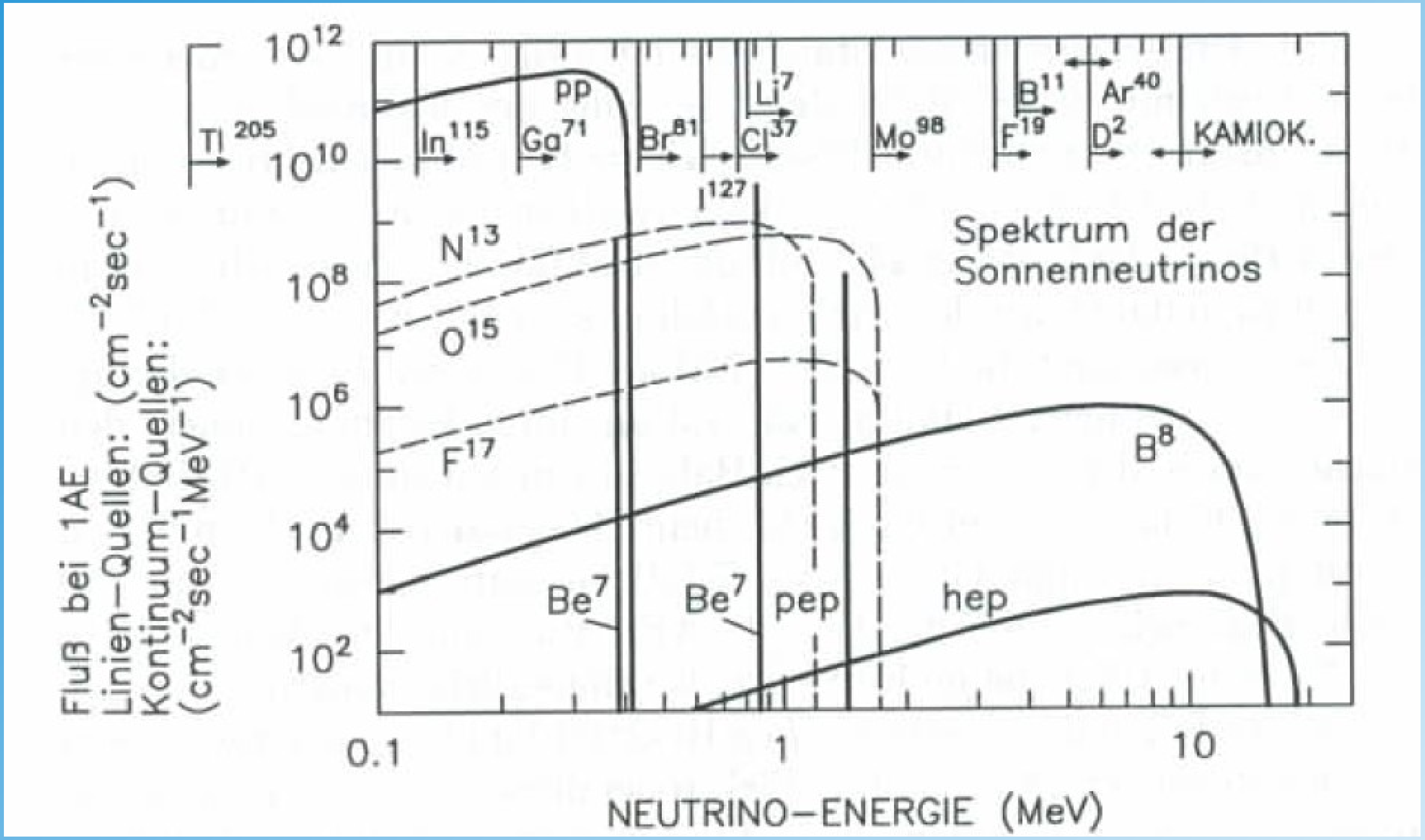
Neutrino Oscillations and Physics Beyond the SM

- Neutrino
- PMNS Matrix
- Maiorana Neutrinos
- (Supersymmetry)

