The Abdus Salam
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United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

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SUMMER SCHOOL ON PARTICLE PHYSICS

13 - 24 June 2005

Astroparticle Physics - Part 1

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Astroparticle physics

A vast field, in which we will take a winding path starting from the lowest energies to the highest energies.

The lowest energy: the inverse size of the universe, $H \sim 10^{-42}$ **GeV**.

The highest energy: probably, the Planck scale, $m_{\rm pl} \sim 10^{19}$ **GeV**.

Astroparticle physics

The smallest energy scale available is the inverse size of the universe, $H \sim 10^{-42}$ **GeV**.

On this scale, one observes an expanding universe. It is remarkable that, by observing this expansion, one can learn about the contents of the universe and the new physics to be discovered. We will discuss **dark energy**, **dark matter**, **ordinary matter**, etc.

These will lead us to concepts of **supersymmetry**, **neutrino physics**, **new physics at colliders**, **ultrahigh-energy cosmic rays**... (*cf.* related material in the other lectures)

Cosmology espresso

- Einstein's equations, Robertson-Walker metric, Friedman equation
- Expansion of a universe filled with
  - radiation
  - matter
  - cosmological constant

Robertson – Walker metric

Metric $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$ determines the space-time geometry in coordinates $x^\mu \equiv \{t, x^i\}$. A homogeneous and isotropic space is described by the Robertson-Walker metric $ds^2 = dt^2 - \vec{dl}^2$ ($\vec{dl}^2 = h_{ij} x^i x^j$) in spherical coordinates:

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right], \qquad (1)$$

where k can be chosen to be 1, (-1), or 0 without loss of generality.

Einstein's equation

The action comprises contributions for matter fields S_M and gravity S_{HE} (Hilbert-Einstein):

$$S = \int d^4x \sqrt{-g}(\mathcal{R} + 2\Lambda + \mathcal{L}_{\rm fields}), \quad (2)$$

where $\mathcal{R} = -8\pi G T^\mu_\mu$ and $T_{\mu\nu}$ is the energy-momentum tensor (defined as a variation of the action with respect to the metric).
Variation of S with respect to metric, $\delta S/\delta g_{\mu\nu} = 0$. This yields the Einstein's equations:

$$\boldsymbol{R_{\mu\nu} - \frac{1}{2}\mathcal{R} g_{\mu\nu} = 8\pi G\, T_{\mu\nu} + \Lambda g_{\mu\nu}} \quad (3)$$

Symmetries, isotropy $\Rightarrow T^{\mu\nu} = \mathrm{diag}(\rho, -p, -p, -p)$. Here ρ is density and p is pressure.

Examples of energy-momentum tensors

Gas of relativistic particles: $p = \rho/3$

Gas of non-relativistic particles: $p \approx \left(\frac{v^2}{c^2}\right) \rho/3 \ll \rho$

cosmological constant Λ: $T_{\mu\nu} = \Lambda \delta_{\mu\nu}$
In terms of density and pressure, $T^{\mu\nu} = \mathrm{diag}(\rho, -p, -p, -p)$, $p = -\rho$.
Pressure is negative !

NB. $T_{00} \geq 0$, conserved: $T^{\mu\nu}{}_{;\nu} = 0$

Thermodynamics

Energy conservation, $T^{0\nu}{}_{;\nu} = 0$ gives the 1st Law of Thermodynamics:

$$d(\rho a^3) = -p\, d(a^3) \tag{4}$$

(change in energy in comoving volume = work)

Equation of state relates density and pressure. Let us *assume* that

$$p = w\rho, \; w = \text{const} \tag{5}$$

From $d(\rho a^3) = -pd(a^3)$, one obtains

$$\rho \propto a^{-3(1+w)} \tag{6}$$

in particular, for different components, one obtains different scaling laws:

radiation	$p=\frac{1}{3}\rho, w=1/3$	$\boldsymbol{\rho \propto a^{-4}}$
matter	$p=0, w=0$	$\boldsymbol{\rho \propto a^{-3}}$
cosmological constant	$p=-\rho=\Lambda, w=-1$	$\boldsymbol{\rho \propto a^{0}} = \mathrm{const}$

Substitute expressions for the Ricci tensor and scalar in RW metric into the Einstein's equation $R_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} = 8\pi G\, T_{\mu\nu} + \Lambda g_{\mu\nu}$. The $\{00\}$ component gives the

Friedman equation:

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \tag{7}$$

The $\{ii\}$ component yields

$$2\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = 8\pi G p \tag{8}$$

Subtracting (7) from (8), one obtains

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \tag{9}$$

Examine

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p). \tag{10}$$

Today the universe is expanding, hence, $\dot{a} > 0$. If $(\rho + 3p) > 0$ at all times (*e.g.*, matter or radiation), then $\ddot{a} < 0$. Therefore, $\dot{a}$ is positive, and is a decreasing function of time.

Therefore, at some $t = 0$, $a = 0$. $\Rightarrow$ **Big Bang**

The Big Bang is a consequence of general relativity and today's expansion, assuming the universe energy density has been dominated by matter or radiation.

Red shift

Expansion of the universe causes a change in the photon wavelength, as well as in distances between objects that are not gravitationally bound.

Red shift:

$$1 + z \equiv \frac{\lambda(t_0)}{\lambda(t)} = \frac{a(t_0)}{a(t)} \tag{11}$$

The Hubble constant

$$H \equiv \frac{\dot{a}}{a} \tag{12}$$

From Friedman equation (7),

$$(H)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \tag{13}$$

Not really a constant. Hubble's Law:

$$z = H_0 d_L + \frac{1}{2}(q_0 - 1)(H_0 d_L)^2 + ... \tag{14}$$

Observations: $H_0 = (71 \pm 7)\mathrm{km/s/Mpc} \approx 1.4 \times 10^{-42}$ **GeV** today.
One defines *critical density*:

$$\rho_c = \frac{3H^2}{8\pi G} = 3H^2 \tilde{m}_{Pl}^2 \quad (15)$$

The case $\rho = \rho_c \Leftrightarrow k = 0$.
One usually presents the energy density (15) in dimensionless units:

$$\Omega = \rho/\rho_c \quad (16)$$

Expansion of the universe

For $p = w\rho$, Friedman equations yield

$$\rho \propto a^{-3(1+w)} \quad (17)$$

$$a(t) \propto t^{2/3(1+w)} \quad (18)$$

radiation	$p = \frac{1}{3}\rho, w = 1/3$	$\rho \propto a^{-4}$	$a \propto t^{1/2}$
matter	$p = 0, w = 0$	$\rho \propto a^{-3}$	$a \propto t^{2/3}$
cosm. const.	$p = -\rho = \Lambda, w = -1$	$\rho \propto \mathrm{const}$	$a \propto \exp(Ht)$

measure expansion to find out the composition of the universe!

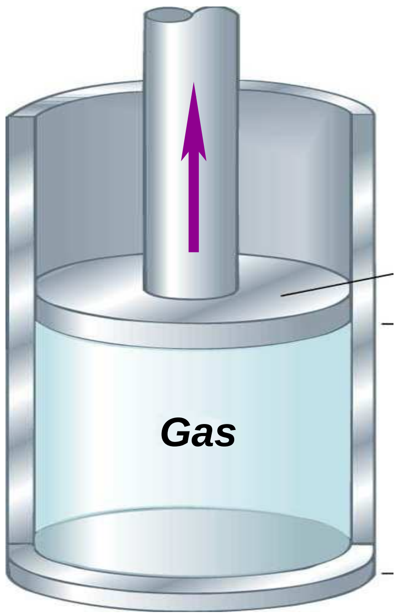
How can negative pressure cause a rapid expansion?

Simple analogy

Expanding gas: work equals the change in energy,

$$\Delta E = -p\Delta V$$

Expansion corresponds to a decrease in E, in accord with $p > 0$.



