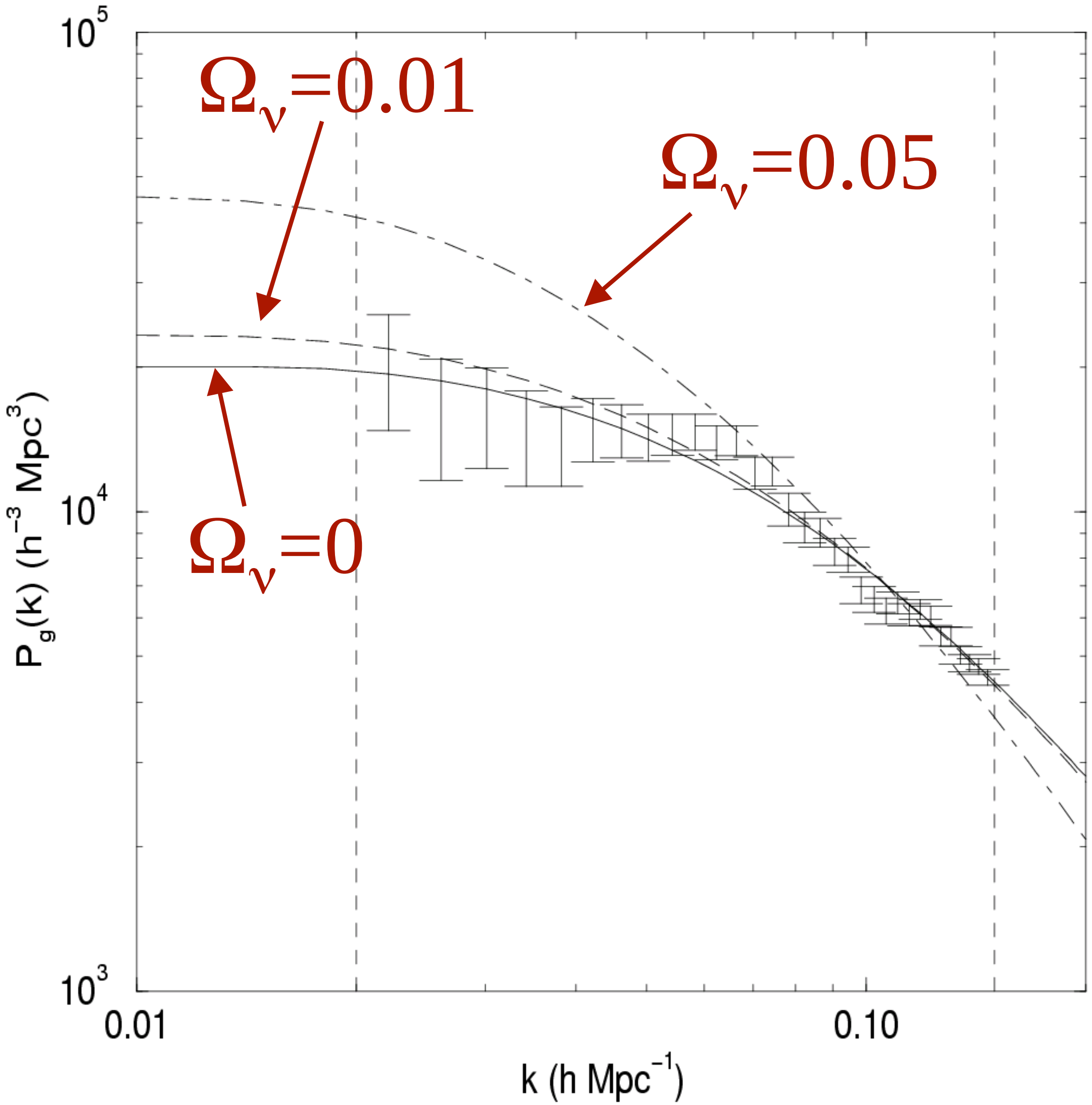
Particle Dark Matter Candidates



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

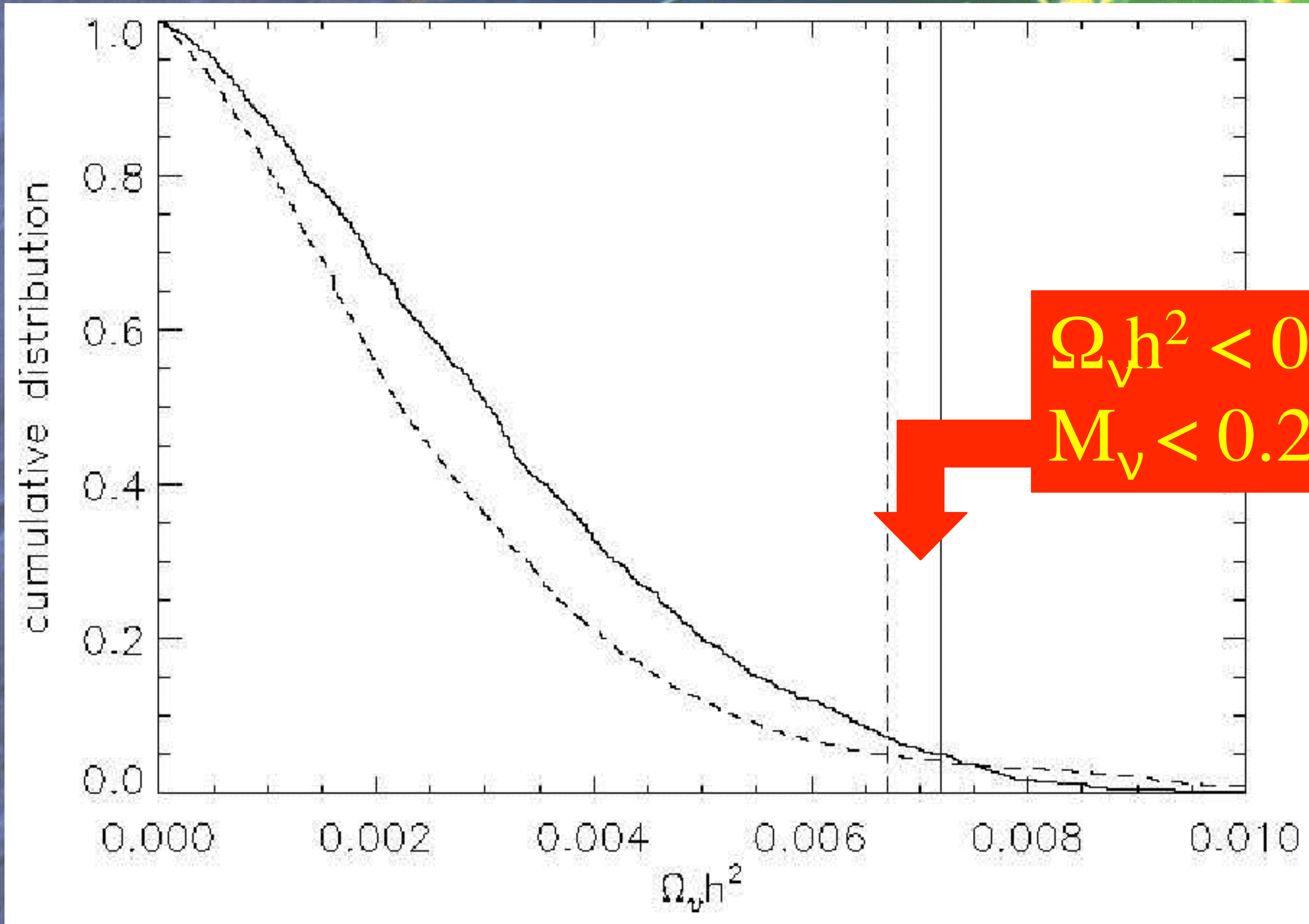


2dF team: astro-ph/0204152

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

‘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

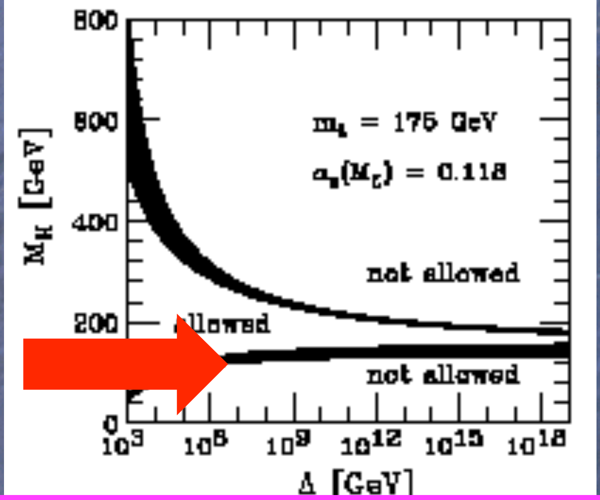
Why Supersymmetry (Susy)?