Solar Neutrino Reactions

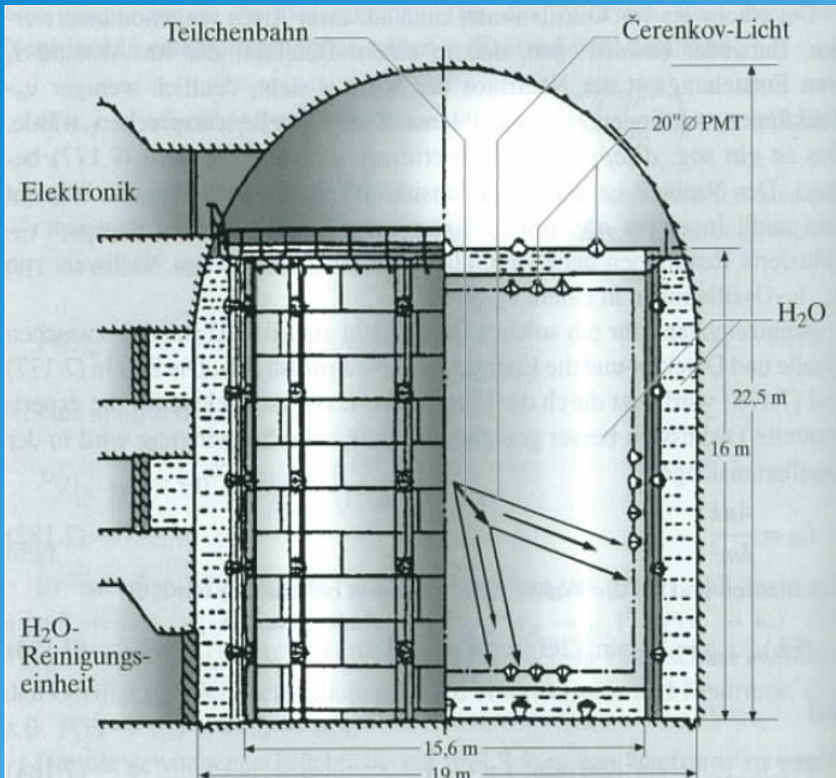


Solar Neutrino Experiments

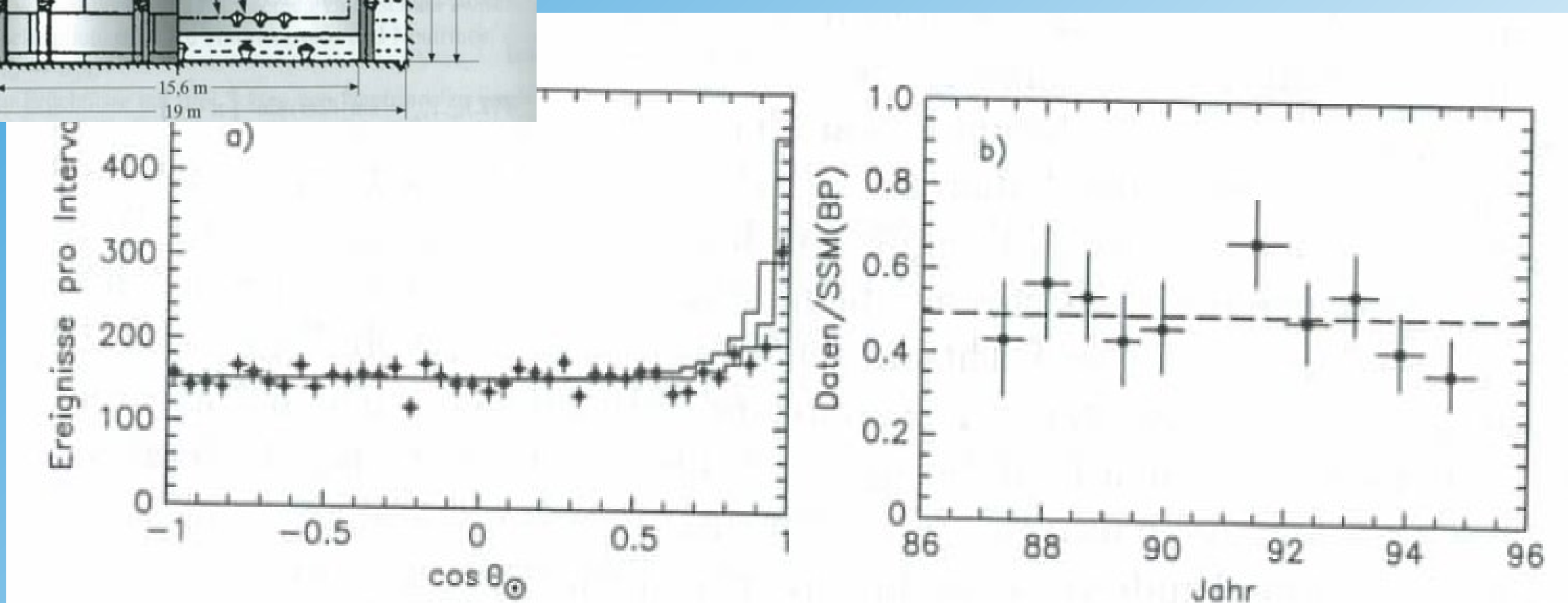
Tab. 7.6 Die vier bisherigen Experimente mit solaren Neutrinos. E_S = Schwellenenergie. Nach [Cre93].

Experiment	Standort	Tiefe (mWÄ)	Reaktion	E_S (MeV)	Hauptquelle	Target
Chlor (radioch.)	Homestake	4100	$Cl^{37}(\nu_e, e)Ar^{37}$	0.814	Be^7 (15%) B^8 (78%)	615 t C_2Cl_4
GALLEX (radioch.)	Gran Sasso	3500	$Ga^{71}(\nu_e, e)Ge^{71}$	0.233	*pp* (54%) Be^7 (27%) B^8 (10%)	30 t Ga ($GaCl_3$)
SAGE (radioch.)	Baksan	4700	$Ga^{71}(\nu_e, e)Ge^{71}$	0.233		30 (57) t Ga (metallisch)
Kamiokande	Kamioka	2700	νe-Streuung	~ 7.5	B^8	3000 t H_2O (680 t Target)