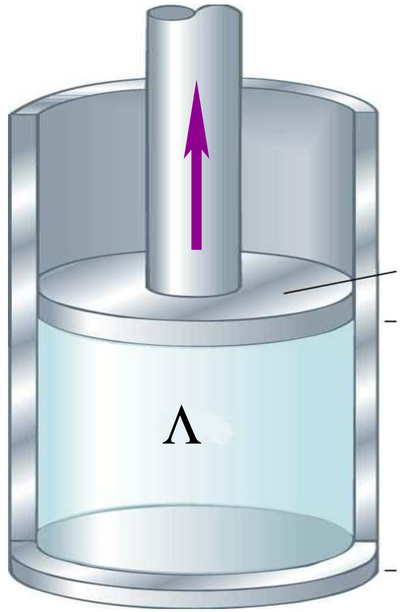
Simple analogy

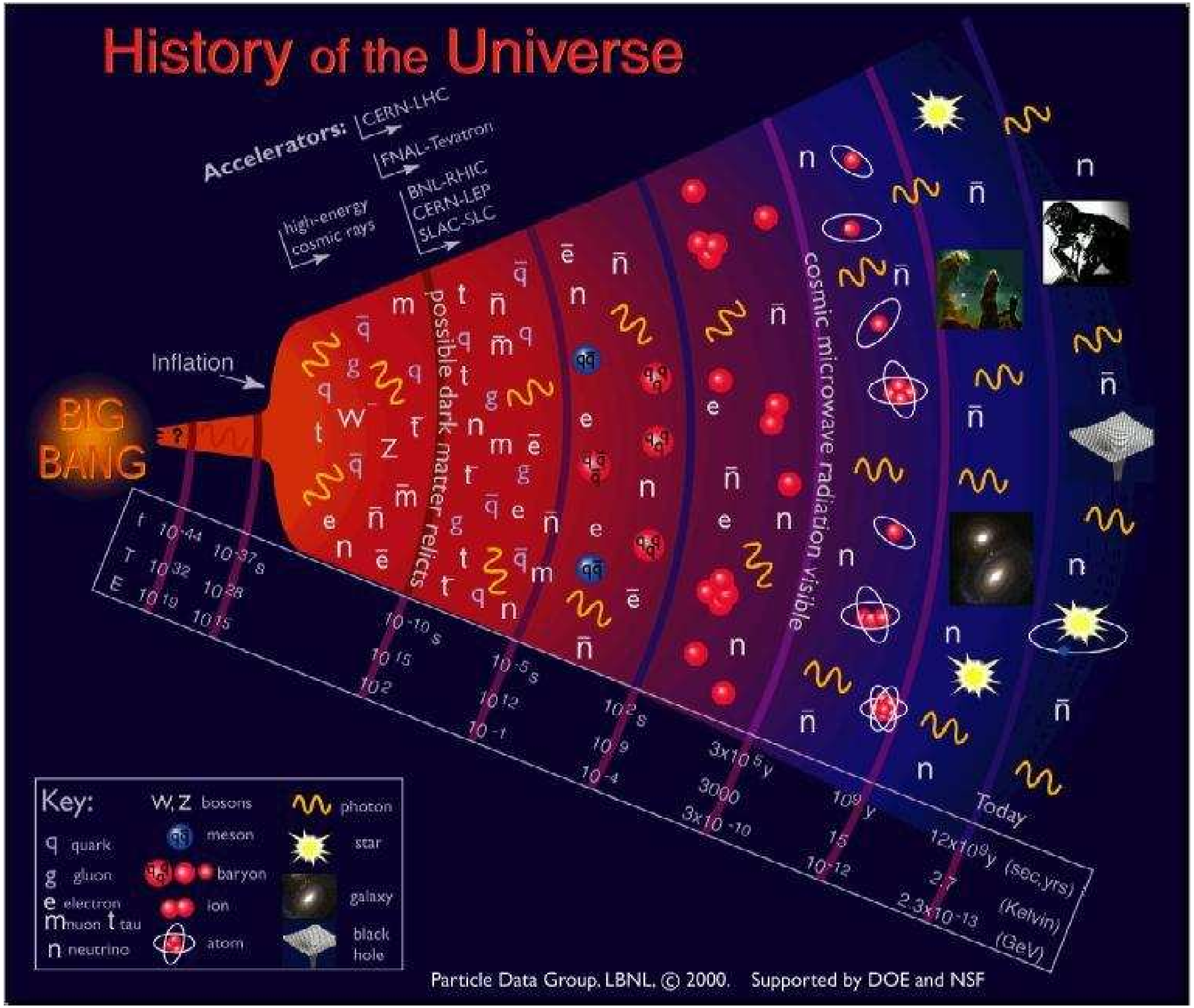
Cosmological constant: integral $\int(\Lambda)\sqrt{-g}d^3x$ increases as the volume increases.

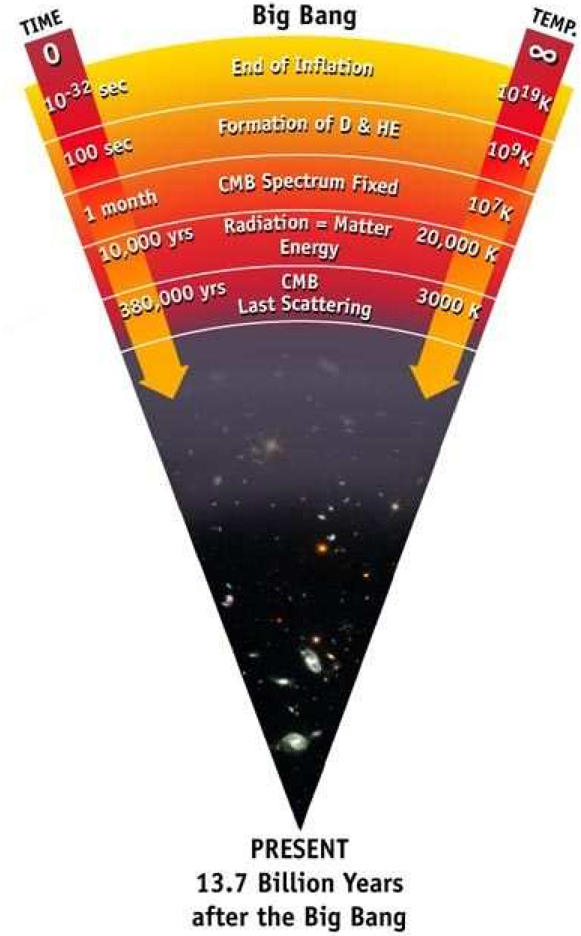
$\Delta E = -p\Delta V$

Energy increases $\Longrightarrow$ work must be negative.

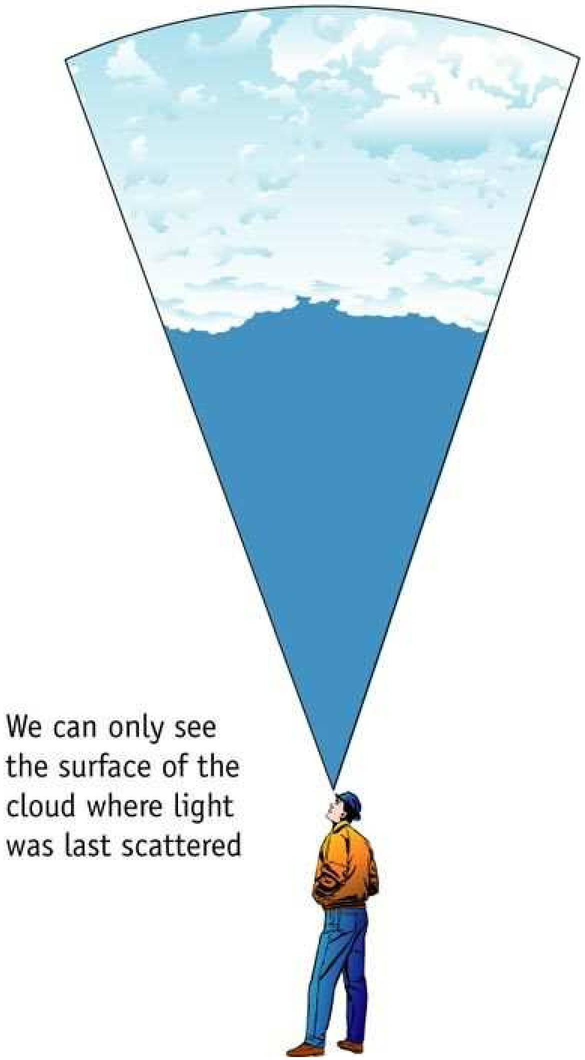
$p < 0$.




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

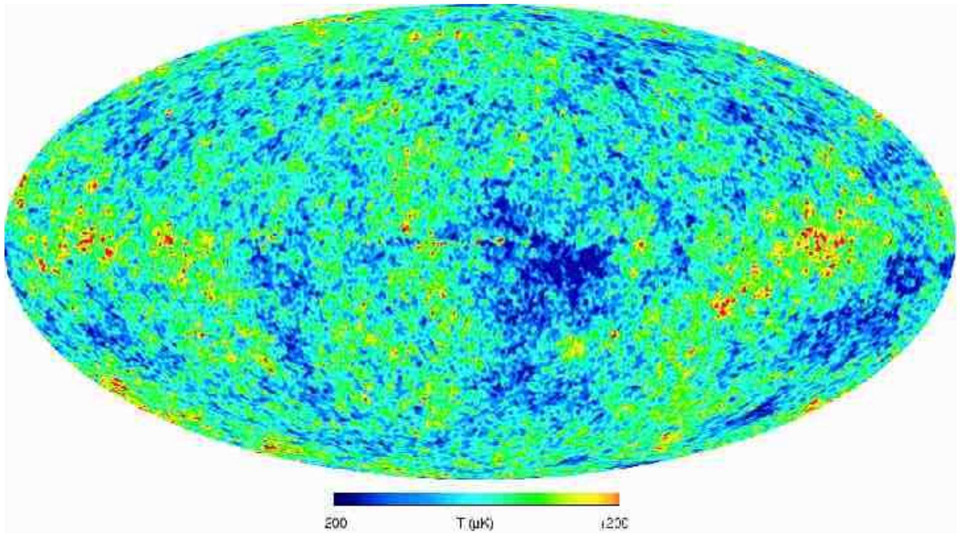


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



Cosmic microwave background radiation (CMBR)

At redshift $z_{\rm dec} = 1089 \pm 1$, the atoms formed and the universe became transparent to radiation. Radiation emitted at that time, $t_{\rm dec} = (379 \pm 8)$ kyr, has been red-shifted into the microwave range. Fluctuations have been measured first by COBE, and later by BOOMERANG, MAXIMA, ..., WMAP:



