The LHC light on Dark Matter and Dark Energy

M.W. Krasny

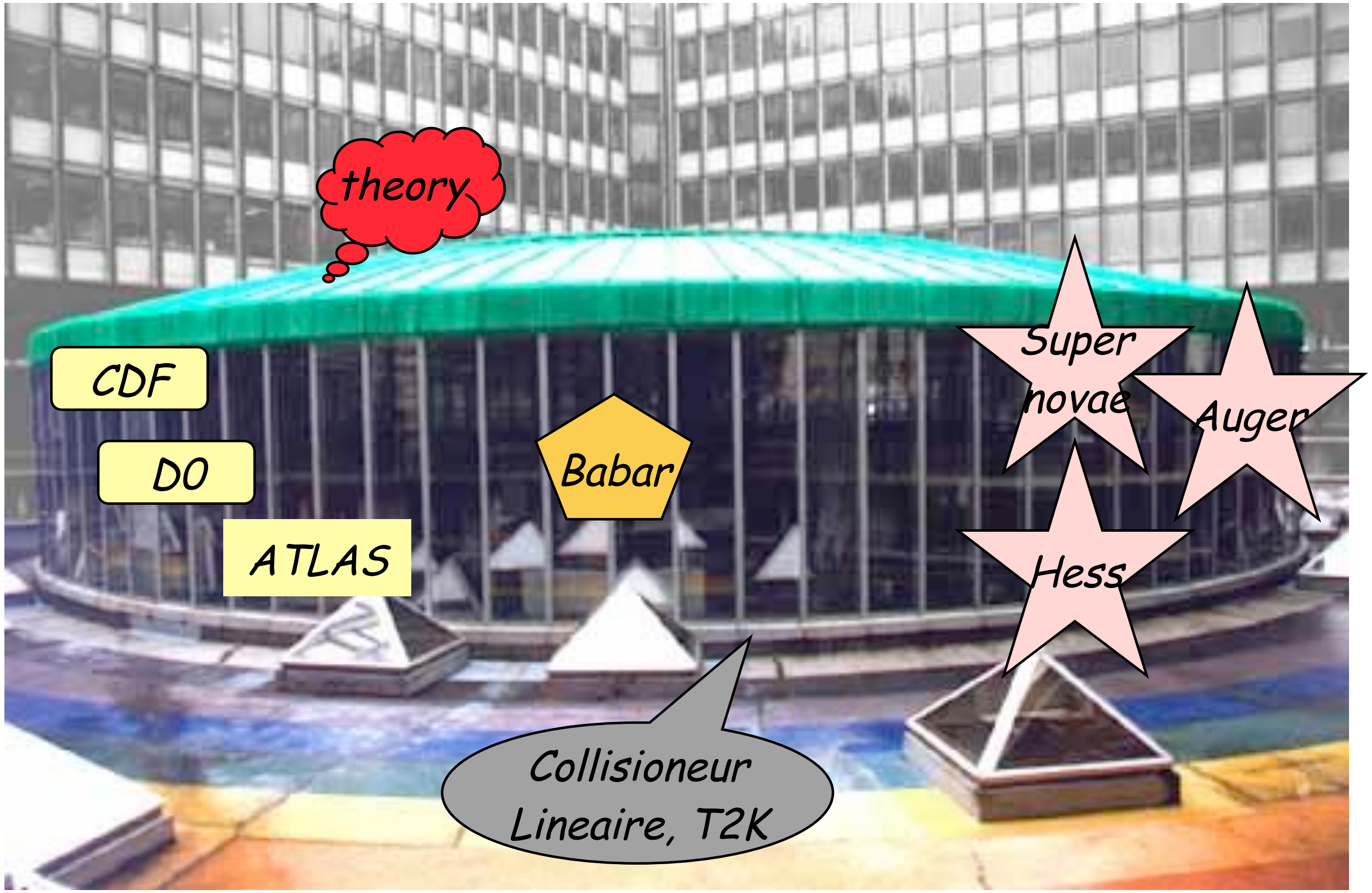
LPNHE, University Pierre and Marie Curie, Paris

krasny@lpnhep.in2p3.fr

This talk:

- The questions
- The cosmo-path
- The parti-path
- Their (possible) convergences
- The (expected) LHC verdicts
- Outlook

In search of a synergy…



- **Two layers of questions**

The technical ones (those that can be asked in the language of the present paradigms (models) how the universe works)

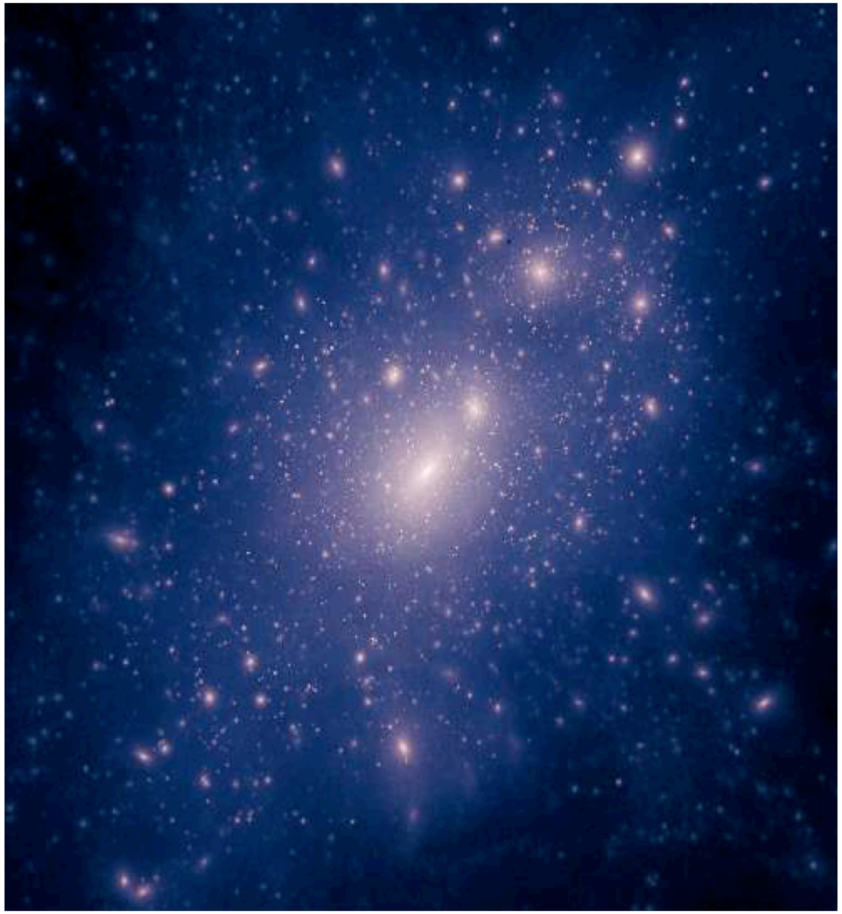
1. *What is the nature of the dark energy of the Universe?*
2. *Are there extra dimensions of space?*
3. *Does the dark matter exist?*
4. *If yes, Is it made of point-like or composite objects?*
5. *How can we produce it in the earthly laboratories?*
6. *Do all the forces become one? And under what conditions?*
7. *Why are there so many kinds of elementary particles?*
8. *Why most of them are massive*
9. *Is there any logic in the pattern of particle masses and their mixings.*
10. *What are neutrinos telling us?*
11. *How did the apparent universe come to be?*
12. *What happened to the antimatter?*
13. *Are the physical constants space-time invariant?*

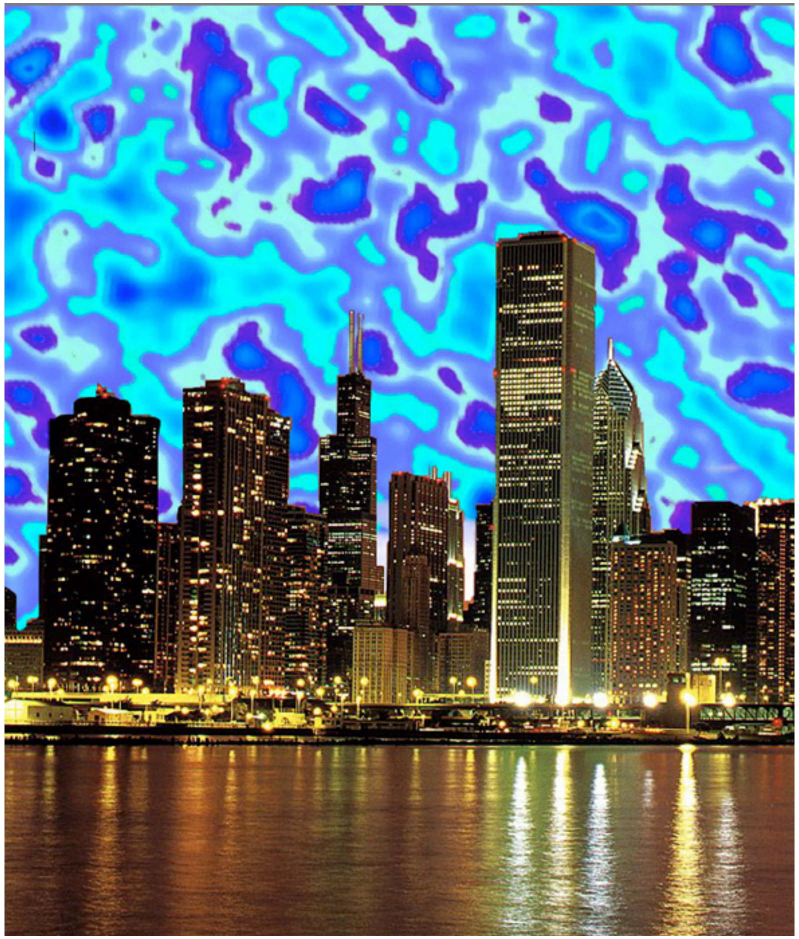
The general ones (those that can be formulated outside the present universe modelling paradigms)

1. Are there undiscovered principles of nature (new physical laws)?
2. Why the Universe obeys Quantum laws?
3. Is it a deep principle … or a temporary fix?
3. What is the deep reason for the successes of gauge theories?
4. How the fact that we exists biases our laws of nature (physics beyond fine-tuned anthropic excuse)?
5. In particular, why should a human-unbiased physics mechanism predict the cosmological constant in the bizarre anthropic range?
6. Is there a place for organized structures in the early evolution of the Universe?
7. Is there an universal mechanism producing the confined energy grains (particles)?

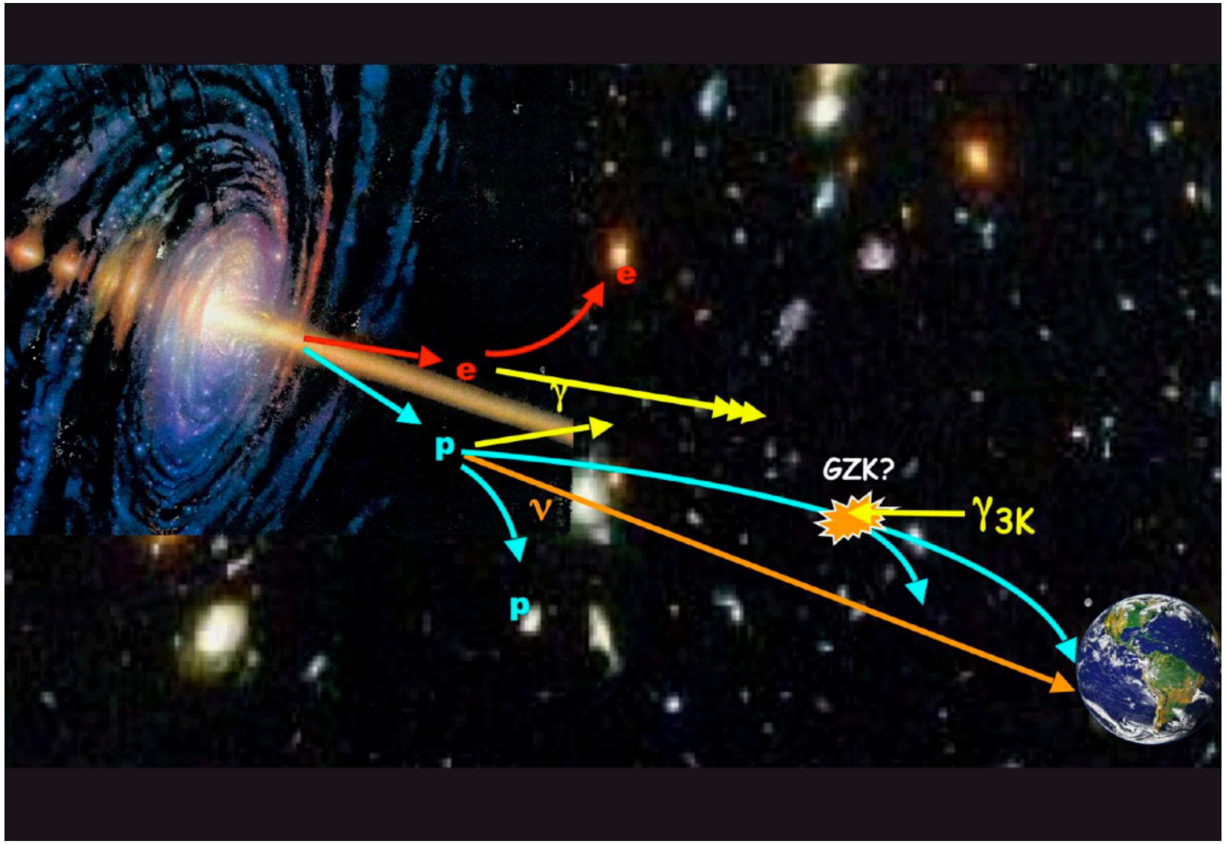
- **The cosmic laboratory and the earthly laboratories**

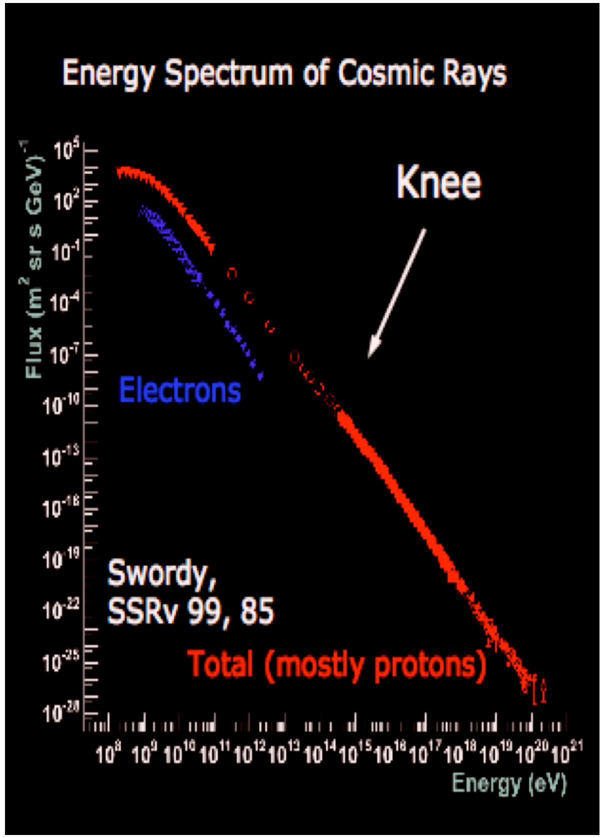
Quanta of low energy



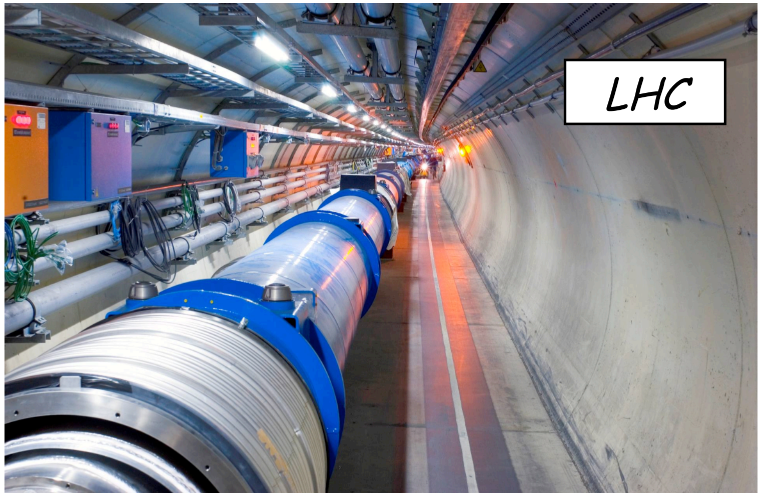


Large-energy quanta from the space



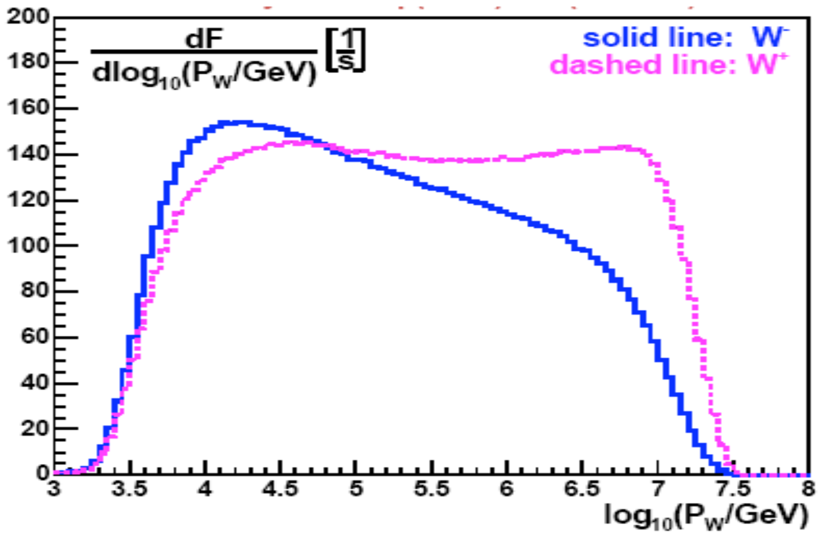


Home-made large-energy quanta



Advantages:

- *Luminosity*
- *Duty cycle*
- *Integrated path vacuum quality*
- *Tuned energy and polarisation*
- *Clean beams of unique particle type:*
- *(protons, ions, electrons, muons, neutrinos, mesons, etc. and e.g. W-bosons*

