NEUTRINOS, DARK MATTER & LEPTOGENESIS

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http://ahep.uv.es

UAM, Sept 17 2009

THE LEPTON MIXING MATRIX

$\mathrm{K} = \omega_{23} \cdot \omega_{13} \cdot \omega_{12}$ Schechter & JV PRD22 (1980) 2227, PRD23 (1981) 1666 & PDG

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & e^{i\phi_{23}} s_{23} \\ 0 & -e^{-i\phi_{23}} s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & e^{i\phi_{13}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\phi_{13}} s_{13} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & e^{i\phi_{12}} s_{12} & 0 \\ -e^{-i\phi_{12}} s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

23=atm+acc | 13=reactor + .. | 12=solar+KL

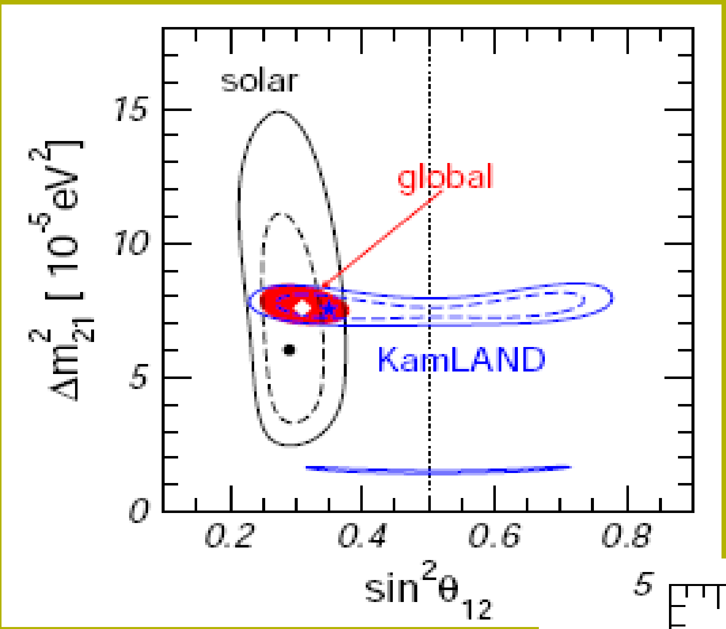
- Even in its simplest unitary form K differs from quark mixing matrix, with two extra (Majorana) phases

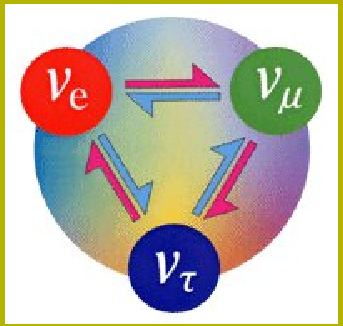
- In seesaw-schemes K is **not** unitary => extra angles & phases => new physics: LFV among charged leptons & new propagation effects

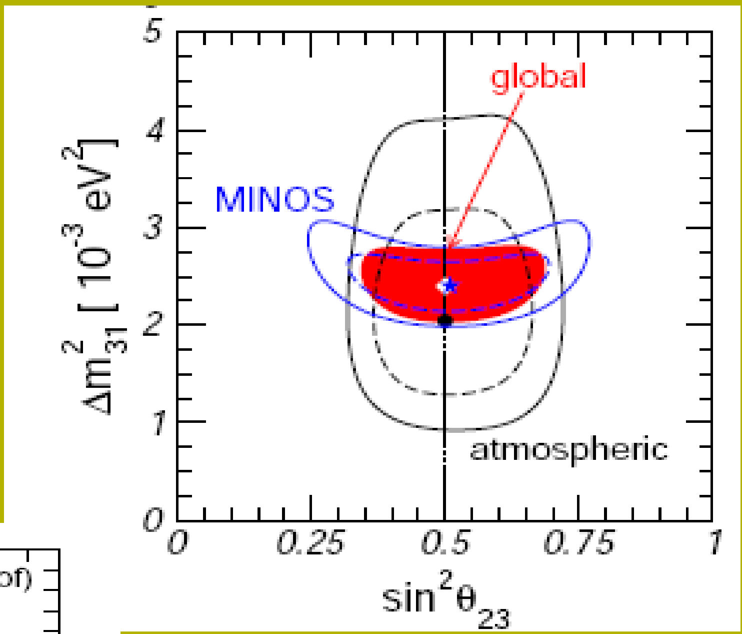
- To describe current oscillation data we assume K real unitary

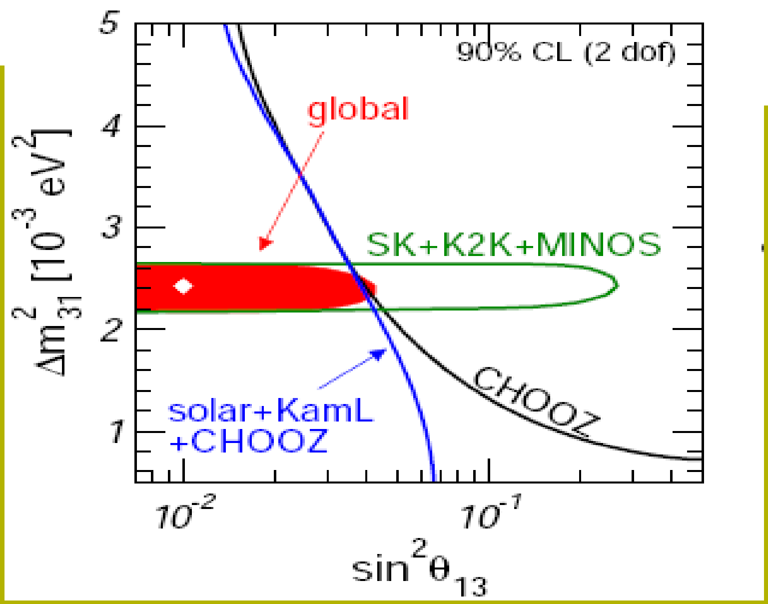
NEUTRINO OSCILLATIONS 2009

Schwetz et al, NJP 10 (2008) 113011 [rev. Maltoni et al, NJP 6 (2004) 122]









Homestake, SAGE+ GALLEX/GNO, Super-K, SNO
Borexino

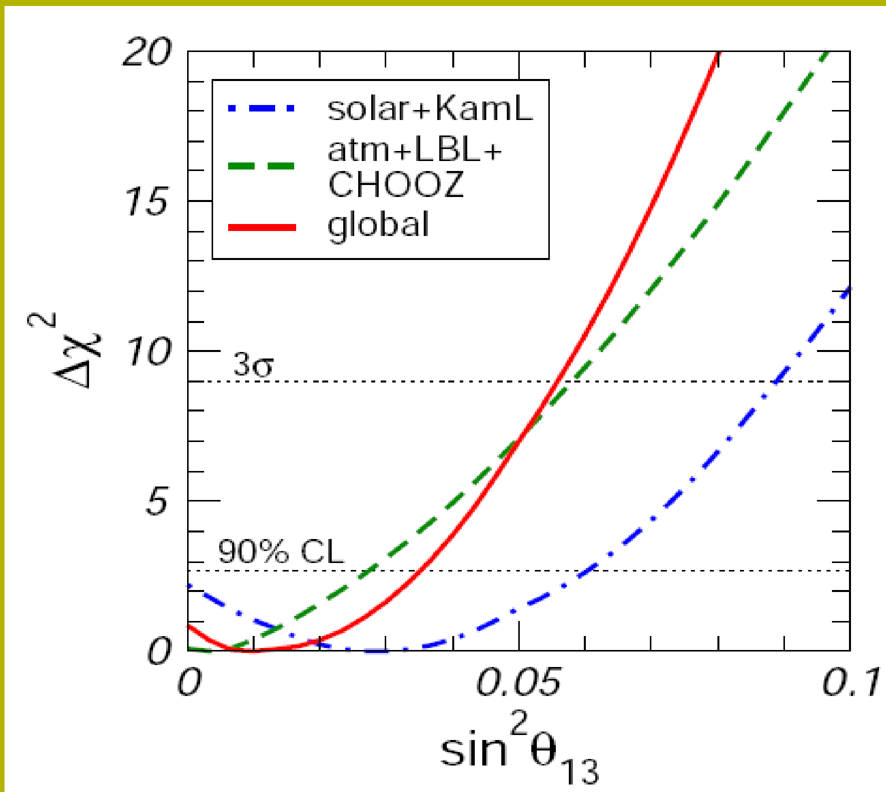
KamLAND (180 Km)

... Super-K

K2K (250 Km)
MINOS (735 Km)

STATUS OF THETA13

Schwetz et al NJP 10 (2008) 113011



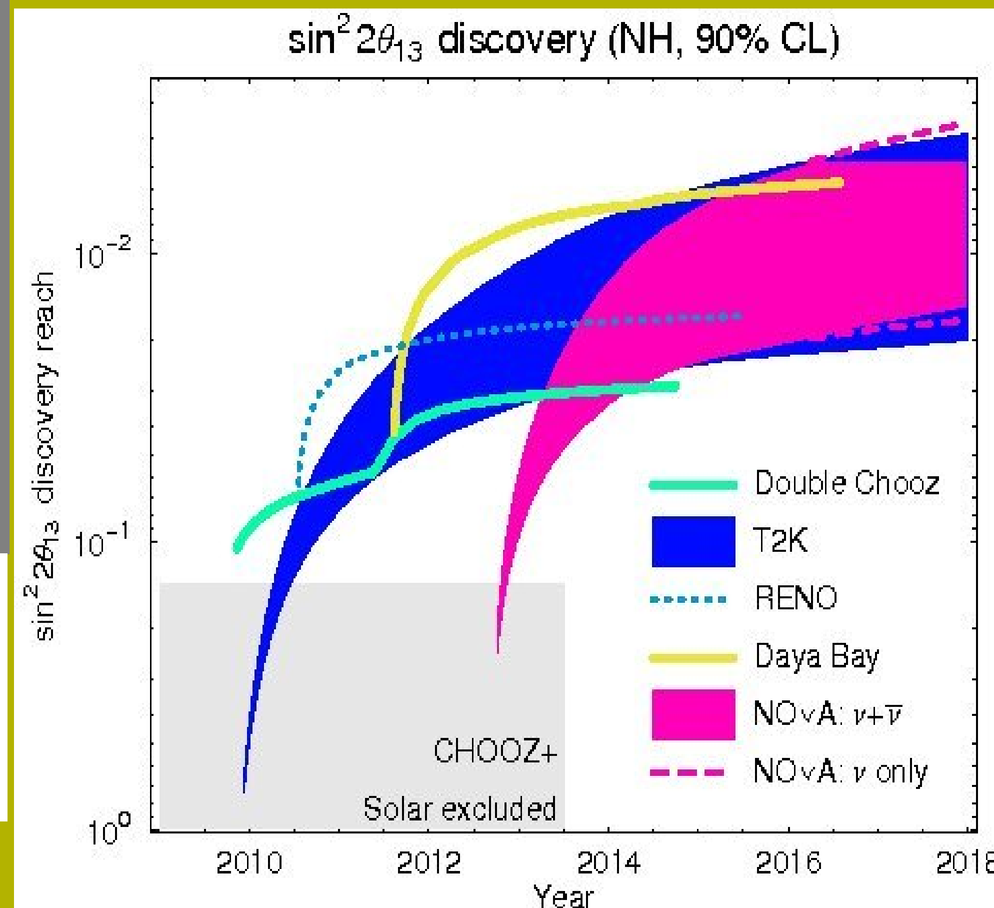
$$\sin^2\theta_{13} \leq \begin{cases} 0.060\ (0.089) & \text{(solar+KamLAND)} \\ 0.027\ (0.058) & \text{(CHOOZ+atm+K2K+MINOS)} \\ 0.035\ (0.056) & \text{(global data)} \end{cases}$$

c.f. Fogli et al, 2008, MINOS & ...

FUTURE "ROADMAP"

Huber, Lindner, Schwetz, Winter, 2009

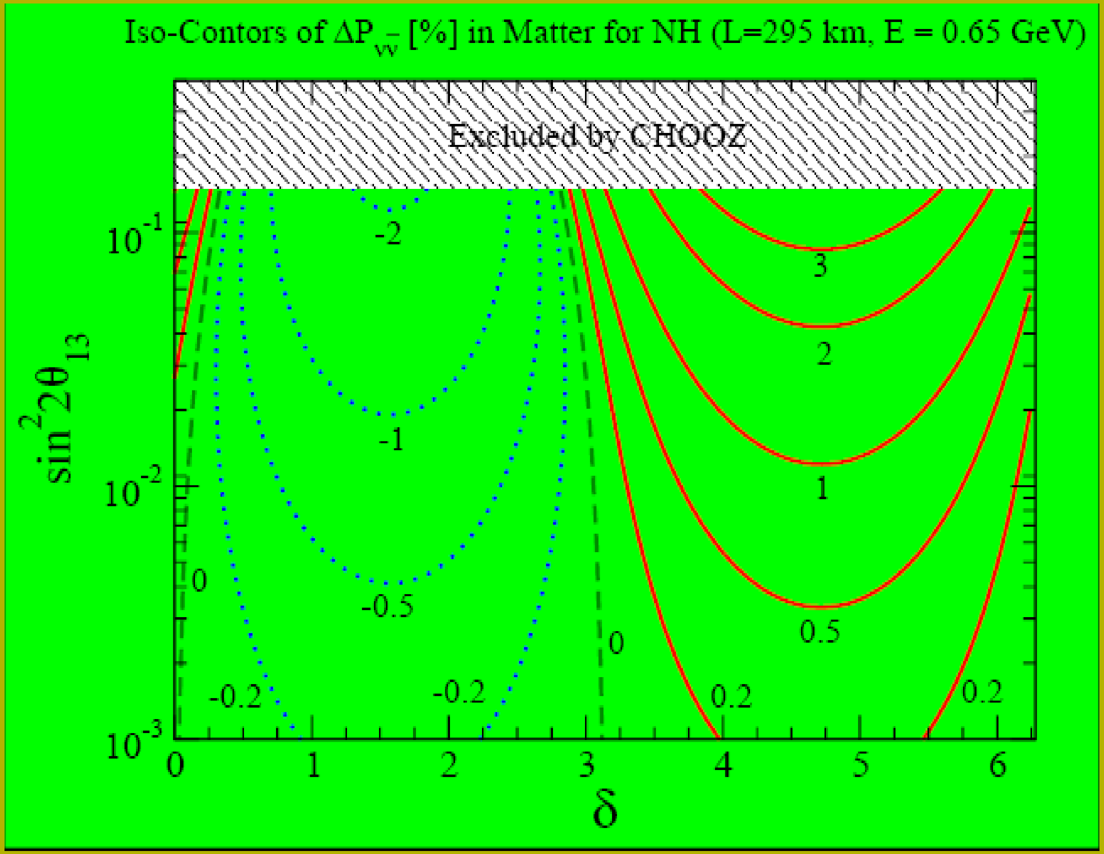
If no NSI



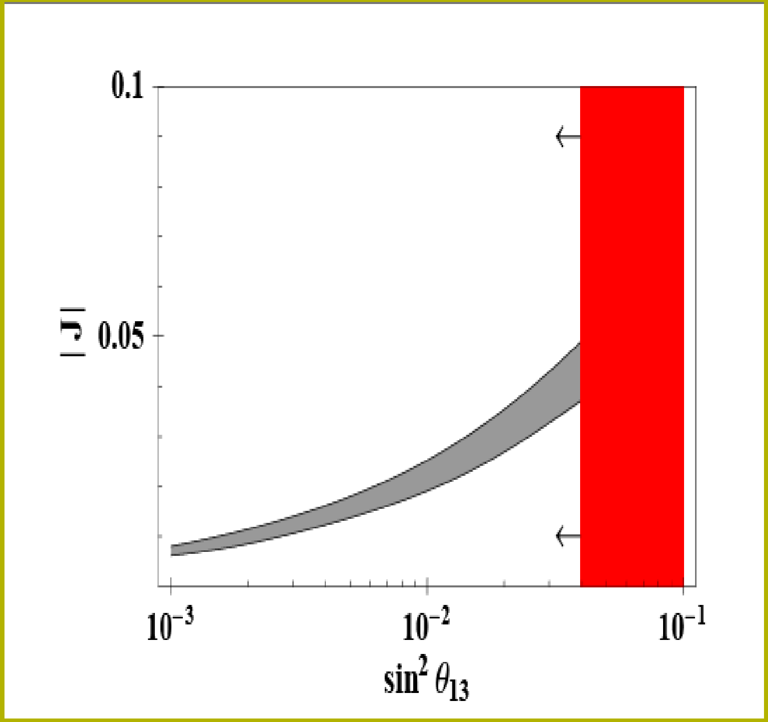
CPV IN NU−OSCILLATIONS

aymmetries at % level

maximal CPV



Hirsch et al PRL99(2007)151802



From Nunokawa et al Prog.Part.Nuc.Phys. 60 (2008) 338

ISS report, S. King et al, Rep. Prog. Phys.

