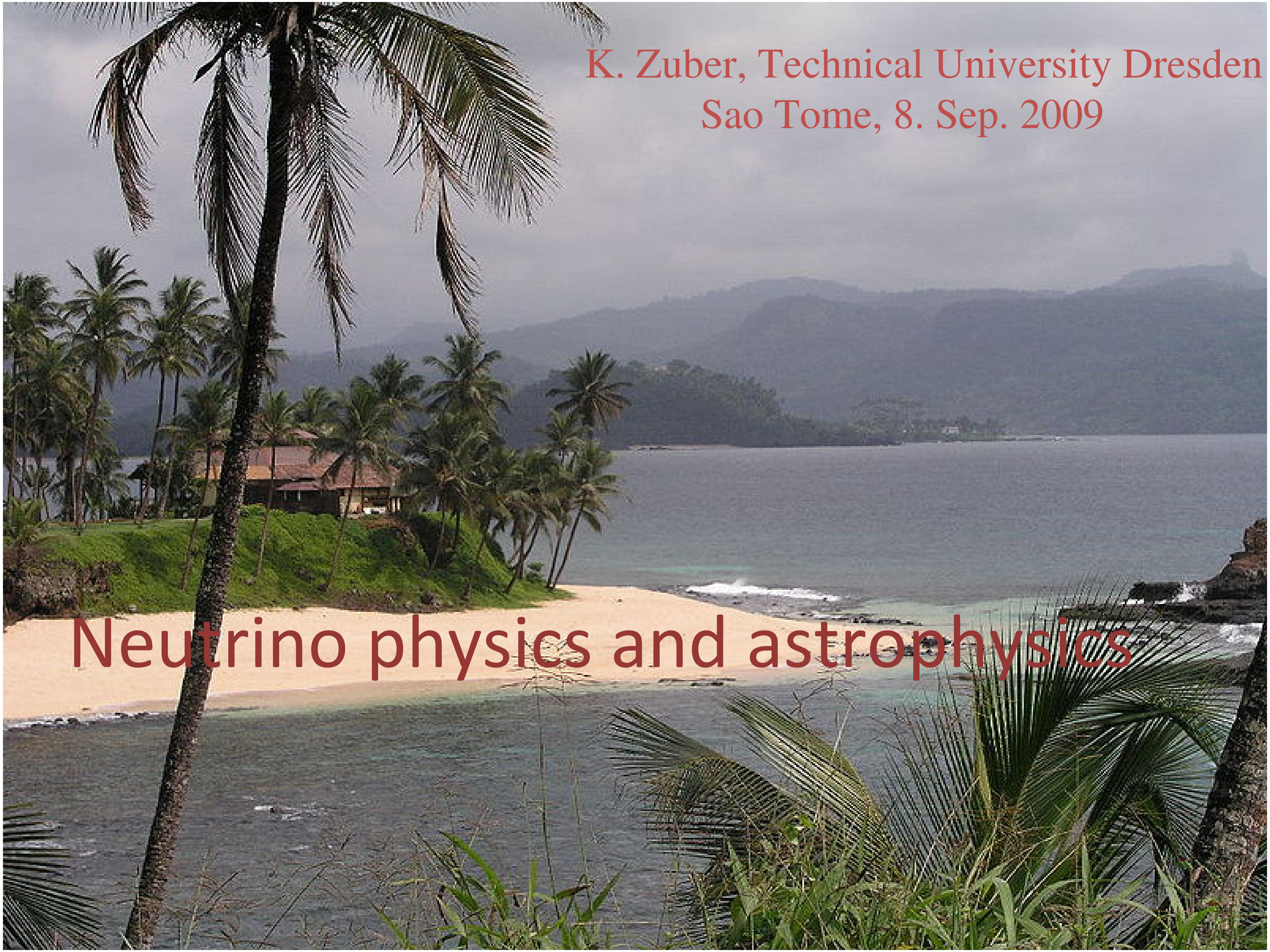
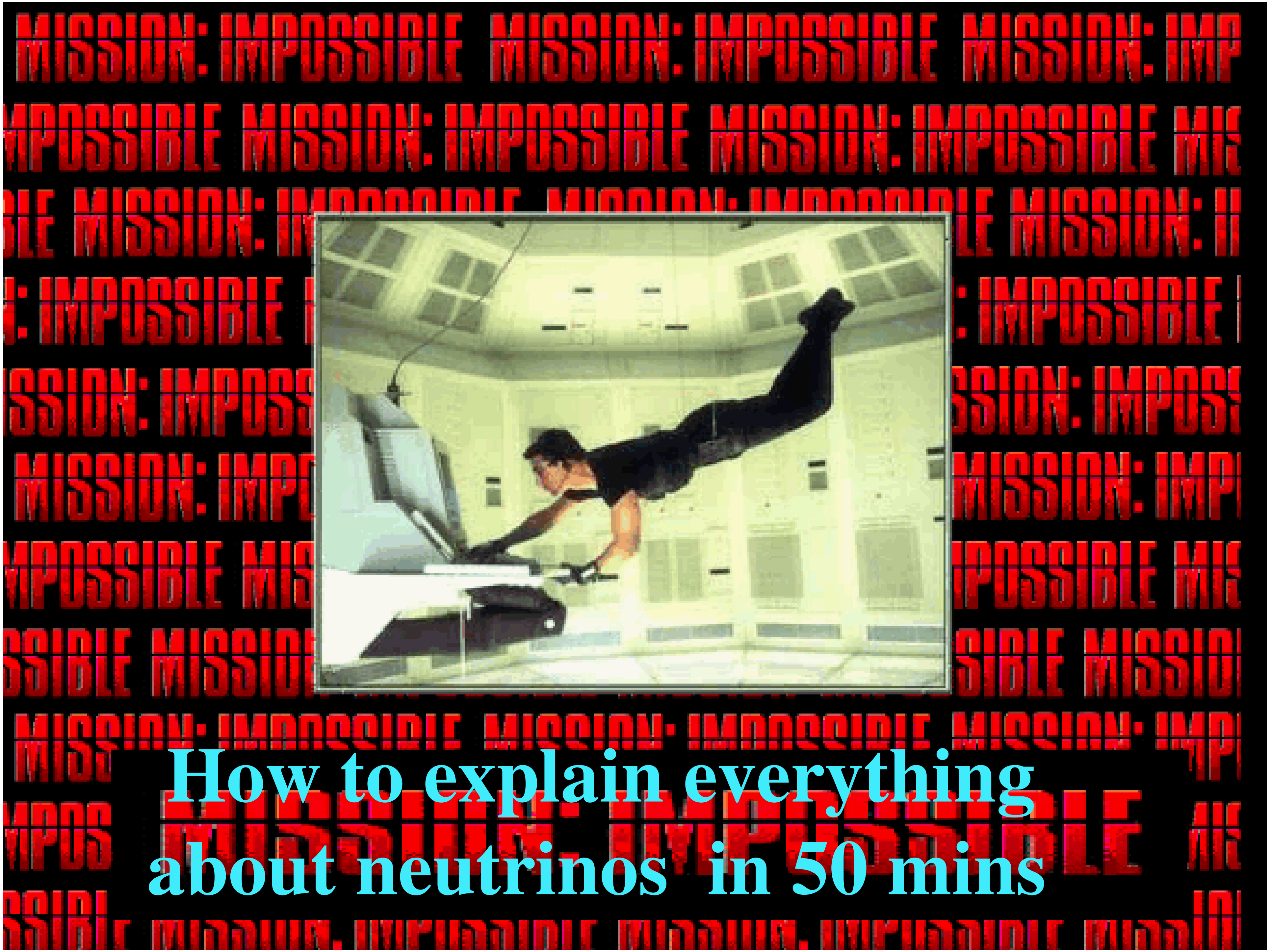


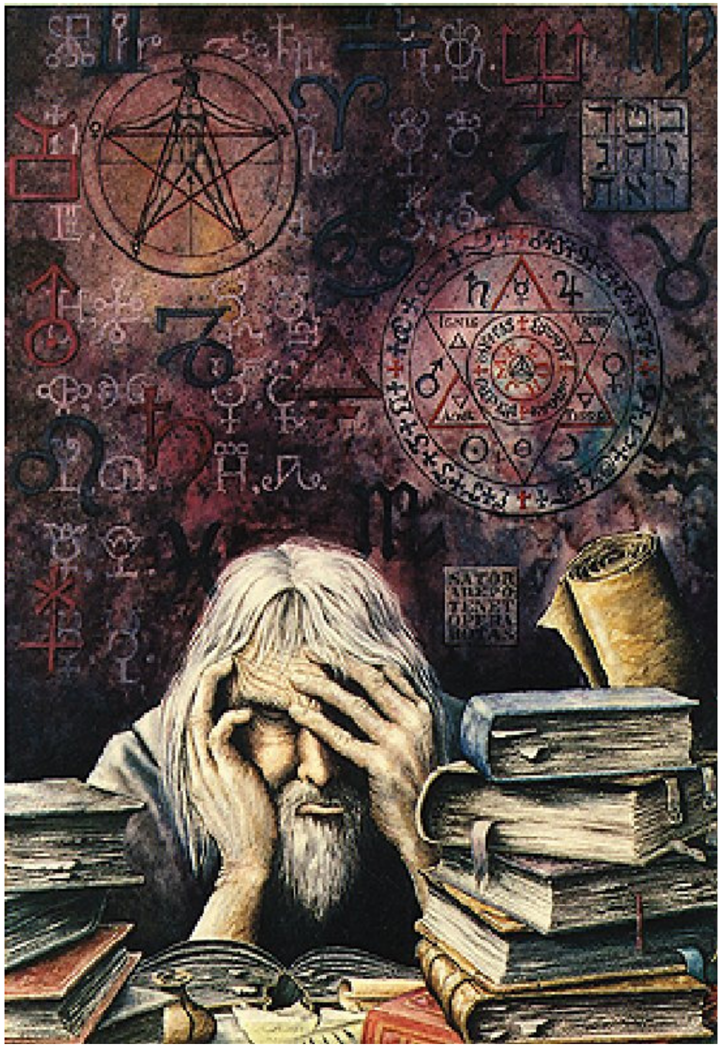
K. Zuber, Technical University Dresden
Sao Tome, 8. Sep. 2009

Neutrino physics and astrophysics



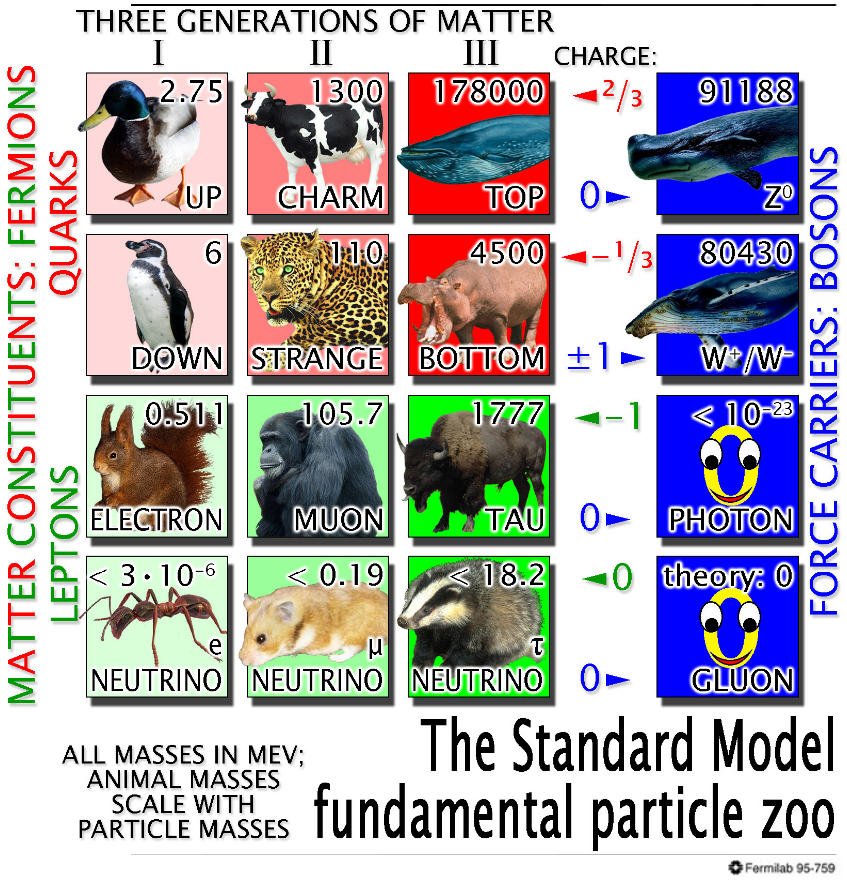
How to explain everything about neutrinos in 50 mins

Contents



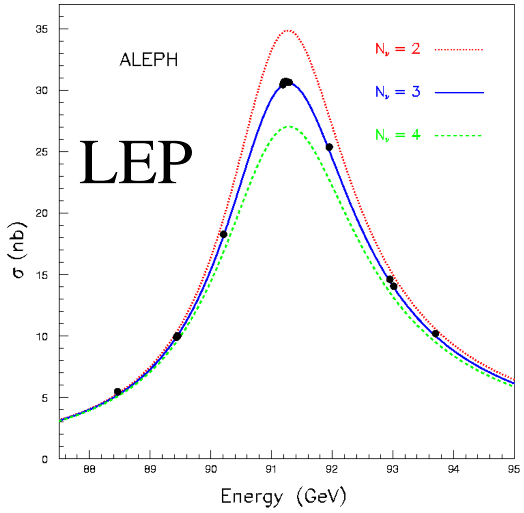
- General introduction
- Evidence for neutrino masses, status 2009
- Future questions/projects
- Neutrino Astrophysics
- Summary

The Standard Model



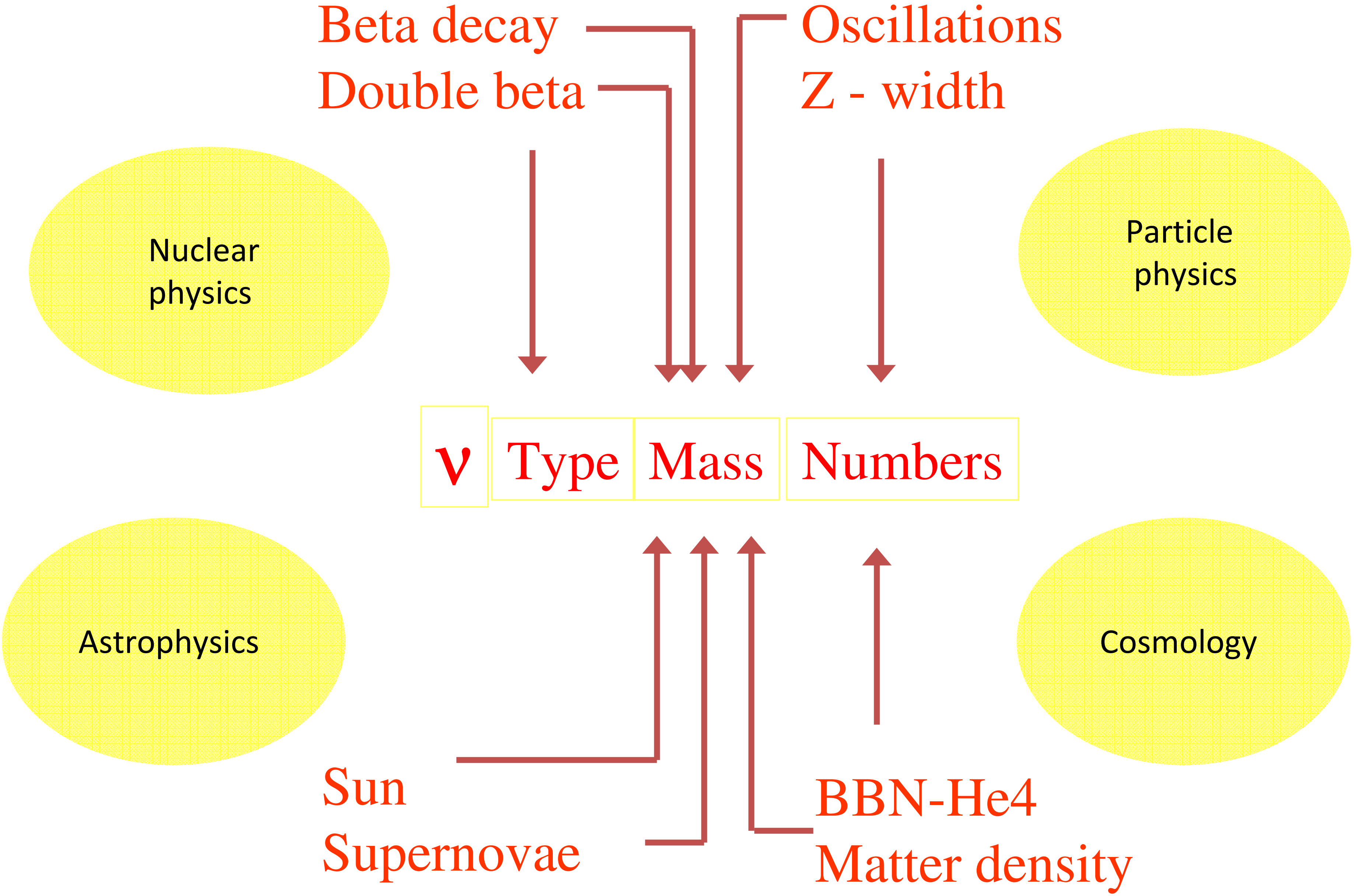
1955: m < 10 keV (< 2% of electron)

In the Standard Model neutrinos are massless particles



+ Higgs boson

Neutrino Physics



Beta decay

Double beta

Oscillations

Z - width

Nuclear physics

Particle physics

ν Type Mass Numbers

Astrophysics

Cosmology

Sun

Supernovae

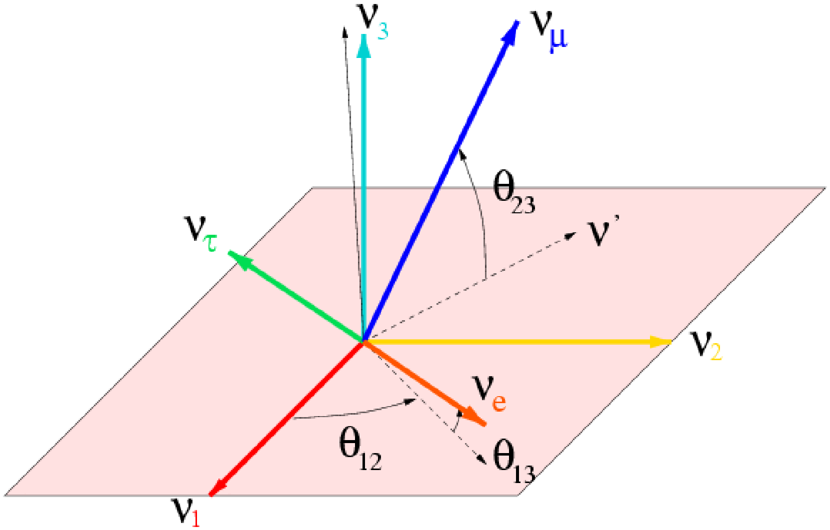
BBN-He4

Matter density

3 Flavour mixing (PMNS)

Weak eigenstates not identical to mass eigenstates,
analogue to CKM mixing in quark sector

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



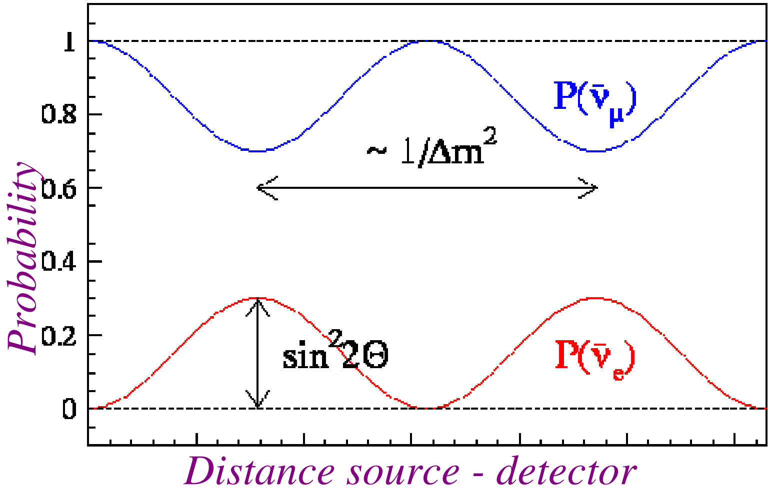
$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

Majorana neutrino: $U = U_{PMNS}\, diag(1, e^{i\alpha_1}, e^{i\alpha_2})$

Neutrino Oscillations

Neutrino mixing might lead to neutrino oscillations

Oscillation probability:



$$P(|\nu_\alpha\rangle \rightarrow |\nu_\beta\rangle) = \sin^2 2\Theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

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

2-flavour scenario, 3-flavour more complex equations

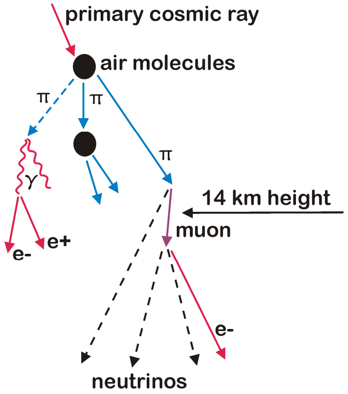
Sensitivity $\Delta m^2 \approx \frac{E}{L}$

2 unknown Parameters: $\sin^2 2\theta$, Δm^2

If you know Δm^2 you can try to tune E and/or L to get the best sensitivity

No absolute neutrino mass measurement!

