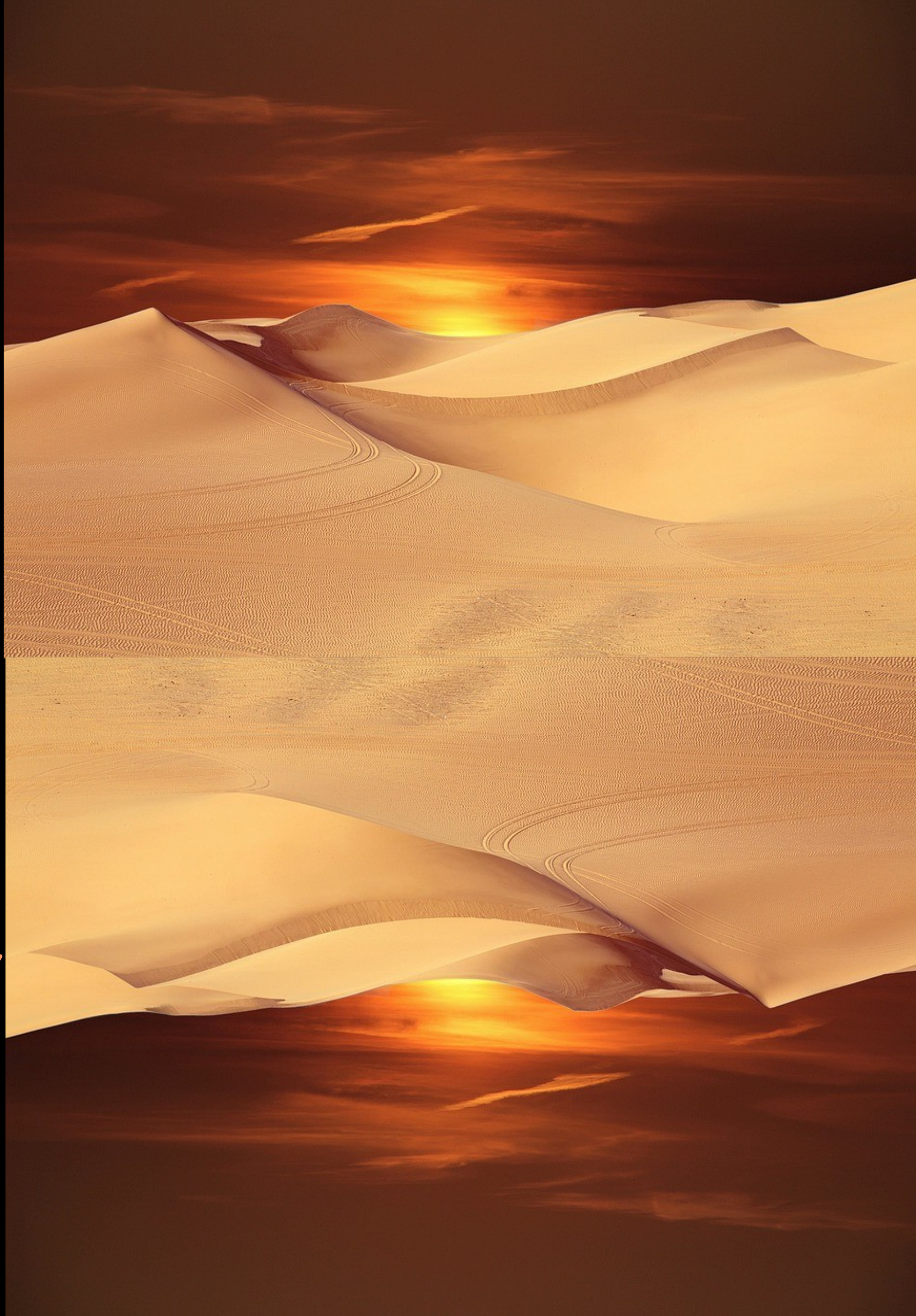
# Neutrinos: between the two deserts



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*Planck 2022, Paris,*
*June 1, 2022*

# Two deserts

Expansion parameter $\frac{V_{EW}}{M_{Pl}}$

Upper desert
14 - 17 orders

SM

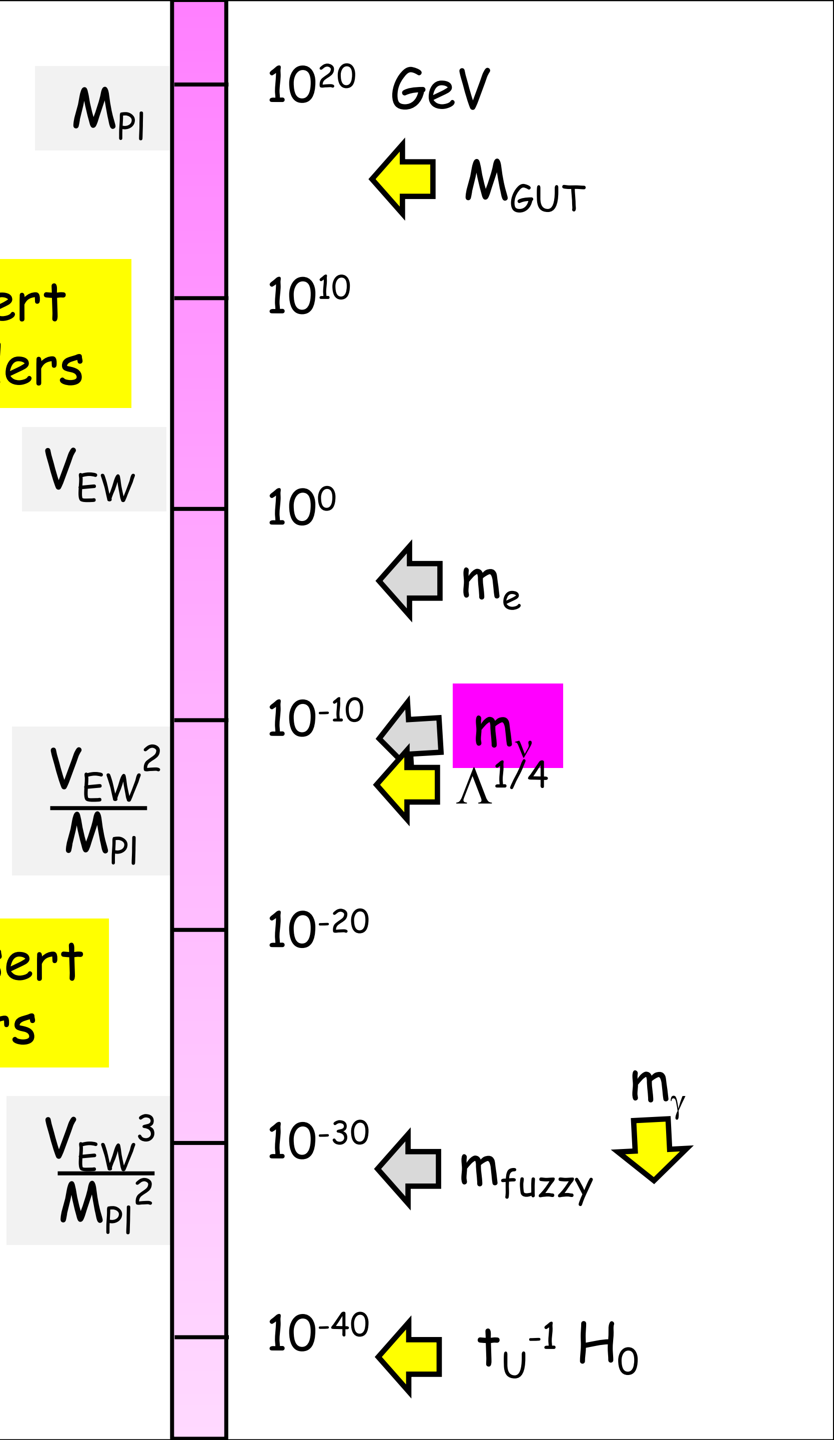
Neutrinos: special role in this picture?

(ν-masss, ν-portal,
ν- anomalies)

Lower desert
> 40 orders

"... From the Planck scale to the Electroweak Scale " ?

New hierarchy problem?



