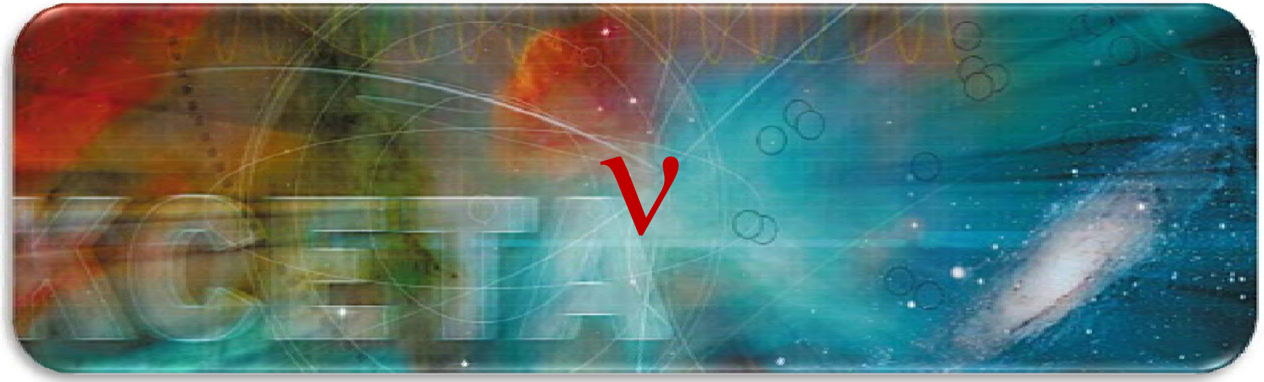


phenomenology of neutrinos and neutrino masses

ν-mixing &
flavour oscillations

ν-masses &
mass patterns

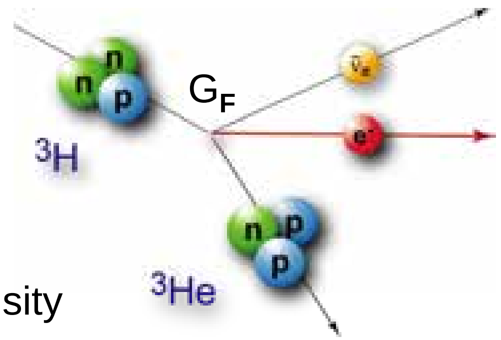
Pauli´s hypothesis & Fermi´s theory

4. December 1930: Wolfgang Pauli postulates a new particle: the neutrino
↳ explanation for the observed continuous energy spectrum of ß-decay electrons to guarantee conservation of energy and angular momentum
ν parameters: massless, neutral, spin s = ½, **weak interaction only**

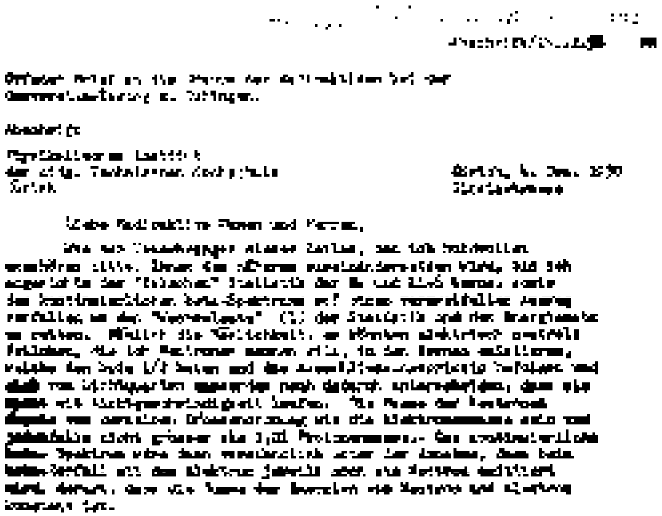
1934: Enrico Fermi formulates a theory of ß-decay
point-like current-current interaction with G_F
golden rule:
transition rate Γ

$$\Gamma = \frac{2\pi}{\hbar} \cdot G_F^2 \cdot \left|\langle f \left| M_{fi} \right| i \rangle\right|^2 \cdot \frac{dn}{dE}$$

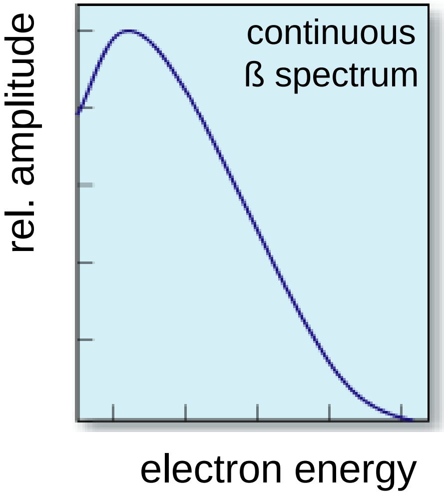
final state density




W. Pauli

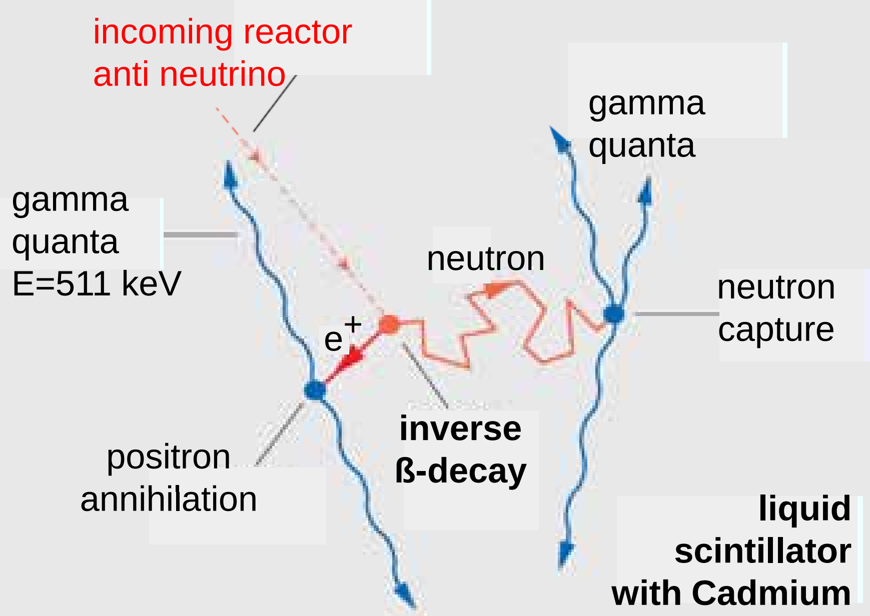



E. Fermi

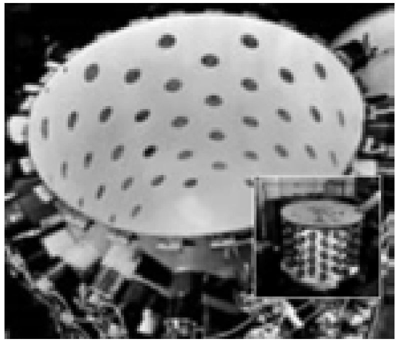


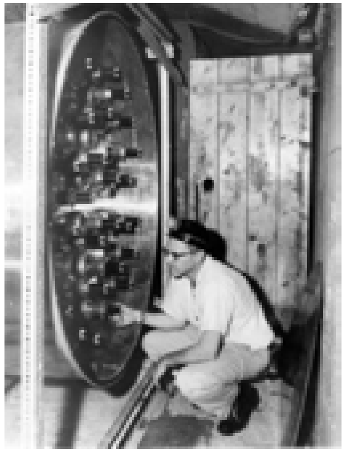
a first glimpse of the elusive ´poltergeist´

1956: first detection of neutrinos by
Fred Reines & Clyde Cowan at the
Savannah River reactor

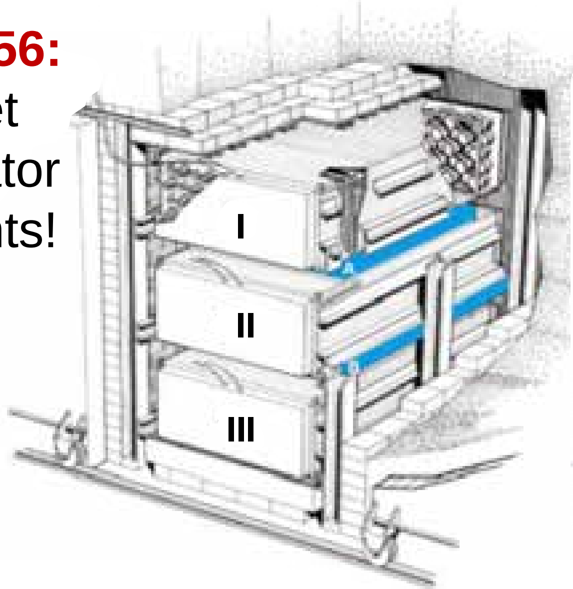


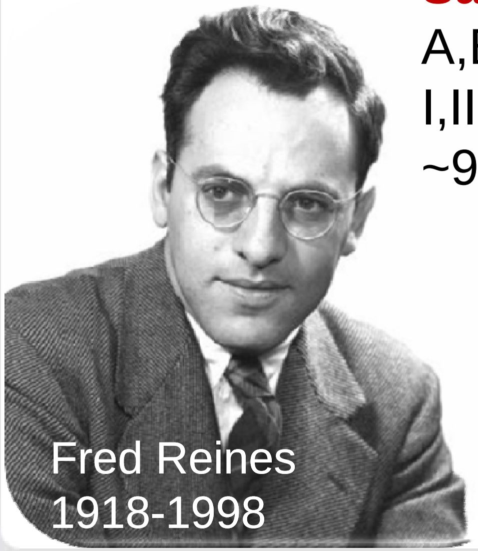
Hanford 1954: first
neutrino detector
´Herr Auge´
300 ℓ liquid scintillator
with 90 PMTs!





Savannah River 1956:
A,B: 200 ℓ H_2O-target
I,II,III: 4200 ℓ scintillator
~900 h measurements!





Fred Reines
1918-1998

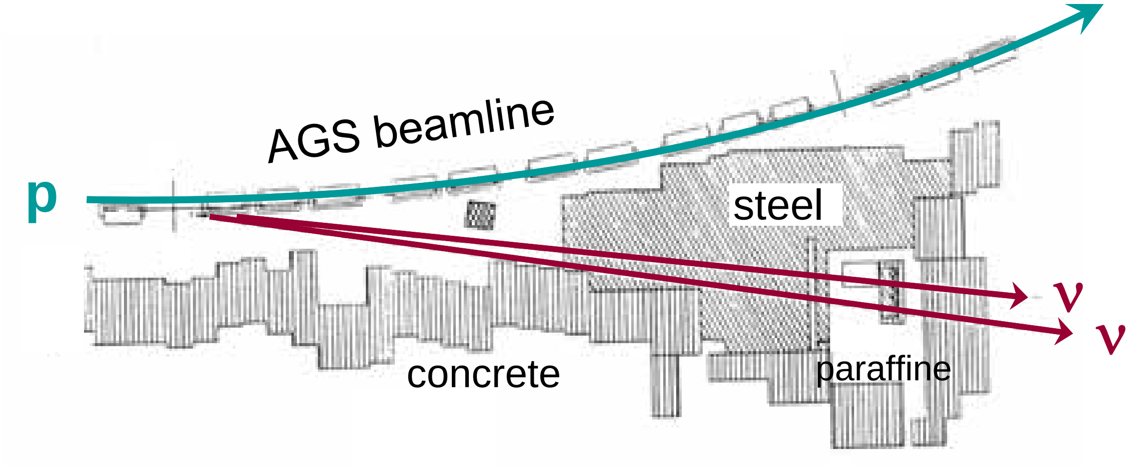
Nobel
1995

project
Poltergeist

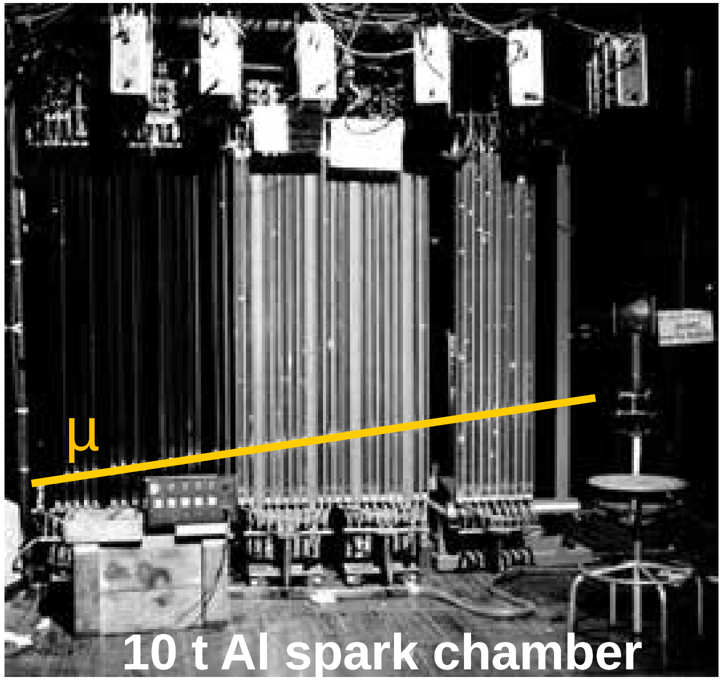
AGS experiment – the second neutrino ν_μ

1962: L.M. Lederman, M. Schwartz, J. Steinberger: proof that $\nu_\mu \neq \nu_e$
identity of neutrinos from pion decay

$\pi^+ \rightarrow \mu^+ + \nu$ $\nu = \nu_\mu$ or ν_e



experimental set-up at BNL



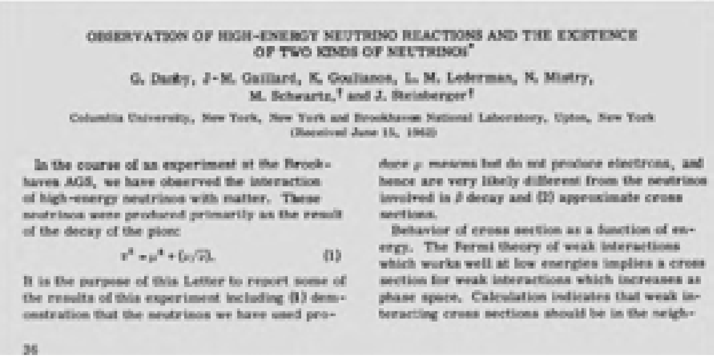
10 t Al spark chamber

Nobel 1988

Leon M. Lederman

Jack Steinberger

Melvin Schwartz



OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry,
M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

$$\pi^{\pm} \rightarrow \mu^{\pm} + (\nu/\bar{\nu}). \quad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

36

experimental results

34 events:

29 muons (d.h. ν_μ-CC)

5 cosmic radiation

➪ $\pi^+ \rightarrow \mu^+ + \nu_\mu$

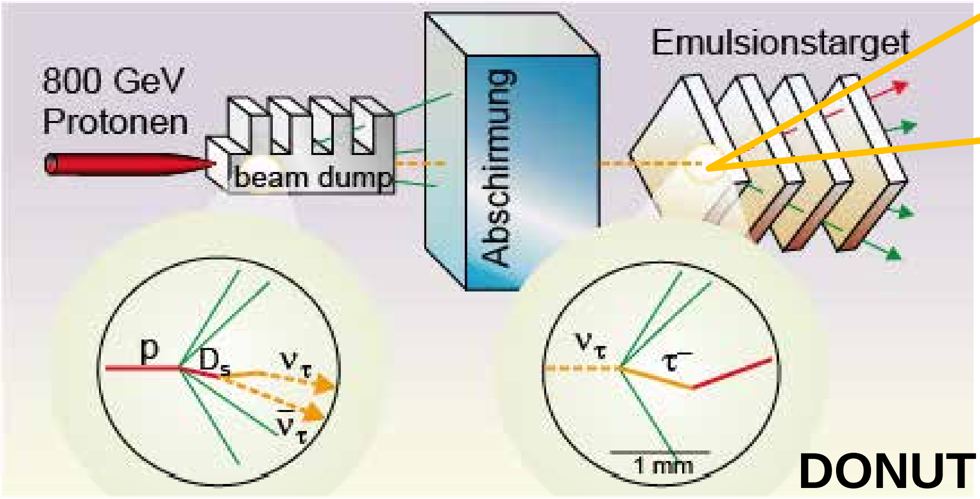
DONUT experiment – the third neutrino ν_τ

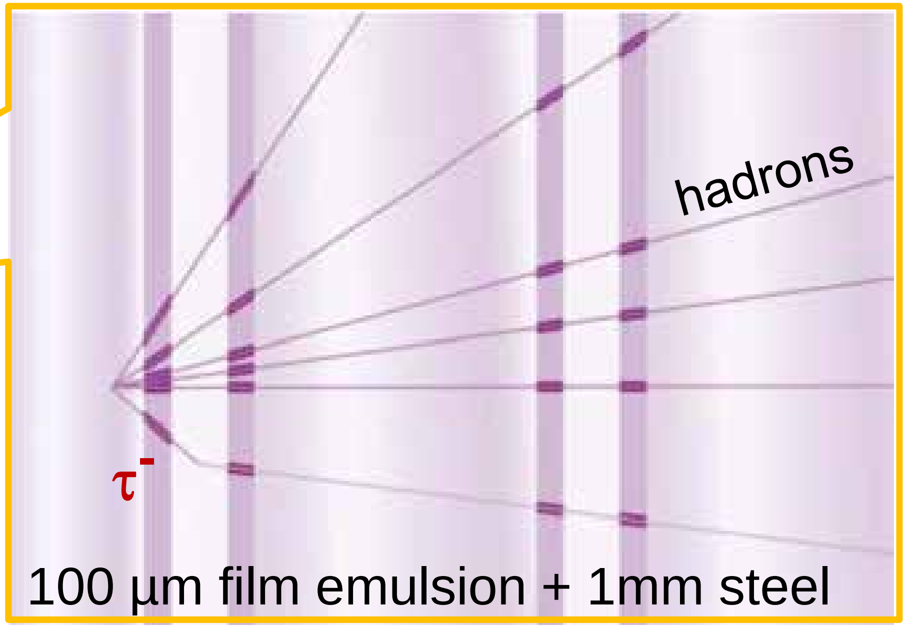
2000 : first detection of ν_τ interactions in the DONUT experiment
(**D**irect **O**bservation of **NU T**au) at Fermilab (Chicago)

experiment: 800 GeV protons hit a tungsten target ↳ D_S-mesons ($c\bar{s}$)
decay ↳ ν_τ with E_ν = 50 GeV ↳ CC-ν_τ-interactions in steel
summer/autumn 1997: 4-months run with 4×10^{17} p.o.t.

results: **4 events** with the topology of ν_τ were identified: ***τ-kink***
τ-life time: $\tau = 3 \times 10^{-13}$ s, range cτ = few mm

DONUT experiment at Fermilab





100 µm film emulsion + 1mm steel

neutrino sources

astrophysical ν–sources to a) study ν-properties b) ν´s as messengers

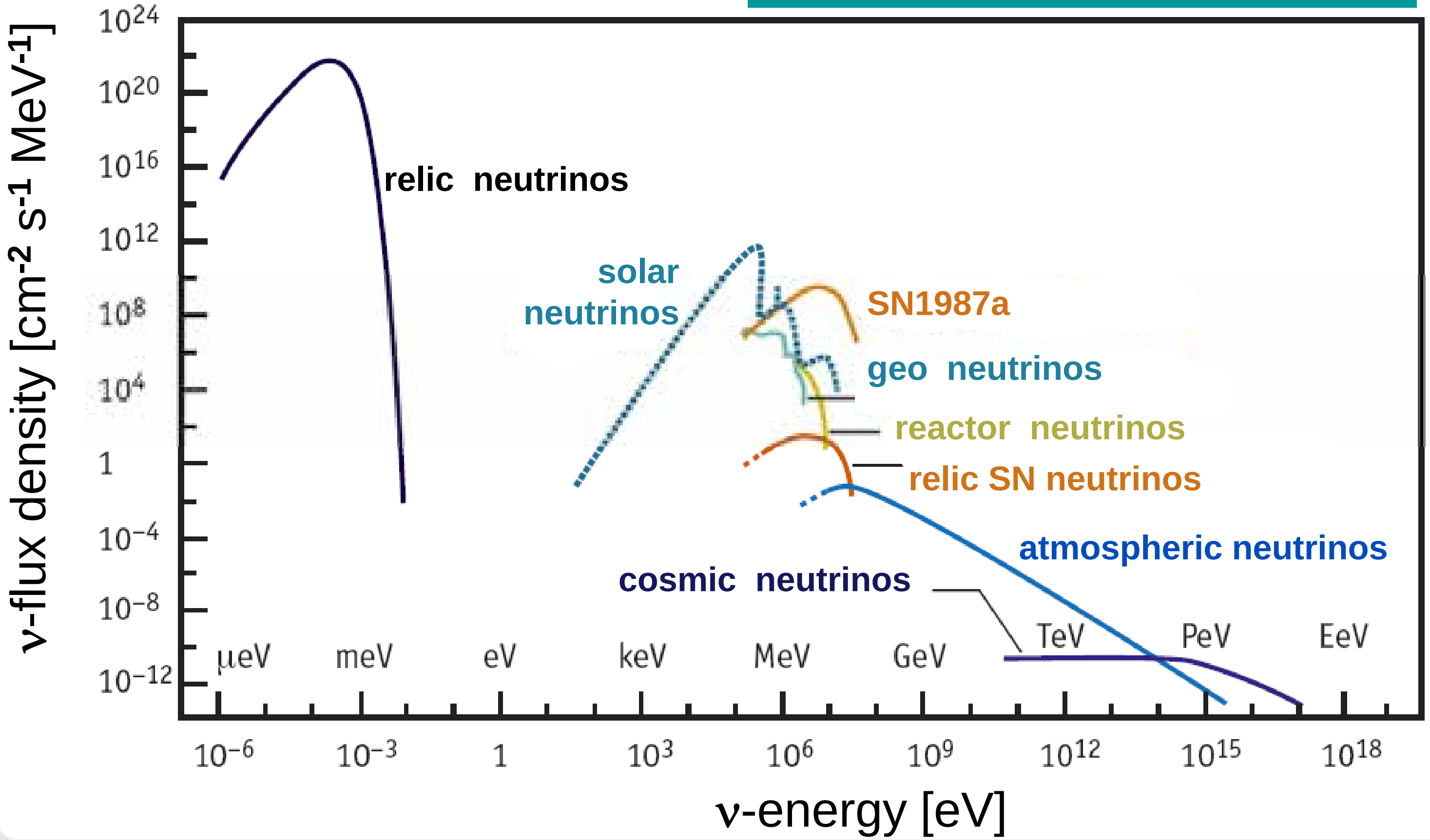
ν-energies: from µeV to EeV (~24 decades)

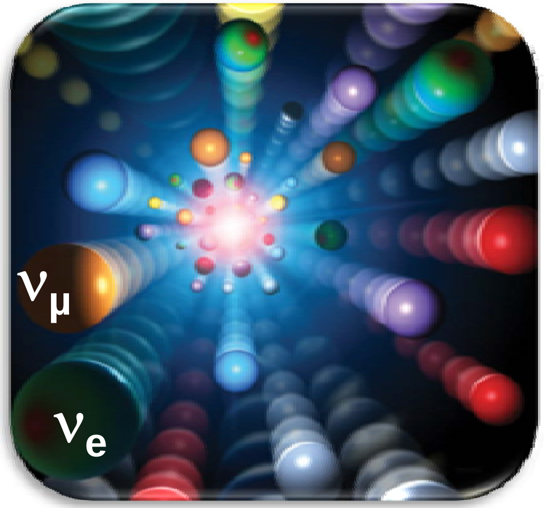
flux-density: $10^{22} – 10^{-12}$ cm^{-2} s-1 MeV^{-1}

detection: elastic ν-e scattering, inverse ß-decay, NC, CC

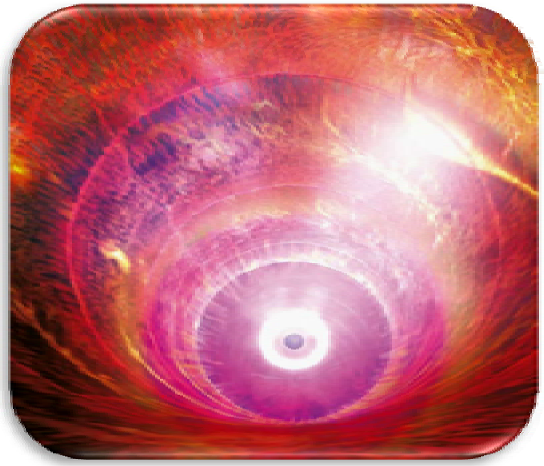
σ_ν increases with E_ν

$$\sigma(\nu_e e \rightarrow \nu_e e) = \pi^{-1} \cdot G_F^2 \cdot s$$





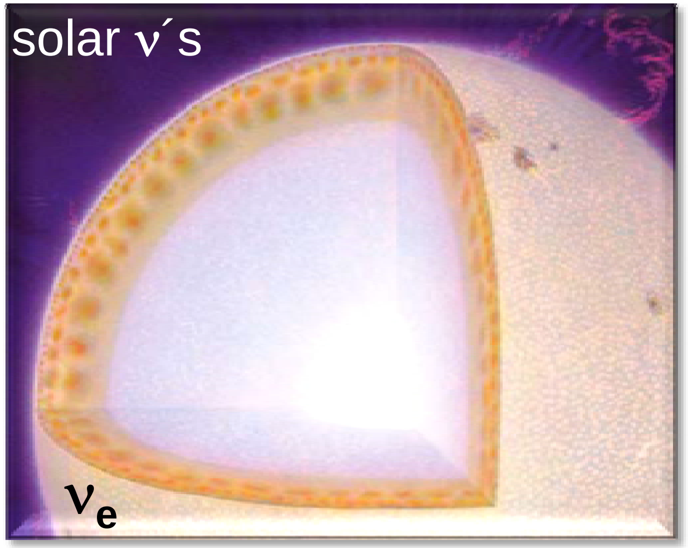
cosmological background ν´s

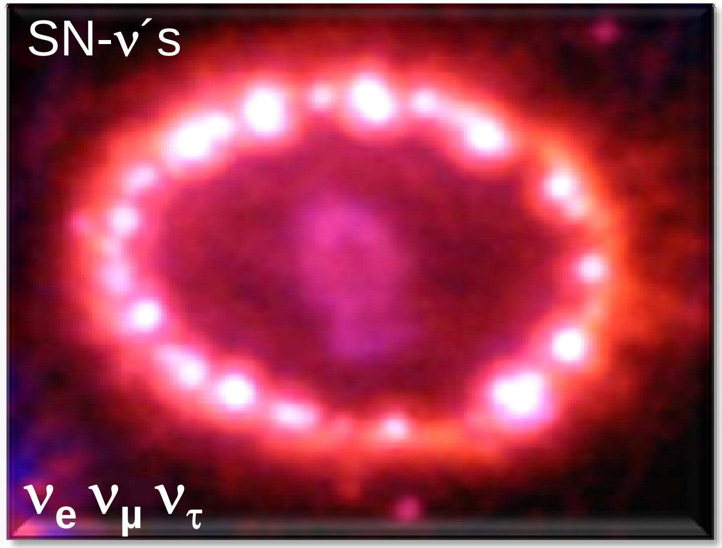


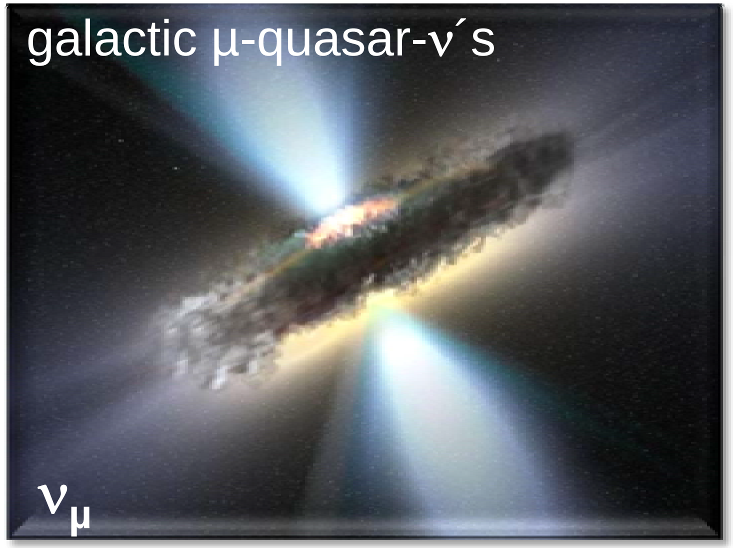
UHE cosmic ν´s

neutrino sources – astrophysical origin

astrophysical ν–sources	energies	weak reactions
Big Bang (thermal, $T_\nu = 1.9$ K)	few μeV	$e^+ + e^- \rightarrow \nu_{e,\mu,\tau} + \nu_{e,\mu,\tau}$
sun (nuclear fusion, pp, ^{7}Be, ^{8}B)	< 15 MeV	$4p + 2e^- \rightarrow {}^4He + 2\,\nu_e$
supernova (thermal, proto-neutron star)	< 50 MeV	$e^+ + e^- \rightarrow \nu_{e,\mu,\tau} + \nu_{e,\mu,\tau}$
atmosphere (cosmic radiation)	< 10^4 GeV	$\pi^\pm \rightarrow \nu_\mu + \mu^\pm \rightarrow e^\pm + \nu_\mu + \nu_e$
galactic accelerators (μ-quasars)	< 10^5 GeV	$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$
extragalactic accelerators (AGN,…)	> 10^5 GeV	$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$







neutrino properties

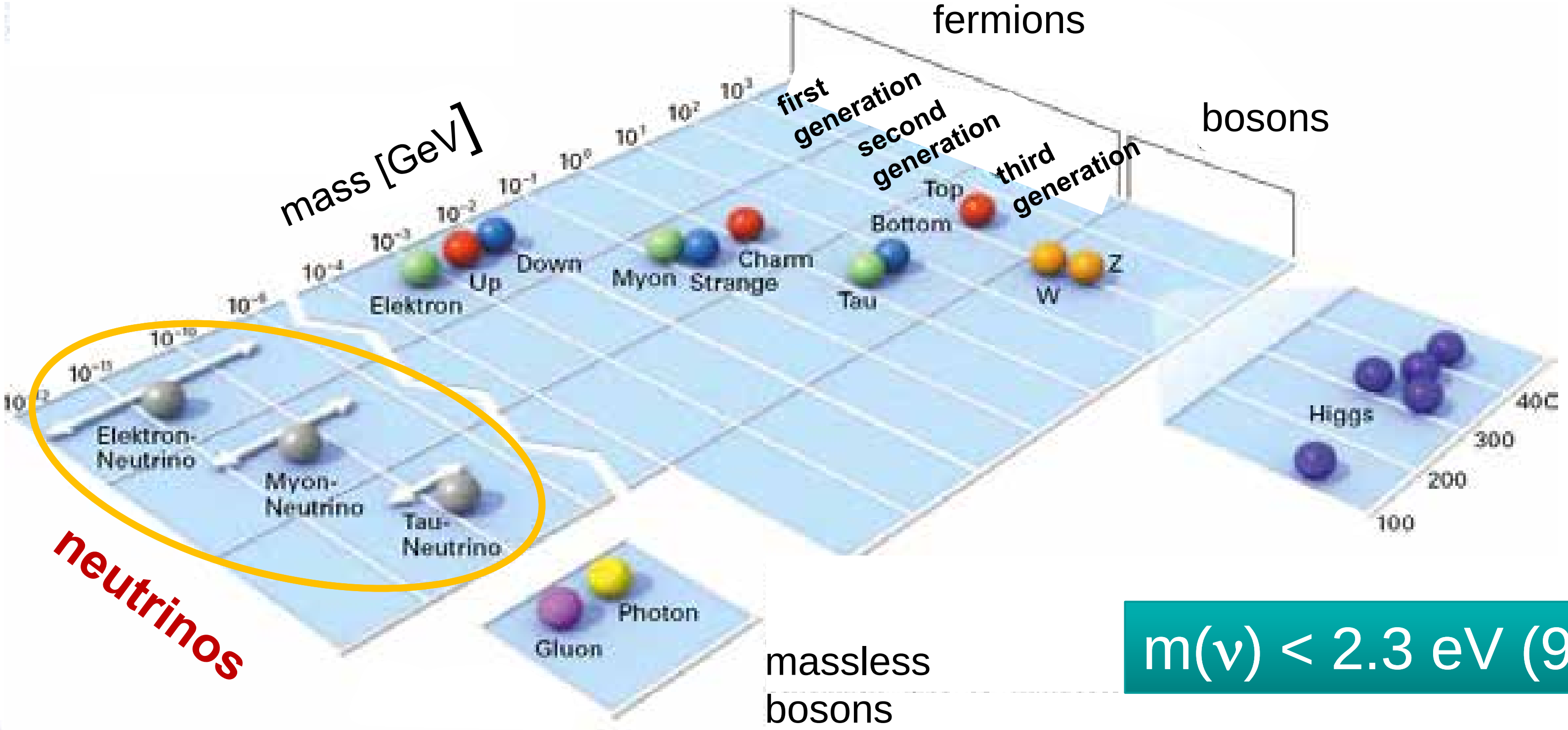
experimental programme for the light SM neutrinos ν_e, ν_μ, ν_τ:

intrinsic neutrino properties	
CP properties: Majorana- or Dirac-ν ($\Delta L = 0,2$)	ν^M or ν^D
absolute masses, (inverted) hierarchy / quasi-degenerated	m_1, m_2, m_3
mixing angles of WMNS matrix	θ_{ij}
(complex) Majorana phases [only for 0νßß]	α_2, α_3
(real) Dirac phase [for ν-oscillations]	δ
life times	τ_1, τ_2, τ_3
decay modes (radiative, non-standard modes)	Γ_i
magnetic dipole moment (static / transition moment)	μ_ν
electric dipole moment	D
mean square charge radius	$\langle r^2 \rangle$
couplings to gauge bosons & Higgs (γ, $W^\pm$, Z^0, H)	g_j

existence of light, sterile neutrinos? (ν_s from extra dimensions, …)
existence of heavy, RH neutrinos? (ν_H from see-saw, …)

neutrino masses in particle physics

why are neutrino masses much smaller than the masses of all other SM particles?