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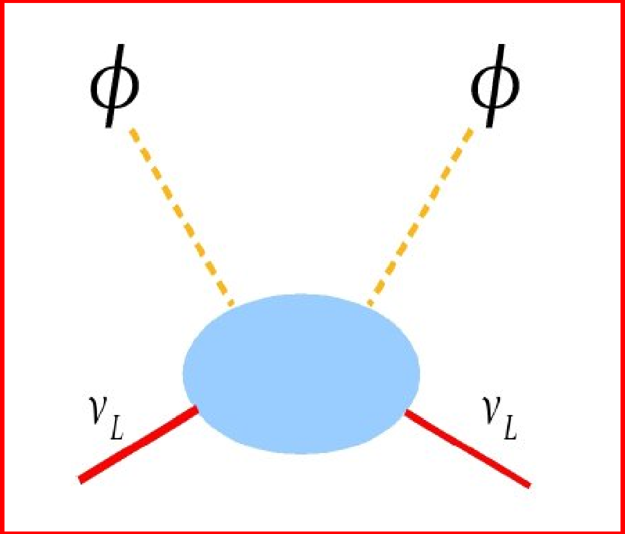
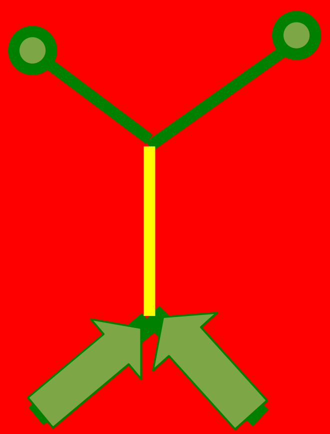
ORIGIN OF NEUTRINO MASS



Singlet / 3plet fermion
Type-I / III

Minkowski 77
Gellman Ramond Slansky 80
Glashow, Yanagida 79
Mohapatra Senjanovic 80
Schechter-Valle, 80
Lazarides Shafi Weterrich 81
Foot et al 89



3plet scalar
type-II

Schechter-Valle 80/82

scale

mechanism

flavor structure

LOW-SCALE SEESAW

Inverse type-I	Mohapatra-JV 86
Linear type-I	Malinsky et al 2005
Inverse type-III	Ibañez et al 2009

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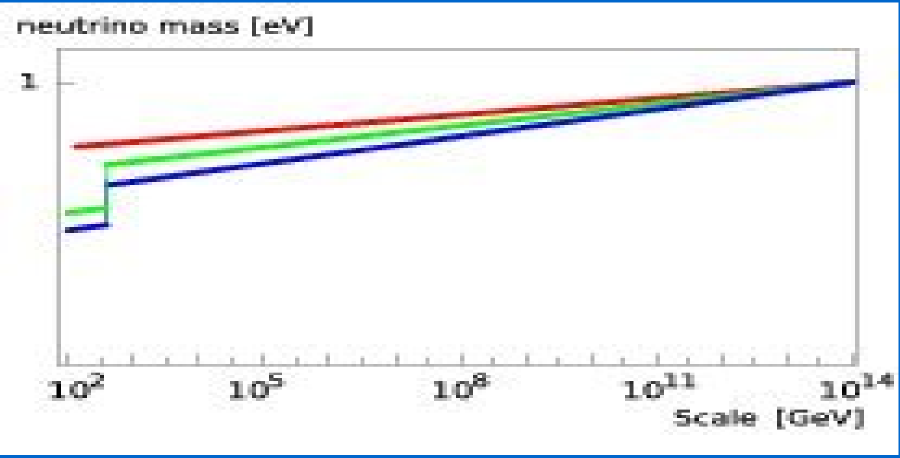
EXPLAINING NEUTRINO PROPERTIES

TBM ansatz Harrison–Perkins–Scott

Babu et al PLB552 (2003) 207
Hirsch et al PRD69 (2004) 093006

$$\begin{pmatrix} \sqrt{\frac{2}{3}}(1-\frac{1}{2}s) & \frac{1}{\sqrt{3}}(1+s) & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+s-a+re^{i\delta}) & \frac{1}{\sqrt{3}}(1-\frac{1}{2}s-a-\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1+a) \\ \frac{1}{\sqrt{6}}(1+s+a-re^{i\delta}) & -\frac{1}{\sqrt{3}}(1-\frac{1}{2}s+a+\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1-a) \end{pmatrix}$$



Antusch, Kersten, Lindner, Ratz, Schmidt, 2005

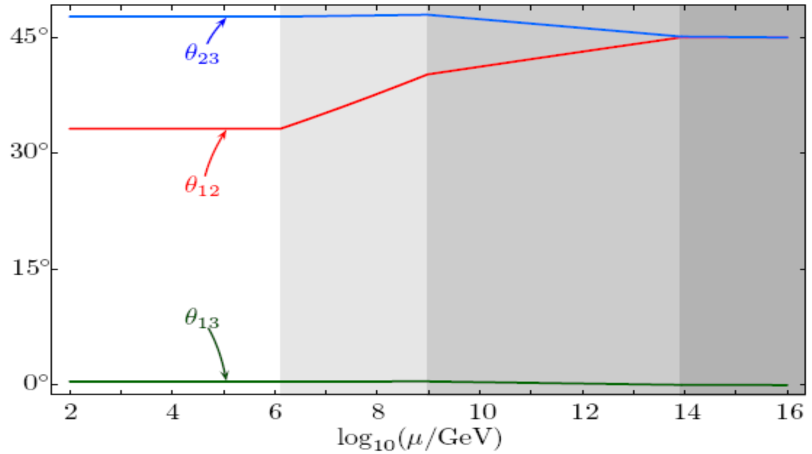


Figure 4: Running from maximal solar mixing at M_{GUT} to the experimentally preferred angle of the LMA solution. The figure shows an example in the SM with a negative CP parity for m_2 and a Yukawa matrix $Y_\nu = 0.5 \cdot \mathrm{diag}(\varepsilon^2, \varepsilon, 1)$ at M_{GUT} with $\varepsilon = 3.5 \cdot 10^{-3}$ and a normal mass hierarchy (from [11]). The lightest neutrino has a mass of 0.004 eV (at low energy). The gray-shaded areas illustrate the validity ranges of the effective theories emerging from integrating out the heavy singlet neutrinos.

TH realizations:

Altarelli, Feruglio, Merlo
Babu et al,
Barr et al
Frampton et al,
Grimus, Lavoura
Hirsch et al ..
King et al, Ross et al
Ma-He, Mohapatra et al,
Plentinger & Rodejohan
Raby et al, Ross et al,
Zhang, ...

SEESAW PHENO

Low- versus High-scale

LOW−SCALE type−1

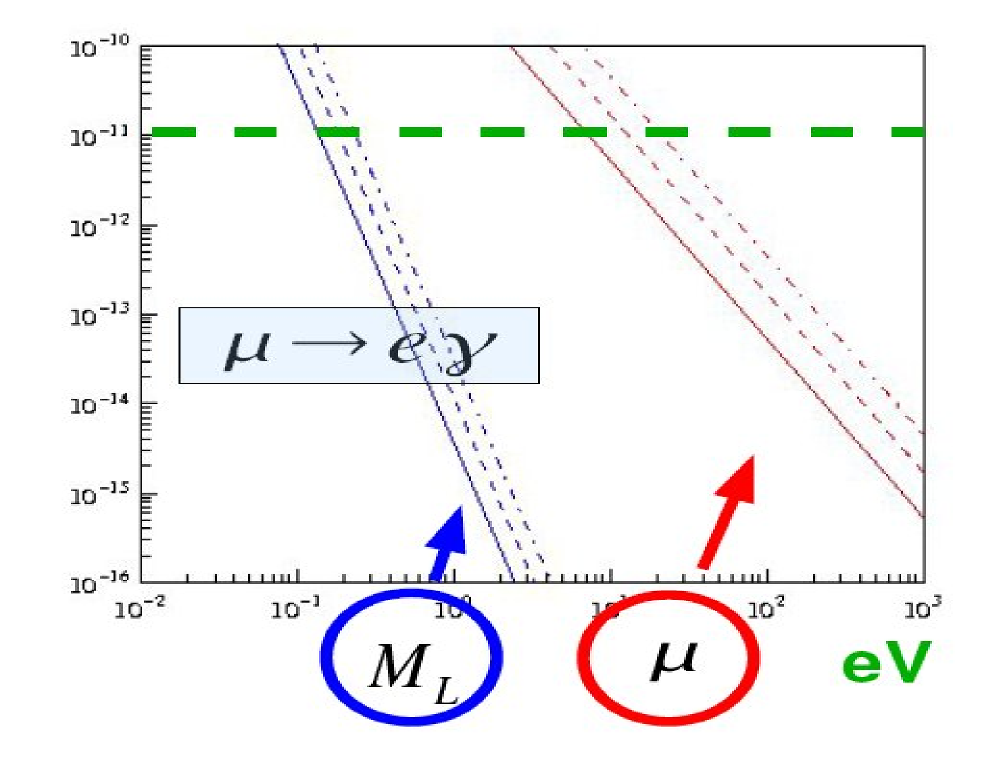
$$\begin{pmatrix} 0 & M_D & M_L \\ M_D^T & 0 & M \\ M_L^T & M^T & 0 \end{pmatrix}$$

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

- **INVERSE SEESAW**
  Mohapatra-Valle, PRD34 (1986) 1642
- **LINEAR SEESAW**
  Malinsky et al PRL95 (2005) 161801

LFV from NHL

M=0.2-1TeV **Hirsch, et al arXiv:0905.3056**



- **natural ...** **t'Hooft**
- **dynamical origin ...**
  Bazzocchi, et al arXiv:0907.1262 [hep-ph]
- **LFV & CPV survive in massless neutrino limit**

