WIMPS, 0-ν $\beta\beta$ decay & xenon

High-pressure ^{136}Xe Gas TPC: An emerging opportunity

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Outline

- 0-ν $\beta\beta$ decay & WIMPs
- Premise and Conclusion
- Background rejection
- Energy resolution
- TPC options - new and evolving
- Scaling to the 1000 kg era
- Synergy revisited
- Perspective

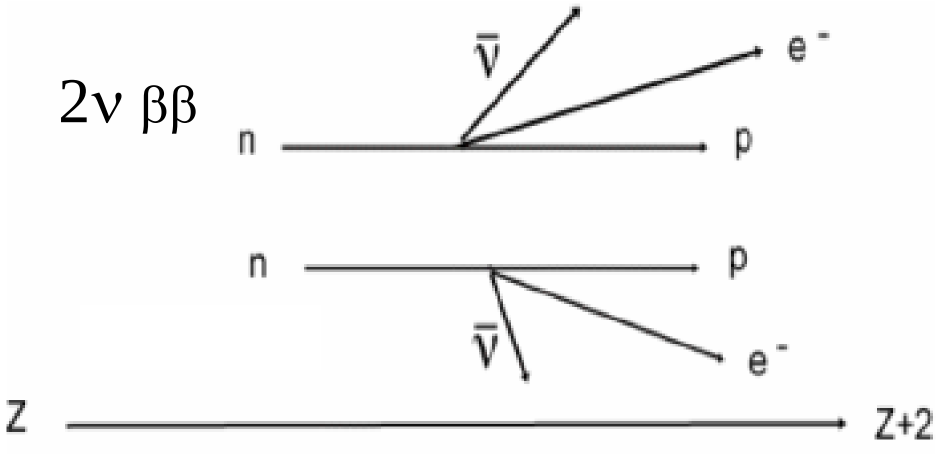
WIMPs

- Dark matter: ~25% of universe mass
  - visible ordinary matter: ~1%
  - invisible ordinary matter $\leq$4%
  - WIMPs - lightest supersymmetric particle?
    - Mass range: ~100 - 1000 GeV/c^2
    - Interaction strength not pinned down
    - Recoil energy: ~ 10 - 100 keV

Very robust evidence shall be required!

Two Types of Double Beta Decay

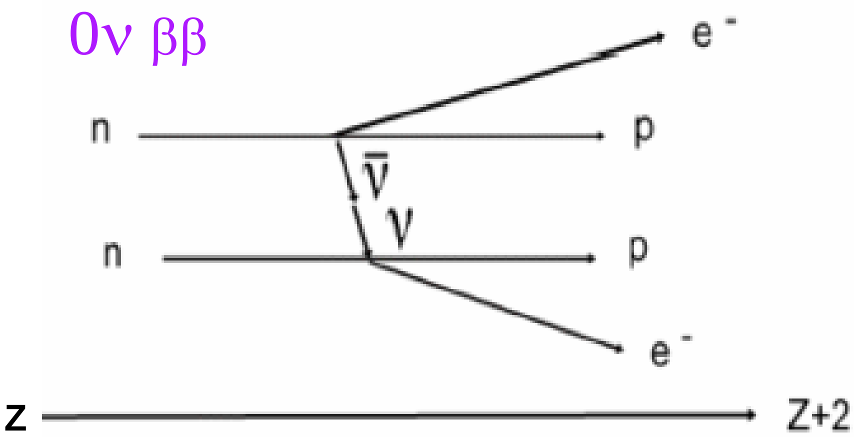
$2\nu\ \beta\beta$



A known standard model process and an important calibration tool

$$T_{\frac{1}{2}} \approx 10^{19}\ yrs.$$

$0\nu\ \beta\beta$



Neutrinoless double beta decay.

If this process is observed:

Neutrino mass ≠ 0

Neutrino = Anti-neutrino!

Lepton number is not conserved!

$$\frac{1}{T_{\frac{1}{2}}} = G \times \|\mathrm{M}\|^2 \times m_{\bar{\nu}}^{\ 2}$$

Neutrinoless double beta decay lifetime

Neutrino effective mass

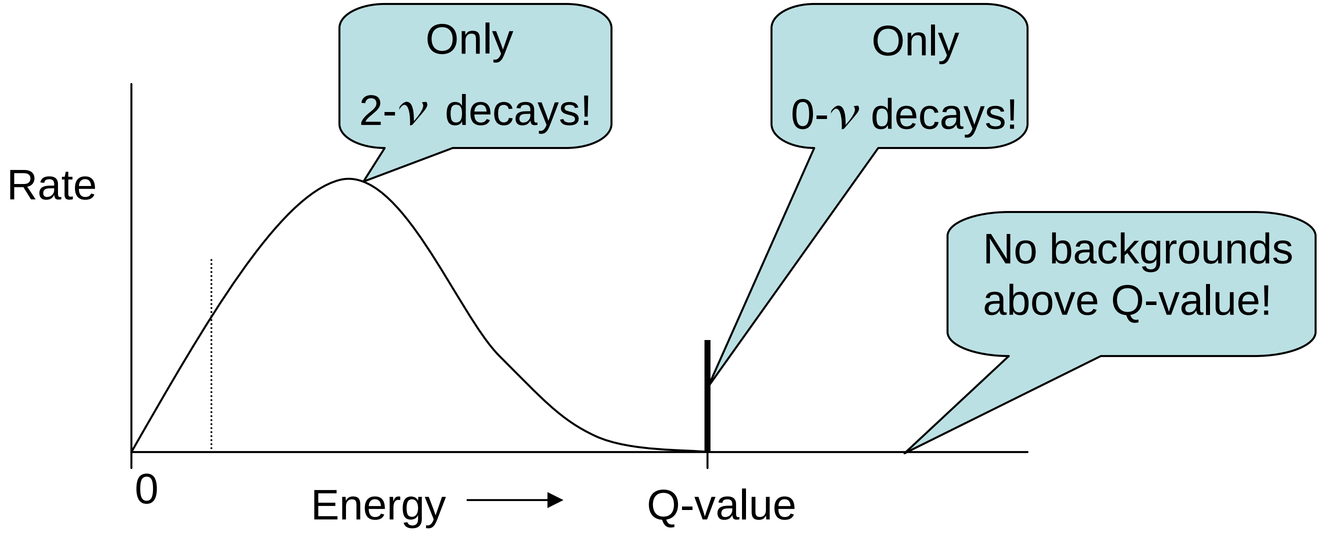
Premise:

- An attempt to optimize a detector for a 0-ν $\beta\beta$ decay search in ^{136}Xe has led me to the following three conclusions:
  - High-pressure xenon **gas** (HPXe ~20 bar) appears much better than liquid xenon (LXe)
  - Optimized energy resolution may require a **proportional scintillation** readout plane
  - Result: **An optimum WIMP detector too!**

Two Identical HPXe TPCs

- **“ββ Detector”**
  - Fill with enriched Xe mainly ^{136}Xe
  - Isotopic mix is mainly even-A
  - Events include all ββ events + background
  - WIMP events include more scalar interactions
- **“WIMP Detector”**
  - Fill with normal Xe or fill with “depleted” Xe
  - Isotopic mix is ~50% odd-A: ^{129}Xe ^{131}Xe
  - Events include only backgrounds to ββ
  - WIMP events include more axial vector interactions

Double beta decay



A robust experimental result is a spectrum of all $\beta\beta$ events, with very small or negligible backgrounds.

Perils of backgrounds

- Sensitivity to active mass M changes if backgrounds begin to appear:
  - $m_{\nu} \sim \{1/MT\}^{1/2}$
  - $m_{\nu} \sim \{(b\delta E)/MT\}^{1/4}$

Ouch!

