SNO: toward the solution of the solar neutrino problem

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Smoking guns start to smoke!

Global fit and its implications

- the best solution
- fate of SMA
- VAC is back ... again
- hunting for a sterile

What is next?

with P. Krastev

Smoking guns start to smoke

SK vs SNO

⇒ Appearance of ν_μ / ν_τ or/and Spectrum distortion

For the first time we have more than 3 σ solar model independent evidence of the neutrino conversion

The is some type of the neutrino flavor conversion

No astrophysical solution

Pure $\nu_e - \nu_s$ (sterile) conversion is strongly disfavored if not excluded

$\boxed{P(\nu_e - \nu_e) < 1/2}$?

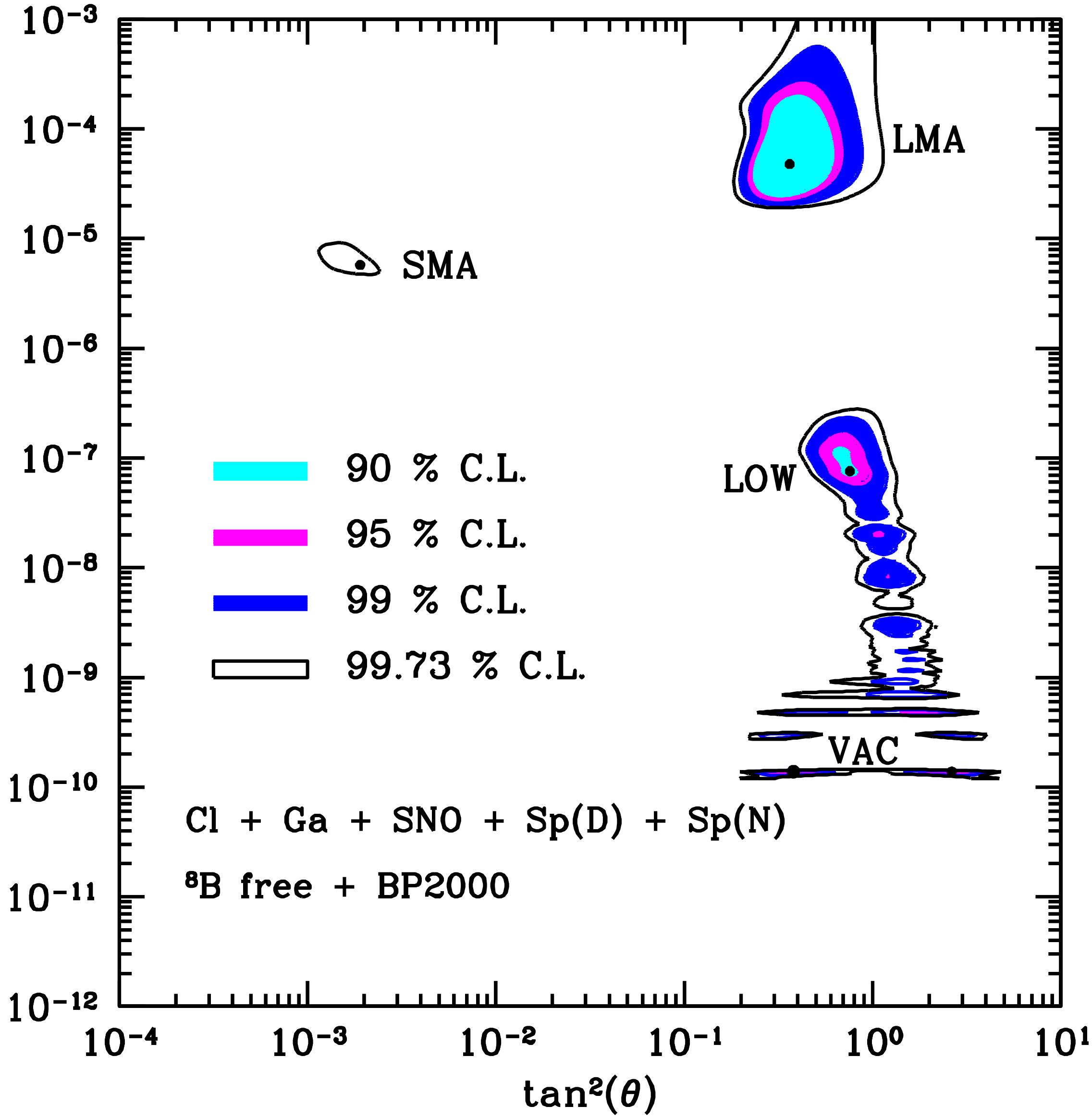
Global fit with SNO

SK: day and night spectra (1248 days)
SNO: CC−event rate
Homestake
SAGE
GALLEX and GNO

BP00
free boron neutrino flux, f_B
free hep neutrino flux f_{hep}

Cross−sections:

as in our previous calculations
ν d as in the SNO paper



LMA
SMA
LOW
VAC
90 % C.L.
95 % C.L.
99 % C.L.
99.73 % C.L.
Cl + Ga + SNO + Sp(D) + Sp(N)
⁸B free + BP2000
Δm^2 (eV²)
$\tan^2(\theta)$

LMA

Best fit point

$$\Delta m^2 = 4.4 \; 10^{-5} \; eV^2$$
$$\tan^2\theta = 0.35$$
$$f_b = 1.13$$
$$f_{hep} = 3$$

- SNO has shifted the b.f. point and the whole region toward larger mixing angles
- Maximal mixing is allowed at 3σ level
- $\Delta m^2 < 1.3 \; 10^{-4}$ 90 % CL
  $< 2.0 \; 10^{-4}$ 95 % CL
  $< 3.5 \; 10^{-4}$ 99 % CL
- $\tan^2\theta > 0.2$ 99 % CL

Fate of SMA

Accepted at $\sim 3\ \sigma$ level

Best fit point:

$$\Delta m^2 = 5.5\ 10^{-6}\ \mathrm{eV}^2$$
$$\tan^2\theta = 1.9\ 10^{-3}$$
$$f_B = 1.05$$
$$f_{hep} = 5.0$$

shift due to SNO/SK ν_μ ν_τ appearance

large!

