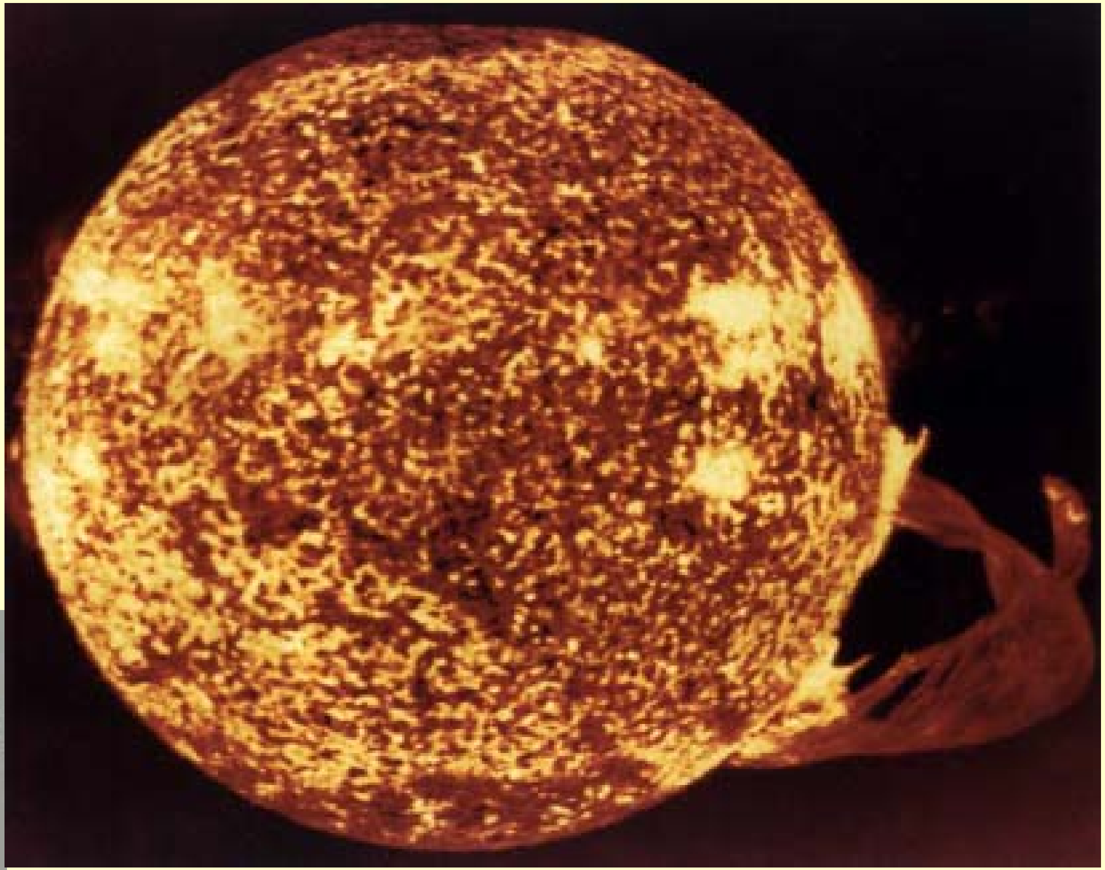
News From the Missing Solar ν's



Michael B. Smy
University of California, Irvine

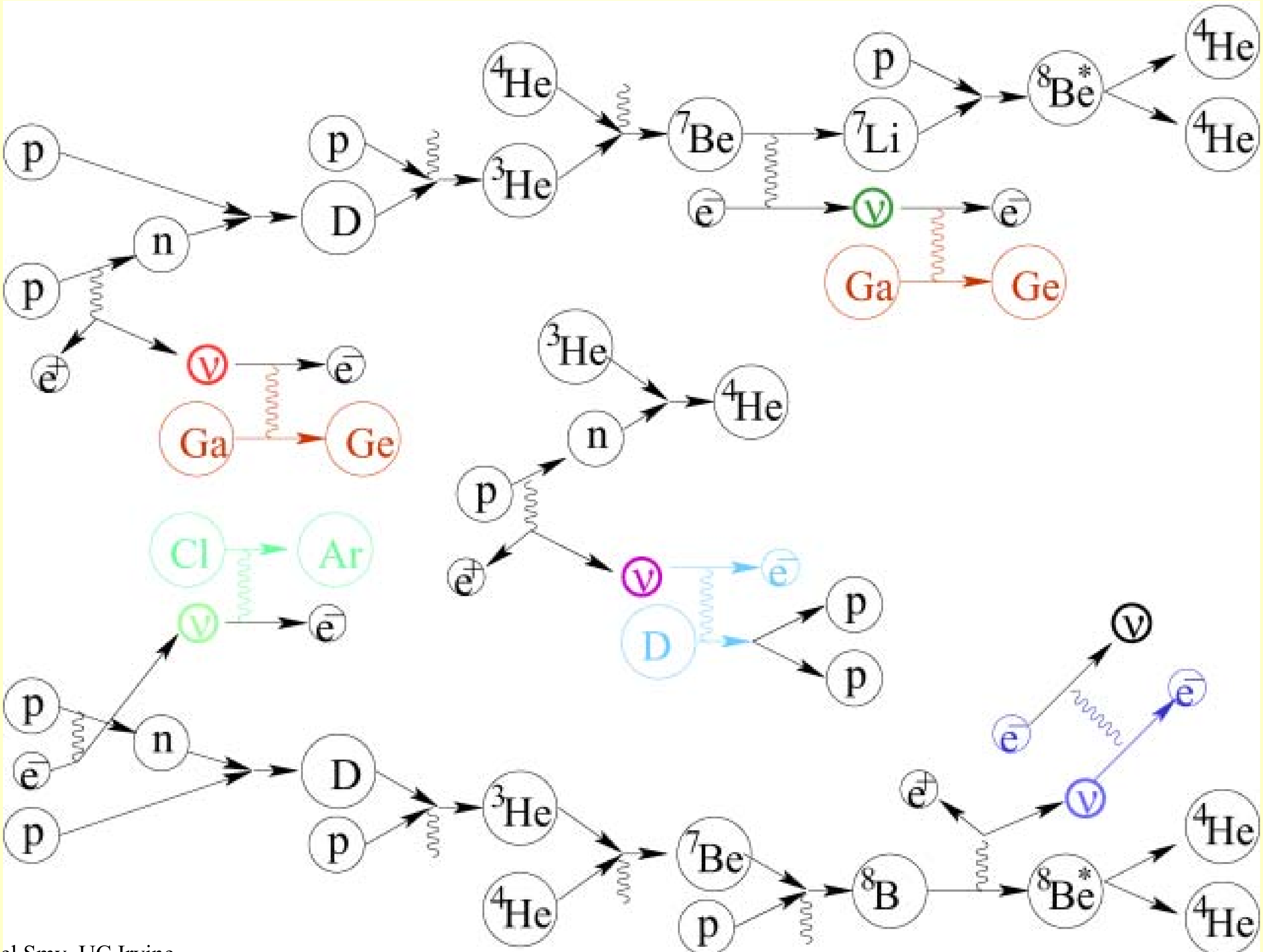
November 2003,

Tokyo Metropolitan University

Solar Neutrino Experiments

- ***Radio-Chemical*** (CC):
  Homestake (Chlorine), Gallex (Gallium),
  SAGE (Gallium), GNO (Gallium)
- ***Electron Elastic Scattering*** (CC+NC):
  Kamiokande (Water-Cherenkov),
  Super-Kamiokande (Water-Cherenkov),
  Borexino (liquid scintillator; in future)
- ***Cherenkov*** (CC): SNO (Deuterium)
- ***Cherenkov*** (NC): SNO (Deuterium)

Solar Neutrino Generation/Detection



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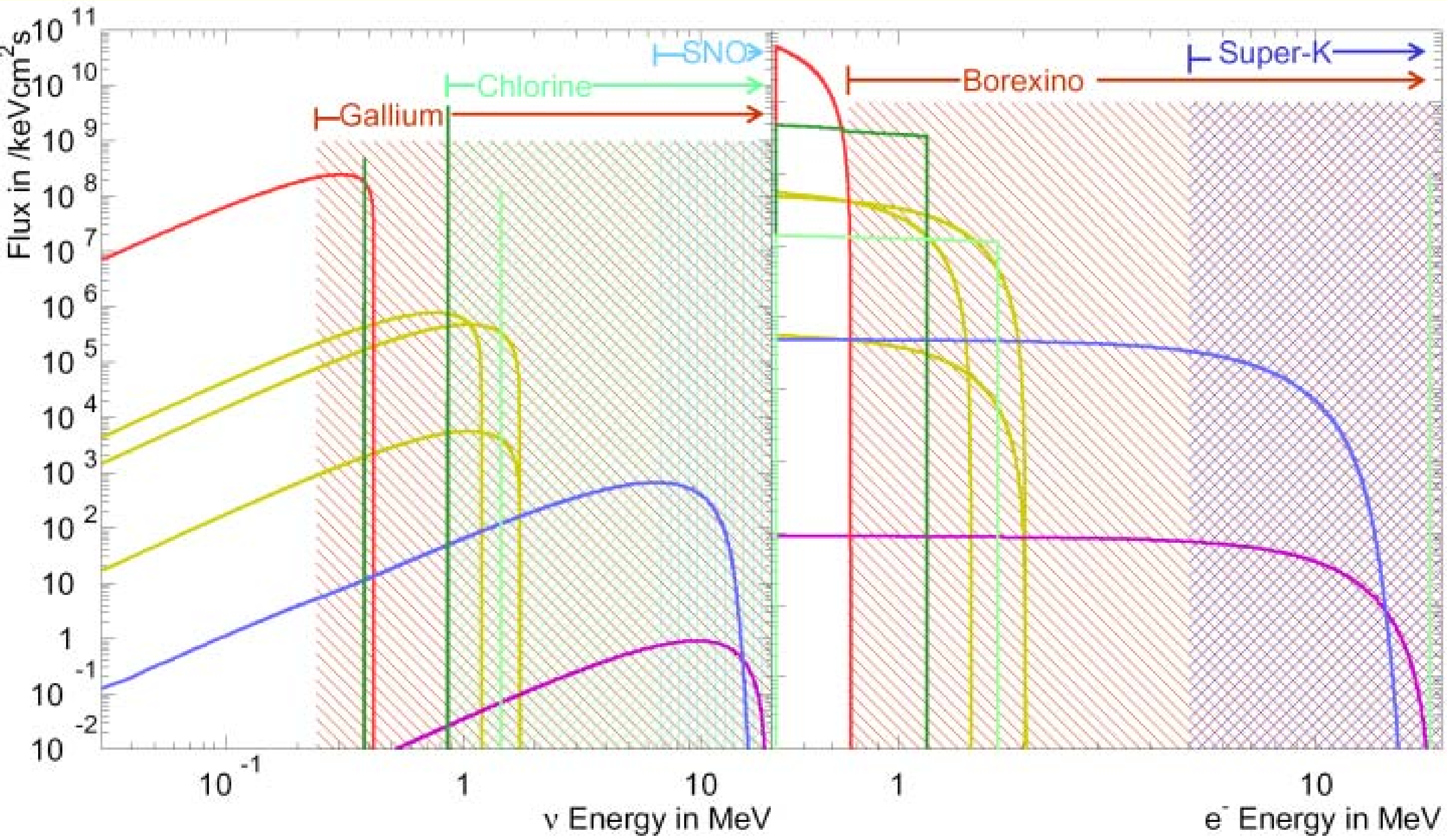
Solar ν Spectrum



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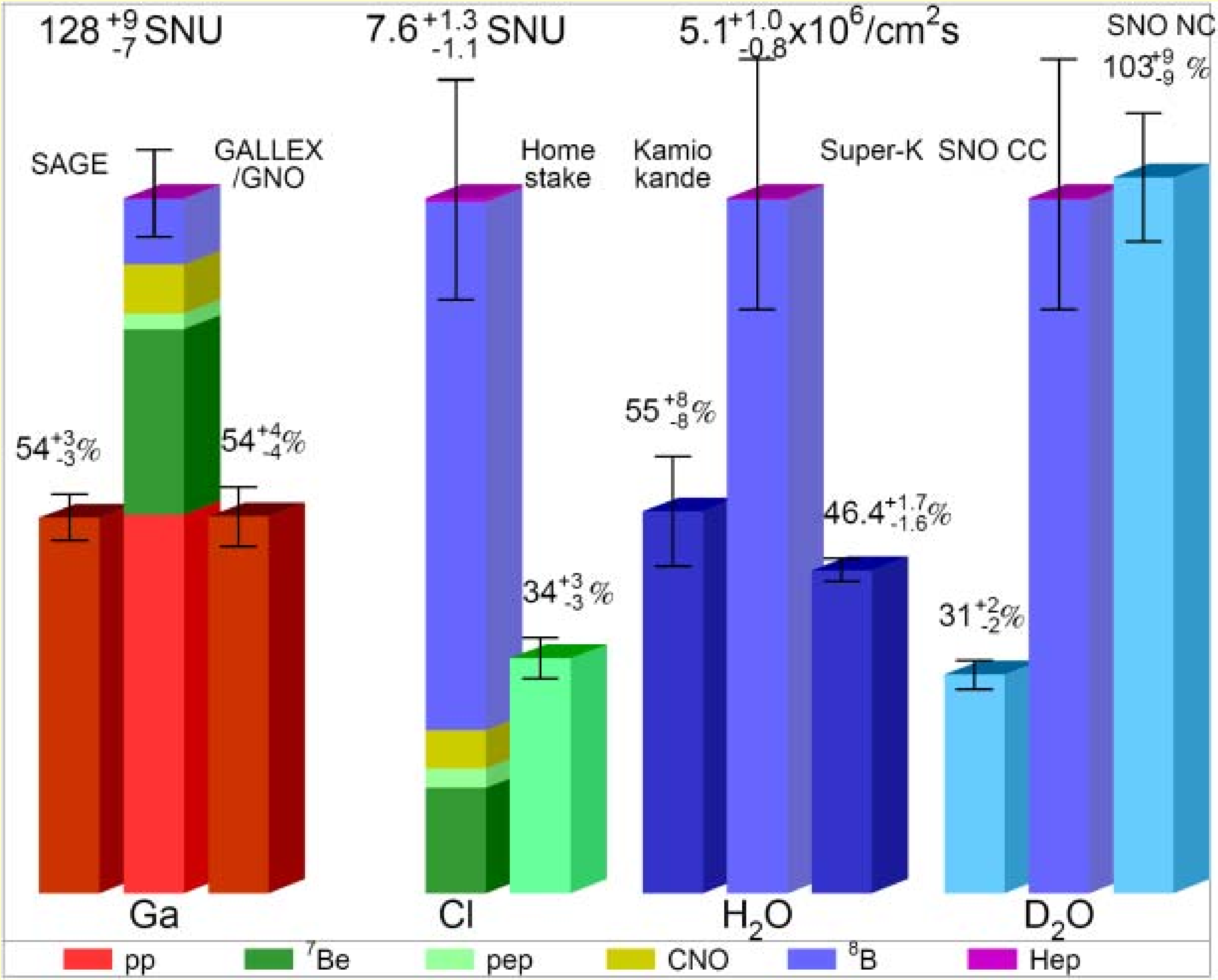
Solar ν Problem



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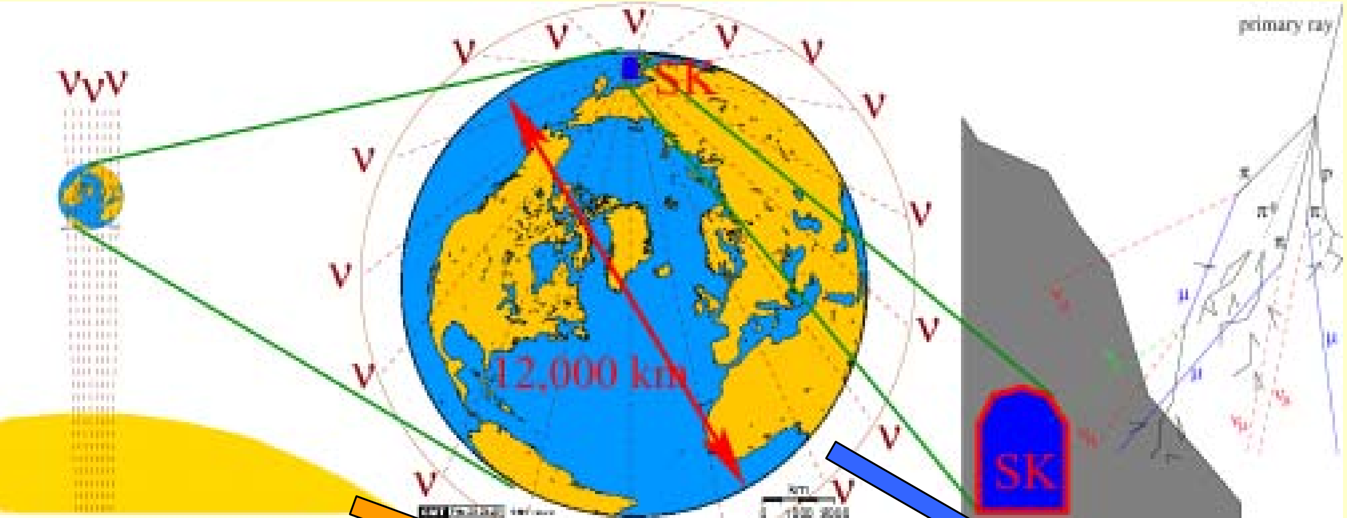
Neutrino Sources and Oscillations



- Atm. Neutrinos: (high energy)
  - e- and μ-type
  - Probe oscill. for Δm^2=0.001eV^2
  - Varying L (zenith angle) and E
  - Probe matter effects
- Solar Neutrinos: (low energy)
  - Only e-type
  - Probe oscill. for Δm^2=10^{-11} eV^2
  - Varying L (season) and E
  - Probe matter effects (solar zenith angle)

Mixing Matrix:

$$U = \begin{pmatrix} \boxed{c_{12}c_{13} \qquad s_{12}c_{13}} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

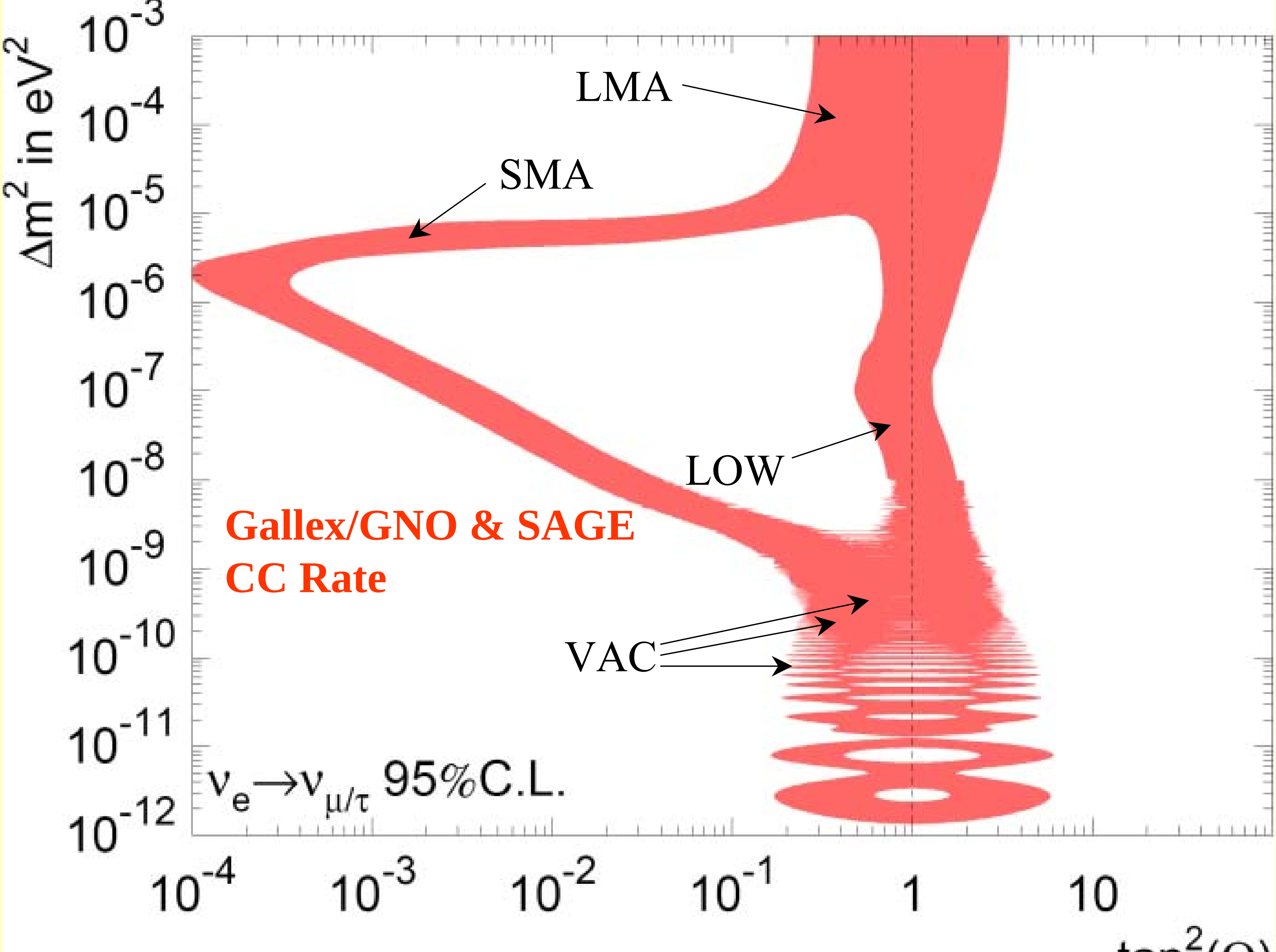
$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$P_{\text{vac}}(\alpha \to \beta) = \delta_{\alpha\beta} - 4\sum_{j<k} U_{\alpha j}U_{\beta j}U_{\alpha k}U_{\beta k}\sin^2\frac{\Delta m^2_{jk}L}{4E}$$

Matter-Effects

$$\left(\Delta m^2_{\mathbf{mat}}\right)^2 = \left(\Delta m^2\right)^2 \times \left[\left(\frac{2EV}{\Delta m^2} - \cos(2\theta)\right)^2 + \sin^2(2\theta)\right]$$

$$\sin^2(2\theta_{\mathbf{mat}}) = \sin^2(2\theta)\frac{\Delta m^2}{\Delta m^2_{\mathbf{mat}}}$$



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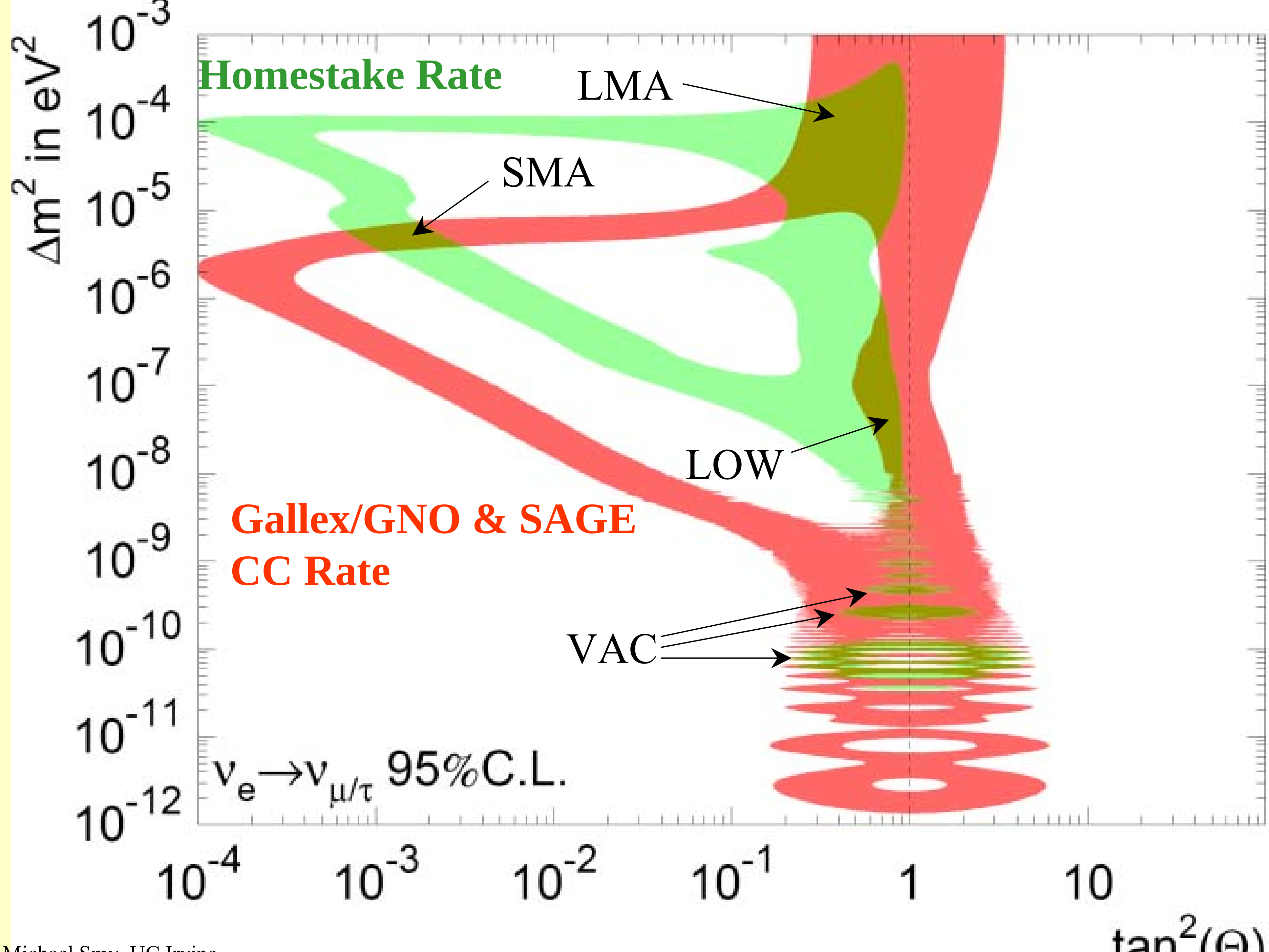

