Neutrinos and New physics at Low energy scales

Valery Rubakov fest

WPC, DESY Hamburg, Nov. 9, 2021

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... or second desert?

Why not worry about the low scale desert?

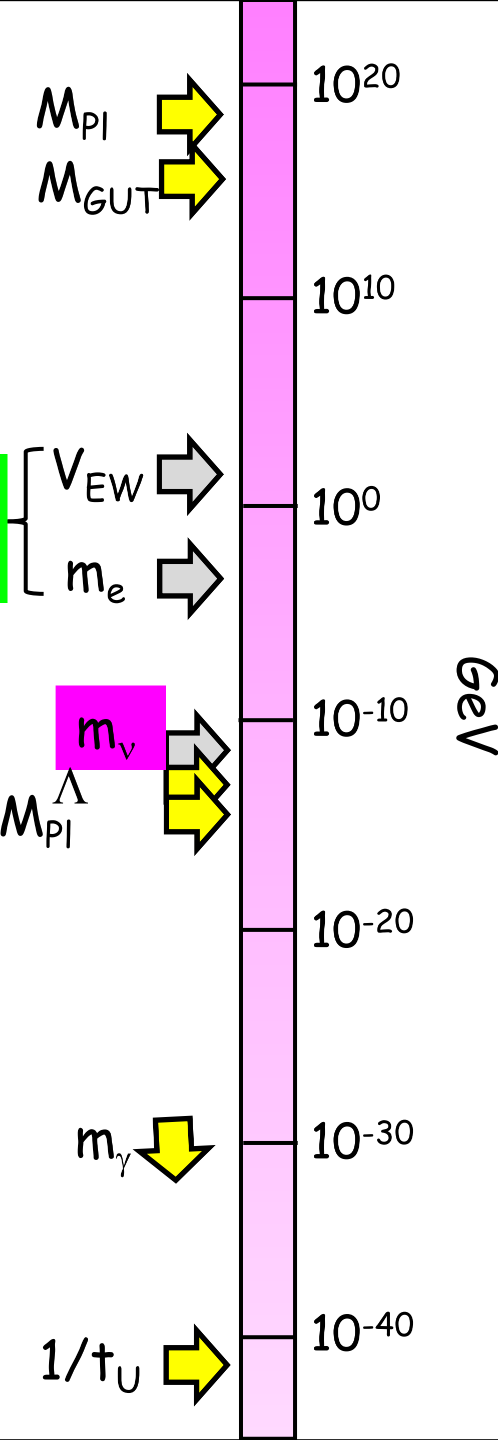
Another hierarchy problem?

High scale desert
14 – 17 orders

Standard masses of the SM particles

BSM origins?

Low scale desert
> 40 orders



Neutrinos can play special role in this picture?

Smallness of ν mass

Neutrino anomalies

→ physics at low E scales

Neutrino mass and low scale physics

"m_ν"

Origin: Low scale physics, refraction with light mediators and scatterers

Inverse seesaw – low (keV) scales of L number violation are involved

Decoupling of high mass scales Weinberg operator

- still from High Scale Physics

Outline:

Neutrinos and evidences of low scale physics

Anomalies

Interactions with light scatterers and mediators

Refraction

effective m_ν

Bounds states – neutrino stars

Evidences?

Solar-KL

CP-tension

Neutrino anomalies

RAA

Reactor ν oscillations

LSND/MB

Ga anomaly

Solar - KamLAND $\Delta m_{21}{}^2$ – tension disappears

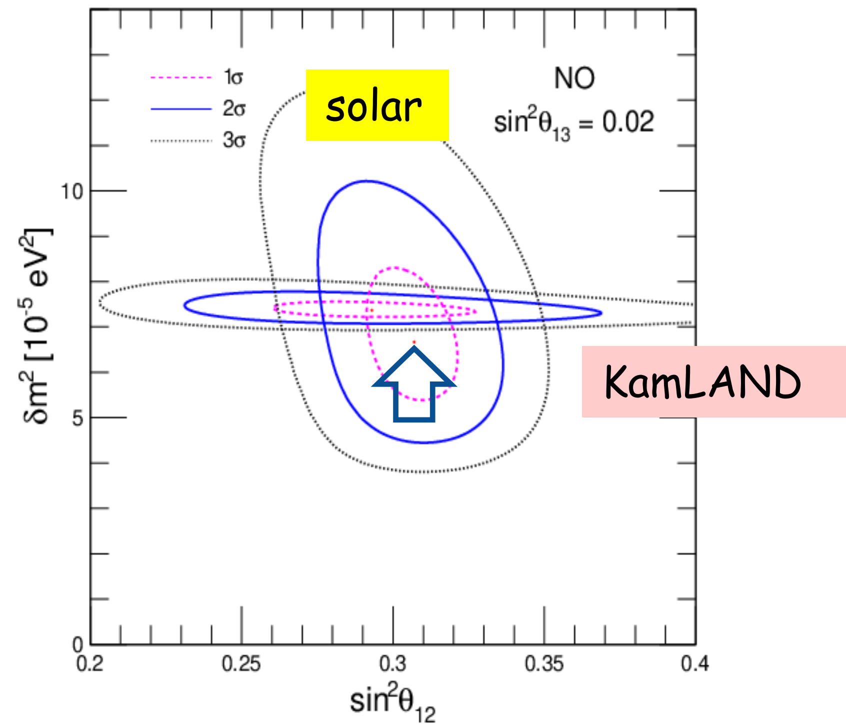
Very light sterile neutrino?

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 $\Delta m_{21}{}^2$ from analysis of the solar neutrino data increased

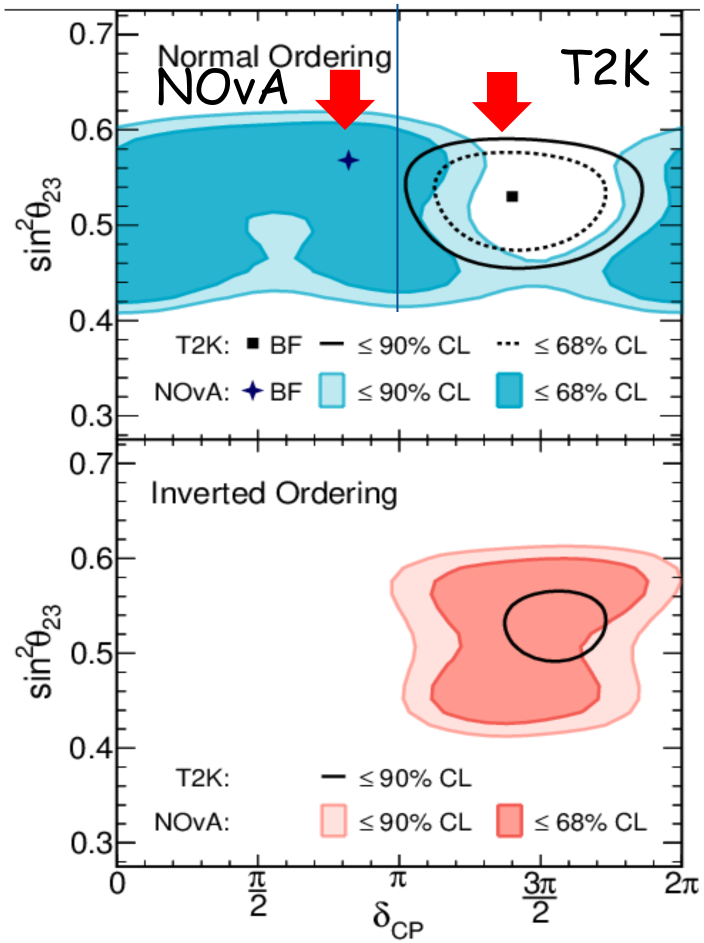
Discrepancy with KamLAND results reduced $2\sigma \rightarrow 1.2\ \sigma$



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]

NOvA: δ_{CP} = 0.82π
disfavors δ_{CP} = 1.5π 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

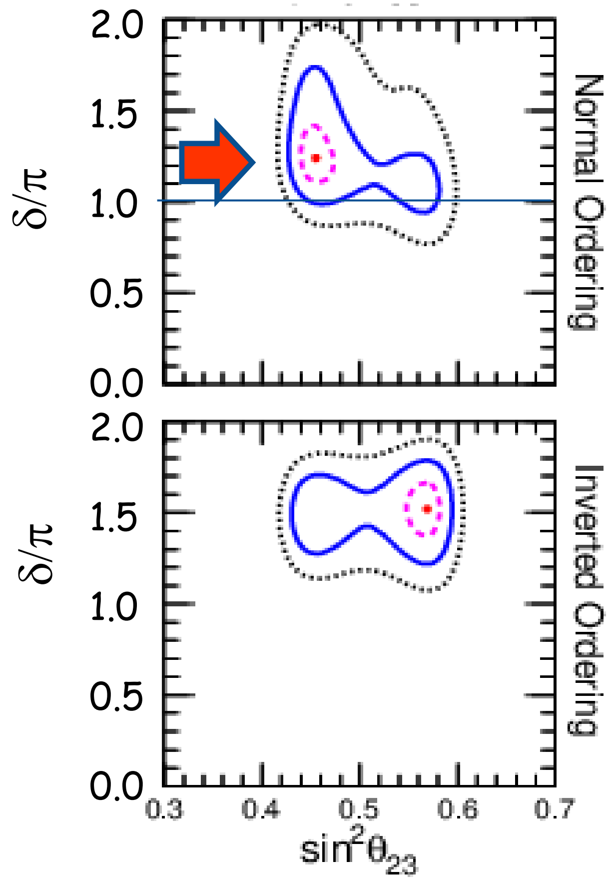
Global fit: $\delta_{CP} \rightarrow \pi$

... or CP-phase close to π?

