IFAE 2007, Napoli

FISICA DEL NEUTRINO

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WHY TO GO BEYOND THE SM

"OBSERVATIONAL" REASONS

•HIGH ENERGY PHYSICS

NO (but $A_{FB}^{Z \to bb}$……)

•FCNC, CP≠

NO (but $b \to s\bar{q}q$ penguin, V_{ub} …)

•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 A "FUNDAMENTAL" THEORY

YES (hierarchy, unification, flavor)

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

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 !

Neutrino Physics: **FACTS (I)**

- ν_μ : THEY DISAPPEAR!

  - EVIDENCE AT >15 σ IN ATMOSPHERIC ν_μ (most likely ν_μ --> ν_τ)

  - K2K: ν_μ disappear at L~250 Km (~2.5-4 σ)

  - MINOS: ν_μ disappear at L~750 Km with E-distortion (~5 σ)

–

K2K	ν_μ at KEK	SK	L=250 km
MINOS	ν_μ at Fermilab	Soundan	L=735 km
Opera	ν_μ at CERN	Gran Sasso	L=740 km

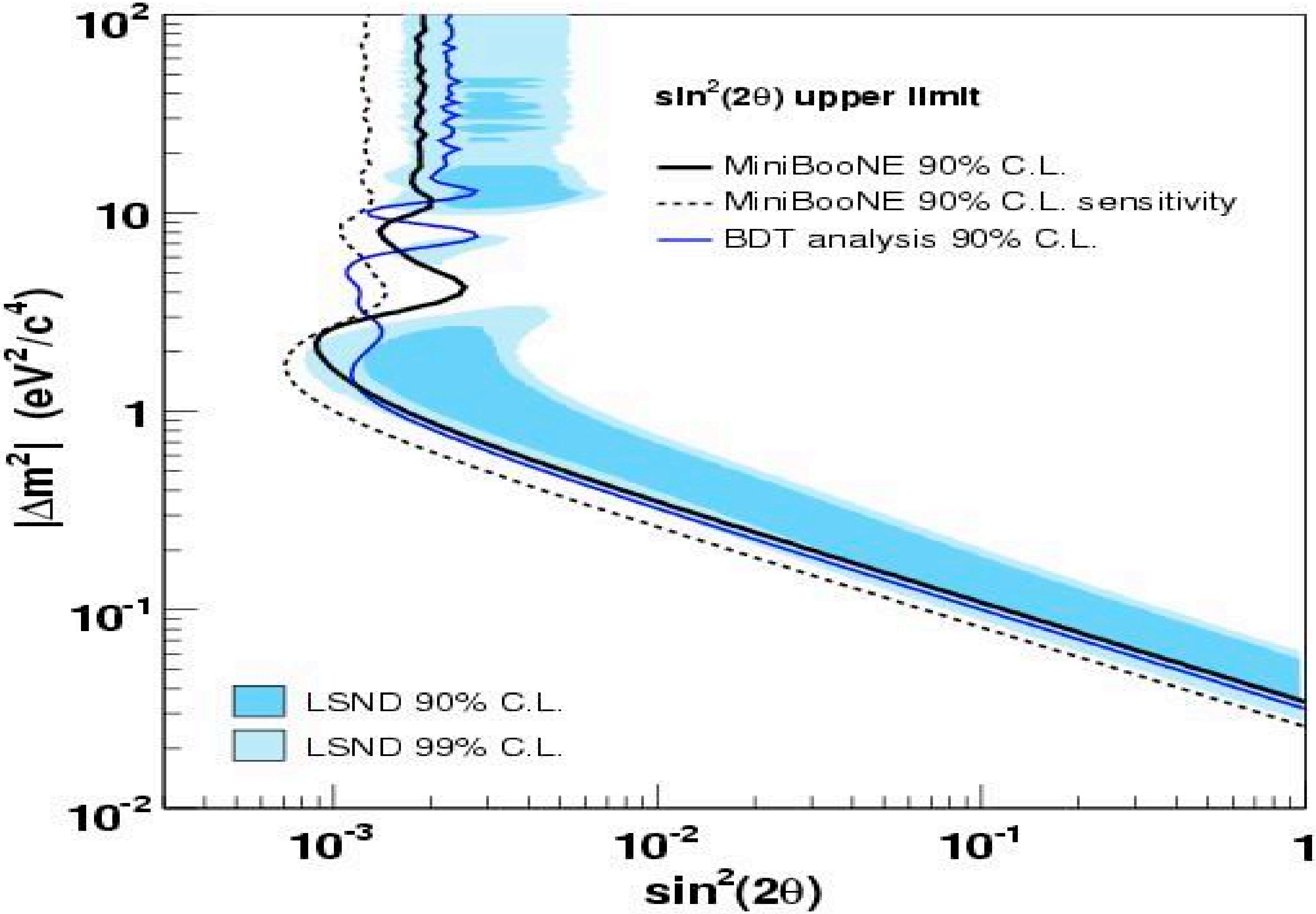
Neutrino Physics: **FACTS (II)**

- ν_e : THEY DISAPPEAR!

  - SOLAR ν_e conversion at $>7\sigma$ (--> ν_μ or ν_τ)
  - KamLAND: reactor $\overline{\nu_e}$ disappear at L ~ 200 Km with E-distortion ($> 3\ \sigma$)

? Pending verdict: LSND found evidence for $\overline{\nu_\mu}$ --> $\overline{\nu_e}$
WAITING FOR MINIBOONE TO TELL US WHAT THEY FOUND IN THE EASTER BOX THEY'VE JUST OPENED!

MiniBooNE researchers showed **conclusively** that the **LSND results could not be due to simple neutrino oscillation**
April 11, 2007 press release



Neutrino Physics: Interpretation of the Facts

- **Neutrino Oscillation is the DOMINANT source of neutrino disappearance** with possible SUBDOMINANT non-oscillatory contributions

- **Energy Dependence** is the major discrimination in favor of the oscillatory explanation:

  - ν decay, ν decoherence, Lorentz invariance violation, non-standard flavor changing ν interactions are all condemned to be subleading effects because they do not account for the observed E dependence of the observed events

- Non-oscillatory explanations for the solar neutrino deficit - mass vaying neutrinos as well as non-standard flavor changing ν interactions and spinflavor precession - fail to account for the solar neutrino data **AND** the KamLAND results at the same time

- **Non-unitarity** of the U neutrino mixing matrix is limited by ν oscillations, W,Z universality tests and LFV to few percent

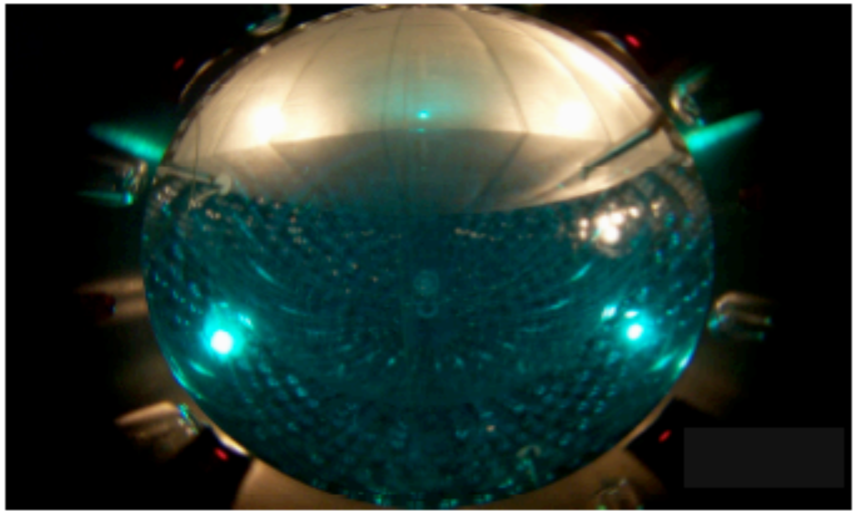
Borexino

Real-time measurement of the solar ^{7}Be neutrino flux

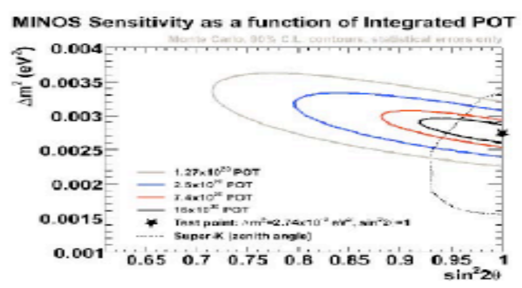
Day-night, seasonal, periodic variations

Detector filling complete in May 2007

Borexino (Oct. 2006)

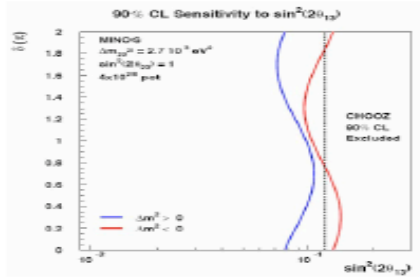


MINOS & OPERA



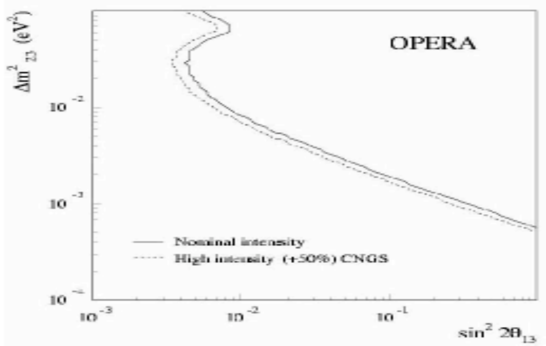
MINOS ν_μ CC (4×10^{20} POT) Can improve limit of CHOOZ

5-10 % error on Δm^2



Harris@win07

5 years of nominal CNGS beam



Sirignano@neutrino2006

Dal talk di Marrone di ieri

THE LOW-ENERGY 6 PARAMETERS OF NEUTRINO PHYSICS

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Delta m^2_{21} = 7.9\,^{+0.27}_{-0.28}\,\left(^{+1.1}_{-0.89}\right) \times 10^{-5}\ \mathrm{eV}^2 \qquad \left|\Delta m^2_{31}\right| = 2.6 \pm 0.2\,(0.6) \times 10^{-3}\ \mathrm{eV}^2$$

$$\theta_{12} = 33.7 \pm 1.3\,\left(^{+4.3}_{-3.5}\right) \qquad \theta_{23} = 43.3\,^{+4.3}_{-3.8}\,\left(^{+9.8}_{-8.8}\right)$$

$$\theta_{13} = 0\,^{+5.2}_{-0.0}\,\left(^{+11.5}_{-0.0}\right) \qquad \delta_{\rm CP} \in [0, 360]$$

Concha Gonzalez-Garcia 07

$$|U|_{3\sigma} = \begin{pmatrix} 0.79 \to 0.86 & 0.50 \to 0.61 & 0.00 \to 0.20 \\ 0.25 \to 0.53 & 0.47 \to 0.73 & 0.56 \to 0.79 \\ 0.21 \to 0.51 & 0.42 \to 0.69 & 0.61 \to 0.83 \end{pmatrix}$$

Bari group at ν Telescopes 07

$$\delta m^2 = 7.92\,(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2 = 2.6\,(1^{+0.14}_{-0.15}) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.314\,(1^{+0.18}_{-0.15})$$

$$\sin^2\theta_{23} = 0.45\,(1^{+0.35}_{-0.20})$$

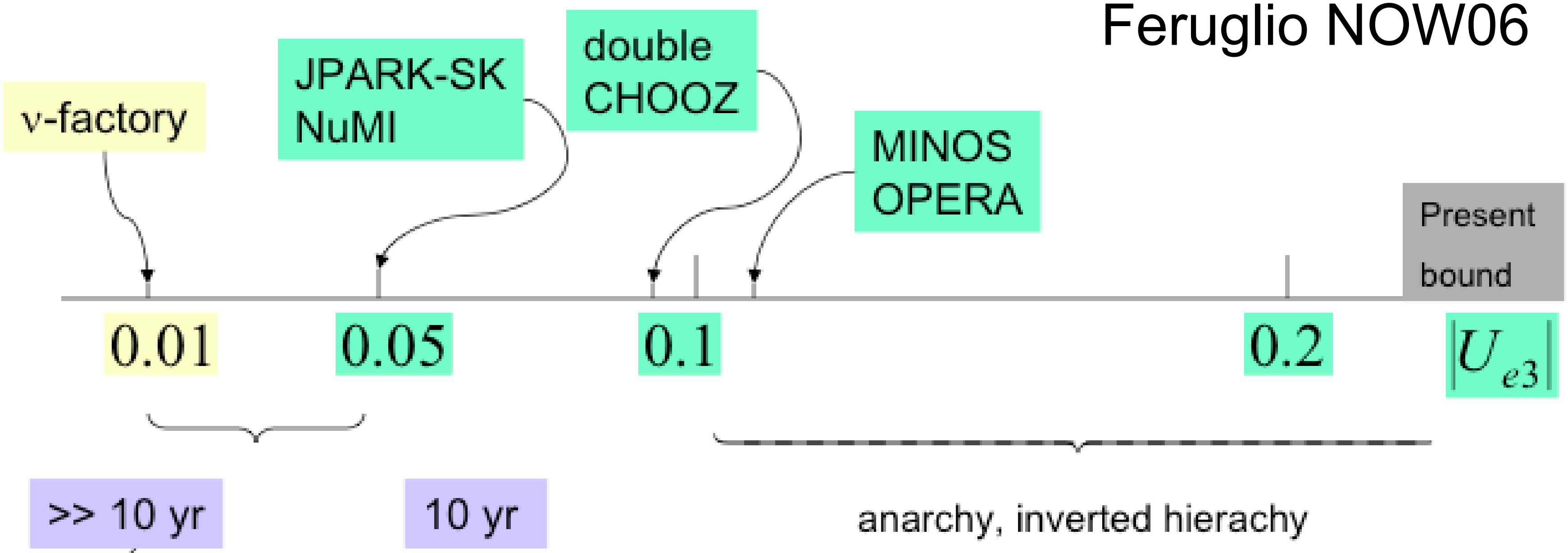
$$\sin^2\theta_{13} < 3.1 \times 10^{-2} \quad \text{(only upper bound)}$$

