β-decay and neutrino mass

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

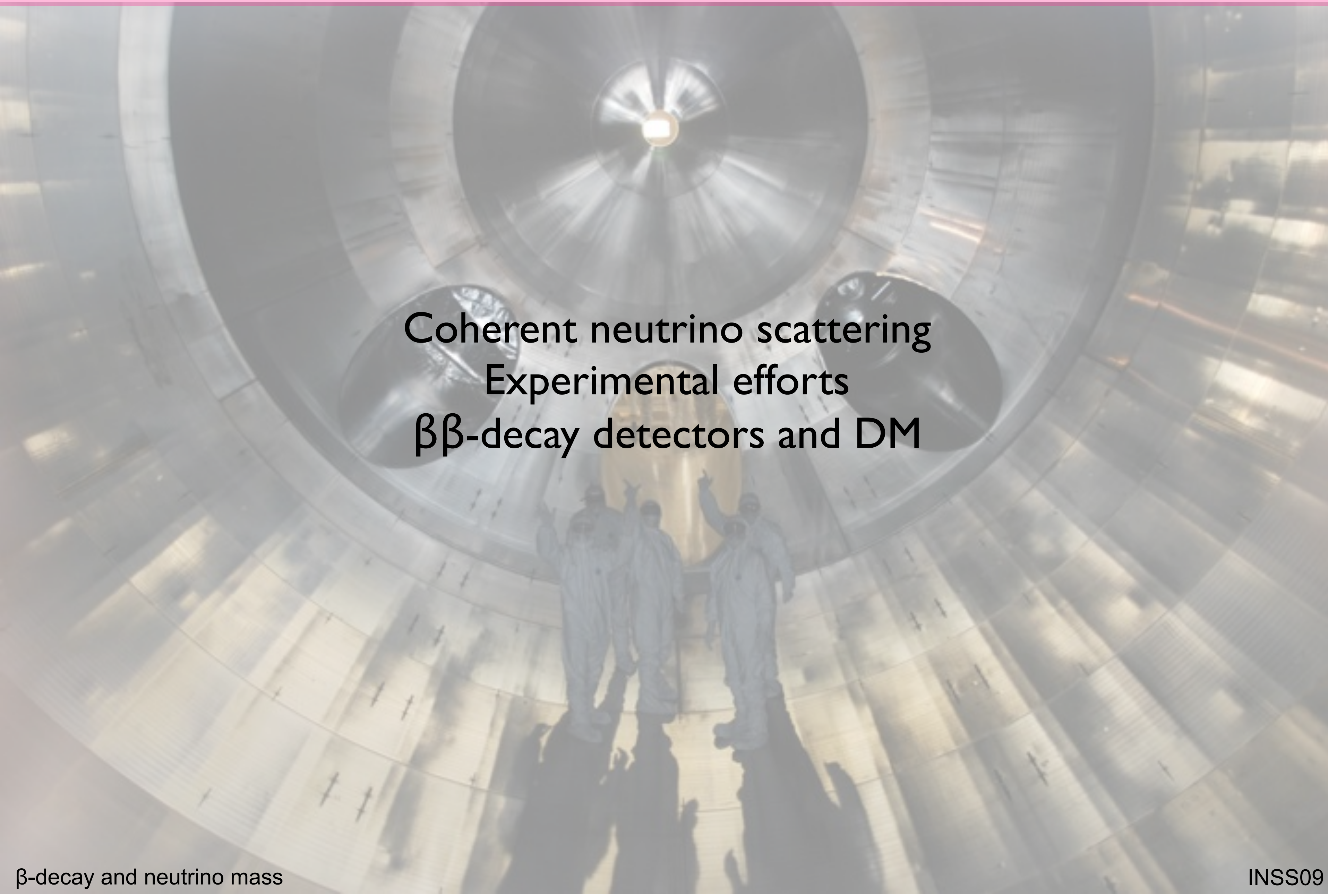
J.F. Wilkerson
International Neutrino Summer School
July 13, 2009

β-decay and neutrino mass

- Coherent neutrino scattering & DM detection (follow-on to yesterday's lecture ββ-decay)

- ν mass, relationship to other masses
- Constraints on ν mass
- Overview of direct measurements
- Determining ν mass from β-decay and electron capture measurements
- Experimental techniques
- Measurements to date
- Current efforts
- Future prospects

Coherent neutrino scattering & DM Detection



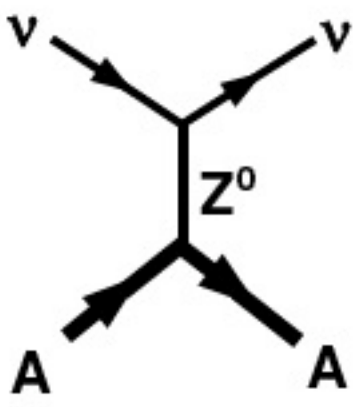
Coherent neutrino scattering
Experimental efforts
ββ-decay detectors and DM

Coherent ν - nucleus scattering

A. Drukier & L. Stodolsky, PRD 30:2295 (1984)   Scholberg, PRD 73, 033005 (2006)

SM Process

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$



- k: neutrino energy
- N: no. of neutrons; Z: no of protons
- θ: scattering angle of ν
- F: form factor (depends on nucleus);
- Q: 4-mom transfer
- G: Fermi constant; θ_w: Weinberg angle

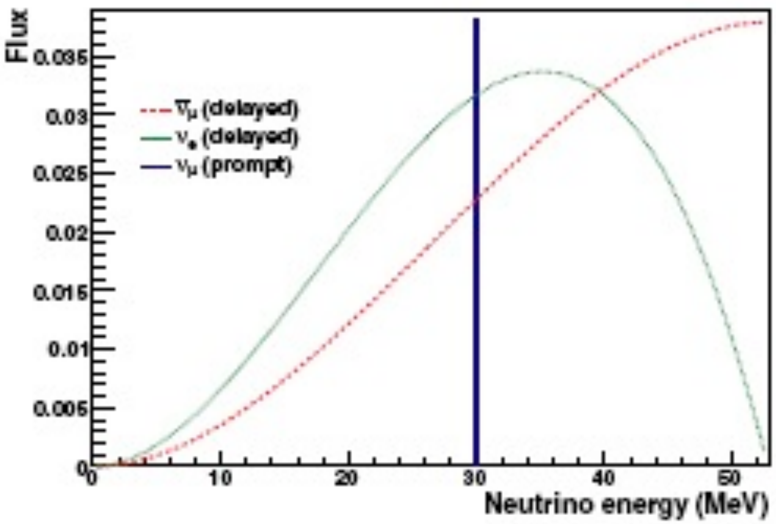
Coherent ν-A elastic $\sigma \sim 10^{-39}$ cm^2

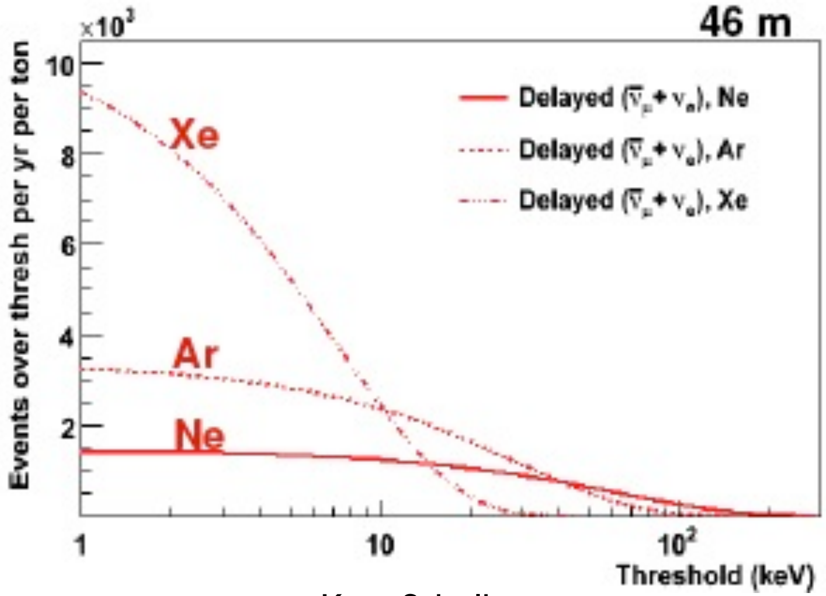
Max Energy of recoil nucleus ~ $2E_\nu^2$ /M

Has never been experimentally observed

Coherent Low Energy A (Nuclear) Recoils CLEAR

Spallation Neutron Source (SNS) Oak Ridge





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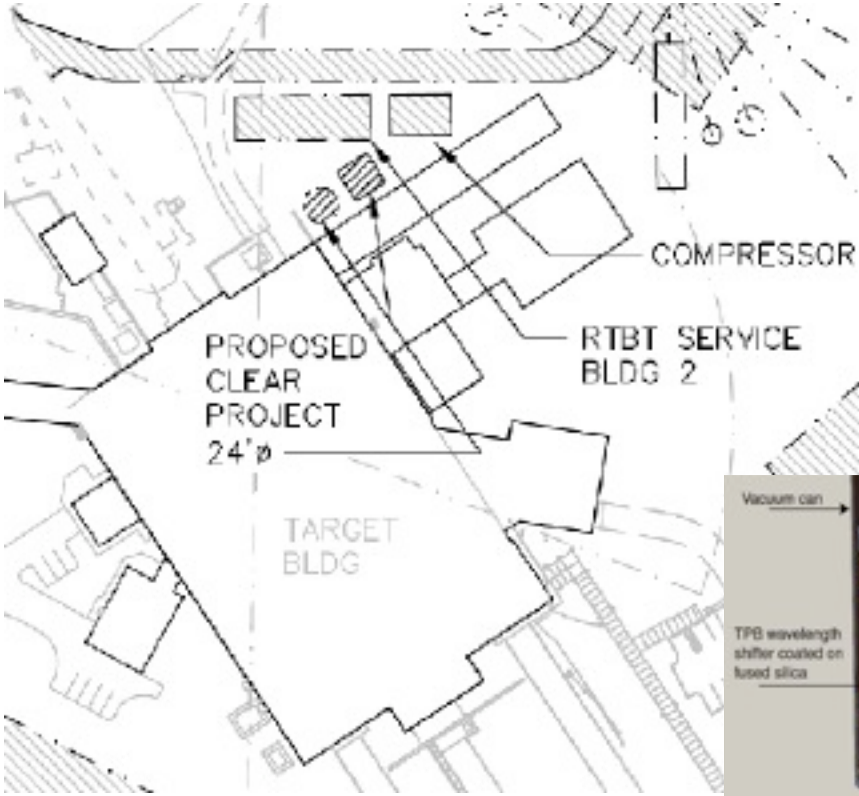
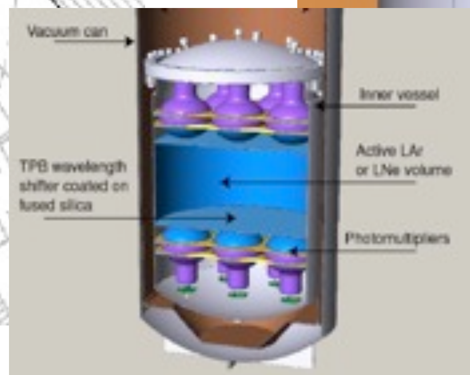
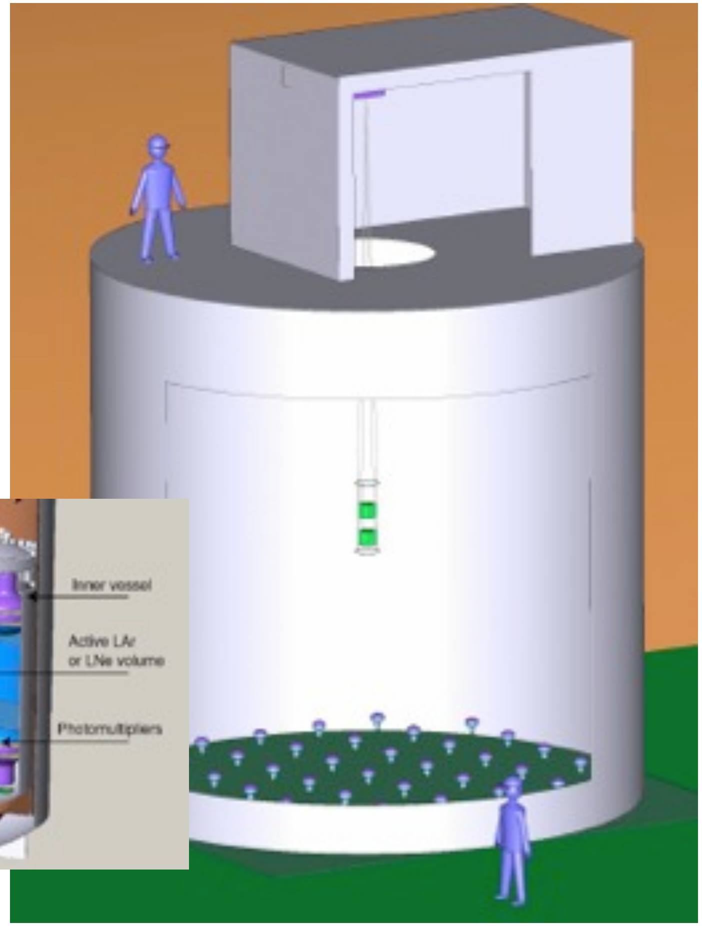
Coherent Low Energy A (Nuclear) Recoils CLEAR

Proposed







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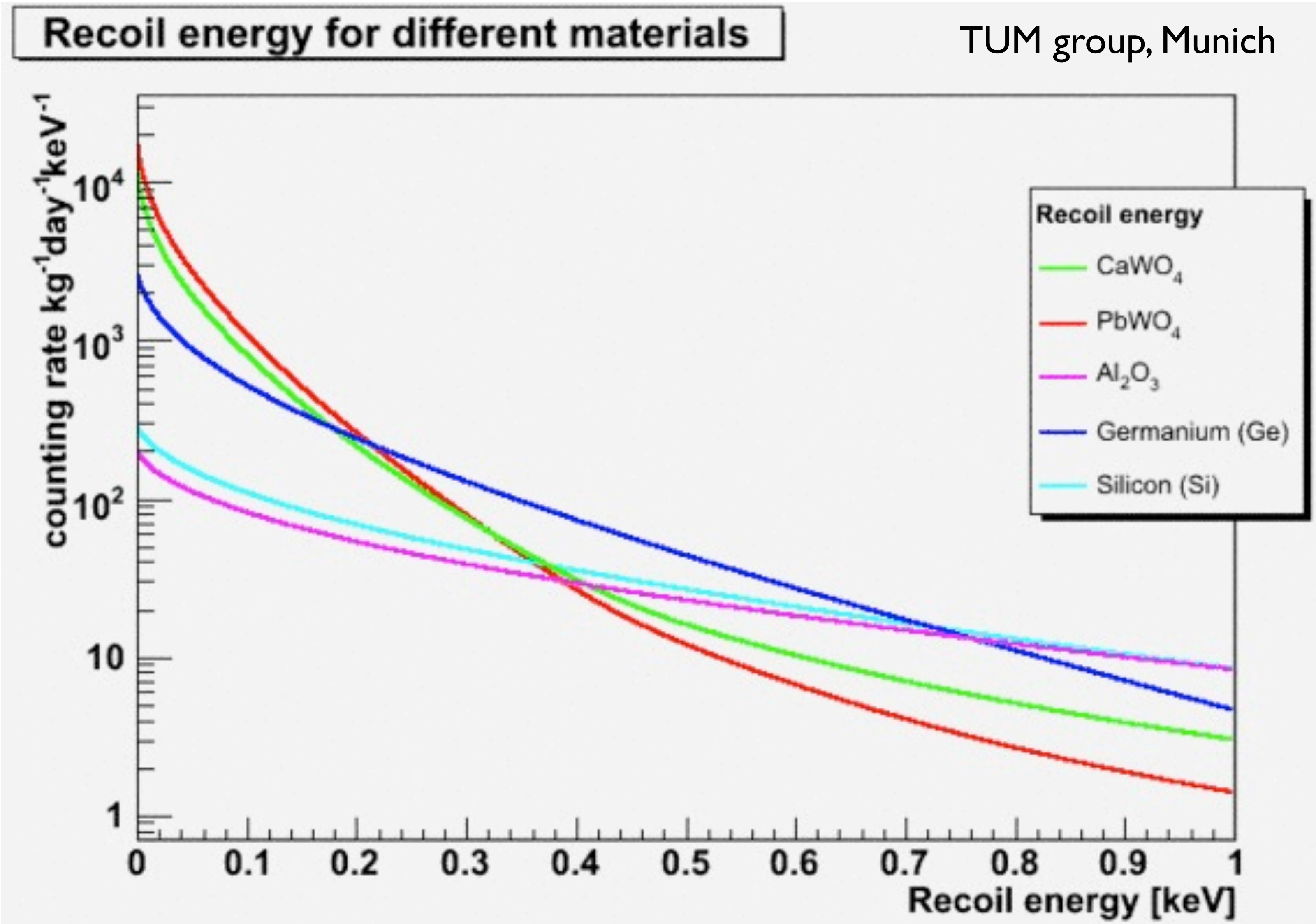
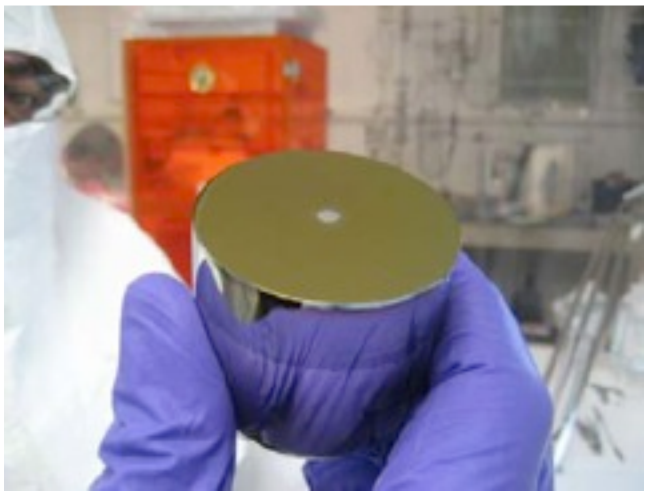
Reactor neutrinos and coherent ν-A

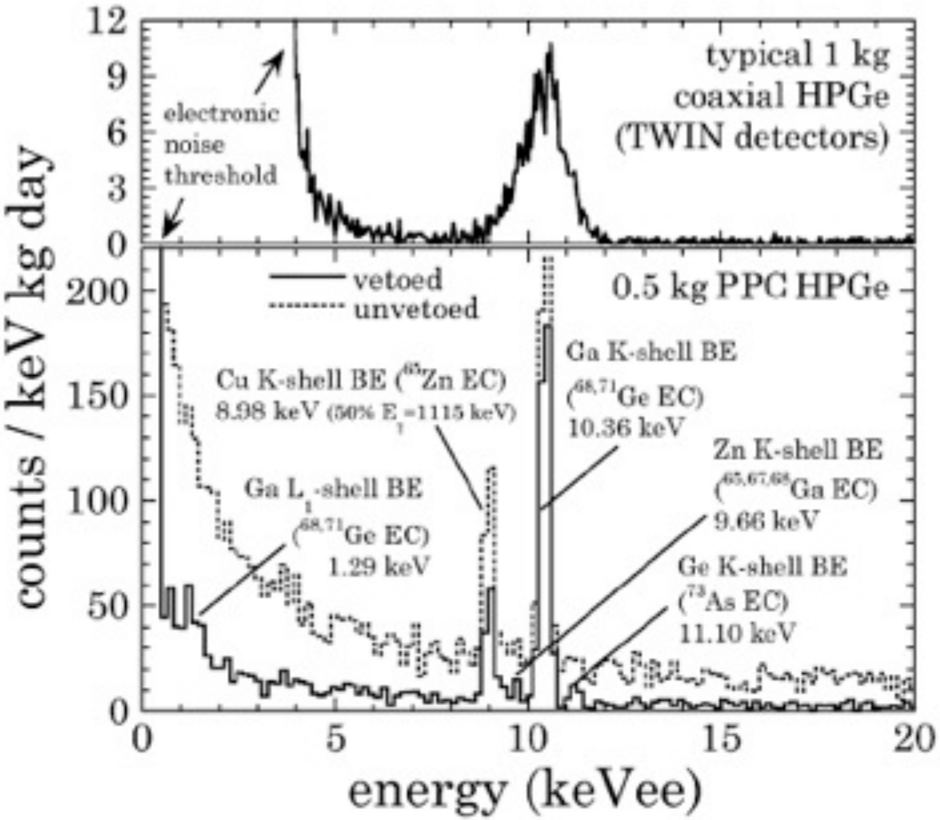


Ultra-low-energy threshold Ge detector

Barbeau, Collar, and Tench, J. Cosmol. Astropart. Phys. 09 (2007) 009.

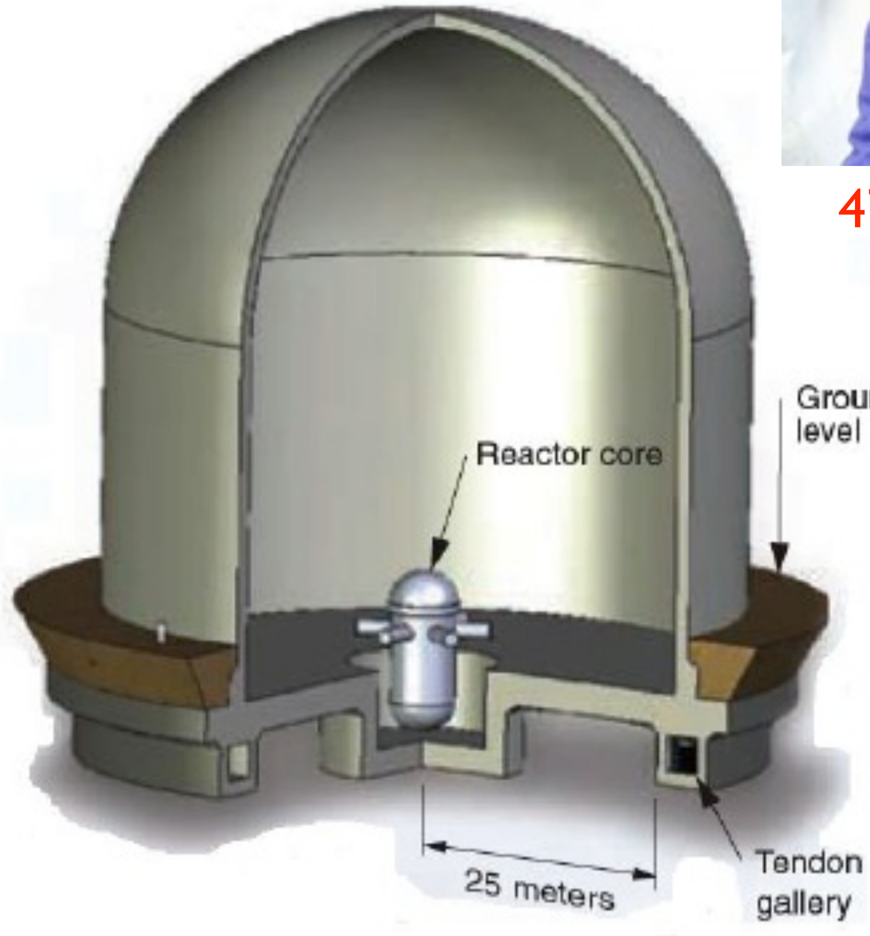
Point Contact Detector
475 g
very low capacitance
special low-background materials