For $f_{hep} = 1$ ⇨ no solution at $3\ \sigma$ level

- Strong distortion of the recoil electron energy spectrum

  Still some agreement with SK data due to interplay of
  conversion probability
  systematic correlated error
  high hep−neutrino flux

- Peak in the deep night bin of the zenith angle distribution

further disfavors SMA solution

LOW: next best?

The best fit point:

$$\Delta m^2 = 1.1\ 10^{-7}\ \mathrm{eV}^2$$
$$\tan^2\theta = 0.68$$
$$f_B = 0.86$$
$$f_{hep} = 2$$

Poor fit of the total rates:

2.4σ larger Ar production rate
1.5σ lower Ge−production rate

VAC is back ?

Very good fit (second after LMA):

$$\Delta m^2 = 1.4\ 10^{-10}\ eV^2$$
$$\tan^2\theta = 0.38\ (2.6)$$
$$f_B = 0.53$$
$$f_{hep} = 7$$

Very good description of the SK energy spectrum

But

- Requires small boron neutrino flux and large hep neutrino flux
- Imposing SSM restrictions on f_B and f_{hep} worsens the fit substantially
- Poor fit of total rates: deviations in the pull−off diagram for Ar−production rate and SK−rate

Strong distortion of the spectrum at SNO is expected

Sterile solutions

The only solution accepted at 3 σ level

$$\Delta m^2 = 1.4 \; 10^{-10} \; eV^2$$
$$\tan^2\theta = 0.38 \; (2.6)$$
$$f_B = 0.54$$
$$f_{hep} = 14$$

Very good description of the SK spectrum

But this solution does not pass additional quality tests:

- Small f_B
- Very large f_{hep}
- Solution disappears when SSM restrictions applied
- Strong deviations in the pull−off diagram

  − low SK rate
  − large Ar−production rate

Pull−off diagrams

Predictions for observables K in the best fit points of global solutions: K_{bf}

Experimental values of observables: K_{exp}
with the experimental error σ_k

Deviation of the predicted values of observables K from the central experimental values expressed in the 1σ unit:

$$\boxed{D_k = \frac{K_{bf} - K_{exp}}{\sigma_k}}$$

K:

