

# OPEN ISSUES IN THE STANDARD MODEL OF PARTICLES AND FIELDS

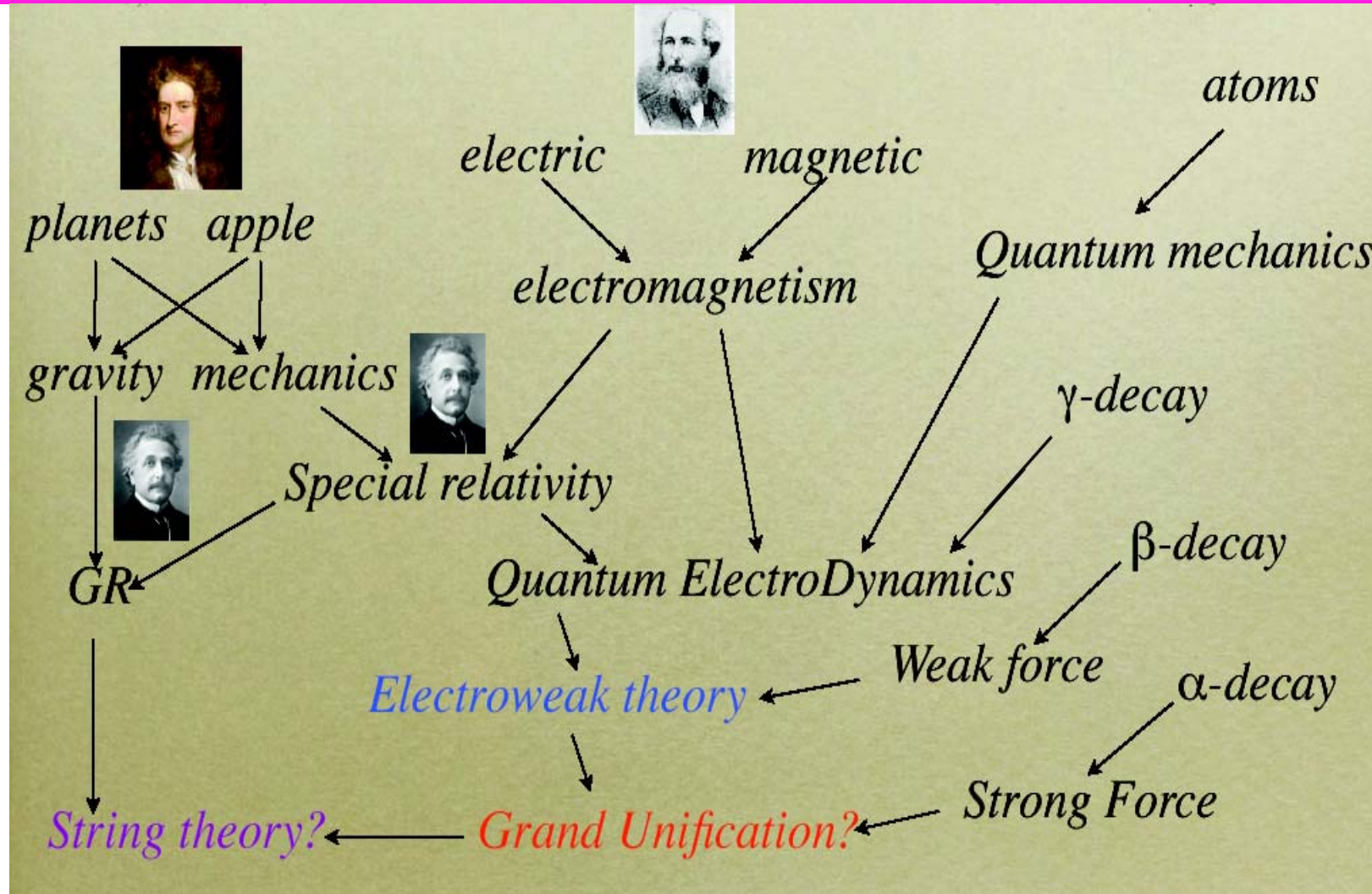
Antonio Masiero

Univ. of Padova and INFN, Padova

➡ Particle Physics SM: (amazingly) good description of fundamental interactions down to distances of  $O(10^{-18} \text{ m.})$

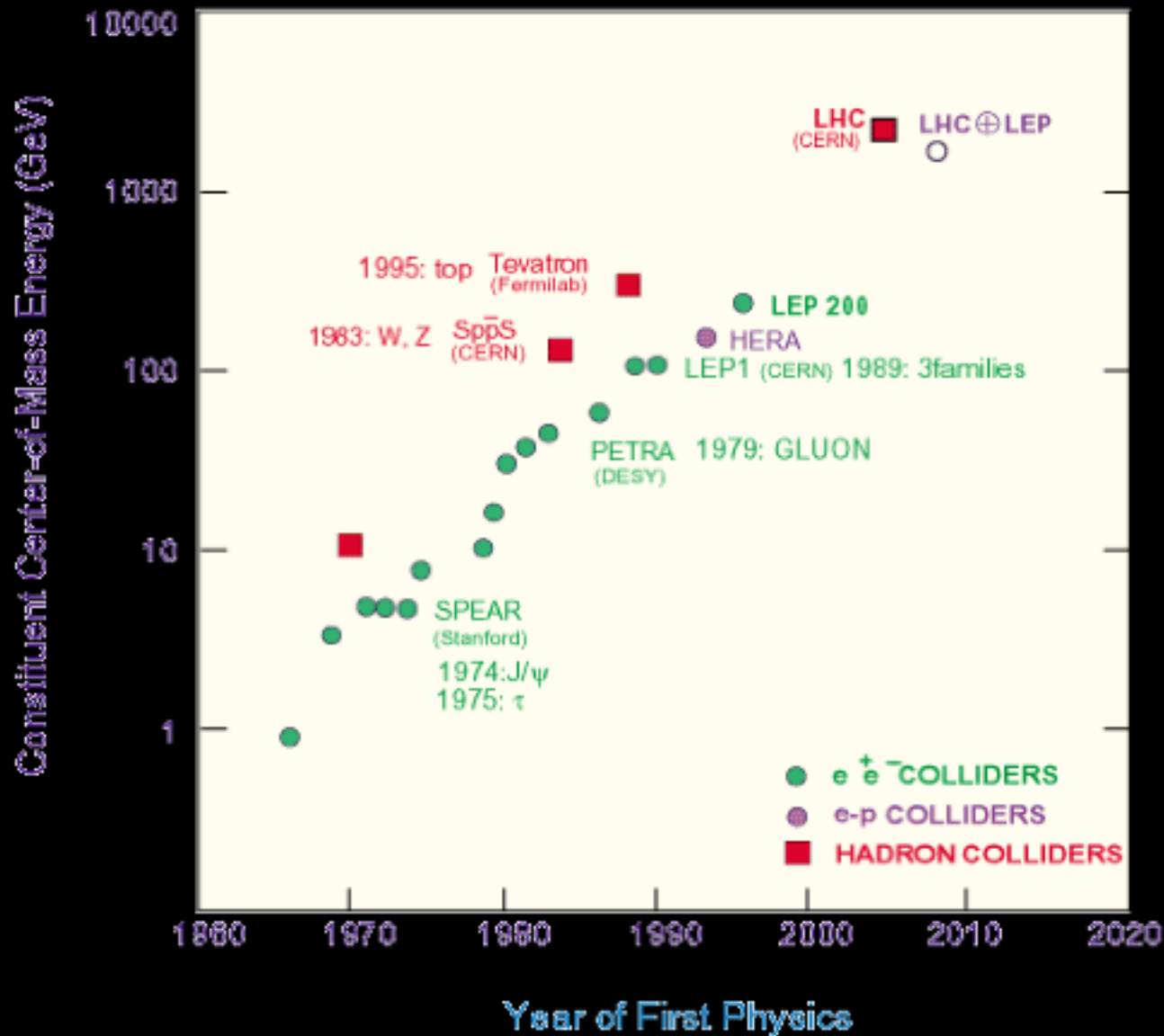
➡ The Standard Models of Particle Physics and Cosmology confront themselves: reasons for New Physics, chances to detect it in experiments on Earth and in Space

# UNIFICATION of FUNDAMENTAL INTERACTIONS

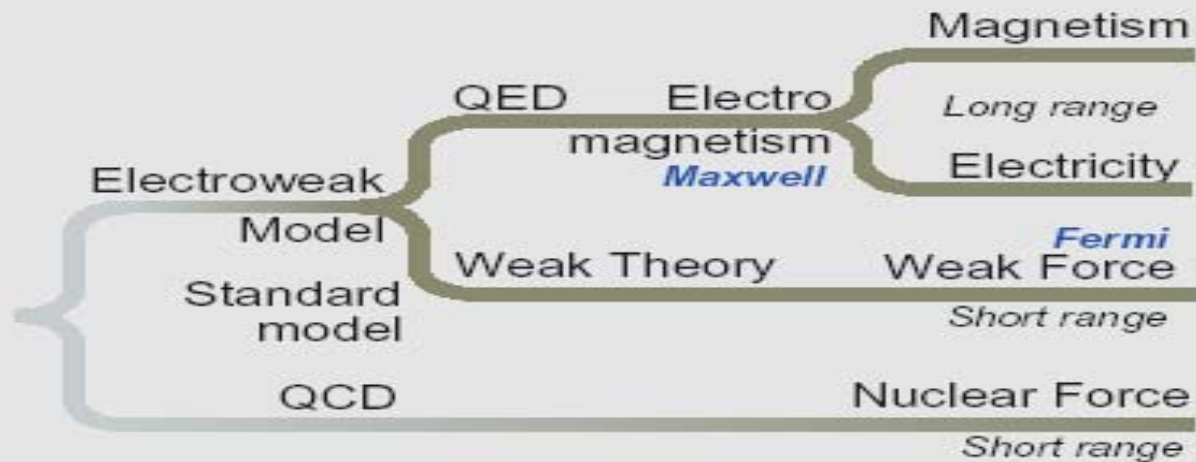
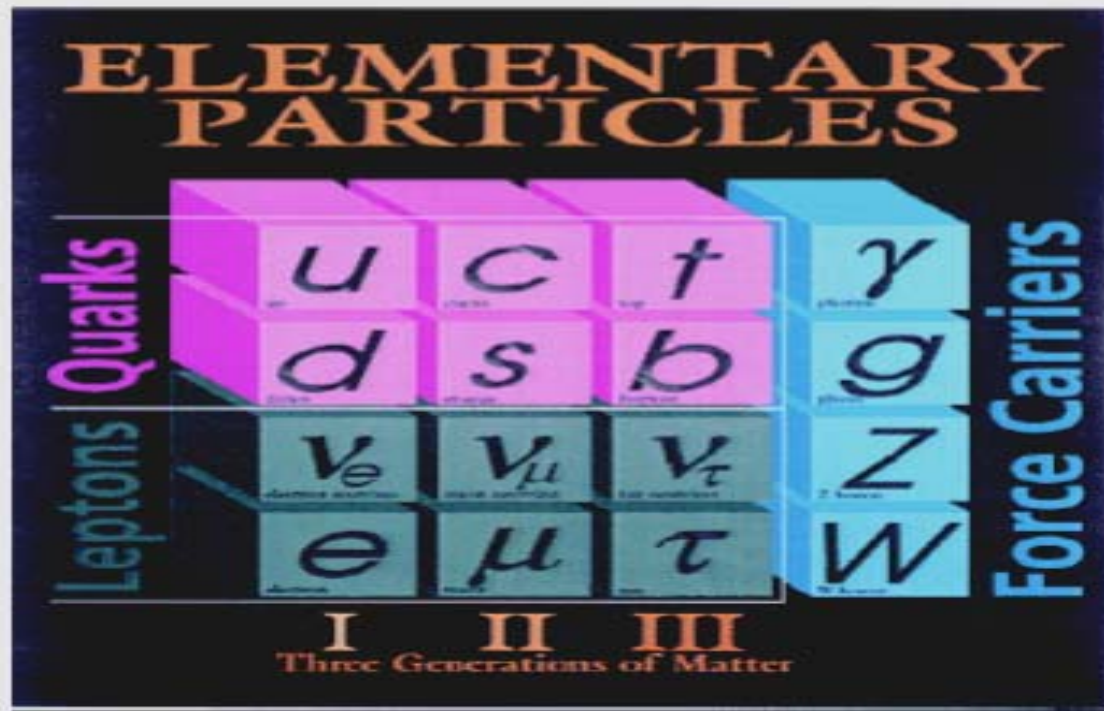


