

II LECTURE AT THE ISAPP07:  
GOING BEYOND THE  
STANDARD MODEL THROUGH  
THE ASTROPARTICLE ROAD

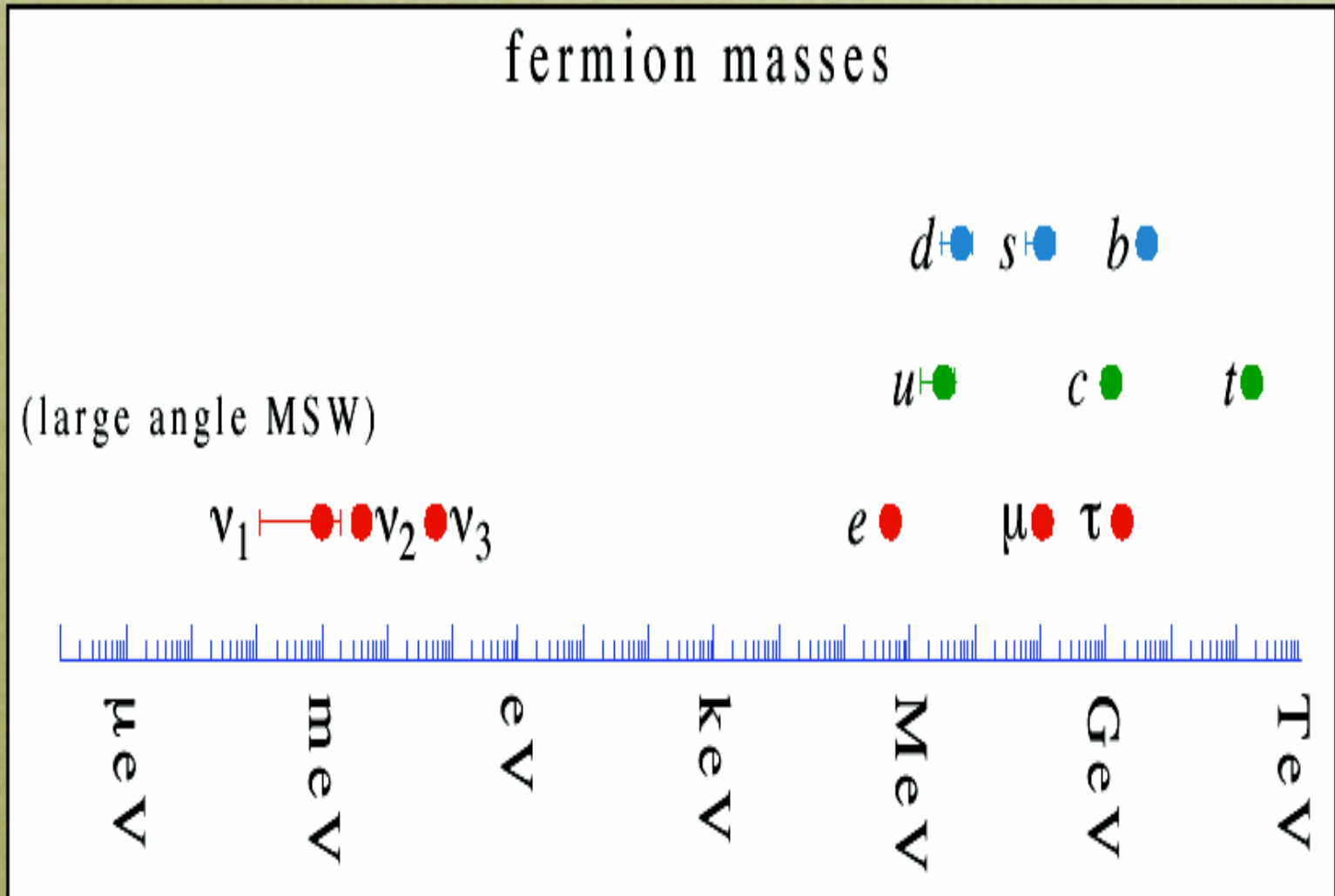
Antonio Masiero

Univ. of Padova and INFN, Padova

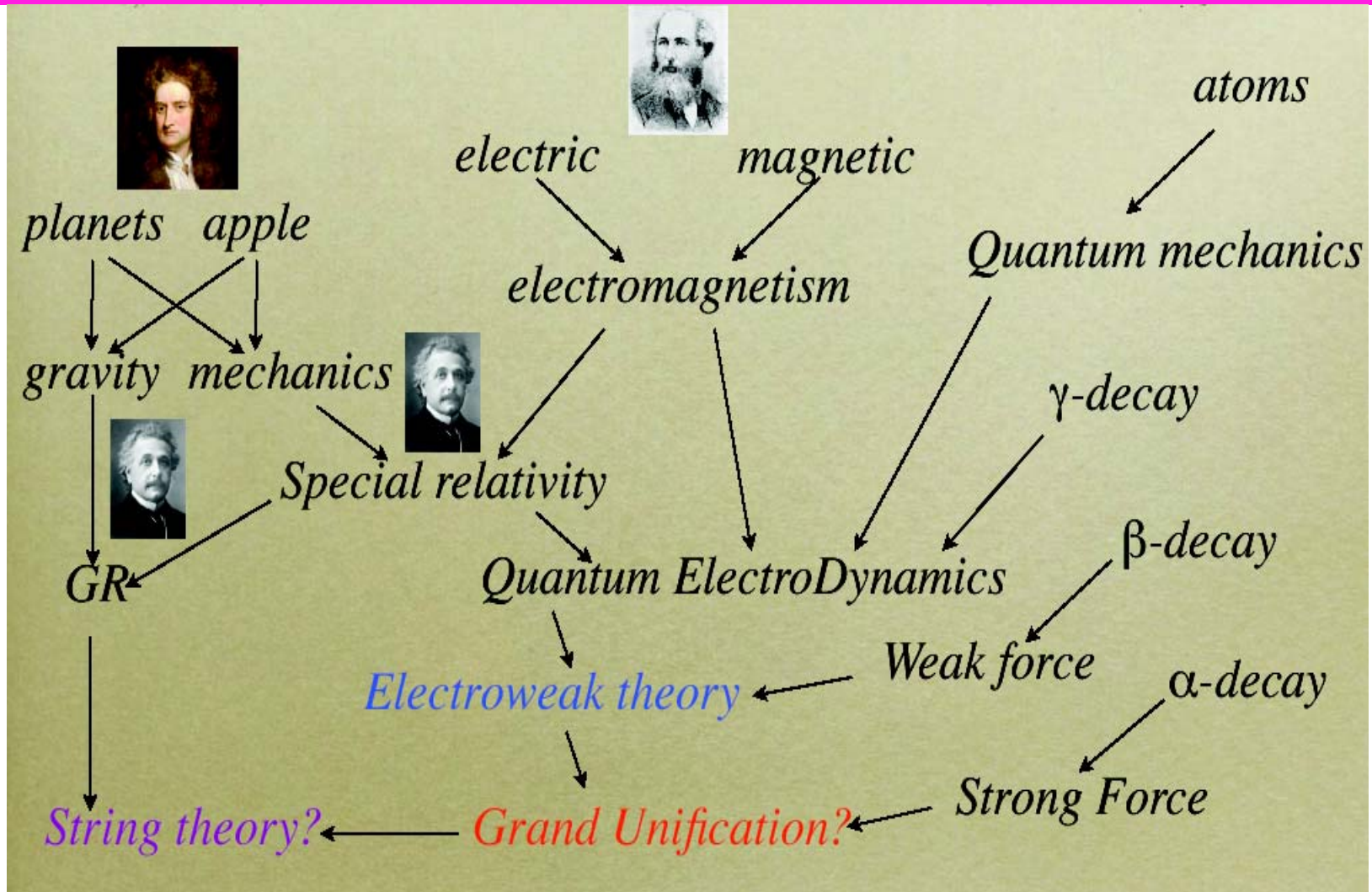
# FIGURE OF MERIT OF THE SM

- **POSITIVE ASPECTS:**
- Renormalizable Spont. Broken Gauge Th.
- Excellent agreement with ALL exps.
- Automatic conservation of Baryon (B) and Lepton (L) quantum numbers
  
- **NEGATIVE ASPECTS:**
- Complete lack of prediction of Fermion masses and mixings, even of the number of fermion generations (**FLAVOR PROBLEM**)
  
- The SM does not “truly” unify fundamental interactions: still three gauge coupling constants to describe the 3 strong, weak and elm. Interactions, not to speak of gravity which is just ignored by the SM (**UNIFICATION PROBLEM**)
  
- **GAUGE HIERARCHY PROBLEM;**
- i) how come that the elm, energy scale is 17 orders of magnitude smaller than the Planck scale? No dynamical reason for that within the SM (“fundamental” aspect of the gauge hierarchy problem);
- li) even if we fix the tree level values of the higgs sector to ensure that the Higgs mass corresponds to the correct elm. scale ( i.e., it is of  $O(100-1000 \text{ GeV})$ , radiative corrections are going to push the mass of the Higgs to the highest available scale present in the theory ( indeed, there exists no symmetry protection for scalar masses differently to what happens for fermion and gauge boson masses) (“technical aspect of the gauge hierarchy problem)

