Neutrinos: between the two deserts

A. Yu. Smirnov

Max-Planck-Institut fur Kernphysik, Heidelberg, Germany

Pushing the Limits of Theoretical Physics, Mainz, May 8 - 12 , 2023

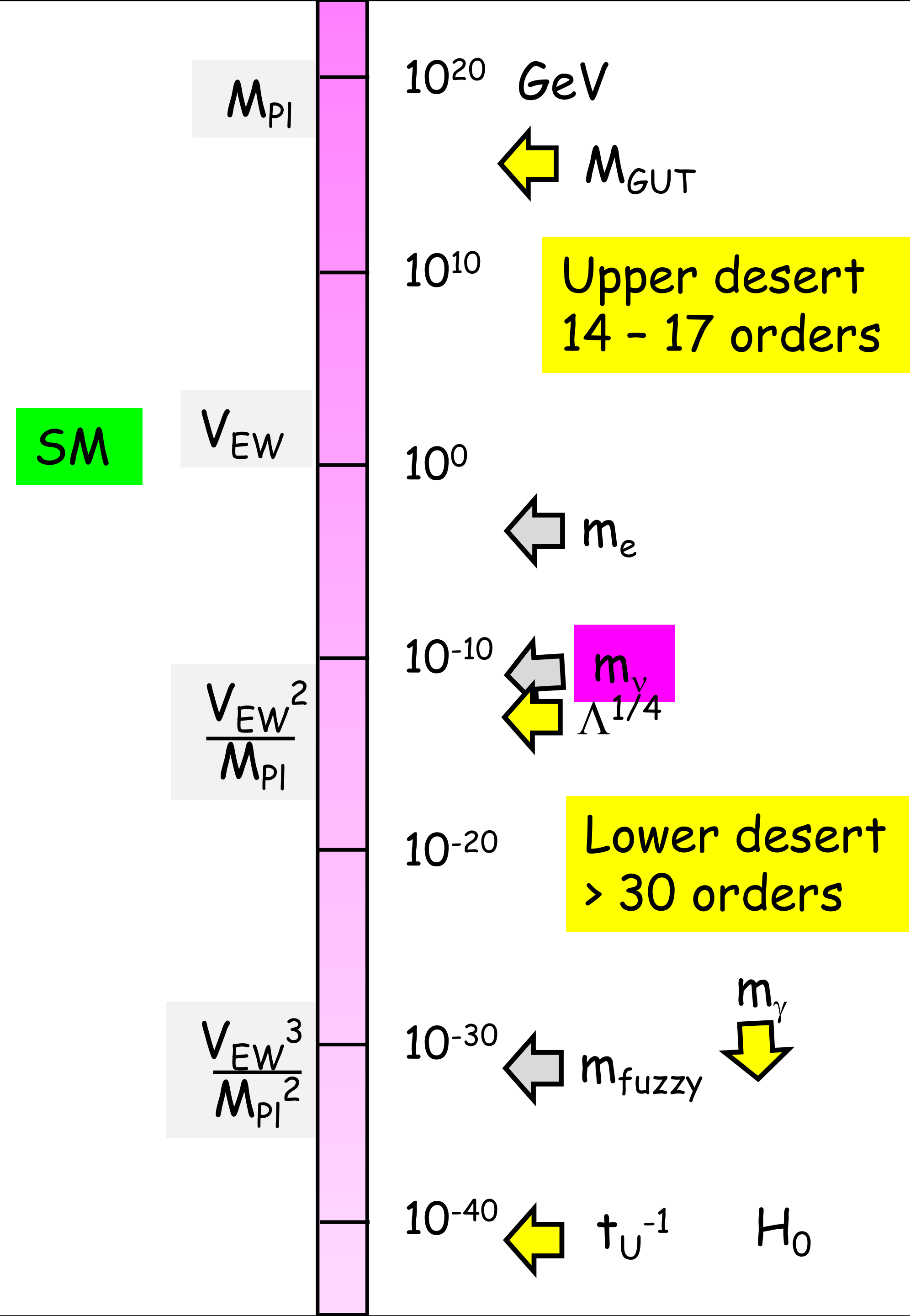
Two deserts

in log scale

It was believed:
due to smallness
neutrino mass is
related to physics
above the HE desert

The same argument:
due to smallness
neutrino mass may
originate from physics
in the LE desert

Both are involved?



Outline:

Comment on the HE scenarios

Nature of neutrino mass and oscillations

Refraction in cold gas

Cosmological consequences

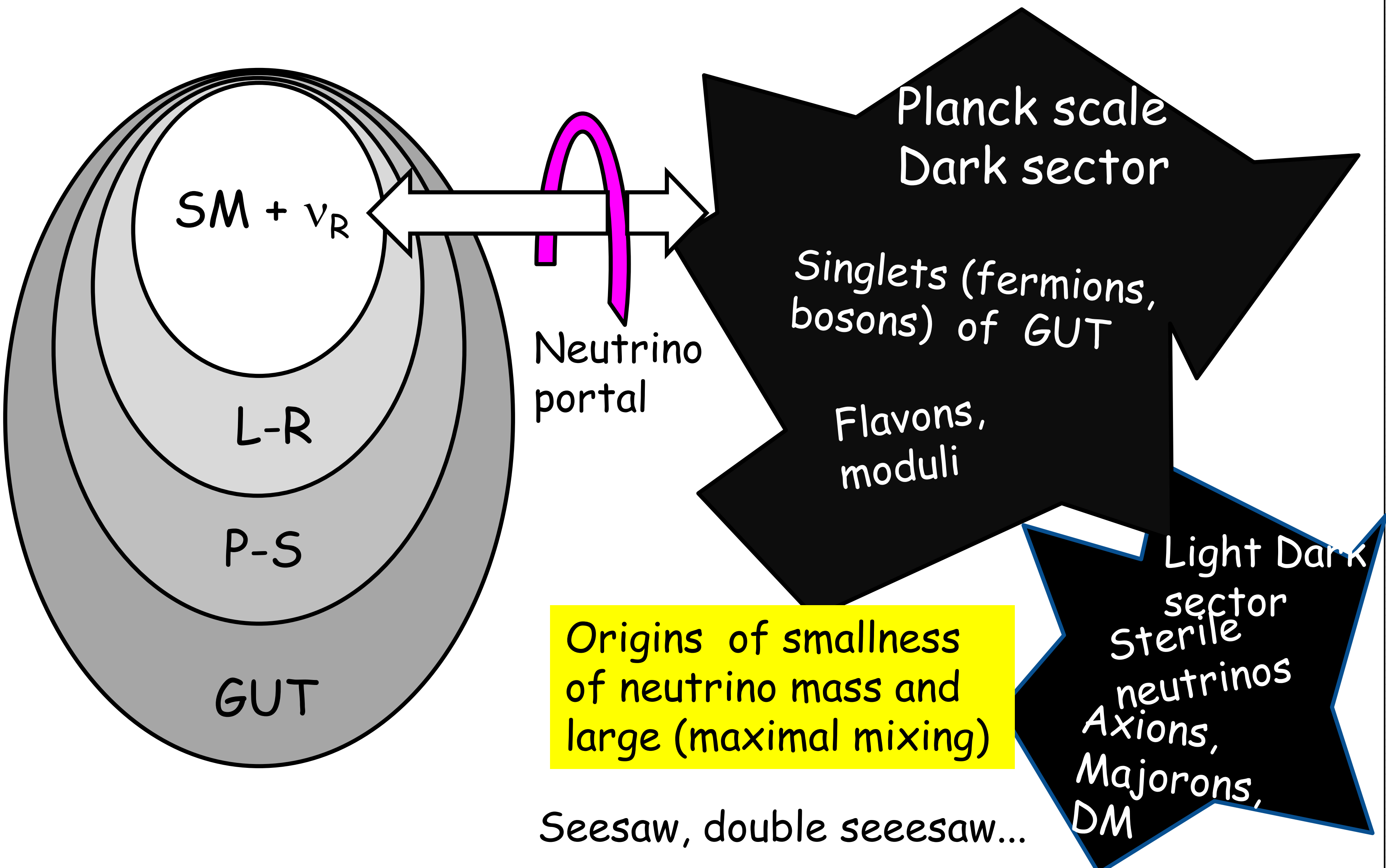
Refraction in classical scalar field

Manibrata Sen, A. Y. S.
to appear

Comment on HE scenario

A HE scenario

Still favorable



... can lead to relation

$$U_{PMNS} = U_{lept}^{+} U_X$$

Common sector for quarks and leptons:

$$U_{lept} \sim V_{CKM}$$

Implies Q - L unification, GUT

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

From the dark sector responsible for large neutrino mixing smallness of neutrino mass

may have special symmetries
which lead to BM or TBM mixing

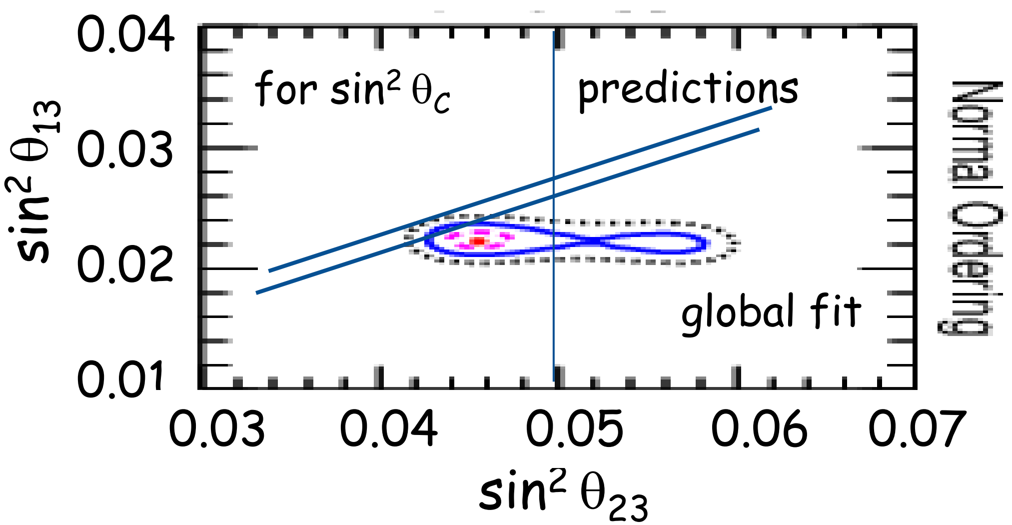
$$U_X = U_{BM} , U_{TBM}$$

Easier realization of symmetries

Prediction

for the 1-3 leptonic mixing:

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



θ_C - Cabibbo angle

Difference can be due to deviation of θ_{12}^l from θ_C related to difference of q and l- masses

Renormalization effects from GUT to low energies

Nature of neutrino mass

Neutrino mass?

We think that we discovered neutrino mass because in 2015 Nobel prize was given

" for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Indeed, oscillation of atmospheric neutrinos (Takaaki Kajita) and adiabatic conversion of Solar neutrinos (Arthur B. McDonald) were discovered.

But how do we know that the mass is behind oscillations?