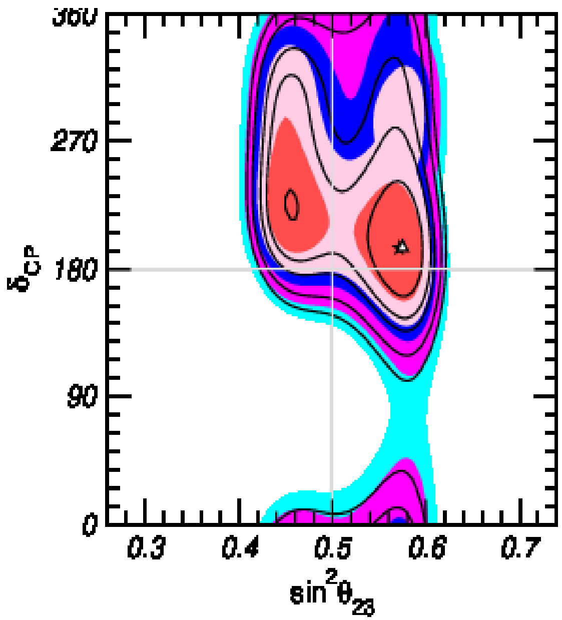
bad news for measurements of CP- asymmetry

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

No CPV (of BM type)

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

λ $\qquad$ λ^3

$\delta_q = 1.2$ +/- 0.08 rad

$\sin \delta_q = 0.93$

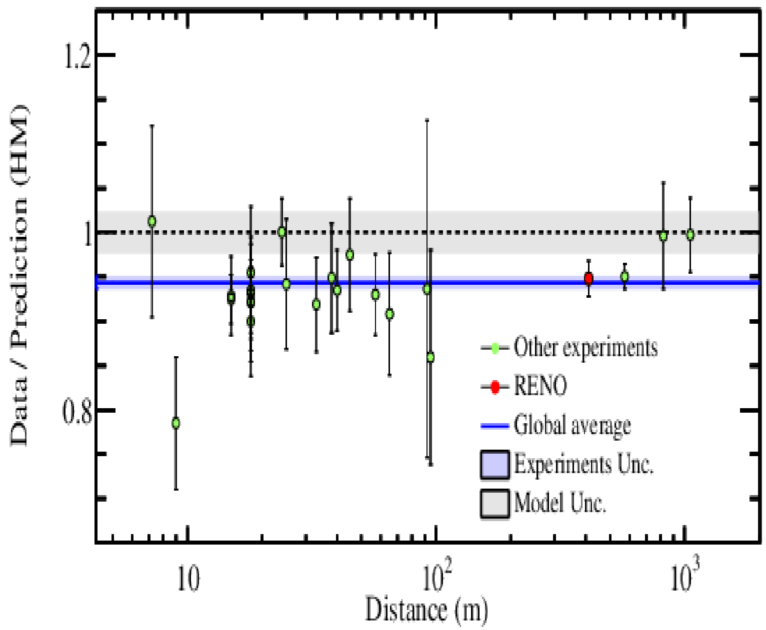
$\sin \delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2 \sim 0.046$

$\delta_{CP} \sim -\delta$ 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

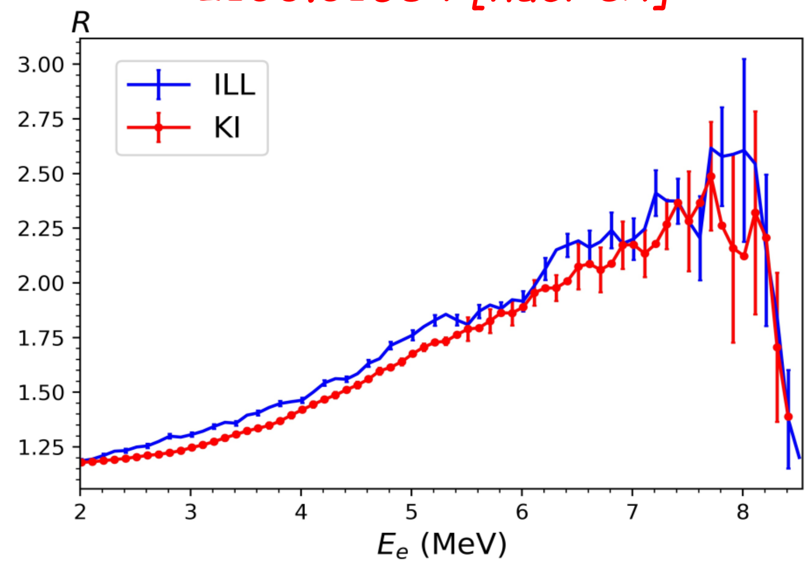
Reactor Antineutrino Anomaly and its re-evaluation



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
$R = S_5 / S_9$

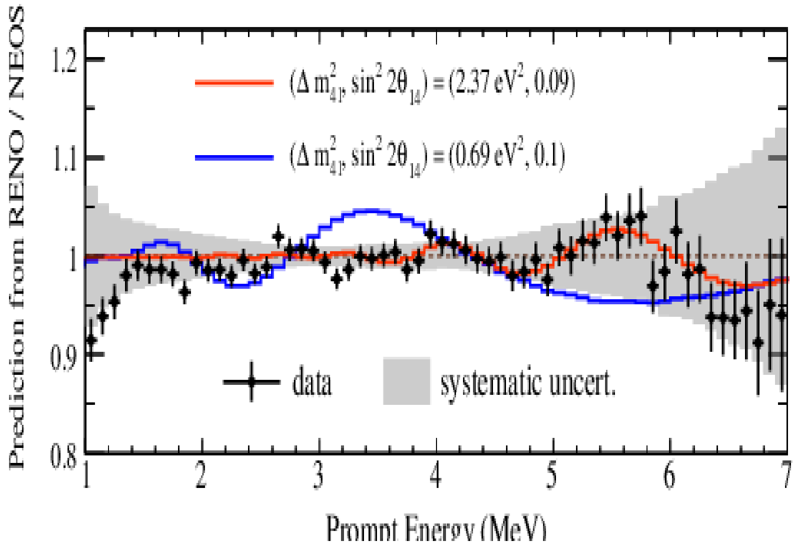
R(ILL) = 0.959 R(KI)

→ explains anomaly

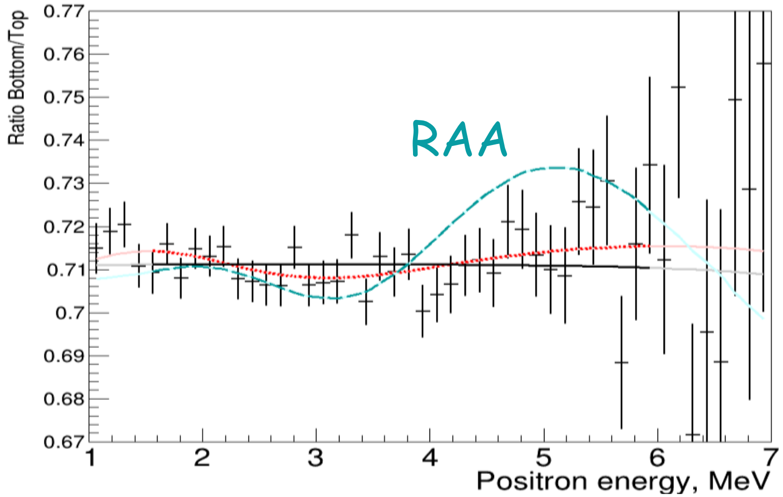
Oscillations or fluctuations?

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]



DANSS
M. Danilov, 2012.10255 [hep-ex]



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

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

RAA (dotted): $\Delta m_{14}^2 = 2.4$ eV^2

$\Delta m_{14}^2 = 1.3$ 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]

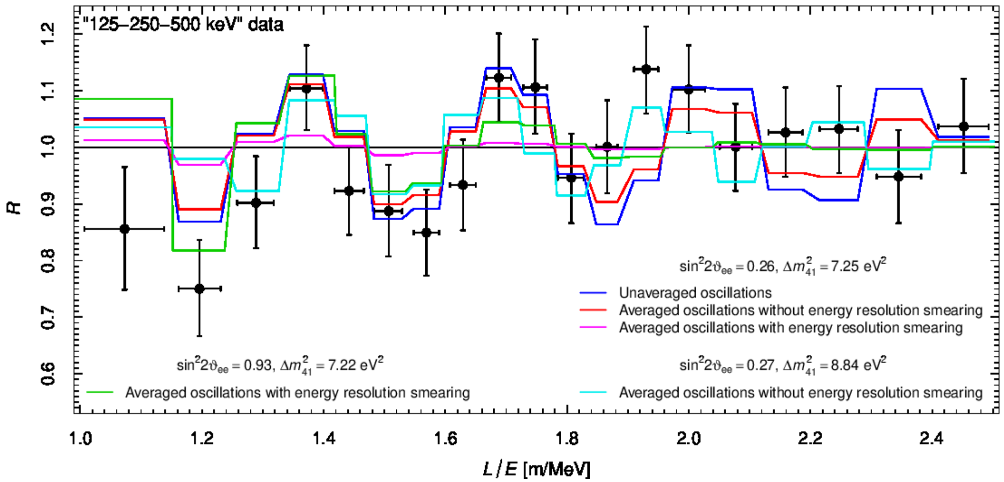
Energy resolution of the detector, more reliable Monte Carlo simulation:

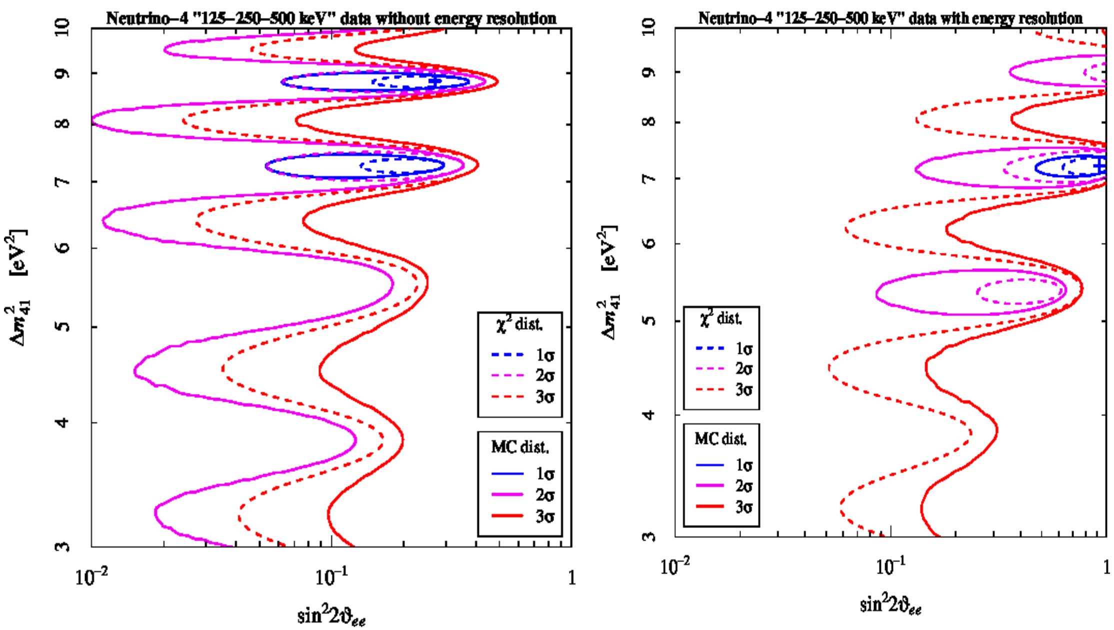
→ Significance reduces:

$3\sigma \rightarrow 2.2\sigma$

→ b.f. point moves to maximal mixing

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



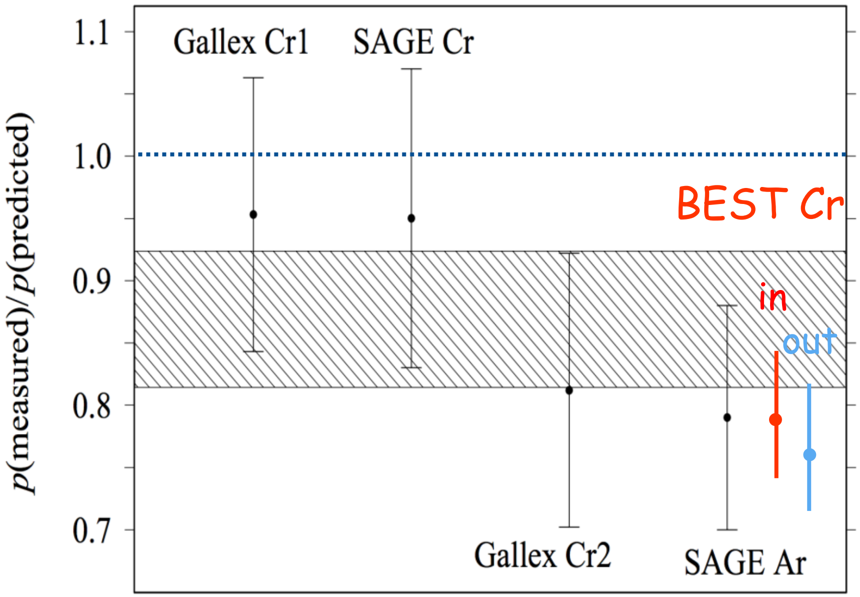


Gallium anomaly and BEST

the Baksan Experiment
on Sterile Transitions

V.V. Barinov, et al, 2109.11482 [nucl-ex]

The gallium anomaly - lacks of electron neutrino events at calibrations of SAGE and GALLEX .