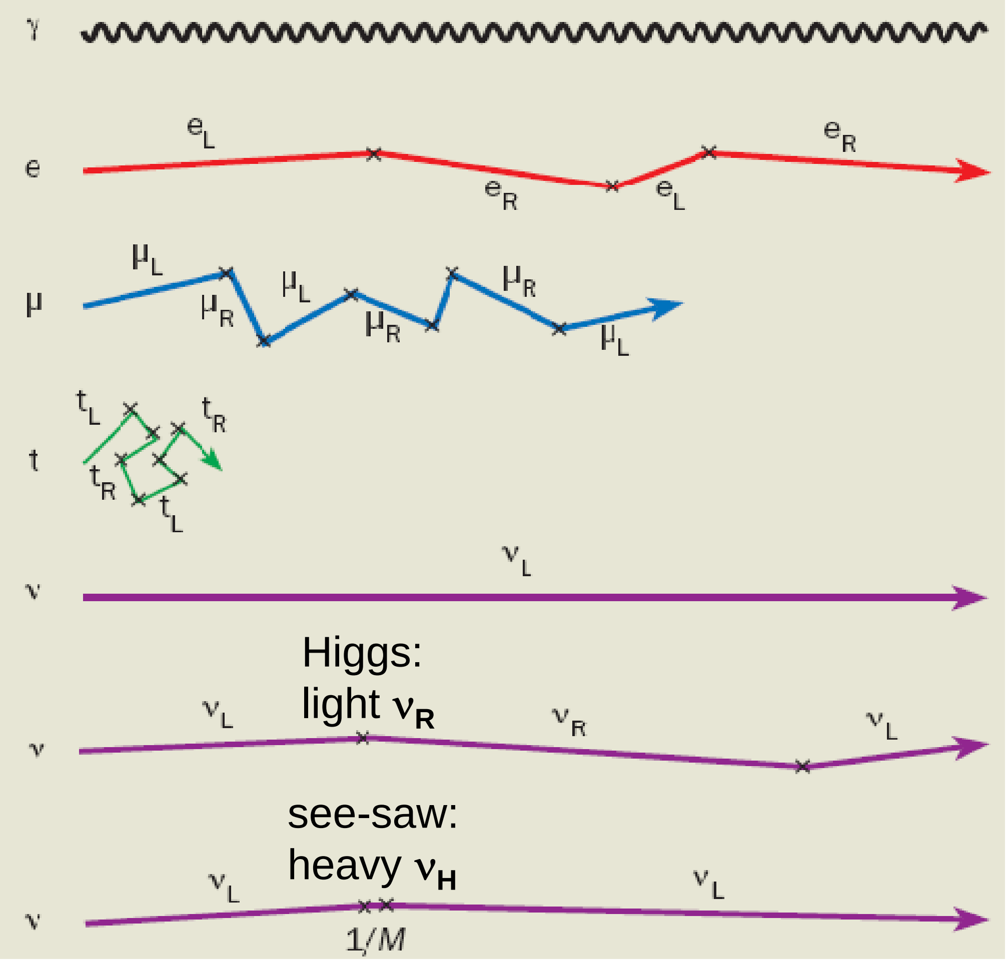


see-saw models:
type I-II-III ?
extra dimensions?
triplett-Higgs?
family symmetry?

m(ν) < 2.3 eV (95% CL)

neutrino masses in particle physics

Higgs mechanism: SM particles acquire mass via interaction with the scalar Higgs boson, this coupling results in a **change of handedness** (lefthanded ↔ righthanded $\nu_{L,R} \leftrightarrow \nu_{L,R}$)



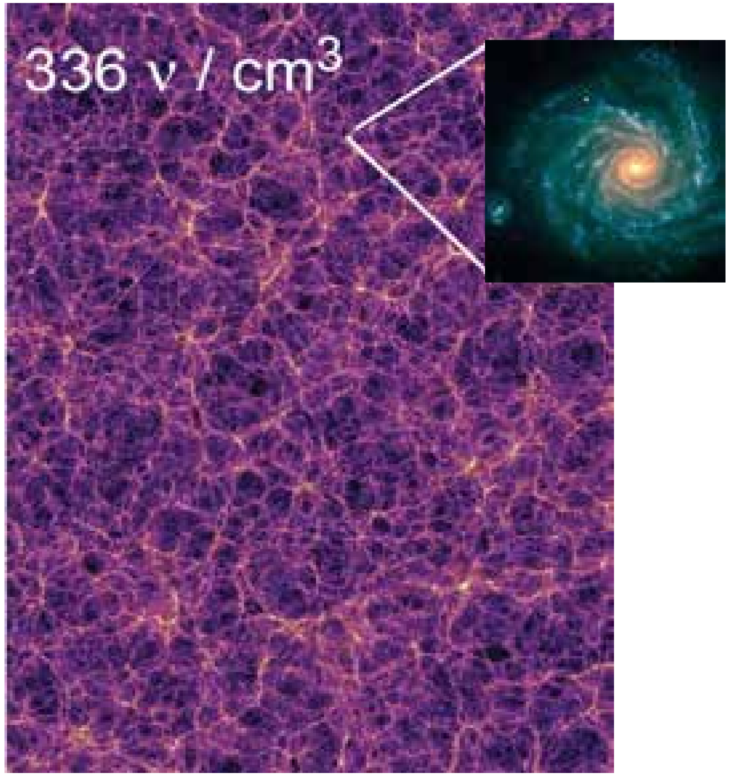
particle	**scale**	**m [MeV]**
photon γ	masselos	0
electron e	light	0.511
muon μ	medium	105.6
top quark t	heavy	$1.71 \cdot 10^5$
SM neutrino ν_L	massless	0
Dirac ν ν^D	very light	$10^{-8} – 10^{-6}$
Majorana ν ν^M	very light	$10^{-8} – 10^{-6}$

neutrinos in in cosmology

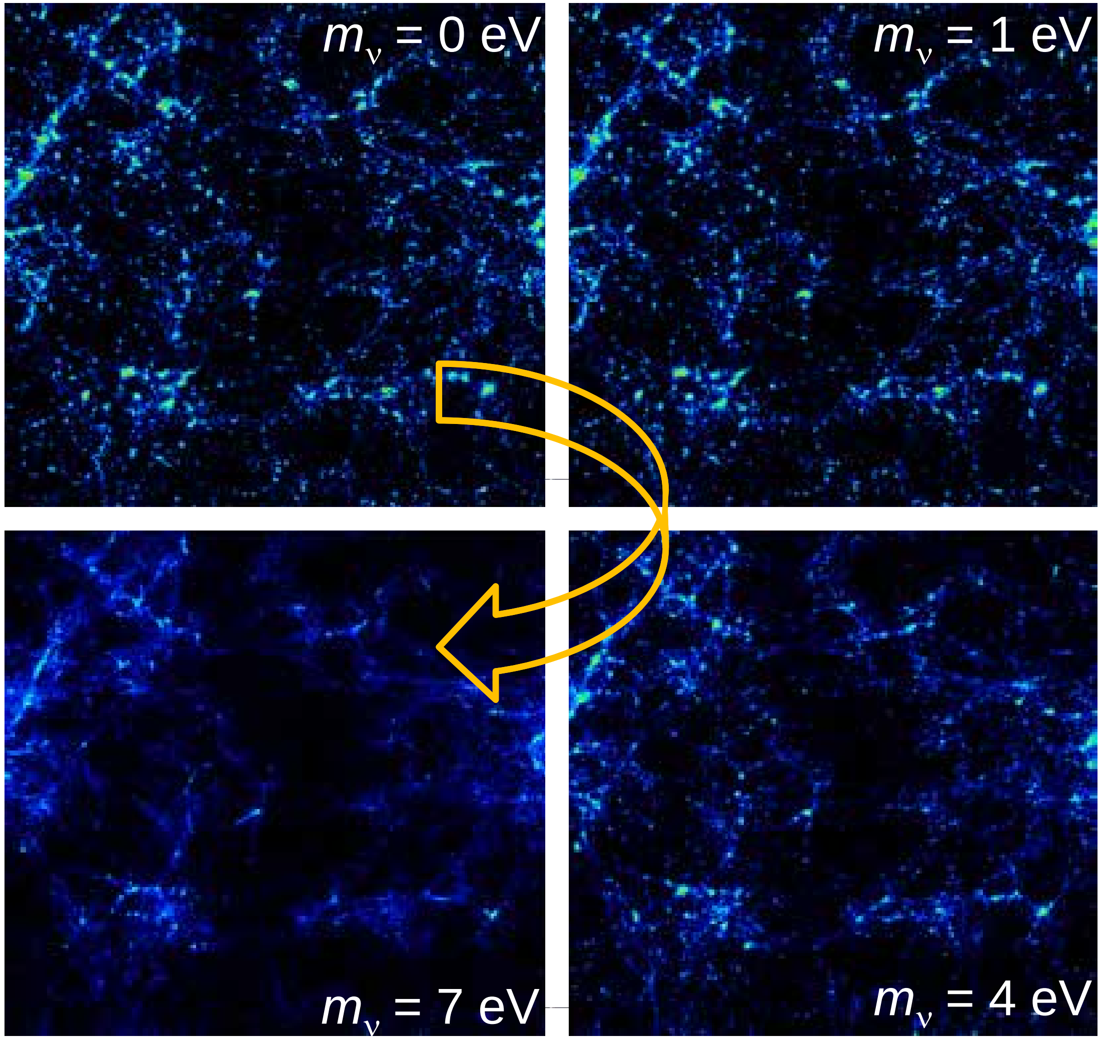
cosmic architects: what is the role of relic ν´s as **hot dark matter**?

large scale structures: free streaming of ν´s on Gpc scales (less small clusters)

cosmology



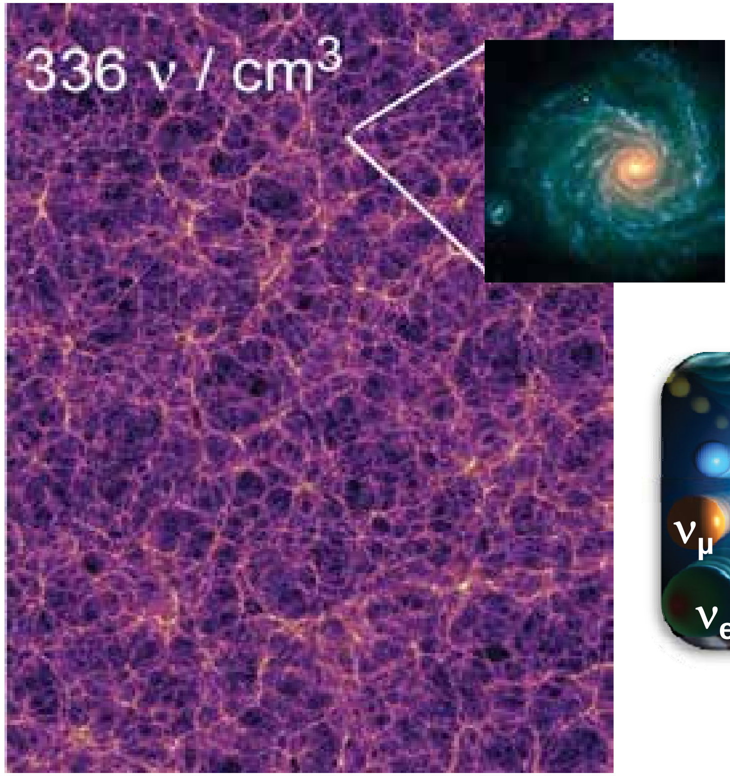
structure of the Universe
(Millenium Simulation)



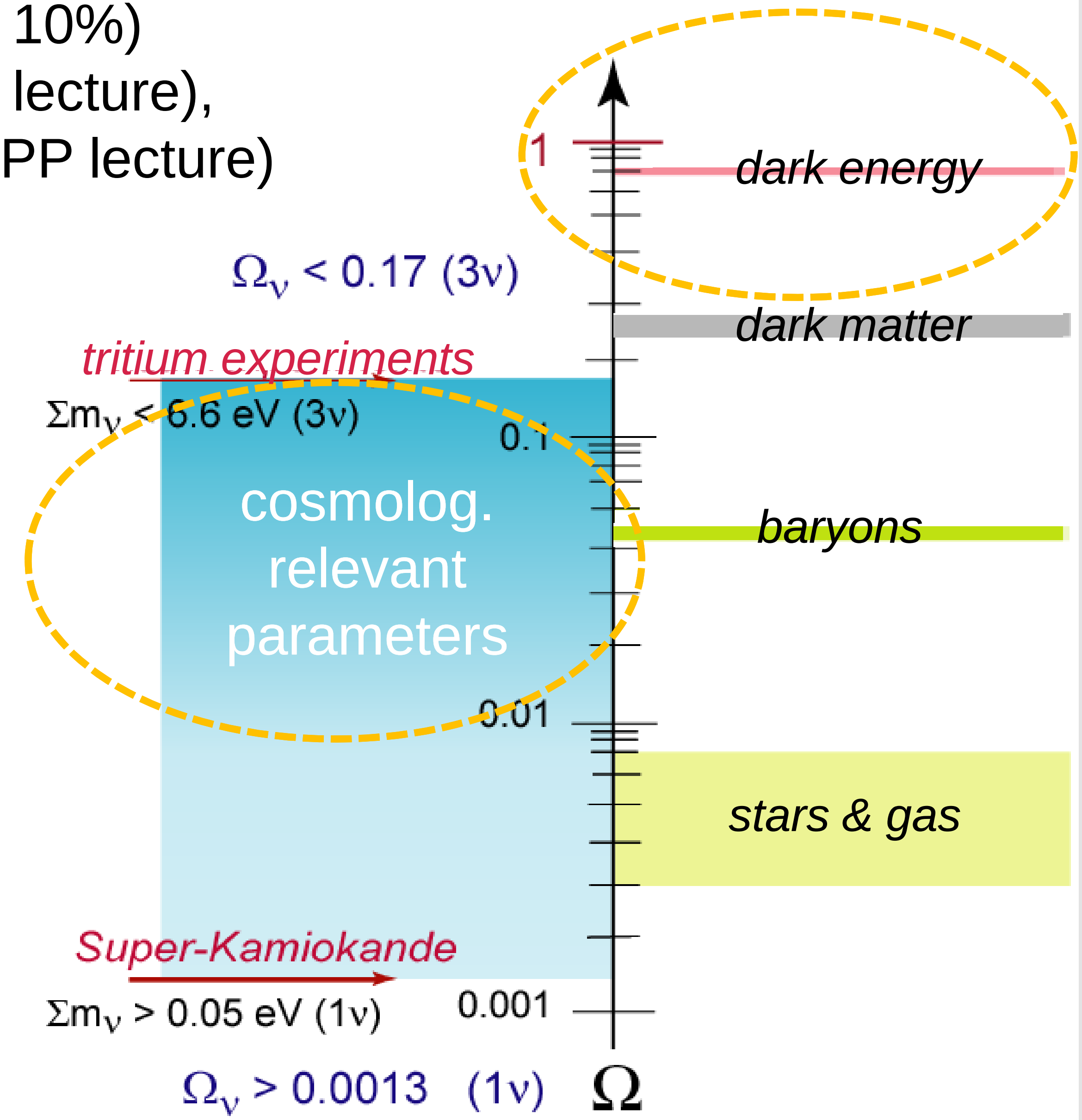
motivation: ν´s in astroparticle physics

HDM contribution: 2 orders (0.1% → 10%)
lower limit: ν-oscillations (this ISAPP lecture),
upper limit: tritium ß-decay (next ISAPP lecture)

$\Omega_\nu h^2 = \Sigma m_\nu / 92$ eV



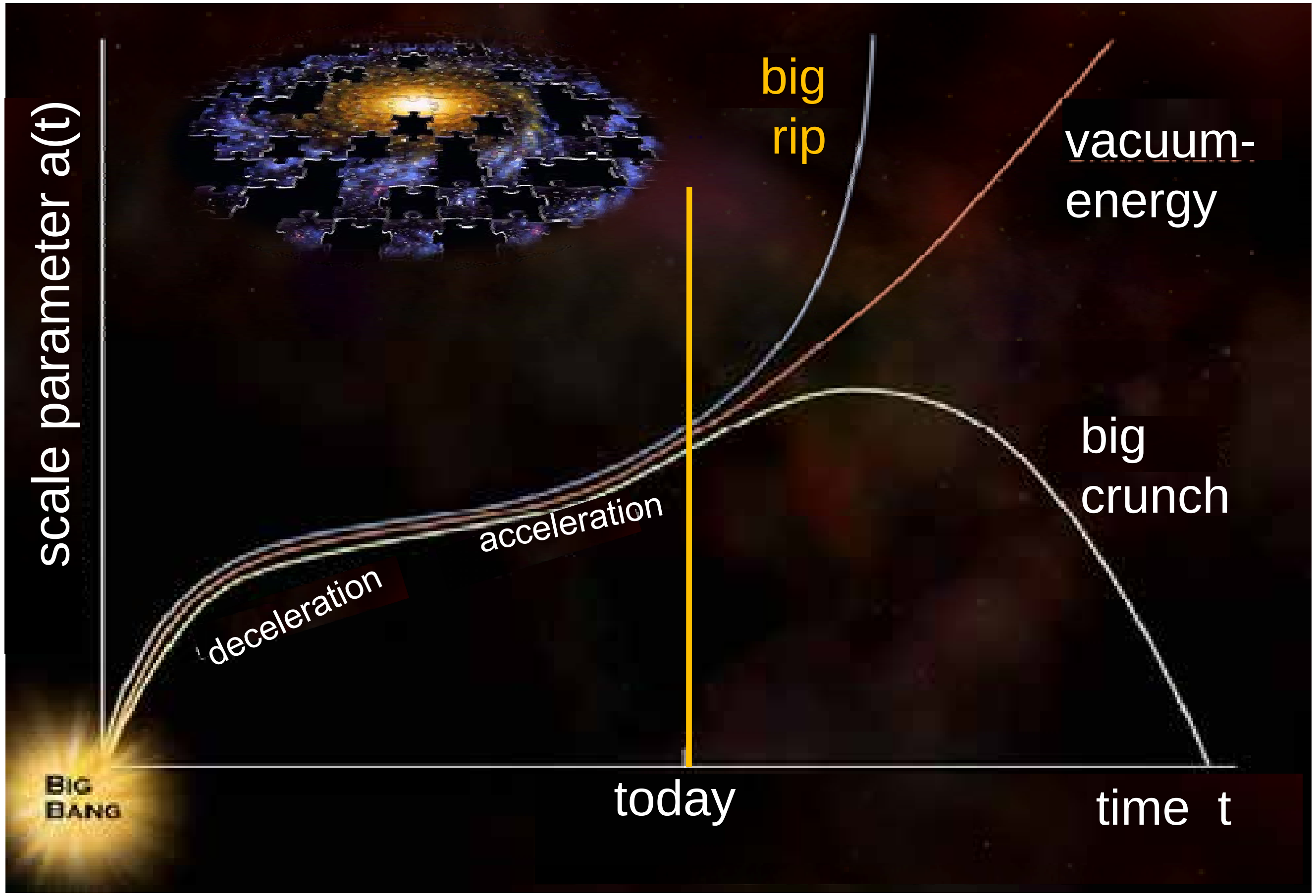
structure of the Universe
(Millenium Simulation)

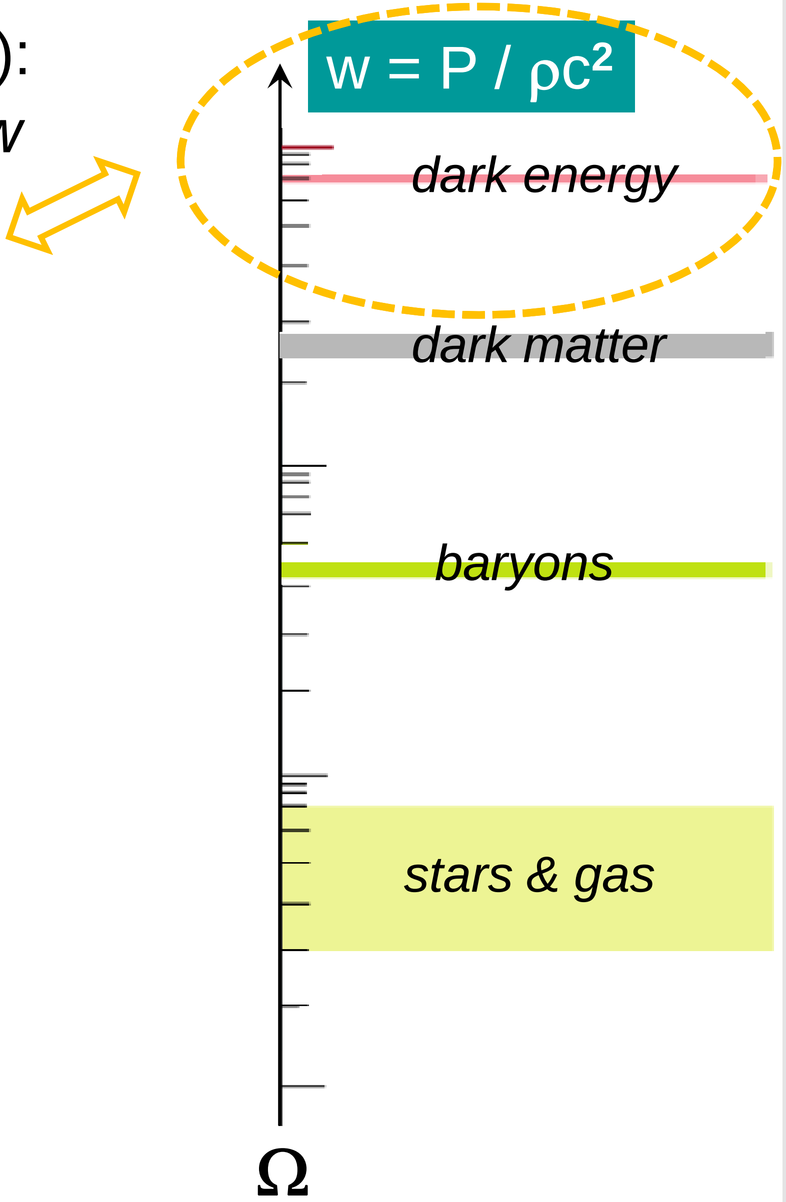


motivation: ν´s in astroparticle physics

global analysis of cosmological data (CMBR & LSS):
correlation of ν–mass m(ν) & DE equation of state *w*

m_ν could fix dark energy equation of state w



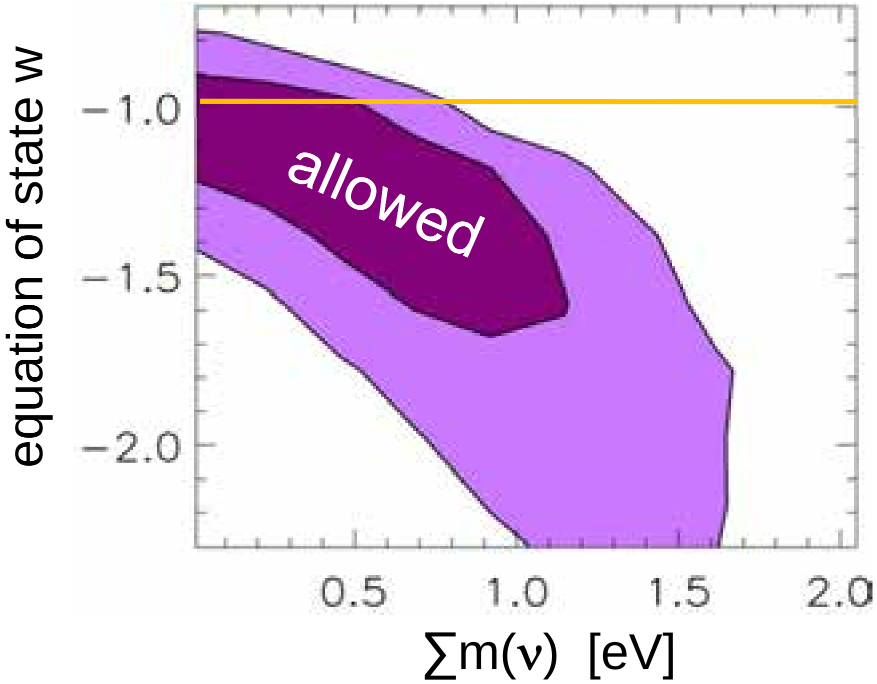


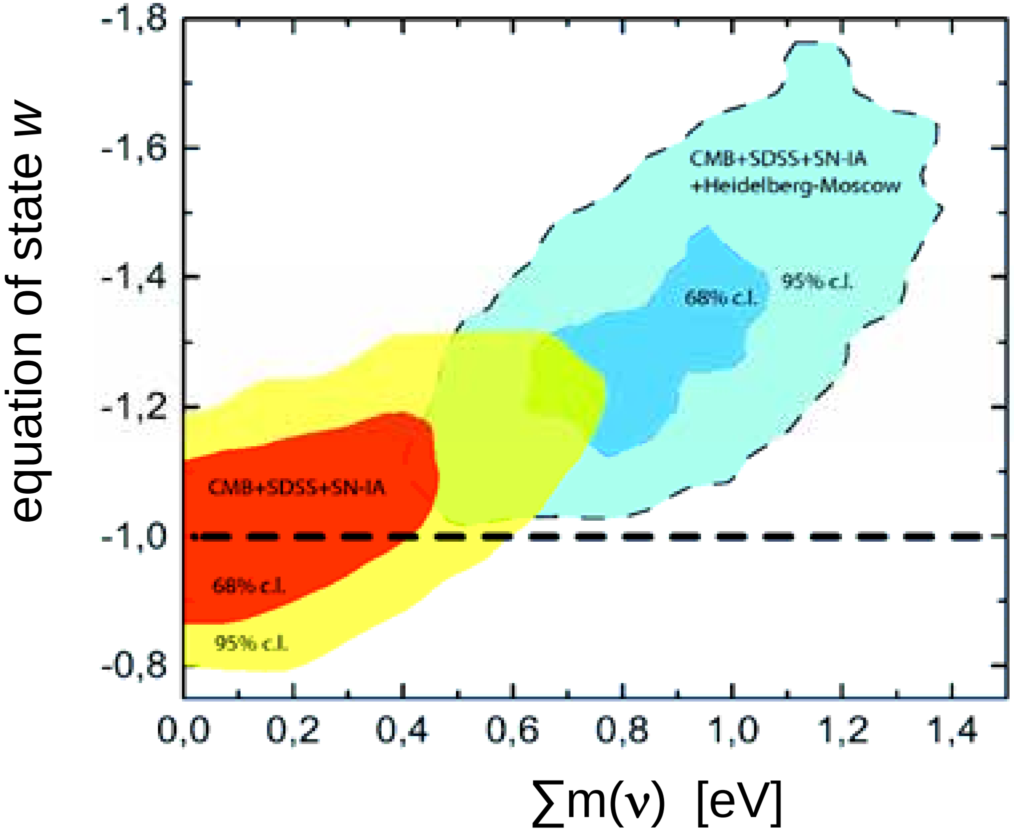
neutrino mass & dark energy

global analysis of cosmological data (CMBR & LSS):
correlation of ν–mass m(ν) & DE equation of state *w*
laboratory measurement of m(ν) > 0.2 eV
could imply *w* < - 1 (quintessence)

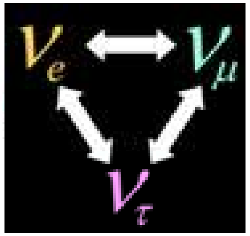
$w = P / \rho c^2$

S. Hannestad, arXiv: 0710.1952v1 [hep-ph]

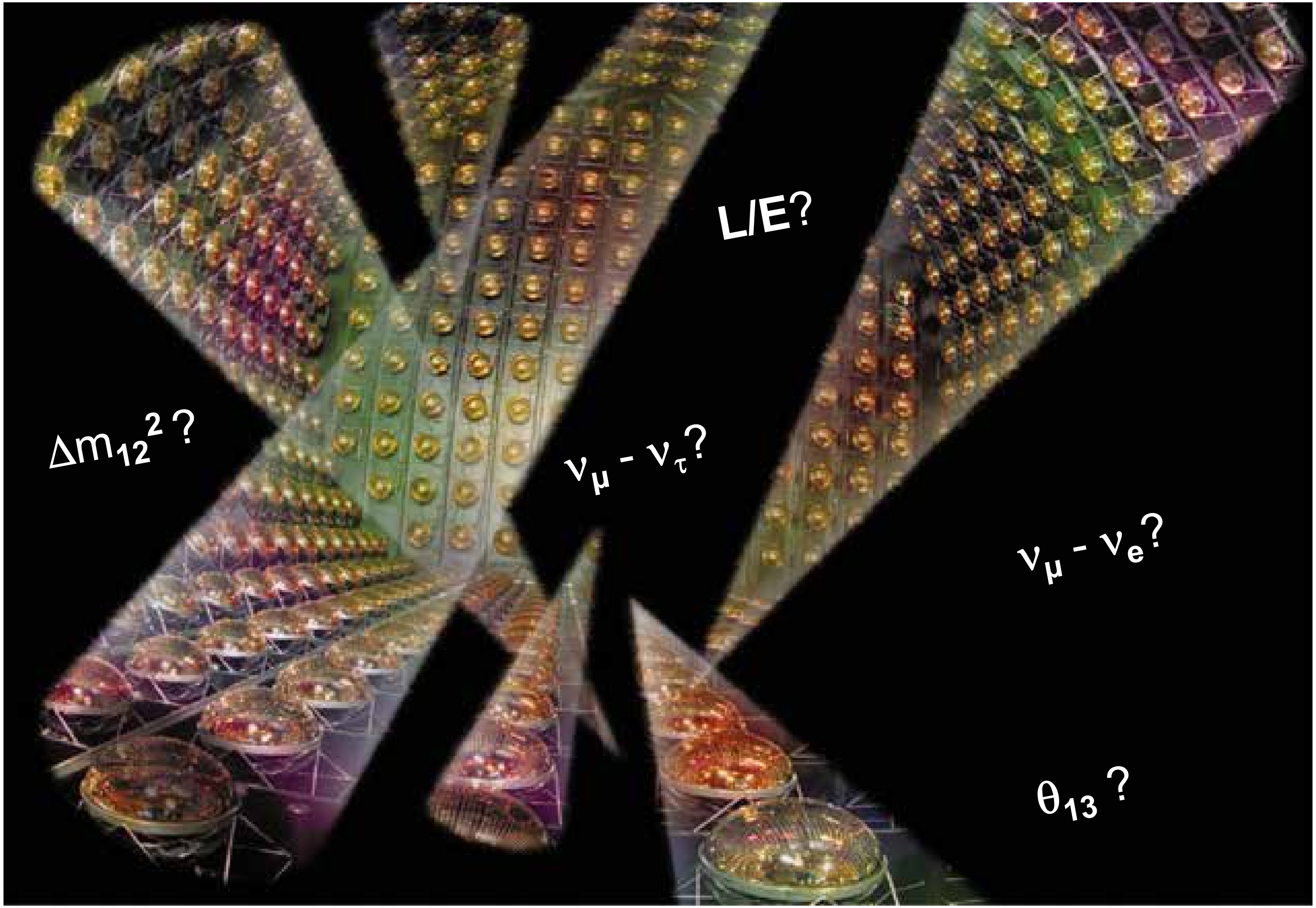




neutrino oscillations – ν´s are massive!



first evidence for new physics beyond the standard model



New York Times
6.6.1998 –
frontpage

Mass Found in Elusive Particle;
Universe May Never Be the Same

Discovery on Neutrino
Rattles Basic Theory
About All Matter

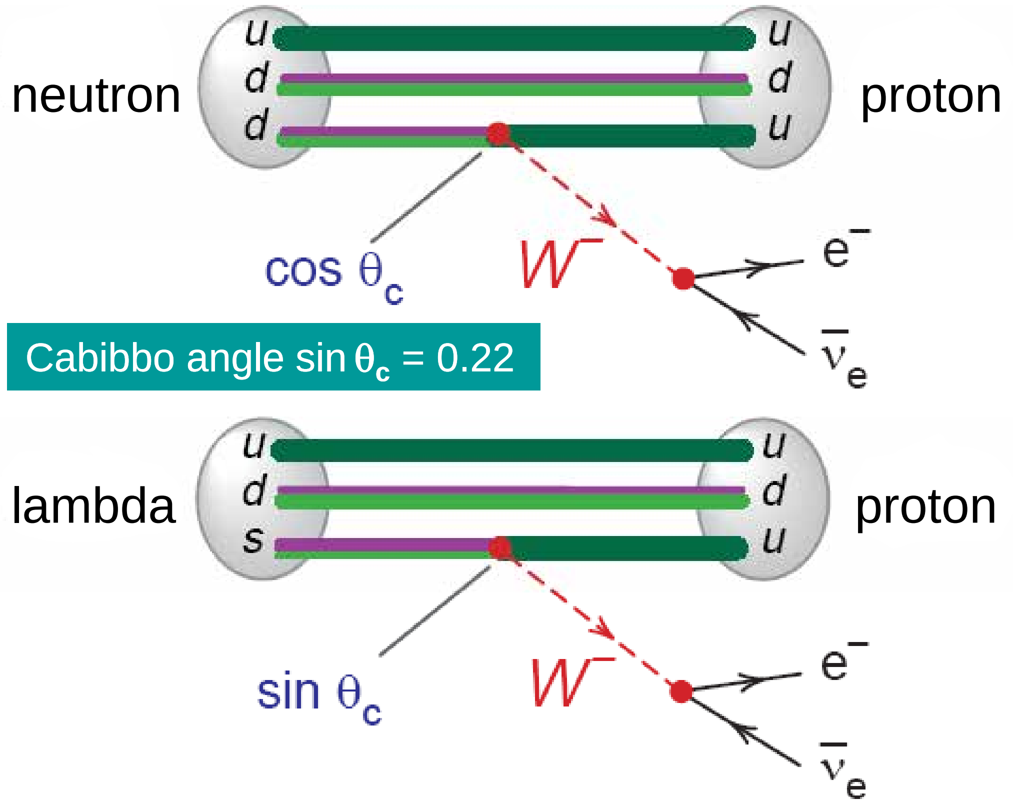
weak interaction – quark mixing

quarks: mass eigenstates ≠ weak flavour eigenstates (caused by interaction with Higgs-field) ↳ **CKM matrix:** 3 mixing angles & 1 CP phase

definition: mixing only in d,s,b – Sektor

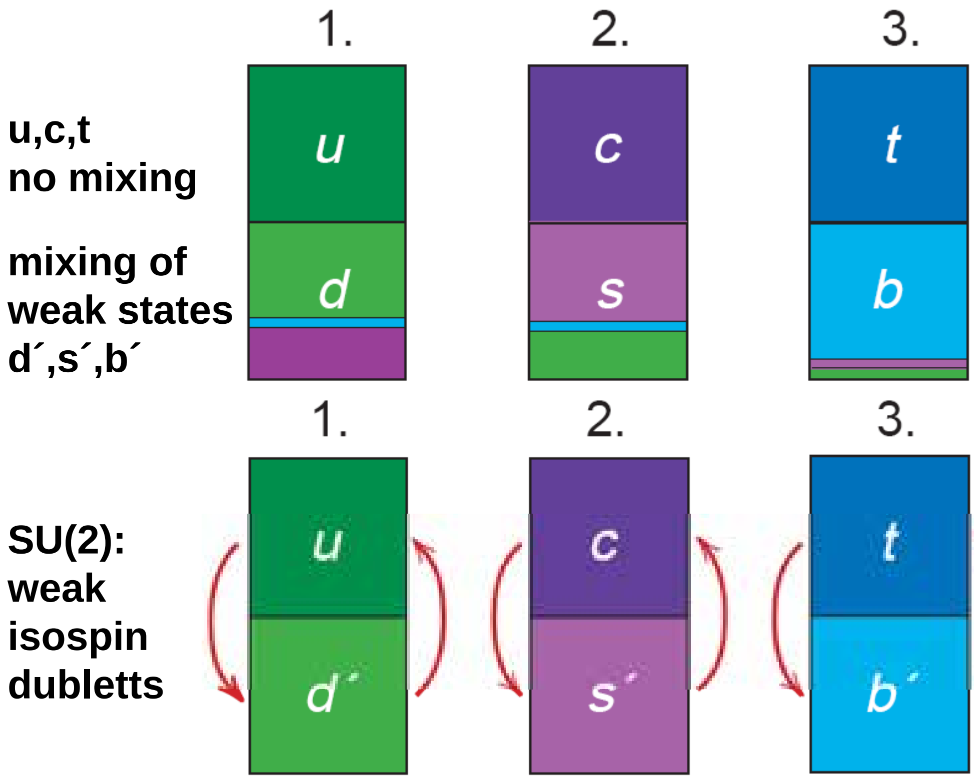
only **left-handed quarks, leptons**

and right-handed anti-particles



Cabibbo angle $\sin\theta_c = 0.22$

mass eigenstates



u,c,t
no mixing

mixing of
weak states
d´,s´,b´

SU(2):
weak
isospin
dubletts

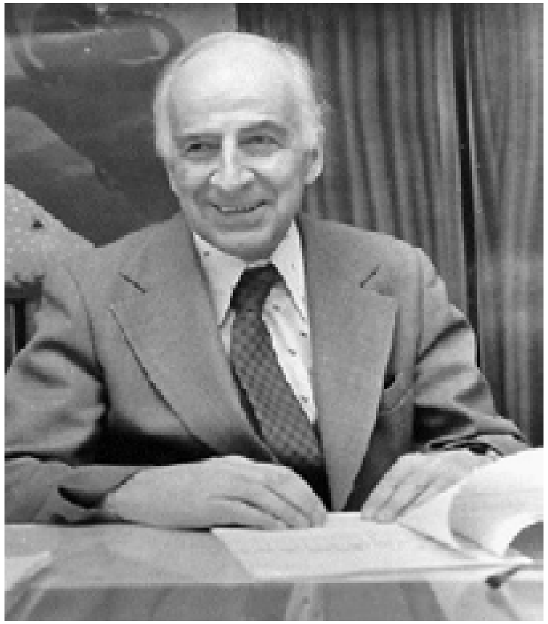
flavour eigenstates

neutrino oscillations – introduction

neutrino oscillations are a **quantummechanical interference phenomenon**

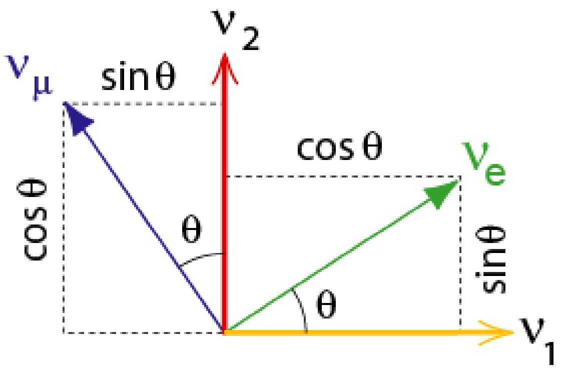
2-flavour mixing:

close analogy to the CKM mixing of the left-handed quarks

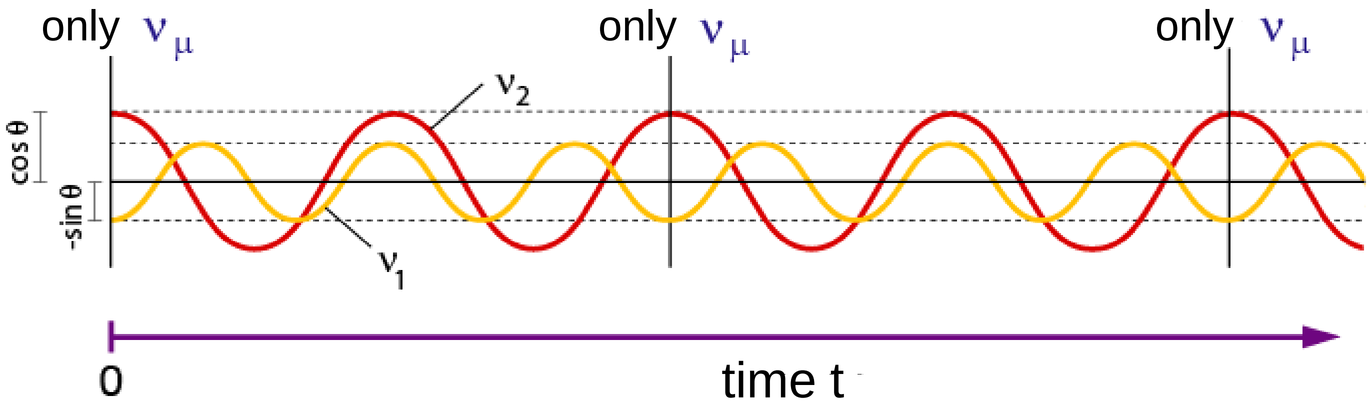


Bruno Pontecorvo:
concept of ν–$\bar{\nu}$ oscillations

mass eigenstates ≠ weak interaction states



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



neutrino oscillations – simplified formalism

t = 0 - weak interaction initially generates a **pure** flavour eigenstate ν_μ :

$$\left|\nu_\mu(0)\right\rangle = \left|\nu_\mu\right\rangle = -\sin\theta\left|\nu_1\right\rangle + \cos\theta\left|\nu_2\right\rangle$$

mass eigenstates are out of phase by exactly 180°

t > 0 : mass eigenstates ν_1, ν_2 are propagating through space:

$$\left|\nu_\mu(t)\right\rangle = -\sin\theta\cdot e^{(-iE_1 t)}\left|\nu_1\right\rangle + \cos\theta\cdot e^{(-iE_2 t)}\left|\nu_2\right\rangle$$

quantum mechanics: time evolution fixed by energy E_i, two states evolve differently

energy E_i – momentum p relation of the relativistic mass eigenstates ν_1, ν_2

$$E_i = \sqrt{p^2 + m_i^2} \cong p + \frac{m_i^2}{2p}$$

with units h,c =1
assumption: identical momenta p for ν_1, ν_2

time evolution of the propagating massive neutrino:

$$\left|\nu_\mu(t)\right\rangle = e^{-it\left(p+m_1^2/2E_\nu\right)}\times\left(-\sin\theta\left|\nu_1\right\rangle + \cos\theta\left|\nu_2\right\rangle\cdot e^{i\Delta m^2 t/2E_\nu}\right)$$

with
$\Delta m^2 = |\, m_1^2 - m_2^2 \,|$

the sensitivity for Δm^2 results from the interference of ν_1, ν_2 in the coherent propagating wave packet

difference of the squares of the masses

neutrino oscillations – formalism

probability P for flavour oscillation of a ν_μ into ν_e after time t:

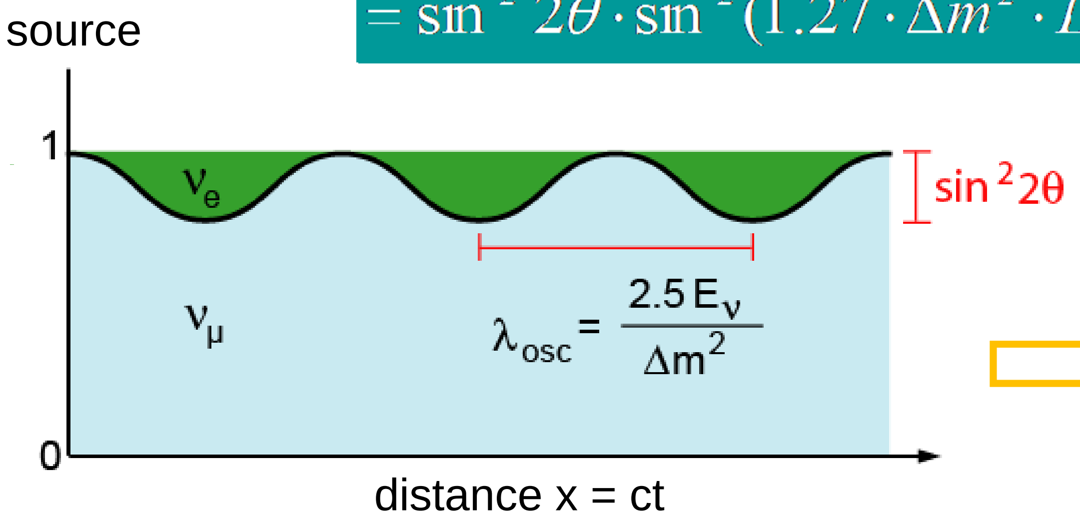
$$P(\nu_\mu \rightarrow \nu_e) = |\cos\theta \cdot \sin\theta \cdot (1 - e^{i\Delta m^2 t/2E_\nu})|^2$$

with $P = |\langle\nu_e|\nu_\mu(t)\rangle|^2$

$$= \sin^2 2\theta \cdot \sin^2(\Delta m^2 L_\nu / 4E_\nu)$$

$$= \sin^2 2\theta \cdot \sin^2(1.27 \cdot \Delta m^2 \cdot L_\nu / E_\nu)$$

L_ν in units of m [km]
E_ν in units of MeV [GeV]