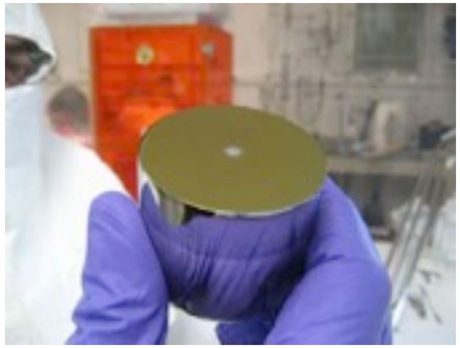




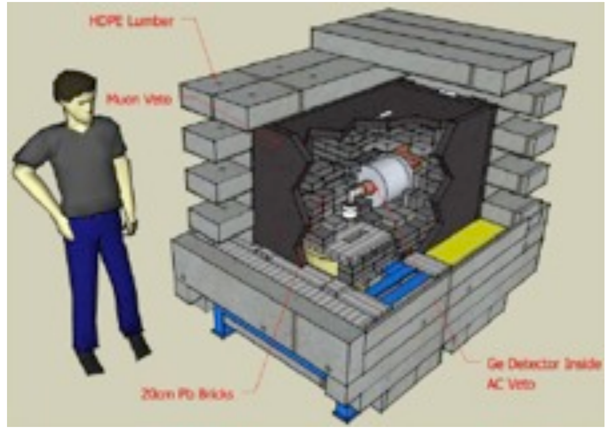
CoGeNT at SONGS

Juan Collar
Journal of Physics: Conference Series 136 (2008) 022009



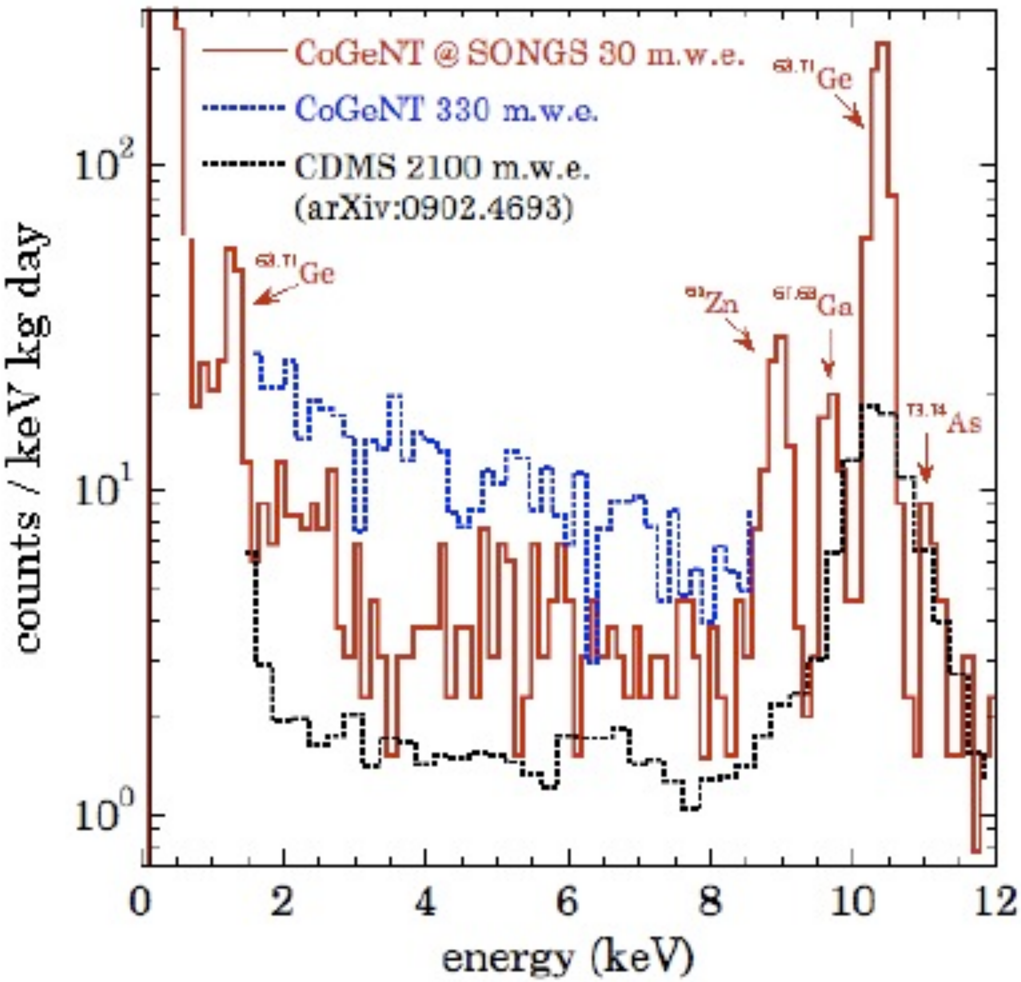


475 g detector

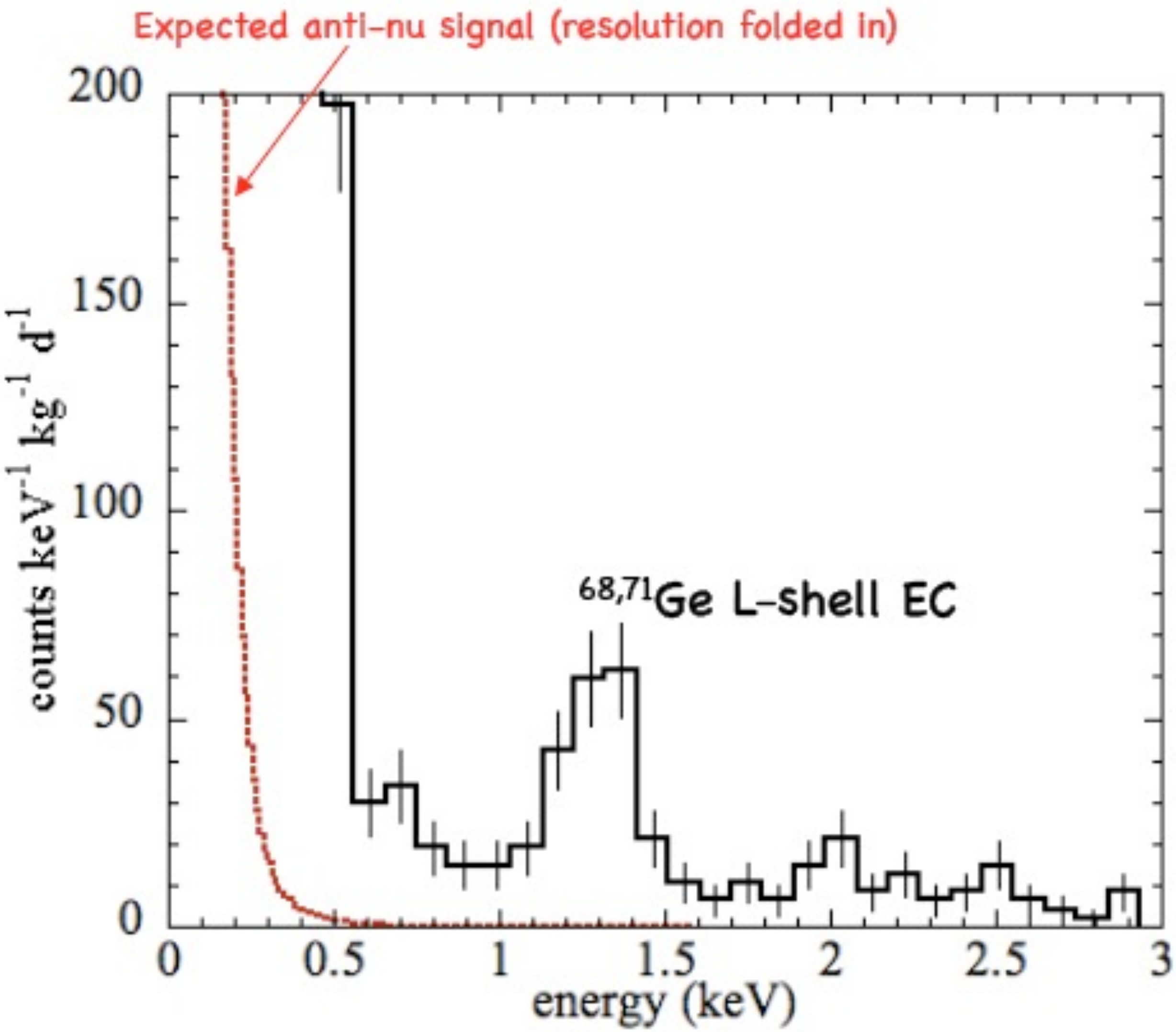


CoGeNT at SONGS

Recent measurements



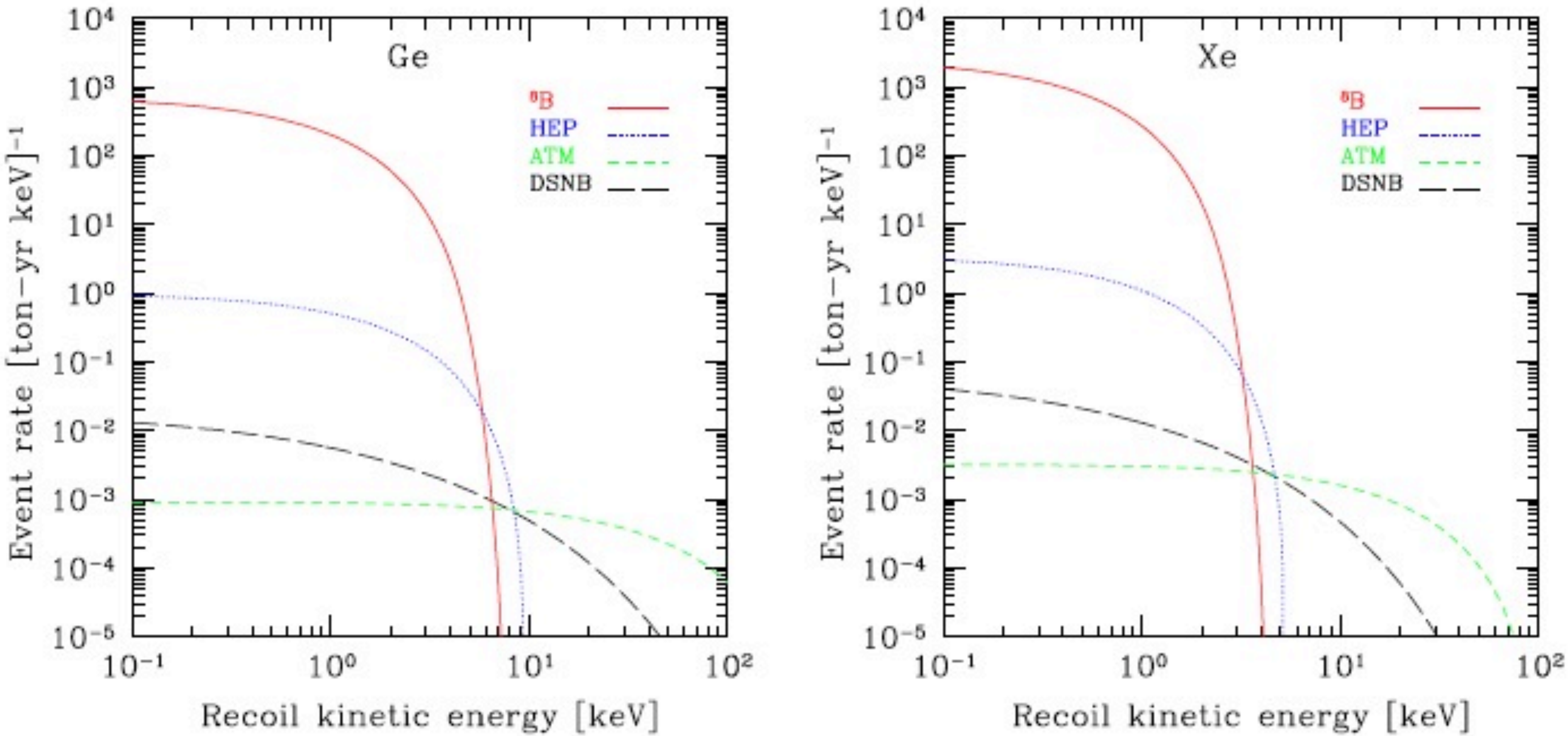
CoGeNT at SONGS



Getting close.
Need to reduce electronics noise by a factor of 2-3

A low-energy background to ββ and DM

Neutrino Coherent Scattering Rates

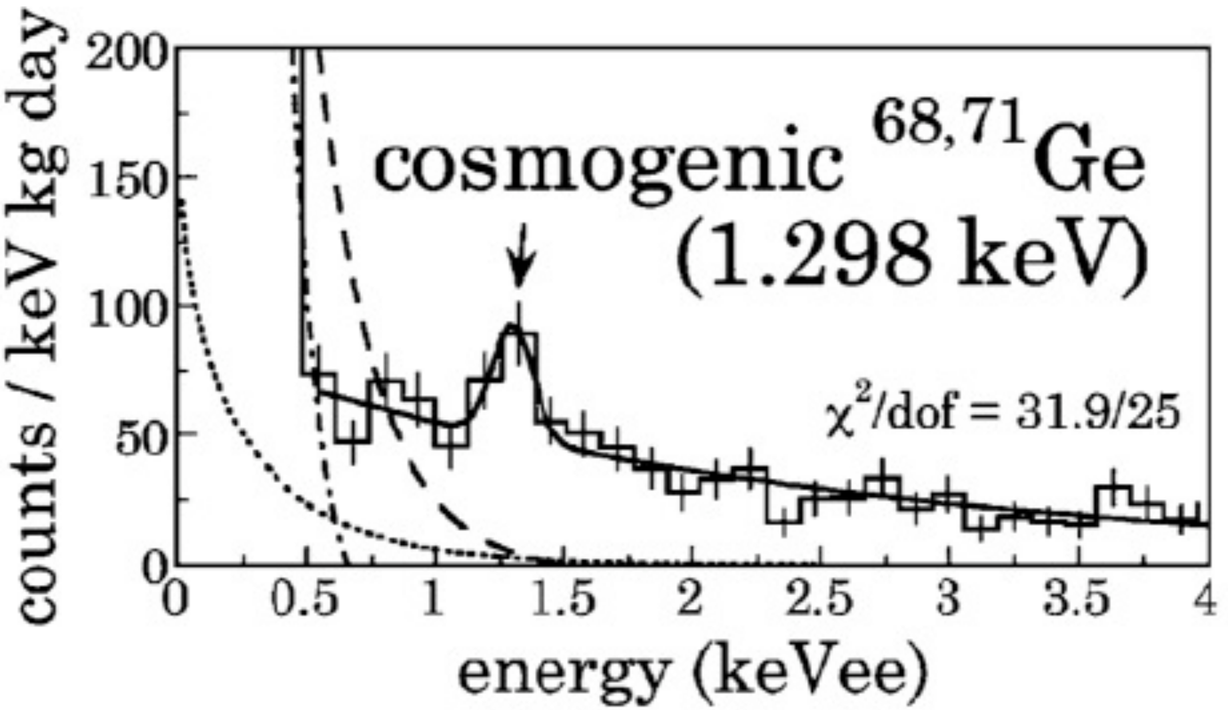


Louis E. Strigari, arXiv 0903.3630

CoGeNT Dark Matter Search

PRL 101, 251301 (2008)

Search for Dark Matter via nuclear recoil



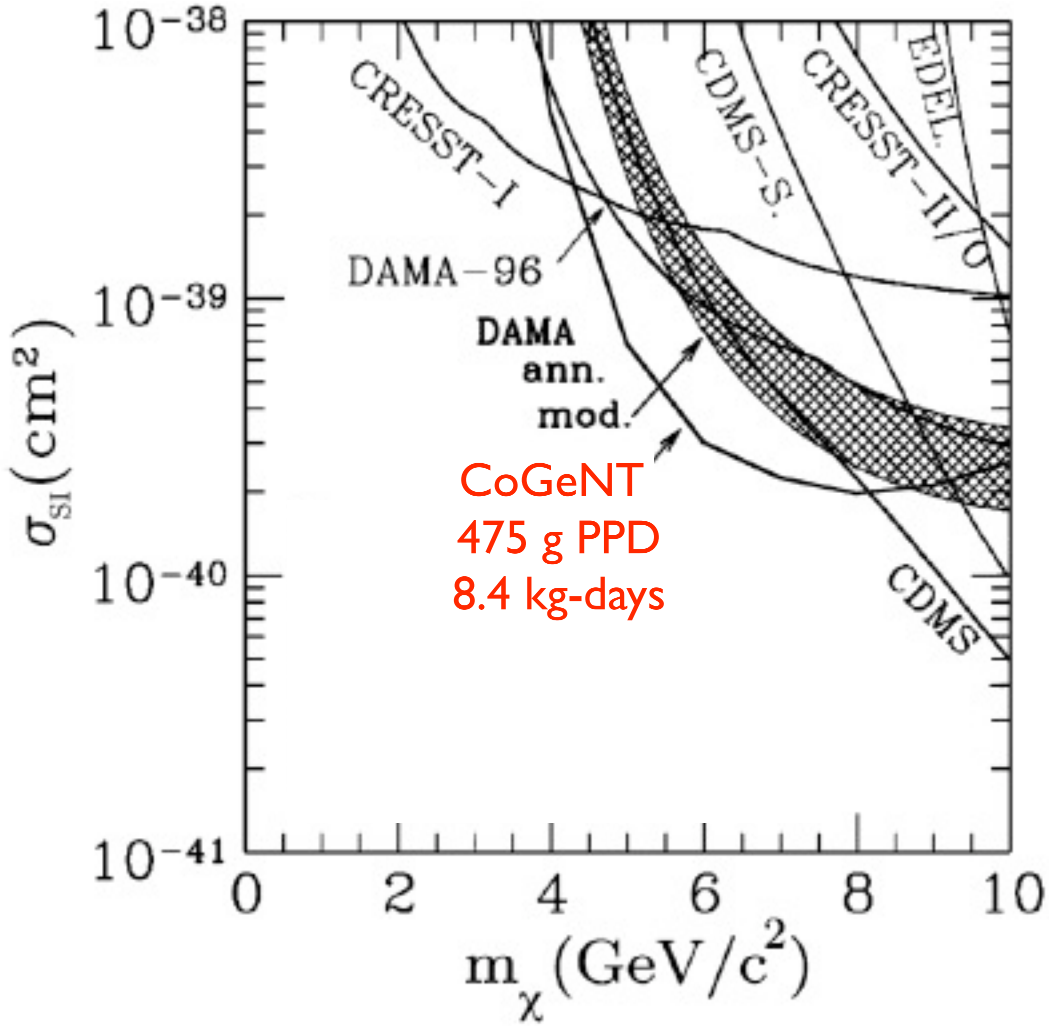
Expected signal from

···········	m_X=8 GeV, $\sigma_{SI} = 10^{-4}$ pb
--------	m_X=6 GeV, $\sigma_{SI} = 2 \times 10^{-3}$ pb
··-·-·-·---	m_X=4 GeV, $\sigma_{SI} = 10^{-2}$ pb

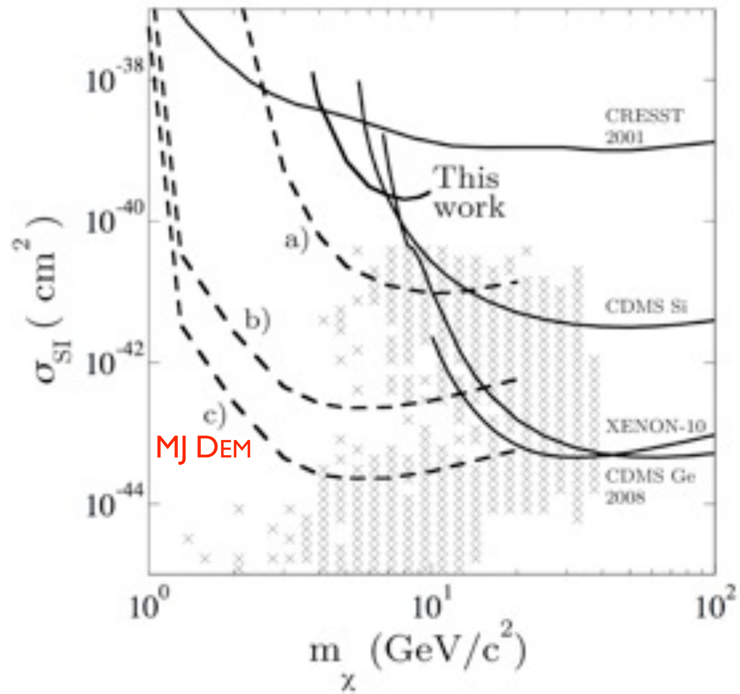
CoGeNT Dark Matter Search

PRL 101, 251301 (2008)

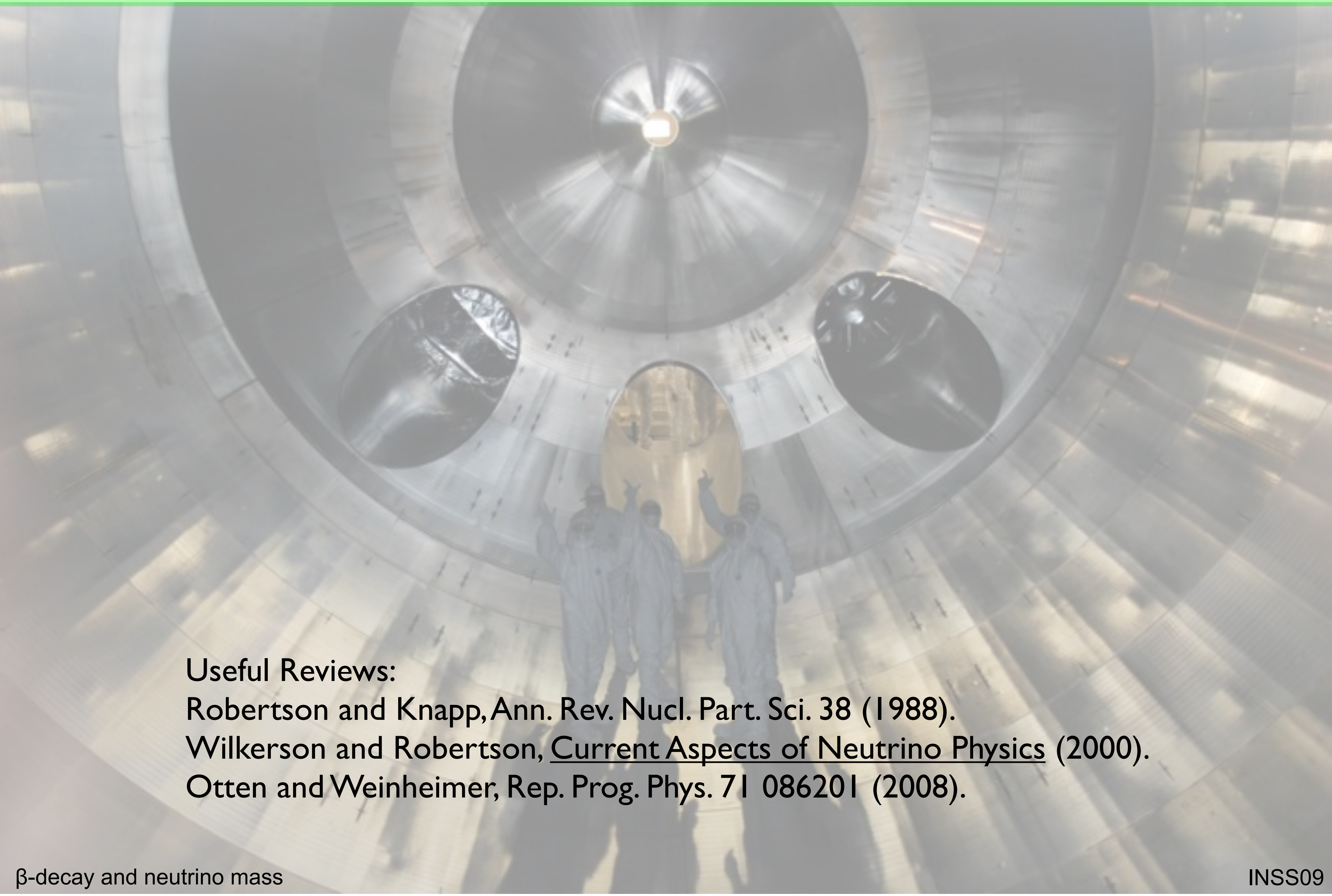
spin-independent couplings from an isothermal light-WIMP halo