Neutrino sources



Nuclear power plants $\bar{\nu}_e$

Accelerators

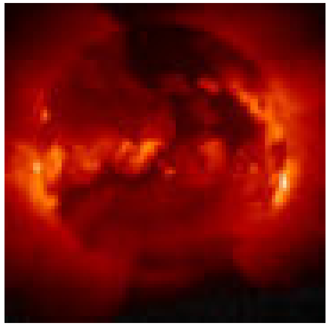
Earth radioactivity $\bar{\nu}_e$

The atmosphere

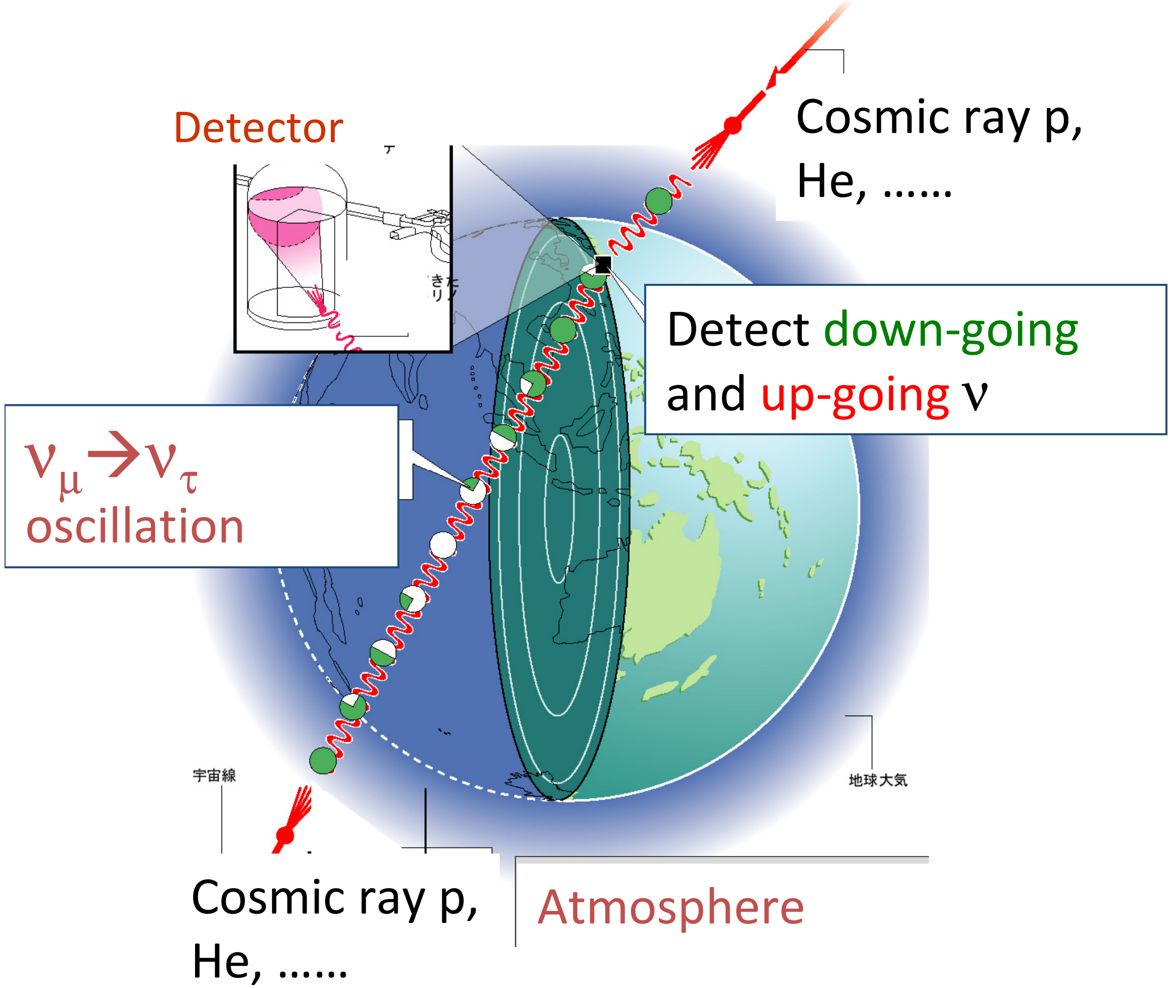
The Sun ν_e

Supernova

The Big Bang



Atmospheric ν - Super-K



Detector

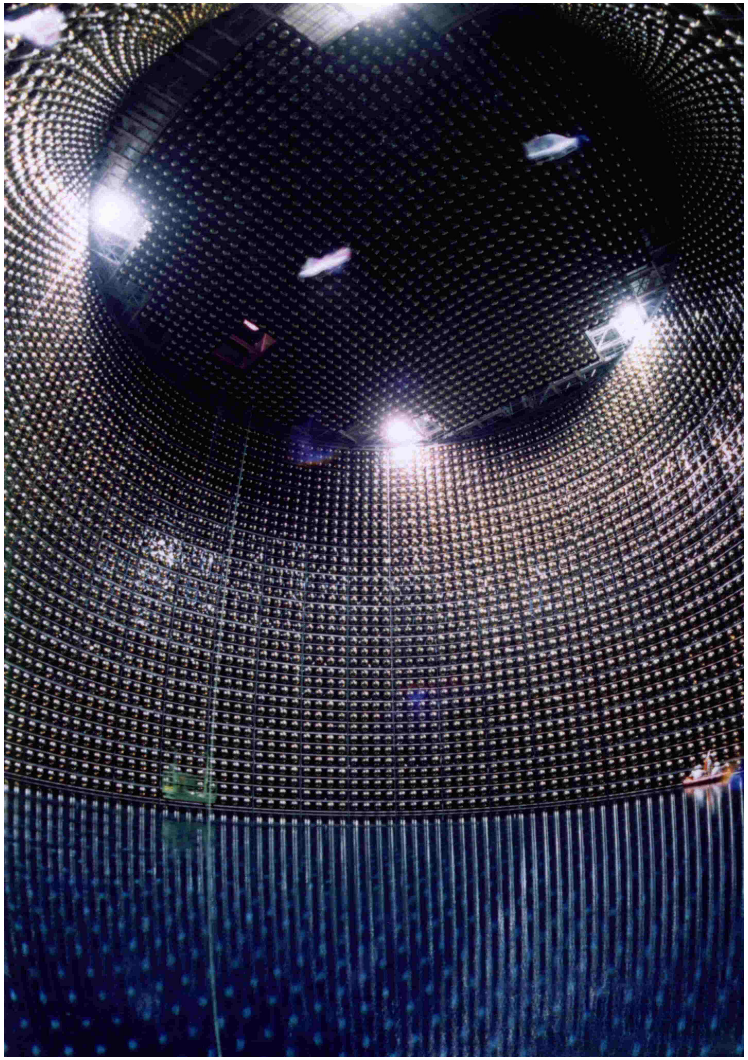
Cosmic ray p,
He, ……

Detect down-going
and up-going ν

$\nu_\mu \rightarrow \nu_\tau$
oscillation

Cosmic ray p,
He, ……

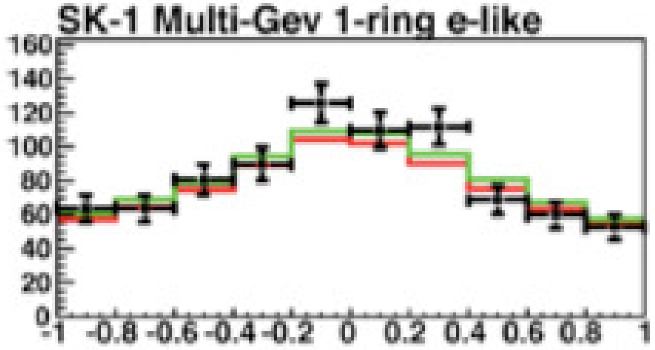
Atmosphere



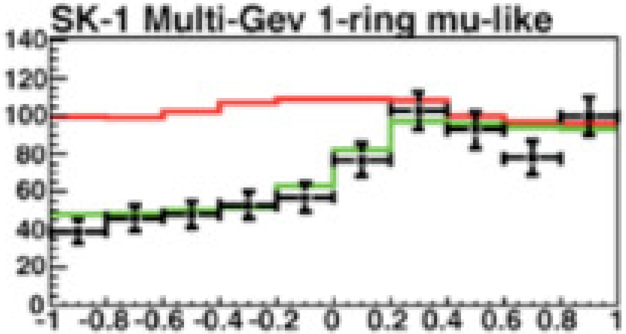
50 kt water Cerenkov detector

Atmospheric ν - Super-K

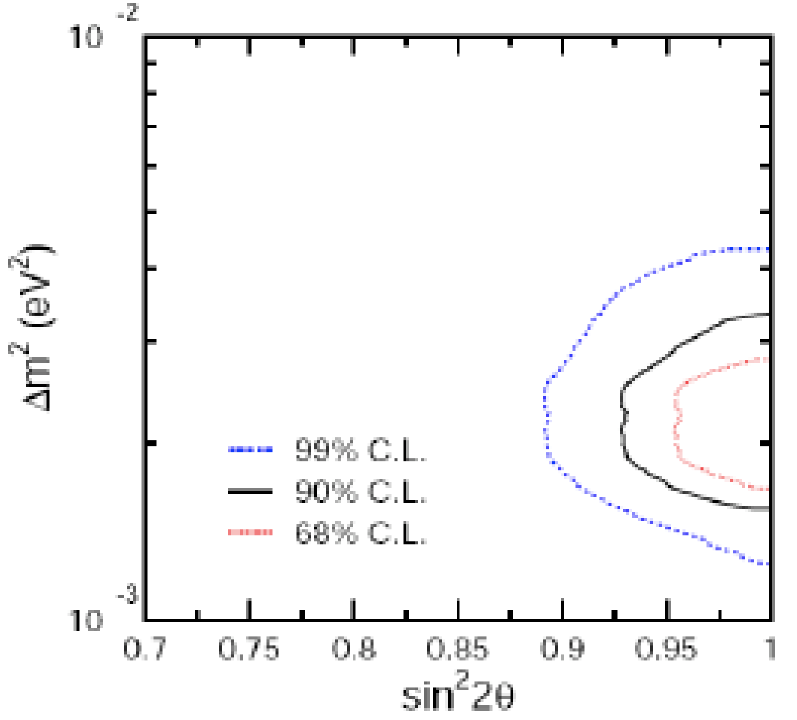
Zenith angle distribution



up horizontal down



Deficit in upward going muons

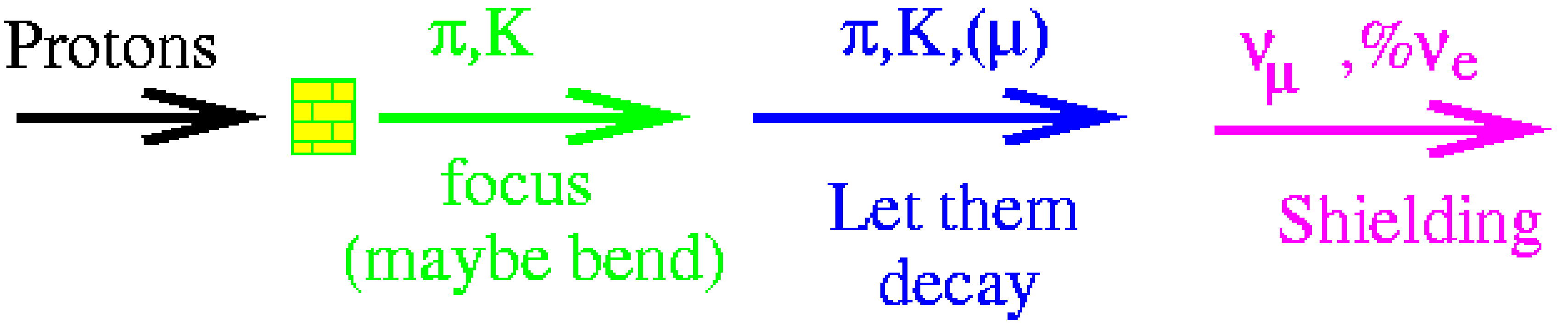


$$\sin^2 2\theta > 0.92 (90\% CL)$$

$$1.5\times10^{-3} < \Delta m^2 < 3.4\times10^{-3}\, eV^2$$

Check with Neutrino beams (Example: MINOS)

Baseline has to be some fraction of Earth diameter > 120 km (1%)



Protons

π,K

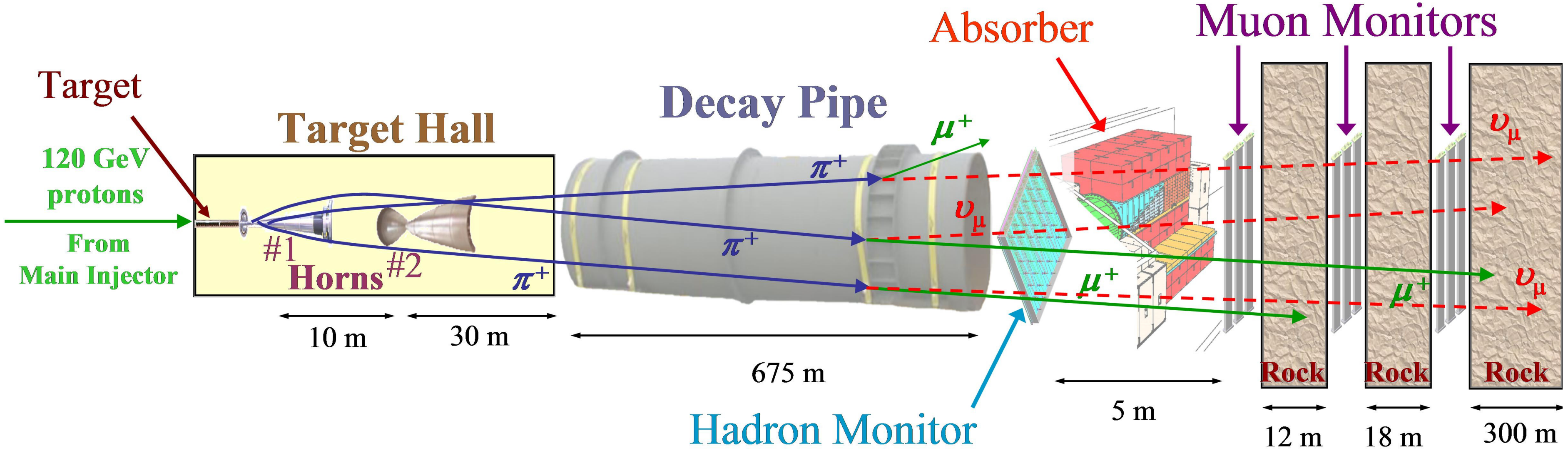
focus
(maybe bend)

π,K,(μ)

Let them
decay

ν_μ ,%ν_e

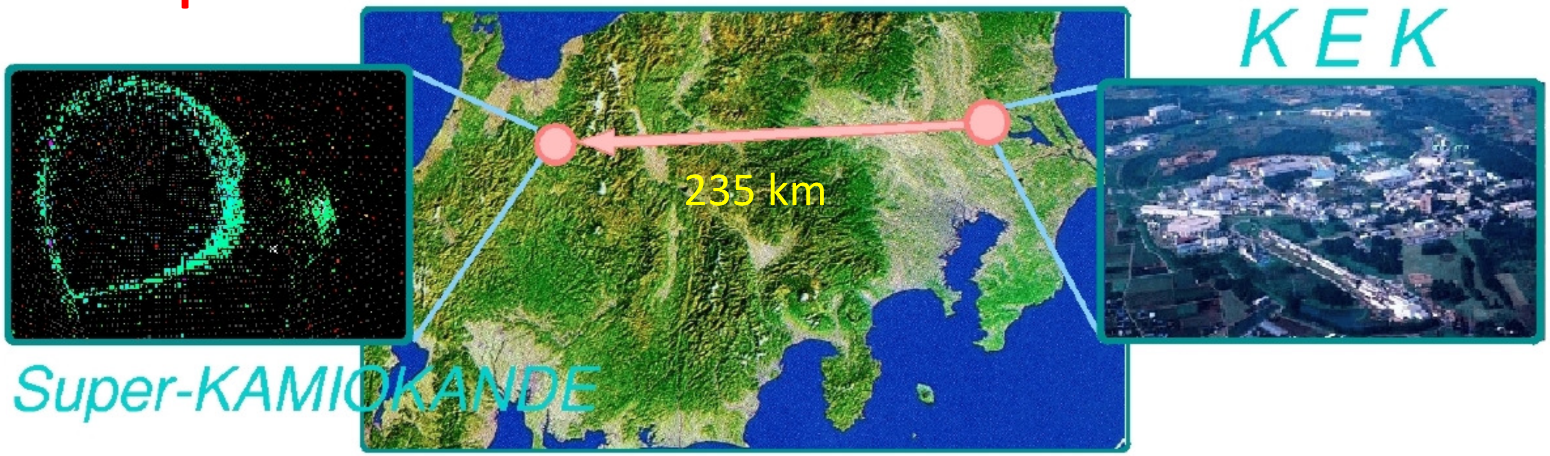
Shielding



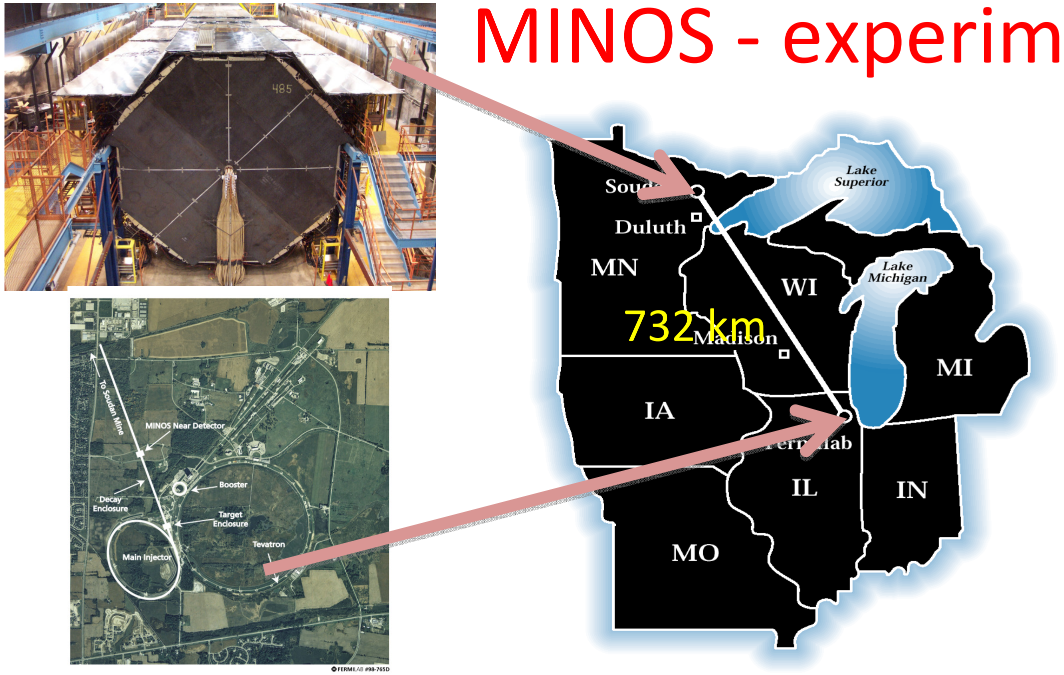
Major problem: Precise knowledge of neutrino energy spectrum at experiment

