Weighing neutrinos: EXO & double beta decay

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Enriched Xenon Observatory for double beta decay

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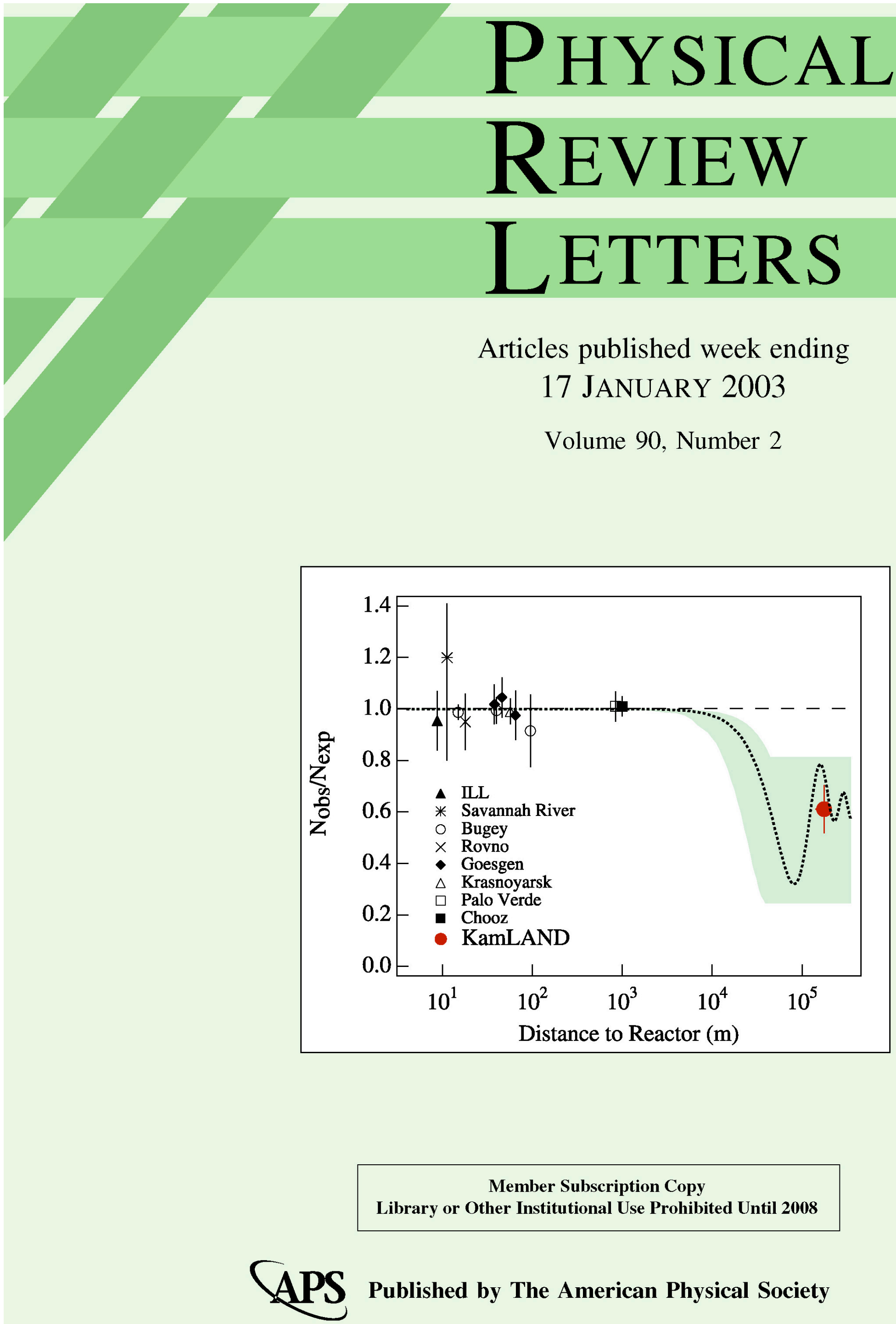
General Outline

- Massive neutrinos
  - Neutrino oscillations
  - Double beta decay
  - State of the art
- The EXO experiment
  - Proposal
  - Expected sensitivities
- Current R&D
  - Ion spectroscopy
  - Liquid xenon resolution
  - Prototype design and construction



Oscillations observed in reactor ν's

KamLAND antineutrino spectrum rate *and* shape

Confirms LMA solar neutrino solution in anti-neutrino sector

K.Eguchi et al., Phys. Rev. Lett. 90 (2003) 021802

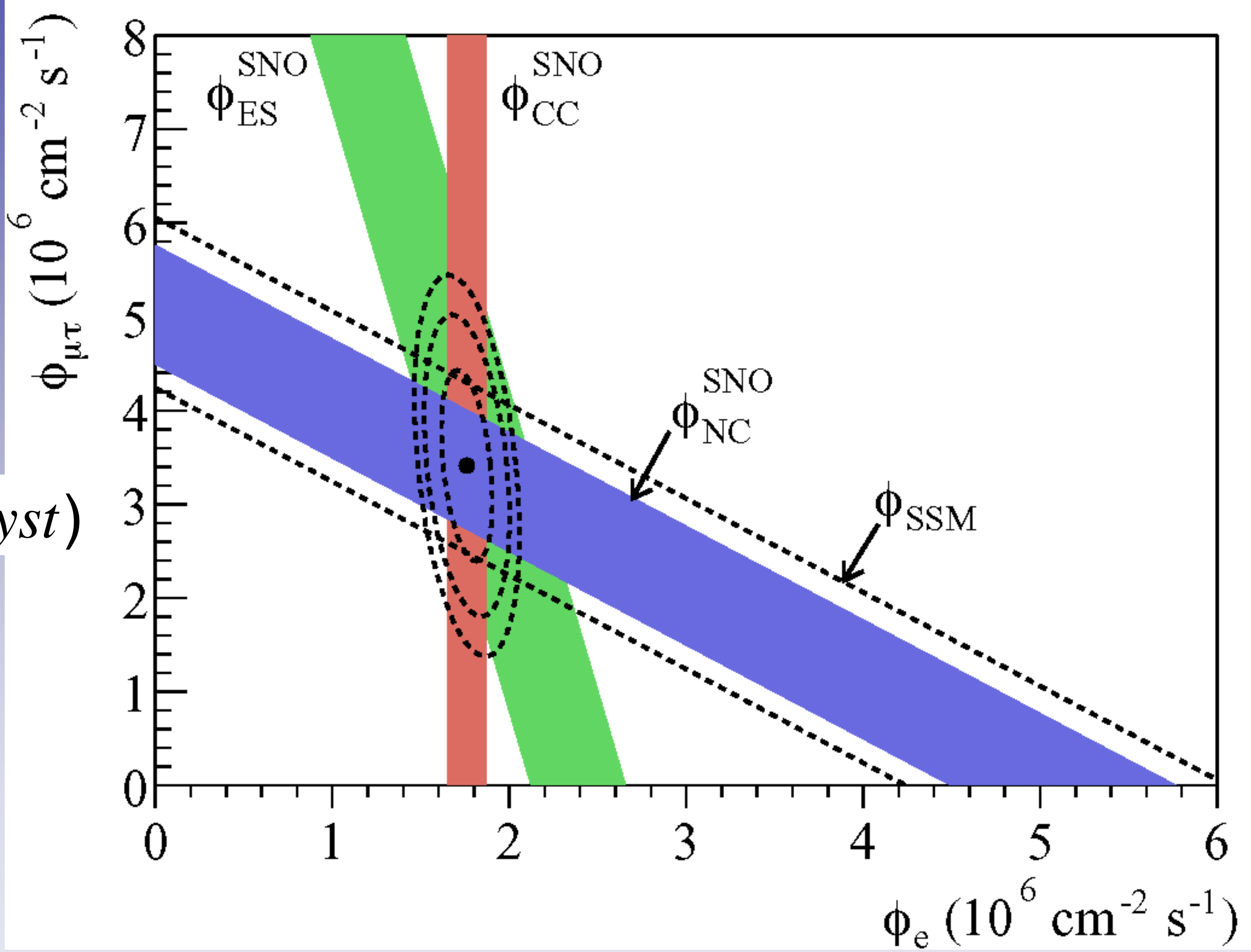
SNO measurement of ν flux

ν flux =

$5.21^{+0.27}_{-0.27}(stat)^{+0.36}_{-0.38}(syst)$

(nucl-ex/0309004)

solar ν_e are missing, but the total number of neutrinos is right



Phys. Rev.Lett. 89 (2002) 011301

Two-flavor ν oscillations

If flavor eigenstates are not mass eigenstates, oscillations are possible:

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{1.3\Delta m^2 L}{E}$$

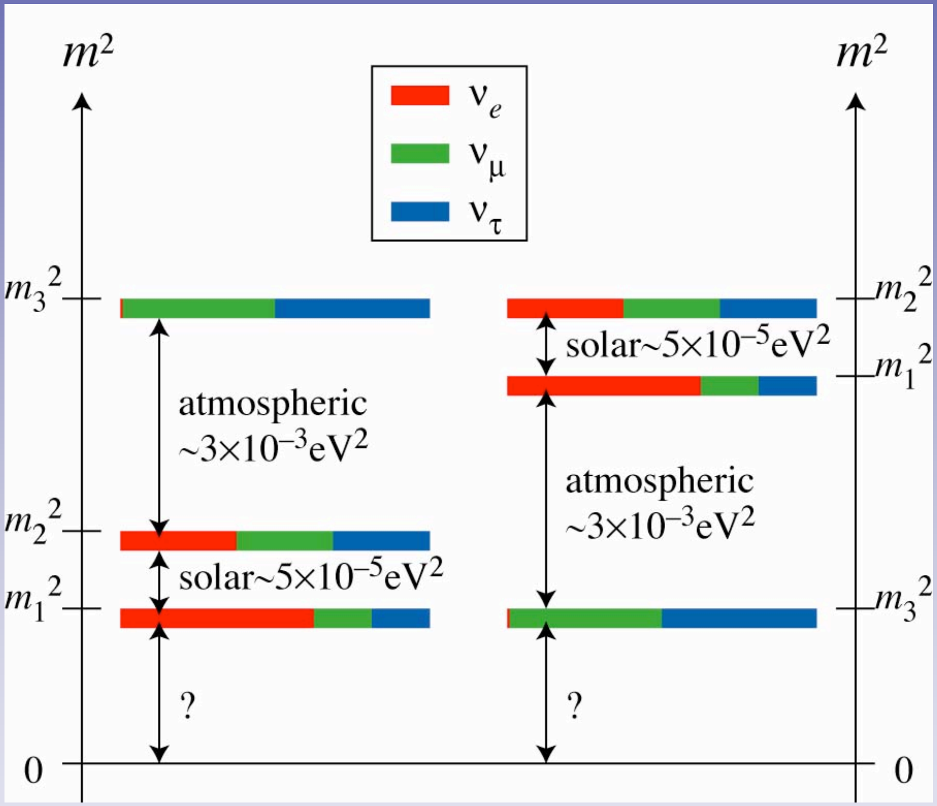
where $\Delta m^2 = m_1^2 - m_2^2$ [eV^2]

L, ν propagation distance [km]

E, ν energy [MeV]

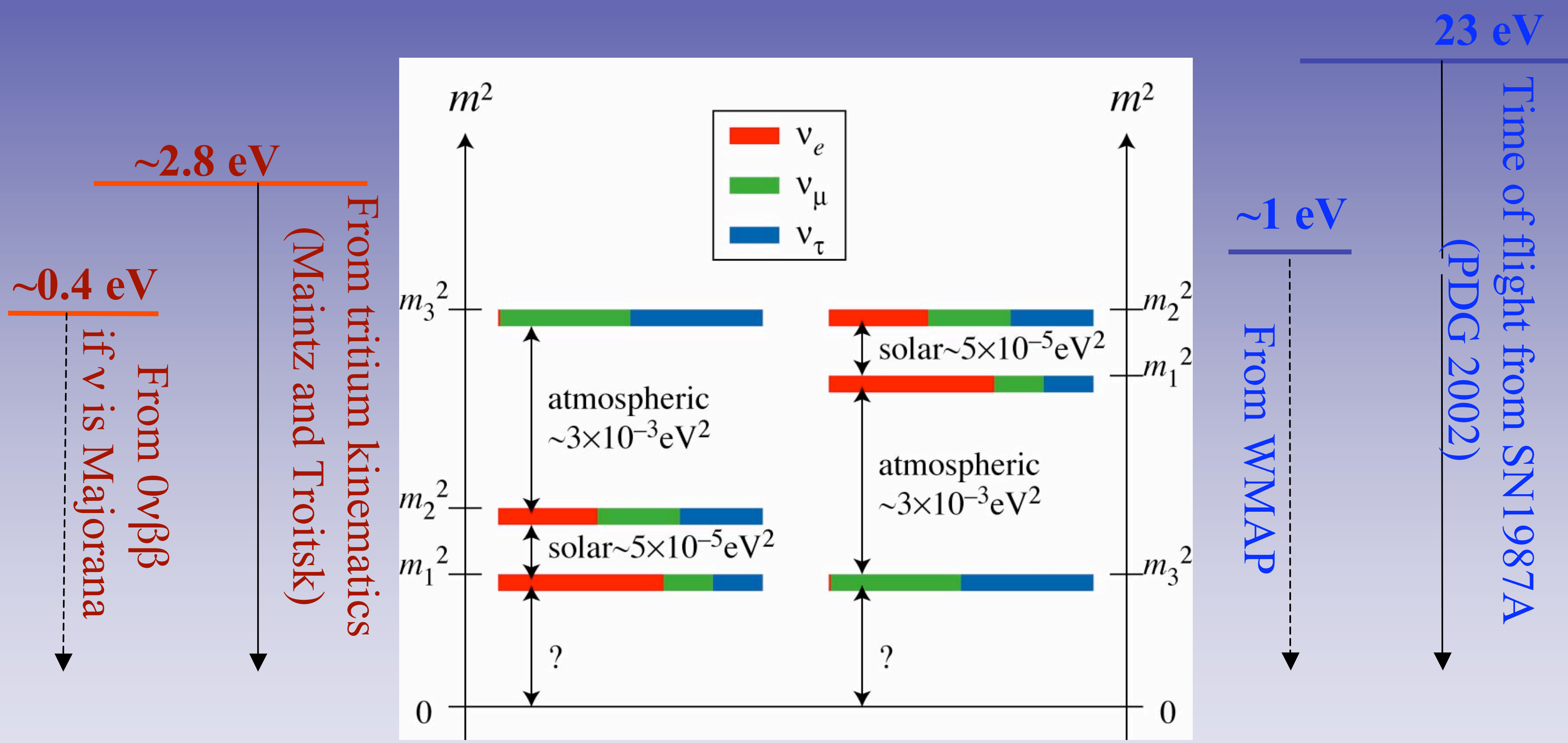
θ, ν mixing angle

ν oscillations are incomplete



No information about the absolute value of ν mass

ν oscillations are incomplete



No information about the absolute value of ν mass

Massive neutrinos: MNS matrix

Maki-Nakagawa-Sakata matrix:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot$$