Provide bounds on low-energy WIMPS

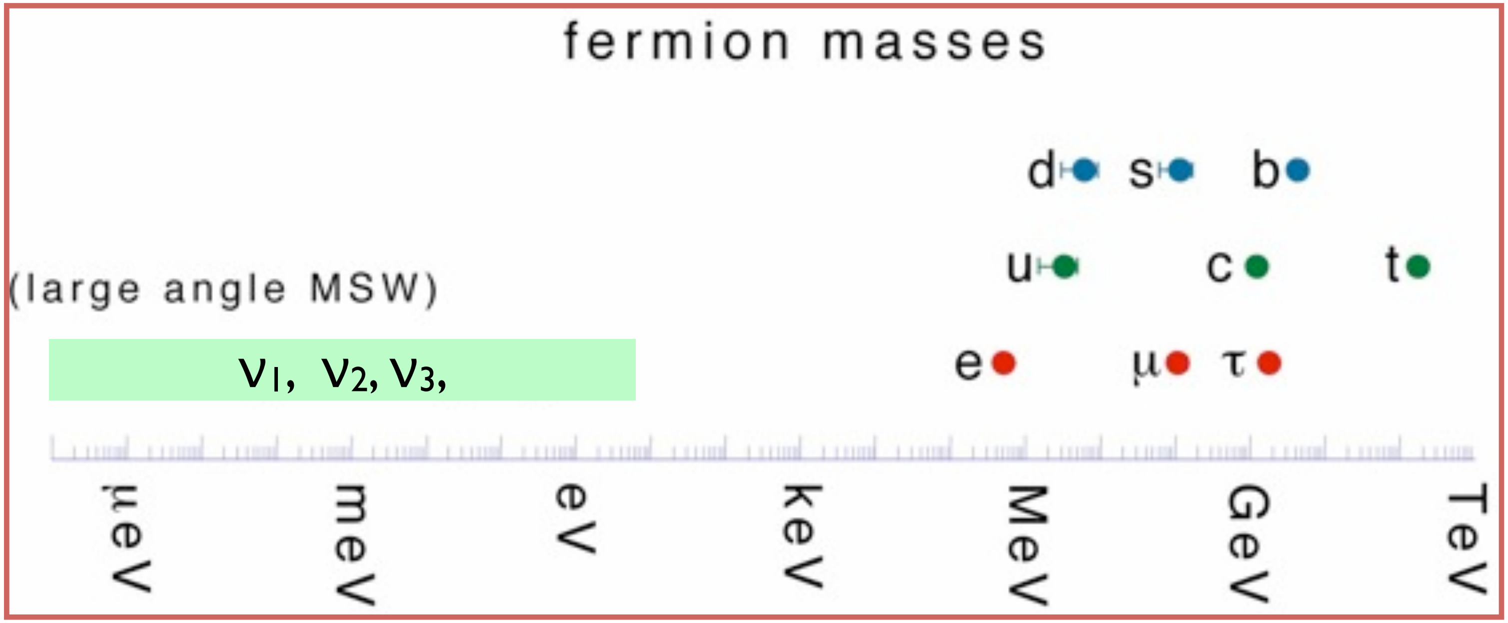


Neutrino mass



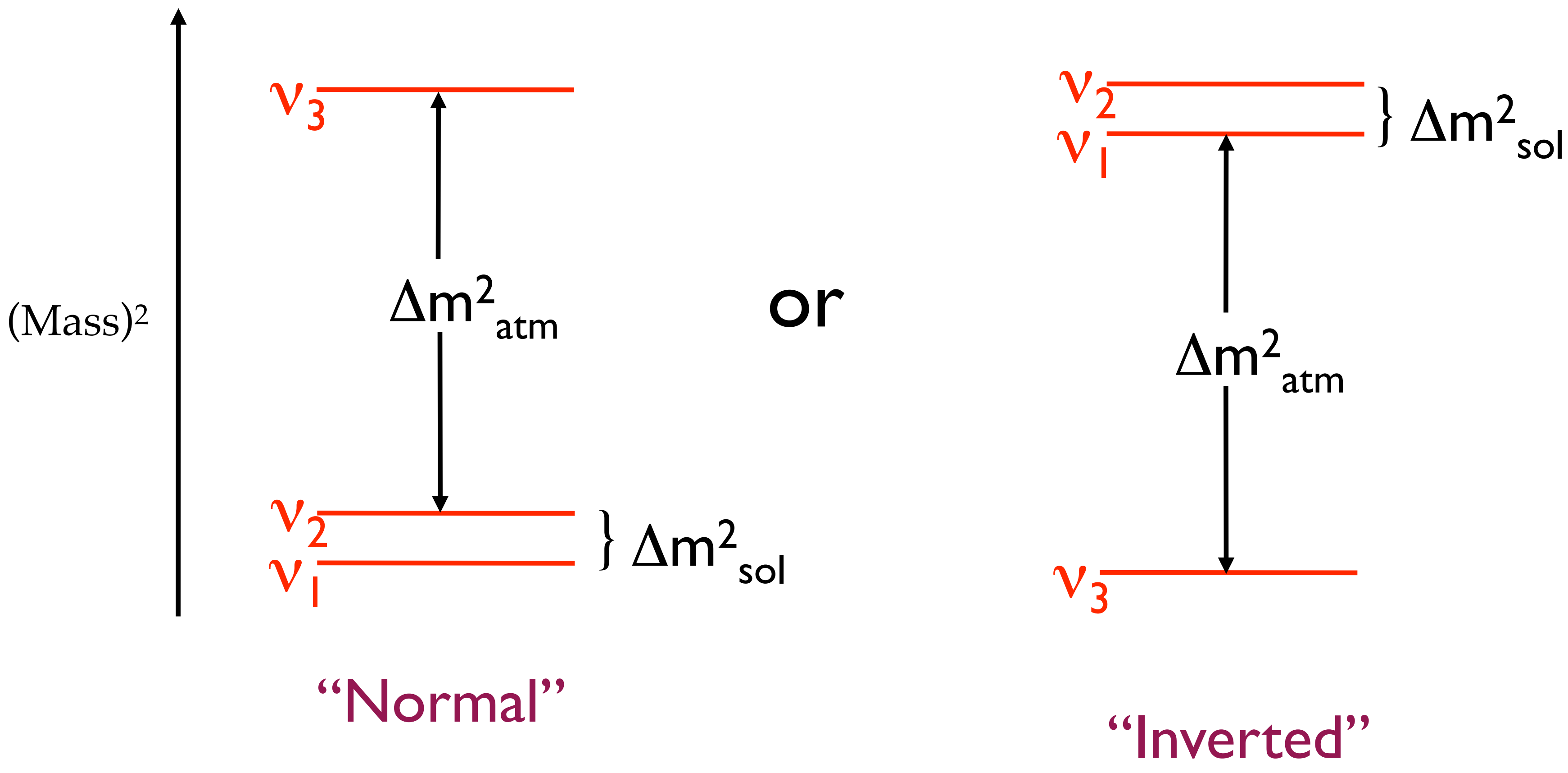
Useful Reviews:
Robertson and Knapp, Ann. Rev. Nucl. Part. Sci. 38 (1988).
Wilkerson and Robertson, Current Aspects of Neutrino Physics (2000).
Otten and Weinheimer, Rep. Prog. Phys. 71 086201 (2008).

Why are neutrino masses so small?



How do we directly measure the mass values?

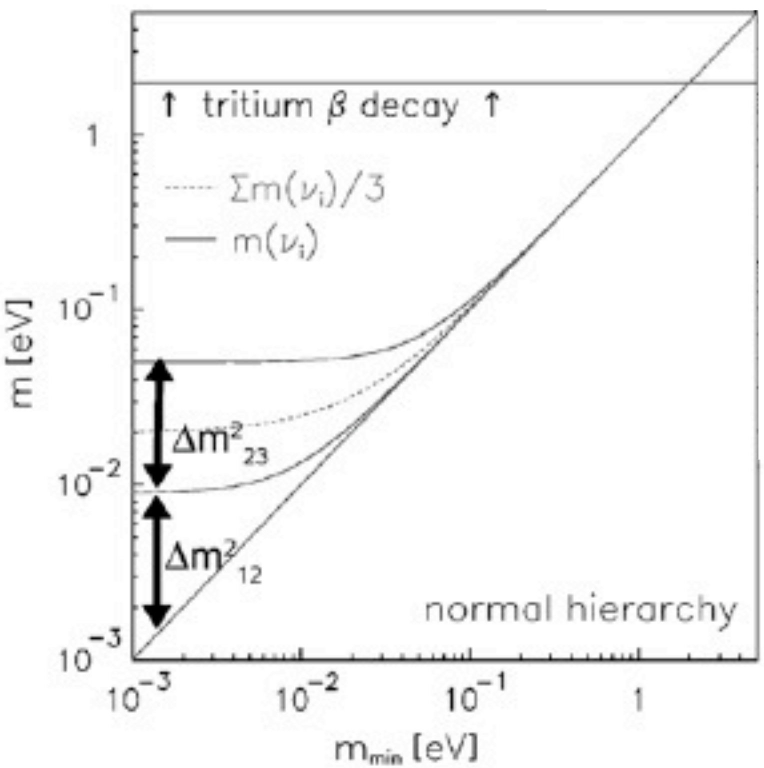
What we know: the ν $(\text{Mass})^2$ Spectrum

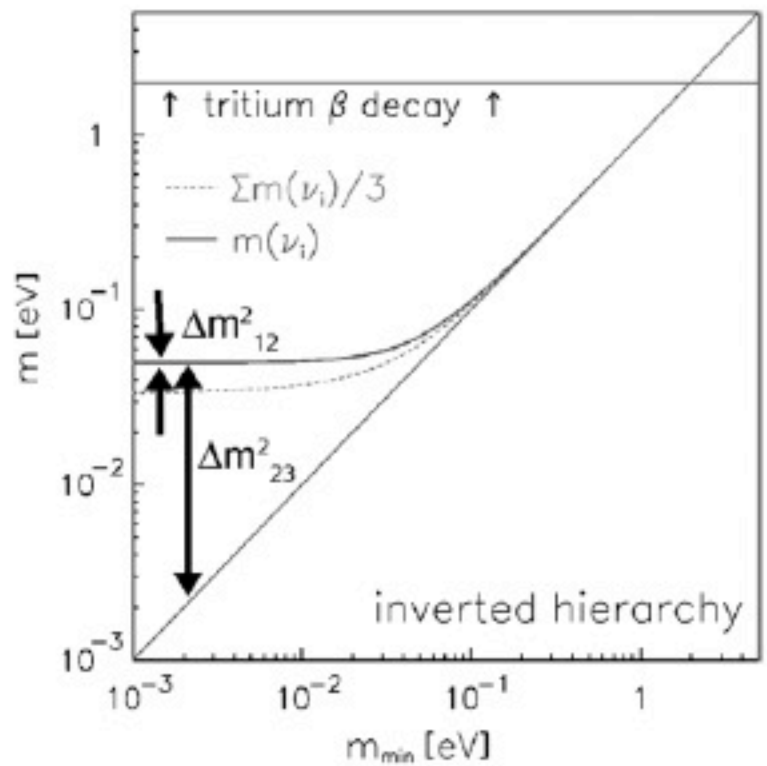


$\Delta m^2_{sol} \approx 8 \times 10^{-5}\ \text{eV}^2$, $\Delta m^2_{atm} \approx 2.5 \times 10^{-3}\ \text{eV}^2$

What do we know about absolute masses?

$\Delta m^2_{sol} \approx 8 \times 10^{-5}\ eV^2, \quad \Delta m^2_{atm} \approx 2.5 \times 10^{-3}\ eV^2$

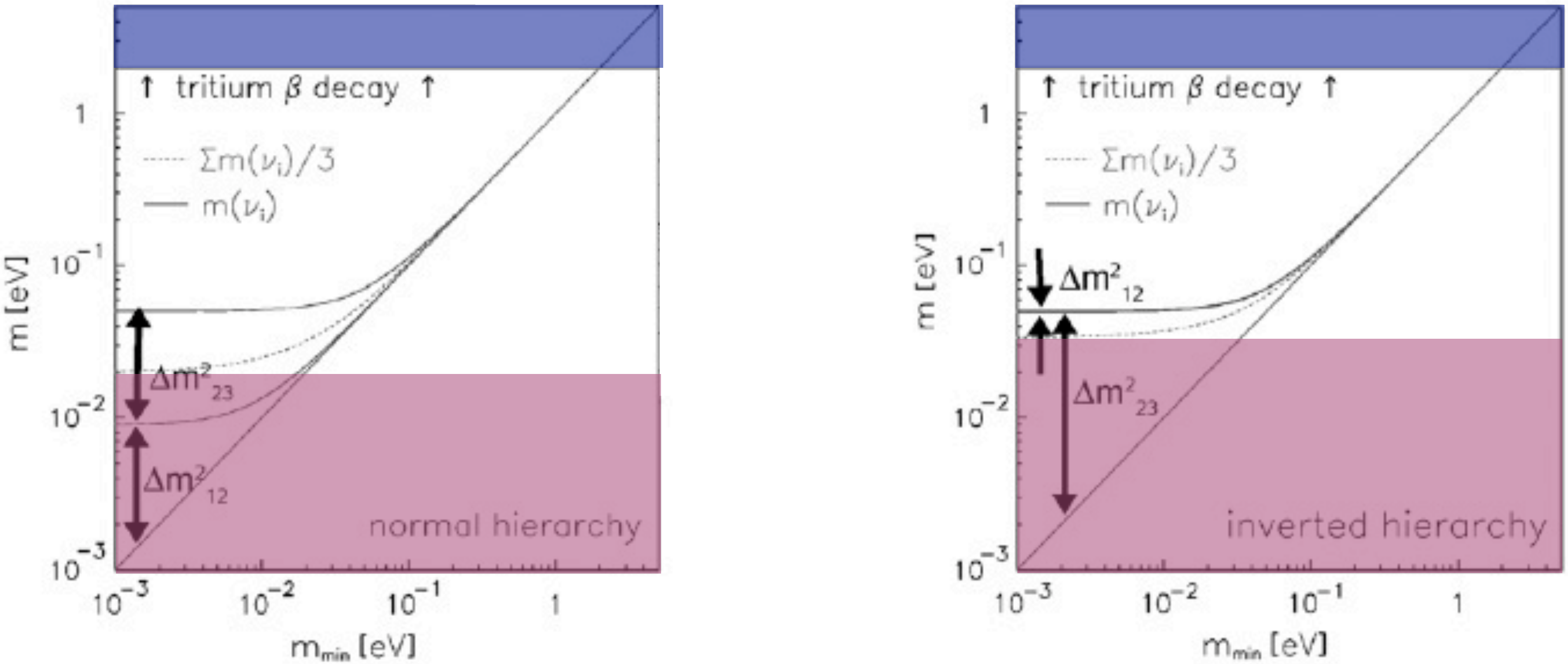




E .W. Otten and C. Weinheimer

What do we know about absolure masses?

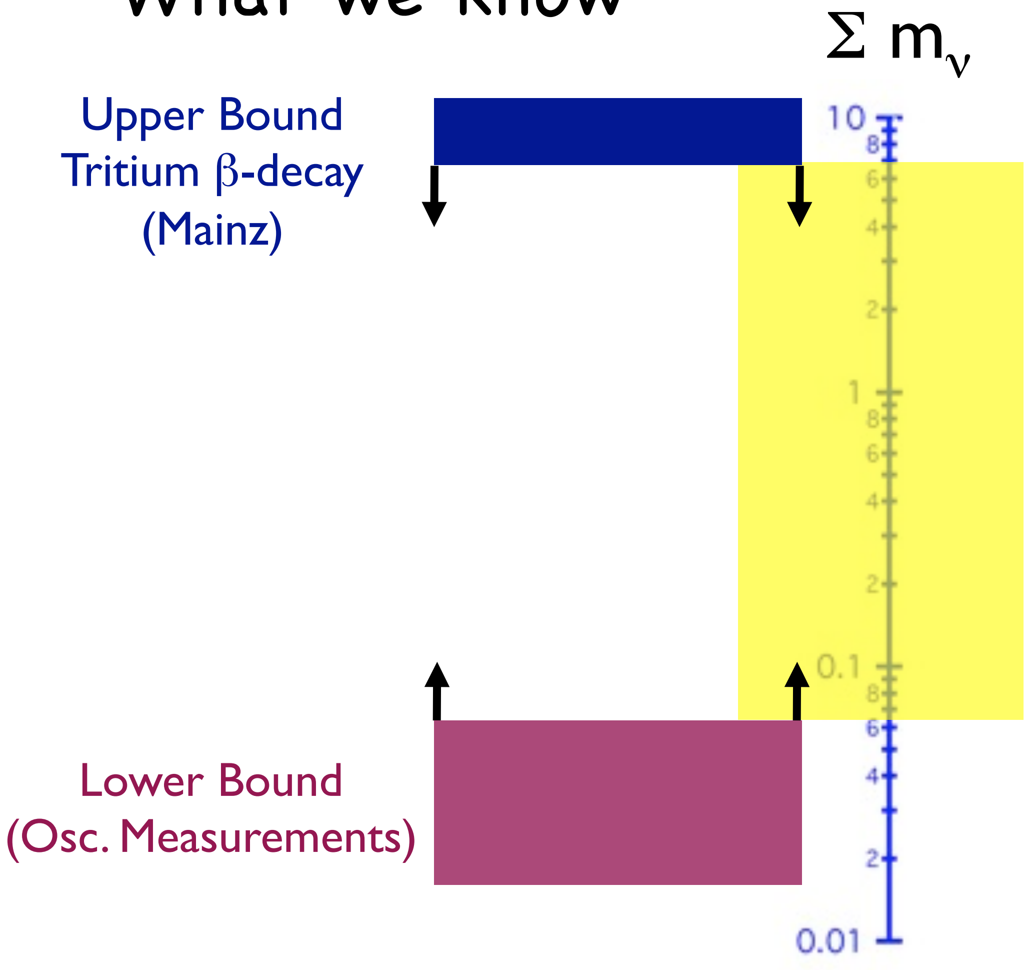
$\Delta m^2_{sol} \approx 8 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm} \approx 2.5 \times 10^{-3}\ eV^2$



E .W. Otten and C. Weinheimer

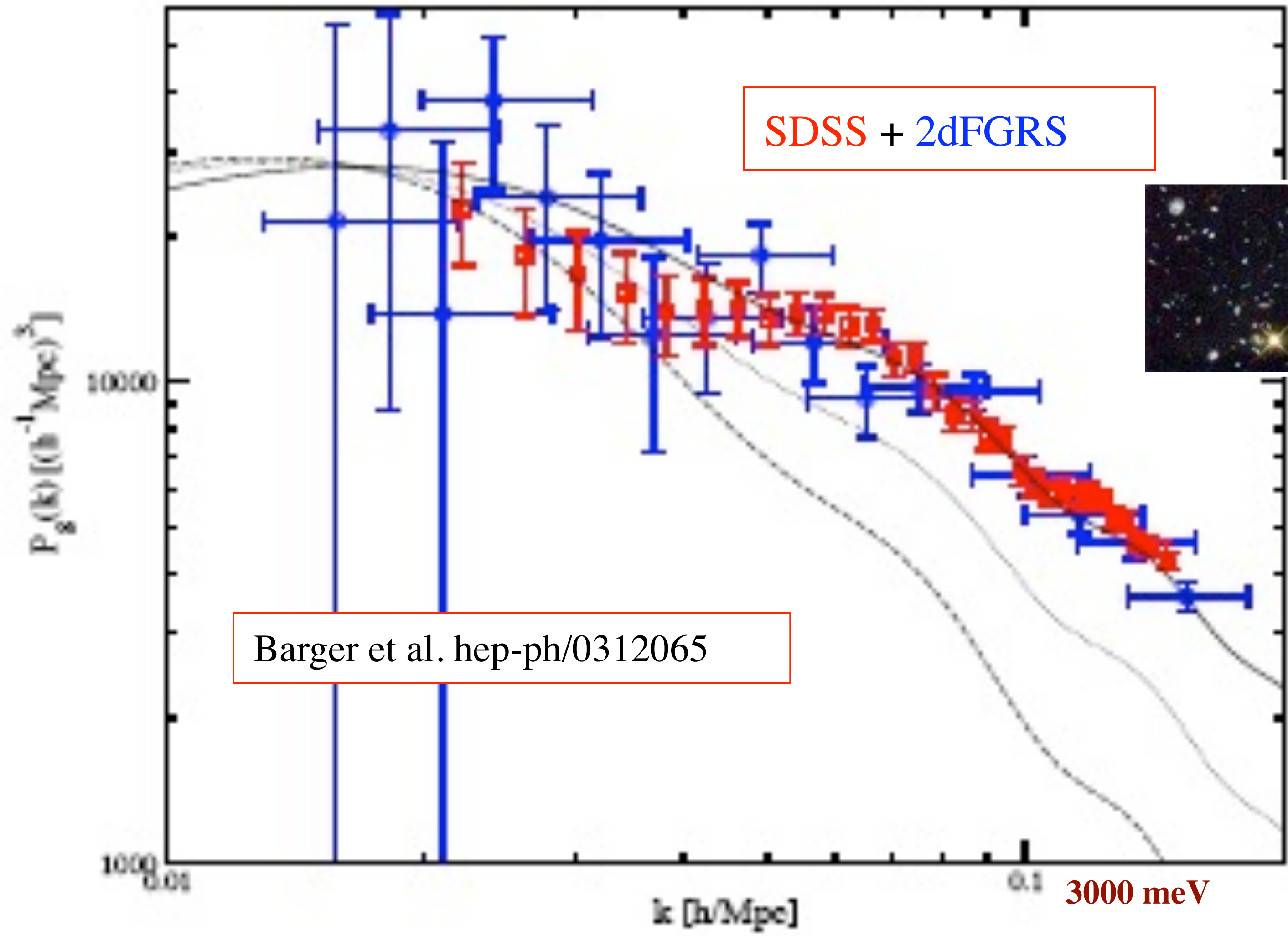
Constraints on ν mass

What we know



(Σ of masses)

