Introduction to particle physics: Standard Model and beyond

José W F Valle

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Lecture 5

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

ASTROPARTICLES
Astroparticles and High Energy Physics Group

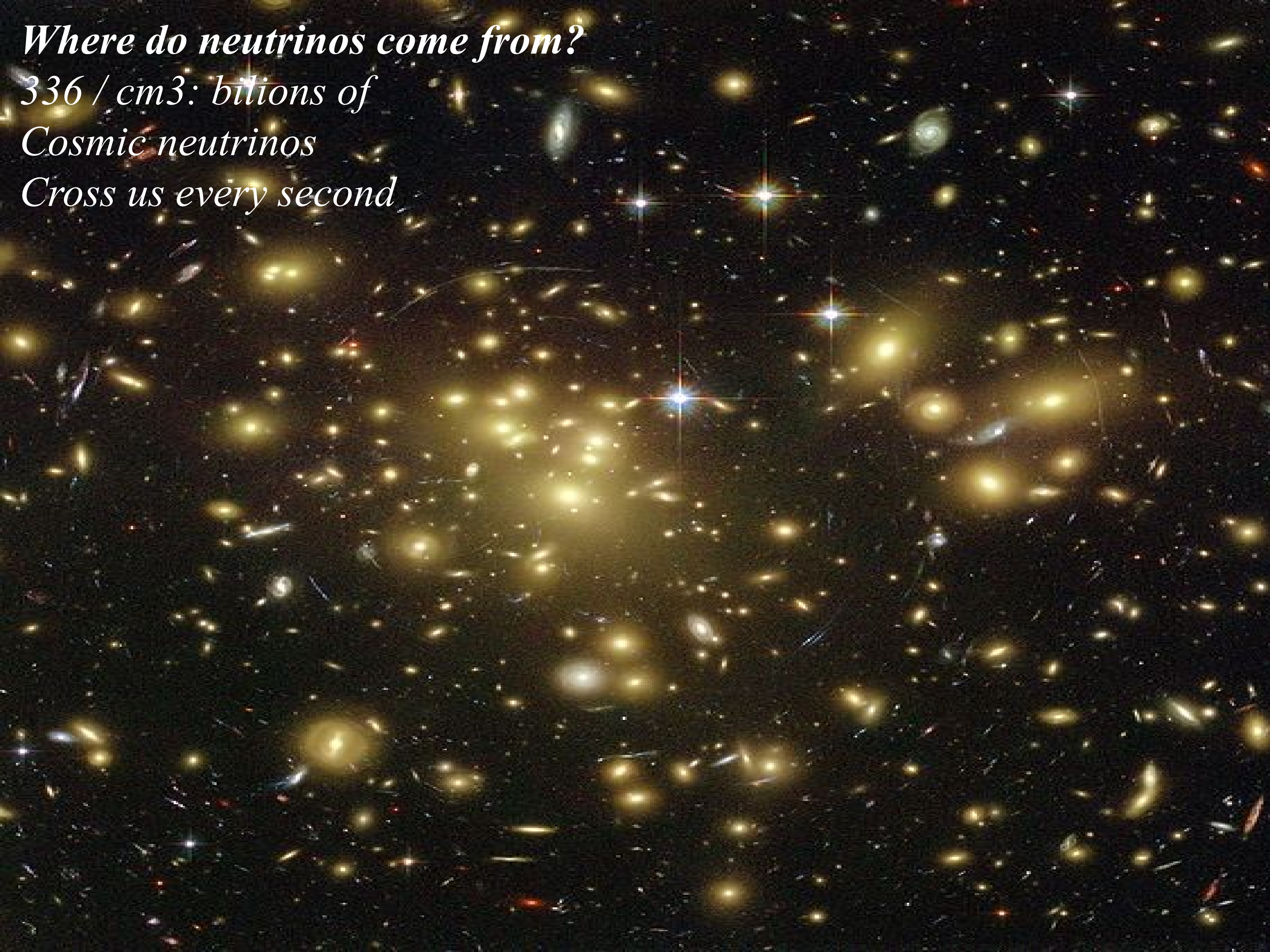
VNIVERSITAT DE VALÈNCIA

http://astroparticles.es/

ISAPP 2014, Belgirate, Lago Maggiore (Italy)

Where do neutrinos come from?

336 / cm3: bilions of
Cosmic neutrinos
Cross us every second



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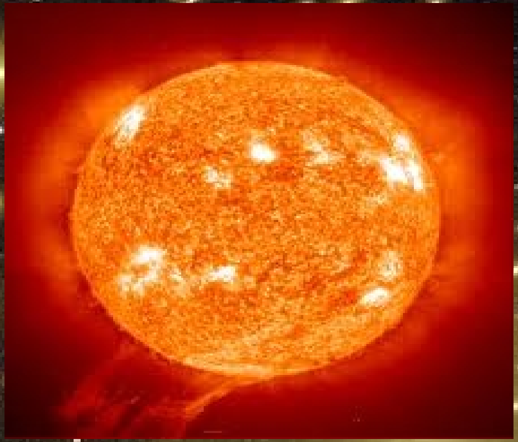

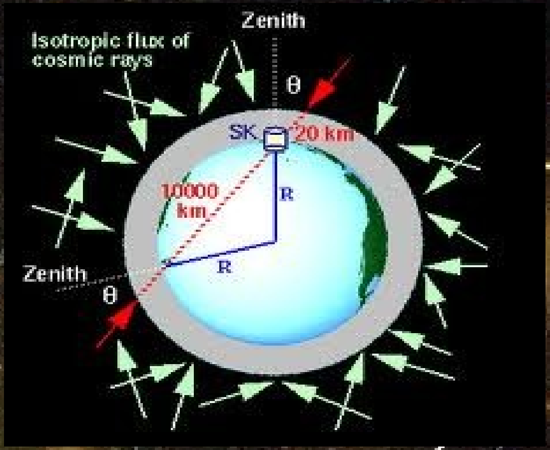

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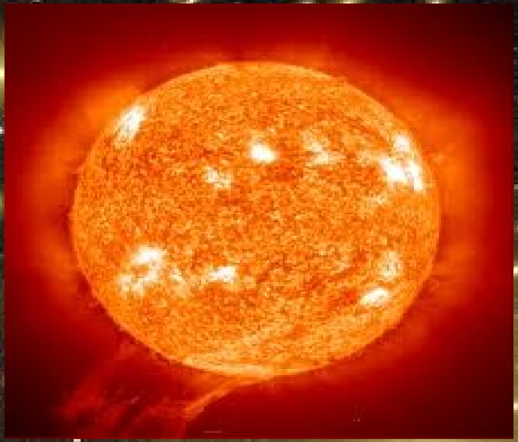

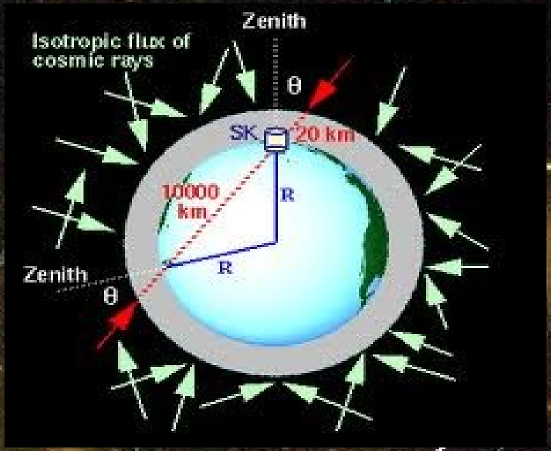

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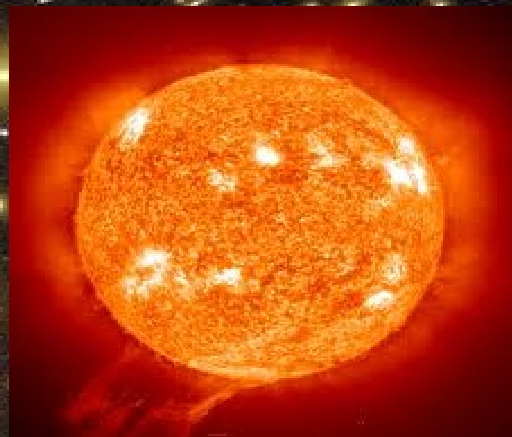
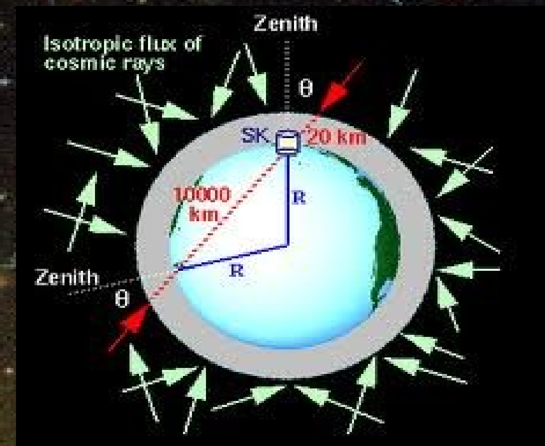
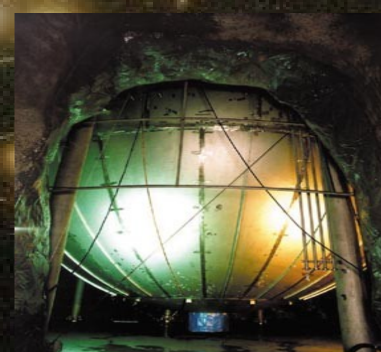


θ_{12}



θ_{23}



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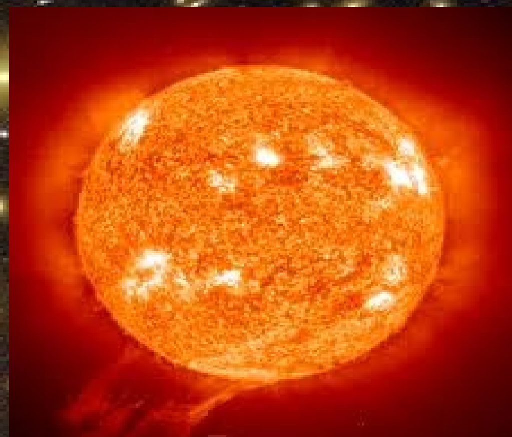
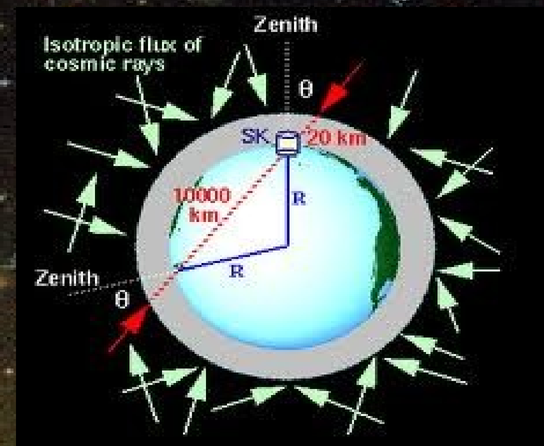


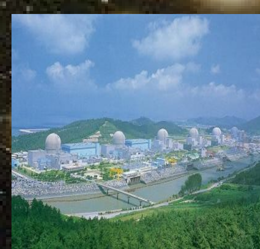


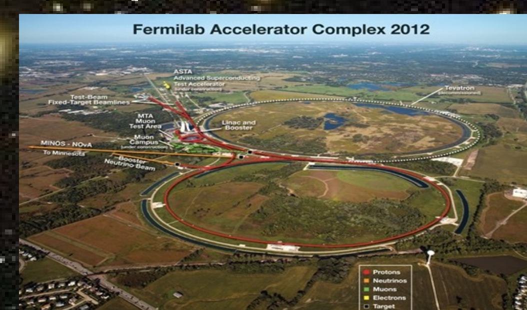
θ_{12}

θ_{23}

θ_{13} δ

confirmed





Where do neutrinos come from?

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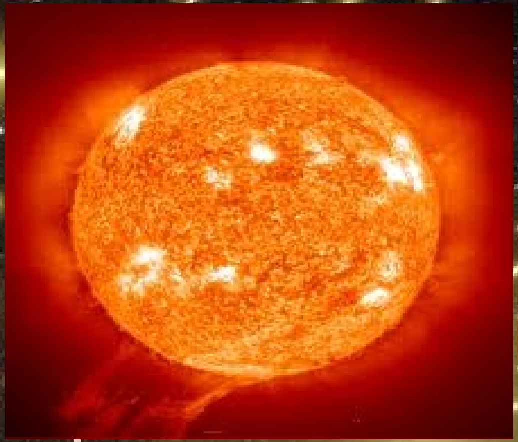
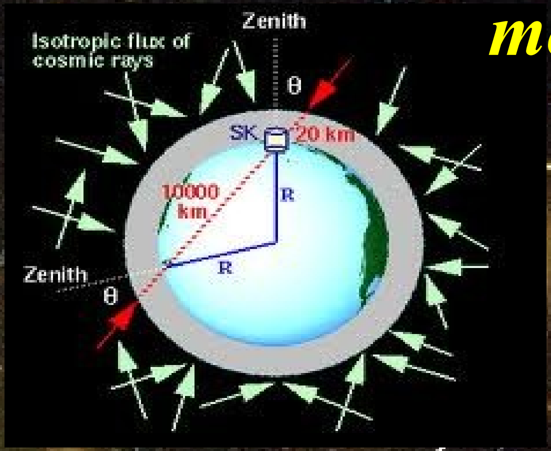
Necessary to revise Standard model





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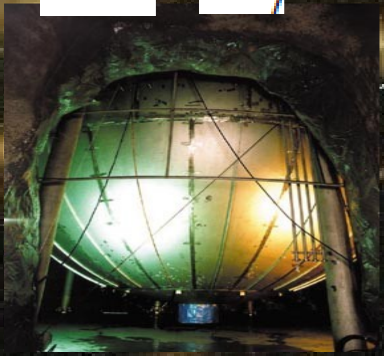
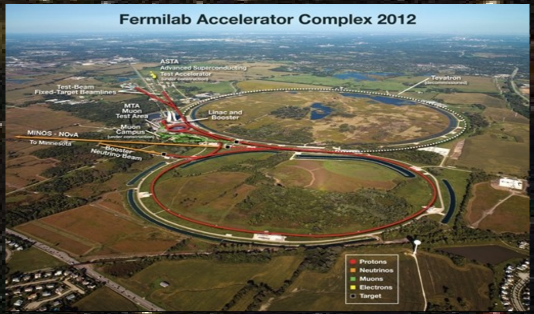


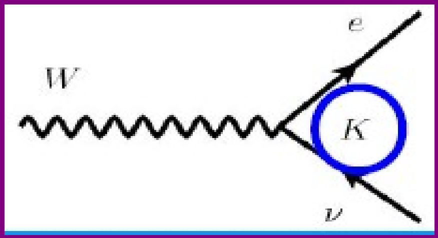


LEPTONIC CKM-MATRIX

$$K = \omega_{23} \cdot \omega_{13} \cdot \omega_{12}$$

Schechter & JV PRD22 (1980) 2227 & PDG

Rodejohann, JV Phys.Rev. D84 (2011) 073011



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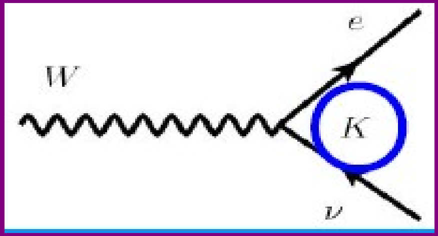

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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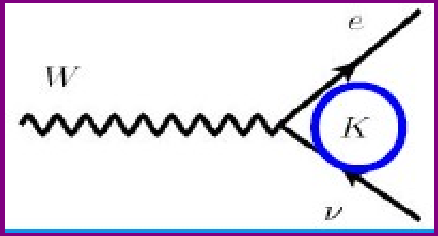

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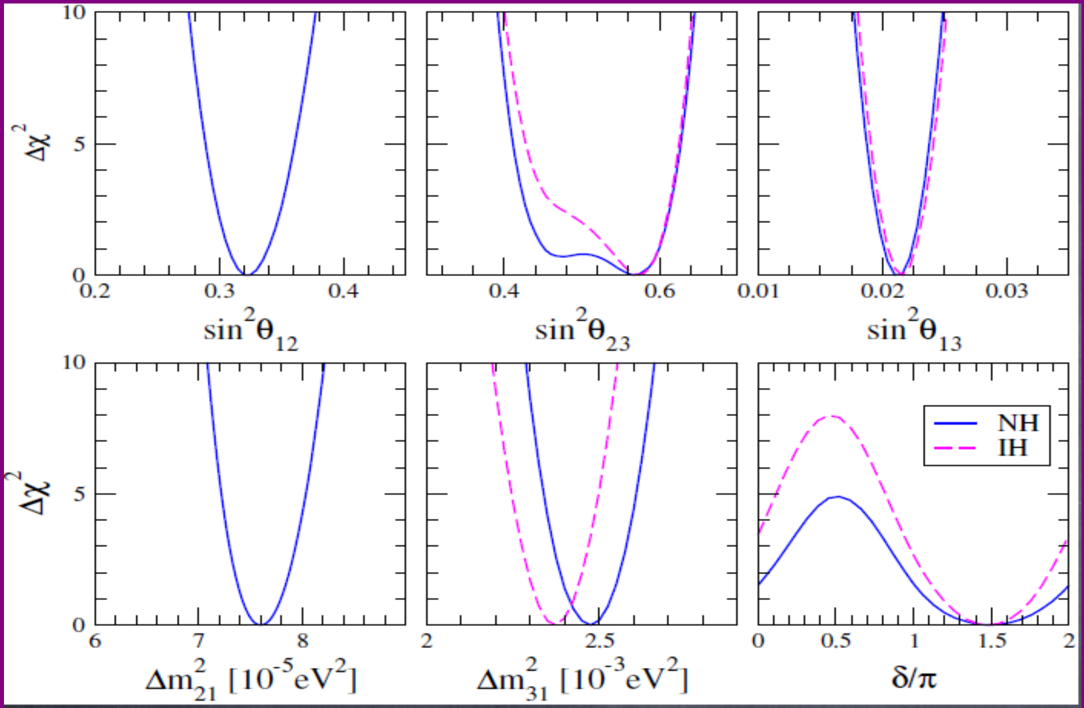
use this approx. in oscillation analyses