⇒

periodic appearance of a **new** neutrino flavour state

periodic decrease / increase of original neutrino flavour fraction

🟩 probability that ν_μ transforms to ν_e

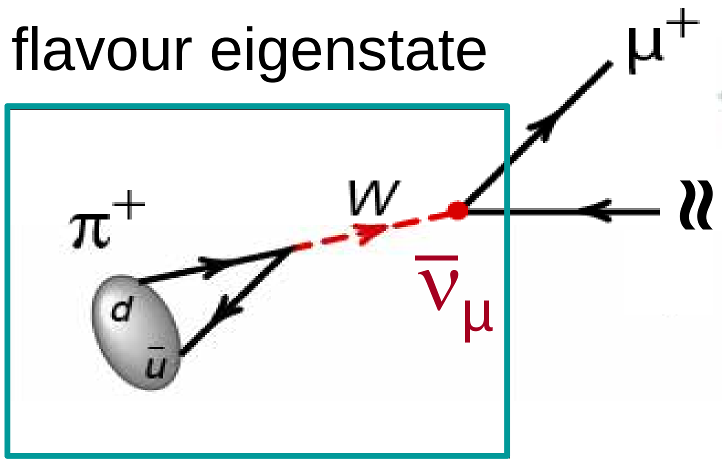
🟦 probability that ν_μ remains ν_μ

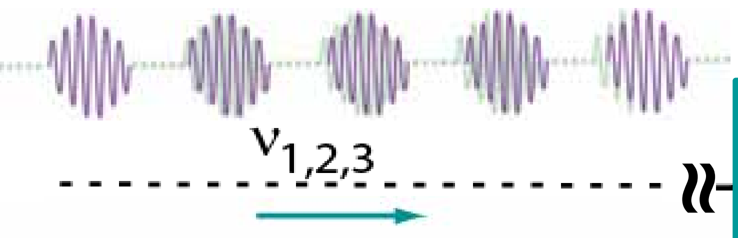
neutrino oscillations – basic concept

neutrino oscillations are a pure QM **propagation effect**

ν–source | **ν–oscillations** | **ν–detection**

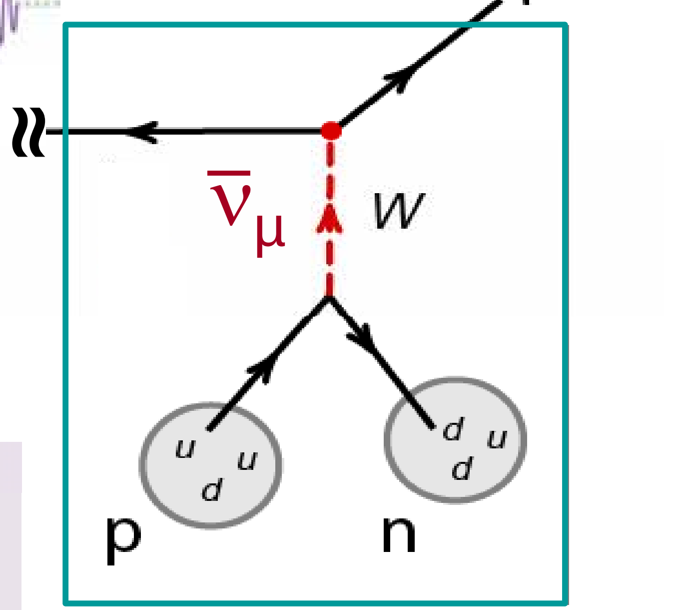
flavour eigenstate





propagation of the ν–mass eigenstates

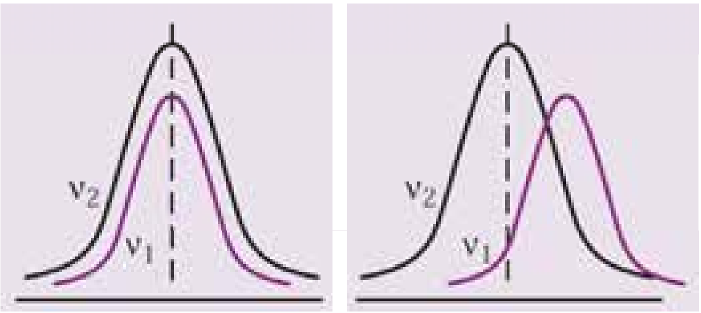
flavour state



source paramenters
to be determined:

ν–energies
ν–fluxes
ν–flavours

L = 10 m … 10.000 km



emission | detection

ν–detection efficiency
ν–energy resolution

neutrino oscillations – systematics

ν-oscillation experiments can be grouped into:

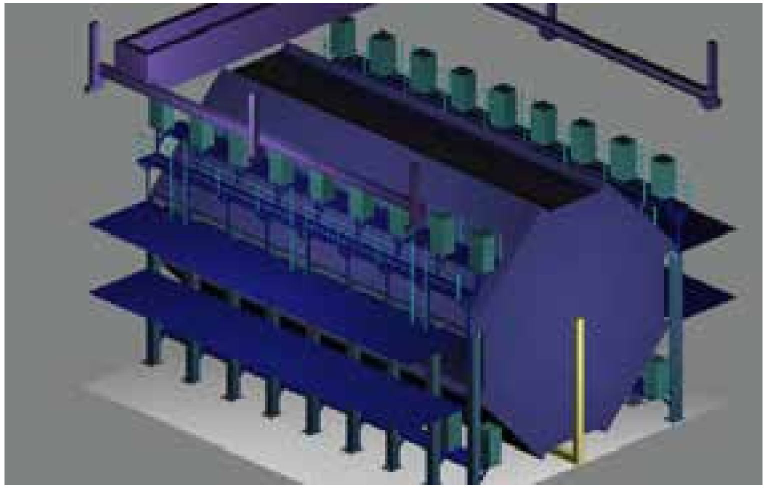
disappearance channel $\nu_\mu \rightarrow \nu_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

statistics: large event ensemble (N > 10^4)

systematics: ν–flux & ν–energies?

preferred for **large** mixing amplitudes



example: NuMI beam - MINOS

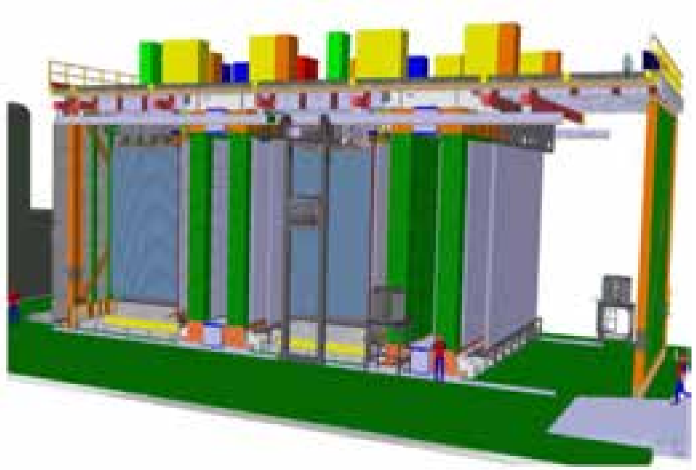
appearance Kanal $\nu_\mu \rightarrow \nu_\tau$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

statistics: small event ensembles (N < 10-50)

systematics: ν–flavour composition?

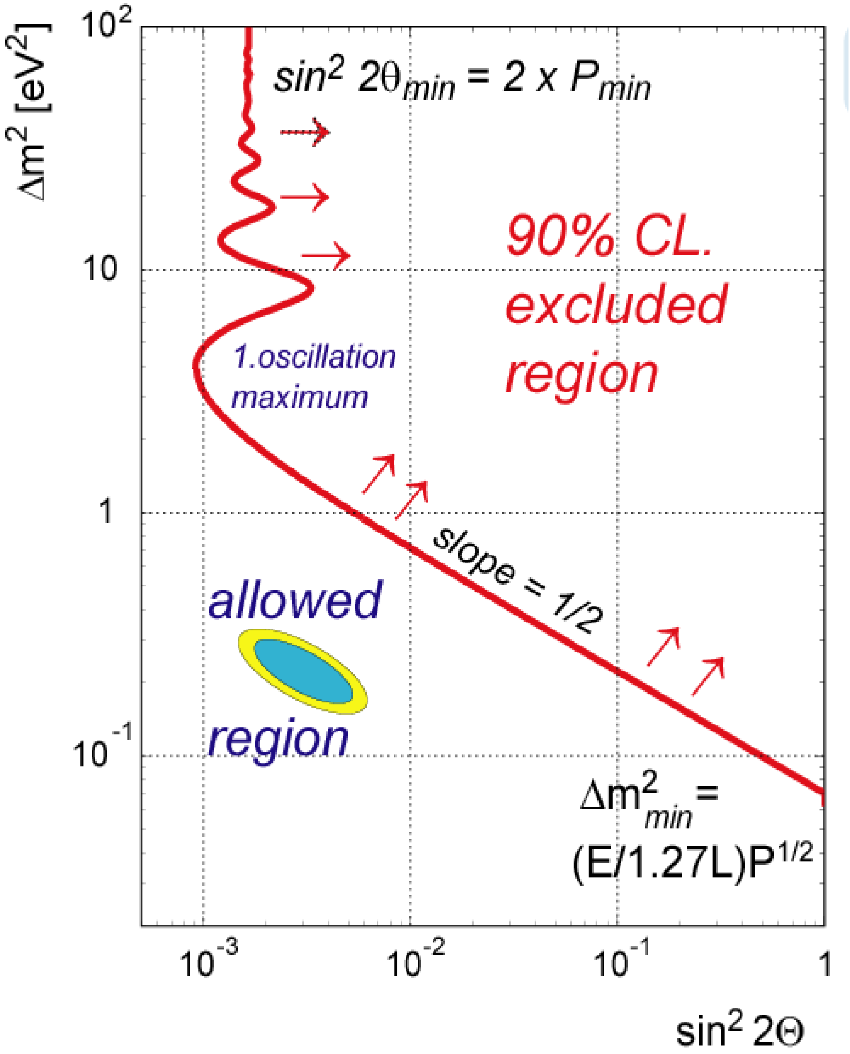
preferred for **small** mixing amplitudes



example: CNGS beam - OPERA

neutrino oscillation diagrams

results (statistical analyses) of different oscillation experiments are displayed and compared to each other in ´**neutrino oscillation plots**´



exclusion curve

no statistically significant oscillation signal

⇘ upper limit for probability P

exclusion of parameter space ($\sin^2 2\theta$, Δm^2)

specific confidence level: 90% (95%) CL.

inclusion curve

statistically significant oscillation signal

⇘ central value for probability P

inclusion of parameter space ($\sin^2 2\theta$, Δm^2)

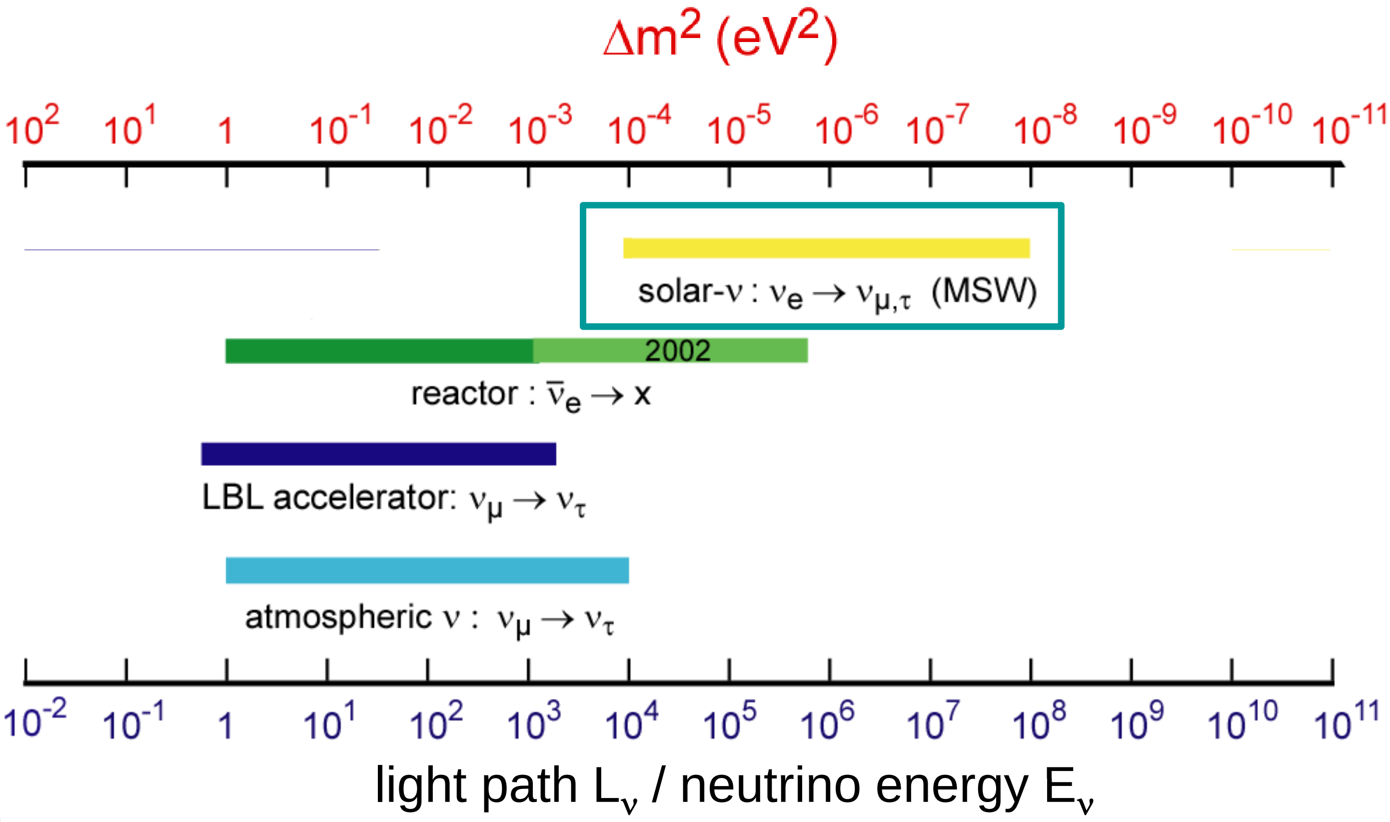
specific confidence level 95% (99%) CL.

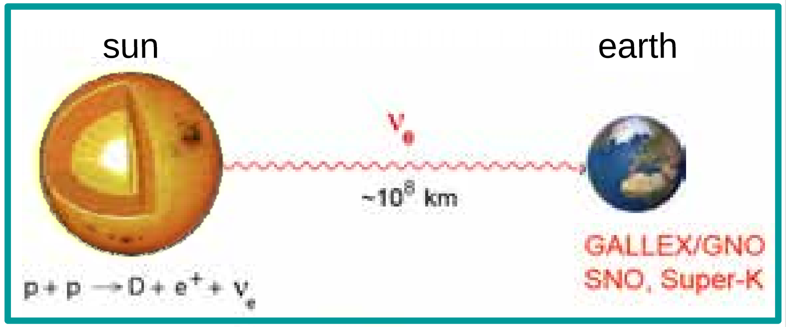
neutrino oscillations: L/E and Δm^2

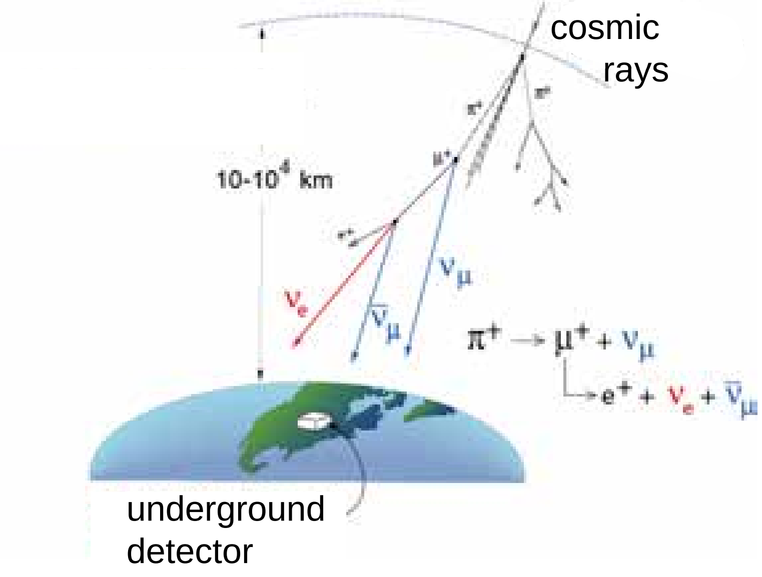
coverage of the entire Δm^2-parameter region requires different experiments

goals: - determination of parameters Δm_{ij}^2, $\sin^2 2\theta_{ij}$
- observation of L_ν/E_ν oscillation pattern
- identification of flavour channels
- matter effects, leptonic CP-violation?

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(1.27\cdot\Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

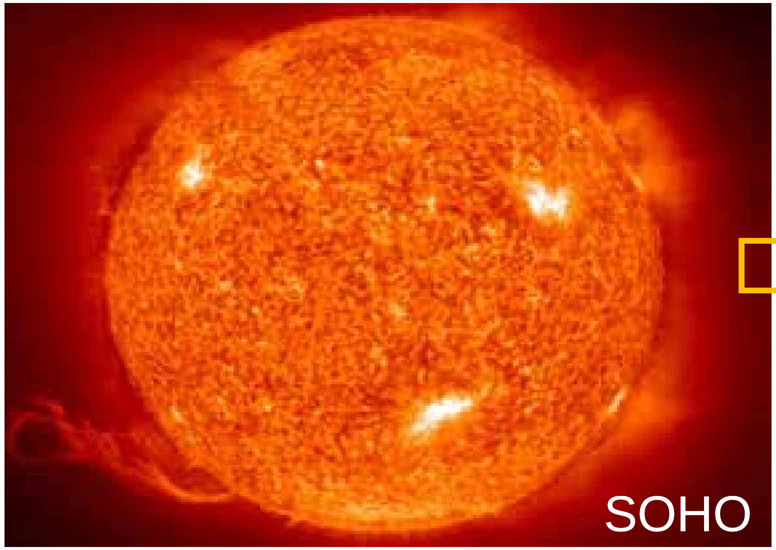




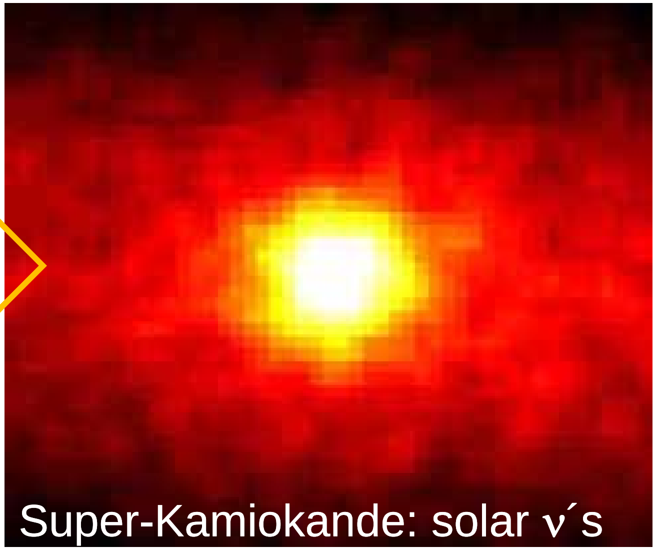


solar neutrinos

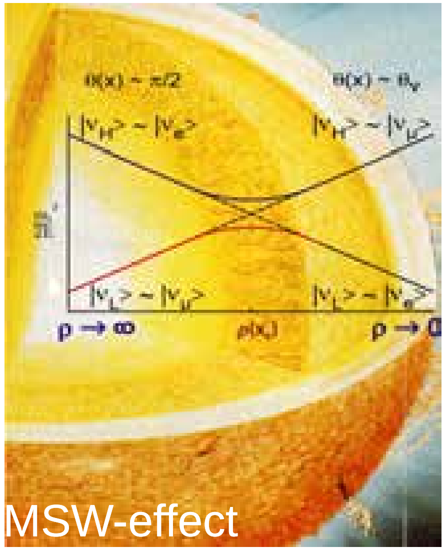
standard solar model SSM – **radiochemical & real time experiments**



SOHO



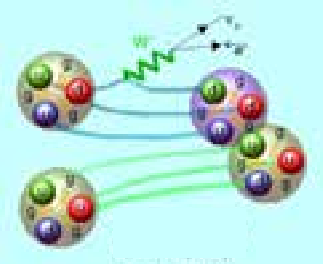
Super-Kamiokande: solar ν´s



MSW-effect

experiment	underground lab	detector	data
Chlorine-37 (Davis)	Homestake, USA	615 t C_2Cl_4	1967 – 1998
Gallex/GNO	LNGS, Italy	30 t Ga	1991 – 2003
SAGE	Baksan, Russia	55 t Ga	1990 – …
Super-Kamiokande	Kamioka, Japan	50.000 t H_20	1996 - …
SNO	Sudbury, Canada	1.000 t D_20	1999 - 2006
Borexino	LNGS, Italy	100 t CH_2	2007 - …

solar pp fusion chain



fusion reactions in the solar core ($T_0 = 14.5 \times 10^6$ K)

$p + p \rightarrow D + e^+ + \nu_e$ 99.6%

$p + e^- + p \rightarrow D + \nu_e$ 0.4 %

$\downarrow$

$p + D \rightarrow {}^3He + \gamma$

pp : $E_\nu < 0.420$ MeV

pep : $E_\nu = 1.442$ MeV

solar neutrinos – energy spectra

detailed model calculations for solar ν–spectrum by J. Bahcall et al.

basic assumptions

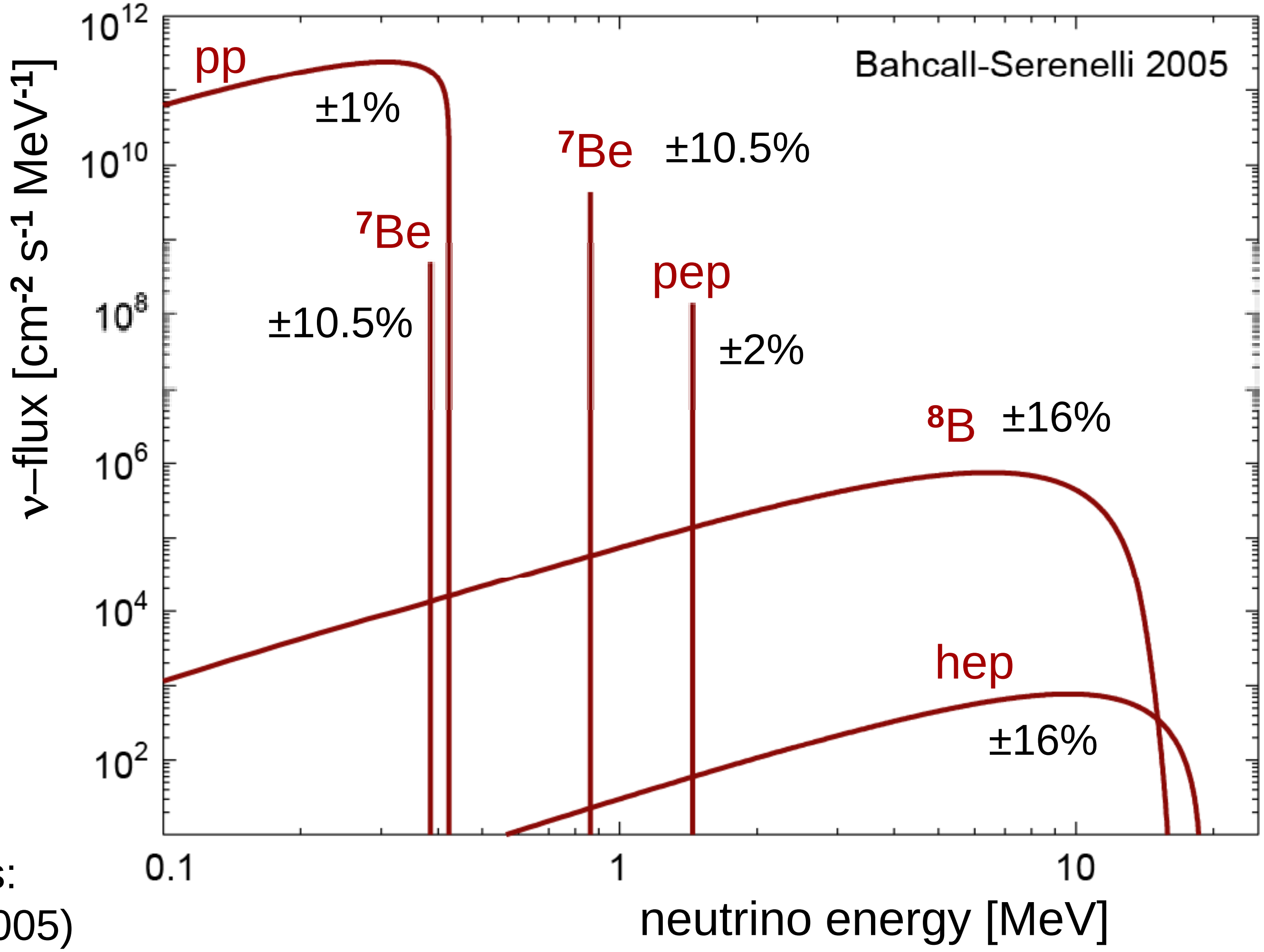
- hydrodynamic equilibrium
- energy transport:
  radiation & convection
- energy generation by fusion

input parameters:

$L_\odot$, $T_\odot$, $R_\odot$, $\rho_{central}$, $T_{central}$,
opacity κ, metallicity Z, ...

comparison to helioseismology

integral solar ν-flux: $\Phi_\nu = 6.6 \times 10^{10}$ / cm² s

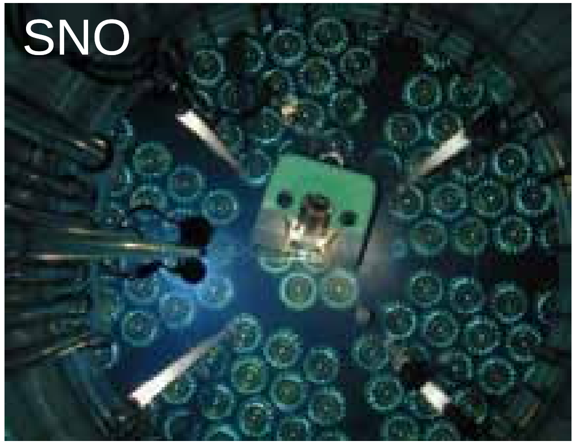


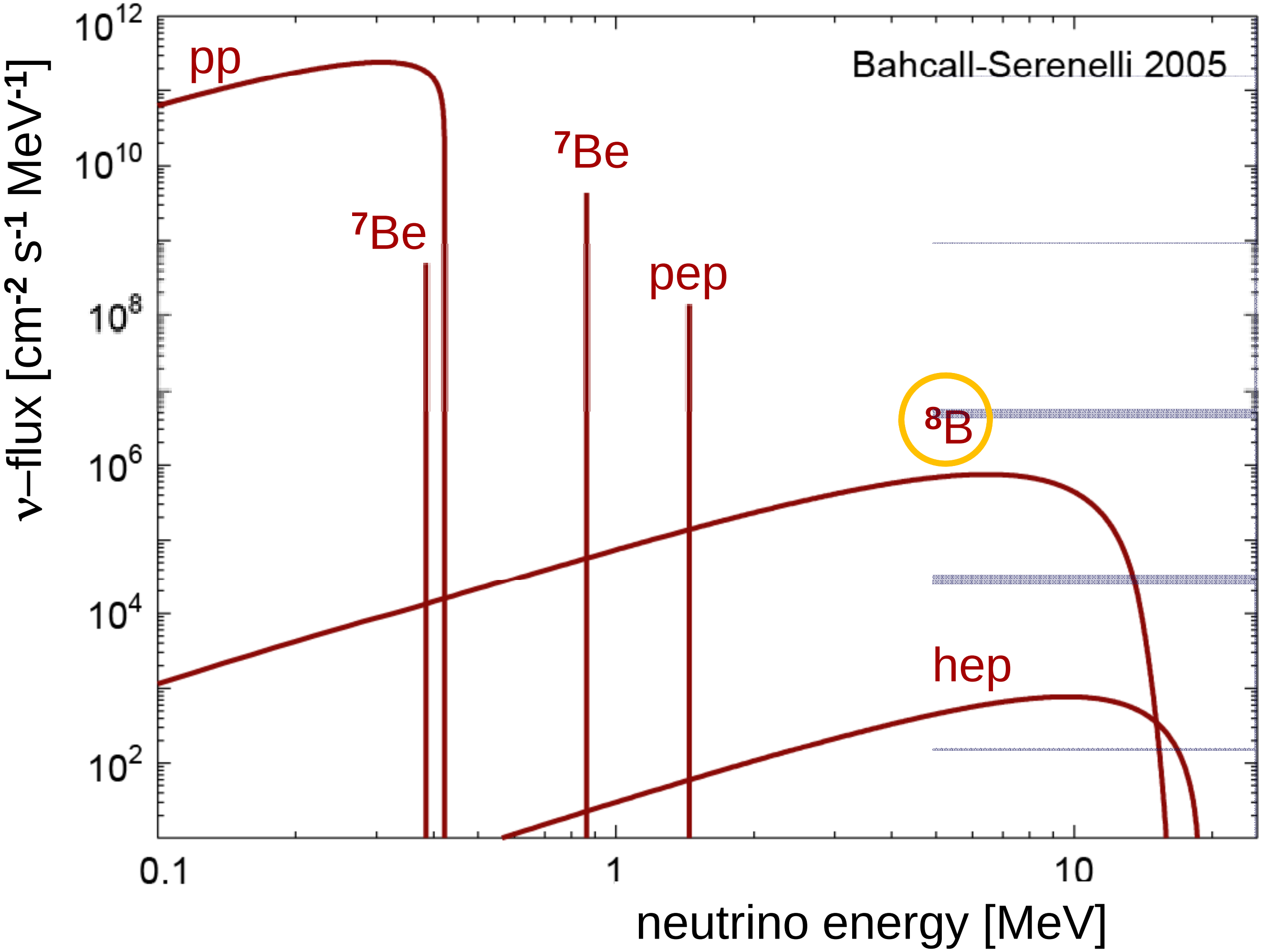
pioneer of the current
standard solar models:
John Bahcall (1934-2005)

solar neutrinos – ^{8}B

water Cherenkov detectors: ´real-time´ detection of ^{8}B-ν´s

measurements of : spectral shape, CC rate, NC rate, day-night effects, earth orbit effects, conversion into $\bar{\nu}_e$? (Super-Kamiokande, SNO) ⟶

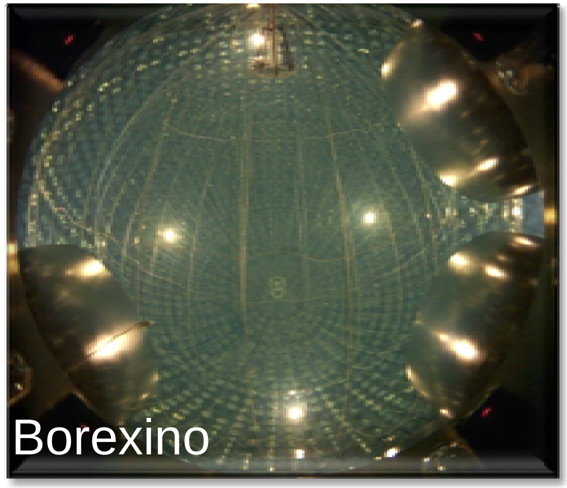


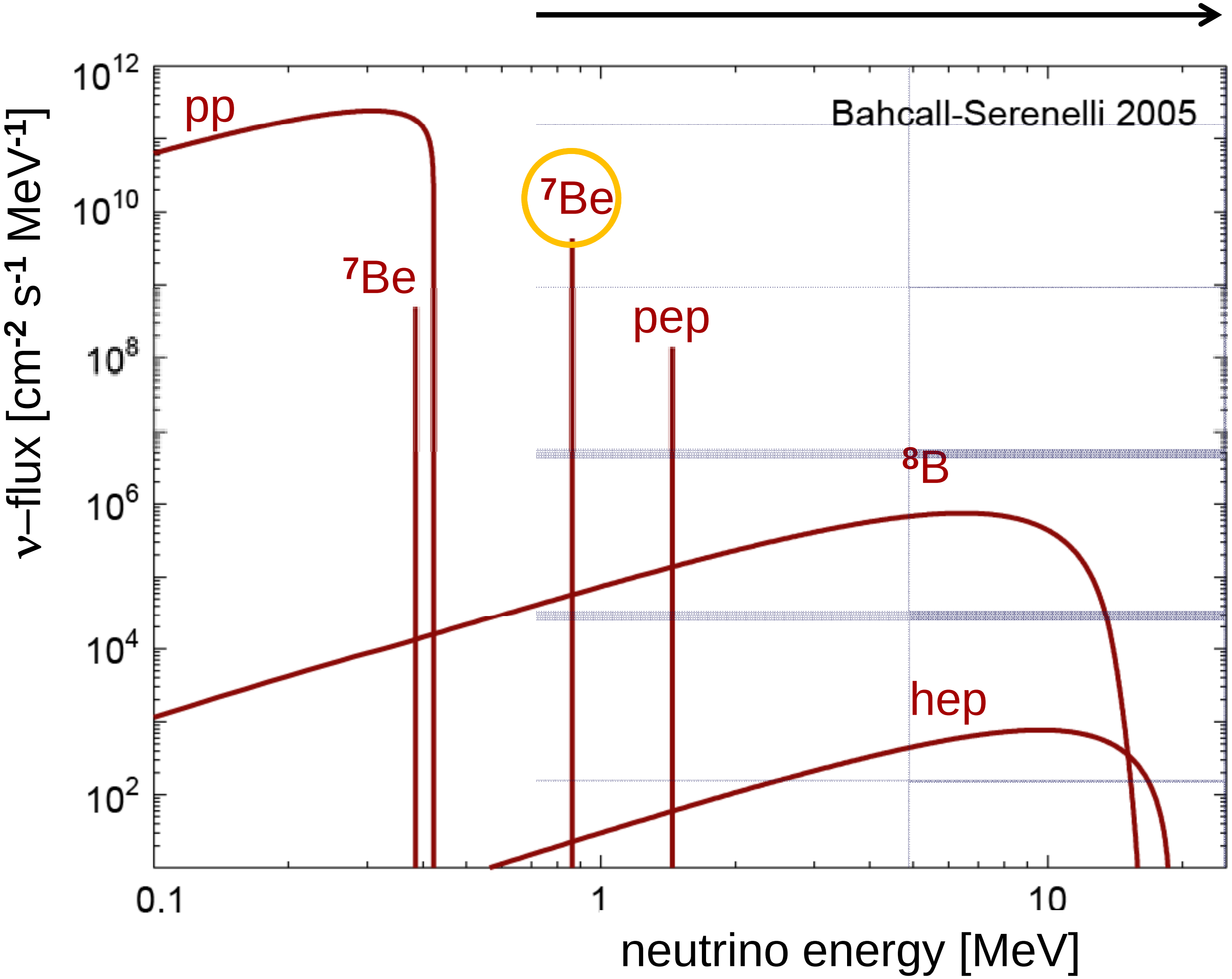


solar neutrinos – ^{7}Be

radiochemical detectors: Cl-37 experiment ↳ solar ν–problem

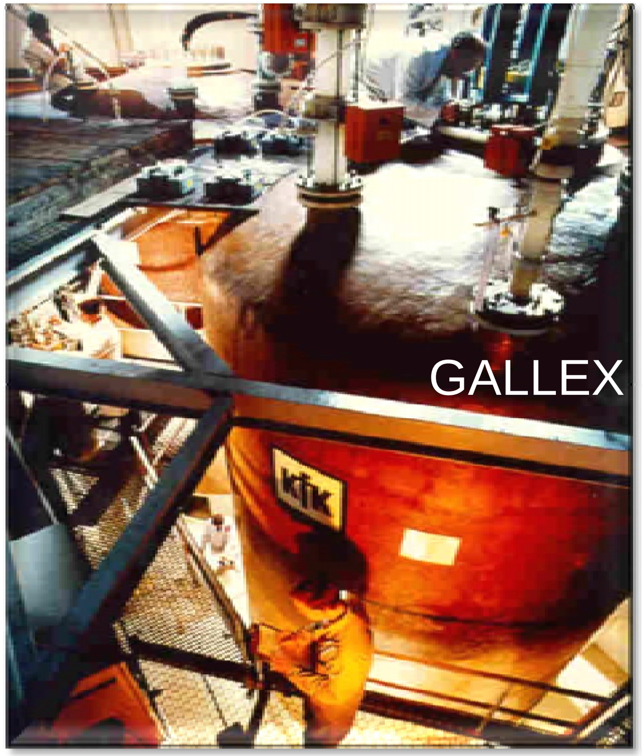
ultra-clean scintillators: Borexino νe-scattering

