Solar neutrinos beyond DUNE

A. Yu. Smirnov

Max-Planck Institute fuer Kernphysik, Heidelberg, Germany

Neutrino platform week, CERN, January 30, 2018

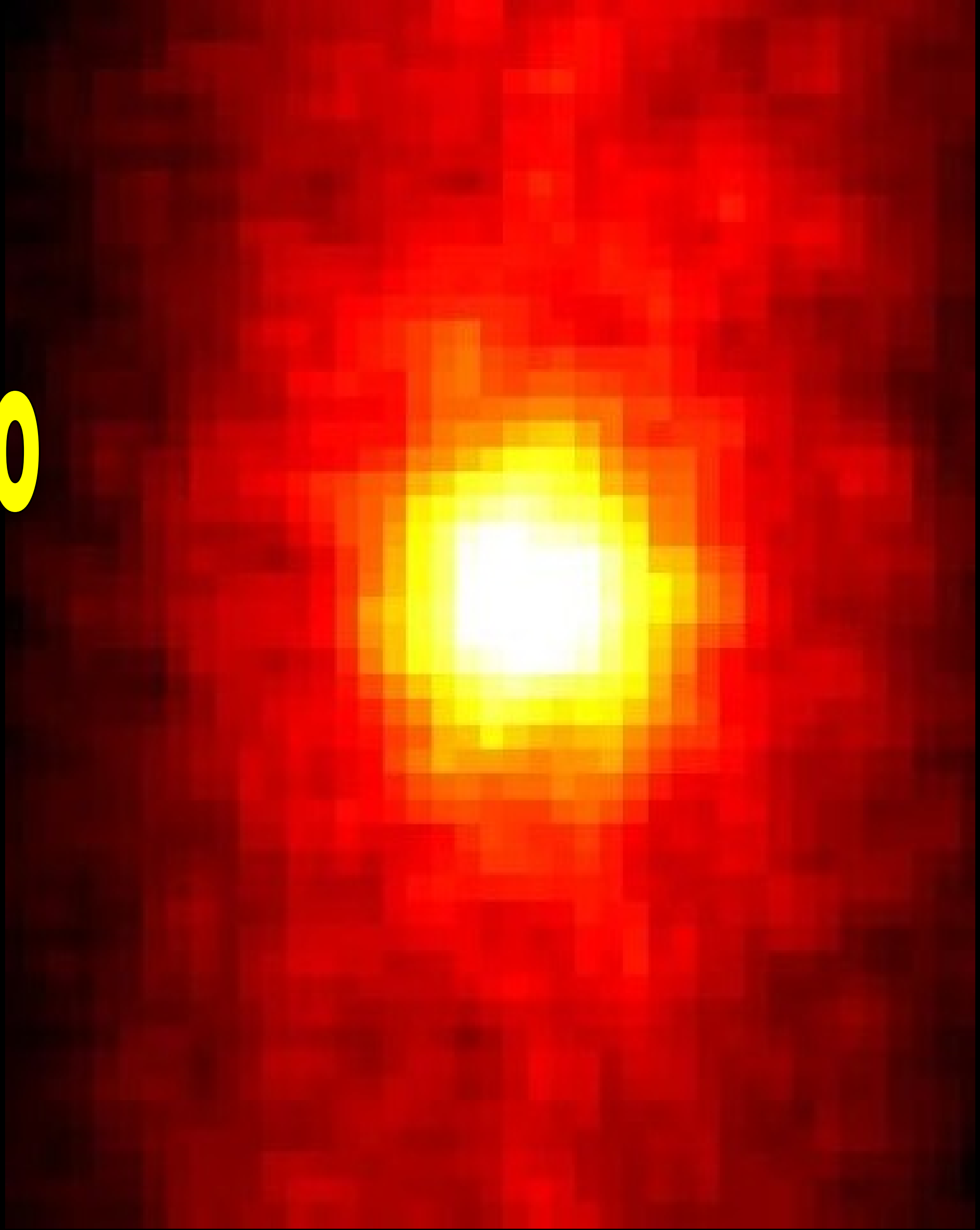
Solar Neutrinos: status and prospects

Outline:

- Status of the solar neutrino studies
- Oscillations in the Earth and oscillation tomography
- Perspectives

A. Y. Smirnov, Solar neutrinos and matter effects. p. 149 - 209. In "The state of the Art of Neutrino physics". World Scientific, 2018

Status of Solar neutrino Studies



in the first approximation

Good agreement between

SSM

New SSM

Metallicity problem

SOHO: g-modes detection → Fast rotation of solar core

LMA MSW

Oscillations in matter of the Earth

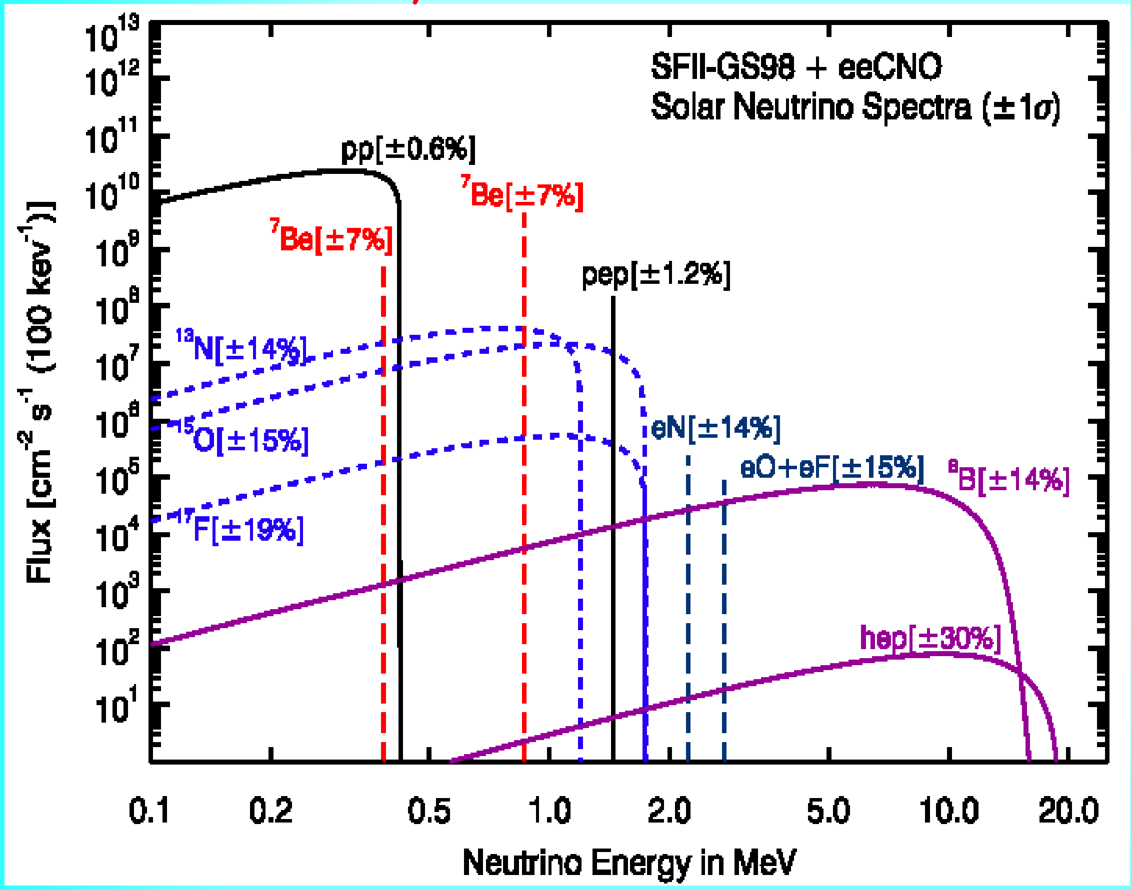
Experimental results

BOREXINO Phase-II

Super-Kamiokande updates

Solar neutrino spectrum

A. Serenelly



pp-, N-, O- asymmetric with sharp decrease after maximum

Be-, Hep – symmetric spectra due to final state

Solar metallicity problem

New 3D models of solar atmosphere (include effects of stratification, inhomogeneities ,etc)

→ Better agreement with absorption line shapes

→ Consistent with observations of neighboring stars

↓

Predict 40% lower abundances of heavy elements (heavier than ^4He) in photosphere

↓

Lower the temperature and density gradients → profiles

↓

Disagreement with helioseismology

Reduces the central temperature of the Sun

Affects solar neutrino fluxes

Be: -10%   B: -20%   N, O: -40%

pp: +...%   → to satisfy the luminosity constraint

Neutrino fluxes

N. Vinyolis et al,
1611.09867 astro-ph.SR

Models with high and low metallicities

Flux	GS98	AGSS09met	Experiment
pp	5.98 (1 +/- 0.006)	6.03 (1 +/- 0.005)	5.97 (1+0.006/-0.005)
pep	1.44 (1 +/- 0.01)	1.46 (1 +/- 0.009)	1.45 (1+0.009)
hep	7.98 (1 +/- 0.30)	8.25 (1 +/- 0.30)	19 (1+0.63/-0.47)
^{7}Be	4.93 (1 +/- 0.06)	4.50 (1 +/- 0.06)	4.80 (1+0.050/-0.046)
^{8}B	5.46 (1 +/- 0.12)	4.50 (1 +/- 0.12)	5.16 (1+0.025/-0.017)
^{13}N	2.78 (1 +/- 0.15)	2.04 (1 +/- 0.14)	< 13.7
^{15}O	2.05 (1 +/- 0.17)	1.44 (1 +/- 0.16)	< 2.8
^{17}F	5.29 (1 +/- 0.20)	3.26 (1 +/- 0.18)	< 85

pp: × 10^{10} cm^{-2} s^{-1} pep, ^{13}N, ^{15}O: × 10^{8}

^{7}Be : × 10^{9} ^{8}B, ^{17}F: × 10^{6} hep: × 10^{3}

Before BOREXINO phase II release

Testing Flux- Luminosity relation

$$F_\nu = \frac{2\,L_{sun}}{Q - 2\langle E\rangle}$$

$Q = 26.73$ MeV

$$\langle E\rangle = \Sigma_i\, E_i \frac{F_i}{F^{tot}} = 0.265 \text{ MeV}$$

$F^{tot} = \Sigma_i\, F_i$

Test of the relation – test of assumptions

1. Photon diffusion time: $t_{diff} \sim 10^5$ years →

   $F_\nu(t_0)$ ⇔ $L_{sun}(t_0 + t_{diff})$

   The present luminosity can be used if changes in the energy release and diffusion parameters can be neglected

2. No additional sources of energy exist.
3. Fraction of unterminated chains is negligible.

Presently $L_{sun}^{inf} / L_{sun} = 1.03 \pm 0.08$ *A. Serenelli*

g - modes and core rotation

E Fossat et al, A&A 604, A40 (2017)

of the Sun's oscillations - driven by gravity with buoyancy as restoration force

SOHO, GOLF 16.5 years data, observation via modulation of the p-(pressure) modes by g-modes.

Mean rotation rate of core | 3.8+/- 0.1 | X | mean rotation rate of the radiative envelope

1644+/-23 nHz (T = 7days)

Difficult to explain by models describing a pure angular momentum evolution without adding new dynamical processes (e.g. internal magnetic breaking at earlier)

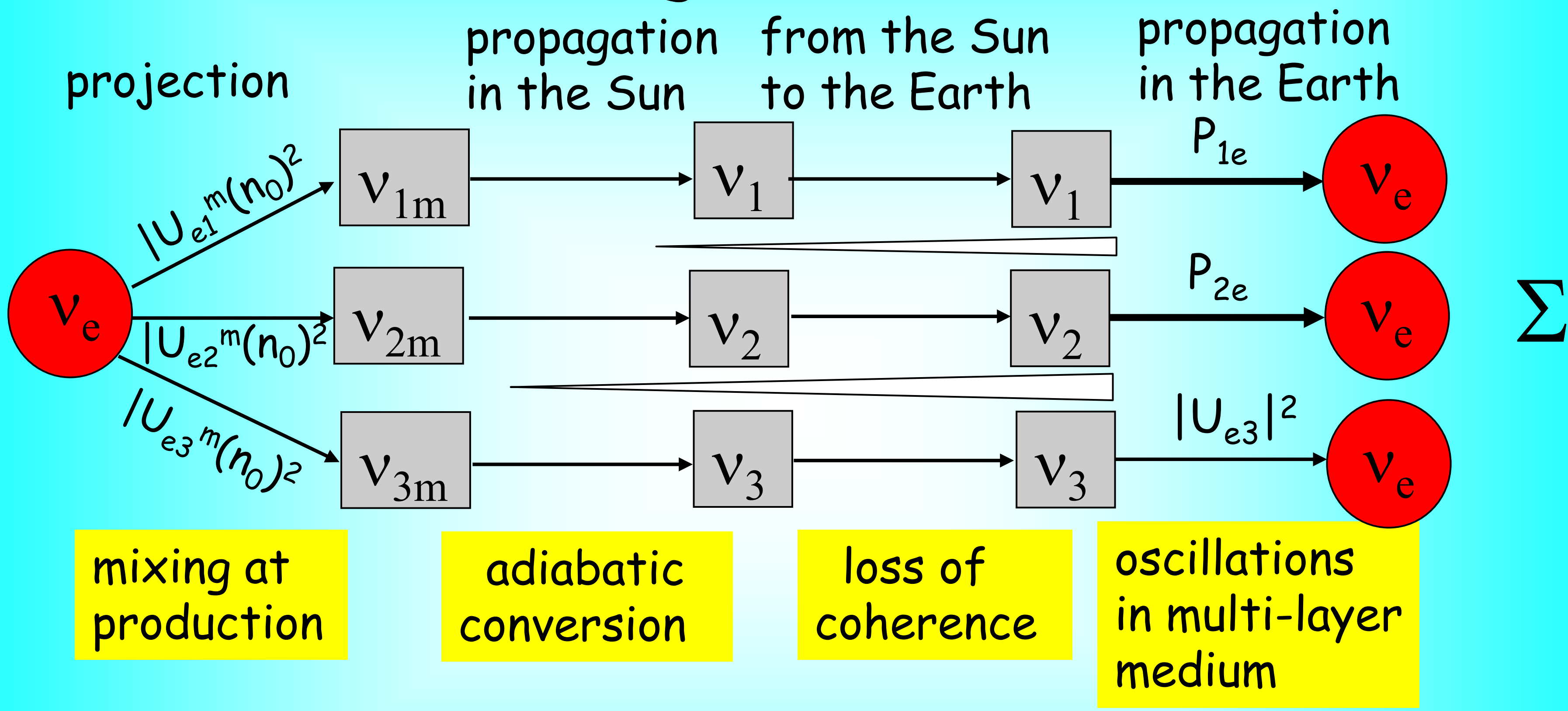
implications

Change of SSM in substantial way → Affect neutrino fluxes

Rotation → diffusion of elements in core → lower neutrino fluxes??

New problem or a way to resolve existing problems?

LMA-MSW physics



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

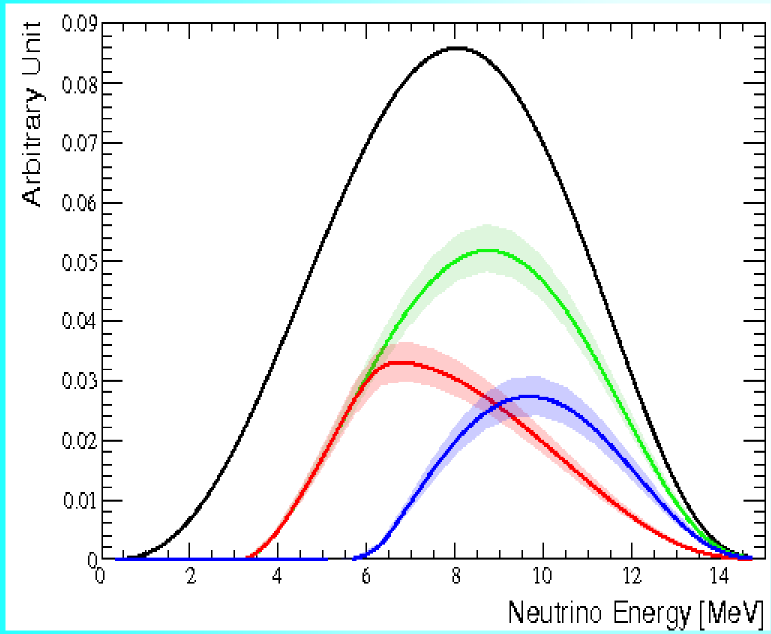
during a day $P_{ie} = |U_{ei}|^2$

Scale invariance:
no dependence on
distance, phase...

