A simulation campaign towards Directional Dark Matter using HPXe

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Purpose

WIMPs are natural and attractive particle candidates for Dark Matter

- Direct detection is one way of searching for them
- Several experiments: XENON100, LUX, CDMS, ...,

Observation of a few WIMP-like events (ton-scale?) may not be enough to claim full discovery

- Backgrounds

Nuclear recoils from elastic WIMP collisions should display modulated directional anisotropy

- Known backgrounds in Earth cannot create a sidereal directional modulation
- Powerful discriminant!

Sensing nuclear recoils directionality may be the key for a definite WIMP discovery claim

Directionality of WIMPs

WIMP halo → WIMP wind

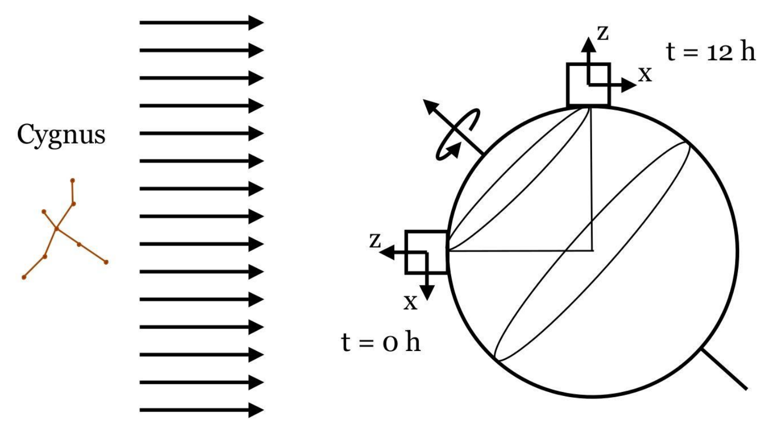
- Solar system orbit (~230 km/s)

Annual rate modulation

- Earth orbit (±30 km/s, few % effect)
- Background signal may be also annually modulated

Sidereal direction modulation

- Angle between WIMP wind & E
- Directionality signature (unique to WIMPs)
- O(10) rate variation between forward and backward directions (large effect)



[S. Ahlen et al, Int. J. Mod. Phys. 25 (2010) 1]

Directionality may be the most robust signature of the WIMP nature of DM.

Existing approaches (directionality)

Even without evidence of WIMPs, people are trying to sense nuclear recoil directionality

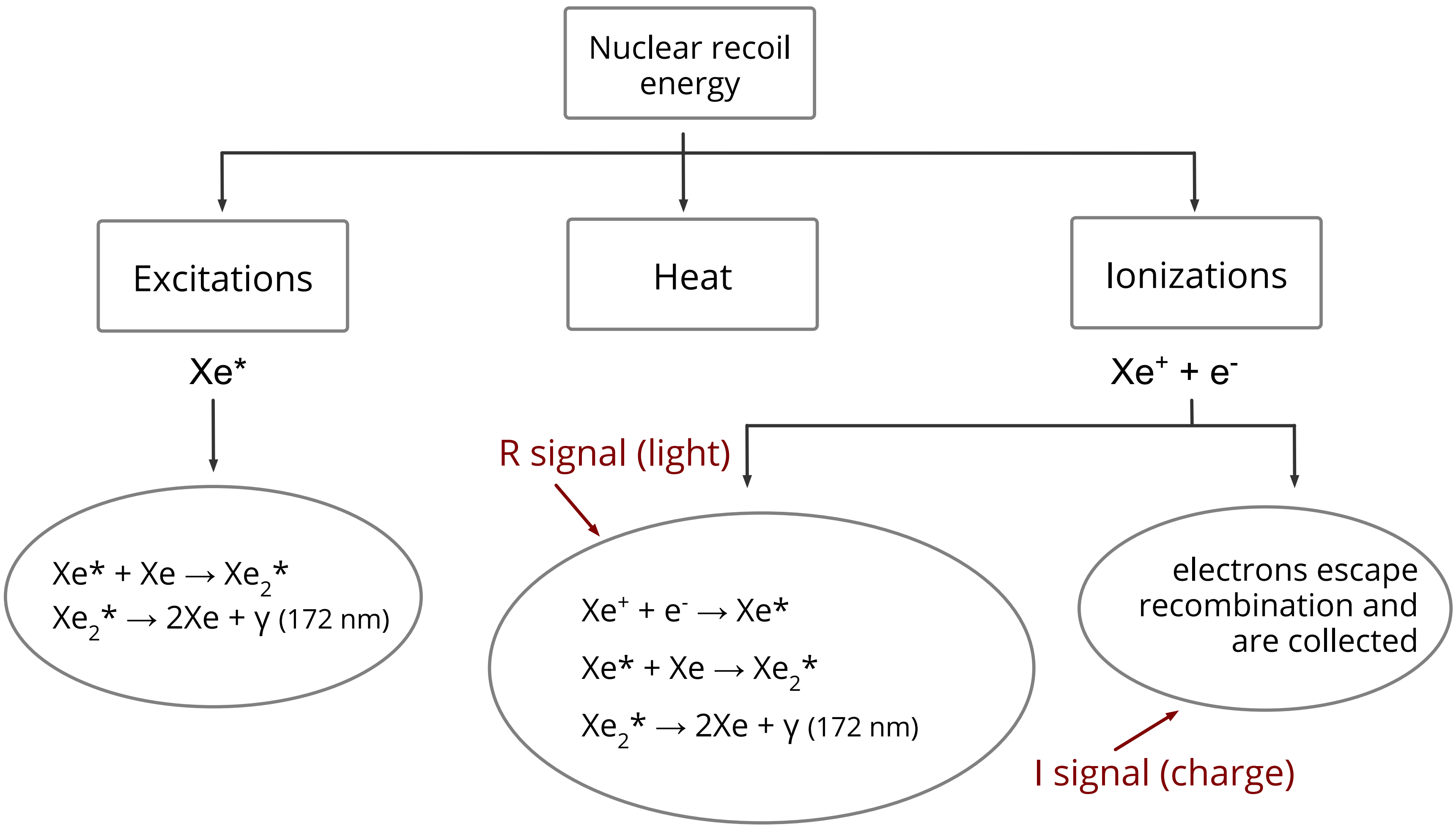
- D3, DMTPC, DRIFT, MIMAC, NWAGE, …
- Low pressure TPCs for track imaging
- Need to use dilute gas for extended tracks due to
  - Diffusion during drift
  - Visualization / reconstruction noise
- m_{max} ~ 100 g

Difficult to scale to ton-scale!