m_ν influences structure in the universe



Σm_ν

280 meV

1500 meV

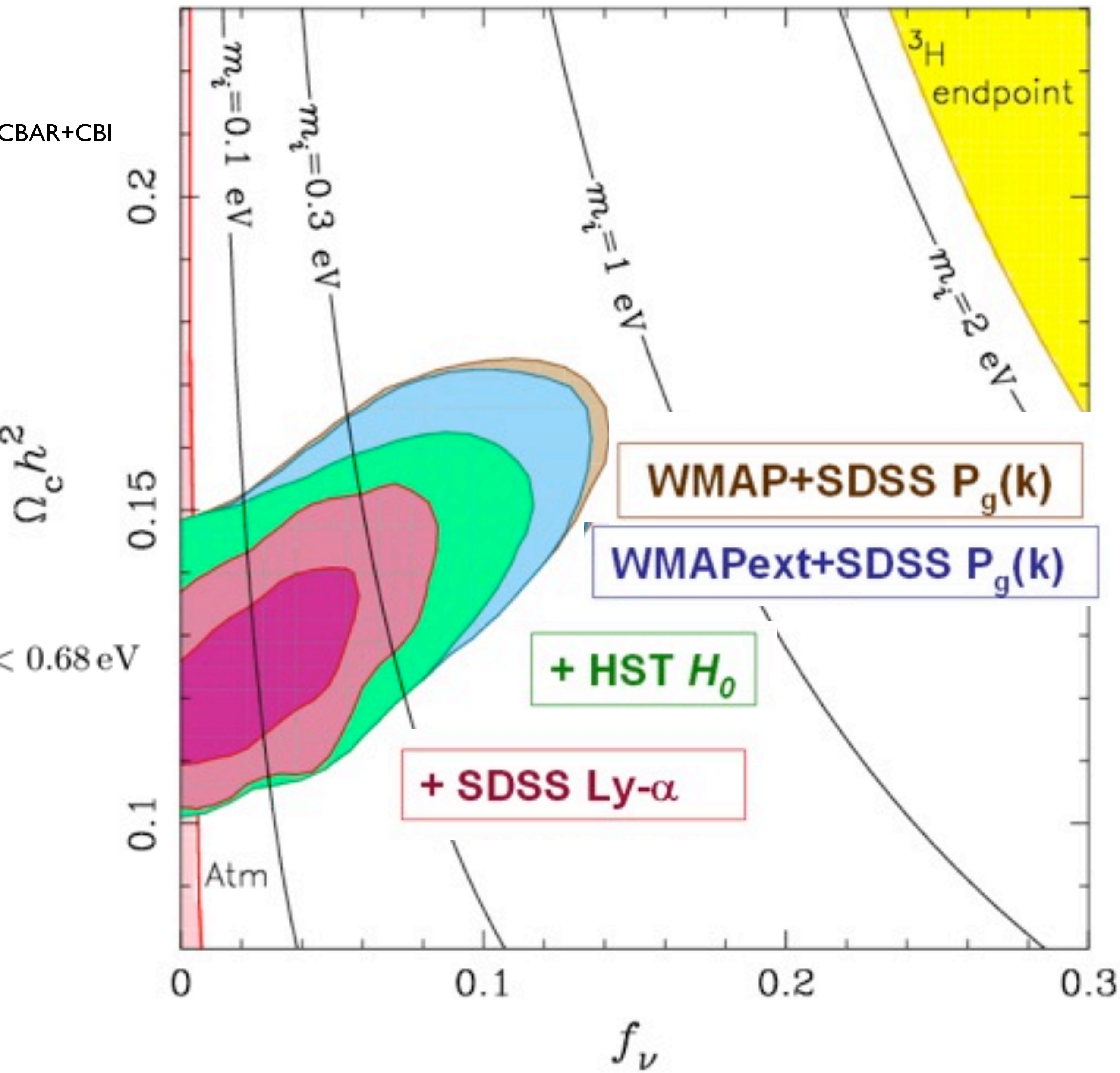
3000 meV

Cosmological constraints on neutrino rest mass

WMAP$_{+ACBAR+CBI}$
+ SDSS
+ HST

WMAP $\sum m_\nu < 0.68\,\mathrm{eV}$

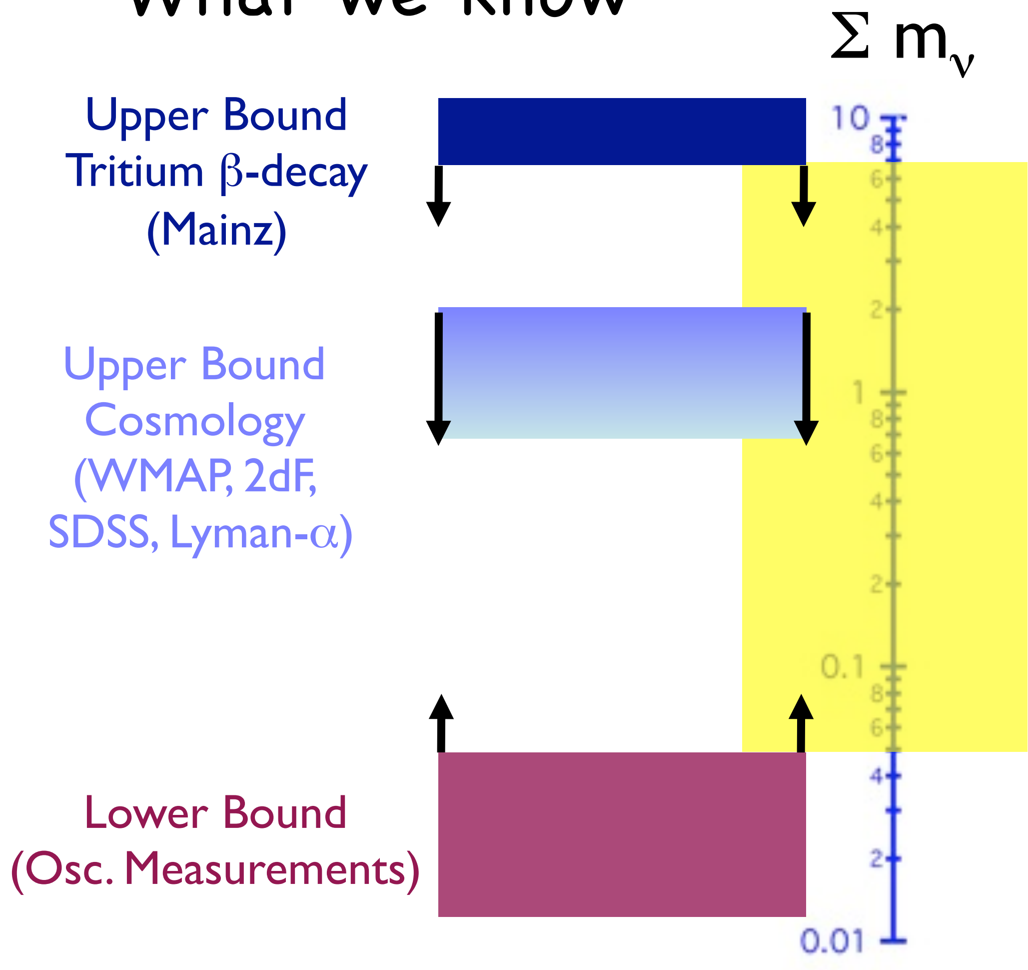
K. Abazajian



Constraints on ν mass

What we know

Future Experiments

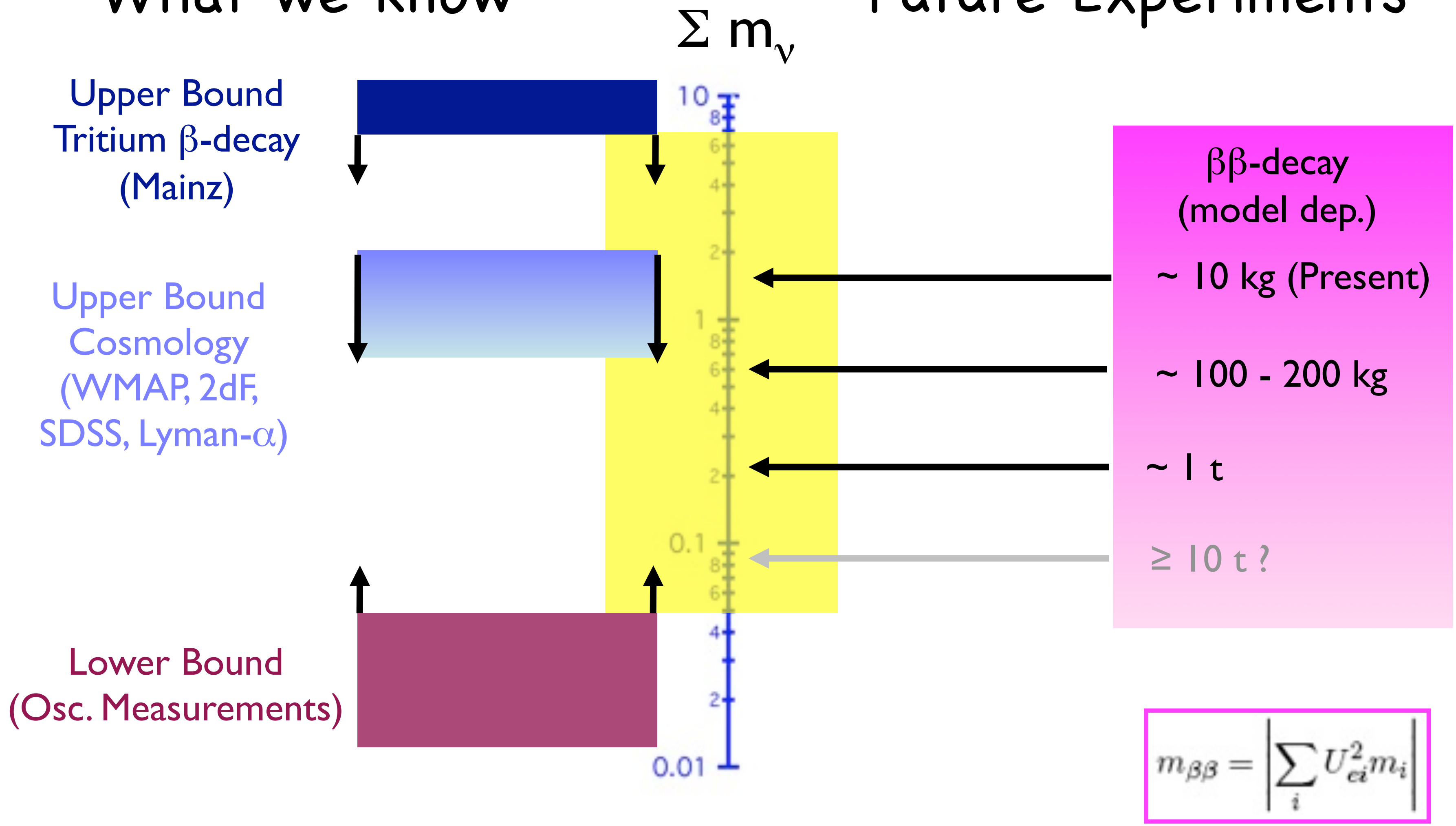


(Σ of masses)

Constraints on ν mass

What we know

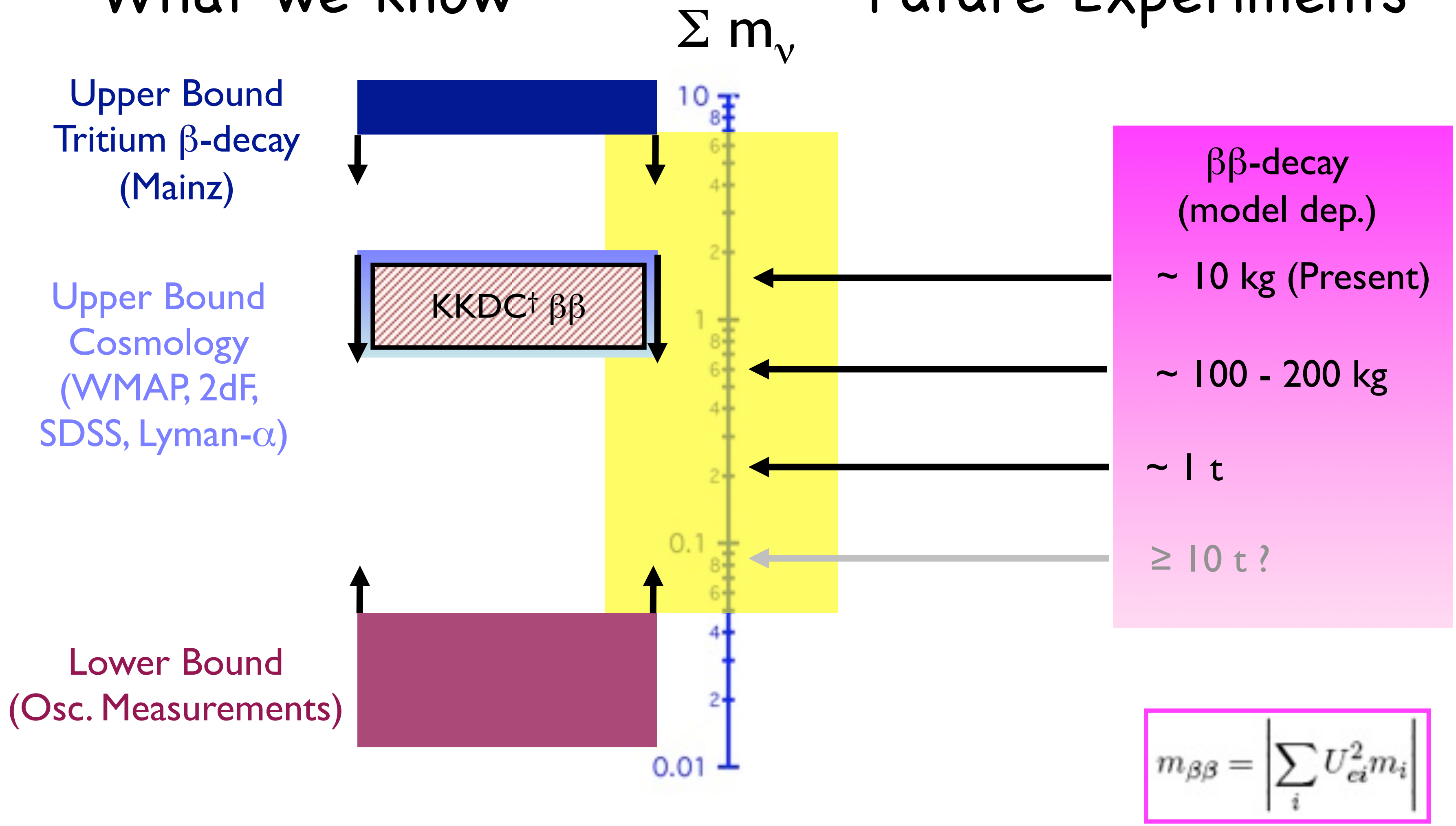
Future Experiments



(Σ of masses)

Constraints on ν mass

What we know | Future Experiments



(Σ of masses)

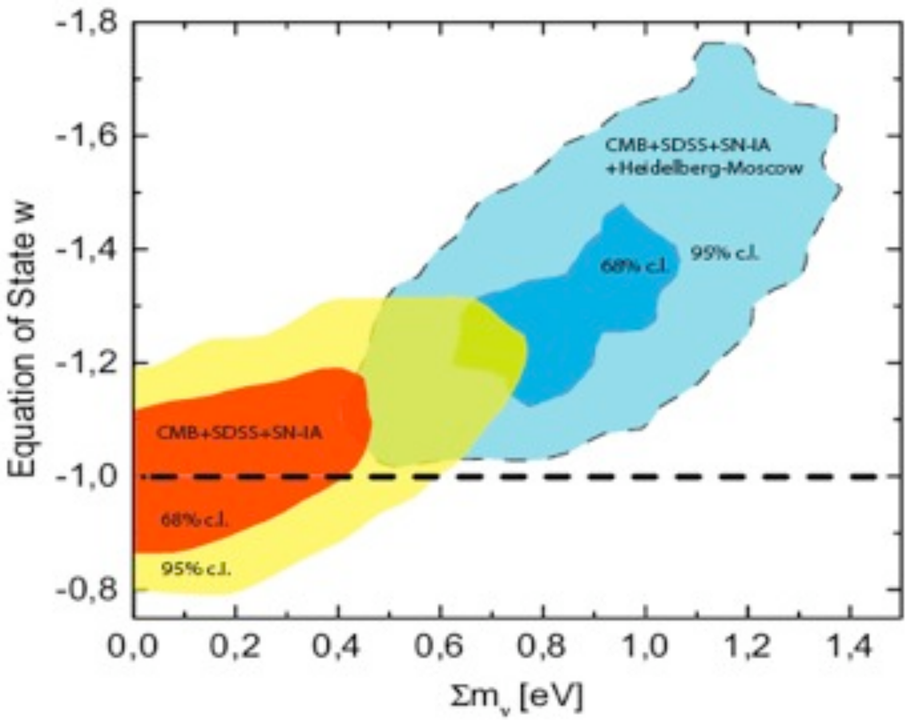
Complementarity of ν mass measurements

What if one observes 0νββ at a larger value than for example that found from cosmology?

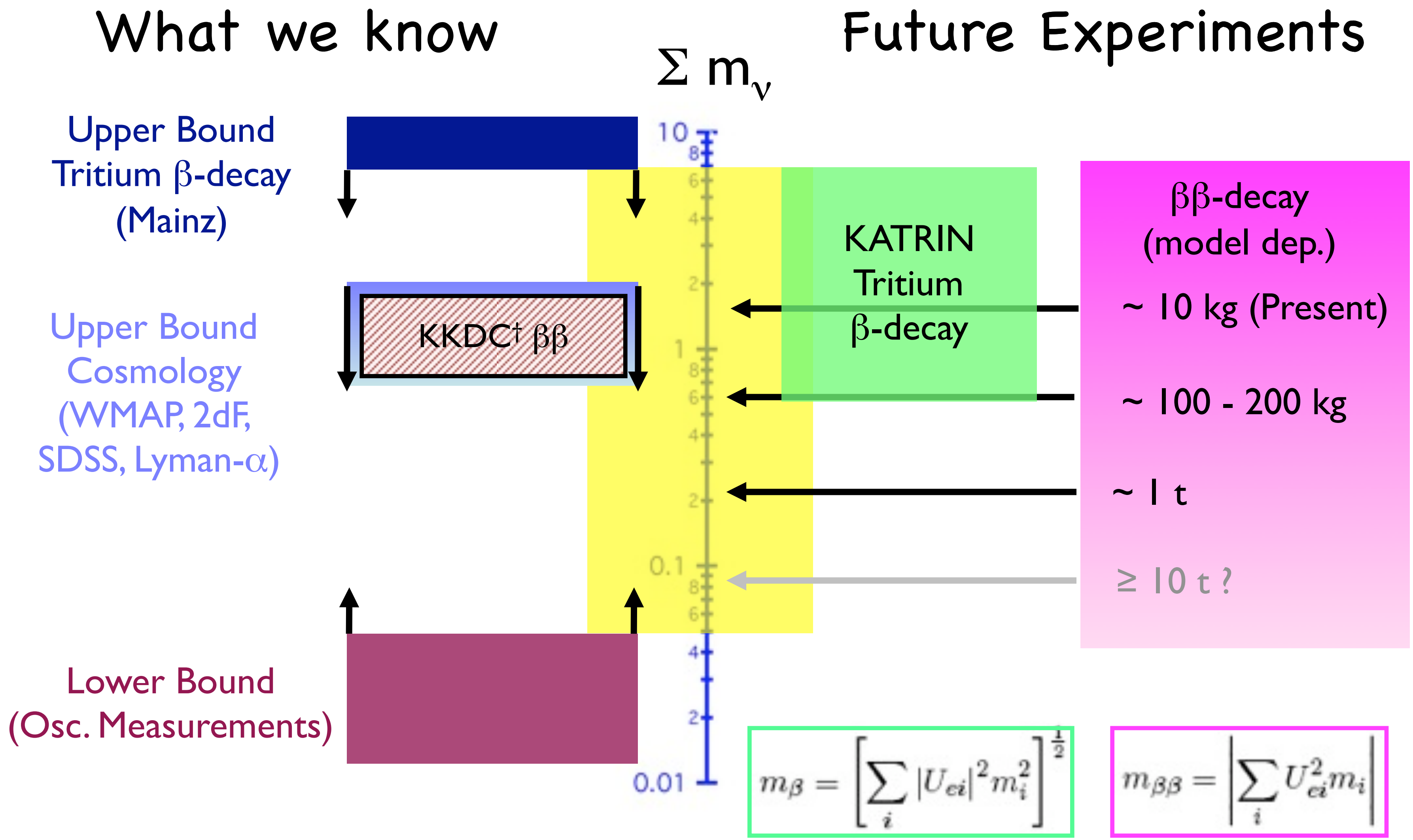
- Effective majorana mass (the decay amplitude) might not arise from the exchange of light Majorana neutrinos.
- Underlying model dependent assumptions of the cosmological model may be incorrect.

De La Macorra, Melchiorri, Serra, & Bean
arXiv astro-ph/0608351

If Klapdor-Kleingrothaus (KKDC) is correct then a global analysis (blue) implies that the Dark Energy equation of state, w, must be more negative than -1.



Constraints on ν mass



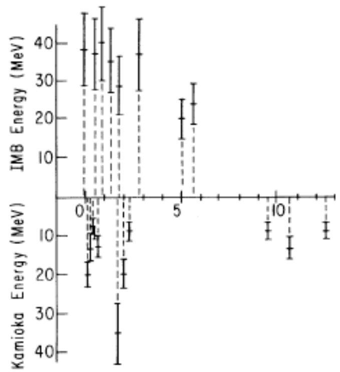
(Σ of masses)

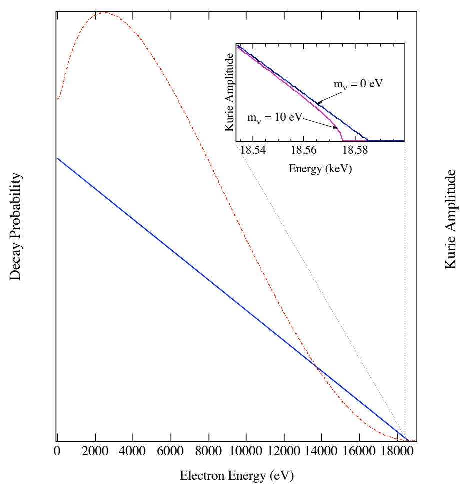
Direct measurements of neutrino mass

Direct measurements of neutrino mass

- **Techniques**
  - time of flight from supernovae
    - Not able to reach sub-eV sensitivity
    - A direct measurement or limit will be used to help understand supernovae dynamics.
  - particle decay kinematics
    - beta decay (and electron capture) spectrum shape
    - muon momentum in pion decay
    - invariant mass studies of multiparticle semileptonic decays

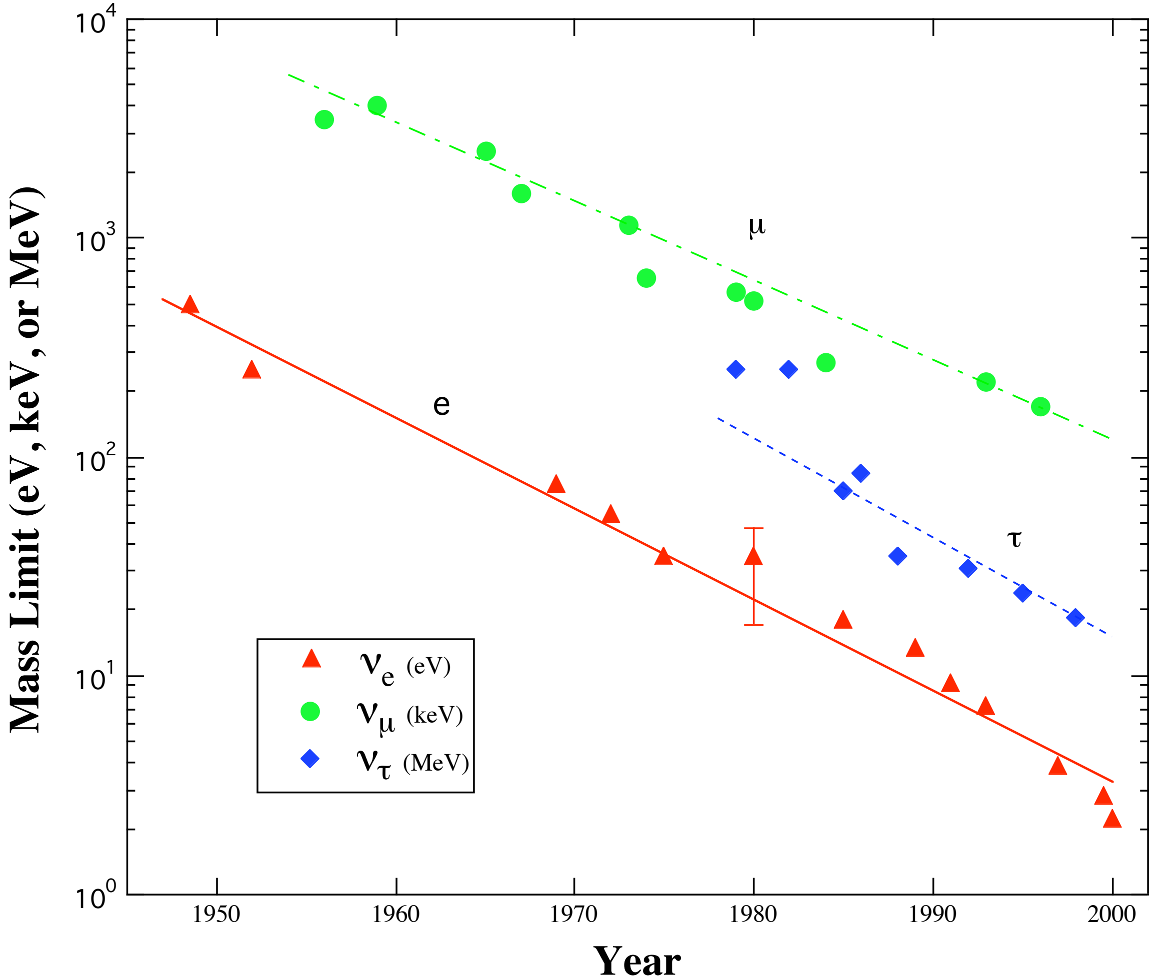
SN1987a





Past: history of direct ν mass measurements

In terms of flavor eigenstates



$m_{\nu_\mu} < 170$ keV (90%CL)

(PSI 1996)

$m_{\nu_\tau} < 18.2$ MeV (95% CL)

(ALEPH 1998)

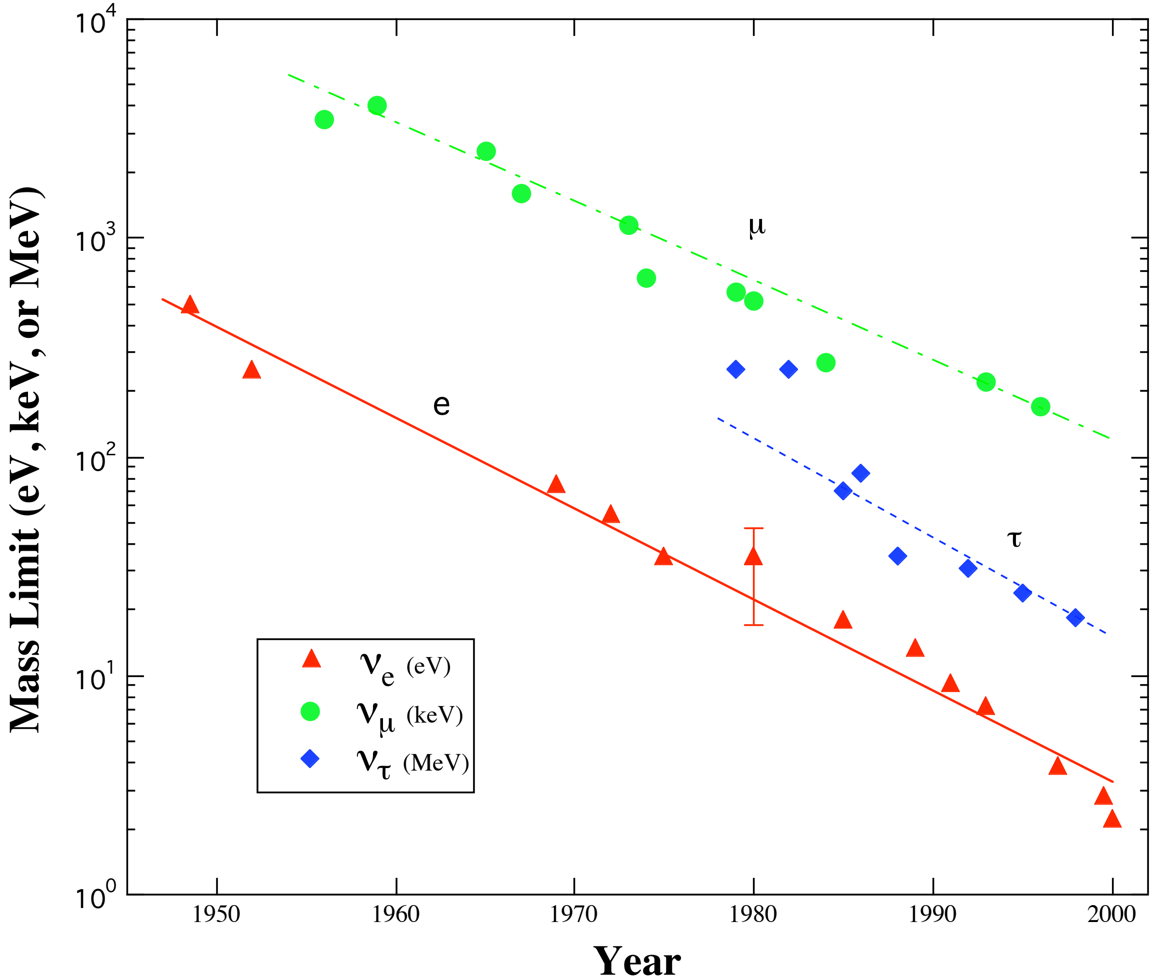
$m_{\nu_e} < 2.3$ eV (95% CL)