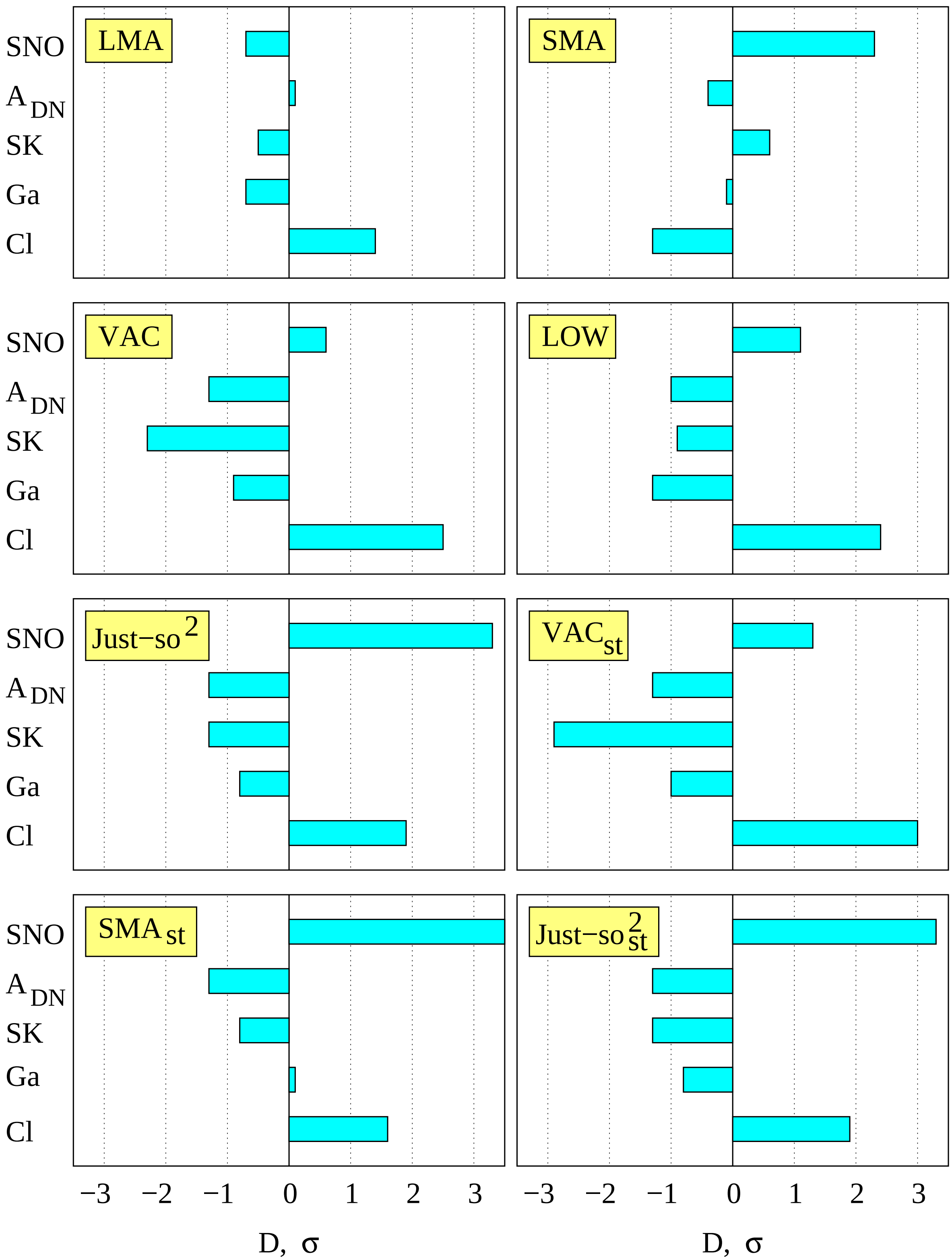
Ar−production rate

Ge−production rate

A_{DN} for ν e event rate (at SK)

SK total rate

SNO total rate


LMA
SMA
VAC
LOW
Just−so^2
VAC$_{st}$
SMA$_{st}$
Just−so$^2_{st}$
SNO
A_{DN}
SK
Ga
Cl
−3 −2 −1 0 1 2 3
D, σ

What is the next?

- Day−Night asymmetry at SNO

  In the LMA region can be as large as 15 − 20 % !
  In the best fit point of LMA:

  $$\boxed{A_{DN} = (7 - 8)\,\%}$$

  For LOW and SMA: the asymmetry ~ 2 − 3 %

  Important discrimination of solutions
  Observation of $A_{DN} > 5\,\%$ will further favor LMA

- Spectrum distortion

  Strong distortion is expected for VAC and SMA solutions

  forthcoming SNO data can affect these solutions

  It will be difficult to see distortion predicted by LMA and LOW

- Correlations of observables
- Zenith angle distribution at SNO and SK
- KAMLAND
- BOREXINO

Day−Night asymmetry at SNO and SK

$$A_{DN} = 2\,\frac{N - D}{N + D}$$

Difference of the SNO and SK asymmetries due to

1. Damping factor (for SK) due to contribution from ν_μ, ν_τ scattering to the SK signal

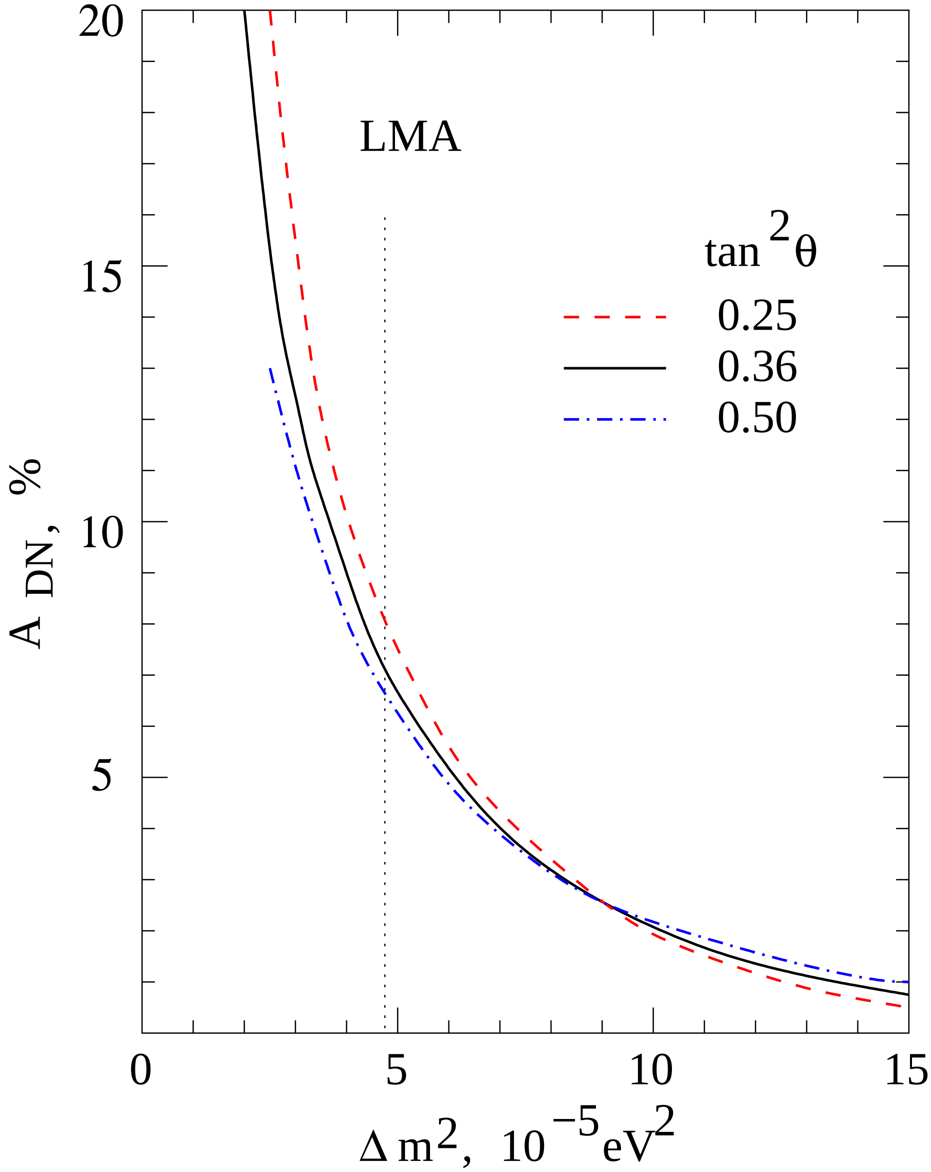
$$A_{DN}^{SNO} \sim \eta_{damp}\, A_{DN}^{SK}$$