[D. Nygren, J. Phys: Conf. Ser. 460 (2013) 012006]

D. Nygren proposed a concept for WIMP directionality discrimination in monolithic ton-scale gaseous HPXe detectors (Columnar Recombination)

Nuclear recoils in pure HPXe



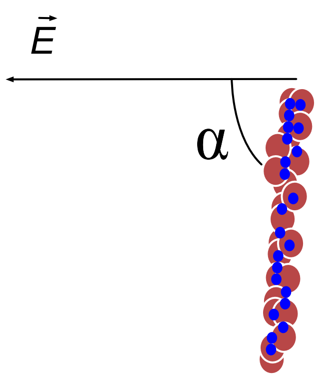
Columnar recombination

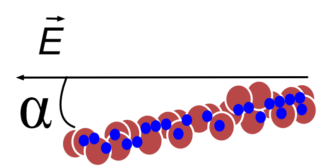
Columnar Recombination (CR) occurs when

- Drift field exists (e^-s & ions need to pass by each other)
- High ionization density (stronger collective charge effects)

For DM directionality:

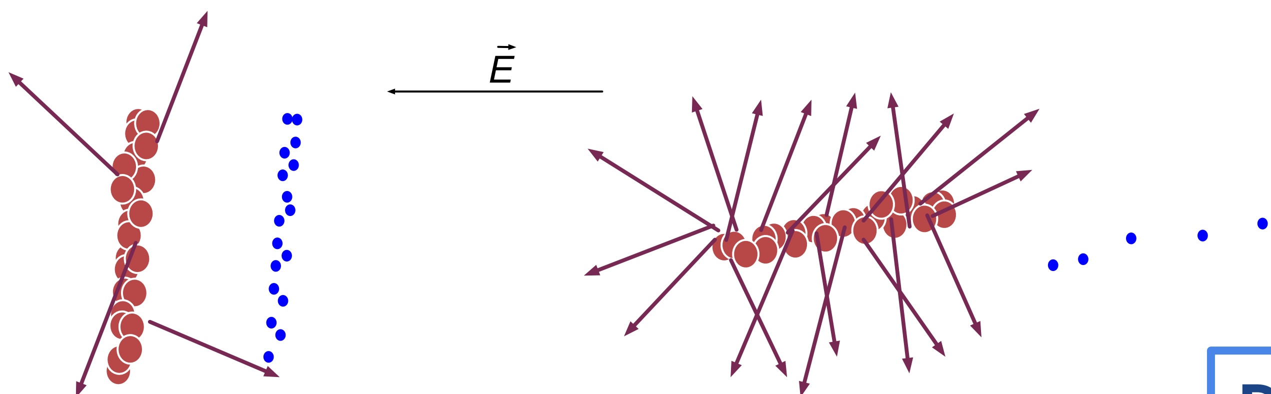
- Nuclear recoil tracks should show a linear shape
- alpha: angle between track and electric field vector





Columnar recombination

CR increases as □ increases



Negligible CR

Substantial CR

$$\boxed{D = R / I}$$

D – directionality signal
R – recombination signal
I – ionization signal

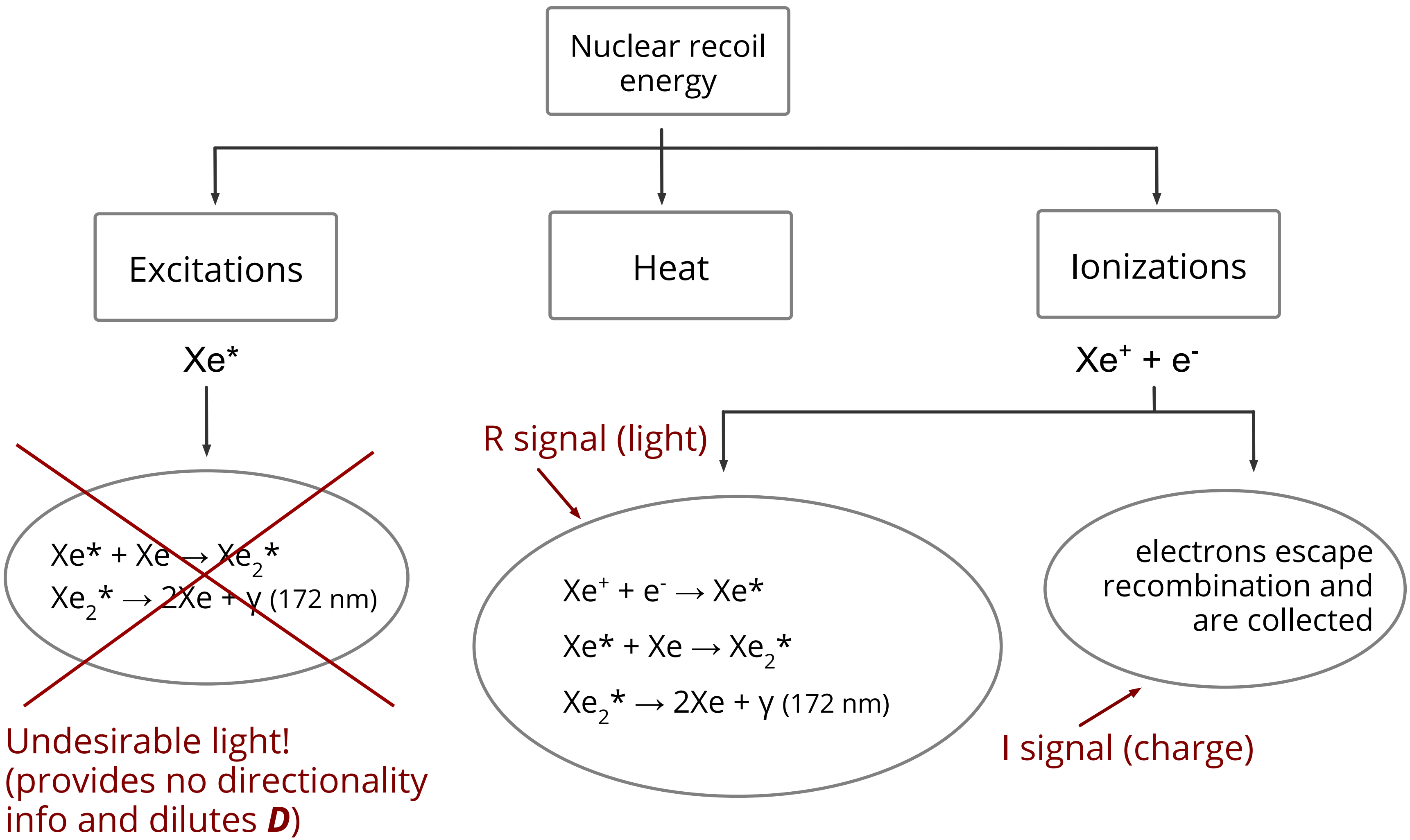
Sensing directionality:

- Determine *D* in a event-by-event basis
- The method may be optimal at densities ~100x higher than current LP TPCs
- Diffusion doesn't degrade *D* (information extracted before drift of electrons)

Recombination signal

- Low energy nuclear recoils
  - Quenching is large
  - *R* and *I* signals are small
- *I* is easy to detect (drift + EL amplification)
- *R* is a challenge
  - Low detection efficiency
  - Recombination is not the only source

Excitations need to be converted into ionizations



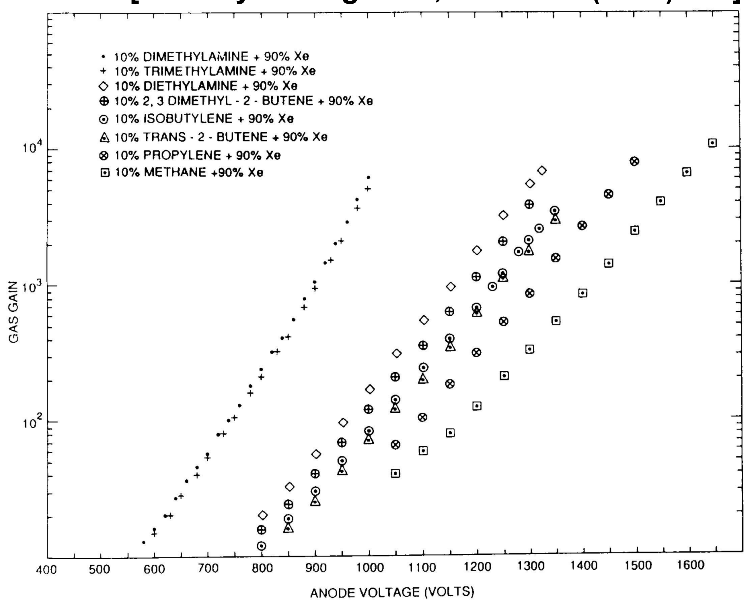
The Penning effect does it

Happens when an additive with lower IP than the 1st excited state of the gas is added

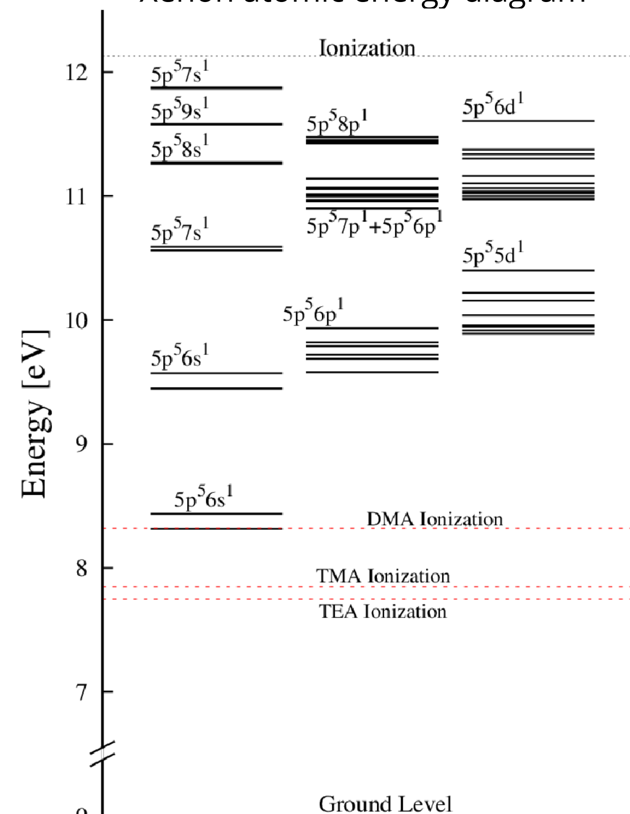
Evidence from enhanced avalanche gain

TMA seems to be the “magic” molecule but others may work (DMA, TEA, … ?)

[Ramsey and Agrawal, NIMA 278 (1989) 576]