Ratio of suppression factors

R_{out}/R_{in} = 0.97 +/- 0.07

No evidence of oscillations

BEST confirms Ga anomaly with the stat. significance > 5 σ.

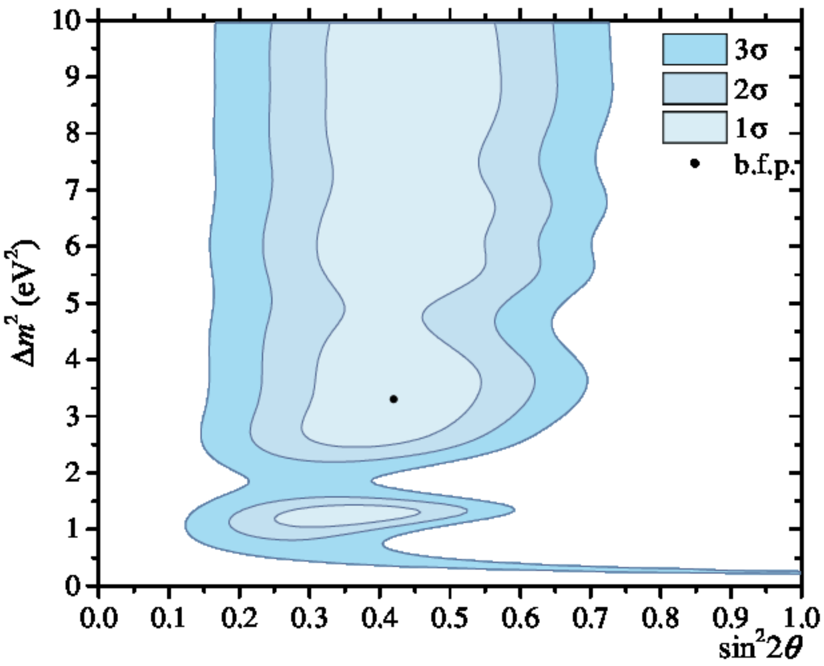
R_{out} = 0.791 +/- 0.050

R_{out} = 0.766 +/- 0.050

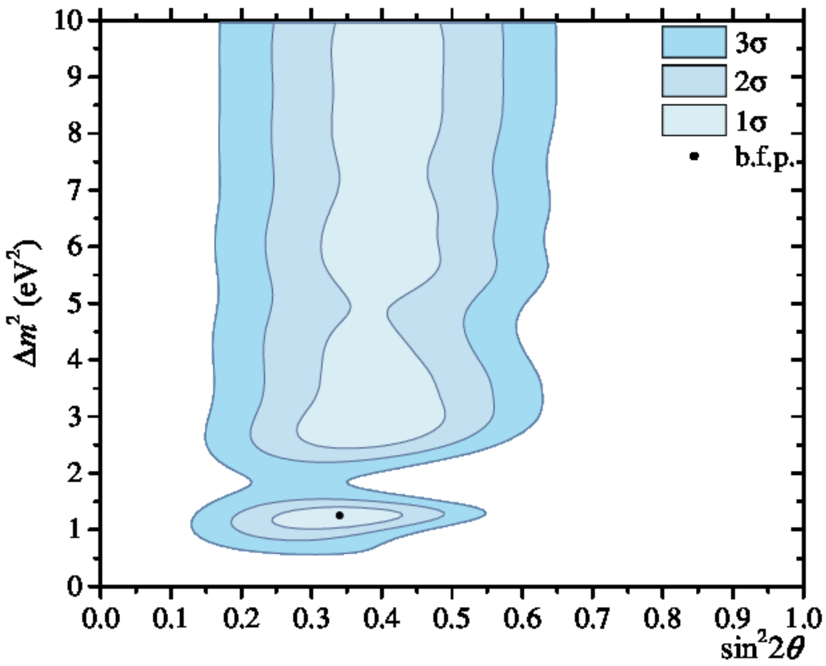
Deficit of events,
Comparison of inner - outer volume signals (two distances)

BEST and oscillations

V.V. Barinov, et al, 2109.11482 [nucl-ex]



BEST only



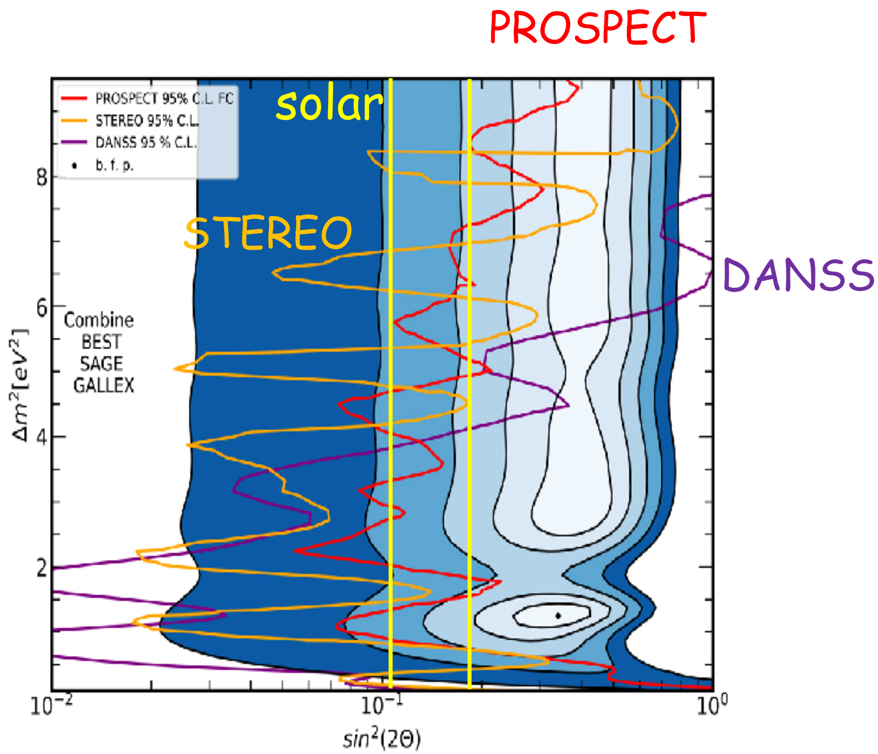
BEST + SAGE + Gallium

$\Delta m_{41}{}^2$ = 3.3 eV^2, $\sin^2 2\theta = 0.42$

$\Delta m_{41}{}^2$ = 1.25 eV^2 , $\sin^2 2\theta = 0.34$

Oscillations at BEST?

V.V. Barinov, D. Gorbunov, 2109.14654 [hep-ph]



Combined fit of BEST, SAGE, Gallex. 95% C.L. limits from reactor experiments STEREO, PROSPECT and DANSS.

Solar neutrinos: 99% CL AGSS09 (L) and GS98 (R) models

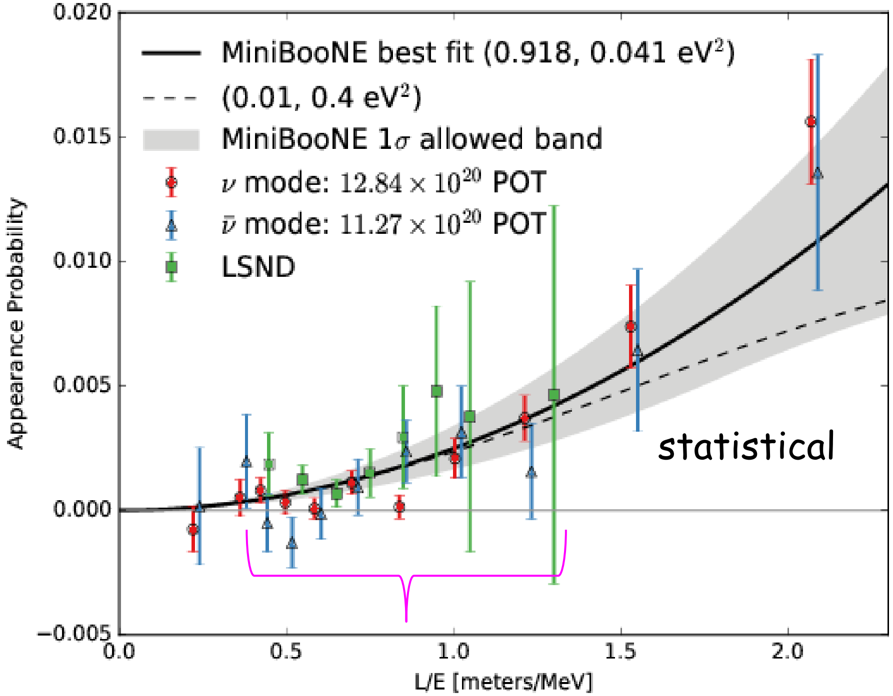
K. Goldhagen et al, 2109.14898 [hep-ph]

Non-oscillatory explanations:

- Extraction efficiency
- Counting efficiency
- Cross-section

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

$\nu_\mu \rightarrow \nu_e$

oscillation interpretation nearly excluded by disappearance data

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

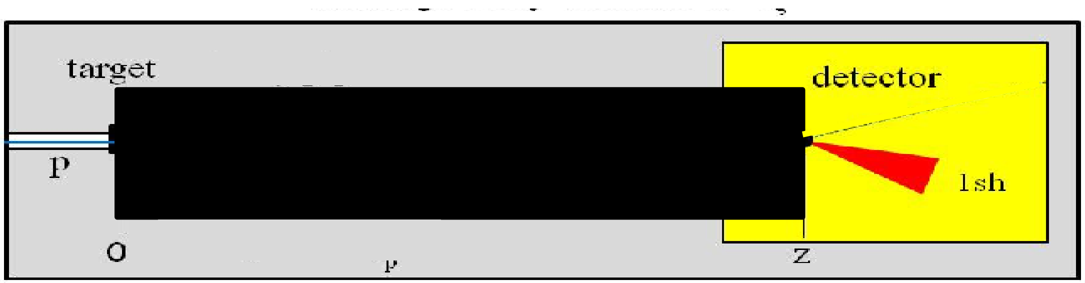
1σ line - for $\sin^2 2\theta = 0.01$ Strongly disfavored

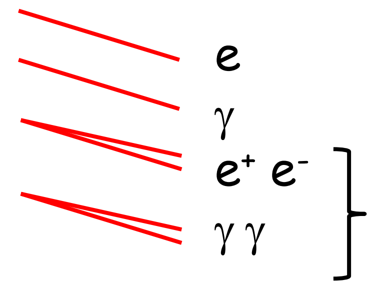
No oscillatory dependence: Non-oscillatory explanations are possible