Long baseline results

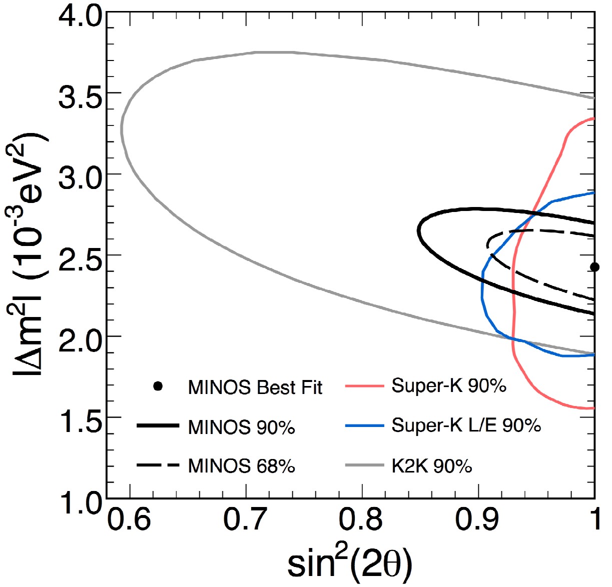
K2K - experiment



MINOS - experiment



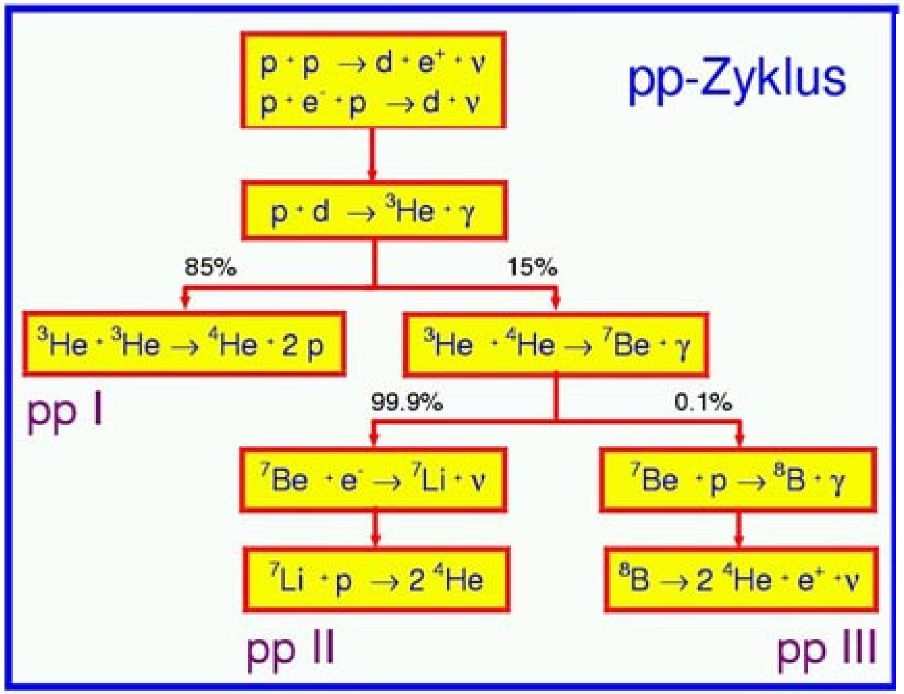
$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2
(68% C.L.), maximal mixing

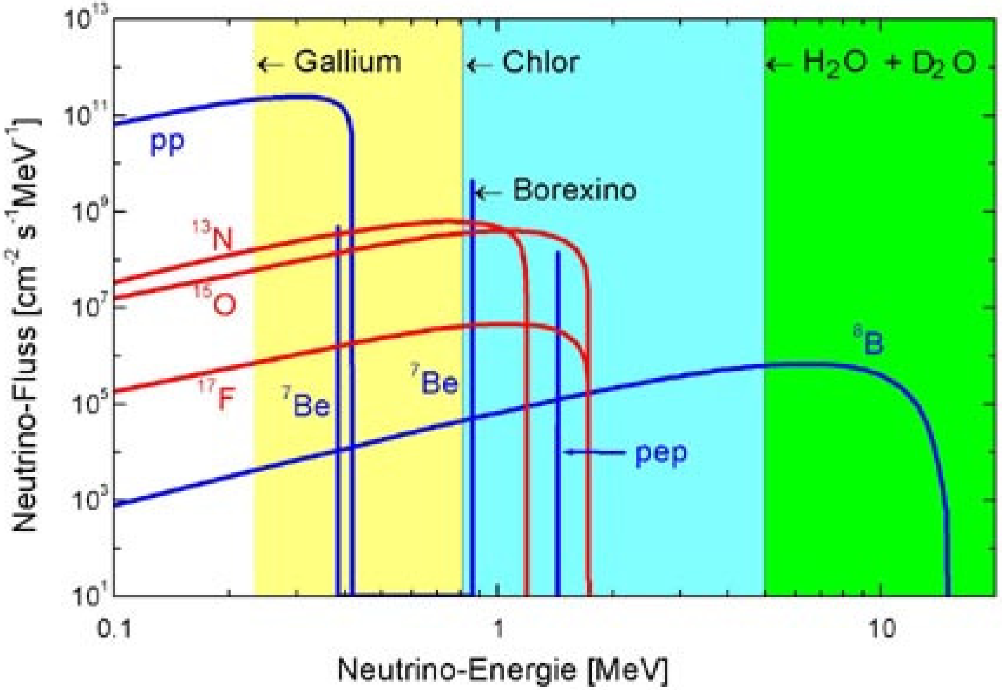


Standard Solar Models

Assumption: Sun is producing energy by nuclear fusion

$$2e^- + 4p \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}$$





60 billion neutrinos pass the Earth per cm² every second

Detection principle

radiochemical (CC)

$$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)$$

+: low energy -: not real-time

1 SNU = 10^{-36} captures/target atom/s

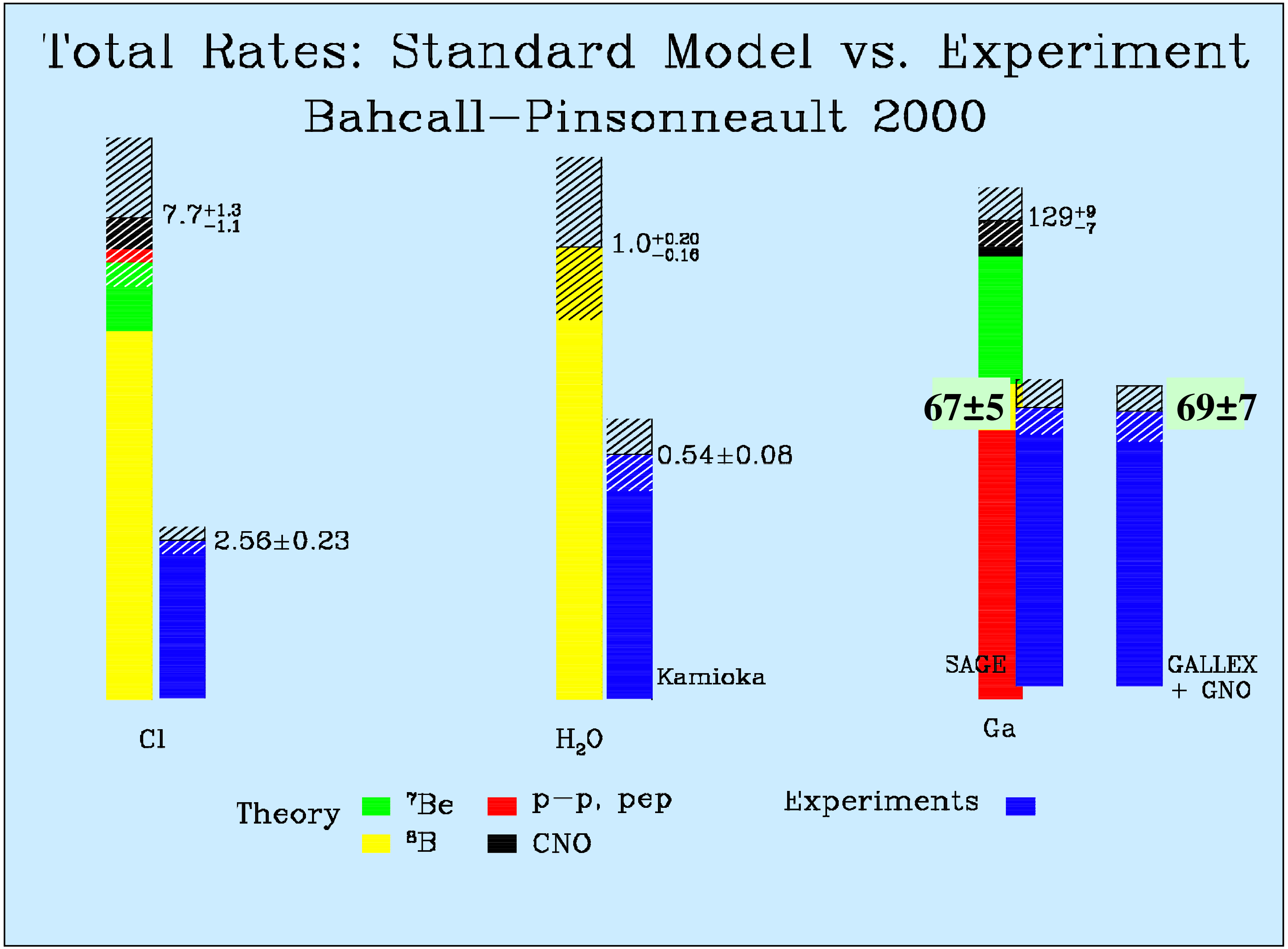
elastic electron-neutrino scattering (ES)

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

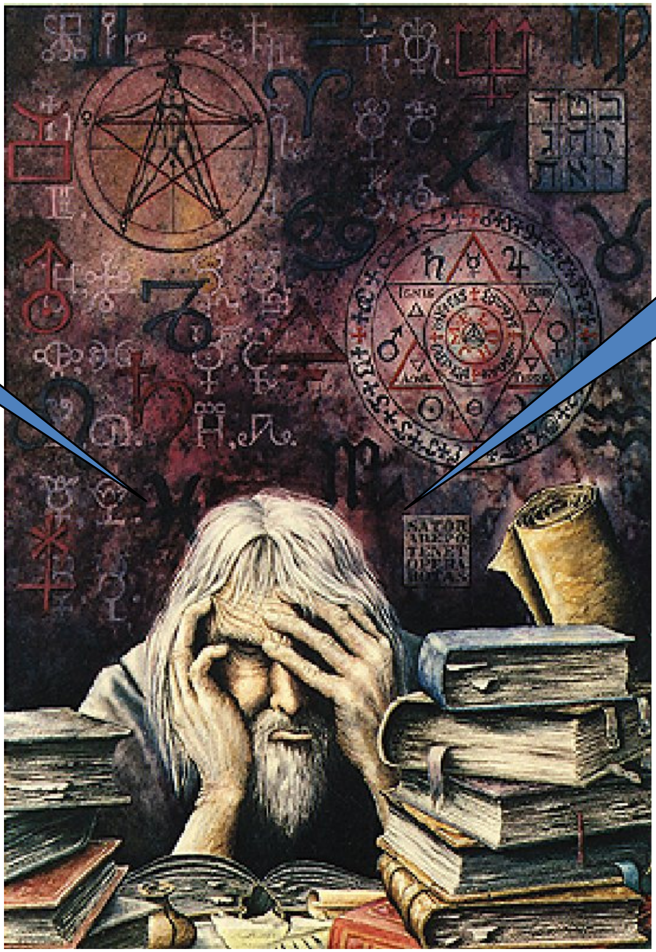
+: real time -: high energy

reactions on deuterium (CC + NC)

All experiments measure only 30-50% of predicted flux (status 2001)



Who is responsible?



Sun

Core temperature

$\phi(^{8}B) \propto T^{18}$

Chem. composition

Magnetic field

Cosmions

Nuclear cross sections

Astrophysicists:
5% change in core
temperature is too much

Neutrino

Vacuum oscillations

Matter oscillations

Magnetic moment

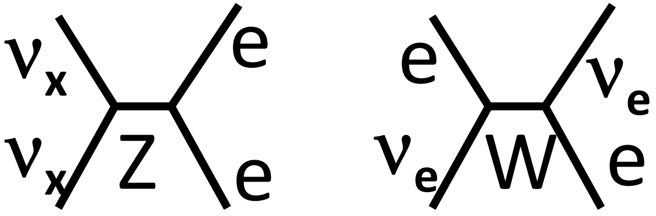
Neutrino decay

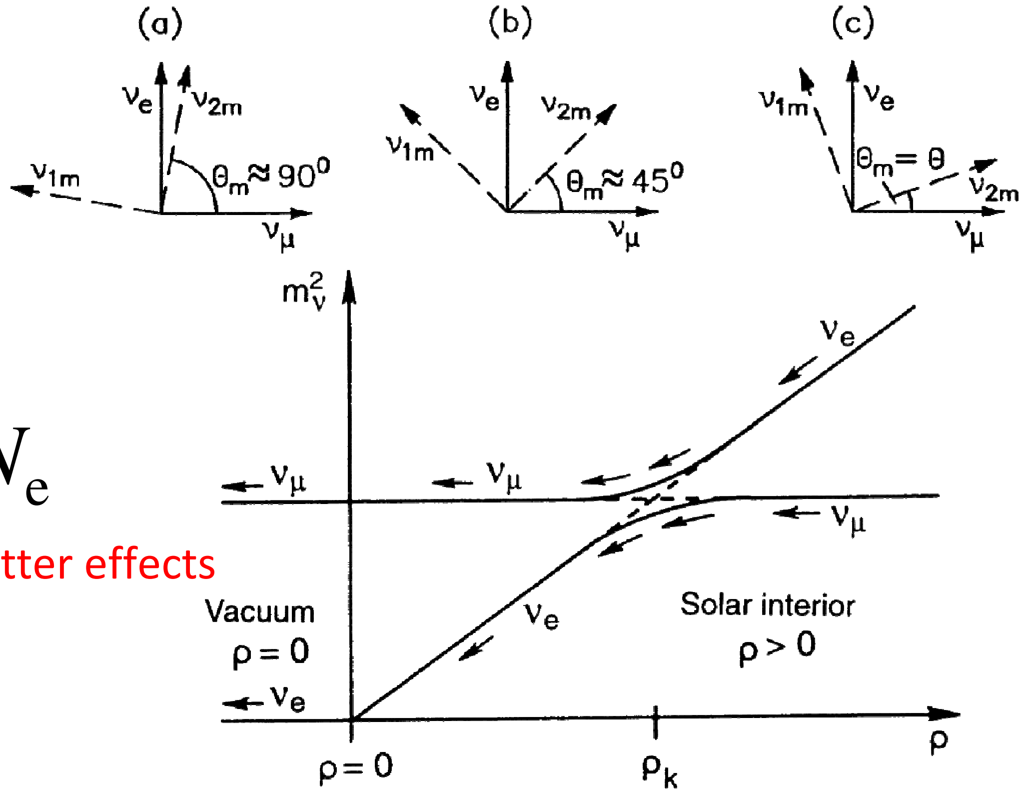
All require neutrino mass

Oscillation-Solutions

If vacuum oscillations: $$\Delta m^2 \approx \frac{E}{L} \approx \frac{1 MeV}{10^{11} m} = 10^{-11} eV^2$$

If matter oscillations (MSW-Effect)





Results in an "effective mass" for ν_e in matter proportional to electron density N_e

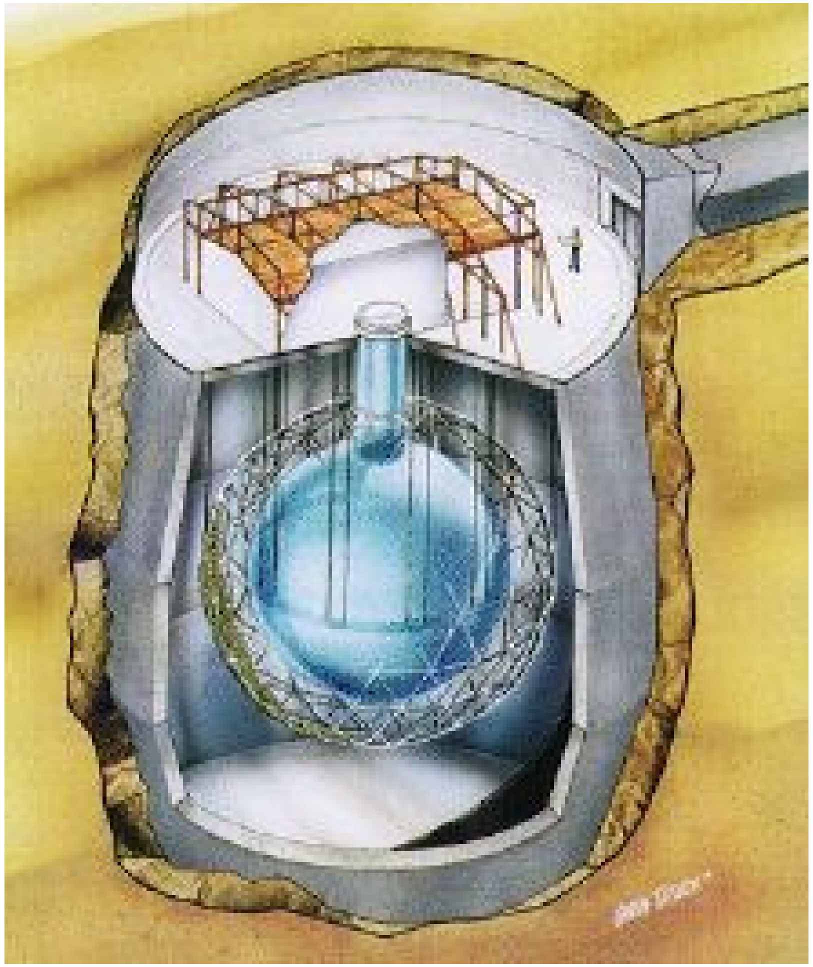
To solve the solar neutrino problem via matter effects

$$\Delta m^2 \approx 10^{-4} - 10^{-7} eV^2$$

The Sudbury

Neutrino Observatory (SNO)

SNO – The smoking gun



1000 t heavy water ($D_2 0$)

