Theoretical aspects of Neutrino physics: Recent developments

A. Yu. Smirnov

Max-Planck Institut fur Kernphysik, Heidelberg, Germany

Corfu, Greece, September 3, 2021

Outline:

Neutrinos in the Standard model: SM + m_ν

Neutrinos and BSM

Anomalies and connections

Neutrino and new physics at the low energy scales

Masses, mixing and flavor symmetries

Massive neutrinos and the Standard Model

Standard Model + "m_ν"

Oscillations
Adiabatic conversion

Physics BSM responsible for m_ν can be introduced in such a way that feedback on SM is negligible

Dirac mass

$$Y \bar{L} \nu_R H$$

Majorana mass

$$\frac{1}{\Lambda} LL\, HH$$

D5 Weinberg operator

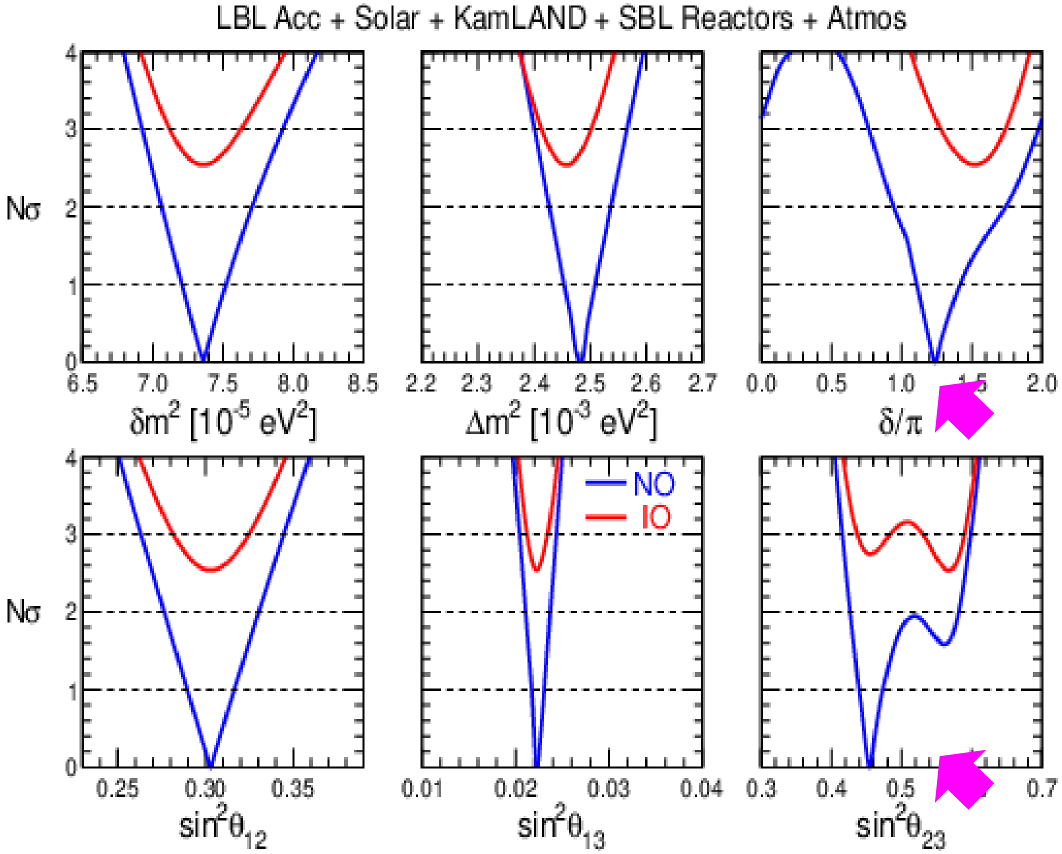
Effective mass

$$m_\nu (E, n, ..)$$

generated by interactions with medium, e.g. DM

Summary, Global fit

F Capozzi, et al
2107.00532 [hep-ph]



Data – more consistent, analysis – stable, agreed with results of NuFIT

Data agree with hard mass: no dependence on E, environment.
CPT -OK

For NO δ_{CP} - closer to π
Deviation of 2-3 mixing from $\pi/4$ is smaller
Preference of NO is less significant than before

Tensions inside the global?

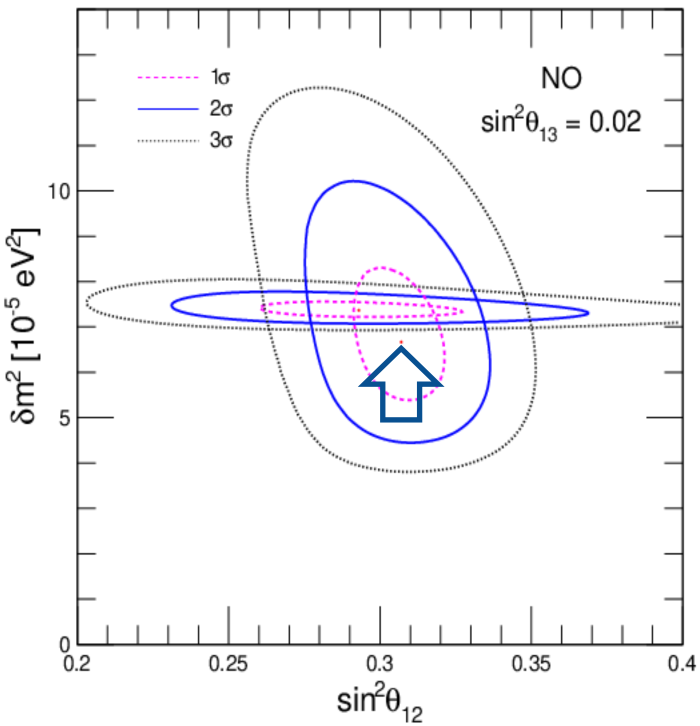
Solar - KamLAND Δm_{21}^2 – tension disappears

SK (also SNO+) observe the upturn of spectrum (SNO, SK)

The D-N asymmetry at SK is reduced 3.3% → 2.1%

Best fit value of Δm_{21}^2 from analysis of the solar neutrino data increased

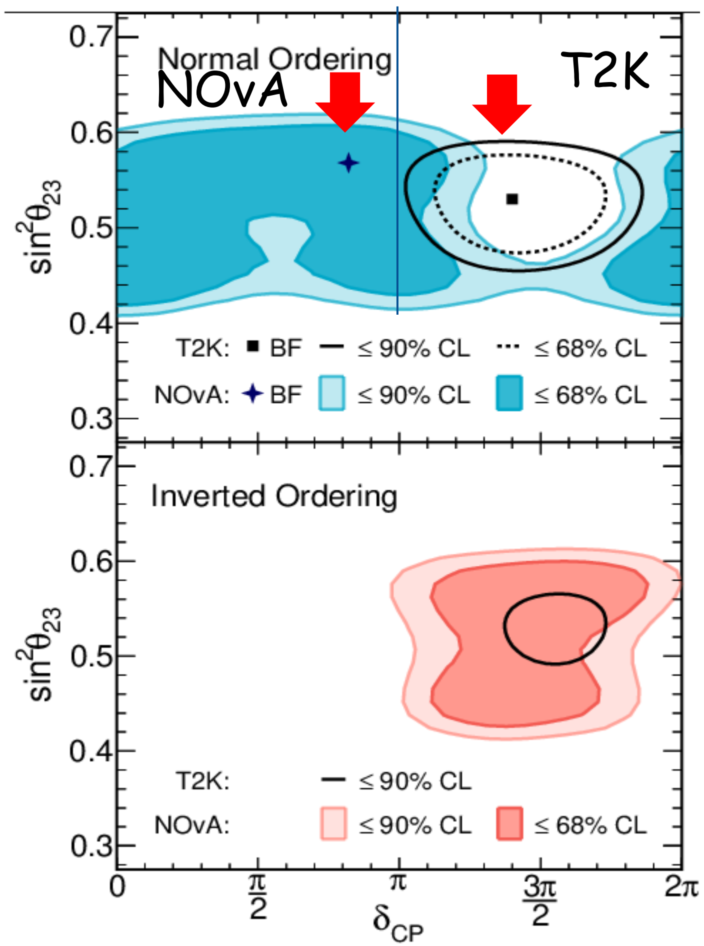
Discrepancy with KamLAND results reduced $2\sigma \rightarrow 1.2\,\sigma$



1, 2, 3σ CL contours

F Capozzi, et al 2107.00532 [hep-ph]

NOvA - T2K tension or CP phase close to π?



2108.08219 [hep-ex]

See talk by A. De Roeck

NOvA: $\delta_{CP} = 0.82\pi$
disfavors $\delta_{CP} = 1.5\pi$ by 2σ

NOvA-T2K difference can be related to different baselines and matter effects

Reconcile with NSI or sterile neutrinos:

S. Chatterje, A. Palazzo, 2008.04161 [hep-ph], 2005.103338 [hep-ph]

No tension in the case of inverted ordering

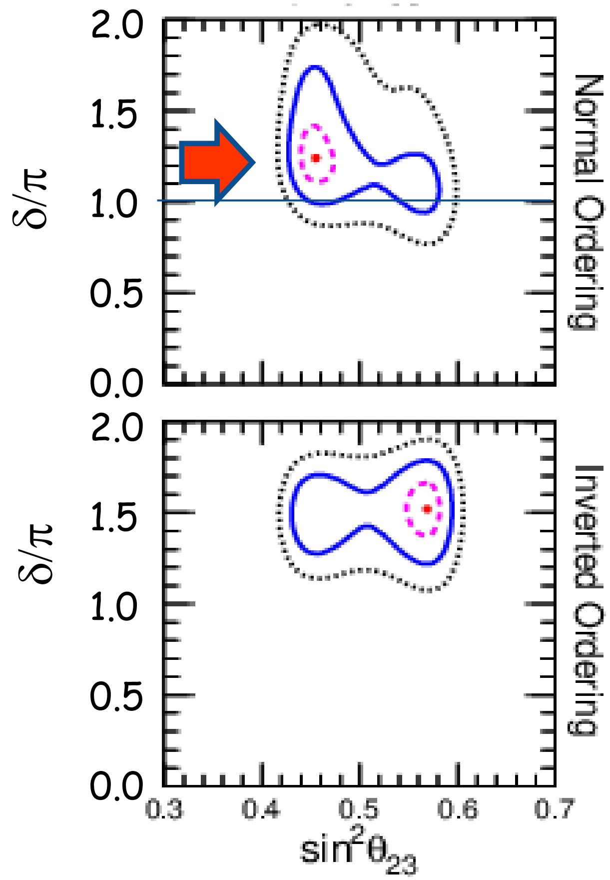
Global fit: $\delta_{CP} \rightarrow \pi$

... or CP-phase close to π?

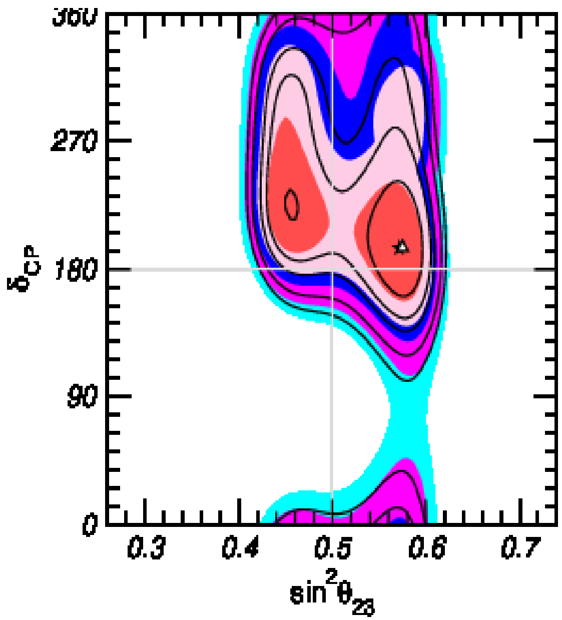
bad news for measurements of CP- asymmetry

Global fits

F Capozzi, et al 2107.00532 [hep-ph]



NuFit 2020



even closer to π

Why CP phase is large in quark sector and not in lepton sector ?

$\delta_{CP} = \pi$?