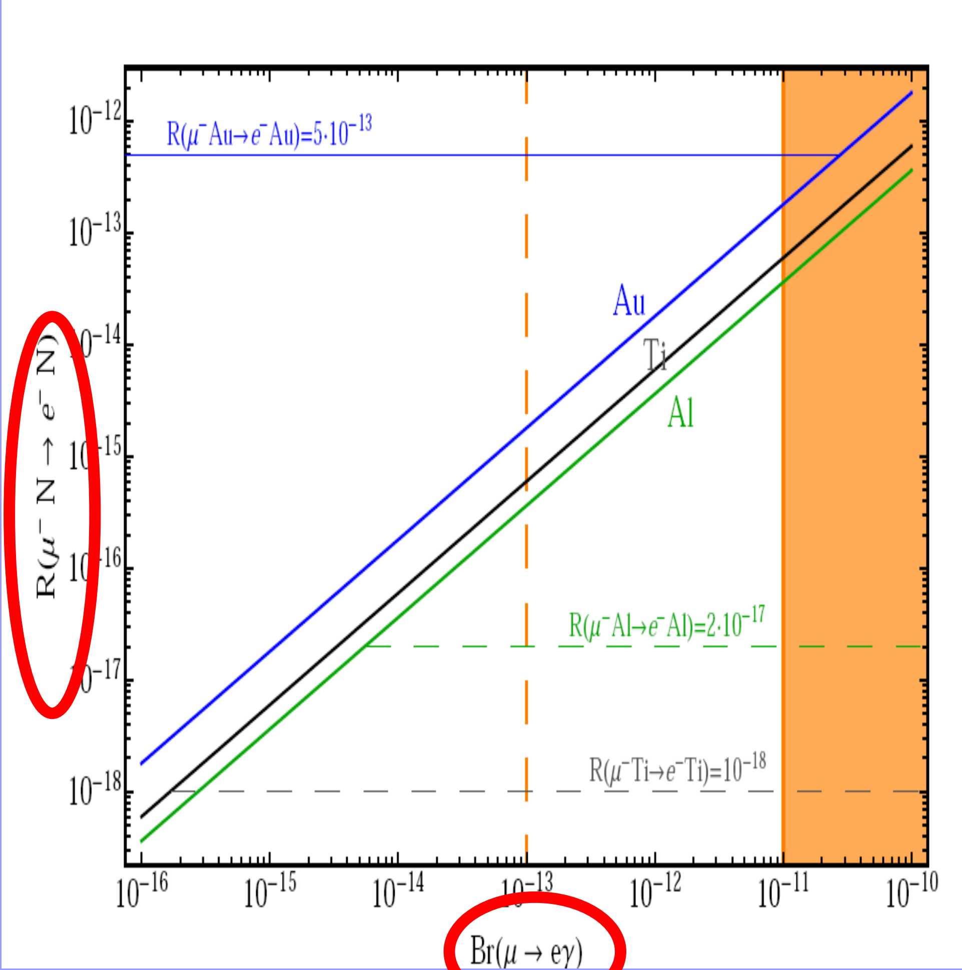
  ⇩
- **unsuppressed by m-nu**

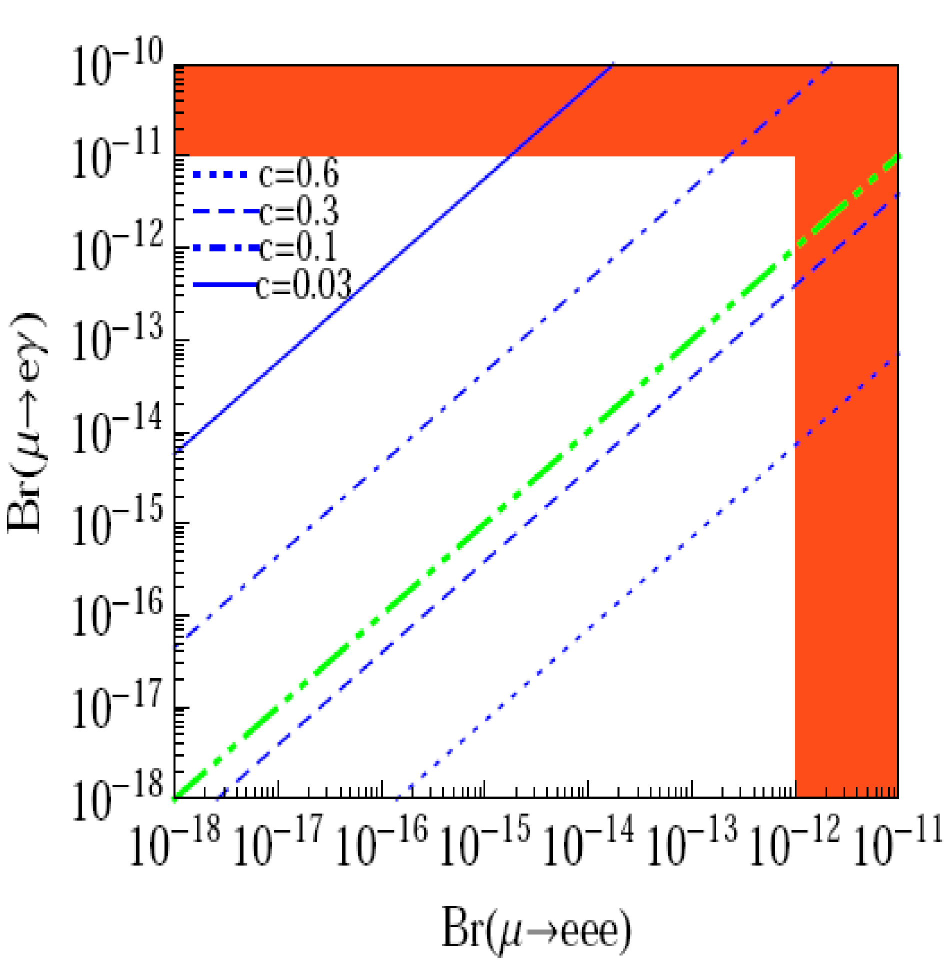
INVERSE type−3

Ibanez Morisi JV, arXiv:0907.3109

mu-e conversion in nuclei

mu->3e vs mu->e gamma





Deppisch, Kosmas & JV NPB752 (2006) 80

Heavy leptons@LHC

HIGH–SCALE SEESAW
SUSY LFV DECAYS@LHC

Hirsch et al PRD 78 (2008) 013006, Esteves et al JHEP05 (2009) 3

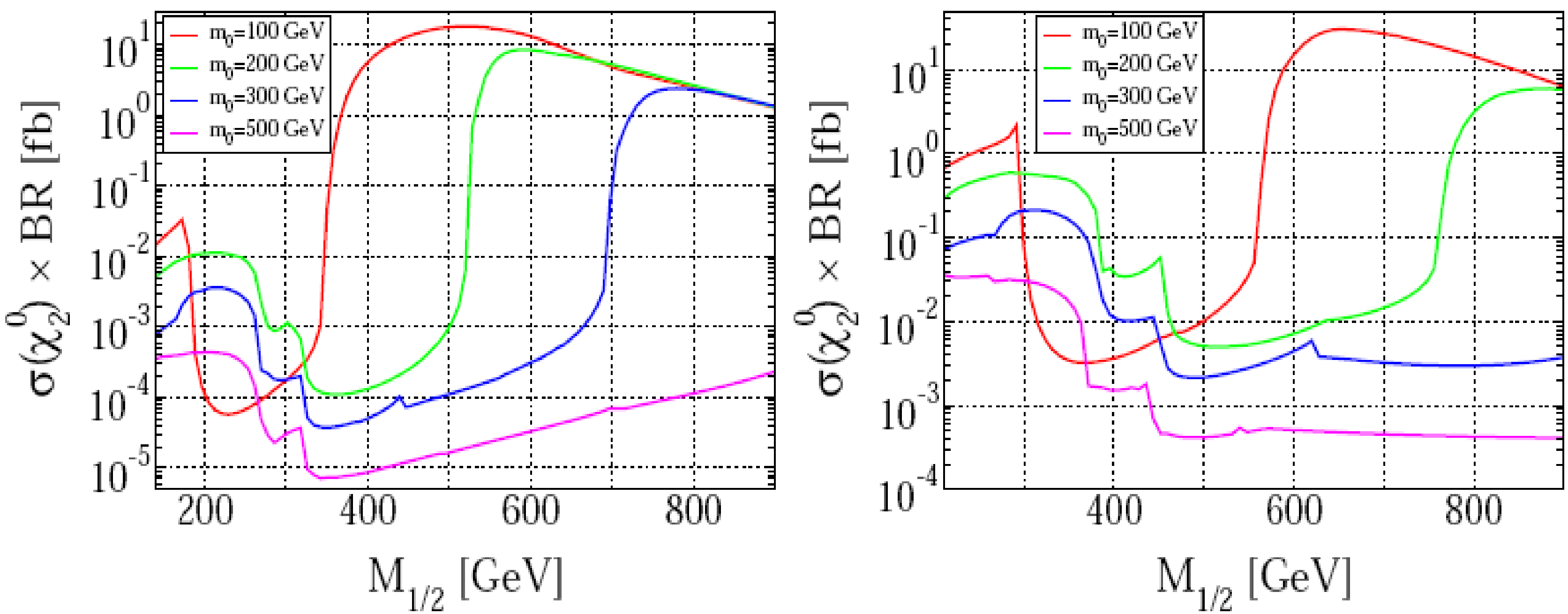
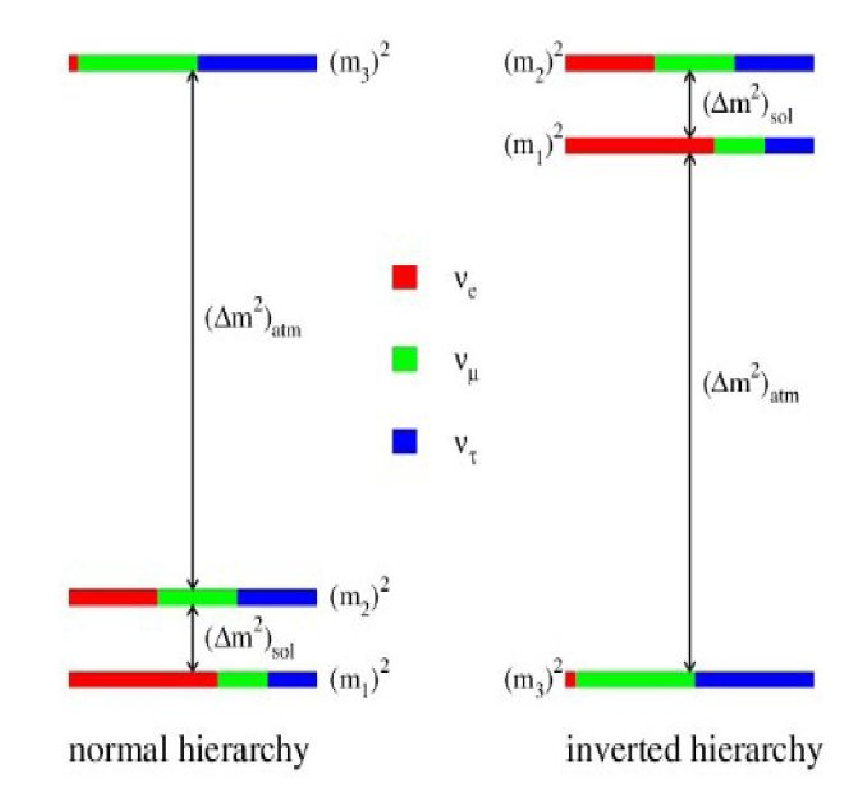
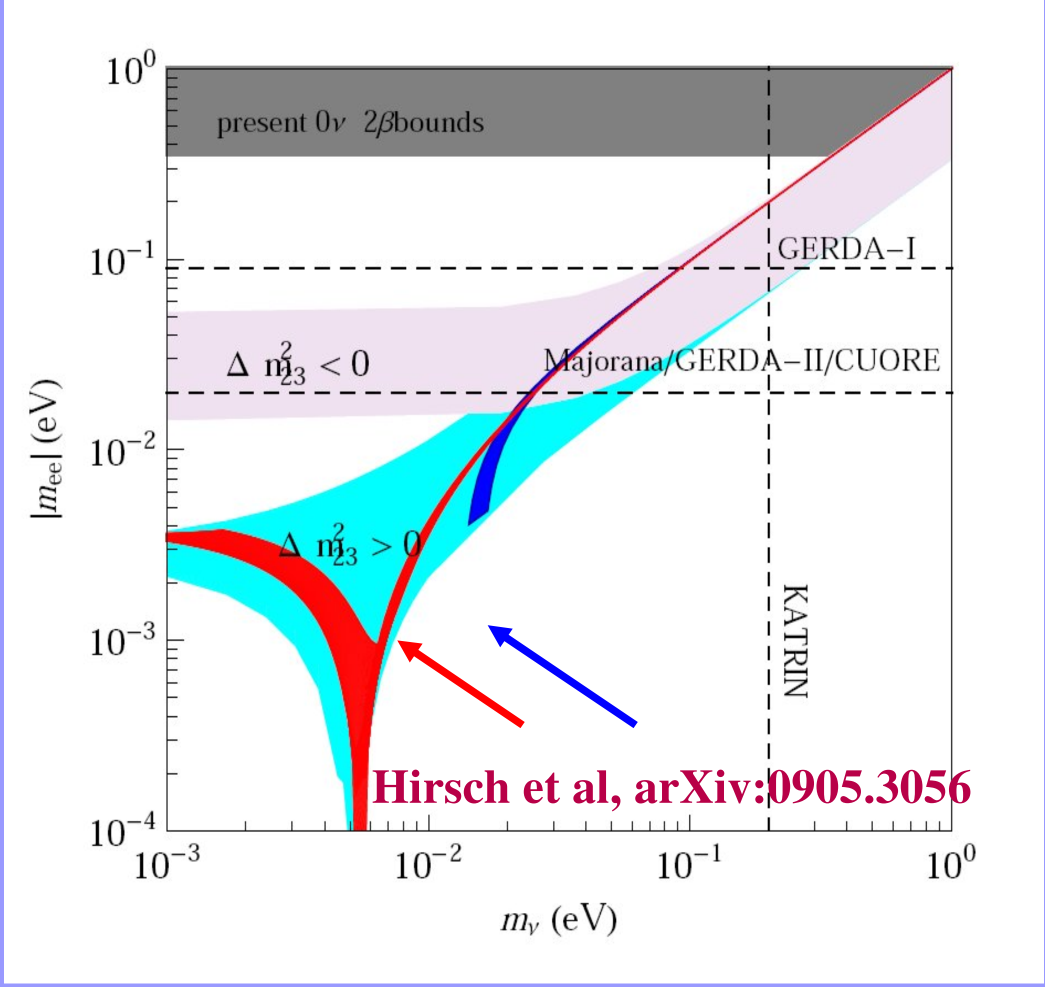


FIG. 12: Production cross section (at leading order) of χ_2^0 times BR of χ_2^0 going to μ-τ lepton pair versus $M_{1/2}$ for $m_0 = 100$ GeV (red), 200 GeV (green), 300 GeV (blue) and 500 GeV (magenta), and for our standard choice of parameters: $\mu > 0$, $\tan\beta = 10$ and $A_0 = 0$ GeV, for type-I (left panel) and for type-II seesaw (right panel) with $\lambda_1 = 0.02$ and $\lambda_2 = 0.5$, imposing $\mathrm{Br}(\mu \to e + \gamma) \leq 1.2 \cdot 10^{-11}$.

ABSOLUTE NEUTRINO MASS

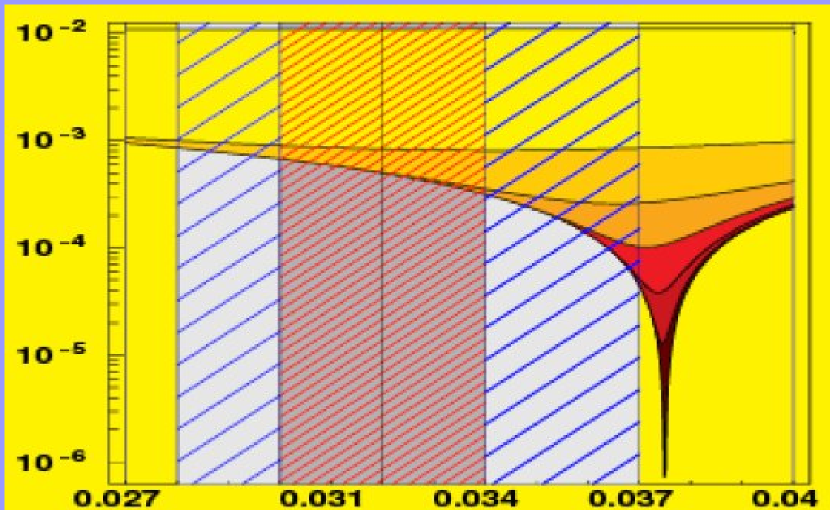
- beta decay Katrin
- cosmology CMB LSS ... sensitivities vs flavor predictions
- **DBD**





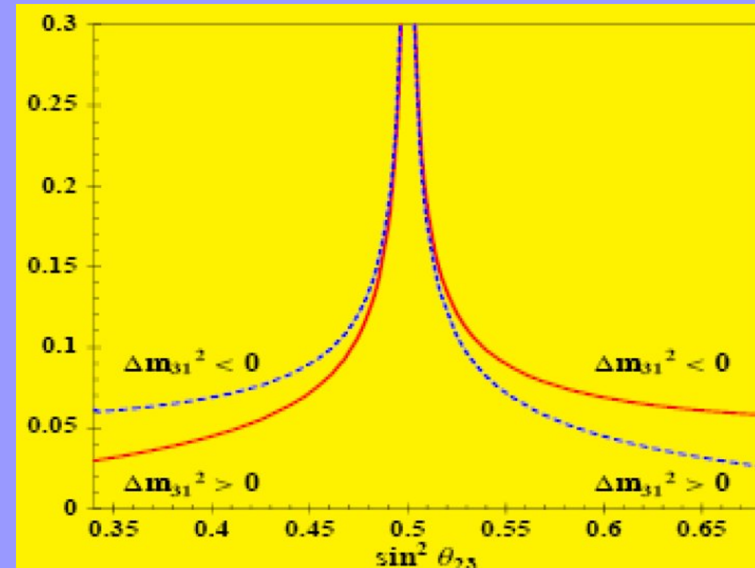
DBD & FLAVOR

PRD78:093007 (2008)



