Neutrinos

selected topics

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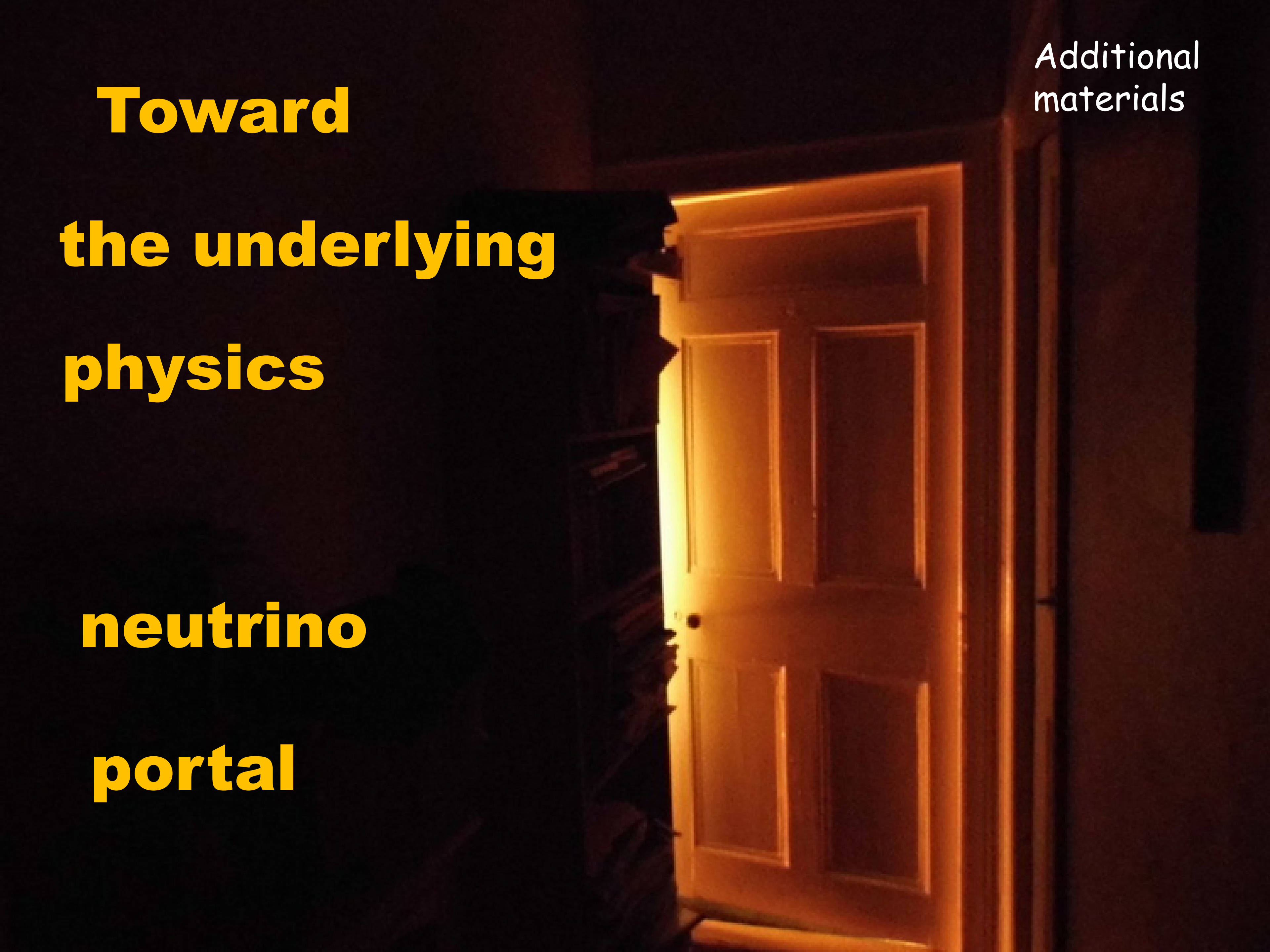

Toward
the underlying
physics
neutrino
portal
Additional
materials

3ν - paradigm

All well established/confirmed results fit well a framework with

- three neutrinos
- interactions described by the standard model
- with masses and mixing

It is widely believed that Connection exists

Where is ν_R

Scales of new physics

28 orders of magnitude

GUT - Planck mass

$\frac{V_{EW}^2}{m_\nu}$

High scale seesaw
Quark- lepton symmetry /analogy
GUT

PeV

Electroweak – LHC

Low scale seesaw, radiative mechanisms, RPV, high dimensional operators

eV- sub-eV

m_ν

Scale of neutrino masses themselves
Relation to dark energy, MAVAN?

Spurious scale?

Neutrino mass itself is the fundamental scale of new physics

EW – LHC scale

- No hierarchy problem (even without SUSY)
- testable at LHC, new particles at 0.1 – few TeV scale
- LNV decays

Low scale seesaw

νMSM

L-R

Low scale

$\not{R}_p$-SUSY

Neutralino as RH neutrino

Inverse seesaw

Small VEV

Higgs Triplet

New Higgs doublets

Radiative

One loop

Two loops

Three loops

Four loops

High dimensional operators

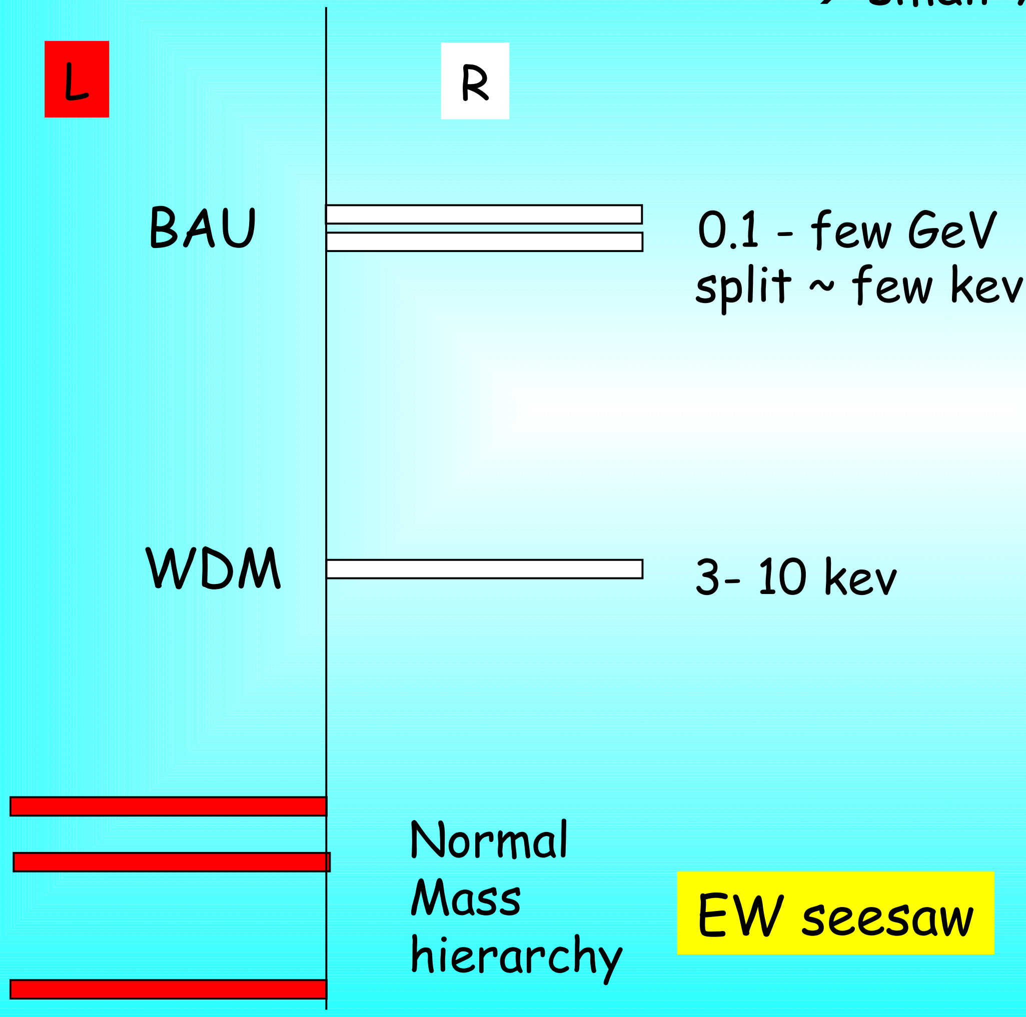
Connection to Dark Matter

Radiative seesaw

ν MSM

M. Shaposhnikov et al

Everything below EW scale
→ small Yukawa couplings

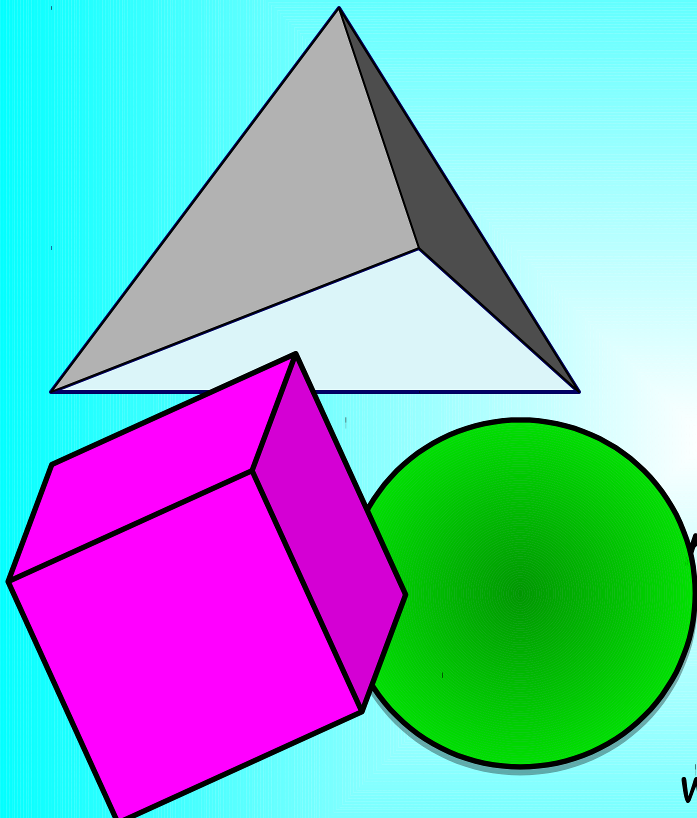


- small neutrino mass
- generate lepton asymmetry in the Universe via oscillations
- can be produced in B-decays (BR ~ 10^{-10}) etc, SHiP

- warm dark matter
- radiative decays → X-rays

EW seesaw

Mixing



from symmetry
to anarchy and
randomness

with
intermediate
possibilities

Complicated constructions,
especially if quarks are
included

Not much to add
- String landscape
- Multiverse?

Trends and implications

No new physics is found

No new physics at LHC in particular new physics which could be associated to low scale mechanisms of neutrino mass generation

- right Handed neutrinos, new heavy leptons
- right handed gauge bosons of the L-R symmetric models
- double charged scalars (of seesaw type II), etc
- new fermions and scalars which can participate in the radiative mechanism of neutrino mass generation

→ Bounds on masses / couplings of these new particles

No Lepton number violation, MEG, ….

Nothing yet at well motivated TeV-scale.
The next motivated scales are intermediate and then GUT

Bottom - up

observations

and hints

Analysing data

Smallness of mass?

Special

comparing within generation:

$$\frac{m_3}{m_\tau} \sim 3\ 10^{-11}$$

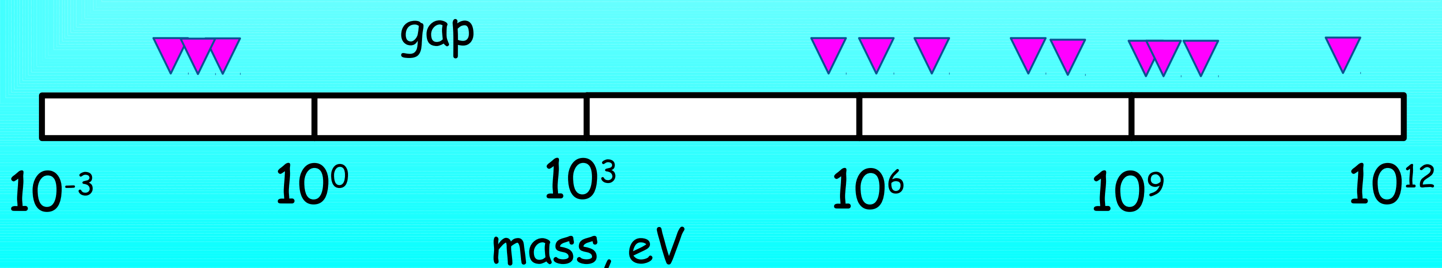
Similar for other generations
if spectrum is hierarchical

Normal?

Neutrinos: no clear generation structure and correspondence light flavor – light mass, especially if the mass hierarchy is inverted or spectrum is quasi-degenerate

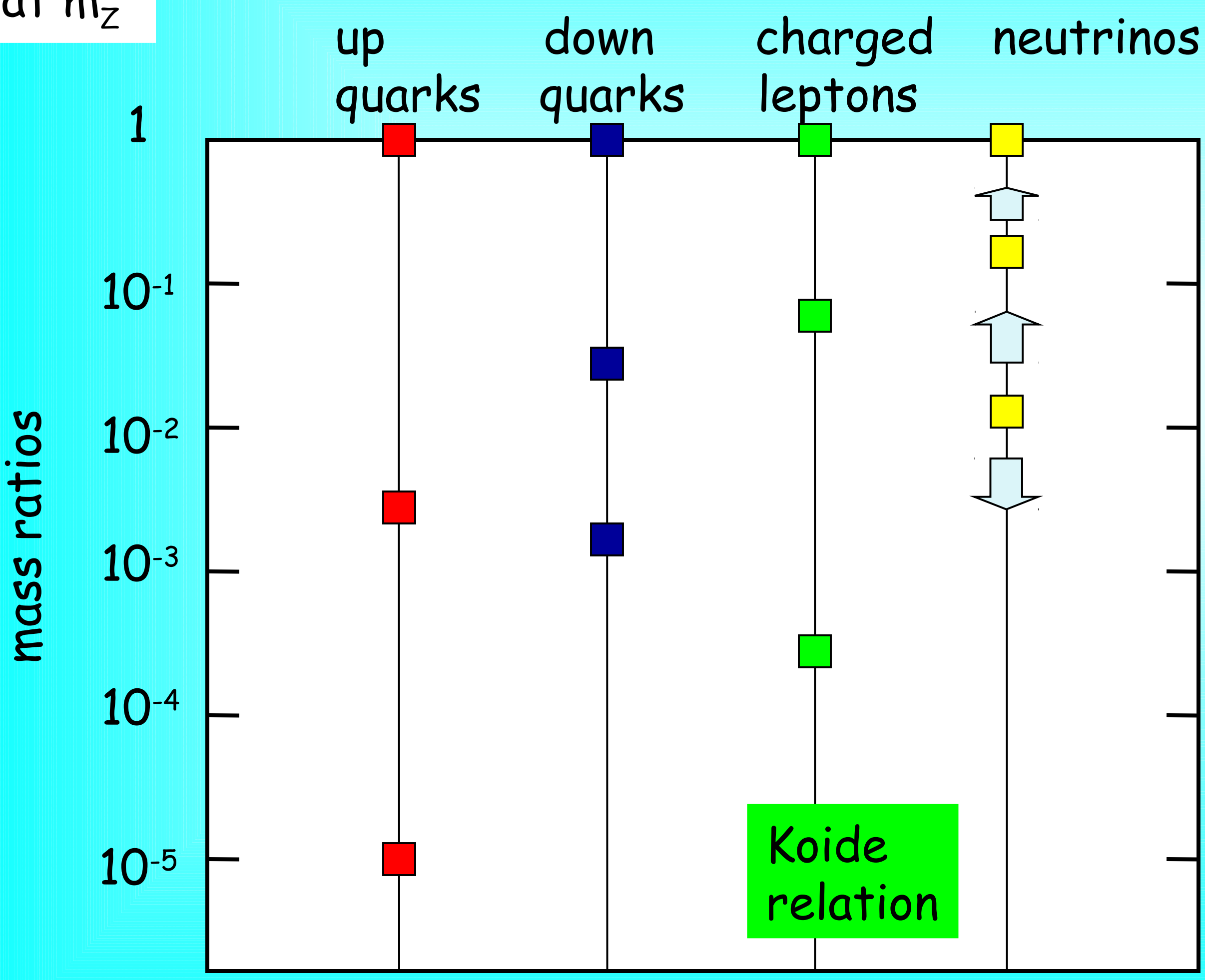
$$\frac{m_3}{m_e} \sim 3\ 10^{-6}$$

$$\frac{m_e}{m_t} \sim 3\ 10^{-6}$$



Mass hierarchies

at m_Z



$$\frac{m_2}{m_3} \geqslant \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}}$$

~ 0.18

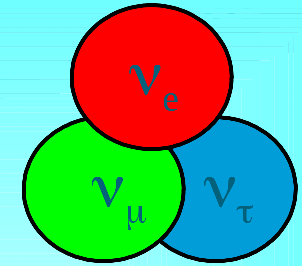
Neutrinos have the weakest mass hierarchy (if any) among fermions

Related to large lepton mixing?