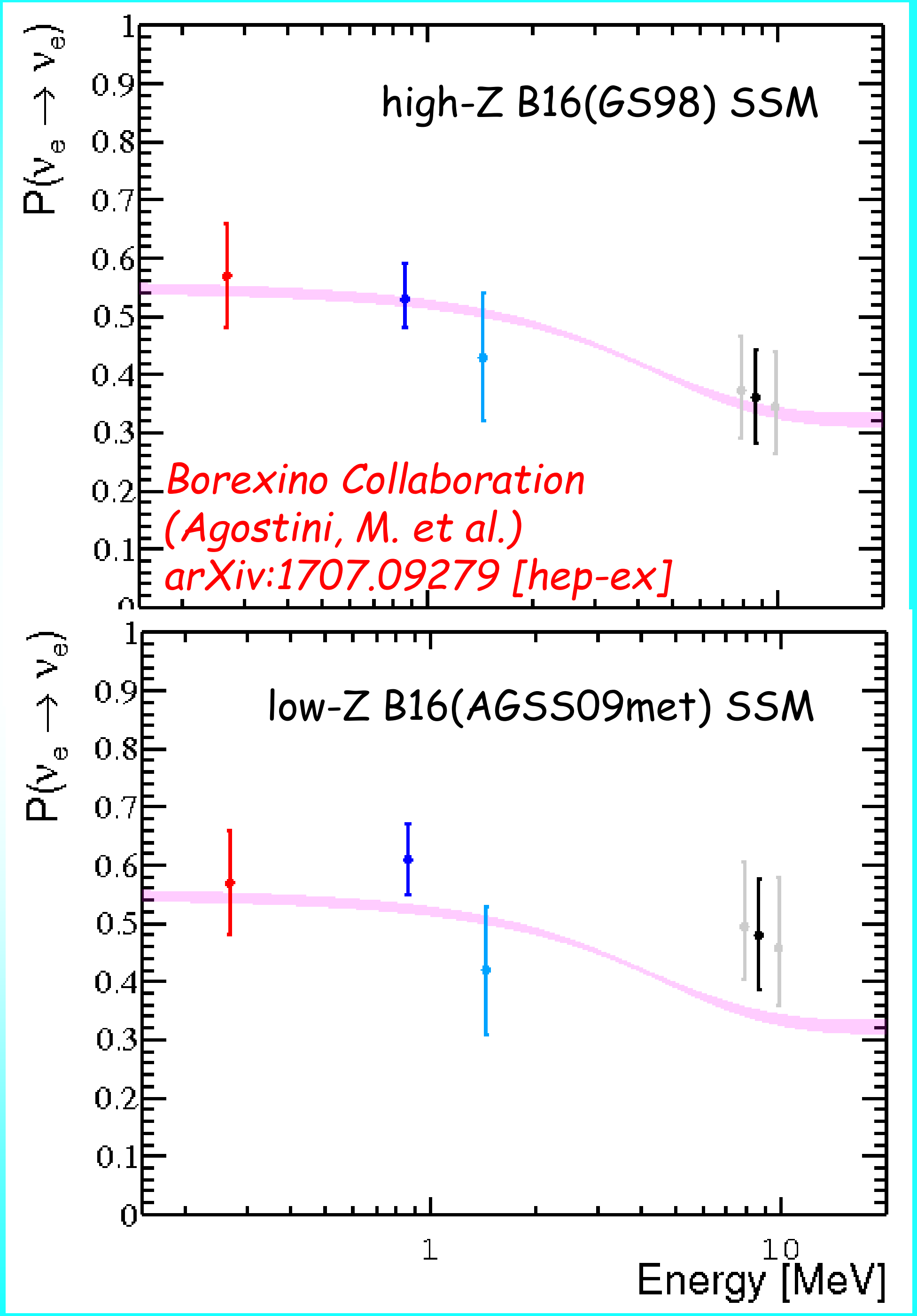
BOREXINO-II

8B spectrum with 1.5 kton y exposure

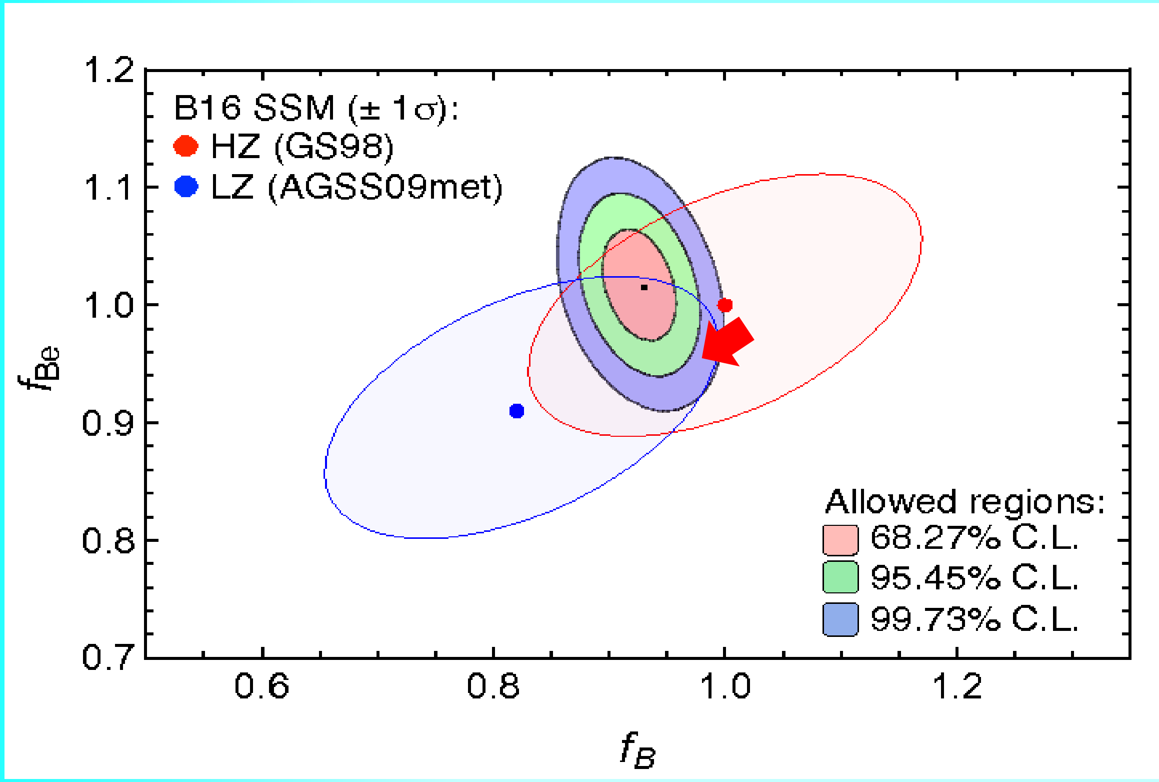
Borexino Collaboration
(Agostini, M. et al.) 1709.00756 [hep-ex]



the portions of the nu spectrum contributing to the LE (red), HE (blue), and LE+HE (green) energy windows used in the analysis.



Distinguishing metallicity models with neutrinos



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

Theoretical uncertainties should be reduced

LZ is disfavored at 3.1σ level

with new models

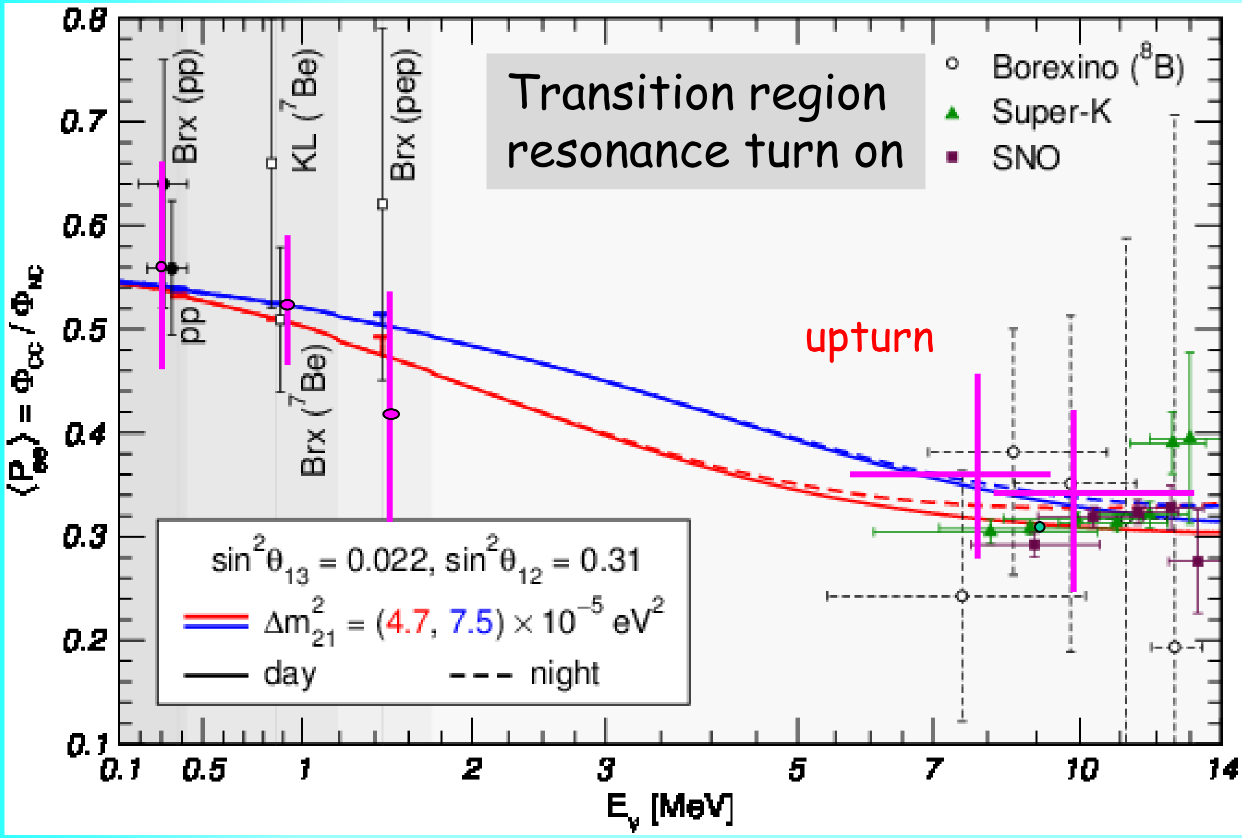
A. Di Leva

Allowed contours obtained by combining the new result on 7Be ν's with solar and KamLAND data. $\sin^2\theta_{13} = 0.02$

BOREXINO spectroscopy

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

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



LMA MSW predicion for two different values of Δm_{21}^2

best fit value from solar data

best global fit

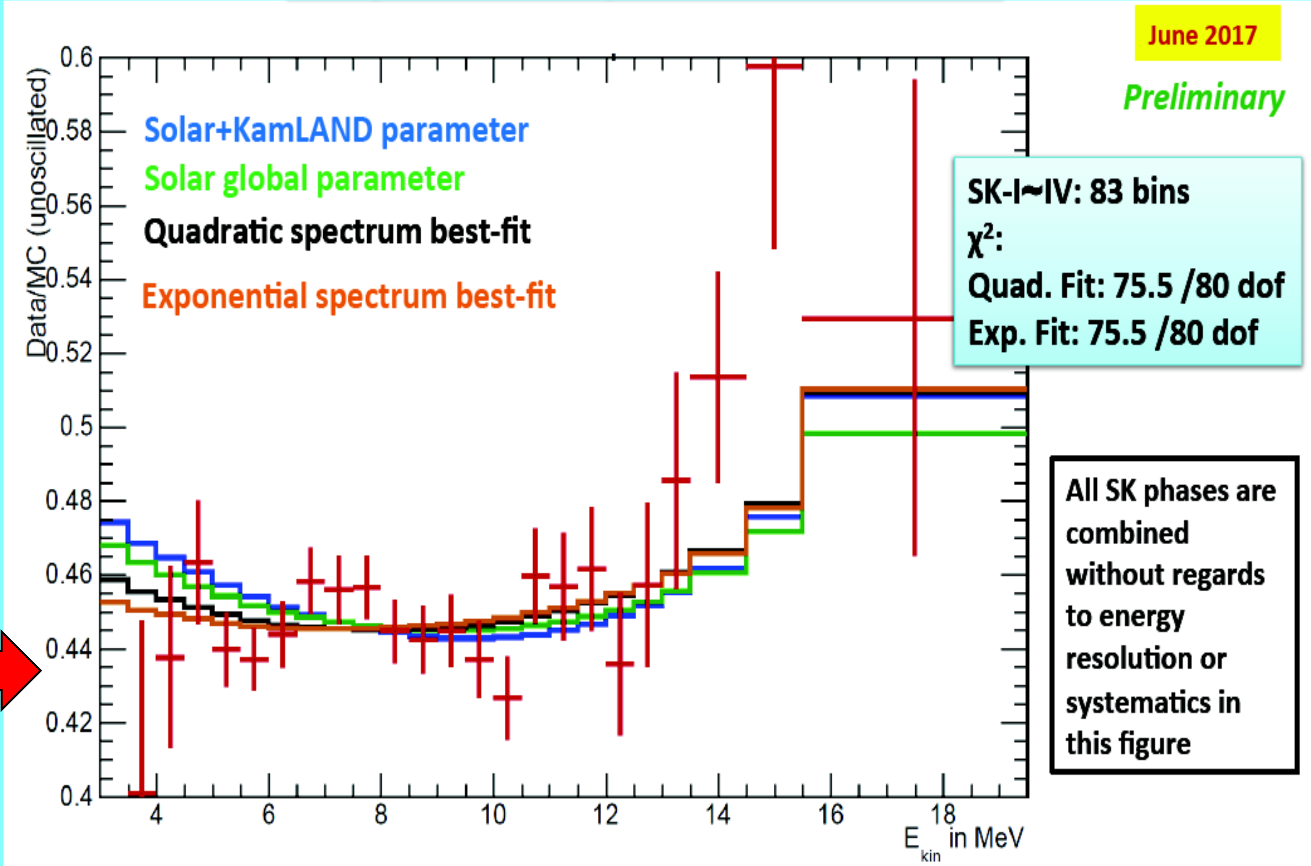
Reconstructed exp. points for SK, SNO and BOREXINO at high energies

BOREXINO

pp: agreement with global fit result
Be: higher accuracy
pep: (phase I + phase II – ideal agreement)
B: 2 times smaller errors, upturn...

Precision measurements in 5 – 10 MeV

Super-Kamiokande spectrum



T. Yano. ICRC 2017

turn down?

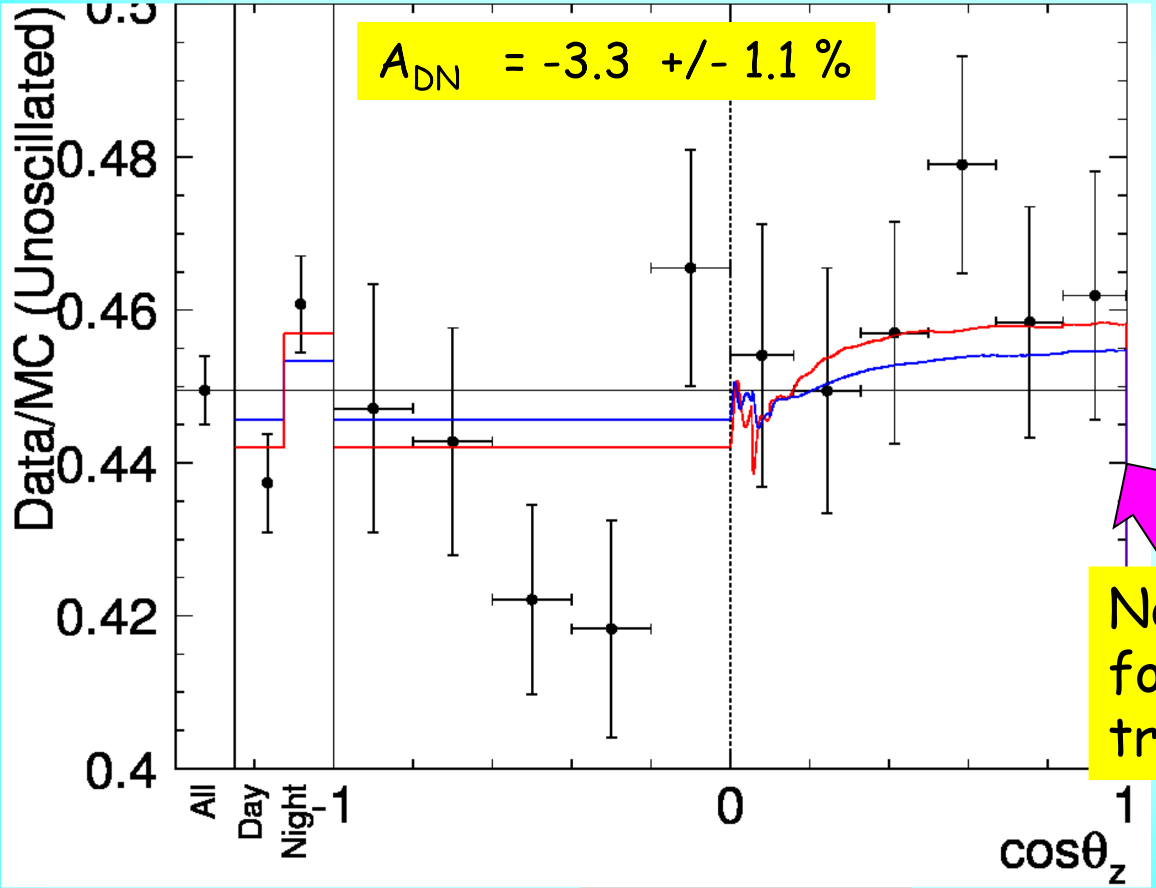
SK-IV 18 events/day + 280 days until march 17,
E = 3.5 – 19.5 MeV, SK I – IV total 5480 days

Data/MC(no-osc) = 0.4486 +/- 0.0062

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

Generic features:

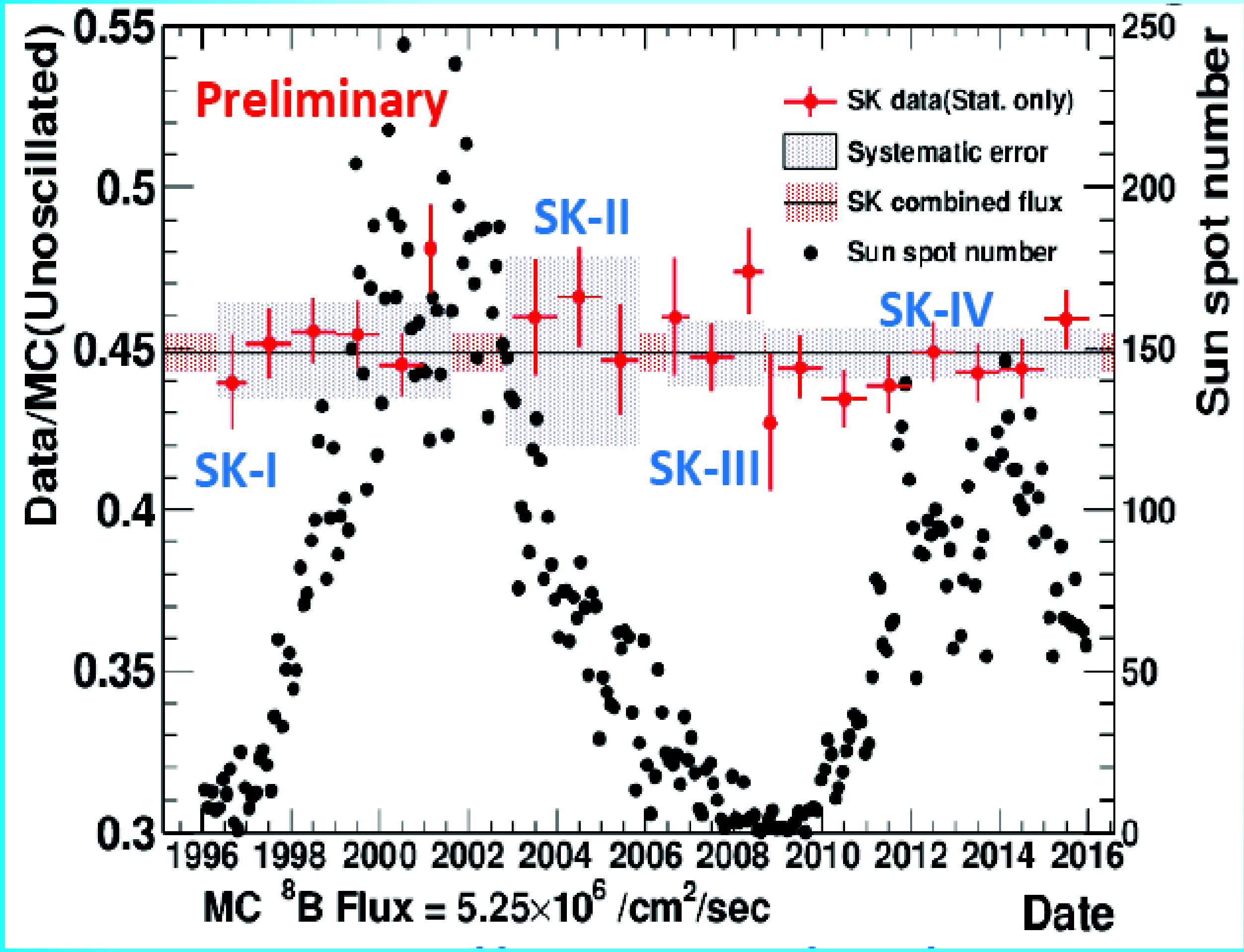
Oscillatory pattern

dip

Explained by the Attenuation effect

Super-Kamiokande

Y. Koshio



Compare with Homestake signal anti-correlations with solar activity

Related to lower Ar production rate?