Many alternative scenarios have been proposed

Effective theory of the MiniBooNE excess

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

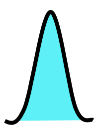


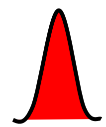


unresolved

proton hits target

EM shower in detector





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

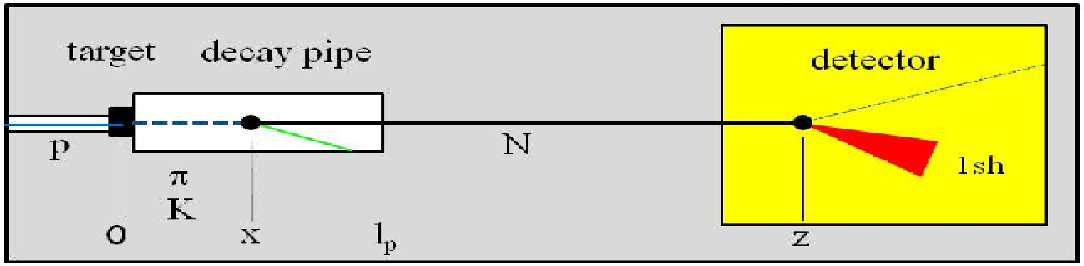
Black box

Production via
Propagation
Decays
Un-scattering
of new particles

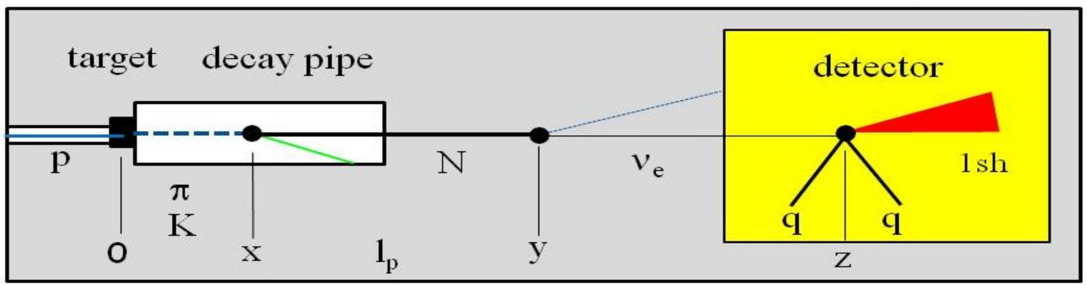
mixing with usual ν
up-scattering of ν

Opening black box

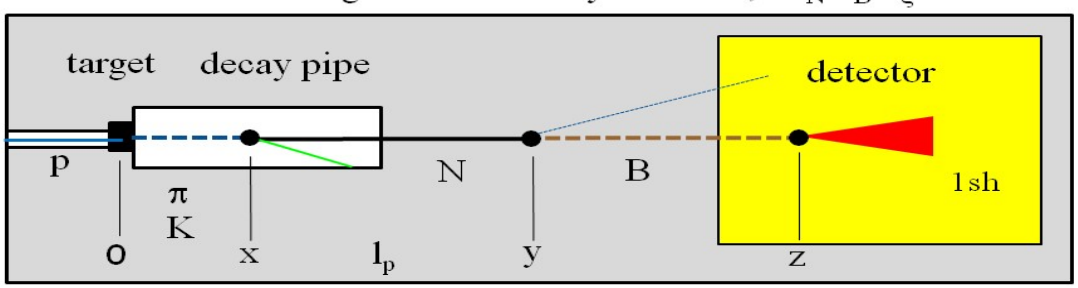
Mixing-Decay scenario MD_ξ



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



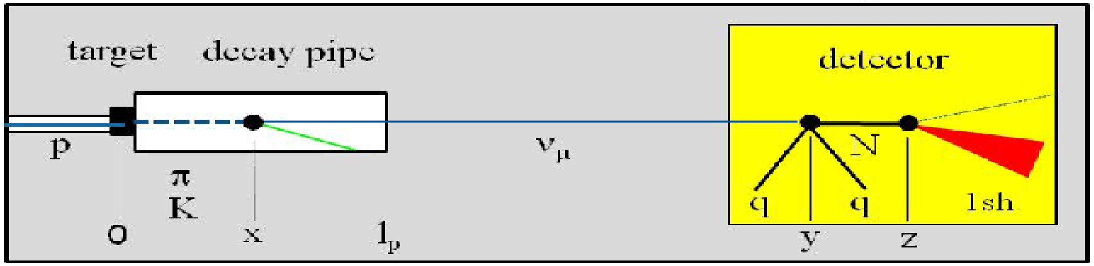
Mixing-Double Decay scenario, $M_N D_B D_\xi$



Opening black box

$U_N\ D_\xi$

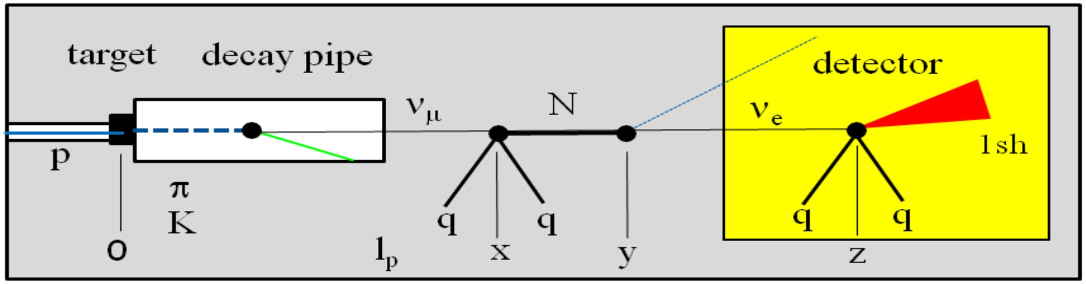
Upscattering-Decay scenario UD_ξ



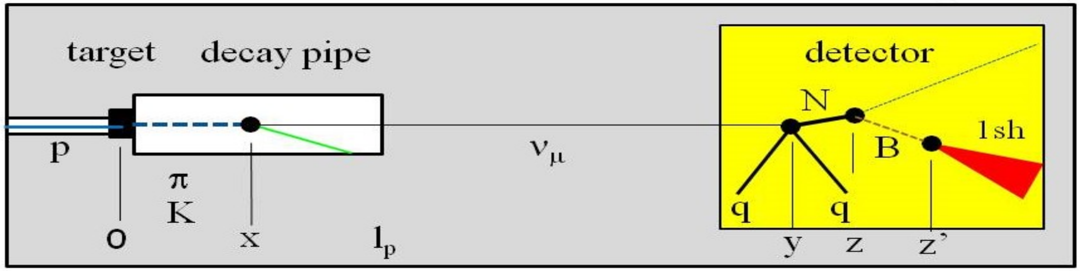
a.

c.

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



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



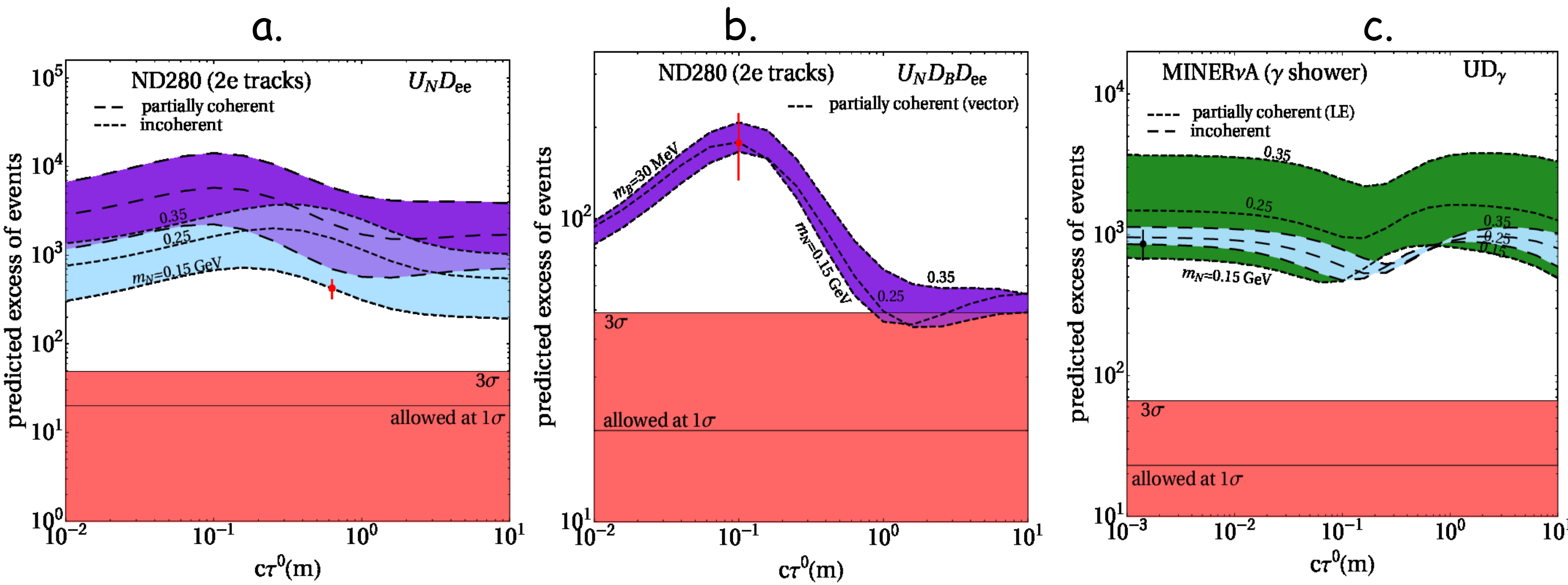
b.

