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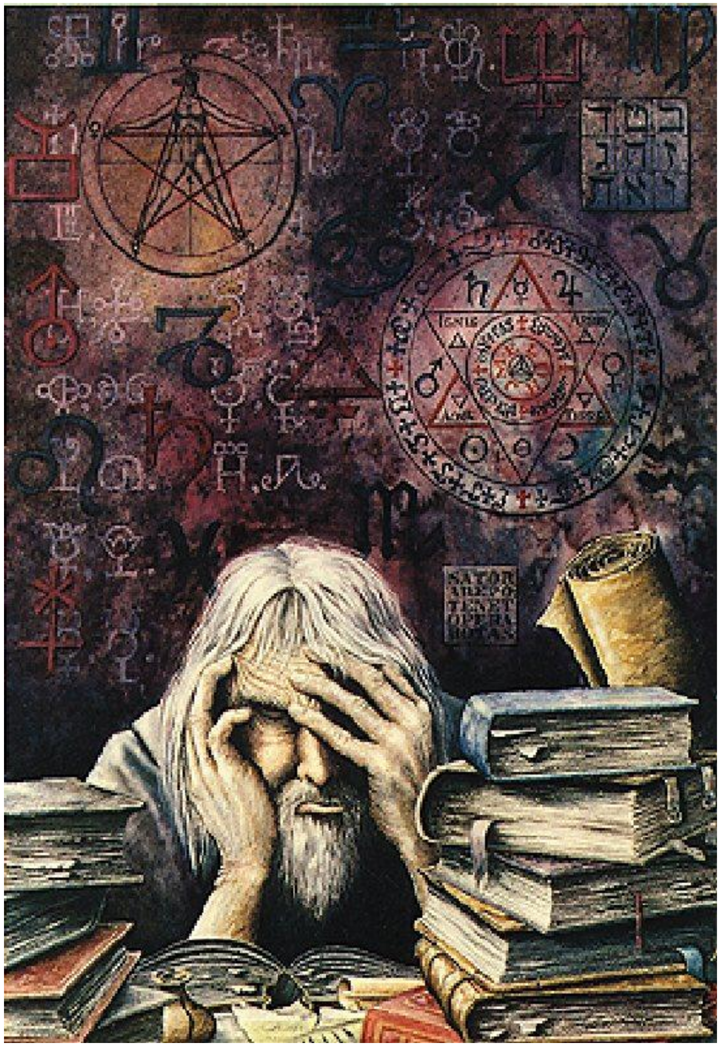


- Lecture 1:
  History
  Neutrinos in the Standard Model
  Evidence for neutrino masses (oscillations)
- Lecture 2:
  Evidence for neutrino masses (c‘td)
  Absolute neutrino mass measurements (beta, double beta decay)
- Lecture 3:
  Double beta decay (c‘td)
  What‘s next? Future activities
  Things to do

Back of an envelope

This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

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

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

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

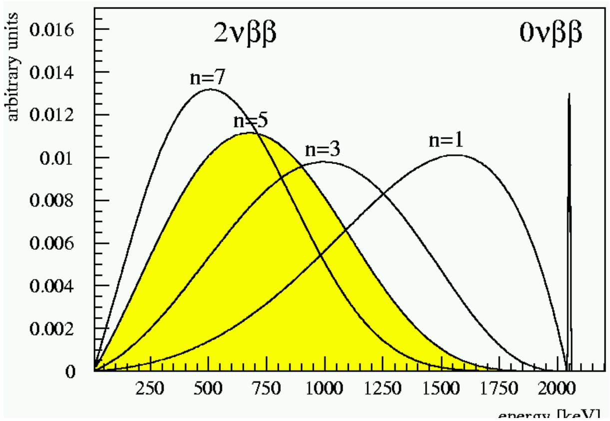
This is about 1000 moles of isotope, implying about 100 kg

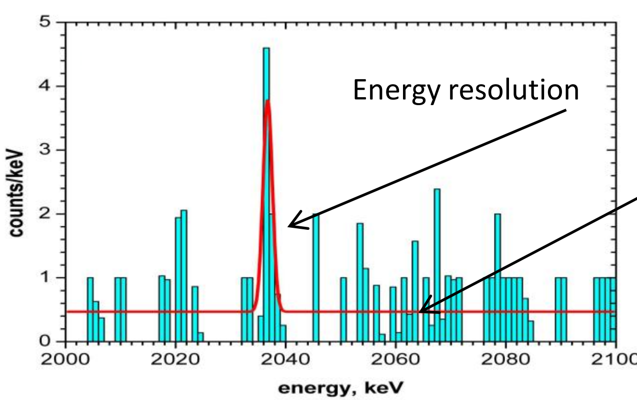
Now you only can loose: nat. abundance, efficiency, background, ...

Spectral shapes

0νββ: Peak at Q-value of nuclear transition

Sum energy spectrum of both electrons





Measured quantity: Half-life

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

Experimental sensitivity depends on

$$T_{1/2}^{-1} \propto a\varepsilon\sqrt{\frac{Mt}{\Delta E B}}$$ (BG limited)

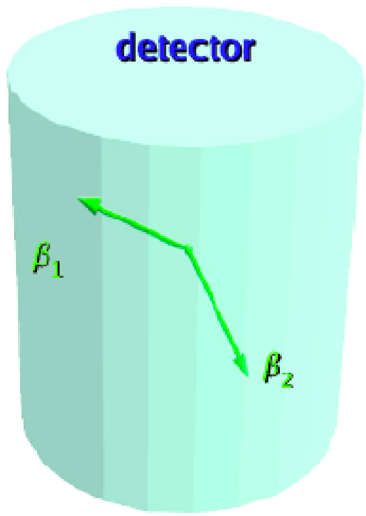
$$T_{1/2}^{-1} \propto a\varepsilon Mt$$ (BG free)

If background limited $$m_\nu \propto \sqrt[4]{\frac{\Delta E B}{Mt}}$$

Signatures and approaches

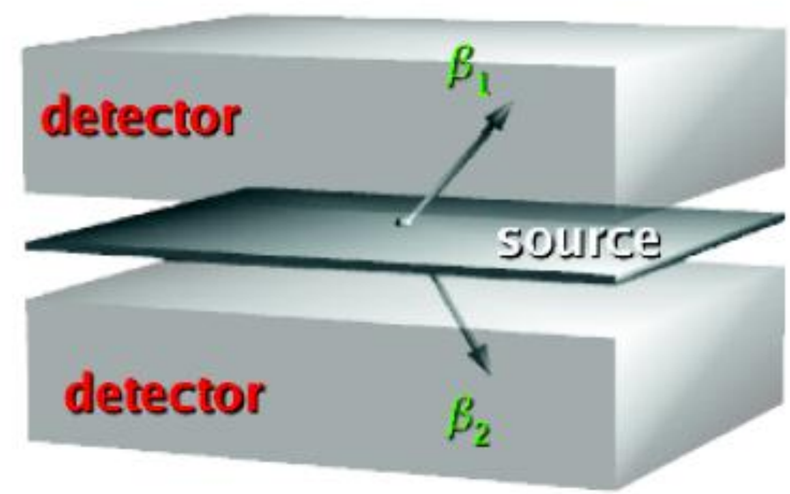
- Sum energy of both electrons
- Single electron spectra and opening angle
- Detection of daughter ion

Source = detector



- Semiconductors
- Cryogenic bolometers
- Scintillators
- Liquid Noble gases

Source ≠ detector



- TPCs (foils)
- Scintillators (foils)

All low background

The dominant problem - Background

How to measure half-lives beyond 10^{20} years???

The first thing you need is a mountain, mine,...

- The usual suspects (U, Th nat. decay chains)
- Alphas, Betas, Gammas
- Cosmogenics
- thermal neutrons
- High energy neutrons from muon interactions
- $2\nu\beta\beta$

Experimental approaches

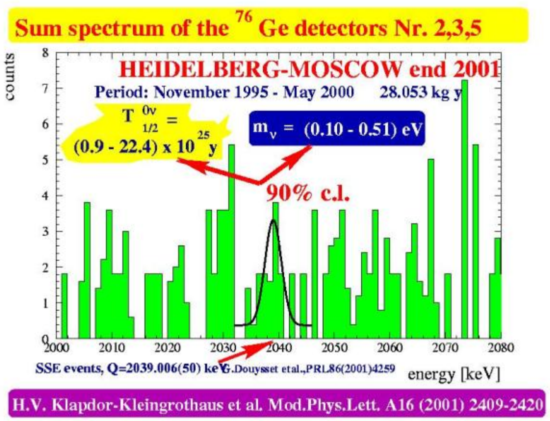
$0\nu\beta\beta$ decay rate scales with Q^5 → only those with Q>2000 keV

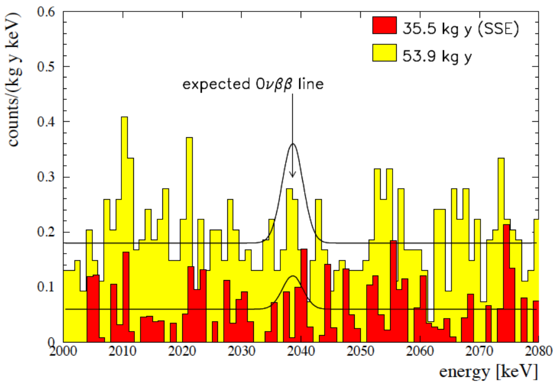
11 isotopes of interest

Isotope	*Q-Value (keV)*	*Nat. abund. (%)*	
Ca 48	4271	0.187	Candles
Ge 76	2039	7.8	GERDA, Majorana
Se 82	2995	9.2	SuperNEMO, LUCIFER
Zr 96	3350	2.8	
Mo 100	3034	9.6	MOON
Pd 110	2013	11.8	
Cd 116	2809	7.5	COBRA
Sn 124	2288	5.64	
Te 130	2529	34.5	CUORE
Xe 136	2479	8.9	EXO, KamLAND-Zen, NEXT, XMASS
Nd 150	3367	5.6	SNO+, DCBA, SuperNEMO(?)

Evidence ?

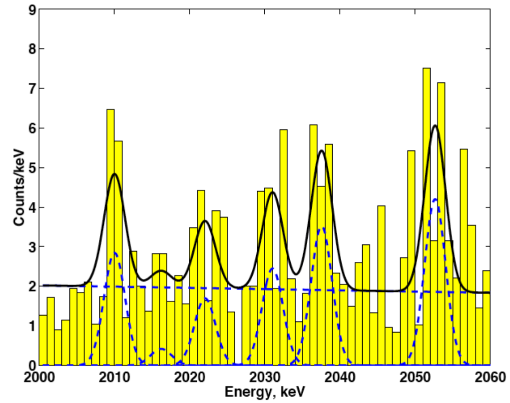
2001





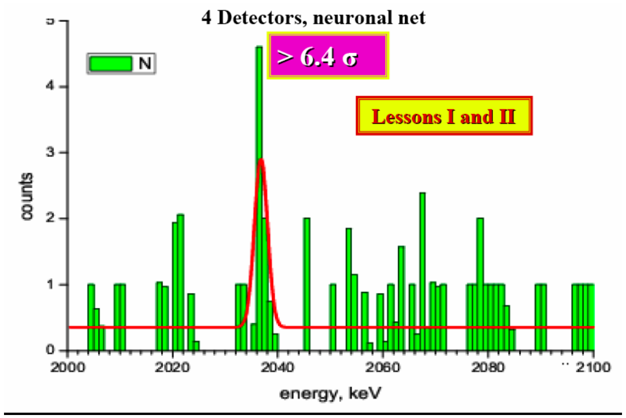
H.V. Klapdor-Kleingrothaus et al.,
Eur.Phys.J. A12 (2001) 147-154

2004



H.V. Klapdor-Kleingrothaus et al.,
Phys. Lett. B 586, 198 (2004)

2006



Mod.Phys.Lett.A21:1547-1566 (2006)