# Content

Oases and Mirages

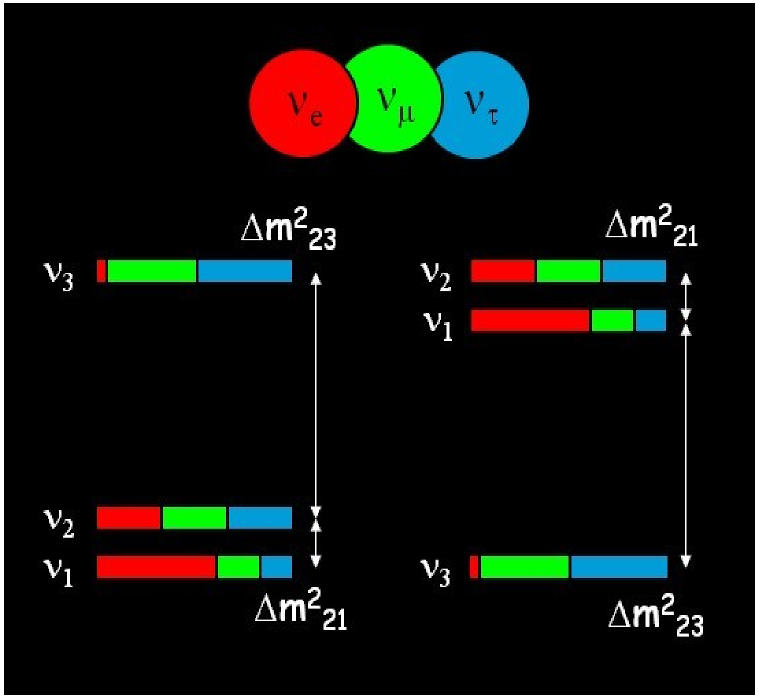
High energy desert

Low energy desert

Signs, evidences of things in the deserts
Mapping...

# Oases and Mirages

# Standards and anomalies



Sterile Mirages

**Ga anomaly**

BEST result, $> 5\sigma$

**LSND / MiniBooNE**

MicroBooNE,
Fermilab SBL,
JSPS$^2$

(1 – 10)TeV scale oases?

**CDFII $m_W$ - shift**

**$\theta_C$ - anomaly**

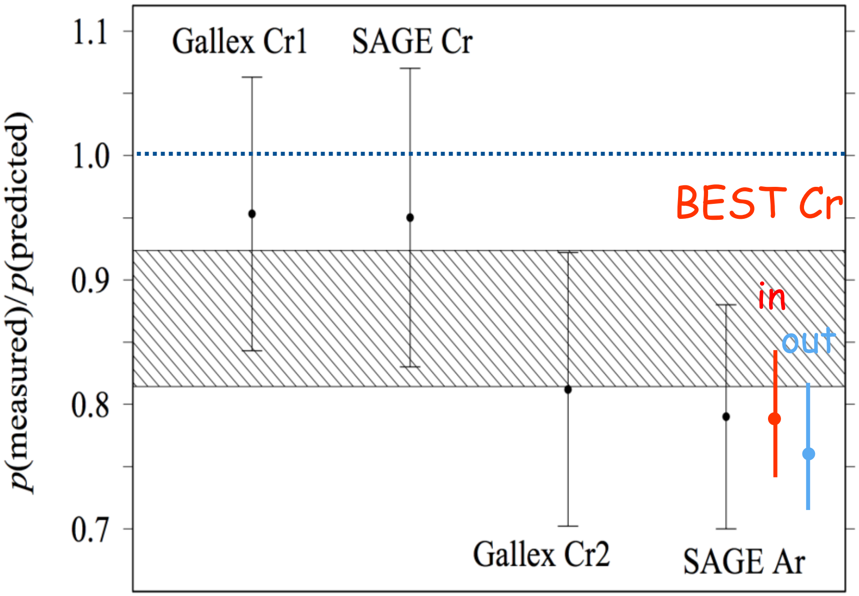
**$(g-2)_\mu$**

**XENON1T**

**B-anomalies**

# Gallium anomaly and BEST

Radiative $^{51}$Cr source
(e capture) – Gallium detector



Comparison of inner - outer volume signals (two distances)

$R_{out}/R_{in} = 0.97 \pm 0.07$

- no evidence of oscillations, but

the Baksan Experiment
on Sterile Transitions

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

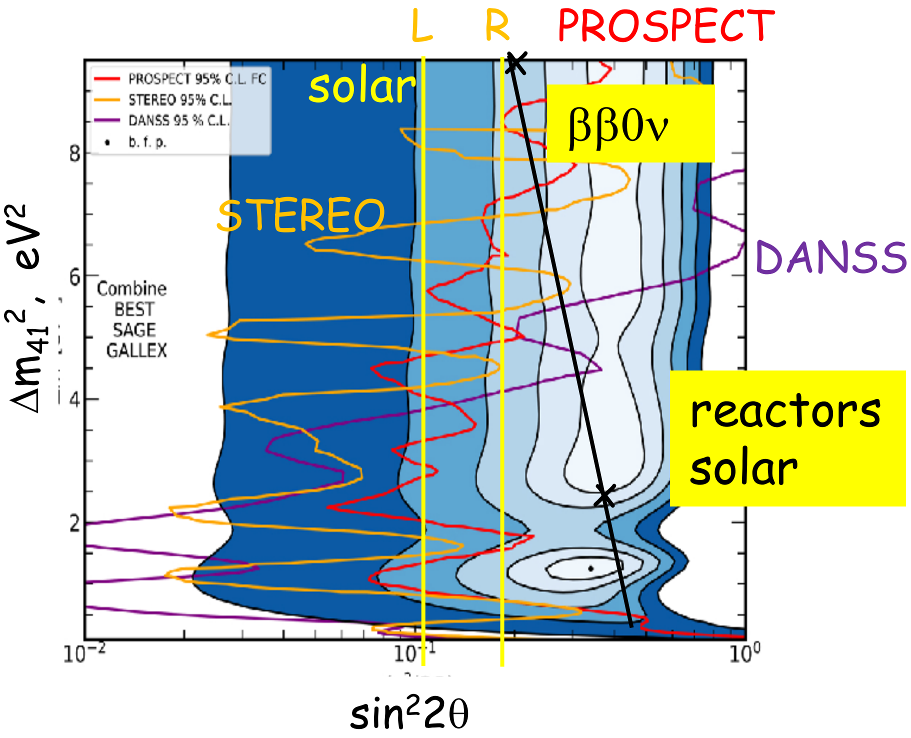
BEST confirms Ga anomaly
deficit of - events
with stat. significance > 5σ.

Oscillation interpretation

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

# 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, DANSS.

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

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

Assuming CPT

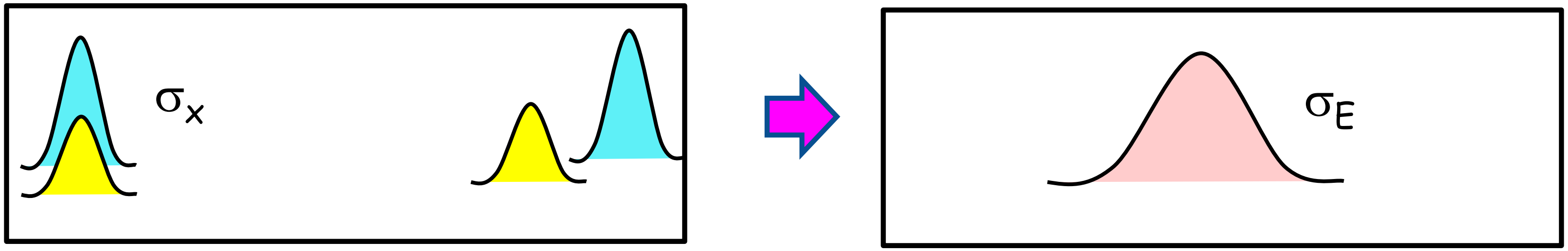
reconcile BEST result with reactor bounds via propagation decoherence

*C.A.Arguelles et al,*
*2201.05108 [hep-ph]*

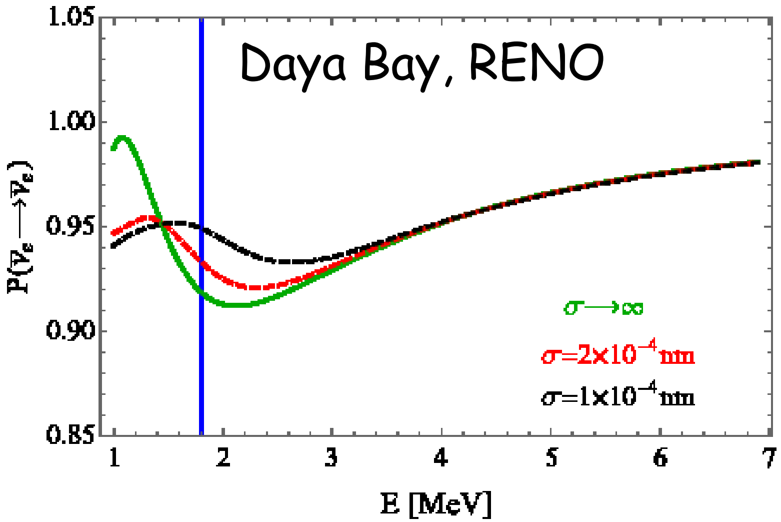
# Propagation decoherence

x –t space: separation of wave packets of mass states due to differnce of group velocities

E-p space: equivalent to integration over the energy uncertainty due to $\sigma_x \sim 1/\sigma_E$