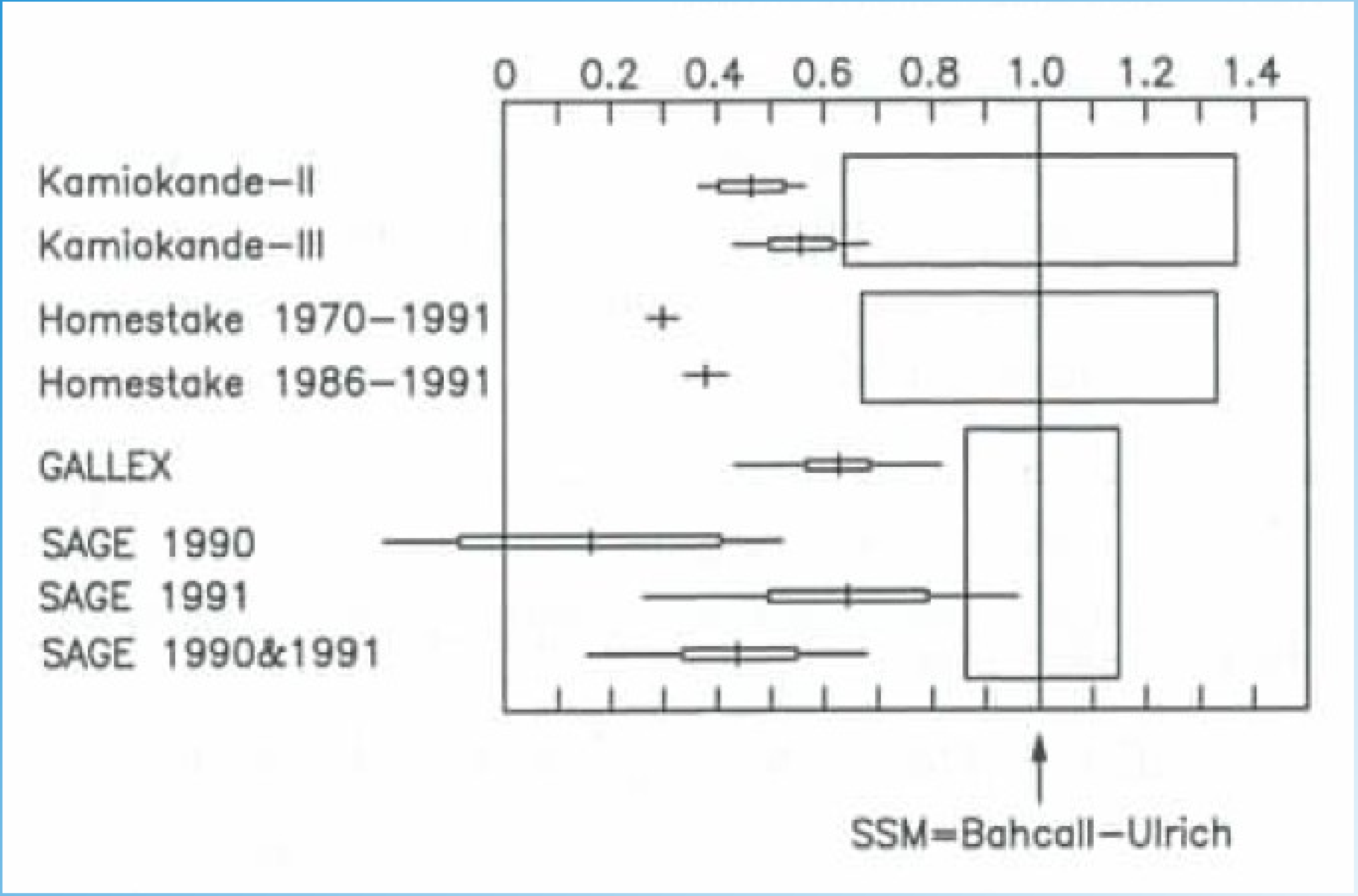
Kamiokande



Big Water Cerenkov Detector

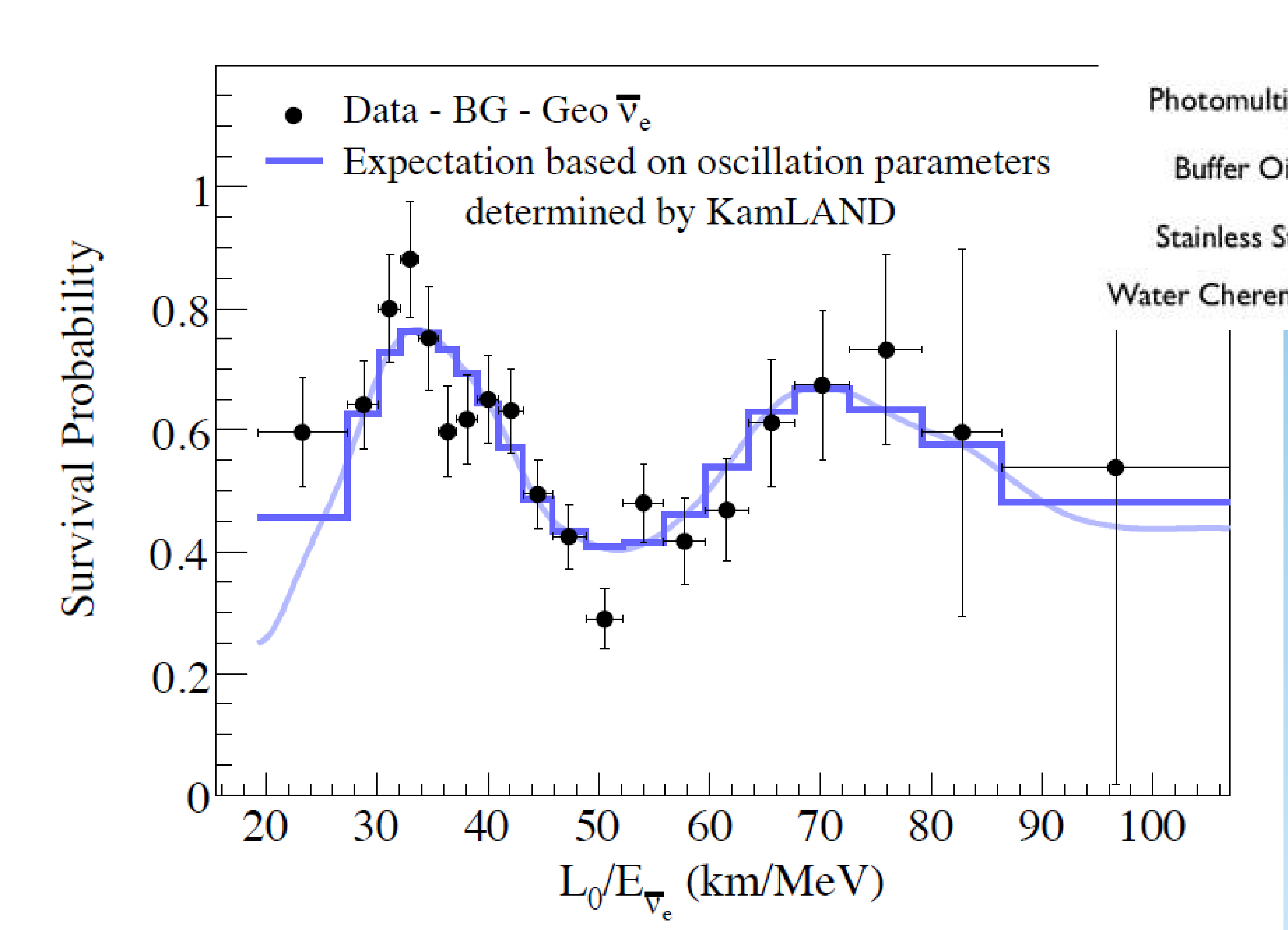


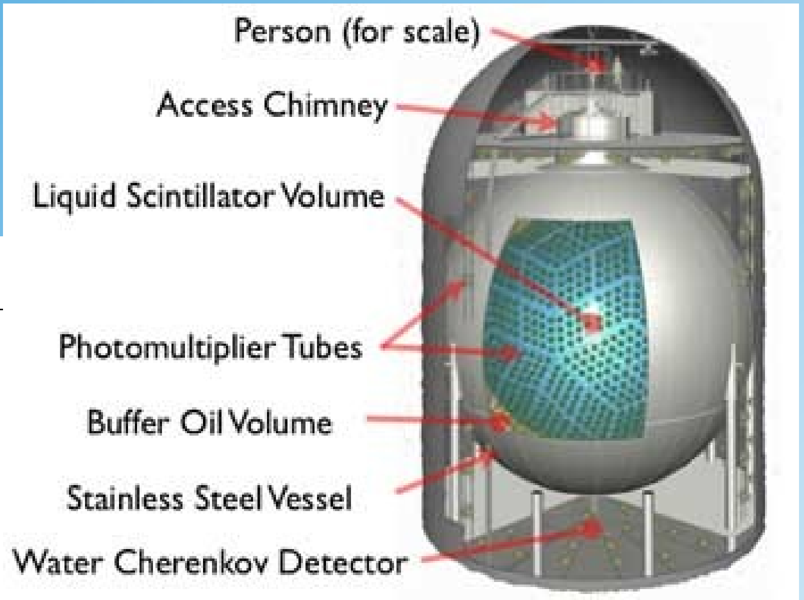
Solar Neutrino Deficits



Reactor Neutrino Oscillations

KAMLAND: anti electron neutrinos





Neutrino Oscillations

- "Classical" SM: ν_e, ν_{mu}, ν_{tau} are massless → no mixing

- Massive neutrinos:

$$|\nu(t)\rangle = |\nu(0)\rangle\, e^{-i(Et-kz)}$$

$$|\nu(t)\rangle \approx |\nu(0)\rangle\, e^{-i\frac{m^2 t}{2k}}\, e^{-i(kt-kz)}$$

