Dark Nature of the neutrino mass

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Content

Neutrino oscillations and neutrino mass

Refraction in cold gas of scalar bosons and classical scalar field

Cosmological and astrophysical consequences

Based on Manibrata Sen, AYS,
2306.15718 [hep-ph]
2407.02462 [hep-ph]

Neutrino oscillations
and neutrino mass

As we know from the Nobel Prize Committee citation, 2015

" ... the discovery of neutrino oscillations ... shows that neutrinos have mass"

Indeed,

oscillations of atmospheric neutrinos and adiabatic conversion of Solar neutrinos were discovered, and later reactor and accelerator neutrino oscillations were observed

But how do we know that

the mass behind oscillations?

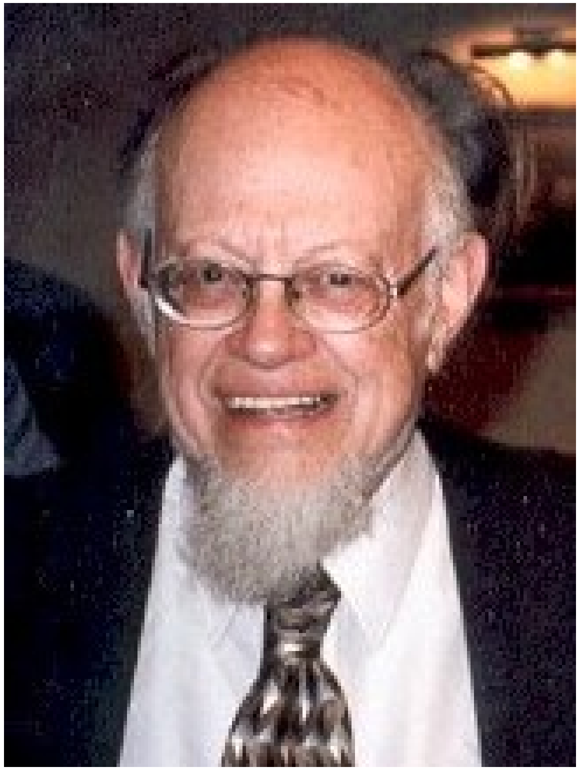
What is this mass?

the same as masses of other fermions of the SM?

If not - what are their properties and origins?

Oscillations without mass

Lincoln Wolfenstein 1978



Oscillations of massless neutrinos

Introduced:

Non-standard interactions of neutrinos – non-diagonal in the flavor basis → produce both diagonal and nondiagonal potentials V_i

This gives both energy split and mixing

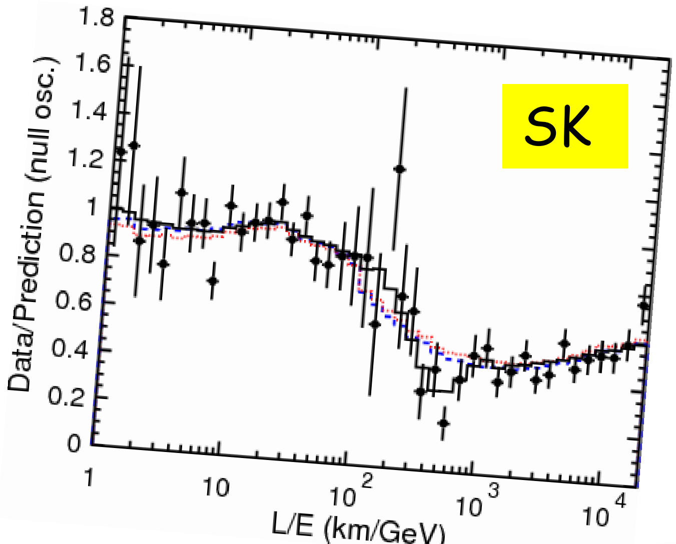
$$E_i = p + V_i$$

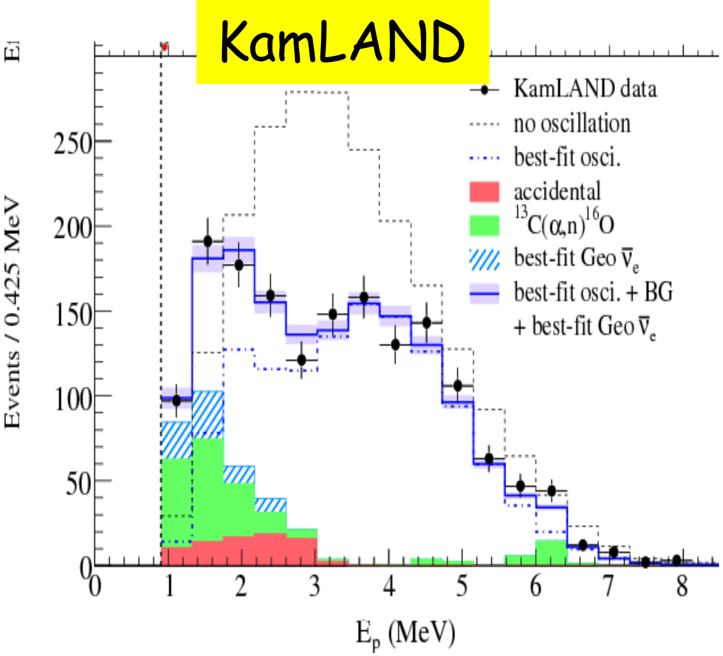
Introduced 4 –fermionic (local) interactions
→ imply heavy mediators

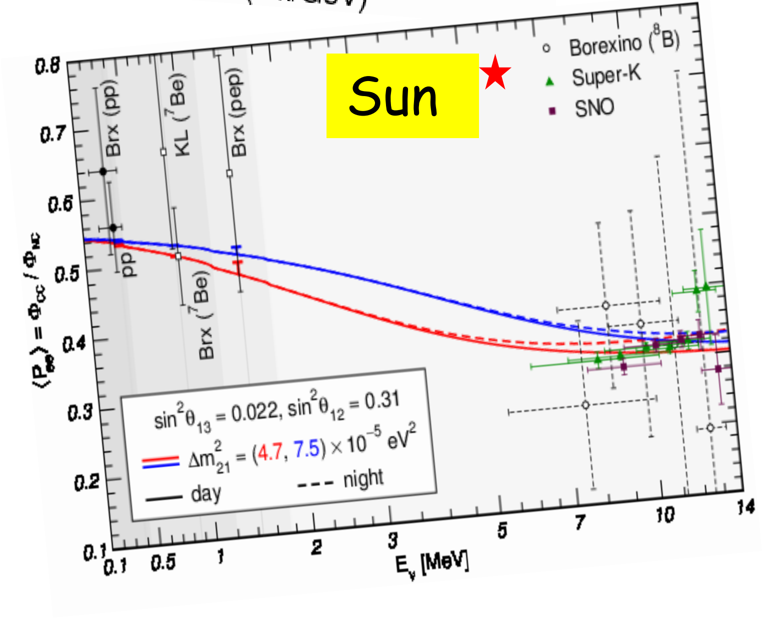
The key:

→ no energy dependence of the oscillation effects

The energy dependence found !







also MINOS, Daya Bay, RENO , T2K, NOvA ...

in agreement with the presence of the mass term in the Hamiltonian of evolution:

Mass and oscillations

Hamiltonian of evolution responsible for oscillations

$$H = E = \sqrt{p^2 + |m|^2} = p + \frac{|m|^2}{2E}$$

the energy dependence of oscillation effects originates from 1/E term

For 3 neutrinos: $m \rightarrow M$

$|m|^2 \rightarrow MM^+$

3x3 mass matrix

$$H = p\,I + \frac{MM^+}{2E} + V$$

matter potential if oscillations occur in matter

Mass and oscillations

Comments:

Oscillations of relativistic neutrinos probe $(\text{mass})^2$ and not mass directly

The mass changes chirality while mass square does not.

Mass and mass squared of neutrinos have different gauge properties and can have different symmetry breaking features

And conclusion:

Any contribution to the Hamiltonian of evolution which has A/E form with constant A can reproduce the oscillation data.