(Mainz 2004)

points without error bars represent upper limits

Past: history of direct ν mass measurements

In terms of flavor eigenstates



But ν oscillations with large mixing angles - requires one to consider direct techniques in terms of ν mass eigenstates!

points without error bars represent upper limits

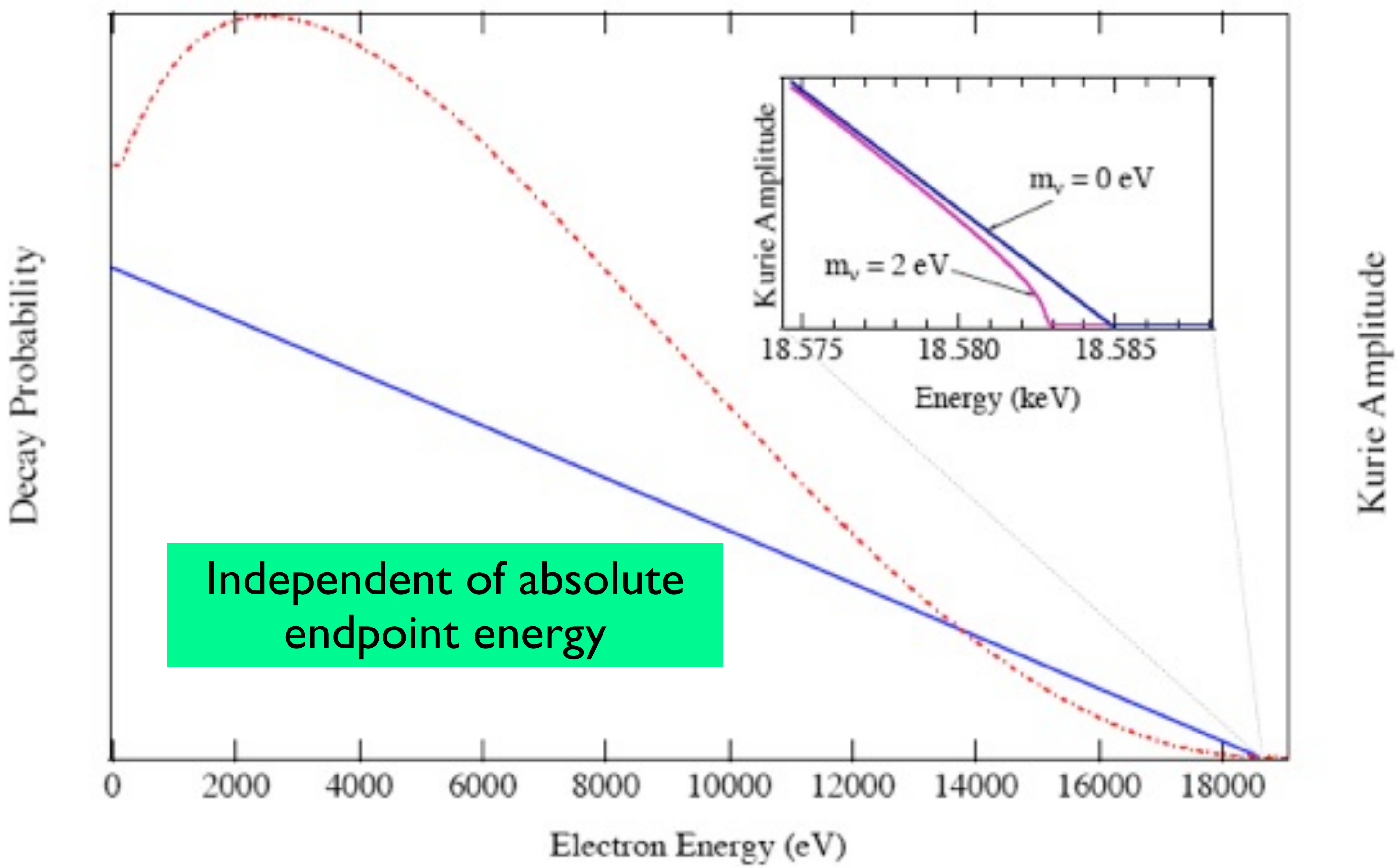
Direct kinematical measurement of neutrino mass

- model independent, purely kinematical observables
- direct probe of absolute mass scale
- independent of Majorana or Dirac nature of neutino
- independent of nuclear models (NME)
- measures superposition of mass eigenstates, but not dependent on phases (incoherent sum)
- With the large mixing angles and small energies (Q-value), β-decay is far and away the most sensitive technique

Using β-decay to measure neutrino mass

Simple Technique: measurement of spectrum shape at the endpoint.

$$\frac{dN}{dE} = |< l| < \nu_l|T|I >|^2 = \left|\sum_i U^*_{li} < l| < \nu_i|T|I >\right|^2 \propto p_e E(E-E_0)^2\left[1-\frac{m_\nu^2}{(E-E_0)^2}\right]^{1/2}$$



β-decay in terms of ν mass eigenstates

Taking into account ν mass eigenstates, the original spectrum

$$dN(E) = K|M|^2F(Z,R,E)\, p_e E\, (E_0-E)\, \{(E_0-E)^2-m^2_{\nu_e}c^4\}^{1/2}\, dE$$

becomes

$$dN(E) = K|M|^2F(Z,R,E)\, p_e E\, (E_0-E) \sum_i |U_{ei}|^2 \{(E_0-E)^2-m^2_{\nu_i}c^4\}^{1/2}\, dE$$

The observed beta spectrum shape depends on:

- the neutrino eigenstate masses
- the leptonic mixing matrix elements
- the resolution/response function of the measurement

For 3 ν mass spectrum, with quasi-degenerate states, the beta spectrum simplifies to an "effective mass" $m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2\right]^{\frac{1}{2}}$

Choosing a β-decay nucleus

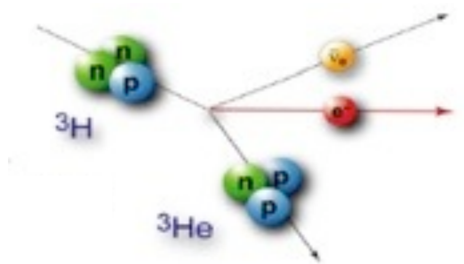
Measurement & Sensitivity Considerations:

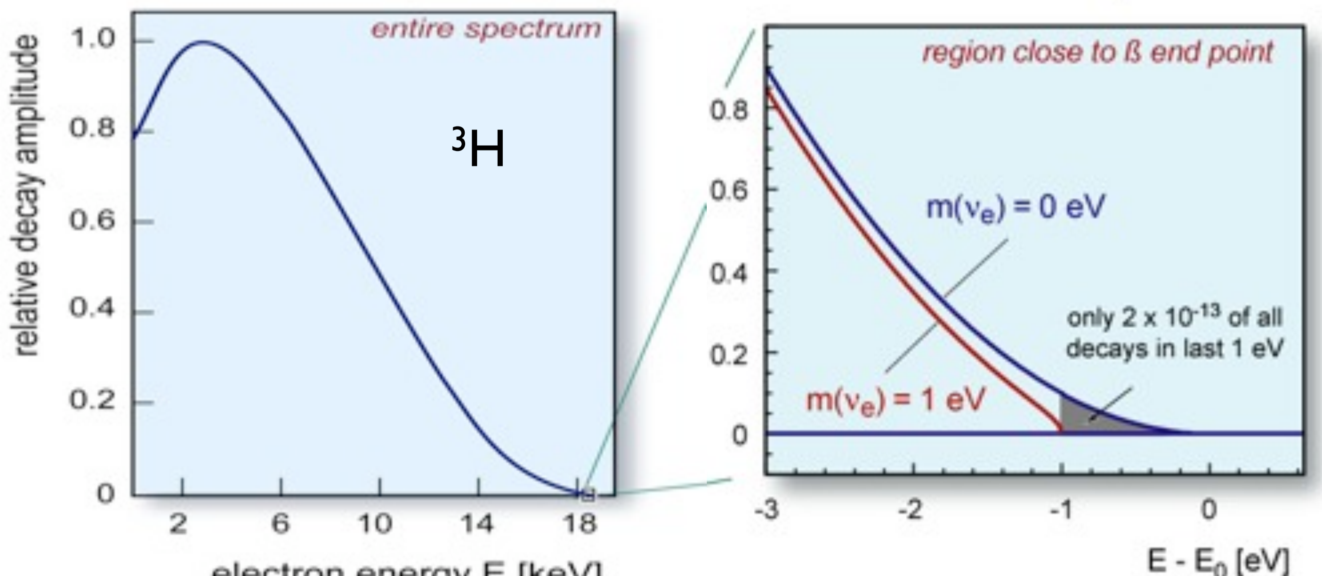
- Strong source
- Excellent energy resolution
  - Small endpoint energy E_0
- Long term stability (reasonable lifetime)
- Minimal systematics (energy loss, atomic states, ..)
- Low backgrounds

Most sensitive measurements have been done in ^3H, so will focus on these results

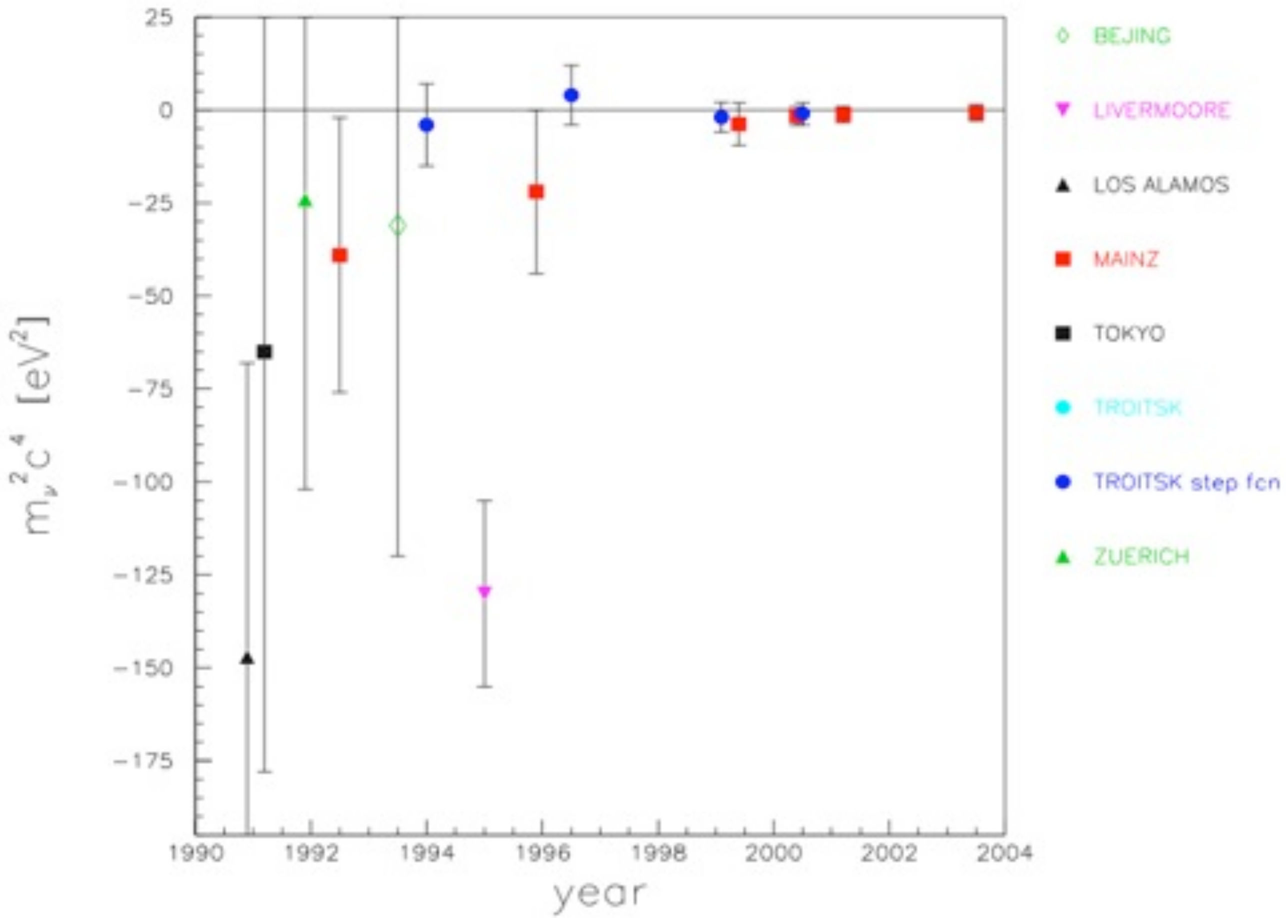
"Best" nuclei

- ^3H ($T_{1/2}$ = 12.3 y; E_o 18.6 keV; superallowed)
- ^{187}Re ($T_{1/2}$ = 4.3 10^{10} y; E_o 2.6 keV; first forbidden)



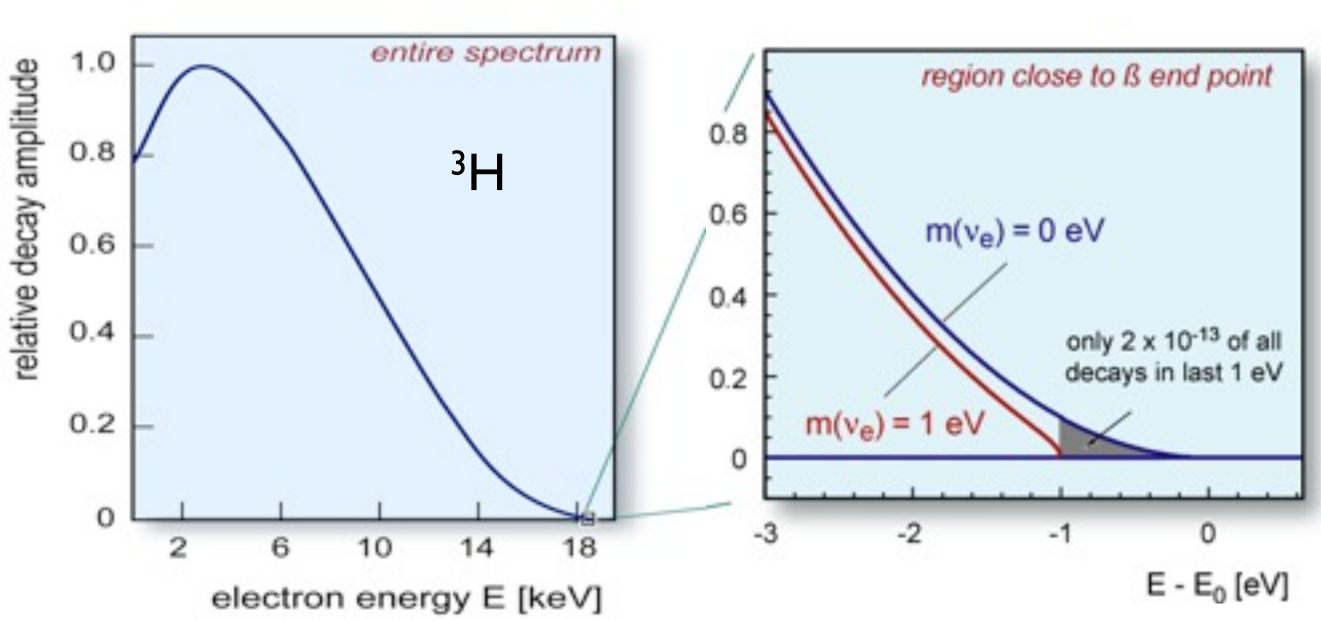


“Simple” technique - “Complex” results



Negative m_ν^2 ?

Negative mass² implies opposite spectrum curvature

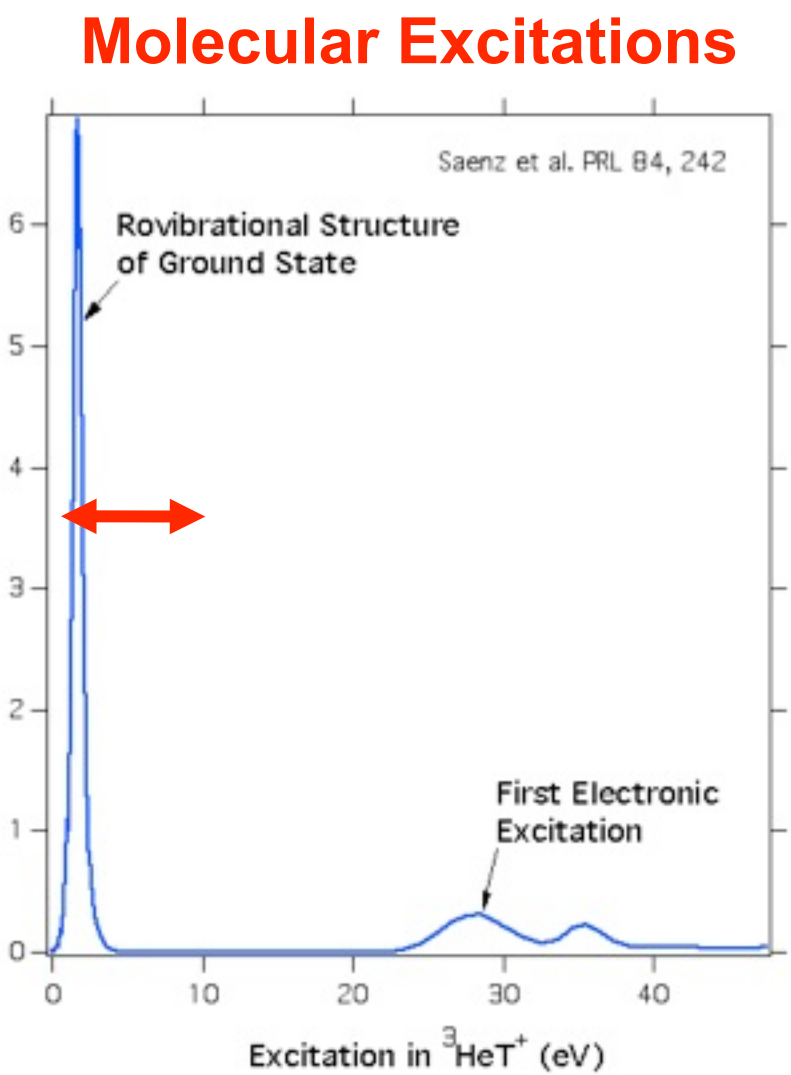


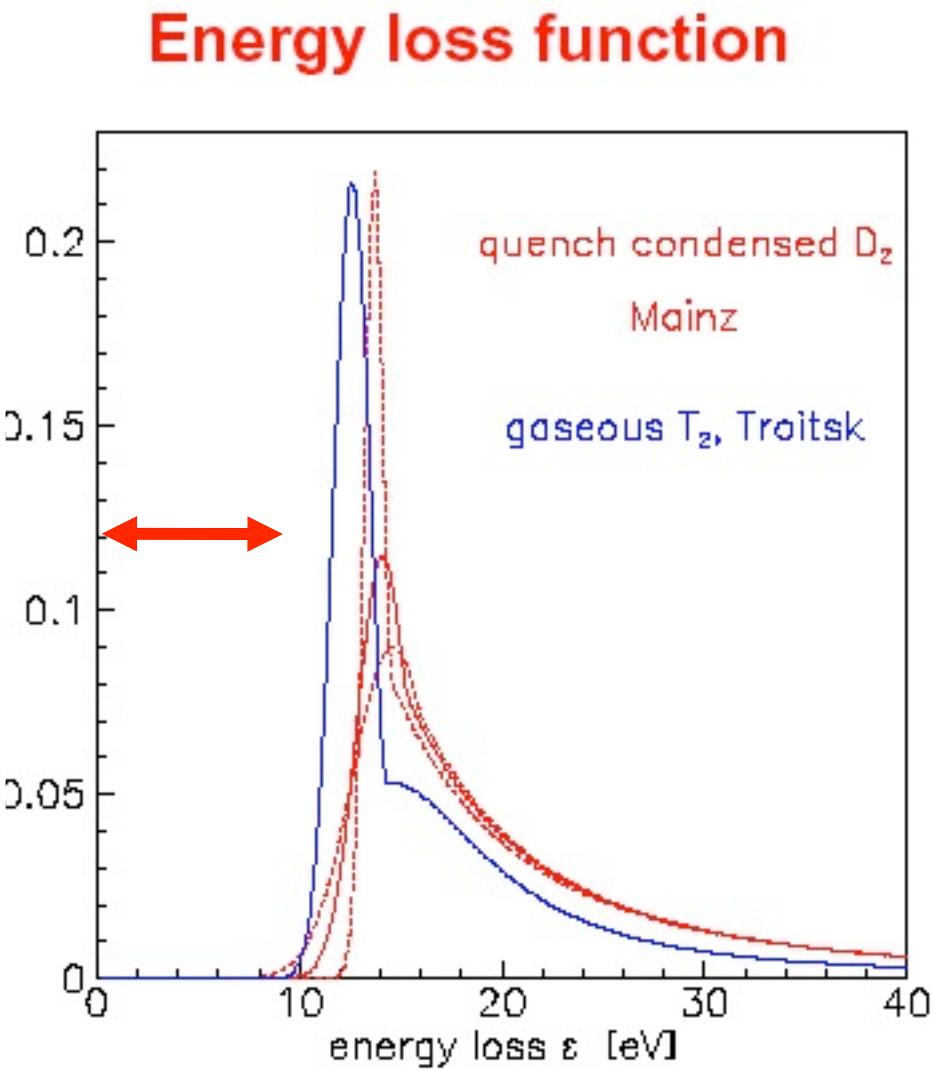
Must understand response function and all systematic effects

Keys to β-decay shape measurements

- **Statistics and uncertainty budget**
  - Only $2 \cdot 10^{-13}$ decays in last 1 eV below endpoint.
  - For 10 eV sensitivity, 100 eV^2, for 1 eV sensitivity, 1 eV^2
  - Must reduce backgrounds (~mHz) and ensure that they are very stable with time.
- **One must precisely eliminate or characterize all possible shape effects**
  - atomic final state effects
    - use atomic or molecular tritium source ($^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$)
    - utilize spectrum above atomic states (last 20 eV below endpoint)
  - energy loss shape effects
    - directly measure
    - use only no-loss portion of spectrum (last 9 eV below endpoint)
  - instrumental shape effects
    - direct measurements, using $^{83}Kr^m$
    - use integral spectrometers with very good resolution (~ eV)

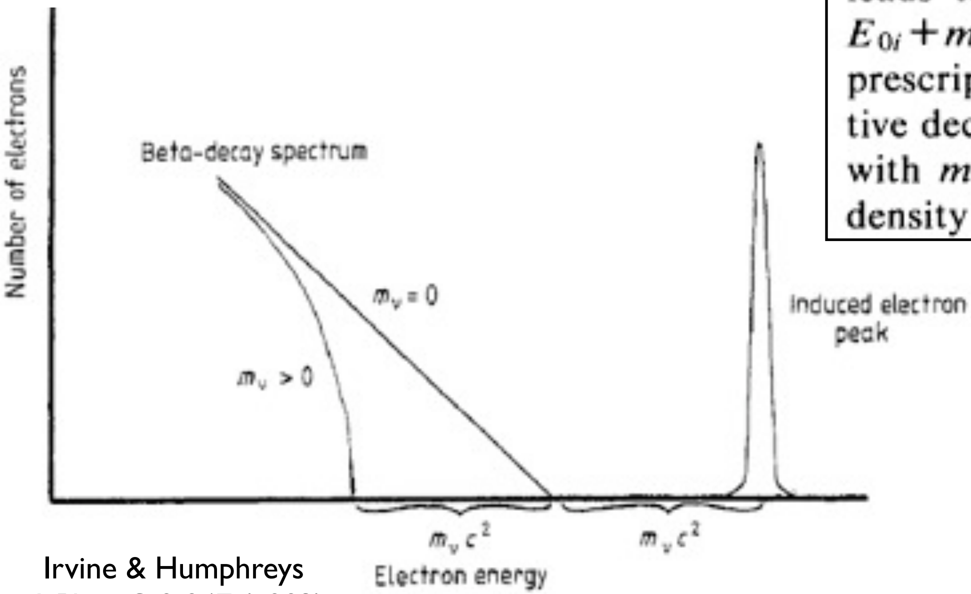
Quantum Mechanics helps





Searches for Relic neutrinos (see Formaggio talk)

