VII Seminario sul software della fisica nucleare, subnucleare ed applicata, Alghero, 31 Maggio 2010

LHC, MATERIA OSCURA E NUOVA FISICA AL DI LA' DEL MODELLO STANDARD

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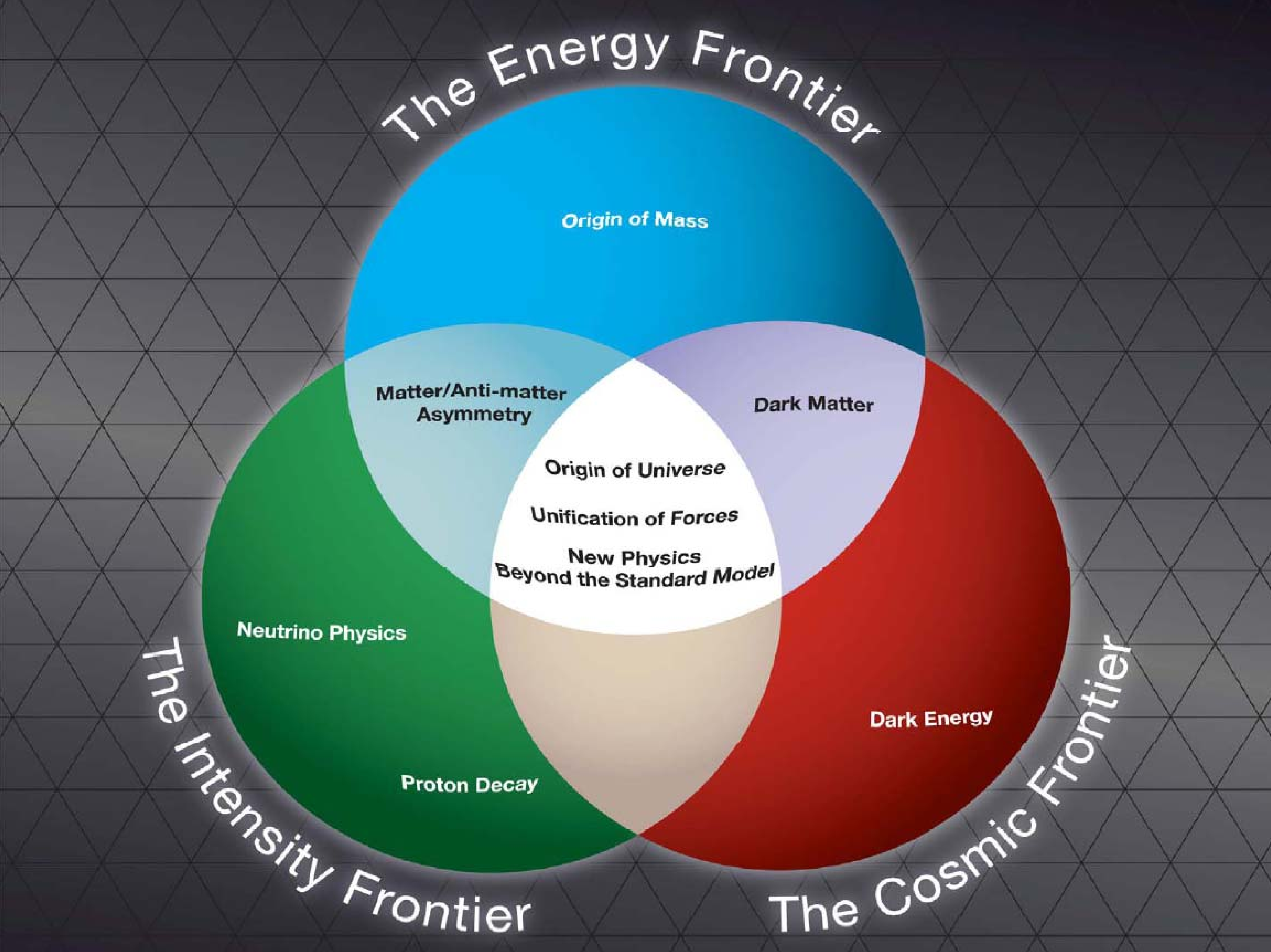

The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

PERCHE' OLTRE IL MODELLO STANDARD

"OBSERVATIONAL" REASONS

- HIGH ENERGY PHYSICS

NO (but $A_{FB}^{Z \to bb}$……)

- FCNC, CP≠

NO (but $b \to s\bar{q}q$ penguin …)

- HIGH PRECISION LOW-EN.

NO (but $(g-2)_\mu$ …)

- **NEUTRINO PHYSICS**

YES $m_\nu \neq 0$, $\theta_\nu \neq 0$

- **COSMO - PARTICLE PHYSICS**

YES (DM, ΔB_{cosm}, INFLAT., DE)

THEORETICAL REASONS

- INTRINSIC INCONSISTENCY OF SM AS QFT

NO (spont. broken gauge theory without anomalies)

- NO ANSWER TO QUESTIONS THAT "WE" CONSIDER "FUNDAMENTAL" QUESTIONS TO BE ANSWERED BY "FUNDAMENTAL" THEORY

YES (**hierarchy, unification, flavor)**

MICRO

PARTICLE PHYSICS

GWS STANDARD MODEL

MACRO

COSMOLOGY

HOT BIG BANG
STANDARD MODEL

HAPPY MARRIAGE
Ex: **NUCLEOSYNTHESIS**

NUCLEAR ASTROPHYSICS

BUT ALSO

POINTS OF FRICTION

NEW SOURCE OF CP VIOLATION

- COSMIC MATTER-ANTIMATTER ASYMMETRY

- INFLATION ***NEW SCALAR POTENTIAL***

- DARK MATTER + DARK ENERGY

NEW PARTICLES AND INTERACTIONS

"OBSERVATIONAL" EVIDENCE FOR NEW PHYSICS BEYOND THE (PARTICLE PHYSICS) STANDARD MODEL

SM FAILS TO GIVE RISE TO A SUITABLE COSMIC MATTER-ANTIMATTER ASYMMETRY

:

- **NOT ENOUGH CP VIOLATION IN THE SM**

  NEED FOR ***NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX***

- FOR M_{HIGGS} > 80 GeV THE ELW. PHASE TRANSITION OF THE SM IS A SMOOTH CROSSOVER

NEED *NEW PHYSICS BEYOND SM*. IN PARTICULAR, FASCINATING POSSIBILITY: THE ENTIRE MATTER IN THE UNIVERSE ORIGINATES FROM THE SAME MECHANISM RESPONSIBLE FOR THE EXTREME SMALLNESS OF NEUTRINO MASSES

MATTER-ANTIMATTER ASYMMETRY $\longleftrightarrow$ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

$\longrightarrow$ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such **LEPTON ASYMMETRY** can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (**Fukugita-Yanagida mechanism for leptogenesis**)

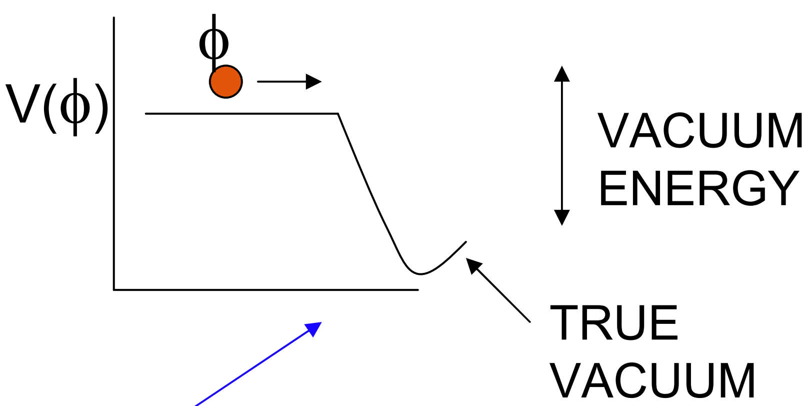
INFLATION

SEVERE COSMOGICAL PROBLEMS

- **CAUSALITY** (isotropy of CMBR)
- **FLATNESS** (Ω close to 1 today)
- **AGE OF THE UNIV.**
- **PRIMORDIAL MONOPOLES**

COMMON SOLUTION FOR THESE PROBLEMS

VERY FAST (EXPONENTIAL) EXPANSION IN THE UNIV.



Ω dominated by vacuum en.

NO WAY TO GET AN “INFLATIONARY SCALAR POTENTIAL” IN THE STANDARD MODEL

NO ROOM IN THE PARTICLE PHYSICS STANDARD MODEL FOR INFLATION

$V=\mu^2\,\phi^2 + \lambda\phi^4 \longrightarrow$ no inflation

Need to extend the SM scalar potential

Ex: GUT’s, SUSY GUT’s,…

ENERGY SCALE OF “INFLATIONARY PHYSICS”:

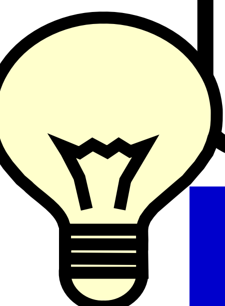
LIKELY TO BE $\gg$ Mw

DIFFICULT BUT NOT IMPOSSIBLE TO OBTAIN ELECTROWEAK INFLATION IN SM EXTENSIONS

<u>For some inflationary models → large amount of primordial gravitational waves</u>

The Energy Scale from the “Observational” New Physics

neutrino masses
dark matter
baryogenesis
inflation



NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the “Theoretical” New Physics

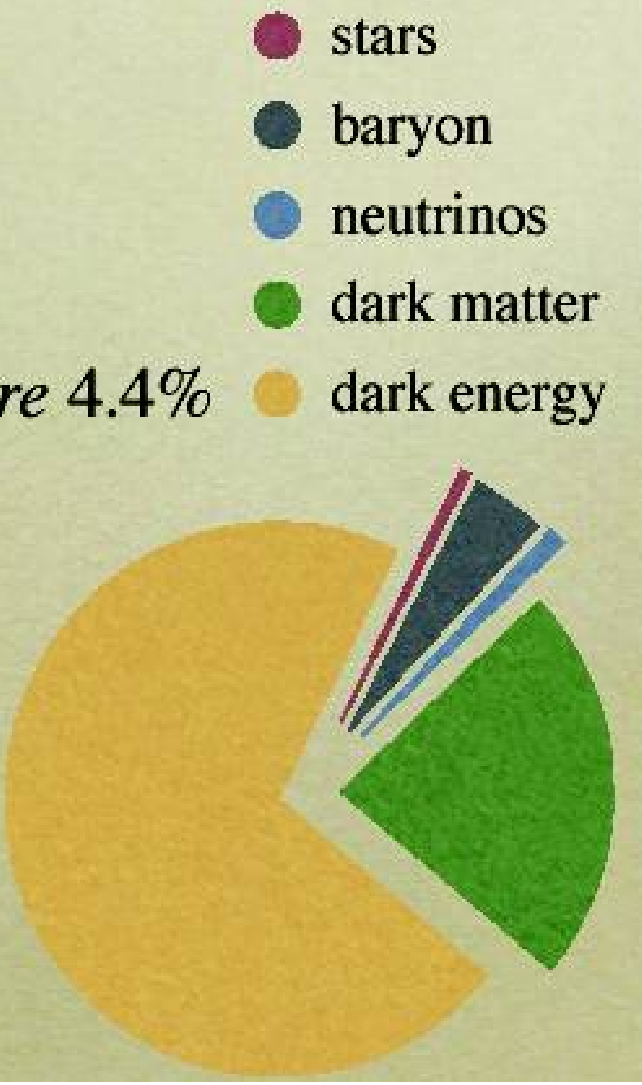
Stabilization of the electroweak symmetry breaking at M_W calls for an ***ULTRAVIOLET COMPLETION of the SM already at the TeV scale***

+

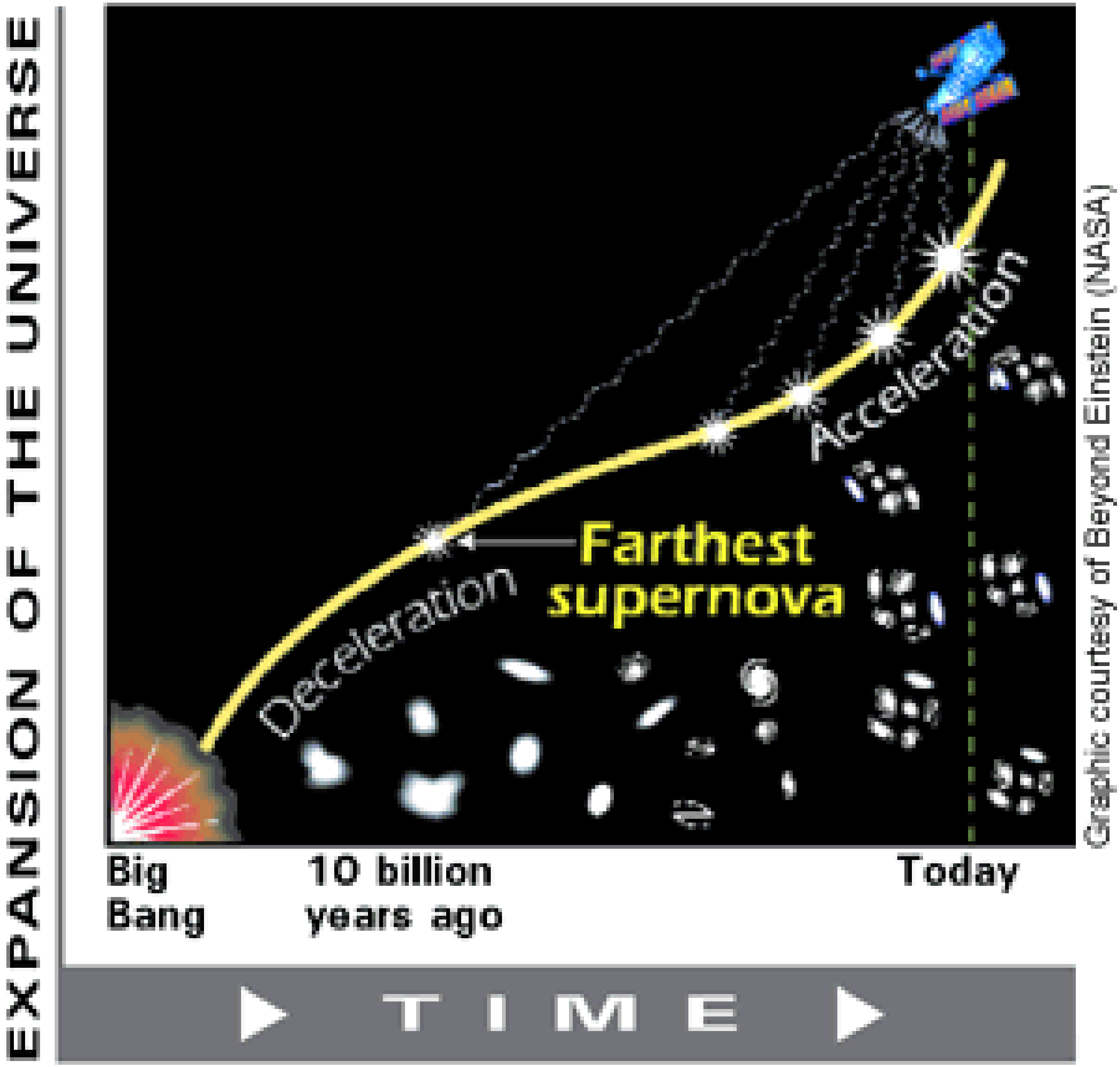
CORRECT GRAND UNIFICATION “CALLS” FOR NEW PARTICLES AT THE ELW. SCALE

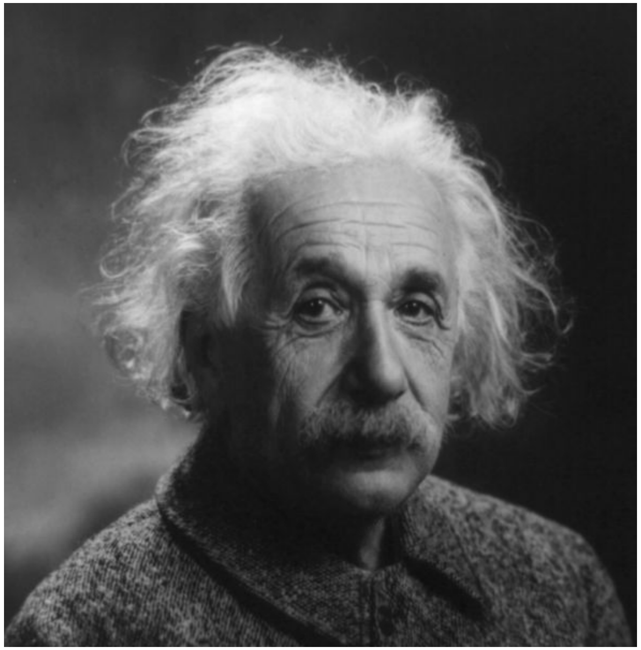
DM, DE, ANTIMATTER AND VACUUM ENERGY

- *Stars and galaxies are only ~0.5%*
- *Neutrinos are ~0.1–1.5%*
- *Rest of ordinary matter (electrons, protons & neutrons) are 4.4%*
- *Dark Matter 23%*
- *Dark Energy 73%*
- *Anti-Matter 0%*
- *Higgs Bose-Einstein condensate ~10^{62}%??*

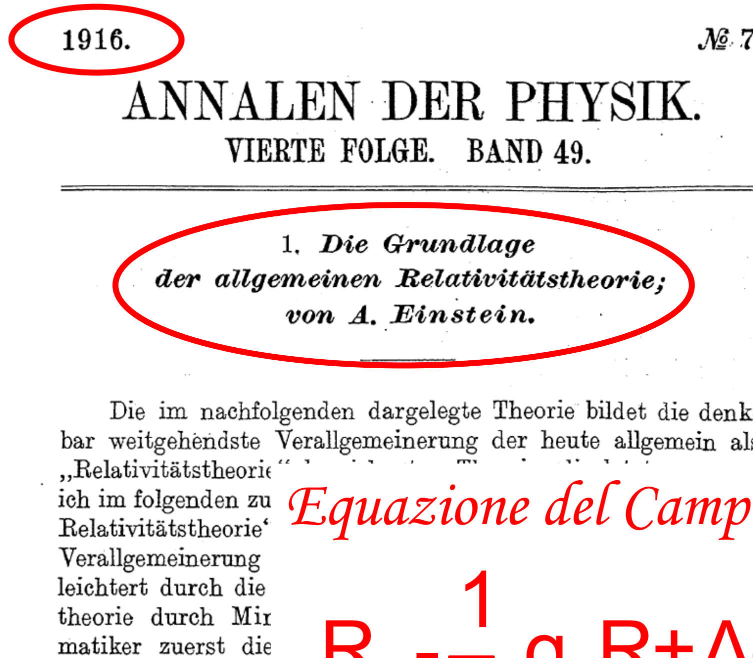


Courtesy of H. Murayama


EXPANSION OF THE UNIVERSE
Farthest supernova
Deceleration
Acceleration
Big Bang
10 billion years ago
Today
TIME
Graphic courtesy of Beyond Einstein (NASA)



Albert Einstein (1879-1955)



1916. №. 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;*
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie ich im folgenden zu Relativitätstheorie“ Verallgemeinerung leichtert durch die theorie durch Mir matiker zuerst die

Equazione del Campo di Gravitazione

$$R_{ik} - \frac{1}{2} g_{ij} R + \Lambda g_{jk} = \frac{8\pi G}{c^4} T_{jk}$$

Costante Cosmologica

IS THE COSMOLOGICAL CONSTANT THE SOURCE OF THE DARK ENERGY OG THE UNIVERSE AND THE CAUSE OF ITS ACCELERATED EXPANSION?

HIERARCHIES, FLAVOR and ELW. SYMMETRY BREAKING

The Higgs problem is central in particle physics today

ALTARELLI, LP09

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2 + [\bar{\psi}_{Li}Y_{ij}\psi_{Rj}\phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ eV)^4$

Possible instability
depending on m_H

Origin of quadratic
divergences.
Hierarchy problem

The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

LEP and ELW. SYMMETRY BREAKING

- **EXPERIMENTALLY** (in particular thanks to LEP) WE KNOW THAT THE GAUGE SYMMETRY OF ELECTROWEAK INTERACTIONS UNDERGOES A **SPONTANEOUS BREAKING**, i.e. LEP HAS PROVEN THAT **THE HIGGS MECHANISM IS OPERATIVE IN NATURE**

- WHAT IS UNKNOWN IS **THE WAY THE HIGGS MECHANISM IS IMPLEMENTED BY NATURE**

SOMETHING is needed at the TeV scale to enforce the unitarity of the electroweak theory

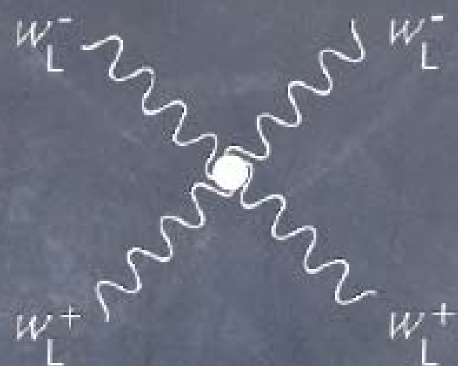
What is the mechanism of EWSB?

susy, LH... models assume that we already know the answer to

What is unitarizing the WW scattering amplitudes?

W_L & Z_L part of EWSB sector ⊃ W scattering is a probe of Higgs sector interactions

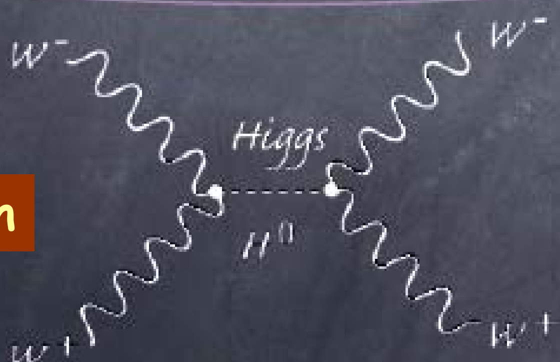
$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M}\frac{\vec{k}}{|\vec{k}|}\right)$$



$$A = g^2\left(\frac{E}{M_W}\right)^2$$

loss of perturbative unitarity
around 1.2 TeV

Weakly coupled models

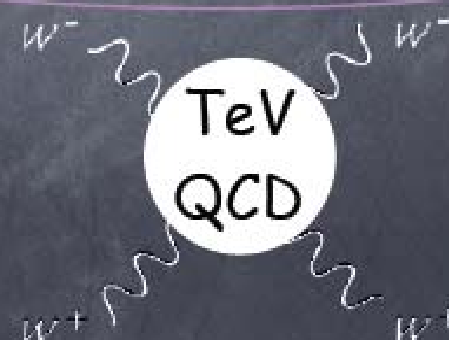


prototype: Susy

susy partners ~ 100 GeV

Different signatures at the LHC!

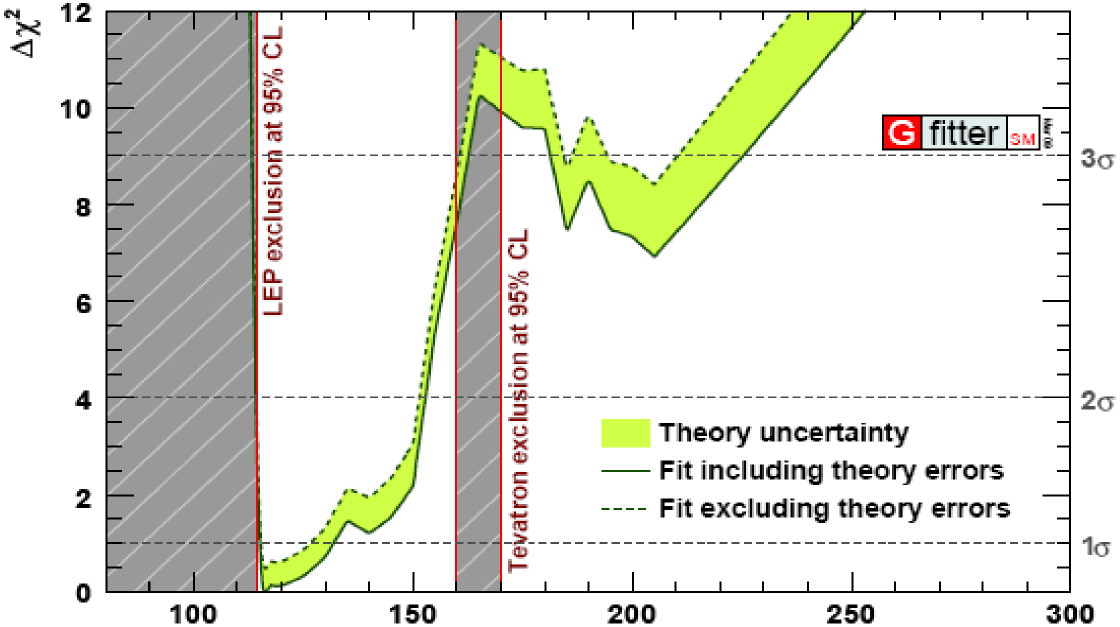
Strongly coupled models



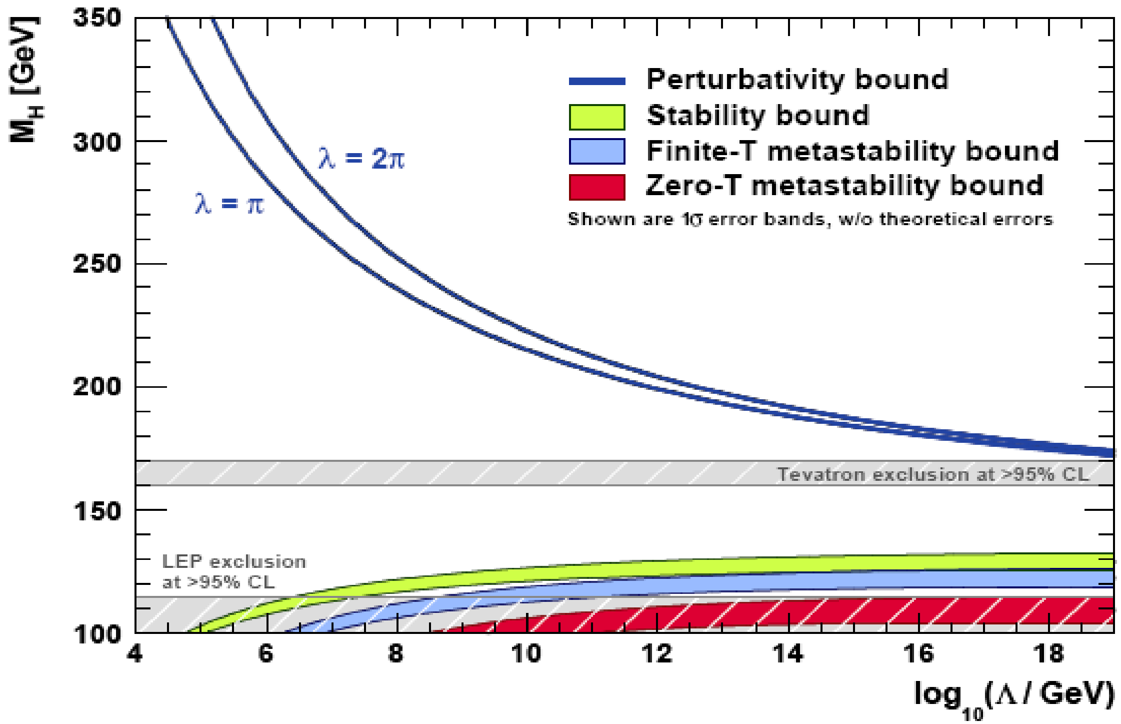
prototype: Technicolor

rho meson ~ 1 TeV

Grojean



a light higgs (or something mimicking it) is definitely favored



the big desert between the TeV and the GUT scales only if the higgs is a narrow band between 130 and 180

Ellis, Espinosa, Giudice, Hoecker, Riotto

Is it possible that there is “only” a light higgs boson and no NP?