- Hierarchy problem: why is $m_W << m_P$?
  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is
  $G_F = 1/ m_W^2 >> G_N = 1/m_P^2$?
- Or, why is
  $V_{Coulomb} >> V_{Newton}$? $e^2 >> G\, m^2 = m^2 / m_P^2$
- Set by hand? What about loop corrections?
  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- Cancel boson loops ⇔ fermions
- Need $| m_B^2 – m_F^2| < 1\ TeV^2$

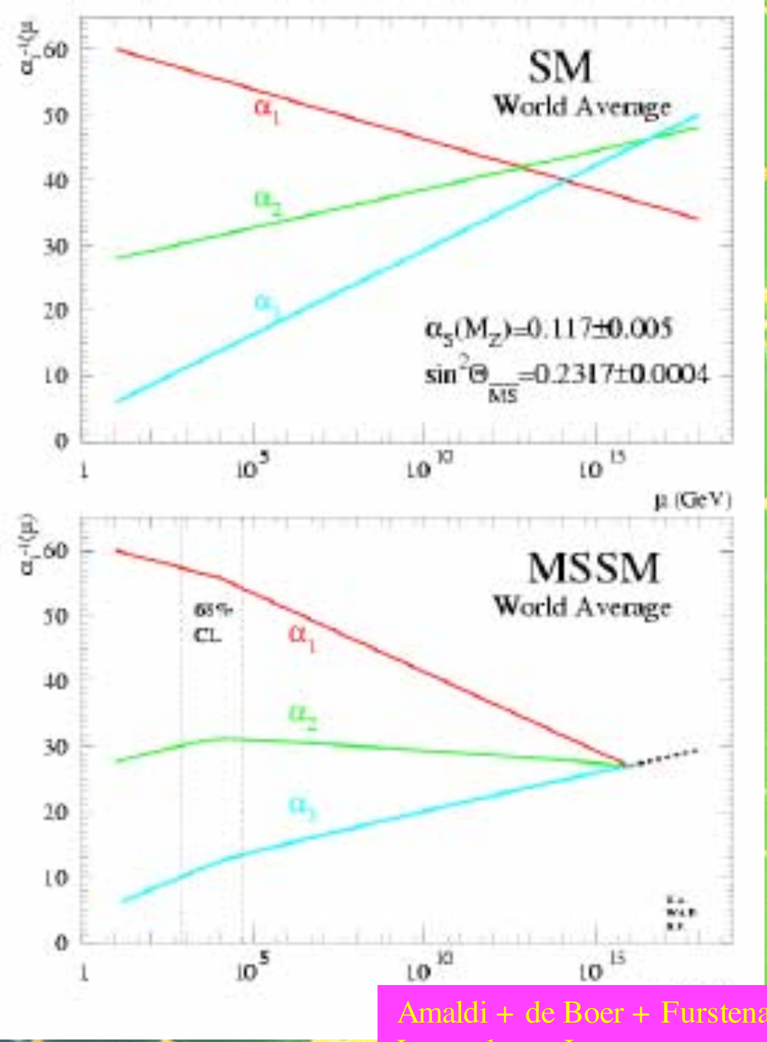
Other Reasons to like Susy

It enables the gauge couplings to unify

It stabilizes the Higgs potential for low masses



Approved by Fabiola Gianotti



Amaldi + de Boer + Furstenau,
Langacker + Luo,
JE + Kelley + Nanopoulos

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

Minimal Supersymmetric Extension of Standard Model (MSSM)

Particles + spartners + 2 Higgs doublets

- Soft supersymmetry-breaking parameters:

  Scalar masses m_0, gaugino masses $m_{1/2}$, trilinear soft couplings A_λ
- Often assume universality:

  Single m_0, single $m_{1/2}$, single A_λ
- Called constrained MSSM = CMSSM
- Gravitino mass?

  $m_{3/2} = m_0$ in minimal supergravity

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #
- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles
- Lightest supersymmetric particle (LSP) stable

Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ
    - (spartner of Z, γ, H)
  - Gravitino
    - (nightmare for dark matter detection)

Constraints on Supersymmetry

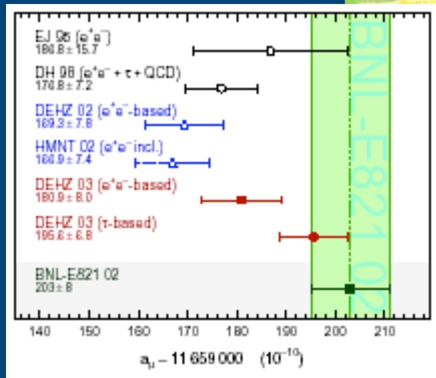
- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 250 GeV

- Indirect constraints

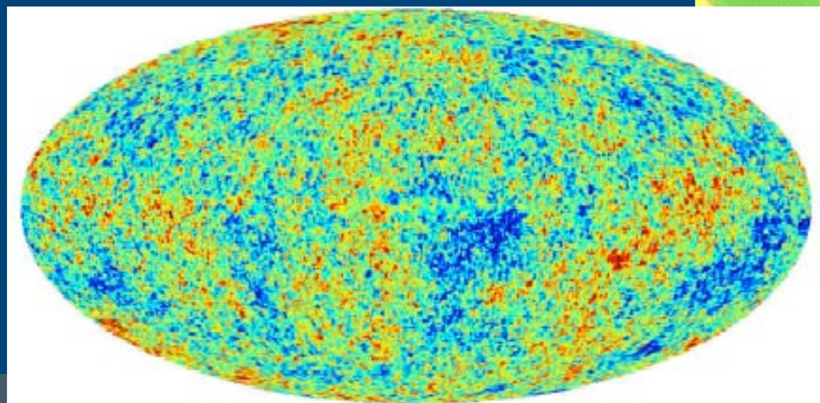
  Higgs > 114 GeV, b -> s γ g_μ - 2



- Density of dark matter

  lightest sparticle χ:

WMAP: $0.094 < \Omega_\chi h^2 < 0.124$



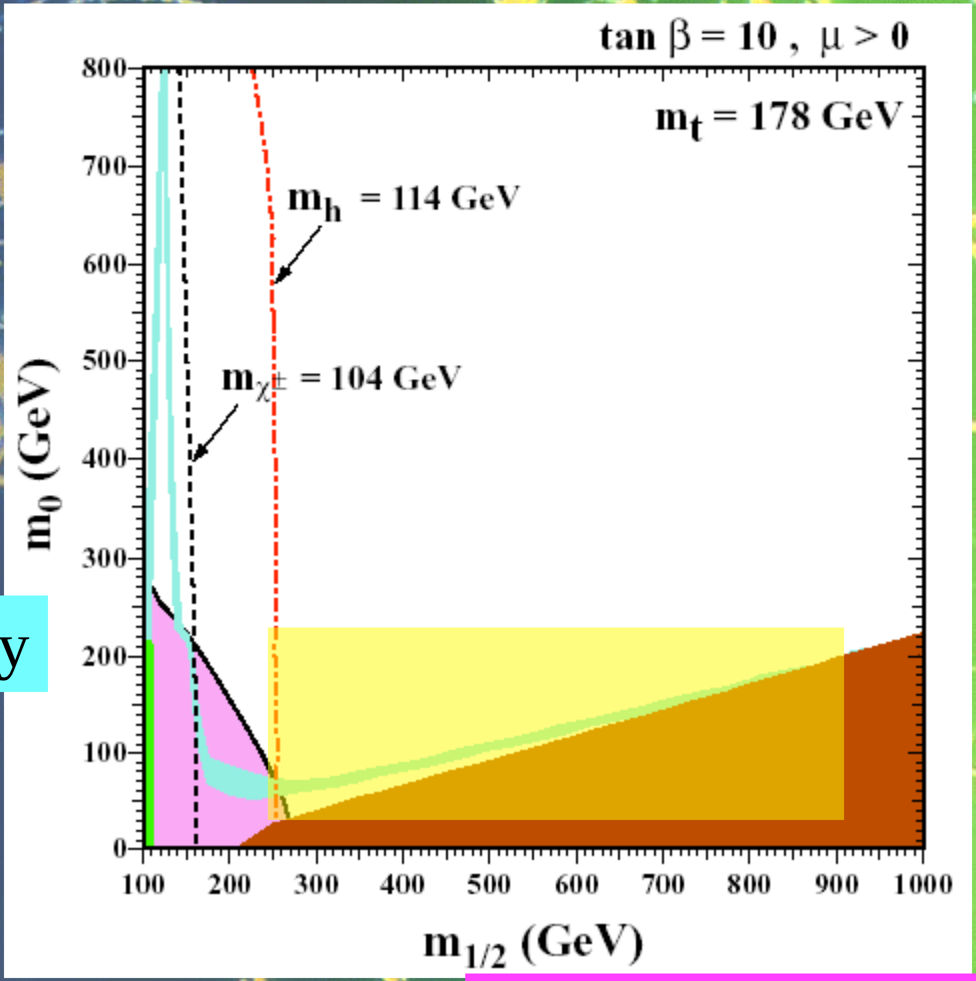
Current Constraints on CMSSM

Excluded because stau LSP

Excluded by b → s gamma

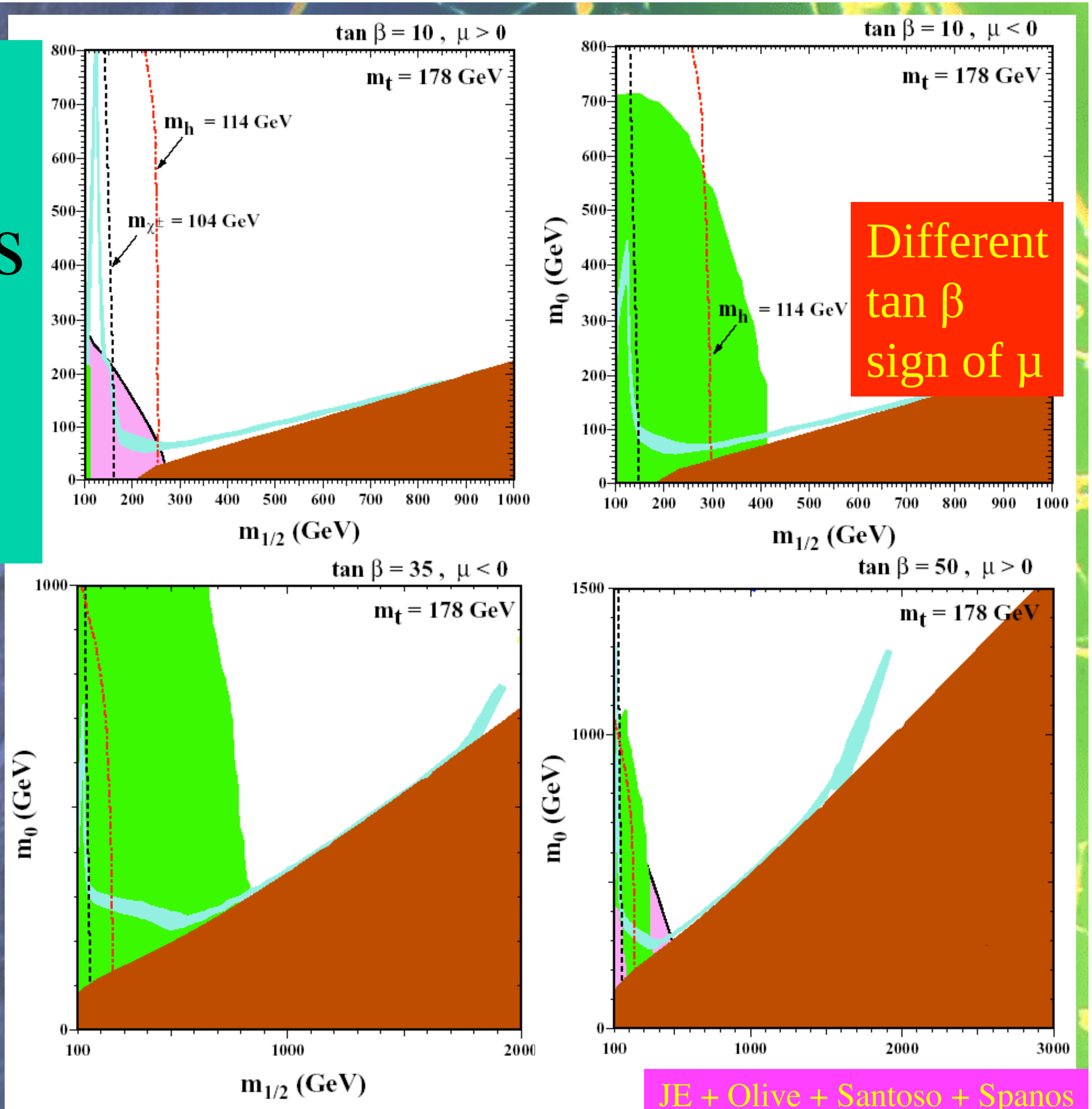
WMAP constraint on relic density

Excluded (?) by latest g - 2



JE + Olive + Santoso + Spanos

Current Constraints on CMSSM



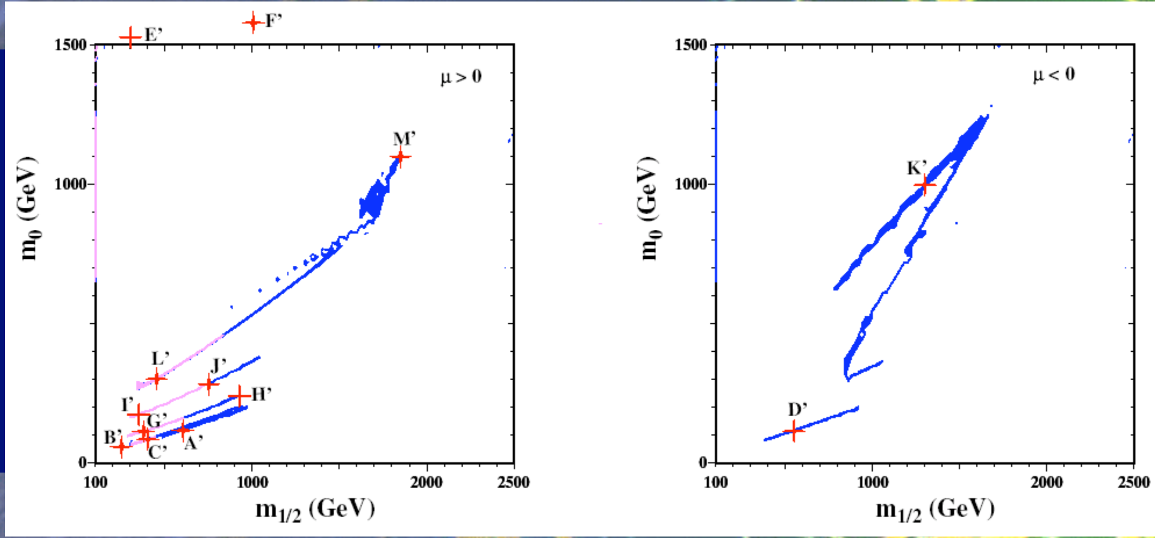
Different tan β sign of μ

Impact of Higgs constraint reduced if larger m_t, focus-point region far up

