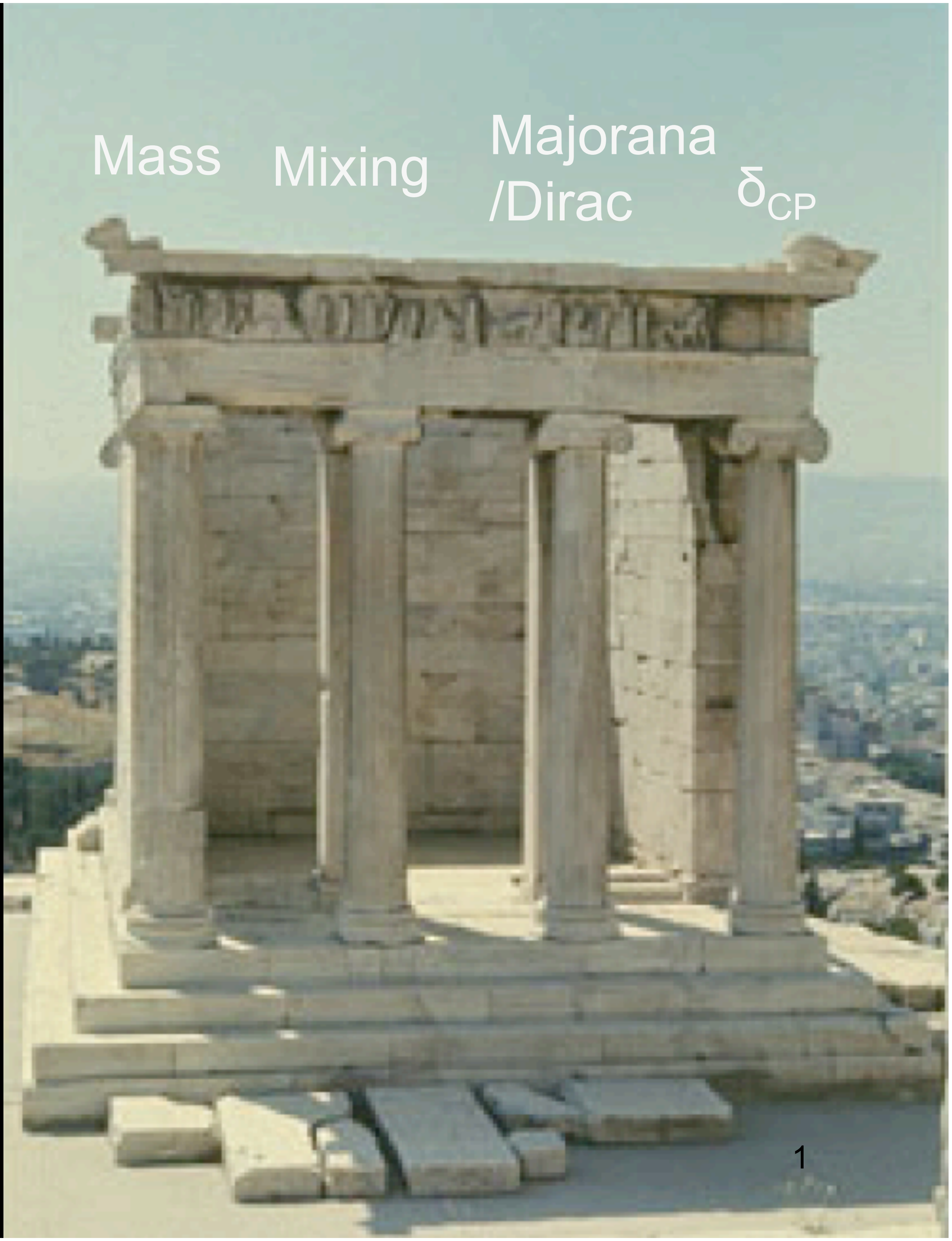
Neutrino Experiments: A Summary



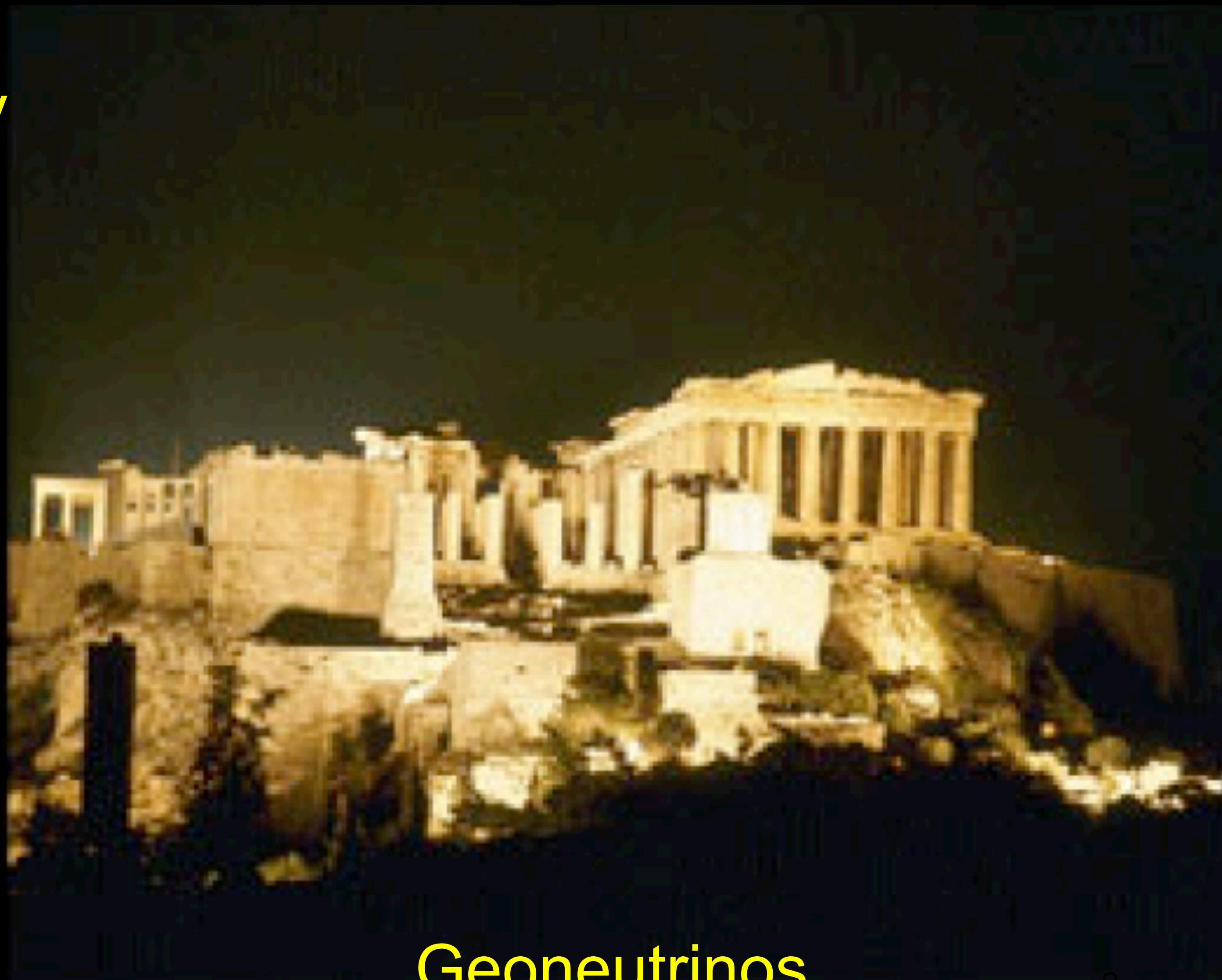
Hamish Robertson
Athens, June 19, 2010

Relic ν

Solar ν

UHE ν

Supernova ν



ν Cross Sections

Geoneutrinos

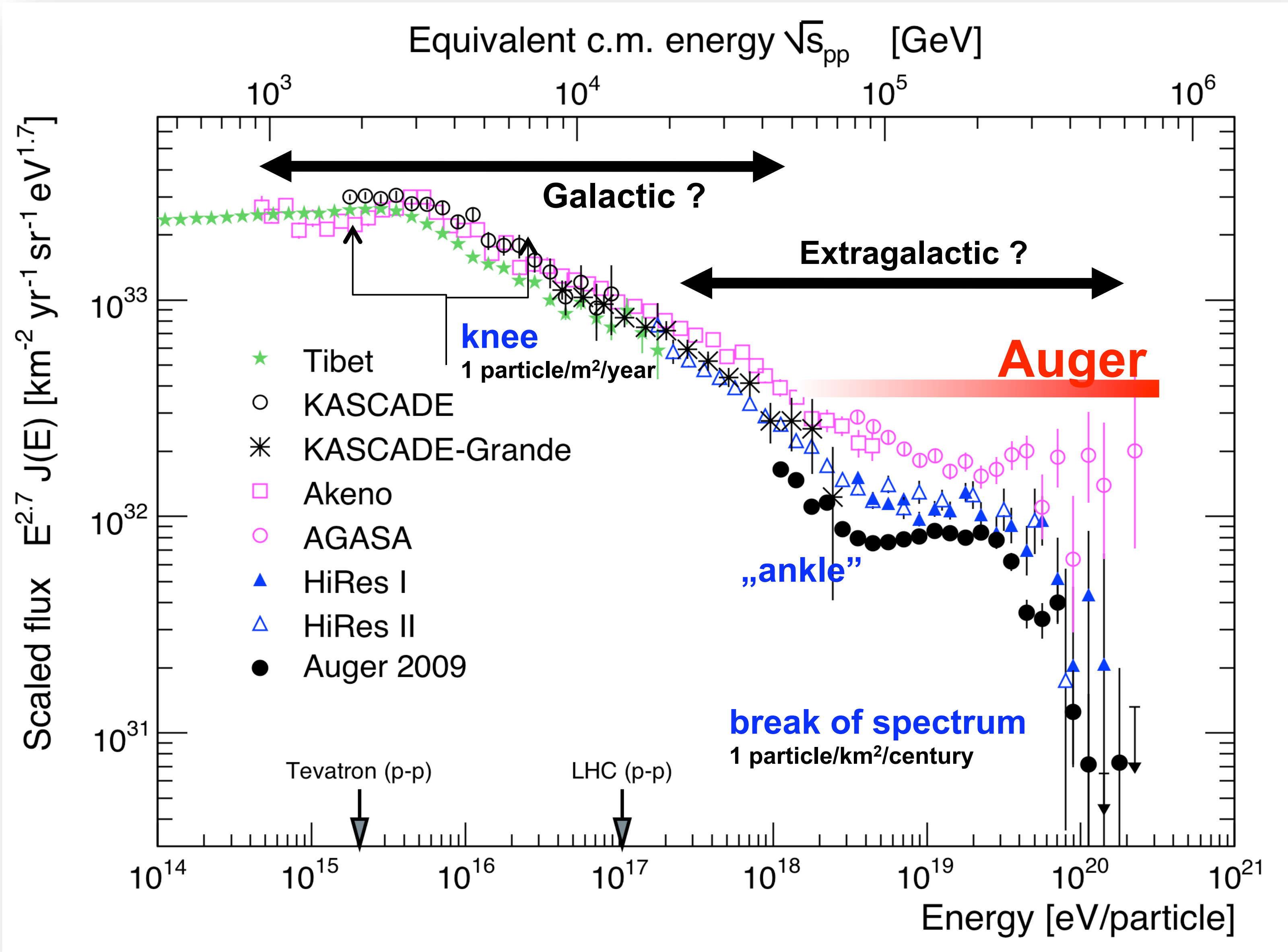
My Competition

- Australia *vs.* Ghana
- Netherlands *vs.* Japan
- Denmark *vs.* Cameroon

And…my apologies in advance:
I will leave out much that is important.

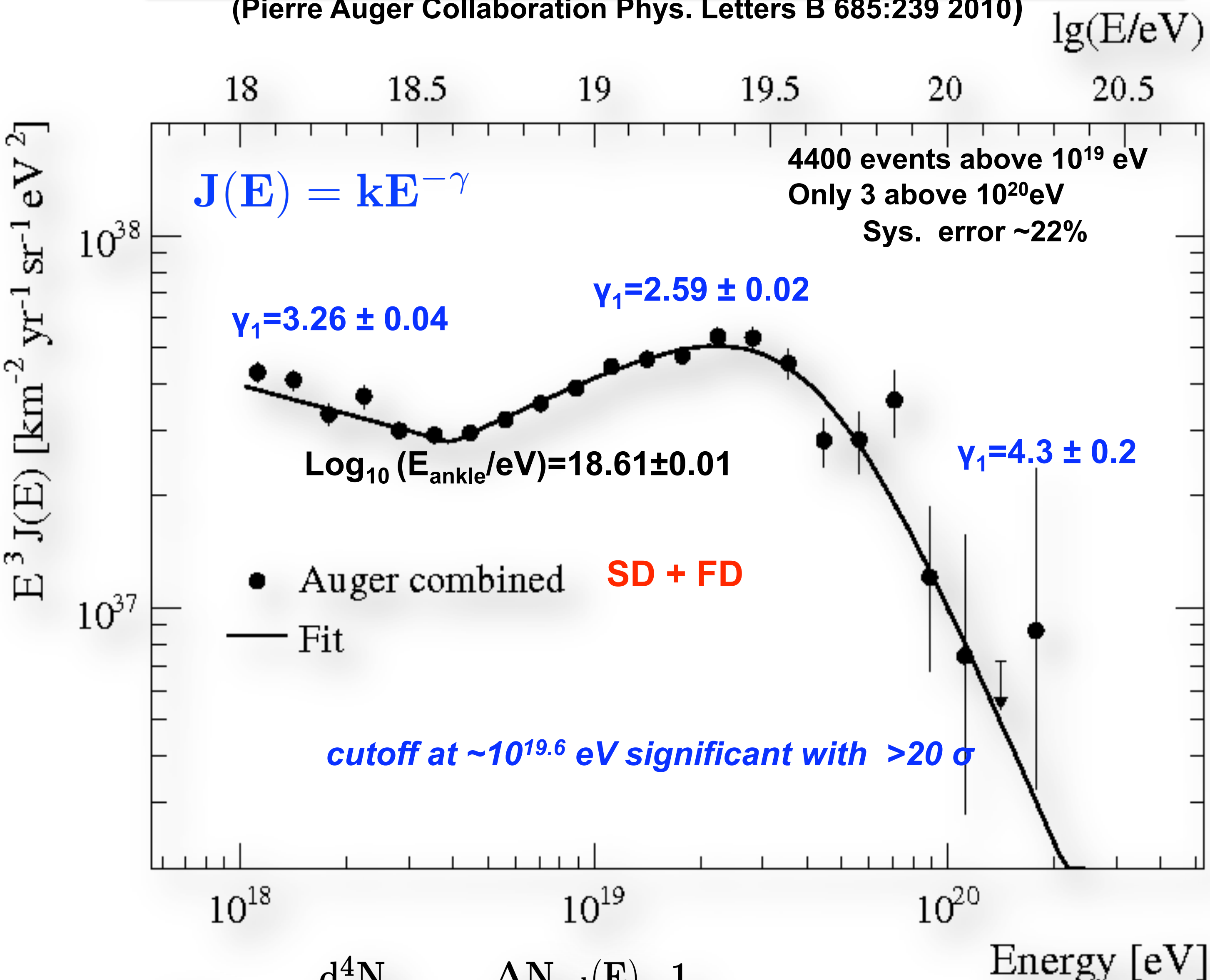
Cosmic ray energy spectrum

Dariusz Gora



Suppression of CR spectrum

(Pierre Auger Collaboration Phys. Letters B 685:239 2010)



$$J(E) = \frac{d^4N}{dE\,dA\,d\Omega\,dt} \simeq \frac{\Delta N_{sel}(E)}{\Delta E}\frac{1}{\epsilon(E)}$$

IceCube: E. Resconi

Final Configuration:

- 5160 DOMs / 86 strings

- O(100) neutrinos/day
O(10^{8}) muons/day

- threshold: ~10 GeV

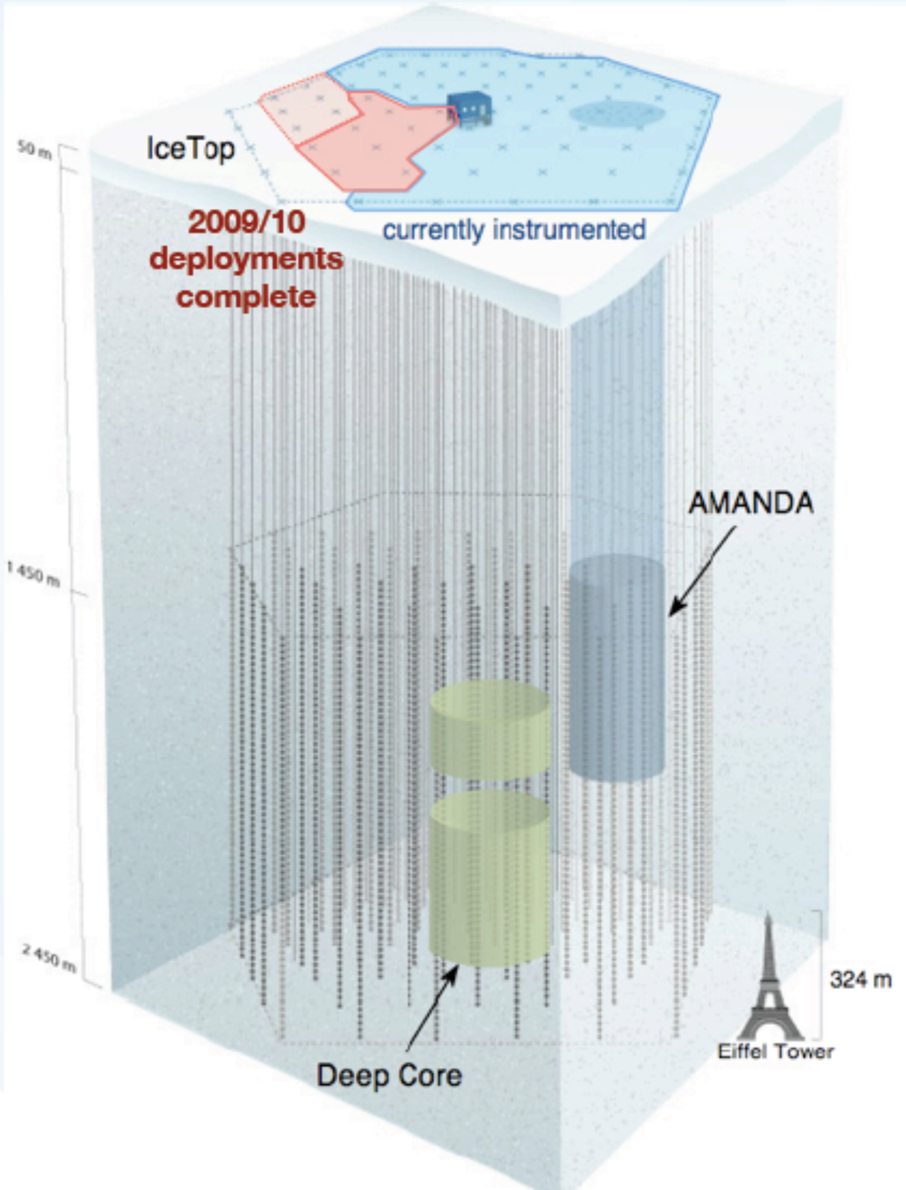
- angular resolution: 0.4-1 deg

Currently deployed:

4790 DOMs/ 79 strings

Data samples:

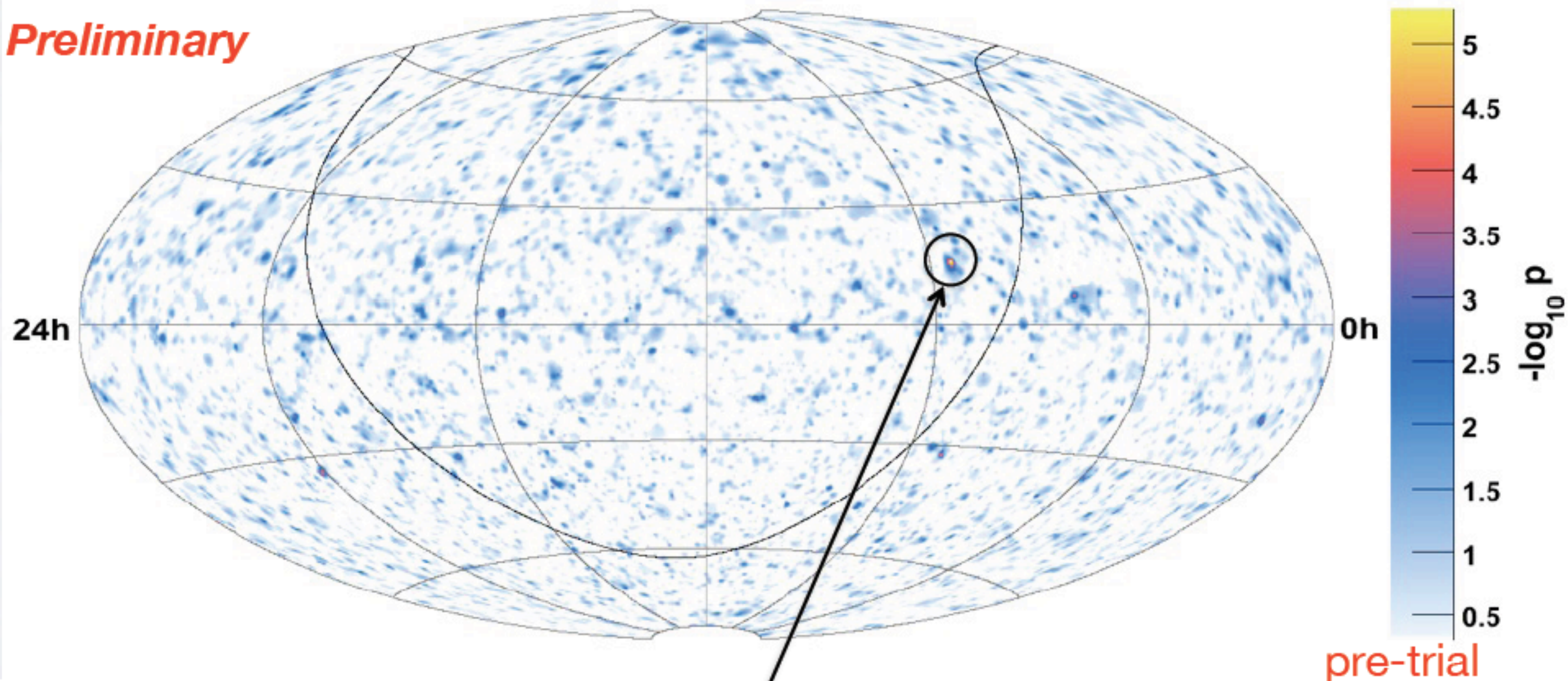
IceCube-22 IceCube-40
IceCube-59 IceCube-79



Elisa Resconi, for the IceCube Coll.