Courtesy of H. Murayama

# Going up in Energy

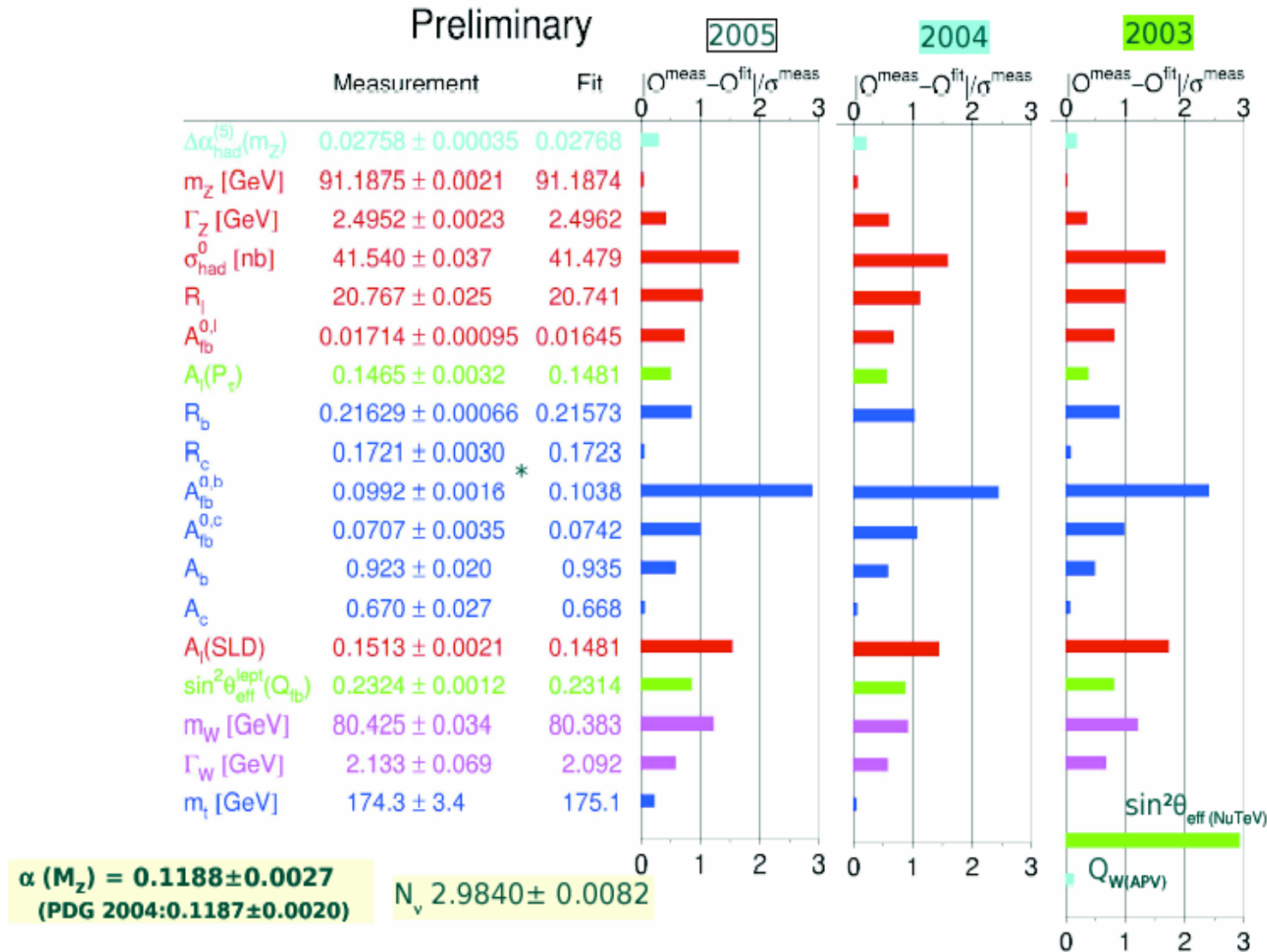


# THE G-W-S STANDARD MODEL



# Electroweak Precision Tests: SM Confirmed!

## The EW fit: picture confirmed

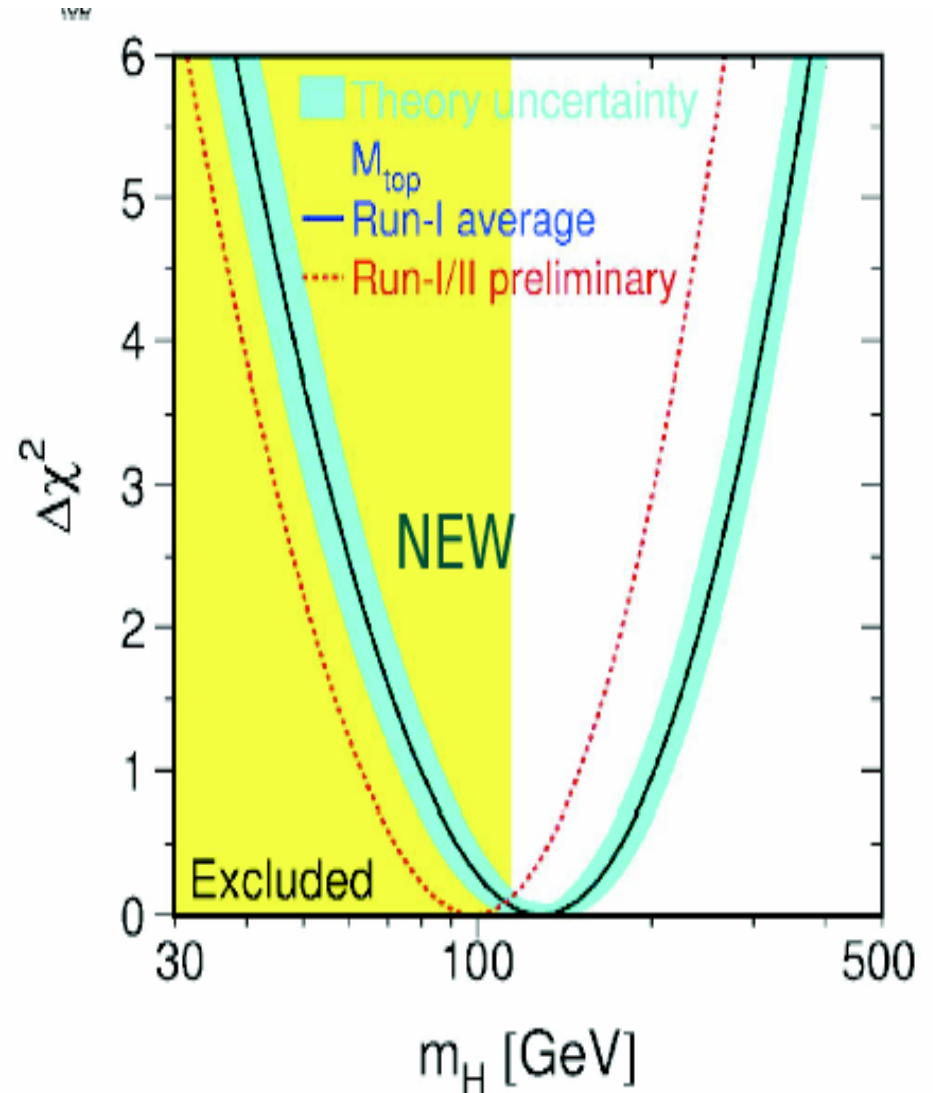


# Where all masses come from: the **HIGGS** particle

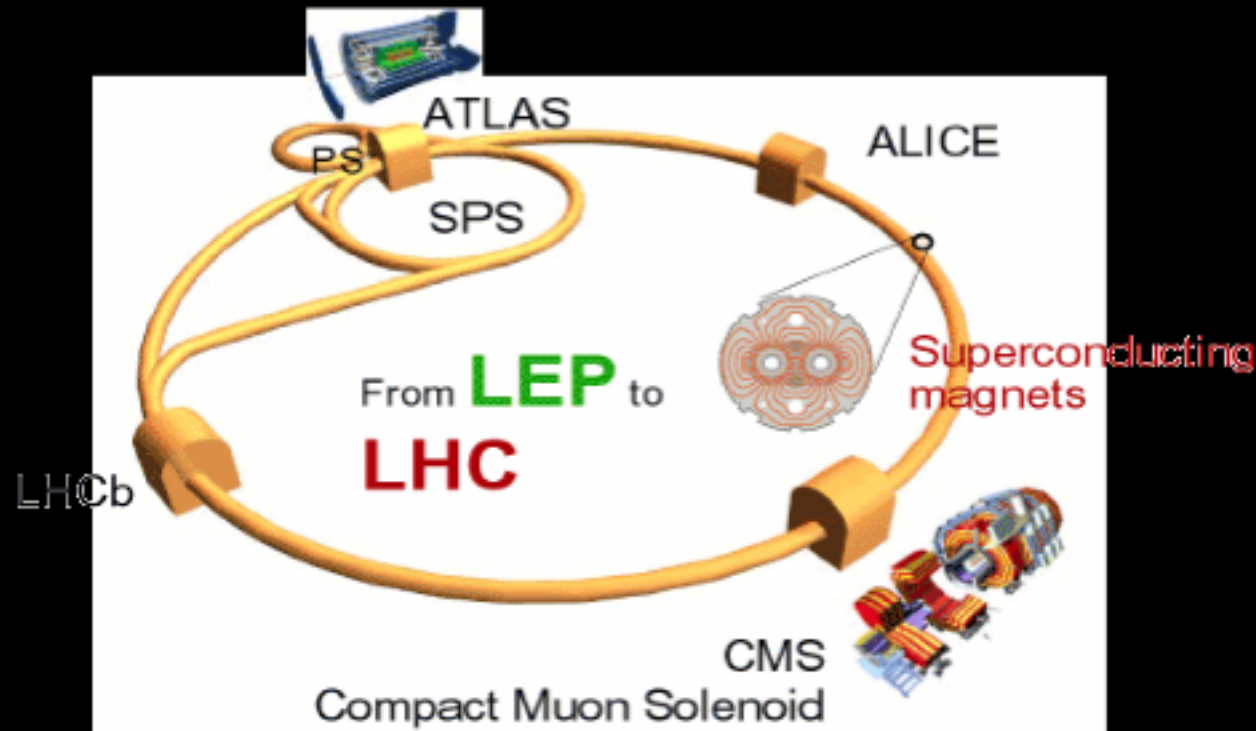
$$M_{\text{Higgs}} = 98^{+52}_{-26} \text{ GeV}$$

$$M_{\text{Higgs}} < 208 \text{ GeV @95\% C.L.}$$

The Higgs has already “shown up” as a **VIRTUAL** particle in electroweak radiative effects



# LHC: THE DISCOVERY MACHINE FOR THE NEW PHYSICS AT THE TEV SCALE



	Beams	Energy GeV	Luminosity
<b>LEP</b>	e <sup>+</sup> e <sup>-</sup>	200	10 <sup>32</sup> cm <sup>-2</sup> s <sup>-1</sup>
<b>LHC</b>	p p	<b>14000</b>	<b>10<sup>34</sup></b>
	Pb Pb	1,312,000	10 <sup>27</sup>

# Flavor Physics: the Triumph of the CKM flavor structure of the SM

## *Quark Sector*

- 1964 *Fitch and Cronin* discover *CP* violation (indirect *CP* in neutral *K*)
- 1999 *CPLEAR* establishes *T* violation in *K* mixing
- 2000 *KTeV/NA48* establish direct *CP* violation in  $\epsilon'/\epsilon$
- 2002 *BABAR/Belle* establish indirect *CP* violation in  $B_d$  meson, confirming Kobayashi-Maskawa theory

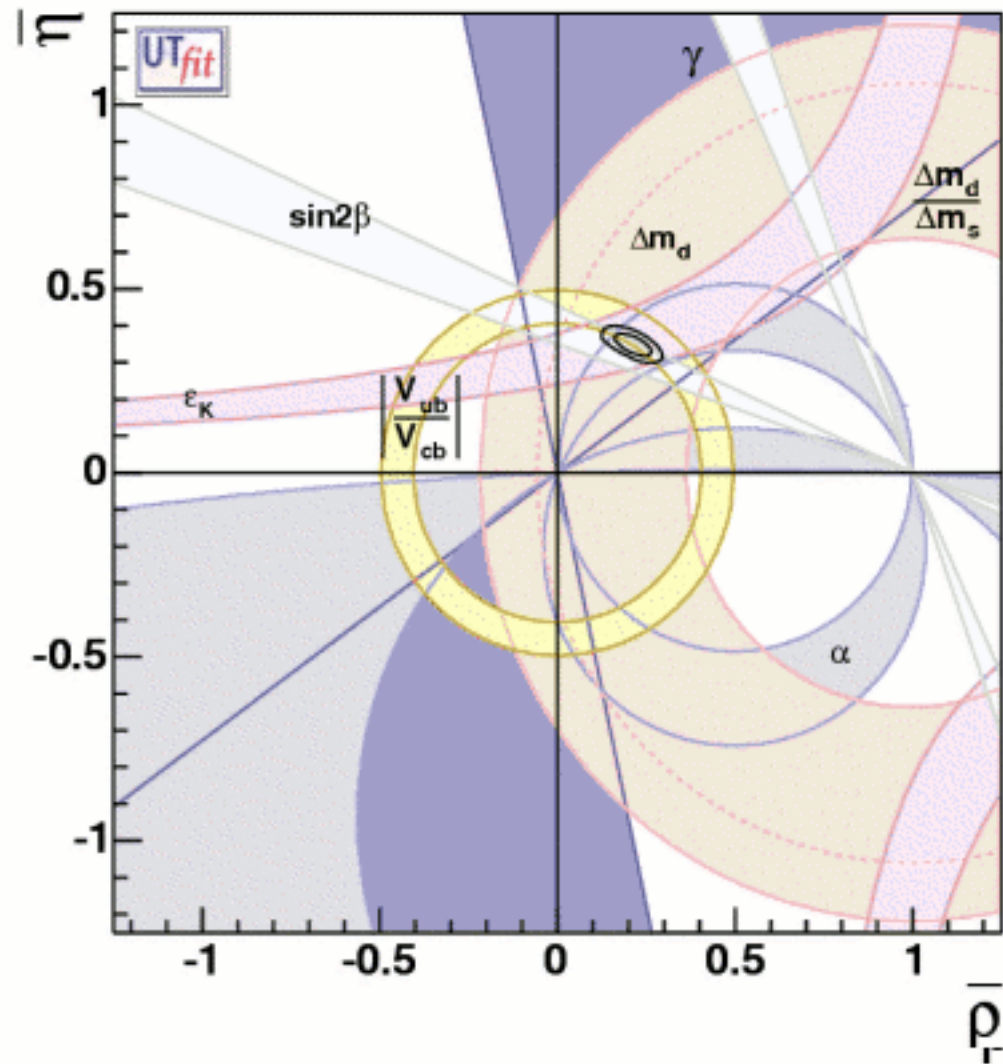
By now we have achieved a “redundant” determination of the CKM mixing elements entering the quark mixing in the SM, i.e. we are probing the validity of the CKM ansatz predicted by the SM



The CKM flavor structure of the SM is the **DOMINANT SOURCE** of the hadronic flavor mixing ( with new physics sources of flavor confined to be not larger than 20% of the CKM source)



# PROBING THE CKM PARADIGM OF THE SM THROUGH THE UNITARITY TRIANGLE FIT



# WHY TO GO BEYOND THE SM

## “OBSERVATIONAL” REASONS

- HIGH ENERGY PHYSICS

NO (but  $A_{FB}^{Z \rightarrow bb}$  .....

- FCNC,  $CP \neq$

NO (but  $b \rightarrow sq\bar{q}$  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

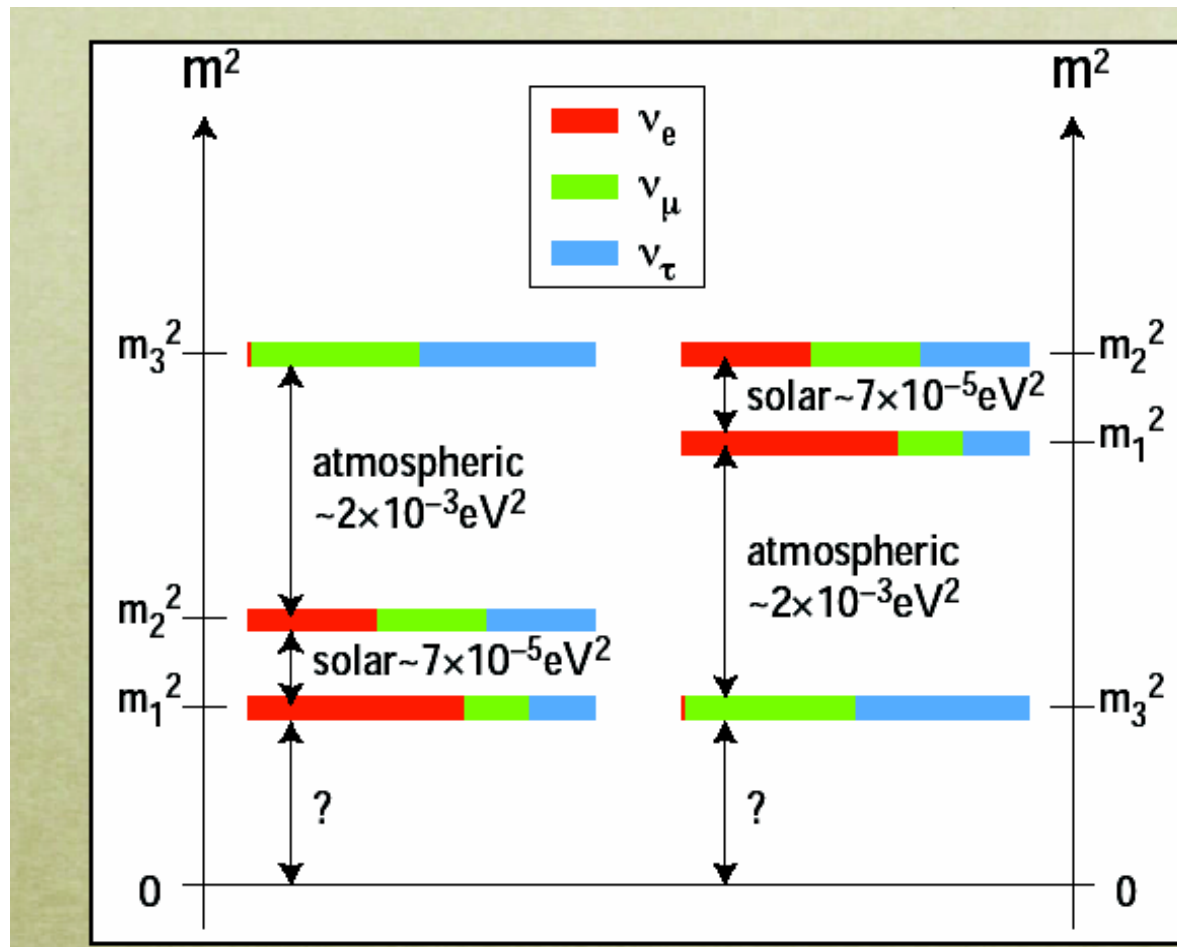
- INTRINSIC INCONSISTENCY OF SM AS QFT

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!