Results in suppression of interference → damping of oscillations



*A. de Gouvea, et al, 2104.05806 [hep-ph]*

From absence of damping:

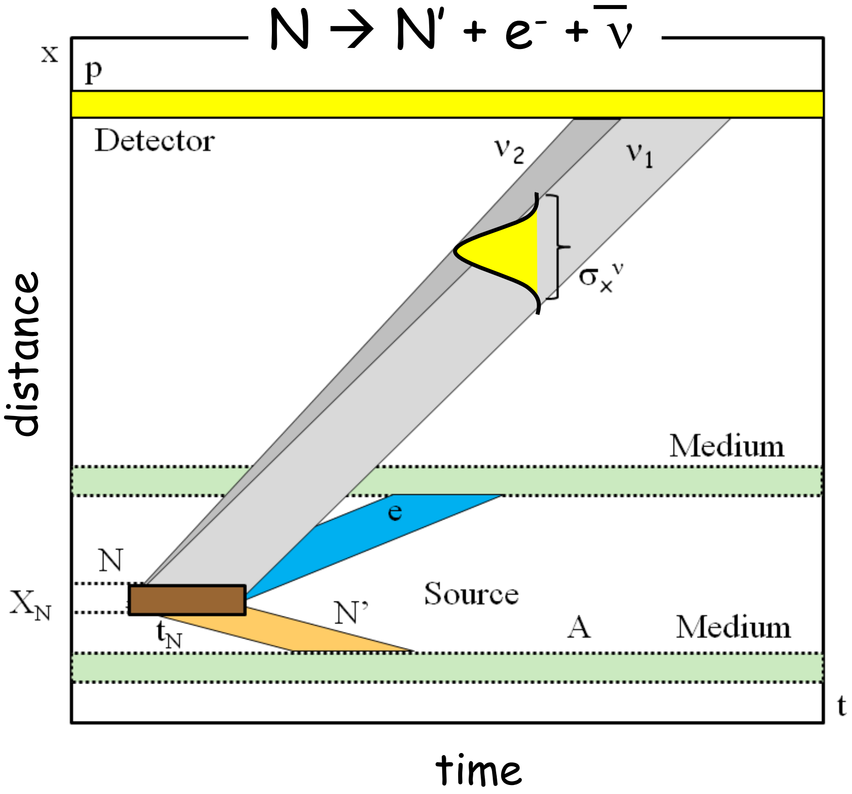
$\sigma_x > 2.1 \times 10^{-11}$ cm

# Computing the size of WP

*E.Kh. Akhmedov and A.Y.S.*
*in preparation*

Space-time localization diagram
for β-decays (reactor neutrinos)

$N \rightarrow N' + e^- + \bar{\nu}$



The slopes of bands are
determined by group velocities

Localization of N is determined by time between two collisions of atoms $t_N$

$\sigma_x \sim v_\nu t_N \sim X_N\, c/v_N$

enhancement factor

$\sigma_x \sim 10^{-2}$ cm

Interactions of N' and $e^-$ can further decrease down to

$\sigma_x \sim 10^{-4}$ cm $\gg$ $\sigma_x$ (exp. bound)

$\sigma_E \sim 1/\sigma_x \sim 0.2$ eV

- negligible correction to energy resolution of a detector

BEST-reactor tension is not removed

# Bounds on the eV sterile neutrinos

BEST, reactors,
LSND/MB

$$\begin{pmatrix} \boxed{\begin{matrix} m_{ee}^0 & \cdots \\ \cdots & \cdots \end{matrix}} & \begin{matrix} m_{es}^0 \\ \cdots \end{matrix} \\ \begin{matrix} m_{es}^0 & \cdots \end{matrix} & m_{ss}^0 \end{pmatrix}$$

After decoupling of sterile neutrino:

$$m_{ee} = m_{ee}^0 - \tfrac{1}{4} \sin^2 2\theta_{41} \sqrt{\Delta m_{41}^2}$$

oscillations of active
neutrinos, Cosmology

$\beta\beta_{0\nu}$ - decay

sterile neutrino

$$\boxed{\Delta m_{41}^2 < \frac{16(m_{ee}^0 - m_{ee})^2}{\sin^4 2\theta_{41}}}$$

$m_{ee}^0 < 0.156$ eV (90% C.L.)

*KamLAND-Zen , S. Abe et al.*
*2203.02139 [hep-ex]*

$\sin^2 2\theta_{41} = 0.4$

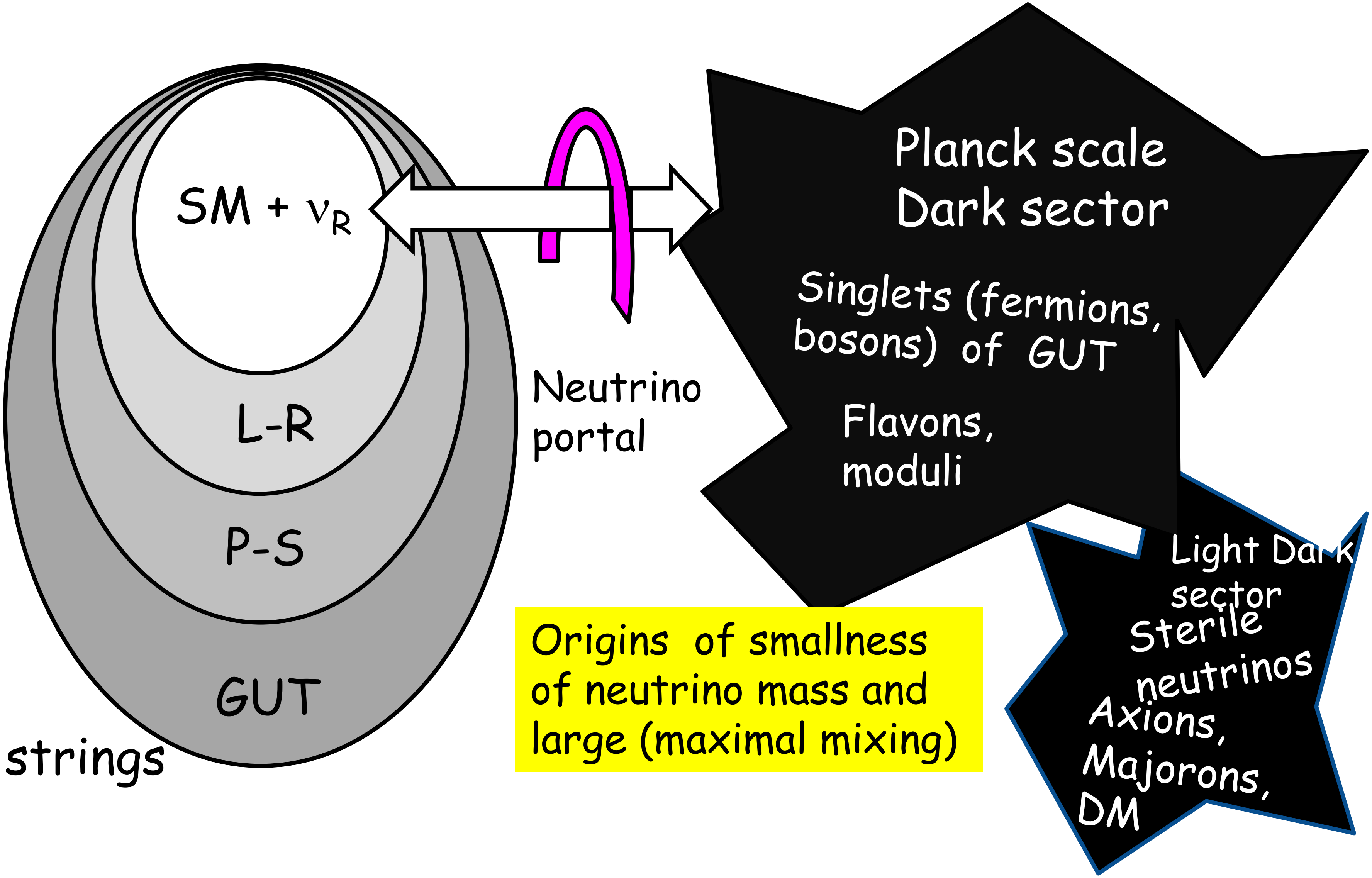
For NH: $m_{ee} \sim m_2 \sin^2 \theta_{21} = 2.5\ 10^{-3}$ eV $\quad \Delta m_{41}^2 < 2.4$ eV$^2$

For quasi-degenerate: $m_{ee} < 0.03$ eV $\quad \Delta m_{41}^2 < 1.6$ eV$^2$

disfavour
BEST,
Neutrino-4

# Upper desert

# A scenario



SM + $\nu_R$

L-R

P-S

GUT

strings

Neutrino portal

Planck scale
Dark sector

Singlets (fermions, bosons) of GUT

Flavons, moduli

Light Dark sector

Sterile neutrinos

Axions,
Majorons,
DM

Origins of smallness of neutrino mass and large (maximal mixing)