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

$$\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot$$

$$\begin{pmatrix}1 & 0 & 0\\ 0 & e^{-i\alpha/2} & 0\\ 0 & 0 & e^{-i\alpha/2+i\beta}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Massive neutrinos: MNS matrix

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Atmospheric ν
K2K/Minos
θ_{23}~45°

CP violation

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

Chooz/Palo Verde
Superbeams, reactors
θ_{13}<10° @ 90%CL

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot$$

Solar ν
KamLAND
θ_{12}~30°

assuming miniBoone gives a negative result…

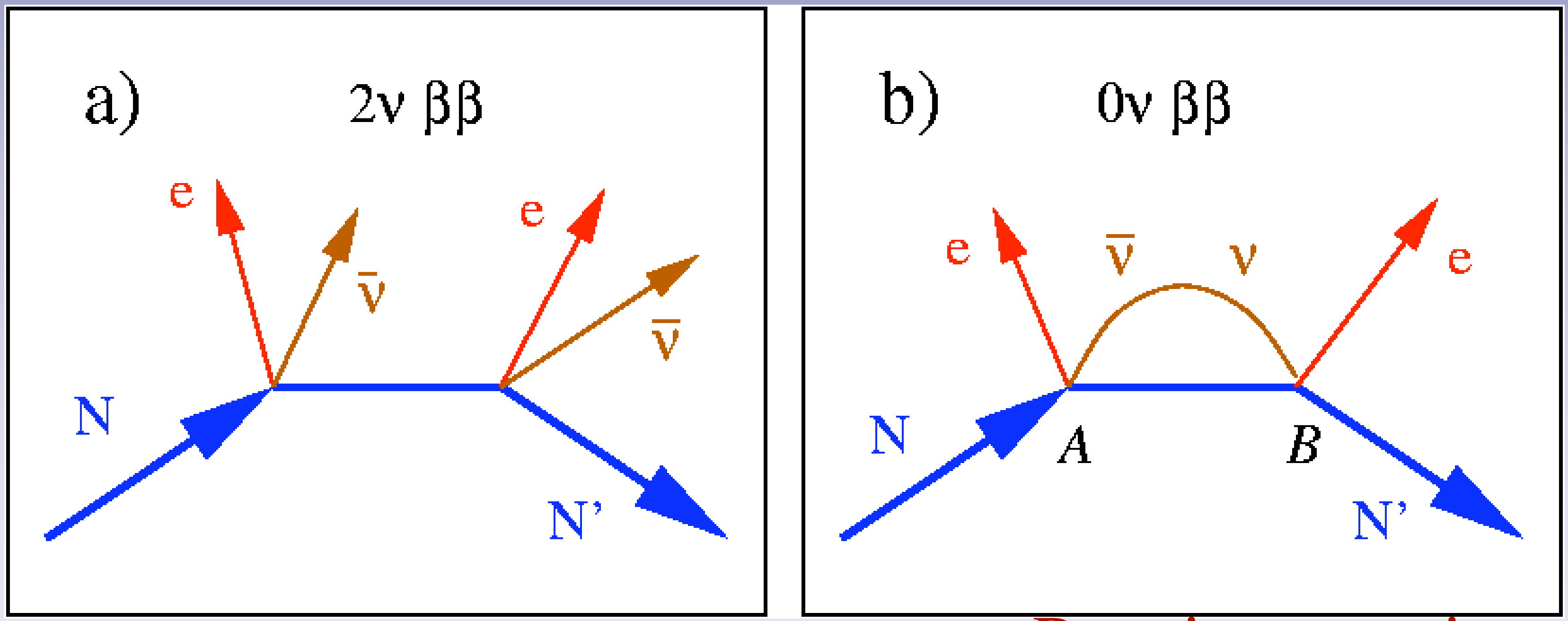
neutrinoless double beta decay

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Double beta decay

The possibility of neutrinoless decay was first discussed in 1937

- *G. Racah, Nuovo Cimento 14 (1937) 322*
- *E. Majorana, Nuovo Cimento 14 (1937) 171*



Requires massive majorana ν's

0νββ half life probes m_ν

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \, G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phase space factor

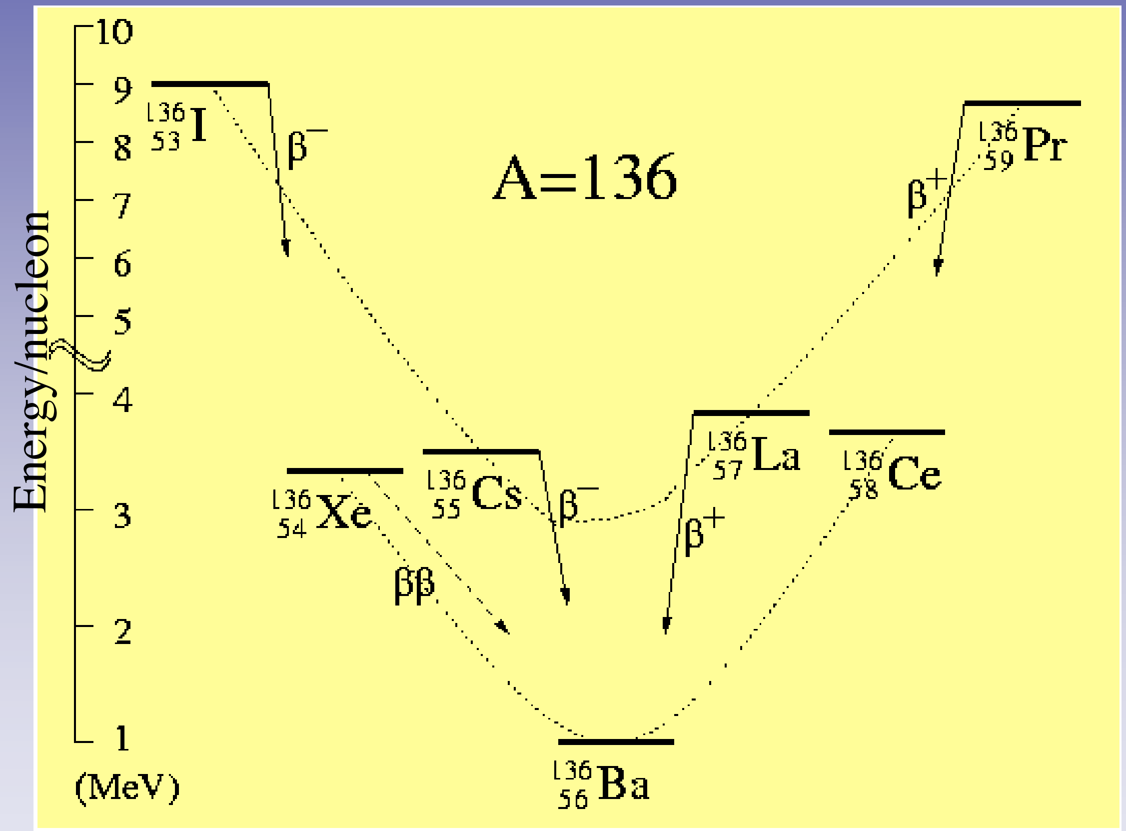
$T_{1/2}^{0\nu\beta\beta}$ is the quantity measured

$$\langle m_{\nu_e} \rangle = \left| \sum_{i=1}^{3} U_{e,i}^2 m_i \epsilon_i \right|$$

effective Majorana ν mass

($\varepsilon_i = \pm 1$ if CP is conserved)

Conditions for ββ decay



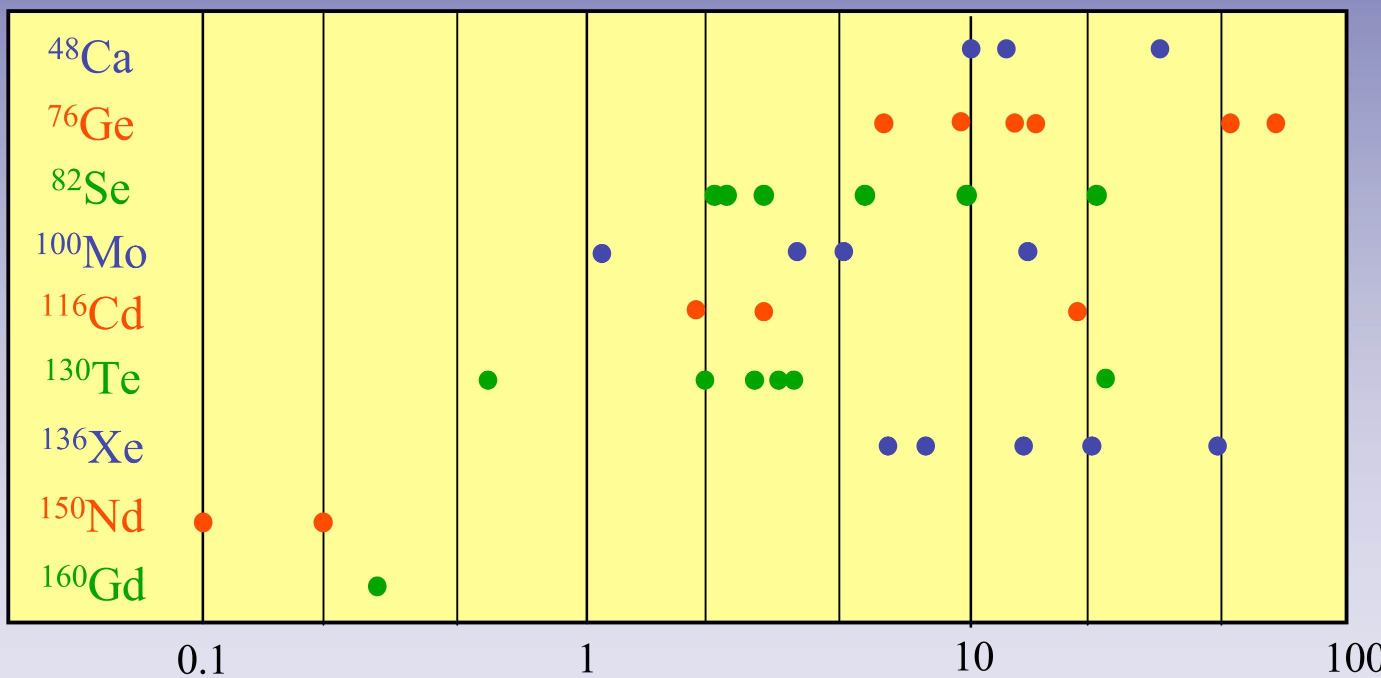
From Table of Isotopes

For ββ decay to be observed, β decay must be prohibited.

Limits available nuclei

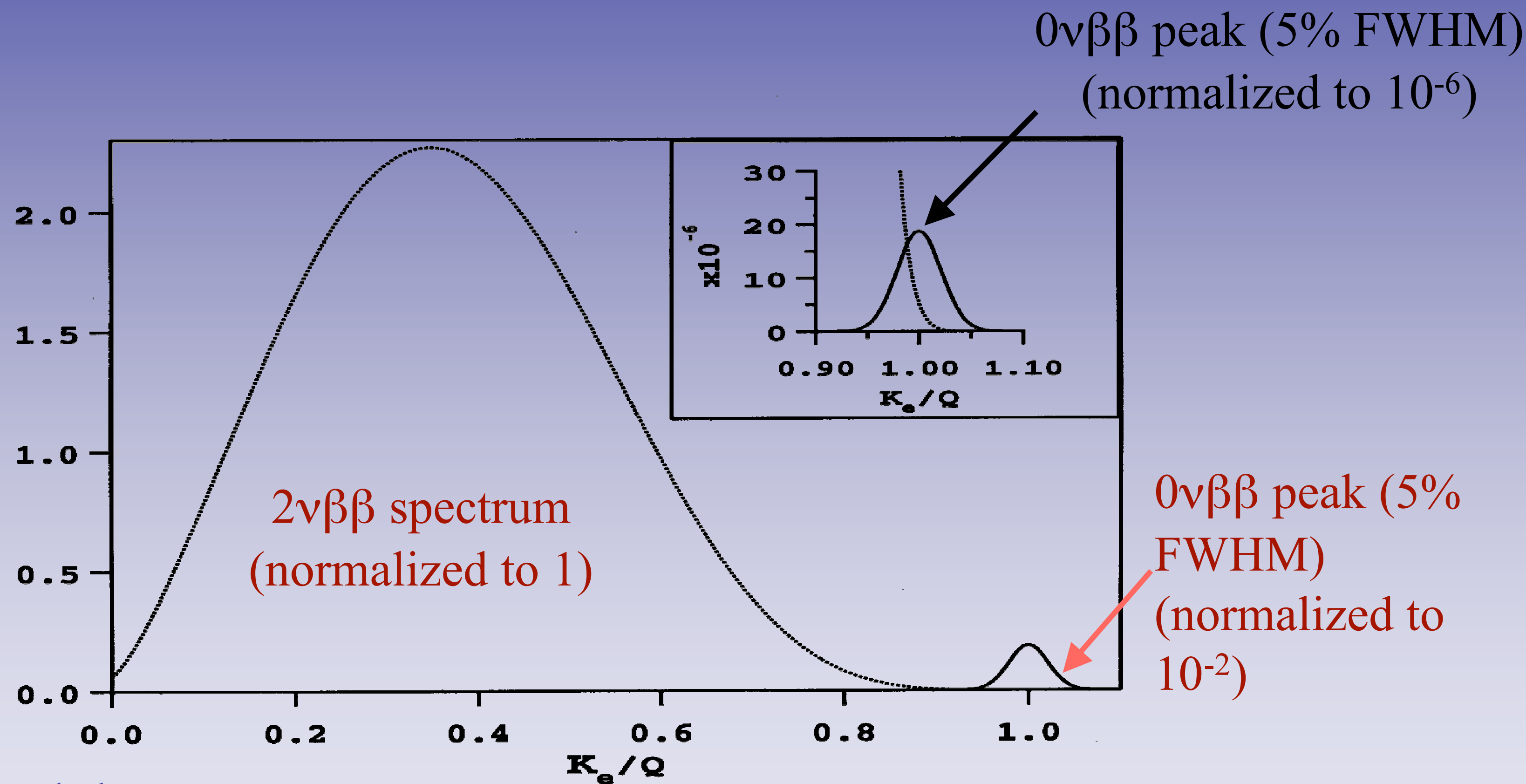
$0\nu\beta\beta$ matrix elements

Calculated $0\nu\beta\beta$ decay half lives in 10^{26} yr units for $\langle m_\nu \rangle = 50$ meV



[adapted from S.R.Elliott & P.Vogel Ann. Rev. Nucl. Part. Sci. 52 (2002) 115]

Two-neutrino background



Summed electron energy
in units of the kinematic endpoint (Q)

from S.R. Elliott and P. Vogel,
Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.

