Absolute Neutrino Mass Measurements

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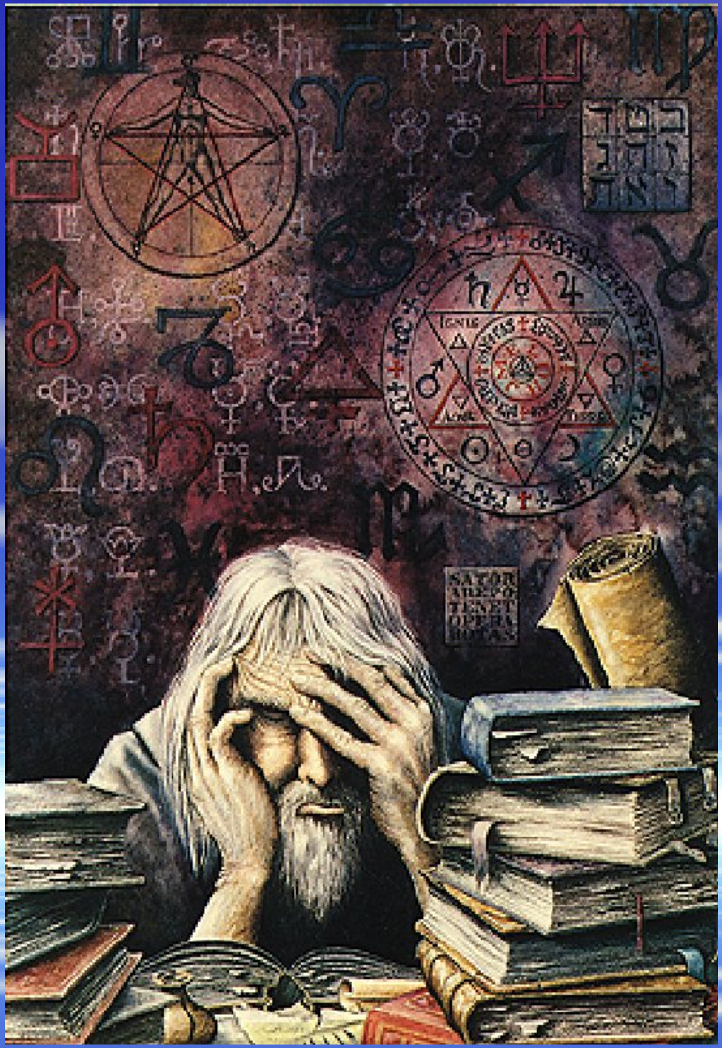


- Beta decay
- Double beta decay
- Cosmological neutrino mass bounds
- Summary and conclusions

Oscillation evidences

LSND

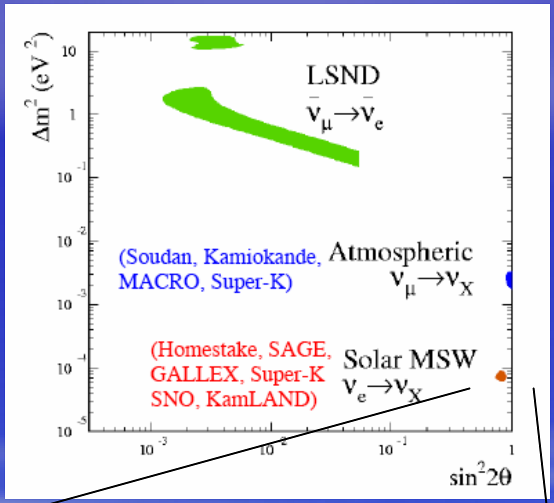
$\sin^2 2\theta = 10^{-1}\text{-}10^{-3}$, $\Delta m^2 = 0.1\text{-}6\ eV^2$

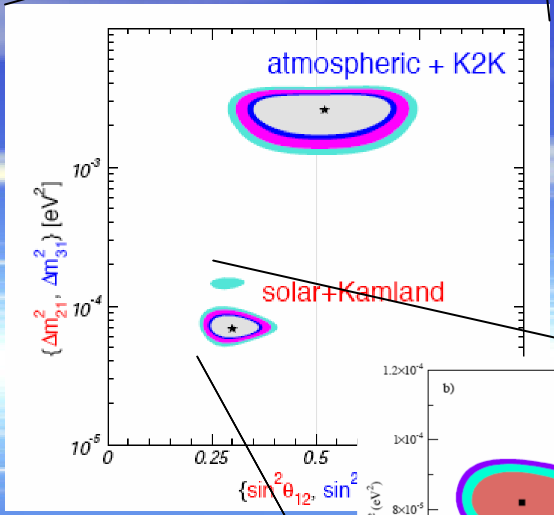
Atmospheric

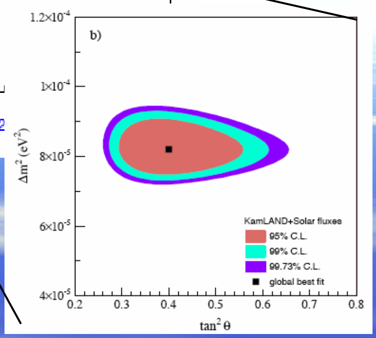
$\sin^2 2\theta = 1.00$, $\Delta m^2 = 2.1 \times 10^{-3}\ eV^2$

Solar + reactors

$\sin^2 2\theta = 0.81$, $\Delta m^2 = 8.2 \times 10^{-5}\ eV^2$

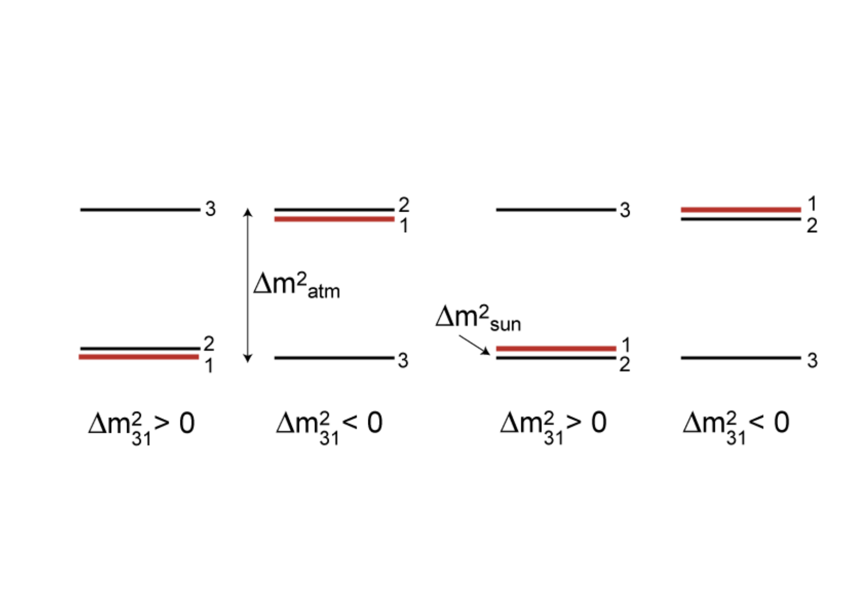






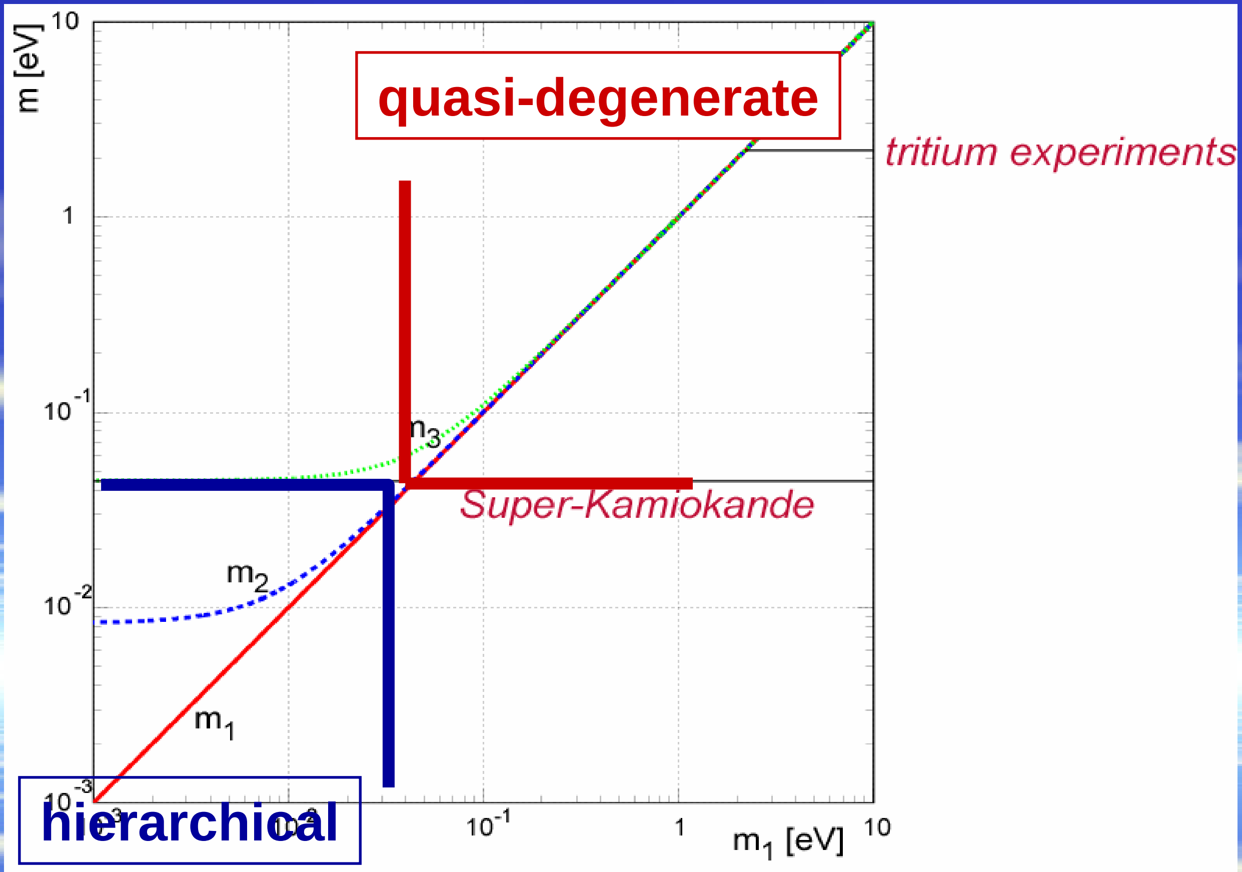
If all three are correct... we need more (sterile ones)