oscillation frequency depends on neutrino mass

depends on neutrino species

common factor for all neutrinos

- Two generation mixing

$$P(\nu_e \rightarrow \nu_e)(t) \approx 1 - \sin^2(2\Theta)\, \sin^2\left(\frac{\Delta m_{12}^2\, t}{4k}\right)$$

$$P(\nu_e \rightarrow \nu_\mu)(t) \approx \sin^2(2\Theta)\, \sin^2\left(\frac{\Delta m_{12}^2\, t}{4k}\right)$$

$$\sin^2 \frac{\Delta m_{12}^2\, t}{4k} = \sin^2(\pi L / L_0)$$

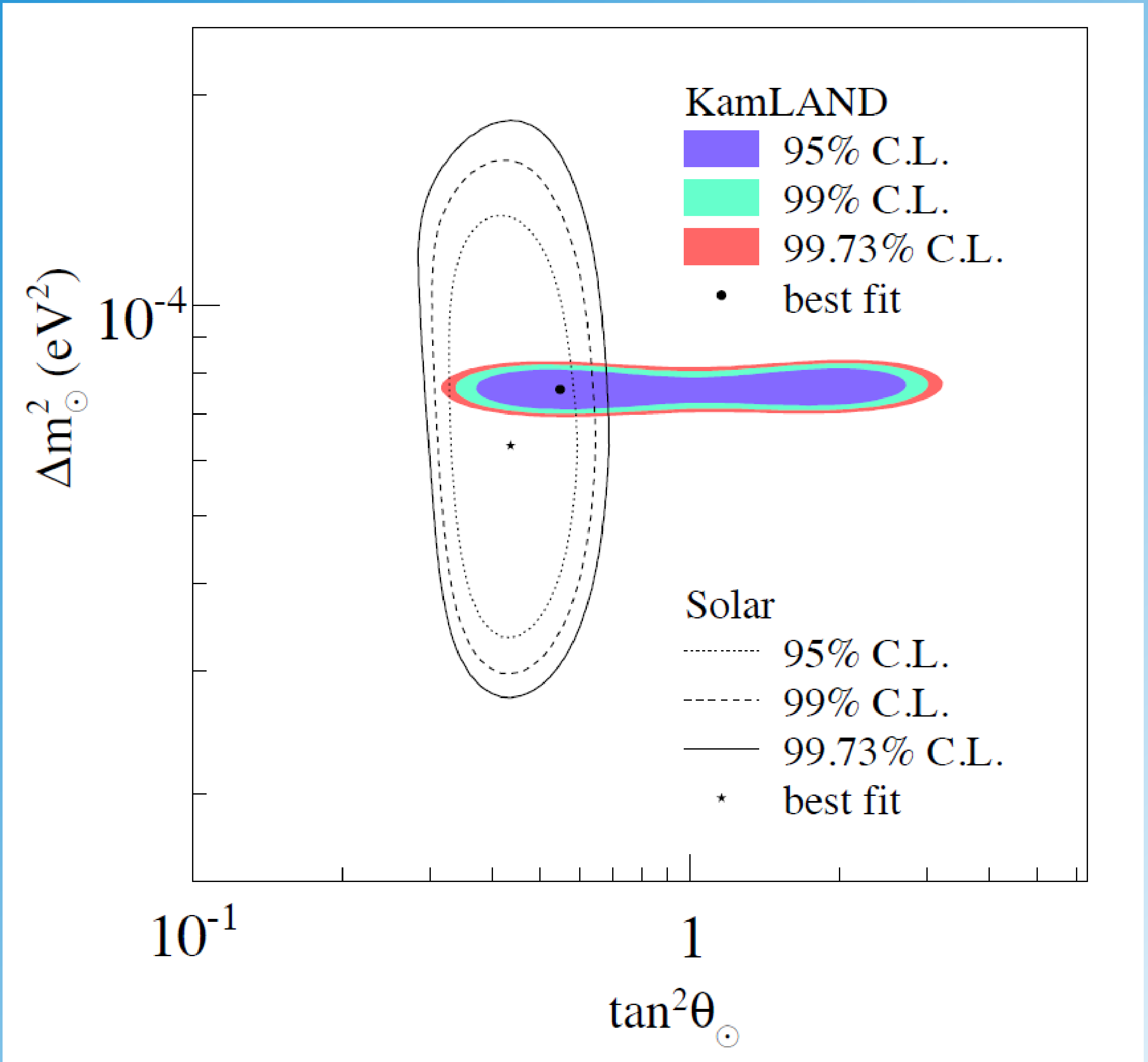
Θ = mixing angle

Δm_{12}^2 = mass^2 difference

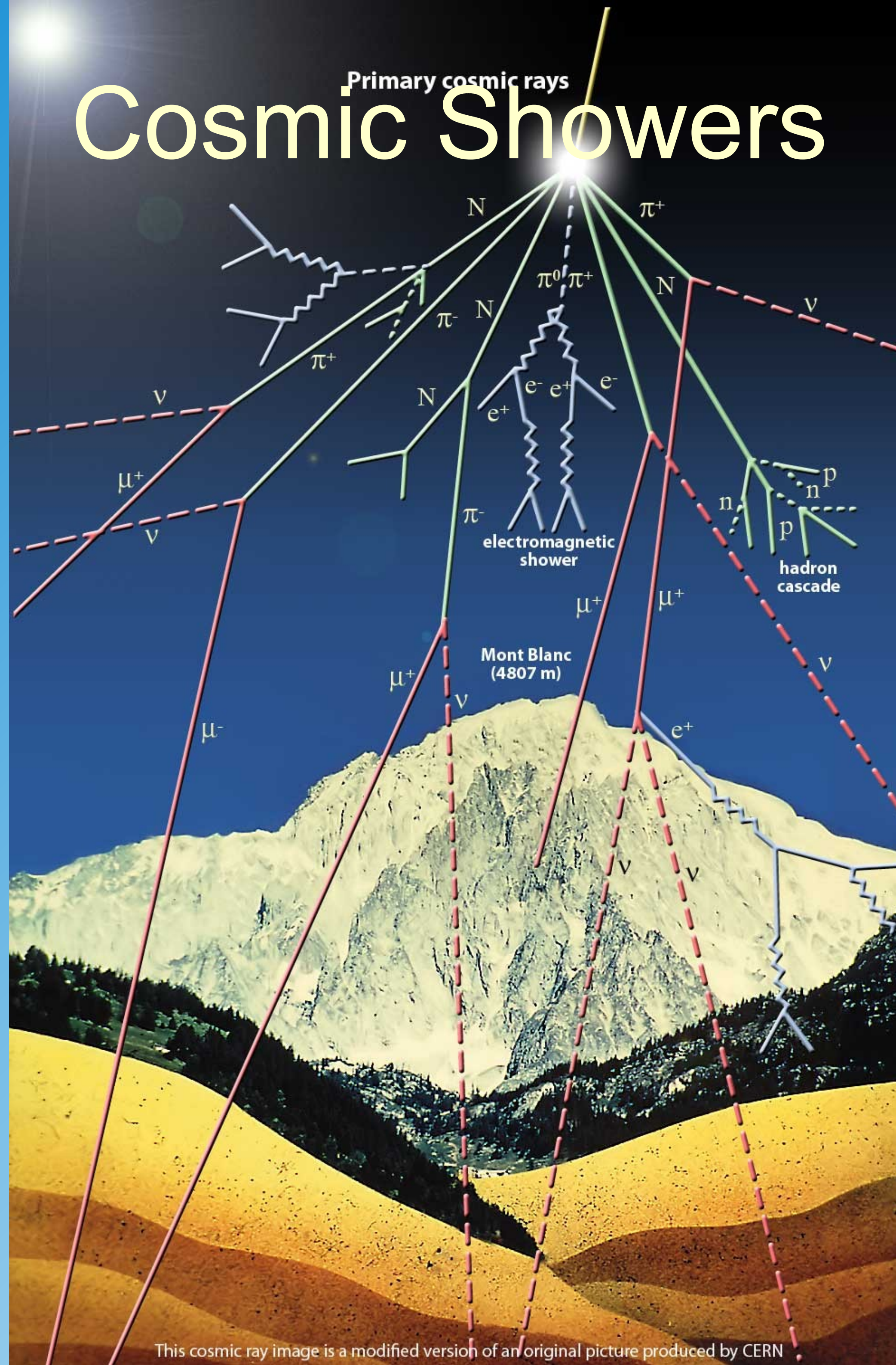
$$L_0 = 2.47\, \frac{p}{\Delta m_{12}^2}\, \frac{eV^2 m}{MeV}$$

sun ν: ~MeV
atmospheric ν: ~GeV
reactor ν: ~ 100 keV

Solar Neutrino Mixing

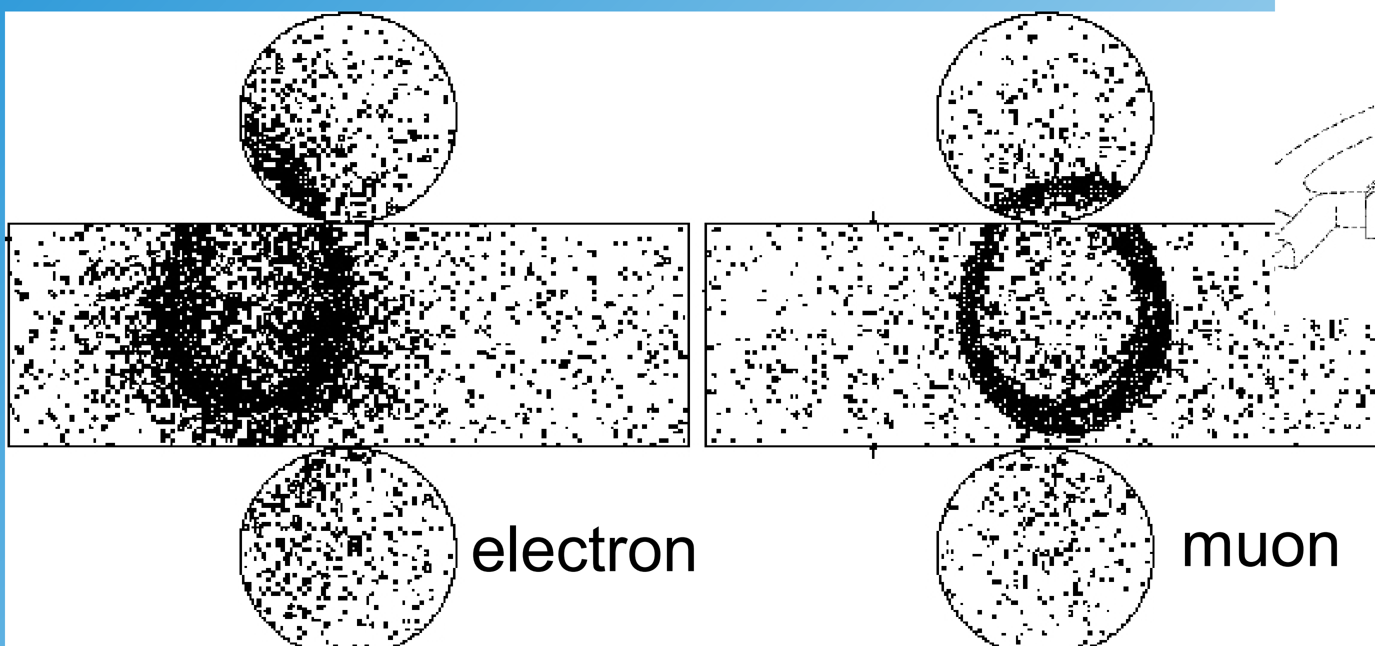


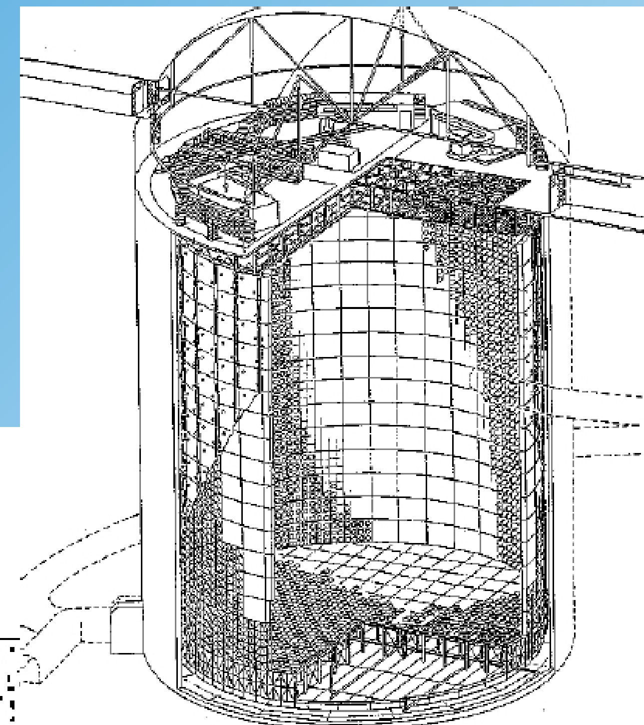
Cosmic Showers



Super Kamiokande

Cerenkov Images:



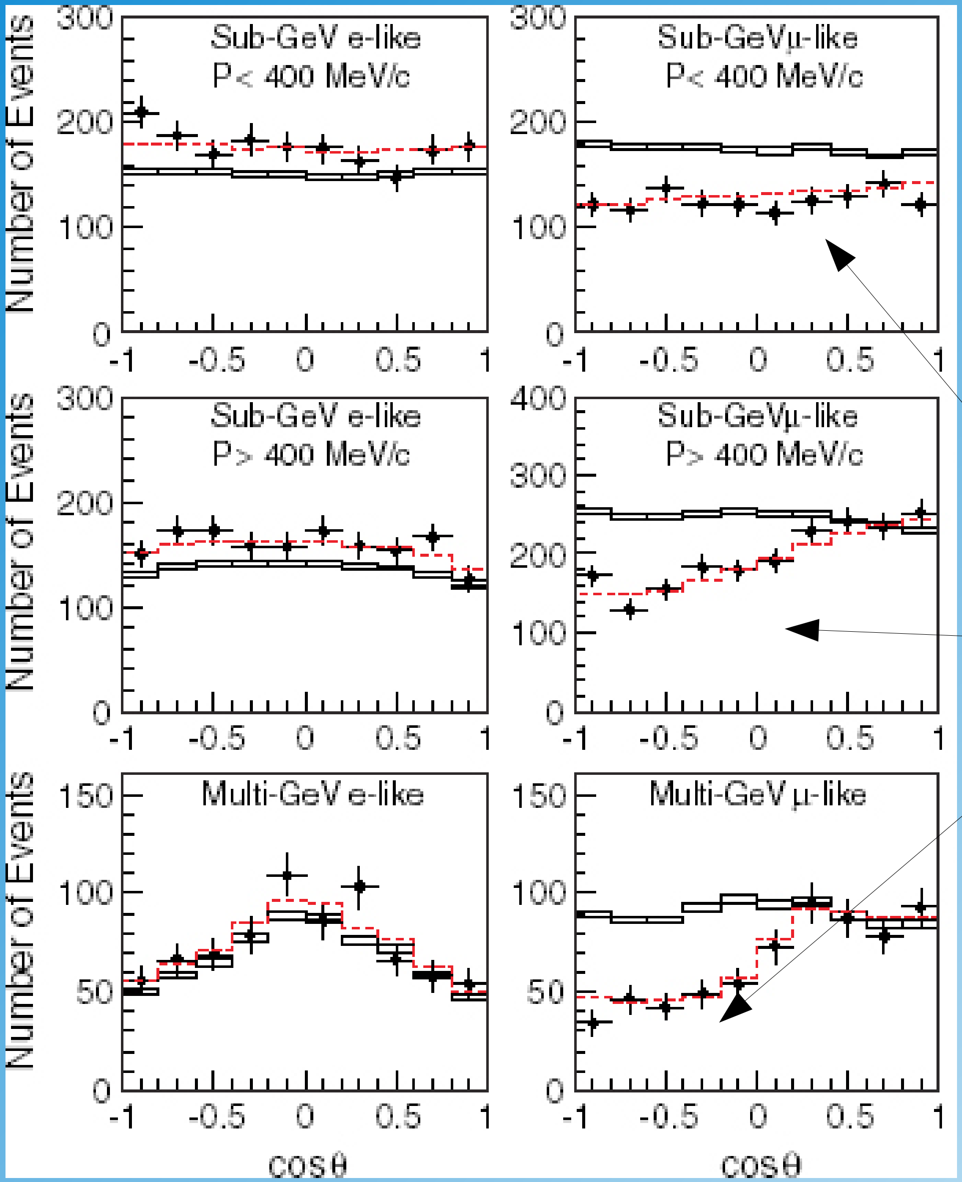


photomultipliers in water tank

$\nu_e \rightarrow e\, W^+$

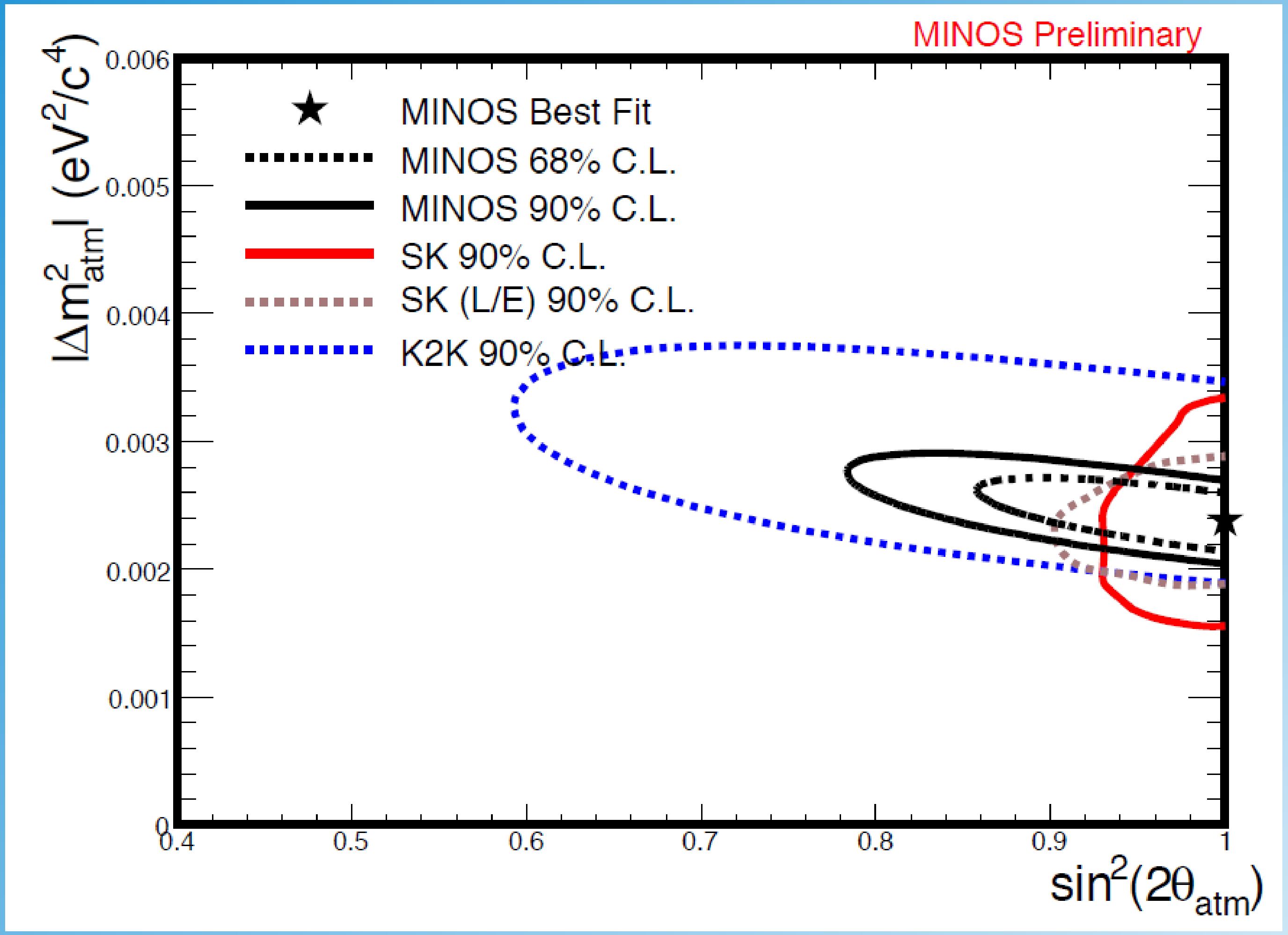
$\nu_\mu \rightarrow \mu\, W^+$

Super-Kamiokande Atmospheric Neutrinos



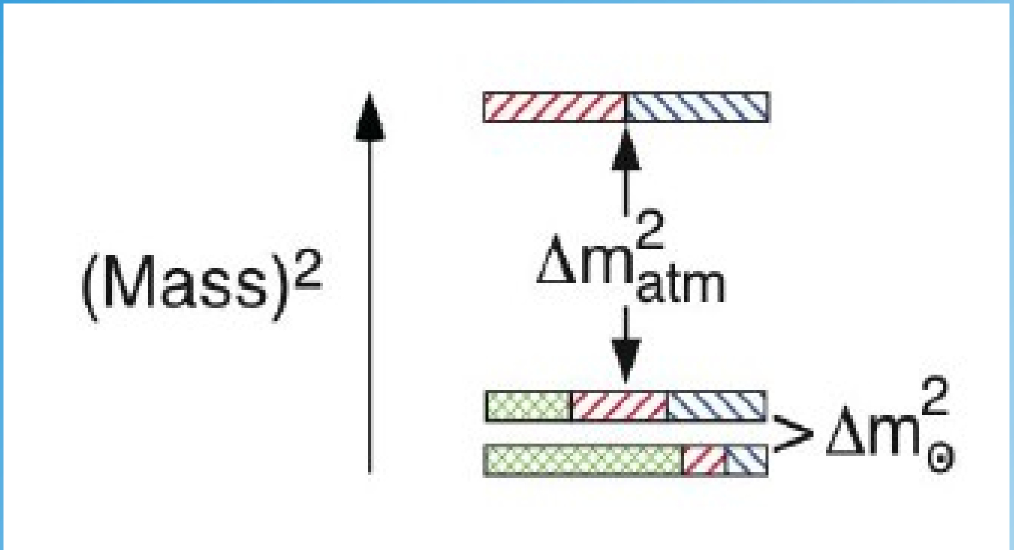
deficit of upgoing muon neutrinos

“Atmospheric Mixing”



MINOS and K2K are muon-neutrino-beam experiments

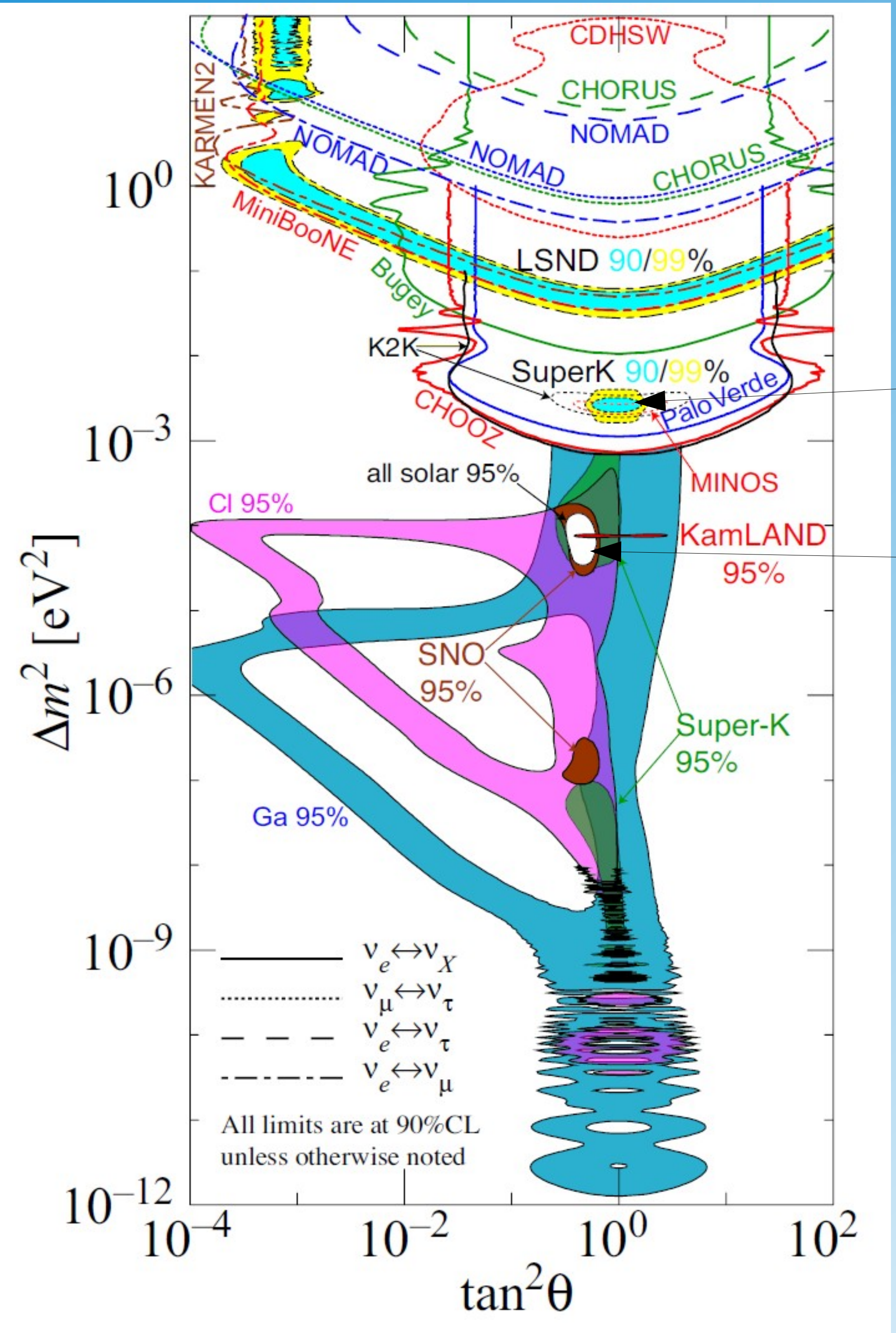
PMNS Matrix and Hierarchy



Θ ~45°

Θ ~35°

$$U = \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$
$$\times \operatorname{diag}(e^{i\alpha_1/2},\ e^{i\,\alpha_2/2},\ 1)\ .$$



solar neutrinos

atmospheric neutrinos

Beyond the SM

Observations not explained by (extended) SM

- dark matter

Problems of the SM

- generations of fermions
- fermion masses and mixing
- neutrinos (Maiorana or Dirac) and generation of masses
- **Hierarchy problem**