- This is acceptable if one argues that no ultraviolet completion of the SM is needed at the TeV scale simply because there is no actual fine-tuning related to the higgs mass stabilization (**the correct value of the higgs mass is “environmentally” selected**). This explanation is similar to the one adopted for the cosmological constant

- Barring such wayout, **one is lead to have TeV NP to ensure the unitarity of the elw. theory at the TeV scale**

THE LITTLE HIERARCHY PROBLEM

SUSY CASE

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\ln\frac{m_{stop}^2}{m_t^2}$$

$$m_h > 115\ \text{GeV} \quad \Rightarrow \quad m_{stop} \geq O(1\ \text{TeV})$$

$$\frac{1}{2}M_Z^2 \approx -(m_{H_u}^2 + \mu^2)|_{tree} + 0.1 M_{SUSY}^2 \ln\frac{\Lambda_{MSSM}}{M_{SUSY}}$$

$$10^{-2}\text{TeV} \quad \text{vs} \quad O(1)\text{TeV}|_{tree} + O(1)\text{TeV}$$

% FINE-TUNING FOR THE NEW PHYSICS AT THE ELW. SCALE

- **Elementary Higgs** → In the **MSSM** % fine-tuning among the SUSY param. to avoid light SUSY particles which would have been already seen at LEP and Tevatron

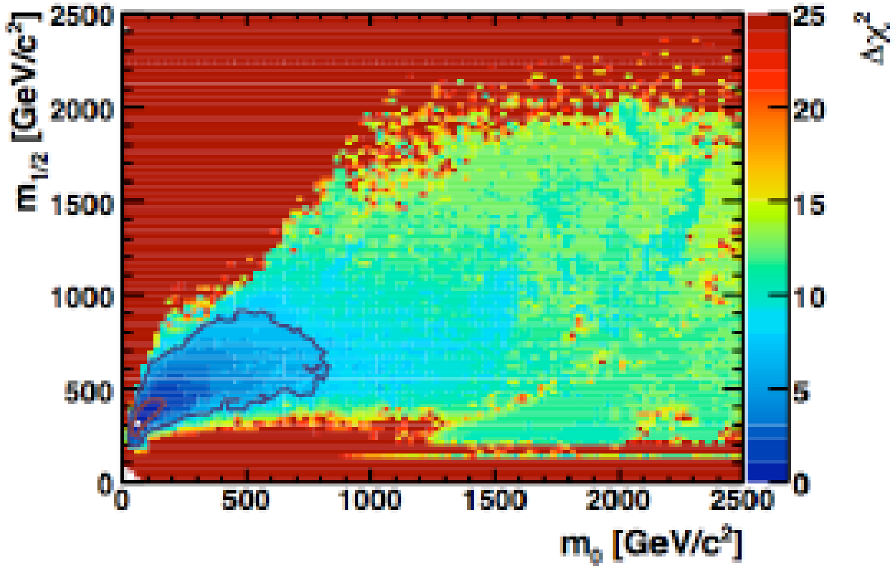
- **Elementary Higgs** → **PSEUDO-GOLDSTONE boson in the LITTLE HIGGS model** → Λ^2 div. cancelled by new colored fermions, new W,Z, γ, 2Higgs doublets… → % fine-tuning to avoid too large elw. corrections

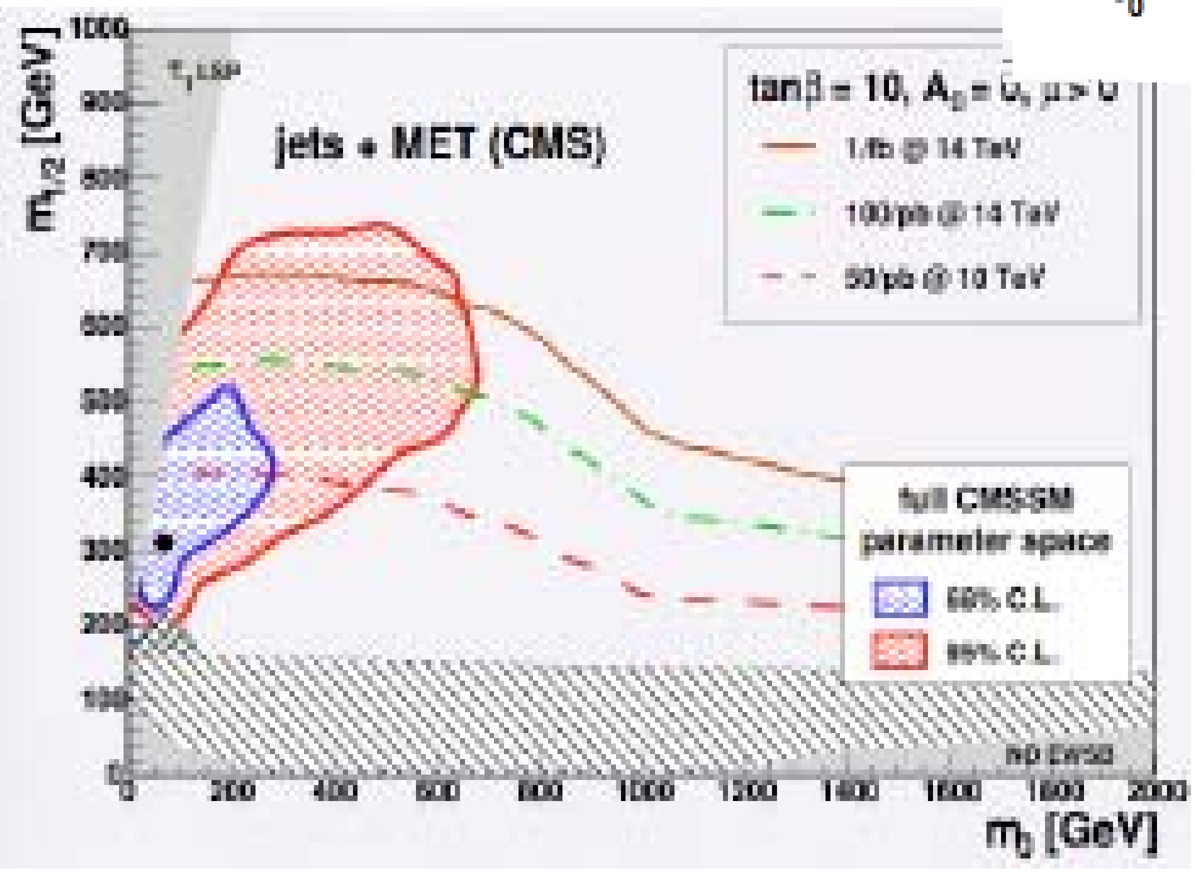
- **COMPOSITE HIGGS** in **a 5-dim**. holographic theory: the Higgs is a **PSEUDO-GOLDSTONE** boson and the elw. symmetry breaking is triggered by bulk effects (in 5 dim. the theory is **WEAKLY** coupled, but in 4 dim. the bulk looks like a **STRONGLY** coupled sector) → also here % fine-tuning needed to survive the elw. precision tests

GENERAL FEATURES OF NEW PHYSICS AT THE ELW. SCALE

- Some amount of **fine-tuning** (typically at the % level) is required to pass unscathed the elw. precision tests, the higgs mass bound and the direct search for new particles at accelerators.
- The **higgs is typically rather light** (<200 GeV) apart from the extreme case of the "Higgsless proposal"
- All models provide **signatures which are (more or less) accessible to LHC physics** (including the higgsless case where new KK states are needed to provide the unitarity of the theory)

LIGHT SUSY IS PREFERRED BY DATA!





LIGHT SUSY IS TESTABLE AT THE LHC

ELLIS ET AL.

Baer, Barger, Lessa, Tata (2009)

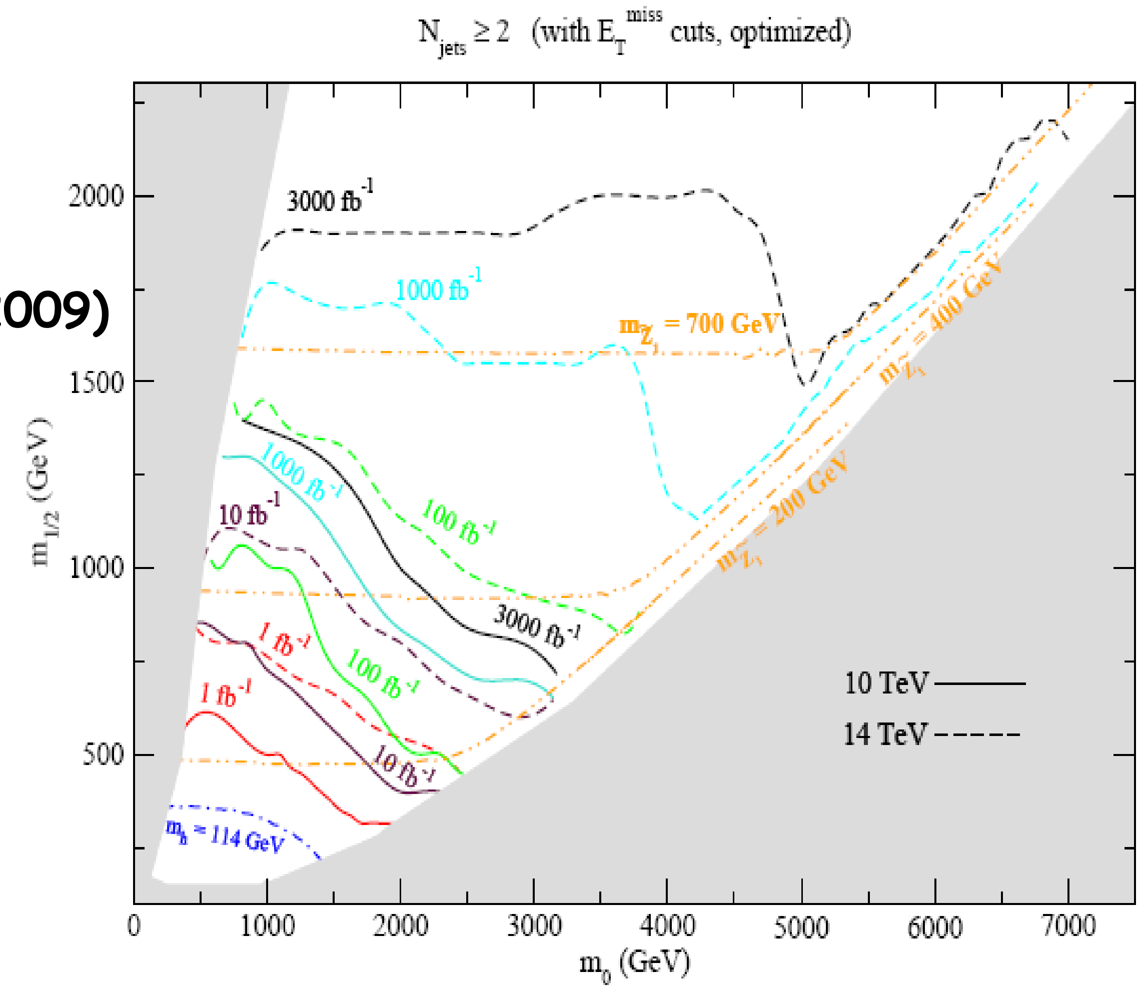


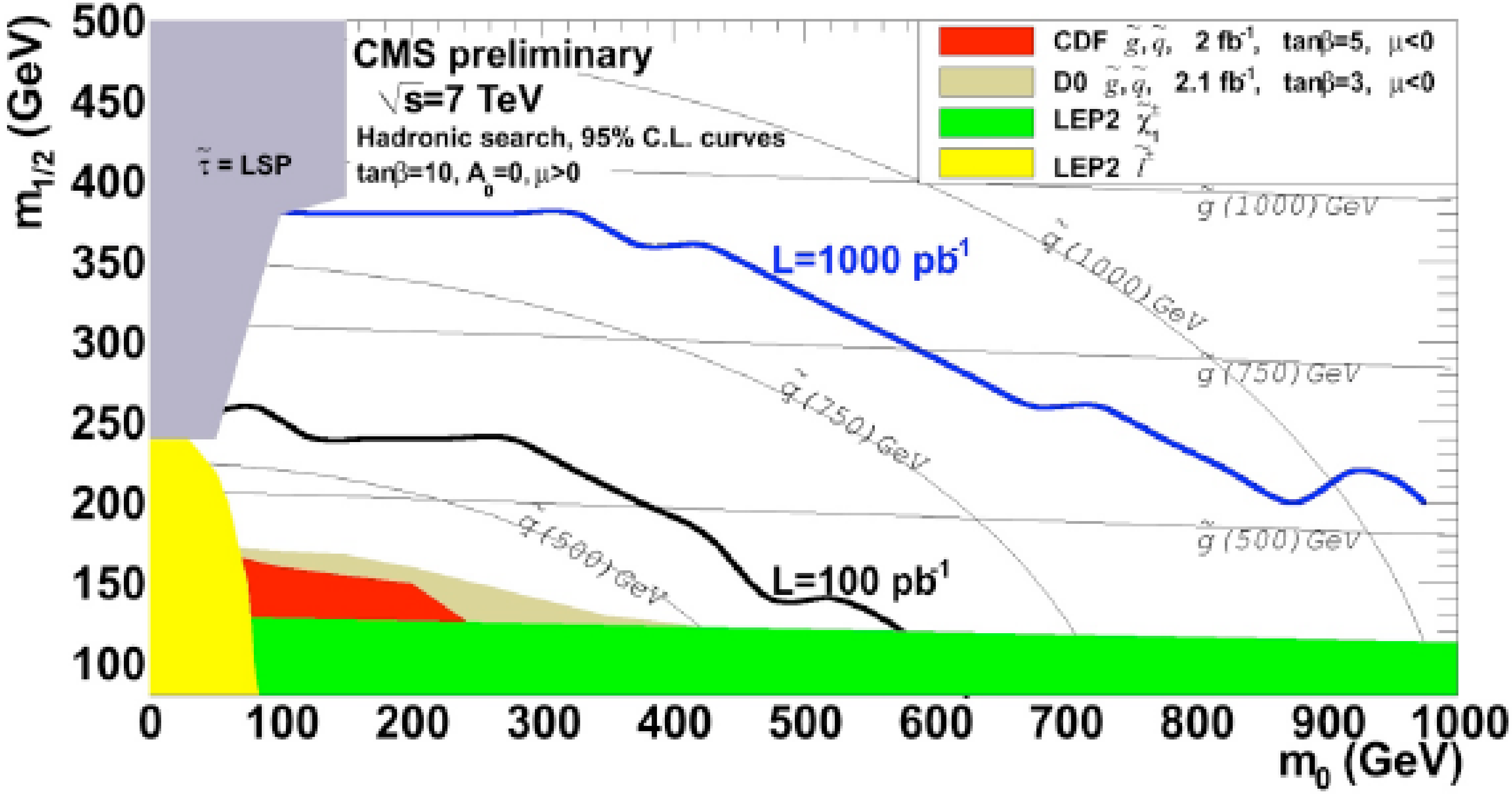
Figure 21: The ultimate SUSY reach of LHC within the mSUGRA framework for $\sqrt{s} = 10$ TeV (solid) and $\sqrt{s} = 14$ TeV (dashed) for various values of integrated luminosities. The fixed mSUGRA parameters are $A_0 = 0$, $\tan\beta = 45$ and $\mu > 0$. Isomass contours for the LSP (double dot-dashed) and for a 114 GeV light Higgs scalar (dot-dashed) are also shown. The shaded areas are excluded

SUSY: jets + missing E_T

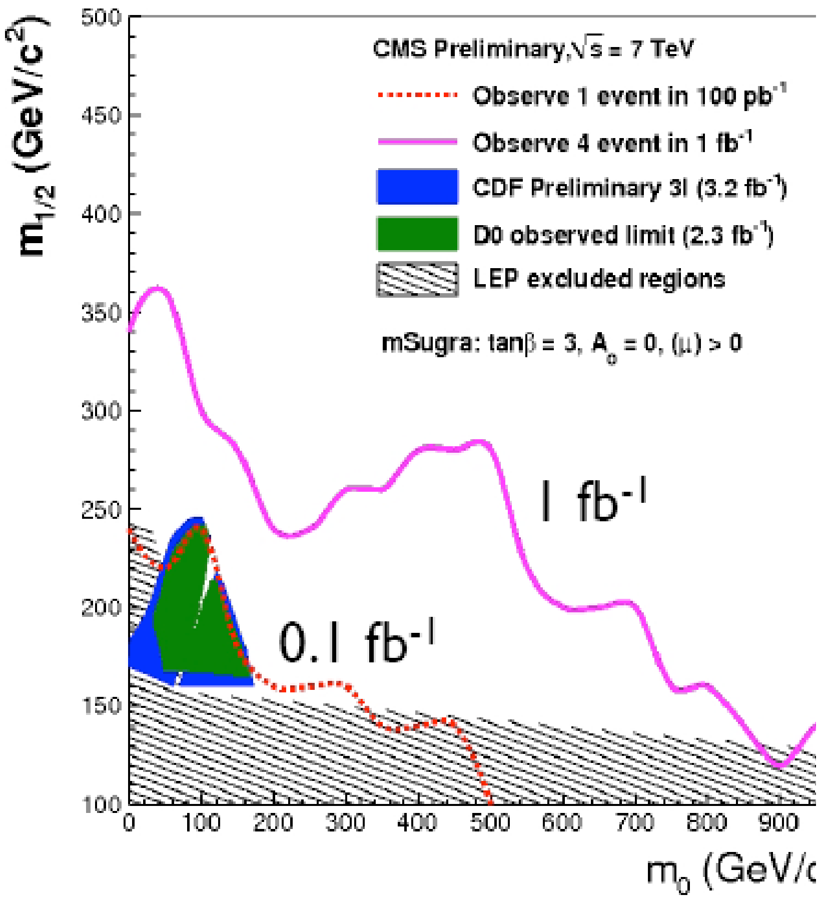
"Classic" all-jets search:

- 3 or more jets, E_T > 50 GeV
- missing E_T > 250 GeV
- no leptons

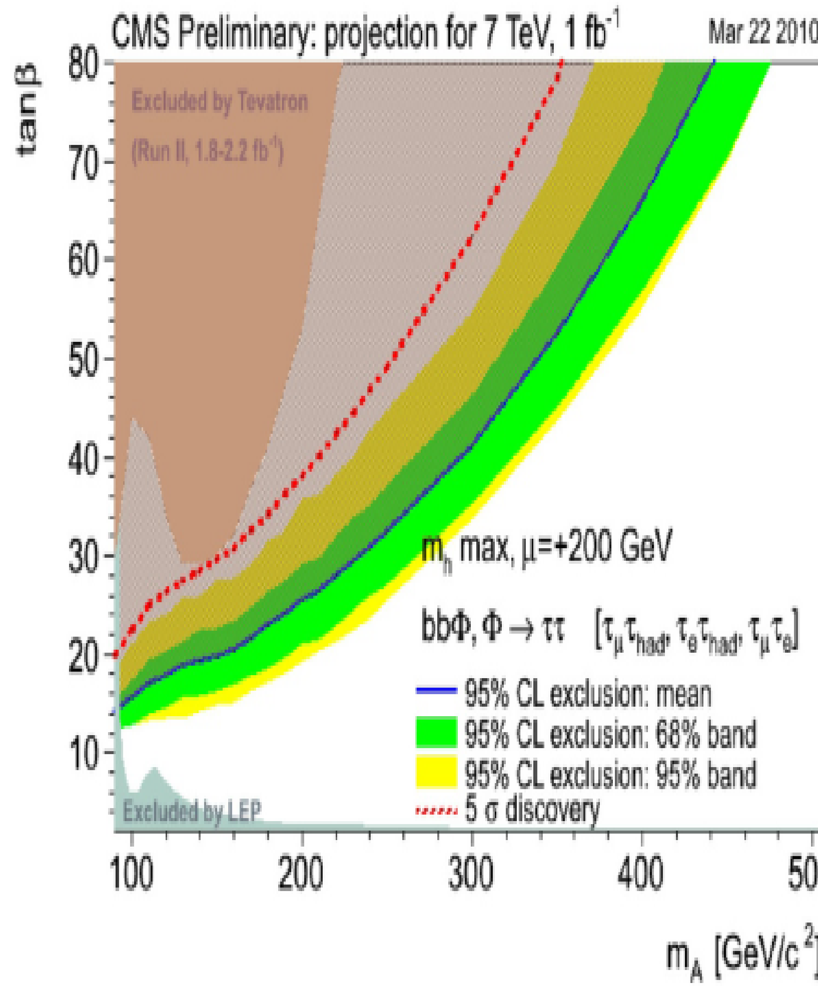
J. CONWAY
PHENO10



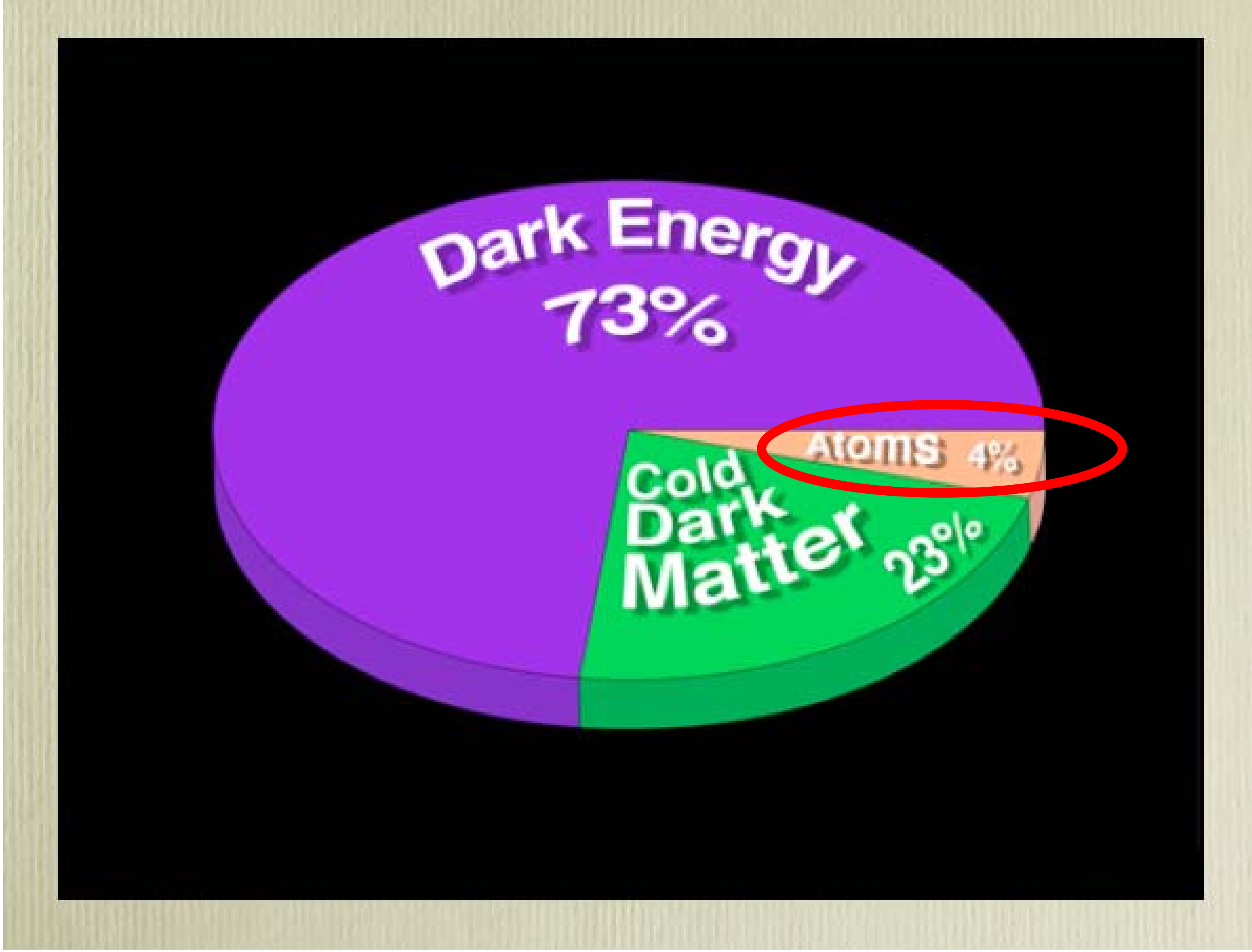
SUSY: like-sign dilepto



di-tau sensitivity for H/A will soon exceed Tevatron!



J. CONWAY PHENO10



La conoscenza che abbiamo riguarda solo il 4% dell'Universo il resto è ancora ignoto !!