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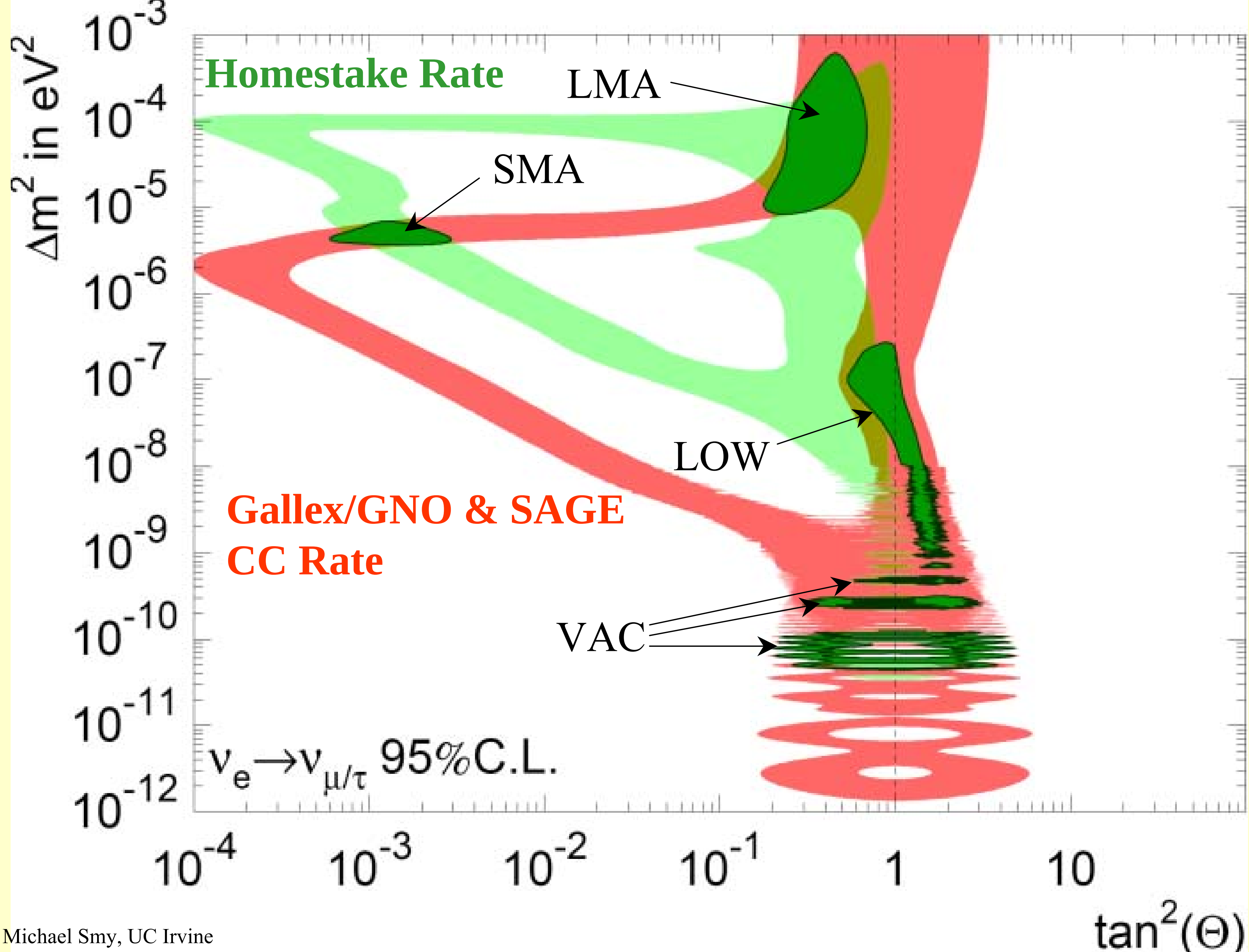

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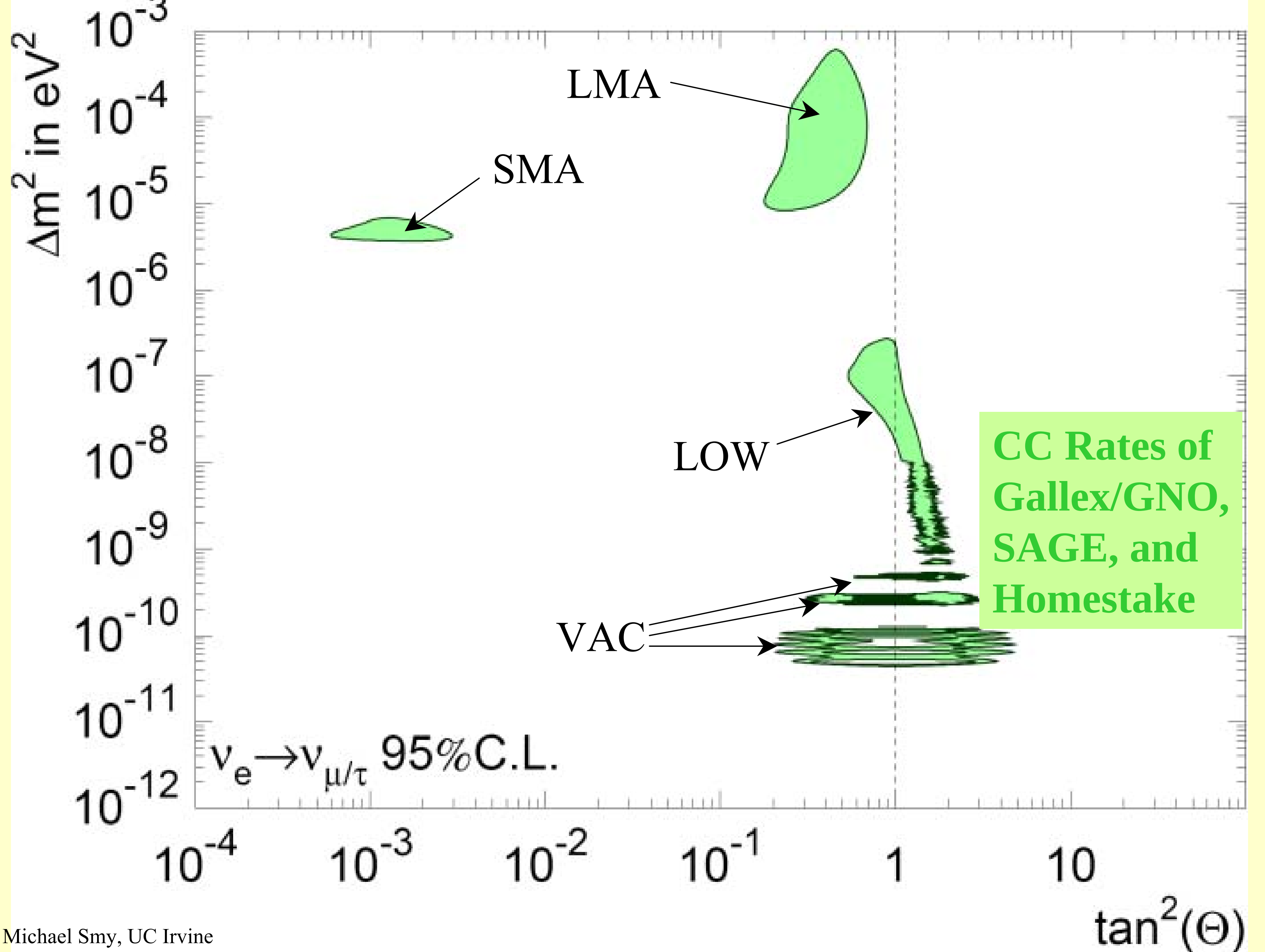

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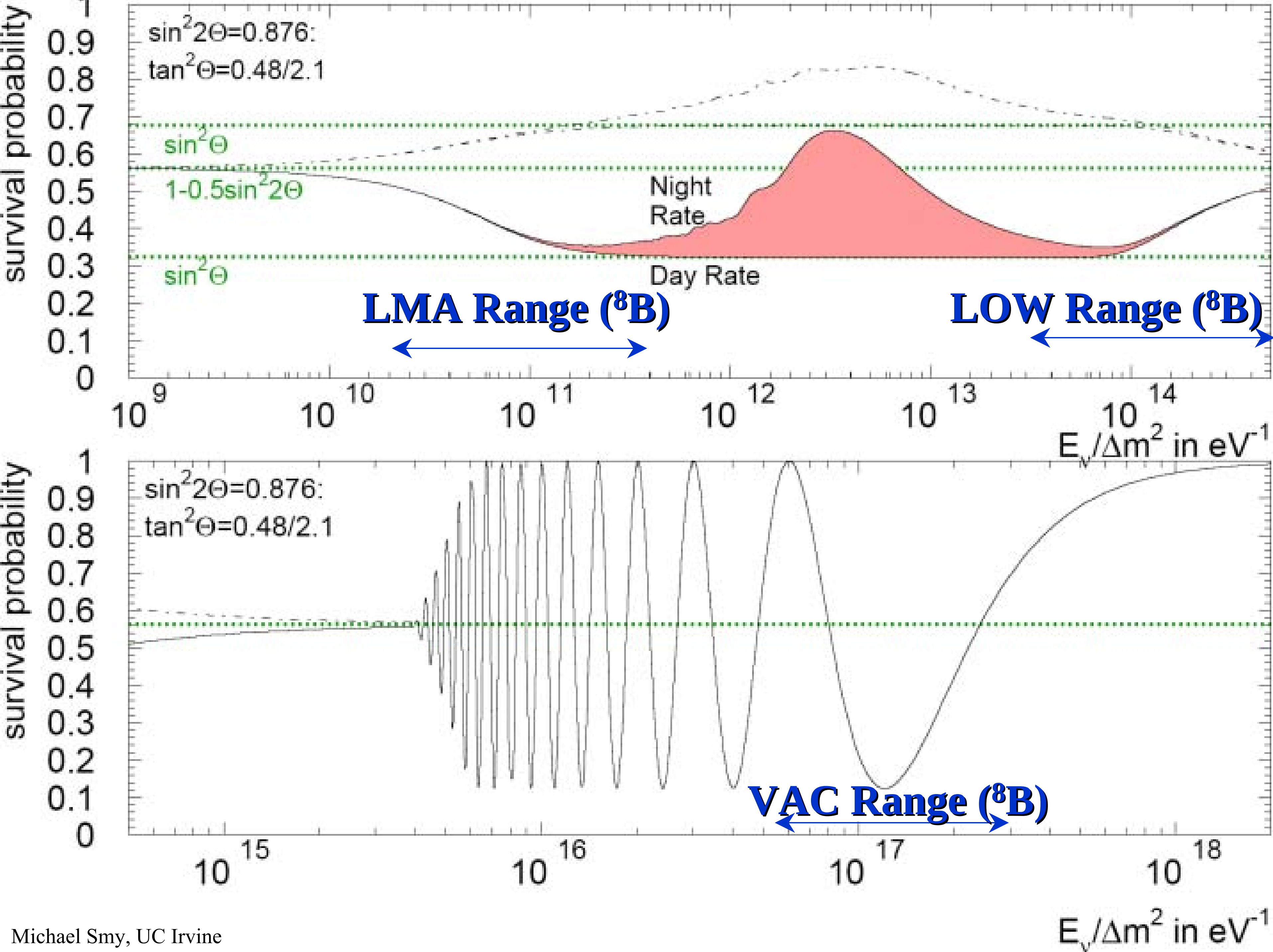
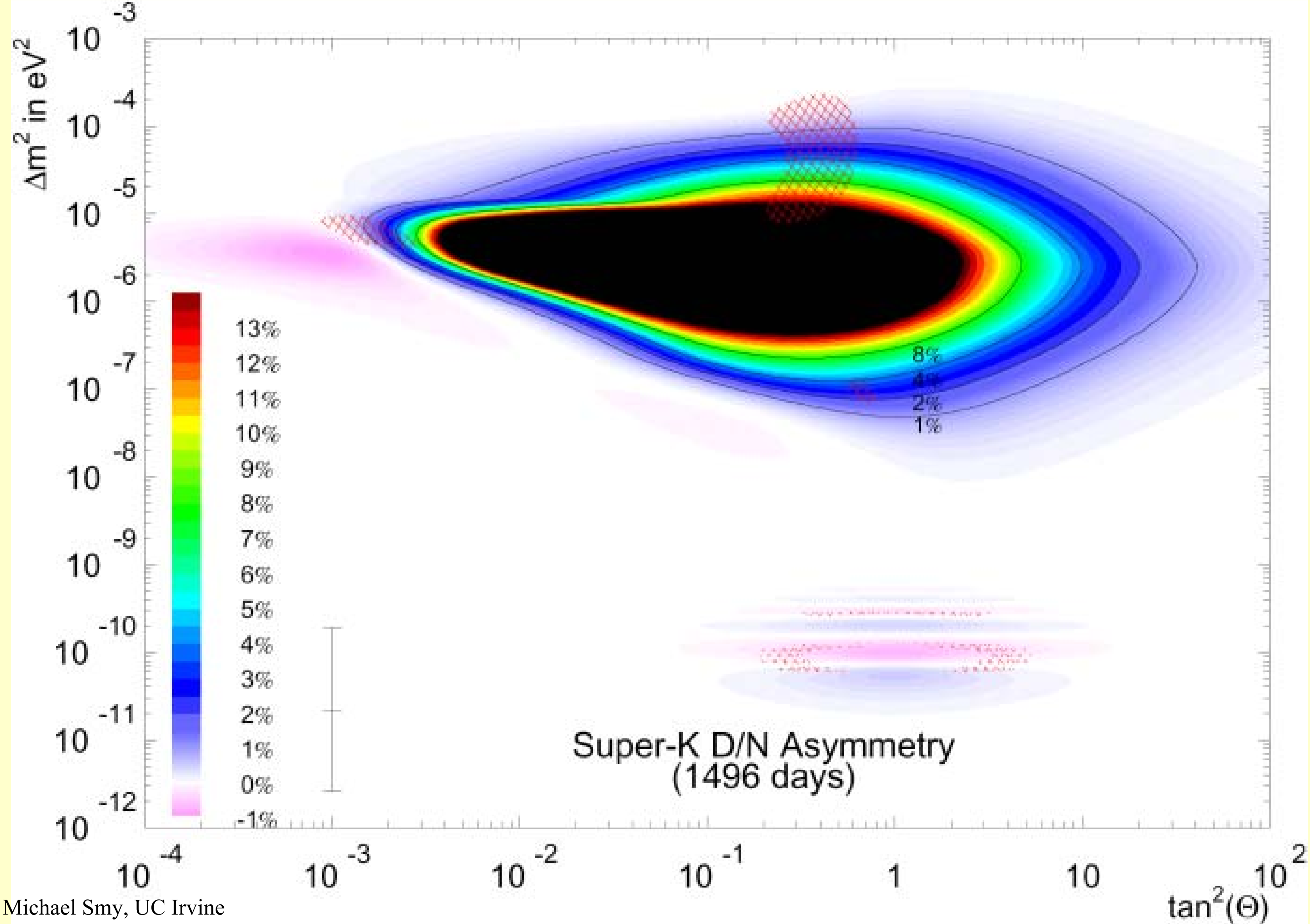
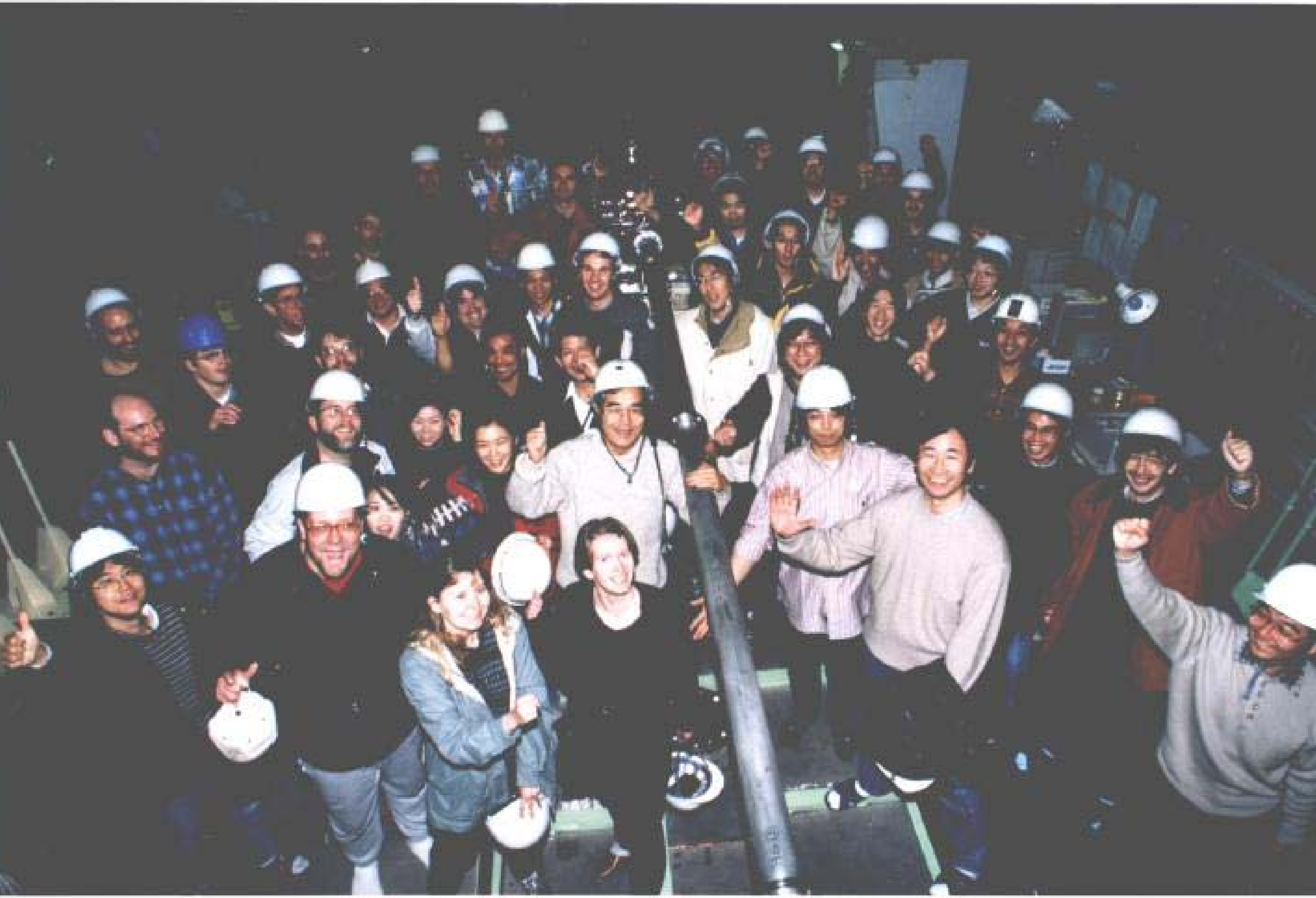


sin²2Θ=0.876:
tan²Θ=0.48/2.1
sin²Θ
1-0.5sin²2Θ
Night Rate
Day Rate
sin²Θ
LMA Range (⁸B)
LOW Range (⁸B)
survival probability
Eν/Δm² in eV⁻¹
sin²2Θ=0.876:
tan²Θ=0.48/2.1
VAC Range (⁸B)
survival probability
Eν/Δm² in eV⁻¹

Super-K Expected Day/Night



Super-K Collaboration



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H.I. Kim, S.B. Kim, J. Yoo

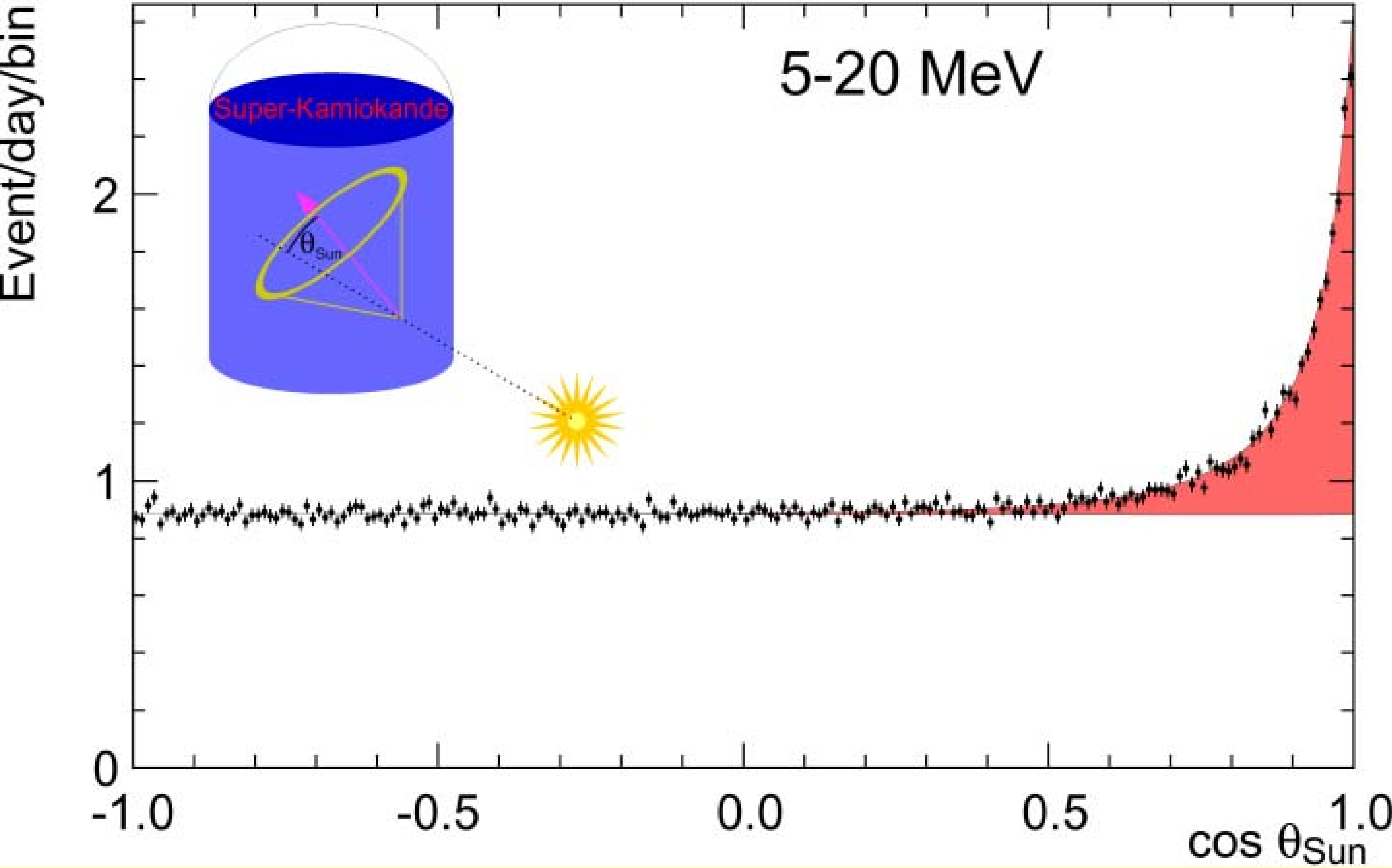
Super-K Solar Neutrinos

- 1496 Live Days between May 31st, 1996 and July 15th, 2001
- High Statistics
- Measures ^{8}B, limits *hep* flux
- ^{8}B flux time variations
- Studies energy spectrum
- Some sensitivity to other than *e*-type neutrinos

Oscillation Signatures

- Suppression of ^{8}B flux
- Appearance of other active flavors (with SNO)
- Spectral Distortion
- Daily variations of ^{8}B flux
- Anomalous yearly variations of ^{8}B flux

Solar ν Candidates above 5 MeV



Super-K Solar Neutrino Rate

1496 Day Final Sample:

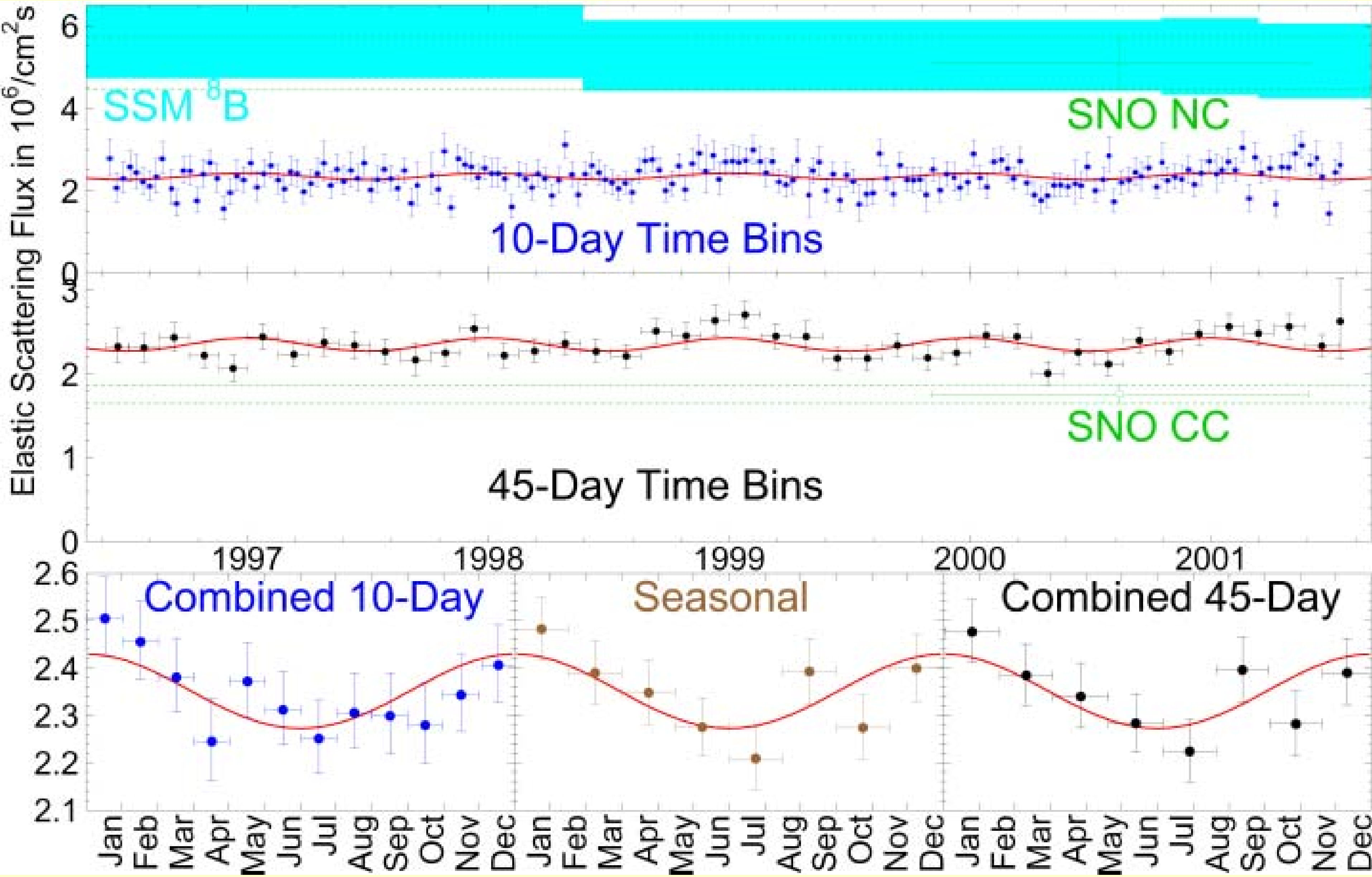
flux is
$2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\text{cm}^2 \cdot \text{s}$
or $0.465 \pm 0.005(\text{stat.})^{+0.016}_{-0.015}(\text{sys.}) \times \text{SSM}$

- 22,400 solar neutrino events
- 18-21 MeV: 4.9±2.7 events
- Expect ~1 *hep* neutrino (SSM)
- Expect ~2 *hep* neutrinos (oscillation best fit: ~4x SSM)
- 90% C.L. upper limit of *hep* flux: $73 \times 10^3/\text{cm}^2\text{s}$ (7.9xSSM)

Expect:

- 48,200 solar neutrinos (from SSM)
- 16,700 *e*-type solar neutrinos (from SNO)
- About 5,700 μ/τ-type solar neutrinos