B. Dasgupta, A Y.S. ,
Nucl.Phys. B884 (2014) 357
1404.0272 [hep-ph]

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

If the only source of CP violation (V_{CKM}^{+})

No CPV (of BM type) (U_X)

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

λ $\qquad$ λ^3

$\delta_q = 1.2$ +/- 0.08 rad

$\sin\delta_q = 0.93$

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

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

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

Leptonic CP is small because the leptonic 1-3 mixing is large

To the theory of neutrino propagation and oscillations

Surprisingly, big activity recently

Challenging theory:

reformulations, reinterpretations, improvements, corrections, entanglement, quantumness

Changing evolution equation:

Lorentz invariance violation, metric change, Equivalence principle violation

Oscillations at extreme conditions:

high – low densities, high - low energies, dense neutrino background → collective oscillations

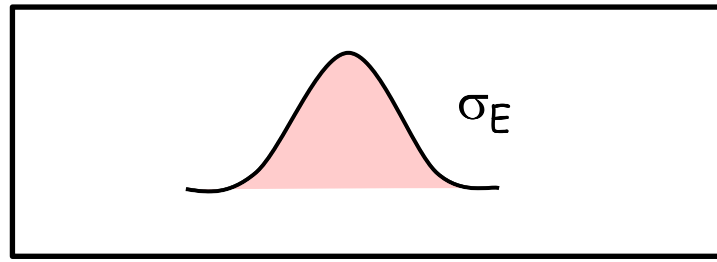
New interactions: NSI, long range forces, interaction with DM

Searches for new neutrino states, sterile neutrinos

Coherence and de-coherence

x –t space: separation of wave packets

E-p space: integration over the energy uncertainty



results in suppression of interference   L. Stodolsky

Equivalence due to $\sigma_x \sim 1/\sigma_E$

Coherence length: $L_{coh} = \frac{\sigma_x}{\Delta v_g}$

Δv_g -difference of group velocities $v_{gi} = dH_i / dp$

In vacuum: $\Delta v_g = \Delta m^2 / 2E^2$ ⇒ $L_{coh} = \sigma_x \frac{2E^2}{\Delta m^2}$

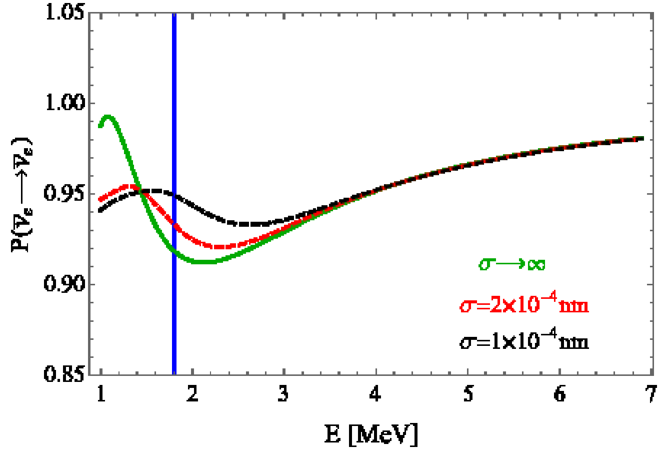
Decoherence of reactor neutrinos

A de Gouvea, V De Romeri, C.A. Termes, 2104.05806 [hep-ph]

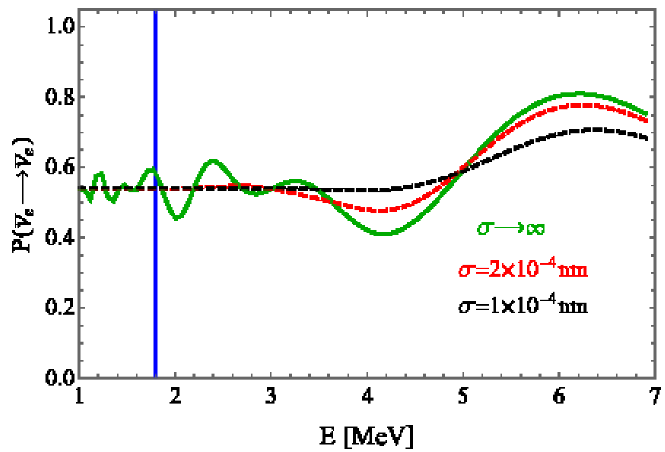
Bound on size of the WP

Averaging effect

Daya Bay, RENO



KamLAND



Absence of decoherence (averaging) effects means

$$L \ll L_{coh} \quad \Rightarrow \quad \sigma_x > L \frac{\Delta m^2}{2E^2}$$

Analysis of data: $\sigma_x > 2.1 \times 10^{-11}$ cm

Expected: $\sigma_x \sim 10^{-9}$ cm

Coherence in matter

S.P. Mikheyev, A.Y.S.

Y. P. Porto-Silva , A Y S
2103.10149 [hep-ph]

Matter changes group velocities $v_i \to L_{coh}$

Constant density

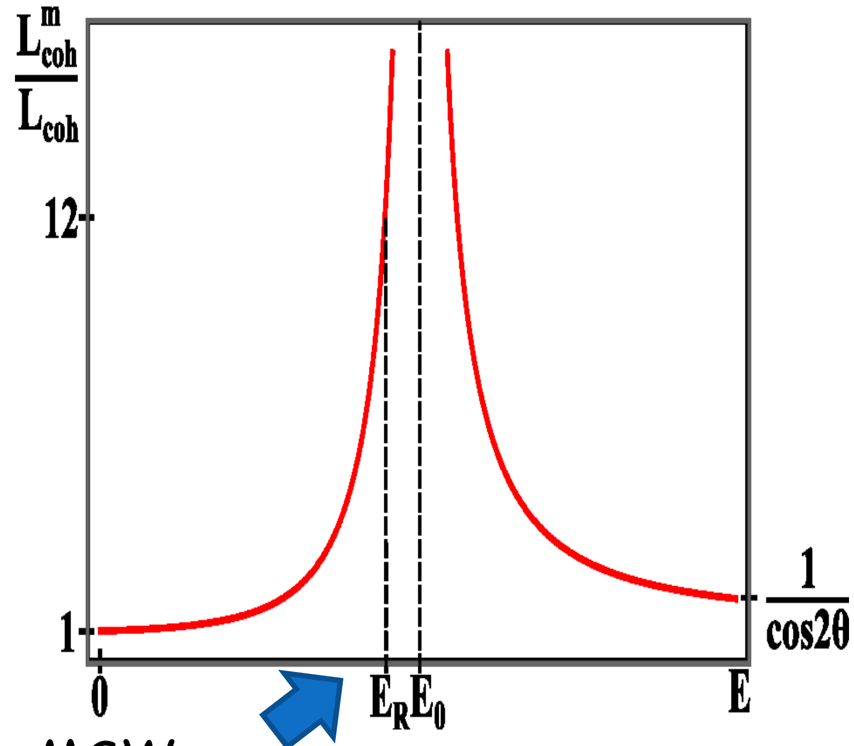
At certain E_0 $L_{coh} \to$ infty

corresponds to equality of the group velocities:

$\Delta v = v_{2m} - v_{1m} = 0$

→ no separation of the wave packets

E_0 coincides with the MSW resonance in oscillations of mass states



MSW resonance energy of flavor oscillations

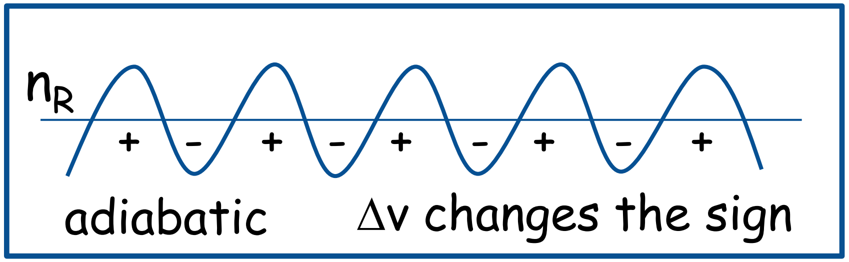
$L_{coh}^m \to L_{coh}/\cos 2\theta \sim L_{coh}$

At high densities the coherence length as in vacuum

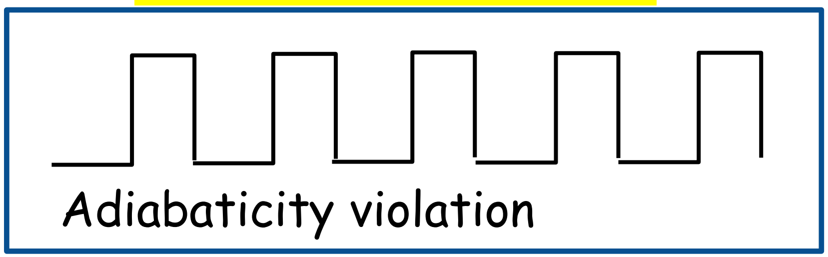
Infinite coherence

Y. P.. Porto-Silva , A Y S
2103.10149 [hep-ph]

n Periodic modulations of density



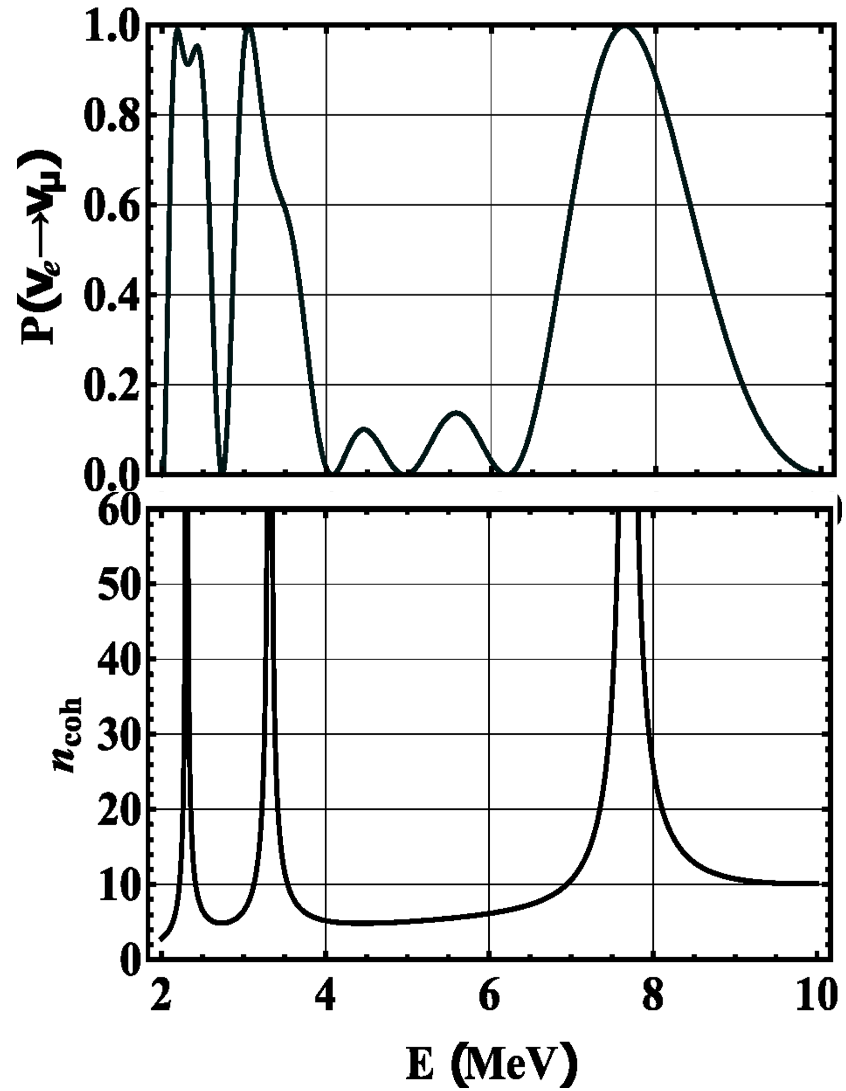
n Castle wall profile



Number of coherence periods

Several E_{inf} associated with parametric resonances

Applications to SN neutrino collective oscillations



Neutrino anomalies
Status & implications

RAA: Reactor Antineutrino Anomaly

Oscillatory pictures - fluctuations

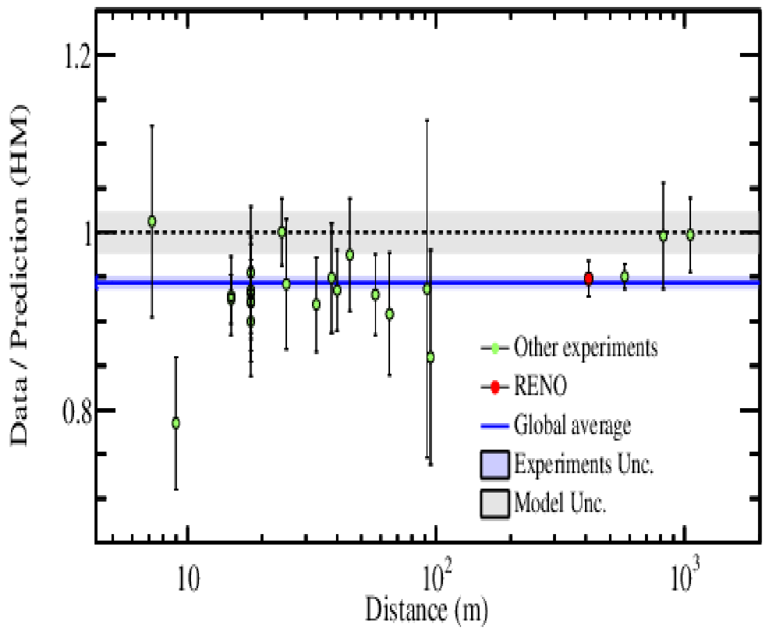
NEUTRINO-4

Gallium anomaly (Cross sections – reduced significance)