CP violating phase δ : unknown

mass spectrum hierarchy : unknown

- Most of plausible range for Ue3 explored in 10 yr from now

Feruglio NOW06



|Ue3|<0.05 would select a very narrow (not empty) subset of existing models

similar conclusion by:
Barbieri, Hambye, Romanino 0302118
Ibarra, Ross 0307051
Chen, Mahanthappa 0305088
Lebed, Martin 0312219
Joshipura @ NOON 2004

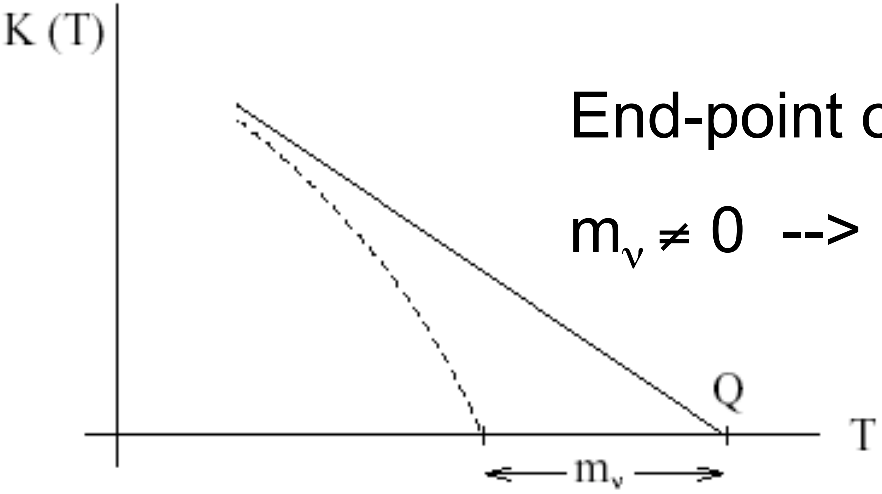
NEUTRINOS: WHAT WE'LL KNOW

Present and Future of Neutrino Parameters

Concha Gonzalez-Garcia 07

3-ν parameter	Present knowledge ($\sim 3\sigma$ C. L.)	Near and Not so Near Future
θ_{12}	$0.34 \leq \tan^2\theta_{12} \leq 0.61$	KamLAND, Future LE Solar
θ_{23}	$0.47 \leq \tan^2\theta_{23} \leq 1.8$	$P(\nu_\mu \to \nu_\mu)$ MINOS, OPERA
θ_{13}	$\sin^2\theta_{13} \leq 0.04$	$P(\bar{\nu}_e \to \bar{\nu}_e)$ Reactor, $P(\nu_\mu \to \nu_e)$ LBL
$\lvert\Delta m^2_{21}\rvert$	$7.0 \leq \Delta m^2_{21}/10^{-5}\text{eV}^2 \leq 9.0$	$P(\bar{\nu}_e \to \bar{\nu}_e)$ KamLAND
$\lvert\Delta m^2_{31}\rvert$	$2.4 \leq \lvert\Delta m^2_{31}\rvert/10^{-3}\text{eV}^2 \leq 3.2$	$P(\nu_\mu \to \nu_\mu)$ MINOS, OPERA LBL
$\text{sgn}(\Delta m^2_{31})$	unknown	$P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ LBL
δ	unknown	$P(\nu_\mu \to \nu_e)$ versus $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ LBL
Majorana	unknown	$0\nu\beta\beta$
m_ν	$\sum m_\nu < \mathcal{O}(1)$ eV	β-decay, $0\nu\beta\beta$

ON THE ABSOLUTE SCALE OF NEUTRINO MASSES



End-point of the Tritium β decay spectrum:

$m_\nu \neq 0$ --> distortion from the straight line

$$m_{\nu_e}^{eff} \equiv \sqrt{\sum m_j^2 |U_{ej}|^2} < 2.2 \text{ eV} \quad \text{(at 95 \% CL)}$$

(Mainz & Troisk experiments)

KArlsruhe TRItium Neutrino experiment - KATRIN

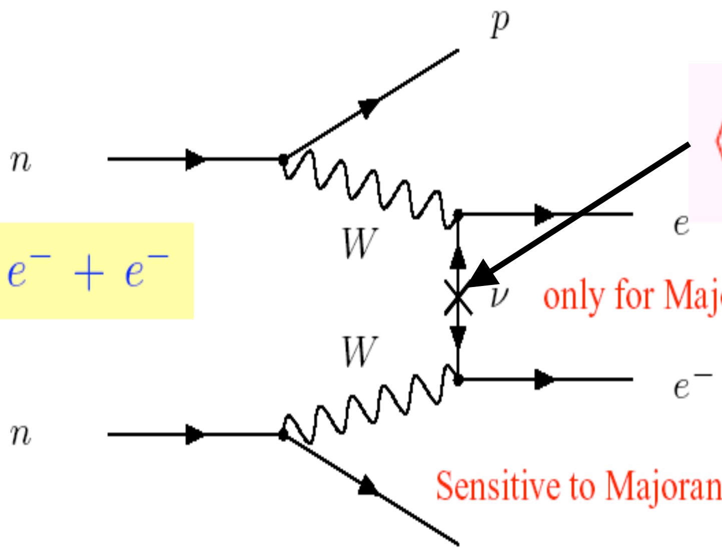
Planned sensitivity ~ 0.3 eV

First data Fall 2009

Full sensitivity 2015

MAJORANA OR DIRAC?

$$(A, Z) \to (A, Z+2) + e^- + e^-$$



$$\langle m_{ee} \rangle = |\sum U_{ej}^2 m_j|$$

If only the neutrino Majorana mass is responsible for the $\Delta L = 2$ jump → Neutrinoless double β decay rate is ∝ $\langle m_{ee} \rangle^2$

Present bound: $|\langle m_{ee} \rangle| < 0.35$ eV +theor. uncert.

At 90% C.L.

IGEX: < 0.33 -1.35 eV

Cuoricino: < 0.2 - 1.1 eV

Mainly on the nuclear matrix elements

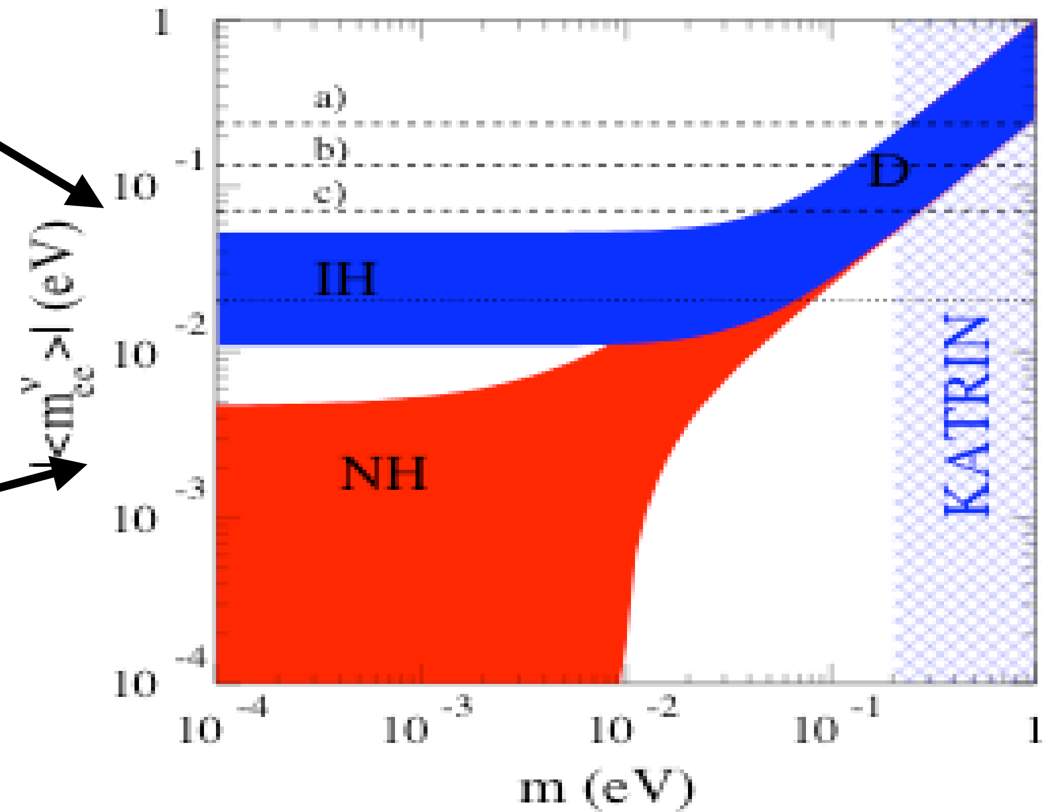
CLAIM :mν(eV)=0.24-0.58 (99.997% C.L.) Klapdor et al.

CUORE	^{130}Te	(30-50) meV
Majorana	^{76}Ge	(20-70) meV
GERDA	^{76} Ge	(90-290) meV (phase II)
		10 meV (phase III ?)

Allowed region at 90% c.l. for inverted hierarchy and degenerate neutrinos

Feruglio, Strumia, Vissani; Pascoli, Petcov; Bahcall, Murayama, Pena-Garay

Allowed region at 90% c.l. for normal hierarchy



Cosmological (Active) Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1 MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

That, for a massive neutrino translates in:

$$\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \approx \frac{1}{h^2}\frac{m_k}{92.5 eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum_k m_k}{92.5 eV}$$