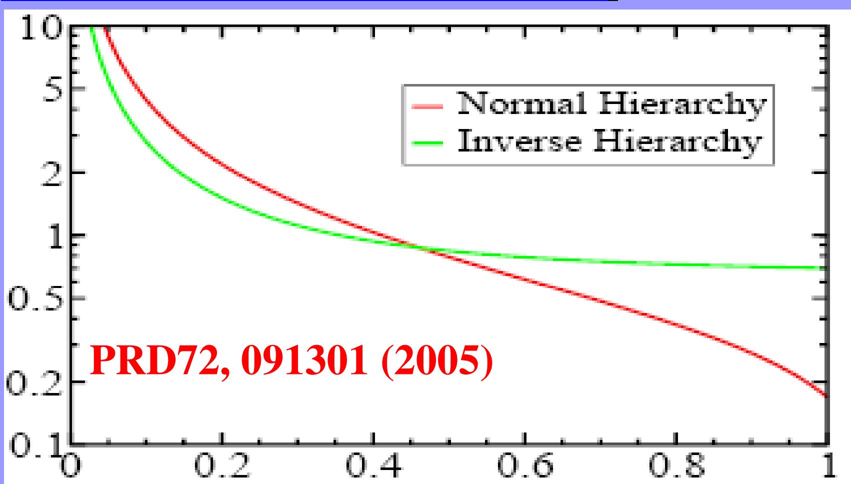
correlates with $\alpha = \frac{\Delta m^2_{SOL}}{\Delta m^2_{ATM}}$

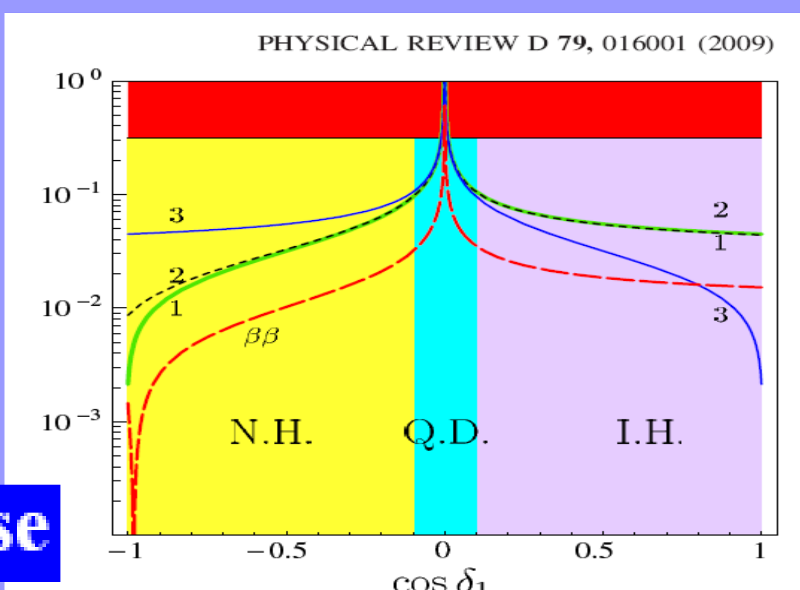
PRL 99 (2007) 151802



correlates with ATM angle

A4



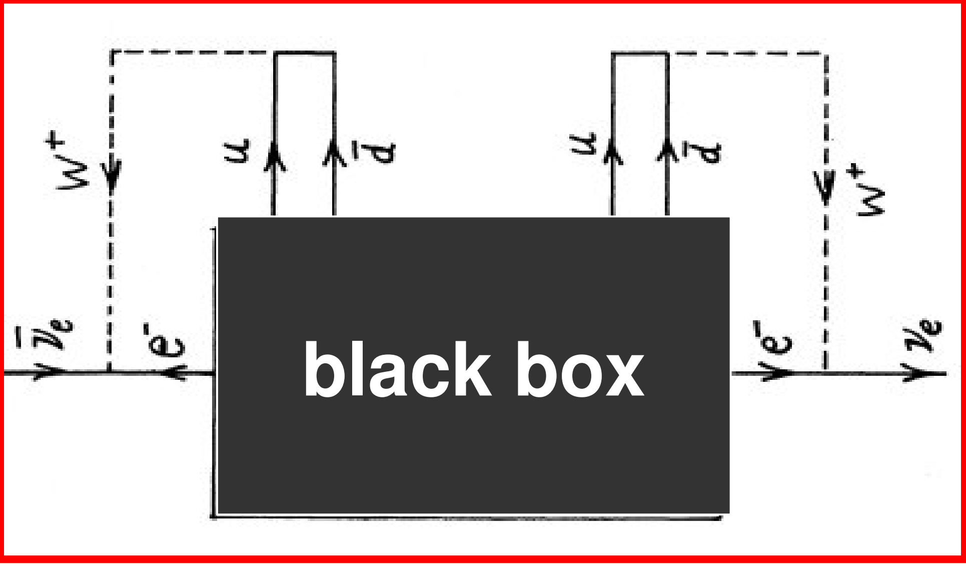


correlates with Majorana phase

WHY RELEVANT?

PRD25 (1982) 2951

0-nu DBD ⇆ majorana



Neutrinoless double-β decay in SU(2)×U(1) theories

J. Schechter and J. W. F. Valle
Department of Physics, Syracuse University, Syracuse, New York 13210
(Received 14 December 1981)

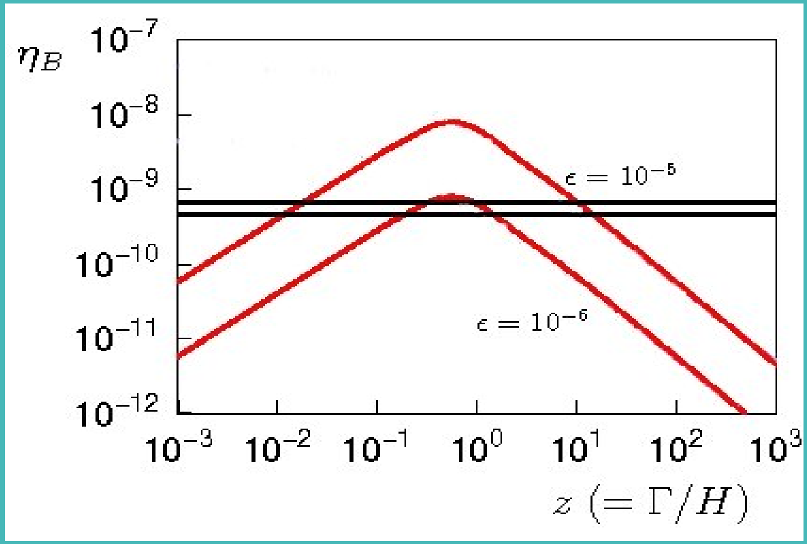
It is shown that gauge theories give contributions to neutrinoless double-β decay [$(\beta\beta)_{0\nu}$] which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $(\beta\beta)_{0\nu}$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

neutrinos may be relevant before EWPT: LG & DM

nu-mass relevant in CMB & LSS

COBE, WMAP, PLANCK

THERMAL SEESAW−1 LEPTOGENESIS

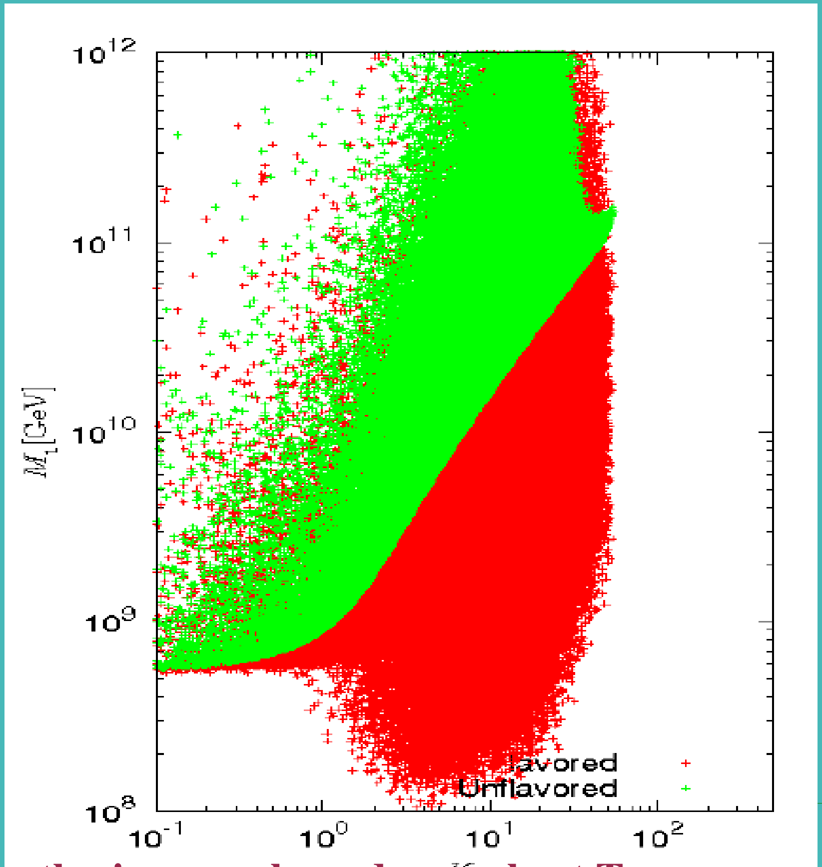


From PRD77 (2008) 055002

Sakharov, KRS, Fukugita, Yanagida

Giudice et al 2004

Buchmuller, Di Bari, Plumacher, 2005



Lower bound on M1:

Flavored vs unflavored LG

From Blanchet & di Bari NPB807 (2009) 155

Cf nucleosynthesis upper bounds on reheat T

Abada, Davidson, Ibarra, Josse-Michaux, Losada & Riotto JHEP 09 (2006) 010

Blanchet, di Bari, Raffelt, 2006

Nardi, Nir, Roulet Phys. Rept. 466 (2008) 105

Garayoa, et al 2009

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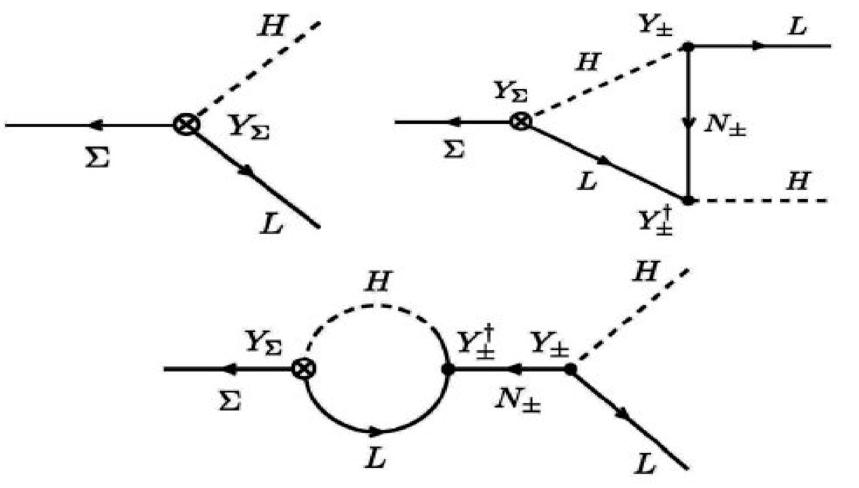
=> gravitino problem

Kawasaki, Kohri & Moroi, PRD71 (2005) 083502

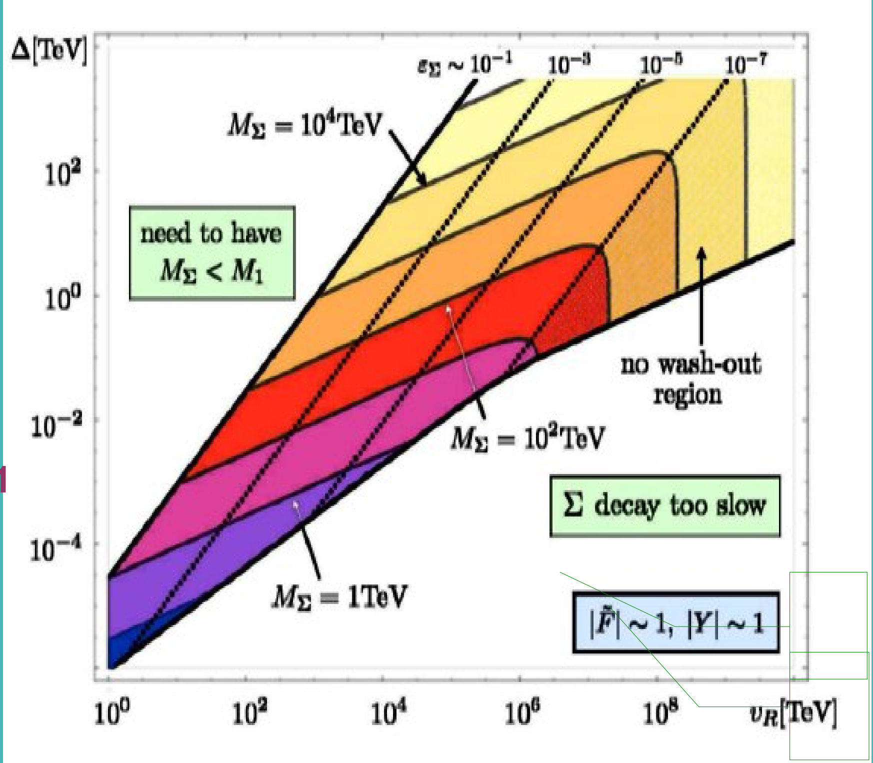
LOW–SCALE THERMAL LG IN SO10

Hirsch et al PRD75 (2007) 011701
D77 (2008) 055002



Extra gauge singlet drives LG

- **Suggests NEW Z' at LHC**



- **alternatives:**
  - axino — Asaka, Yanagida, 2000
  - tiny RPV — Farzan, JV PRL96 (2006) 011601
  - gauge mediation — Olechowski, et al 2009