Q_{Ar}^{LMA}= 3.1 SNU

Q_{Ar}^{Hom} = 2.56 +/- 0.25 SNU

Tensions

Absence of spectral upturn

SK, SNO, BOREXINO?

Large Day-night asymmetry

SK

M. Smy, SK improve sensitivity: reduce background to increase F.V.

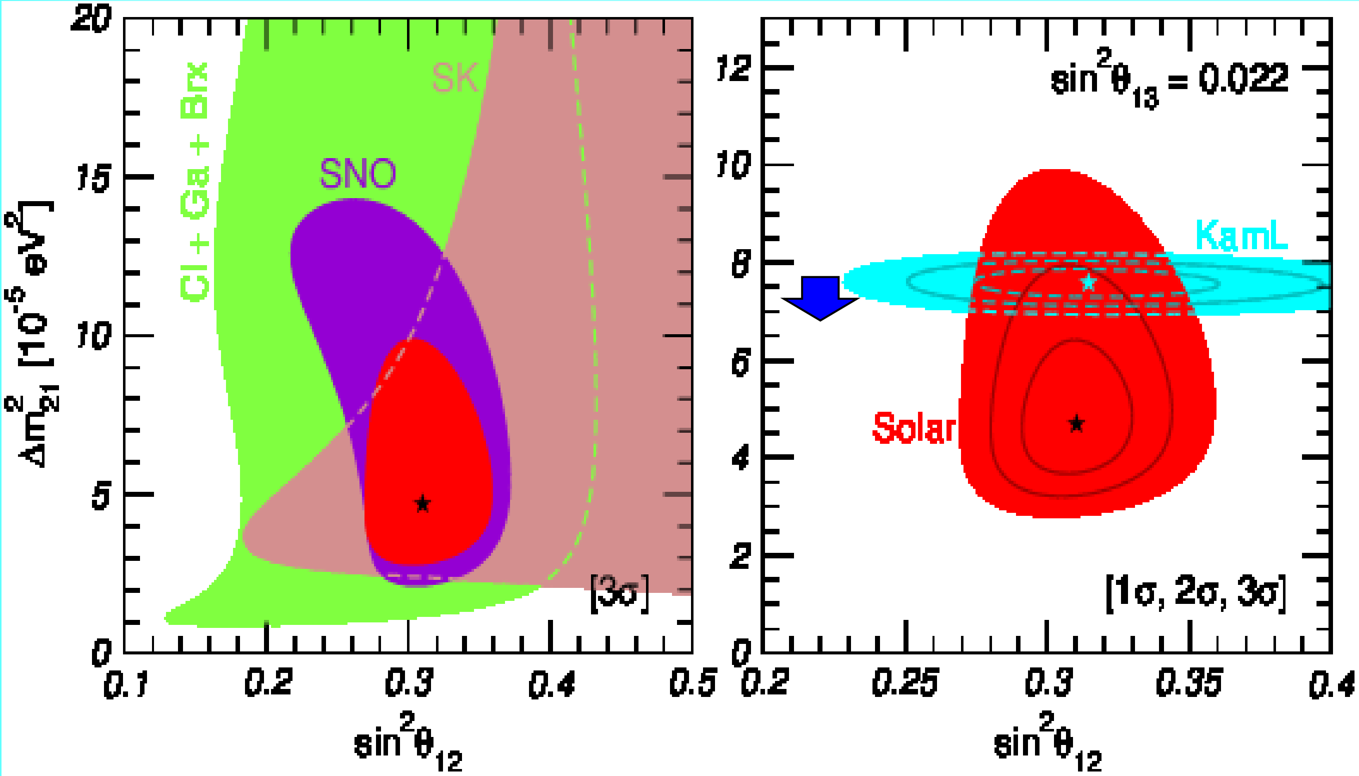
Different Δm_{21}^2 from solar and KamLAND

1.6 Larger V

$P = P(\Delta m_{21}^2 / V)$

Neutrino parameters

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



Red: all solar neutrino data

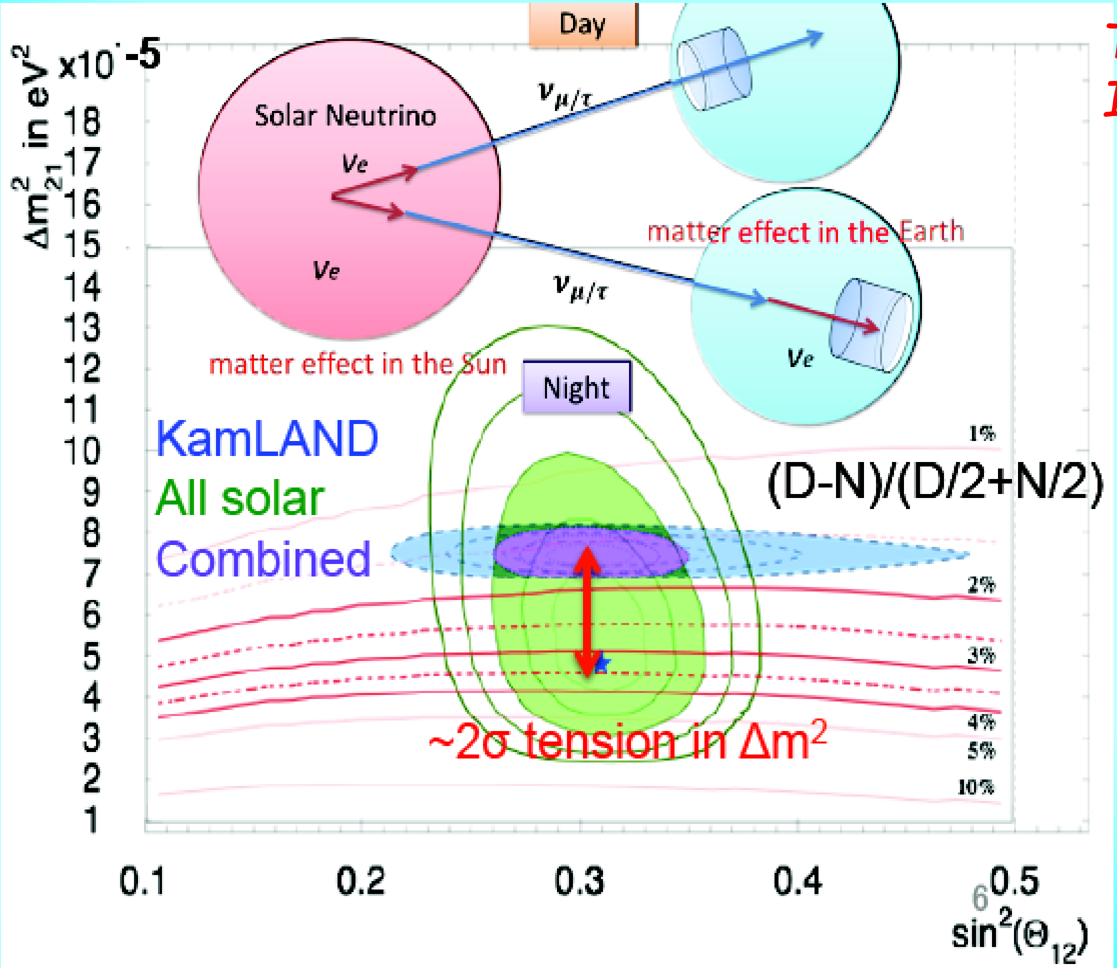
Δm^2_{21} (KL) > Δm^2_{21} (solar) 2 σ

KamLAND data reanalized in view of reactor anomaly (no front detector) bump at 4 -6 MeV

Δm^2_{21} decreases by 0.15 10^{-5} eV^2

SK analysis

similar result:

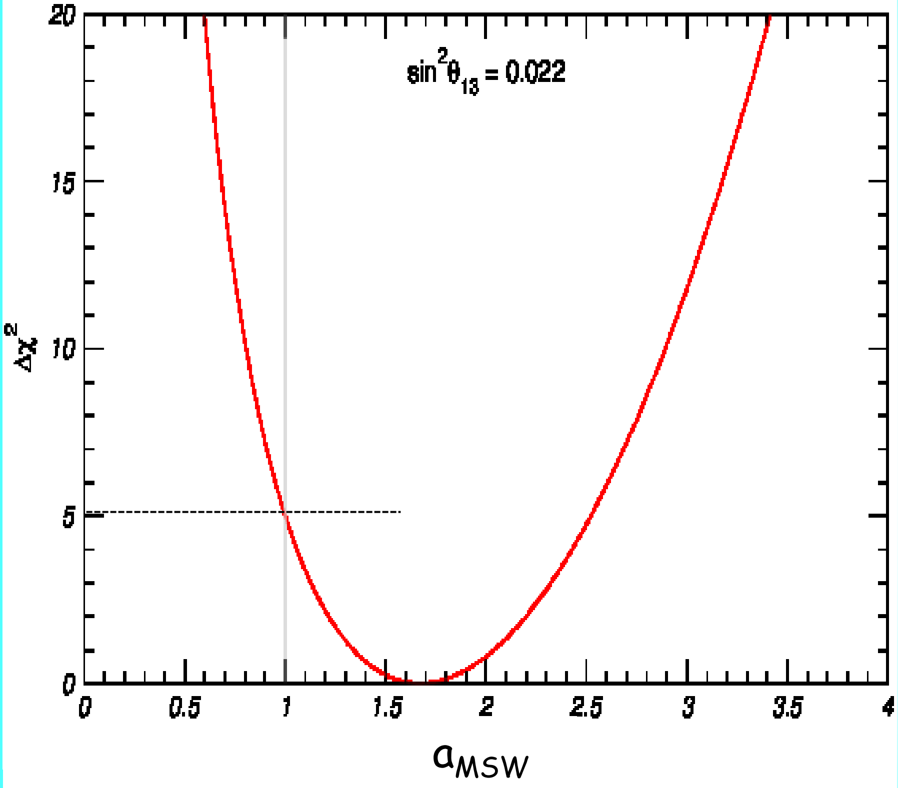


T. Yano.
ICRC 2017

M. Smy: improve
Sensitivity to D-N
Lower bkgr- increase
F.V for high energy
Solar meutrinos

Matter potential

G. L Fogli et al hep-ph/0309100
C. Pena-Garay, H. Minakata, hep-ph 1009.4869 [hep-ph]
M. Maltoni, A.Y.S. 1507.05287 [hep-ph]



$V = a_{MSW} V_{stand}$

$a_{MSW} = 0$ is disfavoured by > 15 σ

the best fit value $a_{MSW} = 1.66$

$a_{MSW} = 1.0$ is disfavoured by > 2 σ

related to discrepancy of Δm^2_{21} from solar and KamLAND:

$$\frac{\Delta m^2_{21}\,(KL)}{\Delta m^2_{21}\,(Sun)} = 1.6$$

Determination of the matter potential from the solar plus KamLAND data using a_{MSW} as free parameter

Potential enters the probability in combination

$$\frac{V}{\Delta m^2_{21}}$$

KamLAND and bump

M. Maltoni 2017

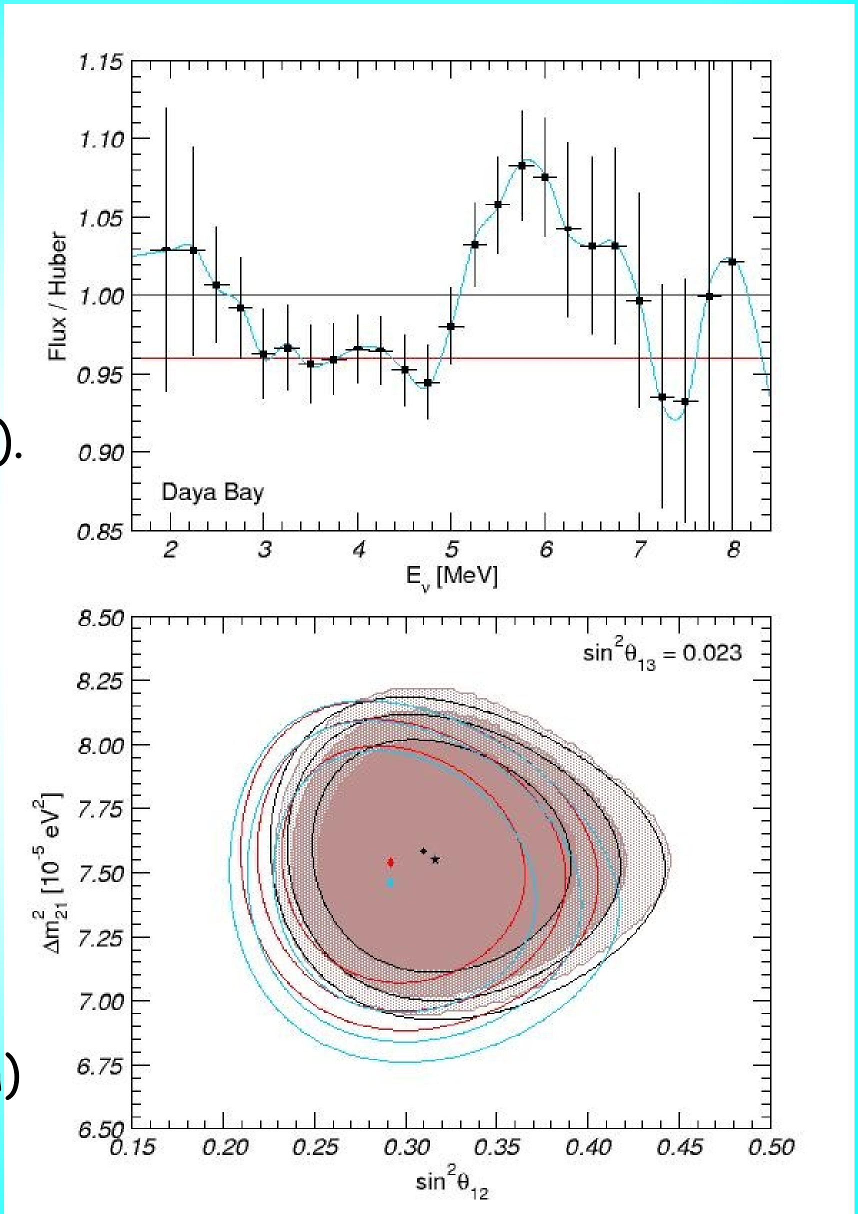
Subtracting 5 MeV bump

Different flux assumptions:
- Huber (black),
- Huber reduced by 4% (red),
- Daya-Bay (cyan) measurements of the reactor spectrum (arXiv:1607.05378) (syan).

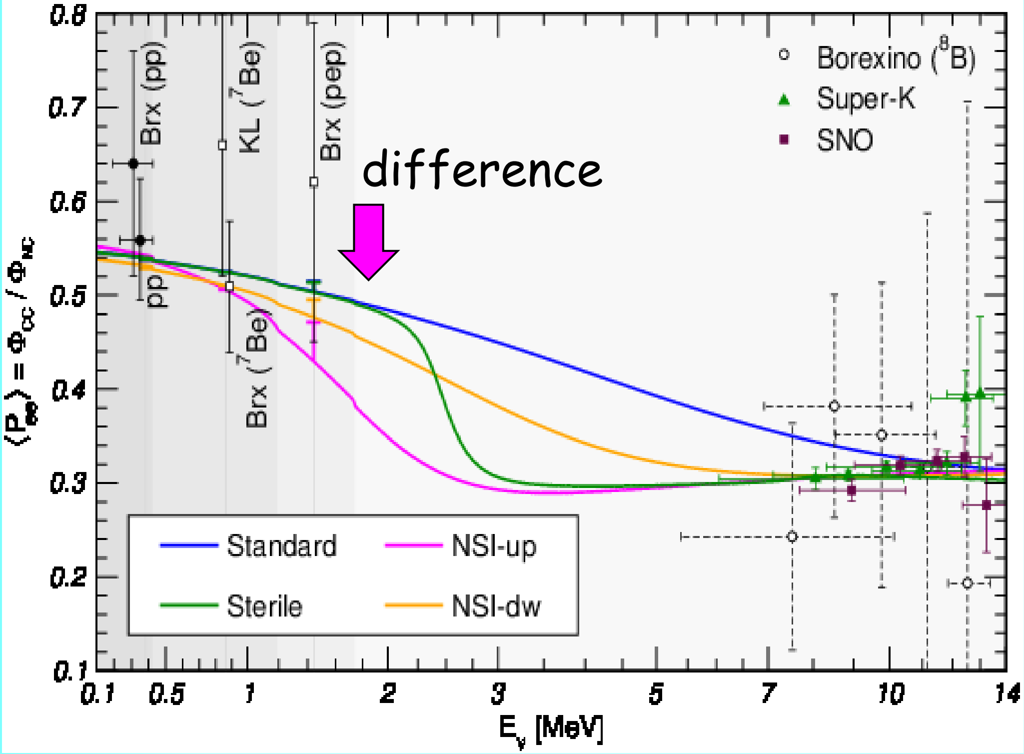
- The shaded brown areas - the KamLAND 2013 matched well the fit with Huber's fluxes (black).

- Reducing the flux by 4% (red) induces a shift of the region to lower theta12: the lower flux is compensated larger probability .