# THE FERMION MASS PUZZLE



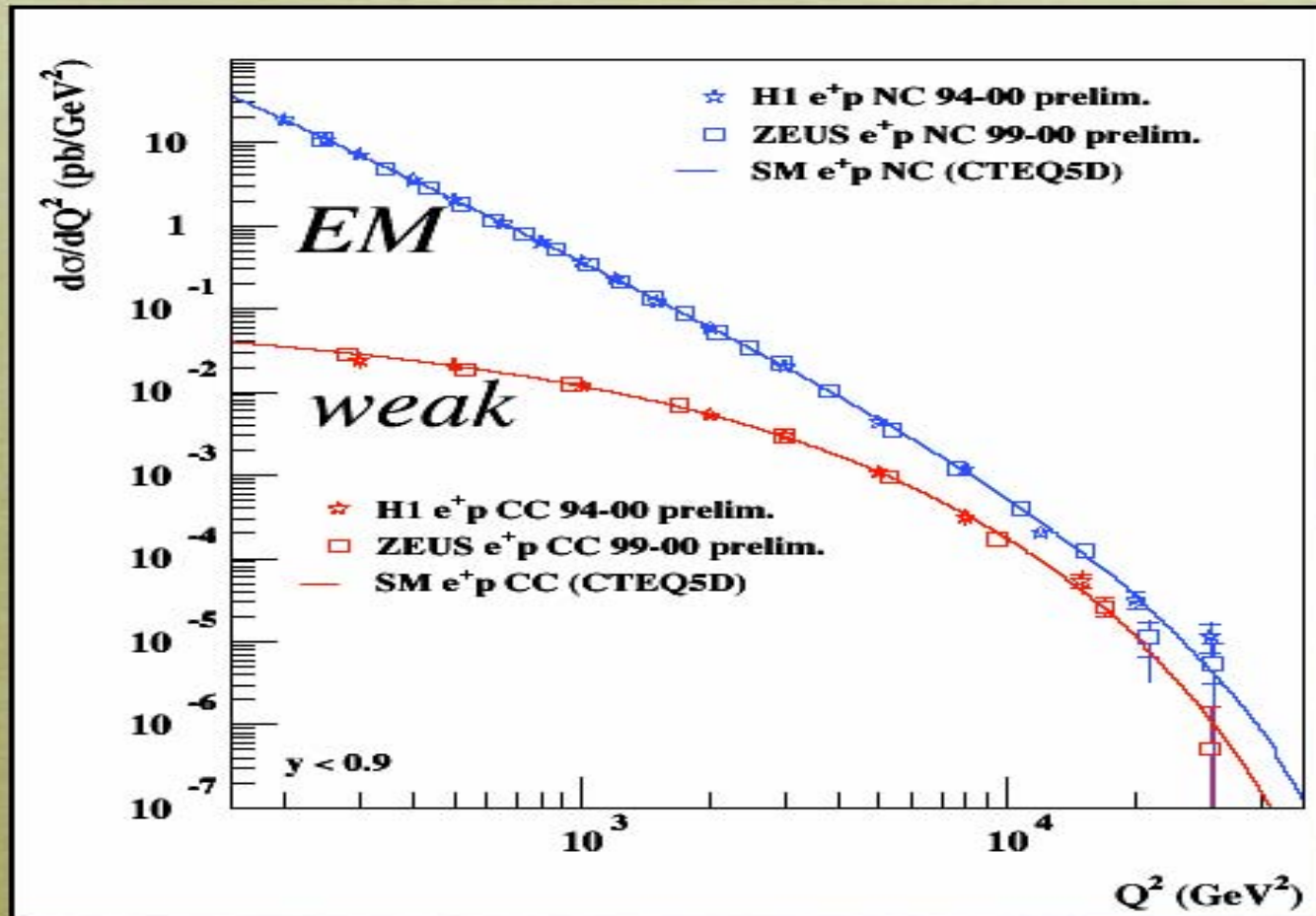
# UNIFICATION of FUNDAMENTAL INTERACTIONS



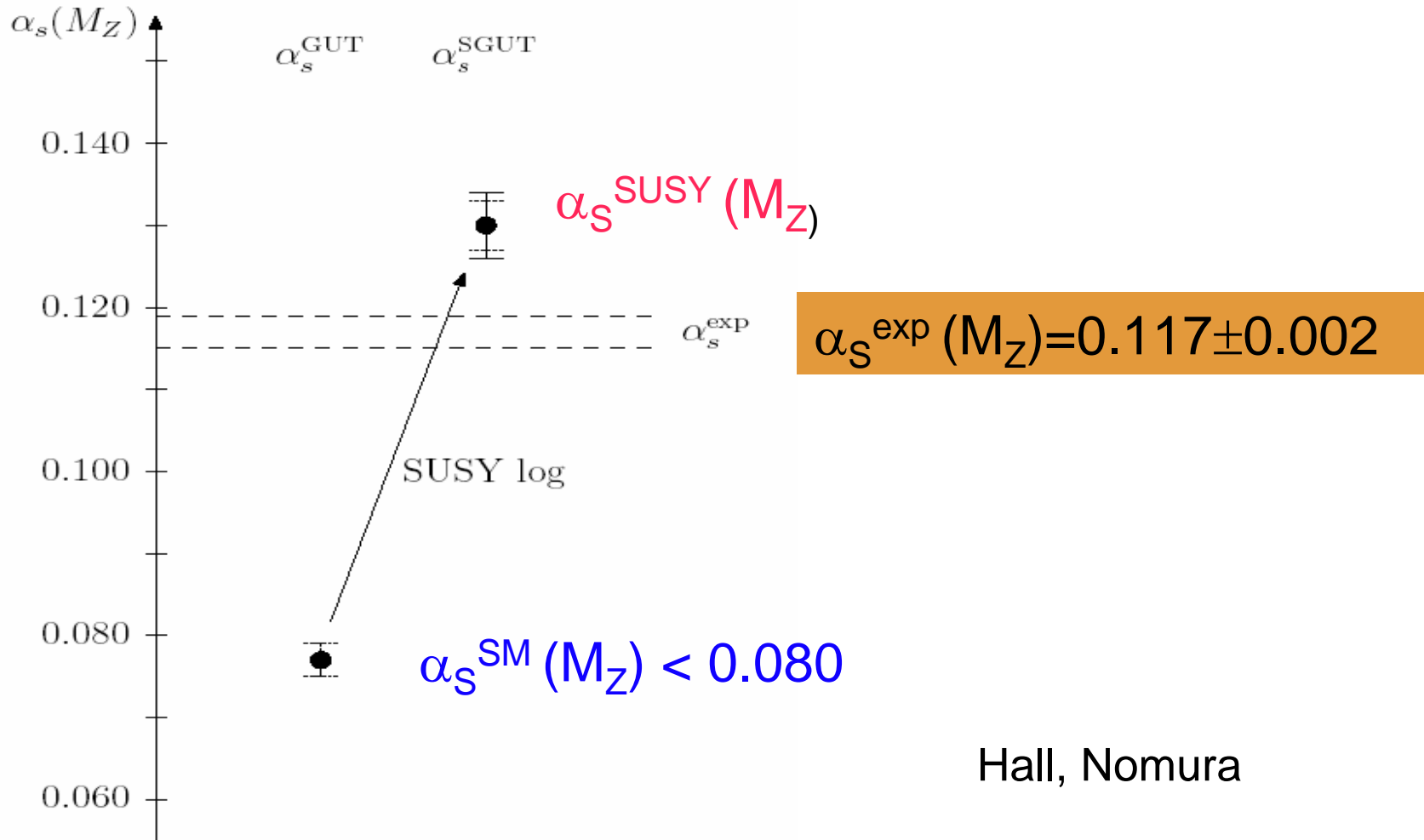
Courtesy of H. Murayama

# Fundamental COUPLING CONSTANTS are NOT CONSTANT

*HERA ep collider*



# Fundamental interactions unify



# “MASS PROTECTION”

For FERMIONS, VECTOR (GAUGE) and SCALAR BOSONS

SIMMETRY  
PROTECTION

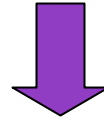
-FERMIONS → chiral symmetry

$f_L f_R$  not invariant  
under  $SU(2) \times U(1)$

-VECTOR BOSONS → gauge symmetry

→ FERMIONS and W,Z VECTOR BOSONS can get a mass only when the elw. symmetry is broken  $m_f, m_w \leq \langle H \rangle$

NO SYMMETRY PROTECTION FOR SCALAR MASSES



“INDUCED MASS PROTECTION”

→ Create a symmetry (SUPERSIMMETRY)

Such that FERMIONS ↔ BOSONS

So that the fermion mass “protection” acts also on bosons as long as SUSY is exact

→ SUSY BREAKING ~ SCALE OF 0 ( $10^2$ - $10^3$  Gev)

→ LOW ENERGY SUSY

UV COMPLETION OF THE SM AND THE ORIGIN  
OF THE ELW. SYMMETRY BREAKING

DYNAMICS RESPONSIBLE FOR  
ELW. SYMMETRY BREAKING



WEAKLY COUPLED

LIGHT HIGGS

Favored by  
LEP1

STRONGLY COUPLED

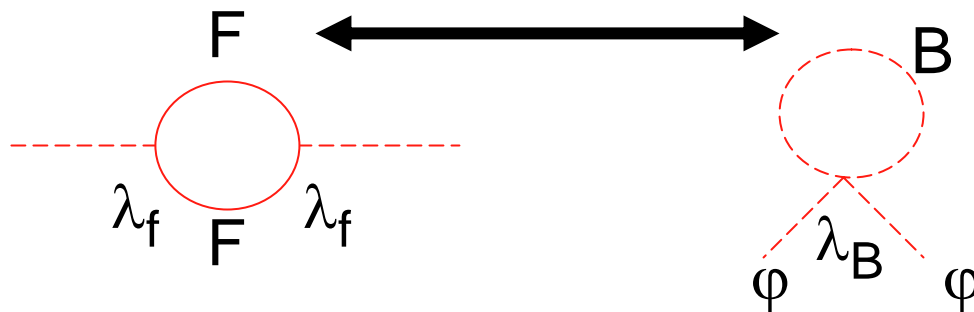
NEW QCD SCALED  
AT 1 TEV

Disfavored by LEP1

# HIERARCHY PROBLEM: THE SUSY WAY

SUSY HAS TO BE BROKEN AT A SCALE CLOSE TO 1TeV  $\longrightarrow$  **LOW ENERGY SUSY**

$m_\phi^2 \propto \Lambda^2$   $\longrightarrow$  Scale of susy breaking



$$8m_\phi^2 \sim \frac{(\lambda_B - \lambda_f^2) \Lambda^2}{16 \pi^2}$$

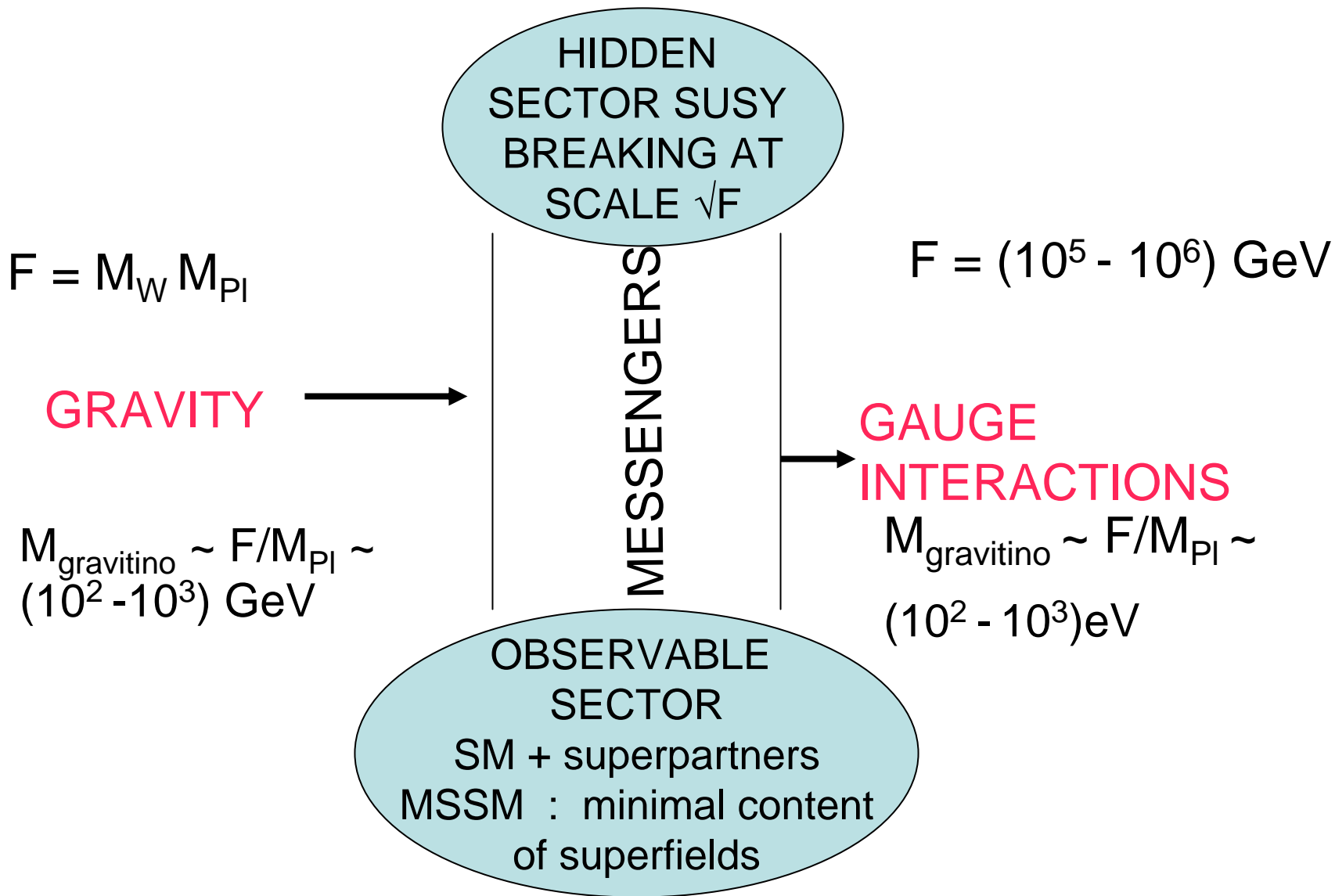
$$\longrightarrow [m_B^2 - m_F^2]^{1/2} \sim 1/\sqrt{G_F}$$