LSND

MiniBooNE

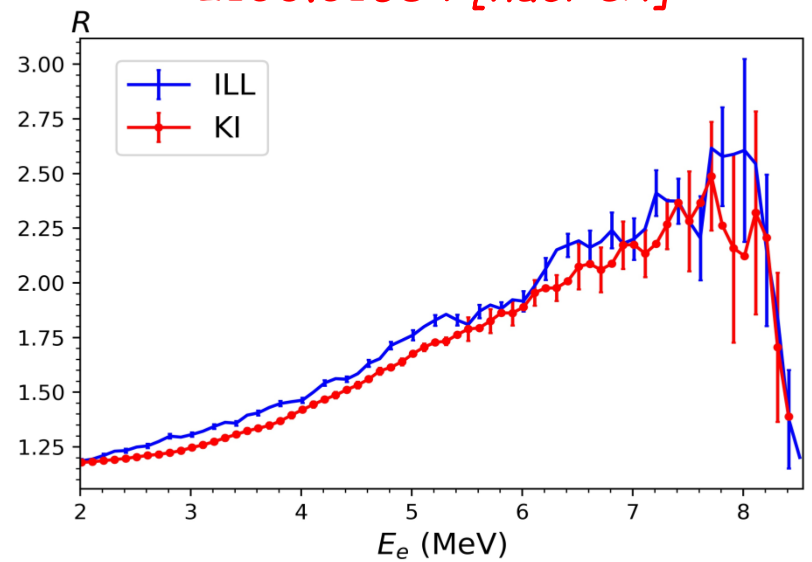
Reactor Antineutrino Anomaly and its re-evaluation



The ν_e event rates as a function of the distance from a reactor, relative to the Huber-Mueller prediction based on ILL spectra.

IBD yield/HM: 0.941 ± 0.019

V. Kopeikin, et al. 2103.01684 [nucl-ex]



KI – Kurchatov institute new measurements of the ratio between 235U and 239Pu spectra

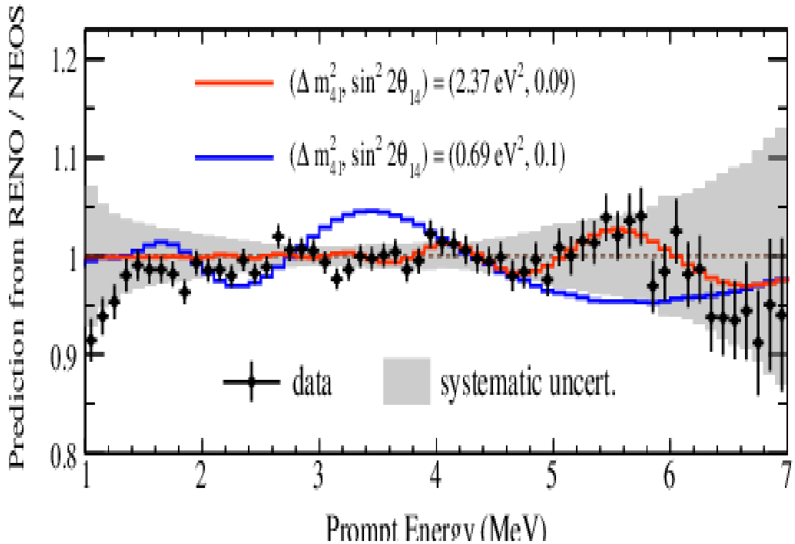
Ratio of cumulative spectra
$R = S_5 / S_9$

R(ILL) = 0.959 R(KI)
→ explains anomaly

Oscillations or fluctuations?

Oscillatory curve with two free parameters always gives better fit of fluctuating data points than constant

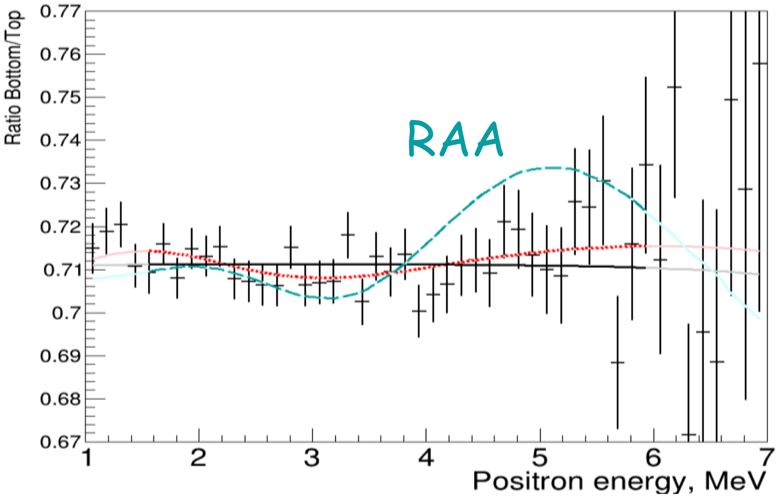
NEOS
Z. Atif et al 2011.00896 [hep-ex]



Points: NEOS observed prompt spectrum over prediction for NEOS using RENO spectrum

Δm_{14}^2 = 2.37 eV^2, $\sin^2 2\theta_{14}$ = 0.09

DANSS
M. Danilov, 2012.10255 [hep-ex]



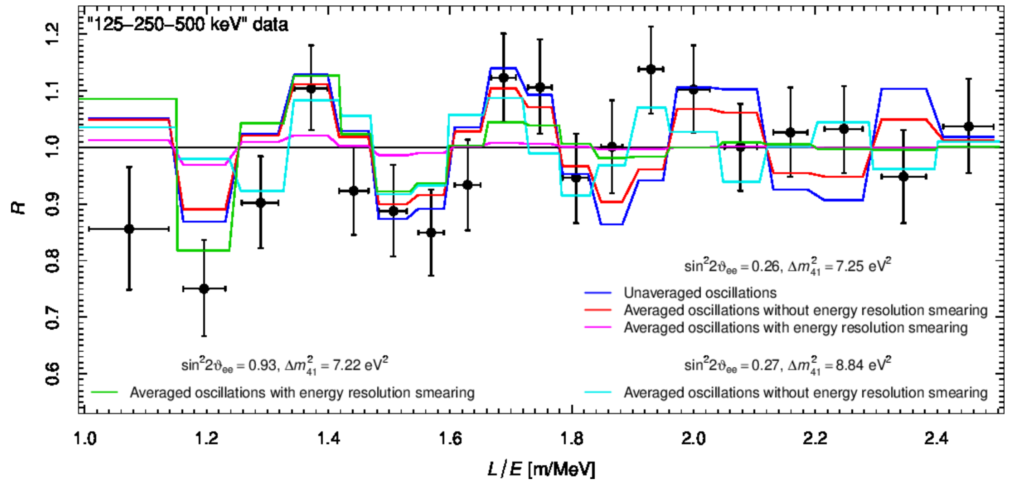
RAA (dotted): Δm_{14}^2 = 2.4 eV^2

Δm_{14}^2 = 1.3 eV^2, $\sin^2 2\theta_{14}$ = 0.02

Now different ...

Neutrino-4

C. Giunti, et al, P.L. B816 (2021) 136214
2101.06785 [hep-ph]



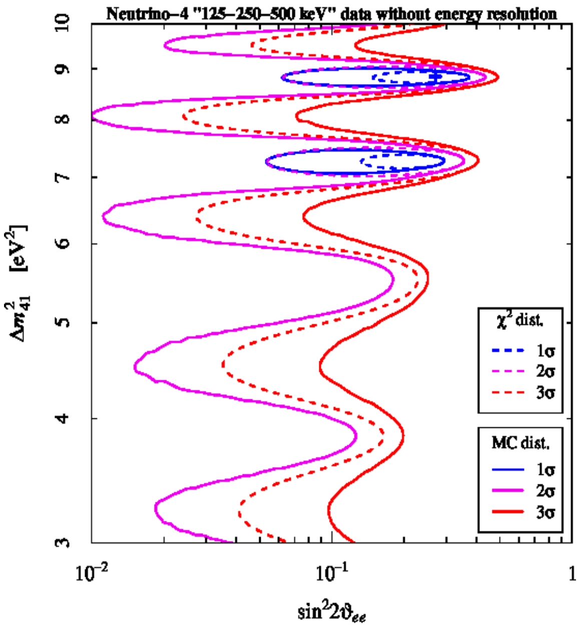
Energy resolution of the detector, more reliable Monte Carlo simulation:

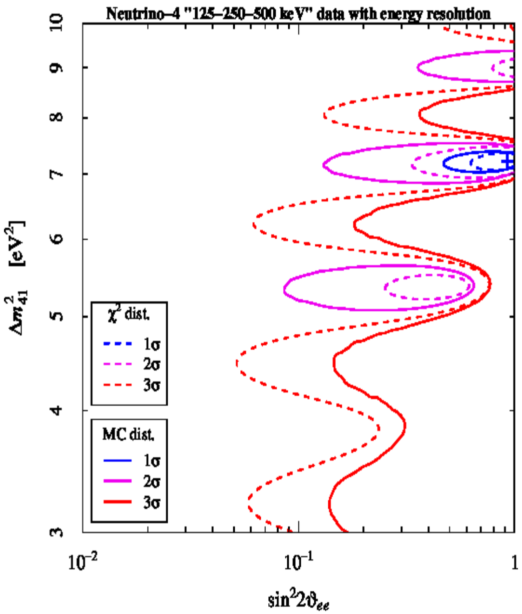
→ Significance reduces:

$3\sigma \rightarrow 2.2\sigma$

→ b.f. point moves to maximal mixing

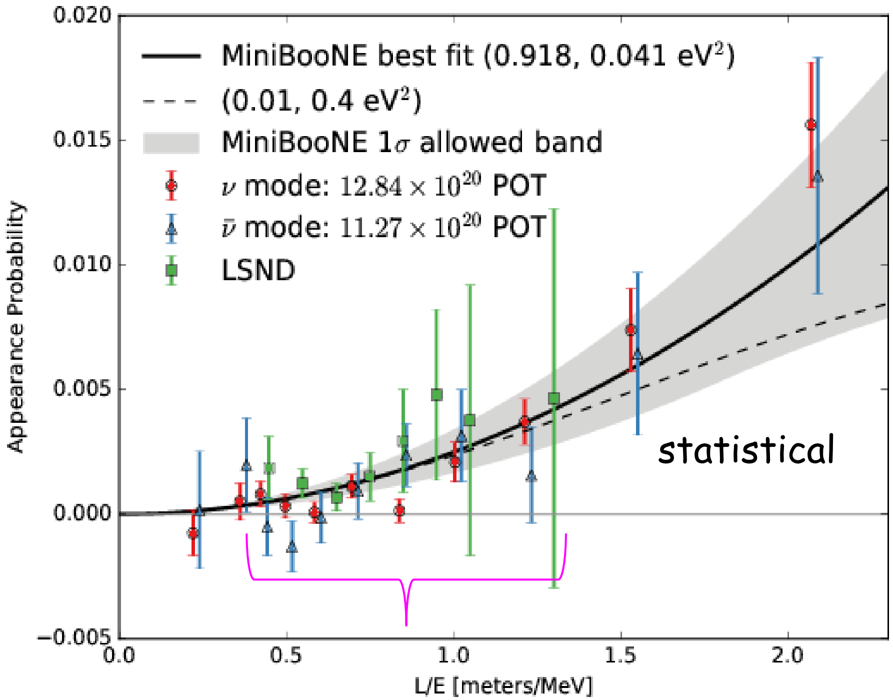
Strong tension with the KATRIN, PROSPECT, STEREO, solar ve bounds





MiniBooNE and LSND

A.A. Aguilar-Arevalo et al
Phys.Rev.Lett. 121 (2018) no.22, 221801)
1805.12028 [hep-ex] |



