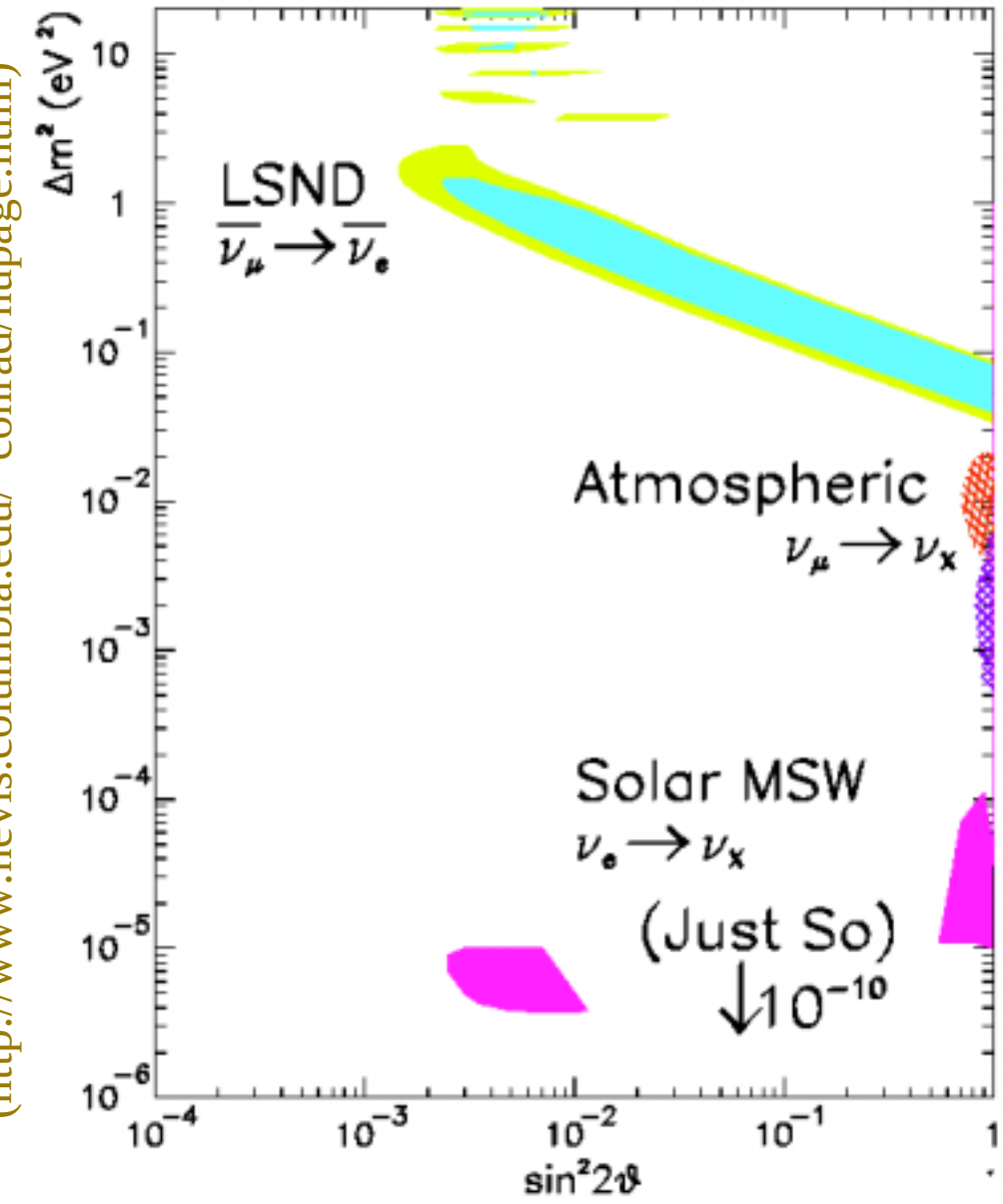
Evidence for Neutrino Oscillations (1999)

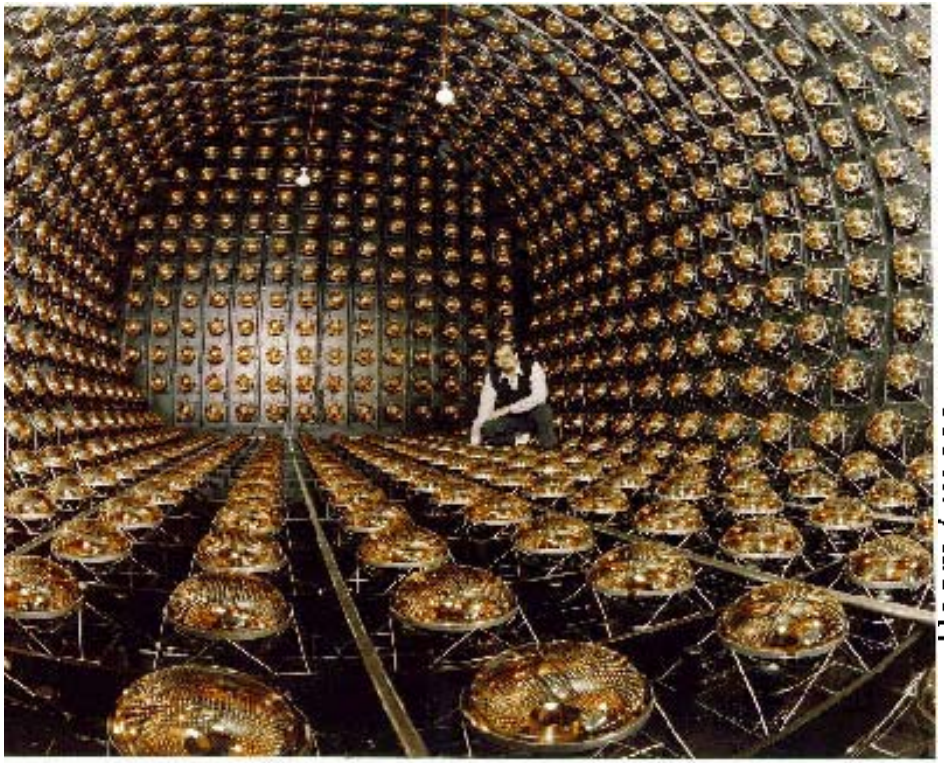


(http://www.nevis.columbia.edu/~conrad/nupage.html)

Explanations for Dark Matter require m_ν~ few eV.

The different "index of refraction" for different neutrinos leads to enhanced (MSW) mixing.