Forero, Tortola, JWFV arXiv:1405.7540



T2K result →

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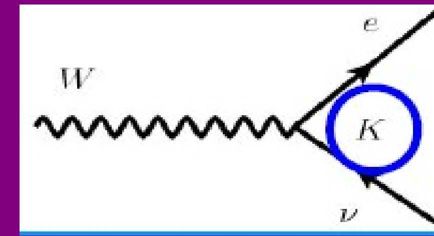
Schechter & JV PRD22 (1980) 2227 & PDG



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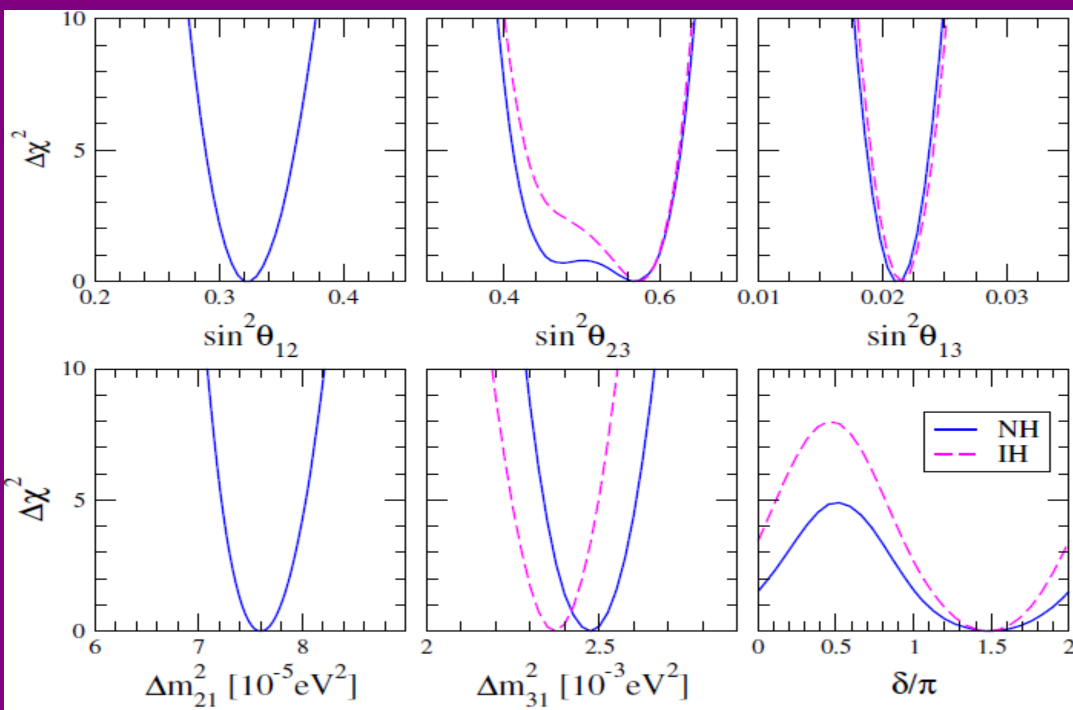
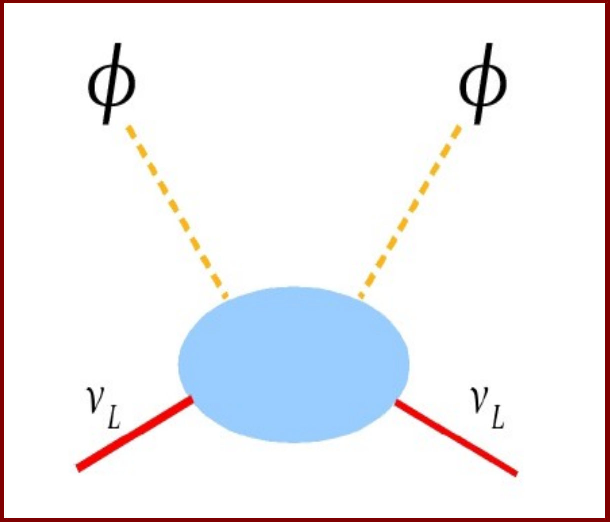


parameter	best fit $\pm1\sigma$
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.60^{+0.19}_{-0.18}$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NH)	$2.48^{+0.05}_{-0.07}$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IH)	$2.38^{+0.05}_{-0.06}$
$\sin^2\theta_{12}/10^{-1}$	3.23 ± 0.16
$\sin^2\theta_{23}/10^{-1}$ (NH)	$5.67^{+0.32}_{-1.15}$
$\sin^2\theta_{23}/10^{-1}$ (IH)	$5.73^{+0.25}_{-0.38}$
$\sin^2\theta_{13}/10^{-2}$ (NH)	$2.10^{+0.14}_{-0.09}$
$\sin^2\theta_{13}/10^{-2}$ (IH)	$2.16^{+0.10}_{-0.12}$
δ/π (NH)	$1.48^{+0.43}_{-0.39}$
δ/π (IH)	$1.48^{+0.28}_{-0.29}$

T2K result

ORIGIN OF NEUTRINO MASS AND SEESAW



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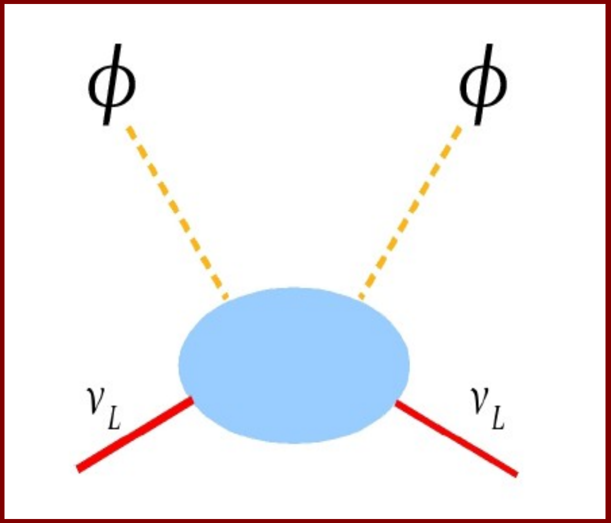
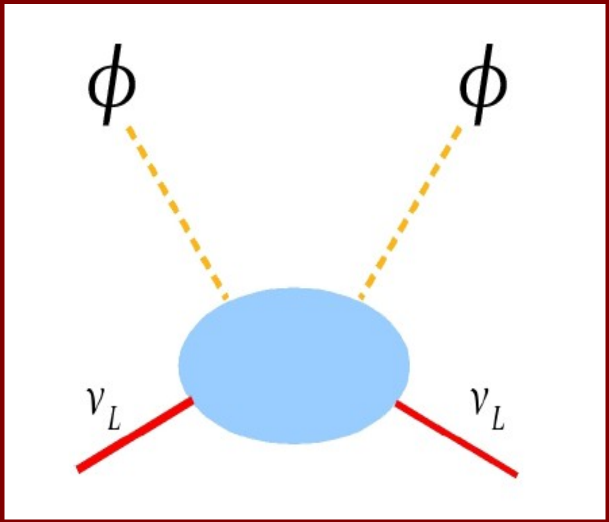


SCALE

MECHANISM

FLAVOR STRUCTURE

ORIGIN OF NEUTRINO MASS AND SEESAW



$$v_3 v_1 \sim {v_2}^2 \quad \text{with} \quad v_1 \gg v_2 \gg v_3$$

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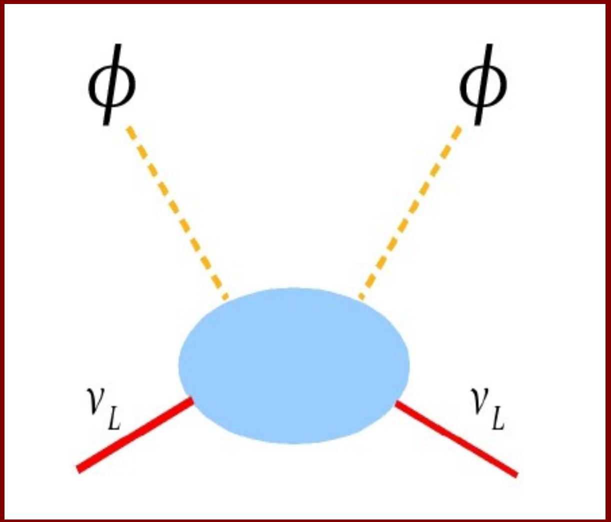

fermion exchange

TYPE I

Minkowski 77
Gellman Ramond Slansky 80
Glashow, Yanagida 79
Mohapatra Senjanovic 80
Lazarides Shafi Weterrich 81
Schechter-Valle, 80 & 82

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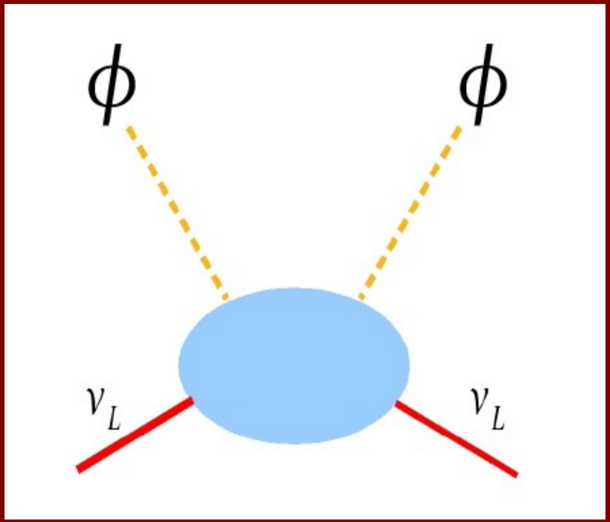

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Scalar-exchange

TYPE II

Schechter-Valle 80/82

SCALE

MECHANISM

FLAVOR STRUCTURE

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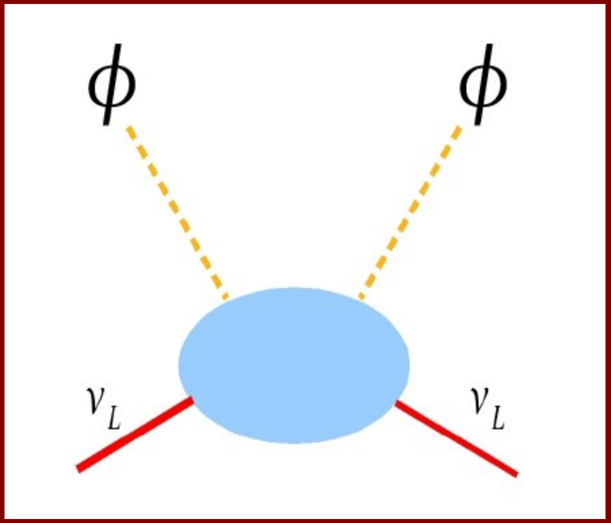

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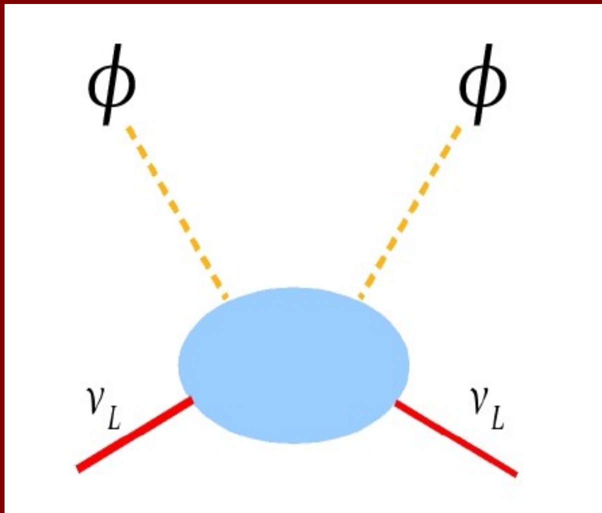
Number & properties of messengers

ORIGIN OF NEUTRINO MASS AND SEESAW



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SCALE

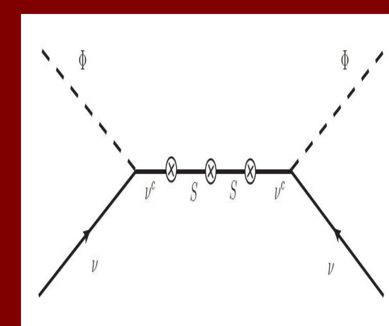
MECHANISM

FLAVOR STRUCTURE

Number & properties of messengers

LOW-SCALE SEESAW

Mohapatra-Valle 86
Akhmedov et al PRD53 (1996) 2752
Malinsky et al PRL95(2005)161801
Bazzocchi et al, PRD81 (2010) 051701



Radiative neutrino mass in 331 scheme

$$SU(3)_L \otimes U(1)_X \xrightarrow{n_{1,2}} SU(2)_L \otimes U(1)_Y \xrightarrow{k_{1,2}} U(1)_Q .$$

$$\begin{pmatrix} \ell^- \\ \nu_\ell \\ N_\ell^c \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \\ s' \end{pmatrix}_L \quad \begin{pmatrix} b \\ t \\ t' \end{pmatrix}_L$$

$$\begin{aligned} Q &= T_3 + \frac{1}{\sqrt{3}} T_8 + X \\ L &= \frac{4}{\sqrt{3}} T_8 + \mathcal{L} \quad . \end{aligned}$$

Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

Boucenna, Morisi & JWFV arXiv:1405.2332

Radiative neutrino mass in 331 scheme

generations = # colours

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$$\langle \phi_1 \rangle = \begin{bmatrix} k_1 \\ 0 \\ 0 \end{bmatrix}, \langle \phi_2 \rangle = \begin{bmatrix} 0 \\ 0 \\ n_1 \end{bmatrix}, \langle \phi_3 \rangle = \begin{bmatrix} 0 \\ k_2 \\ n_2 \end{bmatrix}$$

Add 3 gauge singlets ...

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ & 0 & M \\ & & 0 \end{pmatrix}$$

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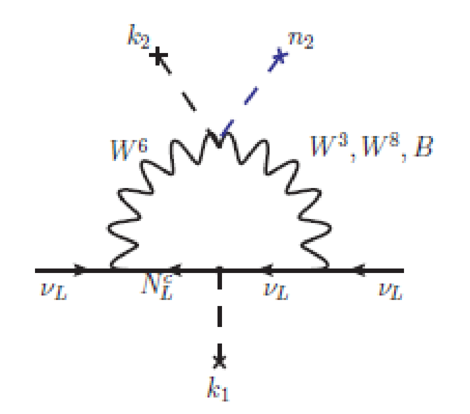

$$\epsilon \sim \frac{k_2 n_2}{n_1^2 + n_2^2} \ll 1 \qquad \beta \simeq m_D/M \ll 1$$

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ & 0 & M \\ & & 0 \end{pmatrix}$$

$$m_{\nu_{\rm light}} \simeq \frac{g^2\, \epsilon\, \beta}{16\pi^2} M_D \frac{m_{Z'}^2}{M_D^2 + m_{Z'}^2} \log \frac{m_{Z'}^2}{M_D^2}$$

Radiative neutrino mass in 331 scheme

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Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

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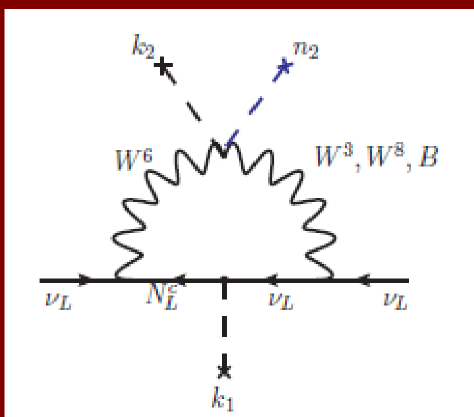

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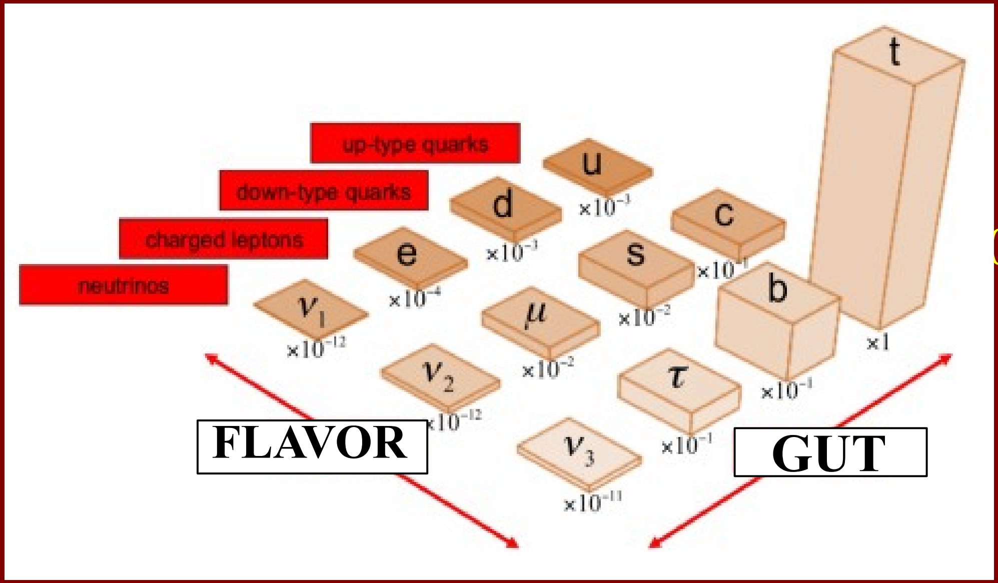
more on the low-scale approach to neutrino masses ... arXiv:1404.3751

Order in the chaos?