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



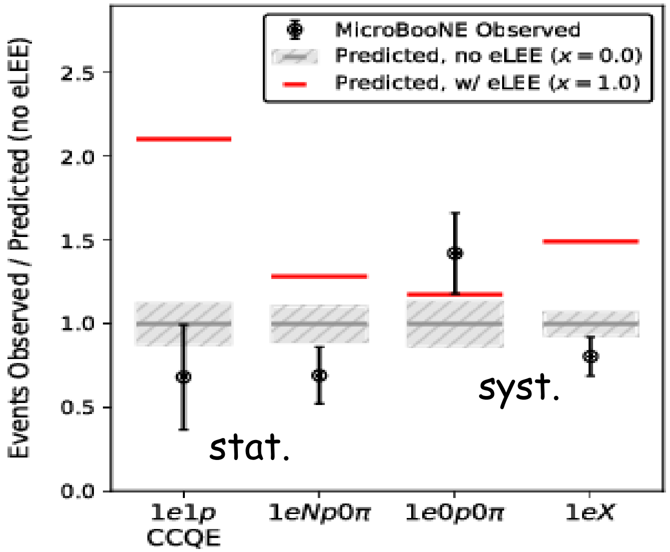
lifetime of heavy neutrino N

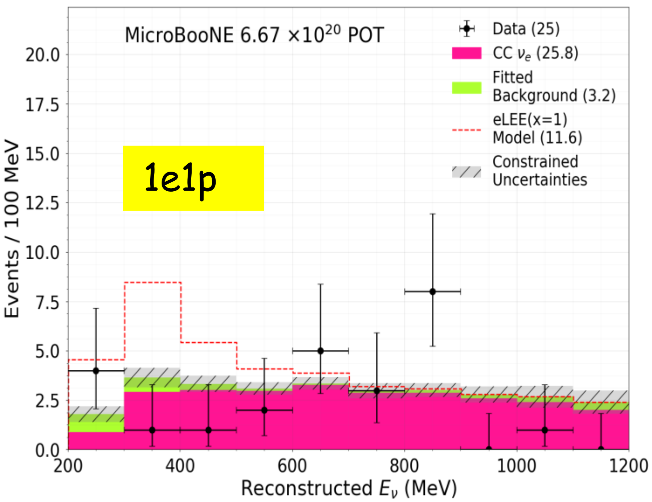
MicroBooNE

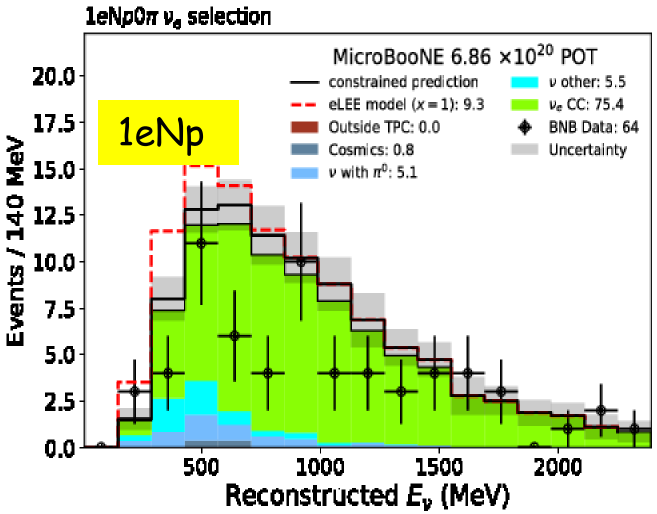
MicroBooNE Collaboration
P. Abratenko, et al, 2110.14054 [hep-ex]

Search for an excess of ν_e interactions with different final states

LAr TPC, 85 t , 72.5 m upstream of MB
468.5 m from Booster ν Beam (BNB)





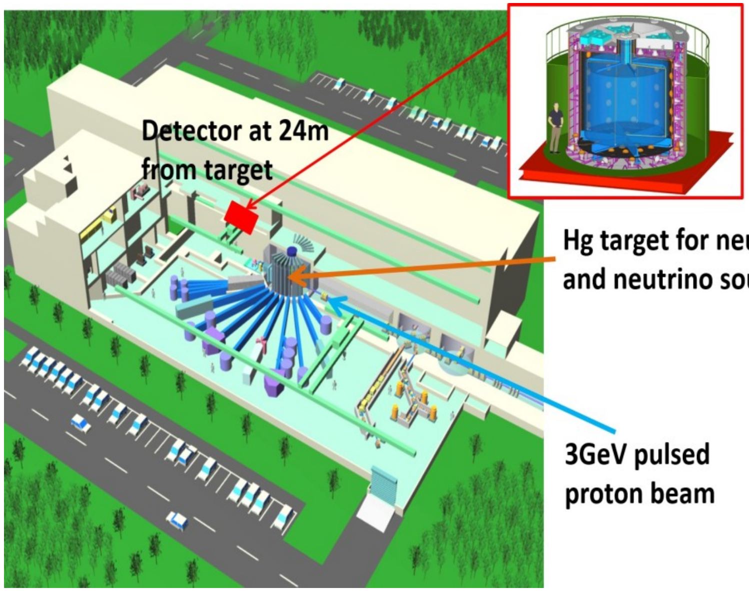


Red – expected with rescaled MB excess

No excess. MB - disfavored
Energy distribution?

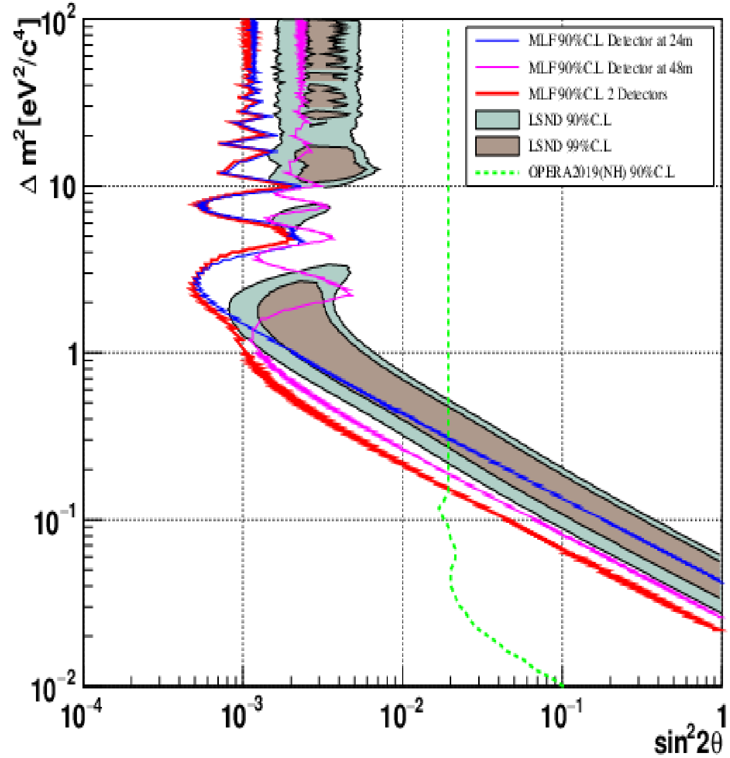
JSNS^2: Ultimate tests?

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

Interactions with light
Scatterers and mediators

The simplest example

M.Kawasaki
H. Murayama
T. Yanagida,
1991

Scalar interaction

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

where χ - fermion (can be RH neutrino), ϕ - scalar

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

L can be generated via the RH neutrino portal

Rich phenomenology

Refraction

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 $\sim g^2/q_{min}^2$

Effective m_ν

Bound neutrino systems

May have important cosmological and astrophysical consequences

Long range forces

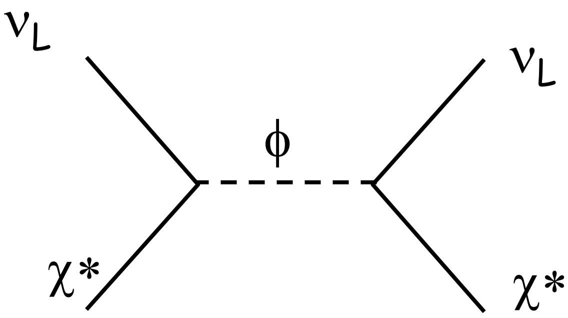
Resonance neutrino refraction

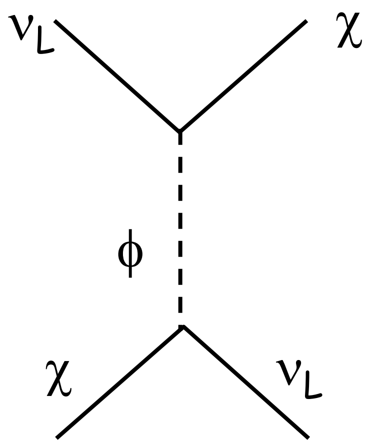
A.S. , V.Valera,
2106.13829 [hep-ph]

Neutrino elastic forward scattering on background fermions χ with scalar ϕ mediator

in SM: due to Z, W

C. Lunardini, A.S.





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

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

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

$$y = E/E_R$$

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

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

width of resonance

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

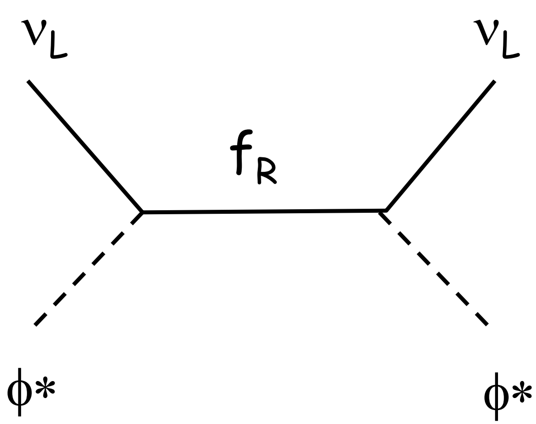
$$\xi = \Gamma/E_R$$

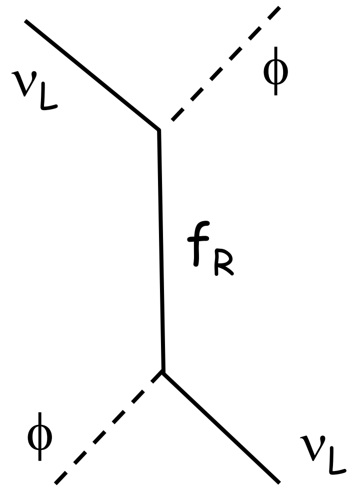
Neutrino refraction on scalar DM

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

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

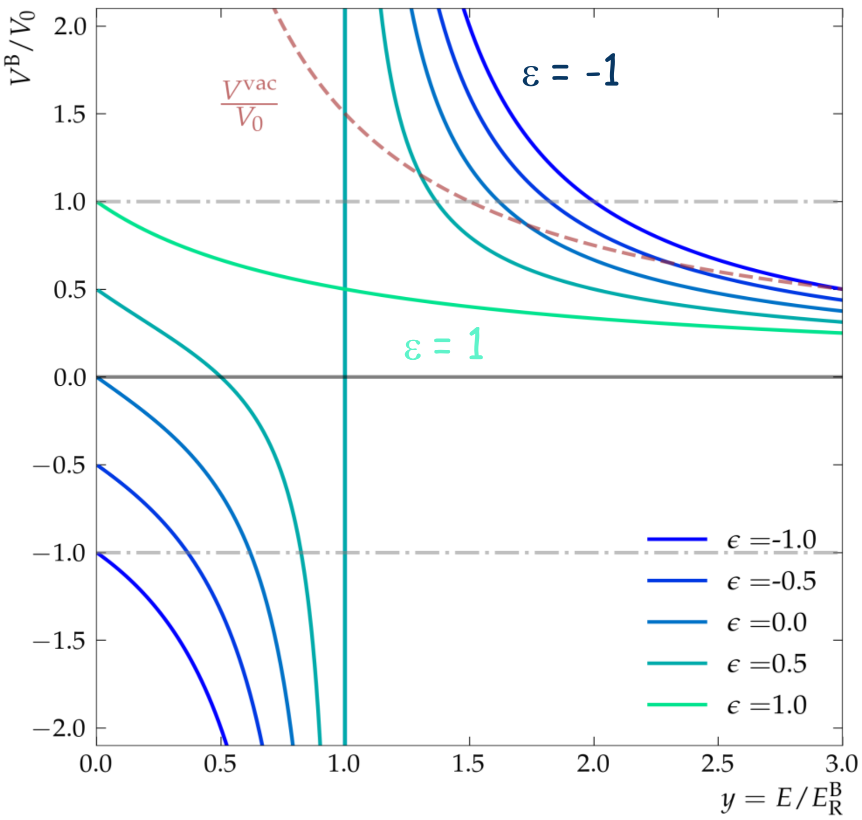
n and $\bar{n}$ – the number densities of ϕ and ϕ^*