$\left[ \begin{array}{c} B \\ F \end{array} \right]$

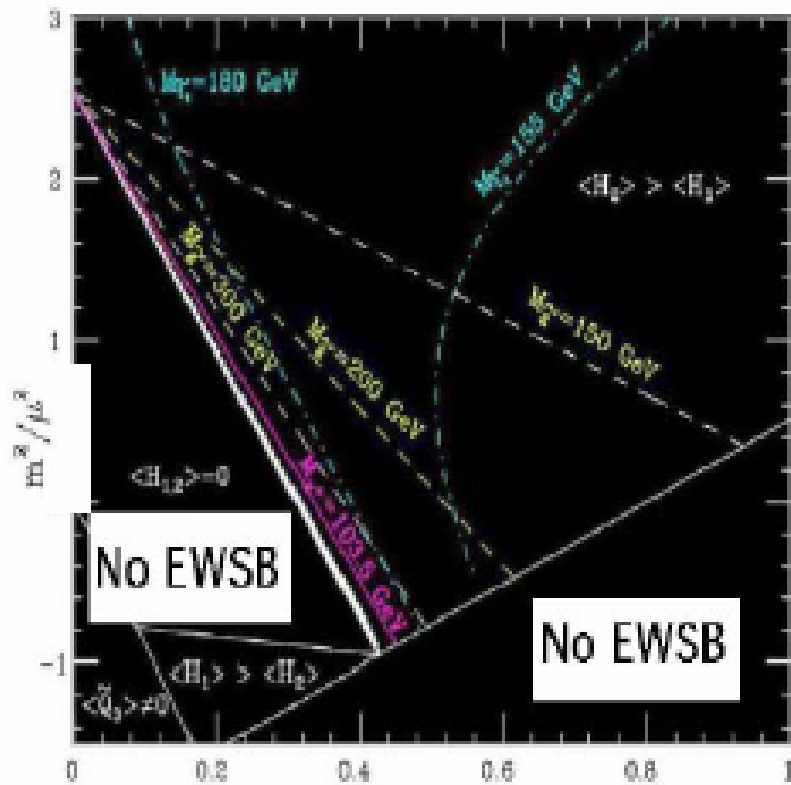
In SUSY multiplet

**SPLITTING IN MASS BETWEEN B and F of O ( ELW. SCALE)**

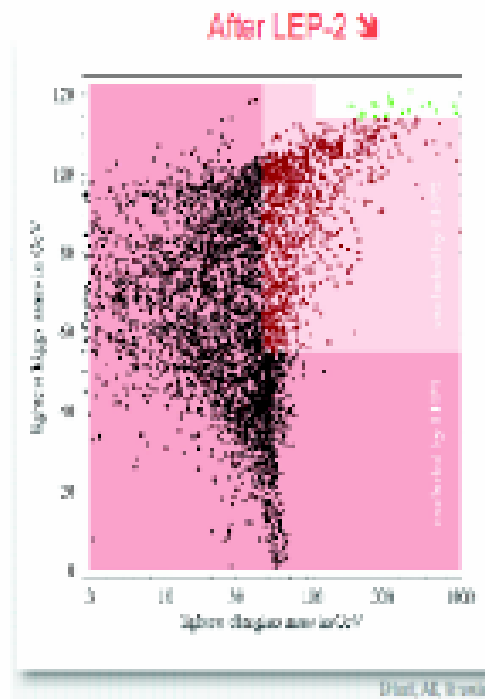
# WHICH SUSY



# THE LOW-ENERGY SUSY TENSION between the UV COMPLETION SCALE and the POST-LEP SUSY EXCLUSIONS



lightest  
Higgs  
mass  
(GeV)



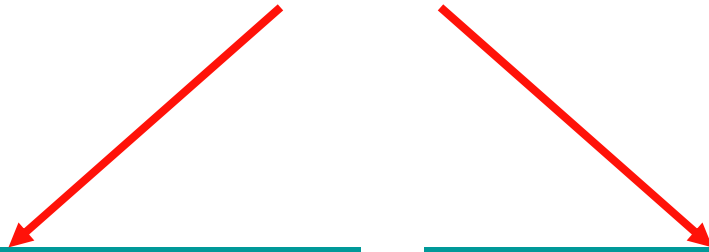
lightest chargino mass (GeV)

Giudice, Rattazzi

$M^2/\mu^2$

Zwirner

# WHY TO GO BEYOND THE SM



## “OBSERVATIONAL” REASONS

### •HIGH ENERGY PHYSICS

**NO** (but  $A_{FB}^{Z \rightarrow b\bar{b}}$ .....)

### •FCNC, $CP \neq$

**NO** (but  $b \rightarrow s\bar{q}q$  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,  $\Delta B_{\text{cosm}}$ , INFLAT., DE)

## THEORETICAL REASONS

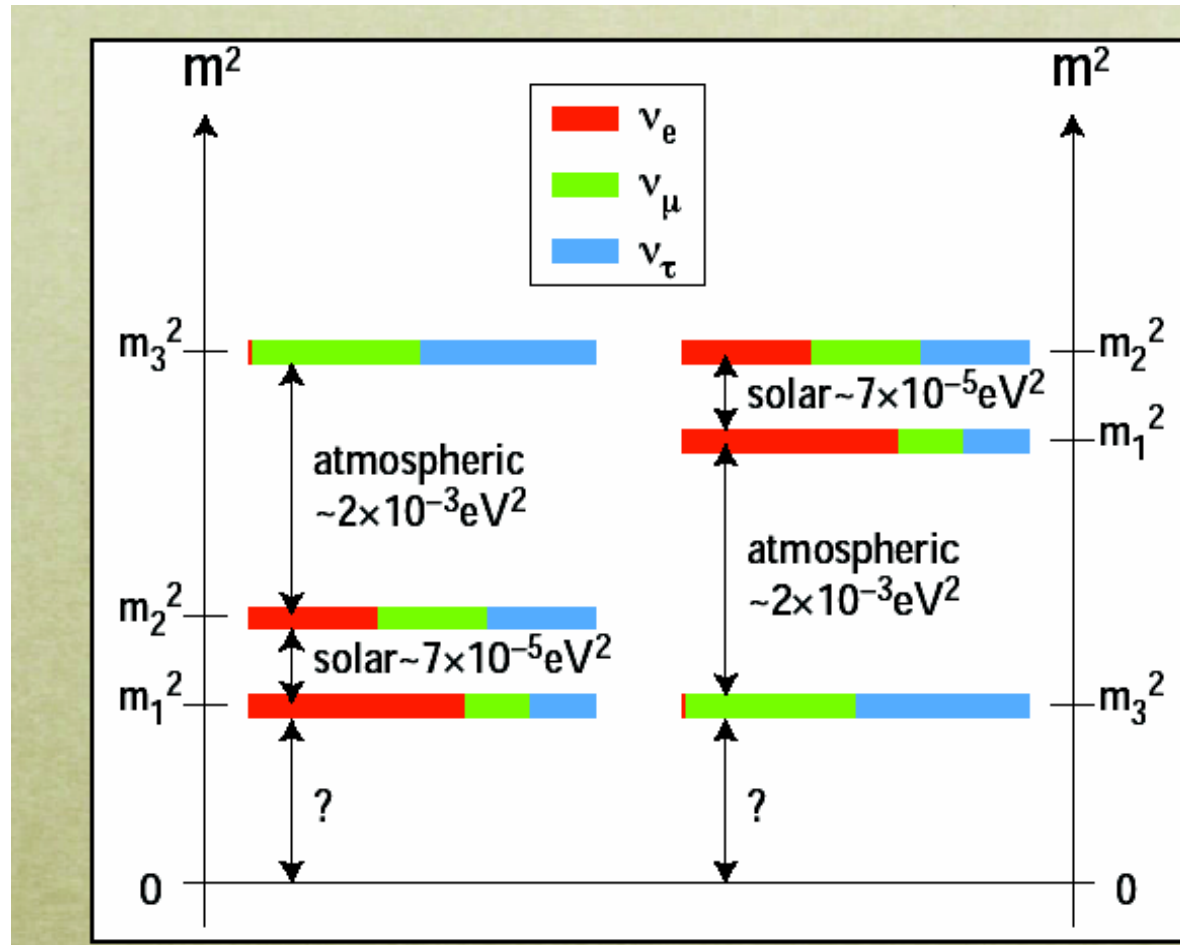
### •INTRINSIC INCONSISTENCY OF SM AS QFT

**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)

# Neutrinos are MASSIVE: New Physics IS there!



# THE FATE OF LEPTON NUMBER

L VIOLATED

L CONSERVED

$\nu$  Majorana ferm.

$\nu$  Dirac ferm.  
(dull option)

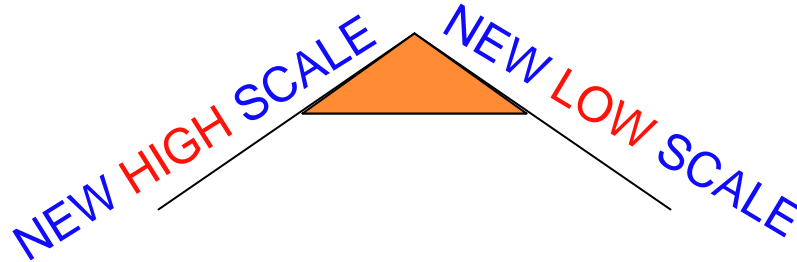
SMALLNESS of  $m_\nu$

$$h \bar{\nu}_L H \nu_R \rightarrow m_\nu = h \langle H \rangle$$

$$M_\nu < 5 \text{ eV} \rightarrow \hbar < 10^{-11}$$

EXTRA-DIM.  $\nu_R$  in the bulk: small overlap?