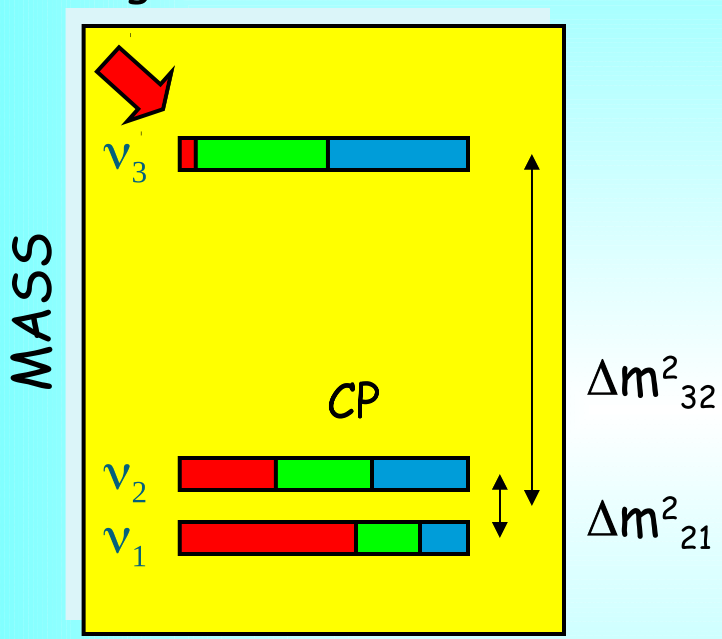
$m_u\, m_t = m_c^2$

$\sin\theta_C \sim \sqrt{m_d/m_s}$ Gatto–Sartori–Tonin relation

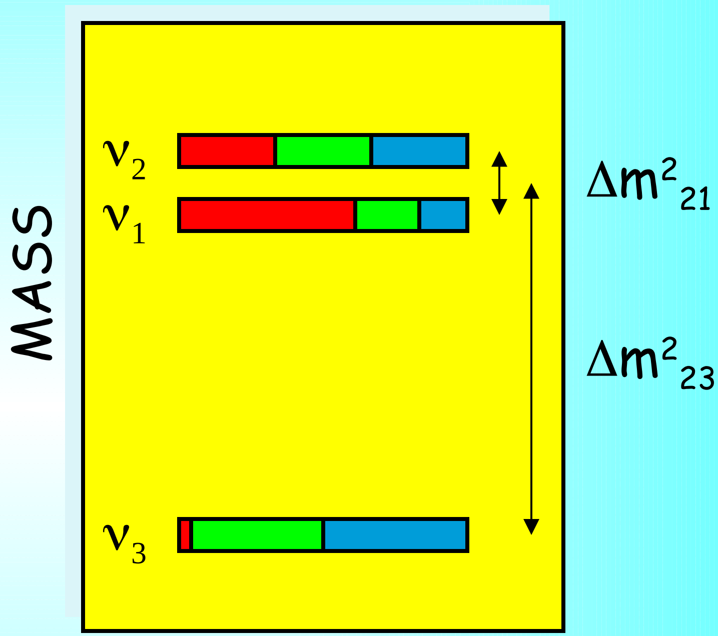
Lepton Mixing



1-3 mixing
2%



Normal mass hierarchy



Inverted mass hierarchy

$\Delta m^2_{32} = 2.4 \times 10^{-3}\ eV^2$

$\Delta m^2_{21} = 7.5 \times 10^{-5}\ eV^2$

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

$\sin^2\theta_{23} = 1/2$

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

TBM,
Symmetry?

For antineutrinos spectra are different (distribution of the ν_μ and ν_τ - flavors in ν_1 and ν_2) due to possible CP-violation

TBM Mixing pattern

P. F. Harrison, D. H. Perkins, W. G. Scott

L. Wolfenstein

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

0.15

0.62

0.78

$U_{tbm} = U_{23}(\pi/4)\, U_{12}$

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

0.30- 0.31

Accidental, numerology, useful for bookkeeping

Accidental symmetry (still useful)

Not accidental

Lowest order approximation which corresponds to weakly broken (flavor) symmetry of the Lagrangian

with some other physics and structures associated

There is no relation of mixing with masses (mass ratios)

Parameters look like C-G coefficients

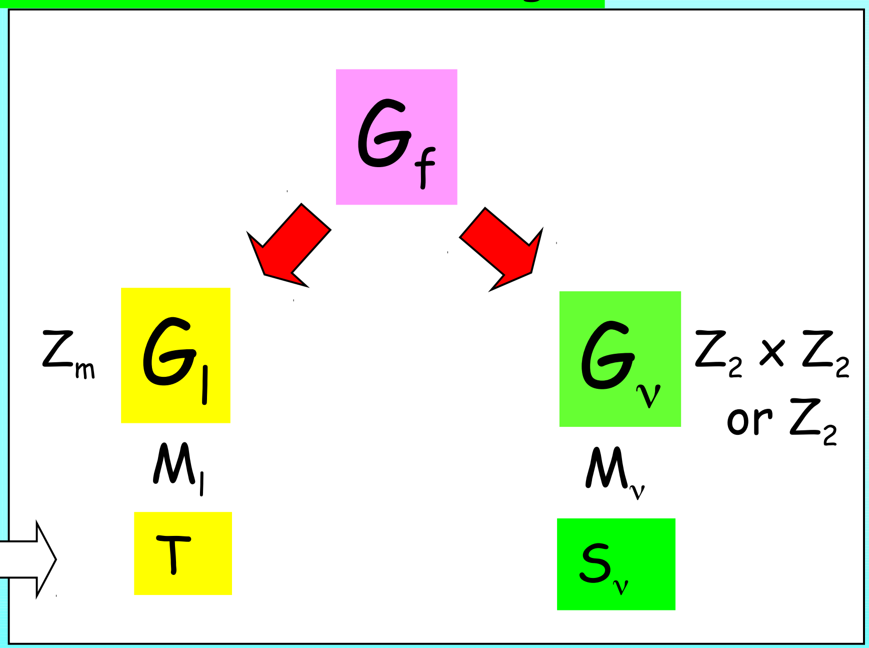
Residual symmetries approach

E. Ma, C. S. Lam ....

Mixing appears as a result of different ways of the flavor symmetry breaking in the neutrino and charged lepton (Yukawa) sectors.

No connection of masses and mixing

A_4 S_4 T_7 T'



Symmetry transformations in mass bases

Residual symmetries of the mass matrices

Generic symmetries which do not depend on values of masses

$$S_\nu M_\nu S_\nu^T = M_\nu$$

Discrete finite groups

Flavons to break symmetries

Flavons

Realizations: too complicated ....

Intrinsic symmetries

Realized for arbitrary values of neutrino and charged lepton mass

D. Hernandez, A.S.

Assumptions

- Majorana neutrinos
- symmetry can be embedded in SU(3)

in the mass basis

$m = \mathrm{diag}(m_1, m_2, m_3)$

G_ν

$S_1 = \mathrm{diag}(1, -1, -1)$

$S_2 = \mathrm{diag}(-1, 1, -1)$

$S_i^2 = I$ $\quad Z_2 \times Z_2$

The Klein group

$m_l = \mathrm{diag}(m_e, m_\mu, m_\tau)$

G_l

$T = \mathrm{diag}(e^{i\phi_e}, e^{i\phi_\mu}, e^{i\phi_\tau})$

$\phi_\alpha = 2\pi k_\alpha / m$

$T^m = I$ $\quad Z_m$

$\Sigma \phi_\alpha = 0$

the simplest discrete symmetries which left the matrix diagonal

in flavor basis $\quad S_i^f = U_{PMNS} S_i U_{PMNS}^+$

nsic symmetries = residual symmetri

If intrinsic symmetries are residual symmetries of the unique symmetry group (follow from breaking of unique group)
→ bounds on elements of mixing matrix

D. Hernandez, A.S.
1204.0445

$$(U_{PMNS} S_i U_{PMNS}^+ T)^p = I$$

P -integer

Symmetry group condition

Equation gives 2 relations between mixing parameters

Two such equations for i = 1,2 fix the mixing matrix completely
→ TBM

Equivalent to

$$Tr (U_{PMNS} S_i U_{PMNS}^+ T) = a$$

$$a = \Sigma_j \lambda_j$$

$$\lambda_j^p = 1 \qquad j = 1,2,3$$

$$Tr (W_{iU}) = a$$

λ_j - three eigenvalues of W_{iU}

$Z_2 \times Z_2$ → TBM

Example

$G_\nu = Z_2$

Two relations

D. Hernandez, A Y S. 1304.7738 [hep-ph]

In the residual symmetries approach

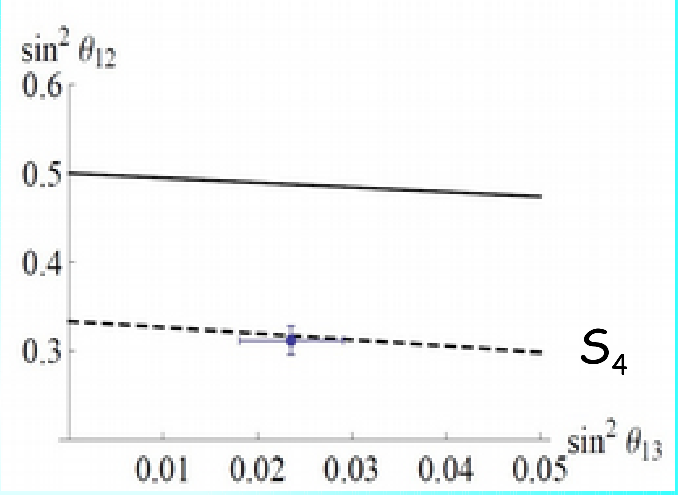
for column of the mixing matrix:

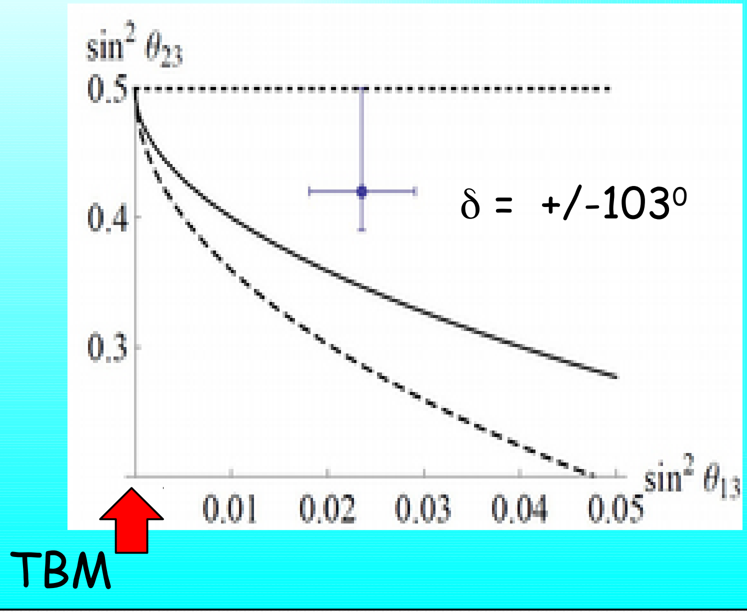
$$|U_{\beta i}|^2 = |U_{\gamma i}|^2$$

$$|U_{\alpha i}|^2 = \frac{1 + a}{4 \sin^2 (\pi k/m)}$$

k, m, p integers which determine symmetry group

$k_\alpha = 0$





olation of TBM: 1-3 mixing

The same value with completely different implications

	relation	implications
$\sin^2\theta_{13}$	$\sim \frac{1}{2}\sin^2\theta_C$	Quark-Lepton Complementarity GUT, family symmetry, ...
	$O(1)\frac{\Delta m_{21}^2}{\Delta m_{32}^2}$	\`\`Naturalness" , absence of fine tuning of mass matrix
	$\frac{1}{4}\sin^2\theta_{12}\sin^2\theta_{23}$	Analogy with quark mixing relation
	? $\sim \frac{1}{2}\cos^2 2\theta_{23}$	universal $\nu_\mu - \nu_\tau$ - symmetry violation
	> 0.025	Mixing anarchy

$\theta_{13} = 2^{1/2}(\pi/4 - \theta_{23})$

Eby, Frampton, Matsuzaki

One can use $G_\nu = Z_2$ to relax symmetry restrictions and accommodate non-zero 1-3 mixing

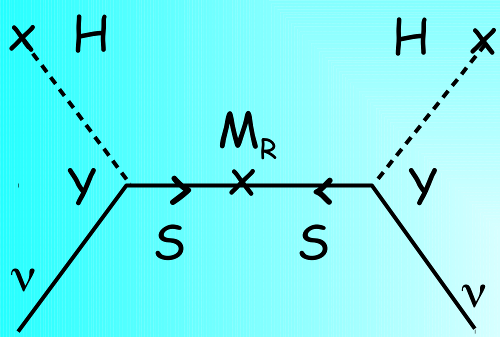
Smallness of

Neutrino mass and seesaw

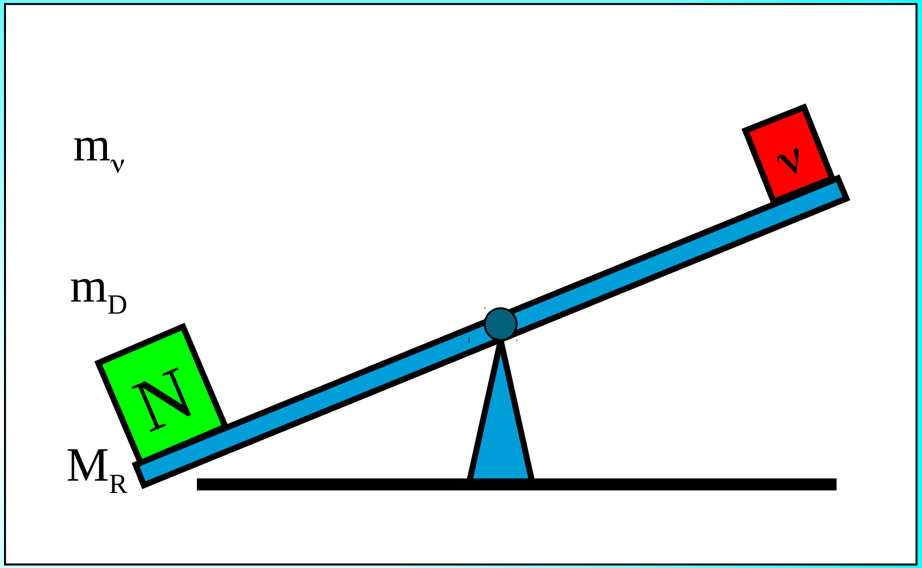
See-saw

P. Minkowski
T. Yanagida
M. Gell-Mann, P. Ramond, R. Slansky
S. L. Glashow
R.N. Mohapatra, G. Senjanovic

Type 1



$m_D = y\langle H\rangle$



Mass matrix:

$$\begin{array}{c|cc} & \nu & N \\ \hline \nu & 0 & m_D \\ N & m_D^T & M_R \end{array} \qquad \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

if $M_R \gg m_D$ ⇒

$$m_\nu = - m_D^T \frac{1}{M_R} m_D$$

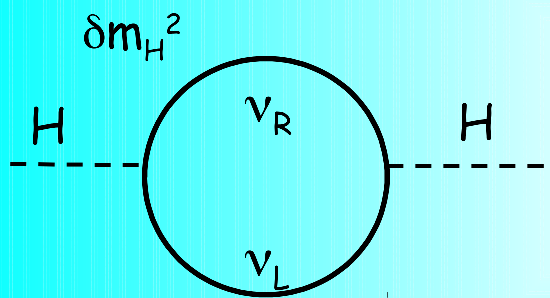
small out of large: small = $\dfrac{(\text{usual})^2}{\text{LARGE}}$

IMPORTANT: M_R can be related to GUT / Planck scale

ν- mass and Higgs physics

bottom -up

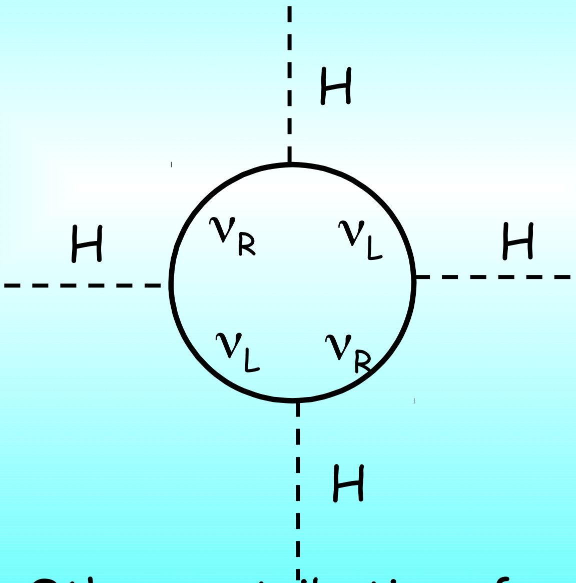
Correction to Higgs mass



Upper bound on mass
$M_R < 10^7$ GeV
→ leptogenesis ?
→ cancellation (a kind of SUSY)

F. Vissani ...
J Elias-Miro et al,
R Volkas, et al,
M. Fabbrichesi ...

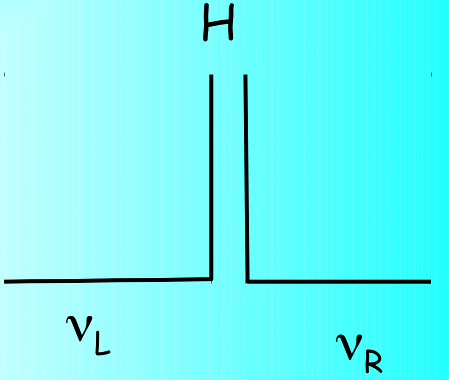
Correction to λ - 4 point coupling – vacuum stability



Other contributions from particles associated to neutrino mass generation, e.g. Higgs triplets

C. Bonila et al, 1506.04031

Higgs as composite state of neutrinos



New strong int. Generate 4 fermionic coupling

Recent:
J. Krog, C. T. Hill 1506.02843

Neutrinos and

Hidden world

Theoretical

perspective

Guide-lines

with
Borut Bajc
Patric Ludl
Xiaoyong Chu,
Daniel Hernandez

Testability with the present facilities
is not the problem of NATURE

Unified description of quarks and leptons,

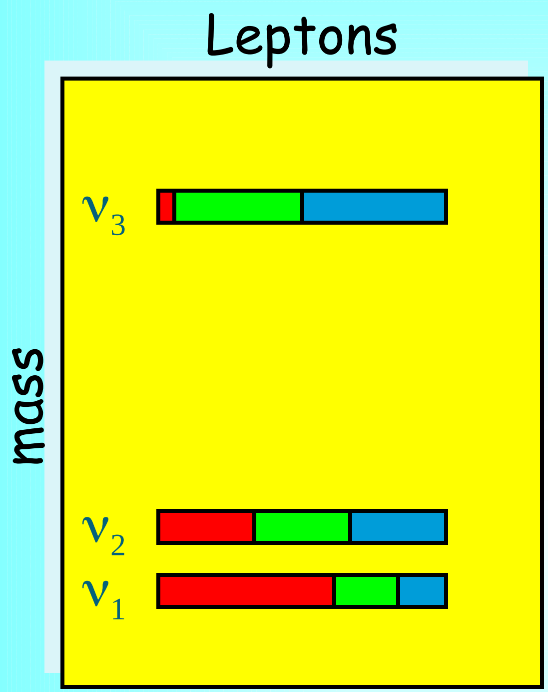
GUT?