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

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

Background potential

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



V^B as function of energy for different values of asymmetry ε

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

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

Wolfenstein's limit $y \to 0$

Neglecting width ξ

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

ε = 1 : no resonance

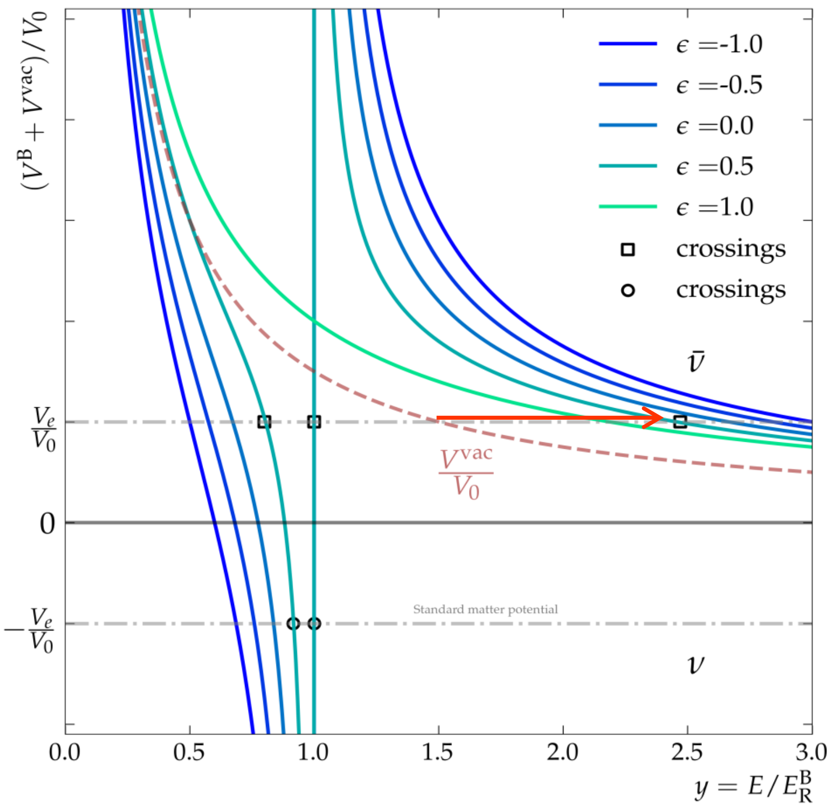
Relative contribution of the background wrt. the vacuum terms

$r = V_0/V_R^{vac}$

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

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

Phase factor & MiniBooNE excess

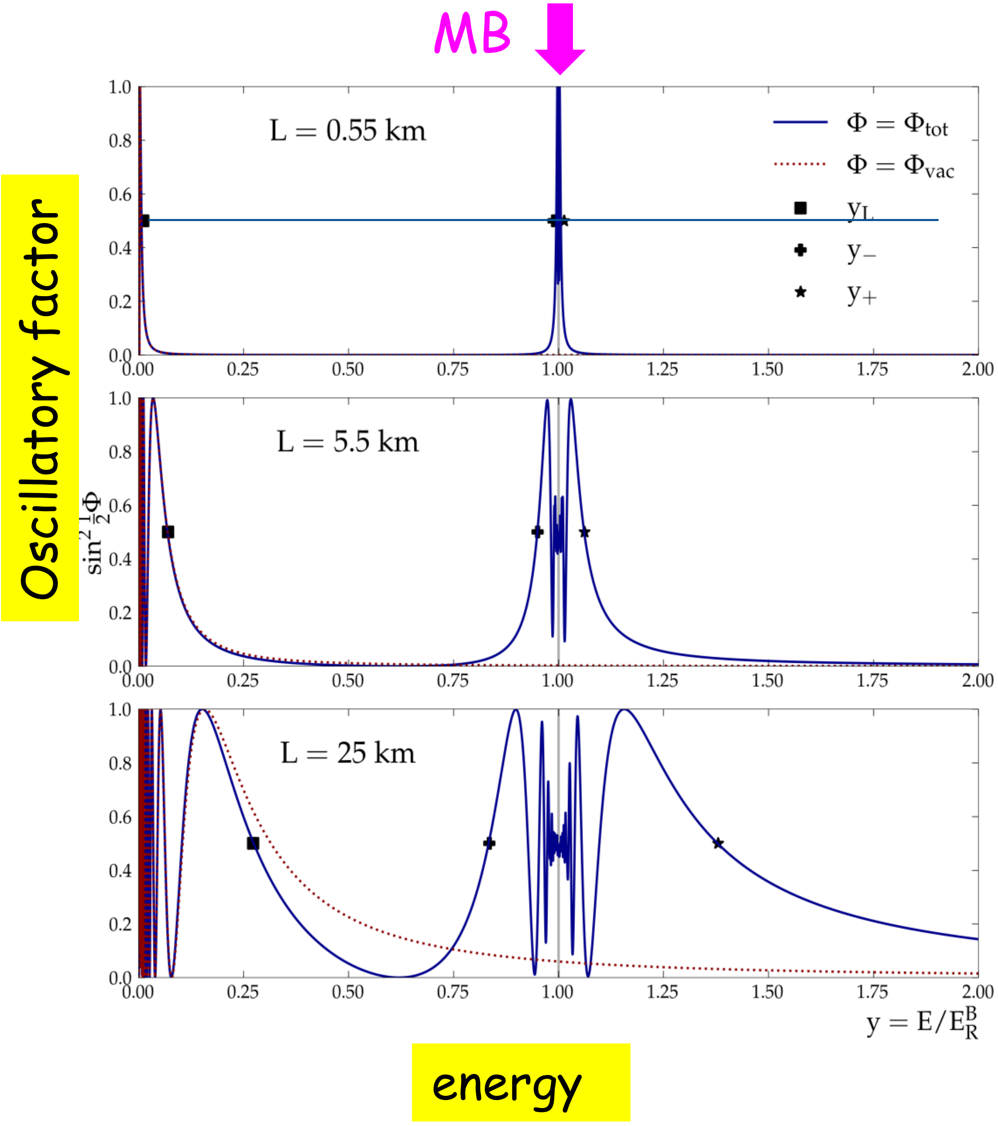
Oscillation probability

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

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

MiniBooNE excess is
a bump for relatively small L.
Apart from resonance region,
200 - 400 MeV, the phase and
oscillation effect are small.

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



Excluding MiniBooNE explanation

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

Based on dependence on energy of

Δm_{eff}^2 (E)

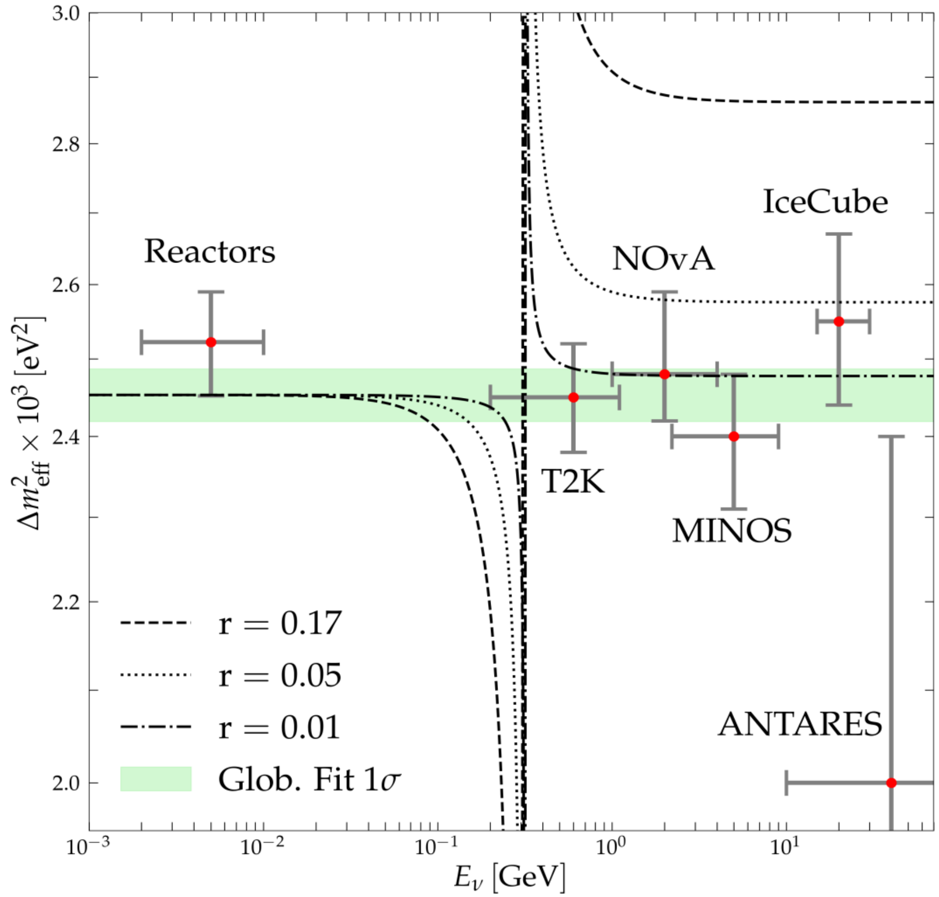
It is expected that

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



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

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

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

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 $m_{eff}^2 \sim \dfrac{g^2 n_\chi}{4\, m_\chi}$

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)

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

- 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

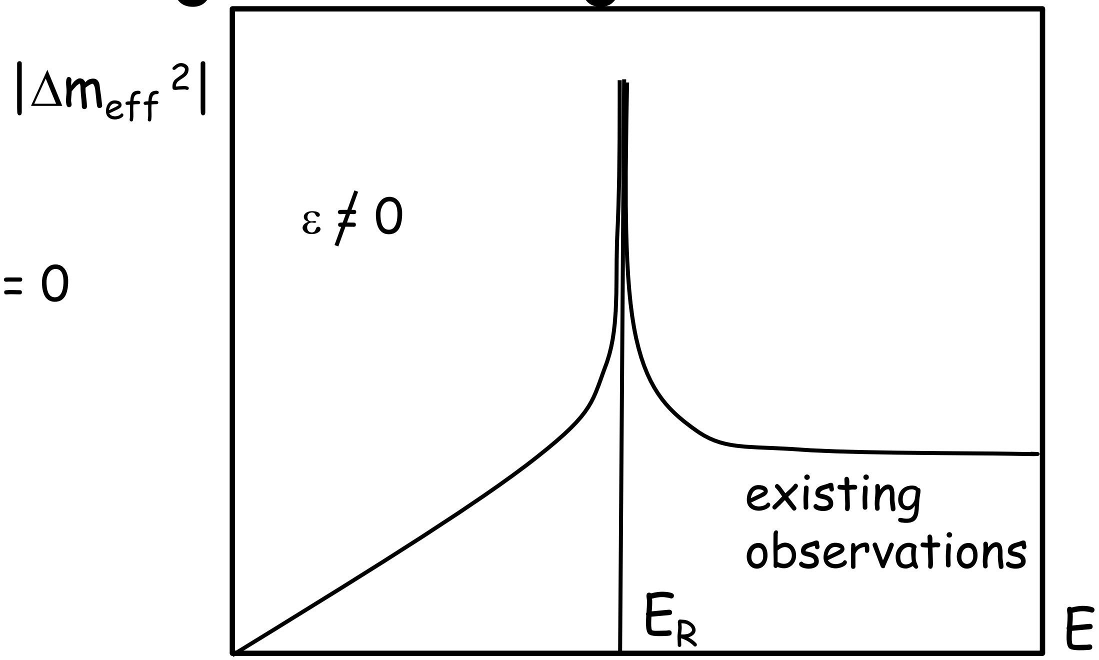
For not very small E_R one should take into account dependence (decrease) of $m_{eff}(loc)$ with neutrino energy