$$\boxed{\eta_{damp} = \frac{r}{(1 - r)\, P}}$$

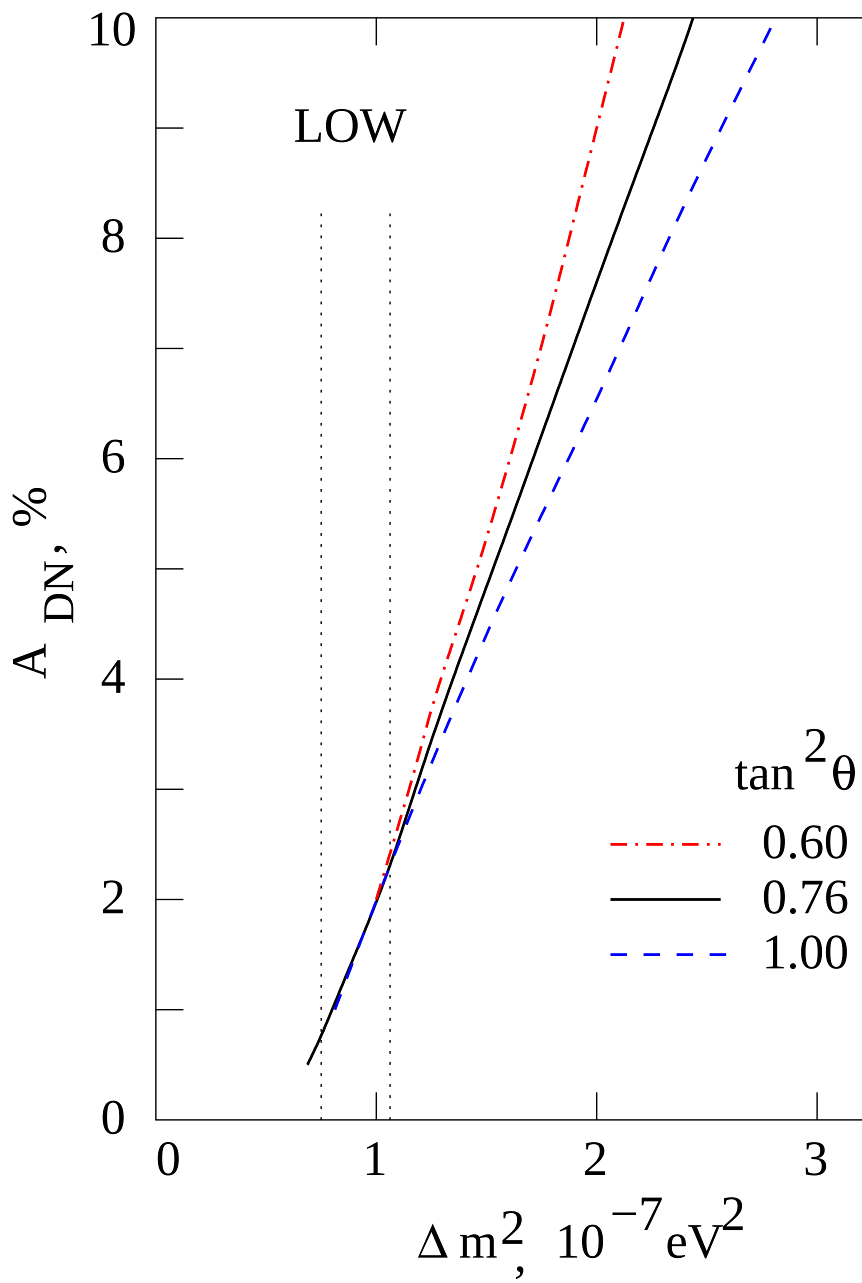
here r is the ratio of cross−sections $\nu_\mu e$ and $\nu_e e$
P is the averaged survival probability