Very controversial discussion in the community

TECHNISCHE UNIVERSITÄT DRESDEN

The fantastic 4

Because they‘re starting this year

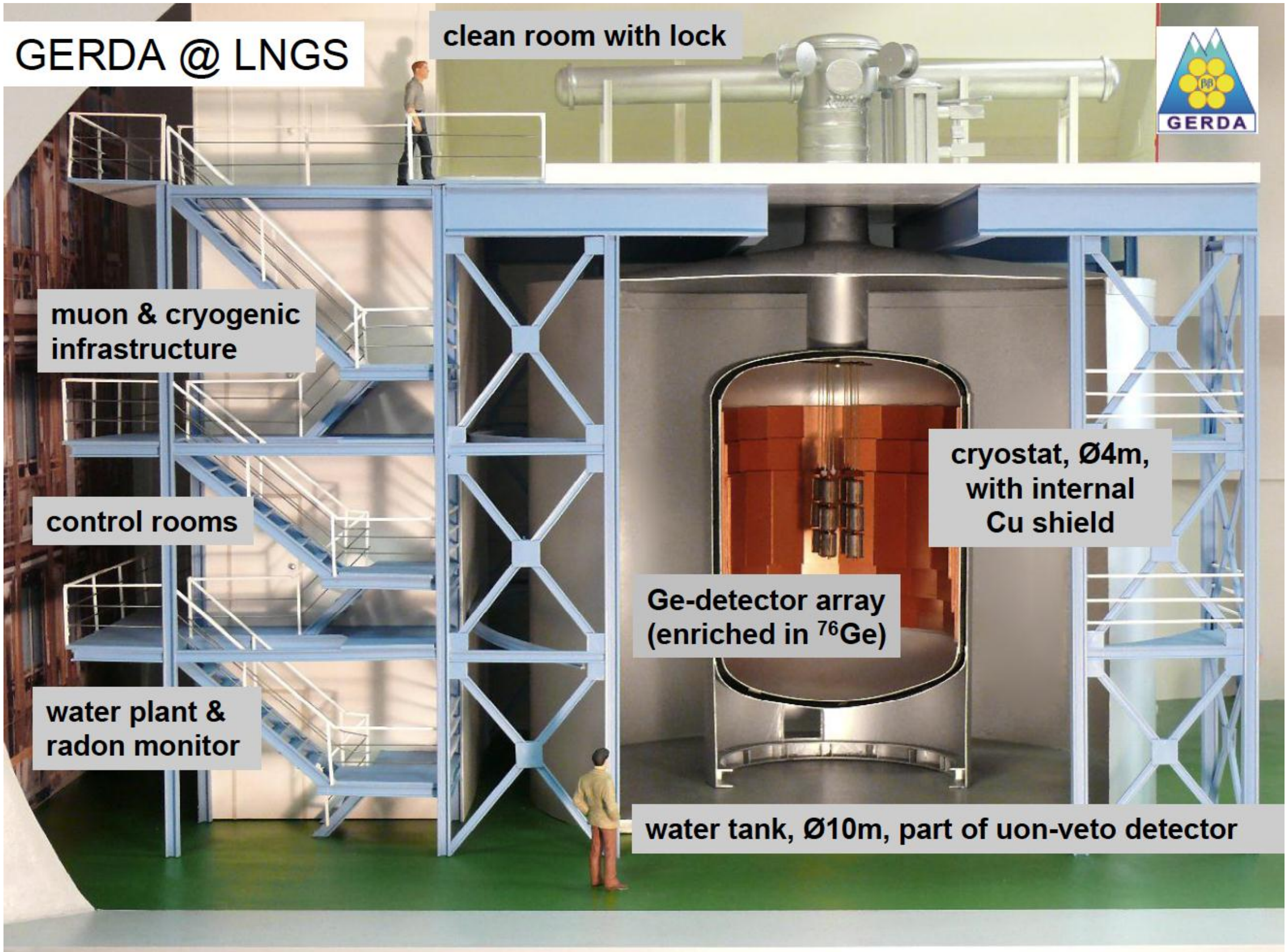
GERDA

Enriched Xenon Observatory

EXO

for double beta decay

GERDA-Principal Setup

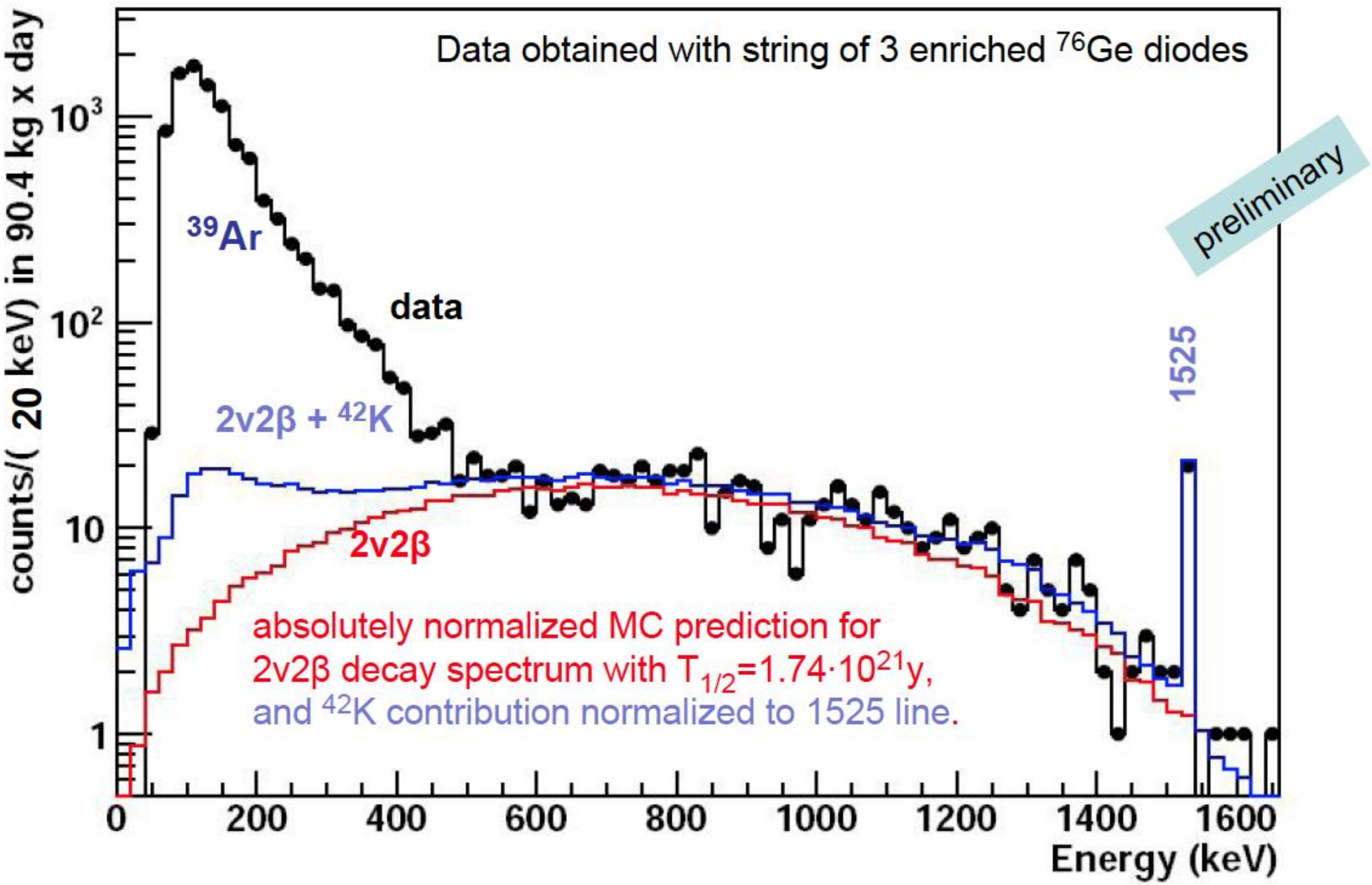


Installation

GERDA

Glove-box for Ge-detector handling and mounting into commissioning lock under N_2 atmosphere installed in clean room

GERDA – First enriched data



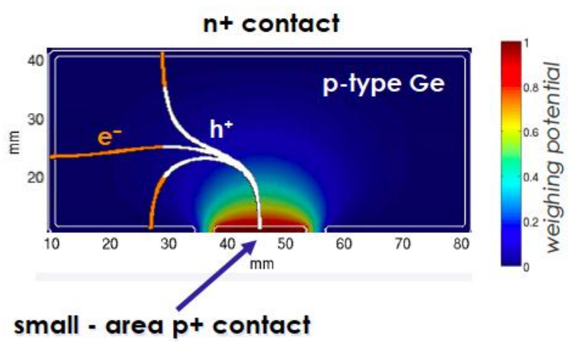
Phase 1: 8 enriched detectors (former Hd-Moscow and IGEX detectors)

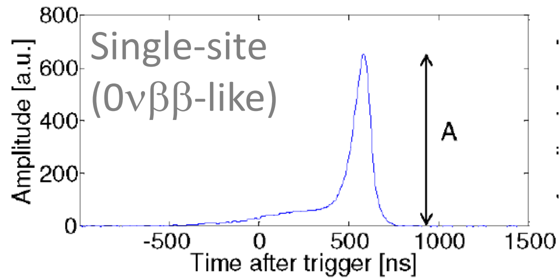
Stay tuned!

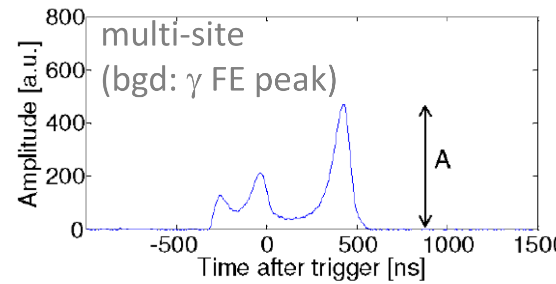
GERDA Detectors – Phase 2

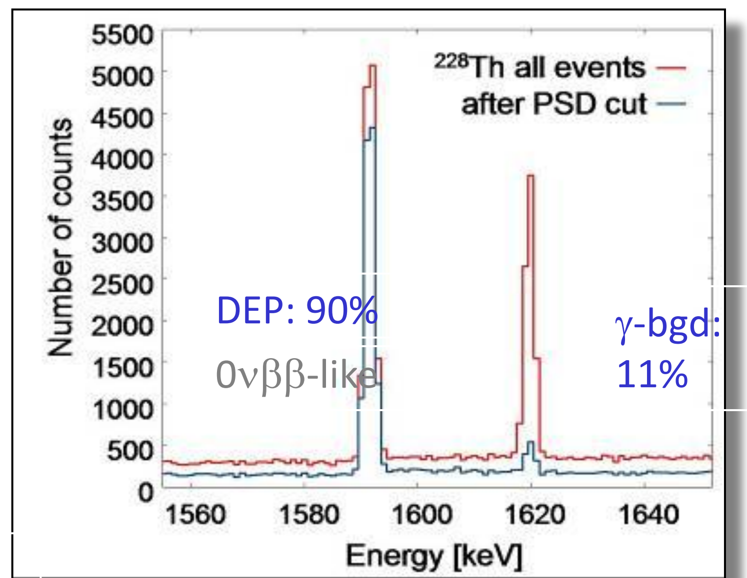
Phase II: 35.4 kg enriched Ge purified to 6N (+ 1.1 kg tail), awaiting crystal growing

