0-neutrino Double-beta Decay and WIMPs:

Will the Search Converge?

David Nygren

LBNL / Stockholm U

Two scientific curiosities - both born in the 1930’s

- **Zwicky:** “The stars near the edges of galaxies are moving much faster than they should be! There must be a lot more matter than we can see.”

- **Goeppert-Mayer:** “It is possible for some nuclei to decay by simultaneous emission of two electrons and two neutrinos, a double beta decay.”

History

- **Dark matter didn't go away:**
  – Only in 1970's did this very startling observation begin to be studied seriously. Still unknown…
  – Simulations of the development of large scale structure require the presence of dark matter.
- **And, dark energy appeared, too!**
  – Type IA supernovae, acting as "standard candles" revealed the expansion history of the universe
- **Cosmology became a quantitative science**

Concordance

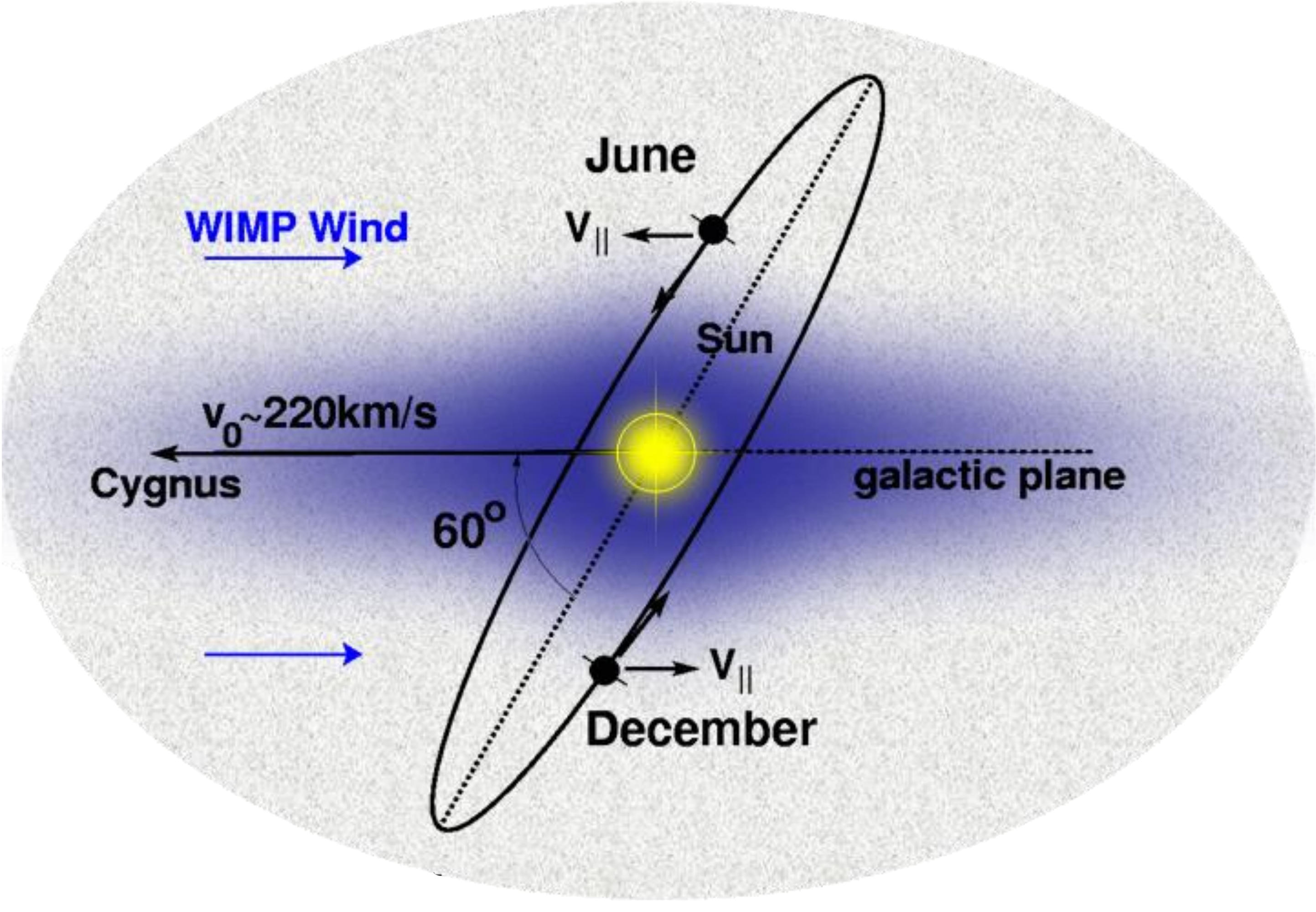
- From WMAP (cosmic μ-wave) + Sn +…
  - Age of Universe: 13.73 ± 0.12 Gyr
  - Total energy density: $\Omega = 1.0052 \pm 0.0064$
  - Dark energy density: $\Omega_\Lambda = 0.721 \pm 0.015$
  - Dark matter density: $\Omega_{DM} = 0.233 \pm 0.013$
  - Baryons $\Omega_b = 0.0462 \pm 0.0015$
  - Neutrinos: **$\sum m_\nu < 0.61$ eV** (three families)

  But there are ~10^9 relic neutrinos for each baryon, so the total ν mass could be $\approx \sum$all visible matter

What is the Dark Matter?

- **No strong or electromagnetic interactions**
  - Gravity for sure, and probably weak, too.
  - Many theoretical possibilities have been advanced
  - Popular: the “Weakly Interacting Massive Particle”
  - Might be the “Neutralino” of supersymmetry (TeV)
- **Can WIMPs be detected?**
  - Direct: WIMP-nuclear recoils transfer 5 - 50 keV
  - Indirect: annihilation in sun, earth, galactic center $\rightarrow$ multi-GeV γ’s {GLAST}, or ν’s {IceCube}

Where is the Dark Matter?



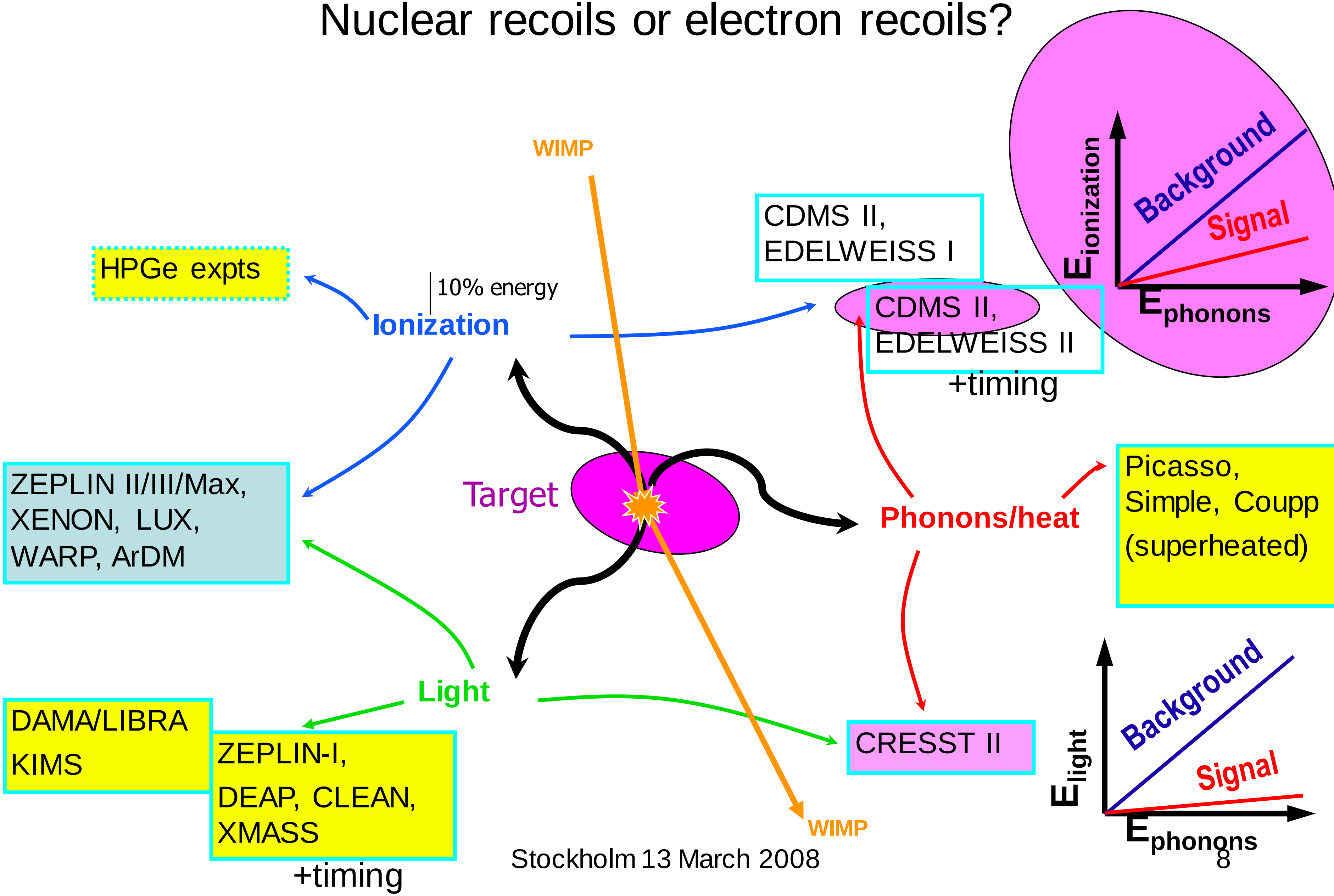
Huge world-wide DM effort

- Direct, directional
- Ionization + heat
- Ionization + light
- Light + heat
- Light only
- Heat only

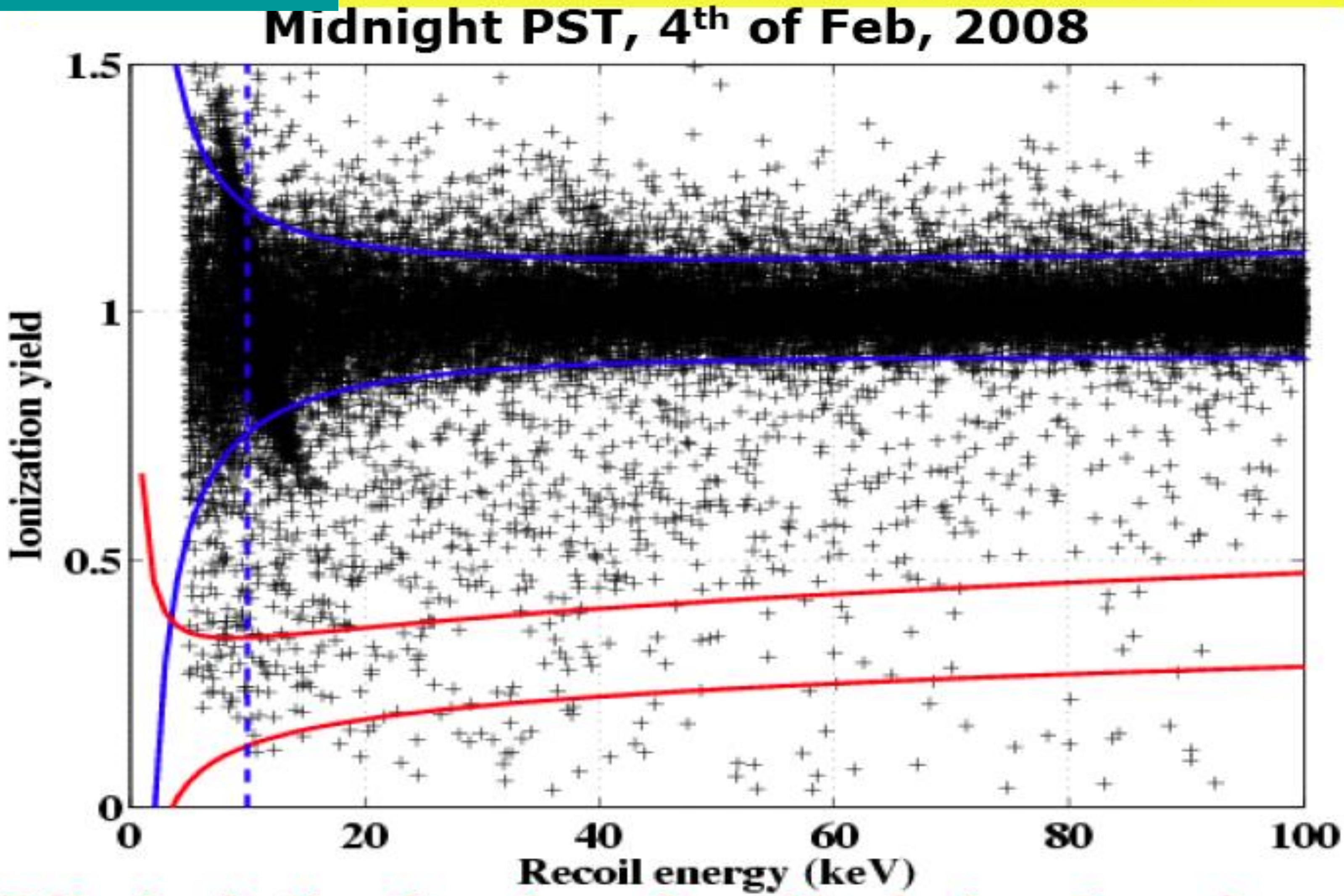
{Axions!}

- low-density TPC
- Cryogenic Ge, Si, …
- Liquid xenon, argon
- Cryogenic scintillator
- LXe, NaI, …
- Bubble Chambers!
- μ-wave photons…

Nuclear recoils or electron recoils?