- Inclusion of the Daya-Bay spectrum (cyan) with the 5-MeV bump leads to extension of the KamLAND region to lower dmqSL. The tension with solar slightly reduced



New physics effects



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

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

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

How things may develop

Solar value of Δm_{21}^2 7×10^{-5} eV^2 (before 2010) was reduced after SK data on D-N asymmetry and measurements of spectrum

JUNO: precise measurements of Δm_{21}^2 with 0.7 -1% accuracy

$\sigma(\Delta m_{21}^2) = (0.05 - 0.07) \times 10^{-5}$ eV^2

Difference of solar and KamLAND

$\Delta(\Delta m_{21}^2) = 2.5 \times 10^{-5}$ eV^2

If

$\Delta m_{21}^2(\text{JUNO}) = \Delta m_{21}^2(\text{solar})$ problem solved

$\Delta m_{21}^2(\text{JUNO}) = \Delta m_{21}^2(\text{KL})$ problem sharpens

Stronger bounds on NSI from COHERENT and other experiments

SNO+ spectrum measurements above 3 MeV (testing upturn)

Hyper-Kamiokande

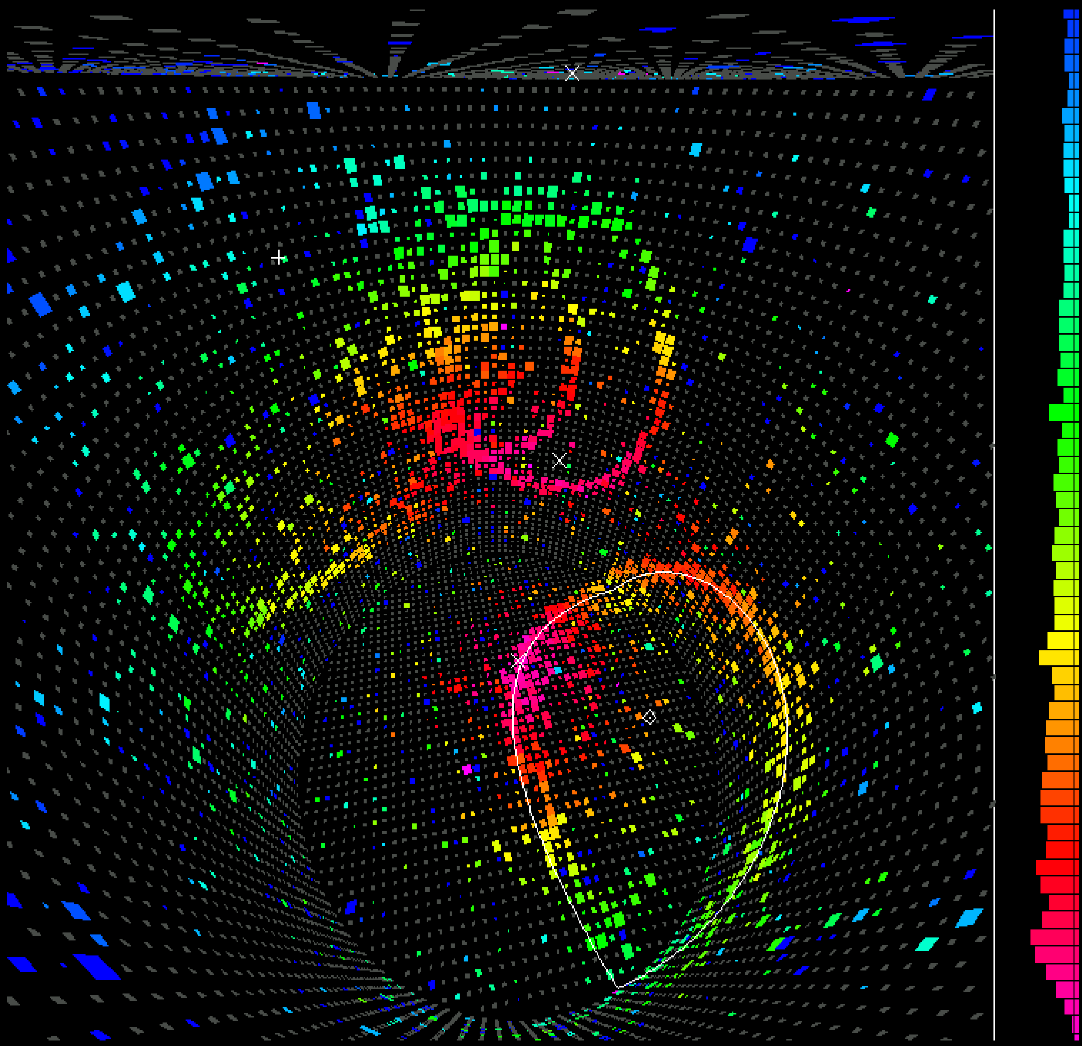
Day-night asymmetry

spectrum

DUNE

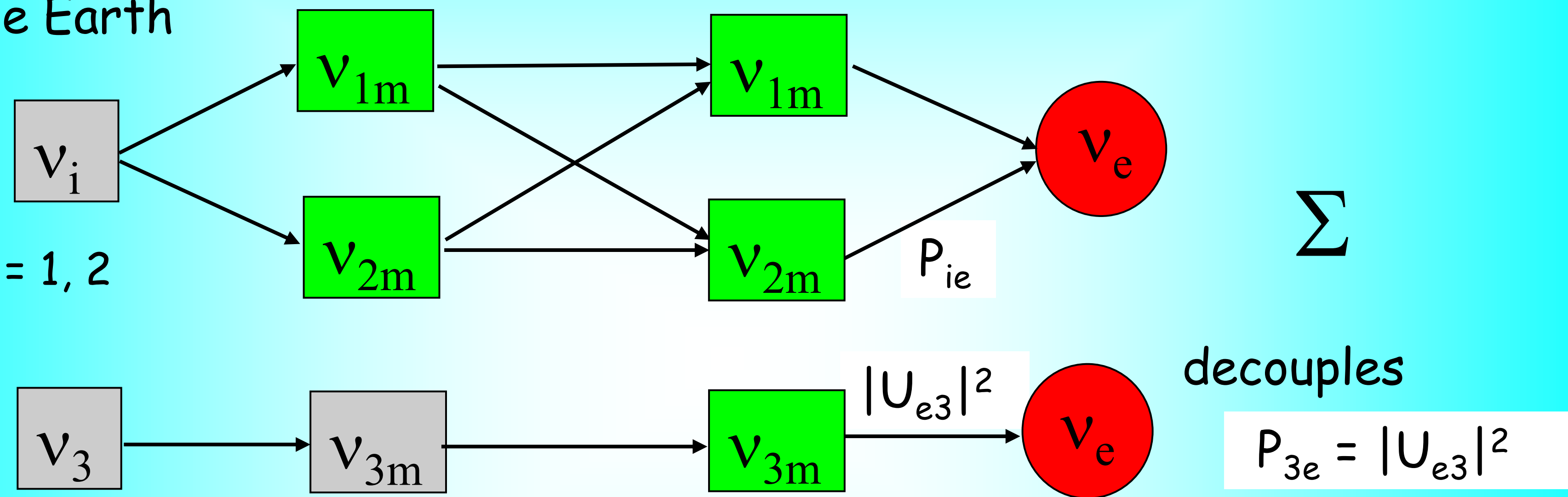
J. Beacom

Oscillations in the Earth and Oscillation tomography



Oscillations in the Earth

surface of the Earth | propagation in the Earth | detector



Projection mixing of mass states

mixing at Production in the Sun

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

oscillations in multi-layer medium

Adiabaticity violation at the border between layers

Projection flavor mixing

Oscillations in the Earth

Incoherent fluxes of mass state arrive at the Earth.
They split into eigenstates in matter and oscillate.

Mixing of the mass states in matter

$$U^{mass} = U_{PMNS}^{+} U^{m}$$

For 2ν case

$$\sin 2\theta' = \frac{c_{13}^2 \varepsilon \sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - c_{13}^2 \varepsilon)^2 + \sin^2 2\theta_{12}}} = c_{13}^2 \varepsilon \sin 2\theta_{12}^m$$

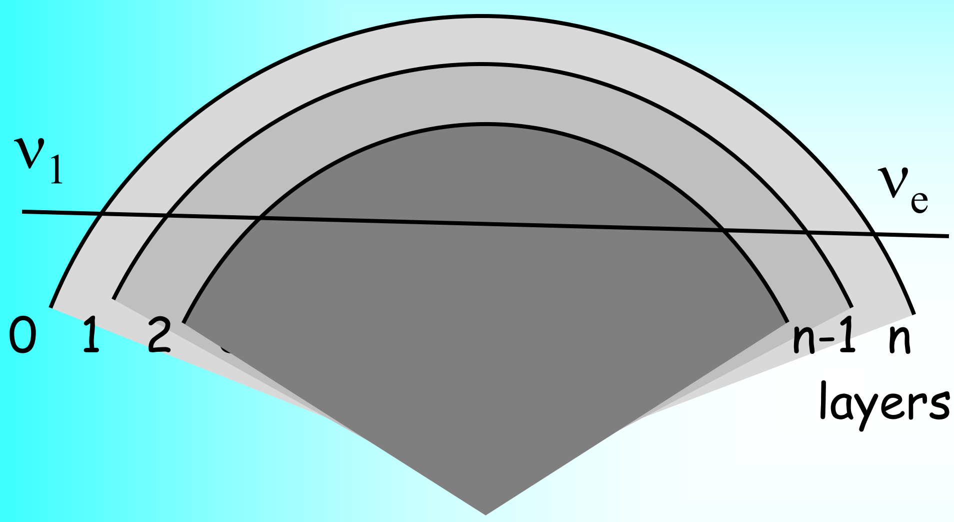
$$\varepsilon = \frac{2VE}{\Delta m_{21}^2} = 0.03\, E_{10}\, \rho_{2.6}$$

determines smallness of effects
Low density regime

MeV g/cm^3

Regeneration

A. Ioannisian, A. Smirnov, D. Wyler,
Phys.Rev. D96 (2017) no.3, 036005
arXiv:1702.06097 [hep-ph]



Layers with slowly changing density and density jump

Evolution matrix (matrix of transition amplitudes)

$$S = U^m{}_n \, \Pi_k \, D_k U_{k,k-1}$$

$U^m{}_n$ - flavor mixing matrix, projects onto flavor state in the end

D_k - describe the adiabatic evolution within layers

$$D_k = \mathrm{diag}\,(e^{-0.5i\phi_\kappa},\ e^{0.5i\phi_\kappa})$$

$$\phi_\kappa = \int dx (H_{2m} - H_{1m})$$

adiabatic phase acquired in k layer

$U_{k,k-1}$ - describes change of basis of eigenstates between k and k-1 layers

$$U_{k,k-1} = U(-\Delta\theta_{k-1})$$

$\Delta\theta_{k-1}$ -change of the mixing angle in matter after k-1 layer

...continued

~

$$P_{1e} = c_{13}^2 |S_{e1}|^2$$

due to transition to 3ν basis

Approximate (lowest order in ε) result

$$U_{k,k-1} \simeq I - i\sigma_2 \sin \Delta\theta_{k-1}$$

Inserting this expression into formula for S and taking the lowest order terms in $\sin\Delta\theta_{k-1} \sim \varepsilon$

$$P_{1e} \sim c_{13}^2 \cos^2\theta_n^f + c_{13}^2 \sin 2\theta_n^f \, \Sigma_{j = 0 \ldots n-1} \sin\Delta\theta_j \cos \phi_j^{after}$$

the 1-2 angle in matter near detector

sum over jumps

total phase acquired after jump j

$$\sin \Delta\theta_j \simeq c_{13}^2 \sin 2\theta_{12} \, \Delta V_j \, \frac{E}{\Delta m_{21}^2}$$

ΔV_j - j density jump

The lowest order plus waves emitted from different jumps

Integral formula

Substituting summation (with small spatial intervals) by integration:

$$f_{reg} = -\tfrac{1}{2}\, c_{13}^{4} \sin^2 2\theta_{12} \int_{x_0}^{x_f} dx\, V(x)\, \sin \phi^m(x \rightarrow x_f)$$

The phase acquired from the point x to the final point of trajectory (phase after)

Attenuation effect

A. Ioannisian, A. Y. Smirnov,
Phys.Rev.Lett., 93, 241801 (2004),
0404060 [hep-ph]

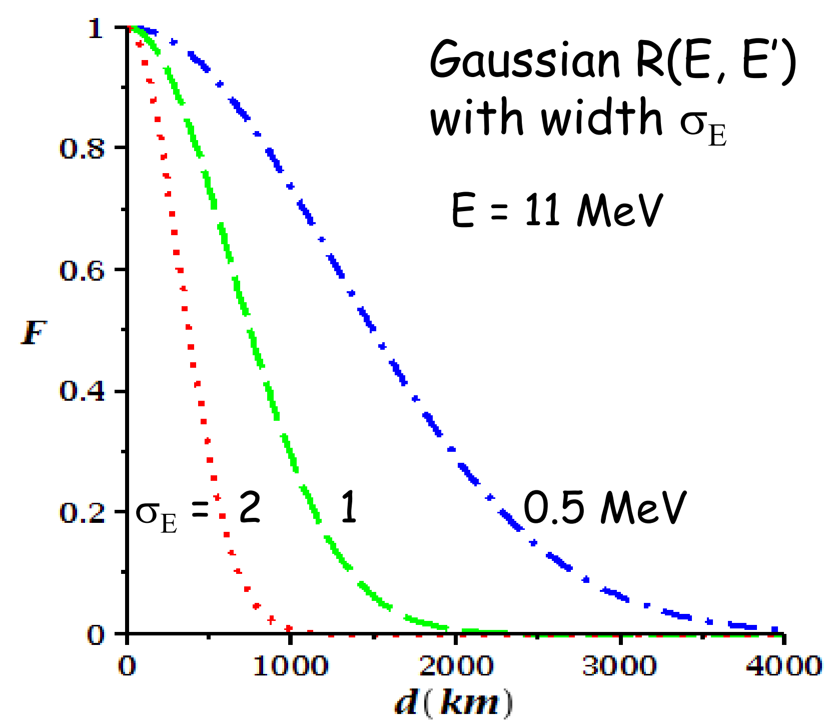
Integration with the energy resolution function R(E, E'):

$$\langle f_{reg} \rangle = \int dE' \, R(E, E') \, f_{reg}(E')$$

$$\langle f_{reg} \rangle = 0.5 \sin^2 2\theta \int_{x_0}^{x_f} dx \, F(x_f - x) \, V(x) \, \sin\Phi^m(x \rightarrow x_f)$$

F(d)

Attenuation factor



The sensitivity to remote structures d > λ_{att} is suppressed

Attenuation length

$$\lambda_{att} = l_\nu \frac{E}{\pi\sigma_E}$$

l_ν is the oscillation length

The better the energy resolution, the deeper structures can be seen

Attenuation and decoherence

A.N. Ioannisian, A. Yu. S.
Phys.Rev. D96 (2017) no.8, 083009, 1705.04252 [hep-ph]

The oscillation phase acquired along the attenuation length:

$$\phi = 2\pi \frac{\lambda_{att}}{l_\nu} = 2\pi \frac{E}{\pi\sigma_E}$$

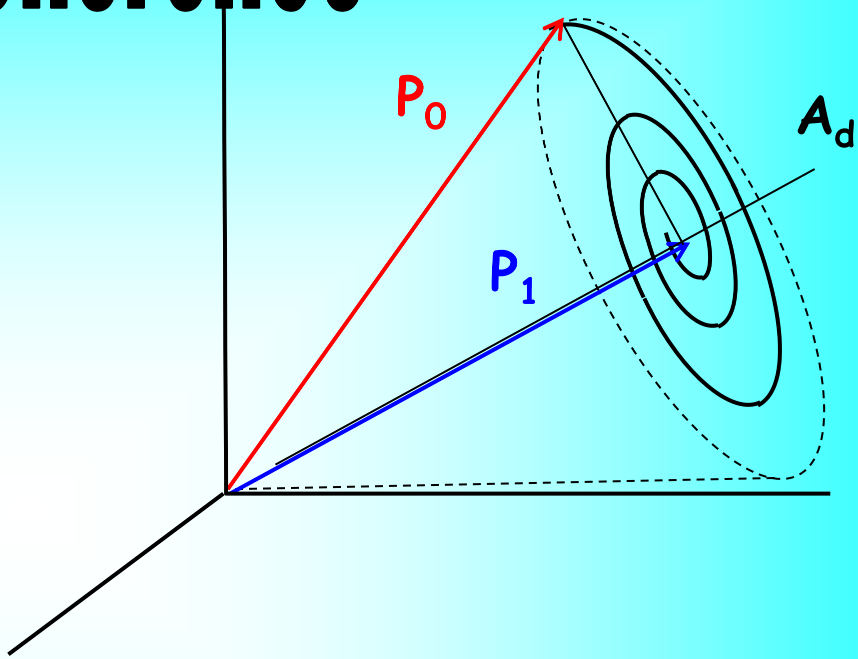
Difference of phases with ΔE

$$\Delta\phi = 2\pi \frac{\Delta E}{\pi\sigma_E}$$

For $\Delta E = \pi\sigma_E$ $\quad \Delta\phi = 2\pi$

- integration over the energy resolution interval leads to averaging of oscillations

- λ_{att} is the distance over which oscillations observed with the energy resolution σ_E are averaged



Averaging – loss of coherence

$P_0 \rightarrow P_1$

converges to its projection onto axis of eigenstates A_d

Paradoxes of attenuation

A.N. Ioannisian, A. Yu. Smirnov
Phys.Rev. D96 (2017) no.8, 083009
arXiv:1705.04252 [hep-ph]

Not only decoherence: effect does not disappear completely.
Even for very large distances: it survives in the ε^2 level

$\nu_1 \rightarrow \nu_e$ - channel

Remote structures are attenuated the ε^2 level;
near structures are seen at ε

$\nu_e \rightarrow \nu_1$ - channel

Near structures are attenuated the ε^2 level;
remote structures are seen at ε

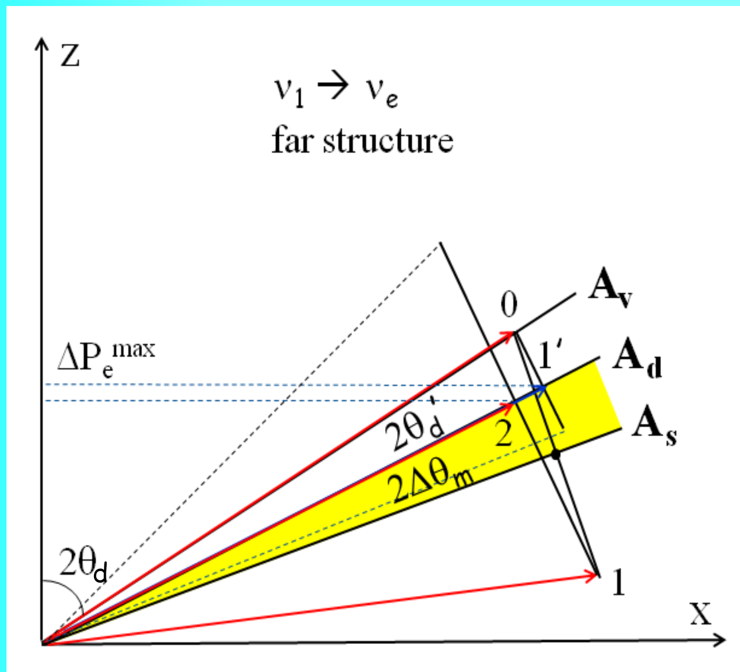
T-symmetry

Three layer case: first layer prepare incoherent states:
applications for flavor – flavor transitions

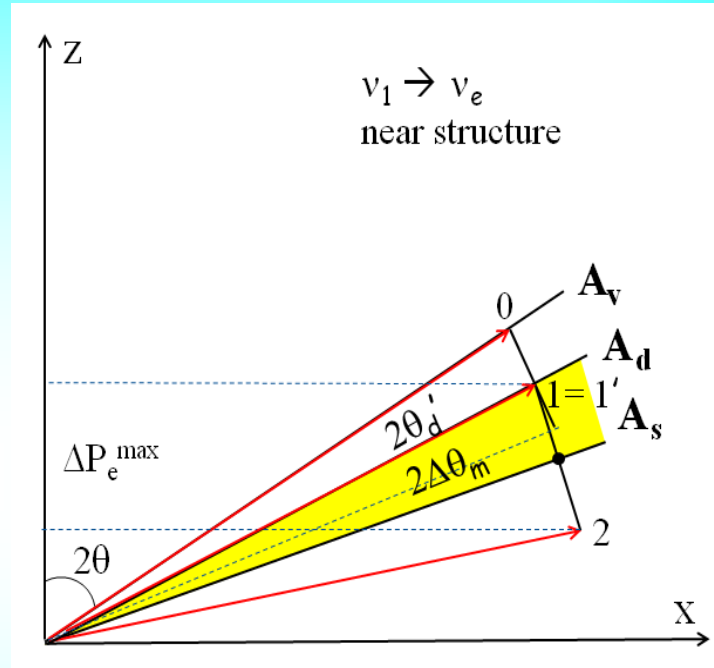
Attenuation and tomography

$2\Delta\theta_m = 2\theta_s' - 2\theta_d'$

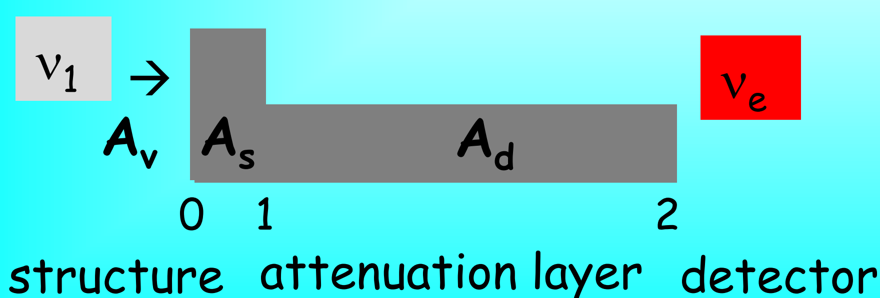
$J_m = \sin 2\Delta\theta_m \sim \varepsilon$