Melchiorri Venice07

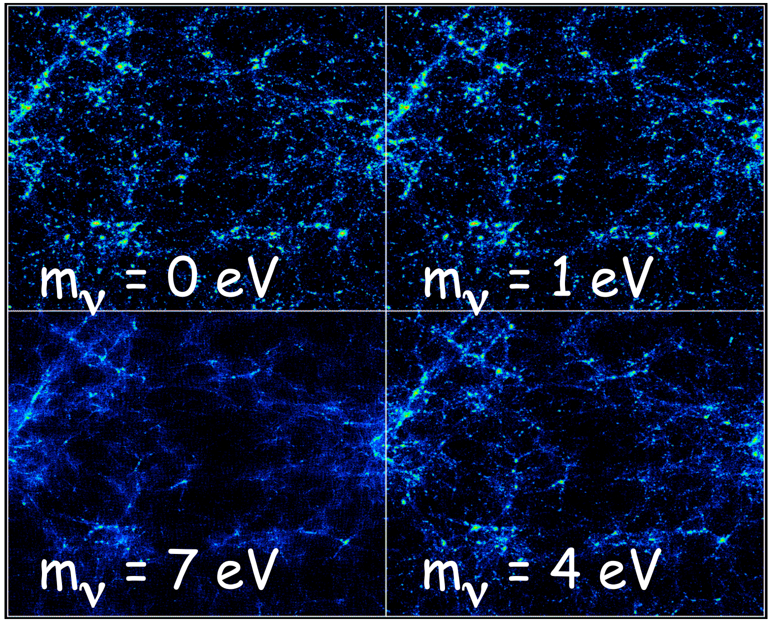
THE RISE AND FALL OF NEUTRINOS AS DARK MATTER

- 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

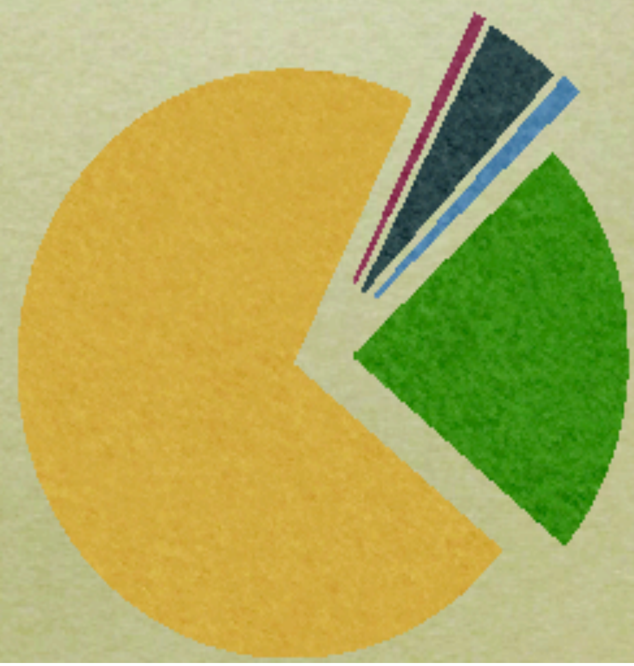
LSS PATTERN AND NEUTRINO MASSES

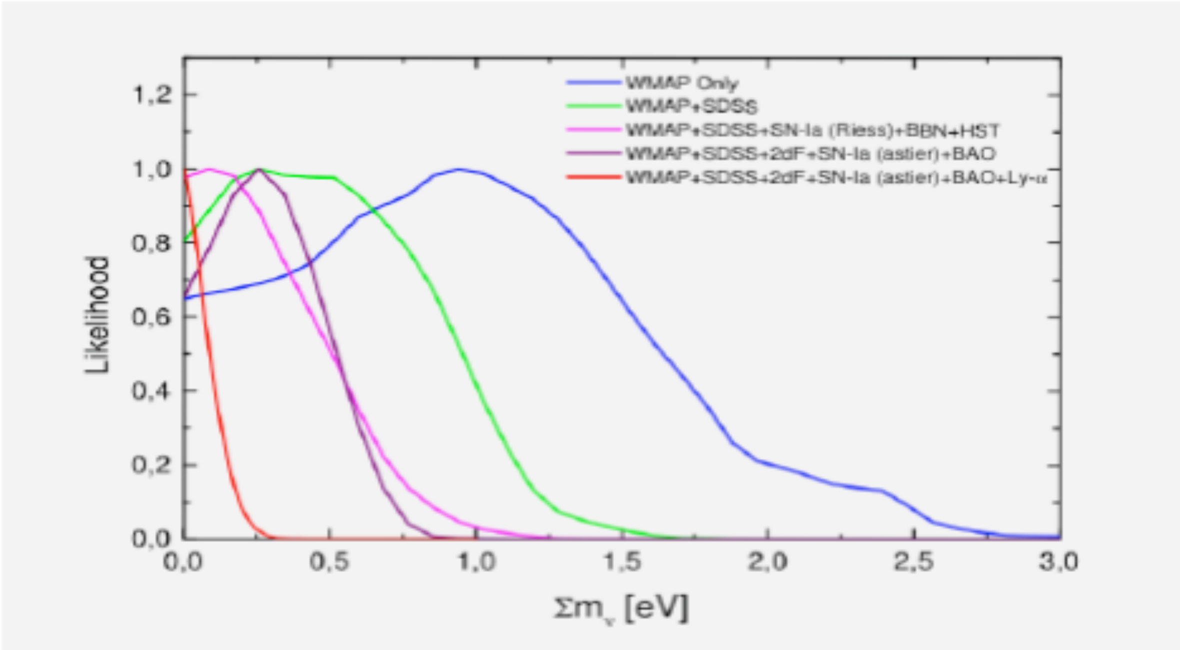


(E..g., Ma 1996)

THE UNIVERSE ENERGY BUDGET

- *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*
  $\sim 10^{62}$*%??*





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)

Neutrinos are MASSIVE: New Physics IS there!

Is the above a TRIVIAL statement?

→ SM built to have massless neutrinos (no RH neutrino, no isospin triplet scalar higgs)

→ find that neutrinos are massive and claim that you have discovered New Physics!

- NO, NEUTRINO MASS IS "REAL" NP WITH A NEW ENERGY SCALE ASSOCIATED TO IT

THE FATE OF LEPTON NUMBER

L VIOLATED → υ Majorana ferm.

L CONSERVED → υ Dirac ferm. (dull option)

$h\,\bar{\upsilon}_L H\,\upsilon_R \rightarrow m_\upsilon = h\,\langle H\rangle$ $M_\upsilon < 1\,\text{eV} \rightarrow h < 10^{-11}$

EXTRA-DIM. ν_R in the bulk: small overlap?

SMALLNESS of m_υ

↓

PRESENCE OF A NEW PHYSICAL MASS SCALE

NEW HIGH SCALE → SEE - SAW MECHAN.

Minkowski; Gell-Mann, Ramond, SlansKy, Vanagida

↓

ν_R ENLARGEMENT OF THE FERMIONIC SPECTRUM

$M\upsilon_R\upsilon_R + h\,\bar{\upsilon}_L\,\bar{\phi}\,\upsilon_R$

	υ_L	υ_R
υ_L	~O	$h\langle\bar{\phi}\rangle$
υ_R	$h\langle\bar{\phi}\rangle$	M

LR Models?

NEW LOW SCALE → MAJORON MODELS

Gelmini, Roncadelli

↓

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

$h\,\upsilon_L\upsilon_L\,\Delta$

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

N.B.: EXCLUDED BY LEP!

The Energy Scale from the "Observational" New Physics

- neutrino masses
- dark matter
- baryogenesis
- inflation

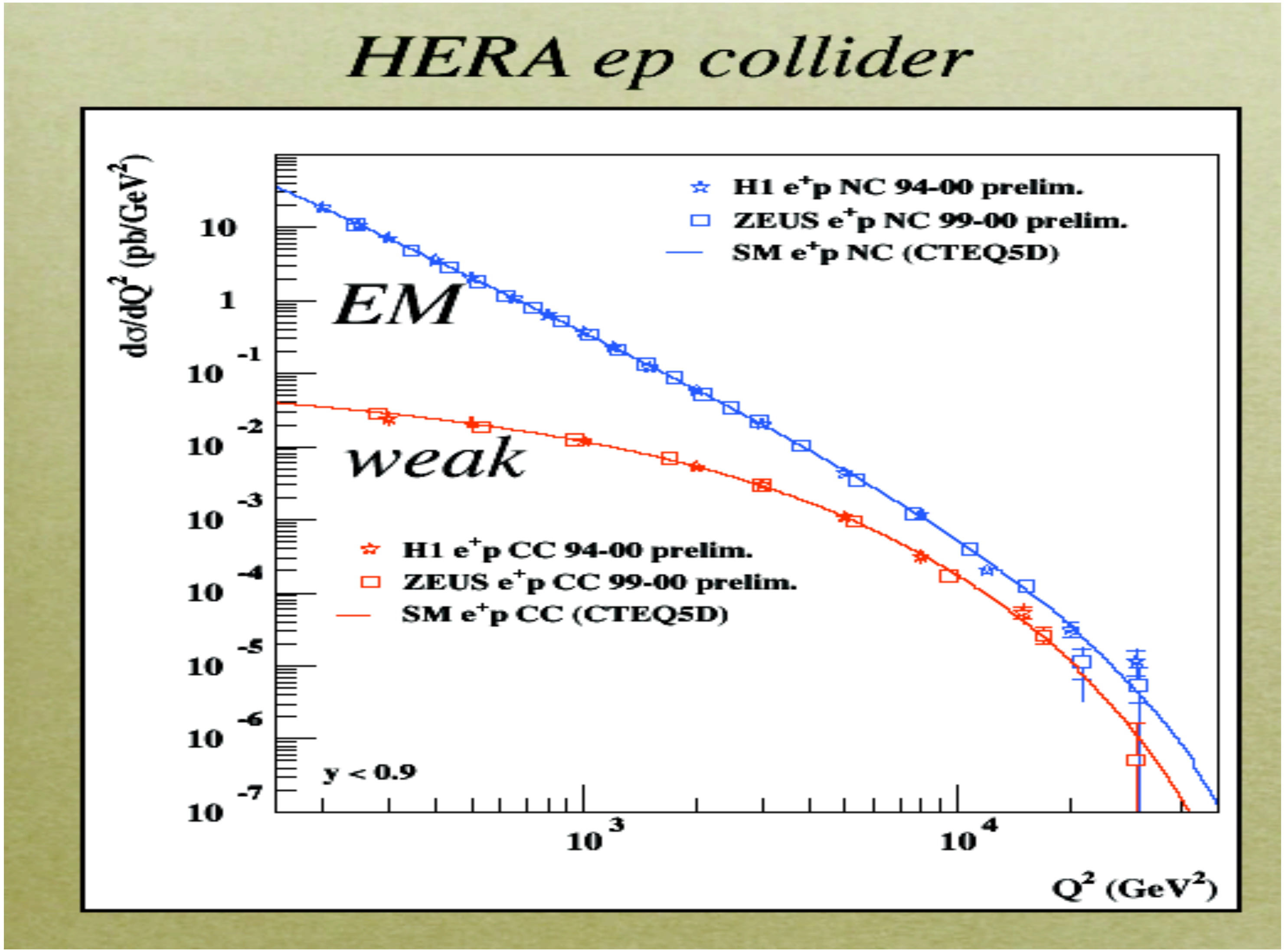
→ NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the "Theoretical" New Physics

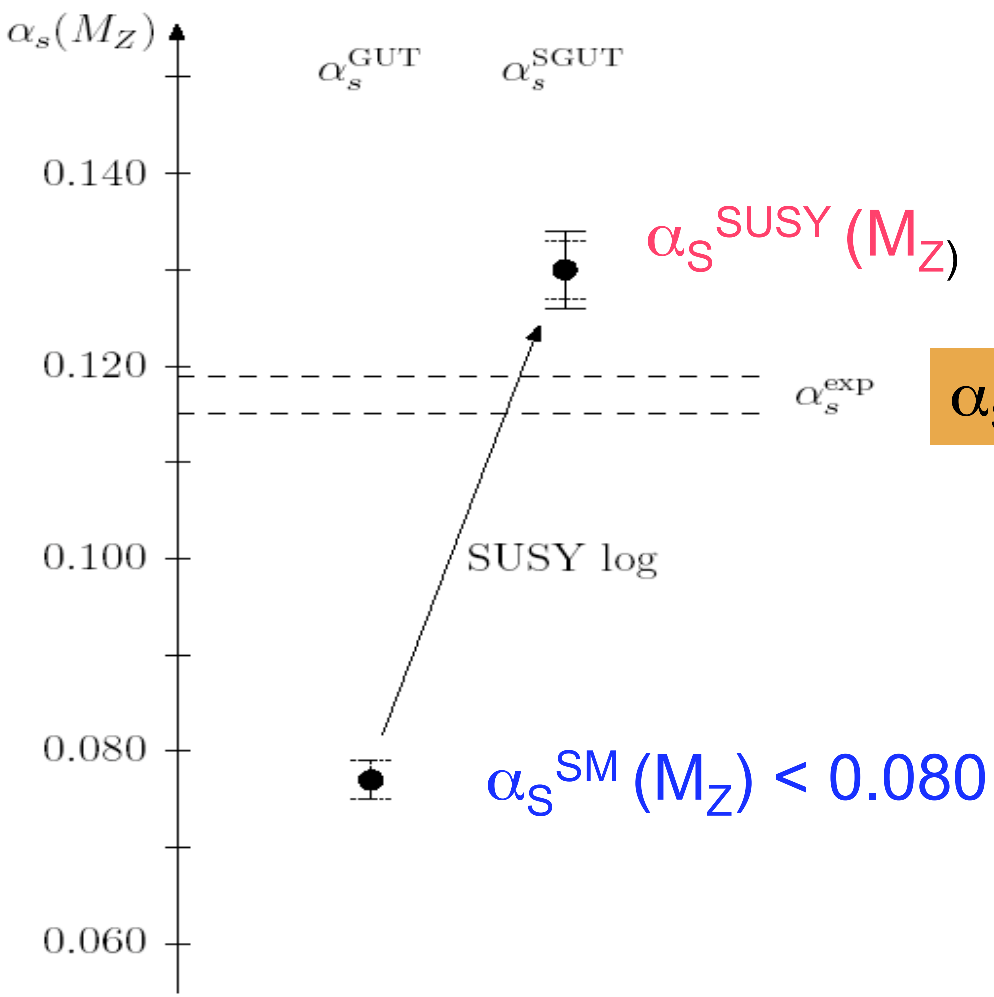
☆ ☆ ☆ Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale +

☆ CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE

Fundamental COUPLING CONSTANTS are NOT CONSTANT



Fundamental interactions unify



$\alpha_S^{exp}(M_Z)=0.117\pm0.002$

Hall, Nomura

STABLE ELW. SCALE WIMPs from PARTICLE PHYSICS

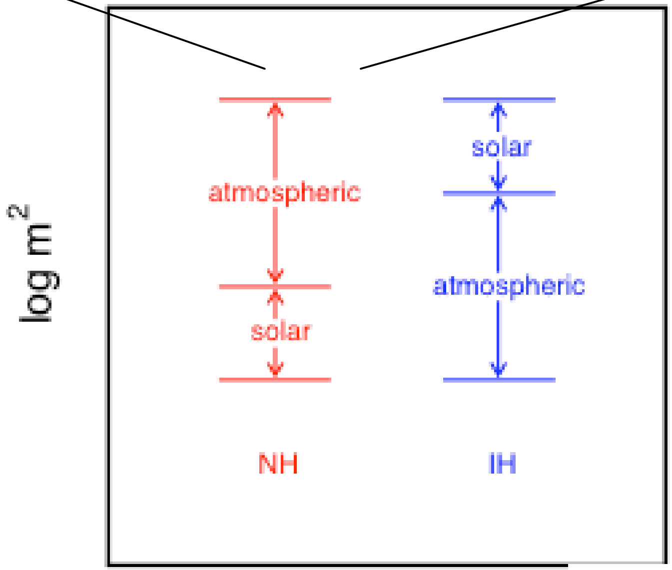
	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) ENLARGEMENT OF THE SM	(x^{μ}, θ) Anticomm. Coord.	(x^{μ}, j^{i}) New bosonic Coord.	SM part + new part to cancel Λ^2 at 1-Loop
2) SELECTION RULE → DISCRETE SYMM. → STABLE NEW PART.	R-PARITY LSP Neutralino spin 1/2	KK-PARITY LKP spin1	T-PARITY LTP spin0
3) FIND REGION (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

