Impact of the Borexino and, Gallex results on interpretation of solar neutrino data in terms of neutrino flavor conversion

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Solar neutrino physics at LNGS , Rome, September 12, 2023

Solar neutrino problem and its solutions

Neutrino flavor conversion, the MSW effect

GALLEX: Identifying the solution

BOREXINO: Confirmation of LMA, bounds on new physics

Collaborations themselves formulated impact of their results on solution of the problem in terms of flavor conversion

Solar neutrino problem and its solutions

History of solar neutrino problem

60 years long exciting story (still to be written) started by Bruno Pontencorvo

Solutions before the problem appeared

Solutions: explanation of deficit of Ar production rate observed in Cl-Ar (Homestake) experiment

Solutions → signatures ("smoking guns") → predictions for forthcoming and possible future experiments

Interpretation of expected experimental results prepared in advance, conclusions were drawn almost immediately once data appeared

conclusions in terms of

favored

disfavored

excluded

solutions and ranges of parameters

It was process of identification (selection) of correct solution out of many proposed in advance. ... A kind of quiz

Predicting the problem

Бруно Понтекорво

Father of the problem

Detection of solar neutrinos Cl-Ar method

Introduced neutrino oscillations

Predicted possible deficit of solar neutrino due to oscillations on the way to the Earth

1967: “If the oscillation length is large … from th point of view of detection possibilities an ideal object is the Sun”

Only ν_e are detected by Cl-Ar method, ν_e - ν_x oscillations reduce the signal

The solar neutrino problem

R Davis Jr.

R. Davis, D.S. Hamer, K.S. Hoffman, 1968

Deficit (1/3) of signal in Cl-Ar

Origins

- Astrophysics
- Nuclear physics
- Neutrino (particle) physics

Time variations of signals in anti-correlation with 11 years of solar activity (sun spots number)

Solar magnetic field → large magnetic moments of neutrinos

Davis believed in time variations of signal and solution based on spin-flavor precession: in final Homestake publication (1998) there no even reference to MSW solution

Solar neutrino spectroscopy

also J. Bahcall

G. T. Zatsepin, 1917 - 2010

Solar neutrino spectroscopy:
measurements of fluxes of different
components of the neutrino fluxes

Program of several experiments
with different thresholds.
In this framework

Ga-Ge - V. Kuzmin, 1965

Li – Be

SAGE

Catalogue of solutions

Vacuum oscillations	V.N. Gribov, B. M. Pontecorvo, 1969
Neutrino decay, $\nu \rightarrow \nu' + \phi$	J. Bahcall, N. Cabibbo, A. Yahill, 1971
Neutrino spin precession in the magnetic field due to large magnetic moment	A. Cisneros, 1971 M. B. Voloshin, M. I. Vysotsky, L. B. Okun, 1986
Resonant oscillations in matter, MSW effect	L. Wolfenstein, 1978, S. Mikheyev, A. Y. Smirnov, 1985
"Just-so oscillations"	S. L. Glashow and L M. Krauss, 1987
Resonant Spin-flavor precession in matter, RSFP	C. S. Lim, W. J. Marciano, 1988 E.Kh. Akhmedov, 1988
MSW with new flavor changing neutrino interaction	E. Roulet, 1991, M. M. Guzzo, A. Masiero, S. Petcov 1991
…	

Selecting the solution

Pioneering experiments after Homestake

Kamiokande, 1990 SAGE, 1991 GALLEX, 1992

- Existence of the problem was reinforced
- Astrophysical solutions: disfavored – nearly excluded
- Energy dependence of the effect showed up:
  weaker suppression than in Cl-Ar suppression,
  0.46 at SK and 0.5 - 0.6 in Gallium
- Significant time variations of signals were not observed
- Some discrimination of solutions
- Three MSW solutions were coined: SMA LMA LOW

1998 year: big turn

SuperKamiokande

Atmospheric neutrino oscillations confirmed. Maximal mixing: prejudice of small mixing disappeared. (Still oscillations into steriles?)

Solar neutrinos: two key observations

- Flat energy spectrum of events, no significant distortion as expected e.g. in the SMA solution
- No significant Day-Night and seasonal variations due to Earth matter effect

J. Bahcall, P. Krastev, A. Smirnov

1998: global analysis of solar neutrino data

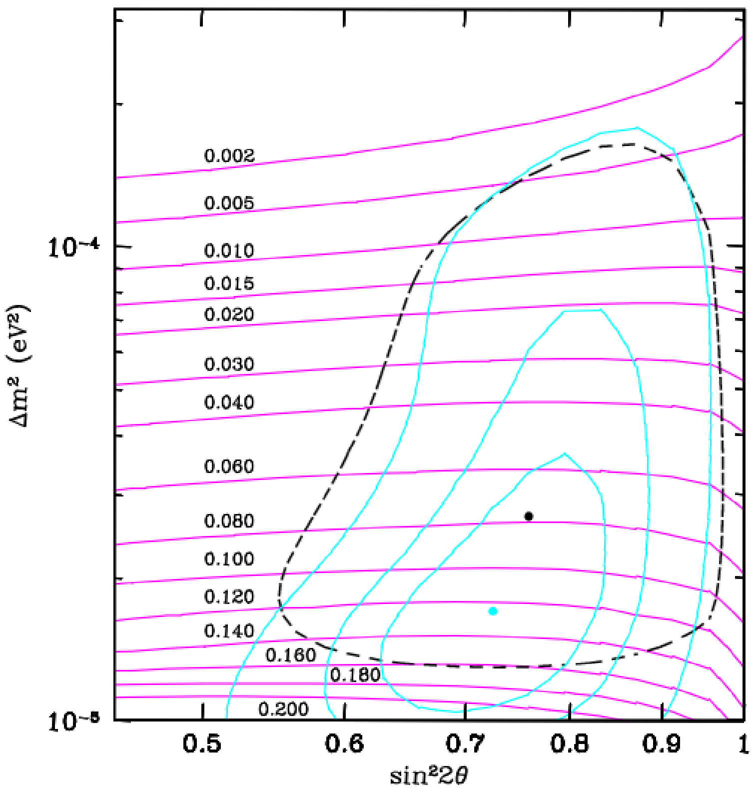
1999: Is LMA MSW the solution of the solar neutrino problem?

LMA –favored, leading in the race...

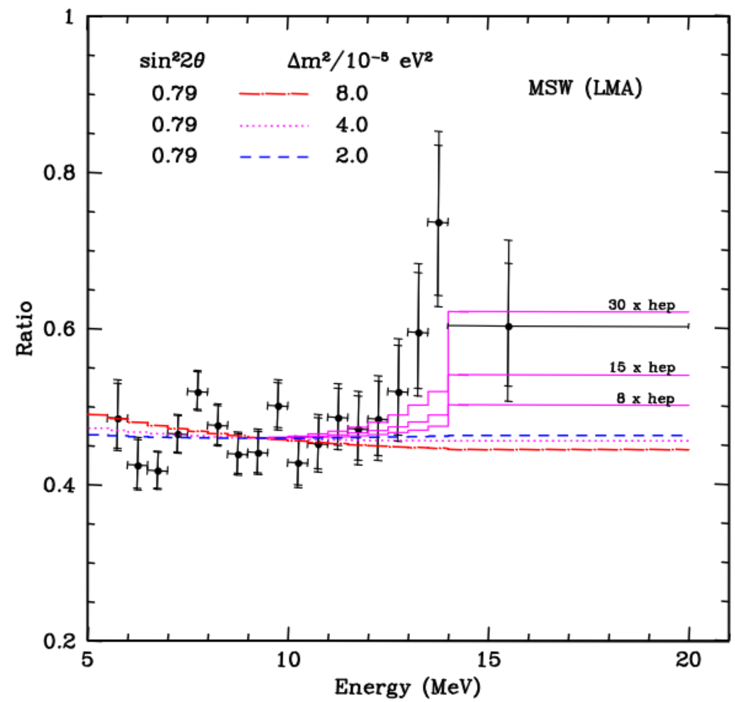
SMA, Just-so and LOW - disfavored

The MSW-LMA

John N. Bahcall, P.I. Krastev
A.Yu. S., Phys.Rev.D 60 (1999)
093001 hep-ph/9905220



present DN asymmetry



rates only, 90, 95, 99% C.L.

with DN, 99% C.L.

"Recent results on solar neutrinos provide hints that the LMA MSW solution could be correct".

“Annus mirabilis...”

2002

Milla Baldo-Ceolin
Here and in Venice...

The solution identified!

SNO, April 2002

Neutral currents measured (salt result) in agreement with total neutrino flux
Proof of the $\nu_e \rightarrow \nu_\mu , \nu_\tau$ transition

KamLAND, December 2002

Oscillations of reactor antineutrinos

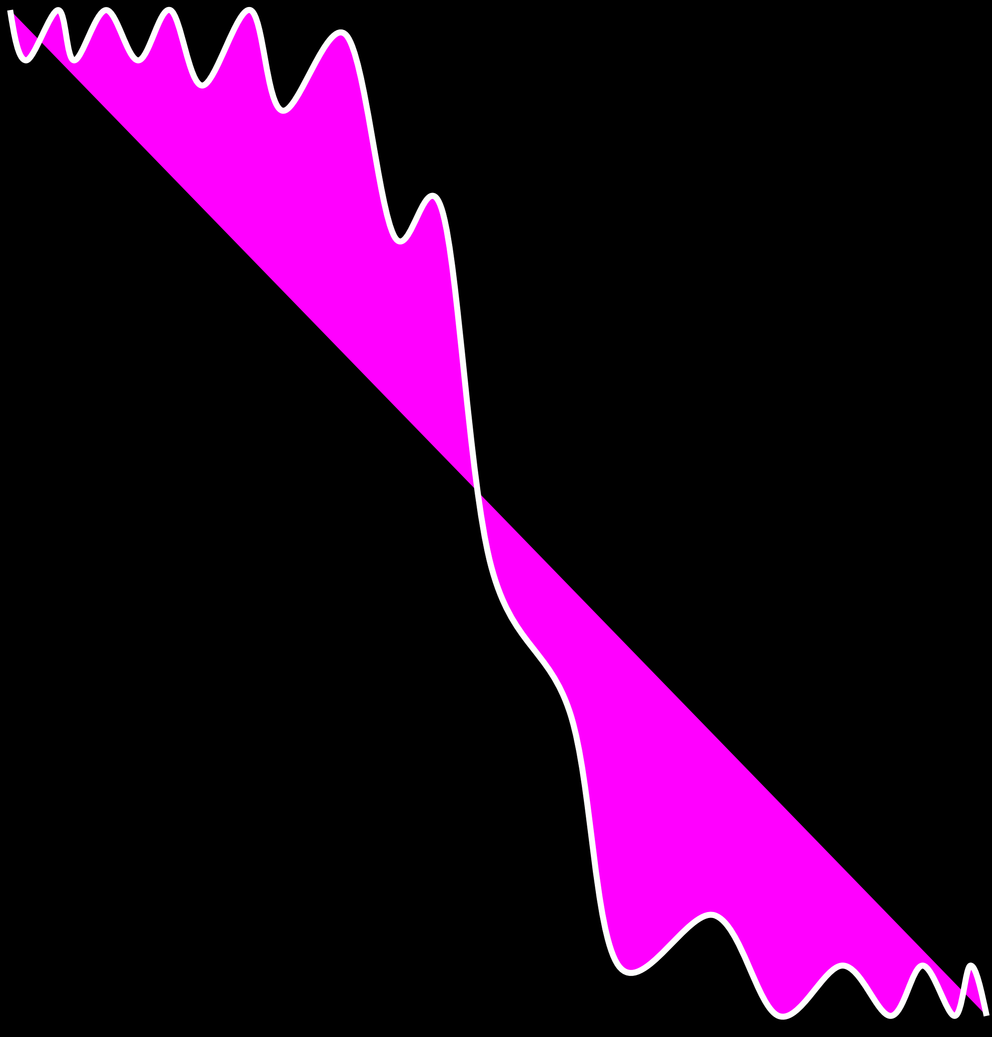
Oscillation parameters coincide with those of LMA-MSW
(in assumption of CPT symmetry)

KamLAND oscillation parameters +
MSW adiabatic conversion (standard physics)
SNO excludes transition to sterile

$\Rightarrow$ LMA MSW uniquely

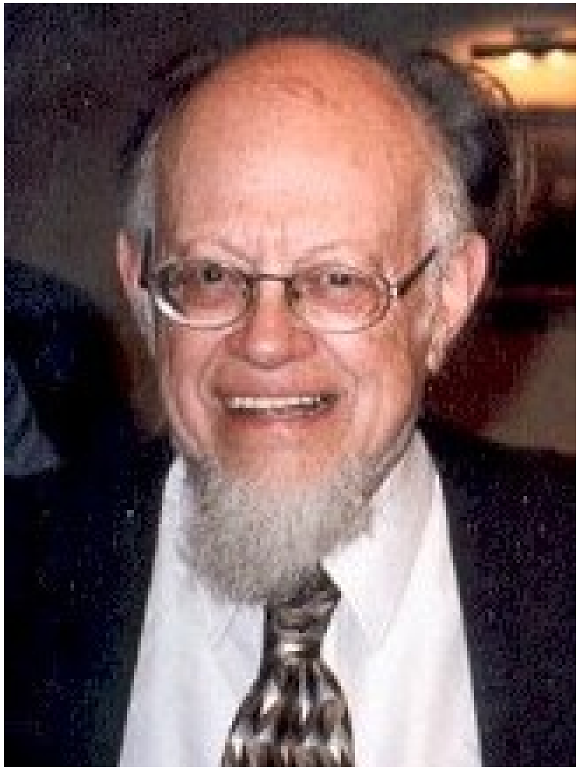
Other mechanisms (solutions) : at most sub-leading effects

Resonant flavor conversion MSW



Neutrino oscillations in matter

L. Wolfenstein, Phys. Rev. D17 (1978) 2369



Lincoln Wolfenstein
1923 - 2015

Matter potential V

Oscillations of massive neutrinos
in matter with Standard potential

Evolution equation in matter

Hamiltonian of the evolution equation

$$H = H(V, \Delta m^2, \theta)$$

Concluded:
no observable effect on solar neutrinos

Eigenstates and Mixing in matter

in vacuum:

H_0

ν_f $\quad \nu_e \ \nu_\mu$

θ $\quad \theta_m$

$\nu_1 \ \nu_2$ $\quad \nu_{mass}$

Eigenstates of H_0 in vacuum

in matter:

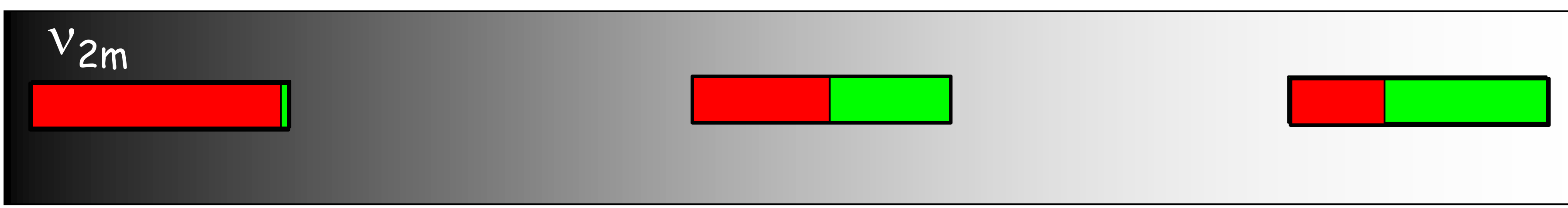
$H(n_e, E) = H_0 + V$

ν_m $\quad \nu_{1m} \ \nu_{2m}$

Eigenstates of H in medium

θ_m depends on n_e, E

Mixing angle determines flavor content of eigenstates of propagation

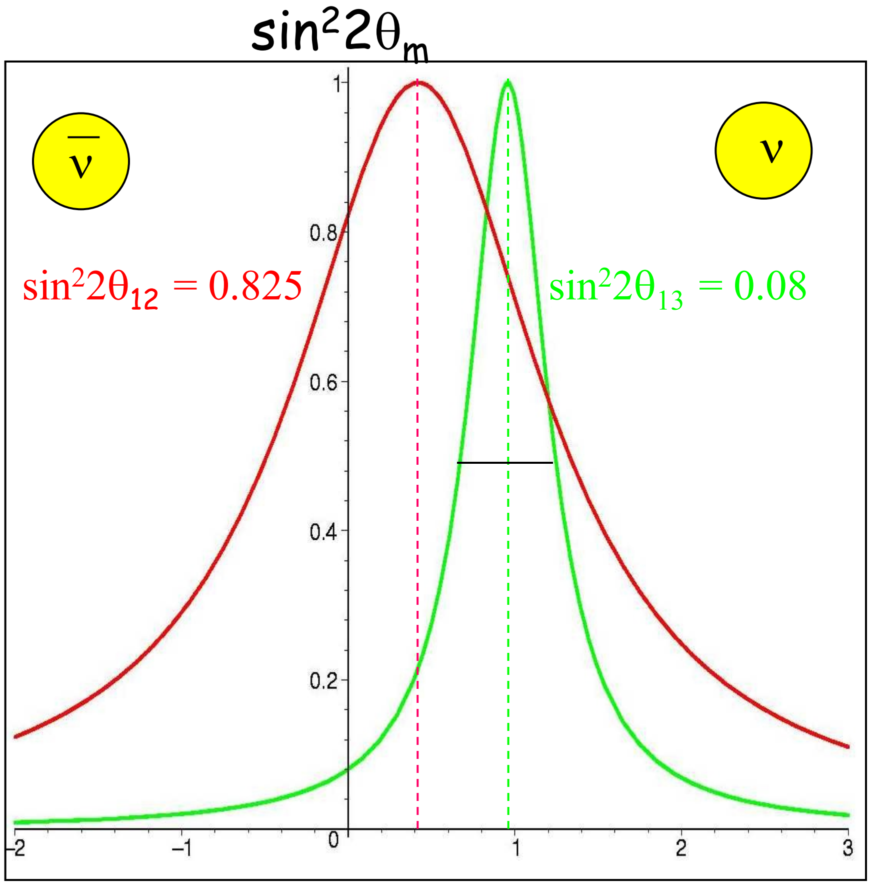


High density
mixing suppressed

Resonance: $l_\nu = l_0 \cos 2\theta$
- maximal mixing

Low density
Vacuum mixing

Resonance



$l_\nu / l_0 \sim n\,E$

$\theta_m \rightarrow 0$ | $\theta_m = \theta$ | $\theta_m = \pi/4$ | $\theta_m \rightarrow \pi/2$