Models of neutrino masses



Neutrino mass schemes

„normal“ mass hierarchy $m_1<m_2<m_3$



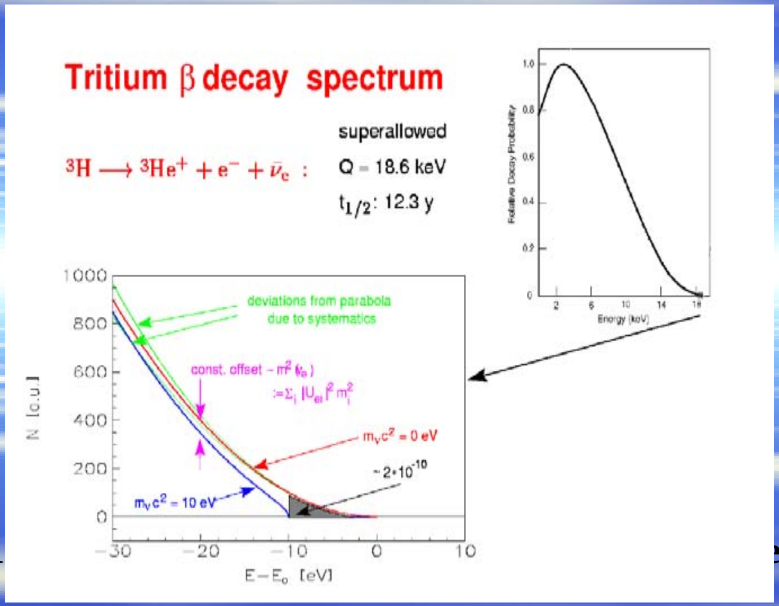
Current neutrino mass limits

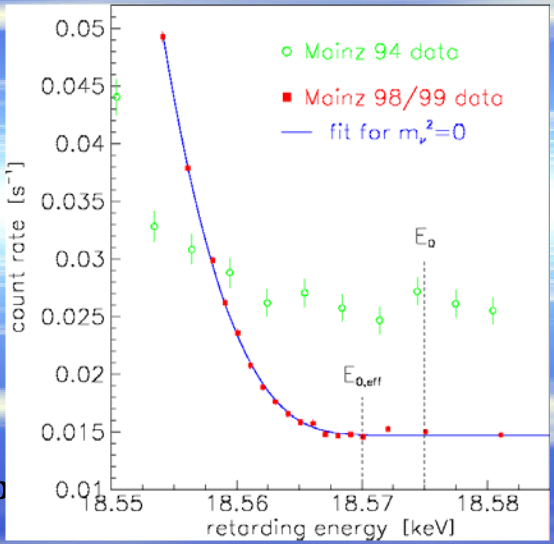
Direct kinematical limits

^{3}H decay: $m_{\nu e} < 2.3$ eV — Mainz, Troitzk

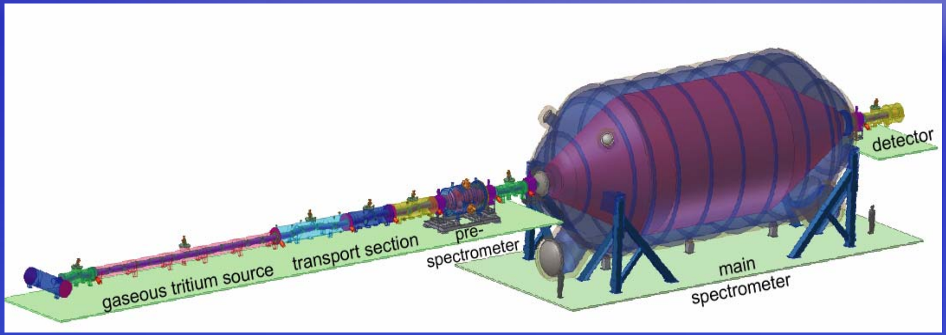
Pion decay: $m_{\nu\mu} < 190$ keV — PSI

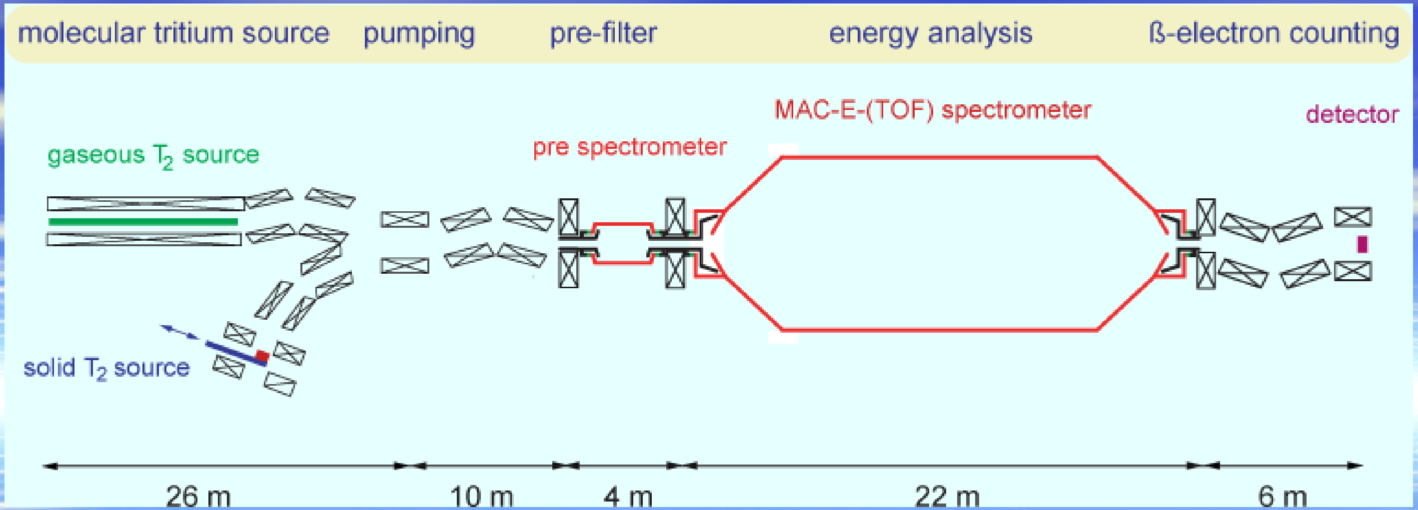
Tau decay: $m_{\nu\tau} < 18.2$ MeV — LEP (Aleph)





KATRIN-The ultimate beta-decay experiment



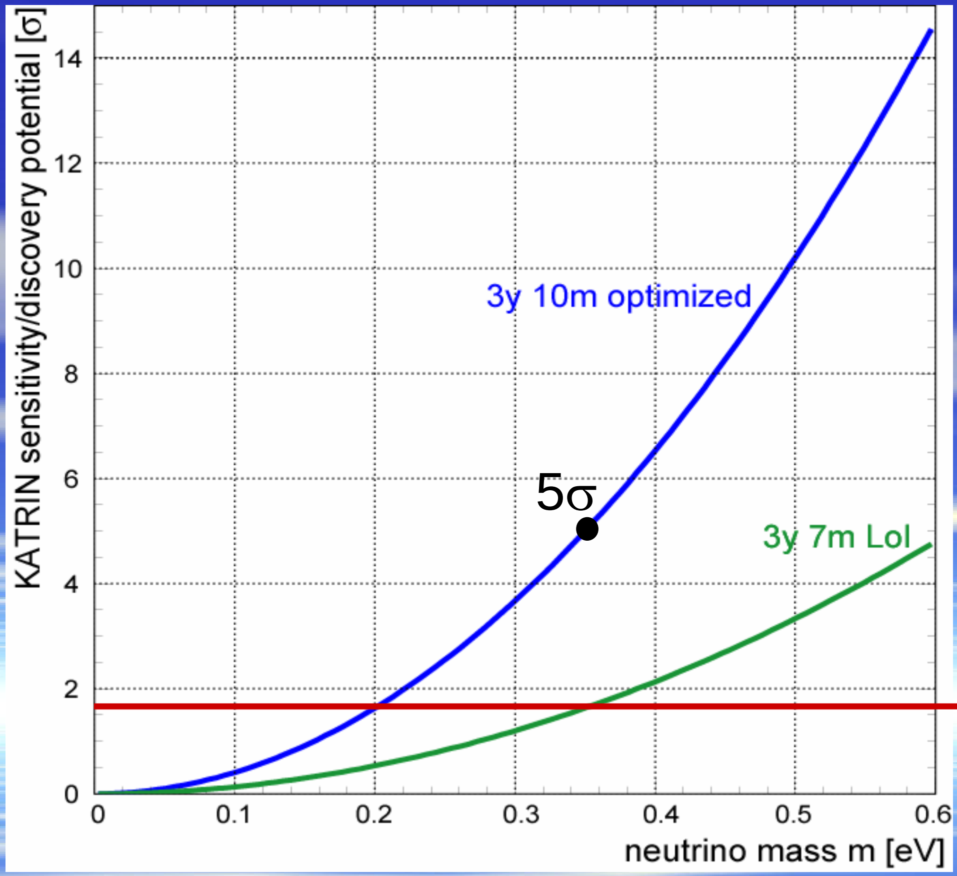


Discovery potential $m_{\nu e} = 0.35$ eV at 5σ

Sensitivity $m_{\nu e} < 0.2$ eV (90% CL)

Commisioning in 2008

KATRIN sensitivity & discovery potential



expectation:

after 3 full beam years

$\sigma_{syst} \sim \sigma_{stat}$

m_ν = 0.35eV (5σ)

m_ν = 0.3eV (3σ)

discovery potential

m_ν < 0.2eV (90%CL)

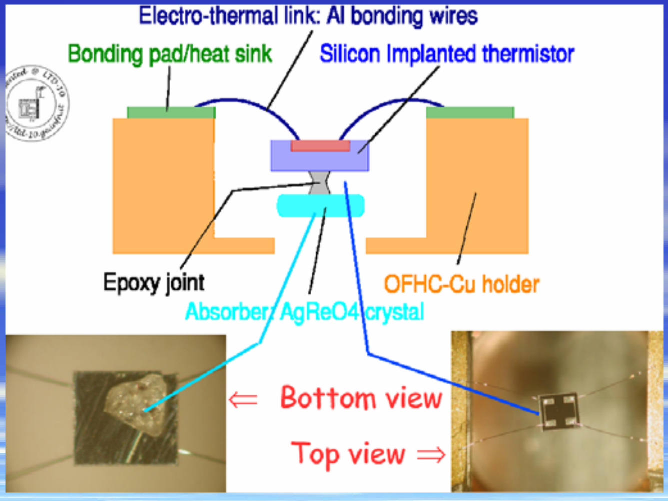
sensitivity

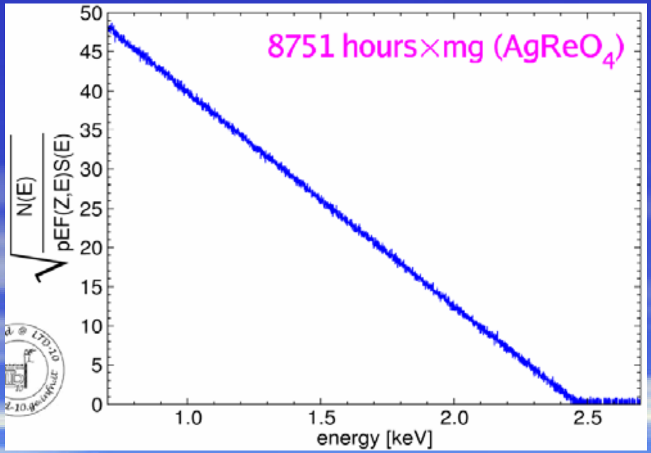
Alternative approaches I

$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^{-} + \overline{\nu}_e$$

$$n(Q-\Delta E) \propto \left(\frac{\Delta E}{Q}\right)^3$$

μ-calorimeters working at mK





MIBETA, Genua

Q = 2465.3 ± 0.5$_{stat}$ ± 1.6$_{syst}$ eV

(8751 h*mg, NIMA520, 2004)