JE + Olive + Santoso + Spanos

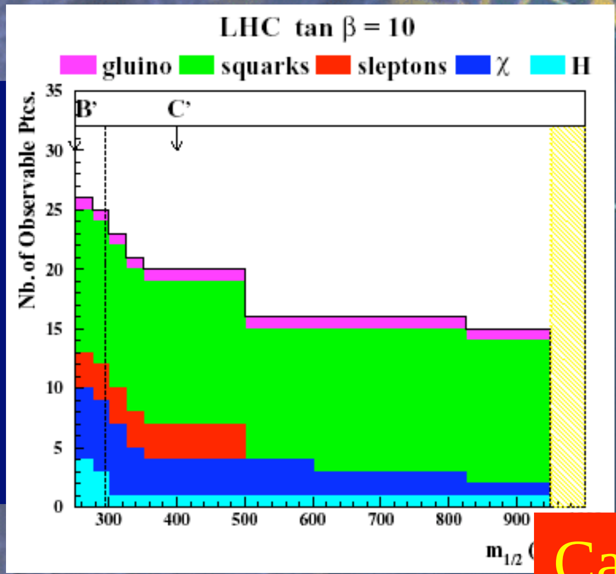
Supersymmetric Benchmark Studies

Lines in susy space allowed by accelerators, WMAP data

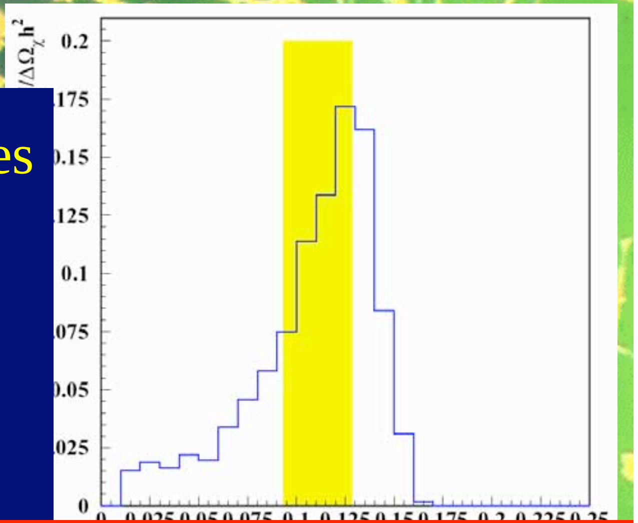


Specific benchmark Points along WMAP lines

Sparticle Detectability @ LHC along one WMAP line



LHC enables calculation of relic density at a benchmark point

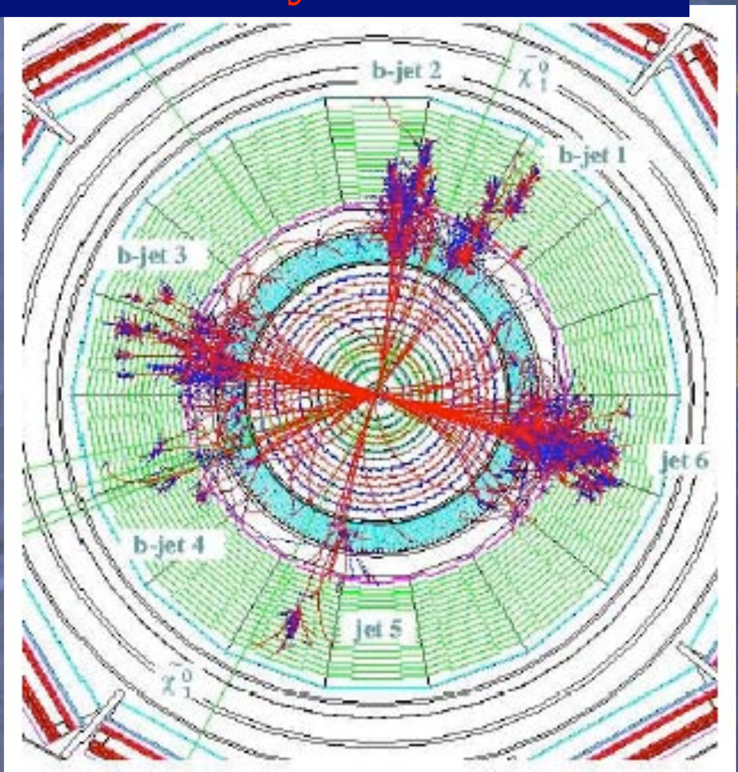