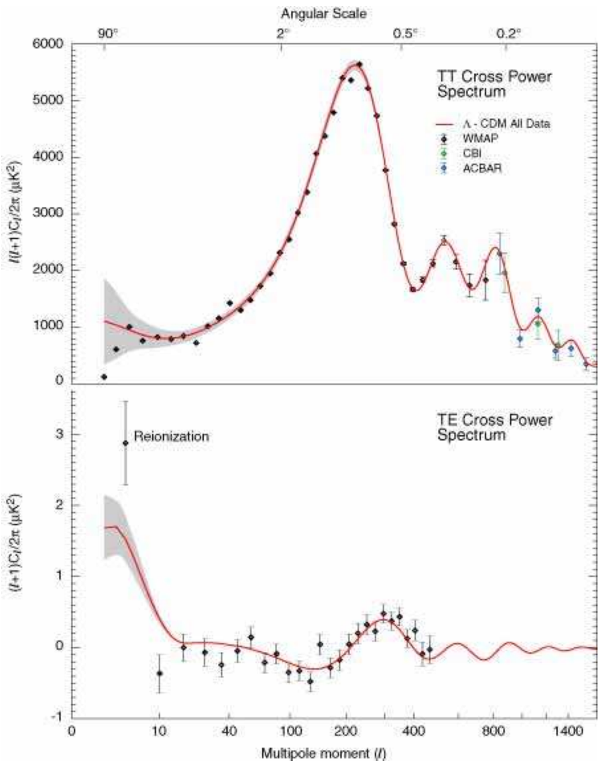
These fluctuations can be represented in the form of a power spectrum C_l. First, one expands in spherical harmonics:

$$\frac{\Delta T}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi)$$

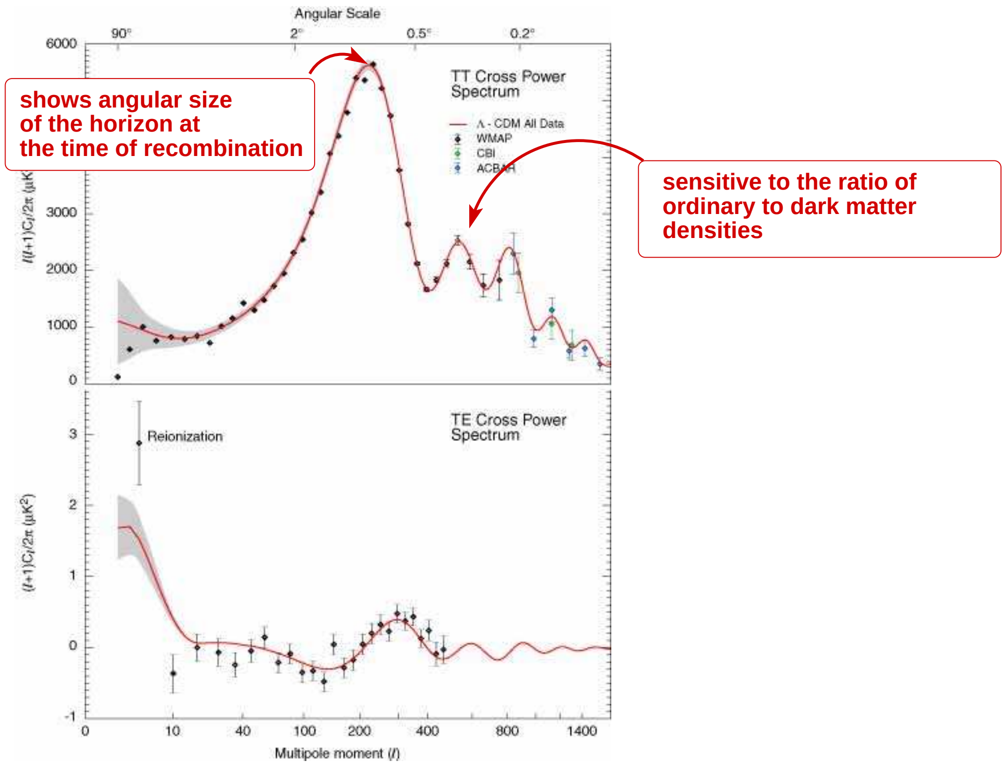
And then one plots

$$C_l \equiv \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

Power spectrum measured by WMAP

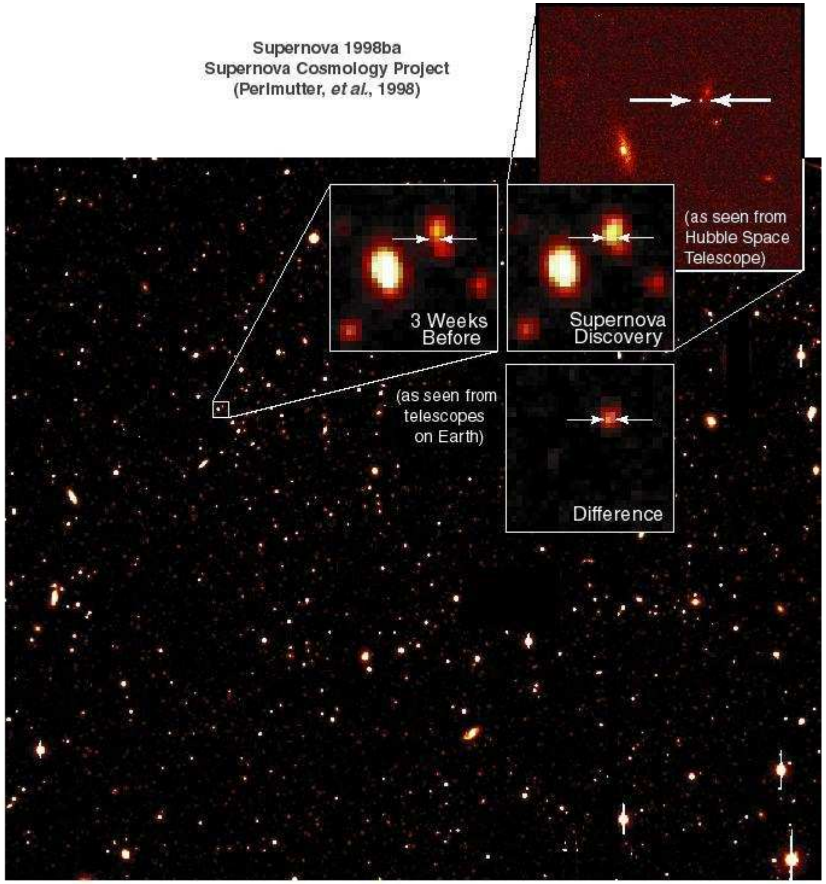


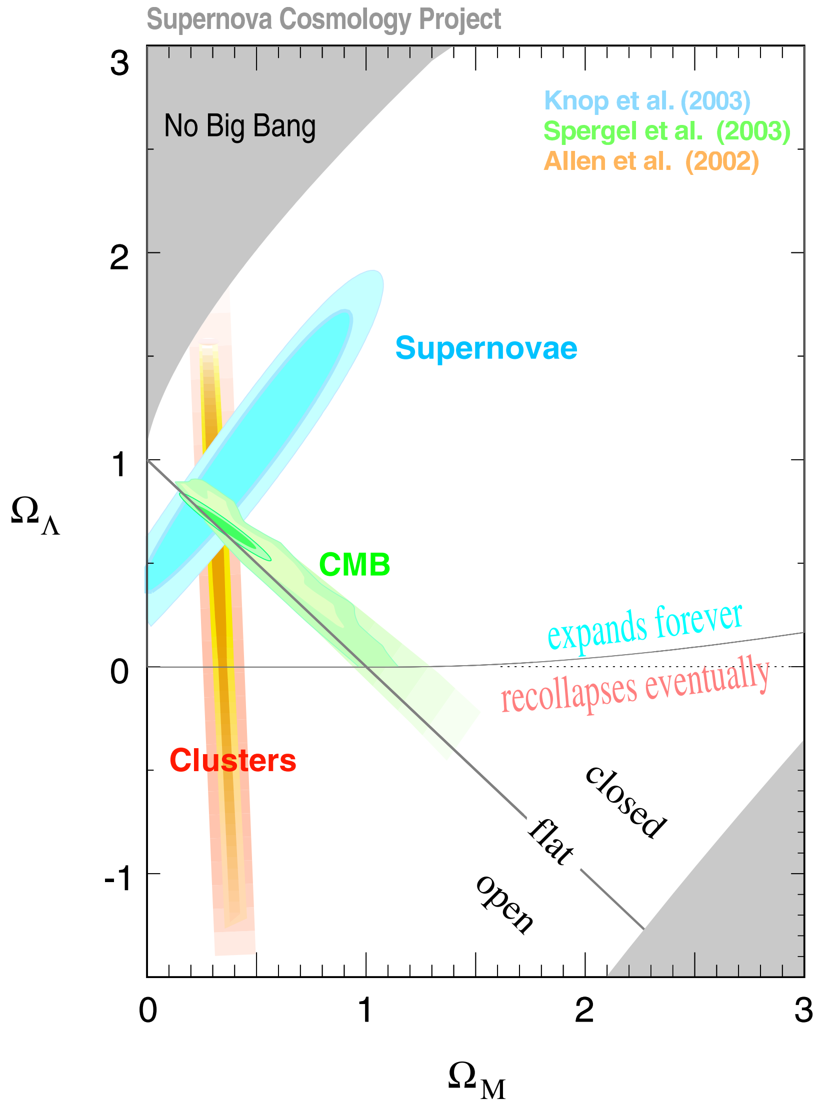
Power spectrum measured by WMAP



The first peak shows the angular size of the horizon at recombination.