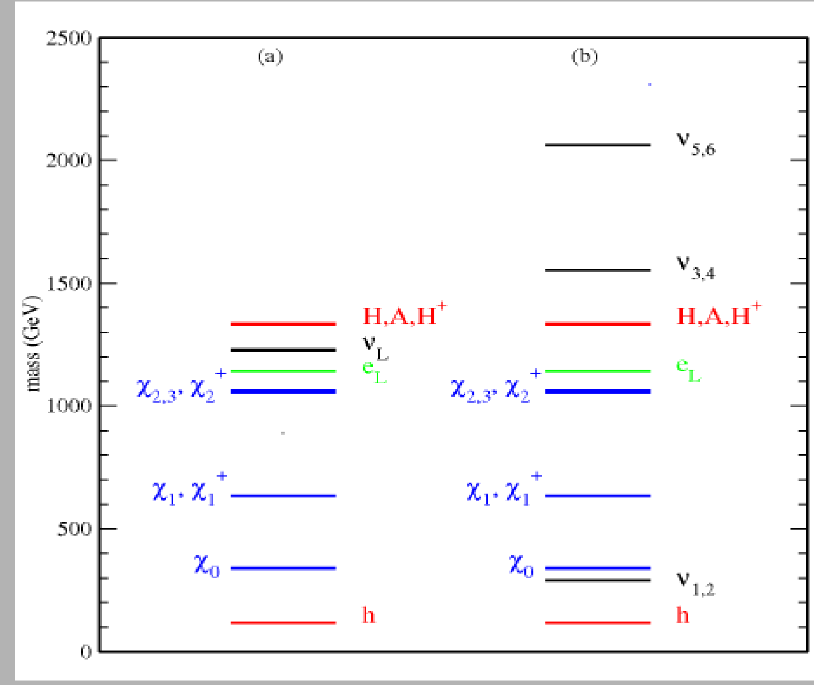
neutrinos may give the clue to DM

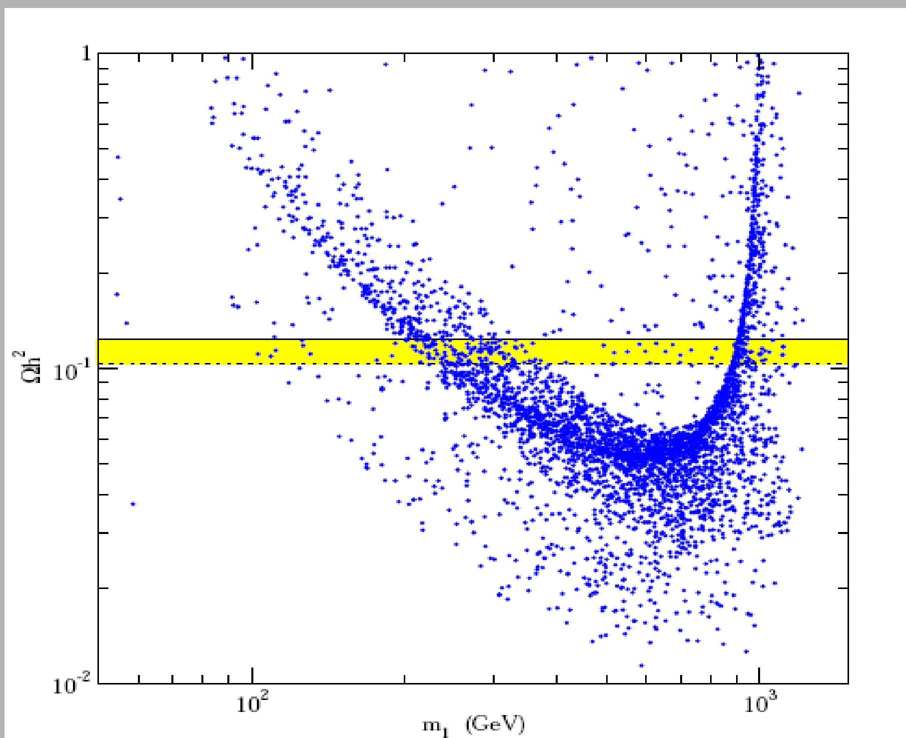
“SNEUTRINO” DM

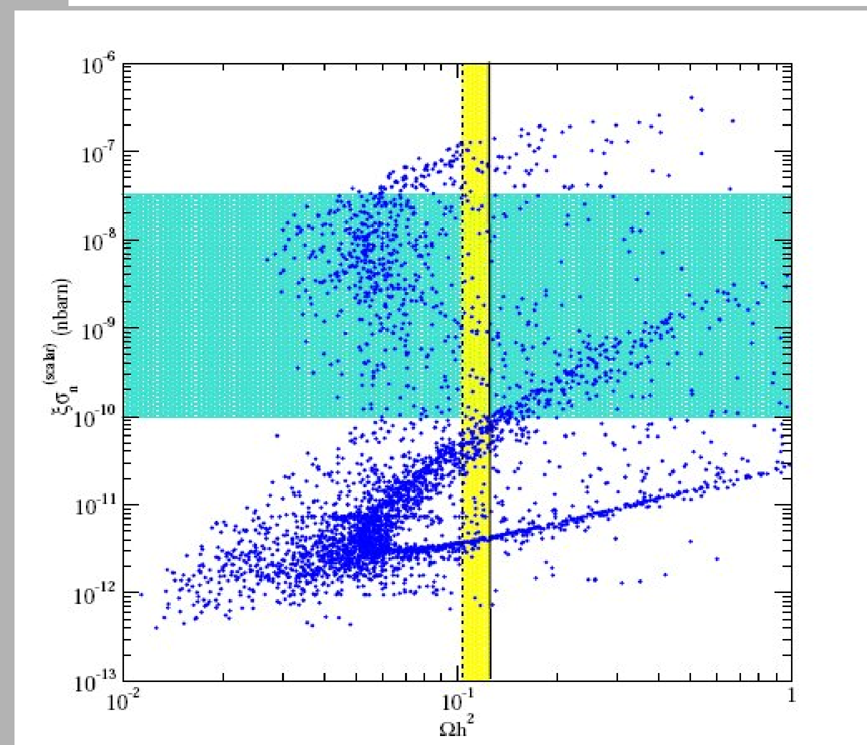
- **inverse seesaw**

  Arina & al PRL101 (2008) 161802
  Bazzocchi, et al arXiv:0907.1262 [hep-ph]

- **mu-problem** Cerdeno, Munoz, Seto 2009







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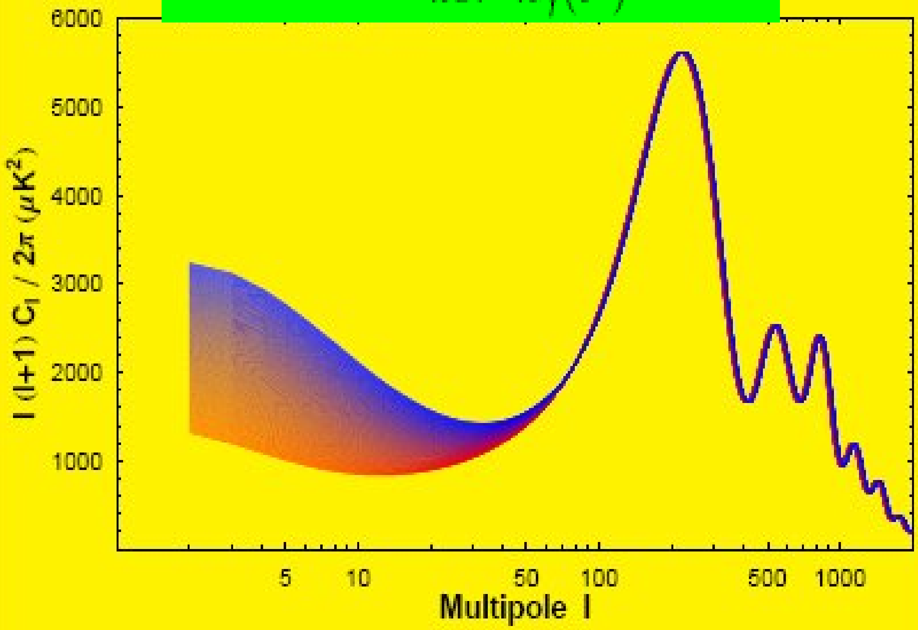
DARK MATTER NEED NOT BE STABLE

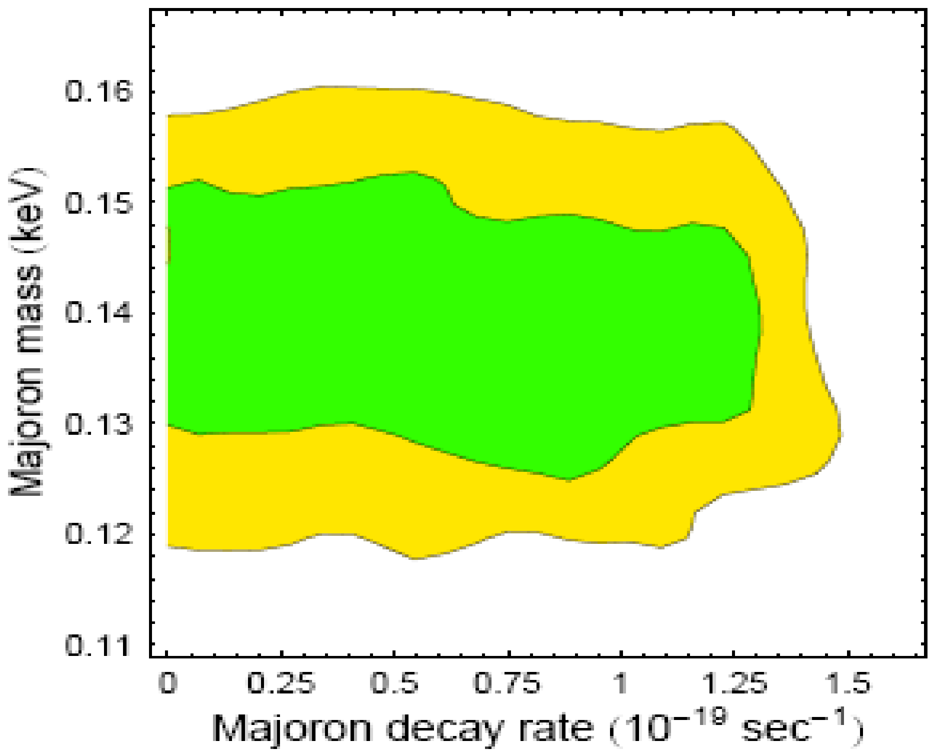
Coleman NPB310 (1988) 643, Kallosh, Linde, Linde, Susskind PRD52, Nelson-Seiberg 94 **applies to LSP** **Berezinsky et al PRD57(1998) 147**

also applies to KEV MAJORON DM

Lattanzi & Valle, PRL99 (2007) 121301

$$\Omega_J h^2 = 1.6\,\frac{m_J}{keV}\frac{n_J(t^*)}{n_\gamma(t^*)}e^{-t_0/\tau}$$





Detection: Bazzocchi & al JCAP 0808 (2008) 013 & **arXiv:0906.1788 Xenia mission**

OSCILLATIONS MAINLY ROBUST

but NEED NON-OSCILLATION TESTS: B&DBD, COSMO & ASTRO

STILL DO NOT UNDERSTAND FLAVOR

- **if linked to unification, hard to reconcile L- & Q-mixings**
- **flavor models correlate LFV phenomena**

ORIGIN OF NEUTRINO MASS REMAINS A MYSTERY

- **High-scale seesaw testable only indirectly e.g. through LFV SUSY PARTICLE DECAYS @ LHC**
- **LOW-SCALE SEESAW (e.g. inverse & linear) give large LFV effects &**
- **NEW TeV PARTICLES**

NEUTRINOS SUGGEST DM CANDIDATES:

- **SNEUTRINO -like**
- **MAJORON DM**

MAY INDUCE THERMAL LG@LOW-SCALE => new TeV NEUTRAL Z

SUSY ORIGIN OF MNU

BAU & GALACTIC MAG-FIELDS ? arXiv:0905.3365

THE END
THANK YOU

next slides are backup/complementary with no logical order among them

DOES BAU RELATE TO GALACTIC MAG-FIELDS?

Semikoz, Sokoloff, JV

arXiv:0905.3365

- **Seed hyper-mag-field polarizes early Universe hot plasma before EWPT => lepton asym**

- **lepton asymmetry converts into BAU by t'Hooft anomaly**

- **mag-field strength inferred from such "leptogenic" ansatz matches the large-scale GMFs estimated from current astronomical observations**

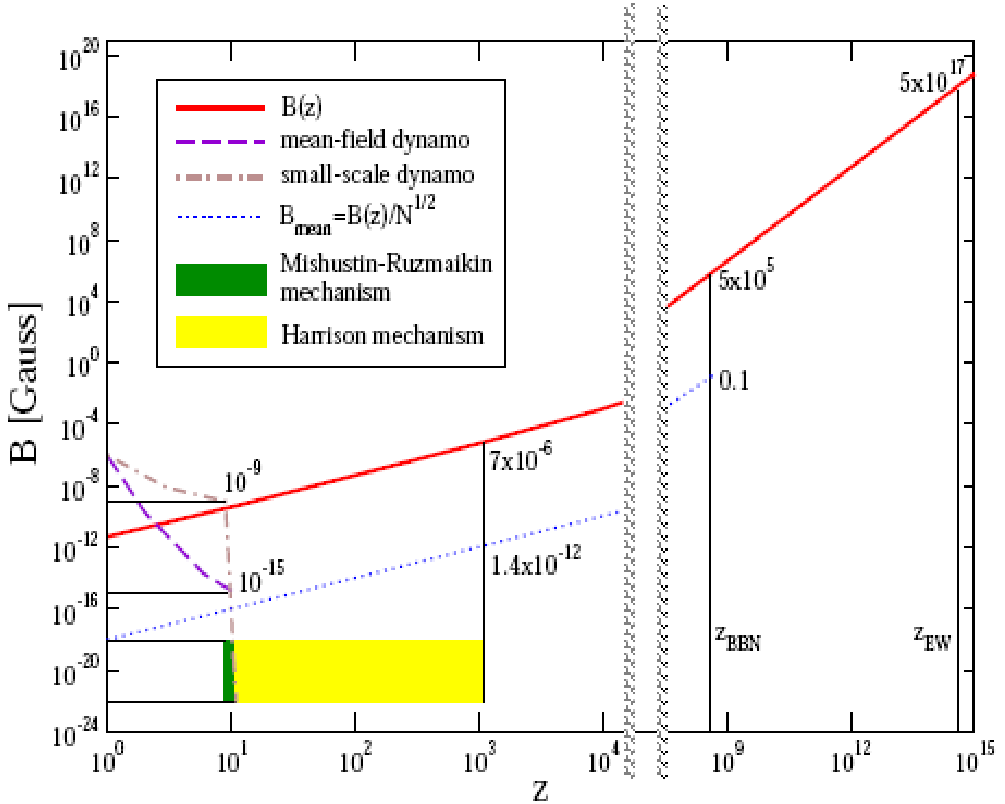


FIG. 1: Magnetic field evolution after EWPT. The solid (red) line represents the Maxwellian magnetic field evolved from the hypermagnetic one as frozen-in plasma, while the dotted (blue) line represents the large-scale (1 pc at the epoch of galaxy formation) component of magnetic field which becomes causal at a moment after the EWPT. The dashed line denotes the galactic magnetic field generated by mean-field dynamo, while the dash-dotted one represents the galactic magnetic field generated by small-scale and then mean-field dynamo, starting from 10^{-9} G. For comparison we also show in the boxes the magnetic field models in Refs. [22].