Candidate: **BEGe**









Optimal for pulse shape discrimination

GERDA Detectors – Phase 2

M/V Philadelphia Express
Bremerhaven, Germany
October 2, 2011

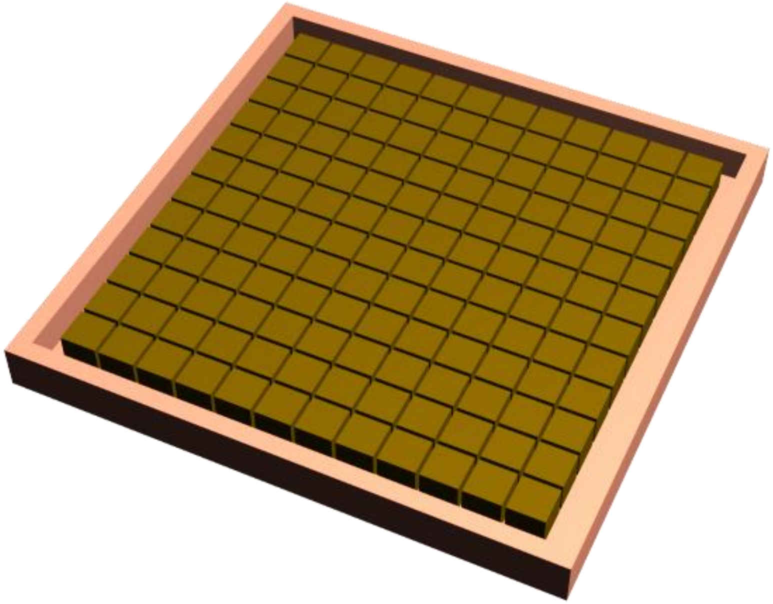
TECHNISCHE UNIVERSITÄT DRESDEN

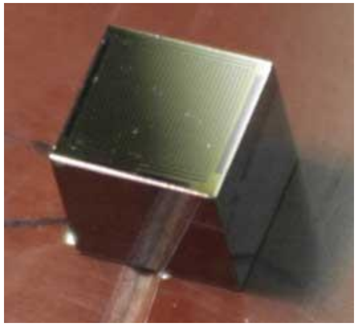
The magnificent 7

Because they should be online 2014

COBRA

Use large amount of CdZnTe Semiconductor Detectors

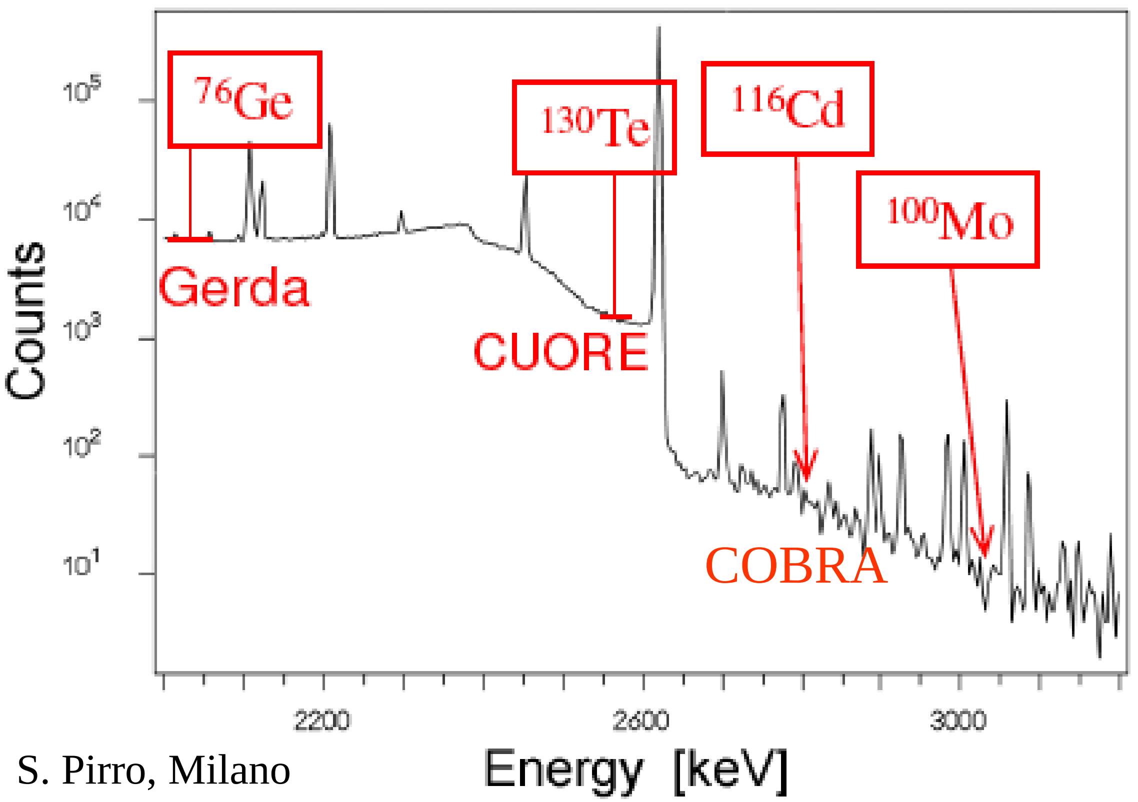




Large array of CdZnTe detectors

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

Background



S. Pirro, Milano

Beyond 2.614 MeV background a priori much lower

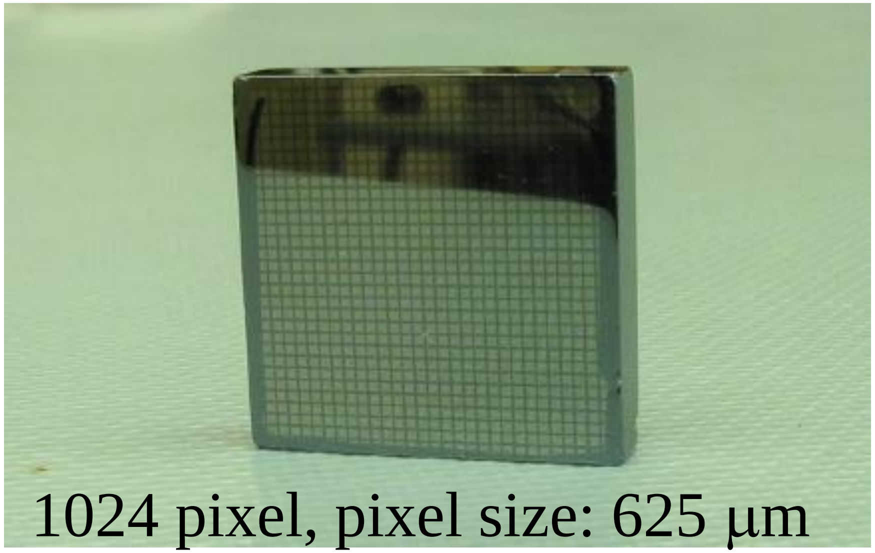
It‘s all about background

Background from:
natural radioactivity, cosmogenic produced radioisotopes, cosmic rays, neutrons

Two options

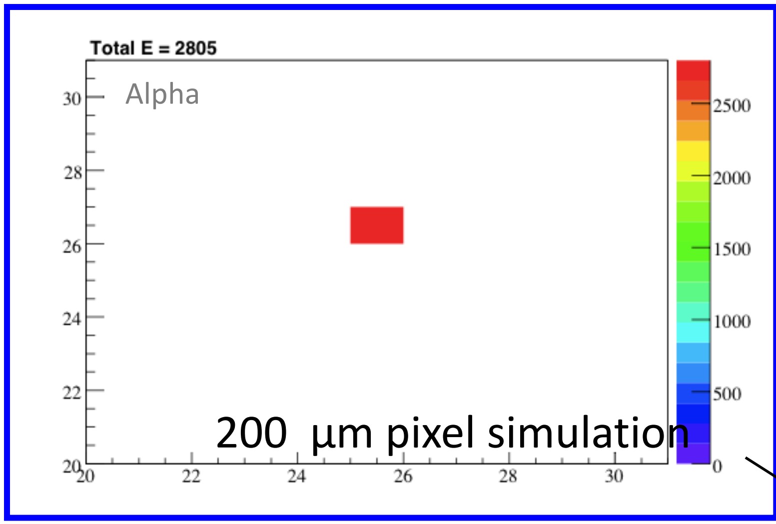
Energy measurement only

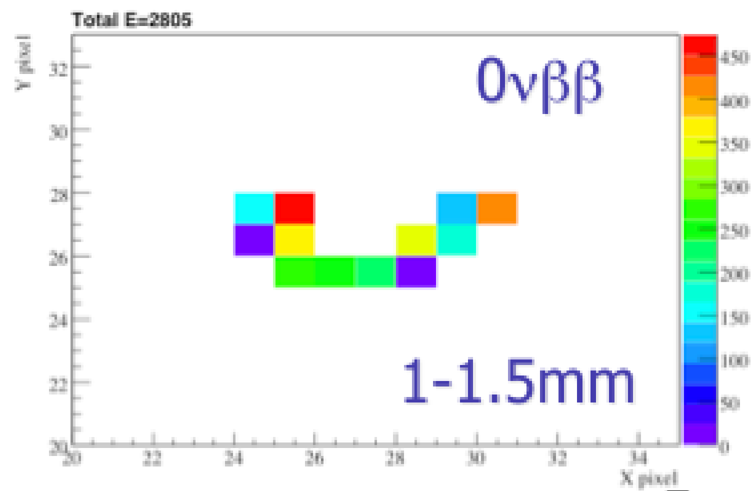
Energy measurement and tracking

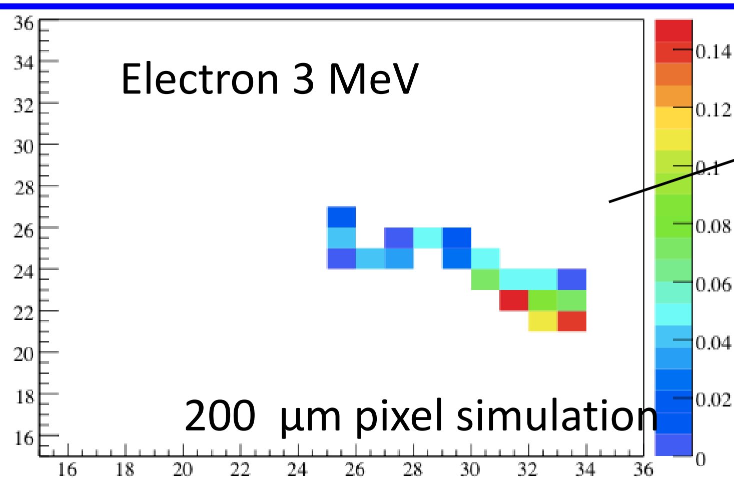


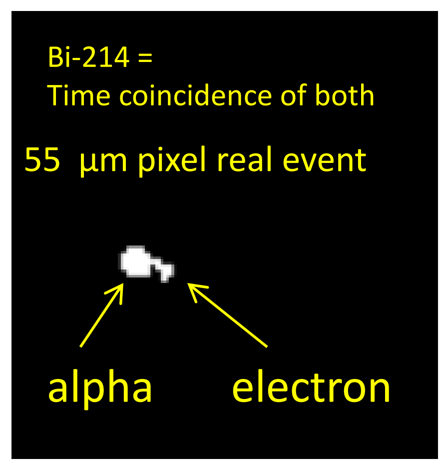
COBRA - Pixel

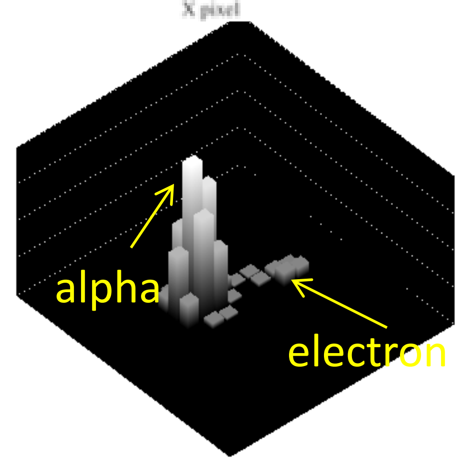
Idea: Massive background reduction by particle identification





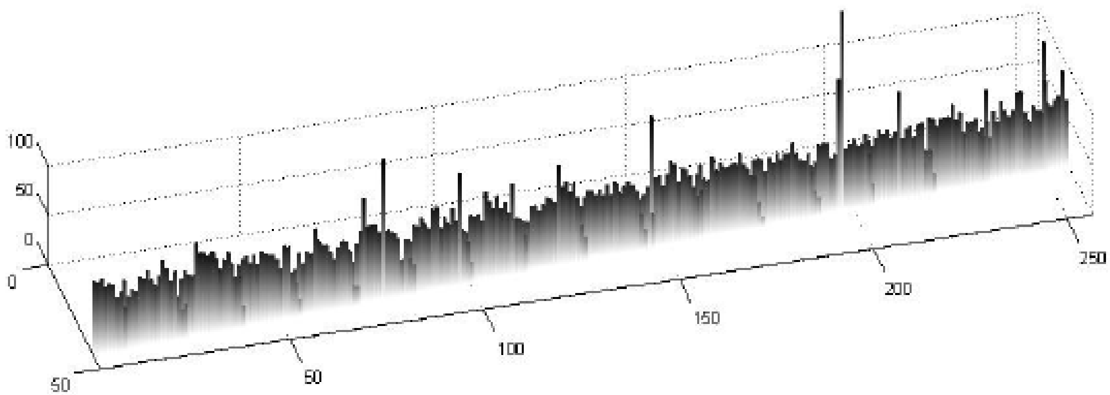


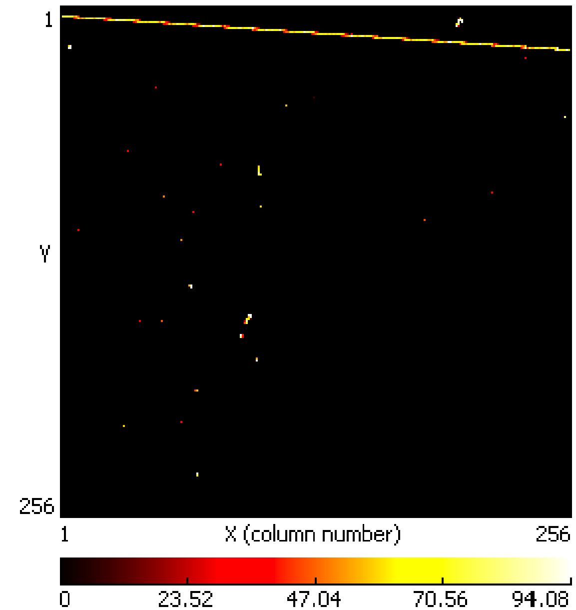




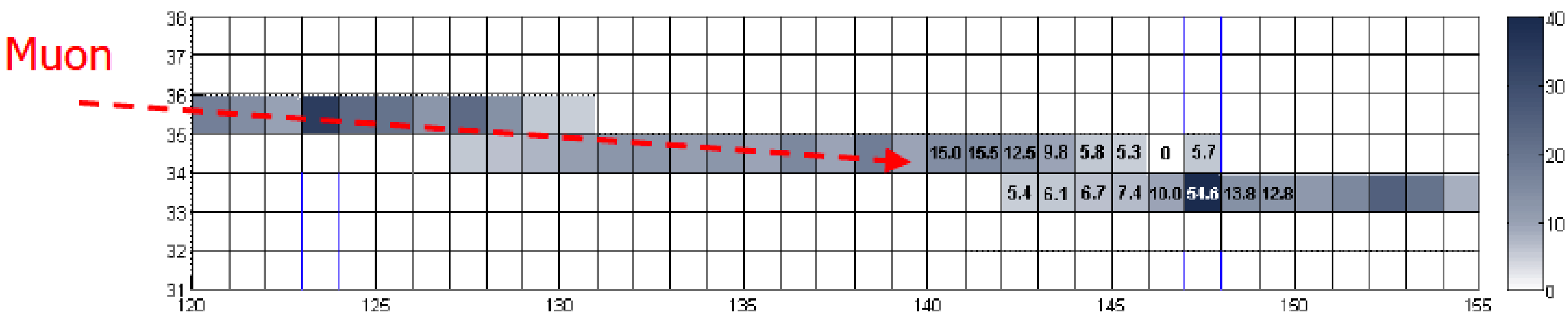
A nice muon.