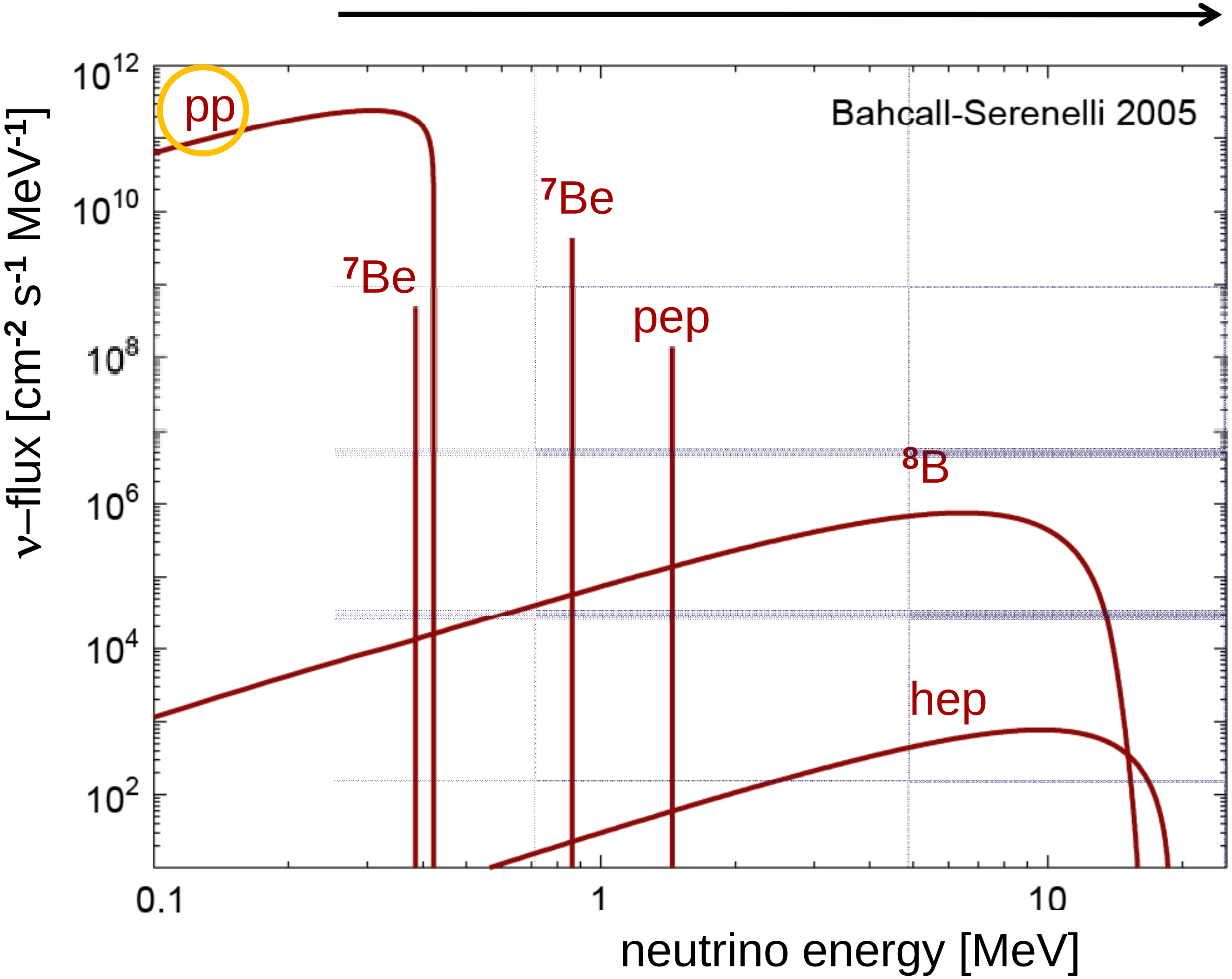




solar neutrinos – pp

radiochemical detectors: Gallex & SAGE measure low-energy pp-ν´s
successful calibration with ^{51}Cr-ν-source





radiochemical experiments

experimental method: solar neutrino exposition (run) of a specific target nucleus ^{Z}A (detector mass ~ 10-100 tonnes) in a well-shielded underground laboratory (LNGS, Homestake, Baksan,…)

neutrino reactions in the target: $\nu_e + {}^{Z}A \rightarrow {}^{Z+1}A + e^-$ inverse ß-decay

daughter nuclei ^{Z+1}A: extraction by highly efficient radiochemical methods from the target volume, identification of the delayed electron capture process by observation of Auger electrons (de-excitation process $^{Z}A^* \rightarrow {}^{Z}A + e^-$)

reverse reaction in counters: $^{Z+1}A + e^- \rightarrow \nu_e + {}^{Z}A^*$ electron capture (EC)

↳ keV Auger electrons

advantage: low threshold, detection of sub-MeV neutrinos (pp- and ^{7}Be-ν´s)

disadvantage: missing spectroscopic and real time information

Solar Neutrino Unit: 1 SNU = 1 ν–reaction/second per 10^{36} target atoms

typical targets ~10^{30} target atoms

Chlorine-37 – the solar ν-problem

pionieering experiment of R. Davis in Homestake mine: 108 runs (1970-1995)

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- \quad \xrightarrow[t_{1/2} = 35\ \mathrm{T}]{} \quad {}^{37}\mathrm{Ar} + e^- \rightarrow \nu_e + {}^{37}\mathrm{Cl}^*$$

Q-value = 814 keV

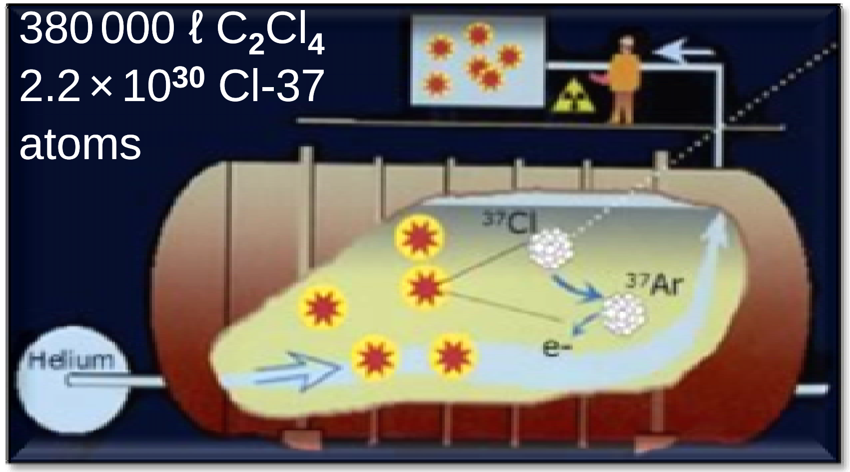
↳ 2.8 keV Auger electrons

experimental rate (Davis): $R_{exp} = 2.56 \pm 0.16\ (\mathrm{stat.}) \pm 0.16\ (\mathrm{syst.})\ \mathrm{SNU}$

$= 0.48\ {}^{37}\mathrm{Ar}\text{-atoms/day}$

theoretical expectation (Bahcall): $R_{theo} = 7.6 \pm 1.2\ (\mathrm{syst.})\ \mathrm{SNU}\ \ ({}^{7}\mathrm{Be} + {}^{8}\mathrm{B}\ \nu\text{´s})$

= SSM (standard solar model)



380 000 ℓ C_2Cl_4

2.2×10^{30} Cl-37 atoms

Ray Davis

Nobel 2002

solar neutrino problem

$$R_{exp} = \tfrac{1}{3} R_{theo}$$

↳ **SSM?**

↳ **neutrinos?**

GALLEX/GNO – hunting the pp-ν´s

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ ⇒ $t_{1/2}$ = 11.4 d ⇒ ${}^{71}Ge + e^- \rightarrow \nu_e + {}^{71}Ga^*$

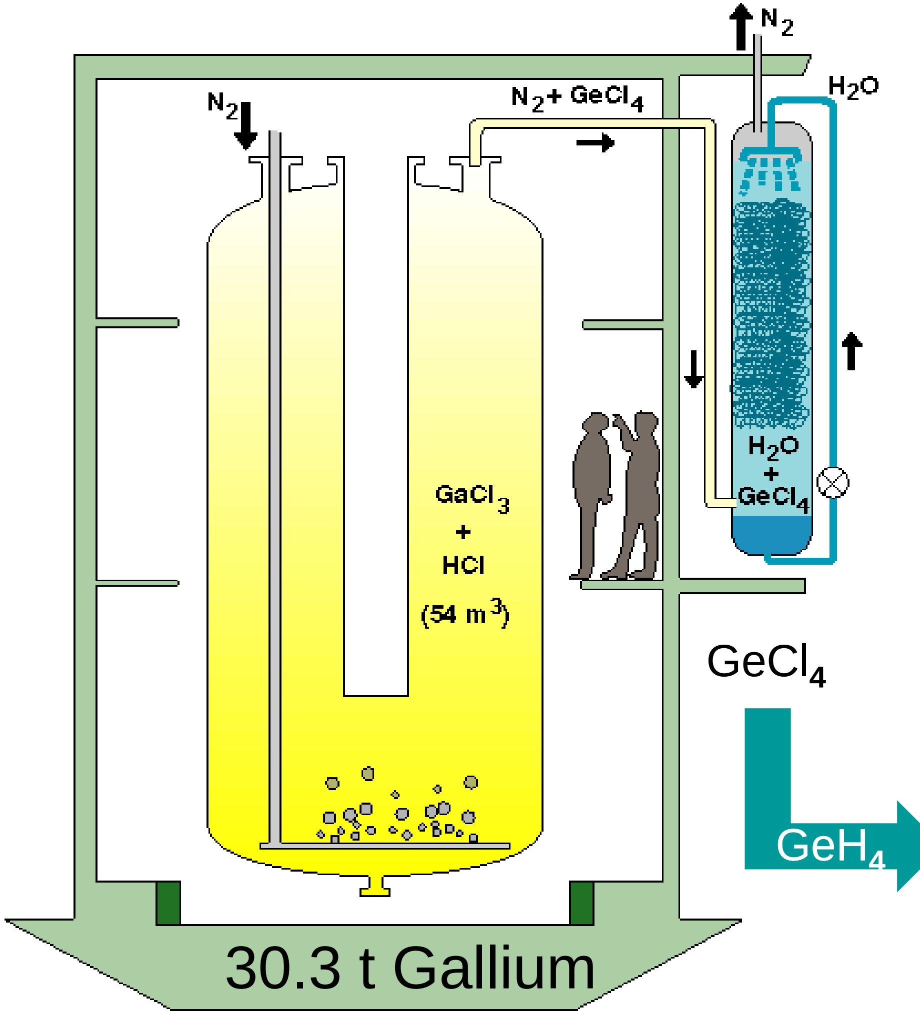
Gallium Experiment

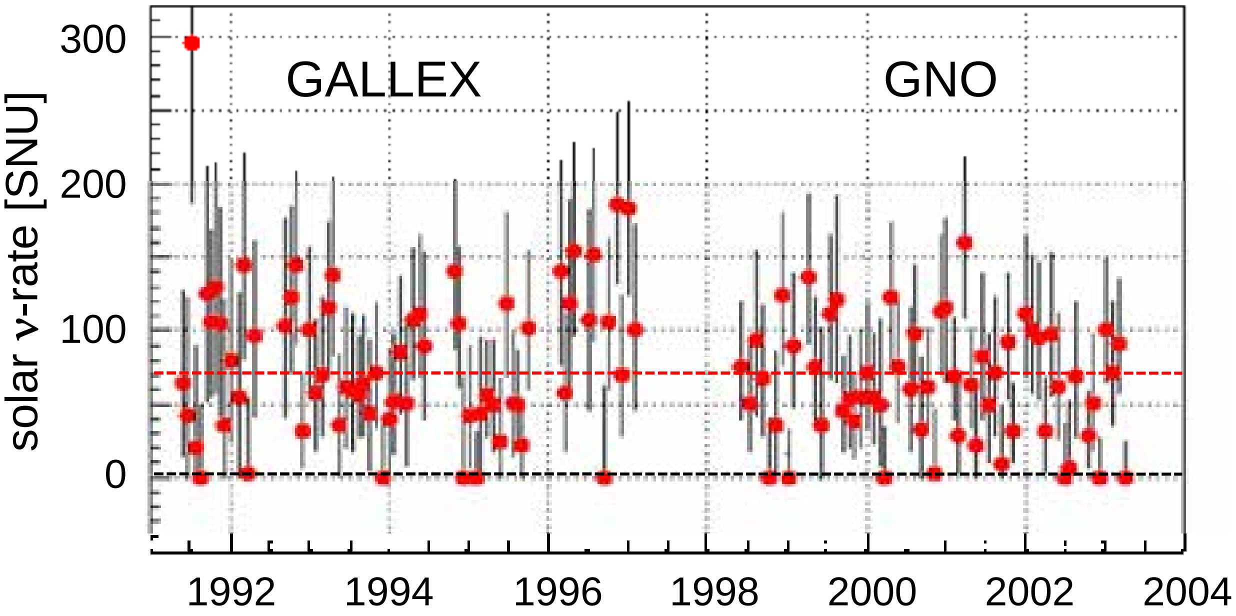
Gallium Neutrino Observatory

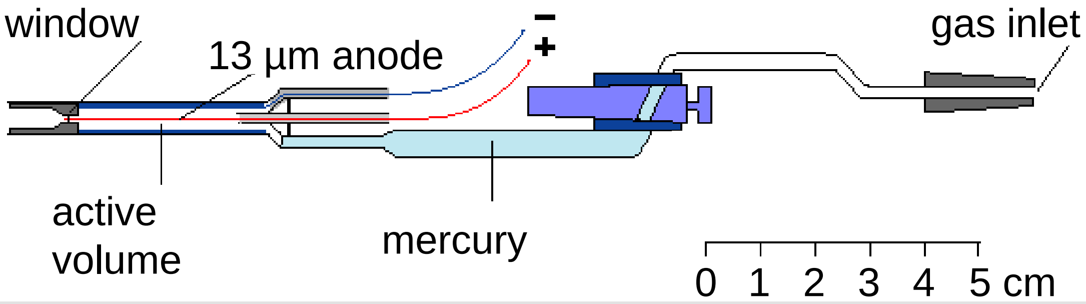
reaction-Q-value = 233 keV

R_{theo} = 130 SNU

R_{exp} = 69.3 ± 4.1 (stat.) ± 3.6 (syst.) SNU



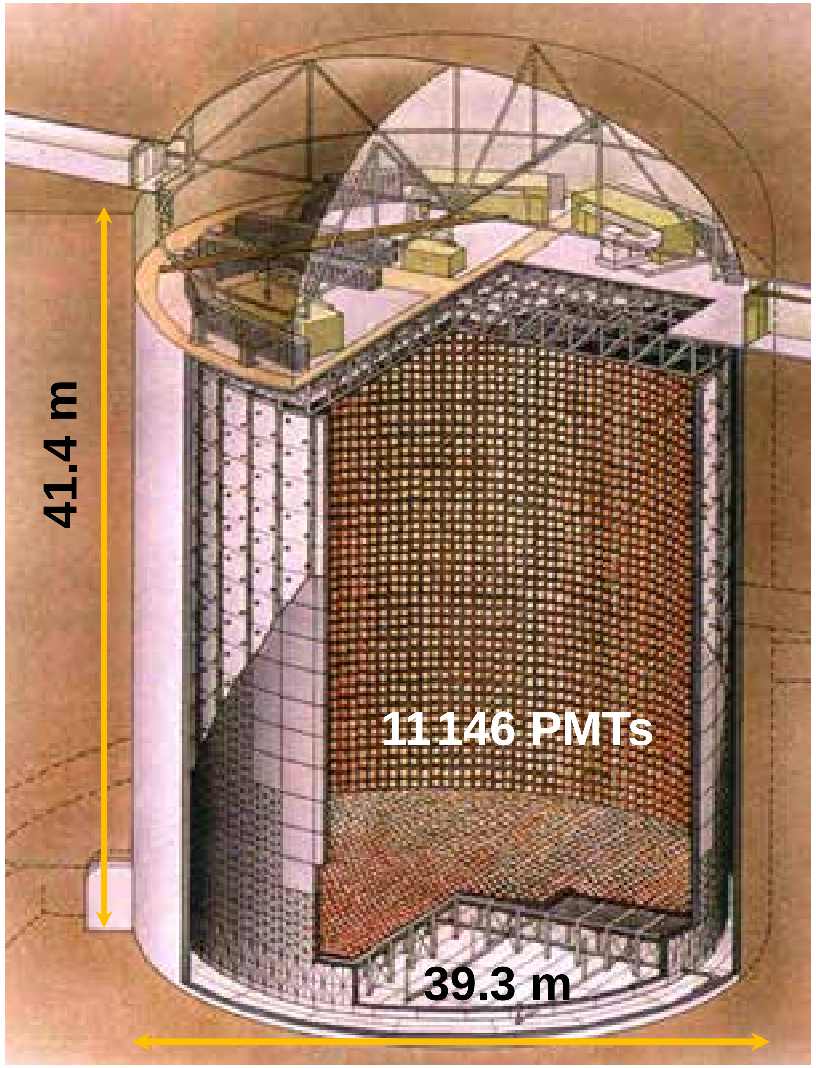




Super-Kamiokande experiment

detection of solar ν´s in a **50 kt water Cherenkov detector**

elastic ν-e scattering kinematics: Čerenkov cone defines direction & energy

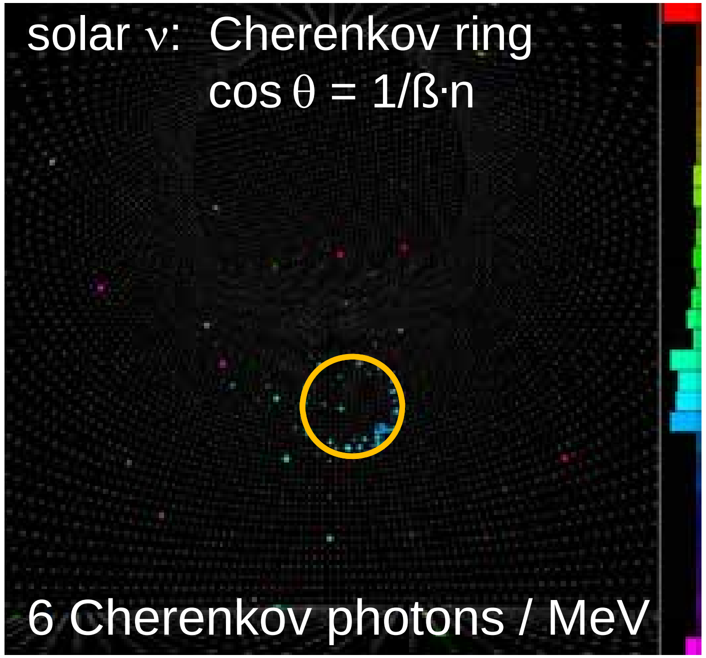


aim: detection of solar ν´s in real time with high statistics, rate ~ 10 - 20 solar ν´s / day

↳day/night- or seasonal effects?

↳ modification of the energy spectrum?

↳ transformation of ν_e into $\bar{\nu}_e$?

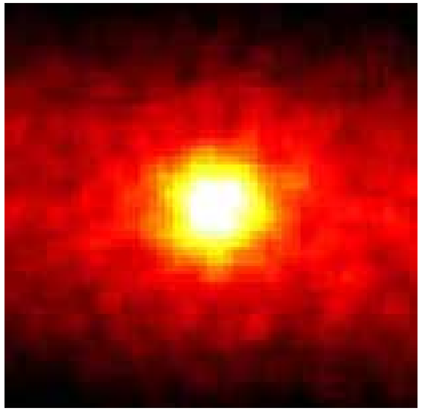


energy threshold:

E_{thres} = 5 MeV

↳ only sensitive for ^{8}B neutrinos

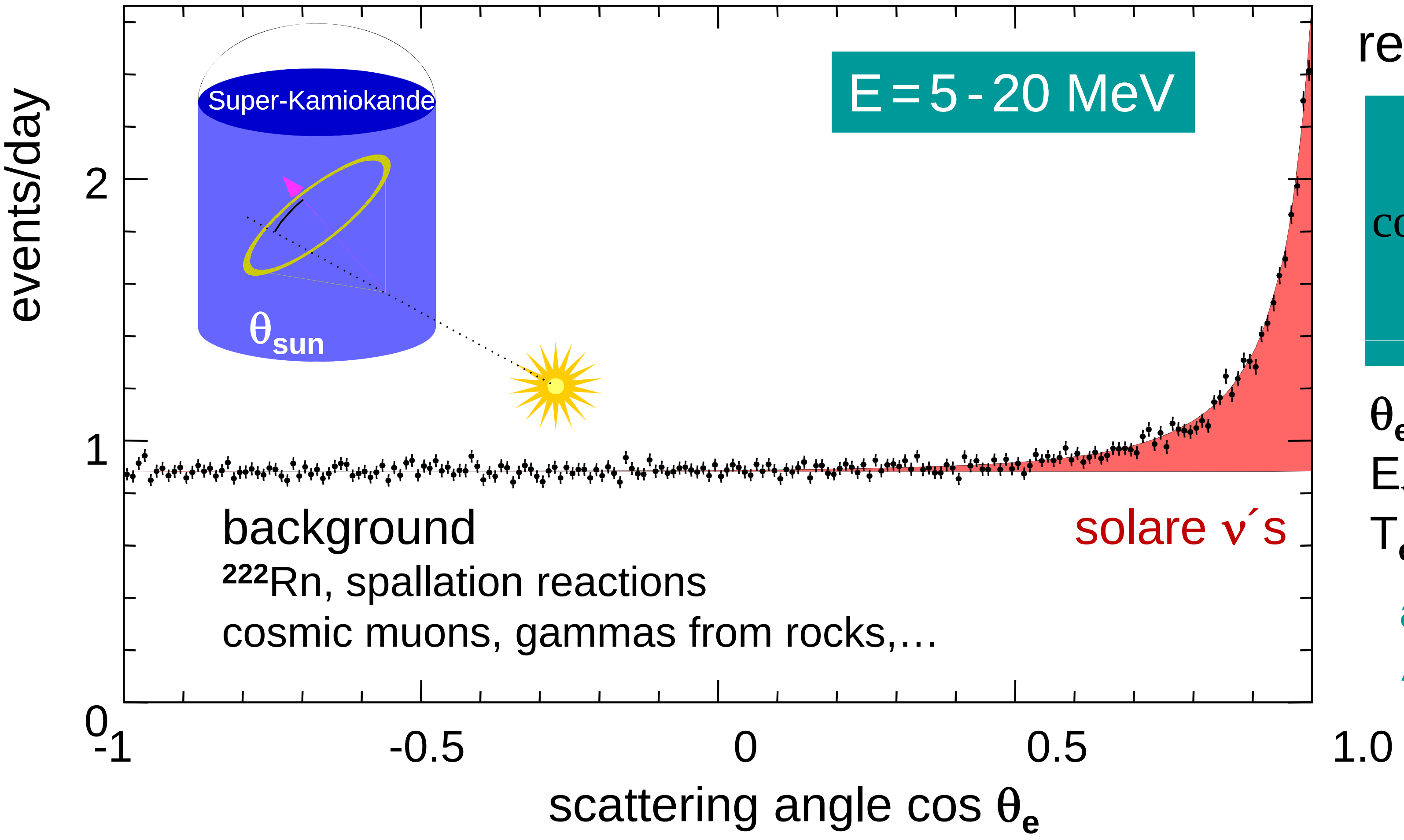
Super-Kamiokande-I: angular distribution



kinematics of **elastic neutrino-electron scattering**:

high-energy electron is emitted into a forward cone

angular correlation to separate background, „ν-imaging“ of sun



background

^{222}Rn, spallation reactions

cosmic muons, gammas from rocks,…

reaction kinematics:

$$\cos\theta_e = \frac{1 + \dfrac{m_e}{E_\nu}}{\sqrt{1 + \dfrac{2m_e}{T_e}}}$$

θ_e: angle to sun

E_ν: neutrino energy

T_e: kinetic energy e^-

angular resolution
Δθ = 25° at 10 MeV

Super-Kamiokande: ^{8}B-flux

Super-Kamiokande – I : number of observed ^{8}B-ν-events		
SK-I	[22 204 ± 226 (stat.) ± 750 (syst)] ν – e events	E_{thres} = 5 MeV
SSM theory	[48 200 + 9600 – 7700] ν – e events	Bahcall 2004

R = 0.465

1496 active days : mean solar ν–rate 14.5 events/day

Super-Kamiokande - results for the flux of ^{8}B-ν´s		
SK-I	[2.35 ± 0.02 (stat.) ± 0.08 (syst)] × 10^6 ν´s / cm^2 s	E_{thres} = 5 MeV
SK-II	[2.38 ± 0.05 (stat.) ± 0.16 (syst)] × 10^6 ν´s / cm^2 s	E_{thres} = 7 MeV
theory	5.79 × 10^6 ν´s / cm^2 s (±16%)	[Bahcall 2004]

consistent

significant deficit of solar ^{8}B neutrinos:

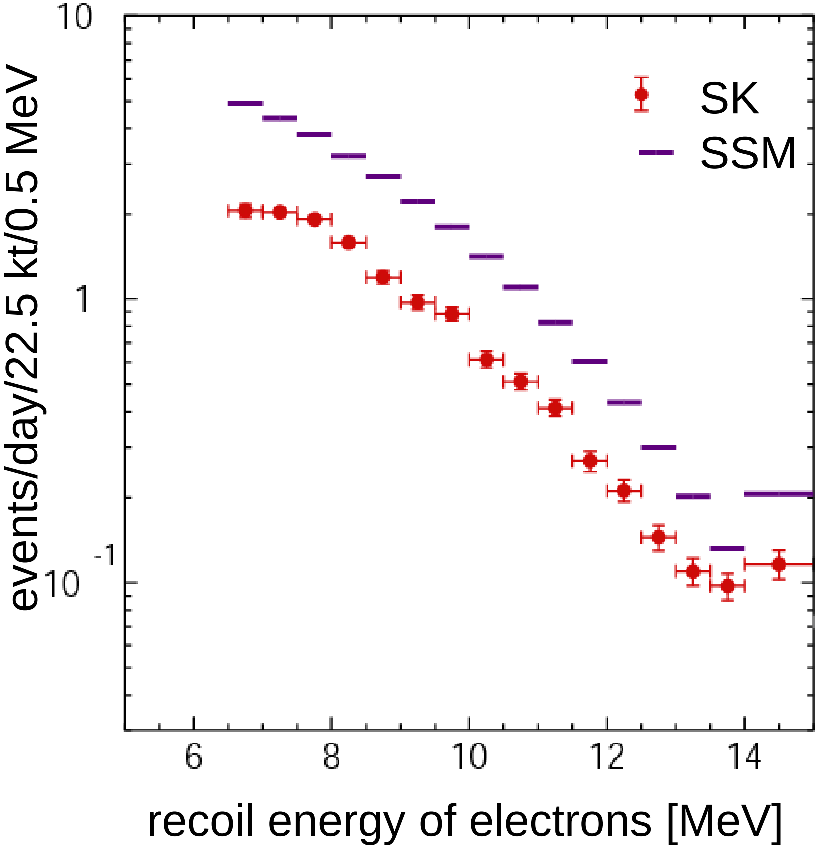
confirms earlier results from Homestake, GALLEX/GNO, Kamiokande…

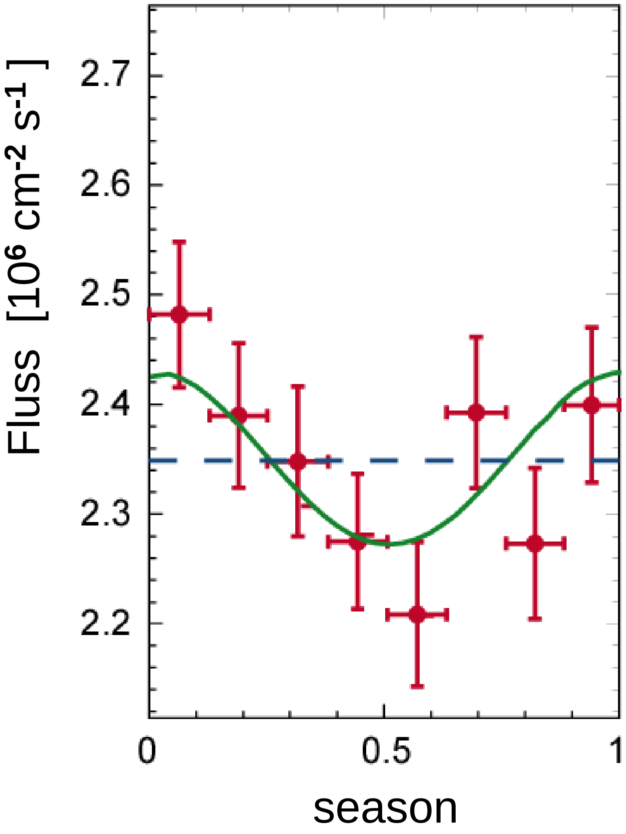
real time experiment SK allows additional analyses:

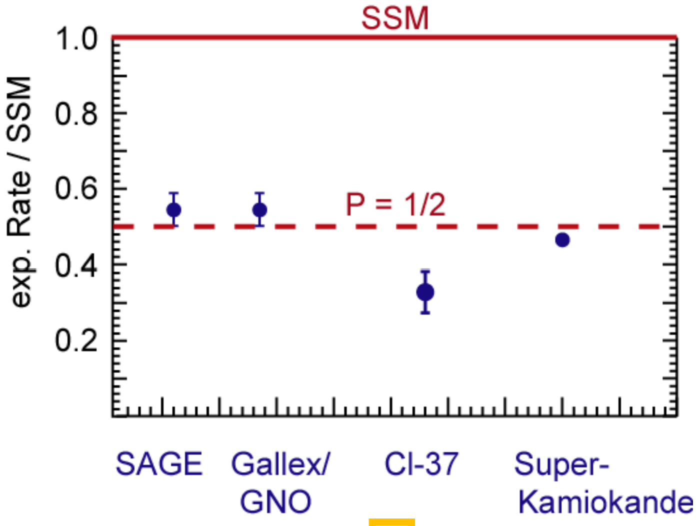
- energy spectrum (oscillation effects with E_ν)
- seasonal variations (oscillation effects with L_ν)
- day/night effects (oscillation effects from ν–interactions in matter)

Super-Kamiokande results

- analysis of the energy spectrum: **no modification with E_ν** is observed
- seasonal variation corresponds to expectation from excentricity of the earth orbit: **no variation with L_ν** is observed
- **no day/night differences** in rate (theory: possible regeneration of ν_e rate in the earth interior by matter effects): day/night ratio = $(-1.8 \pm 1.6_{stat.} \pm 1.2_{syst.})\%$

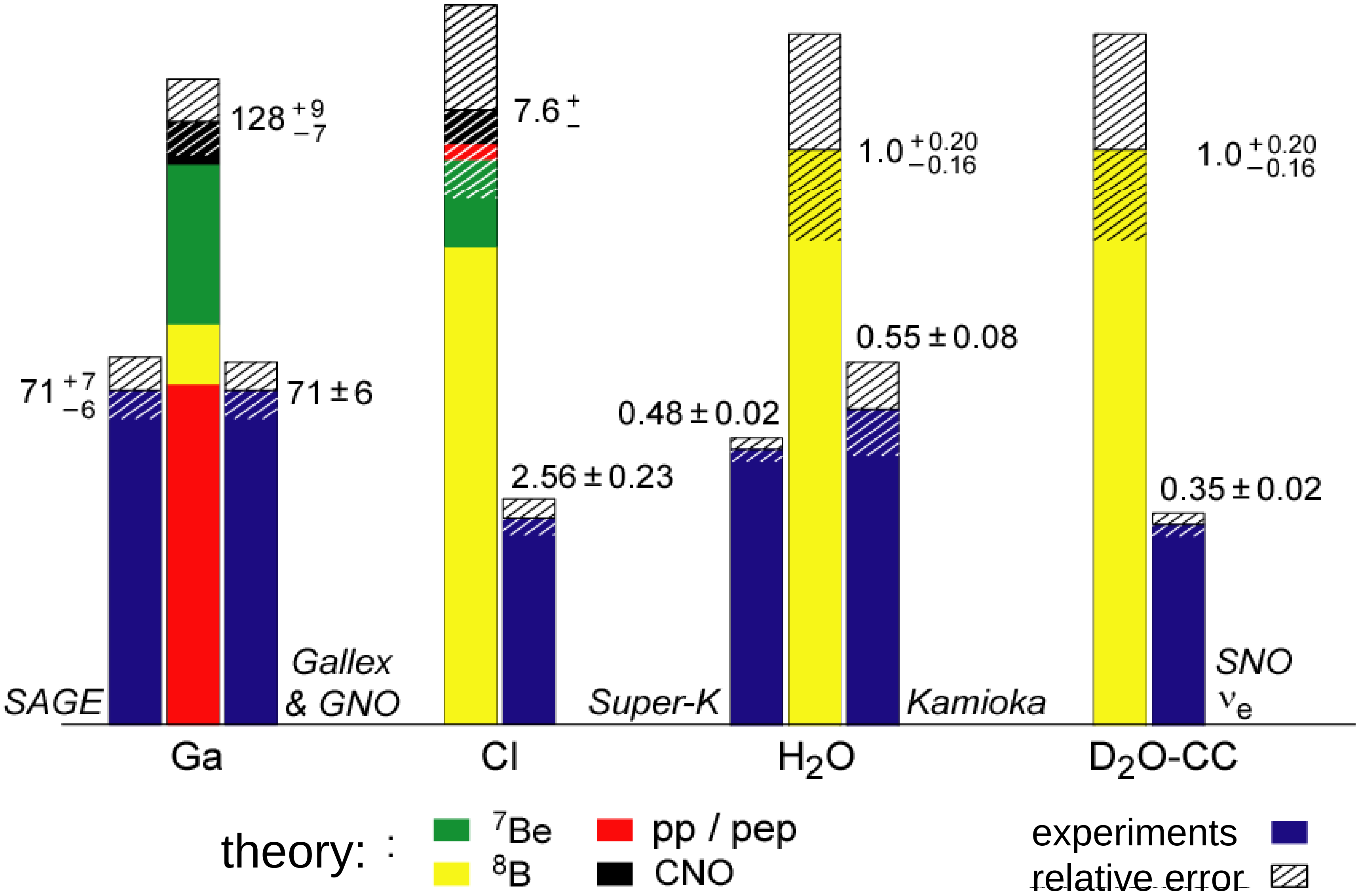






origin of reduction?

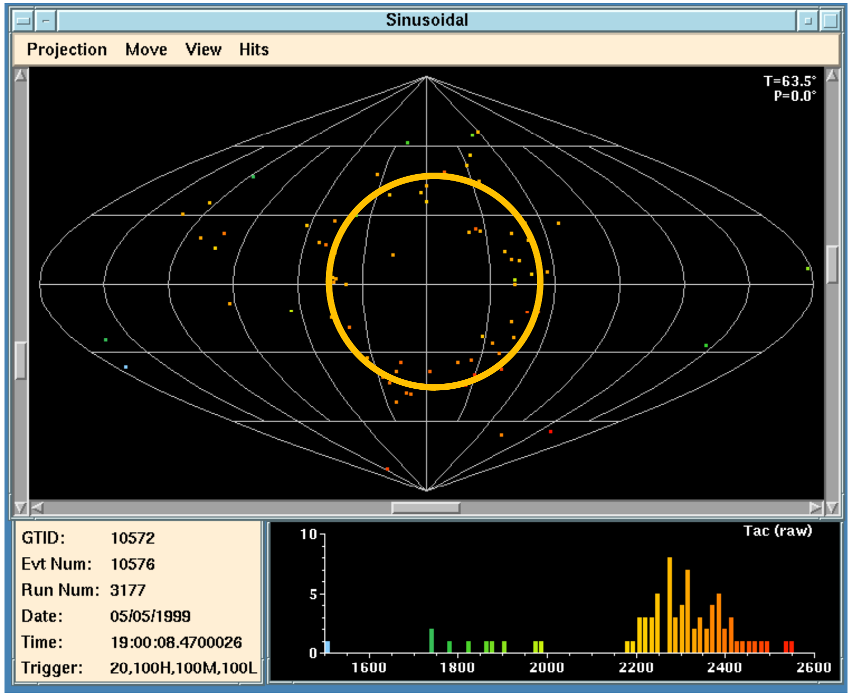
survey of results of all solar–ν experiments



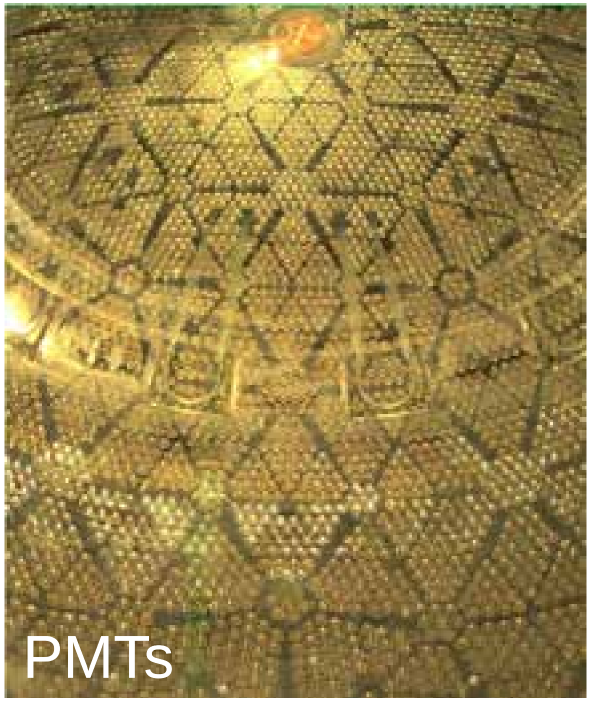
SNO – Sudbury Neutrino Observatory

SNO: 1000 t heavy water (D_2O)- Čerenkov-detector
in the 2 km deep Creighton mine in Sudbury/Ontario
primary objective: **NC rate of solar neutrinos**
via ν–induced deuteron break-up (neutron detection)

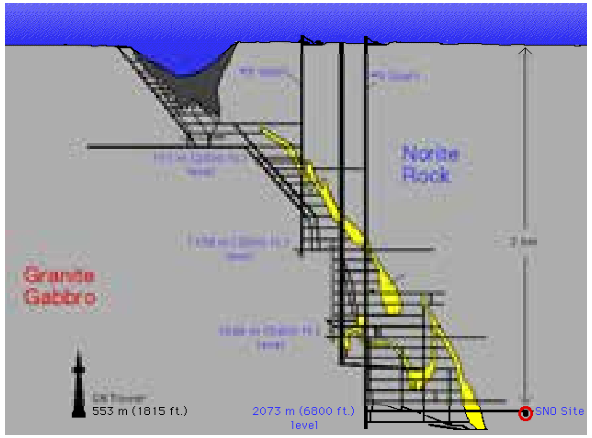
2001 – NC & the solution of the solar neutrino problem



GTID: 10572
Evt Num: 10576
Run Num: 3177
Date: 05/05/1999
Time: 19:00:08.4700026
Trigger: 20,100H,100M,100L



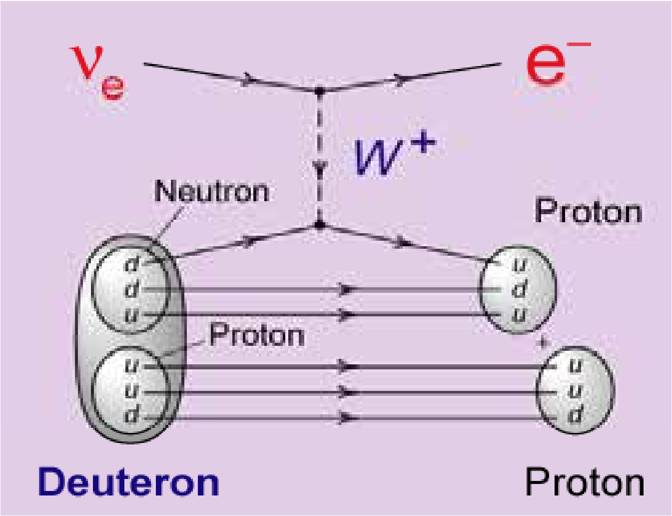
Creighton mine (2km)



SNO – experimental programme

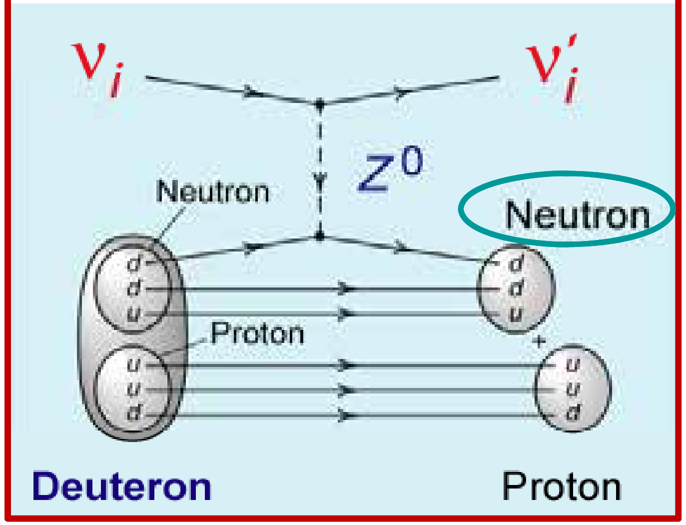
detection of solar ν´s by CC & NC-reactions (ν_eD & ν_ee – Prozesse)

charged current (CC)