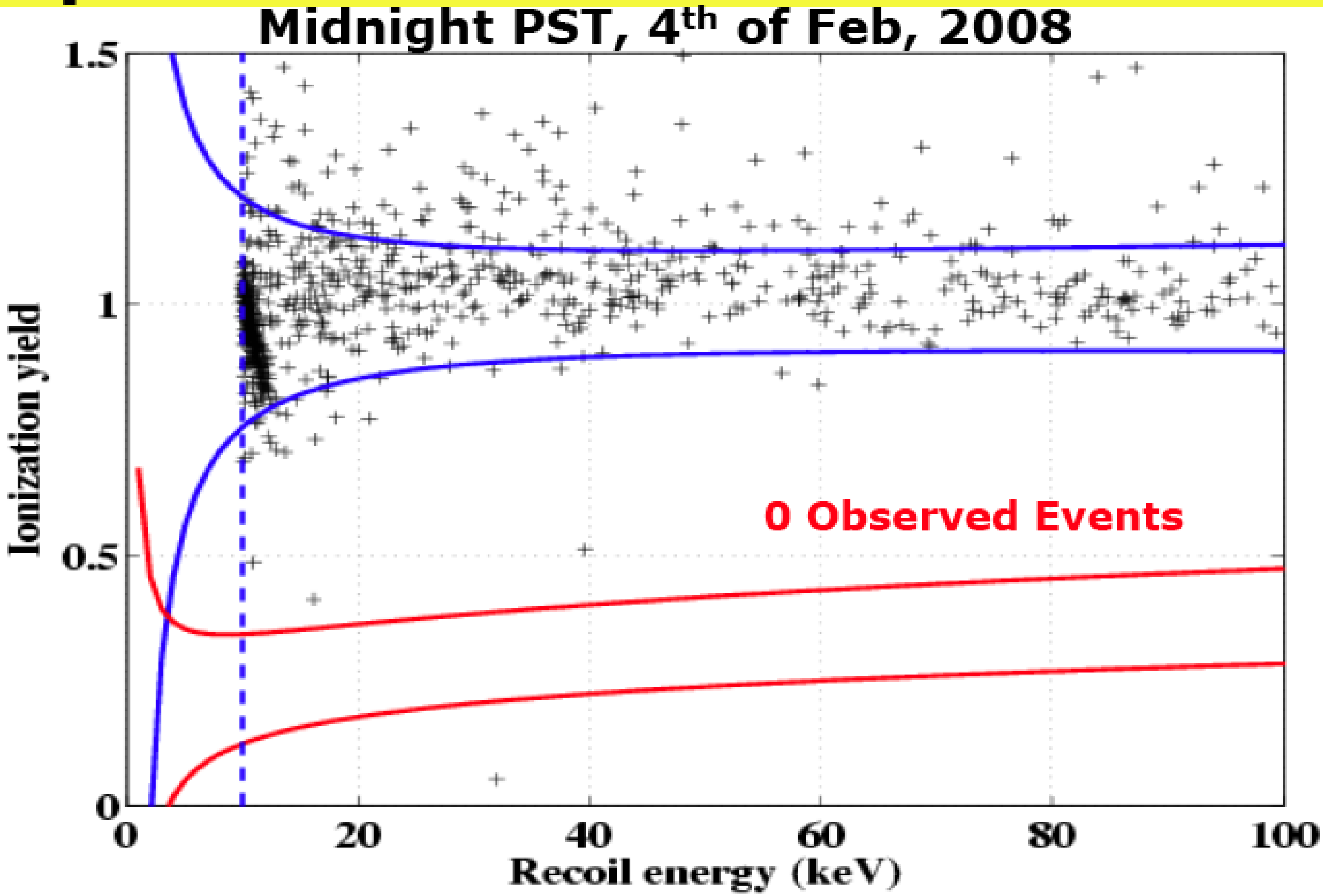


CDMS WIMP Search Data



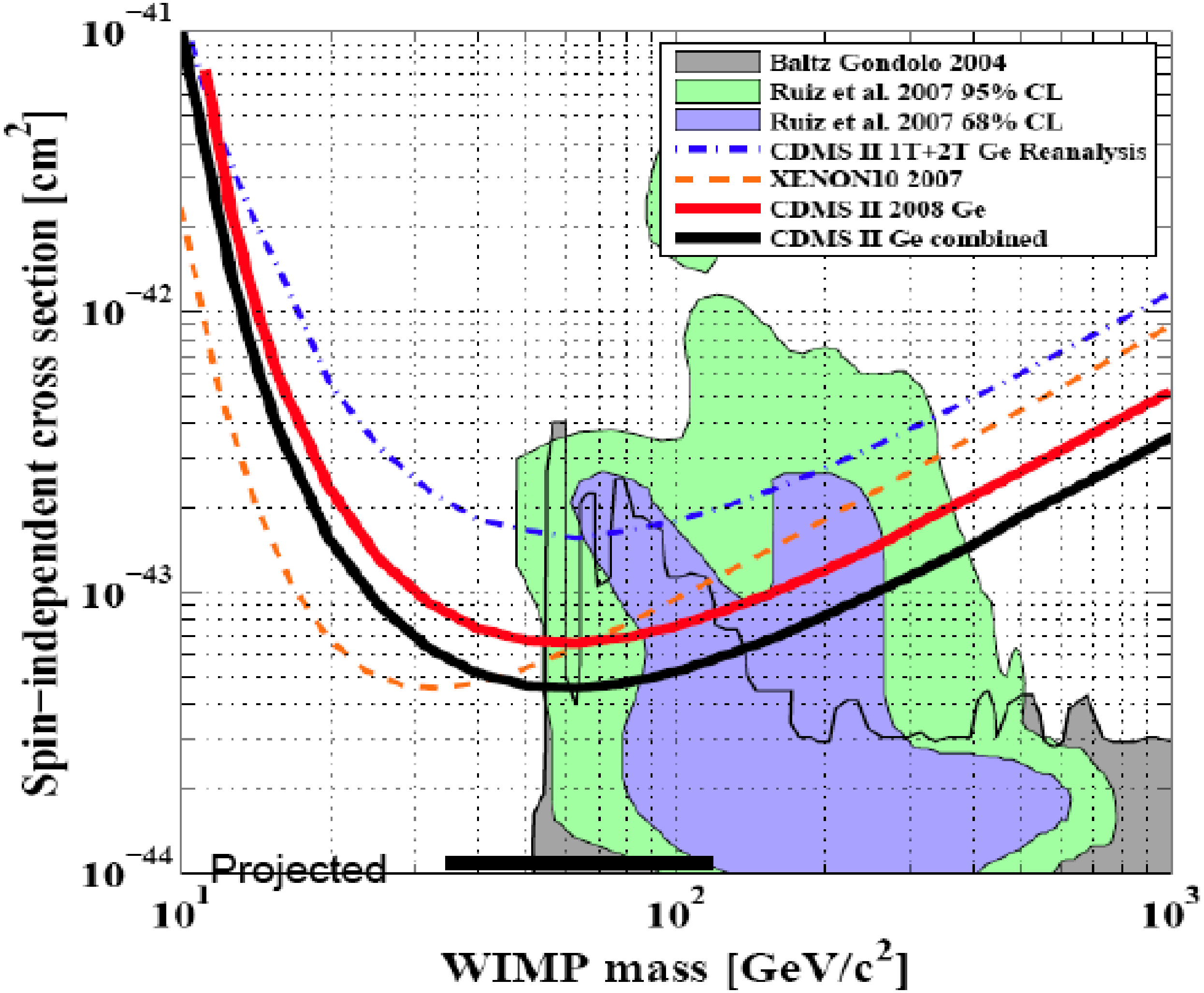
97 Singles in Signal region rejected by Surface Event Cut

Open The Box: Surface Event Cut



Expected Background: 0.6 ± 0.5 surface events and < 0.2 neutrons

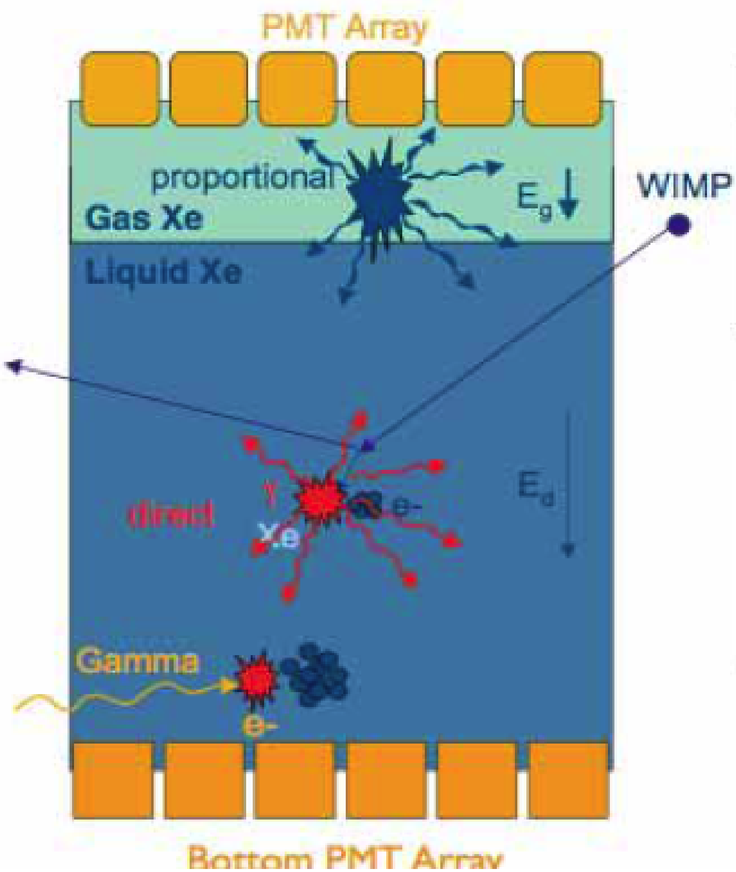
Spin-Independent Exclusion Limit

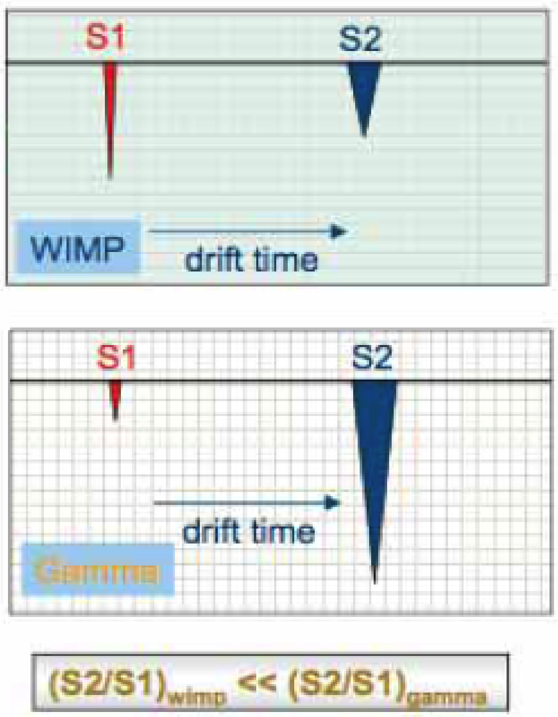


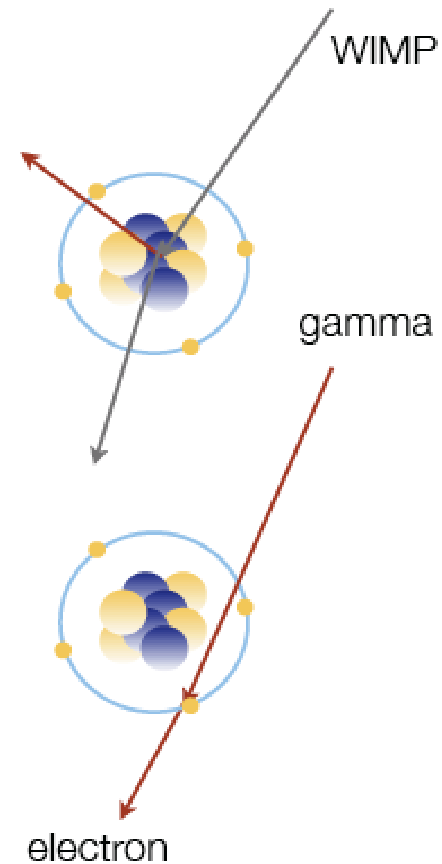
Results announced at 2008 UCLA Symposium on Dark Matter, Energy