- Track crossing whole detector



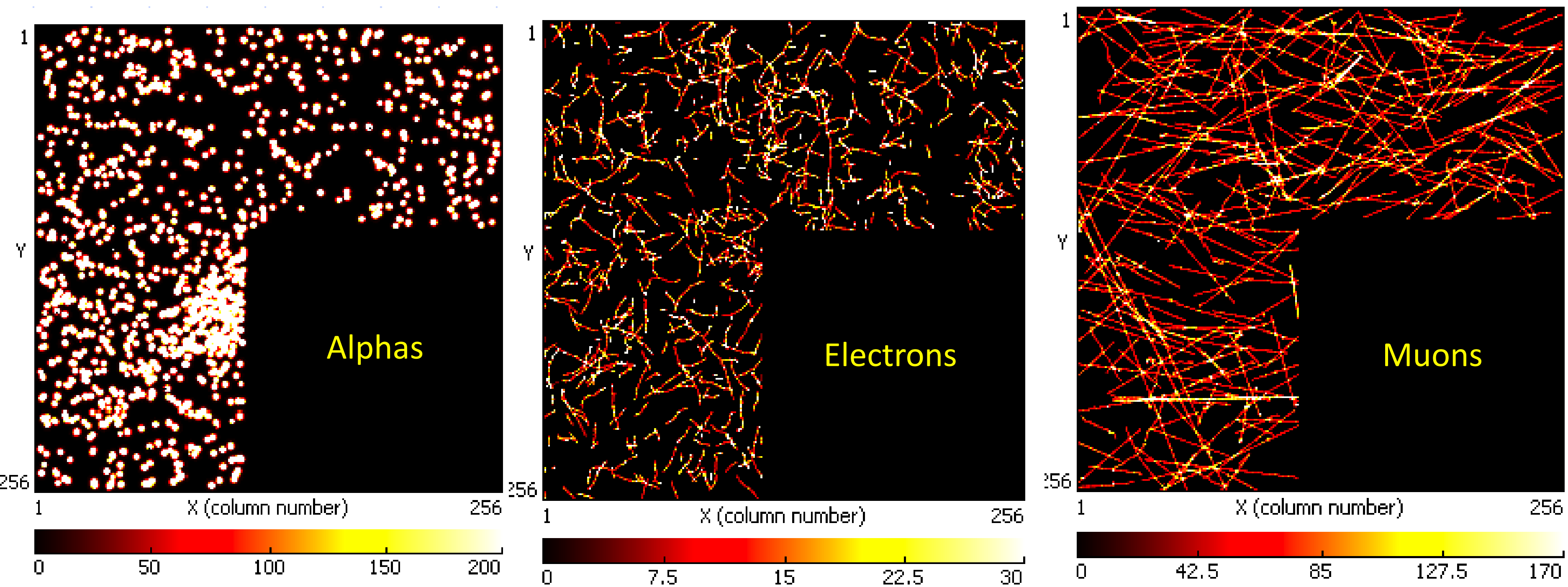


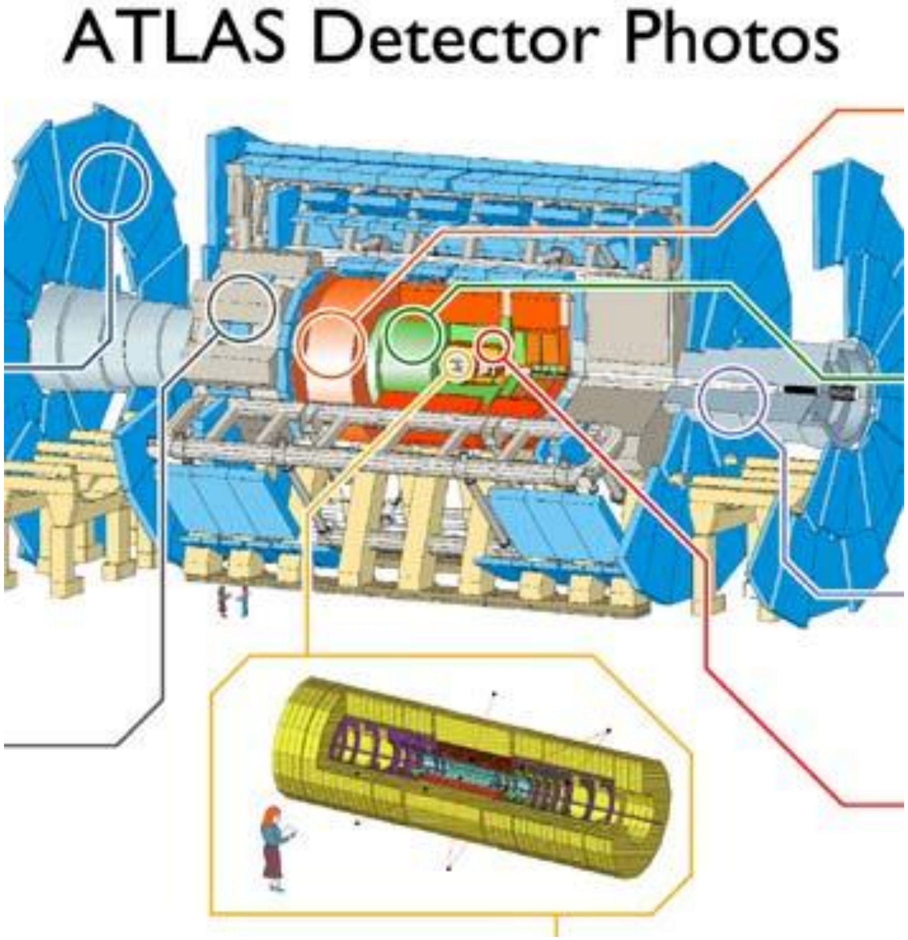
- Top view + deposited energy, charge sharing effect



COBRA – Timepix

256x256 pixels, 55μm





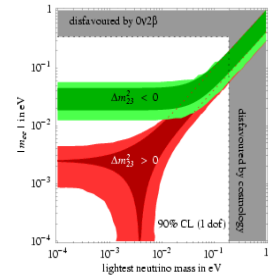
Yes we can! B. Obama

2 Tackling 50 meV

Inverse hierarchy:

$$
\begin{aligned}
\langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\
&\simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 \\
&\sim (c_\odot^2 - s_\odot^2)\sqrt{\Delta m^2_{Atm}} \\
&\simeq 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}}\ \text{eV} \ \simeq 19\ \text{meV}
\end{aligned}
$$

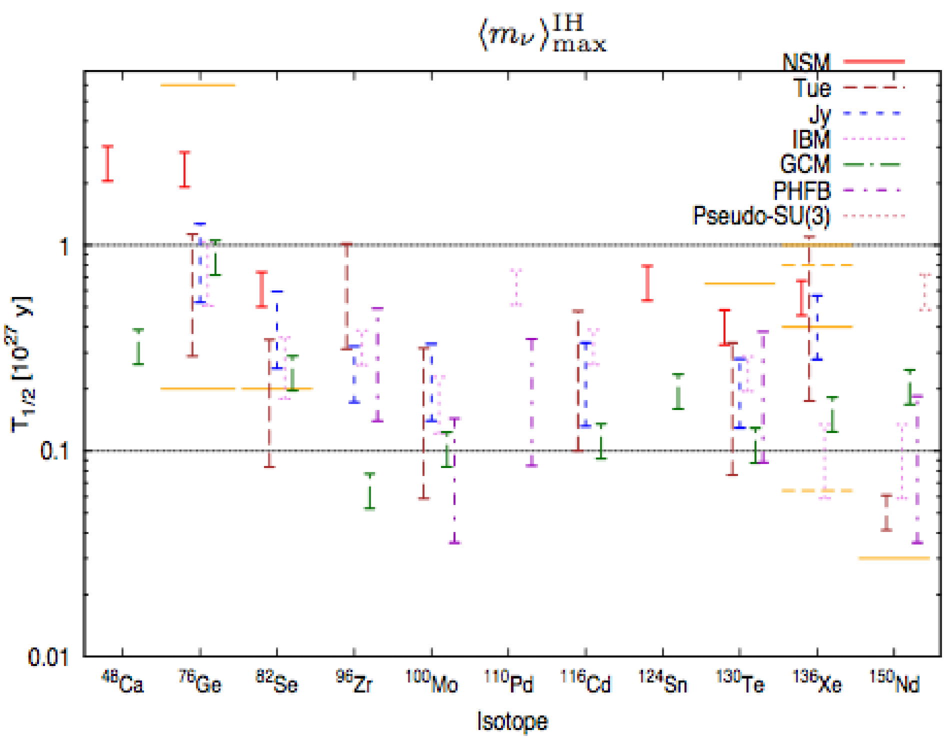
→



Just to touch the IH

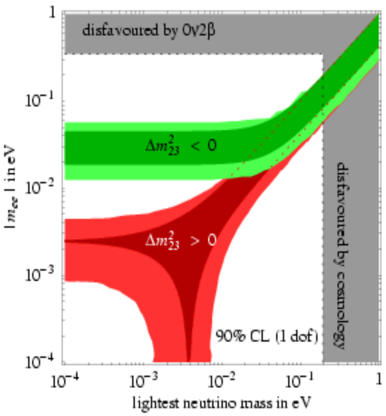
^{100}Mo and ^{150}Nd seems most promising

Dependence on solar mixing angle



A. Dueck, W. Rodejohann, K. Zuber, arXiv:1103.4152, PRD 83, 113010 (2011)

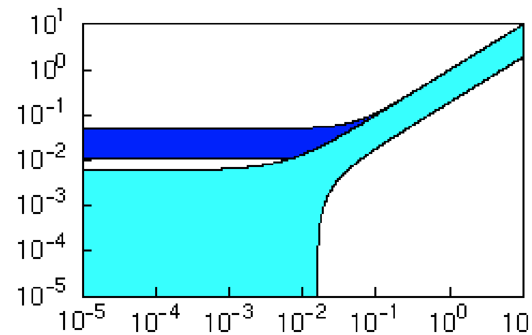
3 Tackling the normal hierarchy



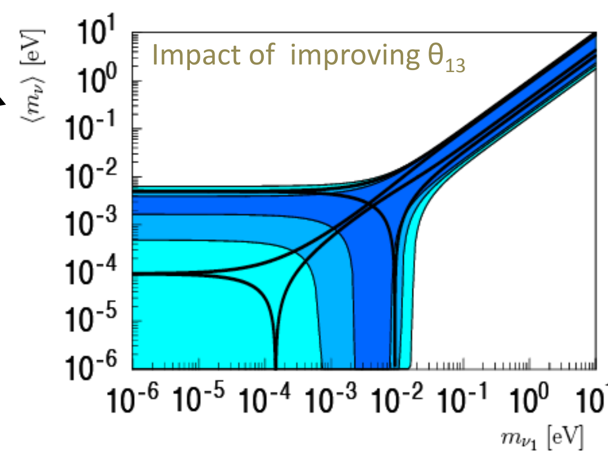
No real proposal yet

- Will be tough and expensive
  > tonne scale detectors
- Needs more precise data from oscillations

Oscillation parameters from Gonzalez-Garcia et al. JHEP 1004, 056 (2010)



$$\langle m_\nu \rangle = \sum_i U_{ei}^2 m_{\nu_i} = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3$$



$\sin^2\theta_R =$
$[0, 5.1 \cdot 10^{-2}]$
$[0, 2.5 \cdot 10^{-2}]$
$[0, 5.1 \cdot 10^{-3}]$

$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}$ eV^2, $\sin^2\theta_{\odot} = [0.23, 0.38]$

M. Hirsch, hep-ph/0609146

- New background components (f.e. solar neutrino-electron elastic scattering)

N. deBarros, K. Zuber, arXiv:1103.5757, JPG 38, 105201 (2011)

- More accurate matrix elements

HOW???

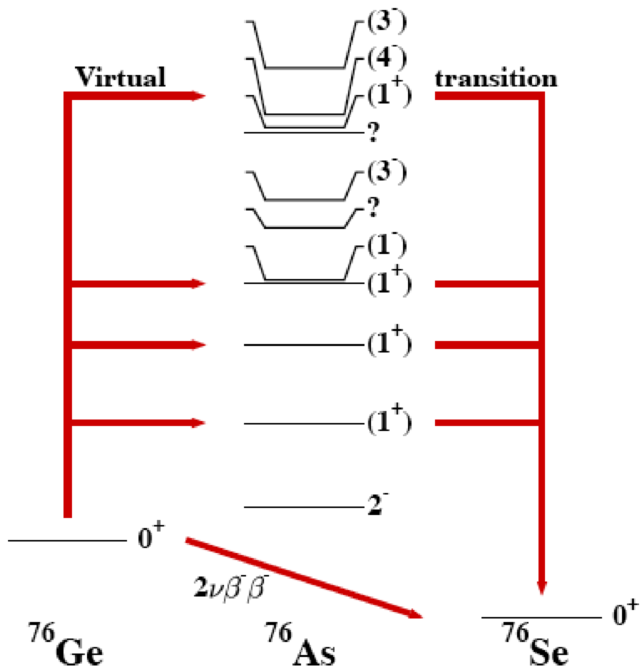
Nuclear matrix elements

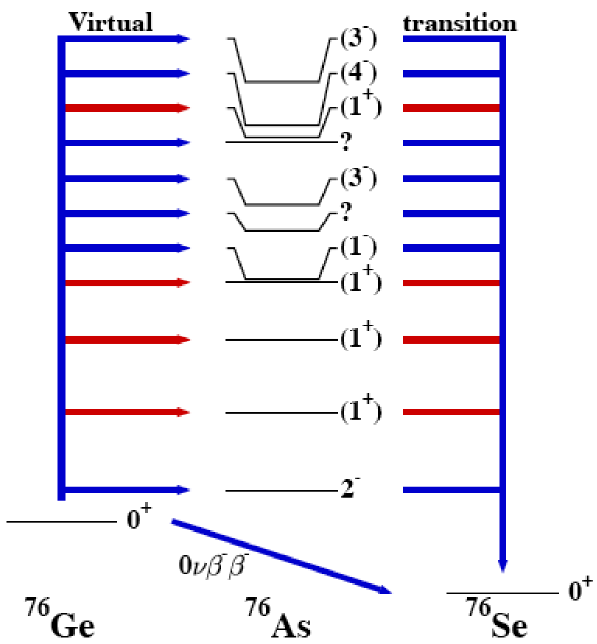
The dark side of double beta decay

Charge exchange reactions

2νββ: Only intermediate 1^+ states contribute

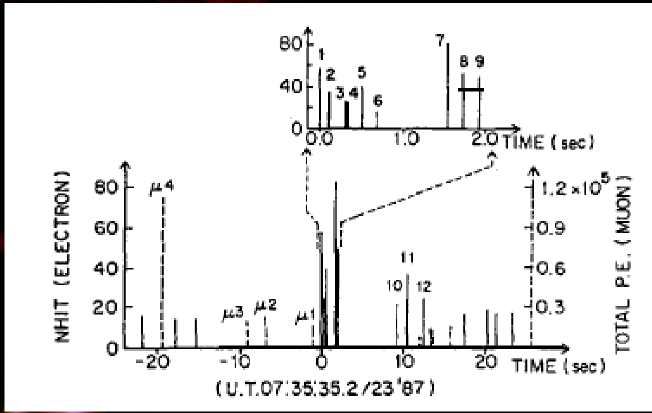
Supportive measurements from accelerators