CC $\nu_e + \mathrm{d} \Rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$

NC $\nu_x + \mathrm{d} \Rightarrow \mathrm{p} + \mathrm{n} + \nu_x$

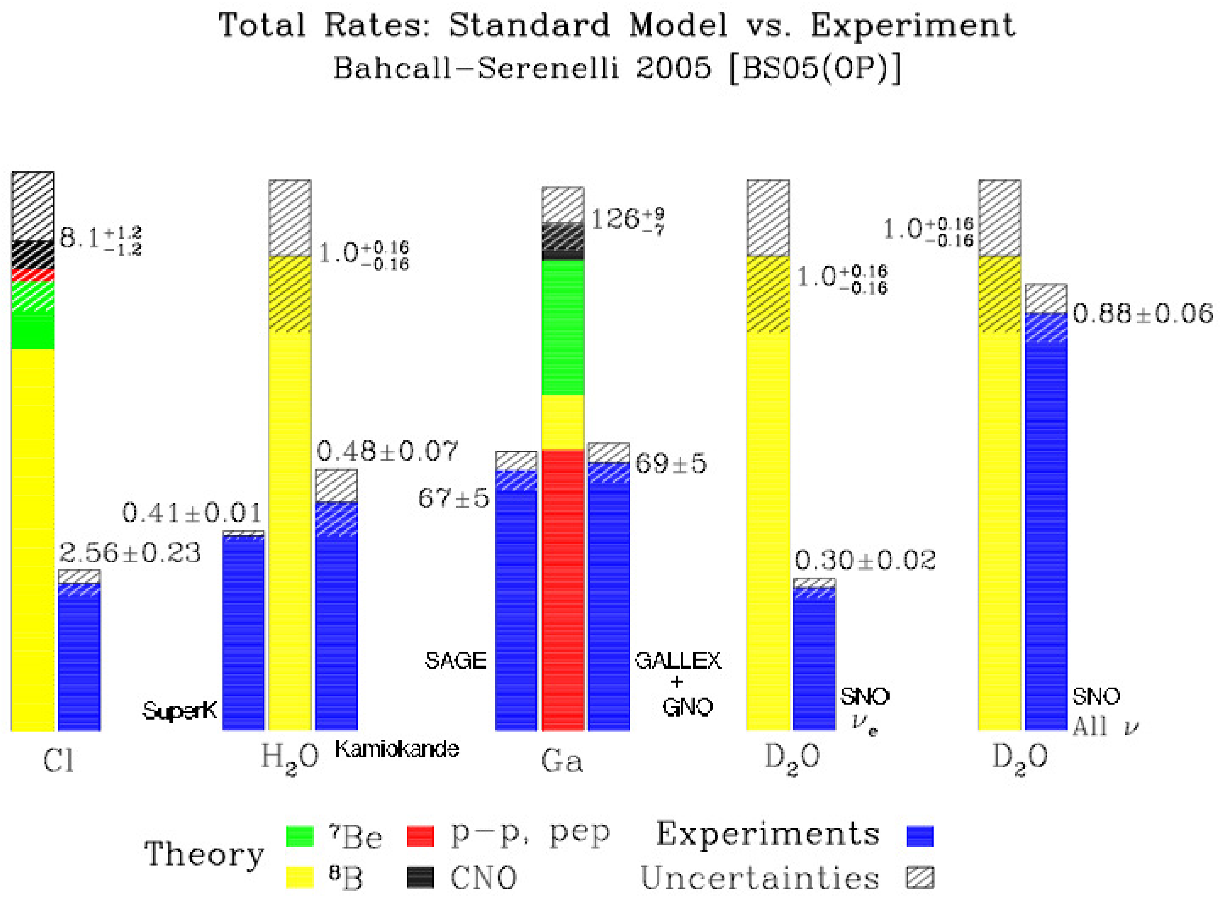
ES $\nu_x + \mathrm{e}^- \Rightarrow \nu_x + \mathrm{e}^-$

$$\frac{\mathrm{CC}}{\mathrm{ES}} = \frac{\nu_\mathrm{e}}{\nu_\mathrm{e} + 0.14(\nu_\mu + \nu_\tau)}$$

$$\frac{\mathrm{CC}}{\mathrm{NC}} = \frac{\nu_\mathrm{e}}{\nu_\mathrm{e} + \nu_\mu + \nu_\tau}$$

See talk J. Maneira

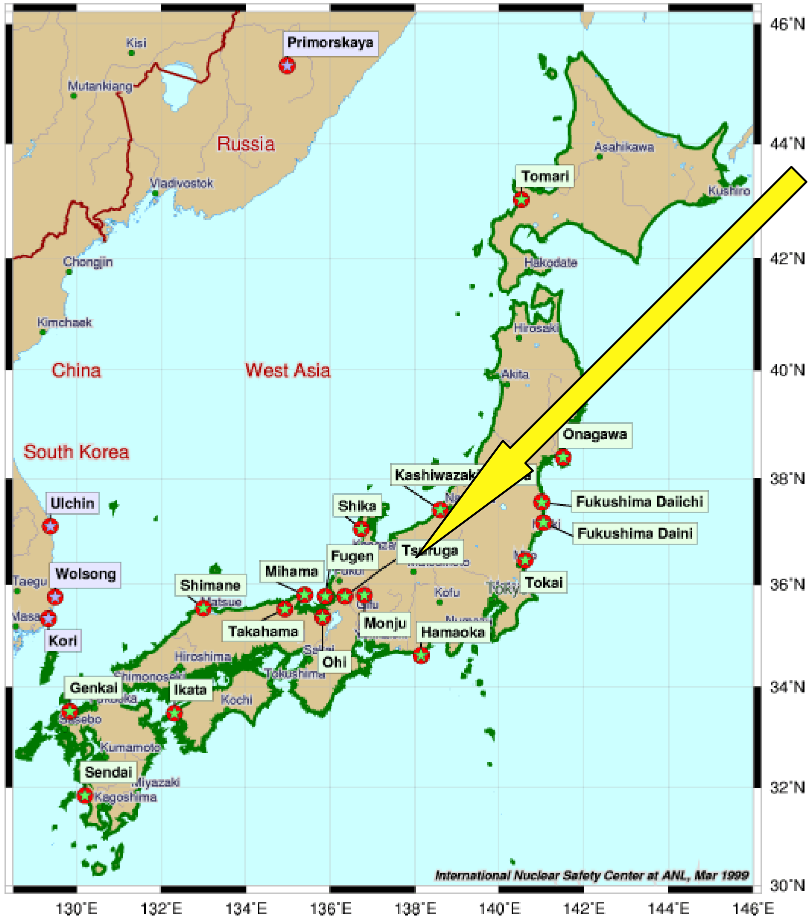
Status 2009

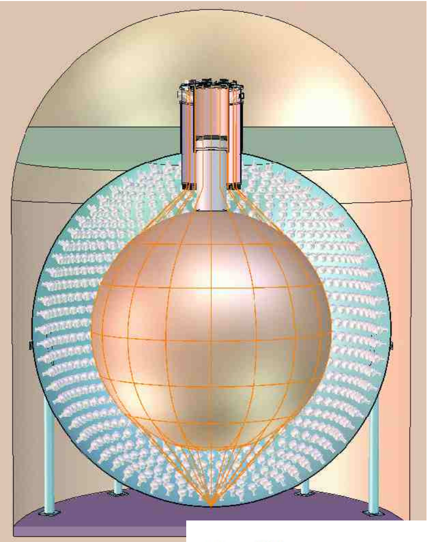


Neutrinos are guilty!!!

KamLAND

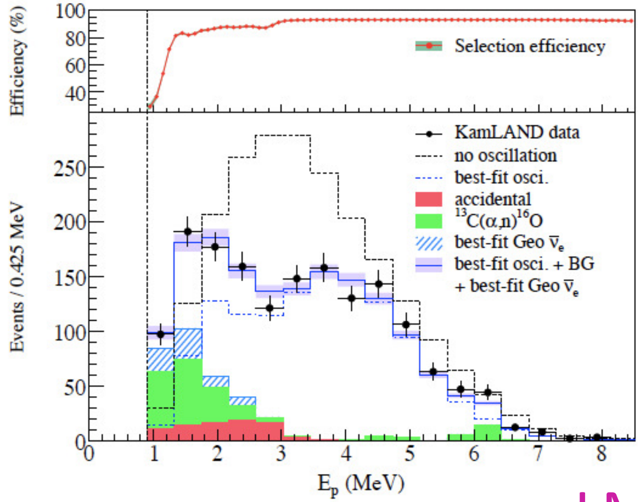
$$\bar{\nu}_e + p \rightarrow e^+ + n$$





Concentration of Reactors at about 180 km distance

1000 t Liquid scintillator



$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

LMA solution is correct

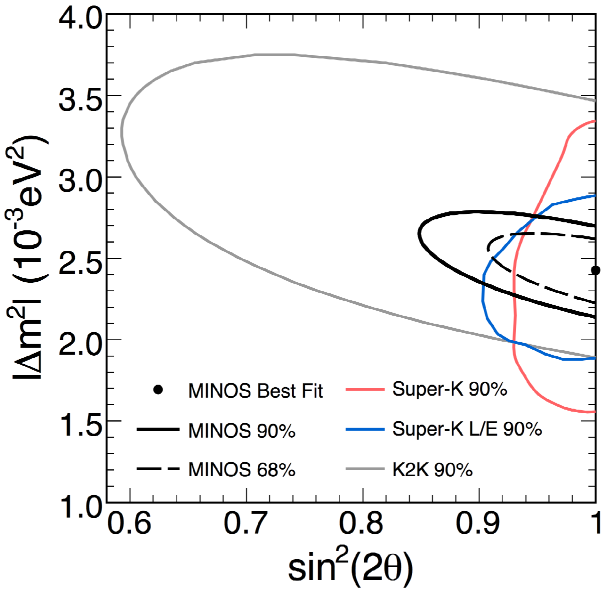
+ new BOREXINO results

Oscillation - evidences

depending on $\boxed{\Delta m^2 = m_i^2 - m_j^2}$

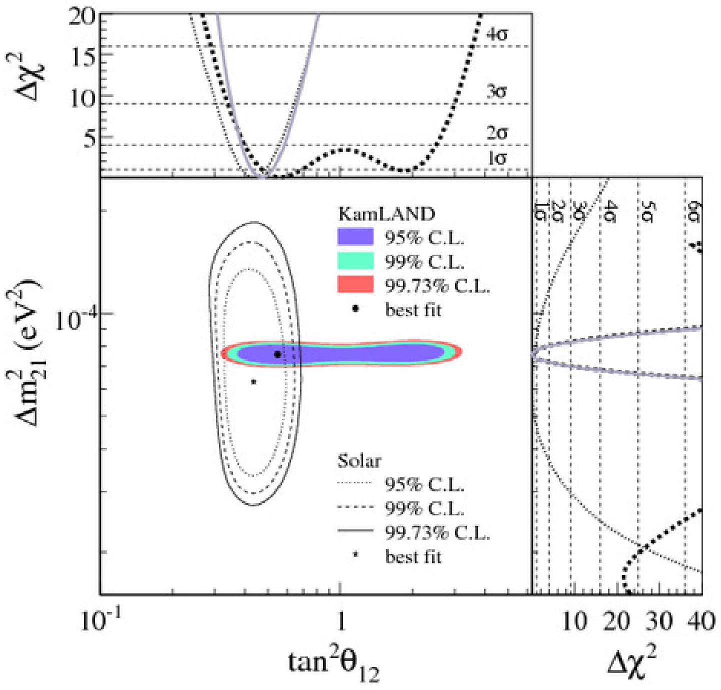
Atmospheric neutrinos

$\sin^2 2\theta_{23} = 1.00$, $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2



Solar and reactor

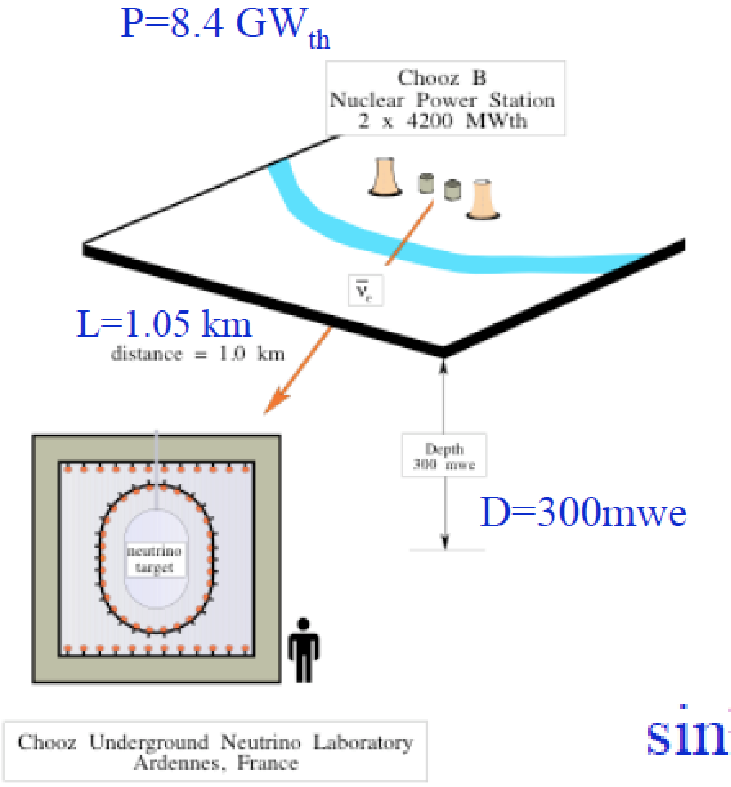
$\sin^2 2\theta_{12} = 0.81$, $\Delta m^2 = 7.6 \times 10^{-5}$ eV^2



Incredible progress in last 10-15 years !!!!

Limits on Θ_{13}

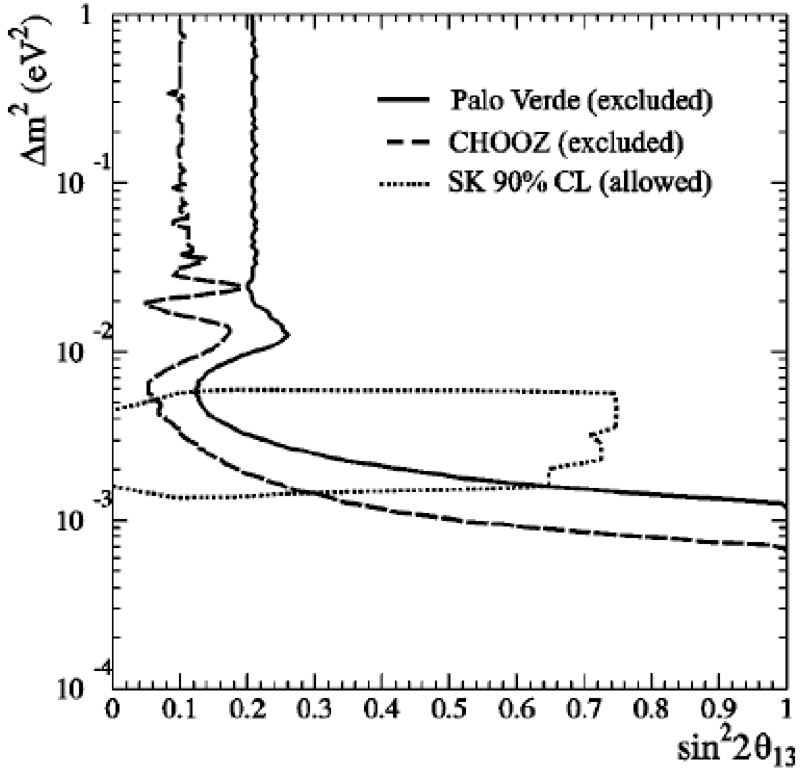
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



P=8.4 GW_{th}

L=1.05 km

D=300mwe



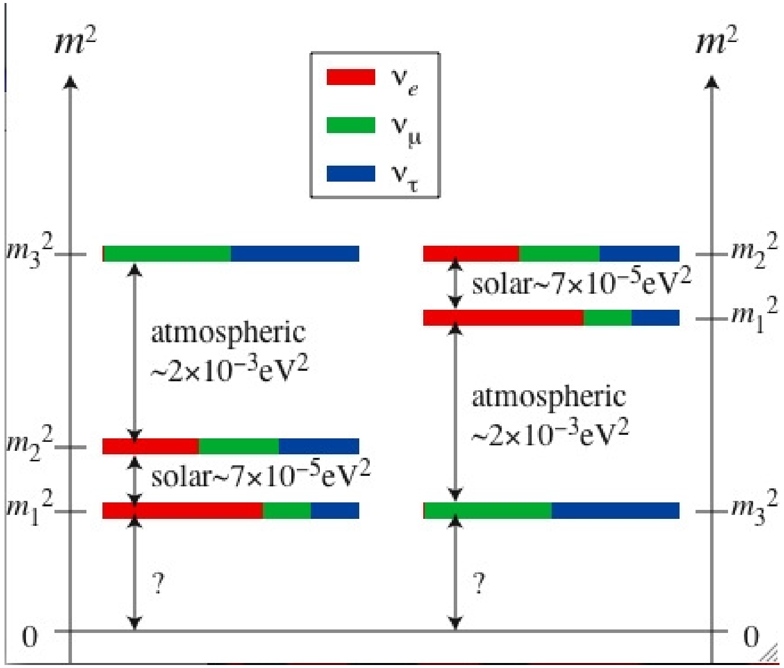
$\sin^2 2\theta_{13} < 0.15$ for $\Delta m^2 = 2.5\times10^{-3}$ eV^2

m = 5 tons, Gd-loaded liquid scintillator

Neutrino mass schemes and mixing

- almost degenerate neutrinos $m_1 \approx m_2 \approx m_3$
- hierarchical neutrino mass schemes

Mass



normal inverted

Mixing

$$V_{CKM} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

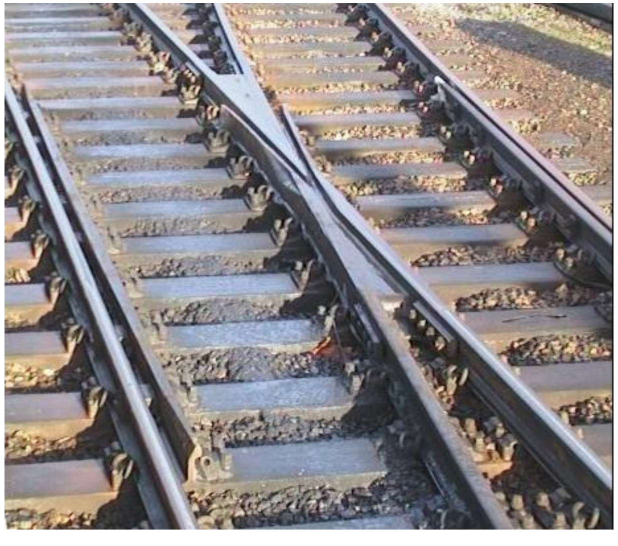
$$U_{MNSP} \sim \begin{pmatrix} Big & Big & Small\,? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

Why is quark and lepton mixing so different???

The twofold way....

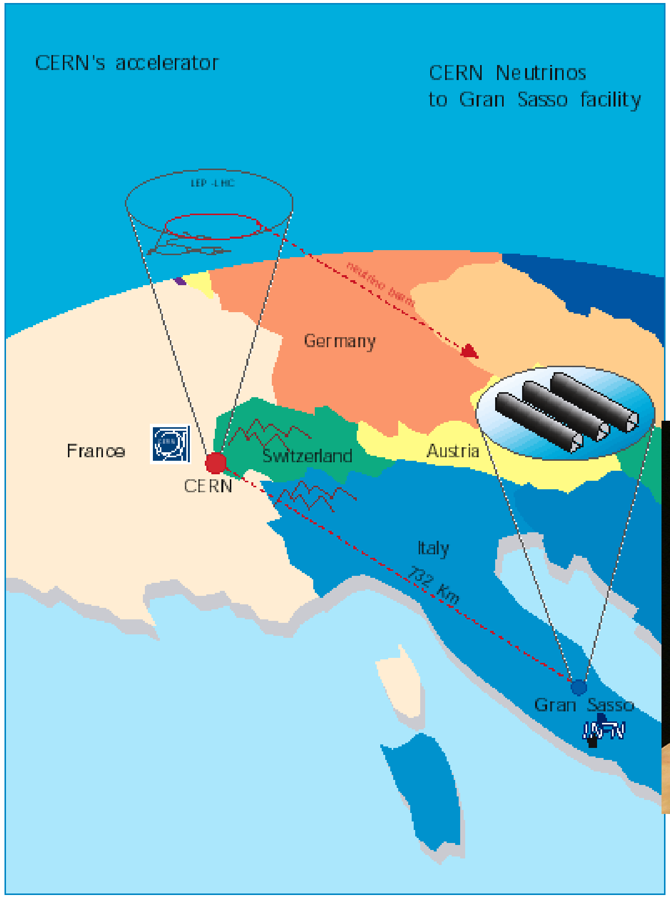
- Precision determination of mixing matrix elements (PMNS), CP violation in lepton sector, Majorana phases?