The Two-Phase XeTPC Concept

- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e⁻





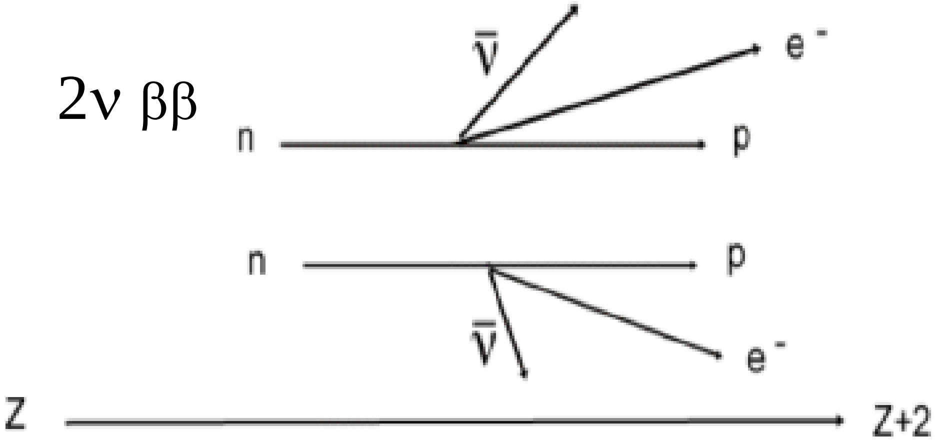


WIMP Quest

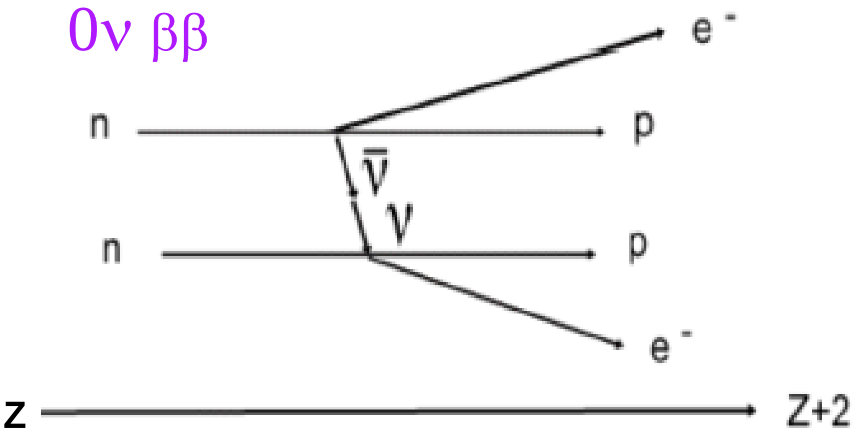
- **Now:** limits placed at ~5 x 10^{-43} cm^2
  - Detectors can cope with backgrounds at the level of 1 - 10 kg mass. *Heroic* efforts have been successful, so far.
- **Future:** 100 - 1000 - 10,000 kg - but how?
  - Backgrounds must be reduced x10, x100, x1000, …
  - Dark matter might not be WIMPs, …
  - A worthy quest, for the very brave, and the very patient.
- **Next**, another high-risk,high value topic…

Two Types of Double Beta Decay

$2\nu\ \beta\beta$



$0\nu\ \beta\beta$



Neutrinoless double beta decay.

A known standard model process and an important calibration tool

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

If this process is observed:

Neutrino mass ≠ 0

Neutrino = Anti-neutrino!

Lepton number is not conserved!

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

?

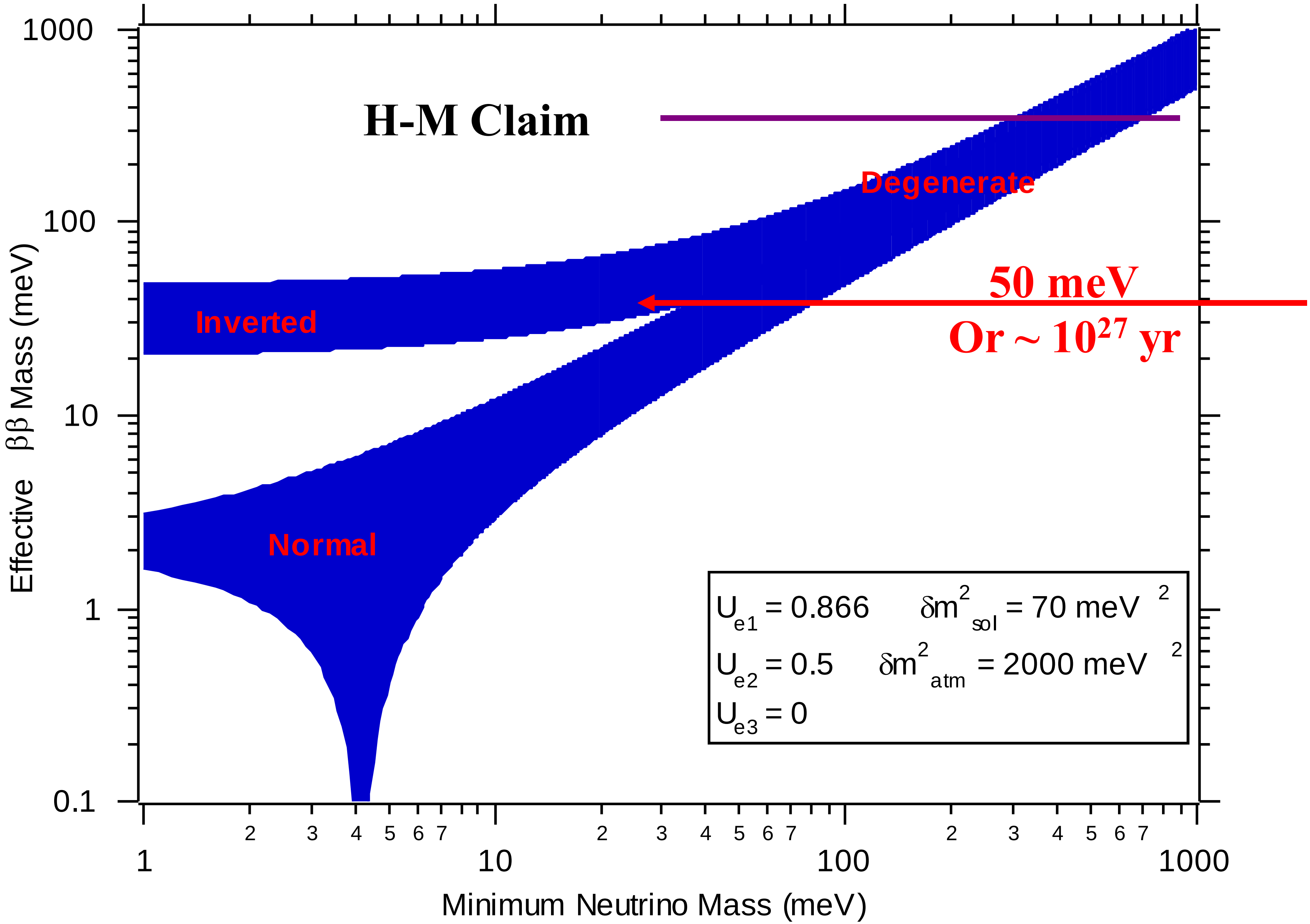
Neutrinoless double beta decay lifetime

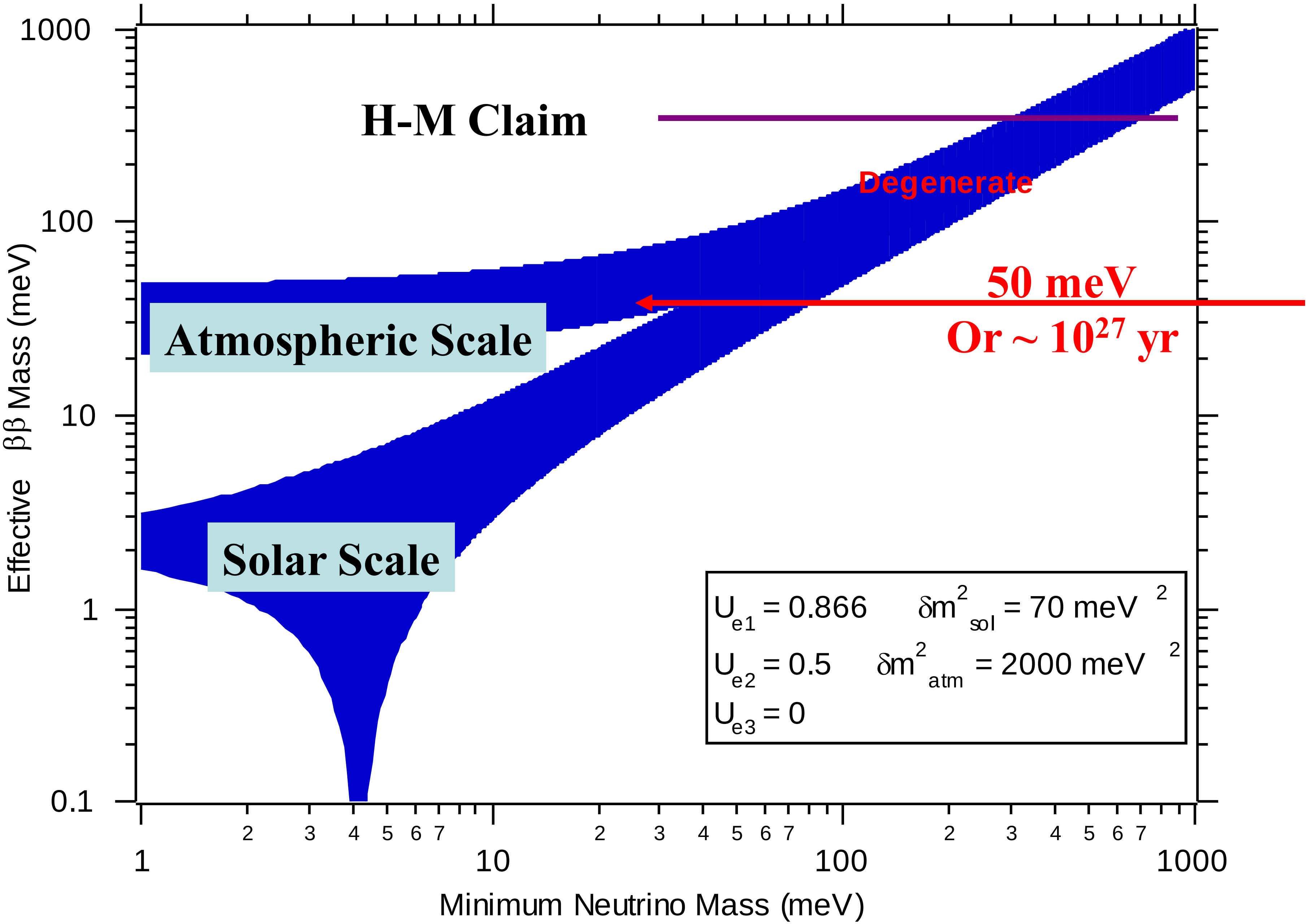
Neutrino effective mass

Neutrinos do have mass >0

- Abundant evidence now exists supporting this
  - Neutrinos made in the sun change flavor on the way here
    - chlorine, gallium, SNO experiments
  - Neutrinos made in the atmosphere change flavor, too,
    - SuperKamioka
  - Neutrinos made in reactors change flavor too…
    - KamLAND, CHOOZ,

- Flavor changes imply oscillation, require that $m_\nu > 0$
  - Oscillation experiments measure only $\Delta m^2 = m_1^2 - m_2^2$
  - Two mass differences δm^2_{sol} & δm^2_{atm} are measured rather well
  - The mass scale, and hierarchy, remains unknown!


H-M Claim
Degenerate
50 meV
Or ~ 10^{27} yr
Inverted
Normal
U_{e1} = 0.866 δm^2_{sol} = 70 meV^2
U_{e2} = 0.5 δm^2_{atm} = 2000 meV^2
U_{e3} = 0
Effective ββ Mass (meV)
Minimum Neutrino Mass (meV)
1000
100
10
1
0.1
1
10
100
1000



H-M Claim
Degenerate
50 meV
Or ~ 10^27 yr
Atmospheric Scale
Solar Scale
U_e1 = 0.866 δm²_sol = 70 meV²
U_e2 = 0.5 δm²_atm = 2000 meV²
U_e3 = 0
Effective ββ Mass (meV)
Minimum Neutrino Mass (meV)
1000
100
10
1
0.1
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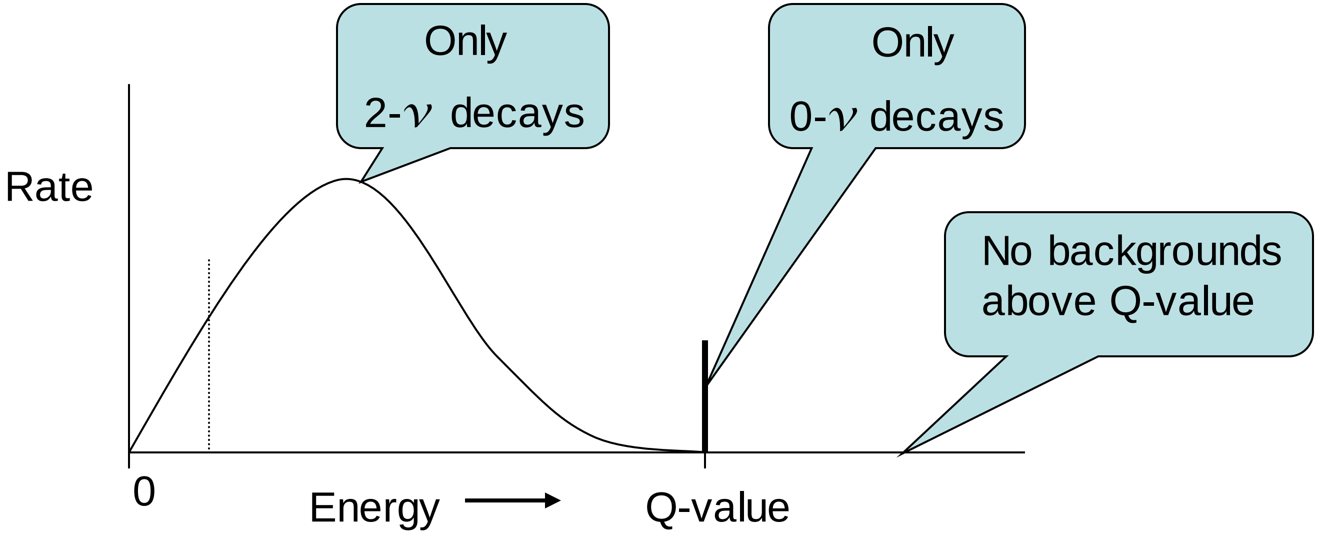
10
100
1000