Dependence of mixing on density,

In resonance: $\sin^2 2\theta_m = 1$

$\rightarrow$ flavor mixing is maximal

Vacuum oscillation length $\approx$ Refraction length

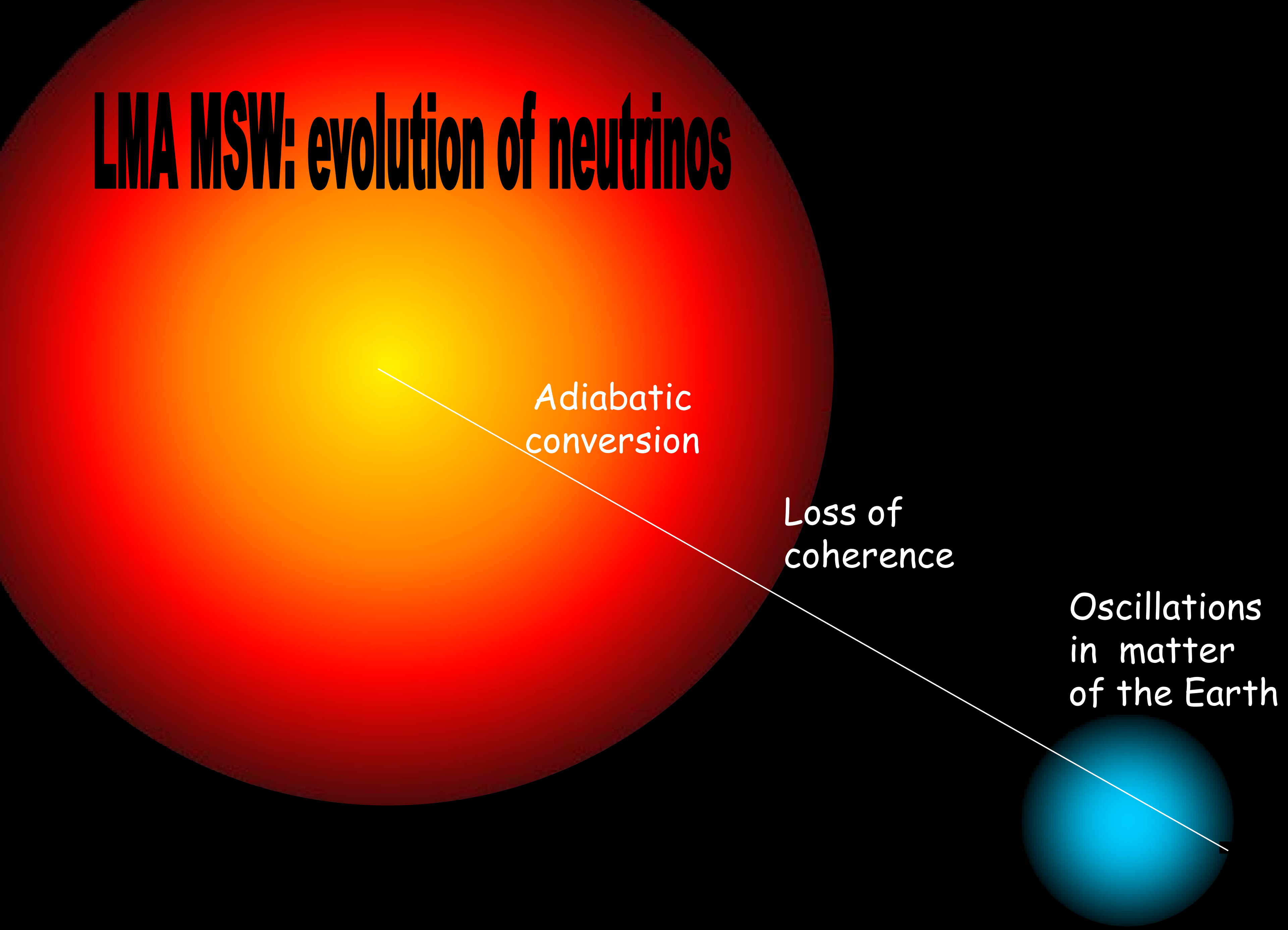
$$l_\nu = l_0 \cos 2\theta$$

Resonance width:

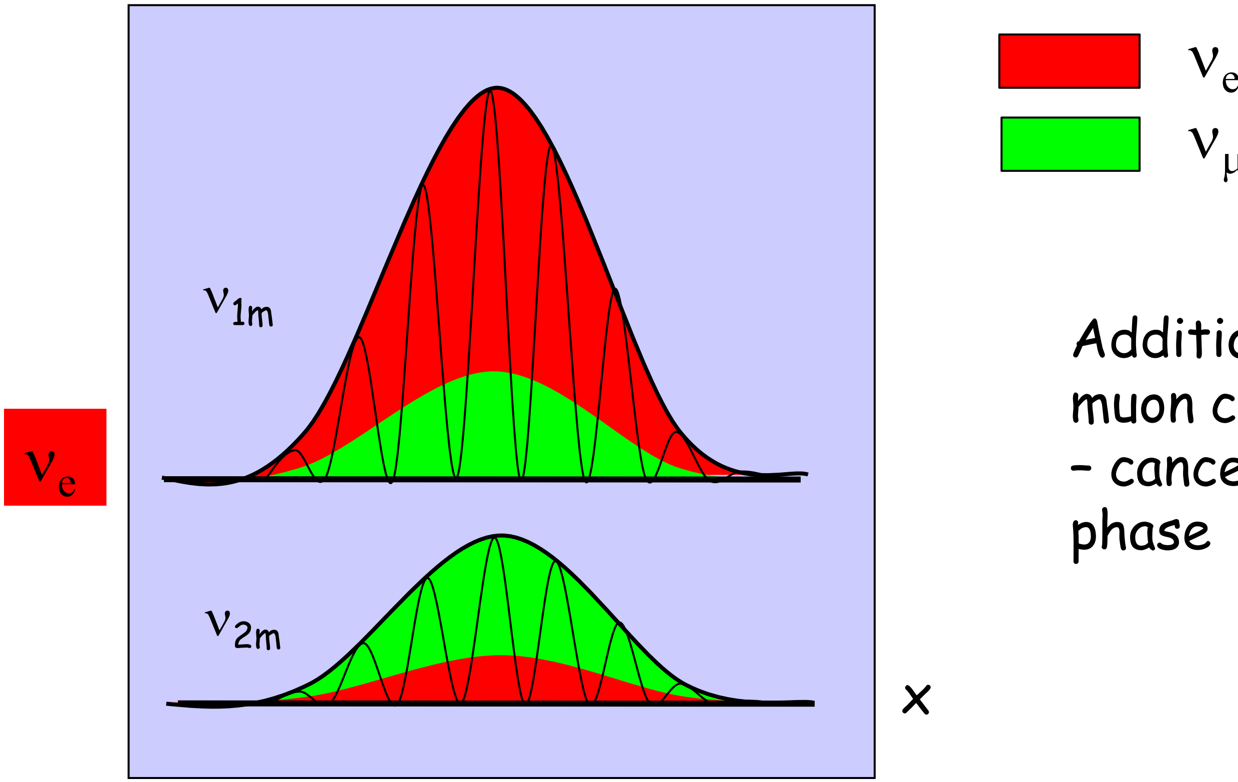
$\Delta n_R = 2 n_R \tan 2\theta$

$$|V| = \frac{\Delta m^2}{2E} \cos 2\theta$$

LMA MSW: evolution of neutrinos



Oscillations: phase effect



Additional minus sign for muon component in ν_{1m} – cancel if have the same phase

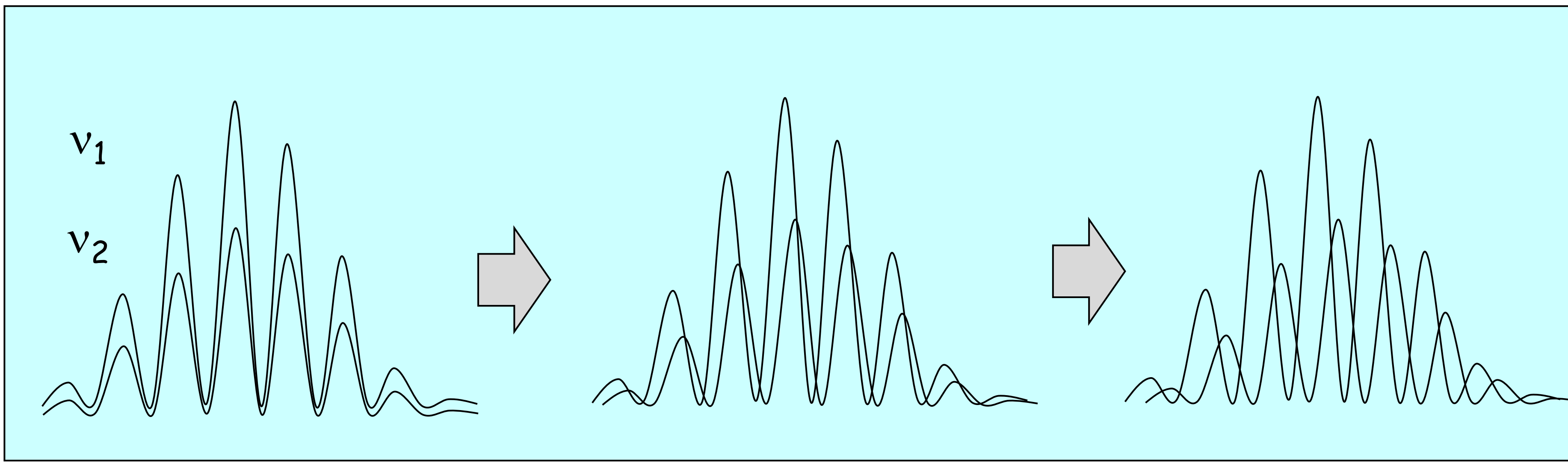
Electron neutrino propagation wave packet description

Oscillations

Difference of masses of ν_1 and ν_2 → Difference of phase velocities → Phase difference increase with distance

$$\phi = \frac{\Delta m^2 L}{2E}$$

$$\Delta m^2 = m_2^2 - m_1^2$$



distance

shift of oscillatory patterns

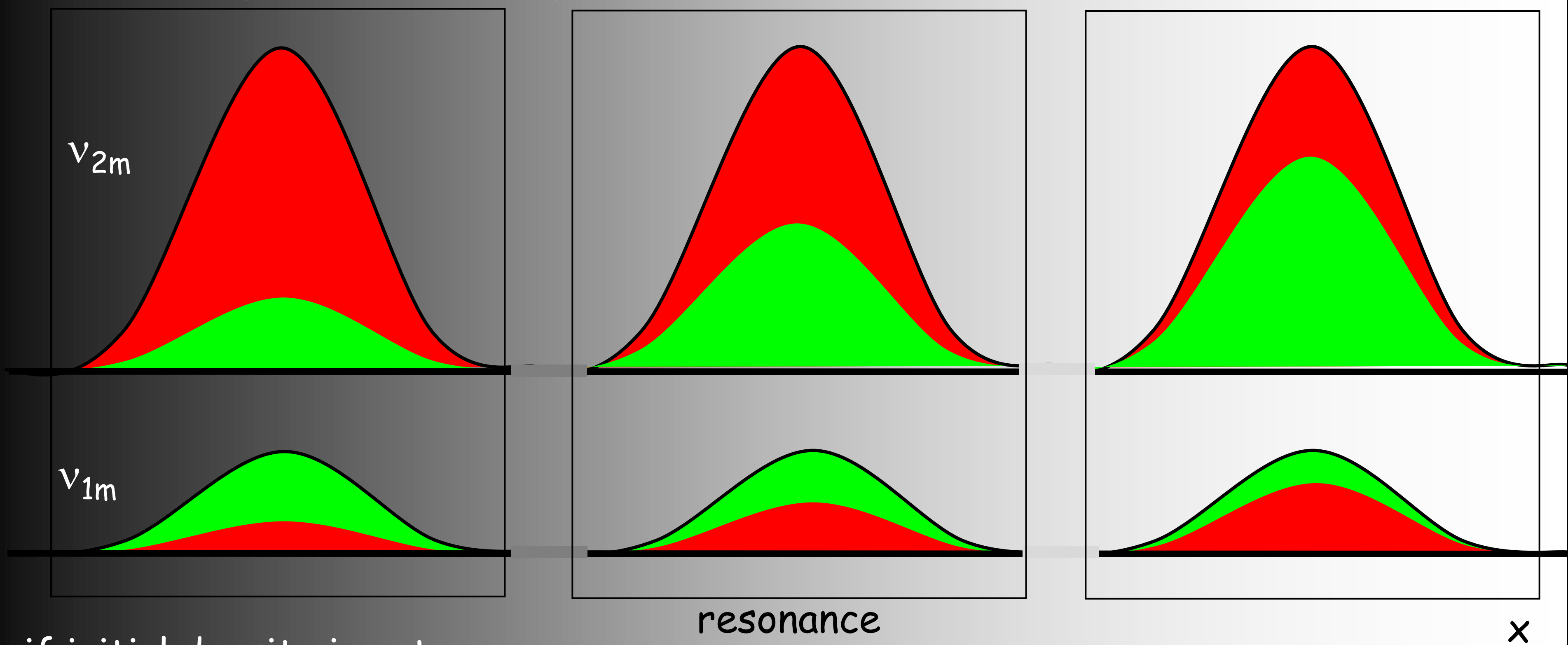
L

$\phi = 0$

ν_e

Adiabatic conversion

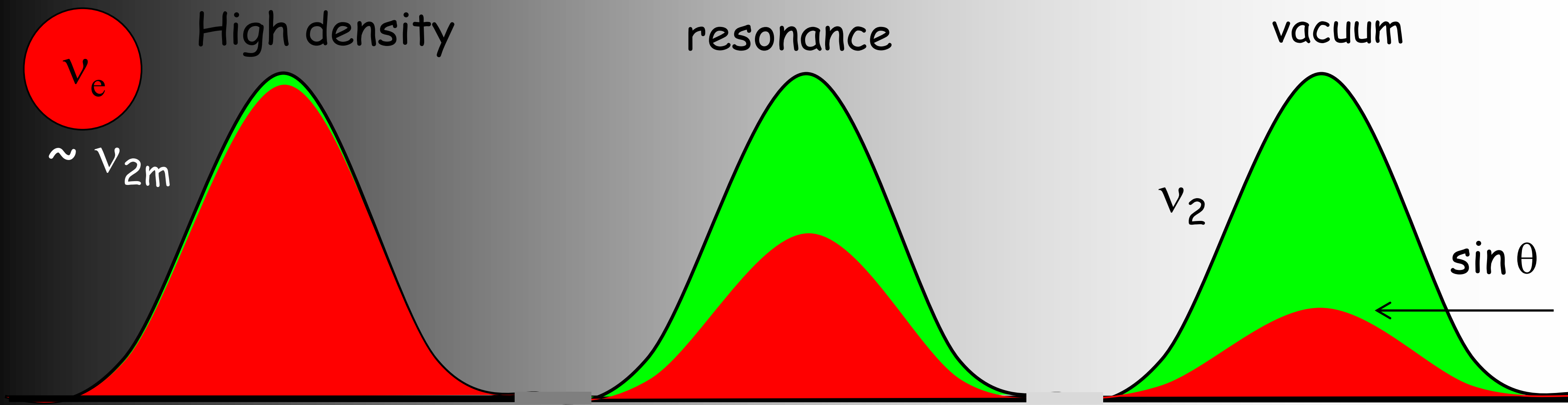
if density changes slowly $d\theta_m / dx \ll H_{2m} - H_{1m}$ no ν_{2m} - ν_{1m} transitions



if initial density is not very big: mixing is not suppressed
→ both eigenstates are produced
→ interference

- the amplitudes of the wave packets do not change
- flavors of the eigenstates change being determined by mixing angle, follow the density change

Non-oscillatory transition



$\langle \nu_e | \nu_2 \rangle = \sin\theta$ x

mixing is very small

Single eigenstate:
→ no interference
→ no oscillations
→ phase is irrelevant

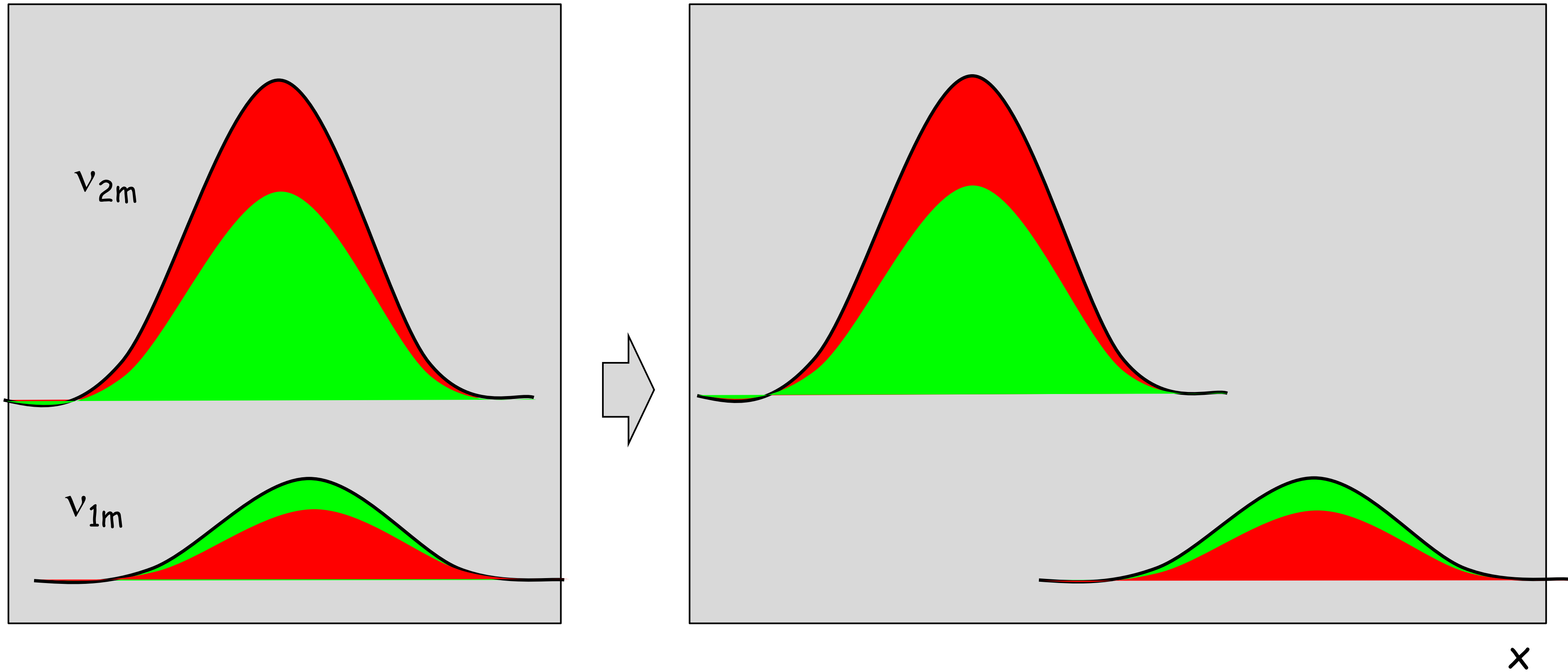
Survival probability $P_{ee} = \sin^2\theta$

if density changes slowly (adiabatically)
→ no other eigenstate appear

$\nu_{2m} \rightarrow \nu_2$

Mixing and therefore the flavor content change according to density change

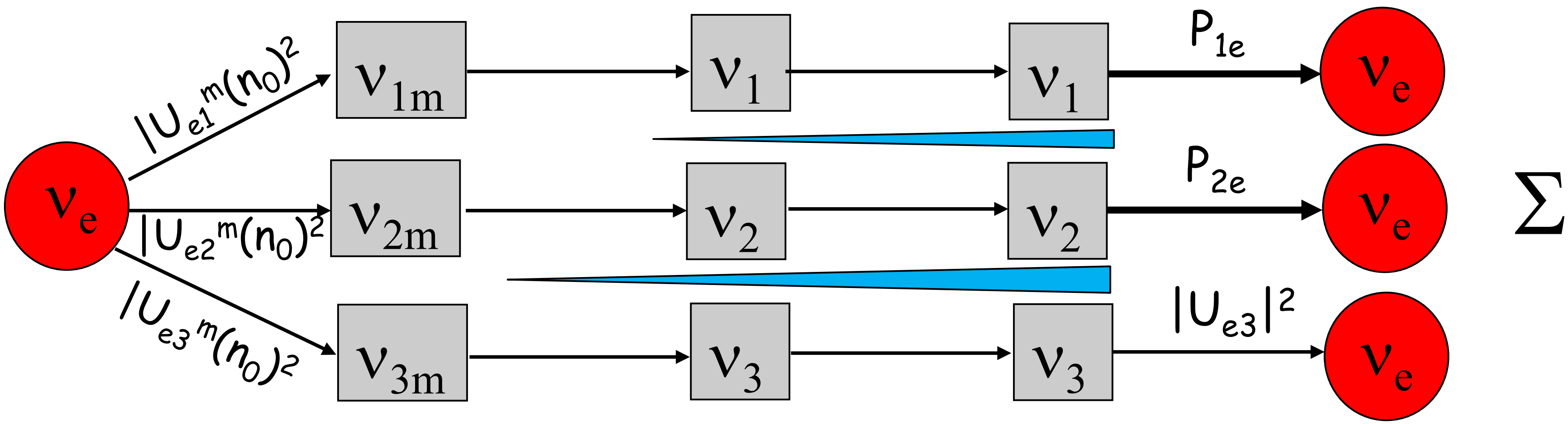
Loss of coherence



From the Sun to the Earth

LMA-MSW physics

projection | propagation in the Sun | from the Sun to the Earth | propagation in the Earth