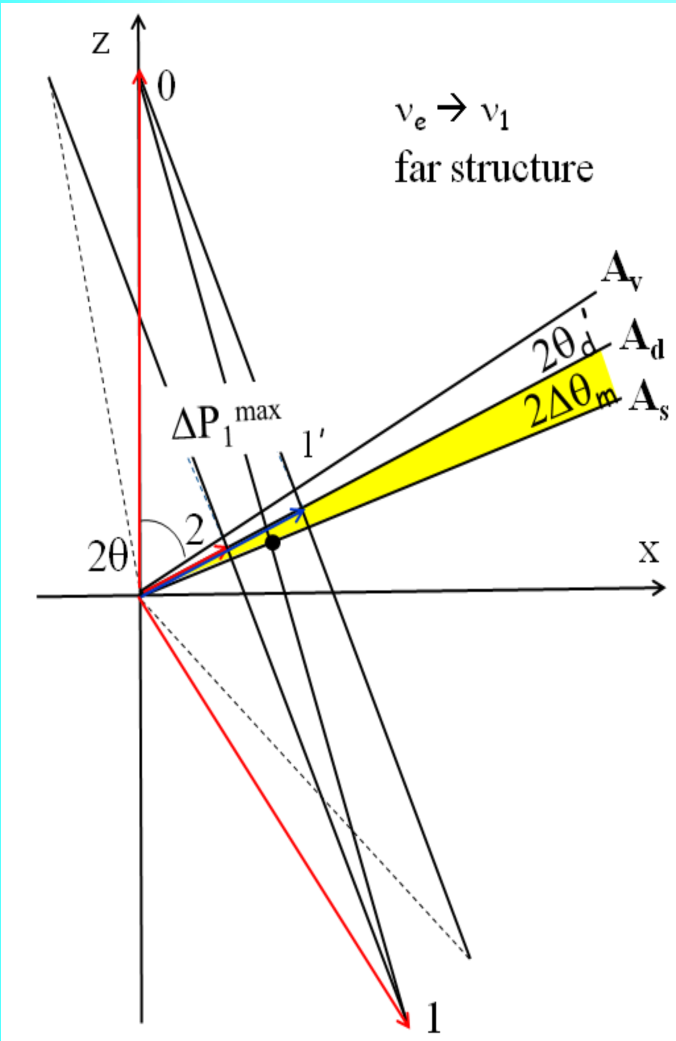
$\Delta P_e^{max} = \cos 2\theta_d \ \sin 2\theta_s' \, J_m \sim \varepsilon^2$

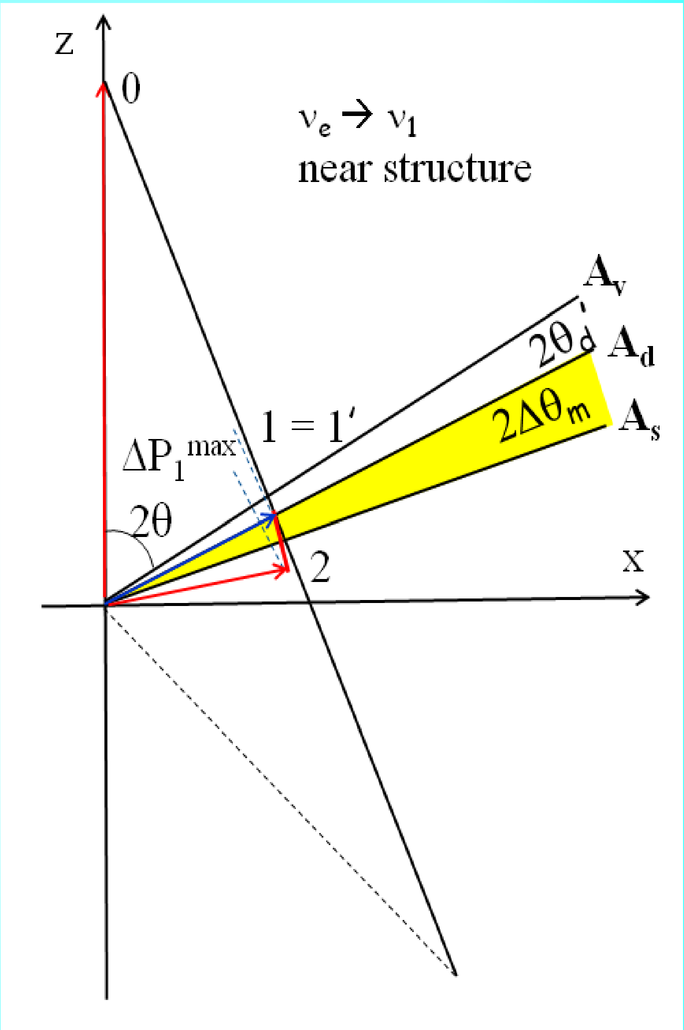


$\Delta P_e^{max} = \cos 2\theta_d' \, \sin 2\theta_s \, J_m \sim \varepsilon$



Attenuation

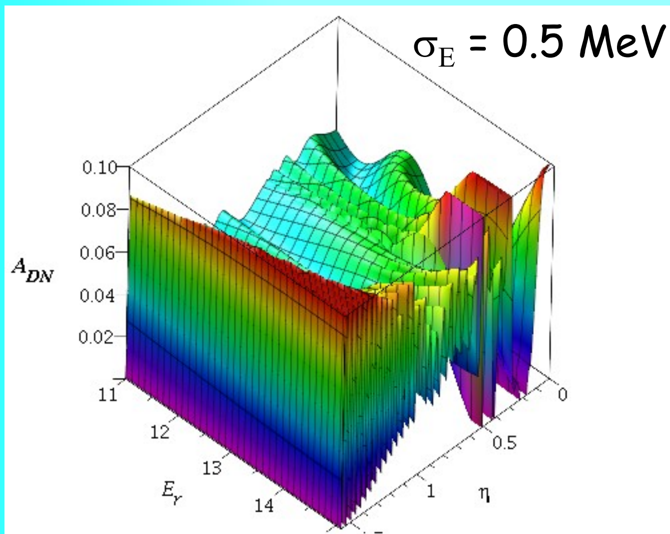


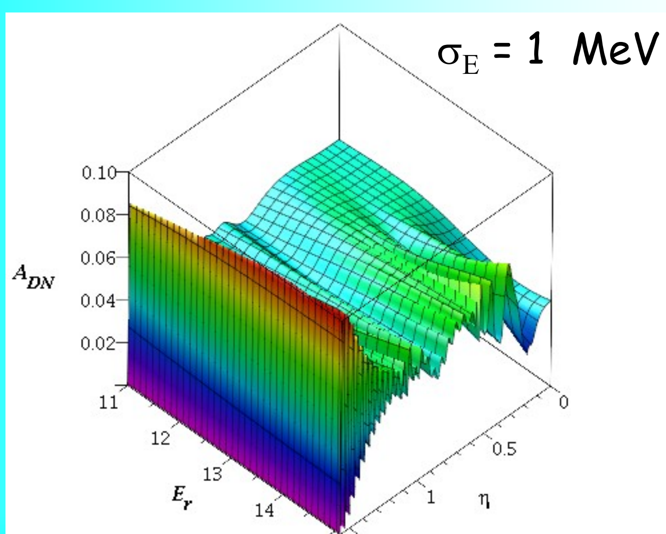


no attenuation

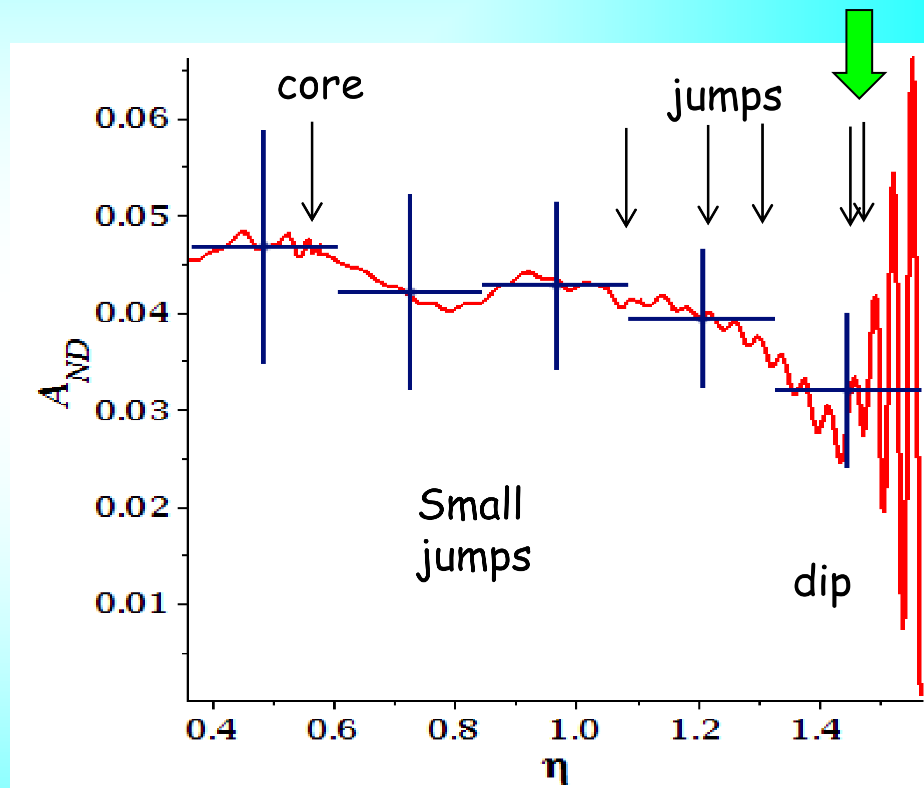
Relative D-N asymmetry

A. Ioannisian,
B. A.Y.S., D. Wyler
1702.06097 [hep-ph]





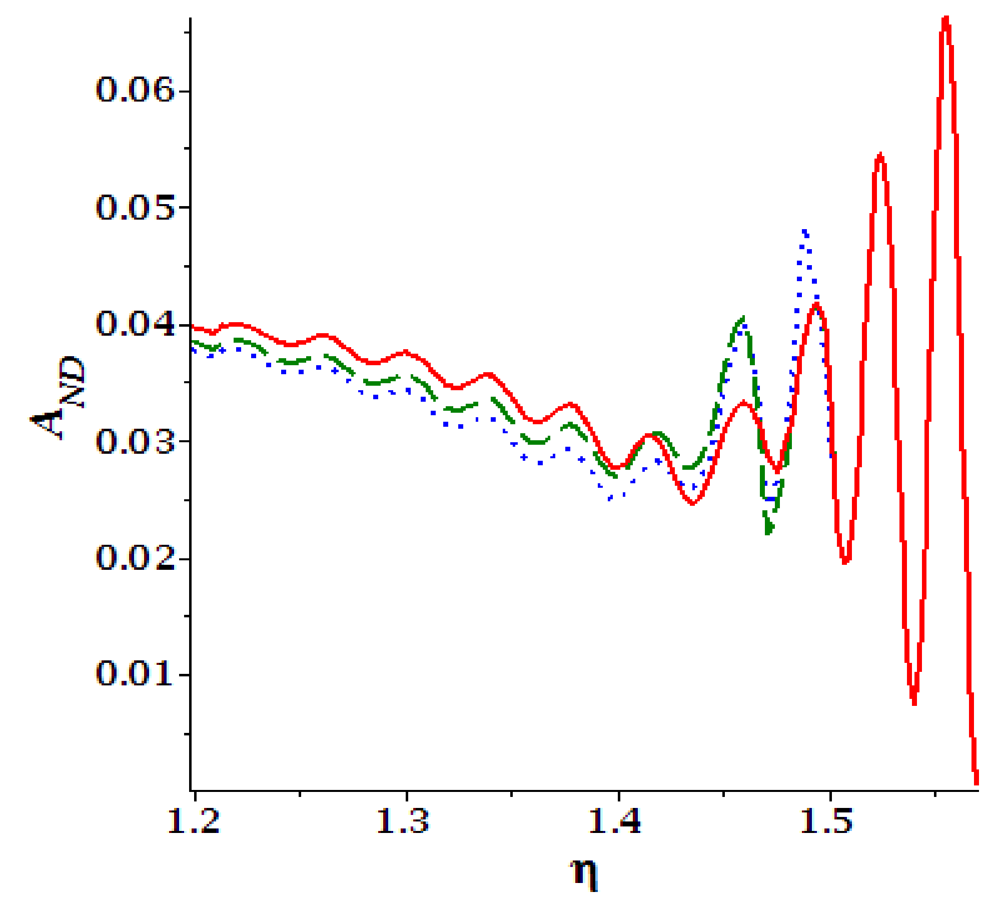
$$A_{DN} = \frac{N - D}{D}$$



Relative excess of the night events integrated over E > 11 MeV
Sensitivity of DUNE experiment
40 kt, 5 years

Tomography

A. Ioannisian, A. Smirnov, D. Wyler,
Phys.Rev. D96 (2017) no.3, 036005
arXiv:1702.06097 [hep-ph]



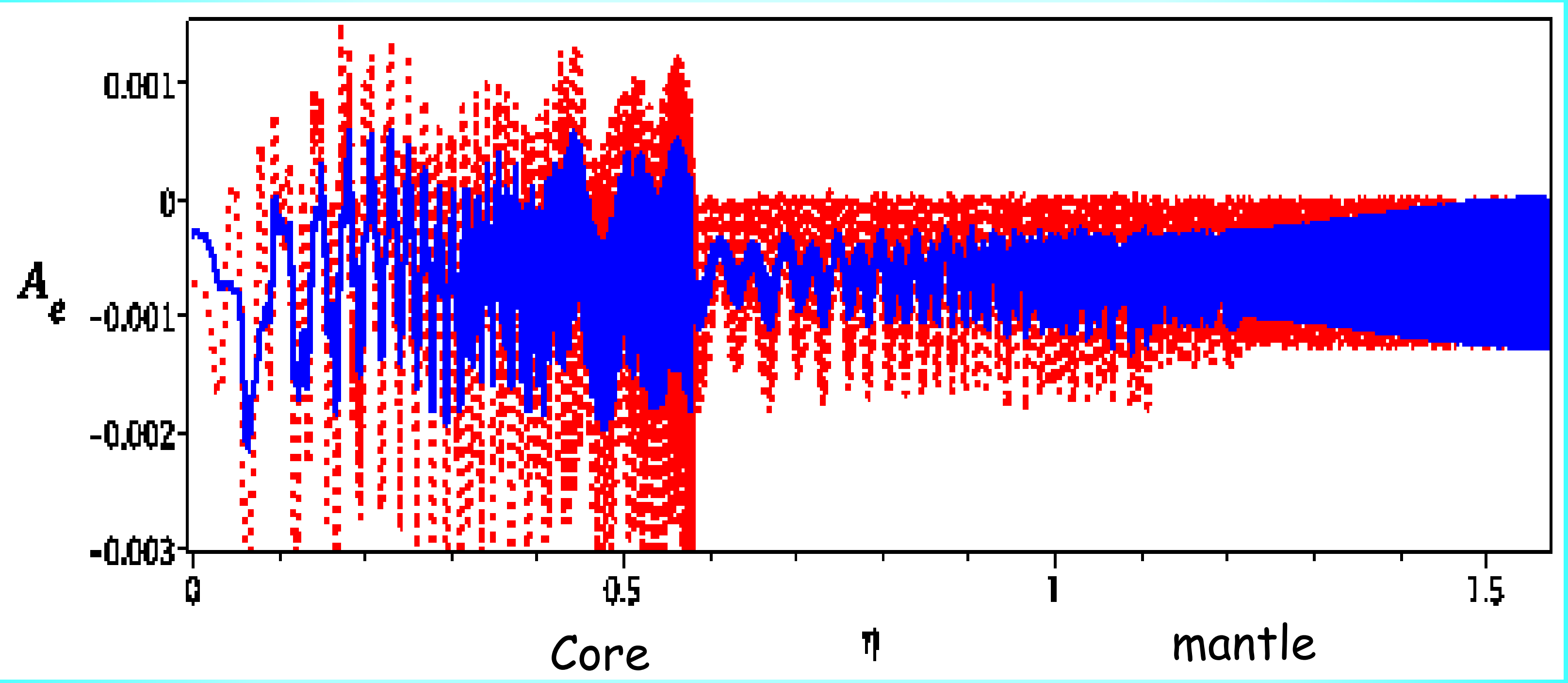
The relative excess of night events integrated over E > 11 MeV as function of the nadir angle for different positions of the density jumps. Jumps at

15 km and 25 km (red)
20.5 km and 30 km (blue dotted)
15 km and 30 km (green-dashed).

Parametric enhancement of oscillations is seen in the 3rd and 4th periods.