PRESENCE OF A NEW PHYSICAL MASS SCALE



SEE - SAW MECHAN.

MAJORON MODELS

Minkowski; Gell-Mann,  
Ramond, Slansky,  
Vanagida

Gelmini, Roncadelli

$\nu_R$  ENLARGEMENT OF THE  
FERMIONIC SPECTRUM

$\Delta$  ENLARGEMENT OF THE  
HIGGS SCALAR SECTOR

$$M \nu_R \nu_R + h \bar{\nu}_L \phi^- \bar{\nu}_R$$

$$h \bar{\nu}_L \nu_L \Delta$$

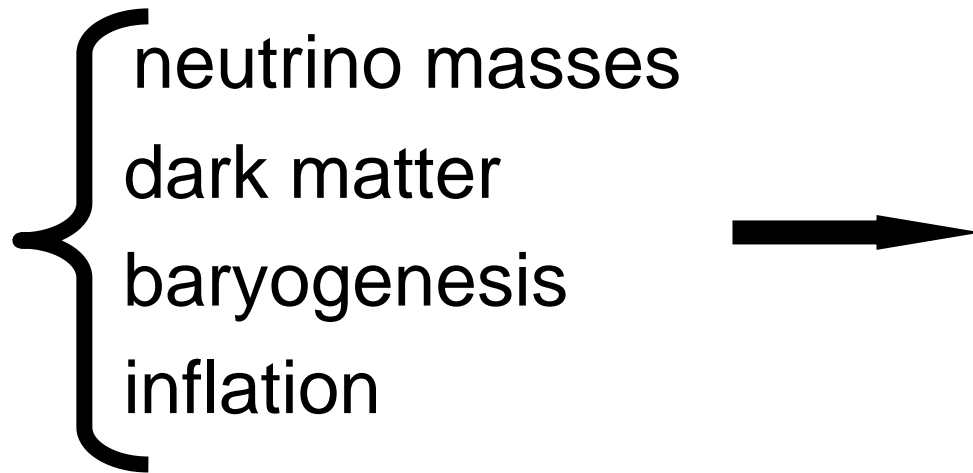
$$m_\nu = h \langle \Delta \rangle$$

$$\begin{array}{ccc} \nu_L & \sim \bar{O} & \nu_R \\ \nu_R & h \langle \Phi \rangle & M \end{array}$$

LR  
Models?

N.B.: EXCLUDED BY LEP!

# The Energy Scale from the “Observational” New Physics



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

# MICRO

## PARTICLE PHYSICS

### GWS STANDARD MODEL

# MACRO

## COSMOLOGY

### HOT BIG BANG STANDARD MODEL

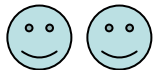


HAPPY MARRIAGE  
Ex: NUCLEOSYNTHESIS

BUT ALSO



POINTS OF  
FRICTION



- COSMIC MATTER-ANTIMATTER ASYMMETRY
- INFLATION
- DARK MATTER + DARK ENERGY

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

# THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:

-why only baryons

-why  $N_{\text{baryons}}/N_{\text{photon}} \sim 10^{-10}$

- NO EVIDENCE OF ANTIMATTER WITHIN THE SOLAR SYSTEM
- ANTIPROTONS IN COSMIC RAYS: IN AGREEMENT WITH PRODUCTION AS SECONDARIES IN COLLISIONS
- IF IN CLUSTER OF GALAXIES WE HAD AN ADMIXTURE OF GALAXIES MADE OF MATTER AND ANTIMATTER  $\longrightarrow$  THE PHOTON FLUX PRODUCED BY MATTER-ANTIMATTER ANNIHILATION IN THE CLUSTER WOULD EXCEED THE OBSERVED GAMMA FLUX
- IF  $N_{\text{bar.}} = N_{\text{antibar}}$  AND NO SEPARATION WELL BEFORE THEY DECOUPLE WE WOULD BE LEFT WITH  $N_{\text{bar.}}/N_{\text{photon}} \ll 10^{-10}$
- IF BARYONS-ANTIBARYONS ARE SEPARATED EARLIER  $\longrightarrow$  DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE



ONLY MATTER IS PRESENT



HOW TO DYNAMICALLY PRODUCE A BARYON-ANTIBARYON ASYMMETRY STARTING FROM A SYMMETRIC SITUATION

# COSMIC MATTER-ANTIMATTER ASYMMETRY

10,000,000,001

$q$


10,000,000,000

$\bar{q}$

Murayama


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

- SM DOES **NOT** SATISFY AT LEAST TWO OF THE THREE SACHAROV'S NECESSARY CONDITIONS FOR A DYNAMICAL BARYOGENESIS:
- NOT ENOUGH CP VIOLATION IN THE SM  $\longrightarrow$  NEED FOR NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX
- FOR  $M_{\text{HIGGS}} > 80 \text{ GeV}$  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 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 violation; if these decays are accompanied by a new source of CP violation in the leptonic sector, then
-  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

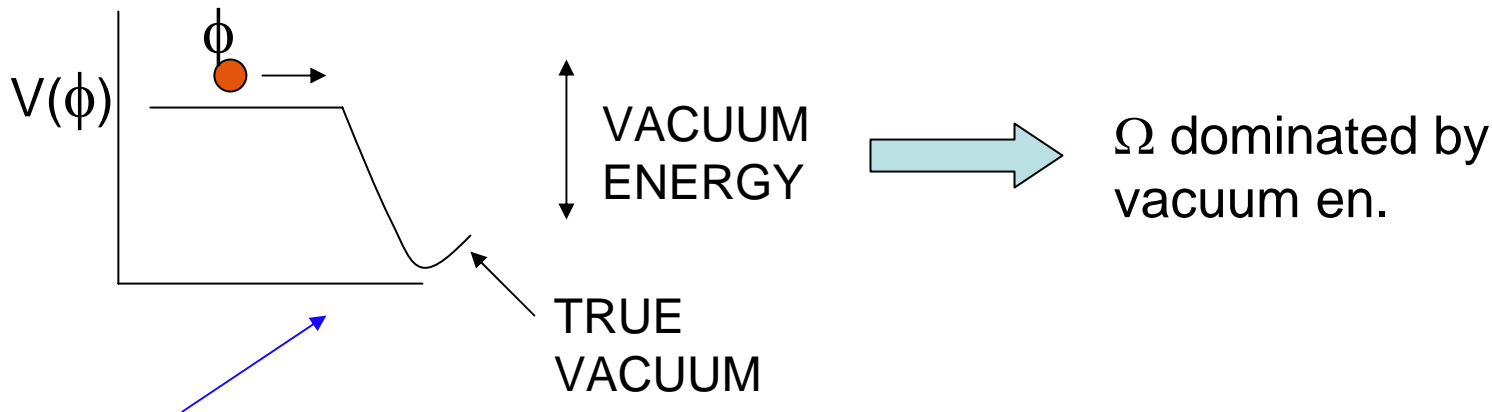
SEVERE  
COSMOLOGICAL  
PROBLEMS



- CAUSALITY  
(isotropy of CMBR)
- FLATNESS  
( $\Omega$  close to 1 today)
- AGE OF THE UNIV.
- PRIMORDIAL MONOPOLES

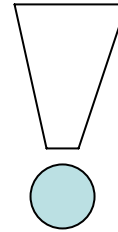
COMMON SOLUTION FOR THESE PROBLEMS

VERY FAST (EXPONENTIAL) EXPANSION IN THE UNIV.



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  $\gg M_w$

DIFFICULT BUT NOT IMPOSSIBLE TO OBTAIN  
ELECTROWEAK INFLATION IN SM EXTENSIONS



The dark components of the Universe as the most pressing cry for NEW PHYSICS BEYOND THE PARTICLE PHYSICS SM



$$\Omega_{\text{DM}} = 23\% \pm 4\% ; \Omega_{\text{B}} = 4\% \pm 0.4\% ; \Omega_{\Lambda} = 73\% \pm 4\%$$

DM: the most impressive evidence at the “quantitative” and “qualitative” levels of

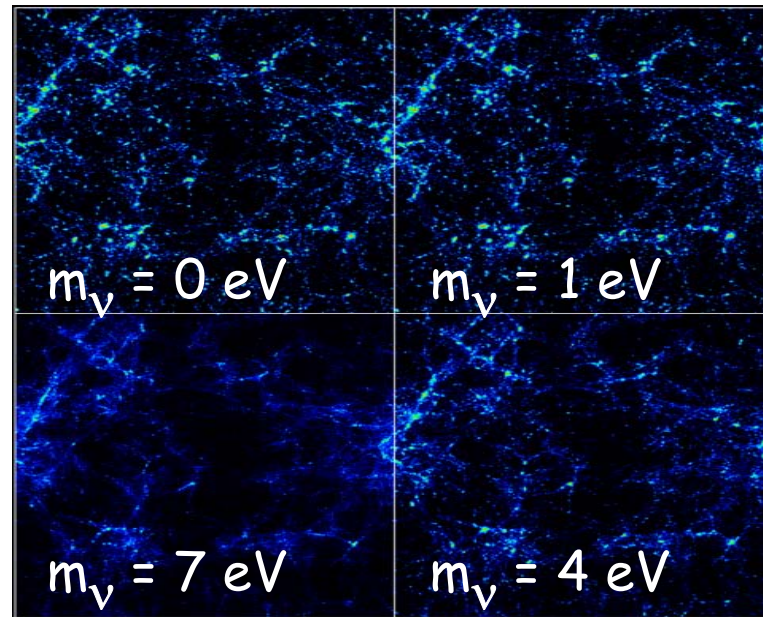
## New Physics beyond SM

- **QUANTITATIVE**: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on  $\Omega_{\text{DM}}$  and  $\Omega_{\text{B}}$   **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 !**

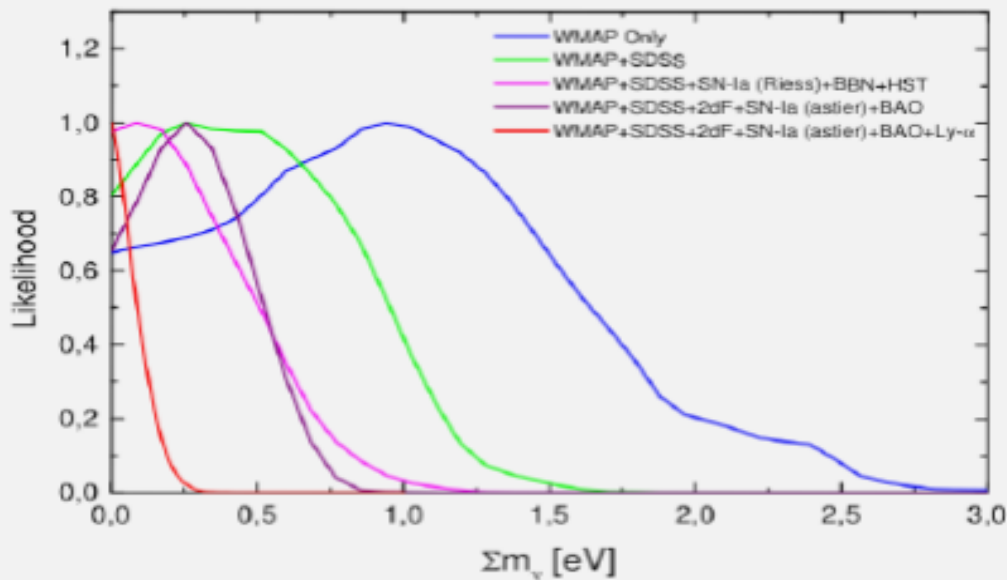
# THE RISE AND FALL OF NEUTRINOS AS DARK MATTER