L/E dependences of QE events excess in LSND and MiniBooNE

No good LSND –MB agreement in the overlapping region

b.f. line- for $\sin^2 2\theta$ = 0.918 excluded

1σ line - for $\sin^2 2\theta$ = 0.01 Strongly disfavored

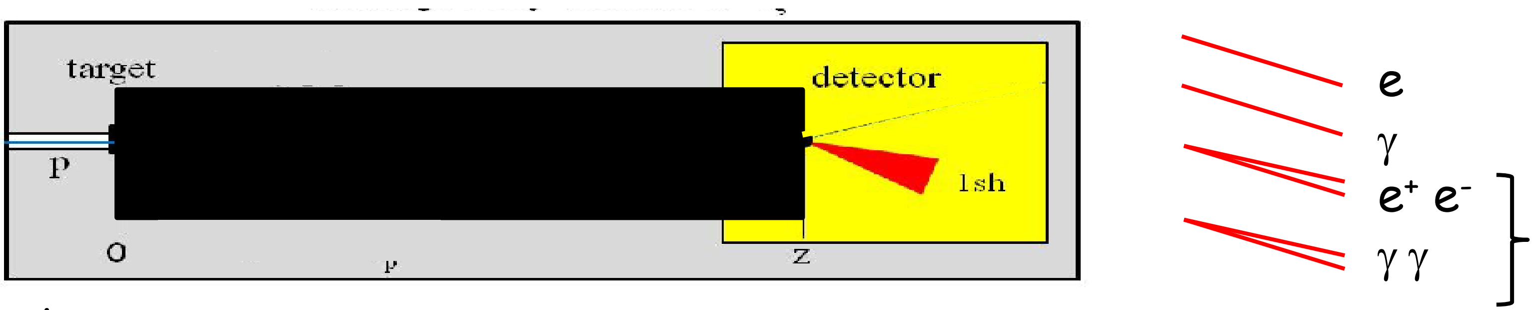
Oscillation interpretation nearly excluded by disappearance data

No oscillatory dependence:
Non-oscillatory explanations are possible

Many alternative scenarios have been proposed

Effective theory of the MiniBooNE excess

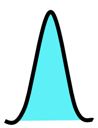
V. Brdar, O. Fisher, A.S.
2007.14411 hep-ph

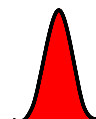


proton hits target

EM shower in detector

unresolved





p bunches hits and appearance of showers are time correlated

Time delay is consistent with v = c, i.e. propagation of neutrinos
Put upper bounds on masses of new particles excludes some scenarios

Black box

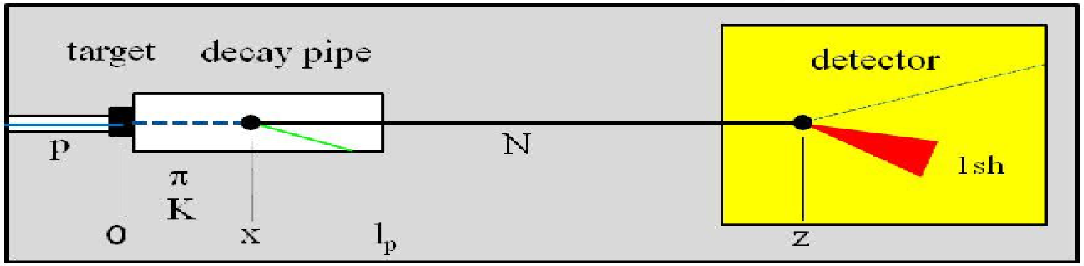
Production via
Propagation
Decays
Un-scattering
of new particles

mixing with
up-scattering of

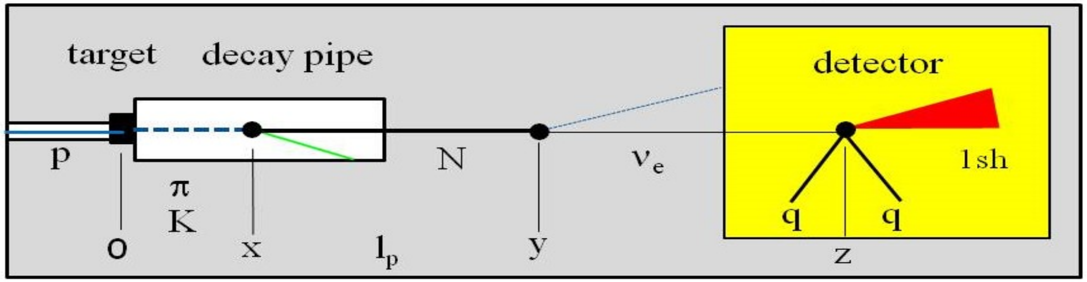
usual neutrinos

Opening black box

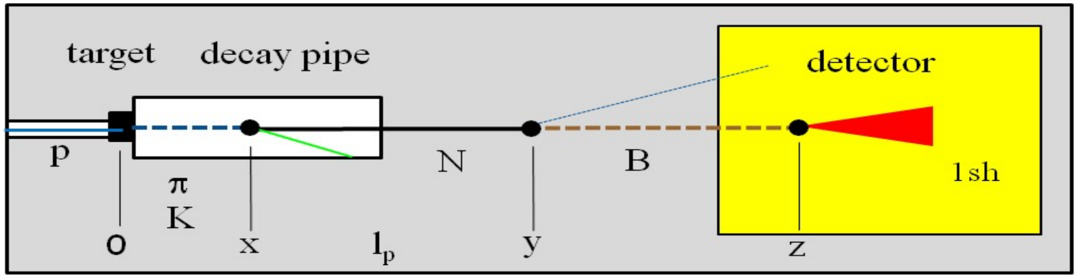
Mixing-Decay scenario MD_{ξ}



Mixing-Decay ν_e scenario $M_N D_\nu U_e$



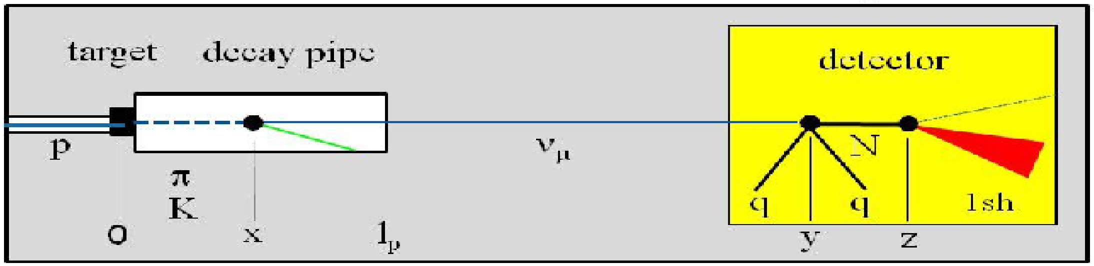
Mixing-Double Decay scenario, $M_N D_B D_{\xi}$



Opening black box

$U_N \, D_\xi$

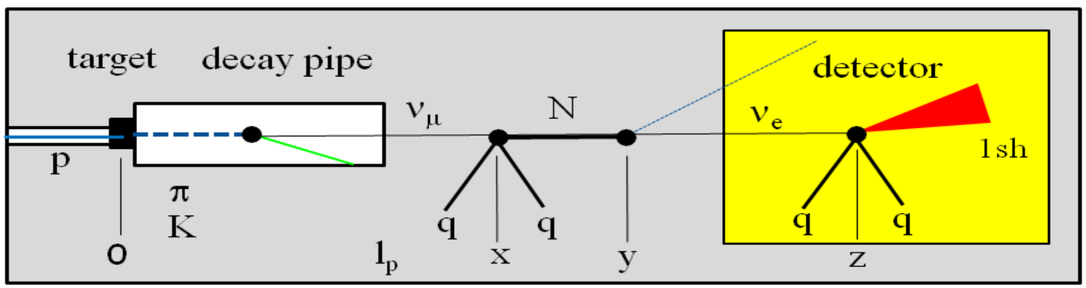
Upscattering-Decay scenario UD_ξ



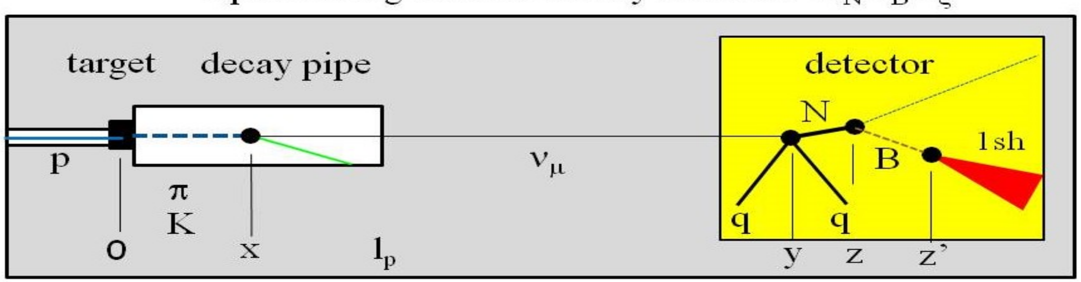
a.

c.

Upscattering-Decay into ν_e scenario, $U_N D_\nu U_e$



Upscattering-Double Decay scenario $U_N D_B D_\xi$



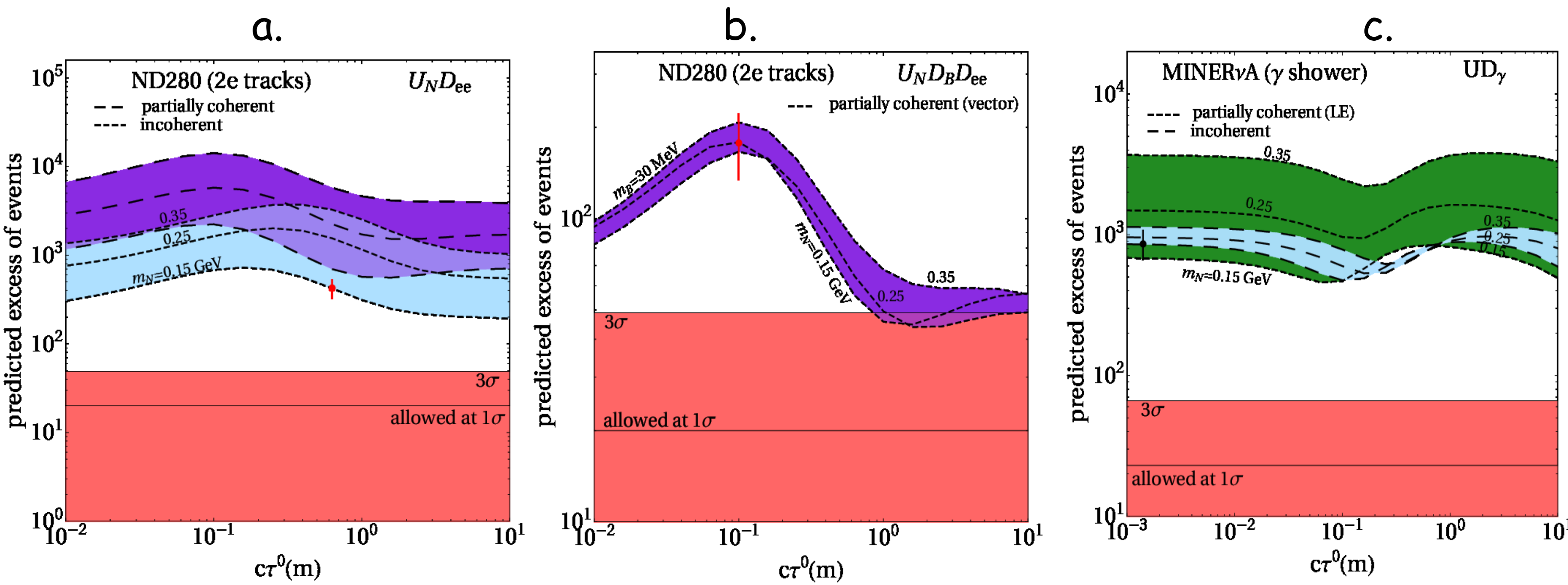
b.