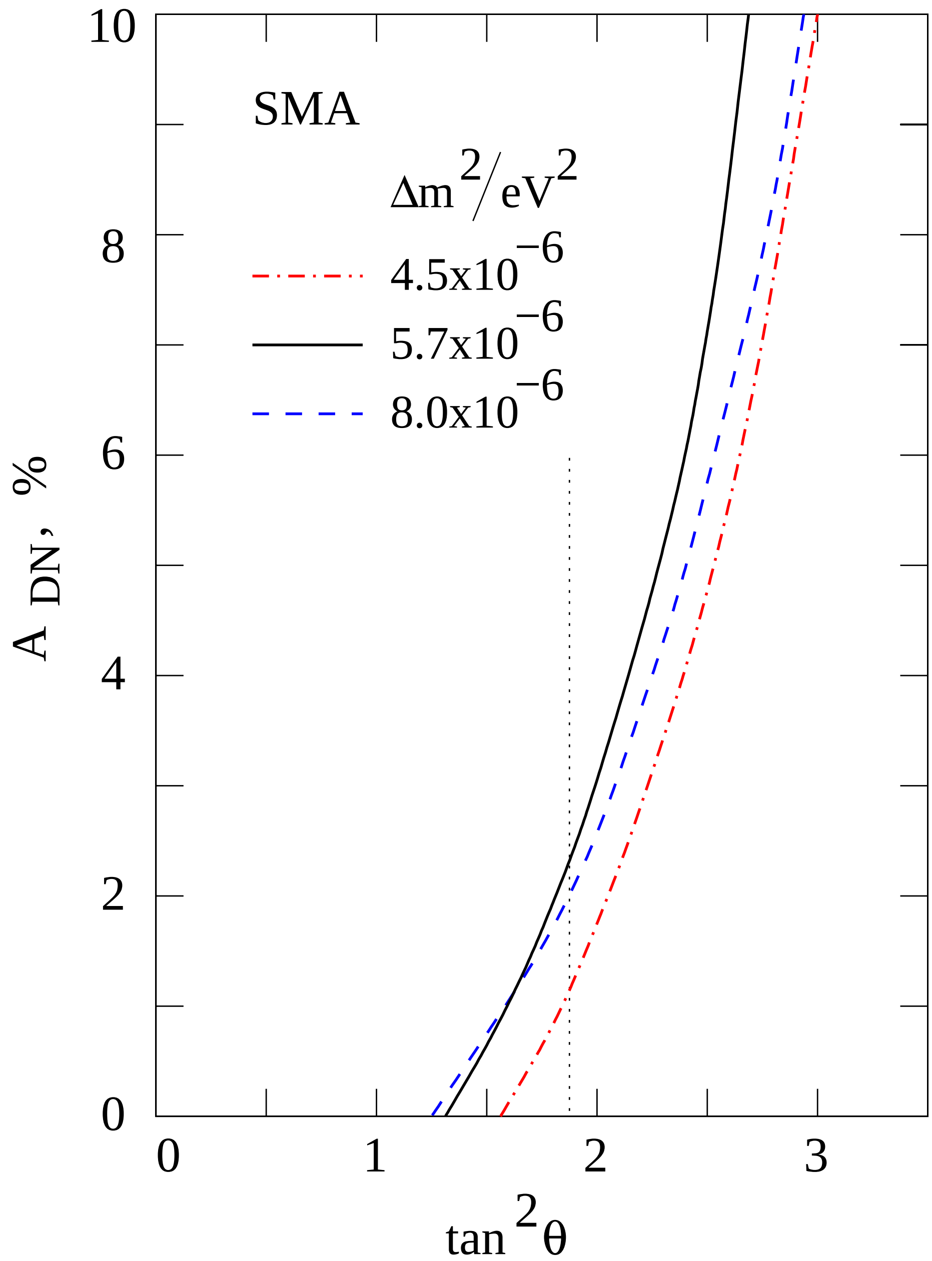
2. Difference of the energy thresholds
3. Difference of the geographical latitudes

The damping factor and the difference of thresholds enhance the asymmetry for LMA



20
15
10
5
0
5
10
15
LMA
tan²θ
0.25
0.36
0.50
A DN, %
Δm², 10⁻⁵eV²


LOW
tan $^2\theta$
0.60
0.76
1.00
A_{DN}, %
Δm^2, 10^{-7} eV^2
0
1
2
3
0
2
4
6
8
10



SMA
$\Delta m^2/eV^2$
$4.5x10^{-6}$
$5.7x10^{-6}$
$8.0x10^{-6}$
A_{DN}, %
$\tan^2\theta$
0
2
4
6
8
10
0
1
2
3

Spectrum distortion at SNO

P.I.Krastev, A. Yu. S.
hep−ph/0108177

LMA: turn up of the spectrum at low energies
due to effect of the adiabatic edge
With increase of Δm^2 the turn−up first
increases, reaches maximum at
$\Delta m^2 \sim 1.6\ 10^{-4}\ eV^2$ and then decreases