Double beta decay

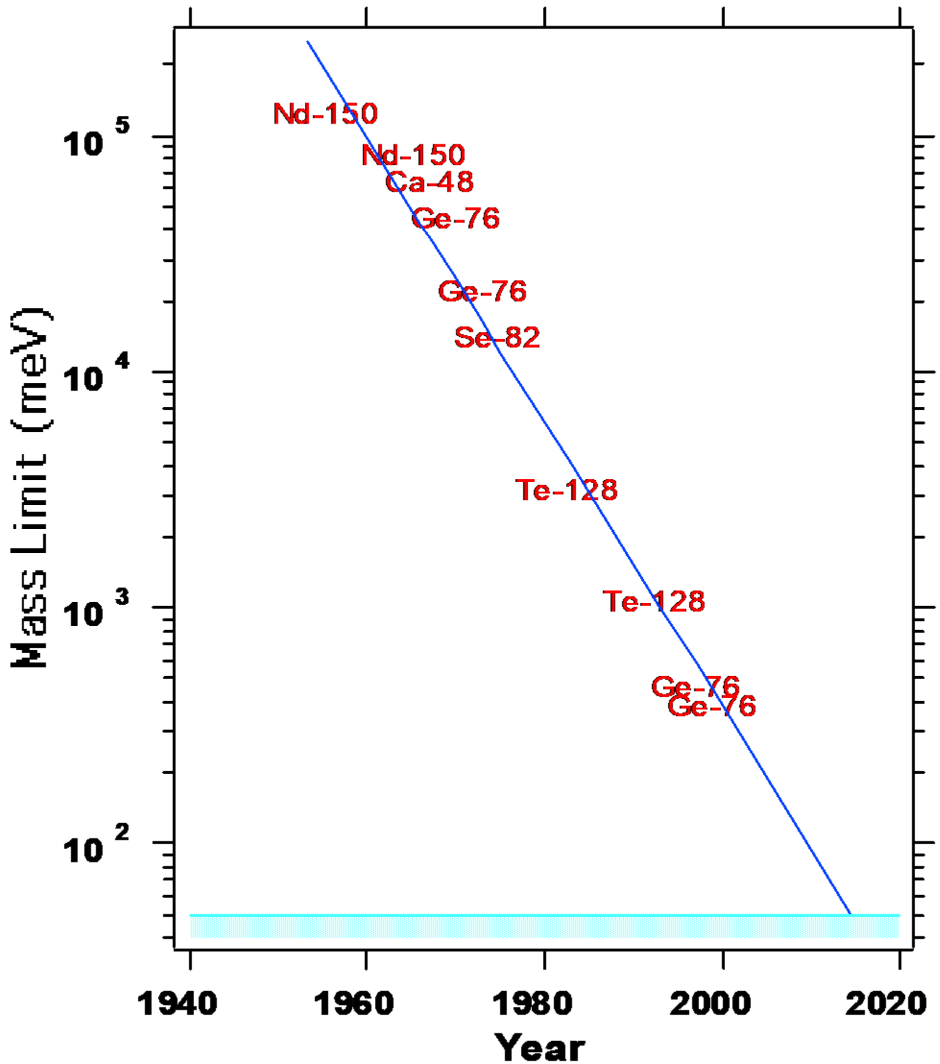


The ideal result is a spectrum of all ββ events, with negligible or very small backgrounds.

Elliott & Vogel
Annu. Rev. Part. Sci. 2002 52:115

Past Results

^{48}Ca	>1.4x10^{22} y	<(7.2-44.7) eV
^{76}Ge	>1.9x10^{25} y	<0.35 eV
^{76}Ge	>1.6x10^{25} y	<(0.33-1.35) eV
^{76}Ge	=1.2x10^{25} y	=0.44 eV
^{82}Se	>2.1x10^{23} y	<(1.2-3.2) eV
^{100}Mo	>5.8x10^{23} y	<(0.6-2.7) eV
^{116}Cd	>1.7x10^{23} y	<1.7 eV
^{128}Te	>7.7x10^{24} y	<(1.1-1.5) eV
^{130}Te	>3.0x10^{24} y	<(0.41-0.98) eV
^{136}Xe	>4.5x10^{23} y	<(1.8-5.2) eV
^{150}Nd	>1.2x10^{21} y	<3.0 eV

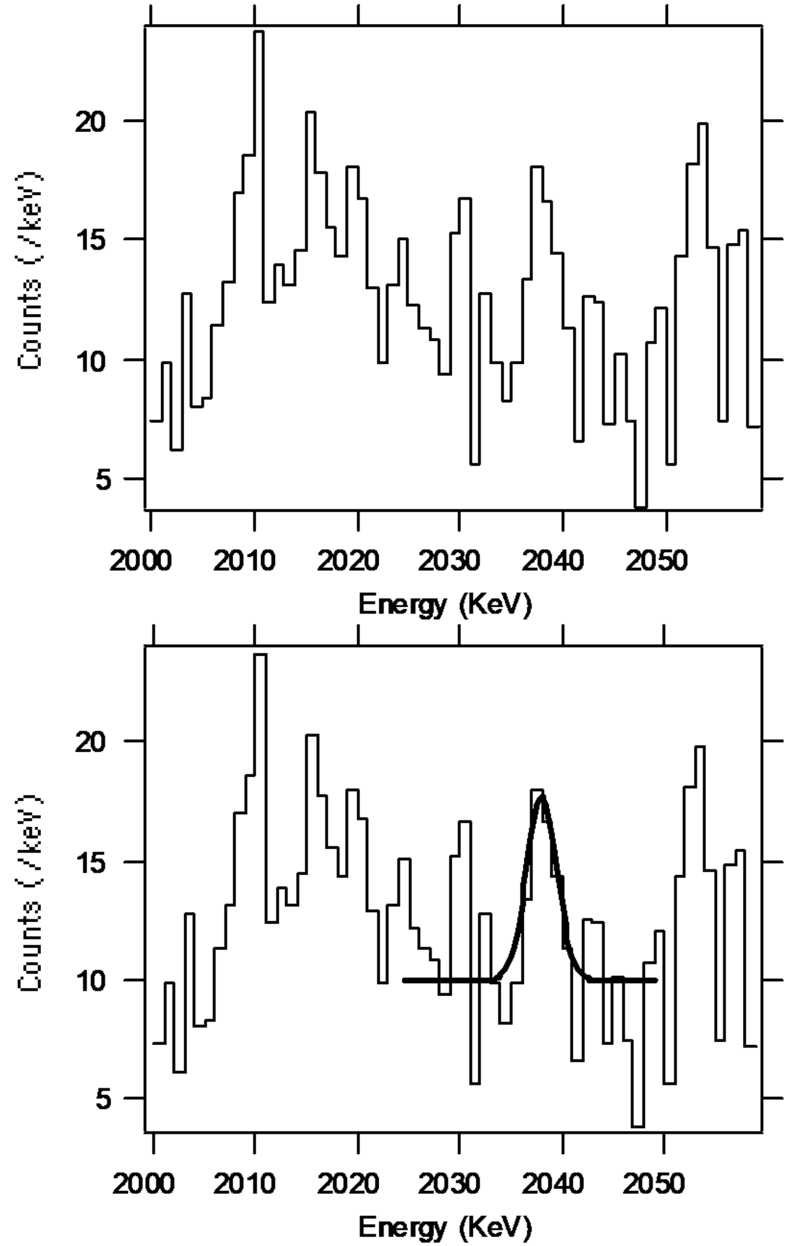


The H-M Result has become a litmus test for future efforts

ββ has been a search for a *very* rare peak on a continuum of background.

~70 kg-years of data
13 years

The “feature” at 2039 keV is arguably present, but is not the result of a “blind” analysis.



NIM A522, 371 (2004)