Stochastic background

With no background, ν mass sensitivity only depends on the source mass and exposure time

$$T_{1/2}^{0\nu\beta\beta} \propto Nt \rightarrow \langle m_\nu \rangle \propto \frac{1}{\sqrt{Nt}}$$

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$$T_{1/2}^{0\nu\beta\beta} \propto Nt \rightarrow \langle m_\nu \rangle \propto \frac{1}{\sqrt{Nt}}$$

For backgrounds that scale with detector size, half life sensitivity depends on the Poisson statistics of the background events:

$$T_{1/2}^{0\nu\beta\beta} \propto \sqrt{Nt} \rightarrow \langle m_\nu \rangle \propto \frac{1}{(Nt)^{1/4}}$$

Current 0νββ results

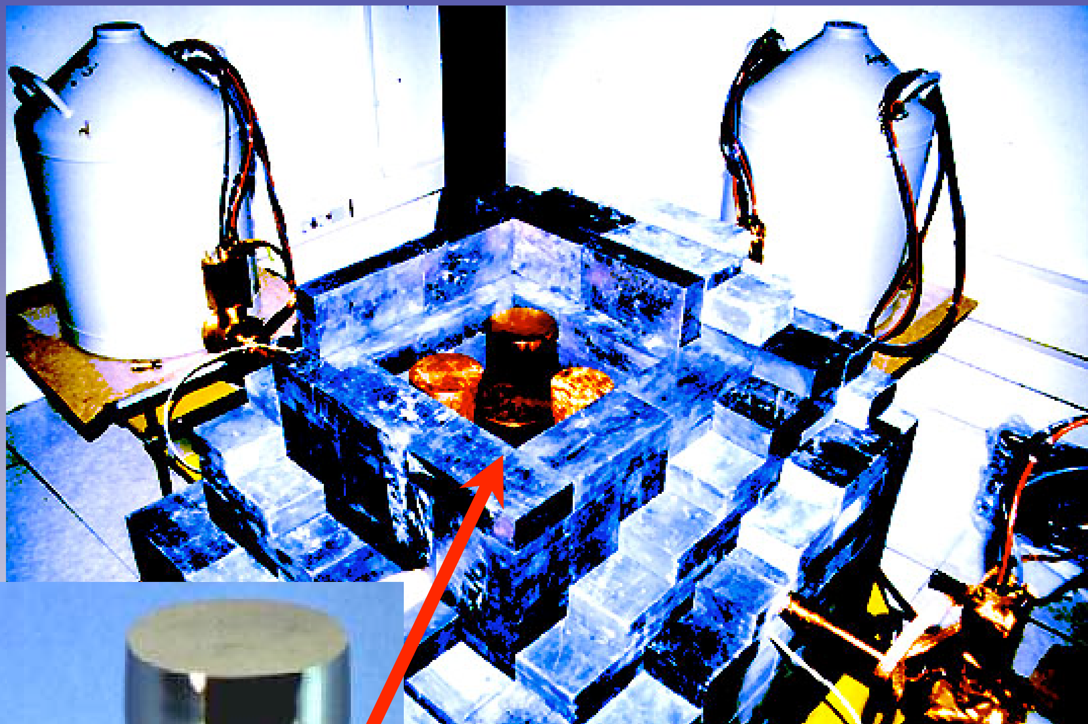
Nucleus	Detector	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>9.5*10^{21}$ (76%CL)	
$^{76}Ge^{\dagger}$	Ge diode	~30	$>1.9*10^{25}$ (90%CL)	$< 0.39^{+0.17}_{-0.28}$
^{82}Se			$>9.5*10^{21}$ (90%CL)	
^{100}Mo			$>5.5*10^{22}$ (90%CL)	
^{116}Cd			$>7.0*10^{22}$ (90%CL)	
^{128}Te	TeO_2 cryo	~3	$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~3	$>2.1*10^{23}$ (90%CL)	< 1.1 - 2.6
^{136}Xe	Xe TPC	~10	$>1.2*10^{24}$ (90%CL)	< 2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

- Adapted from the Particle Data Group 2003

† Controversial claim of positive 0ν signal with m = .39 eV

c.f. Klapdor-Kleingrothaus ***Mod. Phys Lett. A27 (2001) 2409***

Heidelberg-Moscow experiment



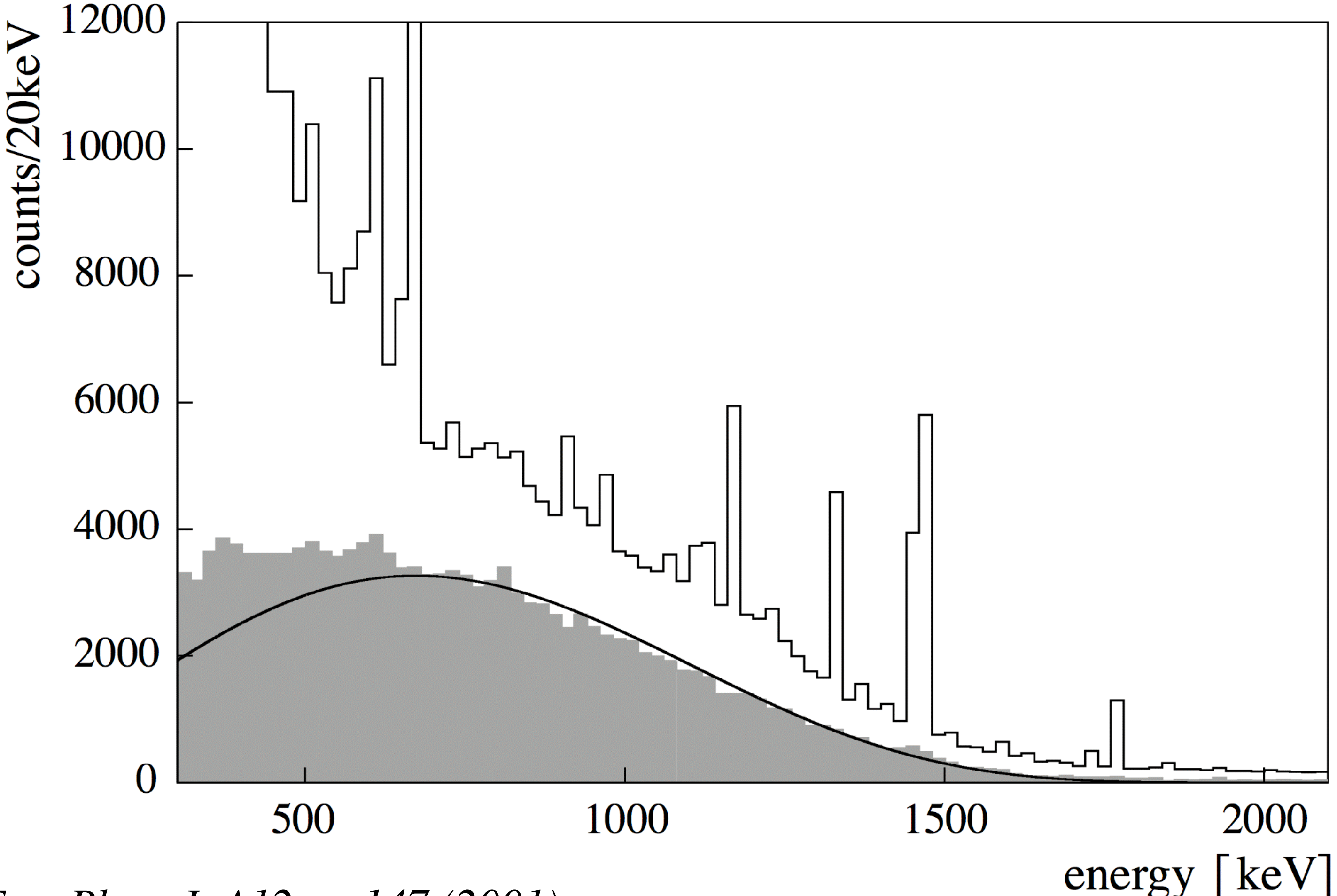
www.mpi-hd.mpg.de/non_acc/bigpict.html

- 10.96 kG enriched, shielded HPGe detectors
- Q = 2039 keV
- ~ .1% energy resolution
- Gran Sasso: 3500 mwe muon shield
- Use pulse-shape to remove multi-site events
- Remove backgrounds by modeling observed lines

Eur. Phys. J. A12 pg 147 (2001)

Heidelberg-Moscow results

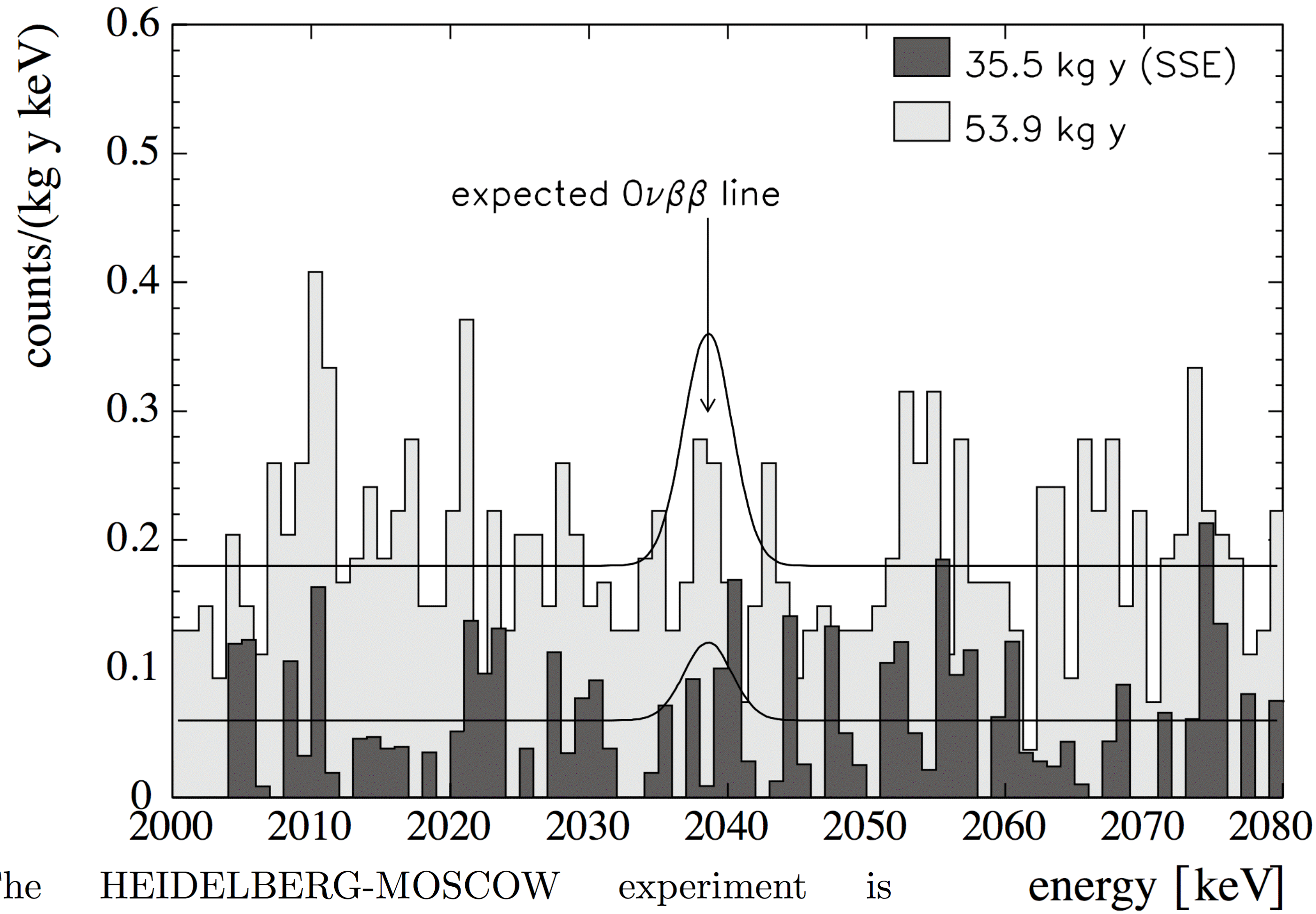
Two-neutrino



Eur. Phys. J. A12 pg 147 (2001)

Heidelberg-Moscow results

Zero-neutrino



The HEIDELBERG-MOSCOW experiment is presently giving the most stringent upper limit on the Majorana-neutrino mass, of 0.35 eV at 90% C.L. (0.27 eV at 68% C.L.).