Time Dependence of SK Rate



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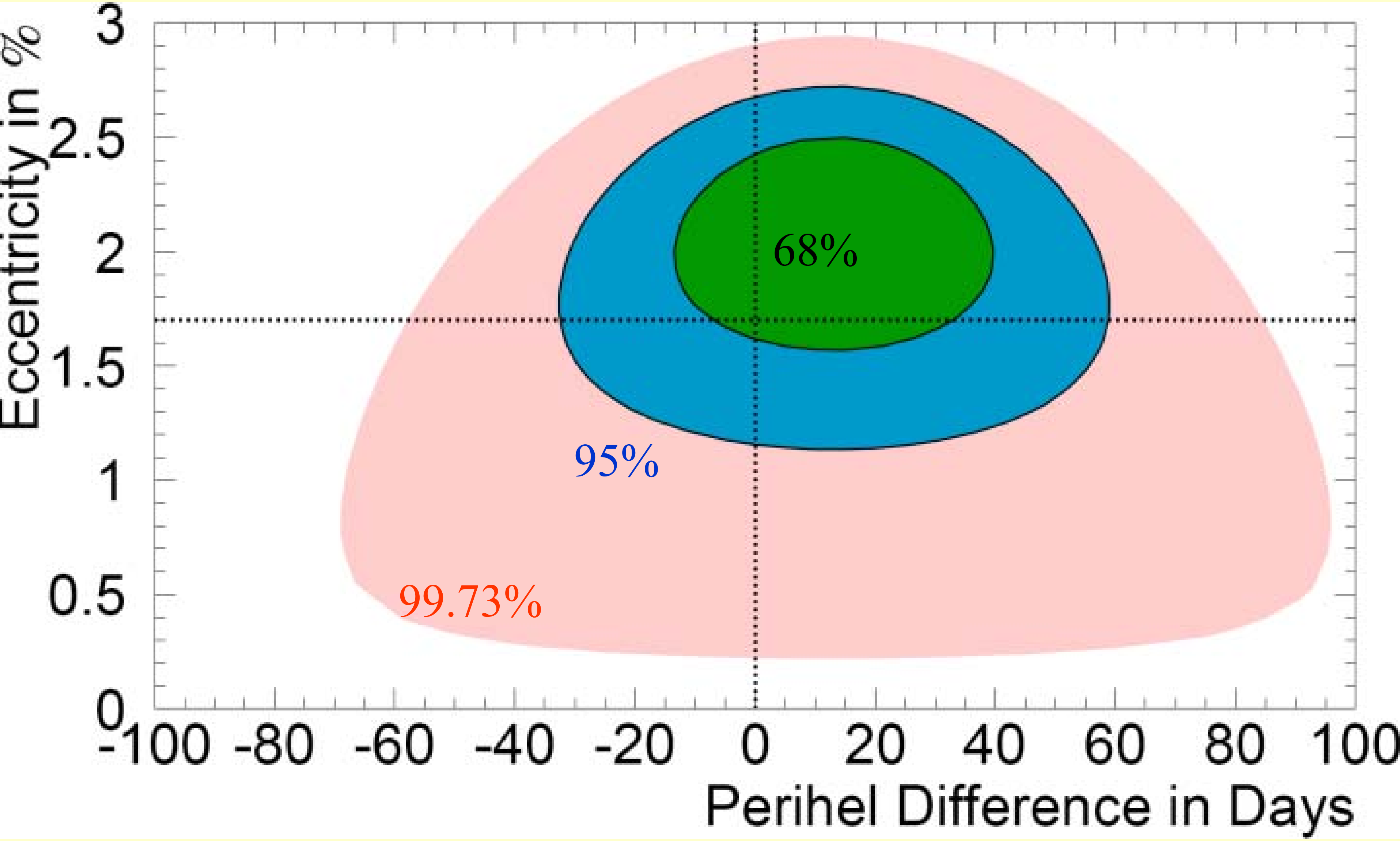
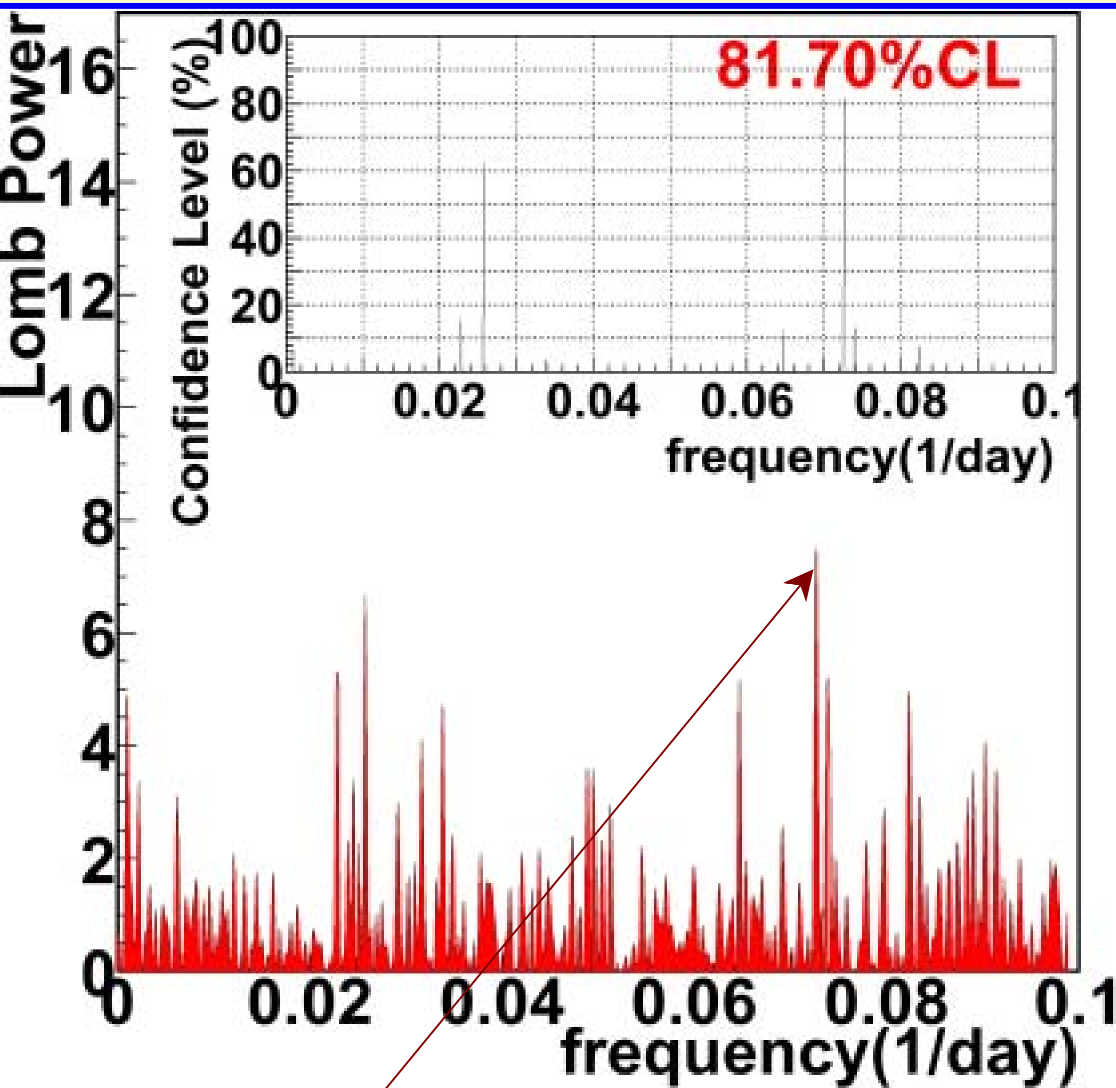
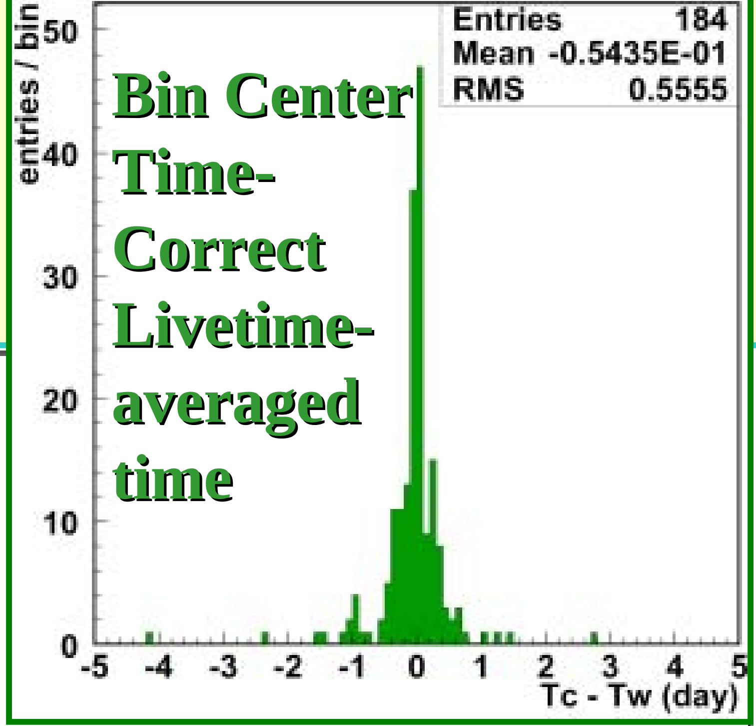
Allowed Eccentricity Region

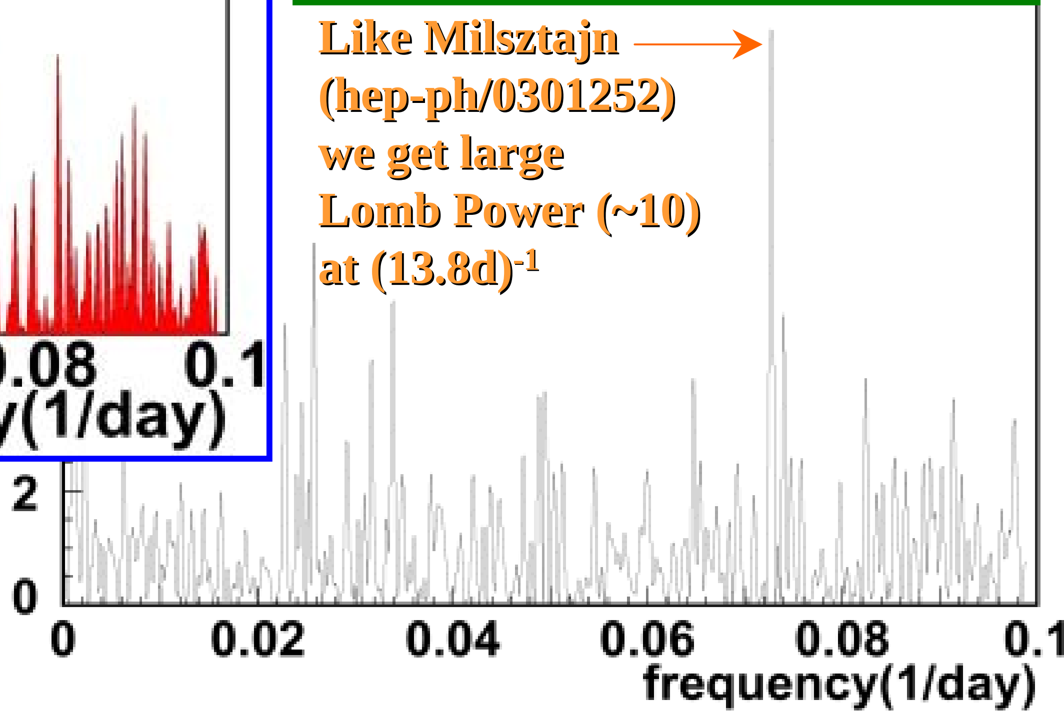


Time Variations:



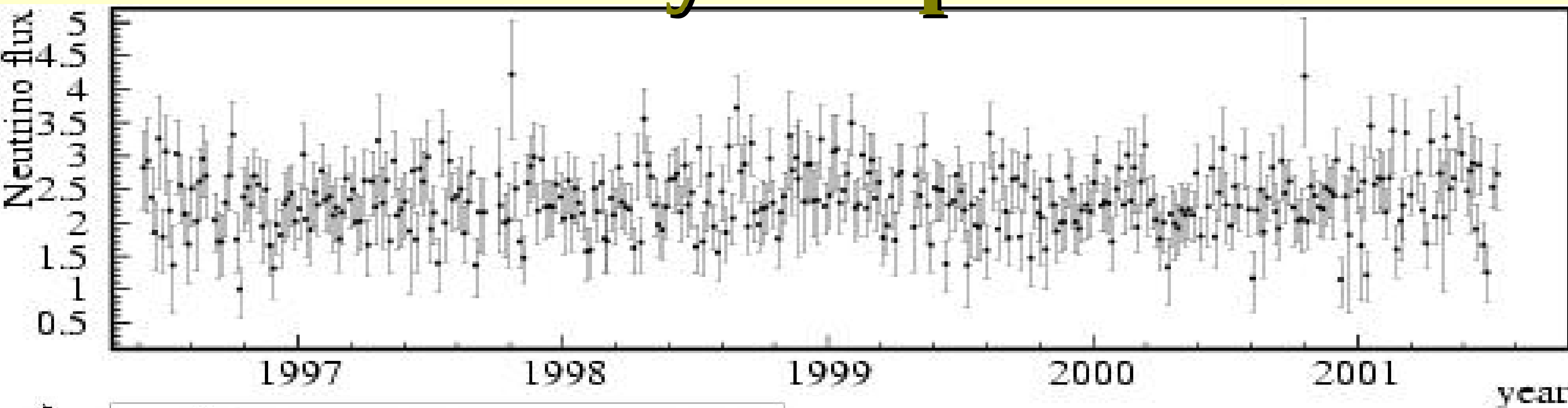


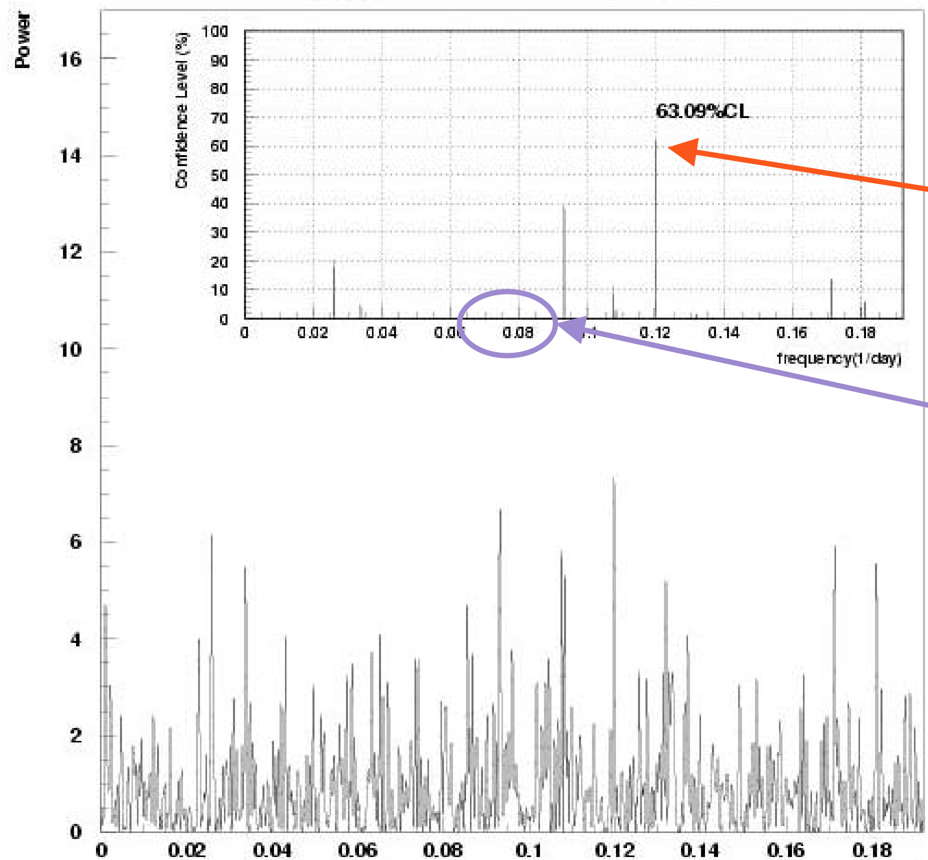
Like Milsztajn (hep-ph/0301252) we get large Lomb Power (~10) at $(13.8d)^{-1}$



Lomb Power decreases, if Correct bin-time is used!!

5 Day Sample



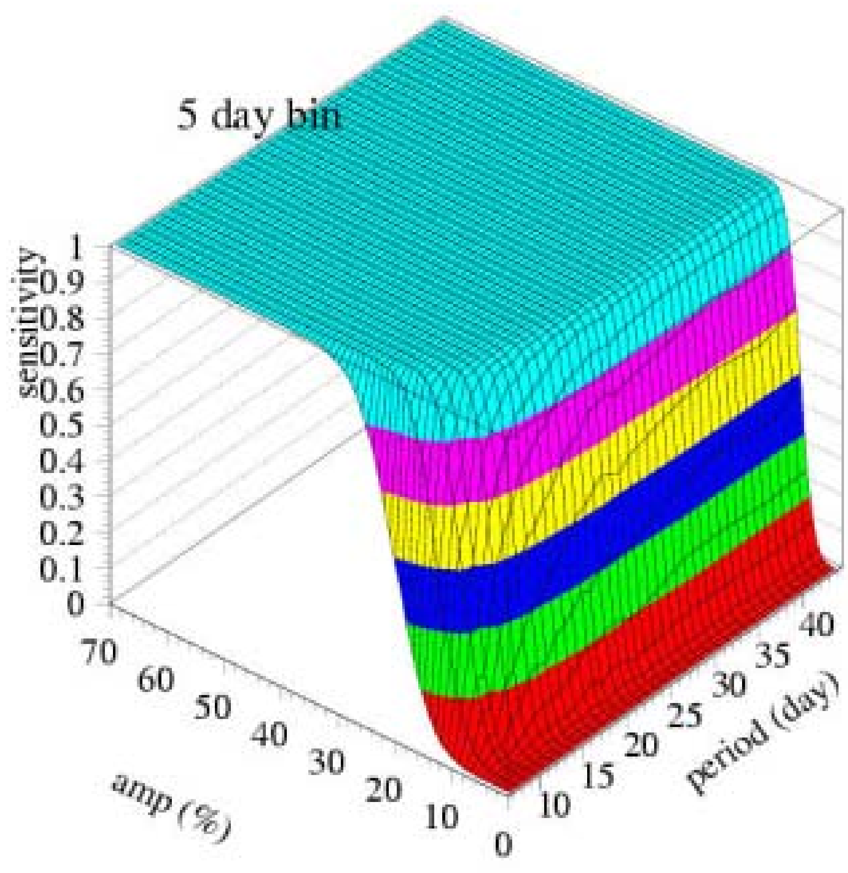


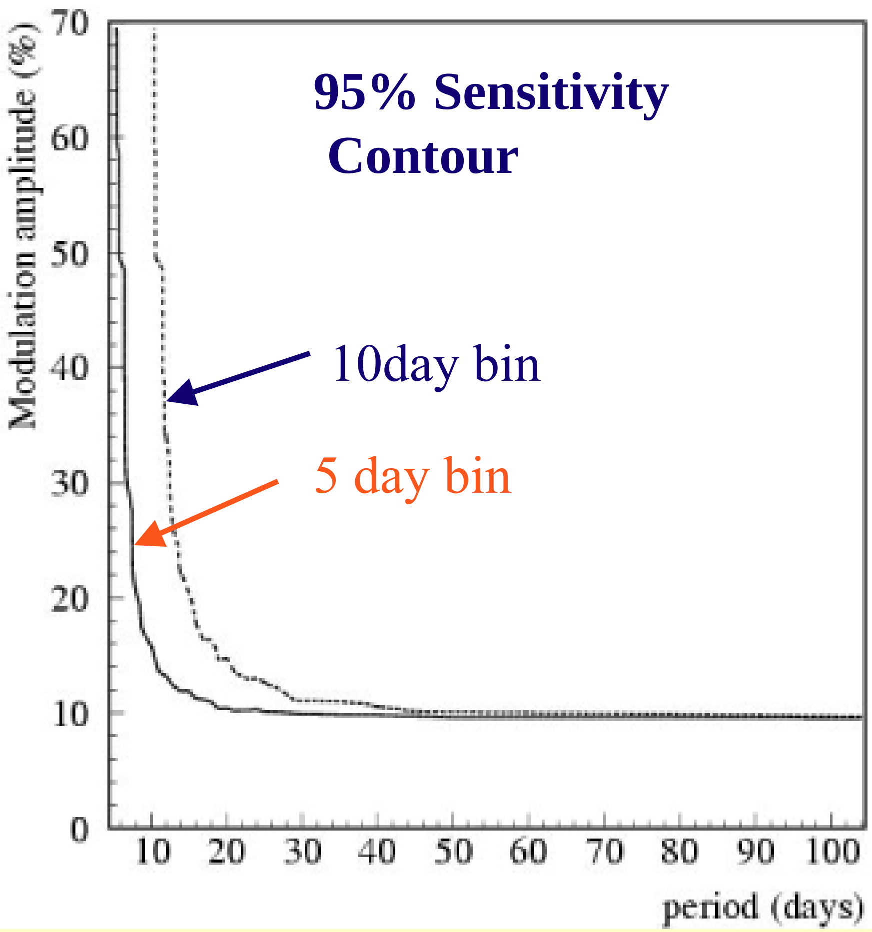
8.35 day (63.09%CL)

@13.75 day (0.00% CL)

No Significant Periodicity

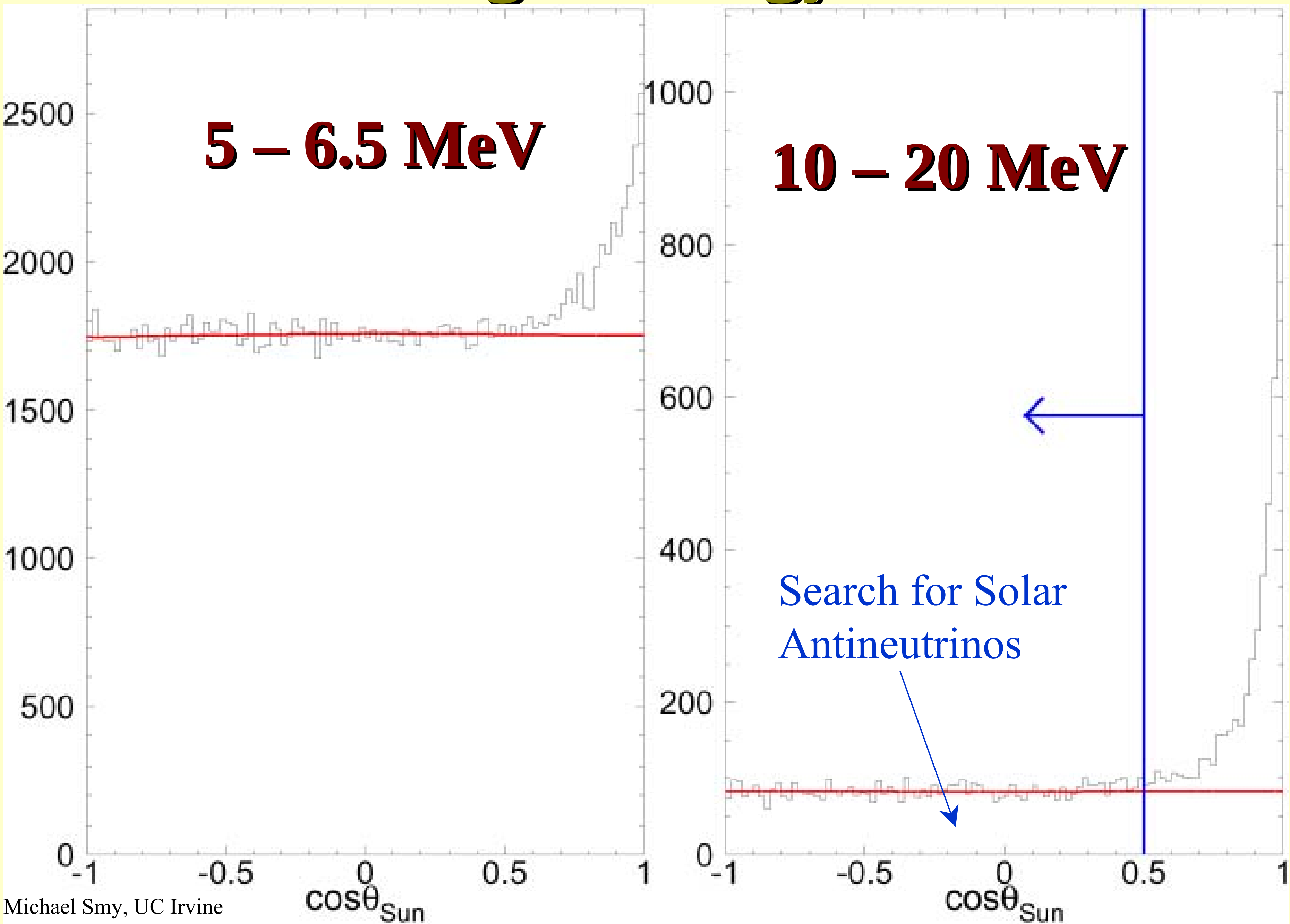
Sensitivity to Modulations



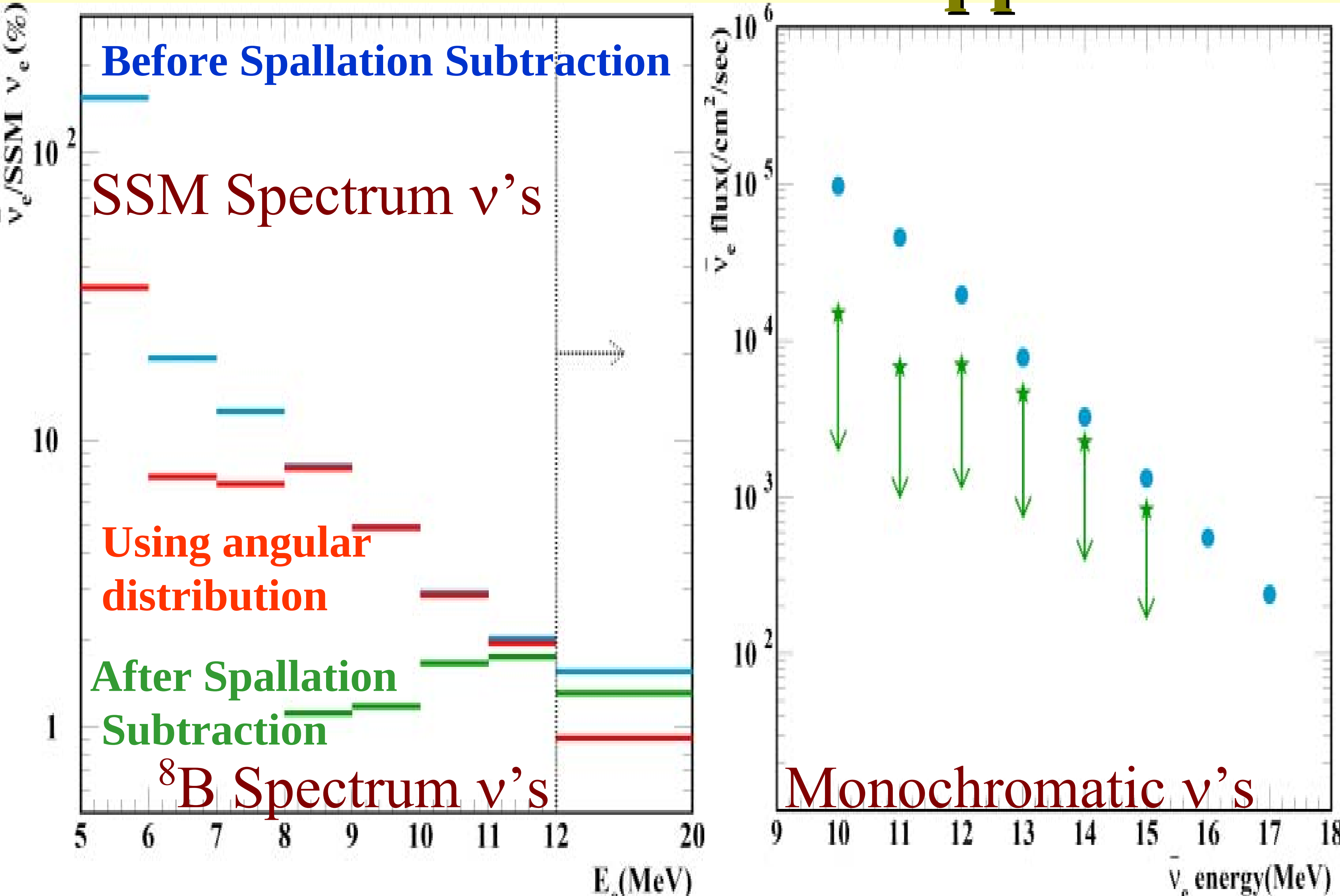


Anti-Neutrinos from the Sun?