- 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  $\sim 1$  MeV ; being their mass  $\ll$  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



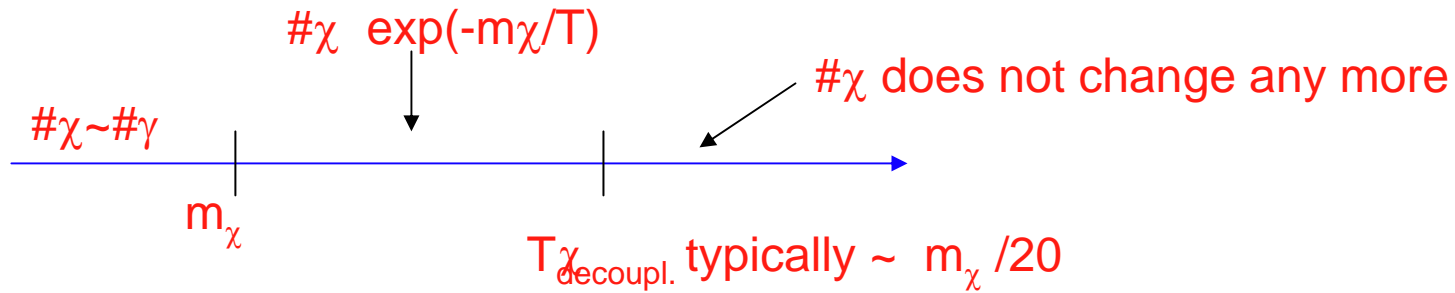
(E.g., Ma 1996)



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

Case	Cosmological data set	$\Sigma$ bound ( $2\sigma$ )
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- $\alpha$	$< 0.21$ eV
7	CMB + LSS + $SN_{Astier}$ + BAO + Ly- $\alpha$	$< 0.17$ eV

# WIMPS (Weakly Interacting Massive Particles)



$\Omega_\chi$  depends on particle physics ( $\sigma_{\text{annih.}}^\chi$ ) and “cosmological” quantities ( $H, T_0, \dots$ )

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\underbrace{\langle (\sigma_{\text{annih.}}) v_\chi \rangle}_{\sim \alpha^2 / M_\chi^2} \text{ TeV}^2}$$

From  $T^0 M_{\text{plae}}^2$

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

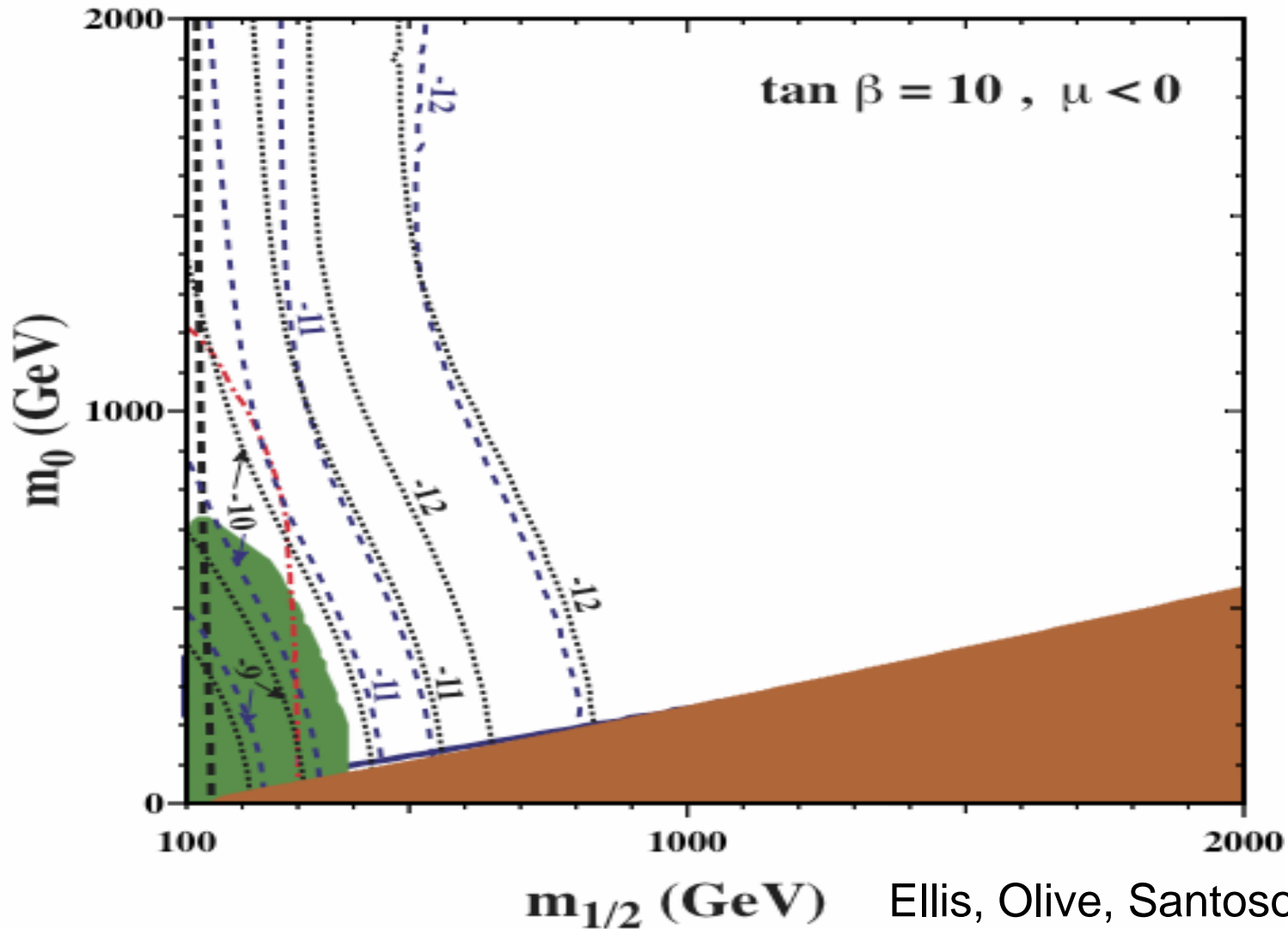
$$m_\chi \sim 10^2 - 10^3 \text{ GeV (weak interaction)} \quad \Omega_\chi h^2 \sim 10^{-2} - 10^{-1} !!!$$

# STABLE ELW. SCALE WIMPs from PARTICLE PHYSICS

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

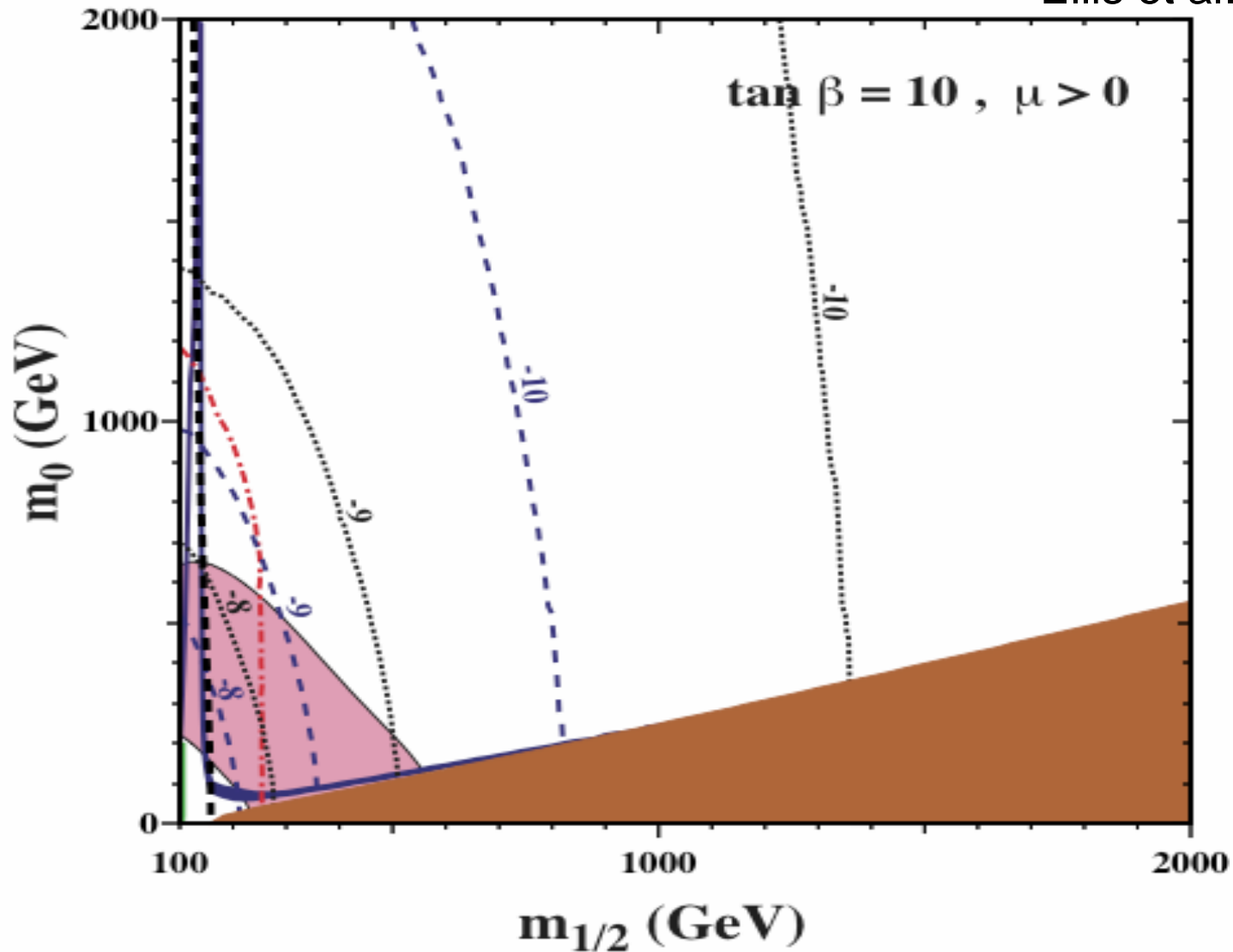
\* But abandoning gaugino-masss unif. → Possible to have  $m_{LSP}$  down to 7 GeV