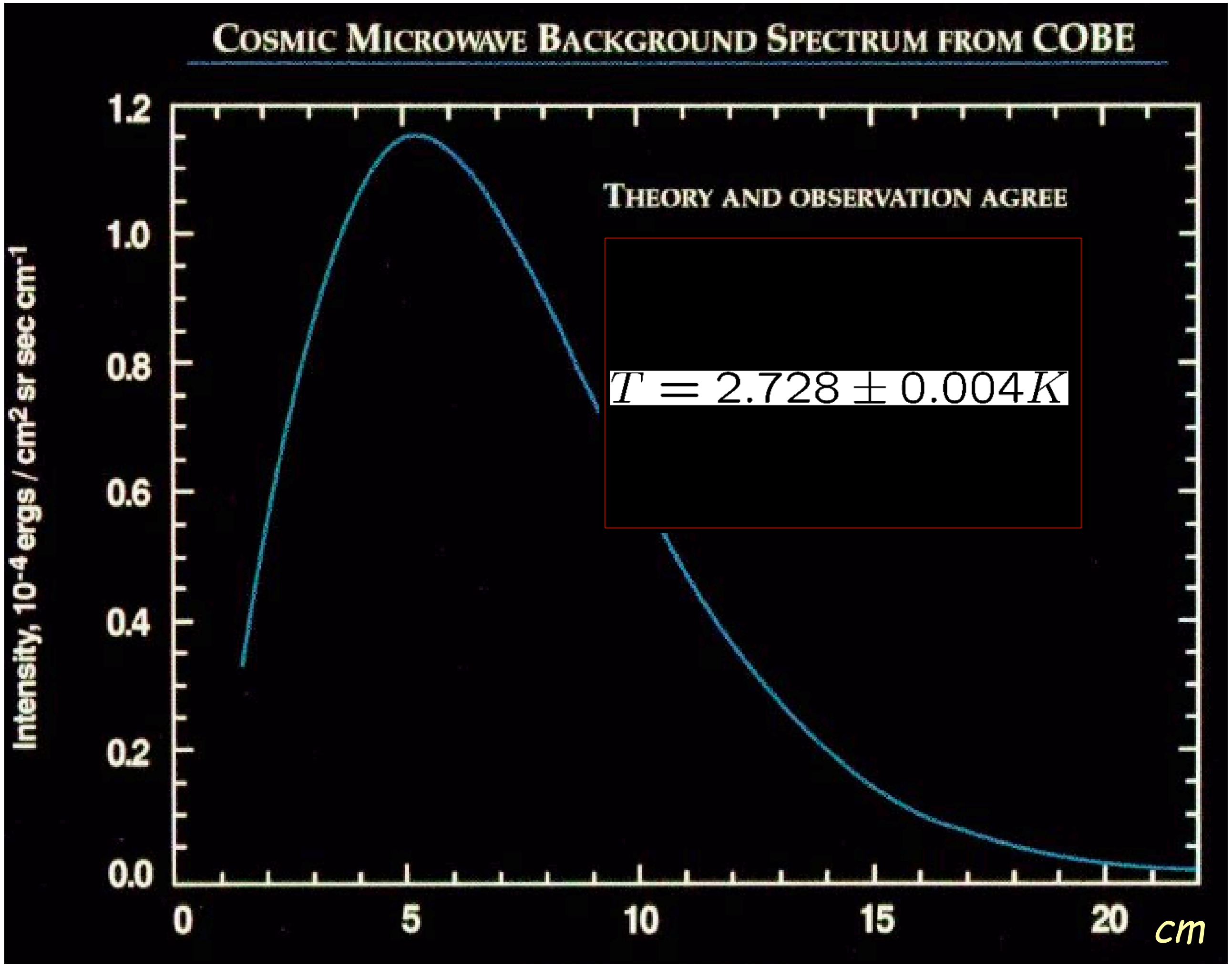


- **Two cosmo-path**

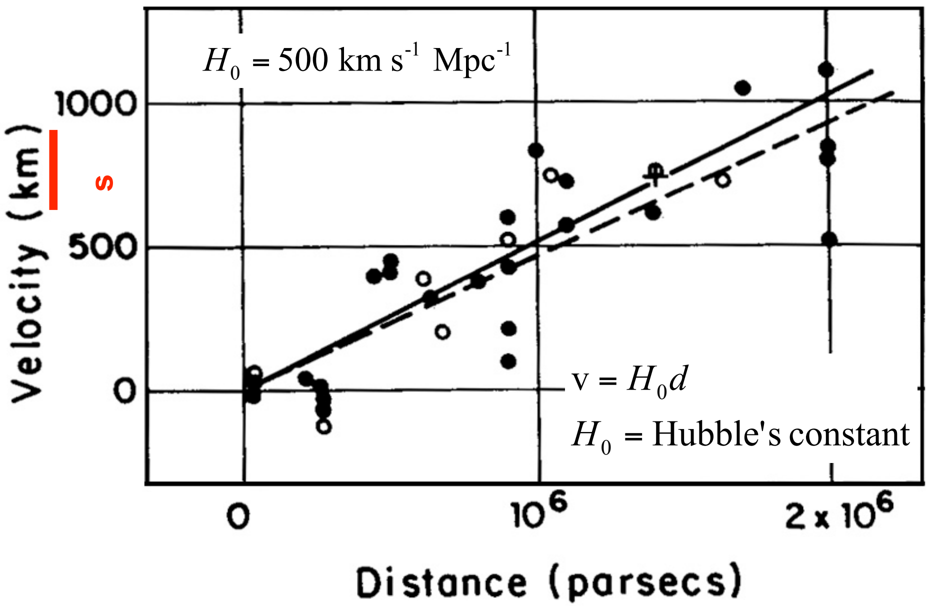
The link between particle physics astro-particles and cosmology is founded on one principle and two observations:

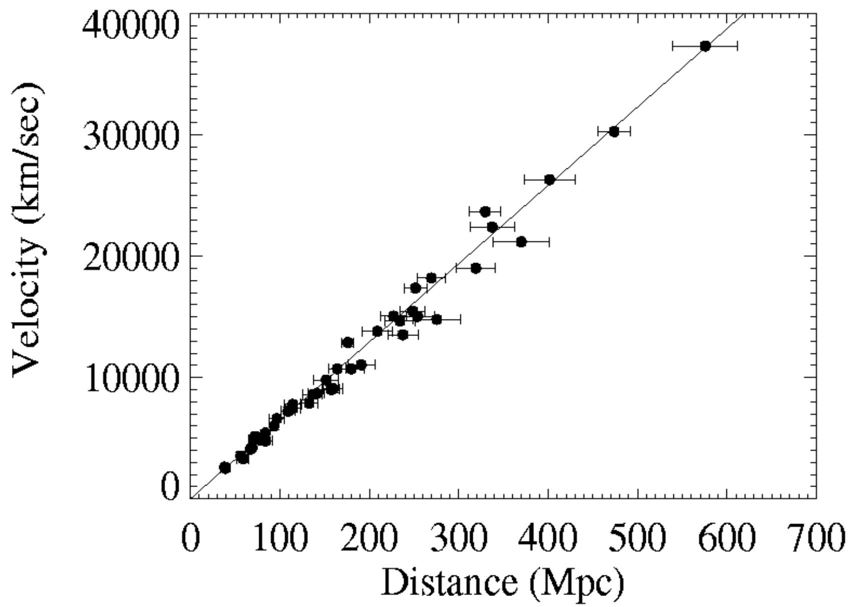
- The physics laws do not depend upon the space time position of an observer, its movement and its matter type
- The observed universe is thermally isolated
- The universe is expanding

From the age of 380 000 years till now the visible universe it thermically isolated (a perfect black-body spectrum)



The visible universe is expanding (… since thermally isolated - from a dense, high-temperature system)





Hubble's Discovery Paper - 1929

Present status (LP2007)

The cosmologist map of the geometry and the content of the universe

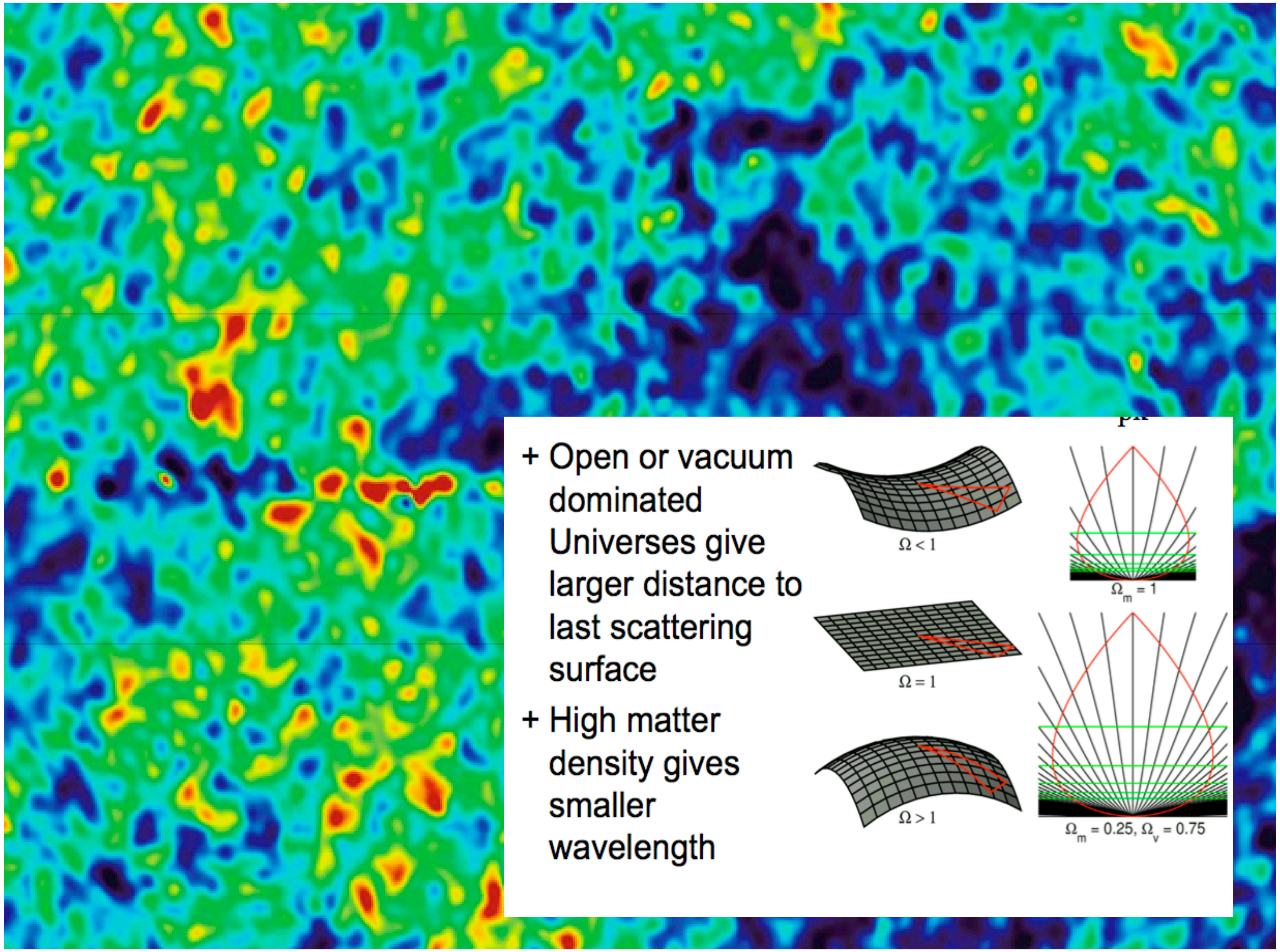
division of the universe into:

- ambient energy filling the space time,
- space-time-localized energy grains (photon-blind stuff and photon-visible stuff clumping under the influence of gravity and called respectively:

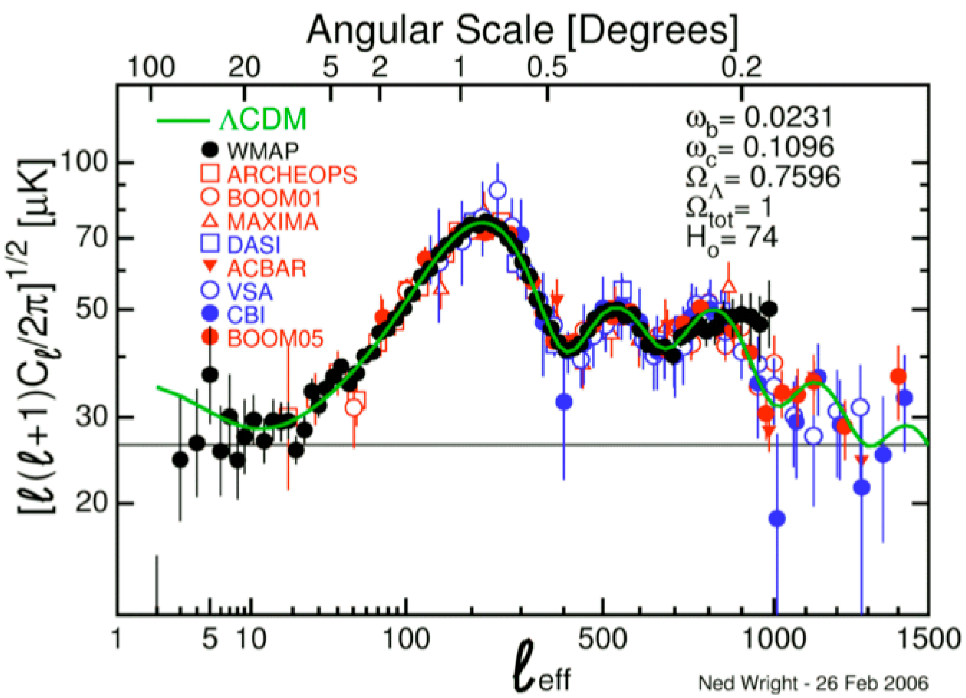
  dark energy, dark matter and visible matter

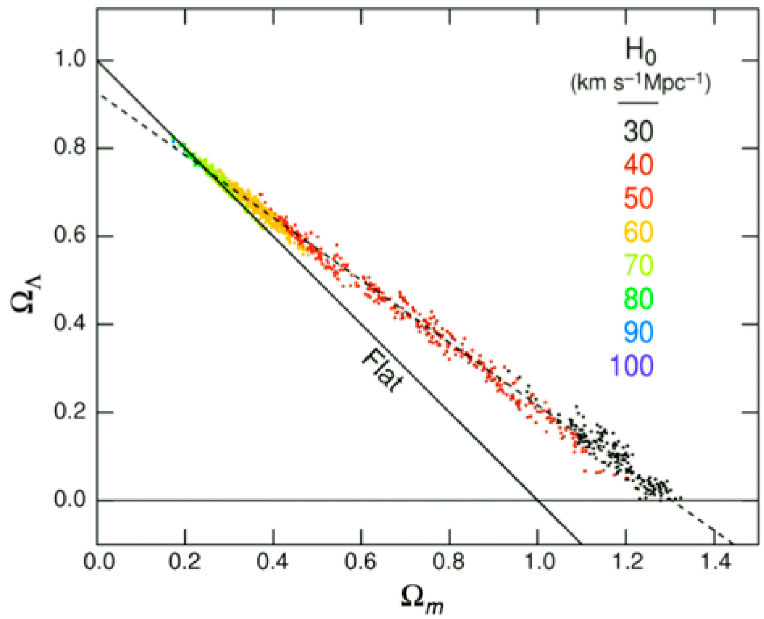
All these components determine the geometry of the universe.

The first detailed picture of the infant Universe by WMAP (...the colours illustrate the distance scales of the temperature fluctuations)



Its quantitative analysis (…fitting the content of the universe)



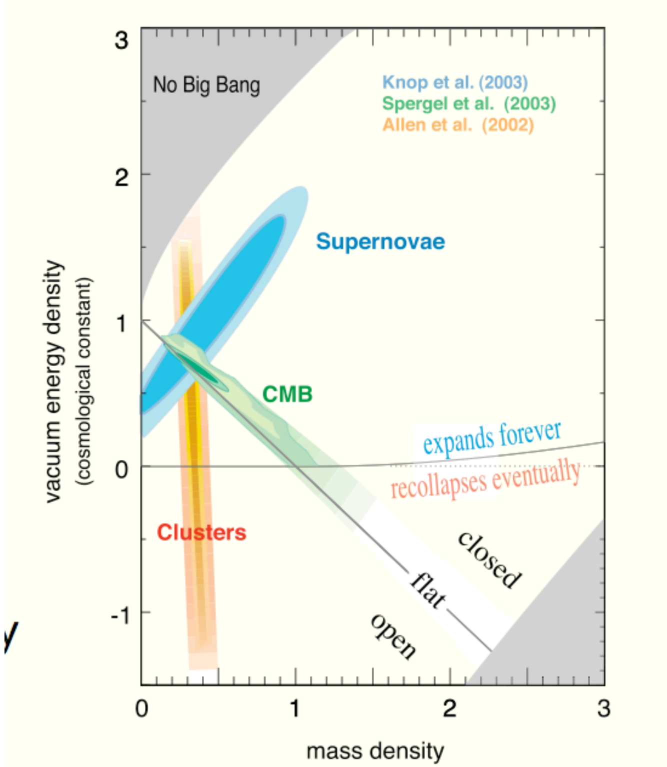


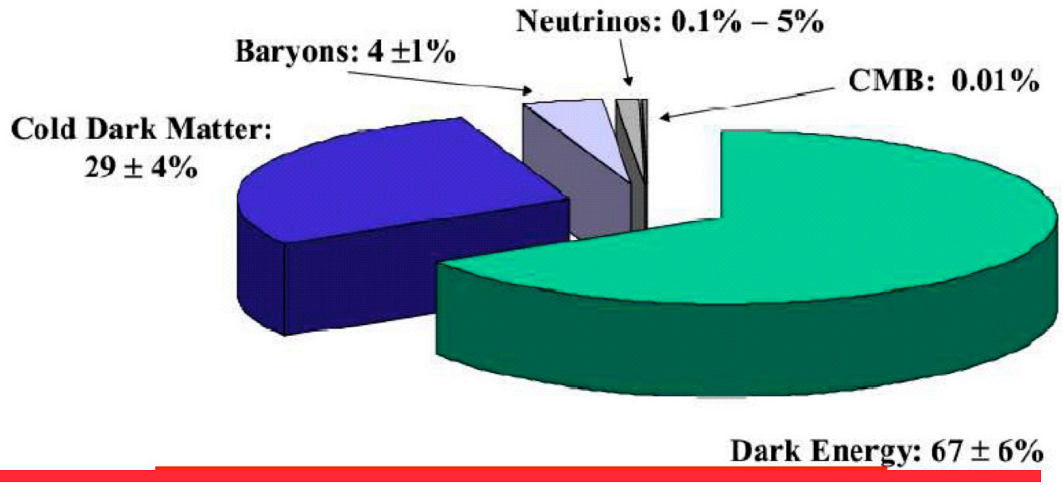
The location of the peaks and their relative heights determine the relative proportions of dark matter, visible matter and dark energy

NOTE:

The CMB data do not imply flatness of the Universe, it needs supplementary data e.g. the the Hubble constant measurement to imply flatness!