$\nu_e + {}^3H \rightarrow {}^3He + e^-$



Irvine & Humphreys
, J. Phys. G 9 847 (1983)

Another possibility is capture of relic neutrinos, which leads to emission of monoenergetic electrons of energy $E_{0i} + m_\nu c^2$. Our data can be fitted well by such a prescription. The partial half-life of ^3H for such a putative decay branch is found to be $1.3\times 10^{10}/(1.0\pm 0.5)$ yr, with $m_\nu = 0$. Long though this is, it requires a neutrino density of order 10^{16} cm^{-3}, far above plausible estimates

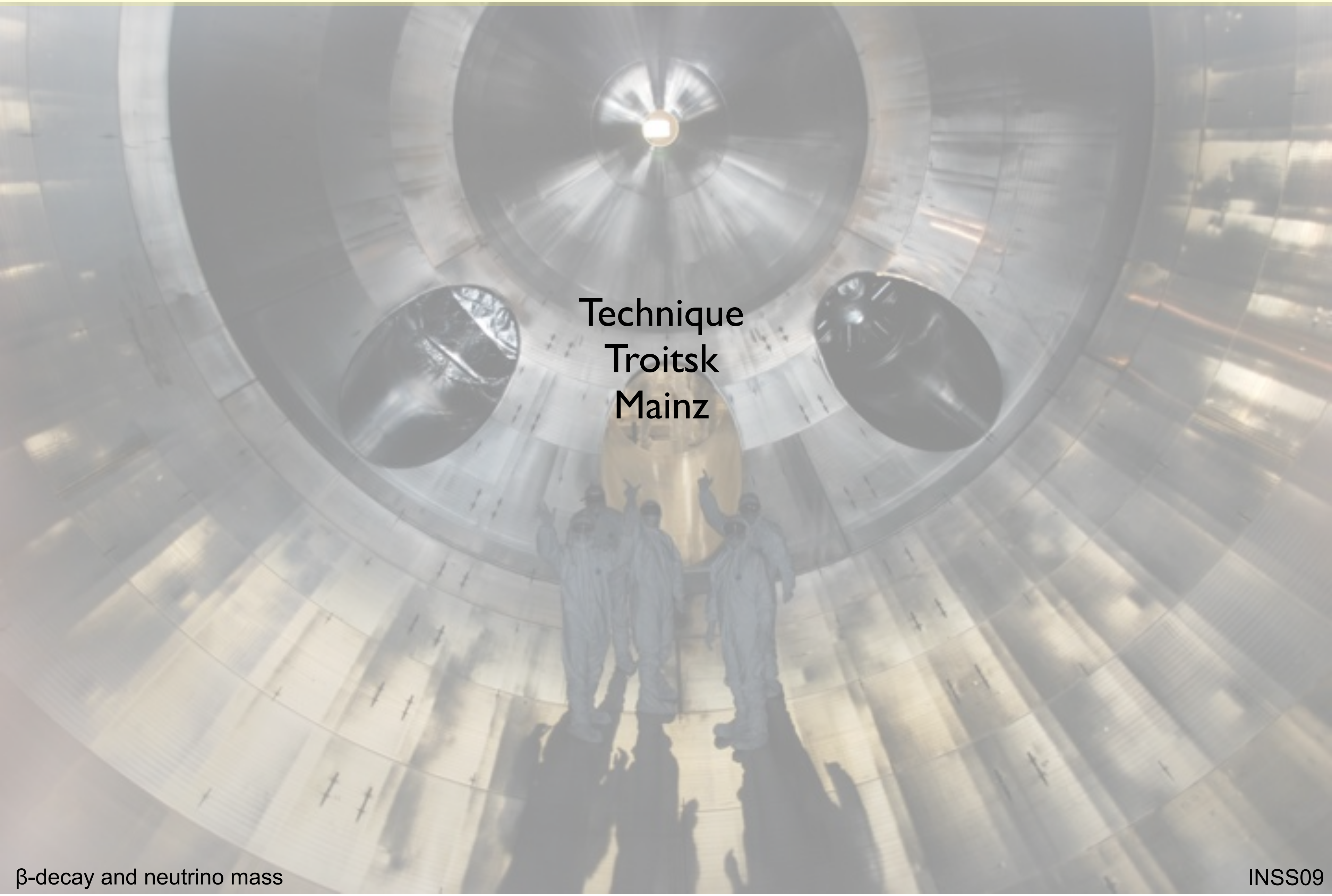
VOLUME 67, NUMBER 8 PHYSICAL REVIEW LETTERS 19 AUGUST 1991

Limit on $\bar{\nu}_e$ Mass from Observation of the β Decay of Molecular Tritium

R. G. H. Robertson, T. J. Bowles, G. J. Stephenson, Jr., D. L. Wark,[a] and J. F. Wilkerson
Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

D. A. Knapp
Physics Division, Lawrence Livermore National Laboratory, Livermore, California 94550

Recent Measurements



Technique
Troitsk
Mainz

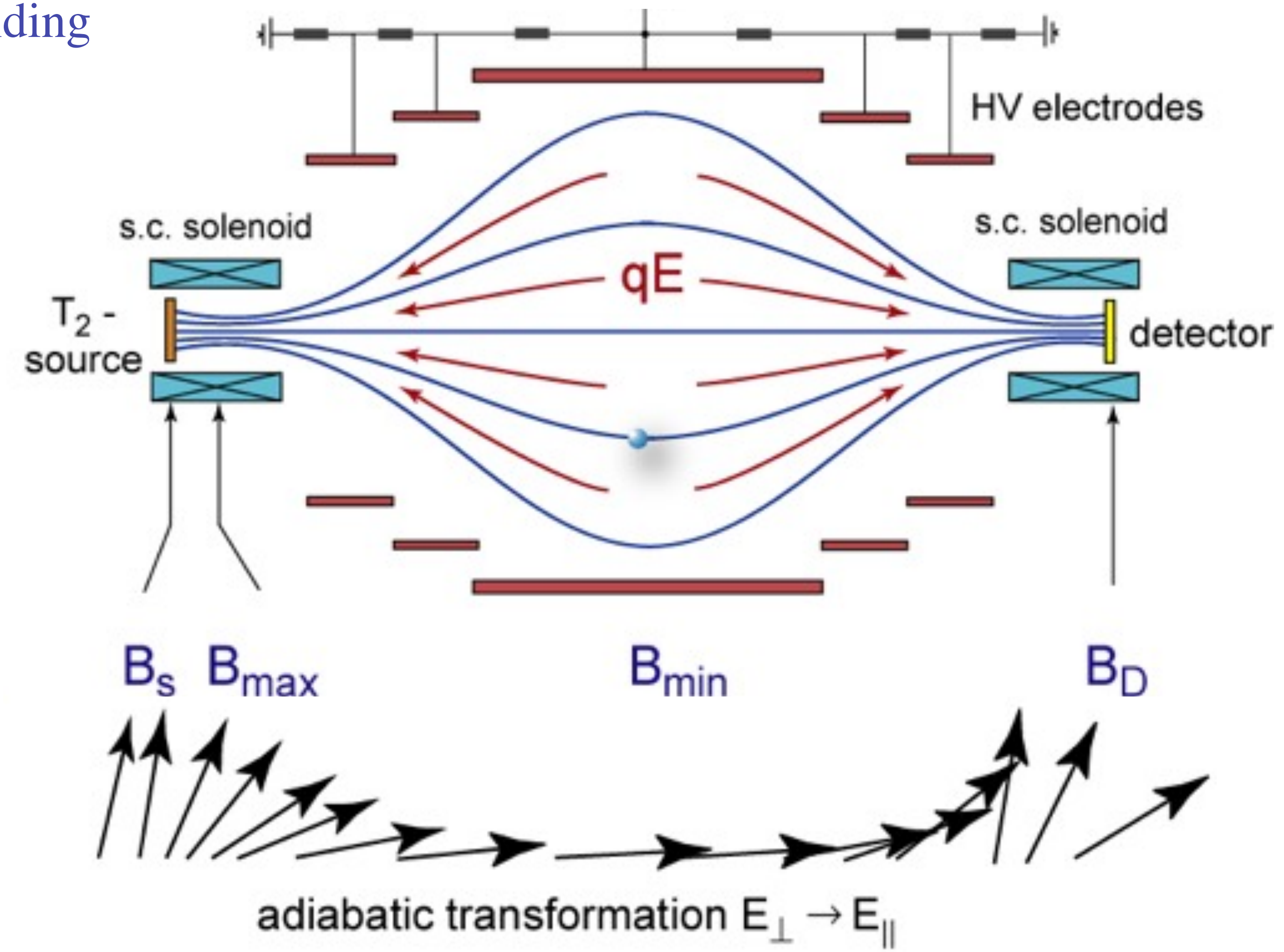
Principle of MAC-E Filter

Magnetic Adiabatic Collimation followed by an Electrostatic filter

Adiabatic magnetic guiding of β´s along field lines in stray B-field of s.c. solenoids:

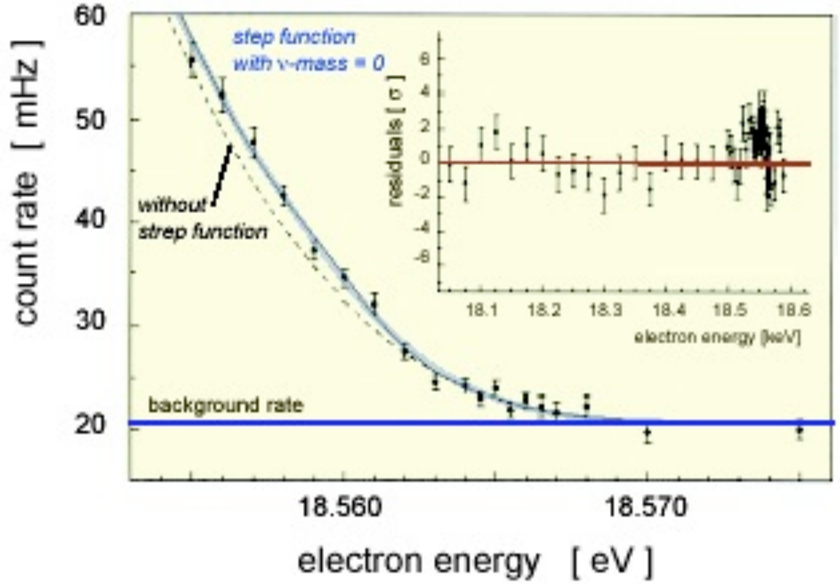
Energy analysis by static retarding E-field with varying strength:

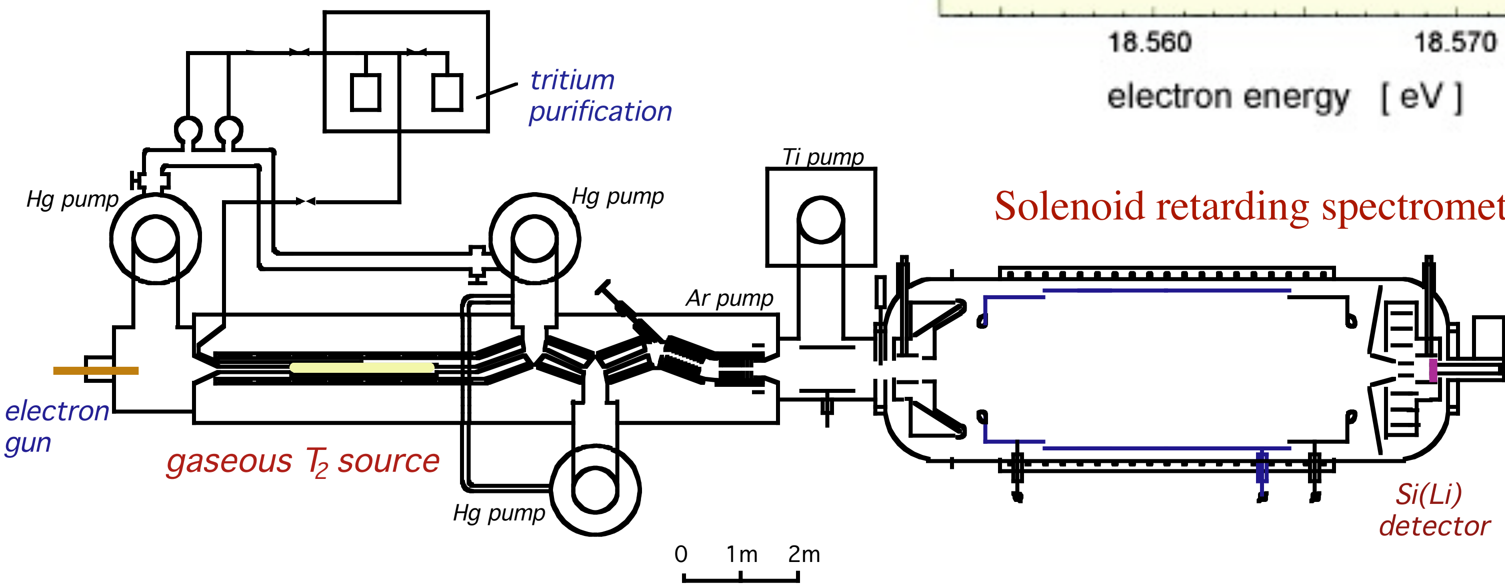
High pass filter with integral β transmission for E>qU



Troitsk tritium β-decay experiment

200 days of data since 1994

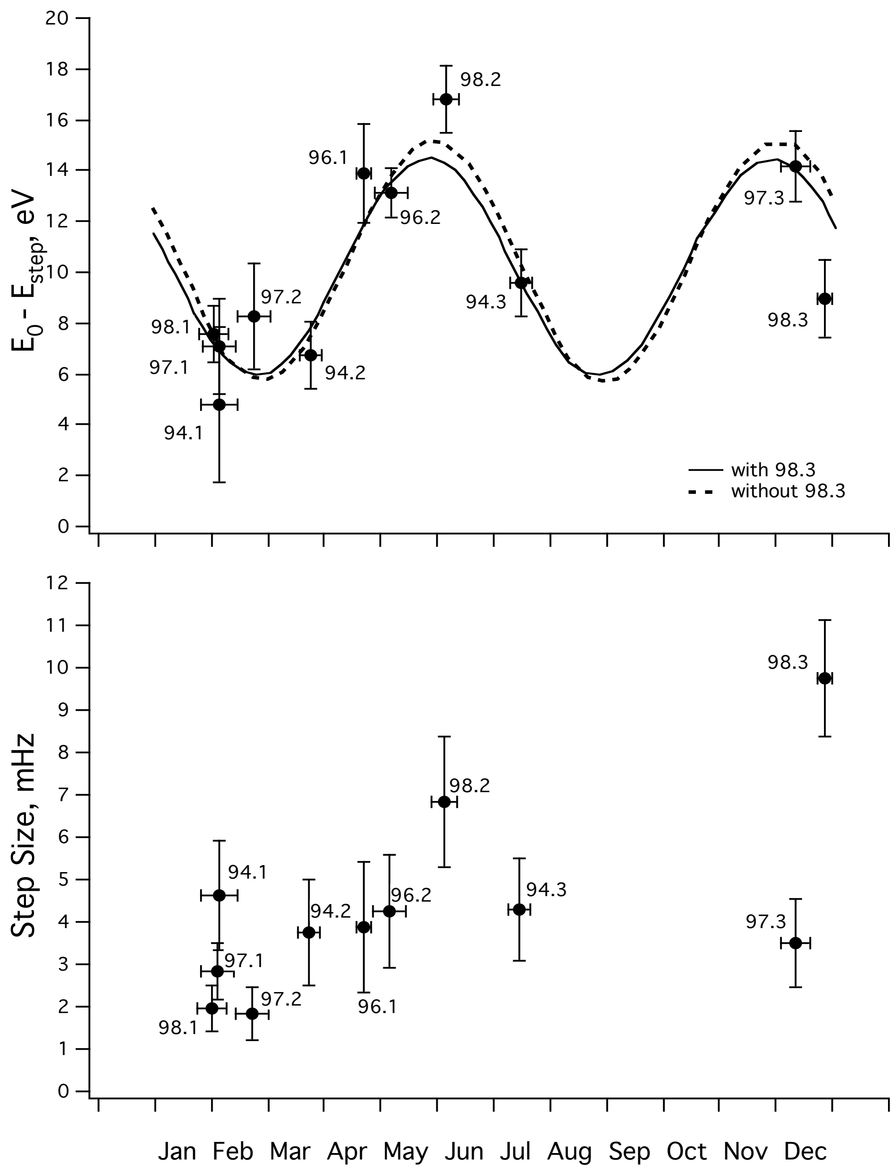




Solenoid retarding spectrometer

Troitsk Results

Claims there is a step function anomaly that varies in **both** amplitude and position above the endpoint.



It is not possible to have confidence in their reported limit

$m_\beta \leq 2.5$ eV (95%CL)

since it requires including the step function (excess counts)

Systematic problems

Step intensity ~ $6 \cdot 10^{-11}$ of total T_2 decay rate

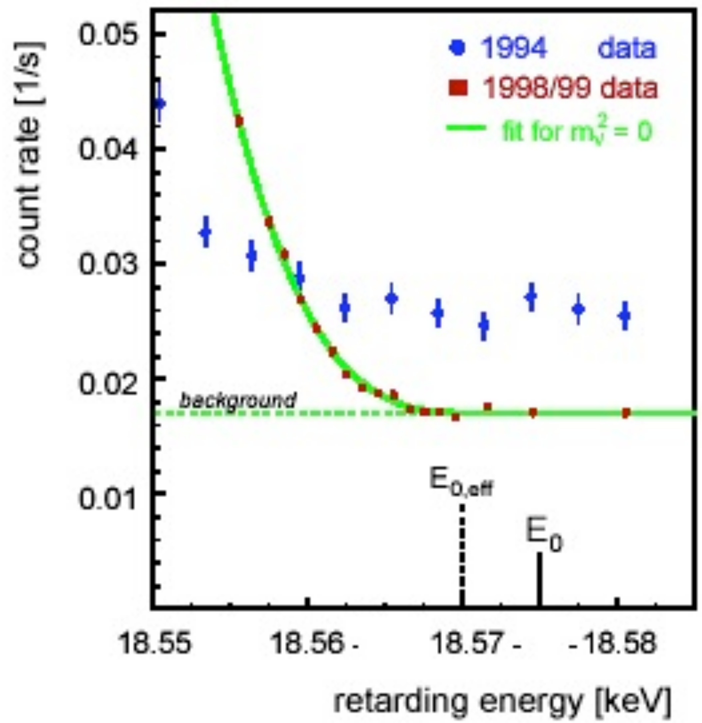
Lobashev et al., Phys. Lett. **B460** 227 (1999)

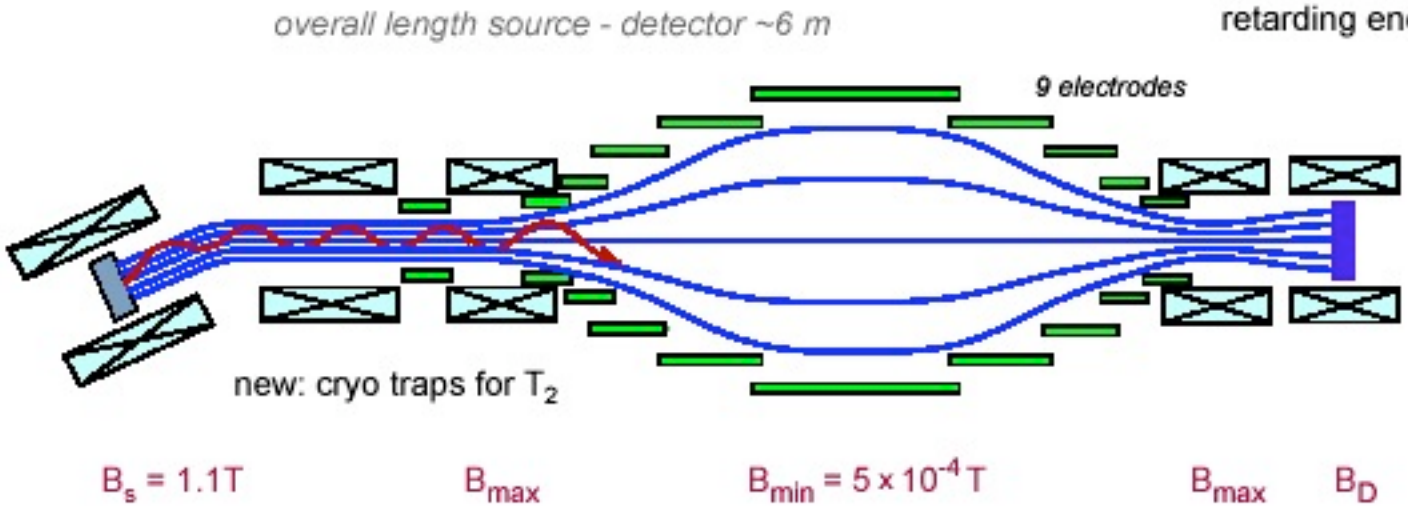
Mainz Neutrino Mass Experiment

Quench condensed solid T_2 source

Early results (94) showed systematic effects, traced to source film roughening transition. (fixed by lowering temperature)

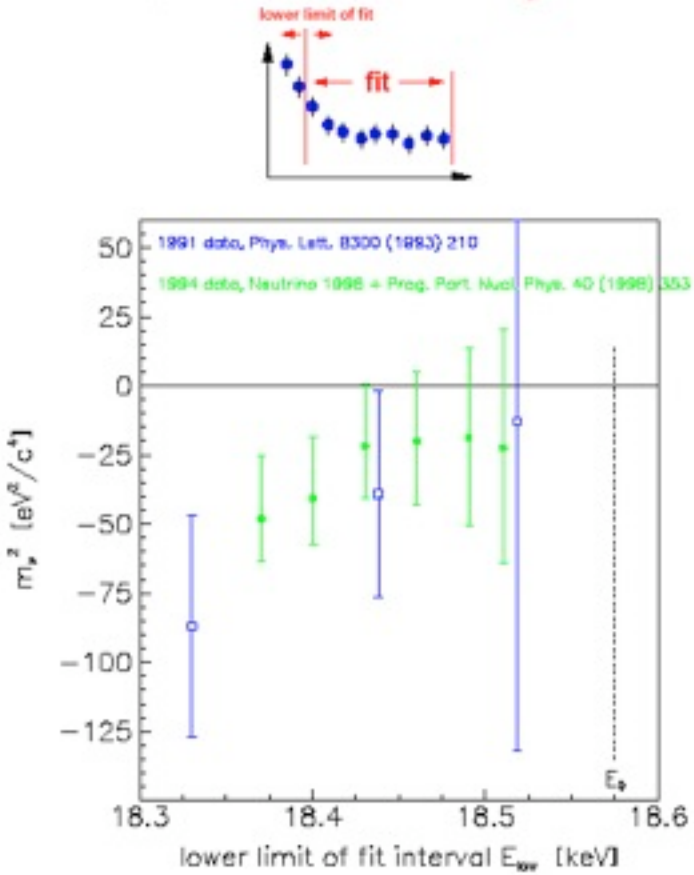
95-97 significant background reduction, signal improvement





Mainz Systematics Resolved

Former problem of negative m_ν^2 at Mainz



⇒ Problem of missing energy loss
was caused by roughening transition
⇒ should be solved by much lower T_2 temperatures