mixing at production

adiabatic conversion

loss of coherence

oscillations in multi-layer medium

$$P_{ee} = \Sigma_i |U_{ei}^m(n_0)|^2 \, P_{ie}$$

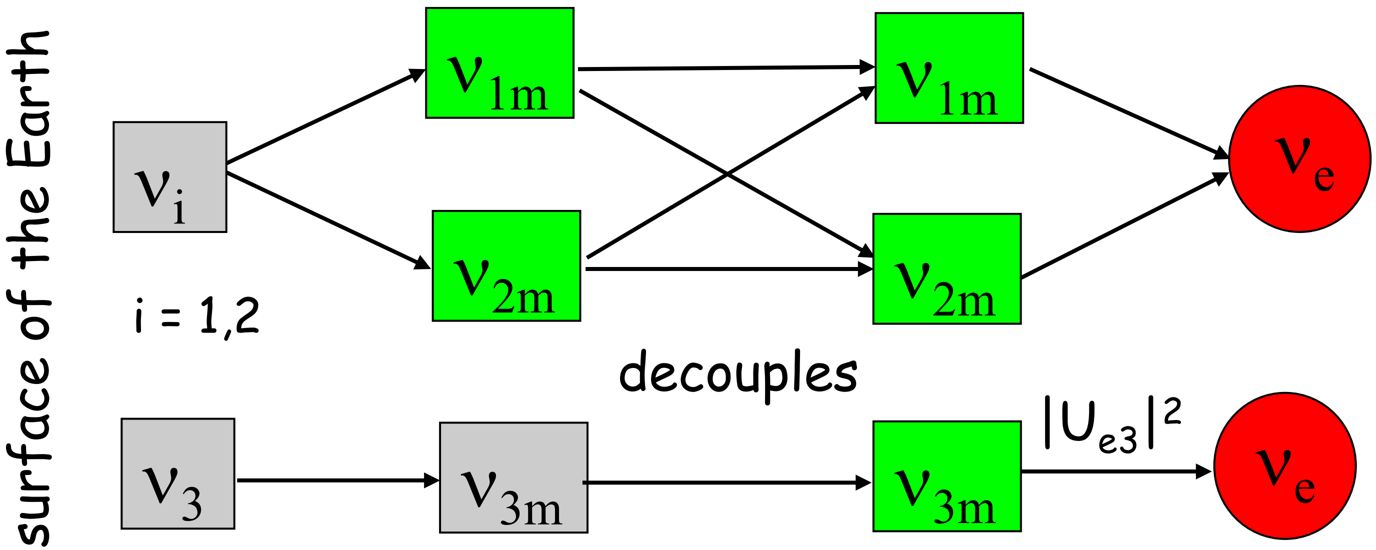
during a day projection back: $P_{ie} = |U_{ei}|^2$

In the Sun: scale invariance: no dependence of P_{ee} on distance and phase - oscillations irrelevant

Oscillations in the Earth

Distance and phase matter

propagation in the Earth projection



P_{ie}

$P_{3e} = |U_{e3}|^2$

mixing of mass states in matter

oscillations in multi-layer medium

flavor mixing in matter

Σ

$P_i = |U_{ei}^m(n_0)|^2$

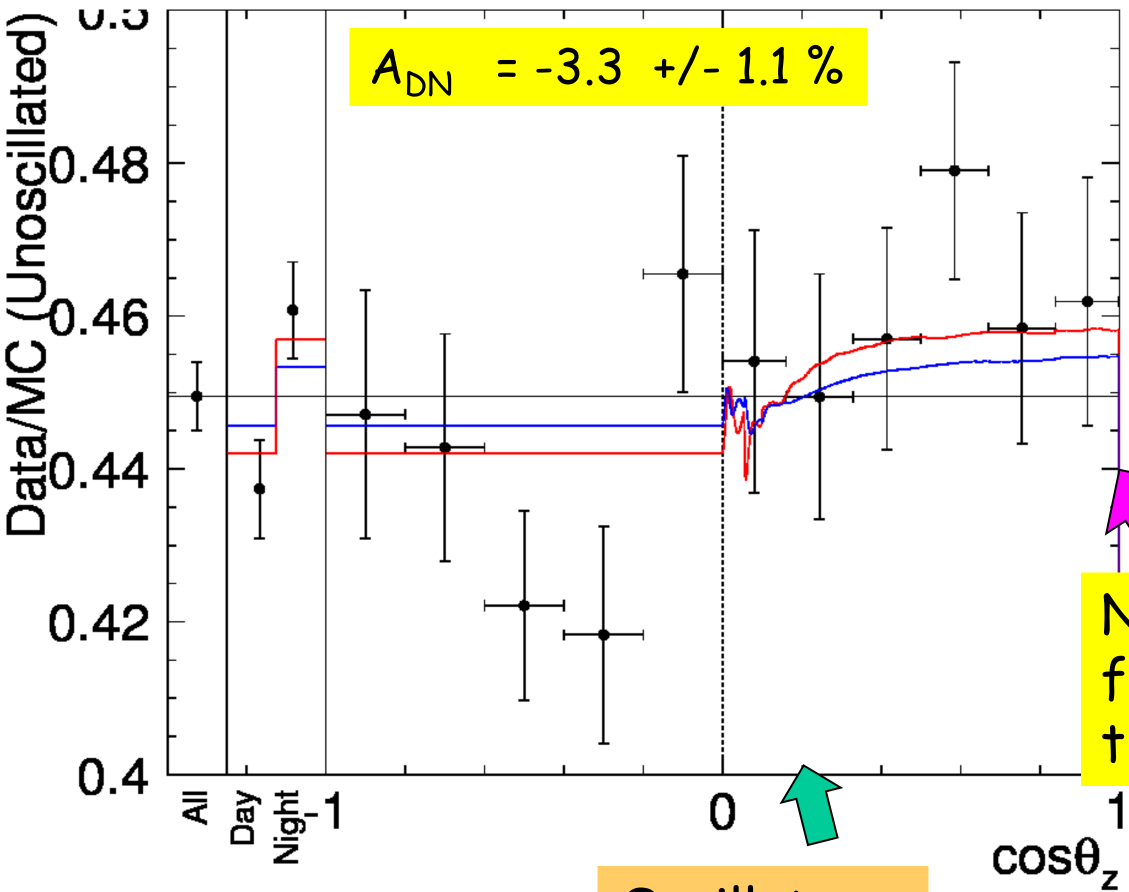
mixing at production in the Sun

Adiabaticity violation at the border between layers

SK: Earth matter effect

SK Collaboration (Abe, K. et al.)
arXiv:1606.07538 [hep-ex]

SK-IV solar zenith angle dependence



No enhancement for core crossing trajectories

Oscillatory pattern

dip

Generic features:

Explained by Attenuation effect

GALLEX: identifying the solution

Ga-Ge: disfavoring astrophysical solutions

Q_{ge} = 83 +/- 19 +/-8 SNU   Stellar models: 124 -132 SNU

Already first GALLEX result: 2σ below, latter GALLEX/GNO → 9σ

P. Anselmann et al, PLB (1992) 390

Luminosity – pp-neutrino flux – contribution to Ge production Q_{Ge}

Extracting pp-neutrino flux, suppression probability

"By 1997 GALLEX established both the presence of pp-neutrinos and a significant deficit (≈ 40 %) in the sub-MeV neutrino induced rate. This was the strongest indication for neutrino transformations on the way between the solar core and the Earth, implying non-zero neutrino mass and non-standard physics"

Restricting other solutions

Neutrino decay	to sterile neutrinos	Excluded by SN87A
	to active antineutrinos	Q_{GE} < 45 SNU strongly disfavored

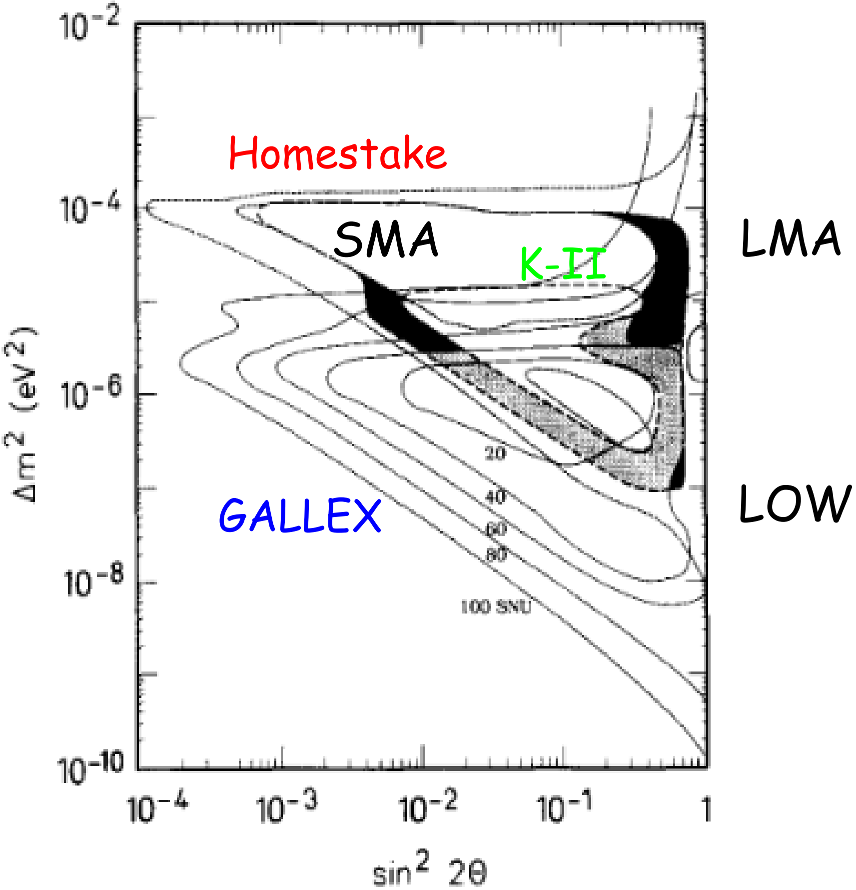
Time variations as observed by Homestake...

Successful explanation of Cl time variation and Kamiokande II non-observation of variations - predict even larger variations of signal in GALLEX:

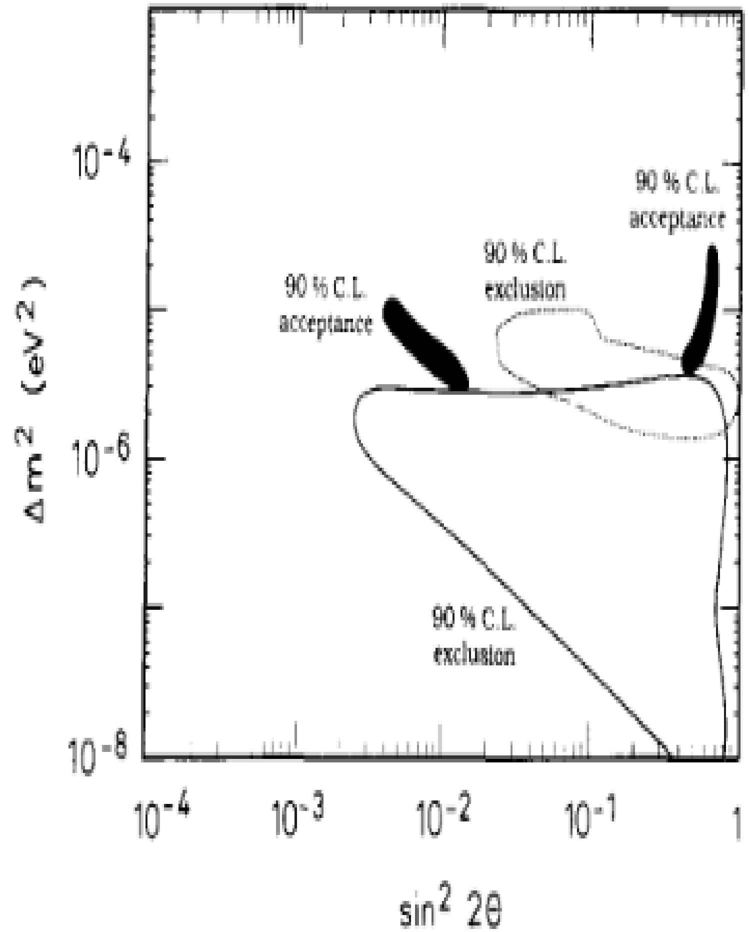
from 75-80 to 25 SNU

Restricting parameters of MSW solution

Ga + Homestake + Kamiokande



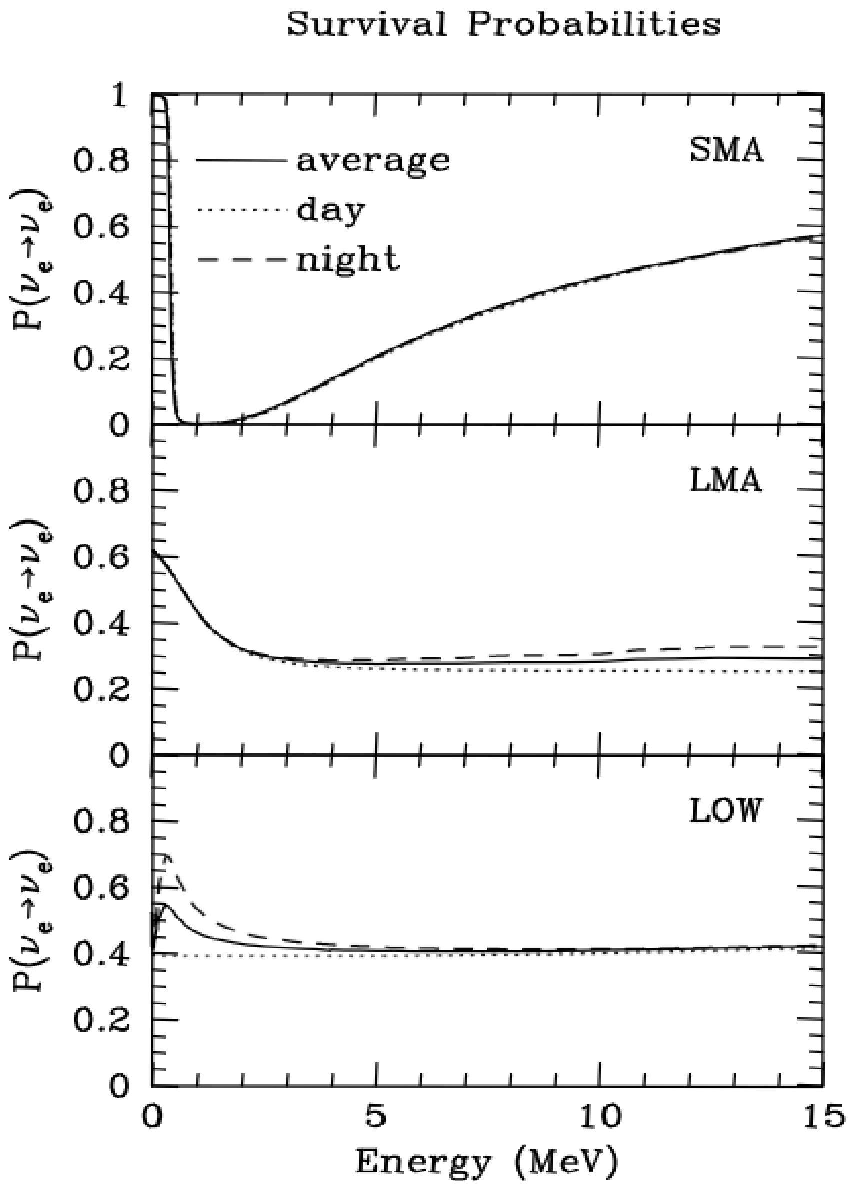
P. Anselmann et al, PLB (1992) 390



Solid -GALLEX
Dotted – Homestake
Dashed – K-II

Suppression pit (bath)

LMA: energy dependence is determined by dependence of the mixing angle at the production (with averaging over distribution of sources)



Extracting probability in sub-MeV range

GNO collaboration
M . Altmann, Phys.Lett. B 616 (2005) 174-190

Subtract from GALLEX+GNO result contributions from experimentally determined fluxes of 8B-(SNO/SK) neutrino flux.

Assume BP04 SSM neutrino fluxes

This gives the survival probability for sub-GeV (pp- and Be-neutrino) fluxes

P_{ee} (sub-MeV) = 0.556 ± 0. 071

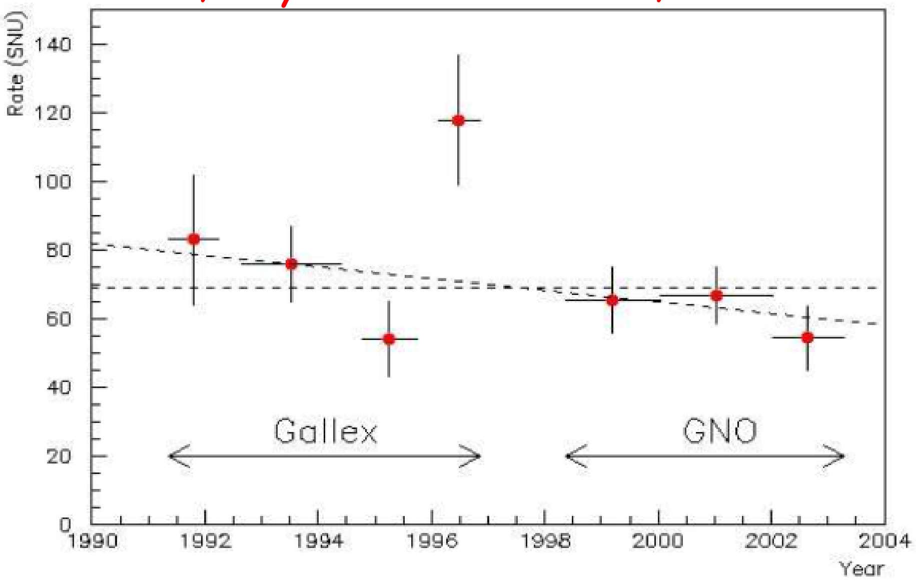
Subtract from GALLEX+GNO result contributions of experimentally determined fluxes of 8B-(SNO/SK) and 7Be-(BOREXINO) gives

P_{ee}(pp only) = 0.52 ± 0.12

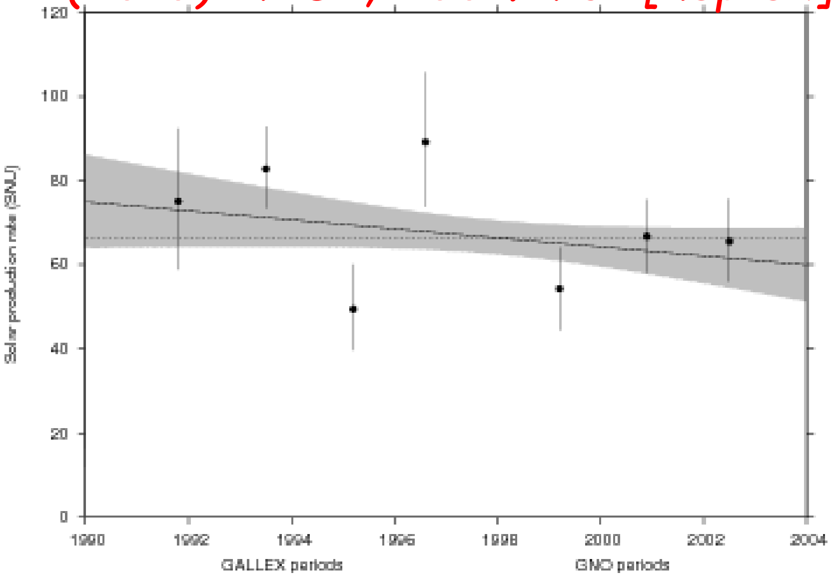
- implies the experimental verification of the solar model and of the neutrino oscillation mechanisms at sub-MeV energies that are otherwise inaccessible.