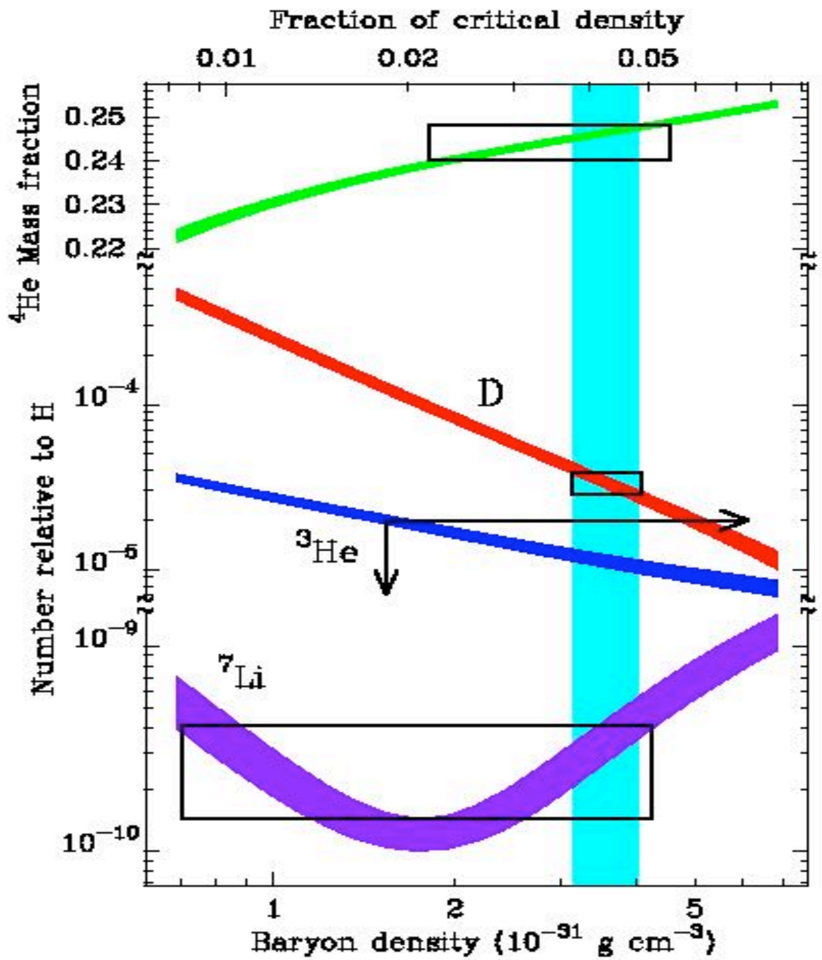
Result: A strange recipe for a Universe





… The direct evidence for the visible matter and its weighting with nuclear physics tools

Abundance of light nuclei



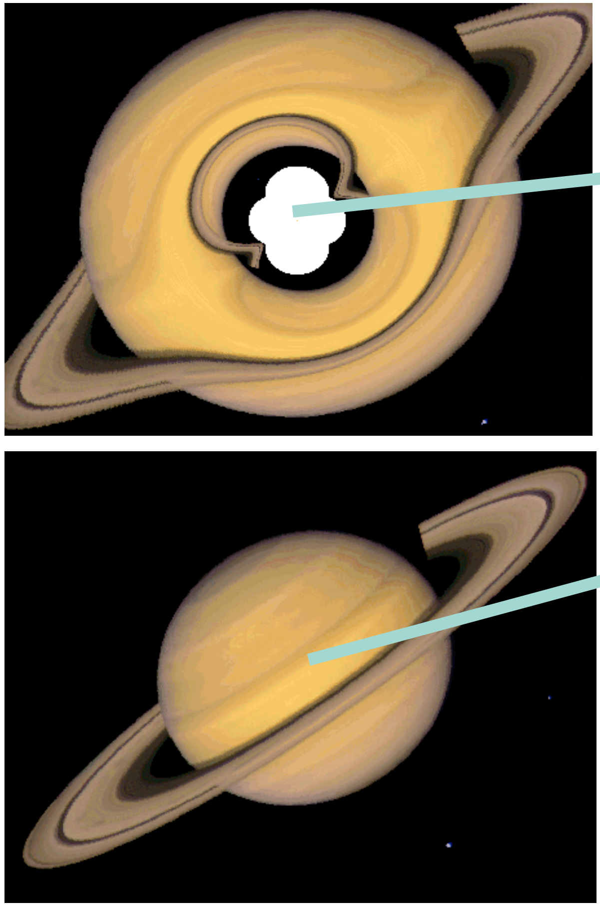
The "direct" evidence for dark matter:

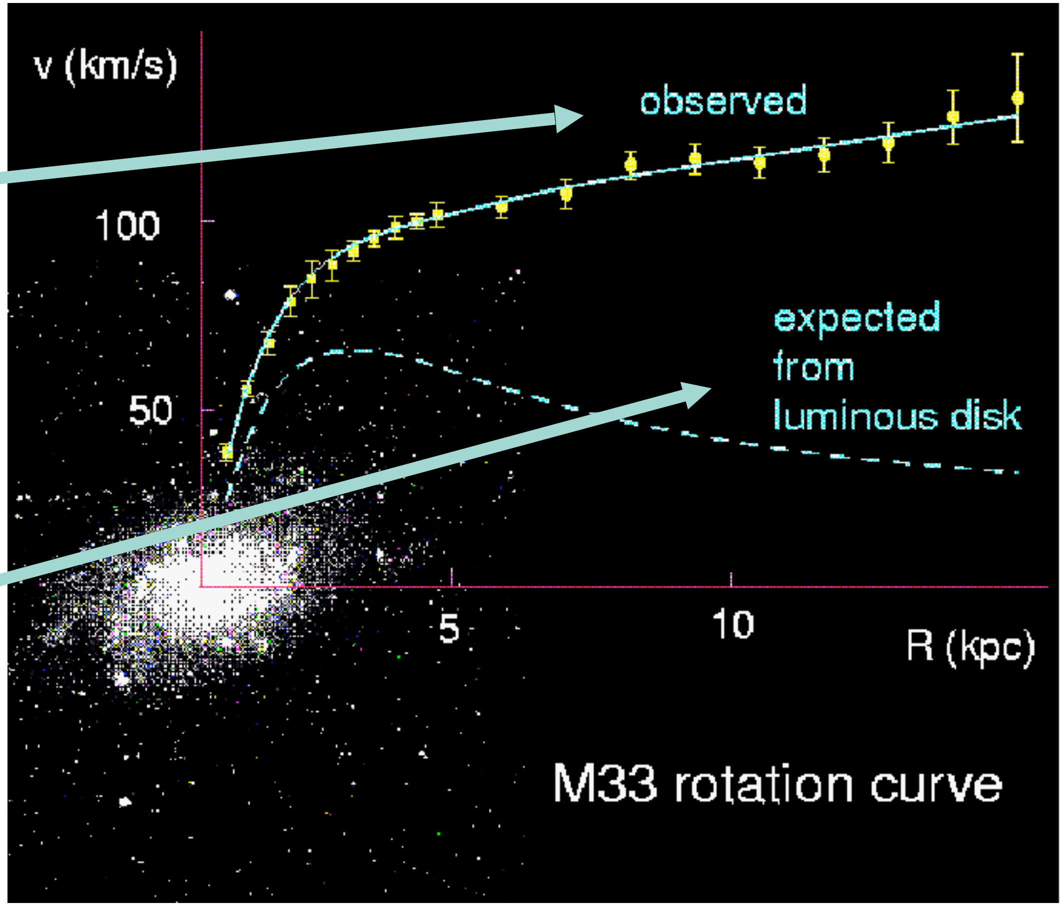
Stars rotate more rapidly then allowed by the centripetal force generated by the visible matter (unless MOND - Modified Newtonian Dynamics)

… even in dark galaxies

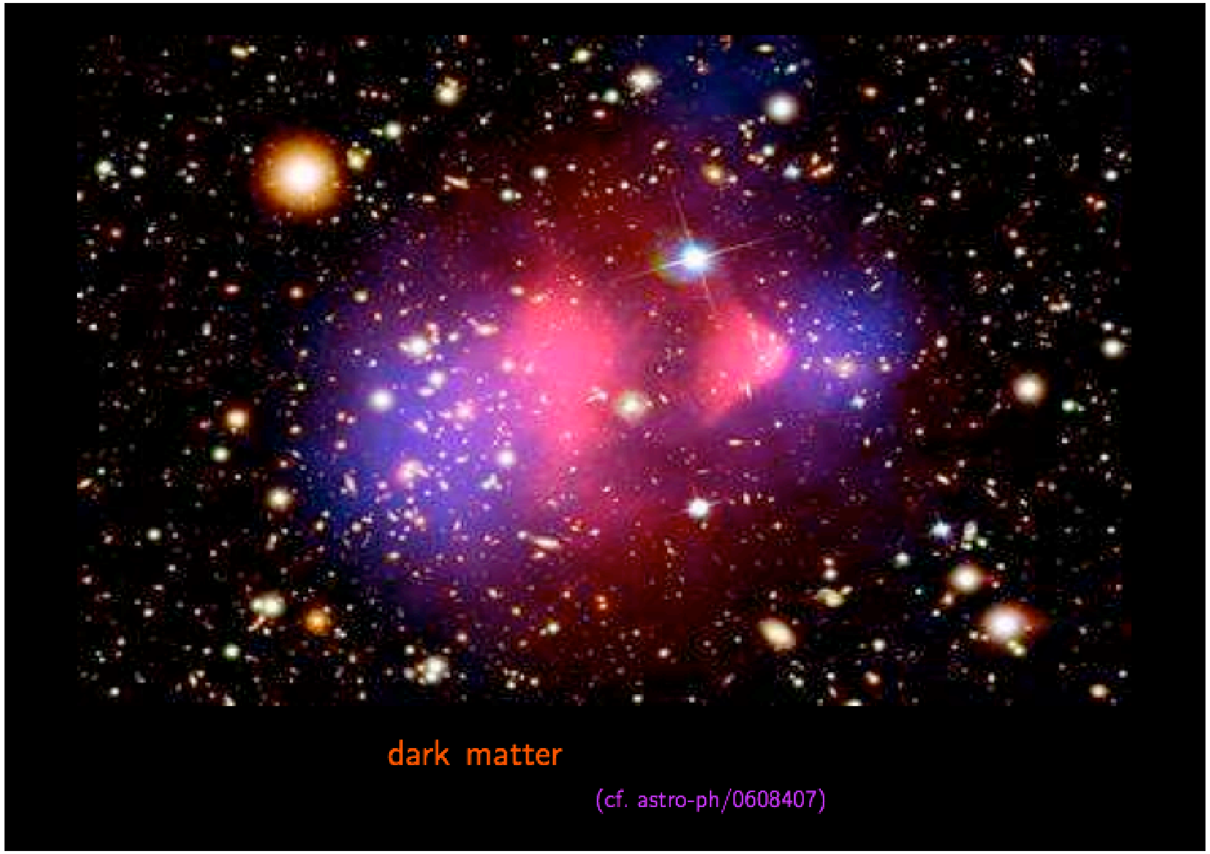
X-ray emitting gas held in place by the cold matter

The measurement principle





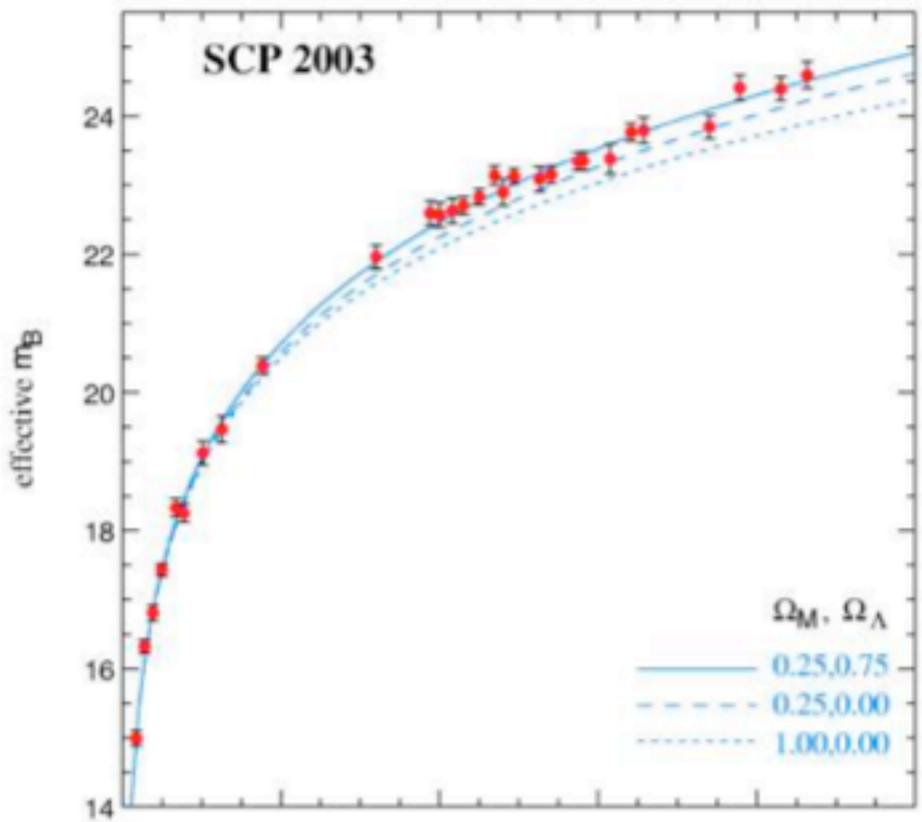
"Direct" observation of remnants of dark matter collisions



The two pink clumps represent the hot X-ray emitting gas, which contains most of the ordinary baryonic matter, The blue areas Show where most of the mass is concentrated following the collision (note: in MOND such Such a separation is not possible

… and the "direct" evidence for the dark energy

The accelerating expansion of the universe



The LPNHE pride:

Pierre Astier et al.
Astron.Astrophys.447:31-48,2006

The expected properties of dark matter and dark energy and the link to particle physics

Required Dark matter characteristics

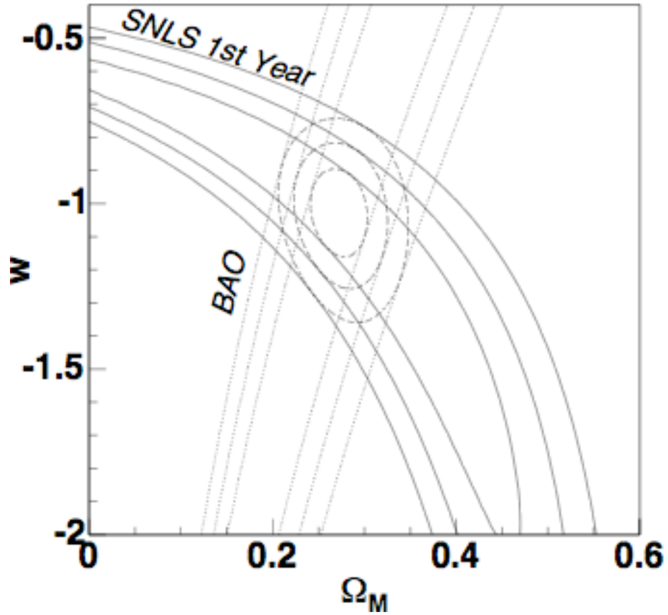
- Dark matter must have two important characteristics to satisy observations
  - Cold/warm (not hot):
    - must be nonrelativistic at the time of matter-radiation equality (z ~ 3500) in order to collapse gravitationally and seed the large-scale structure we see. M < keV (e.g., neutrinos) is hot and not allowed at significant levels.
  - Nonbaryonic
    - Light element abundances + Big Bang Nucleosynthesis fix baryon density; we need more matter than is allowed in baryons
    - Baryonic matter would not be able to begin collapse until recombination (z ~ 1100) due to coupling to photon plasma

Required Dark energy characteristics

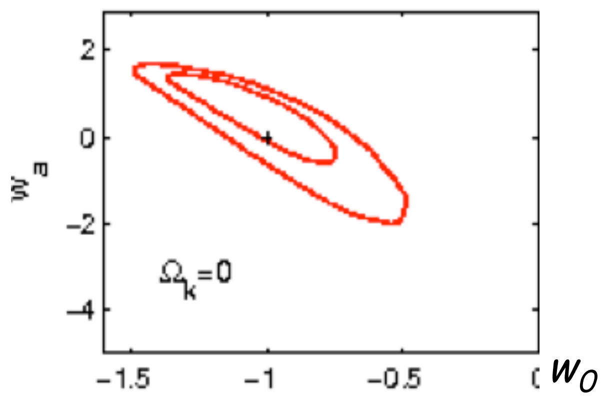
The pressure to density ratio:

$$-w \equiv p_X/\rho_X,$$

$\rho_X \sim a^{-3(1+w)}$, where a is the scale factor



Time dependence



$w(z) = w_0+w_a(1-a)$

$1+z = 1/a$

z: cosmological redshift

a: cosmic scale factor

WMAP3

+182 SNe Ia (Riess et al. 2007, inc SNLS and nearby SNe)

+SDSS BAO

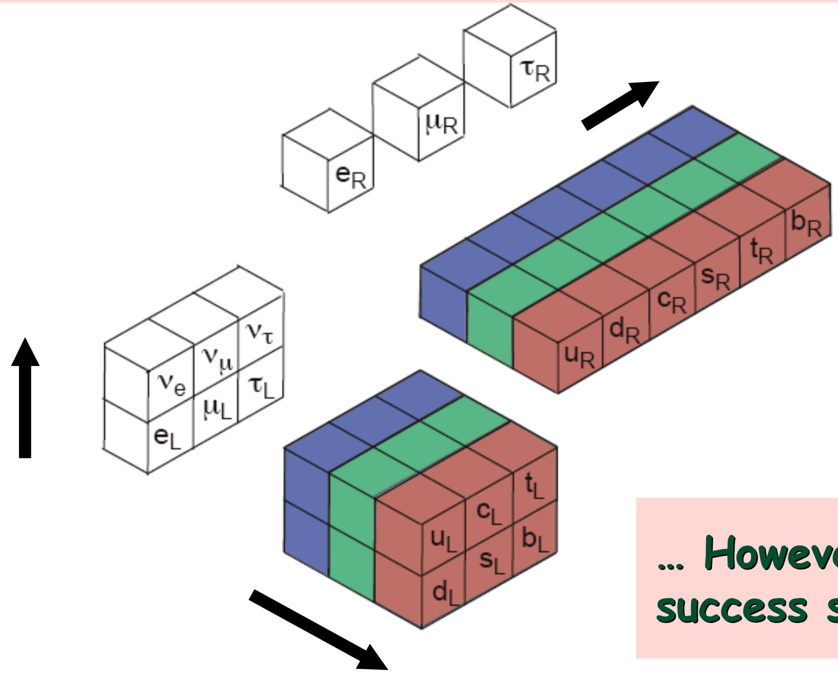
(Wang & Mukherjee 2007)

THE PRESSURE ASSOCIATED WITH THE SIMPLE COSMOLOGICAL CONSTANT (W= -1) IS SUFFICIENTLY NEGATIVE TO BE DRIVING ACCELERAATED EXPENSIAN TODAY

- **The parti-path**

The successes of Standard Model as a reference and its failures as a guide where to search

The beauty of the Standard Model: Symmetries and gauge invariance define the particle types and their interaction



$$\mathbf{SU(3)_c} \otimes \mathbf{SU(2)}_L \otimes \mathbf{U(1)}_Y$$

… However the SM is not only the success story…

Problem 1: CP violation in strong interactions

$$\frac{1}{32\pi^2}\bar{\theta}\,\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}=\bar{\theta}\{F\tilde{F}\}$$

$$\bar{\theta}=\theta_{QCD}+\theta_{weak},\quad \theta_{weak}=\arg.Det.M_q$$

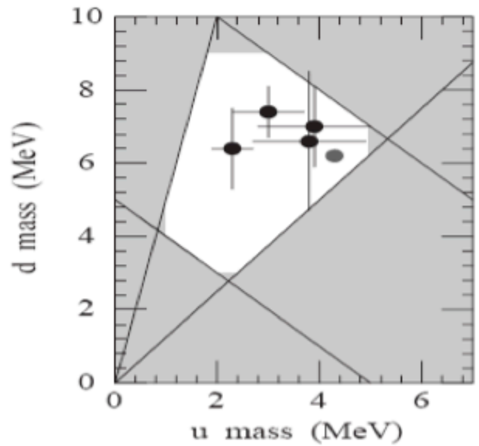
Here theta-bar is the final value taking into account the electroweak CP violation. Weak interactions can contribute O(10-17) [George-Randall]. For QCD to become a correct theory, this CP violation must be sufficiently suppressed.