Predicting events in other experiments. Bounds

Excess of 1 sh events at MB → scenario → Number of events of a given type at other experiments

Similar setups: T2K ND280, MINERvA, NOvA, NOMAD

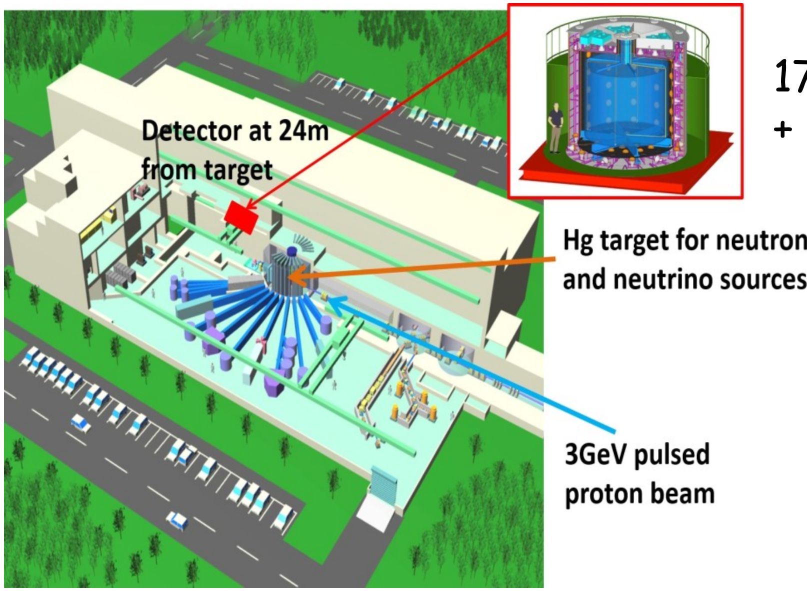
Confront with experimental bounds



lifetime of heavy neutrino N

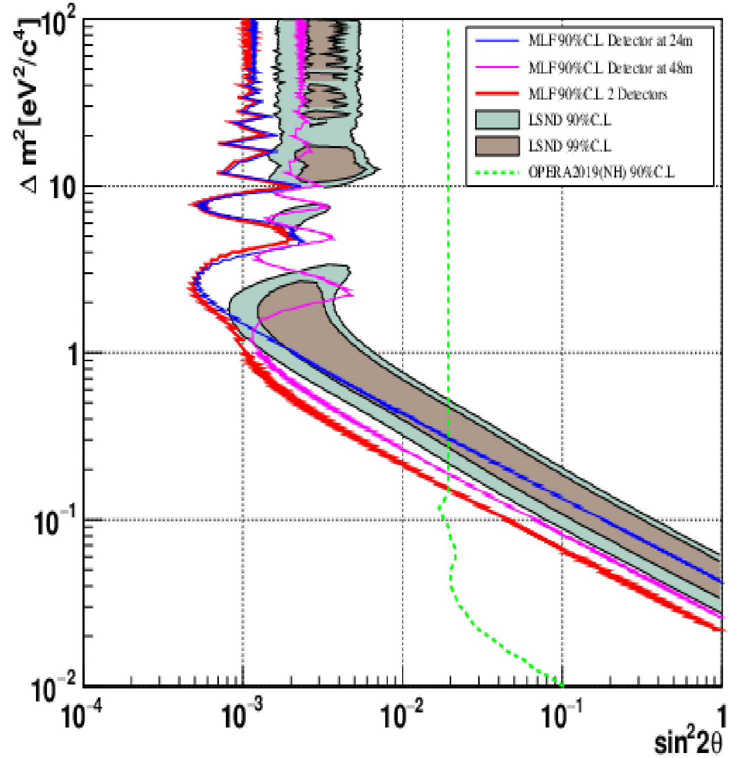
JSNS^2: Ultimate tests?

Ajimura, S. et al. 2012.10807 [hep-ex]
2104.13169 [physics.ins-det]



17t LS + Gd

J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source (at Material Life Facility MLF)



Repeating LSND: μ–decay at rest, searches for $\bar{\nu}_\mu$ - $\bar{\nu}_e$ oscillations

Sensitivity of JSNS^2 and upgrade JSNS^2-II: second detector at 48m

JSNS^2 operates now

ICARUS at Fermilab detects first events

Neutrinos and
non-neutrino anomalies,
connections

Neutrinos and DM

Is the (hot) component of the DM

Mechanism of generation of small neutrino masses is related to DM

RH neutrinos as DM particles

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

Refraction on DM produces the effective neutrino mass

m_ν ↔ $(g\text{-}2)_\mu$

m_ν ↔ B-anomalies

R_{K^*}

R_{D^*}

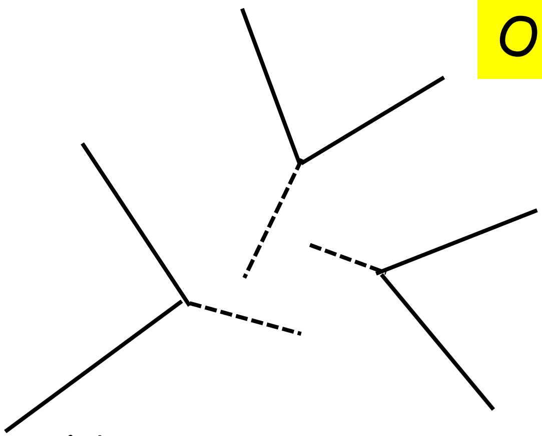
Lepton non-universality

Model building without model builder

Systematic way to search for connection is to use effective FT

Opening

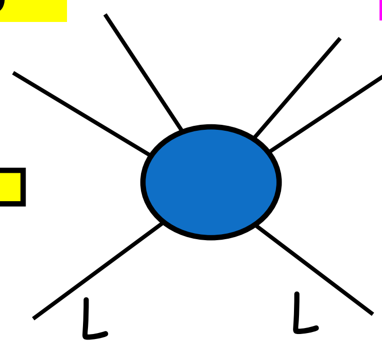
Closure



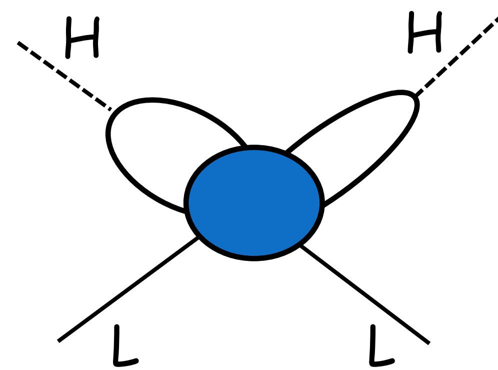
New interactions with new (often exotic) particles

Contribute to R_{K^*}

$(g\,\text{-}2)_\mu$ R_{D^*}



gauge inv. operators constructed out of SM fields , with $\Delta L = 2$

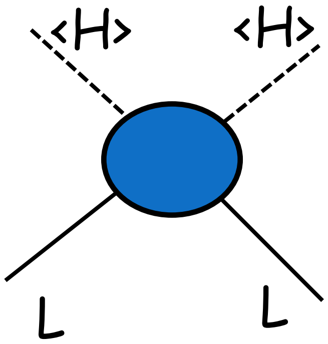


D5 operator

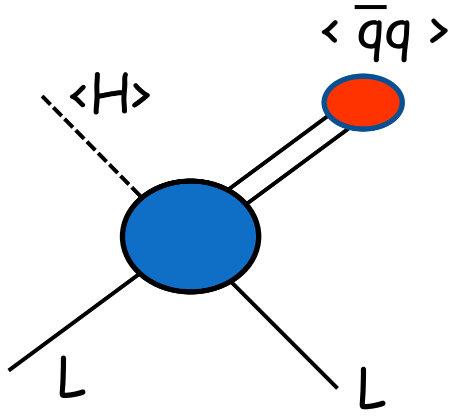
m_ν

UV completion

In addition



D5 operator



Generated by

Substitute Higgs VEV by quark chiral condensate

A. Babic at al, 1911.12189

following original

S D Thomas and R.-M. Xu
PLB 284,341 (1992)

$$O_7 = \frac{g}{\Lambda^3} \; L^c L \overline{H} \, [(Q u_R) \overline{(d_R} \, Q)]$$

$$m_\nu = g \langle H \rangle \frac{\langle \bar{q} q \rangle}{\Lambda^3}$$

$\langle qq \rangle = 300$ MeV $\quad \Lambda =$ few TeV

Issues

How D5 operator is suppressed
UV completion

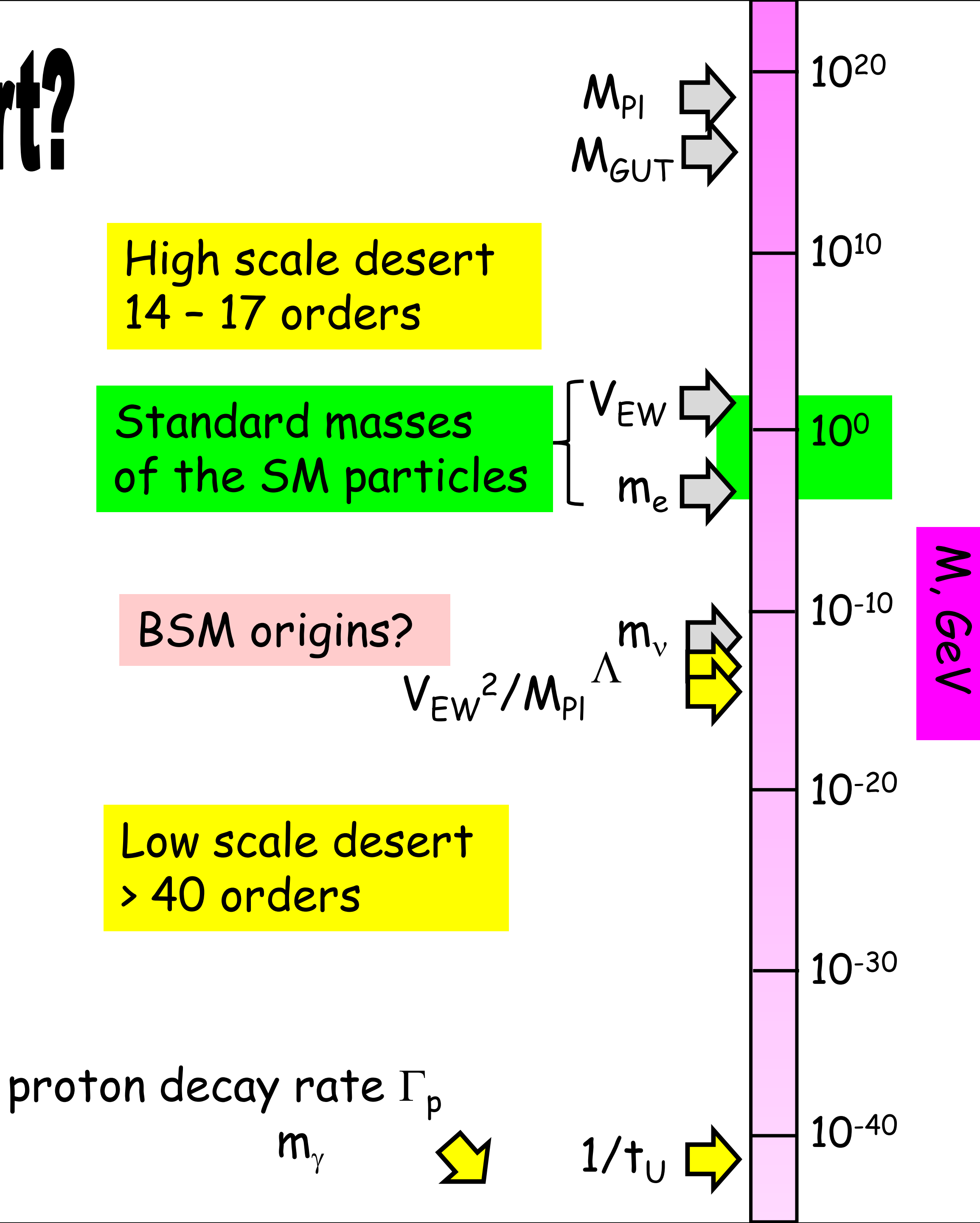
Neutrinos and New physics
at the low energy scales

... or second desert?

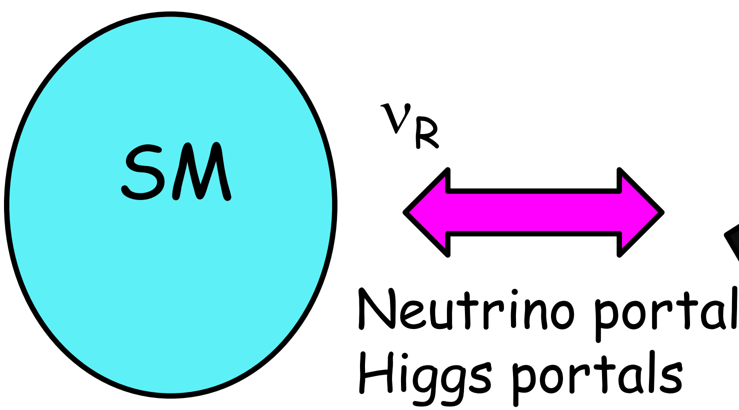
Why not worry about the low scale desert?

Another hierarchy problem?