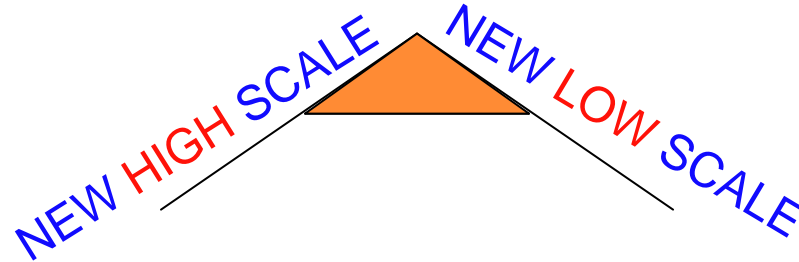
# THE FATE OF LEPTON NUMBER

L VIOLATED

$\nu$  Majorana ferm.

SMALLNESS of  $m_\nu$

PRESENCE OF A NEW PHYSICAL MASS SCALE



SEE - SAW MECHAN.

Minkowski; Gell-Mann,  
Ramond, Slansky,  
Vanagida

$\nu_R$  ENLARGEMENT OF THE  
FERMIONIC SPECTRUM

$$M\nu_R\nu_R + h\nu_L\bar{\phi}\nu_R$$

$$\begin{array}{ccc} \nu_L & \sim 0 & h \langle \bar{\phi} \rangle \\ \nu_R & h \langle \bar{\phi} \rangle & M \end{array}$$

LR  
Models?

L CONSERVED

$\nu$  Dirac ferm.  
(dull option)

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

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

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

MAJORON MODELS

Gelmini, Roncadelli



ENLARGEMENT OF THE  
HIGGS SCALAR SECTOR

$$h\nu_L\nu_L \Delta$$

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

N.B.: EXCLUDED BY LEP!

**MICRO**

PARTICLE PHYSICS

GWS STANDARD MODEL

**MACRO**

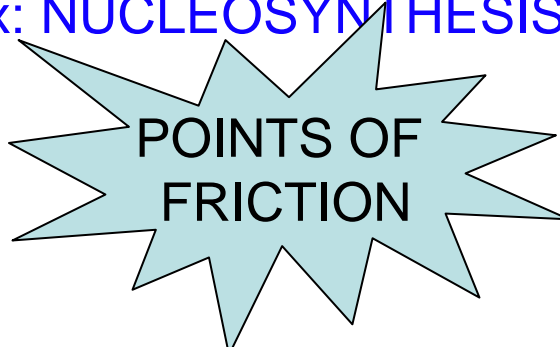
COSMOLOGY

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

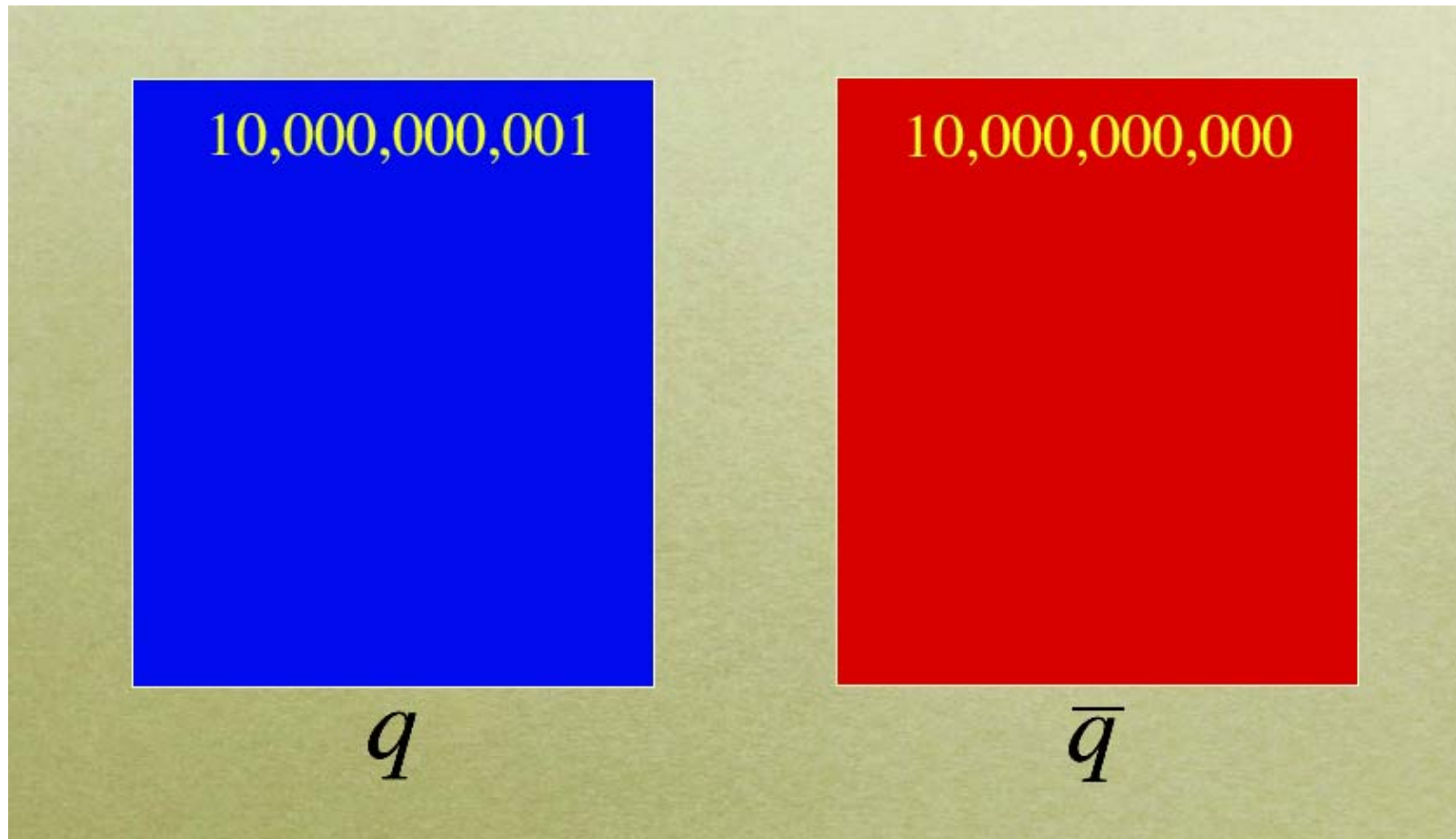
-why  $N_{\text{baryons}}/N_{\text{photon}} \sim 10^{-10}$

- NO EVIDENCE OF ANTIMATTER WITHIN THE SOLAR SYSTEM
- ANTI-PROTONS 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



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



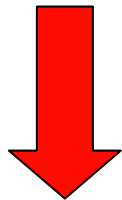
# MATTER-ANTIMATTER ASYMMETRY $\longleftrightarrow$ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

- 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 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

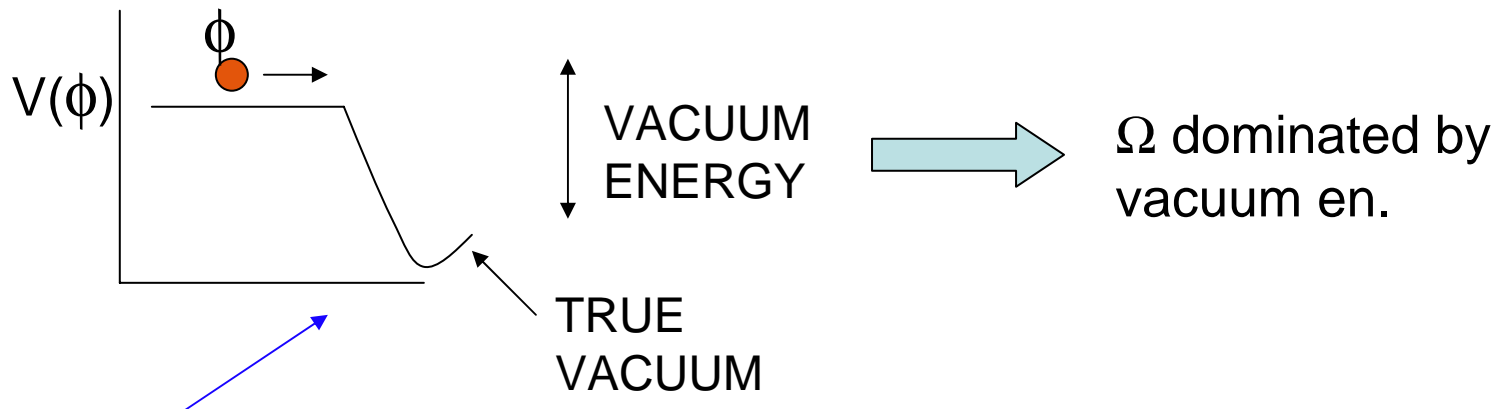
SEVERE  
COSMOLOGICAL  
PROBLEMS



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

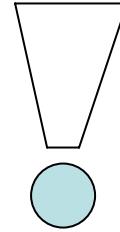
COMMON SOLUTION FOR THESE PROBLEMS

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



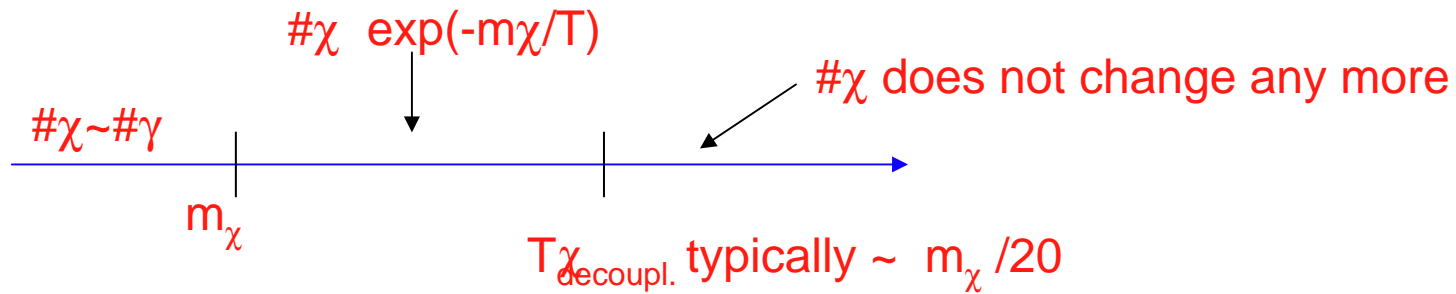
$$\Omega_{DM} = 23\% \pm 4\% ; \Omega_B = 4\% \pm 0.4\% ; \Omega_\Lambda = 73\% \pm 4\%$$

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 !**

# WIMPS (Weakly Interacting Massive Particles)



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

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\underbrace{\langle (\sigma_{\text{annih.}}) v_\chi \rangle}_{\sim \alpha^2 / M_\chi^2} \text{ TeV}^2} \quad \leftarrow \text{From } T^0 M_{\text{plaeli}}$$

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

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

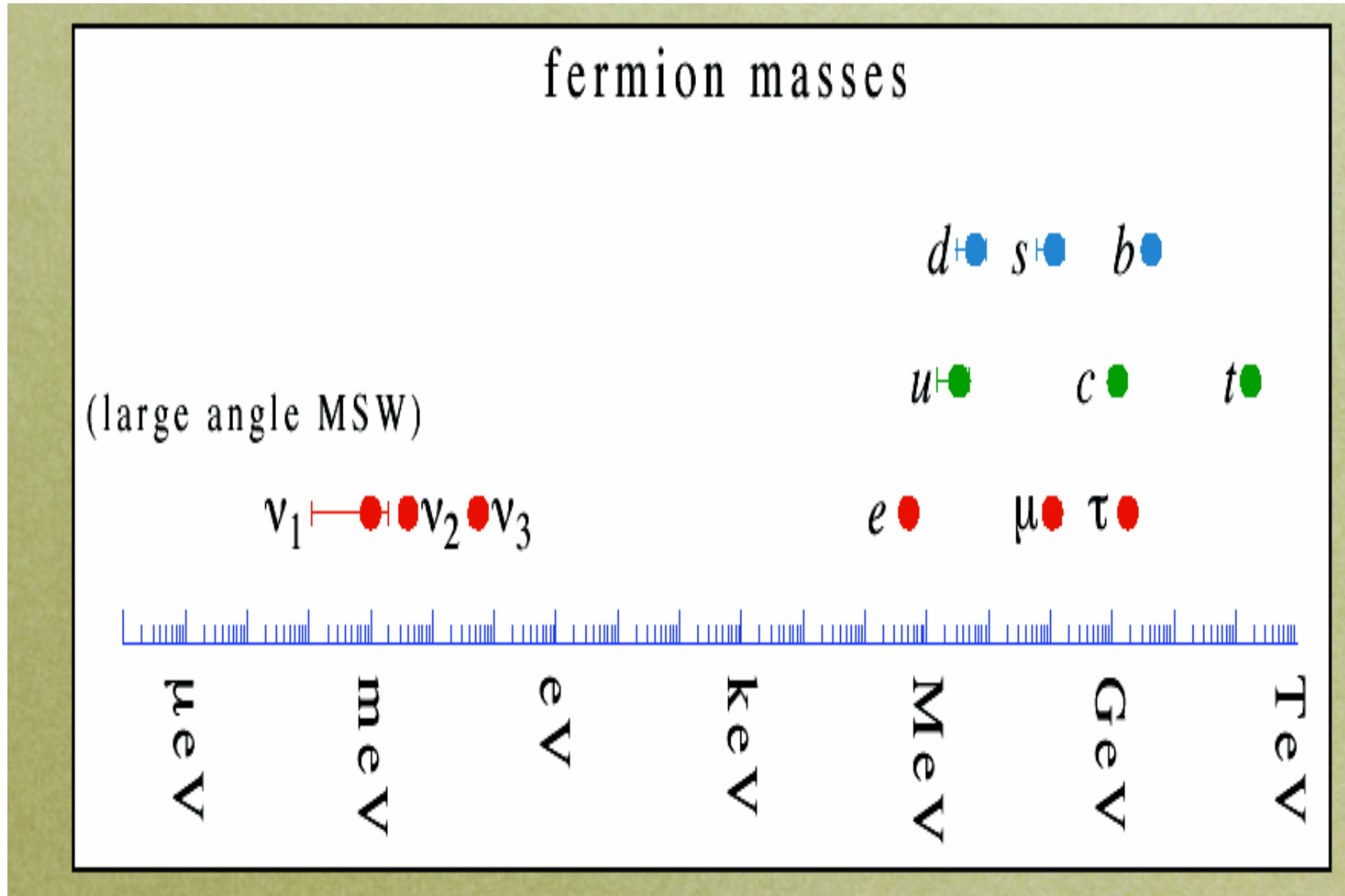
# STABLE ELW. SCALE WIMPs from PARTICLE PHYSICS