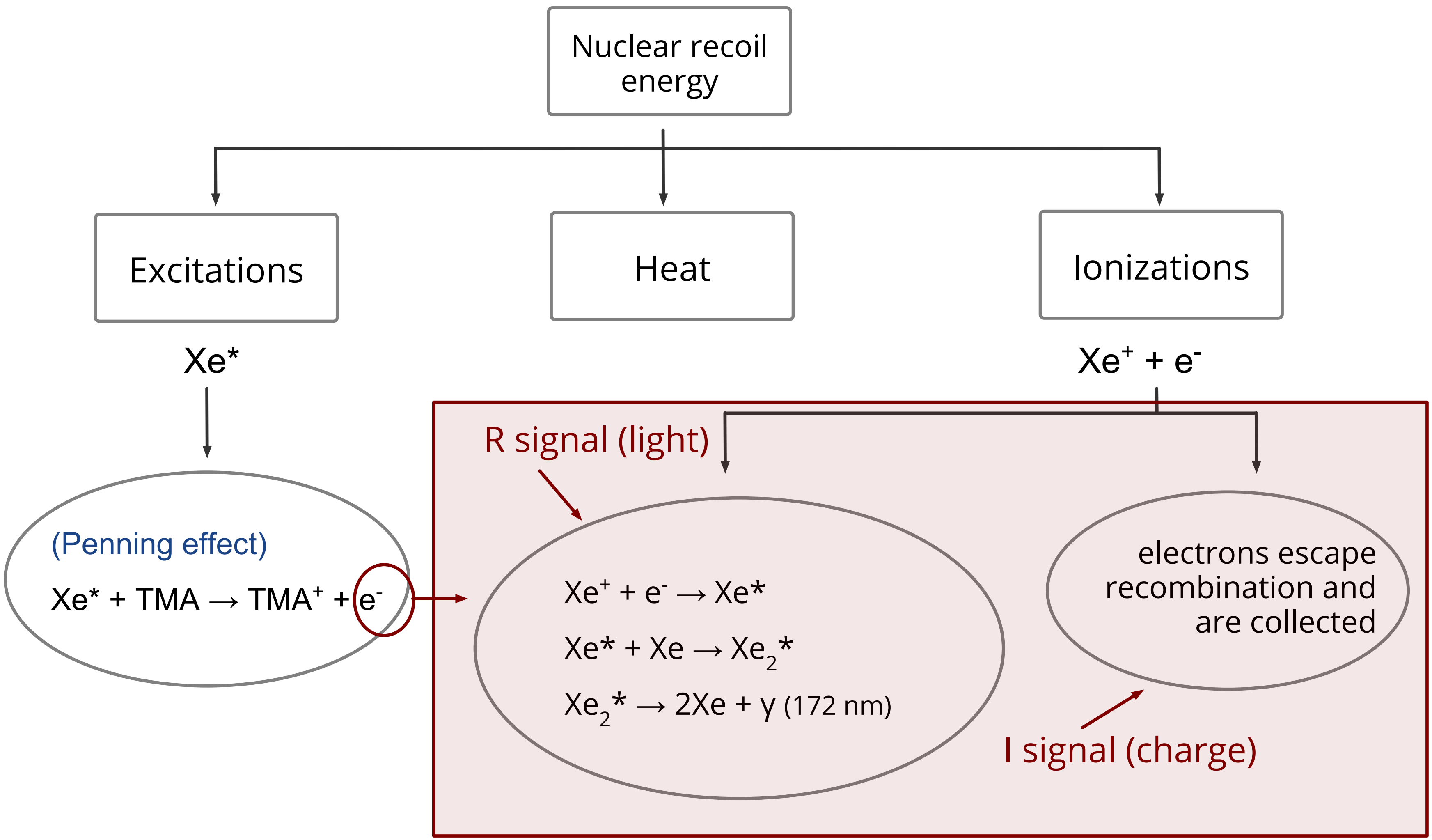


Xenon atomic energy diagram



What is the Penning efficiency?
Broken TMA bonds?

The Penning effect does it



TMA fluorescence (WL-shifting)

[Cureton et al, Chem Phys 63 (1981) 31]

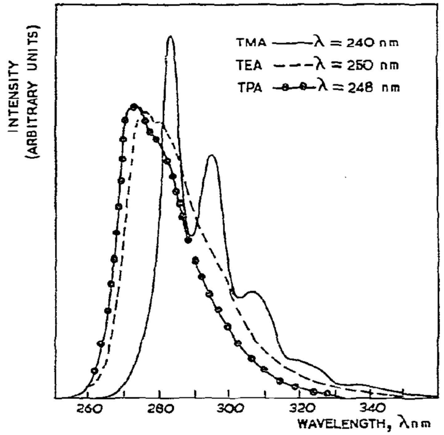


Fig. 4. Vapour-phase fluorescence spectra of TMA, TEA and TPA at excitation wavelengths indicated.

Charge exchange efficiency?
Time Scale?
Fluorescence efficiency?

$Xe^+ + e^-$

R signal (light)

e^-

(charge exchange)

$Xe^+ + TMA \rightarrow Xe + TMA^+$

(recombination)

$TMA^+ + e^- \rightarrow TMA^*$

$TMA^* \rightarrow TMA + \gamma$ **(300 nm)**

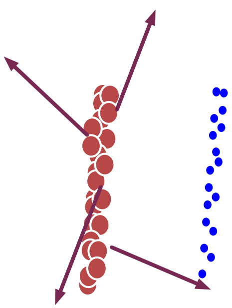
electrons escape recombination and are collected

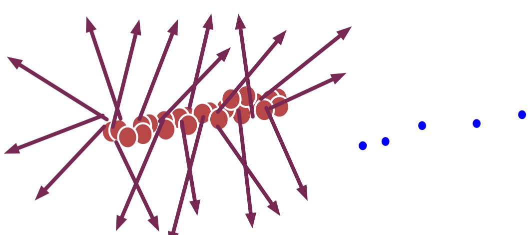
I signal (charge)

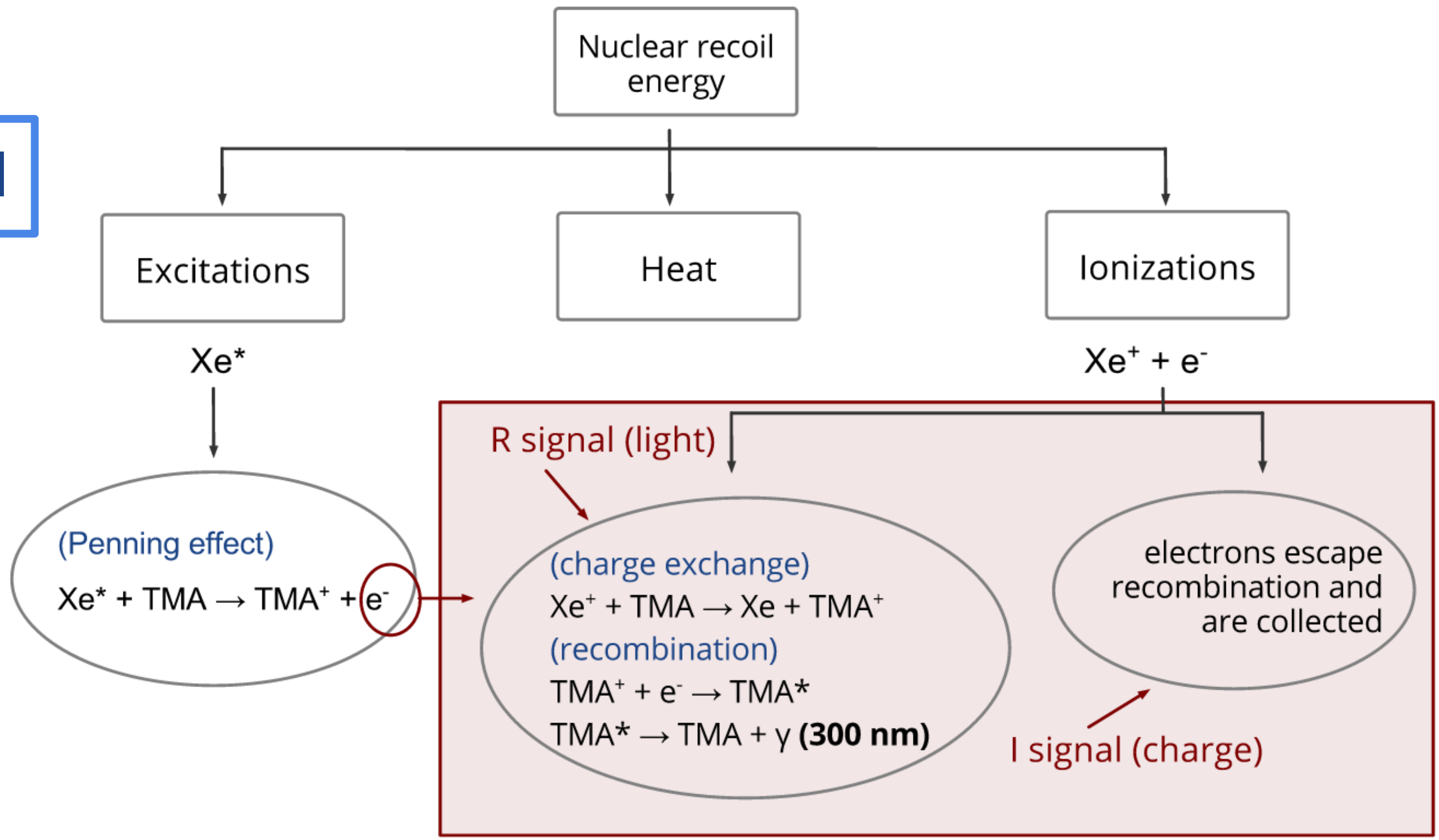
TMA also helps because cools down electrons promoting recombination