Can be refined with LC measurements

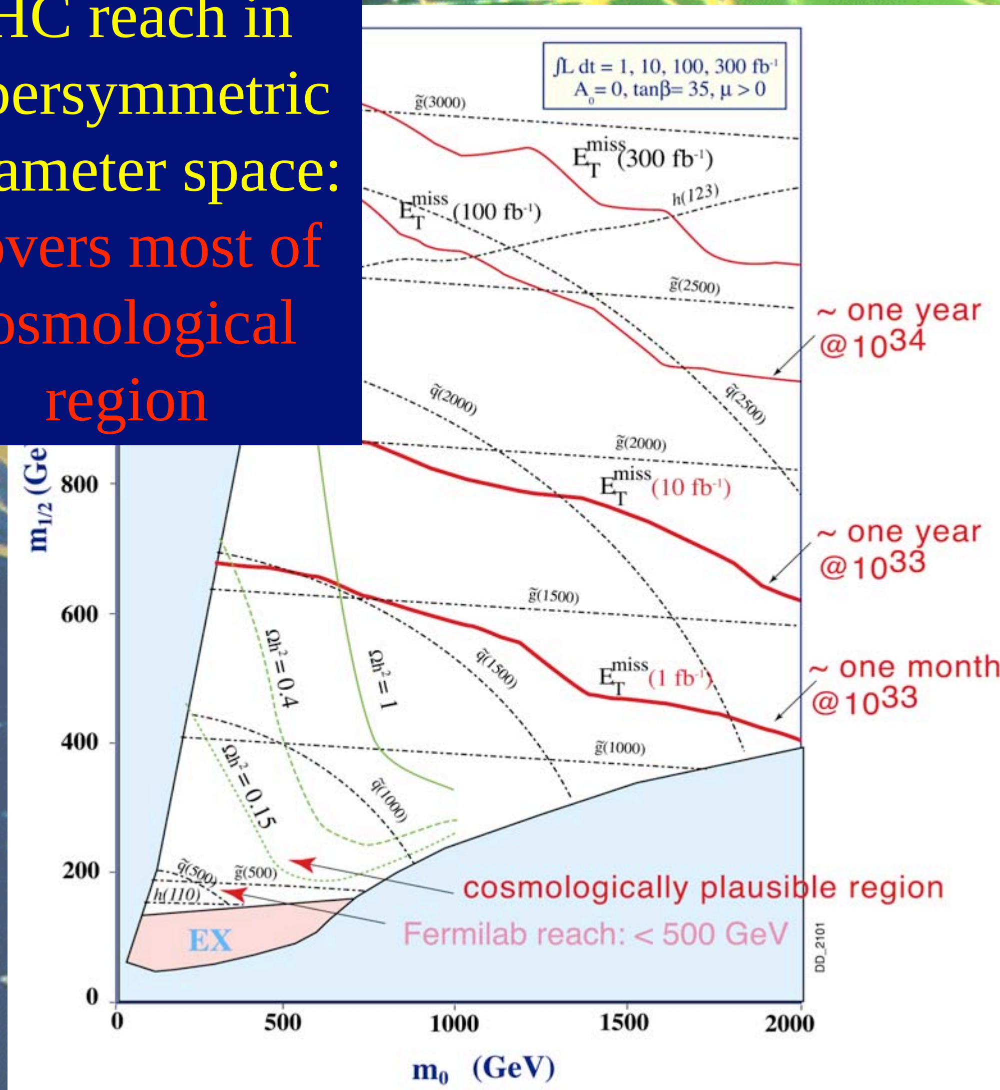
Battaglia et al

Supersymmetry Searches at LHC

`Typical' supersymmetric Event at the LHC:
'Easy' to see

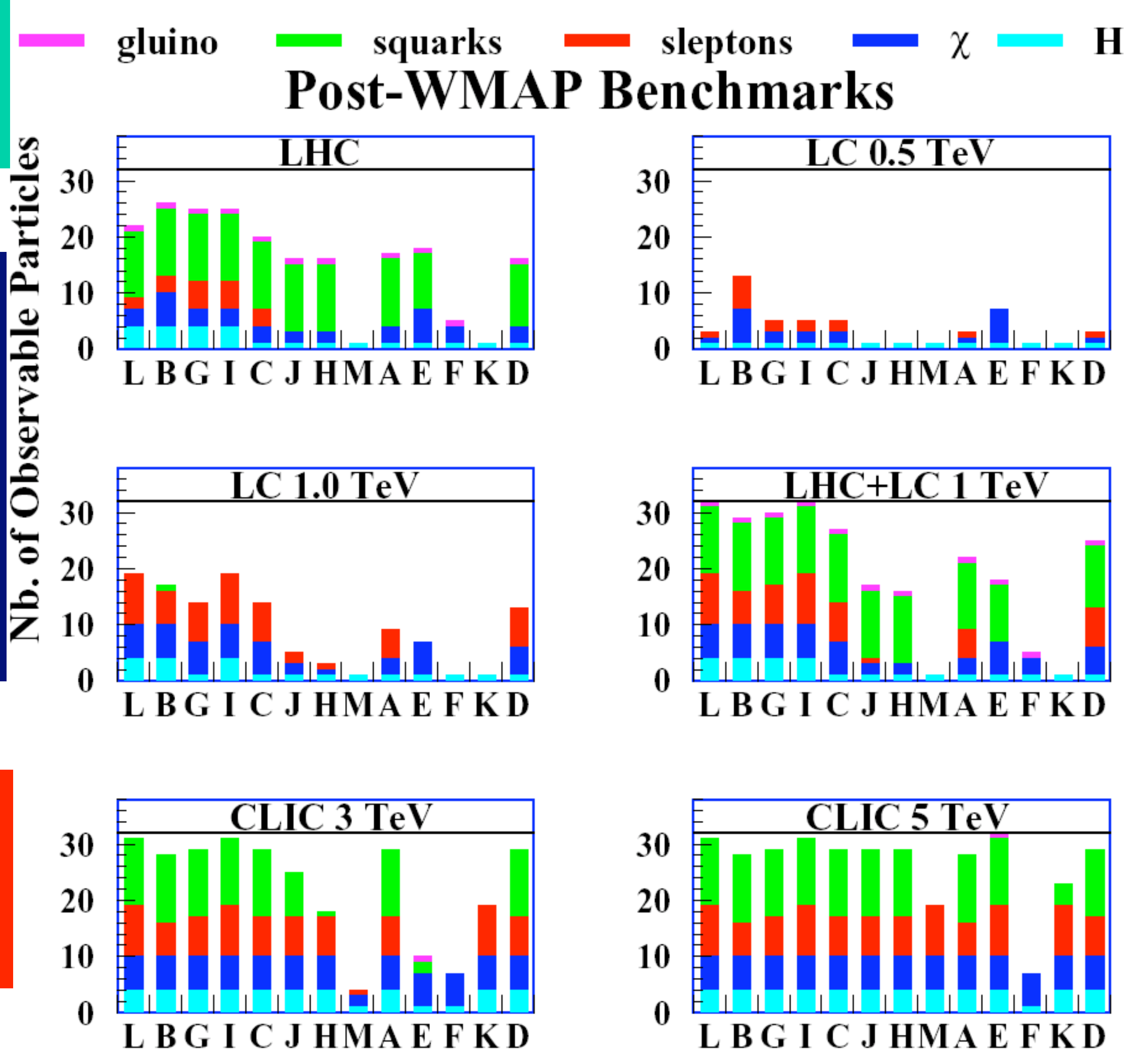


LHC reach in supersymmetric parameter space:
Covers most of cosmological region



LHC and LC Scapabilities

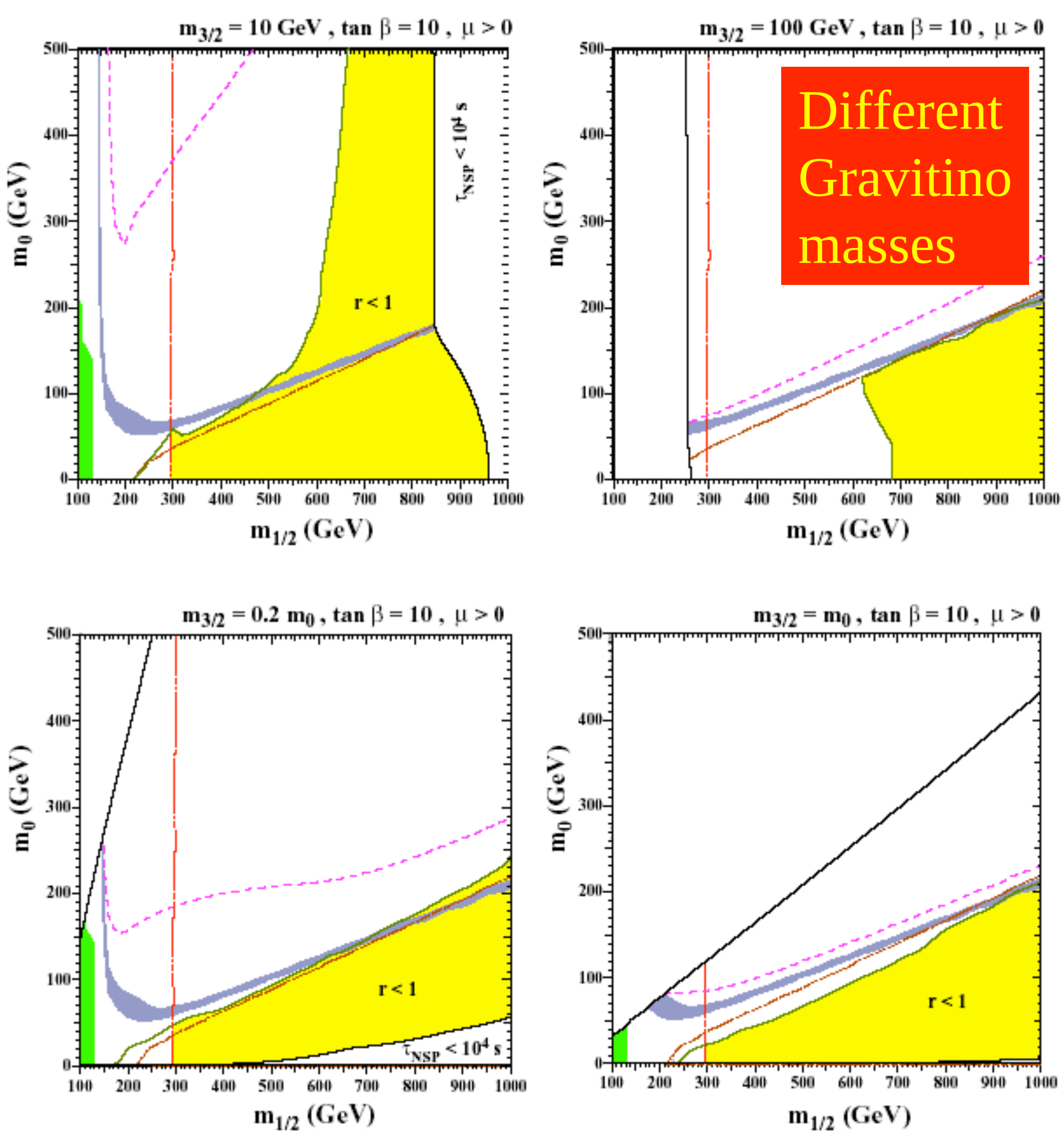
LHC almost
`guaranteed'
to discover
supersymmetry
if it is relevant
to the mass problem