  (requires 3-flavour analysis of data)
- Absolute neutrino mass measurement



CNGS

Same baseline as Fermilab – Soudan

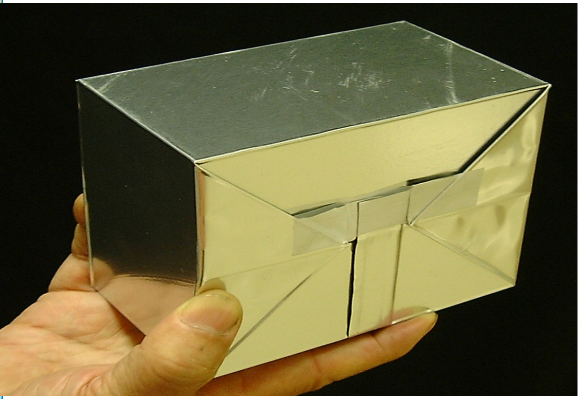


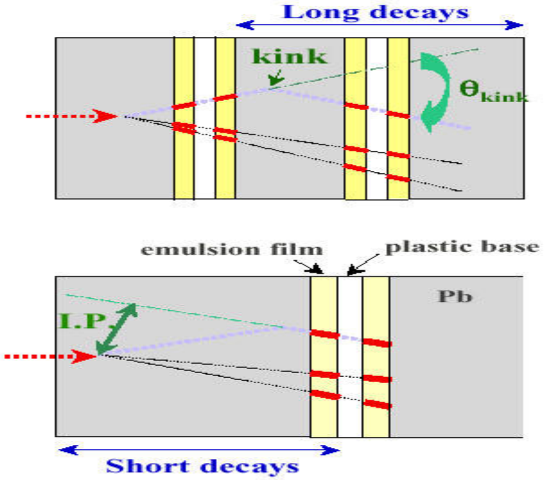
Beam energy optimised for detection

Appearance experiment

$$\nu_\tau + N \rightarrow \tau^- + X$$

OPERA detection strategy





Taking data

T2K

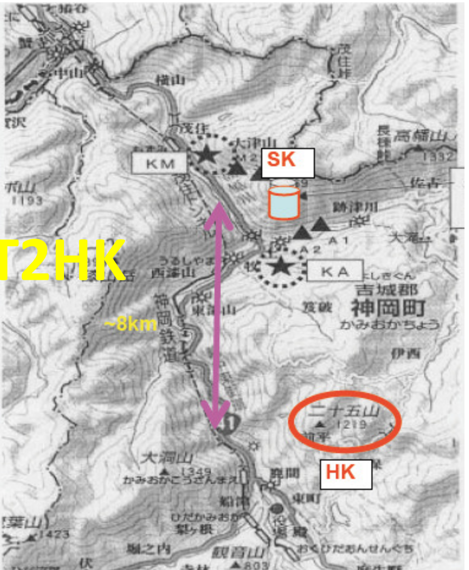
goal :
(1) measure appearance of

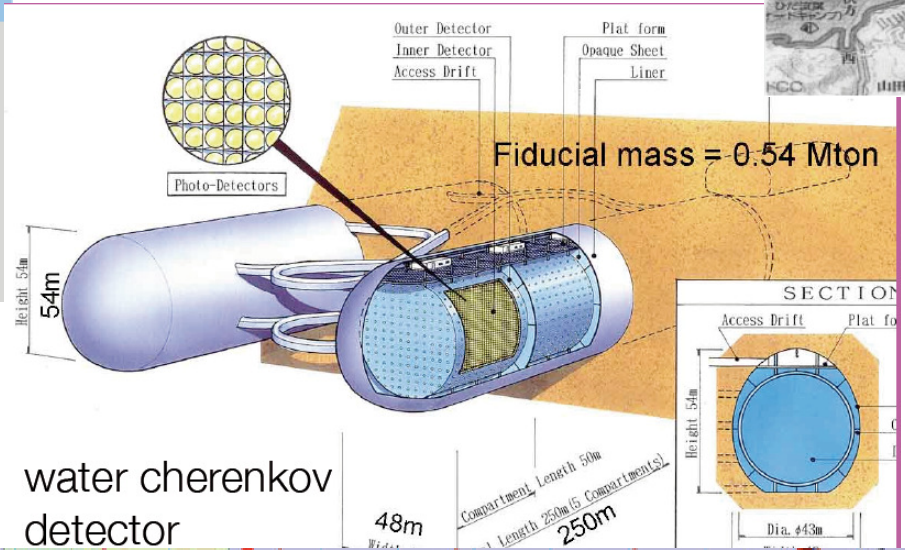
$$\nu_\mu \to \nu_e$$

(2) measure disappearance of

$$\nu_\mu \to \nu_\mu$$

Started commissioning of neutrino beam april 2009

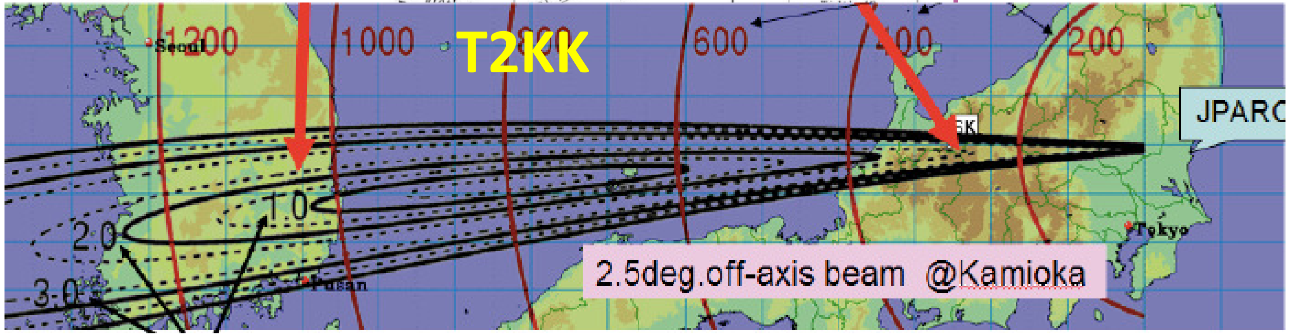




water cherenkov detector

First goal:
Precision
Determination
of

$$\sin^2 2\theta_{23}, \Delta m^2_{23}$$



Reactor Neutrinos

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E};$$

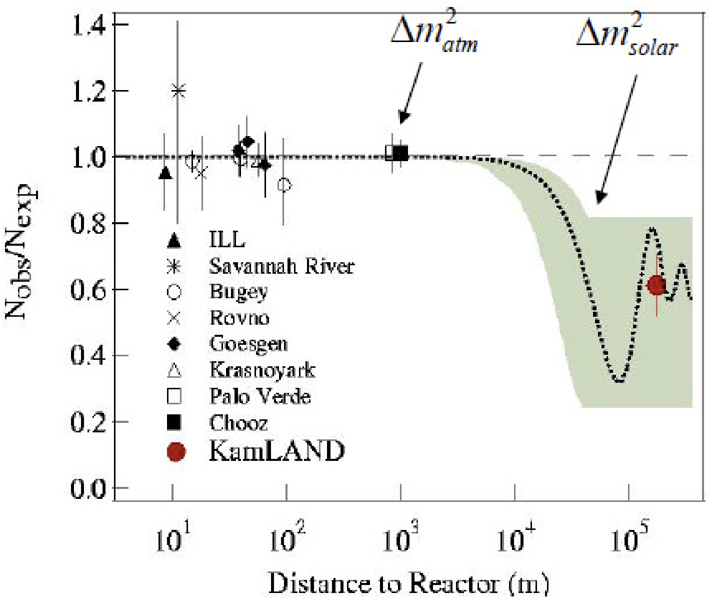
where $\Delta m^2_{ij} = m^2_i - m^2_j$.

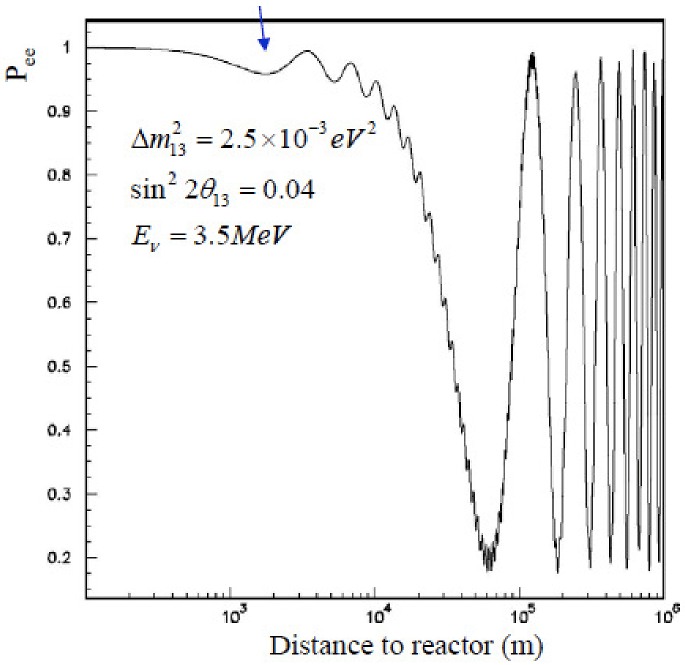
Experiments look for non-$1/r^2$ behavior of antineutrino rate.

Oscillation maxima for E_ν=3.6 MeV:

$\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2 ➡ L ~ 1.8 km

$\Delta m^2_{13} \sim 2.5\times10^{-3}$ eV^2 ➡ L ~ 60 km





Double Chooz

+ Daya Bay, Reno .... It‘s all about systematic errors...

Knowledge of θ_{13} important as always $\sin^2\theta_{13}$ x $e^{i\delta}$, if θ_{13} is too small no hope to see CP-violation

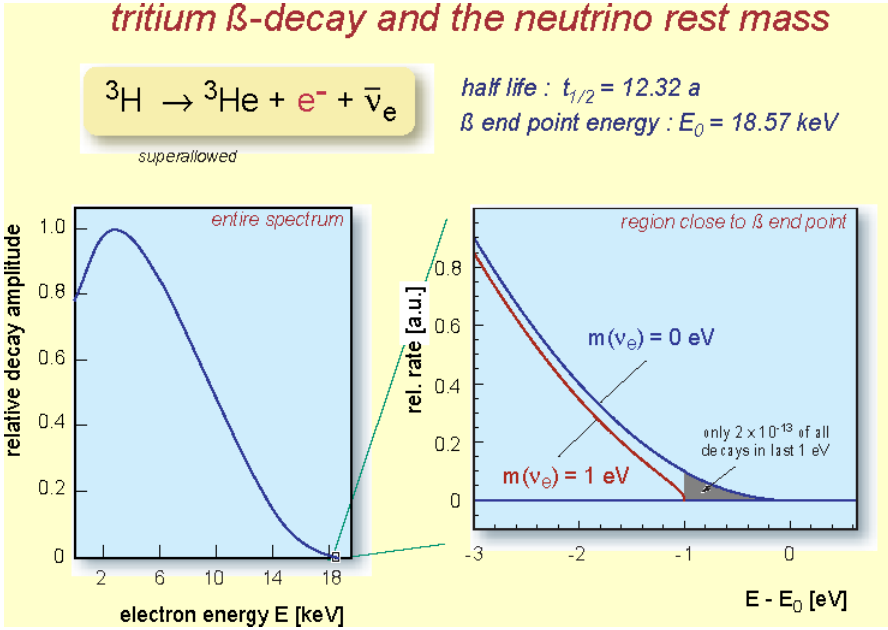
E.W. Otten, C. Weinheimer, Rep. Prog. Phys. 71,086201 (2008)

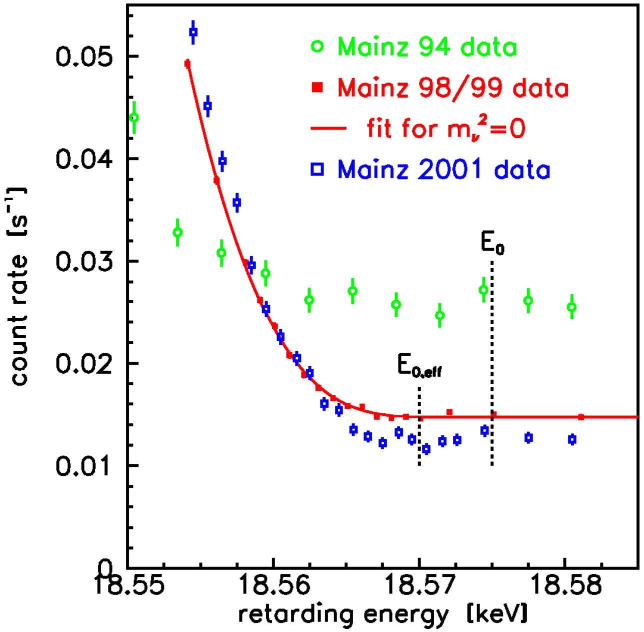
Beta decay

- $(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$

Fit parameter endpoint

$$m_\nu^2 = \sum \left|U_{ei}^2\right|^2 m_i^2$$





Mainz und Troitsk: $m_{\nu e} < 2.2\ (2.05)$ eV (95% CL)

Cryogenic bolometers as alternative approach under investigation

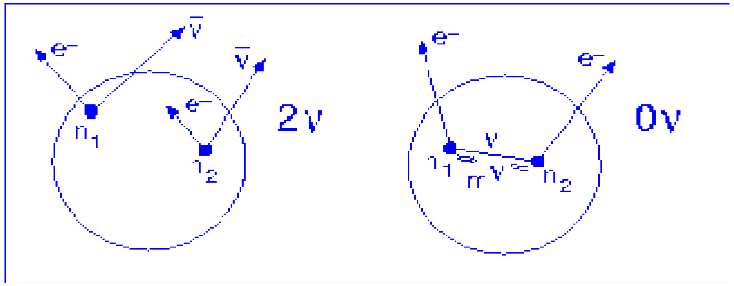
KATRIN- The next step

Aim: Sensitivity down to 0.2 eV

Take the long way home...

Double beta decay

- $(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$ $2\nu\beta\beta$
- $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ $0\nu\beta\beta$



Unique process to measure the mass of the neutrino

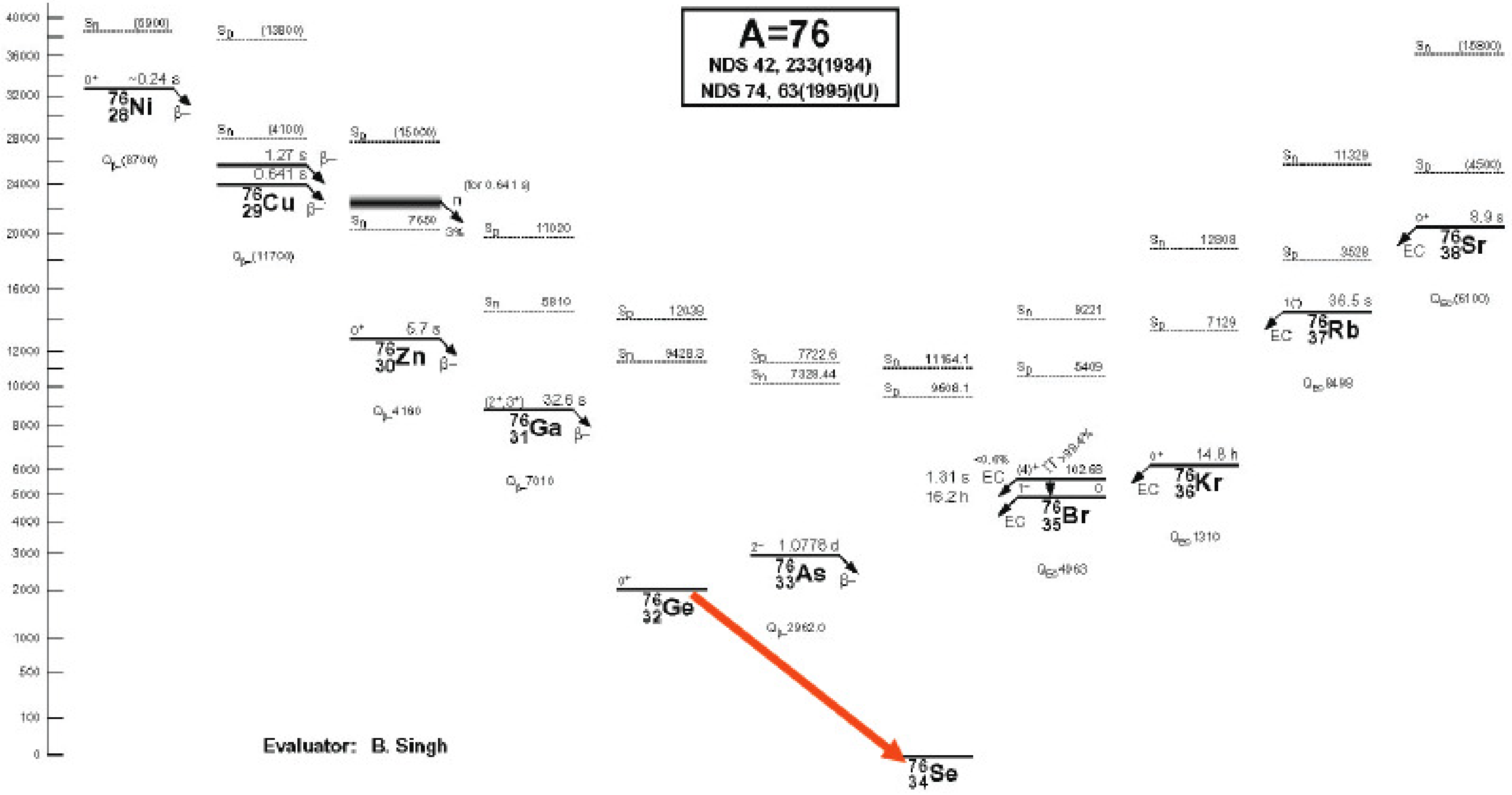
Unque process to measure character of neutrino

Requires half-life measurements well beyond 10^{20} yrs!!!!