EVIDENCE FOR DM

Various astrophysical sources have confirmed the existence of Dark Matter (DM)

- Binding of Galaxies in Clusters (F. Zwicky, 1933)
- Rotation curves of Galaxies (V.C. Rubin and W.K. Ford, 1970)
- Bindings of hot gases in clusters
- Gravitational Lensing observations
- Large Scale Stucture simulations
- High z - Supernovae
- Observations of colliding clusters of Galaxies

The most direct and accurate evidence comes from WMAP by measuring arisotropies of the CMB power spectrum

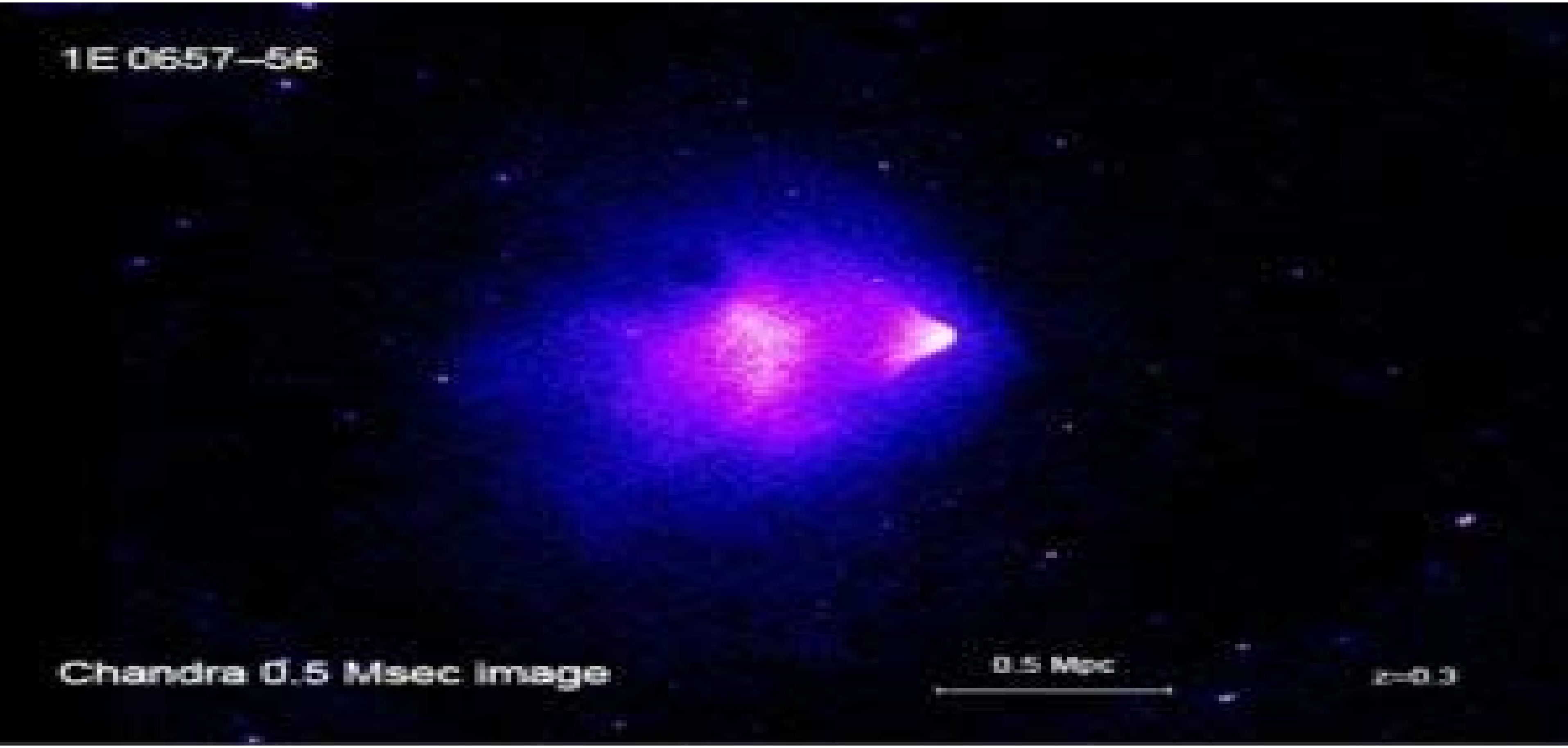
$$\sim 73\% \ \text{DarkEnergy}, \sim 23\% \ \text{DarkMatter}, 4\% \ \text{Baryons}$$

MODIFICARE LA GRAVITA' (MOND)

- DM e' sempre derivata dalle osservazioni **assumendo la validita' della legge standard della gravita**' $\rightarrow$ possibile evitare l'introduzione di DM se modifico la legge di gravita' su varie scale astronomiche
- Possibili problemi per CDM
- Fit di MOND a >100 **curve di rotazione galattiche** con successo
- Problemi a riprodurre i dati relativi alla **dinamica di clusters**: necessita' di introdurre materia invisibile (neutrini, barioni oscuri)
- **Versione relativistica di MOND** (Tensor-Vector Scalar Th. - TeVeS) + **covarianza** (Bekenstein '04, Sanders '05)
- TeVeS : OK per strong lensing, invece necessita di materia invisibile per riprodurre il weak lensing. **Barioni oscuri** necessari anche per fenomeni quali il **Bullet Cluster** (Milgrom '08)

The **BULLET CLUSTER**: **two colliding clusters of galaxies**

Stars, galaxies and putative DM behave differently during collision, allowing for them to be studied separately. In **MOND** the lensing is expected to follow the baryonic matter, i.e. the X-ray gas. However the lensing is strongest in two separated regions near the visible galaxies → **most of the mass in the cluster pair is in the form of collisionless DM**



DM → NEW PHYSICS BEYOND THE (PARTICLE PHYSICS) SM - if Newton is right at scales>size of the Solar System

- $\Omega_{DM} = 0.233 \pm 0.013$ *
- $\Omega_{baryons} = 0.0462 \pm 0.0015$ **

*from CMB (5 yrs. of WMAP) + Type I Supernovae + Baryon Acoustic Oscillations (BAO)

**CMB + TypeI SN + BAO in agreement with Nucleosynthesis (BBN)

DM: the most impressive evidence at the "quantitative" and "qualitative" levels of **New Physics beyond SM**

- QUANTITATIVE: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on Ω_{DM} and Ω_B → **EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM**

- QUALITATIVE: it is NOT enough to provide a mass to neutrinos to obtain a valid DM candidate; LSS formation requires DM to be COLD → **NEW PARTICLES NOT INCLUDED IN THE SPECTRUM OF THE FUNDAMENTAL BUILDING BLOCKS OF THE SM !**

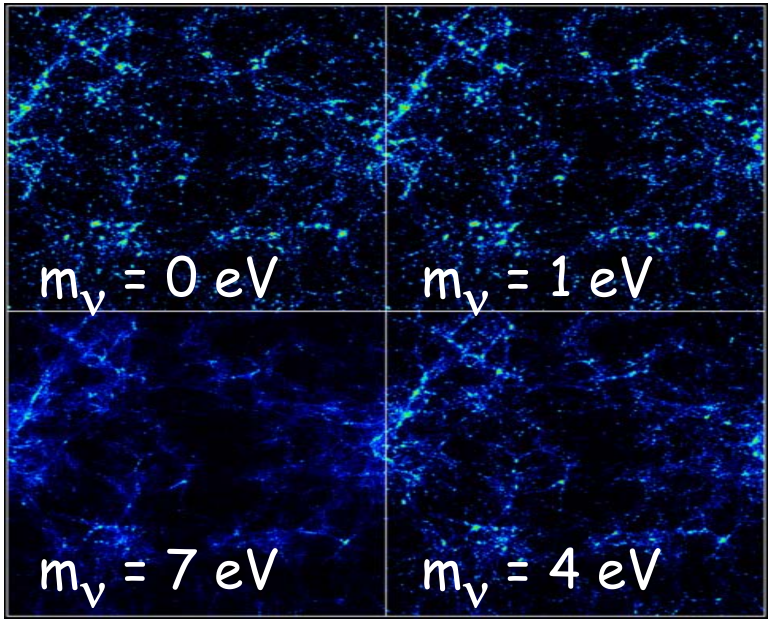
THE RISE AND FALL OF NEUTRINOS AS DARK MATTER

- Massive neutrinos: only candidates in the SM to account for DM. From here the “prejudice” of neutrinos of a few eV to correctly account for DM

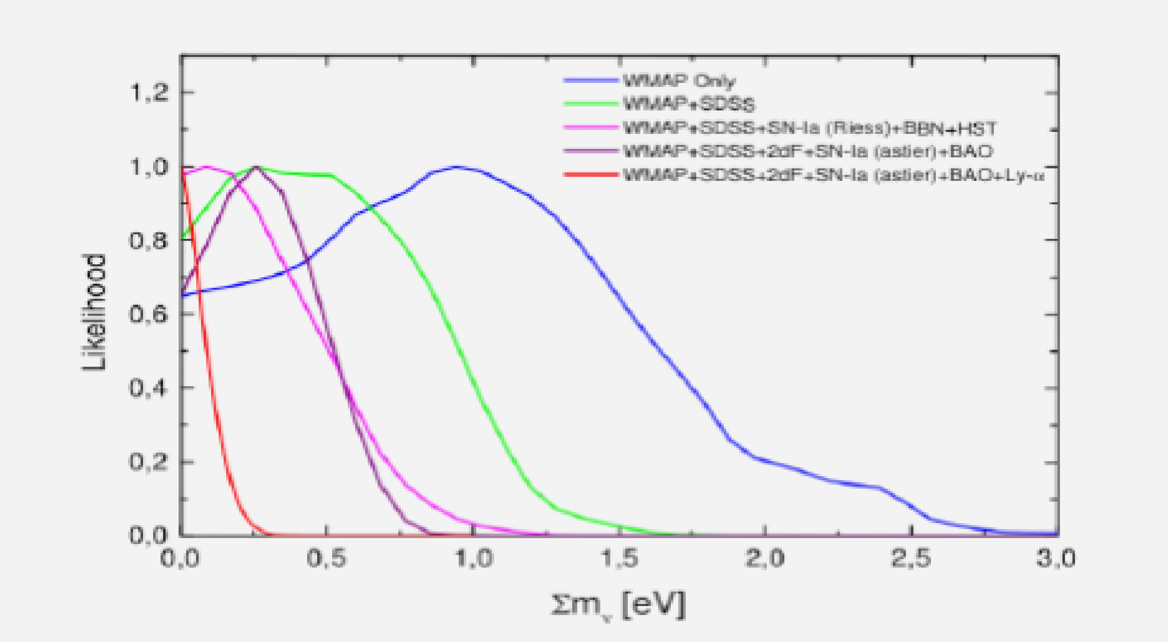
- Neutrinos decouple at ~1 MeV ; being their mass<<decoupling temperature, neutrinos remain relativistic for a long time. Being very fast, they smooth out any possible growth of density fluctuation forbidding the formation of proto-structures.

- The “weight” of neutrinos in the DM budget is severely limited by the observations disfavoring scenarios where first superlarge structures arise and then galaxies originate from their fragmentation

LSS PATTERN AND NEUTRINO MASSES



(E..g., Ma 1996)



Cosmological Bounds on the sum of the masses of the 3 neutrinos from increasingly rich samples of data sets

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + SN_{Astier}	< 0.75 eV
5	CMB + LSS + SN_{Astier} + BAO	< 0.58 eV
6	CMB + LSS + SN_{Astier} + Ly-α	< 0.21 eV
7	CMB + LSS + SN_{Astier} + BAO + Ly-α	< 0.17 eV

Fogli et al., Phys. Rev. D 75, 053001 (2007)

***THE DM ROAD TO NEW PHYSICS BEYOND THE SM*:**

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE*** **?**

TEN COMMANDMENTS TO BE A “GOOD” DM CANDIDATE

BERTONE, A.M., TAOSO

- **TO MATCH THE APPROPRIATE RELIC DENSITY**
- **TO BE COLD**
- **TO BE NEUTRAL**
- **TO BE CONSISTENT WITH BBN**
- **TO LEAVE STELLAR EVOLUTION UNCHANGED**
- **TO BE COMPATIBLE WITH CONSTRAINTS ON SELF – INTERACTIONS**
- **TO BE CONSISTENT WITH DIRECT DM SEARCHES**
- **TO BE COMPATIBLE WITH GAMMA – RAY CONSTRAINTS**
- **TO BE COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS**
- **“TO BE PROBED EXPERIMENTALLY”**

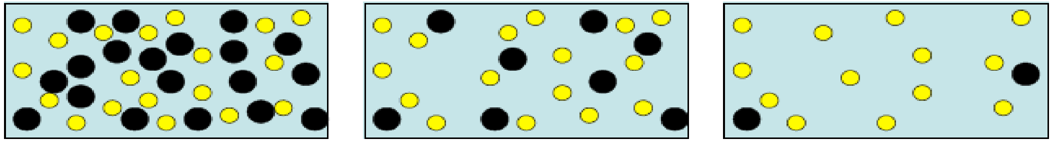
THE "*WIMP MIRACLE*"

Bergstrom

Table 1. Properties of various Dark Matter Candidates

Type	Particle Spin	Approximate Mass Scale
Axion	0	μeV-meV
Inert Higgs Doublet	0	50 GeV
Sterile Neutrino	1/2	keV
Neutralino	1/2	10 GeV - 10 TeV
Kaluza-Klein UED	1	TeV

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a VIABLE DM CANDIDATE AT THE ELW. SCALE



T >> M   T ≈ M   T << M

WIMPS (Weakly Interacting Massive Particles)

$\#\chi \sim \#\gamma$ m_χ $\#\chi$ exp$(-m\chi/T_\chi)$ $\#\chi$ does not change any more

$T_{decoupl.}$ typically ~ m_χ /20

Ω_χ depends on particle physics ($\sigma_{annih.}\chi$) and "cosmological" quantities (H, T_0, …

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\underbrace{<(\sigma_{annih.}) V \chi >}_{\sim\, \alpha^2 / M^2_\chi} \quad TeV^2}$$

TeV² → From $T^0\, M_{Planck}$

COSMO – PARTICLE CONSPIRACY

$\Omega\chi h^2$ in the range 10^{-2} -10^{-1} to be cosmologically interesting (for DM)

$m\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\Omega\chi h^2 \sim 10^{-2}$ -10^{-1} !!!

THERMAL RELICS (WIMP in thermodyn.equilibrium with the plasma until $T_{decoupl}$)

SUSY & DM : a successful marriage

- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be **supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.**
- Certainly the simplest and maybe also the most attractive solution is **to impose the discrete R-parity** symmetry
- MSSM + R PARITY $\longrightarrow$ LIGHTEST SUSY PARTICLE (LSP) IS STABLE .
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).

WHO IS THE LSP?

- **SUPERGRAVITY** (transmission of the SUSY breaking from the hidden to the obsevable sector occurring via gravitational interactions): best candidate to play the role of LSP:

  NEUTRALINO (i.e., the lightest of the four eigenstates of the 4x4 neutralino mass matrix)

In **CMSSM**: the LSP neutralino is almost entirely a BINO

DM $\Longleftrightarrow$ THE ORIGIN OF THE SUSY BREAKING

HIDDEN
SECTOR SUSY
BREAKING AT
SCALE $\sqrt{F}$

MESSENGERS

DM
NEUTRALINO

$F = M_W M_{Pl}$

GRAVITY

M$_{\text{gravitino}}$ $\sim F/M_{Pl} \sim$

(10^2 -10^3) GeV

DM
GRAVITINO

$F = (10^5 - 10^6)$ GeV

GAUGE
INTERACTIONS

M$_{\text{gravitino}}$ $\sim F/M_{Pl} \sim$

(10^2 - 10^3) eV

OBSERVABLE
SECTOR
SM + superpartners
MSSM : minimal content
of superfields

GRAVITINO LSP?

- **GAUGE MEDIATED SUSY BREAKING**

(GMSB) : LSP likely to be the GRAVITINO (it can be so light that it is more a warm DM than a cold DM candidate)

Although we cannot directly detect the gravitino, there could be interesting signatures from the **next to the LSP (NLSP)** : for instance the s-tau could decay into tau and gravitino, Possibly with a very long life time, even of the order of days or months

DIFFERENT FROM THE THERMAL HISTORY OF WIMPS

SWIMPS (Super Weakly Interacting Massive Particles)

- - LSP Gravitino in SUSY
- - First excitation of the graviton in UED …

They inherit the appropriate relic density through the decay of a more massive thermal species that has earlier decoupled from the thermal bath

$$\Omega_{\mathrm{SWIMP}} = \frac{m_{\mathrm{SWIMP}}}{m_{\mathrm{NLP}}} \Omega_{\mathrm{NLP}}$$

Collider experiments do not distinguish between stable ($\tau > 10^{17}$ s) and long-lived ($\tau > 10^{-7}$ s) particle

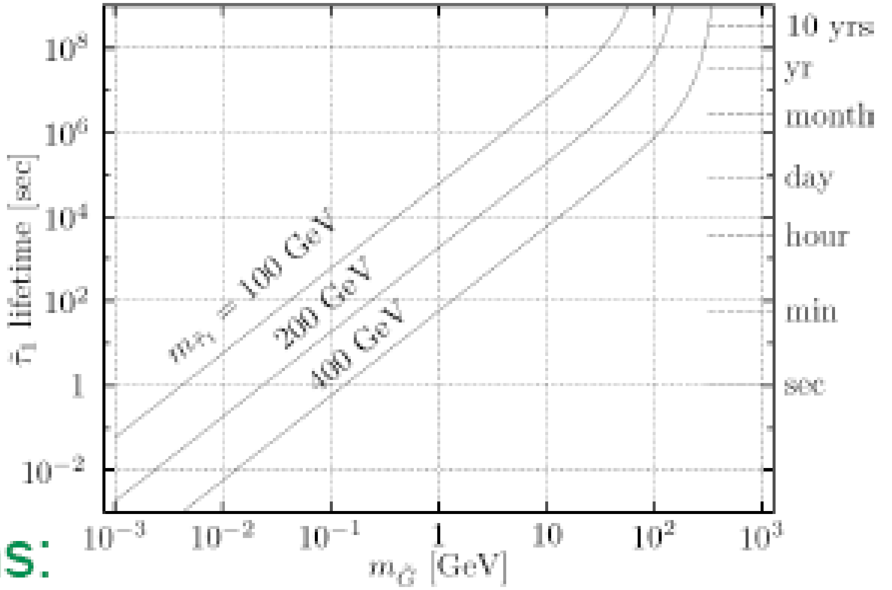
$$P' \to P \;\Rightarrow\; \Omega_{P'} = \frac{m_{P'}}{m_P}\Omega_P$$

Gravitino

Long-lived charged particle at the LHC ($\tilde{\tau} \to \tau \tilde{G}$)

Hamaguchi-Kuno-Nakaya-Nojiri; Feng-Smith; Ellis-Raklev-Øye; Hamaguchi-Nojiri-de Roeck

Distinctive ToF and energy loss signatures



"Stoppers" in ATLAS/CMS caverns:

- Measure position and time of stopped $\tilde{\tau}$; time and energy of τ
- Reconstruct susy scale and gravitational coupling

G. GIUDICE

STABLE ELW. SCALE WIMPs from PARTICLE PHYSICS

	SUSY	**EXTRA DIM.**	**LITTLE HIGGS.**
1) **ENLARGEMENT OF THE SM**	(x^{μ}, θ)	(x^{μ}, j^{i})	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	**R-PARITY LSP**	**KK-PARITY LKP**	**T-PARITY LTP**
→ **DISCRETE SYMM.**	Neutralino spin 1/2	spin1	spin0
→ **STABLE NEW PART.**	↓	↓	↓
3) FIND REGION (S) PARAM. SPACE WHERE THE "L" NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV *	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

* But abandoning gaugino-masss unif. ➞ Possible to have m_{LSP} down to 7 GeV

Bottino, Donato, Fornengo, Scopel

IS THE "*WIMP MIRACLE*" AN ACTUAL MIRACLE?

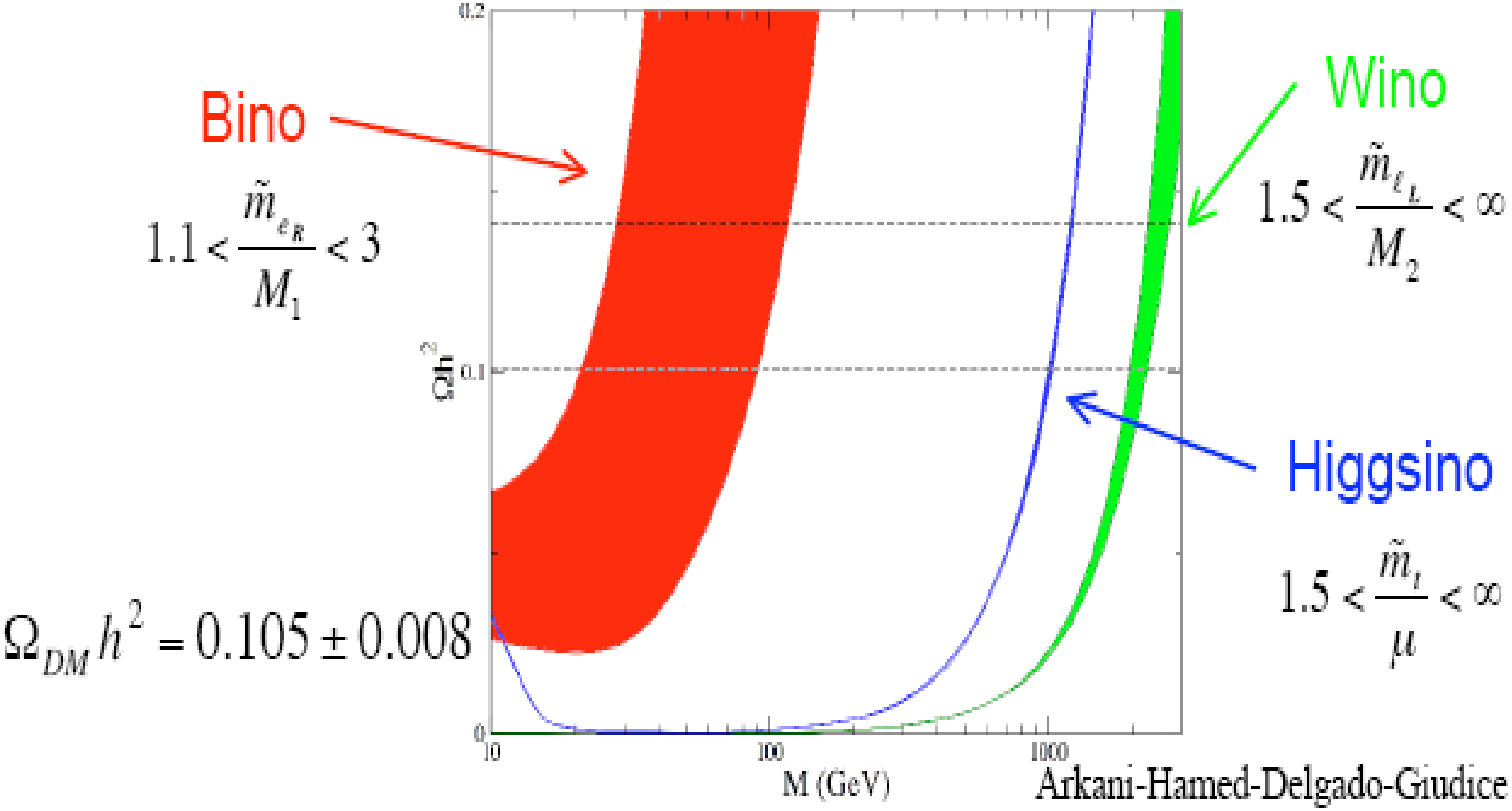
USUAL STATEMENT

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a VIABLE DM CANDIDATE AT THE ELW. SCALE

HOWEVER

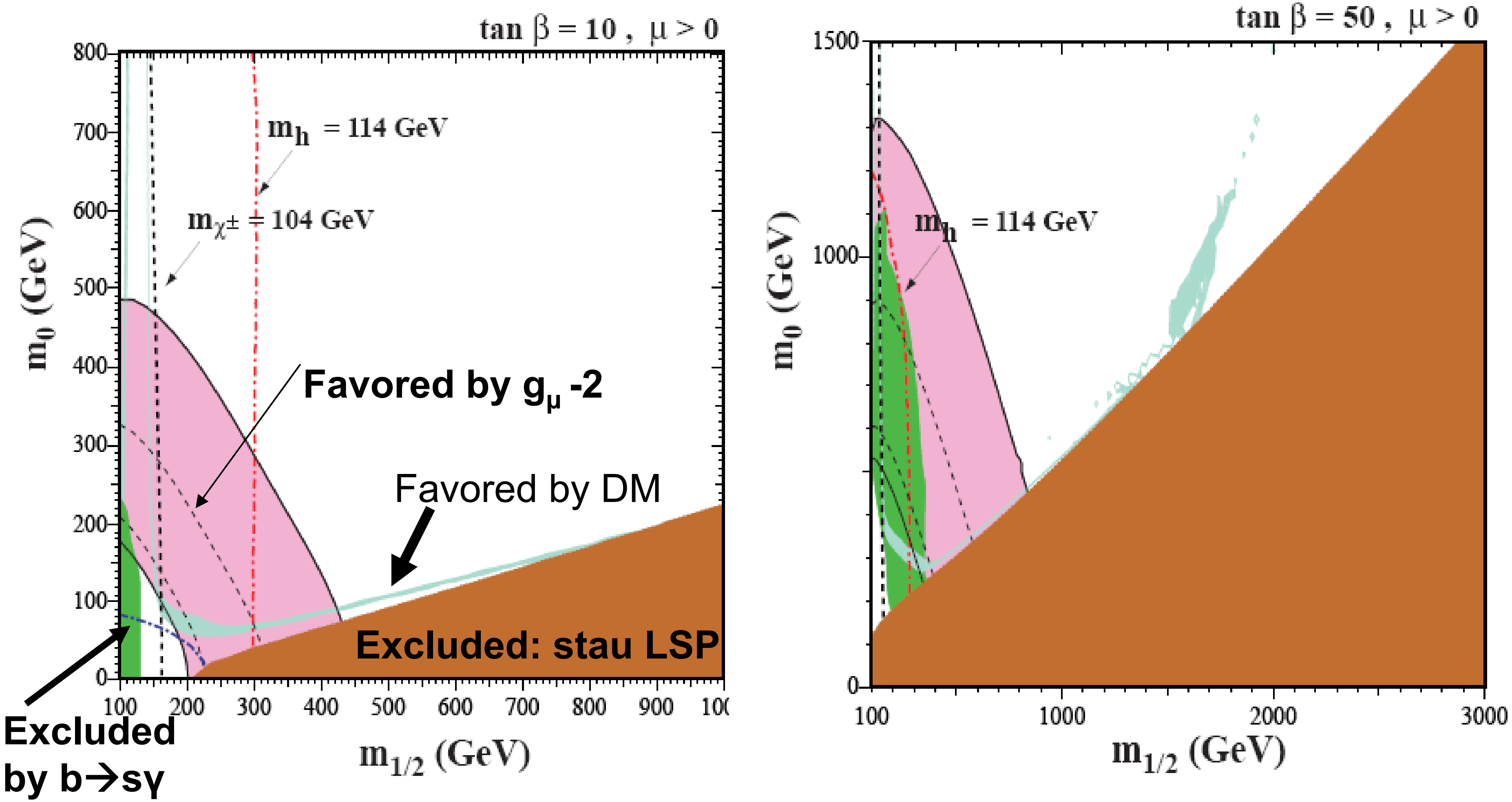
when it comes to quantitatively reproduce the precisely determined DM density → once again the fine-tuning threat…

After LEP: tuning of the SUSY param. at the % level to correctly reproduce the DM abundance: NEED FOR A "WELL-TEMPERED" NEUTRALINO



Arkani-Hamed-Delgado-Giudice

NEUTRALINO LSP IN THE CONSTRAINED MSSSM: A VERY SPECIAL SELECTION IN THE PARAMETER SPACE?