	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	$\sim 100 - 200$ GeV *	$\sim 600 - 800$ GeV	$\sim 400 - 800$ GeV

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

Bottino, Donato, Fornengo, Scopel

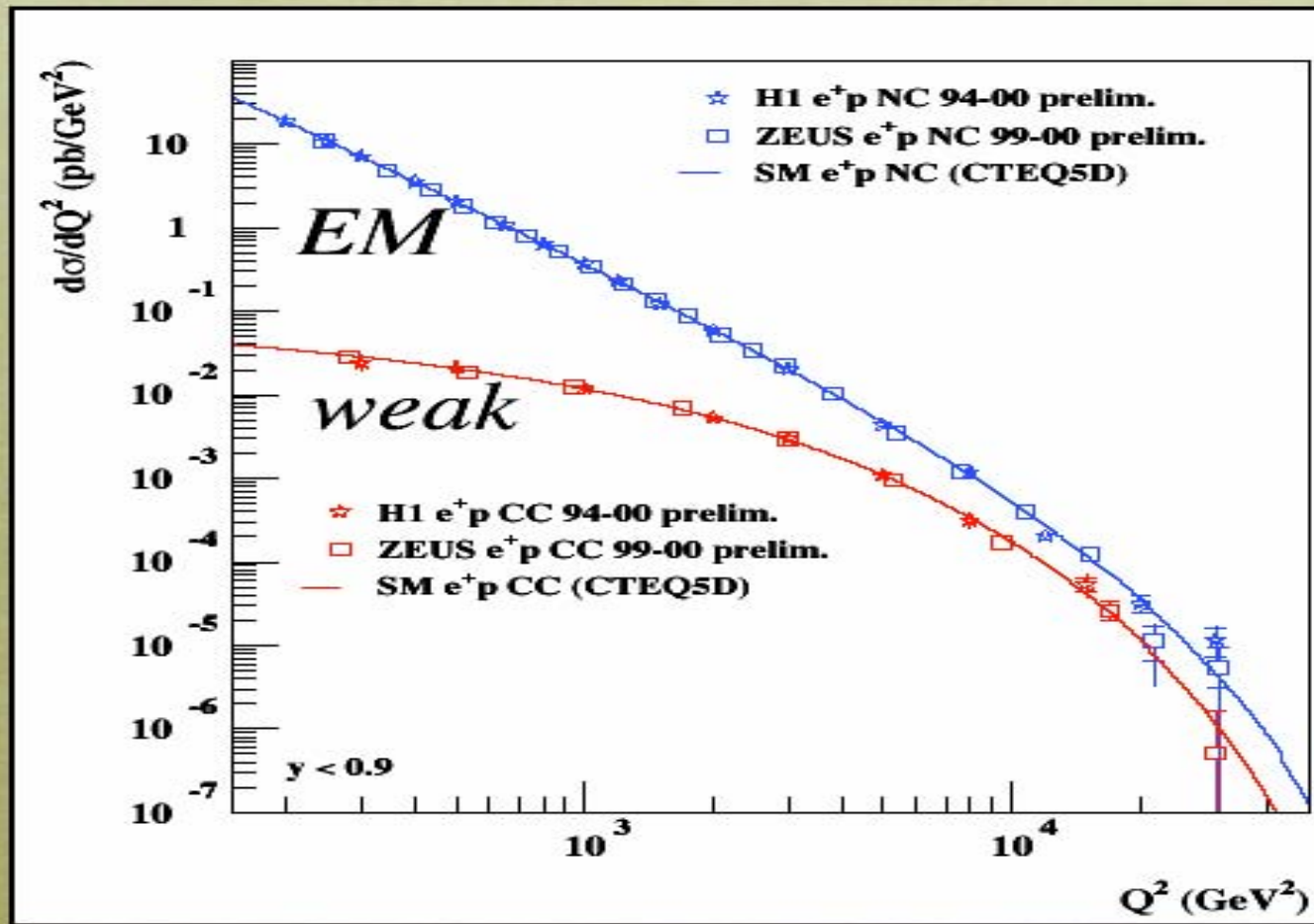
# THE FERMION MASS PUZZLE



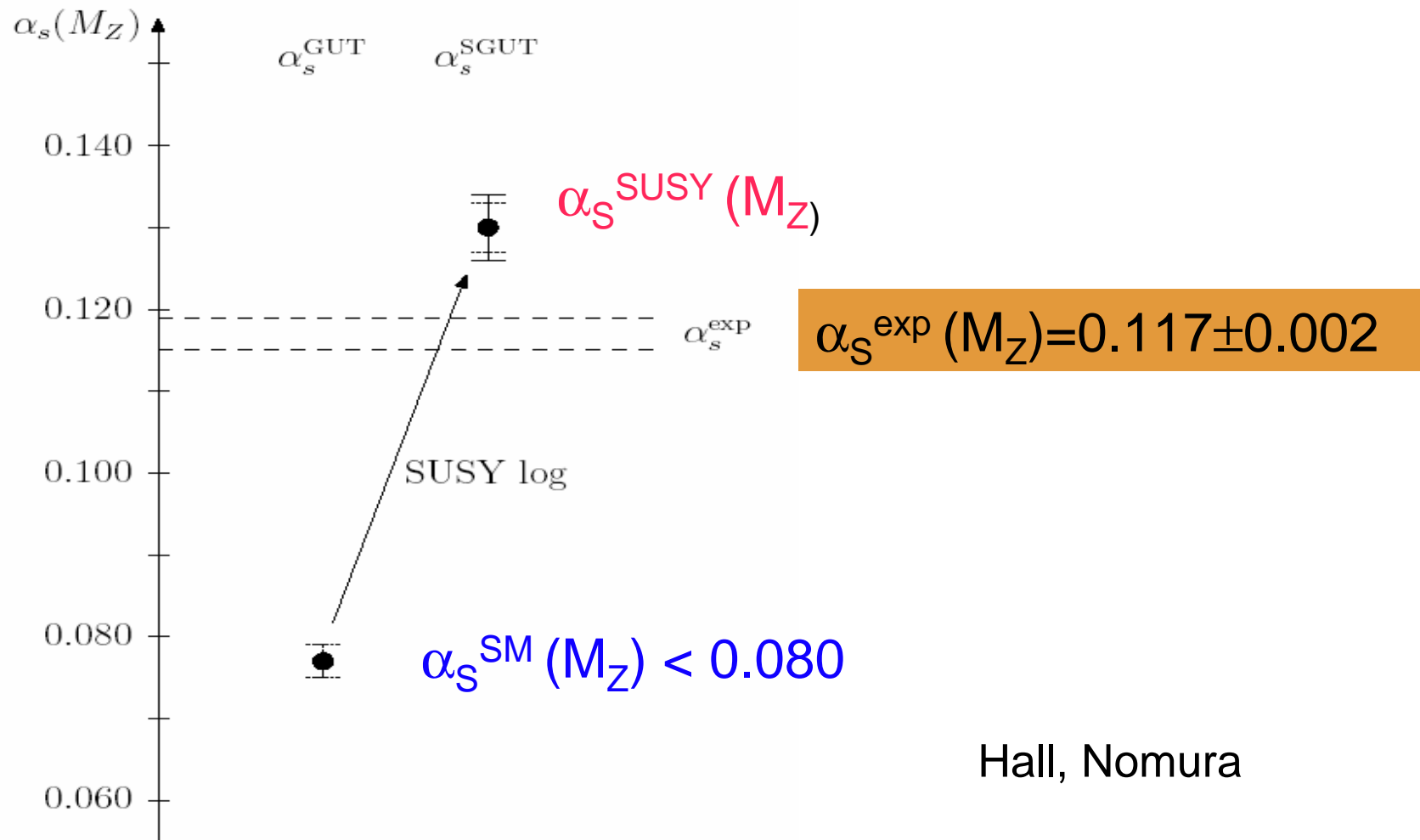


# Fundamental COUPLING CONSTANTS are NOT CONSTANT

*HERA ep collider*



# Fundamental interactions unify



# “MASS PROTECTION”

For FERMIONS, VECTOR (GAUGE) and SCALAR BOSONS

SYMMETRY  
PROTECTION

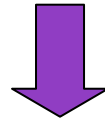
-FERMIONS → chiral symmetry

$f_L f_R$  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 (SUPERSYMMETRY)  
Such that FERMIONS ↔ BOSONS

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

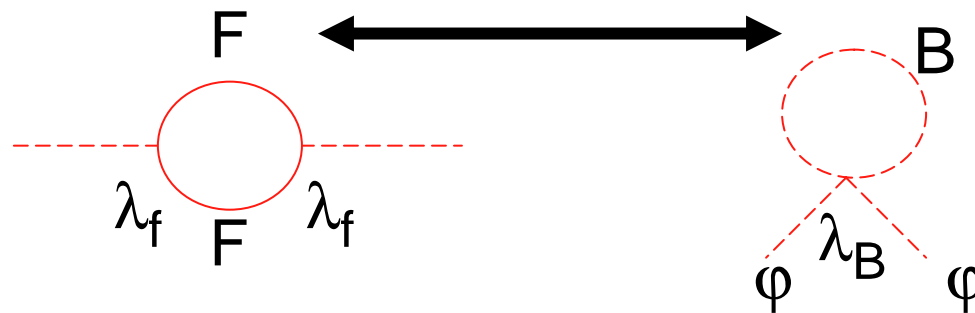
→ SUSY BRAKING ~ SCALE OF 0 ( $10^2$ - $10^3$  GeV)

→ LOW ENERGY SUSY

# 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



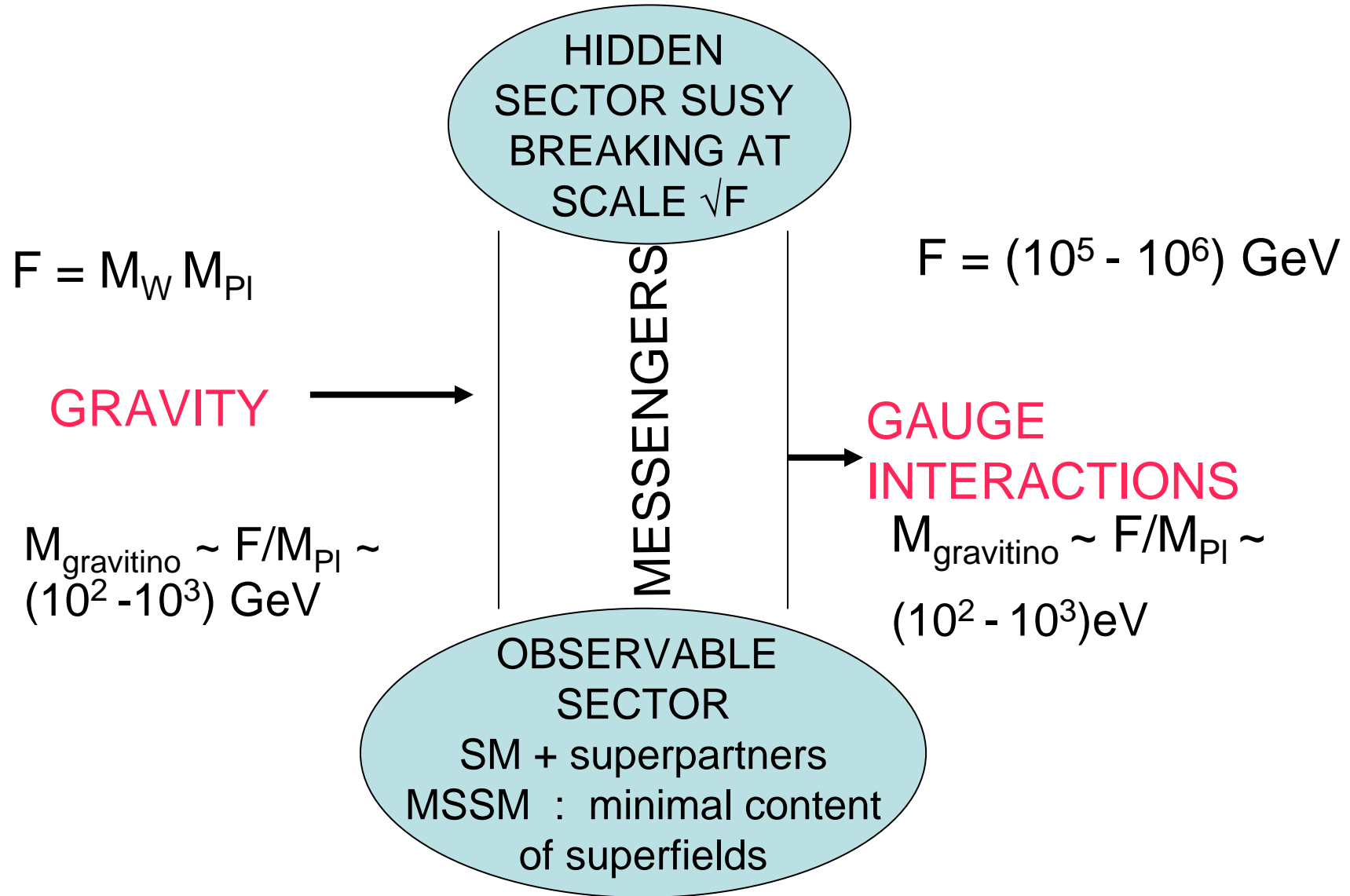
$$8m_\phi^2 \sim \frac{(\lambda_B - \lambda_f^2) \Lambda^2}{16 \pi^2}$$