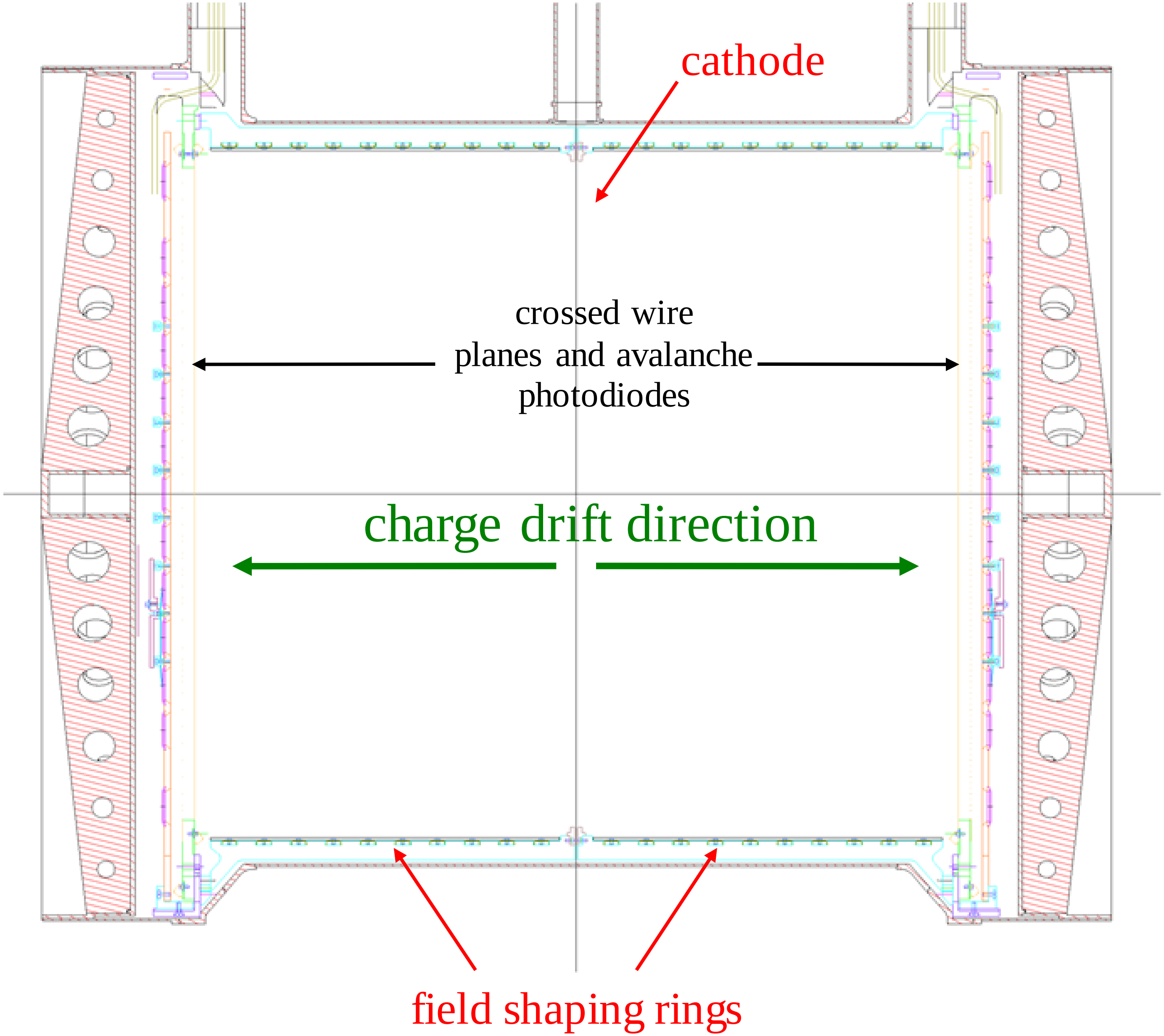
Great Number of Proposed Experiments

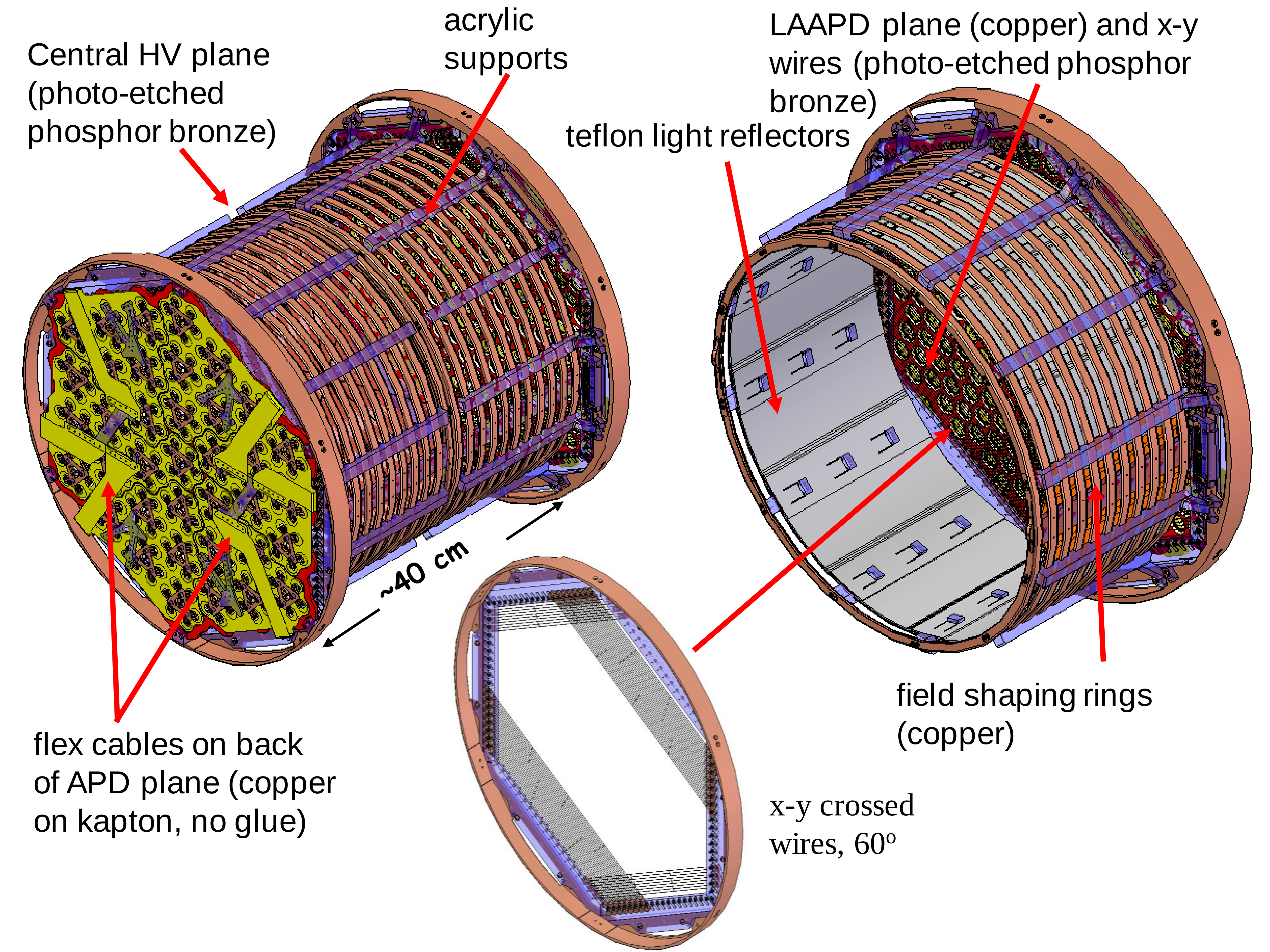
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

$\beta\beta$ Current Status

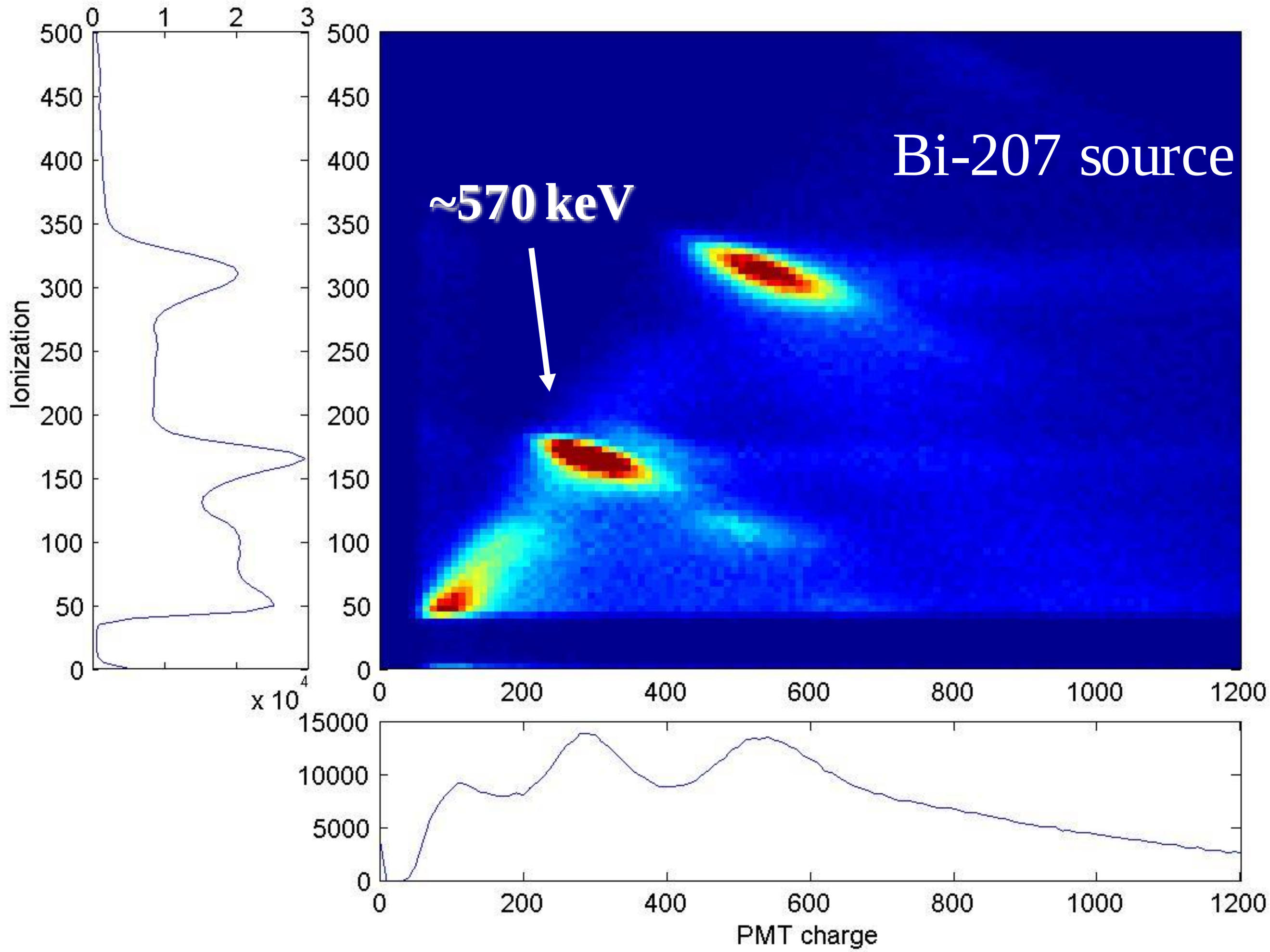
- Target (from oscillations): $\langle m_{\beta\beta} \rangle$ ~0.050 eV = 50 meV
    - But, masses could be higher…
- Goal: 100's to 1000's kg active mass likely to be necessary!
    - Rejection of internal/external backgrounds in ~10^{27} atoms!
    - Excellent energy resolution: $\delta E/E$ <<10 x 10^{-3} FWHM
- Present status (partial):
    - **Heidelberg-Moscow** (^{76}Ge) **result**: $\langle m_\nu \rangle$ = **0.440 $^{+0.014}_{-0.020}$** eV - *disputed!*
    - **Cuoricino** (^{130}Te): cryogenic bolometers, taking data, but - *background limited...*
    - **Cuore** x20 Cuoricino, with improved radiopurity
    - **GERDA** (^{76}Ge): under construction at LNGS
    - **Majorana** (^{76}Ge): (proposal & R&D stage)
    - **NEMO** $\rightarrow$ Super-NEMO: various foils: (proposal + R&D stage)
    - **NEXT** ^{136}Xe High-pressure xenon gas TPC (proposal + R&D stage)
    - **EXO** (^{136}Xe) liquid xenon TPC, now installing at WIPP

The EXO-200 detector: a dual TPC




Central HV plane (photo-etched phosphor bronze)
acrylic supports
LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)
teflon light reflectors
~40 cm
field shaping rings (copper)
flex cables on back of APD plane (copper on kapton, no glue)
x-y crossed wires, 60°

Liquid xenon data show an "anti-correlation" between ionization and scintillation



Energy resolution (predicted): 3.3 %FWHM @ Q(ββ)

Xenon: Strong dependence of energy partitioning on density!

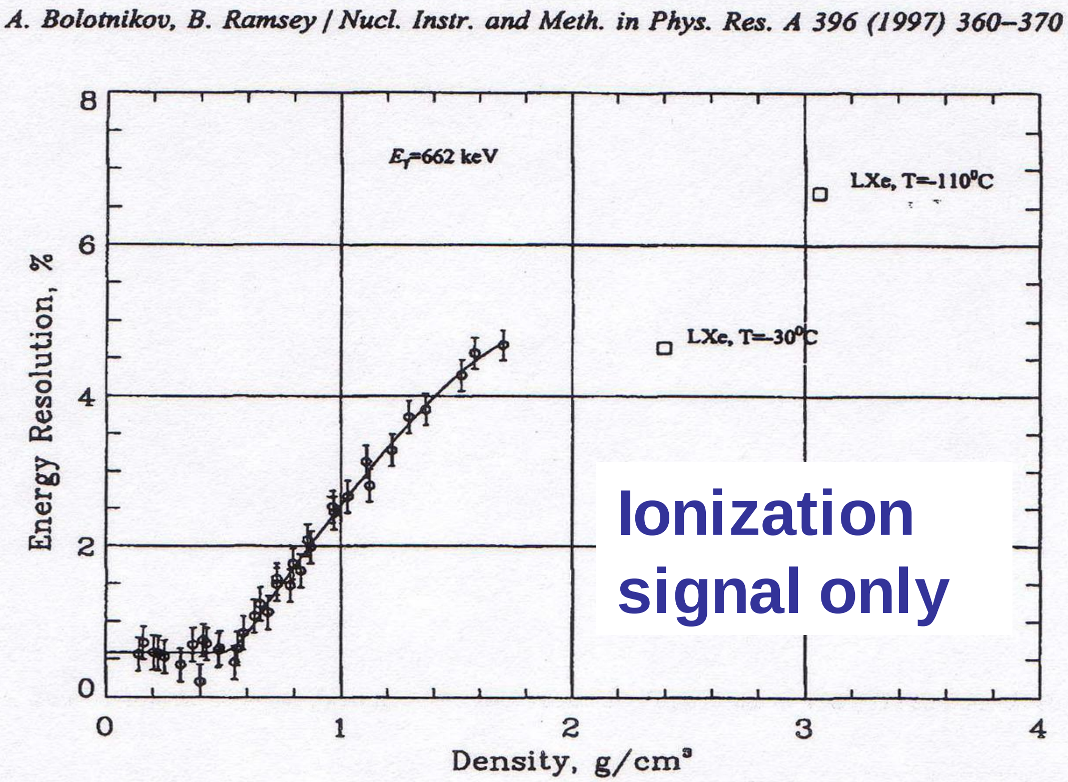


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ >0.55 g/cm^3, energy resolution deteriorates rapidly

What's happening at densities $\rho > 0.55$ g/cm^3 ?

Two phases of xenon can co-exist (fog,...)

- High atomic density + ionization density

  $\Rightarrow$ sites of complete recombination

  Energy is returned as <u>scintillation & heat</u>
- Landau: $\Rightarrow$ large dE/dx fluctuations + δ-rays

  $\Rightarrow$ non-Gaussian partition of energy
- Anomalously large partition fluctuations

  {Scintillation $\Leftrightarrow$ Ionization} *(+ HEAT...)*

Big Impact for WIMP Search in LXe

Scintillation (S_1) & Ionization (S_2) are signals that are used to reject electron recoils

But, in LXe:

S_2/S_1 fluctuations are anomalously large

Bad news for discrimination power in LXe!

What do events in LXe look like?

Log10 S2/S1

QuickTime™ a
TIFF (LZW) decomp
are needed to see this

Gamma events (e-R)

Latest Xenon-10 results look better, but nuclear recoil acceptance still needs restriction

Neutron events (N-R)

Impact for WIMP Search

Scintillation (S_1) & Ionization (S_2) are signals that can be used to reject electron recoils

But, in LXe:

S_2/S_1 fluctuations are anomalously large

Bad news for discrimination power in LXe!

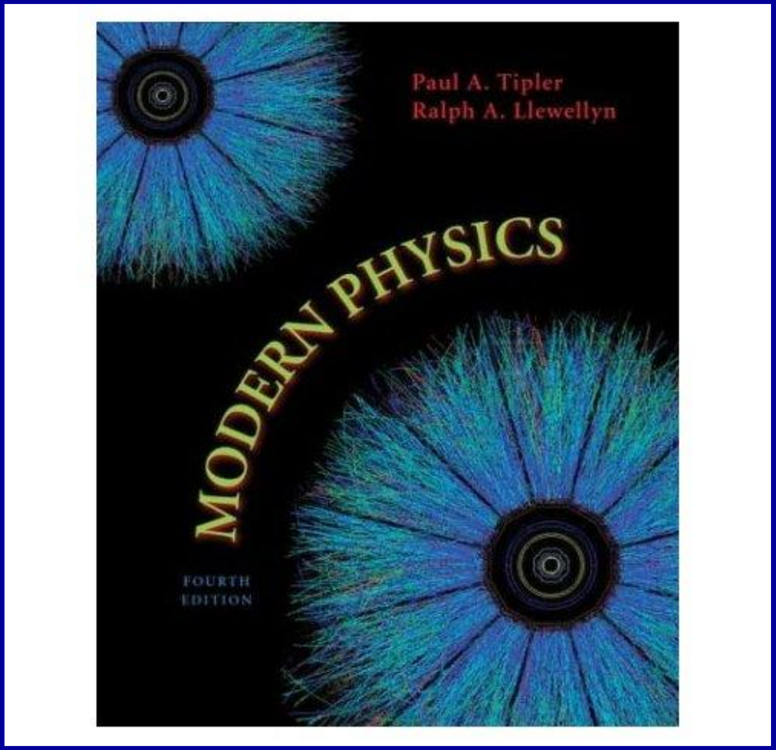
$\rho < 0.55$ g/cm^3: normal S_2/S_1 fluctuations

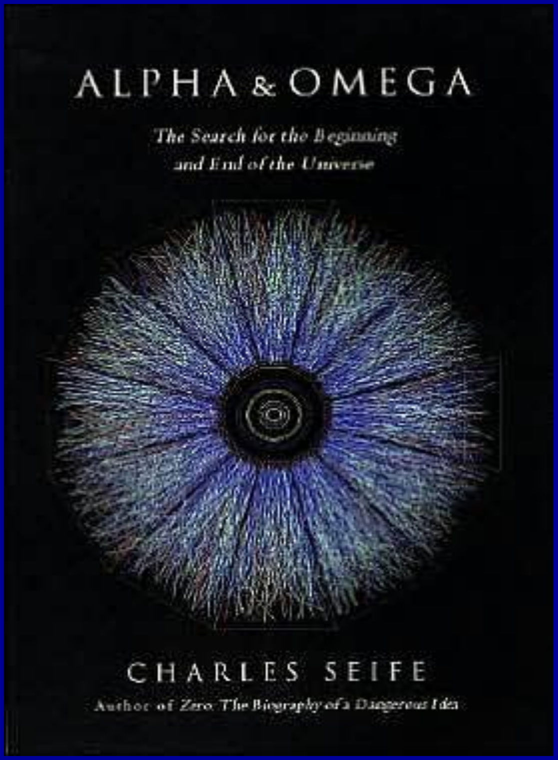
Maybe,... Xenon gas is better (...much better) ??