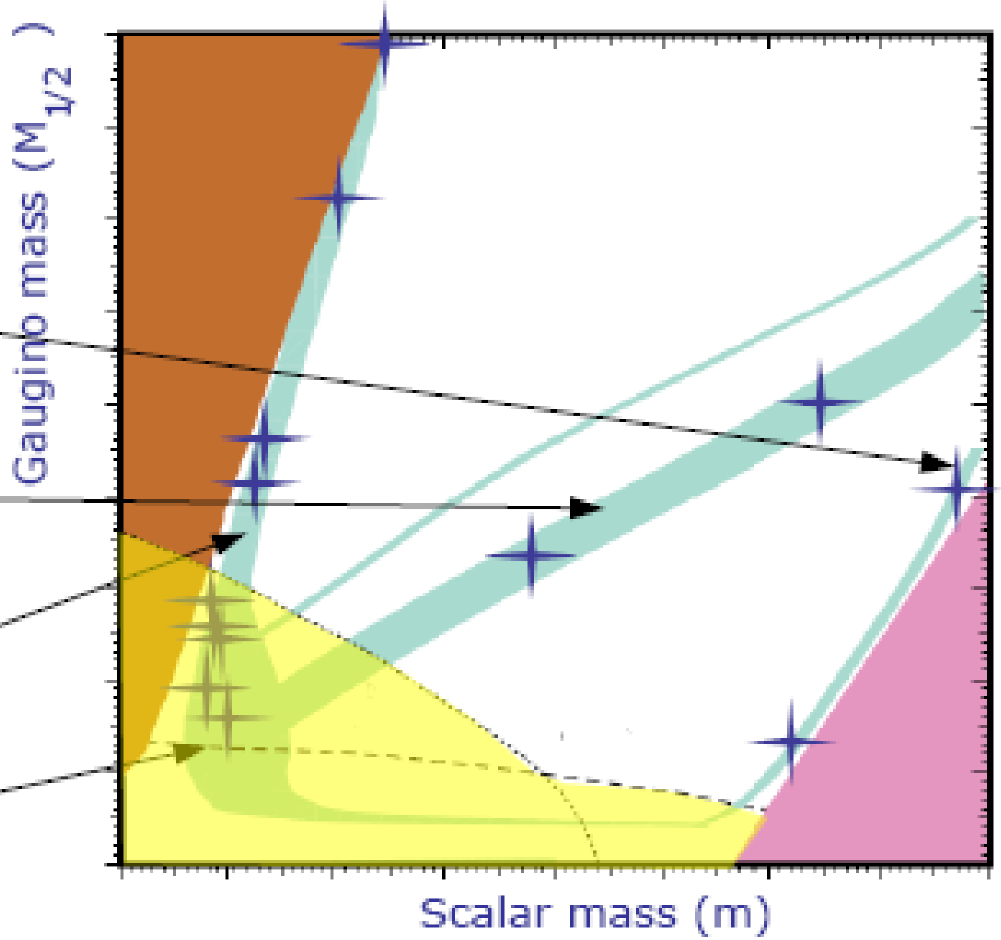
Ellis, Olive, Santoso, Spanos

LHC reach in the SUSY parameter space (example CMSSM – A, M, m, tanβ, μ)

Regions compatible with Neutralino DM (having correct relic density)

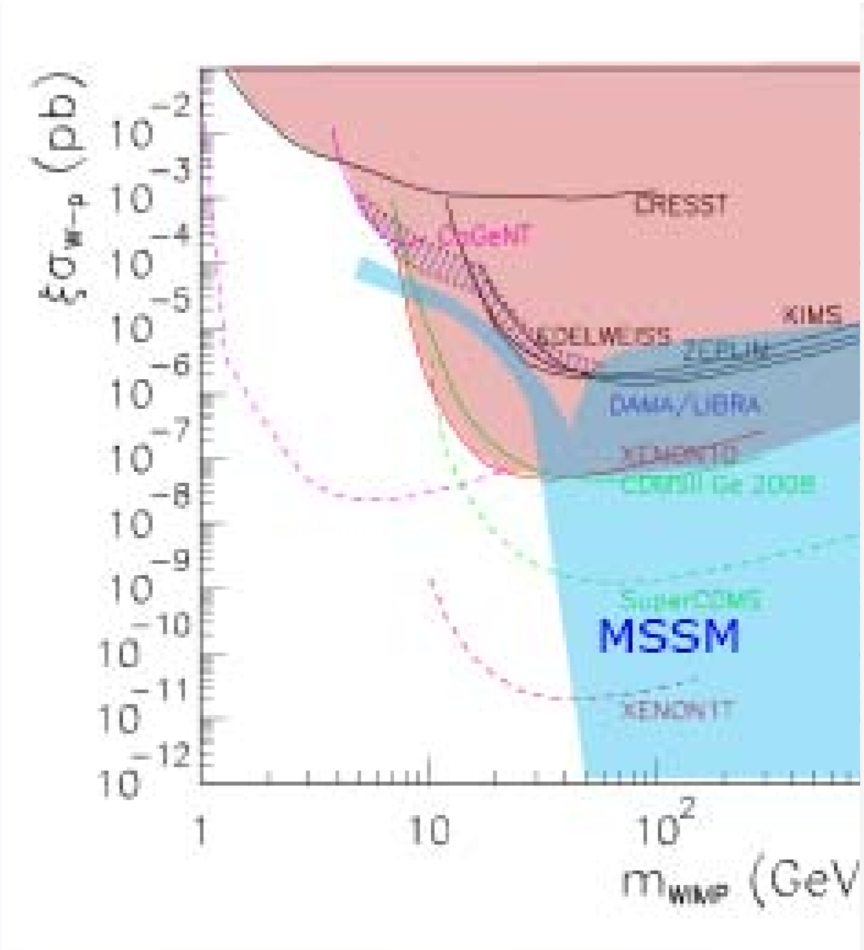
- Focus-Point region (Higgsino-Bino neutralino)
- Resonant annihilation (with pesudoscalar Higgs
- Coannihilation region (small LSP-NLSP mass difference)
- Bulk (small SUSY masses)

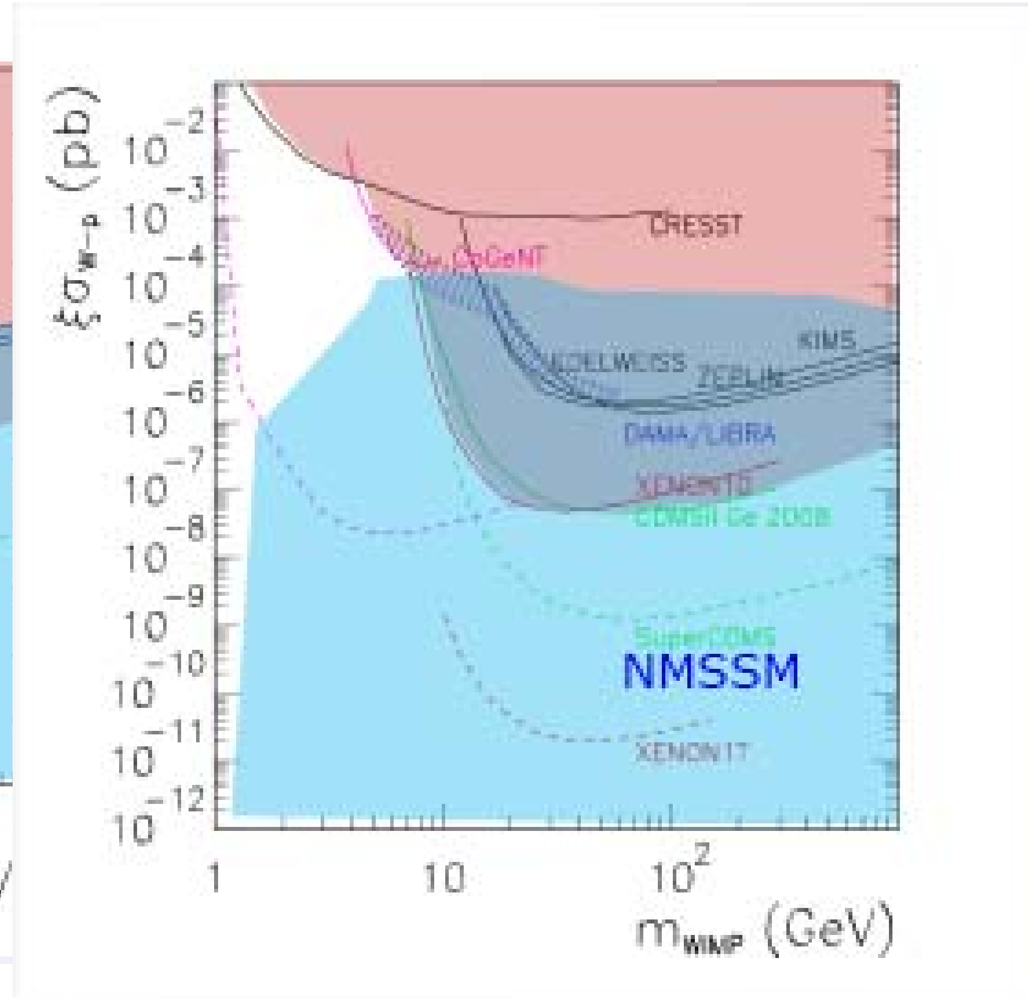
  Mostly excluded by LEP constraints (still available in non-minimal models)



(see e.g., Ellis, Ferstl, Olive)

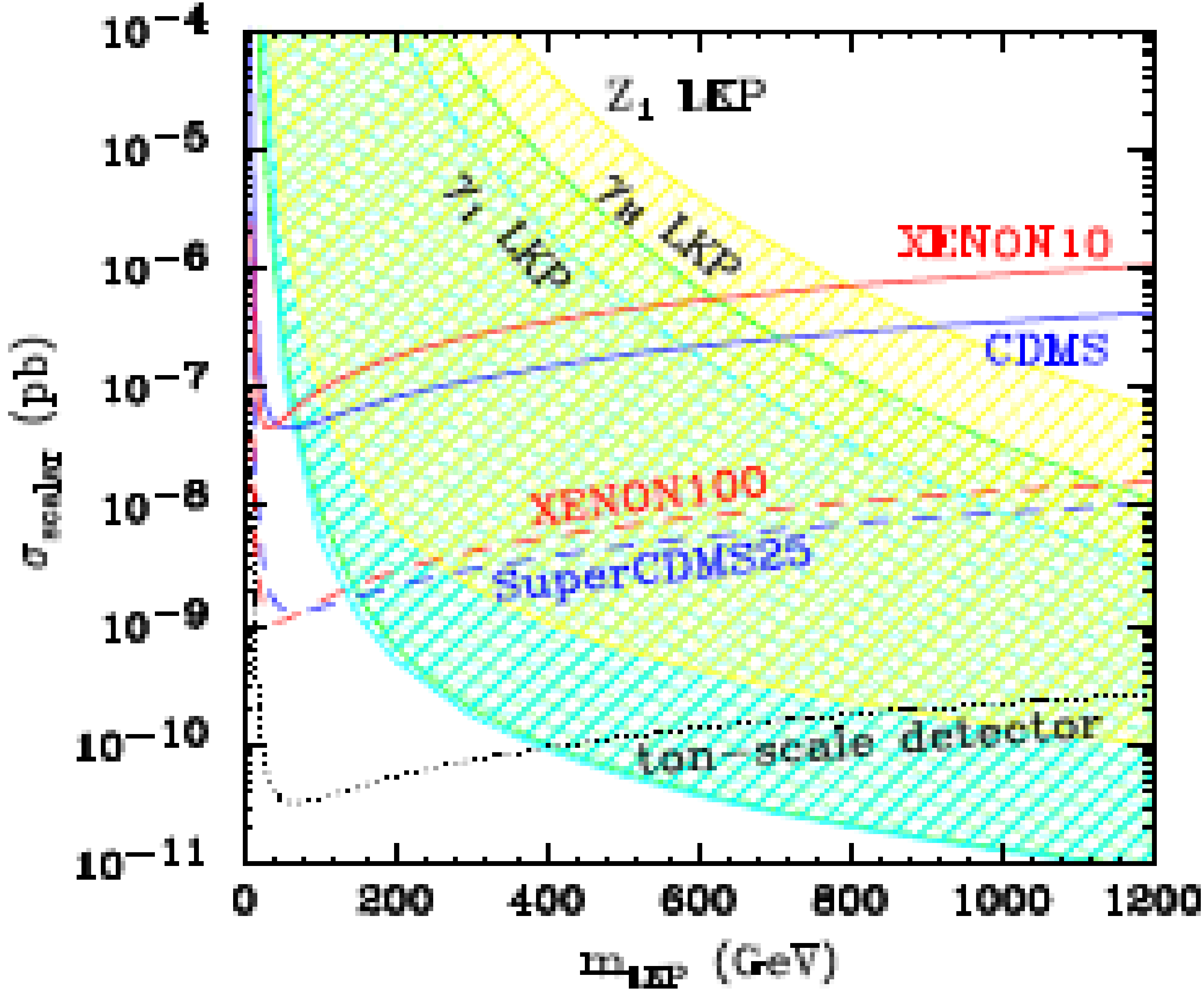
DM and the SUSY parameter space



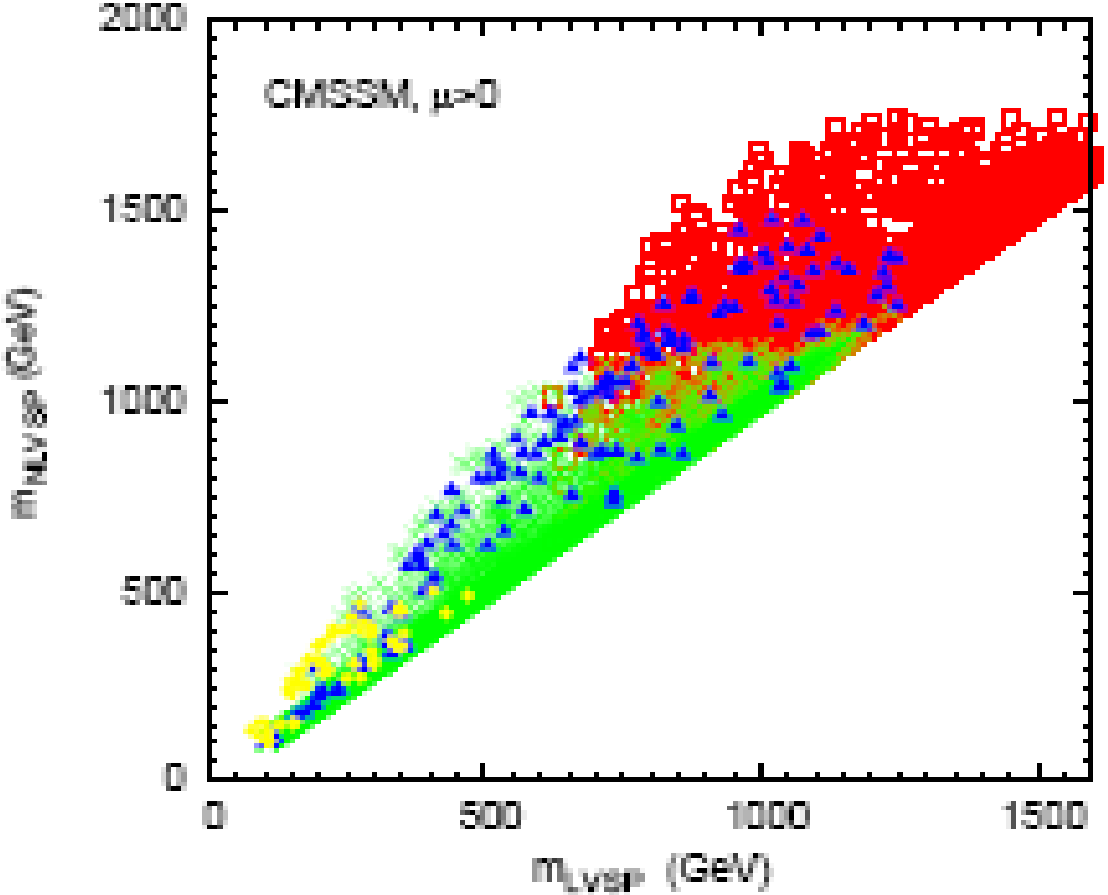


D. Cerdeno, WONDER10

Arrenberg, Baudis, Kong, Matchev, J. Yoo



PROSPECTS FOR DISCOVERING THE CMSSM AT THE LHC IN LIGHT OF WMAP



RED: FULL SAMPLE OF CMMS MODELS

BLUE: POINTS COMPATIBLE WITH WMAP

GREEN: POINTS ACCESSIBLE TO LHC

YELLOW: POINTS ACCESSIBLE TO PRESENT DIRECT DM SEARCHES

Ellis et al.

HUMAN PRODUCTION OF WIMPs

WIMPS HYPOTHESIS

DM made of particles with mass 10Gev - 1Tev

ELW scale

With WEAK INTERACT.

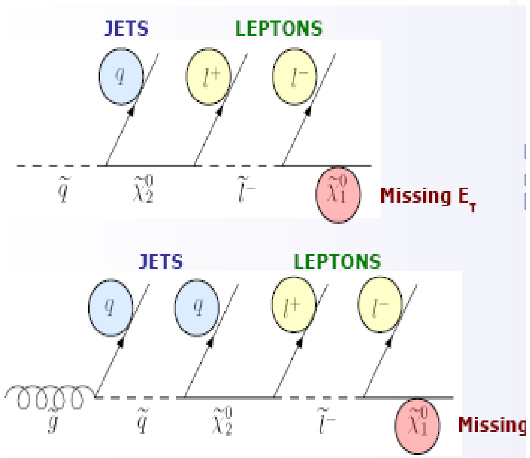
LHC, ILC may PRODUCE WIMPS

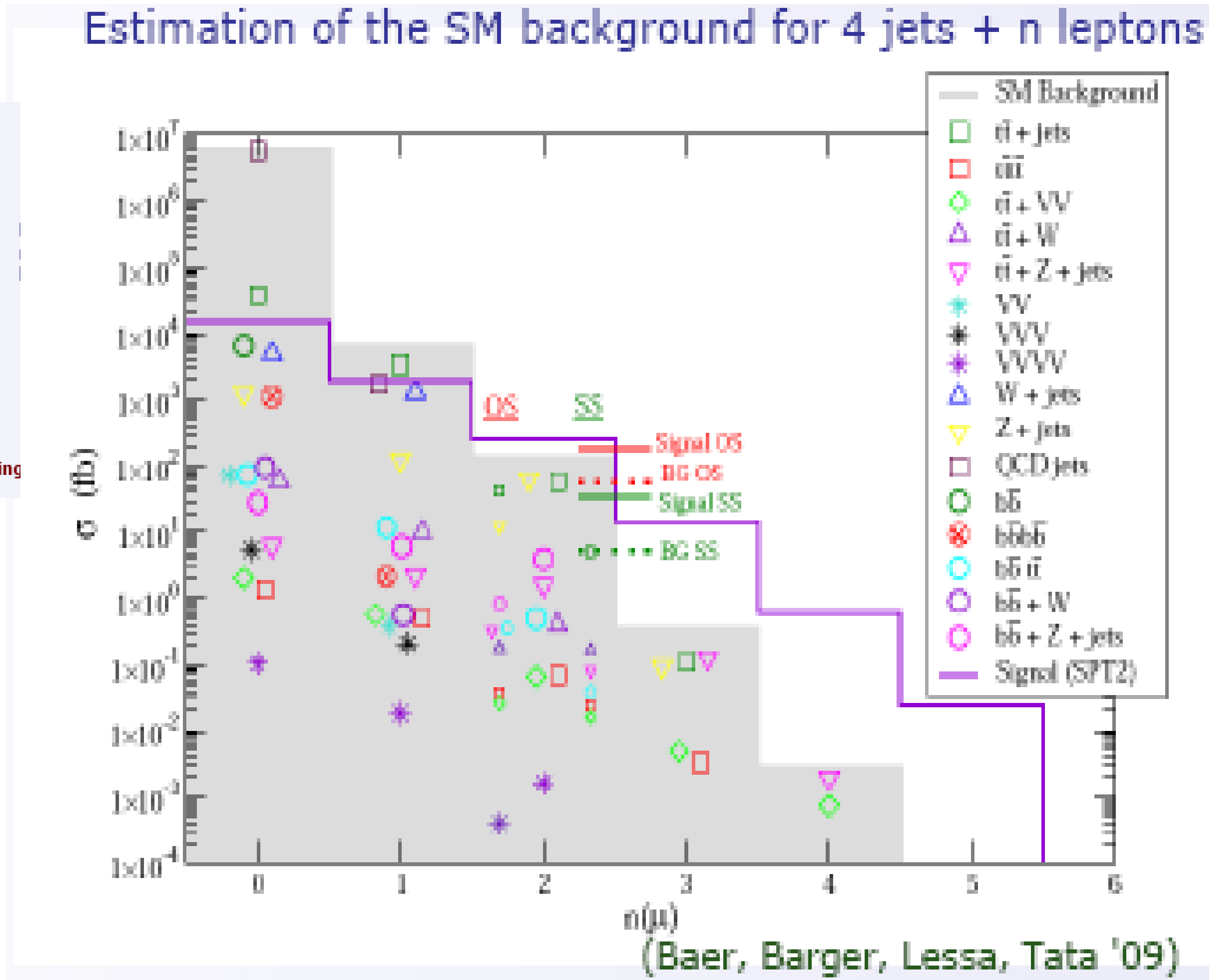
WIMPS escape the detector

→ MISSING ENERGY SIGNATURE

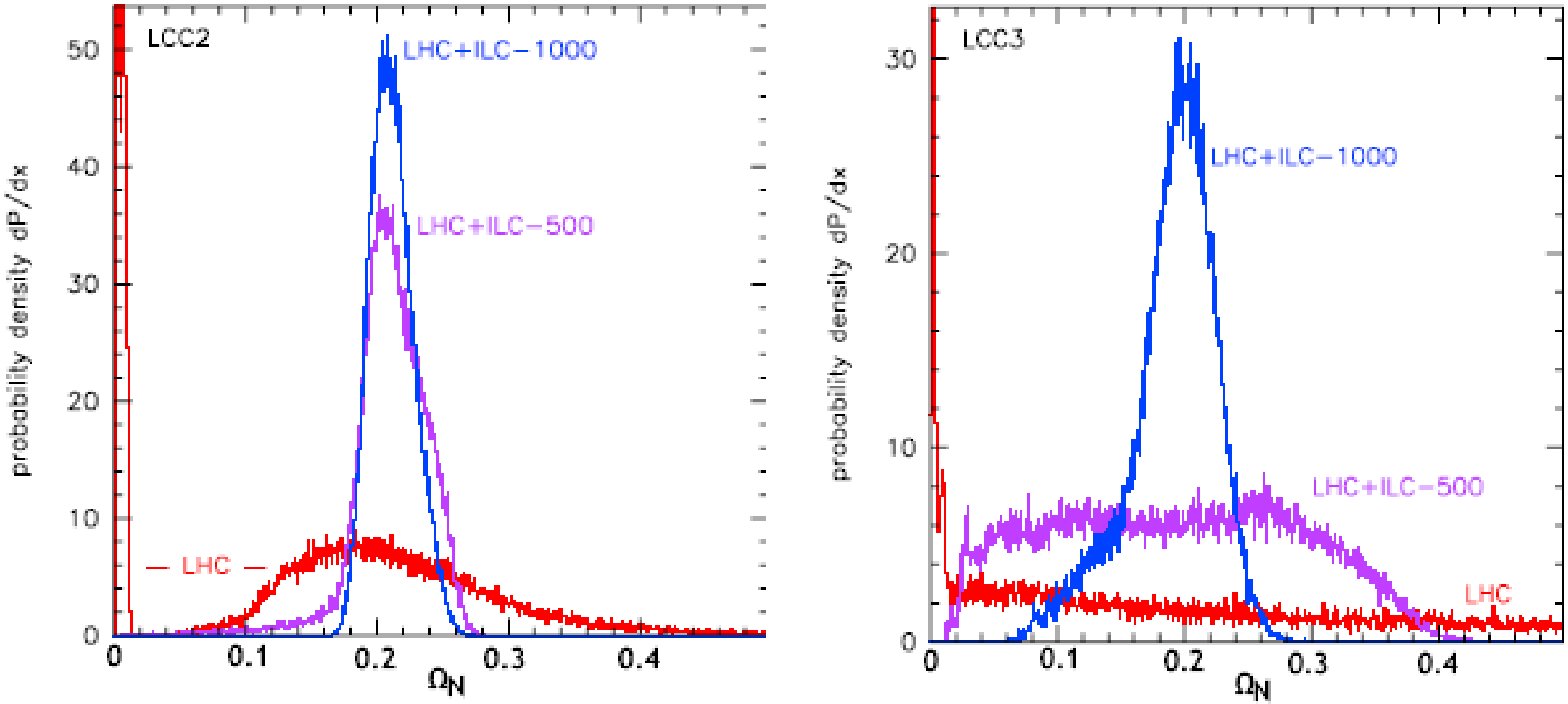
POSSIBILITY TO CREATE OURSELVES IN OUR ACCELERATORS THOSE DM PARTICLES WHICH ARE PART OF THE RELICS OF THE PRIMORDIAL PLASMA AND CONSTITUTE 1/4 OF THE WHOLE ENERGY IN THE UNIVERSE