NEUTRINO OSCILLATIONS 2009

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

$$\sin^2\theta_{13} \leq \begin{cases} 0.060\ (0.089) & \text{(solar+KamLAND)} \\ 0.027\ (0.058) & \text{(CHOOZ+atm+K2K+MINOS)} \\ 0.035\ (0.056) & \text{(global data)} \end{cases}$$

New J.Phys.10:113011,2008

θ_{13} measurement by ν_e appearance

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}$$

θ_{13}

$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CPC

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CPV

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$

solar

$$-8C_{13}^2 S_{13}^2 S_{23}^2 (1-2S_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

matter effect
(small in T2K)

L = 295 km, $\langle E_\nu \rangle$ ~0.6GeV

$\sin\Phi_{21}$ ~ 0.05

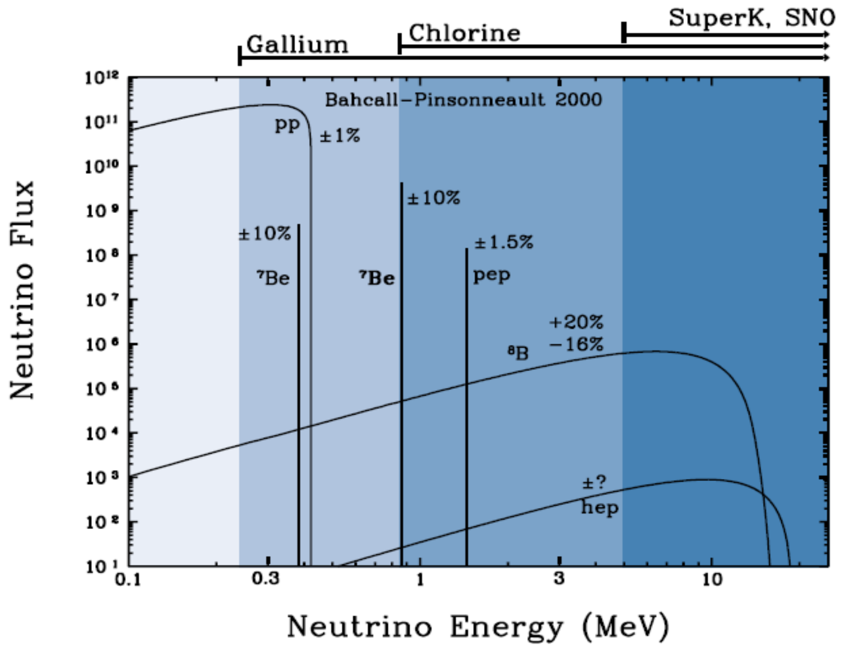
$\delta \to -\delta,\ a \to -a$ for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

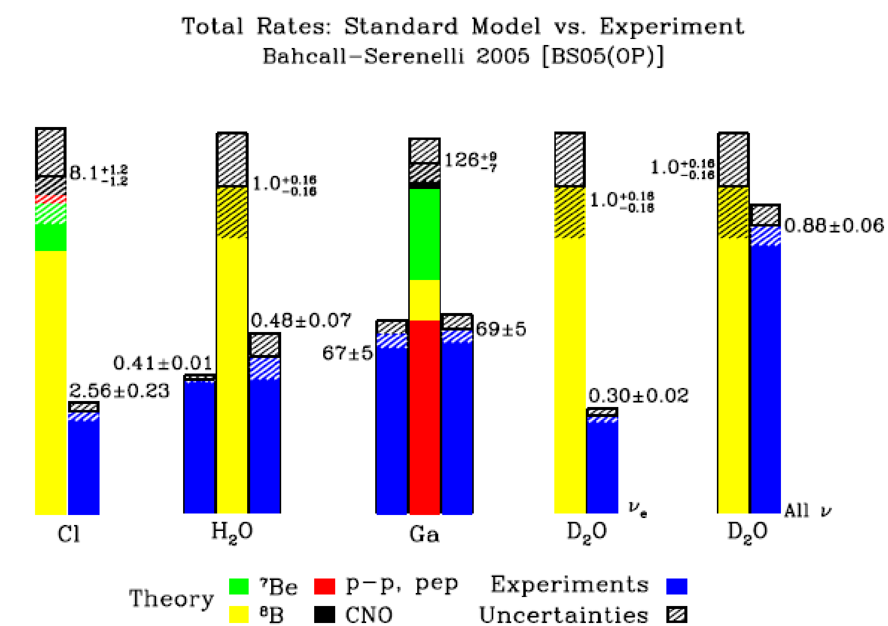
$$\frac{aL}{4E} = 7.6 \times 10^{-5}[\mathrm{eV}^2]\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\left(\frac{E}{[\mathrm{GeV}]}\right)\frac{L}{4E} \propto L$$

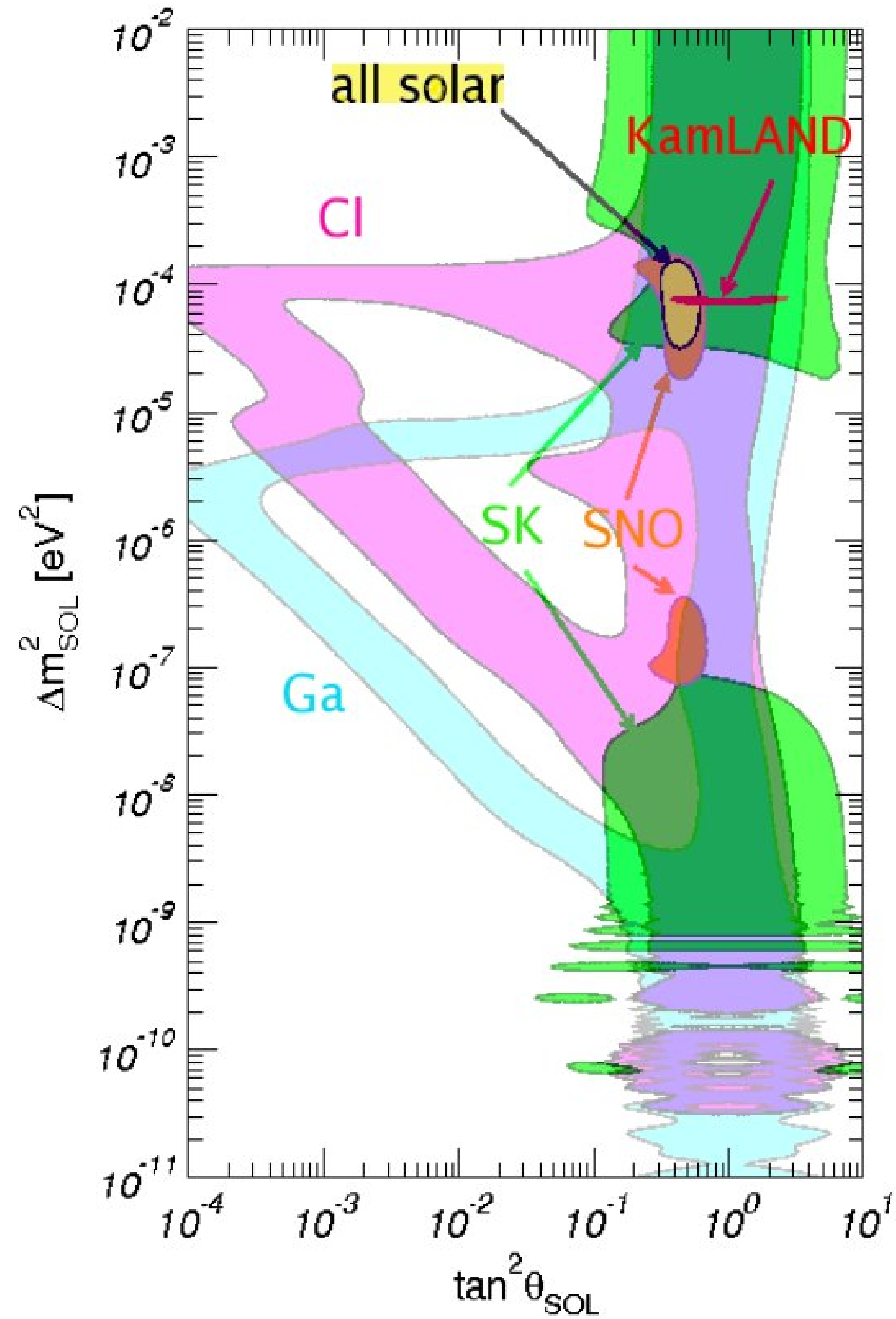
- $P(\nu_\mu \to \nu_e) \to \sin^2(2\theta_{13})$: some ambiguity due to unknown params.
- It is possible to measure CPV by comparing ν and $\bar{\nu}$

Sakashita (t2k)@eps09

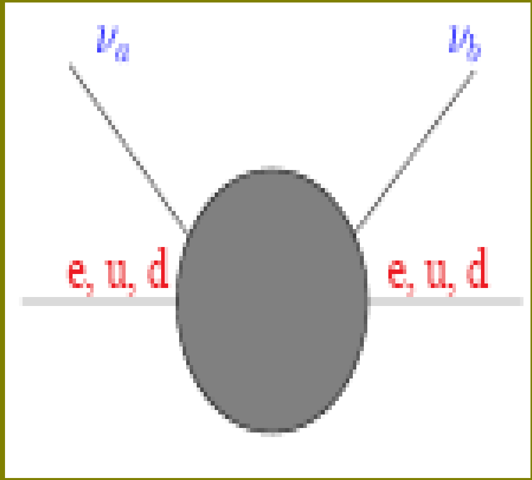
SOLAR NEUTRINOS







NON–STANDARD NEUTRINO INTERACTIONS



FC or NU sub-weak strength dim-6 terms εGF

- from non-trivial (rectangular) CC & NC in seesaw-type models
- from loops

- can induce resonant oscillations of massless neutrinos in Snovae

Valle PLB199 (1987) 432

- E-independent, converts both neutrinos & anti-nu's,

Wolfenstein; Roulet 91; Guzzo et al 91; Barger et al 91,...

- give excellent description of solar data at odds with KamLAND.

Guzzo et al NPB629 (2002) 479

Pakvasa & Valle

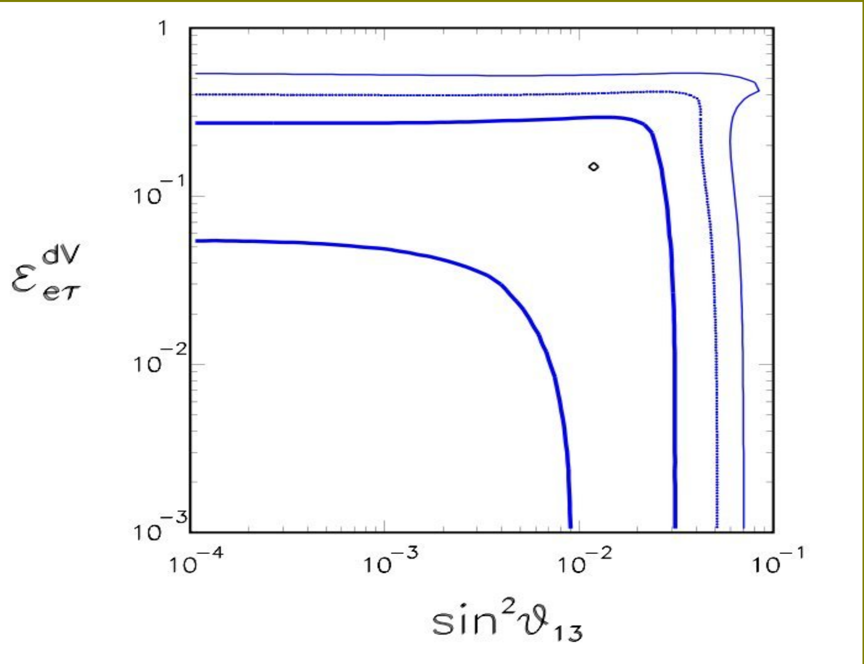
may affect neutrino oscilation solution

Confusing nonstandard neutrino interactions with oscillations

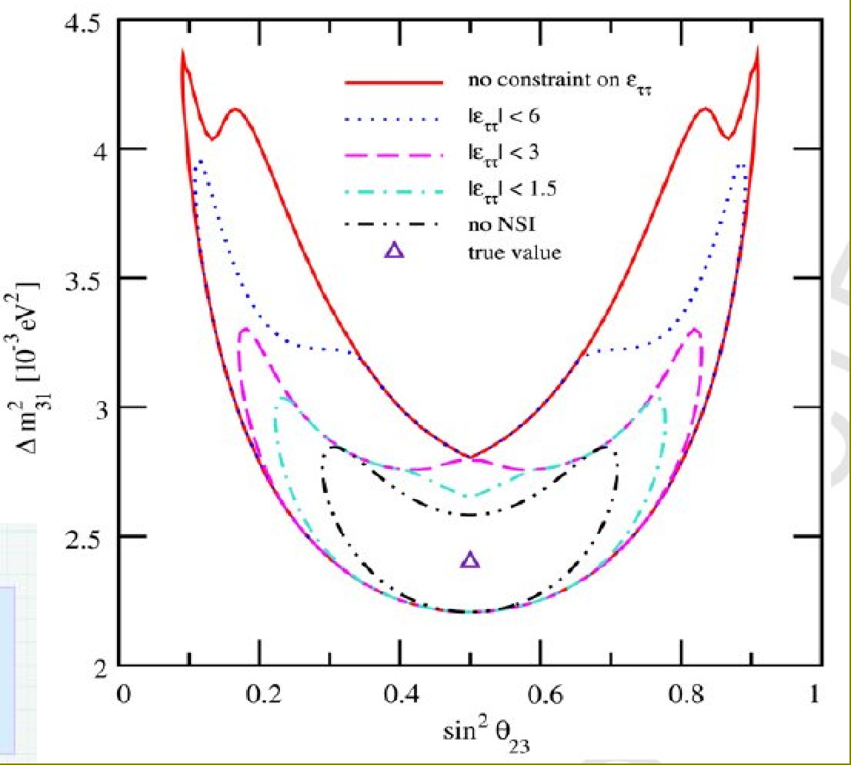
Palazzo & JV, 2009

- similar to situation at a neutrino factory

Huber, Schwetz, JV PRL88:101804,2002
PRD66:013006,2002



Davidson et al JHEP (2003) 0303:011
Barranco, et al , D73 (2006) 113001, D77 (2008) 093014
Abada, Biggio Bonnet, Gavela, Hambye PRD78
Esteban Huber JV PLB668:197201,2008
M. B. Gavela, D. Hernandez, T. Ota, W. Winter, PRD79
Escrihuela et al arXiv:0907.2630 [hep-ph]
Malinsky et el, arXiv:0905.2889 [hep-ph]
Bolaños et al PRD79 (2009) 113012

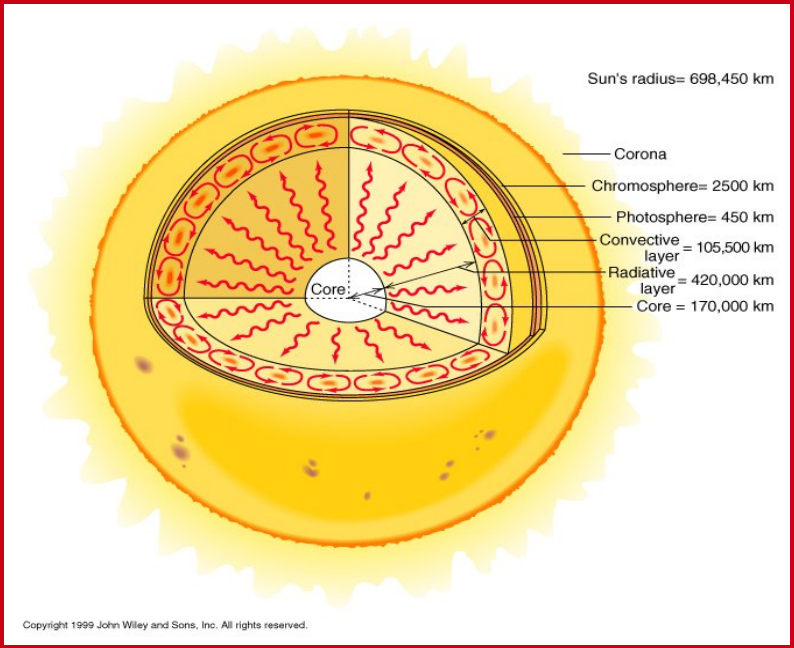


current bounds (90% CL):

$-0.6 < \varepsilon_{\tau\tau}^{eL} < 0.4$ → $-0.16 < \varepsilon_{\tau\tau}^{eL} < 0.11$

$-0.4 < \varepsilon_{\tau\tau}^{eR} < 0.6$ → $-1.05 < \varepsilon_{\tau\tau}^{eR} < 0.31$

SOLAR NU–OSCILLATIONS ROBUST?