LOW: weak positive slope due to effect of
the non−adiabatic edge

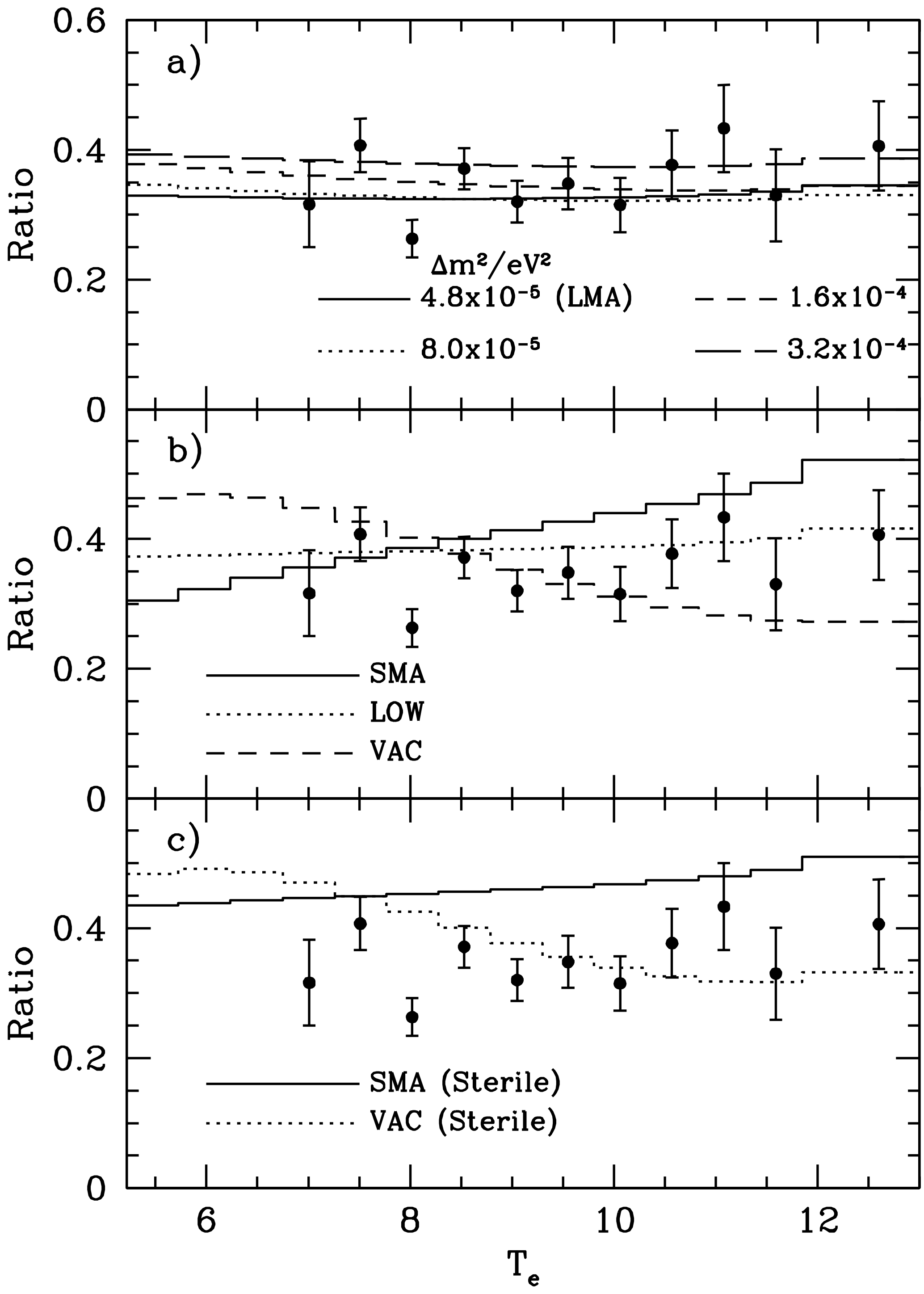
⇨ difficult to see with SNO

SMA: strong distortion in the best fit point
effect of correlated systematic error
(not shown) can improve agreement

⇨ SNO should have significant impact here

VAC: in the best fit point one predicts
bump at E ~ 5 − 7 MeV and dip at E = 11 − 12 MeV

⇨ Can be seen at SNO
measurements with lower threshold are important



a)
b)
c)
Ratio
Ratio
Ratio
0.6
0.4
0.2
0
Δm²/eV²
4.8x10⁻⁵ (LMA)
1.6x10⁻⁴
8.0x10⁻⁵
3.2x10⁻⁴
SMA
LOW
VAC
SMA (Sterile)
VAC (Sterile)
6
8
10
12
Tₑ