IC40: all-sky scan, significance map

Analysis described in J. Dumm et al., 31st ICRC, Łódź 2009



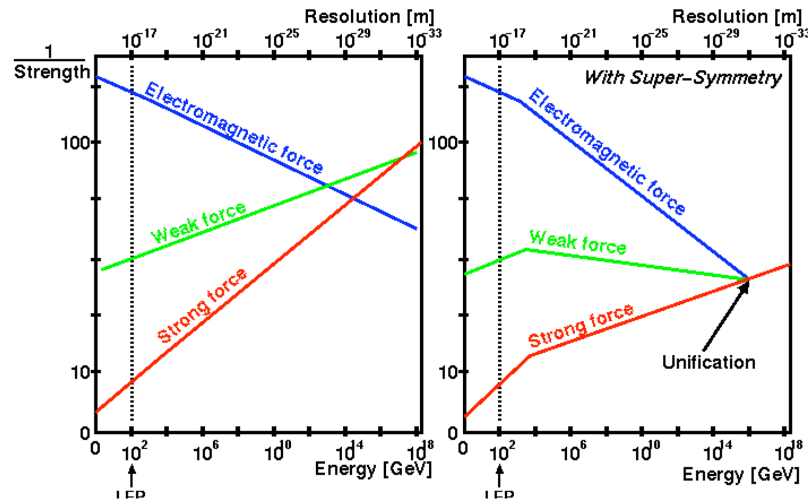
Hottest location in the all-sky search is:
Ra=113.75, Dec=15.15

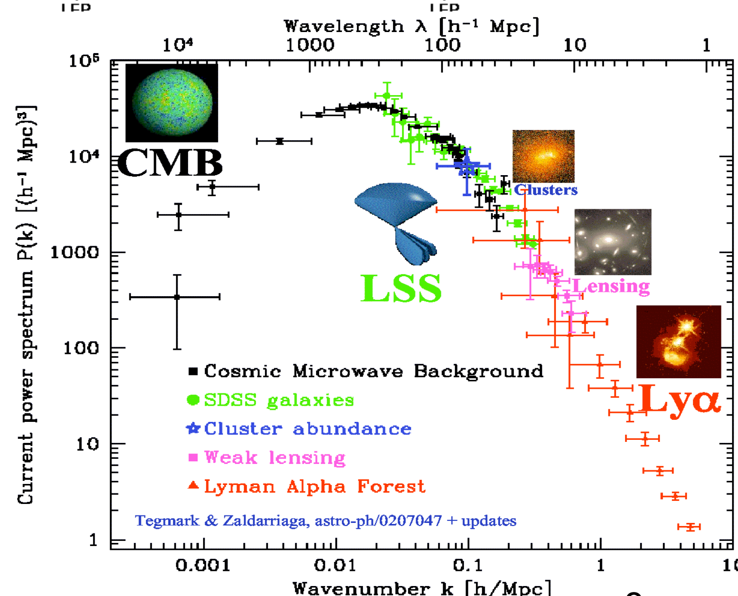
all-sky p-value = 18%

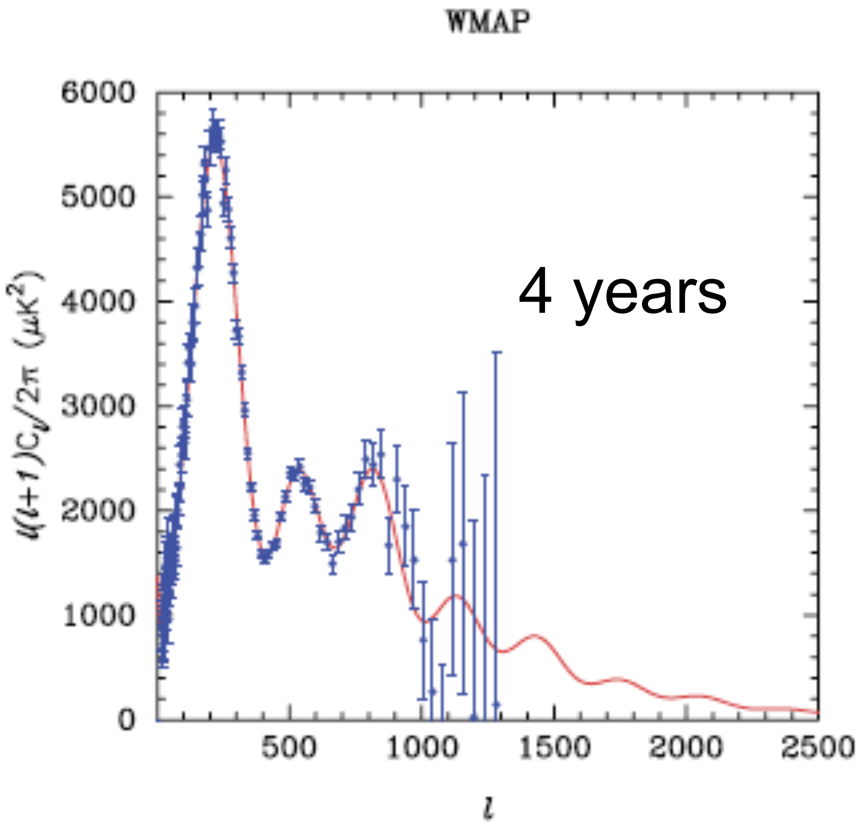
not significant, no evidence of neutrino source

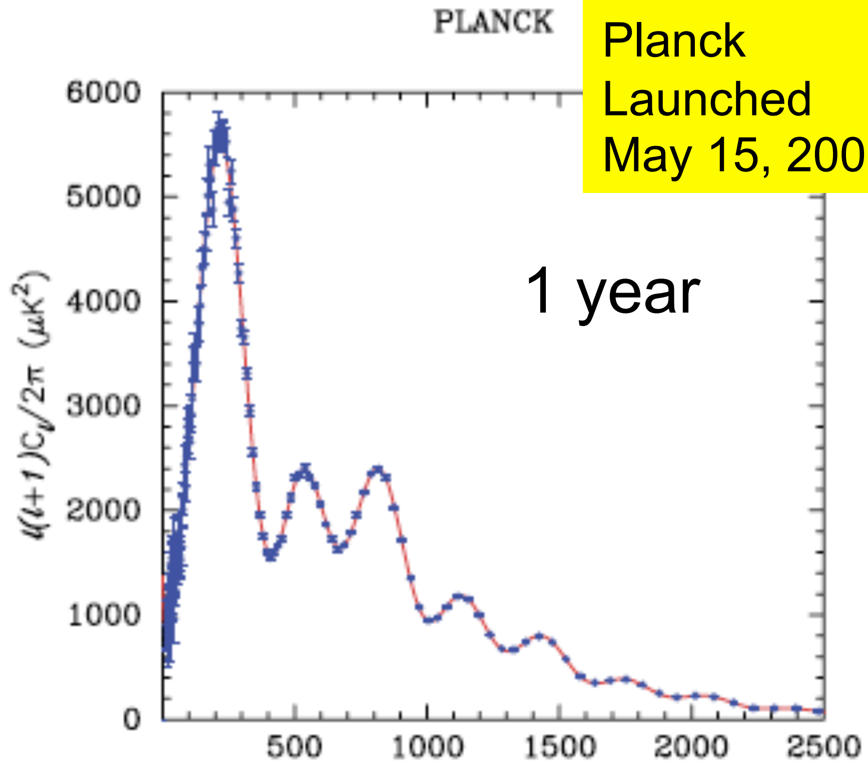
Mass

- Neutrino Oscillations
- Beta Decay
  - Tritium
  - ^{187}Re
  - ^{163}Ho
- Double beta decay
- Cosmology





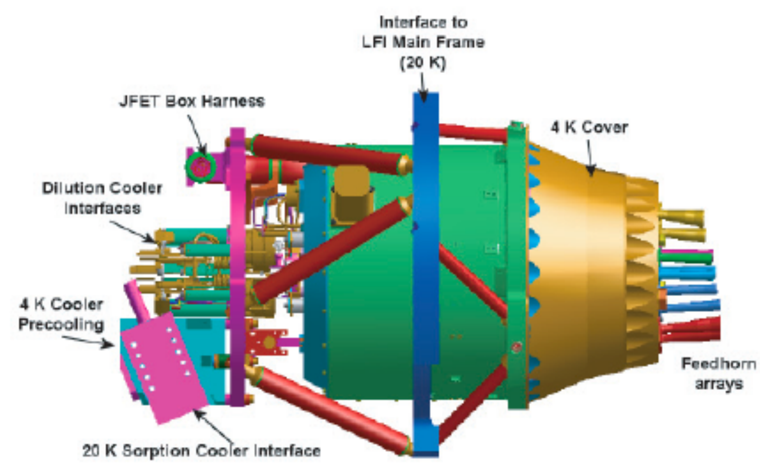




Planck
Launched
May 15, 2009

Planck will provide 3 separate ΛCDM constraints on Σm_ν:

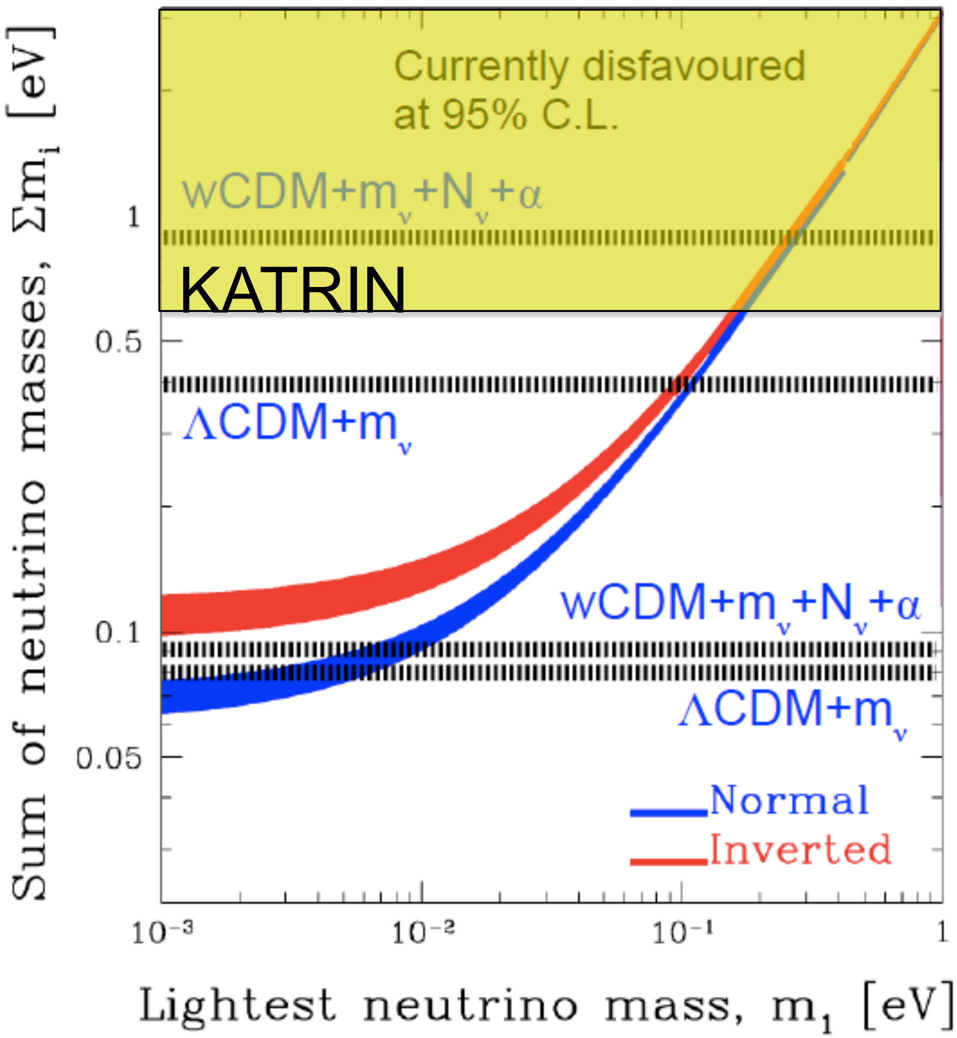
1. Planck only 0.26 eV
2. Planck + SDSS 0.20 eV
3. CMBR + grav. lensing 0.15 eV

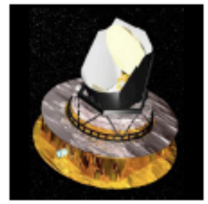


From Planck "Bluebook"

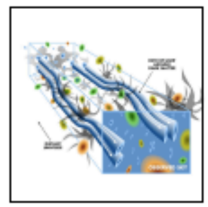
Projected 95% sensitivities...

Yvonne Wong





Planck
Lesgourgues et al. 2006
Perotto, Lesgouruges, Hannestad, Tu & Y^{3}W 2006

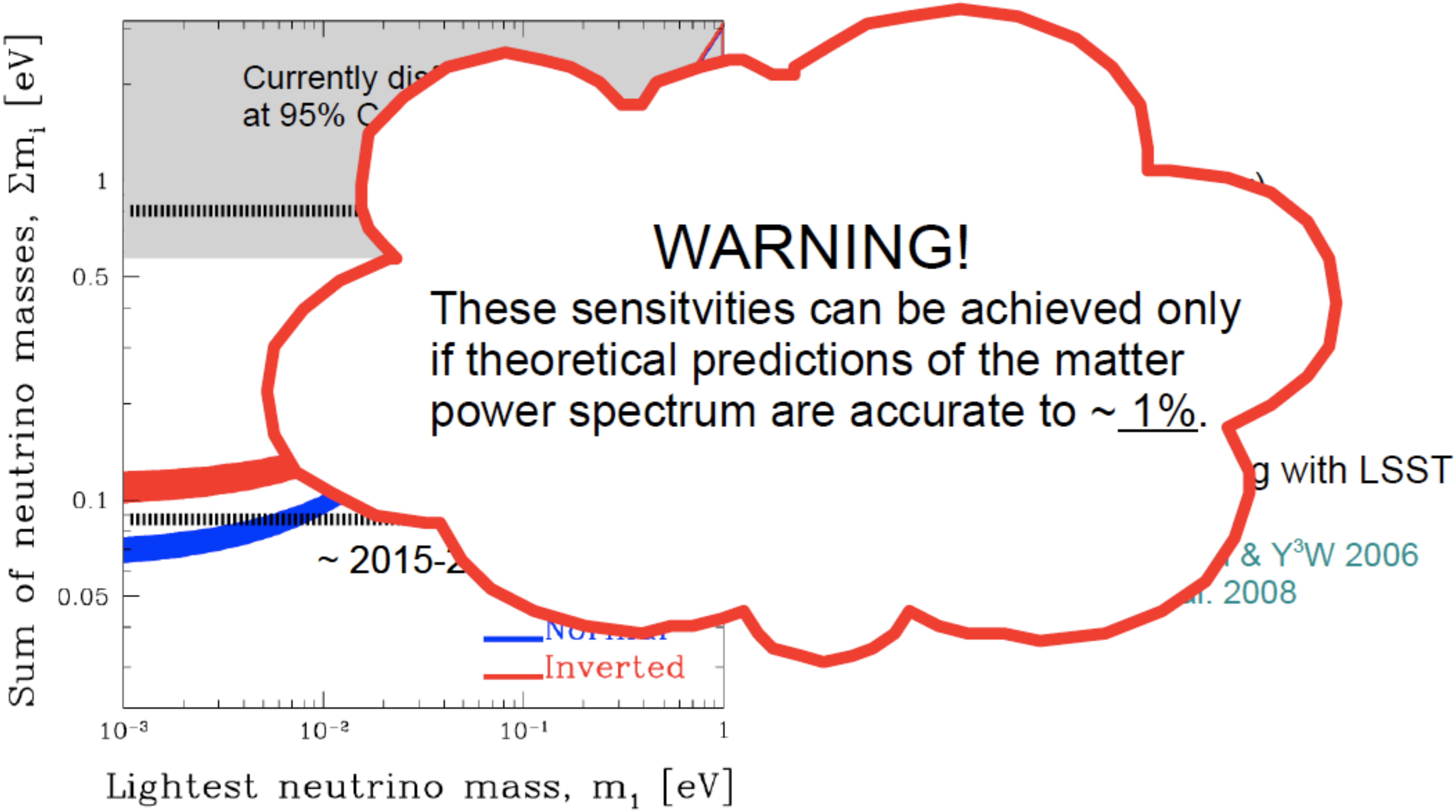


+ Weak lensing with LSST (tomography)
Hannestad, Tu & Y^{3}W 2006
Kitching et al. 2008

~ 2015-2020

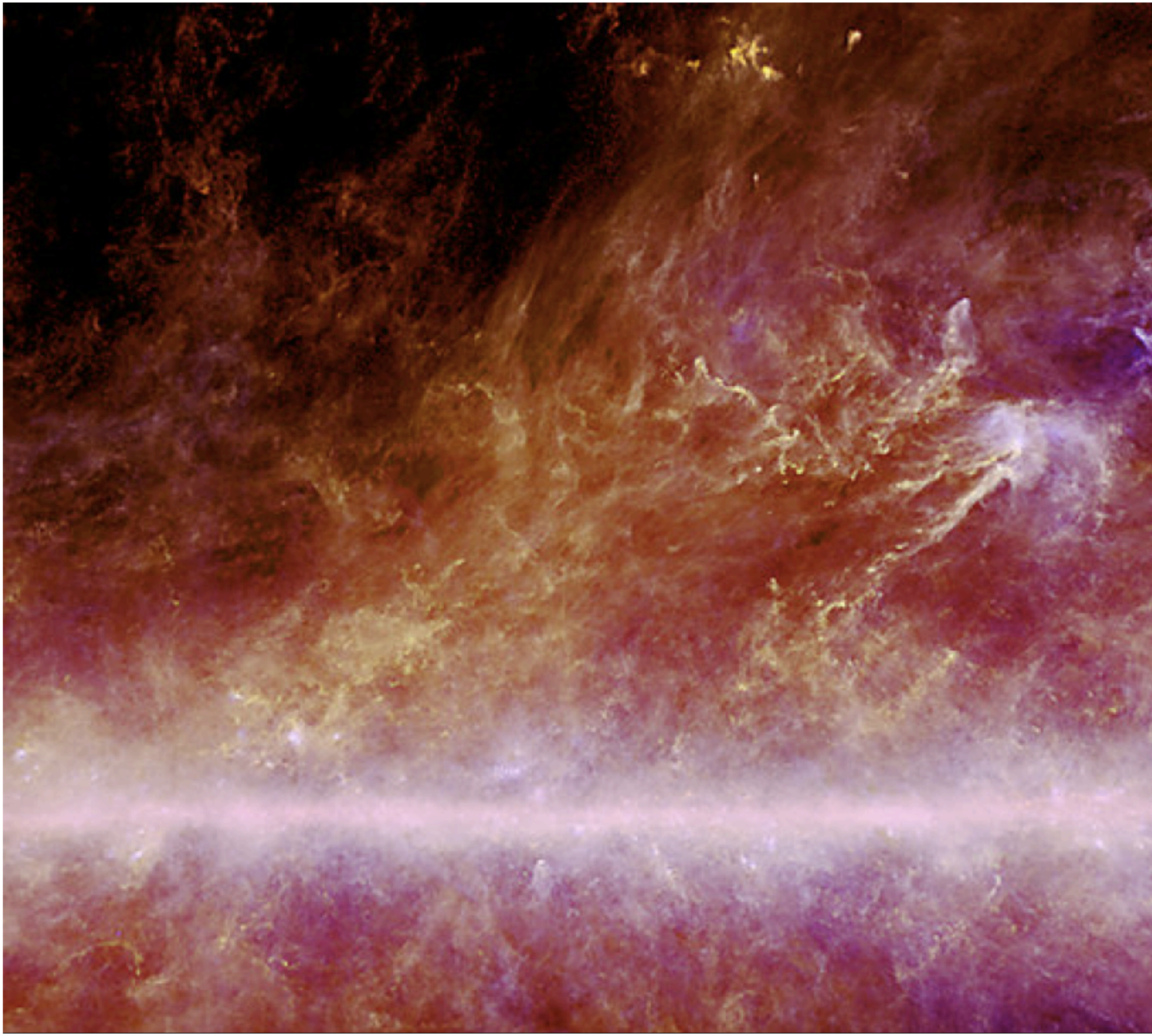
Projected sensitivities...