Neutrino mass – physics at low scales



Neutrinos and interactions with light dark sector



Interactions affect oscillations

Neutrinos provide probes of the light dark sector

The simplest example

Scalar interaction

M.Kawasaki
H. Murayama
T. Yanagida,
1991

$$L = g\, \bar{\nu}_L\, \chi\, \phi + h.\,c.$$

where χ - fermion, ϕ - scalar

g - effective coupling   pheno bound $g < 10^{-7}$

L can be generated via the RH neutrino portal

Long range forces

Rich phenomenology

Refraction

Effective m_ν

Bound neutrino systems

elastic forward scattering, $q^2 = 0$

Potential $V \sim g^2 / m_{med}^2$

do not disappear when g , $m_{med} \to 0$

while inelastic interactions $\sim g^2/q_{min}^2$

May have important cosmological and astrophysical consequences

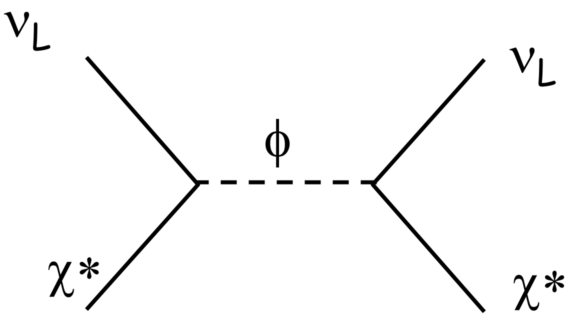
Resonance neutrino refraction

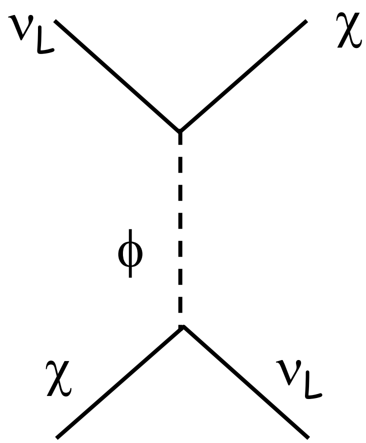
A.S. , V.Valera,
2106.13829 [hep-ph]

in SM: due to Z, W

C. Lunardini, A.S.

Neutrino scattering on background fermions χ with scalar ϕ mediator





Asymmetry of bgr:

$$\varepsilon = (n_\chi - \bar{n}_\chi)/(n_\chi + \bar{n}_\chi)$$

n_χ and $\bar{n}_\chi$ – the number densities of χ and χ^*

Effective potential

$$V^B = \tfrac{1}{2} V_0 \left(\frac{(1-\varepsilon)(y-1)}{(y-1)^2 + \xi^2} + \frac{1+\varepsilon}{y+1} \right)$$

Refraction index

$$n_{ref} = 1 + V/p$$

$$V_0 = \frac{g^2}{2m_\phi^2}(n_\chi + \bar{n}_\chi)$$

$$y = E/E_R$$

$$E_R = m_\phi^2/2m_\chi$$

Resonance: $y = 1$ corresponds to $s = m_\phi^2$

width of resonance

$$\Gamma = \frac{g^2}{4\pi} m_\phi$$

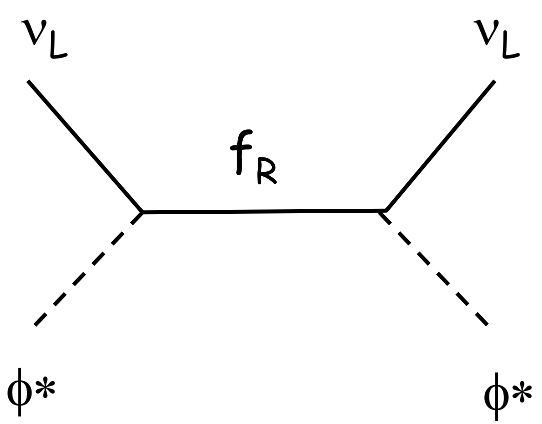
$$\xi = \Gamma / E_R$$

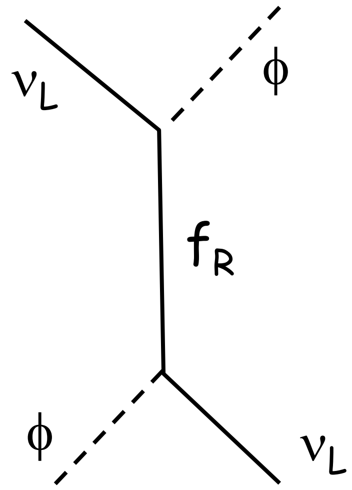
Neutrino refraction on scalar DM

S. F Ge and H Murayama, 1904.02518 [hep-ph]

Ki-Yong Choi, Eung Jin Chun, Jongkuk Kim, 1909.10478 [hep-ph]

2012.09474 [hep-ph]





Neutrino scattering on DM particles ϕ (target) with f_R - mediator

$$V_s \sim \frac{(s - m_f^2)\,\bar{n}}{(s - m_f^2)^2 + s\,\Gamma^2} \qquad V_u \sim \frac{n}{u - m_f^2}$$

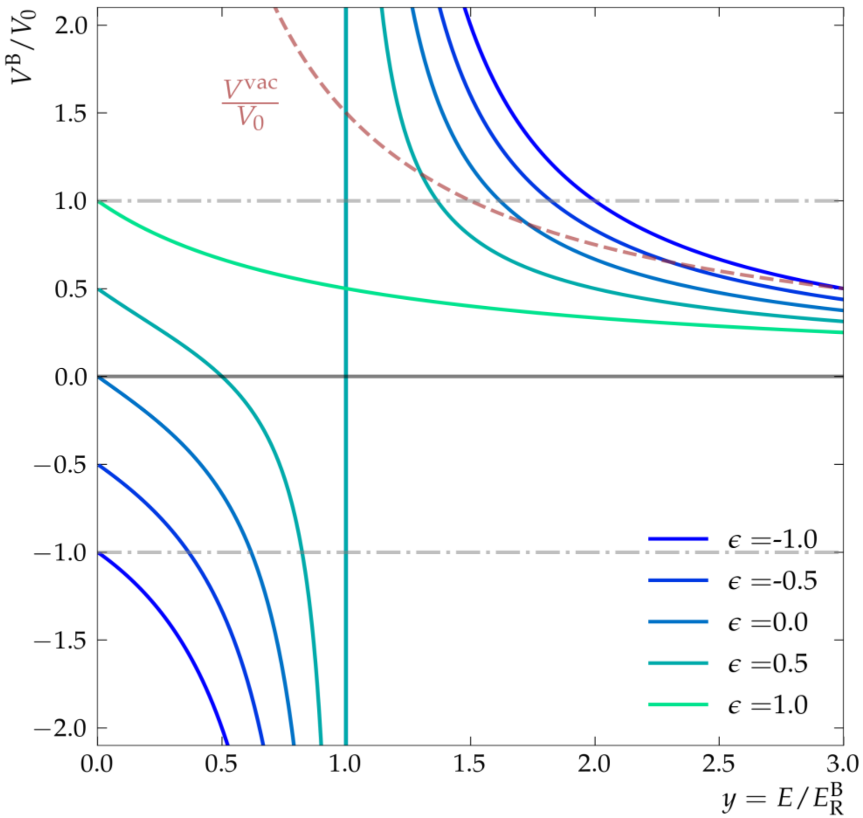
n and $\bar{n}$ – the number densities of ϕ and ϕ^*

$$\Gamma = \frac{g^2}{32\pi} m_f$$

Resonance: $s = m_f^2 \rightarrow E_R = m_f^2/2m_\phi$

Background potential

A.S. , V.Valera,
2106.13829 [hep-ph]
JCAP



Potential depends on energy

$$V^B = V_0 \frac{y - \varepsilon}{y^2 - 1}$$

	V^B/V_0
$y = 0$	ε
$y \to \inf$	$1/y$
$\varepsilon = 1$	$1/(y+1)$
$\varepsilon = 0$	$y/(y^2 - 1)$
$\varepsilon = -1$	$1/(y-1)$

$V^{vac} = \Delta m^2/2E$ $= V_R^{vac}/y$

$V_R^{vac} = \Delta m^2/2E_R$

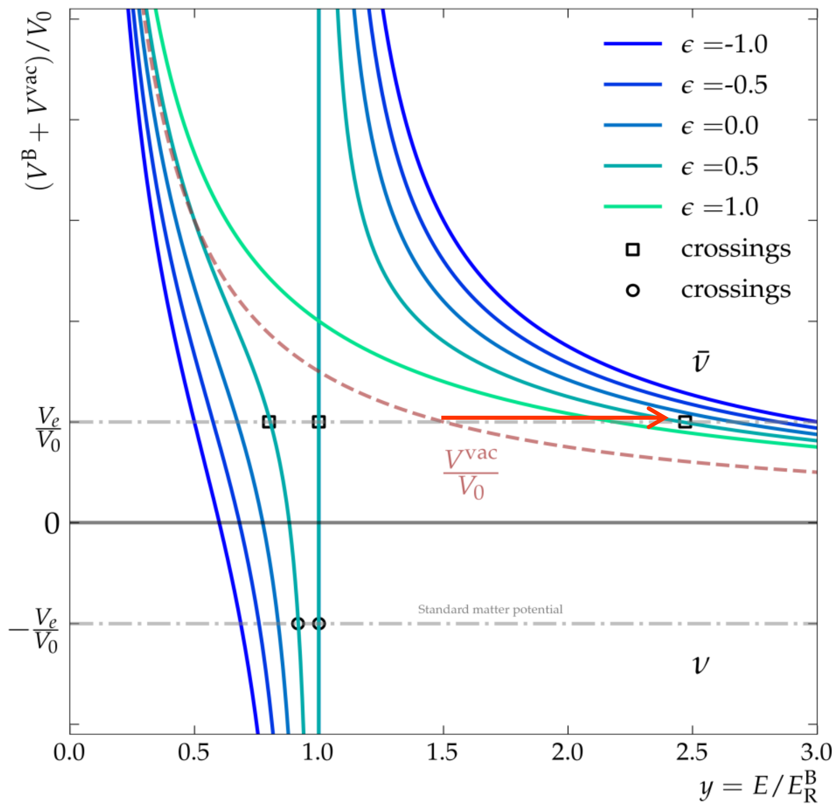
Relative contribution of the background and vacuum terms

$r = V_0/V_R^{vac}$

Effective kinetic term and MSW resonances

$(V^B + V^{vac})/V_0$

A.S. V.Valera, 2106.13829 [hep-ph]



$V_e = \sqrt{2}G_F n_e$ - usual matter potential

Boxes - MSW resonances

shift of the usual MSW resonance

2 new resonances in ν-channel

2 new resonances in $\bar{\nu}$-channel

V^B included into effective kinetic term

Effective mass squared difference

$\Delta m_{eff}^2 = 2E(V^{vac} + V^B) = \Delta m^2 (1 + V^B/V^{vac})$

Effective mass squared splitting

A.S. , V.Valera,
2106.13829 [hep-ph]

$|\Delta m_{eff}^2 / \Delta m^2|$ as function of y
for different $r = V_0/V_R^{vac}$

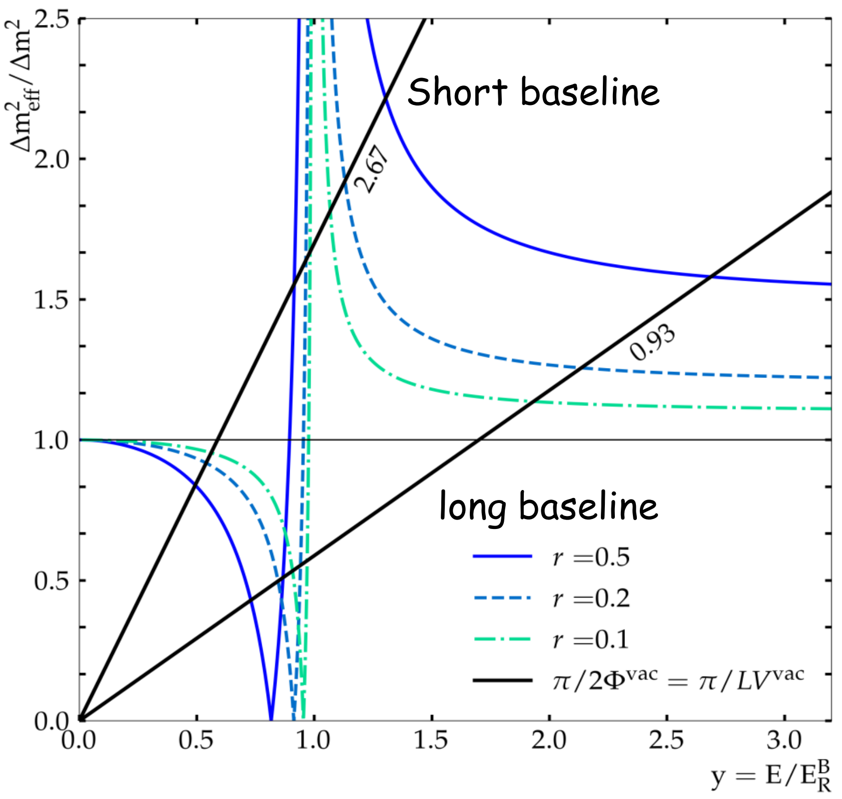
The oscillation phase:

$$\Phi = \frac{\Delta m_{eff}^2}{2E} L = \frac{\Delta m_{eff}^2}{\Delta m^2} \Phi^{vac}$$