033

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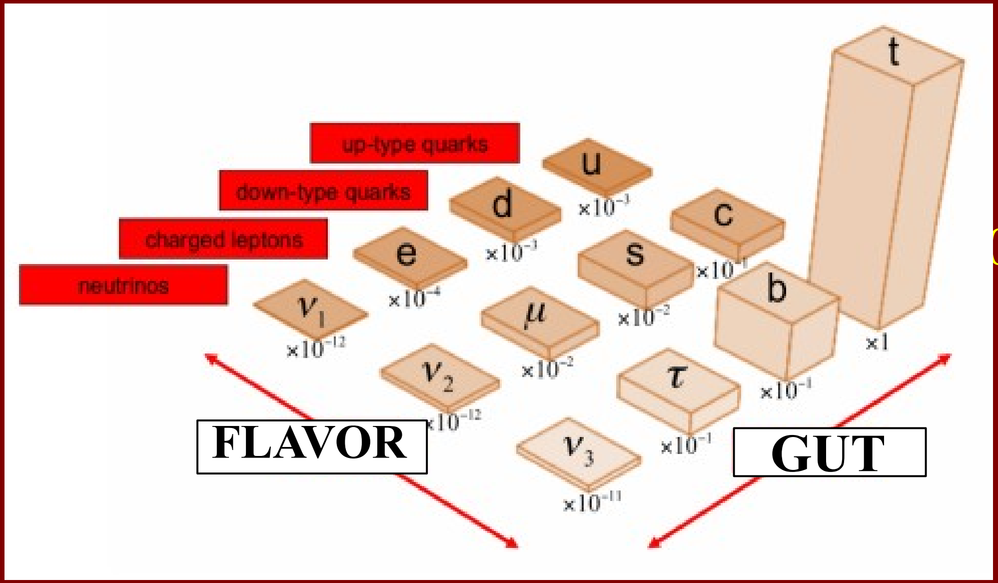

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PHYSICAL REVIEW D **84**, 036003 (2011)

Relating quarks and leptons without grand unification

S. Morisi,[1,*] E. Peinado,[1,†] Yusuke Shimizu,[2,‡] and J. W. F. Valle[1,§]

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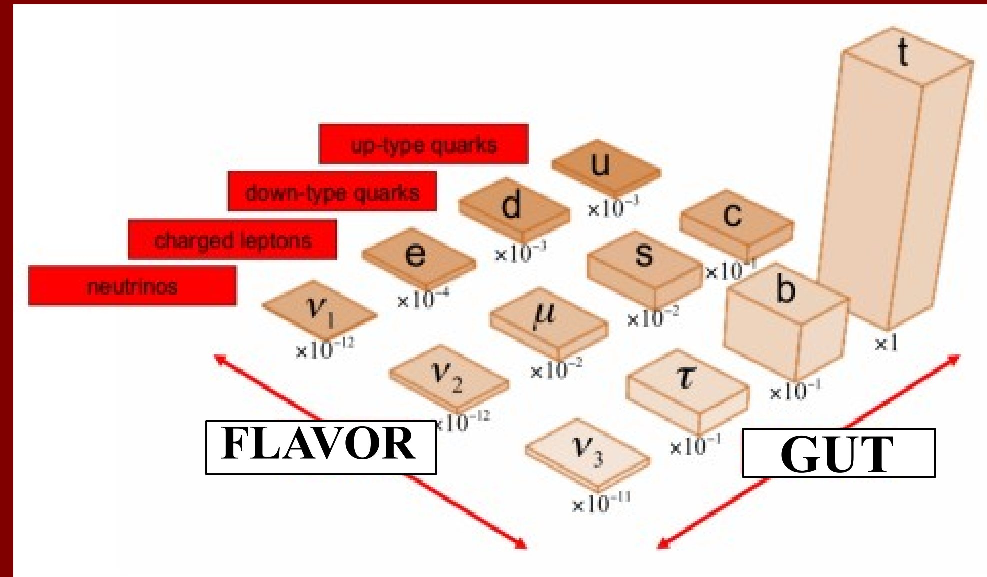

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$$\frac{m_\tau}{\sqrt{m_e m_\mu}} \approx \frac{m_b}{\sqrt{m_d m_s}},$$

King et al — Phys. Lett. B 724 (2013) 68-72

Morisi et al — Phys.Rev. D88 (2013) 036001

THE FLAVOR PROBLEM

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$e_R \quad \mu_R \quad \tau_R$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

THE FLAVOR PROBLEM

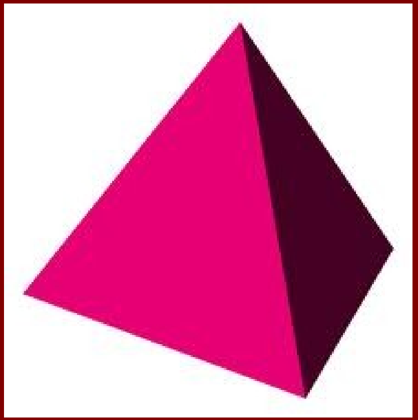
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$e_R \quad \mu_R \quad \tau_R$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$



A4

$$\sin^2\theta_{23} = 0.5 \qquad \sin^2\theta_{13} = 0$$

Babu et al PLB552 (2003) 207

Hirsch et al PRD69 (2004) 093006

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$$

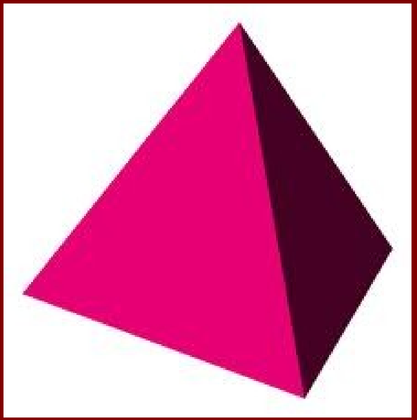
$$e_R \quad \mu_R \quad \tau_R$$

$$\begin{pmatrix}u\\ d\end{pmatrix}_L \quad \begin{pmatrix}c\\ s\end{pmatrix}_L \quad \begin{pmatrix}t\\ b\end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

THE FLAVOR PROBLEM



A4

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

$$\sin^2\theta_{23} = 0.5$$

$$\sin^2\theta_{13} = 0$$

Tri-BiMaximal ansatz

Harrison, Perkins, Scott 2000

Altarelli, Feruglio 2005

$$\sin^2\theta_{12} = 1/3$$

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

(CP assummed)

arXiv:1305.6774

PHYSICAL REVIEW D **88**, 016003 (2013)

Neutrino mixing with revamped A_4 flavor symmetry

D. V. Forero,[1,2,*] S. Morisi,[3,†] J. C. Romão,[1,‡] and J. W. F. Valle[2,§]

PHYSICAL REVIEW D 88, 016003 (2013)

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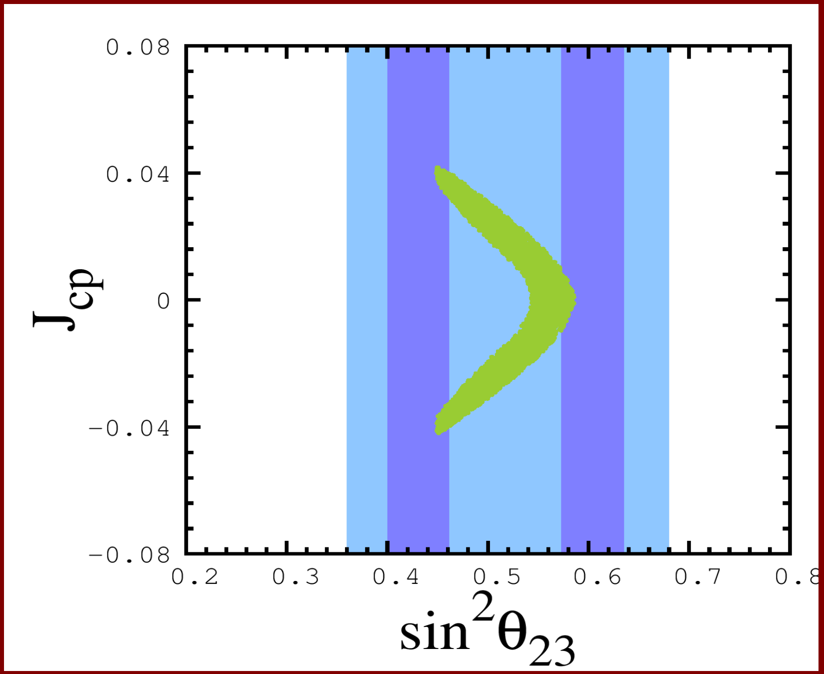
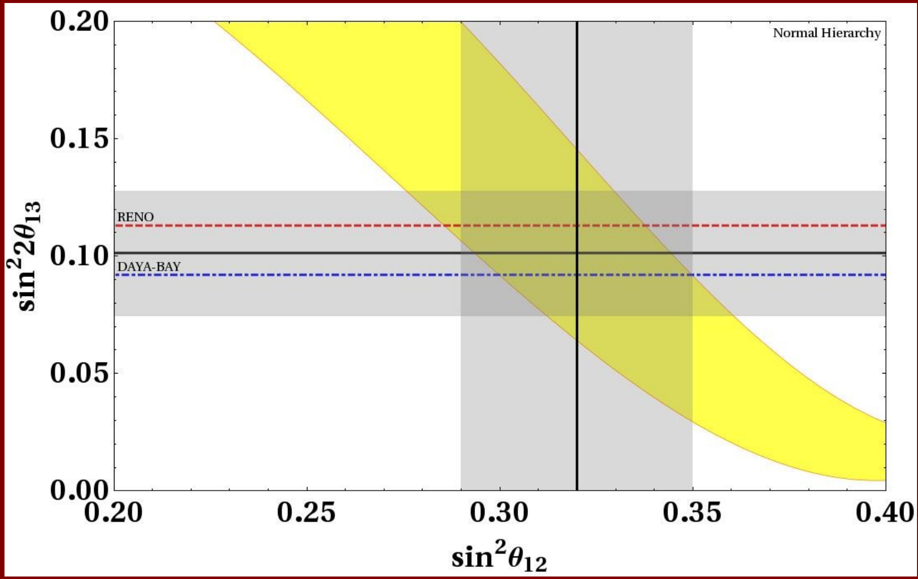
STRIKING CORRELATION



OSCILLATION PARAMETER CORRELATIONS

Boucenna et al
PhysRevD.86.073008



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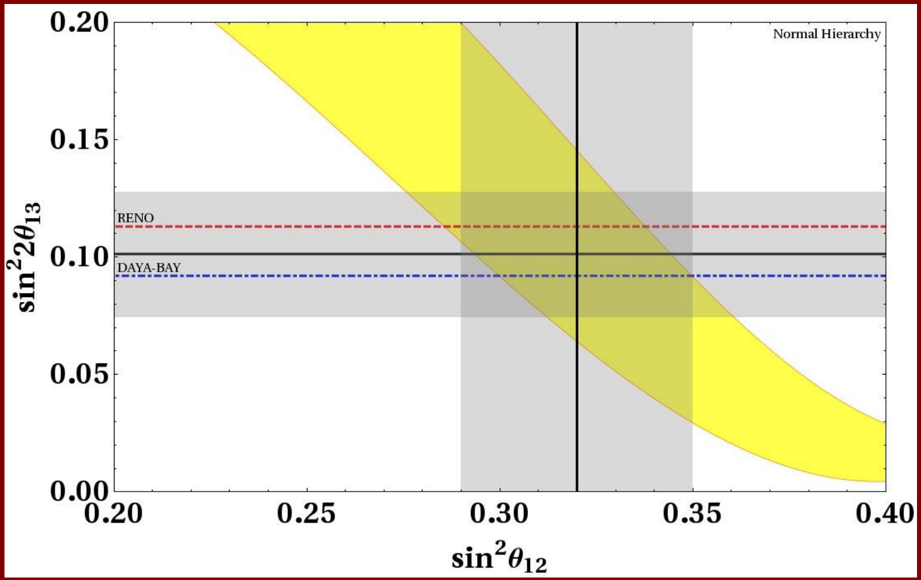
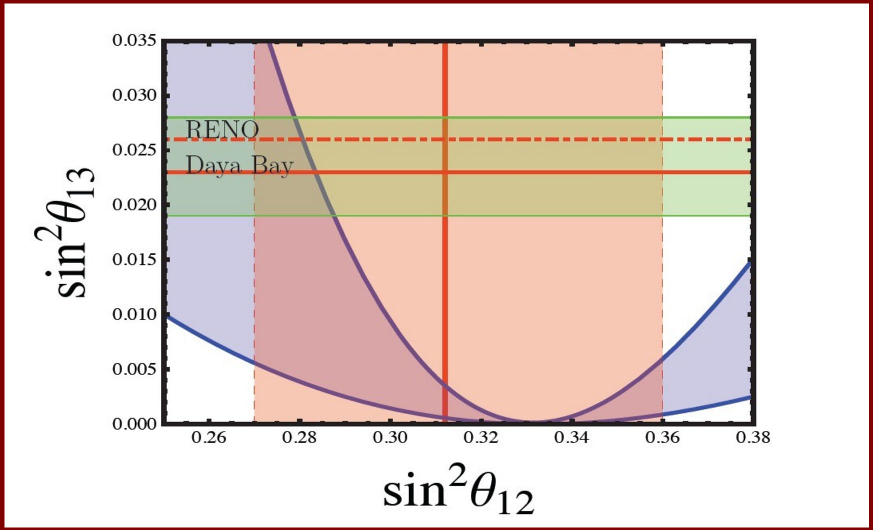


Dorame et al Nucl Phys B861, 259–270



FLASY
2011, 2012,
2013, 2014, ...

GFLAVOR

FLASY
2011, 2012,
2013, 2014, ...

GFLAVOR

DEVIATION OF TBM

Ishimori.etal ProgTheor Phys Suppl 183 (2010) 1

Holthausen et al 1212.2411

FLASY
2011, 2012,
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Holthausen et al 1212.2411

CHANGE ANSATZ:

Albright,Dueck,Rodejohann 1004.2798
Boucenna,M,Tortola, JV PRD86 (2012) 051301

Gflavor

FLASY
2011, 2012,
2013, 2014, ...

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Ishimori.etal ProgTheor Phys Suppl 183 (2010) 1

Holthausen et al 1212.2411

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Abelian

Ding, Morisi, JV PRD87 (2013) 1211.6506

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ANARCHY

Donoghue et al PRD73
Hall,Murayama,Weiner,PRL
Altarelli, Feruglio,Masina,JHEP

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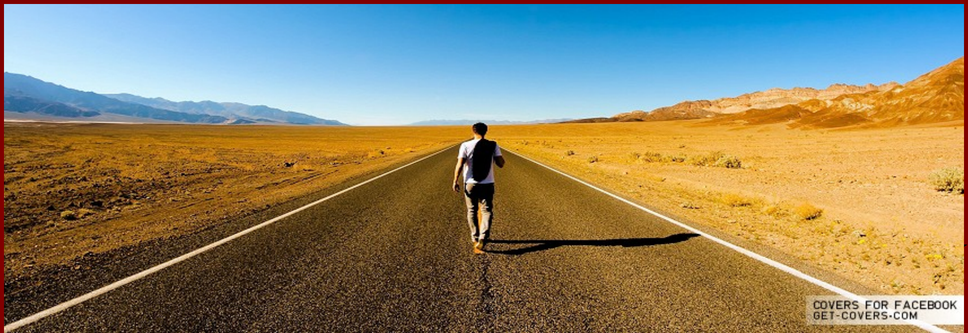

Flavor roadmap

Fortsch.Phys. 61 (2013) 466-492

Bi-large mixing & Cabibbo angle

Abelian Flavor Models

Boucenna et al, Phys. Rev. D 86, 051301(R)

Bi-large mixing & Cabibbo angle

Abelian Flavor Models

Boucenna et al, Phys. Rev. D 86, 051301(R)

reactor seeds solar & atm

$$\sin\theta_{13} = \lambda\,;$$
$$\sin\theta_{12} = s\,\lambda\,;$$
$$\sin\theta_{23} = a\,\lambda\,,$$

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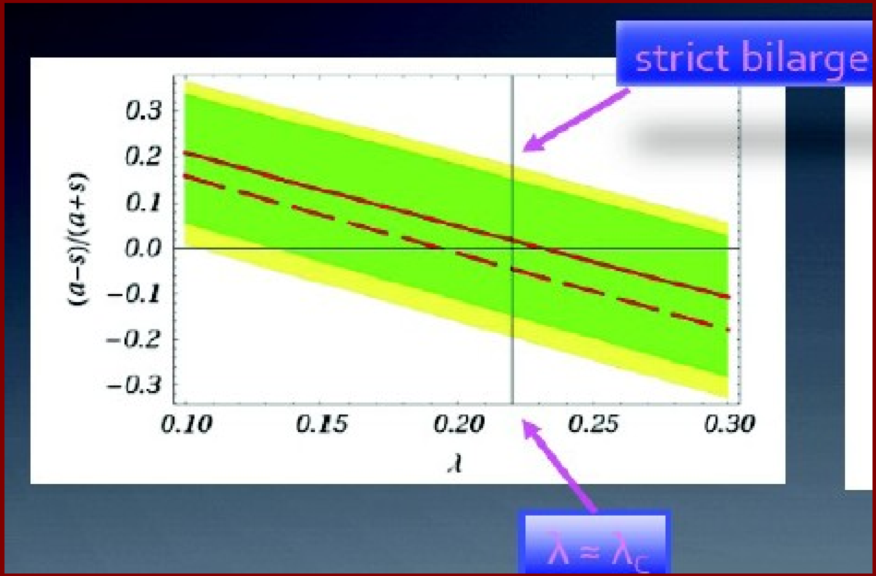
Ref.	λ	s	ϵ
Forero *et al.* [14]	0.23 ± 0.04	$2.8^{+0.5}_{-0.4}$	$0.067^{+0.035}_{-0.025}$
Fogli *et al.* [16]	$0.19^{+0.03}_{-0.02}$	$3.0^{+0.5}_{-0.3}$	$0.038^{+0.019}_{-0.018}$