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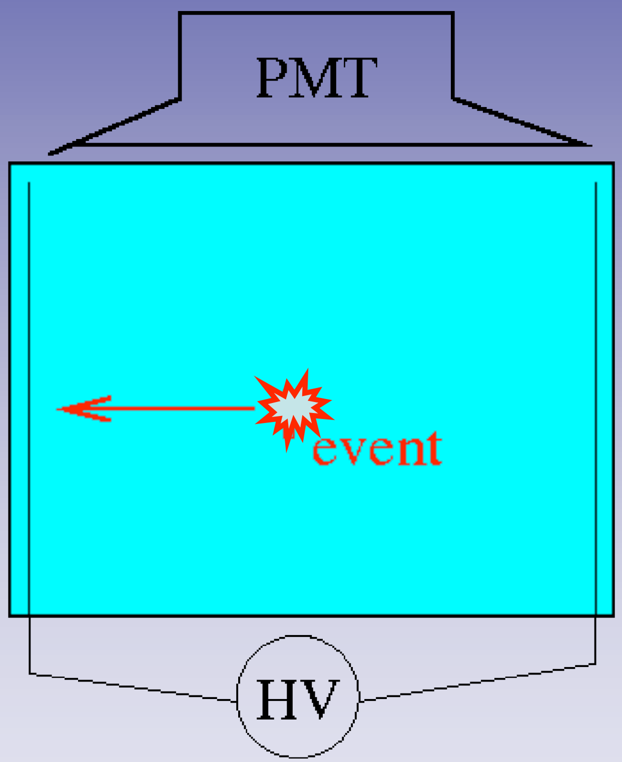
Xenon's attractive properties

- Xenon is a noble gas
  - No crystals
  - Continuous purification
  - Easy(er) purification
- No long lived cosmogenic isotopes
- Efficient ultracentrifuge enrichment

Homogenous Detector



- Source = detector minimize backgrounds, maximize source mass
- Xenon Time Projection Chamber (TPC)
- Can read out ionization, scintillation, or both
- Liquid or gas phase

Xe offers a qualitatively new tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$ final state can be identified using optical spectroscopy.

(M.Moe PRC44 (1991) 931)

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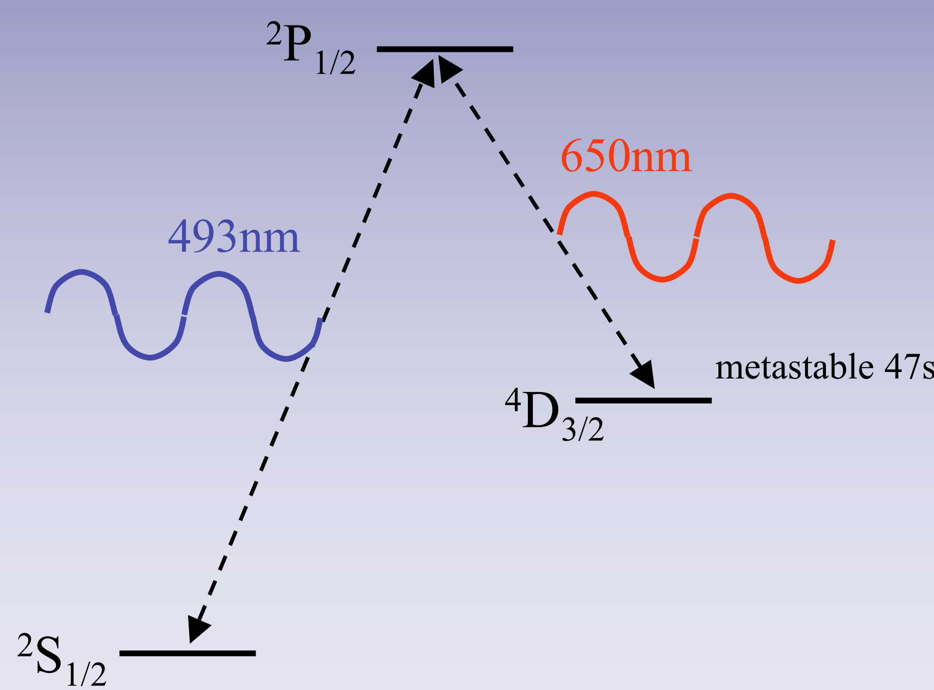
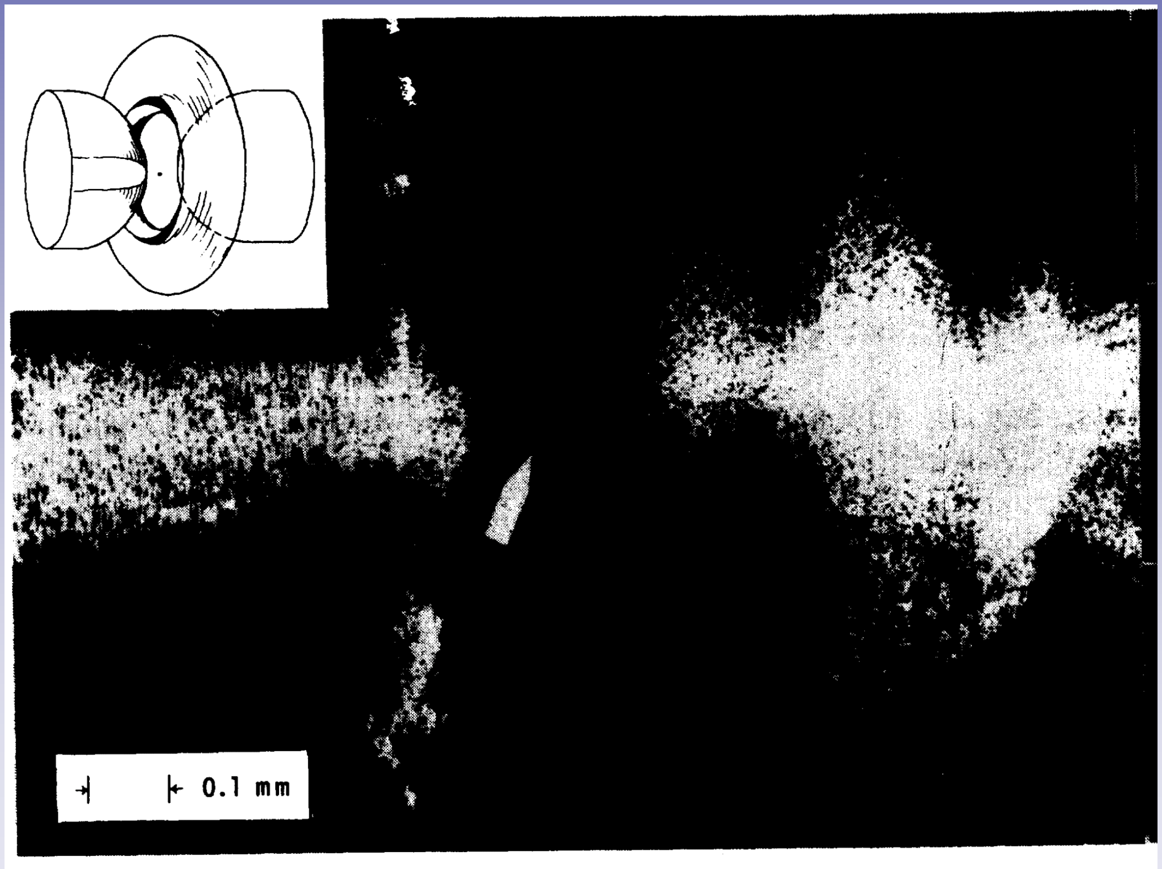
Ba^{+} system well studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)

Very specific signature "shelving"

Single ions can be detected from a photon rate of 10^7/s



Everyone's a critic



Neuhauser et.al., PRA22, 1137 (1980)

Single Ba^+ ion

Localized

T ~ 30 mK

Assume an "asymptotic" fiducial mass of 10 tons of ^{136}Xe at 80% enrichment

A "natural" scale:

- World production of Xe is ~30 ton/yr
- ^{136}Xe ~ 8% of natural xenon
- Detector size ~ 5 m^3
- $2x10^3$ source mass increase:
  good match to the
  10^{-2} eV mass region

EXO m_ν sensitivity (I)

Assumptions:

1) 80% enrichment of ^{136}Xe
2) Intrinsic low background and barium tagging eliminates all radioactive background
3) Use energy resolution to separate the 0ν from 2ν modes
4) Use $T_{1/2} > 1 \cdot 10^{22}$yr for 2νββ (Bernabei et al. measurement)

EXO m_ν sensitivity (II)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡	(NSM)#
Conservative	1	70	5	1.6*	0.5 (use 1)	2×10^{27}	33	(95)
Aggressive	10	70	10	1†	0.7 (use 1)	4.1×10^{28}	7.3	(21)

* $\sigma(E)/E = 1.6\%$ obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

† $\sigma(E)/E = 1.0\%$ considered as an aggressive but realistic guess with large light collection area

‡ QRPA: A.Staudt et al. Europhys. Lett.13 (1990) 31; Phys. Lett. B268 (1991) 312

NSM: E.Caurier et al. Phys Rev Lett 77 (1996) 1954

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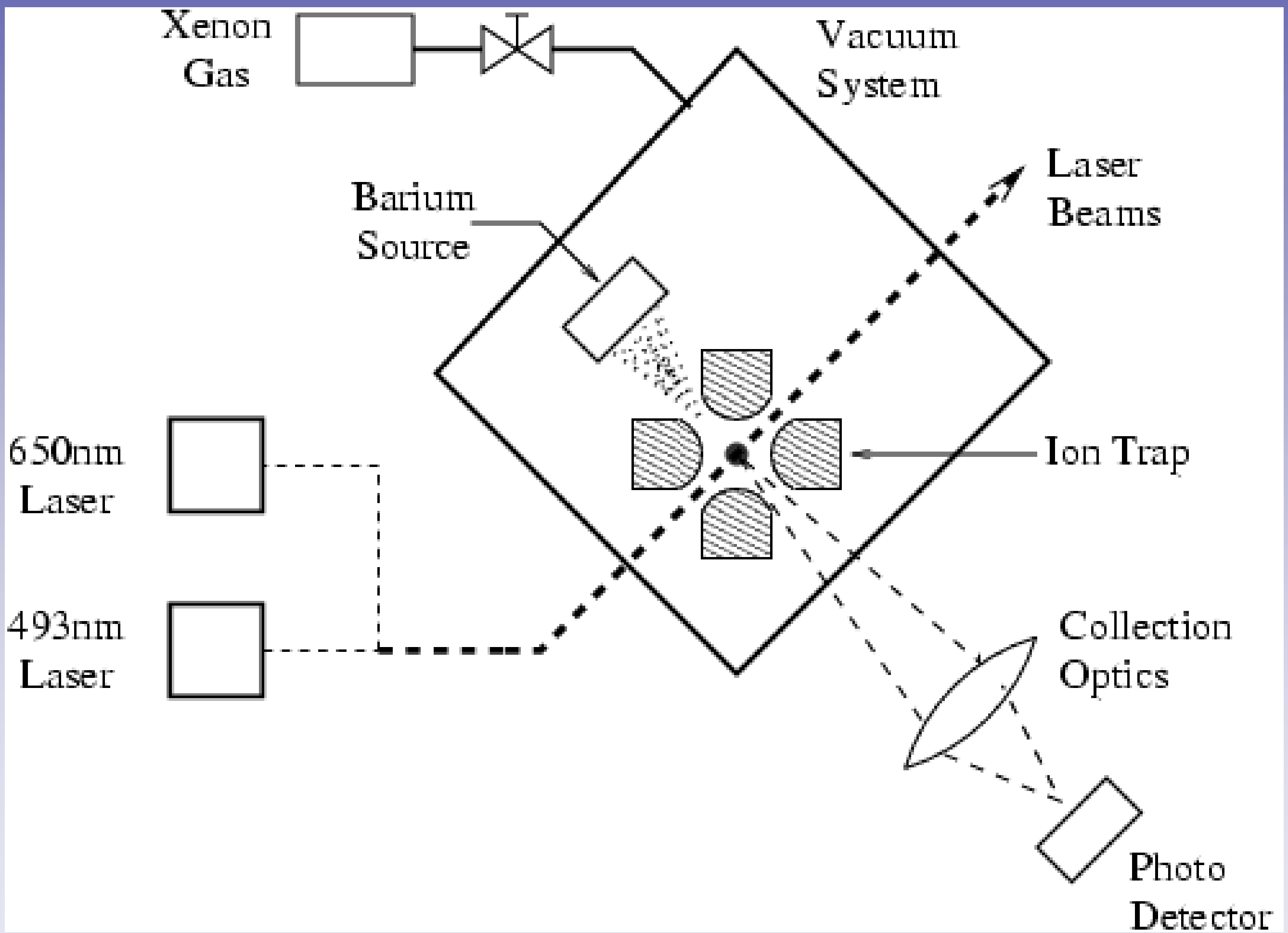
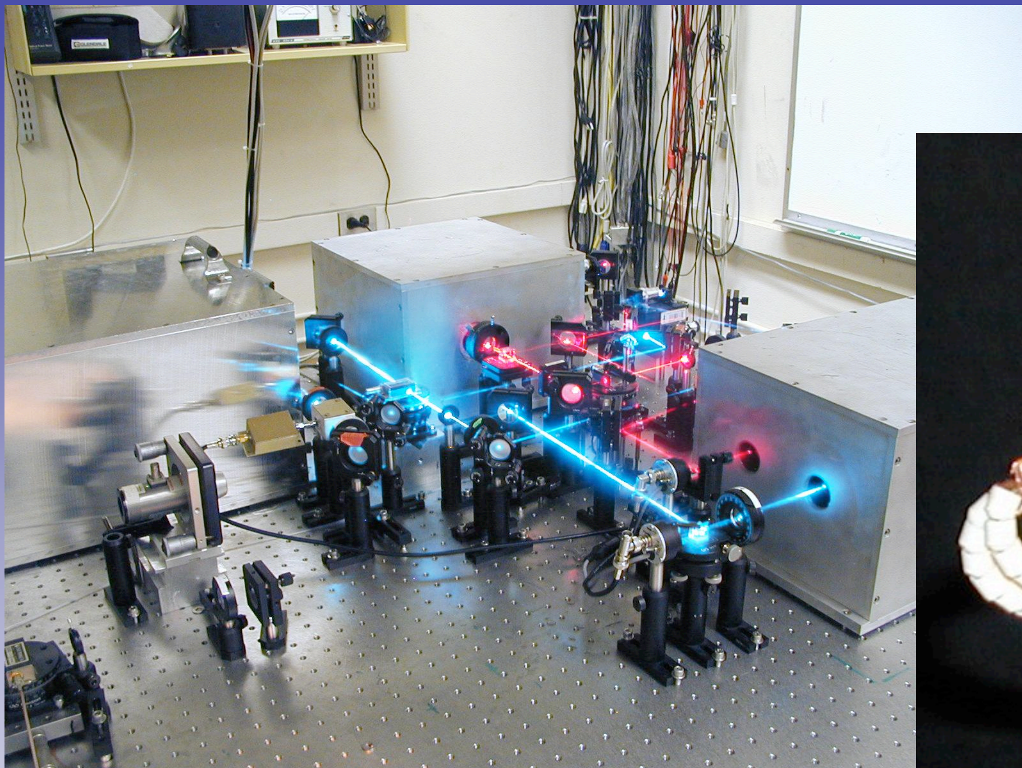
UHV single ion spectroscopy