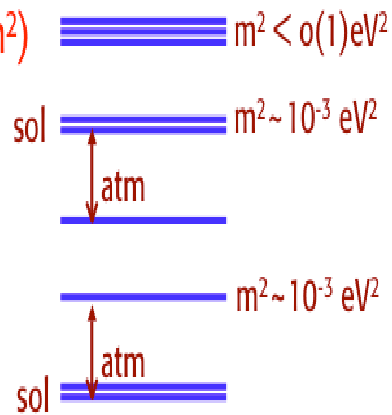
Bottino, Donato, Fornengo, Scopel

NORMAL HIERARCHY

INVERSE HIERARCHY



- Degenerate ($m^2 >> \Delta m^2$)
- Inverse hierarchy
- Normal hierarchy



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_\odot \ll \Delta M^2_{atm} \simeq \pm \Delta m^2_{32} \simeq \pm \Delta m^2_{31}$

$r \sim \Delta m^2_{sol} / \Delta m^2_{atm} \sim 1/30$

For the hierarchical case

$$\frac{m_2}{m_3} \approx \sqrt{r} \approx 0.2$$

"Normal" models: θ_{23} large but not maximal,
θ_{13} not too small (θ_{13} of order λ_C or λ_C^2)

"Exceptional" models: θ_{23} very close to maximal and/or θ_{13} very small
or: a special value for θ_{12}....

Altarelli

$$\left(\frac{\pi}{4} - \vartheta_{23}\right) = 0.06^{+0.10}_{-0.12} \quad \text{rad} \quad (2\sigma)$$

$$\vartheta_{12} + \vartheta_C - \frac{\pi}{4} = 0.035^{+0.060}_{-0.056} \quad \text{rad} \quad (2\sigma)$$

Models for neutrino masses and mixings

- HIERARCHY IN MASSES AND MIXINGS RELATED TO DIFFERENCES IN SOME QUANTUM FLAVOR NUMBERS: simplest example $U(1)_F$ symmetry. Models with seesaw+ $U(1)_F$ can account for all small numbers in quark and lepton spectra, are "natural" and can be nicely accommodated in GUT schemes, ex. $SU(5)\times U(1)_F$. Problem: choice of $U(1)_F$ quantum numbers to reproduce the fermionic spectrum, not prediction of it.
- Symmetries larger than $U(1)_F$: more predictive, but also less flexible
- "Exceptional" models: they lead to "special" values of some mixings. Example: Models for tri-bimaximal mixing

The most general mass matrix for $\theta_{13}= 0$ and θ_{23} maximal is given by (after ch. lepton diagonalization!!!):

$$m_\nu = \begin{bmatrix} x & y & y \\ y & z & w \\ y & w & z \end{bmatrix}$$

Harrison, Perkins, Scott

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Neglecting Majorana phases it depends on 4 real para
(3 mass eigenvalues and 1 mixing angle: θ_{12})

Altarelli

Comparison with experiment:

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

At 1σ: Fogli et al '05

$\sin^2\theta_{12} = 1/3 : 0.290\text{-}0.342$

$\sin^2\theta_{23} = 1/2 : 0.39\text{-}0.53$

$\sin^2\theta_{13} = 0 : \ < 0.02$

The HPS mixing is clearly a very good approx. to the data!

Also called:
Tri-Bimaximal mixing

$$\nu_3 = \frac{1}{\sqrt{2}}(-\nu_\mu + \nu_\tau)$$

$$\nu_2 = \frac{1}{\sqrt{3}}(\nu_e + \nu_\mu + \nu_\tau)$$

Models based on the A4 discrete symmetry (even permutations of 1234) are very interesting (minimal solution)

Ma...;
GA, Feruglio hep-ph/0504165, hep-ph/0512103
GA, Feruglio hep-ph/0610165
....

Alternative models based on $SU(3)_F$ or $SO(3)_F$

Verzielas, G. Ross King
....

Table of neutrino mass models by F. Feruglio at NOW06

model	θ_{23}	θ_{13}	comments
`NATURAL' TEXTURES [1] providing 2 relations	O(1)	>0.03 (90% C.L.)	for all cases but case ``D'': θ_{13}<0.02
3 ZERO TEXTURES [2] for m_ν + large θ_{23} from U_e	O(1)	>0.025	
ANARCHY [3]	O(1)	O(1)	structure-less neutrino mass matrix
FLAVOUR DEMOCRACY [4]	35.3^0 (off by 2σ)	$(0.03 \div 0.1)$	
INVERTED HIERARCHY U_ν bimaximal, θ_{12} corrected by U_e	O(1)	>0.1	θ_{13} much smaller if U_e does not contribute to θ_{12}
NORMAL HIERARCHY see-saw dominance of light ν_R lopsided m_ν and m_e	O(1)	$\underbrace{(0.03 \div 0.2)}_{\text{from } U_\nu} \oplus \underbrace{(0.02 \div 0.1)}_{\text{from } U_e}$	
SU(5)xU(1) [5] [abelian flavour symmetries]	O(1)	O(0.1)	U(1) SB parameter optimized to fit the data; unknown O(1) coefficients generated at random

[1] Barbieri, Hambye, Romanino 0302118
[2] Watanabe, Yoshioka 0601152
[3] Hall, Murayama, Weiner 9911341
[4] Fritzsch, Xing PLB 372 (1996)
[5] Altarelli, F, Masina 0210342

θ_{23} maximal only by a fine-tuning

THE FATE OF FLAVOR NUMBERS

HADRONIC FLAVOR NUMBERS: strangeness, charm, beauty.. ALL VIOLATED IN FLAVOR CHANGING CHARGED CURRENTS → mismatch in the simultaneous diagonalization of the up- and down- quark sectors allows for W intergenerational hadronic couplings

LEPTONIC FLAVOR NUMBERS: L_i i= e, μ, τ violated

in υ oscillations → massive neutrinos

→ mismatch in the simultaneous diagonalization of the up- (υ) and down- (l) sectors allows for W intergenerational leptonic couplings

LFV IN CHARGED LEPTONS FCNC

L_i - L_j transitions through W - neutrinos mediation

GIM suppression $(m_\nu / M_W)^2$ ⟶ forever invisible

New mechanism: replace SM GIM suppression with a new GIM suppression where m_ν is replaced by some $\Delta M >> m_\nu$.

Ex.: in SUSY L_i - L_j transitions can be mediated by photino - SLEPTONS exchanges,

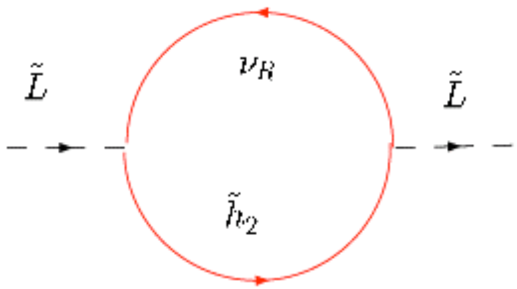
BUT in CMSSM (MSSM with flavor universality in the SUSY breaking sector) $\Delta M_{sleptons}$ is O($m_{leptons}$), hence GIM suppression is still too strong.

How to further decrease the SUSY GIM suppression power in LFV through slepton exchange?

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

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

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



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

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

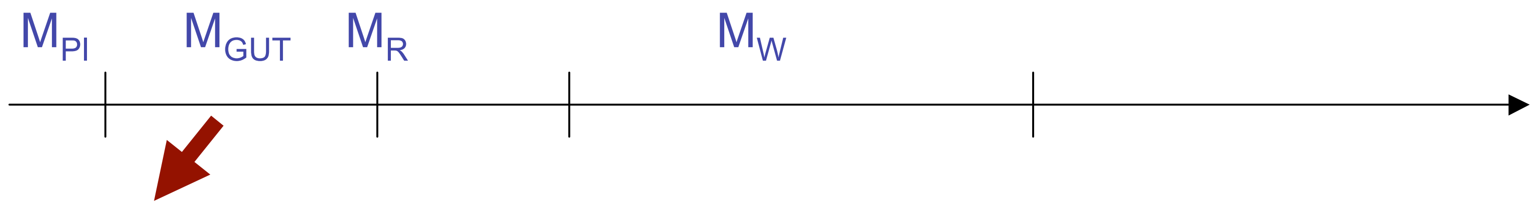
How Large LFV in SUSY SEESAW?

- 1) Size of the Dirac neutrino couplings f_ν
- 2) Size of the diagonalizing matrix U

1) → in MSSM seesaw or in SUSY SU(5) (Moroi):
not possible to correlate the neutrino Yukawa couplings to known Yukawas;
in SUSY SO(10) (A.M., Vempati, Vives) at least one neutrino Dirac Yukawa coupling has to be of the order of the top Yukawa coupling → one large of O(1) f_ν

2) U → two "extreme" cases:
a) U with "small" entries → U = CKM;
b) U with "large" entries with the exception of the 13 entry
→ U=PMNS matrix responsible for the diagonalization of the neutrino mass matrix

LFV in SUSYGUTs with SEESAW



Scale of appearance of the SUSY soft breaking terms resulting from the spontaneous breaking of supergravity

Low-energy SUSY has “memory” of all the multi-step RG occurring from such superlarge scale down to M_W

→ potentially large LFV

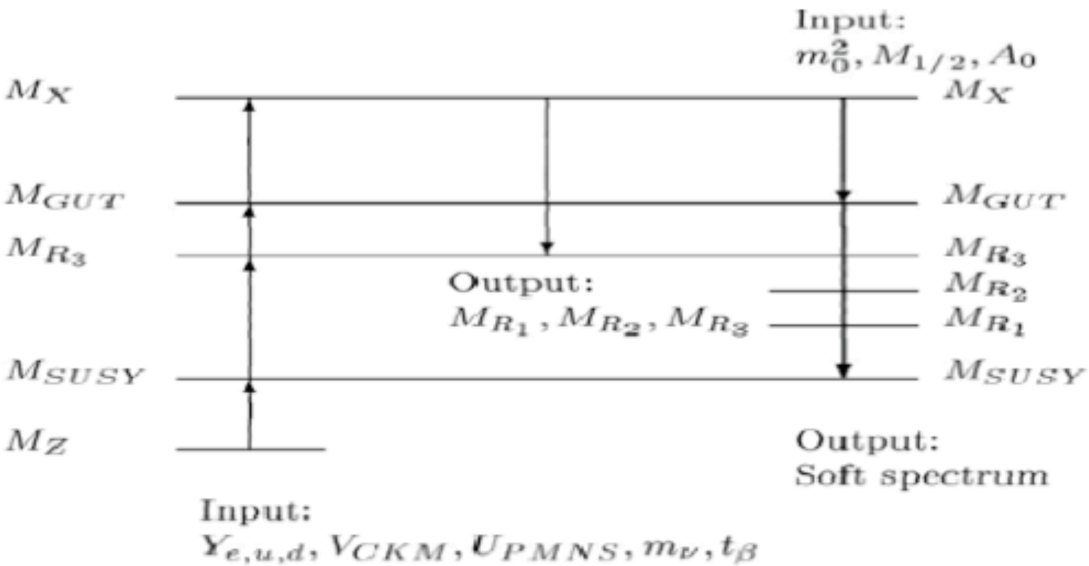
Barbieri, Hall; Barbieri, Hall, Strumia; Hisano, Nomura, Yanagida; Hisano, Moroi, Tobe Yamaguchi; Moroi;A.M.,, Vempati, Vives; Carvalho, Ellis, Gomez, Lola; Calibbi, Faccia, A.M, Vempati

LFV in MSSM seesaw: $\mu \to e\gamma$ Borzumati, A.M.

$\tau \to \mu\gamma$ Blazek, King;

General analysis: Casas Ibarra; Lavignac, Masina,Savoy; Hisano, Moroi, Tobe, Yamaguchi; Ellis, Hisano, Raidal, Shimizu; Fukuyama, Kikuchi, Okada; Petcov, Rodejohann, Shindou, Takanishi; Arganda, Herrero; Deppish, Pas, Redelbach, Rueckl; Petcov, Shindou

LFV with MULTIPLE RUNNING THRESHOLDS



CALIBBI, FACCIA, A.M., VEMPATI ;

For previous related work, see, in particular, HISANO et al.