Yvonne Wong



WARNING!

These sensitivities can be achieved only if theoretical predictions of the matter power spectrum are accurate to ~ 1%.



Micro-
wave
image
from
Planck

Galactic
Plane

Oscillations and Neutrino Mass

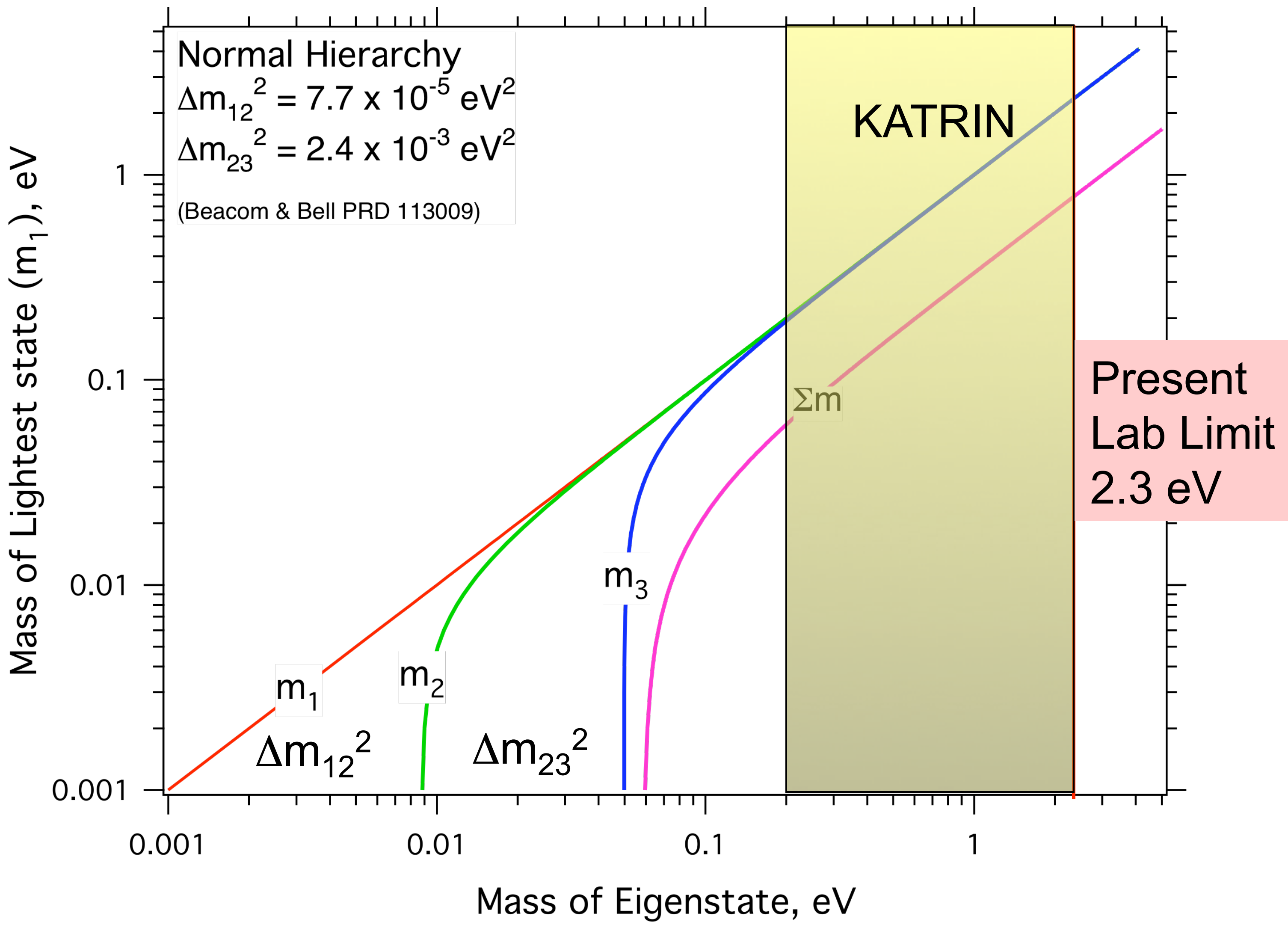
- Neutrino oscillations tell us three important things:
  - Neutrinos HAVE mass
  - The sum of the masses $\Sigma m_i > 55$ meV
  - We can use *electron* neutrinos to get *all* the masses.

KATRIN, MARE, Project 8

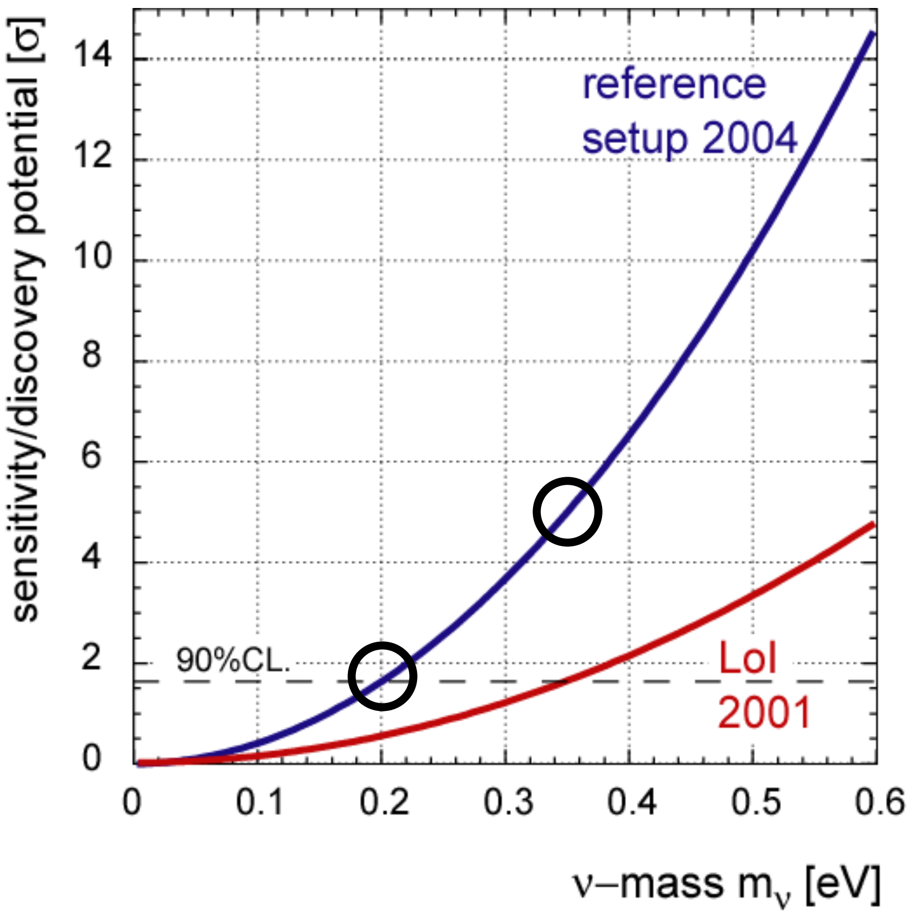
Model-independent determination of mass.
Independent of:

- whether neutrinos Dirac or Majorana,
- nuclear matrix elements,
- phases,
- cosmological models.

Mass Range Accessible



KATRIN Sensitivity



After 3 years data (5y realtime):

discovery potential
$m(\nu) = 0.35$ eV (5σ)

sensitivity (90% CL)
$m(\nu) < 0.2$ eV

$\Delta m_{tot}^2 = (\Delta m_{stat}^4 + \Delta m_{sys,tot}^4)^{1/2}$

$\Delta m_{tot}^2 \approx 0.025\ eV^2/c^4$

and

$\Delta m_{stat} = \Delta m_{sys,tot}$

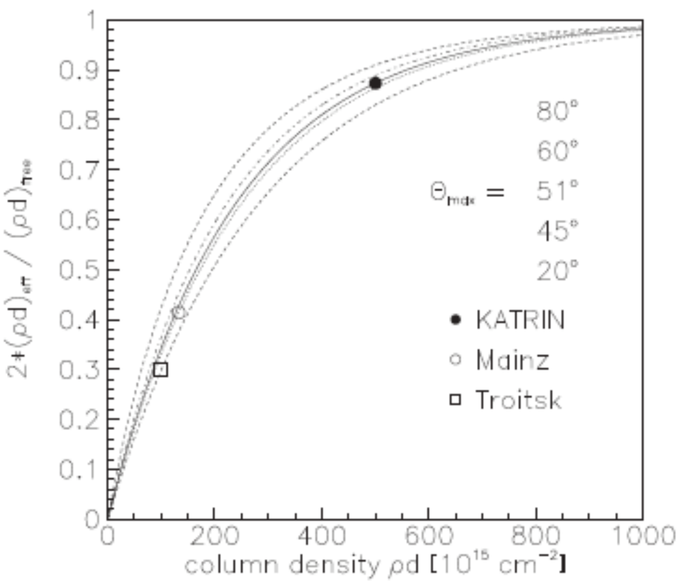
$\Delta m_{stat}^2 = 0.018\ eV^2/c^4$

$\Delta m_{sys,tot}^2 \leq 0.017\ eV^2/c^4$

Thomas Thümmler

The Last Order of Magnitude

If the mass is NOT in the 200-2300 meV window, but < 200 meV, how can we measure it?
KATRIN may be the largest such experiment possible.

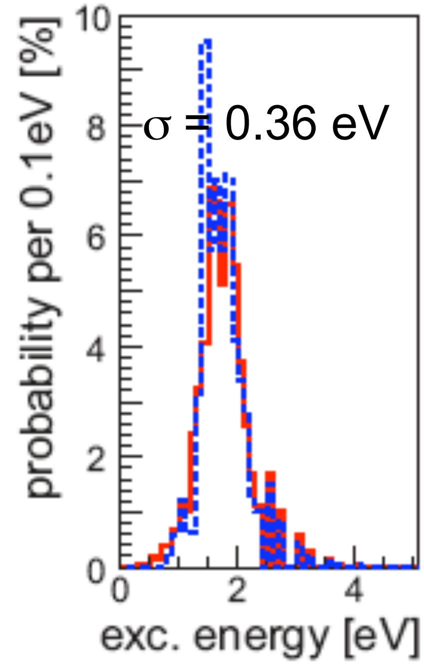


Source T_2 column density near max

Size of experiment now: Diameter 10 m.

$$\sigma(m_\nu^2) = k\frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

Next diameter: 300 m!



Rovibrational states of THe^+, HHe^+ molecule

The Last Order of Magnitude

KATRIN-type experiment limit: Source and detector are separate. Can evade by making them the same. Spectrum is point-by-point.
MARE ^{187}Re uses microcalorimeters: source=detector. BUT pileup limits size of each to few mg.

	Tritium	^{187}Re	
Endpoint	18.58 keV	2.47 keV	
Branch to last eV	2×10^{-13}	6×10^{-11}	300x
Half-life	12.32 y	4.32×10^{10} y	
Mass (1 dis/d in last 200 meV)	20 μg	13 kg	
Mass (1 dis/d in last 20 meV)	20 mg	13000 kg	

But, taking whole spectrum at once gains about 100x

PROJECT 8

Cyclotron Frequency

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

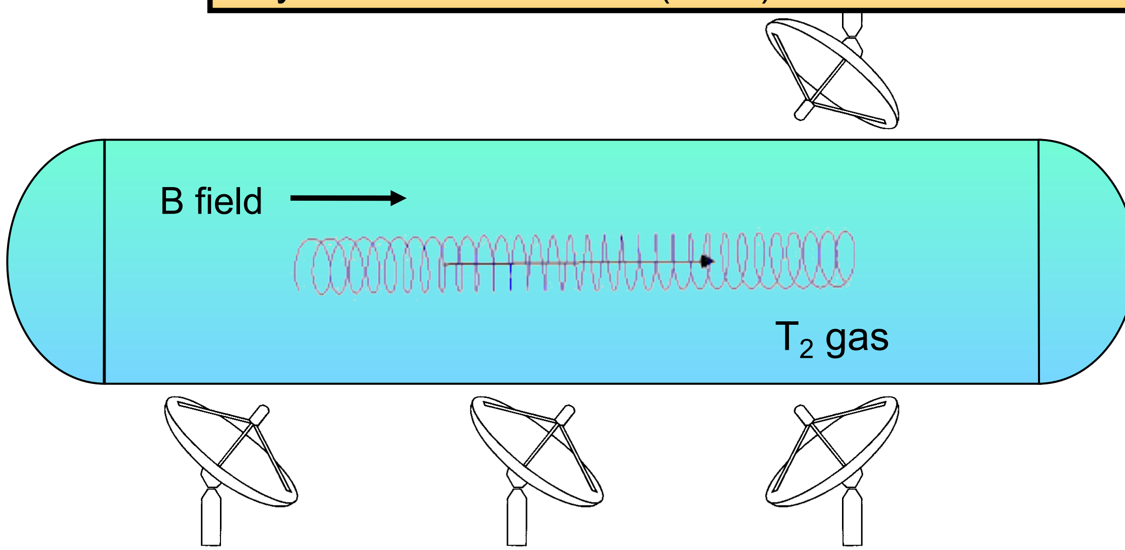
- Coherent radiation emitted in beta decay can be collected and used to measure the energy of the electron in a non-destructive manner.

Radiative Power Emitted

$$P_{\mathrm{tot}}(\beta_{\|}, \beta) = \frac{1}{4\pi\epsilon_0}\frac{2e^2\omega_0^2}{3c}\frac{\beta_{\|}^2}{1-\beta^2}$$

B. Monreal and J. Formaggio
Phys. Rev. D80:051301 (2009).

- Uniform B field
- Low pressure T_2 gas.
- Antenna array for cyclotron radiation detection.



K. Nakamura

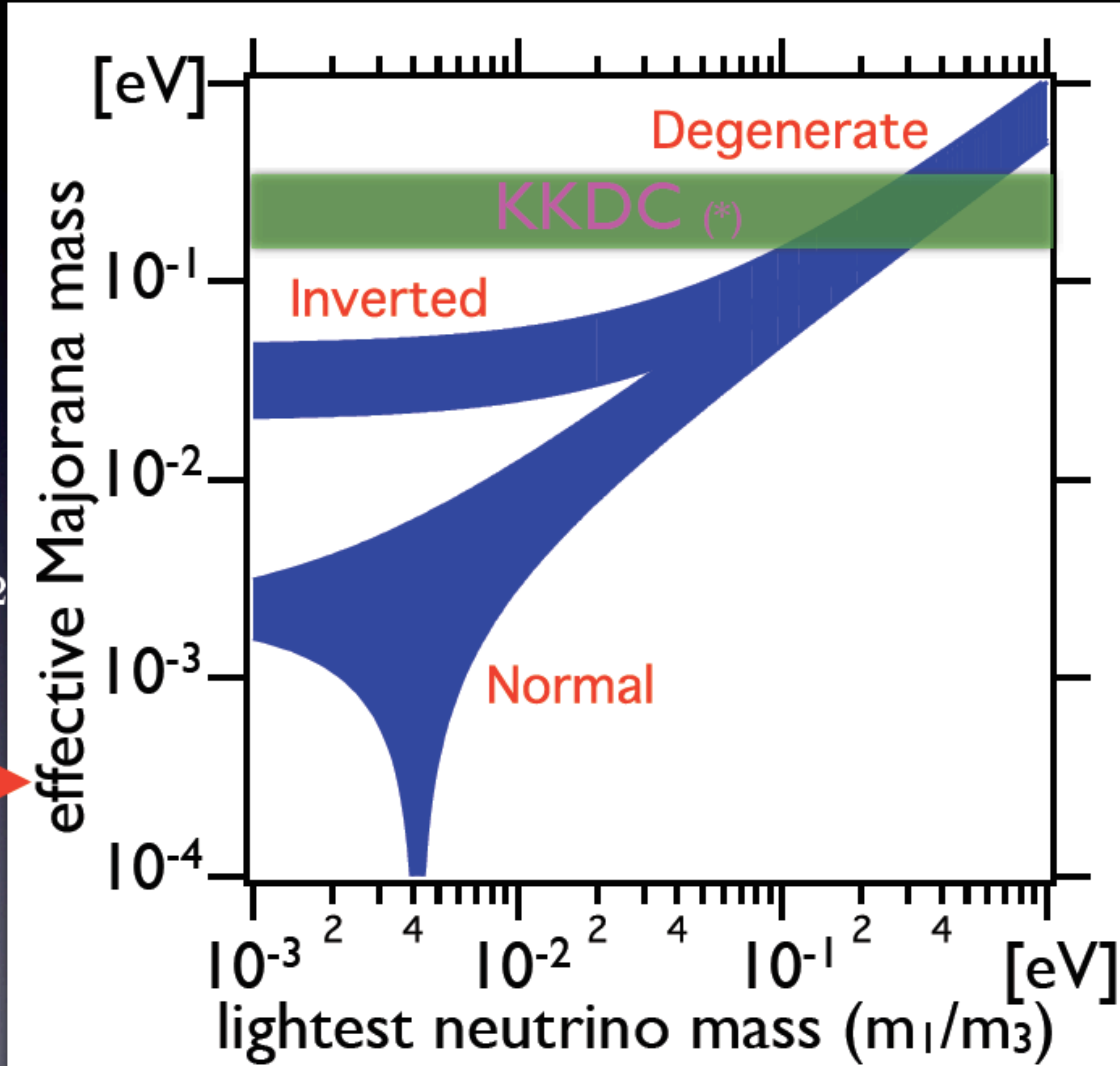
Observable

=

$$\left[T_{1/2}^{0\nu}\right]^{-1}$$

=

$$G^{0\nu}\left|M^{0\nu}\right|^{2}\left|m_{\beta\beta}\right|^{2}$$



(*) PLB586,198(2004)