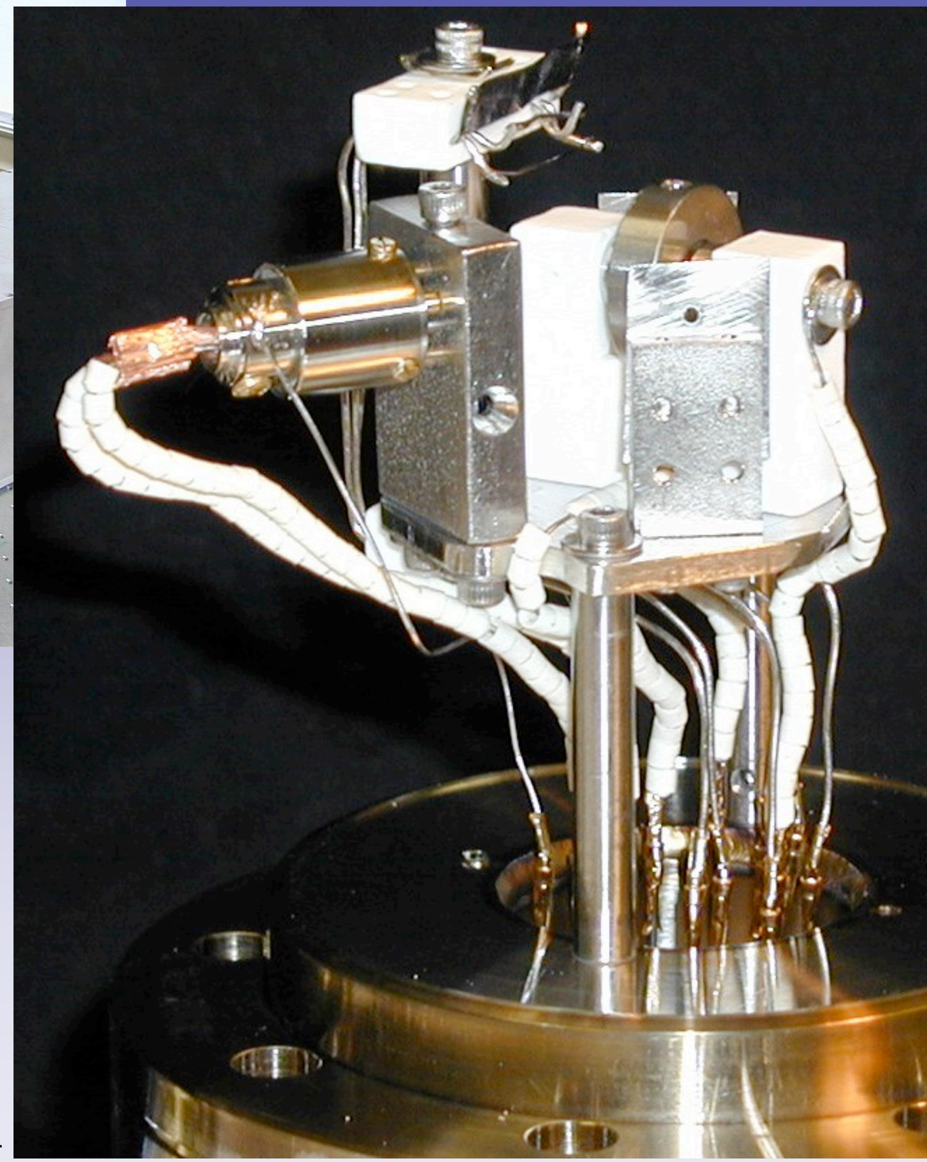


RF ion trap ~ revolved quadrupole mass filter

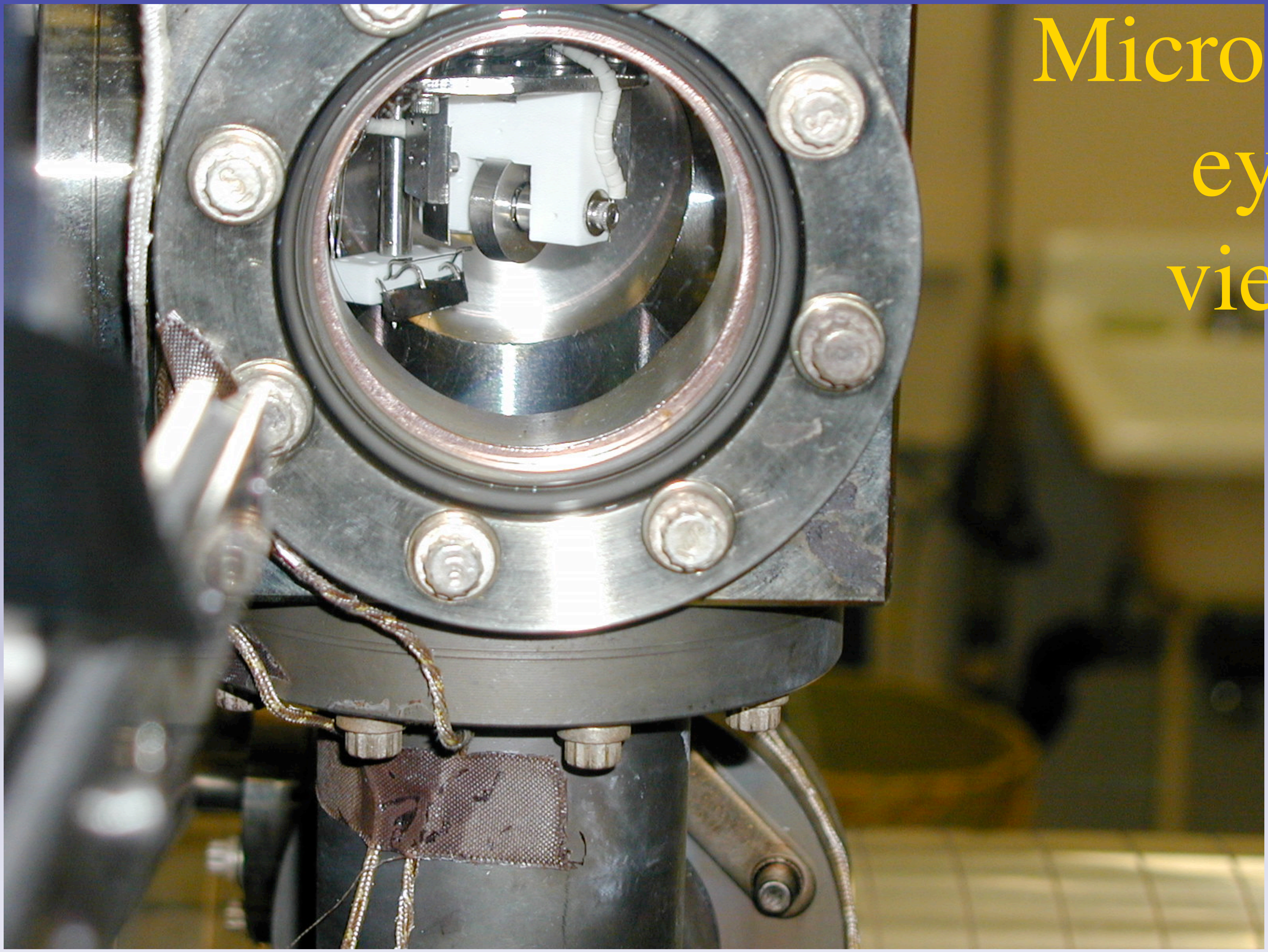
$P = 10^{-10}$ torr to .1 torr

In the lab

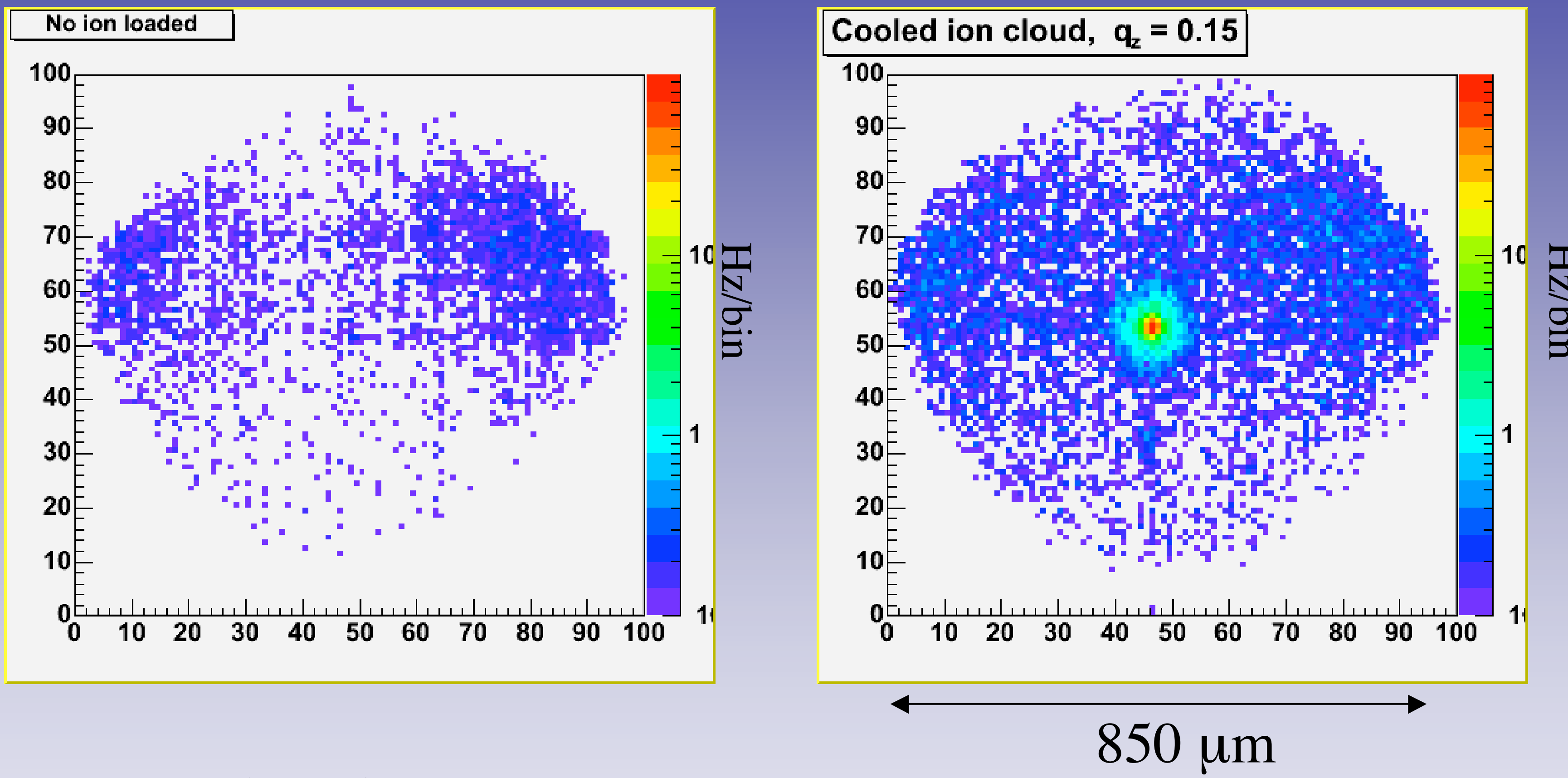




Microscope eye view

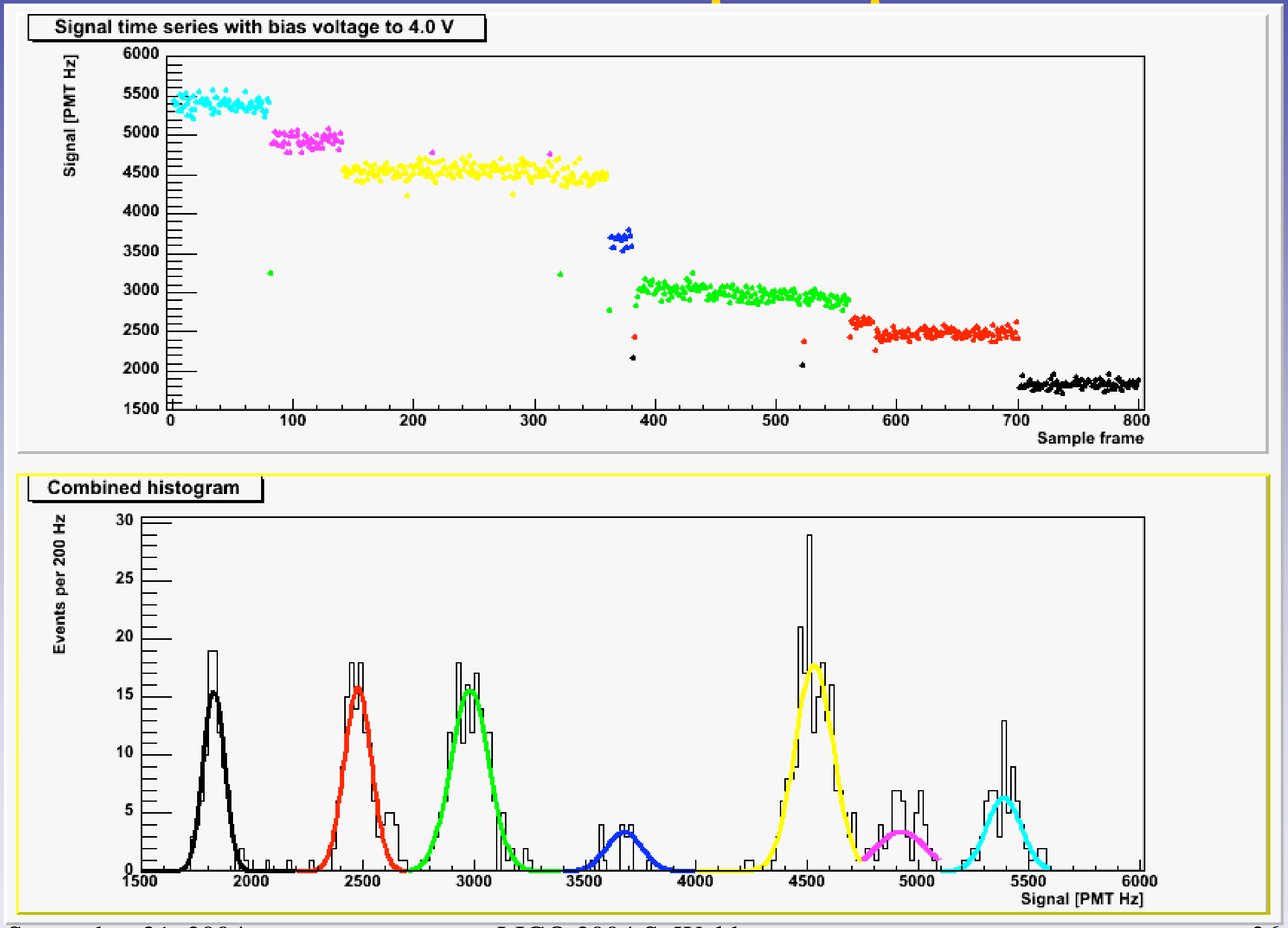


Vacuum single ion pictures

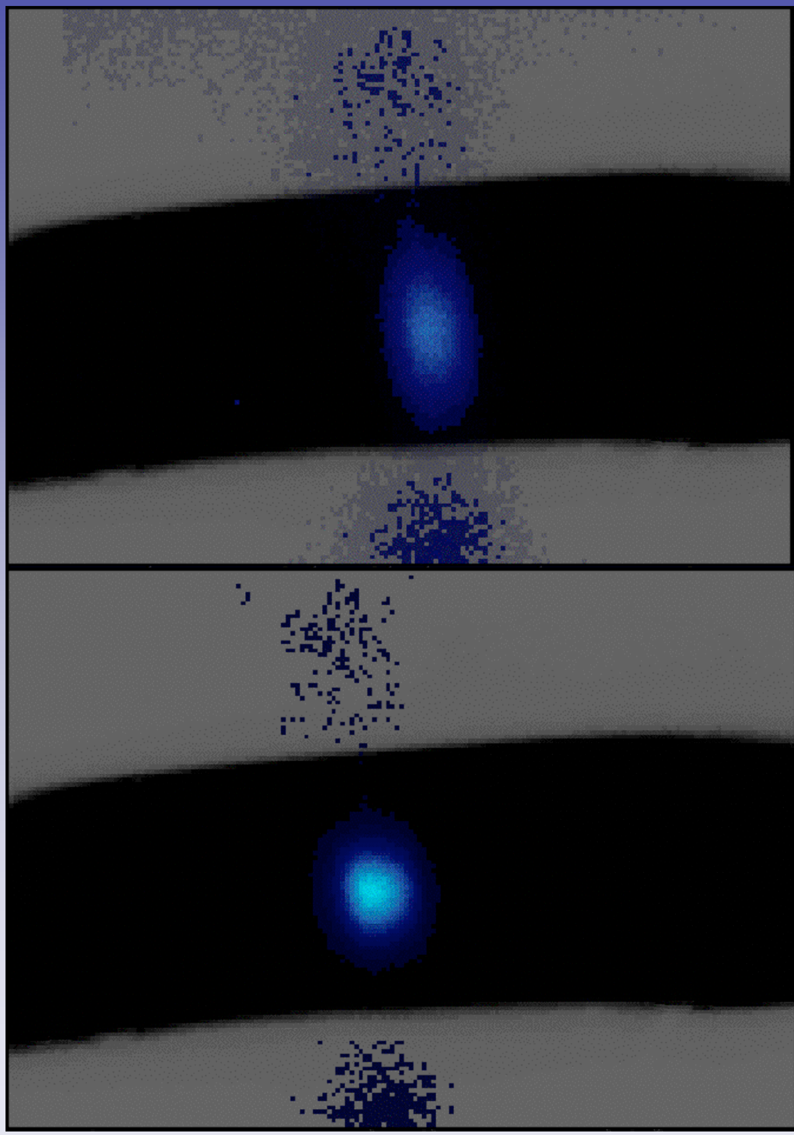


- From imaging PMT
- ~150 MHz frequency FWHM
- CW SNR of 100:1

Millikan ion drop experiment



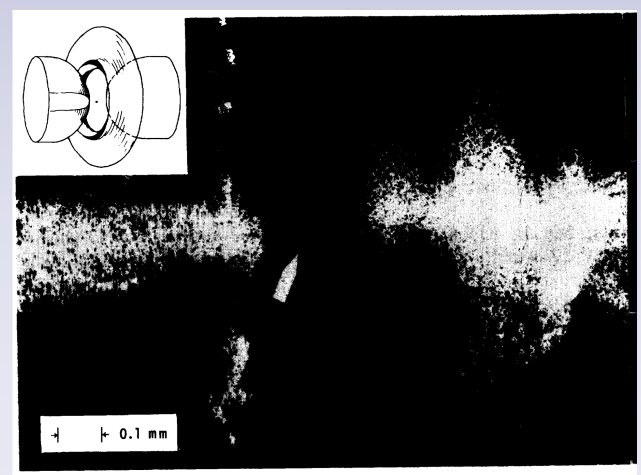
Ions in gas



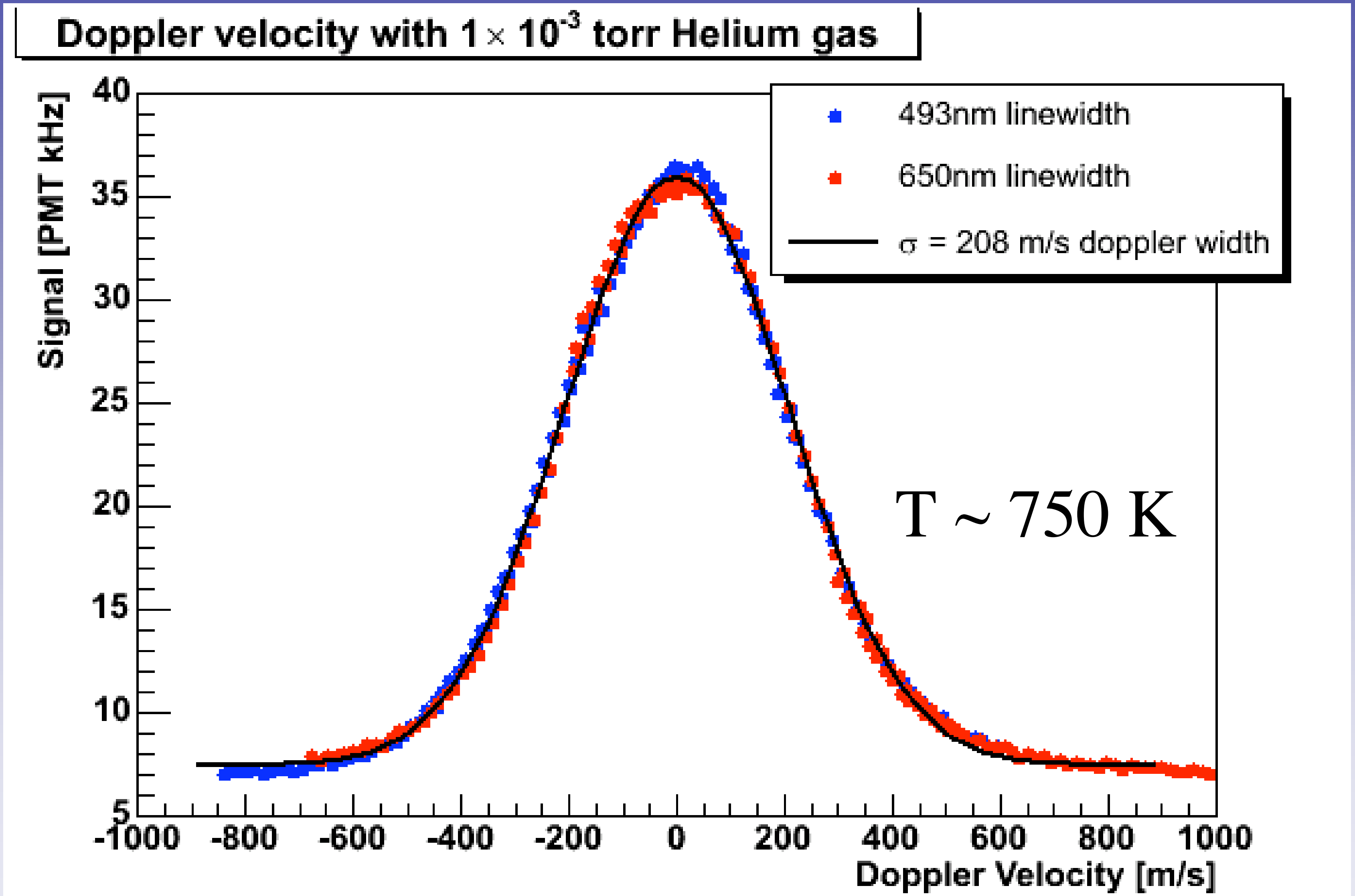
10^{-6} torr

10^{-3} torr helium