Currently: (d,^{2}He) and (^{3}He,t)

Supernova 1987A

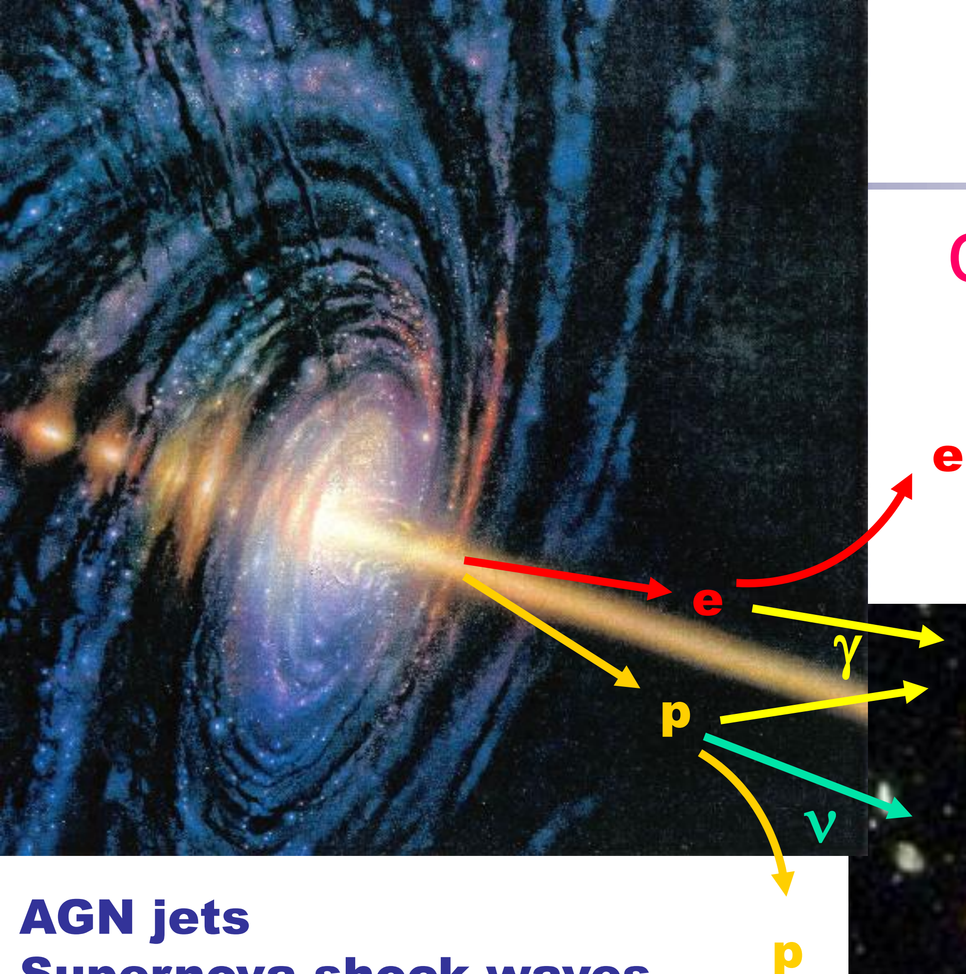


SNO+

Using 1000 tons of (Nd-loaded) scintillator

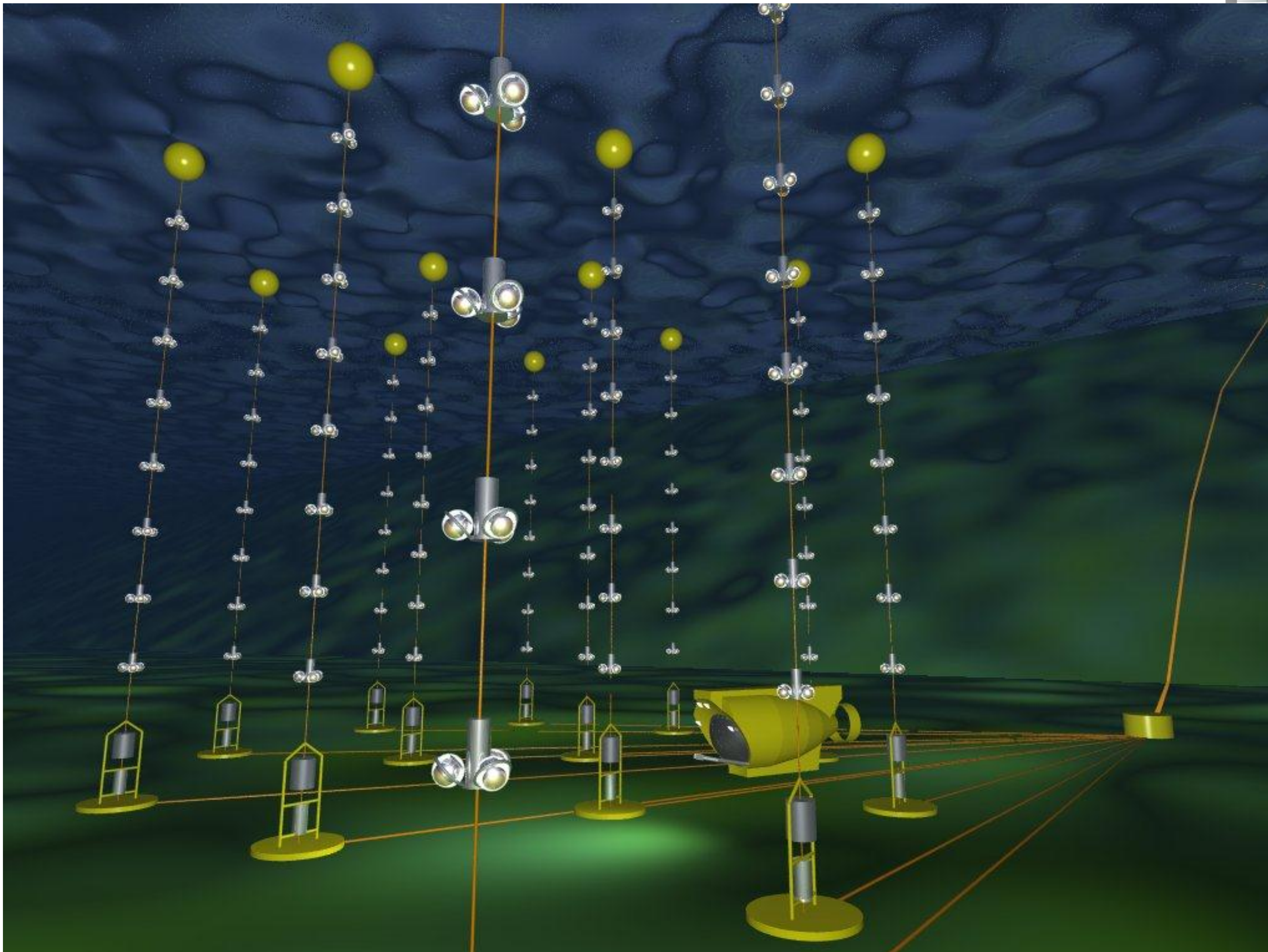
Solar neutrinos, reactor neutrinos, geoneutrinos, supernova neutrinos, double beta decay

Cosmic sources of high-energy particles



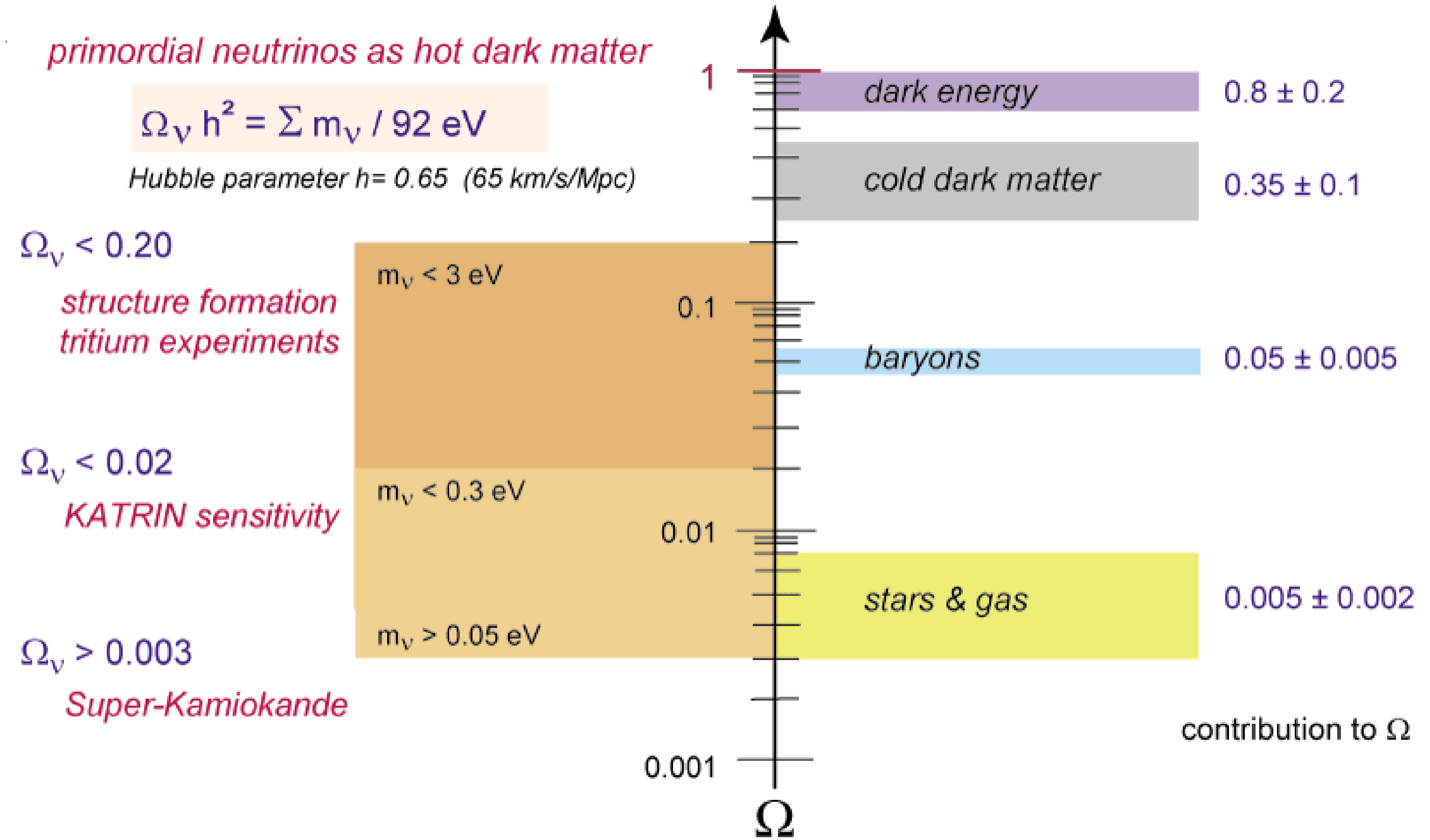
AGN jets
Supernova shock waves
Decaying strings
Annihilating SUSY particles
...

Identify mechanisms using
- **Particle composition**
- **Wide-band energy spectra**
- **Spatial and temporal characteristics**



