III. Neutrino oscillations and Dark matter

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1. Neutrino oscillations and neutrino mass
2. Refraction in cold gas of scalar bosons
3. Refraction in classical scalar field
4. Cosmological and astrophysical consequences

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

1. Neutrino oscillations and neutrino mass

We know that

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? Is it
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 non-diagonal potentials V_i

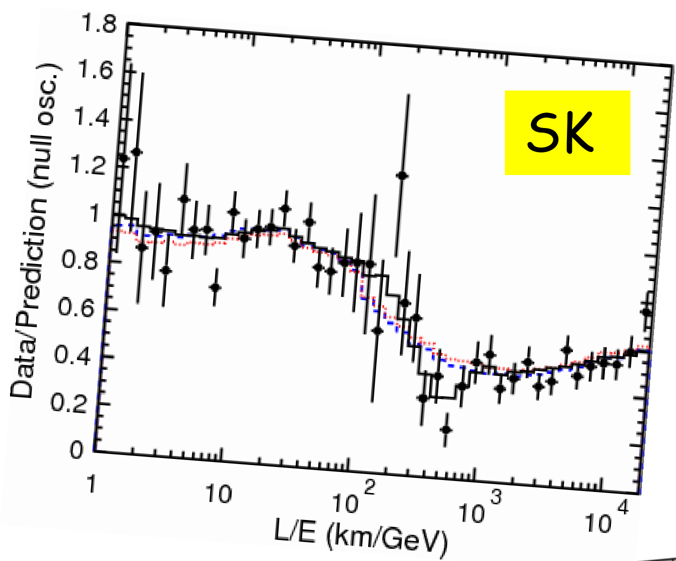
This gives both flavor mixing and energy split:

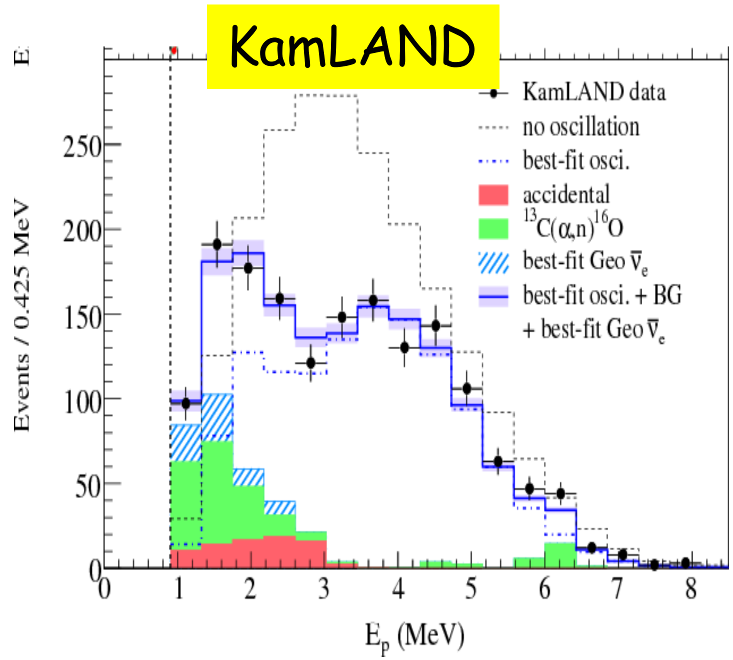
$$E_i = p + V_i$$

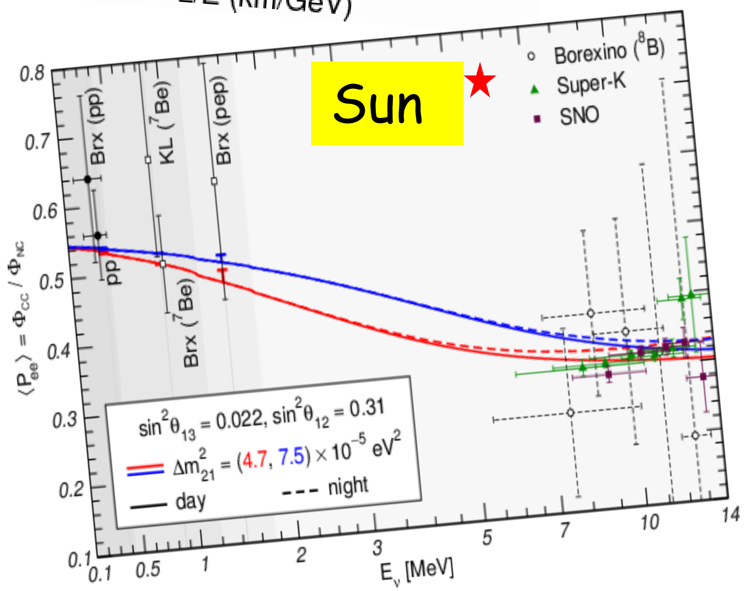
Introduced 4 –fermionic (local) interactions
→ imply heavy mediators
→ no energy dependence of the oscillation effects

The keyfeature:

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: $m \to M$

$|m|^2 \to MM^+$ — 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

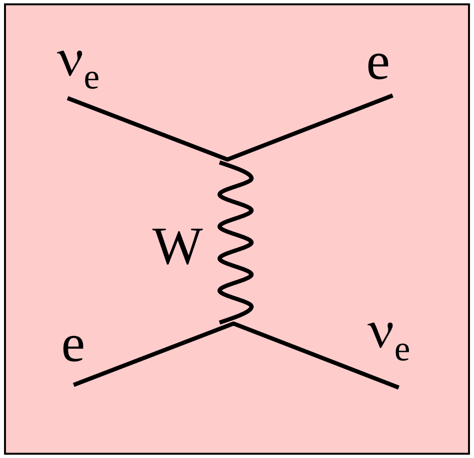
Difference of potentials matters:

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

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

The Wolfenstein limit

for ν_e ν_μ



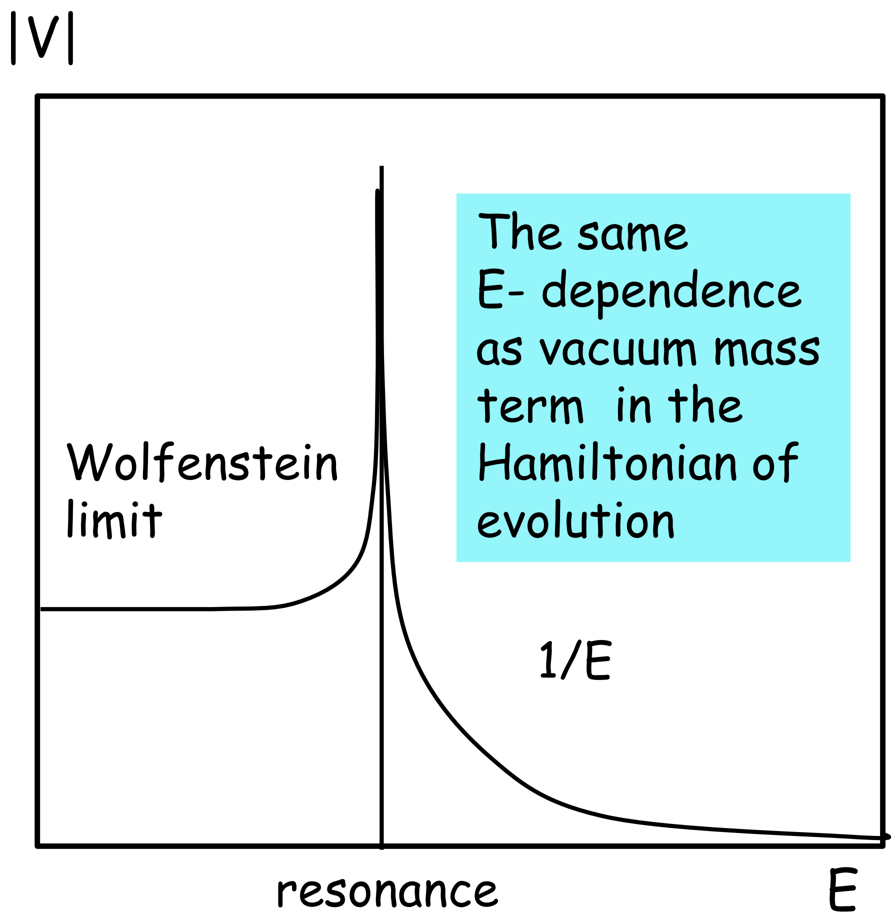
$V \sim 10^{-13}$ eV inside the Earth

Refraction index:

$$n - 1 = V/p$$

Energy dependence of Matter potential

C. Lunardini, A.S.



The same E- 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 energy dependent potential substitute neutrino mass?

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

What is usual neutrino mass? (see lecture 1)

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]

2. Refraction in a cold gas of scalars and refractive mass

Neutrino – DM interaction

Target: light complex scalar field ϕ with mass m_ϕ singlet of SM compose at least part of Dark matter

Mediator: χ_k – light Majorana fermions with masses $m_{\chi k}$
at least two χ are needed to explain data

Effective Lagrangian of interactions:

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

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

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

Assume zero VEV $\langle \phi \rangle = 0$

The masses of χ_k can also be effective, generated by some new interactions

Neutrino – DM interaction

The gauge non-symmetric interaction in L with effective coupling $g_{\alpha k}$

$$g_{\alpha k} \, \bar{\nu}_{\alpha L} \, \chi_{kR} \, \phi + h.c.$$

can be generated via

1. effective operator $\frac{h}{\Lambda} \bar{\nu}_{\alpha L} \chi_{kR} H \phi \rightarrow \frac{h\langle H\rangle}{\Lambda} \bar{\nu}_{\alpha L} \chi_{kR} \phi$

$$g_{\alpha k} = h \langle H\rangle / \Lambda$$

2. mixing of ϕ with SM Higgs

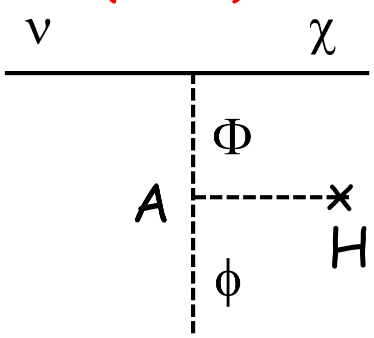
Y. Farzan et al JHEP 05 (2018) 066

3. new Higgs doublet Φ with couplings

$$h \bar{L} \chi_R \Phi^* + A H \phi \Phi^* + h.c.$$

Z_2 = -1 +1 -1 + 1

$$g_{\alpha k} = hA \langle H\rangle / M_\Phi^2$$

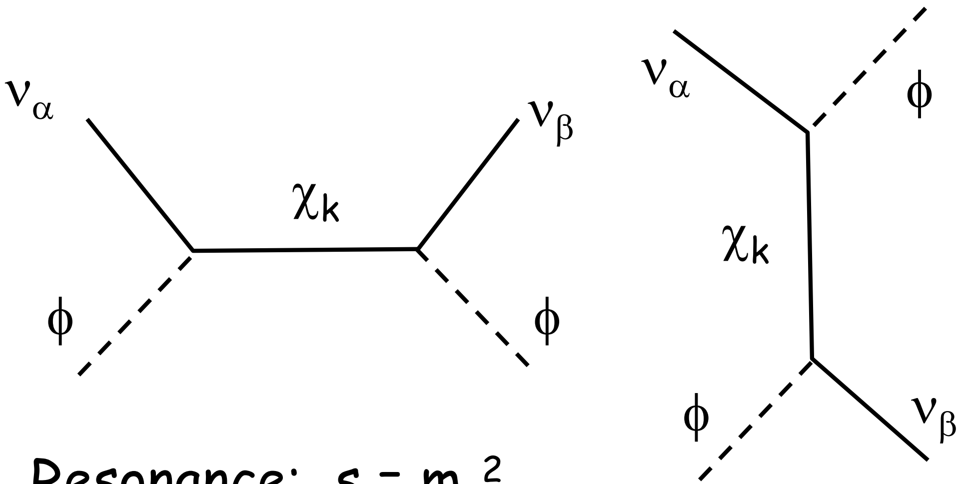


4. Via the RH neutrino portal: coupling $\chi_{\alpha R}^T \chi_{kR} \phi$

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: $s = m_\chi^2$

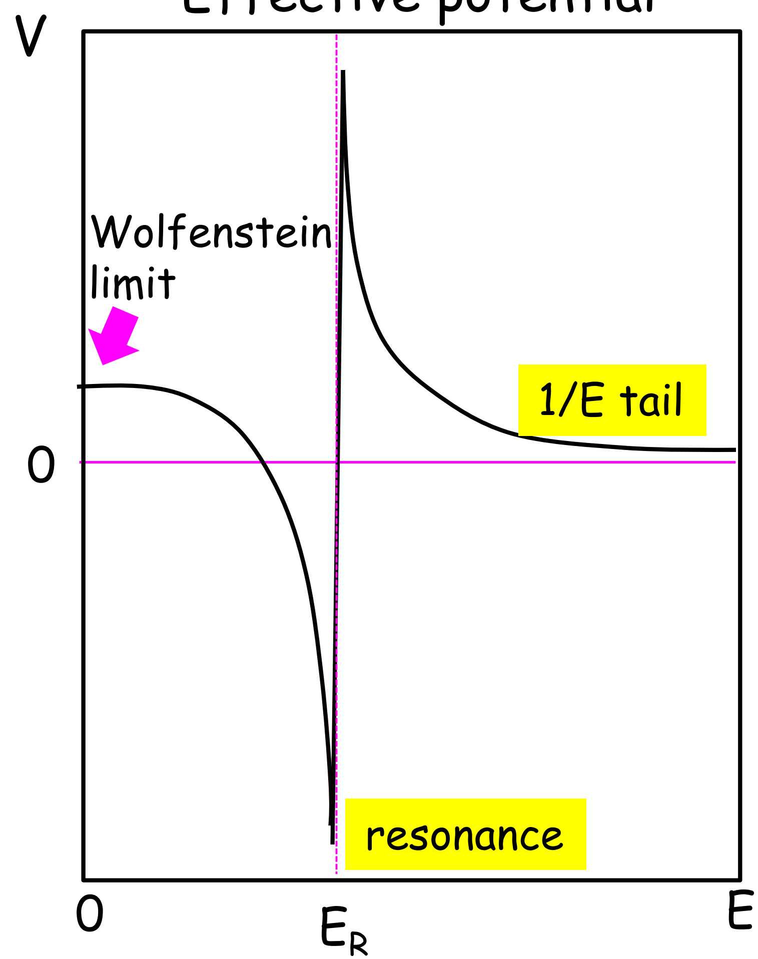
for ϕ at rest the resonance ν energy:

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

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 we take $m_{\chi 1} = m_{\chi 2} = m_\chi$

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

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

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

$\xi \ll 1$ 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

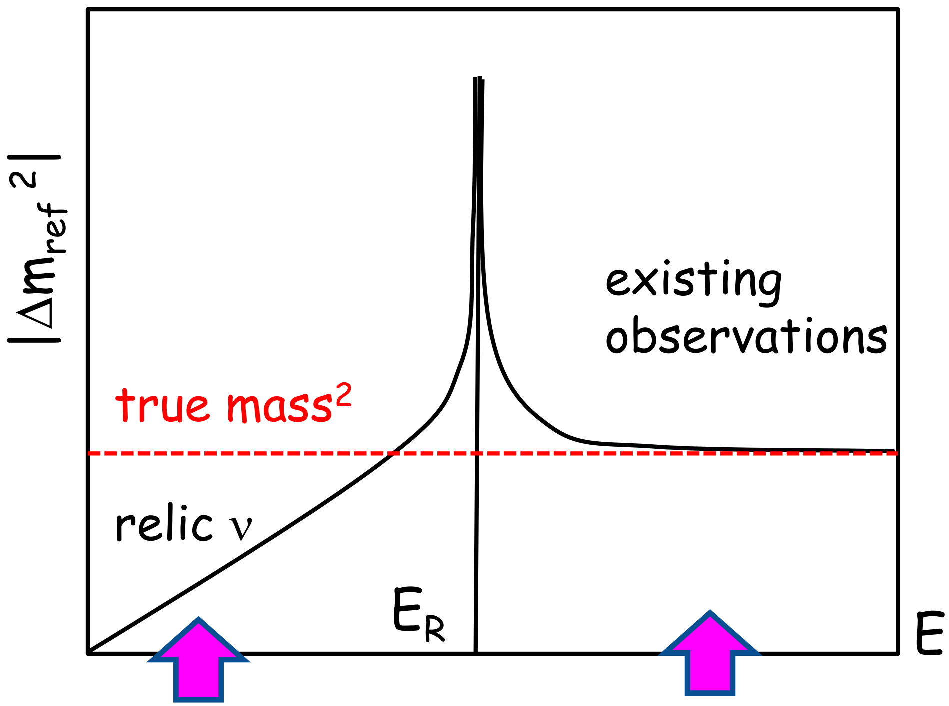
$$m_{ref}^2 = 2EV$$

so that the Hamiltonian of evolution

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

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

→ E_R << 0.1 MeV



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

Refractive mass squared, asymptotic

$m_{ref}^2 = 2EV$

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

where

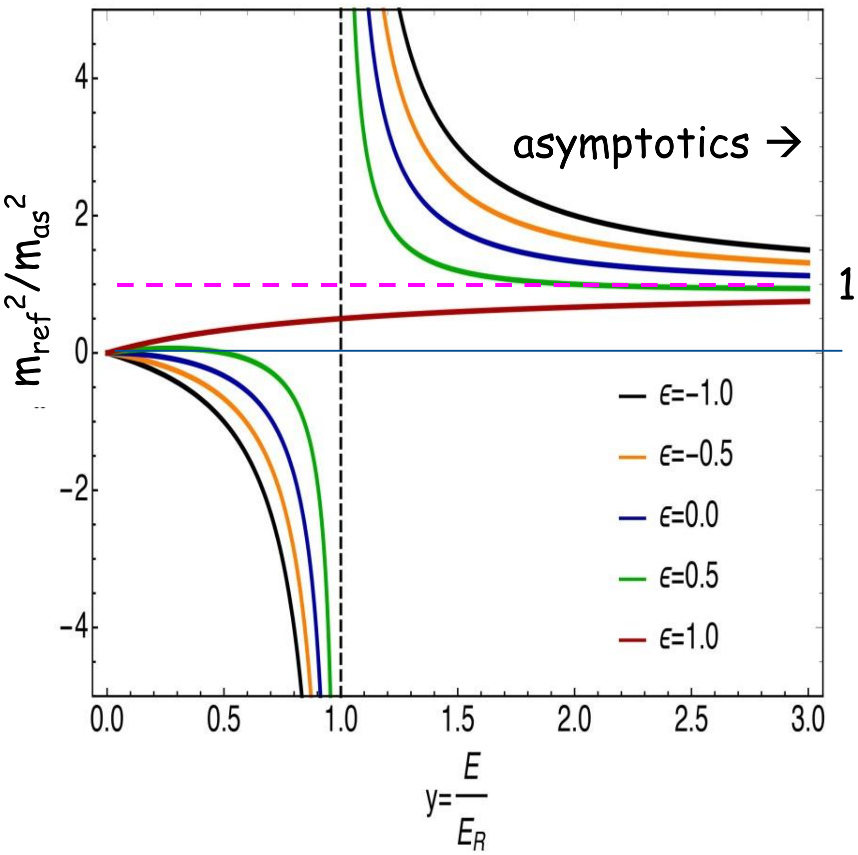
$$m_{as}^2 = \Sigma_k \, g_{\alpha k} \, g_{\beta k}^* \frac{(\bar{n}_\phi + n_\phi)}{m_\phi}$$

is the refractive mass squared in asymptotic: $y \to$ infty

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

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

Near resonance



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

Properties of m_{ref}^2

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

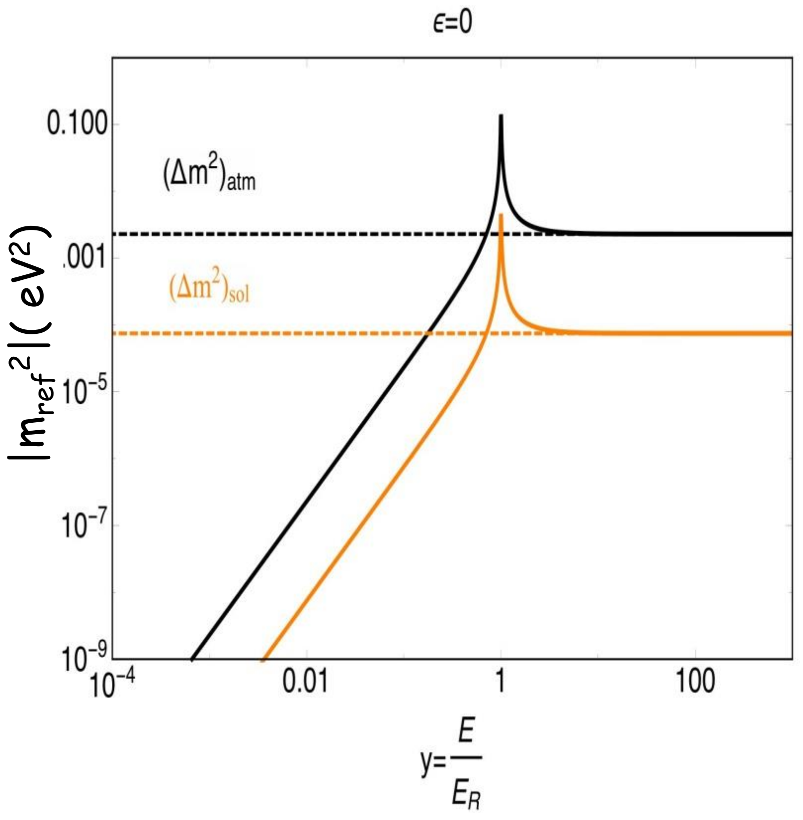
reproducing the Wolfenstein result

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

y >> 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 $\varepsilon \to -\varepsilon$