BACK

RZ Burgess et al JCAP0401 (2004) 007

CZ Miranda et al PRL93 (2004) 051304 & PRD70 (2004) 113002

Both strongly disfavored by KamLAND

NSI exception **JHEP** 0610 (2006) 008

degenerate dark-side solution still exists !!

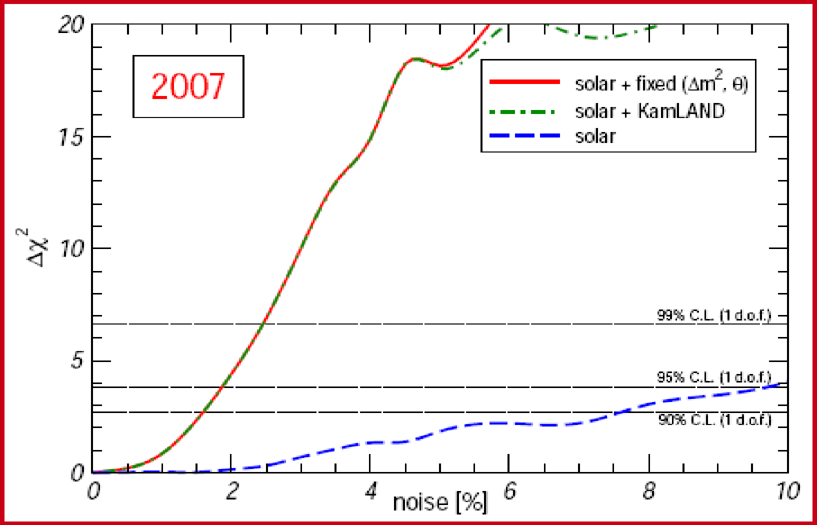
FROM NEUTRINO PROPERTIES TO SOLAR PHYSICS

Test SSM fluxes Borexino ...

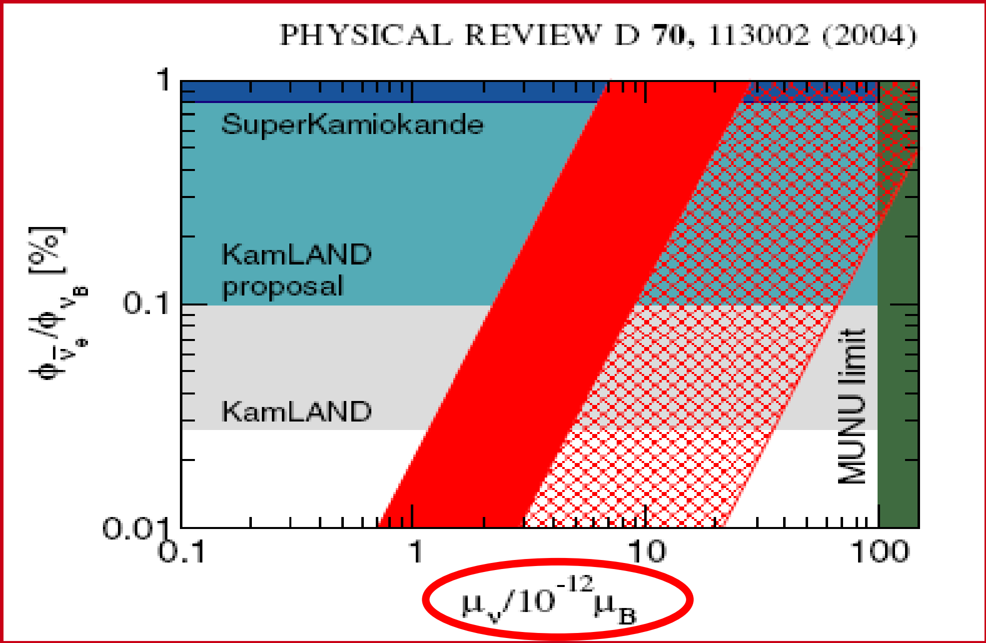
· **Probe RZ mag-fields & RZ-density fluctuations**

helioseismology & magneto-gravity waves ...

Burgess et al MNRAS.348 (2004) 609



PROBING TRANSITION MOMENTS – SFP



FROM PROPAGATION EFFECT

Miranda et al PRL93 (2004) 051304

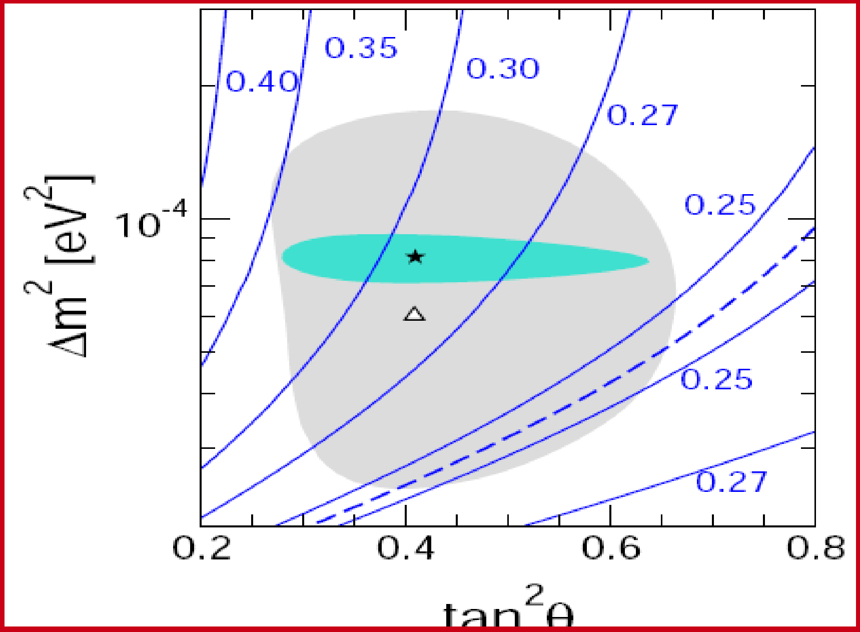
KamLAND anti-nu-e flux limit =>

SFP must be subdominant w.r.t. LMA oscillations

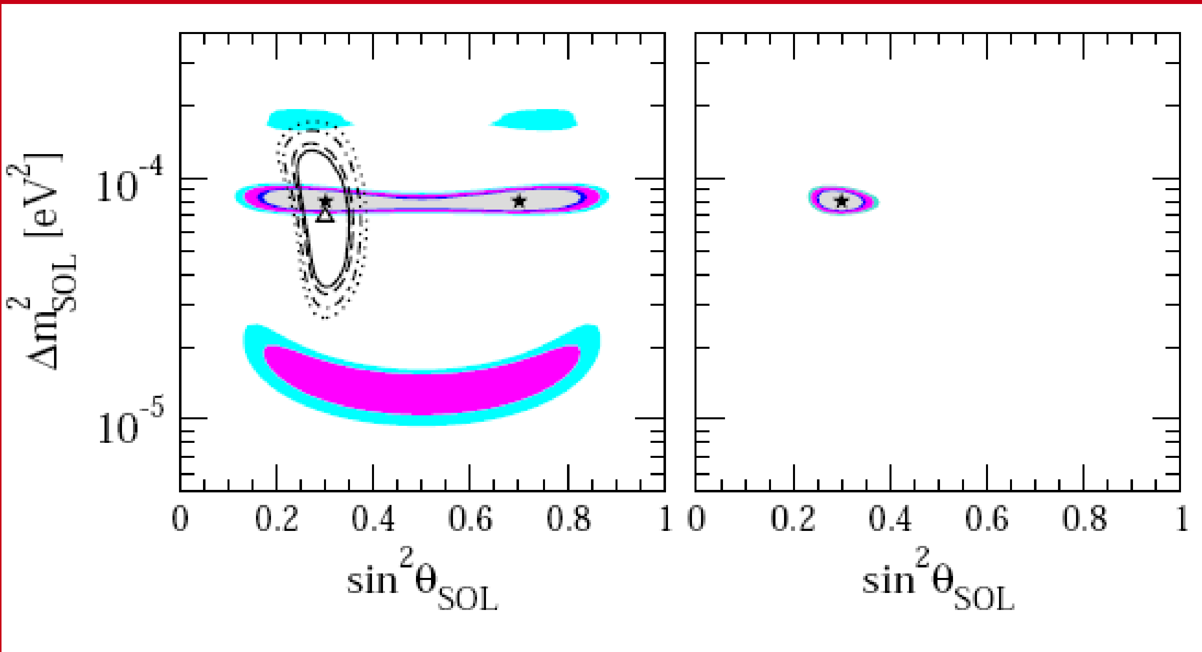
bounds on transition mag-moment in a turbulent magnetic field model

FROM THEIR EFFECT ON THE NEUTRINO-ELECTRON SCATTERING CROSS SECTION

Grimus et al, NPB648, 376 (2003)