Recall

Matter potential

L. Wolfenstein, 1978

Elastic forward scattering ⇨ V_e, V_μ potentials

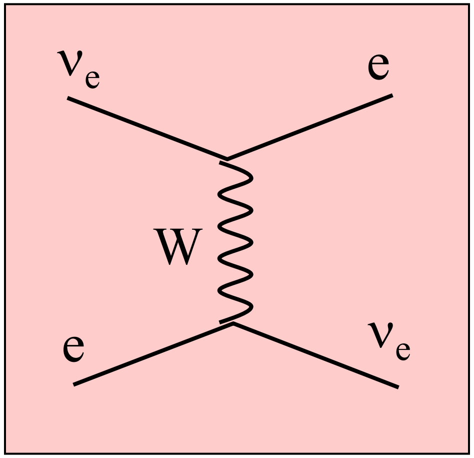
Difference of potentials matters:

$$V = V_e - V_\mu = \sqrt{2}\, G_F\, n_e$$

At low energies: below the W-boson resonance $E \ll m_W^2 / 2m_e$

The Wolfenstein limit

for ν_e ν_μ



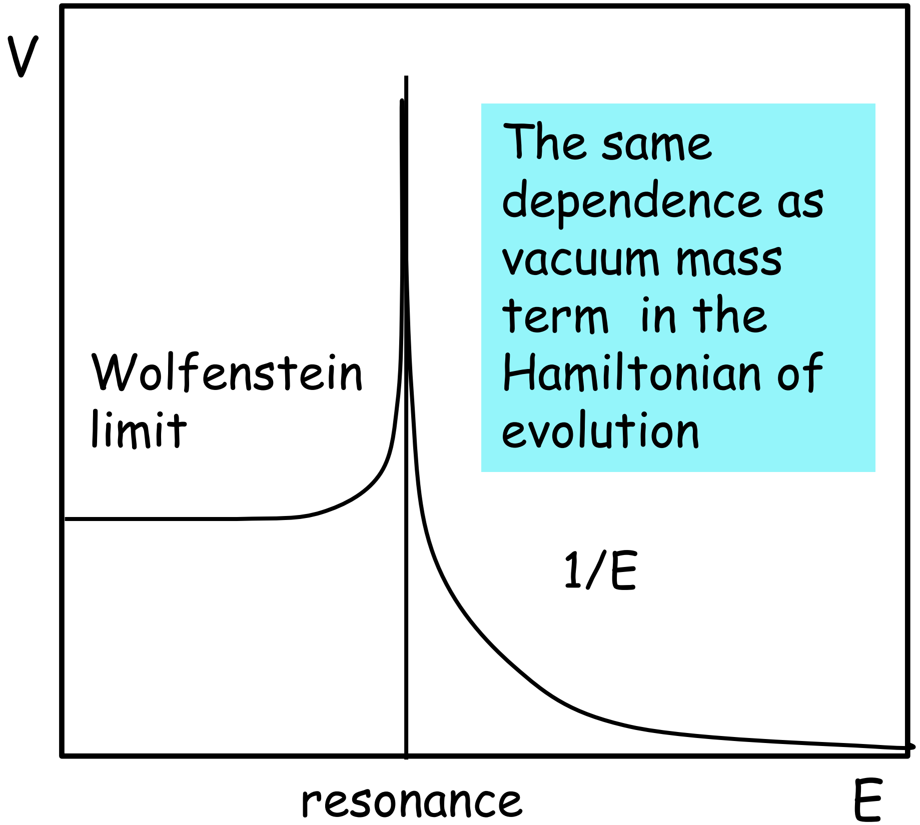
$V \sim 10^{-13}$ eV inside the Earth

Refraction index:

$$n - 1 = V/p$$

Energy dependence of Matter potential

C. Lunardini, A.S.



The same dependence as vacuum mass term in the Hamiltonian of evolution

Generic feature of scattering

Even in the SM:

$$V \sim \begin{cases} 1/m_W^2, & s \ll m_W^2 \\ 1/2m_W E, & s \gg m_W^2 \end{cases}$$

Above resonance V ~ 1/E → potential can substitute the mass term

If mediator is light as well as target particle is light, the 1/E dependence shows up at low explored energies.

Ki-Yong Choi, Eung Jin Chun, Jongkuk Kim, 1909.10478, 2012.09474 [hep-ph],

Can the potential substitute neutrino mass?

Why we may not be happy with "usual " neutrino mass?

What is usual neutrino mass?

Can one exclude the potential as source of oscillations?

Manibrata Sen, AYS,
2306.15718 [hep-ph]

Ki-Yong Choi, Eung Jin Chun,
Jongkuk Kim,
1909.10478 [hep-ph]
2012.09474 [hep-ph]

"Usual" masses in the Standard model

Recall

Masses of quarks and leptons in the Standard Model are not fundamental constants or bare masses but dynamical quantities

They appear due to interactions with Higgs field

$$m = h \langle H \rangle$$

Yukawa coupling may in turn depend on fields and consequently x, t:

$$h = h(\phi\,(x,t))$$

Vacuum expectation value of the Higgs field (the field in the low energy state)

$$\langle H \rangle = \langle H \rangle\,(x,t,\,T\,\ldots)$$

Mass may depend on space-time coordinates, environment

Neutrinos – even more complicated case

Why not the same for neutrinos?

$h \sim 2\ 10^{-13}$ too small and with gap

New Higgs with small VEV?

S. Weinberg: $\frac{1}{\Lambda} L\,L\,H\,H \Rightarrow m_\nu = \frac{\langle H\rangle^2}{\Lambda}$

If not invent new scale $\Lambda = M_{Pl} \Rightarrow m_\nu = 10^{-5}$ eV –too small

additional contribution, or new energy mass scale below M_{Pl}

In seesaw: $\frac{h^2 \langle H\rangle^2}{M_R} \sim \frac{h^2 \langle H\rangle^2}{gV}$ depends on two VEV's

Refraction in a cold gas of scalars

and refractive mass

Neutrino – DM interaction

Target (DM): complex scalar field ϕ with mass $m_\phi$singlet of SM

Mediator: χ_k – light Majorana fermions with masses $m_{\chi k}$

At least two χ are needed to explain data

$$L = g_{\alpha k} \bar{\nu}_{\alpha L} \chi_{kR} \phi + \frac{1}{2} m_{\chi k} \chi_{kR}{}^T \chi_{kR} + h.c.$$

$k = 1,2, \ \alpha = e, \mu, \tau$

$g_{\alpha k} < 10^{-7}$ bound from SN, ...

Assume zero VEV $< \phi > = 0$

The (gauge non-symmetric) interaction in L can be generated via

effective operator $\frac{1}{\Lambda} \bar{\nu}_{\alpha L} \chi_{kR} H \phi$

mixing of ϕ with SM Higgs or new Higgs doublet

RH neutrino portal: coupling $\chi_{\alpha R}{}^T \chi_{kR} \phi$

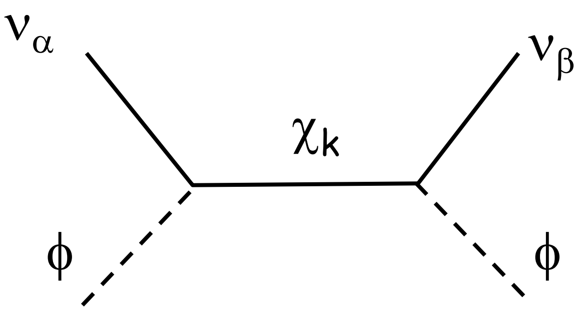
Refraction on scalar DM

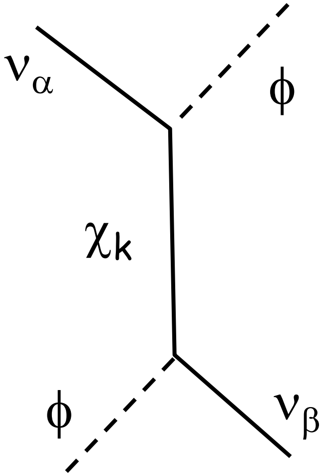
S. F Ge and H Murayama, 1904.02518 [hep-ph]

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

2012.09474 [hep-ph]

Elastic forward scattering of ν on background scalars ϕ with fermionic χ mediator





