High Pressure Gaseous Xe+TMA mixtures for improved 0νββ decay and DM searches: initial experimental studies

C. A. B. Oliveira

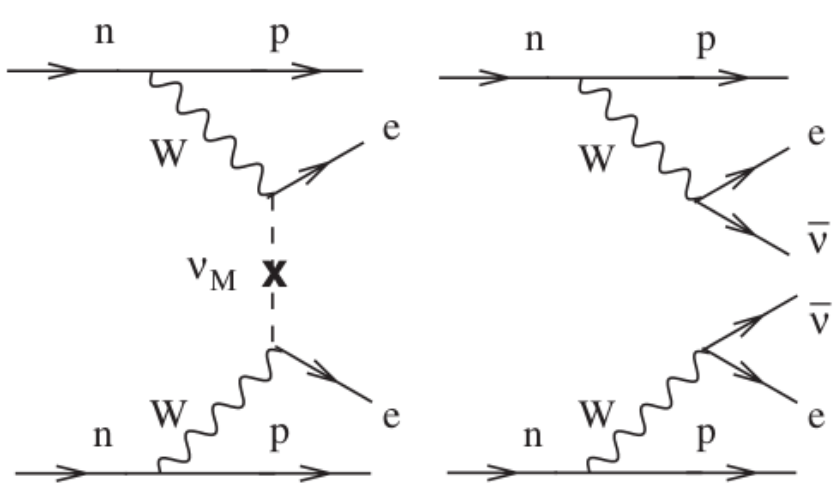
INPA, LBL, May 21 2015 | Berkeley, CA, USA

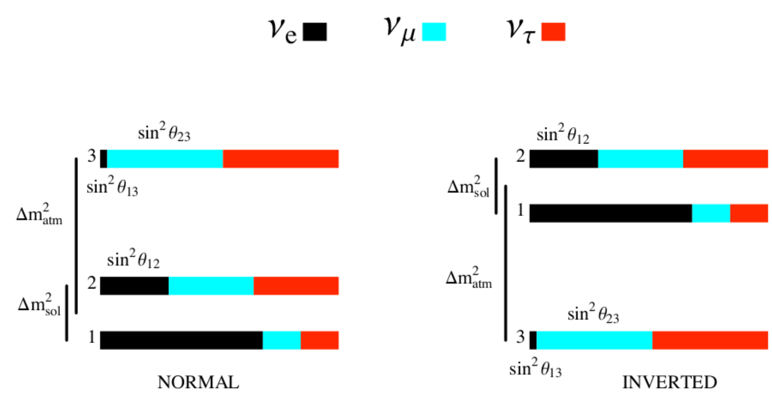
0νββ decay | Majorana neutrinos

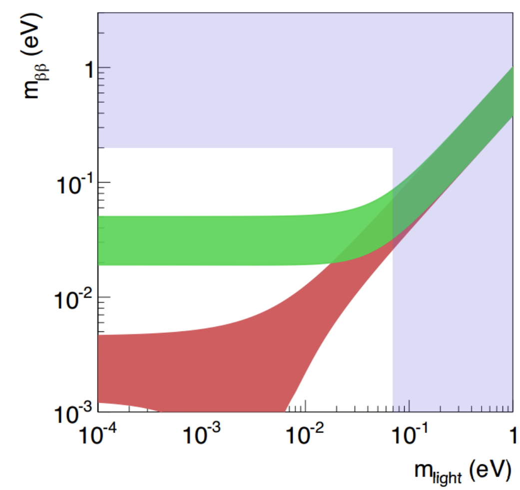
Neutrinos mix and have mass

Dirac or Majorana?

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 m^2_{\beta\beta}$$







$0\nu\beta\beta$ decay searches with ^{136}Xe

Explore different isotopes

^{28}Te (CUORE), ^{76}Ge (GERDA, MAJORANA), ^{150}Nd (SNO+), ^{82}Se (superNEMO), **^{136}Xe** (EXO - liquid, **NEXT - gaseous**)

Xenon:

- Relatively inexpensive
- Easy to enrich
- Homogeneous detectors
- Scalable technology