# ... can realize relation

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

Common sector for quarks and leptons:

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

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

Implies
Q - L unification, GUT

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

may have special symmetries
which lead to BM or TBM mixing

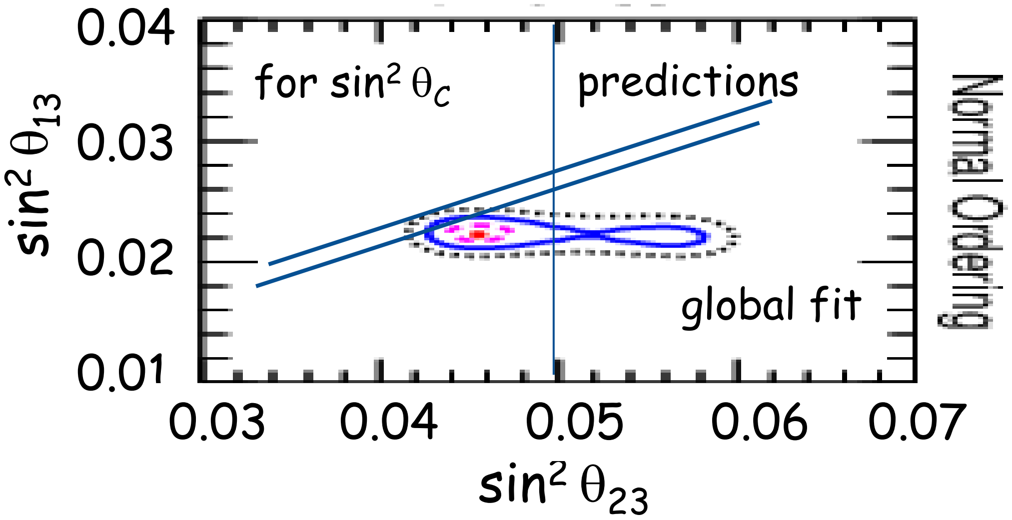
$$U_X = U_{BM} , U_{TBM}$$

Easier realization of symmetries

# Prediction

for the 1-3 leptonic mixing:

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



$\theta_C$ - Cabibbo angle

Difference can be due to deviation of $\theta_{12}{}^{l}$ from $\theta_C$ related to difference of q and l- masses

Renormalization effects from GUT to low energies

# Predictions for $\delta_{CP}$

*B. Dasgupta, A Y.S. ,*
*N.P. B884 (2014) 357*
*1404.0272 [hep-ph]*

If $U_X = U_{BM}, U_{TBM}$ , then $U_{lept} \sim V_{CKM}$ can be the only source of CP violation. Leads to the relation

$$\sin\delta_{CP} = -\sin\delta_{CP}^q \cos\theta_{23} \frac{\sin \theta_{13}^q}{\sin \theta_{13}}$$

$\lambda^3$

$\lambda$

$\lambda = \sin \theta_C$

0.93 0.75 $\lambda^2$

$\sin \delta_{CP} \sim \lambda^2 \sim 0.046$ or $\delta_{CP} = 2.6^\circ$

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

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

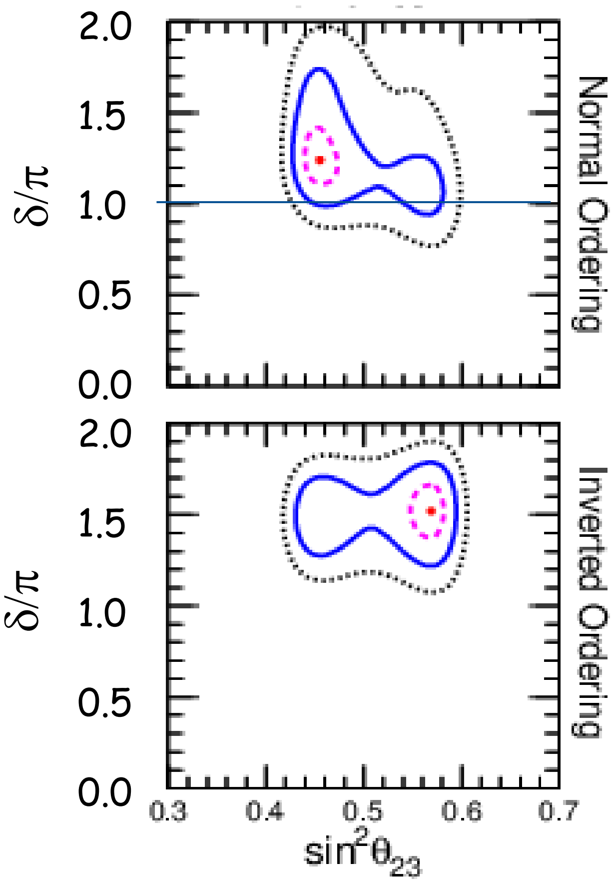
# Experiment: CP-phase is close to $\pi$?

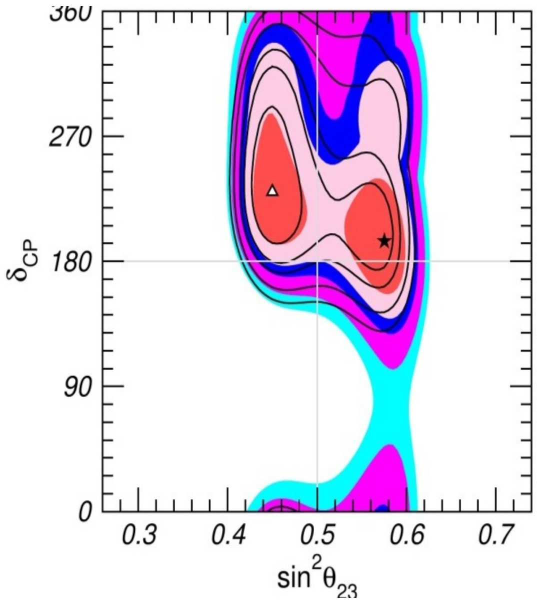
NOvA-T2K 2$\sigma$ tension NOvA: $\delta_{CP} = 0.82\pi$, T2K $\delta_{CP} = 1.5\pi$