Resonance: $s = m_\chi^2$

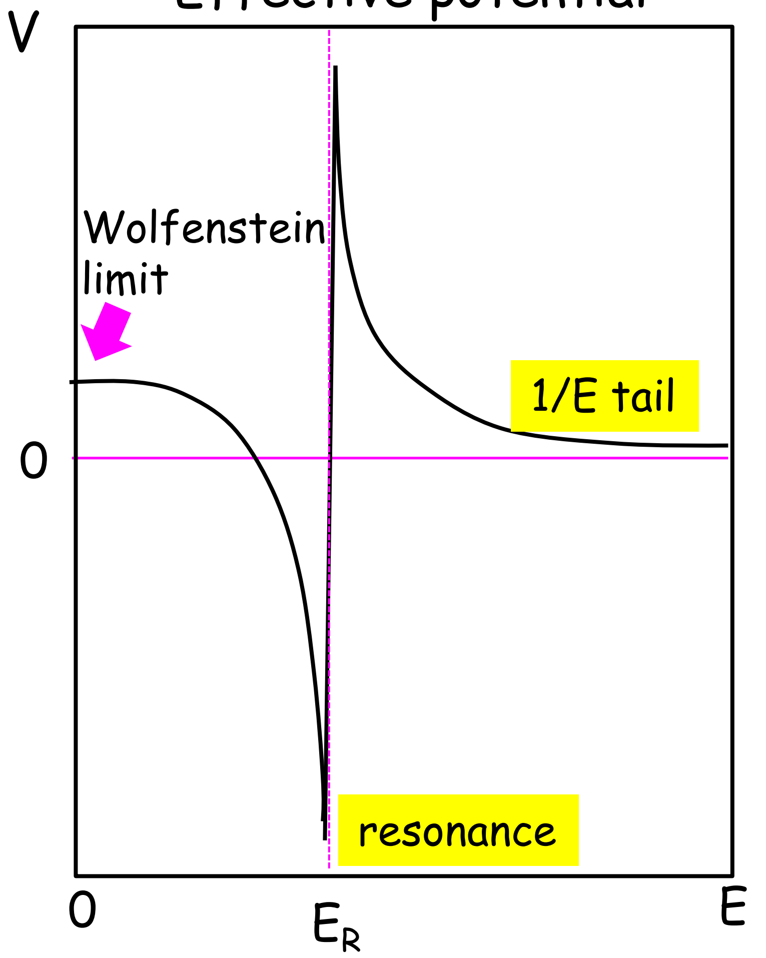
for ϕ at rest the resonance ν energy:

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

For small m_ϕ resonance at low, observable energies

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

Effective potential



Potential: standard computations

$$V_{\alpha\beta} = \Sigma_k V^0_{\alpha\beta k} \left(\frac{(1 - \varepsilon)\,(y - 1)}{(y - 1)^2 + \xi_k^2} + \frac{1 + \varepsilon}{y + 1} \right)$$

$V^0_{\alpha\beta k} = \frac{g_{\alpha k}\, g_{\beta k}^*}{2m_\chi^2} (\bar{n}_\phi + n_\phi)$ n_ϕ and $\bar{n}_\phi$ – the number densities of ϕ and ϕ^*

For simplicity $m_{\chi 1} = m_{\chi 2} = m_\chi$

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

$\varepsilon = (\bar{n}_\phi - n_\phi)/(\bar{n}_\phi + n_\phi)$ C-asymmetry of the ϕ gas

$\xi = \Gamma/E_R$ $\Gamma = \frac{g^2}{4\pi} m_\chi$ width of resonance

ξ << 1 can be neglected

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

$V_0 = m_{as}^2 /2\, E_R$

Refractive mass squared

Manibrata Sen, AYS, 2306.15718 [hep-ph]

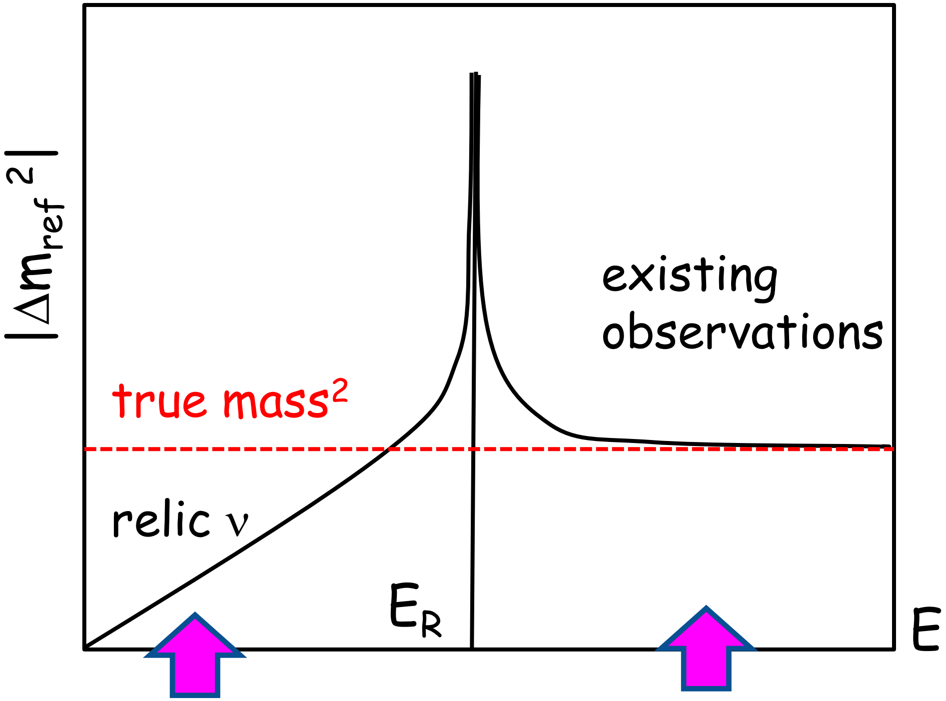
Introduce the refractive mass squared as

$m_{ref}^2 = 2EV$

m_{ref}^2 = constant – checked down to 0.1 MeV

→ $E_R \ll 0.1$ MeV

$$H = p\,I + V(E) = p + \frac{m_{ref}^2}{2E}$$



The decrease of m_{ref}^2 with E allows to avoid cosmological bound on sum of neutrino masses

~ constant m_{ref}^2 explains oscillation data

Refraction mass squared

$m_{ref}^2 = 2EV$

$$m_{ref}^2 = m_{as}^2 \frac{y(y - \varepsilon)}{y^2 - 1}$$

where

$$m_{as}^2 = \Sigma_k \, g_{\alpha k} \, g_{\beta k}^* \, \frac{(\overline{n_\phi} + n_\phi)}{m_\phi}$$

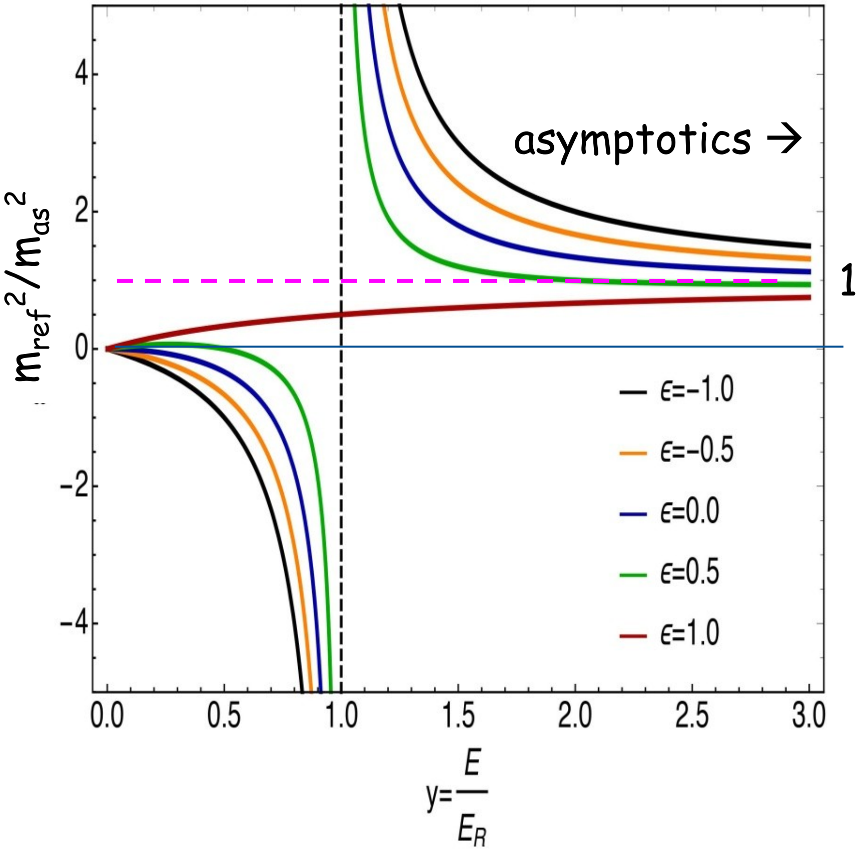
is the refraction mass squared in asymptotic y → infty

$$m_{as}^2 = \Sigma_k \, g_{\alpha k} \, g_{\beta k}^* \, \frac{\rho_\phi}{m_\phi^2}$$