ν_e – spectrum
ν_e – rate

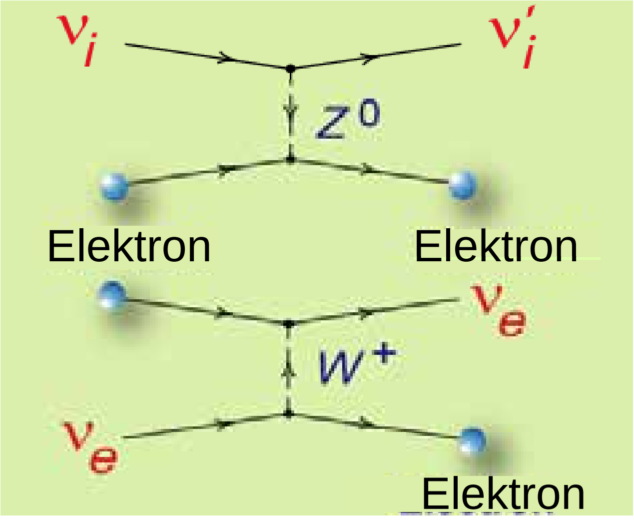
neutral current (NC)



NC - rate
$\nu_{\mu,\tau}$ - fraction

NC- deuteron break-up
for $E_\nu > 2.2$ MeV

elast. scattering (ES)



ES - rate
direction

SNO – three phases for NC

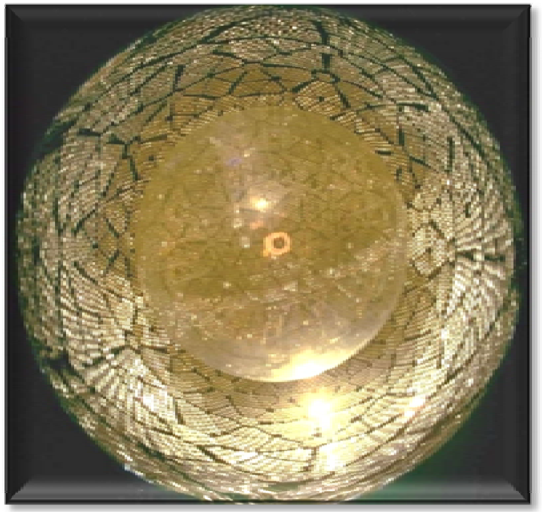
SNO was measuring NC reactions in three experimental configurations : different methods for **neutron detection from NC processes**

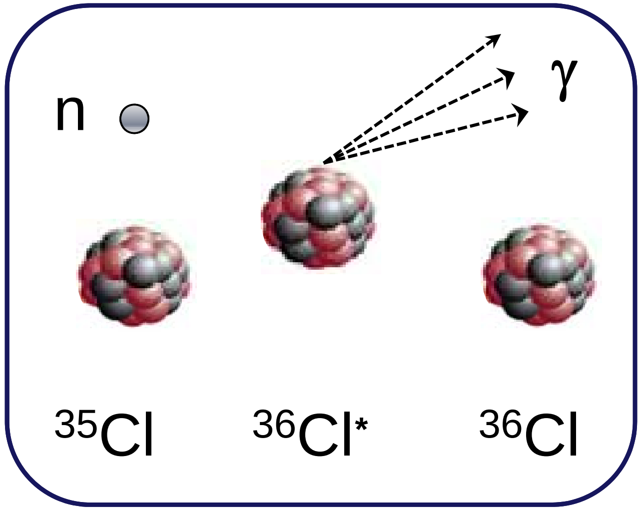
phase	n-capture	γ-energy	capture xsec	objectives
I – pure D_2O	$^2H(n,\gamma)$	6.25 MeV	0.0005 b	CC spectrum & ν_e-rate
II – NaCl (salt)	$^{35}Cl(n,\gamma)\,^{36}Cl$	**8.64 MeV**	44 b	NC spectrum & ν_μ/ν_τ-rate
III- NCD-counter	$^3He(n,p)^3H$	-	**5330 b**	separation CC-NC, θ_{12}

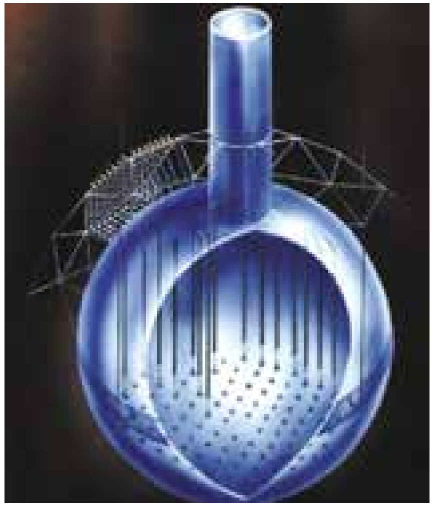
I: 11/99 - 5/01 (306 d)
pure D_20

II: 7/01 - 9/01 (391 d)
D_20 with 2 t NaCl (salt)

III: 10/04 - 12/06 (385 T)
NCD-counters (^{3}He)







SNO – Resultate: Phase-II

SNO results (salt phase)

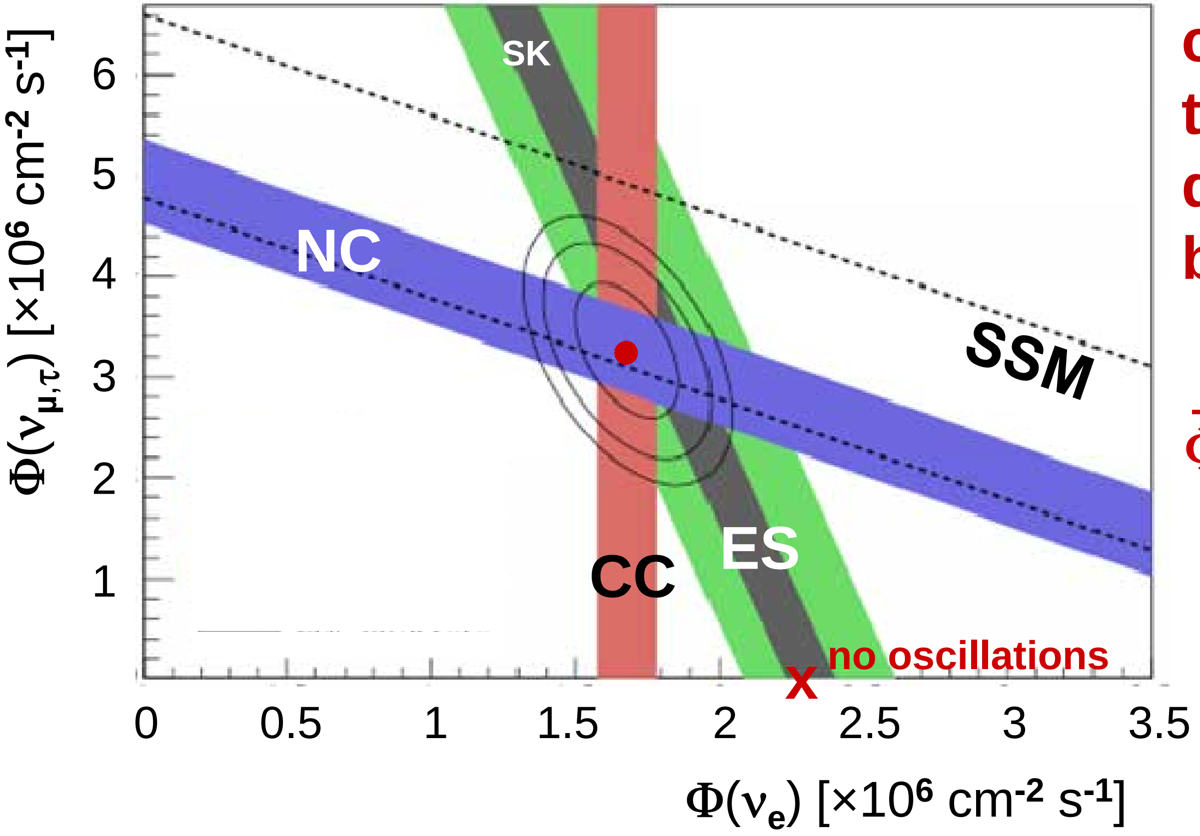
391 run days : 4722 ν´s

CC: (2176 ± 76) evts (ν_e)

NC: (2010 ± 85) evts ($\nu_{e,\mu,\tau}$)

ES: (279 ± 26) evts

SNO results for Phase-II	
$\Phi(\nu_e)$	$(1.68 \pm 0.06_{stat} \pm 0.09_{syst}) \times 10^6\ cm^{-2}\ s^{-1}$
$\Phi(\nu_{e,\mu,\tau})$	$(4.94 \pm 0.22_{stat} \pm 0.15_{syst}) \times 10^6\ cm^{-2}\ s^{-1}$
$\Phi(SSM)$	$(5.69 \pm 0.91_{theo}) \times 10^6\ cm^{-2}\ s^{-1}$



clear evidence for flavour-transformations $\nu_e \rightarrow \nu_{\mu,\tau}$ via the detection of the $\nu_{\mu,\tau}$ component by NC

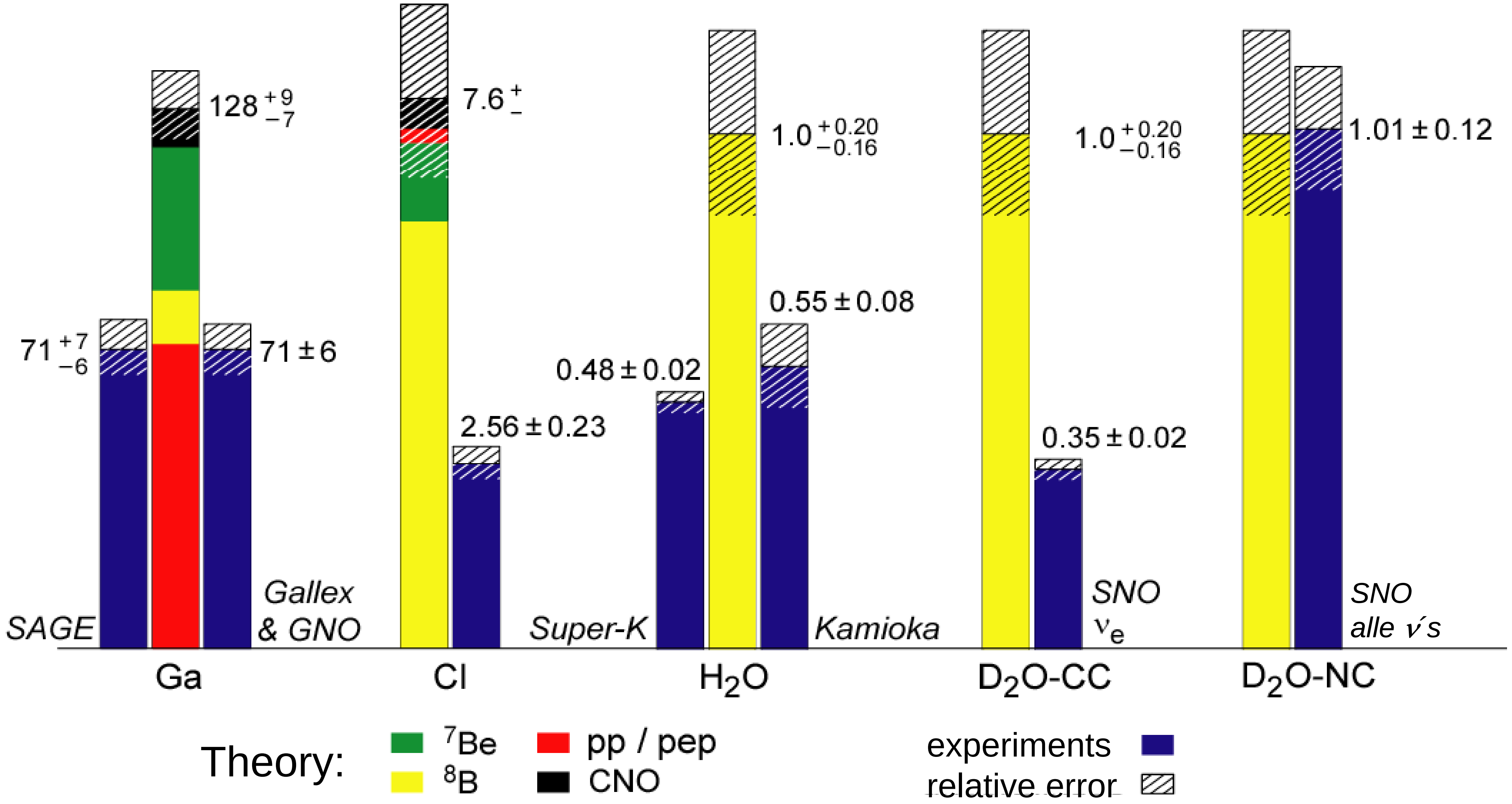
$$\frac{\Phi(\nu_e)}{\Phi(\nu_{e,\mu,\tau})} = 0.340 \pm 0.023_{stat} \pm 0.03_{syst}$$

results of SNO Phase-III:

(983±77) NC events in the NCDs

$\Phi(\nu_{e,\mu,\tau}) = 5.5 \times 10^6\ cm^{-2}\ s^{-1}$

survey of results of all solar–ν experiments



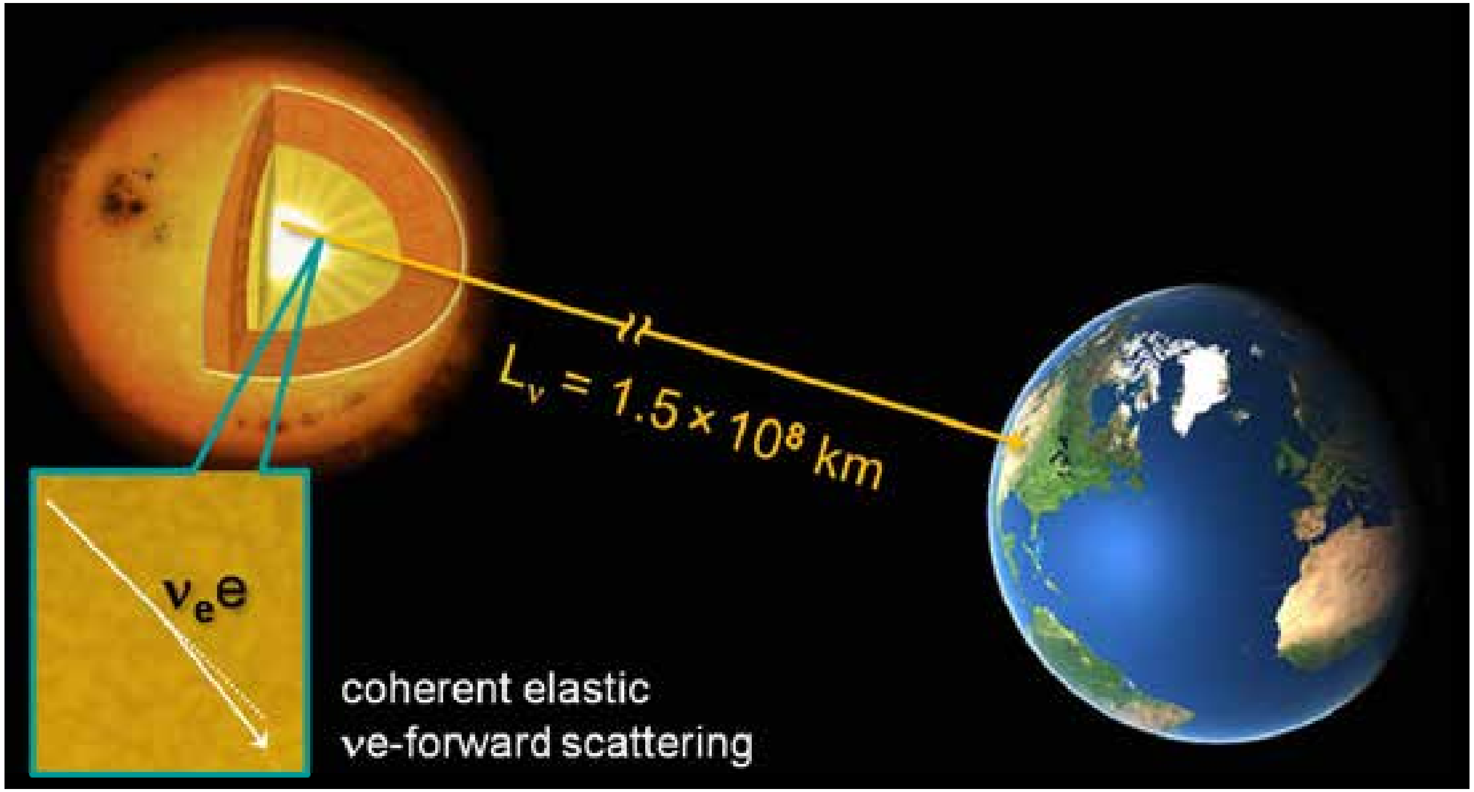
oscillations of solar neutrinos: MSW effect

vacuum oscillations oscillation length: $n \cdot \lambda_{osc} \sim 1.5 \times 10^{8}$ km, $\Delta m^2 \sim 10^{-10}$ eV^2

solar neutrinos are oscillating over the distance sun-earth ´in vacuum´

matter oszillationen oscillation length: $\lambda_{osc} \sim 1 \times 10^{2}$ km, $\Delta m^2 \sim 10^{-4}$ eV^2

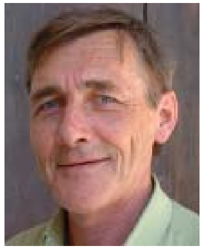
interaction of ν_e in the solar interior causes resonance-like transformation



coherent elastic
νe-forward scattering

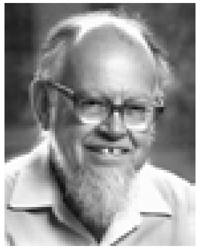
MSW effect

Mikheyev, **S**mirnov, **W**olfenstein:
matter influences propagation/oscillation



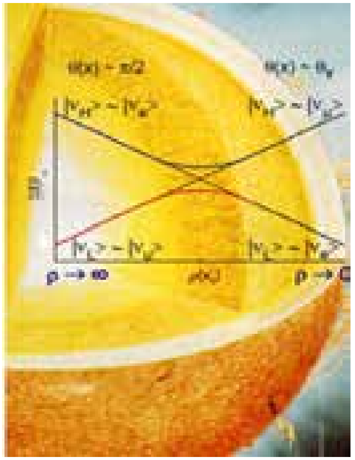
S.P.
Mikheyev

Alexej Y.
Smirnov



Lincoln
Wolfenstein

MSW effect: ν–oscillations in matter



- electron neutrinos ν_e: charged (CC) & neutral (NC) reactions
- muon & tau neutrinos ν_μ, ν_τ: neutral (NC) reactions only

↳ additional potential V for ν_e (effective variable mass)

$$\boxed{V = \sqrt{2} \cdot G_F \cdot N_e}$$

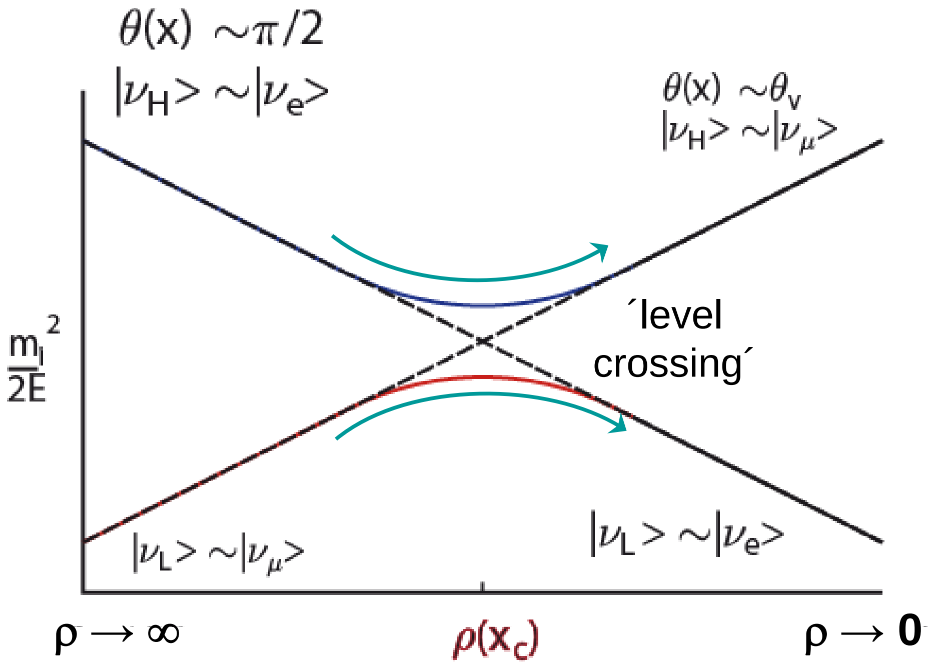
N_e: electron density

↳ strong phase change

MSW-´enhancement´ of oscillations

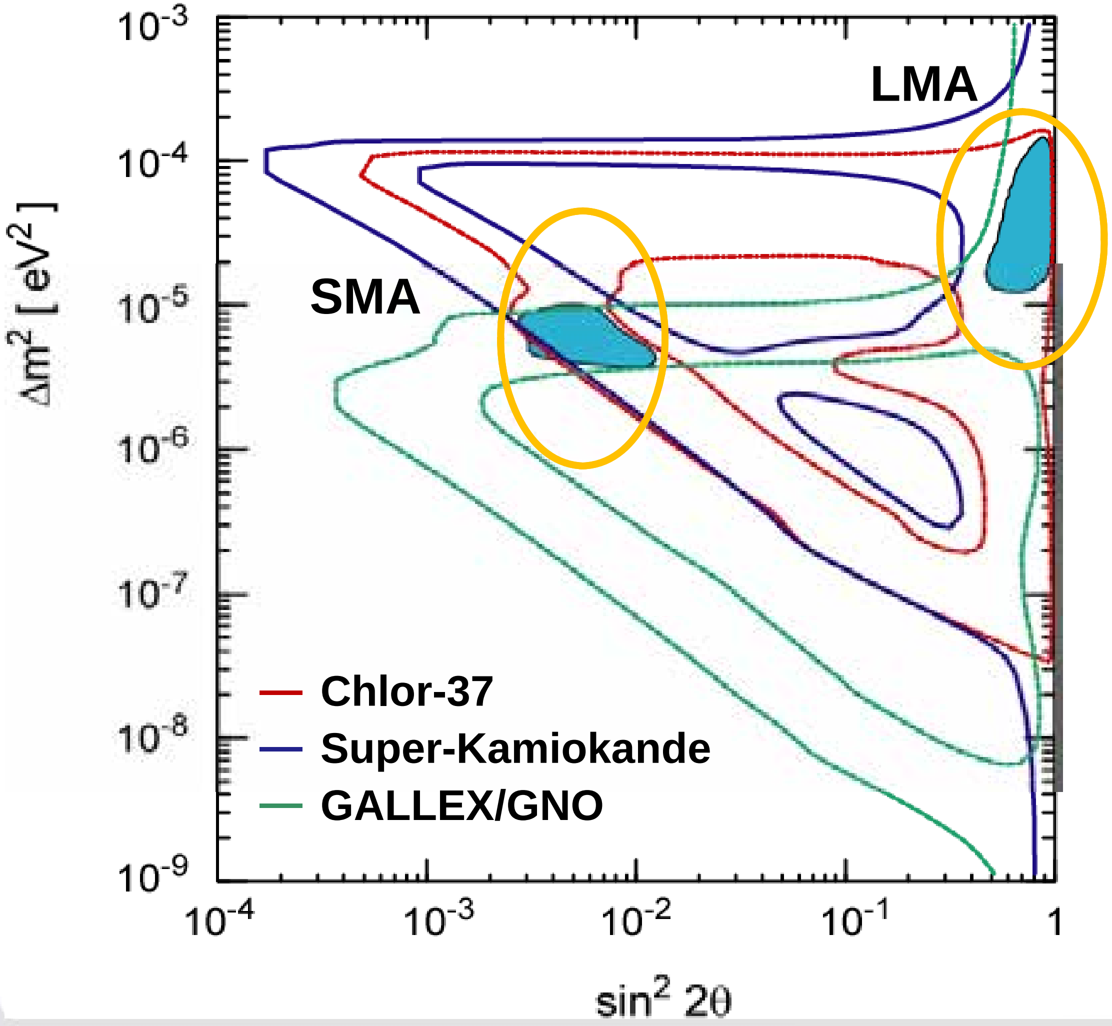
- neutrinos acquire an effective mass, in the core: ν_e heavy ↔ ν_μ light
- electron density N_e slowly decreases from solar core to surface
- critical density $\rho(x_c)$ is reached: **resonance-like transformation of ν_e in ν_μ** , depends on Δm^2, $\sin^2 \theta_{vacuum}$, N_e
- **strongly reduced ν_e flux** for parameters $\Delta m^2 = 10^{-9} \ldots 10^{-4}$ eV^2 also for small mixing angles θ_{vacuum}

Landau-Zener effect

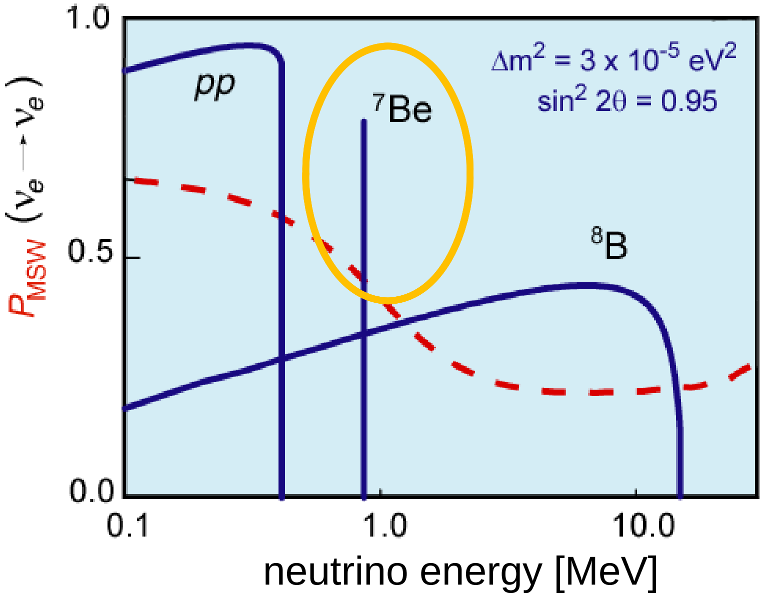


MSW Effekt – LMA & SMA

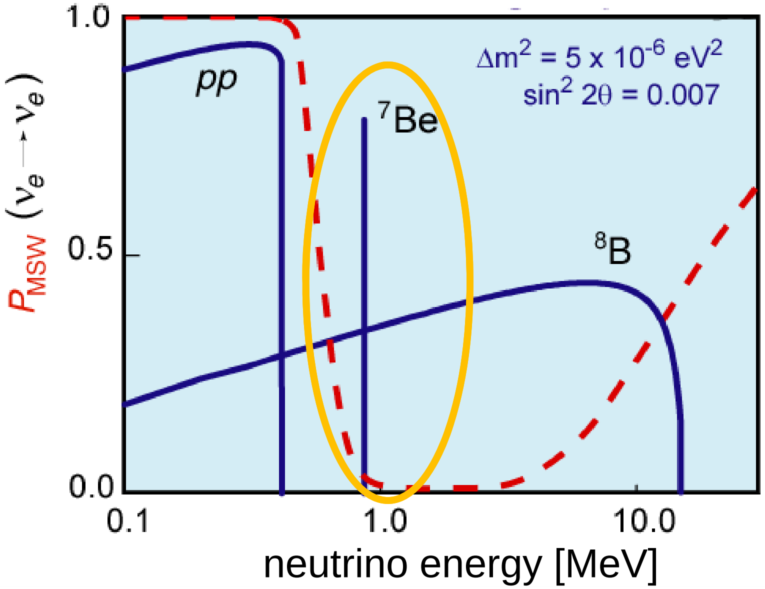
MSW analysis of data from Homestake, Super-Kamiokande and GALLEX/GNO:
2 MSW-parameter areas: **SMA, LMA**



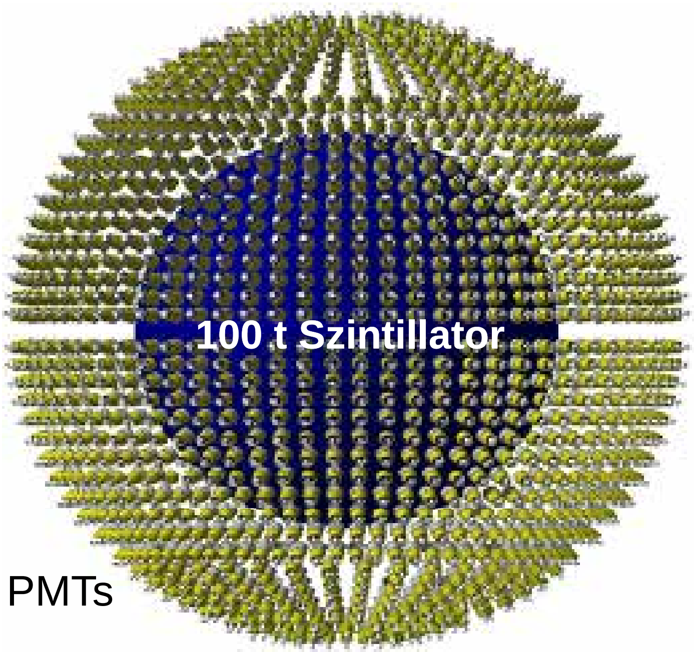
LMA – Large Mixing Amplitude



SMA – Small Mixing Amplitude



Borexino experiment




May 15, 2007
Borexino filled with scintillator

^{7}Be-solar-ν-experiment at LNGS, hall C

aim: real-time observation of the ^{7}Be-line

astrophysics of the sun

improved knowledge ϕ(^{7}Be) 40% → 5-10%

↳ improved precision ϕ(pp), ϕ(CNO)

challenge: extremly small impurities with with primordial isotopes (background)

detector: ultra-clean liquid scintillator surrounded by mineral oil buffer and water veto

principle: elastic ν-e-scattering

results: reduction of the ^{7}Be-rate (MSW-LMA)

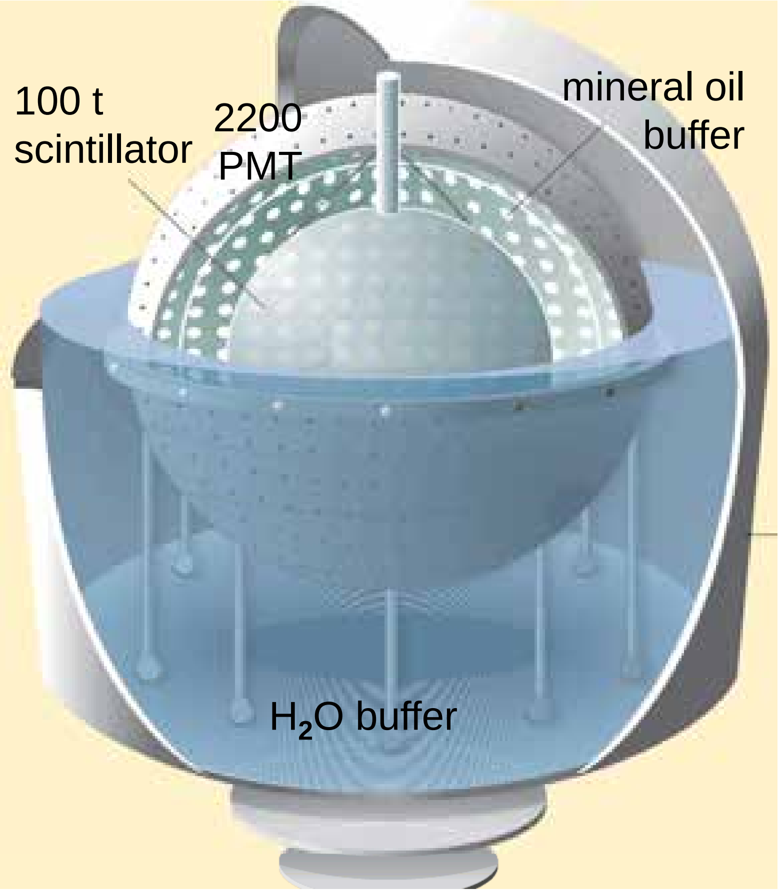
background requirements:

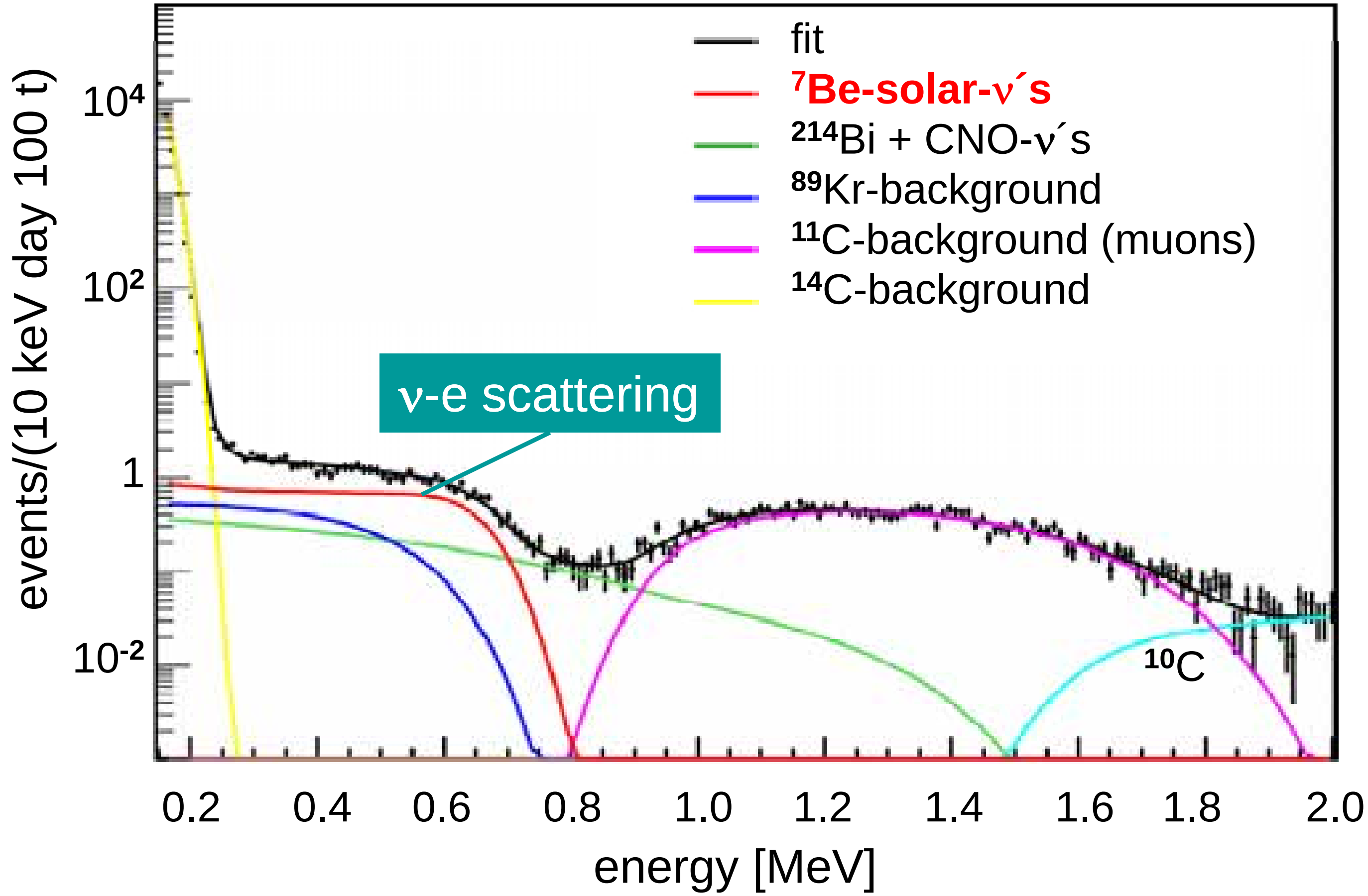
isotope	isotope purity
^{238}U	< 10^{-16} g/g
^{232}Th	< 10^{-16} g/g
^{40}K	< 10^{-14} g/g

Borexino experiment - results

data analysis:
16.5.07-12.4.08
192 days =
41.3 t years

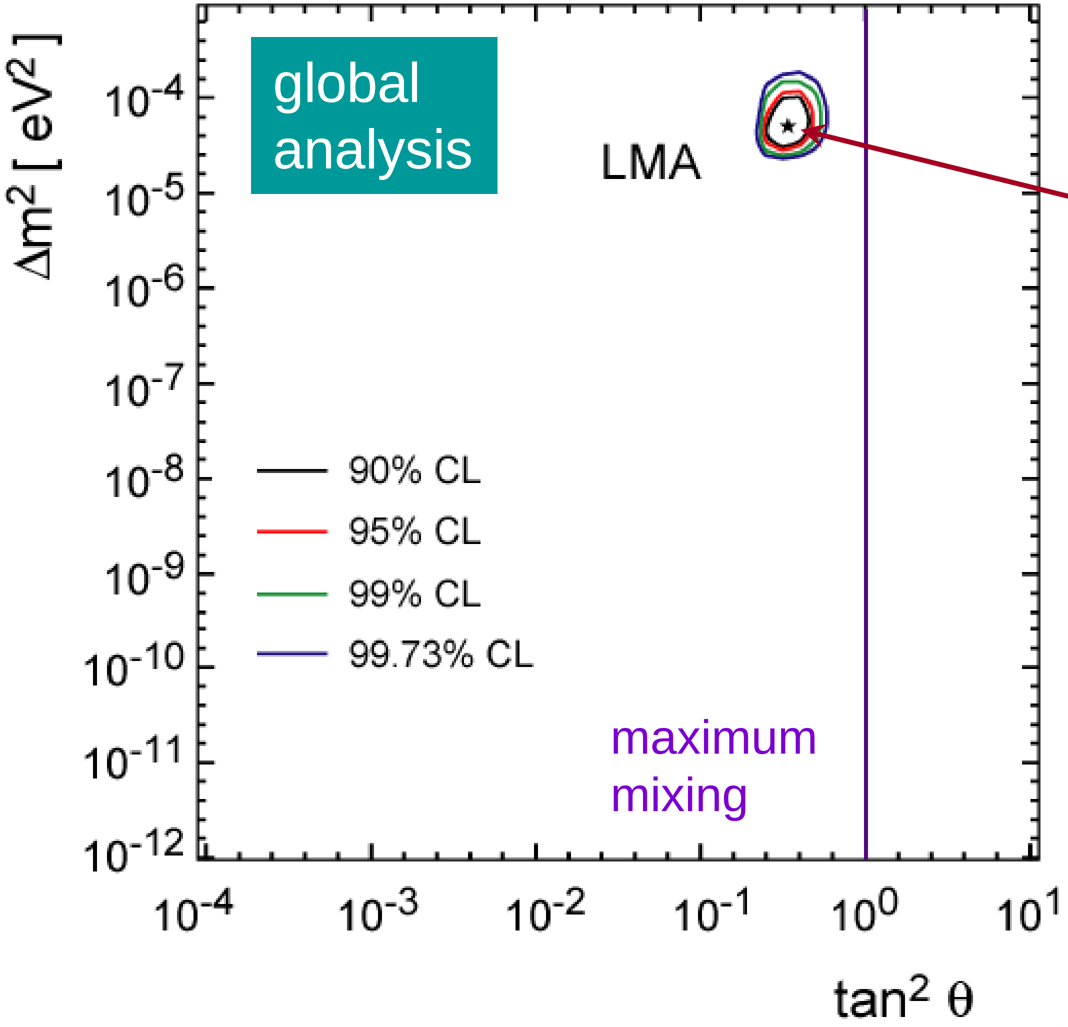
parameter	Borexino result	LMA
^{7}Be-ν rate (per day per 100 tonnes)	49 ± 3 (stat.) ± 4 (syst.)	48 ± 4
^{7}Be-ν flux ($\times 10^9$ cm^{-2} s^{-1})	5.18 ± 0.52	5.1
ν_e-survival probability P_{ee}	0.56 ± 0.10	0.541 ± 0.017





solar neutrinos: actual oscillation parameters

global analysis of all solar neutrino experiments (as well as of the **KamLAND reactor oscillation experiment**) gives