Oscillations without mass

Lincoln Wolfenstein, 1978: Oscillations of massless neutrinos

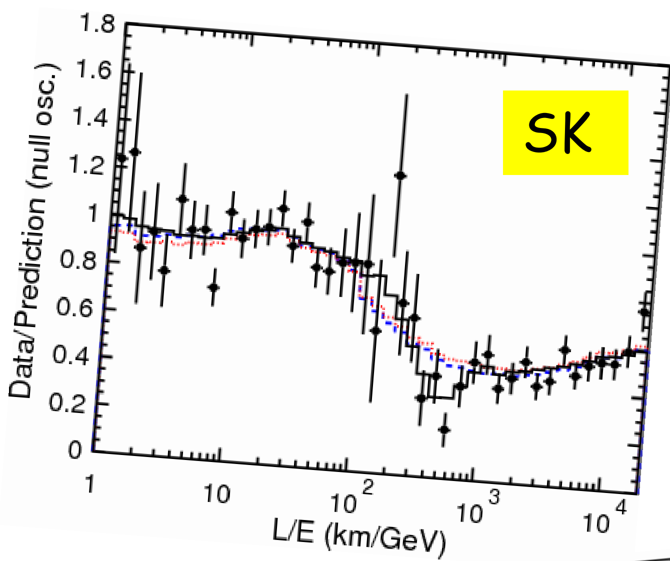
Introduced:

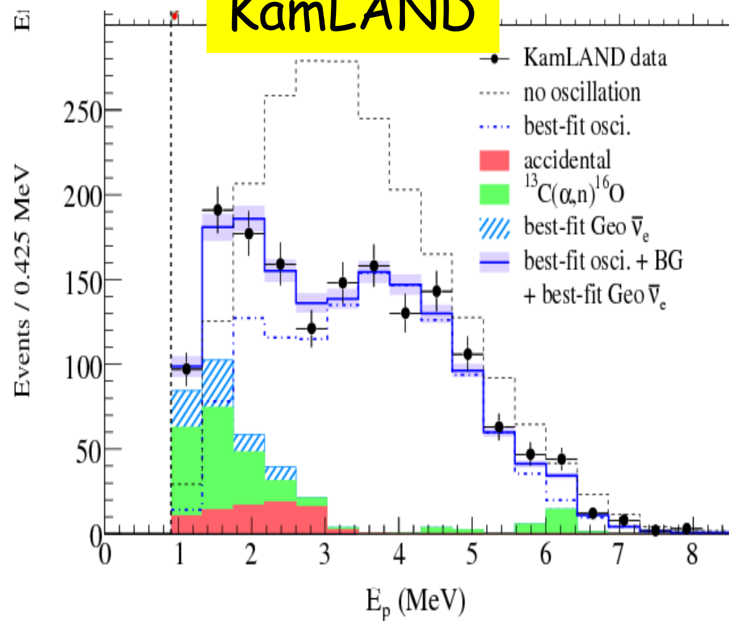
Non-standard interactions of neutrinos –
Non-diagonal in the flavor basis → potentials

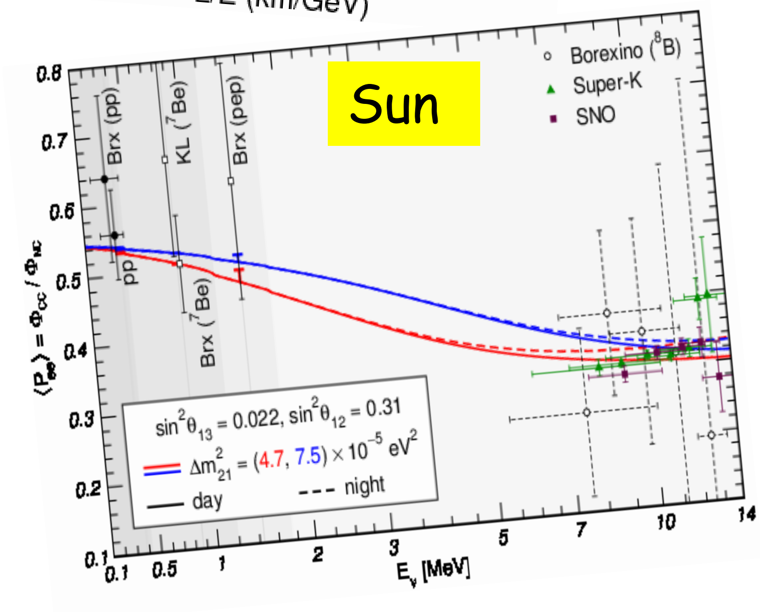
$$E_i = p + V_i$$

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

The energy dependence found !







also MINOS, Daya Bay, RENO ...

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

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

Mass and oscillations

It is this energy dependence of the oscillation effects which leads to conclusion that neutrinos have a mass

Few comments:

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

The mass changes chirality while mass square does not.

Mass operator of neutrinos has gauge charge and appears as a result of symmetry breaking. Mass squared is gauge invariant and does not require the symmetry breaking