If masses of the quarks were zero theta Is not a physical quantity and there Is no strong CP problem:

$$q\to e^{i\gamma_5\alpha}q \quad : \quad \int(-m\bar{q}q+\frac{\theta}{32\pi^2}F\tilde{F})$$

$$\to\int(-m\bar{q}e^{2i\gamma_5\alpha}q+\frac{\theta-2\alpha}{32\pi^2}F\tilde{F})$$

… but apparently this not the case…



Particle Data (2006), p.510

A putative solution: axions

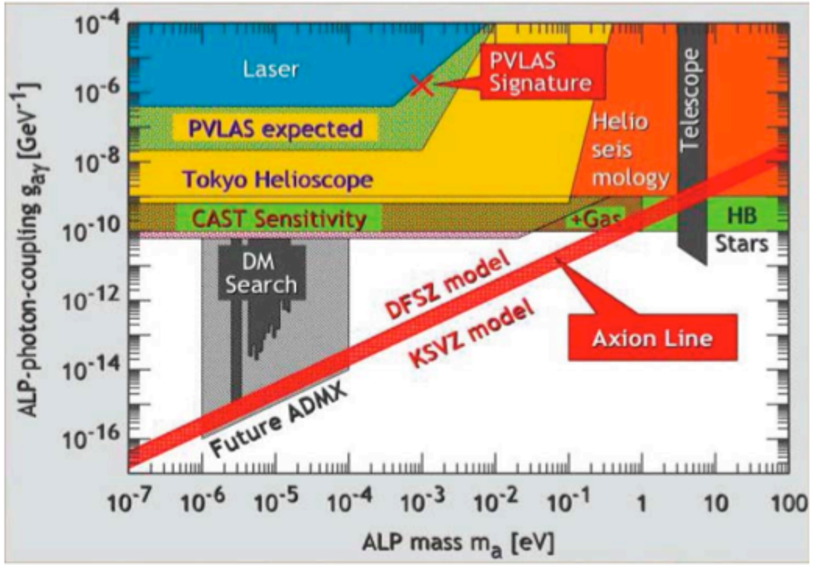
… Peccei and Quinn proposed another way of "rotating out" the theta parameter by introducing the Field H_u which couples only to up-type Quarks and H_d which couples to down-type quarks…

$$L = \bar{q}_L u_R H_u + \bar{q}_L d_R H_d - V(H_u, H_d) + \cdots$$

The Lagrangian is invariant under changing $\Theta \to \Theta - 2\alpha$. Thus, it seems that Θ is not physical, since it is a phase of the PQ transformation. But, Θ is physical, which can be seen from the free energy dependence on $\cos\Theta$. At the Lagrangian level, there seems to be no strong CP problem. But $\langle H_u \rangle$ and $\langle H_d \rangle$ breaks the PQ global symmetry and there results a Goldstone boson, axion *a* [Weinberg,Wilczek]. Since Θ is made field, the original $\cos\Theta$ dependence becomes the potential of the axion *a.*

If its potential is of the $\cos\Theta$ form, always $\Theta = a/Fa$ can be chosen at 0 [Instanton physics,PQ,Vafa-Witten]. So the PQ solution of the strong CP problem is that the vacuum chooses

$$\theta = 0$$



Compilation by G. Raffelt, 05.2007

Why axion solution of the strong CP may be attractive for cosmologists?

… allows for adjustments of the of cosmological parameters using low-mass cold dark matter

Axion field values right after inflation can take any value between [0,π]. So Ω_a may be at the required value by an appropriate misalignment angle for any F_a in the new inflation scenario. [Pi(84)]

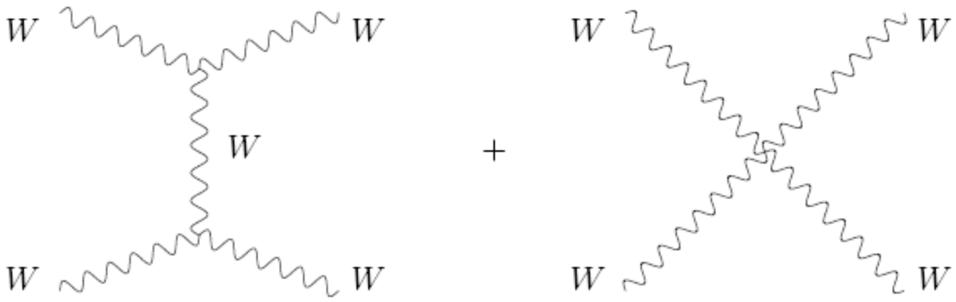
The axion potential is of the form

The vacuum stays there for a long time, and oscillates when the Hubble time(1/H) is larger than the oscillation period($1/m_a$)

$$H < m_a$$

This occurs when the temperature is about 1 GeV.

Problem 2: The unitarity of EW amplitudes at high energies



The amplitude for elastic W boson collisions (the contribution due to virtual W-exchanges to collisions of longitudinally polarized W-bosons) grows as s^2 at high energies and breaks the unitarity limit at the TeV scale.

:

Cure: Cancellation of the leading divergence by introducing a quadrilinear coupling among the W boson, which must be quadratic in the coupling g_W

...the following condition must be fulfilled:

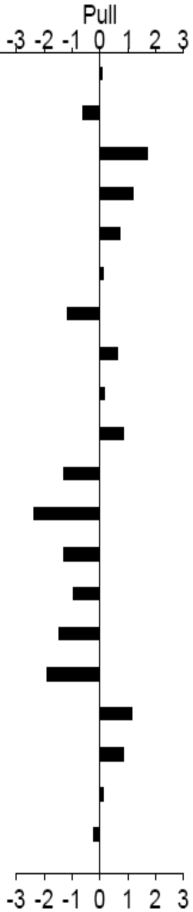
$$\lambda_{klmn} = g_W^2 \varepsilon_{klp'} \varepsilon_{p'mn}$$

for the couplings of the W bosons: k,l,m,n.

Unitarity is however not fully restored!!! (the amplitude grows as s at high energies)
... but all theory-intrinsic mechanisms exhausted –
need a mechanism which is external to the field theory of massive vector bosons...

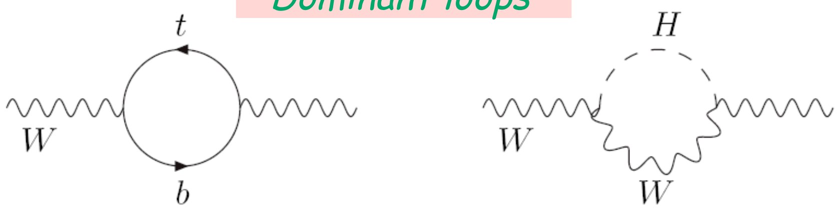
A putative solution: Higgs particle

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.07
Γ_Z [GeV]	2.4944 ± 0.0024	-.62
σ^0_{hadr} [nb]	41.544 ± 0.037	1.72
R_e	20.768 ± 0.024	1.19
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.70
A_e	0.1483 ± 0.0051	.13
A_τ	0.1425 ± 0.0044	-1.16
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.65
m_W [GeV]	80.401 ± 0.048	.15
R_b	0.21642 ± 0.00073	.85
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.34
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.29
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.47
$\sin^2\theta^{lept}_{eff}$	0.23096 ± 0.00026	-1.87
$\sin^2\theta_W$	0.2255 ± 0.0021	1.17
m_W [GeV]	80.448 ± 0.062	.88
m_t [GeV]	174.3 ± 5.1	.11
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.20



Absorbing unknown into Higgs mass

Dominant loops



$$\sin^2\vartheta^\ell_{\text{eff}}\left(1-\sin^2\vartheta^\ell_{\text{eff}}\right)=\frac{\pi\alpha}{\sqrt{2}G_F M_Z^2\left(1-\Delta r_Z\right)}$$

$$\Delta r_Z=\Delta\alpha-\Delta\rho^t+\Delta r_Z^H+\cdots$$

$$\Delta\rho^t=\frac{3G_F m_t^2}{8\pi^2\sqrt{2}}+\cdots$$

$$\Delta r_Z^H=\frac{G_F M_W^2}{8\pi^2\sqrt{2}}\frac{1+9\sin^2\vartheta_W}{3\cos^2\vartheta_W}\log\frac{M_H^2}{M_W^2}+\cdots$$

An evidence? *....or just an arbitrary absorption of inconsistency into a mass parameter...*

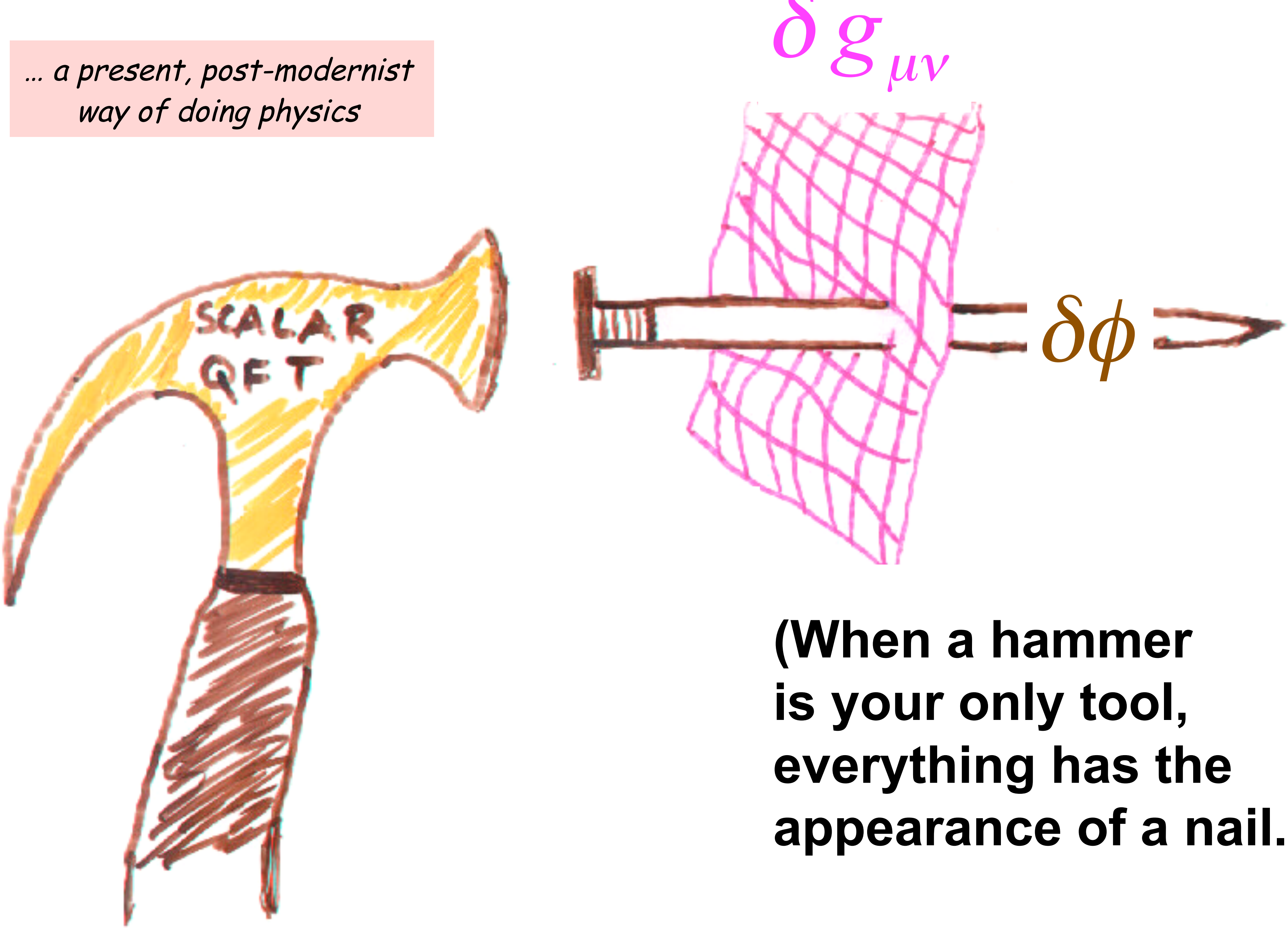
Why the Higgs solution of the unitarity problem is attractive for cosmologists ?

It would provide the first ever "evidence" of the elementary scalar field
… many of them have been proposed e.g. quintessence, k-essence, inflatons, dilatons… …
…and none discovered so far

I leave out for the moment the fine-tuning problem of the vacuum energy density and come back to it later…

… as nicely depicted by R. Kolb

… a present, post-modernist way of doing physics



(When a hammer is your only tool, everything has the appearance of a nail.)

Problem 3: Quantum stability

- Consider generic fermion and boson loops:

- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

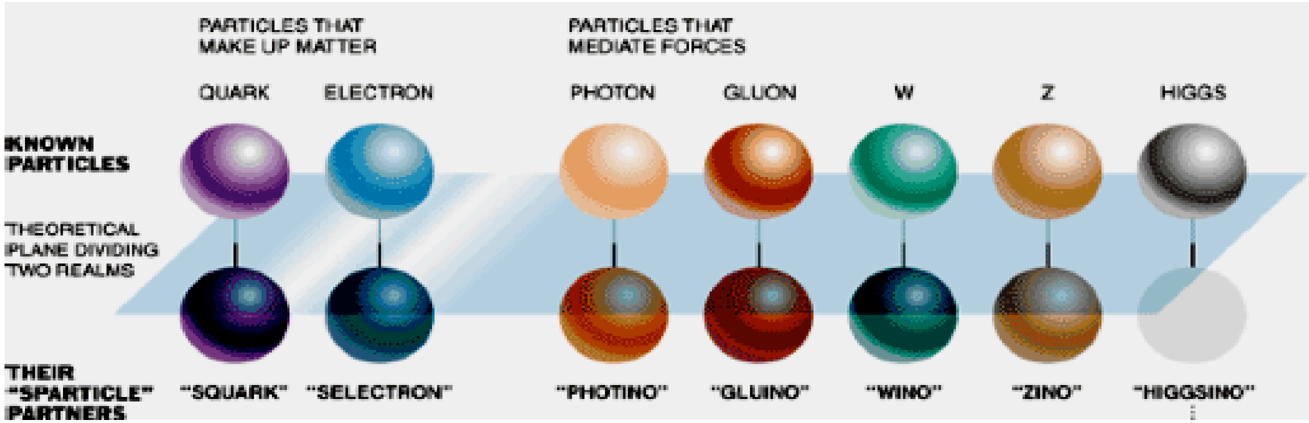
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

$\lambda_S = y_f^2$ x 2 **Supersymmetry!**

A putative solution 3: super-symmetry

fermions **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

Why super-symmetry is so beloved by (most of) the theorists?

- Helps to stabilize the weak scale—Planck scale hierarchy
- Supersymmetry algebra contains the generator of space-time translations. Necessary ingredient of theory of quantum gravity.
- Minimal supersymmetric extension of the SM : Leads to Unification of gauge couplings.
- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.
- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Why super-symmetry is attractive for the cosmologists?