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

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

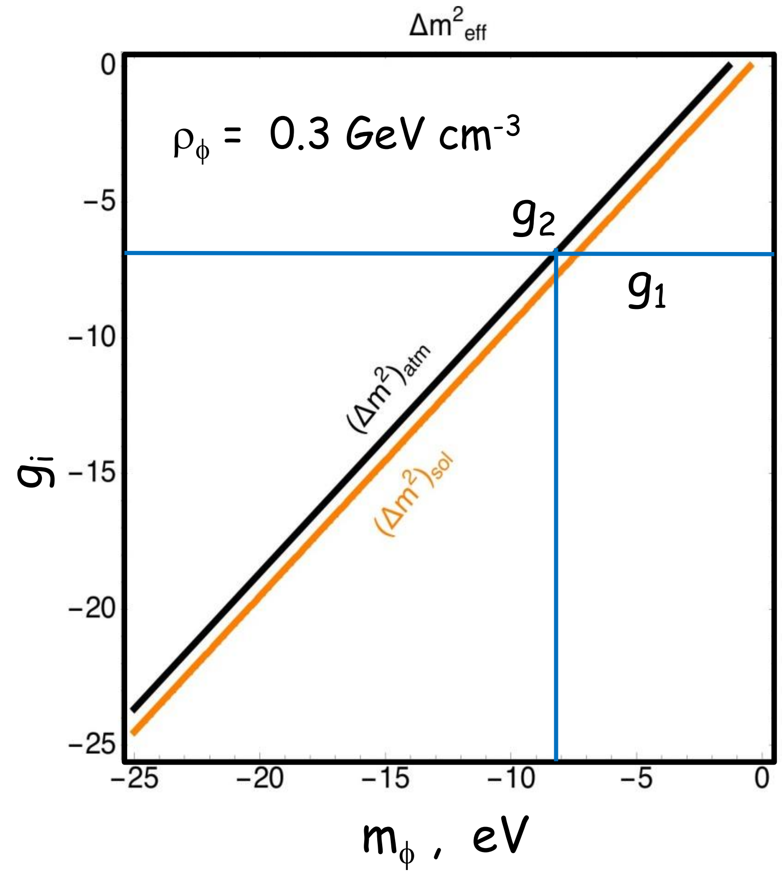
Fitting the oscillation data

Approximate 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, $m_1 = 0$

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



Required g as functions of m_ϕ

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

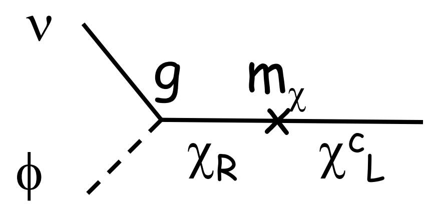
$\rho_\phi \sim \rho_{DM} \sim 0.3$ GeV cm^{-3}

$g_2 < 10^{-7}$ (bound from SN)

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

$\nu - \chi$ mixing and transitions

$\nu_L \, \phi^* \rightarrow \chi_R \rightarrow \chi^c{}_L$



Coherence: states of medium with ϕ absorbed from different space-time points separated by Δx are coherent if

$\Delta x < \lambda_{DB} = 2\pi / v \, m_\phi \rightarrow \nu - \chi$ potential $V_{\nu\chi}$

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

sum over scatterers on the unit of length; $\langle \chi^c{}_{kL}(p_\chi) | \chi_{kR}$: $m_{\chi k} / 2E$; $\phi(x) | \ldots \phi^*(p_j) \rangle$: $e^{-i p_j x}$

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

non-relativistic

random phase summation

Potential:

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

from normalization of WF of ϕ

Total 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 ν - χ^c mixing on oscillations of active neutrinos can be small

Unusual setup

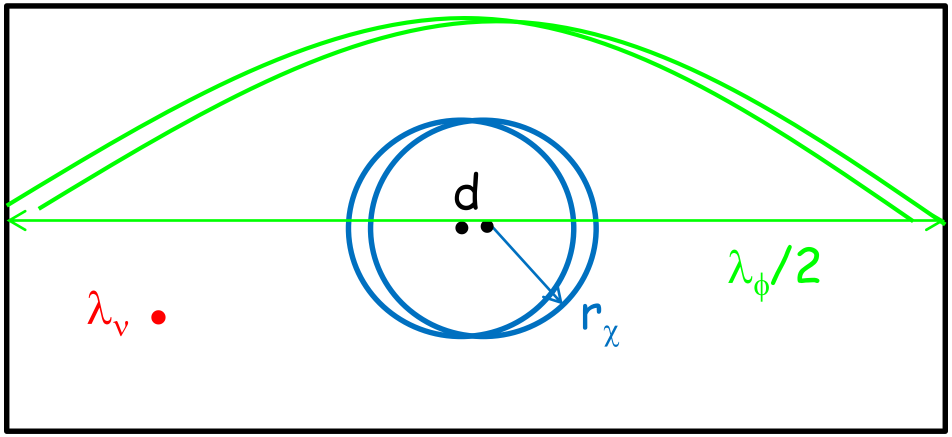
$\lambda_\nu \ll d \ll r_\chi \ll \lambda_\phi$

λ_ν - de Broglie wave of neutrino

d - distance between ϕ

r_χ - radius of interaction

λ_ϕ - De Brogle wave of ϕ



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?

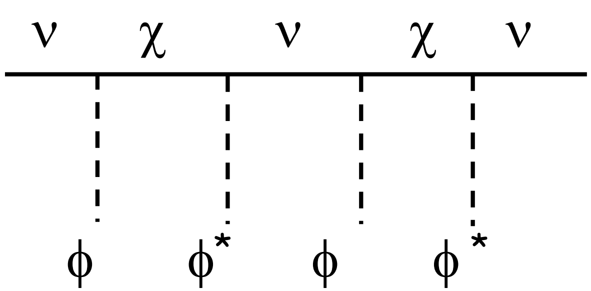
High order corrections?

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

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

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

Just usual refraction?
Double counting?

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

3. Refraction in classical scalar field

Refraction in a classical field

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

Resonance in classical picture?