    - b = number of background events/unit energy
    - δE = energy resolution of detector system

Current Status

- Present status (partial list):
  - Heidelberg-Moscow (^{76}Ge) result: $\langle m_\nu \rangle$ = **440 $^{+14}_{-20}$** meV - *disputed!*
  - Cuoricino (^{130}Te): taking data, but - background limited...
  - EXO (^{136}Xe): installation stage, but - $\delta E/E$ shape/resolution issue...
  - GERDA (^{76}Ge): under construction at LNGS
  - Majorana (^{76}Ge): proposal & R&D stage
  - NEMO $\rightarrow$ Super-NEMO (foils): proposal & R&D stage
- Global synthesis: Σm_i < 170 meV (95% CL)*

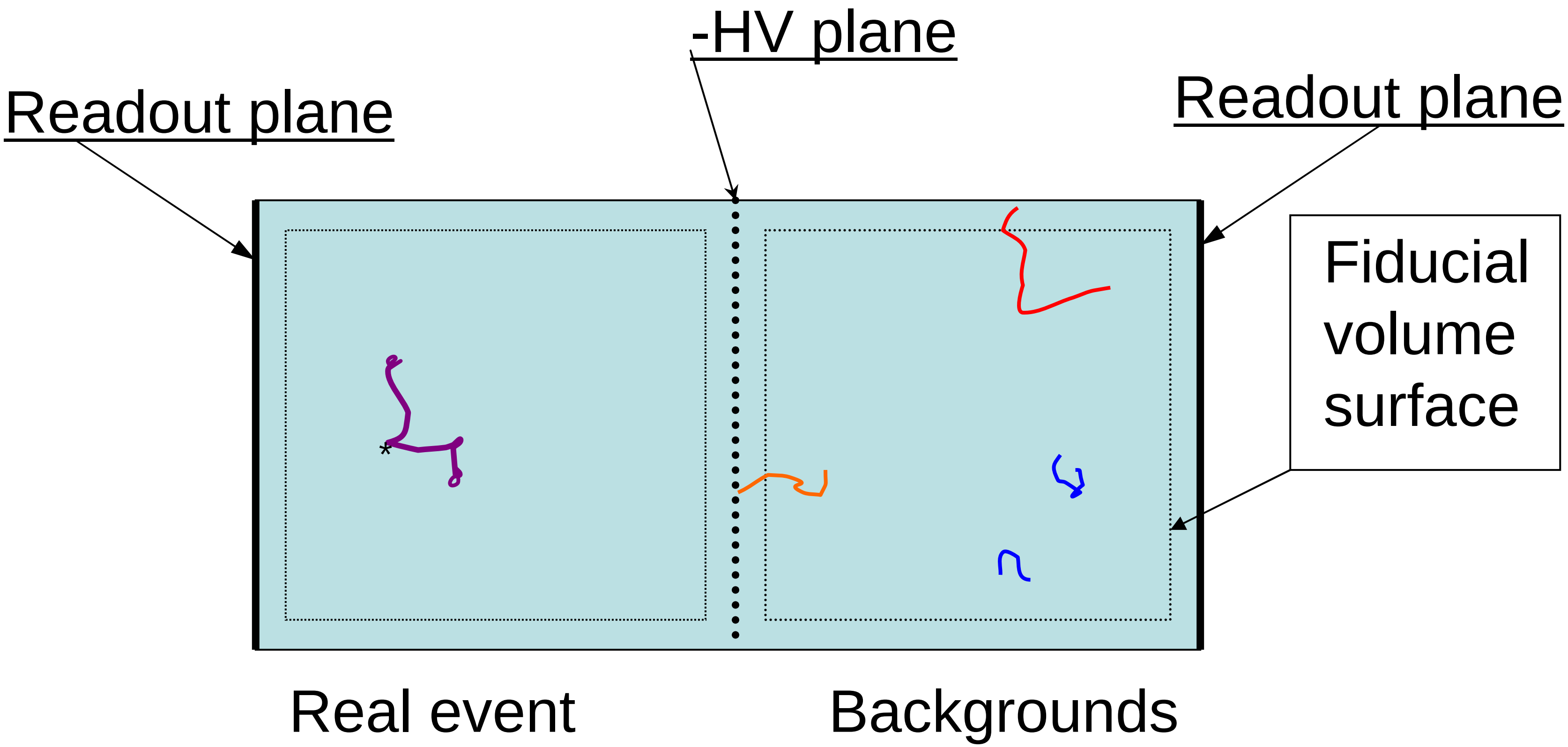
  $\Rightarrow$ 100's to 1000 kg active mass likely to be necessary!
  - Rejection of internal/external backgrounds in ~10^{27} atoms!
  - Excellent energy resolution: $\delta E/E$ <10 x 10^{-3} FWHM - at least!
- Target (from oscillations): $\langle m_{\beta\beta} \rangle$ ~50 meV

*Mohapatra & Smirnov 2006 *Ann. Rev. Nucl. Sci.* **56** - (other analyses give higher values)

Background rejection

- With a TPC, a fiducial volume surface can be defined with all the needed characteristics:
  - deadtime-less operation
  - fully closed
  - 100% active - no partially sensitive surfaces
  - surface is variable *ex post facto*
- Charged particles: cannot penetrate fiducial surface unseen; 100.0% rejection
- γ-rays (most serious source, and needs work)
  - photo-conversion fluorescence: 85% (λ ~1 cm @ 20 bar)
  - multiple Compton events more likely at large scale
- Neutrons: to get self-shielding, bigger is better

HPXe TPC Fiducial volume



EXO-200: LXe TPC

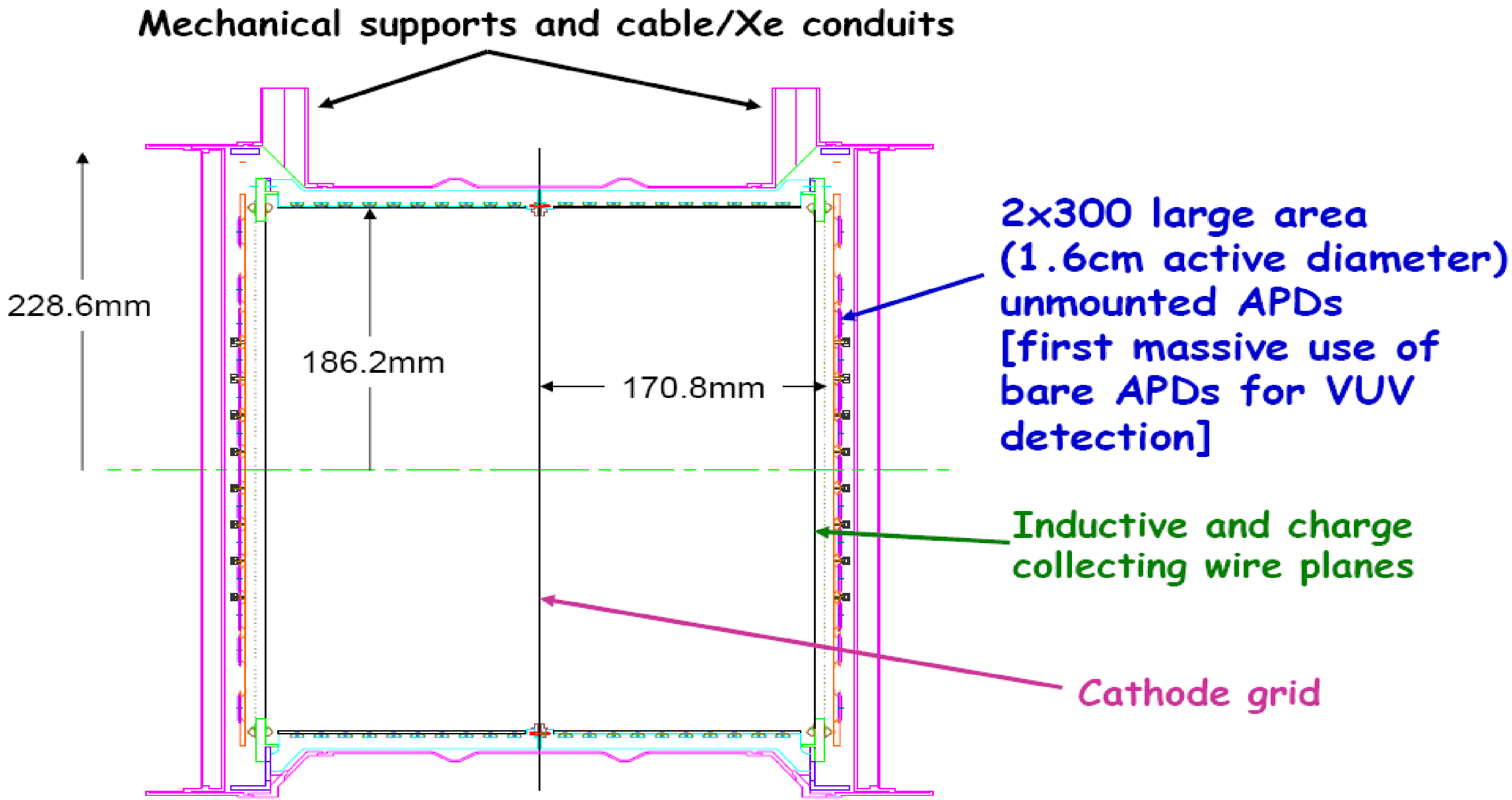
Installation now, at WIPP:

- 200kg of 80% enriched ^{136}Xe
- Liquid xenon TPC
- Localization of the event in x,y,z (using scintillation for T_0)
- APDs used to detect scintillation
- Strong anti-correlation of scintillation & Ionization components
- Expect $\delta E/E$ = 3.3% FWHM for $0\nu\beta\beta$

For a subsequent phase of experiment:

- Barium daughter tagging by optical spectroscopy
- Liquid or gas under consideration
- Can this work?

EXO Experimental Design

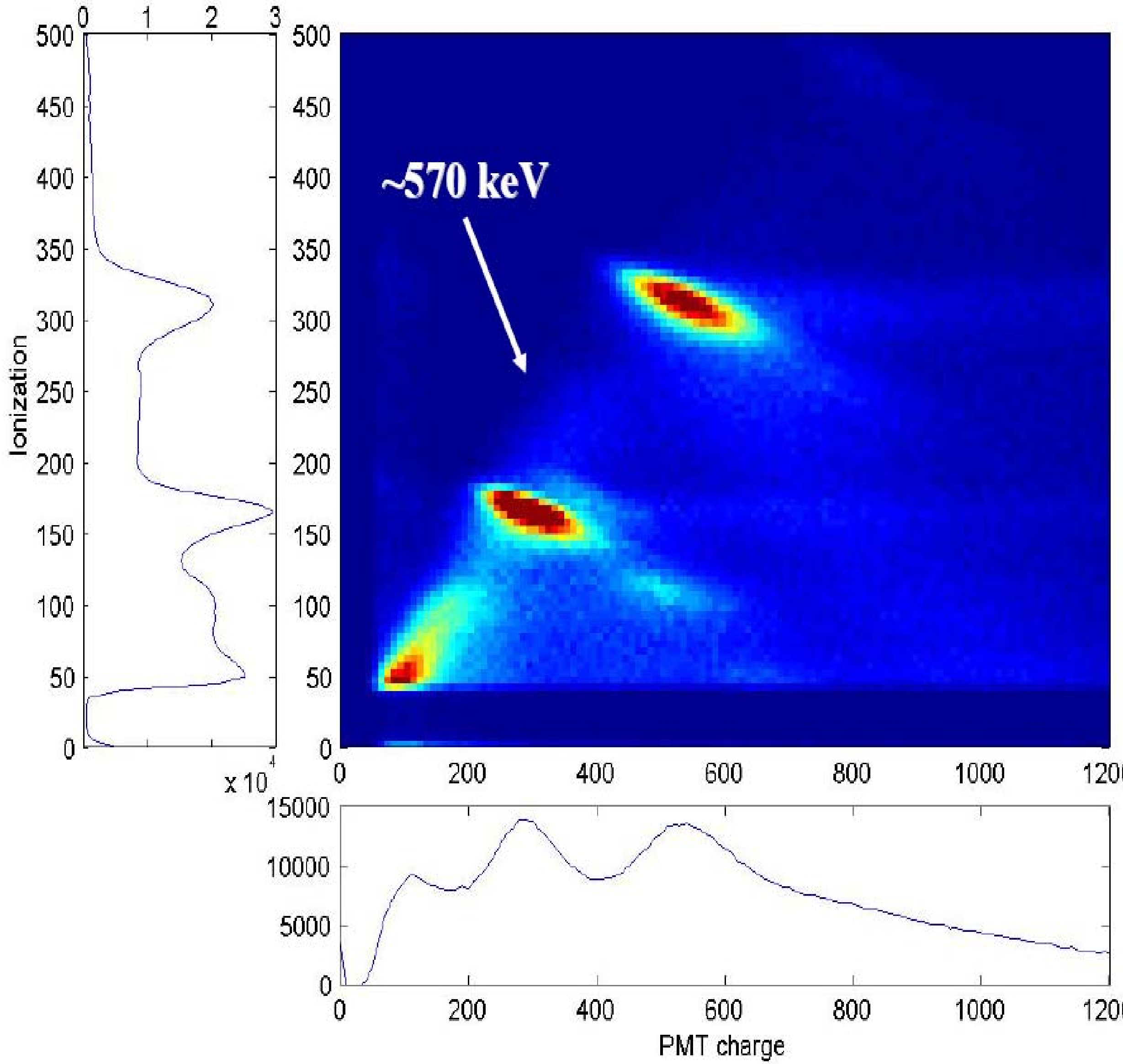


EXO:

•Strong anti-correlation observed between scintillation and ionization signals

•Anti-correlation also observed in other LXe data

□$\delta E/E$ = 3.3% FWHM for $0\nu-\beta\beta$, expected resolution (2480 KeV)