Time dependence of Ga-Ge signal?

GNO , Phys.Lett.B616:174, 2005



F. Kaether, et al Phys.Lett.B685 (2010) 47-54, 1001.2731 [hep-ex]



the results are consistent with a flat behaviour; however a weak time dependency (of unknown origin) is not excluded.

Re-evaluation after calibration

Varying neutrino masses and mixing?

SAGE – no indication of t-dependence, BOREXINO?

BOREXINO
Confirmation of LMA
Bounds on new physics

Spectroscopy of whole
solar neutrino spectrum

After LMA-MSW

After SNO and KamLAND: LMA-MSW conversion was identified as the leading (dominant) mechanism which explains the solar neutrino data

Next goals:

- Checks of the solution
- Precision measurements of parameters
- 1-3 mixing effect
- Searches of possible deviations from LMA-MSW predictions
- Bounds on new physics

Other proposed mechanisms can produce sub-leading effects

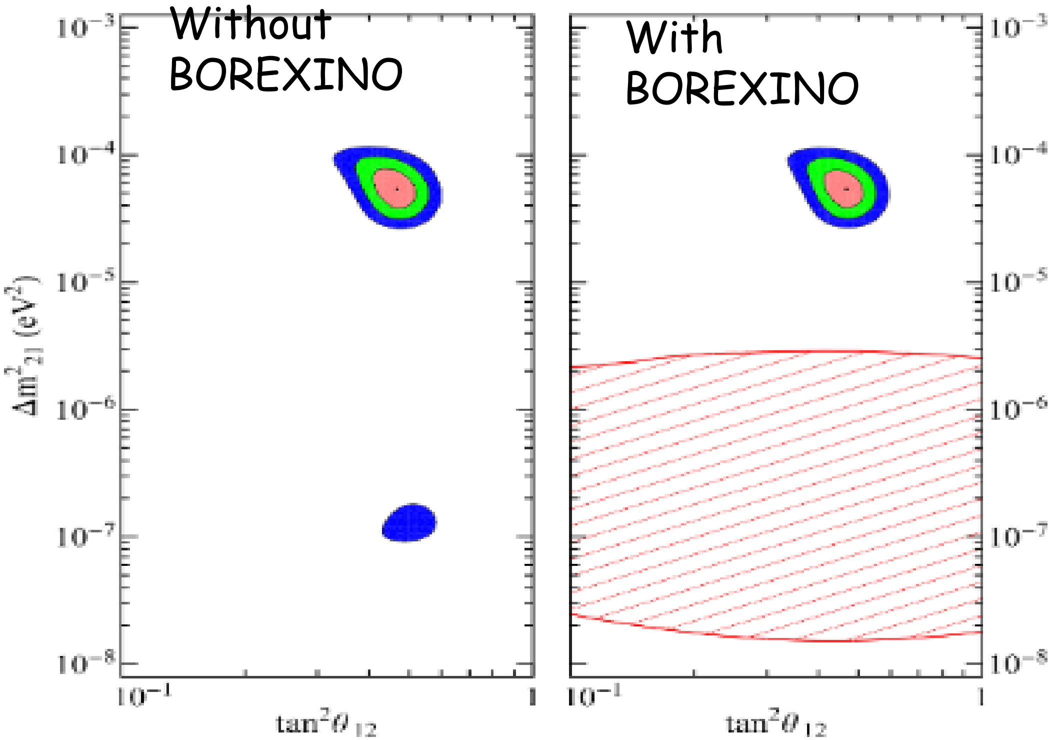
- Oscillations of pseudo-dirac neutrinos
- Spin-flavor precession
- Oscillations to sterile neutrinos
- NSI

Dark LMA solution

Astrophysics of the Sun

^{7}Be: Day-Night effect

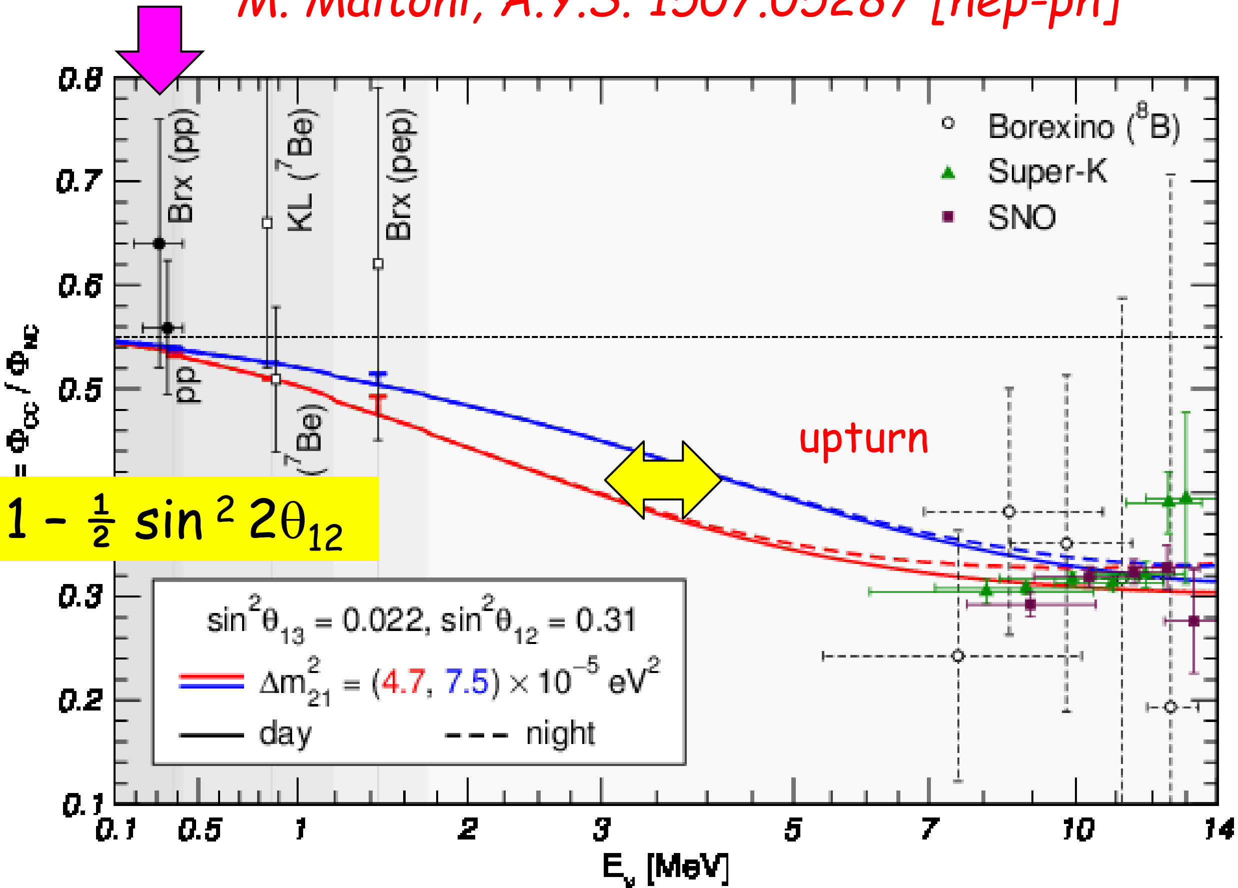
Excluding LOW solution



Neutrino oscillations parameter
99.73% c.l. excluded region by the Borexino 7Be day–night data (hatched red region in the right panel);
The LOW region is strongly excluded by the 7Be day–night data the allowed LMA parameter region does not change significantly

Energy profile of LMA-MSW

M. Maltoni, A.Y.S. 1507.05287 [hep-ph]



$1 - \frac{1}{2} \sin^2 2\theta_{12}$

for two different values of Δm_{21}^2

best fit value from solar data

best global fit

$\sin^2\theta_{12}$

Vacuum dominated

Transition region resonance turn on

Matter dominated region

Reconstructed exp. points for SK, SNO and BOREXINO at high energies

Tensions, transition region

Absence of spectral upturn

SK, SNO

Large Day-night asymmetry

SK

Different Δm_{21}^2 from solar and KamLAND

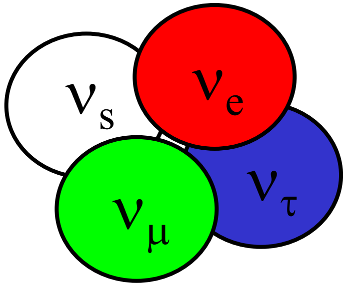
1.6 Larger V

Low rate in Homestake

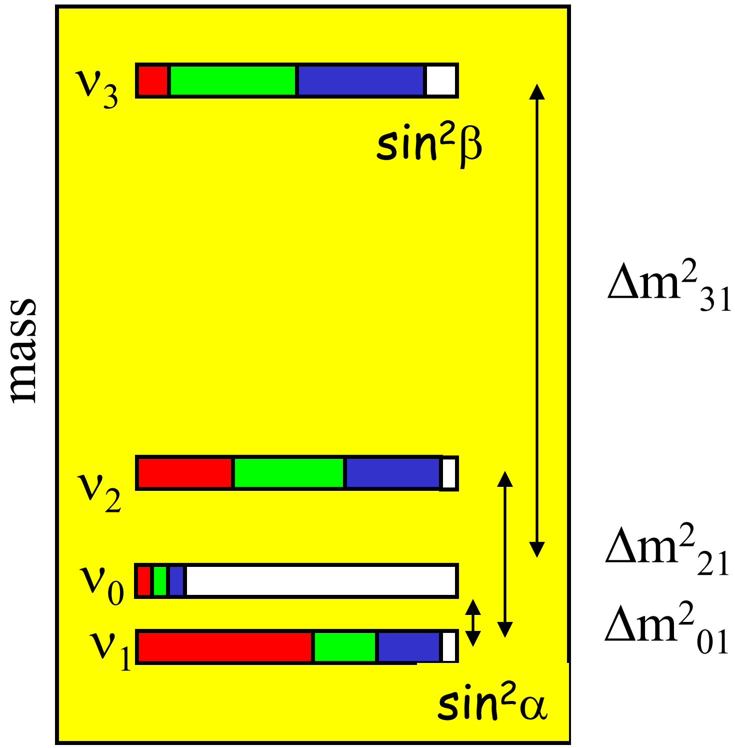
> 2σ

Something happens in the transition region, E = 1 -5 MeV?

meV sterile neutrino



sterile neutrino $m_0 \sim 0.003$ eV



For solar nu: $\sin^2 2\alpha \sim 10^{-3}$

Conversion for small mixing angle - Adiabaticity violation

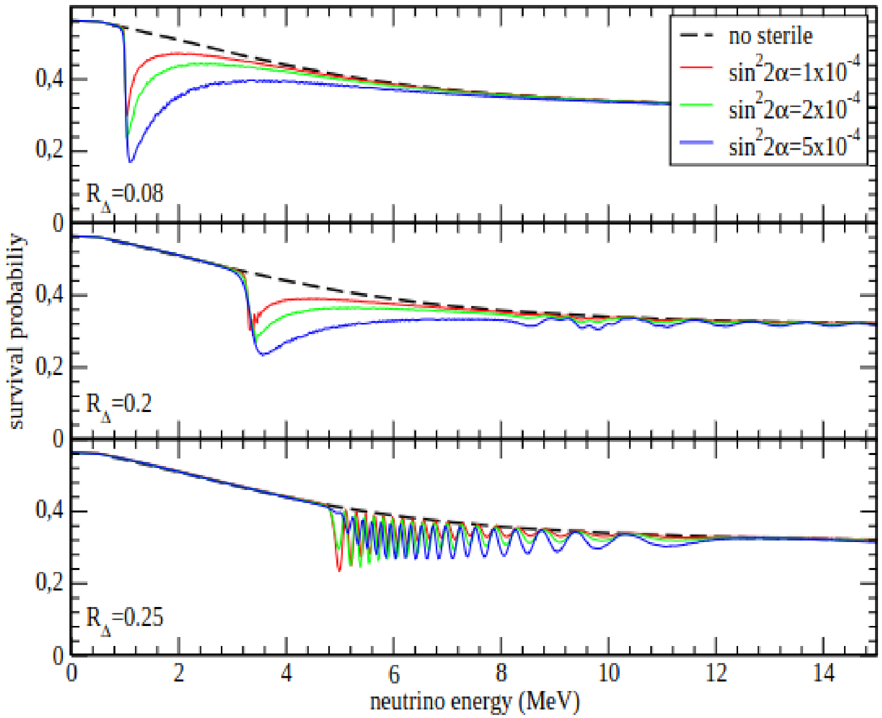
Allows to explain absence of upturn and reconcile solar and KAMLAND mass splitting but not large D-N asymmetry

Additional radiation in the Universe

$\Delta N_{eff} \sim 0.1$

Searches for this sterile in atmospheric neutrinos if mixes with ν_3

Light sterile neutrino

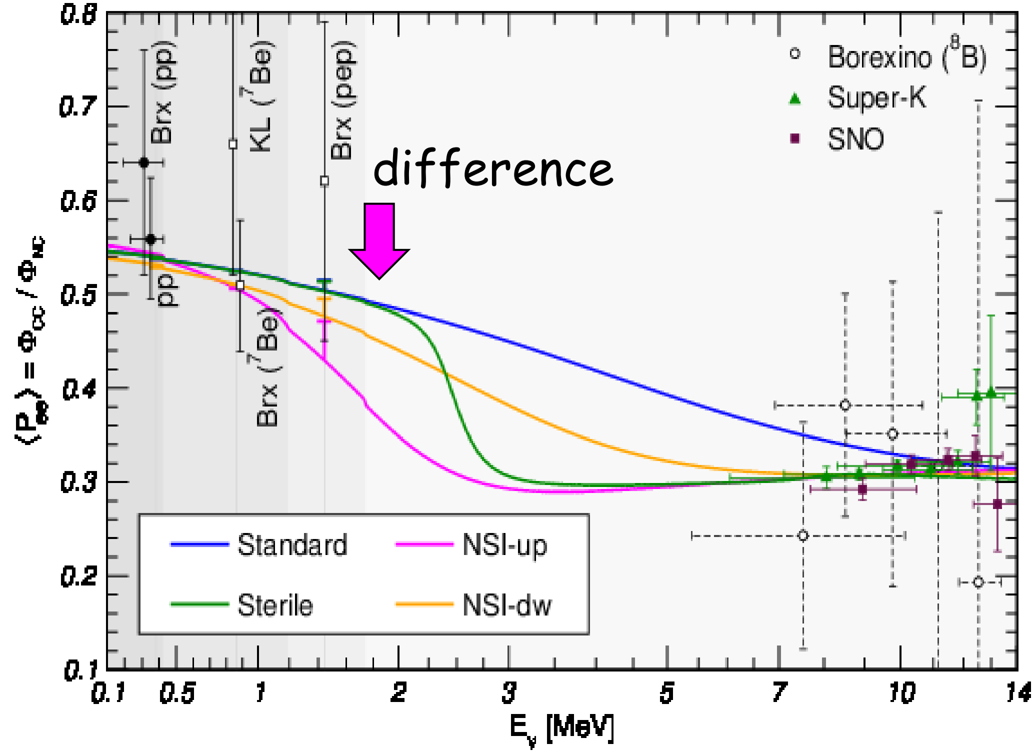


$R_\Delta = \Delta m_{01}^2 / \Delta m_{21}^2$

α - mixing angle with active neutrinos

P. C. de Holanda, A. Yu. Smirnov, 1012.5627 [hep-ph] Phys.Rev.D83:113011,2011

New physics effects



M. Maltoni, A.Y.S.
1507.05287 [hep-ph]

Extra sterile neutrino with $\Delta m^2_{01} = 1.2 \times 10^{-5}$ eV^2, and $\sin^2 2\alpha = 0.005$

Non-standard interactions with
$\varepsilon^u_D = -0.22$, $\varepsilon^u_N = -0.30$
$\varepsilon^d_D = -0.12$, $\varepsilon^d_N = -0.16$

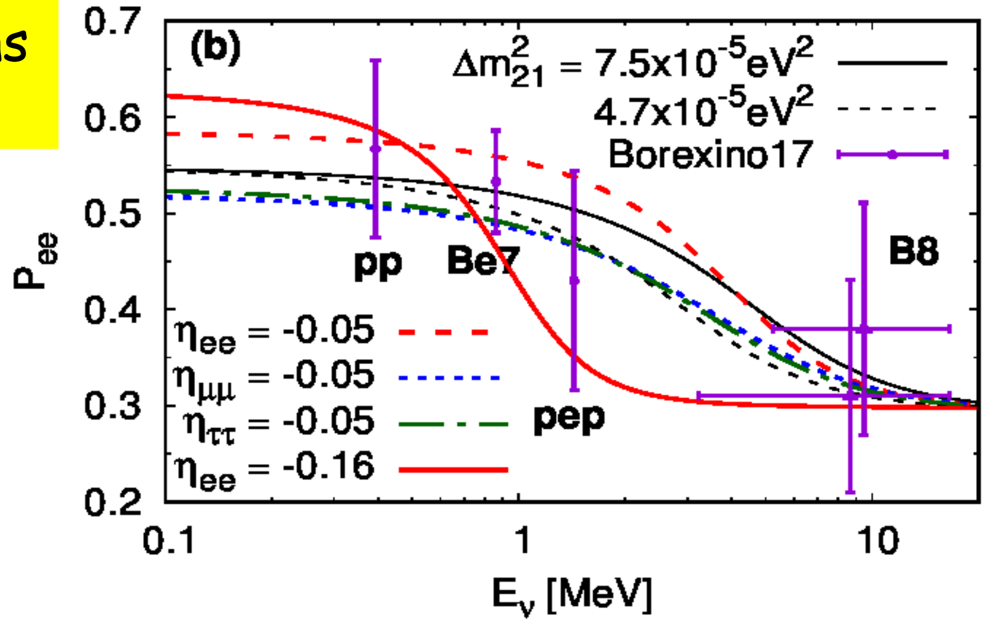
Also enhances the D-N asymmetry

Refraction due to very light scalar mediator

Shao-Feng Ge, S. Parke, 1812.08376 [hep-ph]

Neutrino scattering on electrons via very light scalar exchange

The solar neutrino conversion probabilities with scalar NSIs vs. Borexino results.