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

$y = E/E_R$

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

Avoiding cosmological bound



$V_{vac} = 0$

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

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

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

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

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: $M = 4\times10^{20} M_{sun}$, $R = 5\times10^{26}$ 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

... continued

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

Long range scalar Yukawa 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 stars, revisited

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

The latest bounds on m_ν and g are used.
Detailed description of final configurations both relativistic and non-relativistic cases,

Equations of motion and equations for stars

$$i\partial\!\!\!/\,\nu - m^*\nu = 0$$

$$(\partial^2 + m_\phi^2)\phi + y\,\bar{\nu}\nu = 0$$

$m^* = m_\nu + y\phi$ - effective mass of neutrino in medium

V

$$\bar{\nu}\nu \rightarrow \langle \bar{\nu}\nu \rangle = \frac{1}{2\pi^2}\int p^2 dp \frac{m_\nu}{E_p} f(p)$$

distribution of neutrinos over p

Final configuration – degenerate neutrino gas

$$f(p) = \begin{cases} 1, & p < p_F \\ 0, & p > p_F \end{cases}$$

Fermi momentum

Non-relativistic case

$p_F < m_\nu$ $\qquad$ $\nu\nu \rightarrow \langle \bar{\nu}\nu \rangle = n$

Equations of motion are reduced to equation of hydrostatic equilibrium for degenerate gas

$$F_{deg}(r) = - F_{yuk}(r)$$

Reduced to the Lane-Emden equation

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{dn^{2/3}}{dr}\right) = - \kappa y^2 n$$

$$\kappa = \frac{2\, m_\nu}{(6\pi^2)^{2/3}}$$

$\gamma = 3/2$ - solution with finite radius

Solved with boundary condition in the center:

$n(0) = n_0$ or $p_F(0) = p_{F0}$

Relativistic case

$$(\nabla^2 - m_\phi^2)\, m^* = y\, n^*$$

$$m^* \frac{dm^*}{dr} = -\, p_F \frac{dp_F}{dr}$$

$$n^* = \frac{1}{2\pi^2} \int_0^{p_F} \frac{m^*}{\sqrt{p^2 + m^{*2}}}\, p^2 dp$$

Equations for m^* and p_F with boundary conditions

$$m^*(0) = m^*_0\,, \quad p_F(0) = p_{F0}$$

and $m^* \to m_\nu$ $r \to$ infty

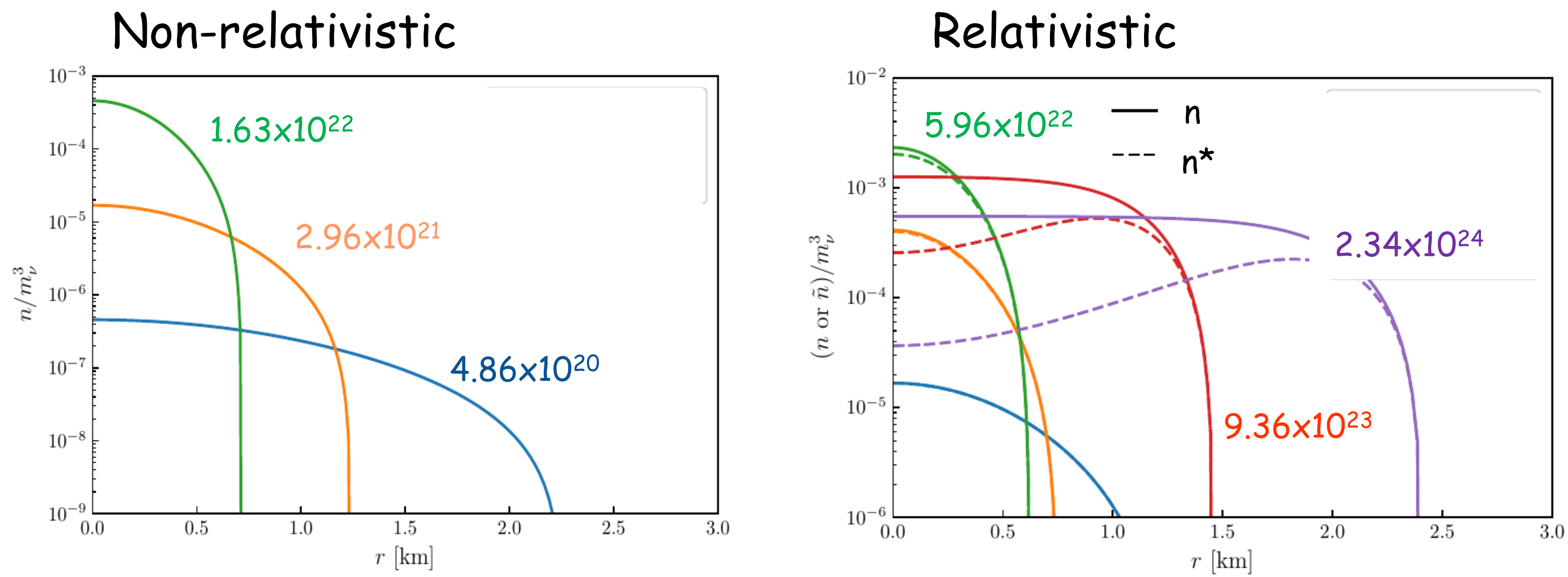
No collapse due to suppression of the attractive force, in contrast to the case of usual stars

Solutions: neutrino stars

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

Density and effective density distributions in the clouds for different N

for $y = 10^{-7}$, $m_\nu = 0.1$ eV, $m_\phi = 0$



Dependence on coupling – scaling:

$N \sim 1/y^3$ $R \sim 1/y$

Characteristics of neutrino stars

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

Global characteristics for different total numbers of neutrinos N for $y = 10^{-7}$, $m_\nu = 0.1$ eV, $m_\phi = 0$

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

non-relativistic ⟷ ultra relativistic

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

n^0 - central density

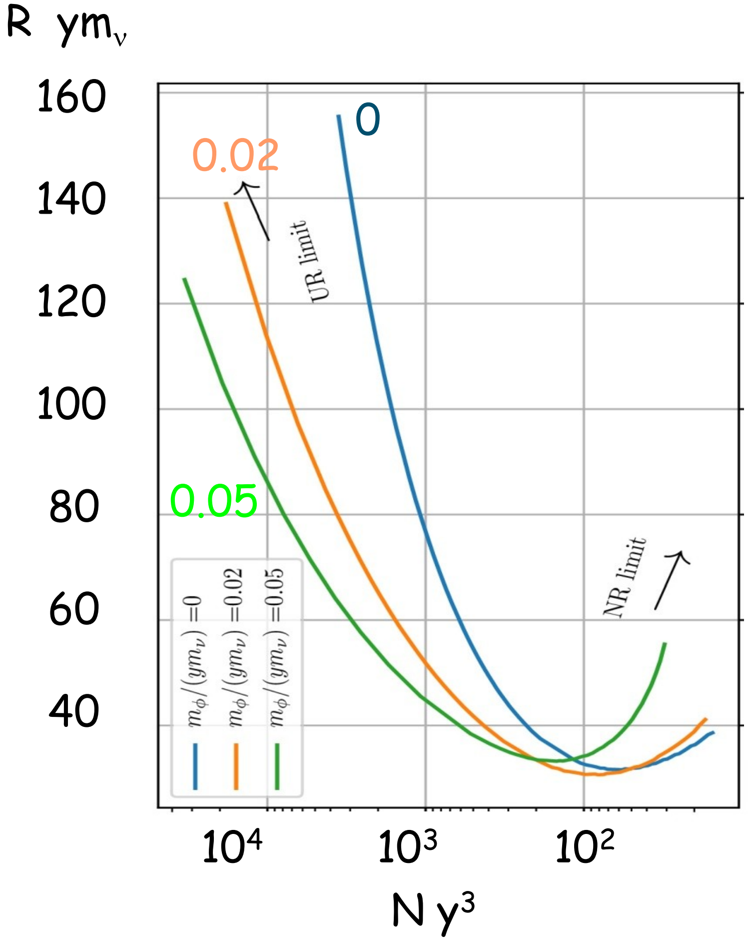
Dependence on coupling – scaling:

$N \sim 1/y^3$ $R \sim 1/y$

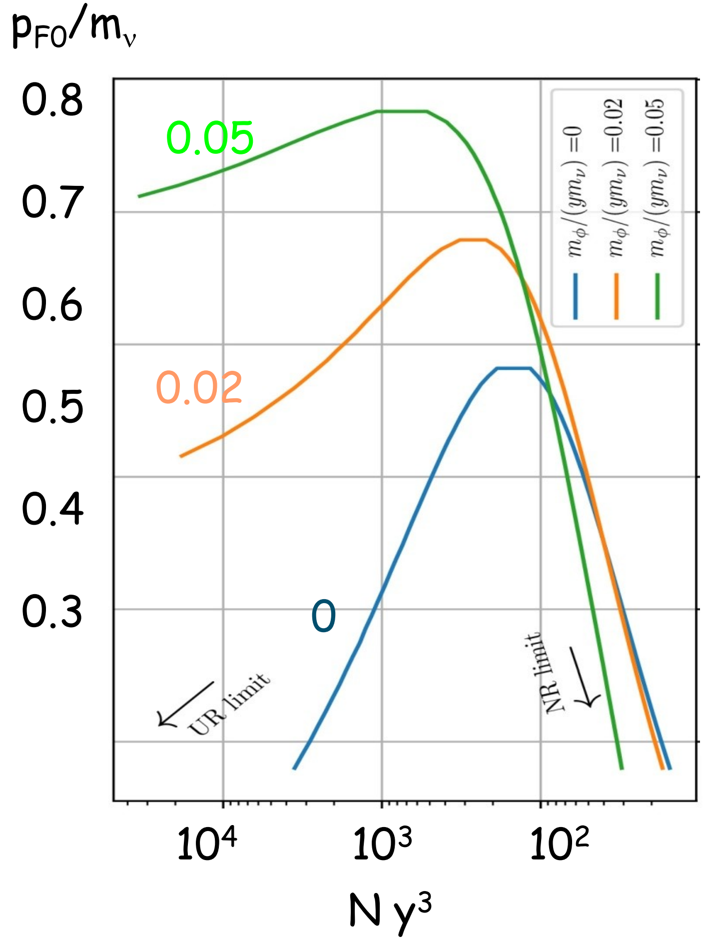
For $y = 10^{-14}$ and $n = 4\ 10^8$ cm^{-3}: $R = 2.4\ 10^{12}$ cm, $N = 2.3\ 10^{45}$, $M = 3.3\ 10^{12}$ g

Properties of Neutrino stars

For non-zero m_ϕ



Radius as function of total number of neutrinos for different values of m_ϕ/m_ν



Fermi momentum in center as function of total number ofneutrinos for different values of m_ϕ/m_ν

Formation of neutrino stars

From the cosmological neutrino background

At early epoch (large n) the effective mass $m^* \ll m_\nu$

With decrease of density $m^* \rightarrow m_\nu$ due to decrease of kinetic energy
$\rightarrow$ formation of degenerate neutrino gas

G. J. Stephenson ,et al.

Total energy in a system per neutrino (for infinite in space system)

$$\varepsilon^{tot}(p_F) = \varepsilon_\nu + \varepsilon_\phi$$

as function of p_F (density) has minimum at

$$p_F^{min} \sim m_\nu$$ for large enough y / m_ϕ

With further decrease of p_F - neutrino sea fragments onto clouds

Total energy for finite systems decreases with N:

$$\varepsilon^{tot}(N, p_F^{min}) \sim N^{-1/3}$$ - due to surface effect

Larger stars are preferable

If $\varepsilon^{tot}(p_F^{min}) < m_\nu$ a star is stable

For $y < 10^{-7}$ cooling mechanisms, (ϕ -emission, ν–annihilation into $\phi\phi$) are negligible

Formation of ν-stars in analogy to formation of DM halos?