arXiv:0708.1033

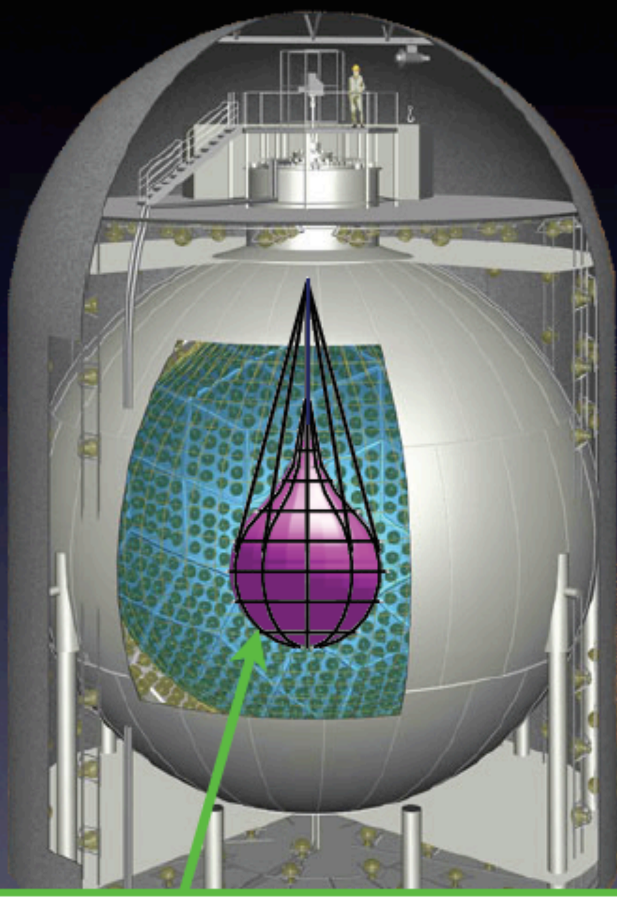
Overview of Experiments

Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

S. Schönert, TAUP 2009

KamLAND-Zen



^{136}Xe 400 kg loaded LS
in mini-balloon, R=1.7m

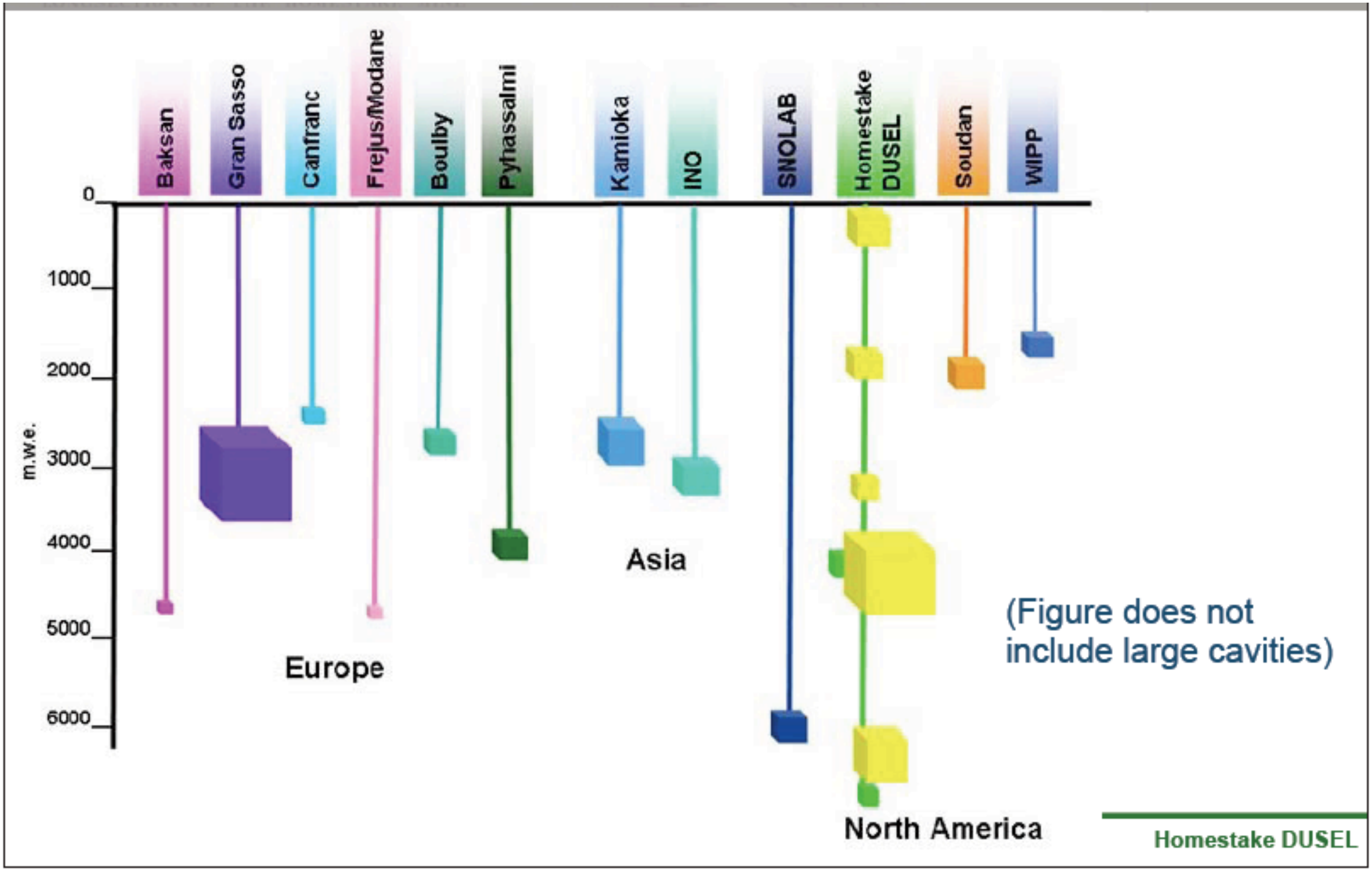
^{136}Xe 400 kg:

- 2.7 wt% dissolved into LS
- easy handling/ enrichment (90%)
- longer 2ν beta decay life time
- $T^{2\nu}$ >10^{22} years (cf: ~$10^{19\text{-}20}$)

KamLAND exists:

- ultra pure environment (U/Th~10^{-17} g/g)
- LS techniques
- Balloon experience
- LS Density control techniques
- Reactor/Geo neutrino

INTERNATIONAL UNDERGROUND LABORATORIES
(Present and Planned)

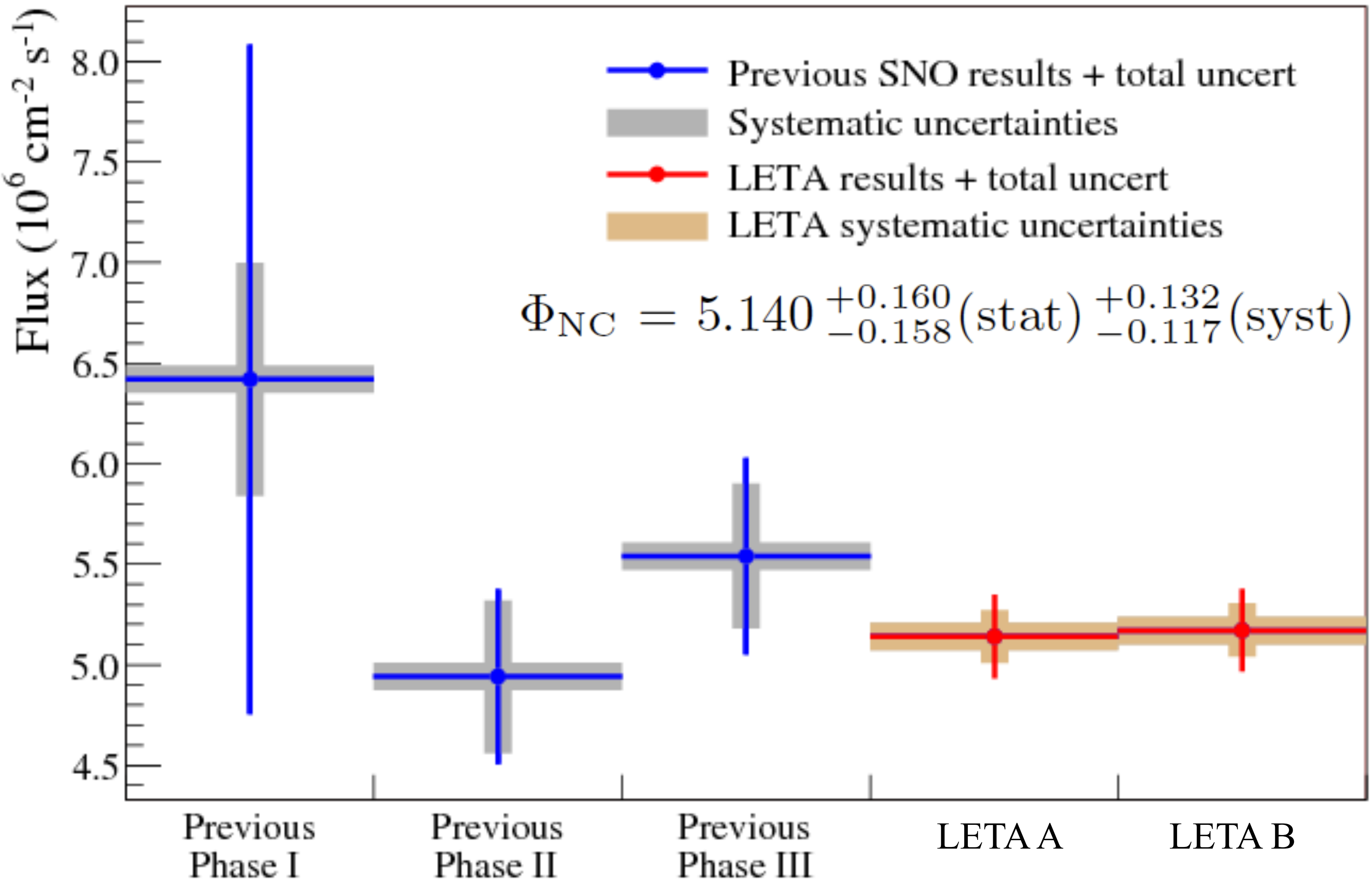


Mixing

- SK
- SNO
- Borexino
- LENS
- MINOS
- OPERA
- MiniBooNE
- T2K
- NOvA

- Double Chooz
- Daya Bay
- RENO

SNO ^{8}B Flux Result

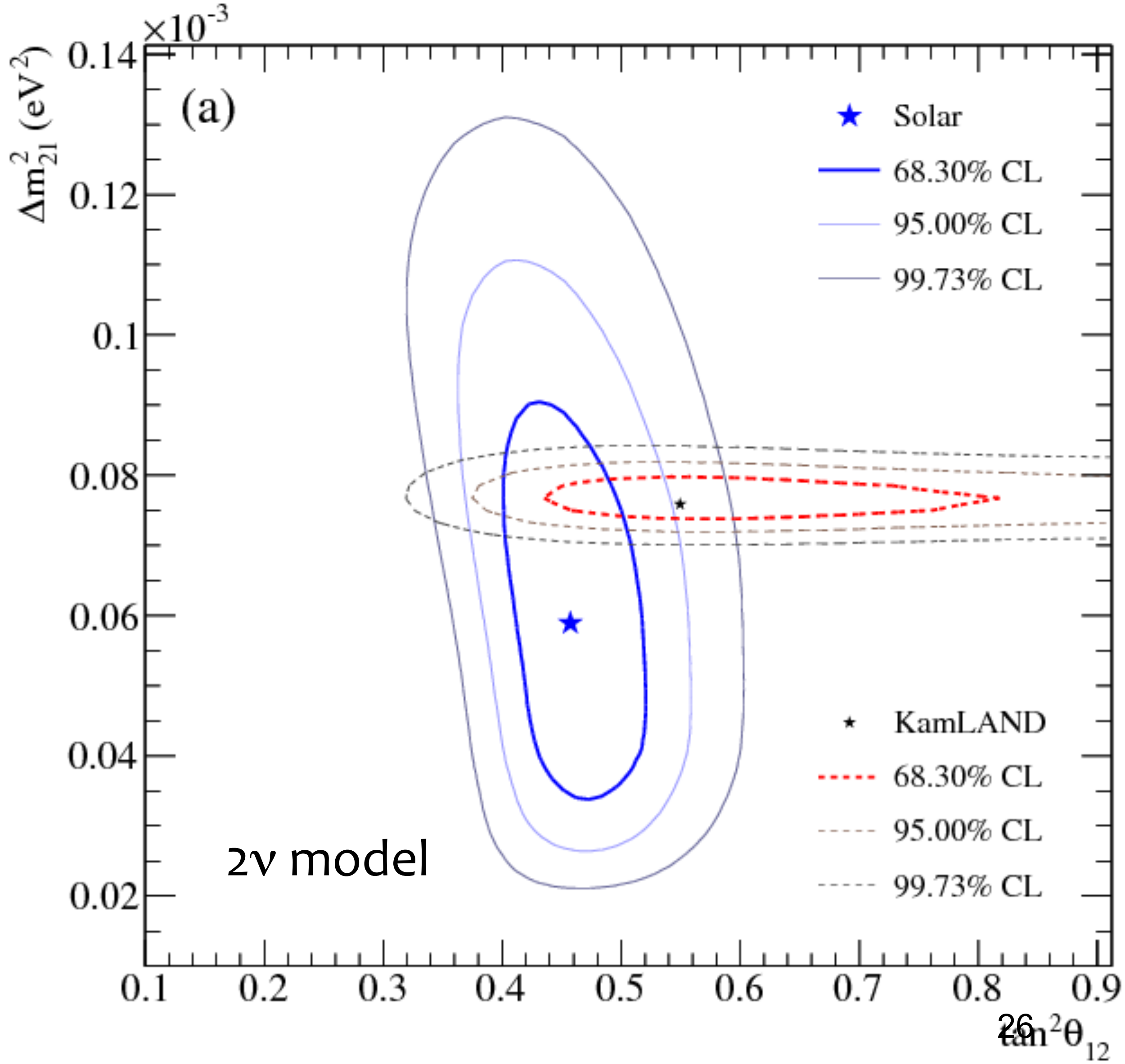


Josh Klein

Solar + KamLAND 2-flavor Overlay

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

2-flavor overlay



Solar + KamLAND 3-flavor Overlay

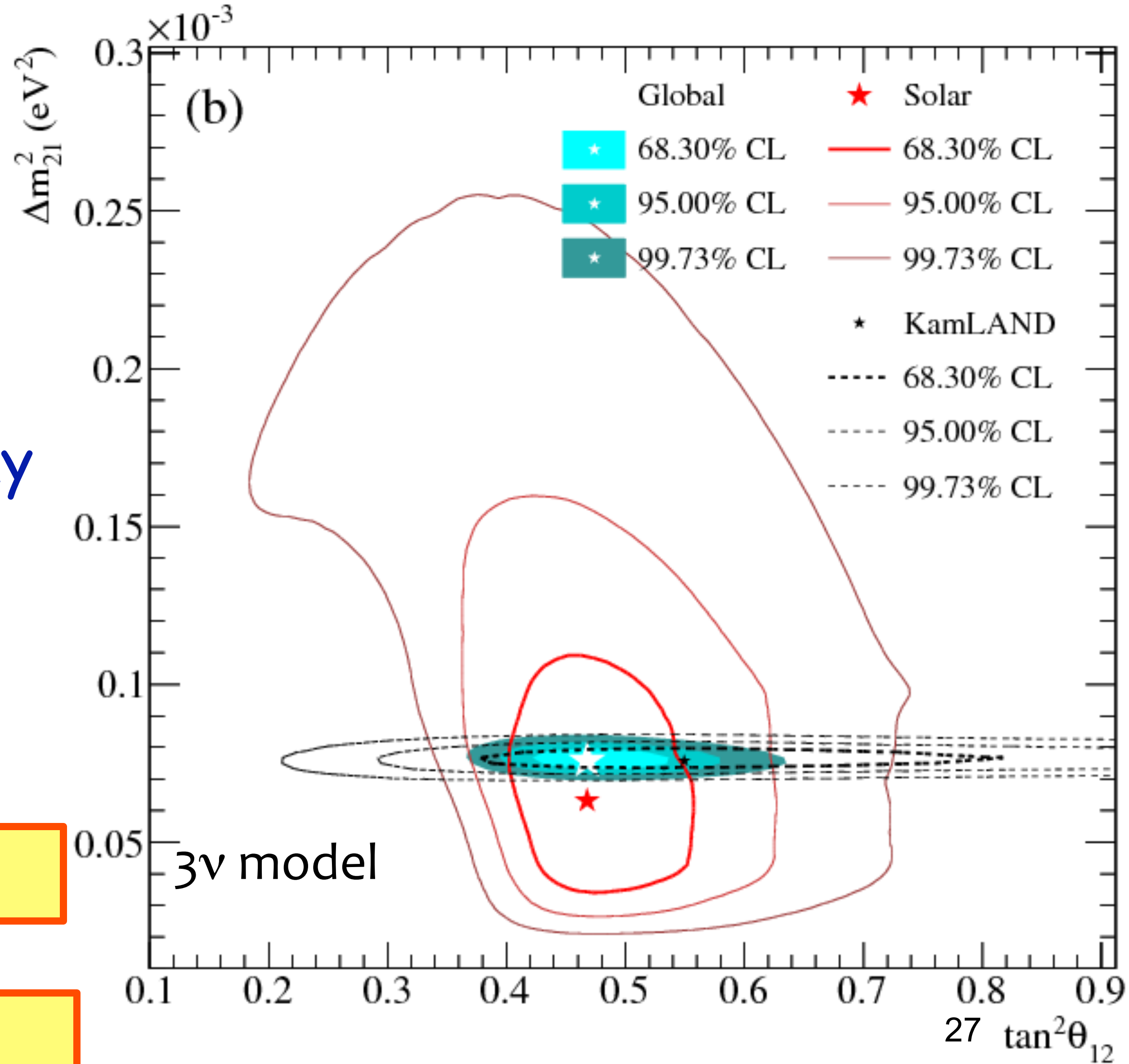
LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

3-flavor fit/overlay
-> Pointed out by
many authors

Best-fit:

$\sin^2\theta_{13}=2.00^{+2.09}_{-1.63}\times10^{-2}$

$\sin^2\theta_{13} < 0.057$ (95% C.L.)