Low and High Energy Solar Peak



Solar Antineutrino 90% Upper Limit



Signal and D/N Asymmetry Extraction in Super-Kamiokande

"Solfit": Ext. Max. Likelihood

Background Events in 21 bins

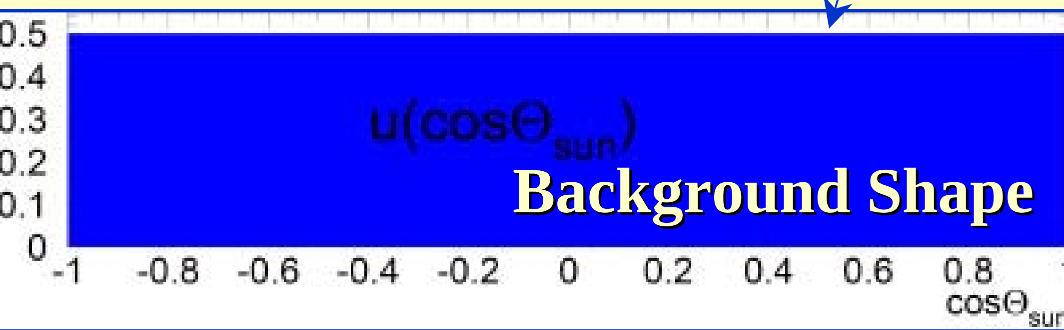
Signal Events

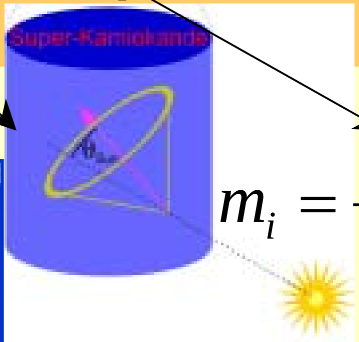
Event Energy

Event "Time"

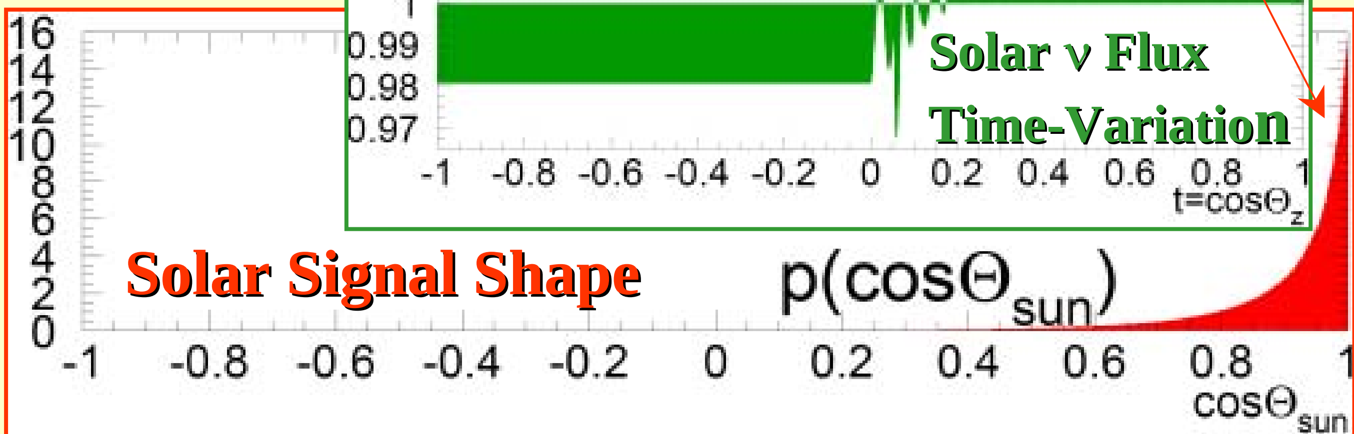
$$\mathbf{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(B_i \cdot u_i(c_\nu) + m_i S \cdot p(c_\nu, E_\nu) \times z_i(t_\nu) \right)$$

21 Energy bins





$$m_i = \frac{\mathrm{MC}_i}{\sum_j \mathrm{MC}_j}$$



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Time Dependence Factor z(t)

Scale "Time"-Dependent rate $r_1(t)$ (expected from ν oscillation) by α, using livetime distribution $l(t)$:

$$z_\alpha(t)=\frac{r_\alpha(t)}{R_\alpha}=\frac{1+\alpha\times\left(z_1(t)(1+a_1)-1\right)}{1+\alpha\times a_1}$$

$$R_\alpha=\frac{1}{L}\int_{-\tau}^{+\tau} r_\alpha(t)l(t)dt \text{ with } L=\int_{-\tau}^{+\tau} l(t)dt$$

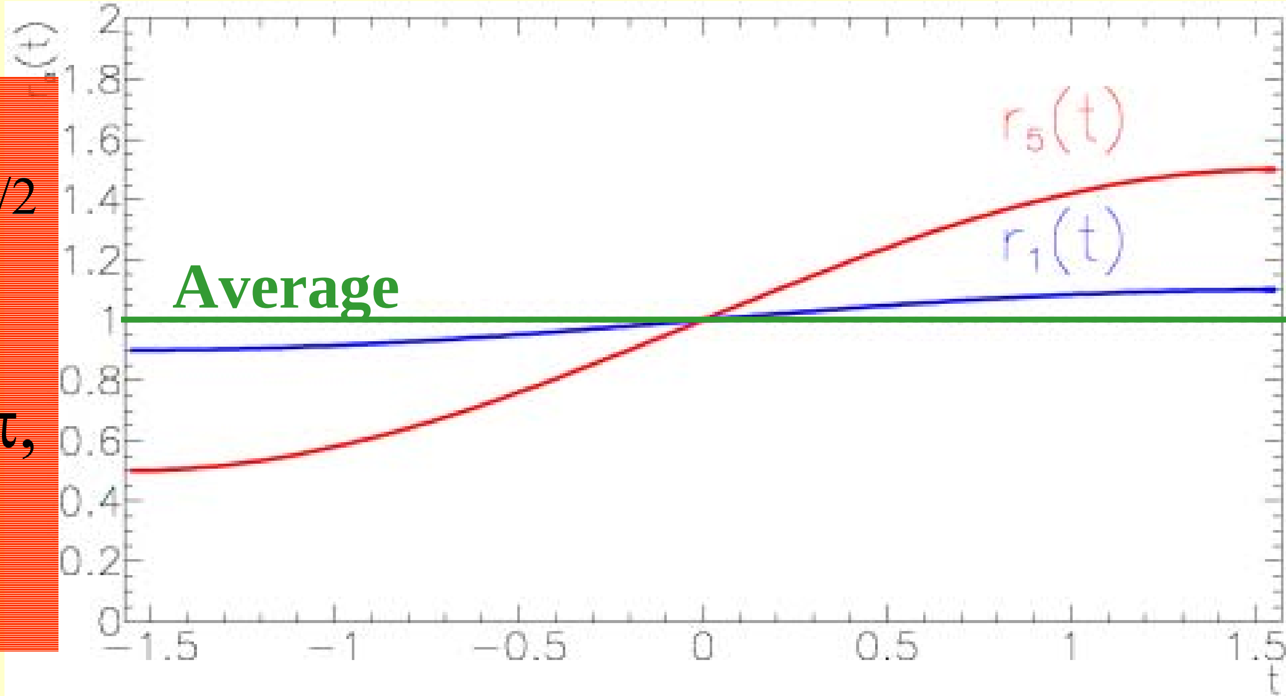
$$P_\alpha=\frac{1}{L_+}\int_0^{\tau} r_\alpha(t)l(t)dt,\quad M_\alpha=\frac{1}{L_-}\int_{-\tau}^{0} r_\alpha(t)l(t)dt$$

$$L_{+-}=\frac{L_+-L_-}{\frac{1}{2}(L_++L_-)},\ a_\alpha=\frac{1}{2}A_\alpha\times\frac{1}{2}L_{+-}=\alpha\times a_1$$

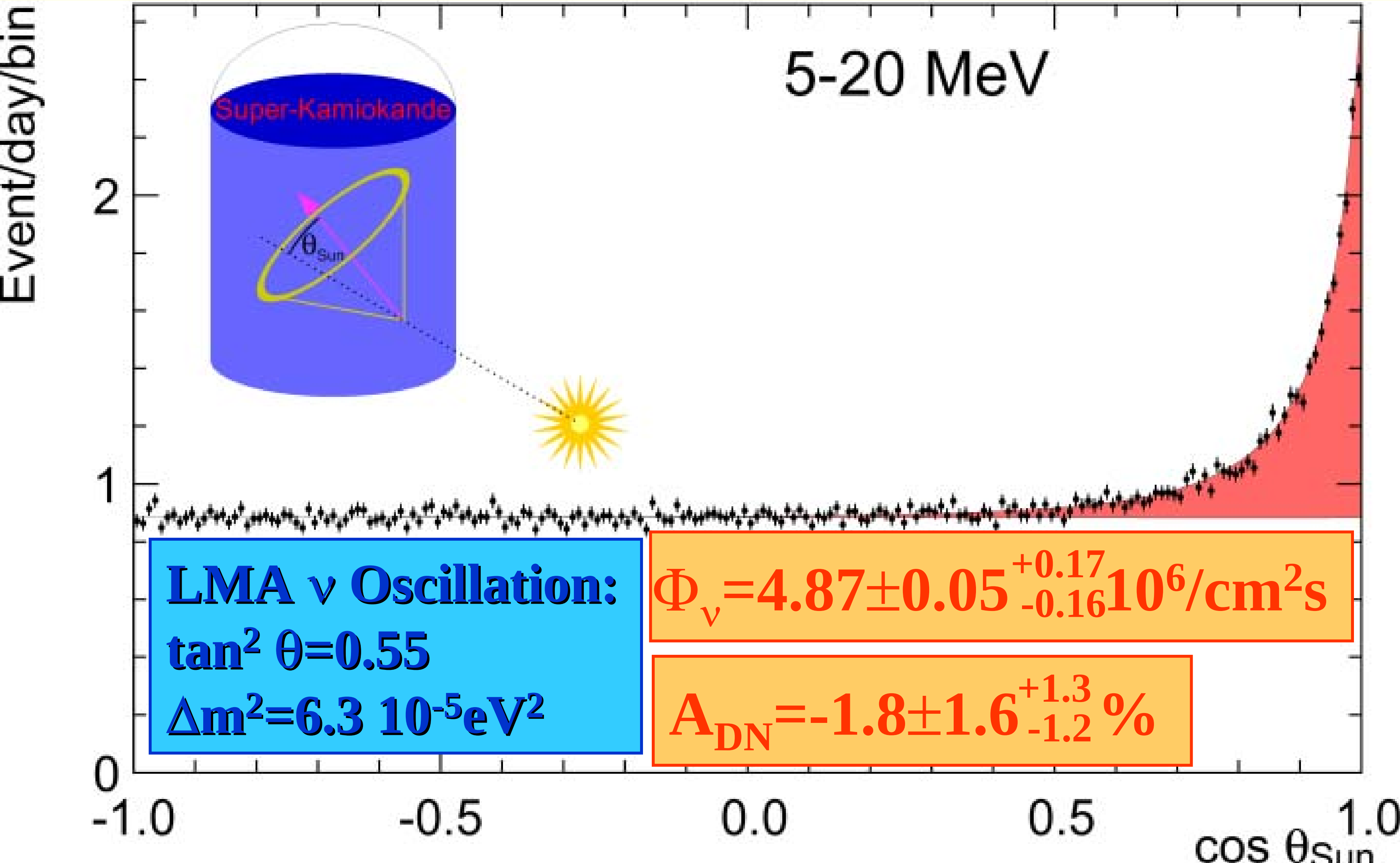
$$A_\alpha=\frac{P_\alpha-M_\alpha}{\frac{1}{2}(P_\alpha+M_\alpha)}=\alpha\times A_1,\quad R_\alpha=R_1$$

Example:

- **$r_1(t)=1+0.1\sin(t)$:**
  $l(t)=0.99/\pi$ ($t<0$) with $\tau=\pi/2$
  $l(t)=1.01/\pi$ ($t>0$) so
  $\rightarrow R=1.001$, $L=1$,
  $L_{+-}=0.02$, $A_1=0.2/\pi$,
  $a_1=0.001$
- **$r_\alpha=1+0.1\alpha\sin(t)$**



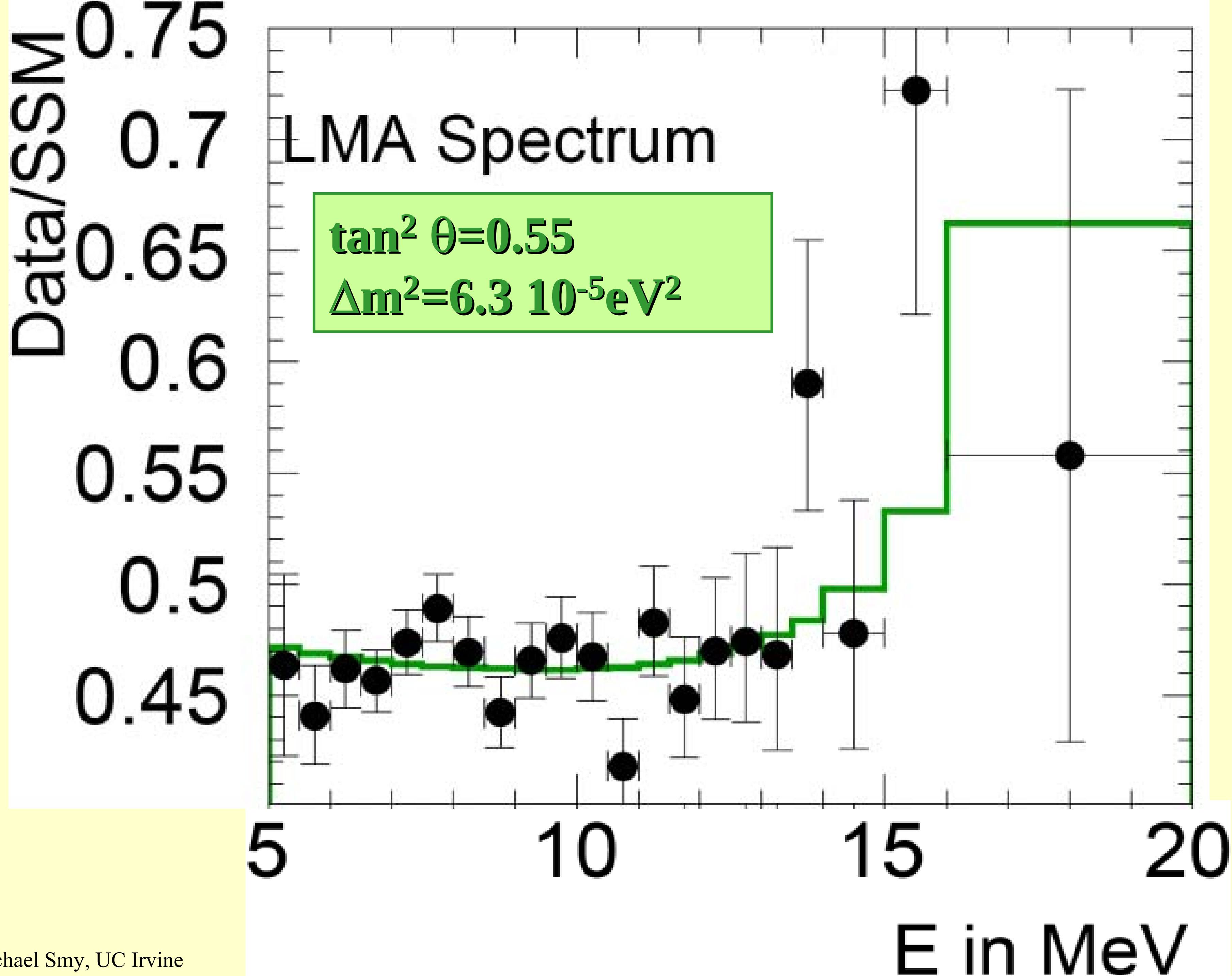
Solar ν Candidates above 5 MeV

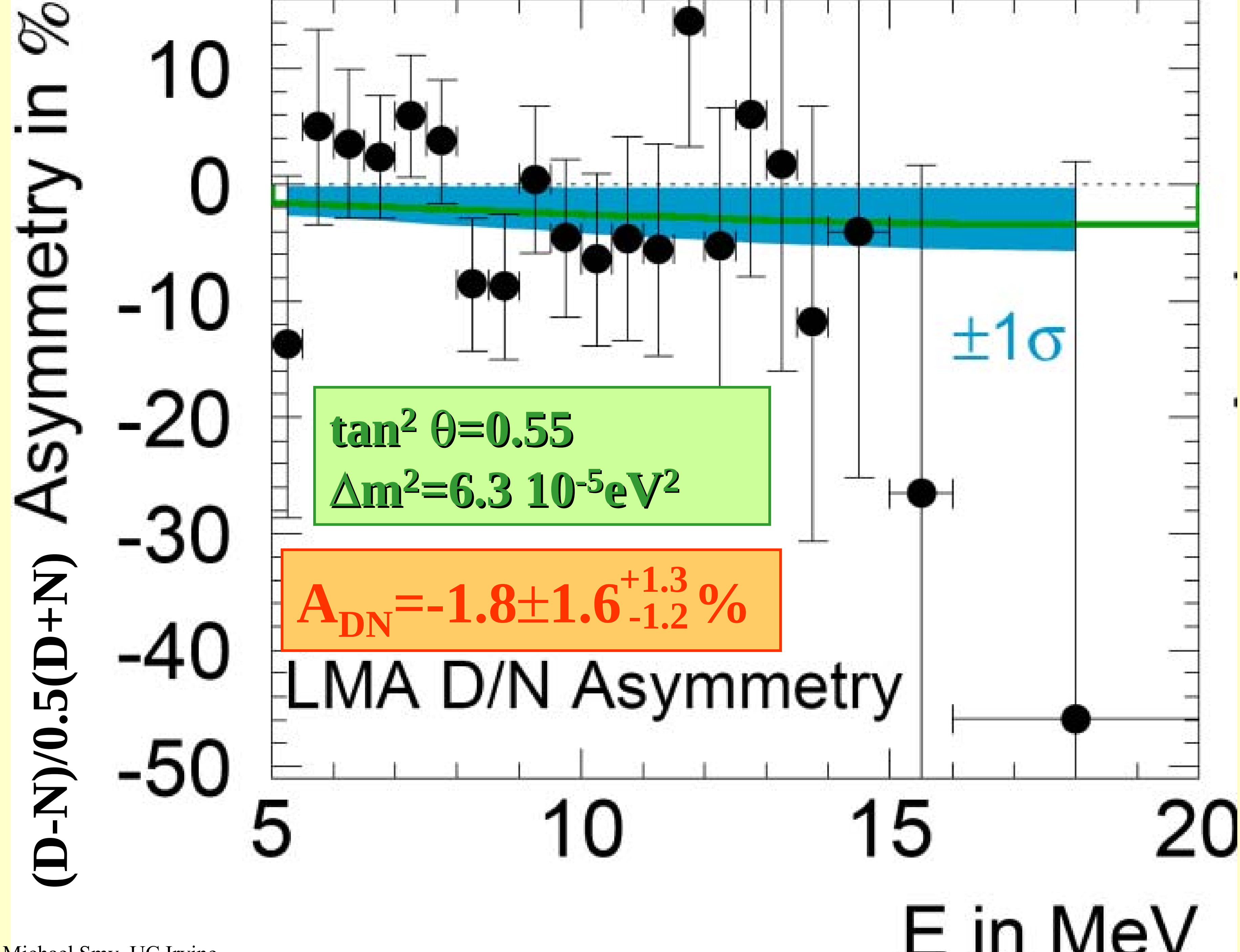


LMA ν Oscillation:
$\tan^2\theta=0.55$
$\Delta m^2=6.3\ 10^{-5}\mathrm{eV}^2$

$\Phi_\nu=4.87\pm0.05^{+0.17}_{-0.16}10^6/\mathrm{cm}^2\mathrm{s}$

$A_{DN}=-1.8\pm1.6^{+1.3}_{-1.2}\ \%$


Data/SSM
0.75
0.7
0.65
0.6
0.55
0.5
0.45
LMA Spectrum
tan² θ=0.55
Δm²=6.3 10⁻⁵eV²
5
10
15
20
E in MeV



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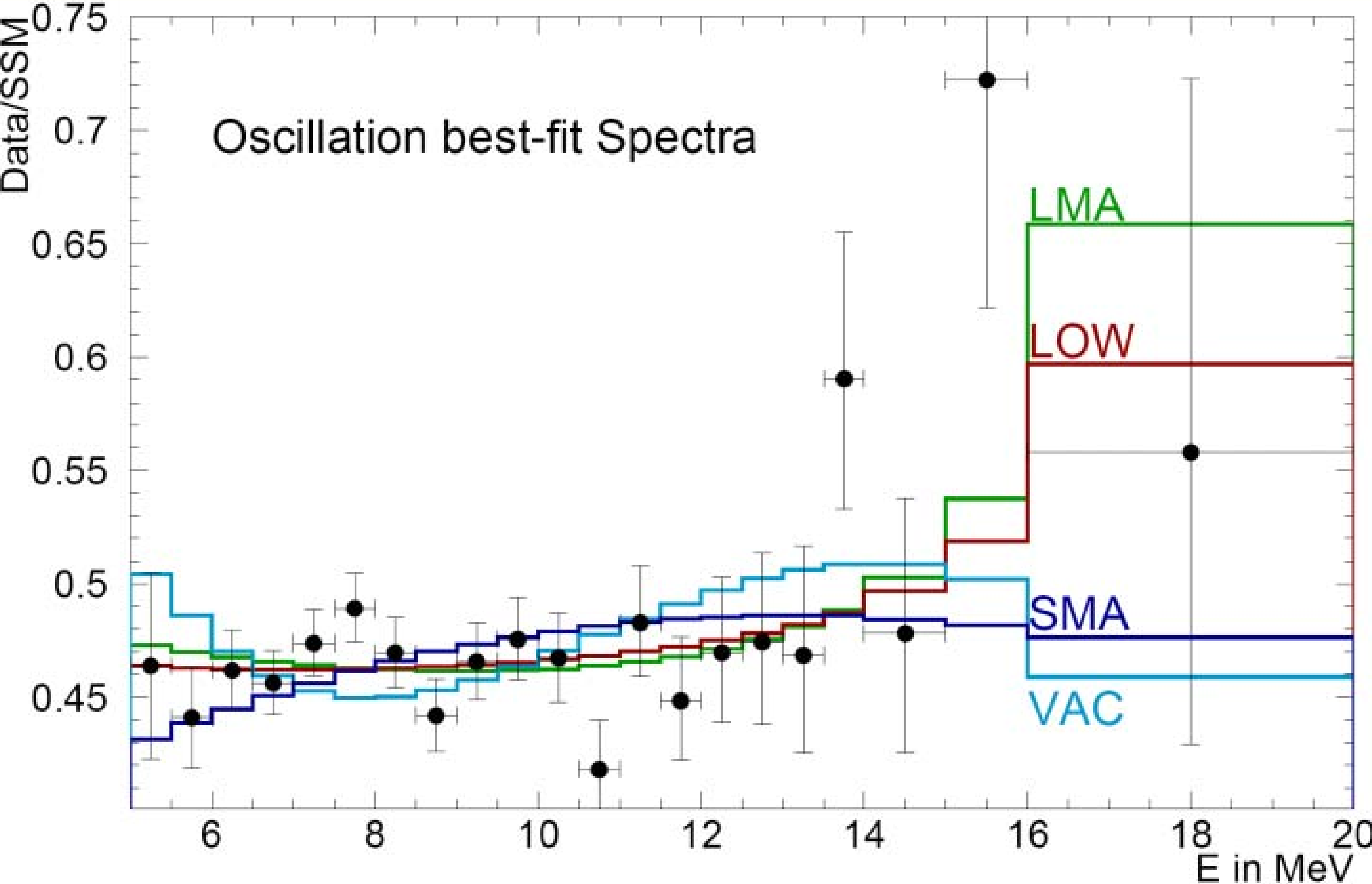
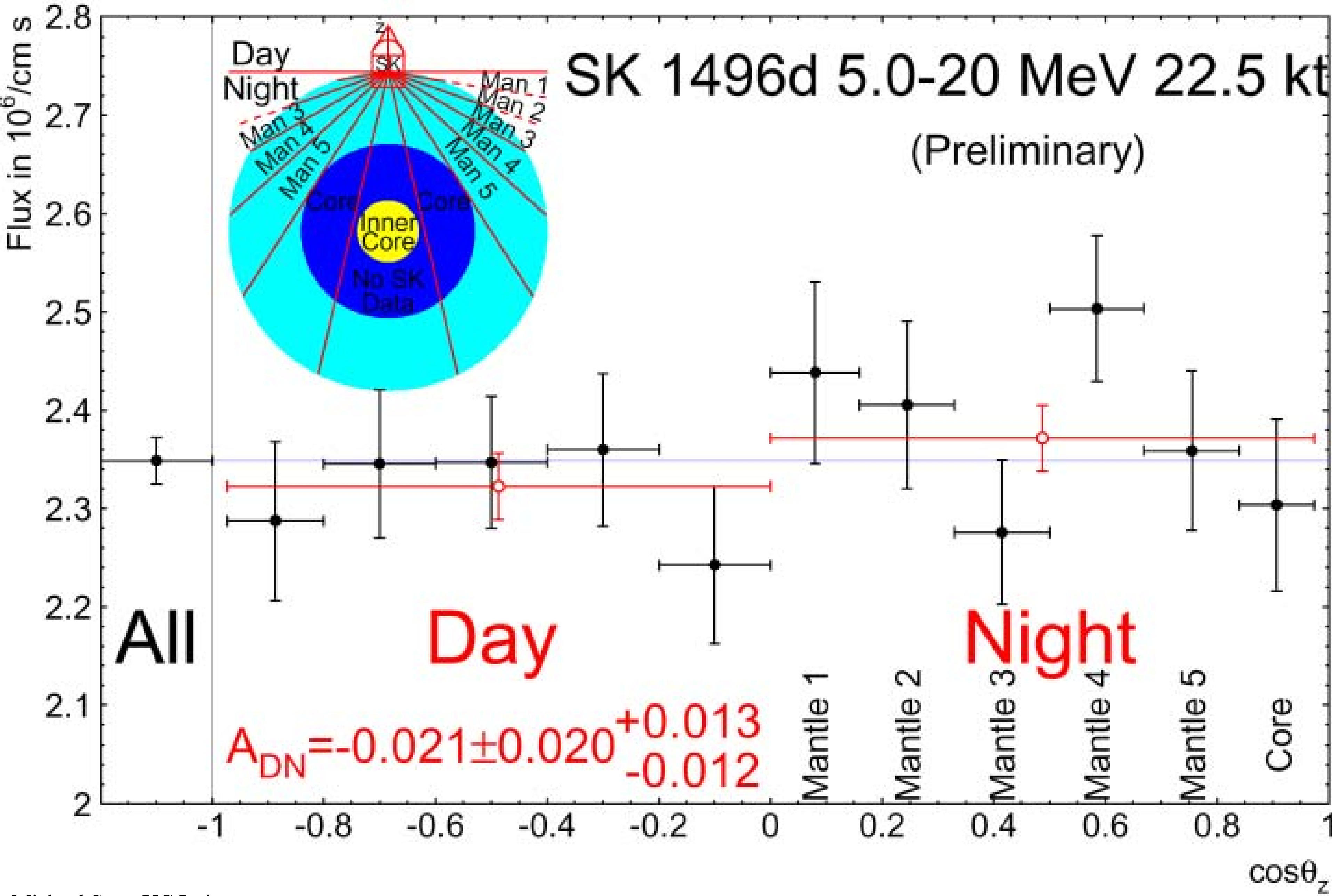
Oscillation-induced Spectral Distortions