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

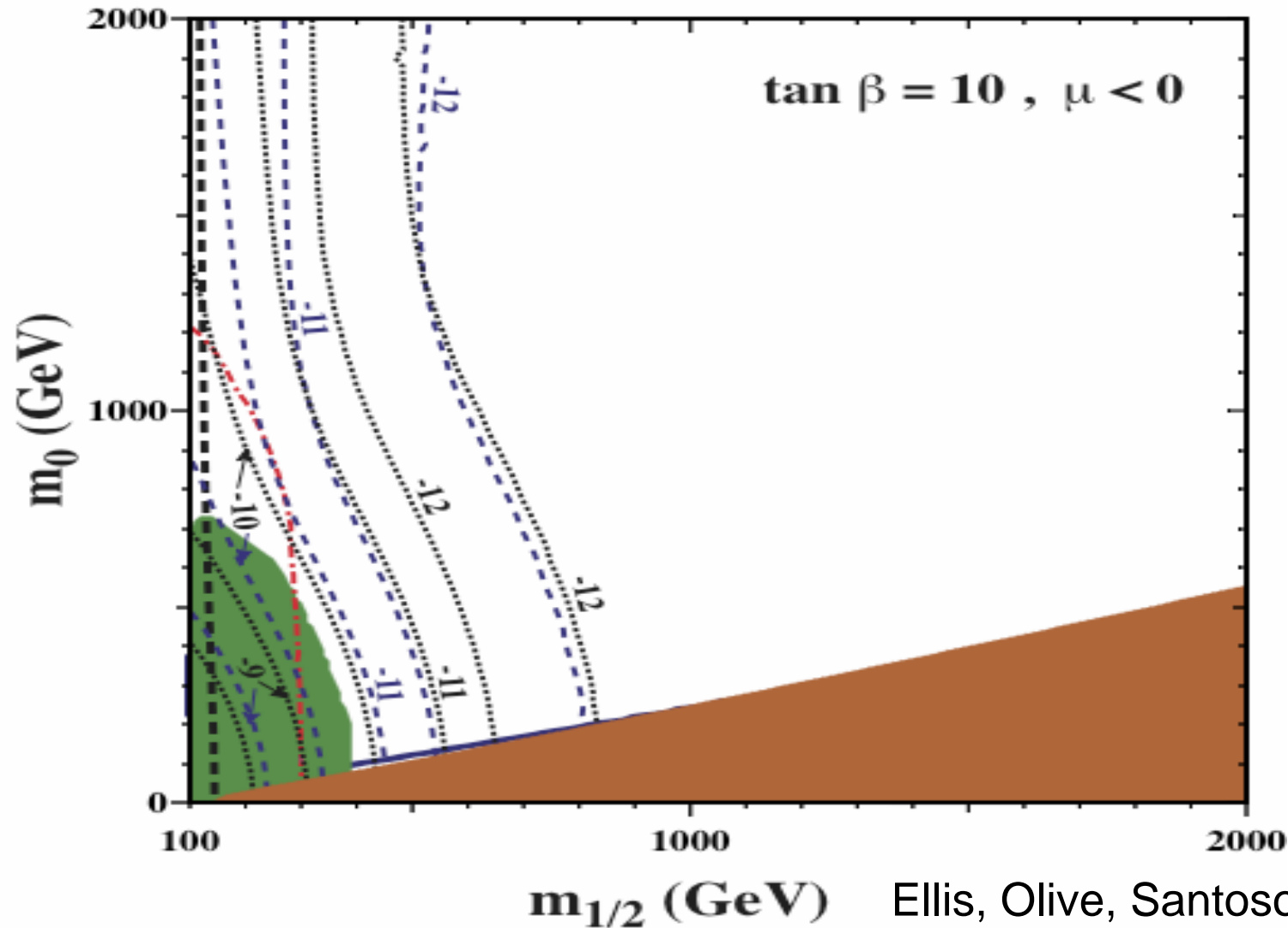
$\left[ \begin{array}{c} B \\ F \end{array} \right]$  In SUSY multiplet

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

# WHICH SUSY

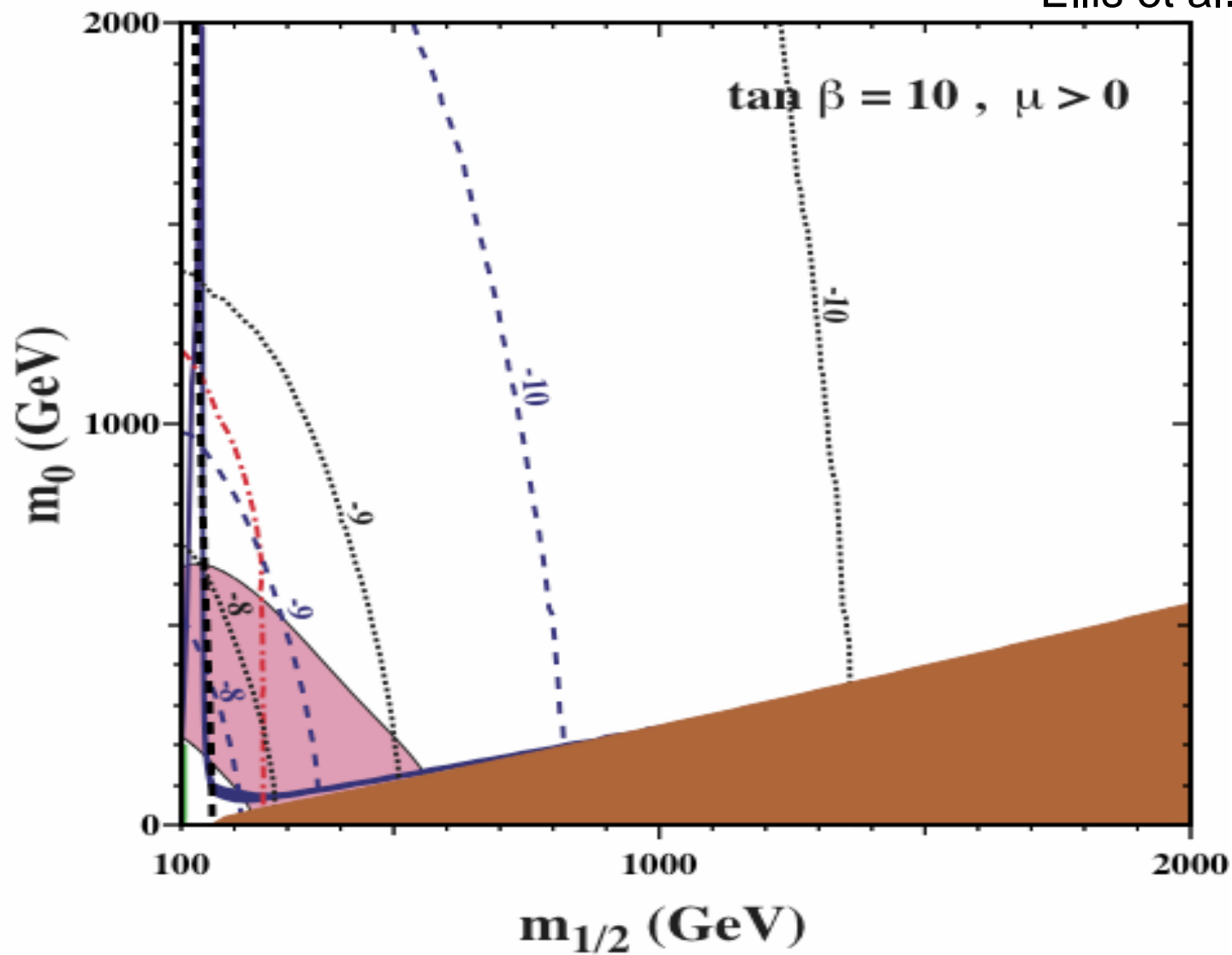


# Tightness of the DM constraint on minimal supergravity

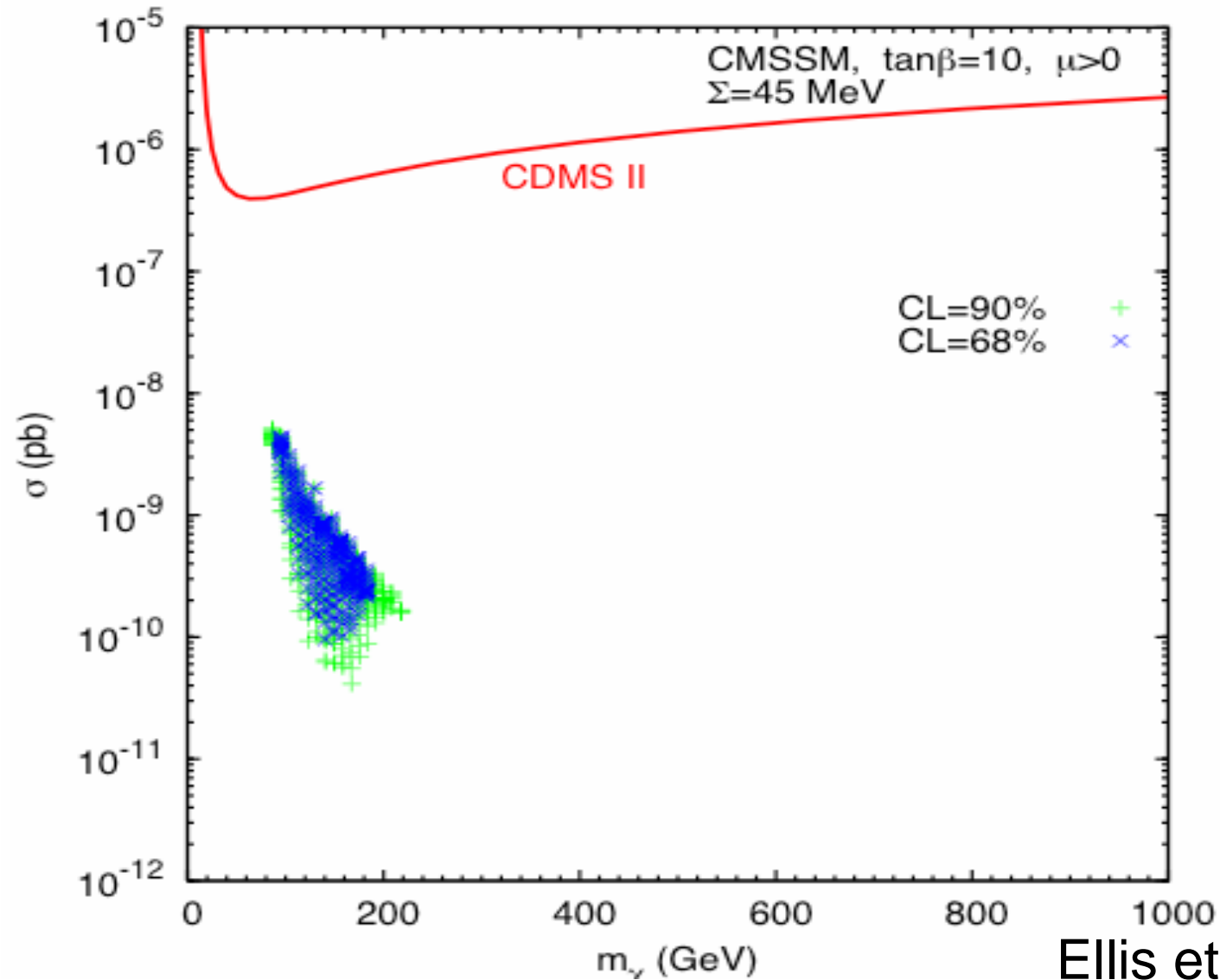


# Tightness of the DM constraints in Minimal Supergravity

Ellis et al.



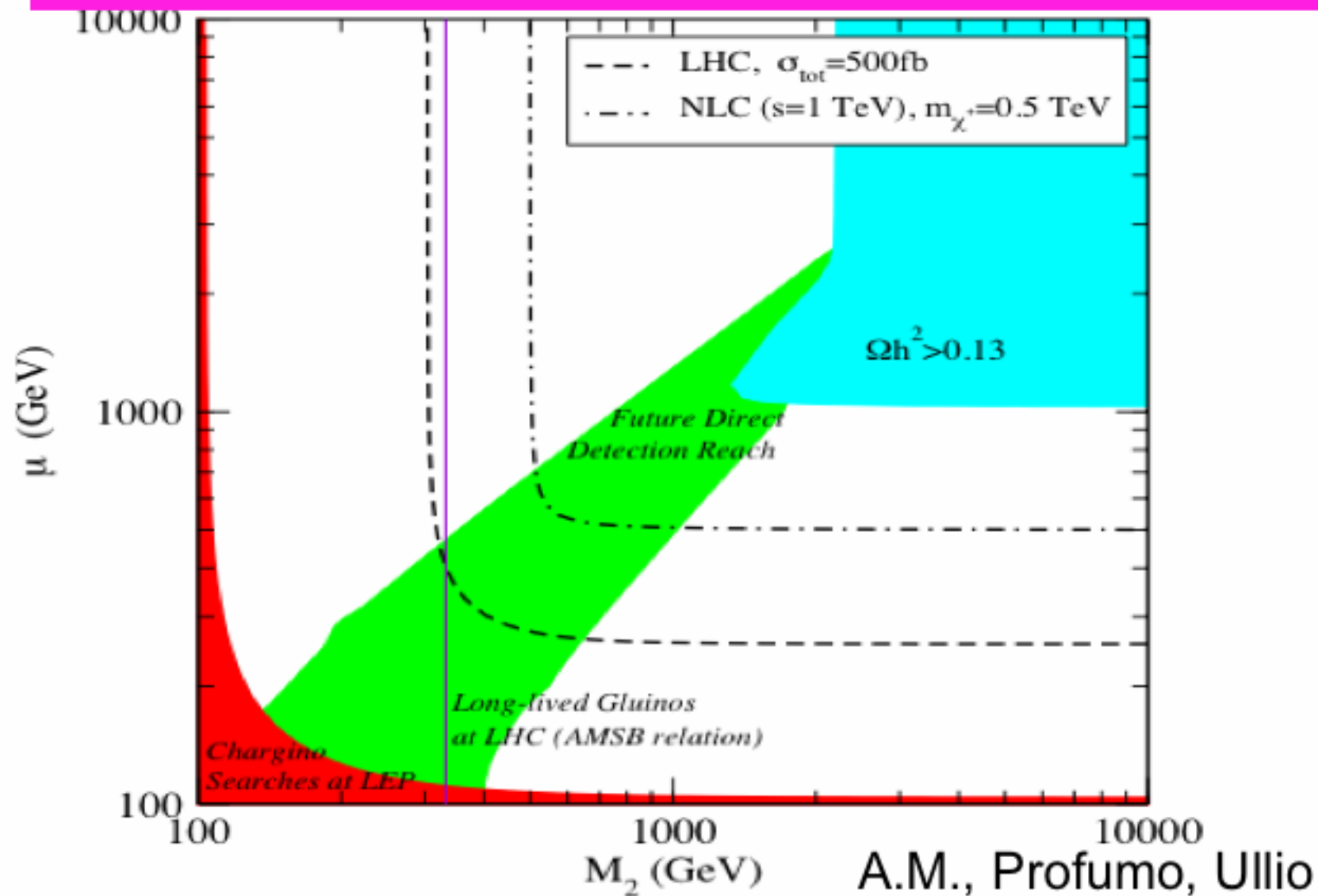
# DM SUSY: HOW FAR ARE WE IN DIRECT SEARCHES?