**Global fits**

*F Capozzi, et al 2107.00532 [hep-ph]*

*NuFIT 5.1 (2021), www.nu-fit.org*

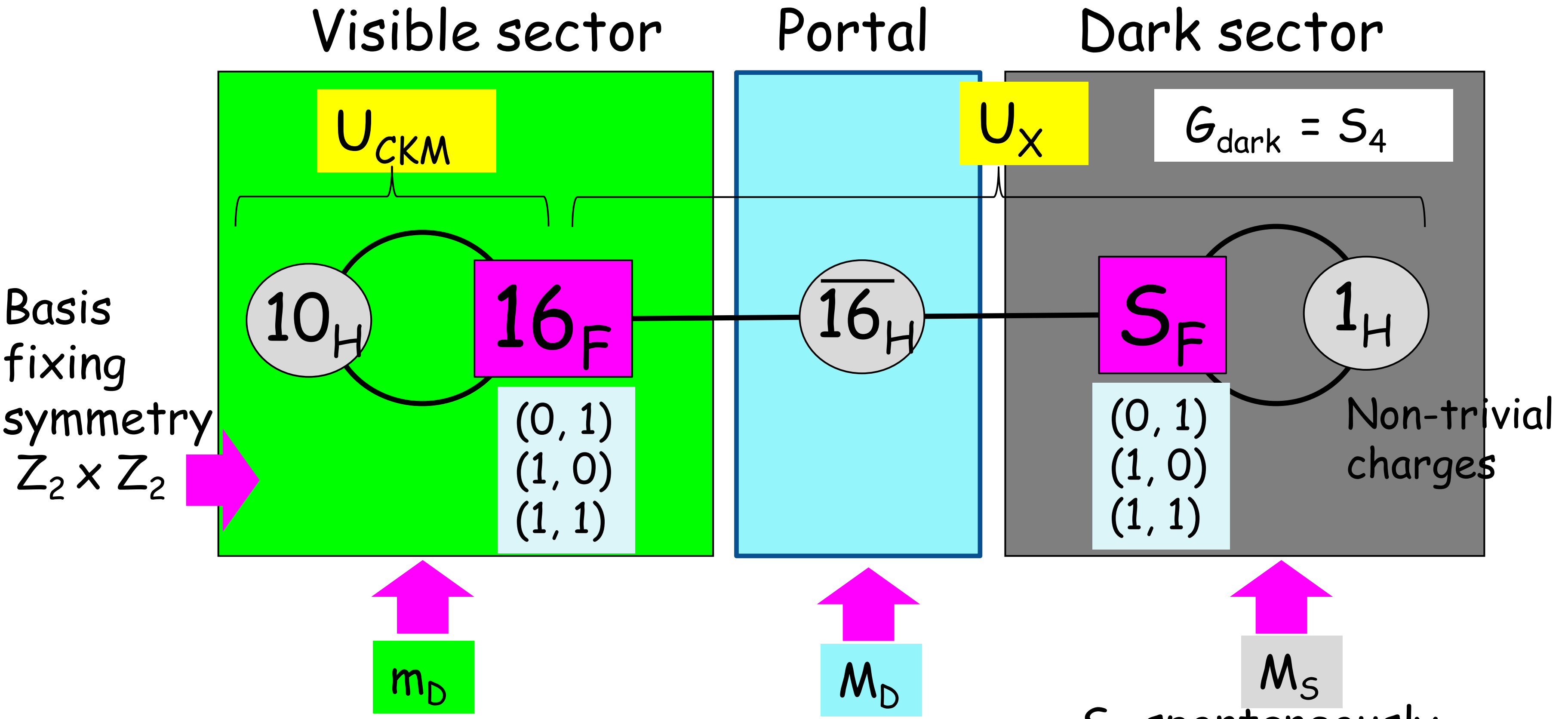




even closer to $\pi$

# Realization in SO(10) GUT

*Xun-Jie Xu , A.Y.S.*
*1803.07933 [hep-ph]*



Visible sector

Portal

Dark sector

$U_{CKM}$

$U_X$

$G_{dark} = S_4$

Basis fixing symmetry $Z_2 \times Z_2$

$10_H$

$16_F$

(0, 1)
(1, 0)
(1, 1)

$\overline{16}_H$

$S_F$

$1_H$

(0, 1)
(1, 0)
(1, 1)

Non-trivial charges

$m_D$

mass hierarchy

CKM mixing - additional structure

$M_D$

no mixing

$M_S$

$S_4$ spontaneously broken by flavons $1_H$ down to $Z_2 \times Z_2$

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

# Features

Neutrino masses from the Double seesaw with

$M_S \sim M_{PL}$, $M_D \sim \langle 16_H \rangle \sim M_{GUT}$     $m_D$, $M_D$ = diagonal

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

Similar non-SUSY structure with $10_H$ , $16_H$, $45_H$
(responsible for gauge symmetry breaking)

*A. Preda, G. Senjanovic,*
*M. Zantedeschi,*
*2201.02785[hep-ph]*

High dim. operators, correspond to the integrated out dark sector but with $\Lambda \sim 10\ M_{GUT}$, $M_{GUT} \sim 4\ 10^{15}$ GeV

$M_D \sim \langle 16_H \rangle \sim M_I \sim 5\ 10^{14}$ GeV

Unification is achieved by strong mass splitting in $45_H$ with weak tripled and color octet, as well as in $10_H$ with scalar quark doublet (leptoquarks) having masses below 10 TeV

accessible to LHC ?

→ low scale anomalies ?

# Lower desert

Populated by light particles
with masses down to $10^{-23}$ eV

Interactions of neutrinos
with light scatterers
via light mediators

Not seen due to smallness
of couplings

Smallness: portal - dark sector

# The simplest example

Scalar interaction

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

$\chi$ - fermion (can be RH neutrino), $\phi$ - scalar

$y$ -coupling, $y < 10^{-7}$

L can be generated via the RH neutrino portal

Rich phenomenology

Refraction

Effective $m_\nu$

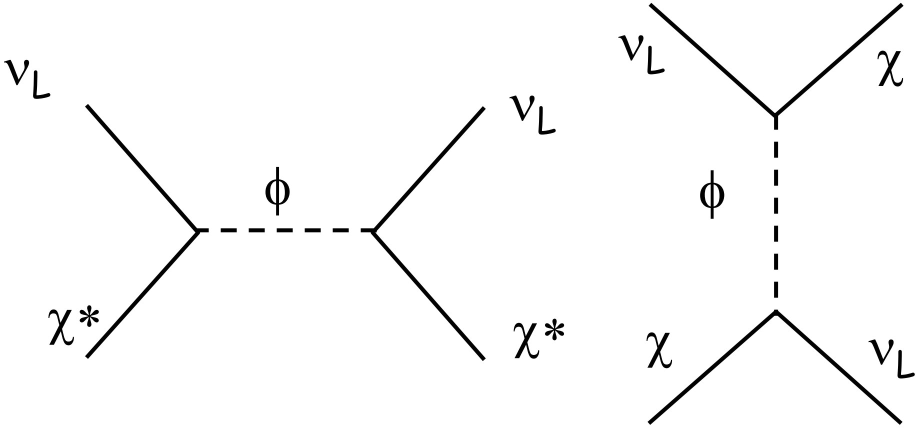
Bound neutrino systems

elastic forward scattering, $q^2 = 0$

# Resonance neutrino refraction

Elastic forward scattering of $\nu$ on background fermions $\chi$ with scalar $\phi$ mediator

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



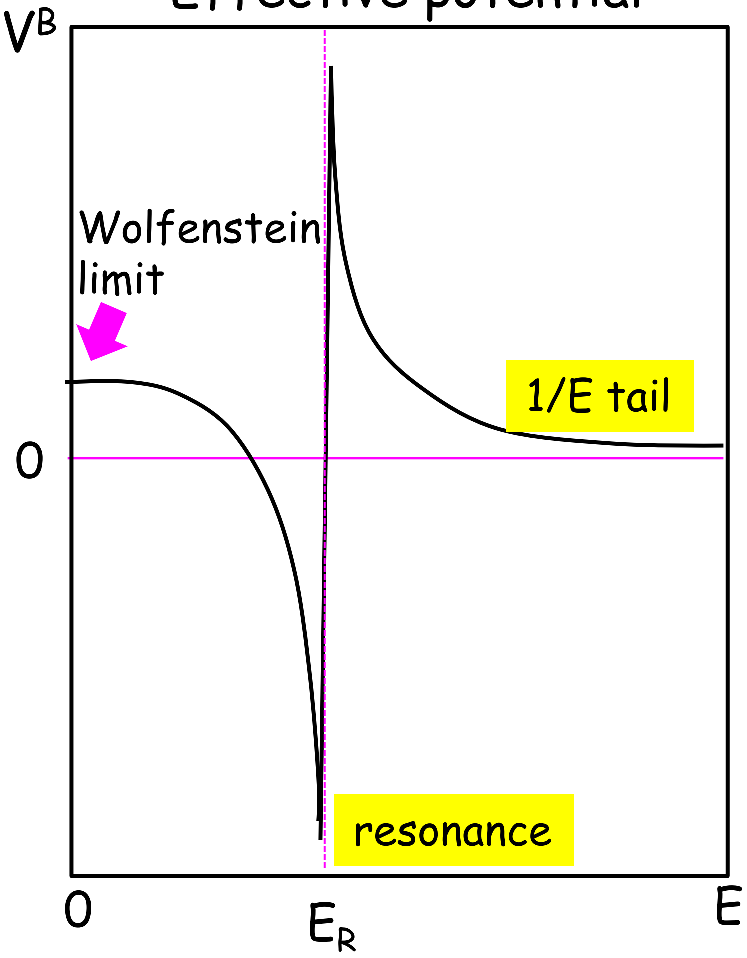
Resonance: $s = m_\phi^2$

for $\chi$ at rest resonance $\nu$ energy:

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

For small $m_\phi$ resonance at low, observable energies

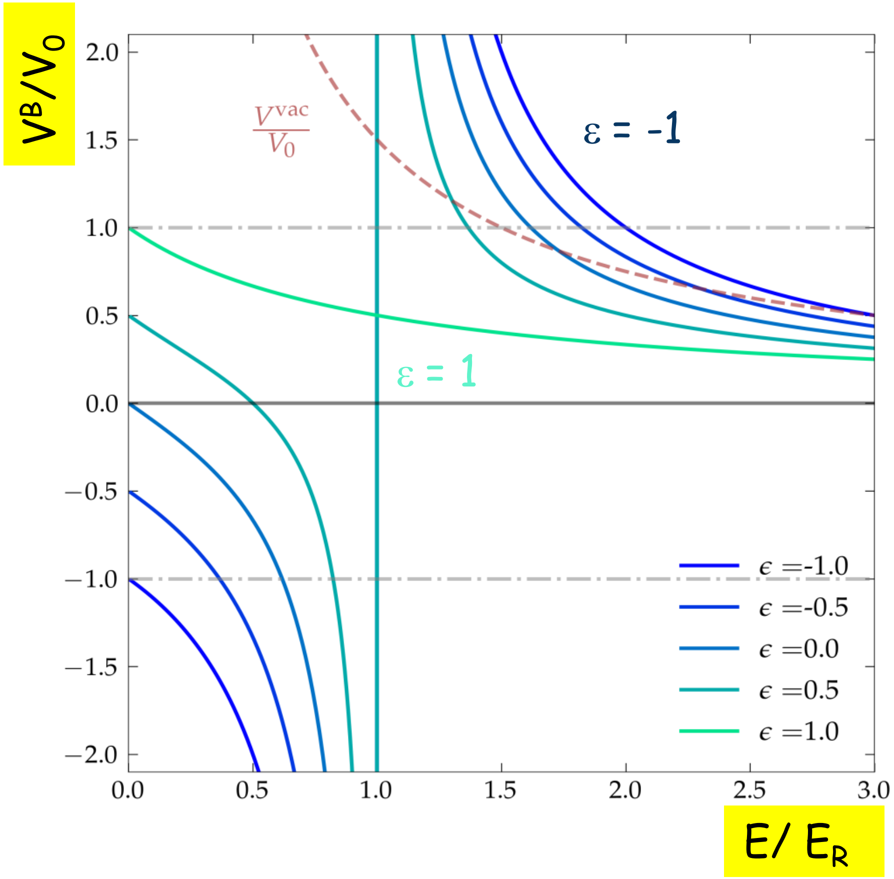
Effective potential



# Background potential

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

$V^B$ as function of energy for different values of asymmetry $\varepsilon$



Neglecting width of resonance

$$V^B = V_0 \frac{E/E_R - \varepsilon}{(E/E_R)^2 - 1}$$

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

number densities

Asymmetry:

$$\varepsilon = \frac{n_\chi - \bar{n}_\chi}{n_\chi + \bar{n}_\chi}$$

Relative contribution of the background wrt. the vacuum term in resonance

$$r = V_0/V_R^{vac} = V_0\, 2E_R/\Delta m^2$$

# Effective neutrino mass and MiniBooNE

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

$\Delta m_{eff}^2 = \Delta m^2 + 2EV^B$

(includes potential)

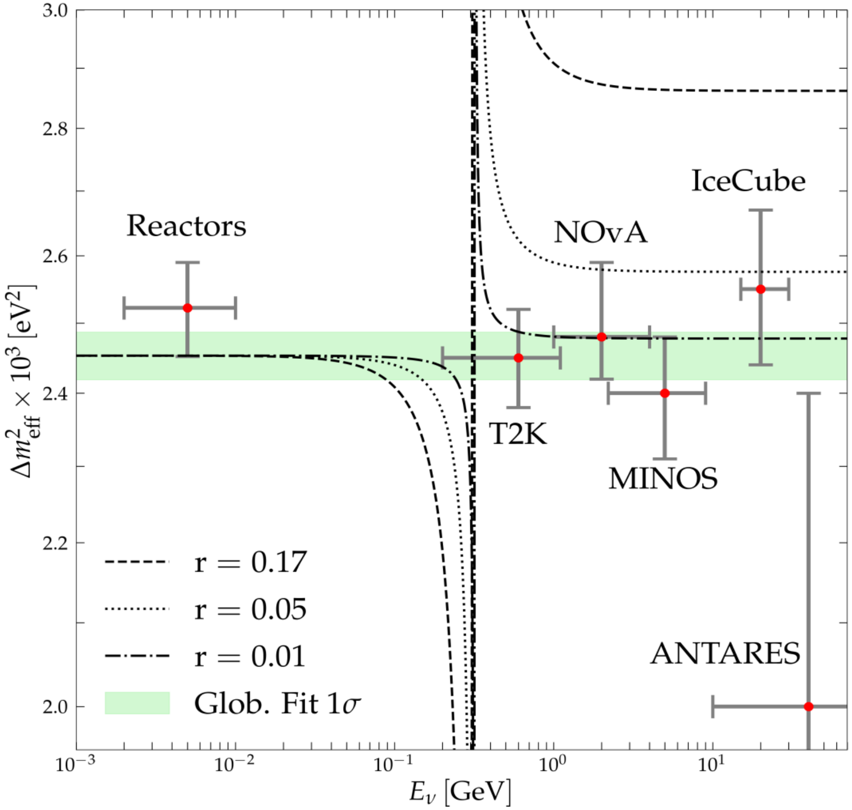
$$\Delta m_{eff}^2 = \begin{cases} \Delta m^2, & E \ll E_R \\ r\Delta m^2, & E \gg E_R \end{cases}$$

$r = V_0\, 2E_R / \Delta m^2$

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

MiniBooNE explanation:
$E_R$ = 0.2 – 0.3 GeV, r > 1.6
Enhanced oscillation effect

$\Delta m_{eff}^2$



Experimental results:

consistent with $\Delta m_{eff}^2$ = const,
give bound $r < 0.01$

# Effective 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, $\Delta m^2/2E$

$$\Delta m_{eff}^2 = 2EV^B = \text{const}$$

Can the vacuum mass be substituted by a potential completely, and oscillations be explained at $\Delta m^2 = 0$?

Phenomenologically less restricted case: scalar background, fermionic mediator

Similar results and dependences as before with substitution

$n_\chi \to n_\phi$ , $m_\chi \to m_\phi$

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

# Effective mass for $\Delta m^2 = 0$

$E >> E_R$

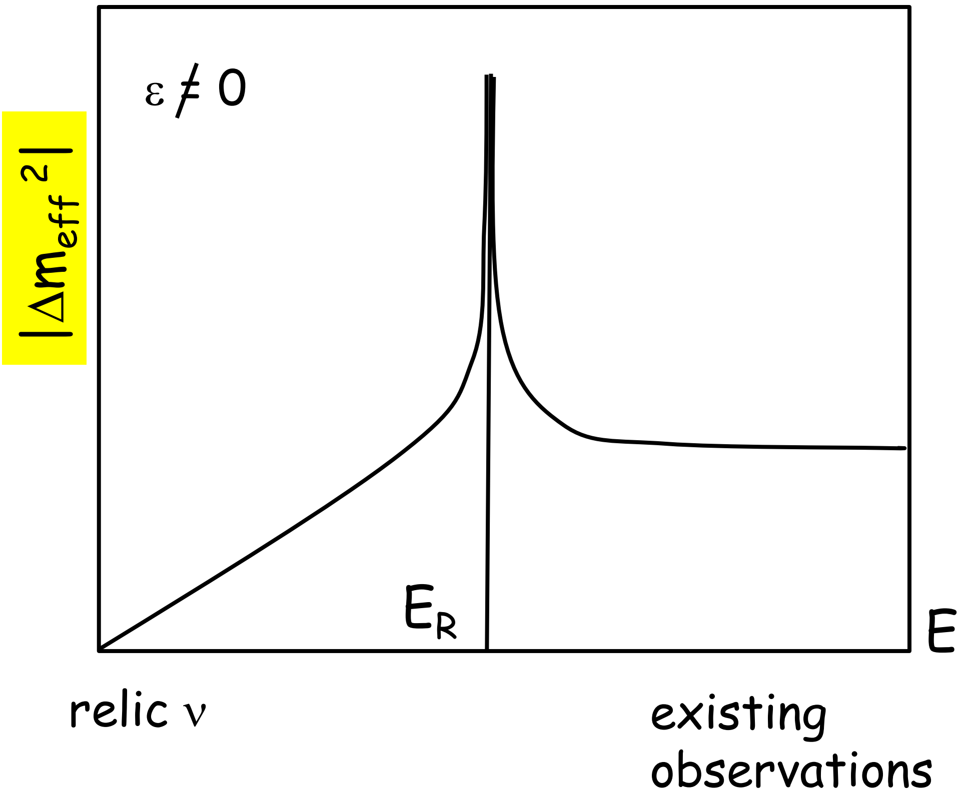
$$\Delta m_{eff}^2 \sim 2EV^B \sim \frac{y^2 n_\phi}{4\, m_\chi}$$

$E << E_R$

$$\Delta m_{eff}^2 \sim \varepsilon\, \Delta m_{eff}^2(>> E_R)\, \frac{E}{E_R}$$

1/E dependence checked down to 0.1 MeV

→ take $E_R << 0.1$ MeV



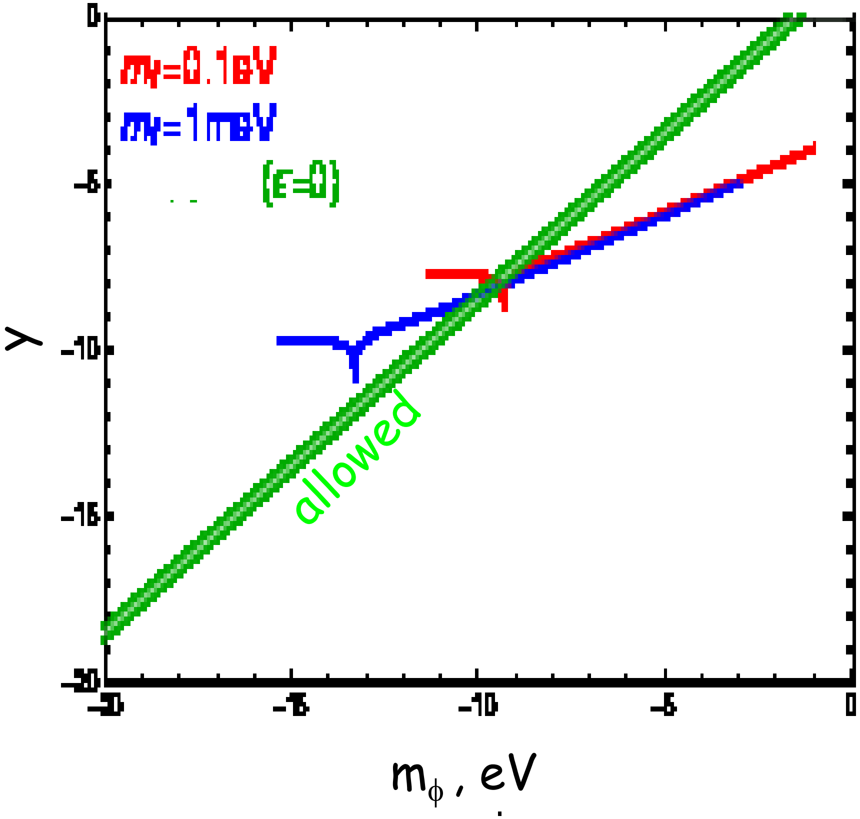
For $E_R = 0.01$ MeV:

**KATRIN, E = 1 eV:** $m_{eff} < 2\ 10^{-4}$ eV - undetectable

**Relic ν, E = $10^{-4}$ eV:** $m_{eff}(0) < 5\ 10^{-6}$ eV: $m_{eff}(z = 1000) \sim 5\ 10^{-4}$ eV, no problem with Cosmology

# Bounds on parameters

*Ki-Young Choi, Eung Jin Chun, Jongkuk Kim, 2012.09474 [hep-ph]*



Green band: $\Delta m_{eff}^2 = \Delta m_{atm}^2$

Upper bounds on y from scattering of neutrinos from SN1987A on DM $\phi$ with zero C- asymmetry and two different masses of mediator f

Similar bound from Ly$\alpha$ (relic neutrinos) .

Allowed values:

$m_f < 10^{-3}$ eV
$m_\phi < 10^{-10}$ eV
$y < 10^{-9}$

the corresponding resonance energy $E_R$ = 0.01 MeV

Cosmological bound is satisfied

# Neutrino bound systems

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

Neutrino superstars: Massive neutrinos + gravity, analogy with neutron stars

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

Gravity, $m_\nu$ = (10 – 100) keV

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

Long range scalar Yukawa forces, $m_\nu$ = 13 eV, motivated by $^3$H exp. anomaly, negative $m^2$

*M.B. Wise and Y. Zhang, Phys. Rev. D 90, 055030 (2014), JHEP 02, 023 (2015)*
*M.I. Gresham, H.K. Lou and K.M. Zurek, Phys. Rev. D96, 096012 (2017), Phys. Rev. D 98, 096001 (2018)*

Dark matter nuggets: Dirac fermions with $m_D$ ~ 100 GeV and coupling constant with scalar $\alpha_\phi$ = 0.01 – 0.1

*A.Y.S, and Xun-Jie Xu, arXiv: 2201.00939* [hep-ph] + update

# $\nu$ - $\phi$ system

Long range attractive forces due to Yukawa interactions,
neutrino gas with density n and momentum distribution f(p, t, x)

Neutrino density (expectation value) – source of the scalar field

$$\boxed{\langle \bar{\nu}\nu \rangle = n^* = \frac{1}{2\pi^2} \int p^2 dp \, \frac{m^*}{E_p} f(p)}$$

$$E_p = \sqrt{p^2 + m^{*2}}$$

$$m^* = m_\nu + y\phi$$

effective neutrino
mass in the field

In non-relativistic limit $p \ll m^*, m_\nu$ $n^* \to n$

In the relativistic case $p \gg m^*$ - chiral suppression $n^* \ll n$

→ the field (potential) is suppressed, attraction force is suppressed
→ difference from gravity – no collapse

# Relativistic equations

Static case, degenerate Fermi gas

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

$$m^* \frac{dm^*}{dr} = - p_F \frac{dp_F}{dr}$$ equilibrium equation, $d\mu / dr = 0$,
Eq. of Hydrostatic equilibrium

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

$p_F$ → neutrino density

**Boundary conditions:**

$p_F(0) = p_{F0}$ - external (given) parameter

$m^*(0) = m^*_0$ $m^*_0$ is tuned so that at $r \to$ infty $m^* \to m_\nu$

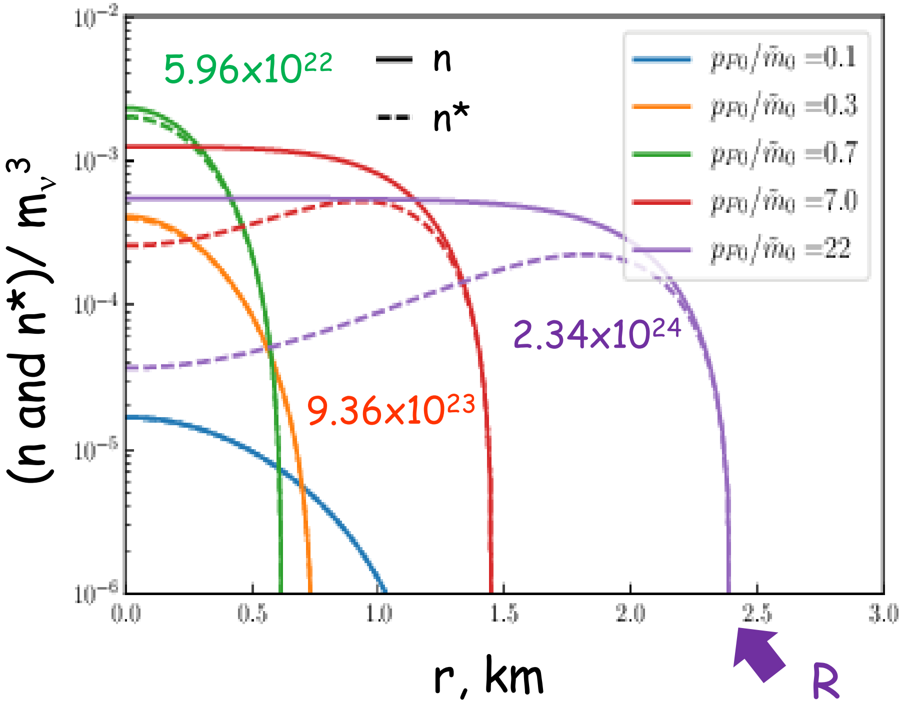
In non-relativistic case (*) is reduced to the Lane-Emden equation

# Density distribution

*A.Y.S, and Xun-Jie Xu, 2022 …*

Density and effective density distributions for different values of $p_{F0}/m_\nu$ (corresponding values of N indicated)

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



With increase of N

for $N < 6\ 10^{22}$
R decreases, $n_0$ increases

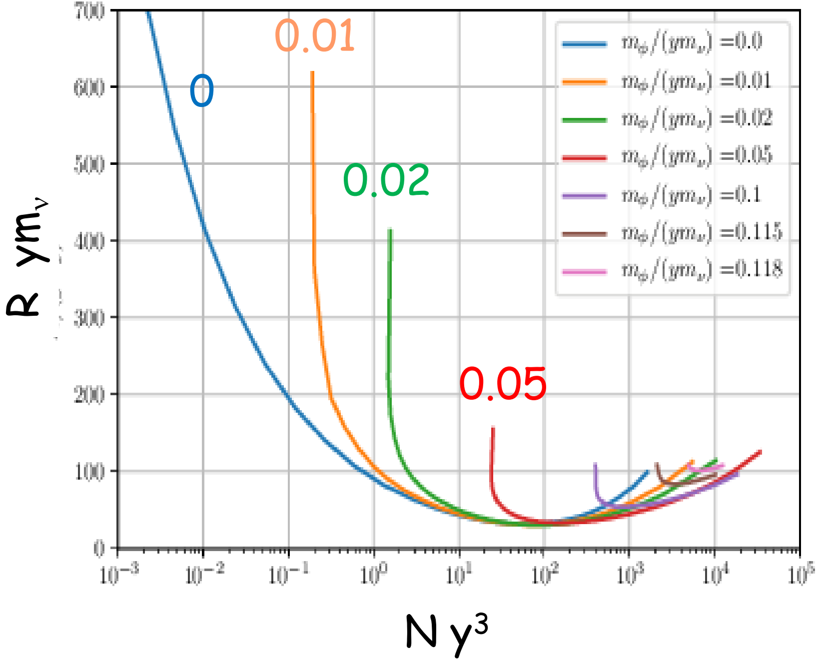
for $N > 6\ 10^{22}$
R increases, $n_0$ decreases