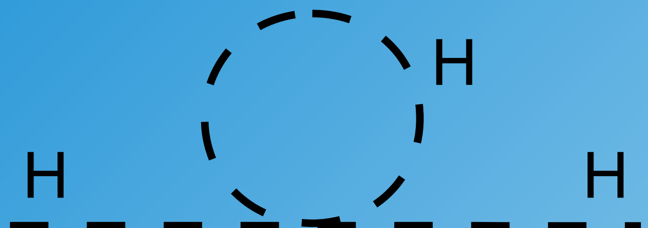
The SM Hierarchy (Fine Tuning) Problem

• Fermion-Higgs couplings do not decouple in the SM $\propto \frac{g}{2}\frac{m_t}{M_W}$

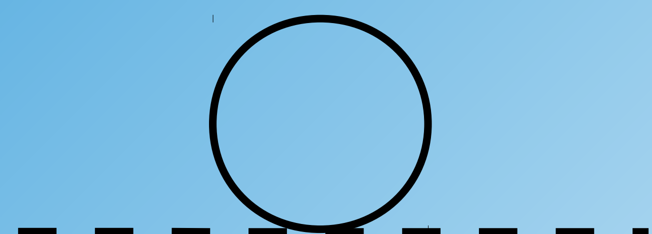
→ leading to large negative radiative contributions to Higgs mass

• Similar contributions from Higgs self-coupling, but positive

scalar loop



fermion



$$\delta M_{Hs}^2 = \frac{|\lambda_s^2|}{16\pi^2}\left[\Lambda^2 + 2m_s^2 \log \Lambda / m_s\right]$$

$$\delta M_{Hf}^2 = \frac{|g_f^2|}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \log \Lambda / m_f\right]$$

note factor 2

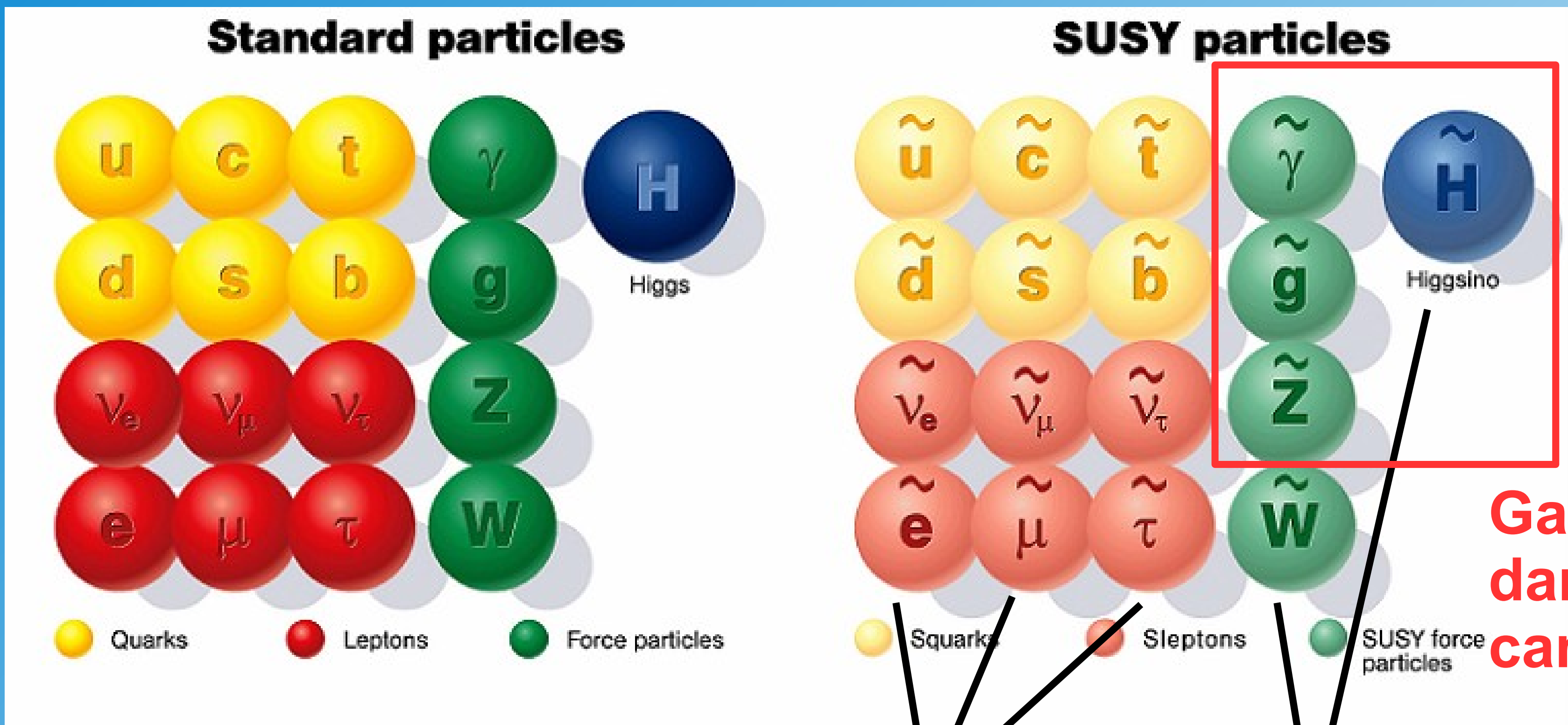
Higgs mass then given by $\delta M_H^2 = M_{H,bare}^2 + \delta M_H^2$

$M_{Higgs} / M_{Planck} = 10^{-17}$ is considered to be unnatural → fine tuning problem

→ In SUSY the quadratic divergences from fermion loops are compensated by additional **scalar fermions**. Only usual logarithmic divergences remain.

Supersymmetry

J=1/2 J=1 J=0 J=0 J=1/2 J=1/2



Gauginos are dark matter candidates

scalar particles fermions

Unification of Gauge Couplings