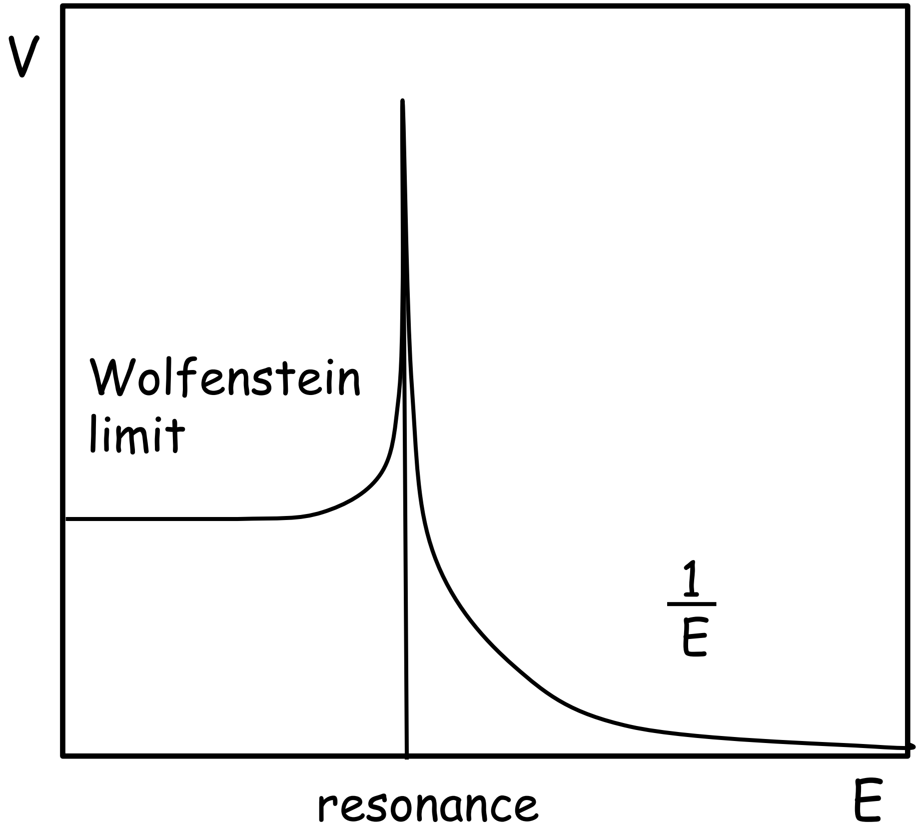
In oscillations there is no direct probe of mass,

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

Matter potential

C. Lunardini, A.S.

Matter potential at high energies (above resonance related to mediator particles) has 1/E dependence



In the SM:

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

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],

Questions:

Can the potential with 1/ E dependence substitute the mass completely?

Can one distinguish these two cases in oscillations or in some other ways ?

Kinematic measurements of mass?
Neutrinoless double beta decay?
Non-relativistic neutrinos?

Effective mass squared

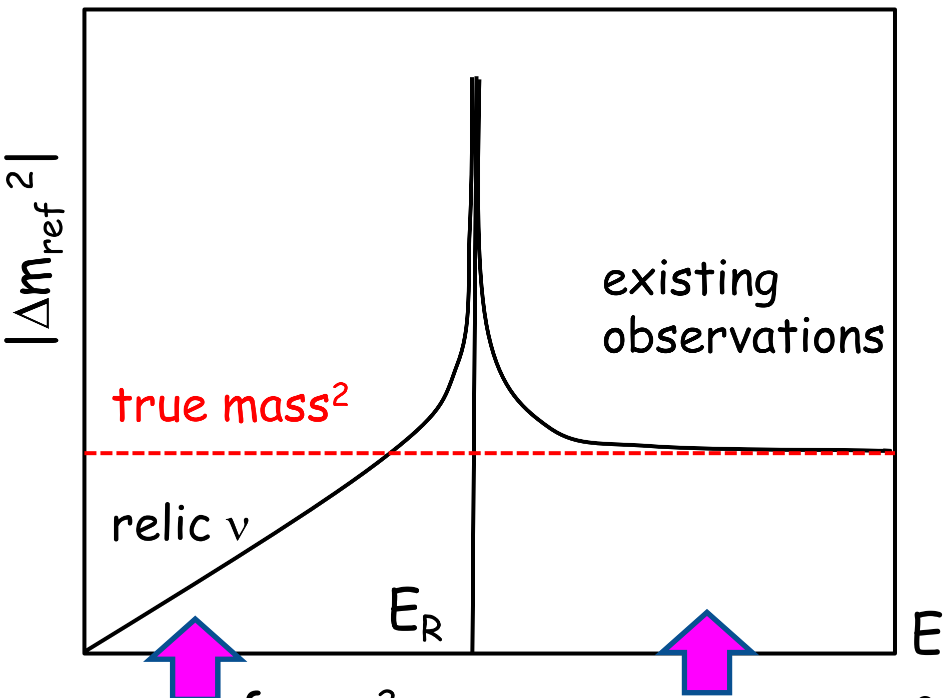
Introduce the effective or refractive mass squared as

$V = m_{ref}^2/2E$

$m_{ref}^2 = 2EV$

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

→ $E_R \ll 0.1$ MeV



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

~ constant m_{ref}^2 explains oscillation data

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

Refraction in a cold gas

A realization

Target (DM): complex scalar field ϕ with mass m_ϕ

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, ...

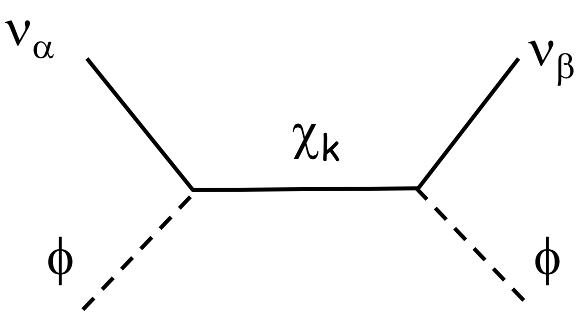
We assume zero VEV $\langle \phi \rangle = 0$

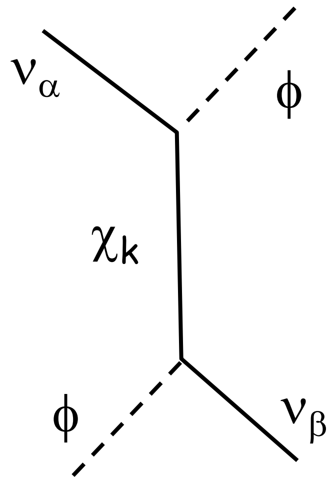
The interaction can be generated via mixing of ϕ with SM Higgs boson