HE Neutrino Astrophysics

Neutrino-Mass

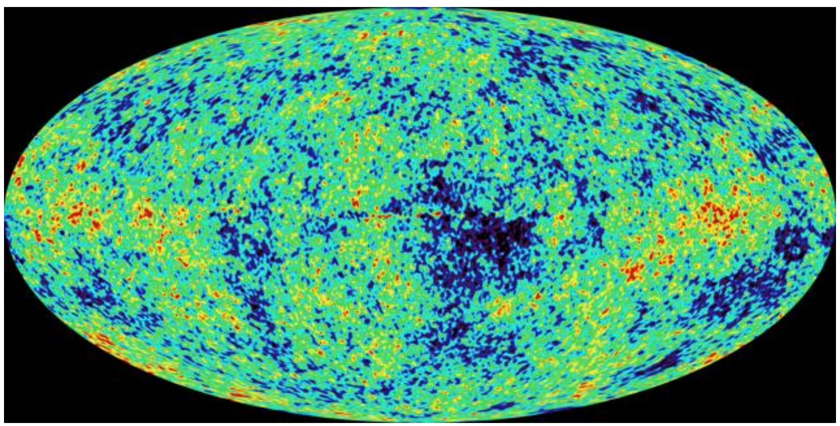


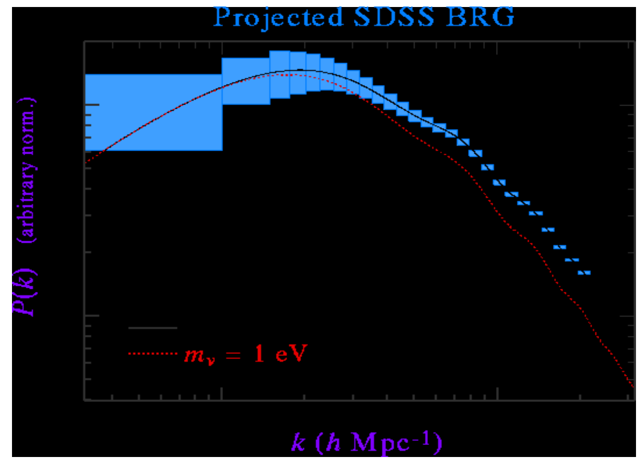
Neutrino masses from cosmology

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

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

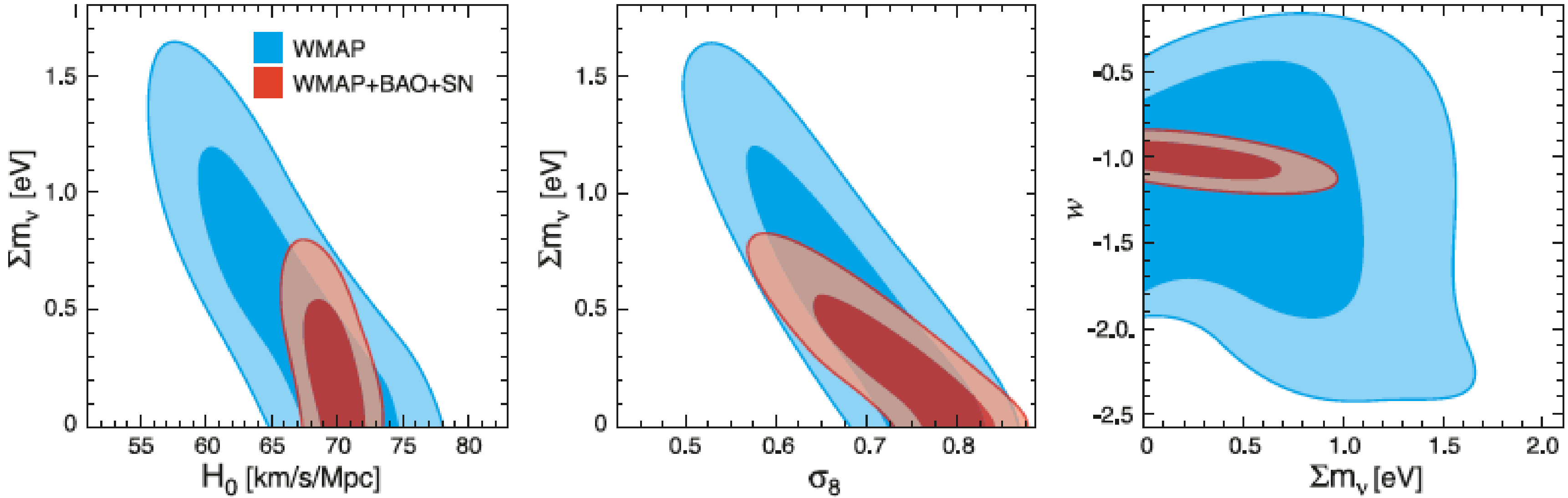
New WMAP measurement + SDSS data





Mass bound model dependent, currently done within ΛCDM

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

Neutrino mass from cosmology

O. Lahav, Neutrino 2004

Data	Authors	$m_\nu = \Sigma\, m_i$
2dFGRS	Elgaroy et al. 02	< 1.8 eV
WMAP+2dF+…	Spergel et al. 03	< 0.7 eV
WMAP+2dF	Hannestad 03	< 1.0 eV
SDSS+WMAP	Tegmark et al. 04	< 1.7 eV
WMAP+2dF+ SDSS	Crotty et al. 04	< 1.0 eV
Clusters +WMAP	Allen et al. 04	$0.56^{+0.30}_{-0.26}$ eV

All upper limits 95% CL, but different assumed priors !

A unique cosmological bound on m_ν DOES NOT exist !

The future

- ★ Absolute neutrino mass measurement ✔
- ★ Which mass scheme?
- ★ Understanding mixing pattern
- ★ The value of θ_{13}
- ★ Three flavour analysis
- ★ Is there CP-violation in the lepton sector (is it observable)?
- ★ Neutrino astronomy
- ★ Are there sterile neutrinos?
- ★ Unexpected things?

Exploring the PMNS matrix

The ± is ν or $\bar{\nu}$

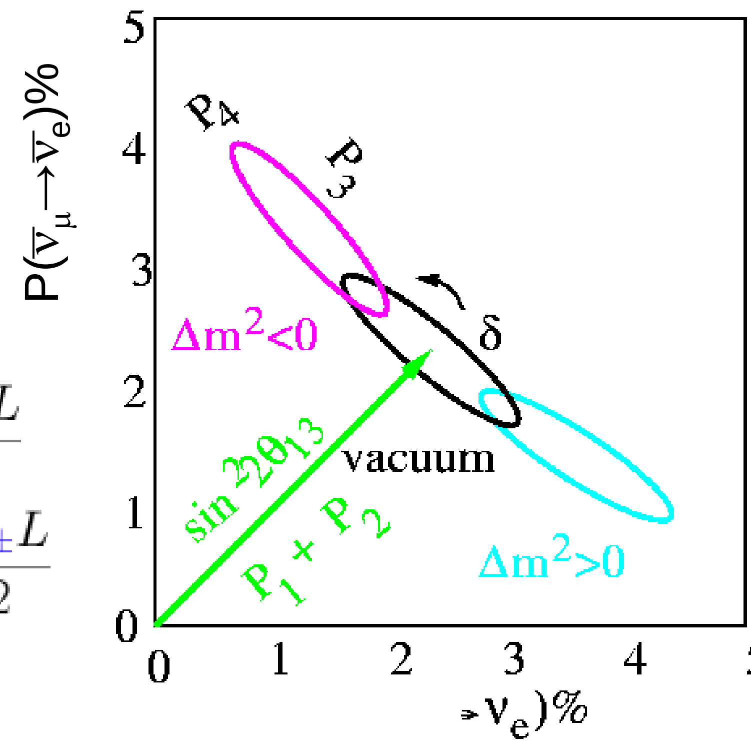
$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$



Minakata & Nunokawa JHEP 2001

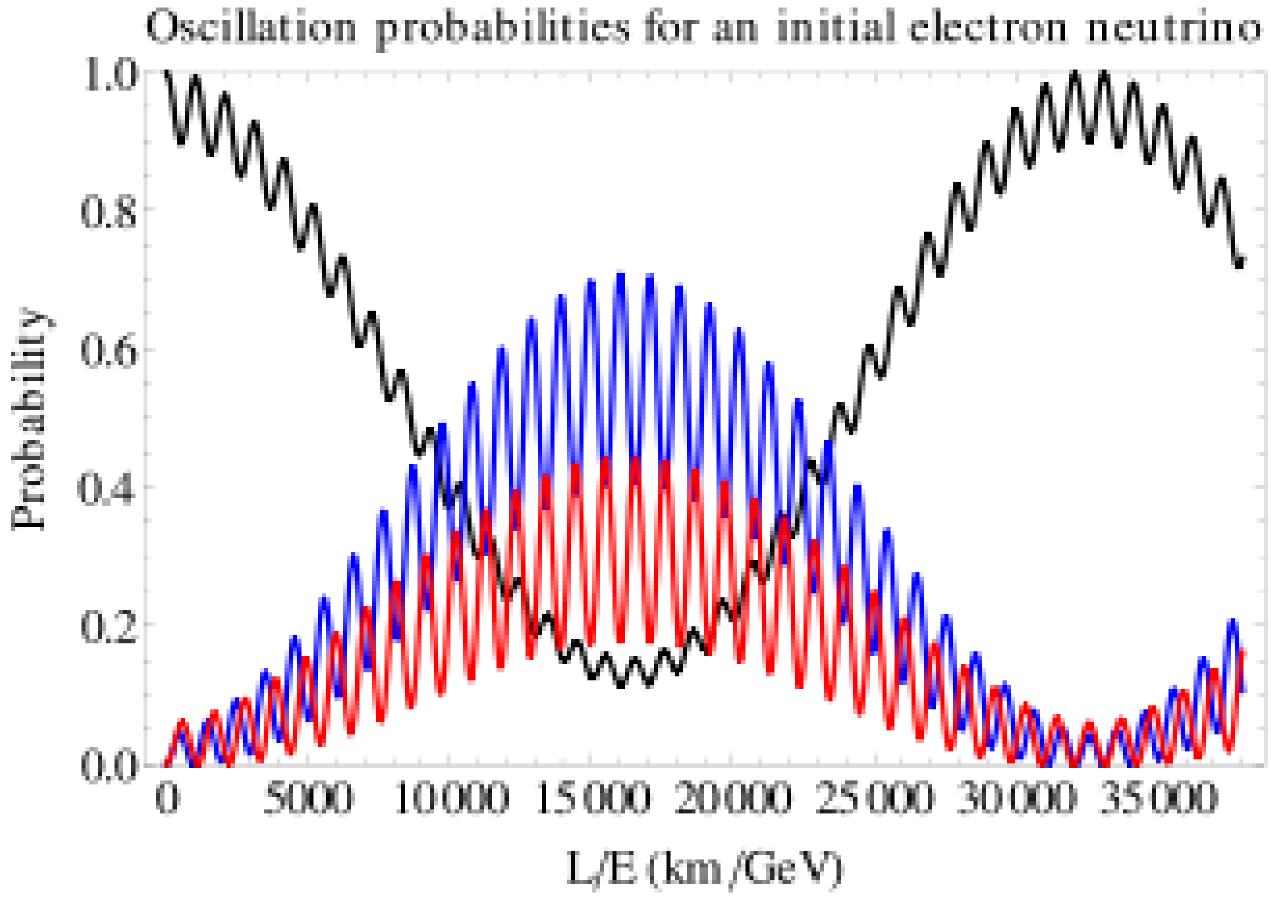
$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu} \qquad B_\pm = |A \pm \Delta_{13}|$$

$$A = \sqrt{2}G_F n_e \qquad J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

8-fold degeneracy among parameters

Magic baseline: $\sqrt{2}G_F n_e L = \frac{\pi}{2} \rightarrow \sin(\frac{AL}{2}) = 0$ L ≈ 7500 km

3-flavour oscillations



http://neutrinopendel.tu-dresden.de

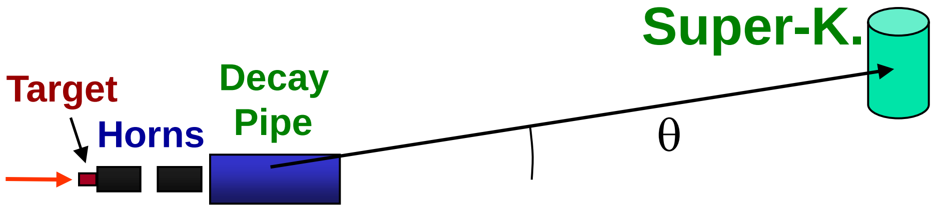
New beams

Aim: Precision

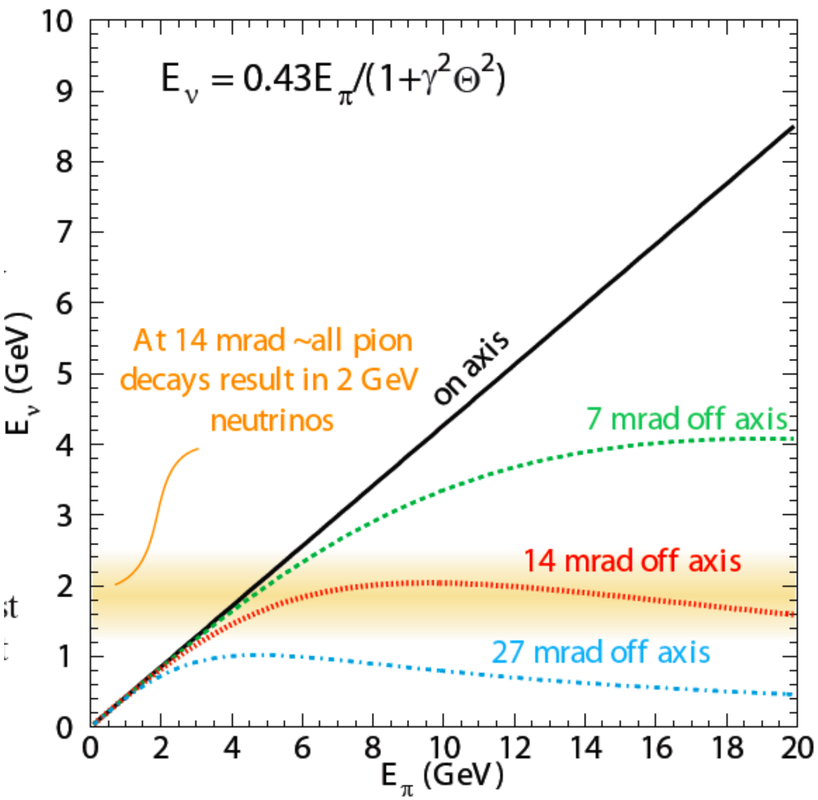
Problem: Flavour content of the beam

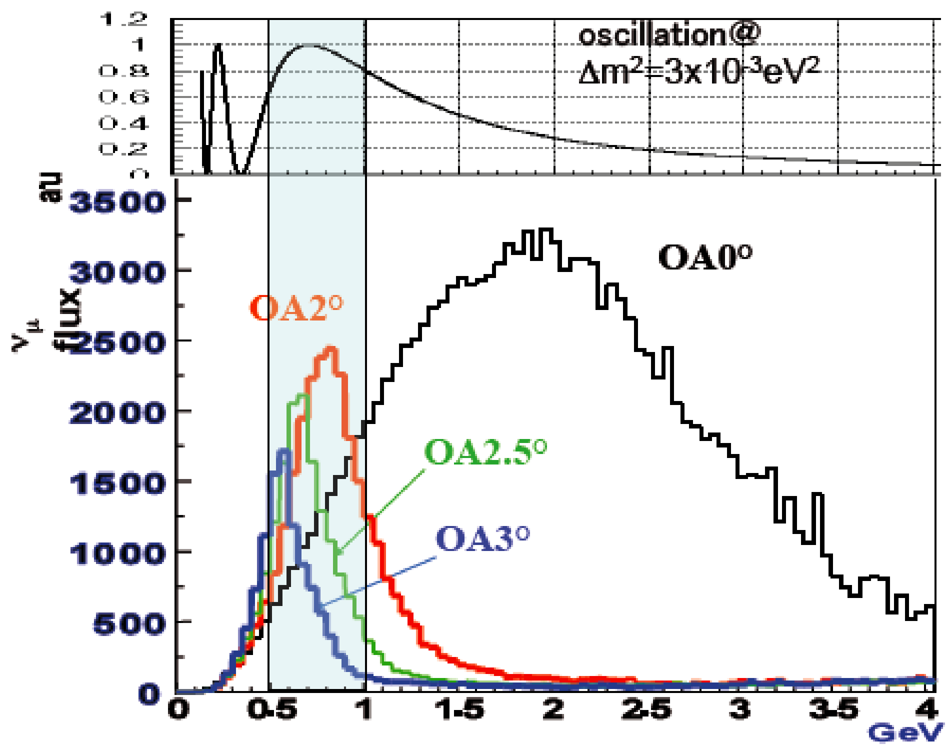
- Superbeams (off axis)
- Beta beams
- Neutrino factory