The smaller the neutrino mass the longer the half-life

Example - Ge76

All ground state transitions are $0^+ \rightarrow 0^+$

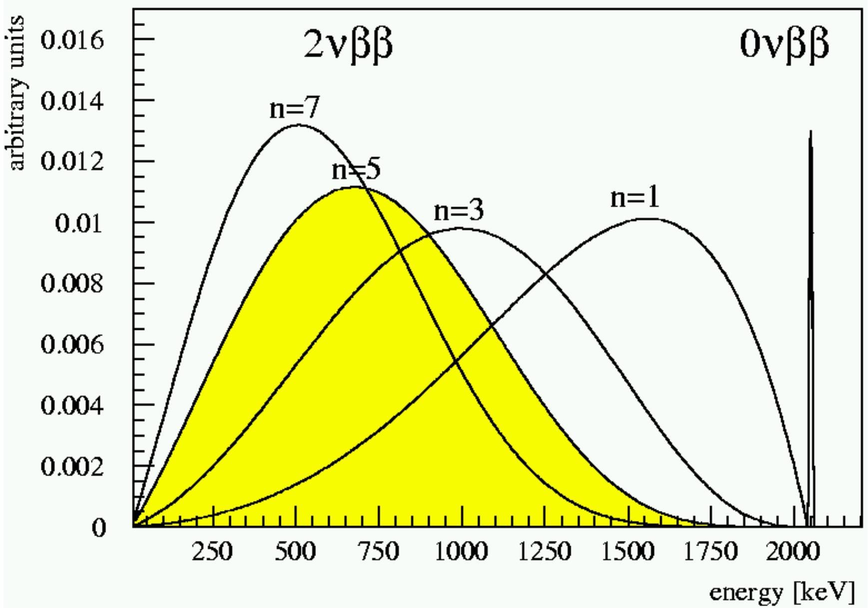


There are only 35 candidates

Spectral shapes

0νββ: Peak at Q-value of nuclear transition

Sum energy spectrum of both electrons



Measured quantity: Half-life

$1 / T_{1/2} = PS * ME^2 * (m_\nu / m_e)^2$

Quantity of interest:

Effective Majorana neutrino mass

$$\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| m_1 U_{e1}{}^2 + m_2 U_{e2}{}^2 e^{i\alpha_1} + m_3 U_{e3}{}^2 e^{i\alpha_2} \right|$$

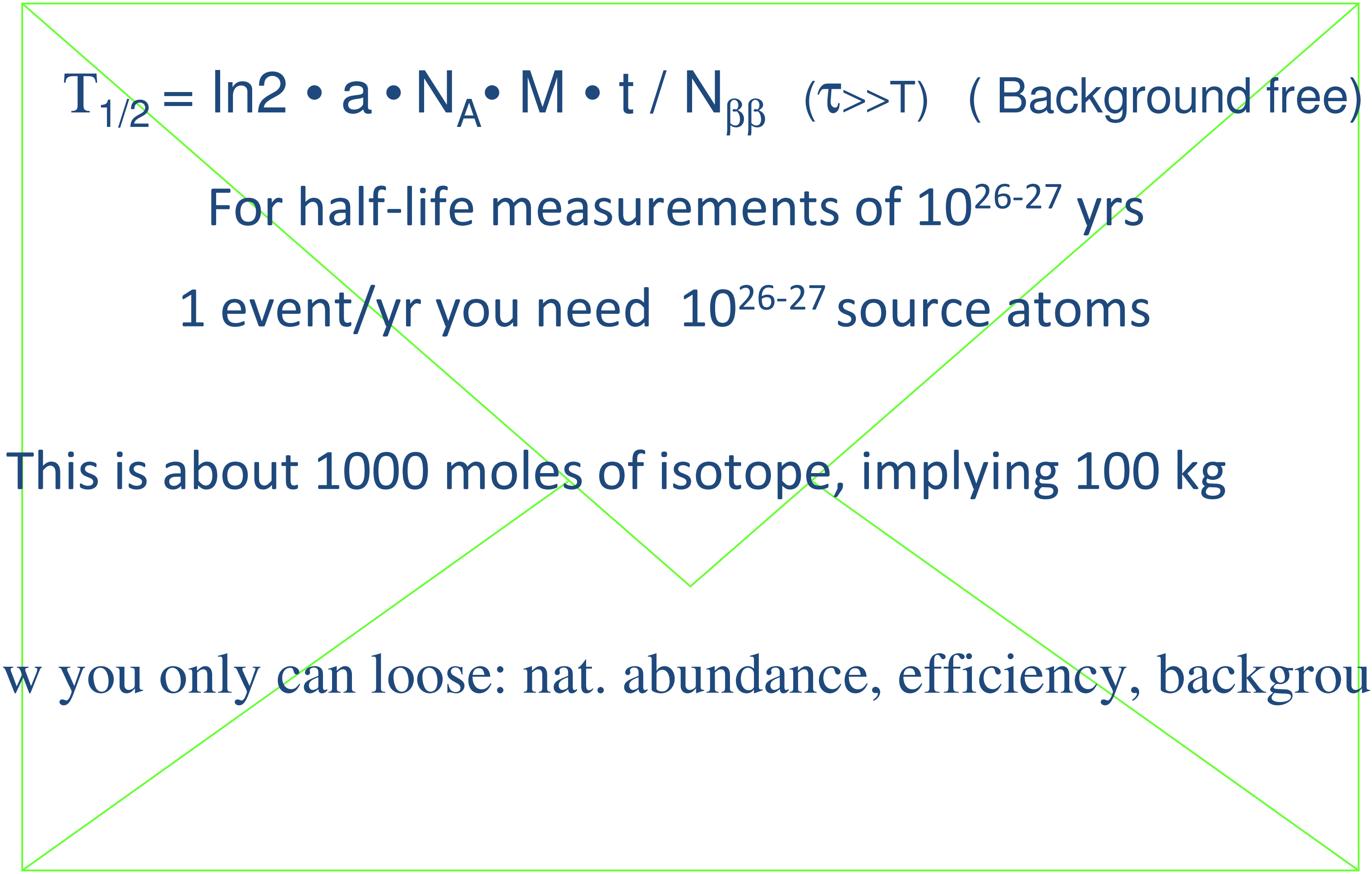
CP-invariance: $\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| m_1 |U_{e1}|^2 \pm m_2 |U_{e2}|^2 \pm m_3 |U_{e3}|^2 \right|$

Beta and double beta measurements are complementary

The search for 0νββ

or

Back of the envelope



$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta}$ ($\tau >> T$) (Background free)

For half-life measurements of $10^{26\text{-}27}$ yrs

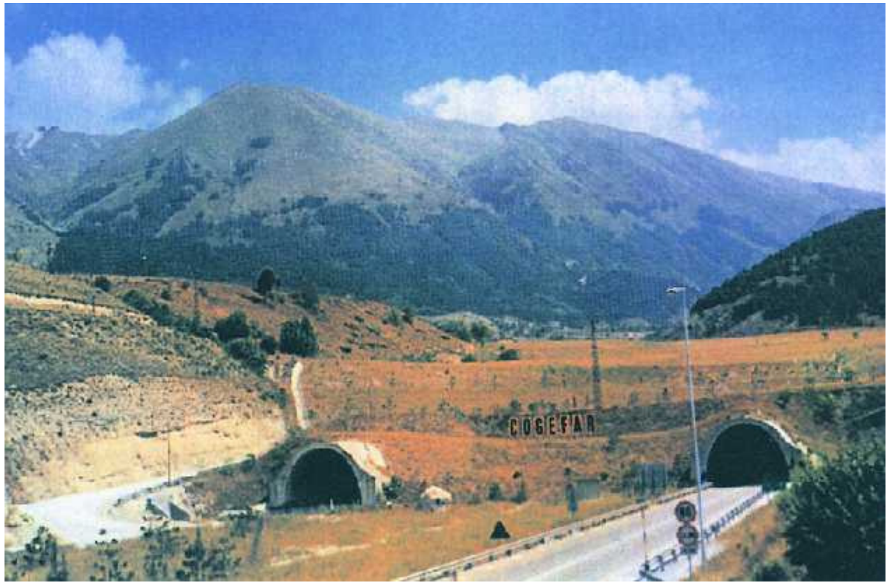
1 event/yr you need $10^{26\text{-}27}$ source atoms

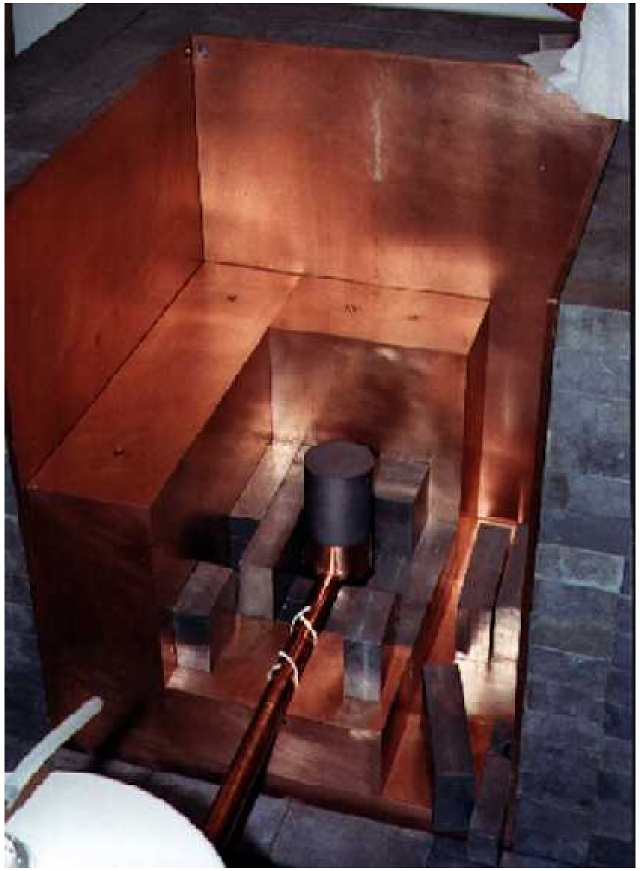
This is about 1000 moles of isotope, implying 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...

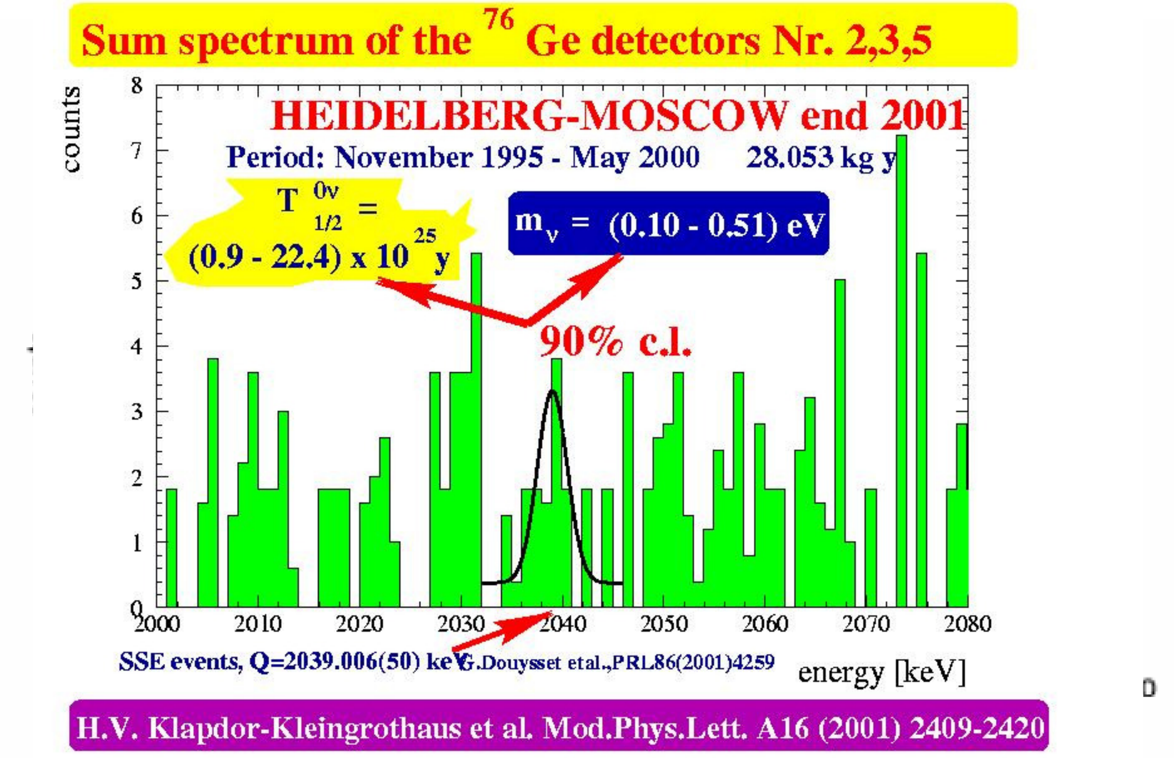
Heidelberg -Moscow

- **The detectors are decaying!!**
- **5 isotopical enriched Ge-detectors**
- **Peak at 2039 keV**





Heidelberg -Moscow



Part of collaboration: $T_{1/2} = 2.23 \pm 0.4 \times 10^{25}$ yr → m = 0.32 ± 0.03 eV

H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586, 198 (2004), Mod.Phys.Lett.A21:1547-1566,2006

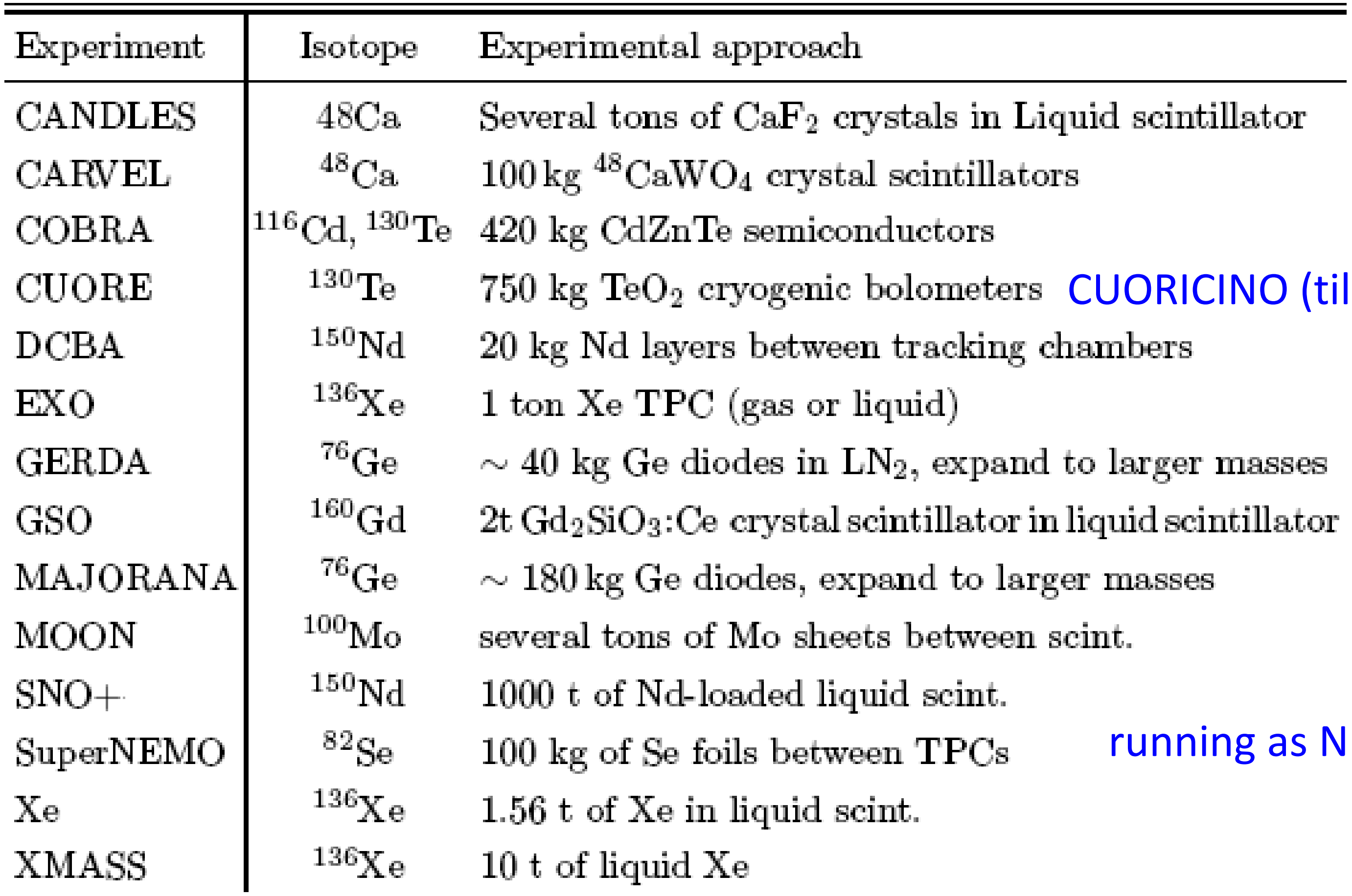
Current aims of double beta searches

- Check whether observed peak claimed in ^{76}Ge is true
- If yes, observe it with at least one other isotope to confirm that it is double beta decay
- If not, next milestone will be 50 meV suggested by oscillation results
- If still no observation, down to range 1-10 meV

Remember: $m_\nu \propto \sqrt[4]{\frac{\Delta E B}{M t}}$

Future projects, ideas

K. Zuber, Acta Polonica B 37, 1905 (2006)



Experiment	Isotope	Experimental approach
CANDLES	48Ca	Several tons of CaF_2 crystals in Liquid scintillator
CARVEL	^{48}Ca	100 kg $^{48}CaWO_4$ crystal scintillators
COBRA	^{116}Cd, ^{130}Te	420 kg CdZnTe semiconductors
CUORE	^{130}Te	750 kg TeO_2 cryogenic bolometers
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)
GERDA	^{76}Ge	$\sim$ 40 kg Ge diodes in LN_2, expand to larger masses
GSO	^{160}Gd	2t Gd_2SiO_3:Ce crystal scintillator in liquid scintillator
MAJORANA	^{76}Ge	$\sim$ 180 kg Ge diodes, expand to larger masses
MOON	^{100}Mo	several tons of Mo sheets between scint.
SNO+	^{150}Nd	1000 t of Nd-loaded liquid scint.
SuperNEMO	^{82}Se	100 kg of Se foils between TPCs
Xe	^{136}Xe	1.56 t of Xe in liquid scint.
XMASS	^{136}Xe	10 t of liquid Xe

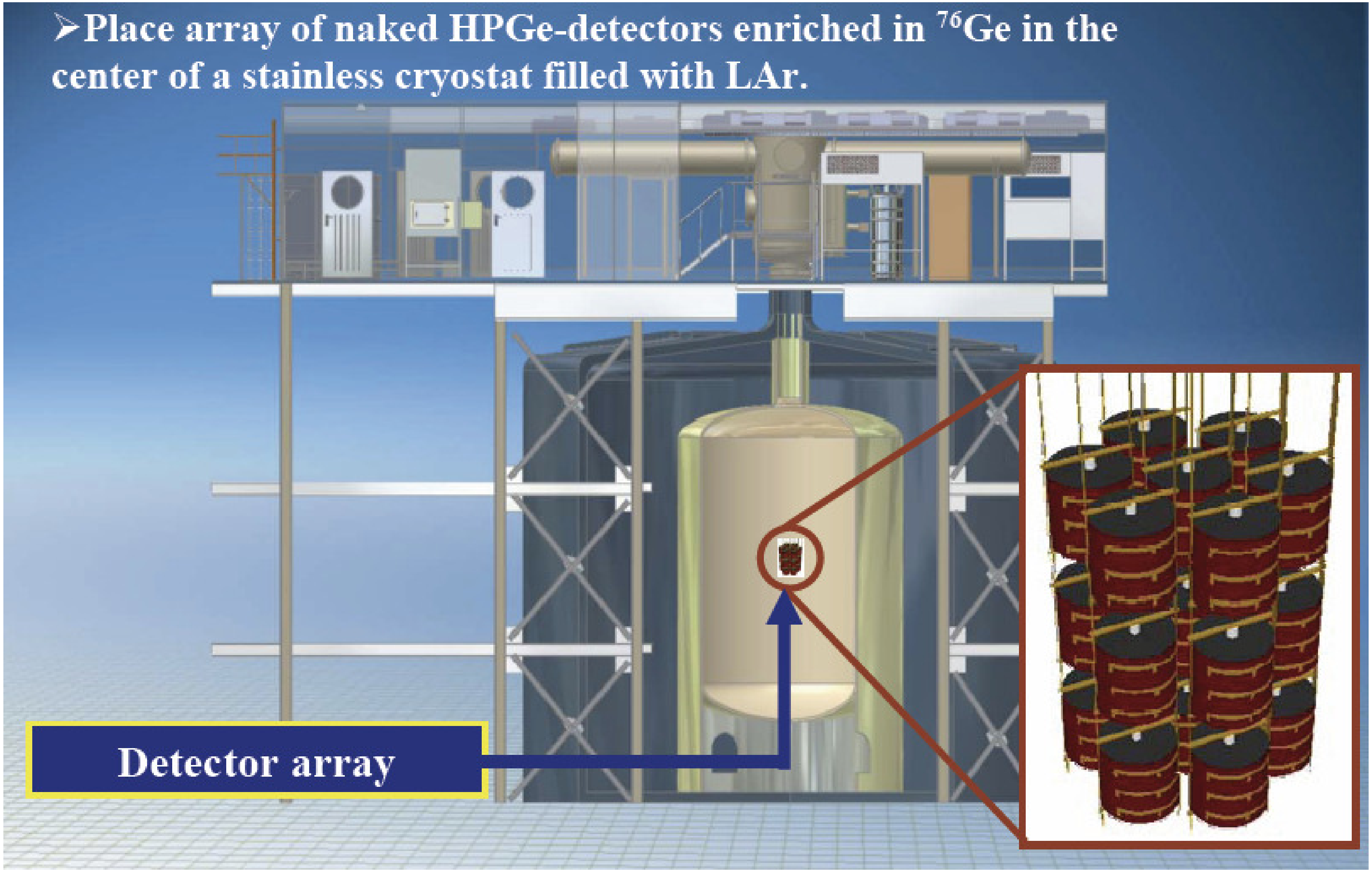
CUORICINO (til 06/08)