Borexino sensitivity



#Slide 5

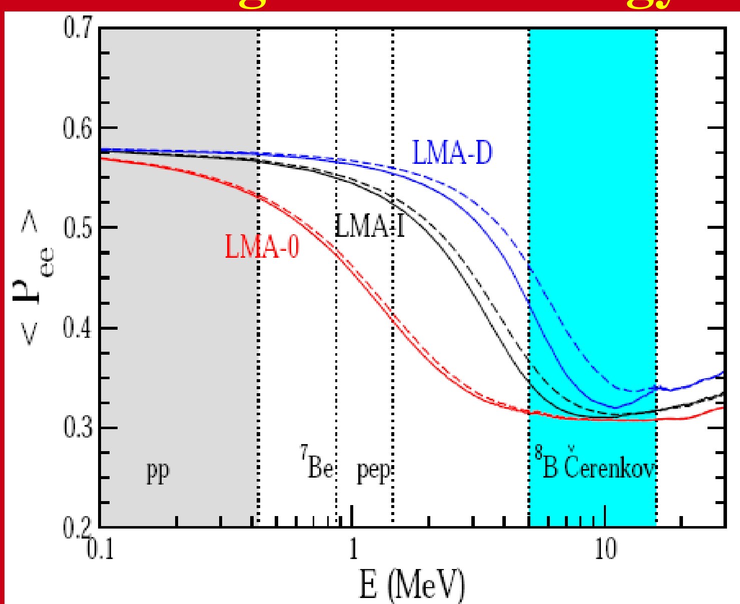
#Slide 25

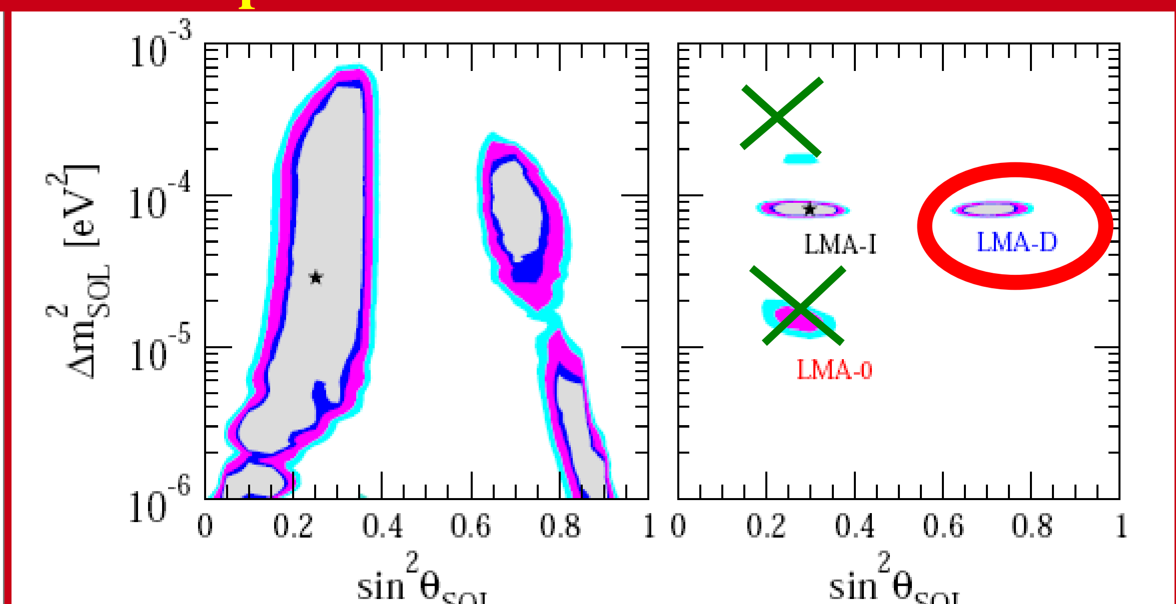
pure oscillation

osc+nsi

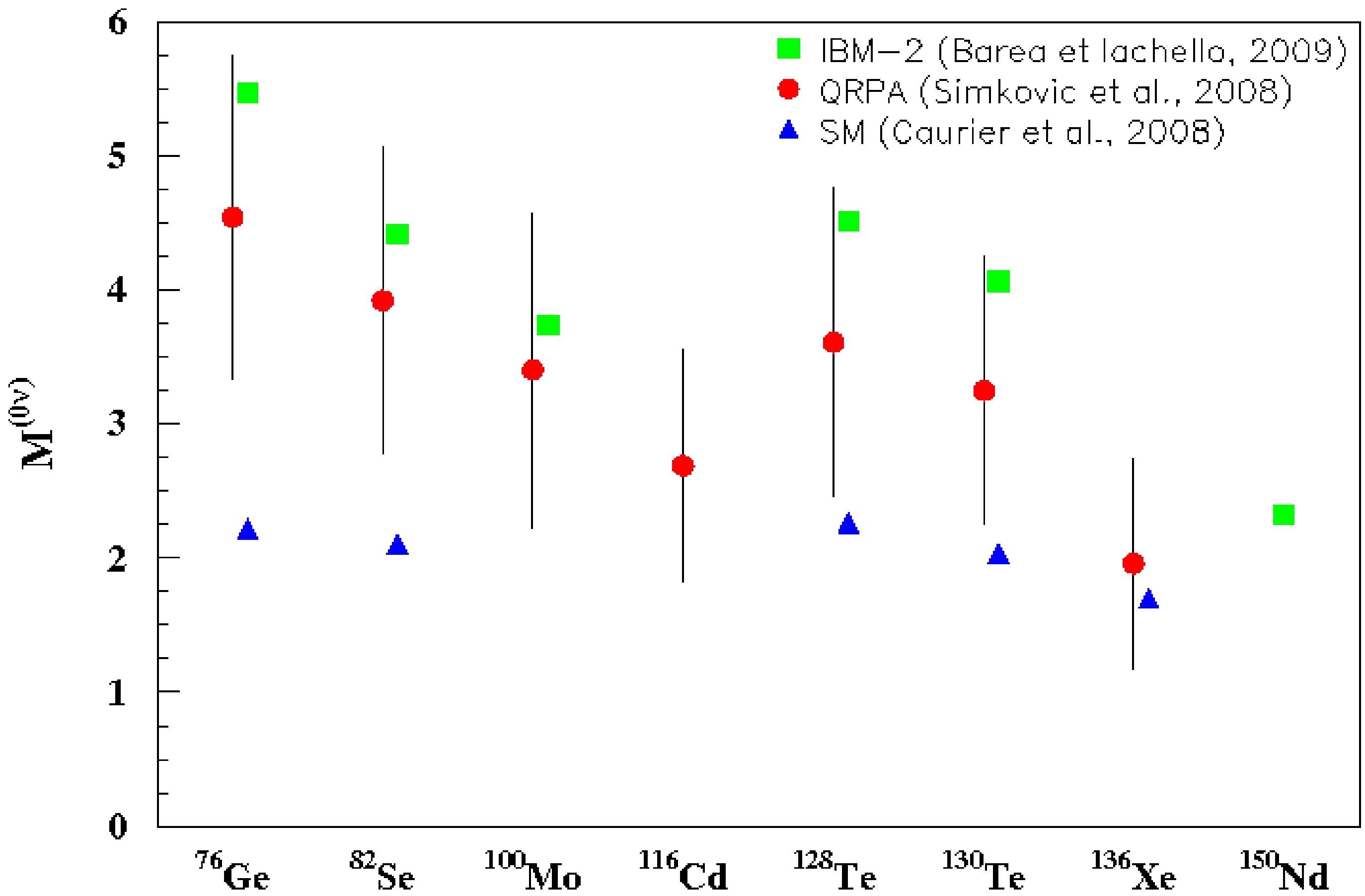
Miranda, Tortola & Valle JHEP 0610:008,2006.

resolving with low-energy solar-nu expts?





dbd matrix elements



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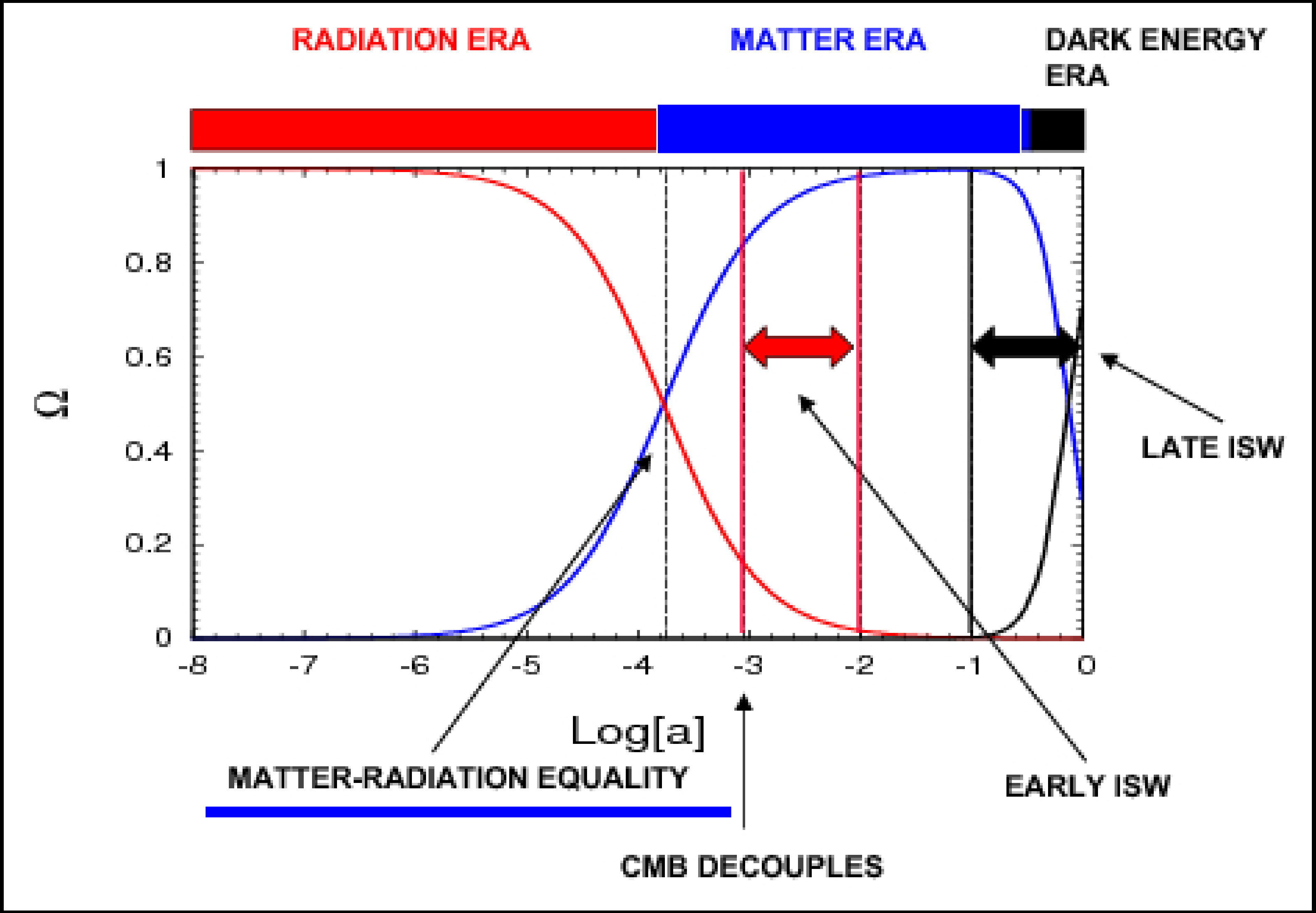
Thanks to S Schonert

UNIVERSE CONTENT IN LATE–DECAYING DM COSMOLOGY



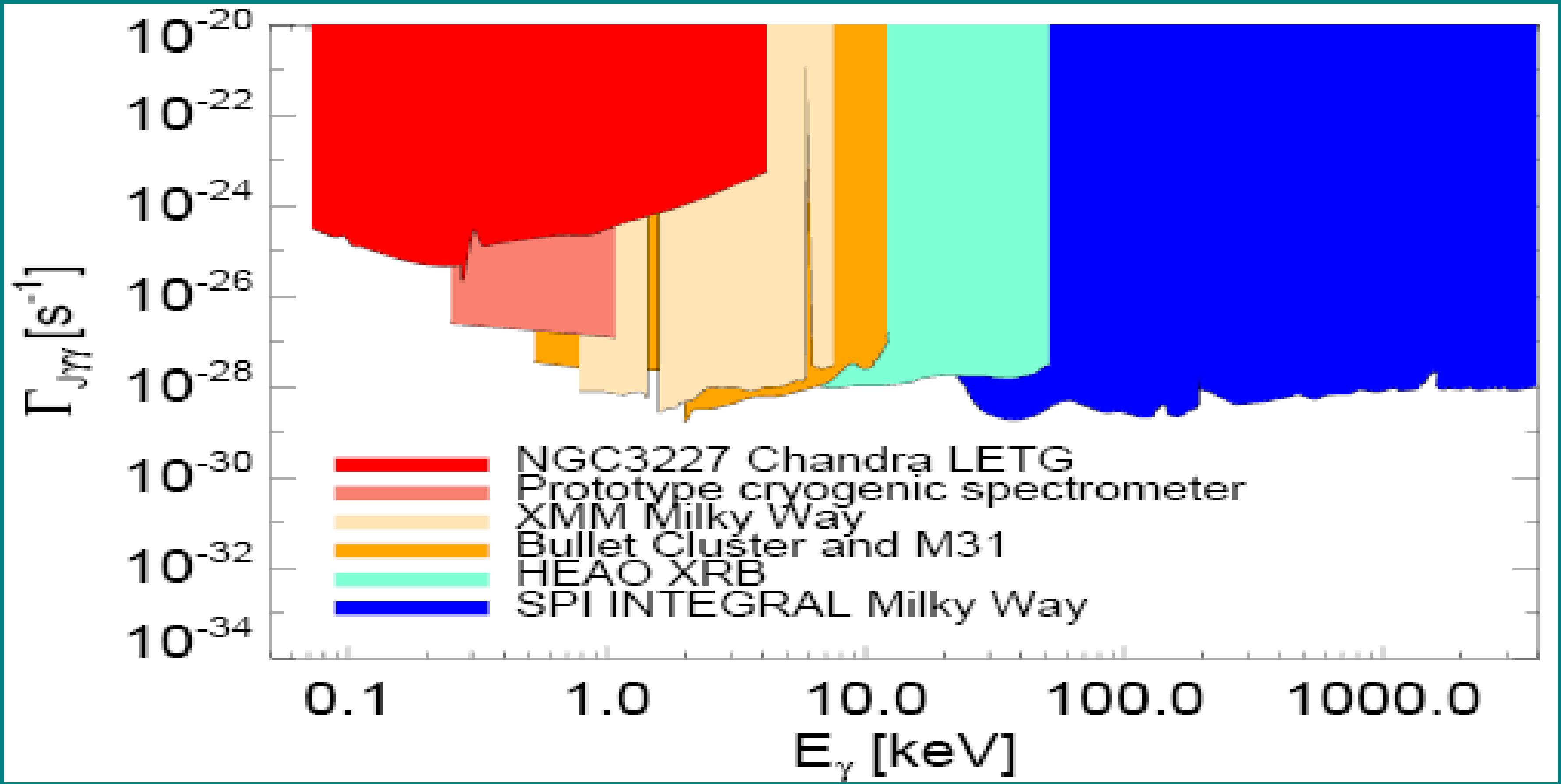
PROBING SEESAW−2 MAJORON DM

$g_{J\gamma\gamma} J \epsilon^{\nu\mu\rho\sigma} F_{\nu\mu} F_{\rho\sigma}$

Schechter & JV PR**D22** (1980) 2227
PR**D25** (1982) 774

Bazzocchi & al JCAP 0808 (2008) 013

X-rays from DM decay, diffuse gammas ...



Riemer-Sorensen, Boyarsky et al

DM-mass in (multi)-Kev

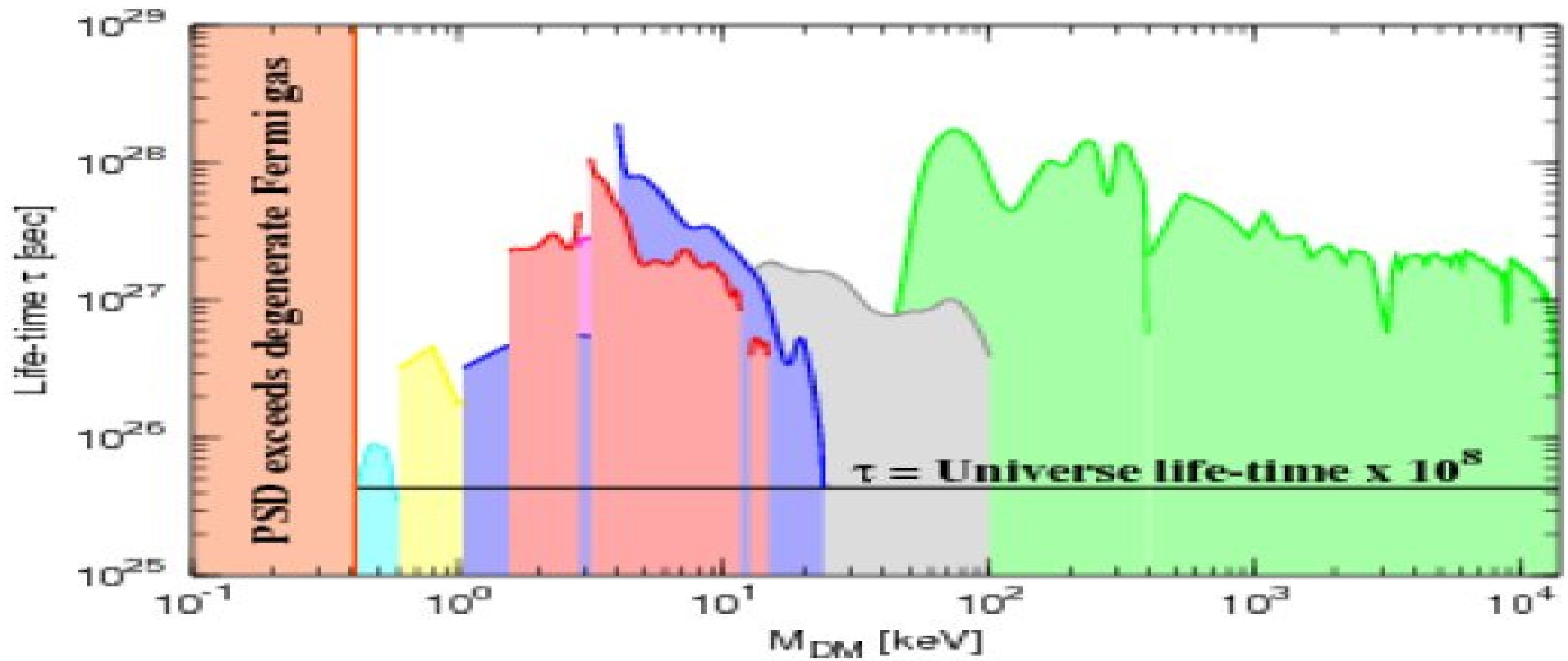


Figure 1 The lower bound on the lifetime of decaying DM: combined exclusion plot from X-ray observation. The vertical shaded region marks the universal Tremaine-Gunn lower mass bound [52]. The constraints are from Suzaku, XMM-Newton, Chandra, HEAO-1, INTEGRAL (SPI) as well as a prototype spectrometer of McCammon ([38] in [12]).

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