To satisfy bounds on h_ν h_e (especially from searches of 5th force):

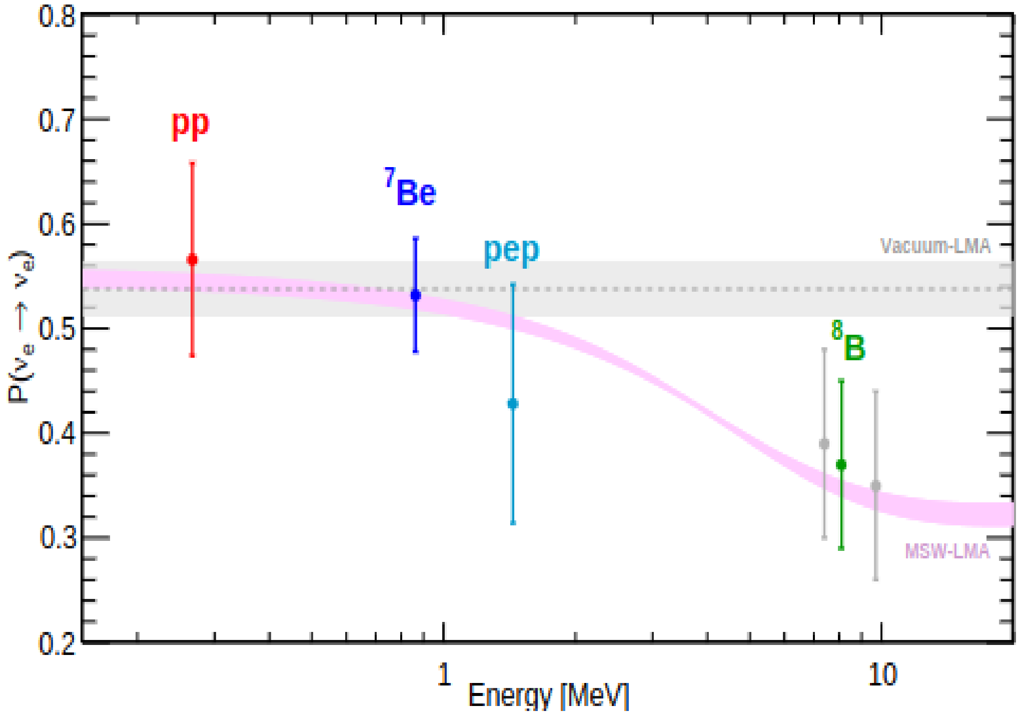
$$1/m_\phi \gg R_{Earth}$$

→ strong suppression of the potential $V = V_0\, m_\phi R_{Earth}$

To avoid bounds – cancellations in 5th force experiments – not shown if this is possible

BOREXINO spectroscopy

Borexino Collaboration (Agostini, M. et al.) arXiv:1707.09279 [hep-ex]



BOREXINO trademark: No deviations in the transition region

- Slight upturn
- pep - in agreement with expectations

The survival probability Pee as a function of neutrino energy.
The data points for HZ-SSM flux predictions, 8B: grey for the separate HER-I and HER-II sub-ranges and green for the combined HER range).
The error bars include experimental and theoretical uncertainties.
The gray band: Pee predicted by the Vacuum-LMA scenario,
the pink band represents the MSW-LMA solution. The width of the bands is $\pm 1\sigma$.

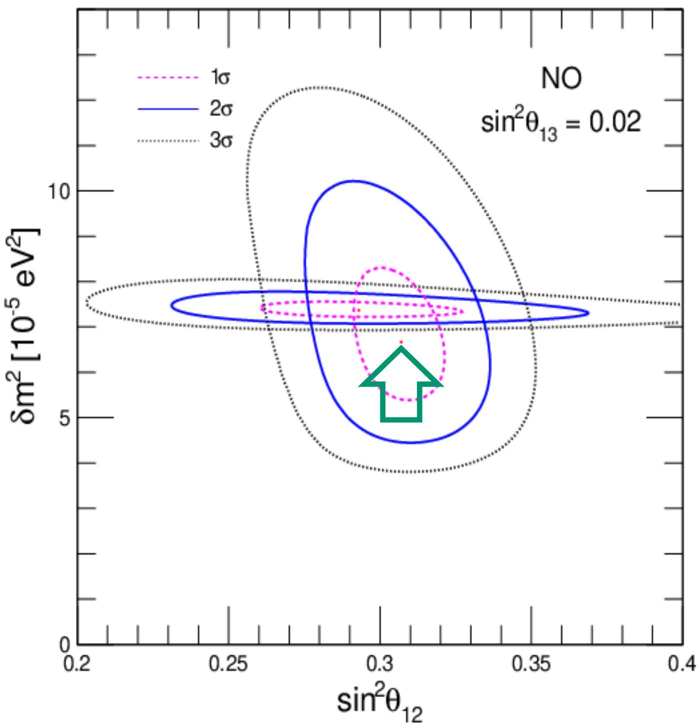
Solar - KamLAND Δm_{21}^2 – tension disappears

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 Δm_{21}^2 from analysis of the solar neutrino data increased

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

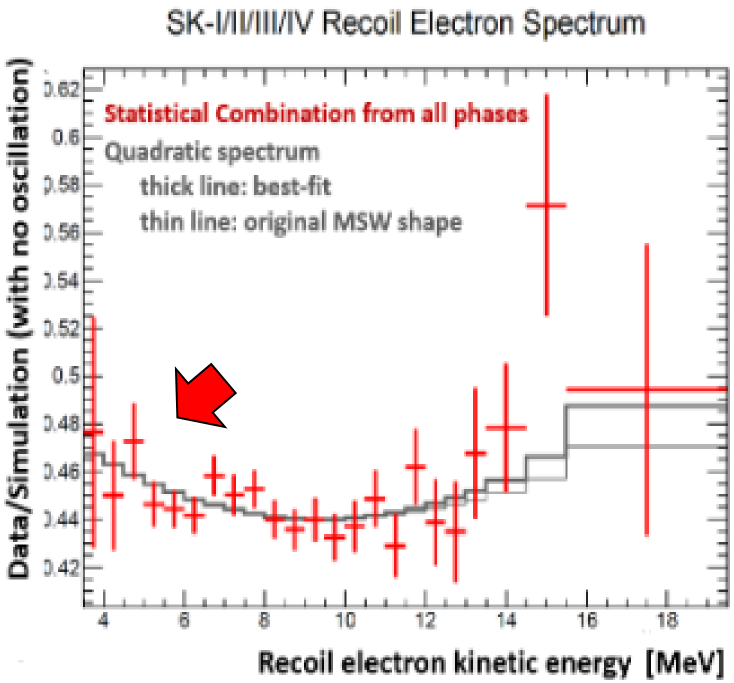


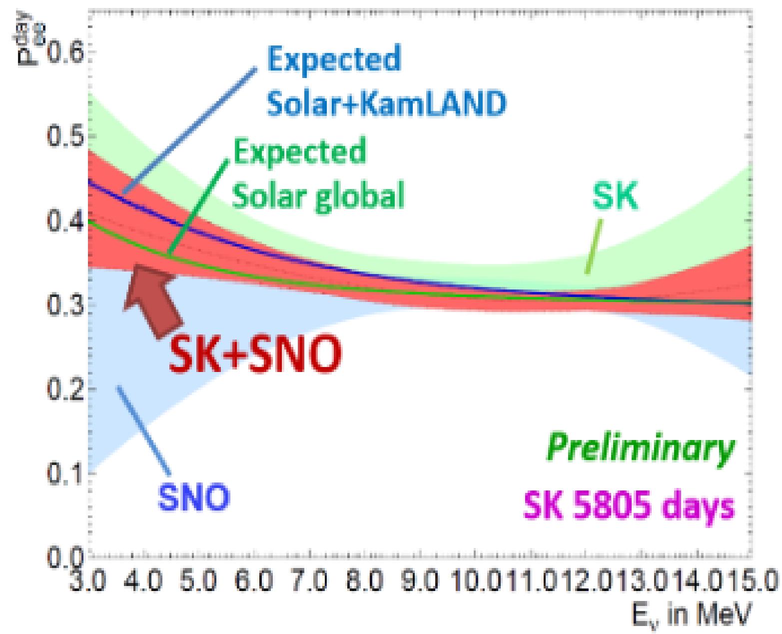
1, 2, 3σ CL contours

F Capozzi, et al
2107.00532 [hep-ph]

SK- upturn shows up

Yasuo Takeuchi for the Super-Kamiokande Collaboration*





Preliminary energy distributions of observed solar neutrino events (left) and allowed ee-survival probability in daytime (right). The plot on the left is the statistical combination of the observed spectra during SK-I, II, III, and IV.

Astrophysics, tool for searches Beyond LMA

After the main mechanism of was identified and parameters well measured

Solar neutrino fluxes at production

+

LMA-MSW conversion

Neutrino flux at the detector

Studies of interactions in the detector → bounds on new physics

Magnetic moments

NSI

Interactions with light mediators

Feedback of this new physics on produced fluxes

... ways to account, suppress feedback , flux independent analysis...

BSM: "Standard set"

Steriles

NSI B

Interactions with DM

Decays

ν_{sun}

Magnetic moments B

Decoherence

Long range forces

Violation of fundamental symmetries

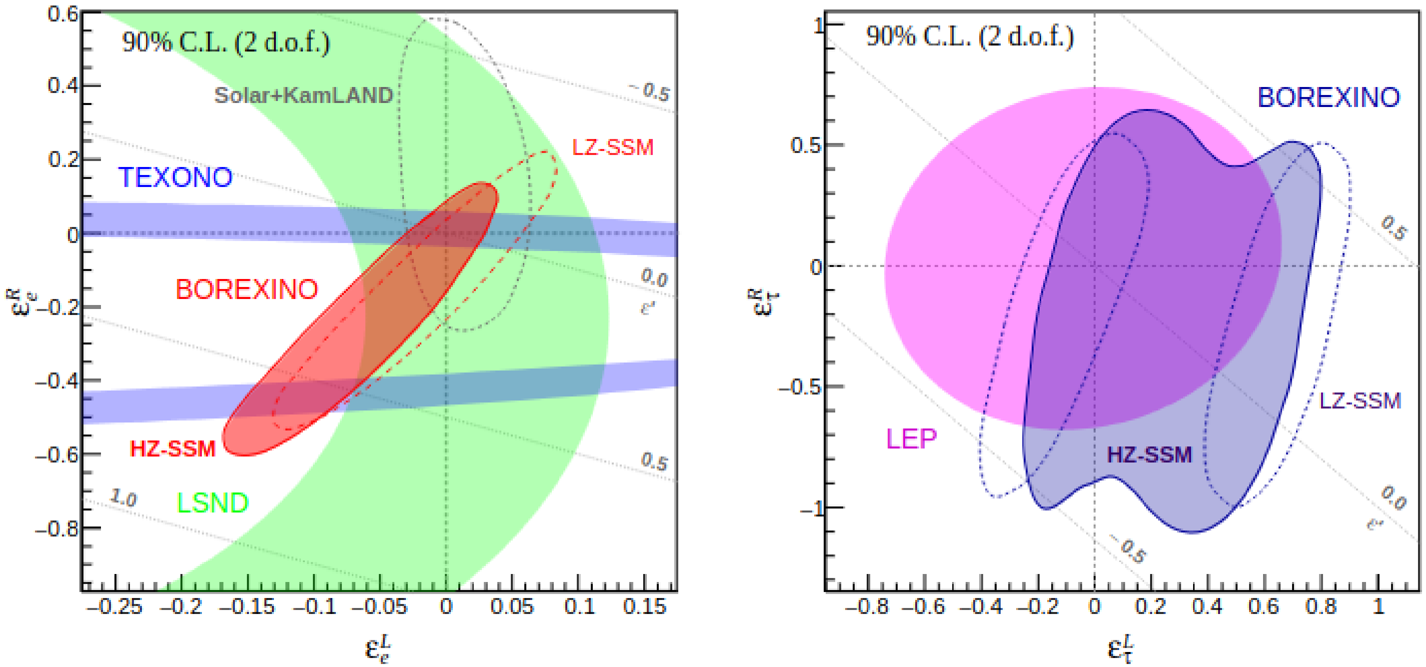
~ E^n

Lorentz CPT

B – studied by BOREXINO

BOREXINO: bounds on NSI interactions

Phase-II dataset

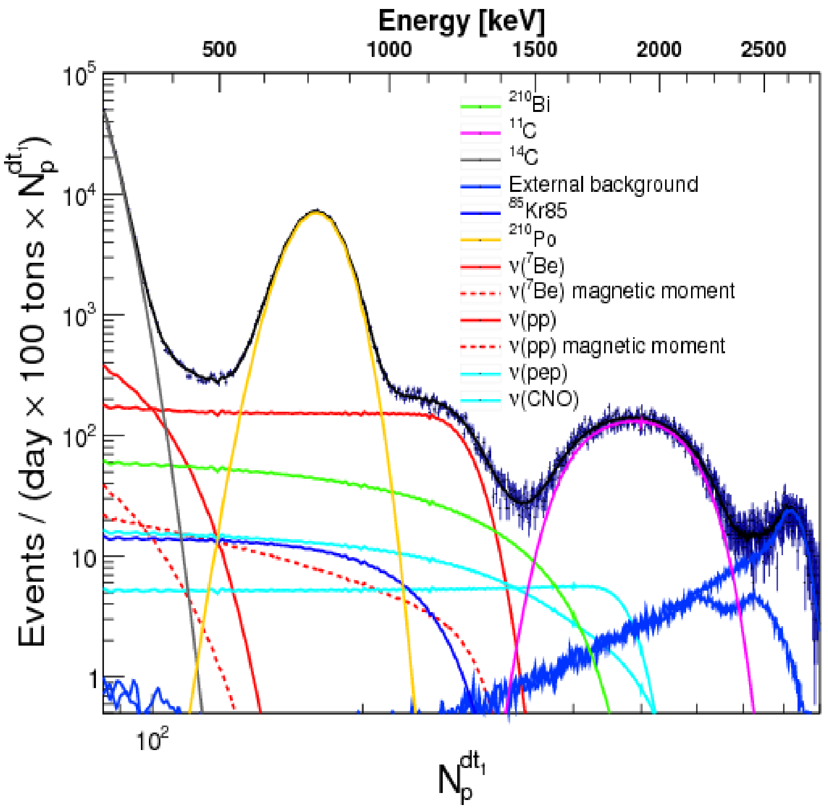


a) Allowed region for the NSI parameters ε_e^R and ε_e^L.
b) Allowed region for the NSI parameters ε_τ^R and ε_τ^L .
For both HZ-SSM and LZSSM metallicity scenarios.

Excludes 1.6 bigger potential, dark solution on electrons

Neutrino magnetic moment

Borexino Collaboration, M. Agostini et al., arXiv:1707.09355



Spectral fit with the neutrino effective magnetic moment fixed at the upper limit

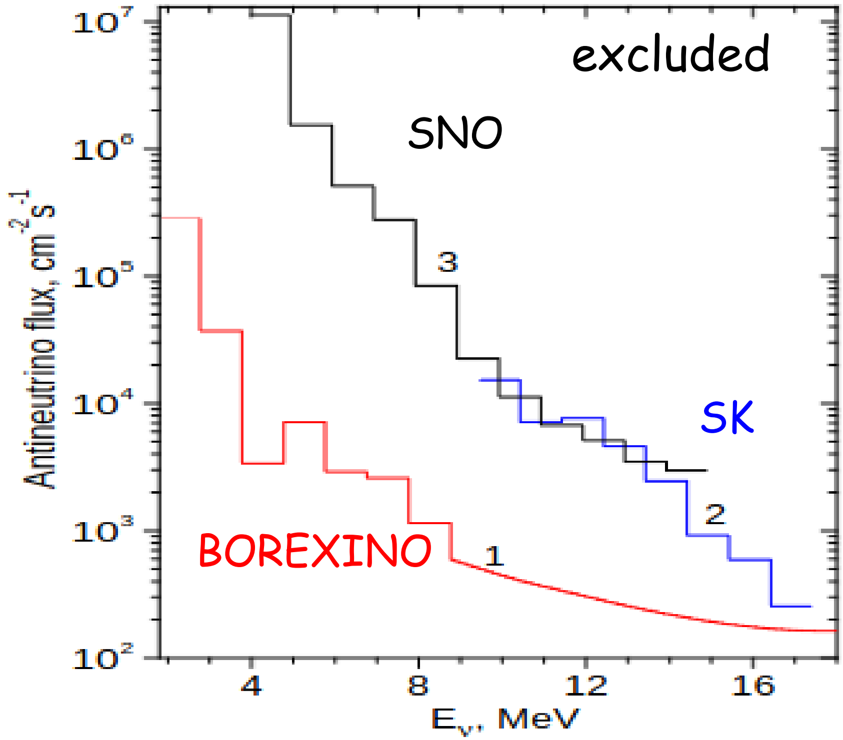
data from 1291.5 days exposure during phase II of the Borexino. No significant deviations from the expected shape of the electron recoil spectrum have been found .

upper limit on the effective neutrino magnetic moment:

$\mu_{eff} < 2.8 \cdot 10^{-11}\ \mu_B$, 90% C.L.

(constraints on the sum of the solar neutrino fluxes implied by gallium experiments has been used)

Antineutrinos from the Sun

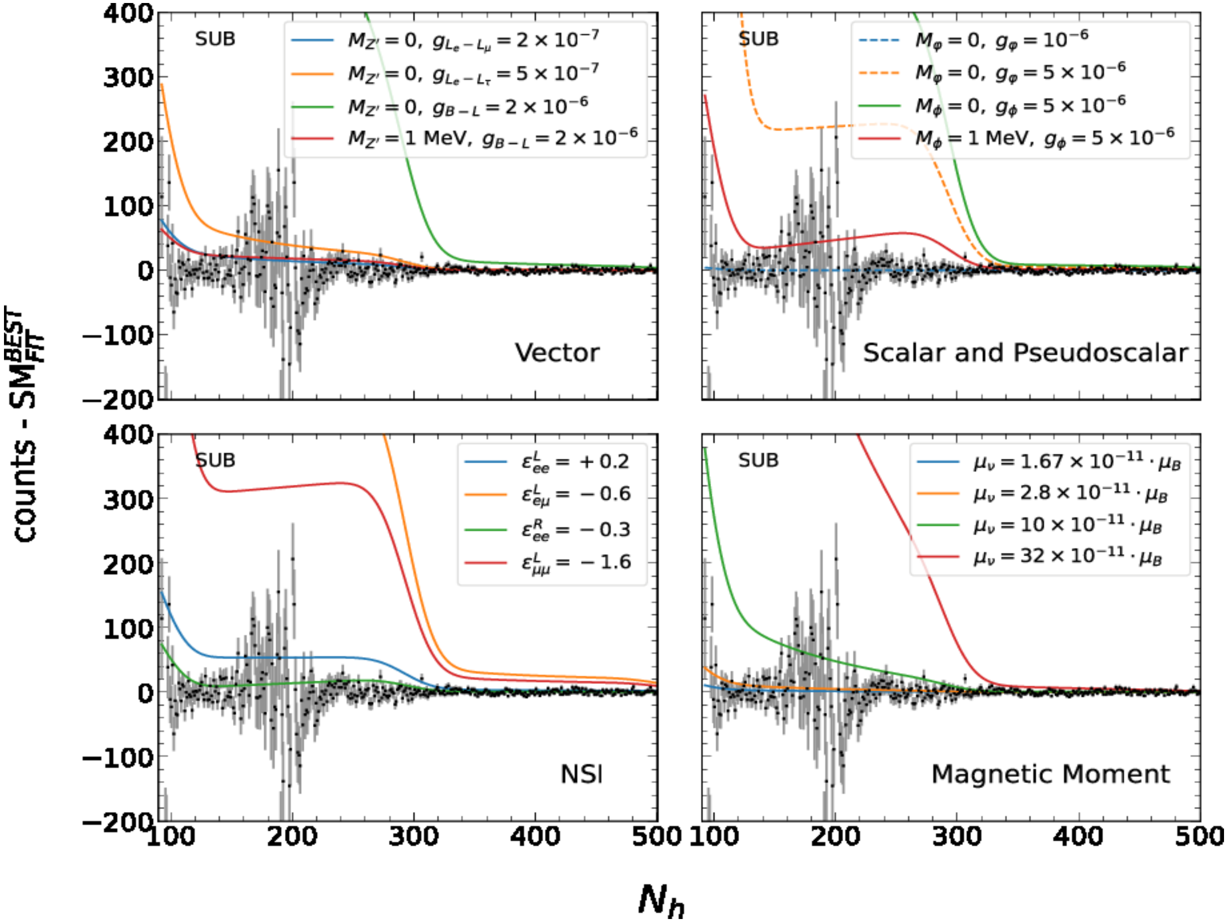


Expected in the case of spin-flavor conversion

Upper limits on the monochromatic $\bar{\nu}_e$ flux from:
1- the present Borexino data (red line);
2- SuperKamiokaNDE (blue line) and
3- SNO (black line)