GUT effect, e.g. SU(5), if $M_X > M_{GUT}$

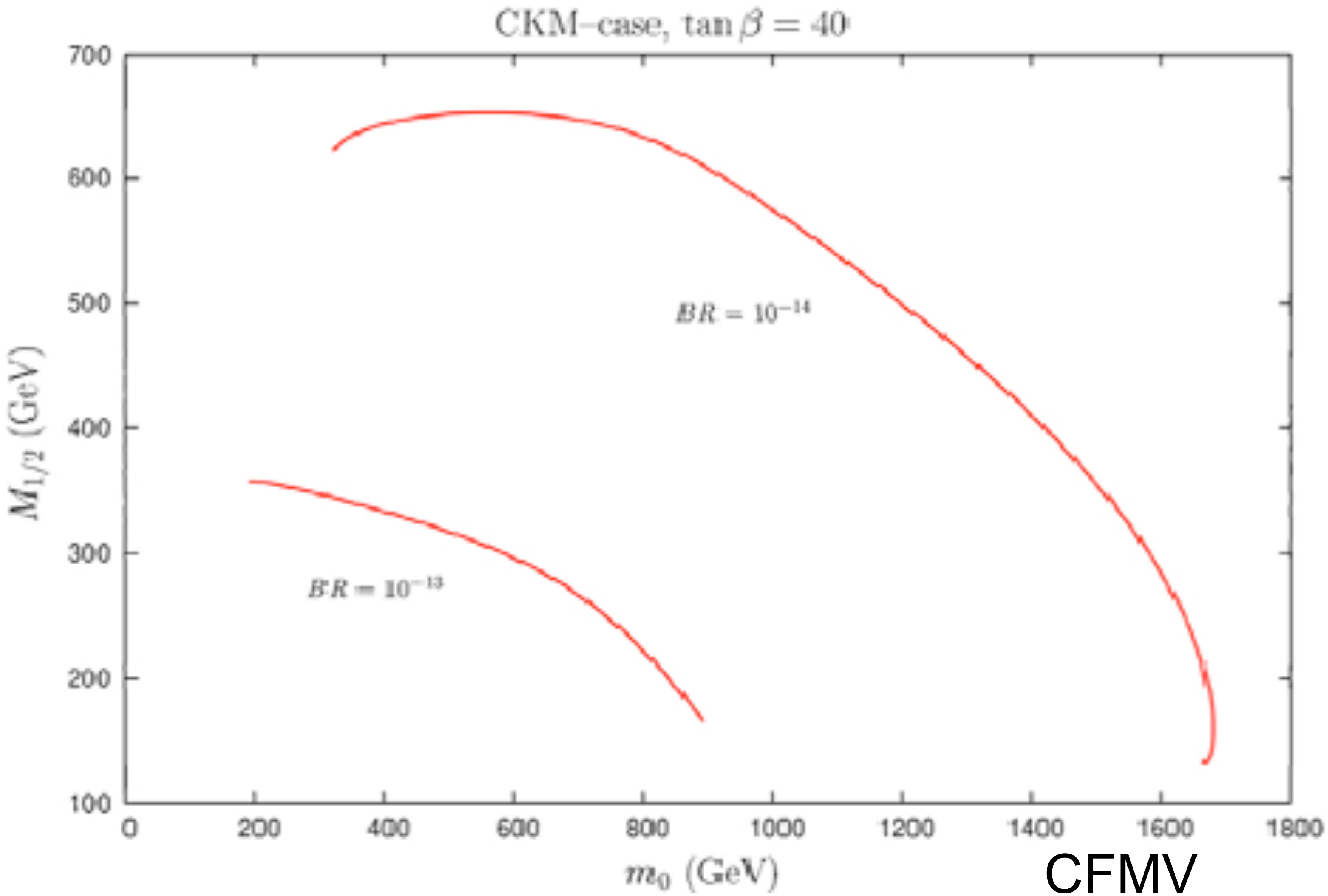
$$(\Delta_{RR})_{i\neq j} = -3 \cdot \frac{3m_0^2 + a_0^2}{16\pi^2} Y_t^2 V_{i3} V_{j3} \ln\left(\frac{M_X^2}{M_{GUT}^2}\right)$$

See-saw:

$$m_\nu = -Y_\nu \hat{M}_R^{-1} Y_\nu^T \langle H_u \rangle^2$$

$$(\Delta_{LL})_{i\neq j} = -\frac{3m_0^2 + A_0^2}{16\pi^2} Y_{\nu\, i3} Y_{\nu\, j3} \ln\left(\frac{M_X^2}{M_{R_3}^2}\right)$$

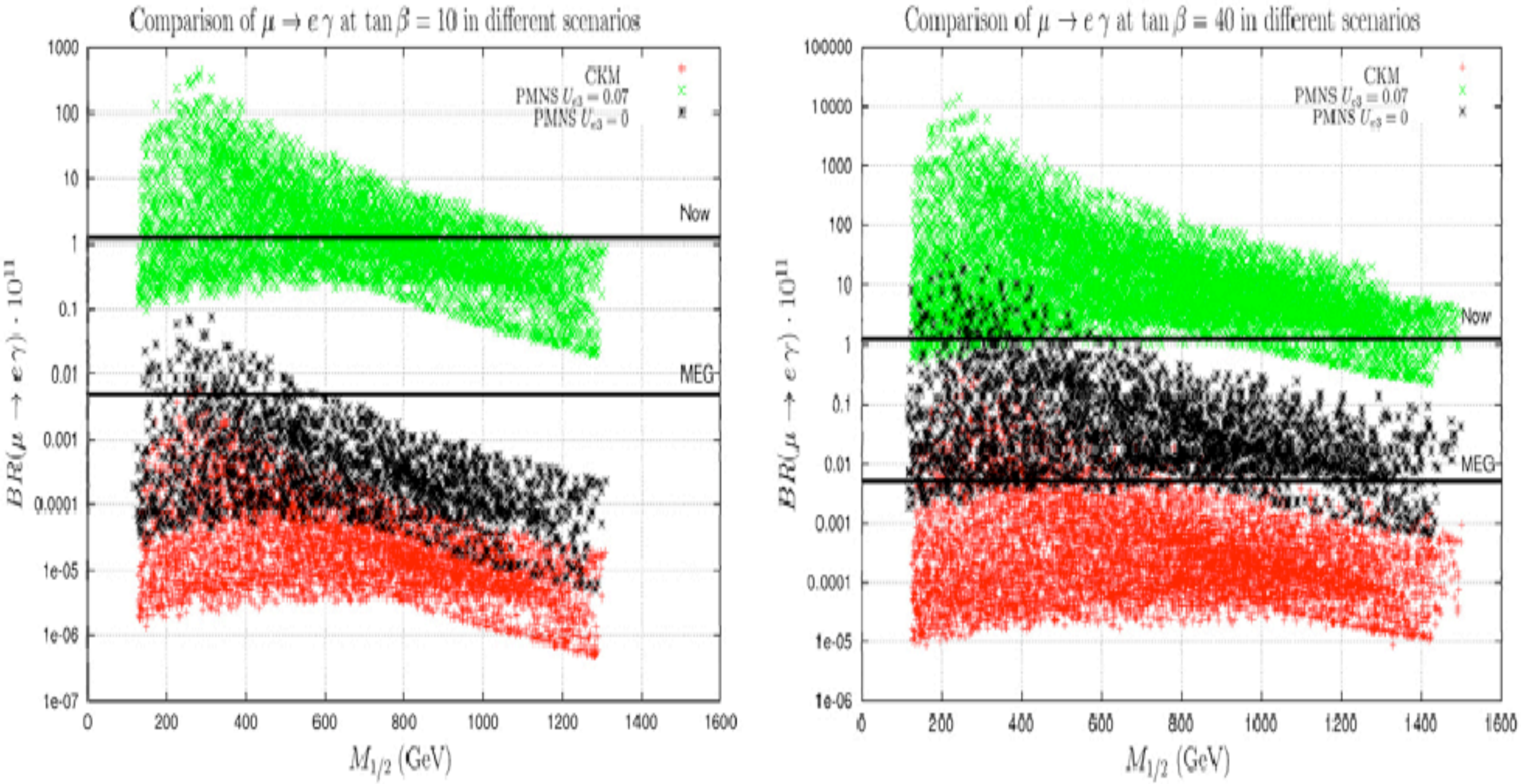
MEG POTENTIALITIES TO EXPLORE THE SUSY SEESAW PARAM. SPACE



CFMV

μ → e+γ in SUSYGUT: past and future

$\mu \to e\gamma$ in the $U_{e3} = 0$ PMNS case

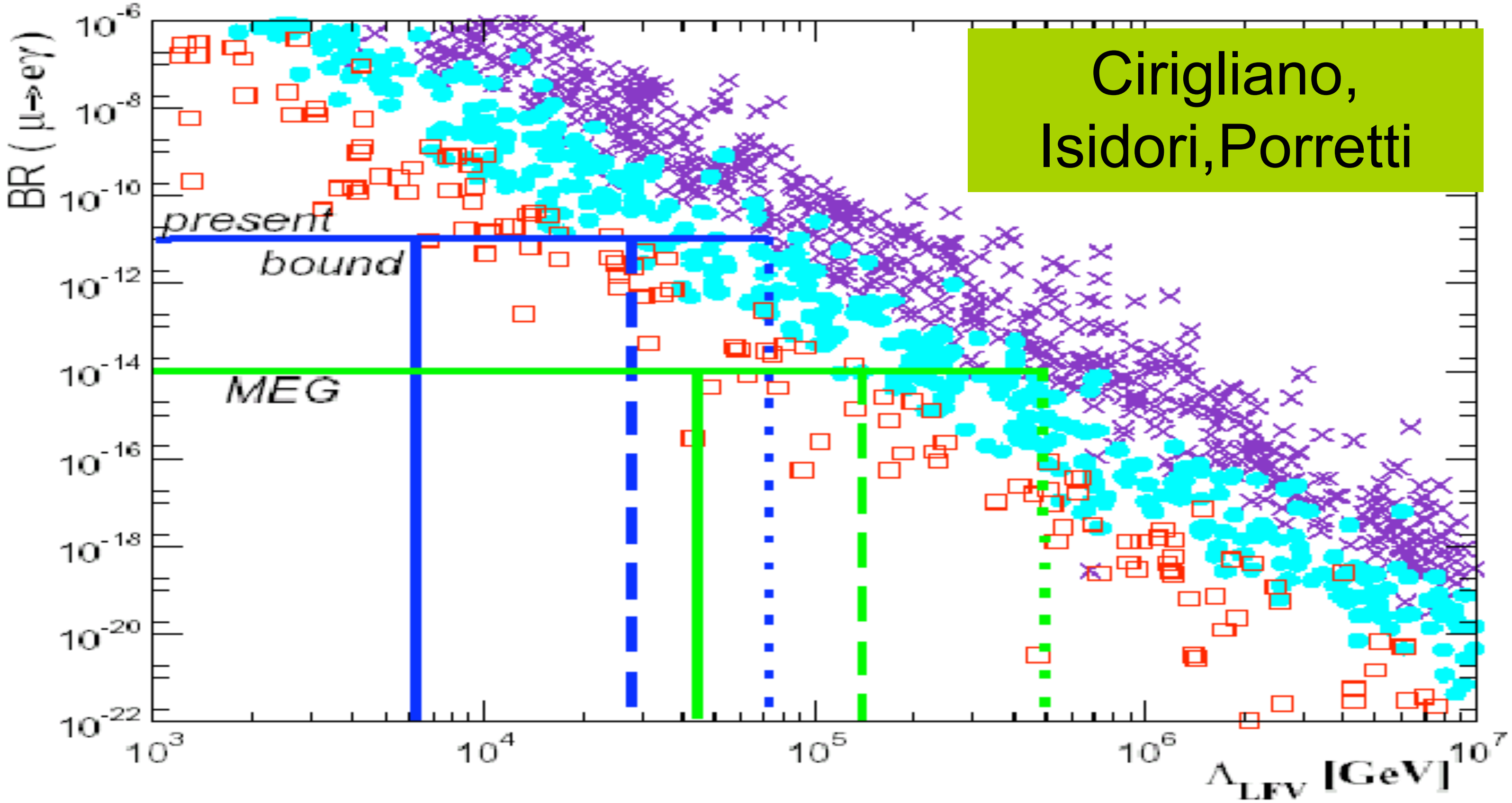


CFMV

Valentina Porretti
Moriond 07

MFV in the lepton sector

we assume only Yukawa's break flavour as in the quark sector →
the Maiorana mass $M_R = 1$