Oscillation Analyses: Solar + KamLAND

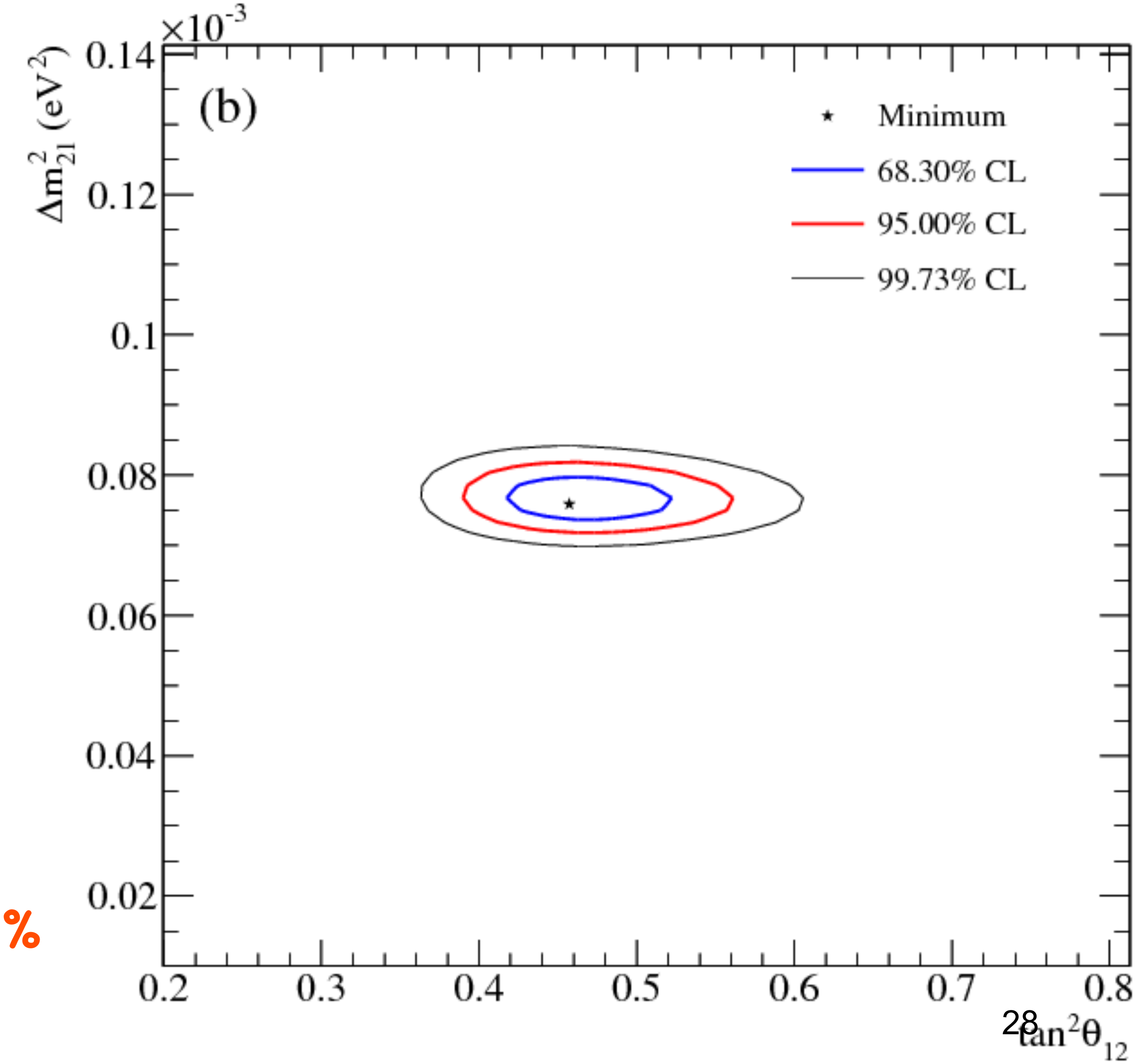
LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

Best-fit LMA point:

$\tan^2\theta_{12} = 0.457$
(+0.040 -0.029)

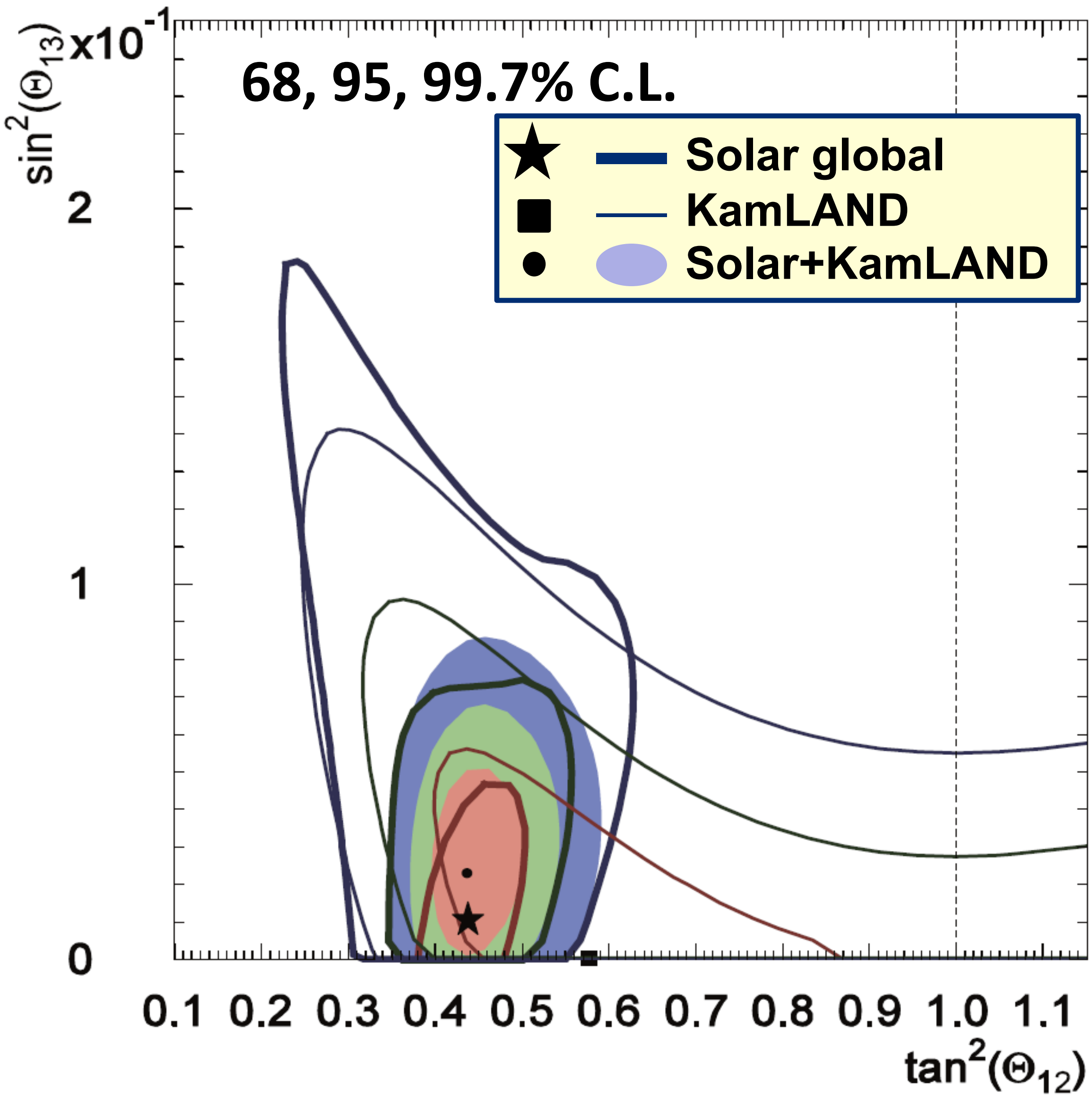
$\Delta m^2 = 7.59\times10^{-5}$ eV^2
(+0.20 -0.21)

Φ_{8B} **uncert** = $^{+2.38}_{-2.95}$ %



SK 3-flavor analysis: θ_{12} - θ_{13} Y. Takeuchi

Preliminary May 2010



Solar global:

$\sin^2\theta_{13}<0.060$ @95%C.L.

Solar global + KamLAND:

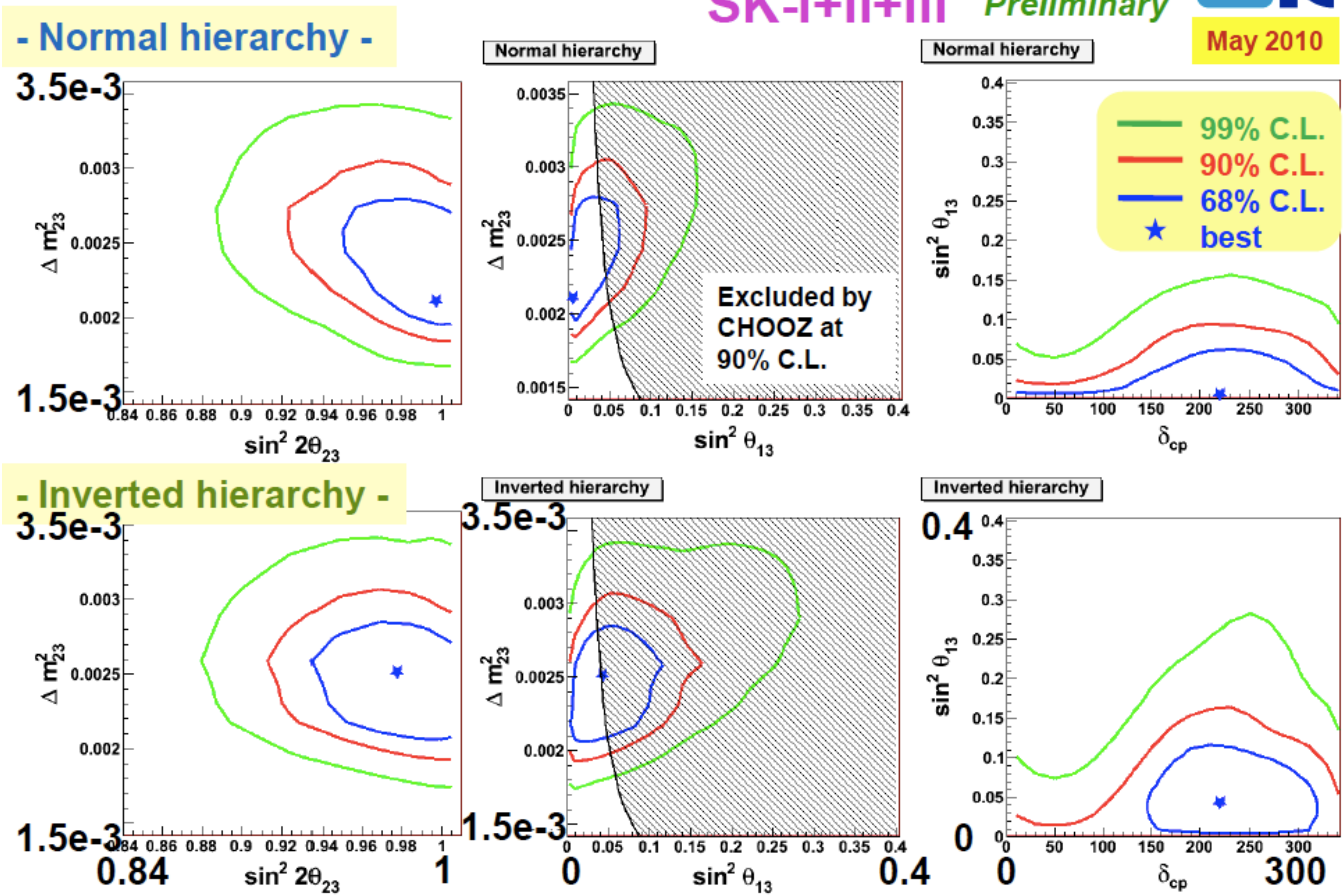
$\sin^2\theta_{13}=0.025^{+0.018}_{-0.016}$
(<0.059 @95%C.L.)

Cf. PRC81, 055504 (2010)
$\sin^2\theta_{13}$=0.020+0.021-0.016
(<0.057 @95%C.L.)