# Tightness of the DM constraint on minimal supergravity

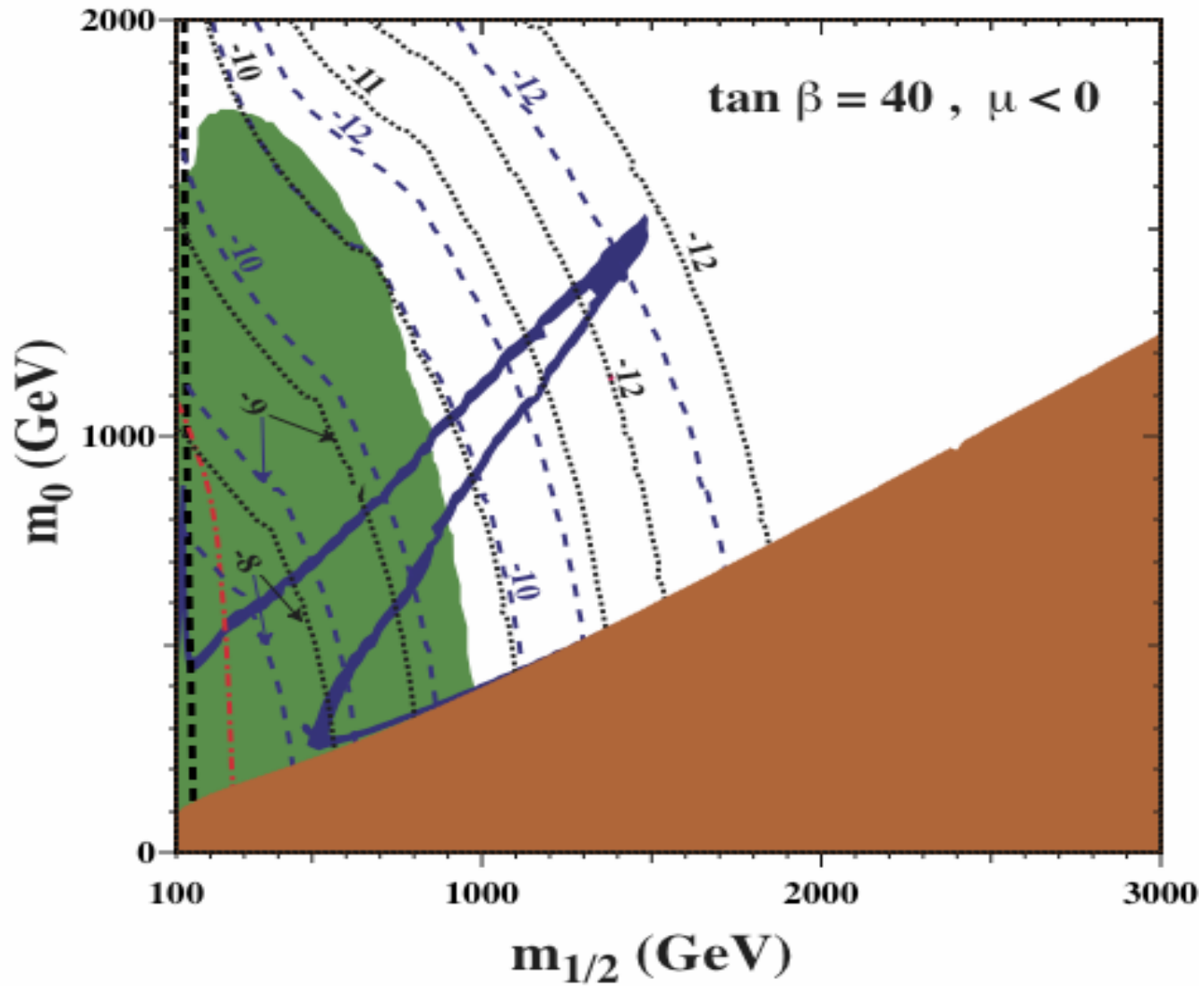


# Tightness of the DM constraints in Minimal Supergravity

Ellis et al.



# Tightness ...3

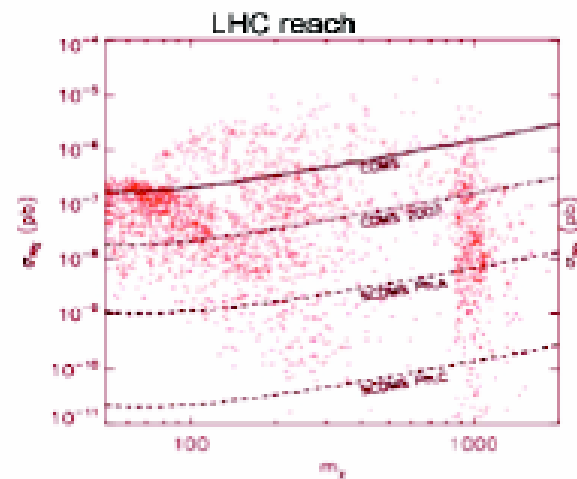
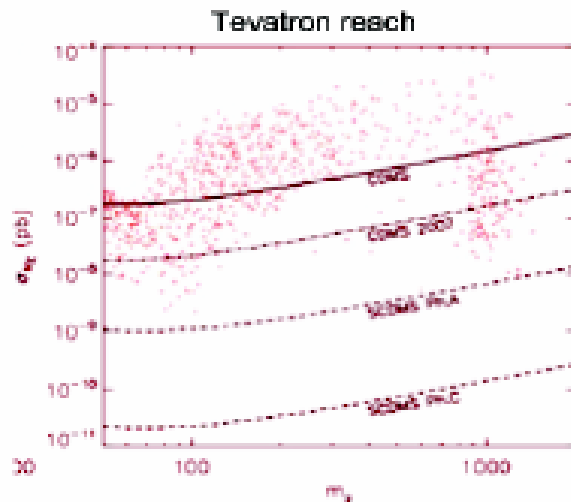


## CDMS DM searches Vs the Tevatron and LHC H/A searches

•If the lightest neutralino makes up the DM of the universe

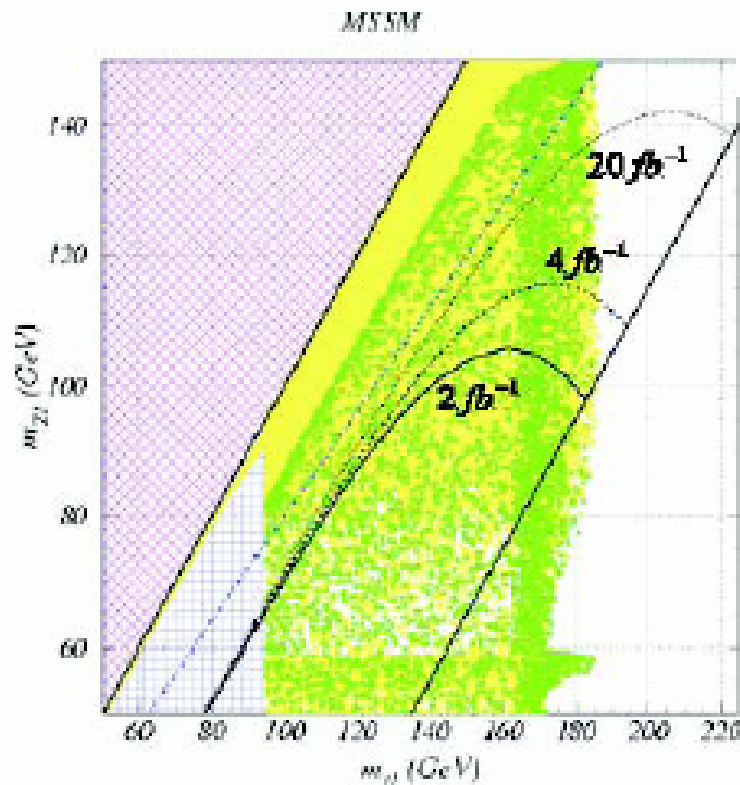
==> Evidence for H/A at the Tevatron (LHC) predict neutralino cross sections typically within the reach of present (future) direct DM detection experiments.

(strong  $\mu$  dependence)



# Tevatron stop searches and dark matter constraints

CARENA, BALAZS, WAGNER



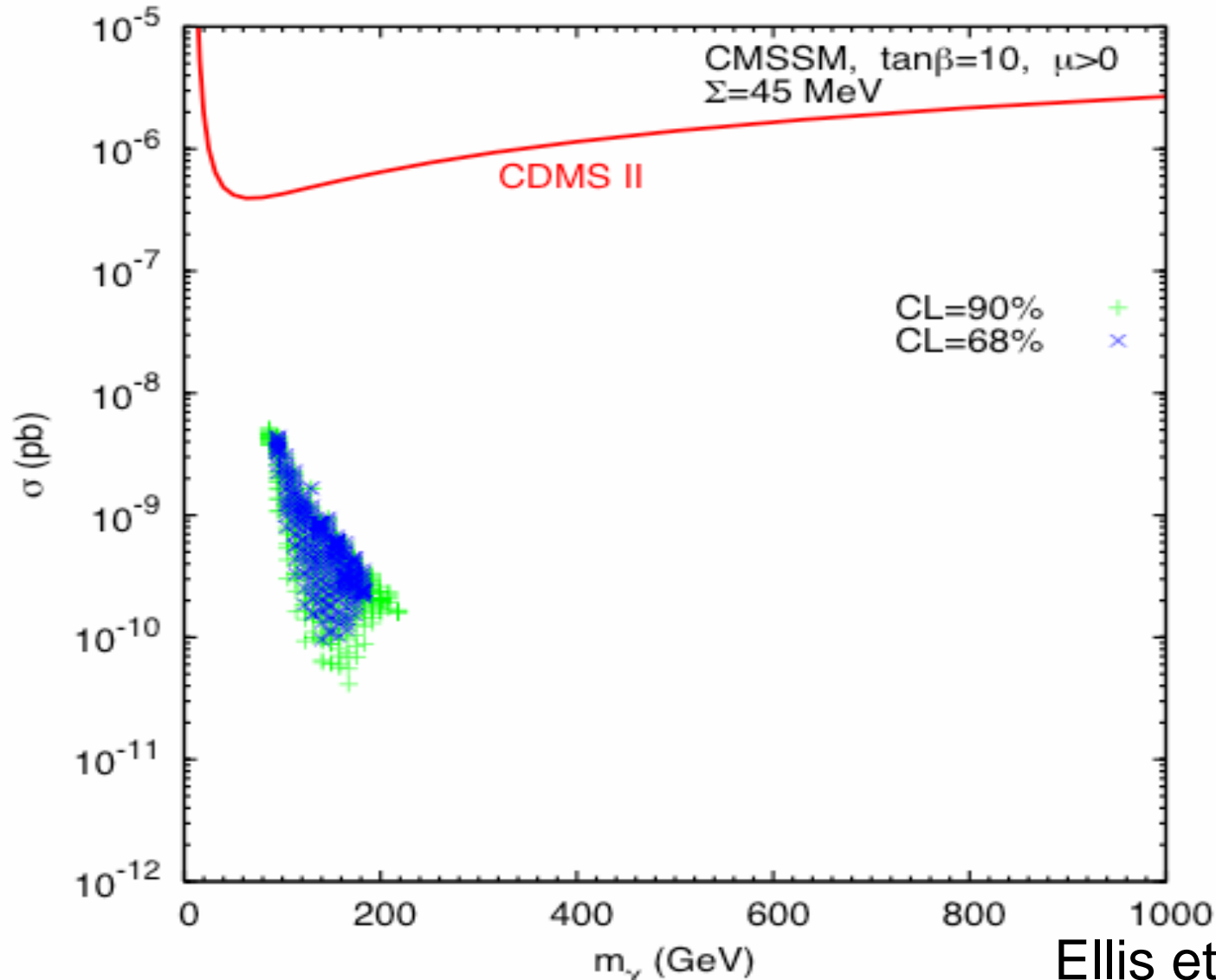
Green: Relic density consistent with **WMAP** measurements.