Variations of the ν_{Be}- flux

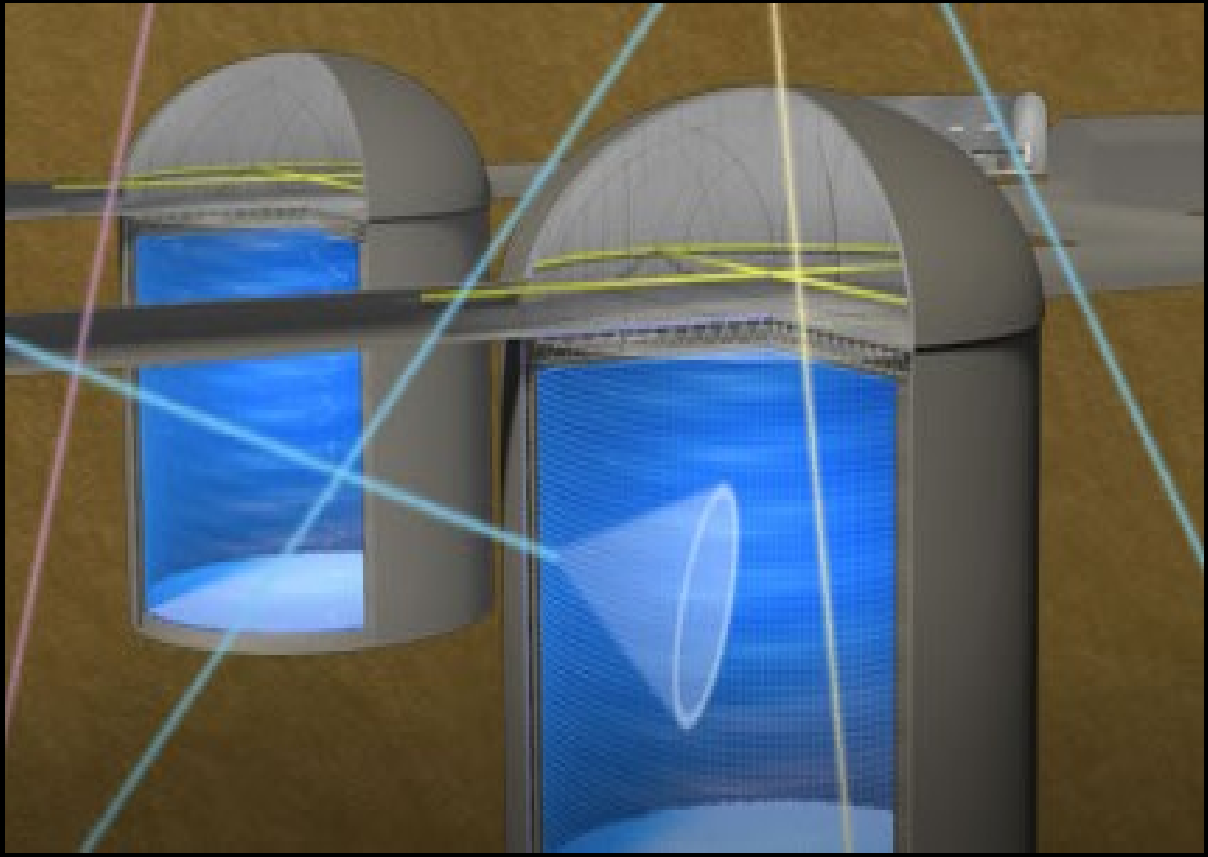
A. Ioannisian, AYS



Nadir angle

Again 0.1% effect

Prospects



CNO neutrinos

Chemical composition metallicity problem

Conversion in the transition region

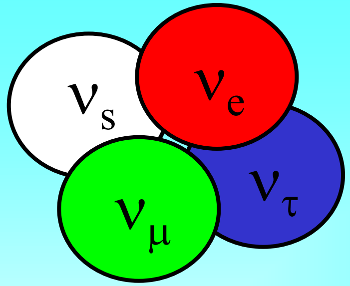
Evolution of stars

1% contribution to energy

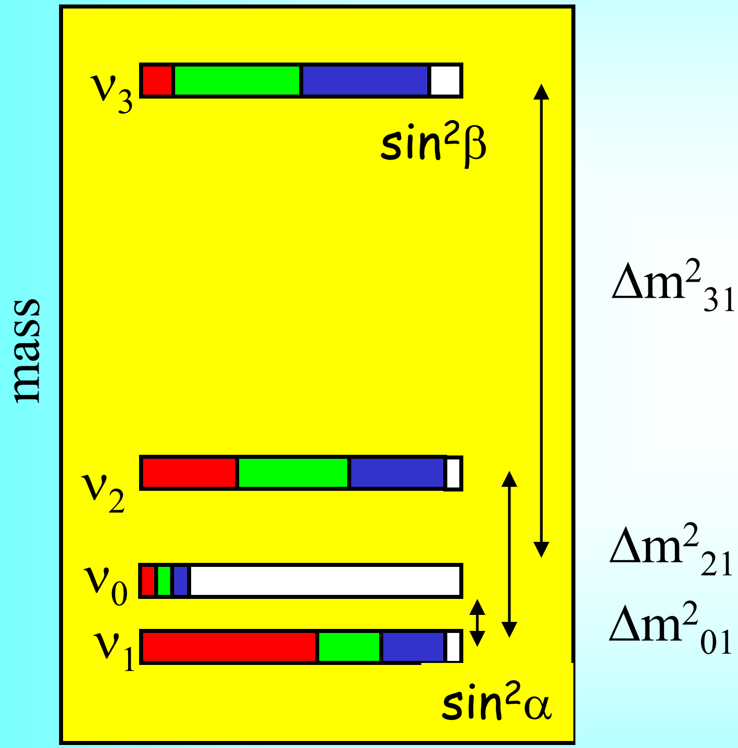
correlate

40% difference for two metallicities

meV physics



sterile neutrino $m_0 \sim 0.003$ eV



Adiabatic conversion
for small mixing angle
Adiabaticity violation

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

Searches for this sterile
in atmospheric neutrinos

additional radiation
in the Universe if mixed in ν_3

no problem with LSS
bound on neutrino mass

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

For dark radiation

$\sin^2 2\beta \sim 10^{-3}$ (NH)

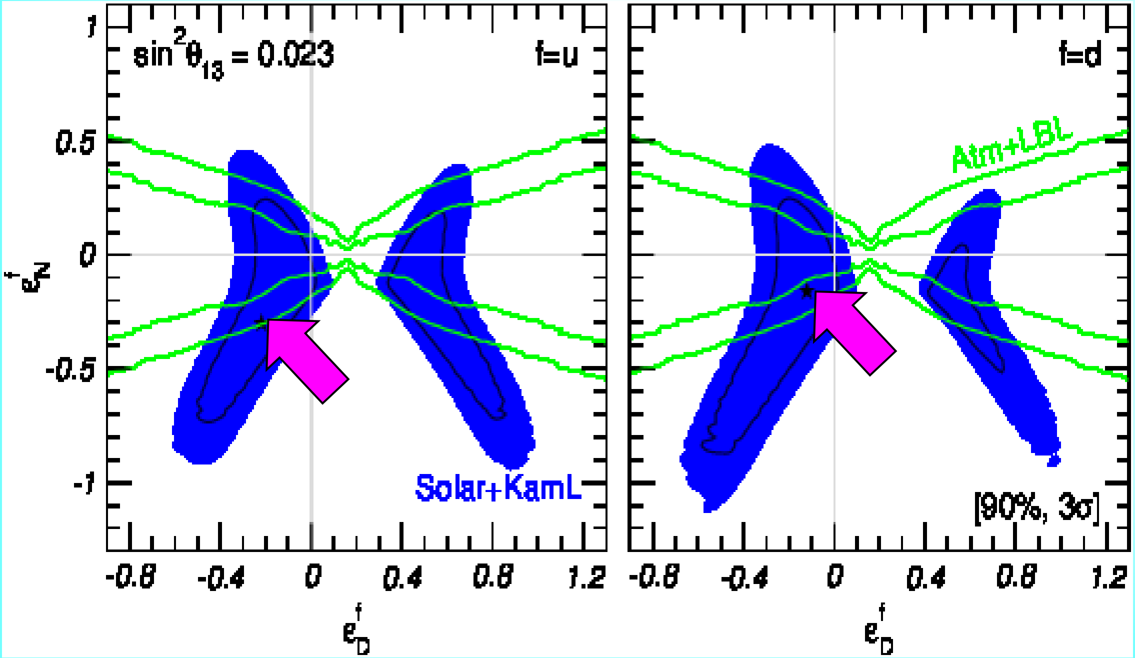
$\sin^2 2\beta \sim 10^{-1}$ (IH)

Non-standard interactions

Additional contribution
to the matrix of potentials
in the Hamiltonian

M C. Gonzalez-Garcia ,
M. Maltoni
arXiv 1307.3092

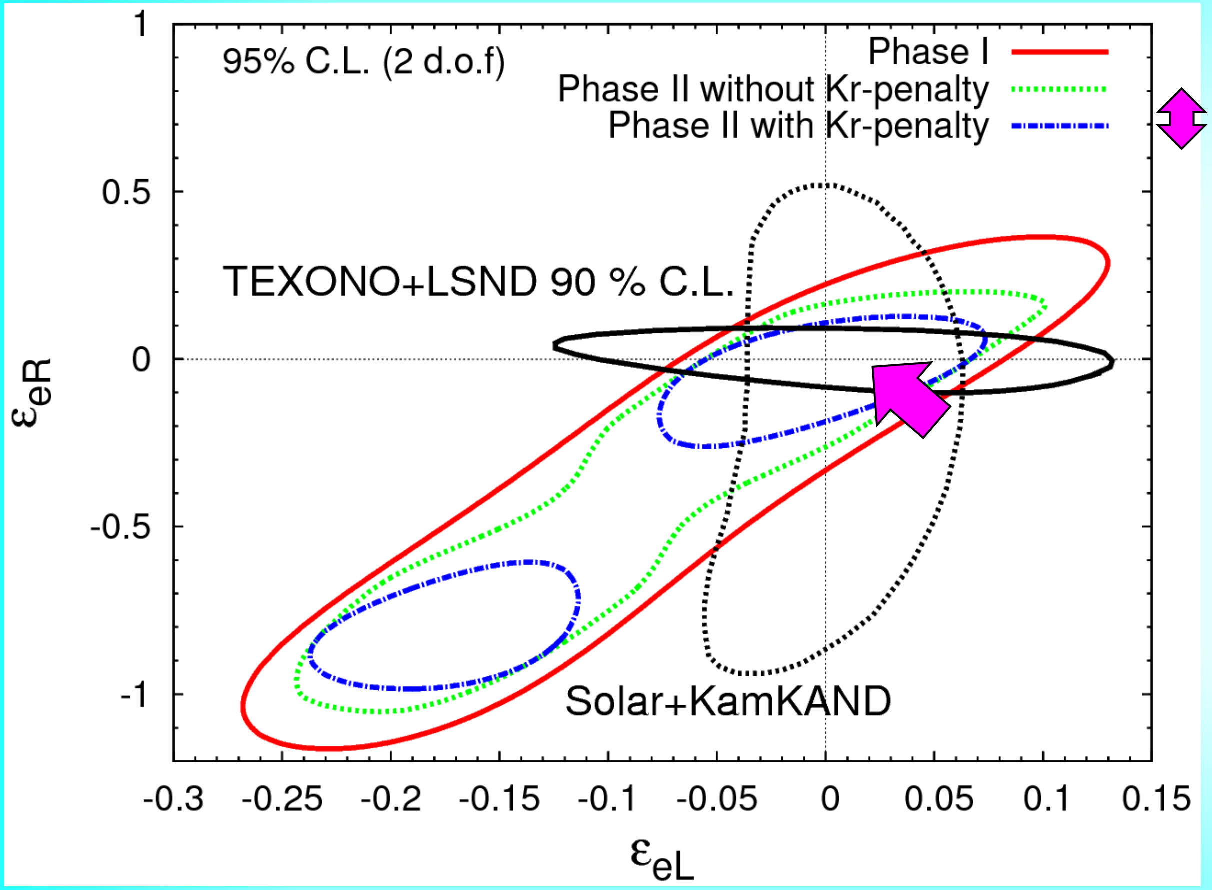
$$V_{NSI} = \sqrt{2}\, G_F\, n_f \begin{pmatrix} \varepsilon^f{}_D & \varepsilon^f{}_N \\ \varepsilon^f{}_N & \varepsilon^f{}_D \end{pmatrix} \qquad f = e, u, d$$



Allowed regions of parameters of NSI

In the best fit points the D-N asymmetry is 4 - 5%

BOREXINO: NSI in interactions



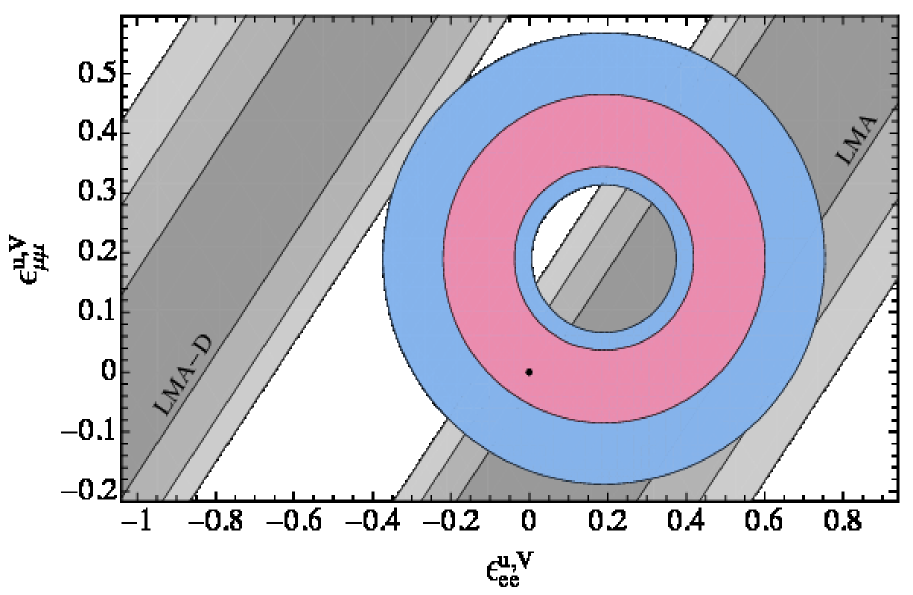
S. Agarwalla

Excludes
1.6 bigger potential,
dark solution on
electrons

ε_e < 0.05 - 0.1

Bounds on NSI

P. Coloma, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, 1708.02899 [hep-ph]

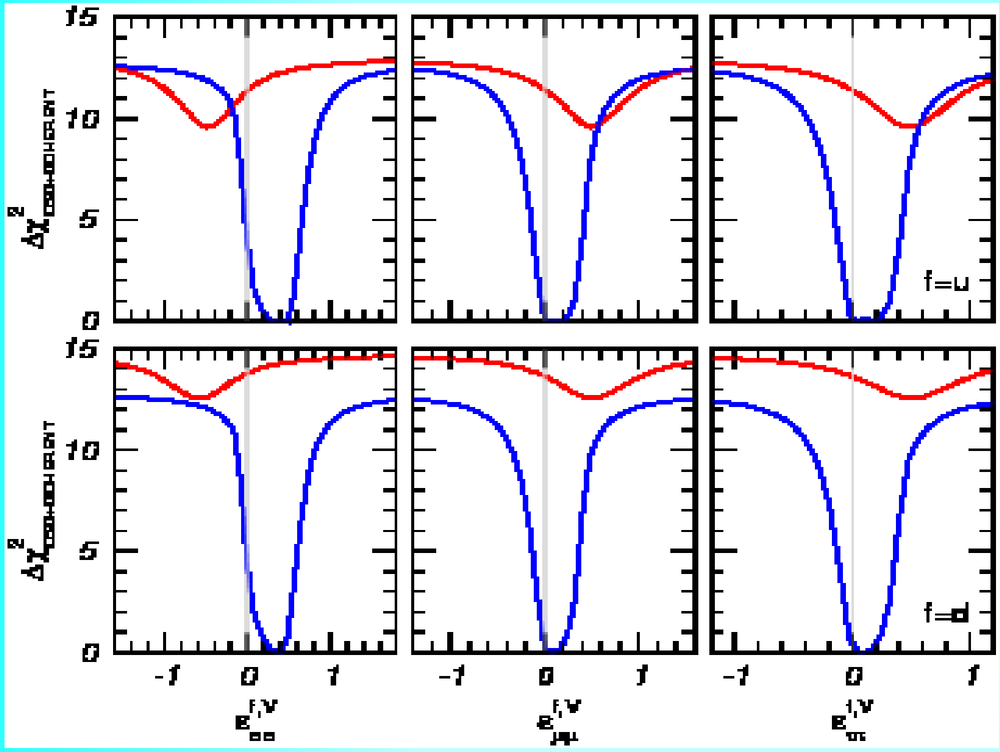


Allowed regions from the COHERENT experiment and allowed regions from the global oscillation fit.

Diagonal shaded bands correspond to the LMA and LMA-D regions as indicated, at 1σ, 2σ, 3σ (2~dof).
The COHERENT regions are at 1σ and 2σ only. 3σ region extends beyond the boundaries of the figure

Bounds on NSI

P. Coloma, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, 1708.02899 [hep-ph]



Bounds on the flavour diagonal NSI parameters from the global fit to oscillation plus COHERENT data.

Blue lines - the LMA solution

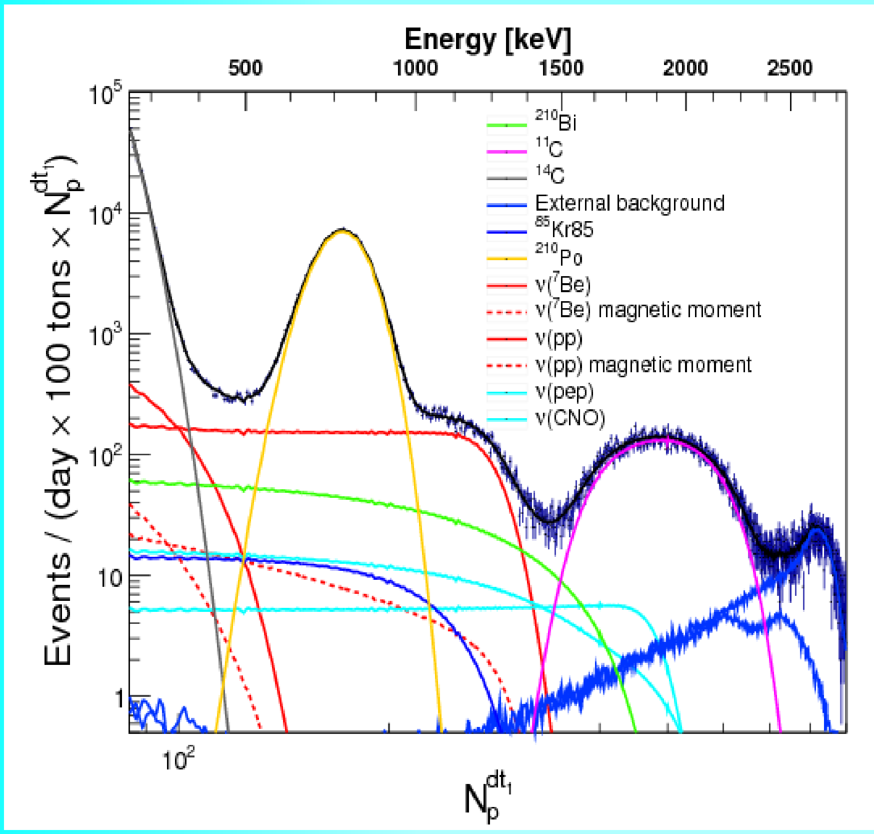
red lines LMA-D solution

COHERENT experiment, in combination with global oscillation data, excludes the NSI degeneracy at the 3.1σ (3.6σ) CL for NSI with up (down) quarks.

Neutrino magnetic moment

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

O. Smirnov



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.

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

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

The main issues

Test of "the ν -flux – Luminosity" relation

Tools: Precise measurements of the pp- and ^{7}Be-neutrino fluxes

- Reveal/restrict additional energy generation or loss mechanisms
- Measure the average energy of neutrinos
- Restrict fraction of non-terminated nuclear chains
- Search for time variations of the energy release/energy transport in the Sun

Measurements of CNO neutrinos

Solar composition/ metallicity problem

Implications to theory of star evolution, physics of intermediate energy scale

... continued

Determination of oscillation parameters

Tools: Precise measurements of the pp-, pep- and ^{7}Be-neutrino fluxes

- Substantial contribution to the global fit
- Reconstruction of energy profile of the effects

Exploration of physics in the Intermediate energy region

The pep-neutrinos special role: at E_{pep} difference of probability ΔP_{ee} = 6% for two different values of Δm_{21}^2

P_{ee} is 8% below the averaged vacuum oscillation probability due to matter effect

P_{ee} (E_{pep}) can be reduced by 15% by NSI and up to 30% by light sterile neutrino.