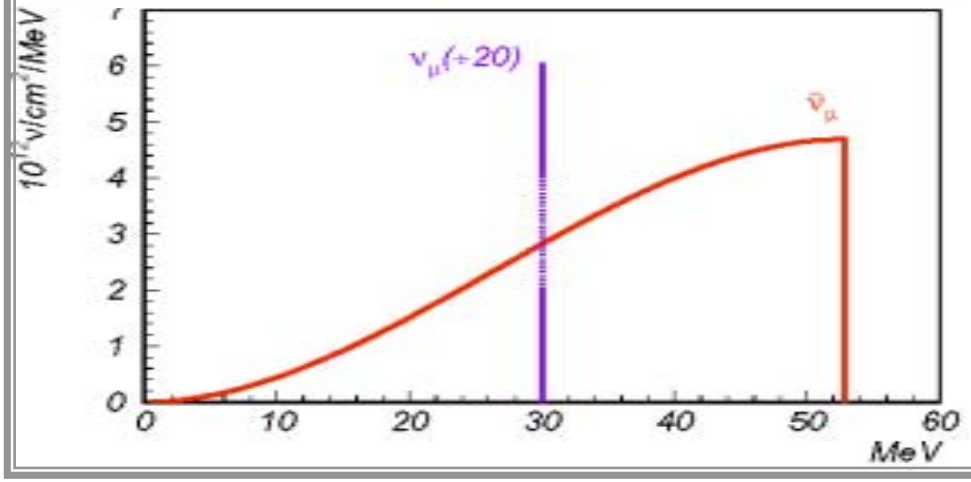
LSND (Liquid Scintillating Neutrino Detector)

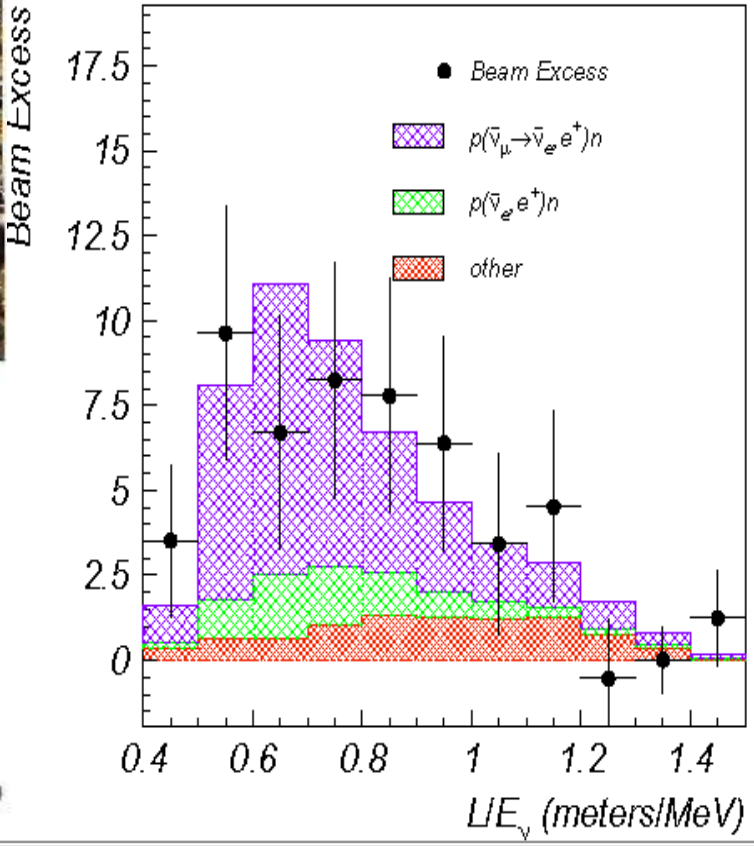


http://www.neutrino.lanl.gov/LSND/

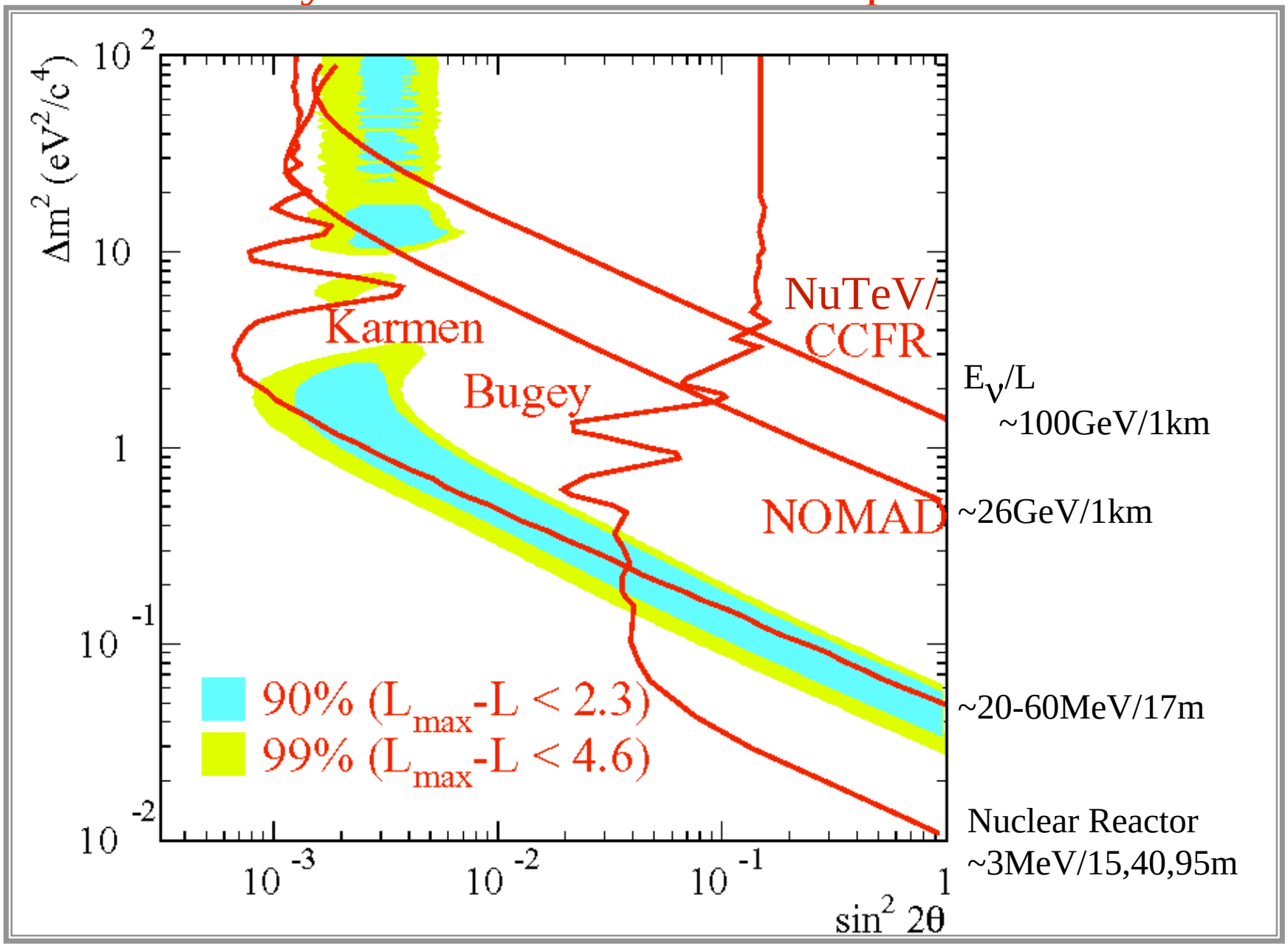
Report excess anti-electron neutrinos in low energy beam made up mostly of anti-muon neutrinos.