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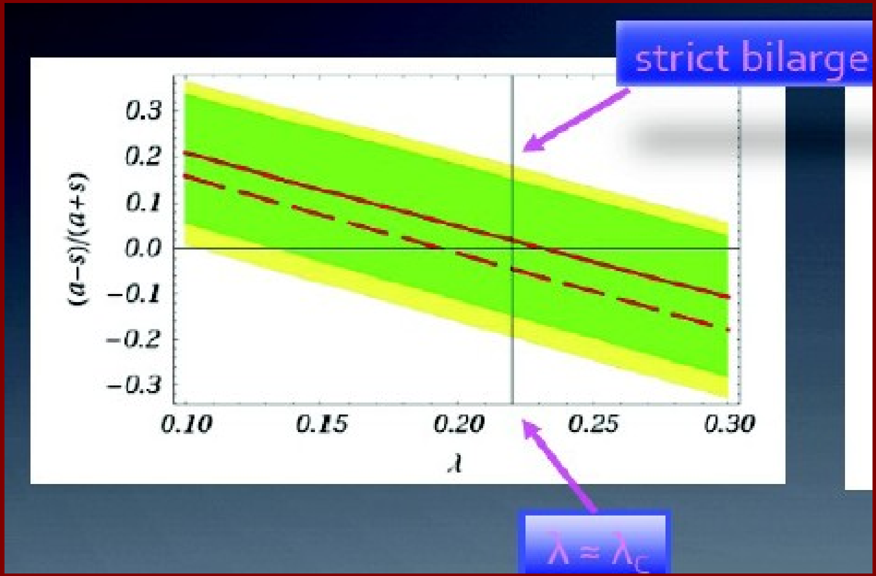
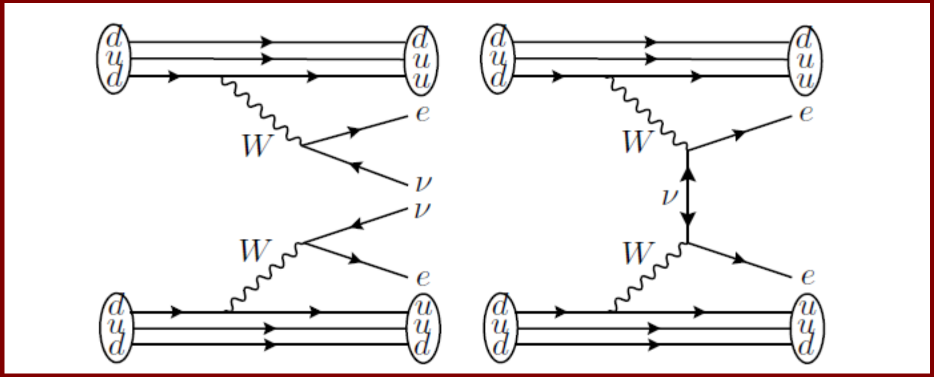


Models

Ding, et al Phys.Rev. D87 (2013) 053013
Roy, Singh, ..arXiv:1211.7207

Neutrinoless Double Beta Decay

A.S. Barabash arXiv:1104.2714



Neutrinoless Double Beta Decay

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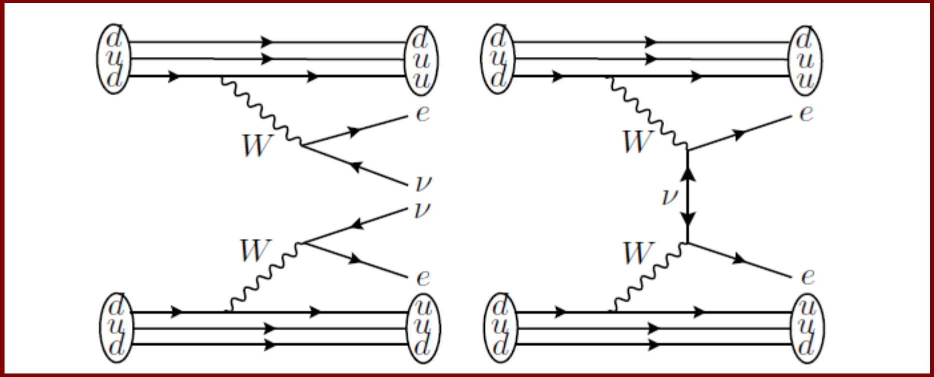
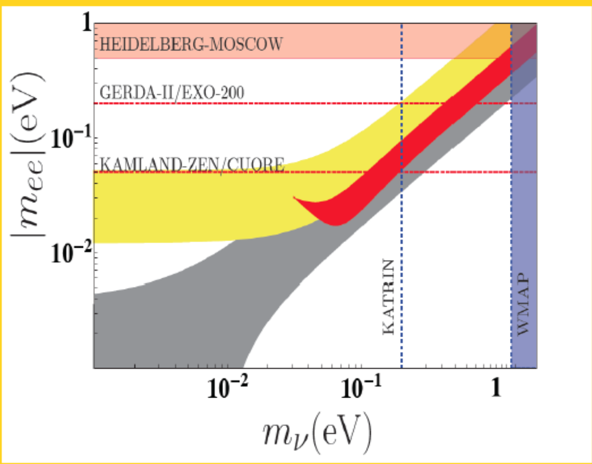
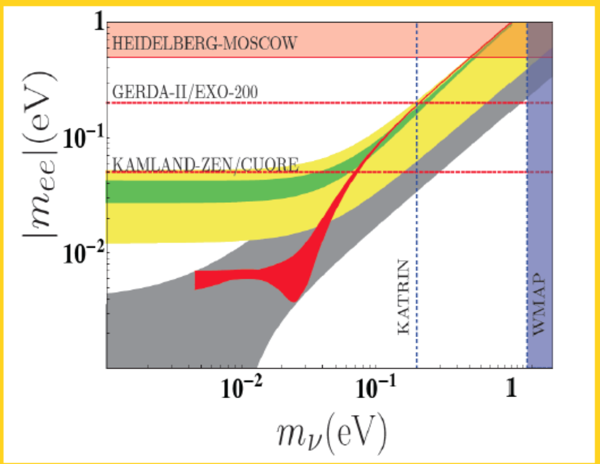
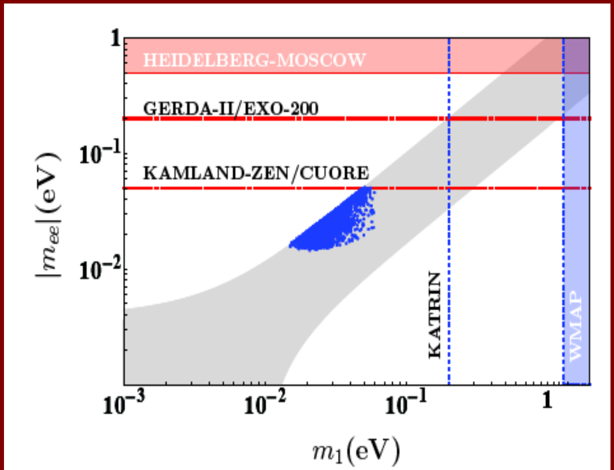


Family symmetry dependent lower bound







Dorame et al
NPB861 (2012) 259-270

PhysRevD.86.056001

King et al Phys. Lett. B 724 (2013) 68

Neutrinoless Double Beta Decay

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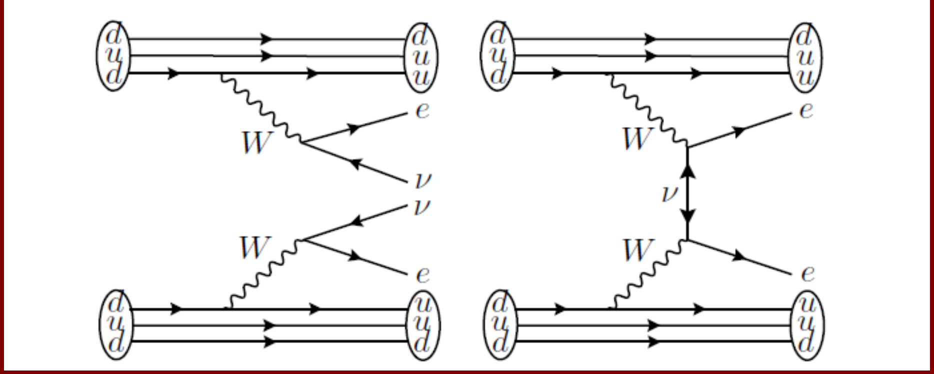
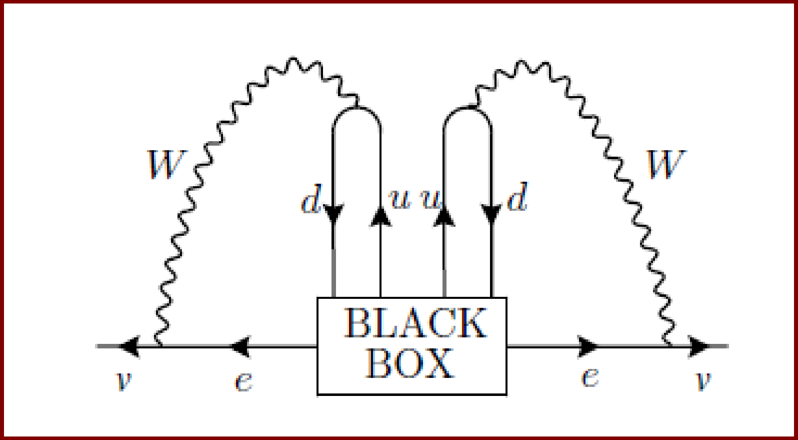
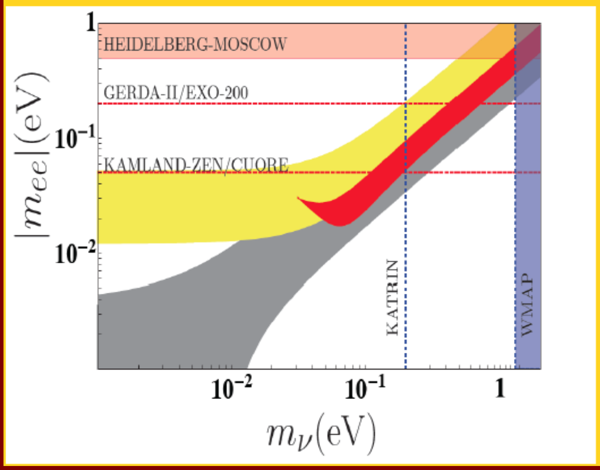
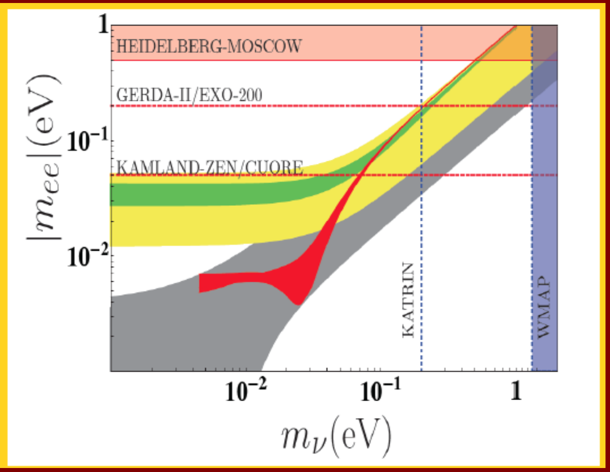


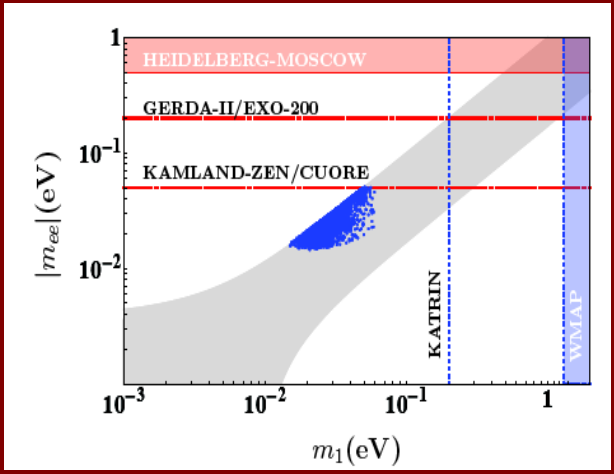


Family symmetry dependent lower bound

Schechter, JWFV 82
Lindner et al JHEP 1106 (2011) 091







Dorame et al
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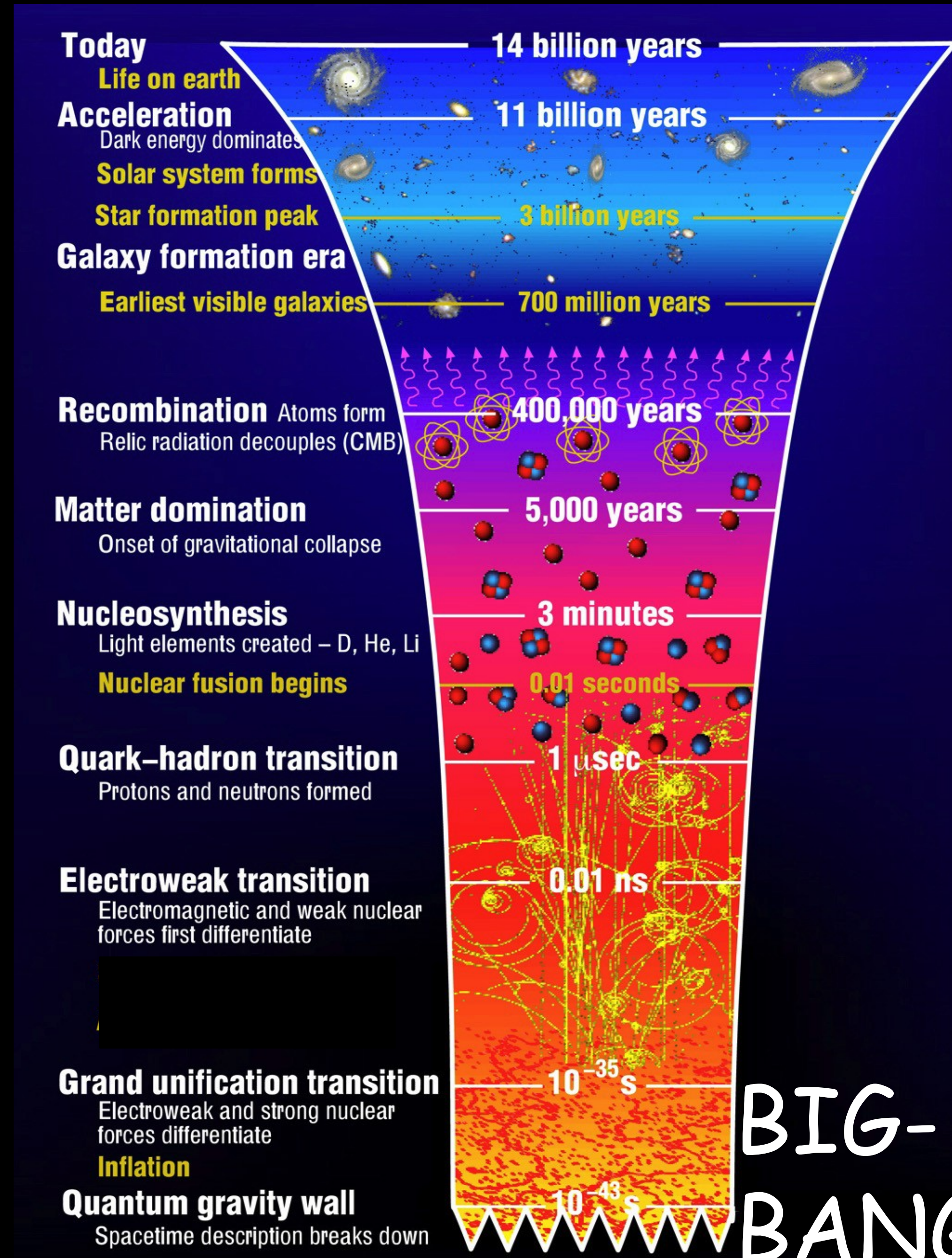
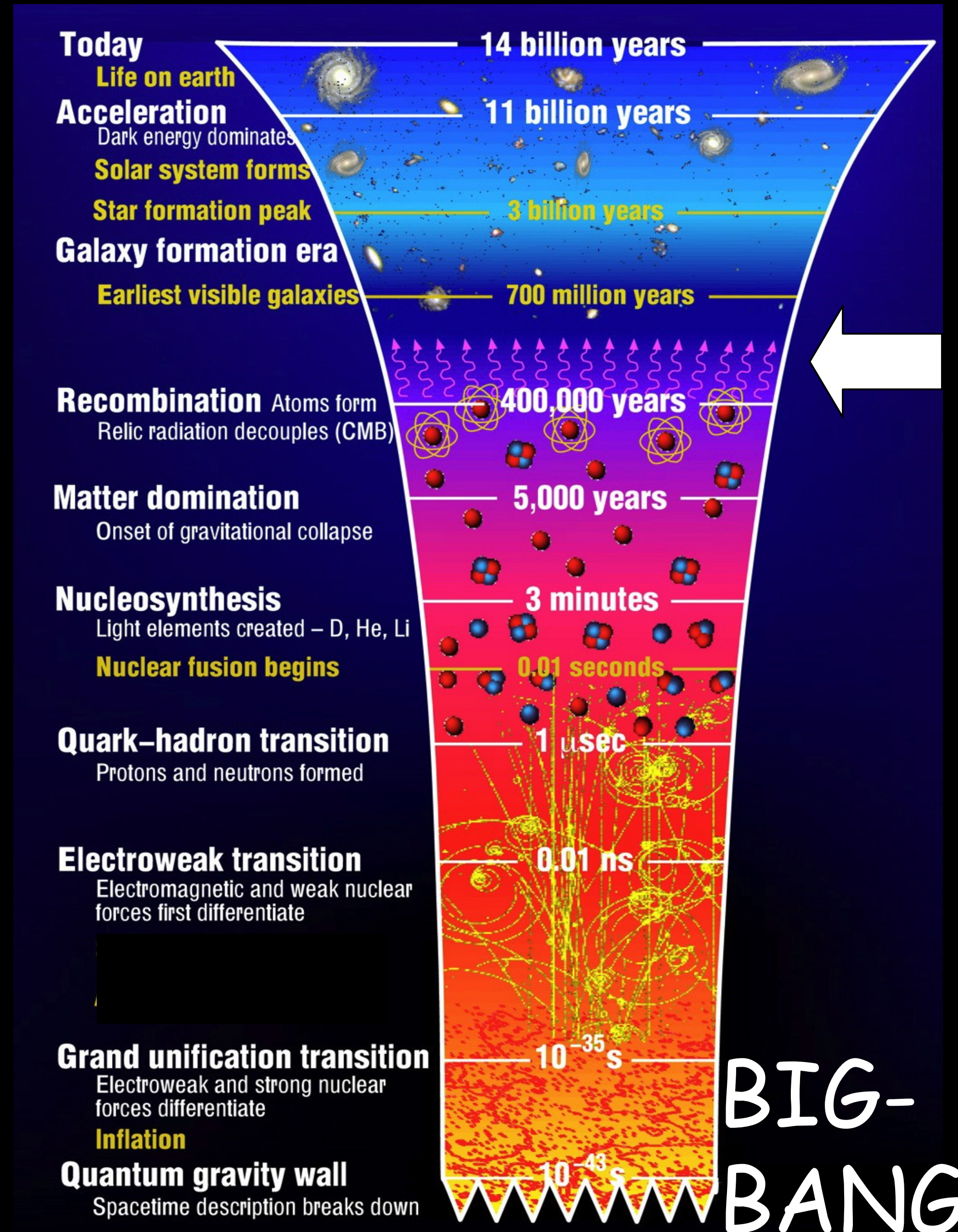
King et al Phys. Lett. B 724 (2013) 68