High-pressure xenon gas TPC

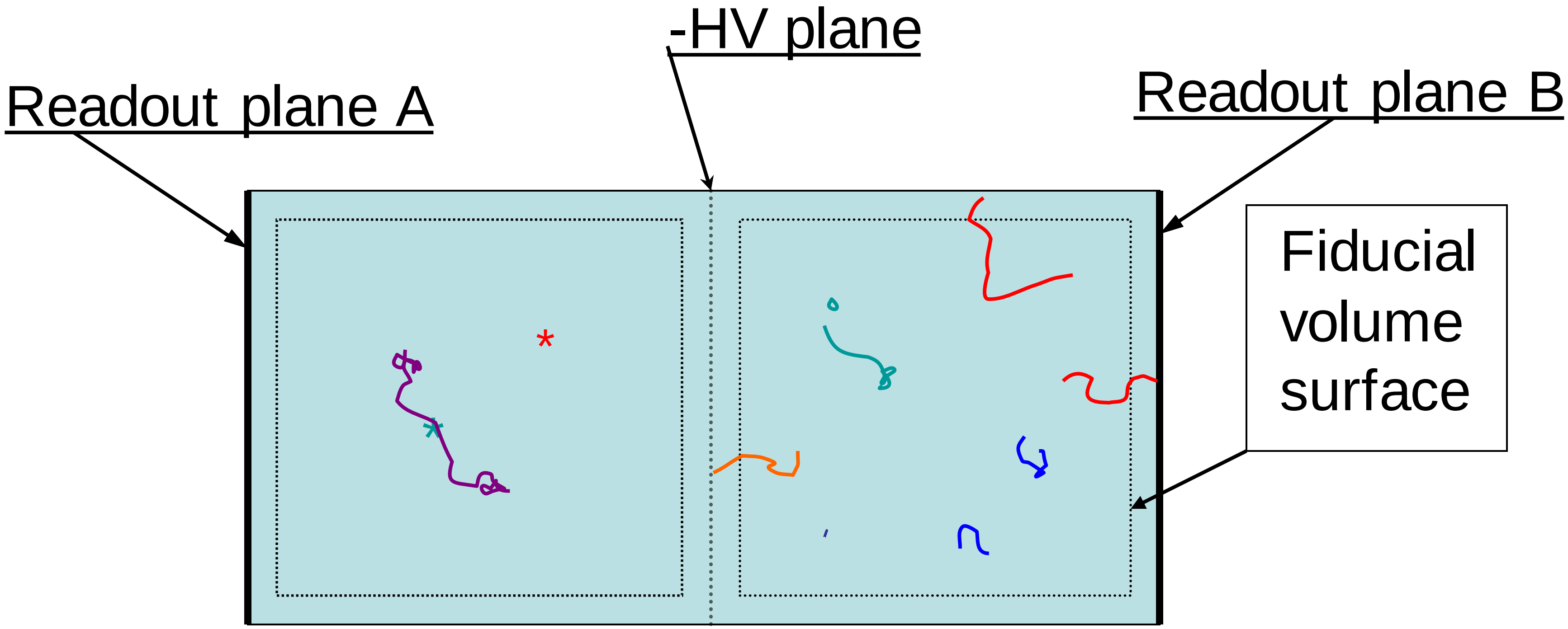
- Fiducial volume surface:
  - Single, continuous, fully active, variable,...
  - 100.0% rejection of charged particles (surfaces)
  - but: TPC needs a t_0 to place event in z
- Tracking:
  - Available in gas phase only
  - Topological rejection of single electron events
  - TPC proven to handle complex events…

From <10 to >10,000 particles





TPC: ββ Signal & Backgrounds



Signal: ββ event or WIMP   Backgrounds

TPC: Basic Advantages...

- Fiducial volume surface: excellent
- Tracking in gas: excellent

But, a TPC is <u>not</u> known for:

Excellent energy resolution

So,

What is possible??

Two questions

What is the best energy resolution that can be obtained with a

high-pressure xenon gas TPC

- in principle?
- in **practice?**

"Intrinsic" Energy Resolution for Ionization at ^{136}Xe Q-value

Q-value ($^{136}Xe \rightarrow {}^{136}Ba$) = 2480 KeV

W = ΔE per ion/electron pair in xenon gas = 21.9 eV, but

W depends on Electric field strength, might be ~24.8 eV

N = number of ion pairs = Q/W

N = 2480 x 10^3 eV/24.8 eV = ~**100,000 electron/ion pairs**

$\boldsymbol{\sigma_N = (FN)^{1/2}}$ F is the Fano factor - constraint on fluctuations

F = 0.13 - 0.17 measured for xenon gas; take **F = 0.15**

$\boldsymbol{\sigma_N = (FN)^{1/2}}$ ~**123** electrons rms @ 2480 keV

This is a rather small number!

"Intrinsic" Energy Resolution for Ionization at ^{136}Xe Q-value

— $\delta E/E = 2.35 \times (FN)^{1/2} = 2.35 \times (FW/Q)^{1/2}$

Answer to question #1:

$\delta E/E \sim 2.8 \times 10^{-3}$ FWHM @ 2480 keV*

(xenon gas - ionization intrinsic fluctuations only)

*This **ideal** result is ~ same as that achieved with germanium diodes, in **practice.**

Energy Resolution Factors in Xenon Gas Detectors

- **Intrinsic fluctuations**
  - Fano factor (partition of energy): small for $\rho < 0.55$ g/cm^3
- Loss of signal (primary):
  - Recombination, quenching by molecular additives (heat)
- Loss of signal (secondary):
  - Capture by grids or electronegative impurities
- **Gain process fluctuations:**
  - Avalanche charge gain fluctuations are large
- Gain process stability:
  - Positive ion effects, density and mix sensitivity,...
- Long tracks $\Rightarrow$ extended signals
  - Baseline shifts, electronic non-linearities, wall effect,...

Generalization

- If fluctuations are uncorrelated, then*

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

  F = Fano factor = 0.15

  L = loss of primary ionization (set to 0)

  G = fluctuations & noise in gain process

  Goal: Keep G no larger than F = 0.15

  Is this possible ??

*D. Nygren, *Nucl. Inst. & Meth.* **A 581** (2007) 632

Avalanche Charge Gain

- One electron liberates others, which liberate…

Early ionization history determines gain

- for wire ($E \sim 1/r$) $0.6 < G < 0.9$ *
- $\sigma_N = ((0.15 + 0.8)N)^{1/2} = 328$
- **$\delta E/E = \sim 7.0 \times 10^{-3}$** FWHM

  Lost the benefit from a small Fano factor

*Alkhazov G D *Nucl. Inst. & Meth*. **89** (1970) 155 (for cylindrical proportional counters)

What is this factor “G”?

- In a very real sense:

  G is a measure of the precision with which a **single** electron can be counted.

- Consider next:
  - Ionization Imaging TPC - no gas gain!
  - Negative Ion TPC - count each electron!
  - Electro-Luminescent TPC ?

“Ionization Imaging” TPC

No avalanche gain

- dn/dx ~ 1 fC/cm: ⇒ ~6,000 (electron/ion pairs)/cm
- gridless “naked” pixel plane (~5 mm pads)
- **very high operational stability**

But, electronic noise must be added!

- σ = 50 e^- rms/pixel
- $G = \sigma^2/n_e = 50^2/3000 = \sim 0.8$
- $\delta E/E \sim$ **7×10^{-3} FWHM**
- **But: complex signals, many channels, ultra-low noise, waveform capture ⇒ much R&D needed**

"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…

Maybe,… $\delta E/E$ = ~3 x 10^{-3} FWHM

Appealing, but will it work in HPXe?...

Much R&D needed

Electro-Luminescence (EL)
(Gas Proportional Scintillation)

- Electrons drift from low to high electric field region
- Electrons gain energy, excite xenon, lose energy
- Xenon generates UV
- Electron starts over, gaining energy again
- Linear growth of signal with voltage
- Photon generation up to ~1000/e, but no ionization
- Early history irrelevant, so $\Rightarrow$ **fluctuations small**
- **Maybe… G ~ F?**

H. E. Palmer & L. A. Braby

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

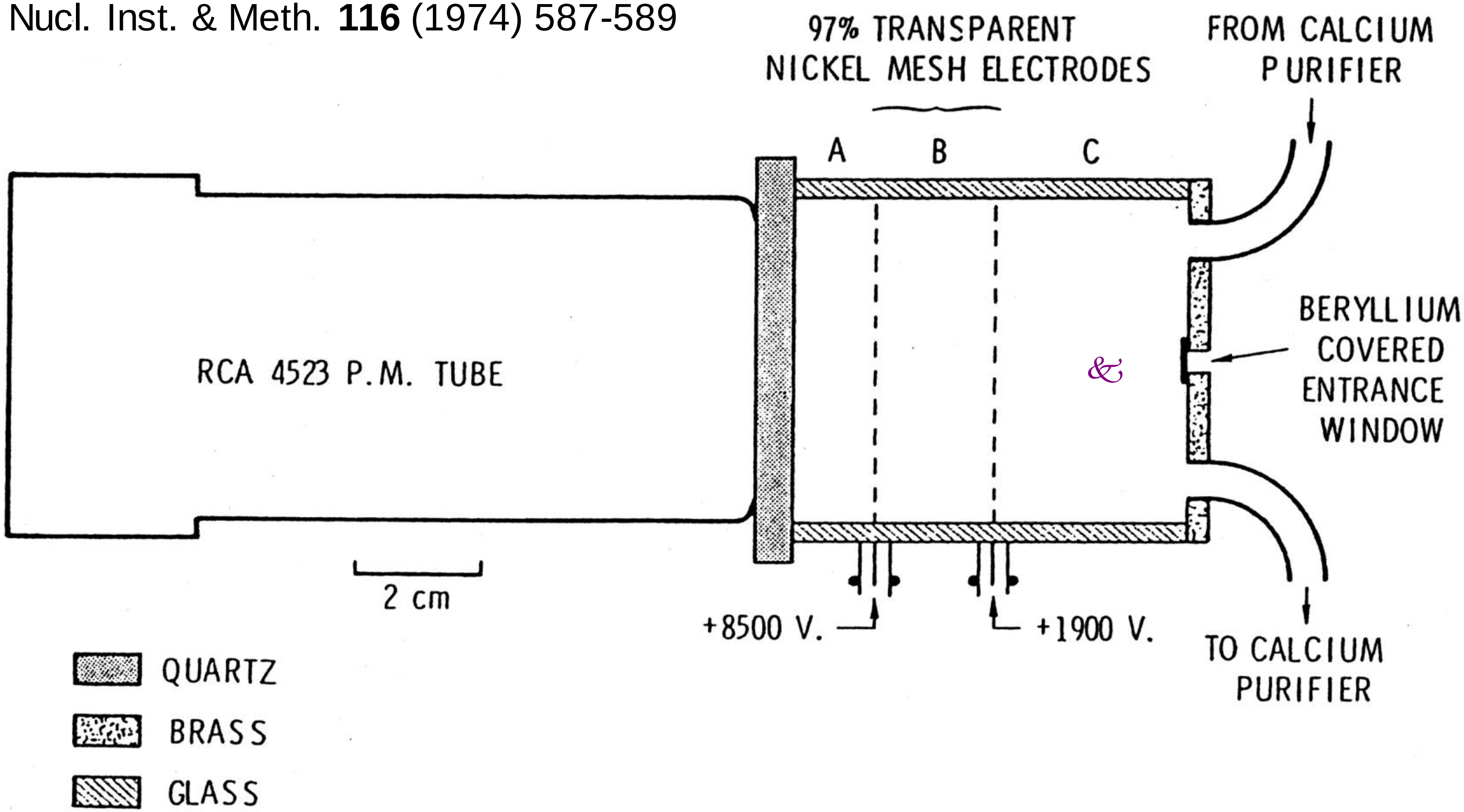


Fig. 1. Sketch of 5 cm diameter parallel plate gas scintillation proportional counter.