- Ions trapped 10^{-10} to 10^{-1} torr
- Helium, N_2, Argon and Xenon
- Spatial and spectral distributions



Frequency spectra in gas



T ~ 750 K

LXe energy resolution

Liquid Xenon has energy resolution in the ionization channel ~10x worse than theoretically predicted (c.f. Fano) -- Why?

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Recombination

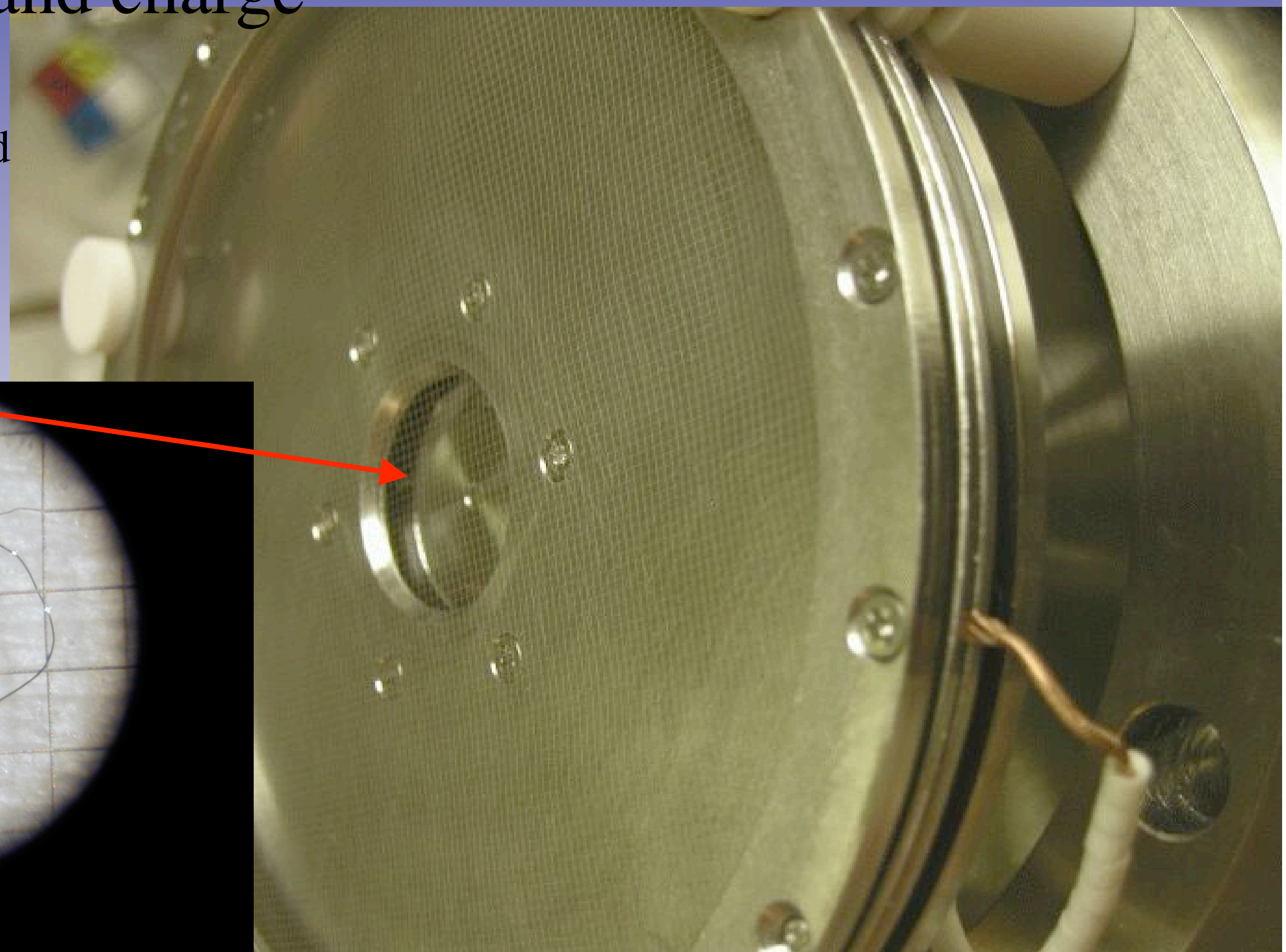
$$\mathrm{Xe}^{+} + e^{-} \rightarrow \mathrm{Xe} + \gamma$$

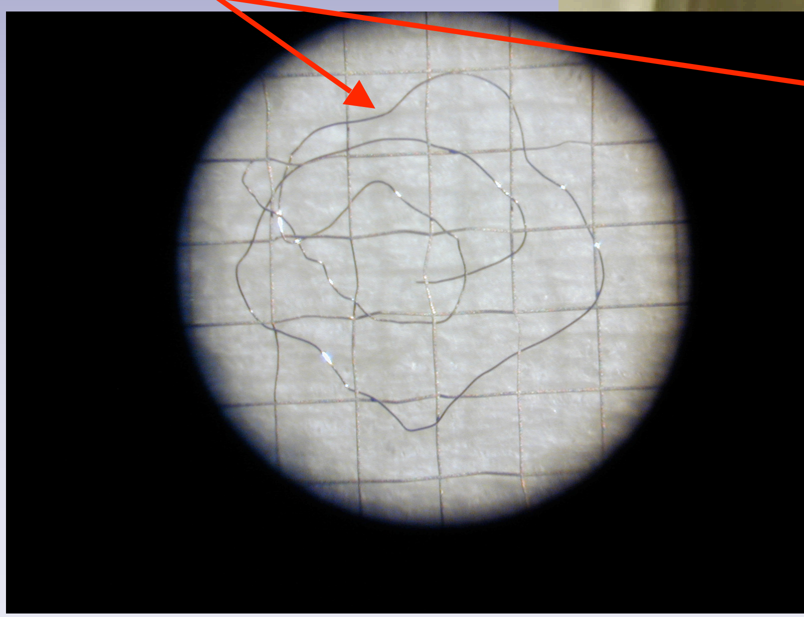
Details depend on event topology - variable "lost" energy decreases resolution