DM through the jets + missing energy signature at the LHC

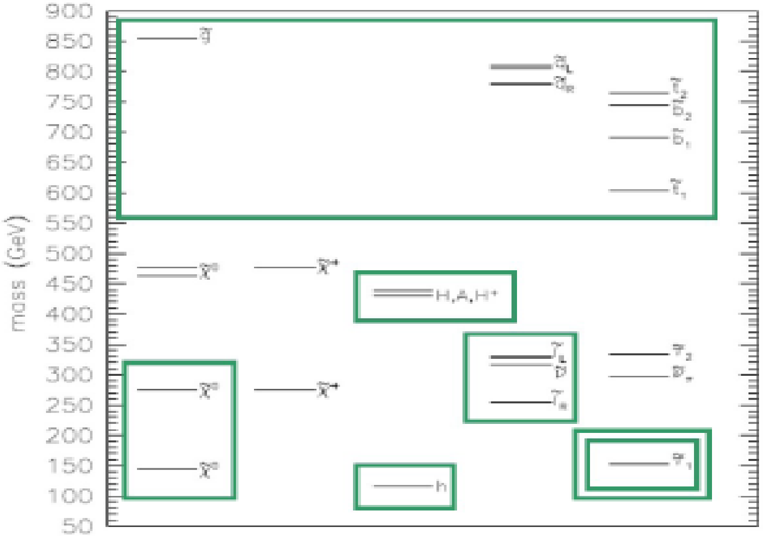




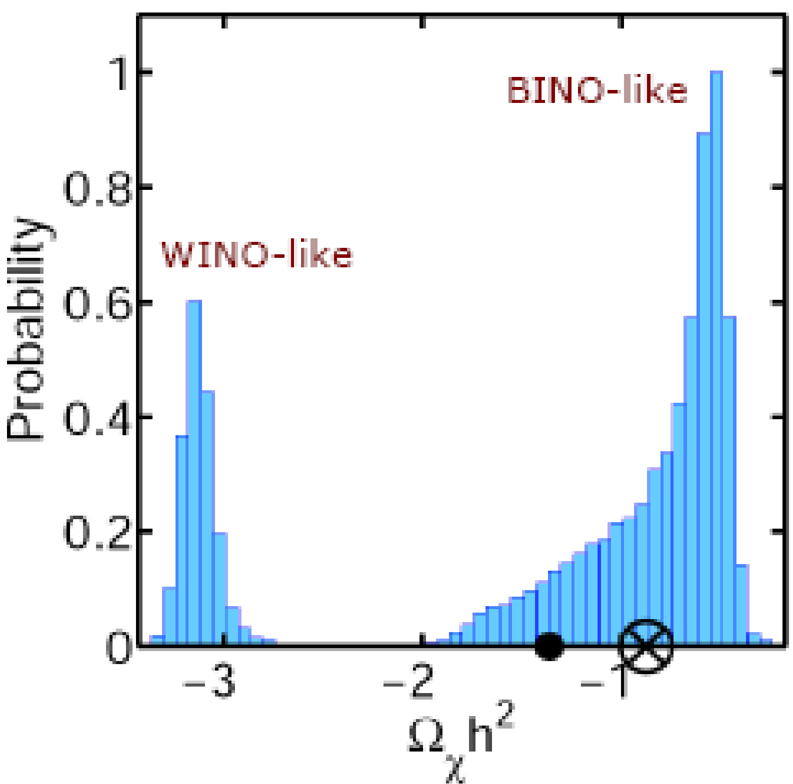
PREDICTION OF Ω DM FROM LHC AND ILC FOR TWO DIFFERENT SUSY PARAMETER SETS

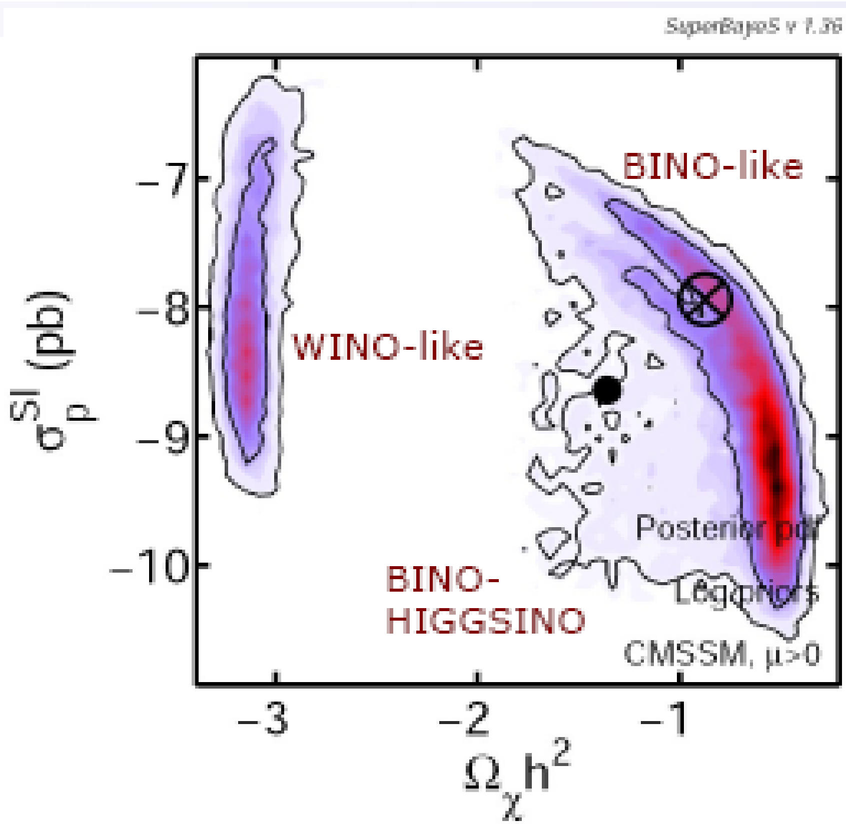


BALTZ, BATTAGLIA, PESKIN, WIZANSKY



Supponiamo di trovare (parte dello spettro di) particelle SUSY a LHC: possiamo “ricostruire” chi sia lo LSP, candidato WIMP di DM?



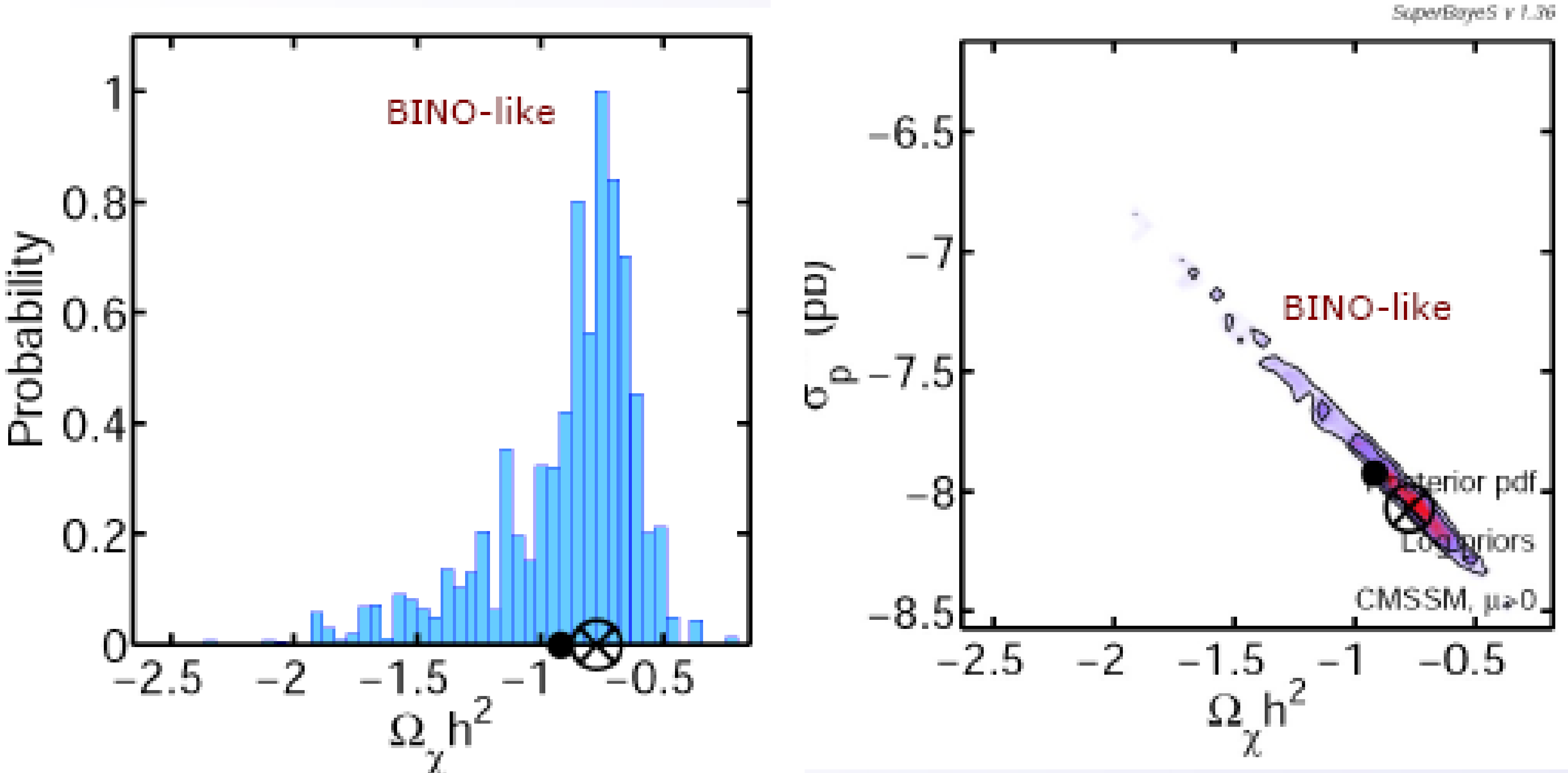


…ma se insieme troviamo la DM
sinergia LHC - DM

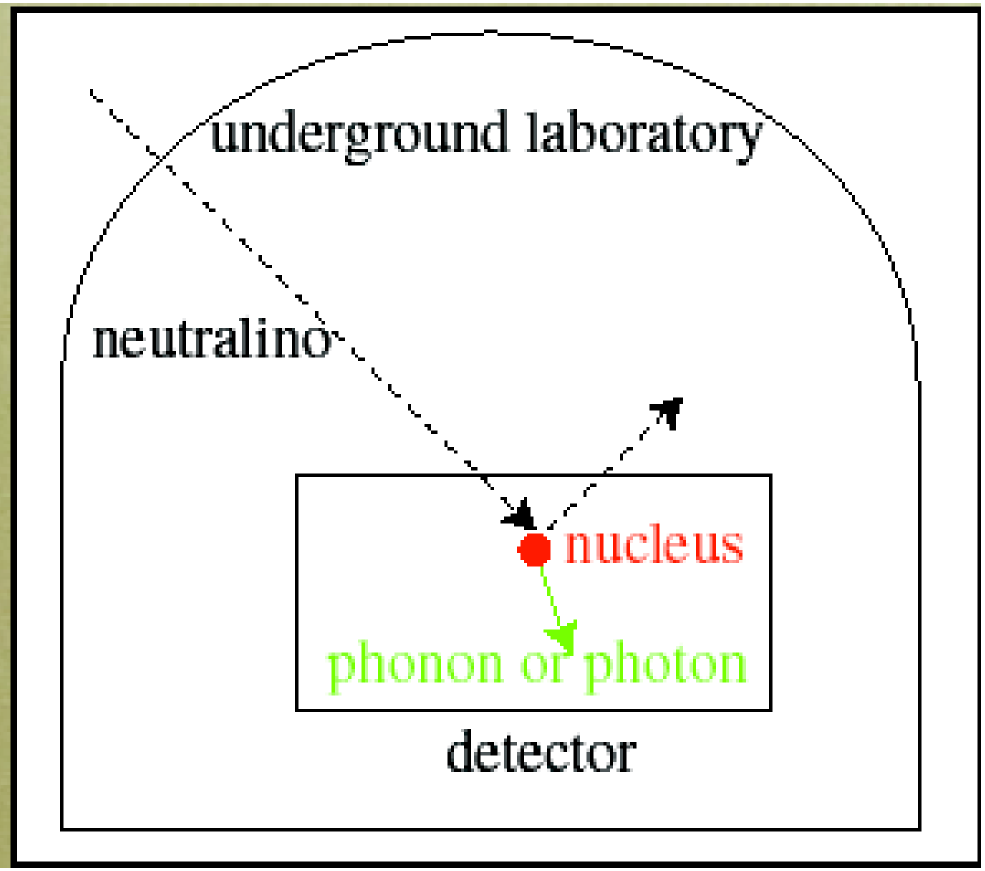
The combination of LHC data with Direct Detection data can resolve the degeneracy

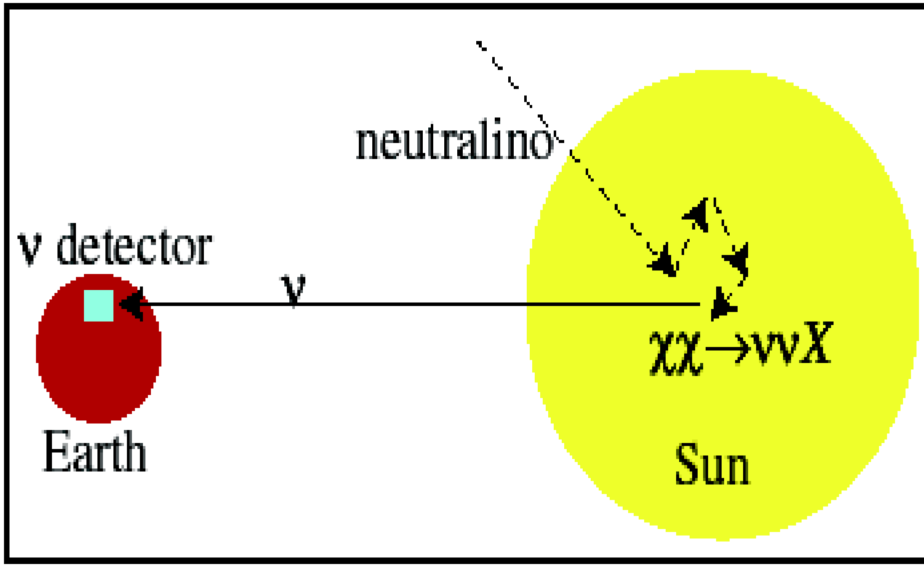
The reconstruction of the relic abundance has a similar accuracy but spurious maxima disappear

(Bertone, Cerdeño, Fornasa, Trotta, de Austri – in preparation)



HUNTING FOR DARK MATTER

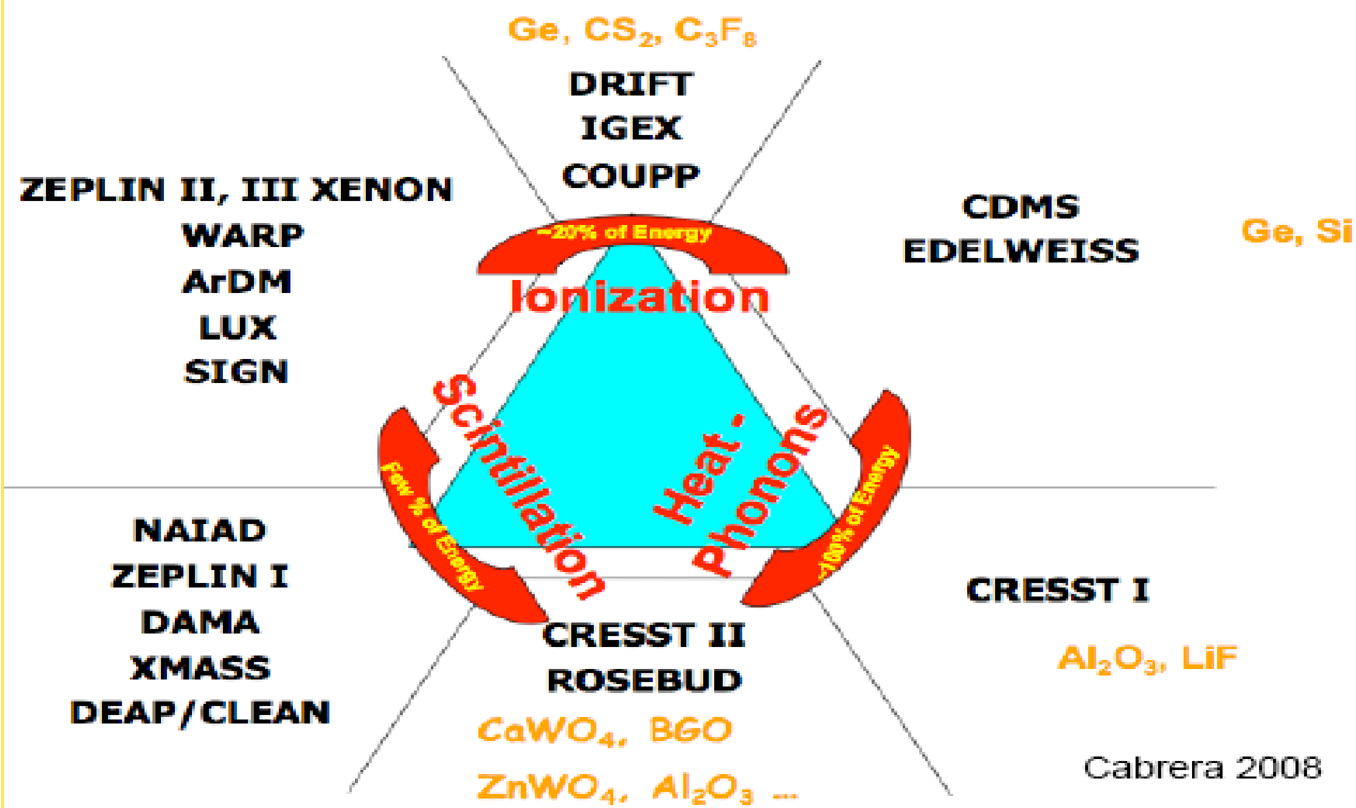


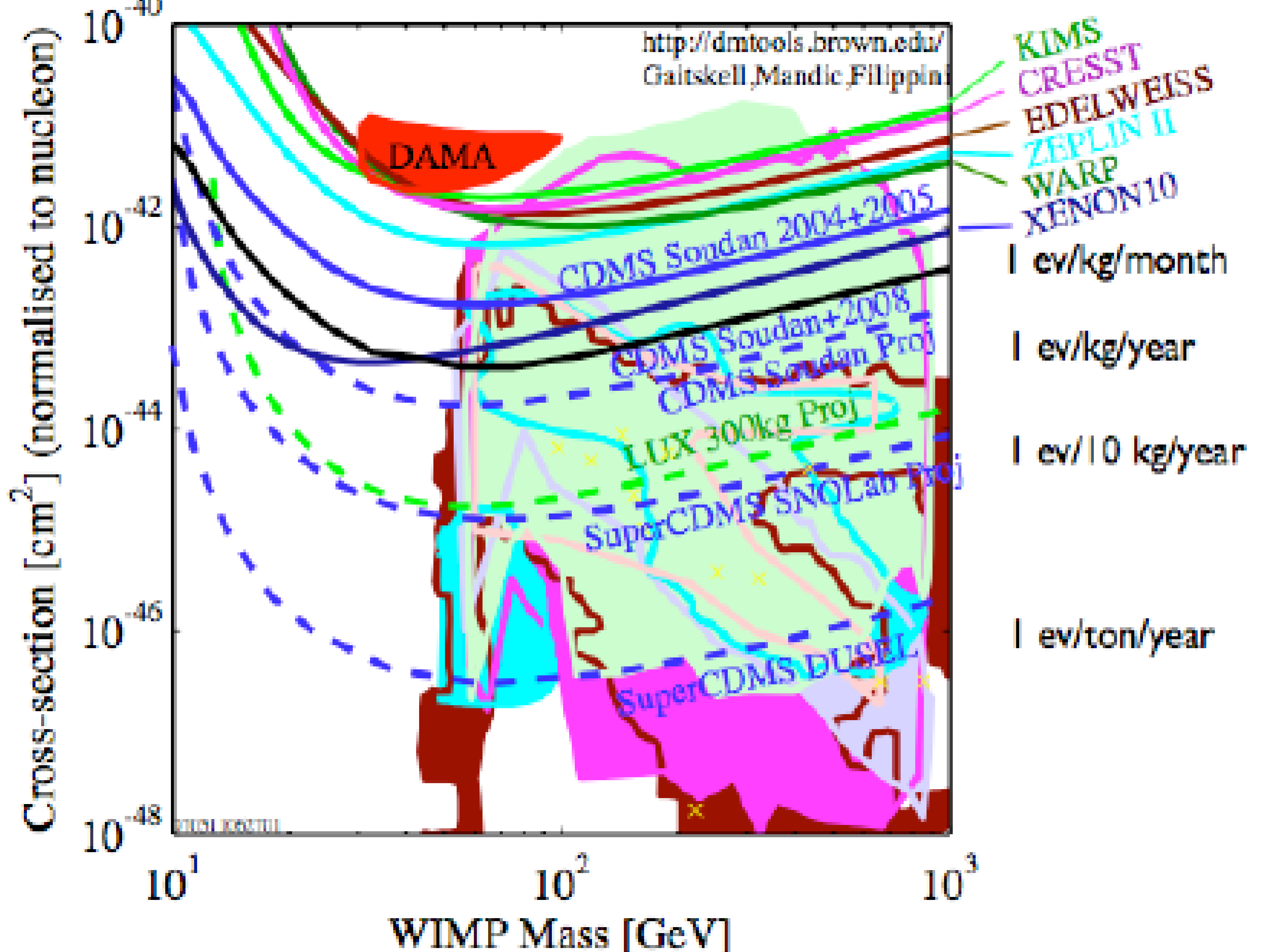


INDIRECT DM SEARCHES

DIRECT DM SEARCHES

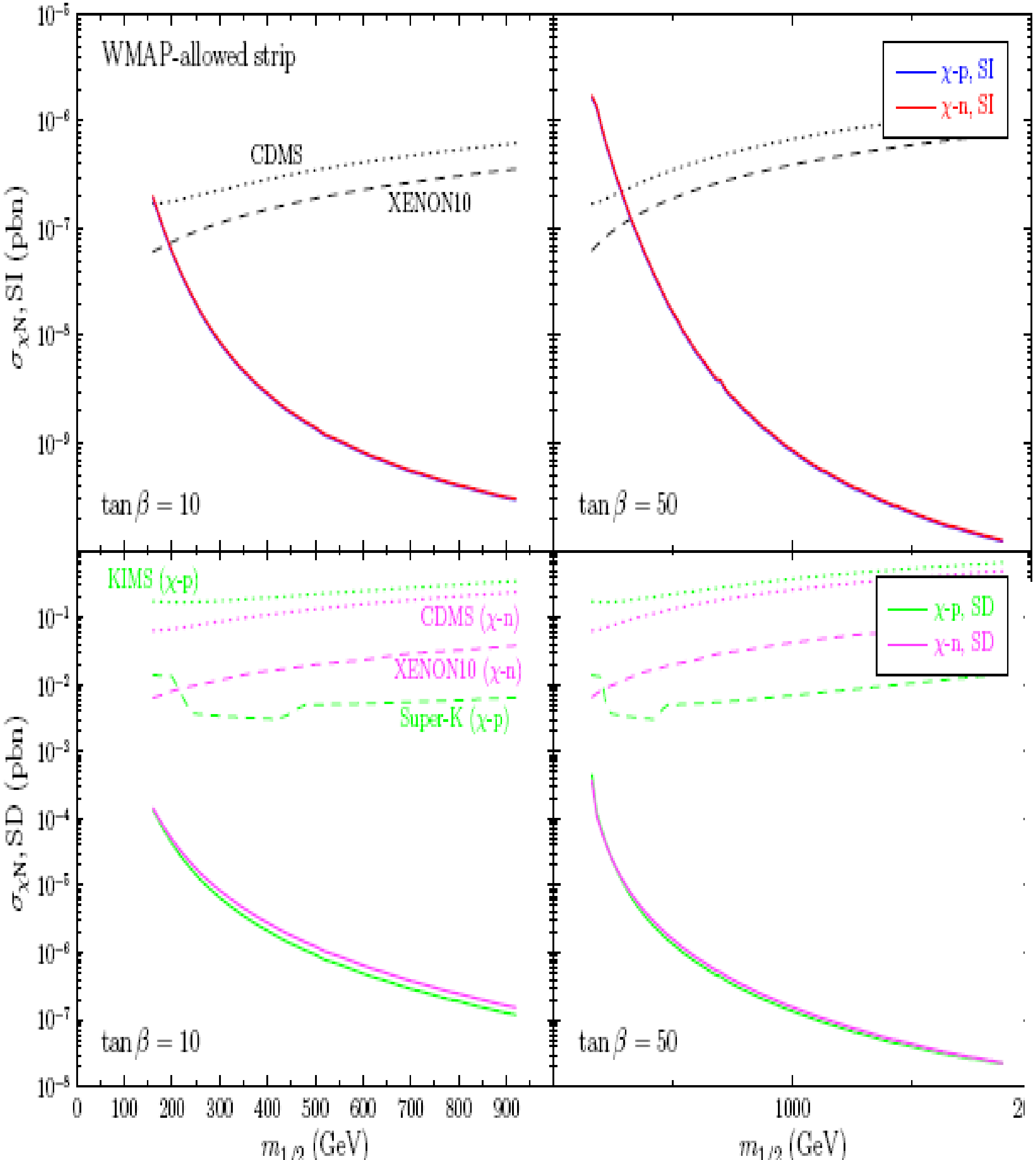
Direct Detection Techniques





http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
DAMA
KIMS
CRESST
EDELWEISS
ZEPLIN II
WARP
XENON10
CDMS Soudan 2004+2005
CDMS Soudan+2008
CDMS Soudan Proj
LUX 300kg Proj
SuperCDMS SNOLab Proj
SuperCDMS DUSEL
1 ev/kg/month
1 ev/kg/year
1 ev/10 kg/year
1 ev/ton/year
Cross-section [cm^2] (normalised to nucleon)
WIMP Mass [GeV]
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^1
10^2
10^3

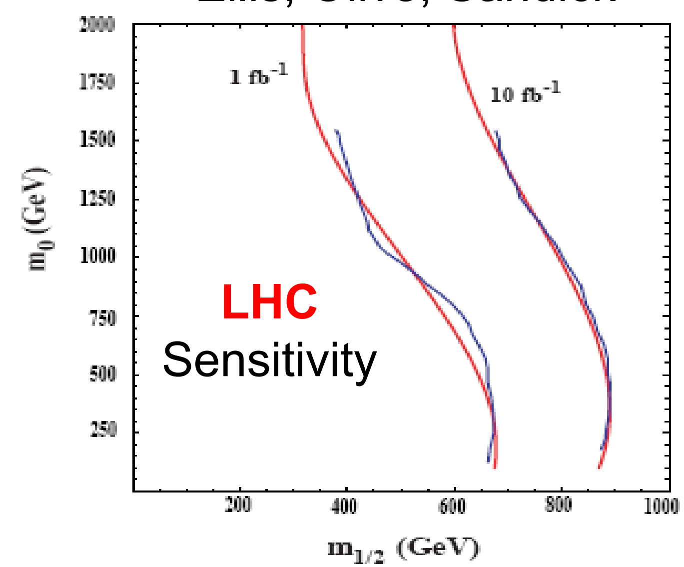
Neutralino-nucleon scattering cross sections along the WMAP-allowed coannihilation strip for tanbeta=10 and coannihilation/funnel strip for tanbeta=50 using the hadronic parameters