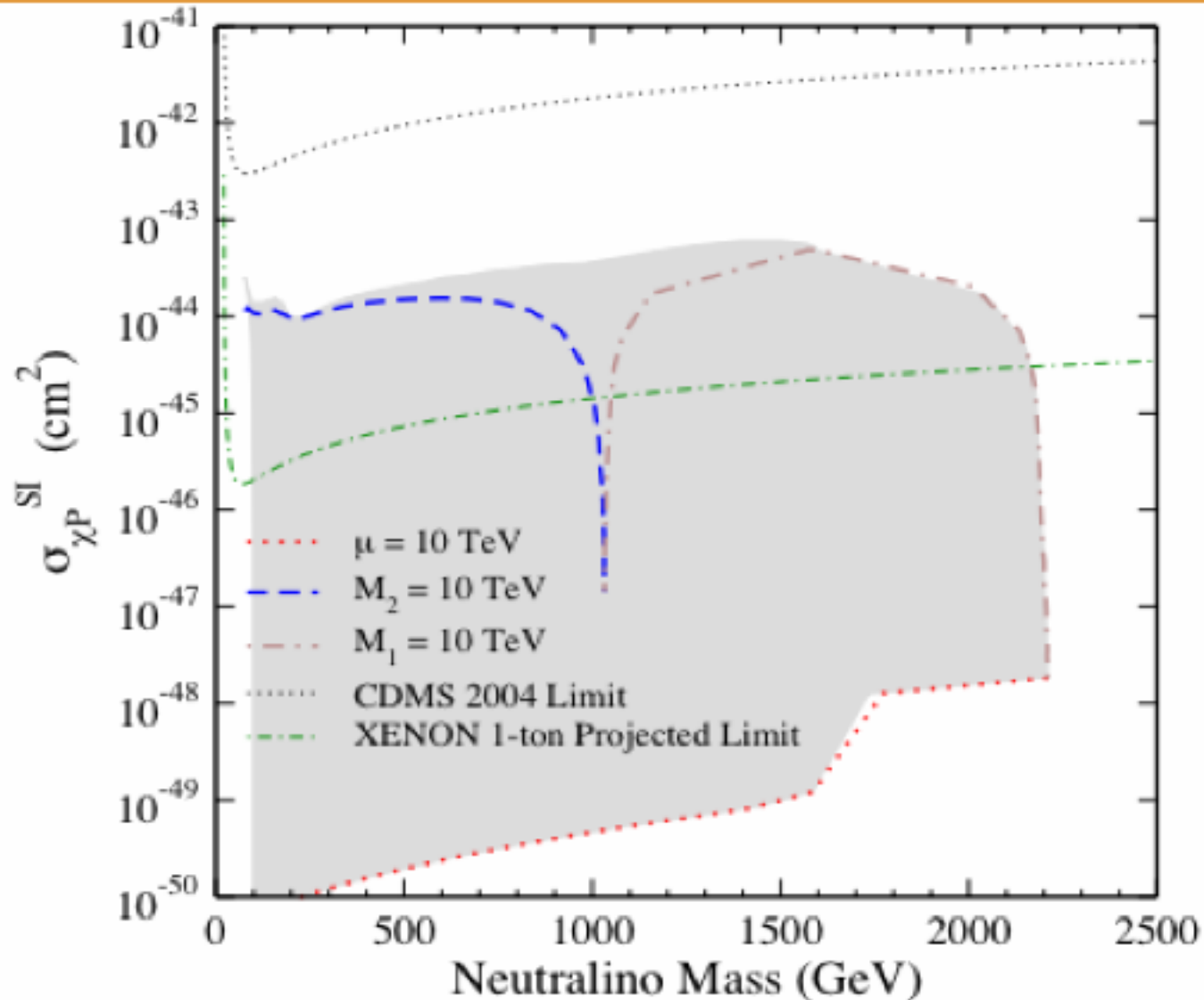
Ellis et al.