= 2466.1 ± 0.8$_{stat}$ ± 1.5$_{syst}$ eV

(4485 h*mg, PRL91,2003)

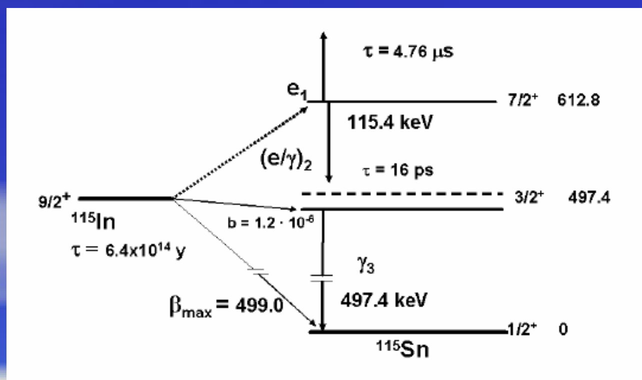
m_ν^2 = -112 ± 207 ± 90 eV^2

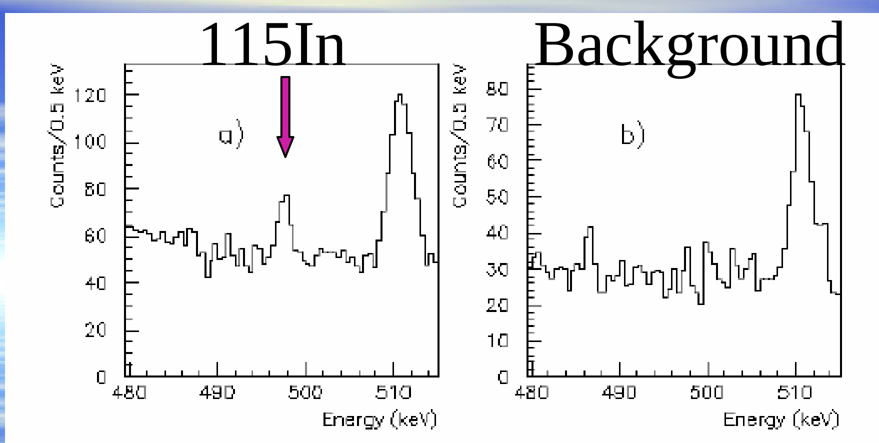
m_ν < 15 eV (90%CL)

future:
proposal for a new calorimeter expt. with ~2-3 eV sensitivity foreseen 2007 (?)

Alternative approaches II

$$^{115}In \rightarrow {}^{115}Sn + e^- + \overline{\nu}_e$$





Observed line at 497.4 keV within test measurements for LENS

If real a Q-value for beta decay of 2 ± 4 keV

Origin of line has to be verified

C. M. Cattadori et al, nucl-ex/0407016

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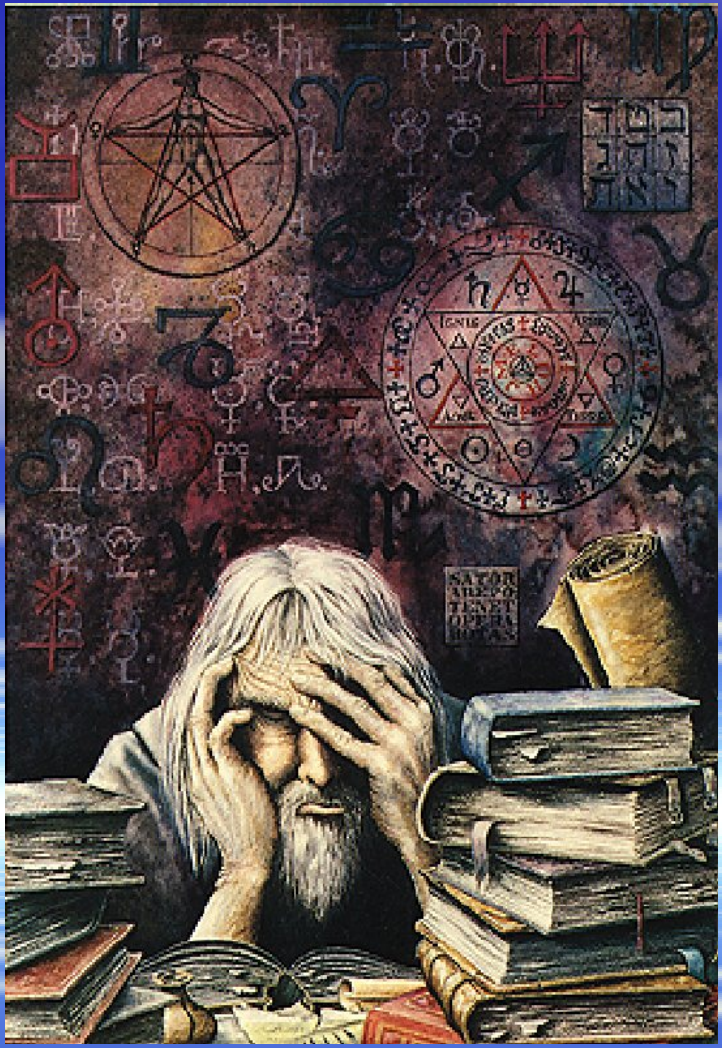

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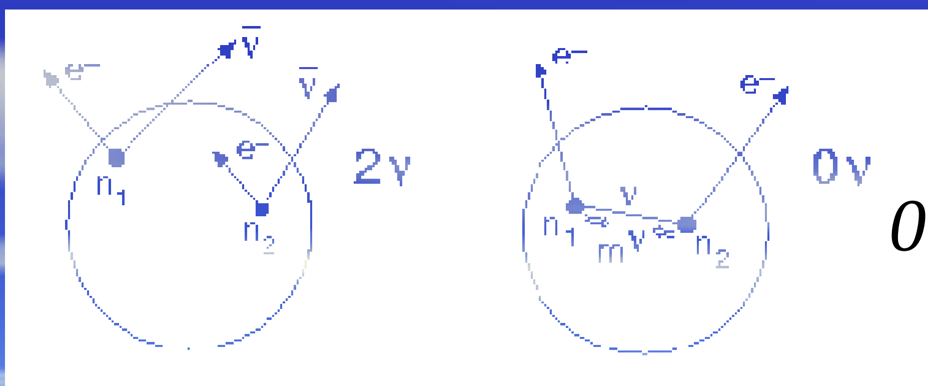
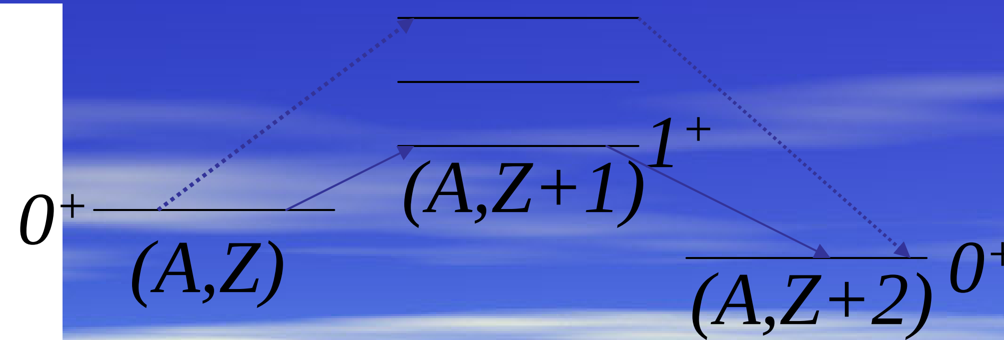
Double beta decay

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





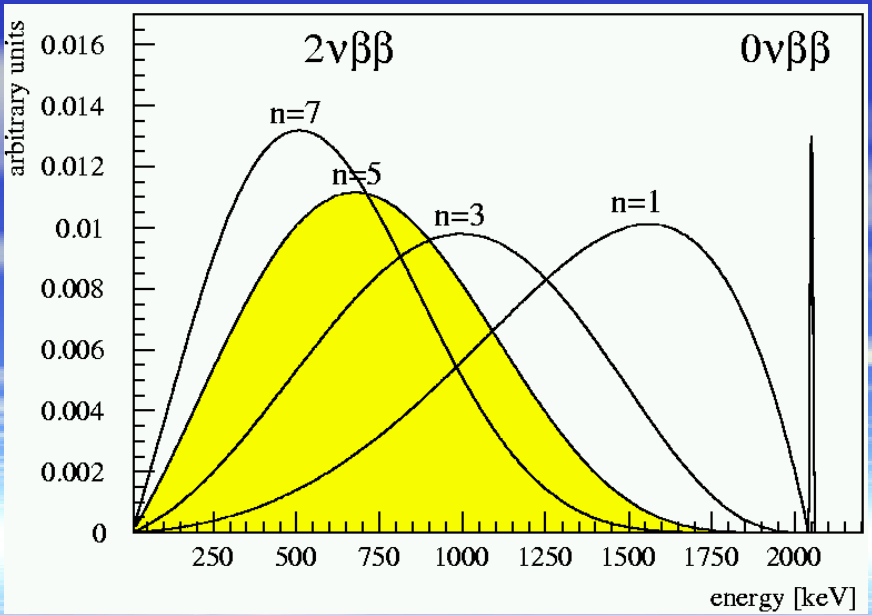
In nature there are 35 isotopes

$2\nu\beta\beta$: Seen in 10 isotopes, important for nuclear physics input

$0\nu\beta\beta$: Only possible if neutrinos are Majorana particles

Spectral shapes

$0\nu\beta\beta$: Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

Measured quantity: Half-life

Dependencies (BG limited)