Daily Variation of SK Rate



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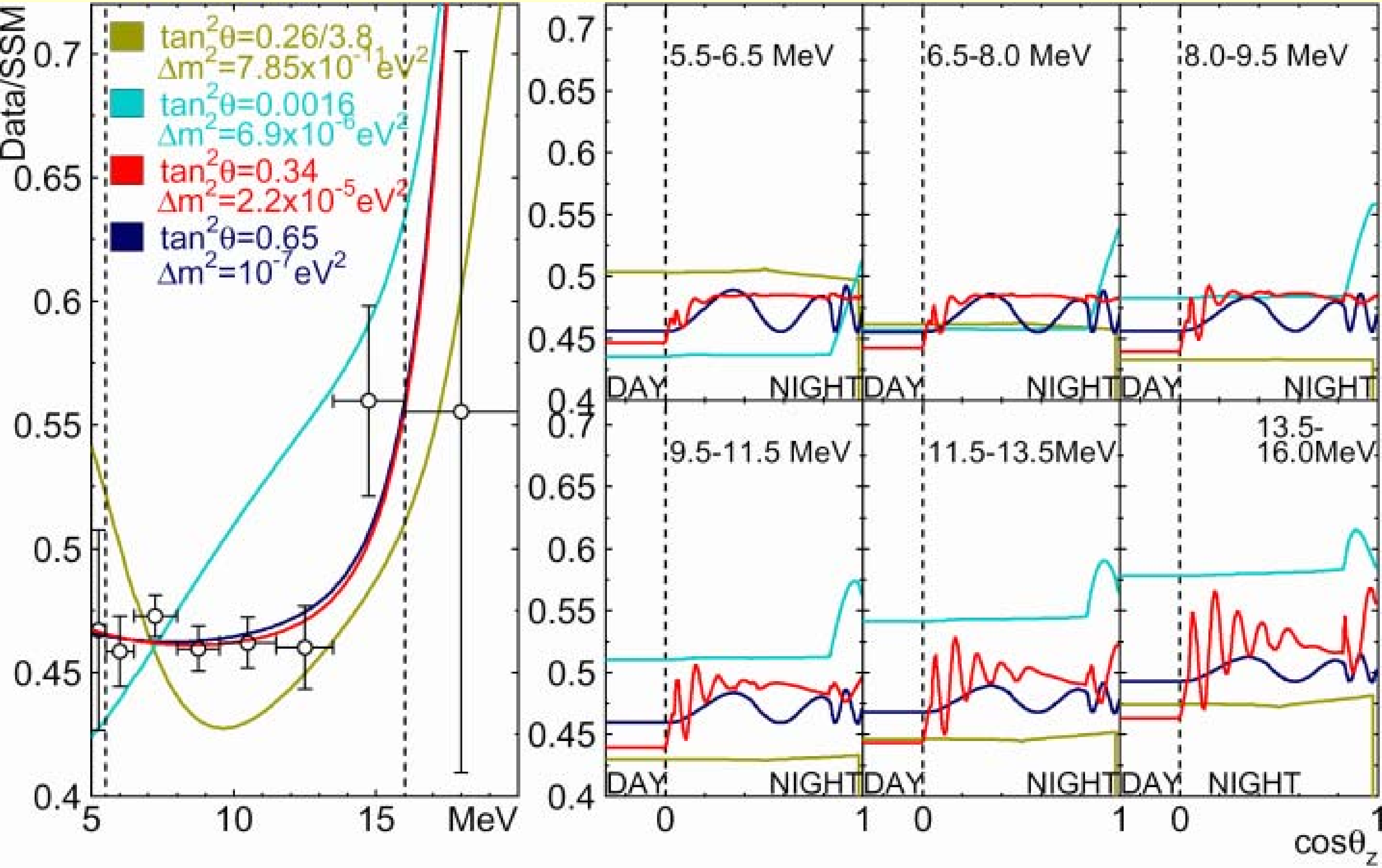
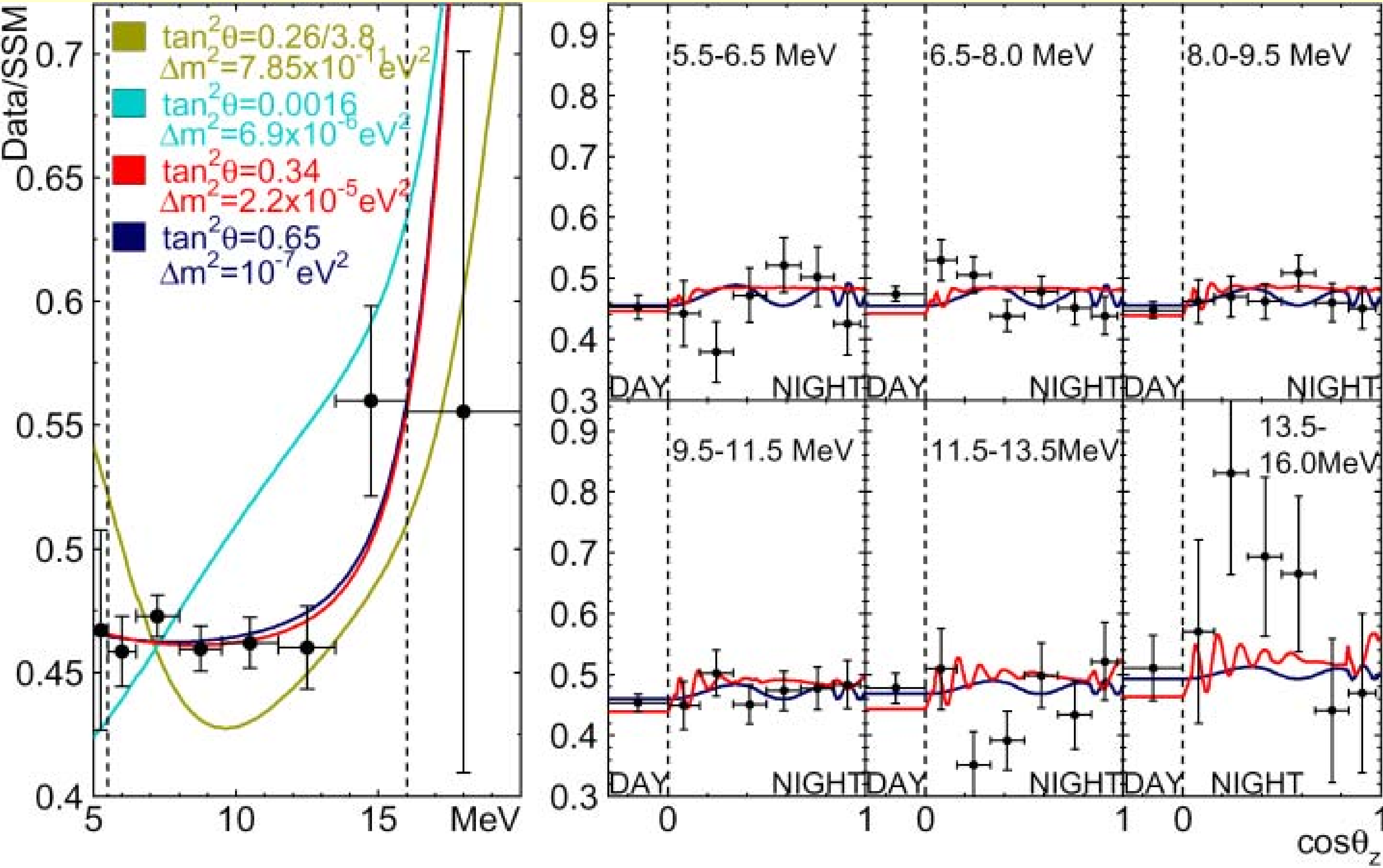
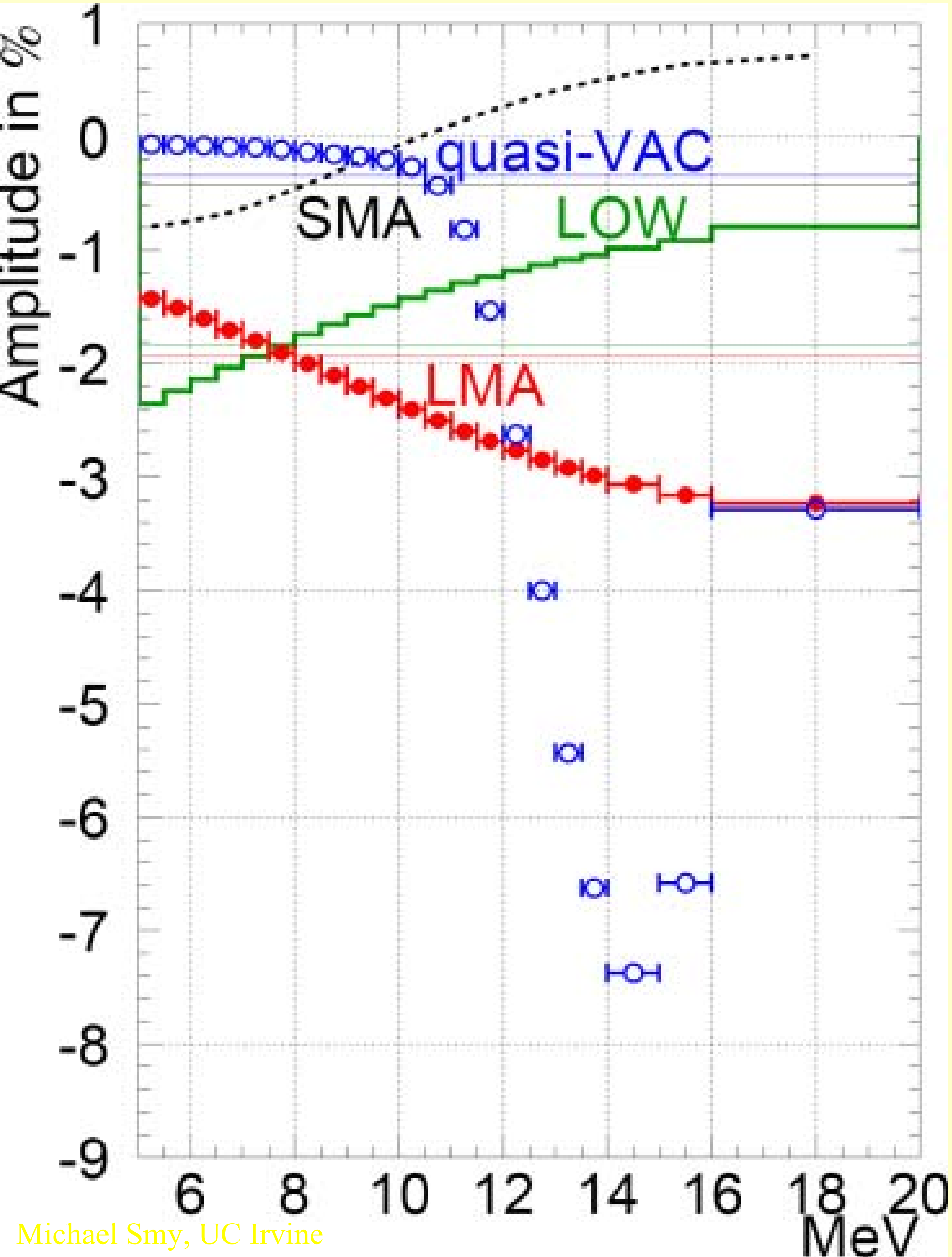
Zenith Spec.: Oscillation Solutions

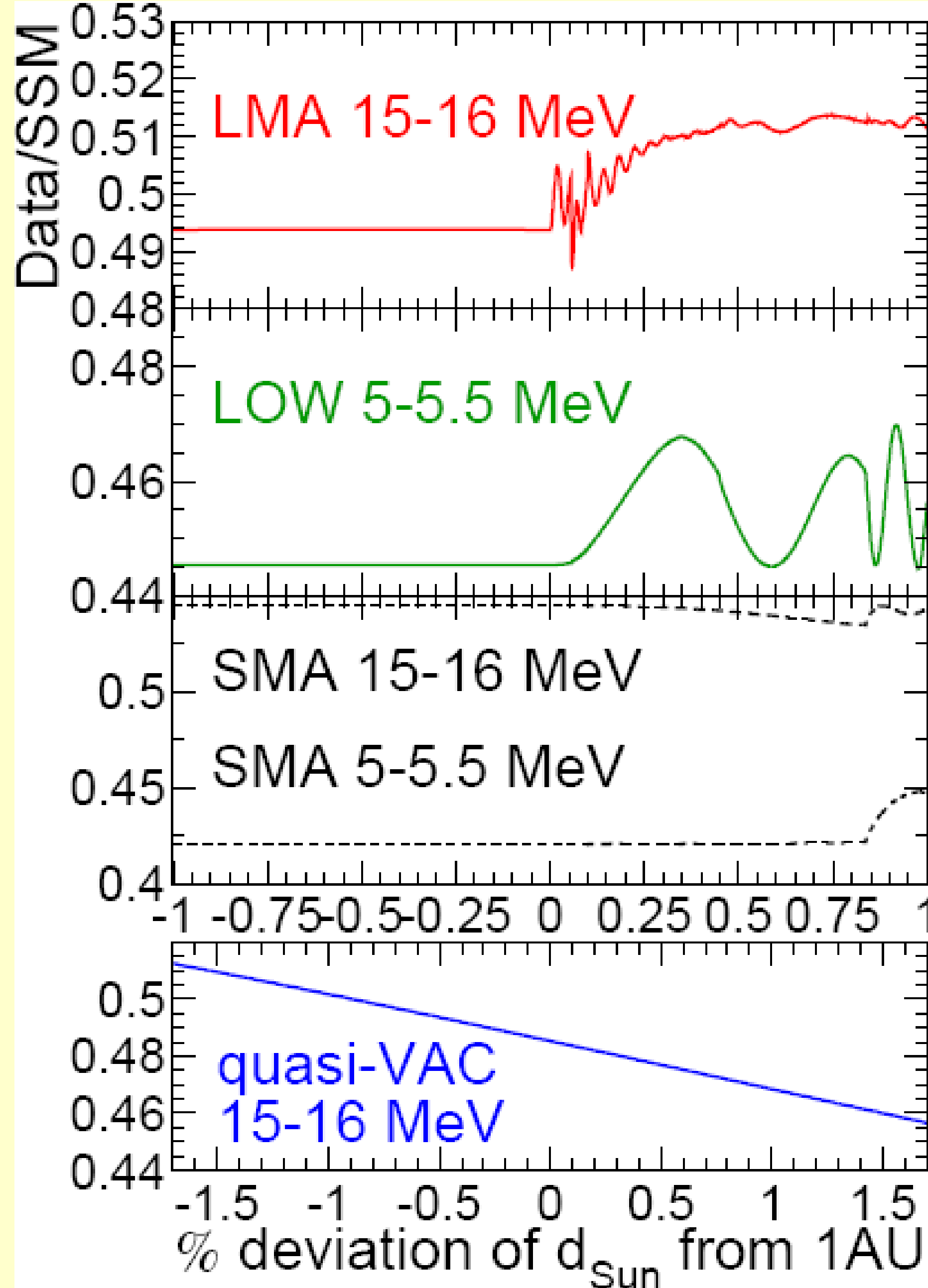


Zenith Spec.: Data & Solutions



D/N of Oscillation Solutions





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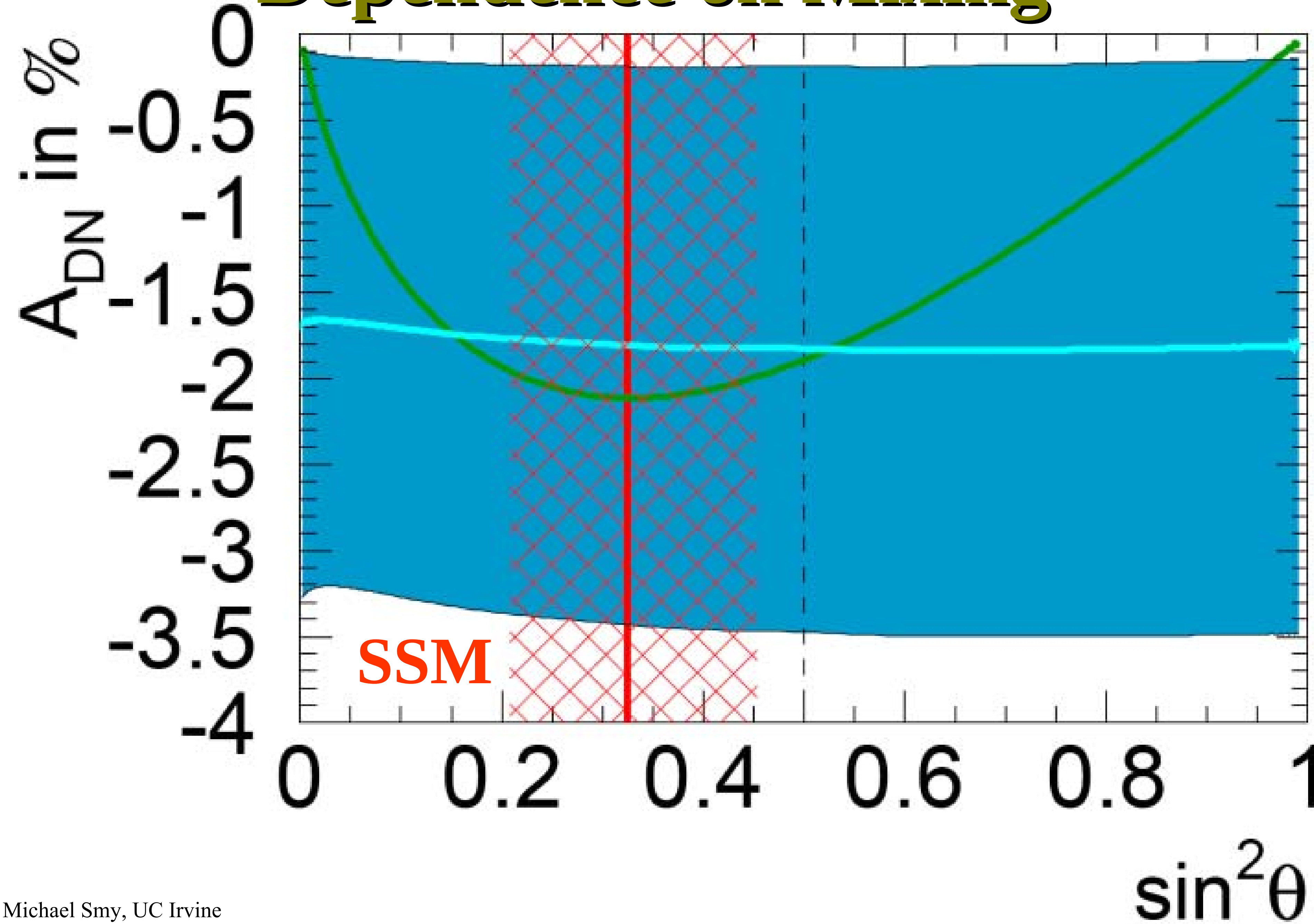
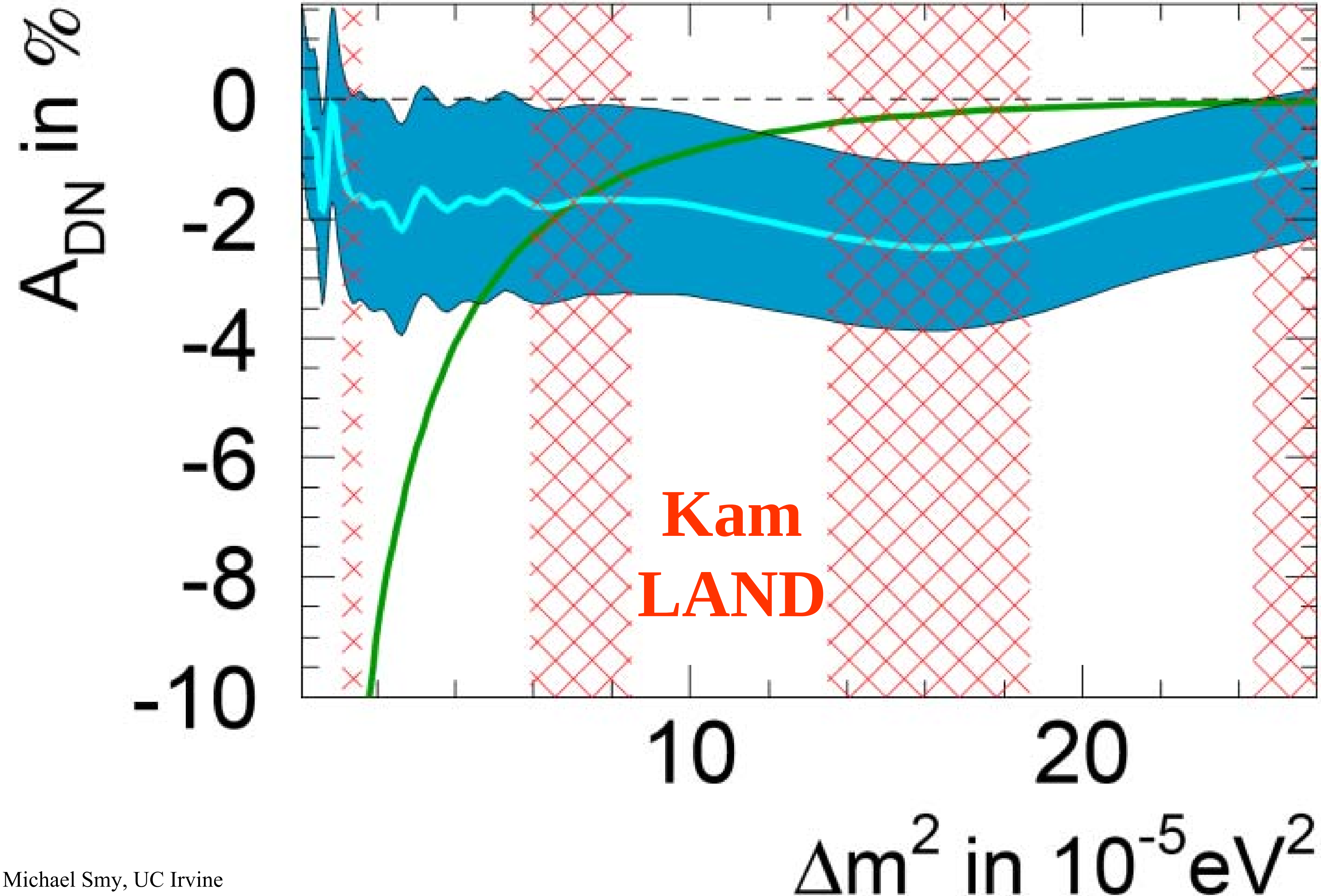
Amplitude Fit (SK Solutions)

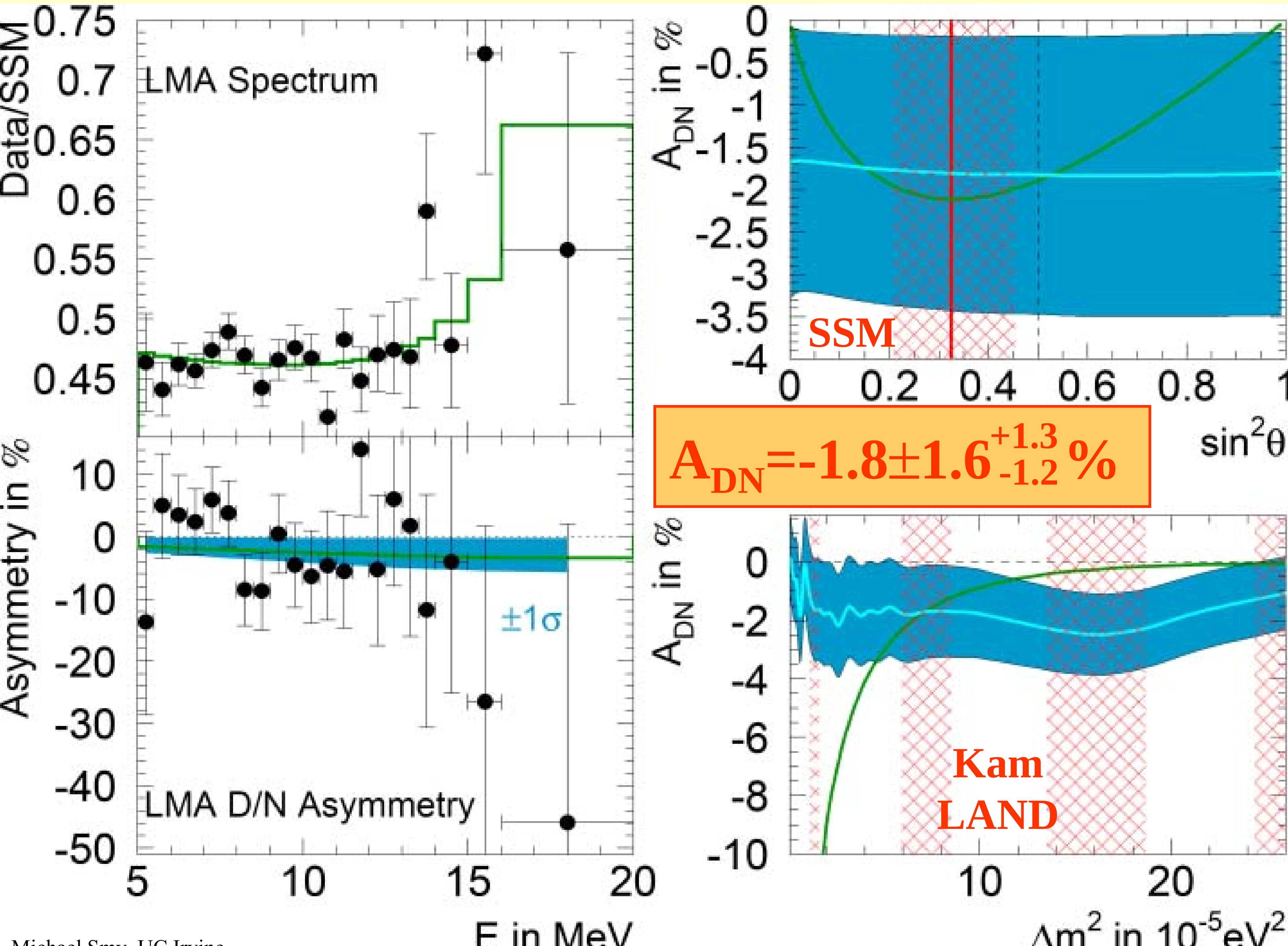
SK Bestfit Solutions	Large Mixing Angle (**LMA**)	Low Δm^2 (**LOW***)	Quasi-Vacuum (**quasi-VAC**)	Small Mixing Angle (**SMA***)
Δm^2 [eV^2]	**$6.3\mathrm{x}10^{-5}$**	**$2.9\mathrm{x}10^{-8}$**	**$6.49\mathrm{x}10^{-10}$**	**$3.5\mathrm{x}10^{-7}$**
$\tan^2\theta$	**0.55**	**0.72**	**1.0**	**0.013**
As. [%]	**-2.1**	**-0.3**	**-0.6**	**+0.03**
Rate [SSM*]	1.001±0.010	0.997±0.010	0.996±0.010	0.996±0.010
As. [%]	**-1.8±1.6**	+0.3±1.4	-0.3±0.7	-0.4±0.8
Scaling f. α	0.86±0.77	-0.9±5.0	0.6±1.2	-14±26
$\phi_{^8B}$ [$10^6/cm^2s$]	4.84	4.20	4.12	3.87
ϕ_{hep} [$10^3/cm^2s$]	33	27	0	20
χ^2 (20 dof; p_{χ^2})	17.3 (63.2%)	19.8 (47.3%)	17.1 (64.9%)	25.3(18.8%)
$\Delta\chi^2$(2 dof;$p_{\Delta\chi^2}$)	0.3 (**88.2%**)	2.7 (**25.9%**)	0.0 (**100%**)	8.3 (**1.6%**)