Solutions of the problems of the Visible
sector can be in the Hidden sector

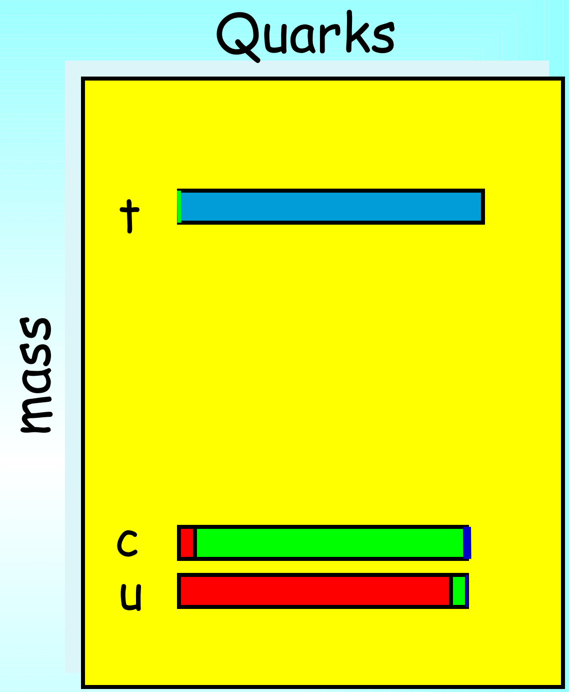
Simplicity, minimality

Old does not mean wrong

Leptons versus quarks



$\nu_f = U_{PMNS}\,\nu_{mass}$



$U_d = V_{CKM}^{+}\,U$ $\quad U = (u, c, t)$

Mixings of quarks and leptons are strongly different but still related

Observation:

$\theta_{12}^{l} + \theta_{12}^{q} \sim \pi/4$

$\theta_{23}^{l} + \theta_{23}^{q} \sim \pi/4$

Sum up to maximal mixing angle
kind of complementarity

In general

C. Giunti, M. Tanimoto
H. Minakata, A Y S
Z - Z. Xing
J Harada
S Antusch , S. F. King
Y Farzan, A Y S
M Picariello ,etc.

$$U_{PMNS} = V_{CKM}^{+} U_X$$

U_X special matrix close to bi-maximal or TBM matrix:

$$U_X = \begin{cases} U_{BM} = U_{23}(\pi/4)\, U_{12}(\pi/4) \\ U_{TBM} = U_{23}(\pi/4)\, U_{12}(\theta_{TBM}) \end{cases}$$

Prediction:
if

$U_X = U_{23}(\pi/4)\, U_{12}$ $\quad$ $\theta_{13}^{X} \sim 0$

permutation - to reduce the lepton mixing matrix to the standard form gives

$$\sin\theta_{13} \sim \sqrt{\tfrac{1}{2}}\, \sin\theta_C$$

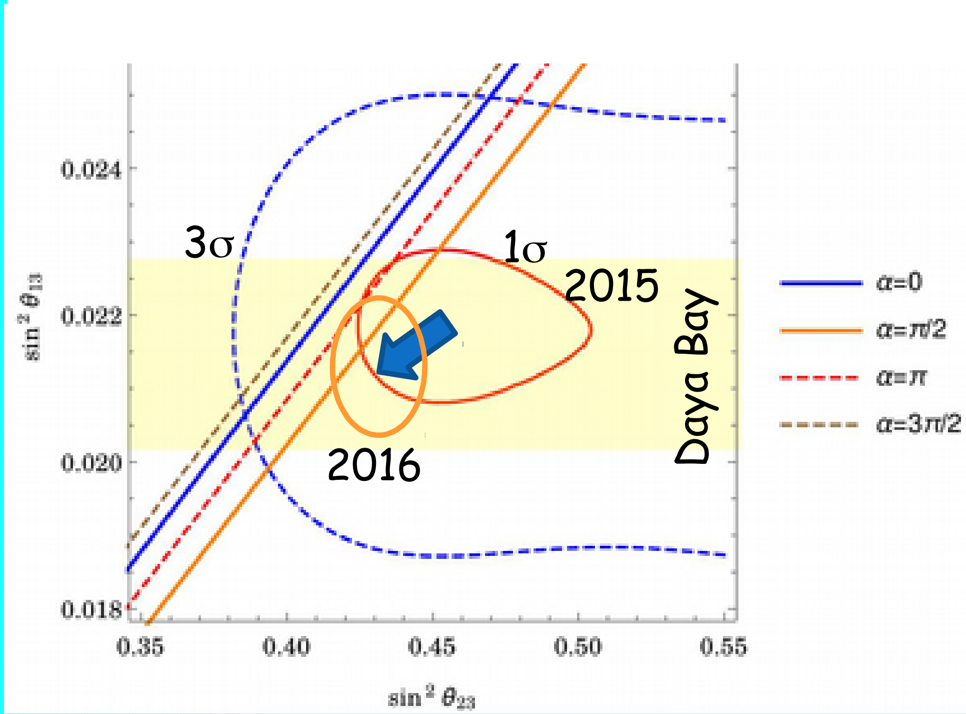
Now more than 3σ off

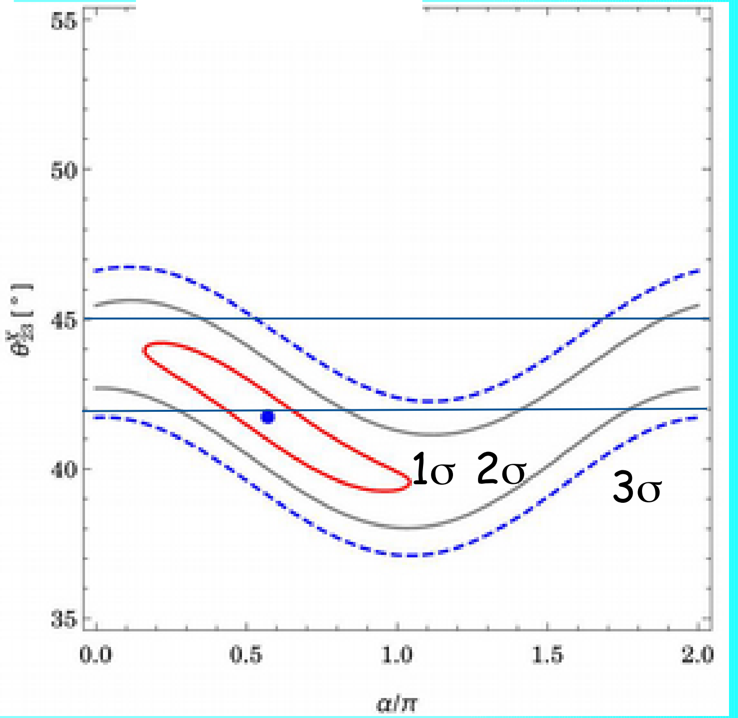
General relation

Normal mass ordering

$\sin^2\theta_{13} = \sin^2\theta_{23} \sin^2\theta_C (1 + O(\lambda^2))$

$\lambda = \sin \theta_C$





Dependence of 1-3 mixing on 2-3 mixing for different values of the phase α. Allowed regions from the global fit NuFIT 2015

Allowed values of parameters of U_X

Best fit value: $\theta^x_{23} = 42^0$

RGE effect from maximal mixing value at high scale

What does this mean?

- Quarks and leptons know about each other,
Q L unification, GUT or/and
Common flavor symmetries

- Some additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the quark and lepton mixing patterns

- Two types of new physics

CKM

Neutrino new physics

Indicates SO(10): no CKM mixing in the first approximation

PMNS & CKM

$$U_{PMNS} = U_{CKM}^{+} U_{X}$$

From the Dirac matrices of charged leptons and neutrinos

Related to mechanism that explains smallness of neutrino mass

New neutrino structure

Two types of new physics ?

M type new physics **Neutrino new physi**

Can be naturally realized in the seesaw type I which after all is the most appealing mechanism of explanation of smallness of neutrino mass

More than usual see-saw?

ale of see-saw

$$M_R = - m_D^T \frac{1}{m_\nu} m_D$$

q – l similarity: $m_D \sim m_q \sim m_l$

for one third generations $M_R \sim 2\ 10^{14}$ GeV

new scale ?

$_R$ - hierarchy

$$M_R = - m_D^{diag} (m_{TBM})^{-1} m_D^{diag}$$

Quadratic hierarchy

avor structure

Difficult to reproduce

Can be explained in the framework of double seesaw

Double Seesaw

R.N. Mohapatra
J. Valle

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & M_S \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$M_S >> M_D$

M_S - scale of B-L violation

RH neutrinos get mass via see-saw

$$M_R = M_D^T M_S^{-1} M_D$$

This explains

1. strong mass hierarchy $M_D \sim m_D$ and M_S has no strong hierarchy
2. intermediate scale of masses if $M_S \sim M_{Pl}$, $M_D \sim M_{GU}$
3. Flavor structure:

$$m_\nu = m_D^T M_D^{-1T} M_S M_D^{-1} m_D$$

if $m_D = A\ M_D$ ⇒ $m_\nu \sim M_S$

Screening of the Dirac structure

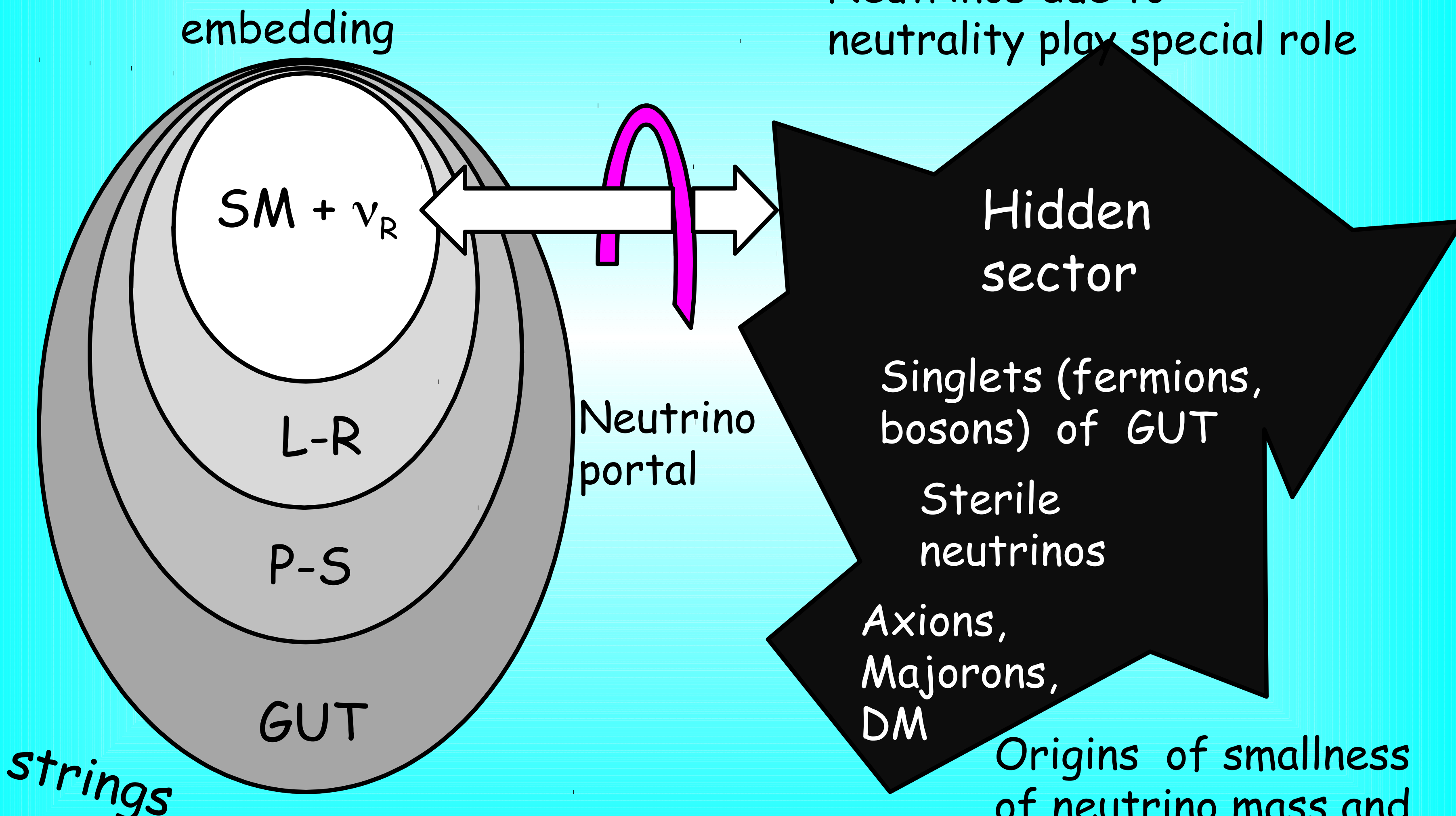
may have certain symmetries

A.Y.S
M. Lindner, M.A. Schmidt
A.Y.S

Setup

S – from the Hidden sector?