$T_{1/2} \propto a \cdot \varepsilon \, (M \cdot t / \Delta E \cdot B)^{1/2}$

link to neutrino mass

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

3 Flavour oscillations (PMNS)

Analogous to CKM matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \frac{m_i^2}{2E_\nu} \Rightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta_1} & 0 \\ 0 & 0 & e^{i\beta_2} \end{pmatrix}$$

solar   If $\sin\theta_{13} \neq 0 \rightarrow$ CP-violation   atmospheric

Majorana: $U = U_{PMNS}\, diag(1, e^{i\alpha}, e^{i\beta})$

Physical quantities

Experimental observable: Half-life

Double beta decay: Effective Majorana neutrino mass

$$\langle m_\nu \rangle \equiv m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k |U_{ek}|^2 e^{i\alpha_{ek}} m_k \right|$$

relative CP phases = ±1

Beta decay

$$m_e = \Sigma \, |U_{ek}|^2 \, m_k$$

Phase space

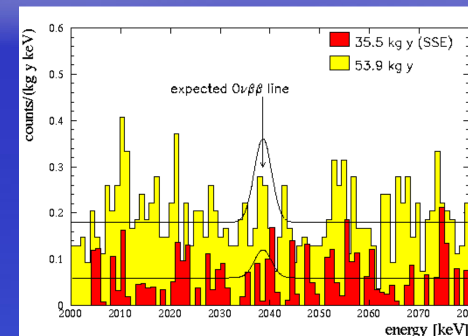
$0\nu\beta\beta$ decay rate scales with Q^5

$2\nu\beta\beta$ decay rate scales with Q^{11}

Isotope	*Q-value (keV)*	*Nat. abund. (%)*	*$(PS\ 0\nu)^{-1}$ (yrs)*	*$(PS\ 2\nu)^{-1}$ (yrs)*
Ca 48	**4271**	**0.187**	**4.10E24**	**2.52E16**
Ge 76	**2039**	**7.8**	**4.09E25**	**7.66E18**
Se 82	**2995**	**9.2**	**9.27E24**	**2.30E17**
Zr 96	**3350**	**2.8**	**4.46E24**	**5.19E16**
Mo 100	**3034**	**9.6**	**5.70E24**	**1.06E17**
Pd 110	**2013**	**11.8**	**1.86E25**	**2.51E18**
Cd 116	**2809**	**7.5**	**5.28E24**	**1.25E17**
Sn 124	**2288**	**5.64**	**9.48E24**	**5.93E17**
Te 130	**2529**	**34.5**	**5.89E24**	**2.08E17**
Xe 136	**2479**	**8.9**	**5.52E24**	**2.07E17**
Nd 150	**3367**	**5.6**	**1.25E24**	**8.41E15**

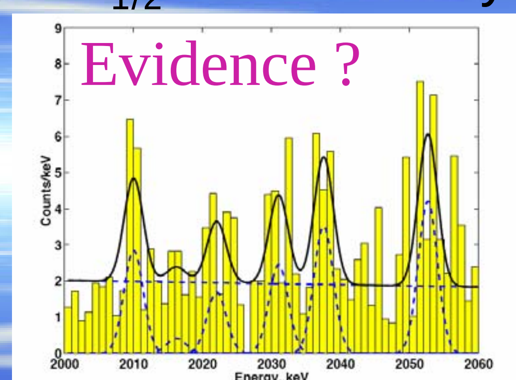
Heidelberg -Moscow

- Five Ge Diodes (mass 10.9 kg)
  Isotopical enriched (86%) in ^{76}Ge
  lead shield and nitrogen purging
  Peak at 2039 keV



H.V. Klapdor-Kleingrothaus et al,
Europ. Phys. J. A 12, 147 (2001)

$T_{1/2} > 1.9 \times 10^{25}$ yr (90% CL) → m < 0.35 eV



Subgroup of collaboration

$T_{1/2} = 0.6 - 8.4 \times 10^{25}$ yr
→ m = 0.17 - 0.63 eV

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

If peak is real...

1.) Go out and check (GERDA, MAJORANA)

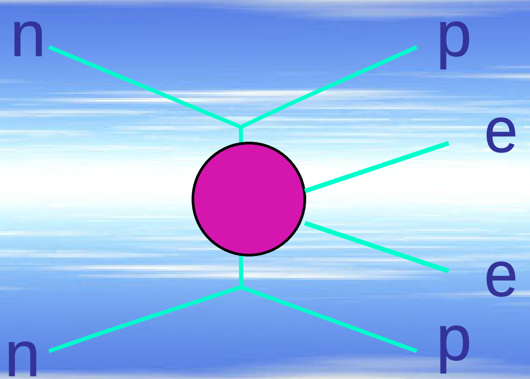
Is peak something specific to Ge?

Uncertainties in the nuclear matrix elements?

→ Check with a different isotope

Physics mechanism at work ?

→ Tracking

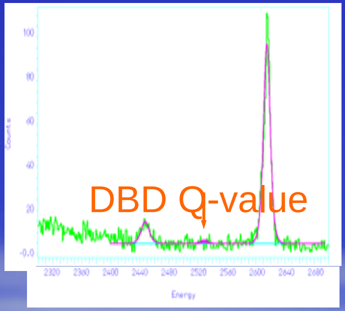


2.) NEMO, COBRA

Running experiments

CUORICINO: cryogenic bolometers

40.7 kg TeO_2



$T_{1/2} > 7.5 \times 10^{23}$ yr (90% CL)

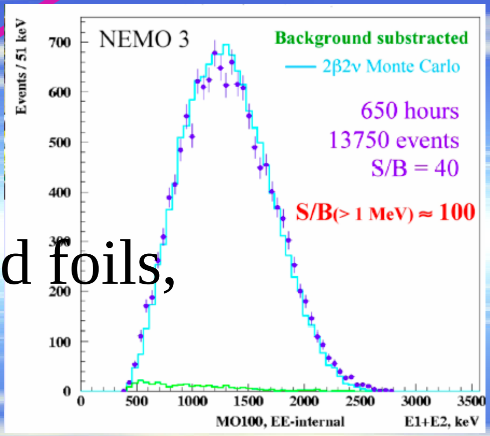
E. Fiorini, Neutrino 2004

Future: CUORE

760 kg TeO_2

approved

NEMO-3: TPC



10 kg enriched foils,

6 kg ^{100}Mo

$T_{1/2} > 3.1 \times 10^{23}$ yr (90% CL)

Idea:

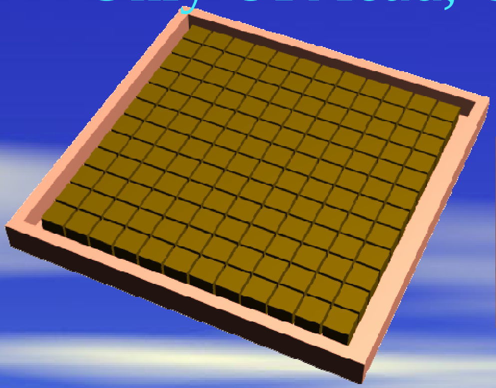
Super-NEMO (100 kg)

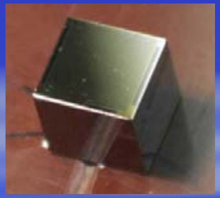
COBRA

Use CdZnTe semiconductors

Only UK lead, UK dominated experiment

already 5 world best limits

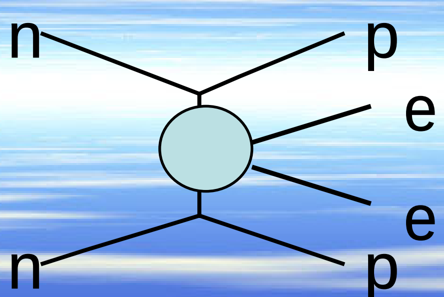




K. Zuber,
Phys. Lett. B 519,1 (2001)

„Solid state TPC“

4 detectors running at LNGS, upgrade to 64 by spring 2005



Sensitivity to right-handed weak currents

- $(A,Z) \rightarrow (A,Z-2) + 2e^{+} (+2\nu_e)$ $\beta^{+}\beta^{+}$
- $e^{-} + (A,Z) \rightarrow (A,Z-2) + e^{+} (+2\nu_e)$ β^{+}/EC
- $2e^{-} + (A,Z) \rightarrow (A,Z-2) (+2\nu_e)$ EC/EC

^{106}Cd

Cobra - The people

C. Gößling, H. Kiel, D. Münstermann, S. Oehl, T. Villett
University of Dortmund

T. Leigertwood, D. McKechan, C. Reeve, J. Wilson, K. Zuber
University of Sussex

P.F. Harrison, Y. Ramachers, D. Stewart
University of Warwick

A. Boston, P. Booth, P. Nolan
University of Liverpool

B. Fulton, R. Wadsworth
University of York

T. Bloxham, M. Freer
University of Birmingham

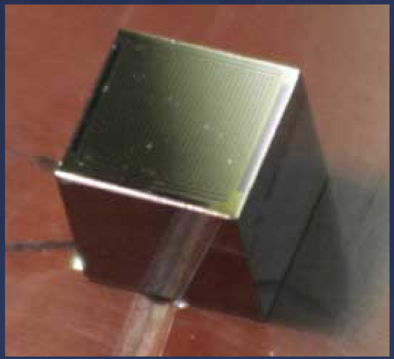
P. Seller
Rutherford Appleton Laboratory

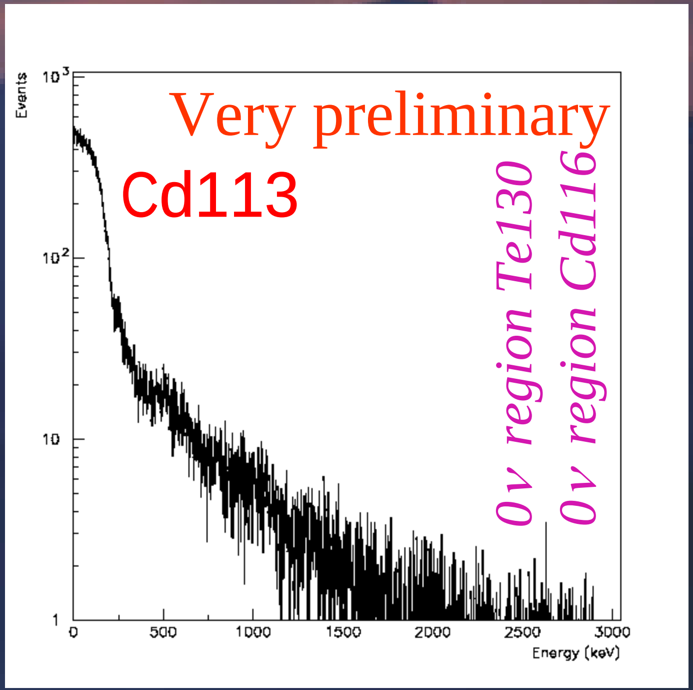
M. Junker
Laboratori Nazionali del Gran Sasso