Dependence on Mixing



Dependence on Δm²





$$A_{DN}=-1.8\pm1.6^{+1.3}_{-1.2}\,\%$$

χ^2 for Oscillation Analysis

Scale "Time"-Dependent rate $r_1(t)$ (expected from ν oscillation) by α, using livetime distribution $l(t)$:

$$z_\alpha(t) = \frac{r_\alpha(t)}{R_\alpha} = \frac{1+\alpha\times\left(z_1(t)(1+a_1)-1\right)}{1+\alpha\times a_1}$$

$$\Delta\log\mathbf{L}_{\text{timevar}} = \log\mathbf{L}_{|\alpha=1} - \log\mathbf{L}_{|\alpha=0}$$

$$R_\alpha = \frac{1}{L}\int_{-\tau}^{+\tau} r_\alpha(t)l(t)dt \text{ with } L = \int_{-\tau}^{+\tau} l(t)dt$$

$$P_\alpha = \frac{1}{L_+}\int_0^{\tau} r_\alpha(t)l(t)dt,\quad M_\alpha = \frac{1}{L_-}\int_{-\tau}^{0} r_\alpha(t)l(t)dt$$

$$L_{+-} = \frac{L_+ - L_-}{1/2\left(L_+ + L_-\right)}, a_\alpha = \frac{1}{2}A_a \times \frac{1}{2}L_{+-} = \alpha\times a_1$$

$$A_\alpha = \frac{P_\alpha - M_\alpha}{1/2\left(P_\alpha + M_\alpha\right)} = \alpha\times A_1,\quad R_\alpha = R_1$$

$$b_i = \frac{{}^8\mathrm{B}_i^{\mathrm{osc}}\left(\Delta m^2, \tan^2\theta\right)}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}},\quad h_i = \frac{hep_i^{\mathrm{osc}}\left(\Delta m^2, \tan^2\theta\right)}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}},\quad \mathrm{d_i} = \frac{\mathrm{Data}_i}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}$$

$$f_i(\delta_\mathrm{B},\delta_S,\delta_R) = f_i^B(\delta_\mathrm{B})\times f_i^S(\delta_S)\times f_i^R(\delta_R),\quad \rho_i = \frac{\beta b_i + \eta h_i}{f_i},\quad m_i = \frac{\rho_i}{\sum_j \rho_j}$$

$$\chi^2 = \sum_{i=1}^{N_{bin}} \frac{(d_i - \rho_i)^2}{\sigma_i^2} + \frac{\delta_B^2}{\sigma_B^2} + \frac{\delta_S^2}{\sigma_S^2} + \frac{\delta_R^2}{\sigma_R^2} - 2\Delta\log\mathrm{L}_{\text{timevar}} + \frac{(\beta-1)^2}{\sigma^2_{{}^8\mathrm{B}_{\mathrm{SSM}}}}$$

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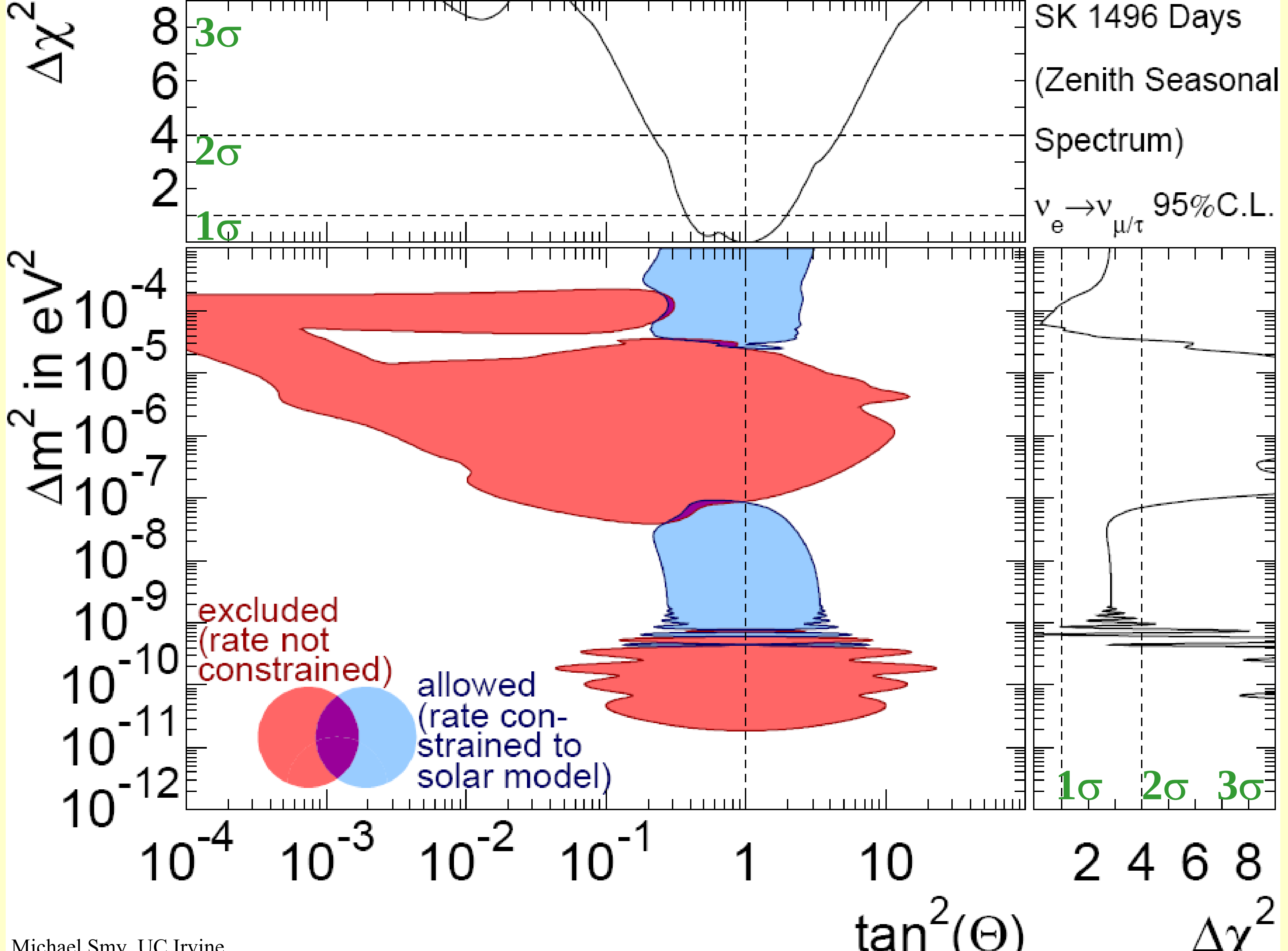

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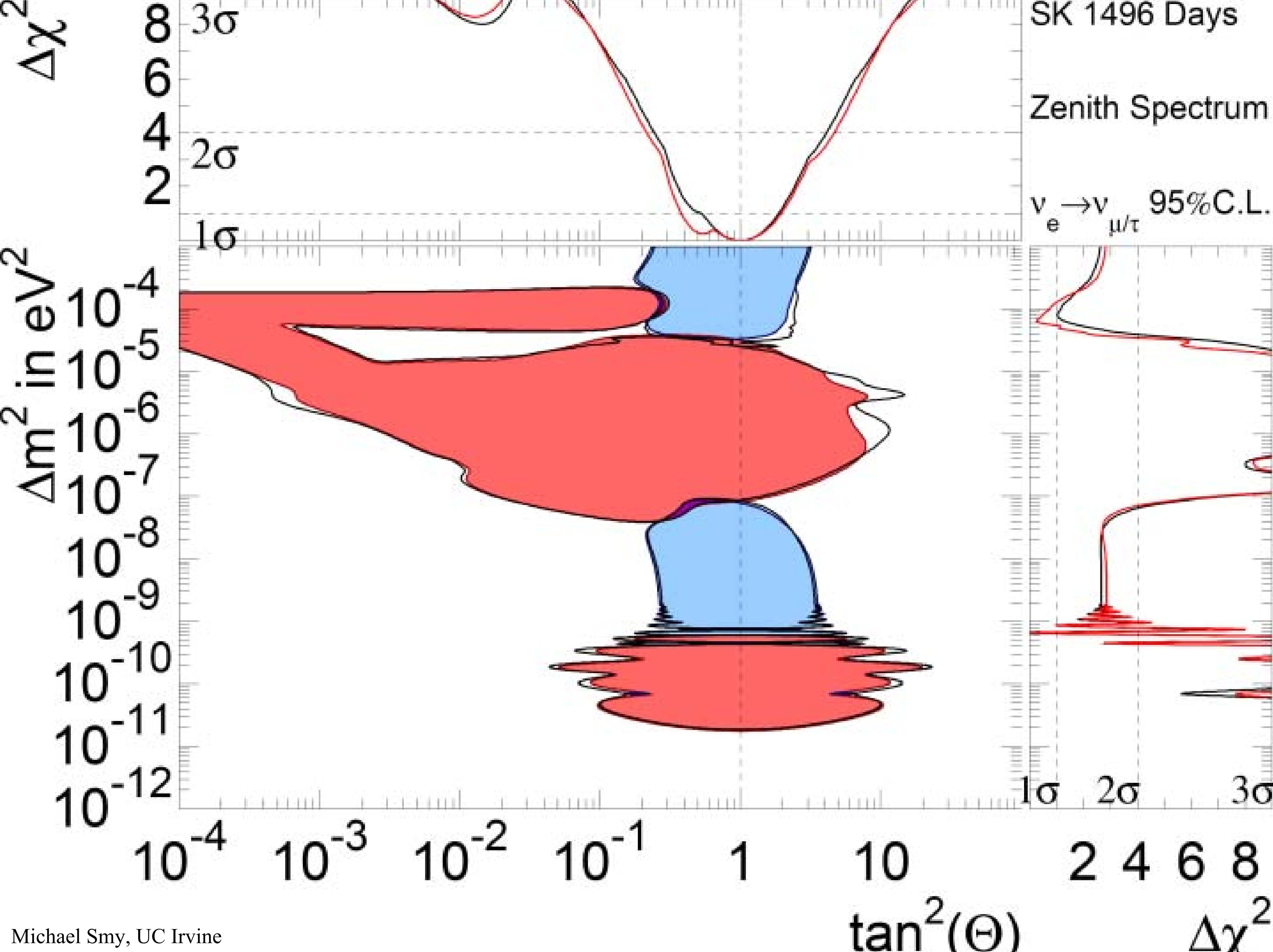

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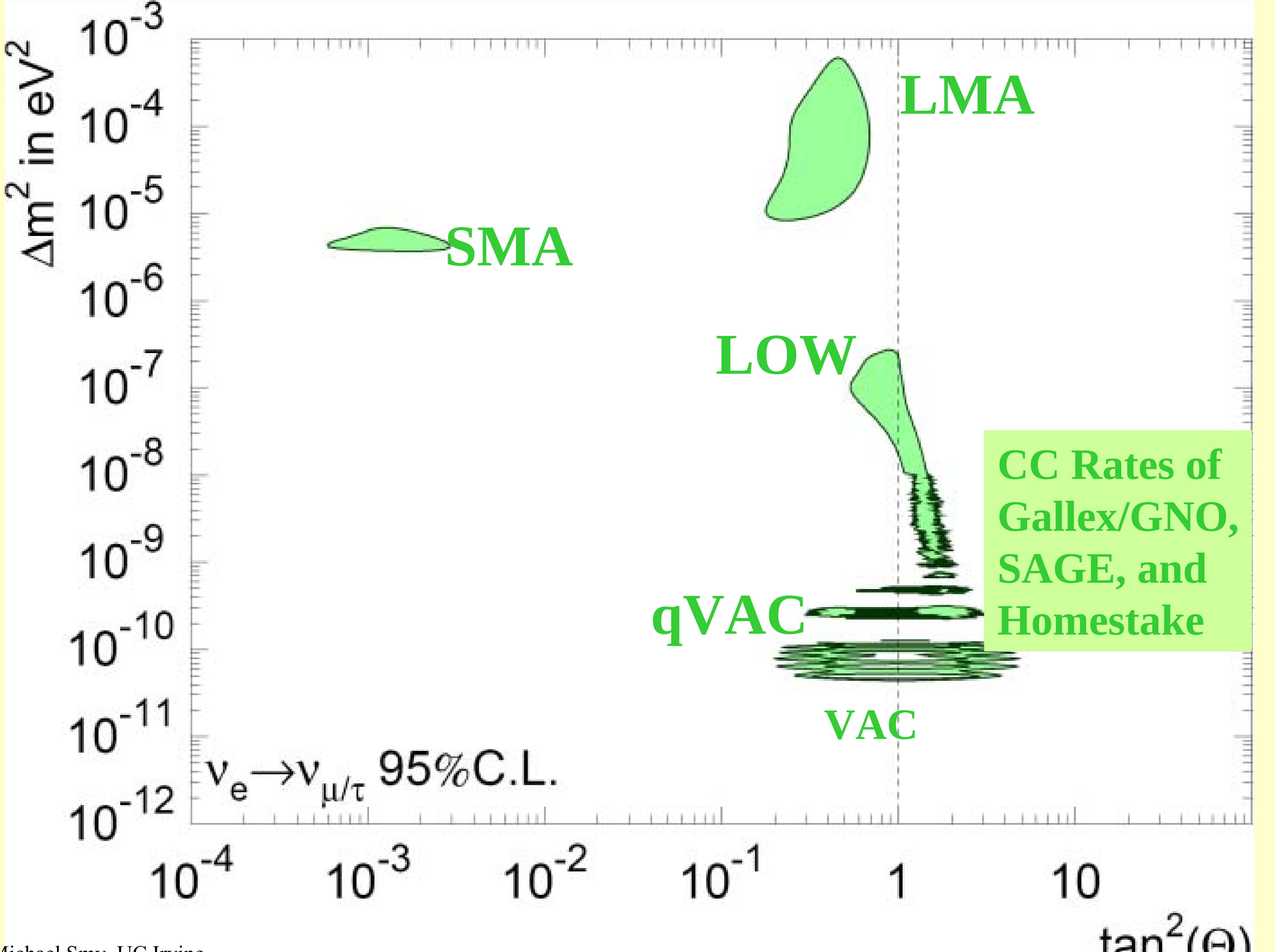
Combined Oscillation Fits with Other Solar Experiments



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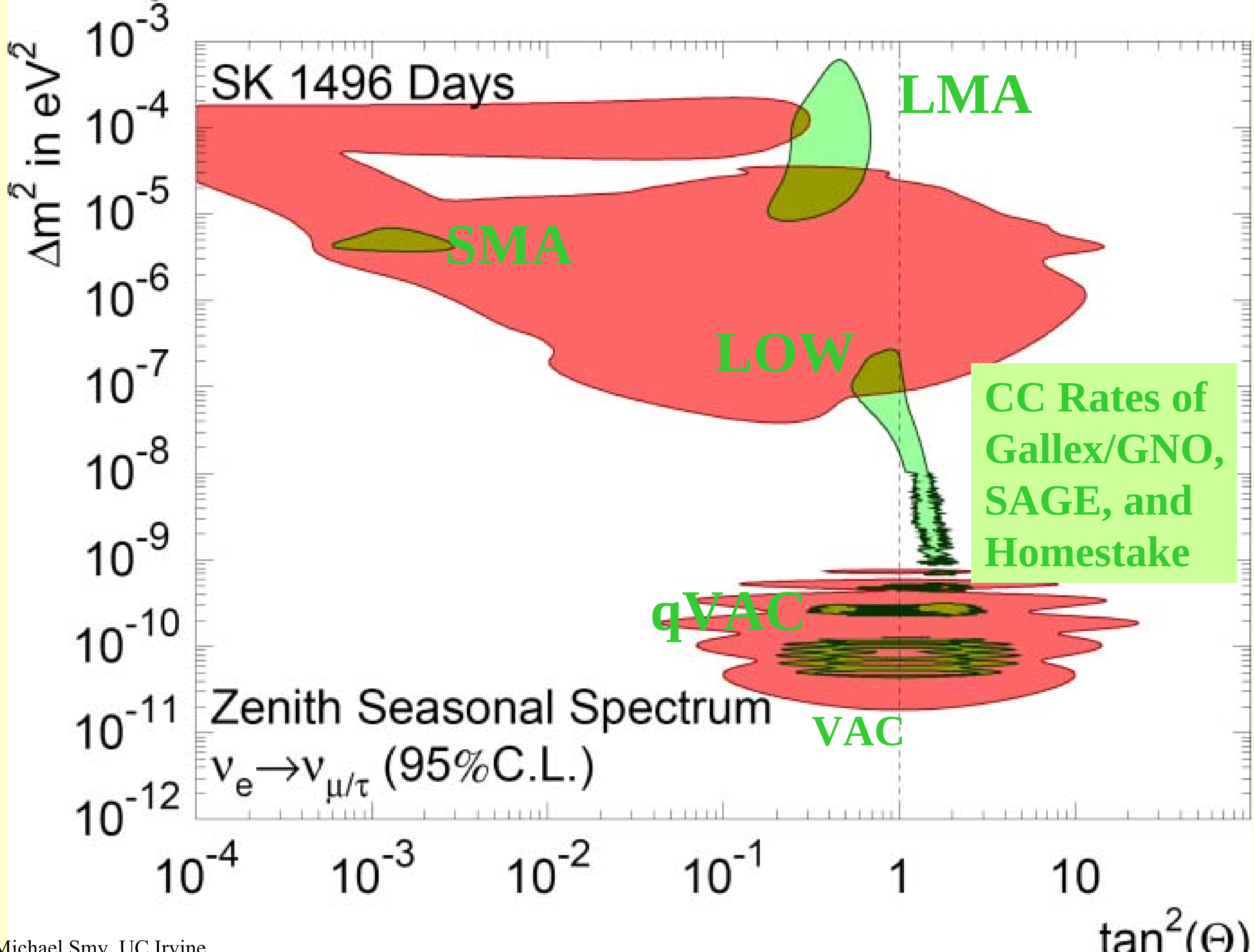

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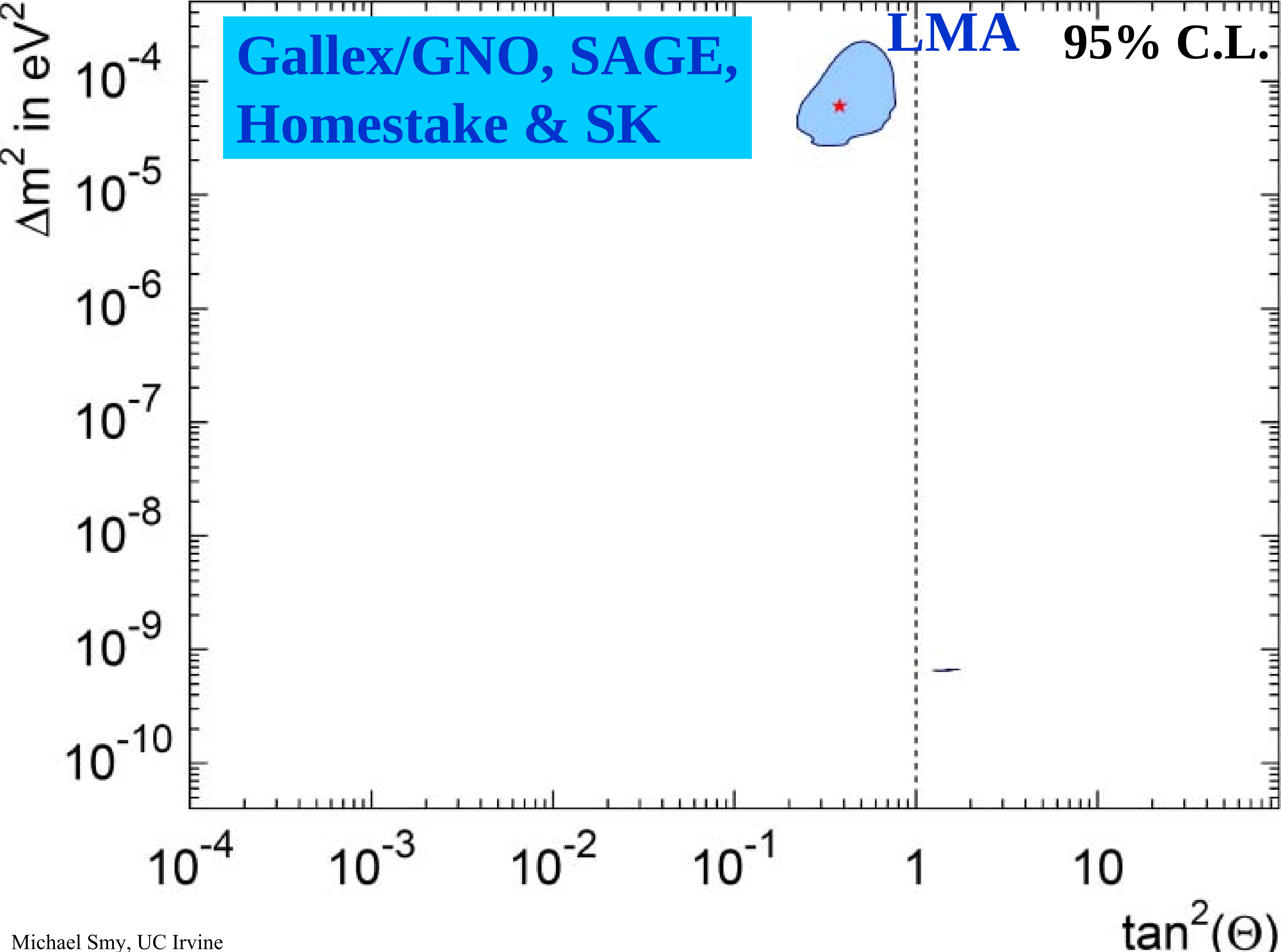
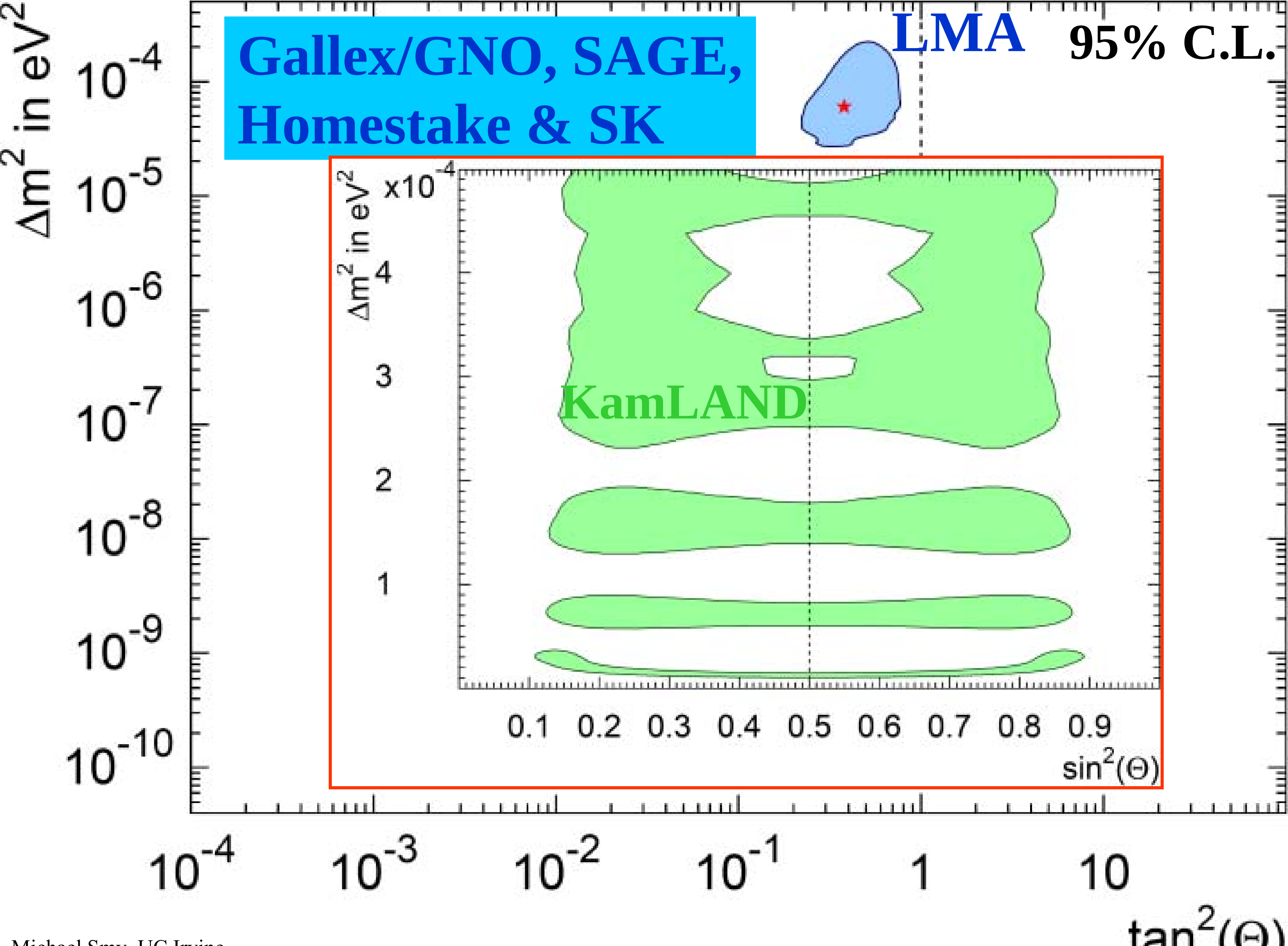


Gallex/GNO, SAGE, Homestake & SK
LMA
95% C.L.
Δm^2 in eV^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
$\tan^2(\Theta)$