Neutrinos due to neutrality play special role

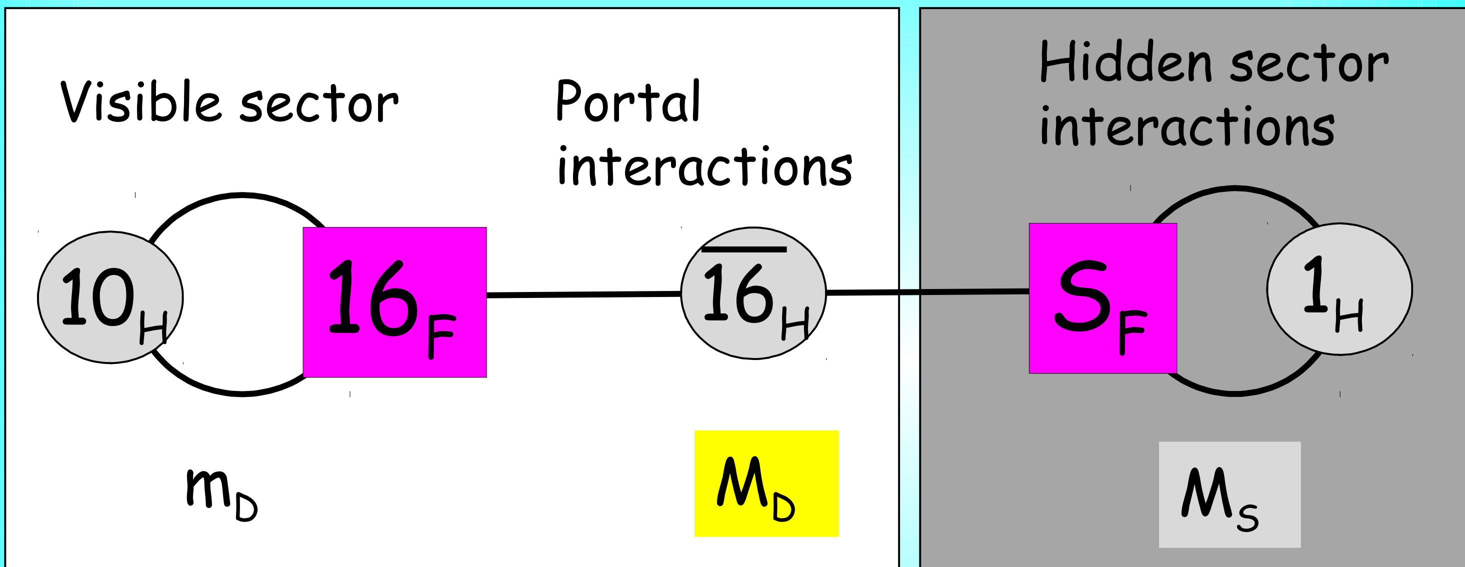


Origins of smallness of neutrino mass and large (maximal mixing)

Yukawa interactions

Patrick Ludl, A.S
1507.03494 [hep-ph]

SO(10)



$Y_{ij}\ 16_F^{\,i}\ 16_F^{\,j}\ 10_H^{\,u}$

$Y_{ij}'\ 16_F^{\,i}\ S^j\ \overline{16}_H$

$h_{ijk}\ S^i\ S^j\ 1_H^{\,k}$

$Y \sim y\,(\langle\phi\rangle/\Lambda)^n$

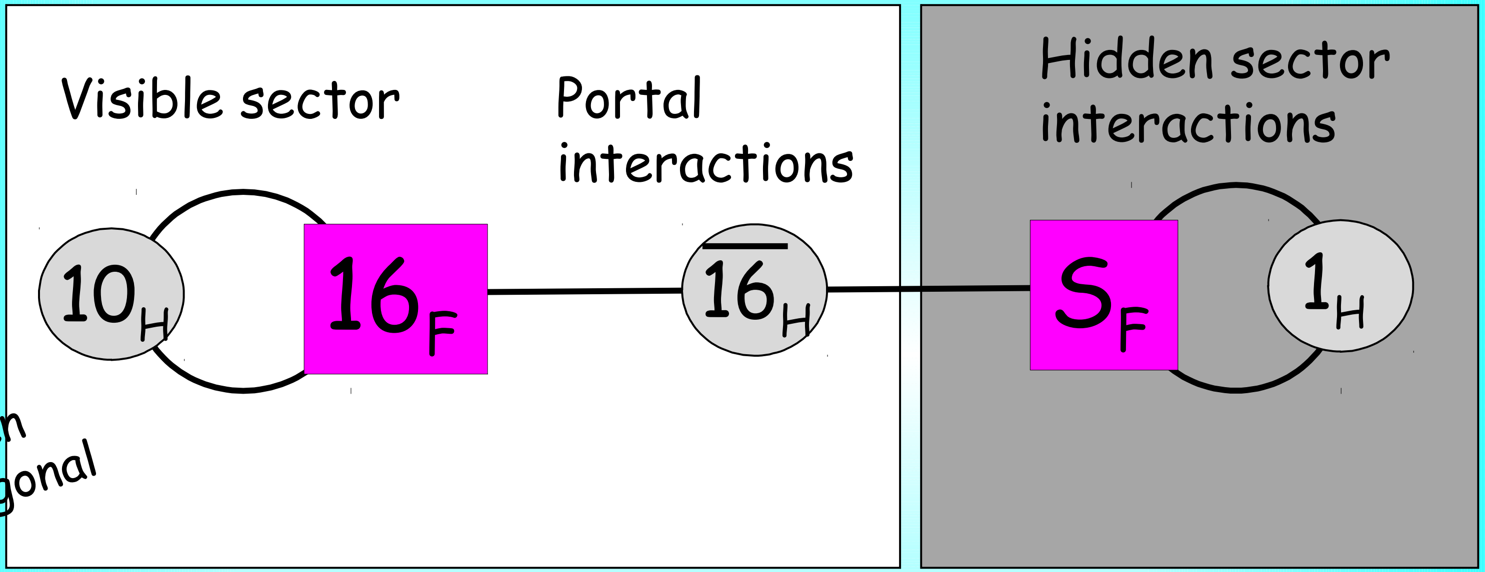
For third generation: n = 0, the mass is generated at the renormalizable level

Second Higgs 10-plet should be introduced to produce the CKM mixing

Intrinsic symmetries

C.S.Lam
1403.7835 [hep-ph]
B. Bajc, AS
1507.03494 [hep-ph]

of SO(10)



better seen in the diagonal basis

$Y_{ii}\ 16_F^i\ 16_F^i\ 10_H^u$

$[\ Z_2\ ]^3$

$16_F^i \rightarrow -16_F^i$

$Y_{jj}'\ 16_F^j\ S^j\ \overline{16}_H$

$[\ U(1)\ ]^3$

$h_{ijk}\ S^i\ S^j\ 1_H^k$

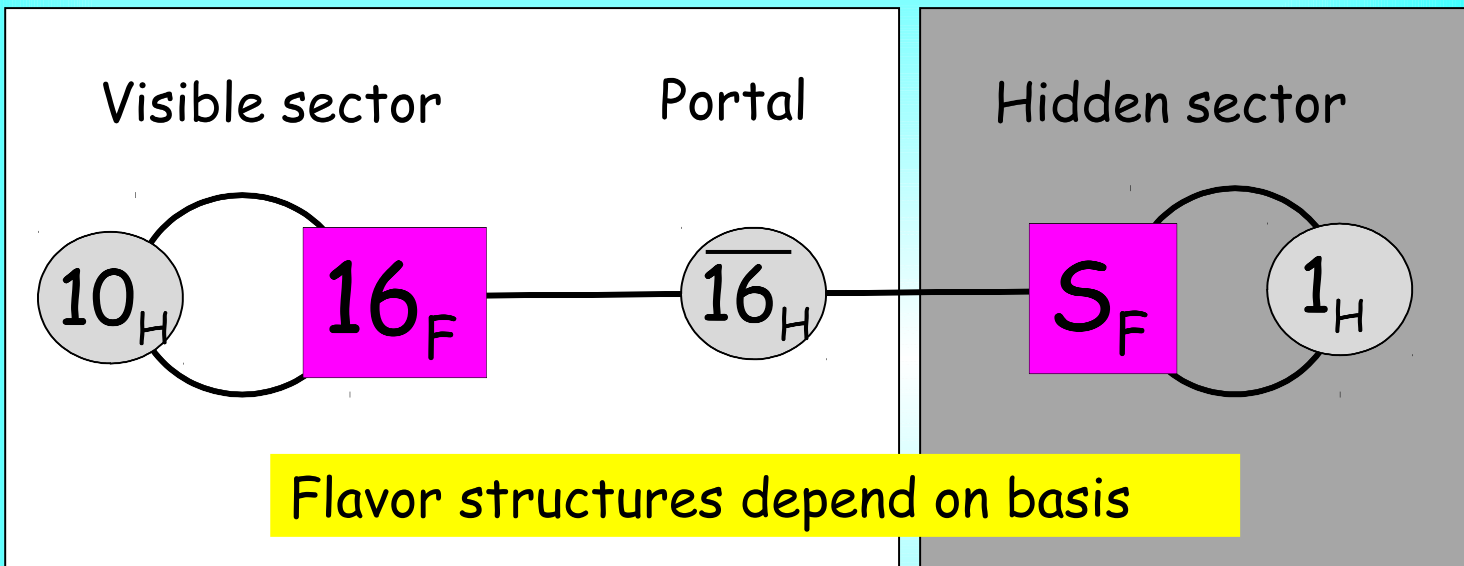
$[\ Z_2\ ]^3$

For the mass matrix in the diagonal basis

munication to the Hidden world

Patrick Ludl, A.S
1507.03494 [hep-ph]

Information about flavor structures in the hidden sector should be communicated (transferred) to the observable sector



Minimal way – to communicate info about bases we use in the Hidden (S) and visible sectors (16)

Introduce the same basis symmetry for F and S and prescribe certain charges for them

G_{basis}

$$G_{basis} = G_{intrinsic} = Z_2 \times Z_2$$

(subgroup)

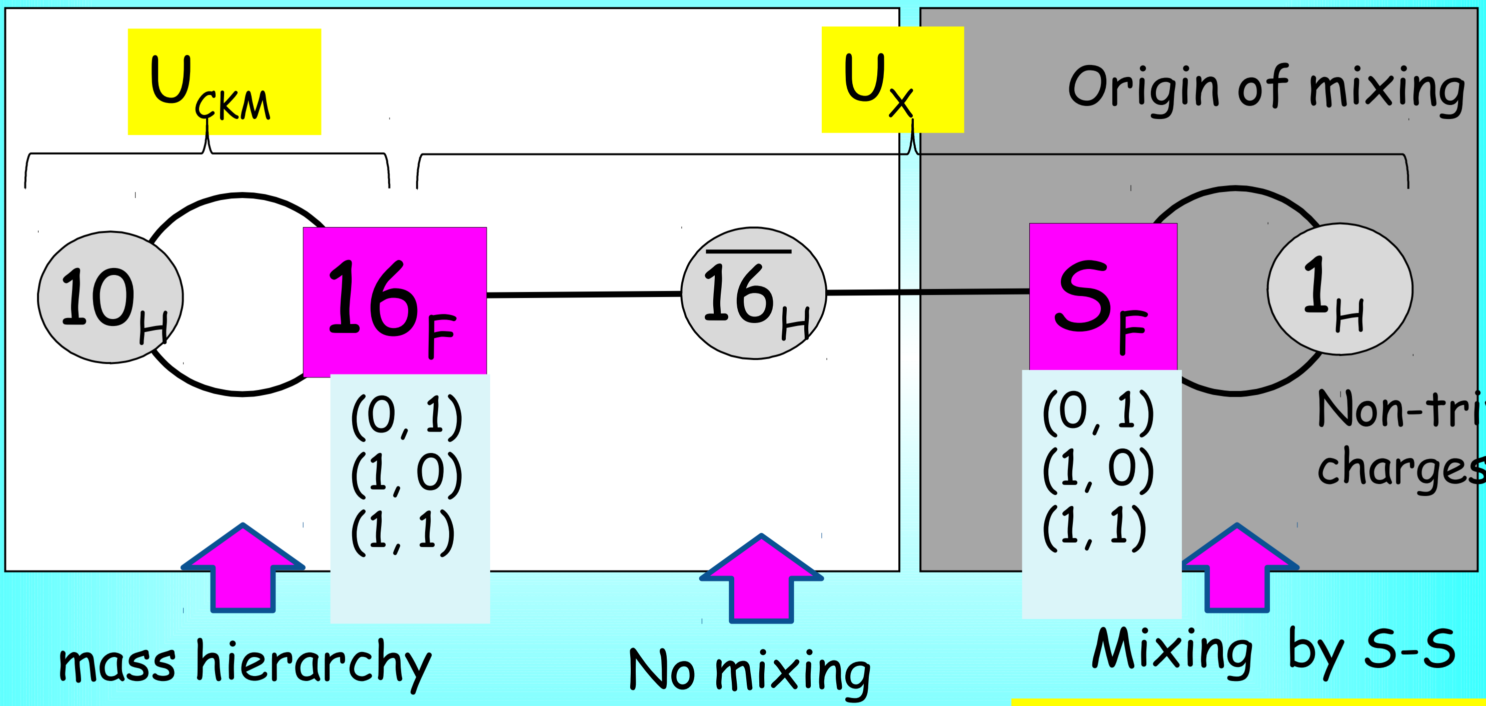
Scheme

Patrick Ludl, A.S
arXiv:1507.03494 [hep-ph]

SO(10)

with basis symmetry $Z_2 \times Z_2$

$Z_2 \times Z_2$



due to non-trivial $Z_2 \times Z_2$ charges of 1_H

CKM mixing - additional structures

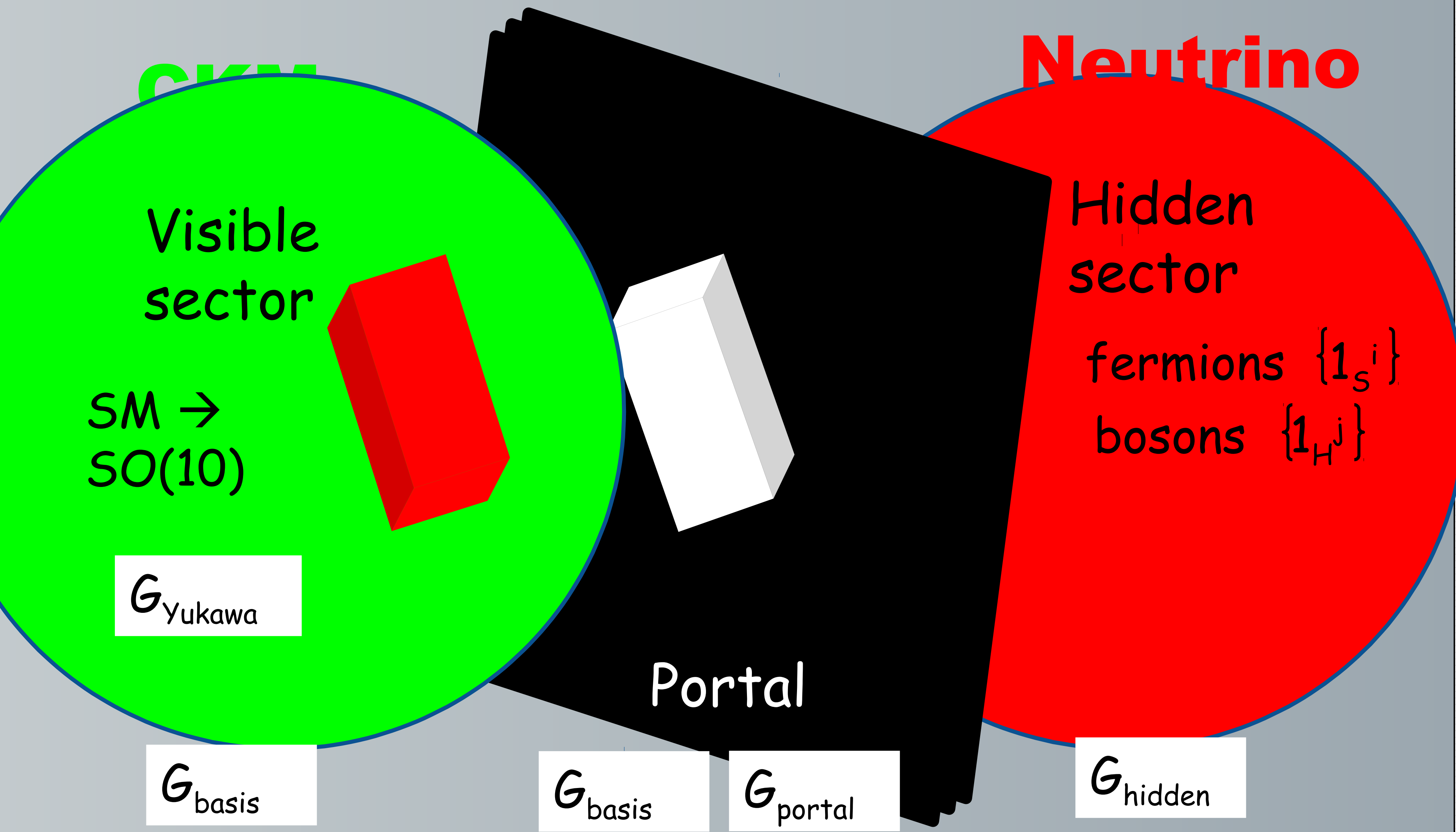
$m_D \sim M_D$ = diag

$M_X = d^T M_S d$

M_S ~ non-diagonal, can be further structured by additional hidden symmetries

Symmetries and set-up

Patrick Ludl A.S



How to test?

Hopeless?