(http://arXiv.org/abs/hep-ex/0104049)

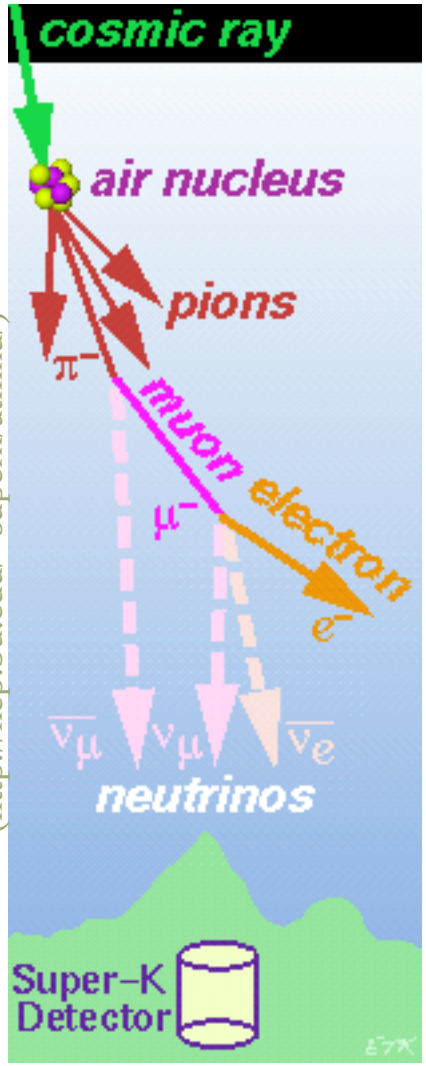




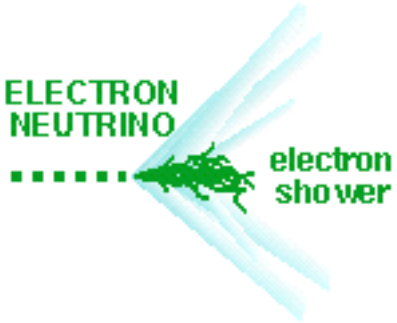
Barely consistent with other experiments

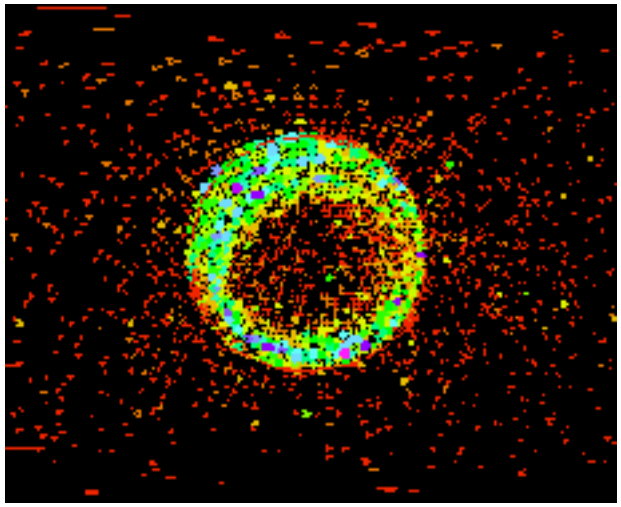


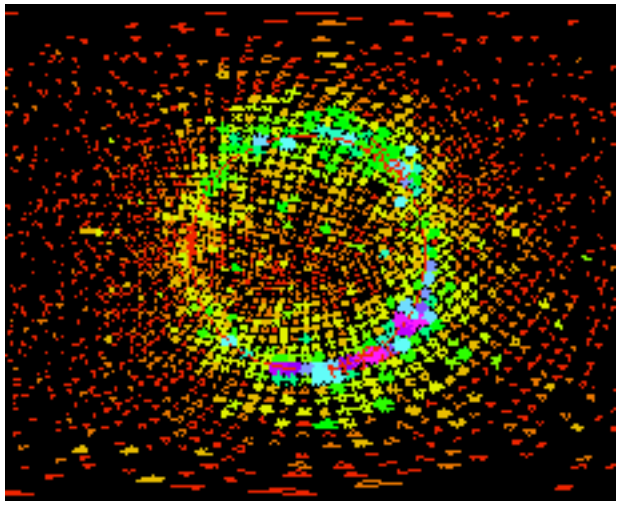
Atmospheric Neutrinos



(http://hep.bu.edu/~superk/atmnu/)