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

Coherent classical field

Due to inequality $d \ll \lambda_\phi$ or $\lambda_\phi^3 n_\phi \gg 1$, (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 classical scalar field ϕ_c can be constructed as an expectation value of the field operator in the coherent state:

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

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

Glauber

$\mathbf{k} = m_\phi \mathbf{v}$

It can be parameterized as

$$\phi_c(x) = F(x\ t)\, e^{-i\Phi}$$

$$F^2 \sim \rho_\phi / m_\phi^2$$

$$F \sim (n_\phi / m_\phi)^{1/2}$$

Neutrino mass in classical field

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

$L = g_{\alpha k}\, \bar{\chi}_{kR}\, \nu_{\alpha L}\, \phi_c^* + h.c.$ ⇒ 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

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

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

refractive

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 time 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 (resonant absorption).

4. Cosmological and astrophysical bounds

Refractive mass vs. VEV mass

Refractive 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

$$m_{ref}^2 (z) \sim \xi \, m_{as}^2 (loc) (1 + z)^4 \, \frac{E_0}{E_R} \left(\frac{E_0}{E_R} (1 + z) - \varepsilon \right)$$

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

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

redshift of energy and number density

$E_0 \sim 5 \; 10^{-4}$ eV - present energy of relic neutrinos

energy dependence of mass at small y

For large enough E_R the mass $m_{ref}^2 (z)$ can be small.
However below resonance it can not be used in the same way as the "usual" mass in consideration of structure formation in the Universe

m_{ref}^2 has opposite sign for neutrinos and antineutrinos

Refractive mass and structure formation

Neutrinos: suppression of power spectrum of perturbations

Determined by fraction of energy density f_ν in non-clustering neutrino component in the epoch of structure formation:

relativistic

$$\frac{P_m(k)}{P_0(k)} = 1 - 8 f_\nu \qquad f_\nu = \rho_\nu/\rho_m$$

For this one needs to compute

- group velocity, using dispersion relation

- energy density

Dispersion relation

$E = p + V$

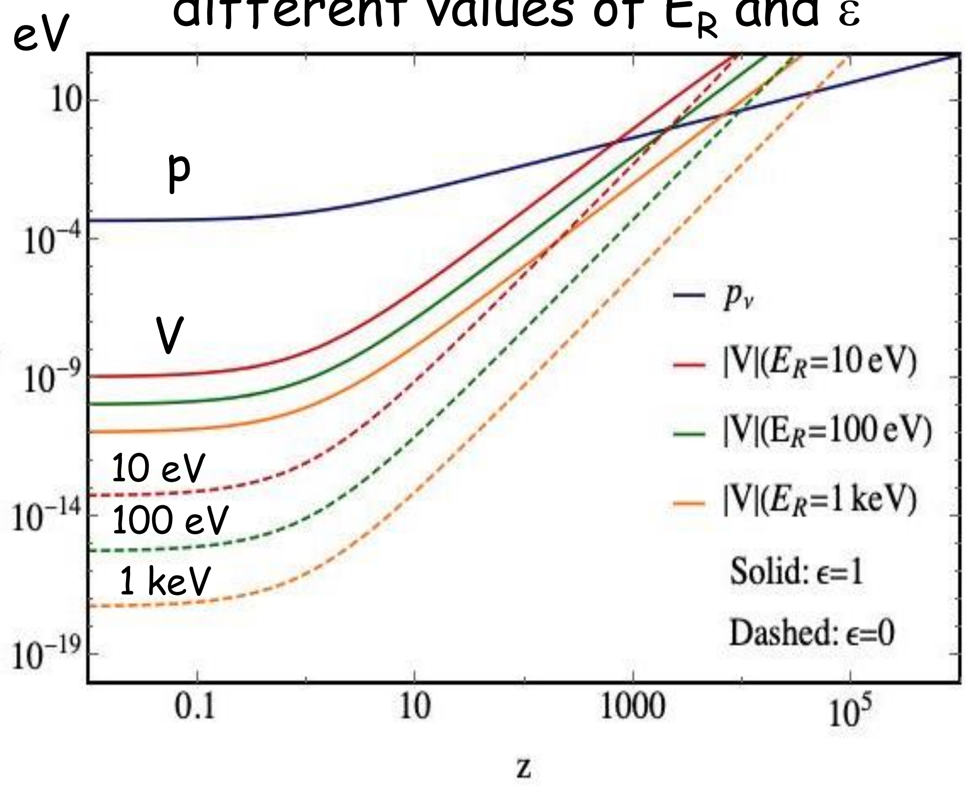
$p(z) = p_0 (1 + z)$

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

$y_0 = E_0/E_R$

$E_0 = p_0 = 5 \times 10^{-4}$ eV is the present 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

P ~ V at z ~ 1000

Group velocity

Manibrata Sen, AYS, 2407.02462 [hep-ph]

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

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

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

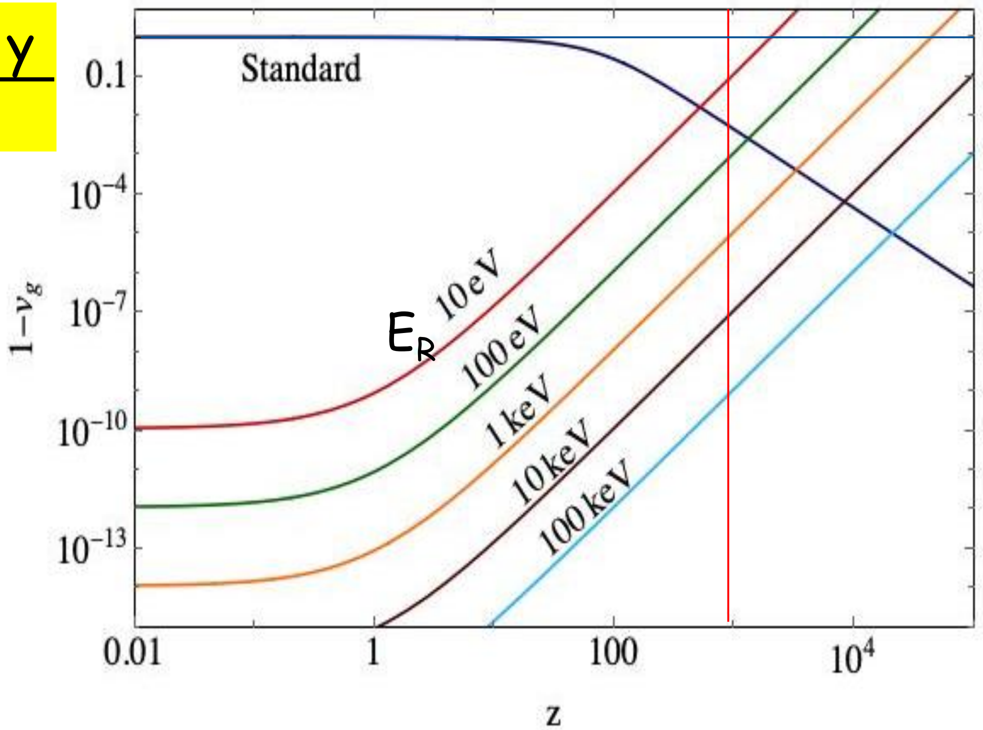
for $y \ll 1$

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

Usual mass case:

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

$1 - v_g$ as function of z for several values of E_R, $m_{as} = 0.05$ eV



With increase of z, v_g decreases neutrinos become non-relativistic

In the epoch of structure formation neutrinos are ultrarelativistic

Structure formation

**

Border of non-relativistic region

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

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

For $(1 + z) < (1 + z)_{nr}$

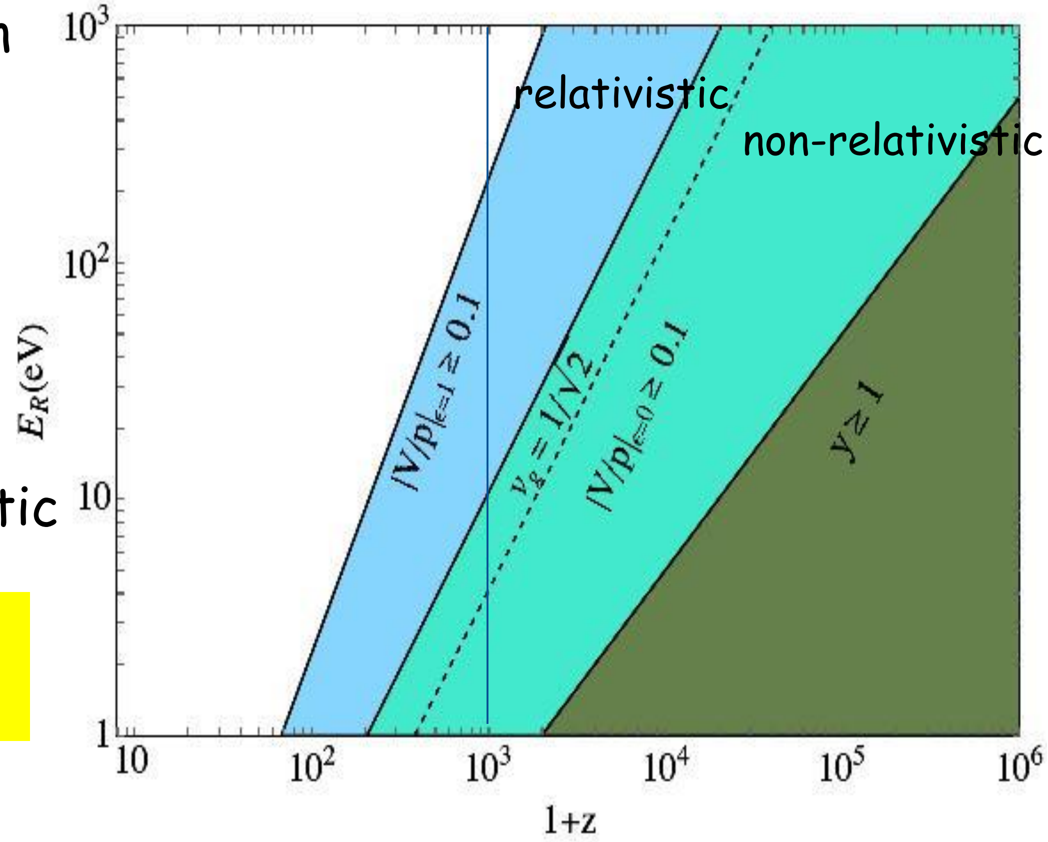
neutrinos become non-relativistic

For $z < 10^3$ neutrinos show up as massless for $E_R > 4$ eV

Perturbativity gives stronger bounds: for $z < 10^3$ perturbativity holds for

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

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



Colored regions shown for $\varepsilon = 1$ and $\varepsilon = 0$ are excluded by perturbativity

Dashed - border of region of non-relativistic neutrinos

Energy density

in neutrinos and antineutrinos:

$$\rho_\nu = (p + V)\, n_\nu , \quad \bar{\rho}_\nu = (p - V)\, \bar{n}_\nu$$

The sum:

$$\rho_{tot} = \rho_\nu + \bar{\rho}_\nu = (\, n_\nu + \bar{n}_\nu \,)\, (p + \varepsilon V)$$

For C-symmetric background, $\varepsilon = 0$,

$$\rho_{tot} = (\, n_\nu + \bar{n}_\nu \,)\, p$$

does not depend on V and the same as for massless neutrinos

Thus in the range $E_R > 10$ eV neutrinos appear as massless in the epoch of structure formation

In this case structure formation data would give effective $m_\nu = 0$

For $E_R < 4$ eV neutrinos become non-relativistic in epoch structure formation and may show up as having non-zero effective mass, but distortion of the spectrum may be different. Here – problem with perturbativity

Refractive mass and DESI bound

This behaviour of refractive masses allows to reconcile the values of masses extracted from oscillations and DESI bound on sum of neutrino masses

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:

D. Wang, et al, 2406.03368

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

ν - χ mixing and oscillations

From the Hamiltonian (slide 28) after ~ TBM rotation one states decouples and the rest 4ν -system splits into two 2ν -systems

$$H_k = \frac{1}{2E}\begin{pmatrix} 0 & m_{ak}\, m_{\chi k} \\ m_{ak}\, m_{\chi k} & m_{\chi k}^2 - 2E\, d\Phi/dt \end{pmatrix}$$

$k = 1, 2$
α -mixed flavor

Oscillation parameters of active-sterile systems:

$$\Delta m_{ak}^2 = 2\sqrt{(m_{\chi k}^2 - 2E\, d\Phi/dt)^2 + m_{ak}^2\, m_{\chi k}^2}$$

$$\tan 2\theta_{ak} = \frac{2 m_{ak}\, m_{\chi k}}{m_{\chi k}^2 - 2E\, d\Phi/dt} \qquad m_{\chi k}^2 \ll m_{a1}^2 = \Delta m_{sol}^2$$

Two viable cases to avoid bounds from active-sterile oscillations of solar neutrinos