Straight lines: $1/\Phi^{vac}$

Their crossing with $\Delta m_{eff}^2 / \Delta m^2$ corresponds to $\Phi = 1$

Above the lines Φ (y) > 1 and the oscillation effect is large



With increase of r the y-region of large phase expands

Phase factor & MiniBooNE excess

Oscillation probability

$P = \sin^2 2\theta \sin^2 \Phi/2$

Signatures:

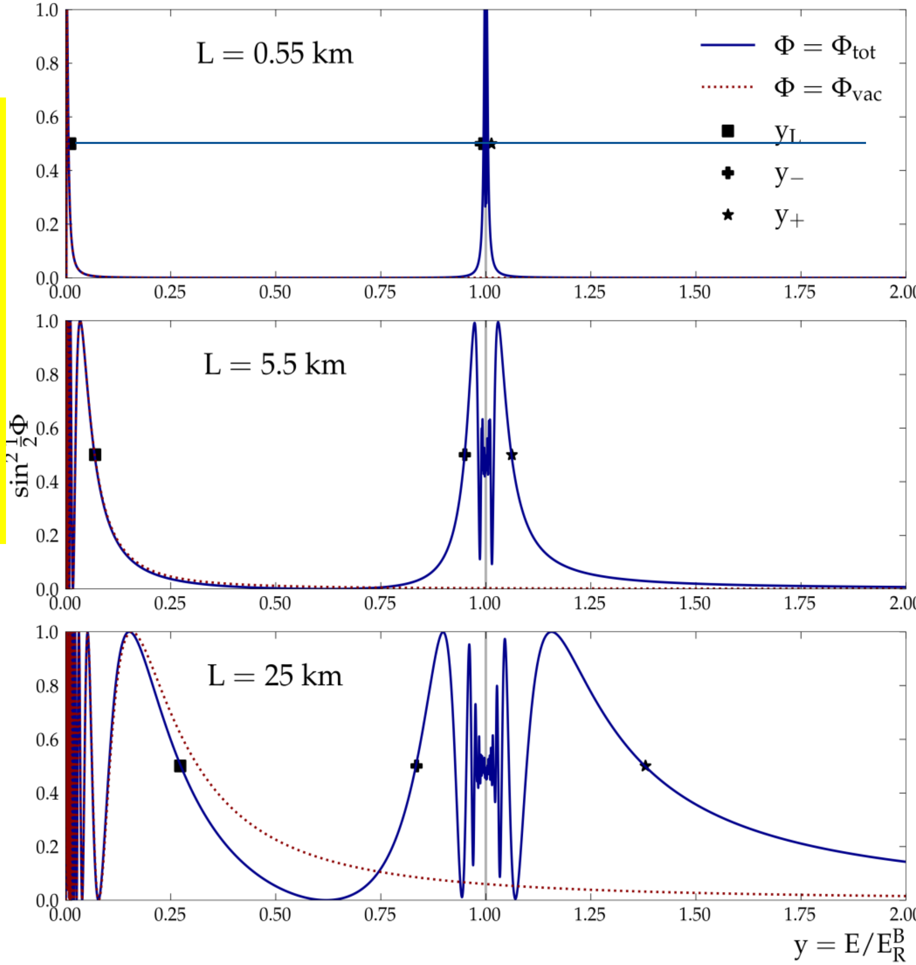
- dip,
- bump (after averaging fast oscillations),
- tail

MiniBooNE excess is
due to bump for relatively small L,
apart from resonance region
200 -400 MeV the phase and
oscillations effect are small.

J. Asaadi et al., PRD 97, 7, 2470, (2018)

MB

Oscillatory factor



energy

Excluding MiniBooNE explanation

A.S. , V.Valera,
2106.13829 [hep-ph]

Based on dependence on energy of

Δm_{eff}^2 (E)

It is expected that

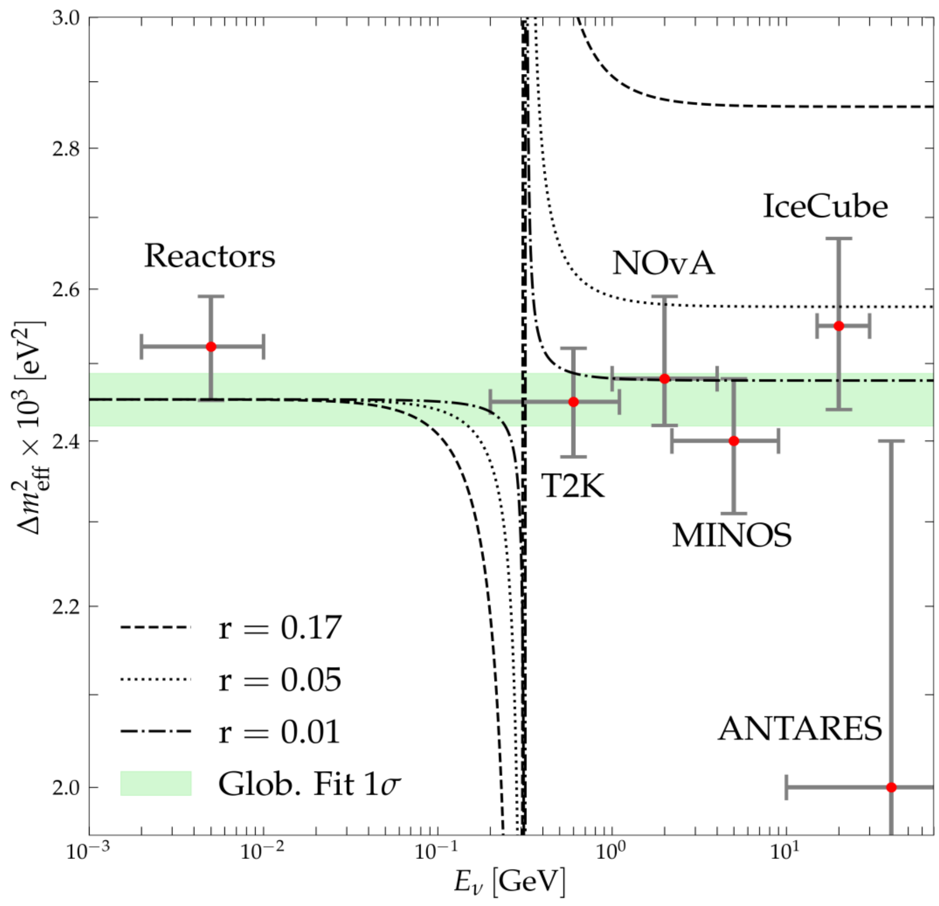
Δm_{eff}^2 (E << E_R) = Δm^2

Δm_{eff}^2 (E >> E_R) = r Δm^2

MB explanation requires r > 1.6

Data are consistent with Δm_{eff}^2 = const and give bound

r < 0.01



Dependence of the

Neutrino oscillations and neutrino mass

C .Lunardini, A.S.
Ki-Yong Choi, Eung Jin Chun, Jongkuk Kim, 2012.09474 [hep-ph],

Above resonance $E \gg E_R$ ($y \gg 1$) the potential

$$V^B \sim \frac{1}{E}$$

has the same behaviour as the kinetic (mass) term $\Delta m^2/2E$

- general dependence at large E

It is proof of the existence of 1/E term in the Hamiltonian of the evolution equation that allowed to conclude: oscillations imply the mass (coupling of neutrinos with VEV) - MAY IMPLY

The conditions for 1/E dependence from scattering:

Light mediator: $m_{med} \ll \sqrt{2Em_{tar}}$

Light target: $m_{tar} \ll E$

Neutrino oscillations without neutrino mass

Effective neutrino mass due to interactions $m_{eff}^2 \sim \frac{g^2 n_\chi}{4\, m_\chi}$

Up to now the condition for 1/E dependence (mass) has been checked down to 0.1 MeV, therefore

$$E_R \ll E^{obs} \sim 0.1 \text{ MeV}$$

Problem?

Due to dependence on energy and number density of scatterers m_{eff} can be different in different space –time points, in contrast to the standard mass due to coupling to VEV (does not depend on z)

$$m_{eff}(z) \sim \sqrt{n(z)} \qquad n(z) = n_0 (1 + z)^3$$

The effective mass increased in the past in contrast to standard generated by VEV.

Dependence of the effective mass on density and energy

$$m_{eff}(z) \sim [\xi (1 + z)^3]^{1/2} m_{eff}(loc)$$

$1/\xi \sim 10^5$ - local (near the Earth) over-density of the background

In the epoch of matter-radiation equality, $z = 1000$, DM should already be formed and structures start to grow.

For $m_{eff}(loc) = 0.05$ eV and $1/\xi \sim 10^5$ ➡ $m_{eff}(1000) \sim 5$ eV

- violates cosmological bound on the sum of neutrino masses

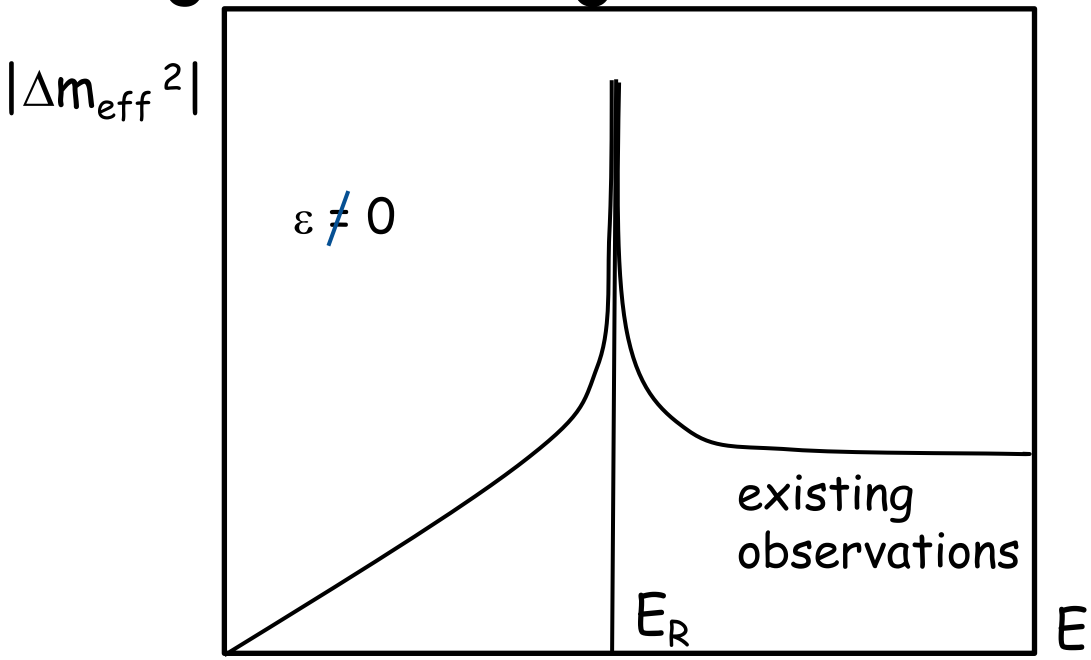
For not very small E_R one should take into account dependence (decrease) of $m_{eff}(loc)$ with neutrino energy

$$\Delta m_{eff}^2(E) \sim \frac{y(y - \varepsilon)}{y^2 - 1} \Delta m^2$$

$y = E/E_R$

and for relic neutrinos $m_{eff}(loc)$ can be very small

Avoiding cosmological bound



$E_R = m_\phi^2/2m_\chi$

For $\varepsilon = 0$ decrease of mass with E is even stronger

Below resonance: $m_{eff}^2(\ll E_R) = m_{eff}^2(\gg E_R)\frac{E}{E_R} = m^2 \frac{E}{E_R}$

Suppose $E_R = 0.01$ MeV

For relic ν, $E = 10^{-4}$ eV , $m_{eff} < 5\ 10^{-6}$ eV CMB bound is satisfied

For KATRIN: $E = 1$ eV: $m_{eff} < 2\ 10^{-4}$ eV - not measurable

Neutrino bound states and systems

Generic consequence of long range scalar forces

M. Markov, Phys.Lett. 10,122 (1964)

Neutrino superstars: Massive neutrinos + gravity, used analogy with neutron stars, m_ν = MeV → $M = 10^6 M_{sun}$, $R = 10^{12}$ cm

For m_ν = 0.05 eV: $M = 4 \times 10^{20} M_{sun}$, $R = 5 \times 10^{26}$ cm

R. D.Viollier et al, Phys.Lett. B306, 79 (1993) ,....

Gravity, m_ν = (10 – 100) keV: $M = (10^8 - 10^{10}) M_{sun}$, $R = (10^{14} - 10^{16})$cm

essentially, warm DM

G. J. Stephenson et al, Int. J. Mod. Phys. A13, 2765 (1998) ...

Scalar forces, m_ν = 13 eV, motivated by ^3H exp. anomaly, negative m^2

Equations of motion → Equations for final configurations → Density profiles

Formation of clouds in the Universe – as phase transition.