^{55}Fe Resolution: **8.4%** FWHM

From this spectrum: **G ~0.19**

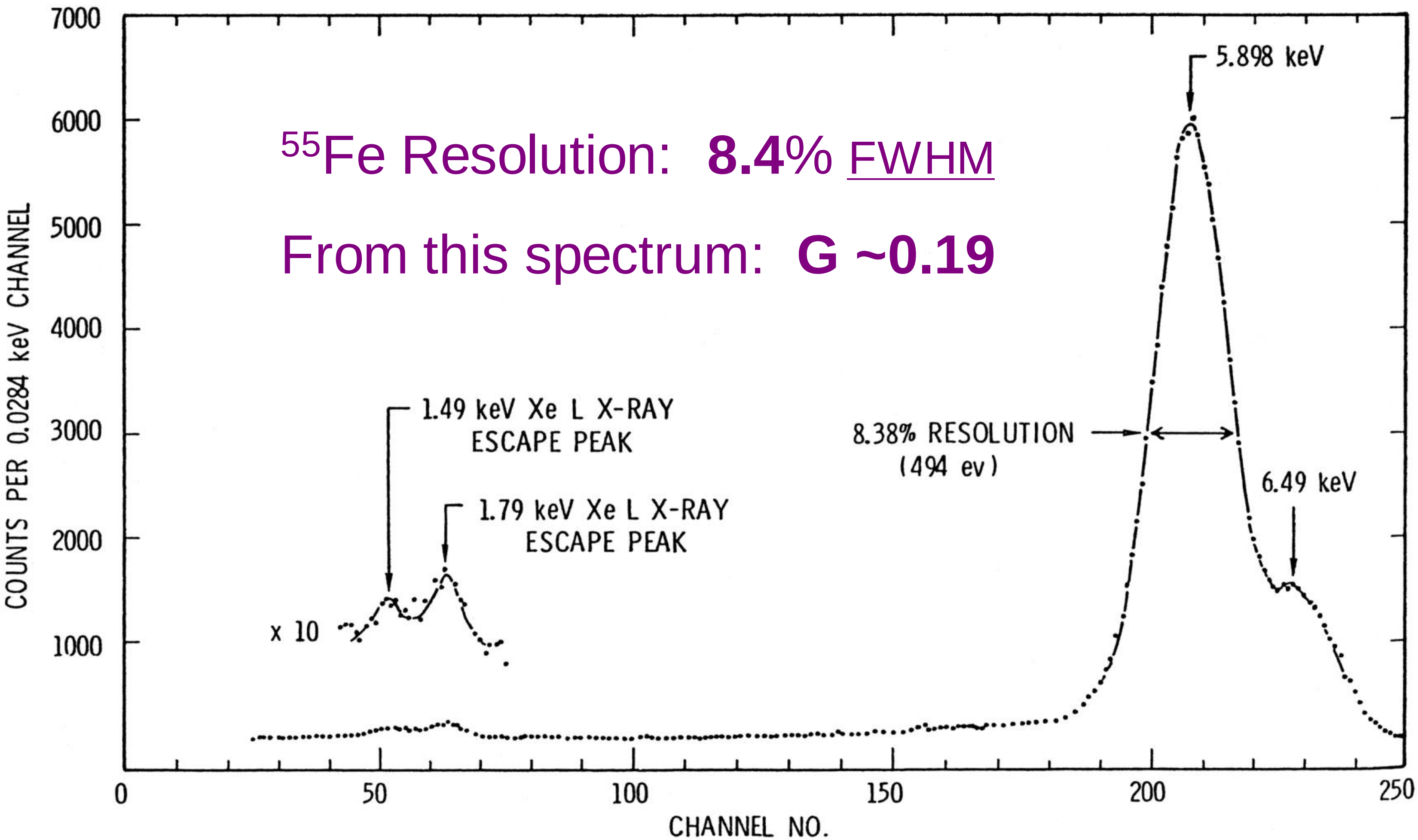


Fig. 2. Pulse-height spectra of an ^{55}Fe source from a parallel plate gas scintillation proportional counter.

Fluctuations in EL

G for EL contains three terms:

1. Fluctuations in $\mathbf{n_{uv}}$ (UV photons per e): $\sigma_{uv} = K/\sqrt{n_{uv}}$
   - $n_{uv} \sim HV/E_\gamma = 6600/10$ eV **~ 660** **K < 1**
2. Fluctuations in $\mathbf{n_{pe}}$ (detected photons/e): $\sigma_{pe} = 1/\sqrt{n_{pe}}$
   - n_{pe} ~ solid angle x QE x WLS x n_{uv} **= 0.1 x 0.25 x 0.5 x 660 ~ 8**
3. Fluctuations in PMT single PE response: $\sigma_{pmt} \sim 0.6$

$$G = \sigma^2 = 1/(660) + (1 + \sigma^2_{pmt})/8) \sim 0.17$$

The more photo-electrons, the better!

EL provides precision electron counting

Assume F = G **=** 0.15

Ideal energy resolution (σ^2 = **0.3** x E/W):

δE/E ~4 x 10^{-3} FWHM @ 2480keV

This is promising!

Electro-Luminescent Readout

- To keep $G < F = 0.15$, then:

$$n_{pe} > 10/\text{electron}$$

$\Rightarrow \Sigma n_{pe} >$ **1,000,000** @ 2480 keV !

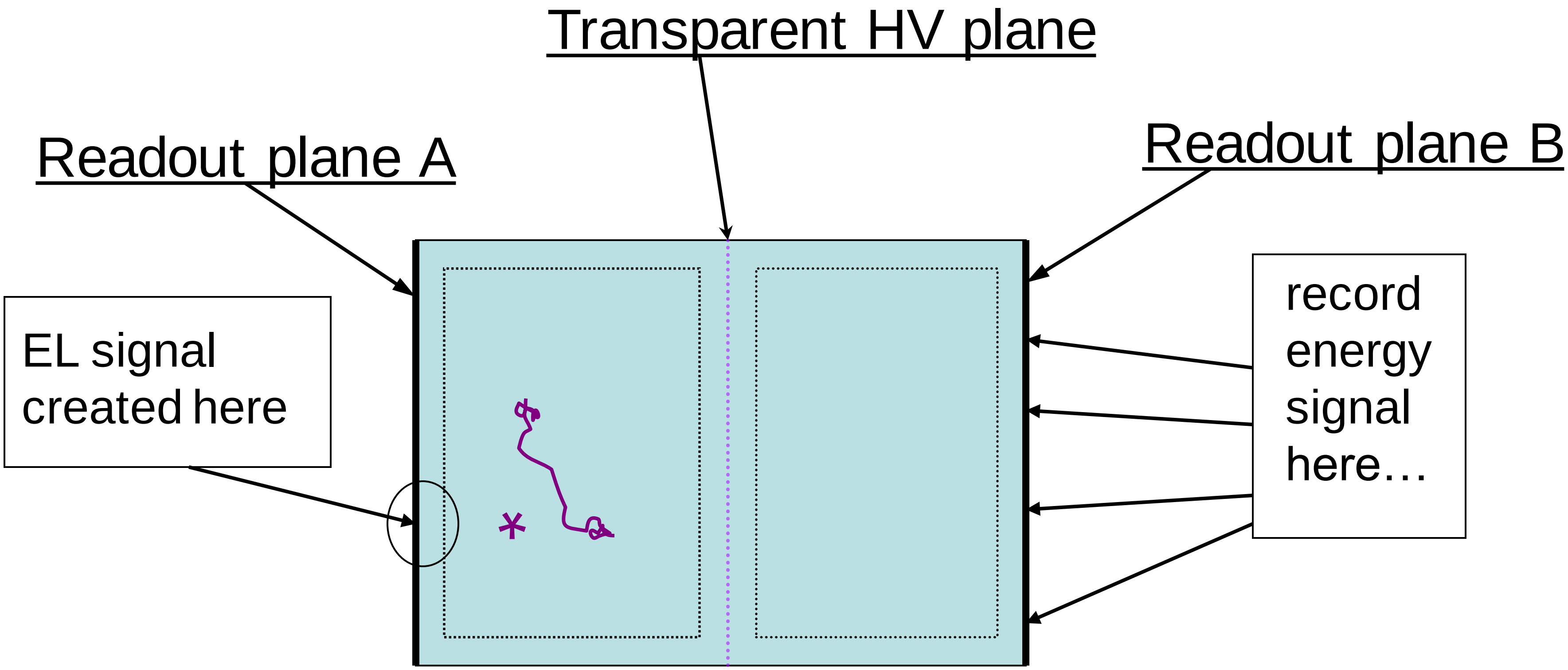
Electro-Luminescent Readout

How to detect this much signal?

Answer: Use <u>both</u> TPC readout planes

- If EL signal is generated in plane “A”
- do “tracking” in Plane “A”
- but: record “energy” in plane “B”

TPC Signal



Signal: ββ event or WIMP

Electron drift in xenon gas

- It is very slow: ~1 mm/μs
- This spreads out the arriving signal in time - up to 100 μs for many ββ events
- The signal is spread out over the entire readout plane "B", many 100's of PMTs
- These two factors greatly reduce the dynamic range needed for readout of the signals

$\Rightarrow$ No problem to read out 5 kev to 5000 keV

EL: How much light?

- Boundary condition: n_{pe}/electron ≥ 10
- Let photon detection efficiency = η

  η = solid angle x transparency x QE_{PMT}

  Assume <u>reflective</u> TPC field cages

  $\eta = \pi/(4 \times 4\pi) \times 2 \times 0.9 \times 0.3 = 0.03$
- n_{pe}/electron = 10 ~ $N_{photons} \times \eta$

$\Rightarrow N_{photons} \geq 300$/electron

Can this be done?

Generation of EL in xenon

$dN/dx = 140(E/p - 0.83)p$ UV photons/cm

- E/p = 8 kV/cm-bar is maximum for EL only
- E/p = 0.83 kV/cm-bar is minimum for EL

Wire plane is ideal, and no charge gain!

– $N_{photons} = 1540\ p\ r_0 \equiv 300$

– **$p\ r_0 \geq 0.2$ (bar-cm)** set p = 20 bars, r_0 = 0.15 mm, then: n_{pe} = 15, G = 0.08

$\delta E/E$ = 3.4 x 10^{-3} FWHM @ 2480keV

Answer to Question #2

- Best <u>practical</u> energy resolution:

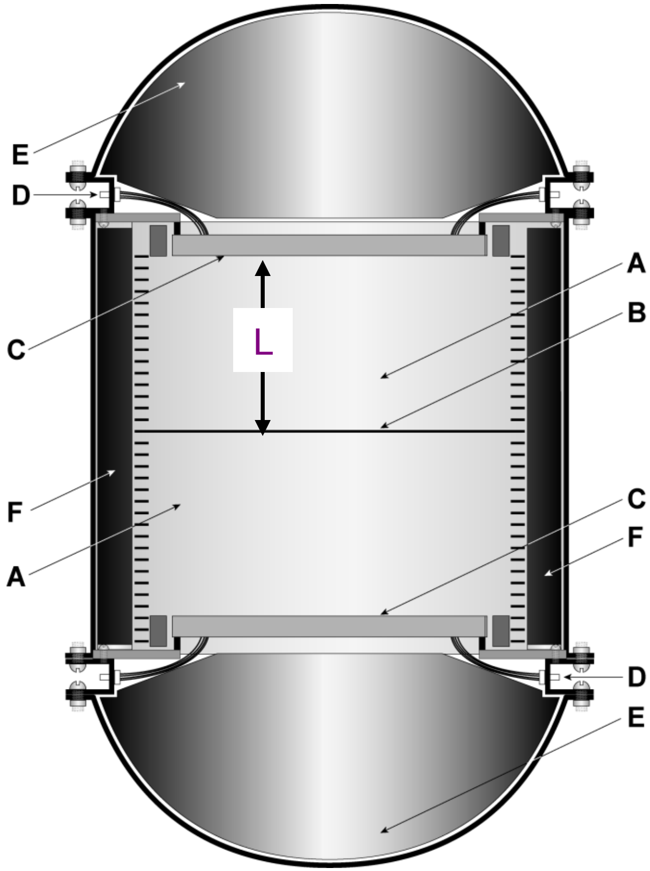
<u>TPC with EL MWPC readout planes</u>

  - separated function: tracking (A) $\leftrightarrow$ energy (B)
  - planes A & B symmetric and equivalent

<u>δE/E = 3.4 x 10</u>$^{-3}$ FWHM @ 2480keV

Maybe a HPXe TPC can offer both excellent particle tracking and energy resolution!

1000 kg Xe: ∅ = 225 cm, 2 x L =225 cm
$\rho \sim 0.1$ g/cm^3 (~20 bars)



A. Sensitive volume

B. HV cathode plane

C. EL MWPC readout planes, with photomultiplier arrays

D. Flange for services

E. Filler and neutron absorber, polyethylene, or liquid scintillator, or …

F. Field cages and HV insulator, (rings are exaggerated here)

Perspective

By realizing that the key idea is counting electrons, we arrive at a new, attractive detector concept:

- ✓ Near-intrinsic energy resolution in HP-Xe EL TPC
- ✓ Ionization signal alone is sufficient to achieve this
- ✓ WIMP + ββ search: **no compromises!**
- ✓ Dynamic range OK: keV - MeV energy range
- ✓ Ionization & scintillation both recorded by PMTs
- ✓ Scintillation UV for S_1 & t_0 automatically available

Outlook

- It may be possible to do two sensitive, (costly & high risk) experiments simultaneously

- It remains to be determined whether this notion will provide <u>all</u> needed performance

- It remains also to be seen if this concept will be built, but for success, a good **acronym**…

EL GRANDE

Electro-**L**uminescence:

Great **R**ewards **A**wait **N**EXT **D**ouble-β **E**xperiment

EL GRANDE

Electro-**L**uminescence:

Great **R**ewards **A**wait **N**EXT **D**ouble-β **E**xperiment

Thank you for your
bravery and patience

Backup Slides

Germanium Diodes

Fano factor: similar to xenon gas: ~0.13 ±0.02

Energy per electron-ion pair: 2.96 eV

More carriers ⇒ Ge diodes better by $(22/3)^{1/2} = 2.7$?