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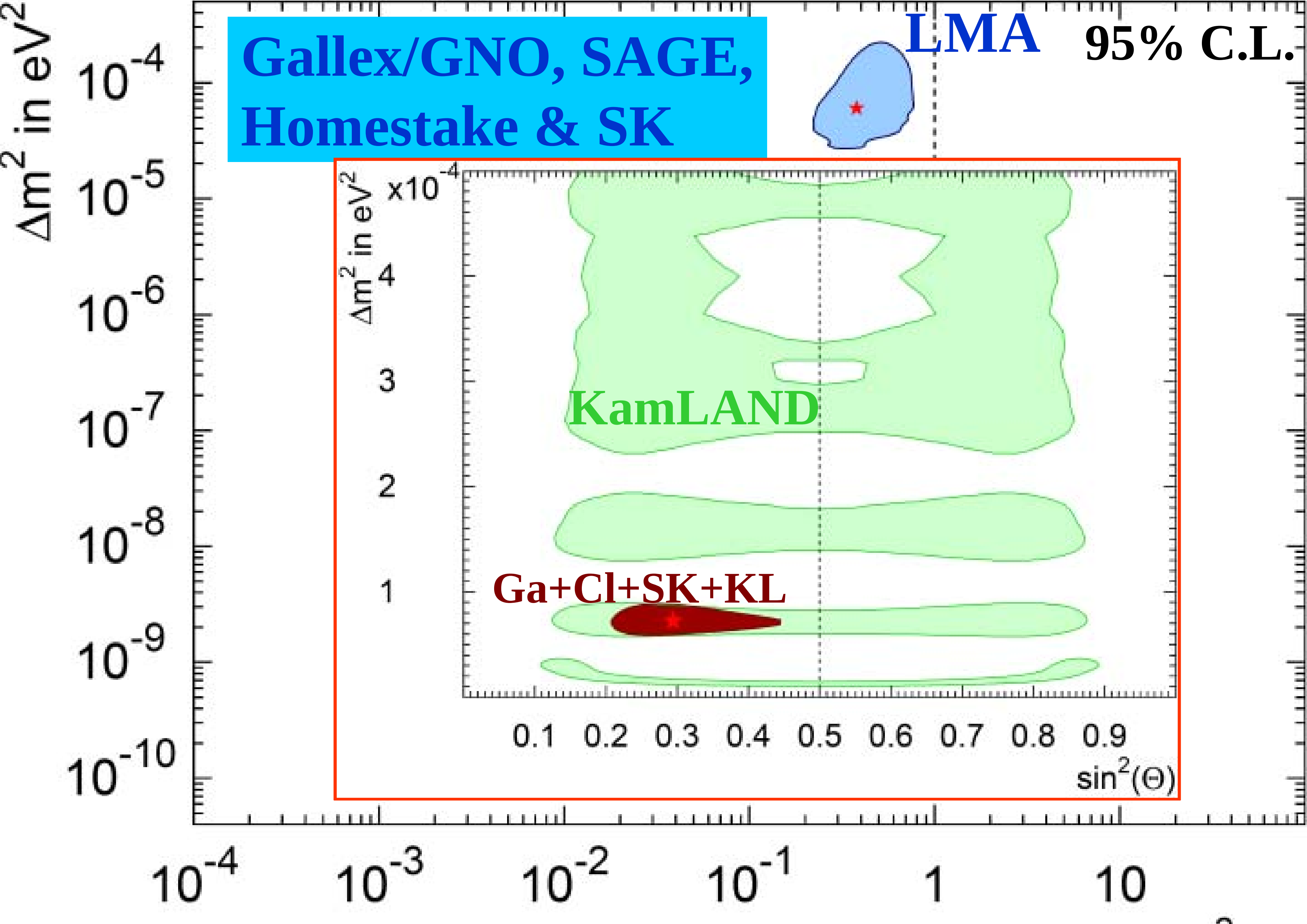
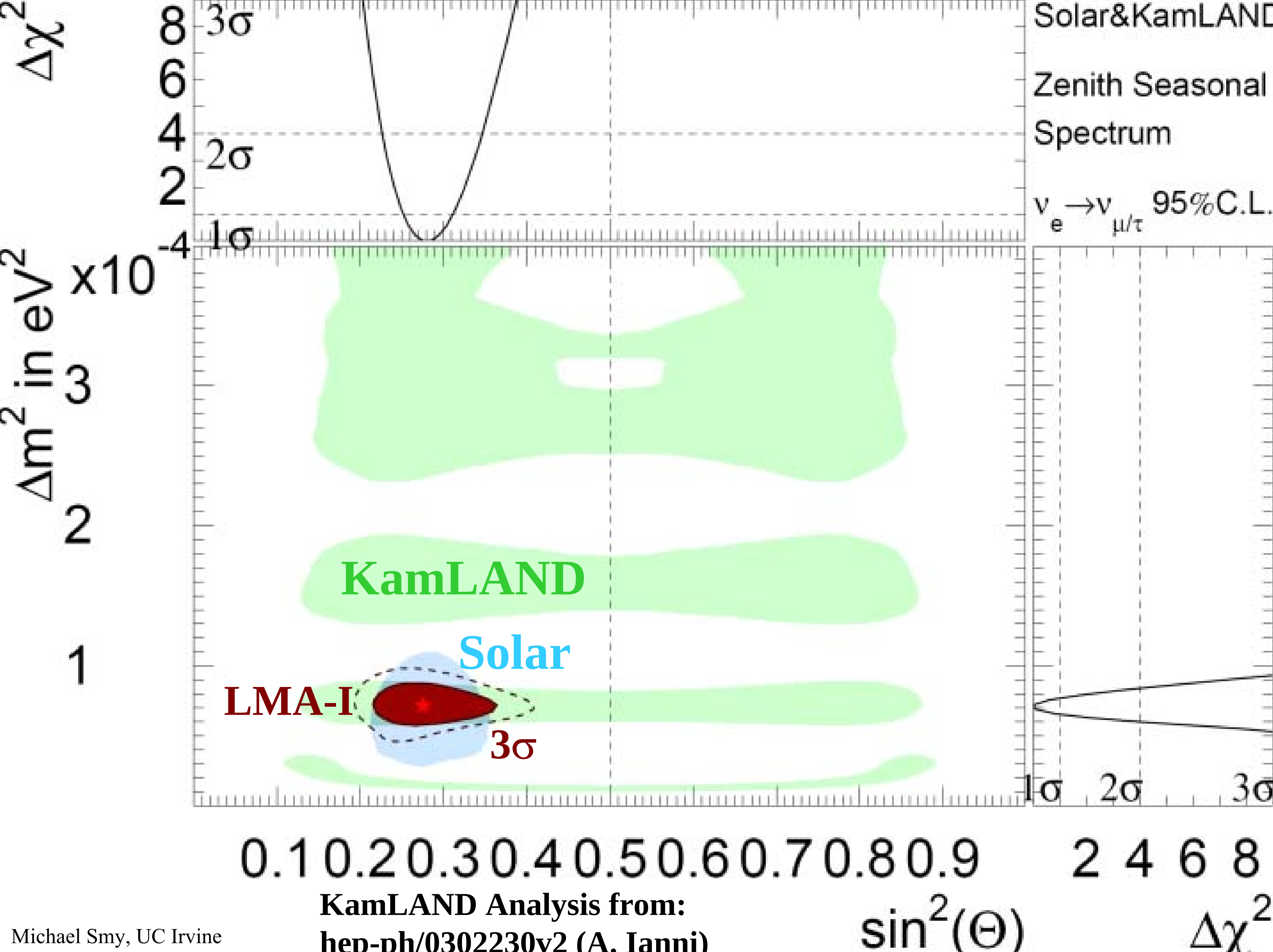
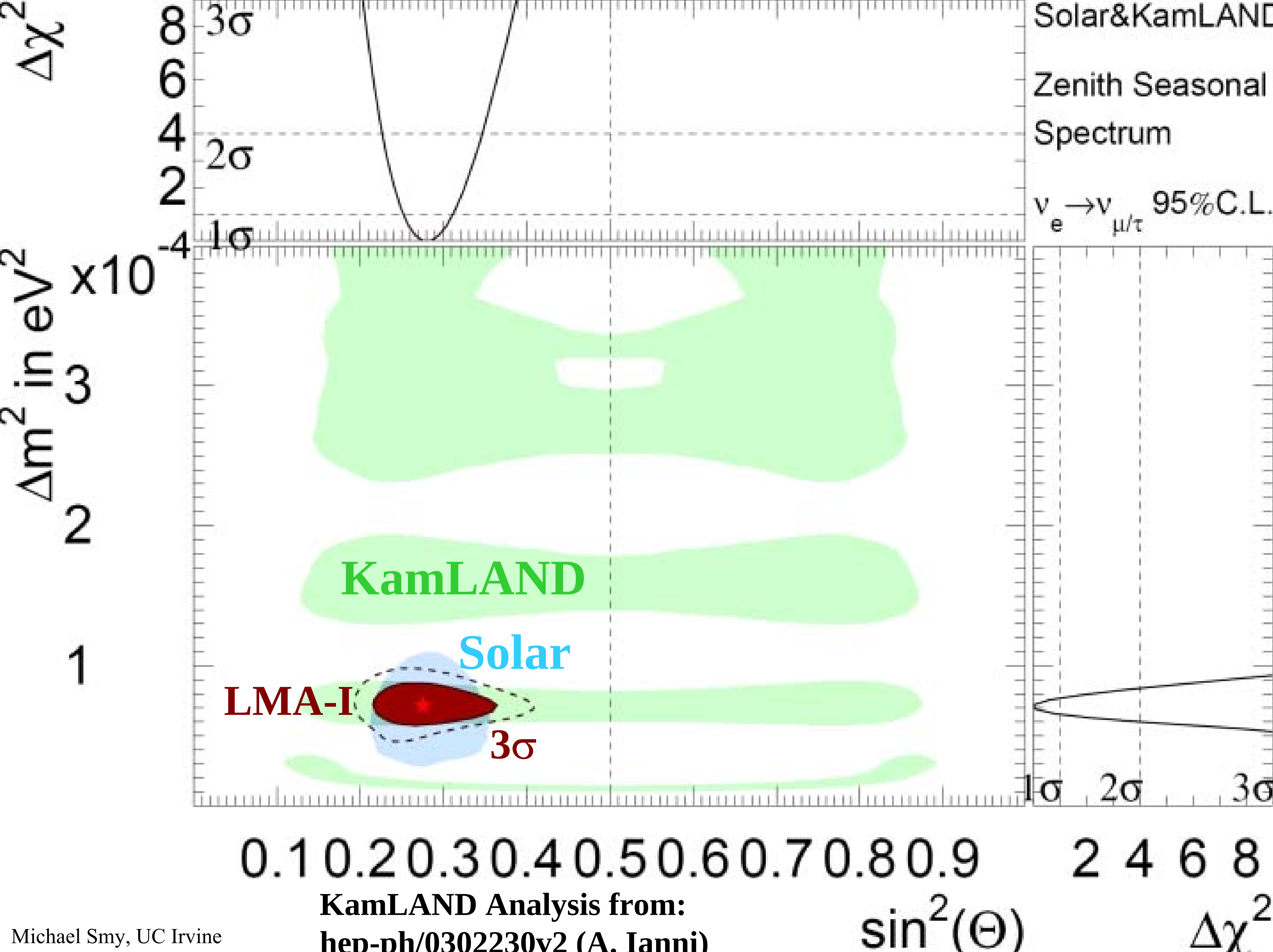


Michael Smy, UC Irvine **KamLAND Analysis from: hep-ph/0302230v2 (A. Ianni)**



KamLAND Analysis from:
hep-ph/0302230v2 (A. Ianni)



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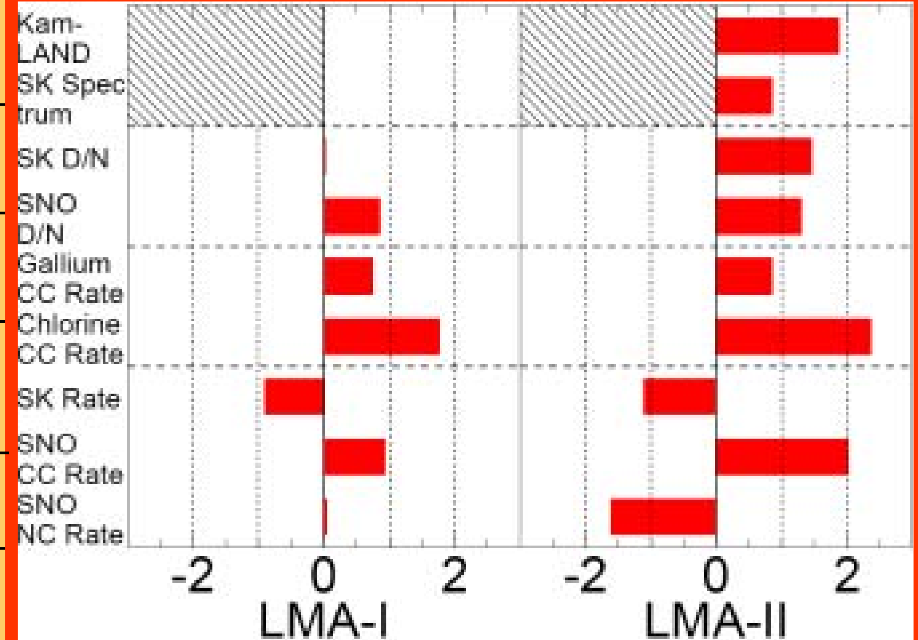
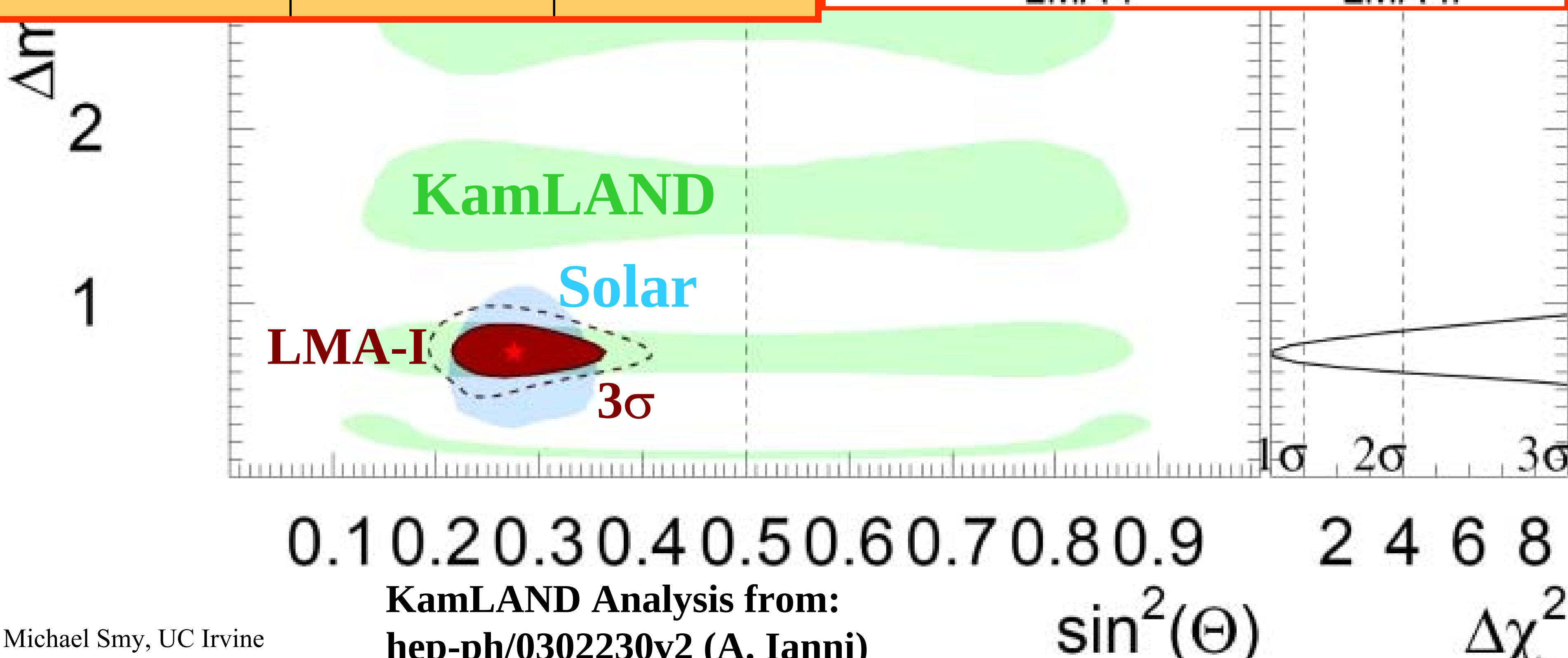
KamLAND Analysis from:
hep-ph/0302230v2 (A. Ianni)

Fits/Param.	All Solar	&KamLAND
$\tan^2\theta$	0.38	0.38
Δm^2 [eV^2]	4.8×10^{-5}	7.2×10^{-5}
$\Delta\chi^2$/CL[%]	14.7/0.06 (LOW)	13.1/0.1 (LMA-II)
$\phi_{^8B}/\phi_{hep}[10^6/cm^2s]$	5.45/0.033	5.21/0.030
SK/SNO A_{DN}[%]	-2.3/-3.8	-1.6/-2.6





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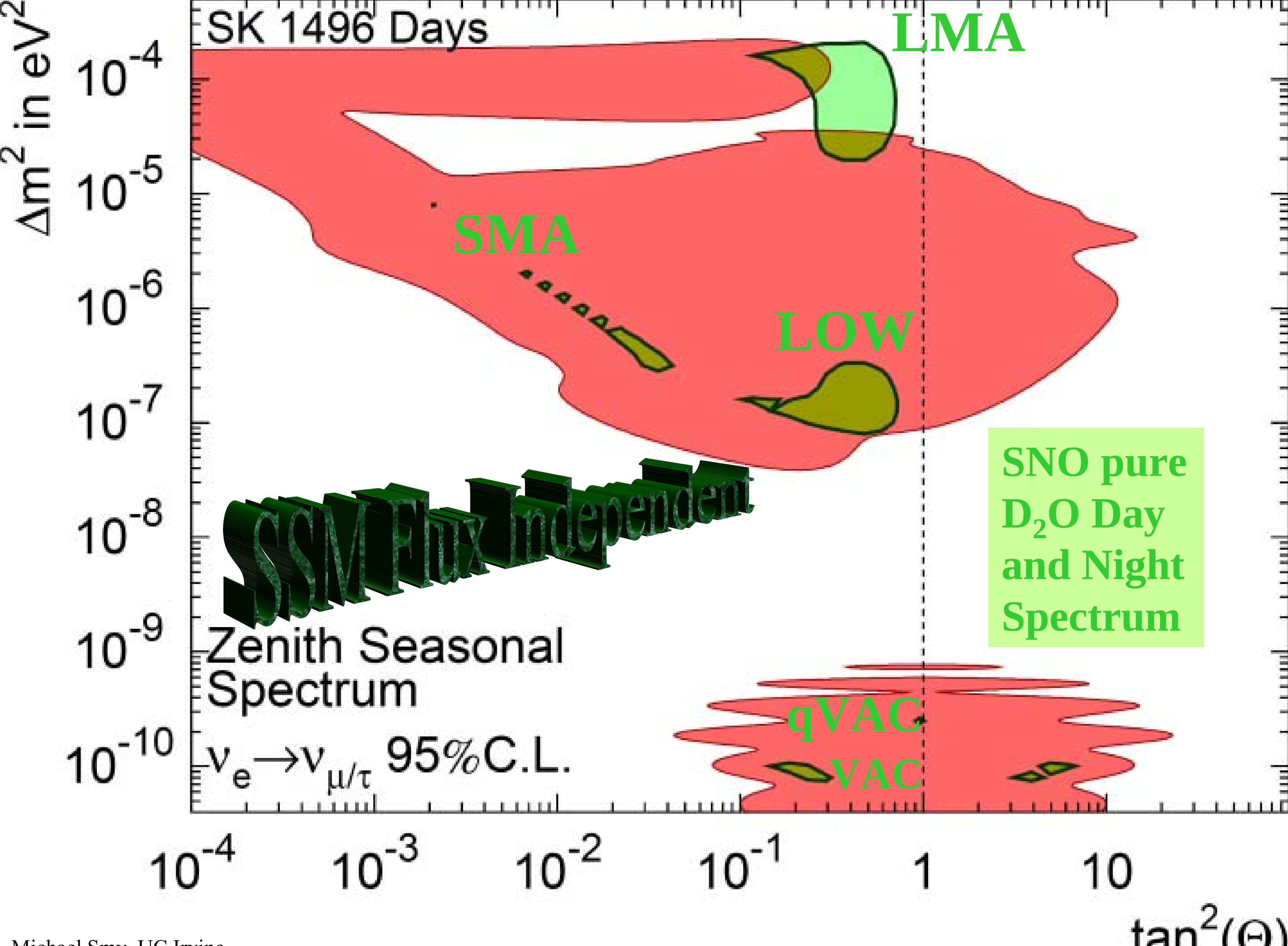
KamLAND Analysis from: hep-ph/0302230v2 (A. Ianni)

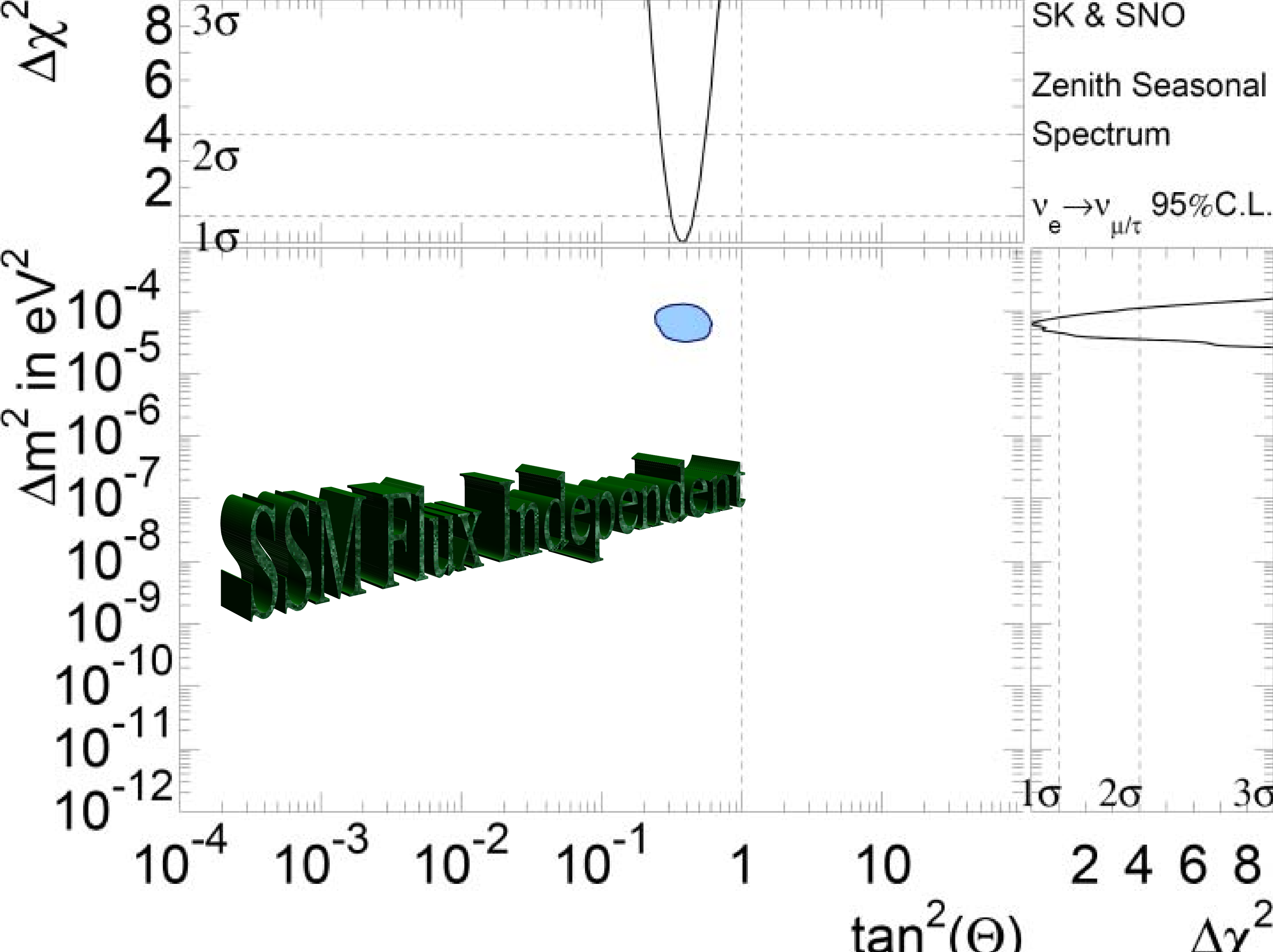
Solar Data + KamLAND

Global Solution	LMA-I	LMA-II
Δm^2 [eV^2], $\tan^2\theta$	**7.2×10^{-5}, 0.38**	**1.4×10^{-4}, 0.40**
$\Delta\chi^2$ (2 d.o.f; $p_{\Delta\chi^2}$)	0.0 (100%)	13.1 (**0.1%**)
$\Delta\chi^2_{SK\text{-}Spec}$ / KamLAND	4.2 (1.5σ) / 0.6 (0.3σ)	**4.9 (1.7σ)** / **4.2 (1.5σ)**
SK A_{DN}: Fit/expect [%]	-1.7$\pm$1.6 /-1.6 (+0.0σ)	**-2.3$\pm$1.4 /-0.3 (+1.5σ)**
SK Rate [%]/SNO A_{DN} [%]	45.3 (-0.9σ) /-2.6 (+0.9σ)	45.1 (-1.0σ)/-0.3 (+1.3σ)
SNO CC / NC [% SSM]	33.4 (+0.9σ)/ 103 (+0.1σ)	**35.5 (+2.0σ)/ 88 (-1.6σ)**
Ga Rate / Cl Rate [SNU]	71.8 (+0.8σ)/2.96 (+1.8σ)	72.1 (+0.8σ)/**3.10(+2.4σ)**
$\phi_{^8B}$ [10^6/cm^{2}s]/ϕ_{hep}[10^3/cm^{2}s]	5.21 (+0.2σ) / 30	4.43 (-0.8σ) / 23
^{8}B Spectrum/SK E-sc/resol.	-0.5σ / -0.7σ / -0.2σ	-0.7σ / -1.0σ / -0.2σ

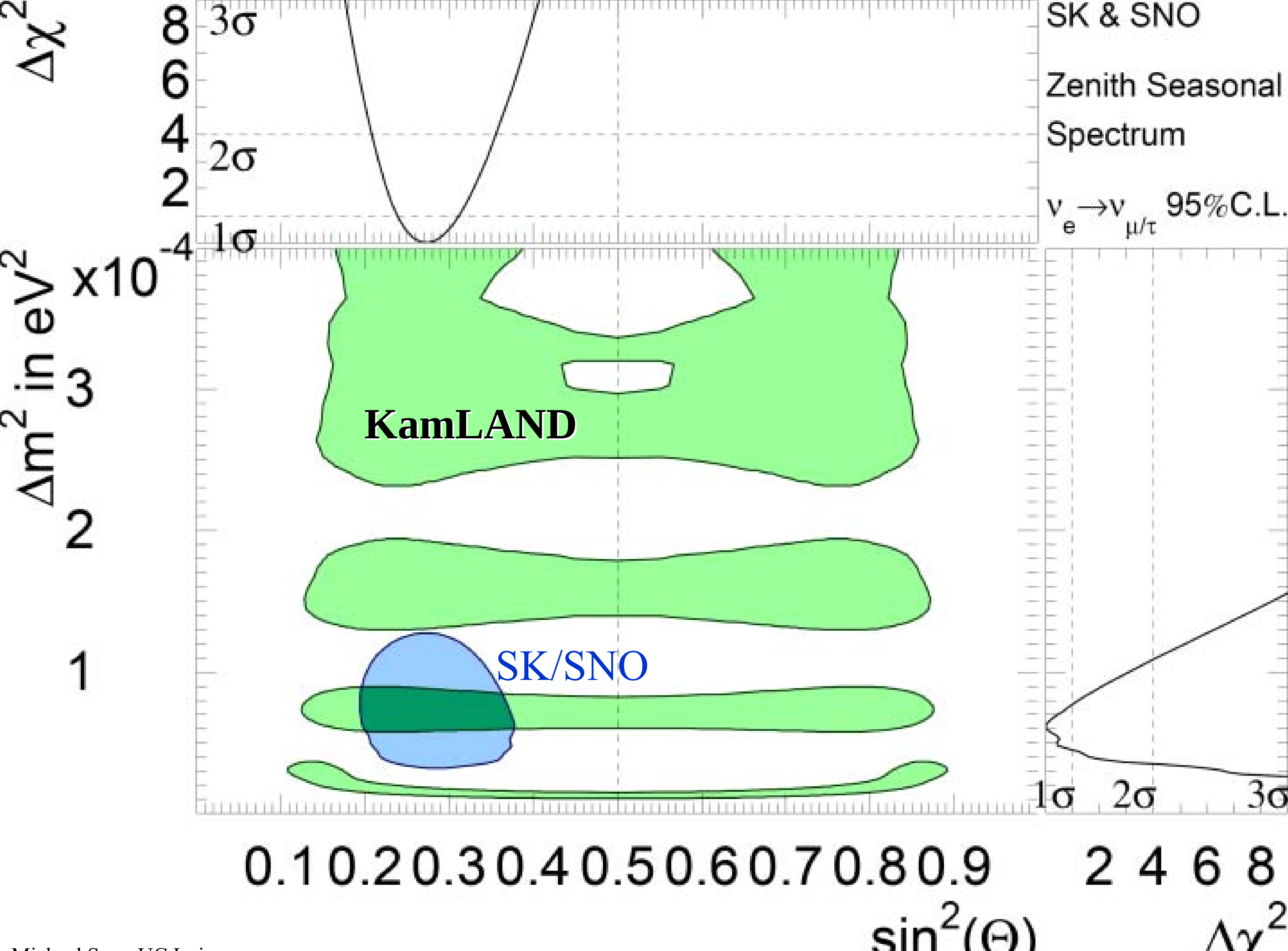
Solar ^{8}B ν Spectral Distortion??
Chlorine CC Rate??