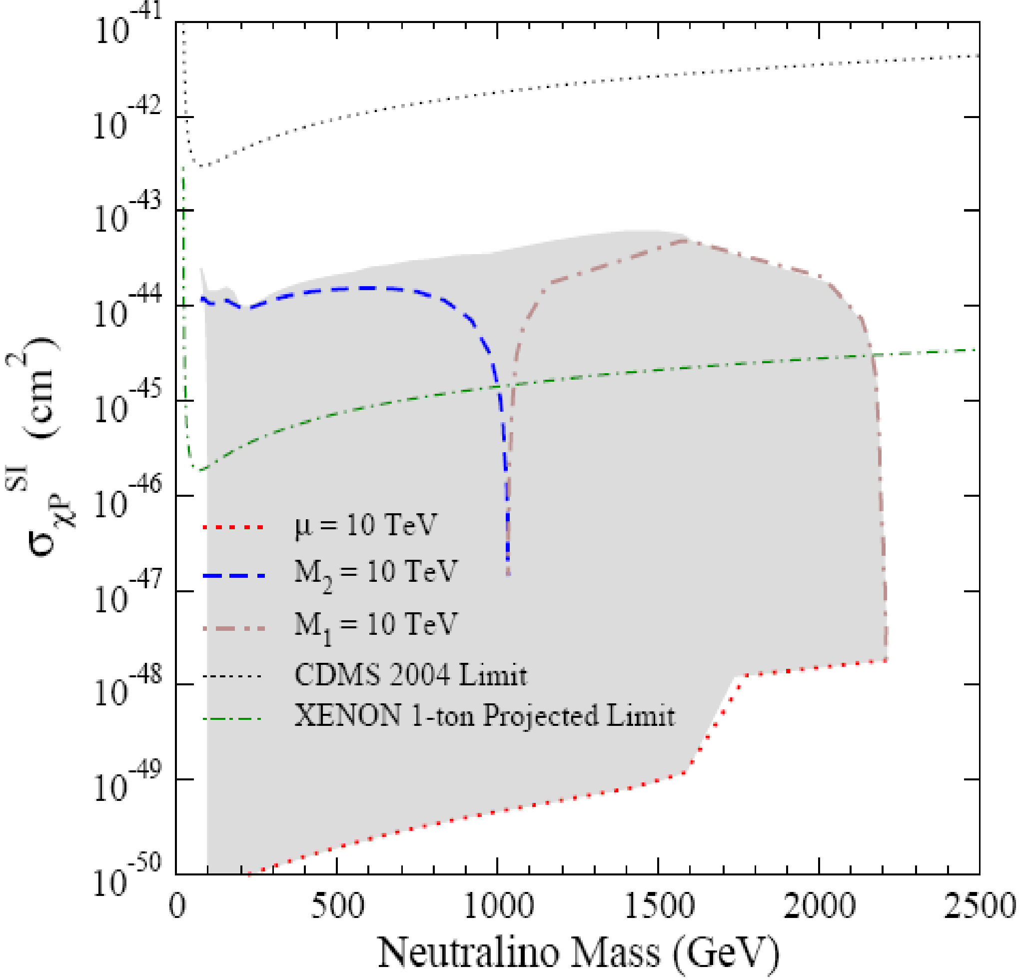
ELLIS. OLIVE. SAVAGE

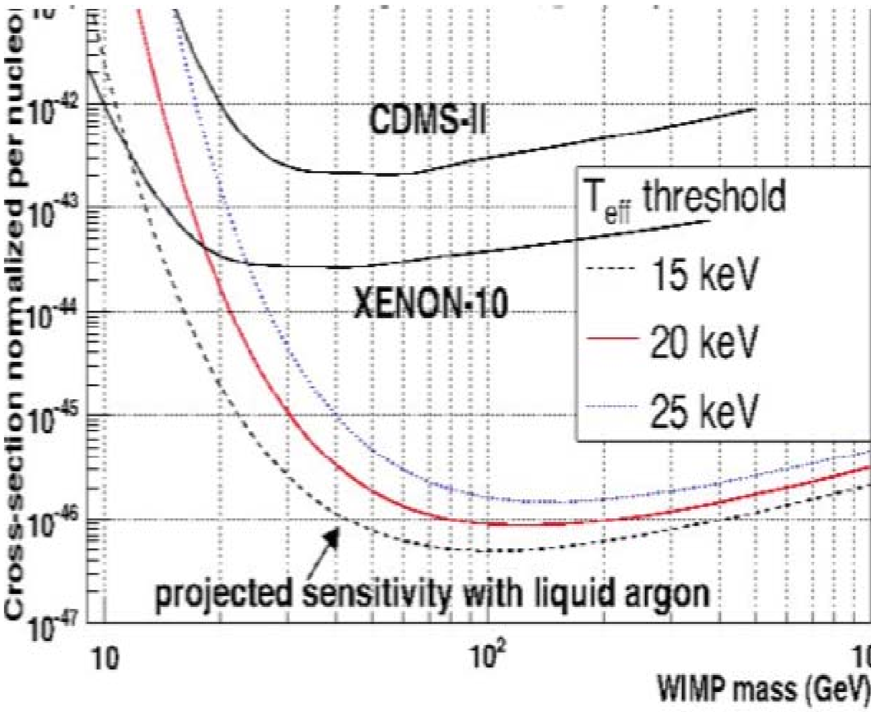
m_u/m_d	0.553	$\pm$ 0.043
m_d	5	$\pm$ 2 MeV
m_s/m_d	18.9	$\pm$ 0.8
m_c	1.25	$\pm$ 0.09 GeV
m_b	4.20	$\pm$ 0.07 GeV
m_t	171.4	$\pm$ 2.1 GeV
σ_0	36	$\pm$ 7 MeV
$\Sigma_{\pi N}$	64	$\pm$ 8 MeV
$a_3^{(p)}$	1.2695	$\pm$ 0.0029
$a_8^{(p)}$	0.585	$\pm$ 0.025
$\Delta_s^{(p)}$	-0.09	$\pm$ 0.03

Ellis, Olive, Sandick

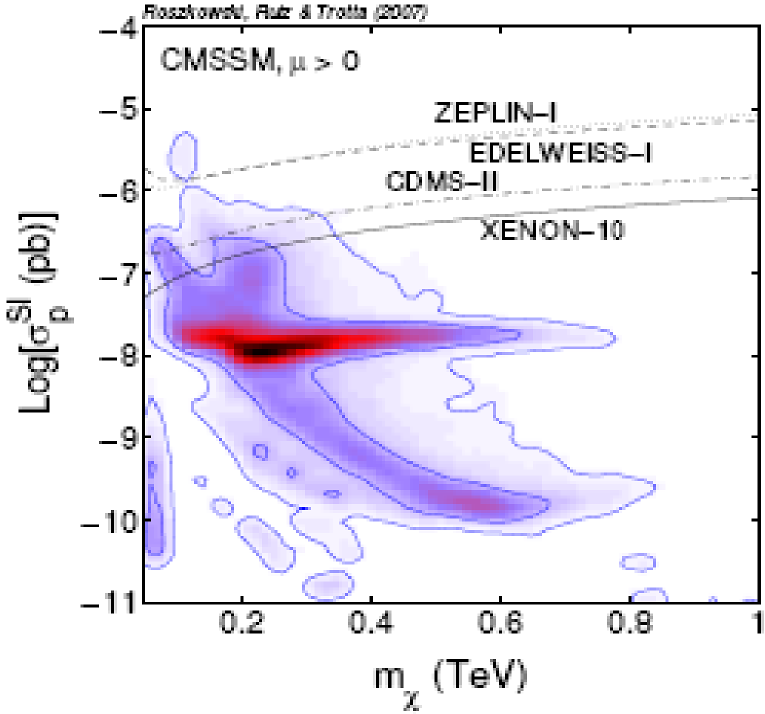


SPIN - INDEPENDENT NEUTRALINO - PROTON CROSS SECTION FOR ONE OF THE SUSY PARAM. FIXED AT 10 TEV





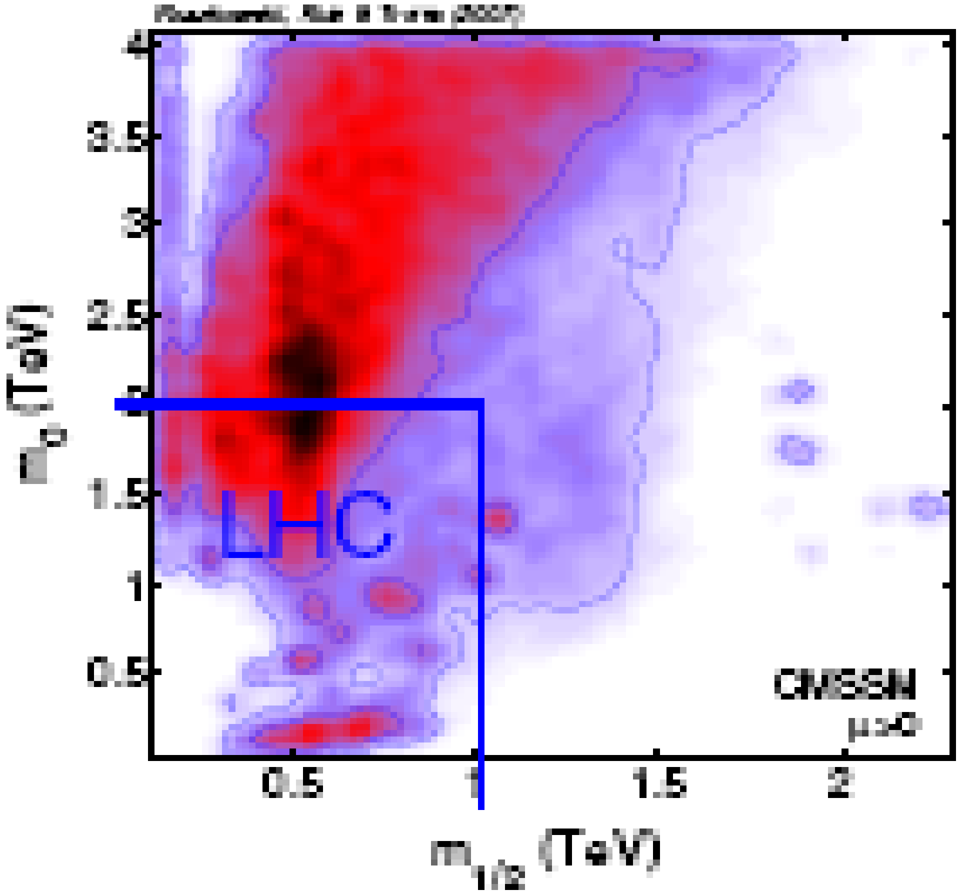
PROFUMO, A.M., ULLIO



ultimately: "1 tonne" detectors:

$\sigma_p^{SI} \lesssim 10^{-10}$ pb

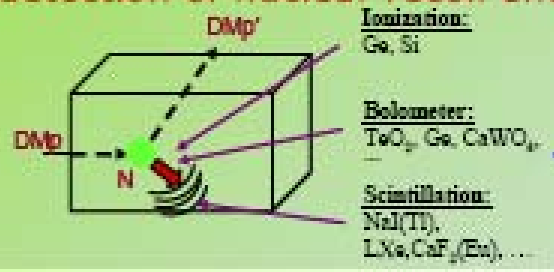
will cover all 68% region



Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



- Inelastic Dark Matter: **W + N → W* + N**

  → W has Two mass states $\chi+$, $\chi-$ with δ mass splitting

  → Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus

$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

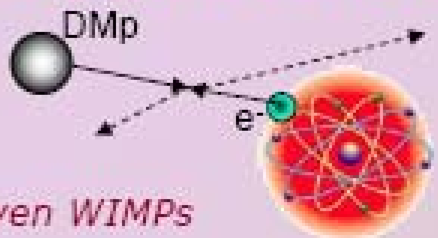
  → detection of recoil nuclei + e.m. radiation

- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-

- Interaction only on atomic electrons

  → detection of e.m. radiation

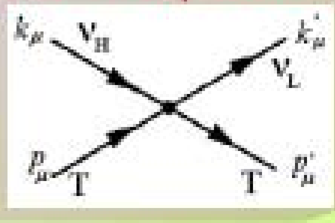


... *even WIMPs*

- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle

  → detection of electron/nucleus recoil energy

e.g. sterile ν



e.g. signals from these candidates are completely lost in experiments based on "rejection procedures" of the e.m. component of their rate

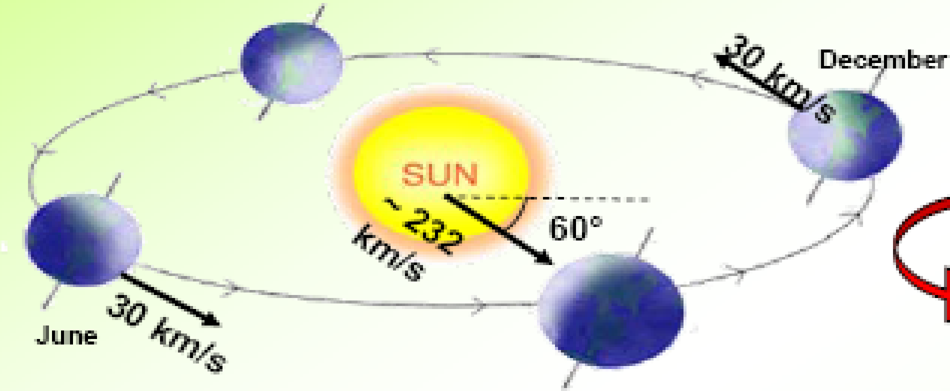
... also other ideas ...

- **... and more**

The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2[nd] June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb}\cos\gamma\cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

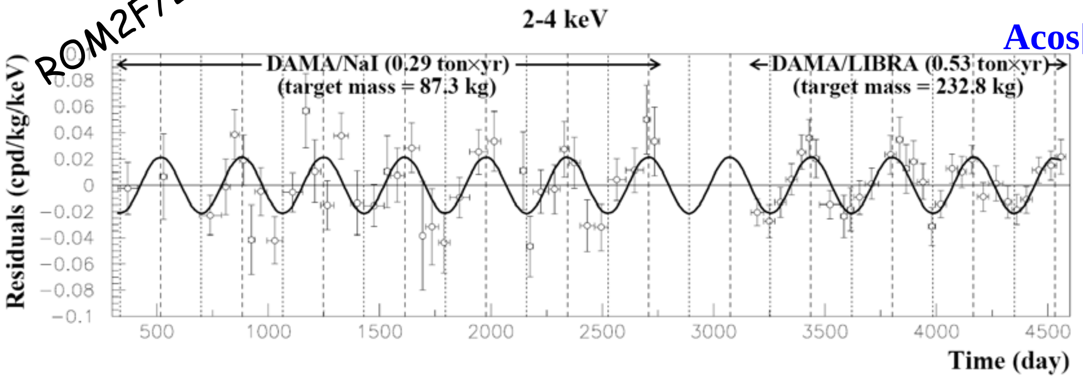
The DM annual modulation signature has a different origin and, thus, different peculiarities (e.g. the phase) with respect to those effects connected with the seasons instead

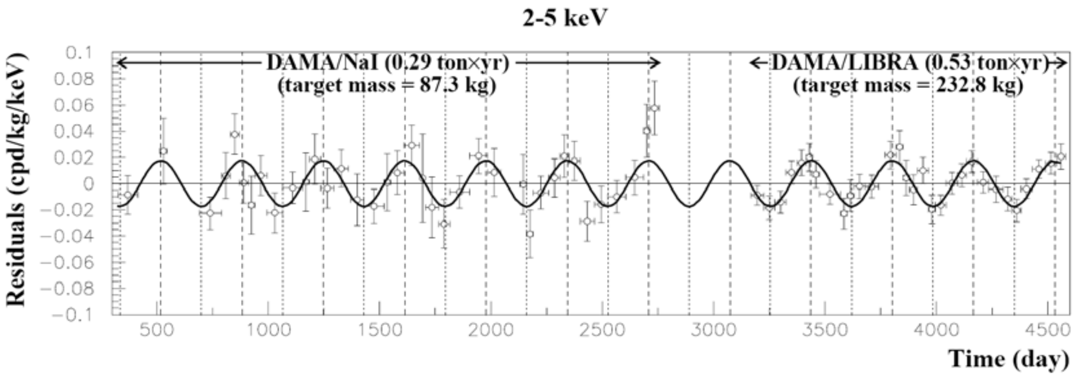
Model Independent Annual Modulation Result

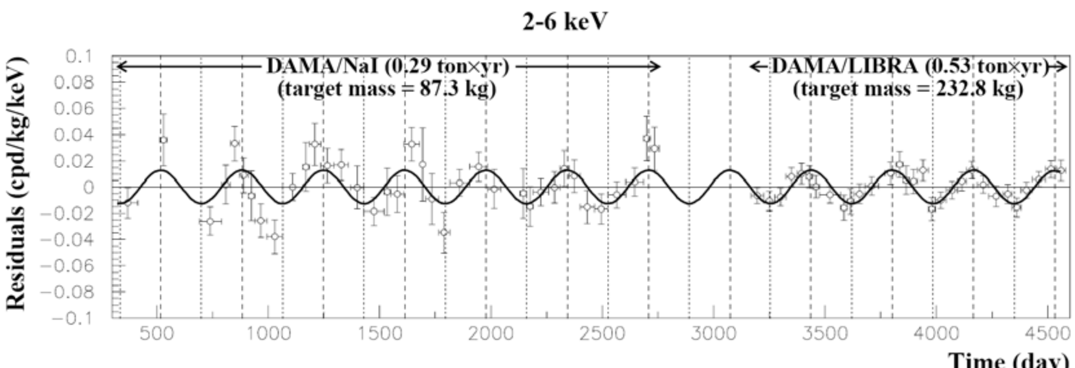
DAMA/NaI (7 years) + DAMA/LIBRA (4 years) Total exposure: 300555 kg×day = 0.82 ton×yr

ROM2F/2008/07

experimental single-hit residuals rate vs time and energy







$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV

A=(0.0215±0.0026) cpd/kg/keV

χ^2/dof = 51.9/66 **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=117.7/67 ⇒ P(A=0) = 1.3×10^{-4}

2-5 keV

A=(0.0176±0.0020) cpd/kg/keV

χ^2/dof = 39.6/66 **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=116.1/67 ⇒ P(A=0) = 1.9×10^{-4}

2-6 keV

A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 **8.2 σ C.L.**

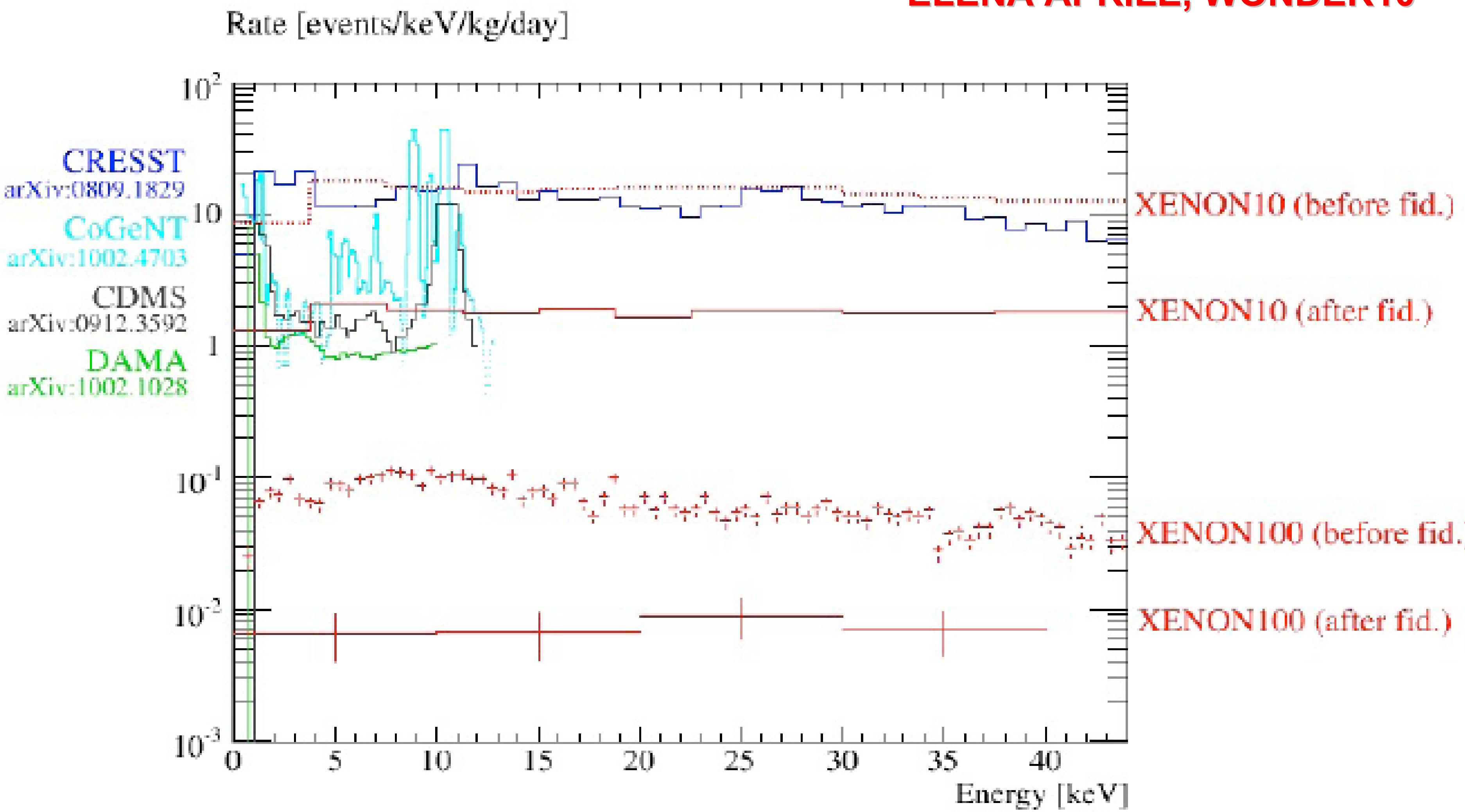
Absence of modulation? No

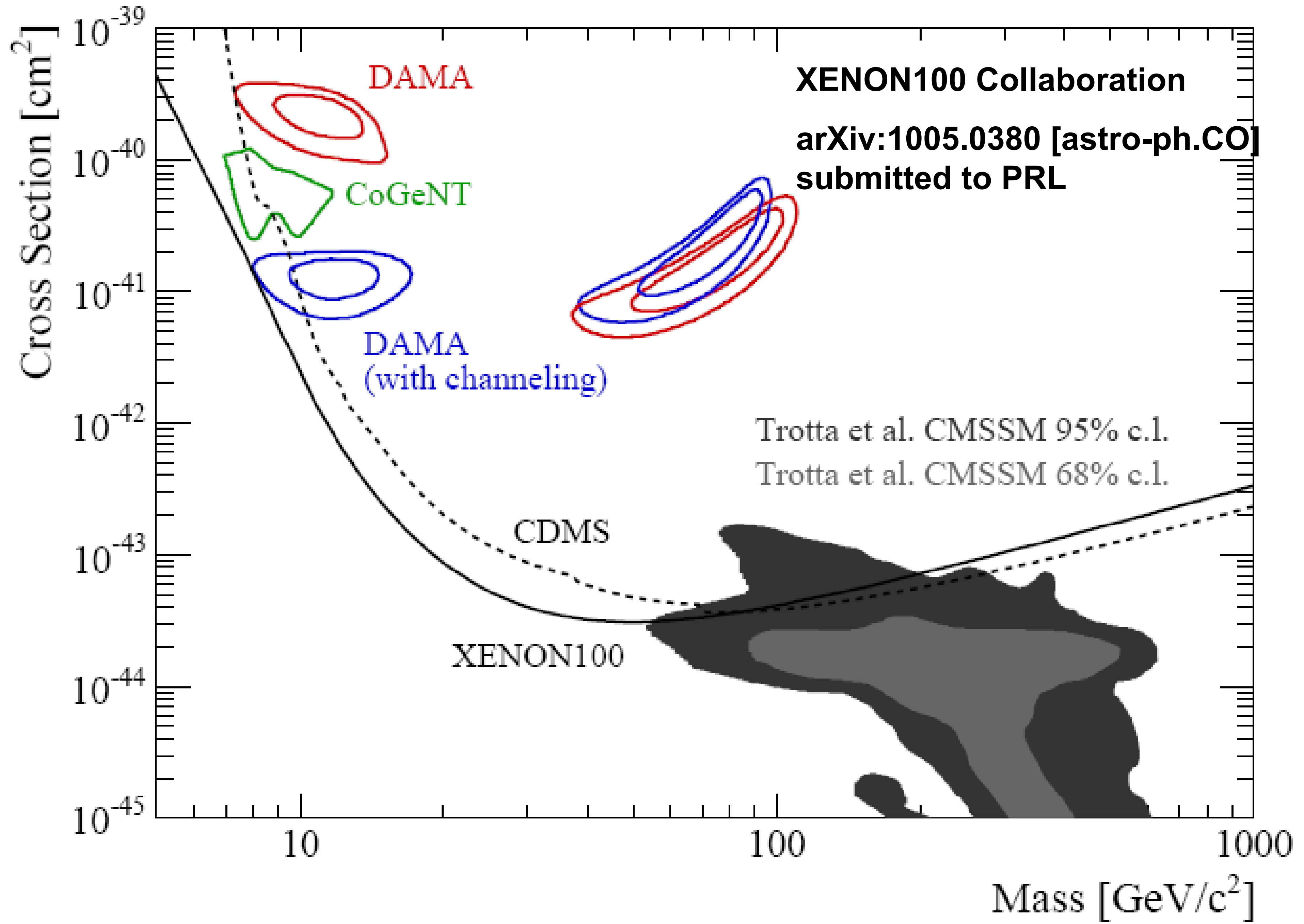
χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8×10^{-4}

The data favor the presence of a modulated behavior with proper features at 8.2σ C.L.