# LHC, ILC, DM SEARCHES SENSITIVITIES

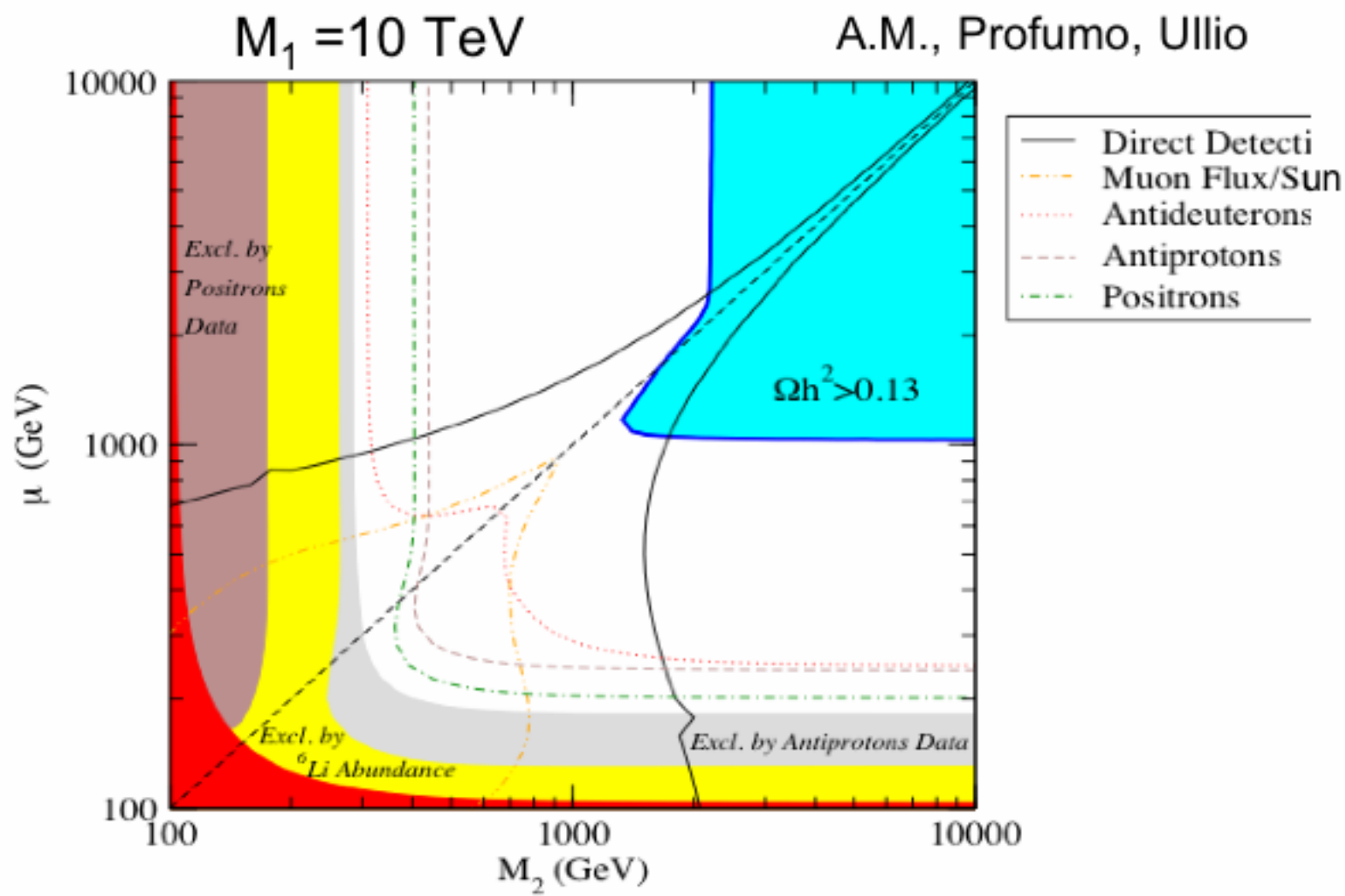


# PRESENT AND NEXT GENERATION DM SEARCHES (TeV SUSY case)

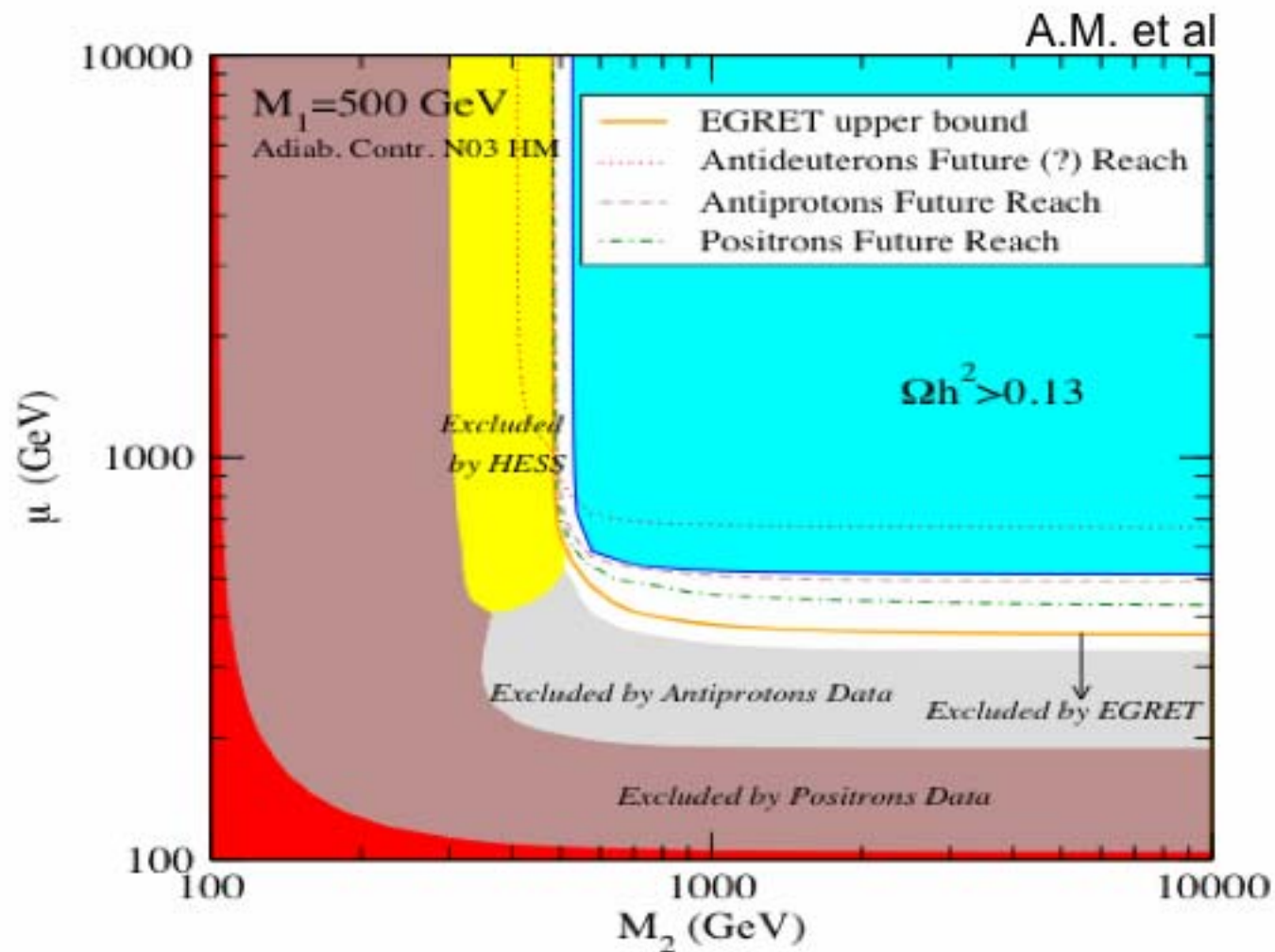


A.M,  
Profumo,  
Ullio

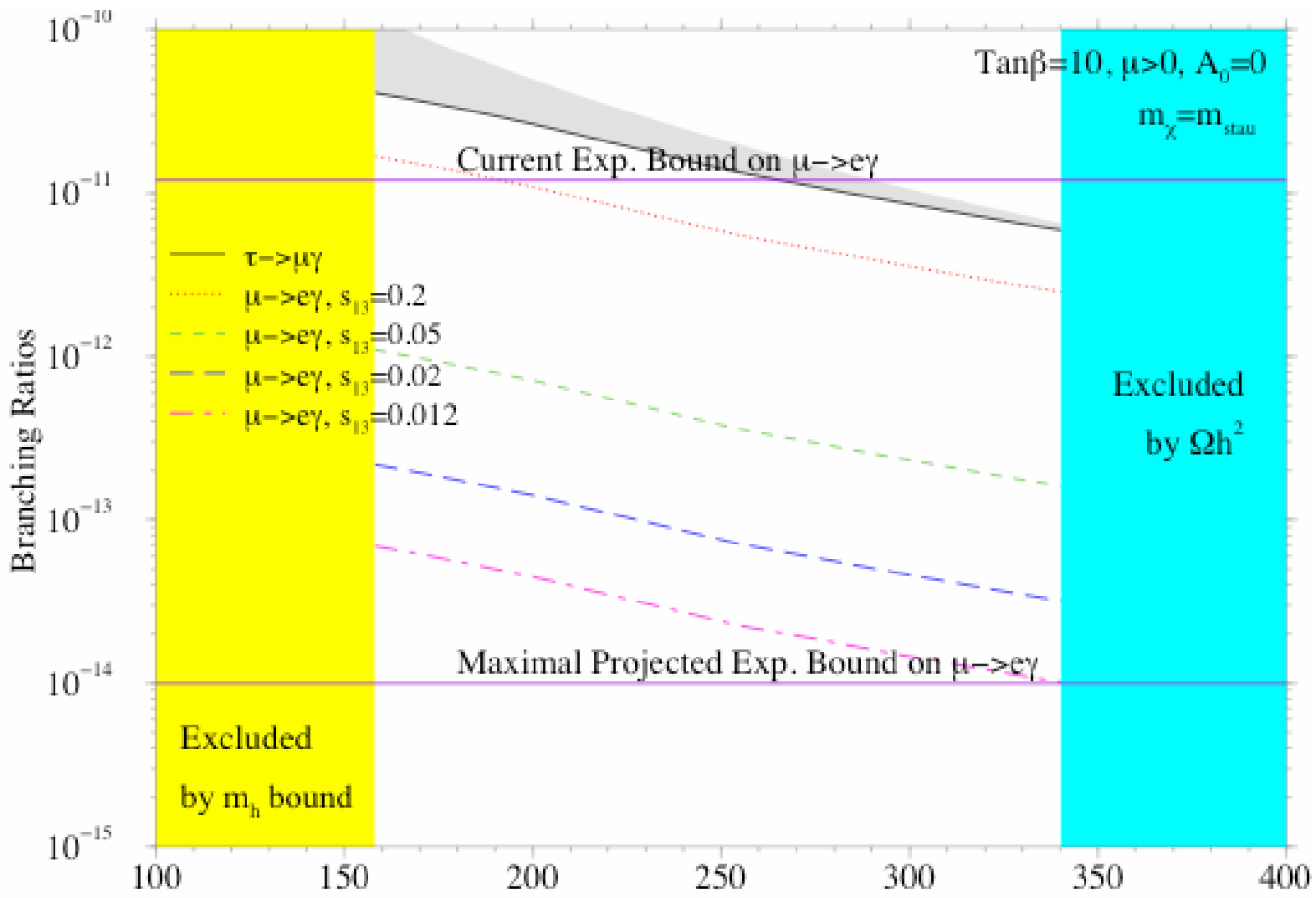
# COMPLEMENTARITY OF DIRECT AND INDIRECT DM SEARCHES



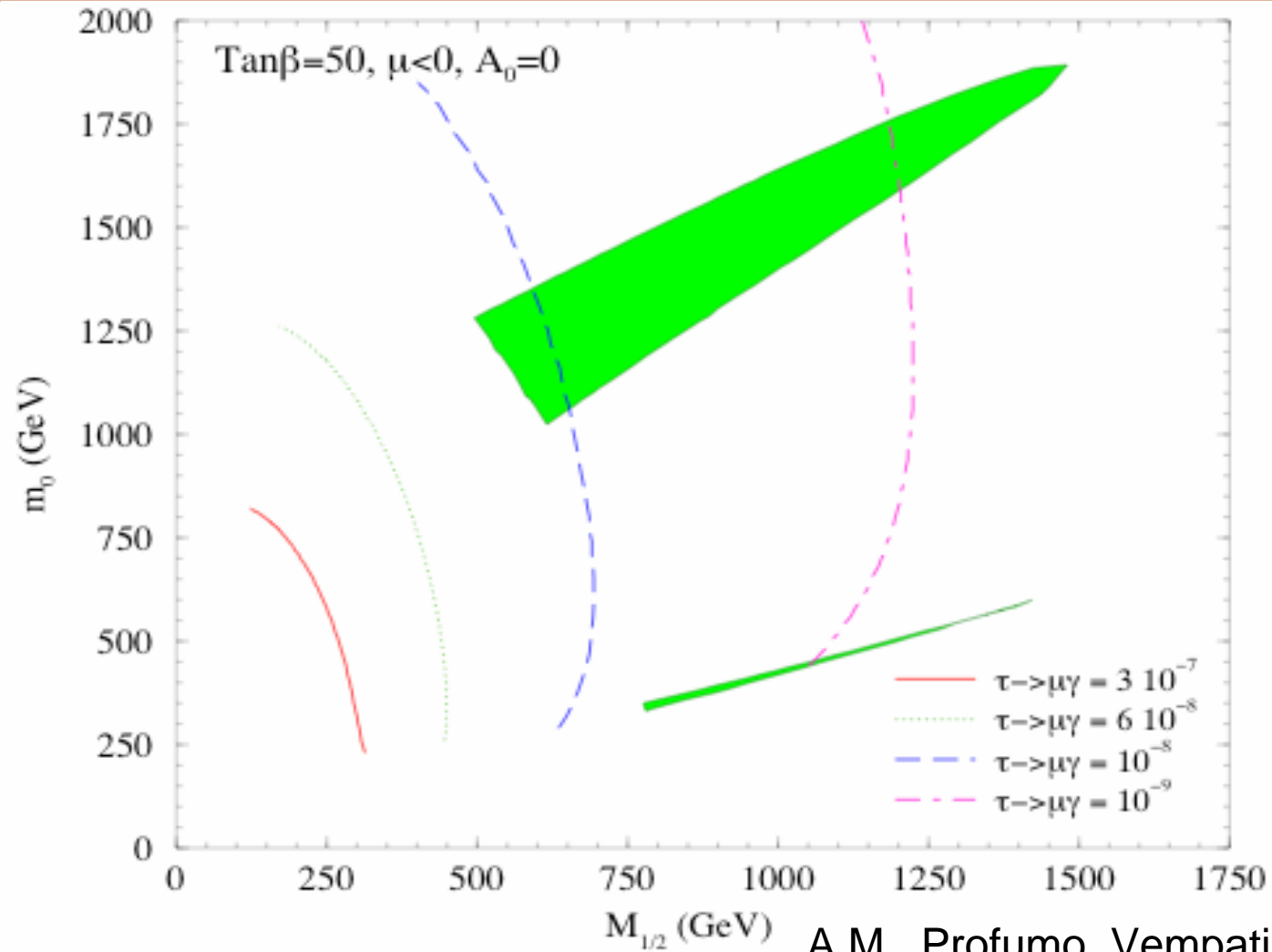
# EXPLORATION OF THE SUSY PARAMETER SPACE USING DIRECT AND INDIRECT DM SEARCHES



# PROBING SUSY THROUGH LFV



# LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY



A.M., Profumo, Vempati, Yaguna

# SEARCHING FOR WIMPs

## WIMPS HYPOTHESIS

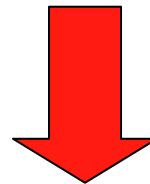
DM made of particles with  
mass 10Gev - 1Tev

ELW scale

With WEAK INTERACT

LHC, ILC may  
PRODUCE WIMPS

WIMPS escape the detector  
→ MISSING ENERGY  
SIGNATURE

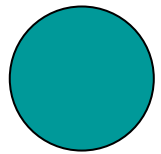


FROM "KNOW" COSM. ABUNDANCE OF WIMPs → PREDICTION  
FOR WIMP PRODUCTION AT COLLIDERS WITHOUT SPECIFYING  
THE PART. PHYSICS MODEL OF WIMPs

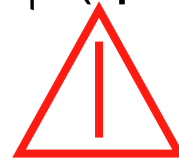
BIRKEDAL, MATCHEV, PERELSTEIN,  
FENG, SU, TAKAYAMA



DO THEY "KNOW" EACH OTHER?



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

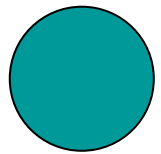


DANGER:

$\phi$  Very LIGHT

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

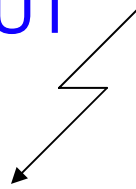
→ Threat of violation of the equivalence principle  
constancy of the fundamental "constants",...



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

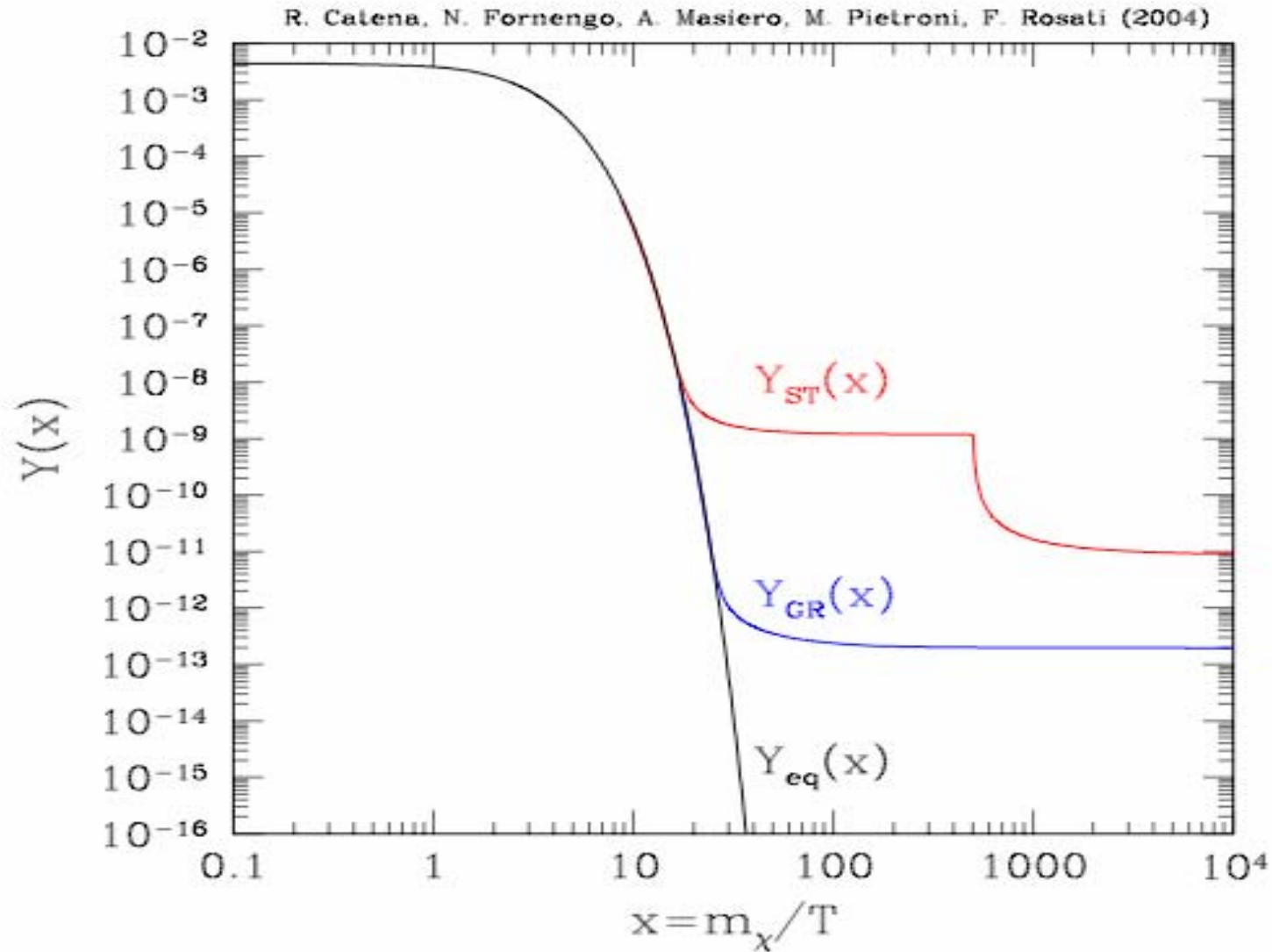
Modifications of the standard picture of  
WIMPs FREEZE - OUT

CDM CANDIDATES





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



LHC

NEW  
PHYSICS AT  
THE ELW .  
SCALE

DARK MATTER

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

LINKED TO COSMOLOGICAL EVOLUTION

→ Possible interplay with dynamical DE

"LOW ENERGY"

PRECISION PHYSICS

FCNC, CP  $\neq$ , (g-2),  $(\beta\beta)_{0\nu\nu}$ ,  
 $m\nu$ ,  $\theta_{13}$ ,

# BACK-UP SLIDES

# Large Hadron collider (LHC) at CERN

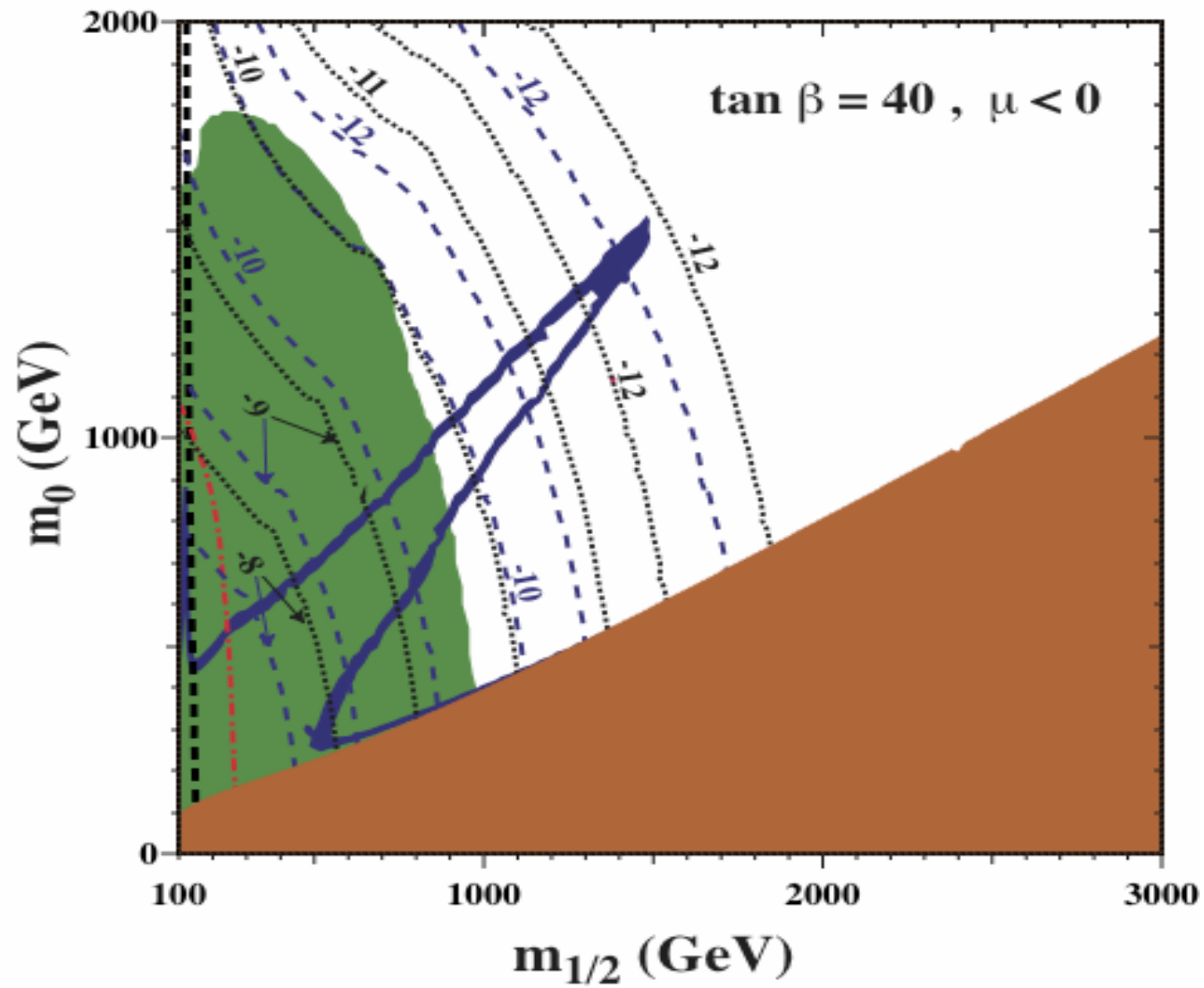
QuickTime™ and a  
TIFF (LZW) decompressor  
are needed to see this picture.