Next step - the 2x2 prototype

Installation of setup at Gran Sasso Underground Laboratory

4 naked 1cm^3 CdZnTe



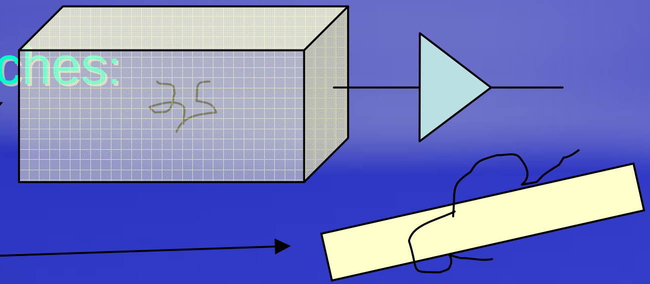


1.34 kg x days of data

0νββ Experimental Situation

2 main experimental approaches:

- Active Source
- Passive Source



Best 0ν2β results involve active source experiments

Experiment	Isotope	$T_{1/2}^{0\nu}$ (y)	$<m_\nu>$ (eV)
You Ke et al. 1998	^{48}Ca	$> 9.5 \times 10^{21}$ (76%)	< 8.3
Klapdor-Kleingrothaus 2001	^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
Aalseth et al 2002		$> 1.57 \times 10^{25}$	< 0.33 - 1.35
Arnold et al. 2004	^{82}Se	$> 1.3 \times 10^{23}$	< 1.5-3.1
Arnold et al. 2004	^{100}Mo	$>3.1 \times 10^{23}$	< 0.33-0.84
Danevich et al. 2000	^{116}Cd	$> 1 \times 10^{23}$	< 2.2
Bernatowicz et al. 1993	$^{130/128}$Te*	$(3.52 \pm 0.11) \times 10^{-4}$	< 1.1 – 1.5
Bernatowicz et al. 1993	^{128}Te*	$> 7.7 \times 10^{24}$	< 1.1 – 1.5
Arnaboldi et al. 2005	^{130}Te	$> 1.8 \times 10^{24}$	< 0.5 – 1.1
Luescher et al. 1998	^{136}Xe	$> 4.4 \times 10^{23}$	< 1.8 – 5.2
Belli et al. 2001	^{136}Xe	$> 7 \times 10^{23}$	< 1.4 – 4.1
De Silva et al. 1997	^{150}Nd	$> 1.2 \times 10^{21}$	< 3
Danevich et al. 2001	^{160}Gd	$> 1.3 \times 10^{21}$	< 26

Back of the envelope

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

50 meV implies 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

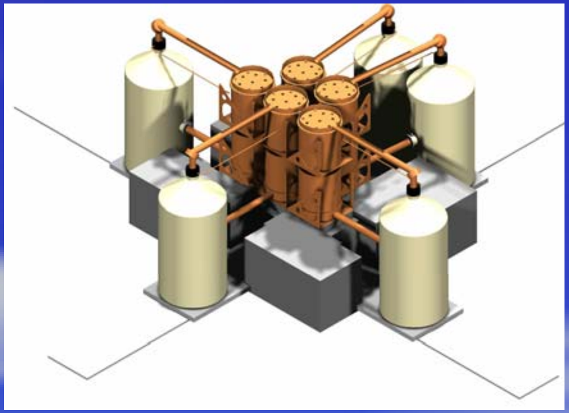
Now you only can loose: nat. abundance, efficiency, background, ...

Future projects

Experiment	Author	Isotope	Detector description	$T^{5y}_{1/2}$(y)	<m_ν>*
COBRA	Zuber 2001	^{116}Cd	10 kg CdTe semiconductors	1×10^{24}	0.71
CUORICINO	Arnaboldi et al 2001	^{130}Te	40 kg of TeO_2 bolometers	1.5×10^{25}	0.19
NEMO3	Sarazin et al 2000	^{100}Mo	10 kg of bb(0n) isotopes (7 kg Mo) with tracking	4×10^{24}	0.56
CUORE	Arnaboldi et al. 2001	^{130}Te	760 kg of TeO_2 bolometers	7×10^{26}	0.027
EXO	Danevich et al 2000	^{136}Xe	1 t enriched Xe TPC	8×10^{26}	0.052
GEM	Zdesenko et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen + water shield	7×10^{27}	0.018
GENIUS	Klapdor-Kleingrothaus et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen	1×10^{28}	0.015
MAJORANA	Aalseth et al 2002	^{76}Ge	0.5 t enriched Ge segmented diodes	4×10^{27}	0.025
DCBA	Ishihara et al 2000	^{150}Nd	20 kg enriched Nd layers with tracking	2×10^{25}	0.035
CAMEO	Bellini et al 2001	^{116}Cd	1 t $CdWO_4$ crystals in liquid scintillator	$> 10^{26}$	0.069
CANDLES	Kishimoto et al	^{48}Ca	several tons of CaF_2 crystal in liquid scintillator	1×10^{26}	
GSO	Danevich 2001	^{160}Gd	2 t Gd_2SiO_5:Ce cristal scintillator in liquid scintillator	2×10^{26}	0.065
MOON	Ejiri et al 2000	^{100}Mo	34 t natural Mo sheets between plastic scintillator	1×10^{27}	0.036
Xe	Caccianiga et al 2001	^{136}Xe	1.56 t of enriched Xe in liquid scintillator	5×10^{26}	0.066
XMASS	Moriyama et al 2001	^{136}Xe	10 t of liquid Xe	3×10^{26}	0.086

* Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990) 31

Future - Ge approaches



MAJORANA

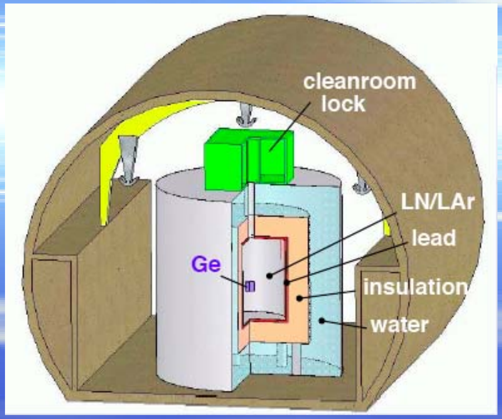
500 kg of enriched Ge detectors

Segmentation and pulse shape discrimination

GERDA

Naked enriched Ge-crystals in LAr with lead shield

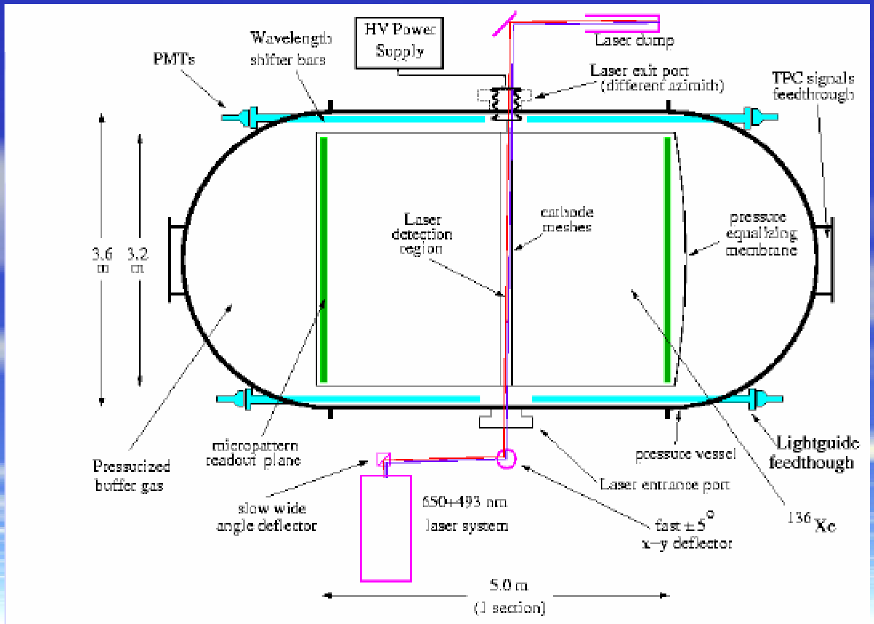
20 kg enriched Ge-detectors at hand (former HD-MO and IGEX)



MERGE

EXO

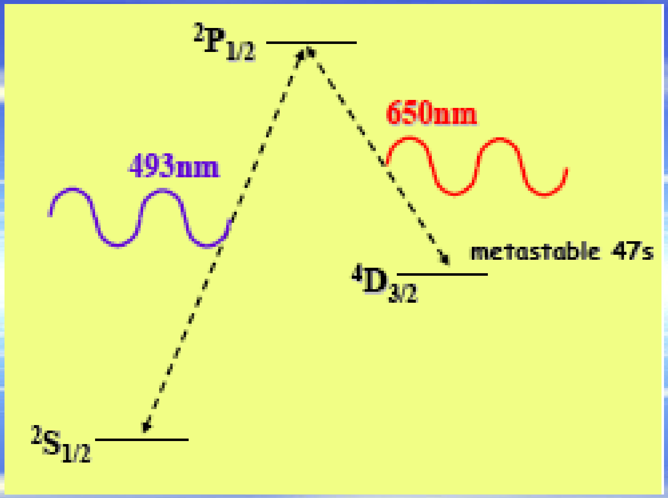
Tracking and scintillation



200 kg enriched Xe prototype under construction at WIPP

New feature:

$^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^-\, e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)



👎L=2 processes

$$\langle m_{\alpha\beta}\rangle = \left|\sum_k U_{\alpha k} U_{\beta k} m_k\right| = \left|\sum_k |U_{\alpha k} U_{\beta k}| m_k \eta_k^{CP}\right|$$

Im general 9 mass terme

- μe-conversion on nuclei
- $\nu_\mu N \rightarrow \mu^- \mu^+ \mu^+ X$

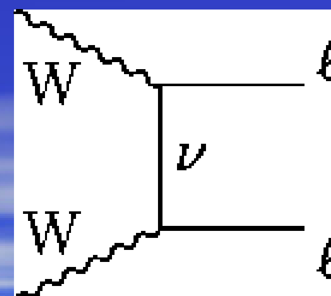
  M. Flanz, W. Rodejohann, K. Zuber, Eur. Phys. J. C 16, 453 (2001)

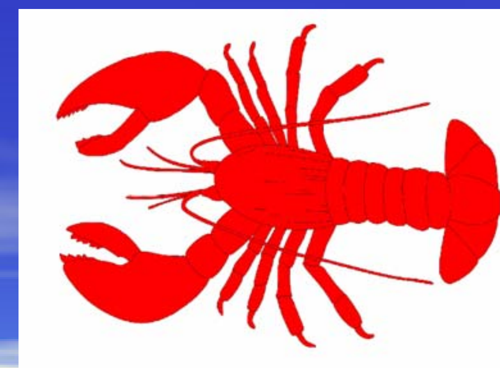
  W. Rodejohann, K. Zuber, Phys. Rev. D 63, 054031 (2001)
- $K^+ \rightarrow \pi^- \mu^+ \mu^+$