The whole microscopic picture

D = R / I







Further optimization of R

R signal collection should be further improved

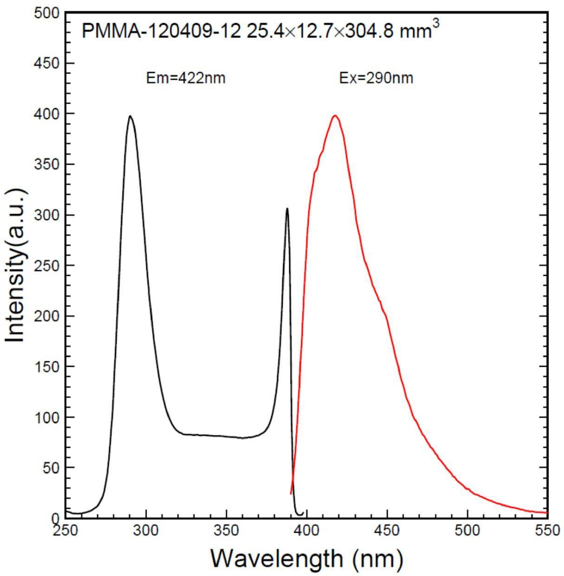
4π optical coverage would be ideal

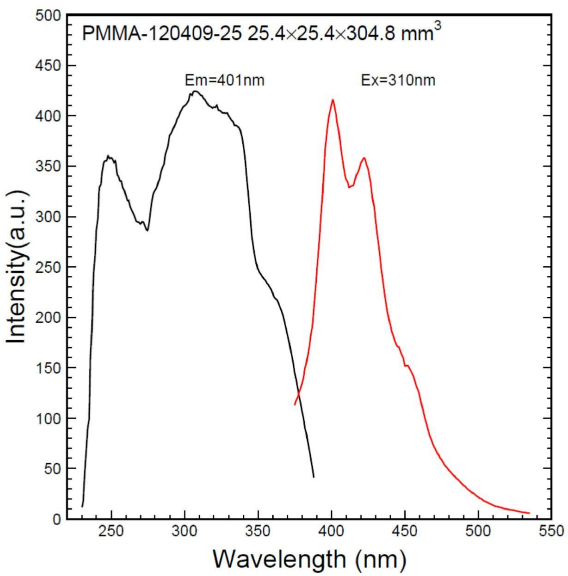
Impractical covering a detector with PMTs (cost, radiopurity)

Plastic bars for WLS

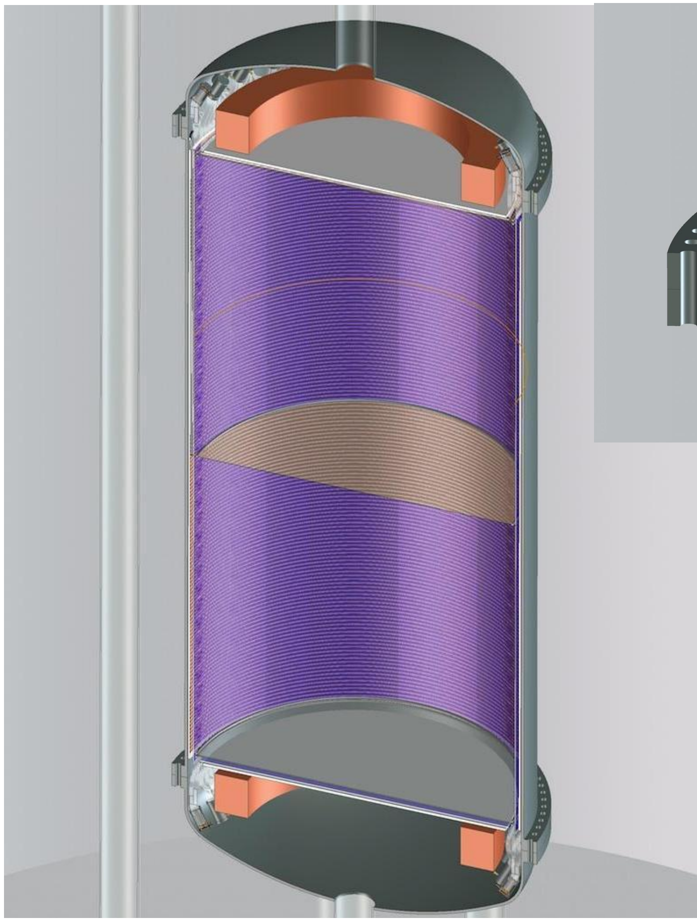
- TMA fluoresces @ 300 nm, WLS bars shift light to ~400 nm

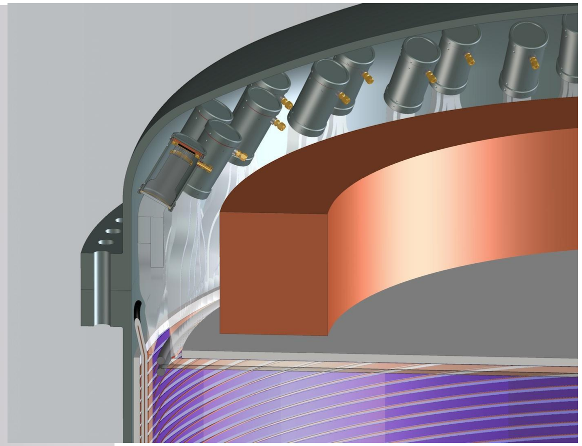
Wavelength shifting is the key.





OSPREY concept





High optical coverage feasible!