<u>Evolution of the Dark Matter Density</u>

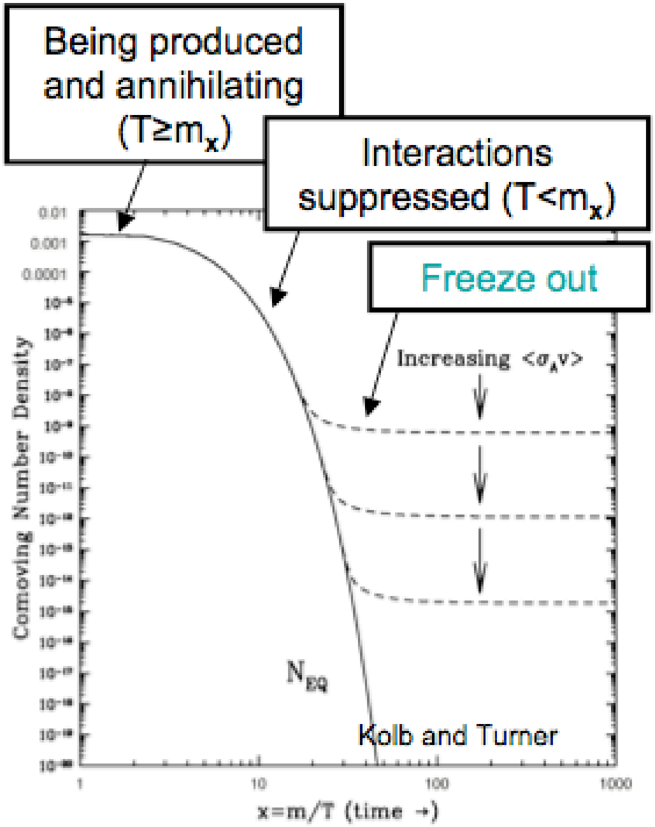
- Heavy particle initially in thermal equilibrium
- Annihilation stops when number density drops

$$H > \Gamma_A \approx n_\chi < \sigma_A v >$$

- i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")

- Leaves a relic abundance:

$$\Omega_{DM} h^2 \approx \ < \sigma_A v >^{-1}$$



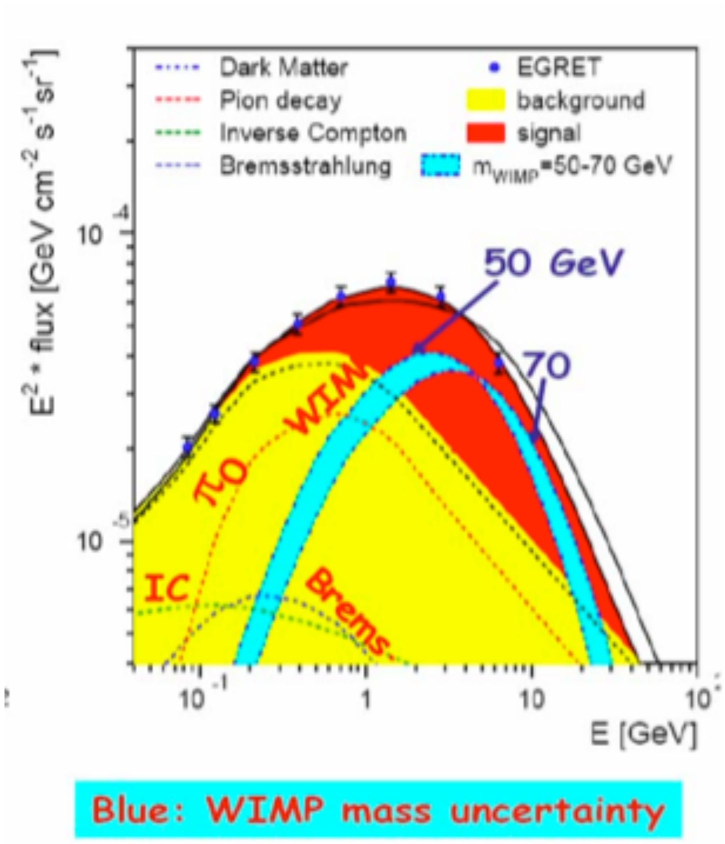
If m_x and σ_A determined by electroweak physics,

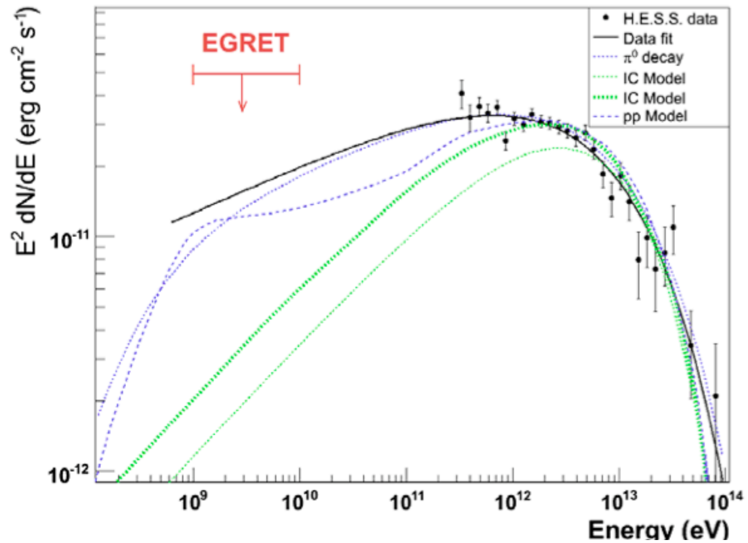
$\sigma_A \approx k\alpha_W^2 / m_X^2 \approx$ a few pb then Ω_{DM}~0.1 for m_x~0.1-1 TeV

Remarkable agreement with WMAP-SDSS → $\Omega_{DM} = 0.104 \pm 0.009$

Why super-symmetry may be useful for astrophysicists?

An extra degree of freedom to fit the observed energy spectrum of the gamma-ray sources



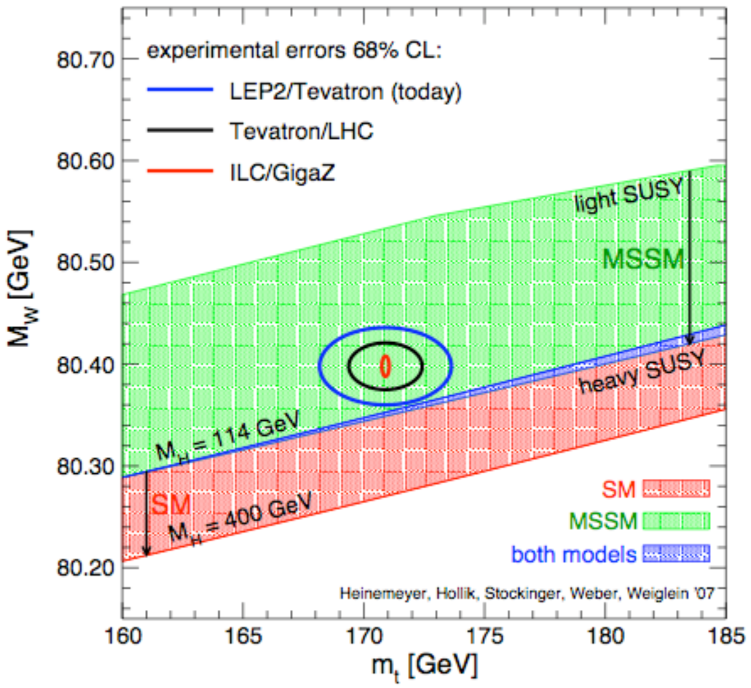


H.E.S.S. - Phys.Rev.Lett.97:221102,2006

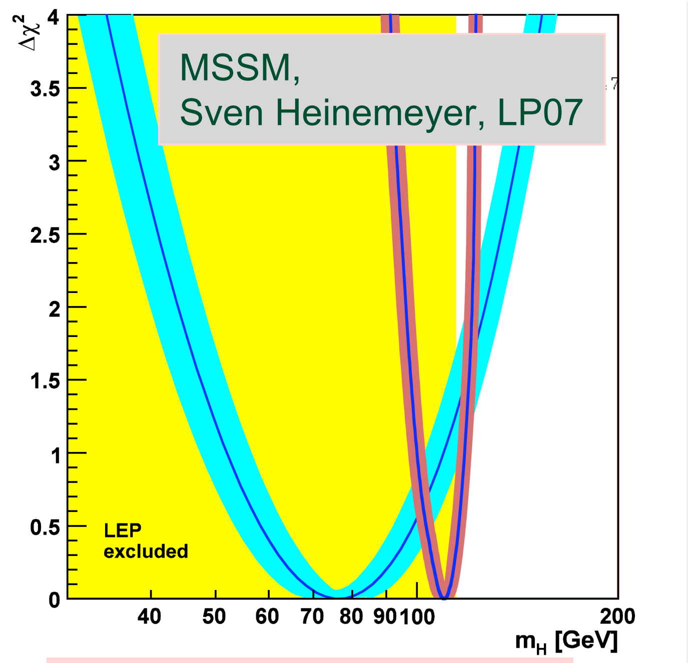
In conclusion, the power-law energy spectrum of the source HESS J1745-290 measured using the H.E.S.S. telescopes show that the observed VHE γ-ray emission is not compatible with the most conventional DM particle annihilation scenarios. It is thus likely that the bulk of the emission is provided by astrophysical non-DM processes.

Why super-symmetry is the focal point for (most of) particle physicists?

… because its discovery may be just behind the the corner…
… or its exclusion



With Electroweak precision measurements
and cold dark matter density (WMAP, …)



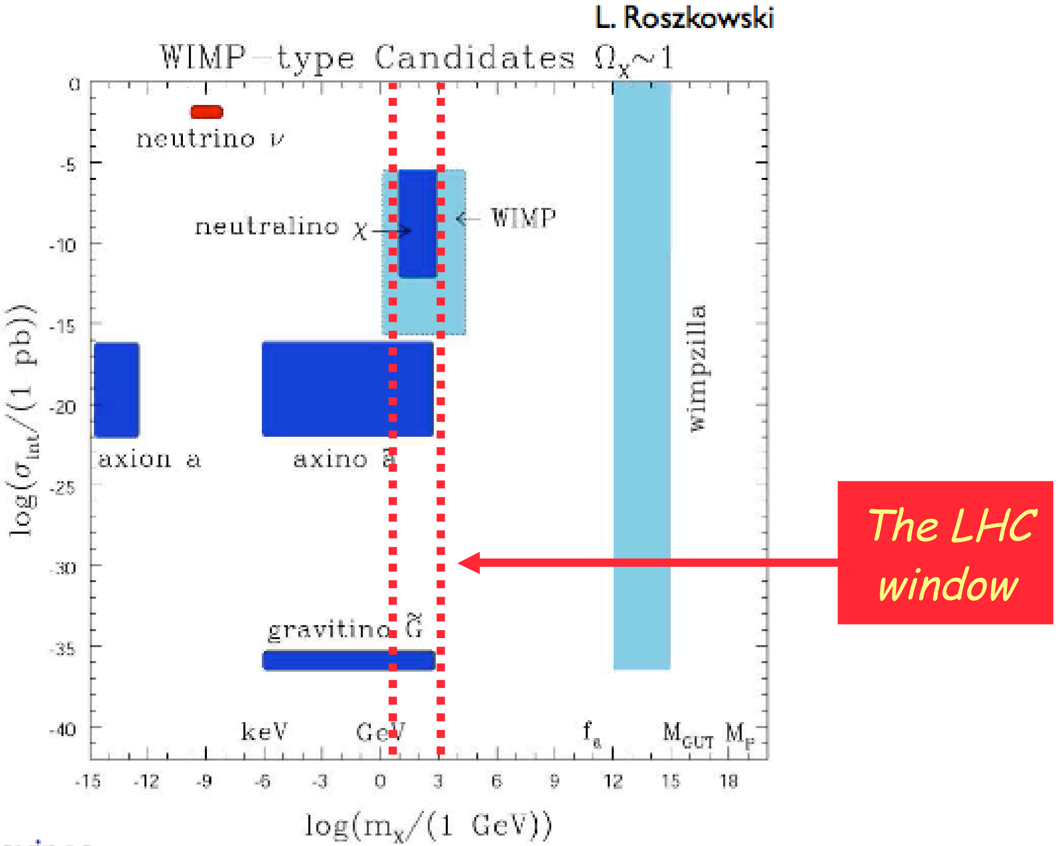
… by precision measurement of the standard model parameters

… or by finding (excluding) The Higgs Boson

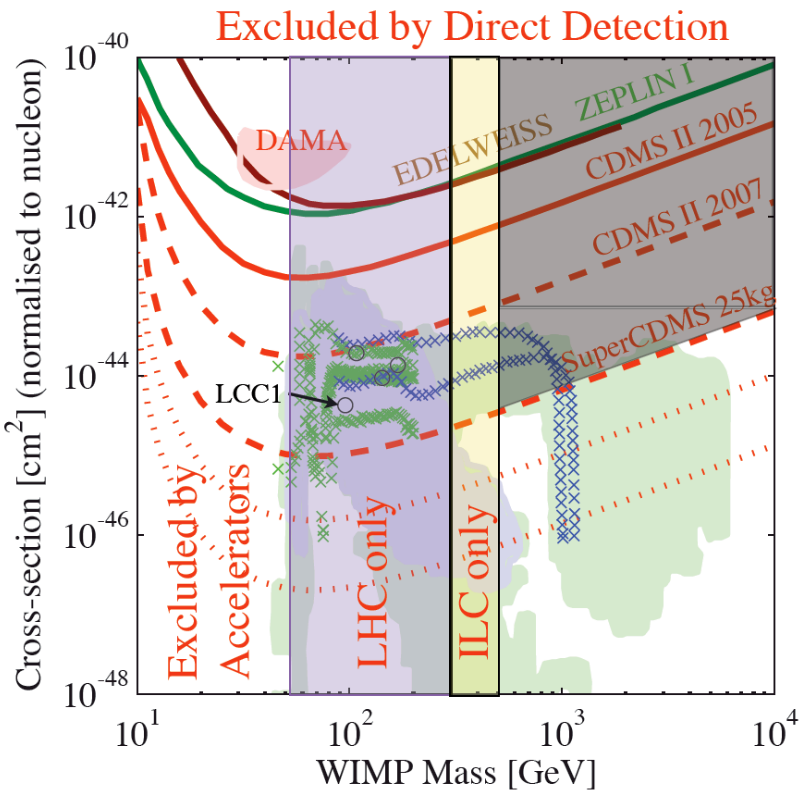
- **The convergence?**

The (point-like) particle dark matter Zoo

- Neutrinos
  - only massive (sterile) neutrinos can be *cold* or *warm*. Low-mass neutrinos make *hot* dark matter.
- Axions
  - Form as Bose condensate in early universe: cold in spite of low mass
- Weakly Interacting Massive Particles (WIMPs)
  - new massive (~100 GeV) particle with electroweak scale interactions with normal matter
  - SUSY neutralino
  - Lightest Kaluza-Klein particle in universal extra dimensions
- Less compelling candidates:
  - SUSY gravitinos (SuperWIMPs) and axinos
  - WIMPzillas, SIMPzillas, primordial black holes, Q-balls, strange quark nuggets, mirror particles, CHArged Massive Particles (CHAMPs), self interacting dark matter, D-matter, cryptons, brane world dark matter...



The complementarities with the direct search experiments



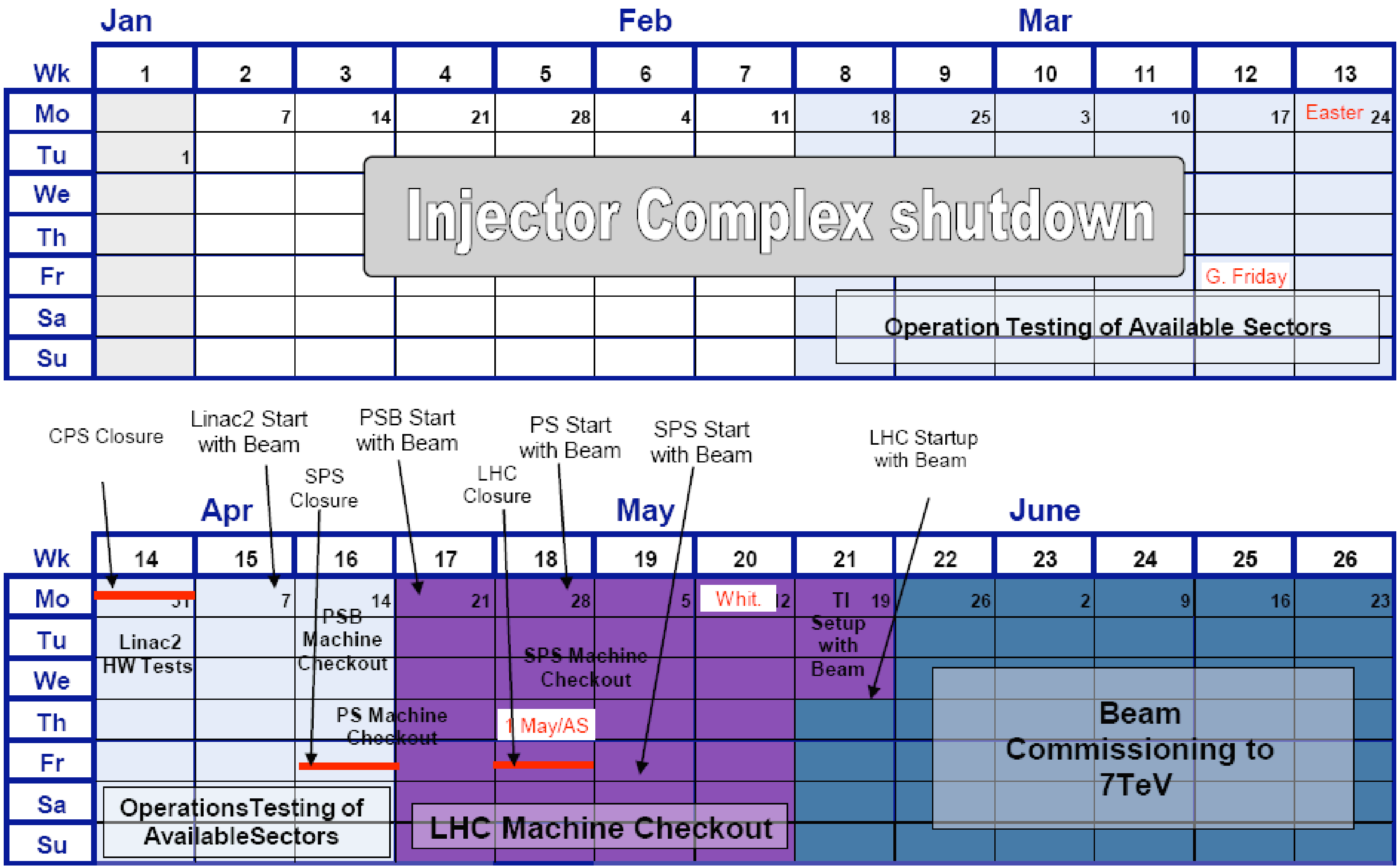
__Note:__

The LHC ILC searches limited to particles with point like coupling to the SM particles