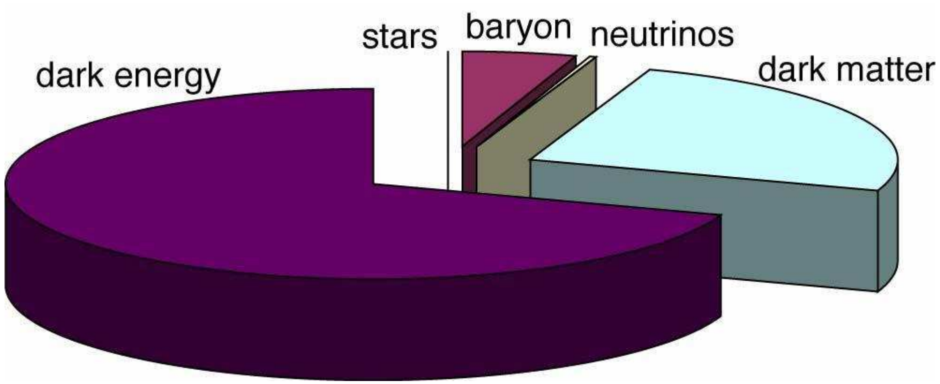
Another way: type 1a supernovae




Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

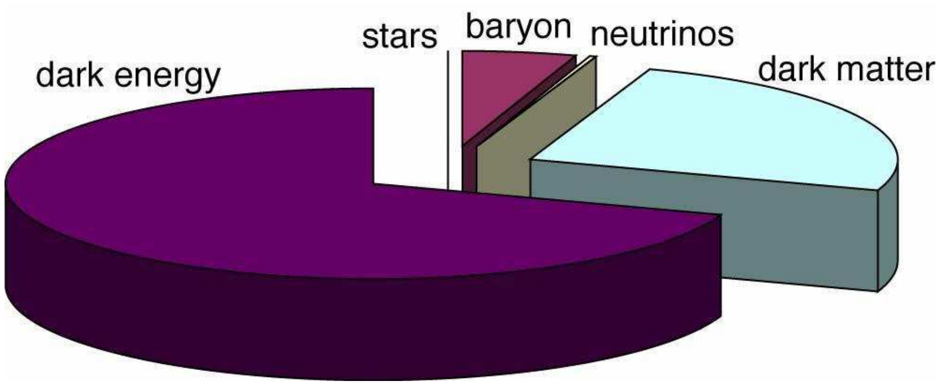
The universe

- 3% ordinary matter
- 27% dark matter
- 70% dark energy (possibly, cosmological constant)



Cosmological Uncertainty Principle

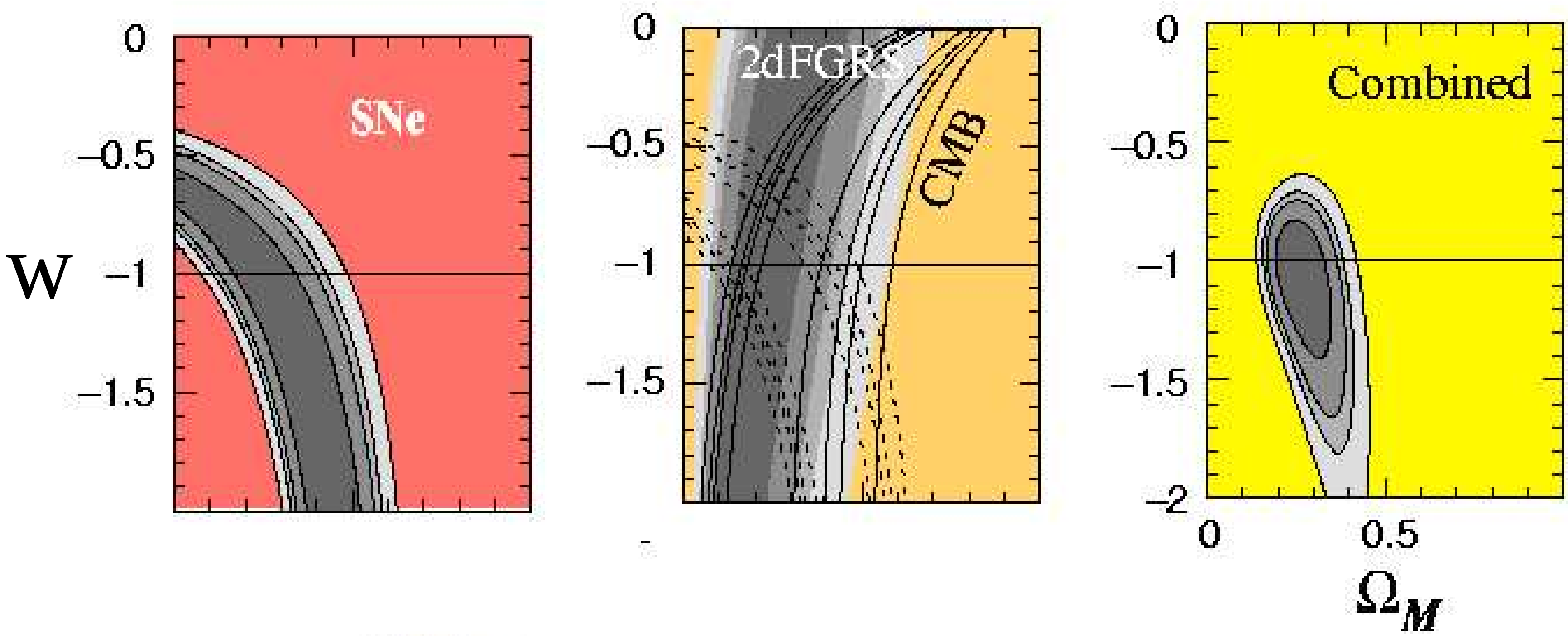
$$\Omega \times (\text{understanding}) \gtrsim \hbar$$



The dark side of the universe: who are they?

Dark energy

A cosmological constant is *sufficient* to describe the data:



Cosmological constant problem

Observed value of cosmological constant is

$$\Lambda^{1/4} \sim 10^{-11}\,\mathrm{GeV}.$$

A natural scale of quantum gravity is the Planck scale,

$$m_{\mathrm{Pl}} \sim 10^{19}\,\mathrm{GeV}$$

"Unnatural"... [*cf.* Alexey Smirnov's comments this morning]

't Hooft's naturalness criterion

Small numbers can be natural if setting them to zero increases the symmetry.

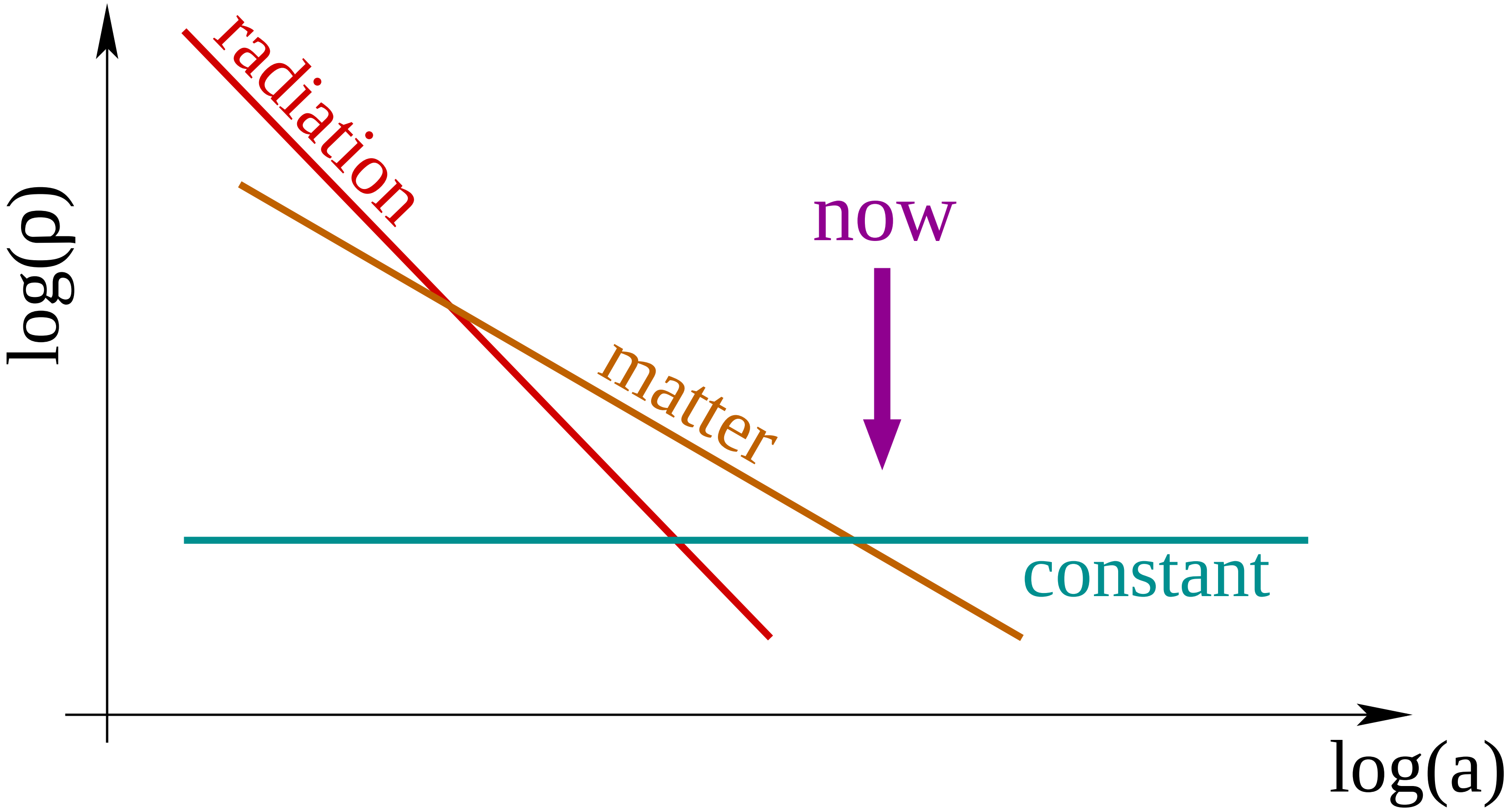
Indeed, some small numbers are known to be associated with a slightly broken symmetry.