$\rho_\phi = m_\phi (\overline{n_\phi} + n_\phi)$ is the energy density in ϕ

m_{as}^2 is identified with observable mass squared

Near resonance



Properties of m_{ref}^2

$y \ll 1$ $m_{ref}^2/m_{as}^2 = y(y - \varepsilon) = - \varepsilon y$

reproducing the Wolfenstein result

For C-symmetric background
$m_{ref}^2/m_{as}^2 = y^2$ - decreases faster

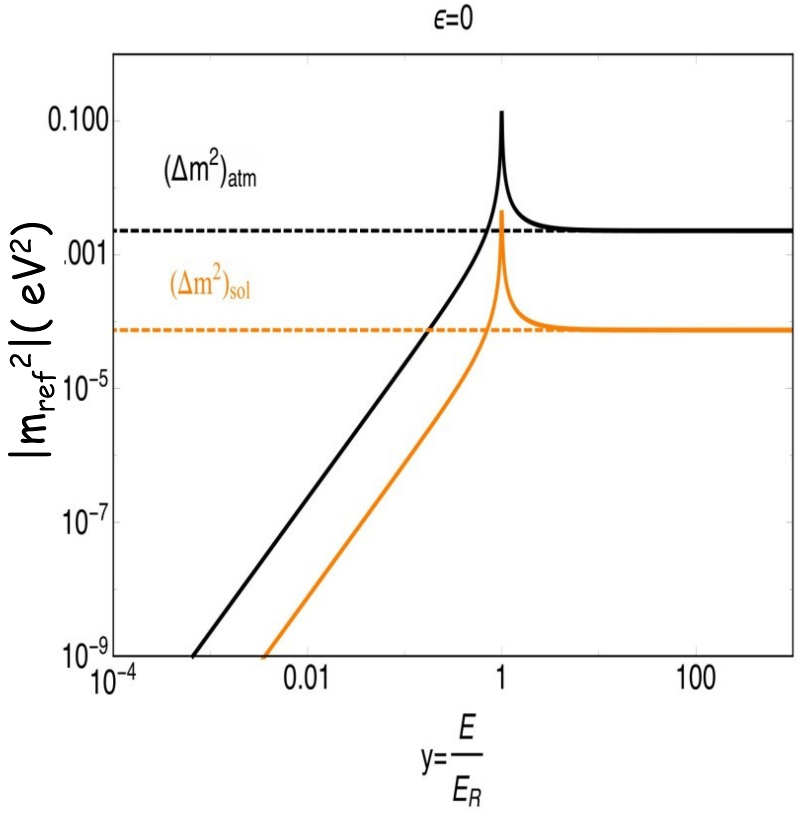
$y \gg 1$

$$m_{ref}^2/m_{as}^2 = \begin{cases} 1 - \varepsilon / y \;, & \varepsilon \neq 0 \\ 1 + y^{-2} & \varepsilon = 0 \end{cases}$$

converges to constant faster

For antineutrinos $\varepsilon \rightarrow - \varepsilon$

$m_{as}^2 (\nu) = m_{as}^2 (\overline{\nu})$



m_{as}^2 has all the properties of usual mass

Fitting the oscillation data

Nearly TBM mixing can be obtained for

$g_{e1} = g_{\mu 1} = g_{\tau 1} = g_1, \; g_{e2} = 0, \; g_{\mu 2} = - g_{\tau 2} = g_2$

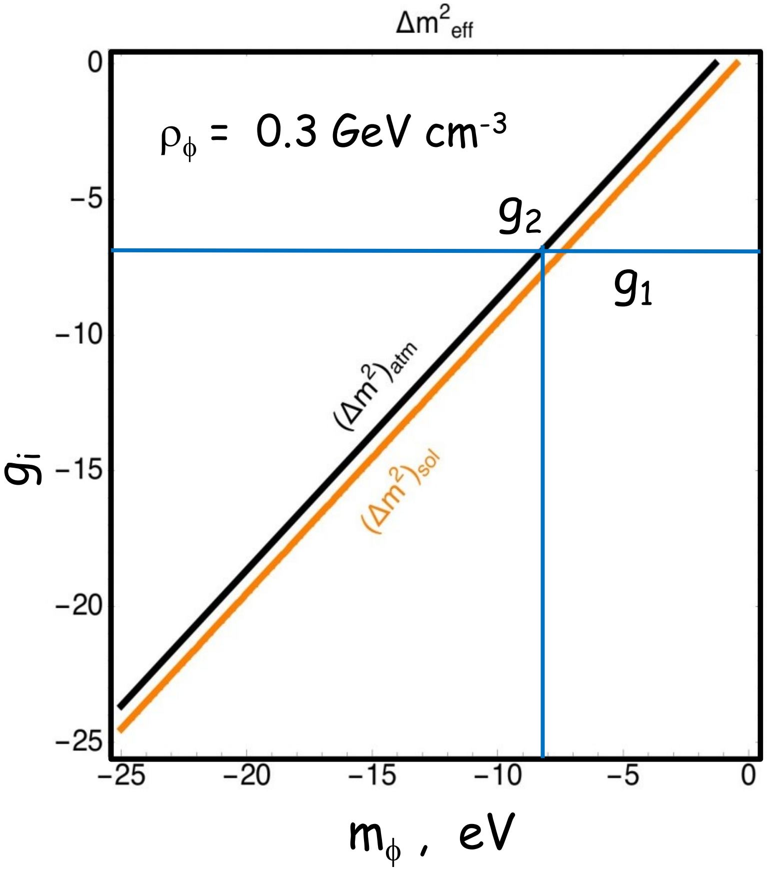
→ normal mass hierarchy, $m_1 = 0$

$$g_1 = m_\phi \sqrt{\frac{\Delta m_{sol}^2}{3\rho_\phi}} \qquad g_2 = m_\phi \sqrt{\frac{\Delta m_{atm}^2}{2\rho_\phi}}$$

Large number density of target particles is required → ϕ form substantial part or whole DM

$\rho_\phi \sim \rho_{DM} \sim 0.3$ GeV cm^{-3}

$m_\phi < 5 \times 10^{-9}$ eV $(g_2/10^{-7})$



Required g as functions of m_ϕ

Hamiltonian of evolution

Hamiltonian in the basis $(\nu_{f,}\, \chi^c{}_L) = (\nu_e, \nu_\mu, \nu_\tau,\ \chi_1{}^c, \chi_2{}^c)$

$$H = \frac{1}{2E} \begin{pmatrix} m_{f\ \alpha\beta}{}^2 & g_{\alpha k}\, m_{\chi k}\, e^{i\Phi}\, (n_\phi/2m_\phi)^{1/2} \\ g_{\beta k}{}^*\, m_{\chi k}\, e^{-i\Phi}\, (n_\phi/2m_\phi)^{1/2} & m_{\chi kk'}{}^2 + m_{rkk'}{}^2 \end{pmatrix}$$