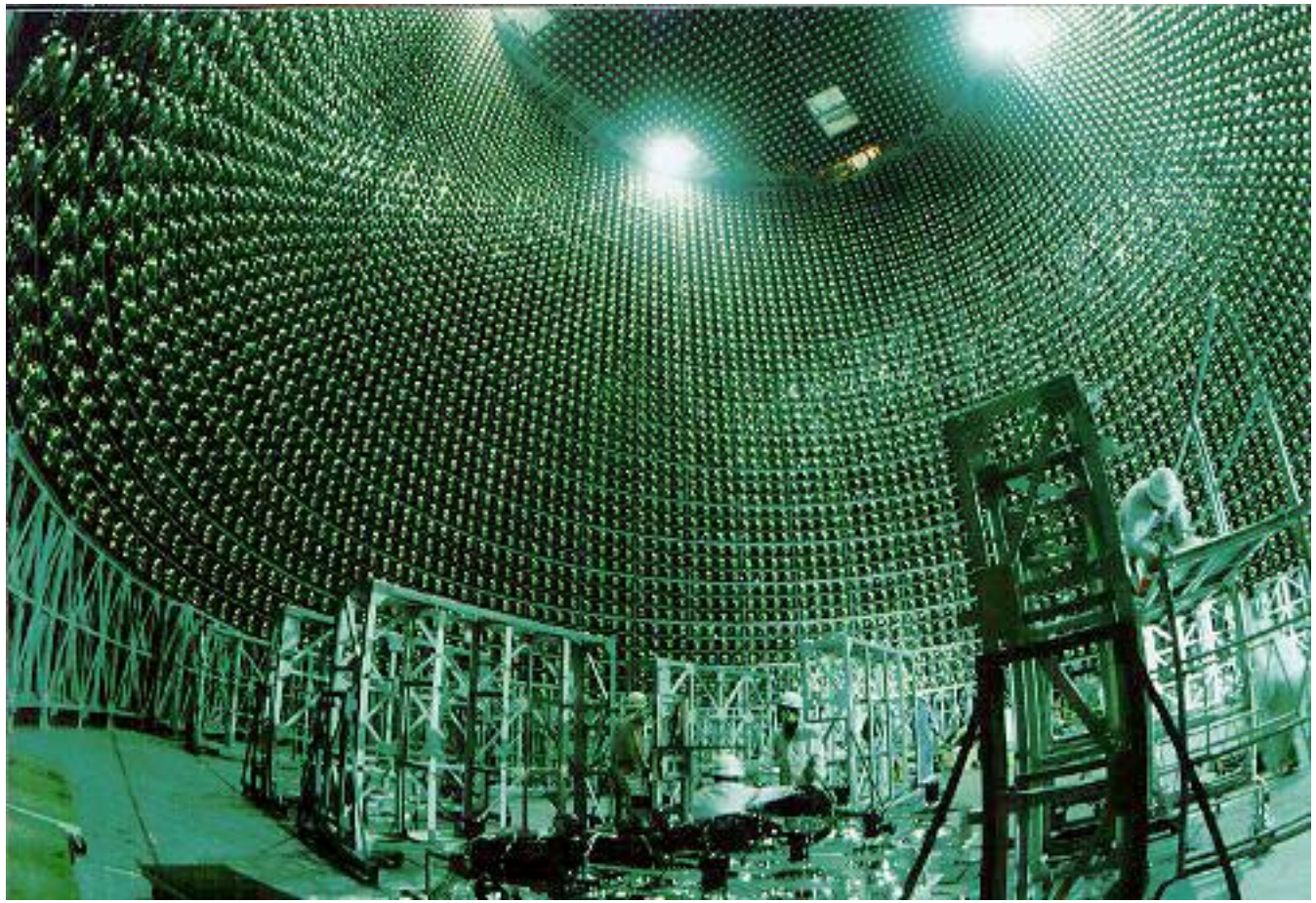




http://superk.physics.sunysb.edu/nngroup/superk/physics/atmospheric-neutrino/

From Super-Kamiokande Groups

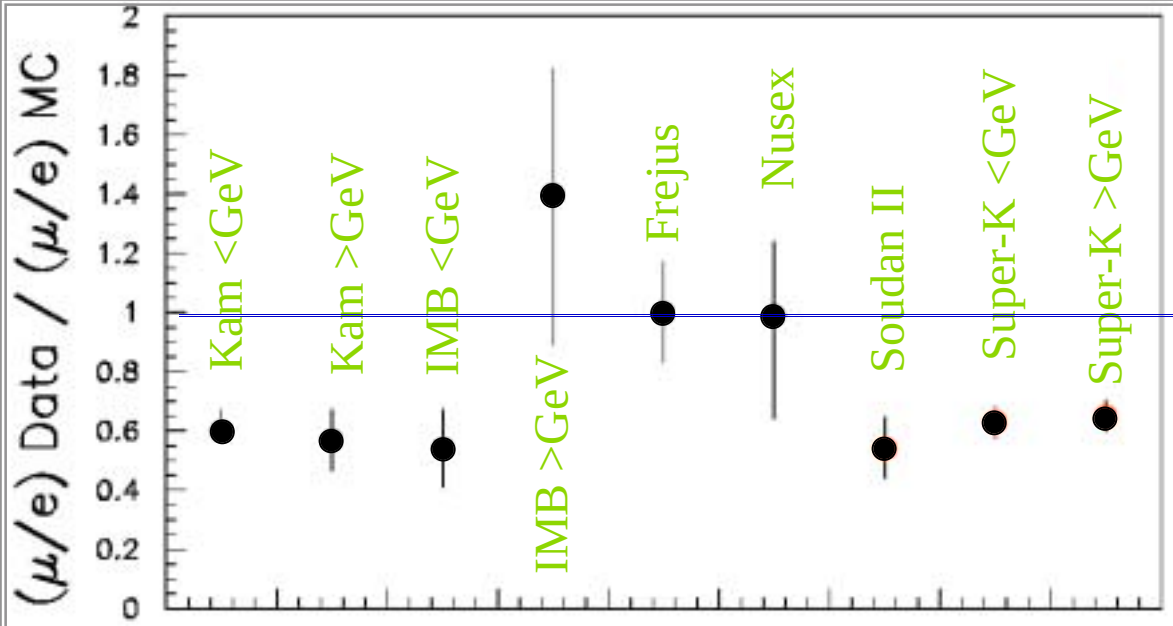
Super-Kamiokande



http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/photo/normal.html/

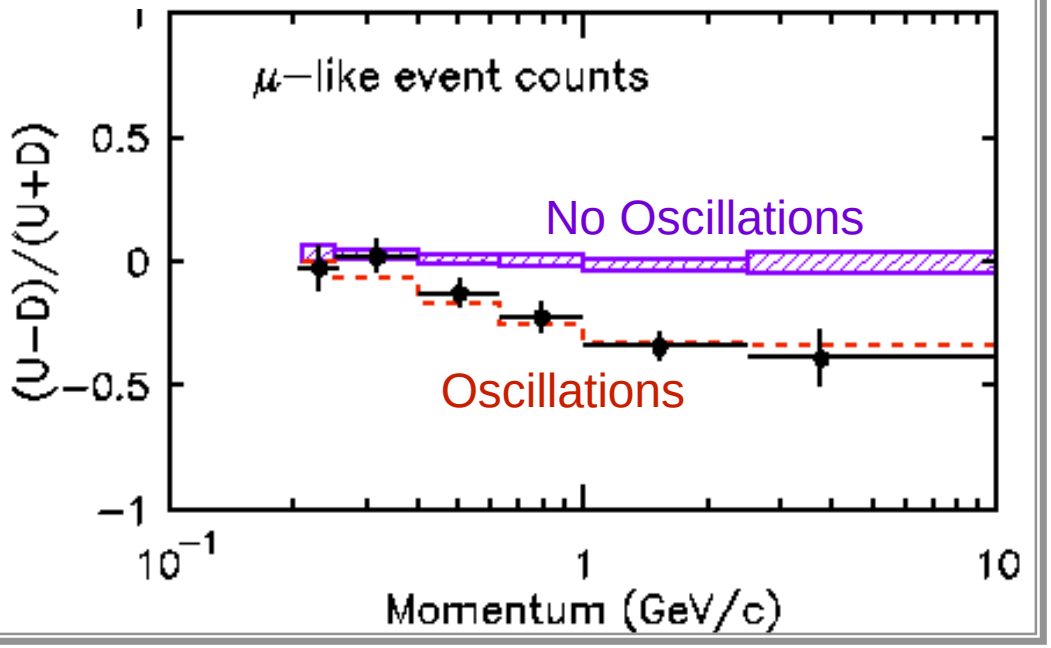
Atmospheric Muon Neutrino Deficit