However, the symmetry group of this action

$$S = \int d^4x \sqrt{-g} (\mathcal{R} + 2\Lambda + \mathcal{L}_{\text{fields}}), \tag{19}$$

does **not** increase if $\Lambda = 0$.

Cosmic coincidence



Cosmological constant problem

- Setting Λ to zero does not help in view of **radiative corrections**

- Λ must cancel almost exactly in the *present* vacuum

  Change in energy density during the electroweak phase transition is $\sim \mathbf{100}$ GeV! [Chris Quigg's lectures]

- Cosmic coincidence.

Anthropic principle

An explanation that invokes human existence, not physics.

The allowed values of parameters are restricted to those consistent with the possibility of intelligent life

Other sciences have encountered this.

A non-physics example.

Question: why is the altitude of Trieste above the sea level, $h \sim 10^4$ cm, is much smaller than the height of Mt. Everest $H \sim 10^6$ cm, or the radius of the Earth, $R_\oplus \sim 10^9$ cm?

Answer: altitudes of order H exist, but life is impossible or unpleasant. Hence, you are likely to observe that your altitude is $h \ll H$.

Anthropic principle

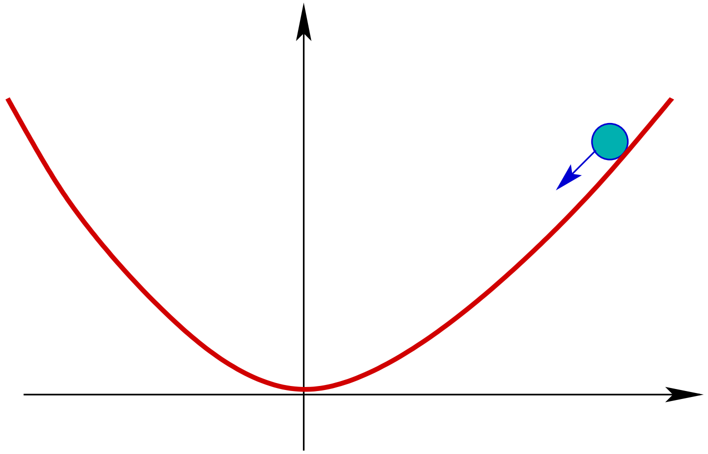
- Implicit assumption: possibility or existence of an ensemble of universes (*cf.* string theories seem to predict *landscapes* of possible vacua).

- AP places the real explanation outside of physics. There are questions, the answers to which lie outside of physics, but physicists don't like it!!

- Really ugly (but not necessarily false)

Dark energy

What if it is not a constant? Quintessence models...



A scalar field, very slowly moving in a very flat potential...

Dark energy

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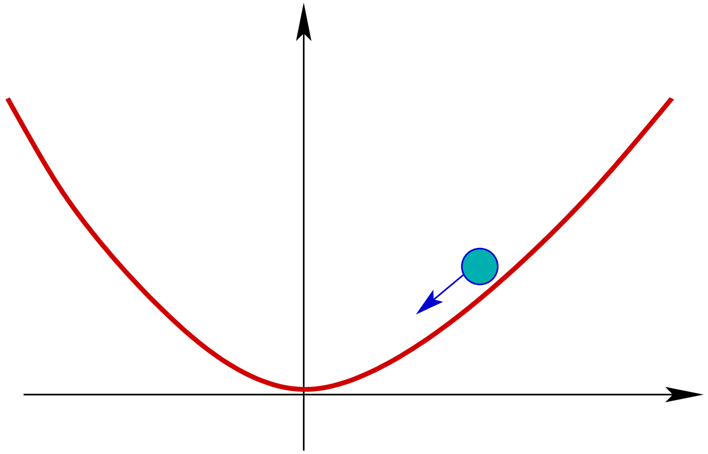

A scalar field, very slowly moving in a very flat potential. The value of w could differ from zero.

Implications of cosmological constant

- Exponential expansion forever.
- $H = \mathrm{const},\ a(t) \propto \exp(Ht)$.
- Future cosmologists $\left(\gtrsim \mathbf{100}\,\mathrm{Gyr}\right)$ out of luck.

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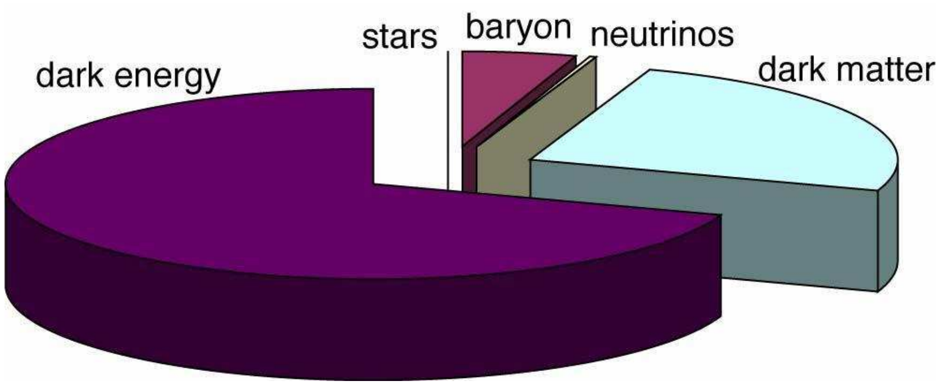


Dark matter: the evidence, the candidates, the clues

- Evidence for dark matter
- Next big discovery?
- Theoretical ideas, clues, and guesses

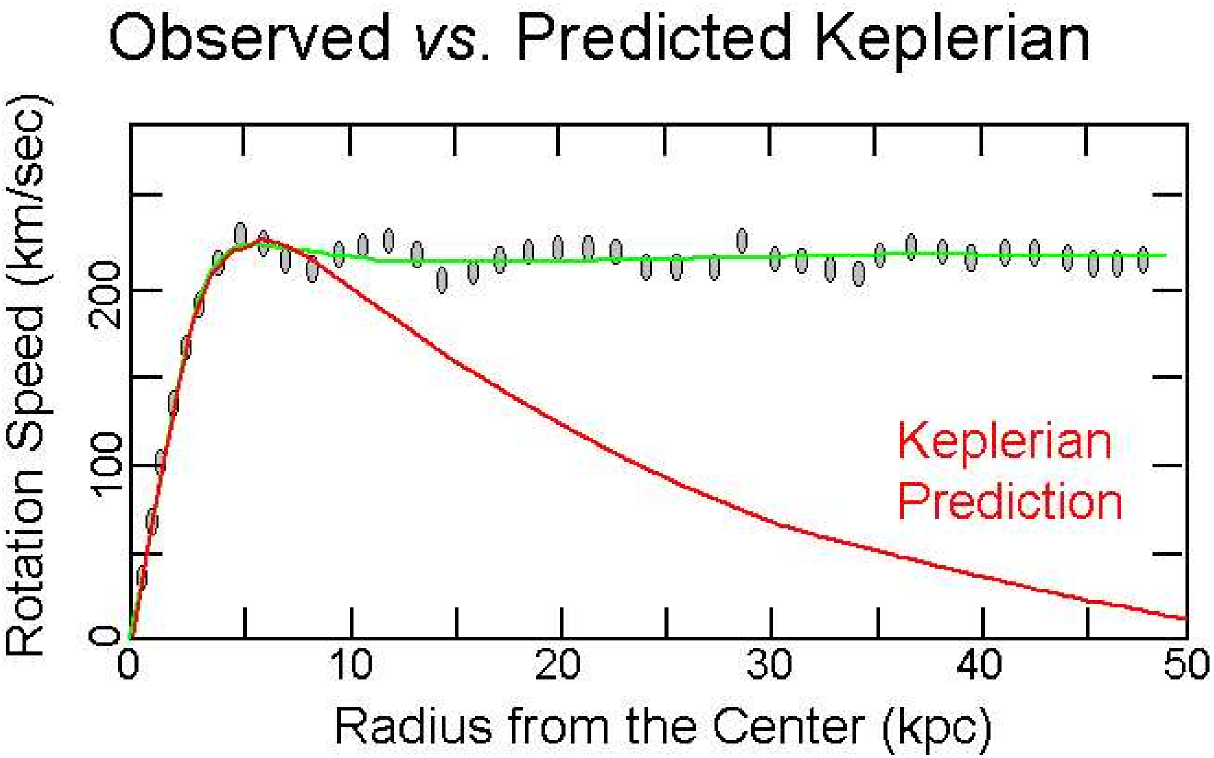
Dark matter

The only data at variance with the Standard Model

The evidence for dark matter is very strong:

- galactic rotation curves cannot be explained by the disk alone
- cosmic microwave background radiation
- gravitational lensing of background galaxies by clusters is so strong that it requires a significant dark matter component.
- clusters are filled with hot X-ray emitting intergalactic gas (without dark matter, this gas would dissipate quickly).