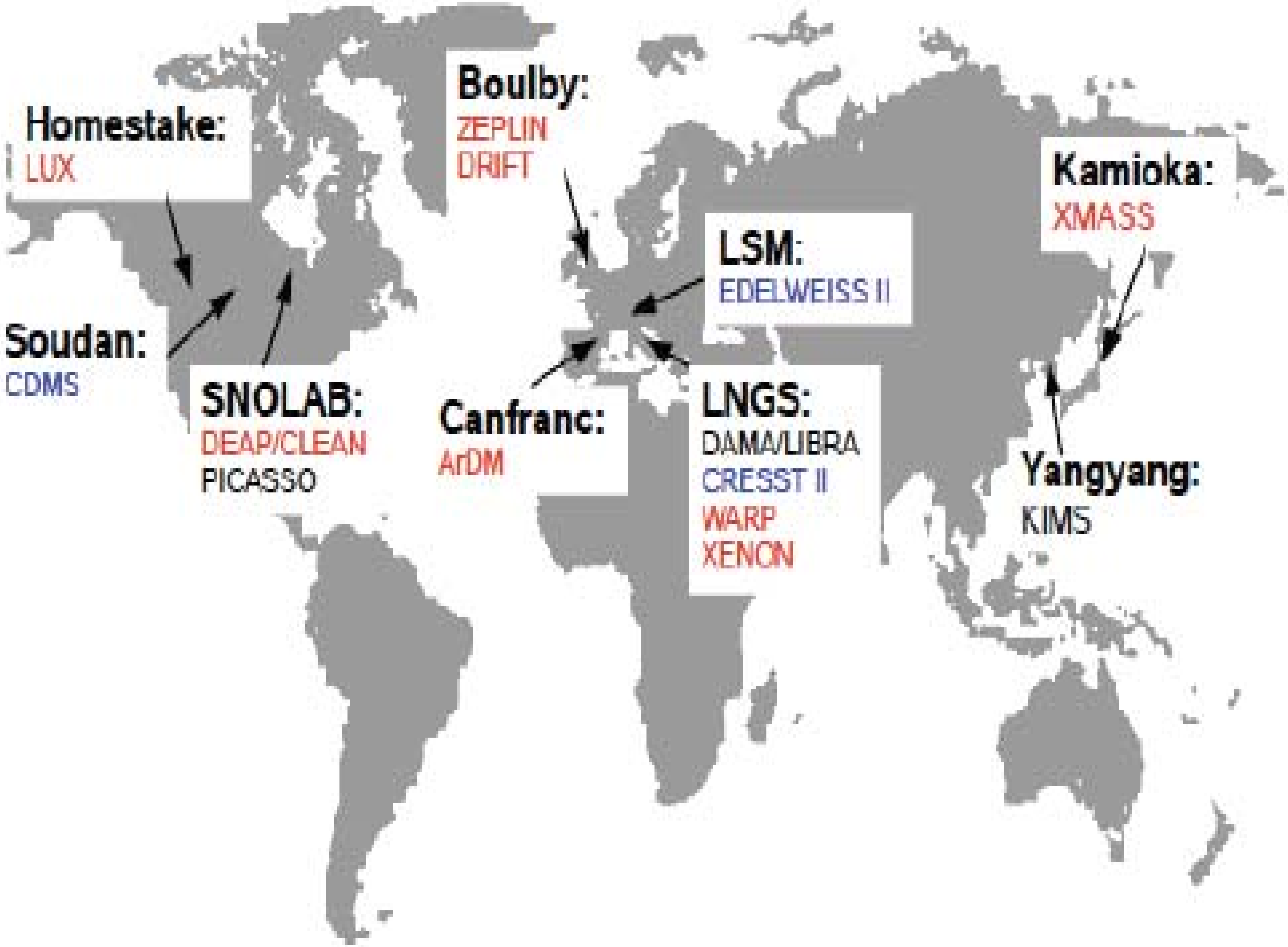
XENON100: the lowest background of all DM detectors

ELENA APRILE, WONDER10



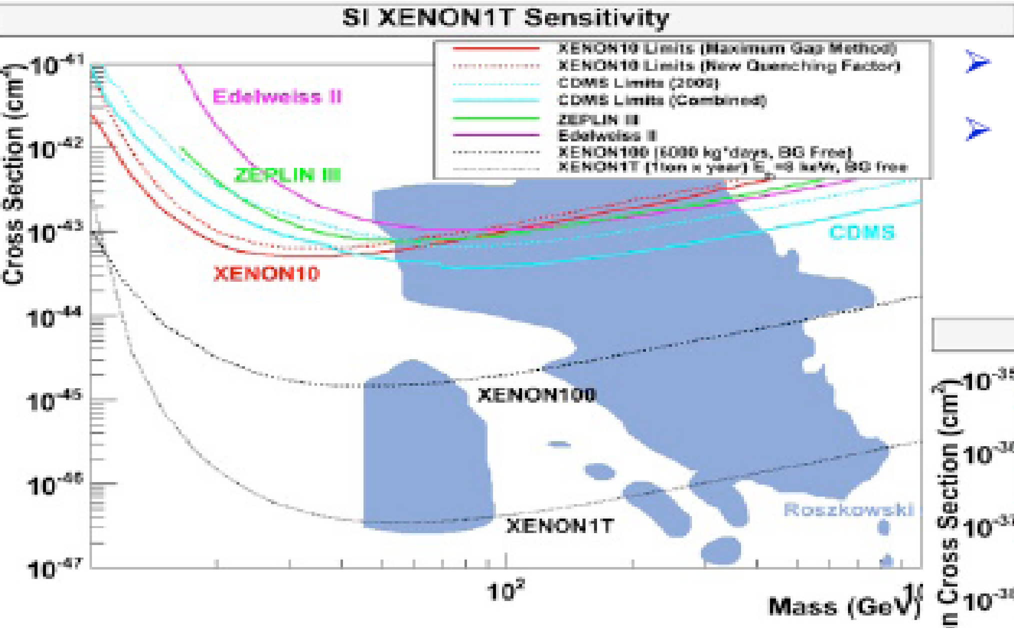


XENON100 Collaboration
arXiv:1005.0380 [astro-ph.CO]
submitted to PRL
DAMA
CoGeNT
DAMA
(with channeling)
Trotta et al. CMSSM 95% c.l.
Trotta et al. CMSSM 68% c.l.
CDMS
XENON100
Cross Section [cm^2]
Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10
100
1000

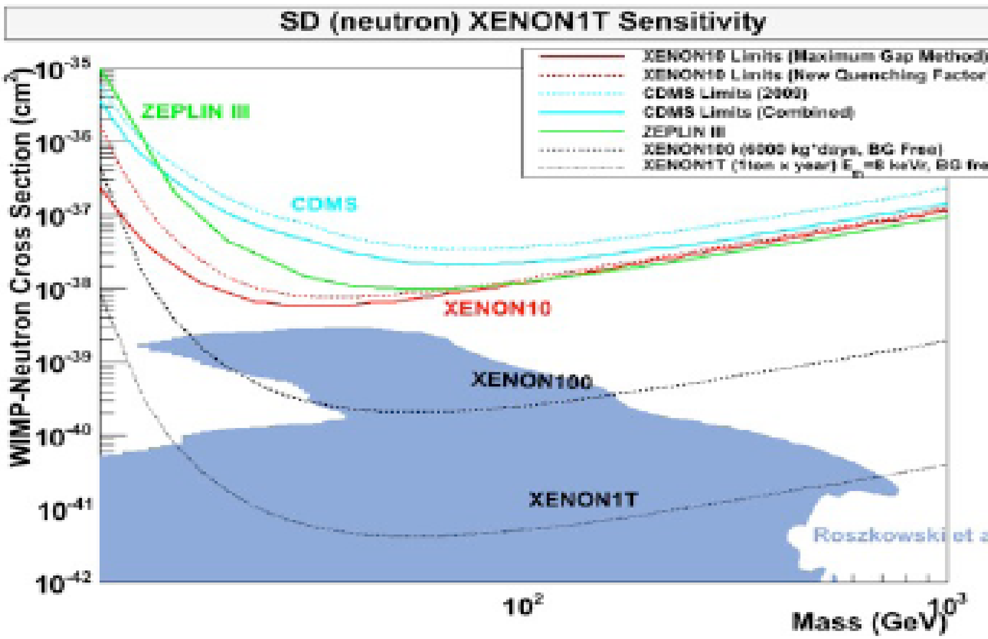

Homestake:
LUX
Boulby:
ZEPLIN
DRIFT
Kamioka:
XMASS
LSM:
EDELWEISS II
Soudan:
CDMS
SNOLAB:
DEAP/CLEAN
PICASSO
Canfranc:
ArDM
LNGS:
DAMA/LIBRA
CRESST II
WARP
XENON
Yangyang:
KIMS

Prospect with a 1-ton detector with noble liquids

XENON1T: A tremendous scientific reach



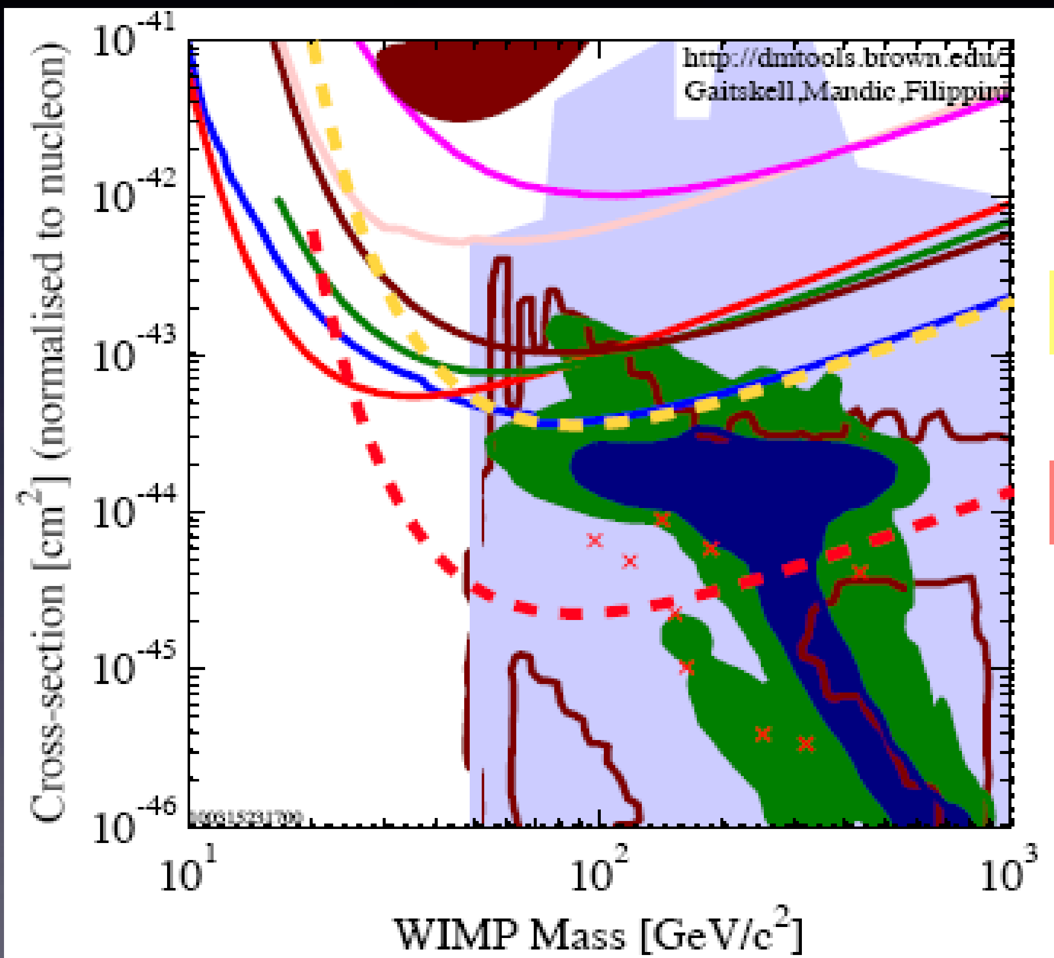
- probe simultaneously SI and SD channels
- explore the entire MSSM parameter space



E. Aprile, WONDER10

Sensitivity for SI case

YAMASHITA XMASS COLL. AT WONDER10

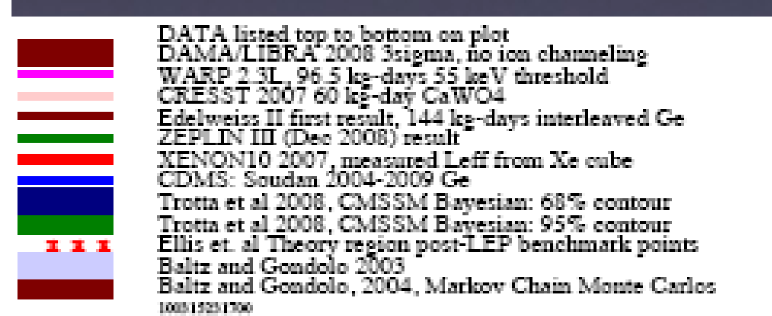


10^{-4} dru, 100 kg fiducial

XMASS 800 kg 10 days

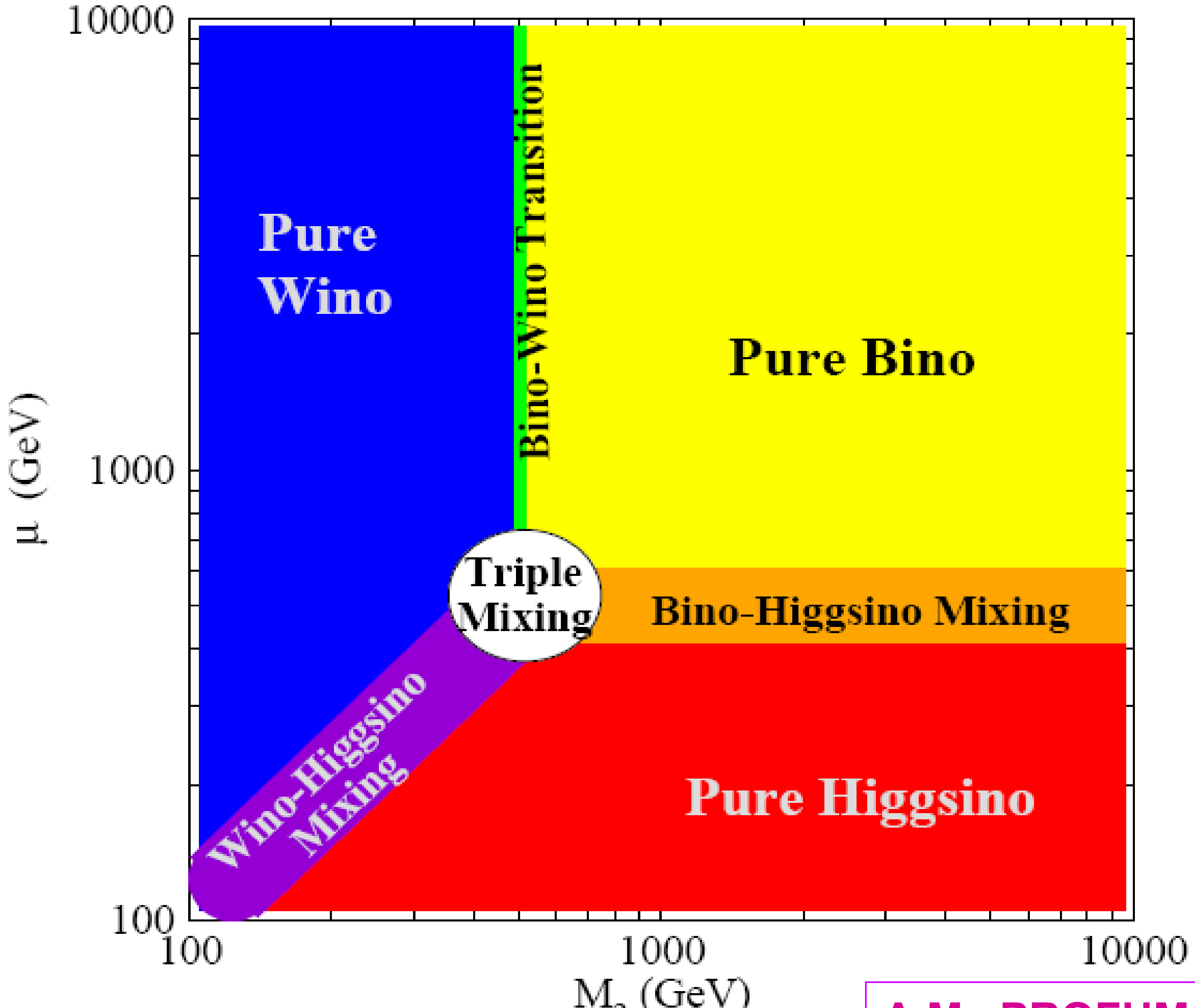
XMASS 800 kg 1 year

(flat bg assumed)



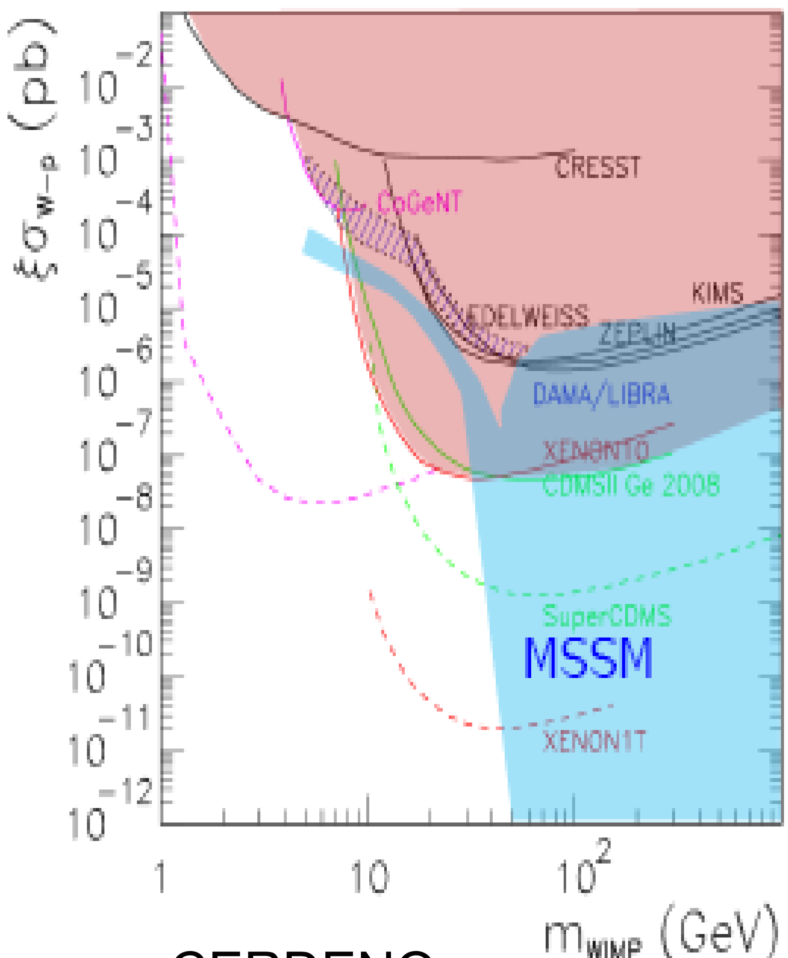
Masaki Yamashita

NEUTRALINO LSP IN SUPERGRAVITY

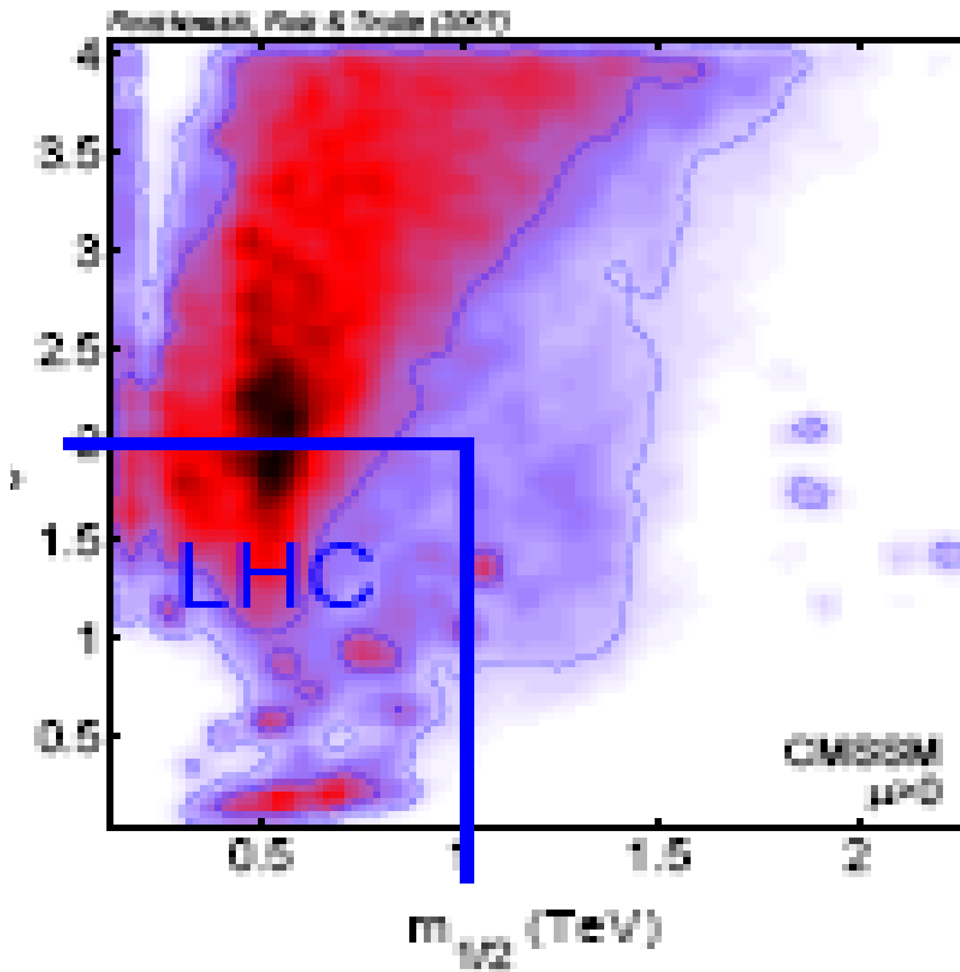


A.M., PROFUMO, ULLIO

On the LHC – Direct DM searches coverage of the MSSM parameter space

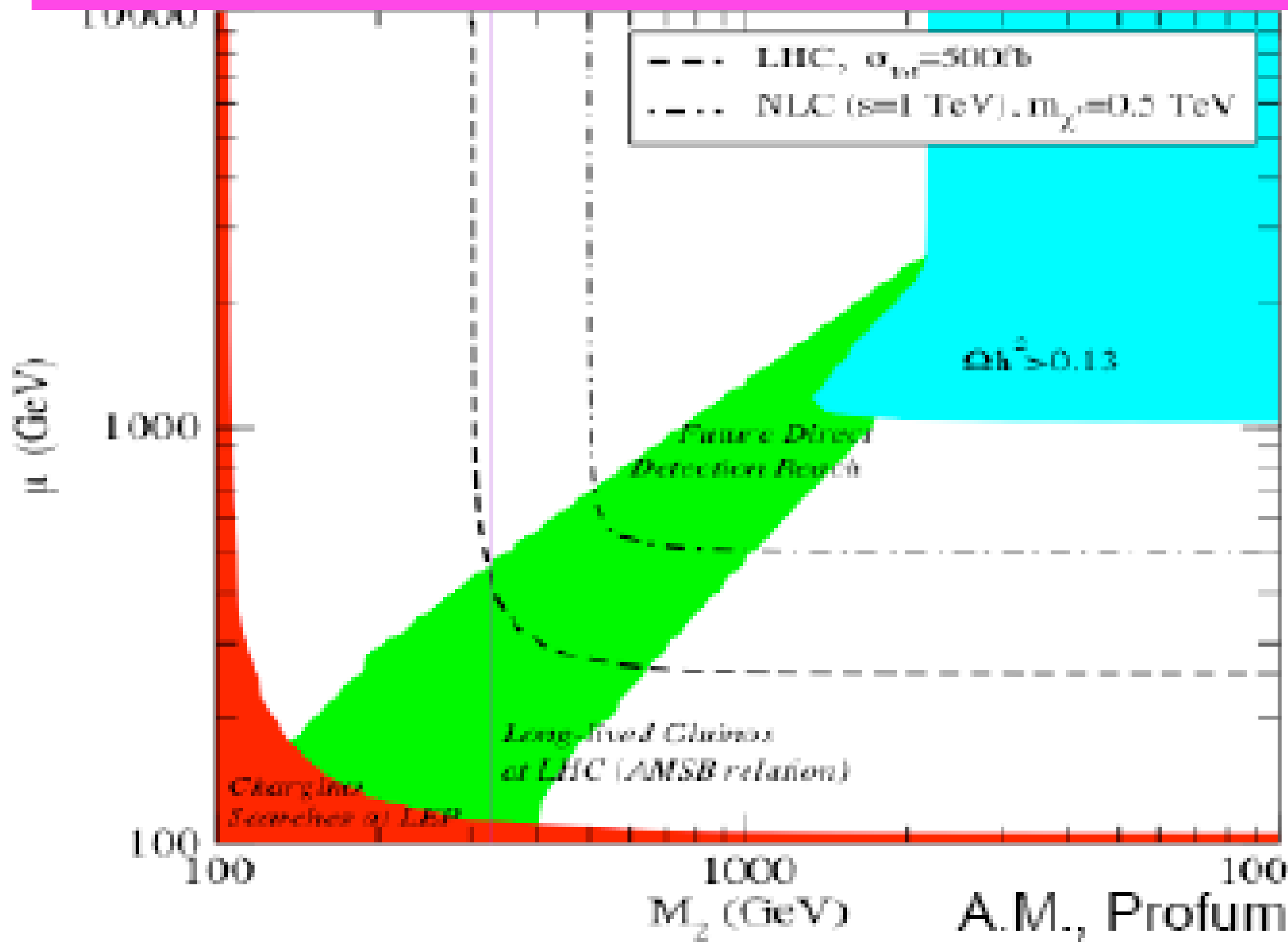


CERDENO
WONDER10



L. Roszwkowski

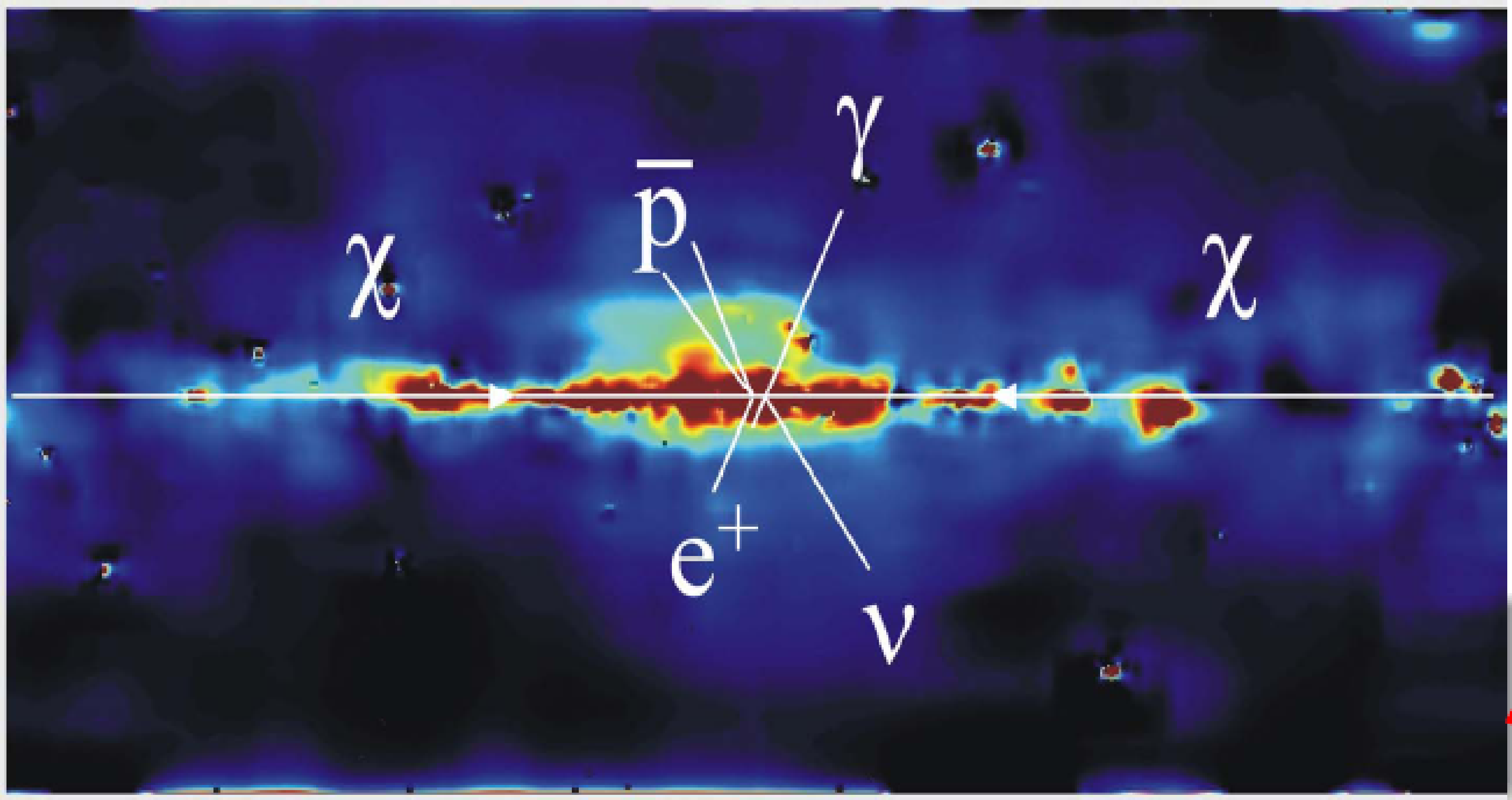
LHC, ILC, DM SEARCHES SENSITIVITIES



A.M., Profumo, Ullio

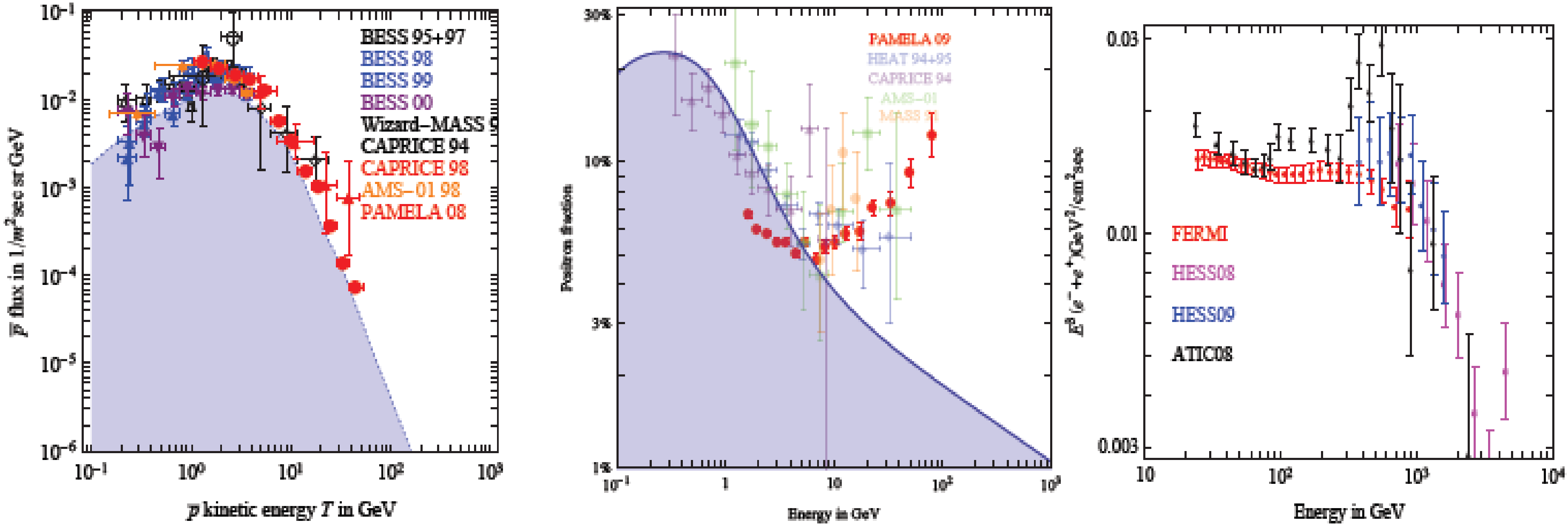
DM INDIRECT DETECTION

- WIMP-WIMP annihilation in the galactic halos may be detected through production of γ, neutrinos, anti-matter.