http://www.nevis.columbia.edu/~conrad/nupage.html

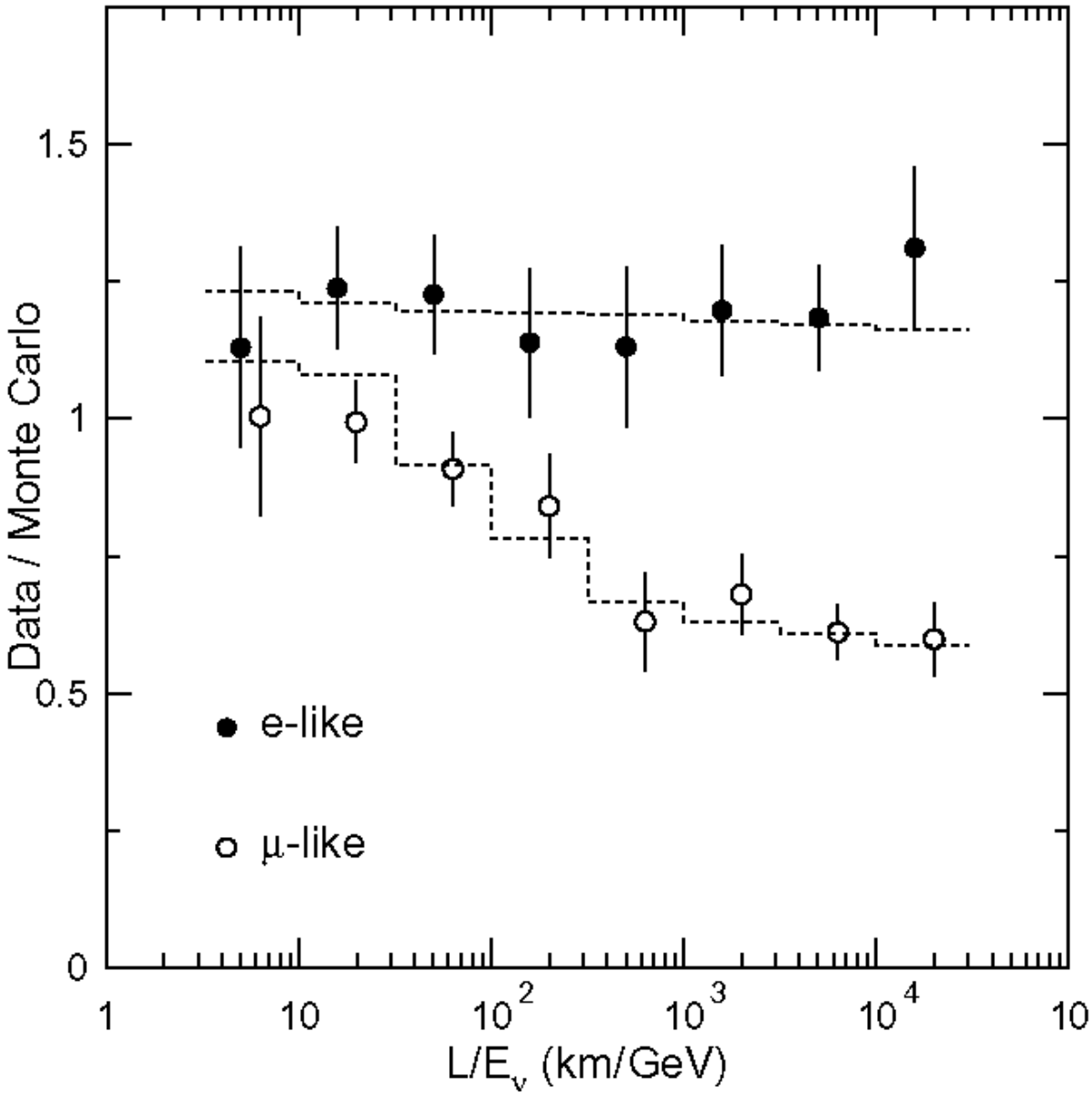


No Oscillations

Also Super-Kamiokande Up-down muon neutrino asymmetry.



"Evidence For Oscillation Of Atmospheric Neutrinos"

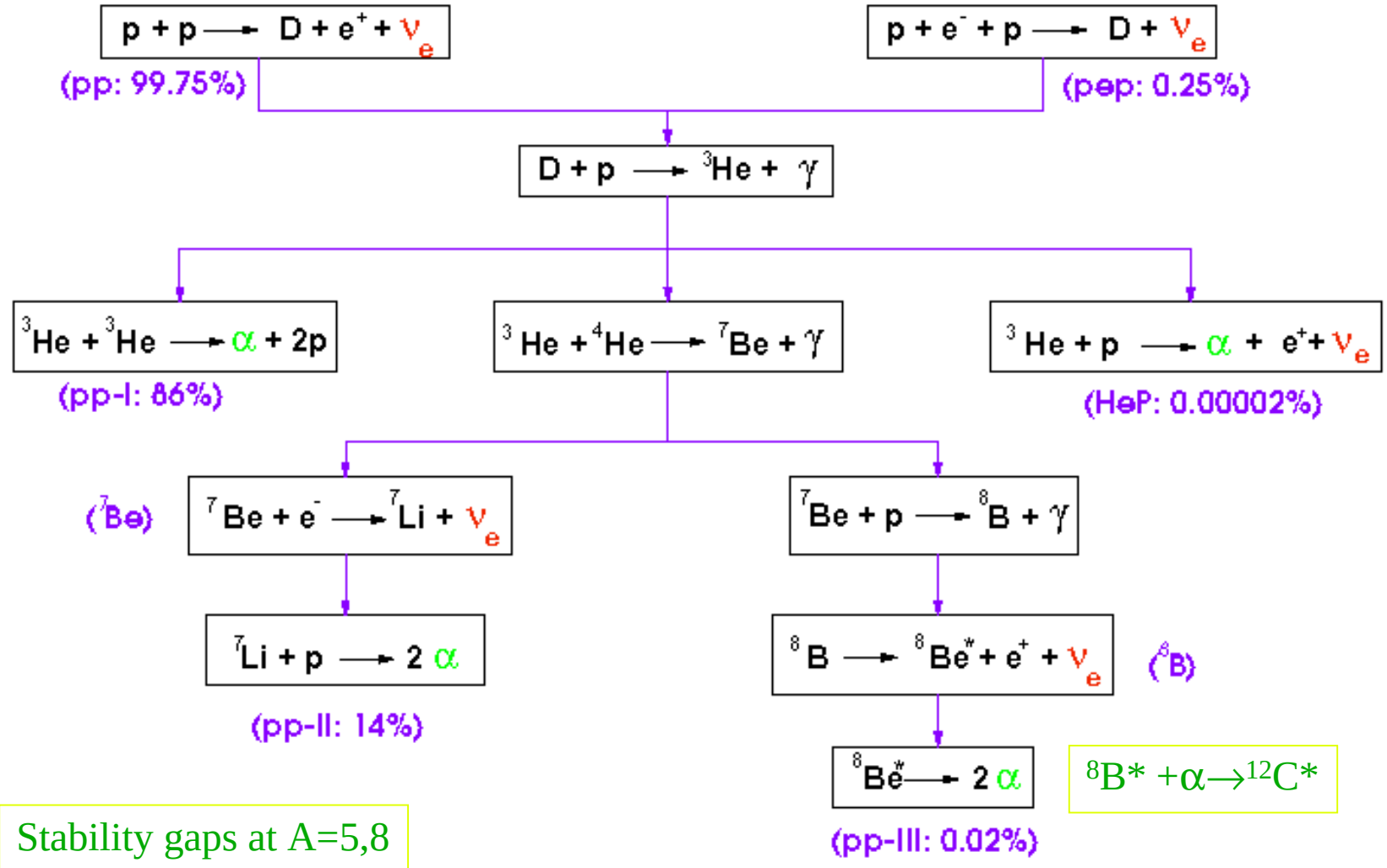


Super-Kamiokande Collaboration (Y. Fukuda et al.), Phys. Rev. Lett. 81 (1998) 1562-1567. (http://arXiv.org/abs/hep-ex/9807003).