M_R= □ 10^{13} GeV ● 10^{14} GeV × 10^{15} GeV

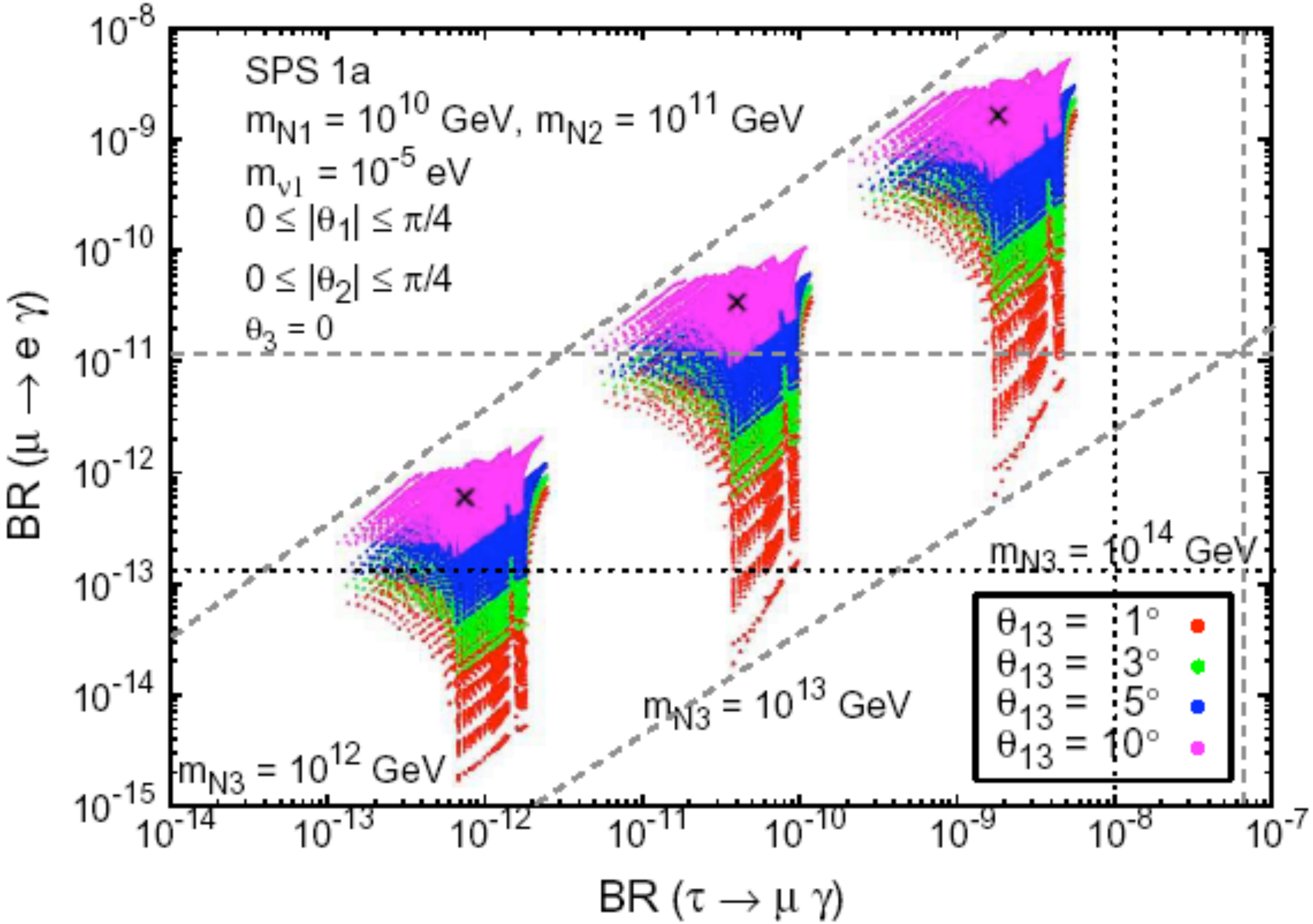
❷ MFV as a restriction on *renormalizable* couplings

F. Palorini

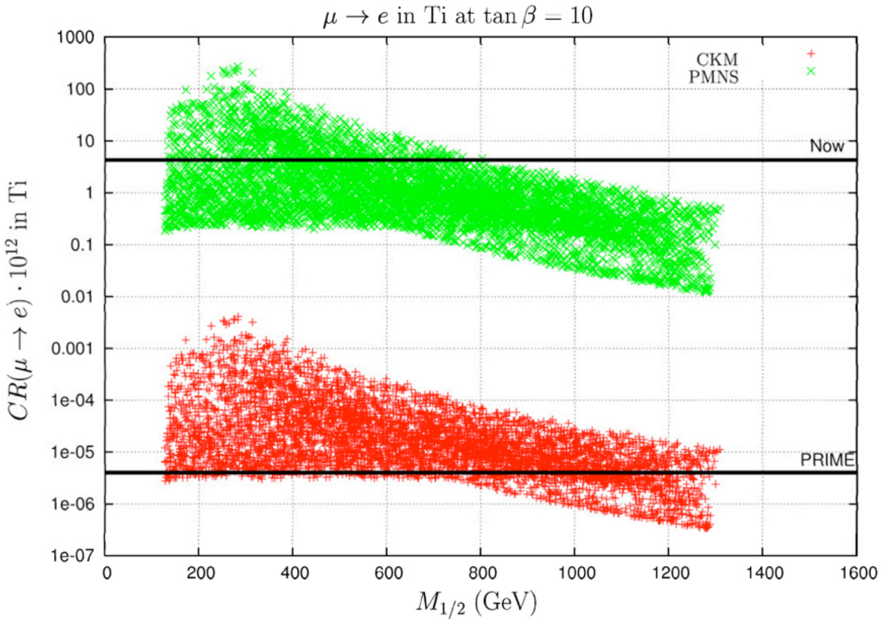
New renormalizable interactions can choose only one more basis in the L space

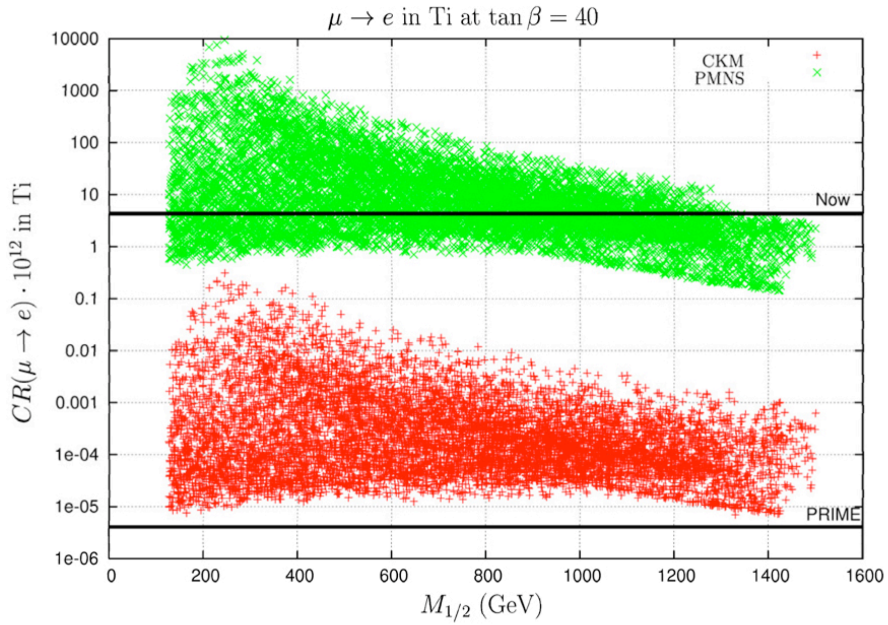
⇒ FV processes are not necessarily controlled by the U_{MNS} mixing matrix

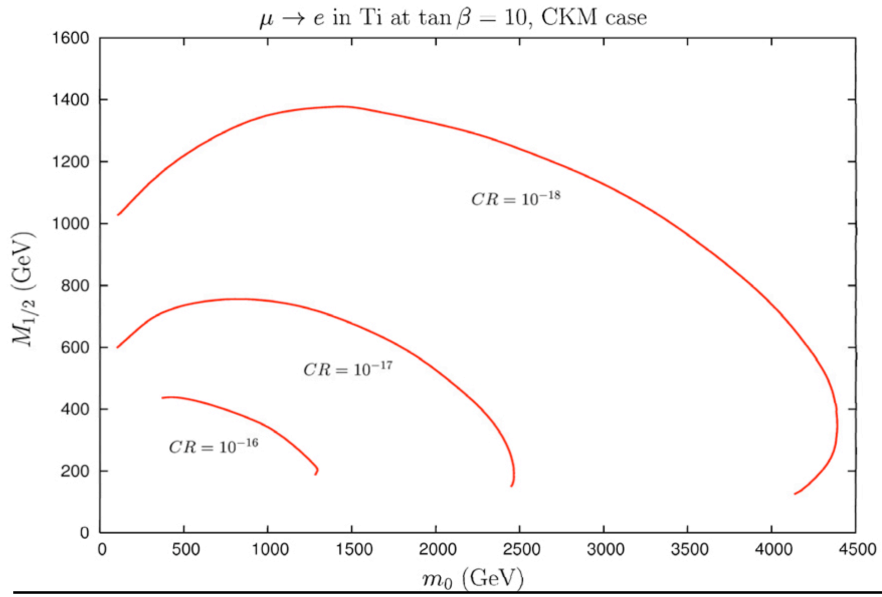
Antusch, Arganda, Herrero, Teixeira

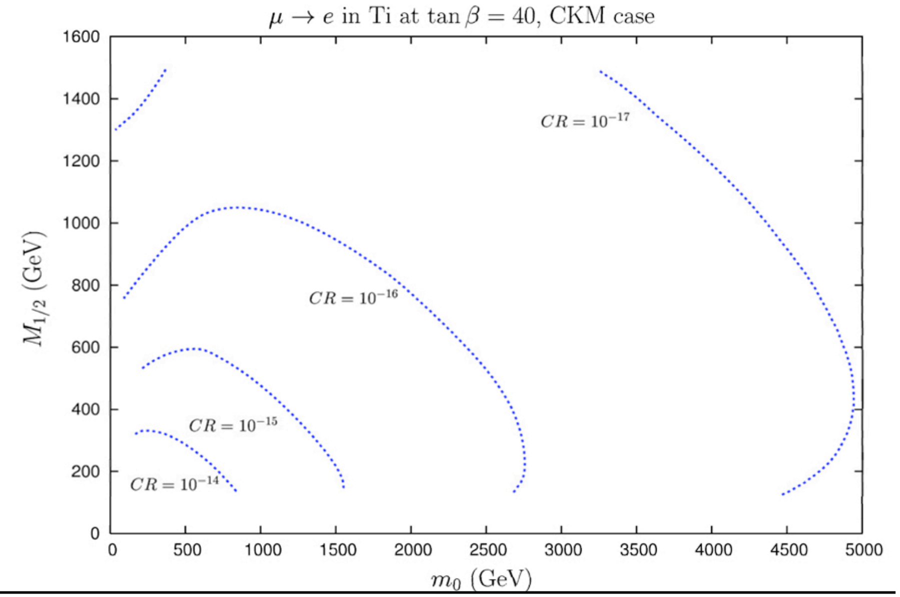


$\mu \to e$ in Ti and **PRISM/PRIME** conversion experiment









LFV ⟷ LHC SENSITIVITIES IN PROBING THE SUSY PARAM. SPACE

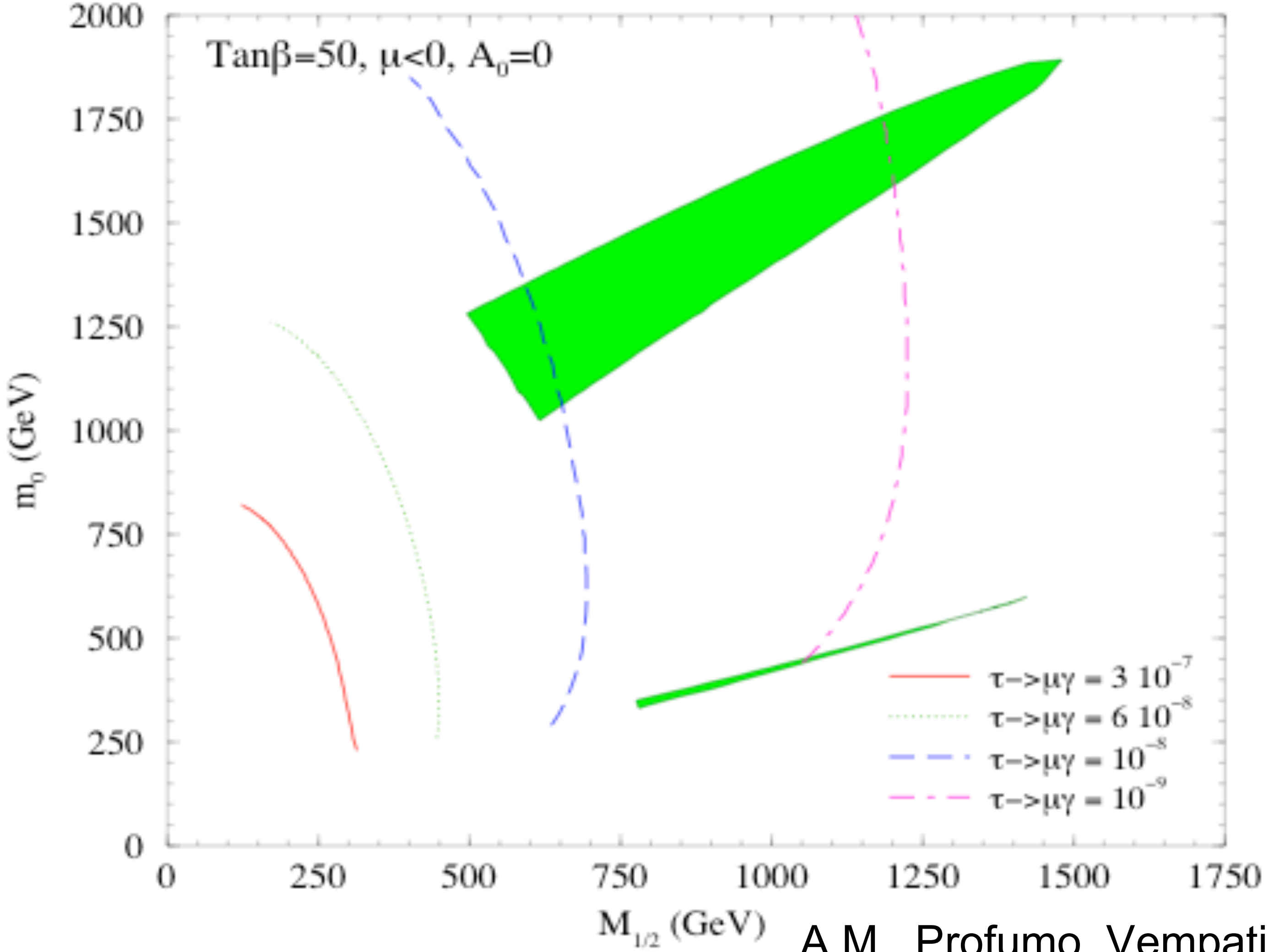
TABLE IX: Reach in $(m_0, m_{\tilde{g}})$ of the present and planned experiment from their $\tau \to \mu\gamma$ sensitivity.