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: $s = m_\chi^2$

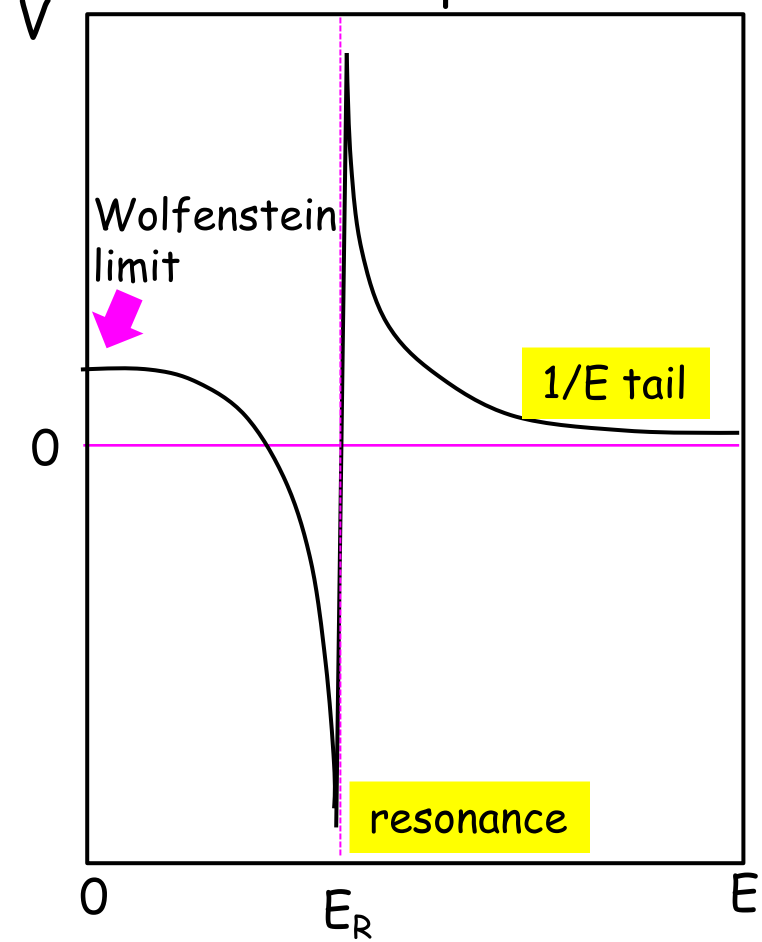
for ϕ at rest the resonance ν energy:

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

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

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

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

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

$\xi \ll 1$ can be neglected

Refraction mass squared

$m_{ref}^2 = 2EV$

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

where

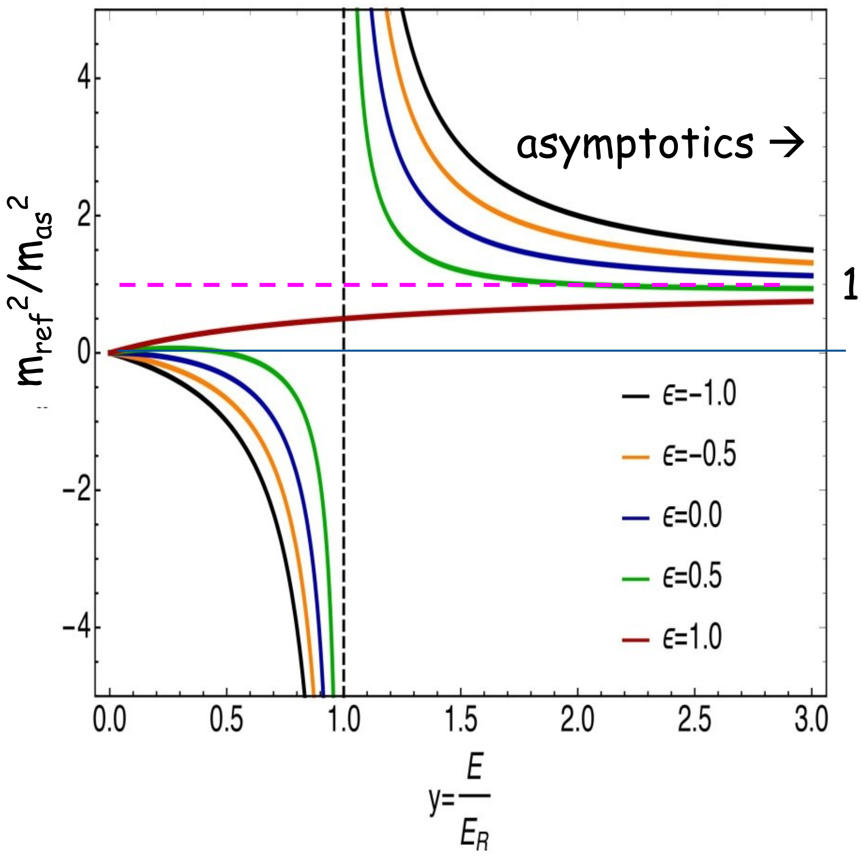
$$m_{as}^2 = \Sigma_k\, g_{\alpha k}\, g_{\beta k}^* \frac{(\overline{n}_\phi + n_\phi)}{m_\phi}$$

is the refraction mass squared in asymptotics $y \to$ 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