Most cited experimental paper ever in experimental particle physics. (Cited 1285 times as of 10:42pm 7 April 2002.)

(Not counting the Review of Particle Properties, only 3 of the 108 HEP papers with >1000 citations are experimental.)

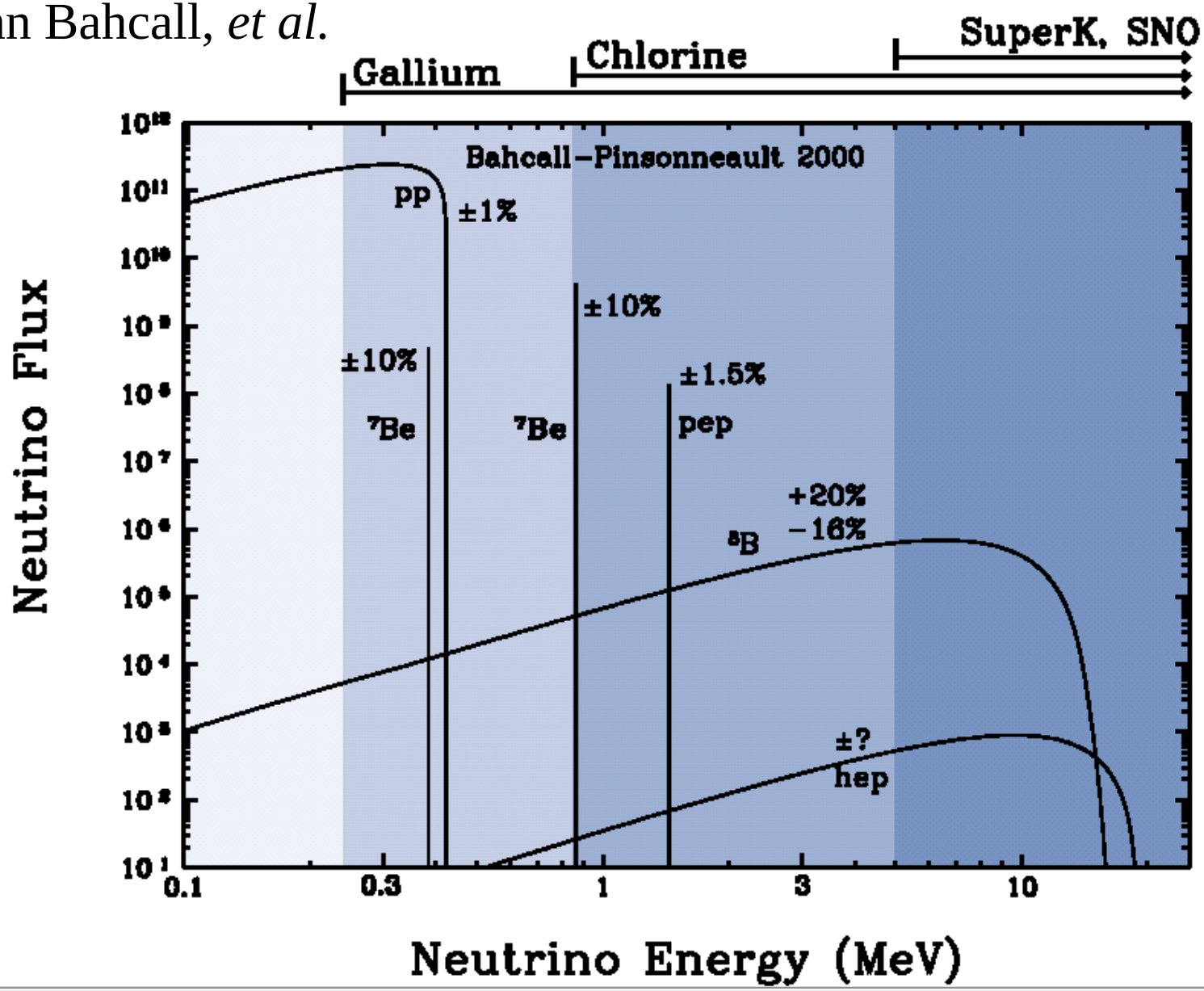
pp Solar Fusion Cycle



Modified Figure 7 from "Developments in Neutrino Physics", M.C. Gonzalez-Garcia and Yosef Nir, http://arXiv.org/abs/hep-ph/0202058.

Standard Solar Model Neutrino Spectrum

John Bahcall, *et al.*



http://www.sns.ias.edu/~jnb/

Homestake C_2CL_4 Solar Neutrino Experiment

Ray Davis, Jr.,
John Bahcall

$$\nu_e + {}^{37}_{17}\mathrm{Cl} \rightarrow \mathrm{e}^- + {}^{37}_{18}\mathrm{Ar}$$