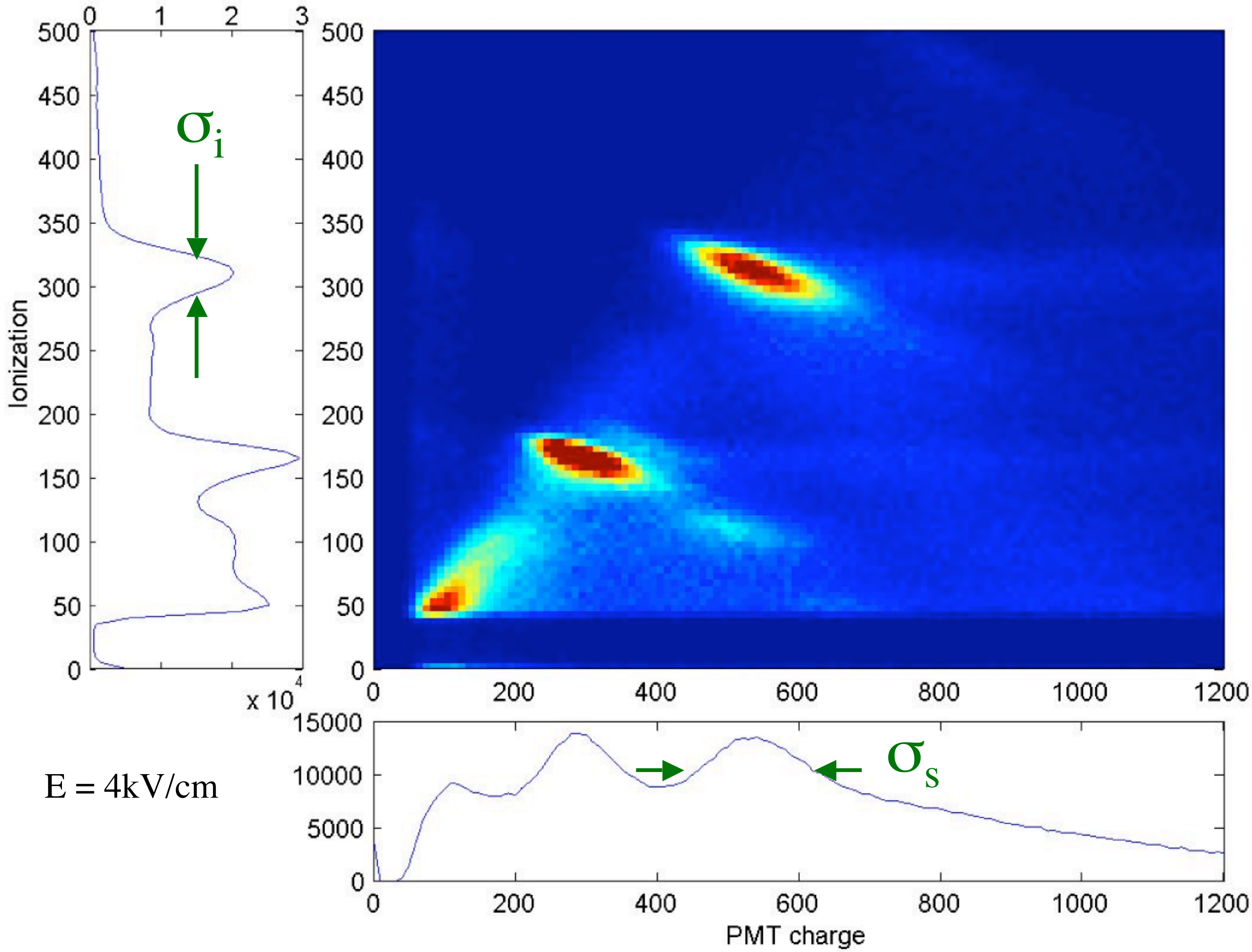
Scintillation plus ionization

To improve resolution -
measure *both* light and charge

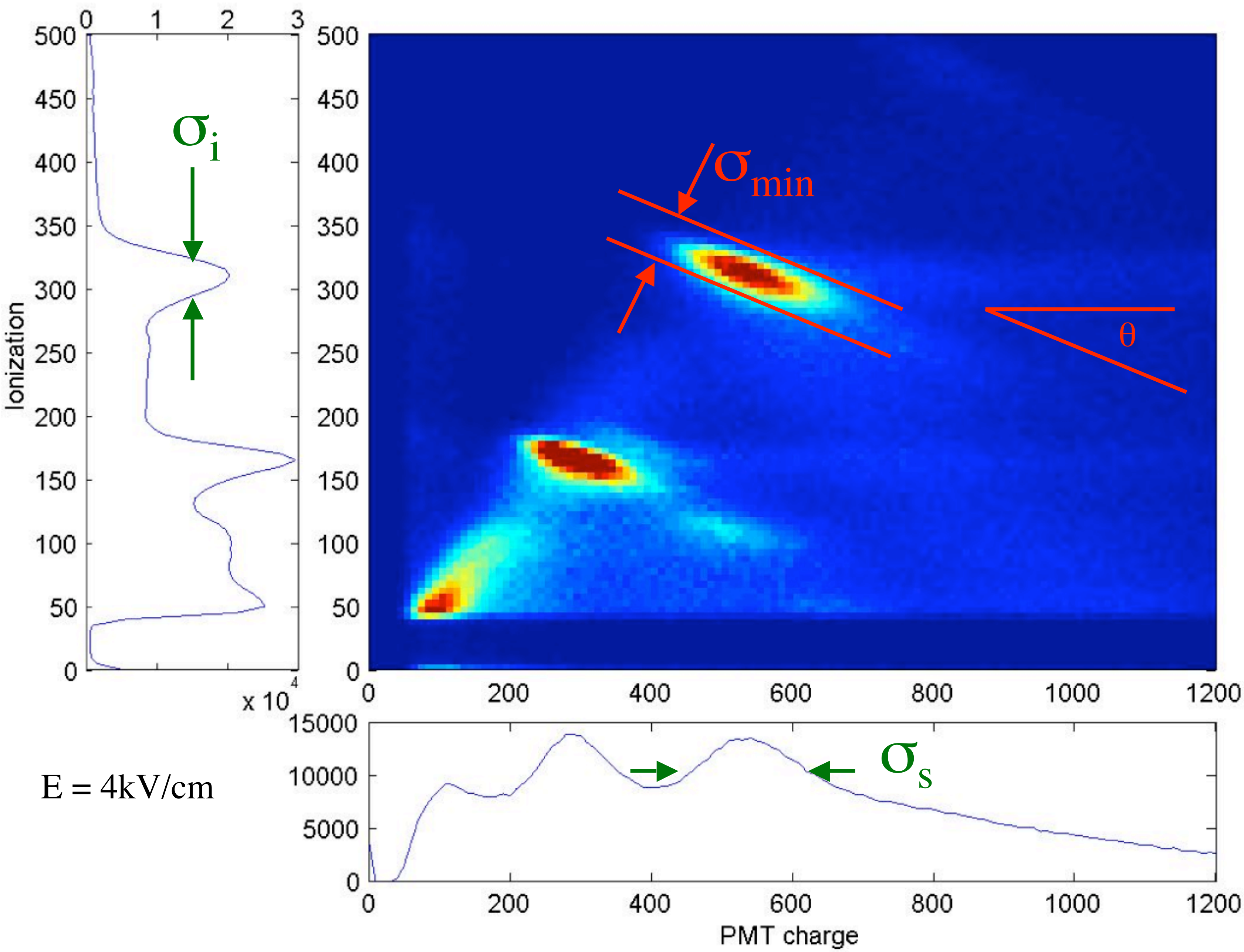
Bismuth emits 1.04 MeV and
570 keV gammas