Energy resolution in xenon shows complexity: ionization↔scintillation

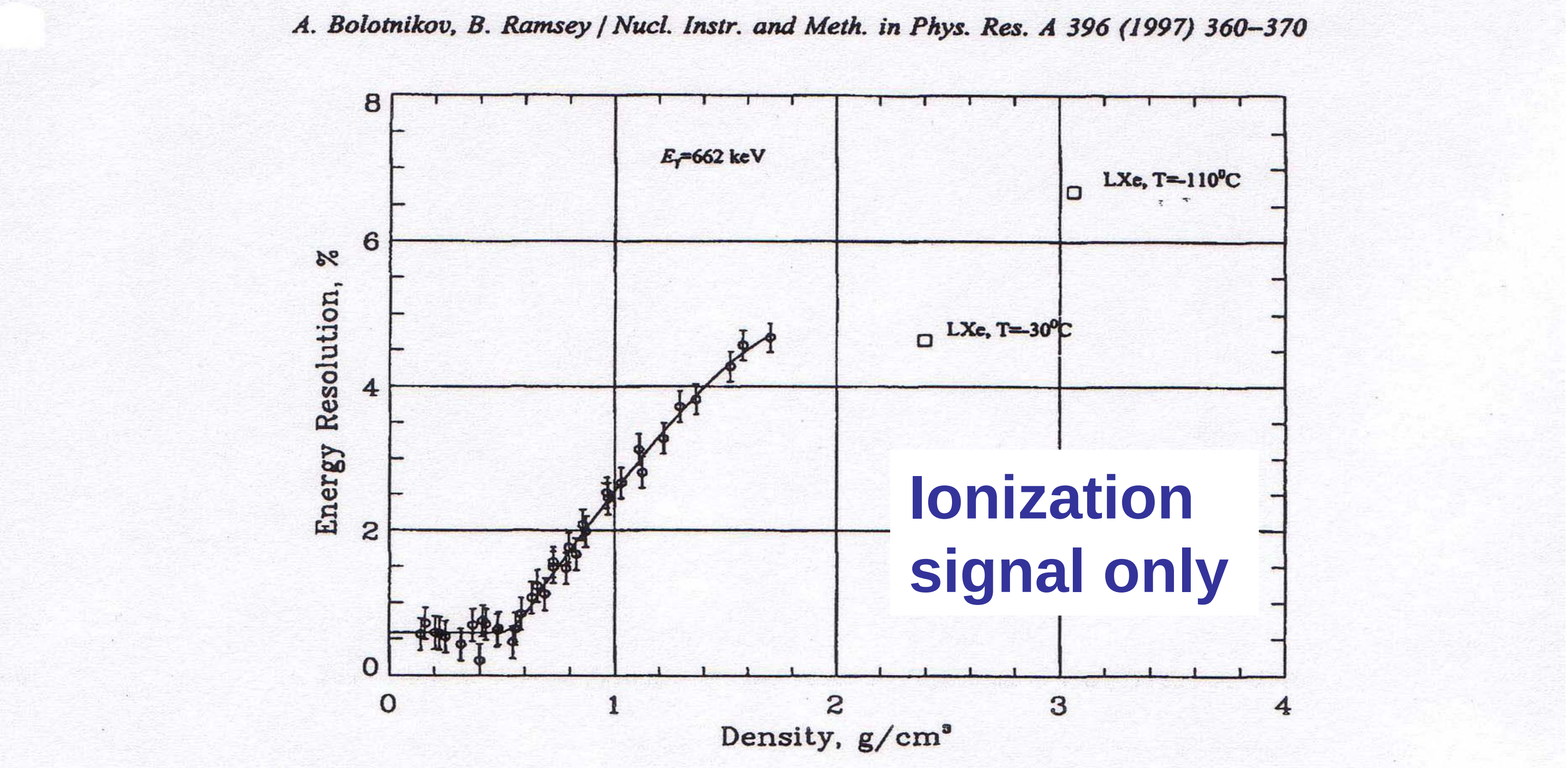


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For $\rho > 0.55$ g/cm^3, energy resolution deteriorates rapidly

Molecular physics of xenon

- Processes not understood completely*...
  - Ionization process creates regions of high ionization density in very non-uniform way
  - As density of xenon increases, aggregates form, with a localized conduction band
  - Recombination is ~ complete in these regions
  - Excimer formation Xe_2^* can lead to delayed scintillation and even ionization...
  - Density dependence of signals is strong

*certainly not by me!

Impact for WIMP search?

- But...wait a second! WIMP searches in LXe **use** the ratio

$$\frac{\text{Primary ionization } (S_2)}{\text{Primary scintillation } (S_1)}$$

to discriminate nuclear from electron recoils

$$(S_2/S_1)_{\text{nuclear}} \ll (S_2/S_1)_{\text{electron}}$$

Impact for WIMP Search...

The anomalous fluctuations in LXe directly degrade the nuclear recoil discriminant S_2/S_1!

Maybe HPXe would be better! ...but

Do the fluctuations depend on

1. atomic density?
2. ionization density?
3. both?

Many γ-induced events reach down to nuclear band in plots of S_2/S_1 versus energy

Gamma events

QuickTime™ and
TIFF (LZW) decompre
are needed to see this pi

Neutron events

“Intrinsic” energy resolution for HPXe ($\rho < 0.55$ g/cm^3)

Q-value of ^{136}Xe = 2480 KeV

W = ΔE per ion/electron pair = 22 eV (depends on E-field)

N = number of ion pairs = Q/W

N $\approx 2.48 \times 10^6$ eV/22 eV = 113,000

$\sigma_N^2 = FN$ (F = Fano factor)

F = 0.13 - 0.17 for xenon gas $\Longrightarrow$

$\sigma_N = (FN)^{1/2} \sim 130$ electrons rms

$\underline{\delta E/E = 2.7 \times 10^{-3}}$ FWHM (intrinsic fluctuations only)

(Ge diodes better by only a factor of ~2.5)

(LXe Fano factor: ~20)

Energy resolution issues in traditional gas detectors

- Main factors affecting ionization:
  - Intrinsic fluctuations in ionization yield
    - Fano factor (partition of energy)
  - Loss of signal
    - Recombination, impurities, grids, quenching,
  - Avalanche gain fluctuations
    - Bad, but wires not as bad as one might imagine...
  - Electronic noise, signal processing, calibration
    - Extended tracks $\Rightarrow$ extended signals

Loss of signal

Fluctuations in collection efficiency ε introduce another factor $L = 1 - \varepsilon$ (similar to Fano's)

$$\sigma_N{}^2 = (F + L)N$$

- Loss on grids is small: $L_{grid} < F$ seems reasonable
  - If $L_{grid} = 5\%$, then **$\delta E/E = \sim 3 \times 10^{-3}$ FWHM**
- Other sources of L include:
  - Electronegative impurities that capture electrons
  - Recombination - track topology, ionization density
  - Quenching - of both ionization and scintillation!