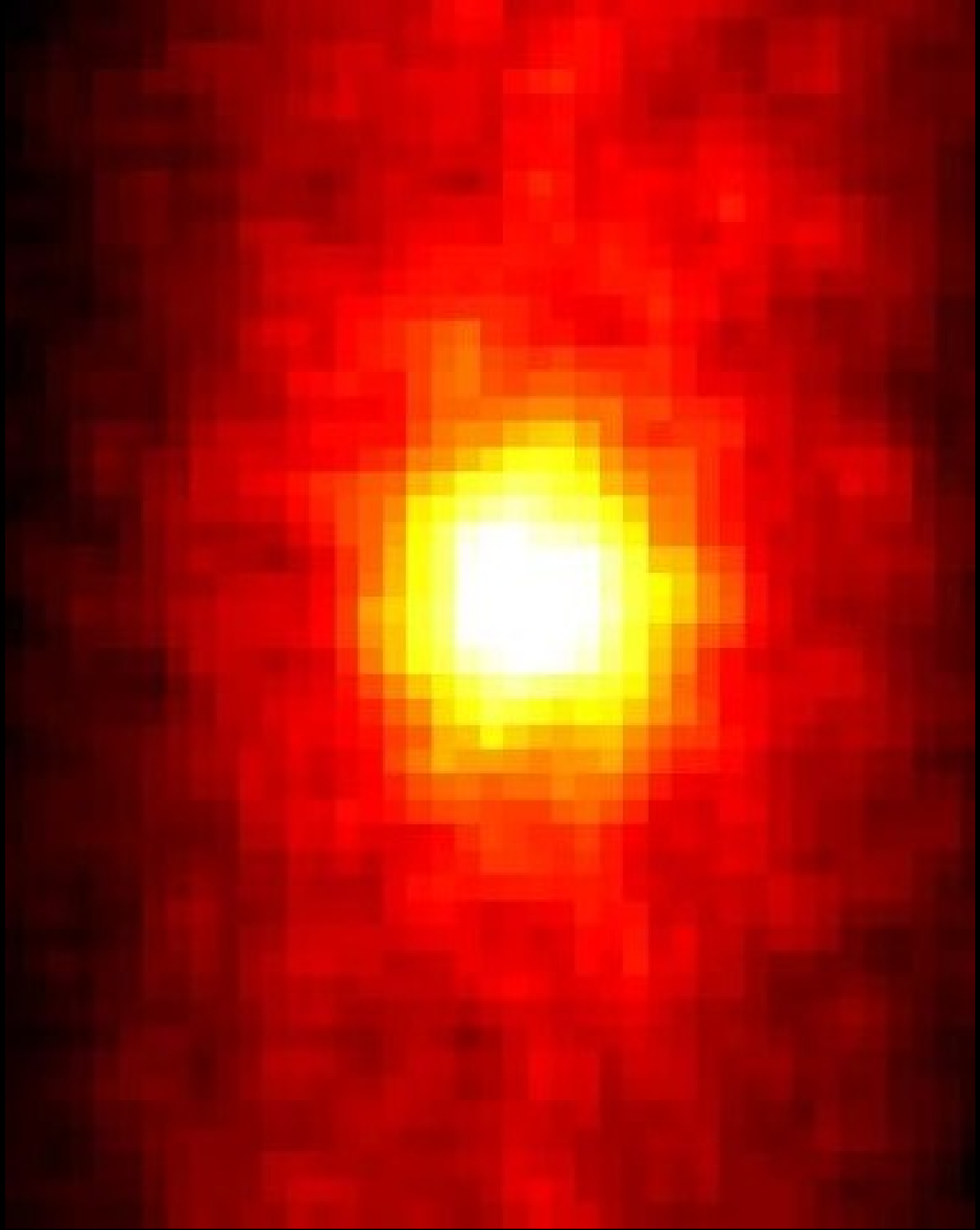
Contribution to the number of events from new physics

Pilar Coloma, M.C. Gonzalez-Garcia, Michele Maltoni
JHEP 07 (2022) 138, 2204.03011 [hep-ph],



Difference between the number of events with respect to the SM expectation,as a function of N_h (number of hits of the PMT).

Conclusion



Ga-Ge experiment played fundamental role in the process of identification of solution of the Solar neutrino problem. Motivated KamLAND

The established LMA MSW solution is based on the adiabatic flavor conversion driven by change of mixing angle in matter with density

BOREXINO provided important check of the LMA MSW solution, in particular, confirming the energy profile of the effect in whole the energy range (all the components of the solar neutrino flux).
It produced bounds on beyond the LMA effects

Opens new phase of studies of astrophysics of the Sun

In addition:

Establishing Nature of neutrino mass

Refractive neutrino mass: VEV vs EV

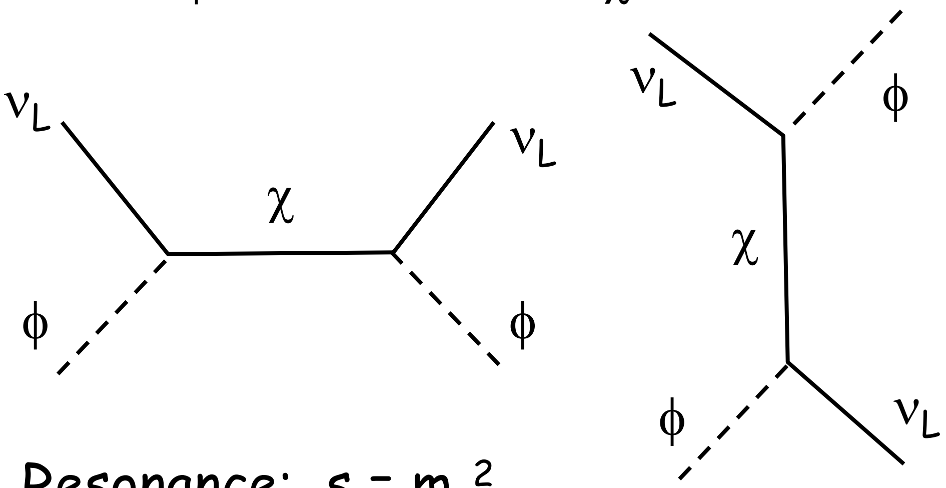
Neutrino mass from neutrino condensate

E, t, environment dependence

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



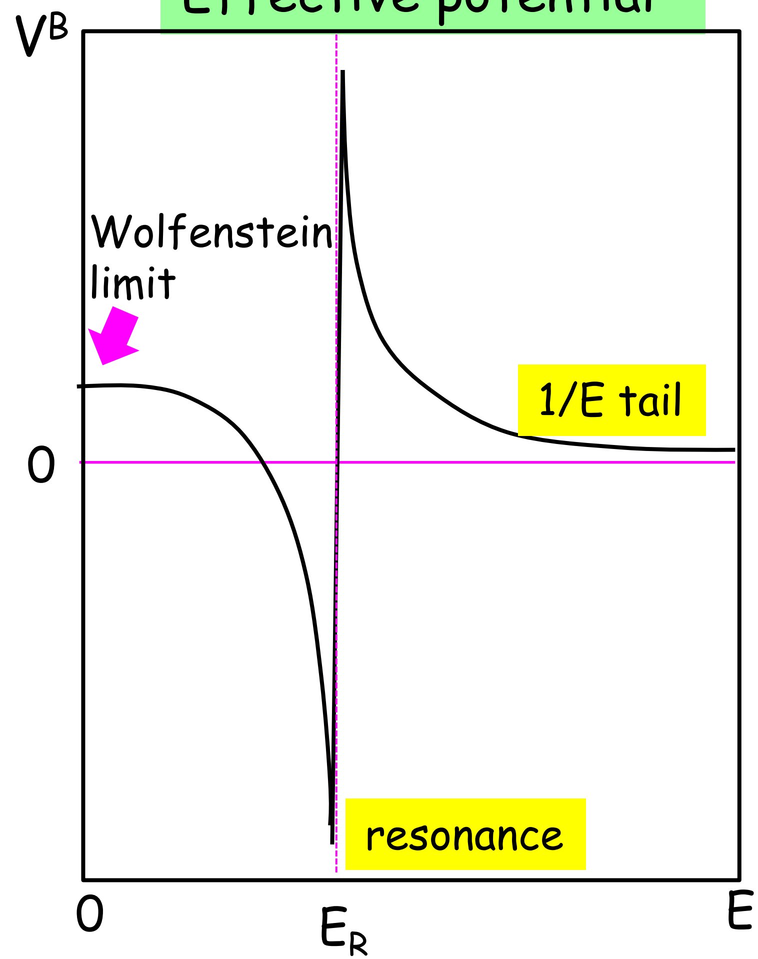
Resonance: $s = m_\chi^2$

for ϕ at rest the resonance ν energy:

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

If mediator and target particle are light, the 1/E dependence shows up at low explored energies.

Effective potential



Refractive mass squared

Manibrata Sen, AYS,
2306.15718 [hep-ph]

Introduce the refractive mass squared as

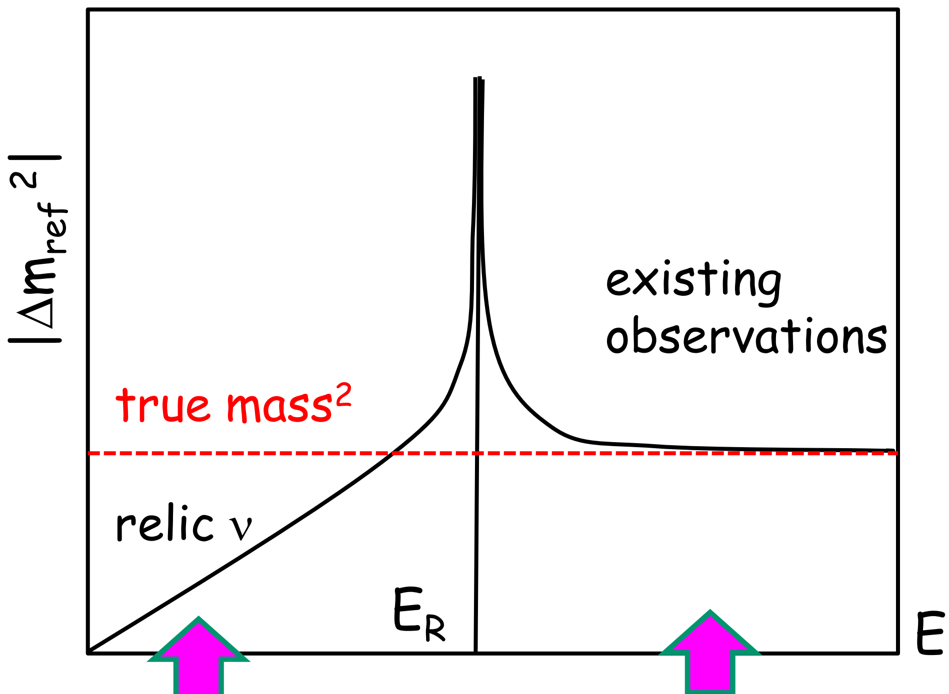
$V = m_{ref}^2/2E$

So that the potential has the form of usual vacuum contribution

$m_{ref}^2 = 2EV$

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

→ E_R << 0.1 MeV



The decrease allows to avoid the cosmological bound

~ constant m_{ref}^2 explains oscillation data

substitute neutrino mass?

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

Effect of classical component

A. Berlin, 1608.01307 [hep-ph]

Solution of equation of motion for classical field has t and x dependence:

$$\phi_c(t, x) \sim \frac{\sqrt{2\rho(x)}}{m_\phi} \cos(\omega t - k x)$$

$\omega \sim m_\phi$, $k = m_\phi v$, $v \sim 10^{-3}$ – virialized velocity in the Galaxy

ϕ_c generates the mass term $m' \nu_L f_R$ + h. c. with $m' = g \phi_c$

Oscillating mass with period $T_{osc} = 2\pi/m_\phi = 4\ 10^{-15}$ sec $(1\ \mathrm{eV}/m_\phi)$

Loss of coherence due to velocity dispersion $\Delta v \sim v$?

⇨ $\Delta\omega = m_\phi v \Delta v \sim m_\phi v^2$

$$\tau_{coh} = \frac{2\pi}{\Delta\omega} = 4\ 10^{-9}\ \mathrm{sec}\ (1\ \mathrm{eV}/m_\phi)$$

System transforms into a cold gas of individual scatterers.
Still in some aspects can be considered as classical field without time variations

Vacuum and properties of oscillations

G.Dvali , L Funcke, 1602.03191 [hep-ph]

Neutrino vacuum condensate due to gravity. Order parameter

$$\langle\Phi_{\alpha\beta}\rangle = \langle\nu_\alpha^T C \nu_\beta\rangle \sim \Lambda_G = \text{meV - 0.1 eV}$$

Cosmological phase transition at $T \sim \Lambda_G$

Neutrinos get masses $m_{\alpha\beta} \sim \langle \Phi_{\alpha\beta} \rangle$

Flavor is fixed by weak (CC) interactions, charged leptons get masses by usual Higgs field

$$m \sim U(\theta)^T \langle\Phi\rangle U(\theta)$$

$\langle\Phi\rangle = \mathrm{diag}\,(\Phi_{11}, \Phi_{22}, \Phi_{33})$, mixing matrix

$T < \Lambda_G$ Relic neutrinos form bound states $\phi = (\nu_\alpha^T \nu_\beta)$ decay and annihilate into ϕ (neutrinoless Universe)

Symmetry of system SU(3)xU(1) is spontaneously broken by neutrino condensate - ϕ are goldstone bosons

ϕ get small masses due explicit symmetry breaking by WI via loops

Mixing and topological defects

G.Dvali , L Funcke,
T Vachaspati
2112.02107 [hep-ph]

Symmetry breaking: $SU(3) \rightarrow Z_2 \times Z_2 \rightarrow I$ ➡ string-wall network

global strings — domain walls

Length scale of strings ~ inter-string separation

$$\xi = 10^{14}\ \mathrm{m}\ (\lambda/a_G) \left(\frac{\Lambda_G}{1\ \mathrm{meV}}\right)^{7/2}$$

(self-coupling of string field Φ/scale factor of phase transition)

Travelling around string winds VEV $\langle\Phi\rangle$ by the SU(3) transformation:

$$\langle \Phi(\theta_S) \rangle = \omega(\theta_W)^T \langle\Phi\rangle\, \omega(\theta_W)$$

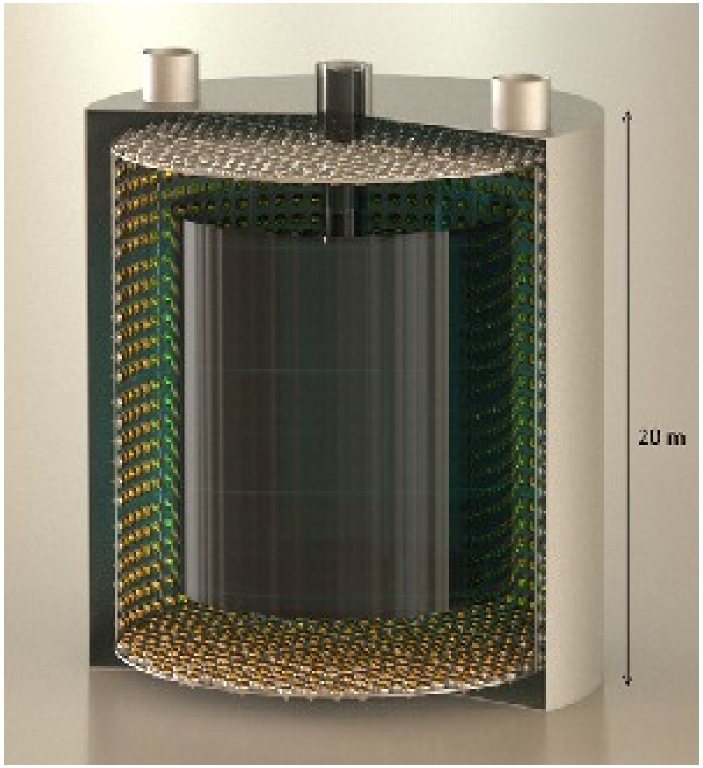
$\omega(\theta_W)$ path - O(3) transformation with angles $\theta_W = (\theta_W^{12}, \theta_W^{13}, \theta_W^{23})$.
After the path ω lepton mixing changes as $U = U(\theta)\,\omega(\theta_W)$
over length ξ, $\theta_W = O(1)$.

Solar system moves through the frozen string-DW background with v = 230 km/sec. For 6 years $d = vt = 4 \times 10^{13}$ m - comparable with expected ξ

Homestake, GALLEX
time variations?

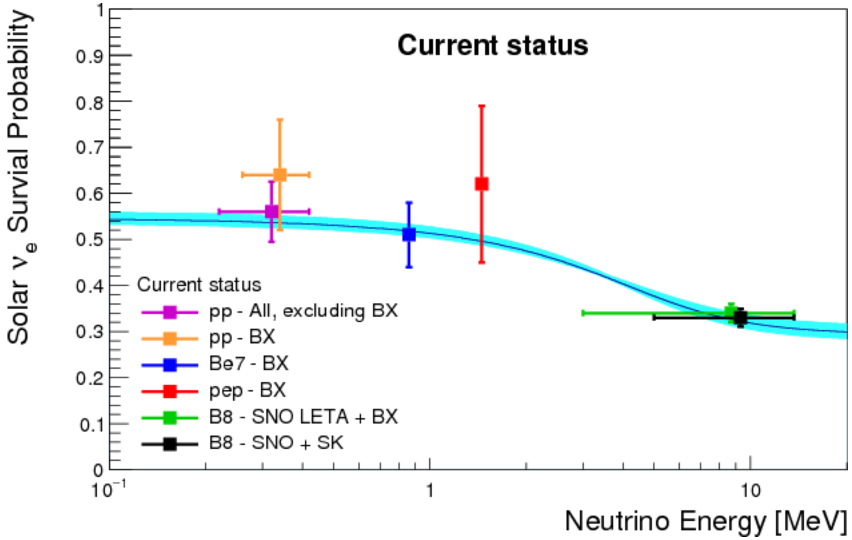
JinPing underground lab

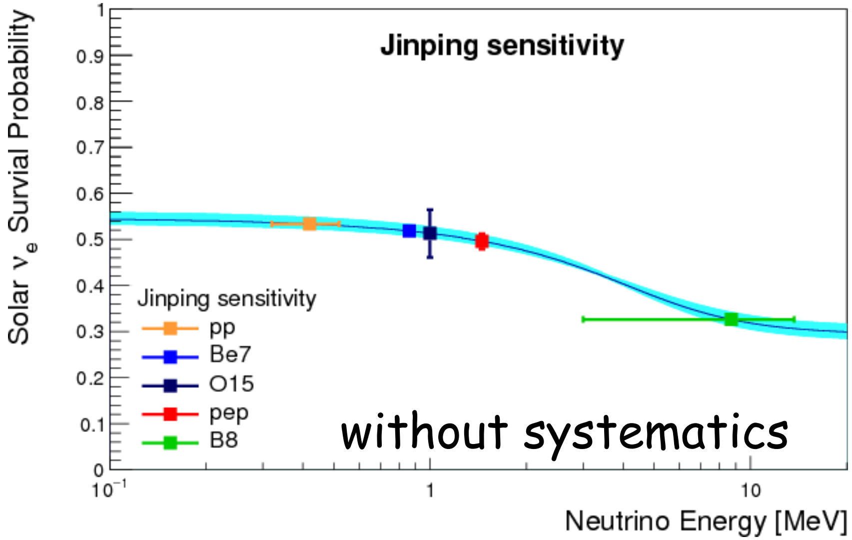
scintillator uploaded
water detectors?