  K. Zuber, Phys. Lett. B 479,33 (2000)
- $e^+ p \rightarrow \bar{\nu}_e \mu^+ (\tau^+) \mu^+ (\tau^+) X$

  M. Flanz, W. Rodejohann, K. Zuber, Phys. Lett. B 473, 324 (2000)

  W. Rodejohann, K. Zuber, Phys. Rev. D 62, 094017 (2000)



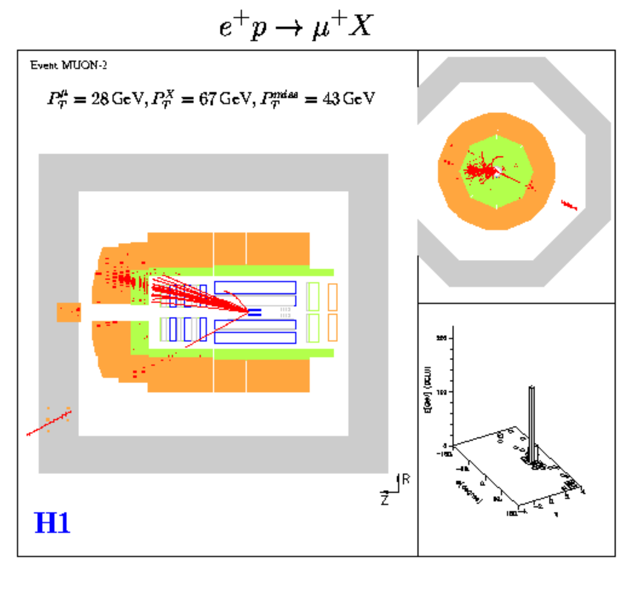


limits on <m♋♌> (in GeV)

$3.5\ 10^{-10}$	$1.7\ (8.2)\ 10^{-2}$	$8.4\ 10^{3}$
	500	$8.7\ 10^{3}$
		$2.0\ 10^{4}$

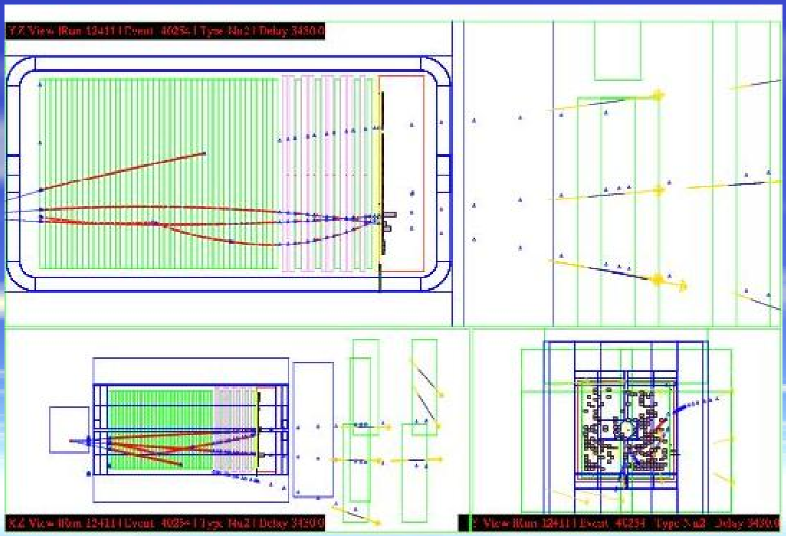
Event candidates

H1 charged current event



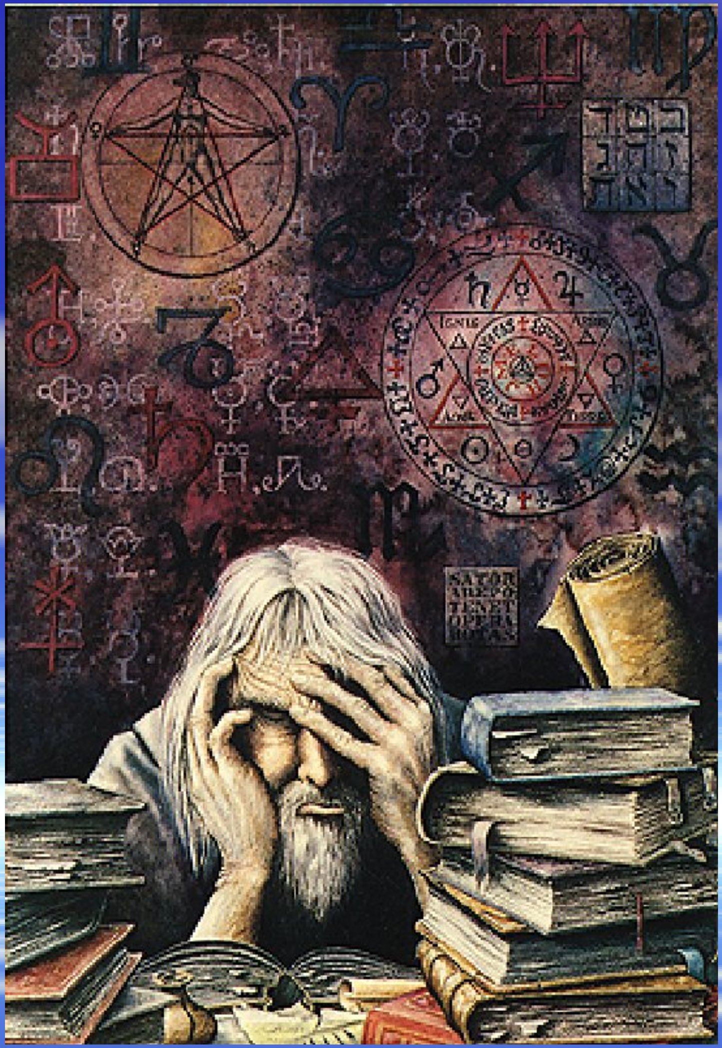
$$e^+p \to \bar{\nu}_e \mu^+(\tau^+)\mu^+(\tau^+)X$$

NOMAD Trimuon event



$$\nu_\mu N \to \mu^- \mu^+ \mu^+ X$$

Contents



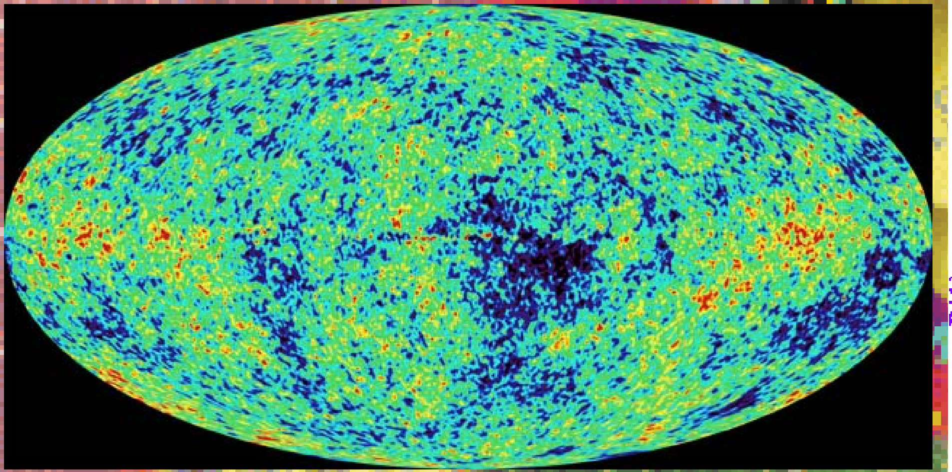
- Beta decay
- Double beta decay
- Cosmological neutrino mass bounds
- Summary and conclusions