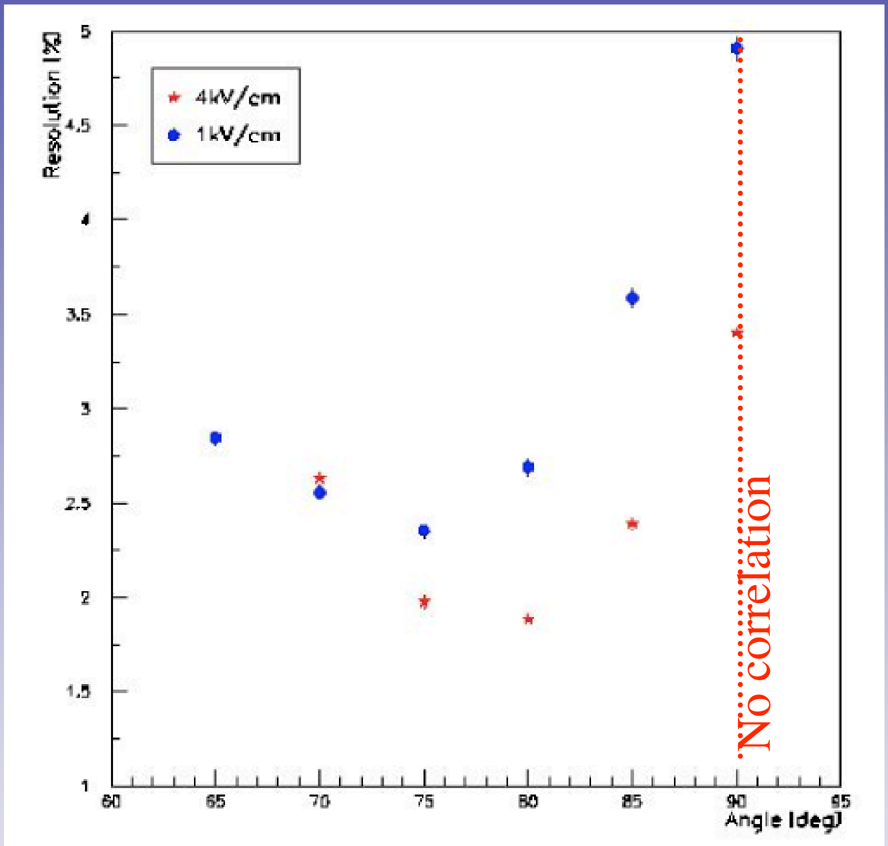


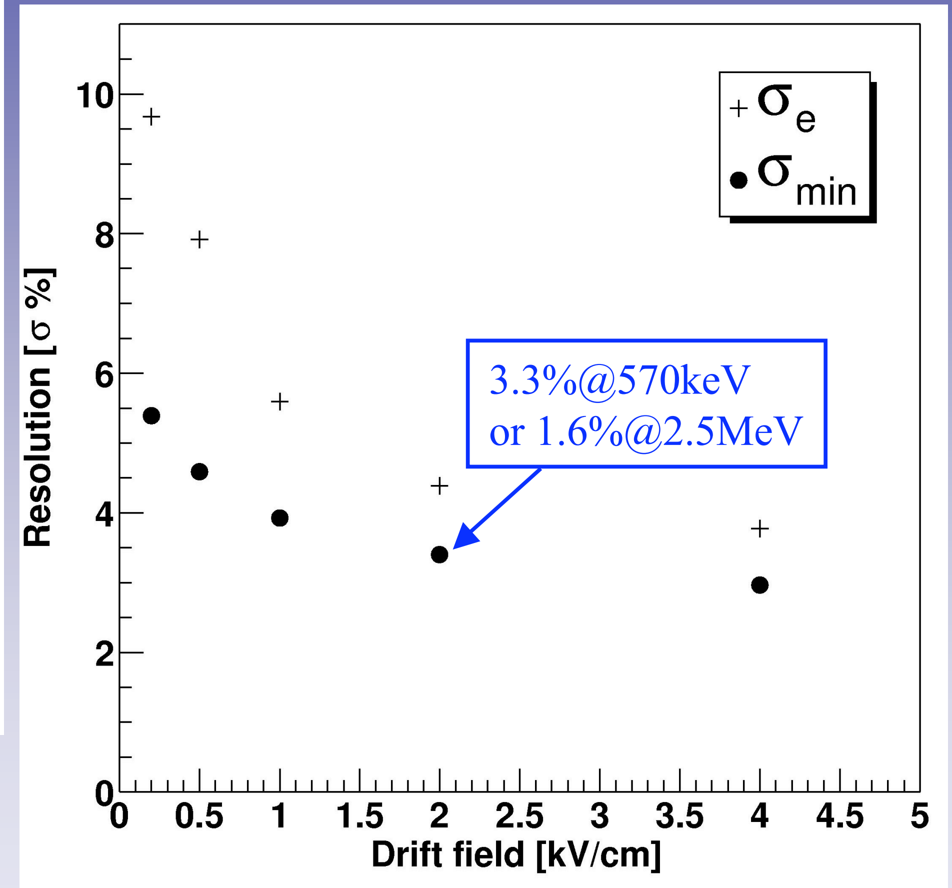


Ionization
σ_i
x 10^4
σ_s
PMT charge
E = 4kV/cm

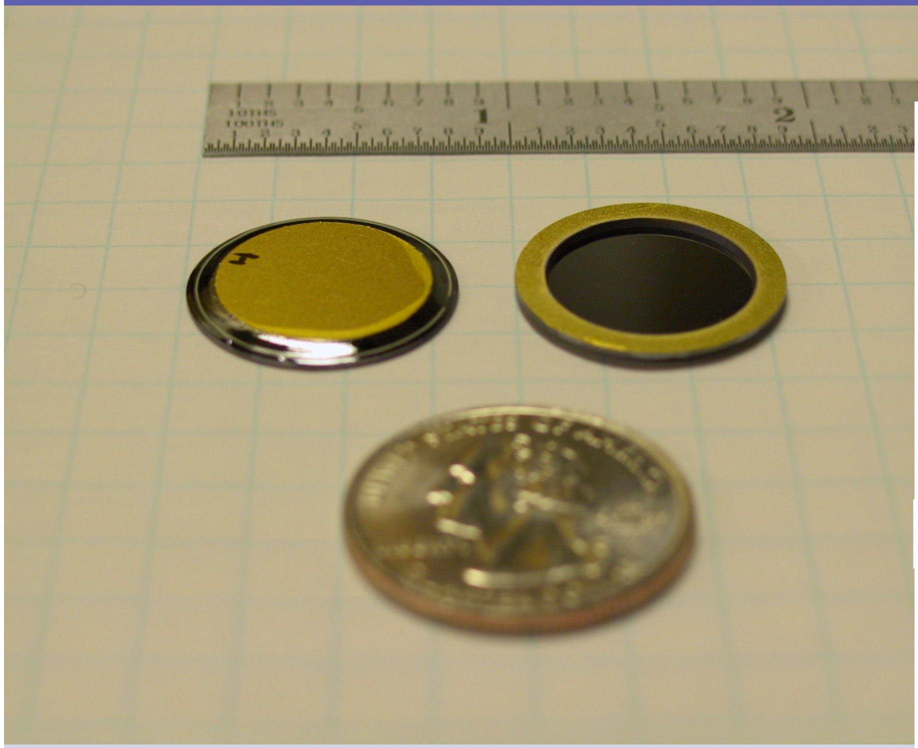

Ionization
PMT charge
x 10^4
σ_i
σ_min
θ
σ_s
E = 4kV/cm

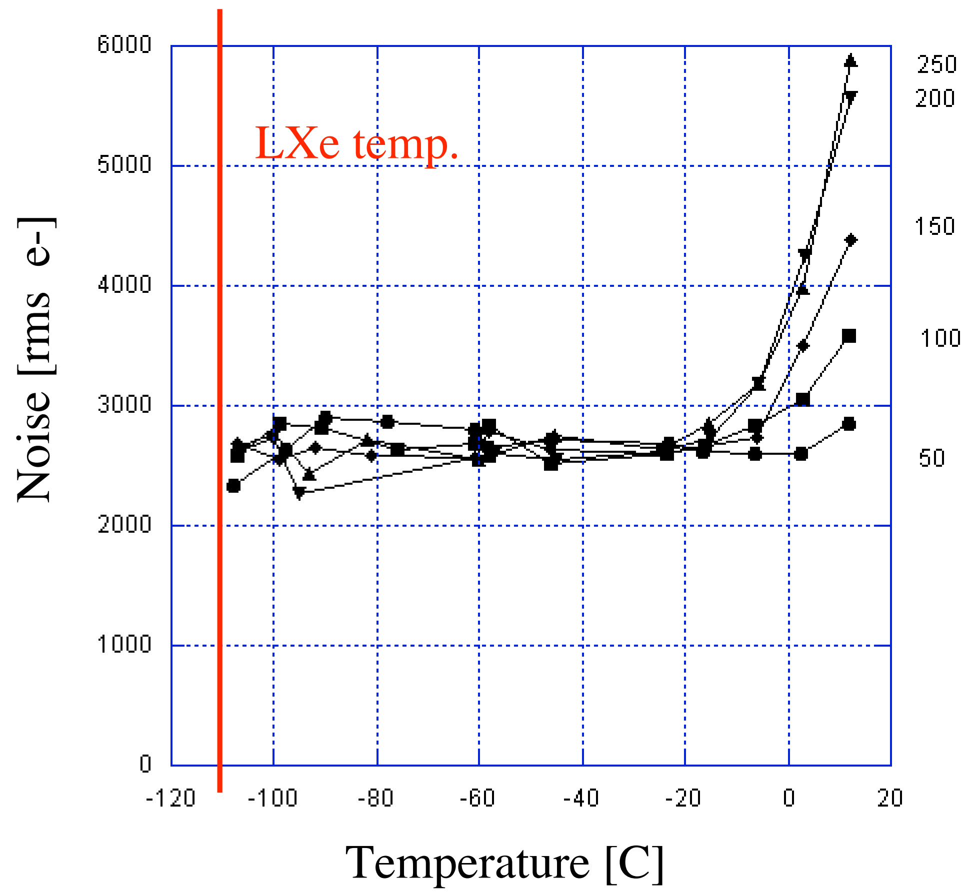
Resolution improvement





Large Area Avalanche Photodiodes





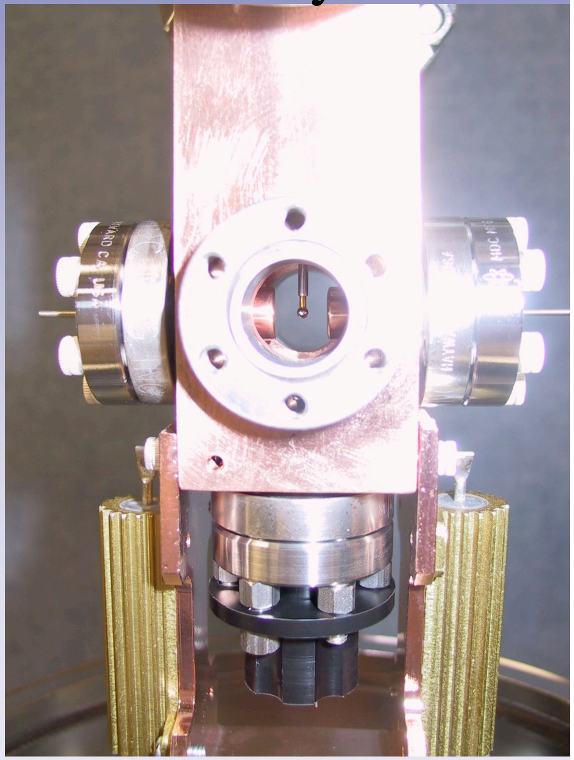
- Gain of several hundred
- Low radioactivity
- High VUV quantum efficiency
- Low noise when cooled

Material verification:
chemical and radio-purity

Neutron Activation Analysis (NAA) studies

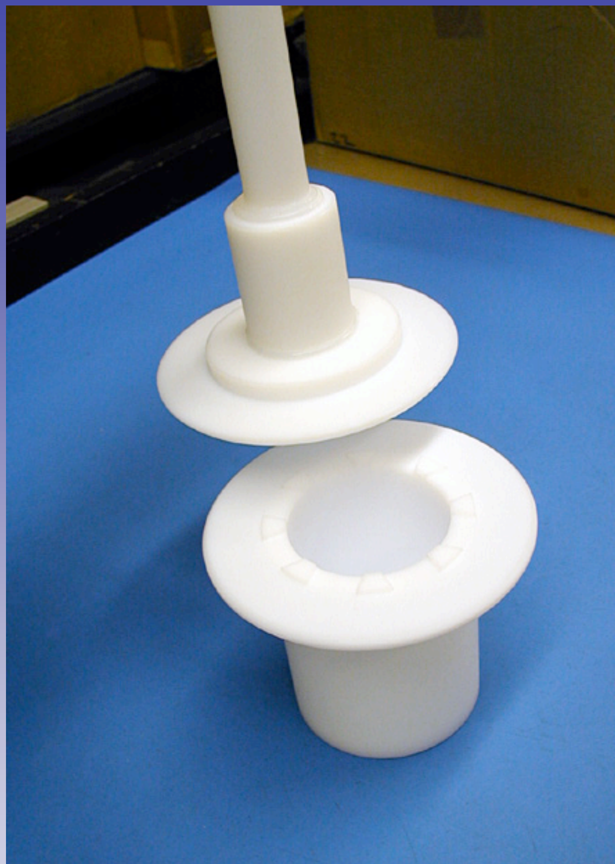
Material	Origin	U(ppt)	Th (ppt)	K (ppt)
Synthetic silica	BaBar DIRC	<4.6	12±2	<4600
Polycarbonate	Dow Corning pellets	<6.5	<33	18000±2000
PTFE teflon	Machine grade	<12	51±5	14000±2000
PTFE teflon	DuPont powder	<44	<1.8	2500±800

Xenon Purity Monitor

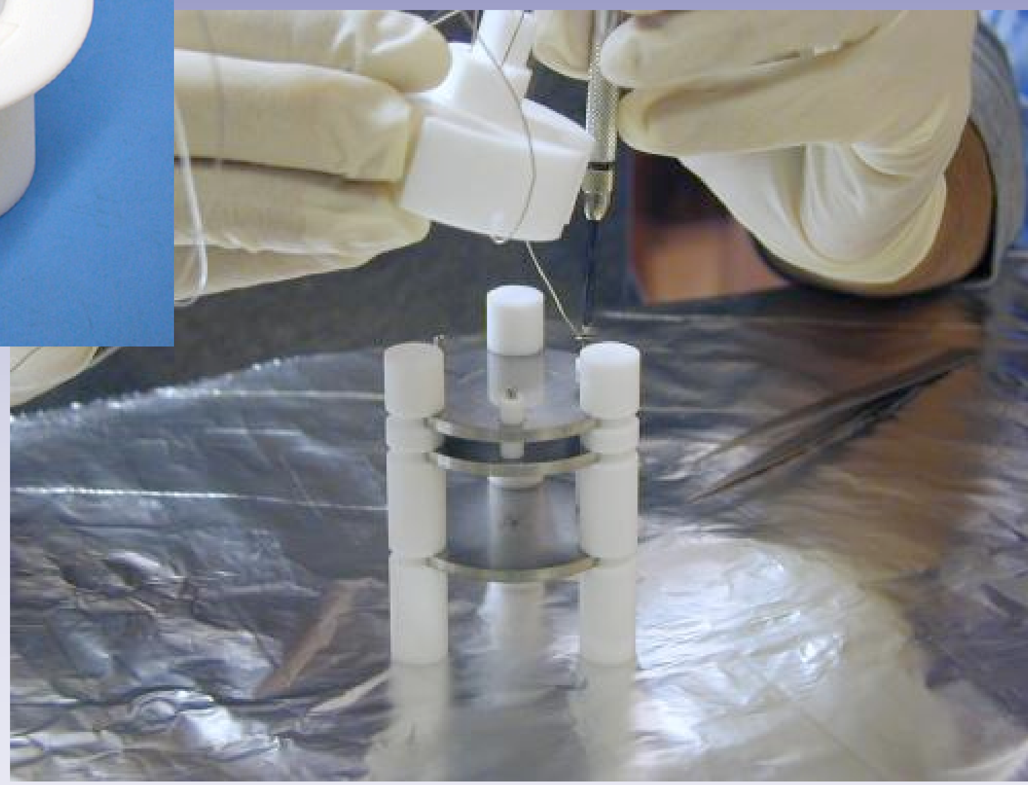


XPM measures drift length in 10 cm LXe cell with test samples immersed in the LXe.

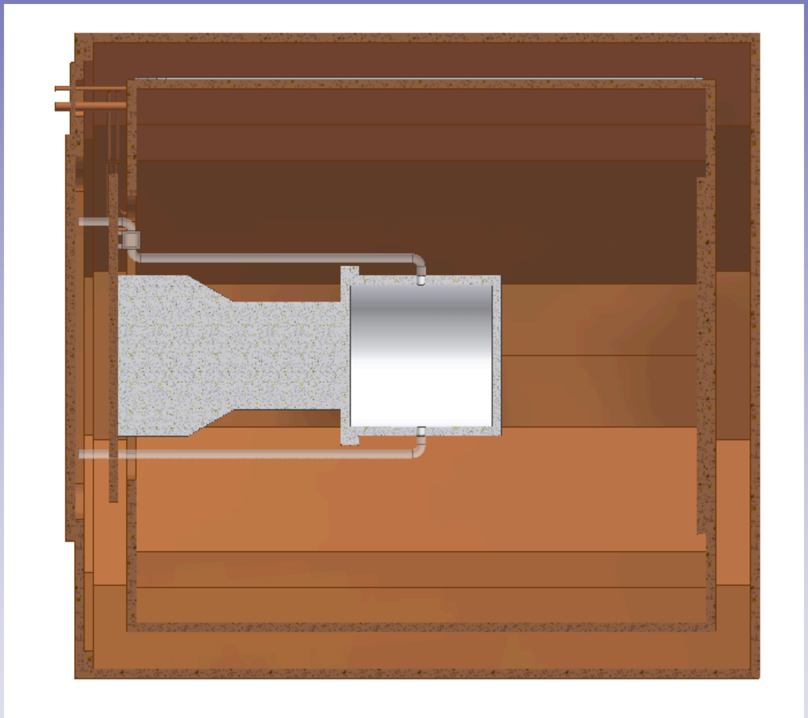
Teflon Chamber



- Chemically inert
- Radiopure
- UV reflecting
- Temperature compatible



200 kg prototype



(40cm x 40cm) Chamber

- $2\nu\beta\beta$ in xenon has never been seen
- Resolve ambiguous ^{76}Ge result
- Verification of materials and technology
- LXe TPC with Avalanche Photo Diode (APD) scintillation readout
- Underground installation summer '05
- 2-3 years runtime

200 kg prototype

Assumptions:

1) 200 kg of 80% enriched ^{136}Xe
2) Finite background: 20 events/year in ±2σ interval around 2.481 MeV endpoint
3) 2ν mode contribution negligible

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactivity Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡ (NSM)#	
Prototype	0.2	70	2	1.6*	40	$6.4*10^{25}$	180	(530)

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For $\langle m_\nu \rangle = 0.44$ eV, ±3σ range (0.24 - 0.58 eV)

(ie. Phys. Lett. B 586 (2004) 198-212)

Case	Mass	Eff.	Time	σ_E/E	Background	Signal	Error
<m>=.44 eV	0.2	70	2	1.6*	40	57	9.0 σ
<m>= .24 eV	0.2	70	2	1.6*	40	17	2.7 σ

Russian ultra-centrifuge

- Centrifuge efficiently cuts ^{87}Kr backgrounds
- Russia has the capacity to process 100 tons of Xe
- The price is right

Enriched Xenon

First 200 kg pilot production started in the Summer of 2001 and was successfully completed in May 2003

Funding by DoE-EM, Stanford and University of Alabama

In-kind natural Xe contribution by ITEP

This is already the largest non-fissile isotope enrichment program ever accomplished…

Waste Isolation Pilot Plant (WIPP) Carlsbad, NM

Conclusions

- Broad R&D effort underway for a multi-ton xenon detector
- 200 kg prototype to be commissioned summer '05
- milli-eV neutrino majorana mass sensitivity

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡ (NSM)#	
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	33	(95)
Aggressive	10	70	10	1	0.7 (use 1)	$4.1*10^{28}$	7.3	(21)