LMA parameter space of the MSW effect

$\sin^2 2\theta_{12} = 0.87$
$\Delta m^2_{12} = 7.6 \times 10^{-5}$ eV^2

strong, but no maximum mixing

⇩

solar ν-flux on earth:
~ 1/3 ν_e ~ 1/3 ν_μ ~ 1/3 ν_τ

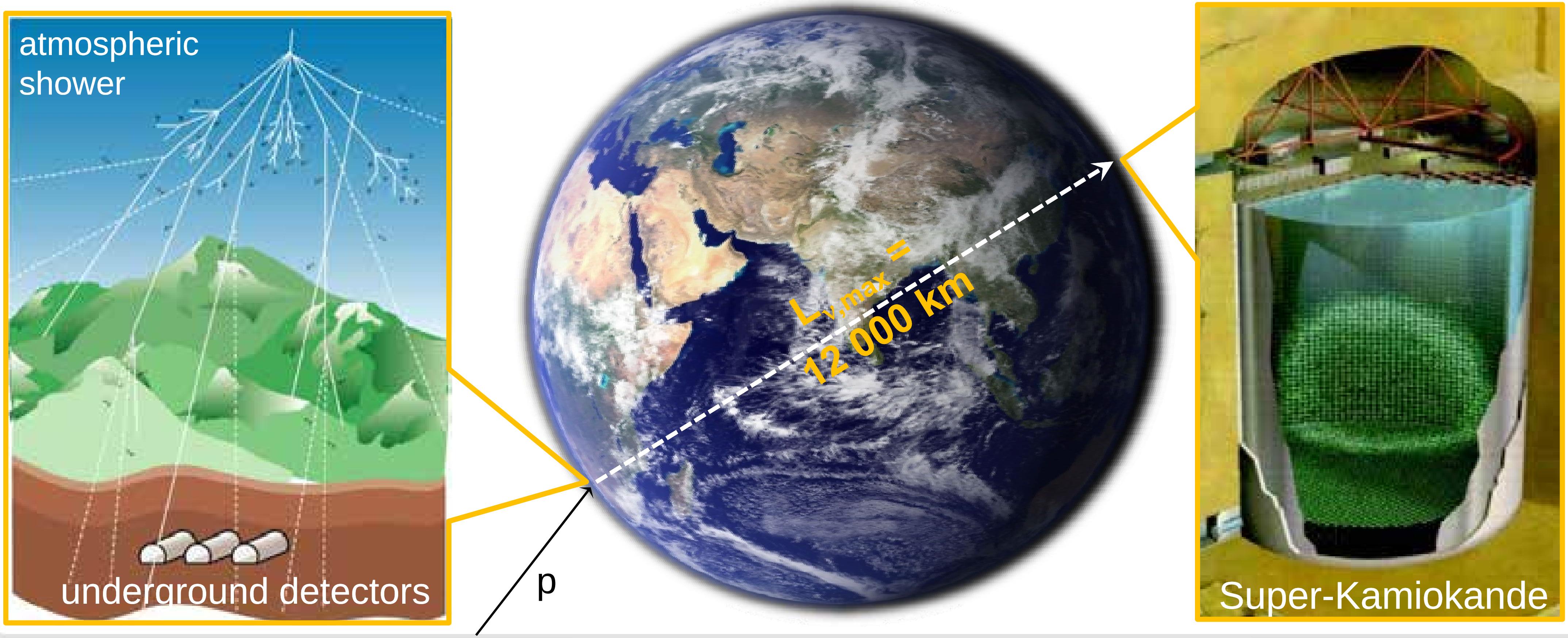
atmospheric neutrinos

interactions of cosmic rays with ^{16}O, ^{12}N nuclei in the upper atmosphere (h = 10 - 20 km) generate air showers: ↳ pion (π^+, π^0, π^-) & kaon production

decay chain of pions/kaons ↳ atmospheric **ν´s in the GeV-range**

energies: $\Phi_{\mathbf{max}}$ at E_ν = 0.25 GeV, then power law $\Phi_\nu \sim E^{-2.7}$ at high energies

flux: $\Phi_\nu \sim 1\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at sea level ↳ multi-kt-detectors (~ 1 event/kt)

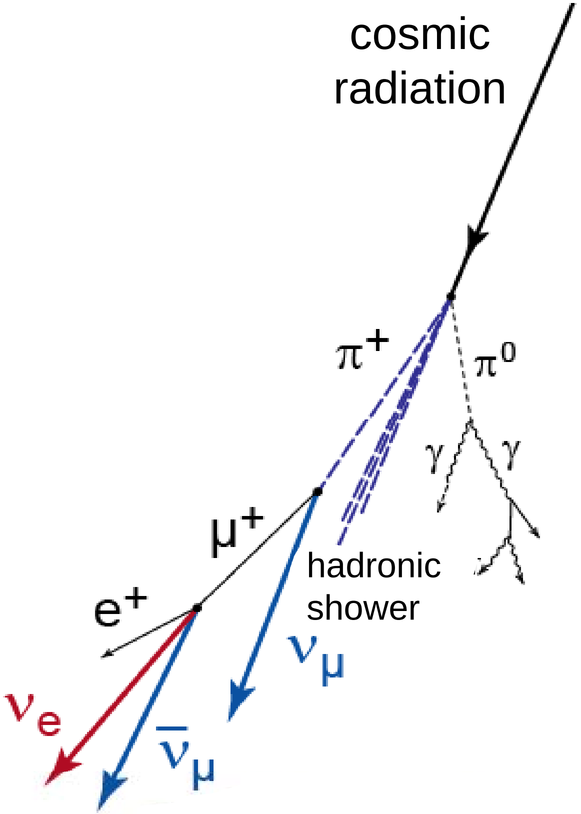


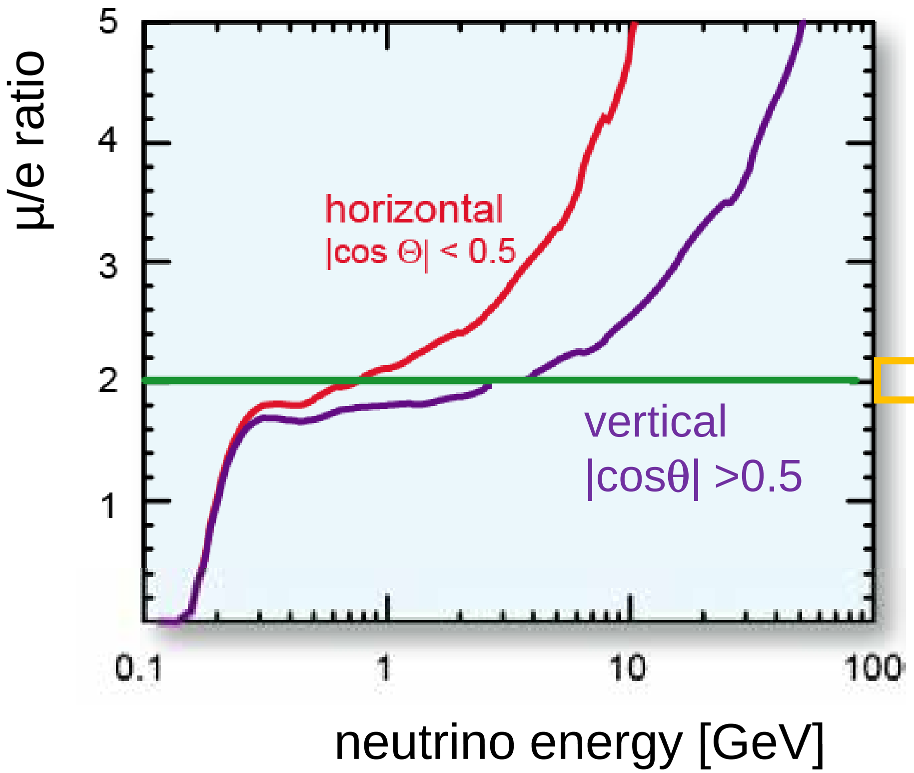
atmospheric neutrinos – flavours

the atmospheric π^+-μ^+ decay chain results in a **$\nu_\mu : \nu_e$ flavour ratio R = 2 : 1** for a wide range of ν-energies (E_ν ~ 0.5 – 10 GeV)

$\pi^+ \rightarrow \mu^+ + \nu_\mu$
(p,He,..)
$\quad\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

the flavour ratio R is modified at low & high energies: E_ν < 1 GeV: π-absorption; E_ν > 10 GeV: muon decay ($\tau_\mu = \gamma \times 2.2\ \mu s$) ➯ no high energy multi-GeV ν_e

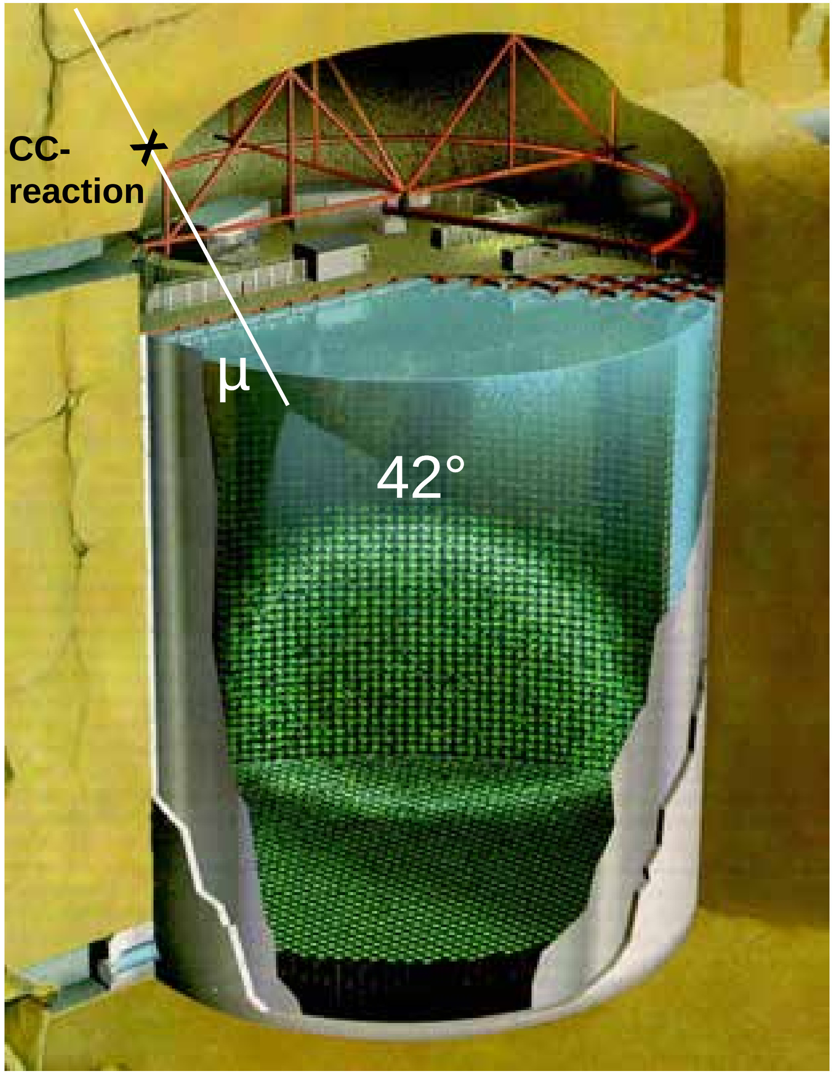




flavour-ratio
$\nu_\mu : \nu_e = 2 : 1$

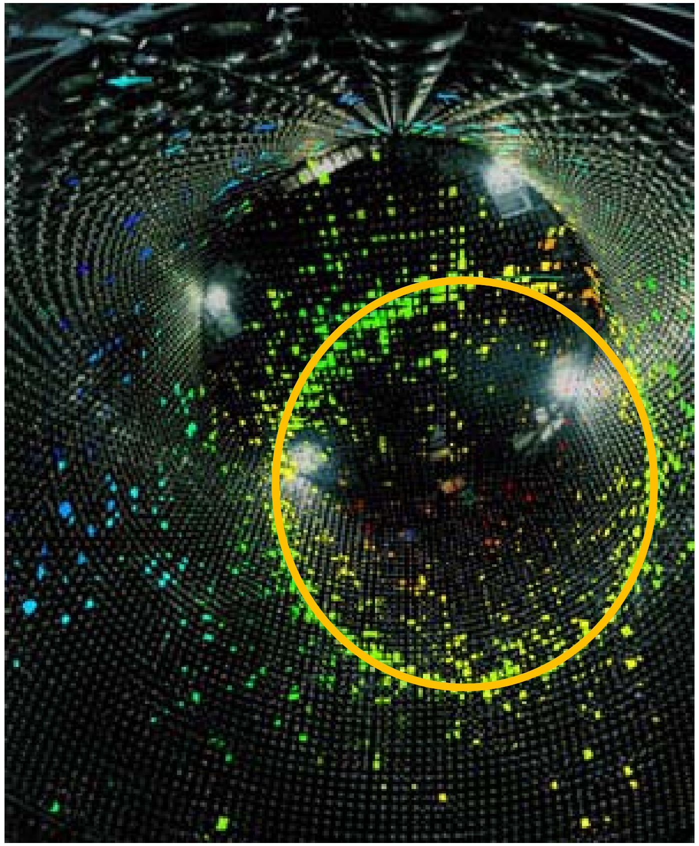
Super-Kamiokande: atmospheric ν´s

detection of atmospheric neutrinos in water Cherenkov detectors:
ν_μ generate Muons via CC reactions, ν_e an electromagnetic shower



PMTs register Cherenkov light (ring structure)

imaging Cherenkov technique



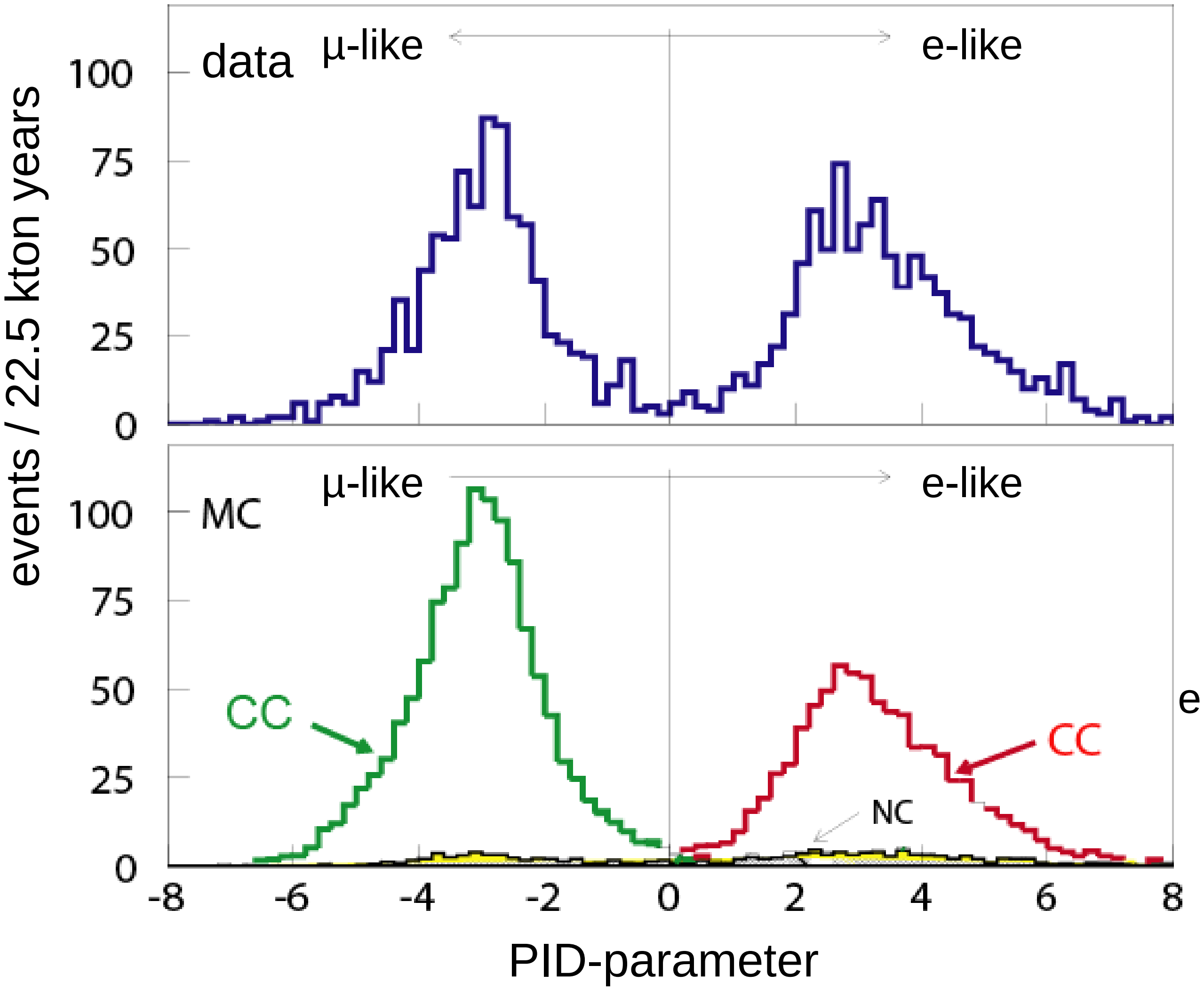
Cherenkov ring:
- PMT charge signal
- PMT time signal

reconstruction of:
- ν-flight direction θ_ν
- ν-flavour ν_e, ν_μ (PID)
- ν-energy E_ν

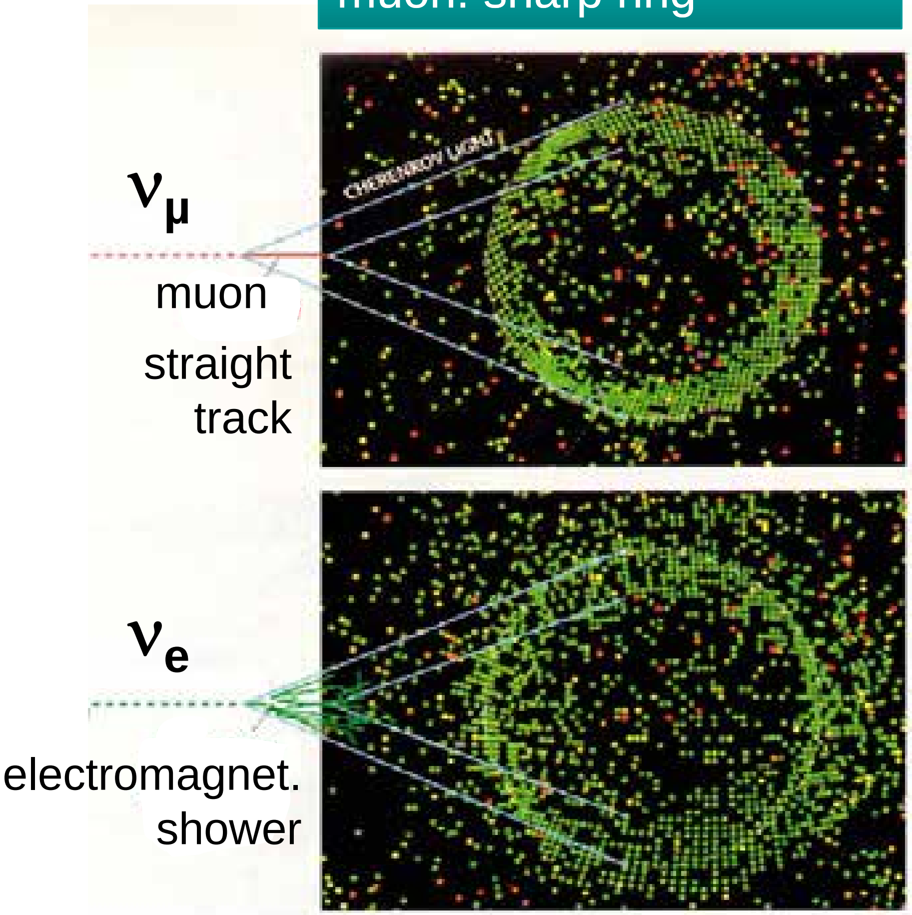
Super-Kamiokande: selecting ν-flavours

analysis of atmospheric ν´s: excellent flavour separation is essential

ν-flavour from final-state lepton-ID



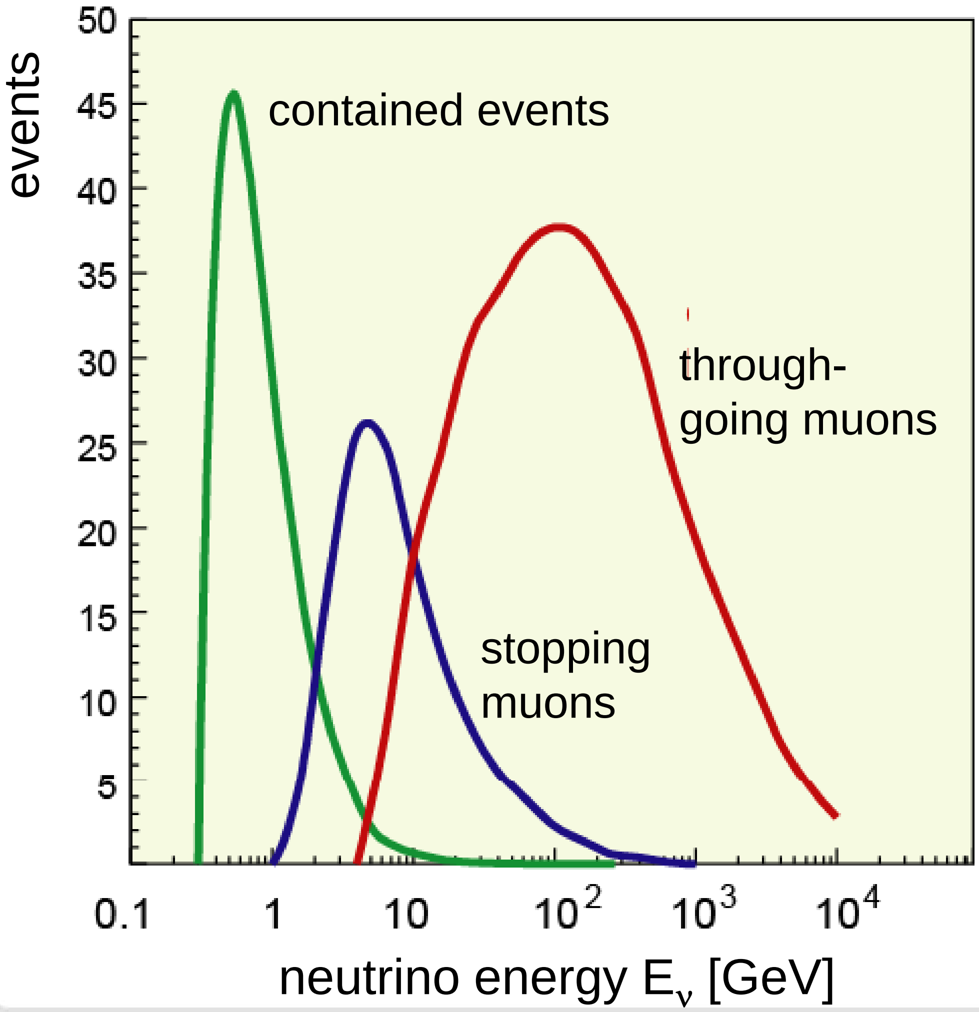
muon: sharp ring

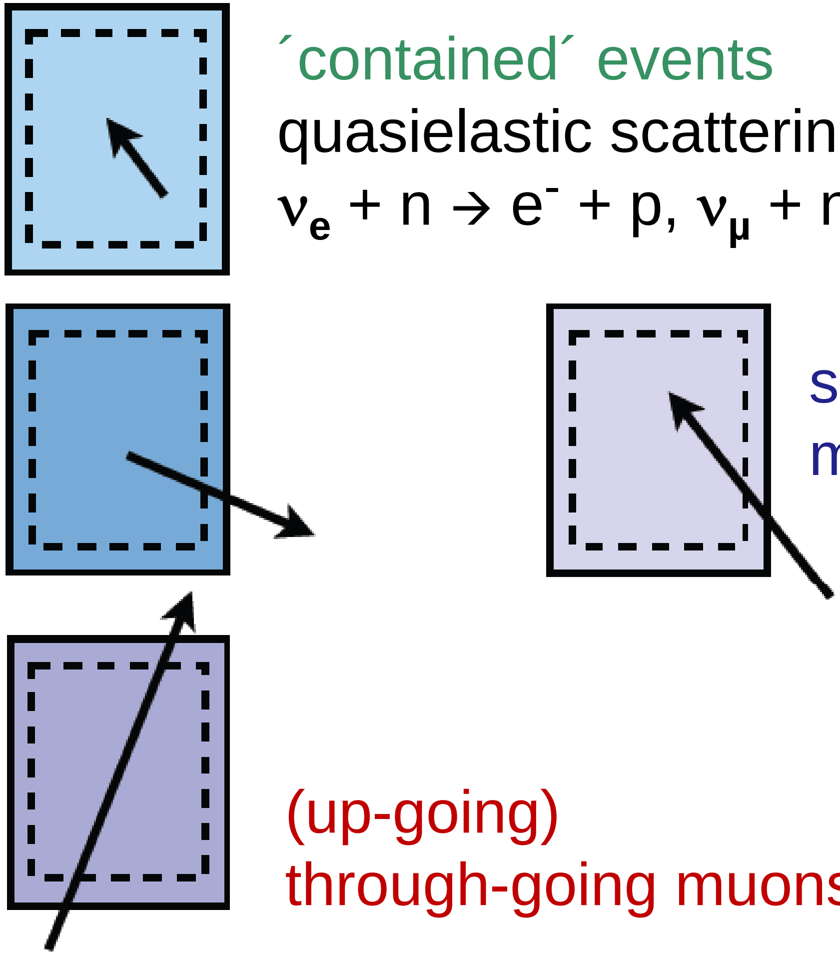


electron: fuzzy ring

atmospheric neutrinos – energies E_ν

subdivision of ν_{atm}-reactions into 3 (energy-dependent) event classes
at Super-Kamiokande: investigation of ν-oscillations as $f(E_\nu)$





´contained´ events
quasielastic scattering,
$\nu_e + n \rightarrow e^- + p$, $\nu_\mu + n \rightarrow \mu^- + p$

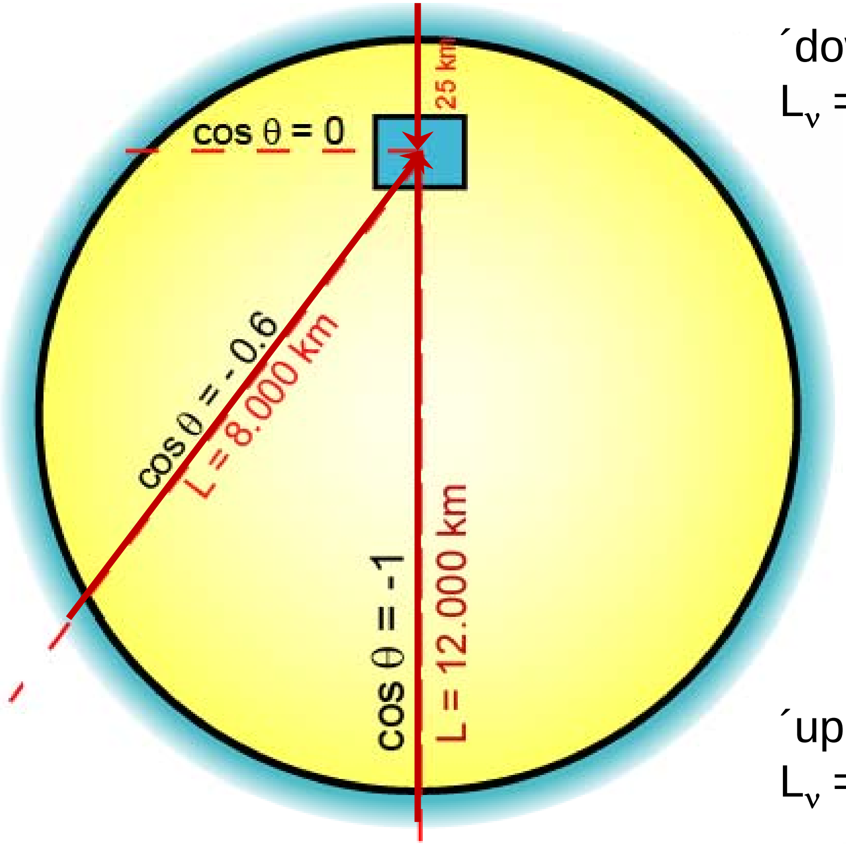
stopping
muons

(up-going)
through-going muons

atmospheric neutrinos – pathlength L_ν

atmospheric neutrinos are an ideal source for ν-oscillations:
detector is fully enclosed in a 4π geometry ⇨ the zenith angle θ of the neutrino defines the ν-pathlength L_ν (20-12.000 km), variation over large factors

azimuth angle θ & pathlength L_ν

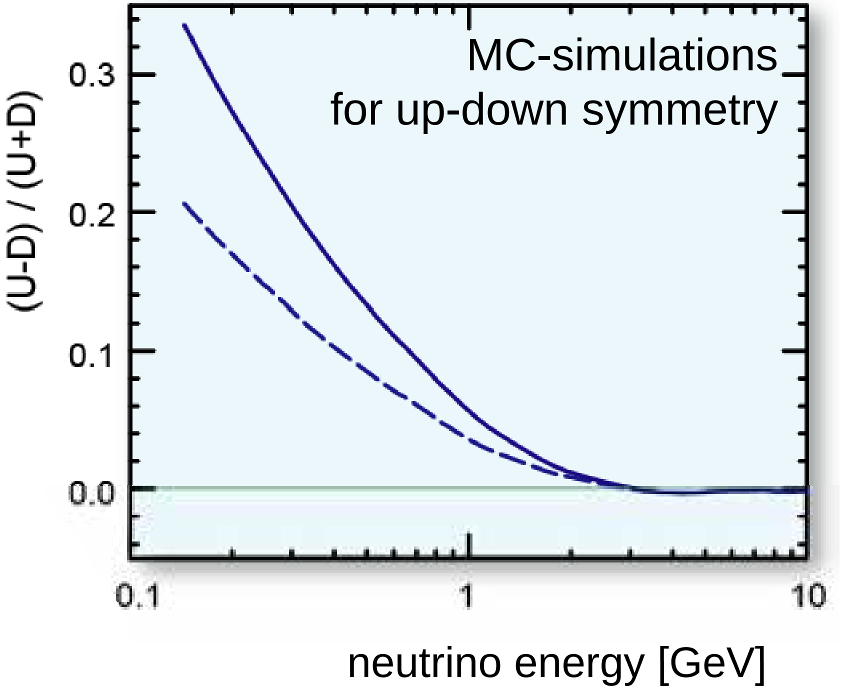


´down-going´ (D)
L_ν = 20-25 km

´up-going´ (U)
L_ν = 12000 km

up/down symmetry

expectation: N(up) = N(down)

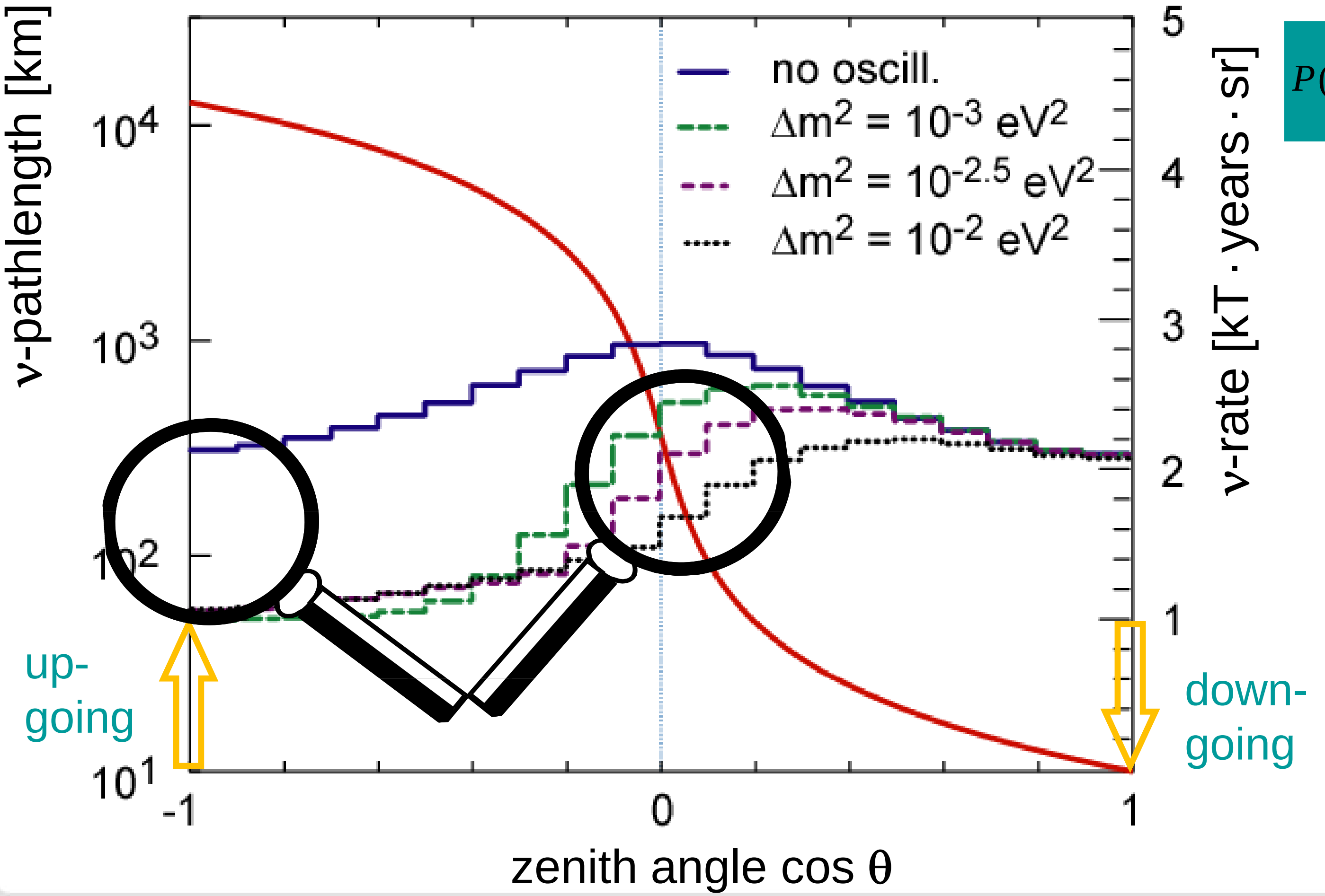


atmospheric neutrinos – zenith angle θ

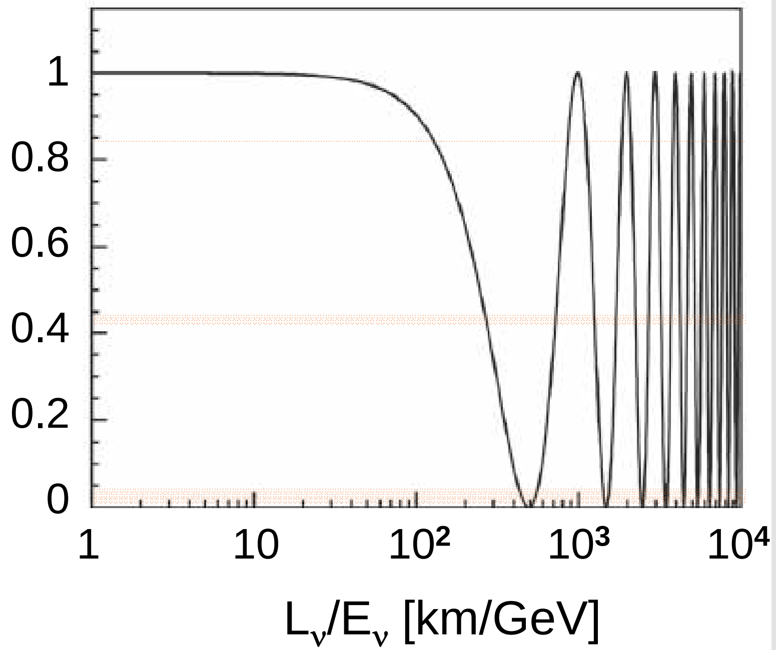
high-energy multi-GeV ν_{atm}: **close correlation of the angle ν-lepton**

zenith angles around cos θ = 0 (horizontal ν_μ) ⇨ define scale Δm^2

zenith angles around cos θ = -1 (up-going ν_μ) ⇨ define scale $\sin^2 2\theta$

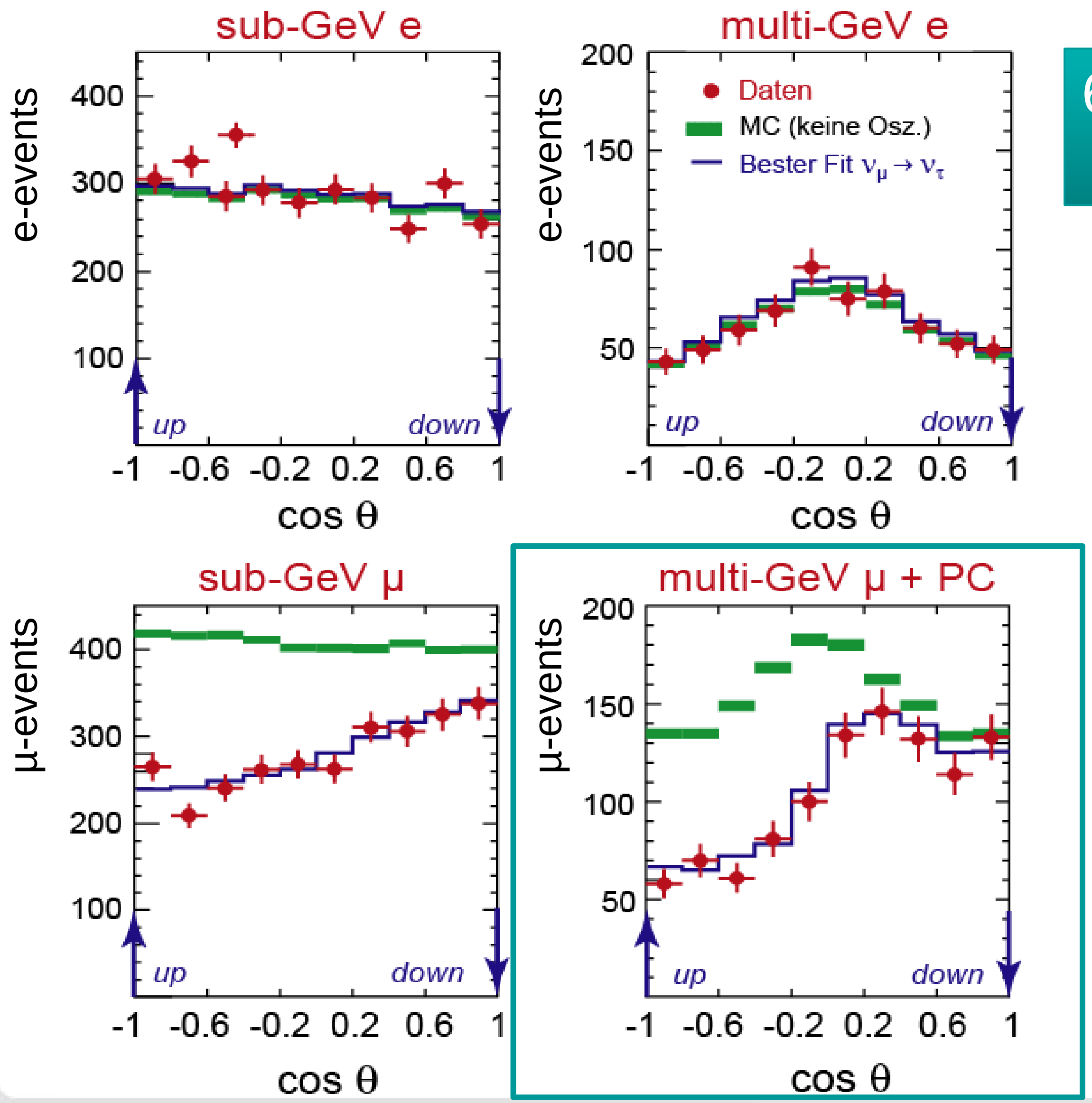


$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \; \sin^2\left(1.27 \cdot \Delta m^2 \, \frac{L_\nu}{E_\nu}\right)$$

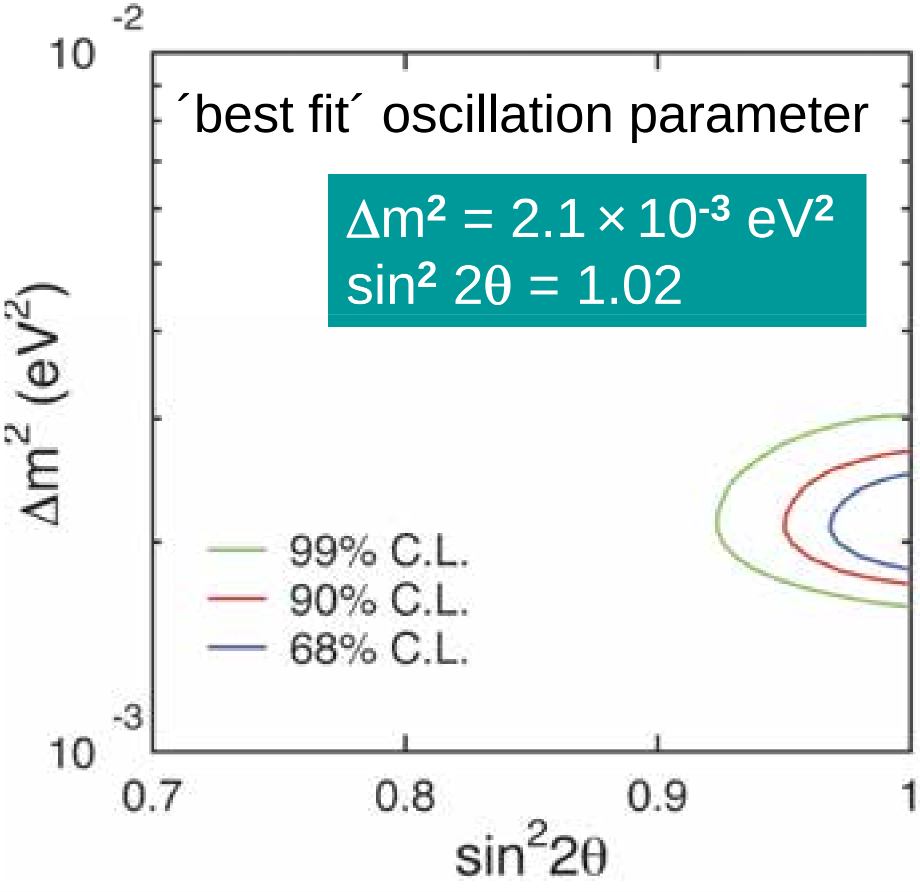


Super-Kamiokande: cosθ distributions

analysis of Super-Kamiokande-I azimuth angle distributions



6.6.1998: evidence for oscillations of atmospheric neutrinos!