Galactic rotation curves



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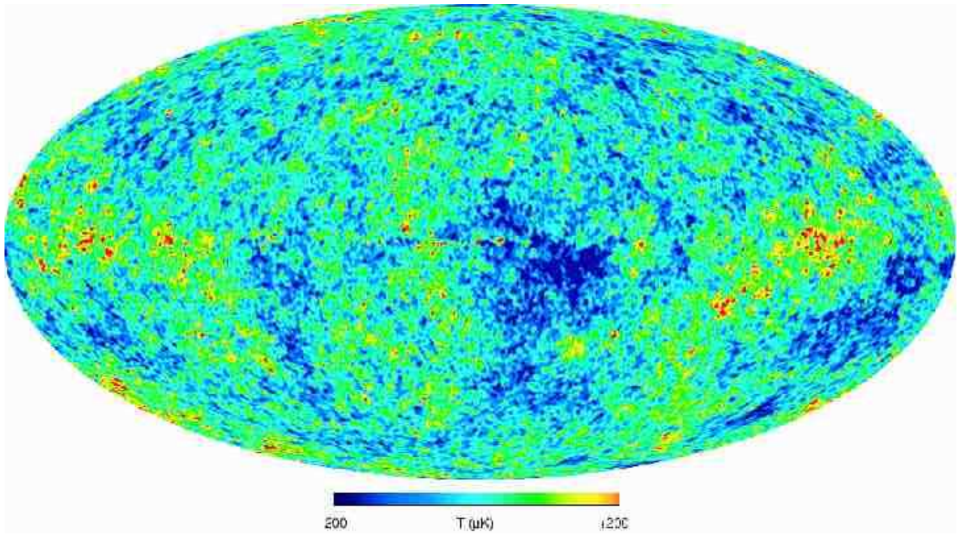

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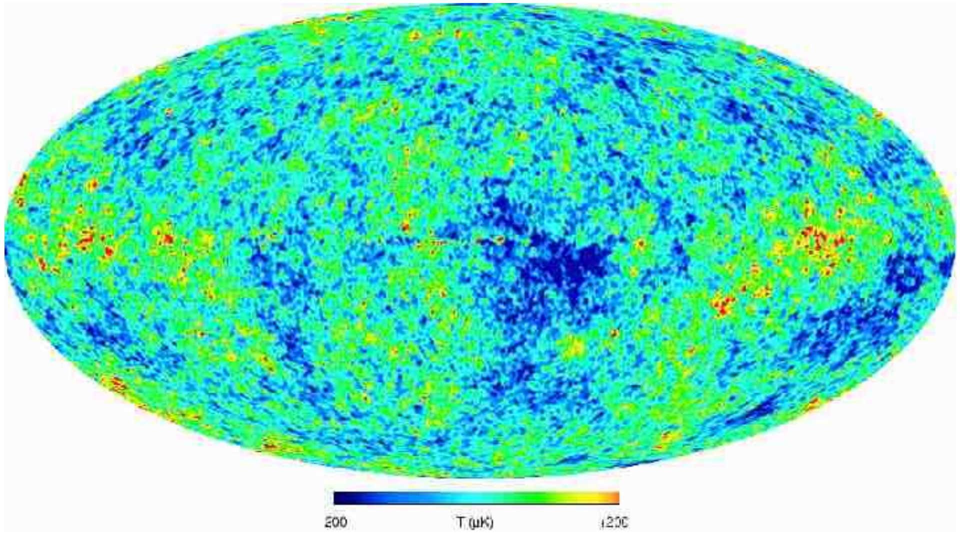

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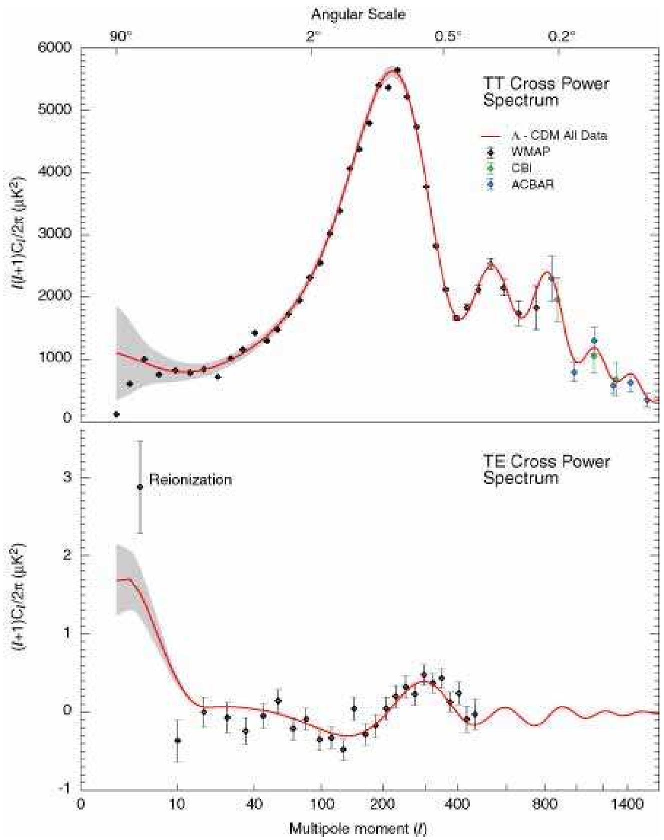
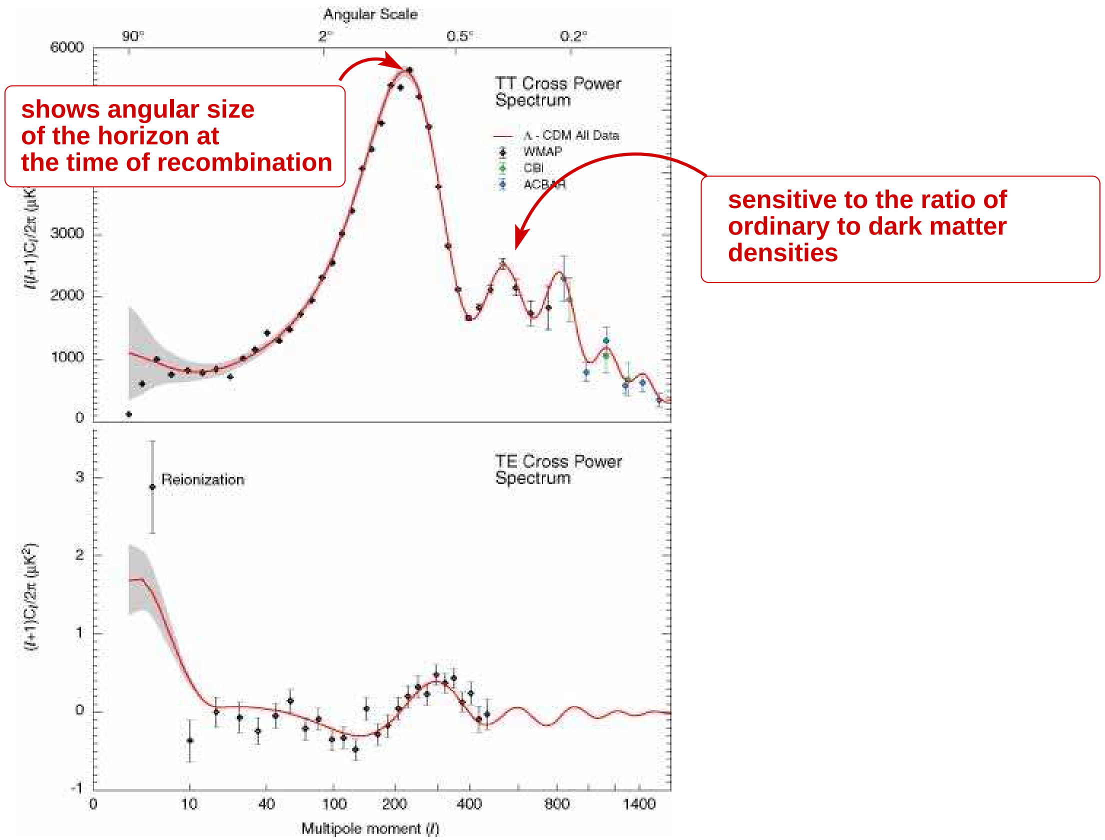
Power spectrum measured by WMAP