Off axis beams



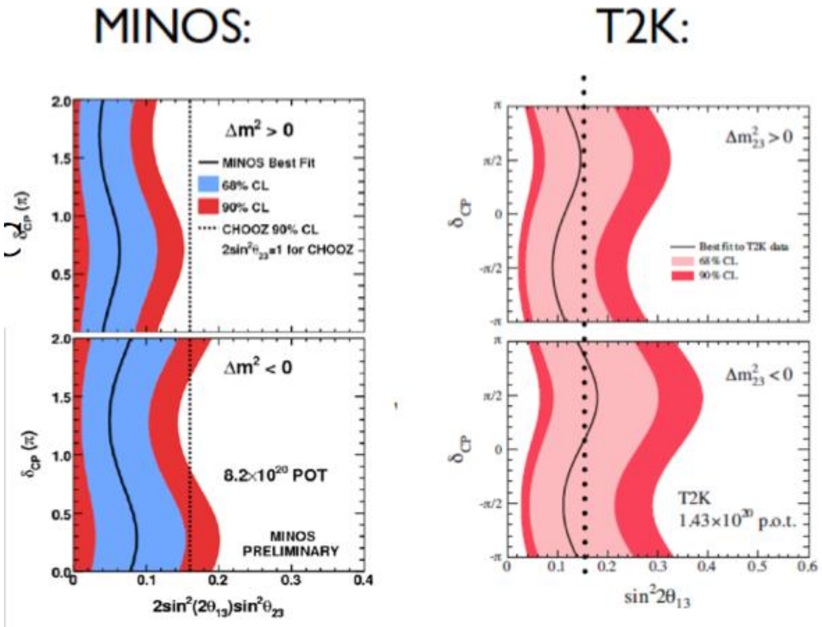
Loose intensity, but get
narrow band beam



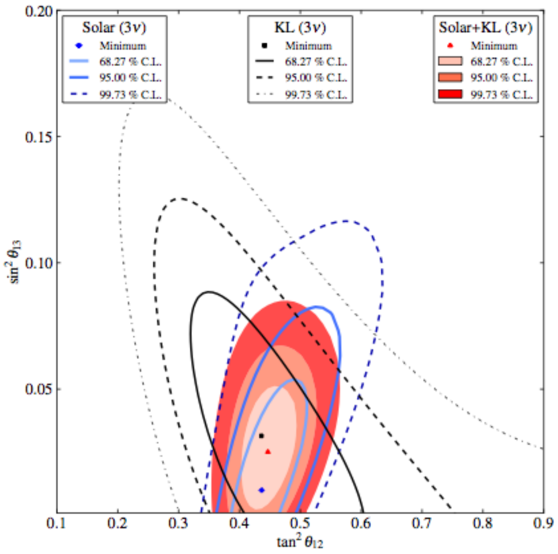


θ_{13}???

goal :
(1) measure appearance of
$\nu_\mu \rightarrow \nu_e$
(2) measure disappearance of
$\nu_\mu \rightarrow \nu_\mu$



Latest solar results
(SNO 3phase)
arXiv:1109.0763



There are good hints that θ_{13} is non zero

Reactor Neutrinos

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

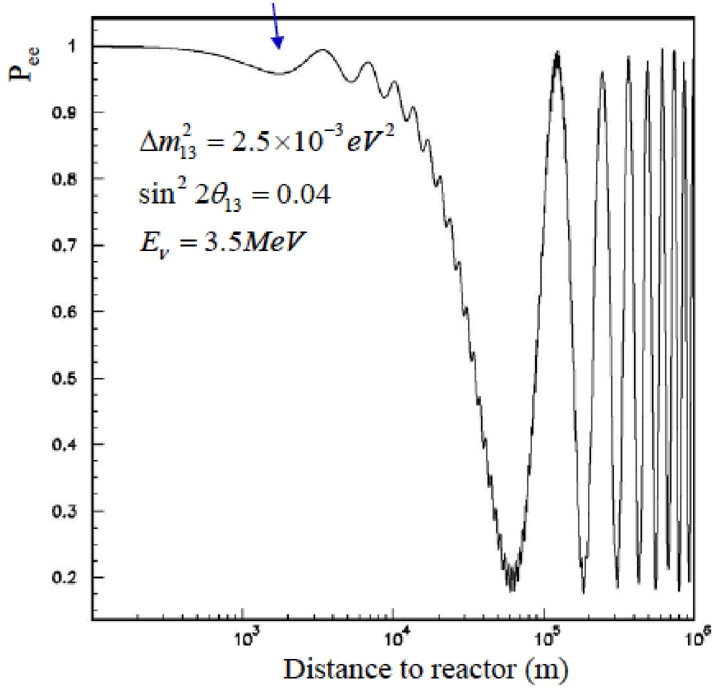
where $\Delta m_{ij}^2 = m_i^2 - m_j^2$.

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

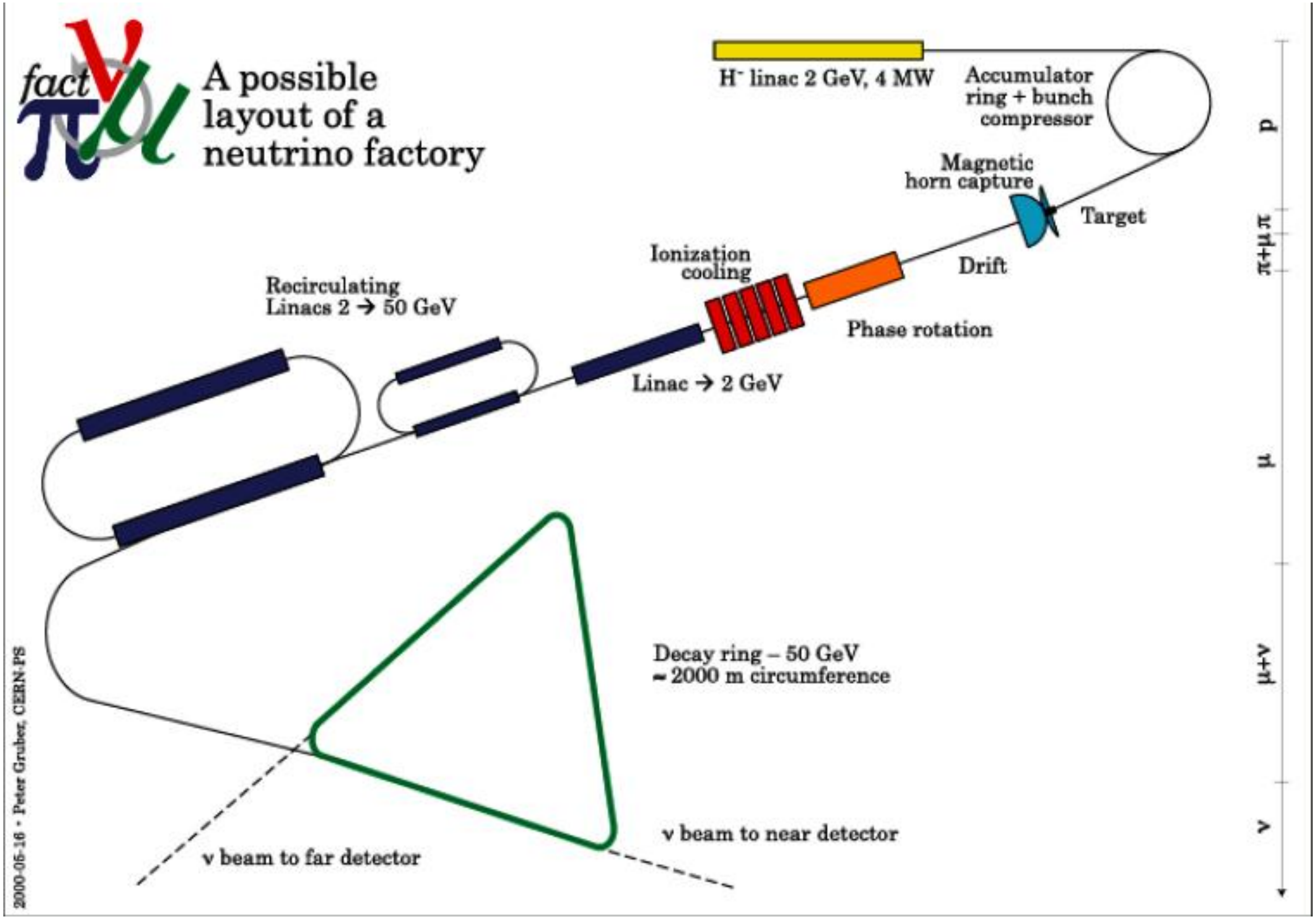


Reactor – θ_{13} hunting

If evidences are right,
Double Chooz should see
something by end of the year!

If true, very good chance to see
CP-violation in the lepton sector
(if there is one)

Neutrino factories

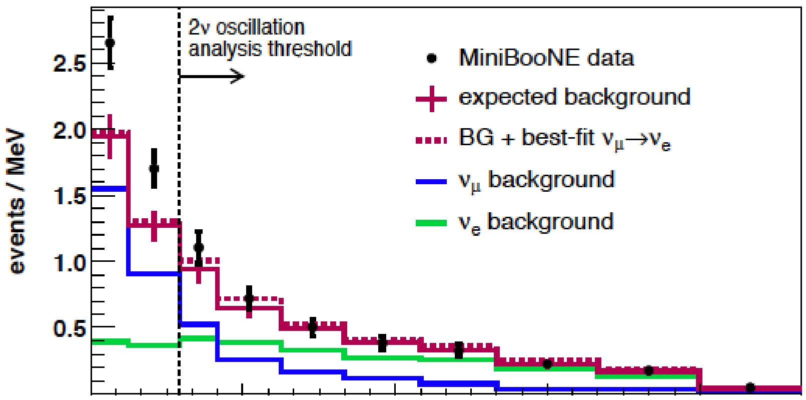


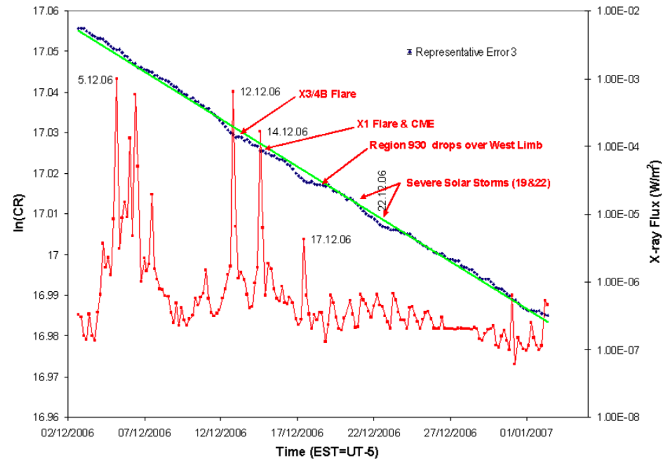
Neutrino factories

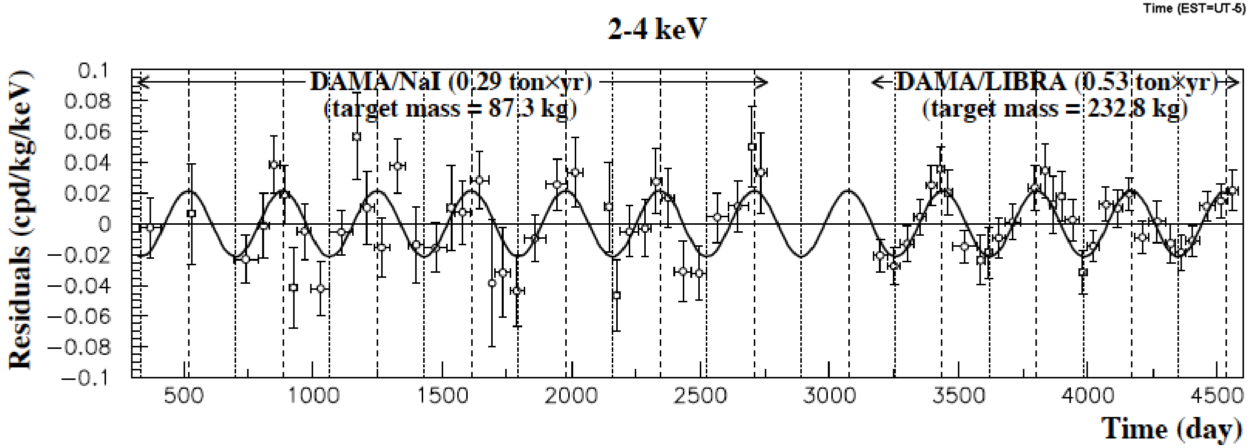
12 Oscillation Processes in a Neutrino Factory

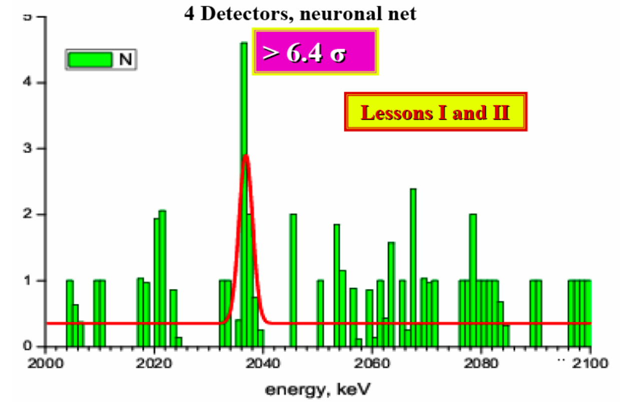
12 Oscillation Processes from (simultaneous) beams of positive and negative muons in a neutrino Factory.