Near resonance



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

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

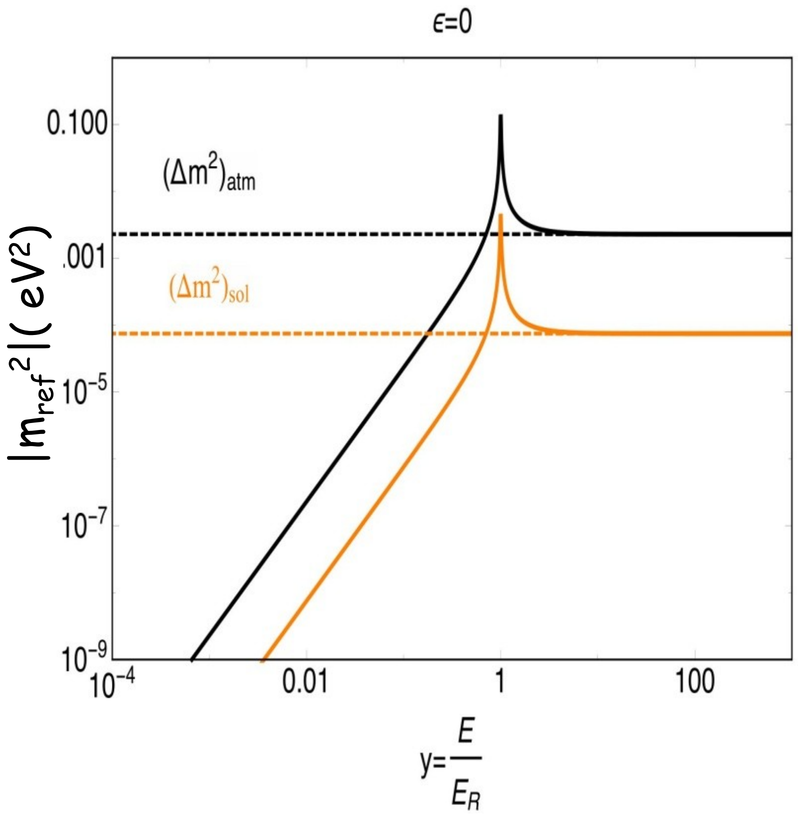
$y \gg 1$

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

converges to constant faster

For antineutrinos $\varepsilon \to -\varepsilon$

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



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

Fitting the oscillation data

Nearly TBM mixing can be obtained for

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

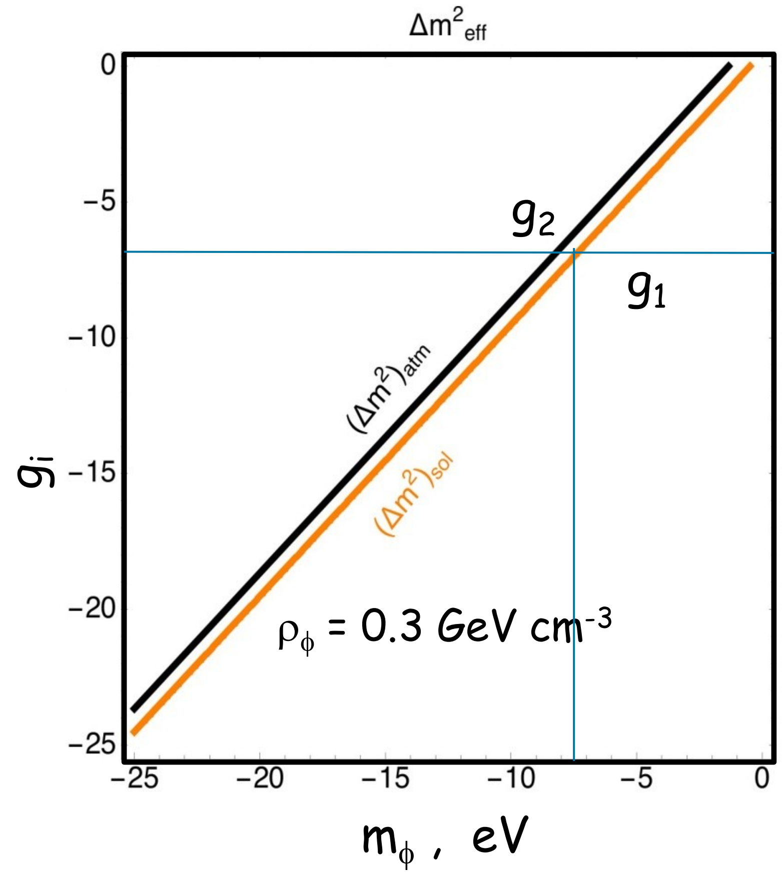
Masses (normal hierarchy) $\quad m_1 = 0$

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

These results do not depend on m_χ

m_χ is determined by m_ϕ and
the resonance energy:

$$m_\chi = \sqrt{2 m_\phi E_R}$$



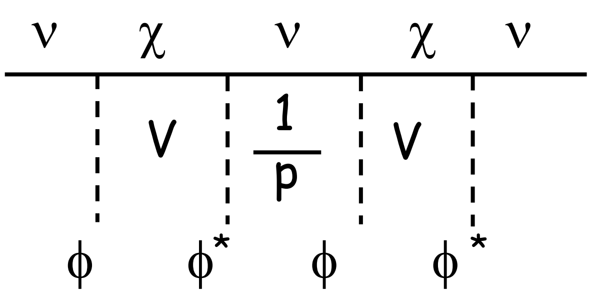
Required g as functions of m_ϕ

Perturbativity and resummation

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

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



$$V^{tot} = V\,[\,1 - 2(V/E) + \ldots\, n!\,(V/E)^n \ldots]$$

Bose enhancement

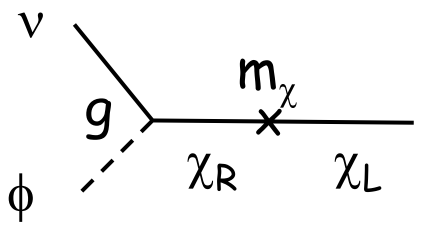
$$\frac{V}{E} = \begin{cases} \dfrac{\varepsilon \Delta m_{atm}^2}{2EE_R} & y \ll 1,\ \varepsilon \neq 0 \\[2ex] \dfrac{\Delta m_{atm}^2}{2E_R^2} & y \ll 1,\ \varepsilon = 0 \\[2ex] \dfrac{\Delta m_{atm}^2}{2E^2} & y \gg 1 \end{cases}$$