Searches for light stops difficult in stop-neutralino coannihilation region.

LHC will have equal difficulties. Searches become easier at a **Linear Collider** !

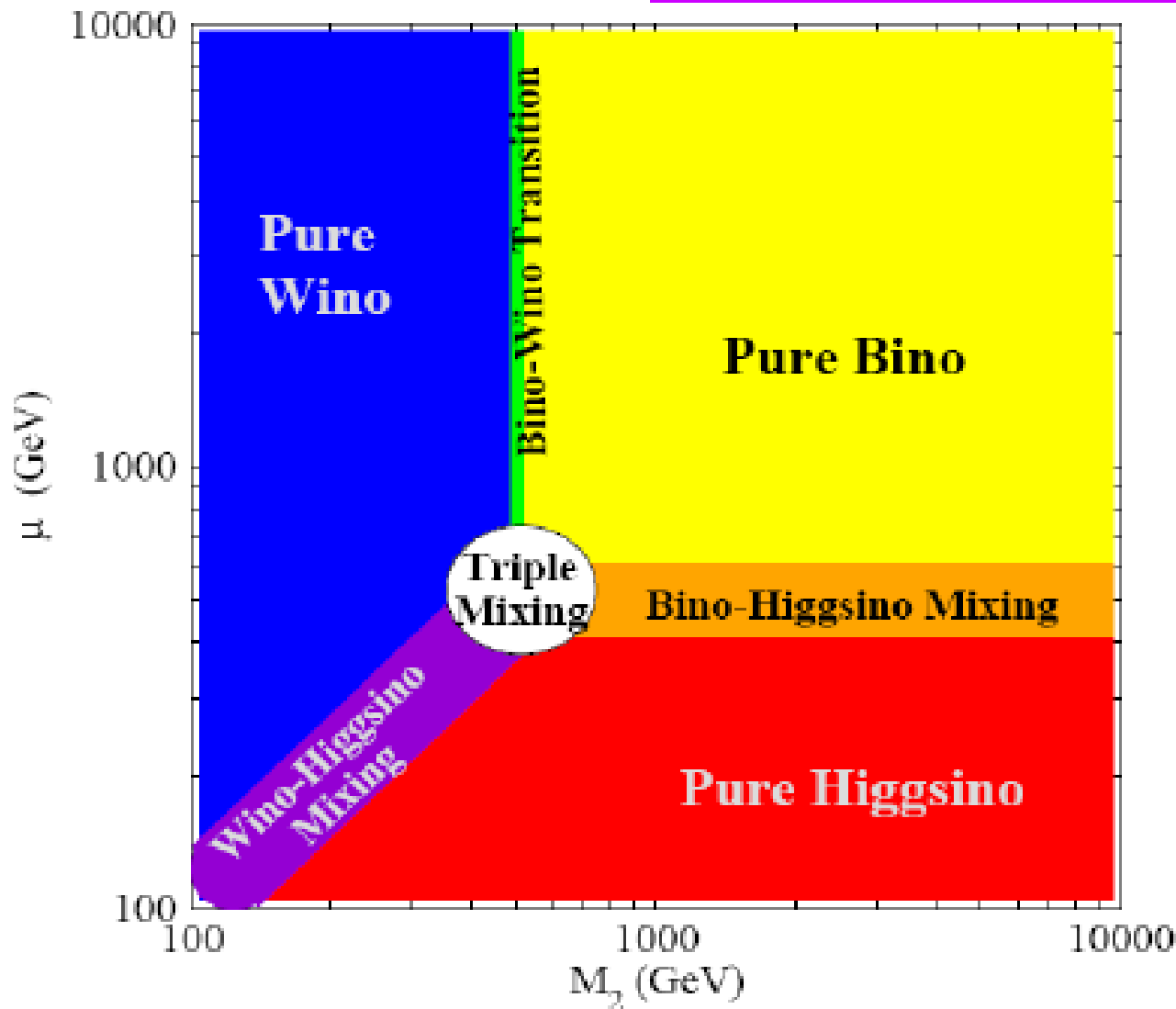
Carena, Freitas et al. '05

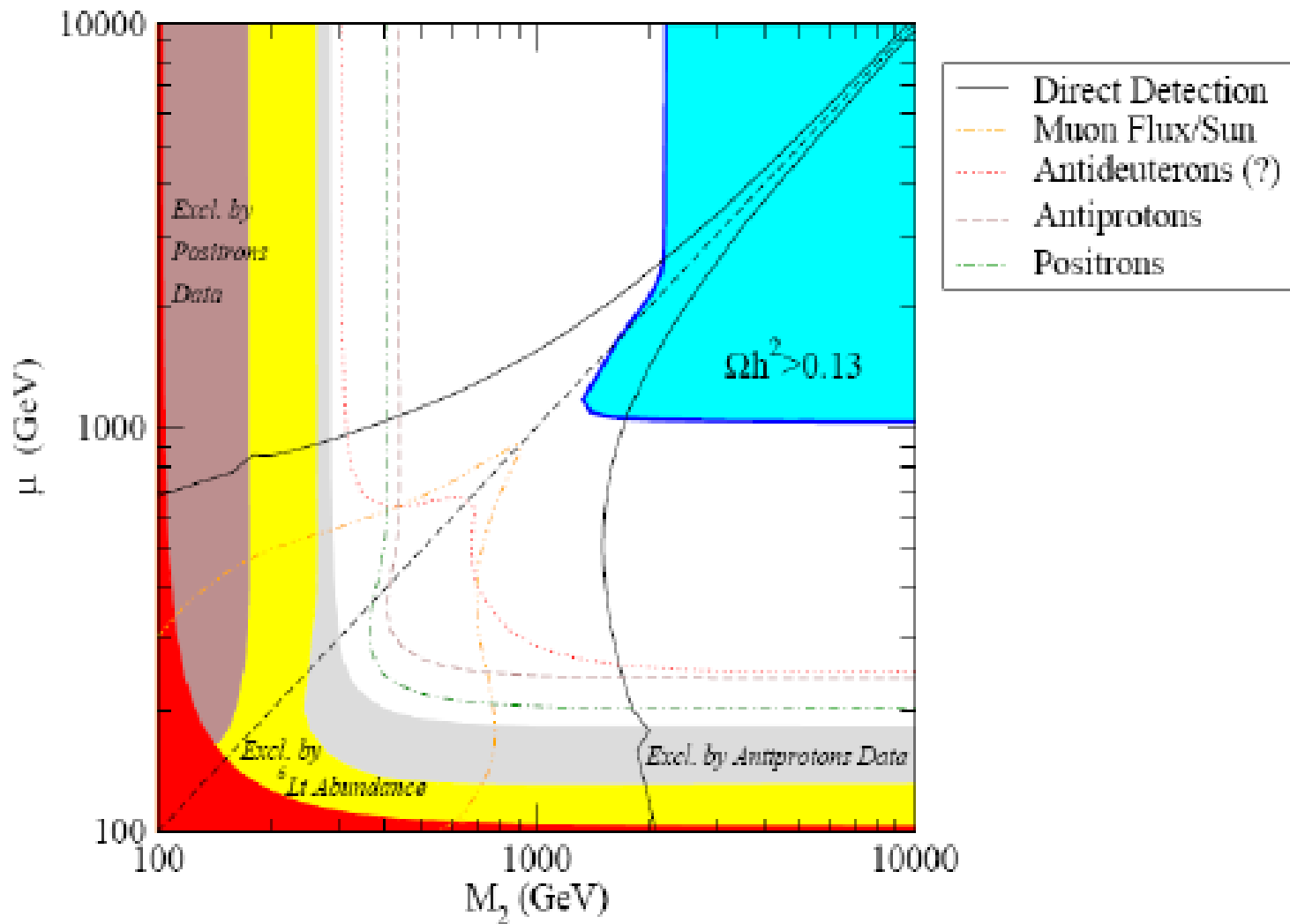
# DM SUSY: HOW FAR ARE WE IN DIRECT SEARCHES?



Ellis et al.