CNO neutrinos can contribute but degeneracy with metallicity

... continued

Time variations of fluxes

Tools: Precise measurements of the pp-, pep- and ^{7}Be-neutrino fluxes

Earth matter effects

Oscillations in multilayer medium, parametric effects, interference of waves "emitted from different borders between layers ", attenuation

Oscillation tomography of the Earth

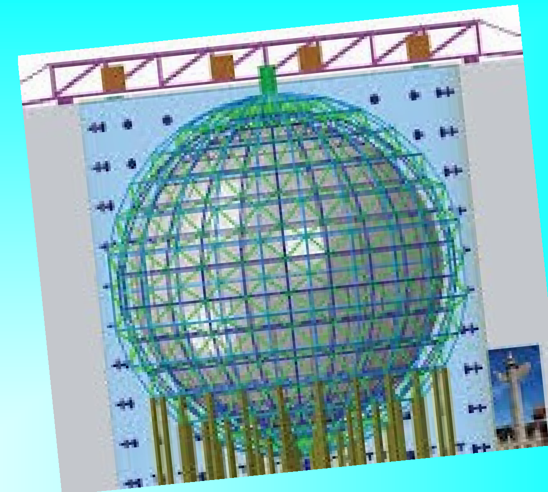
Searches new physics

Large magnetic moments, NSI, sterile neutrinos, violation of fundamental symmetries, CPT, Lorentz

Tests of theory of neutrino oscillations

Applications

Future experiments



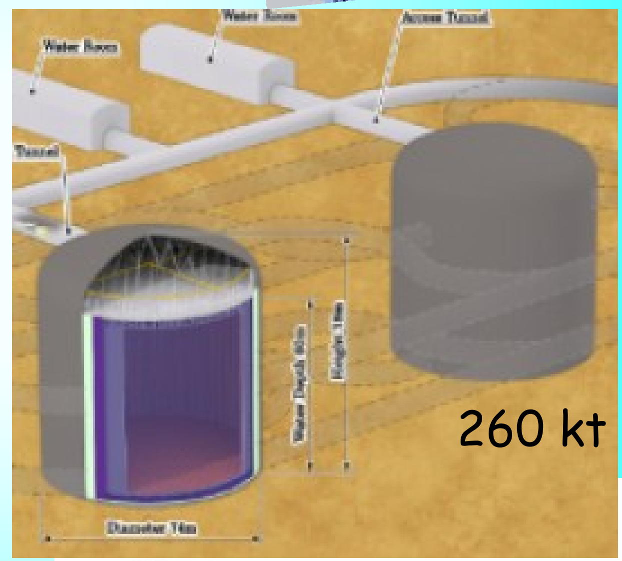
SNO+

870 tons
Double beta decay of Te
Simultaneously solar with E > 3 MeV, upturn
later pep- CNO- later

JUNO

LS 20 kt, too shallow,background?

HyperKamiokande



260 kt each

17 times larger SK. 100 000 νe events/y,
lower PMT coverage, E > 4-5 MeV
shallower than SK, larger background,
> 5 σ D-N in 10 y

DUNE

4 x 11.6 kt (fv) LiAr TPC

$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e$

Earth matter effect ?

... continued

JinPing

The deepest lab - lowest background

$\nu + e \rightarrow \nu + e$

ASDC (WbLS)

(water based Liquid scintillator)

Combining advantages of scintillator (good energy resolution) and cherenkov (directionality) experiments

$\nu + e \rightarrow \nu + e$

Theia

30 t f.v. also 1% Li doped

$\nu_e + {}^7Li \rightarrow {}^7Be + e$

pep, N, O, B Be
Earth tomography

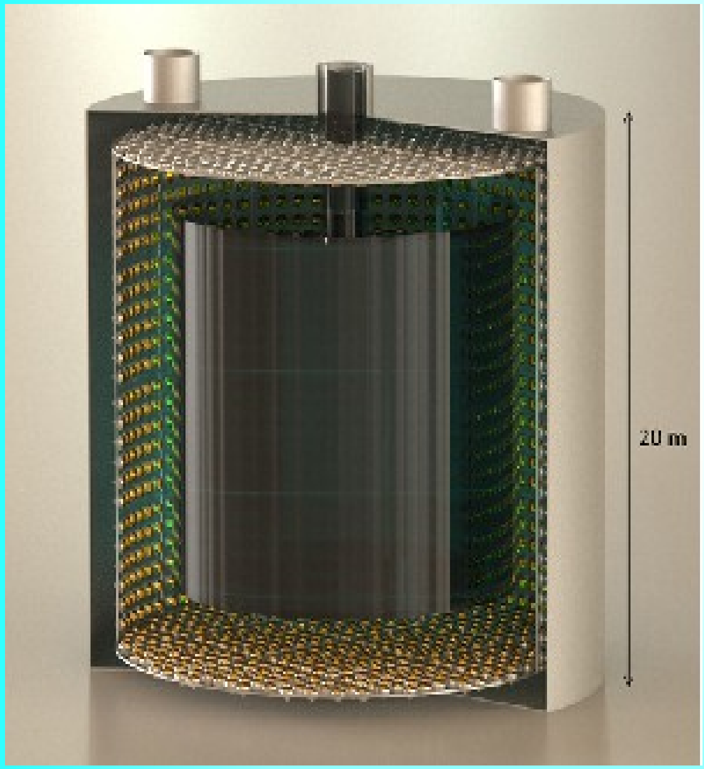
DARWIN

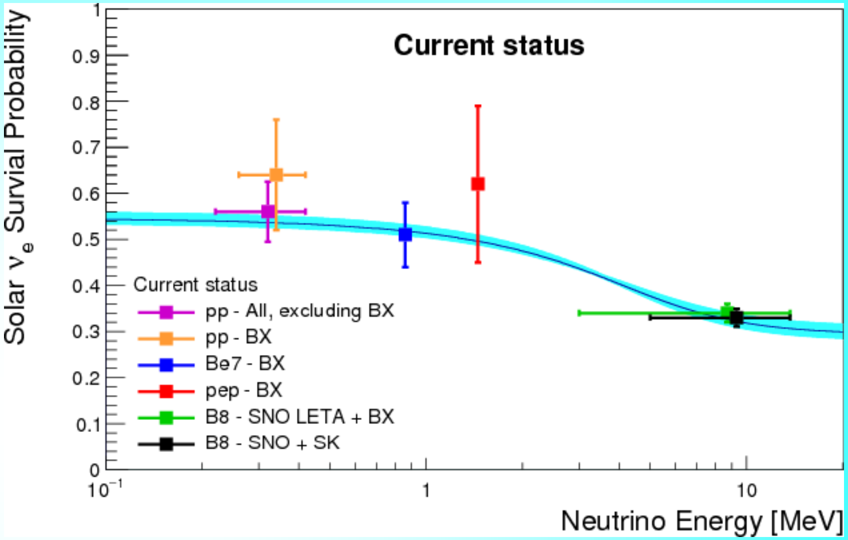
DM experiments hitting neutrino floor
Liquid Xe TPC, 30 t fiducial volume

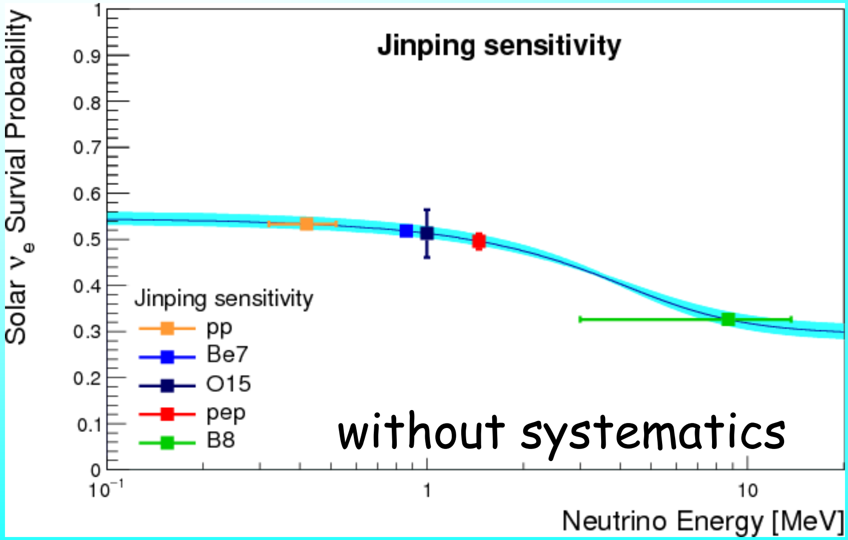
$\nu + e \rightarrow \nu + e$ pp (1%)

JinPing underground lab

scintillator uploaded
water detectors?



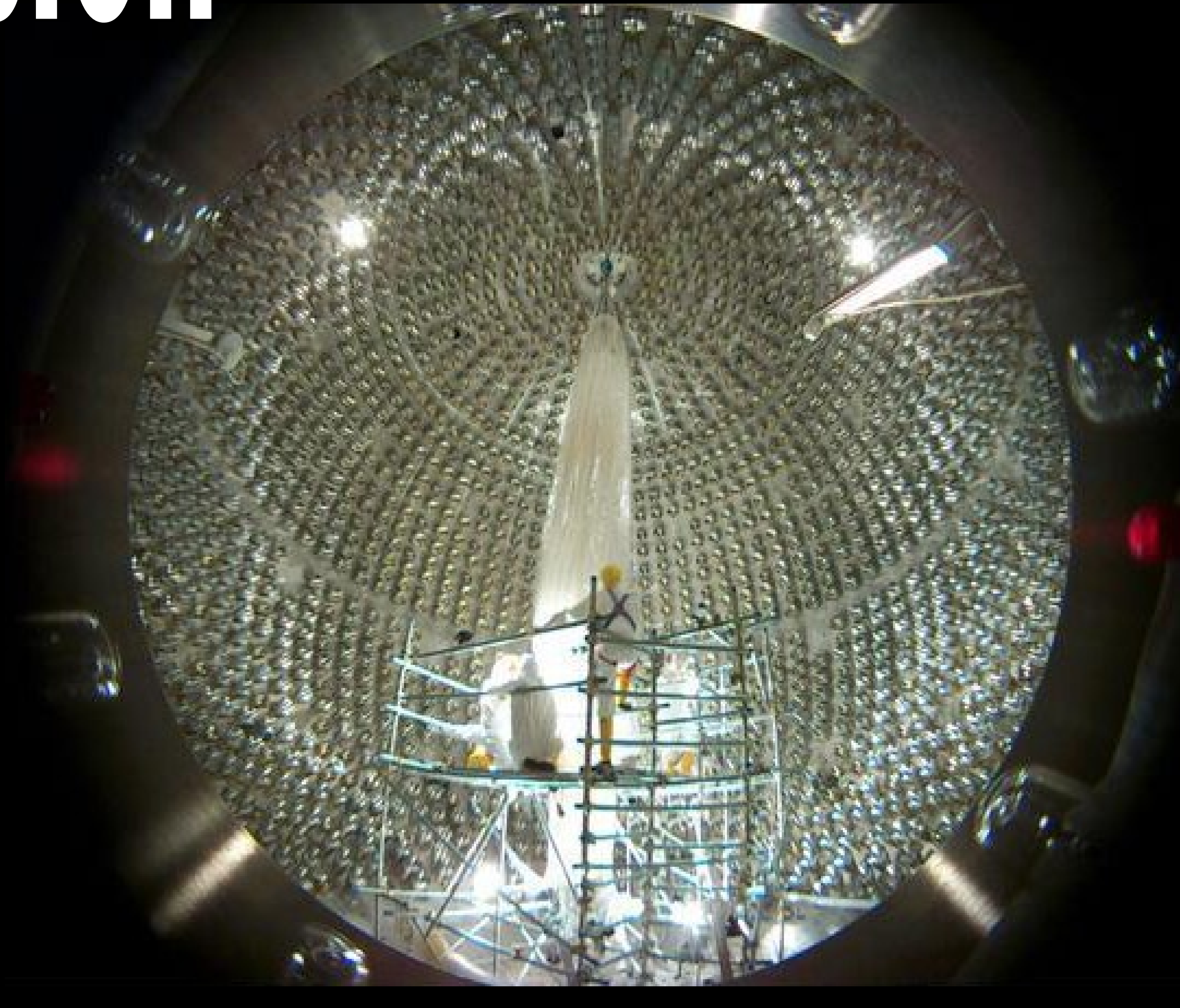




FV: 100 times bigger than BOREXINO

Deeper than SNO

Conclusion



Summarizing

There is continuous progress in the field with new important experimental and theoretical results

Rich physics of neutrino propagation (much richer than e.g. of reactor neutrinos)

Interesting physics of neutrino production

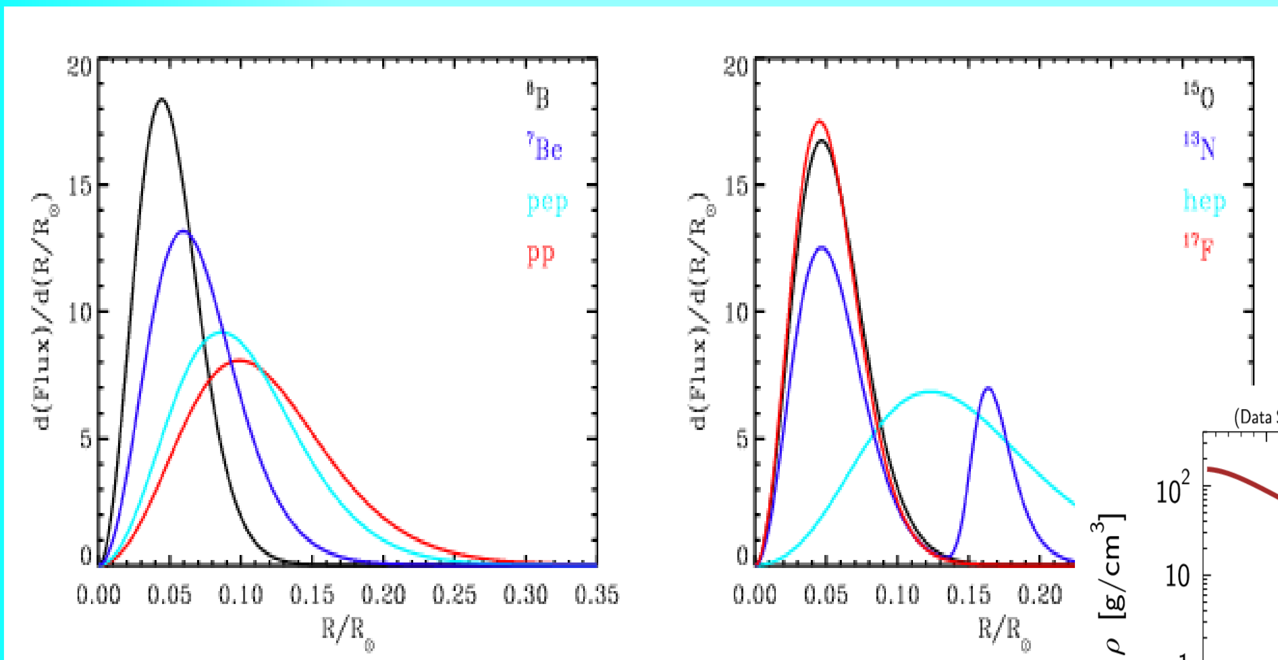
Applications

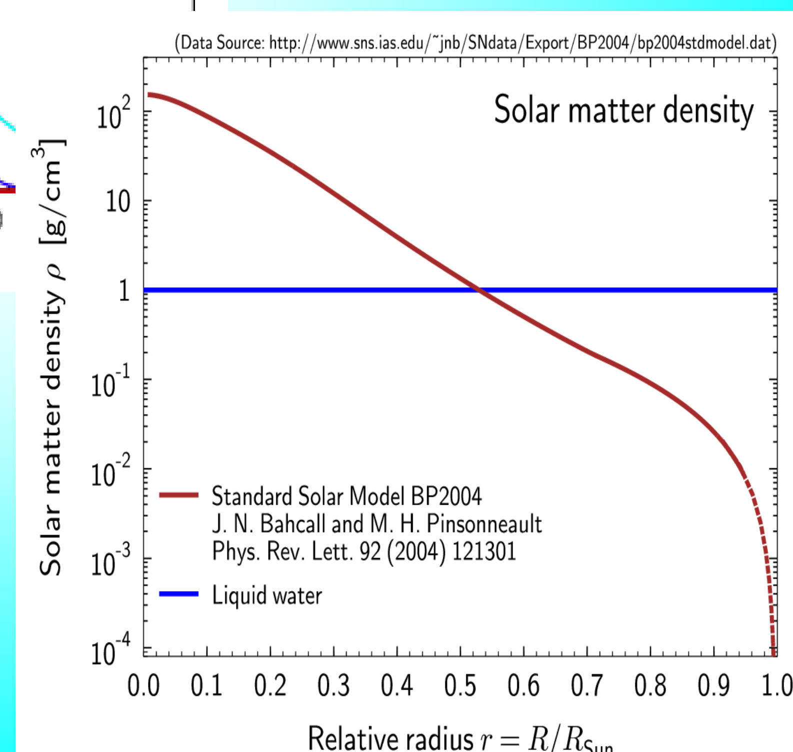
New phase of the field with % - sub % accuracy

New physics, new opportunities,
In particular, full 3 neutrino framework is the must

Backup

Neutrino production region





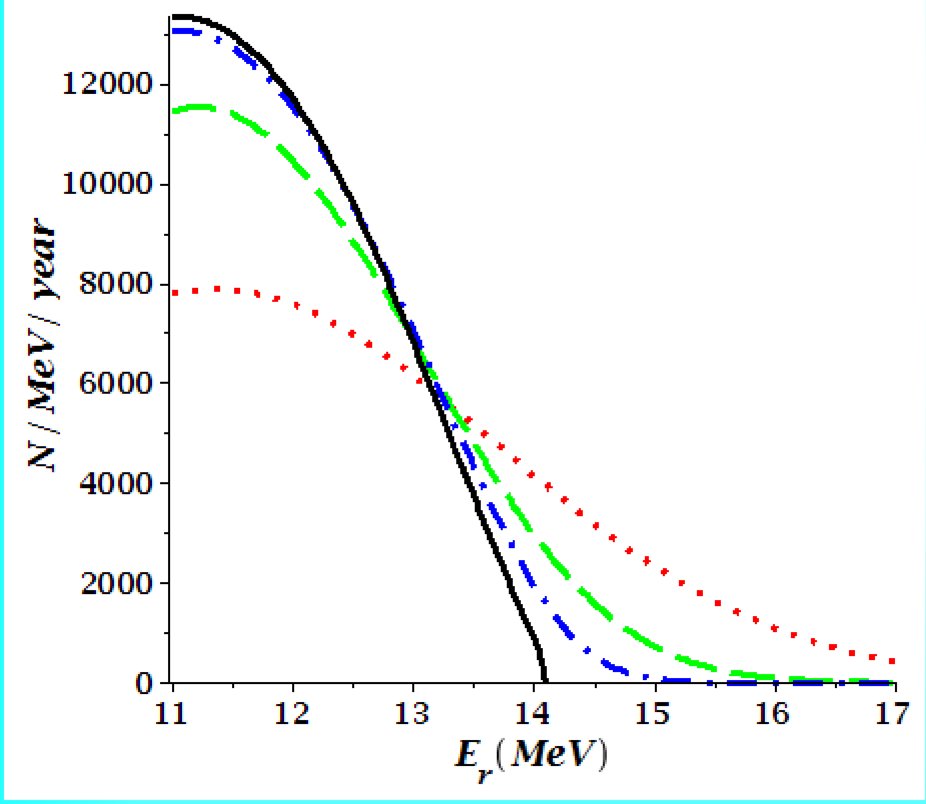
References

A. Ioannisian, A. Smirnov, D. Wyler,
Phys.Rev. D96 (2017) no.3, 036005
arXiv:1702.06097 [hep-ph]

A.N. Ioannisian, A. Yu. Smirnov
Phys.Rev. D96 (2017) no.8, 083009
arXiv:1705.04252 [hep-ph]