´best fit´ oscillation parameter

$\Delta m^2 = 2.1 \times 10^{-3}$ eV^2
$\sin^2 2\theta = 1.02$

Super-Kamiokande: L_ν/E_ν distributions

first detection of the oscillatory nature of the parameter L_ν/E_ν

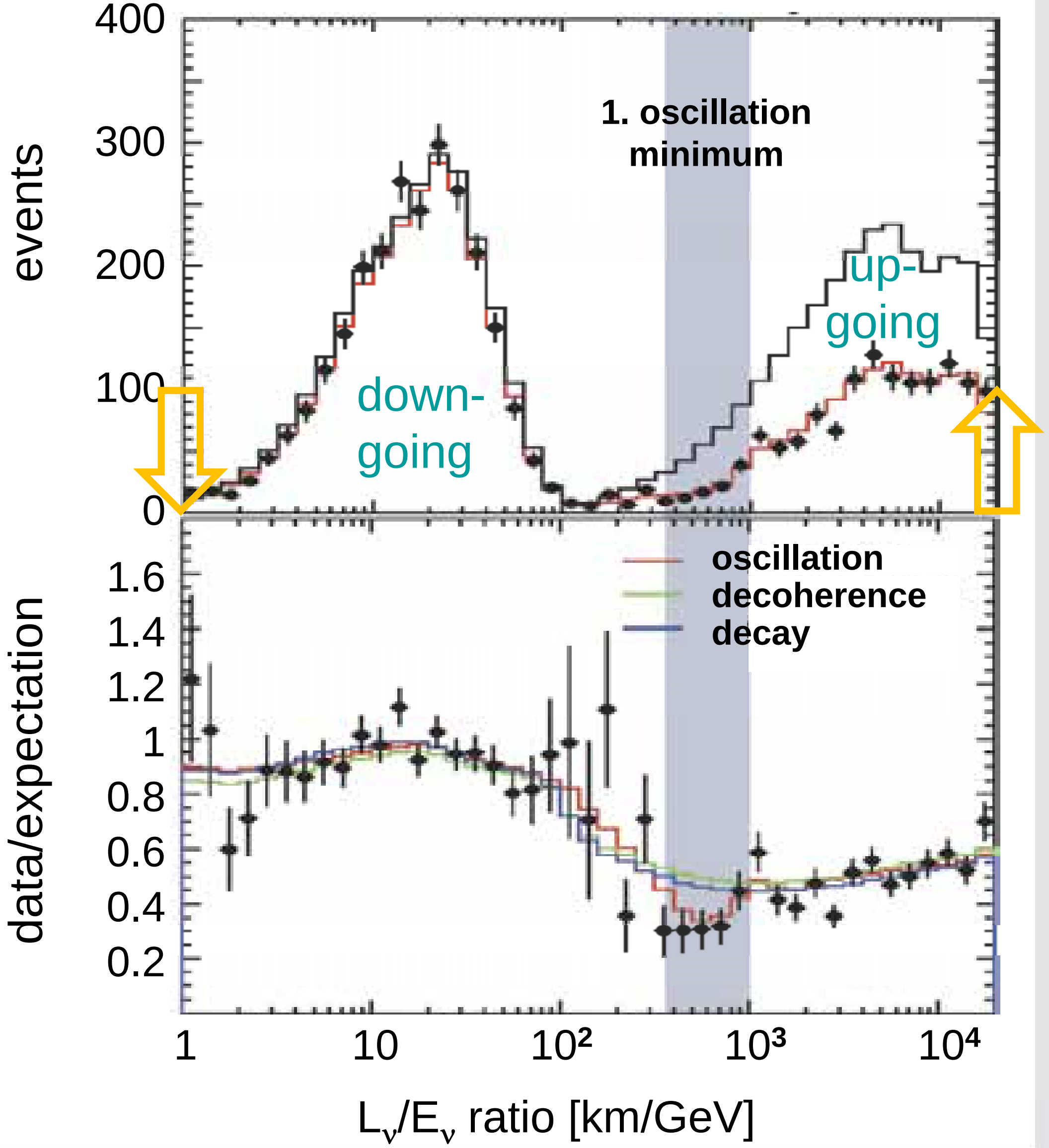
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

selection of a specific data set with very good resolution in L_ν/E_ν

- good agreement with expectation for ν–oscillations
- exclusion of alternative scenarios (ν-decay, quantummechanical decoherence of mass eigenstates)

oscillations = ν-propagation effect

Super-Kamiokande-I & -II

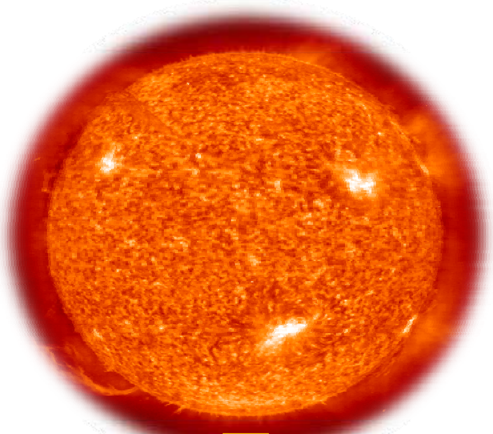


neutrino oscillations: laboratory experiments

test of the oscillation of astrophysical ν´s under laboratory conditions:

reactor & accelerator experiments at long-baseline :

ν-oscillations: **modification of ν-flux and of ν-energy spectrum**



MeV: solar ν_e

ν_e–$\nu_{\mu,\tau}$

oscillations:

$\Delta m^2 = 7.6 \times 10^{-5}$ eV^2

$\sin^2 2\theta = 0.87$

reactor experiments

$\bar{\nu}_e$–

disappearance:

KamLAND

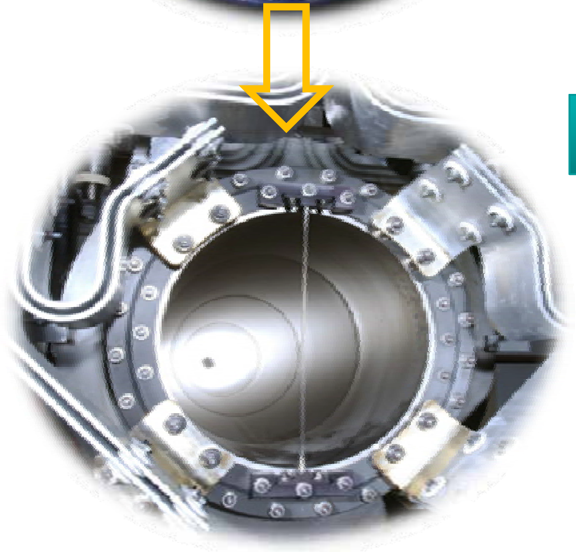
GeV: atmospheric ν_μ

ν_μ–ν_τ

oscillations:

$\Delta m^2 = 2.1 \times 10^{-3}$ eV^2

$\sin^2 2\theta = 1.02$



LBL experiments

ν_μ –

disappearance:

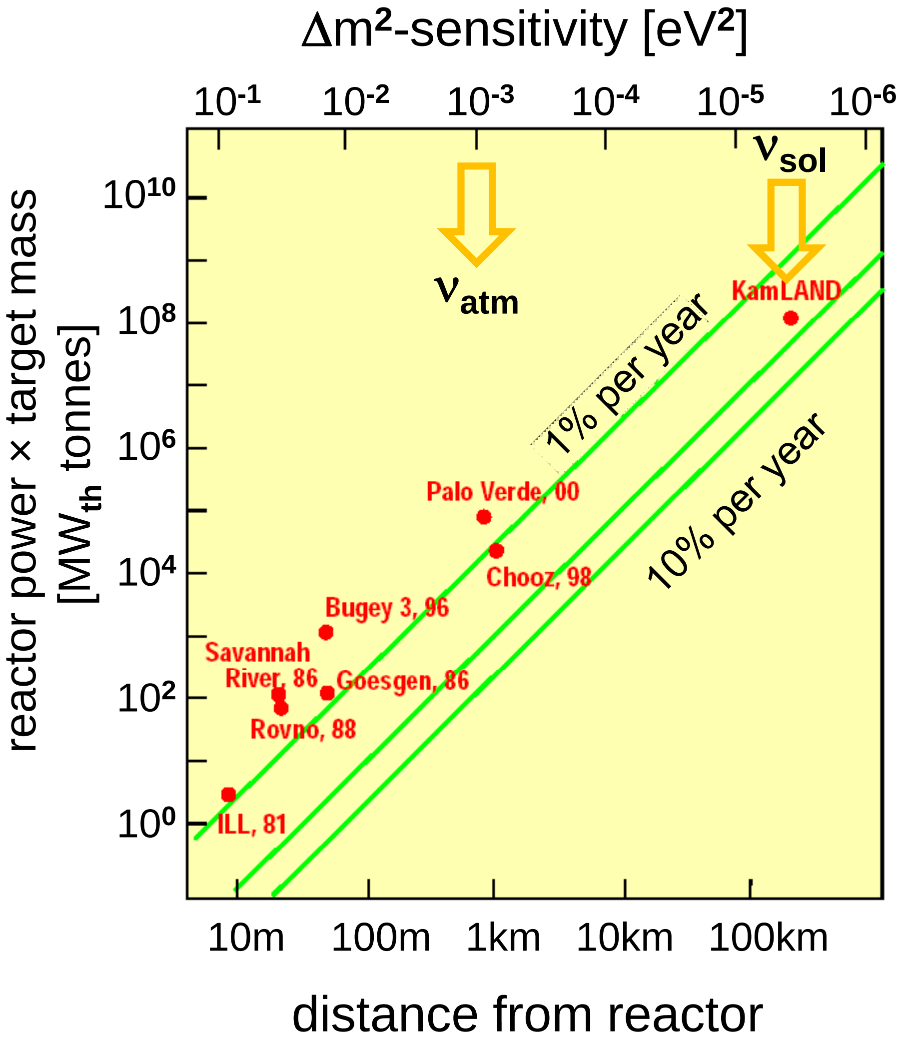
K2K/T2K

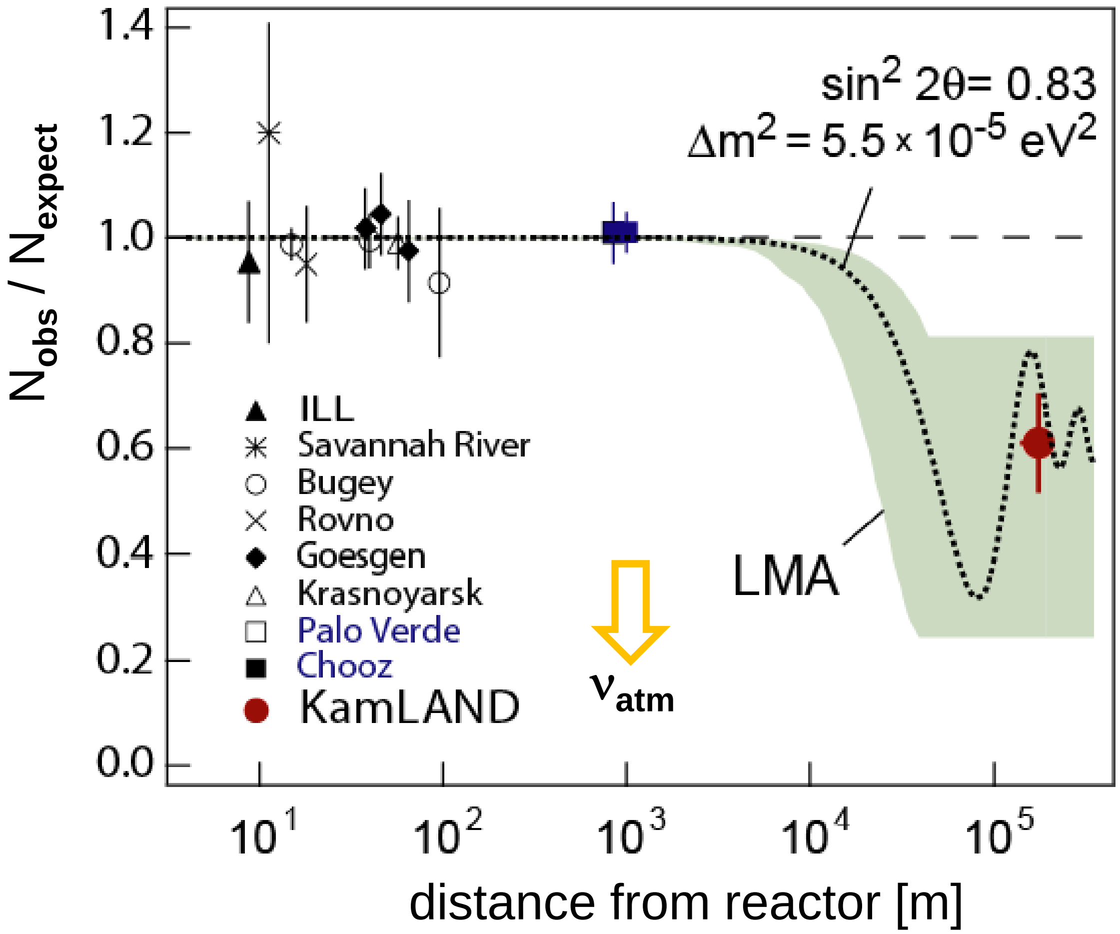
MINOS

OPERA (ν_τ)

results from reactor–ν–experiments

ratio of observed to calculated reactor neutrino events as a function of the distance from the reactor core (10 m – 100 km) & scaling





KamLAND detector

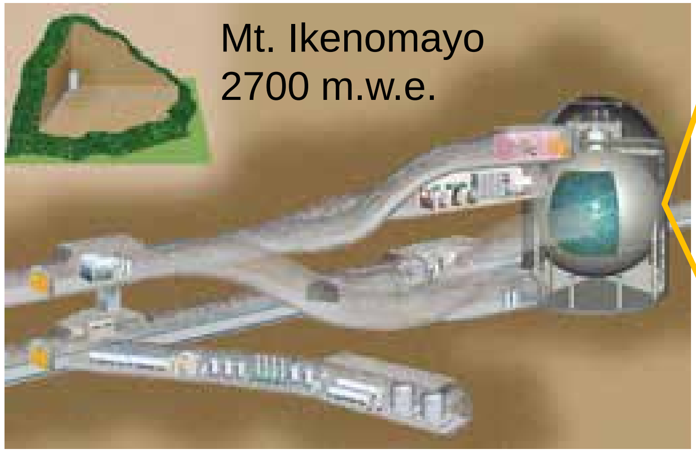
Kamioka Liquid Scintillator Anti-Neutrino Detector (Kamioka mine)

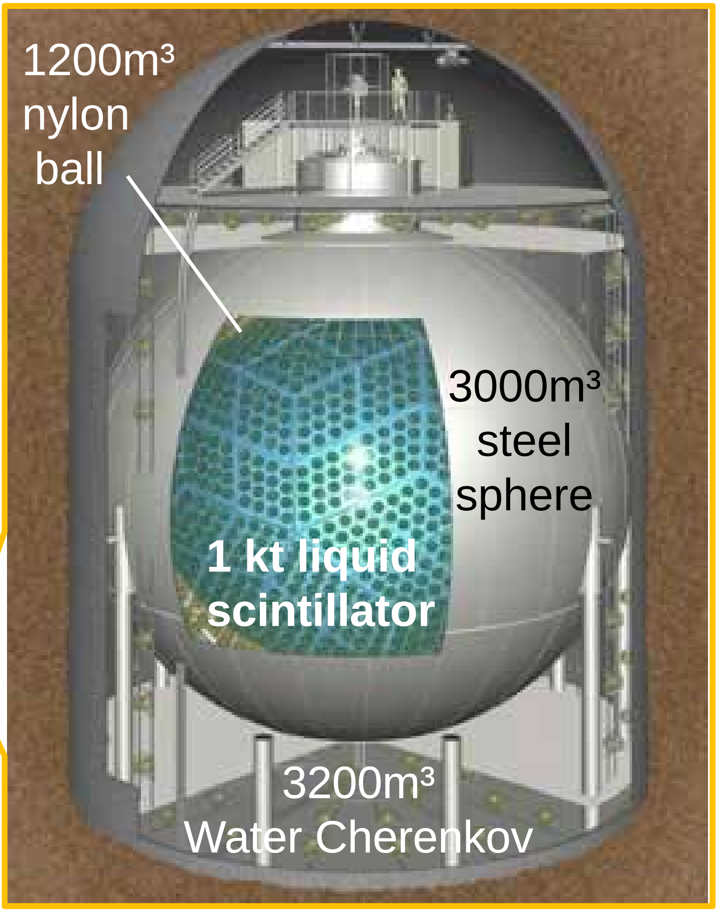
J-US-long-baseline-reactor experiment: **test of the LMA parameter spacee**
disappearance oscillation of $\bar{\nu}_e$ from all J nuclear reactors ($\Phi_\nu \sim 6 \times 10^6$ cm^{-2} s^{-1})
total power: 70 GW (~ 7 % of the world energy!)
distance d = 130 – 220 km, $\langle E_\nu \rangle \sim$ 2-3 MeV

International Nuclear Safety Center at ANL, Mar 1999

inverse ß-decay

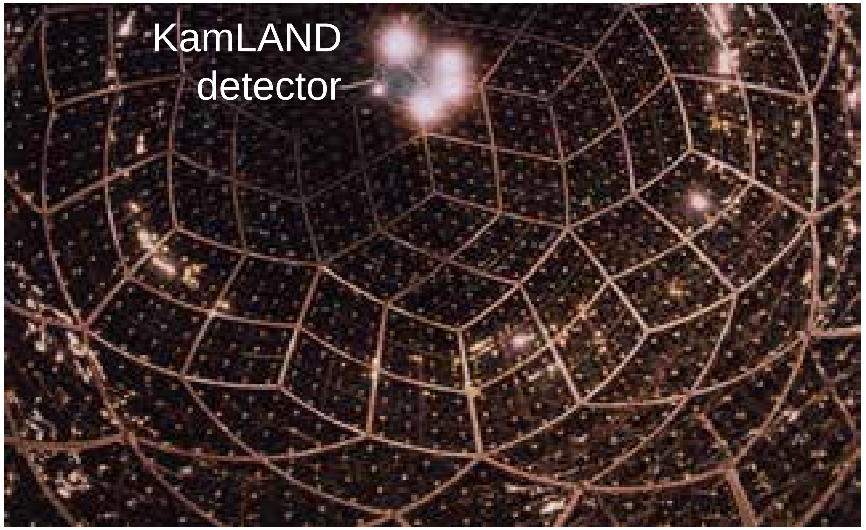
$$\bar{\nu}_e + p \rightarrow n + e^+$$

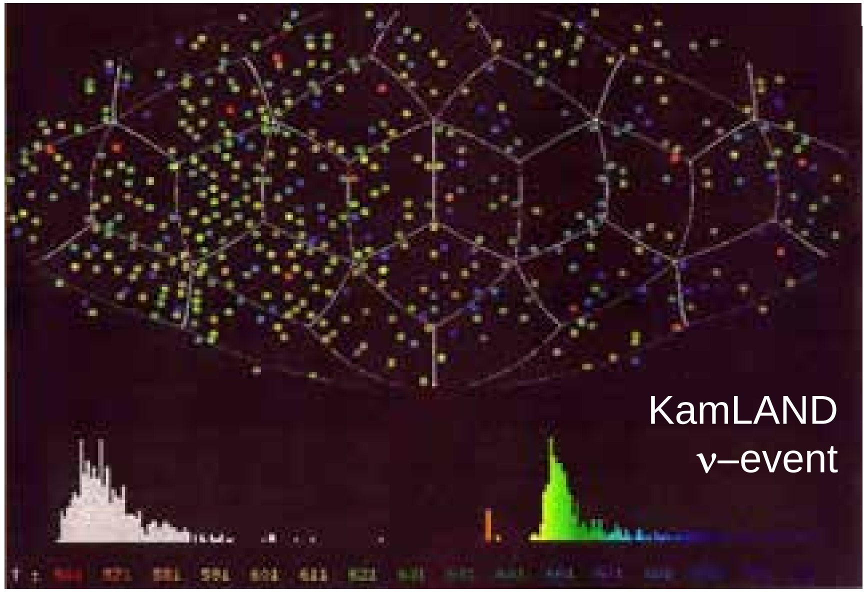




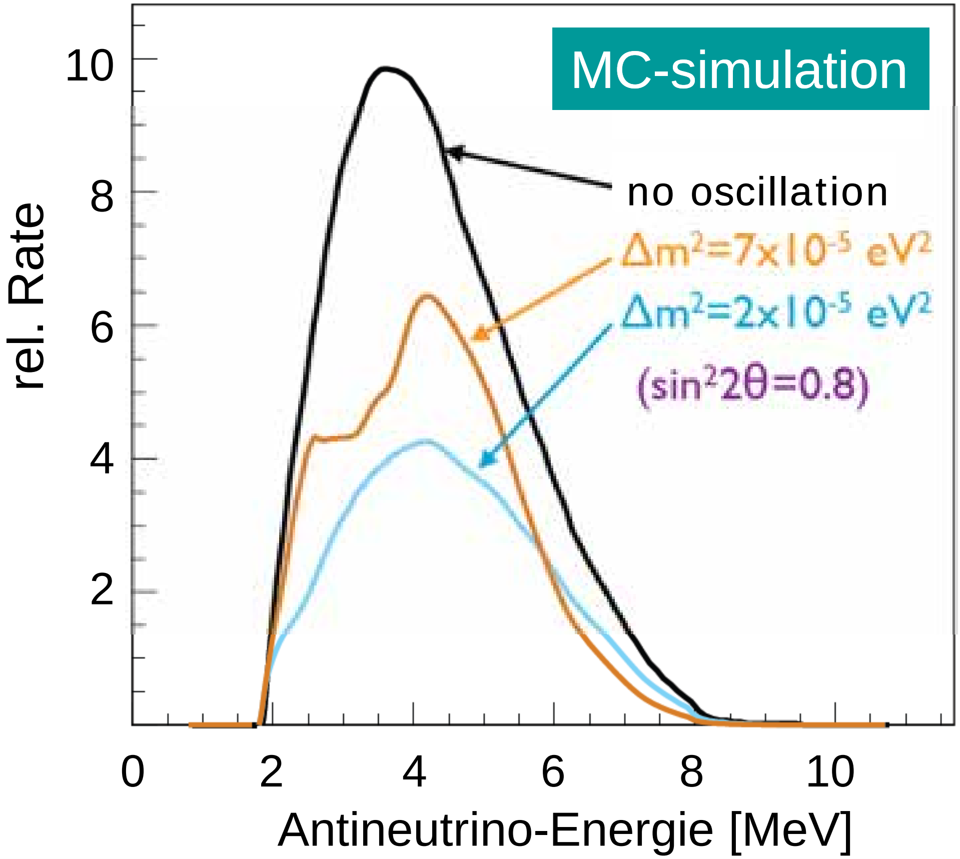
KamLAND – Ereignis & Signal

measurements: 3/2002 – 5/2007 (1491 days, 2881 ton-years)





- very strong sensitivity of the ν–spectrum to the oscillation parameter Δm^2
- ´complementary´ to solar ν´s ($\sin^2 2\theta_{12}$)



KamLAND – results

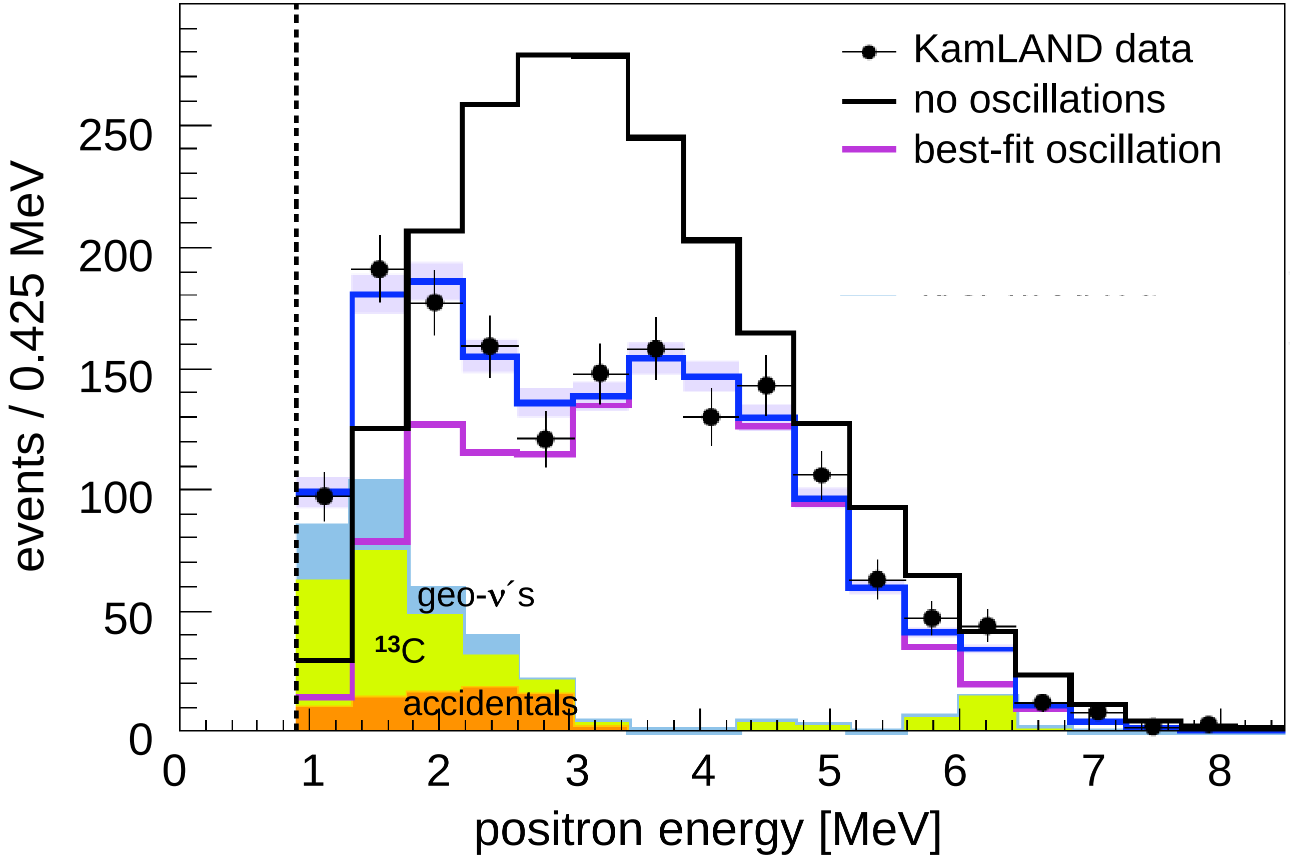
clear & unambiguous evidence for disappearance of reactor neutrinos

spectrum is fitted with components: reactor-ν´s, geo-ν´s, background

$\Delta m^2 = (7.58 \pm 0.14_{stat} \pm 0.15_{syst}) \times 10^{-5}\ \mathrm{eV}^2$

$\tan^2\theta = 0.56 \pm 0.10 \pm 0.10$

KamLAND parameter



KamLAND results	
observed	1609
Background	276.1 ± 23.5
no oscillation	2179 ± 89

⇩

KamLAND and solar ν´s: same parameter space

solar ν´s: MSW effect (matter)

reactor-ν´s: vacuum oscillations

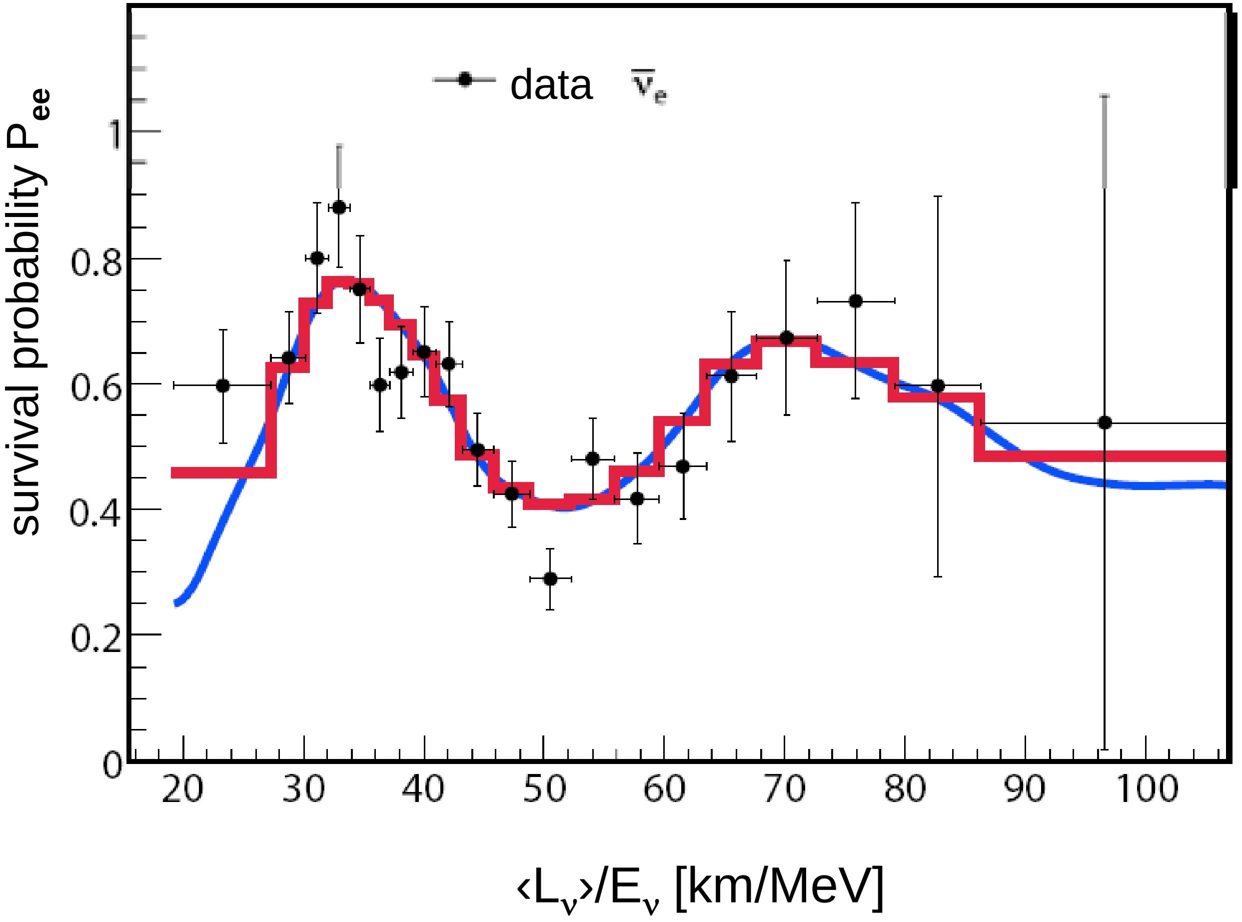
CPT symmetry ☑

KamLAND results

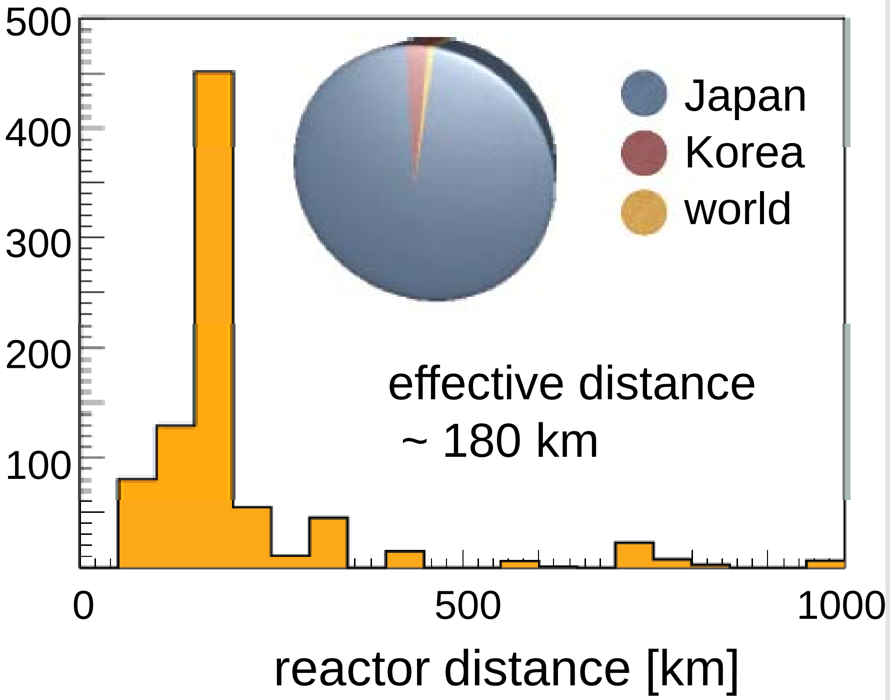
L_ν/E_ν – analysis from KamLAND: L_ν not measurable, effective distance 180 km