δE/E ~1 x 10^{-3} FWHM @ 2480 keV, **germanium, <u>ideal</u>**

δE/E ~2.4 x 10^{-3} FWHM @ 2480 keV **germanium, <u>real</u>**

Why aren't Ge diodes as good as Ge (ideal)?

Factors: electronic noise, edge effects, trapping, complex interactions: Compton, photo-conversion…

ΔE: Three Pathways

- When a particle loses energy in xenon, where does the energy go?
  - Ionization
  - Scintillation: VUV ~170 nm (τ_1, τ_2 …)
  - Heat!
- How is the energy partitioned?
  - Responses differ for α, β, nuclei
  - Dependence on xenon density ρ, E-field
  - Processes still not completely understood

“Effective Fano Factor” for LXe

Conti *et al:* “F” ~ 20 to match their LXe data

Compare: LXe/HPXe Fano factors: $(\text{“20”}/0.15)^{1/2}$ = **11.5**

δ**E/E = 2.35 x (FW/Q)$^{1/2}$ $\Rightarrow$ 31 x 10^{-3}** FWHM

Anti-correlation (use it!):

Using **both** the scintillation and ionization signals together allows recovery of the total signal (except for heat).

But: in practice, only a fraction of the light can be detected; the energy resolution in LXe cannot be as good as intrinsic.

The impact of energy lost to heat on resolution is unknown.

Molecular physics of xenon

- **Macroscopic**:
  - Critical temperature of xenon: **room temperature**
  - **Gas & liquid phases** can **coexist** together at normal temp
  - Strong departures from ideal gas law: **high compressibility**
- **Microscopic**:
  - For densities above ~0.5 g/cm^3, **fog** or lacework forms
  - Aggregates form a localized quasi-**conduction** band
  - Ionization process $\Rightarrow$ very non-uniform **dE/dx**
  - Recombination is ~ **complete** in the regions of high **q/v**
  - Recombination increases **scintillation,** reduces ionization

$\Rightarrow$ **A non-gaussian partition of energy between ionization & scintillation occurs for ρ >0.5 g/cm^3**

“Gotthard TPC”

Pioneer TPC detector for 0-ν $\beta\beta$ decay search

- 5 bars, enriched ^{136}Xe (3.3 kg) + 4% CH_4
- MWPC readout plane, wires ganged for energy
- No scintillation detection $\Rightarrow$
  - no TPC start signal!
  - No measurement of drift distance!
- $\delta E/E \sim 80 \times 10^{-3}$ FWHM (1592 keV)

  $\Rightarrow$ 66 x 10^{-3} FWHM (2480 keV)

Reasons for this less-than-optimum resolution are not clear…

Likely: uncorrectable losses to electronegative impurities

Possible: Undetectable losses to **quenching** (4% CH_4)

α particles

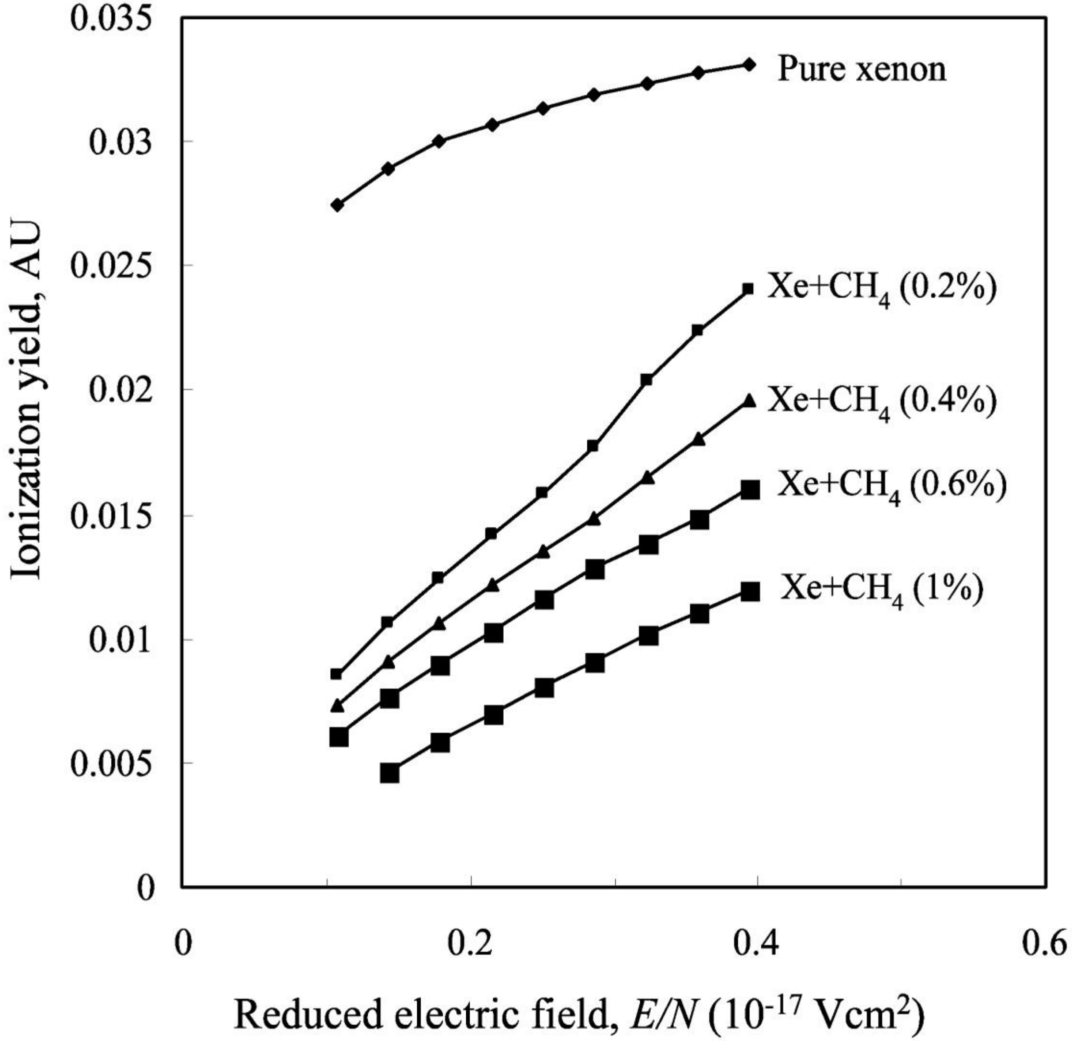


Fig.7. Dependence of ionization yield on reduced electric field (E/N) at a pressure of 2.6 MPa. **(~25 bars)**

K. N. Pushkin *et al,* 2004

IEEE Nuclear Science Symposium proceedings

A scary result: adding a tiny amount of simple molecules (CH_4, N_2, H_2) to HPXe quenches both ionization **and** scintillation for α's

α particle: dE/dx is very high

Gotthard TPC: 4% CH_4

Loss(α): factor of 6

For β particles, what was effect on energy resolution?

Surely small but not known, and needs investigation

Molecular Chemistry of Xenon

- Scintillation:
  - Excimer formation: $Xe^{*} + Xe \rightarrow Xe_2^{*} \rightarrow h\nu + Xe$
  - Recombination: $Xe^{+} + e^{-} \rightarrow Xe^{*} \rightarrow$
- Density-dependent processes also exist:

$$Xe^{*} + Xe^{*} \rightarrow Xe^{**} \rightarrow Xe^{+} + e^{-} + \text{heat}$$

  - Two excimers are consumed to make one photon!
  - More likely for both high ρ **+** high ionization density

– Quenching of both ionization and scintillation can occur!

$Xe^{*} + M \rightarrow Xe + M^{*} \rightarrow Xe + M + \text{heat}$ (similarly for Xe_2^{*}, Xe^{**}, Xe_2^{*+}…)

$Xe^{+} + e^{-}(\text{hot}) + M \rightarrow Xe^{+} + e^{-}(\text{cold}) + M^{*} \rightarrow$

$Xe^{+} + e^{-}(\text{cold}) + M + \text{heat} \rightarrow e^{-}(\text{cold}) + Xe^{+} \rightarrow Xe^{*}$

Barium daughter tagging and ion mobilities…

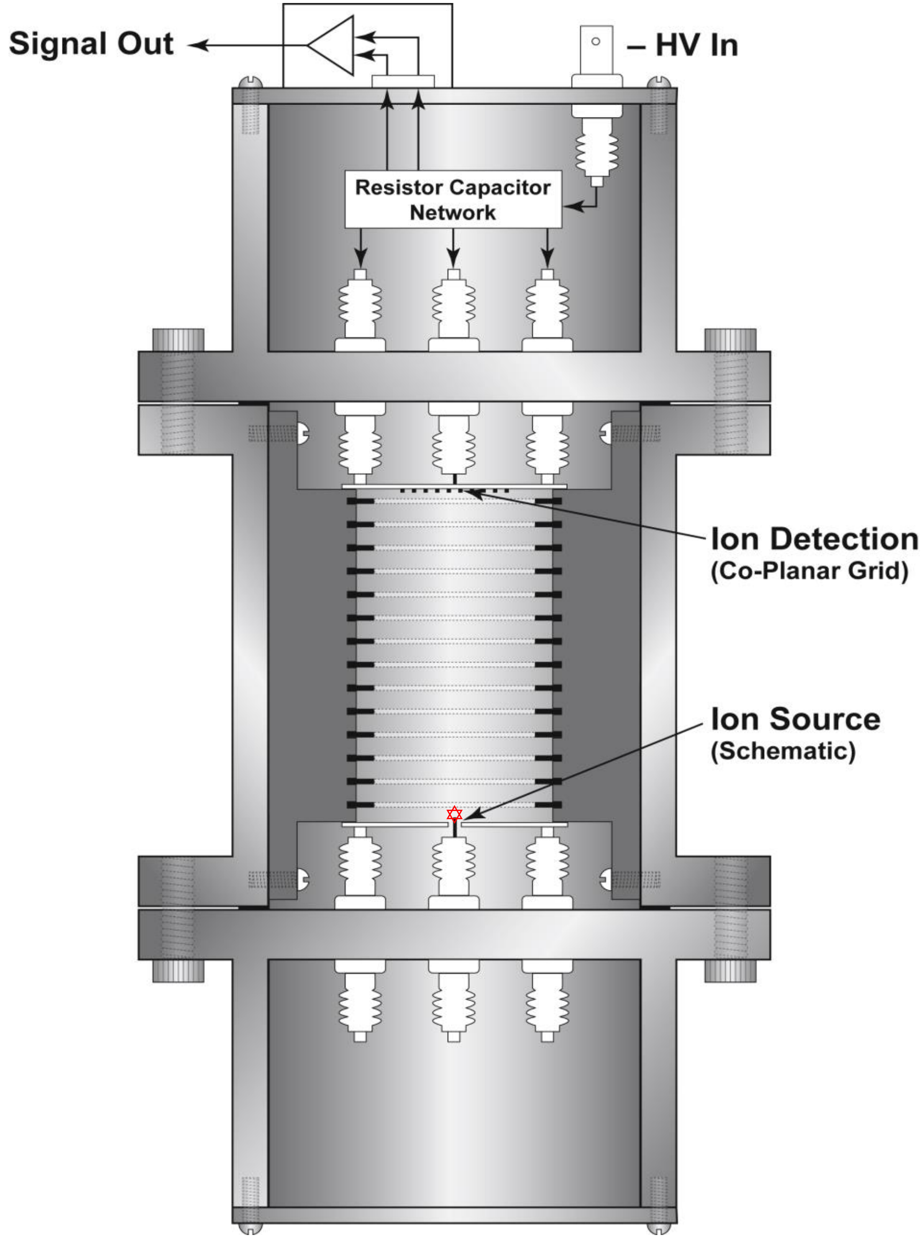
- Ba^+ and Xe^+ mobilities are quite different!
  - The cause is **<u>resonant charge exchange</u>**
  - RCE is macroscopic quantum mechanics
    - occurs only for ions in their parent gases
    - no energy barrier exists for Xe^+ in xenon
    - energy barrier exists for Ba ions in xenon
    - RCE is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

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

Barium daughter tagging and ion mobilities…

- Ba^{++} ion survives drift: IP = 10.05 eV
  - IP of xenon is 12.14 eV
- Ba^{++} ion arrives at HV plane, well ahead of all other Xe^{+} ions
  - Mobility difference, ~50%, is known to be true at low density
- Ba^{++} ion liberates at least one electron at cathode surface
  - May be an unrealistic fantasy
- Electrons drift back to anode plane, make detectable signal
  - Arriving electron signal serves as “echo” of the Ba^{++} ion,
- A very strong constraint on event validity is obtained:
  - Process is automatic!

- Clustering effects are likely to alter this picture!



A small test chamber can show whether ion mobility differences persist at higher gas density (no data now).

This could offer an automatic method to tag the "birth" of barium in the decay, by sensing an echo pulse if the barium ion causes a secondary emission of one or more electrons at the cathode.