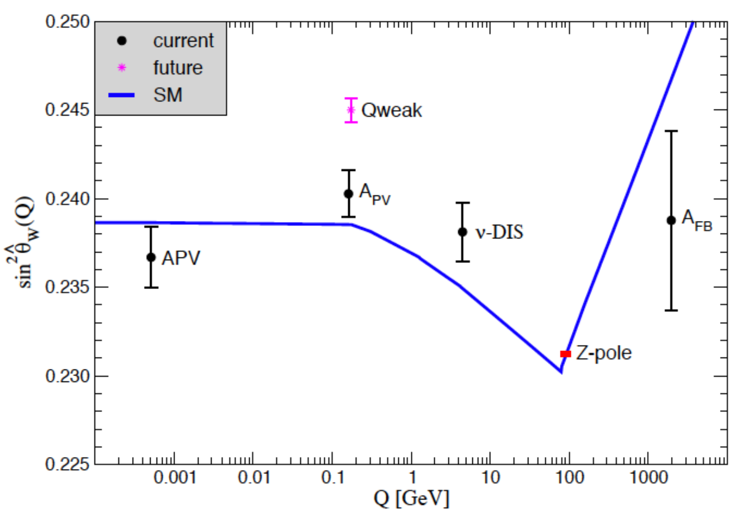
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$		
$\overline{\nu}_\mu \to \overline{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance	
$\overline{\nu}_\mu \to \overline{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)	
$\overline{\nu}_\mu \to \overline{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation	platinum
$\nu_e \to \nu_e$	$\overline{\nu}_e \to \overline{\nu}_e$	disappearance	
$\nu_e \to \nu_\mu$	$\overline{\nu}_e \to \overline{\nu}_\mu$	appearance: "golden" channel	golden
$\nu_e \to \nu_\tau$	$\overline{\nu}_e \to \overline{\nu}_\tau$	appearance: "silver" channel	silver



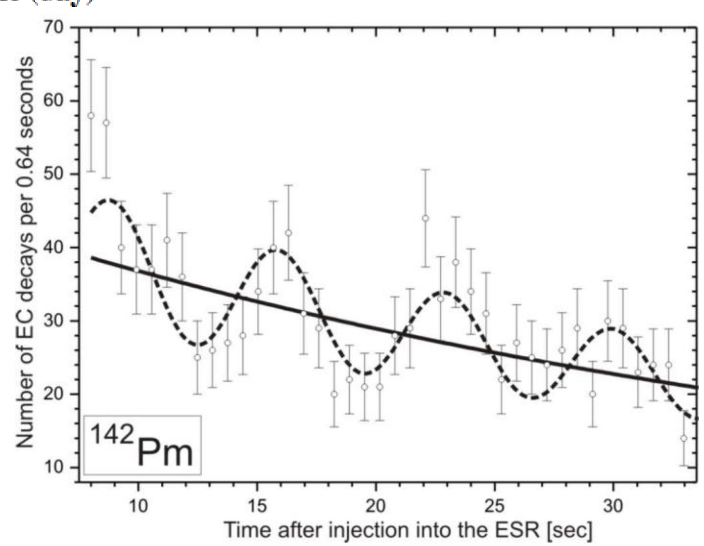




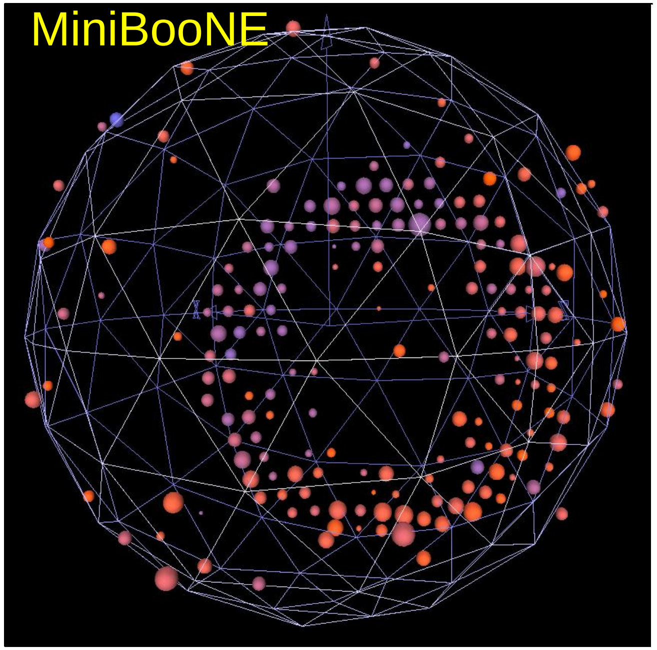


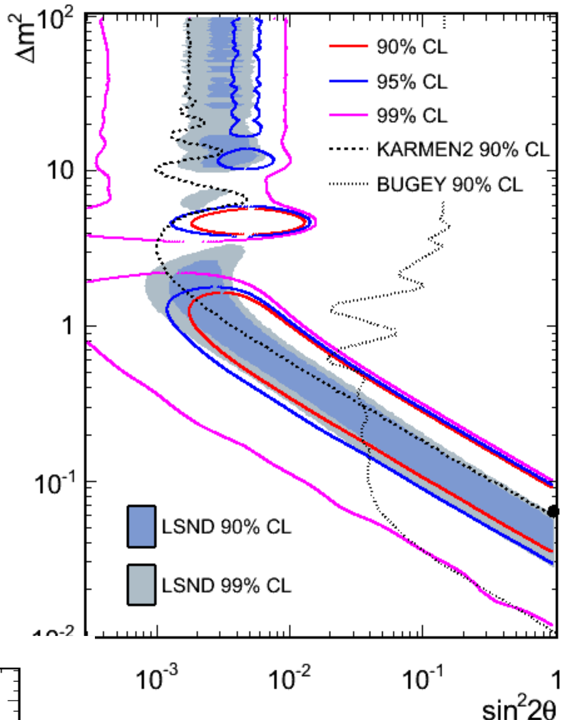


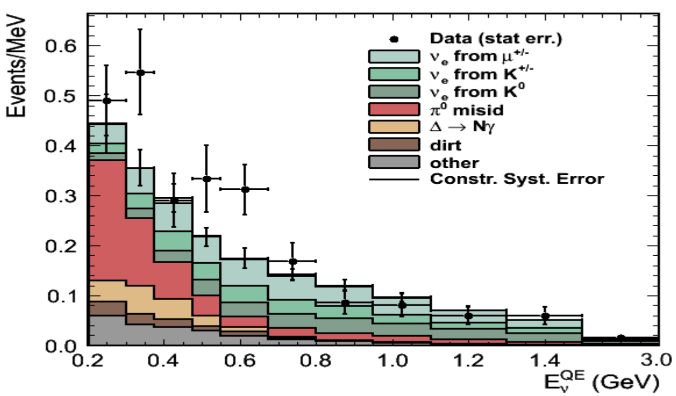
„Effective times“ (anomalies)

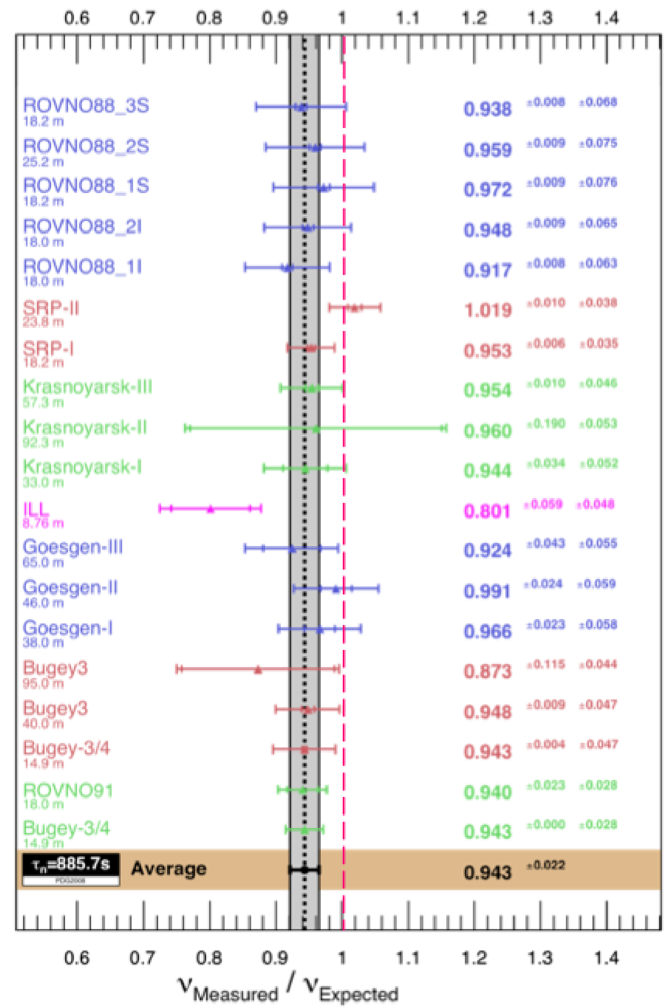


Sterile neutrinos???



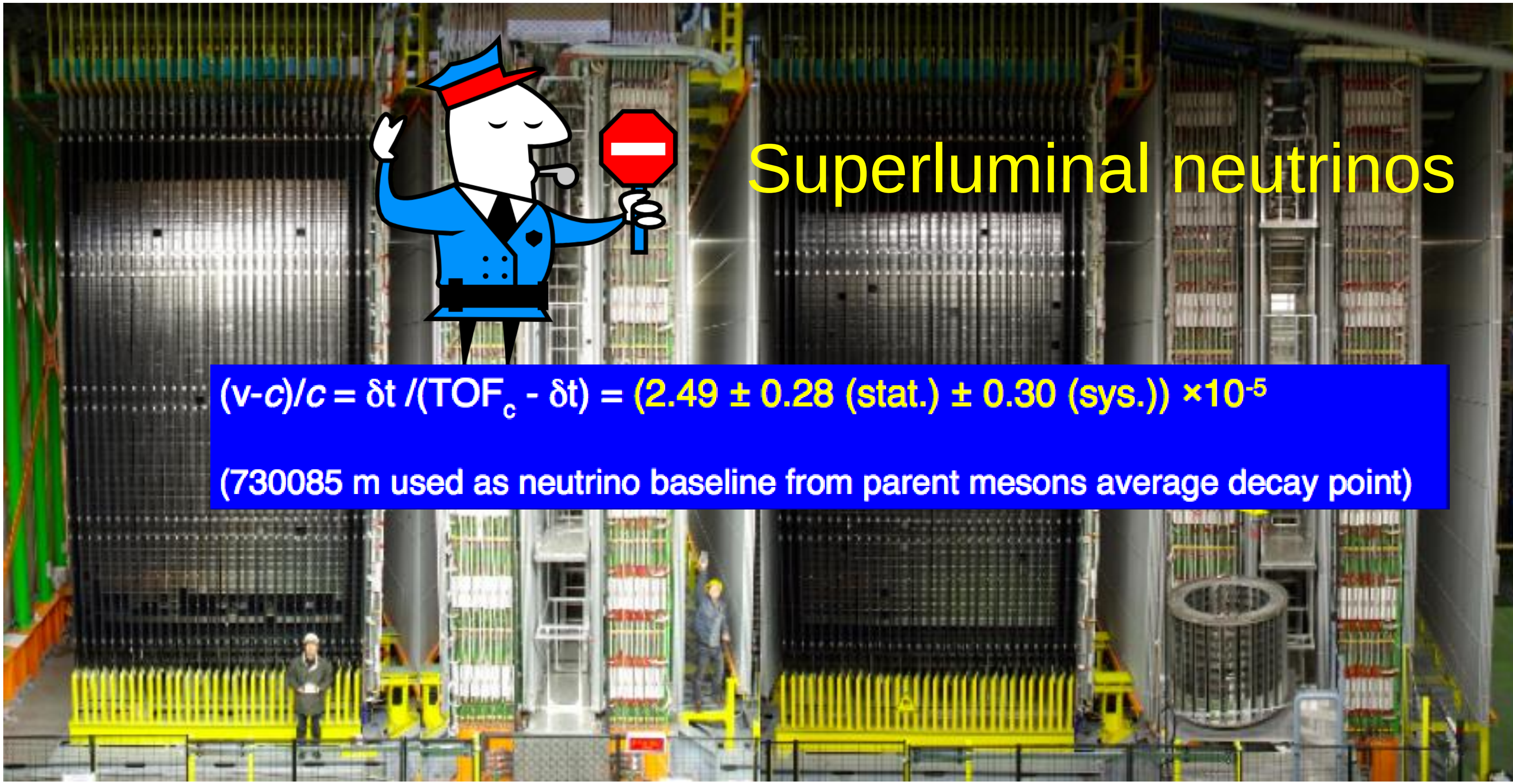






Needs two more neutrino states!!!

OPERA



Explanations from simple hardware issues up to extra dimensions...

Always expect the unexpected