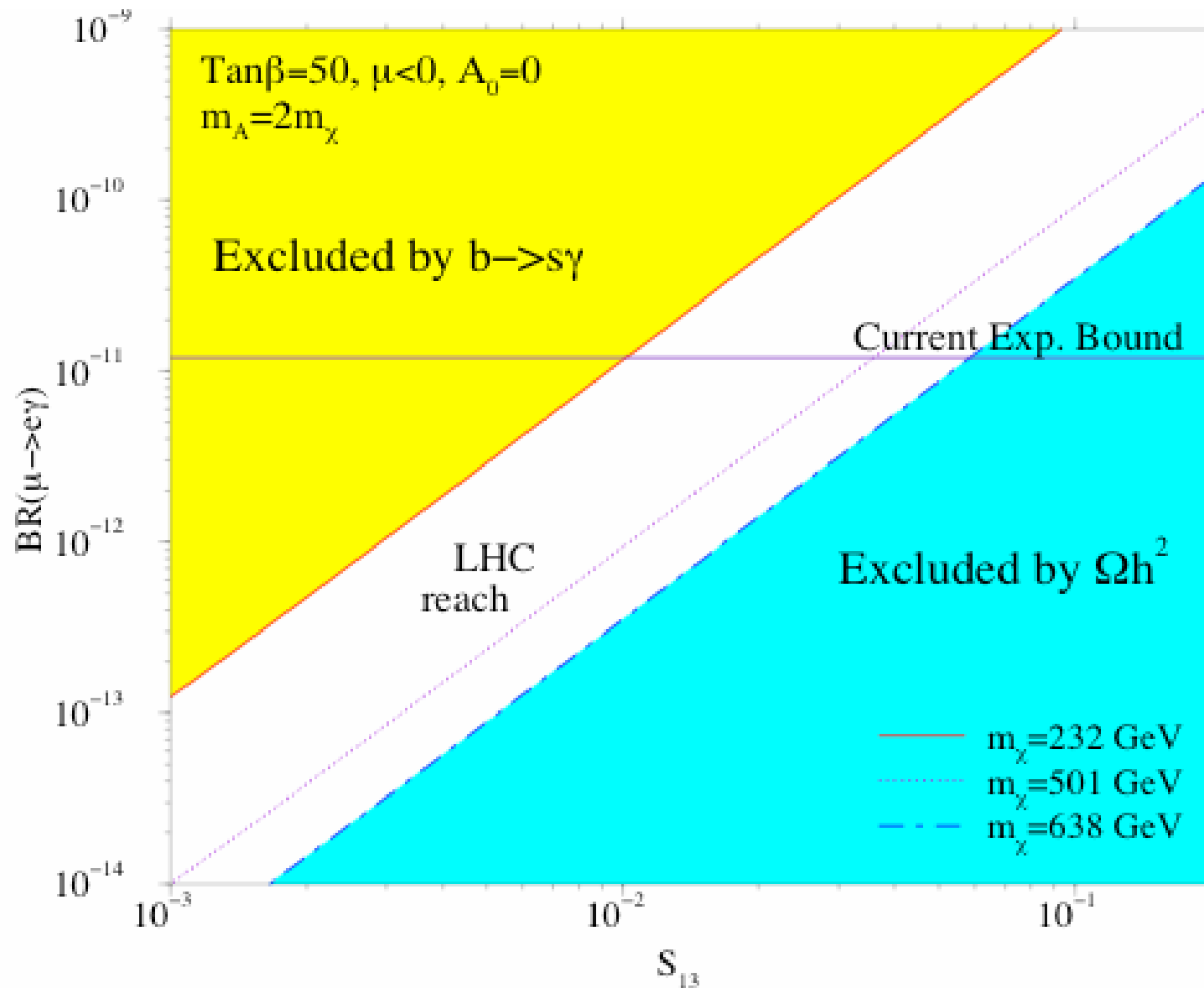
# PROBING SUSY THROUGH ANTIMATTER SEARCHES

QuickTime™ and a  
TIFF (LZW) decompressor  
are needed to see this picture.

# Tightness ...3

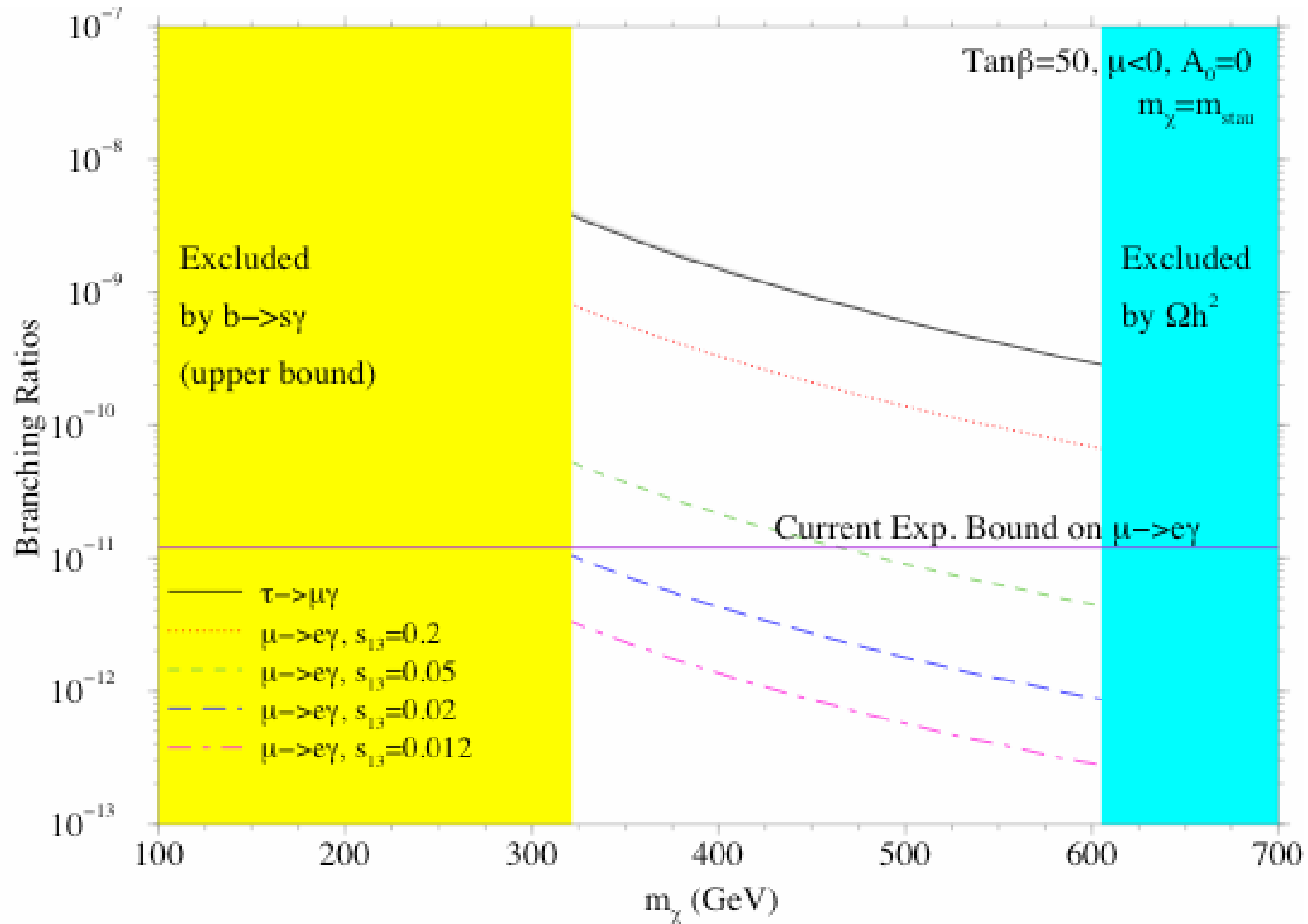


# LHC REACH VS. LFV SENSITIVITY

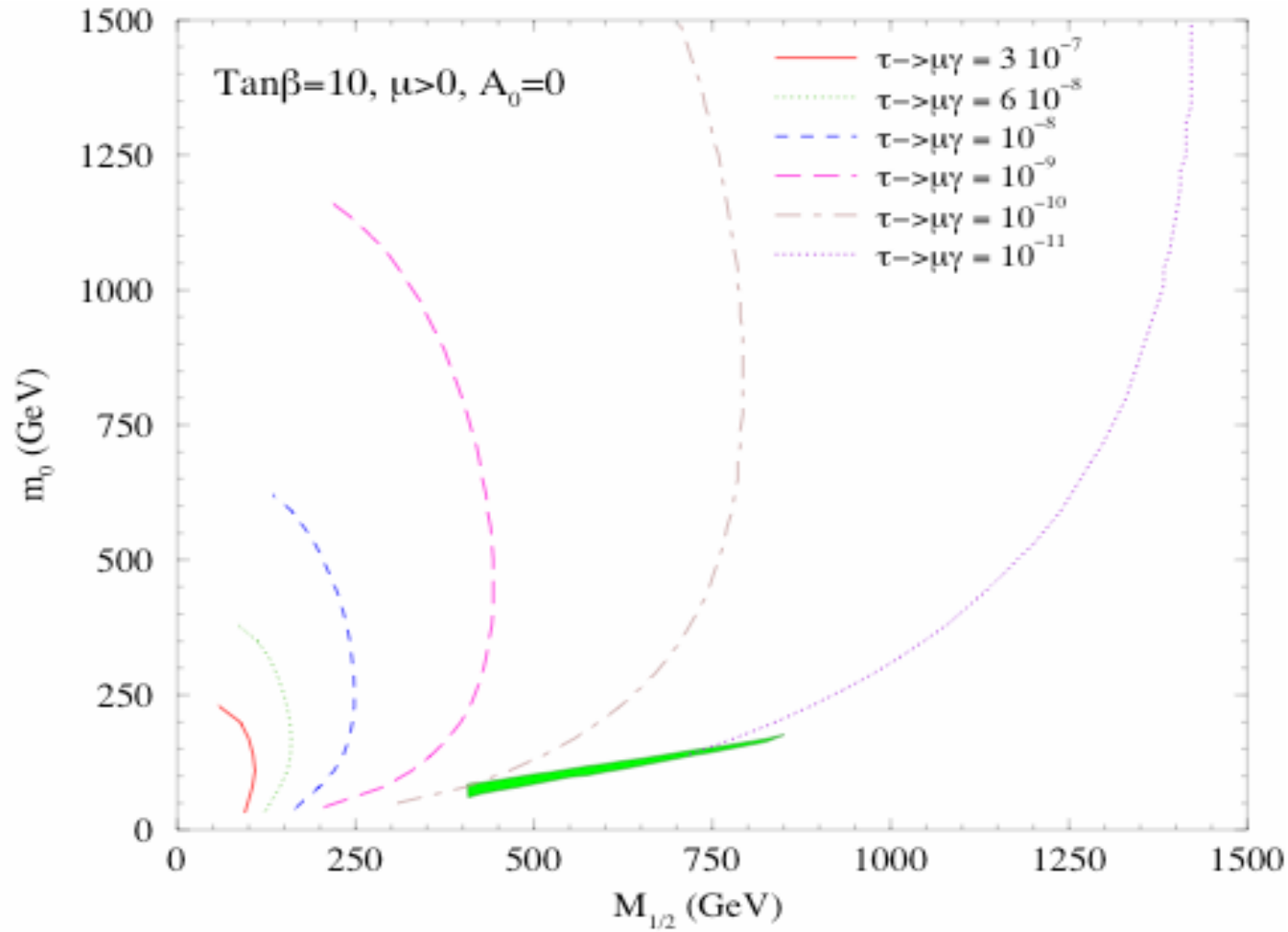




# PROBING SUSY THROUGH LFV 2



# LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY



# Searching for New Physics at the Fermi Scale

## Colliders at Fermi Scale



LEP



HERA



TEVATRON

FERMILAB

-> e+e- collider(2000)  
 $E_{cm}=90-209$  GeV  
 Lumi= $900 \text{ pb}^{-1}/\text{exp.}(\text{phys})$   
 ALEPH, DELPHI  
 L3, OPAL

SLC: polarized e+e-  
 at Z peak



-> e<sup>±</sup>p collider  
 $E_{cm}=320$  GeV  
 H1, ZEUS  
 HERA I  $120 \text{ pb}^{-1}/\text{expt}(\text{phys.})$   
 HERA II 2007 ->  $700 \text{ pb}^{-1}(\text{delivered}, e^{\pm}, \pm P_e)$

-> pp̄ collider: CDF, D0

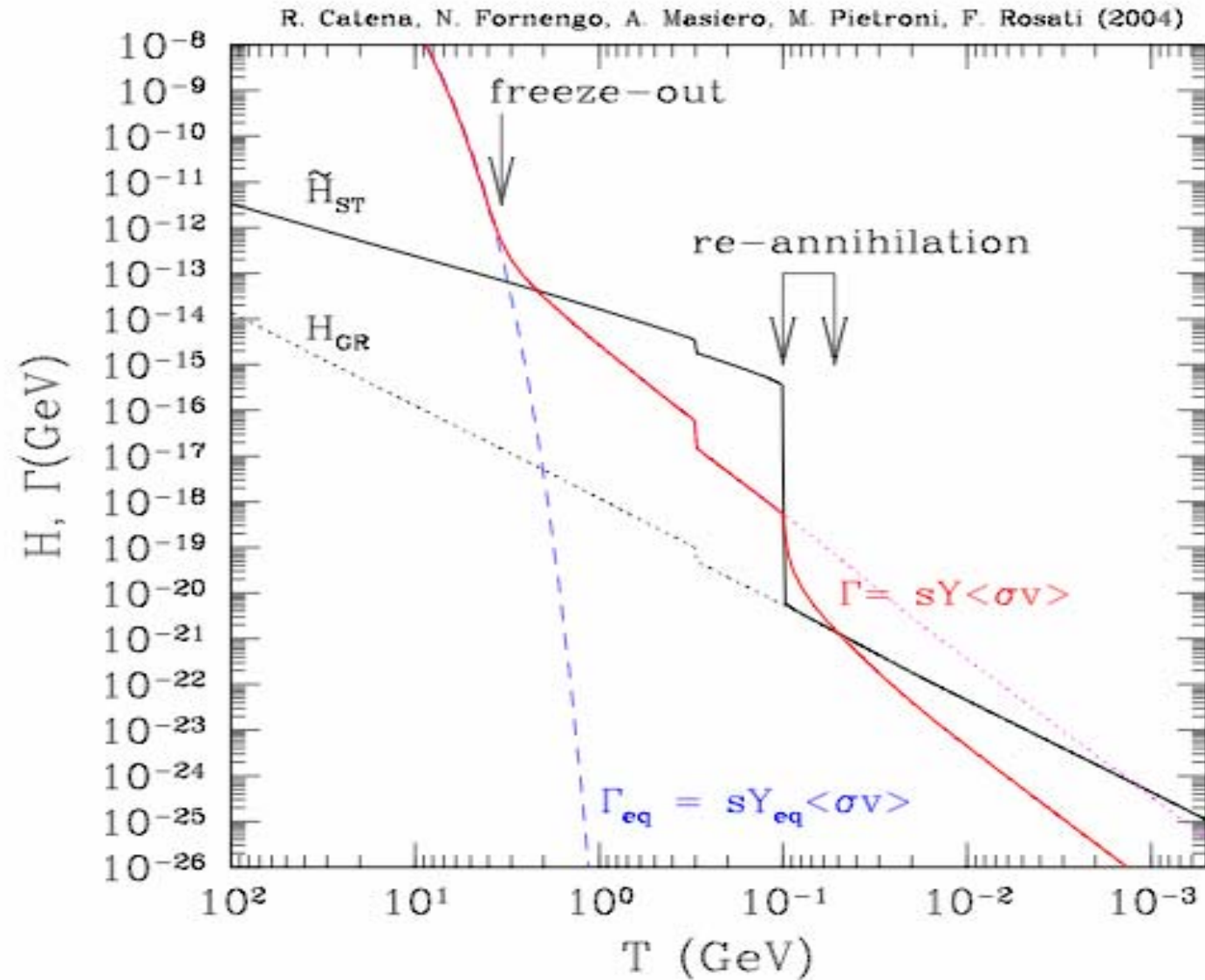
Run I  $E_{cm}=1.8$  TeV  
 $130 \text{ pb}^{-1}/\text{exp.}(\text{phys.})$

Run II  $E_{cm}=1.96$  TeV  
 $1 \text{ fb}^{-1}$  delivered

2009 ->  $4-8 \text{ fb}^{-1}$

Many other interesting results from lower energy facilities

# FREEZE-OUT IN SCALAR-TENSOR THEORIES OF GRAVITY



# The anomalous magnetic moment of the muon

## *The BNL g-2 experiment*

Theory for Muon ( $g - 2$ )