	PMNS		CKM	
Exp.	$t_\beta = 40$	$t_\beta = 10$	$t_\beta = 40$	$t_\beta = 10$
BaBar, Belle	1.2 TeV	no	no	no
SuperKEKB	2 TeV	0.9 TeV	no	no
Super Flavour [a]	2.8 TeV	1.5 TeV	0.9 TeV	no

[a]Post–LHC era proposed/discussed experiment

CFMV

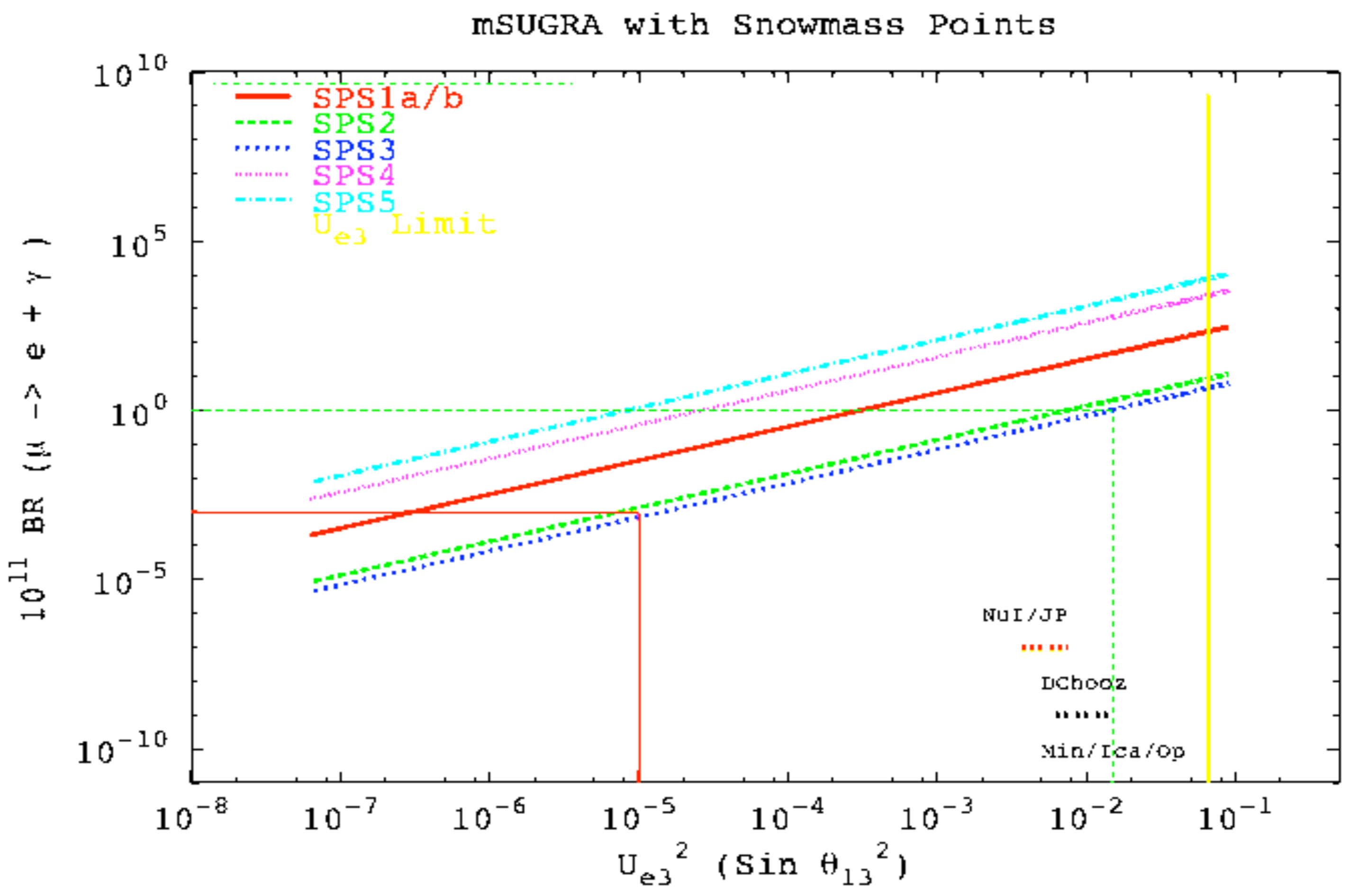
LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY



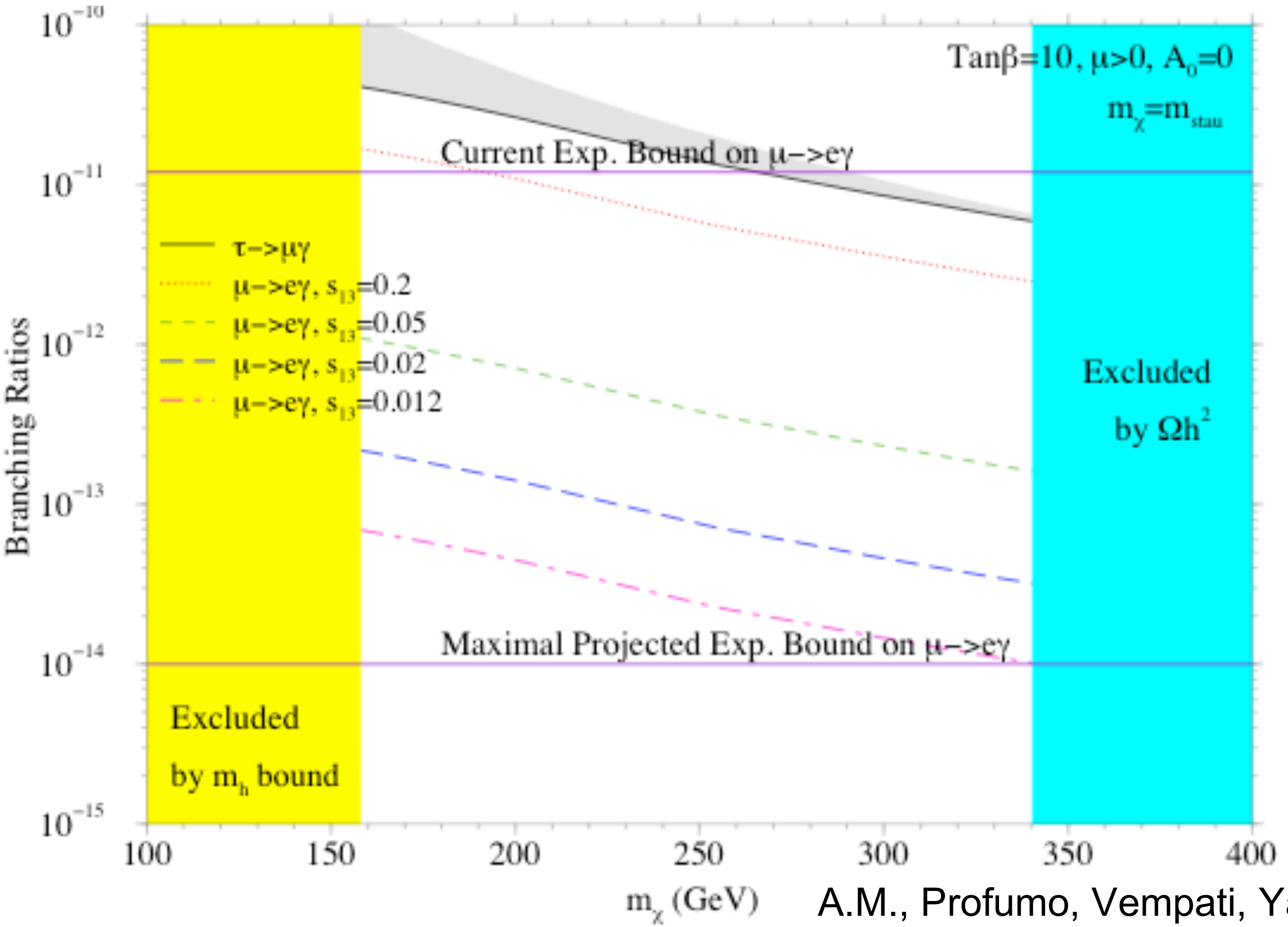
A.M., Profumo, Vempati, Yaguna

Sensitivity of $\mu \to e\gamma$ to U_{e3} for various Snowmass points in mSUGRA with seesaw

A.M.. Vempati. Vives



PROBING SUSY THROUGH LFV



A.M., Profumo, Vempati, Yaguna

Large ν mixing ↔ large b-s transitions in SUSY GUTs

In SU(5) $d_R \longleftrightarrow l_L$ connection in the 5-plet
Large $(\Delta^l_{23})_{LL}$ induced by large f_ν of $O(f_{top})$
is accompanied by large $(\Delta^d_{23})_{RR}$

In SU(5) assume large f_ν (Moroi)
In SO(10) f_ν large because of an underlying Pati-Salam symmetry
(Darwin Chang, A.M., Murayama)

See also: Akama, Kiyo, Komine, Moroi; Hisano, Moroi, Tobe, Yamaguchi, Yanagida; Hisano, Nomura; Kitano,Koike, Komine, Okada

FCNC HADRON-LEPTON CONNECTION IN SUSYGUT

If

soft SUSY breaking terms arise
at a scale > M_{GUT}, they have to respect
the underlying quark-lepton GU symmetry

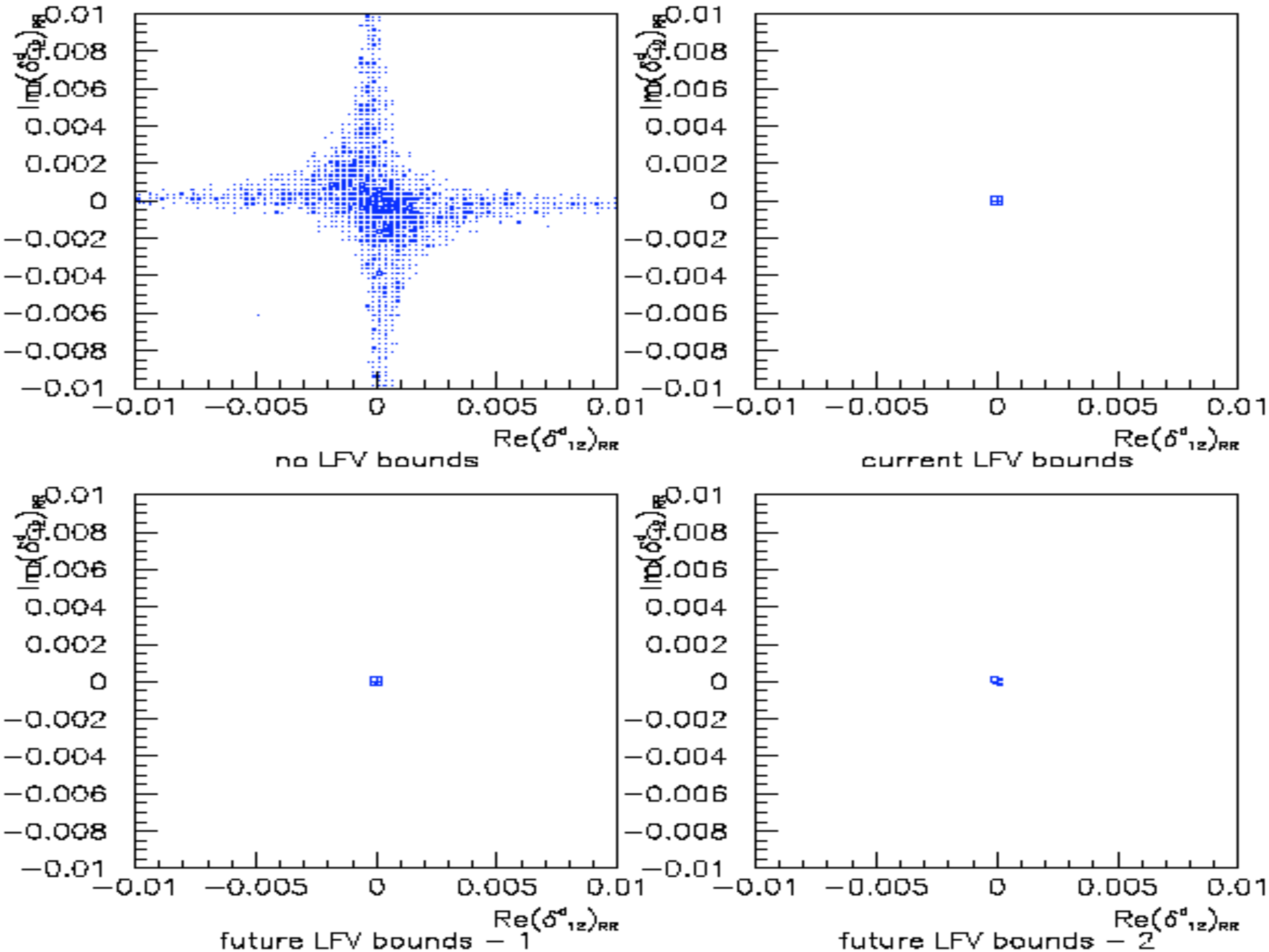
constraints on δ^{quark} from LFV and
constraints on δ^{lepton} from hadronic FCNC