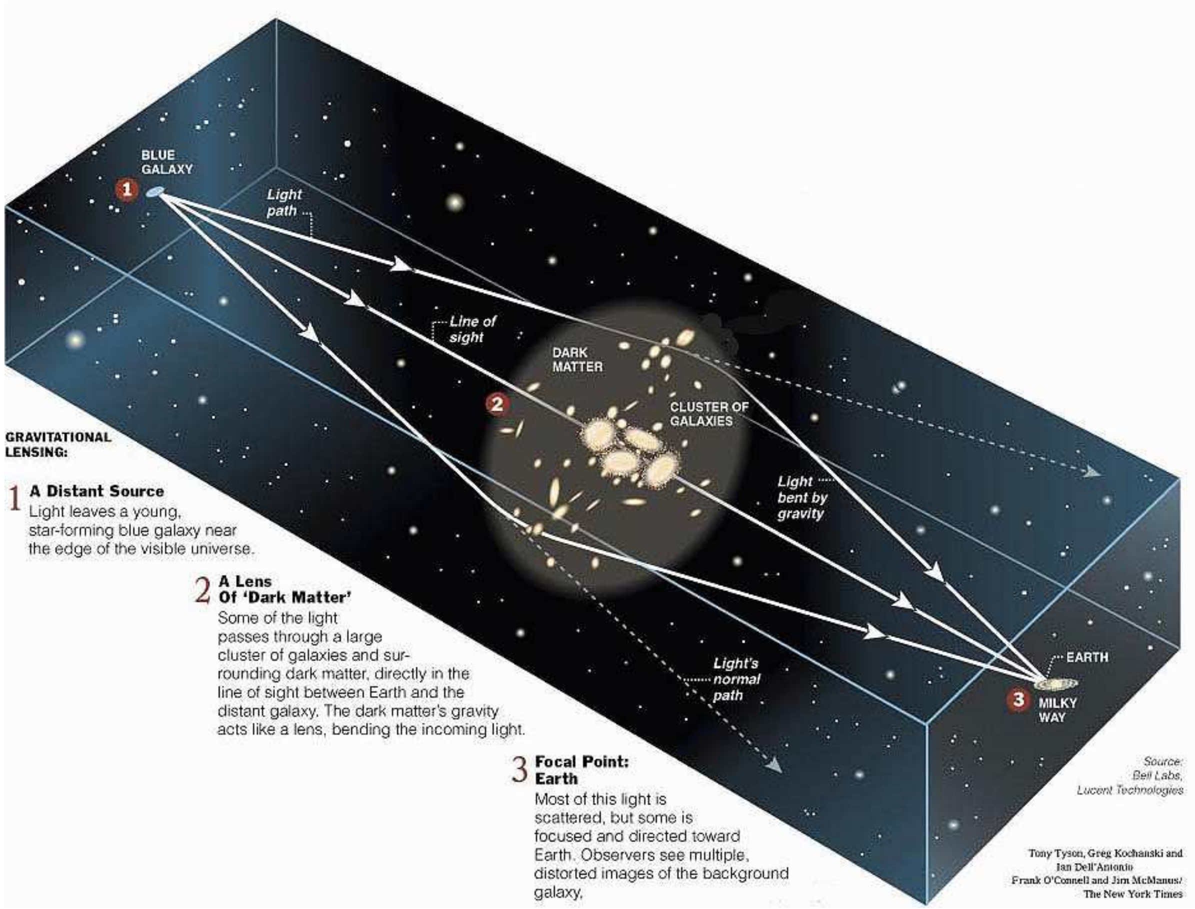


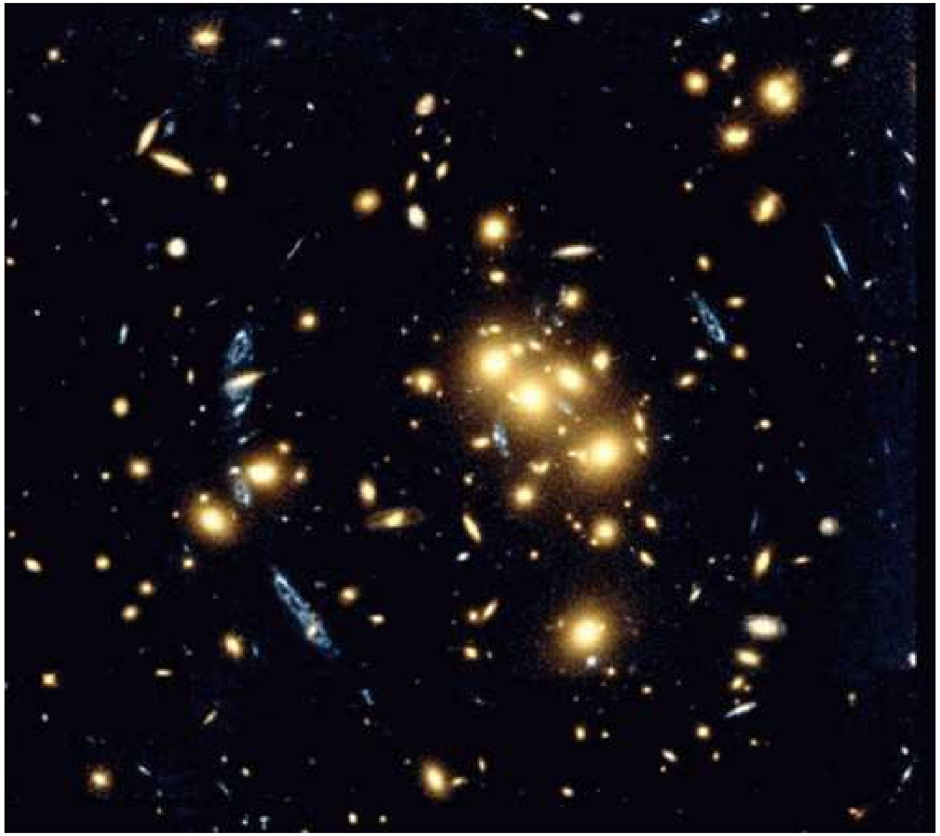
Power spectrum measured by WMAP

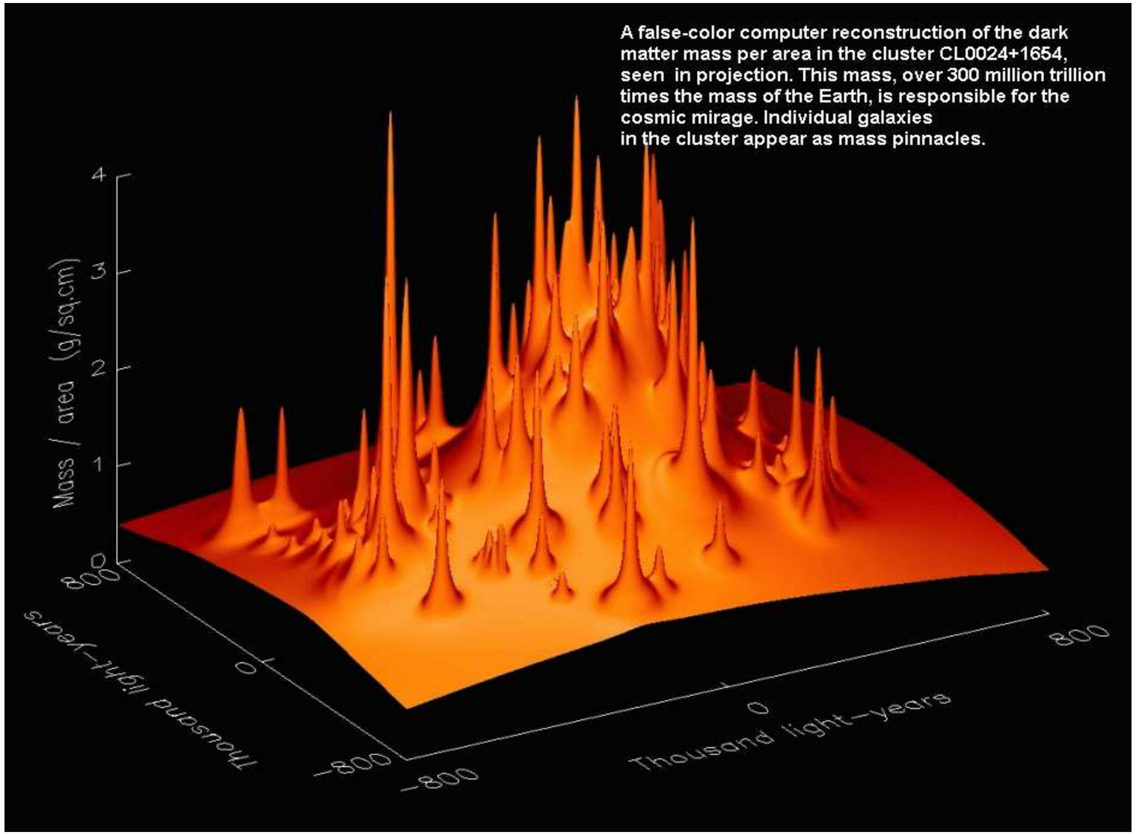


WMAP: $\Omega_{\rm matter} = 0.27 \pm 0.04; \;\; \Omega_{\rm b} = 0.044 \pm 0.004$

Gravitational lensing: seeing the invisible







Foreground cluster CL0024+1654 produces multiple images of a blue background galaxy in the HST image (left). Mass reconstruction (right).

Dark matter ⇒ new physics

- Very strong evidence for $\Omega_m = (0.27 \pm 0.04) > \Omega_b = (0.044 \pm 0.004)$
- This is *not* ordinary matter:
  - WMAP measures the ratio of matter coupled to photons to that which is not
  - BBN doesn't allow more baryons
  - Gas collapses into a disk; we need a spherical halo
- The Standard Model has no candidate for dark matter: need new physics

Dark matter: what is it?

Can make guesses based on...

- ...compelling theoretical ideas
- ...simplicity
- ...observational clues

Dark matter: beautiful theoretical ideas

SUSY is an appealing theoretical idea *[lectures by Steve Martin]*
Dark matter comes as part of the package as one of the following:

- **Lightest supersymmetric particle**
  - **Neutralino**
  - **Gravitino**
  - **Axino**
- **SUSY Q-balls**

Theoretically motivated!! By no means minimal. No experimental evidence so far.