Further precise measurements of the 1-3 and 2-3 mixings (octant)

Nothing should be observed at LHC which is responsible for neutrino masses

If something is observed against (excludes) framework

Proton decay

Special value of CP-phases

Light sterile neutrinos

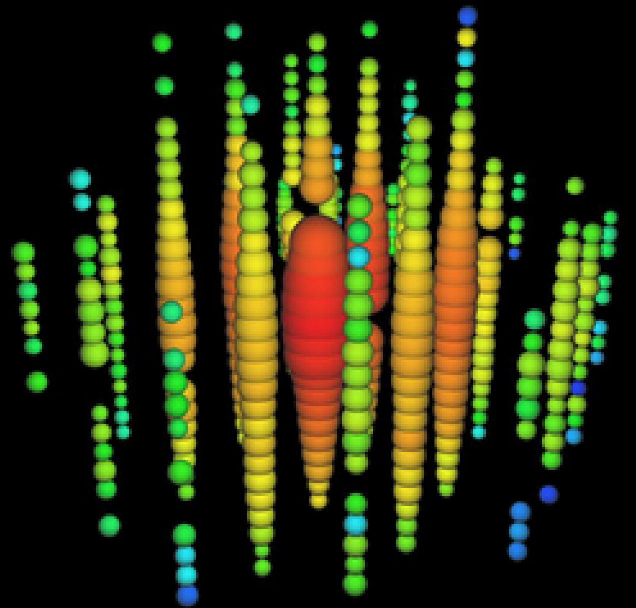
Dark matter

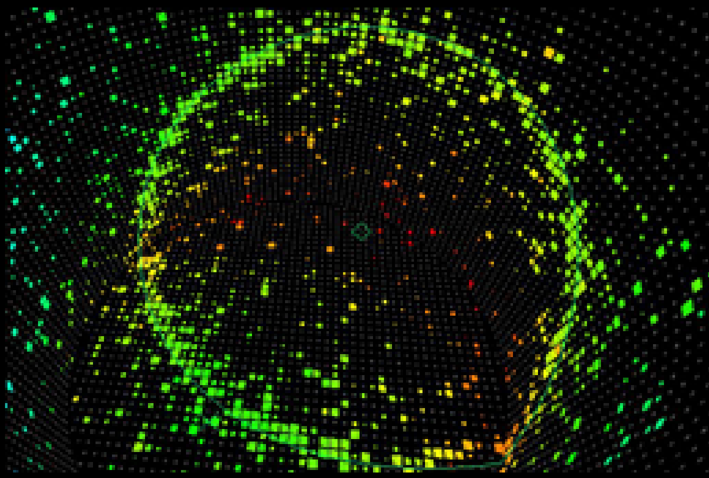
May or may not help

Inflation

Leptogenesis

Framework





In general

Take

1) whole V_{CKM} with small elements V_{td}, V_{cb}, etc.
   → this will give also corrections to 2-3 mixing
2) non-maximal rotation $U_{23}(\theta^x_{23})$:

$$U_X = \Gamma(\alpha)\, U_{23}(\theta^x_{23})\, U_{12}(\theta^x_{12}) \qquad \Gamma(\alpha) = \mathrm{diag}(1, 1, e^{i\alpha})$$

$$\sin^2\theta_{13} = \sin^2\theta^x_{23} \sin^2\theta_C \left[1 - 2\cot\theta^x_{23} \cos(\alpha - \phi_{td})\, |V_{td}|/|V_{cd}|\right]$$

where $\phi_{td} = \mathrm{Arg}\, V_{td}$

In Wolfenstein parametrization

$$\sin^2\theta_{13} = \sin^2\theta^x_{23}\, \lambda^2 \left[1 - 2A\lambda^2[(1-\rho)^2 + \eta^2]^{1/2} \cot\theta^x_{23} \cos(\alpha - \phi_{td})\right]$$

$$\tan^2\theta_{23} = \tan^2\theta^x_{23}\, (1 - \lambda^2) \left[1 - 2A\lambda^2 \sin^{-1} 2\theta^x_{23} \cos\alpha\right]$$

$$\tan^2\theta_{23} = \tan^2\theta^x_{23}\, \kappa(\alpha) \qquad \kappa = (1 - \lambda^2)\left[1 - 4A\lambda^2 \cos\alpha\right]$$

Excluding θ^x_{23} $\quad \sin^2\theta_{13} = f(\theta_{23}, \alpha)$

Hidden sector

singlet of the SM
symmetry group,
also invisible

Populated
by new

fermions – sterile neutrinos, etc
scalar bosons – axions, majorons, flavons

Gauge bosons - dark photons, etc,

Fill in

The Dark universe

DM
DE
BAU

Responsible for

Anomalies

LSND/MiniBooNE
Reactor
Gallum
3.5 keV line?

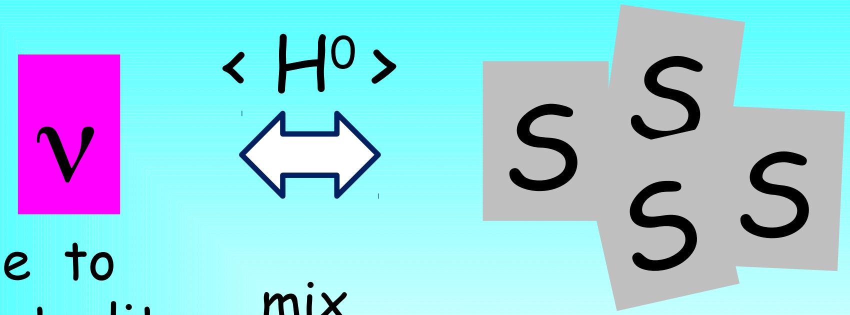
explains

Neutrino masses and mixing

It looks like,
The Problems are in the Visible sector
Solutions - in the Hidden one

Neutrino portal

Neutrinos are special
providing a portal
to the Hidden sector



due to
neutrality

mix

Fermions from
Hidden sector

Mixing due to
interaction with
Higgs field

Through this mixing

Neutrinos can get mass

Observed pattern of lepton mixing, difference from
The quark mixing can be produced

Hidden sector can be probed provide window

Particles fron the Hidden sector can decay/
transform to particles of the visible sector

Neutrino Portal

$L = \begin{pmatrix} \nu \\ e \end{pmatrix}$

$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

LH

$\overline{} \sim$

(LH)

Singlet of SM symmetry group SU(3)xSU(2) XU(1)

ν_R

S

F

$$\frac{1}{\Lambda^{n(F)\ -\ 3/2}}\ L\ H\ F$$

F is composite fermionic operator

singlet of symmetry group of hidden sector

Non-local interactions

Interactions which violated fundamental symmetries

In GUT

$(\bar{5}_F\ 5_H)$ in SU(5)

$(16_F\ \overline{16}_H)$ in SO(10)

P-phase and the framework

$U_{PMNS} \sim V_{CKM}^{+} U_X$

If the only source of CP violation

No CPV

B. Dasgupta, A.S.

$\sin\theta_{13} \sin \delta_{CP} = (-\cos \theta_{23}) \sin\theta_{13}^{q} \sin\delta_{q}$

λ λ^3

$\delta_q = 1.2$ +/- 0.08 rad

$\sin \delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2 \sim 0.046$

$\delta_{CP} \sim -\delta$ or $\pi + \delta$

where $\delta = (s_{13}^{q}/s_{13})\, c_{23} \sin \delta_q$

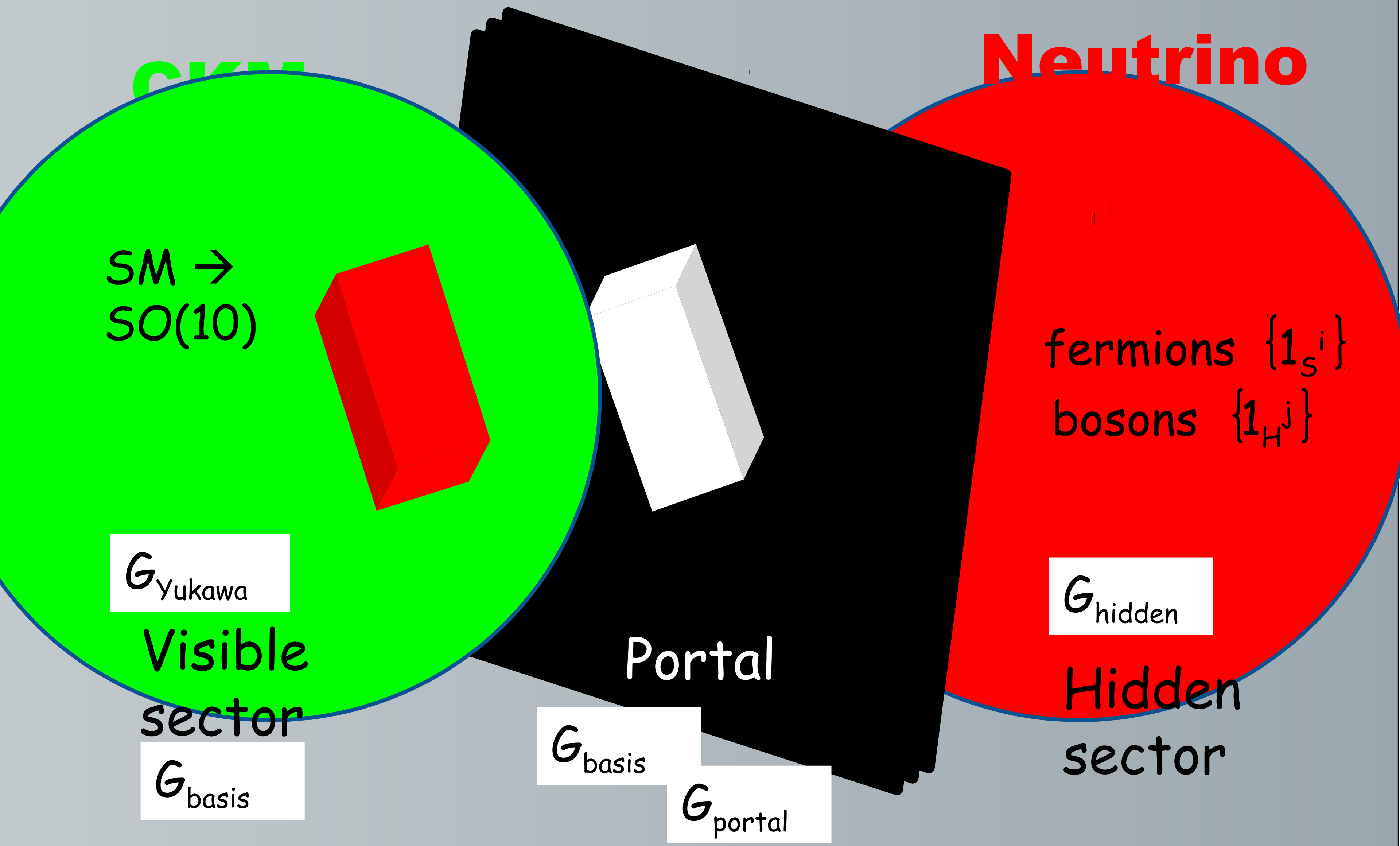
Implications

If the phase δ_{CP} deviates substantially from 0 or π, new sources of CPV beyond CKM

New sources may have specific symmetries which lead to particular values of δ_{CP} e.g. $-\pi/2$

Set-up

Patrick Ludl A.S

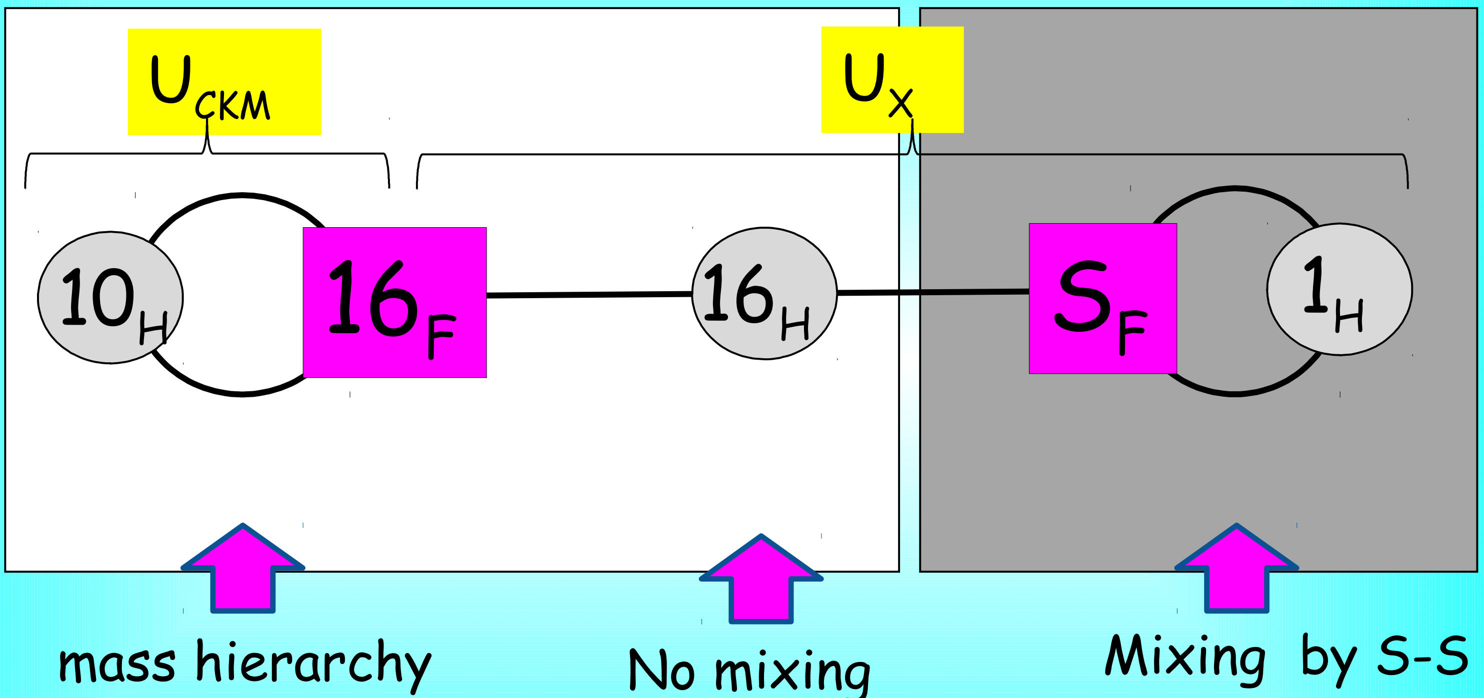


Framework

Patrick Ludl A.S

SO(10)

$M_X = d^T M_S d$



CKM mixing – independently with additional structures

$m_D \sim M_D = \mathrm{diag}$

$d \sim I$

$$M_S \sim \begin{pmatrix} a & b & b \\ \dots & c & d \\ \dots & \dots & c \end{pmatrix}$$

Yukawa interactions

$m_D^l = m_D$

F-F	Visible sector	$Y_{ij}\ 16_F^i\ 16_F^j\ 10_H^u$	m_D
F-S	Portal interactions	$Y_{ij}'\ 16_F^i\ 1_S^j\ 16_H$	M_D
S-S	Hidden sector interactions	$h_{ijk}\ 1_S^i\ 1_S^j\ 1_H^k$	M_S

In general $Y \sim y\ (\langle\phi\rangle / \Lambda)^n$

For third generation: $n = 0$, i.e. the mass is generated at the renormalizable level

No mixing is generated by F-F at this level

Allow to separate CKM and Neutrino new physics

Basis-fixing symmetry

Although mixing is not generated, masses are generated by the F-F term

Information about states with definite masses
should be communicated to the Hidden sector

For this - symmetry which
- distinguishes three 16-plets, and
- makes the F-F interactions diagonal

G_{basis}

The smallest group is $G_{basis} = Z_2 \times Z_2$

with charge assignment (1, 0), (0,1), (0,0) ⇐ powers of $e^{i\pi}$

matrix of charges
of F-F couplings

$$\begin{pmatrix} (0,0), & (1,1), & (1,0) \\ (1,1), & (0,0), & (0,1) \\ (1,0), & (0.1), & (0.0) \end{pmatrix}$$