Full 3-flavor oscillation results

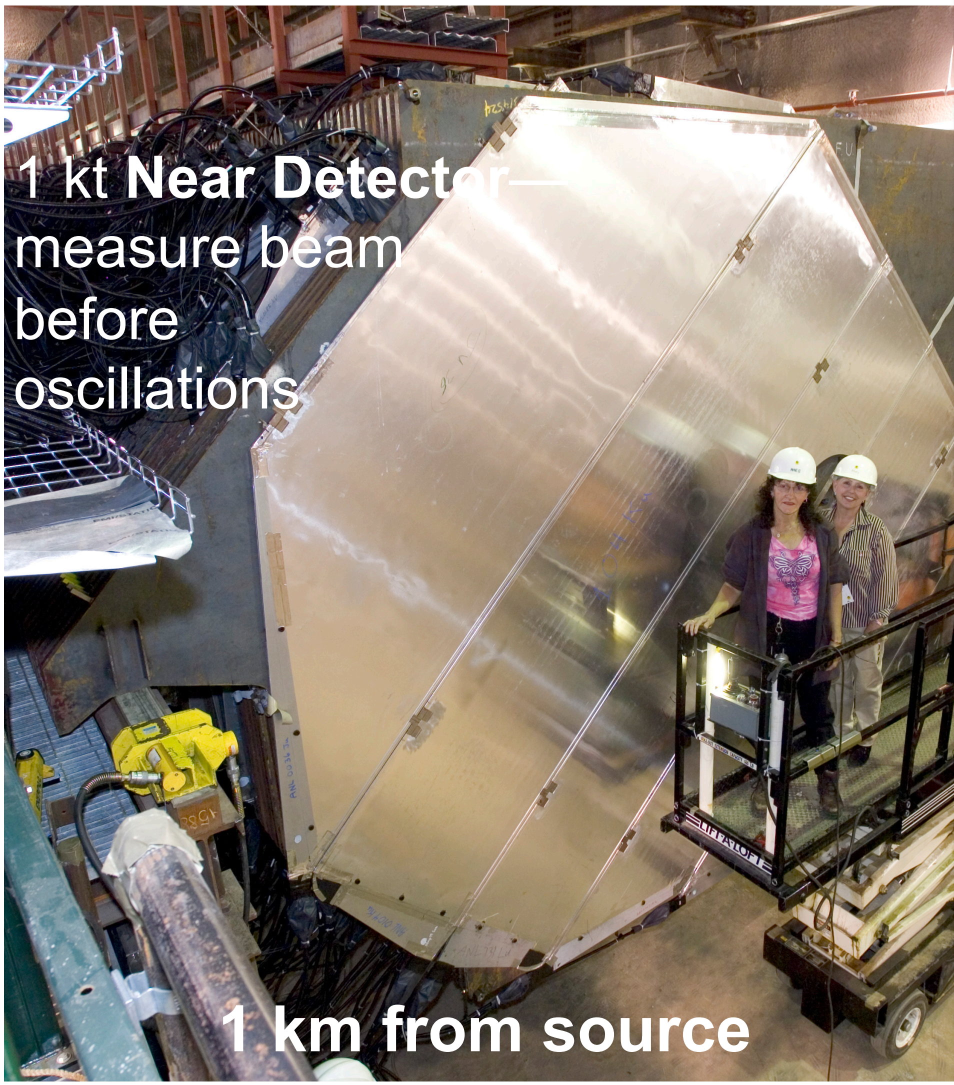
SK-I+II+III Preliminary

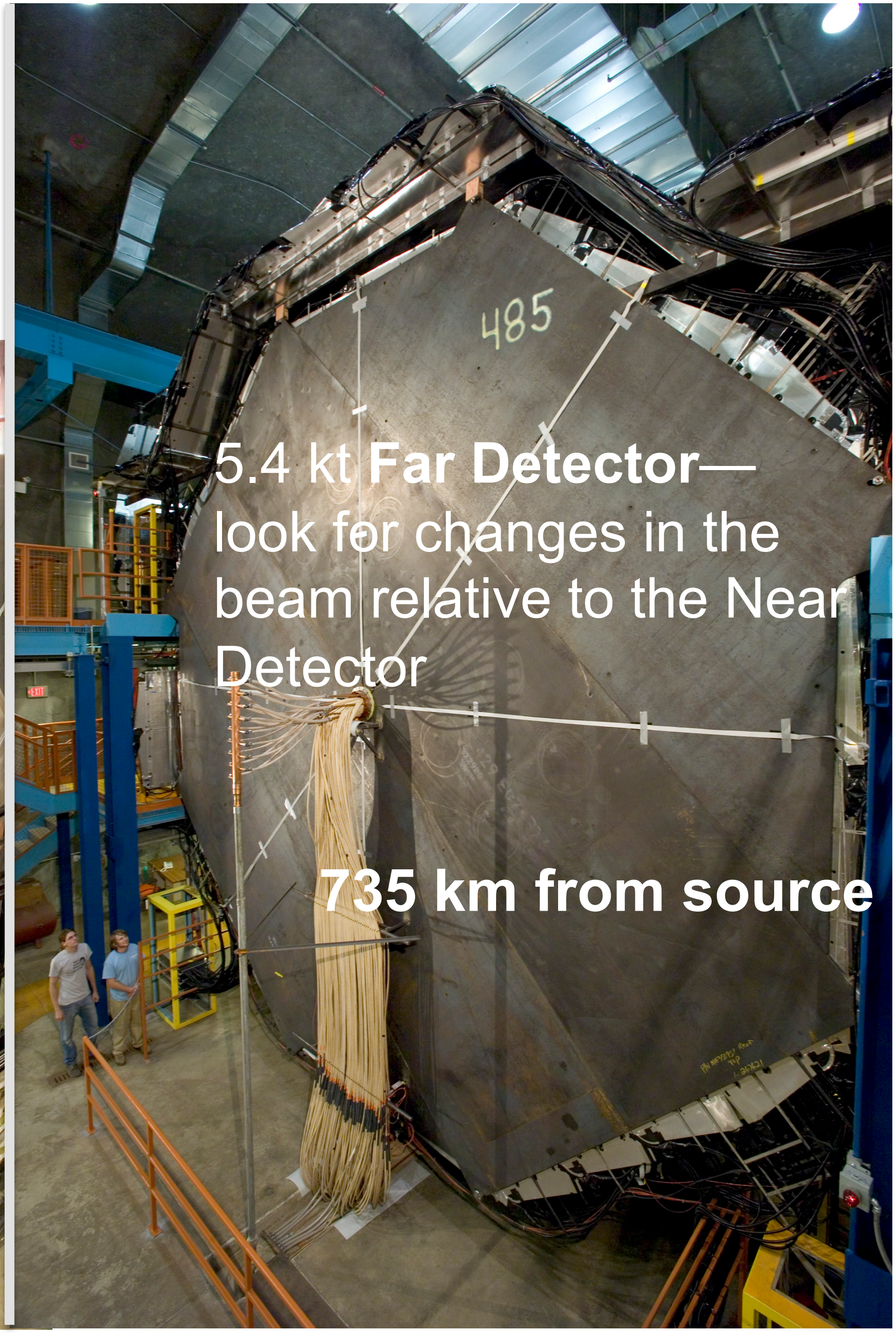
May 2010



P. Vahle: MINOS

Magnetized, tracking calorimeters



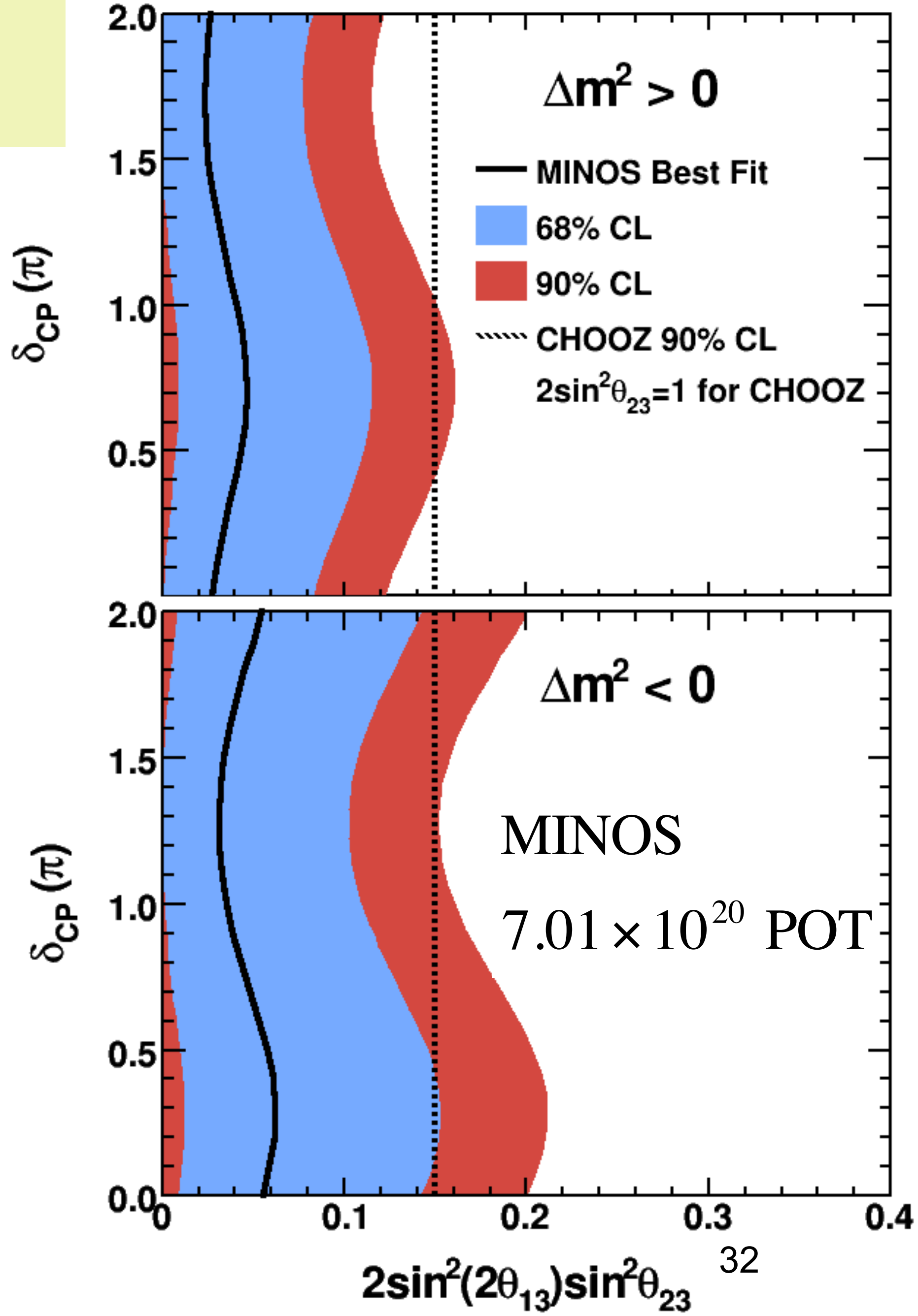


ν_e Appearance Results

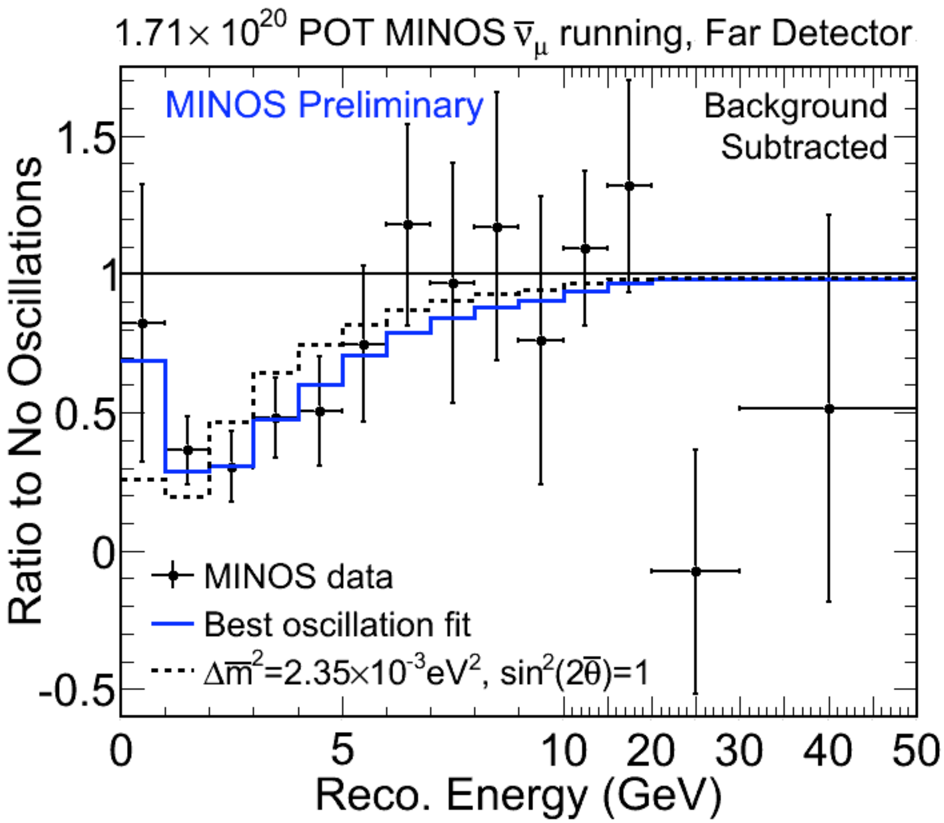
for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$
$|\Delta m^2_{32}| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$

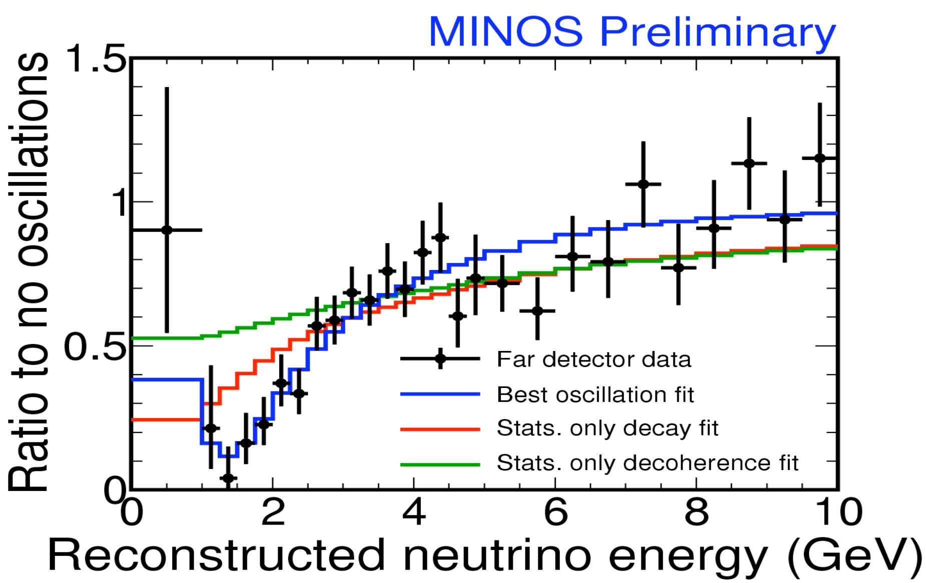
$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy
$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy
at 90% C.L.

arXiv:1006.0996v1 [hep-ex]

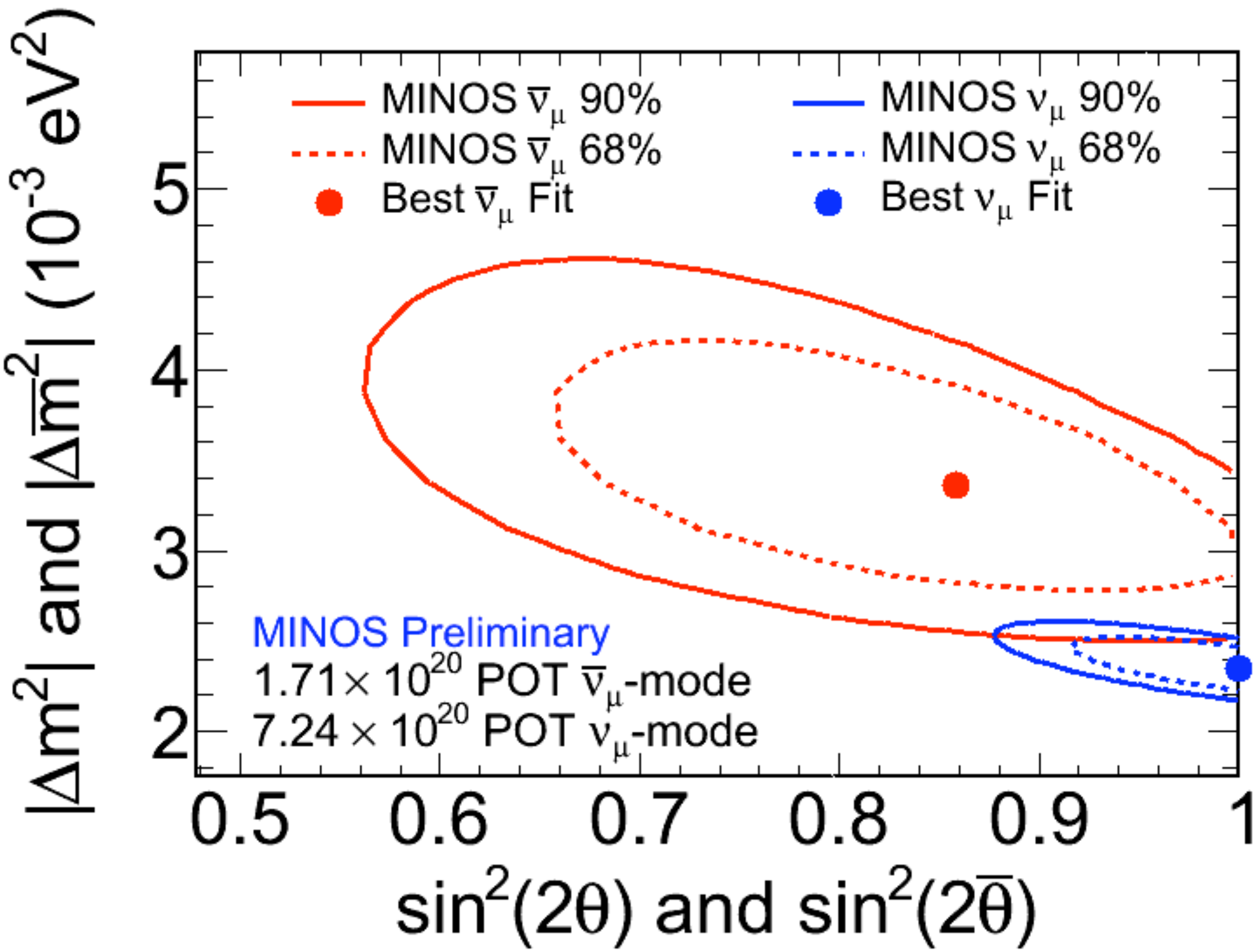


MINOS Antineutrino Data





Comparisons to Neutrinos



What can this be?

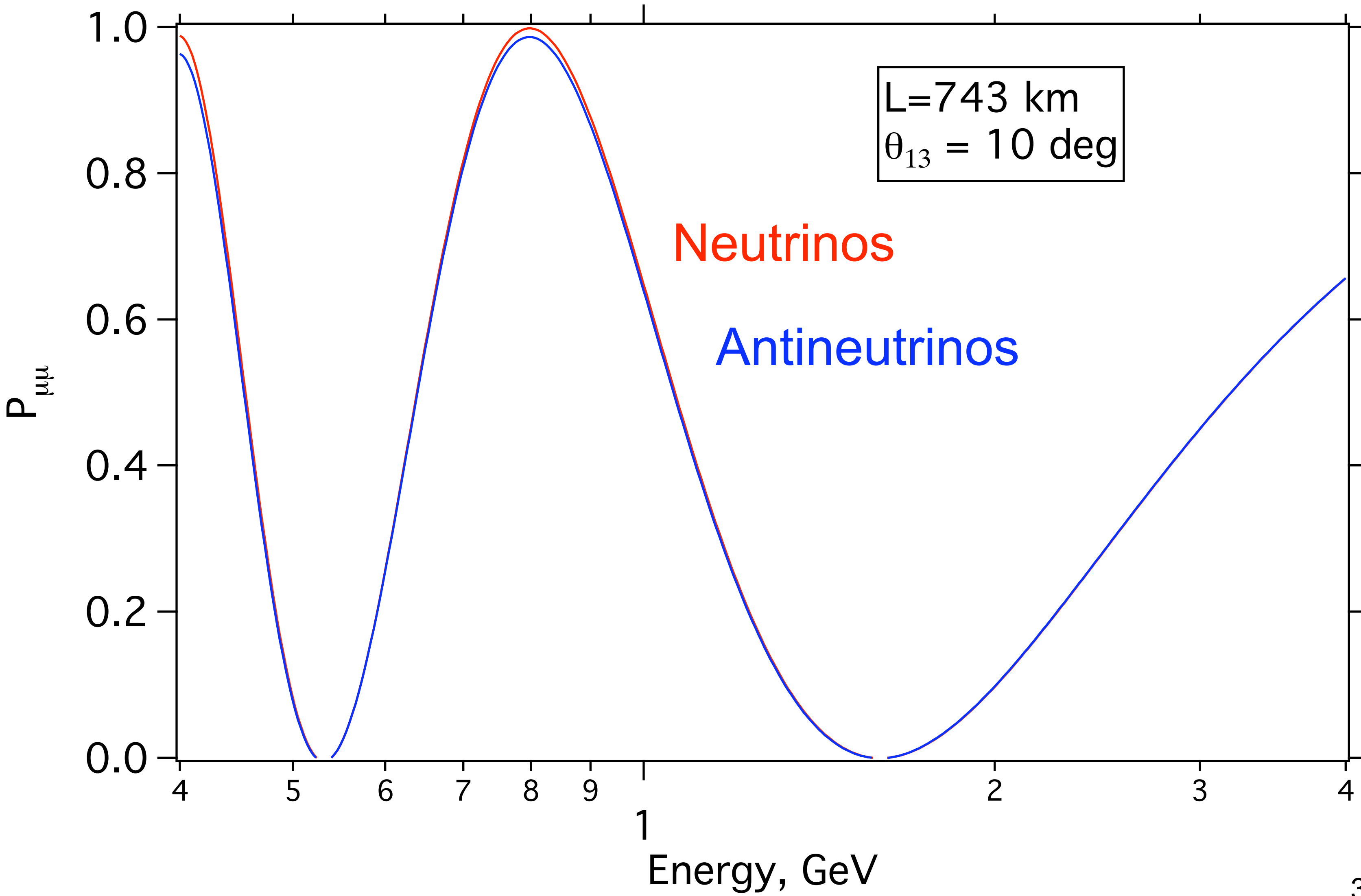
- CPT violation? Probably not.
- Just statistics? Combining the data will probably produce a decent χ^2. But that is a weak test. Is there a parametric hypothesis?
- *"Within standard neutrino mixing, disappearance probabilities for neutrinos and antineutrinos are identical, by CPT conservation!"* (G. Karagiorgi). However, not true when matter is present.
- Could this mean that θ_{13} is showing up??

3-flavor, with matter, expanded

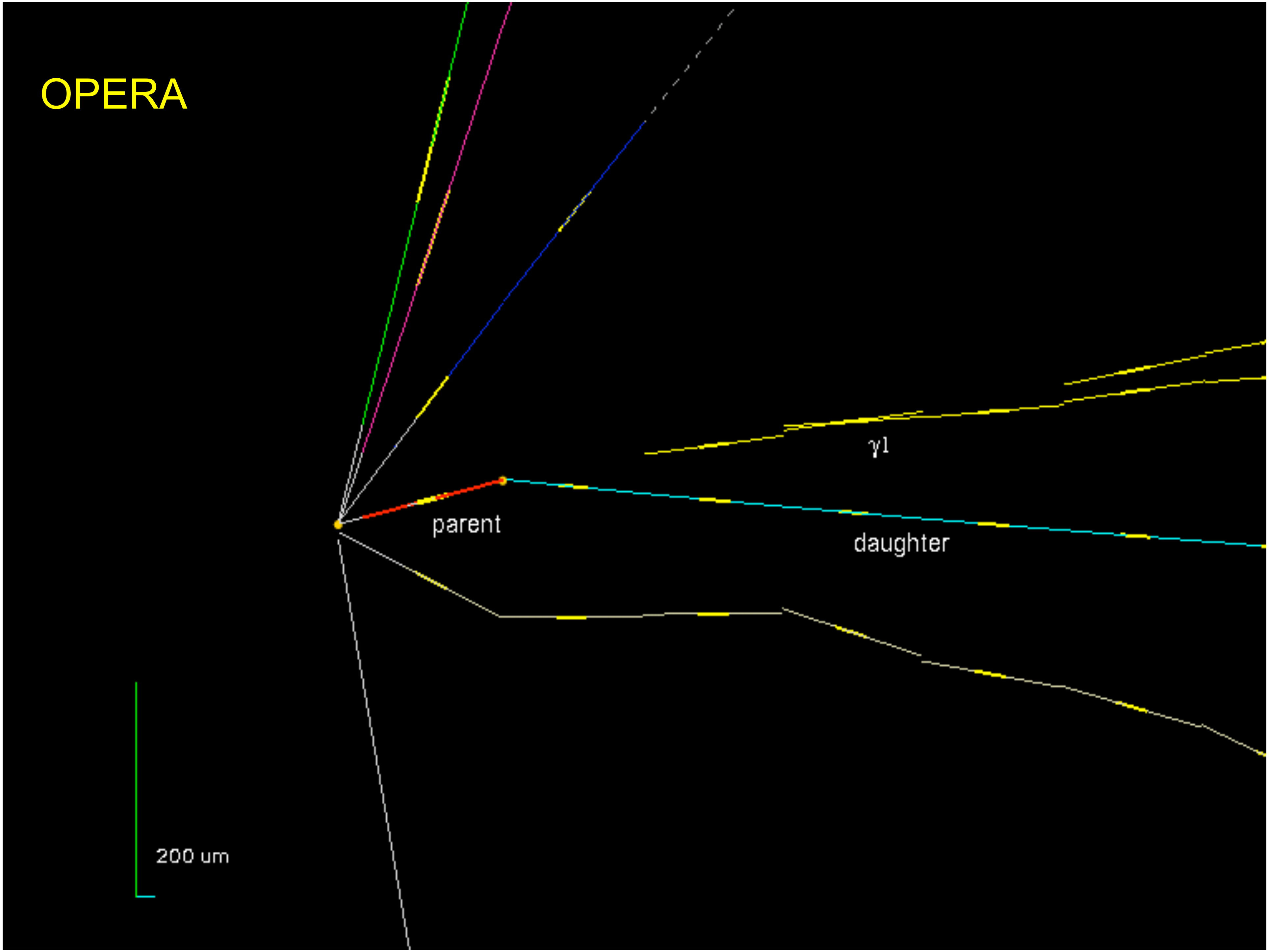
$$
\begin{aligned}
P_{\mu\mu} = {} & 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \alpha\, c_{12}^2 \sin^2 2\theta_{23}\, \Delta \sin 2\Delta - \\
& -\alpha^2 \sin^2 2\theta_{12}\, c_{23}^2 \frac{\sin^2 A\Delta}{A^2} - \alpha^2 c_{12}^4 \sin^2 2\theta_{23}\, \Delta^2 \cos 2\Delta + \\
& + \frac{1}{2A} \alpha^2 \sin^2 2\theta_{12} \sin^2 2\theta_{23} \left(\sin\Delta \frac{\sin A\Delta}{A} \cos(A-1)\Delta - \frac{\Delta}{2} \sin 2\Delta \right) - \\
& -4\, s_{13}^2\, s_{23}^2 \frac{\sin^2(A-1)\Delta}{(A-1)^2} - \\
& - \frac{2}{A-1} s_{13}^2 \sin^2 2\theta_{23} \left(\sin\Delta \cos A\Delta \frac{\sin(A-1)\Delta}{A-1} - \frac{A}{2}\Delta \sin 2\Delta \right) - \\
& -2\,\alpha\, s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta_{\mathrm{CP}} \cos\Delta \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} + \\
& + \frac{2}{A-1} \alpha\, s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos 2\theta_{23} \cos\delta_{\mathrm{CP}} \sin\Delta \times \\
& \times \left(A \sin\Delta - \frac{\sin A\Delta}{A} \cos(A-1)\Delta \right),
\end{aligned}
$$

E. Akhmedov et al. JHEP04 (2004) 078

No difference apparent here



(But don't believe a calculation done the day before!)


OPERA
γ1
parent
daughter
200 um

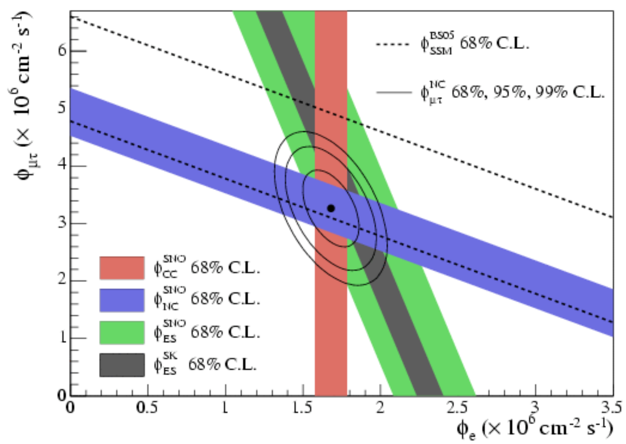
Phantom of OPERA captured!