Today
Life on earth
14 billion years
Acceleration
Dark energy dominates
11 billion years
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation decouples (CMB)
400,000 years
Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
Protons and neutrons formed
1 μsec
Electroweak transition
Electromagnetic and weak nuclear
forces first differentiate
0.01 ns
[redacted]
Grand unification transition
Electroweak and strong nuclear
forces differentiate
10^{-35} s
Inflation
Quantum gravity wall
Spacetime description breaks down
10^{-43} s

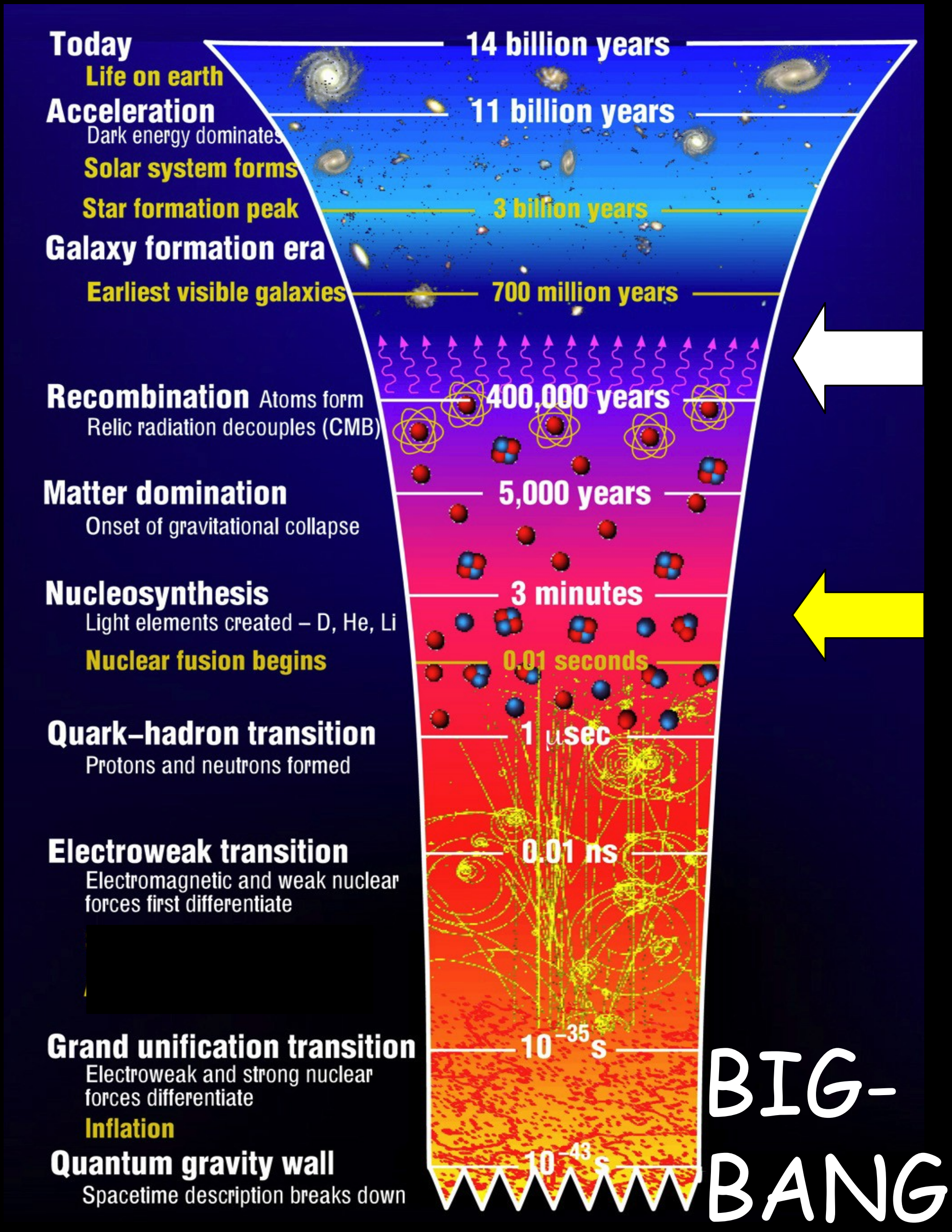
BIG-
BANG

Neutrinos affect the CMB and large scale structure in the Universe …



Neutrinos affect the CMB and large scale structure in the Universe …

are key in the synthesis of light elements



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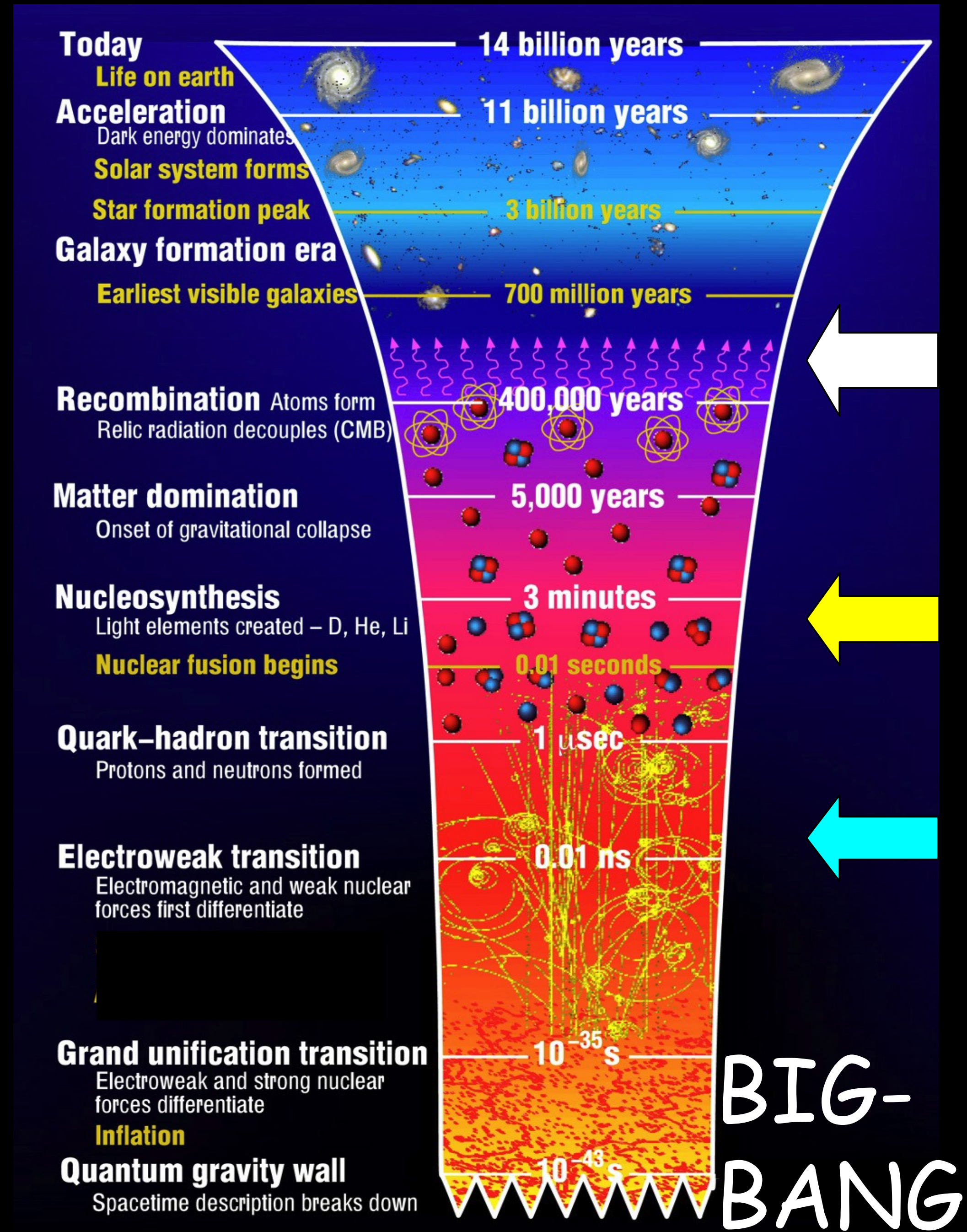

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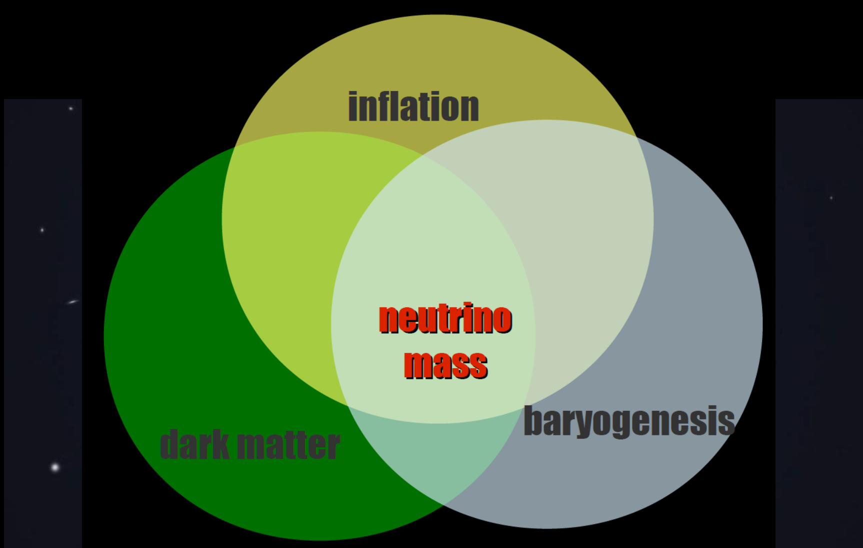
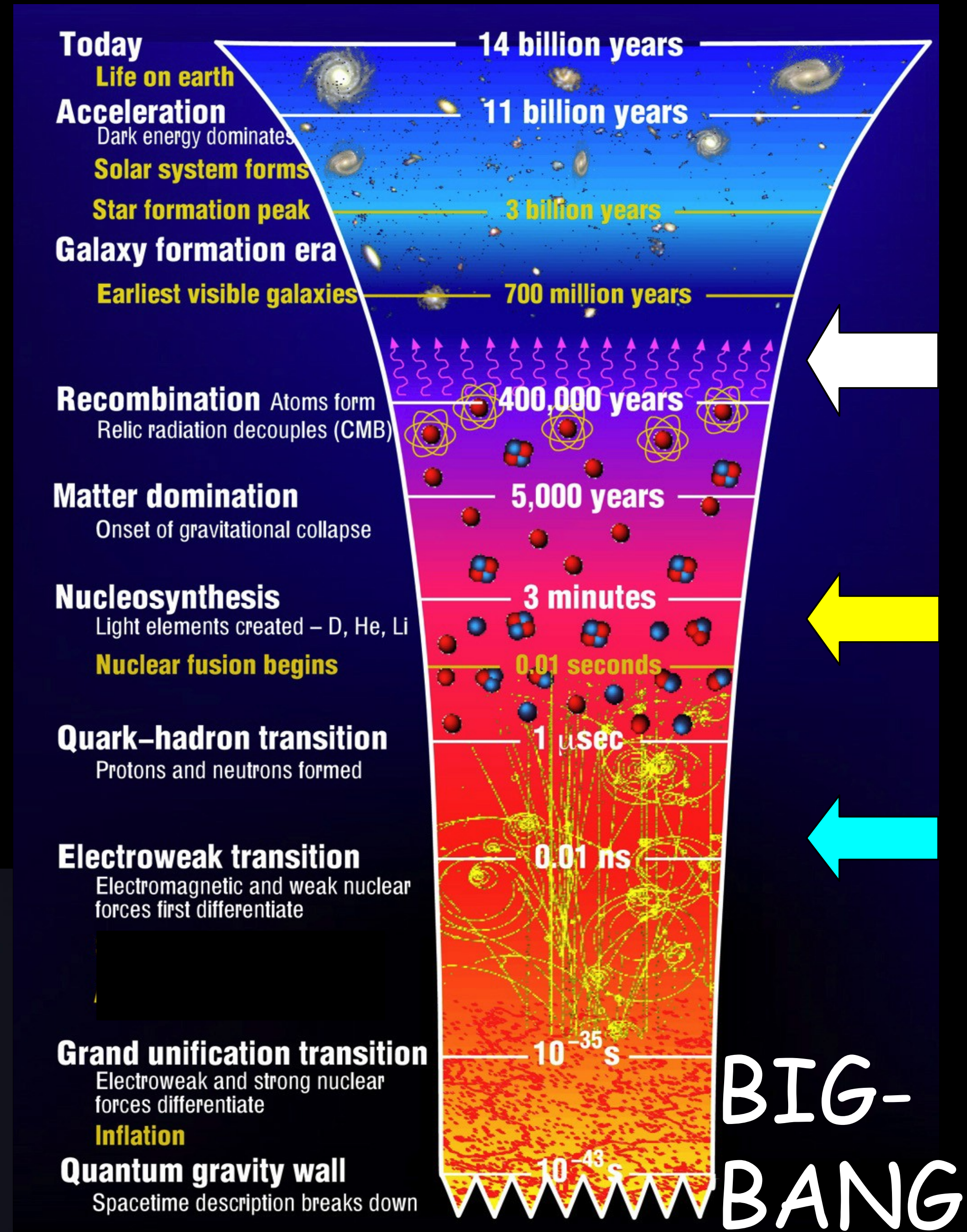




Boucenna et al arXiv:1405.2332

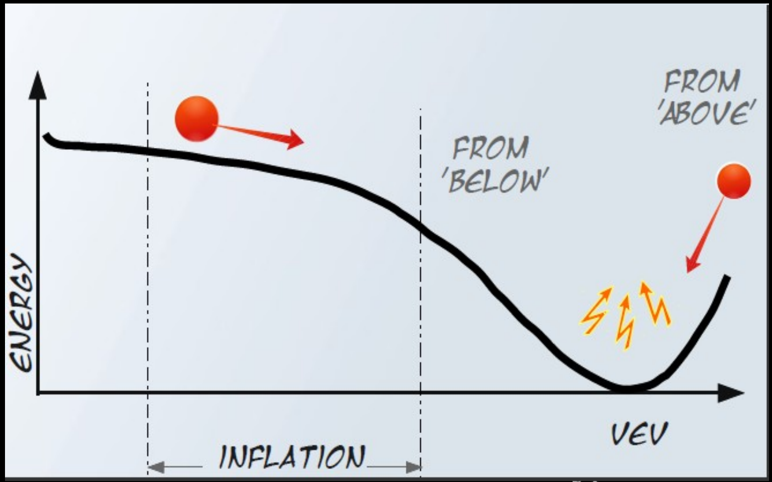
Seesaw inflation & majoron dark matter

type-I seesaw

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_D v_2 \\ {Y_D}^T v_2 & Y_N v_L \end{bmatrix}$$

inflaton

$$\rho \equiv \sqrt{2}\,\Re[\sigma],$$



Boucenna et al arXiv:1405.2332

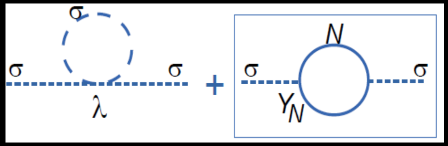
Seesaw inflation & majoron dark matter

$$V = \lambda \left[\frac{1}{4}\left(\rho^2 - v_{\rm L}^2\right)^2 + a \log\left[\frac{\rho}{v_{\rm L}}\right] \rho^4 + V_0 \right]$$

$$\lambda \ll Y_N$$

tree-level

Coleman-Weinberg radiative corrections



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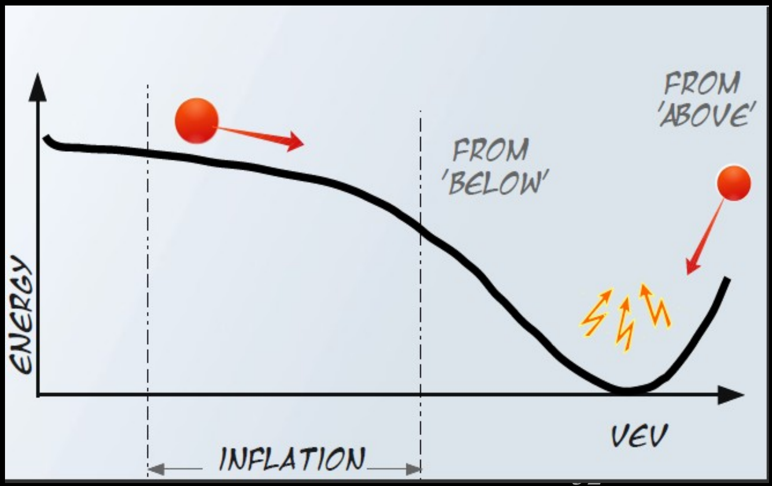