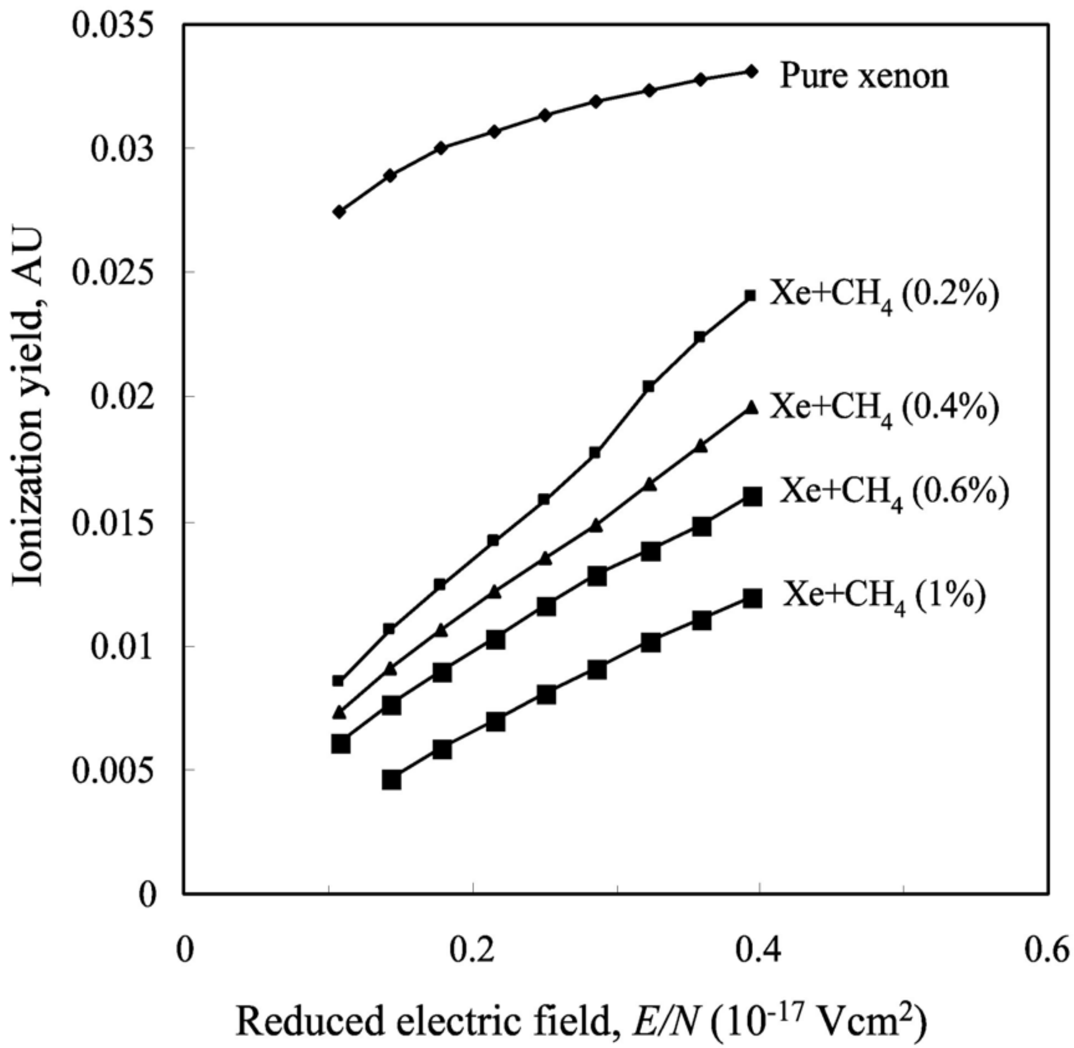


Fig.7. Dependence of ionization yield on reduced electric field (E/N) at a pressure of 2.6 MPa.

Surprising result: adding tiny amount of simple molecules - (CH_4, N_2, H_2 …) - quenches ionization, not just scintillation!

Gotthard TPC: 4%

α dE/dx is very high, so exact impact for βparticles and nuclear recoils is not so clear

K. N. Pushkin *et al,* IEEE Nuclear Science Symposium proceedings 2004

Avalanche gain

– Gain fluctuations: another factor, “G”

- $\sigma_N = ((F + G)N)^{1/2}$ $\quad 0.7 < G < 0.9$ *
- $\sigma_N = ((0.15 + 0.85)N)^{1/2} = 337$
- δ**E/E = 7.0 x 10^{-3}** FWHM - not bad, **but**:
- No more benefit from a small Fano factor
- Very sensitive to density (temperature)
- Monitoring and calibration a big effort
- Space charge effects affect gain dynamically
- Micromegas may offer smaller G

*Alkhazov G D 1970 *Nucl. Inst. & Meth.* **89** (for cylindrical proportional counters)

“Conventional” TPC

- Pure xenon (maybe a tiny molecular admixture...)
  - Modest avalanche gain is possible
  - Diffusion is large, up to ~1 cm @ 1 meter
  - drift velocity very slow: ~1 mm/μs
  - Add losses, other effects,…

$$\sigma_N = ((F + G + L)N)^{1/2}$$

$$\delta \mathbf{E/E} \ \boldsymbol{\sim 7 \times 10^{-3}} \ \text{FWHM}$$

Avalanche gain may be OK, but can it be avoided?

“Ionization Imaging” TPC

1. **<u>No avalanche gain</u>** analog readout (F + L)
    - dn/dx ~ 1.5 fC/cm: ⇒ ~9,000 (electron/ion)/cm
    - gridless “naked” pixel plane (~5 mm pads)
    - **very high operational stability**
    - ⇒ $\delta E/E = 3 \times 10^{-3}$ FWHM (F + L only)
    - Complex signal formation

– but, electronic noise must be added!

- 50 pixels/event @ 40 e^- rms ⇒ N ~280 e^- rms
- $\delta E/E$ = **7×10^{-3} FWHM**
- **Need waveform capture too**

Ionization imaging: Very good, but need experience

"Negative Ion" TPC

"Counting mode" = digital readout, (F + L)

– Electron capture on electronegative molecule
– Very slow drift to readout plane;
– Strip electron in high field, generate avalanche
– Count each "ion" as a separate pulse:
  - Ion diffusion much smaller than electron diffusion
  - Avalanche fluctuations don't matter, and
  - Electronic noise does not enter directly, either
  - Pileup and other losses: L~ 0.04 ?
  - **$\delta E/E = \sim 3 \times 10^{-3}$ FWHM**

– Appealing, but no experience in HPXe...

Proportional Scintillation (PS): "HPXe PS TPC"

- Electrons drift to high field region
  - Electrons gain energy, excite xenon, make UV
  - Photon generation up to ~1000/e, but no ionization
  - Multi-anode PMT readout for tracking, energy
  - PMTs see primary and secondary light
- New HPXe territory, but real incentives exist
  - Sensitivity to density smaller than avalanche
  - Losses should be very low: $L < F$
  - **Maybe: $G \sim F$** ?

H. E. Palmer & L. A. Braby

Nucl. Inst. & Meth. **116** (1974) 587-589

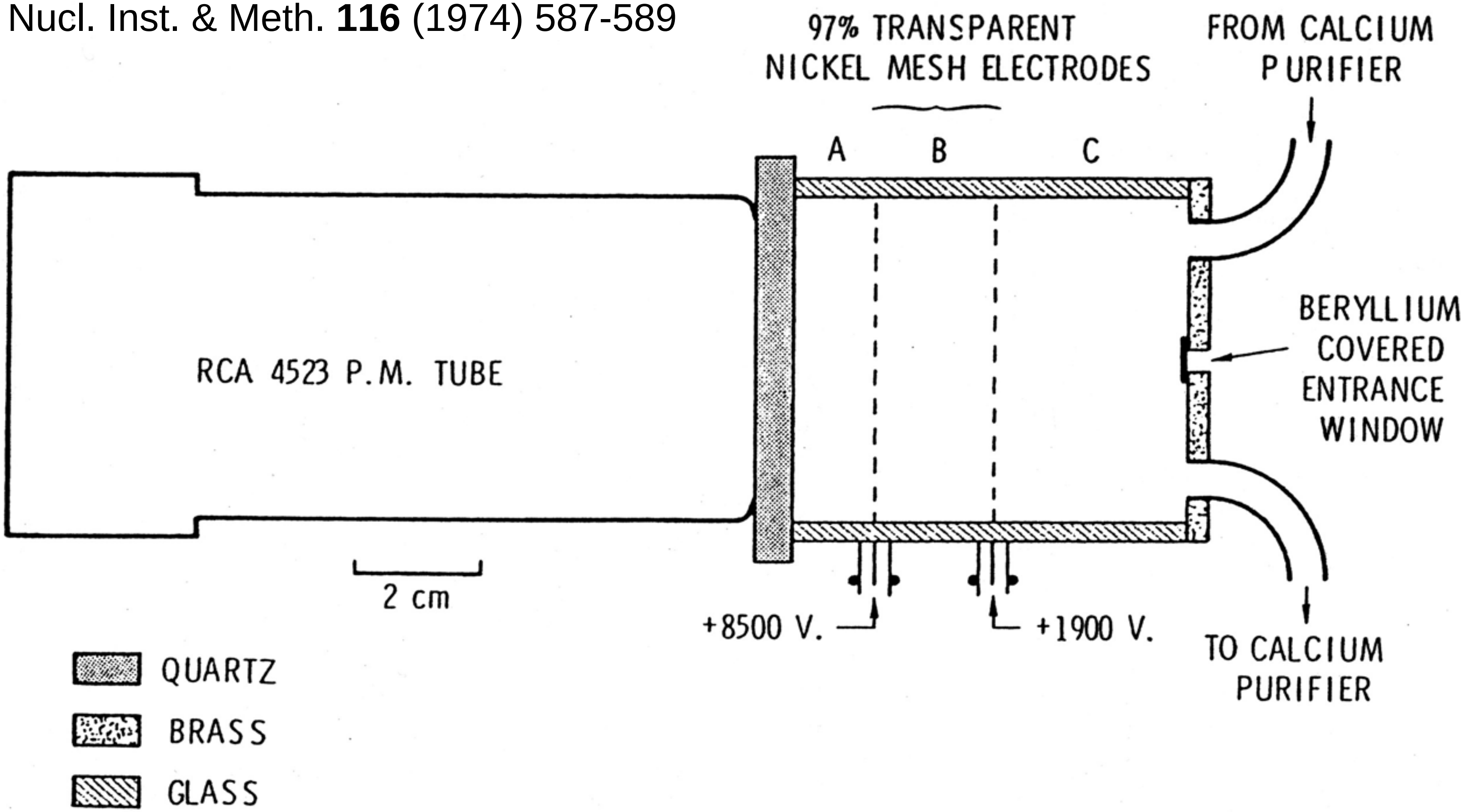


Fig. 1. Sketch of 5 cm diameter parallel plate gas scintillation proportional counter.