O. Sato reports:

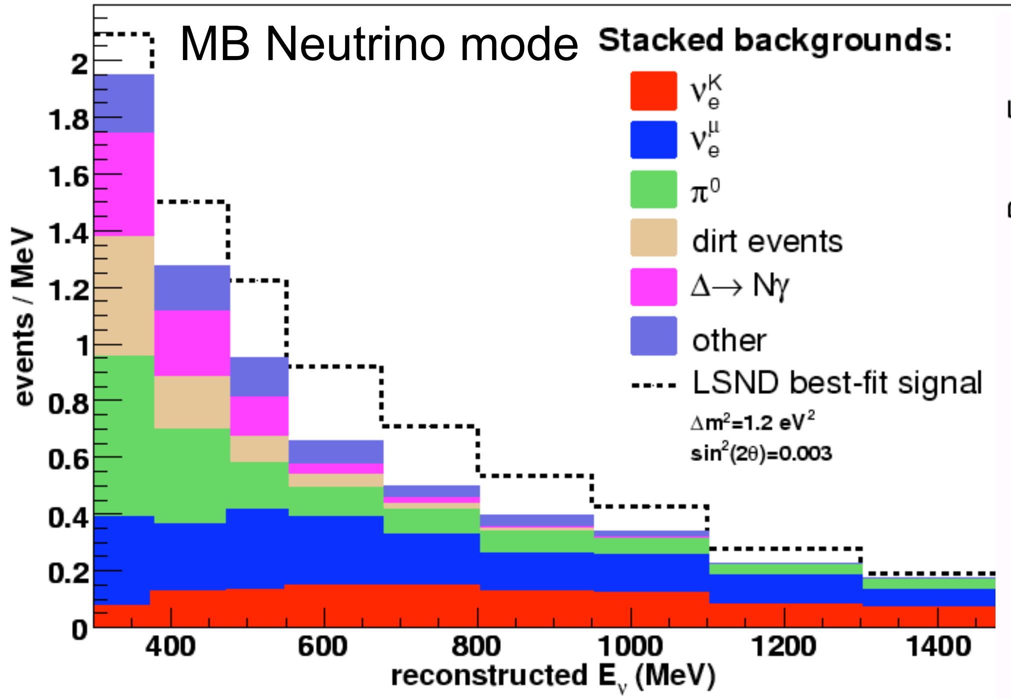
First observation [$2.01\ \sigma$] of a ν_τ produced in appearance by oscillations. $\tau \rightarrow \rho\ (\pi^-\ \pi^0)\ \nu_\tau$

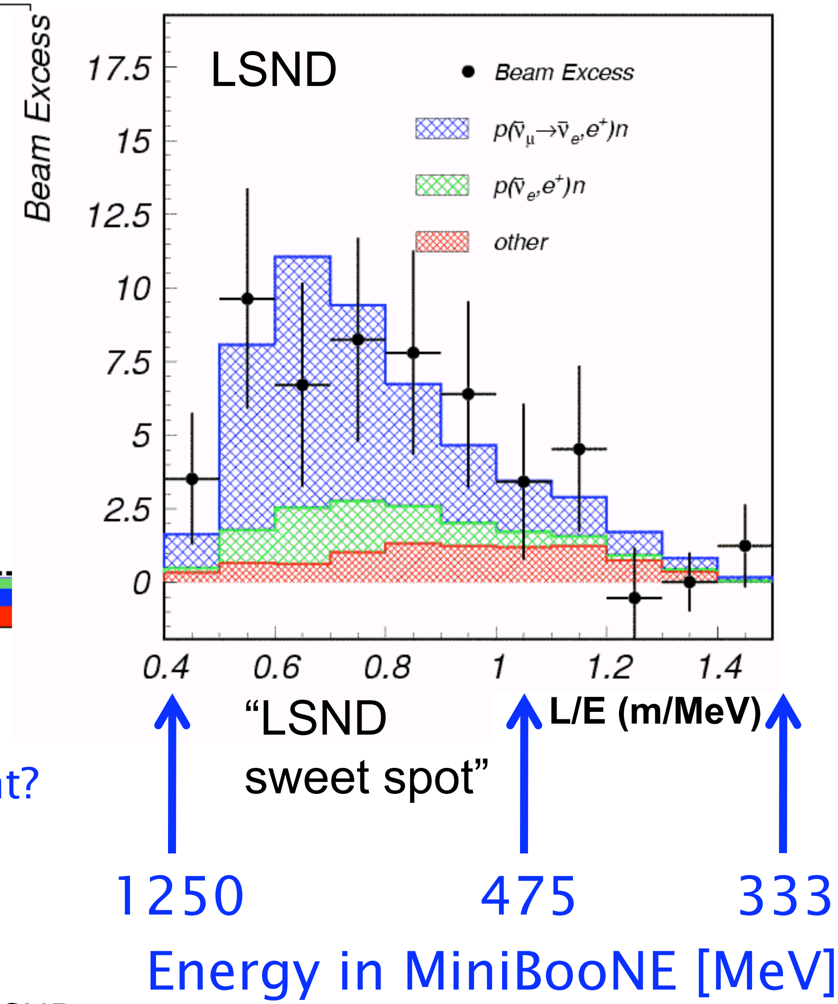
With continued running expect approximately 2 such events per year.

(first observation of *appearance* was actually SNO)



LSND and MiniBooNE (R. Van de Water)

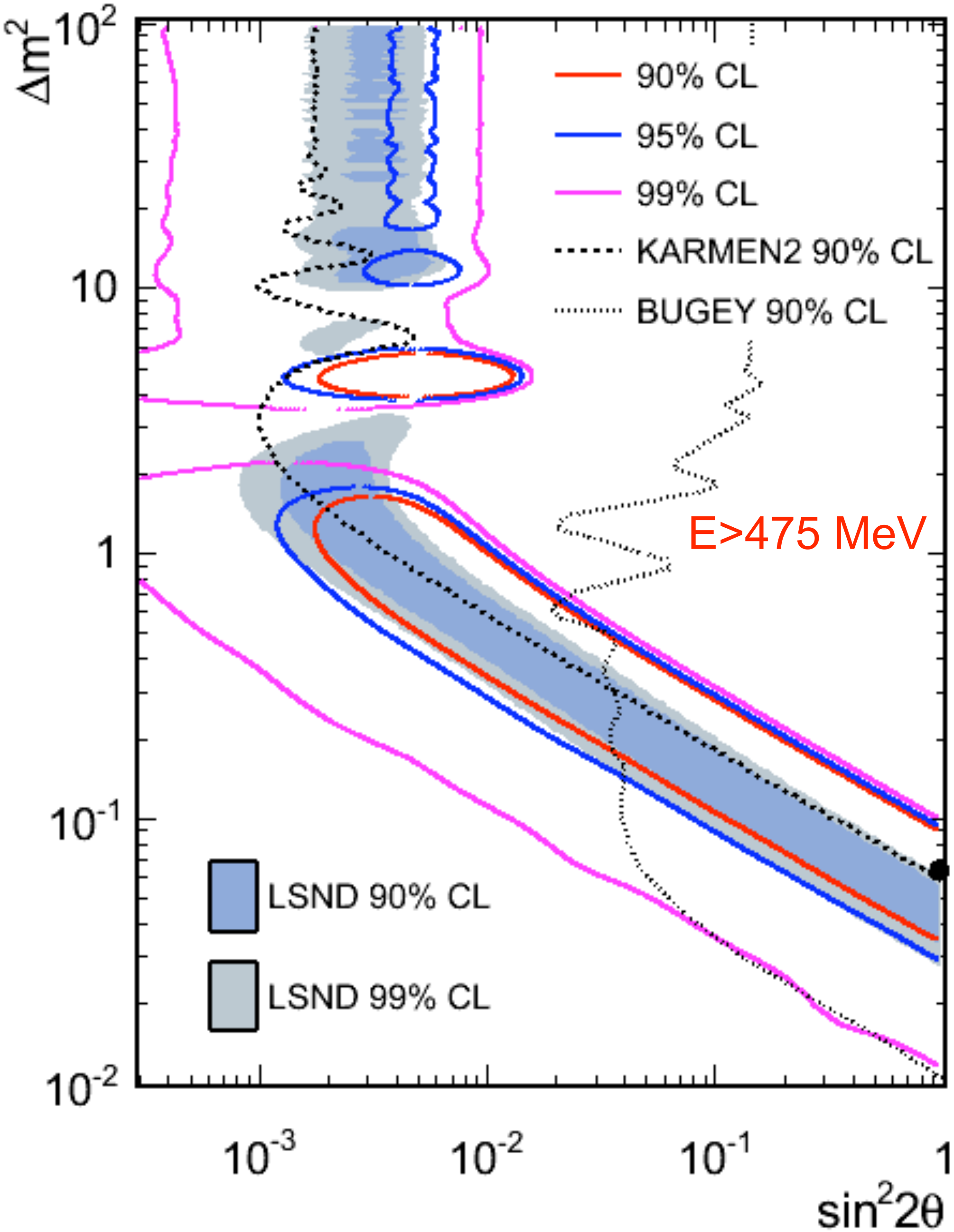




- Why is the 200-475 MeV region unimportant?
  - Large backgrounds from mis-ids reduce S/B.
  - Many systematics grow at lower energies, especially on signal.
  - Most importantly, not a region of L/E where LSND observed a significant signal!

Updated Antineutrino mode MB results for E>475 MeV
(official oscillation region)

- Results for **5.66E20 POT**
- Maximum likelihood fit.
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- Best Fit Point
  $(\Delta m^2, \sin^2 2\theta)$ =
  (0.064 eV^2, 0.96)
  χ^2/NDF= 16.4/12.6
  $P(\chi^2)$= 20.5%
- Results to be published.



MiniBooNE's summary

- The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:
  1) **Neutrino Mode**:
     a) E < 475 MeV: An unexplained 3σ electron-like excess.
     b) E > 475 MeV: A two neutrino fit is inconsistent with LSND at the 90% CL.
  2) **Anti-neutrino Mode**:
     a) E < 475 MeV: A small 1.3σ electron-like excess.
     b) E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.
- **Clearly we need more statistics!**
  – MiniBooNE is running to double antineutrino data set for a total of ~10×10^{20} POT.
  – If signal continues at current rate, statistical error will be ~4σ and two neutrino best fit will be >3σ.

NOW what?

If your experiment needs better statistics, you need a better experiment.

-- Sir Ernest Rutherford

Fine, but Rutherford isn't paying the bills. The experiment exists and needs more antineutrino running on MiniBooNE. Maybe it IS just statistics?

There are opportunities with ICARUS, the near detectors at T2K, and with a new proposal for gallium by V. Gavrin, to address the anomalies.

3. Quo Vadis LSND ?

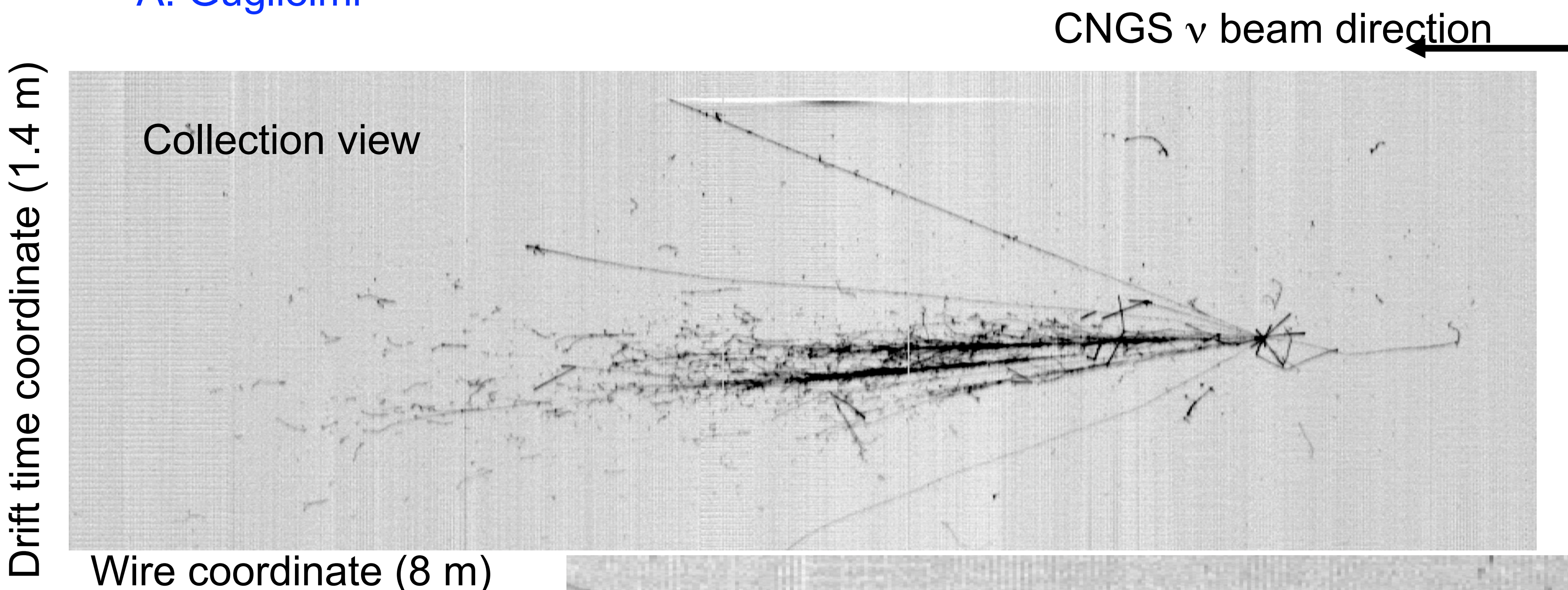
As we heard here [15], a re-analysis of the full LSND data set confirms their previous results for both decays at rest (32.7 ± 9.2 events with $R - \gamma > 10$) and in flight. Their data are neither confirmed nor excluded by KARMEN [16], whose timing anomaly has not reappeared in their latest data set. It is desirable to repeat the previous global analysis [17] of LSND and KARMEN data using their likelihood functions in the $(\sin^2\theta, \Delta m^2)$ plane, so that future experiments know what target region in this plane to aim at.

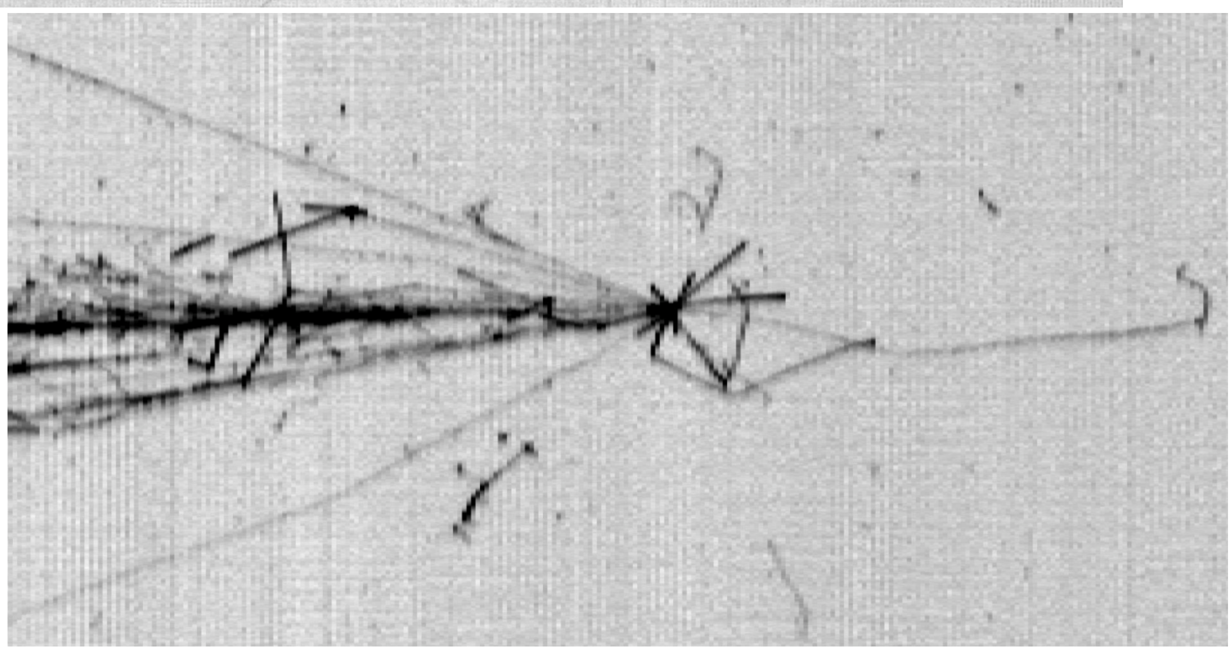
A definitive test of LSND will be made byMiniBooNE [18], working at similar L/E but with $E \sim 1$ GeV and starting at the end of 2001. If needed, this may be followed up by the full BooNE experiment. There is also an opportunity to pursue the LSND effect still further with the ORLaND project at the SNS [19], so I conclude that there is adequate follow-up of the LSND experiment.

From John Ellis' summary at Nu2000

The second CNGS neutrino interaction in ICARUS T600

A. Guglielmi

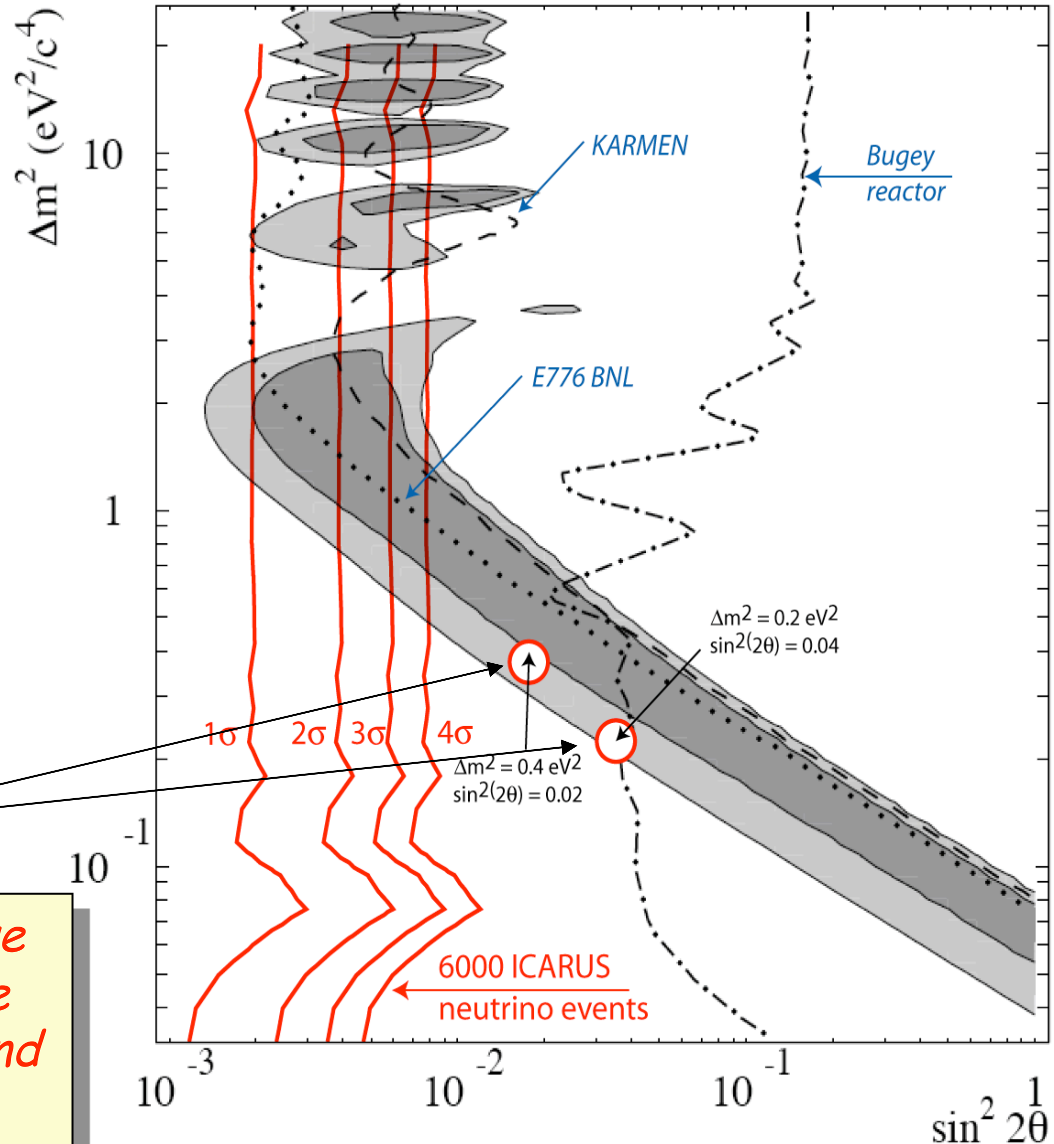




Beautiful!