SUSY dark matter: the LSP

Supersymmetry: a partner for every known particle

R-symmetry: introduced to prevent unwanted couplings

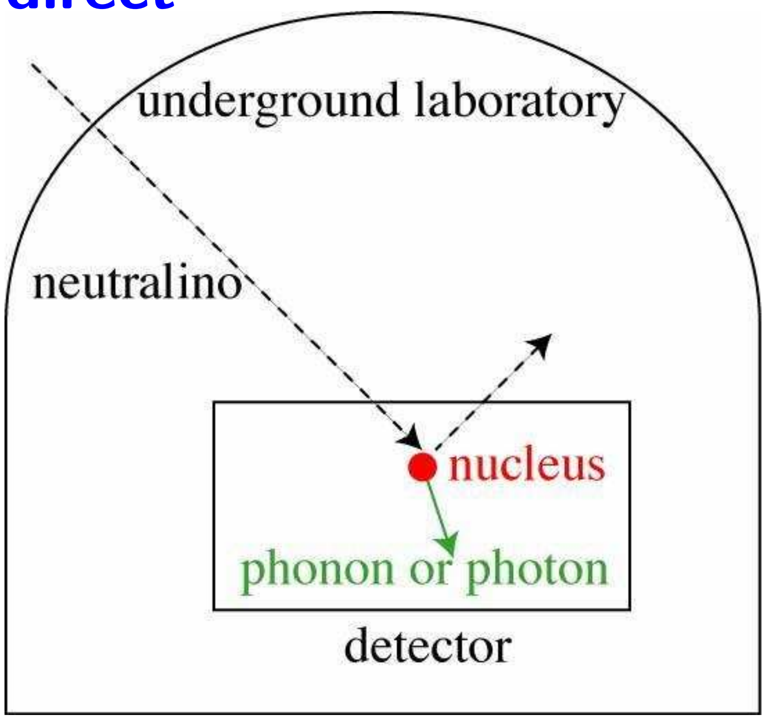
SUSY partners come in pairs in every interaction vertex. Hence, a SUSY partner can decay only if another SUSY partners are among the decay products.

A side benefit: the lightest SUSY partner is stable

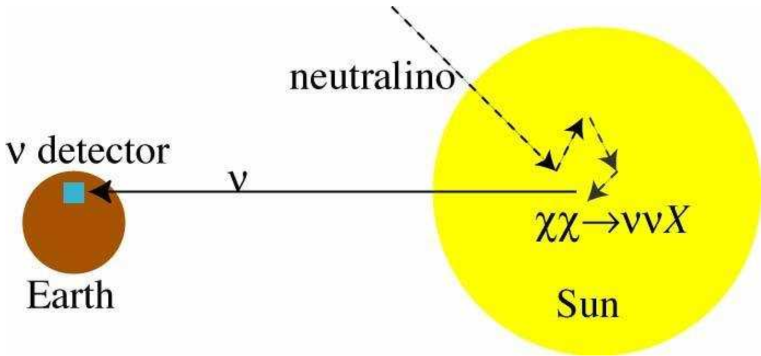
A weak-scale mass ($\sim 10^2$GeV) and **a weak-scale cross section** are the right orders of magnitude to produce the right amount of dark matter.

SUSY LSP dark matter: detection

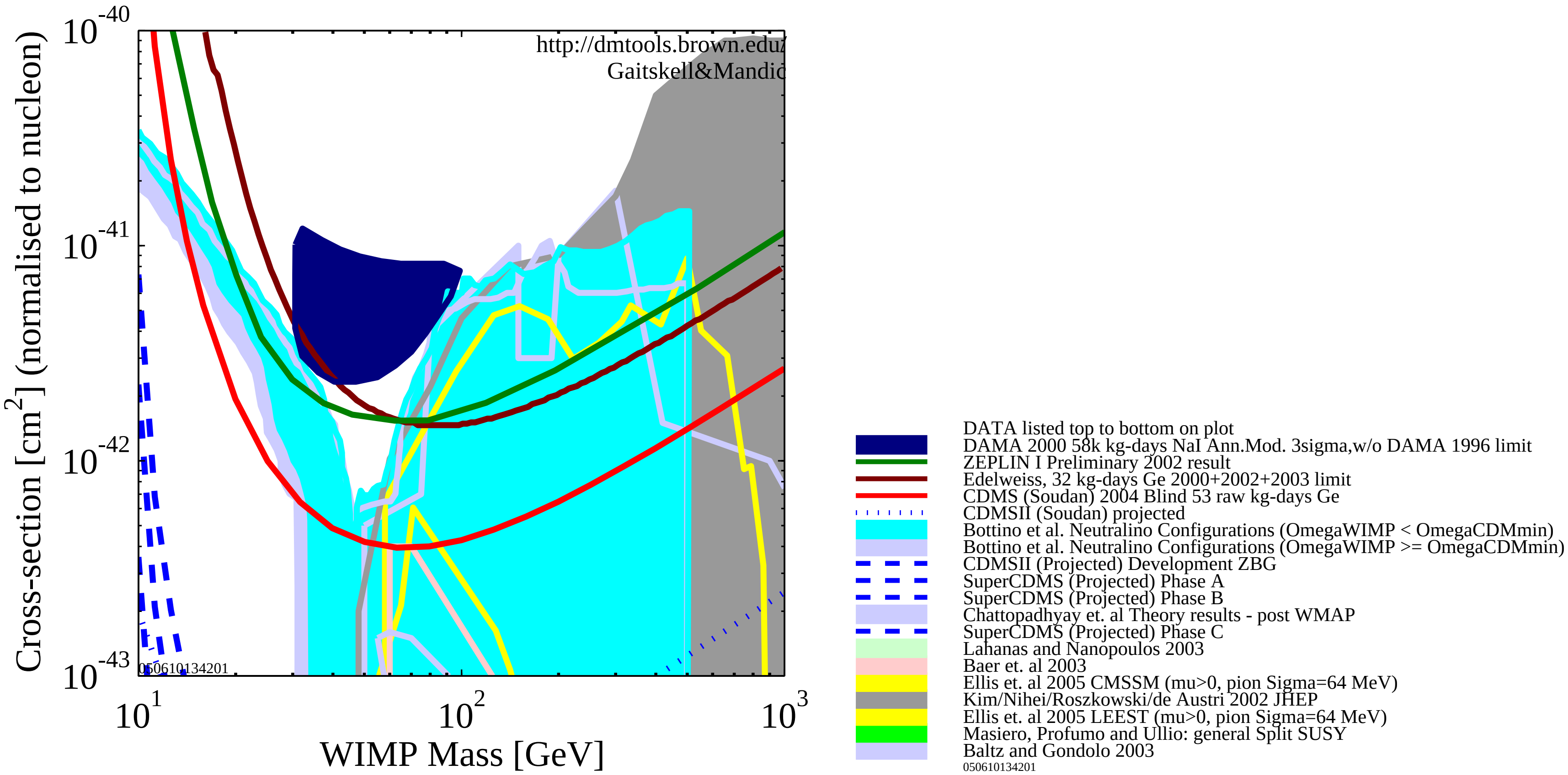
direct



indirect



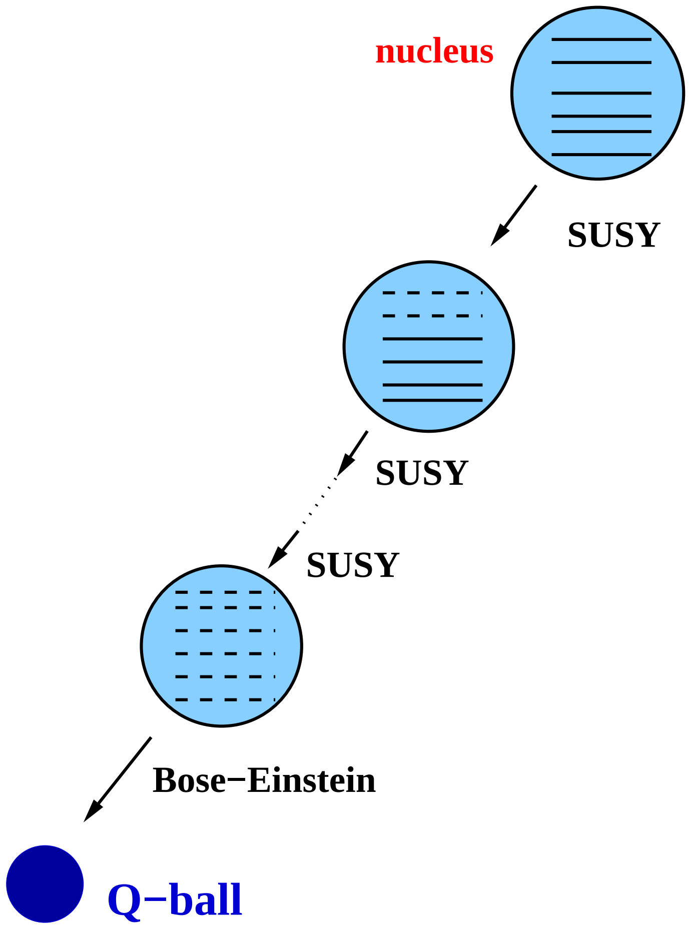
SUSY LSP dark matter: limits



SUSY models: Ellis *et al.*, 2005.

SUSY dark matter: Q-balls

Why would one suspect that
SUSY $\Rightarrow$ Q-balls?



And now for something completely different

Non-SUSY dark matter: extra dimensions

[lectures by Valery Rubakov]

Particles that had not stuck in our brane could make up the dark matter.

Non-SUSY dark matter: WIMPZILLAS

- Superheavy particles can be produced at the end of inflation just from gravity or from new interactions.
- Can be charged or neutral, can have no interactions (except gravity) or can even have strong interactions
- Density small, hard to detect.
- Decays may produce ultrahigh-energy cosmic rays