Initial sizes horizon at the epoch $p_F^{min} \sim m_\nu$ - close to recombination

$R = 10 - 100$ kpc

Further disintegrations since the stable configurations can be of much smaller size (depending on y)

Clouds and voids

Ratio of distances between stars d and radiuses of stars

$$d/R = 10^{-2}\, d_0\, m_\nu\, y^2\, N^{2/3} \quad \sim 100$$

does not depend on y for stable configuration

d_0 - distance between neutrinos without clustering

Affects detection of relic neutrinos...

Conclusions

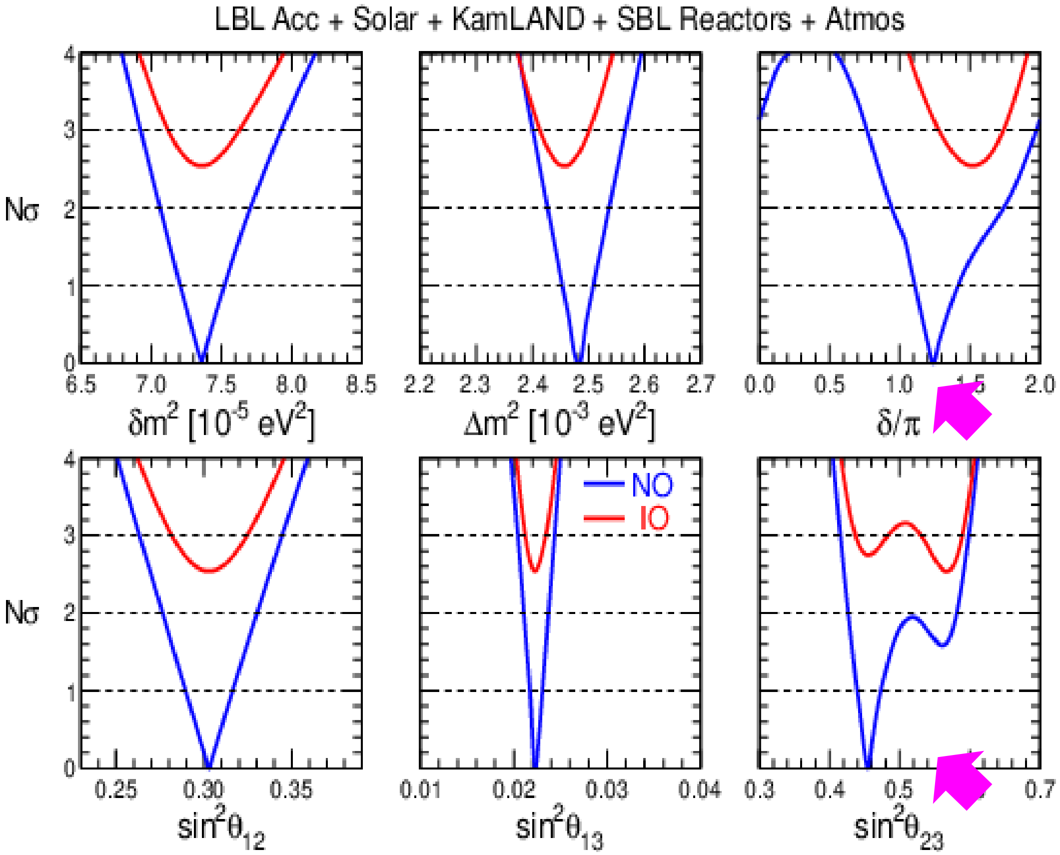
Smallness of neutrino mass and neutrino anomalies could be manifestations of physics at low energy scales. Neutrinos can be portal to new physics at low energy scales.

Evidences? Neutrino anomalies are loosing sigmasLSND/MiniBooNE, RAA, Reactor experiments, BUT Gallium anomaly, BEST?
Sterile neutrinos, keV- MeV mass fermions or bosons,
Neutrino DM connection?

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...

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

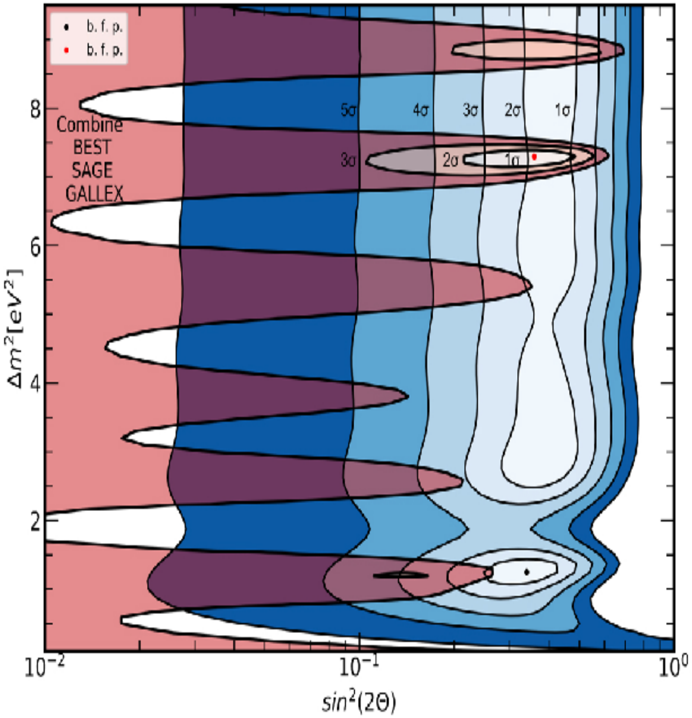
For NO δ_{CP} - closer to π
Deviation of 2-3 mixing from $\pi/4$ is smaller
Preference of NO is less significant than before

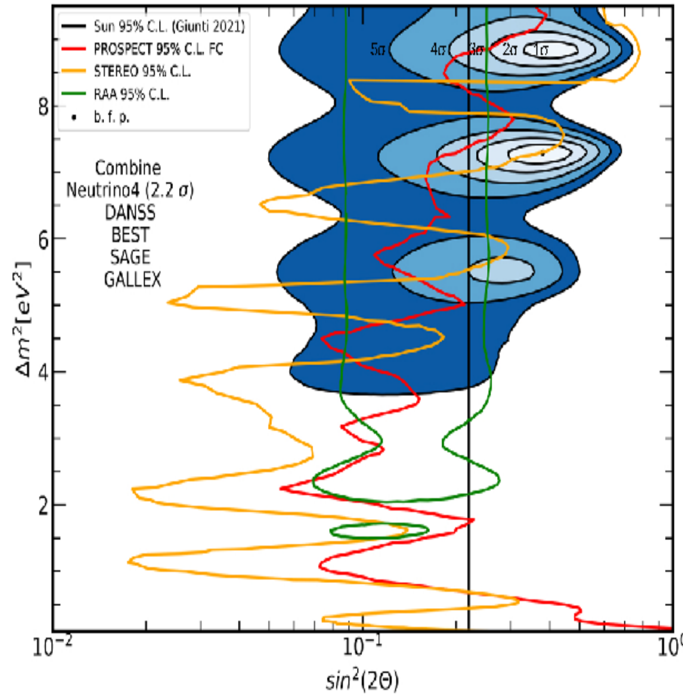
Tensions inside the global?

BEST and others

Tension
goodness
of fit

V.V. Barinov, et al,
2109.11482 [nucl-ex]

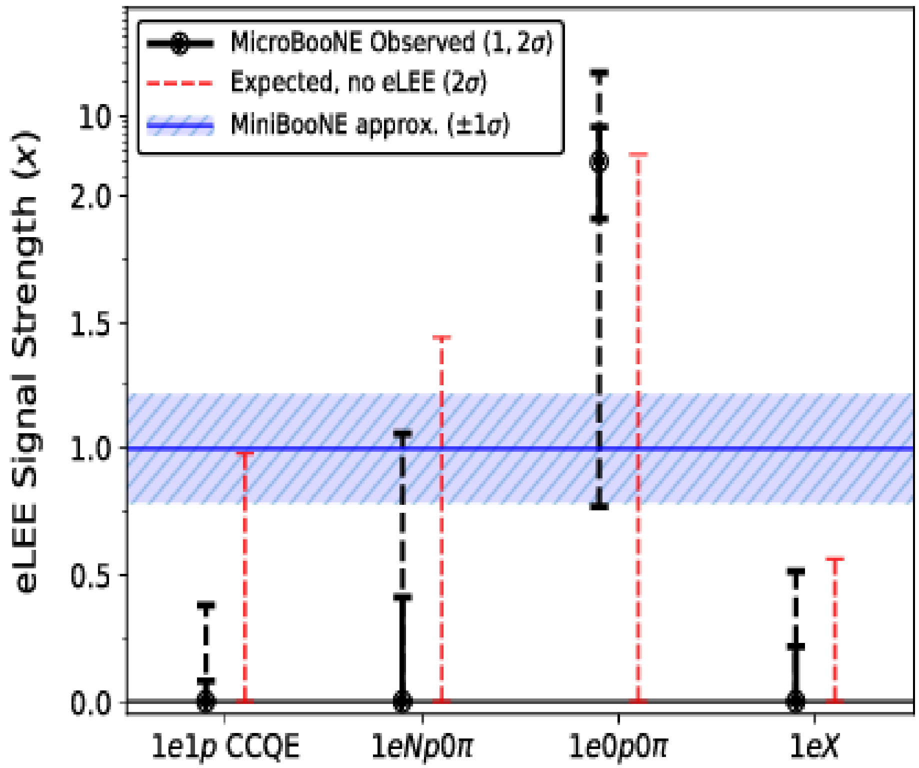




The blue regions - combined fit of BEST, SAGE, Gallex.
Pink regions - favored by NEUTRINO-4

Combined fit of all Gallium experiments and reactor experiments NEUTRINO-4, Prospect, Stereo, DANSS,

MicroBooNE



MicroBooNE Observed (1, 2σ)
Expected, no eLEE (2σ)
MiniBooNE approx. (±1σ)
eLEE Signal Strength (x)
10
2.0
1.5
1.0
0.5
0.0
1e1p CCQE
1eNp0π
1e0p0π
1eX