LC oberves
complementary
sparticles

Battaglia et al

Different Regions of Sparticle Parameter Space if Gravitino LSP



Different Gravitino masses

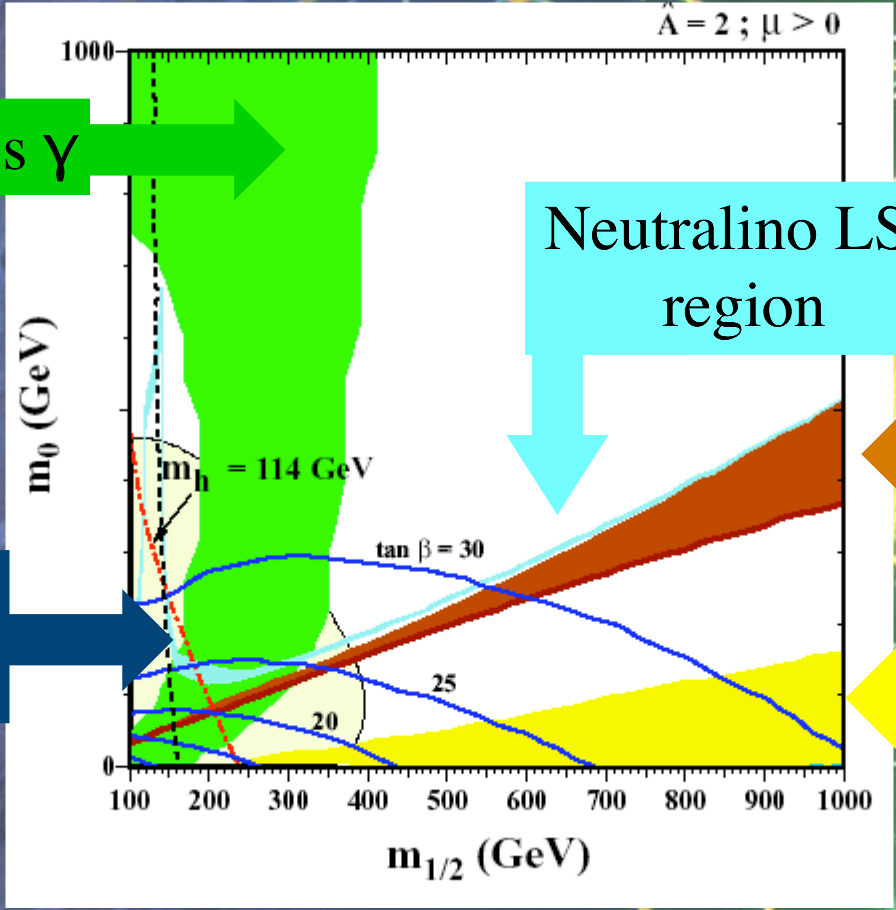
Density below WMAP limit

Decays do not affect BBN/CMB agreement

JE + Olive + Santoso + Spanos

Minimal Supergravity Model

$m_0 = m_{3/2}$



Excluded by b → s γ

Neutralino LSP region

stau LSP (excluded)

LEP constraints On m_h, chargino

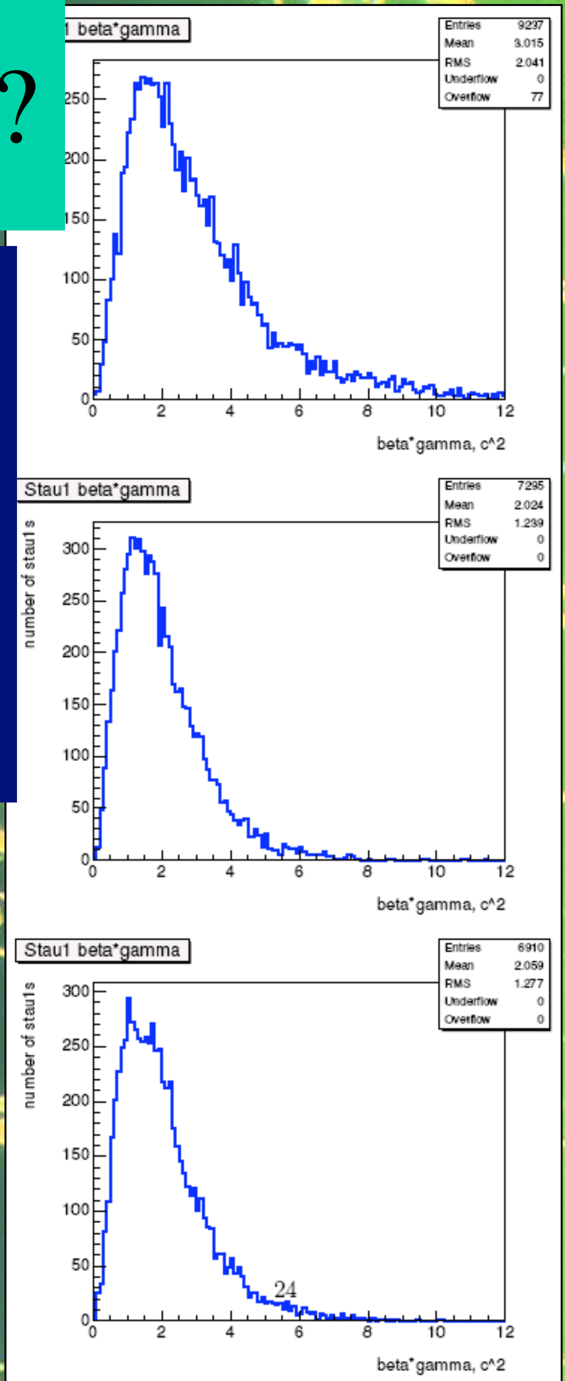
Gravitino LSP Region: Metastable stau: lifetime > 10^4s

JE + Olive + Santoso + Spanos

Slepton Trapping at the LHC?

- βγ typically peaked ~ 2
- Staus with βγ < 1 leave central tracker after next beam crossing
- Staus with βγ < ¼ trapped inside calorimeter
- Staus with βγ < ½ stopped within 10m
- **Can they be dug out?**

Benchmark scenarios →	ϵ	ζ	η
Number of particles with $\beta\gamma < 0.25$	850	7	7
Range in C (cm)	60	136	129
Range in Fe (cm)	29	65	61
Number of particles with $\beta\gamma < 0.5$	7700	100	90
Range in C (cm)	600	1360	1290
Range in Fe (cm)	290	650	610



De Roeck, JE, Gianotti, Moortgat, Olive + Pape

Extract Cores from Surrounding Rock?

- Use muon system to locate impact point on cavern wall with uncertainty < 1cm
- Fix impact angle with accuracy 10^{-3}
- Bore into cavern wall and remove core of size 1cm × 1cm × 10m = $10^{-3}m^3$ ~ 100 times/year
- Can this be done before staus decay?

  Caveat radioactivity induced by collisions!

  2-day technical stop ~ 1/month
- Not possible if lifetime ~10^4s, possible if ~10^6s?

De Roeck, JE, Gianotti, Moortgat, Olive + Pape

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

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

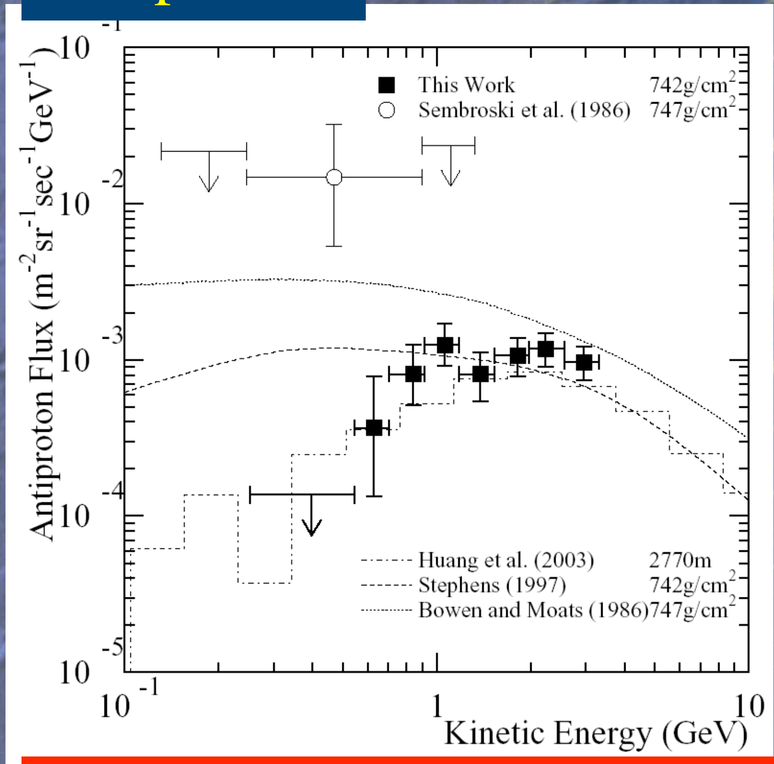
  $\chi - \chi \rightarrow \gamma + \ldots?$
- Annihilation in core of Sun or Earth