DUNE solar neutrino events

A. Ioannisian, A. Smirnov, D. Wyler, Phys.Rev. D96 (2017) no.3, 036005 arXiv:1702.06097 [hep-ph]

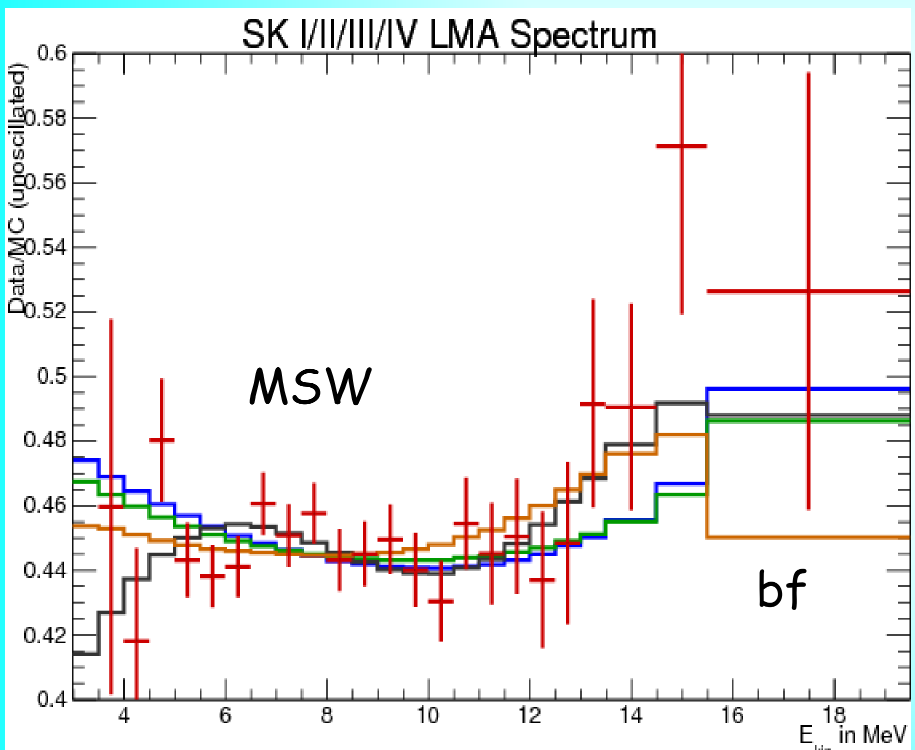


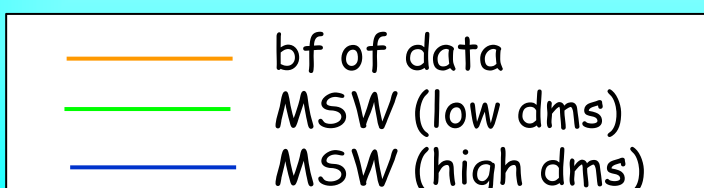
The energy (*ER*) distribution of the annually detected events at DUNE for different energy resolutions σE. The solid (black) line represents perfect resolution, σE=0, the other lines correspond to σE=0.5 MeV - dash-dotted (blue) line, σE=1 MeV dashed (green) line, σE=2 MeV dotted (red) line. The distributions are normalized to annual number of events 27000 at *Er*> 11 MeV.

SK results

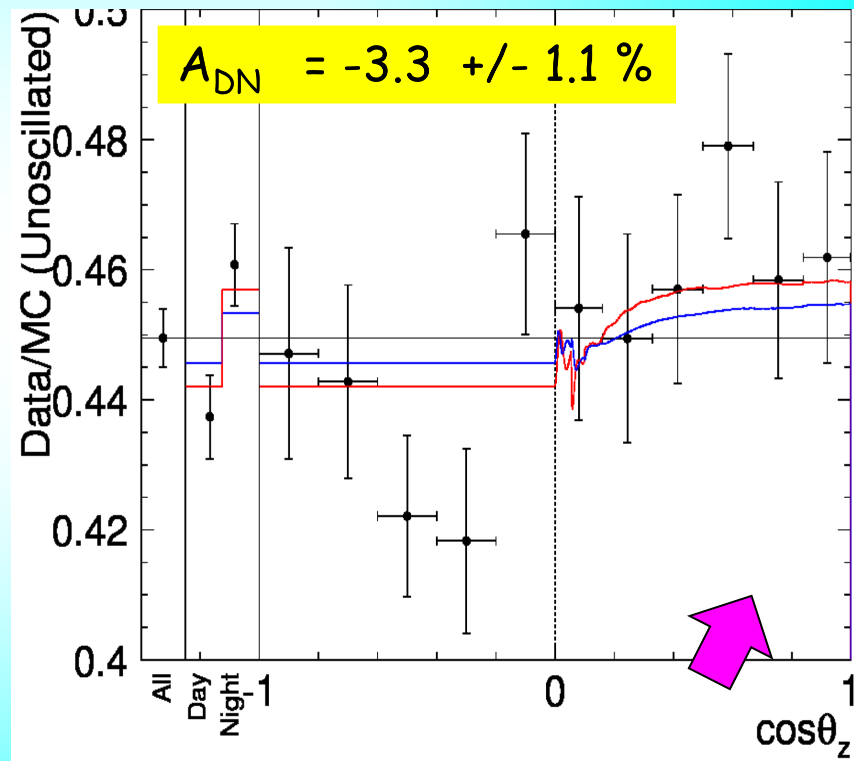
SK Collaboration (Abe, K. et al.)
arXiv:1606.07538 [hep-ex]

Recoil electron energy spectrum



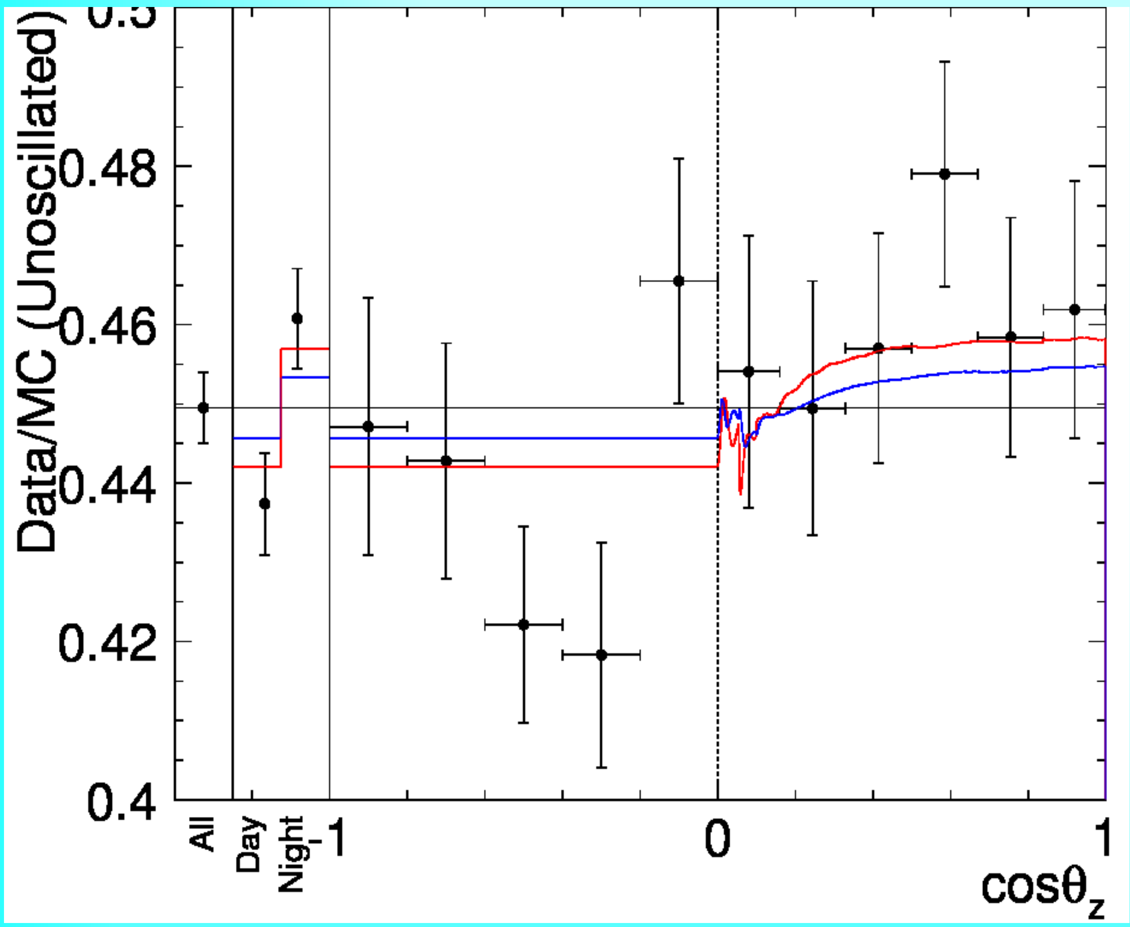


SK-IV solar zenith angle dependence



No enhancement for core crossing trajectories (last bin) -- attenuation effects

Day-Night asymmetry



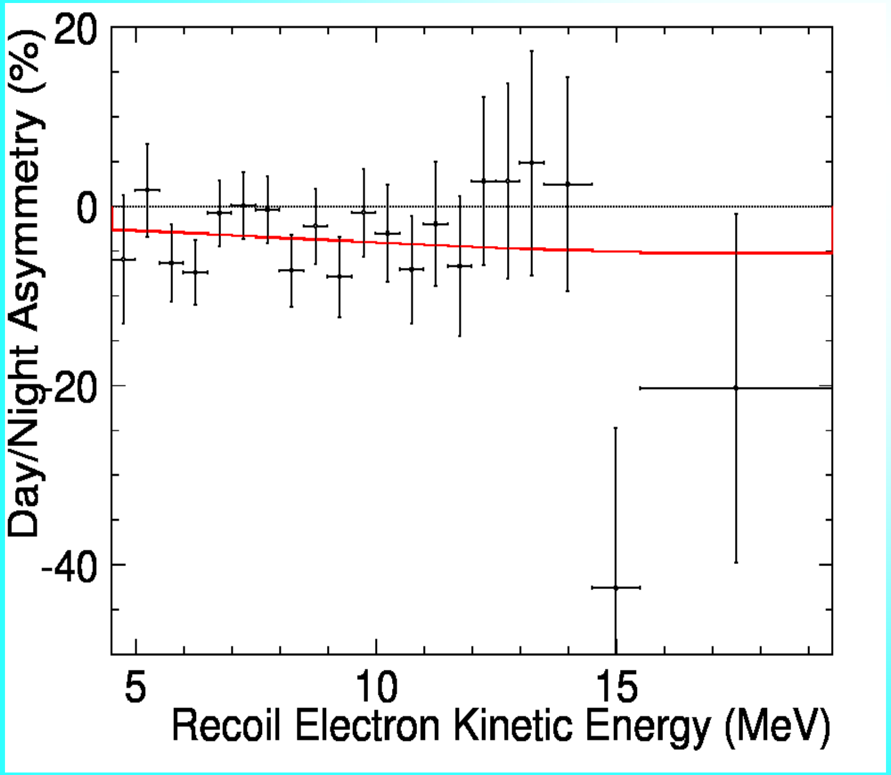
SK-IV solar zenith angle dependence of the solar neutrino data/MC (unoscillated) interaction rate ratio (4.49-19.5 MeV). Red (blue) lines are predictions when using the solar neutrino data (solar neutrino data+KamLAND) best-fit oscillation parameters. The error bars are statistical uncertainties only.

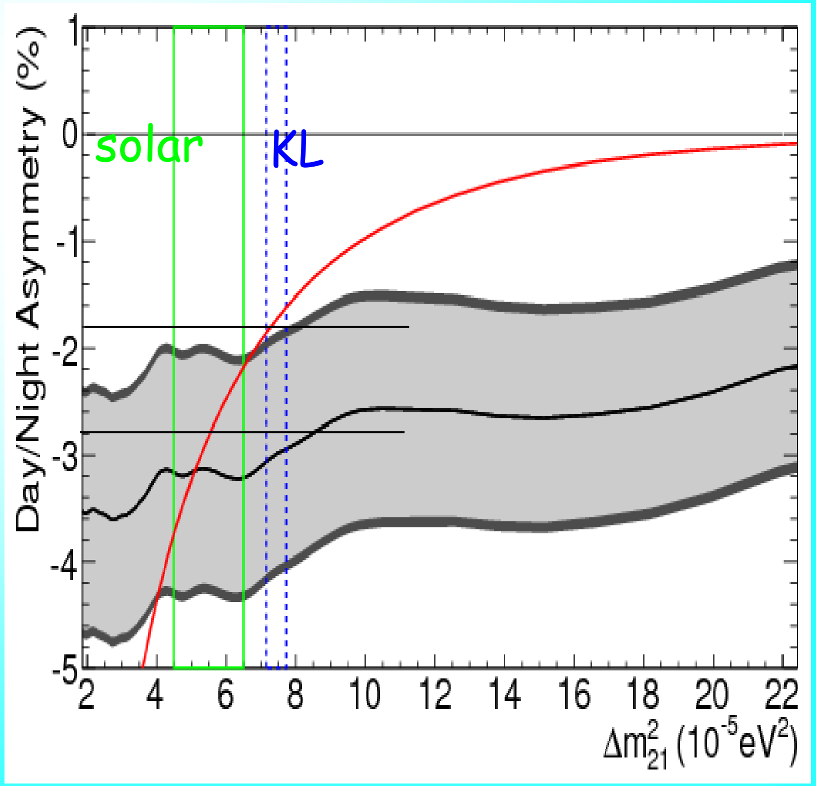
Day-Night effect

First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

Super-Kamiokande collaboration (Renshaw, A. et al.) Phys.Rev.Lett. 112 (2014) 091805 arXiv:1312.5176

> 3 σ





Aspects:

A. Y. Smirnov, Solar neutrinos and matter effects. p. 149 - 209. In "The state of the Art of Neutrino physics". World scientific, 2018

Fluxes

Astrophysics

Nuclear physics

g-modes
rotation

Luna MW

Solar neutrinos

Propagation

Astrophysics

Detection

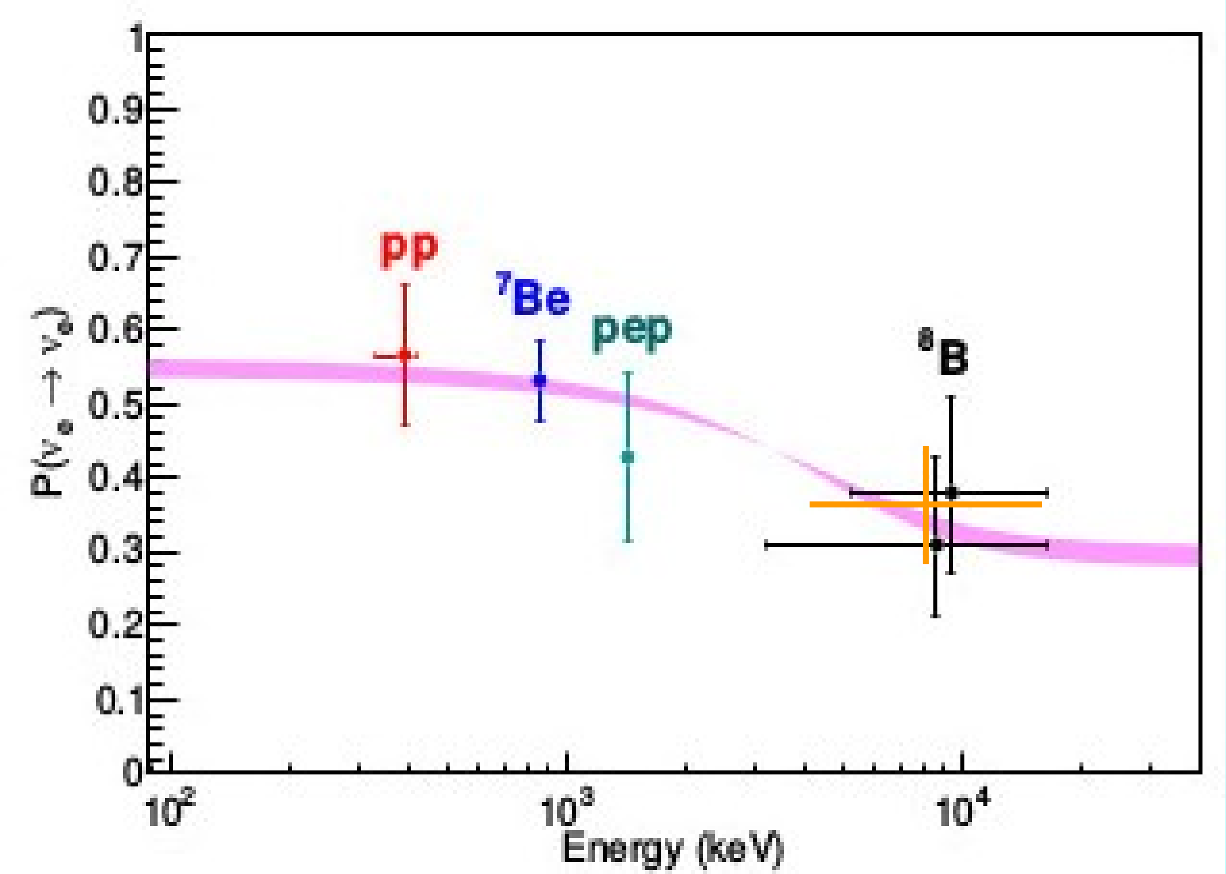
Nuclear physics

Implications & applications

Determination of neutrino parameters
Searches for new physics
Astrophysics of the Sun, metallicity
Tomography of the Earth
Measurements of cross sections

BOREXINO - Solar

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



G. Bellini
B. Caccianiga

Energy profile of the effect is determined by mixing in matter in production point + oscillations inside the Earth

D. Franco

Scaring agreement

Problems in details
% level precision