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

$\bar{\nu}_e$-disappearance

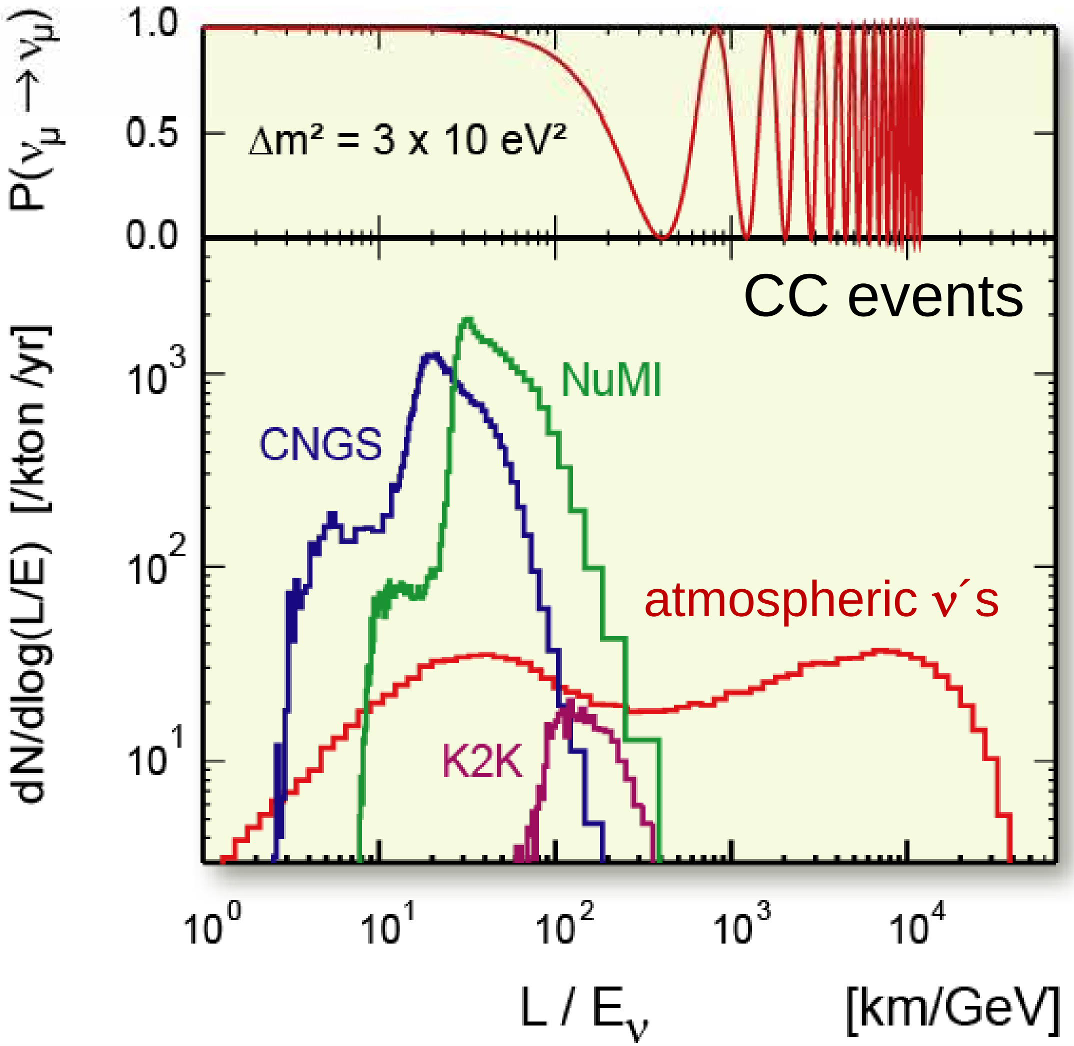


observation of two oscillation cycles



atmospheric ν´s & accelerators

cross-checking the results of atmospheric ν´s with long-baseline accelerator-ν-experiments



atmospheric ν´s:

large Δm² (L_ν/E_ν) space

CNGS :

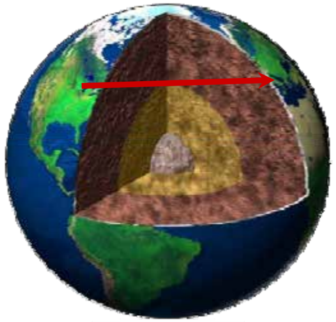
CERN SPS → Gran Sasso

NuMI :

FermiLab → Minos

K2K :

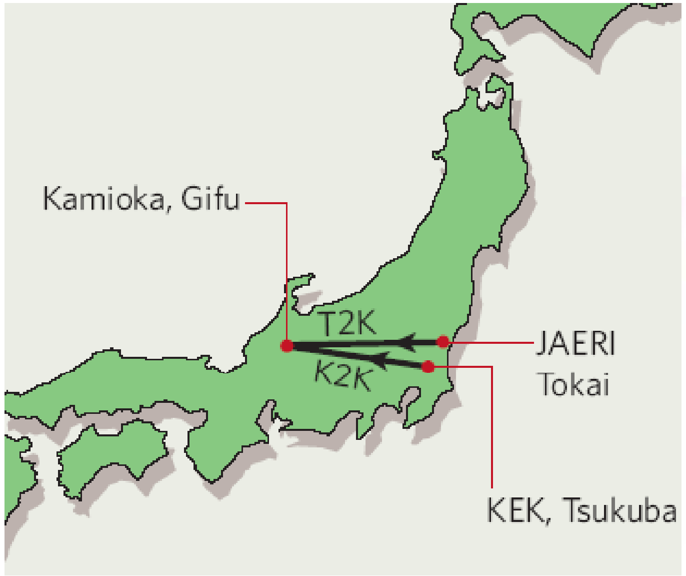
long baseline oscillation experiments

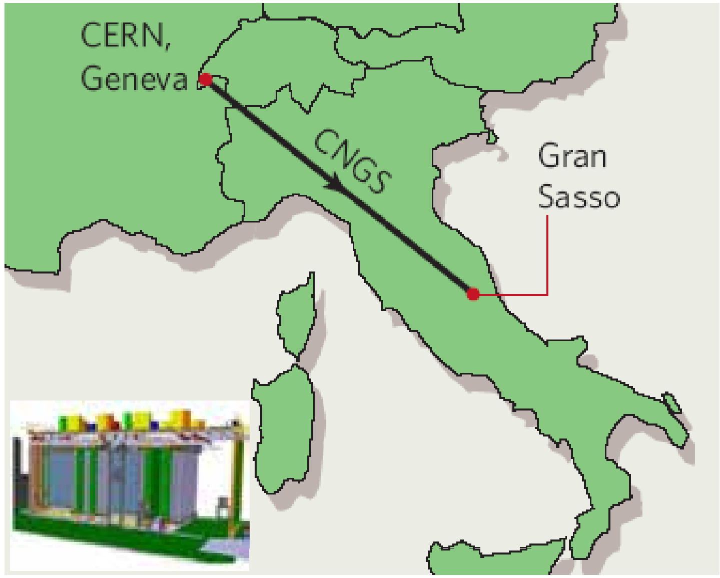


operating and planned long-baseline accelerator-based
ν-oscillation experiments in Japan, US & Europe

long baseline accelerator experiments: overview

LB-ν-beam	place	distance	energy	L/E	start	detector	channel
K2K	J	235 km	1.4 GeV	~150	1999	Super-Kamiokande	ν_μ - x
NuMI	US	735 km	1-30 GeV	50-350	2005	MINOS	ν_μ - x
CNGS	EU	732 km	30 GeV	50-350	2007	OPERA	ν_μ - ν_τ
T2K	J	295 km	GeV		2009	Super-Kamiokande	ν_μ - ν_e



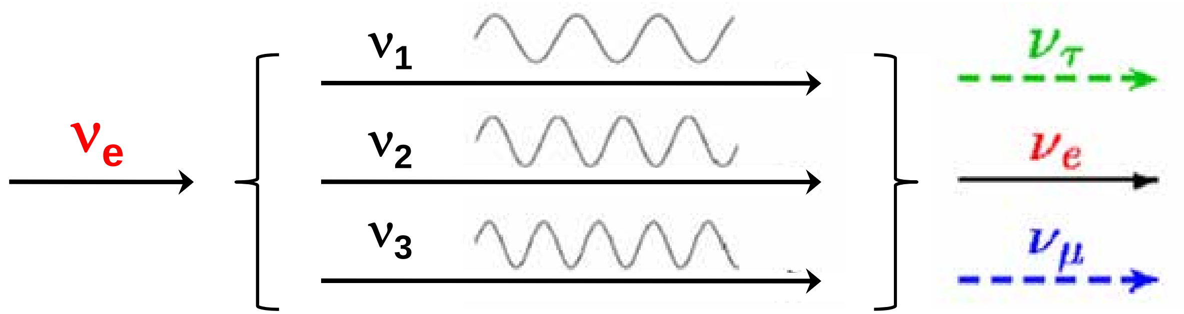


neutrino oscillations: 3-flavour mixing

extension of the 2-flavour oscillations to **3-flavour mixing**:

- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- two independent Δm^2 scales with relation:

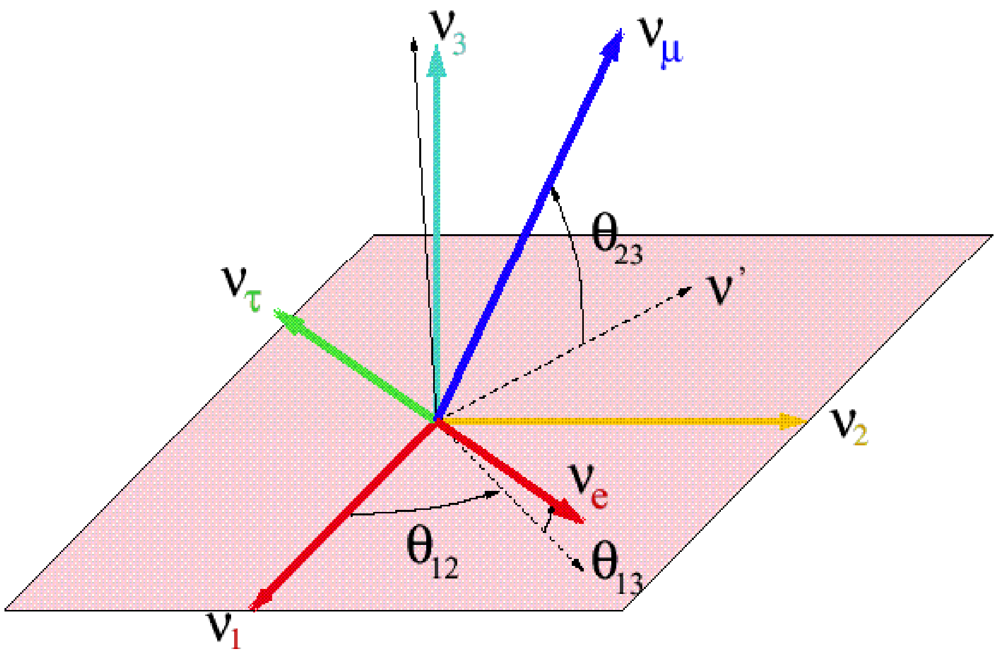
$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$



$\Delta m_{12}^2 = |m_1^2 - m_2^2|$ 1. & 2. generation

$\Delta m_{23}^2 = |m_2^2 - m_3^2|$ 2. & 3. generation

$\Delta m_{13}^2 = |m_1^2 - m_3^2|$ 1. & 3. generation



leptonic PMNS mixing matrix:
Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

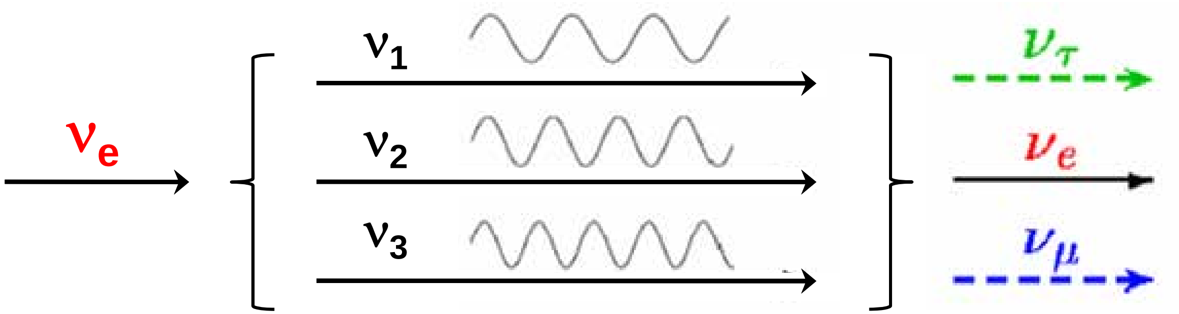
U = unitarity 3 × 3 mixing matrix

neutrino oscillations: 3-flavour mixing

extension of the 2-flavour oscillations to **3-flavour mixing**:

- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- two independent Δm^2 scales with relation:

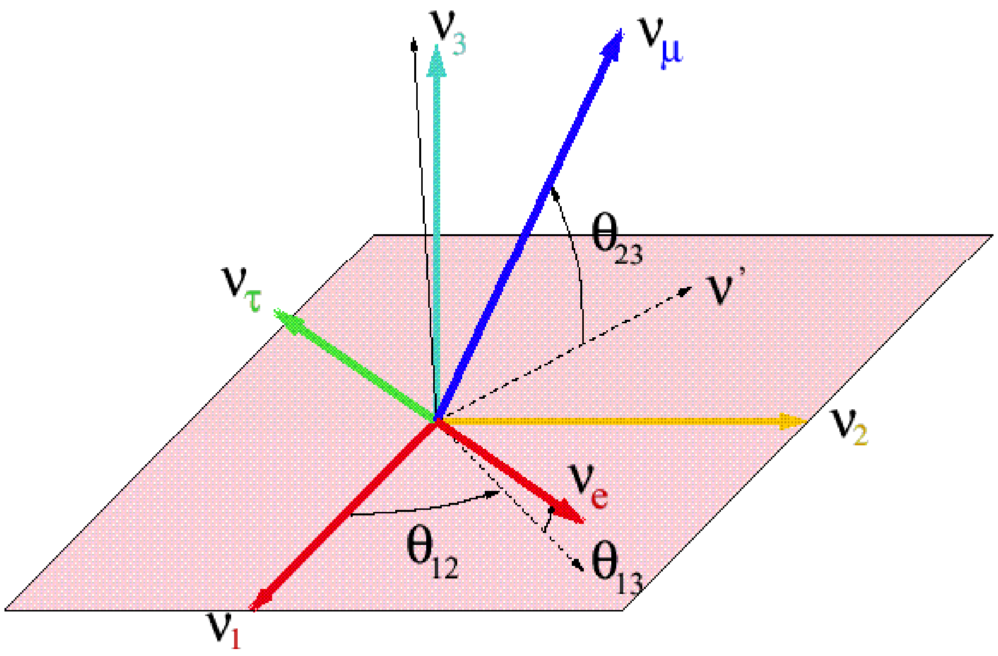
$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$



$$\Delta m_{12}^2 = | m_1^2 - m_2^2 |$$ 1. & 2. generation

$$\Delta m_{23}^2 = | m_2^2 - m_3^2 |$$ 2. & 3. generation

$$\Delta m_{13}^2 = | m_1^2 - m_3^2 |$$ 1. & 3. generation



leptonic PMNS mixing matrix:
Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 0.81\text{–}0.85 & 0.53\text{–}0.58 & 0.00\text{–}0.12 \\ 0.32\text{–}0.49 & 0.52\text{–}0.69 & 0.60\text{–}0.76 \\ 0.27\text{–}0.46 & 0.47\text{–}0.64 & 0.65\text{–}0.80 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U = unitarity 3 × 3 mixing matrix

neutrino oscillations: 3-flavour mixing

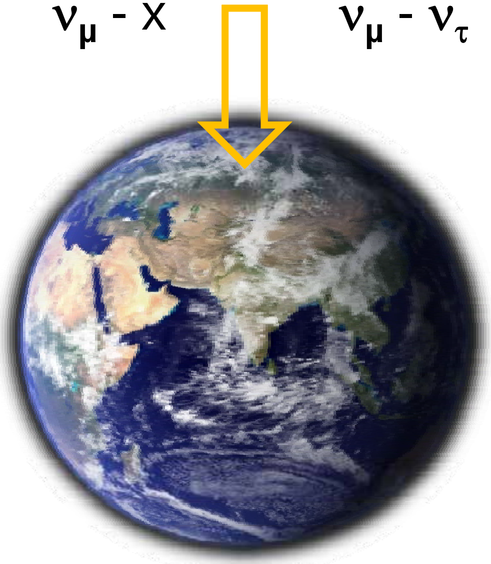
3-flavour oscillations ´decouple´ into three separate mixing terms:

δ: CP-phase

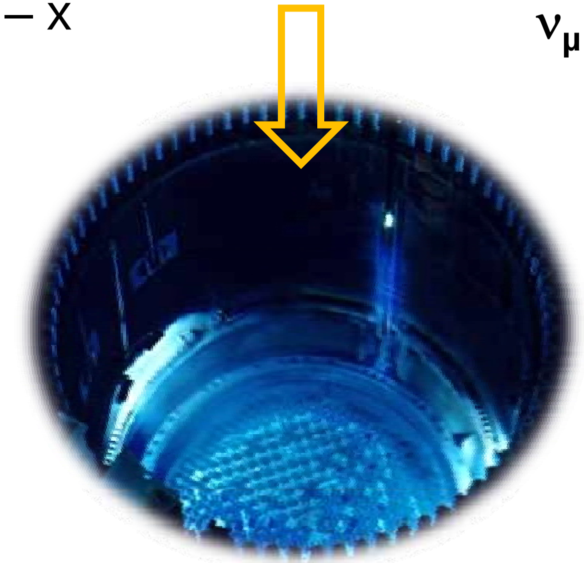
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

2. & 3. generation	1. & 3. generation	1. & 2. generation
atmospheric ν´s	solar / reactor neutrinos	solar neutrinos
long baseline accelerators	long baseline reactor/accelerators	reactor experiments

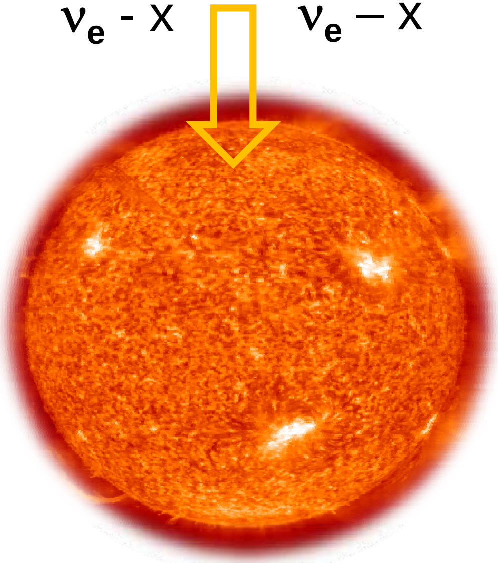
ν_μ - X $\quad$ ν_μ - ν_τ



$\bar{\nu}_e$ – X $\quad$ ν_μ - ν_e



ν_e - X $\quad$ $\bar{\nu}_e$ – X



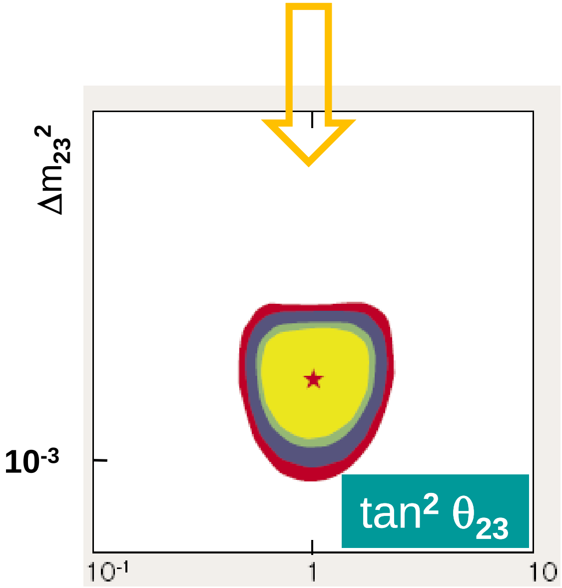
neutrino oscillations: 3-flavour mixing

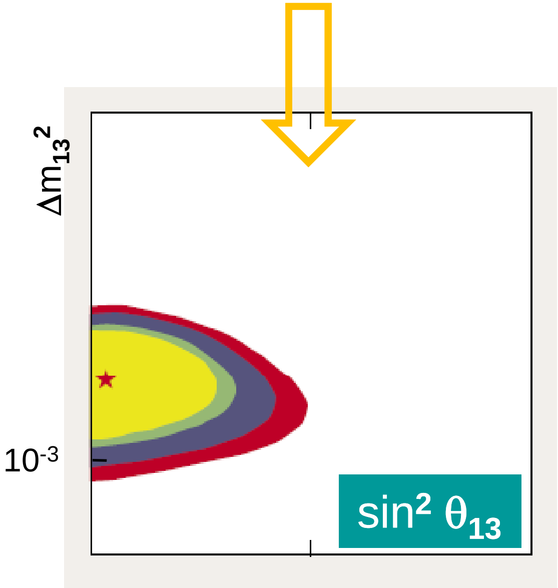
3-flavour oscillations ´decouple´ into three separate mixing terms:

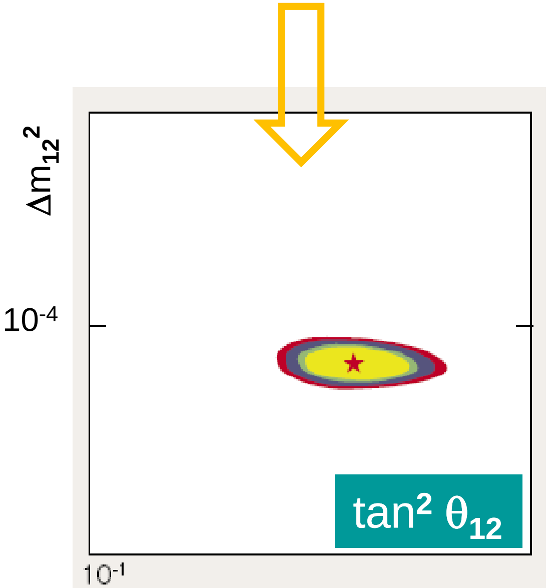
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

δ: CP-Phase

2. & 3. generation	**1. & 3. generation**	**1. & 2. generation**
$\Delta m_{23}^2 = 2.3 \times 10^{-3}$ eV²	$\Delta m_{13}^2 = 2.3 \times 10^{-3}$ eV²	$\Delta m_{12}^2 = 7.9 \times 10^{-5}$ eV²
$\theta_{23} = (45 \pm 4)°$ (maximum)	$\theta_{13} < 15°$ (very small)	$\theta_{23} = (33.7 \pm 1.3)°$ (large)

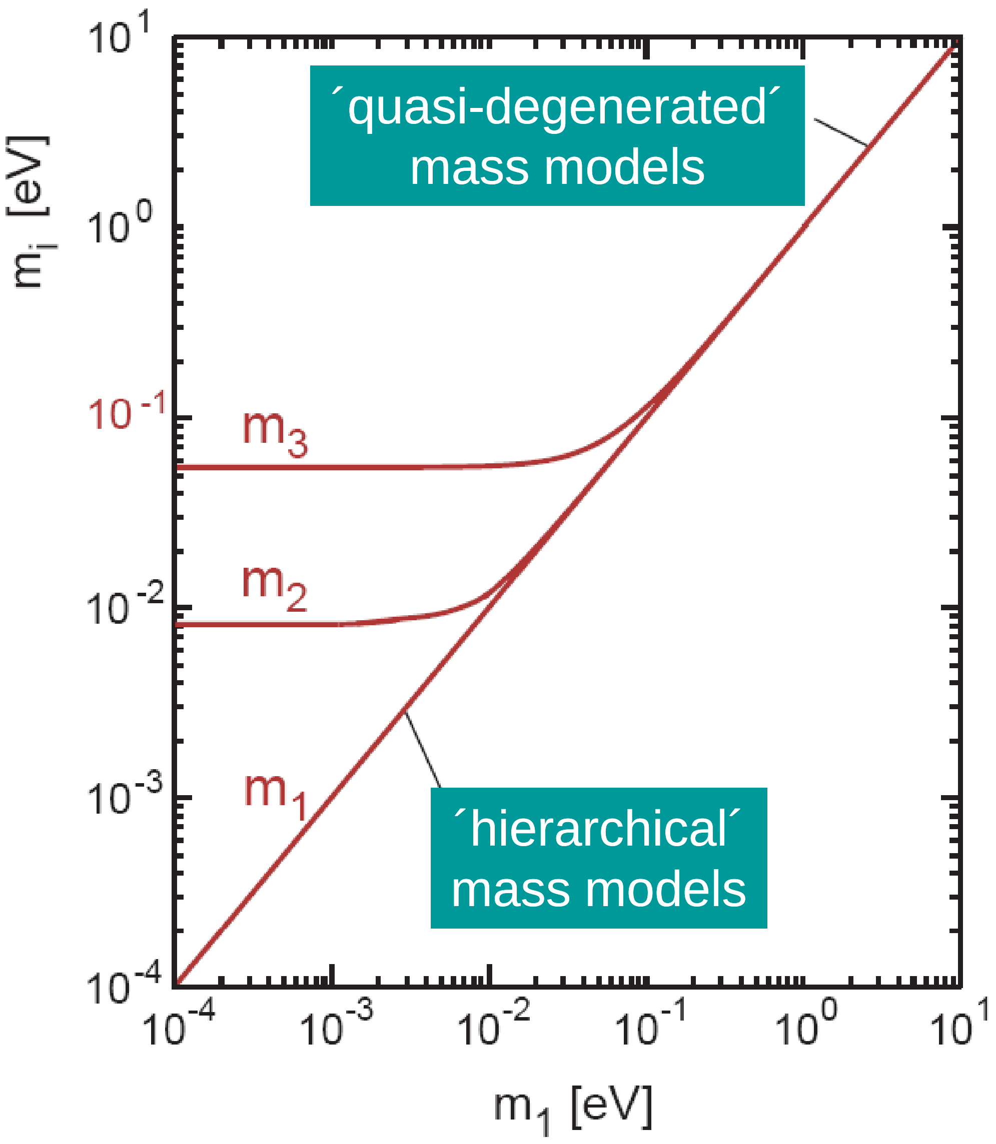


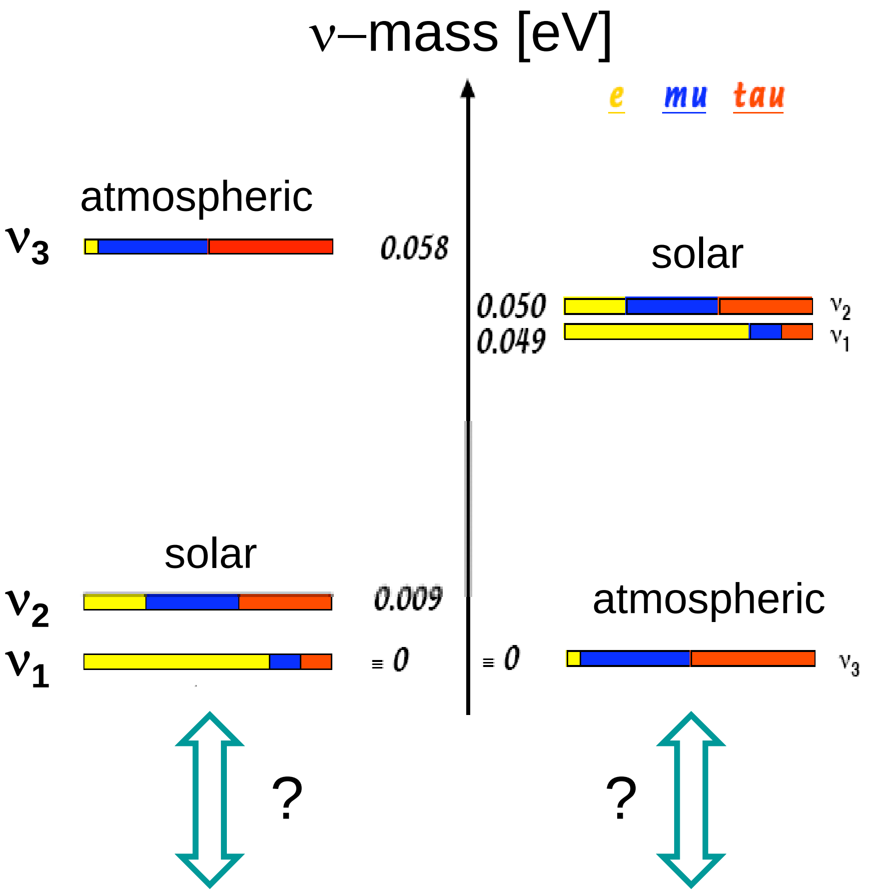




neutrino masses in particle physics

normal hierarchy with $m_1 < m_2 < m_3$

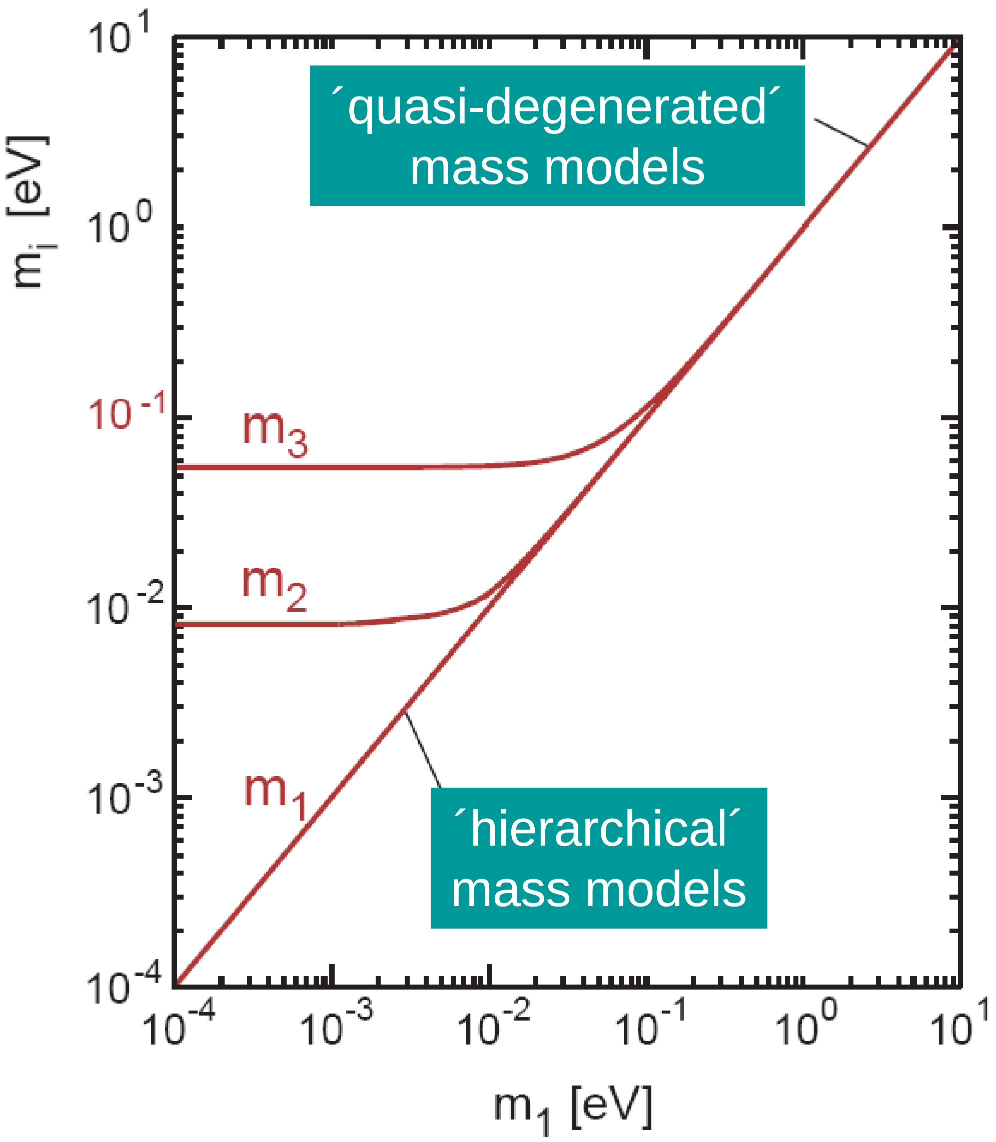


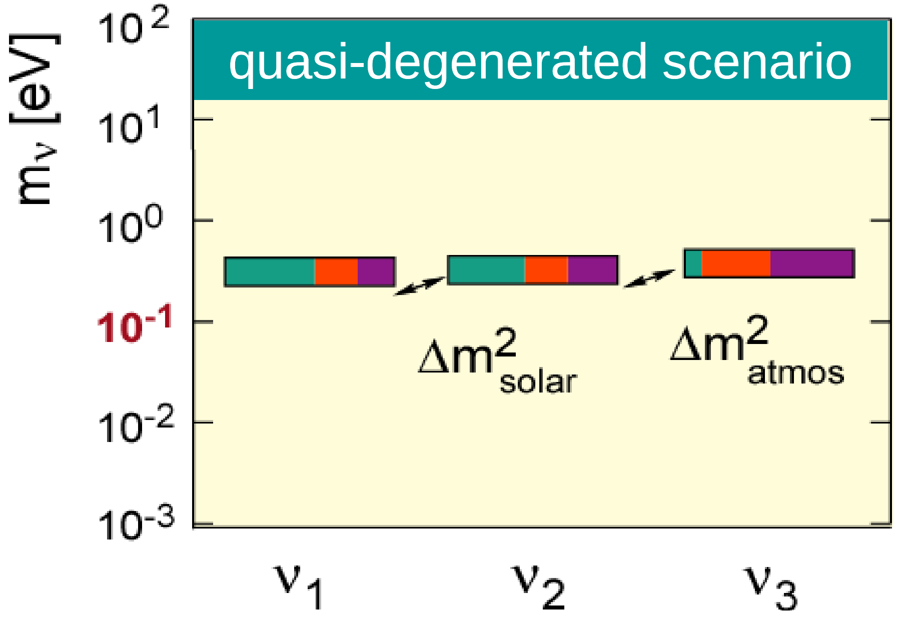


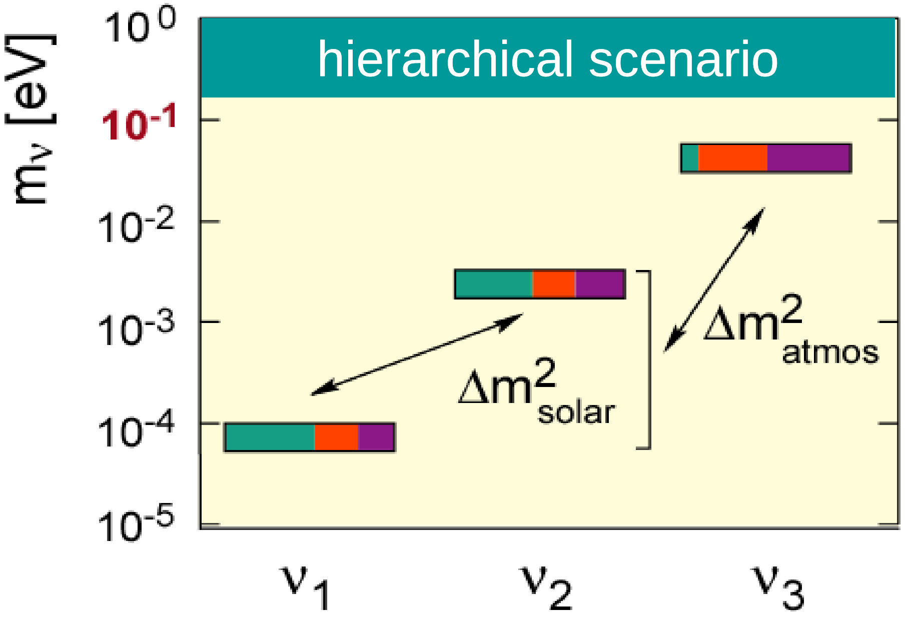
ν–mass offset?
absolute scale m_1?

neutrino masses in particle physics

normal hierarchy with $m_1 < m_2 < m_3$

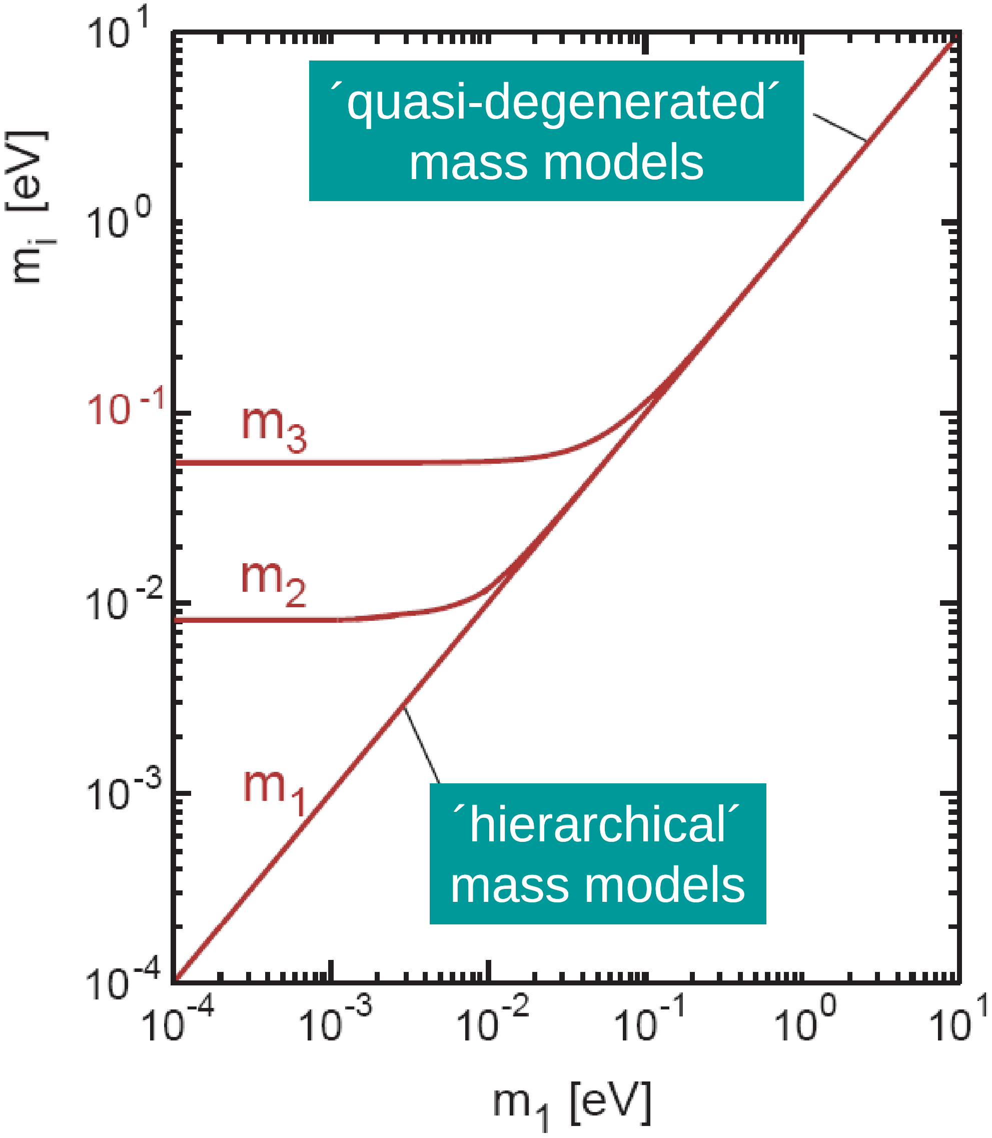






neutrino masses in particle physics

normal hierarchy with $m_1 < m_2 < m_3$



´quasi-degenerated´ mass models

´hierarchical´ mass models

flavour composition of mass eigenstates