Symmetric "ton-scale" HPGXe TPC

WLS plastic in all surfaces

Except HV cathode plane

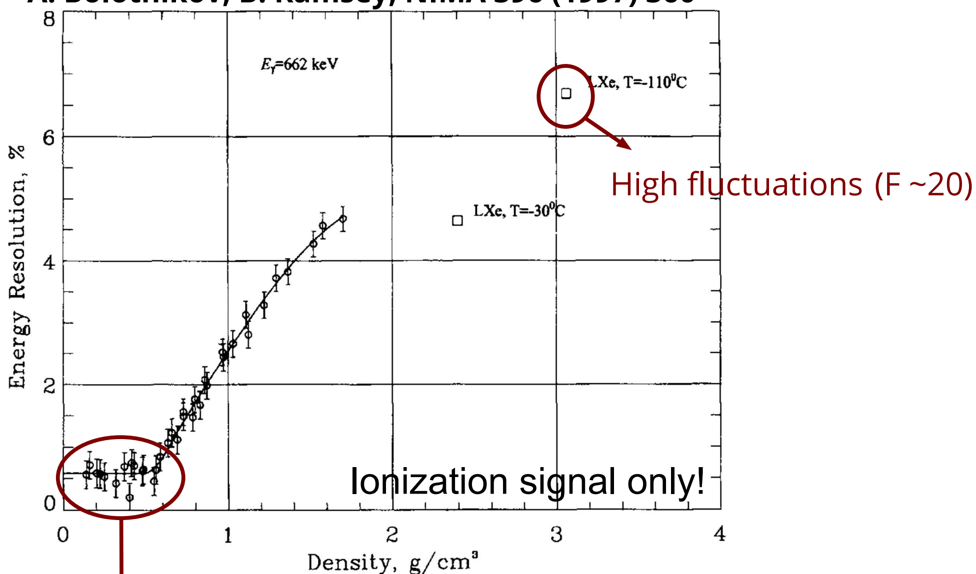
Light guides

PMTs shielded by copper rings (much fewer)

[Rodolfo Orellana, simple geometry] → Preliminary GEANT4: 15 % overall DE

Operating conditions

A. Bolotnikov, B. Ramsey, NIMA 396 (1997) 360



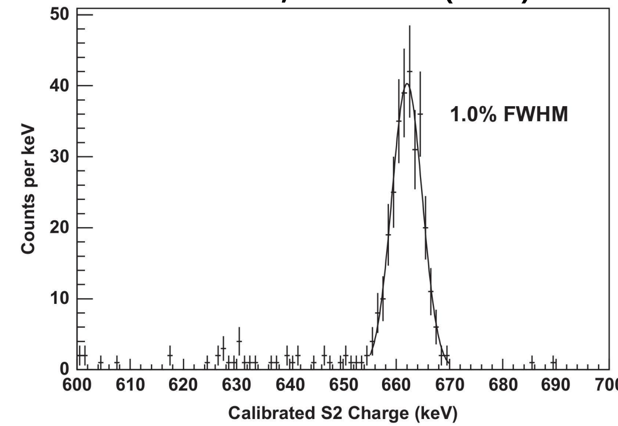
For ρ<0.55 g/cm³ energy resolution is intrinsic (F = 0.15)

Gas density < 0.55 g/cm³ is good for energy resolution

Helps having low fluctuations in D

Helps in discrimination between electron and nuclear recoils (log(S1/S2))

NEXT Collaboration, NIMA 708 (2013) 101



1.0% energy resolution FWHM

^{137}Cs 662 keV γ-rays

15 bar of xenon (room *T*)

NEXT-DBDM:

- TPC based in EL
- ~ Noiseless amplification

Gaseous phase!

Operating conditions (pressure)

Not too much pressure

Electrostatically the track should have a linear shape

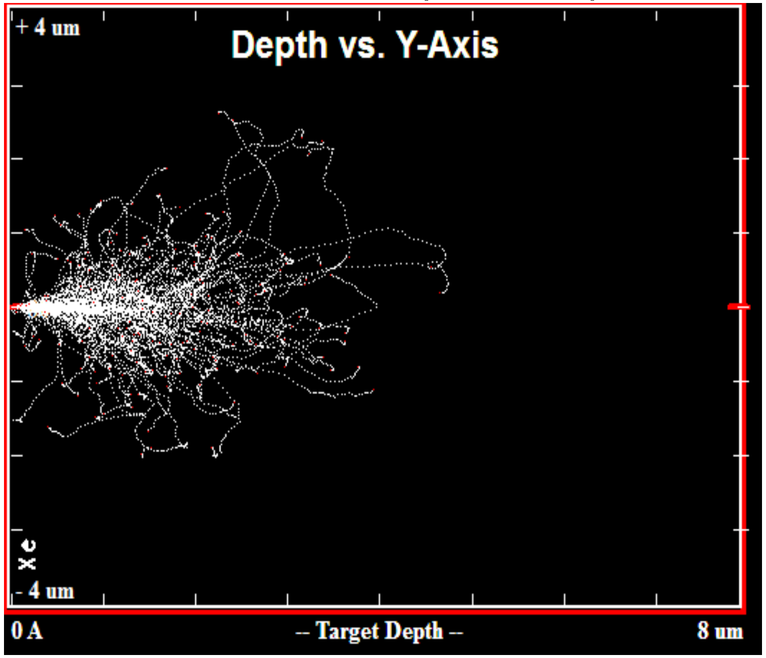
$$r_O = \frac{e^2}{\varepsilon k_B T}$$ (~70 nm @ 10 bar)

Not too small pressure

Penning and charge exchange should be efficient

10 bar seems to be about the right pressure!

SRIM simulation
30 keV Xe recoils | 10 bar Xe | 200 events



Operating conditions (TMA conc.)

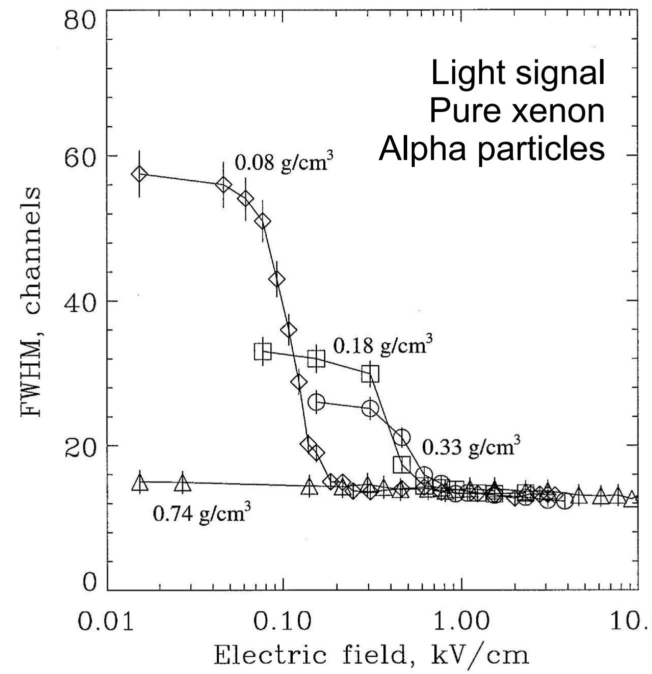
How much TMA?