Sterile (LSND) neutrino search

- Sensitivity region, in terms of Standard Deviations σ, for 6000 raw CNGS neutrino events. The potential signal is above the background generated by the intrinsic νe beam contamination, in the deep inelastic interval 10-30 GeV.
- The Δm^2 distribution extends widely beyond the LNSD and MiniBoone regions.
- Two indicated points are reference values of MiniBoone.

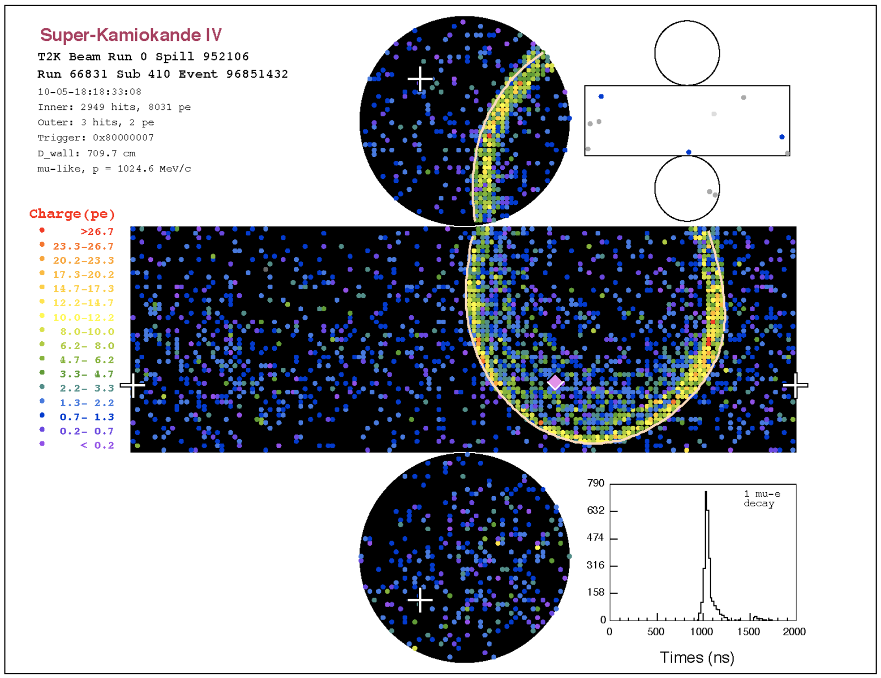


T600 at the CNGS offers an unique possibility of searching for sterile neutrinos, largely complementary and comparable to the Fermilab programme.

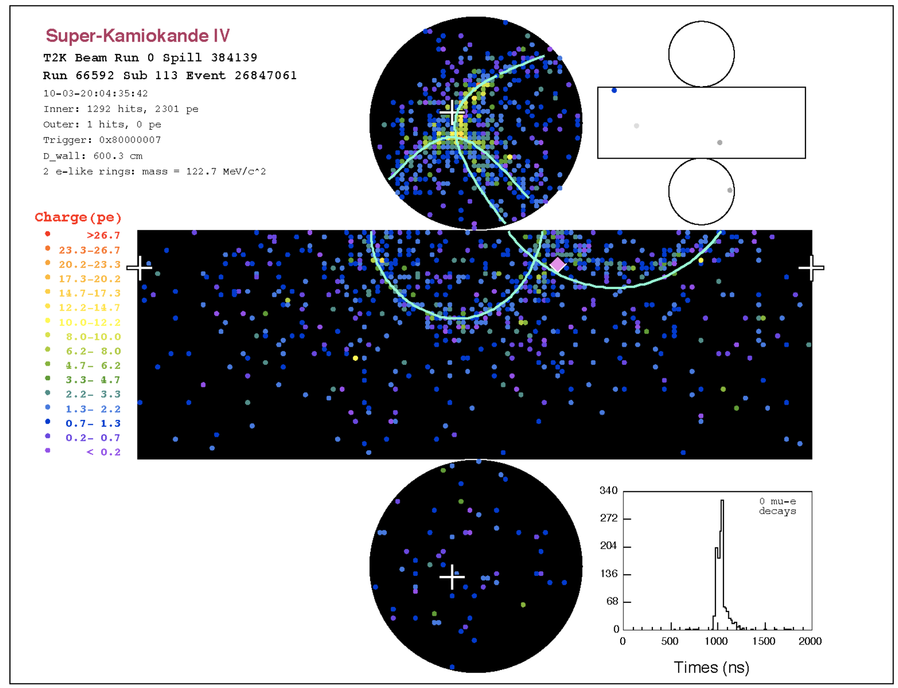
…for a 3+1 oscillation model

T2K Complete: T. Kobayashi

Single-ring μ-like event

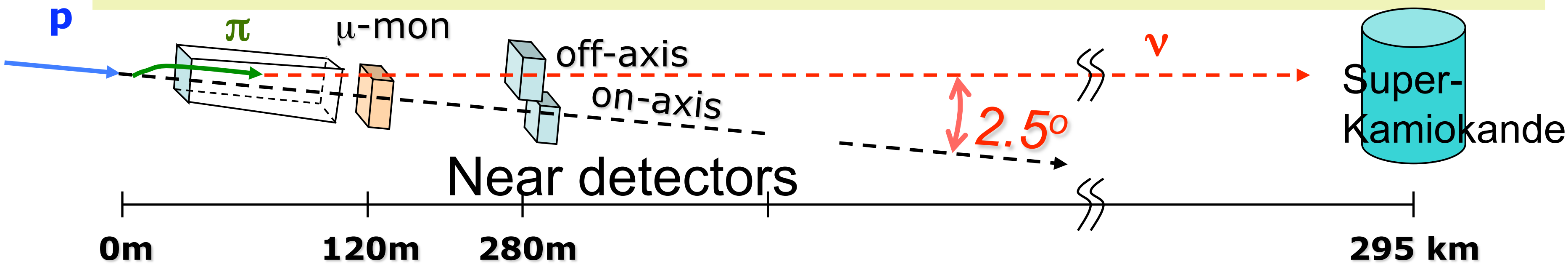


Two-ring event

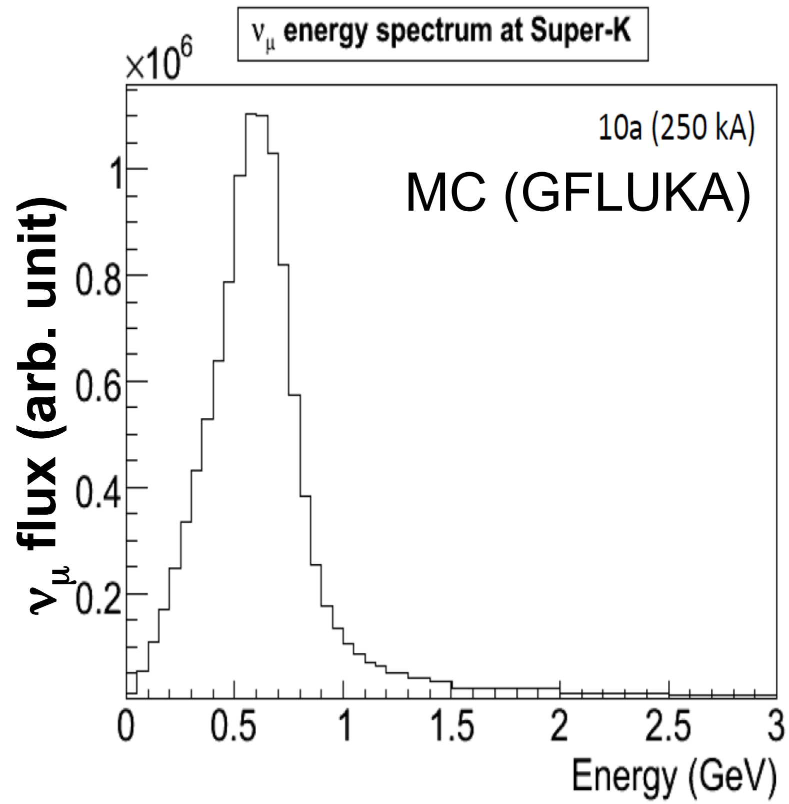


Pink diamonds are placed on the wall in the beam direction starting from the reconstructed vertex.

T2K: Experimental Setup

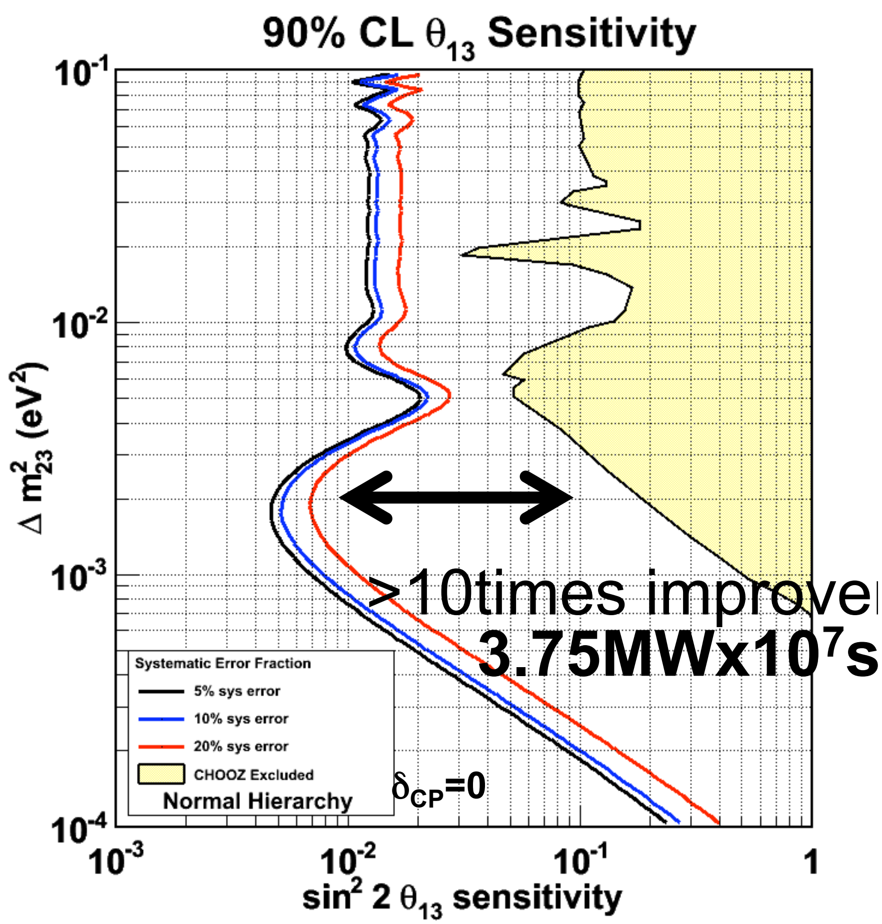


- **2.5 deg Off-axis**
  - **Peak ~600MeV**
  - **Quasi-Elastic interaction dominate**
    - **Less Non-QE background**
- **Muon monitors @ ~120m**
  - Muon > 5GeV
  - Spill-by-spill monitoring of direction/intensity
- **Near detector @280m**
  - On-axis detector “INGRID”
    - Intensity and direction (profile)
  - Off-axis (toward SK direction)
    - Absolute flux/spectrum/νe
- **Far detector Super-Kamiokande @ 295km**

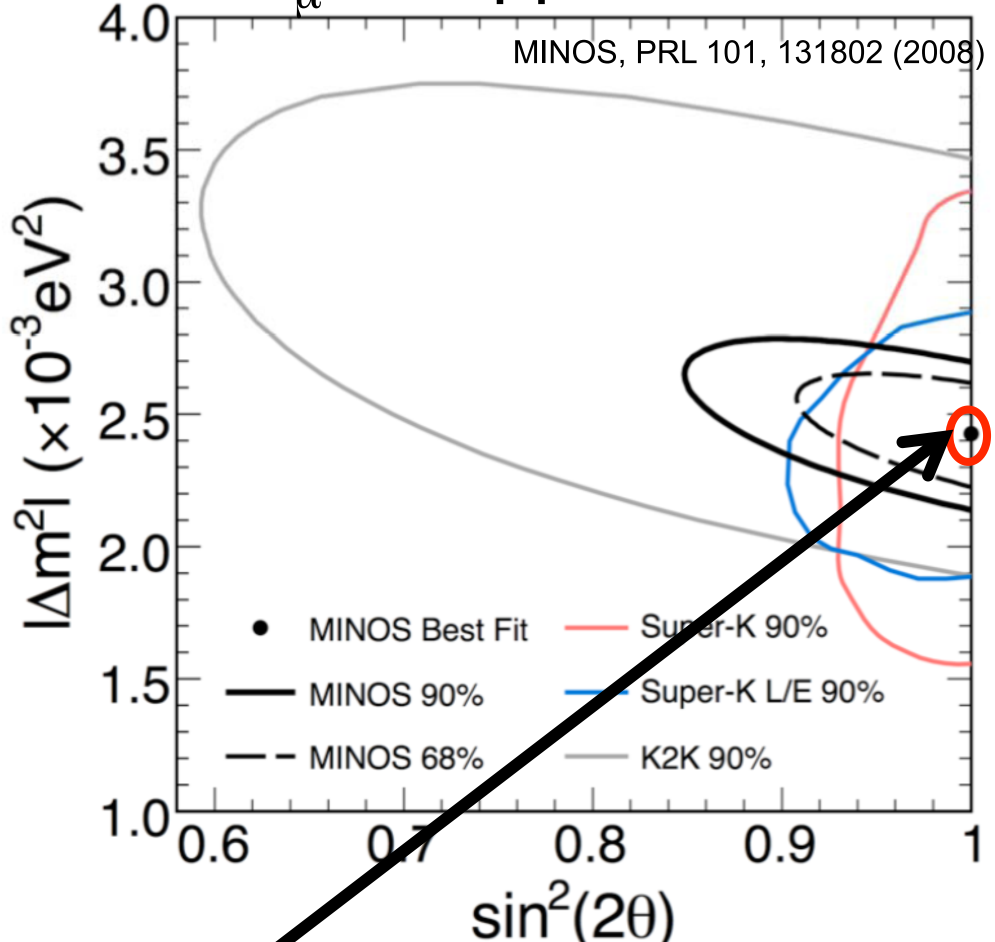


Expected Sensitivity of T2K

ν_μ◊ν_e appearance



ν_μ disappearance



…T2K will have to deal with the LSND Problem somehow.

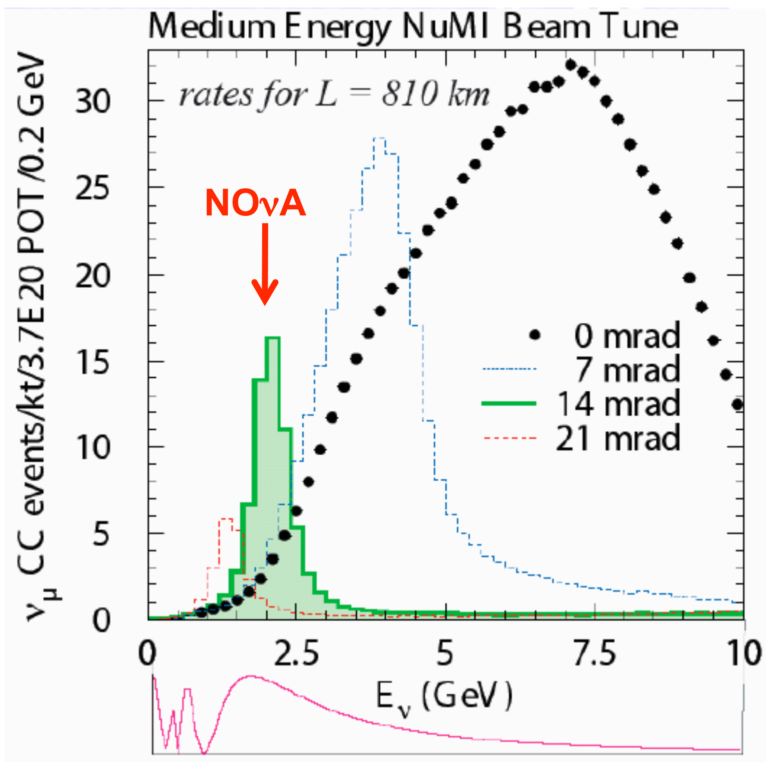
Goal @ 3.75MWx10^7s:

$\delta(\sin^2 2\theta_{23})\sim 0.01$,

$\delta(\Delta m^2_{23})$ <1×10^{-4} [eV^2]

NOνA: K. Heller

- **NOνA:**
  - Fermilab NuMI beamline – off axis gives a narrow band beam
    - Upgrade to 0.7 MW
  - Near detector at Fermilab → Far detector in Northern Minnesota
  - Far detector underground
  - Both detectors same technology
  - Sensitive to Supernovas
- **NOνA baseline: 810 km**
  - Sensitive to neutrino mass ordering.
  - Measures θ_{13} and θ_{23}



How are we doing?

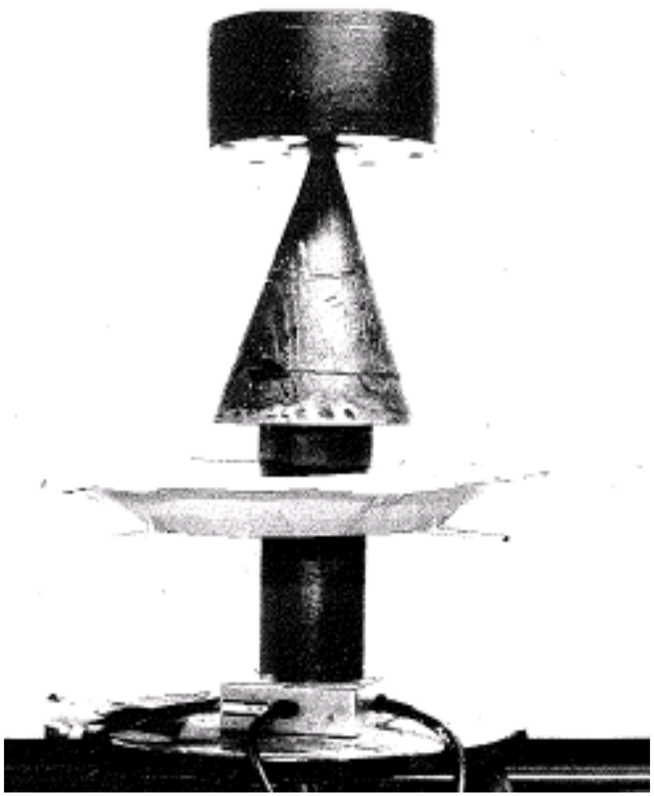
parameter	best-fit$^{+1\sigma}_{-1\sigma}$	2σ	3σ
Δm^2_{21} [10^{-5} eV^2]	$7.59^{+0.23}_{-0.18}$	$7.22 - 8.03$	$7.03 - 8.27$
$\lvert\Delta m^2_{31}\rvert$ [10^{-3} eV^2]	$2.40^{+0.12}_{-0.11}$	$2.18 - 2.64$	$2.07 - 2.75$
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	$0.29 - 0.36$	$0.27 - 0.38$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	$0.39 - 0.63$	$0.36 - 0.67$
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	$\lesssim 0.039$	$\lesssim 0.053$

Schwetz, Tortola, Valle, 0808.2016v3 (Feb 2010)

…and: Surprises!

W. Rodejohann

The Goldhaber-Grodzins-Sunyar Experiment



1956

Equipment	2k
3 guys 2 wks	1k
TOTAL	3k

2010

Proj. Mgmt.	500k
Fire suppr.	300k
Hazmat	100k
Training	100k
Equipment	2k
3 guys 2 wks	free
TOTAL	1002k

To George Tzanakos and his amazing team:

Ευχαριστω!

Fin