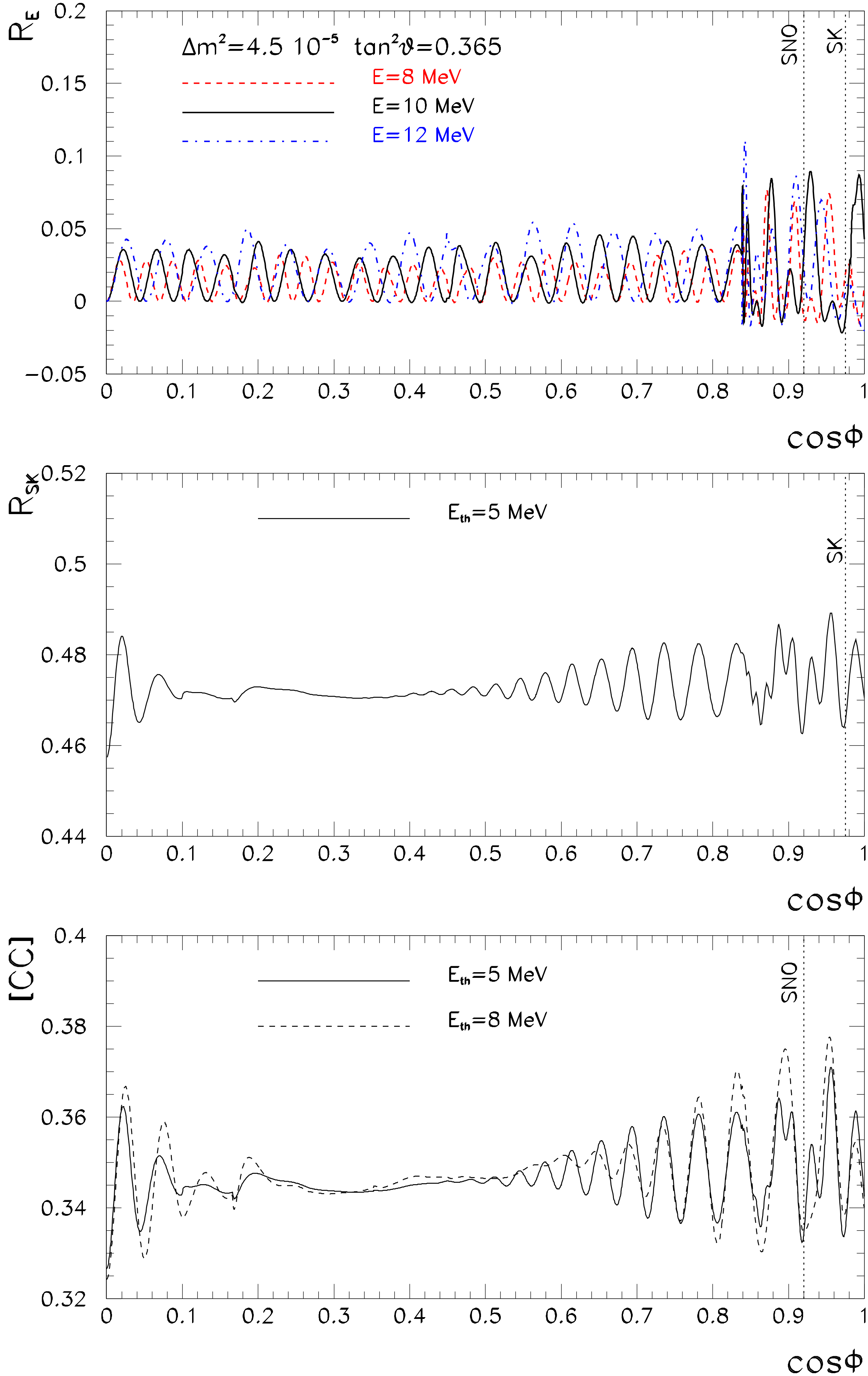
Zenith angle distribution at SNO and SK

M. C. Gonzalez−Garcia
C. Pena−Garay , A Yu. S.
Phys. Rev. D63 113004,2001

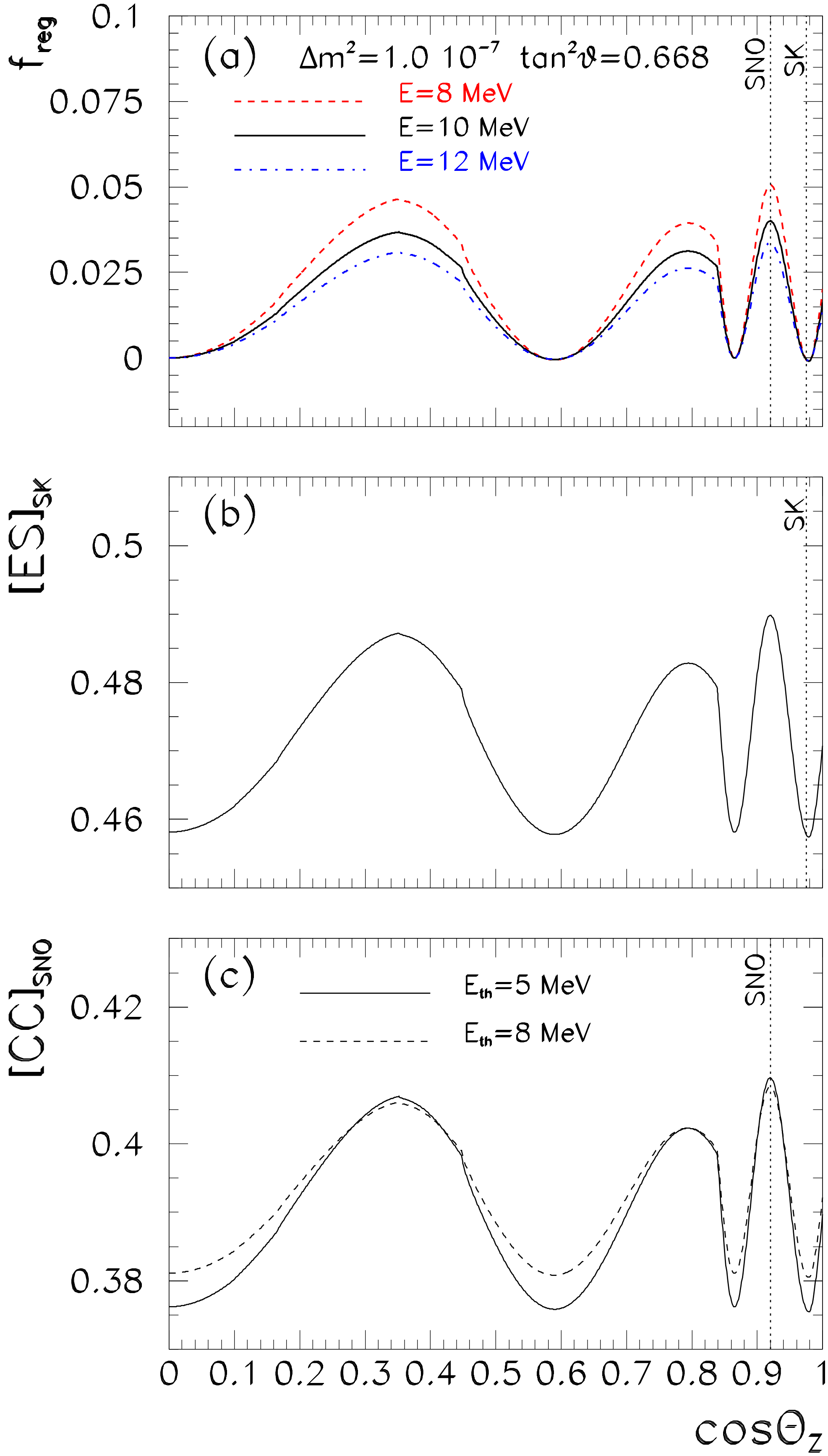
LMA: flat distribution with some oscillatory behaviour for horizontal and vertical trajectories