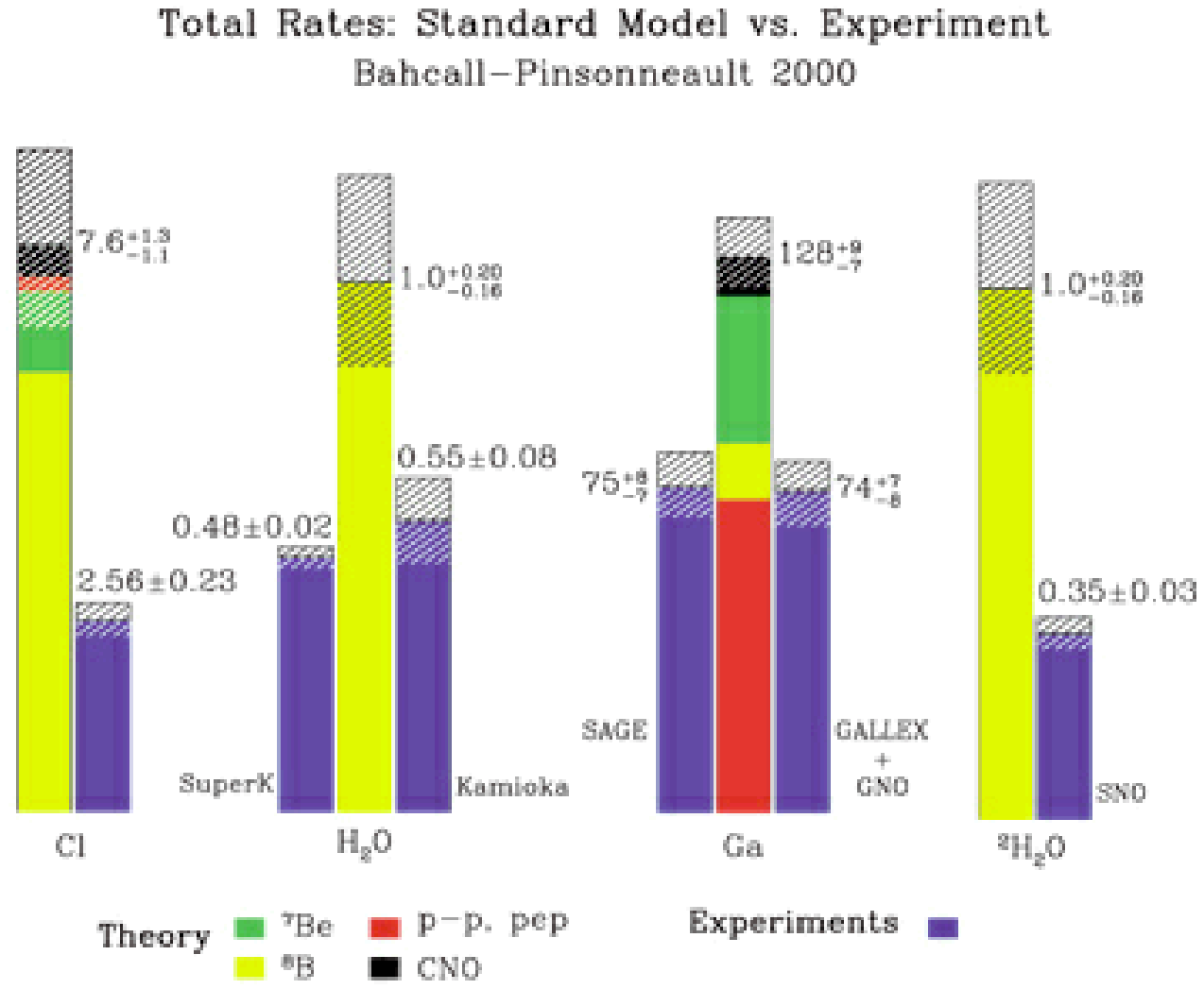
$$\downarrow$$

$${}^{37}_{17}\mathrm{Cl} + \mathrm{e}^+$$

~ 12 Argon atom decays detected per month

Solar Neutrino Problem

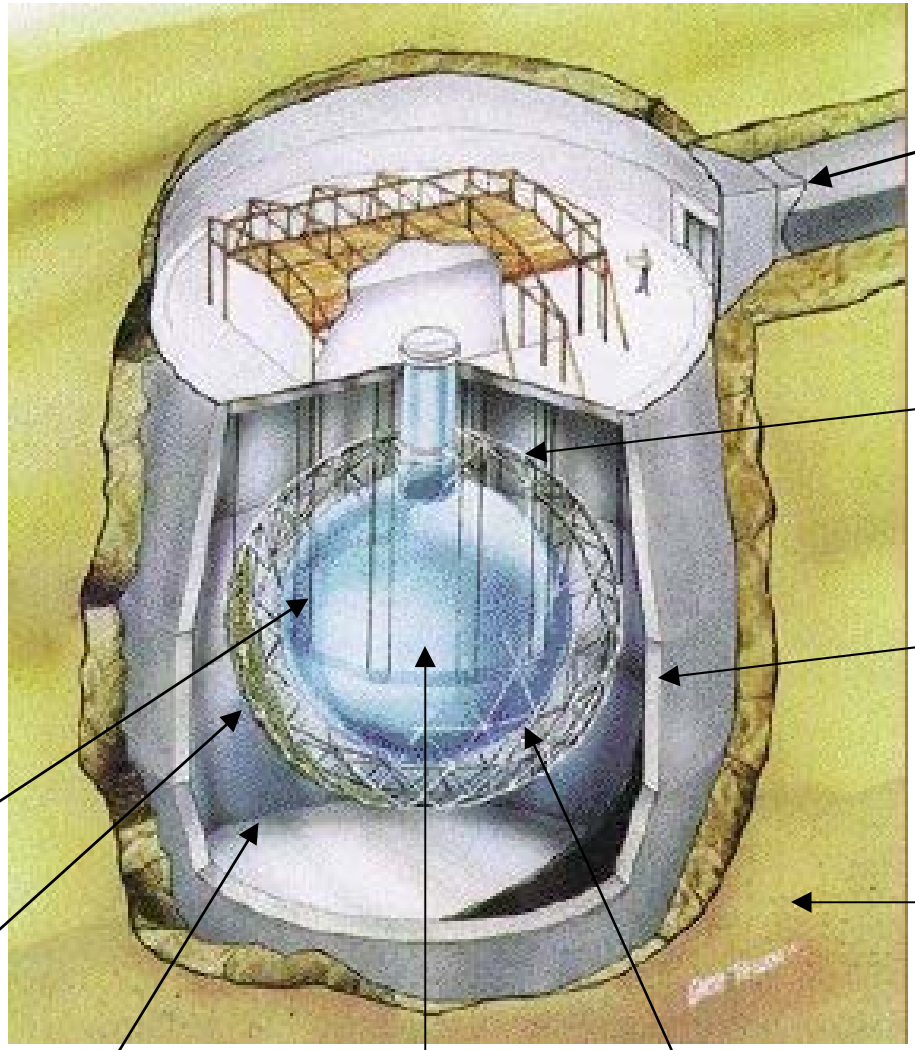
Missing Electron Neutrinos From Sun



http://www.sns.ias.edu/~jnb/

The SNO Detector

- **Location:** 6800 ft. level of INCO's Creighton mine near Sudbury, ON, Canada (~70 muons / day)
- **SNO Detector:** 9438_{inward} + $91_{outward}$ Hamamatsu 8" PMTs + concentrators = 64% coverage



2039 m to surface
10^{11} m to Sun

http://www.sno.phy.queensu.ca/sno/talks/nu2001.ppt

http://www.sno.phy.queensu.ca/sno/talks/nu2001.ppt

SNO Measurements

Charged Current Reaction (D_2O):

CC

$\nu_e + d \rightarrow p + p + e^-$ $\quad E_{thres} = 1.4$ MeV $\quad$ **(only ν_e)**

- ν_e energy spectrum (distortion $\Rightarrow$ MSW effect)
- Some directional sensitivity (1 - 1/3 cos θ_e)

Neutral Current Reaction (D_2O):

NC

$\nu_x + d \rightarrow \nu_x + p + n$ $\quad E_{thres} = 2.2$ MeV $\quad$ **(All ν types)**

- Total solar ^8B neutrino flux (active neutrinos)

Elastic Scattering Reaction (D_2O,H_2O):