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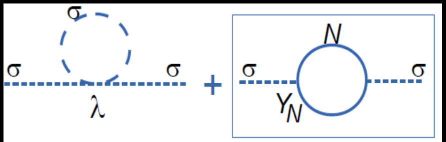


$$a = \frac{\beta_\lambda}{16\pi^2\lambda}$$

$$\beta_\lambda = 20\lambda^2 + 2\lambda\left(\sum_i (Y_N^i)^2\right) - \sum_i (Y_N^i)^4.$$

$\lambda_N \sim 10^{-3}$ versus $\lambda_N \sim 10^{-6}$

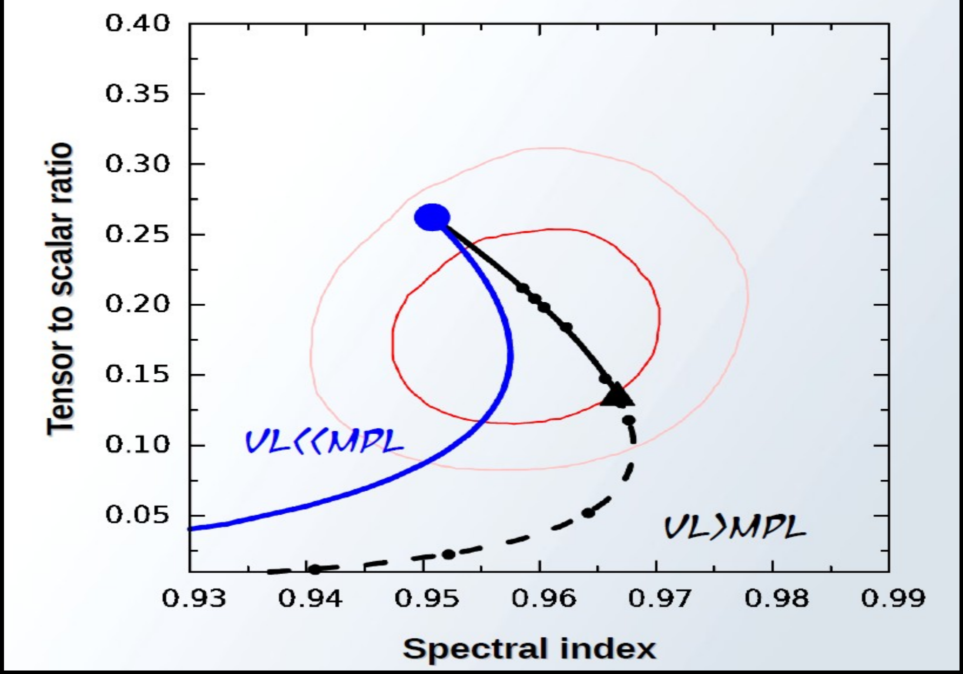
Quartic versus *Higgs Inflation*

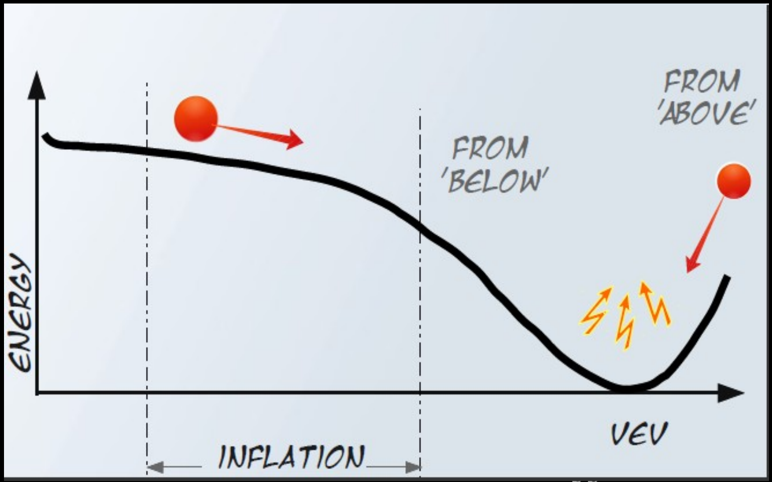
type-I seesaw

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_D v_2 \\ {Y_D}^T v_2 & Y_N v_{\rm L} \end{bmatrix}$$

inflaton

$$\rho \equiv \sqrt{2}\,\Re[\sigma],$$

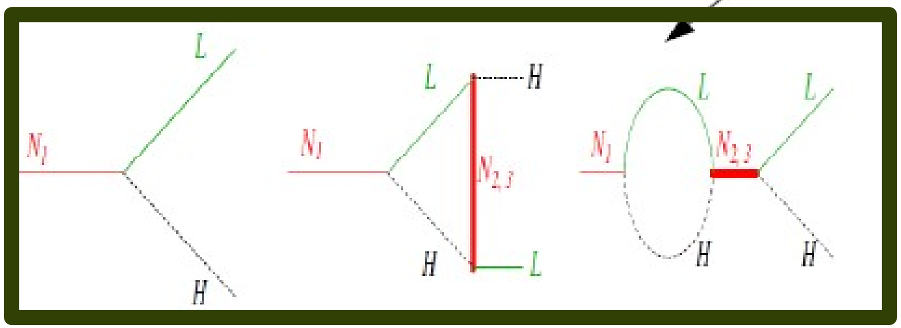


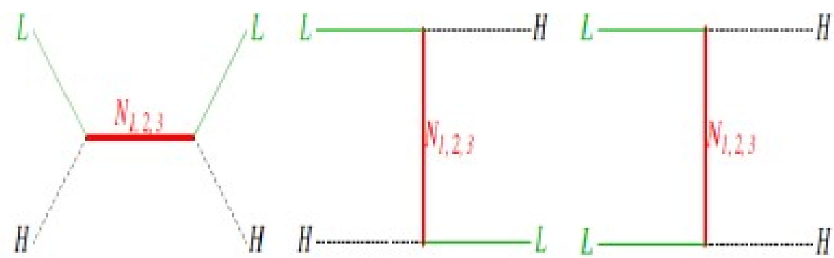


seesaw leptogenesis

Aristizabal et al arXiv:1405.4706

$$Y_{\mathcal{B}-\mathcal{L}} = -\epsilon_{N_1} \; \eta \; Y^{\rm eq}_{N_1}$$





$$\epsilon_{N_1} \equiv \frac{\gamma^{\rm eq}(N_1 \to HL) - \gamma^{\rm eq}(N_1 \to \bar{H}\bar{L})}{\gamma^{\rm eq}(N_1 \to HL) + \gamma^{\rm eq}(N_1 \to \bar{H}\bar{L})}$$

CP violation in N1 decays

Lepton asymmetry washout processes

seesaw leptogenesis

Aristizabal et al arXiv:1405.4706

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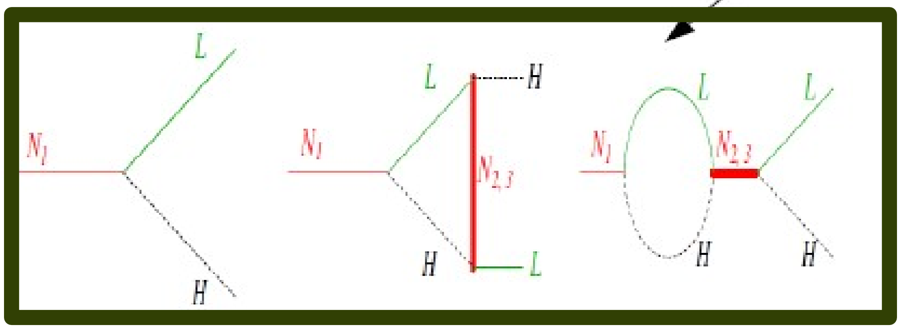
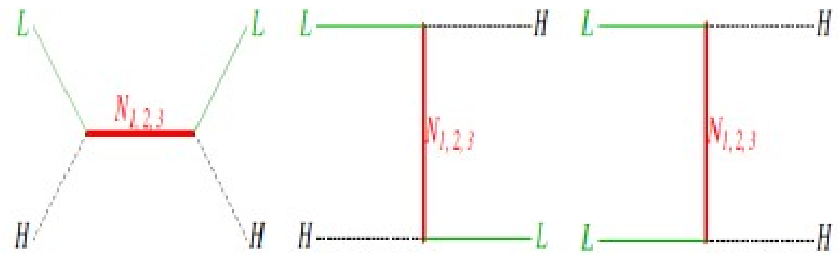


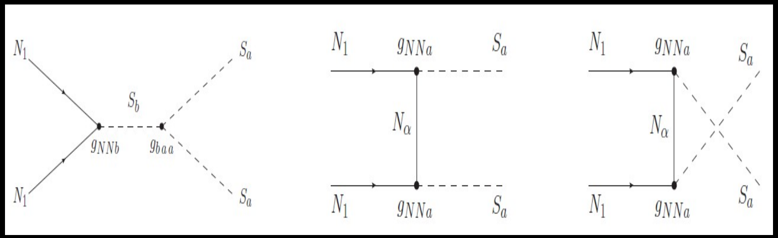


$$\epsilon_{N_1} \equiv \frac{\gamma^{\rm eq}(N_1 \to HL) - \gamma^{\rm eq}(N_1 \to \bar{H}\bar{L})}{\gamma^{\rm eq}(N_1 \to HL) + \gamma^{\rm eq}(N_1 \to \bar{H}\bar{L})}$$

CP violation in N1 decays

Lepton asymmetry
washout processes

RH neutrino scatterings



DARK MATTER

Berezinsky, Valle PLB318 (1993) 360

$$\Gamma_{J\nu\nu} = \frac{m_J}{32\pi} \frac{\sum_i (m_i^\nu)^2}{2v_1^2}$$

MAJORON DARK MATTER

Berezinsky, Valle PLB318 (1993) 360

Consistency with CMB

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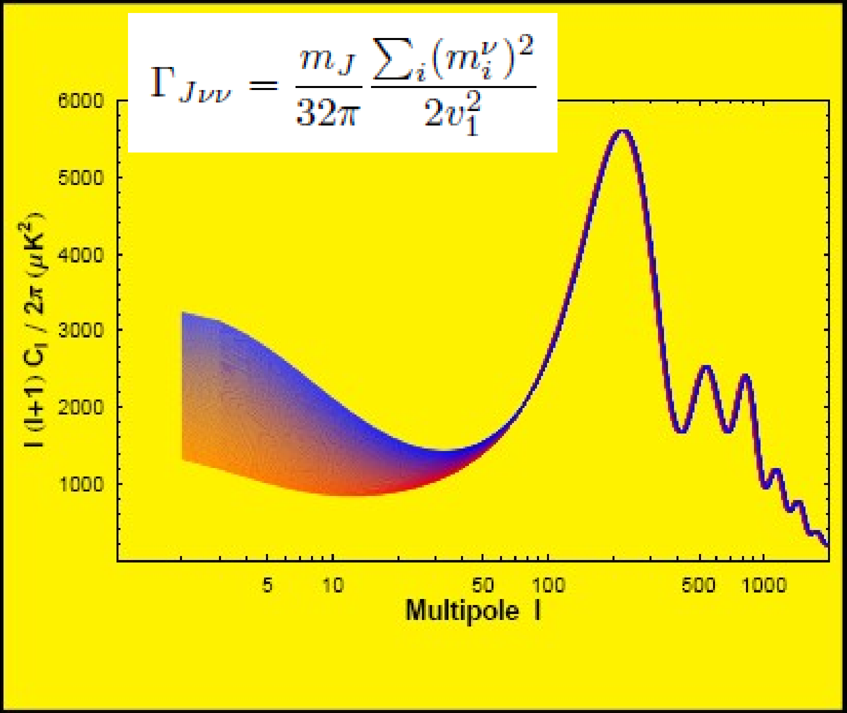
MAJORON DARK MATTER

Berezinsky, Valle PLB318 (1993) 360

Lattanzi & Valle, PRL99 (2007) 121301

Consistency with CMB



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Esteves et al, PRD 82, 073008 (2010)

MAJORON DARK MATTER

Berezinsky, Valle PLB318 (1993) 360

Lattanzi & Valle, PRL99 (2007) 121301

$$J \rightarrow \gamma\gamma$$

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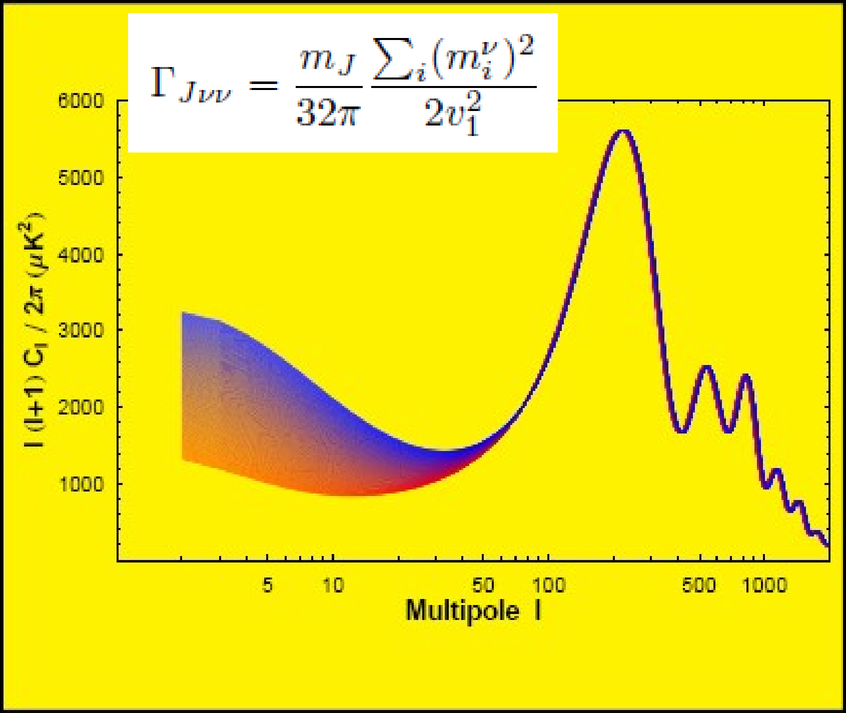

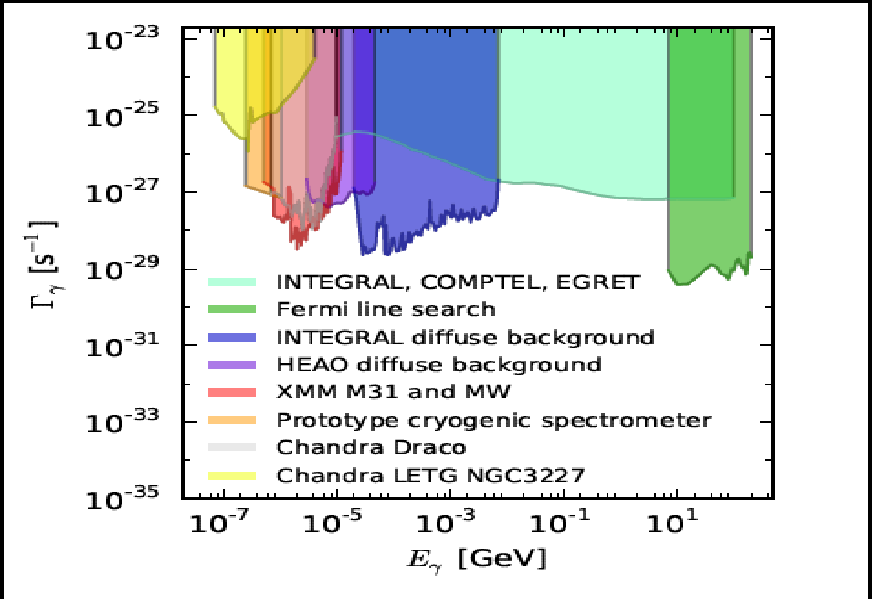

Lattanzi et al PRD88 (2013) 063528

Esteves et al, PRD 82, 073008 (2010)