Data taking in 1998 and 1999

6 Runs (labelled Q3–Q8),
7 months measurement time in total:
(possible due to automation of apparatus)

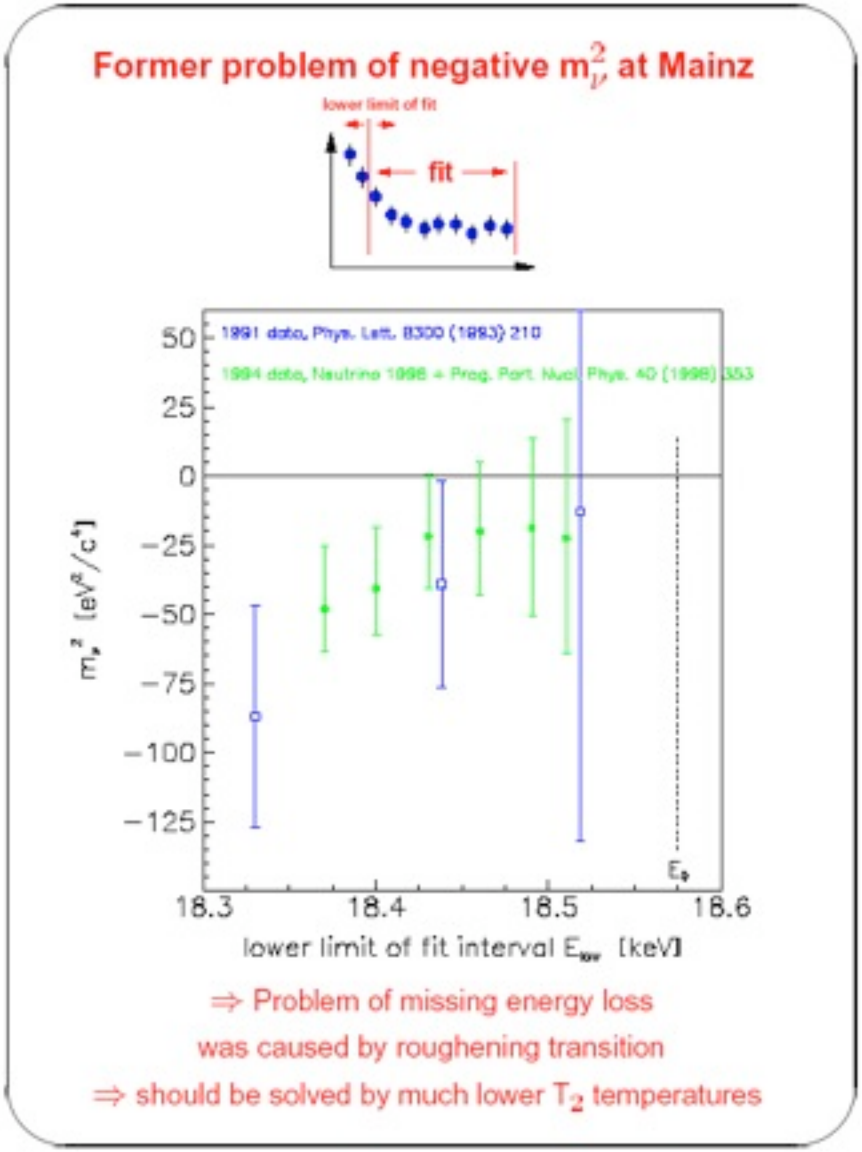
- Increasing of signal by a factor of 5
  Decreasing of background by a factor of 2
  → 10× better signal/background
- Lower T_2 film temperature: T = 1.86 K (instead of ≥ 3 K)

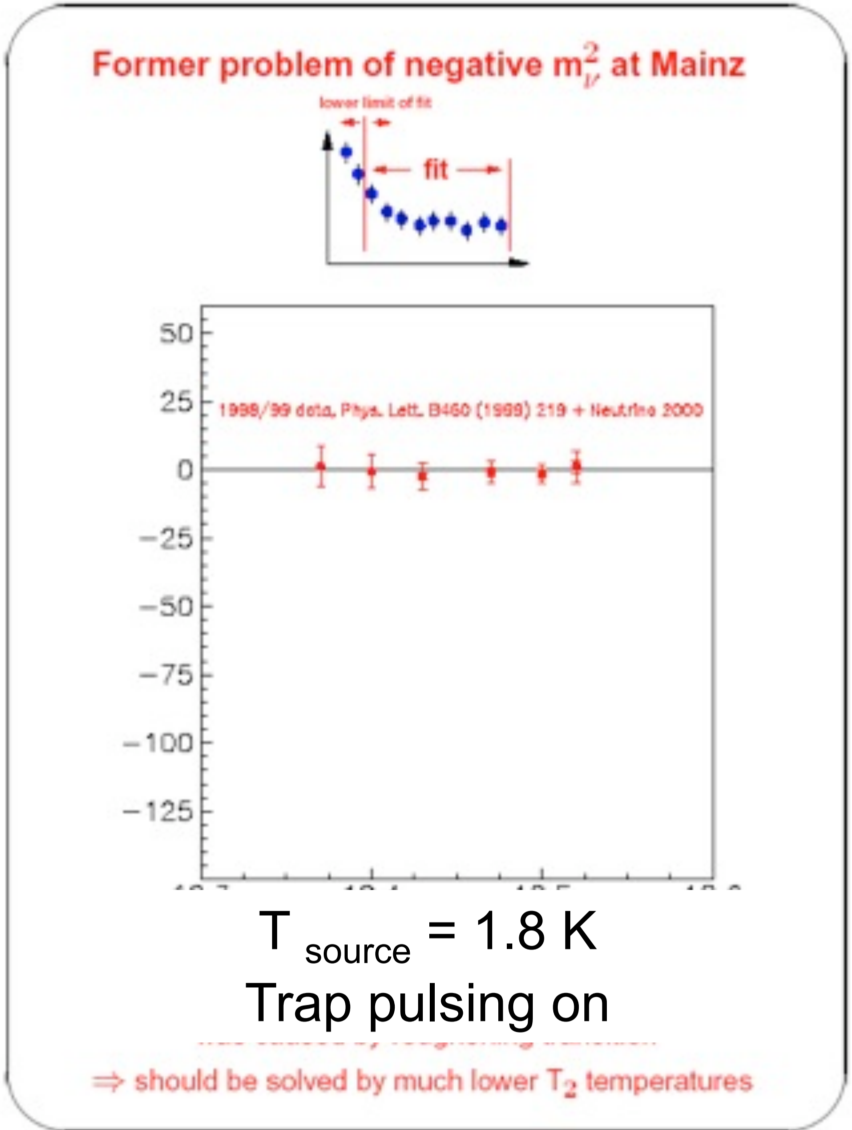
(larger energy losses)
(problems of 1991 and 1994)
(→ negative m_ν^2 value problem)

L. Fleischmann *et al.*, J. Low Temp Phys. **119** (2000) 615,
L. Fleischmann *et al.*, Eur. Phys. J. **B16** (2000) 521

- Better spectrometer resolution: ΔE = 4.8 eV
  (instead of 6.5 eV)
- More stable background:
  HF pulsing on electrodes inbetween measurements from Q5 on

Mainz Systematics Resolved





Mainz Results

Subsequent runs (Q5 and greater) exhibit good reduced χ^2 and are stable over a varying fit interval.

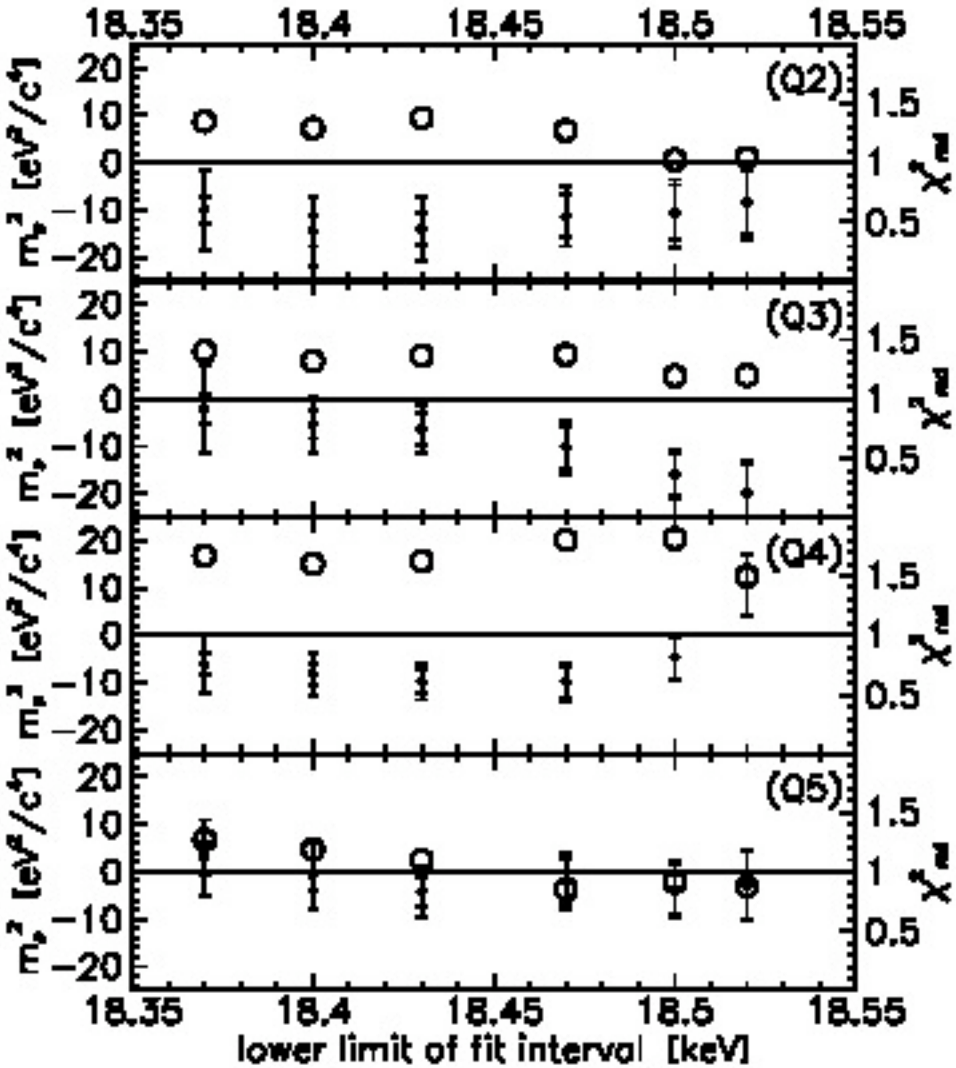
Change made to "sweep" spectrometer backgrounds between data points starting at run Q5.

Detailed studies published on source systematics.

$m_\beta^2 = -1.6 \pm 2.5 \pm 2.1\ \mathrm{eV}^2$

$m_\beta \leq 2.2$ eV (95%CL)

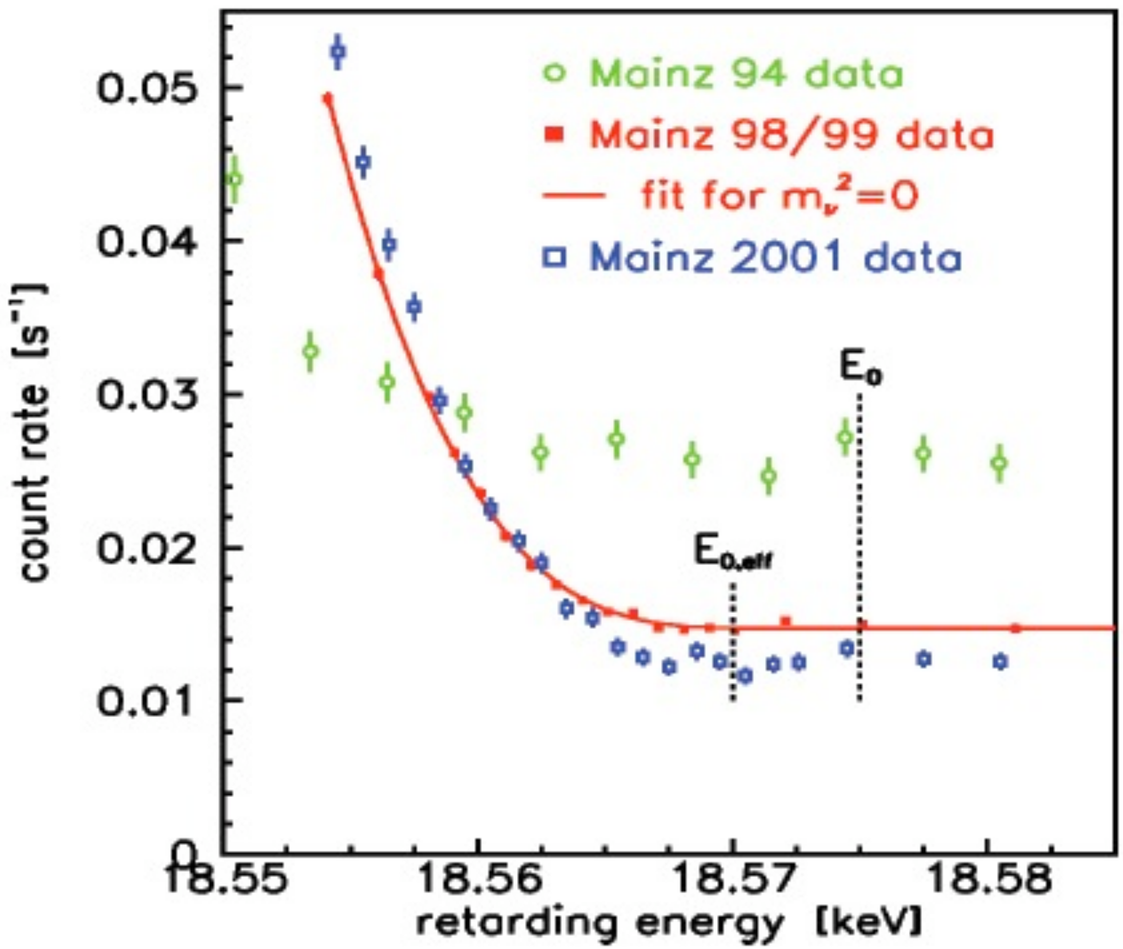
A solid result.



Weinheimer et al., Phys. Lett. **B460** 219 (1999)

Final Mainz Result

Kraus et al. hep-ex/0412056



Improved S/N tenfold over 1994 data

20 weeks of data in 1998, 1999, 2001

Stable background: pulsed RF clearing field applied at 20-s intervals

$$m^2(\nu_e) = (-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}})\ \text{eV}^2/\text{c}^4$$
$$\chi^2/\text{d.o.f.} = 208/194$$

$$m(\nu_e) < 2.3\ \text{eV}/\text{c}^2 \quad (95\%\ \text{C.L.})$$

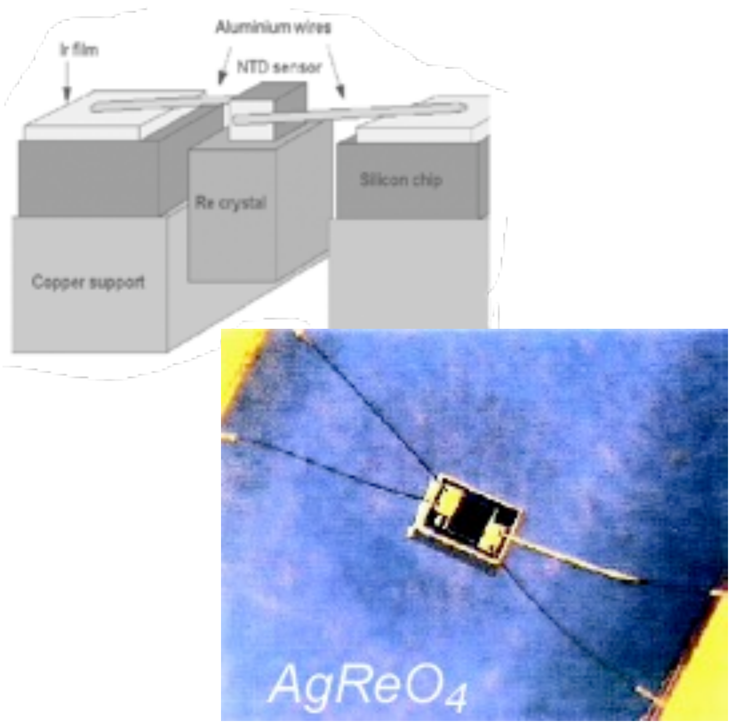
Next generation experiments

^{187}Re : MARE
^{3}H : KATRIN

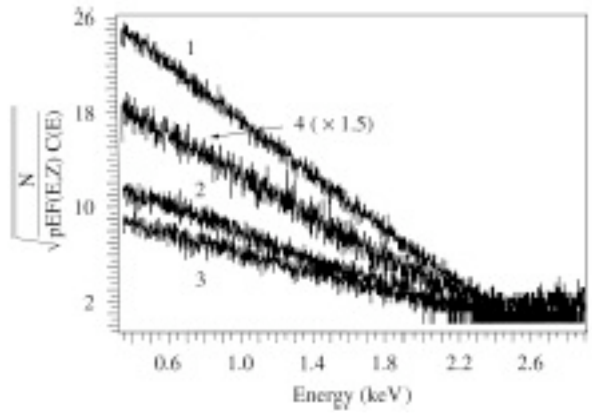
^{187}Re β-decay microbolometers

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

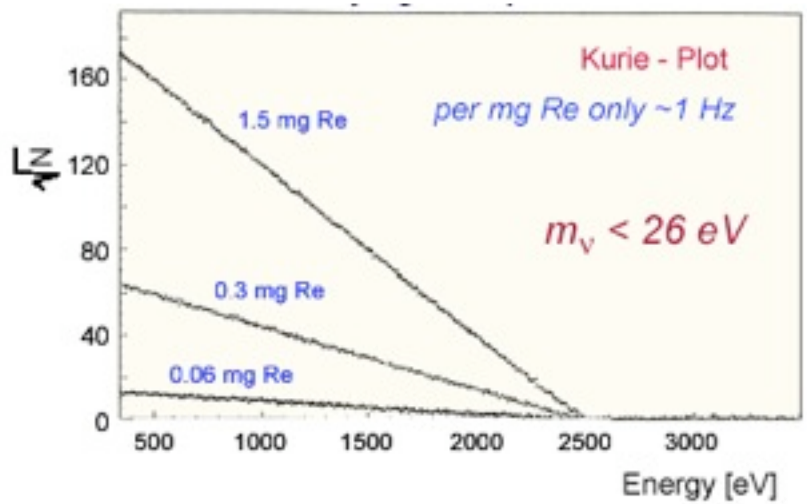
- lowest Q-value: 2.6 keV
- 63% abundance
- $5/2^+ \rightarrow 1/2^-$ first forbidden transition (requires shape correction)



MiBeta: Fiorini, INFN Milano - $AgReO_4$

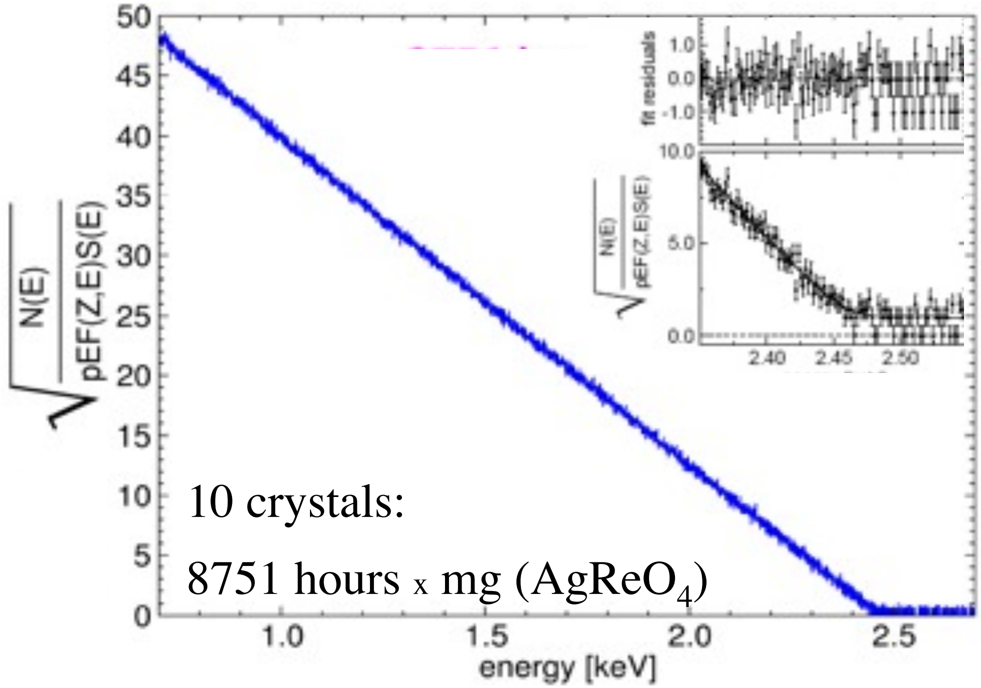


MANU2 Gatti, INFN Genoa - Re crystal



Microcalorimeter Array for a ^{187}Re Experiment (MARE)

MIBETA: Kurie plot of 6.2×10^6 ^{187}Re ß-decay events (E > 700 eV)



MANU2 (Genoa)
metallic Rhenium
m(ν) < 26 eV

Nucl. Phys. B (Proc.Suppl.) 91 (2001) 293

MIBETA (Milano)
$AgReO_4$
m(ν) < 15 eV

Nucl. Instr. Meth. 125 (2004) 125

$E_0 = (2465.3 \pm 0.5_{stat} \pm 1.6_{syst})$ eV

$m_\nu^2 = (-112 \pm 207 \pm 90)$ eV^2

MARE (Milano, Como, Genoa, Trento, US, D)
Phase I : m(ν) < 2.5 eV

300 detectors
ΔE ~10-20 eV
Statistics ~ 10^{10}

hep-ex/0509038

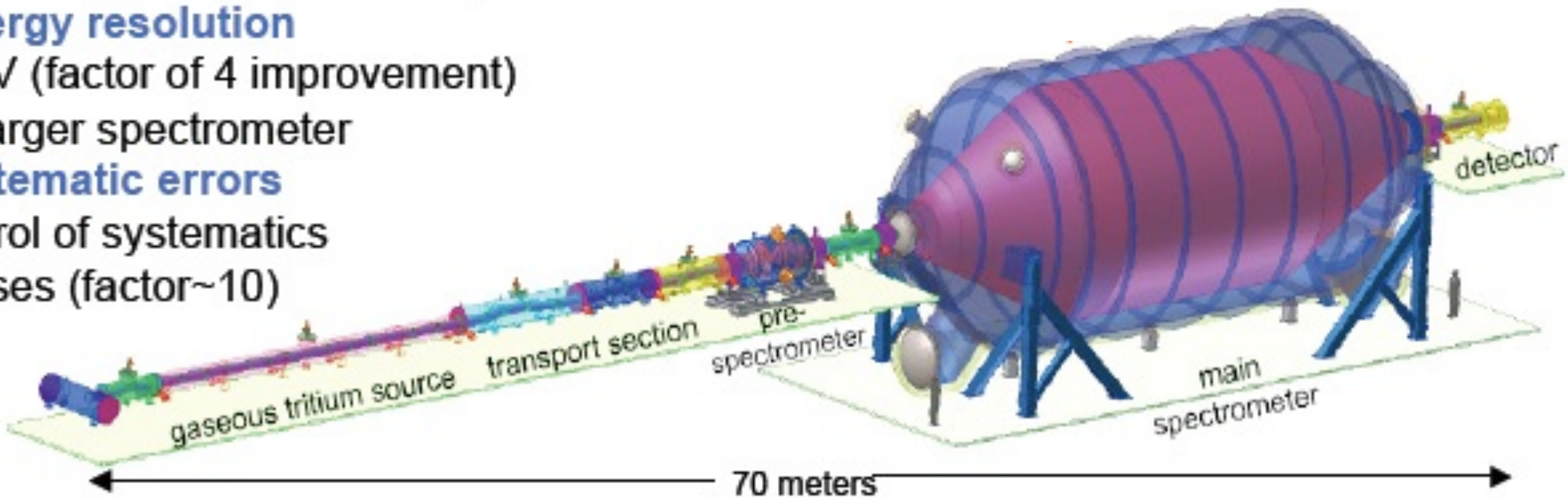
KArlsruhe TRItium Neutrino Experiment

Goal: Improve m_ν sensitivity tenfold
(2 eV $\rightarrow$ 0.2 eV)

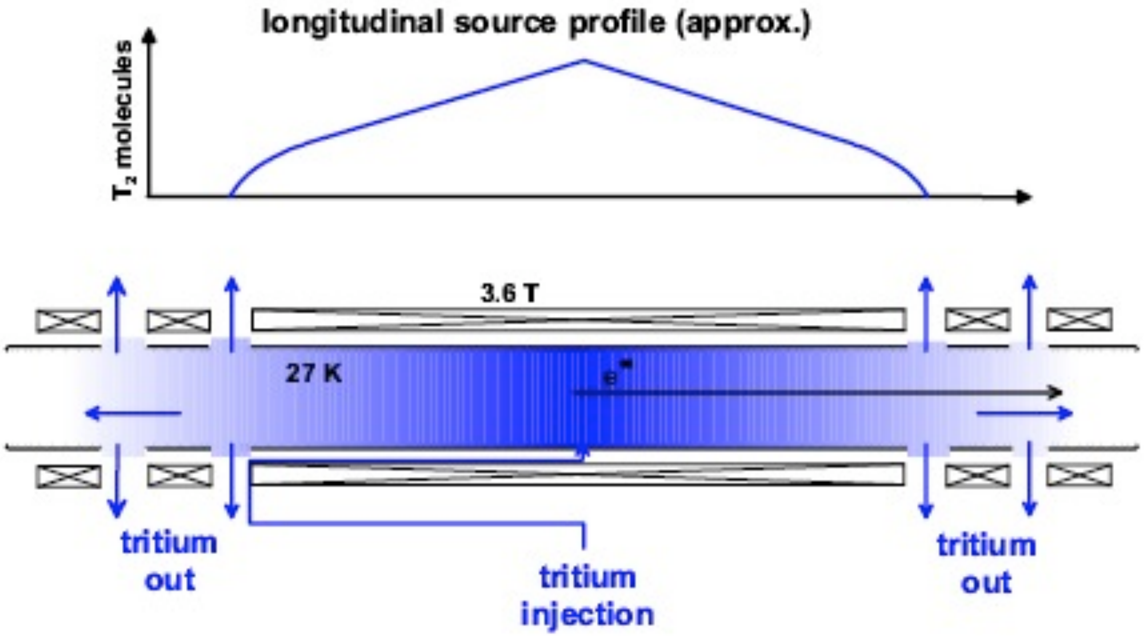
Improve Statistics
- stronger source (factor ~80)
- longer measuring period (factor ~10)