FV: 100 times bigger than BOREXINO

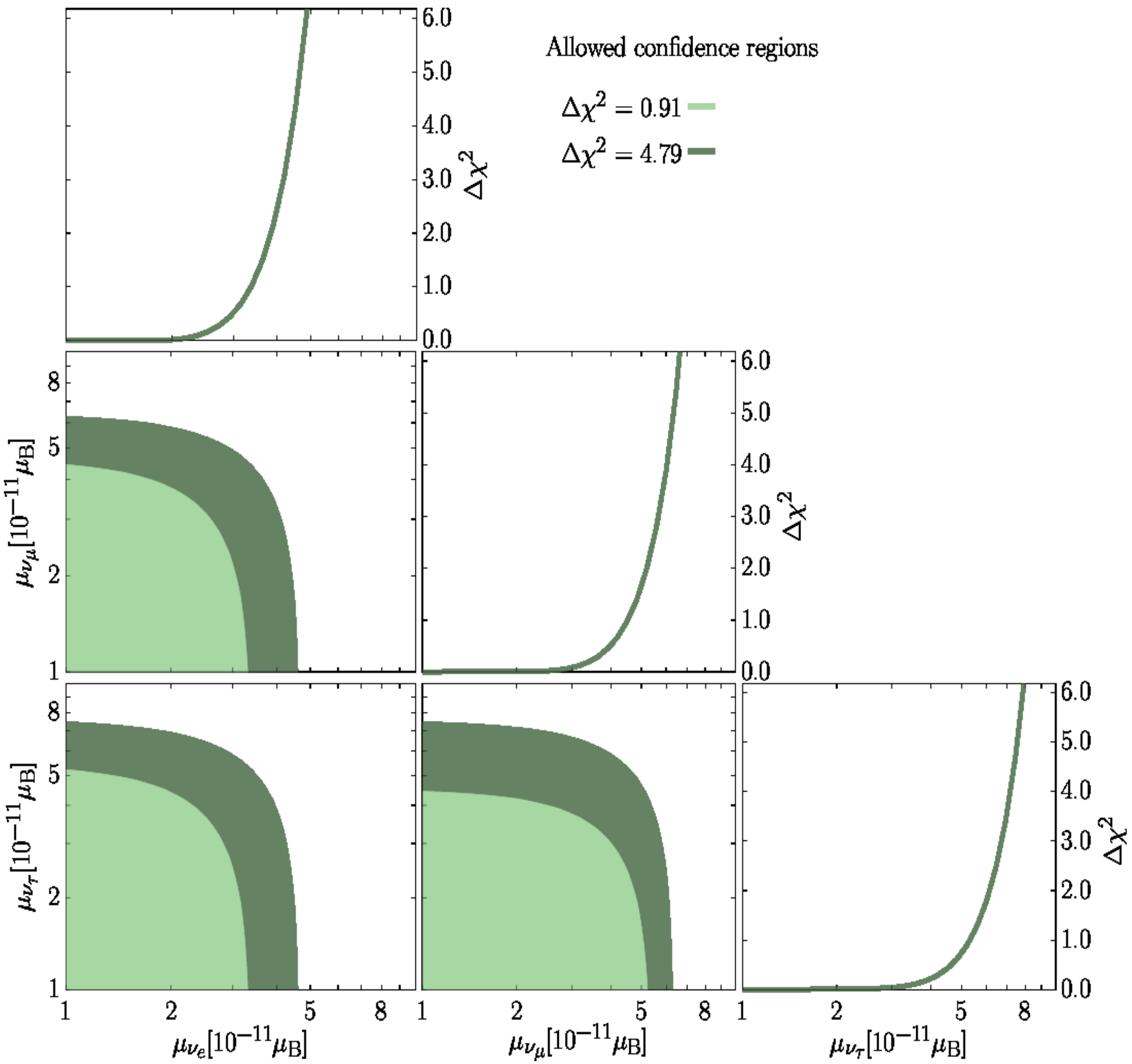
Deeper than SNO





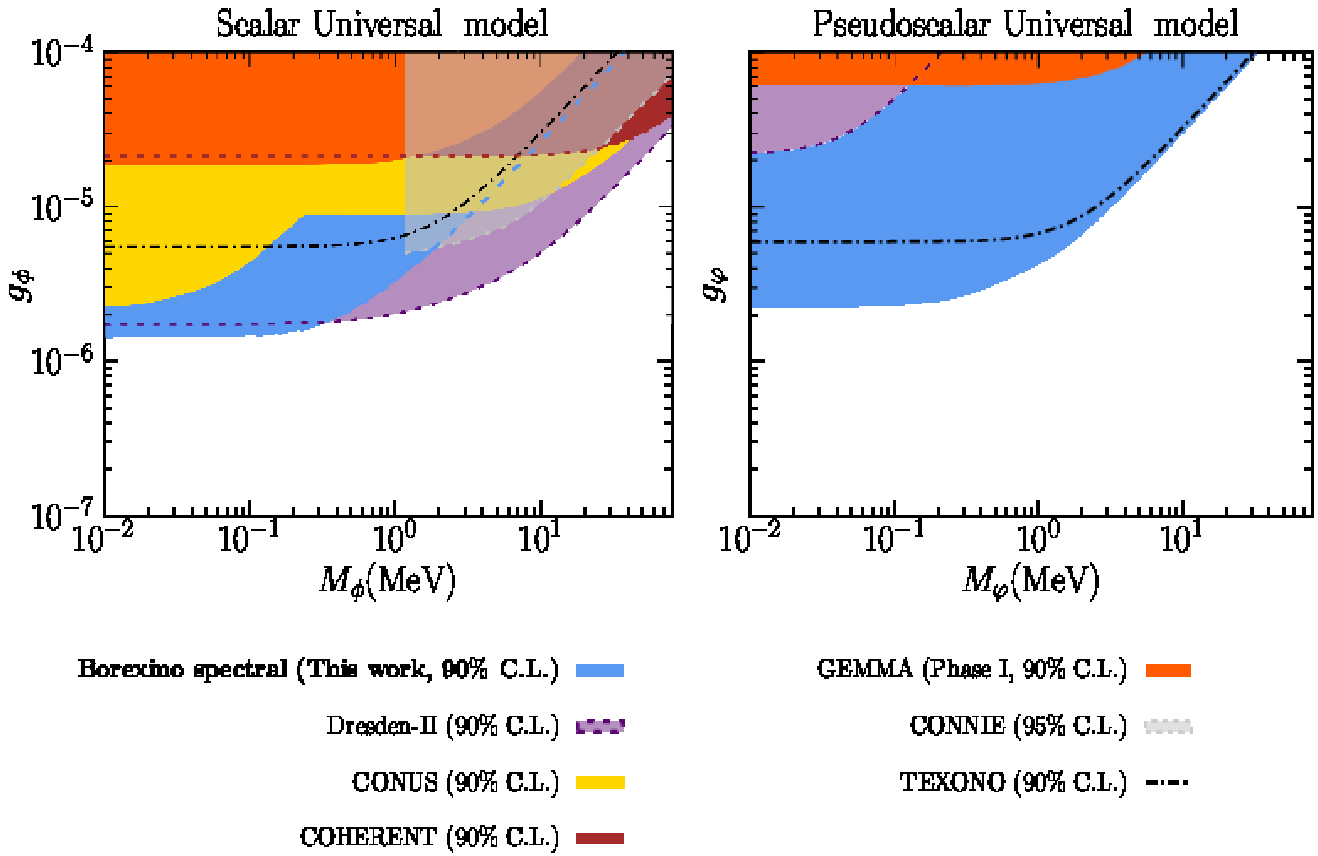
without systematics

Bounds on magnetic moments



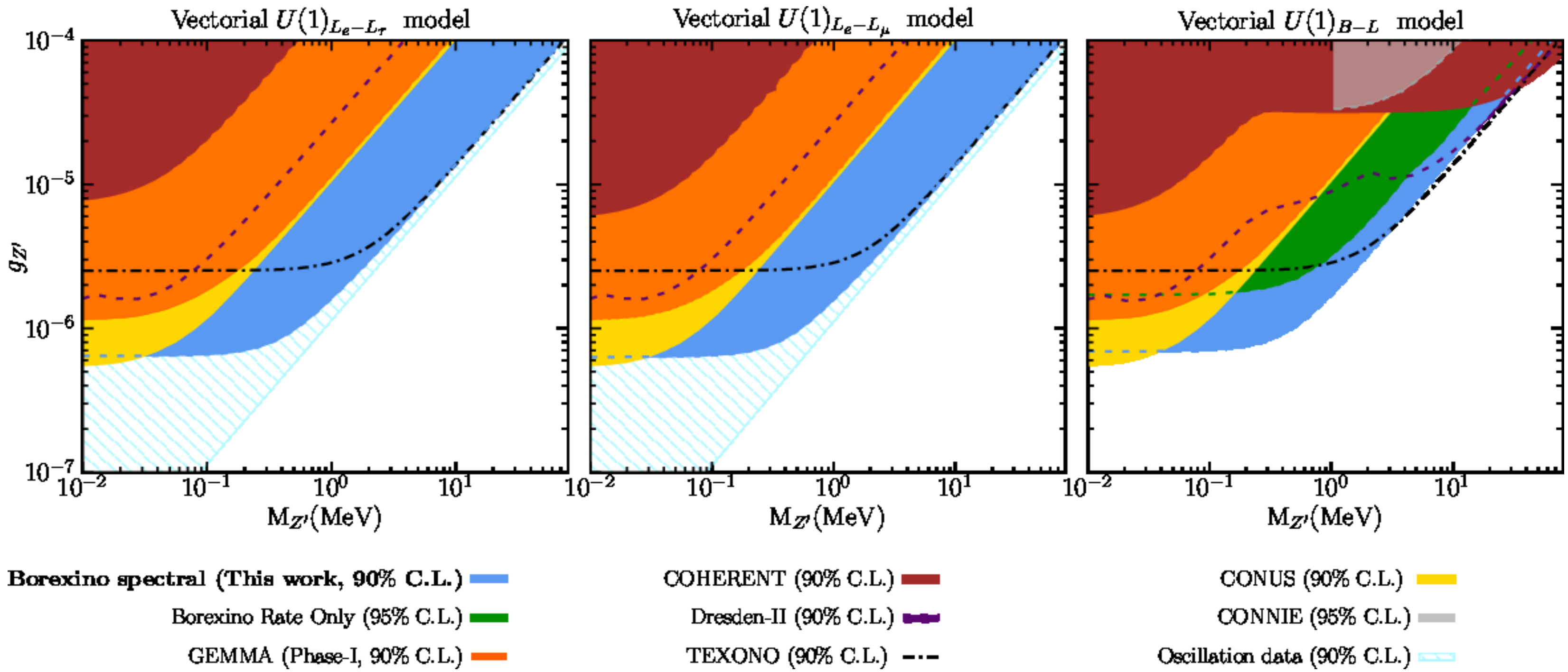
Bounds on interactions due to light mediators

Bounds from Borexino Phase-II spectral data (blue) on a scalar (left panel) and pseudoscalar (right panel) mediator (at 90% CL for 1 d.o.f.,) which couples universally to all fermions in the SM.

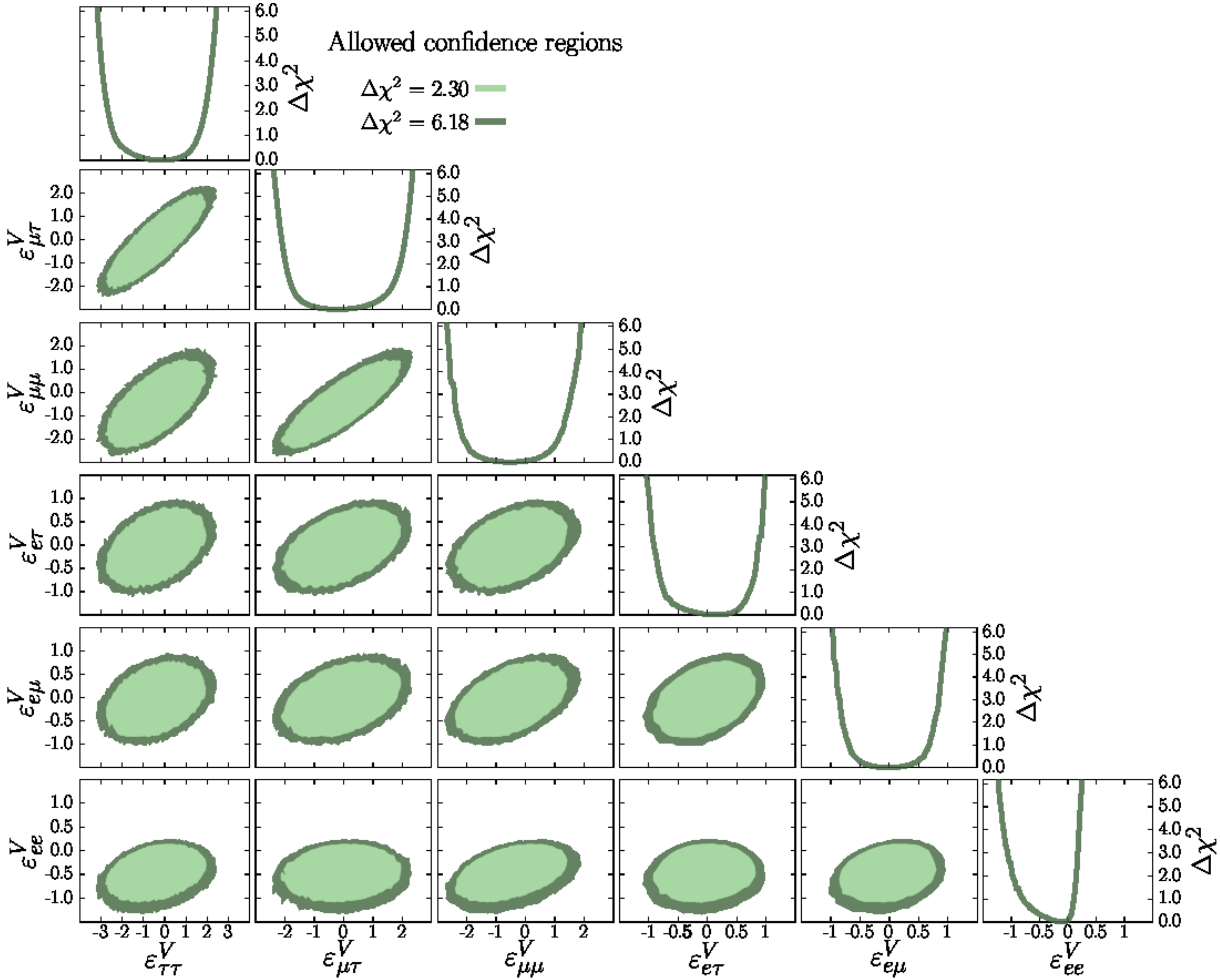


Bounds on new interactions due light mediators

Bounds on couplings as function of mass (blue) from Borexino Phase II spectral data (90% CL for 1 d.o.f).,on the vector mediators associated to a new U(1)' symmetry



Bounds on vector NSI coupling



LMA-Dark solution

O.G. Miranda, M.A. Tortola, J. W. F. Valle, JHEP 19 (2006) 008 hep-ph/0406280

Scaling:

$\Delta m_{21}^2 \rightarrow -\Delta m_{21}^2$, $V \rightarrow -V$

$\rightarrow$ inversion of 1-2 ordering

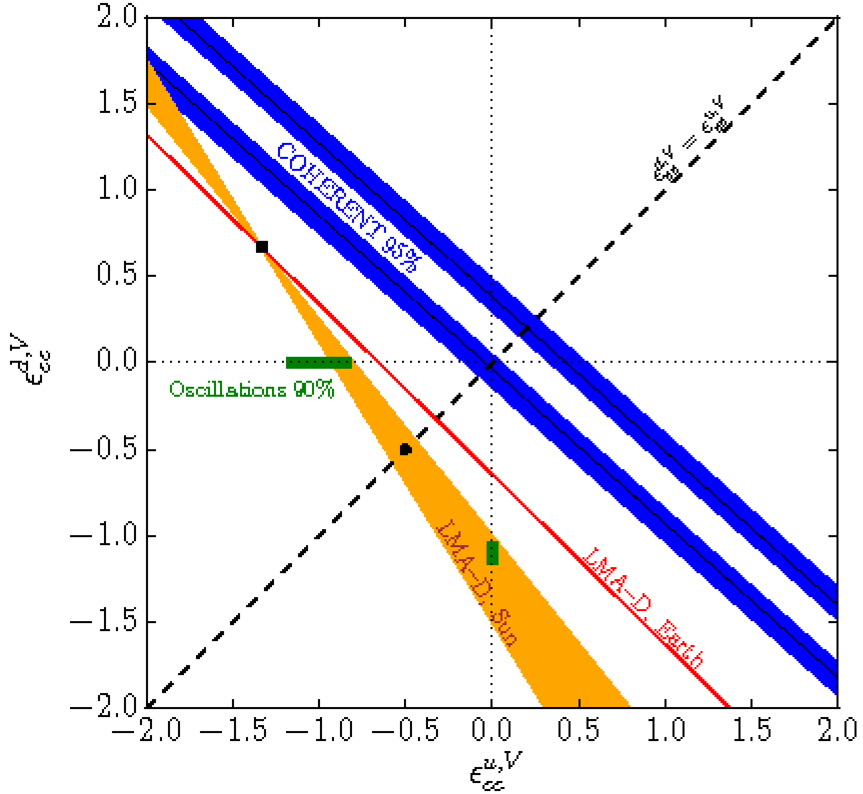
P. B. Denton, et al. arXiv:1804.03660 [hep-ph]