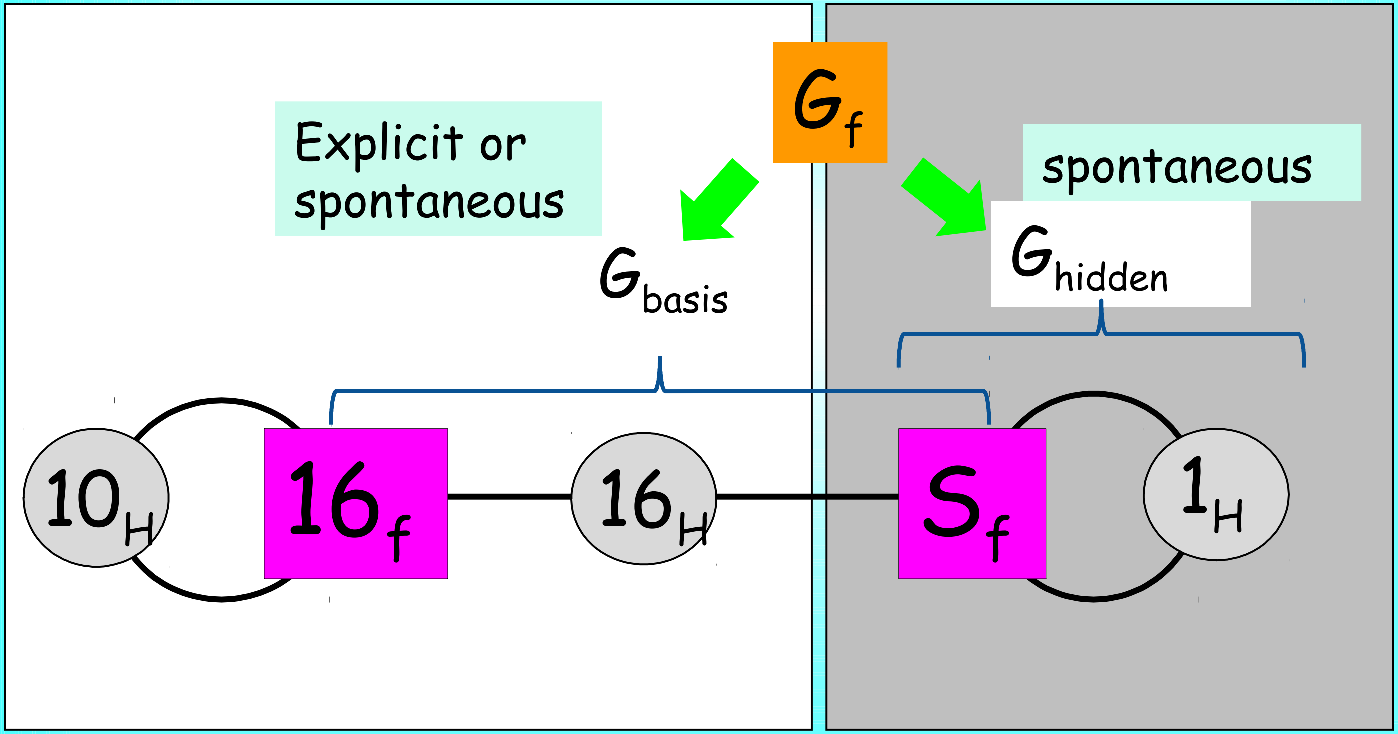
Both distinguishes states and
makes couplings diagonal

assignment

(1, 0), (0,1), (1,1) with 3 nontrivial charges fixes number of generations

Non-Abelian hidden symmetry

S_F as mediators

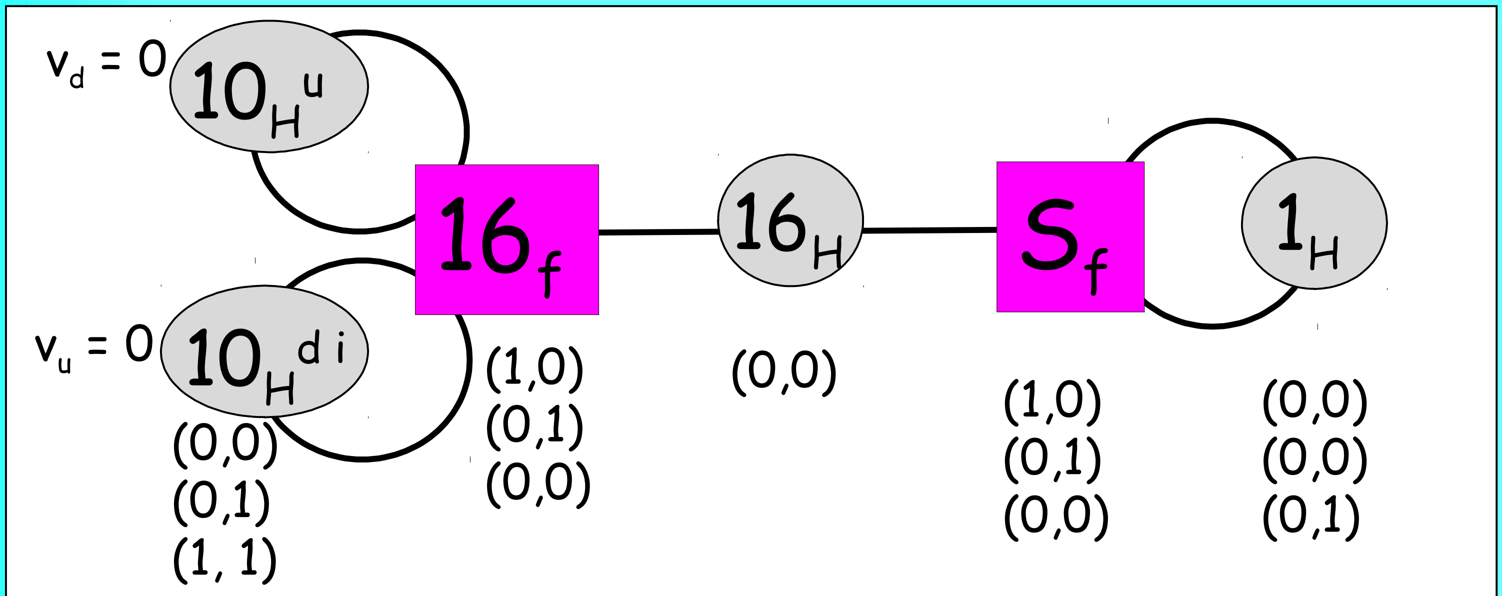


$G_f = A_4 \times Z_2$

$G_{basis} = Z_2 \times Z_2$

CKM mixing

Patrick Ludl A.S



$Z_2 \times Z_2$

Spontaneous breaking of $Z_2 \times Z_2$

(0, 0)	(1,1)	(1,0)
(1, 1)	(0,0)	(0,1)
(1, 0)	(0.1)	(0.0)

Alternatively: additional higgs singlets 1_ξ^i with $Z'_2 = -1$

$10_H^{di} \rightarrow 10_H^{d} (1_\xi^i/\Lambda)$

additional $G'_{aux} = Z'_2$ distinguishes two ten-plets

CKM physics

includes

- hierarchy of Yukawas Y_i , Y'_i
- CKM mixing
- difference of masses of upper and down quarks
- difference of masses of down quarks and charged leptons

Related to breaking of SO(10)

Framework allows to disentangle the CKM physics and neutrino physics

Hierarchy of masses

due to hierarchy of couplings: $Y_1 \ll Y_2 \ll Y_3$, $Y'_1 \ll Y'_2 \ll Y'_3$

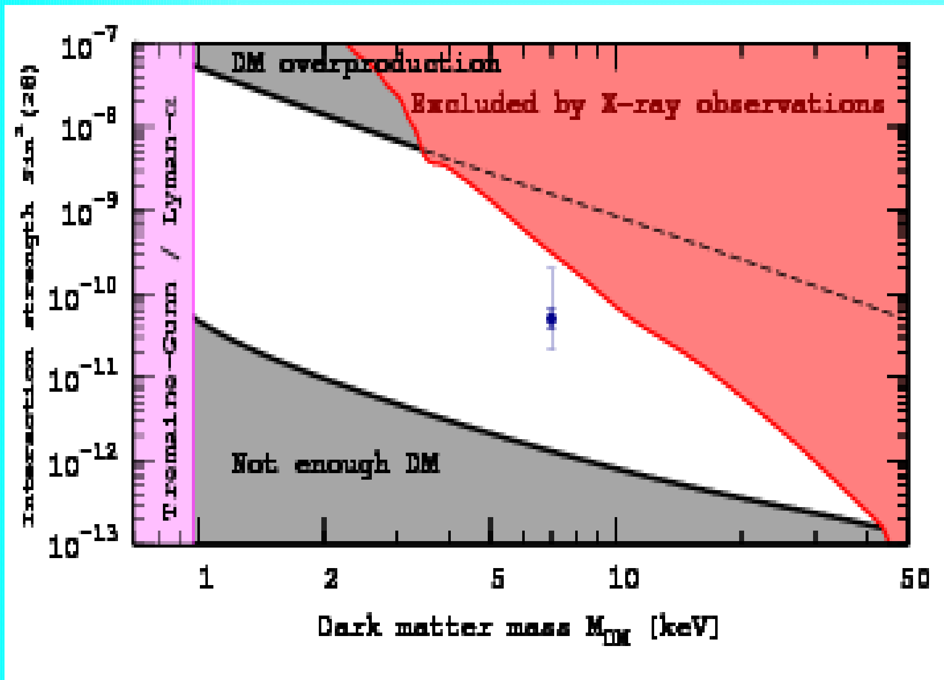
→ in turn, due to operators of different order:

3rd generation renormalizable coupling with , $Y_3 = 1$, $Y'_3 = 1$

2nd generation: $Y \sim y\, (\langle\phi\rangle / \Lambda)$

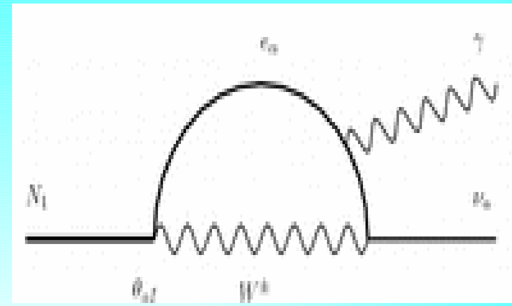
1st generation: $Y \sim y\, (\langle\phi\rangle / \Lambda)^2$

WDM from Hidden sector



The blue point: the best-fit value from M31 (Andromeda galaxy). Thick error bars are $\pm 1\sigma$ limits on the flux. Thin error bars correspond to the uncertainty in the DM distribution in the center of M31.

A Boyarsky et al, 1402.4119



→ $\theta_{aS}^2 \sim 2\ 10^{-11}$

$\delta m \sim \theta_{aS}^2\, m_S \sim (1 - 2)\ 10^{-7}$ eV

- below any relevant scale in the neutrino mass matrix ~ 10^{-3} eV

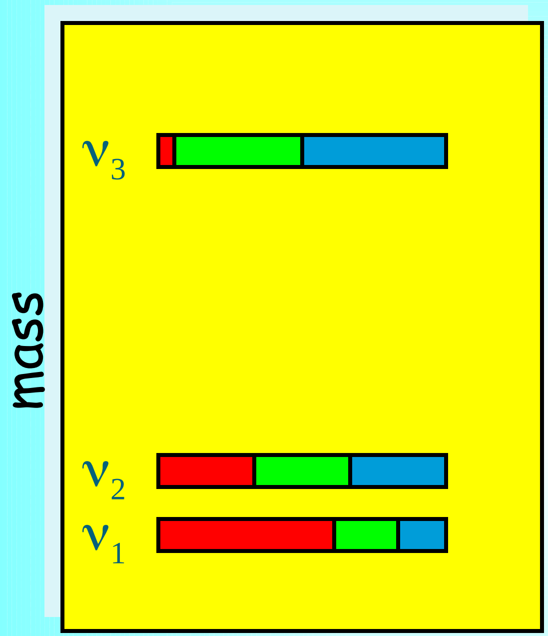
→ does not participate in neutrino mass generation

→ is not RH, but some singlet from HS beside 3 ν_R

→ high mass scales are involved

Leptons versus quarks

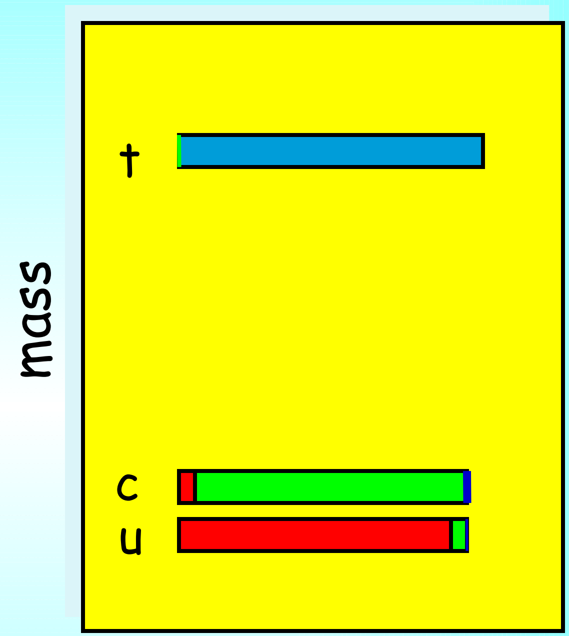
special



Leptons

$\nu_f = U_{PMNS}\, \nu_{mass}$

normal



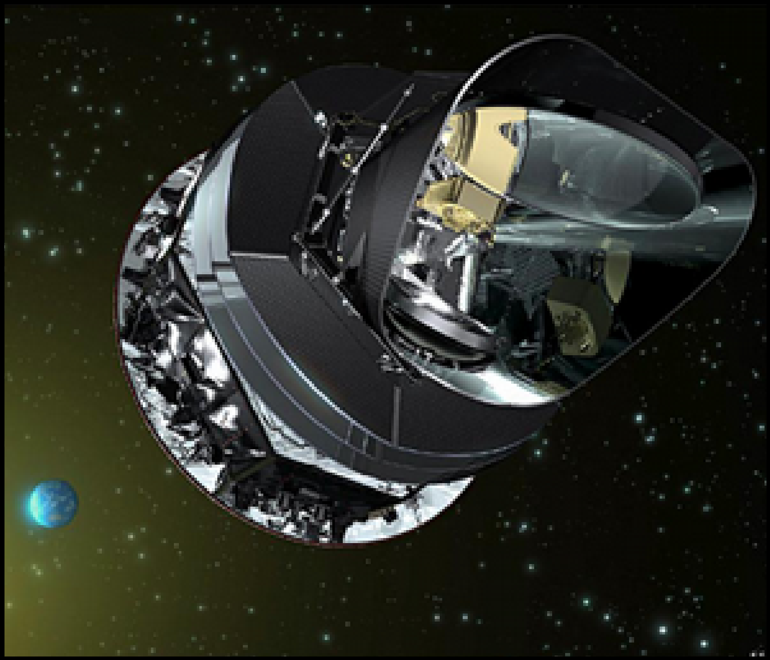
Quarks

$U_d = V_{CKM}^{+}\, U$

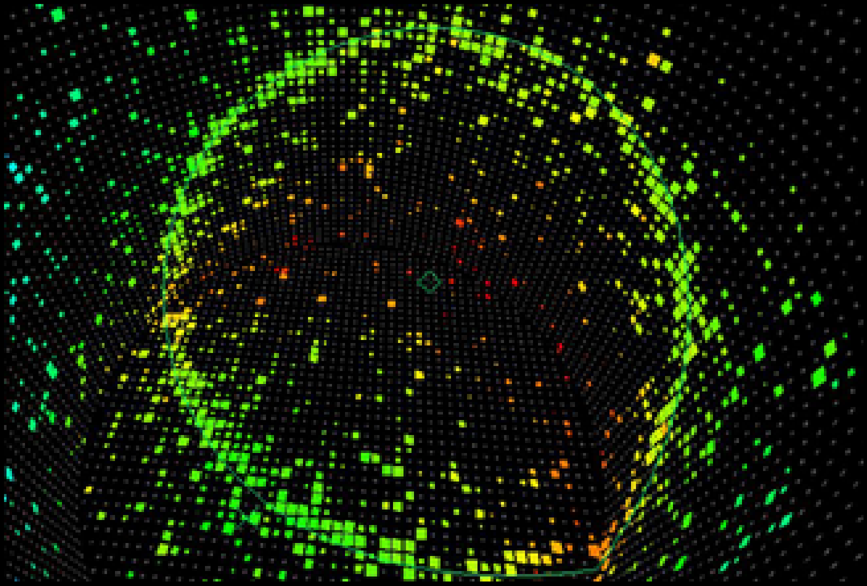
$U = (u, c, t)$

combination of down-quarks
produced with a given up quark

Three neutrino paradigm



Cosmic neutrinos and Supernova



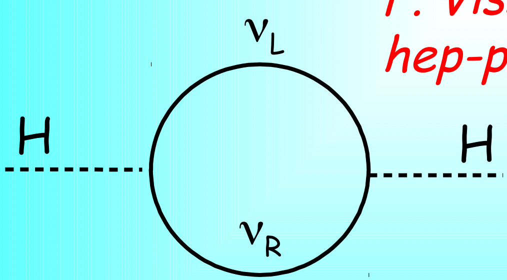
High scale line: the problem

Simplest seesaw implies new physical scale

$M_R \sim m_D^2 / m_\nu \sim 10^{14}$ GeV $\ll M_{Pl}$

(Another indication: unification of gauge couplings)

ν_R



F. Vissani hep-ph/9709409

J Elias-Miro et al, 1112.3022 [hep-ph]

$$\delta m_H^2 \sim \frac{y^2}{(2\pi)^2} M_R^2 \log(q/M_R)$$

$$\sim \frac{M_R^3 m_\nu}{(2\pi v)^2} \log(q/M_R)$$

New physics below Planck scale

$M_R < 10^7$ GeV

Small Yukawas, Leptogenesis ?

M. Fabbrichesi

Cancellation?

"Partial" SUSY?

1-3 mixing: Normal?