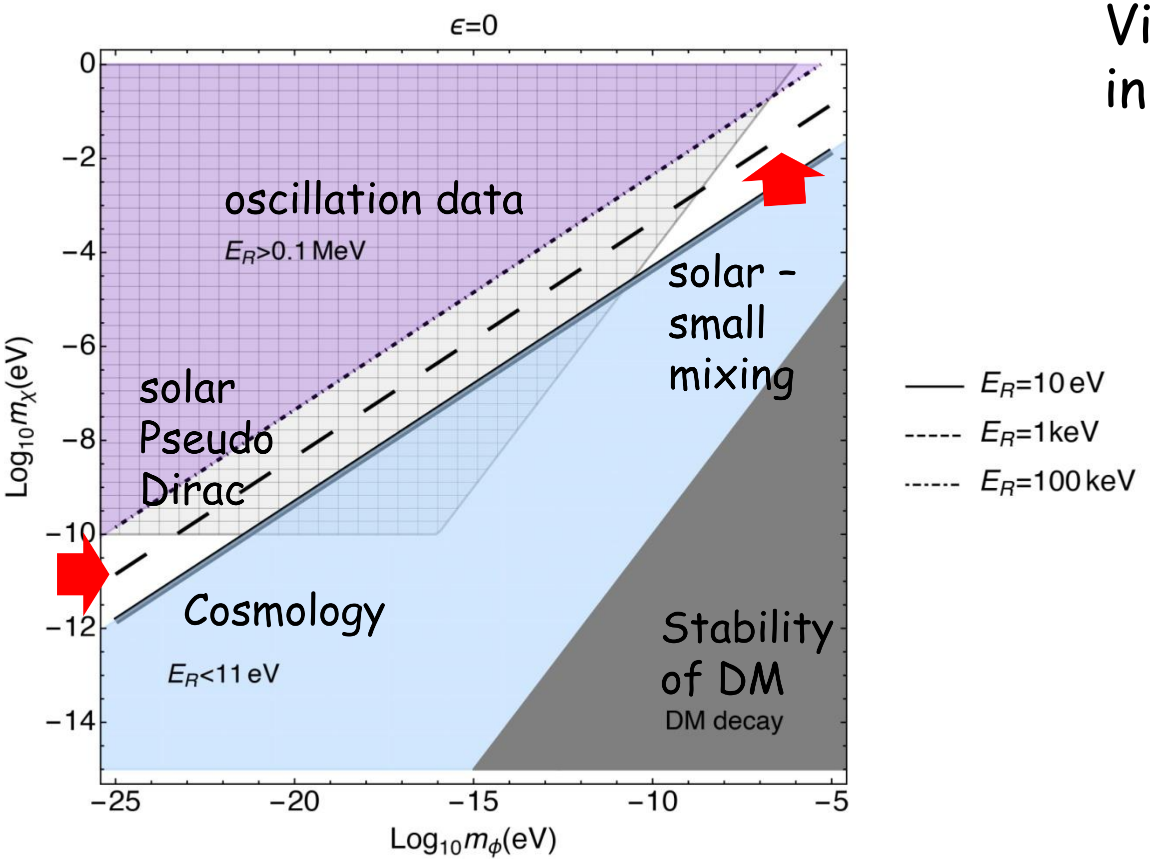
$d\Phi/dt = 0$, pseudo Dirac neutrinos with $\Delta m_{ak}^2 < 10^{-12}$ eV^2

$\rightarrow m_{\chi k} < 10^{-10}$ eV

$E\, d\Phi/dt \sim E m_\phi \gg m_{\chi k}^2$ - small mixing

$\rightarrow m_{\chi k} < 10^6\, m_\phi$

Bounds on parameters



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

Solar neutrinos: bound from oscillations to sterile ν - χ

Astrophysical bounds

Dissipation of the astrophysical neutrino fluxes due to inelastic scattering on ϕ background (energy loss, scattering angle)

$$\nu \, \phi \rightarrow \nu \, \phi$$

For fixed ρ_ϕ gives upper bound on

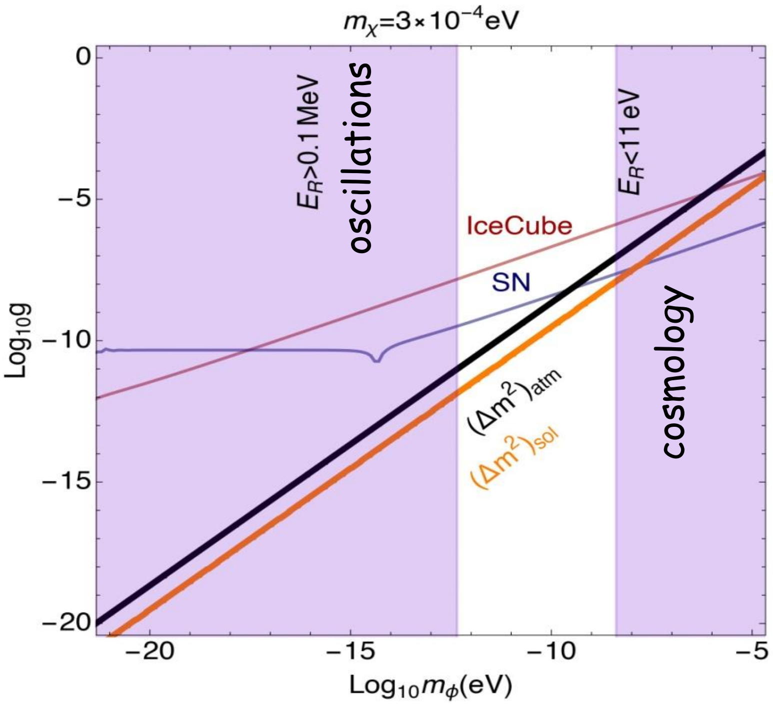
σ_ν / m_ϕ → bounds on g as functions of m_ϕ

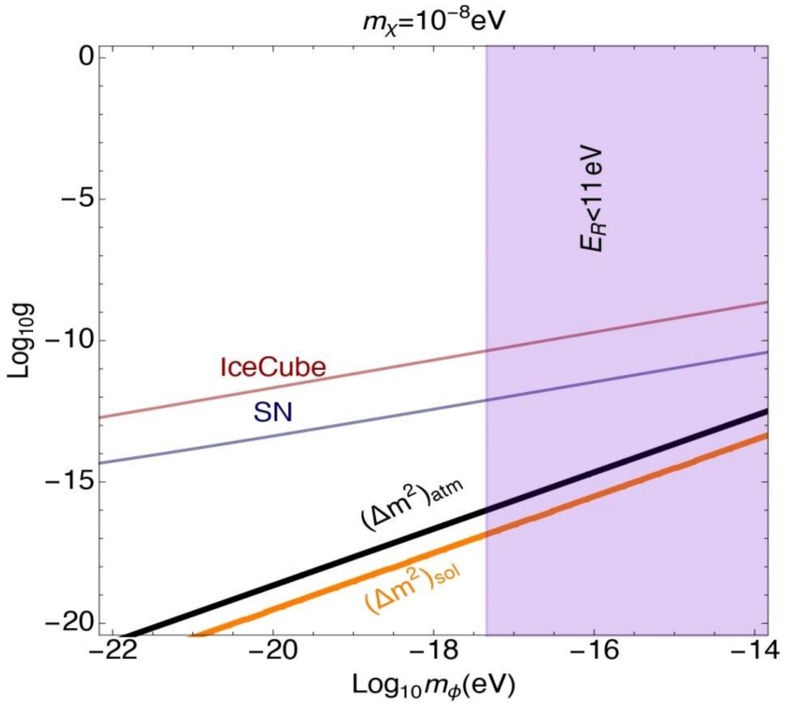
SN1987A, 50 kpc

K.-Y. Choi, J. Kim, C Rott
PRD99 (2019) 8, 083018

Ice Cube observation of neutrino event IC-170922A with E =290 TeV in association with blazar TXS0506+56 (z = 0.3365, 1421 Mpc)