Combined Oscillation Fits with SNO


SK 1496 Days
LMA
SMA
LOW
SSM Flux Independent
SNO pure D_2O Day and Night Spectrum
Zenith Seasonal Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
qVAC
VAC
Δm^2 in eV^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10
$\tan^2(\Theta)$



SK & SNO
Zenith Seasonal
Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
SSM Flux Independent
$\Delta\chi^2$
Δm^2 in eV^2
$\tan^2(\Theta)$
1σ
2σ
3σ



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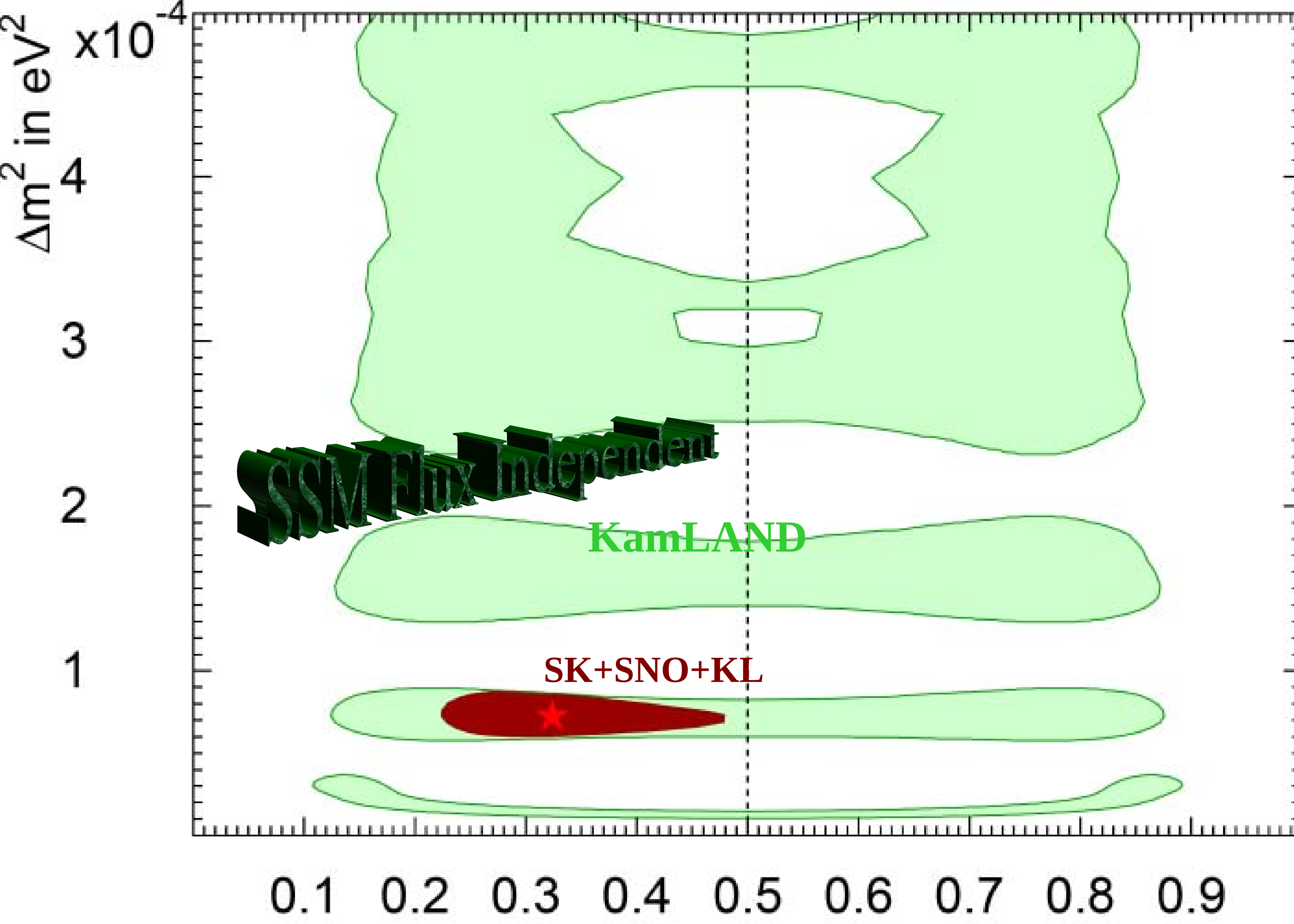

KamLAND Analysis from:
hep-ph/0302230v2 (A. Ianni)

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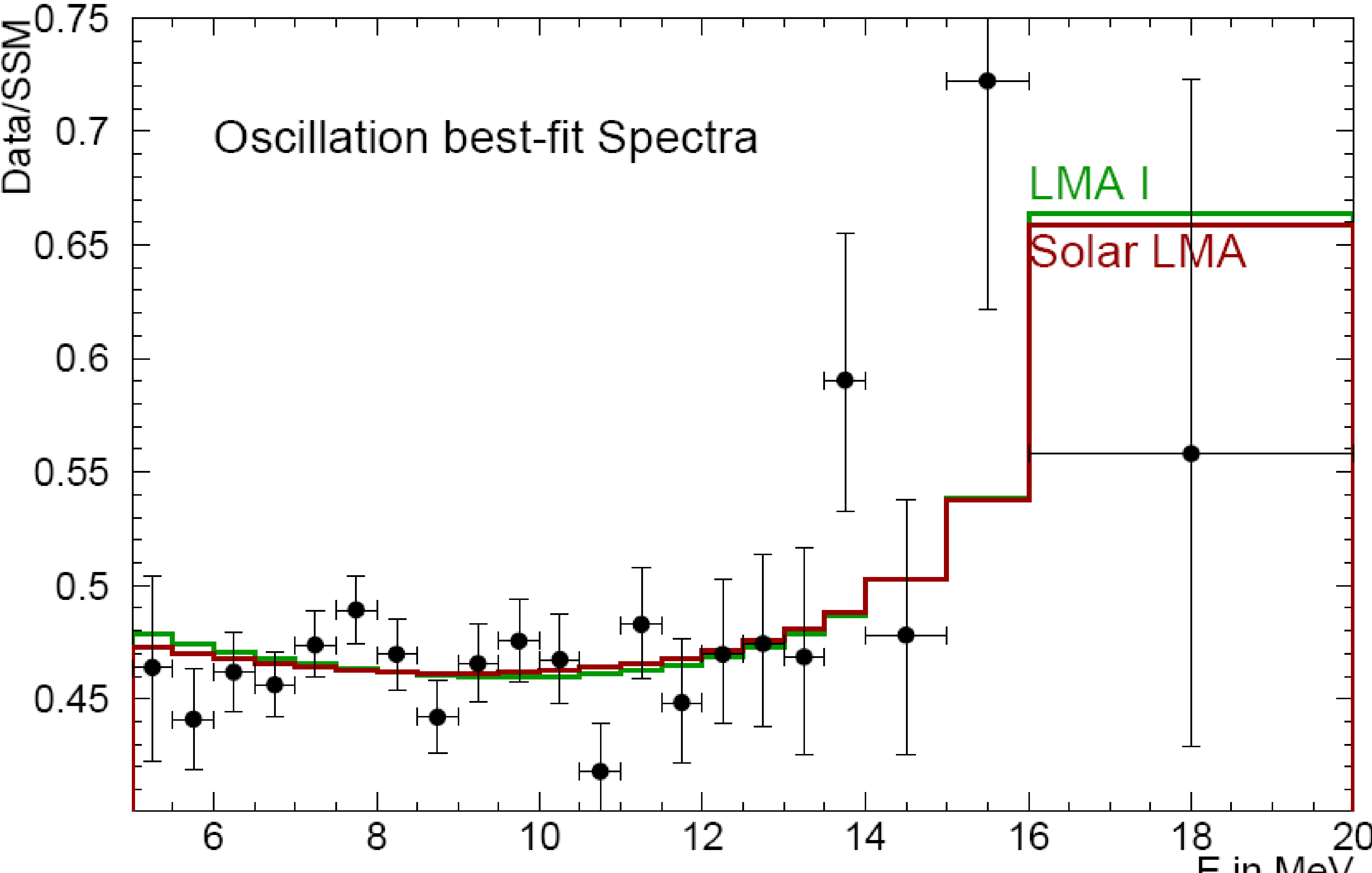
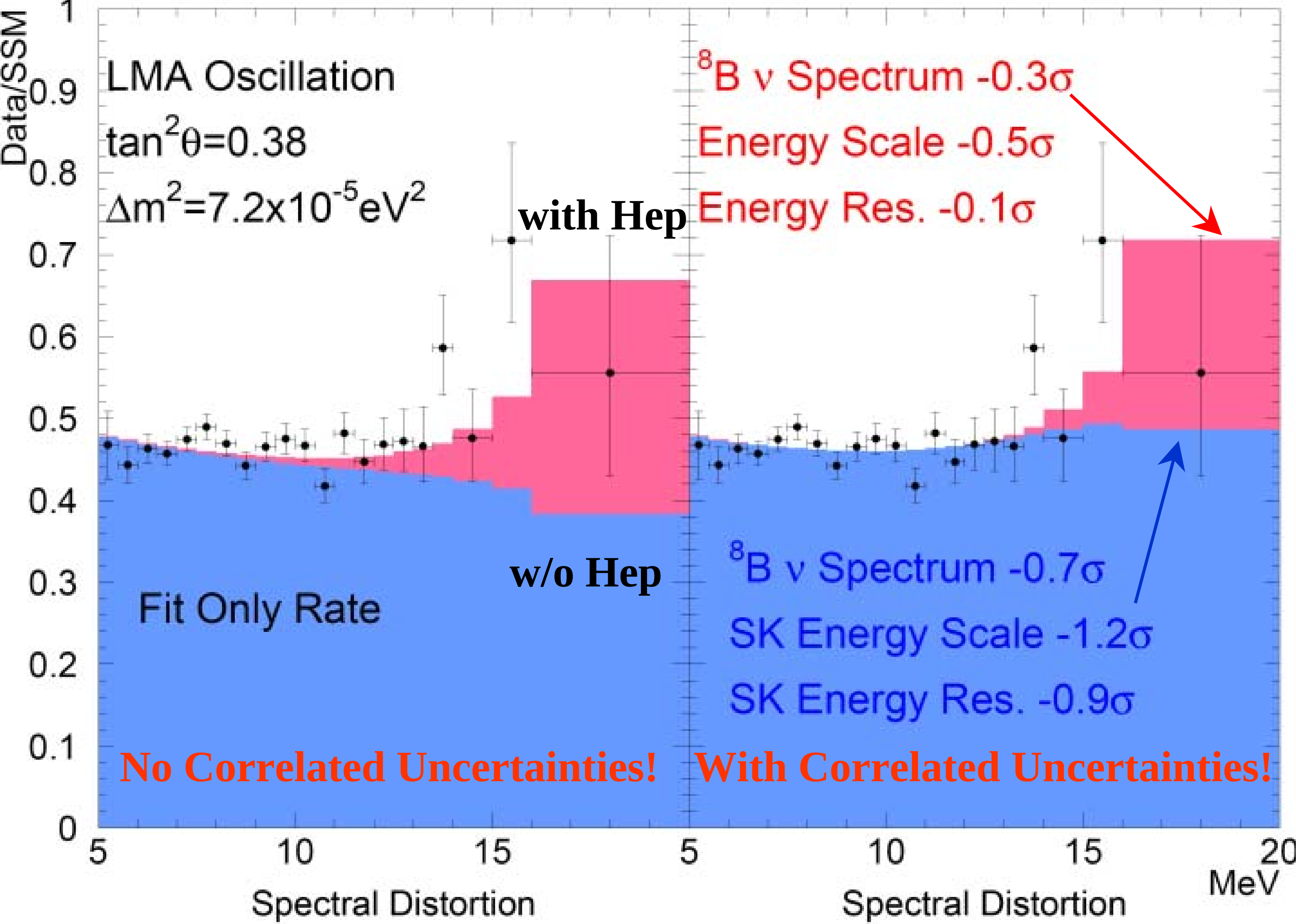
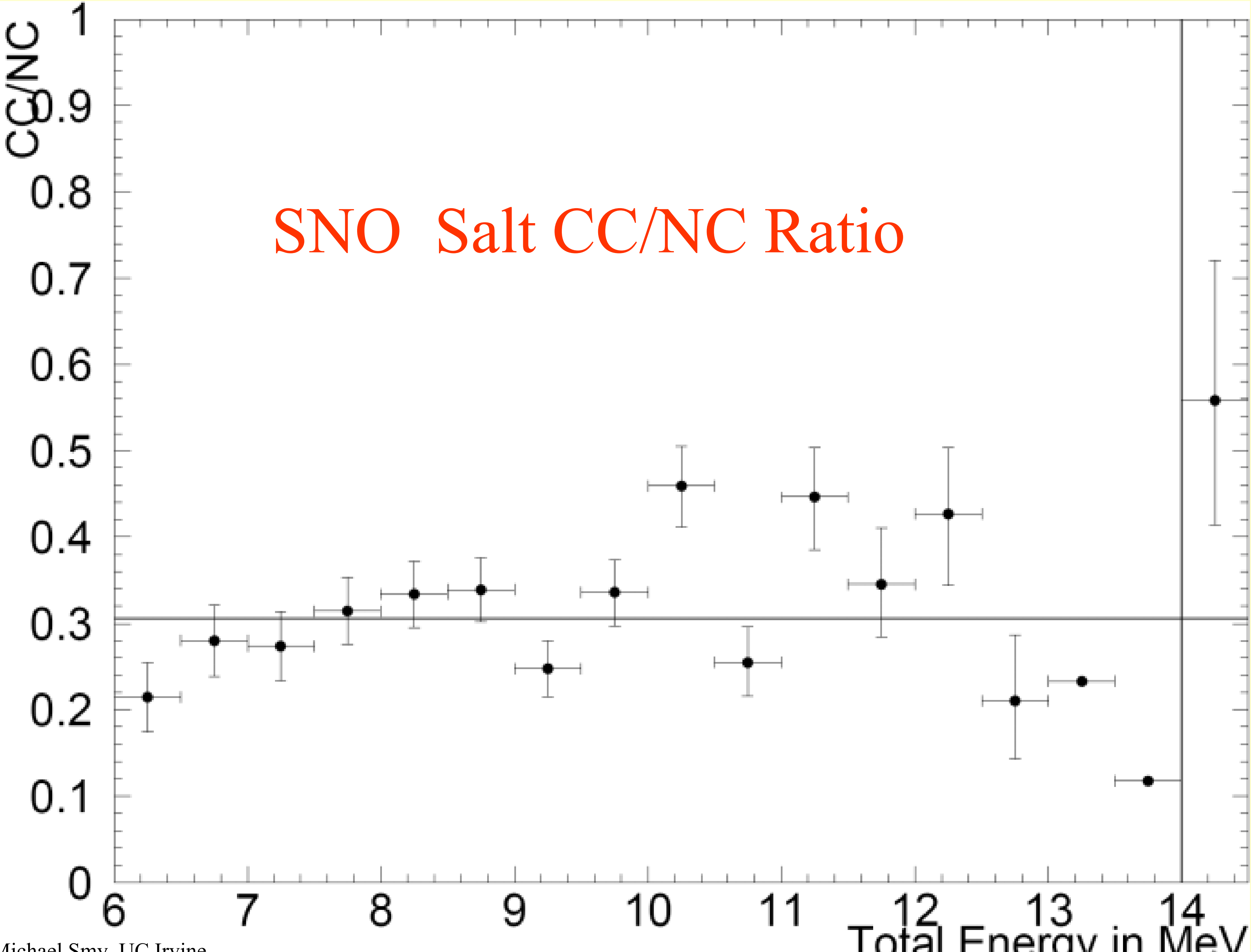
SK Bestfit Solutions	Large Mixing Angle (**LMA**)	Low Δm^2 (**LOW***)	Quasi-Vacuum (**quasi-VAC**)	Small Mixing Angle (**SMA***)
Δm^2 [eV^2]	**6.3×10^{-5}**	**2.9×10^{-8}**	**6.49×10^{-10}**	**3.5×10^{-7}**
$\tan^2\theta$	**0.55**	**0.72**	**1.0**	**0.013**
As. [%]	**-2.1**	**-0.3**	**-0.6**	**+0.03**
χ^2 (20 dof; p_{χ^2})	17.3 (63.2%)	19.8 (47.3%)	17.1 (64.9%)	25.3(18.8%)
$\Delta\chi^2$(2 dof;$p_{\Delta\chi^2}$)	0.3 (**88.2%**)	2.7 (**25.9%**)	0.0 (**100%**)	8.3 (**1.6%**)
$\Delta\chi^2$(Spectrum)	2.7 (1.1σ)	2.8 (1.2σ)	0.1 (0.05σ)	7.4 (2.2σ)
As.-Fit [%]	-1.8 (+0.2σ)	+0.3 (+0.4σ)	-0.3 (+0.3σ)	-0.4 (-0.6σ)
$\phi_{^8B}$ [10^6/cm^{2}s]	4.84 (-0.3σ)	4.20 (-1.0σ)	4.12 (-1.2σ)	3.87 (-1.5σ)
ϕ_{hep} [10^3/cm^{2}s]	33	27	0	20
^{8}B Spectrum	-0.1σ	+0.2σ	+0.0σ	+0.9σ
SK E-scale	-0.1σ	+0.3σ	-0.0σ	+1.3σ
SK E-resol.	-0.1σ	-0.2σ	+0.0σ	-0.2σ

Global Solution	Large Mixing Angle(**LMA**)	Low Δm^2 (**LOW**)	Vacuum (**VAC**)	Small Mixing Angle (**SMA**)
Δm^2 [eV^2]	**$4.8\text{x}10^{-5}$**	**$9.1\text{x}10^{-8}$**	**$6.65\text{x}10^{-11}$**	**$4.4\text{x}10^{-6}$**
$\tan^2\theta$	**0.38**	**0.55**	**3.0**	**0.0021**
χ^2 (24 dof; p_{χ^2})	22.3 (56.4%)	37.0 (4.4%)	43.2 (0.9%)	50.7 (0.1%)
$\Delta\chi^2$(2 dof; $p_{\Delta\chi^2}$)	0.0 (100%)	14.7 (**0.06%**)	21.0 (**0.003%**)	28.5(**0.0001%**)
$\Delta\chi^2_{SK\text{-}Spec}$ ($p_{\Delta\chi^2}$)	3.3 (1.3σ)	3.4 (1.3σ)	**18.0 (3.8σ)**	**15.3 (3.5σ)**
SK A_{DN} [%]	-3.3 (-0.9σ)	**-2.6 (-2.0σ)**	-0.9 (+0.3σ)	**-2.2 (-1.8σ)**
SNO A_{DN} [%]	-5.6 (+0.3σ)	-3.6 (+0.7σ)	0.0 (+1.4σ)	-2.7 (+0.9σ)
Ga Rate [SNU]	70.6 (+0.4σ)	**61.5 (-2.3σ)**	70.0 (+0.2σ)	67.0 (-0.7σ)
Cl Rate [SNU]	**2.90 (+1.5σ)**	**2.90 (+1.5σ)**	**2.99 (+1.9σ)**	2.25 (-1.4σ)
SK Rate [%]	45.2 (-1.0σ)	44.8 (-1.3σ)	**44.5 (-1.6σ)**	**43.8 (-2.1σ)**
SNO CC [%]	32.9 (+0.7σ)	**36.1 (+2.3σ)**	**35.0 (+1.7σ)**	**38.3 (+3.4σ)**
SNO NC [%]	108 (+0.5σ)	93 (-1.1σ)	102 (-0.2σ)	96 (-0.8σ)
ϕ_{8B} [$10^6/cm^2s$]	5.45 (+0.4σ)	4.70 (-0.4σ)	5.14 (+0.1σ)	4.84 (-0.3σ)
ϕ_{hep} [$10^3/cm^2s$]	33	22	2	10
^{8}B Spectrum	-0.3σ	+0.1σ	+0.9σ	+1.1σ
SK E-sc/resol.	-0.4σ /-0.2σ	+0.1σ /-0.3σ	+1.1σ /-0.0σ	+1.5σ /-0.4σ


Data/SSM
0.75
0.7
0.65
0.6
0.55
0.5
0.45
Oscillation best-fit Spectra
LMA I
Solar LMA
6
8
10
12
14
16
18
20
E in MeV



Data/SSM
LMA Oscillation
tan$^2\theta$=0.38
Δm^2=7.2x10^{-5}eV^2
with Hep
w/o Hep
Fit Only Rate
No Correlated Uncertainties!
^{8}B ν Spectrum -0.3σ
Energy Scale -0.5σ
Energy Res. -0.1σ
^{8}B ν Spectrum -0.7σ
SK Energy Scale -1.2σ
SK Energy Res. -0.9σ
With Correlated Uncertainties!
Spectral Distortion
Spectral Distortion
MeV



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Amplitude Fit (Global Solutions)

Global Solution	Large Mixing Angle (**LMA**)	Low Δm^2 (**LOW**)	Vacuum (**VAC**)	Small Mixing Angle (**SMA**)
Δm^2 [eV^2]	**4.8×10^{-5}**	**9.1×10^{-8}**	**6.65×10^{-11}**	**4.4×10^{-6}**
$\tan^2\theta$	**0.38**	**0.55**	**3.0**	**0.0021**
As. [%]	**-3.3**	**-2.6**	**-0.9**	**-2.2**
Rate [SSM]	1.027 ± 0.010	1.038 ± 0.010	1.056 ± 0.011	1.040 ± 0.011
As. [%]	-1.7 ± 1.6	$+0.2\pm1.4$	-1.1 ± 1.0	-0.3 ± 1.1
Scaling f. α	0.53 ± 0.51	-0.08 ± 0.53	1.4 ± 1.1	$0.13\pm^{0.49}_{0.48}$
$\phi_{^8B}$ [10^6/cm^{2}s]	5.45	4.70	5.14	4.84
ϕ_{hep} [10^3/cm^{2}s]	33	22	2	10
χ^2 (23 dof; p_{χ^2})	22.3(56.4%)	37.0(4.4%)	43.2(0.9%)	50.7 (0.1%)
$\Delta\chi^2$(2 dof;$p_{\Delta\chi^2}$)	0.0(**100%**)	14.7(**0.06%**)	21.0(**0.003**)	28.5(**0.0001%**)

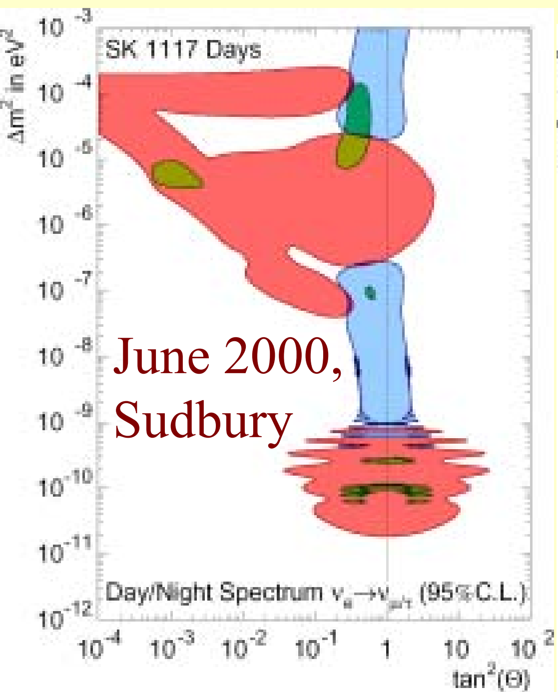
Impact of SK Solar Data on ν Oscillation

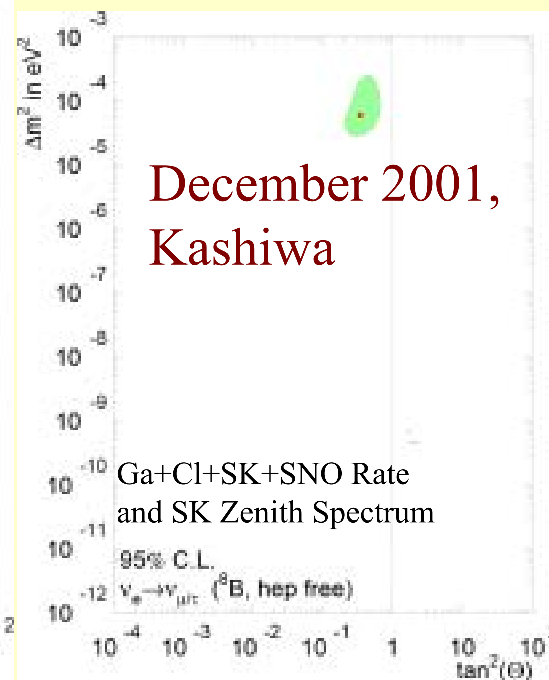
Before Super-Kamiokande:

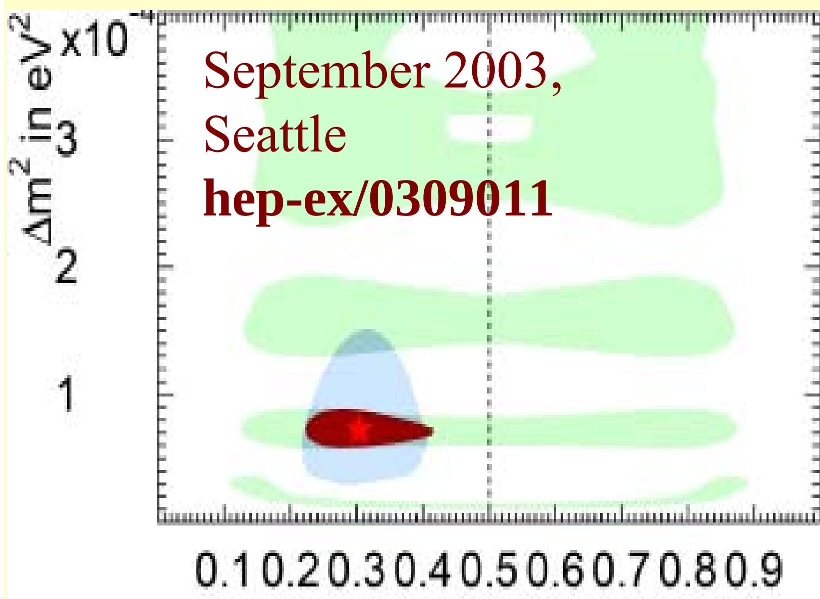
- Really Oscillations?
- Active or Sterile Oscillations?
- SMA, VAC, LMA, LOW?

After Super-Kamiokande:

- ✓ Active Oscillation! (June 2000)
- ✓ Large Angle! (June 2000)
- ➢ Not VAC, SMA! (June 2000)
- ➢ Not LOW! (December 2001)
- ➢ LMA-I (September 2003)
- ✓ Really Osc.! (with SNO: 2001)







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