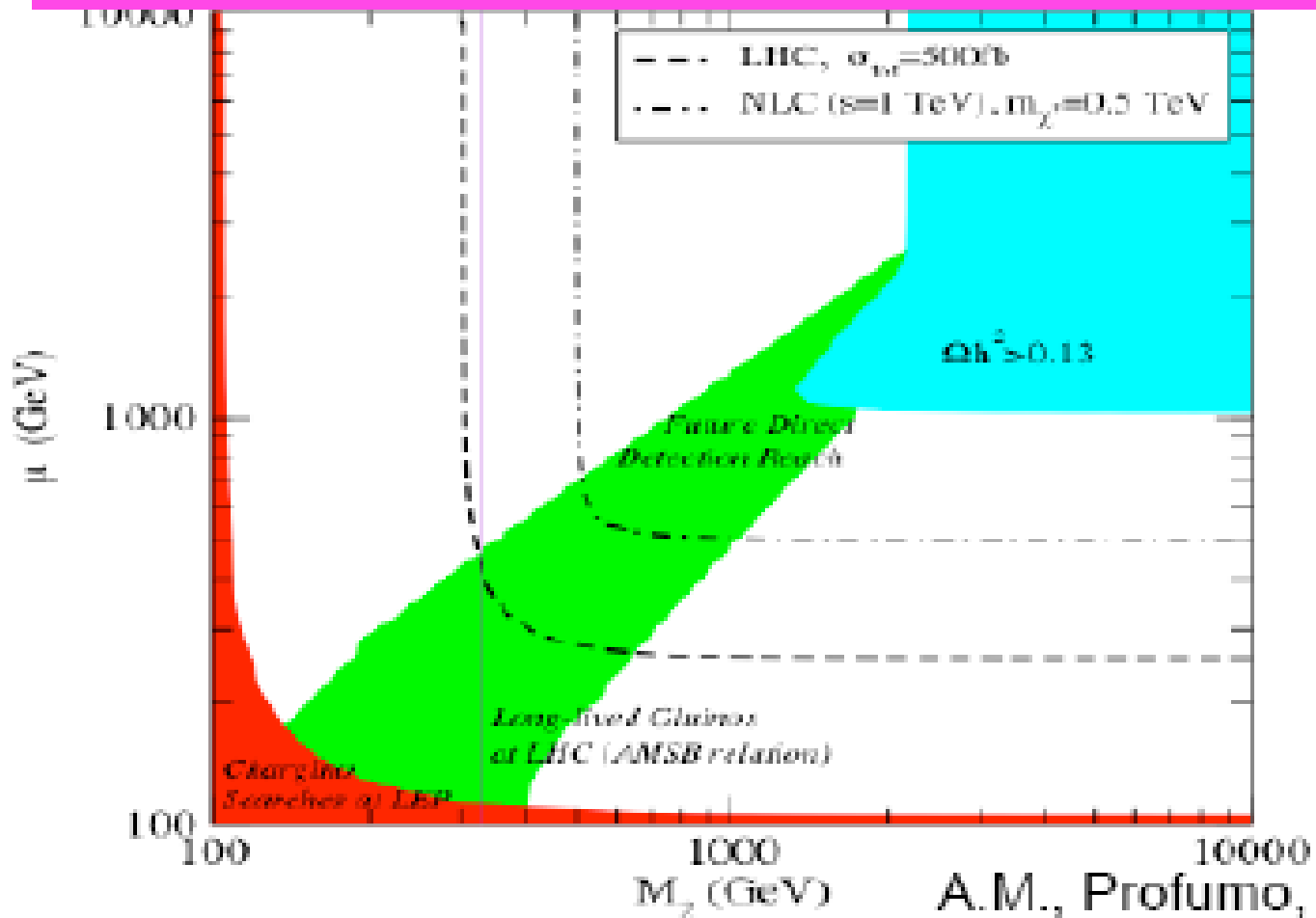
A.M., PROFUMO, ULLIO





A.M., PROFUMO, ULLIO

# LHC, ILC, DM SEARCHES SENSITIVITIES



# SEARCHING FOR **WIMPs**

## WIMPS HYPOTHESIS

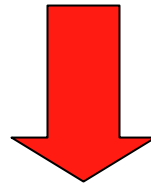
DM made of particles with  
mass 10Gev - 1Tev

**ELW scale**

With **WEAK INTERACT**

LHC, ILC may  
PRODUCE WIMPS

↓  
WIMPS escape the detector  
→ **MISSING ENERGY  
SIGNATURE**

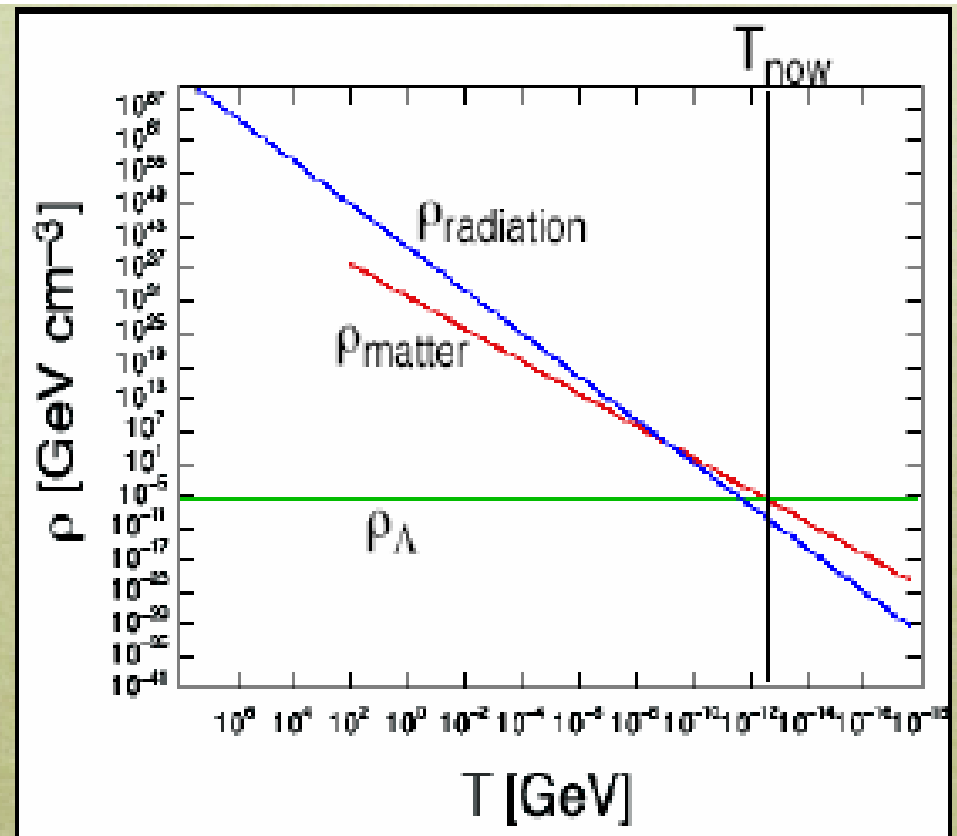


FROM "KNOW" COSM. ABUNDANCE OF WIMPs → PREDICTION  
FOR WIMP PRODUCTION AT COLLIDERS **WITHOUT** SPECIFYING  
THE PART. PHYSICS MODEL OF WIMPs

BIRKEDAL, MATCHEV, PERELSTEIN ,  
FENG,SU, TAKAYAMA

# THE “WHY NOW” PROBLEM

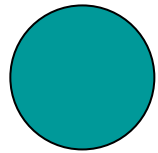
- *Why do we see matter and cosmological constant almost equal in amount?*
- *“Why Now” problem*
- *Actually a **triple coincidence problem** including the radiation*
- *If there is a deep reason for  $\rho_\Lambda \sim ((\text{TeV})^2/M_{\text{Pl}})^4$ , coincidence natural*



Arkani-Hamed, Hall,  
Kolda, HM



DO THEY "KNOW" EACH OTHER?



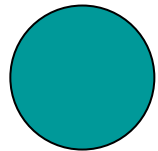
DIRECT INTERACTION  $\phi$  (quintessence) WITH DARK MATTER



DANGER:

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

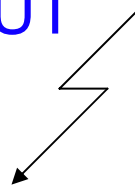
→ Threat of violation of the equivalence principle  
constancy of the fundamental "constants",...



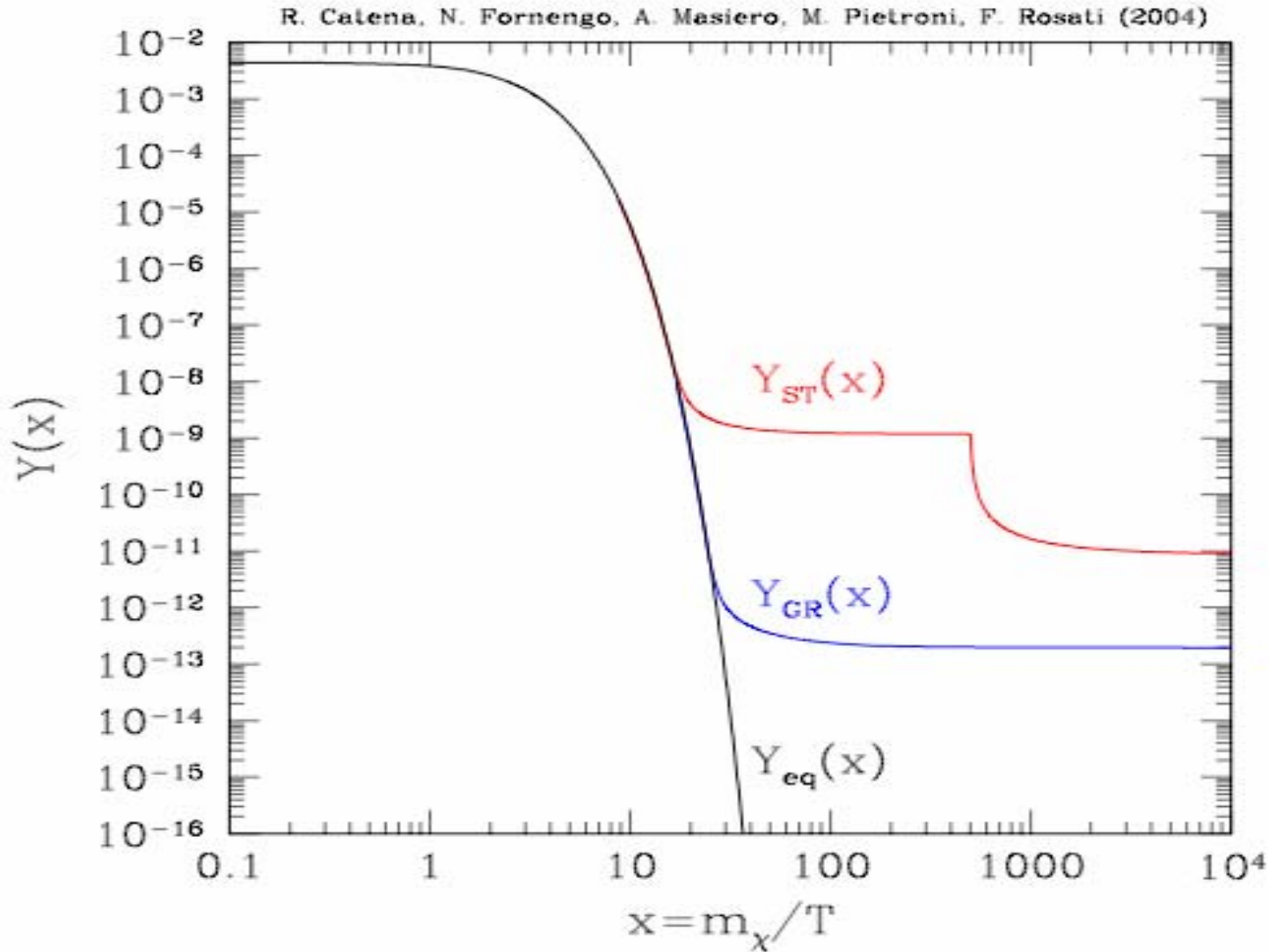
INFLUENCE OF  $\phi$  ON THE NATURE AND THE ABUNDANCE OF CDM

Modifications of the standard picture of  
WIMPs FREEZE - OUT

CDM CANDIDATES



# NEUTRALINO RELIC ABUNDANCE IN GR AND S-T THEORIES OF GRAVITY



**LHC**

DM - FLAVOR  
for DISCOVERY  
and/or FUND. TH.  
RECONSTRUCTION

A MAJOR  
LEAP AHEAD  
IS NEEDED

NEW  
PHYSICS AT  
THE ELW  
SCALE

**DARK MATTER**

"LOW ENERGY"

**PRECISION PHYSICS**

$m_\chi, n_\chi, \sigma_\chi, \dots$

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

LINKED TO COSMOLOGICAL EVOLUTION

→ Possible interplay with dynamical DE

**LFV**

LEPTOGENESIS

NEUTRINO PHYSICS