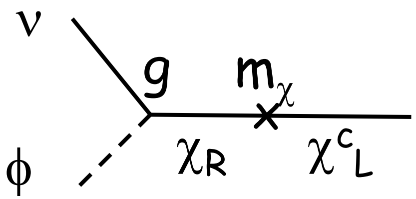
$\Phi = - m_\phi t + \phi'$

$m_{rkk'}{}^2$ - refractive mass squared of χ_k similar to refractive mass of active neutrinos

Feedback of $\nu_{,}$ - χ^c mixing on oscillations of active neutrinos can be small

$\nu - \chi$ mixing and transitions

$\nu_L \phi^* \rightarrow \chi_R \rightarrow \chi^c_L$



Coherence: states of medium with ϕ being absorbed from different space-time points separated by Δx are coherent once $\Delta x < \lambda_{DB} = 2\pi / v\, m_\phi$ → $\nu - \chi$ potential $V_{\nu\chi}$

$$A_{\alpha k}(x) = g_{\alpha k}\, \Sigma_{j=1-n} \langle \chi^c_{kL}\underbrace{(p_\chi)|\chi_{kR}}_{m_{\chi k}/2E}(x)\, \nu_{\alpha L}(x)\, \phi(x) | \nu_{\alpha L}(p_\nu)\, \phi^*(p_j) \rangle$$

sum over scatterers
on the unit of length

$$\Sigma_{j=1-n}\, e^{-i p_j x} = e^{-i m_\phi t}\, \Sigma_{j=1-n}\, e^{-i m_\phi v_j^2 t/2} = e^{-i m_\phi t + i\phi'} \sqrt{n_\phi}$$

non-relativistic

random phase
summation

Potential:

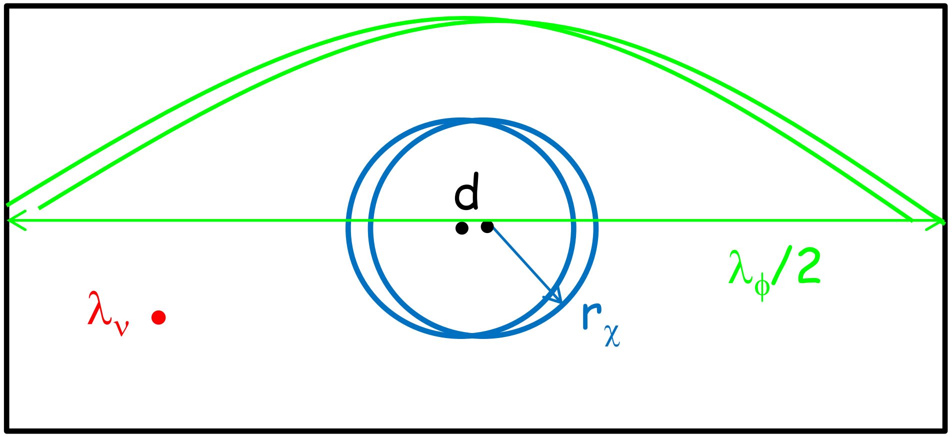
$$V_{\alpha k}(x) = e^{-i m_\phi t + i\phi'}\, g_{\alpha k} \frac{m_{\chi k}}{2E_\chi} \sqrt{\frac{n_\phi}{2m_\phi}}$$

Unusual setup

$d \ll r_\chi \ll \lambda_\phi$

$\lambda_\nu \ll d$

de Broglie wave of neutrino



A number of issues:

How reliable are computations of local potential based on integration over infinite space-time which leads to exact conservation of energy-momentum?

High order corrections

ν - χ - transition, off-diagonal potential and mixing

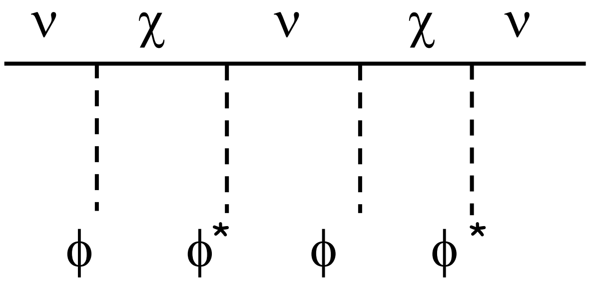
Treatment of the ϕ background as coherent state of scalars – classical scalar field

High order corrections. Perturbativity

Radius of interactions below resonance : $1/m_\chi$

Large number of scatterers ϕ within interaction volume.
Processes with many ϕ should be taken into account

$\nu\,\phi\,\phi \rightarrow \nu\,\phi\,\phi \qquad \nu\,\phi\,\phi\,\phi \rightarrow \nu\,\phi\,\phi\,\phi\ \ldots$



Expansion parameter

$$\zeta = \frac{V}{m_\phi} = \frac{\Delta m_{atm}^2}{2Em_\phi - m_\chi^2} \qquad \text{for } \varepsilon = -1$$

$$\zeta = \frac{V\ E_R}{m_\phi\ E} \qquad \text{for } \varepsilon = 0$$

ζ increases with decrease of energy and
becomes $\zeta = 1$ already above resonance

Refraction in classical field

Previous results of scattering on scalar particles of DM can be confirmed by different approach

Coherent classical field

Due to inequality $d \ll \lambda_\phi$ or $\lambda_\phi^3 n_\phi \gg 1$, i.e. , large occupation number the system of ϕ can be treated as a classical scalar field

➡ Coherent state of scalar bosons

In terms of QFT such a scalar field ϕ_c can be introduced as an expectation value of the field operator in the coherent state:

$$\phi_c = \langle \phi_{coh} | \, \phi \, | \phi_{coh} \rangle$$

$$|\phi_{coh}\rangle = \exp\left(\int \frac{d\mathbf{k}}{(2\pi)^3} \left[f_a(\mathbf{k}) a_k^+ + f_b(\mathbf{k}) b_k \right] \right) |0\rangle \qquad \mathbf{k} = m_\phi \mathbf{v}$$

It can be parameterized as

$$\phi_c(x) = F(x\ t)\, e^{-i\Phi} \qquad F^2 \sim \rho_\phi / m_\phi^2$$

Neutrino mass in classical field

In the Lagrangian: $\phi \rightarrow \phi_c$

$L = g_{\alpha k} \overline{\chi}_{kR} \nu_{\alpha L} \phi_c^* + h.c.$ ➡ mass terms $m_{\alpha k} = g_{\alpha k} \phi_c^*$

Mass matrix in the basis $(\nu_{f,} \chi^c_L) = (\nu_e, \nu_\mu, \nu_\tau, \chi_1^c, \chi_2^c)$

$$M = \begin{pmatrix} 0 & g_{\alpha k} \phi_c^* \\ g_{k\alpha} \phi_c & \mathrm{diag}\,(m_{\chi 1}, m_{\chi 2}) \end{pmatrix}$$

The Hamiltonian

$$H = \frac{1}{2E} M M^+ = \frac{1}{2E} \begin{pmatrix} |F|^2 \Sigma_k g_{\alpha k} g_{\beta k}^* & g_{\alpha k} F m_{\chi k} e^{i\Phi} \\ g_{k\alpha}^* F^* m_{\chi k} e^{-i\Phi} & M_\chi^2 \end{pmatrix}$$

$M_\chi^2 = f(|F|^2, |g_{\alpha k}|^2, m_{\chi k}^2)$ e.g. $M_{\chi 11}^2 = m_{\chi 1k}^2 + |F|^2 \Sigma_\alpha |g_{\alpha 1}|^2$

Properties of the Hamiltonian

For energies above resonance this Hamiltonian coincides with the one for refraction in cold gas

3x3 flavor block coincides with refraction matrix m_{as}^2

Additional time dependence can appear in F for real field:

$$|F|^2 \sim \rho_\phi / m_\phi^2 \cos^2 m_\phi t$$

A.Berlin, 1608.01307, F. Capozzi et al, 1702.08464, G. Krnjaic, ei al, 1705.06740 [hep-ph], V. Brdar et al 1705.09455 [hep-ph], ...

For C-asymmetric background the amplitude of oscillations can be suppressed

Resonance dependence of mass on energy can be reproduced due to periodic time dependence of F:

Resonance in the neutrino ϕ-wave scattering.