Ciuchini, A.M., Silvestrini, Vempati, Vives PRL

general analysis Ciuchini, A.M., Paradisi, Silvestrini, Vempati, Vives

Bounds on the hadronic $(\delta_{12})_{RR}$ as modified by the inclusion of the LFV correlated bound

CMPSVV



DEVIATION from μ - e UNIVERSALITY

A.M., Paradisi, Petronzio

- Denoting by $\Delta r_{NP}^{e-\mu}$ the deviation from $\mu - e$ universality in $R_{K,\pi}$ due to new physics, i.e.:

$$R_{K,\pi} = R_{K,\pi}^{SM}\left(1 + \Delta r_{K,\pi\,NP}^{e-\mu}\right),$$

- we get at the 2σ level:

$$-0.063 \leq \Delta r_{K\,NP}^{e-\mu} \leq 0.017 \quad \text{NA48/2}$$

$$-0.0107 \leq \Delta r_{\pi\,NP}^{e-\mu} \leq 0.0022 \quad \text{PDG}$$

HIGGS-MEDIATED LFV COUPLINGS

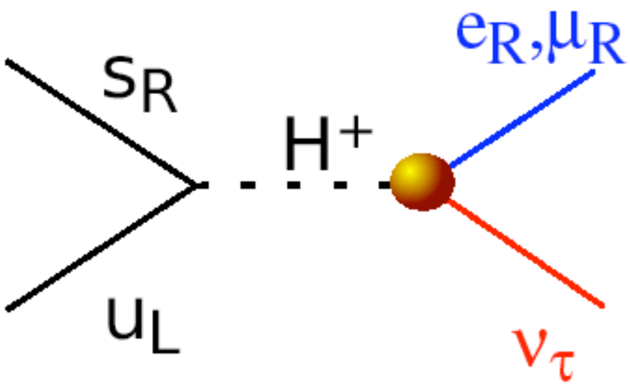
- When non-holomorphic terms are generated by loop effects (HRS corrections)
- And a source of LFV among the sleptons is present
- → Higgs-mediated (radiatively induced) H-lepton-lepton LFV couplings arise

Babu, Kolda; Sher; Kitano,Koike,Komine, Okada; Dedes, Ellis, Raidal; Brignole,Rossi; Arganda,Curiel,Herrero,Temes; Paradisi;

Brignole,Rossi

H mediated LFV SUSY contributions to R_K

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



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

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

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

$$\Downarrow$$

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

Extension to B ⟶ lν deviation from universality

Isidori, Paradisi

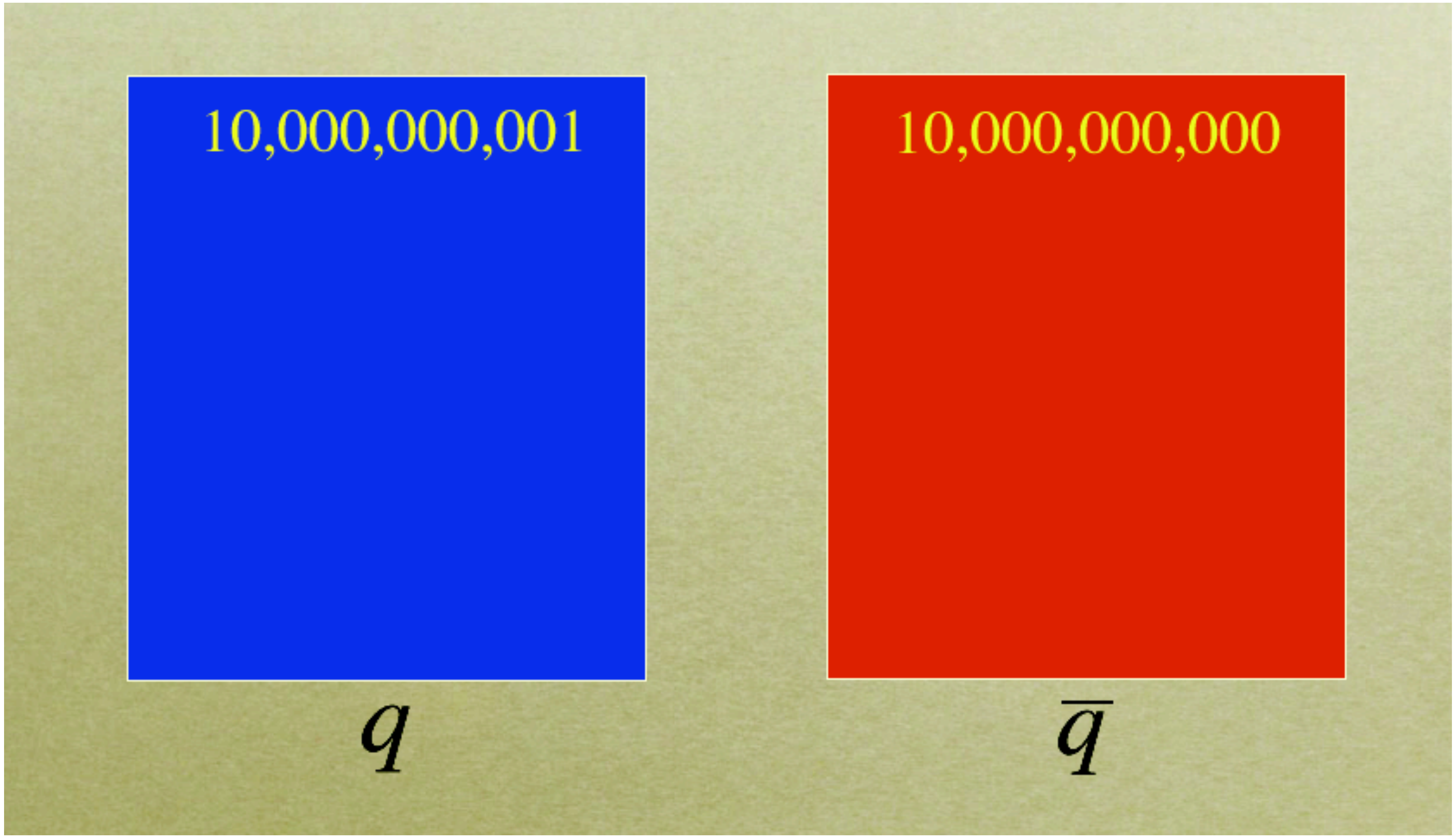
THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$

- 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 $N_{ba.} = N_{antibar}$ AND NO SEPARATION WELL BEFORE THEY DECOUPLE . WE WOULD BE LEFT WITH $N_{bar.}/N_{photon} << 10^{-10}$
- IF BARYONS-ANTIBARYONS ARE SEPARATED EARLIER $\longrightarrow$ DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE

$\Downarrow$

- 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:

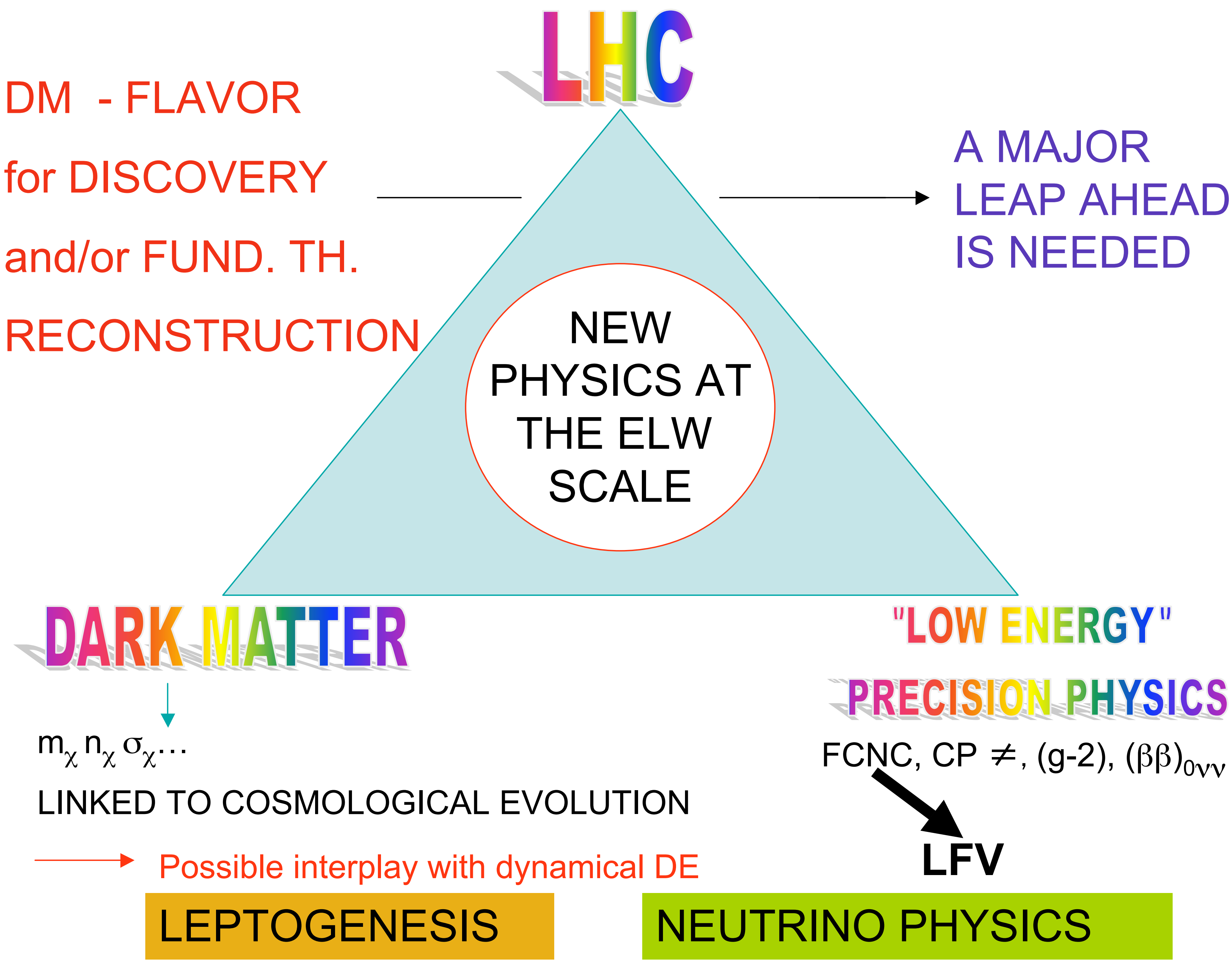
- NOT ENOUGH CP VIOLATION IN THE SM → NEED FOR NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX
- FOR M_{HIGGS} > 80 GeV THE ELW. PHASE TRANSITION OF THE SM IS A SMOOTH CROSSOVER

→ 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 ⟷ 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)


LHC
DM - FLAVOR
for DISCOVERY
and/or FUND. TH.
RECONSTRUCTION
A MAJOR
LEAP AHEAD
IS NEEDED
NEW
PHYSICS AT
THE ELW
SCALE
DARK MATTER
m_χ n_χ σ_χ…
LINKED TO COSMOLOGICAL EVOLUTION
Possible interplay with dynamical DE
"LOW ENERGY"
PRECISION PHYSICS
FCNC, CP $\neq$, (g-2), $(\beta\beta)_{0\nu\nu}$
LFV
LEPTOGENESIS
NEUTRINO PHYSICS