LOW: distribution with three peaks
two peaks correspond to oscillation maxima in the mantle of the Earth
the third peak (for the core crossing trajectories) is due to parametric enhancement of oscillations

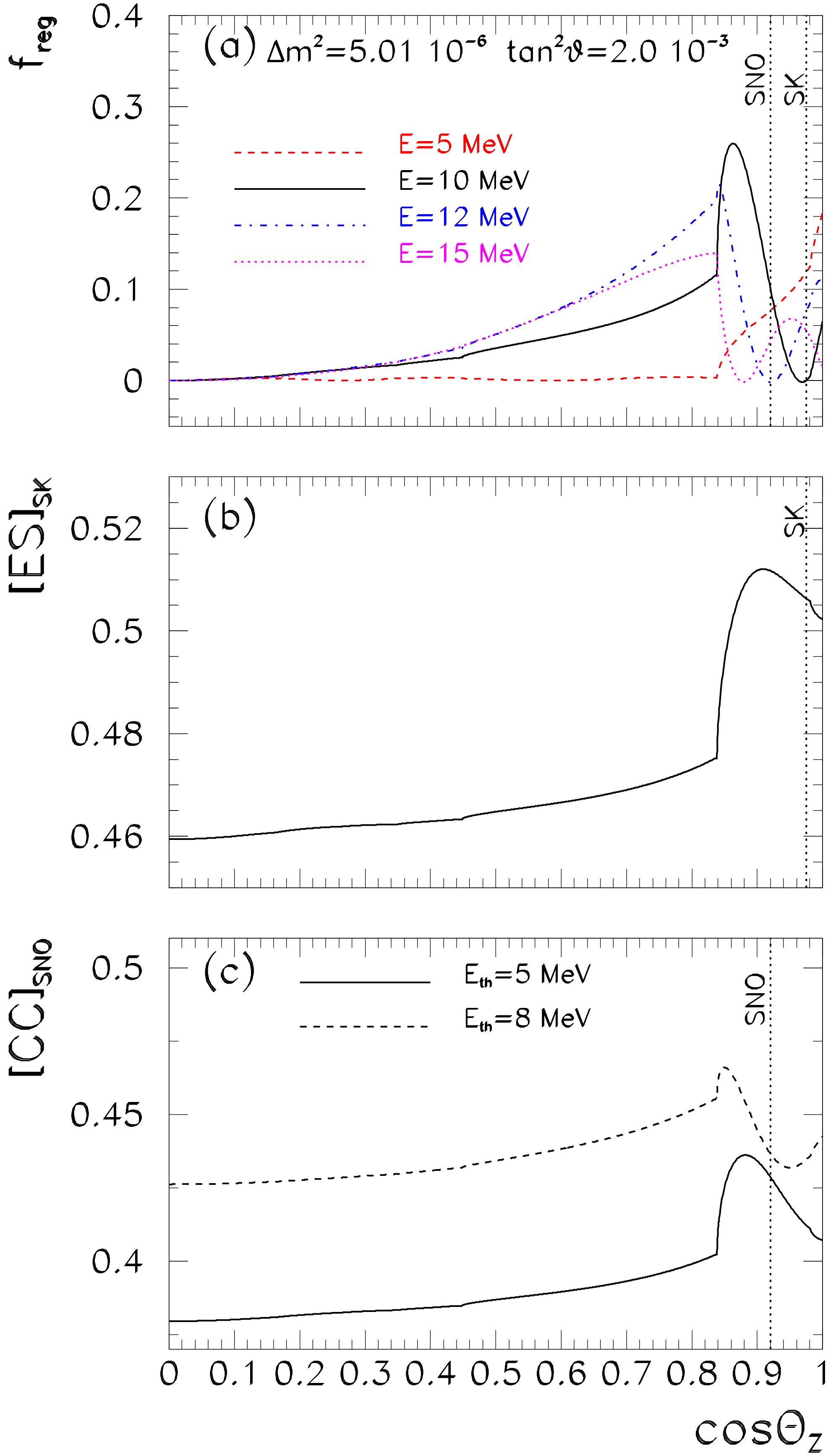
SMA: peak for the core srossing trajectories
due to parametric enhancement of oscillations



R_E
Δm²=4.5 10⁻⁵ tan²ϑ=0.365
E=8 MeV
E=10 MeV
E=12 MeV
SNO
SK
cosΦ
R_SK
E_th=5 MeV
SK
cosΦ
[CC]
E_th=5 MeV
E_th=8 MeV
SNO
cosΦ



(a) Δm^2=1.0 10^{-7} $\tan^2\vartheta$=0.668
E=8 MeV
E=10 MeV
E=12 MeV
SNO
SK
f_{reg}
0.1
0.075
0.05
0.025
0
(b)
$[ES]_{SK}$
0.5
0.48
0.46
(c)
E_{th}=5 MeV
E_{th}=8 MeV
$[CC]_{SNO}$
0.42
0.4
0.38
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$\cos\Theta_Z$



(a) Δm²=5.01 10⁻⁶ tan²ϑ=2.0 10⁻³
E=5 MeV
E=10 MeV
E=12 MeV
E=15 MeV
SNO
SK
f_reg
(b)
[ES]_SK
(c)
E_th=5 MeV
E_th=8 MeV
[CC]_SNO
cosΘ_Z