Cosmological and astrophysical bounds

Refraction mass vs. VEV mass

Refraction mass is different in different space-time points and also depends on energy:

$$m_{ref}^2 (x, t, E) = n_\phi(x, t) f(E)$$

E.g. m_{ref}^2 is different in solar system, center of Galaxy, intergalactic space

The average $m_{ref}^2 (z)$ in the Universe increased in the past.

In contrast, the VEV mass is determined by minimum of the potential and not redshifted.

Cosmology and the refractive mass

In epoch, z, the average refractive mass of relic neutrinos in the Universe

$$m_{ref}^2\,(z) \sim \xi\, m_{as}^2\,(loc)\,(1 + z)^4\;\; E(0)/E_R\;\; [(E(0)/E_R\,(1 + z) - \varepsilon]$$

$\xi \sim 10^{-5}$ - inverse of local overdensity of DM

$m_{as}^2\,(loc) = \Delta m_{atm}^2$

redshift of energy and number density

energy dependence of mass at small y

$E(0) \sim 5\; 10^{-4}$ eV - present average energy of relic neutrinos

For large enough E_R the mass $m_{ref}^2\,(z)$ can be small, however it can not be used in the same way as the “usual” mass below resonance, and consequently, in consideration of effect on structure formation in the Universe

One needs to use dispersion relation, compute the group velocity, energy density and find fraction in non-clustering neutrino component

Dispersion relation

$E = p + V$

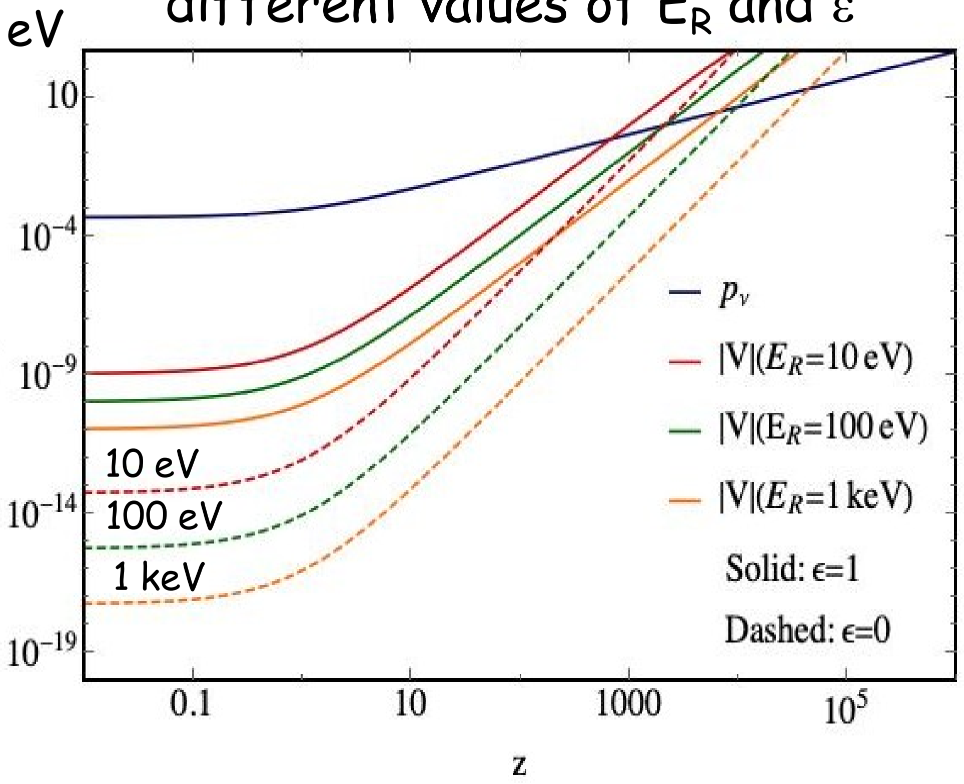
$p(z) = p_0\,(1 + z)$

$$V(z) = \begin{cases} \dfrac{m_{as}^2}{2E_R}\,\varepsilon\,\xi\,(1+z)^3 & \varepsilon \sim 1 \\ \dfrac{m_{as}^2}{2E_R}\,y_0\,\xi\,(1+z)^4 & \varepsilon = 0 \end{cases}$$

$y_0 = E_0/E_R$

$E_0 = 5\ 10^{-4}$ eV is the average energy of relic neutrinos

p and V as functions of z for different values of E_R and ε



$$\frac{V}{p} = \frac{m_{as}^2}{2E_R E_0}\,\varepsilon\,\xi\,(1+z)^2$$ - related to perturbativity of approach

Group velocity

$$v_g = \frac{dE}{dp} = 1 - \frac{dV}{dp}$$

Manibrata Sen, AYS, 2407.02462 [hep-ph]

$$1 - v_g = \frac{m_{as}^2}{2E_R^2}\,\xi\,(1 + z)^3\,\frac{1 + y^2 - 2\,\varepsilon\,y}{(1 - y^2)^2}$$

$$y = y(z) = y_0\,(1 + z)$$

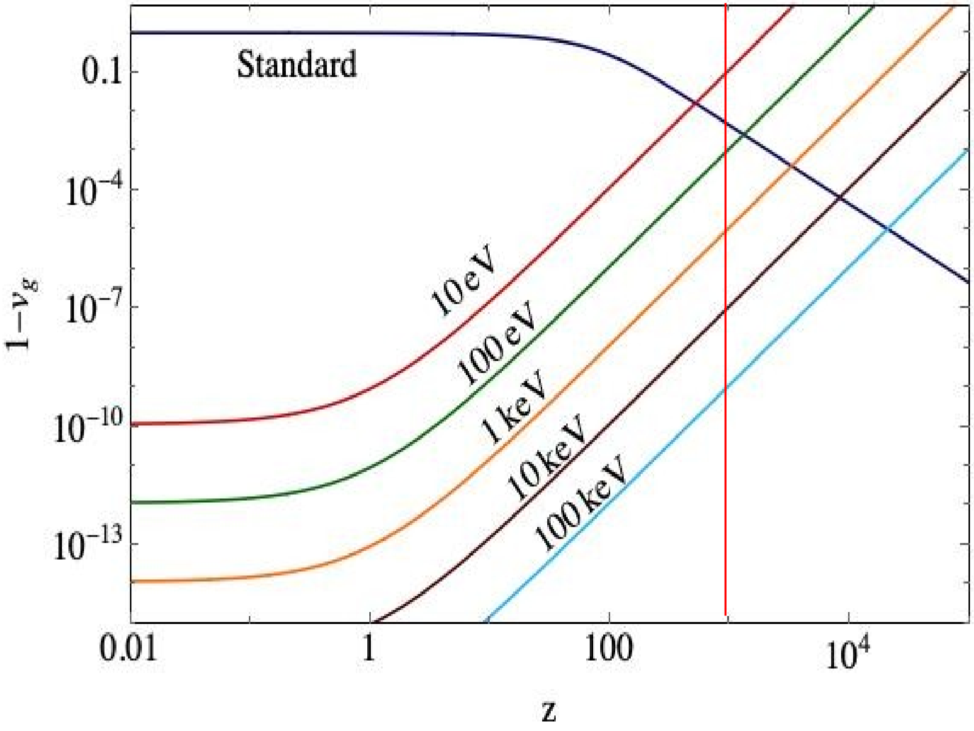
$y \ll 1$

$$1 - v_g = \frac{m_{as}^2}{2E_R^2}\,\xi\,(1 + z)^3$$

Usual mass case:

$$1 - v_g = 1 - [1 + m^2/p^2(z)]^{-1/2}$$

$1 - v_g$ as function of z for different values of E_R



Structure formation and DESI bound

Border of non-relativistic region

$p = m \rightarrow \quad v_g = 1/\sqrt{2}$

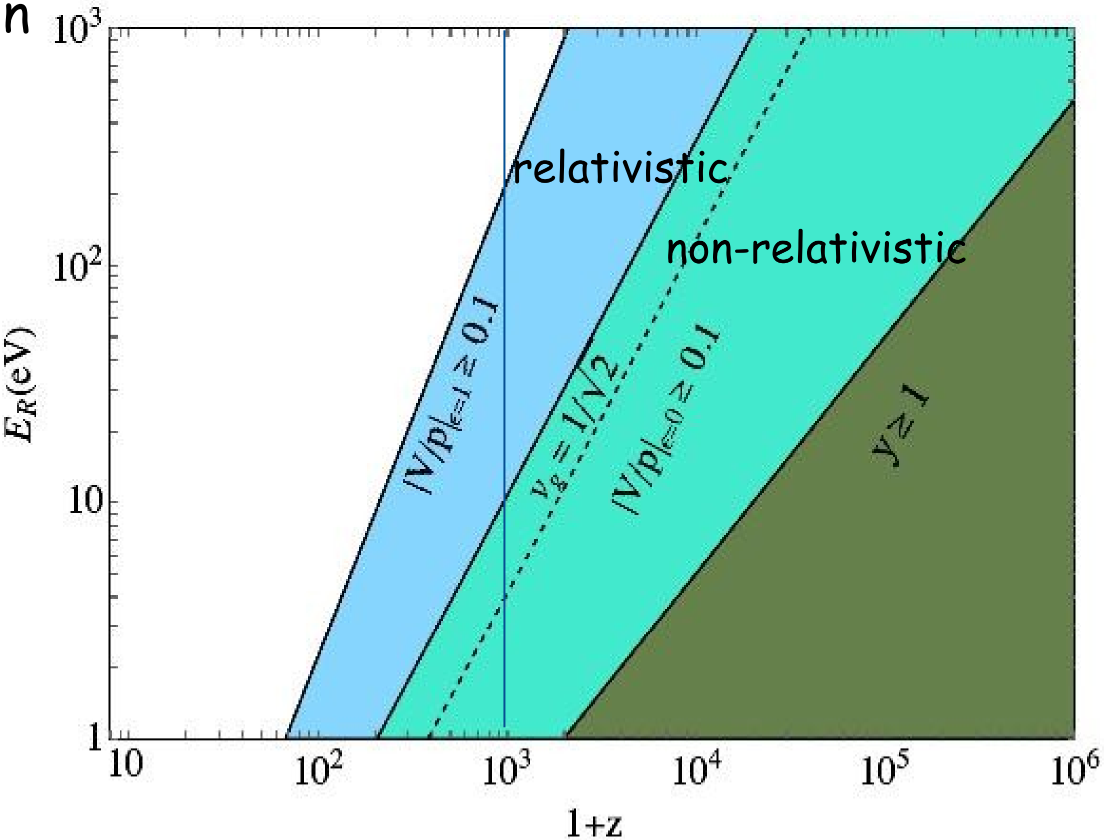
$$(1+z)_{nr} = \left(\frac{E_R^2}{\xi\, m_{as}^2}\right)^{1/3}$$

Suppression of power spectrum of perturbations

$P_m / P_0 = 1 - 8f_\nu$

f_ν – fraction of energy density in non-clustering component

$f_\nu = \rho_\nu / \rho_m$



Borders of the perturbativity regions for two values of ε, and non-relativistic region

For $z < 10^3$ neutrinos show up as massless ($f_\nu = 0$) for

$E_R > 200$ eV ($\varepsilon = 1$)

$E_R > 10$ eV ($\varepsilon = 0$)

Explains DESI bound on sum of neutrino masses

DESI bound on sum of neutrino mass

Dark Energy Spectroscopic Instrument

A G Adame et al, DESI 2024 VI
Cosmological constrains from
the measurements of Baryon
Acoustic Oscillations,
2404 .03002

CMB polarization , temperature,
lensing spectrum
PLANCK, ACT

$\Sigma\, m_\nu <$ 0.072 eV, 95% C.L.

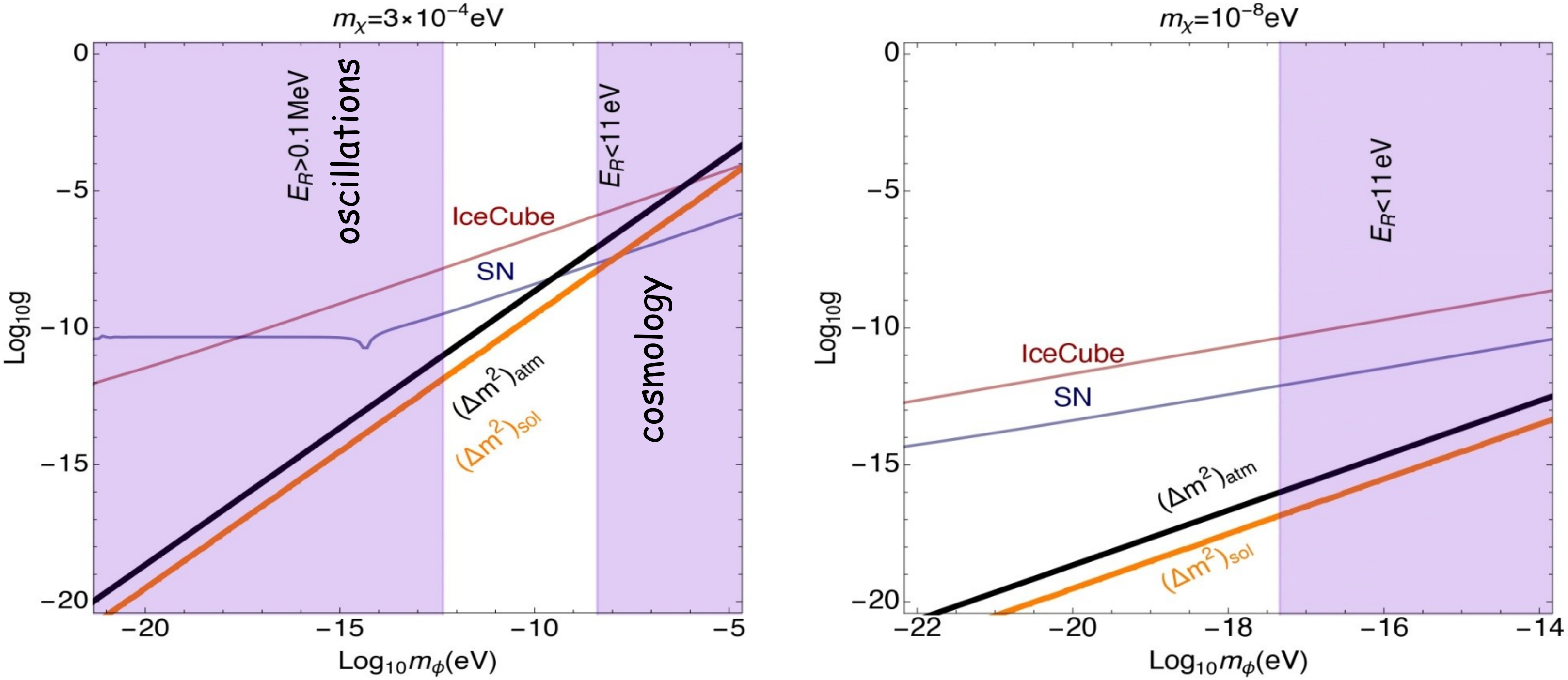
peaks at zero

+ Supernova Ia, GRB, X-ray observation:

$\Sigma\, m_\nu <$ 0.043 eV, 95% C.L.