- **The expected LHC verdicts**

Lyn Evans
SPC 18-June-2007

2008 LHC accelerator schedule



Nice

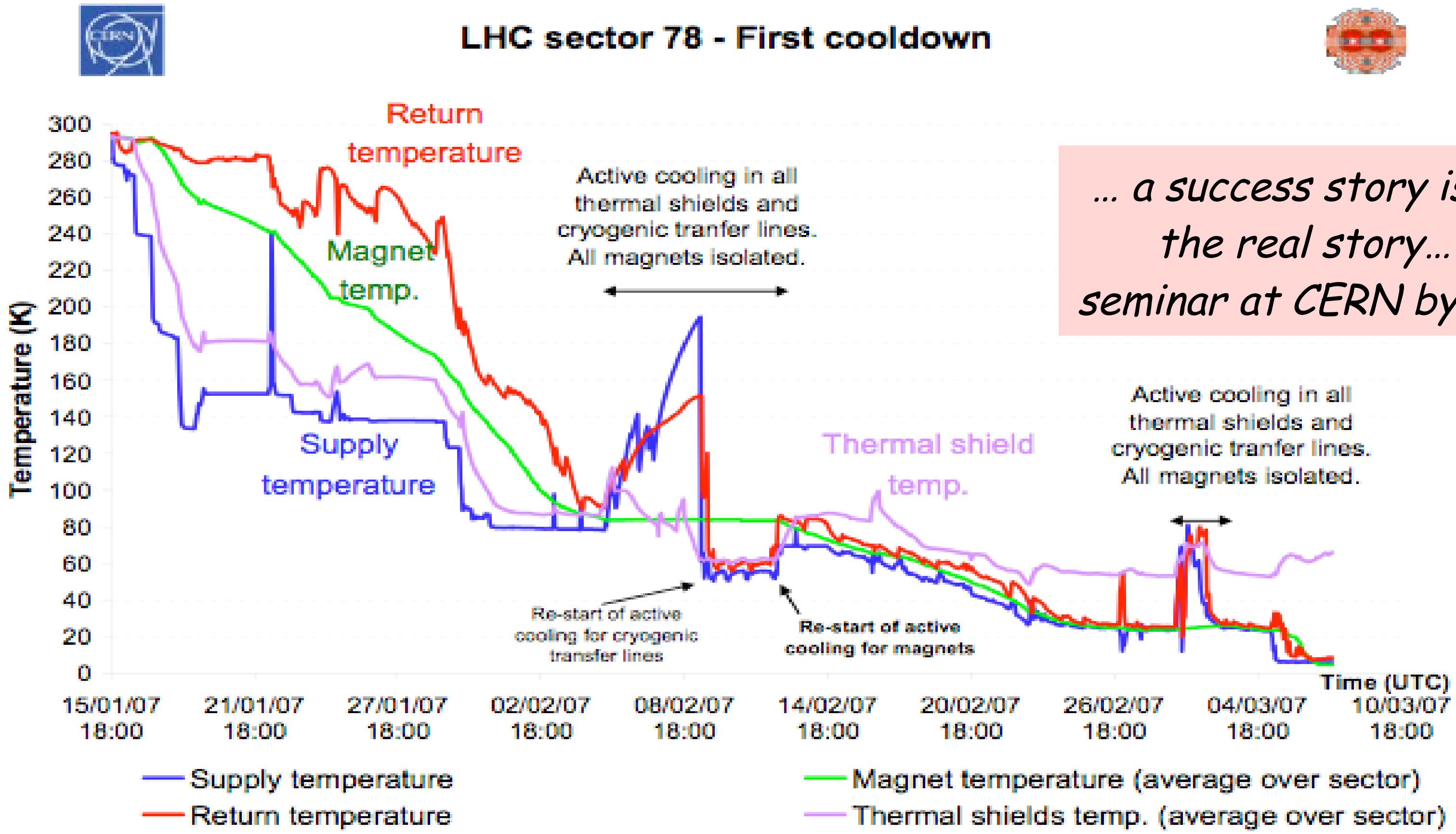
S. Claudet, August-2007

2008 LHC accelerator schedule

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning. 450 GeV operation now part of normal setting up procedure for beam commissioning to high-energy

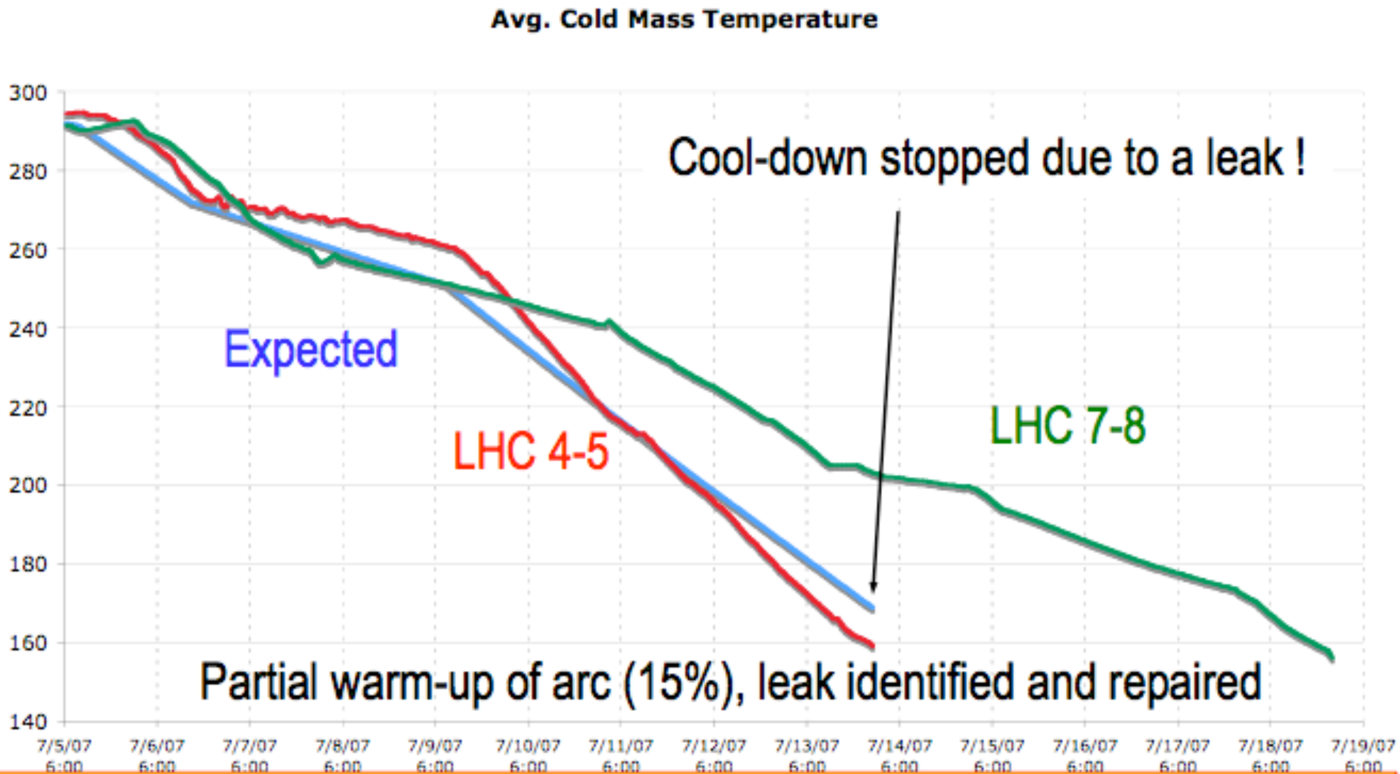
- General schedule has been revised, accounting for inner triplet repairs and their impact on sector commissioning
  - All technical systems commissioned to 7 TeV operation, and machine closed April 2008
  - Beam commissioning starts May 2008
  - First collisions at 14 TeV c.m. July 2008
  - Luminosity evolution will be dominated by our confidence in the machine protection system and by the ability of the detectors to absorb the rates

- Success-oriented schedule without provision for major mishaps, e.g. additional warm-up/cooldown of sector



… a success story is a part of the real story…today's seminar at CERN by Lynn Evans

Cool-down of 2nd sector



Cool-down resumed 06 August 2007, but stopped again 15 Aug 2007 !!!

- **Will super-symmetric dark matter be produced and detected at LHC?**

… the SUSY nomenclature

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:

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

  Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Called constrained MSSM = CMSSM
- Gravitino mass? Minimal supergravity (mSUGRA)

  Additional relations: $m_{3/2} = m_0$, $B_\mu = A_\lambda - m_0$

Simulations of the discovery-capacity of LHC (… or rejection capacity) for super-symmetric scenarios

Simulation (simiŭlēi·ʃən). ME. [a. OF., ad. L. *simulationem*.] 1. The action or practice of simulating, with intent to deceive; false pretence, deceitful profession ME. b. Unconscious imitation 1870. 2. A false assumption or display, a surface resemblance or imitation, *of* something.

… the methodology

SUSY breaking structure

SUSY breaking communicated to visible sector at some high scale

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,$ sgn μ (mSUGRA)

Evolve down to EW scale through Renormalization Group Equations (RGE)

$M_1,\ M_2,\ M_3,\ m(\tilde{f}_R),\ m(\tilde{f}_L),\ A_t,\ A_b,\ A_\tau,\ m(A),\ \tan\beta, \mu$

From 'soft' terms derive mass eigenstates and sparticle couplings.

$m(\tilde{\chi}^0_j),\ m(\tilde{\chi}^\pm_j),\ m(\tilde{q}_R),\ m(\tilde{q}_L),\ m(\tilde{b}_1),\ m(\tilde{b}_2),\ m(\tilde{t}_1),\ m(\tilde{t}_2)$......

105 free parameters

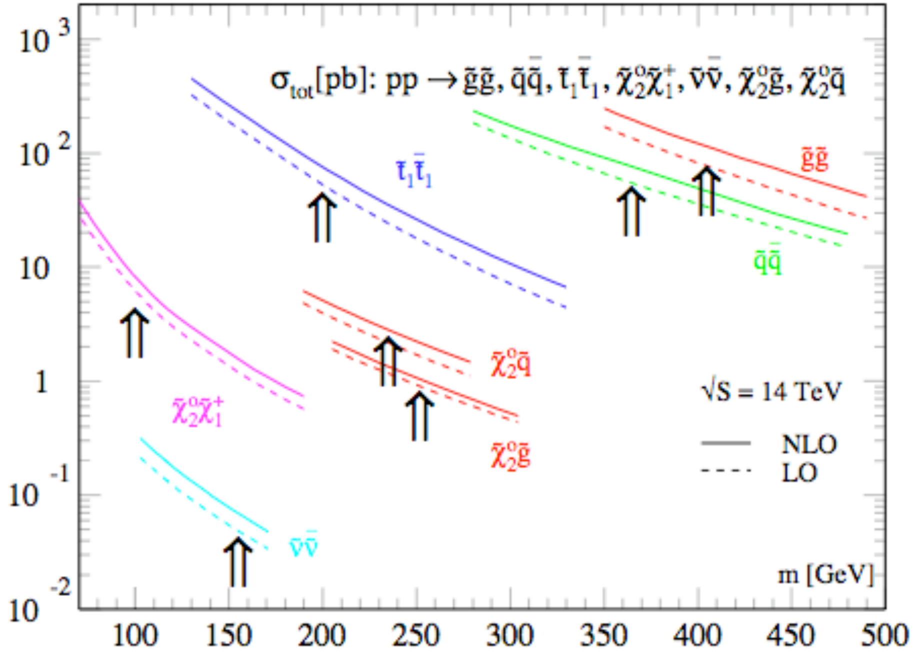
Structure enshrined in Monte Carlo generators (e.g ISAJET)

Task of experimental SUSY searches is to go up the chain, i.e. to measure enough sparticles and branching ratios to infer information on the SUSY breaking mechanism

… the cross sections

Sparticles have same couplings of SM partners ⇒ production dominated by colored sparticles: squarks and gluinos if light enough

Squark and gluino production cross-section ∼ only function of squark and gluino mass



Production cross-section ∼ independent from details of model:

- $\sigma_{SUSY} \sim 50$ pb for $m_{\tilde{q},\tilde{g}} \sim 500$ GeV
- $\sigma_{SUSY} \sim 1$ pb for $m_{\tilde{q},\tilde{g}} \sim 1000$ GeV

… the signatures

Most important features of SUSY events used for discovery:

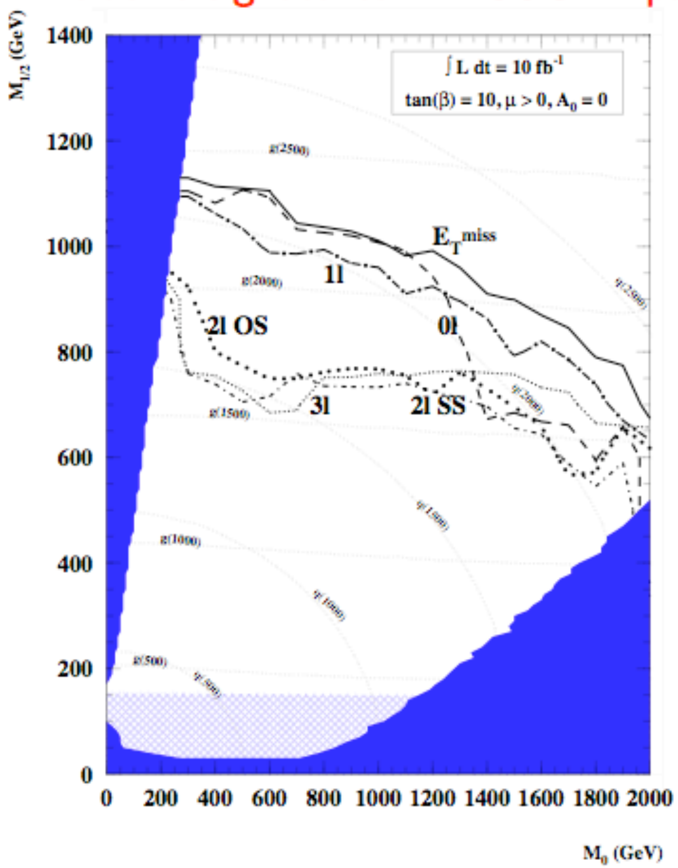
- $\not\!\!E_T$: from LSP escaping detection
- High E_T jets: variables: N_{jets}, $P_T(jet_1)$, $P_T(jet_2)$ $\Sigma_i |p_{T(i)}|$ $\Delta\phi(jet - \not\!\!E_T)$

  guaranteed if squarks/gluinos not too degenerate with gauginos, e.g. if unification of gaugino masses assumed. Variables:
- Spherical events: variable S_T

  From Tevatron limits squarks/gluinos must be heavy ($\gtrsim$ 400 GeV).
- Multiple leptons: from decays of Charginos/neutralinos typically present in cascade

… the exclusion limits (an example)

Inclusive signatures in mSUGRA parameter space



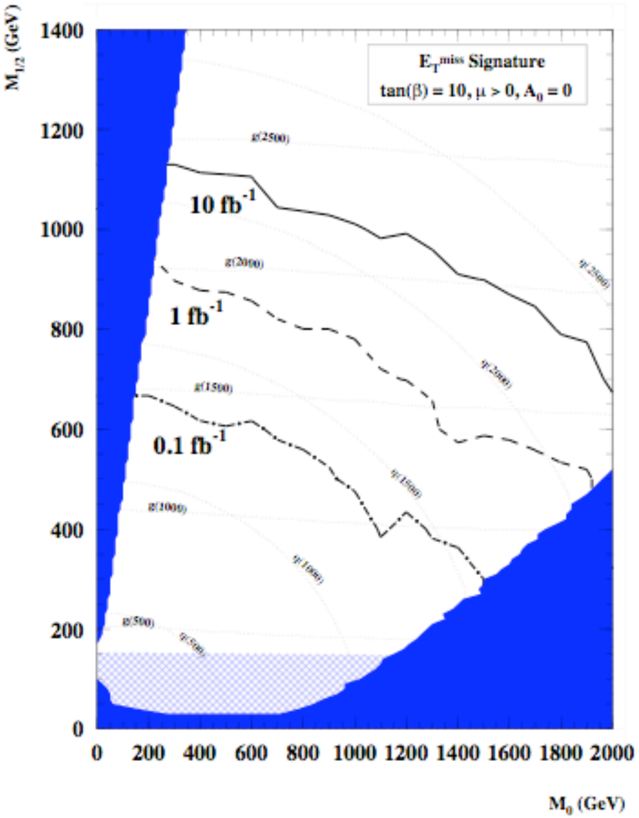
Multiple signatures on most of parameter space

- $\not\!\!E_T$ ⇐ Dominant signature
- $\not\!\!E_T$ with lepton veto
- One lepton
- Two leptons Same Sign (SS)
- Two leptons Opposite Sign (OS)

When first signal observed with a signature, look for it also in other channels

… the exclusion limits (cont.)

Discovery reach as a function of luminosity



- ~1300 GeV in 100 pb^{-1}
- ~1800 GeV in 1 fb^{-1}
- ~2200 GeV in 10 fb^{-1}

Fast discovery from signal statistics

Time for discovery determined by:

- Time to understand detector performance ($\not\!\!E_T$ tails, lepton id, jet scale)
- Time to collect sufficient statistics of SM control samples: W, Z+jets, $\bar{t}t$

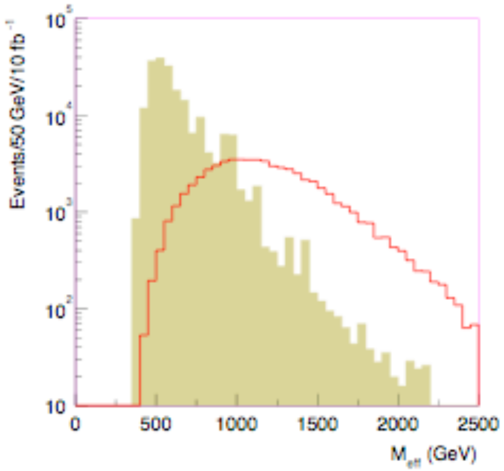
Two main background classes:

- Instrumental $\not\!\!E_T$
- Real $\not\!\!E_T$ from neutrinos

… the mass scale (if signal observed)

Start from multijet + $\not{E}_T$ signature.

Simple variable sensitive to sparticle mass scale: $M_{\text{eff}} = \Sigma_i |p_{T(i)}| + E_T^{\text{miss}}$ where $p_{T(i)}$ is the transverse momentum of jet



M_{eff} distribution: signal (red), background (brown)

mSUGRA $m_0 = 100$ GeV, $m_1/2 = 300$ GeV, $\tan\beta = 10$, $A = 0$, $\mu > 0$

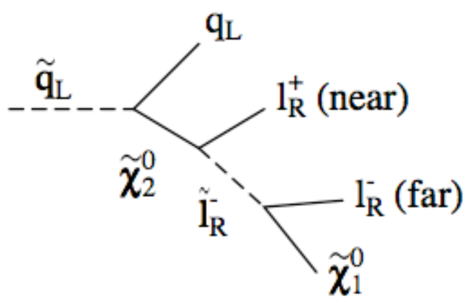
A cut on M_{eff} allows to separate the signal from SM background

The M_{eff} distribution shows a peak which moves with the SUSY mass scale.