``Naturalness" : absence of fine tuning of mass matrix

Connecting solar and atmospheric neutrino sectors

$$\sin^2\theta_{13} = O(1)\,\frac{\Delta m_{21}^2}{\Delta m_{32}^2}$$

0.75

E. K. Akhmedov, G.C. Branco, M.N. Rebelo Phys.Rev.Lett. 84 (2000) 3535, [hep-ph/9912205]

Very small 1-3 mixing would be something special (symmetry)

Yet another "normal" relation:

almost the same relation in the quark and lepton sectors

$$\sin^2\theta_{13} = C \sin^2\theta_{12}\sin^2\theta_{23}$$

K. Patel, A. Y. S.

C_q = 0.380 +/- 0.020 C_l = 0.407 +/- 0.033

→ Similar structure of the mass matrices
Abelian symmetry

Neutrinos - Dark matter

Is the (hot) component of the DM

RH neutrinos as DM particles

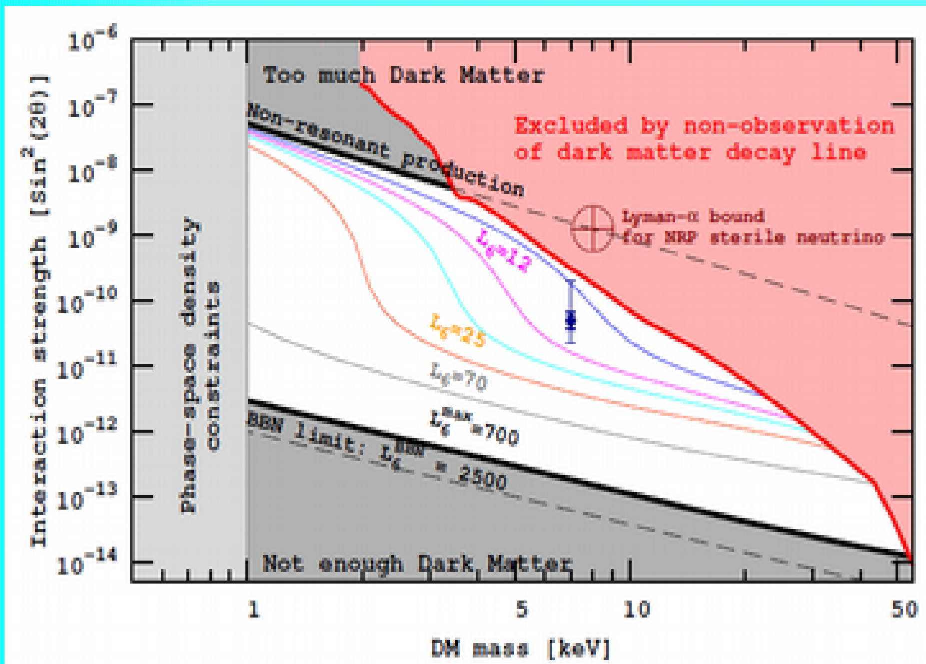
Mechanism of generation of small neutrino masses is related to DM

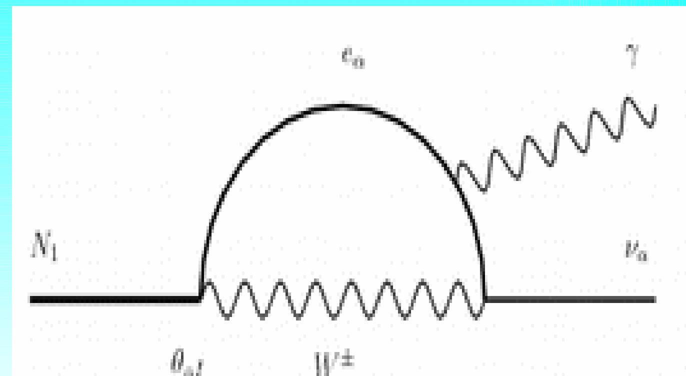
Neutrino portal connects DM and neutrinos

DM particles participate (appear in loops) in generation of neutrino mass

The same symmetry is responsible for smallness of neutrino mass and stability of the DM

WDM sterile neutrino ?





3.5 kev X ray line

$\theta_{aS}^2 \sim 2\ 10^{-11}$

$\delta m \sim \theta_{aS}^2\ m_s \sim (1 - 2)\ 10^{-7}$ eV

→ does not participate in neutrino mass generation

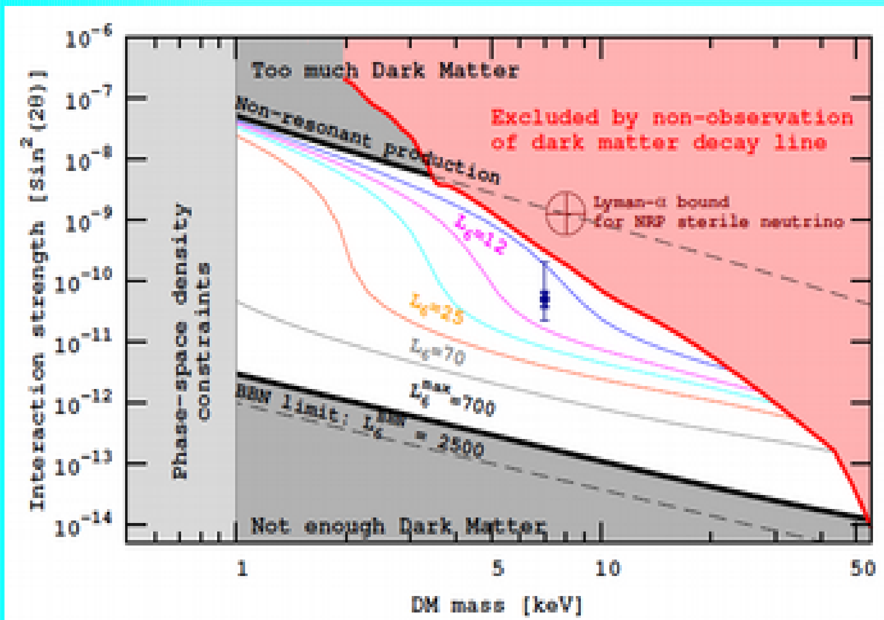
→ is not RH, but some singlet from HS beside 3 ν_R

The blue point: the best-fit value from M31 (Andromeda galaxy). Thick error bars are $\pm 1\sigma$ limits on the flux. Thin error bars correspond to the uncertainty in the DM distribution in the center of M31.

A Boyarsky et al, 1402.4119

WDM sterile neutrino ?

A Boyarsky et al, 1402.4119



3.5 kev X ray line

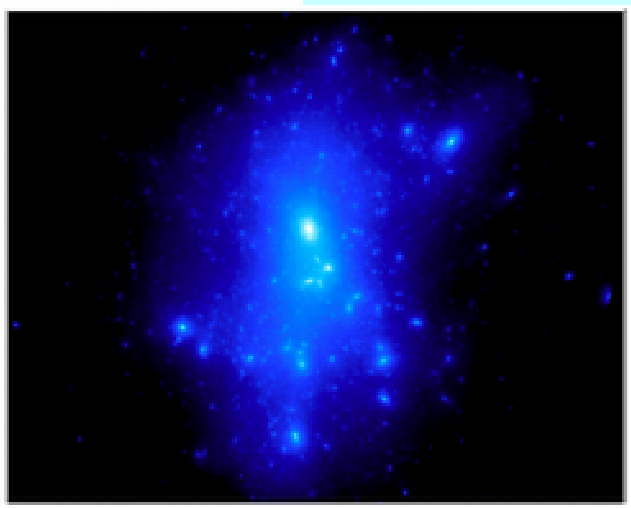
$\theta_{aS}^2 \sim 2\ 10^{-11}$ $m_S \sim 7$ keV

Contribution to active neutrino masses

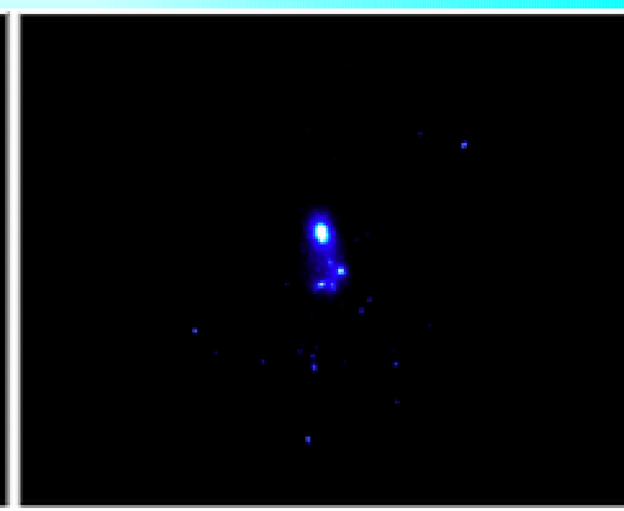
$\delta m \sim \theta_{aS}^2 m_S \sim (1 - 2)\ 10^{-7}$ eV

Too small ν_S is not RH neutrino

Draco dwarf Galaxy:
observations analysis



DM decay signal from a galaxy



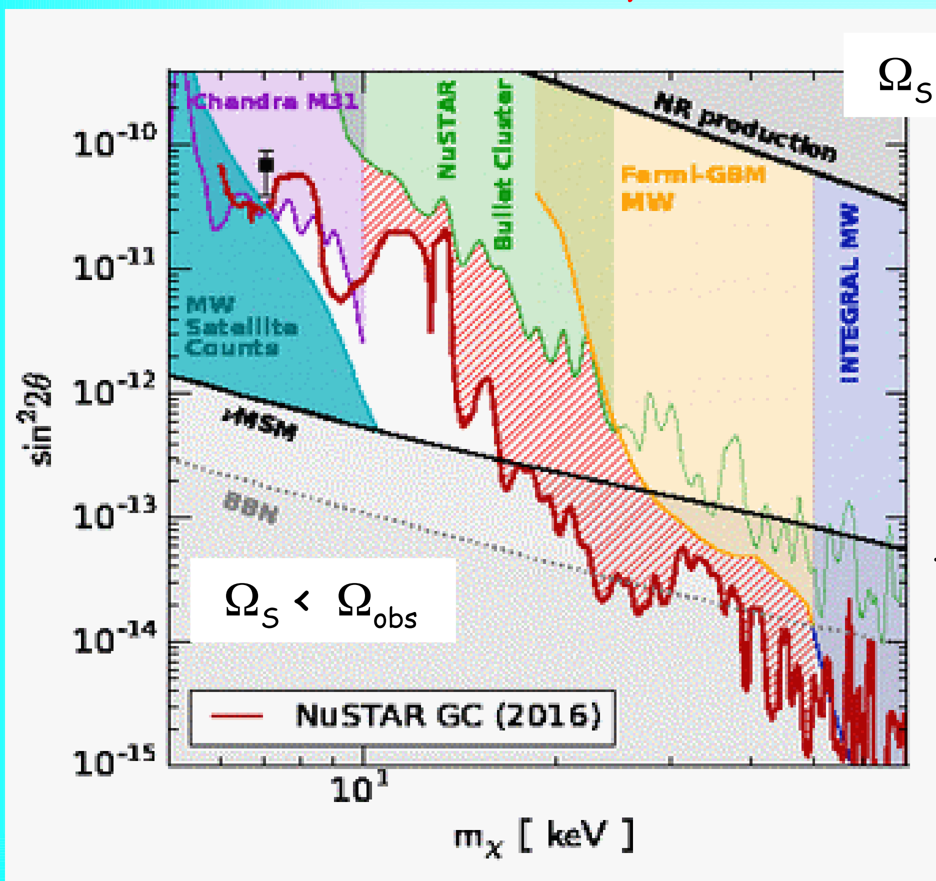
DM annihilation signal from a galaxy

Sterile Neutrinos as Dark matter

(Almost) Closing the Sterile Neutrino Dark Matter Window with NuSTAR

K. Perez, et al.
arXiv:1609.00667 [astro-ph.HE]

Nuclear Spectroscopic Telescope Array, Galactic Center



- zero lepton asymmetry

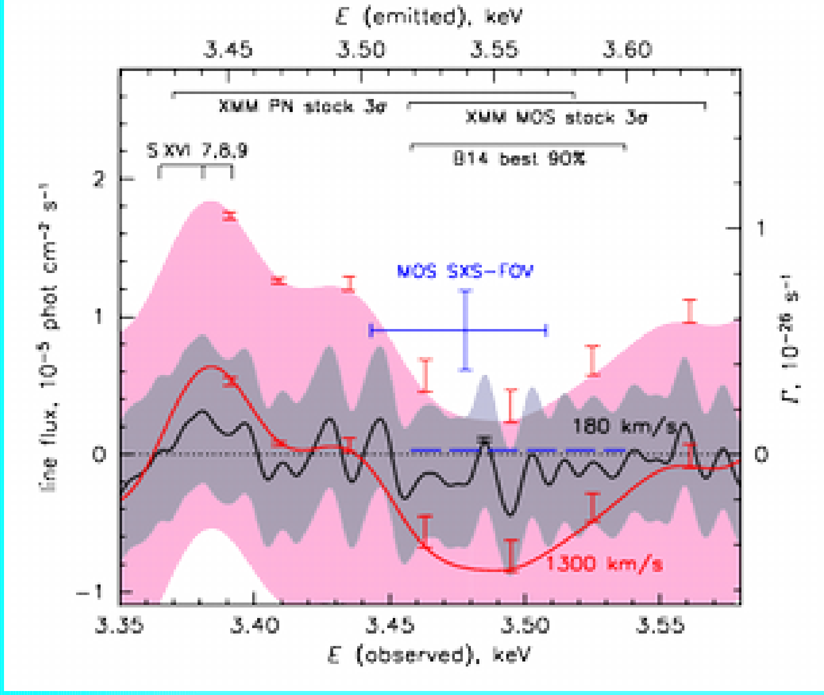
limits from structure formation and astrophysical X-ray observations the colored, regions.

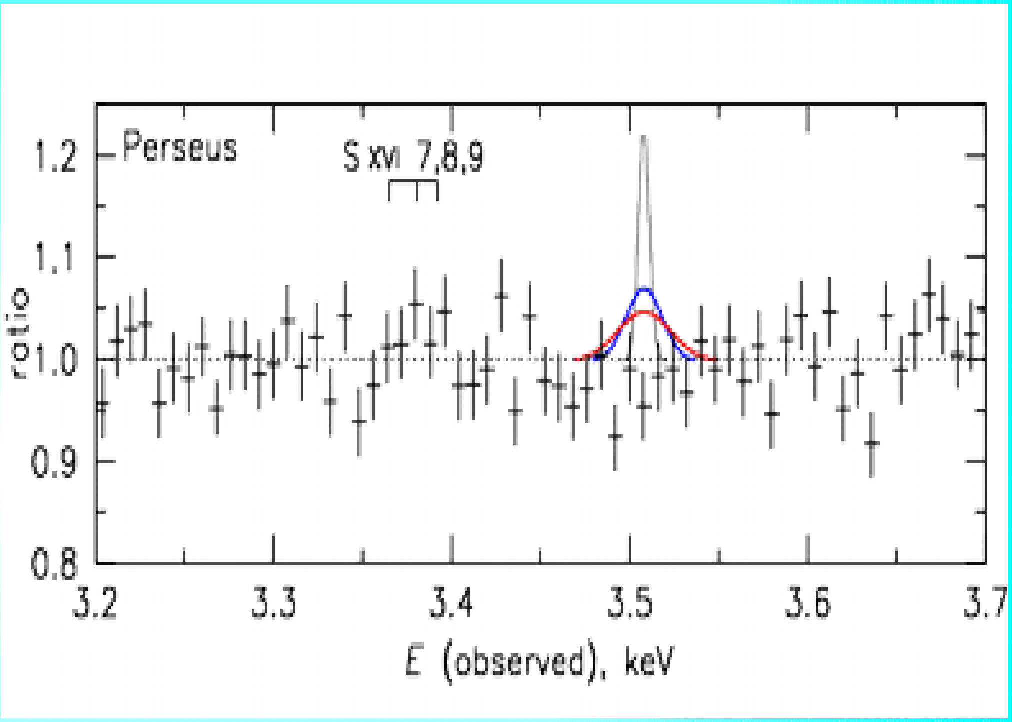
- maximal lepton asymmetry

Hitomi constraints

on the 3.5 keV line in
the Perseus galaxy cluster

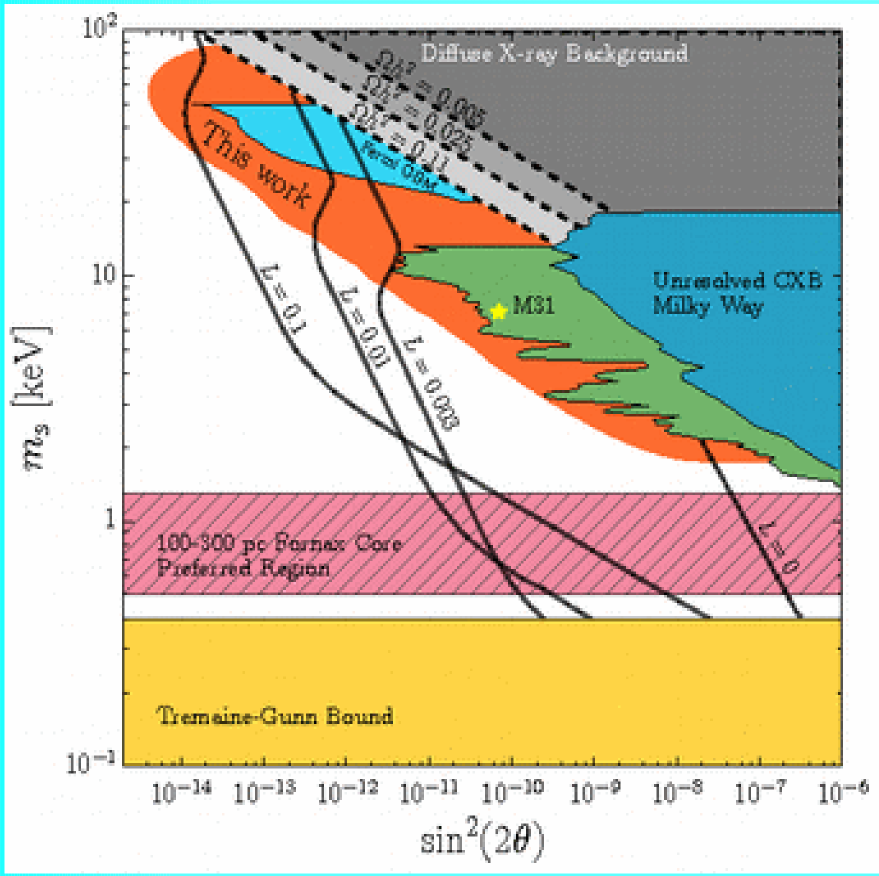
Hitomi Collaboration
(F. Aharonian, et al.)
arXiv:1607.07420 [astro-ph.HE]





Ratio of data to best-fit model .
A line at 3.57 keV (rest-frame) with a flux derived in the SXS FOV is shown with curves of different colors, which denote different l.o.s. velocity dispersions (gray: 180 km/s, blue: 800 km/s, red: 1300 km/s. Position of S feature is marked.