From this spectrum: **G ~0.19**

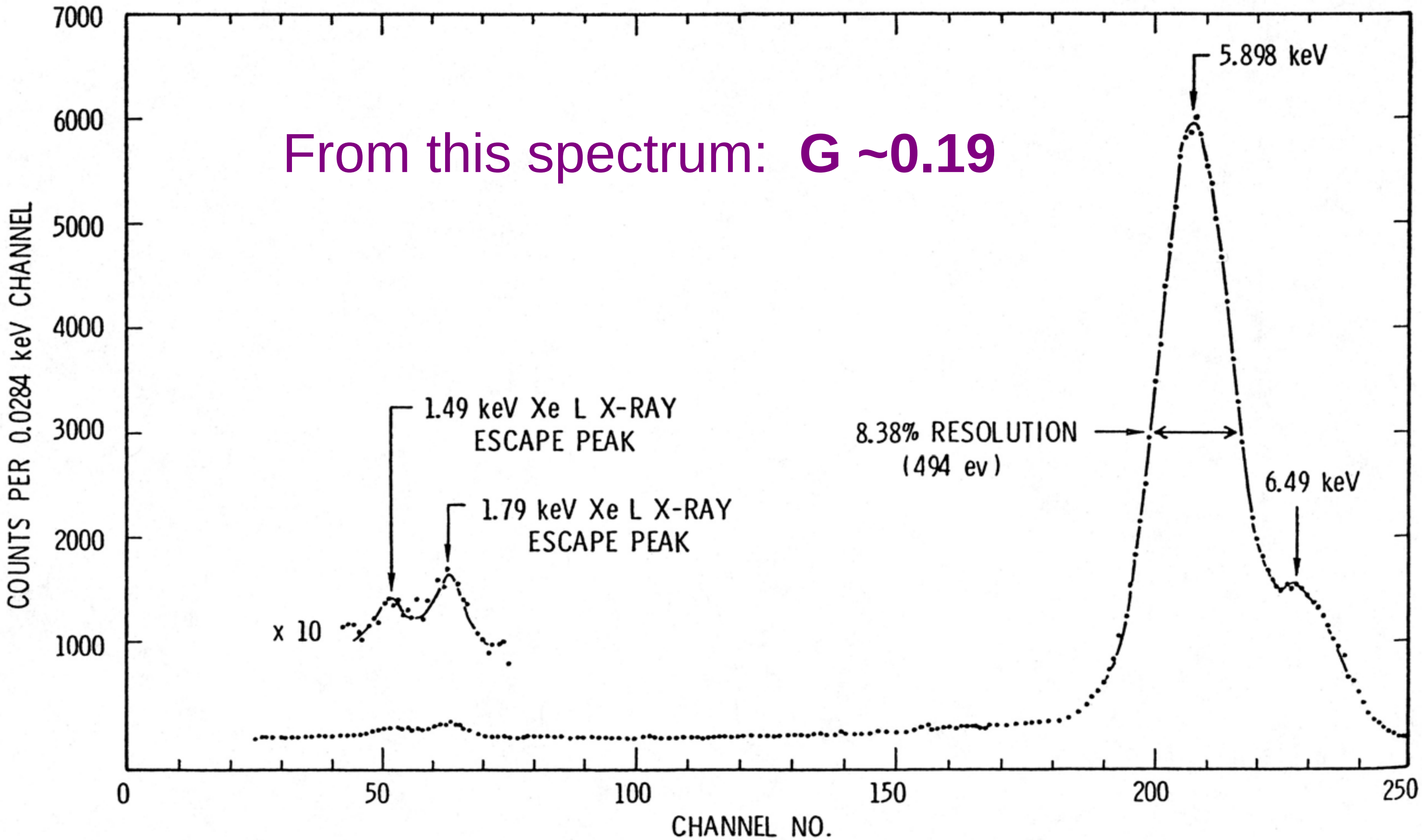


Fig. 2. Pulse-height spectra of an ^{55}Fe source from a parallel plate gas scintillation proportional counter.

Fluctuations in Proportional Scintillation Detectors

- **G** for PS contains three terms:
  - Fluctuations in $n_{\mathbf{uv}}$ (UV photons per e): $\sigma_{\mathbf{uv}} = 1/\sqrt{n_{\mathbf{uv}}}$
    - $\mathbf{n_{uv}}$ ~ HV/E_γ = 6600/10 eV **~ 660**
  - Fluctuations in $n_{\mathbf{pe}}$ (detected photons/e): $\sigma_{\mathbf{pe}} = 1/\sqrt{n_{\mathbf{pe}}}$
    - $\mathbf{n_{pe}}$ ~ solid angle x QE x $n_{\mathbf{uv}}$ x 0.5 **= 0.1 x 0.2 x 660 x 0.5 = 7**
  - Fluctuations in PMT single PE response: $\sigma_{\mathbf{pmt}}$ **~** 0.3

$$\mathbf{G = 1/(}n_{\mathbf{uv}}\mathbf{) + (1 + \sigma^2_{pmt})/}n_{\mathbf{pe}}\mathbf{) \sim 0.16}$$

Assume G + L **=** F, then

Ideal energy resolution (σ^2 = (F + G + L) x E/W):

$$\delta \mathbf{E/E = \sim 4 \times 10^{-3}\ FWHM}$$

HPXe PS TPC is the "Optimum" $\beta\beta$ detector

- Readout plane is high-field layer with PMT array
  - Transparent grids admit both electrons and UV scintillation
  - Multi-anode PMT array "pixels" match tracking needs
  - Two-stage gain: optical + PMT: Noise < 1 electron!
  - No secondary positive ion production
  - Much better stability than avalanche gain
- Major calibration effort needed, but should be stable
  - Beppo-SAX: 7-PMT HPXe (5 bar) GPSC <u>in space</u>
- Alternatives (and R&D projects):
  - CsI on mesh, SiPMT, ITO on quartz, mirrors...

Some Gas Issues:

– Large diffusion in pure xenon
  - Tracking good enough? (I think so…)
  - Integration of signal over area? (needs some study)
  - Role of additives such as: H_2 N_2 CH_4 ?
    – quenching of β signals by molecular additives?
    – small fraction of 1% molecular additive probably OK...

– Role of neon (must add a lot)
  - to increase drift velocity?
  - to diminish bremmstrahlung?
  - to diminish multiple scattering?
  - to facilitate topology recognition by B field?
  - to add higher energy WIMP-nuclear recoil signals?