- Too little: transfer processes too slow
  - Penning transfers
  - Charge exchange
- Too much: quenching of UV light
  - Collisions between TMA* and TMA

Which drift field?

- Too low: no I signal
- Too high: lower R signal
- Optimization of Columnar Recombination

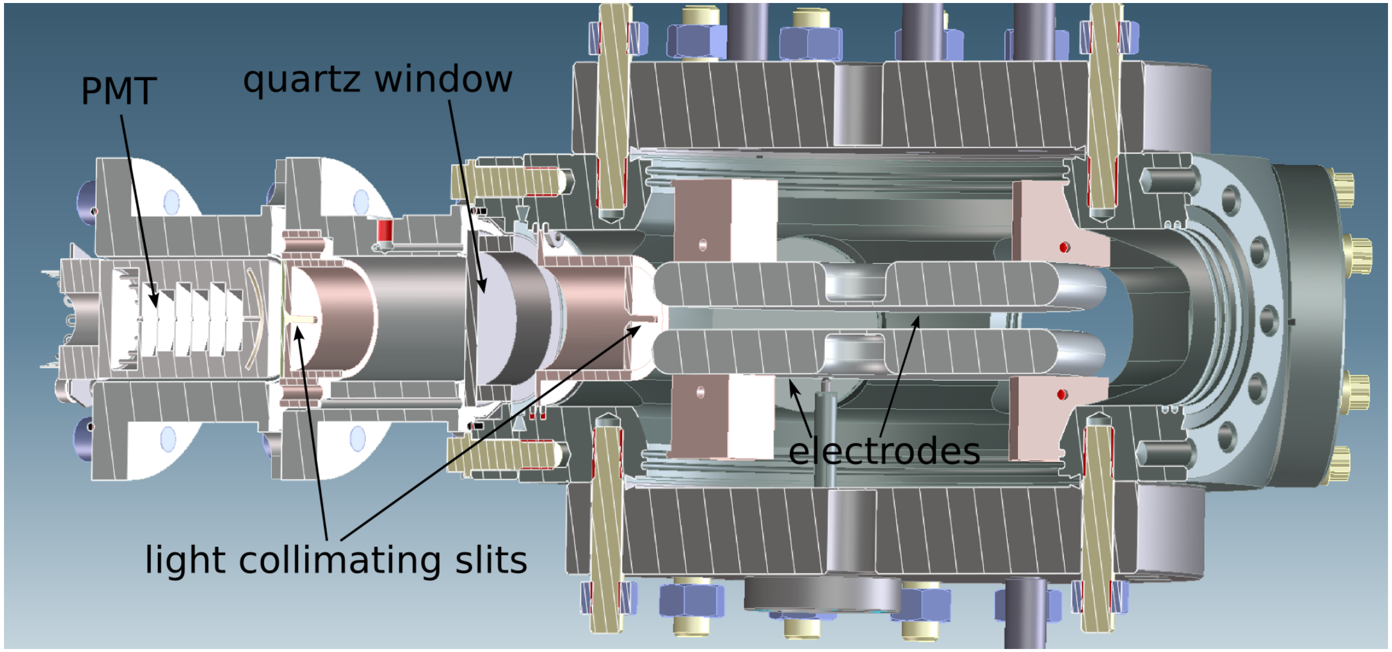
[A. Bolotnikov, B. Ramsey, NIMA 428 (1999) 391]



Need to find the optimum TMA concentration and the optimum drift field.

Experimental efforts

TeaPot



Parallel plate ionization chamber

4 PMTs looking into produced light

Collected charge and light are measured (DC mode)

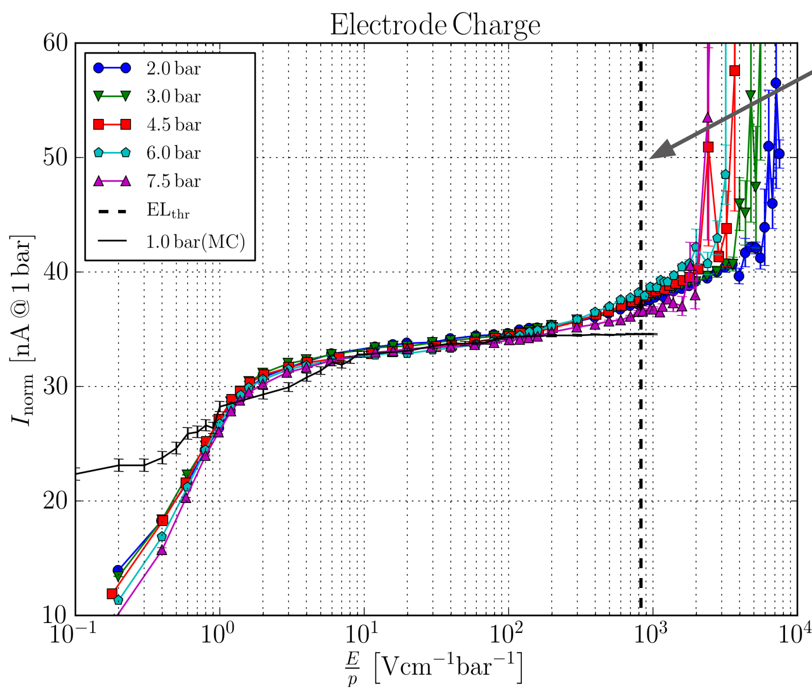
Plan is to measure light and charge as functions of pressure, electric field, TMA concentration, ...