?

PAMELA, FERMI/ATIC, HESS



$\bar{p}$: consistent with bck

e^+/e^-: excess

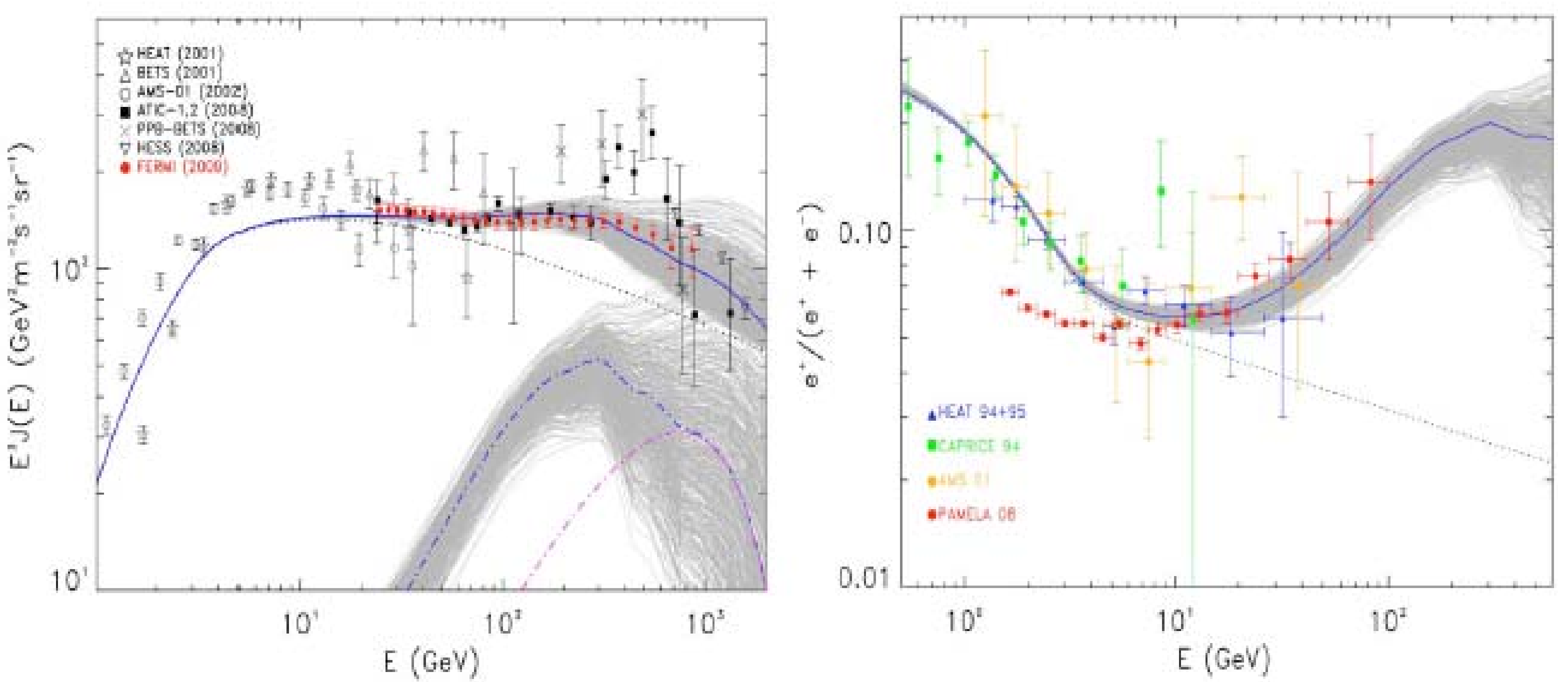
$e^- + e^+$: feature?

Strumia

EPS09

PAMELA excess: October 2008, stimulated enormous theoretical activity; note: statistical errors only! Fermi: feature observed by ATIC not confirmed

Pulsars: Fermi & PAMELA

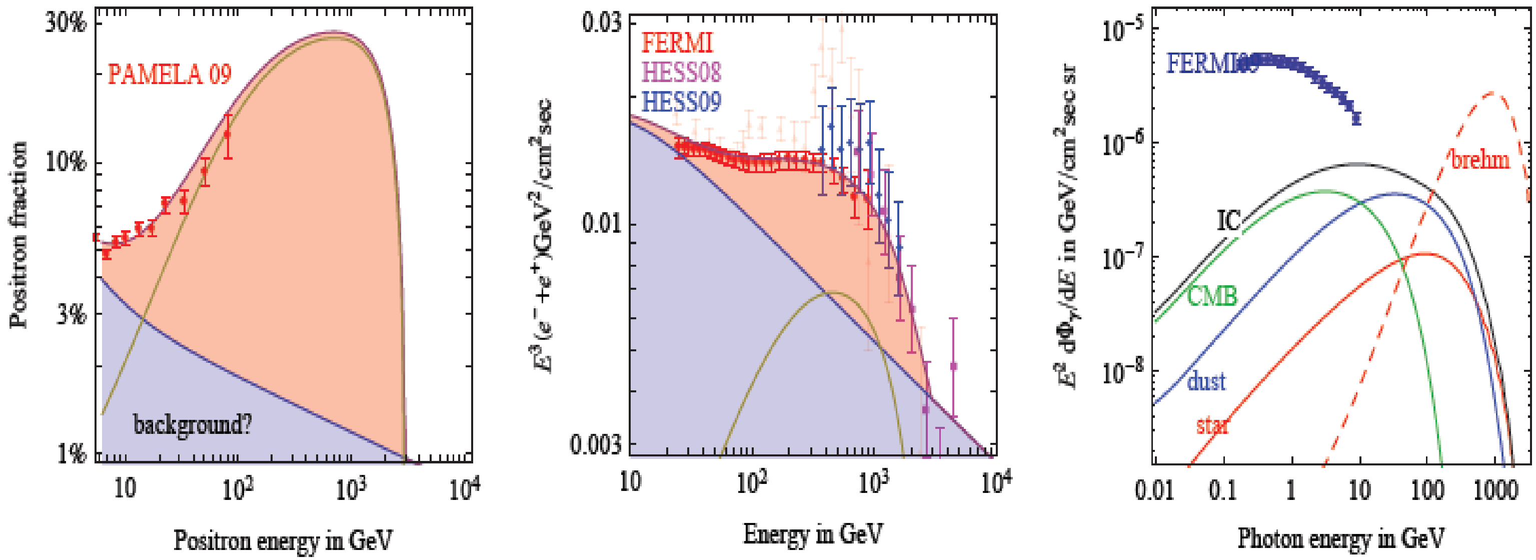


pulsar parameters "randomly" varied!

Grasso et al

Standard Dark Matter best fit

DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.9 \times 10^{-22}$ cm^3/s



(Inverse Compton depends only on the $e^{\pm}$ spectrum)

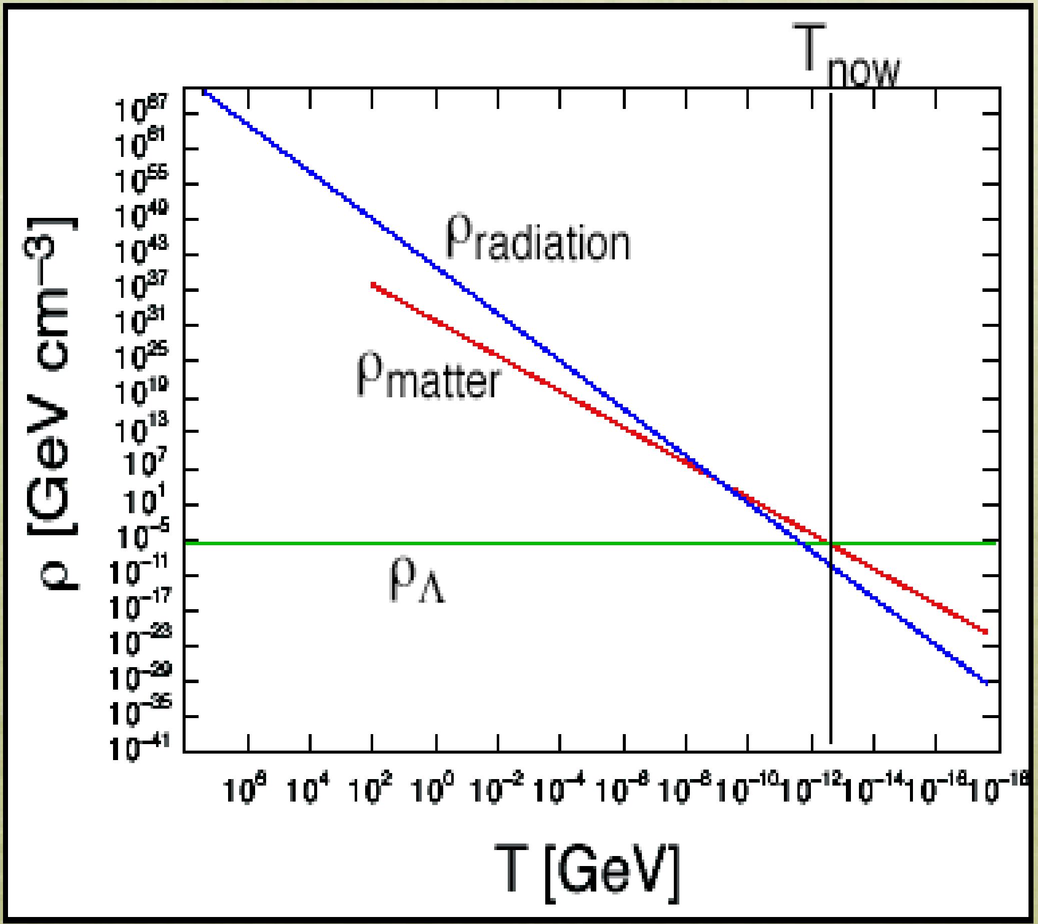
Strumia

EPS09

Watch boost factor! DM particles too heavy for SUSY to be relevant for LHC

THE "WHY NOW" PROBLEM

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- Actually a triple coincidence problem including the radiation
- If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural



Arkani-Hamed, Hall, Kolda, HM

DM DE

DO THEY "KNOW" EACH OTHER?

- DIRECT INTERACTION ϕ (quintessence) WITH DARK MATTER

DANGER:
ϕ Very LIGHT
$m\phi \sim H_0^{-1} \sim 10^{-33}$ eV

→ Threat of violation of the equivalence principle constancy of the fundamental "constants",…

- **INFLUENCE OF ϕ ON THE NATURE AND THE ABUNDANCE OF CDM**

Modifications of the standard picture of WIMPs FREEZE - OUT

CDM CANDIDATES

CATENA, FORNENGO, A.M., PIETRONI, SCHELKE

ELW. SYMM. BREAKING STABILIZATION VS. FLAVOR PROTECTION: THE SCALE TENSION

$$M(B_d\text{-}\bar{B}_d) \sim c_{SM}\frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{new}\frac{1}{\Lambda^2}$$

If $c_{new} \sim c_{SM} \sim 1$

Isidori

$\Lambda > 10^4$ TeV for $O^{(6)} \sim (\bar{s}\,d)^2$

[K^0-$\bar{K}^0$ mixing]

$\Lambda > 10^3$ TeV for $O^{(6)} \sim (\bar{b}\,d)^2$

[B^0-$\bar{B}^0$ mixing]

UV SM COMPLETION TO STABILIZE THE ELW. SYMM. BREAKING: $\Lambda_{UV} \sim O(1\text{ TeV})$

FLAVOR BLINDNESS OF THE NP AT THE ELW. SCALE?

- **THREE DECADES OF FLAVOR TESTS** (Redundant determination of the UT triangle $\longrightarrow$ verification of the SM, theoretically and experimentally "high precision" FCNC tests, ex. $b \to s + \gamma$, CP violating flavor conserving and flavor changing tests, lepton flavor violating (LFV) processes, …) clearly state that:
- A) in the **HADRONIC SECTOR** the **CKM flavor pattern of the SM represents the main bulk of the flavor structure and of (flavor violating) CP violation;**
- B) in the **LEPTONIC SECTOR**: although neutrino flavors exhibit large admixtures, LFV, i.e. non – conservation of individual lepton flavor numbers in FCNC transitions among charged leptons, is extremely small: once again the SM is right (to first approximation) predicting negligibly small LFV

SuperB vs. LHC Sensitivity Reach in testing Λ_{SUSY}

	superB	general MSSM	high-scale MFV
$\vert(\delta^d_{13})_{LL}\vert$ $(LL \gg RR)$	$1.8 \cdot 10^{-2} \frac{m_{\tilde{q}}}{(350\mathrm{GeV})}$	1	$\sim 10^{-3} \frac{(350\mathrm{GeV})^2}{m_{\tilde{q}}^2}$
$\vert(\delta^d_{13})_{LL}\vert$ $(LL \sim RR)$	$1.3 \cdot 10^{-3} \frac{m_{\tilde{q}}}{(350\mathrm{GeV})}$	1	–
$\vert(\delta^d_{13})_{LR}\vert$	$3.3 \cdot 10^{-3} \frac{m_{\tilde{q}}}{(350\mathrm{GeV})}$	$\sim 10^{-1} \tan\beta \frac{(350\mathrm{GeV})}{m_{\tilde{q}}}$	$\sim 10^{-4} \tan\beta \frac{(350\mathrm{GeV})^3}{m_{\tilde{q}}^3}$
$\vert(\delta^d_{23})_{LR}\vert$	$1.0 \cdot 10^{-3} \frac{m_{\tilde{q}}}{(350\mathrm{GeV})}$	$\sim 10^{-1} \tan\beta \frac{(350\mathrm{GeV})}{m_{\tilde{q}}}$	$\sim 10^{-3} \tan\beta \frac{(350\mathrm{GeV})^3}{m_{\tilde{q}}^3}$

SuperB can probe MFV (with small-moderate tanβ) for TeV squarks; for a generic non-MFV MSSM sensitivity to squark masses > 100 TeV !

Ciuchini, Isidori, Silvestrini

SLOW-DECOUPLING OF NP IN FCNC

V. Lubicz, 2008

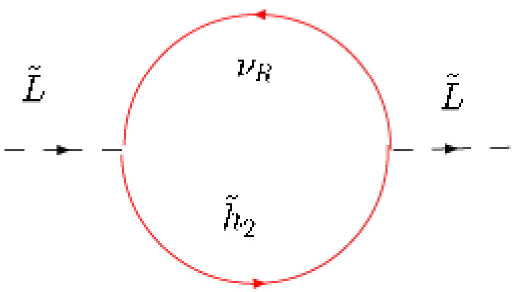
Estimates of error for 2015

Hadronic matrix element	Current lattice error	6 TFlop Year	60 TFlop Year [2011 LHCb]	1-10 PFlop Year [2015 SuperB
$f_{+}^{K\pi}(0)$	0.9% (22% on $1\text{-}f_+$)	0.7% (17% on $1\text{-}f_+$)	0.4% (10% on $1\text{-}f_+$)	**< 0.1% (2.4% on $1\text{-}f_+$)**
$\hat{B}_K$	11%	5%	3%	**1%**
f_B	14%	3.5 - 4.5%	2.5 - 4.0%	**1 – 1.5%**
$f_{Bs}B_{Bs}^{1/2}$	13%	4 - 5%	3 - 4%	**1 – 1.5%**
ξ	5% (26% on ξ-1)	3% (18% on ξ-1)	1.5 - 2 % (9-12% on ξ-1)	**0.5 – 0.8 % (3-4% on ξ-1)**
$\mathcal{F}_{B\to D/D^*l\nu}$	4% (40% on $1\text{-}\mathcal{F}$)	2% (21% on $1\text{-}\mathcal{F}$)	1.2% (13% on $1\text{-}\mathcal{F}$)	**0.5% (5% on $1\text{-}\mathcal{F}$)**
$f_{+}^{B\pi},\ldots$	11%	5.5 - 6.5%	4 - 5%	**2 – 3%**
$T_1^{B\to K^*/\rho}$	13%	----	----	**3 – 4%**

SUSY SEESAW: *Flavor universal SUSY breaking and yet large lepton flavor violation*

Borzumati, A. M. 1986 (after discussions with W. Marciano and A. Sanda)

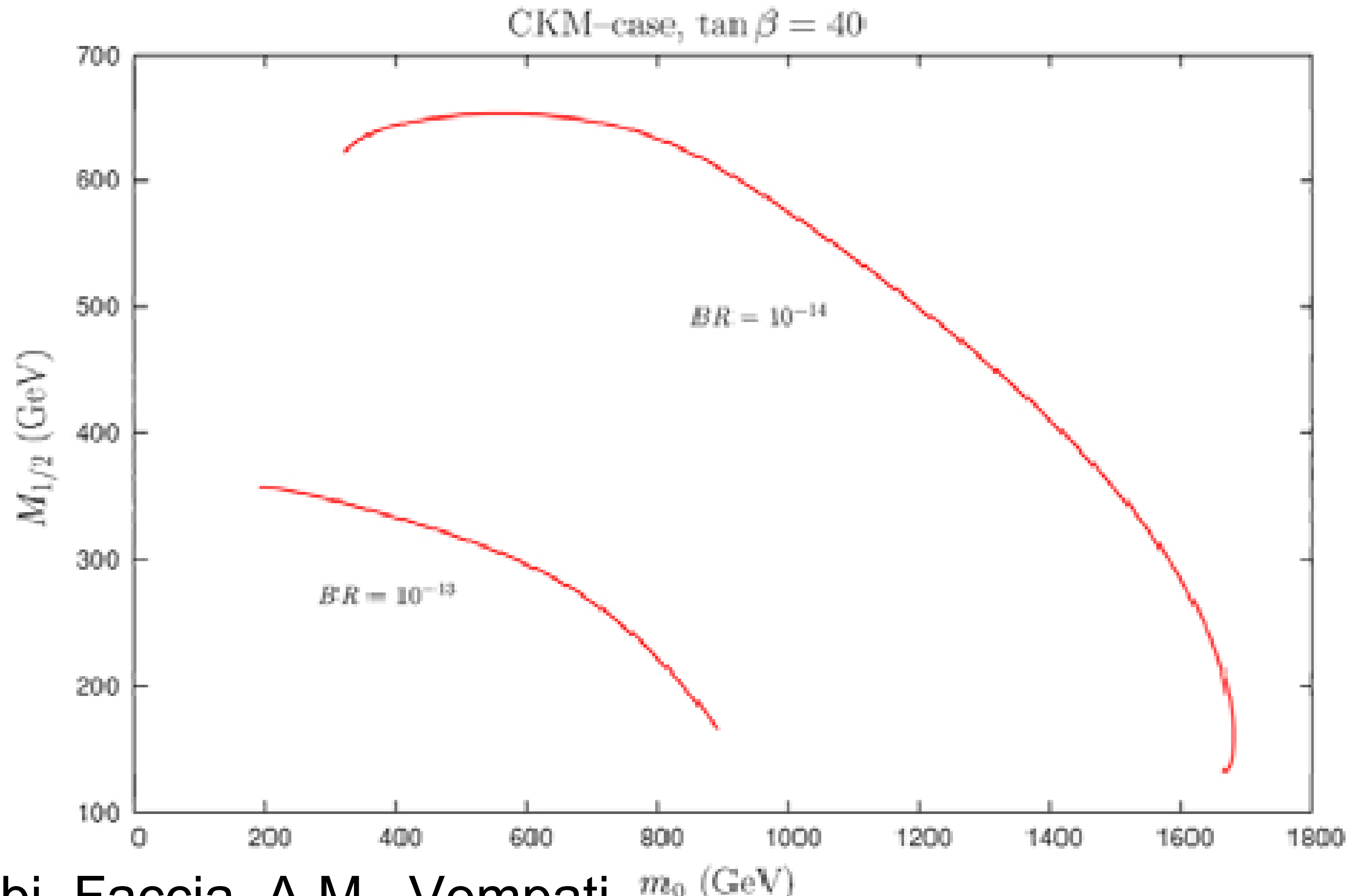
$$L = f_l \, \bar{e}_R L h_1 + f_\nu \, \bar{\nu}_R L h_2 + M \, \nu_R \nu_R$$



$$\left(m^2_{\tilde{L}}\right)_{ij} \sim \frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(f_\nu^\dagger f_\nu\right)_{ij} \log\frac{M}{M_G}$$

Non-diagonality of the slepton mass matrix in the basis of diagonal lepton mass matrix depends on the unitary matrix U which diagonalizes $(f_\nu^+ f_\nu)$

MEG POTENTIALITIES TO EXPLORE THE SUSY SEESAW PARAM. SPACE

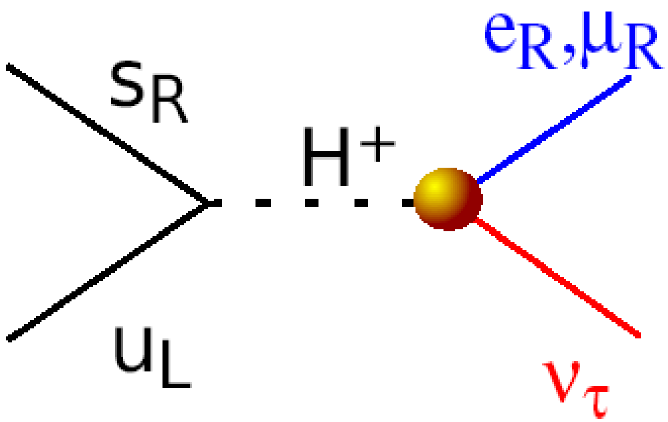


Calibbi, Faccia, A.M., Vempati

DEVIATION from μ - e UNIVERSALITY

A.M., Paradisi, Petronzio

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}\ , \quad i = e, \mu, \tau$$



$$eH^{\pm}\nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500 \mathrm{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\ SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

Exp: now at **0.7%** accuracy (NA62), **0.3%** will be reached when all NA62 data are analyzed

TEVATRON → LHC → I L C

DM - FLAVOR

for DISCOVERY

and/or FUND. TH.

RECONSTRUCTION

NEW PHYSICS AT THE ELW SCALE

A MAJOR LEAP AHEAD IS NEEDED

DARK MATTER

$m_\chi\ n_\chi\ \sigma_\chi \ldots$

DARK ENERGY

LINKED TO COSMOLOGICAL EVOLUTION

LEPTOGENESIS

GW **INFLATION**

"LOW ENERGY"

PRECISION PHYSICS

FCNC, CP ≠, (g-2), $(\beta\beta)_{0\nu\nu}$

LFV, CPV B PHYSICS

NEUTRINO PHYSICS

3 QUESTIONS

- Are we sure that there is new physics (NP) at the TeV scale? YES (barring an antropic approach)

- If yes, are we sure that LHC will see something "new", i.e. beyond the SM with its "standard higgs boson"? YES

- If there is new physics at the TeV scale, what can flavor and DM physics tell to LHC and viceversa? (or, putting it in a less politically correct fashion: if LHC starts seeing some new physics signals, are flavor and DM physics still a valuable road to NP, or are they definitely missing that train? NO, actually to catch the "right train" it is highly desirable, though maybe strictly not necessary, to make use of all the three roads at the same time

G. Martinelli