Bazzocchi & al JCAP 0808 (2008) 013

MAJORON DARK MATTER

Berezinsky, Valle PLB318 (1993) 360

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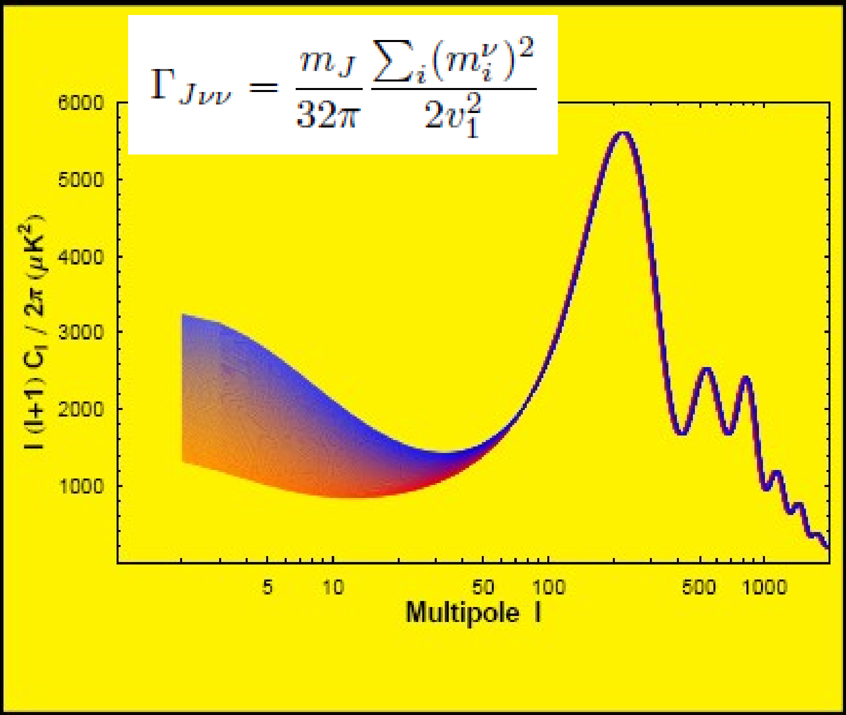
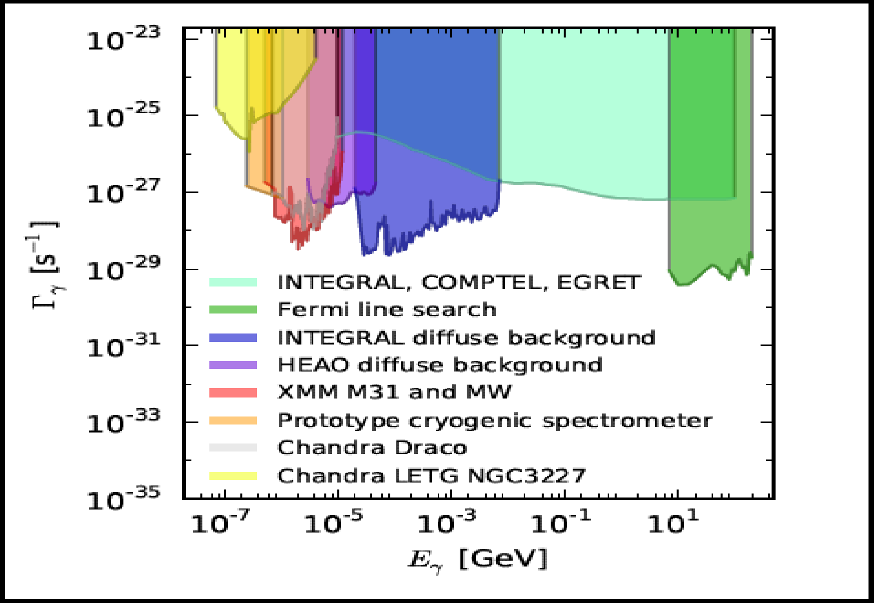


Esteves et al, PRD 82, 073008 (2010)

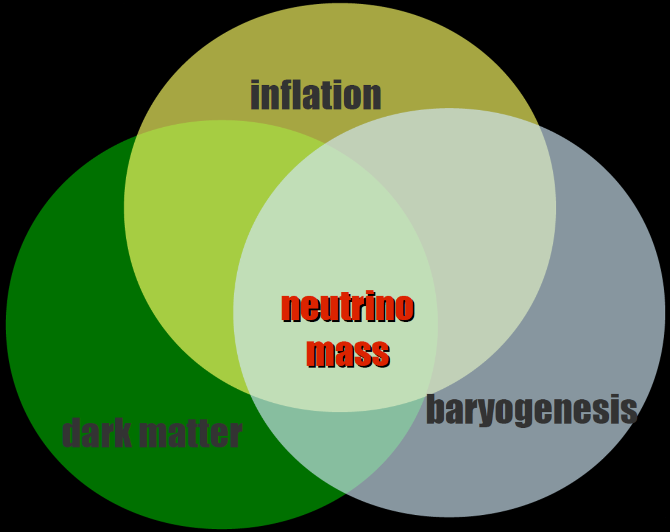
Bazzocchi & al JCAP 0808 (2008) 013

Lattanzi & Valle, PRL99 (2007) 121301

$$J \to \gamma\gamma$$



Lattanzi et al PRD88 (2013) 063528



MAJORON DARK MATTER

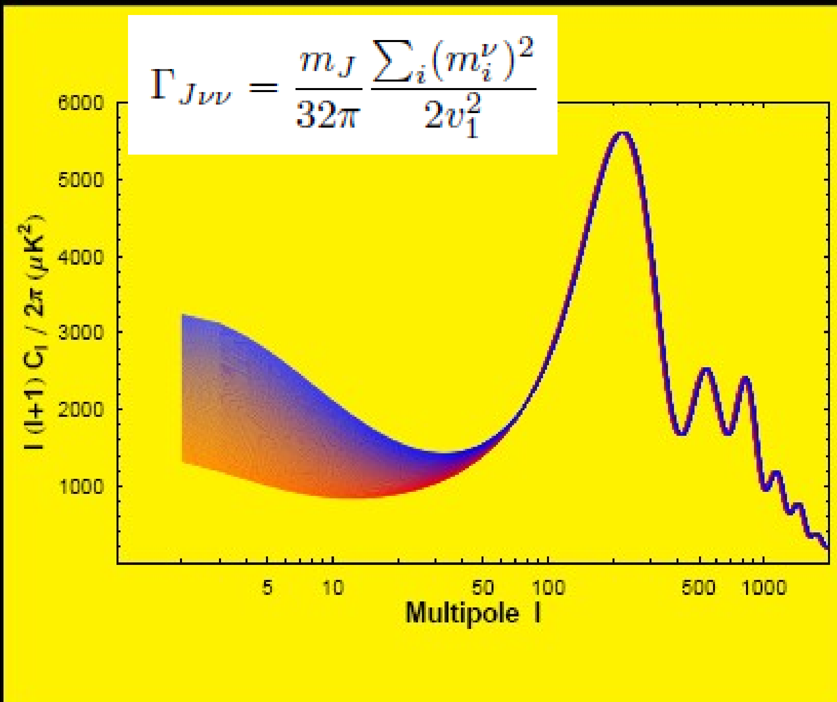
Berezinsky, Valle PLB318 (1993) 360

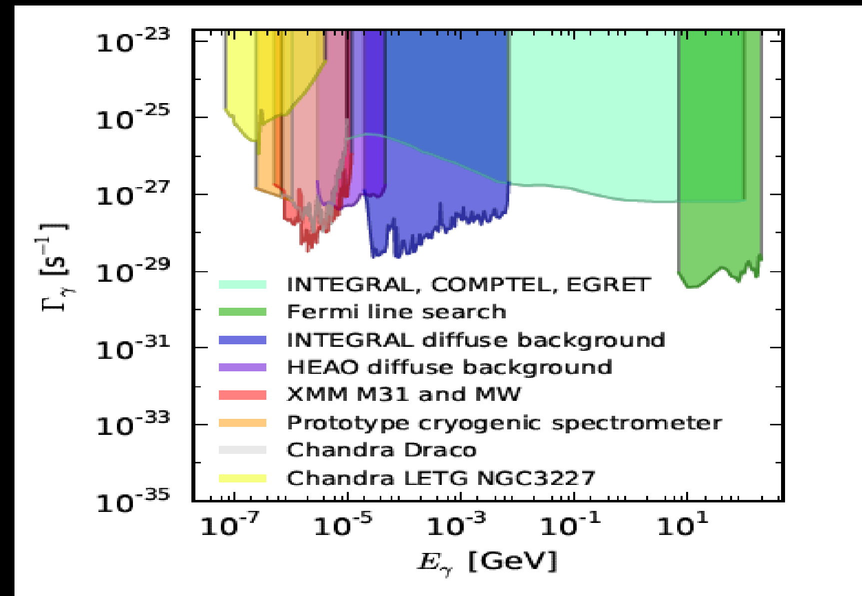
Lattanzi & Valle, PRL99 (2007) 121301

$$J \to \gamma\gamma$$

Consistency with CMB

$$\Gamma_{J\nu\nu} = \frac{m_J}{32\pi}\frac{\sum_i (m_i^\nu)^2}{2v_1^2}$$



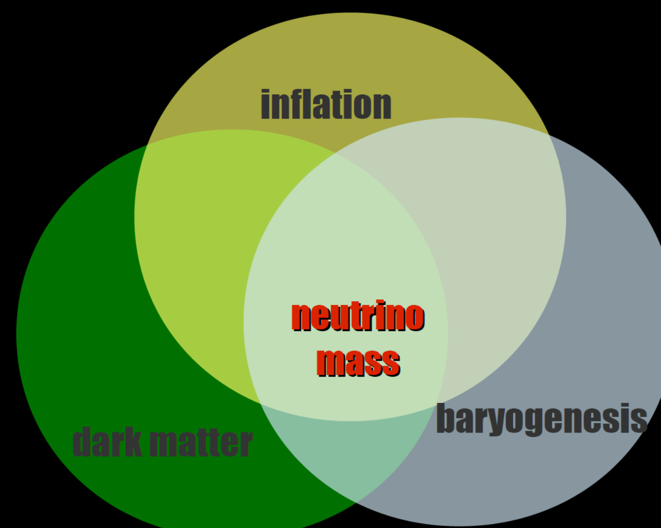


Lattanzi et al PRD88 (2013) 063528

Esteves et al, PRD 82, 073008 (2010)

Bazzocchi & al JCAP 0808 (2008) 013

Add also Dark Energy?
George Smoot arXiv:1405.2776



WIMP DARK MATTER

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If neutrinos get mass a la Inverse seesaw susy Spectrum can change so …

SNEUTRINO-like

instead of neutralino ..

Arina et al   PRL101 (2008) 161802
Bazzocchi, Cerdeno, Munoz, J.V., PRD81 (2010) 051701

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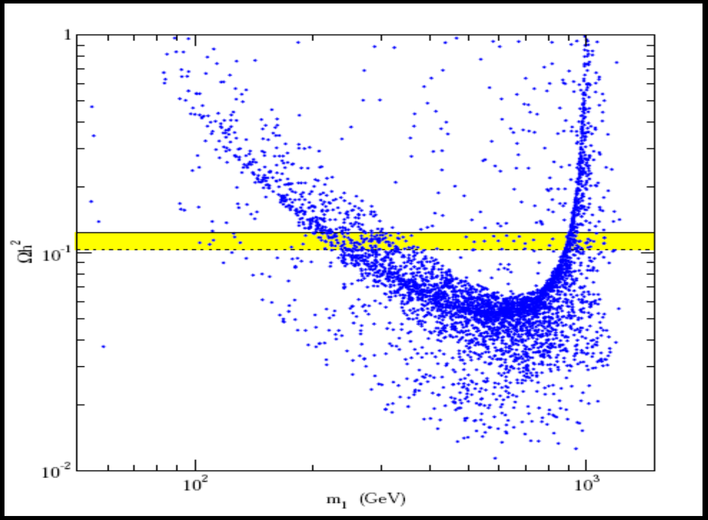
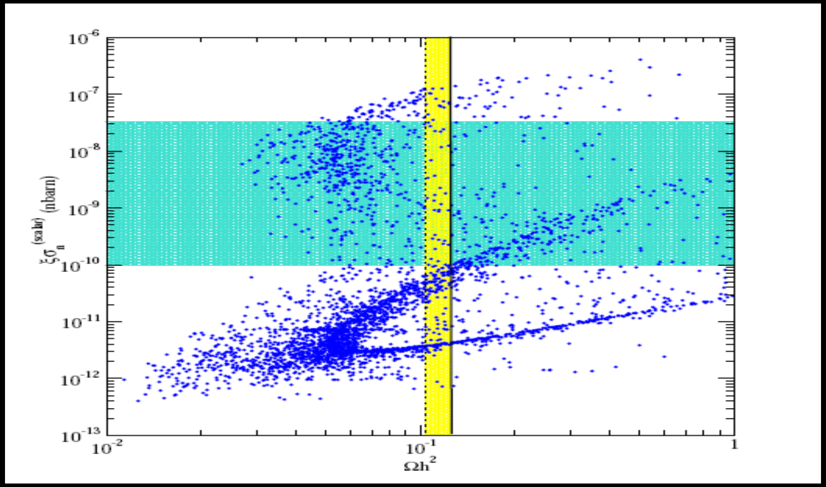


Arina et al   PRL101 (2008) 161802
Bazzocchi, Cerdeno, Munoz, J.V., PRD81 (2010) 051701



Dark Matter

(quasi)

STABILITY

Dark Matter *(quasi)* ***STABILITY***

ACCIDENT? Lavoura, Morisi, JV JHEP 1302(2013) 118

from FLAVOUR SYMMETRY

Dark Matter (quasi) STABILITY

ACCIDENT? Lavoura, Morisi, JV JHEP 1302(2013) 118

from FLAVOUR SYMMETRY

A4

Hirsch, Morisi, Peinado, Valle
PRD82 116003 (2010)

Boucenna, Hirsch, Morisi, Peinado, Taoso, Valle JHEP 1105 037 (2011)

Z2 PARITY

Dark Matter (quasi) STABILITY

ACCIDENT? Lavoura, Morisi, JV JHEP 1302(2013) 118

from FLAVOUR SYMMETRY

A4

Hirsch, Morisi, Peinado, Valle
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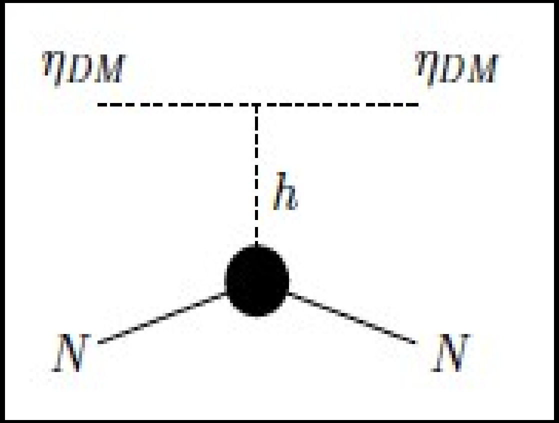
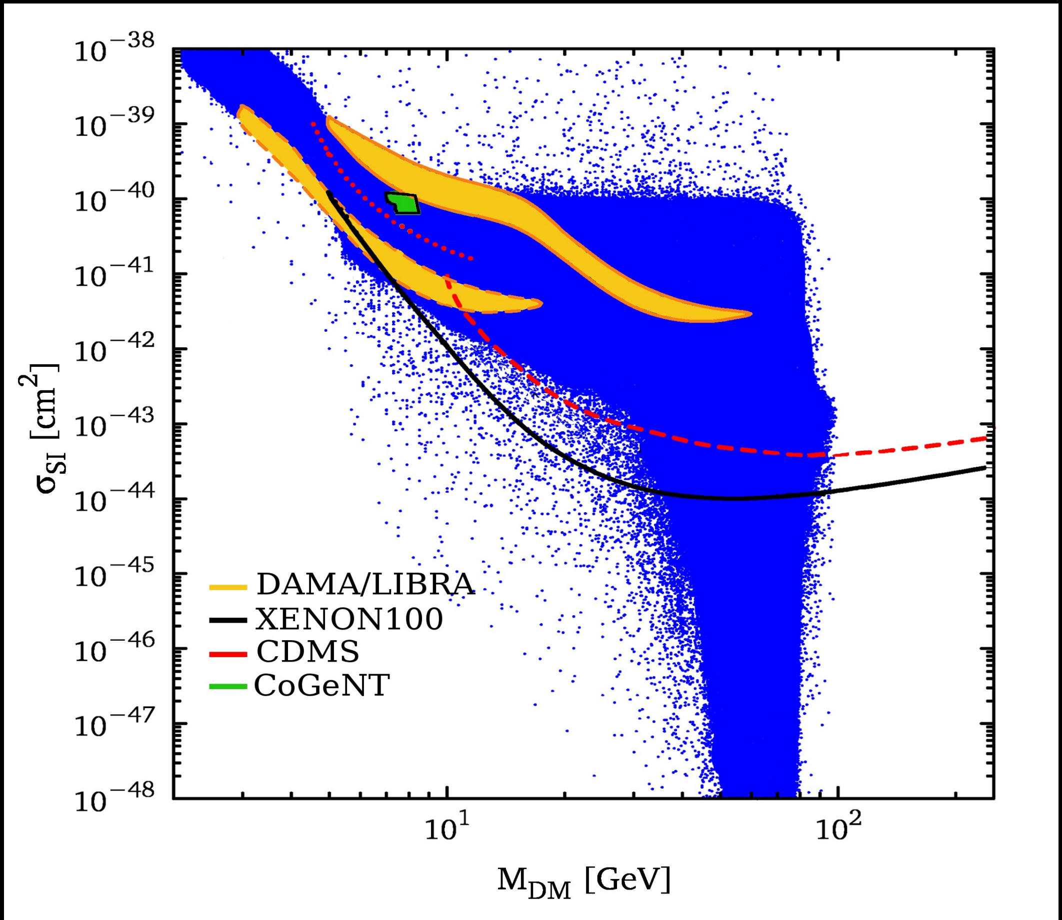
Z2 PARITY

HIGGS PORTAL





OSCILLATIONS ROBUST … PHASE, SPECTRUM, OCTANT, NSI ?

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ORIGIN OF NEUTRINO MASS : WHICH MESSENGER ?

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ORIGIN OF NEUTRINO MASS : WHICH MESSENGER ?

NEUTRINO PROPERTIES : TESTABLE @ LHC ?

FLAVOR PATTERN: ANARCHY OR SYMMETRY ?

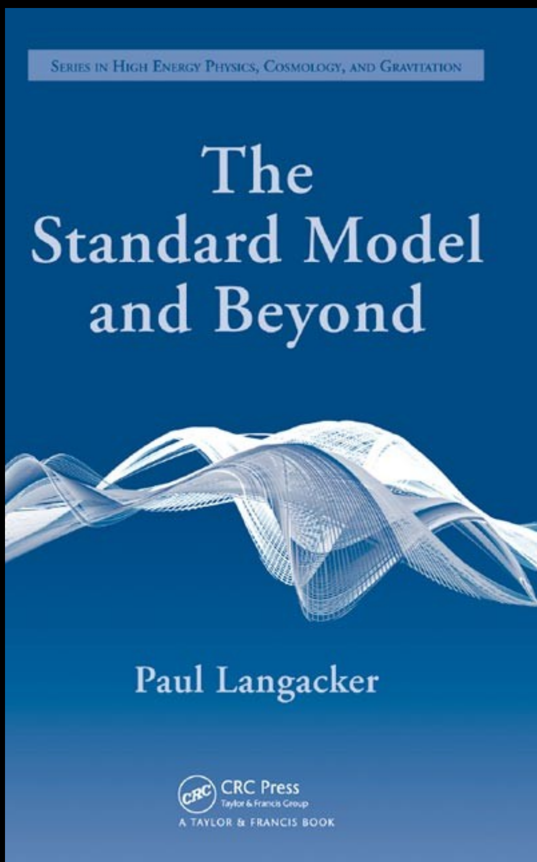
IS DARK MATTER RELATED TO NEUTRINOS ?