$M = (10^8 - 10^{10}) M_{sun}$, $R = 10^{13}$cm, central density: 10^{15} cm^{-3}

Neutrino clouds revisited

A.Y.S, and Xun-Jie Xu, to appear

The latest bounds on m_ν and g are used

Final configuration of clouds found

Non-relativistic case: Lane - Emden equations for scalar forces (essentially eq of hydrostatic equilibrium)

Generalized to relativistic case

Formation in analogy to formation of DM halos

Fragmentation → Virialization → Cooling

Neutrino structure of the Universe: clouds-voids

Applications for detection of relic neutrinos

Characteristics of neutrino clouds

A.Y.S, and Xun-Jie Xu, to appear

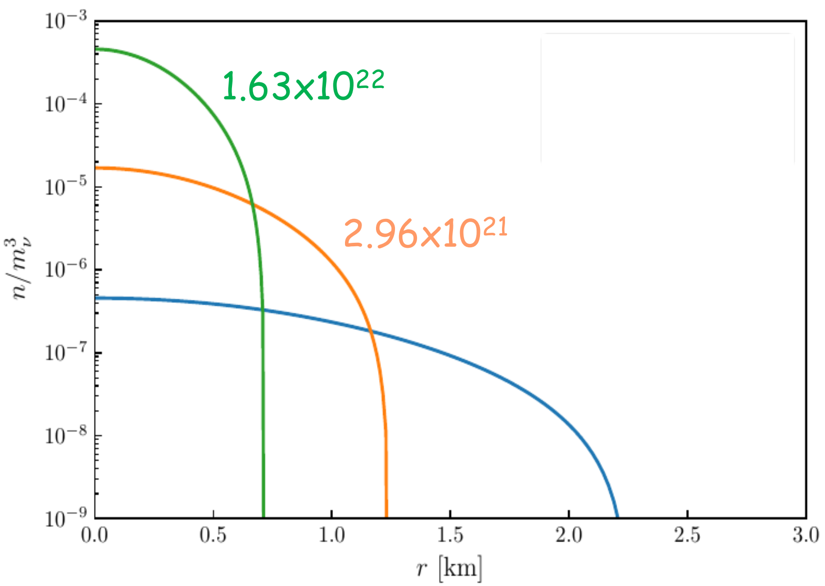
Global characteristics for different total numbers of neutrinos N

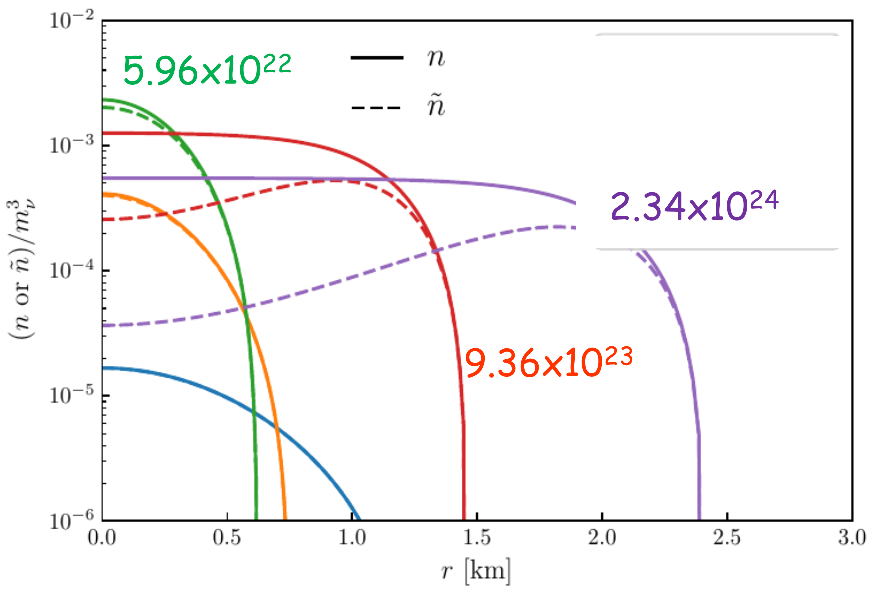
N	2.96×10^{21}	1.63×10^{22}	5.96×10^{22}	9.36×10^{23}	2.34×10^{24}
m_ν^*/m_ν	0.991	0.922	0.688	0.060	0.014
R, km	1.25	0.75	0.62	1.46	2.41
n^0, cm^{-3}	2.0×10^6	4.9×10^7	3.7×10^8	1.5×10^8	6.1×10^7

$y = 10^{-7}$
$m_\nu /= 0.1$ eV

$m_\nu^* = m_\nu + V$ - the effective neutrino mass in medium, n^0 - central density

Density and effective density distributions in the clouds for different N





Neutrino masses, mixing and flavor symmetries

Modular symmetries as flavor symmetries

F. Feruglio

Gui-Jun Ding, S.F. King, Xiang-Gan Liu, S. Petcov, A V. Titov, M. Tanimoto , T. Nomura, H. Okada, T Kobayashi, O.Popov Y. Shimizu, P Novichkov, J. Penedo, T Osaka, A. Romanino, I. De Medeiros Varzielas, X Wang, S. Zhou ...

Nice introduction by J. Penedo

Motivated by string theory

Symmetry related to (orbifold) compactification of extra dimensions and primary realized on the moduli fields τ which describe geometry of the compactified space.

Hope was to

Reduce number of parameters, more predictive - ?
Connect masses and mixing - ?

Modular symmetries

For single modulus field τ the modular transformation γ

$$\tau \rightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d}$$

The 2x2 matrices of integer numbers $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$ with det. $ad - bc = 1$

form the group $\Gamma = SL(2, Z)$ [special, linear, integer ...]

Modular group Γ_N is finite subgroup of Γ, quotient group of the level N:

$$\Gamma_N = \Gamma / \Gamma(N)$$

Isomorphic to the groups considered previously ..

Yukawa couplings are modular forms

- holomorphic functions of modulus field τ
- Form multiplets of the group Γ_N and transform as superfields:

$$Y_i(\tau) \rightarrow Y_i(\gamma\tau) = (c\tau + d)^k \rho(\gamma)_{ij} Y_j(\tau)$$

k is the weight of multiplet

$\rho(\gamma)$ is the representation of γ element of the group Γ_N

dimension of the multiplet is determined by the level N and weight k

Dependence $Y_i(\tau)$ is determined by transformation properties

Invariant Lagrangians

Invariance of terms of the superpotential $\alpha\, Y\, \varphi_1\, \varphi_2\, \varphi_3$ (Y constant) requires

$$\rho_1 \times \rho_2 \times \rho_3 \times \rho_Y = I$$

$$\Sigma_\iota\, k_i + k_Y = 0$$ for weights

The latter condition acts to some extent as Froggatt- Nielsen symmetry it gives additional restrictions, forbids some term →texture zeros

Comparing with usual approach with flavons

$Y_1(\langle\tau\rangle)\ , Y_2(\langle\tau\rangle)\ \ldots\ Y_n(\langle\tau\rangle)$

For a given N,k, r - known functions of the same VEV

$\langle\chi_1\rangle, \langle\chi_2\rangle, \ldots, \langle\chi_n\rangle$

Depend on parameters of potential not controlled by symmetry, independent for different representations

Can do the same

From Model building to Symmetry building

Minimal simpest versions do not reproduce data well.

Generic predictions of masses: weak hierarchy, often quasi-degenerate, Majorana CP-phases

More parameters needed
Several moduli, flavons,

Different representations of the same dimension, fine tuning of corresponding couplings

Different ways of construction of finite groups
In the end: # parameters is comparable to # of observables

Use modular symmetry in wrong way?

CKM and the dark sector physics

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

Common sector for quarks and leptons. Implies

$m_l \sim m_d$ $\qquad m^D_\nu \sim m_u$

Q - L unification, GUT

CKM physics:
hierarchy of masses
and mixings ,
relations between masses and
mixing

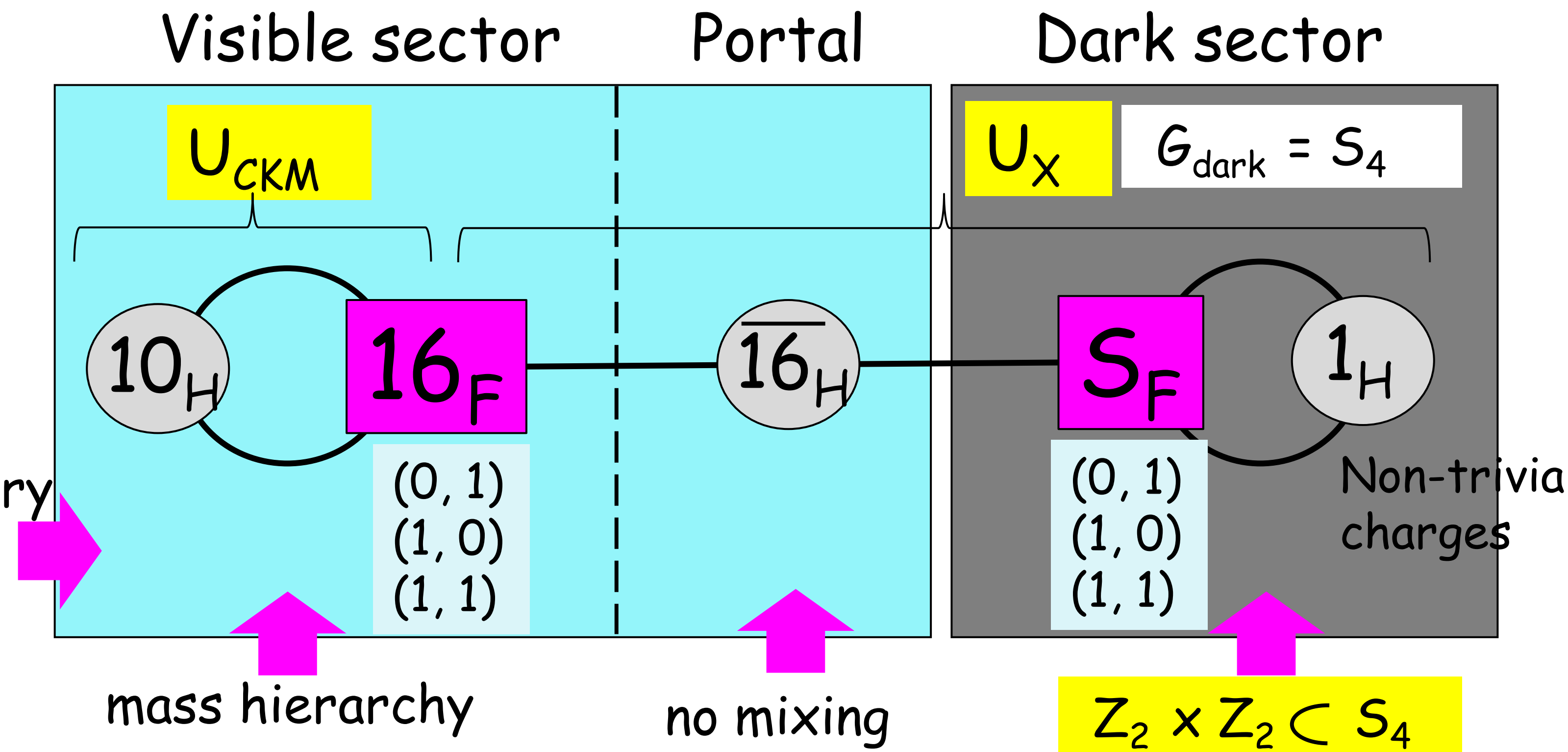
From the dark sector coupled to neutrinos. Responsible for
large neutrino mixing
smallness of neutrino mass

may have special symmetries
Modular symmetries ? which
lead to BM or TBM mixing

An SO(10) GUT with $G_{dark} = S_4$

Xun-Jie Xu , A.S

Basis fixing symmetry $Z_2 \times Z_2$



Spontaneously broken by flavons

CKM mixing - additional structure

Double seesaw
$M_S \sim M_{Pl}$
$M_D \sim M_{GUT}$
$m_D \sim M_D$ = diag

$M_S \sim M_{BM} \rightarrow$ BM mixing

$\delta_{CP} = 144 - 210^0$ (NO)

Conclusions

3 ν - framework works fine, anomalies and tensions found in different oscillation experiments lose sigmas, in particular, the case of sterile neutrino become weaker.

Neutrino interactions with light dark sector –rich phenomenology
- resonance refraction at low energies
- possibility to substitute usual neutrino mass by interactions with medium
- bound neutrino systems...

Modular symmetries – promising, but
in complexity – became comparable to usual symmetries:
simplest versions do not work: can fixed by additional parameters, assumptions now via symmetry building instead of model building. Using MS in the wrong way?