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

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

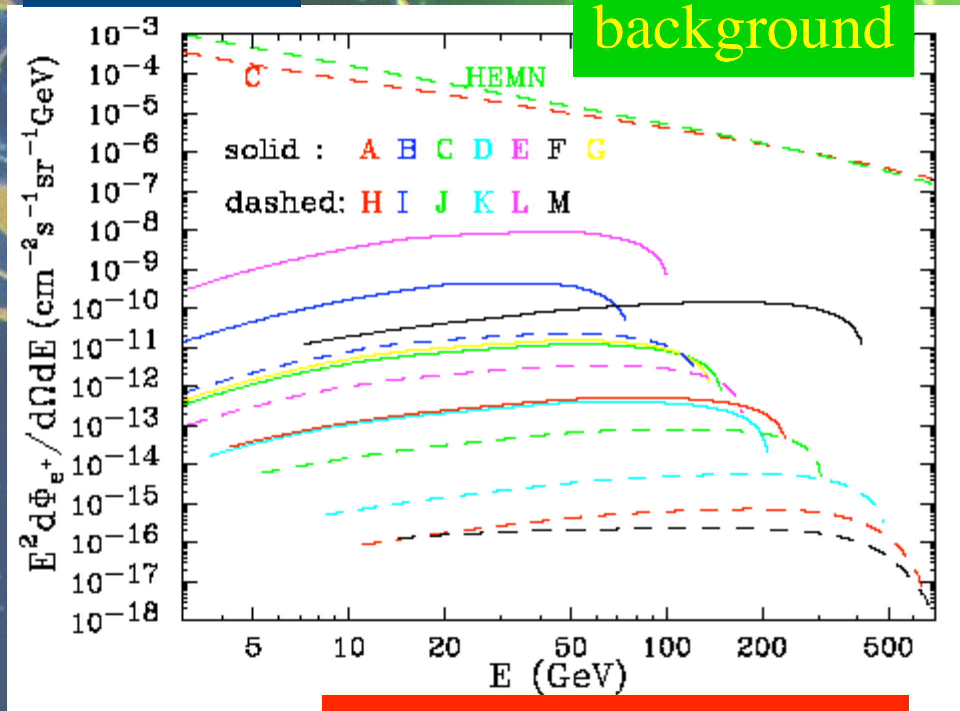
Annihilation in Galactic Halo

Antiprotons



Consistent with production by primary matter cosmic rays

Positrons

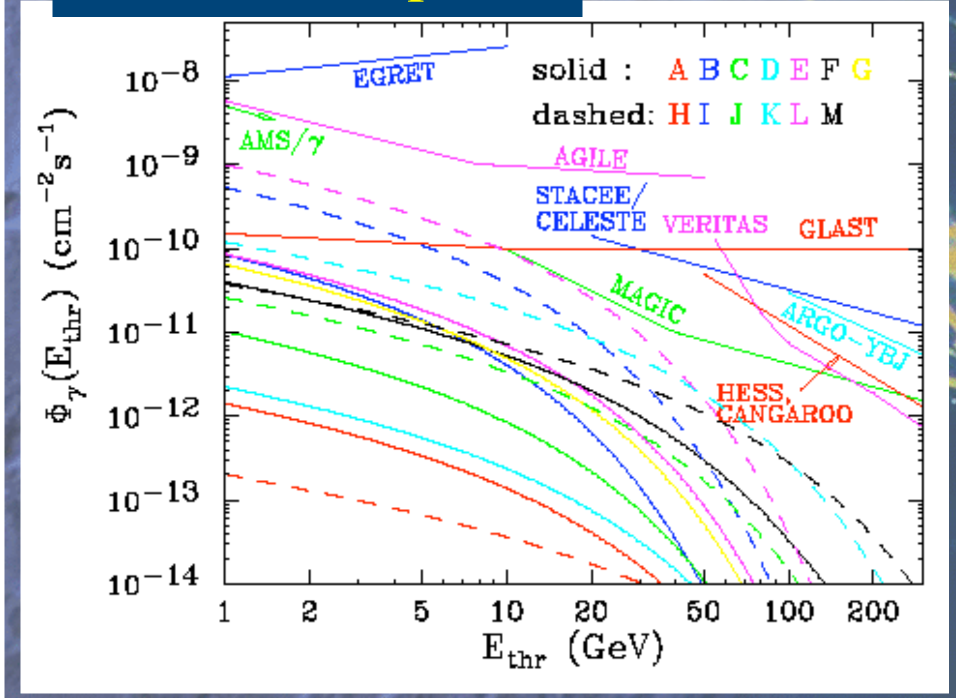


Cosmic-ray background

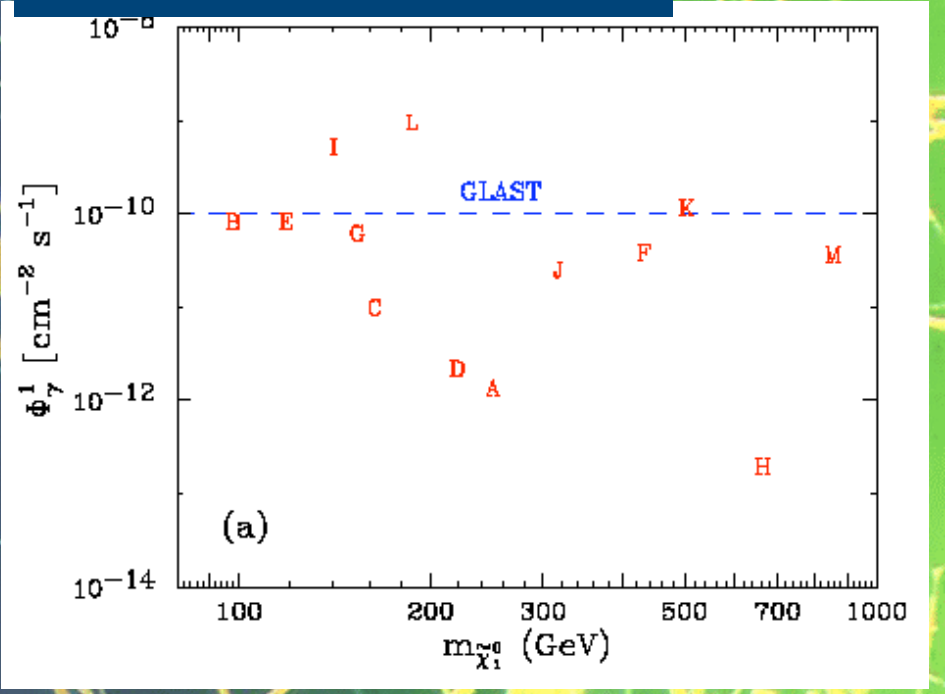
Benchmark scenarios

Annihilations in Galactic Centre

Benchmark spectra



Benchmarks → GLAST

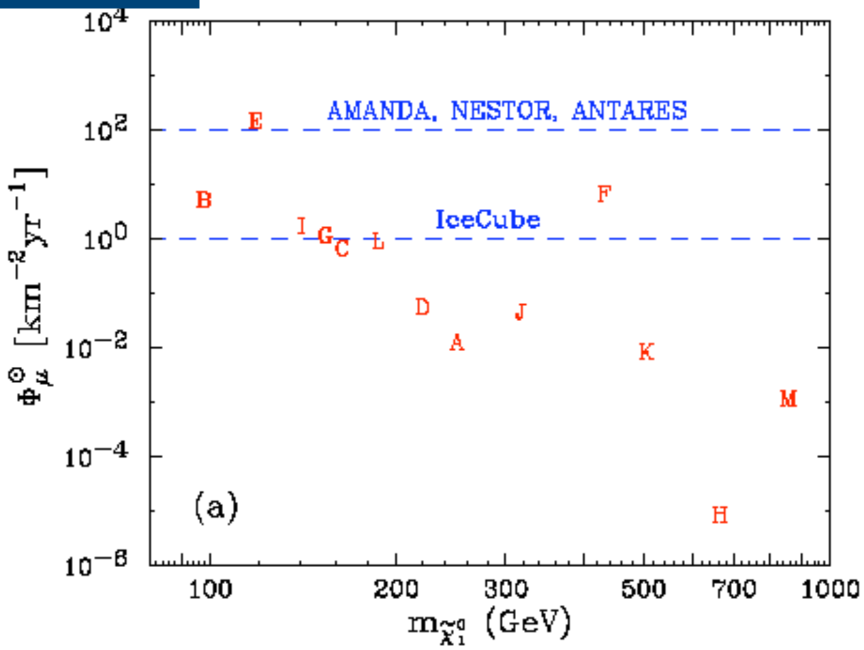


Enhancement of rate uncertain by factor > 100!