D. Wang, et al, 2406.03368

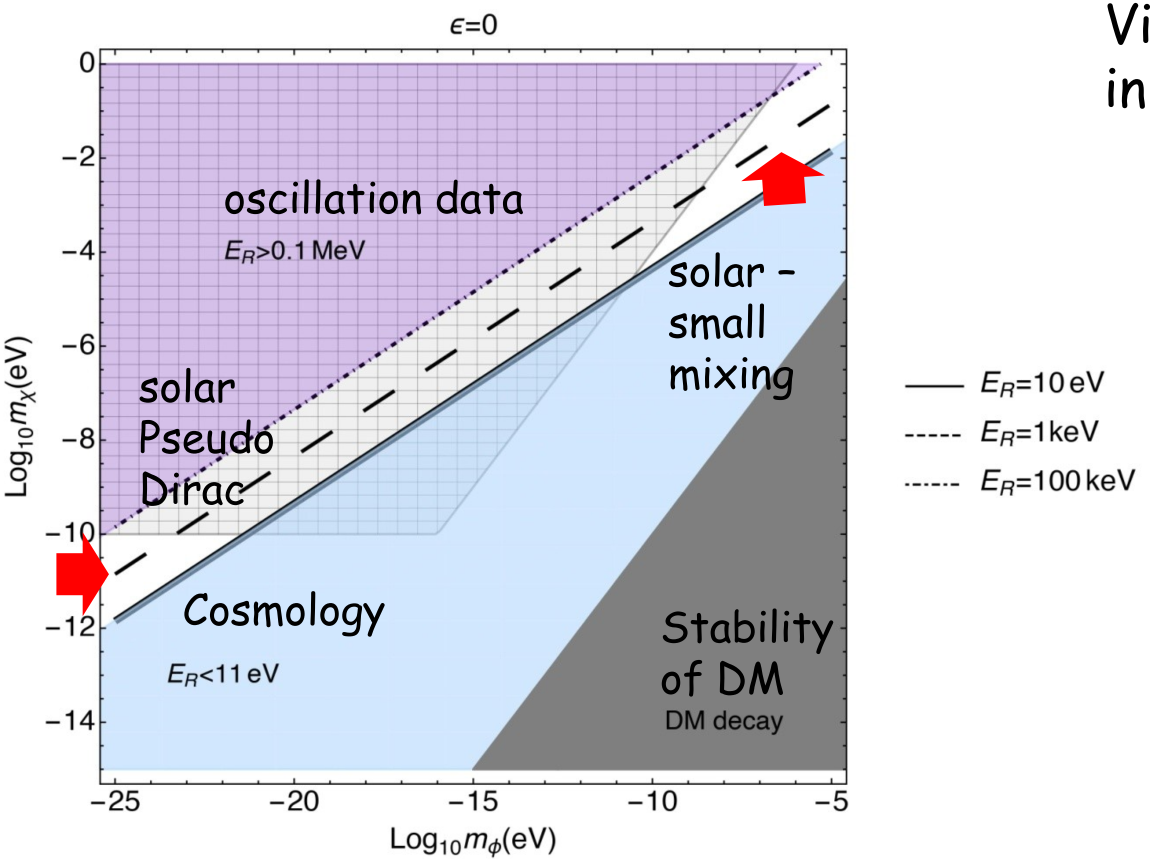
Viable ranges of parameters



Bounds and viable regions of parameters in g – m_ϕ plane for different values of m_χ

$m_\chi = (3\ 10^{-9} - 10^{-4})$ eV
$m_\phi = (10^{-22} - 10^{-10})$ eV
$g = (3\ 10^{-20} - 10^{-7})$

Bounds on parameters



Viable regions of parameters in m_χ - m_ϕ plane $\varepsilon = 0$

Solar neutrinos: bound from oscillations to sterile ν - χ

Probing spatial dependence with SN neutrinos

Shao-Feng Ge, Chui-Fan Kong, AYS, 2404.17352 [hep-ph]

Number density of DM particles increases toward the center of Galaxy

Delay

$$\Delta t = \frac{m_{as}{}^2(x_{sun})D}{2E^2}\,\frac{\int \rho_\phi\,(x)\,dx}{D\,\rho_\phi\,(x_{sun})}$$

$$= \Delta t_{sun}\,\frac{\overline{\rho_\phi}\,(x_*)}{\rho_\phi\,(x_{sun})}$$

standard

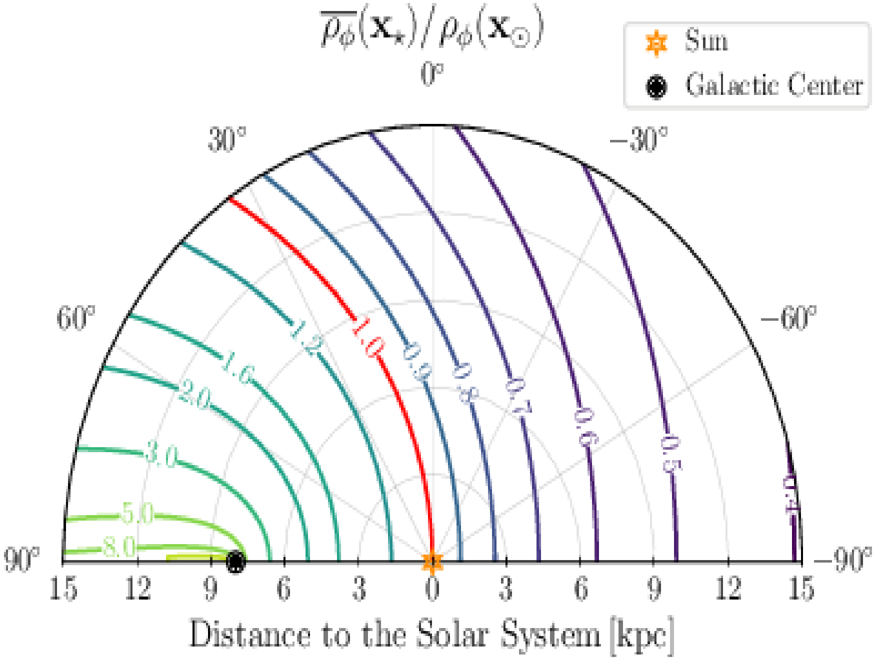
enhancement

x_* - coordinates of SN

x_{sun} - coordinates of solar system

D – distance to SN

Effect depends on integrated over trajectory number density of DM particles



Lines of constant ratio $\overline{\rho_\phi}\,(x_*)/\ \rho_\phi\,(x_{sun})$ in the polar coordinate system

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Energy dependent delay in arrival, spread in time of neutronization burst signal

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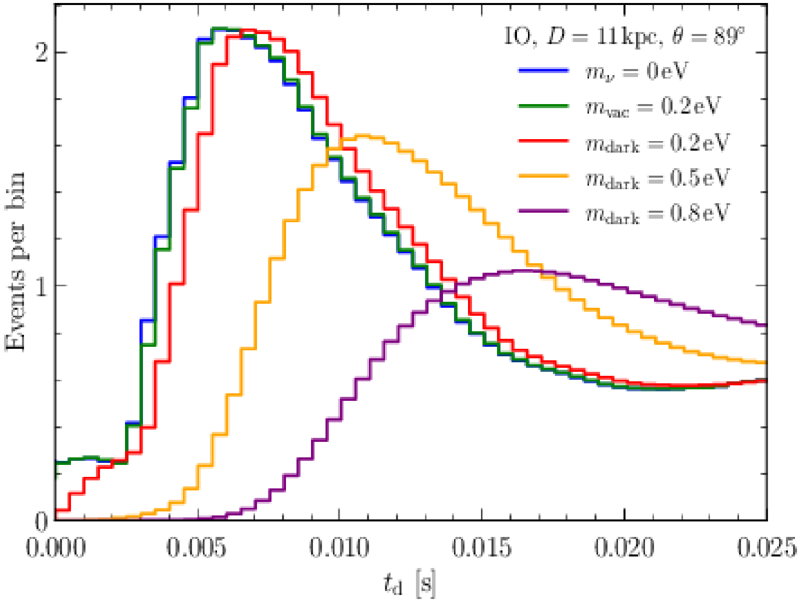
m_{dark} = 0.5 eV can be identified at (3 – 5)σ level

Not restricted by KATRIN



Conclusions

Still origins of neutrino mass are in dark:

Smallness of mass, mixing indicate that origin can be substantially different from that of quarks and charged leptons.

Neutrino oscillations can be explained by refraction effect on very light scalar Dark matter due to light mediator

This is equivalent to refraction on time varying classical scalar field

VEV → EV

Still open questions perturbativity, resummation, but correspondence confirm validity

...continued

Effective mass squared depends on neutrino energy, time and location → rich phenomenology

At small E due to energy dependence and opposite signs for neutrinos and antineutrinos, the refractive mass can not be interpreted and used in the same way as usual mass

in particular, in Cosmology – structure formation

To study influence on structure formation one should use dispersion relation, compute group velocity and explore transition from relativistic to non-relativistic cases

One can use SN neutrinos and their arrival delay to check refraction origins of masses

Establishing refractive nature of neutrino mass may also mean establishing nature of dark matter

Backup

Bounds on refractive mass