Below resonance can be important for relic neutrinos

$$V/E \sim \xi\,(1+z)^2 \qquad \varepsilon \neq 0$$
$$V/E \sim \xi\,(1+z)^3 \qquad \varepsilon = 0$$

$\nu - \chi$ mixing and transitions

$\nu\,\phi \rightarrow \chi_R \rightarrow \chi_L$



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

Energy - momentum conservation OK within $\Delta p < 1/L$ (baseline) and $\Delta E < c/L$

Eung Jin Chun, 2112.05057 [hep-ph]

Potential and production of χ in very narrow energy interval around the resonance energy

$E = E_R\,(1 \;\; +/- \; v)$

$v \ll 1$ - velocity of ϕ

Negligible in the observable energy range

Cosmological evolution, 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 it is not redshifted. Still it can depend on t and x, e.g. in the presence of topological defects and due to thermal corrections to the potential in the Early Universe

Evolution of the refractive mass

In epoch, z, the average refraction 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 over-density of DM

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

redshift of energy and 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 satisfy the cosmological bound on sum of neutrino masses from structure formation

→ lower bound on E_R

Bounds on resonance energy

The structure formation bound at z = 1000:

$$m_{ref}^2(1000) \sim (\Sigma m_\nu)^2 < 10^{-2}\ \text{eV}^2$$

For $y \ll \varepsilon$

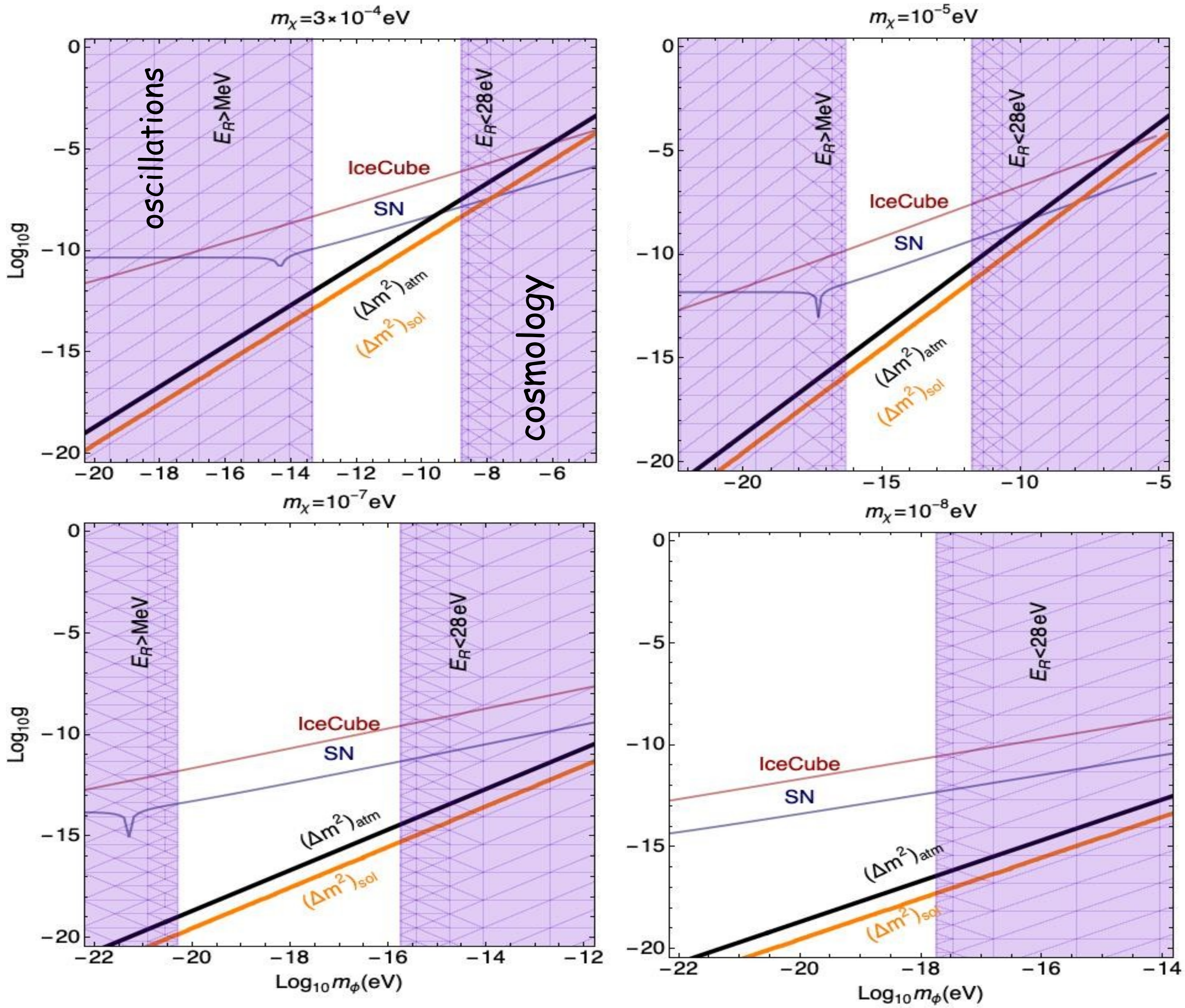
$$E_R > E(0)\, \xi\, \varepsilon\, (1 + z)^4 \frac{\Delta m_{atm}^2}{(\Sigma m_\nu)^2} \Rightarrow E_R > 1.2\, \varepsilon\ \text{keV}$$

For $\varepsilon = 0$

$$E_R > E(0)\, [\, \xi\, (1 + z)^5\,]^{1/2} \frac{\sqrt{\Delta m_{atm}^2}}{\Sigma m_\nu} \Rightarrow E_R > 30\ \text{eV}$$

The bound on refractive masses should be reconsidered
(group velocities, mass in density perturbations, etc…)