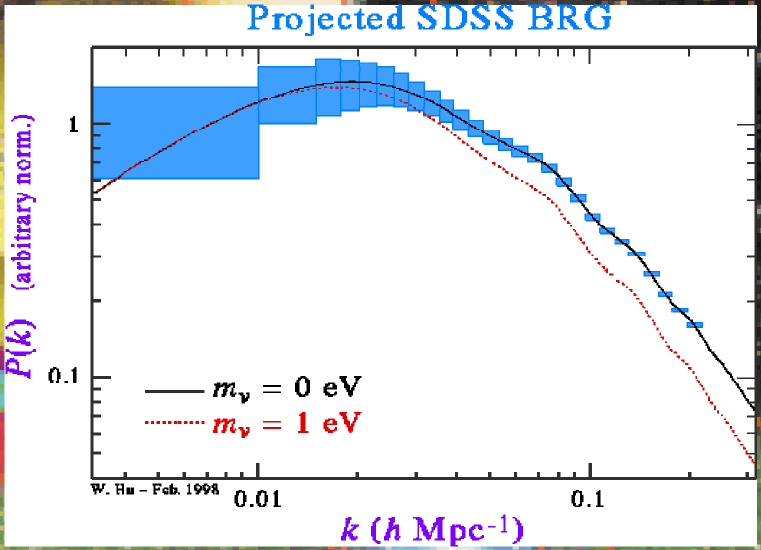
Neutrino masses from cosmology

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

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

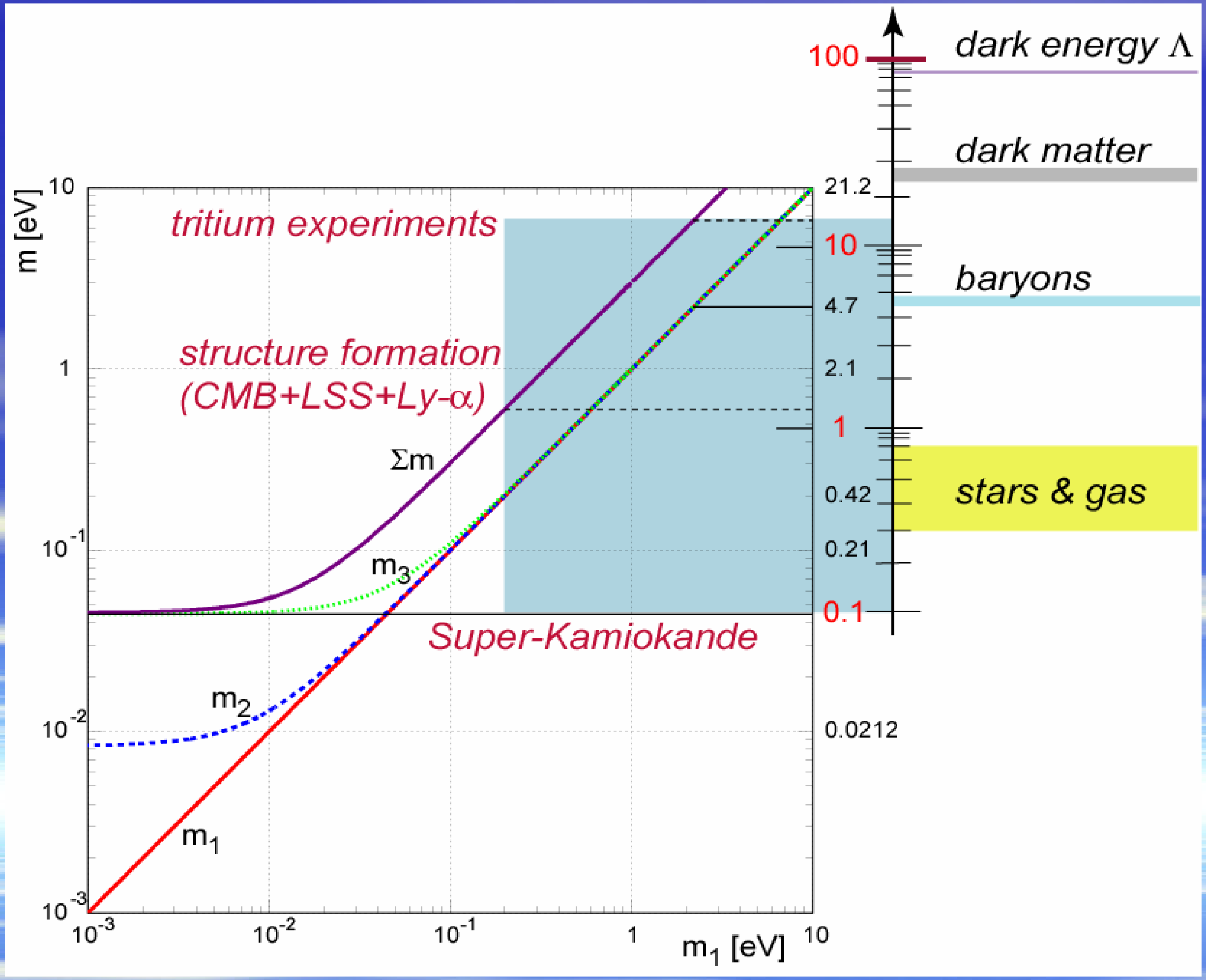
New WMAP measurement + SDSS data



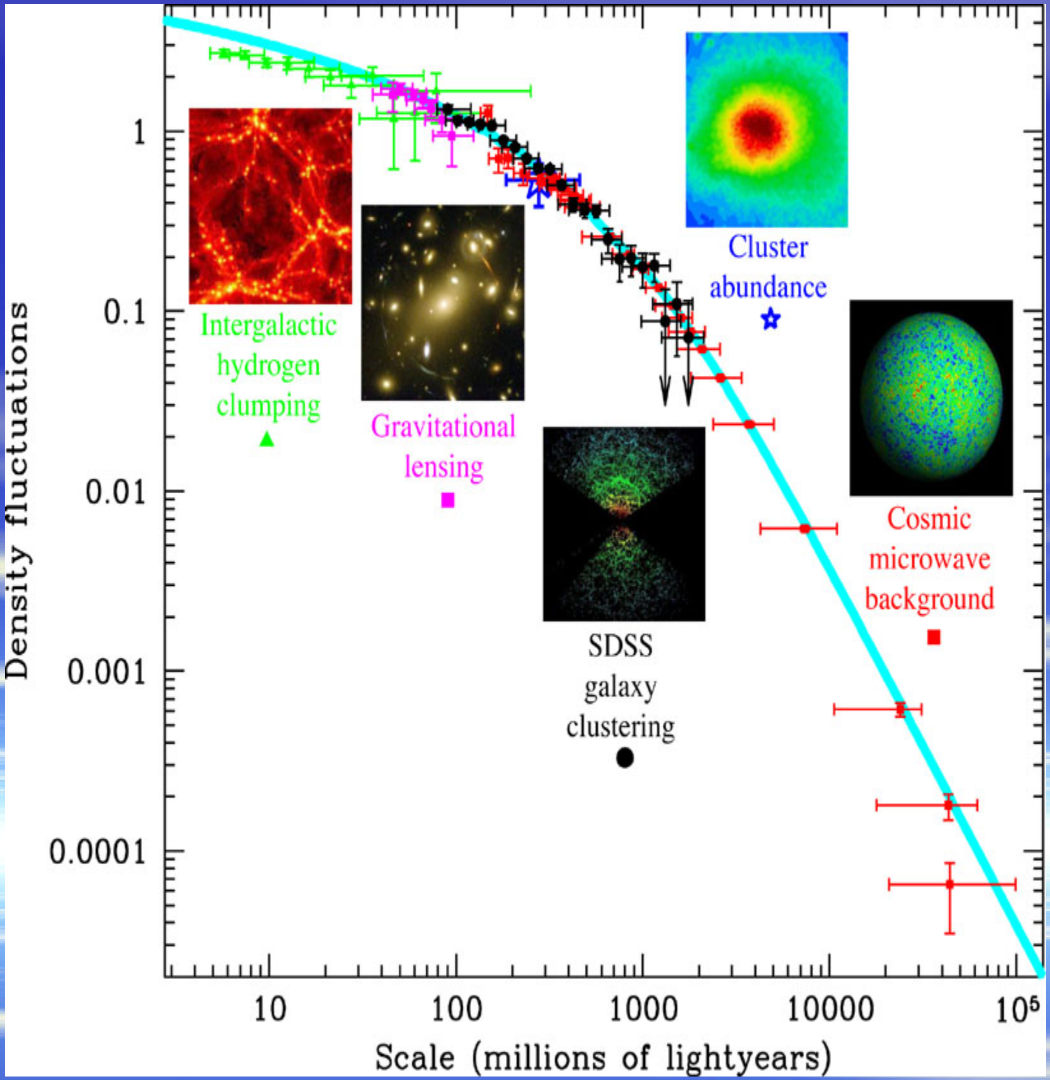


Mass bound model dependent, currently done within ΛCDM

Neutrinos mass density



Density fluctuations versus scale



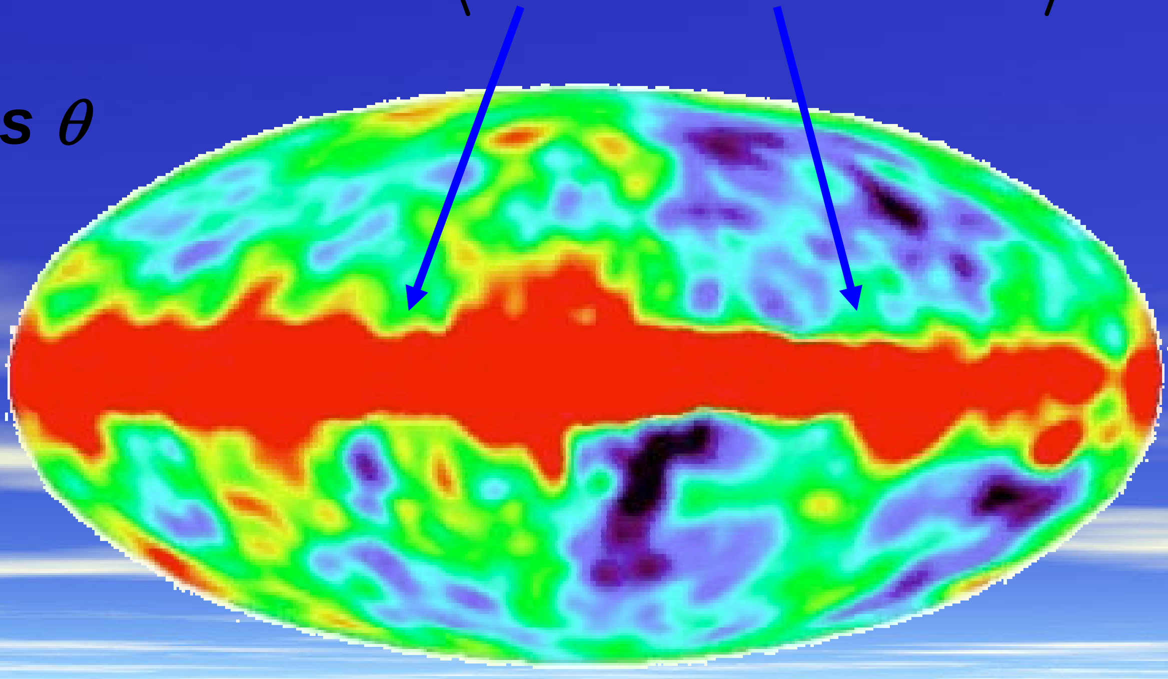
M. Tegmark

(free after Coleridge, 1798)

Structure, structure everywhere

$$C(\theta) = \langle \Delta T(n) \Delta T(n') \rangle$$

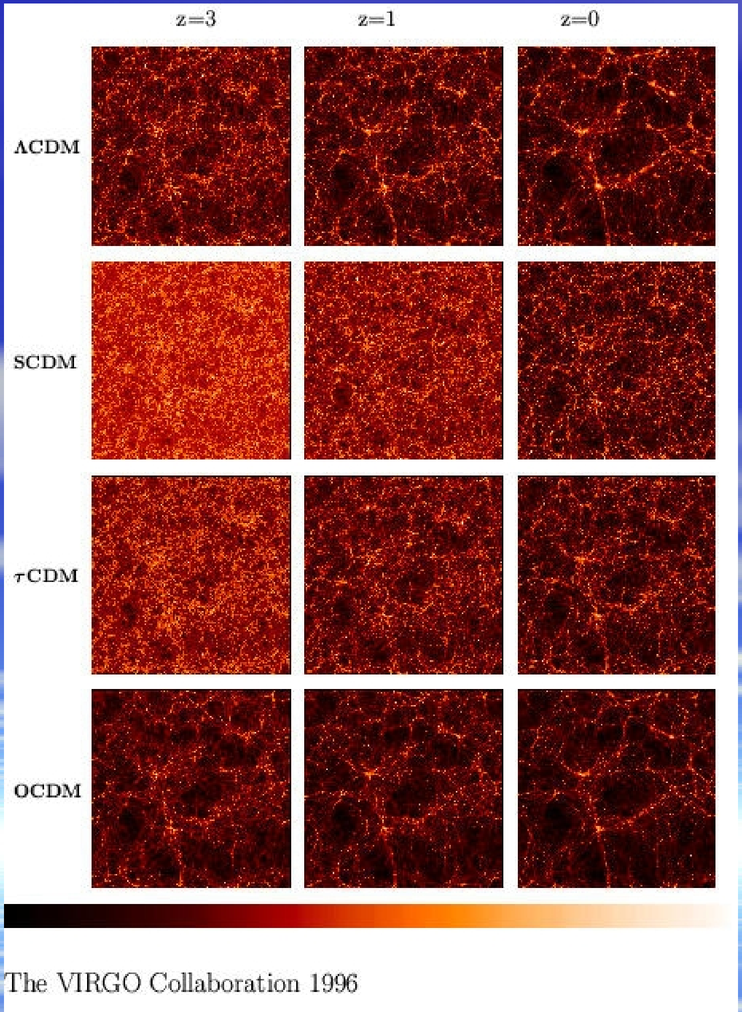
$\vec{n}\vec{n}' = \cos\theta$



Expansion in spherical harmonics

Legendre polynomials

Large scale structure - Description



Measure autocorrelation function

$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle$$

Fourier transformed

$$\xi(r) = \frac{V}{(2\pi)^3} \int |\delta_k|^2 e^{-ikr} d^3k$$

Power spectrum $\left\langle |\delta_k|^2 \right\rangle \propto k^n$

Inflation predicts: n=1

(Harrison - Zeldovich spectrum)

Neutrinos and the CMB

The CMB alone in NOT sensitive to massive neutrinos.