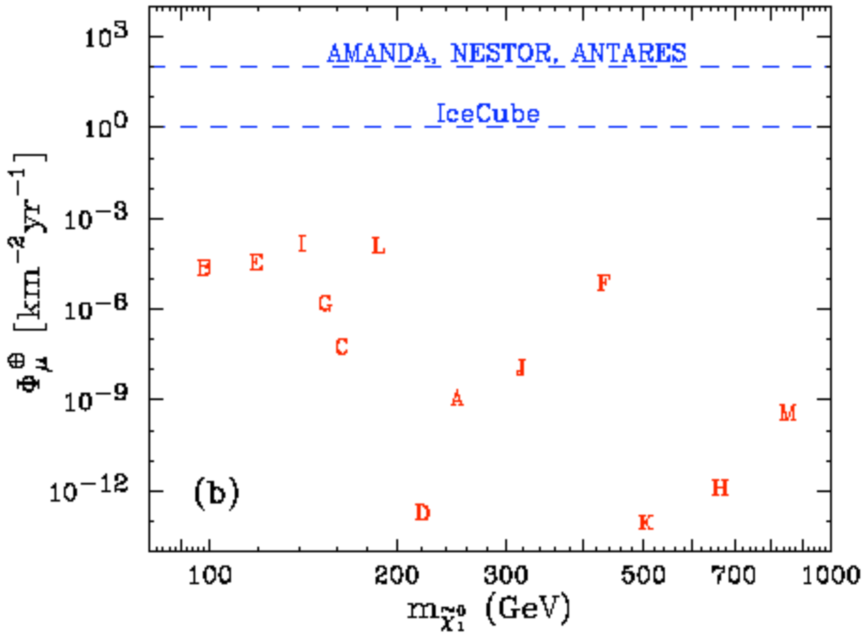
JE + Feng + Matchev + Olive

Annihilations in Solar System …

… Sun



… Earth



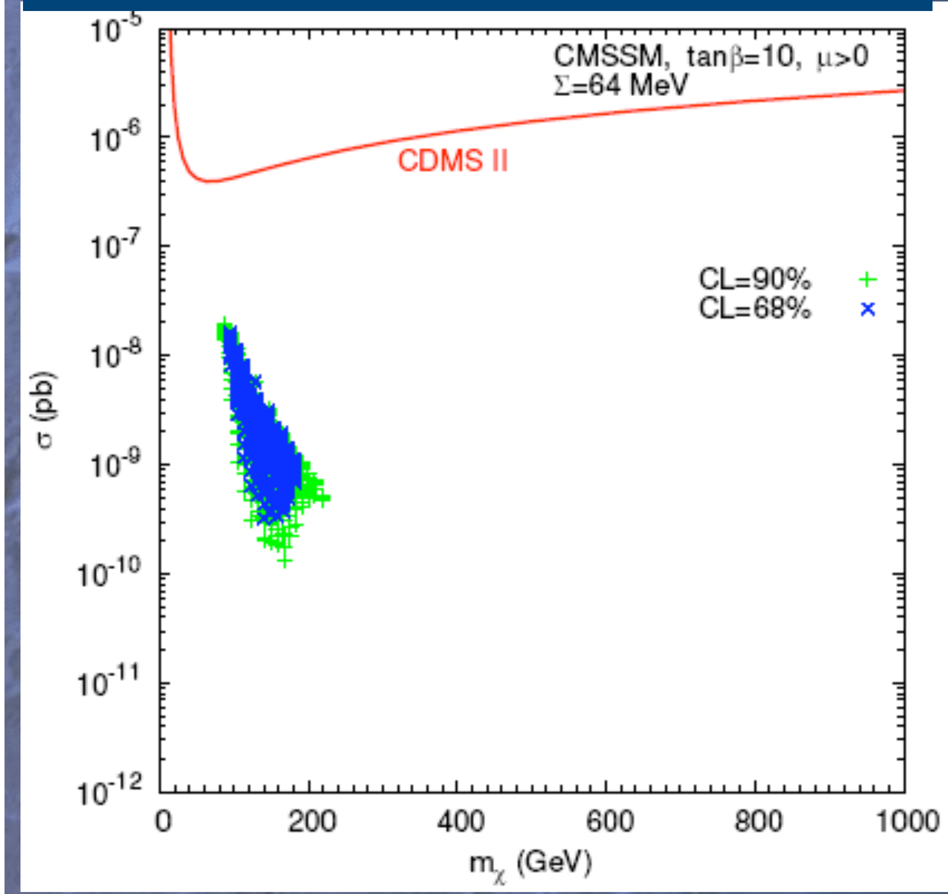
Prospective experimental sensitivities

Benchmark scenarios

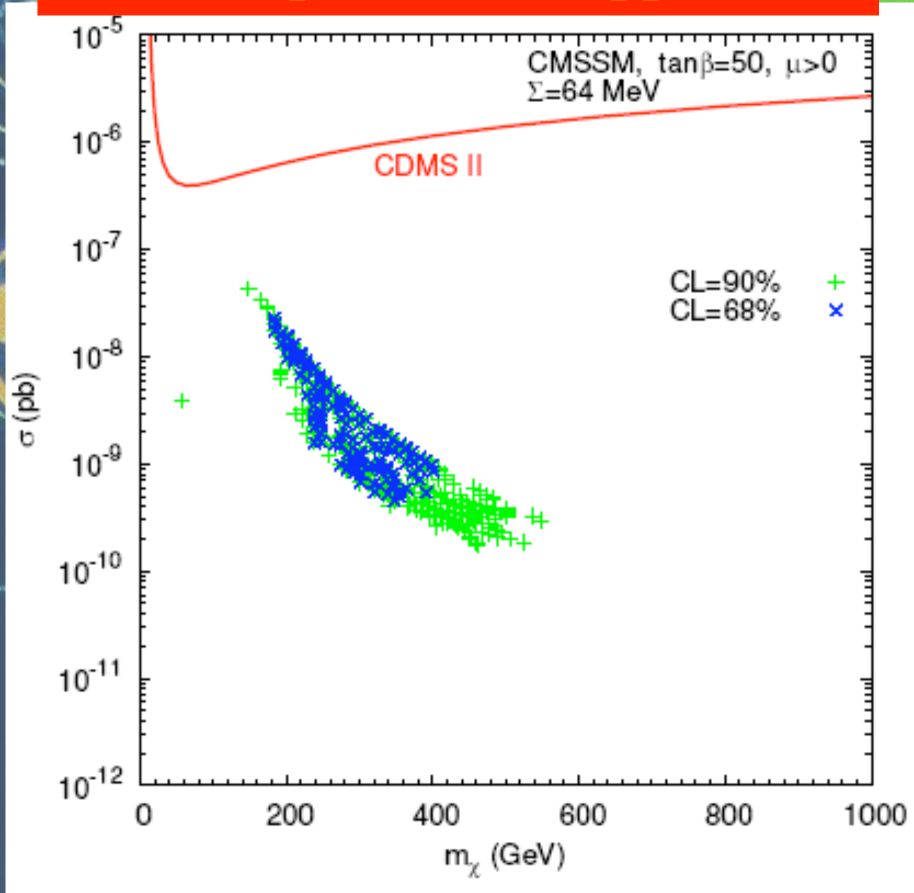
JE + Feng + Matchev + Olive

Elastic Scattering Cross Sections

From global fit to accelerator data



Latest experimental upper limit



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

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