Viable ranges of parameters



Bounds and regions required for explanation of oscillation data by refraction in $g - m_\phi$ plane for different values of m_χ

Astrophysical bounds

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

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

Gives upper bound on

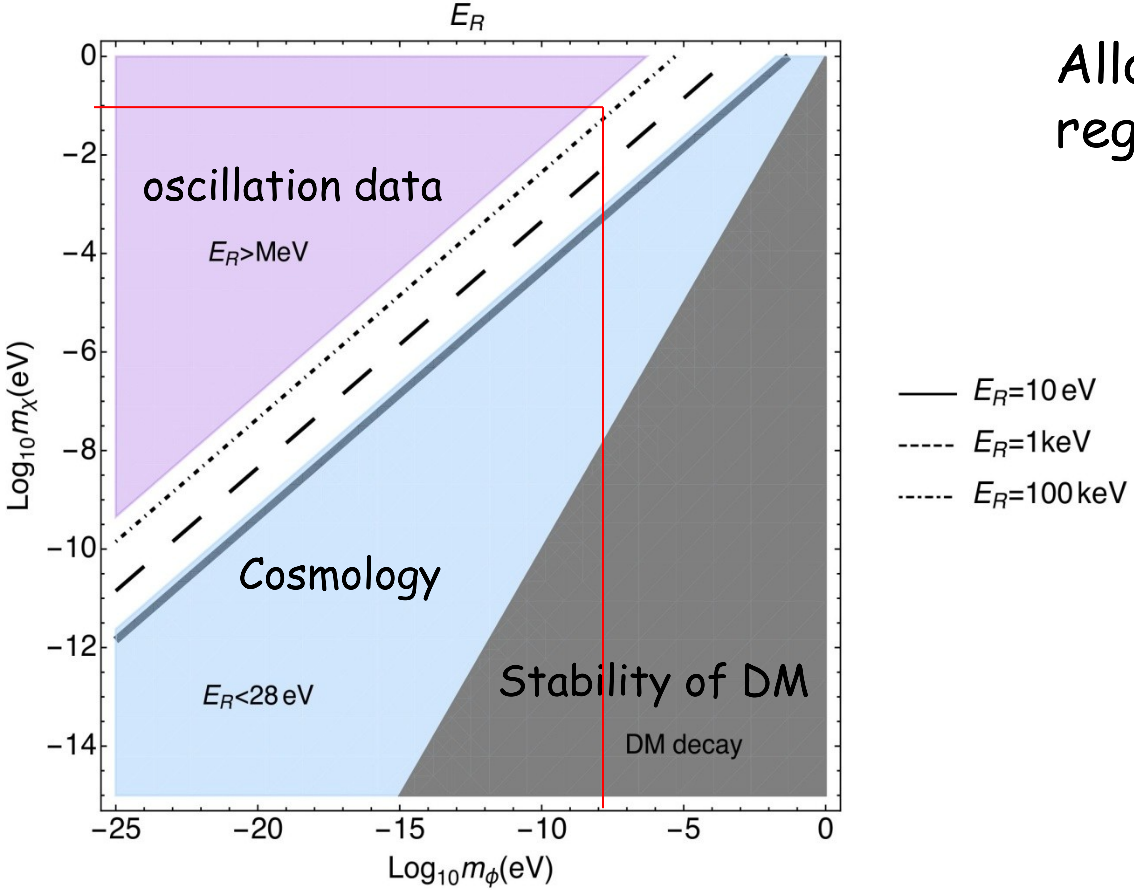
σ_ν / m_ϕ → bounds on g as functions of m_ϕ

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



Allowed and excluded regions in m_χ - m_ϕ plane

Refraction in classical field

Coherent classical field

System of ϕ with large occupation number can be treated as a classical scalar field

Condition $\lambda_\phi^3 n_\phi >> 1$ $\lambda_\phi = 2\pi/k_\phi = 2\pi/vm_\phi$ - de Broglie wave of ϕ

$v \sim 10^{-3}$ - virial velocity in Galaxy

$$\Rightarrow \quad m_\phi << 2\pi \left(\frac{\rho_\phi}{2\pi v^3}\right)^{1/4} \quad \Rightarrow \quad m_\phi << 30 \text{ eV is well satisfied}$$

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:

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

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

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: $\phi \rightarrow \phi_c$

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

$\Rightarrow$ mass terms $m_{\alpha k} = g_{\alpha k} \phi_c^*$

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

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

The Hamiltonian

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

$$M_\chi^2 = f(|F|^2, |g_{\alpha k}|^2, m_{\chi k}^2)$$

Properties of the Hamiltonian

3x3 flavor block has the same form as refraction matrix m_{as}^2

Additional time dependence can appear in F:

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

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

Averaging?

No resonance dependence of mass on energy
No decrease of the mass with energy below resonance
$\nu - \chi$ mixing

ν - χ mixing and oscillations

After TBM rotation of active neutrinos

- one (massless) state decouples
- rest 4 states split into two pairs which evolve independently

$$M_k = \begin{pmatrix} 0 & m_{ak}\, e^{i\Phi} \\ m_{ak}\, e^{i\Phi} & m_{\chi k} \end{pmatrix} \qquad k = 1, 2$$

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

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

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

Summary

Neutrinos (masses and mixing) probe new physics in the deserts:
High energy desert up to string – Planck scale
Low energy desert down to 10^{-23} eV? Or both?

$m_\nu = m_{he} + m_{low}$

We can not exclude that neutrino oscillations are explained the refractive mass squared originating from LE desert

Refraction in cold gas: energy dependent mass at low energies: avoid the cosmological bound on sum of neutrino masses

Refraction on classical coherent field: energy independent mass. Problem with cosmology? Late formation of the field?

Nature of neutrino mass can be related the nature of Dark matter and the Cosmological evolution