➔J. Maneira

running as NEMO-3

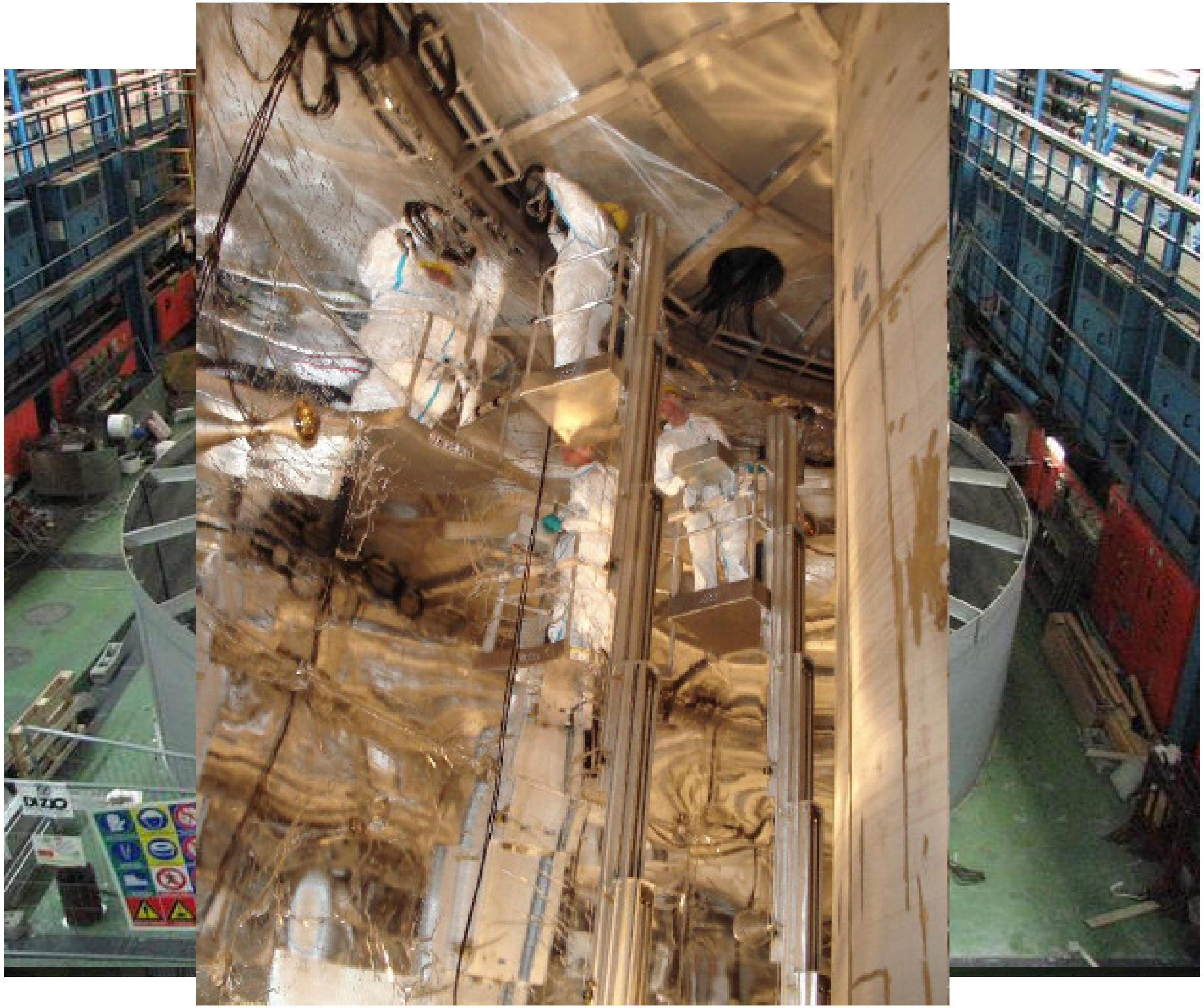
small scale ones will expand, very likely not a complete list...

GERDA-Principal Setup



- Place array of naked HPGe-detectors enriched in ^{76}Ge in the center of a stainless cryostat filled with LAr.

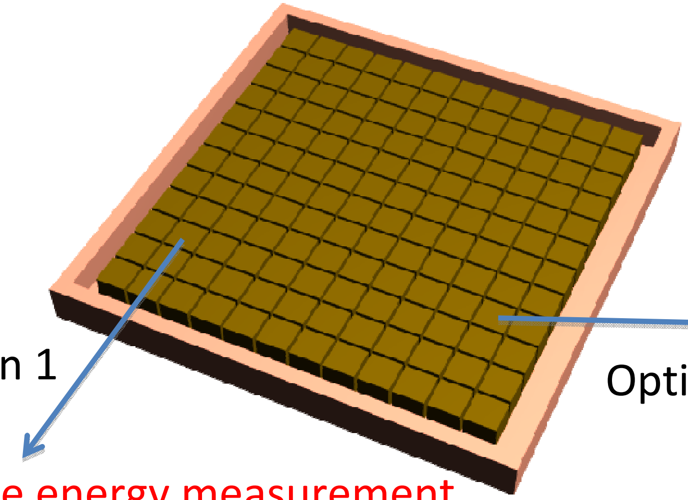
Status GERDA



K. Zuber, Phys. Lett. B 519,1 (2001)

COBRA

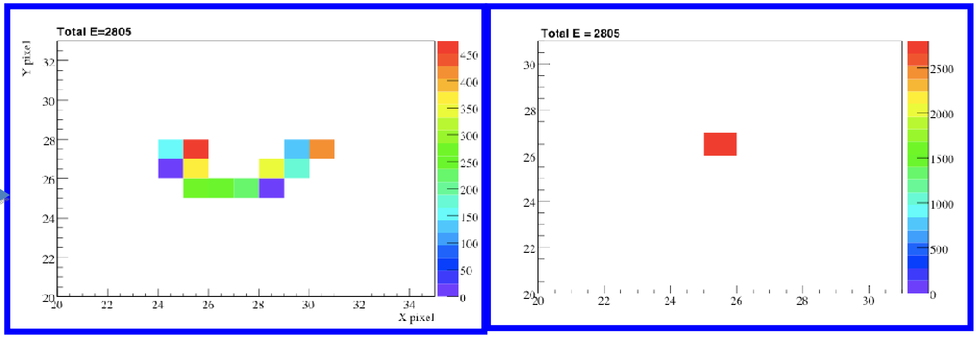
Use large amount of CdZnTe Semiconductor Detectors



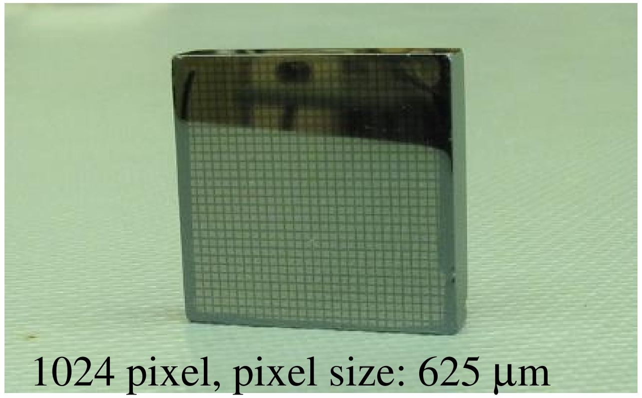
Option 1

Option 2

Semiconductor Tracker, Solid State TPC



Pure energy measurement



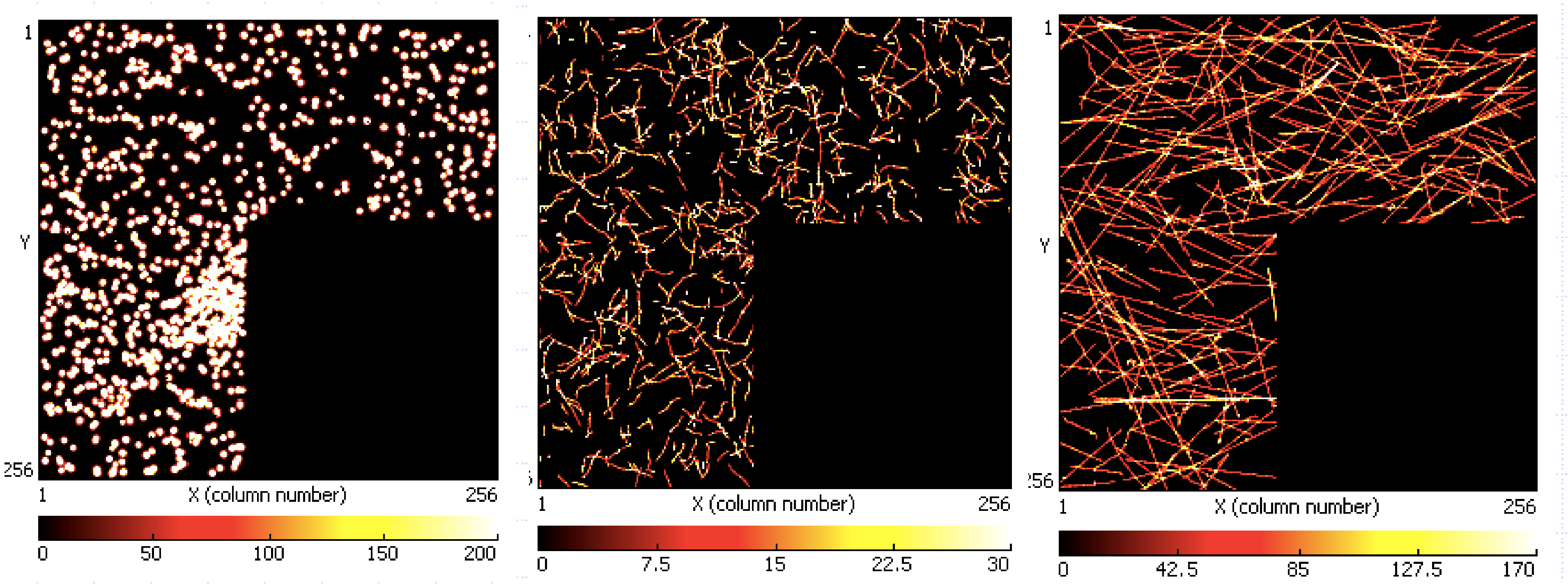
1024 pixel, pixel size: 625 µm

Particles ....

Alphas

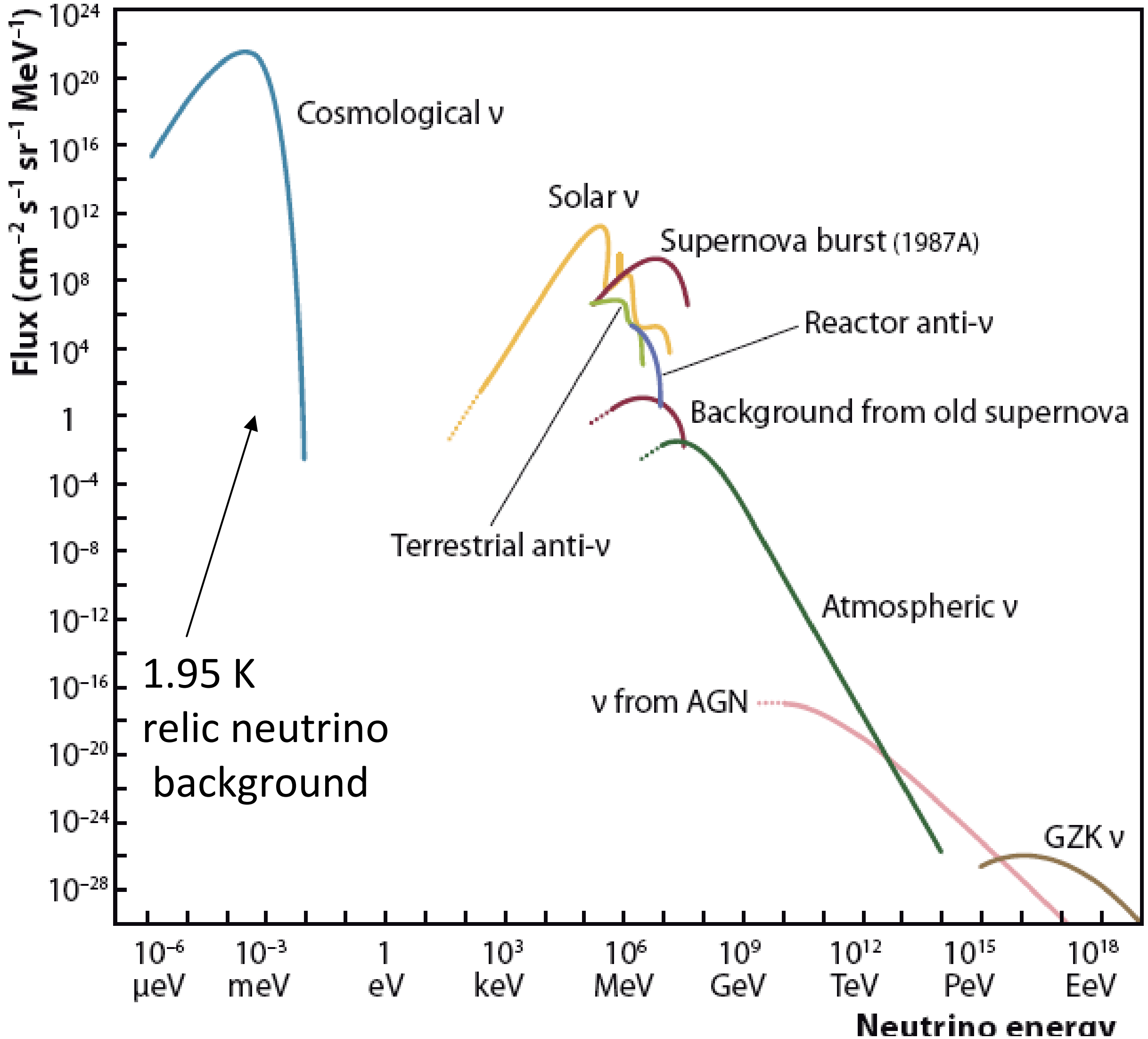
Betas

Muons



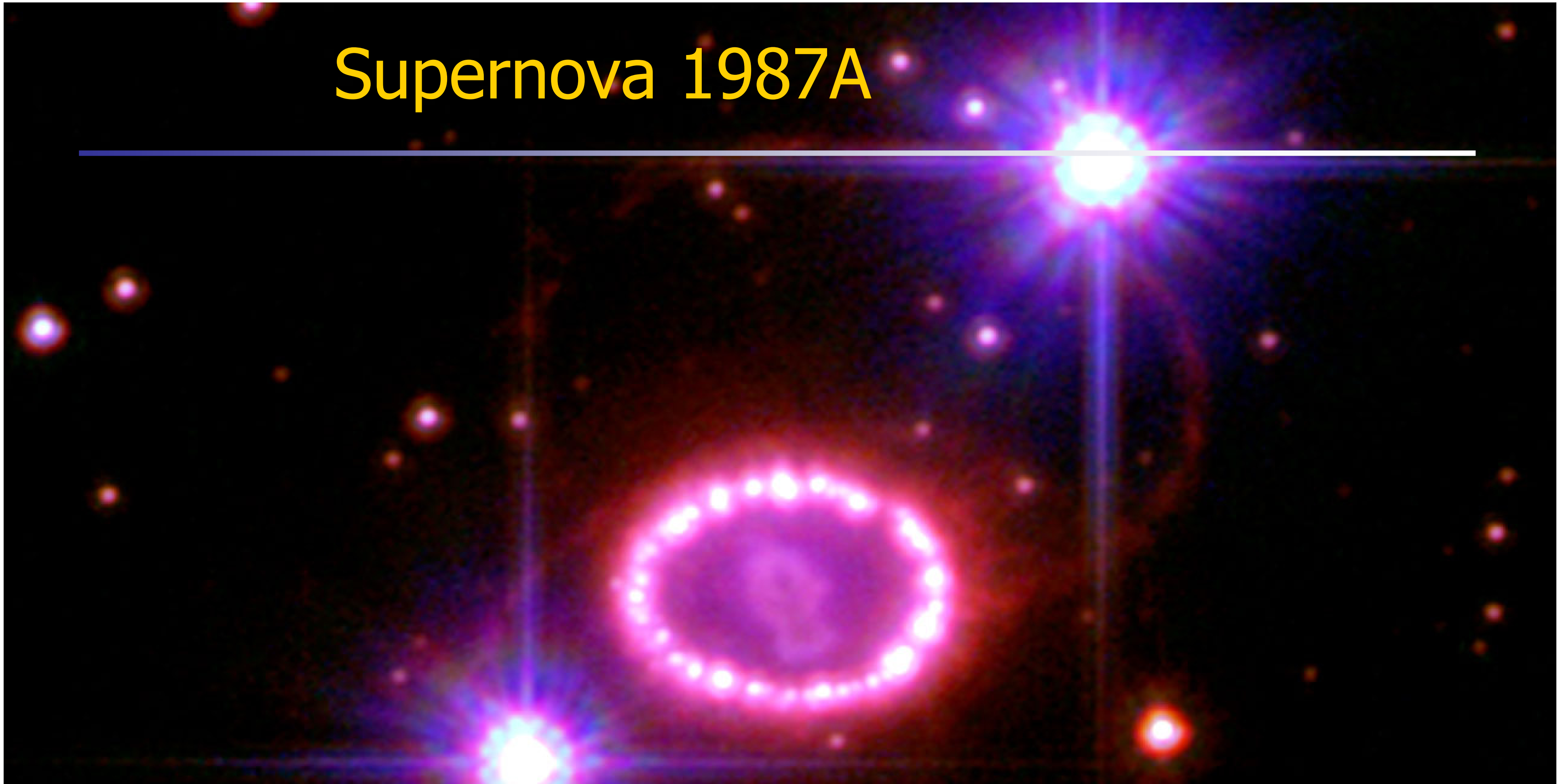
Events obtained with a 55 μm pixel detector, 256x256 pixels

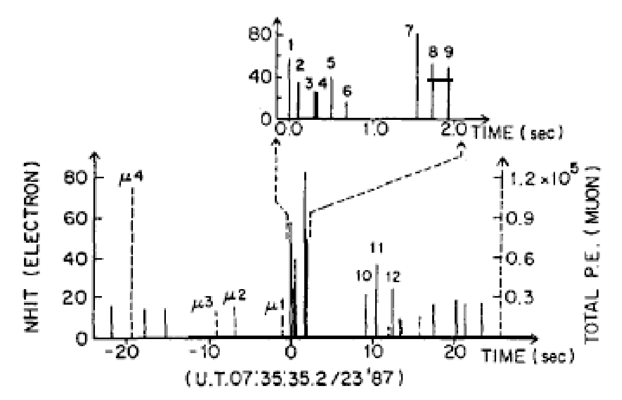
Neutrino Astrophysics



1.95 K
relic neutrino
background

Supernova 1987A

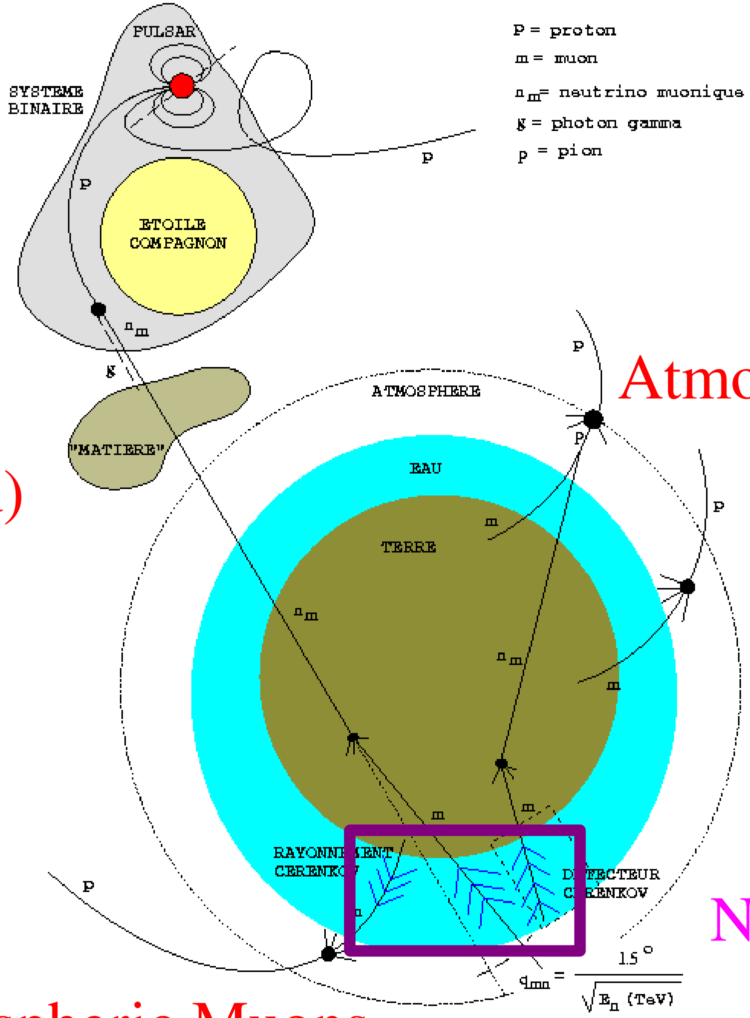




Nowadays: SNEWS network

Cosmic accelerators -Detection Principle

Cosmic Neutrinos
(can’t be attenuated)