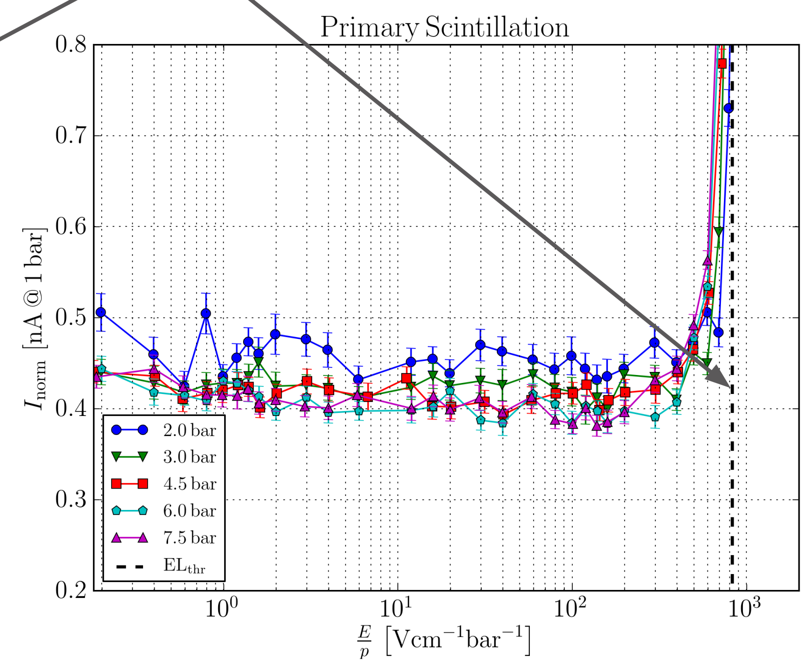
TeaPot - preliminary results (pure Xe)

Pure Xenon

^{241}Am 60 keV Gamma-rays (10 mCi)

C. M. B. Monteiro et al, JINST 2 (2007) P05001





Electrons lost due to diffusion for electric fields < 10 Vcm^{-1}bar^{-1}

No evidence for recombination suppression

Some hardware upgrades ongoing

TMA results soon

Further experimental efforts

NEXT-MM TPC **(Diana Herrera, Zaragozza)**

Explore columnar recombination in Xe+TMA using alpha particles

Angle between track and electric field assessed using rise-time of the ionization signal

Towards OSPREY **(LBNL, ANL, FNAL, Iowa State Univ, Univ. New Mexico, USA)**

CR chamber (micro-TPC)

10 Gev/c pion test beam inducing nuclear recoils with known direction (precision silicon strip hodoscope)

Assess CR as function of angle between track and field (light signal)

NRC-TPC (low pressure 3x3x3 cm^3 chamber)

Do low energy (20 - 50 keV) nuclear recoils retain directionality information?

Simulation needs

Nuclear recoils in HPGXe

Spatial distribution & spectrum of sub-excitation e⁻s?

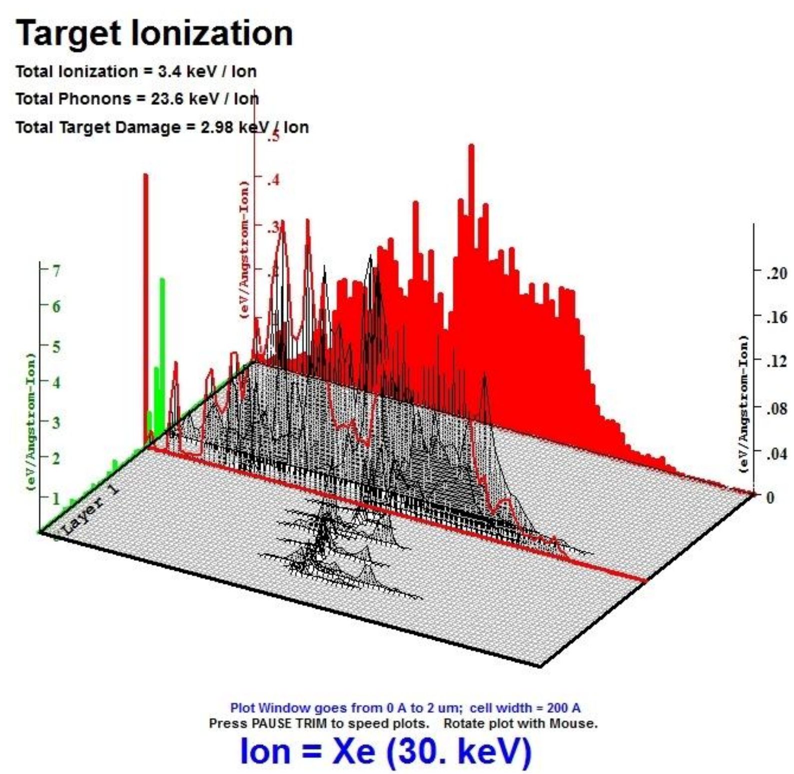
Spatial distribution of individual excitations?

Preliminary simulations (SRIM)

Not enough info for a detailed microscopic description (doesn't output individual excitation and ionizations)

LLNL **(Michael Foxe)** has some code benchmarked for LAr

Atom-atom and atom-ion cross sections for GXe?



Transfer processes & CR

What is the Penning efficiency of HPXe + TMA?

How fast does this process happen?

How efficient and how fast is charge exchange between Xe ions and TMA?

Is TMA fluorescence after recombination efficient?

How to collectively simulate columnar recombination considering all the charges within the track?

Collective recombination simulation

A. Goldschmidt | Megan Long, LBNL

Based in Garfield ++

Implemented atomic thermal motion

Added a method for tracking an electron/ion "cloud" to the AvalancheMicroscopic class

Initial position of electrons at $0.1 \times R_O$ from the parent ions and with E_k up updated to reflect the electric potential from all charges

Forced x10 smaller null collision steps to ensure good tracking in the highly non-uniform field around charges

Recombination condition: $E_k + E_p < 0$ & $d_{closest\_ion} < r_O$

Initial tests and debugging ongoing

Computing time scaling badly with # of charges in the cloud. Room for optimizations!

Stay tuned!

Electroluminescence in HPGXe+TMA

Preferred method for ionization signal amplification is EL (~ noiseless)

Does it happen with TMA instead of Xe?

For what electric fields and TMA concentrations is the process linear?

Will extend my electroluminesce model to accommodate TMA

Magboltz cross sections for TMA may need improvement

Use drift velocity and longitudinal diffusion obtained with NEXT-MM? Better precision needed?

Summary

NR directionality may be the key for a definitive WIMP discovery claim

Atomic / molecular processes happening in Xe+TMA may allow substantial signal for NR directionality

- Through Columnar Recombination
- No tracking / visualization of NR tracks needed! No diffusion!
- Providential match of TMA fluorescence to WLS

This may be possible at the ton-scale

- ~ 3 orders of magnitude higher densities than current LP TPCs
- Only a few dozens PMTs needed (and hidden)

A lot of questions to be answered, optimum parameters to be determined

- **Simulations are a very important piece of the game!**

Thank you!

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Comments and collaborative engagement are most welcome!