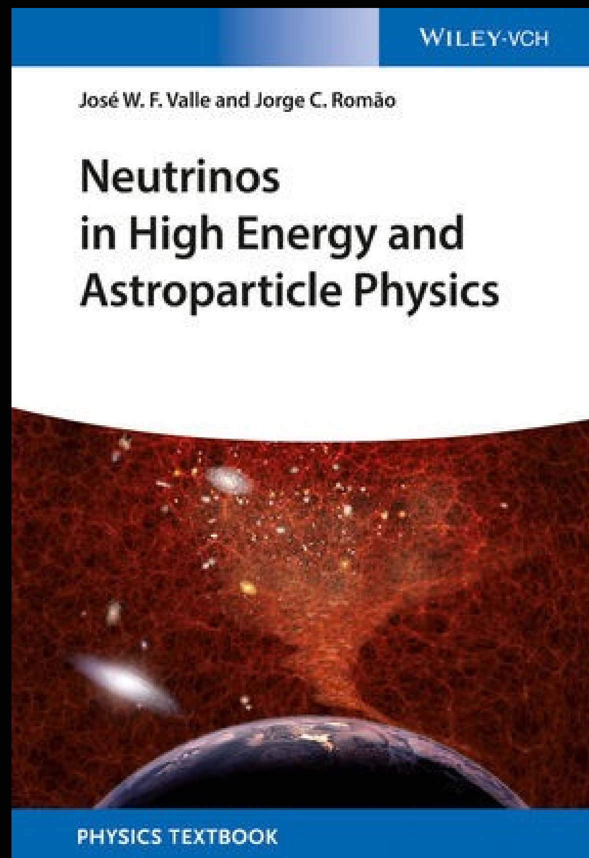
WHY STABLE ?

Non-SUSY WIMP ?

Non-WIMP: MAJORON or GRAVITINO DECAYING DM …

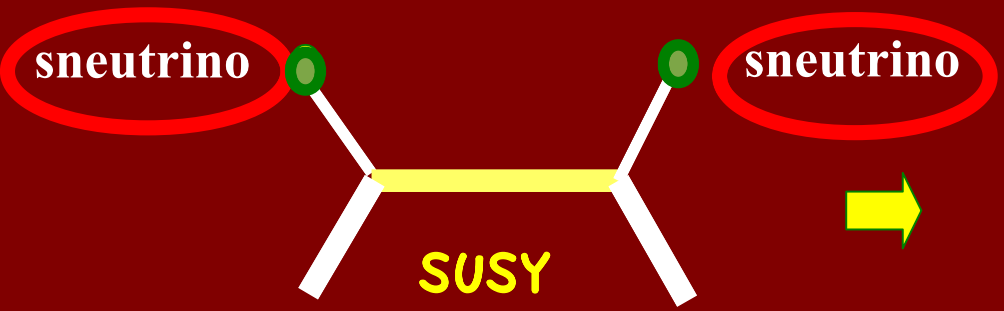
In addition to classics e.g. TP Cheng & Ling Fong Li, Mohapatra & Pal, there are new particle physics books ...





ISBN: 978-3-527-41197-9
456 pages
December 2014

SUSY ORIGIN OF NEUTRINO MASS



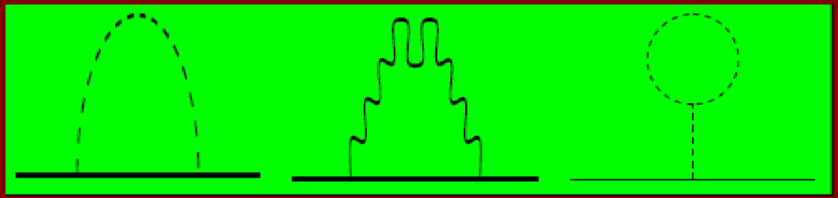
Masiero & Valle, PLB251 (1990) 273
Bhattacharyya & Pal, PRD82 (2010) 055013

EFF. BILINEAR RPV

ATM SCALE
SUSY-SEESAW

PRD65 (2002) 119901; PRD61 (2000) 071703

Hall & Suzuki,
Ross & JV 85, Ellis et al 85, ..



SOLAR SCALE
RADIATIVE

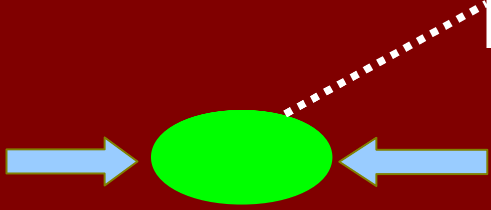
Diaz et al PRD68 (2003) 013009, PRD62 (2000) 113008

Bazzocchi et al JHEP 01 (2013) 033 arXiv:1202.1529

LIGHTEST NEUTRALINO DECAYS: PROBING NUs @ LHC

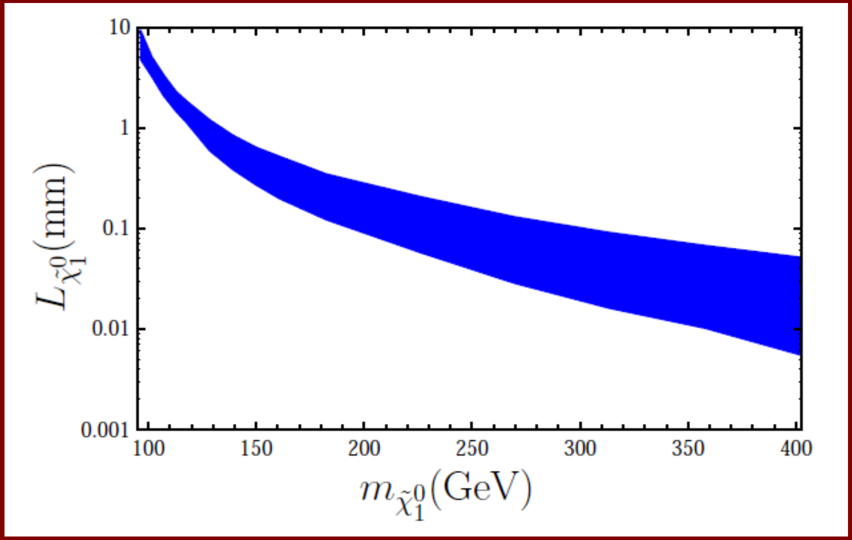
De Campos et al
Phys.Rev. D86 (2012) 075001

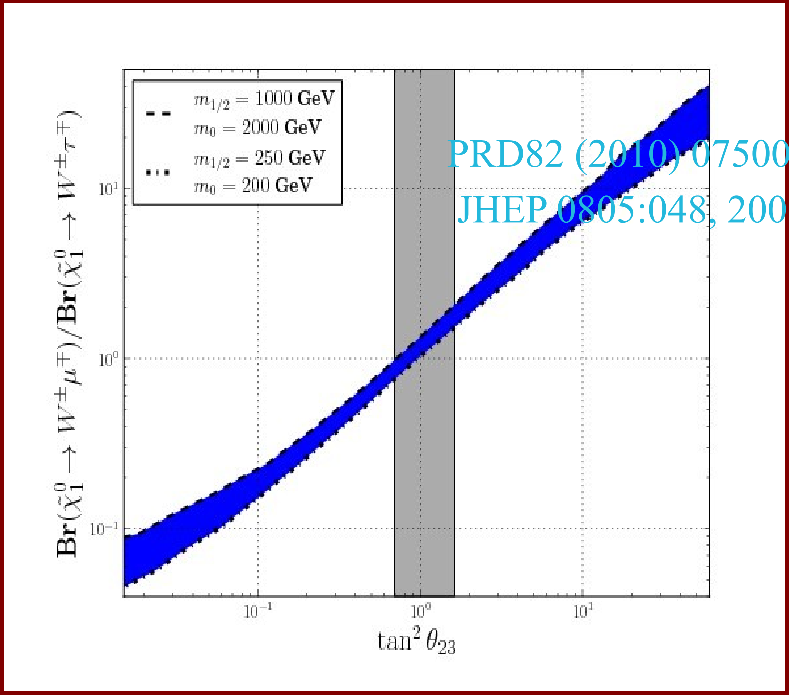
$$\tilde{\chi}_1^0 \rightarrow W^{\pm} l_i^{\mp} \qquad \tilde{\chi}_1^0 \rightarrow Z^0 \nu_i$$



Lightest neutralino decay correlates with atm angle

Lightest neutralino decay length





PRD82 (2010) 075002 &
JHEP 0805:048, 2008

Nath et al NPPS 200-202 (2010) 185-417

Gamma line from decaying Gravitino dark matter

decays suppressed by Planck mass & smallness of m-nu

$$\Gamma = \Gamma(\tilde{G} \rightarrow \sum_i \nu_i \gamma) \simeq \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{\tilde{G}}^3}{M_P^2}$$

chosen to fit neutrino osc. data

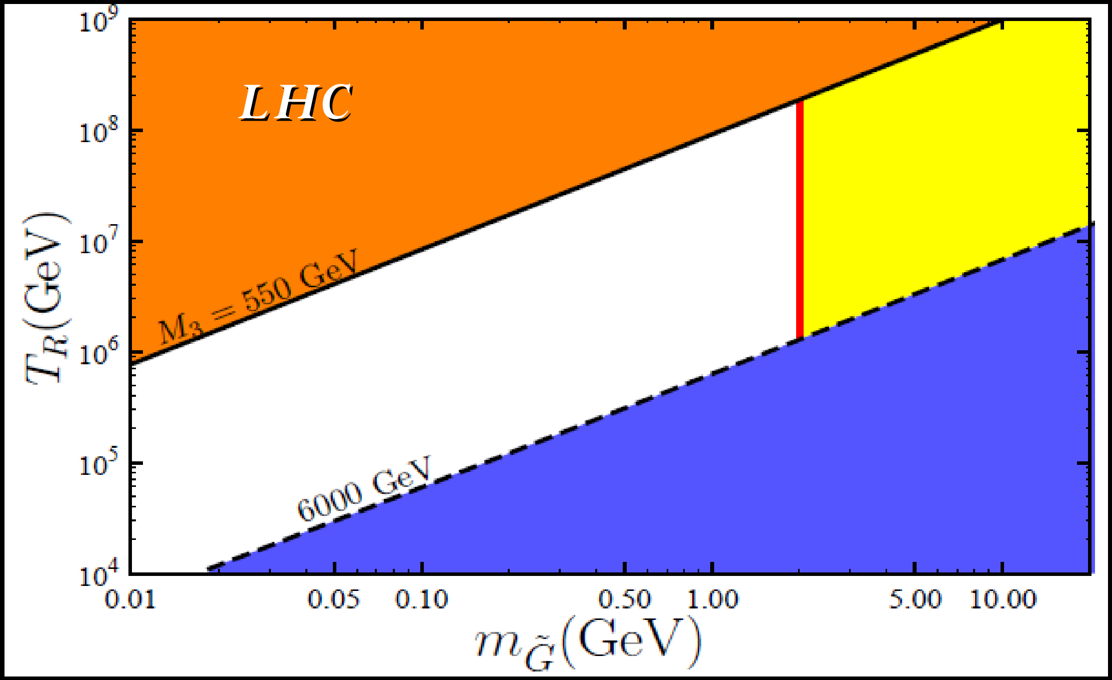
Restrepo et al
PRD85 (2012) 023523

relic abundance

+ LHC searches

excluded by gamma line searches @

Egret & Fermi-LAT

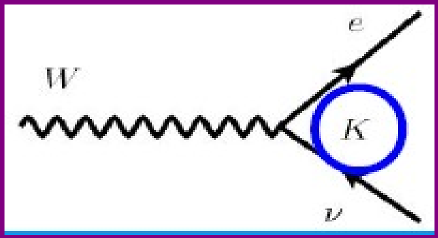


LEPTON MIXING MATRIX

$$K = \omega_{23} \cdot \omega_{13} \cdot \omega_{12}$$

Schechter & JV PRD22 (1980) 2227 & PDG

Rodejohann, JV Phys.Rev. D84 (2011) 073011

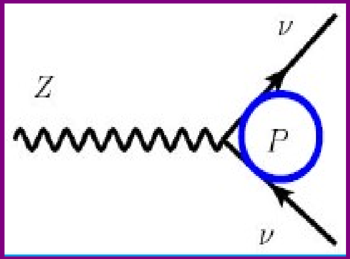


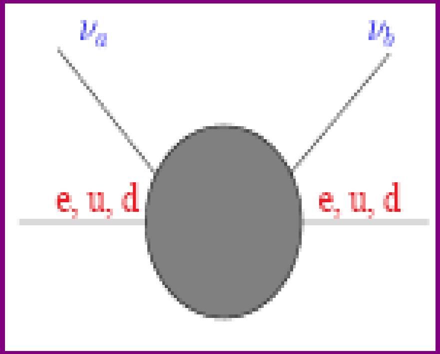
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Approximation used adopted in oscillation analyses

- **majorana phases (cf KM)**
- **oscillations versus L-violating processes**

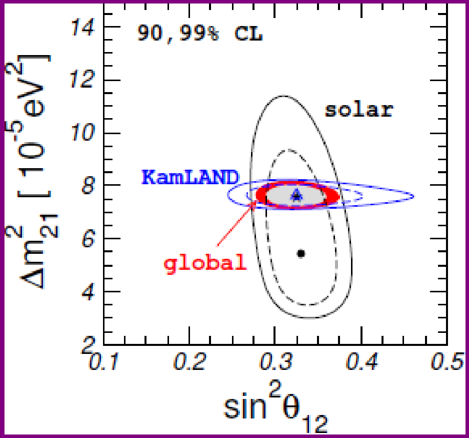
K Rectangular → K_eff. non-unitary
P Non-trivial
NSI & LFV

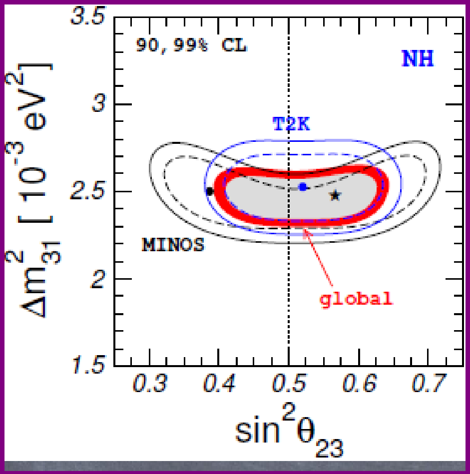


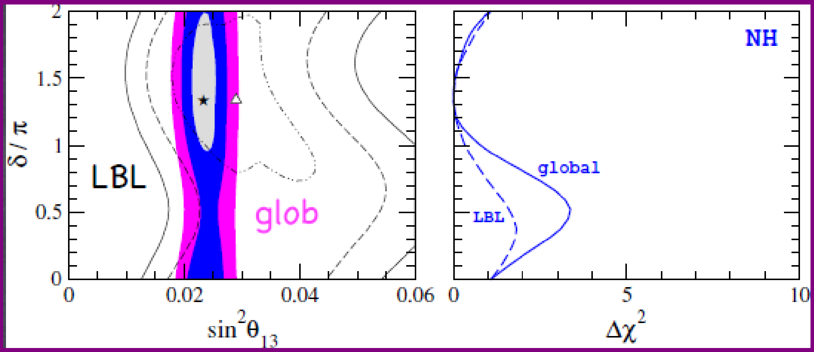


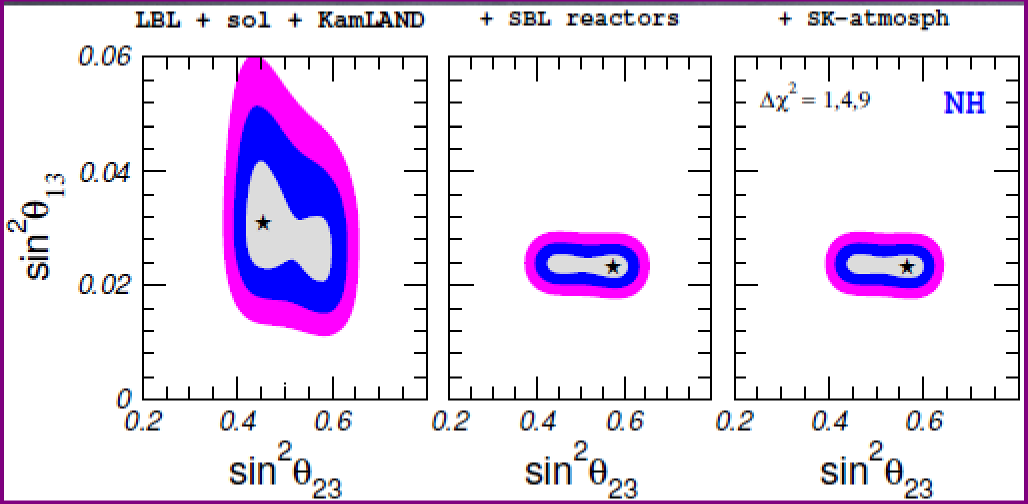
Oscillations after nu2014

Forero, Tortola, JWFV arXiv:1405.7540









Double Chooz: 467.9 days [arXiv:1406.7763]

RENO: 800 days [talk by Seon-Hee Seo@ICHEP2014]

Daya Bay: 621 days of data (6AD + 8AD) [Talk by Chao Zhang@ICHEP2014]