$n^*/n \sim \langle m^*/E \rangle \sim \langle m^*/p_{F0} \rangle$

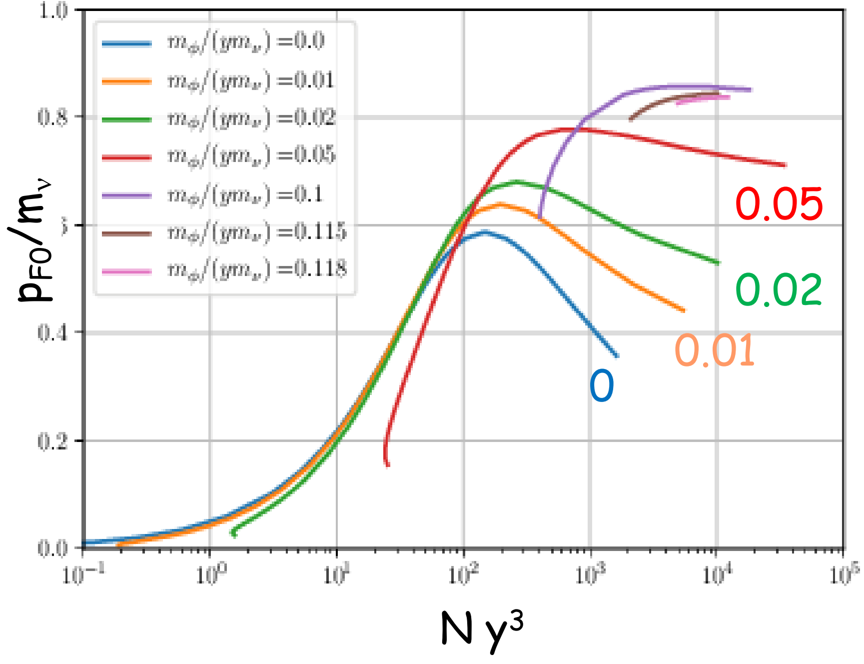
Dependence on coupling – scaling: $N \sim 1/y^3$ $R \sim 1/y$

# Properties of neutrino stars

Radius as function of number of neutrinos for different $m_\phi/ym_\nu$



Fermi momentum in center vs. number of neutrinos for different $m_\phi/ym_\nu$



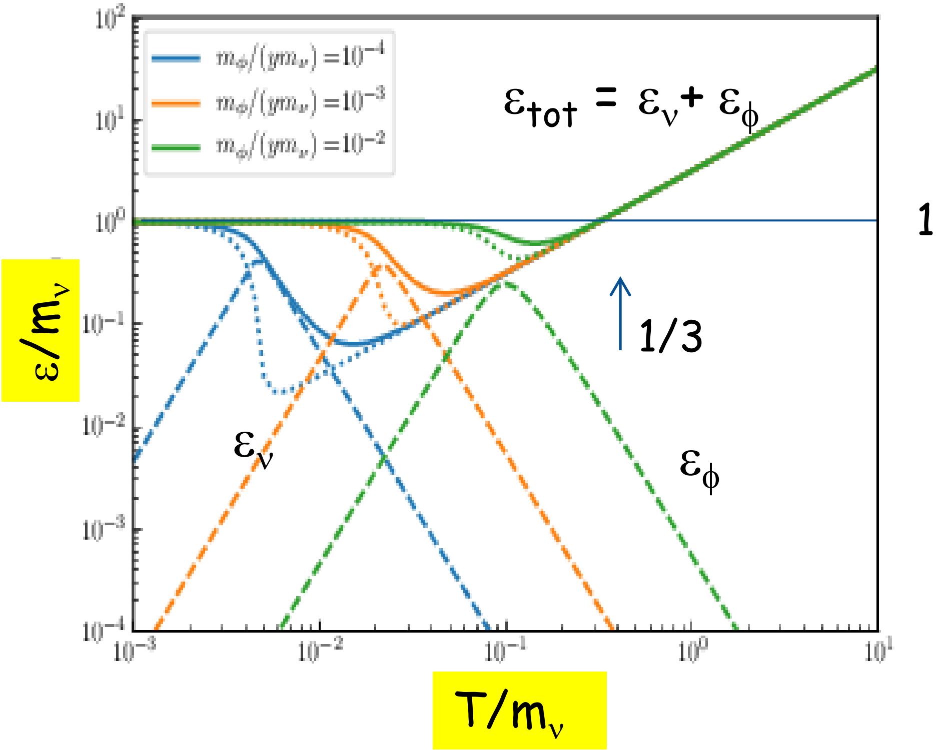
Lover bound on N, for non-zero $m_\phi$ which increases with $m_\phi$

Minimal radius: increases with $m_\phi$ and shifts to larger N

Maximal central density ($p_{F0}$) which is determined by value of neutrino mass

$$n_\nu^{max} = 4\ 10^8\ cm^{-3} \left(\frac{m_\nu}{0.1\ eV}\right)$$

# Formation of the ν - clusters



Dependence of energy per neutrino on $T/m_\nu$ for different values of $m_\phi/ym_\nu$
$\varepsilon_\phi$ - dashed, $\varepsilon_\nu$ – dotted, $\varepsilon_{tot}$ - solid

For strength of interactions $(ym_\nu/m_\phi) > 25$

the dip develops in $\varepsilon^{tot}(T)$ dependence with

$\varepsilon_{tot} < m_\nu$

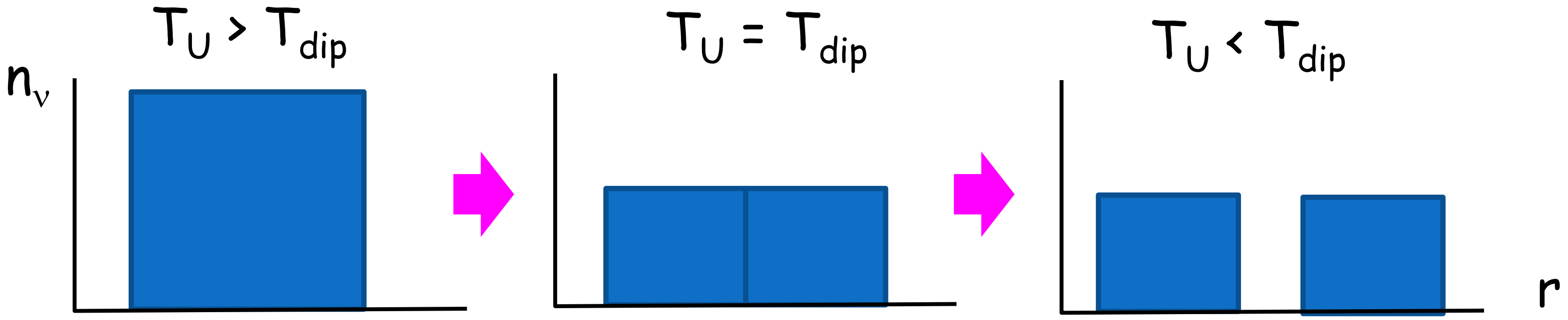
at $T \sim m_\nu/3$, when neutrinos become non-relativistic

implies bound state with binding energy $m_\nu - \varepsilon_{tot}$

With increase of strength the minimum of dip shifts to lower T

# Instability and Fragmentation

Below $T_{dip}$ expansion and cooling require increase of energy of the system → fragmentation without decrease of T and density



$T_U$ - temperature in the Universe

Fragmentation stars at $z_f \sim 200$: corresponds to maximal density
The size of the Universe that epoch $D_U(200) = 20$ Mpc

The biggest structures: $R_f \sim D_U(200)/4 = 5$ Mpc
Distance between structures: $d_f(200) \sim D_U(200)/2 = 10$ Mpc
$N_f = 1.2\ 10^{85}$, $M_f = 4\ 10^{17}\ M_{sun}$

Present size of voids $d(0) \sim z_f d_f = 2000$ Mpc

# Parameters of clusters

The biggest possible structures which would satisfy energy conditions correspond to $m_\phi \sim 3\ 10^{-32}$ eV

If $m_\phi \gg 3\ 10^{-32}$ eV such structures are not stable → further fragmentation occurs down to $R \sim 1/ m_\phi$

For $m_\phi / y m_\nu = 10^{-2}$

| R | y | $m_\phi$ , eV |
|---|---|---|
| 10 kpc | $1.4\ 10^{-26}$ | $1.4\ 10^{-30}$ |
| 1 pc | $1.4\ 10^{-22}$ | $1.4\ 10^{-26}$ |
| 10 km | $4\ 10^{-8}$ | $4\ 10^{-11}$ |

If formation starts at z =200, voids are 200 bigger than clusters

# Summary

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

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

Neutrino interactions with light dark sector - rich phenomenology:
resonance refraction at low energies, medium induced neutrino
mass bound neutrino systems...

Gallium anomaly, BEST, LSND/MB: light sterile neutrinos
representatives of light dark sector or mirage?

The High scale DS – portal to the low scale DS?

PLANCK: from the Planck scale to the Electroweak scale and lower