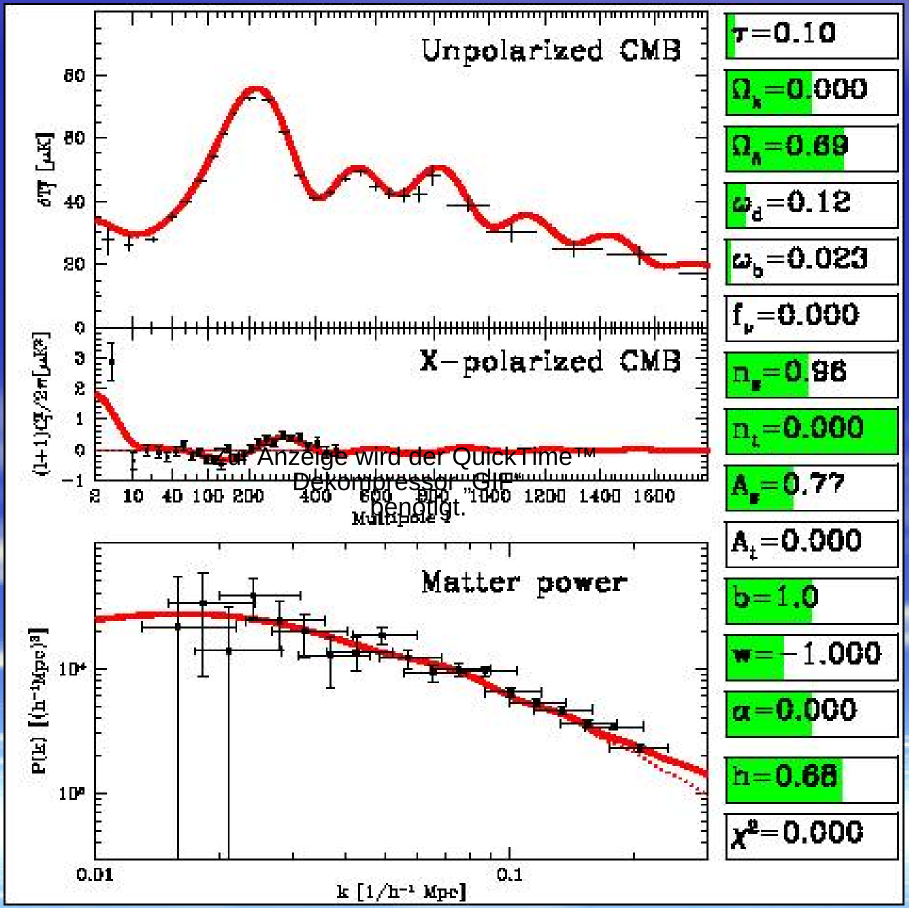
The WMAP result (Spergel at al. 2003) of

m_ν < 0.69 eV (95% CL) is based on

WMAP+2dF+Ly-α

* 2dF is sensitive to Ω_ν/Ω_m
* WMAP constrains Ω_m (and other parameters)

Neutrinos in cosmology



M. Tegmark

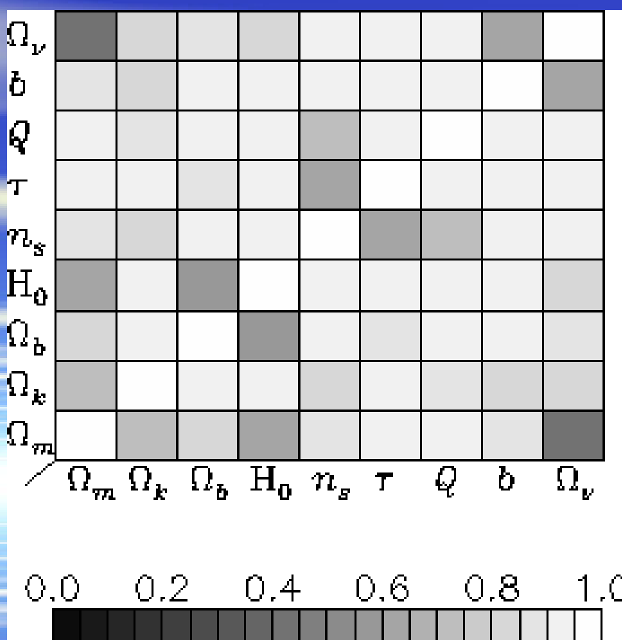
CMB and Large scale structure

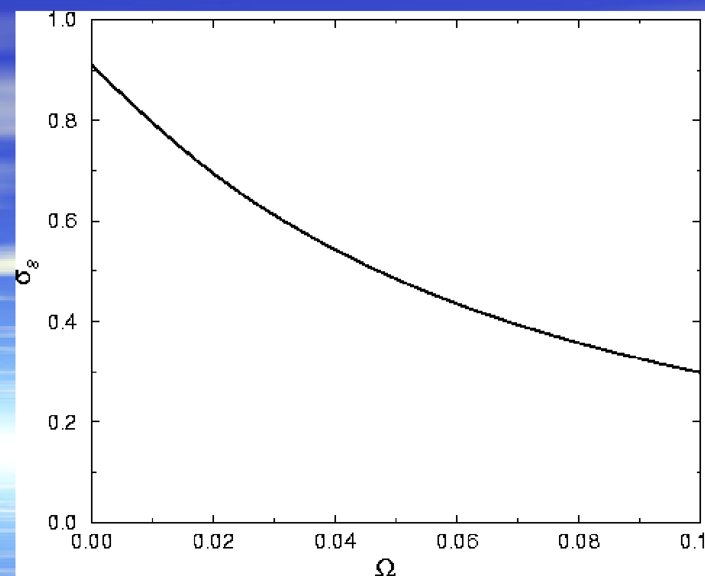
CMB necessary to fix other cosmological parameters

Neutrinos smear out small density fluctuations, change in power spectrum

$$\frac{\Delta P_m(k)}{P_m(k)} \approx -8\frac{\Omega_\nu}{\Omega_m}$$

W. Hu, D. Eisenstein, M.Tegmark, Phys. Rev. Lett. 80, 5255 (1998)

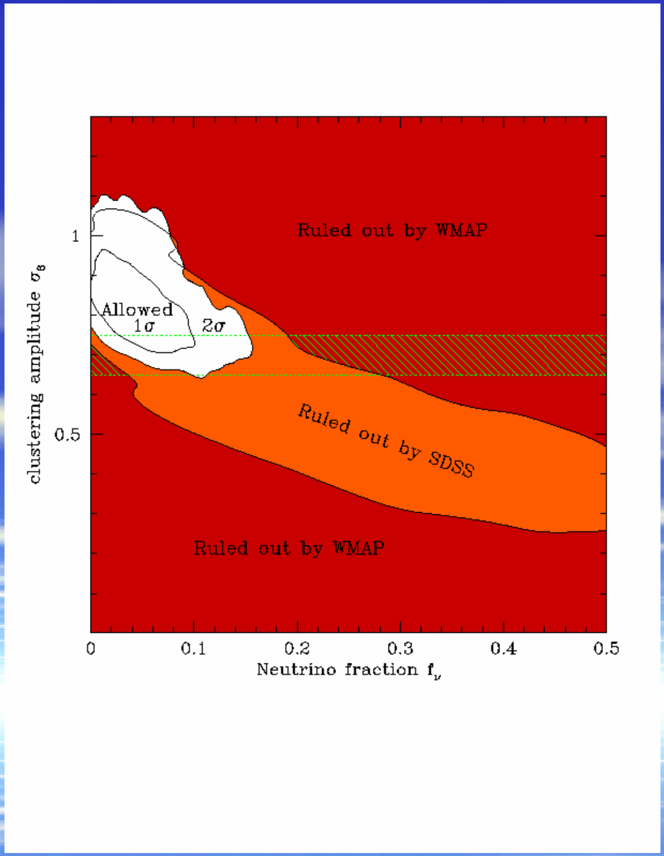


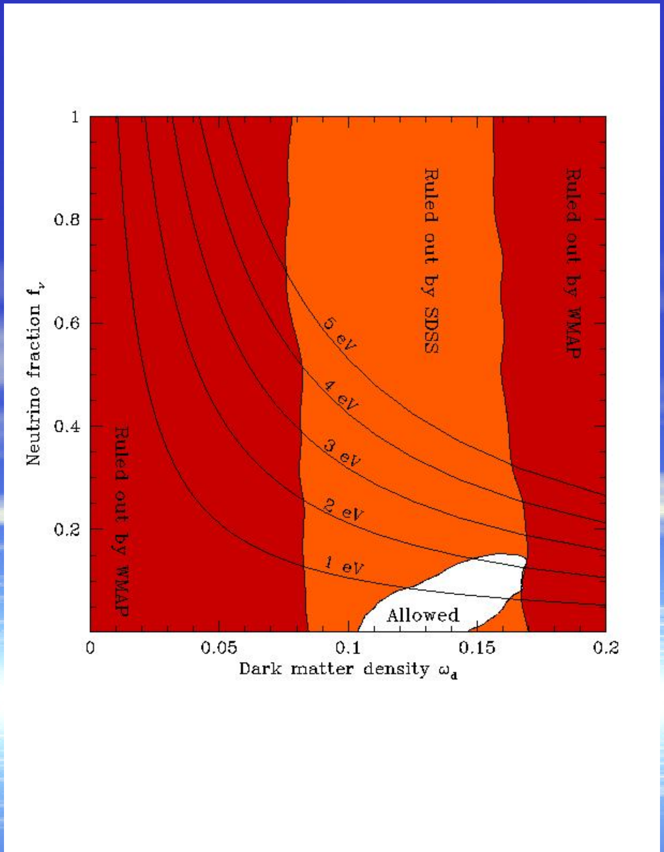


S. Hannestad, Phys. Rev. D 66, 125011 (2002) O.Lahav, O. Elgaroy, astro-ph/0411092

Combined SDSS and WMAP data

M. Tegmark et al., Phys. Rev. D 69, 103501 (2003)





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 !

Conclusion

Beta decay: Independent of neutrino character

$$m_e = \Sigma |U_{ek}|^2 m_k$$

Double beta decay: Requires Majorana neutrinos

$$m_{ee} = | \Sigma U_{ek}^2 m_k |$$

Note: U_{PMNS} + 2 Majorana phases

Cosmology: Requires a cosmological model

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

Currently all of them give limits around 1 eV, future very exciting, because large improvements can be expected