Bounds from Supernova



Supernova bounds on the sterile neutrino parameters from cooling effect $E_S < E^{tot}$

C. A. Argüelles, et al. arXiv:1605.00654 [hep-ph]

Similar bound from SN1987A from the condition that the flux of antinu_e is not suppressed stronger than by factor 10, otherwise no signal could be observe

S.P. Mikheev, A.Yu. S. JETP Lett. 46 (1987) 10-14

dification of the production mechani

via decay

$\phi \rightarrow S + S$

$y \supset\supset \varphi + \wedge H^{+} H \phi \phi$

$y\ ,\ \lambda \sim 10^{-8}$

A.Merle, NOW2016

decreasing mixing

A Berlin, D. Hooper, 1610.03849

"axion assisted ...

Large mixing in earlier epoch during production of S

Small mixing later, to suppress X ray production

$$g_a \frac{a}{f_a} S\, LH + \frac{1}{2} m_S\, SS \quad \Rightarrow \quad \sin^2 2\theta \sim \frac{g_a^{\,2}\, v^2 \rho_a}{m_S}$$

a - axion

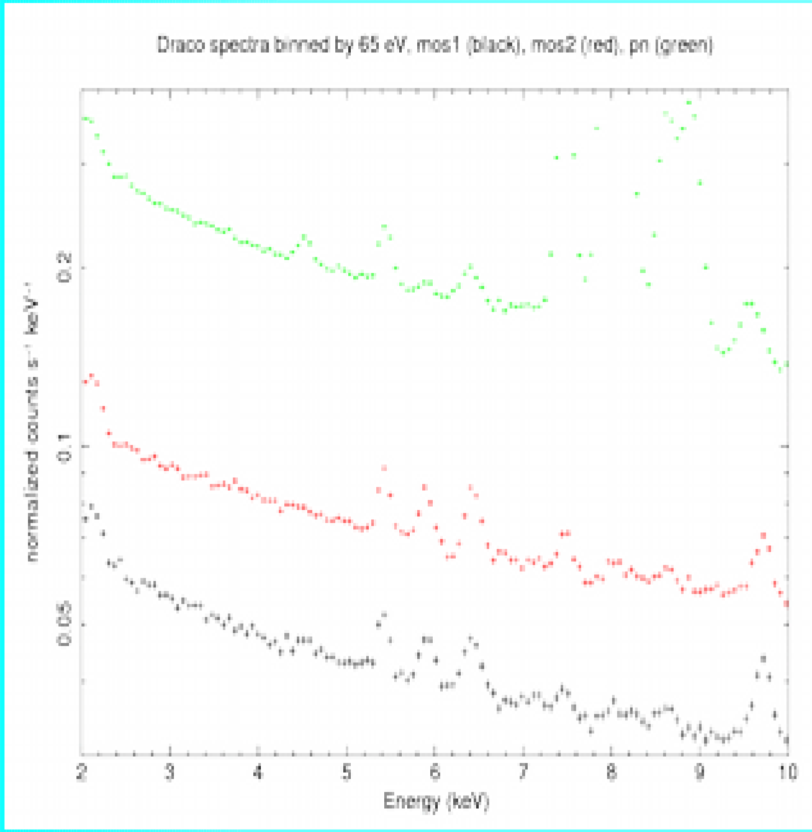
$f_a \sim 10^9$ GeV - scale of PQ symmetry breaking

$g_a \sim 10^{-9}$

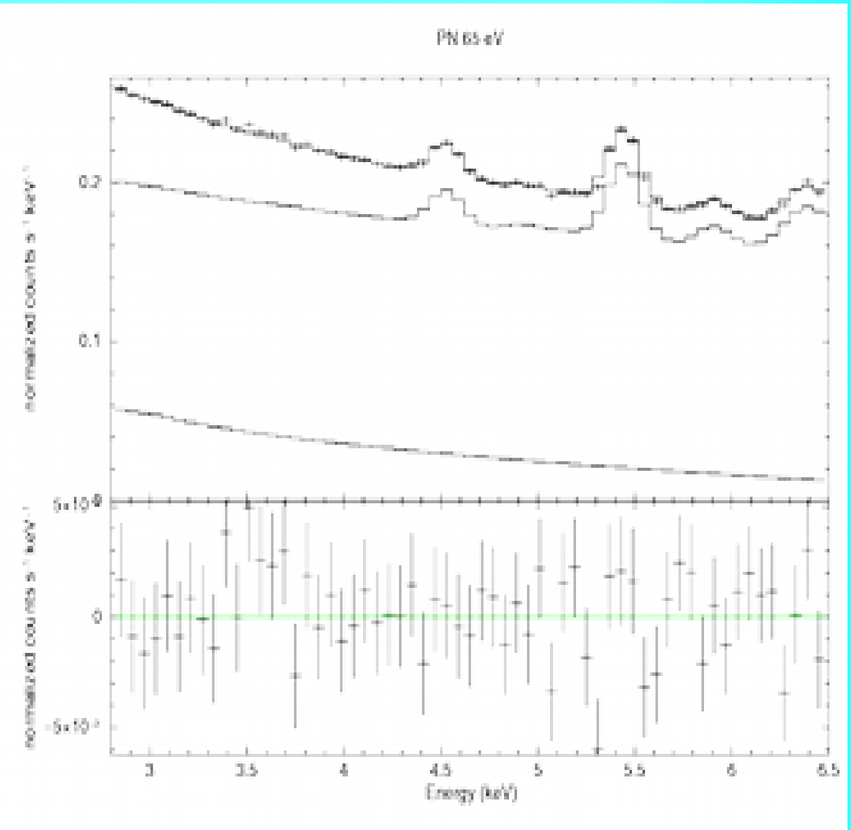
ρ_a - axion energy density decreases with expansion of the Universe

3.5 kev γ–line

O. Ruchayskiy et al,
1512.07217 [astro-ph.HE]



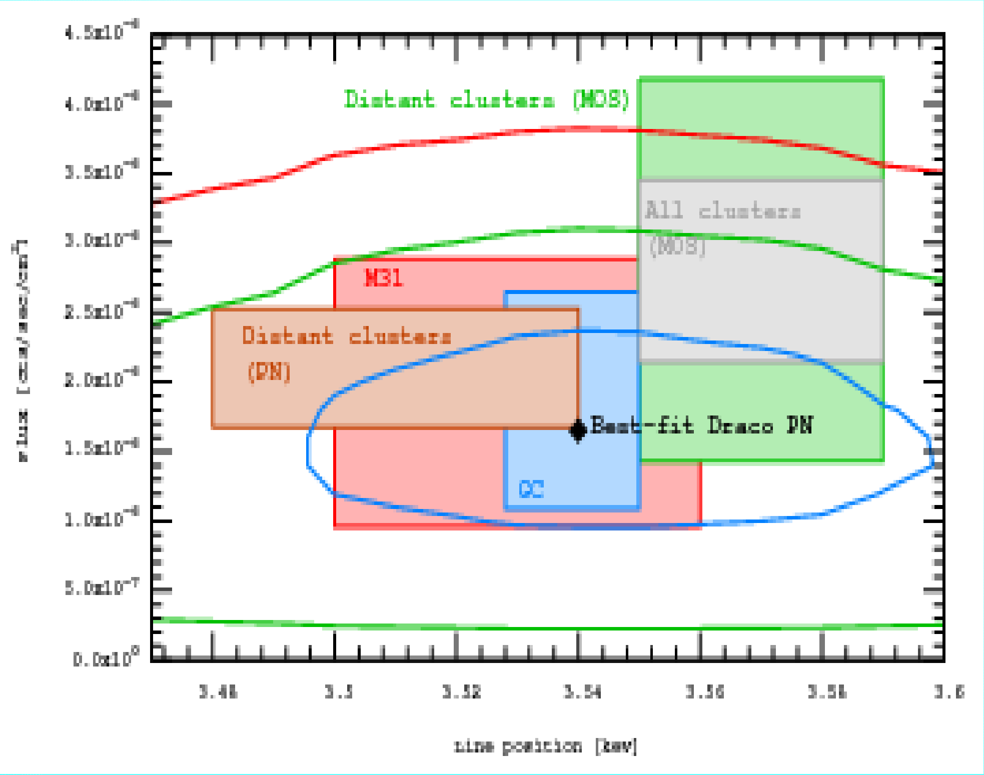
Spectra of Draco dwarf spheroidal seen by MOS1 (black), MOS2 (red) and PN (green) cameras



PN spectrum with unmodeled feature at 3.54 keV.

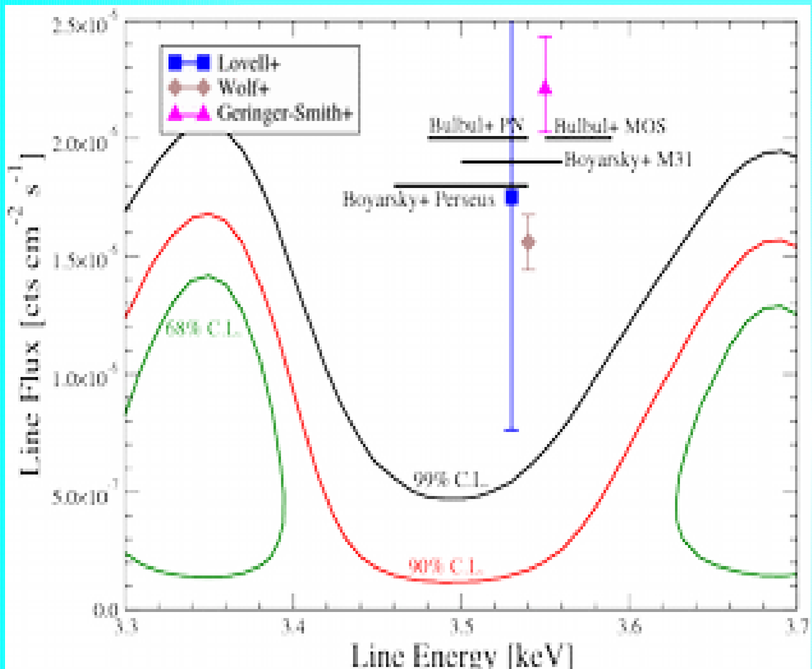
3.5 kev γ–line

O. Ruchayskiy et al, 1512.07217 [astro-ph.HE]

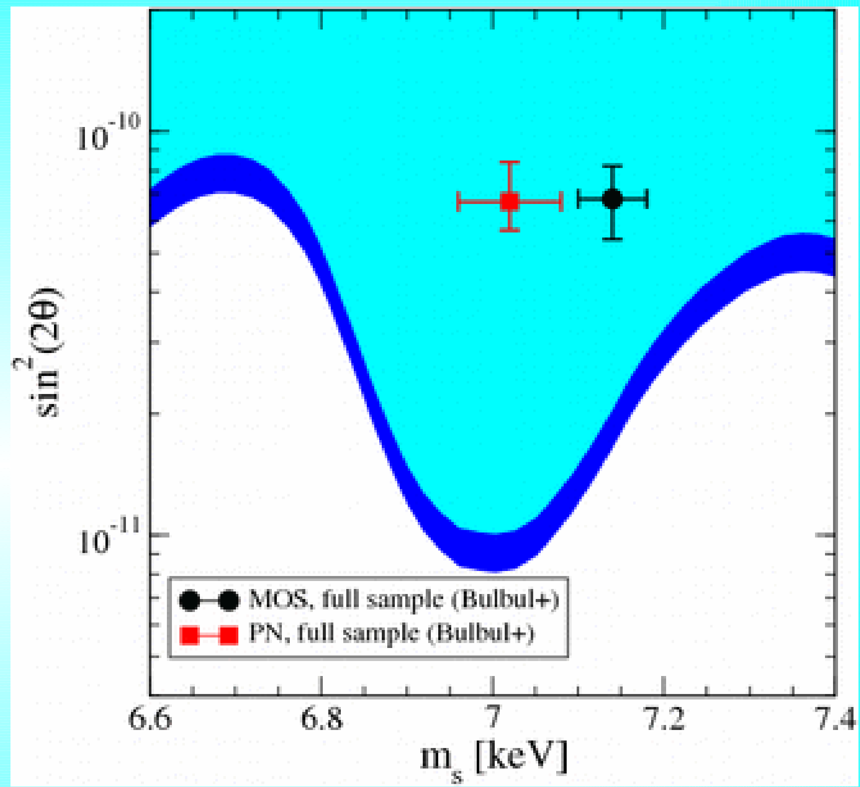


3.5 kev γ−line

T. Jeltema and S Profumo, 1512.01239 [astro-ph.HE]



Limits on the flux of a line from MOS observations of the Draco dSph, and predictions for the flux of a 3.5 keV line assuming a dark matter decay origin for the line detected at that energy from stacked clusters of galaxies and from the Milky Way center .



Constraints on mass of sterile neutrino and its mixing angle with active neutrinos from Draco MOS observations. The most Milky Way dark matter density profile from Malyshev et al. (2014)

High scale seesaw, unification

$$m_\nu = - m_D^T \frac{1}{M_R} m_D$$

q – l similarity: $m_D \sim m_q \sim m_l$

Lepton number violation

$$M_R \sim \begin{cases} M_{GUT} \sim 10^{16} \text{ GeV} \\ 10^{8} - 10^{14} \text{ GeV} \\ 10^{16} - 10^{17} \text{ GeV} \end{cases}$$

for the heaviest in the presence of mixing

$\frac{M_{GUT}^2}{M_{Pl}}$ double seesaw

many heavy singlets (RH neutrinos)

...string theory $N \sim 10^2$

In favor

Gauge coupling unification

Leptogenesis

Seesaw sector is responsible for inflation (scalar which breaks B-L and gives masses of RH neutrinos), dark matter

eV - sub eV scale physics

Very light sector which may include

- new scalar bosons, majorons, axions,
- new fermions (sterile neutrinos, baryonic nu) ,
- new gauge bosons (e.g. Dark photons)

M. Pospelov

Maybe related to Dark energy, MAVAN

Generate finite neutrino masses, usual Dirac masses can be suppressed by seesaw with $M_R = M_{Pl}$

eV scale Seesaw with RH neutrinos
for sterile anomalies LSND/ MiniBooNE ....

A. De Gouvea

Tests:

5^{th} force searches experiments

Modification of dynamics of neutrino oscillations

Checks of standard oscillation formulas, searches for deviations

utrino mass scale - fundamental sca

Neutrino mass scale is not a spurious scale but
the fundamental new physics

This new physics contribution becomes dominant because usual
contributions are strongly suppressed

by seesaw with $M_R = M_{Pl}$

By multi-singlet mechanisms

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & 0 \end{pmatrix} \begin{matrix} \nu \\ \nu^c \\ S \end{matrix} \Rightarrow m = 0$$

It could be whole invisible low scale sector with

- new scalar bosons, majorons, axions,
- new fermions (sterile neutrinos, baryonic nu) ,
- new gauge bosons (e.g. Dark photons)

Data confirm prediction

$$\theta_{13} \sim \sqrt{\tfrac{1}{2}}\,\theta_c$$

$$\sin^2\theta_{13} \sim \tfrac{1}{2}\sin^2\theta_C$$

- Phenomenological level — *C. Giunti, M. Tanimoto*
- From QLC (Quark-Lepton Complementarity) — *H. Minakata, A Y S*
- From TBM-Cabibbo scheme — *S. F. King et al*

Now accuracy of measurements permits detailed comparison

eesaw and PMNS-CKM relation

P. Minkowski
T. Yanagida
M. Gell-Mann,
P. Ramond,
R. Slansky
S. L. Glashow
R.N. Mohapatra,
G. Senjanovic

Right handed components of neutrinos N
Neutrinos get usual Dirac mass terms $m_D = Y\langle H \rangle$
N have large Majorana masses $M_R \gg m_D$

$$\begin{array}{c|cc} & \nu & N \\ \hline \nu & 0 & m_D \\ N & m_D^T & M_R \end{array}$$

diagonalization

$$m_\nu = - m_D (M_R)^{-1} m_D^T$$

$$m_D = U_L (m_D^{diag}) U_R^+$$

If $U_L = V_{CKM}^*$ -- realized in the simplest SO(10)

$$m_\nu = - U_L (m_D^{diag}) U_R^+ (M_R)^{-1} U_R^* (m_D^{diag}) U_L^T$$

produces U_x - we realize the connection

so U_x should diagonalize that is

$$M_X = - m_D^{diag} U_R^+ (M_R)^{-1} U_R^* m_D^{diag}$$

$$M_X = U_X M_X^{diag} U_X^T = U_X m_\nu^{diag} U_X^T \sim m_{TBM}$$

How to reconcile all this?

Special symmetry in lepton sector no symmetry in quark sector

Smallness of neutrino mass

Complementarity relation