$$V_{\alpha\beta}^f = 2V_e \, \varepsilon_{\alpha\beta} \frac{n_f}{n_e}$$

Equivalently, mixing is not changed if

$\cos 2\theta_{12} \rightarrow -\cos 2\theta_{12}$, $V \rightarrow -V$

$\sin^2\theta_{21} \rightarrow 1 - \sin^2\theta_{21}$ dark side: 0.69



Change of sign of the potential requires NSI

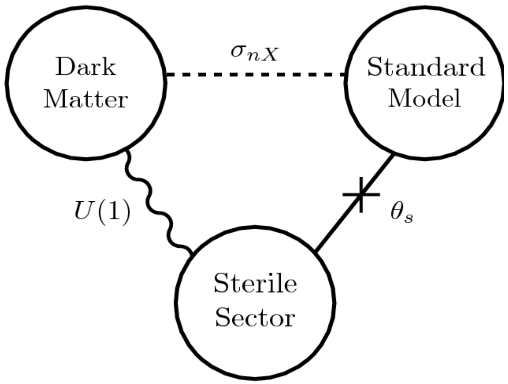
$$V = V_e + V_{NSI}$$

$$V_{NSI} = -2V_e$$

Nature of neutrino mass

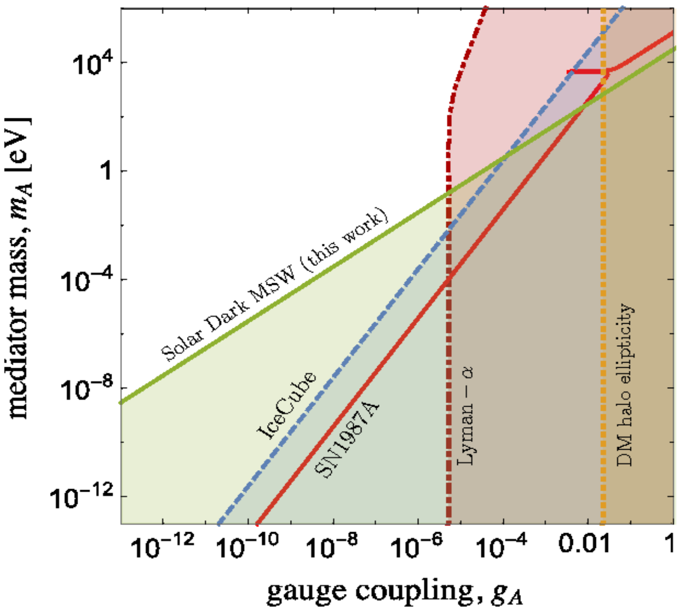
and mass squared probed in oscillations

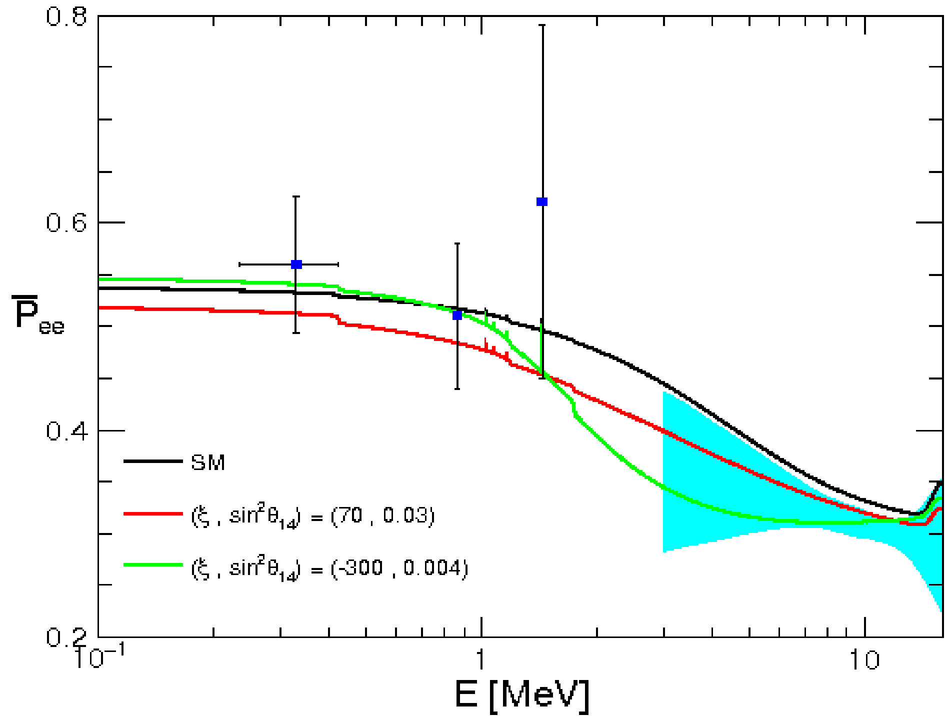
NSI on DM + mixing with sterile



Solar Neutrinos as a Probe of Dark Matter-Neutrino Interactions - F. Capozzi, et al. JCAP 1707 (2017) no.07, 021 arXiv:1702.08464 [hep-ph]

$$\xi = \frac{G_X\, n_X(0)}{V_e(0)}$$ potential on DM





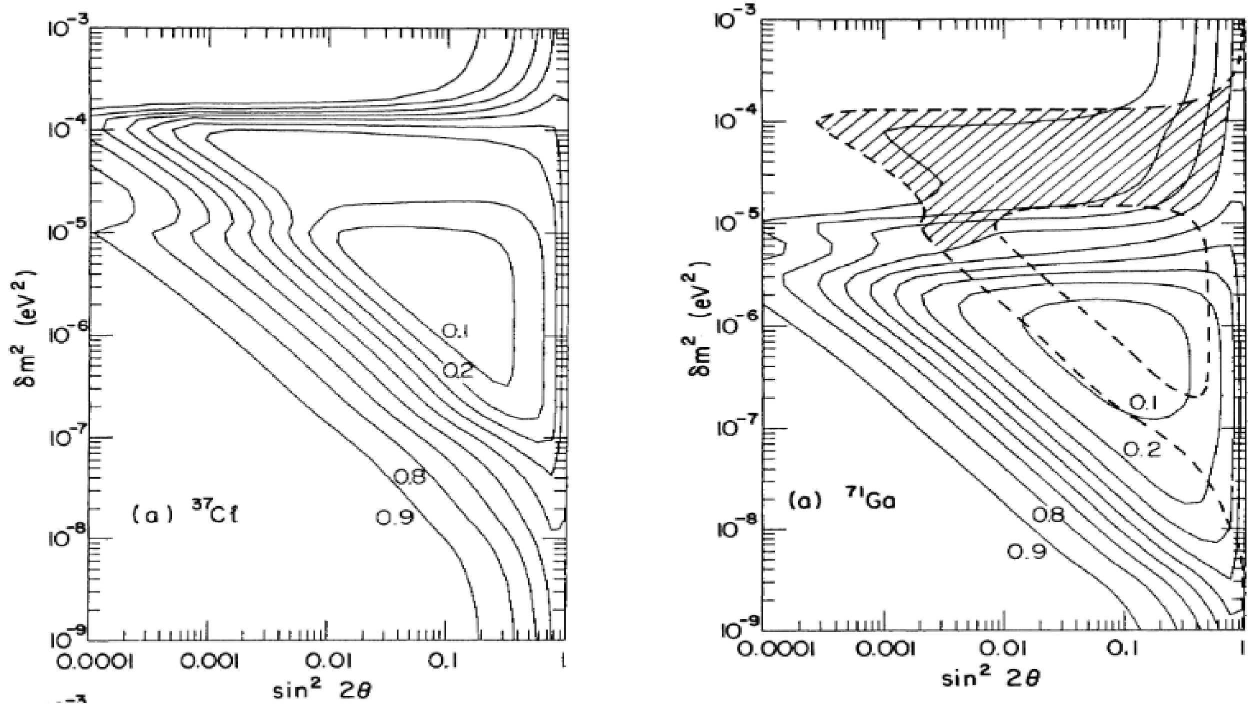
Implications GNO + BOREXINO

GNO	62.9 ± 6.0 5.9 SNU	
GALLEX	77.5 ± 7.6 7.8 SNU	GNO collaboration
GALLEX+GNO	69.3 ± 5.5 SNU	M . Altmann, PLB
SAGE	66.9 ± 5.3 5.0 SNU	(2005)

According to LMA(MSW) (identified by SNO/SK data), vacuum oscillations dominate below 1 MeV and the mixing angle $\theta = (32 \pm 1.6)^o$
The first preliminary results from the BOREXINO experiment on the flux of solar 7Be neutrinos make can be used to deduce the pp-neutrino flux separately. We extract from our data the e-e survival probability Pee for pp-neutrinos subtracting experimentally determined 8B-(SNO/SK) and 7Be-(BOREXINO) neutrino fluxes.
This gives Pee(pp only) = 0.52 ± 0.12.
The results imply the experimental verification of the solar model and of the neutrino oscillation
mechanisms at sub-MeV energies that are otherwise inaccessible.

The MSW triangle

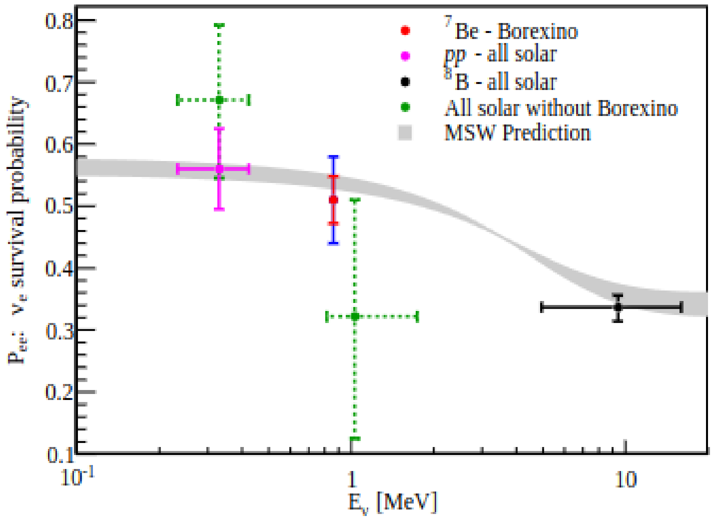
Lines of equal suppression



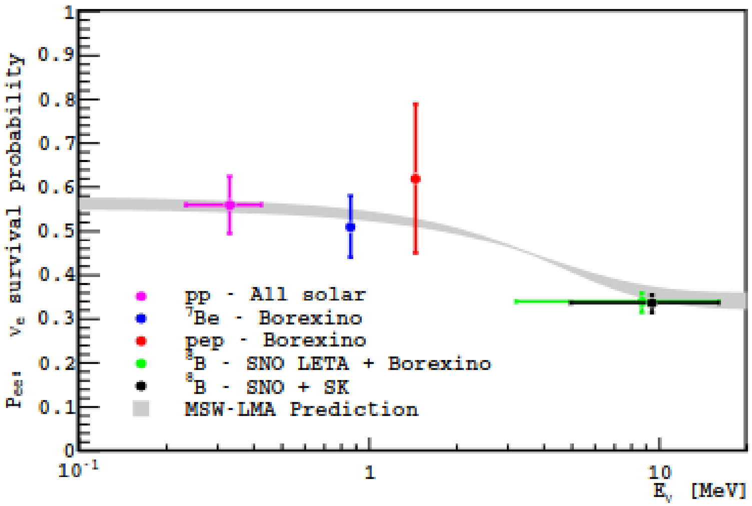
W.C. Haxton, Phys.Rev.D 35 (1987) 2352

Spectroscopy with BOREXINO

After Be measurements



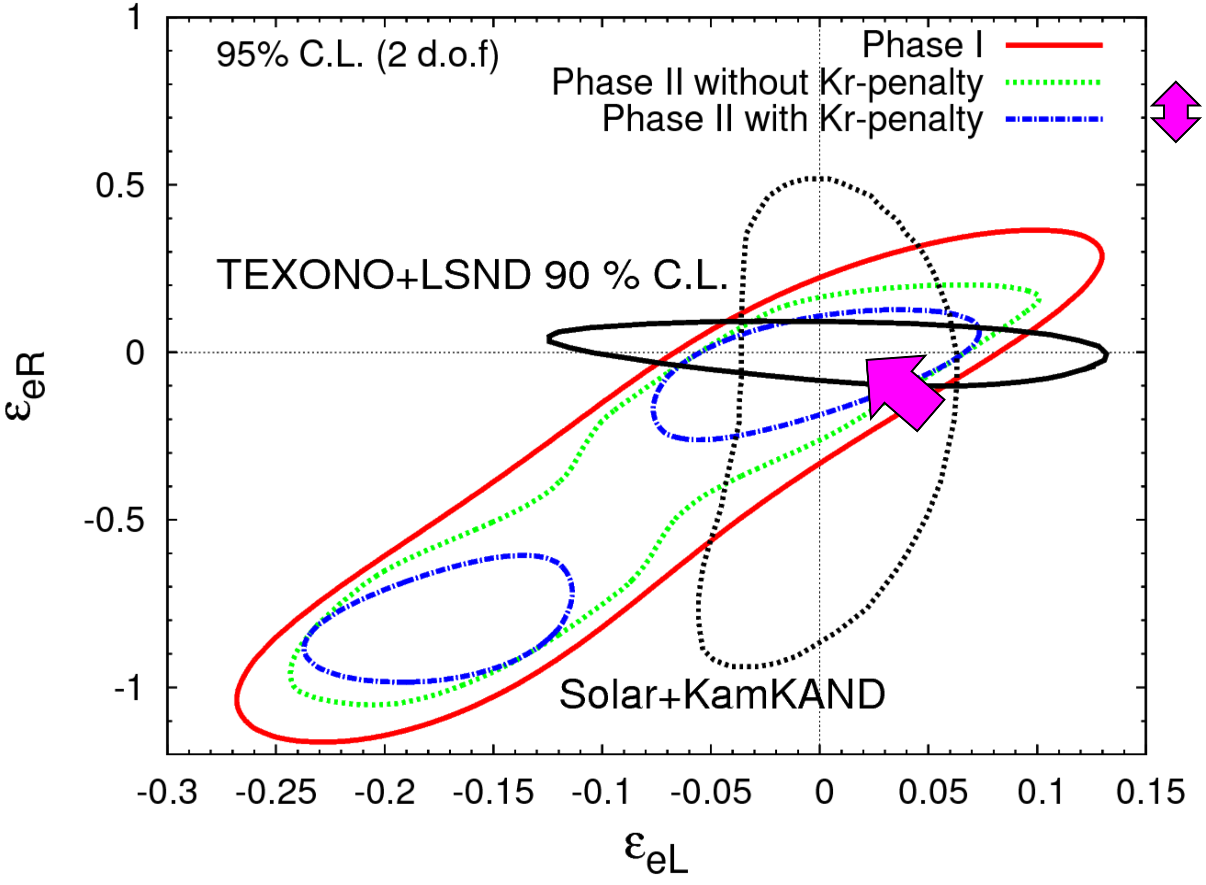
After pep measurements



Electron neutrino survival probability Pee as a function of neutrino energy.

Borexino's effect on the low energy Pee measurements, the green (dashed) points are calculated without using the Borexino data.

BOREXINO: NSI interactions

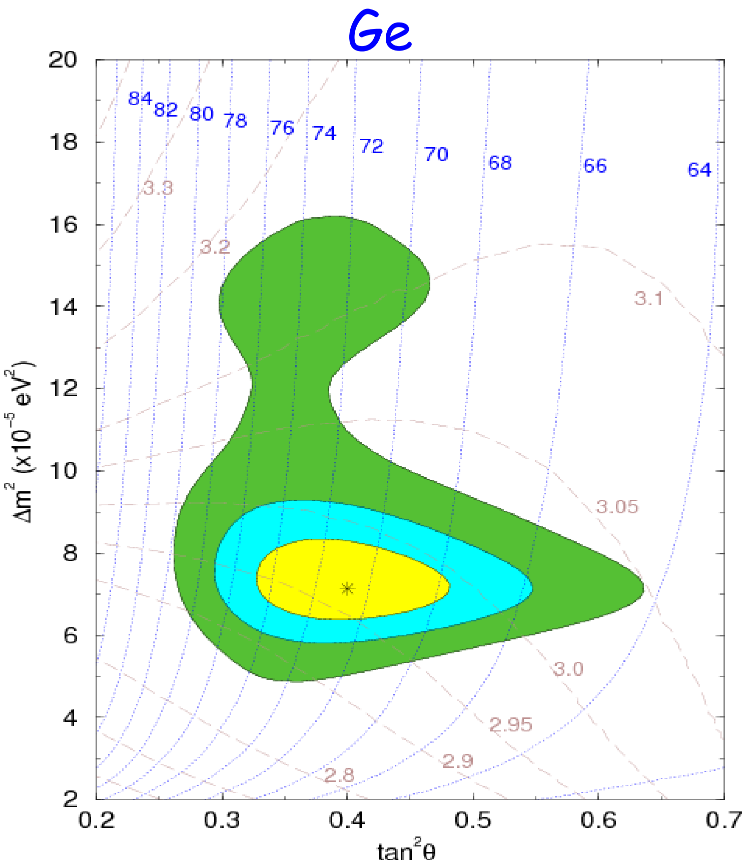


S. Agarwalla

Excludes
1.6 bigger potential,
dark solution on
electrons

$\varepsilon_e < 0.05 - 0.1$

After salt phase of SNO: Ar- and Ge- production rates



P.C. de Holanda, A.Yu. Smirnov
Astropart.Phys. 21 (2004) 287
hep-ph/0309299 [hep-ph]

Predictions for the Germanium and Argon production rates. The allowed regions of the oscillation parameters from the combined fit of the solar neutrino data and the KamLAND spectrum.

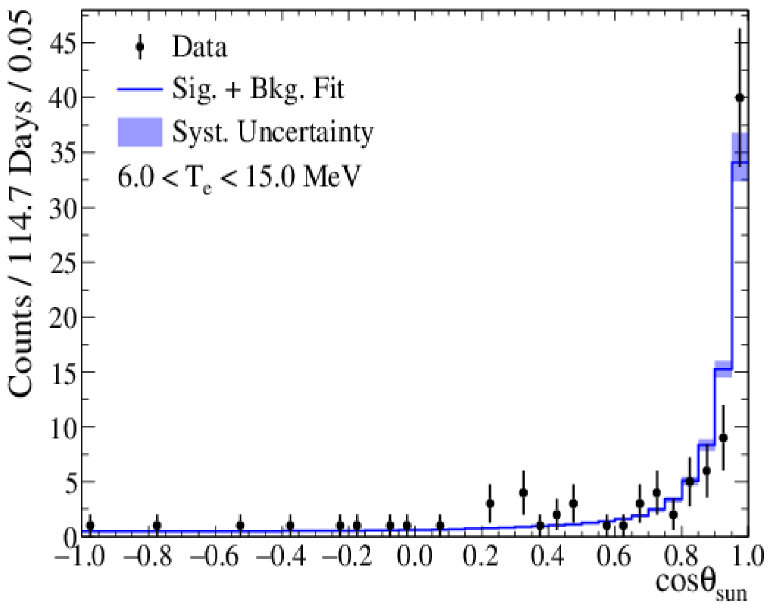
$Q > 2.95$ SNU

Solar neutrinos SNO+ results

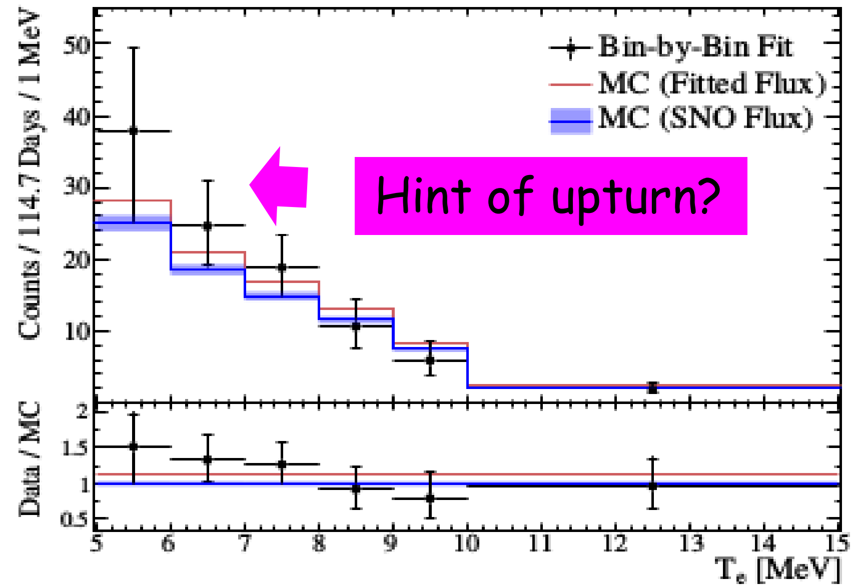
SNO+ Collaboration (Anderson, M. et al.)
Phys.Rev. D99 (2019) no.1, 012012
1812.03355 [hep-ex]

Water phase: Measurement of the 8B solar neutrino flux in SNO+ with very low backgrounds S/B ~ 4, E > 6 MeV

114.7 days of data



Distribution of event directions wrt. solar direction



The extracted event rate as function of reconstructed electron kinetic energy

69.2 kt-day dataset

Flux: $2.53\ [-0.28+0.31(\text{stat})\ \ -0.10+0.13(\text{syst})] \times 10^{-6}\ \text{cm}^{-2}\ \text{s}^{-1}$