Expect $\sim 10\%$ precision on SUSY mass scale for one year at high luminosity

… and detailed S-Zoo masses (example)

Complete results for $\tilde{q}_L \to \tilde{\ell}\ell$ decay chain: (Allanach et al. hep-ph/0007009)



l^+l^- edge $\quad (m_{ll}^{\max})^2 = (\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi})/\tilde{l}$

l^+l^-q edge $\quad (m_{llq}^{\max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{\chi})/\tilde{\xi}$

l^+l^-q thresh $\quad (m_{llq}^{\min})^2 = \begin{cases} [\ 2\tilde{l}(\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{\chi}) \\ +(\tilde{q} + \tilde{\xi})(\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi}) \\ \quad -(\tilde{q} - \tilde{\xi})\sqrt{(\tilde{\xi} + \tilde{l})^2(\tilde{l} + \tilde{\chi})^2 - 16\tilde{\xi}\tilde{l}^2\tilde{\chi}}\ ] \\ /(4\tilde{l}\tilde{\xi}) \end{cases}$

$l^{\pm}_{\text{near}}q$ edge $\quad (m_{l_{\text{near}}q}^{\max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{l})/\tilde{\xi}$

$l^{\pm}_{\text{far}}q$ edge $\quad (m_{l_{\text{far}}q}^{\max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/\tilde{l}$

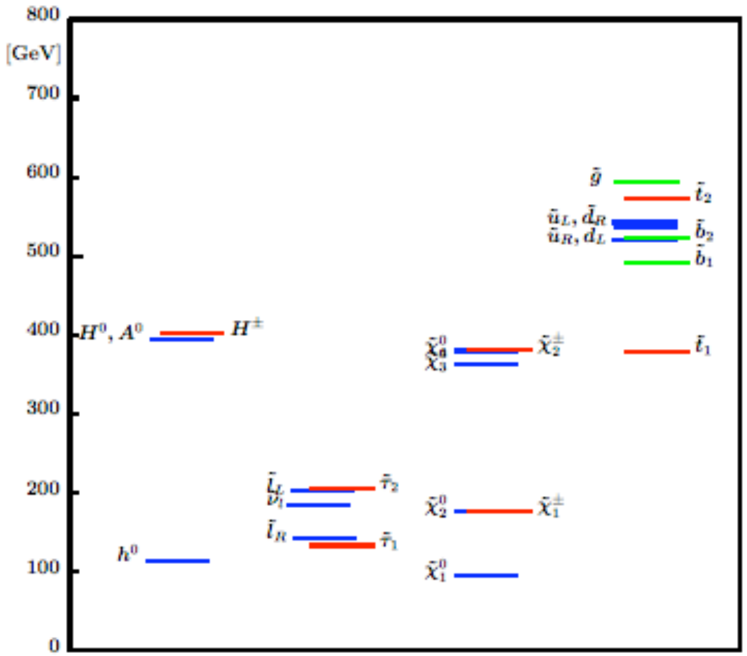
With $\tilde{\chi} = m^2_{\tilde{\chi}_1^0}$, $\quad \tilde{l} = m^2_{\tilde{l}_R}$, $\quad \tilde{\xi} = m^2_{\tilde{\chi}_2^0}$, $\quad \tilde{q} = m^2_{\tilde{q}}$

… and detailed S-Zoo masses (example)

Example: Point SPS1a

$m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A = -100$ GeV, $\tan\beta = 10$, $\mu > 0$

Friendly to a 1 TeV linear Collider, with appropriate Dark Matter density



Total cross-section: ~50 pb

Relevant Branching ratios

BR($\tilde{g} \to \tilde{q}_L q$) ~25%   BR($\tilde{g} \to \tilde{q}_R q$) ~40%

BR($\tilde{g} \to \tilde{b}_1 b$) ~17%

BR($\tilde{q}_L \to \tilde{\chi}_2^0 q$) ~30%   BR($\tilde{q}_L \to \tilde{\chi}^\pm q'$) ~60%

BR($\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell$)=12.6%   BR($\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$)=87%

… the external indirect constraints…

★ LEP2:

- $m_h > 114.4$ GeV for SM-like h
- $m_{\widetilde{W}_1} > 103.5$ GeV
- $m_{\tilde{e}_{L,R}} > 99$ GeV for $m_{\tilde{\ell}} - m_{\widetilde{Z}_1} > 10$ GeV

★ $BF(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ (BELLE, CLEO, ALEPH)

- SM theory: $BF(b \to s\gamma) \simeq (3.0 - 3.7) \times 10^{-4}$

★ $a_\mu = (g-2)_\mu/2$ (Muon $g-2$ collaboration)

- $\Delta a_\mu = (22 \pm 10) \times 10^{-10}$ (PDG value e^+e^-)
- $\Delta a_\mu^{SUSY} \propto \frac{m_\mu^2 \mu M_i \tan\beta}{M_{SUSY}^4}$

★ $BF(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ (CDF)

- constrains at very large $\tan\beta \gtrsim 50$

★ $\Omega_{CDM} h^2 = 0.11 \pm 0.01$ (WMAP)

SUSY as dark matter candidate →

… LHC as SUSY Dark Matter factory (two scenarios)

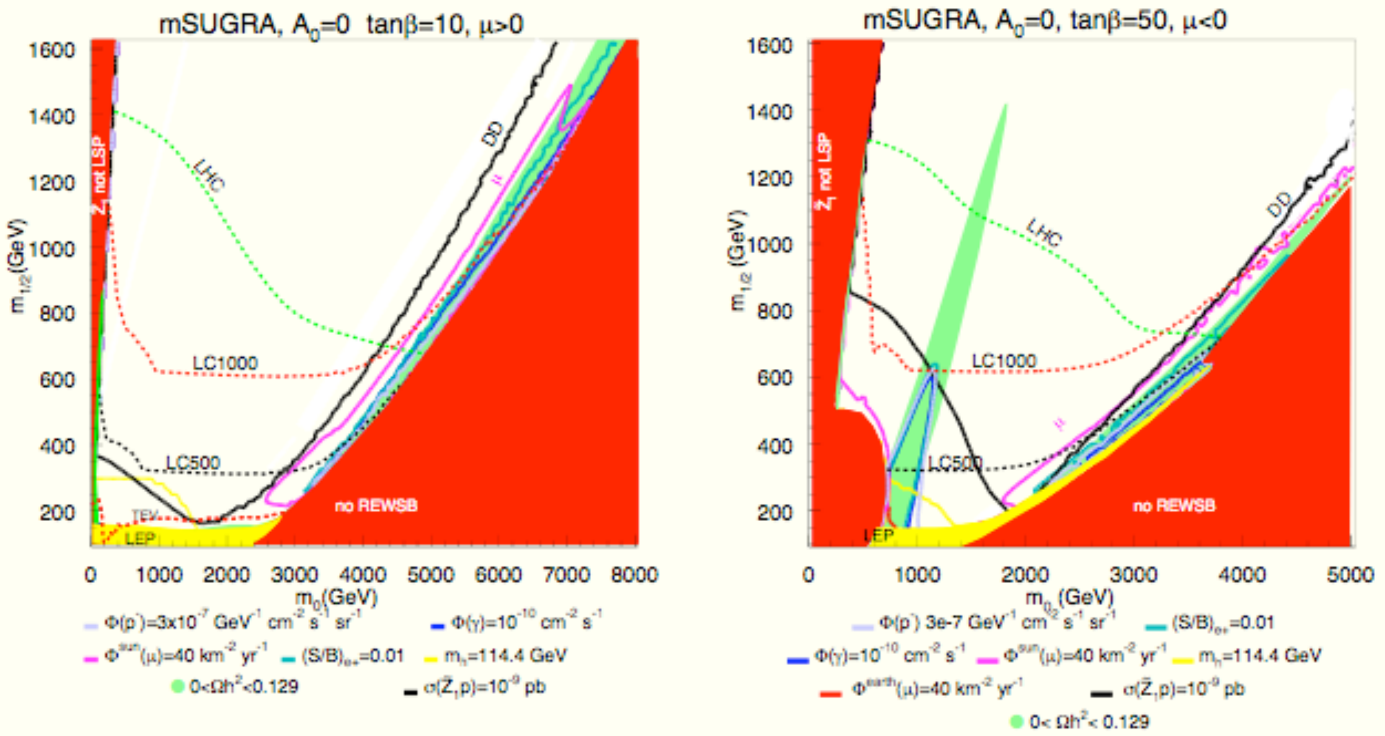
- the neutralino (WIMP), the superpartner of photon, Z and Higgs boson (in some linear combination), most popular, many search experiments !!

- the gravitino, the superpartner of the graviton, gauge fermion of local supersymmetry (analog of W-boson for weak interactions), theoretically most attractive, all interactions fixed via symmetry !! First proposed dark matter candidate (Pagels and Primack '81), with $m_{3/2} \sim 1$ keV (for negligable neutrino masses).

Resulting cosmology →

- 0.1 eV $[10^{13}$ s]: decoupling of photons, CMB
- $0.1 \ldots 10$ MeV $[10^{2} \ldots 10^{-2}$ s]: primordial nucleosynthesis (BBN)
- ~ 10 GeV $[10^{-8}$ s]: WIMP decoupling, standard SUSY dark matter
- 100 GeV $[10^{-10}$ s]: electroweak transition, sphaleron processes
- $10^{6} \ldots 10^{10}$ GeV $[10^{-18} \ldots 10^{-26}$ s]: leptogenesis, gravitino DM

… the existing constraints- neutralino dark matter



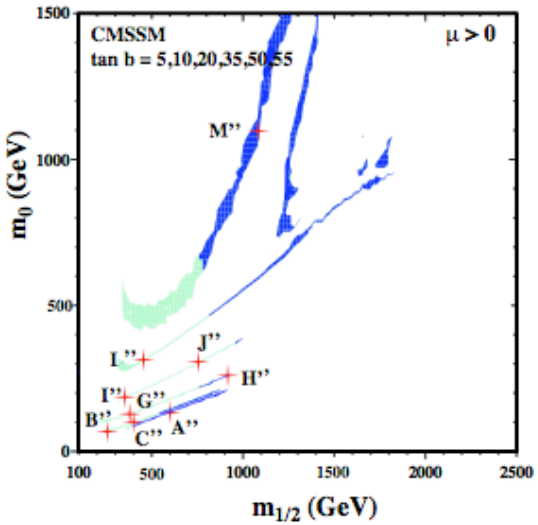
HB, Belyaev, Krupovnickas, O'Farrill: JCAP 0408, 005 (2004)

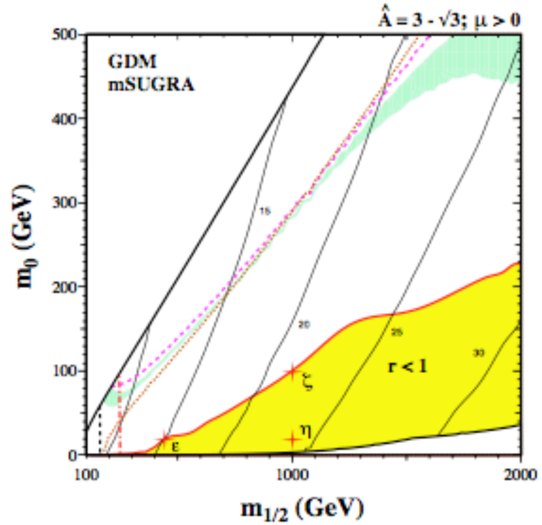
… the existing constraints - gravitino dark matter

Gravitino couplings to τ- and $\tilde{\tau}$-leptons, photons, etc. are determined by symmetries,

$$\mathcal{L}_{3/2} = -\frac{1}{\sqrt{2}M_{\rm P}}\left((D_\nu\,\tilde{\tau}_{\rm R})^*\overline{\psi^\mu}\,\gamma^\nu\,\gamma_\mu\,P_{\rm R}\tau + \ c.c.\right)\ ,$$

Compared to CMSSM with neutralino dark matter, gravitino dark matter with $\tilde{\tau}$-NLSP opens new region in parameter space, e.g. in mSUGRA: small m_0 with $m_{3/2} = m_0$



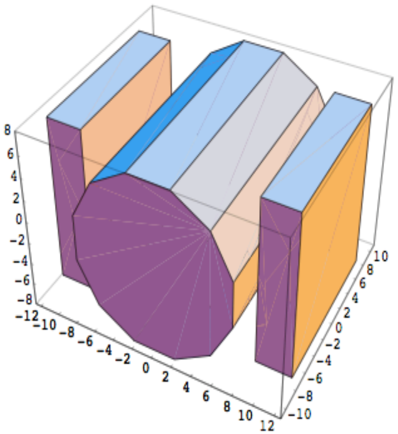


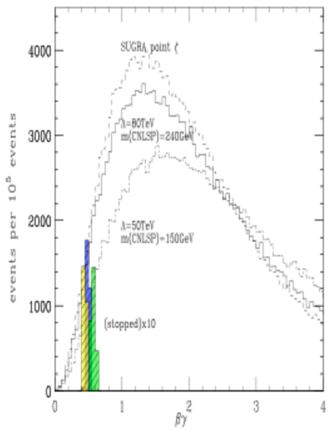
Typical $\tilde{\tau}$-lifetime: $\sim 10^4 - 3\times10^6$ s; other models: CMSSM, gaugino mediation,…; study of $\tilde{\tau}$-decays after trapping them in the walls of ATLAS and CMS caverns ?!

… gravitino search at LHC via stau detection

Stopping $\tilde{\tau}$'s Near CMS (Hamaguchi, Kuno, Nakaya, Nojiri '04; Feng, Smith '04; Hamaguchi, Nojiri, de Roeck '06)

Slow $\tilde{\tau}$ can be stopped in additional detector in the CMS cavern:

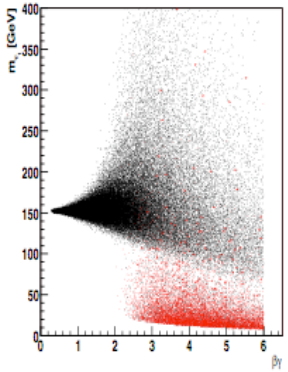


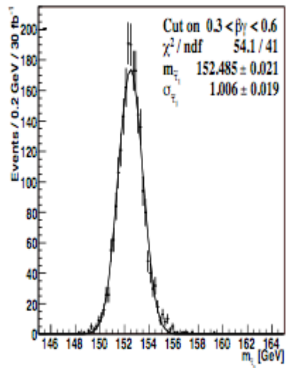


Planck mass measurement with 50% accuracy possible for $m_{3/2}/m_{\tilde{\tau}} > 0.2$, i.e., $\Gamma_{\tilde{\tau}}^{-1} >$ 1 month ($m_{\tilde{\tau}} \sim 200$ GeV)

Measuring the $\tilde{\tau}$-mass with ATLAS (Ellis, Raklev, Oye '06)

$\tilde{\tau}$-mass can be measured from $m_{\tilde{\tau}} = p_{\text{meas}}/\beta\gamma_{\text{meas}}$, slow $\tilde{\tau}$'s important! Background from muon tracks, accurate measurement of $\tilde{\tau}$-mass possible

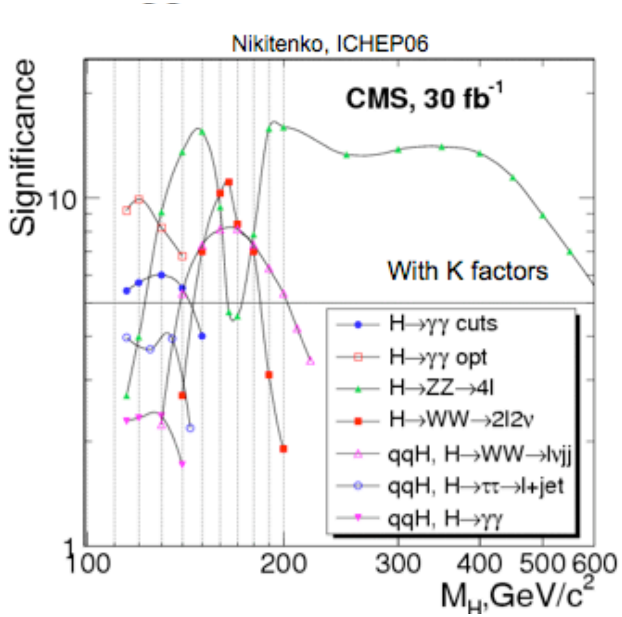




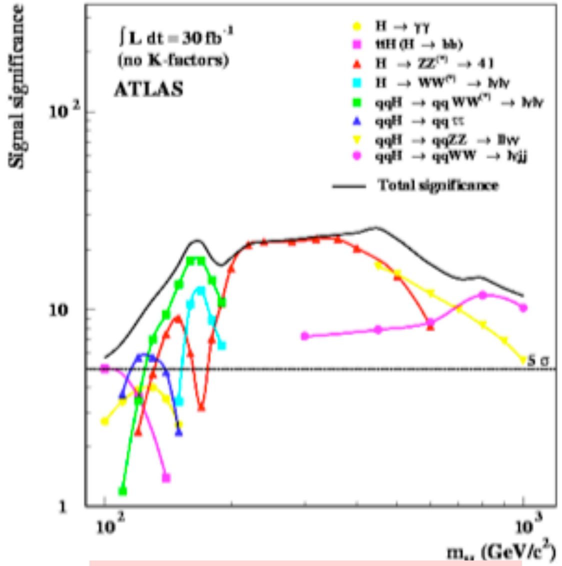
also relevant for shorter $\tilde{\tau}$-lifetimes, e.g. $\mathcal{O}(10^3$ s) and $m_{3/2} = \mathcal{O}(1$ GeV) as in 'Sweet Spot Supersymmetry' (Ibe, Kitano '07)

- **Will elementary scalars (Higgs-boson(s)) be produced and detected at LHC?**

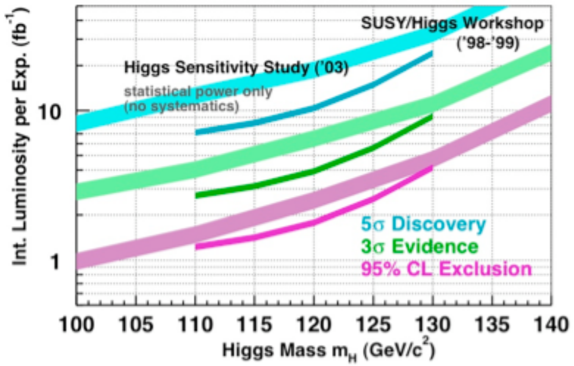
The standard Higgs



CMS



ATLAS



CDF/D0

Higgs' in MSSM

2 Higgs SU(2) doublets ϕ_1 and ϕ_2 : after Higgs Mechanism

→ 2 CP-even h, H with mixing angle α
1 CP-odd A and a charged pair $H^\pm$

All Higgs masses and couplings given in terms of m_A and $\tan\beta = v_2/v_1$

In most of the parameter space: $m_A >> m_Z$

==> lightest Higgs: $m_h \le m_Z$ (SM-like Higgs) and $m_A \approx m_H \approx m_{H^\pm}$

At tree level, one Higgs doublet couples only to down quarks and the other couples to up quarks only

$$-L = \bar{\psi}_L^i \left(\hat{h}_d^{ij^+} \phi_1 d_R^j + \hat{h}_u^{ij^+} \phi_2 u_R^j \right) + h.c. \qquad \bar{\psi}_L^i = \begin{pmatrix} \bar{u}_L \\ \bar{d}_L \end{pmatrix}^i$$

Since the up and down sectors are diagonalized independently, the Higgs interactions remain flavor diagonal at tree level.