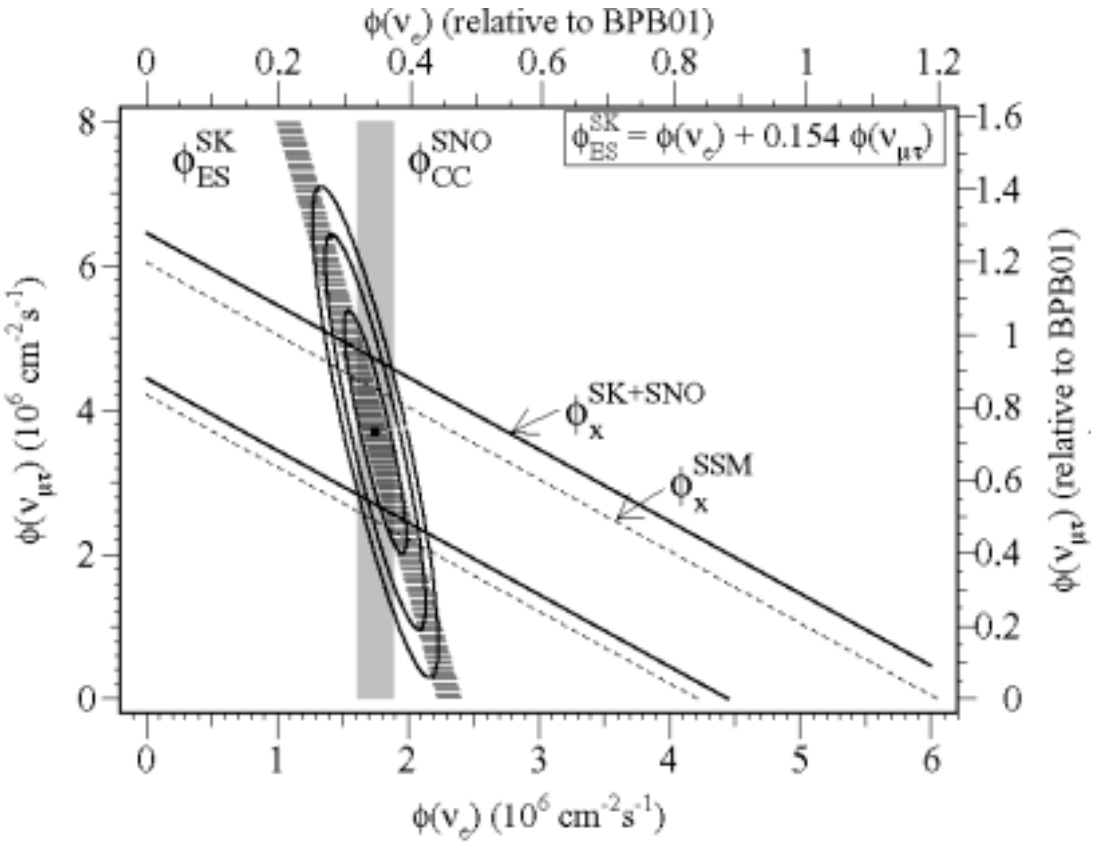
ES

$\nu_x + e^- \rightarrow \nu_x + e^-$ $\quad E_{thres} = 0$ MeV $\quad$ **(86% ν_e)**

- Low counting rate
- Directional sensitivity (very forward peaked)

Solar Neutrinos are all there

"Measurement of the Rate Of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by ^8B Solar Neutrinos at the Sudbury Neutrino Observatory", SNO Collaboration (Q.R. Ahmad et al.), Phys. Rev. Lett. 87 (2001) 071301. (http://arXiv.org/abs/nucl-ex/0106015)



Current Neutrino Oscillation Evidence

All positive evidence is hard to reconcile unless 4th sterile* neutrino exists.

(*Only 3 neutrino flavours couple to normal Z^0 bosons.)

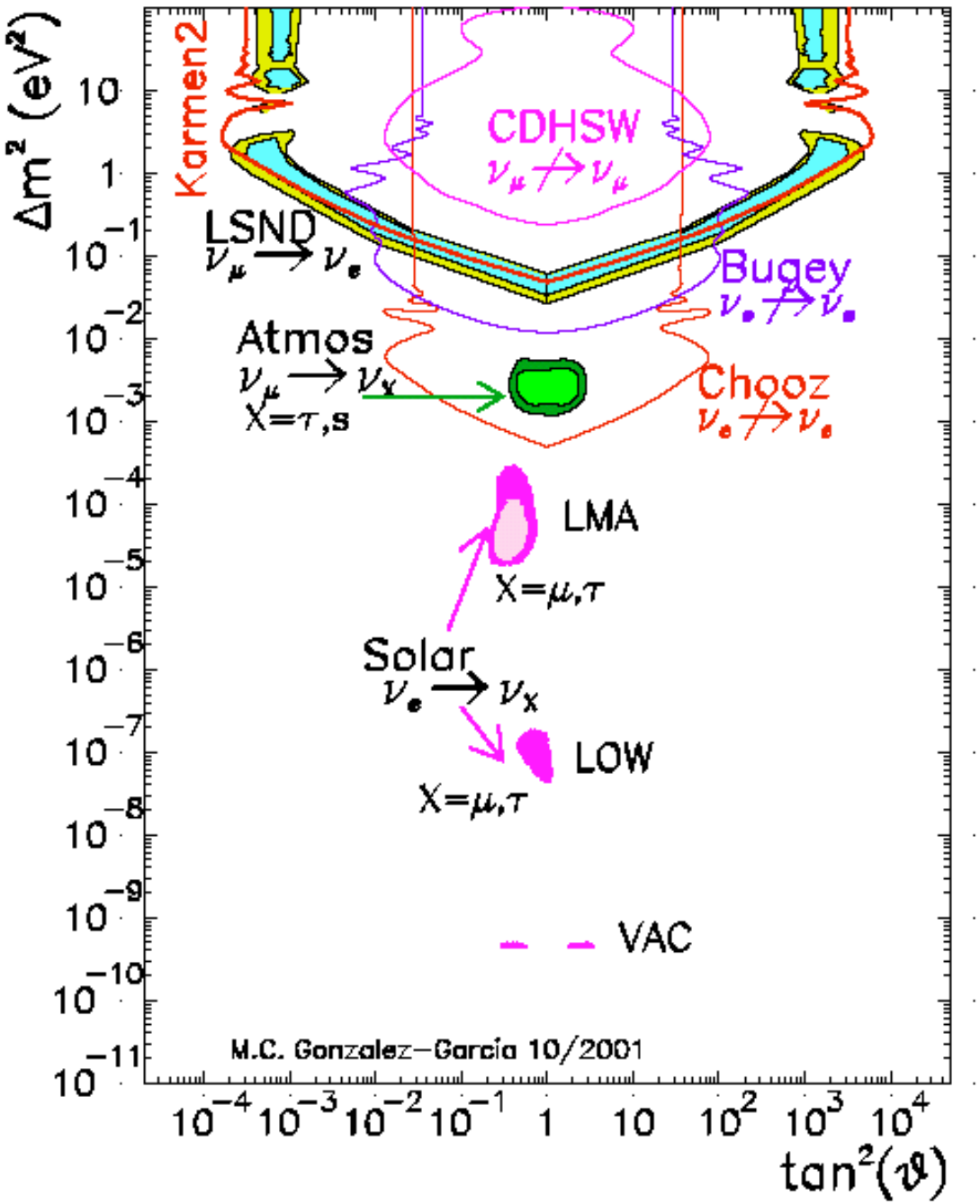


Figure 35 from "Developments in Neutrino Physics", M.C. Gonzalez-Garcia and Yosef Nir, http://arXiv.org/abs/hep-ph/0202058.