More issues

- Operation of PS at 20 bar? should work...
- Operation of PS with neon? should work...
- Detection of xenon 30 keV K-shell fluorescence from γ's
  - $\lambda \approx 1$ cm @ $\rho = 0.1$ g/cm^3 $\Rightarrow$ lower density?)
- Detection of xenon primary UV scintillation (175 nm - 7 eV)
  - $n_{\mathbf{electrons}} \approx n_{\mathbf{photons}}$ (depends on E-field, particle, etc)
  - 0-ν $\beta\beta$ decays (Q = 2480 keV): No problem!
  - WIMP signals (10 - 100 keV): <u>Need very high efficiency</u>!

$\Rightarrow$ **Design must be augmented for primary UV detection**

Add mirror to cathode (corner reflectors?)

Add scintillator bars or reflective surfaces along sides

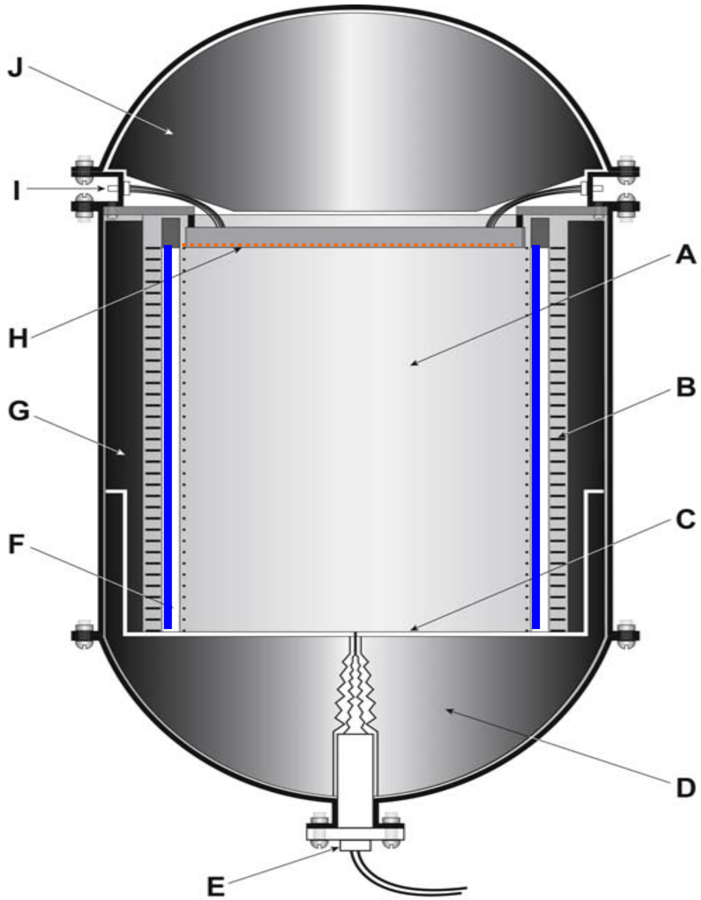
This appears to be the only WIMP enhancement needed

Scaling to 1000 kg

- Minimum S/ V for cylindrical TPC: $L = 2r$
- Fixed mass M & track size ℓ:
  - $\ell/L \propto \rho^{-2/3}$
  - higher density $\Rightarrow$ less leakage
- High voltage $\propto L \propto M^{1/3}$ (fixed ρ)
- Number of pixels involved in event:
- diffusion $\propto L^{1/2}$ so: very little change

Excellent Scaling - higher M is better!

1000 kg Xe: ∅ = 225 cm, L =225 cm
ρ ~ 0.1 g/cm^3 (~20 bars)



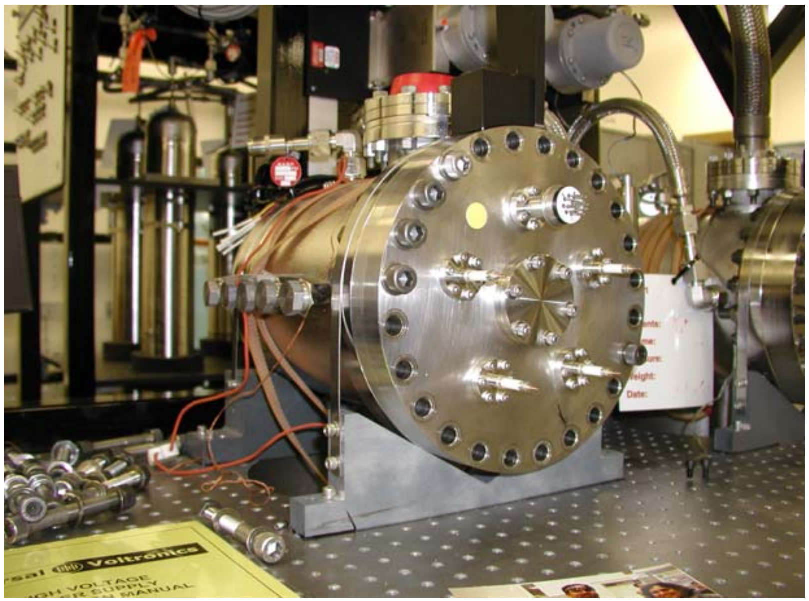
A. Sensitive volume filled with xenon at density ρ = 0.1 g/cm^3 ~20 bars pressure @ 300^o K
B. Field cage, comprised of rings to establish uniform equipotential surfaces;
C. Cathode plane, at negative HV;
D. Neutron absorber, HV insulator, and filler to force xenon into active volume - possibly polyethylene;
E. HV module, or feedthrough;
F. Plastic scintillator or wave-shifter bars to convert UV scintillation for event start time signal and optimize WIMP S_1 signal;
G. HV insulator, neutron absorber, and filler, as in d;
H. Readout plane, with PMTs, electronics;
I. Annular ring supporting service feedthroughs and data flow;
J. Neutron absorber, and filler.

HPXe PS TPC is the "Optimum" WIMP detector!

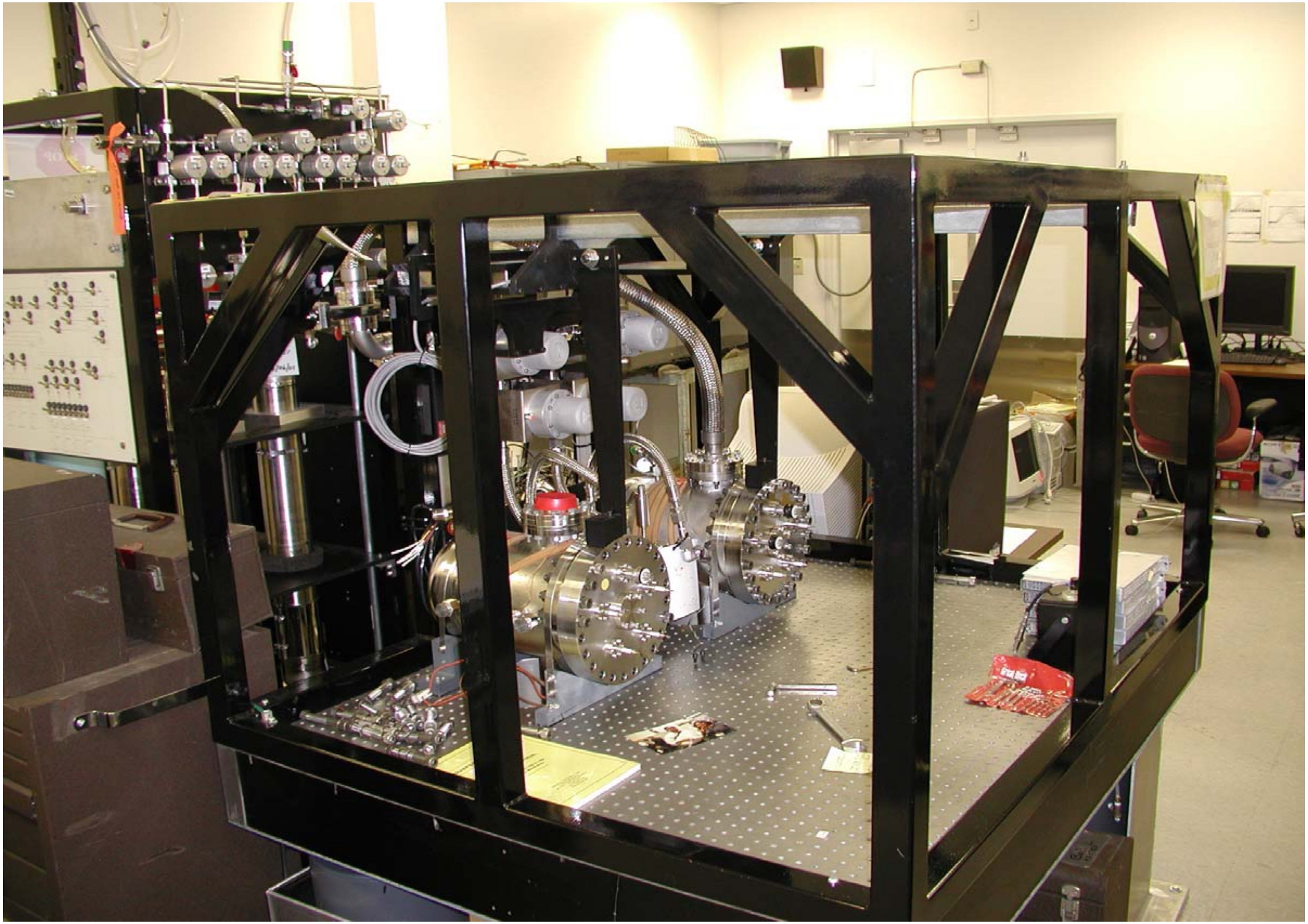
– Do the fluctuations persist in nuclear recoils at HPXe densities of interest?
    - Yes, but with a threshold density $\rho \sim 0.2$ g/cm^3
    - For $\rho \sim 0.1$ g/cm^3, **~0** anomalous fluctuations