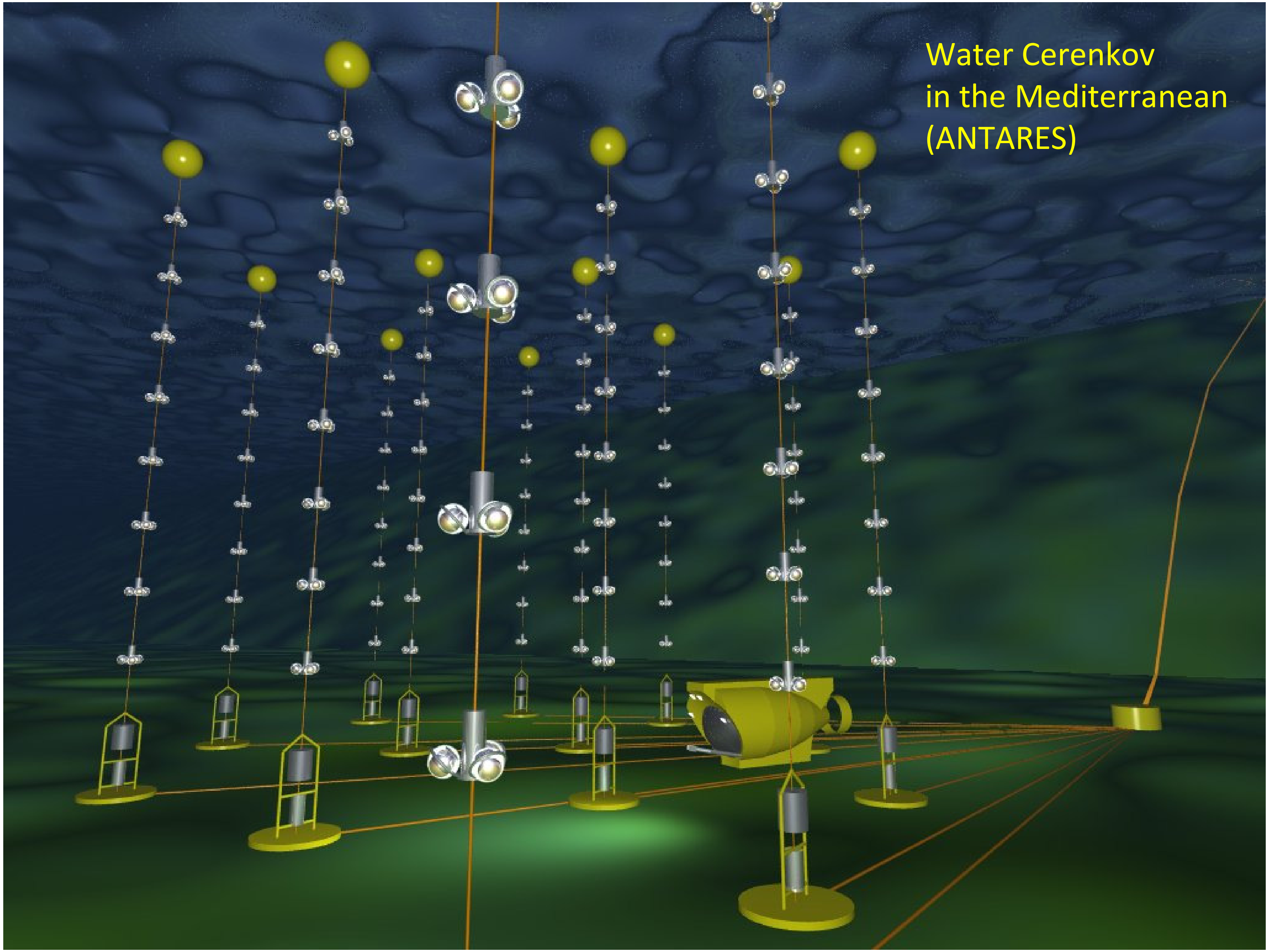


Atmospheric Neutrinos

Neutrino Telescope

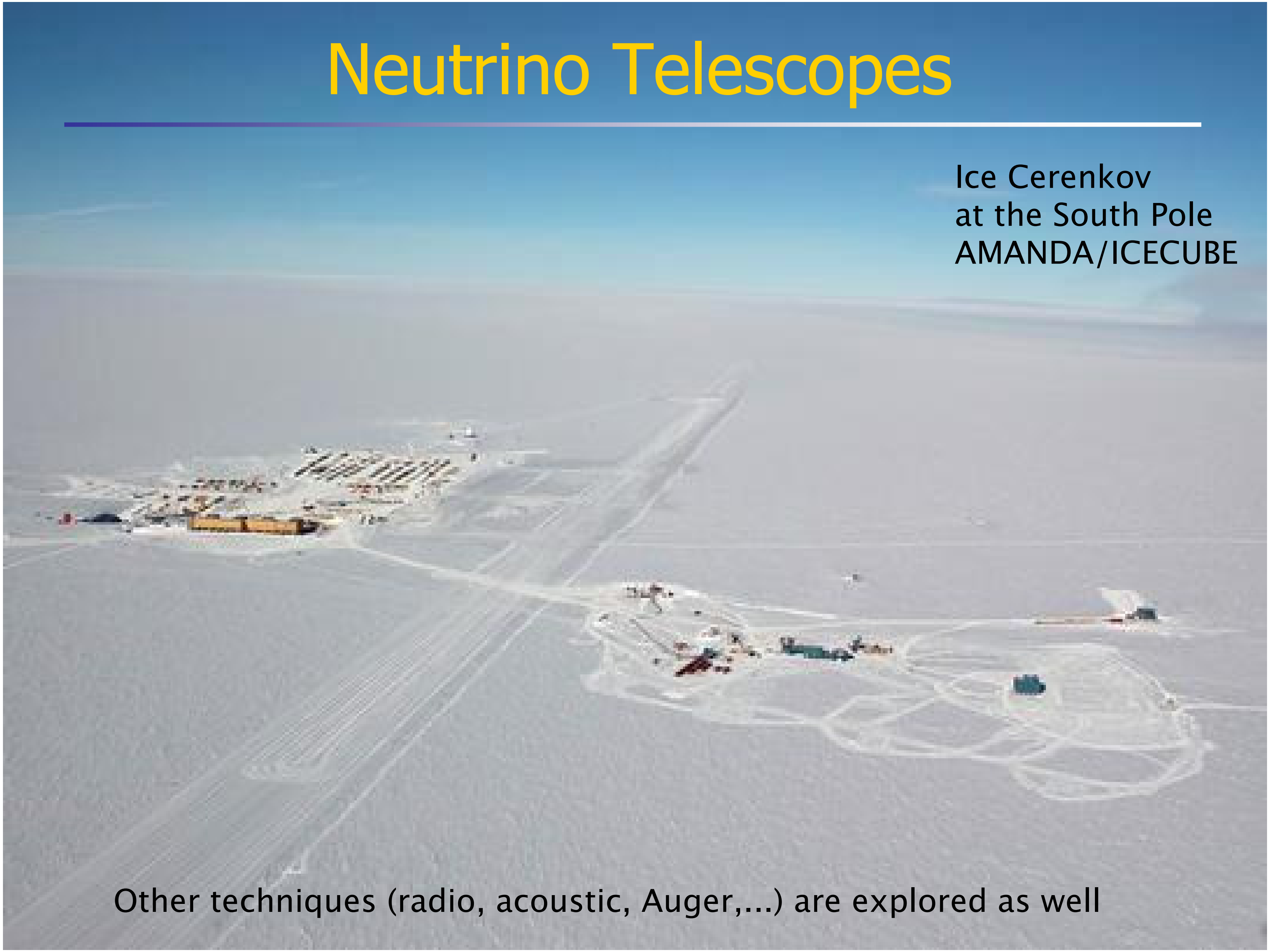
Atmospheric Muons

Signature: Upward going muons



Water Cerenkov
in the Mediterranean
(ANTARES)

Neutrino Telescopes

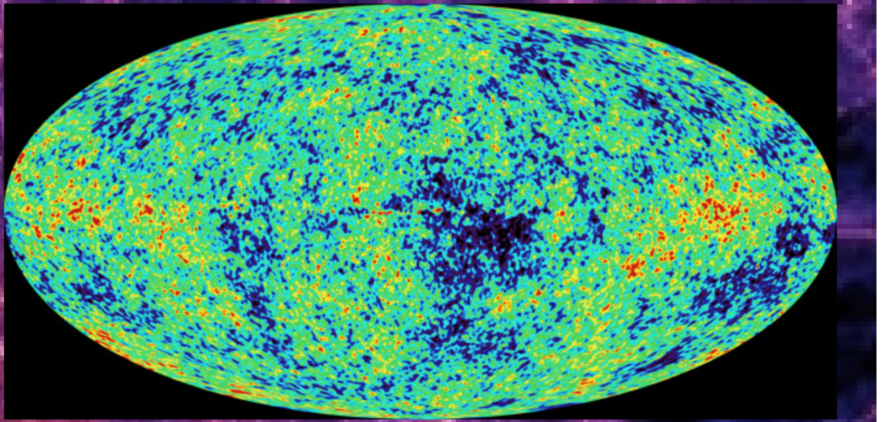


Ice Cerenkov
at the South Pole
AMANDA/ICECUBE

Other techniques (radio, acoustic, Auger,...) are explored as well

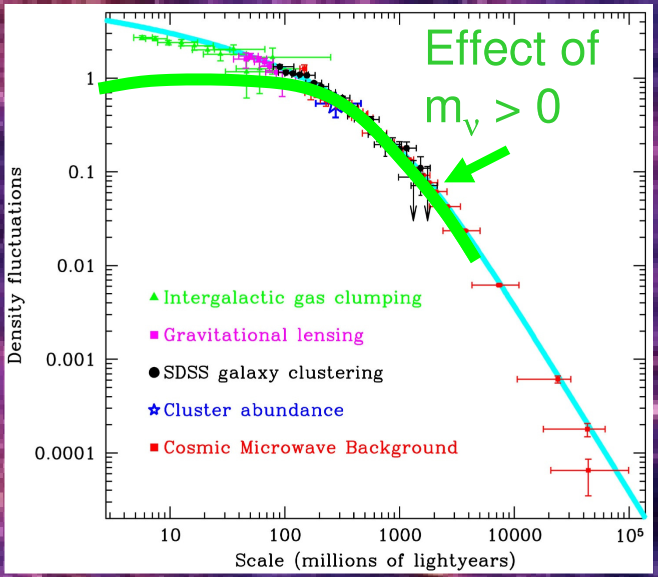
Neutrino masses and cosmology

There is a 1.95 K relic neutrino background...
Still to be detected....

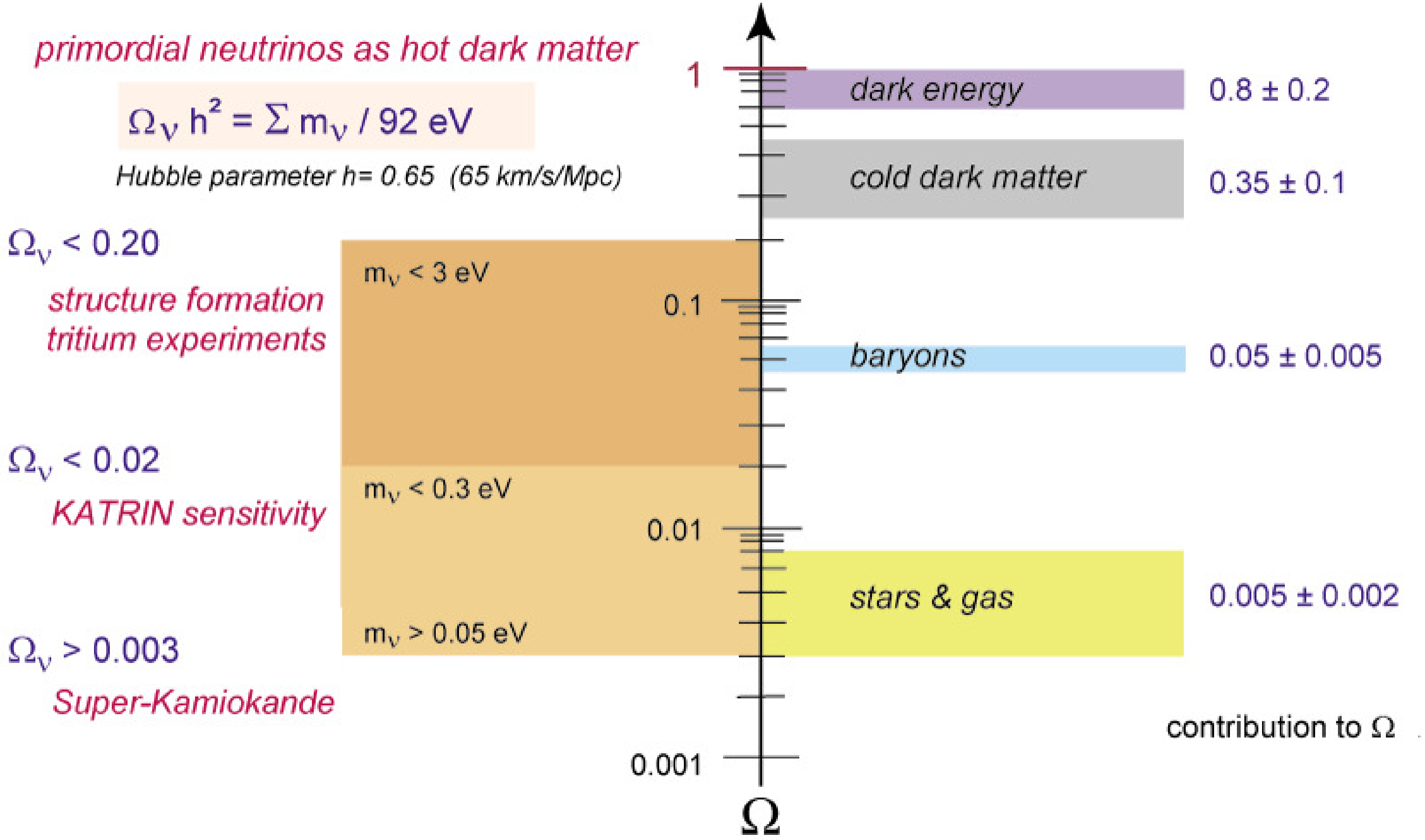


$$n_\nu = \frac{6\varsigma(3)}{11\pi^2} T_{CMB}^3 \approx 112cm^{-3}$$

$$\Omega_\nu h^2 = \frac{m_{\nu,tot}}{94eV}$$



Neutrino masses and cosmology



primordial neutrinos as hot dark matter

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

Hubble parameter h= 0.65 (65 km/s/Mpc)

$\Omega_\nu < 0.20$

structure formation
tritium experiments

$m_\nu < 3$ eV

$\Omega_\nu < 0.02$

KATRIN sensitivity

$m_\nu < 0.3$ eV

$m_\nu > 0.05$ eV

$\Omega_\nu > 0.003$

Super-Kamiokande

dark energy 0.8 ± 0.2

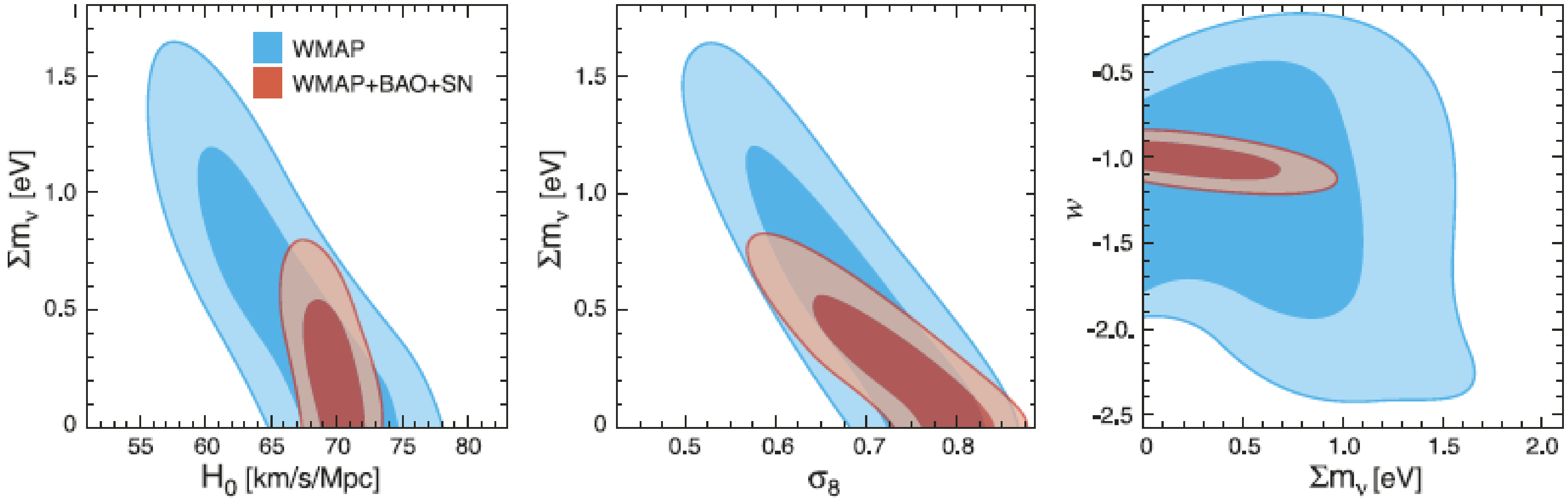
cold dark matter 0.35 ± 0.1

baryons 0.05 ± 0.005

stars & gas 0.005 ± 0.002

contribution to Ω

WMAP 5yr data



Description	Symbol	*WMAP*-only	*WMAP*+BAO+SN
Neutrino density [j]	$\Omega_\nu h^2$	< 0.014 (95% CL)	< 0.0071 (95% CL)
Neutrino mass [j]	$\sum m_\nu$	< 1.3 eV (95% CL)	< 0.67 eV (95% CL)
Number of light neutrino families [k]	$N_{\rm eff}$	> 2.3 (95% CL)	4.4 ± 1.5

A unique cosmological bound on m_ν DOES NOT exist !

Cosmology is discovering systematic errors…

S. Pastor, EPS HEP2005, Lisbon

Summary

- Neutrino physics is an essential part of particle and particle astrophysics
- We know $\Theta_{12} \approx 34^o$ $\Theta_{23} \approx 45^o$ and $\Theta_{13} < 12^o$. Furthermore $m_\nu<2.2$ eV
- Two major directions: Determine absolute neutrino mass, determine PMNS mixing matrix elements (CP-violation)
- Solar neutrino problem has been solved, full information available only if full spectrum (including pp-neutrinos) is measured in real-time
- We are still awaiting good ideas how to detect the relic 1.95K neutrino background
- Neutrino physics is a very lively and exciting field of nuclear-, astro- and particle physics

Always expect the unexpected