Improve energy resolution
- $\Delta E \cong 0.93$ eV (factor of 4 improvement)
- Requires larger spectrometer

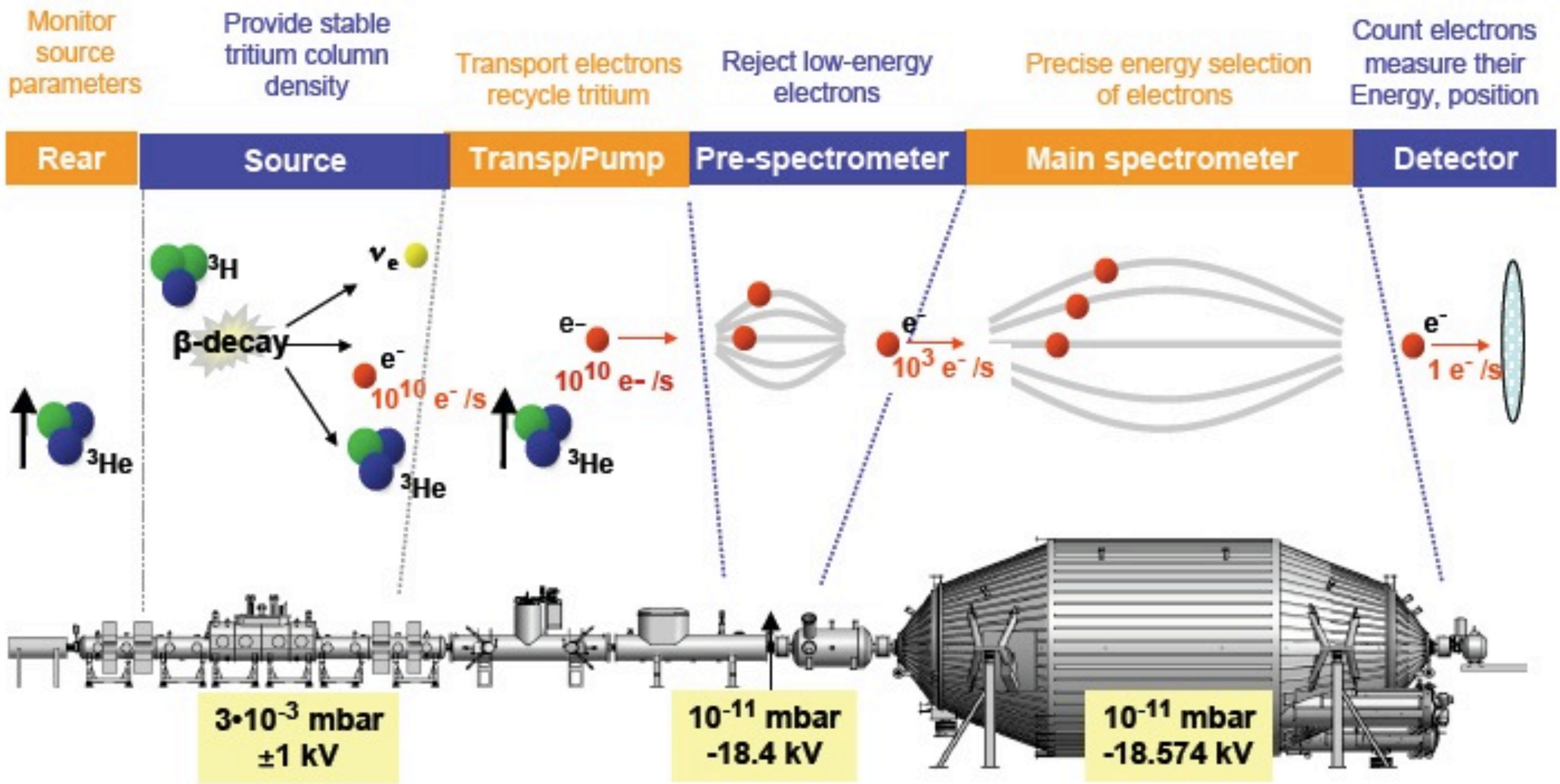
Reduce systematic errors
- better control of systematics
- energy losses (factor~10)



Windowless gaseous T_2 Source



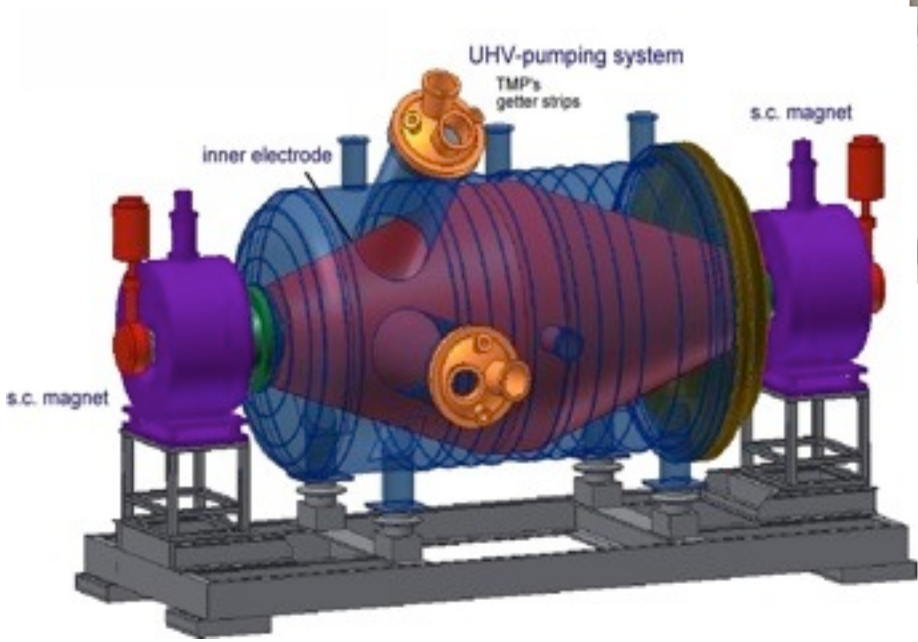
KATRIN Measurement System



Pre-spectrometer

Parameters:

- Length: 3.4 m (flange to flange)
- Diameter: 1.7 m
- Vacuum: < 10^{-11} mbar
- Material: Stainless steel
- Magnets: 4.5 T



Pre-spectrometer

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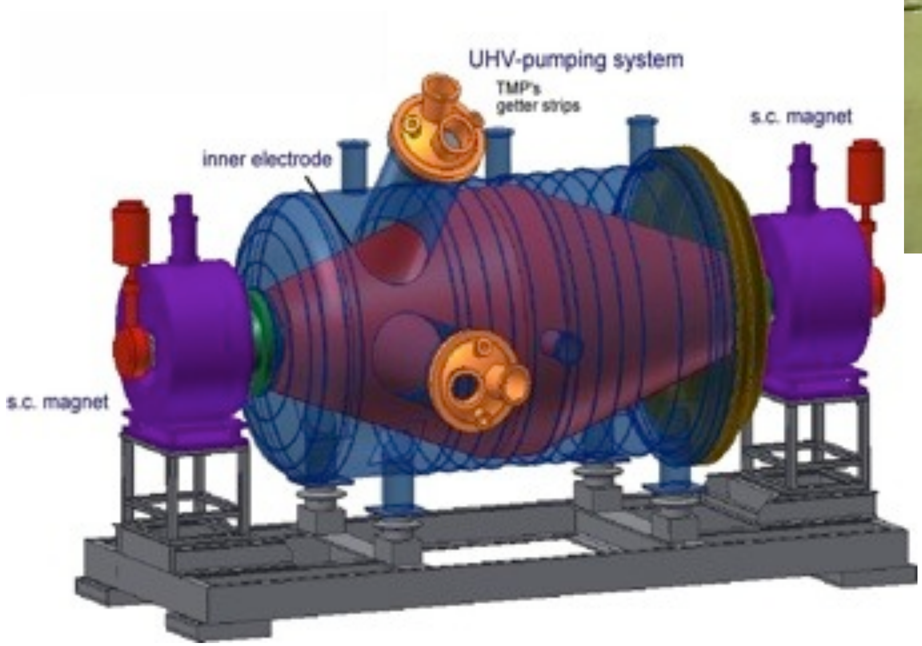


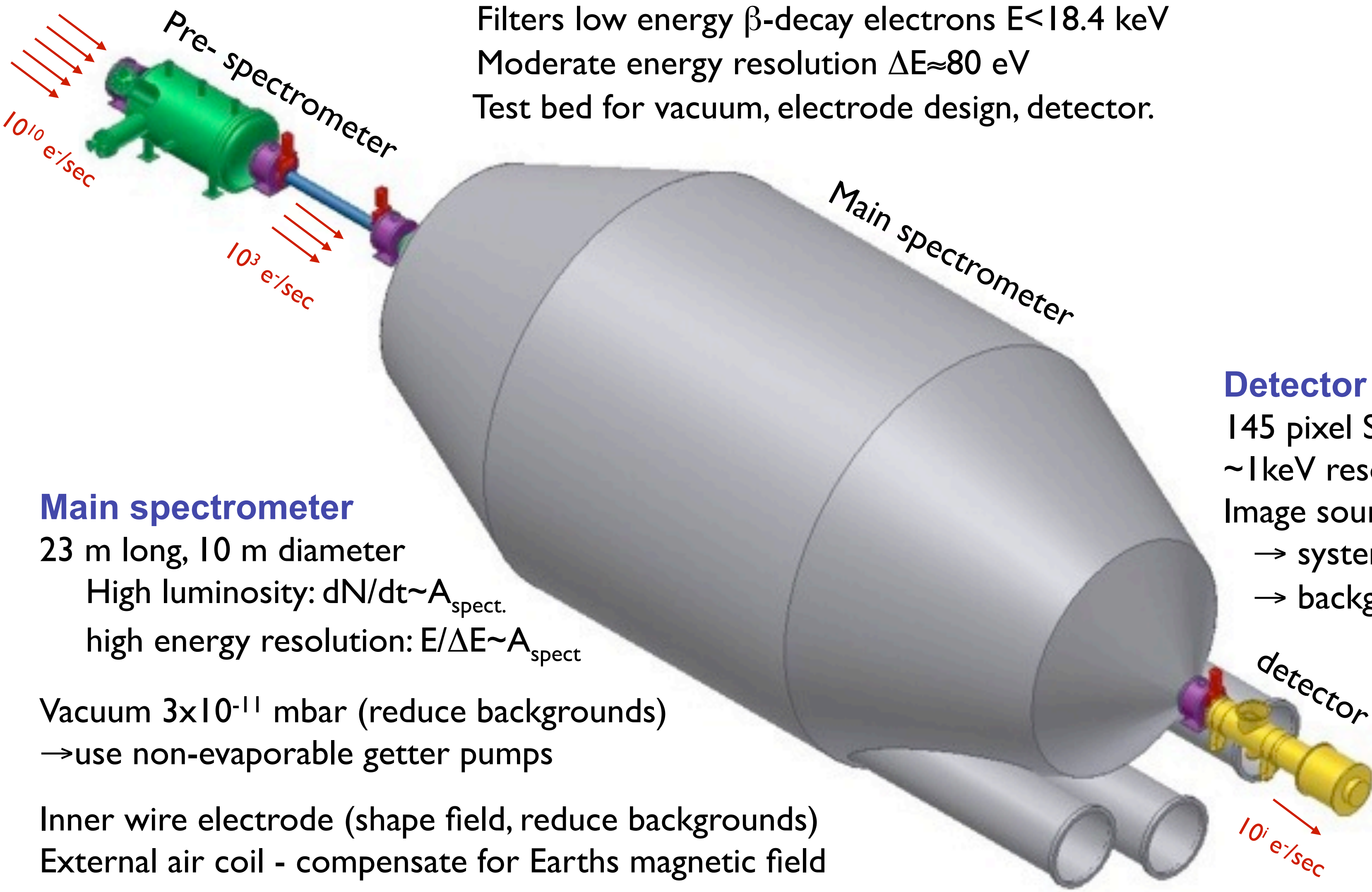
Status:

- •Vacuum $7 \cdot 10^{-11}$ mbar (without getter)
- •Outgassing $7 \cdot 10^{-14}$ mbar l/ s cm^2
- •Measurements in progress

Tandem design: -- Pre-filter, Energy analysis

Pre-spectrometer

Filters low energy β-decay electrons E<18.4 keV
Moderate energy resolution ΔE≈80 eV
Test bed for vacuum, electrode design, detector.



Detector

145 pixel Si PIN diode
~1keV resolution
Image source
→ systematics
→ backgrounds

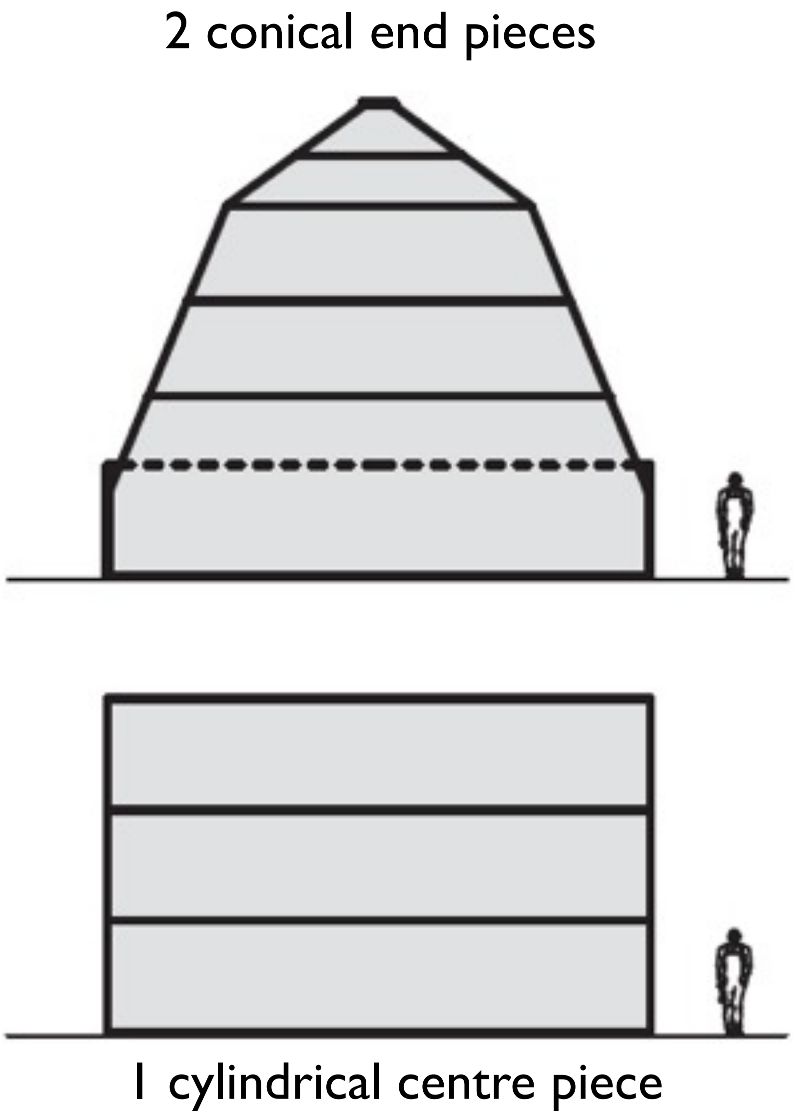
Main spectrometer

23 m long, 10 m diameter
High luminosity: $dN/dt \sim A_{spect.}$
high energy resolution: $E/\Delta E \sim A_{spect}$

Vacuum 3×10^{-11} mbar (reduce backgrounds)
→use non-evaporable getter pumps

Inner wire electrode (shape field, reduce backgrounds)
External air coil - compensate for Earths magnetic field

Main Spectrometer Manufacture



Extreme Voyage of the main spectrometer

Wednesday, July 15, 2009

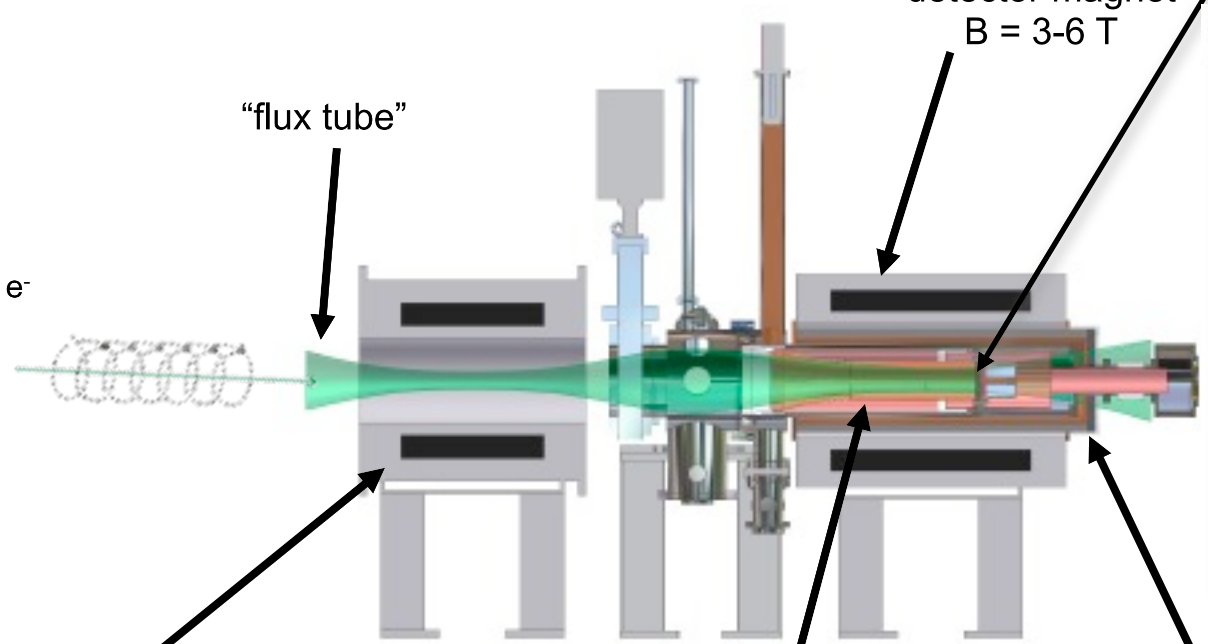
Arrival in Leopoldshafen: Nov. 2006

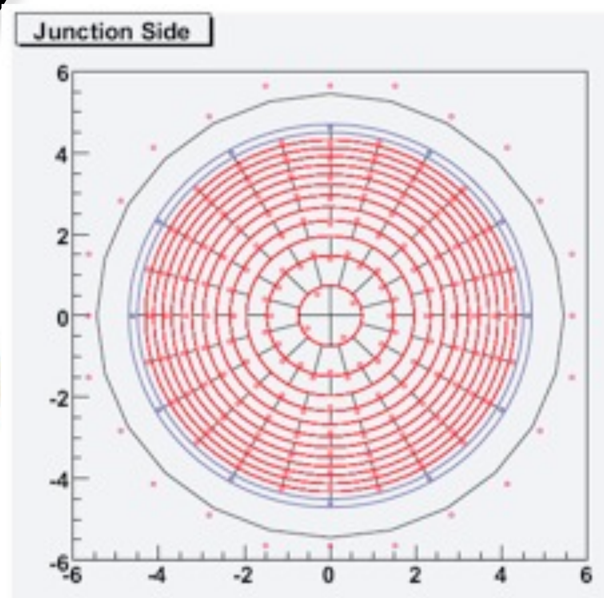
The view from the inside

The Focal Plane Detector

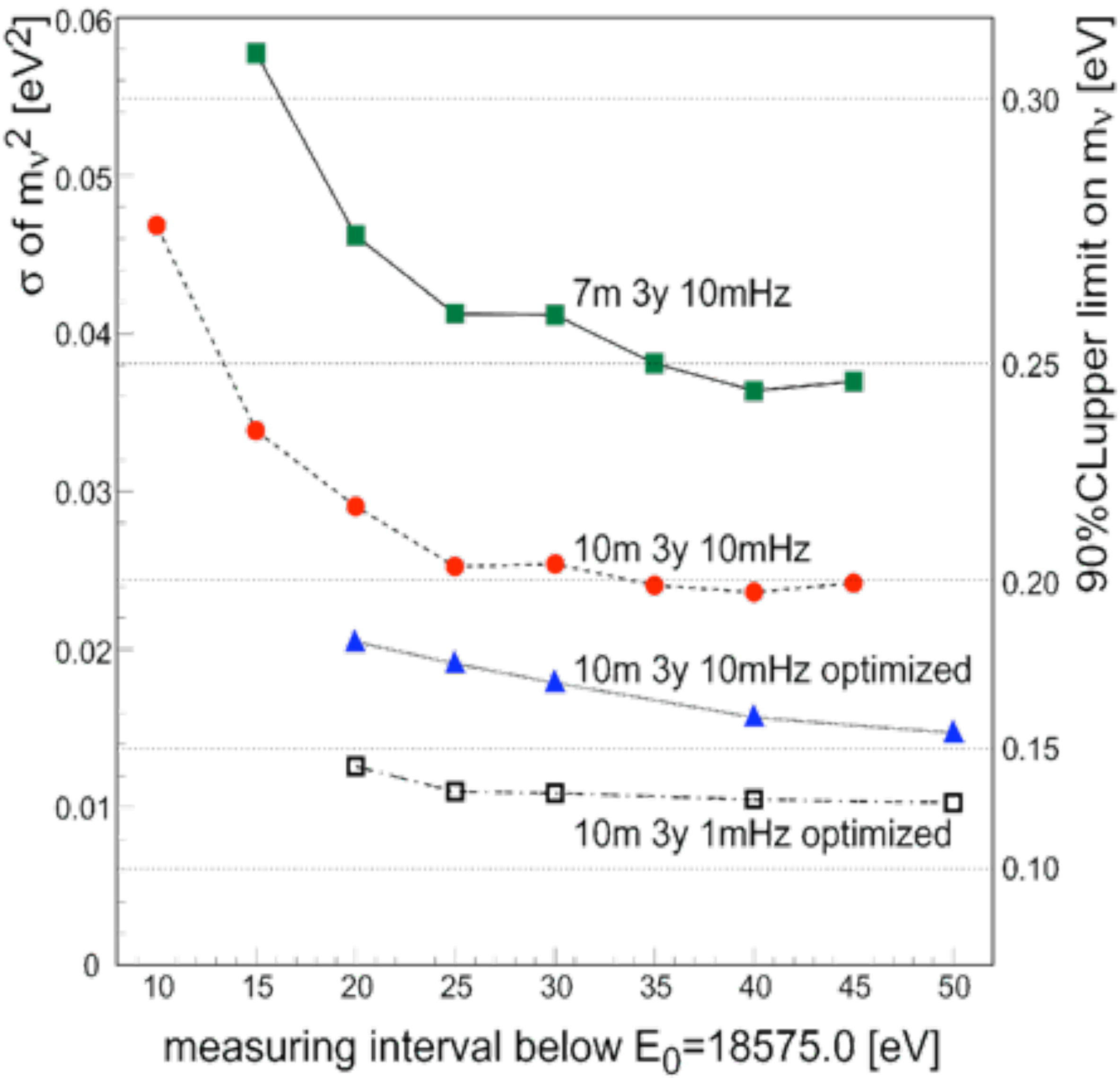
Silicon PIN diode detector

- 9 cm active diameter
- 500 μm thick
- 148 segments





KATRIN Statistical Sensitivity



- Improved over original design (7 m diameter main spectrometer, source luminosity)
- Reduction in background
- Only shows statistical uncertainty

KATRIN Status

- KATRIN can measure neutrino mass directly via kinematics of beta decay -- model independent
- Improvement of order of magnitude over previous best
- Challenging goal of $m_\nu < 0.2$ eV (90% C.L.) looks achievable
  - Focal Plane detector will be shipped to Karlsruhe mid 2010.
  - Pre-spectrometer measurements and characterization complete.
  - Main spectrometer commissioning will start in 2010.
- Full system data taking late 2012

Longer term possibilities

Aside on relic neutrino searches

New schemes (See Formaggio Talk)

- Decay of ^{187}Re ($Q = 2.47$ keV) observed in bolometers.
  - For 20 meV, need 13 T of Re or 20 mg of ^3H.

- Atomic T in a trap, full kinematic reconstruction: arXiv0901:3111
  - For 200 meV, need 1,000's of separate sources.

- Decay of radioactive ions in a storage ring at a specific momentum: arXiv 0904:1089
  - For 200 meV, need $10^{18} – 10^{20}$ decays in beam.

- Detection of RF cyclotron radiation from β orbiting in B-field: arXiv 0904:2860
  - Needs further consideration, might be feasible.

R.G.H. Robertson