– Can we bridge the dynamic range?
    - Yes, $\beta\beta$ instantaneous signal is ~100 keV
    - Optimum density may be $\rho < 0.1$ g/cm^3

One HPXe System at LLNL



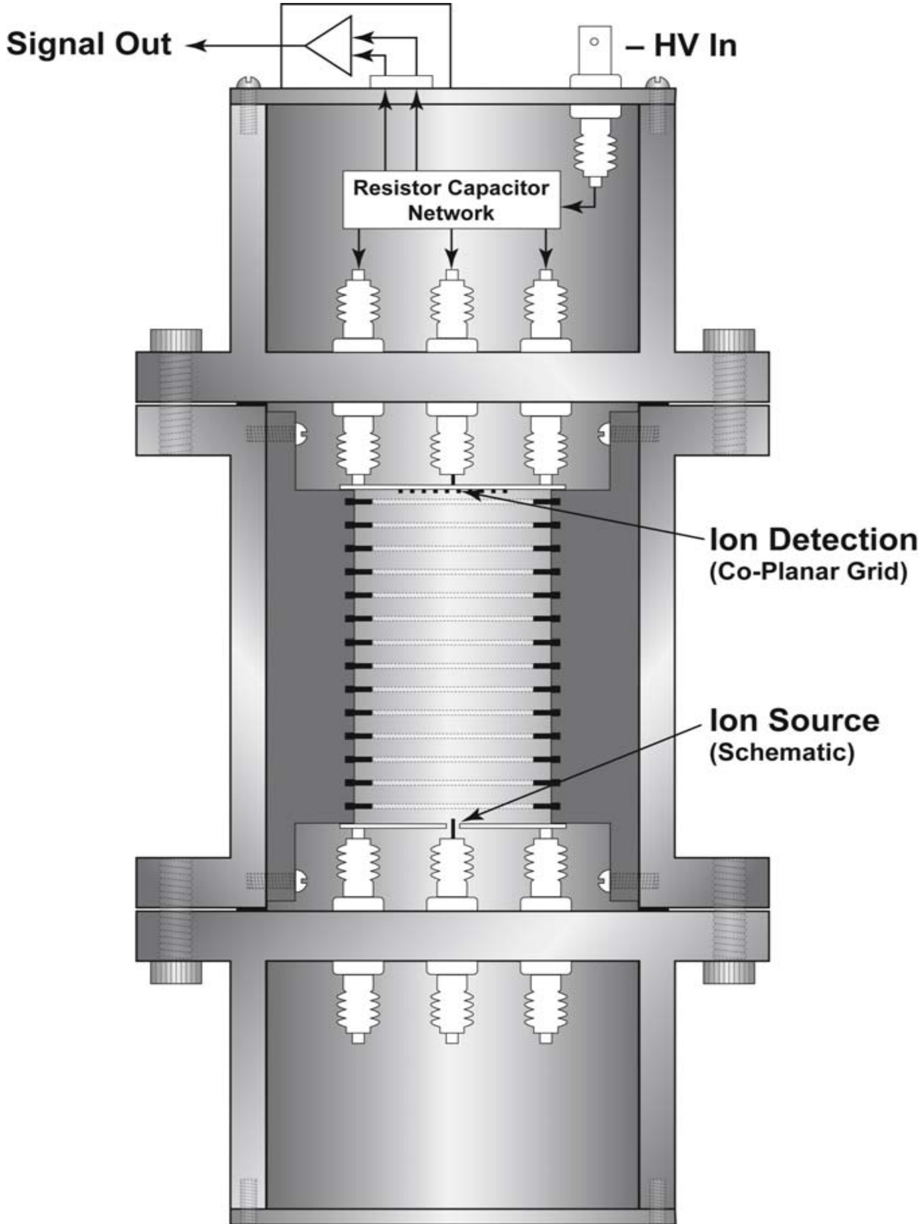
- Built for Homeland Security
- γ spectroscopy goals
- Dual 50 bar chambers!
- Bake-out, with pump
- Gas purification
- Gas storage
- Perfect R&D platform
- Pixel readout modifications underway now, not many $
- NSF and DOE proposals awaiting decision



Barium daughter tagging and ion mobilities…

- Ba and Xe mobilities are quite different!
  - The cause is **<u>resonant charge exchange</u>**
  - RCE is macroscopic quantum mechanics
    - occurs only for ions in their parent gases
    - no energy barrier exists for Xe^+ in xenon
    - energy barrier exists for Ba ions in xenon
    - RCE is a long-range process: $R >> r_{atom}$
    - glancing collisions = back-scatter

RCE <u>increases viscosity</u> of majority ions



The barium daughter, whether singly charged or doubly charged, will move to the HV cathode at a higher velocity than the majority xenon ions.

This could offer a way to tag the “birth” of barium in the decay, perhaps by sensing an echo pulse if the barium ion causes a secondary emission of electrons at the cathode.

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  - Isotopic mix is ~50% odd-A: ^{129}Xe ^{131}Xe
  - Events include only backgrounds to ββ
  - WIMP events include more axial vector interactions

Perspective

It is extremely rare that two challenging physics goals are not only met, but enhanced, by the realization of two identical detector systems, differing only in isotopic content.

Because the impact of success would be so significant, and costs so large, this approach needs to be taken seriously, if correct.

Can two distinct communities collaborate?

Thanks to:

- Azriel Goldschmidt - LBNL NSD
- John Kadyk - LBNL Physics
- Adam Bernstein - LLNL
- Mike Heffner - LLNL
- Jacques Millaud - LLNL
- Leslie Rosenberg - U Washington
- Cliff Hargrove - Carleton
- Madhu Dixit - Carleton
- Jeff Martoff - Temple
- Alexey Bolotnikov - BNL
- Gianluigi De Geronimo - BNL

Thank you!