Higgs in MSSM

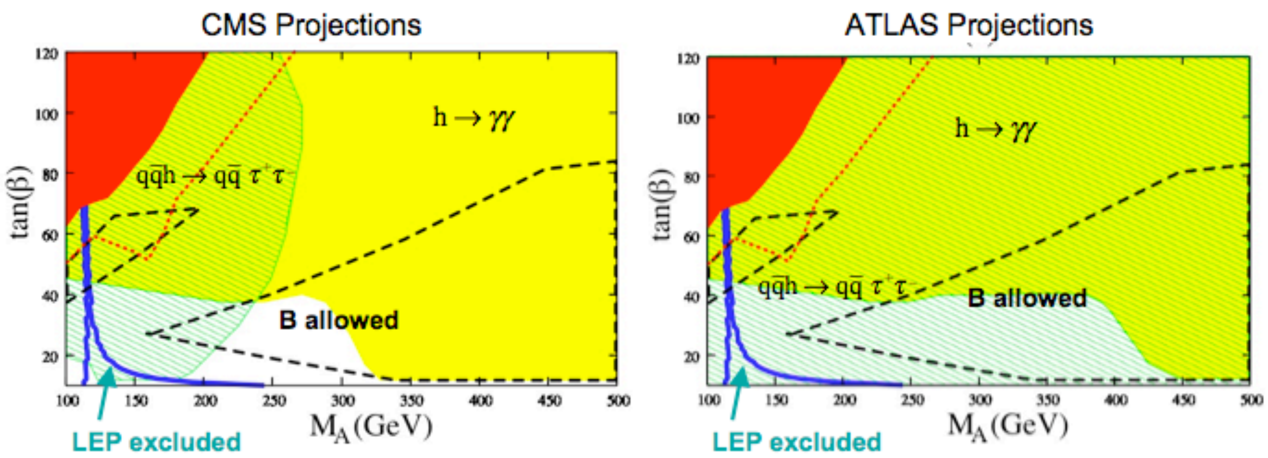
Discovery reach for SM-like MSSM Higgs at the LHC

with 30 fb^{-1}

- The No mixing scenario:

$$M_S = 2\text{ TeV};\quad X_t = 0;\quad m_{\tilde{g}} = 0.8\, M_S;\quad M_2 = 200\text{GeV};\quad A_t = A_b;\quad \mu = 1.5\text{ TeV}$$

Production and decay channels: $q\bar{q}h \rightarrow q\bar{q}\,\tau^+\tau^-$ and $h \rightarrow \gamma\gamma$ inclusive

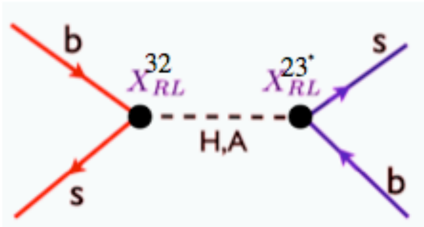


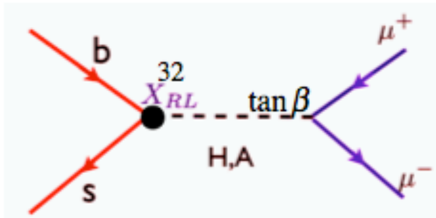
SM-like Higgs needs di-tau and di-photon channels to secure discovery with 30 fb^{-1}
some B allowed regions remain uncovered

-- One can see a SM-like Higgs in the $\gamma\gamma$ channel and not in the $\tau^+\tau^-$ channel

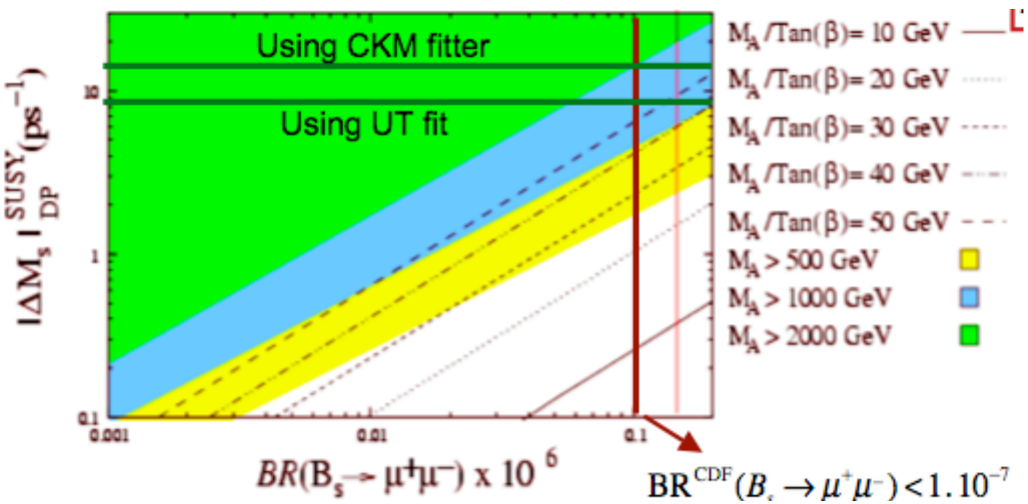
Indirect constraints for the MSSM Higgs

Correlation between Bs mixing and $\mathrm{BR}(B_s \to \mu^+\mu^-)$





$$(\Delta M_{B_s})^{SUSY} \propto \ominus \frac{X_{RL}^{32} X_{LR}^{32}}{m_A^2} \qquad BR(B_s \to \mu^+\mu^-)^{SUSY} \propto \frac{|X_{RL}^{32}|^2 \tan\beta^2}{m_A^4} \propto \frac{|\mu A_t|^2}{m}$$



$\mathrm{BR}^{CDF}(B_s \to \mu^+\mu^-) < 1.10^{-7}$

$\mathrm{BR}(B_s \to \mu^+\mu^-)_{SM}$ of order 10^{-9}

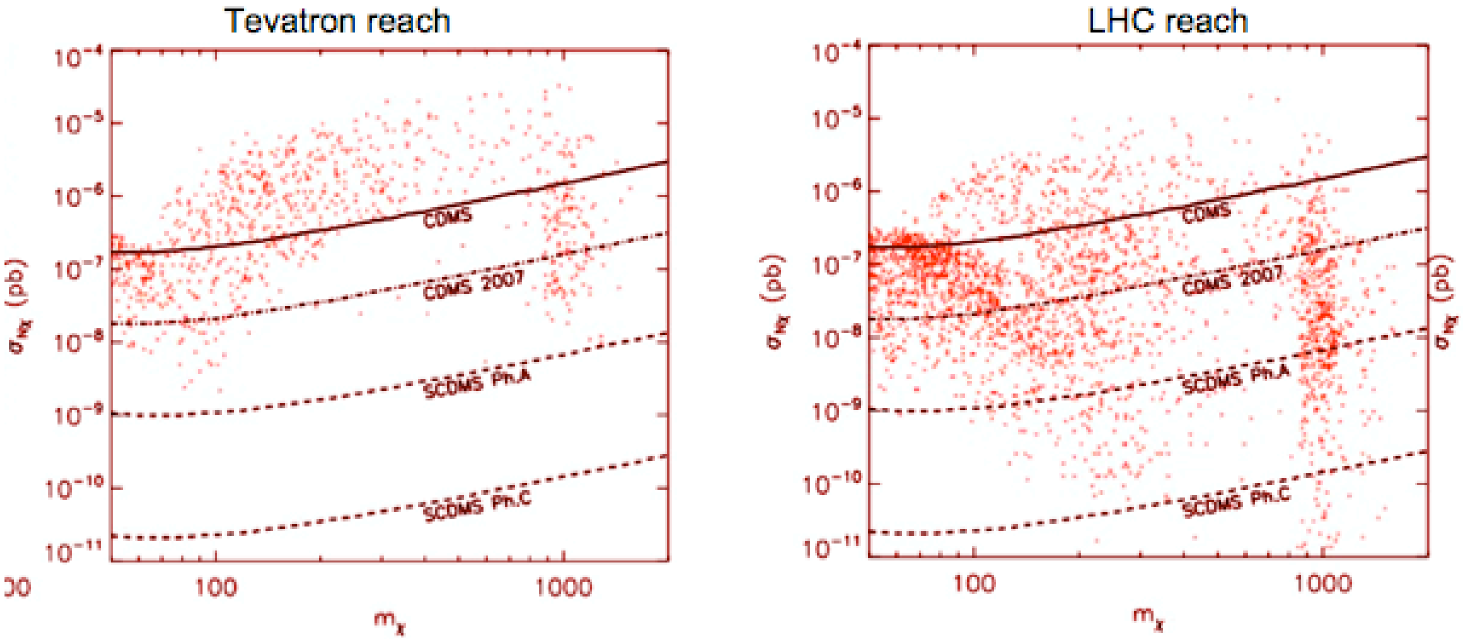
↓

at the reach of LHC(b) with about 10 (a few) fb^{-1}

The link of the MSSM Higgs and the neutralino dark matter

==> Evidence for H/A at the Tevatron (LHC) predict neutralino cross sections typically within the reach of present (future) direct DM detection experiments.

(strong μ dependence)



Instead of answering directly the questions some remarks

Super-symmetry is the most expected discovery at LHC (despite some dose of fine tuning necessary to keep it alive in the post LEP2 epoch)

If a low-mass Higgs boson is not found - it is dead (one has to recall however its past reincarnation capacity)

If a low-mass Higgs boson is found and nothing else …it could be saved giving up naturalness (e.g. split-SUSY)

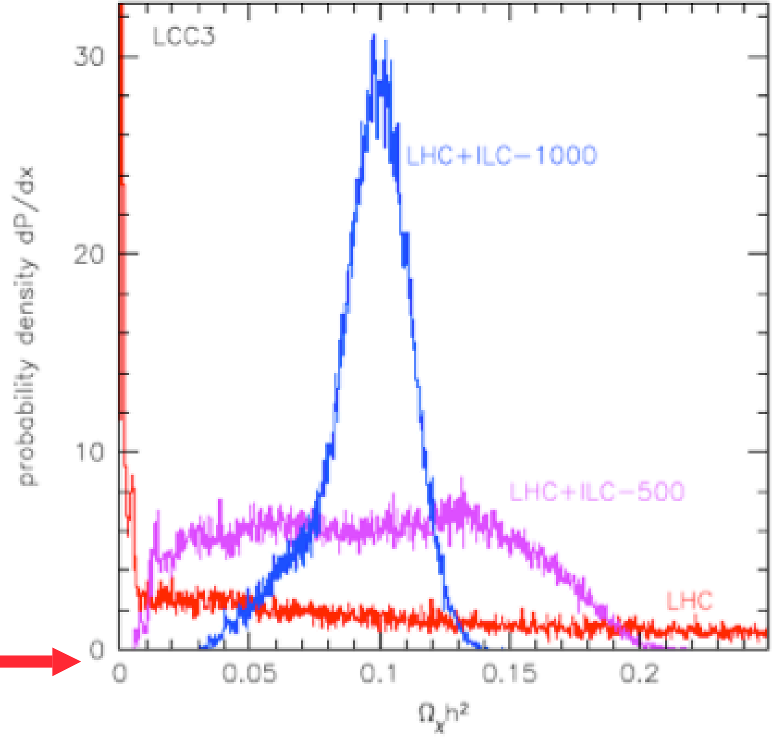
If super-symmetric particles are produced at LHC they are bound to be detected - it this will be the case:

Deciphering the SUSY parameters will be a long and not unambiguous process (given the number of parameters)

… and at the end of the game will not provide a precision estimate of the dark matter content of the universe

Excluding the presence of both the Higgs boson and super-symmetry would lead to overhauling the present paradigms in particle physics and

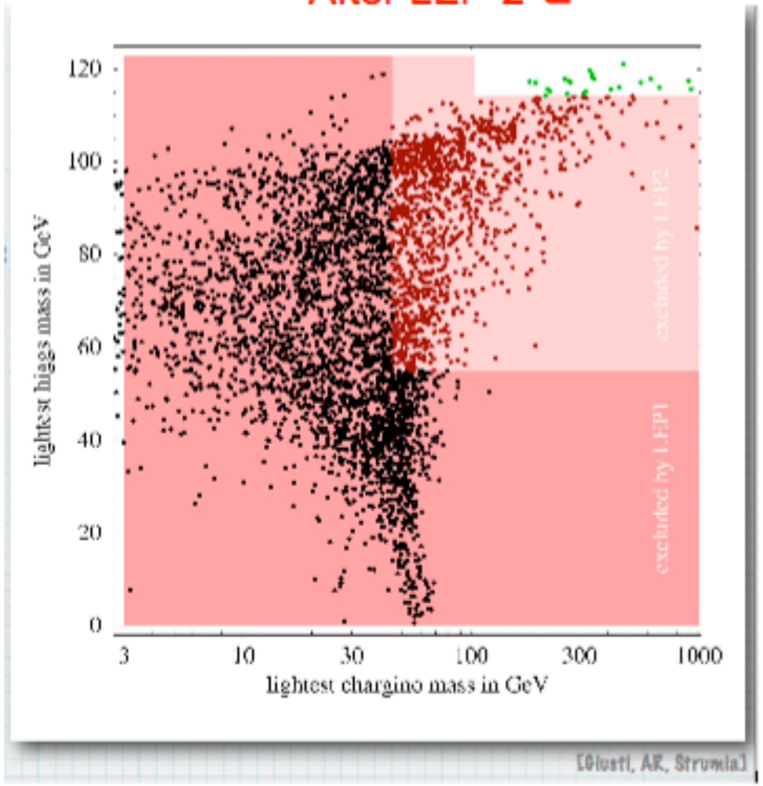
Baltz et al. PRD 2006



… a side remark: naturalness, little hierarchy and an empirical measure of fine tuning

After LEP-2 ↘

lightest Higgs mass (GeV)



← After LEP-1

lightest chargino mass (GeV)

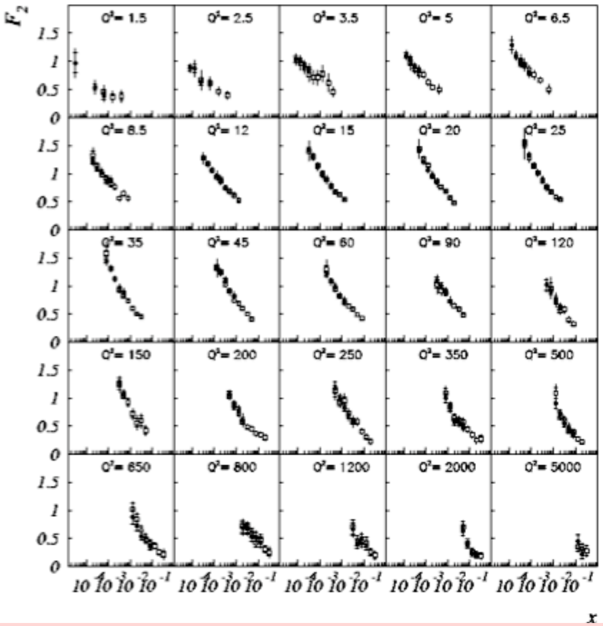
- **An outlook**

The general ones (those that can be formulated outside the present universe modelling paradigms)

1. *Are there undiscovered principles of nature (new physical laws)?*
2. *Why the Universe obeys Quantum laws?*
3. *Is it a deep principle … or a temporary fix?*
3. *What is the deep reason for the successes of gauge theories?*
4. *How the fact that we exists biases our laws of nature (physics beyond fine-tuned anthropic excuse)?*
5. *In particular, why should a human-unbiased physics mechanism predict the cosmological constant in the bizarre anthropic range?*
6. *Is there a place for organized structures in the early evolution of the Universe?*
7. *Is there an universal mechanism producing the confined energy grains (particles)?*

Mass, gauge phases and quantum mechanics

Most of the visible mass in the universe is confined in composite objects - it is the internal Fermi motion of the components (rather then their masses what determines the object inertia



Mapping the point-like content of the proton at variable distance and time scales

… another LPNHE pride: Nucl.Phys.B407:515-538,1993
Nucl.Phys.B470:3-40,1996

Why, on earth, do we expect that most of the dark matter of the Universe is of much simple kind (elementary particles with point like couplings) - this expectation is equivalent to the expectations before the XV century that the earth is in the centre of the Universe.

Mass, gauge phases and quantum mechanics

What if the masses of point-like particles are also the result of a "collaborative" effort?. Nambu, Lassino example:

Dirac particle: a mixture bare fermions With opposite chirality's but the same charge

$$E\psi_1 = \sigma \cdot p\psi_1 + m\psi_2,$$
$$E\psi_2 = -\sigma \cdot p\psi_2 + m\psi_1,$$
$$E_p = \pm (p^2 + m^2)^{\frac{1}{2}},$$

Cooper "Particle": a mixture of a particle and a hole of the same spin

$$E\psi_{p+} = \epsilon_p \psi_{p+} + \phi \psi_{-p-}^*,$$
$$E\psi_{-p-}^* = -\epsilon_p \psi_{-p-}^* + \phi \psi_{p+},$$
$$E_p = \pm (\epsilon_p^2 + \phi^2)^{\frac{1}{2}}.$$

$$\phi \approx \omega \exp[-1/\rho],$$

ω- *the energy bandwidth around the Fermi surface*
ρ - *the average interaction energy*

?

The mass as indirect consequence of 'dark" lattice-vibration energy. Coherence of gauge phases allows to create a rigid quantum-coherent structure in which gauge bosons appear as massive particles.

Vacuum in cosmology and in particle physics

The Einstein gravity is the only example of the theory in which uses the notion absolute vacuum energy density of the Universe:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}.$$

If calculated within the present QFT paradigms it comes out 10^{120} times to high (speculations: fine tuning, Multi-verse, Bubble Universe, quintessence (k-essence) time-evolution, etc. …proliferation of theories)

This problem is very likely artificial. The notion of the absolute energy scale is not well founded in a quantum theory (…from harmonic oscillator to a recent LQCD calculations). An unrevealing of the mechanism of EW symmetry breaking, and/or advanced QCD calculations may shed new light and thus revise the present links between cosmology and particle physics

The synergy of dedicated and generic searches at LHC

- **Dedicated searches**

The form of the Lagrangian of an extension of the standard model (e.g. SUSY), implemented in the form of event generator determines the search method.Searches are equivalent to scans of experimental data using the BSM generator Templates in the phase-space regions which maximizes the signal-to-noise ratio.

Expected discoveries? →

New constraints for the Standard Cosmological Model

- **Generic searches**

(1) Emphasis on scrutinizing the Standard Model processes in the full phase-space accessible (pioneered in 1996/1997 within the H1 collaboration at LPNHE) and implemented subsequently at FNAL. (2) Search for new phenomena unbounded by the perturbative-field-theory paradigms. (3) Emphasis on dedicated experimental tools to establish the physics origin of new phenomena.

Unexpected discoveries? →

May lead to overhauling paradigms …and novel links between cosmology and the particle physics

“Heretical” approaches not discussed in this presentation

- Extra dimensions, ADD model
- GMSB, AMSB, NUHM1, BWCA, LM3DM
- Higsless models
- Gauge-Higgs unification models
- Technicolor
- Little Higgs
- Mini Black Holes
- ….

The Cosmologists', Particle Physicists' and Astrophysicists' paths' must be convergent at the summit (whatever its vision is)…let's stay in touch while climbing them …