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

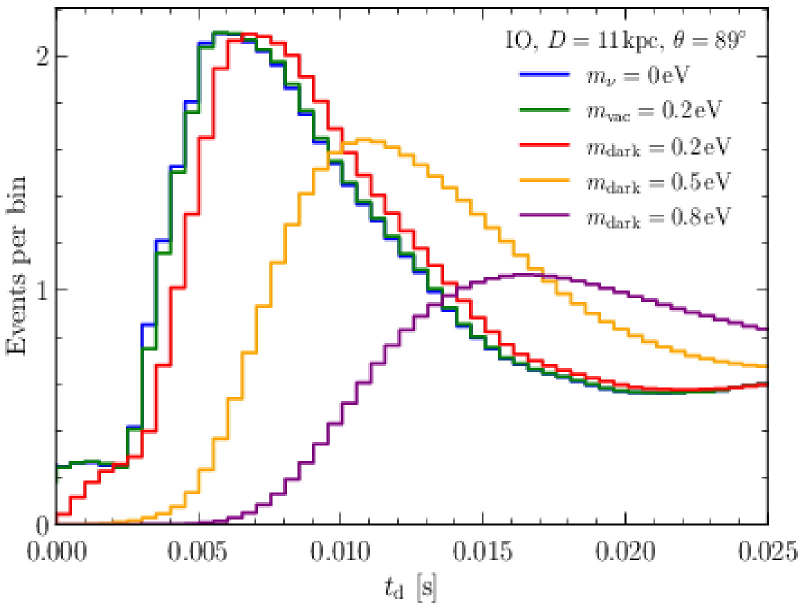
$m_\phi = (10^{-22} - 10^{-10})$ eV

$g = (3\ 10^{-20} - 10^{-7})$

Probing spatial dependence with SN neutrinos

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

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



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

Not restricted by KATRIN

Talk by *Chui-Fan Kong*

Summary

Neutrino oscillation physics

- era of precision measurements
- tool to explore new physics
- applications in extreme conditions

Oscillations set-up

Generalized description of oscillations
which includes production and detection process

Oscillating neutrino state should be computed and not taken
from Lagrangian, that e.g. excludes chiral oscillations

Oscillations of amplitudes of whole process can be reduced
oscillations of neutrino wave packets which encode information
about production and detection processes.
Encoded in the shape factors and effective oscillation phase

For coherence correlations and entanglement can be important

...continued

Challenging matter effect

Described by potential

Different approaches give the same result no deviation from standard result found

Different effects which depend on density profile:

- resonance enhancement (the Earth)
- Adiabatic conversion (the Sun, SN, Early Universe)
- parametric effects (Earth, wavy dark matter, neutrino self-interactions)

...continued

Origins of oscillation: mass or interactions?

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 classical field – particles background correspondence confirm validity

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

Allows to reconcile masses from oscillation measurements and strong bounds from Cosmology

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

Backup

...continued

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

"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: $\frac{1}{\Lambda} L L H H$ ⇒ $m_\nu = \frac{\langle H \rangle^2}{\Lambda}$

If not invent new scale $\Lambda = M_{Pl}$ ⇒ $m_\nu = 10^{-5}$ 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

Phenomenology. Bounds on parameters

ν - DM inelastic scattering

$$\sigma \sim \frac{g^4}{16\pi} \begin{cases} \dfrac{2Em_\phi}{m_\chi{}^4} & E \ll E_R \\ \dfrac{1}{2Em_\phi} & E \gg E_R \end{cases}$$

Experiment: upper bounds on optical depth $\tau = \int dl\, \rho_\phi\, \sigma / m_\phi$

➡ Bounds on σ/m_ϕ for a given neutrino energies E_{exp} → bound on $g = g(m_\phi)$

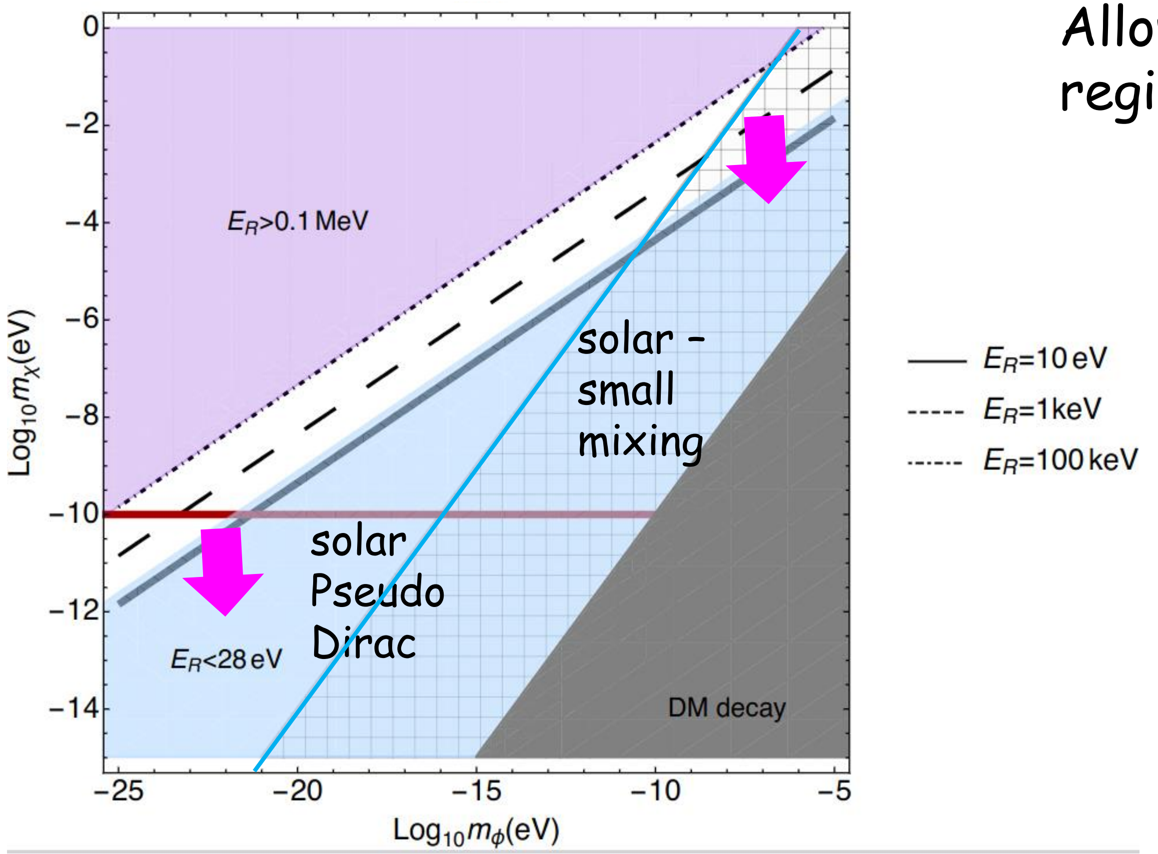
$$g < \begin{cases} A\, m_\xi\, E^{-1/4} & E \ll E_R \\ A'\, m_\phi{}^{1/2}\, E^{1/4} & E \gg E_R \end{cases}$$

← does not depend on m_ϕ

Critical value of ϕ mass: $m_\phi{}^R = m_\chi{}^2/2E_{exp}$

Bounds on parameters

$\varepsilon = 0$



Allowed and excluded regions in m_χ - m_ϕ plane