^{136}Xe 0νββ decay | γ-Backgrounds

Underground

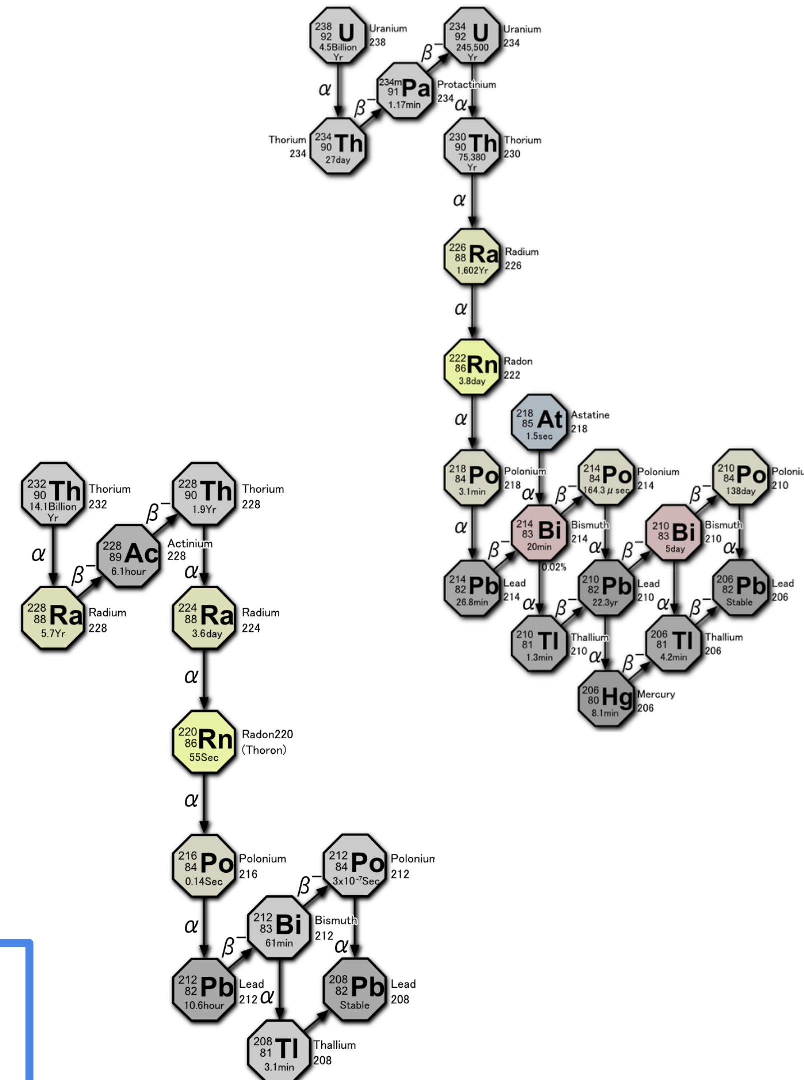
- Shields from cosmic muon induced γs
- $Q_{\beta\beta}$ = 2.458 MeV

Main backgrounds

- Detector Materials (^{232}Th, ^{238}U chains)
- ^{208}Tl (2.615 MeV) & ^{214}Bi (2.448 MeV) γs
- Radon (lab air)

Experiments need

- Radiopurity screening programs
- Radon monitoring
- Background MC models

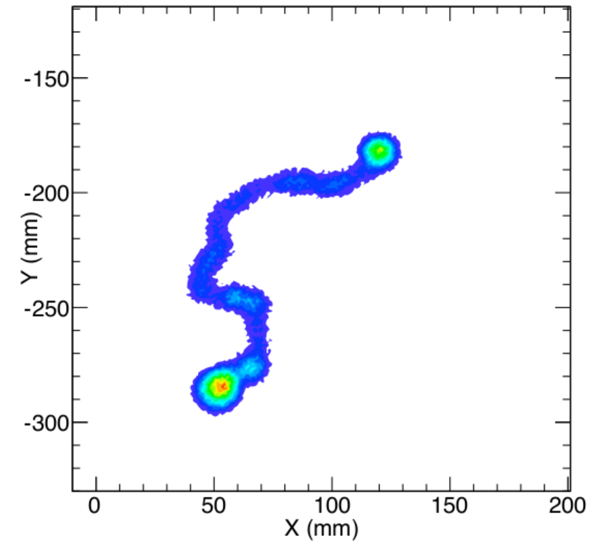


Background suppression is very important!

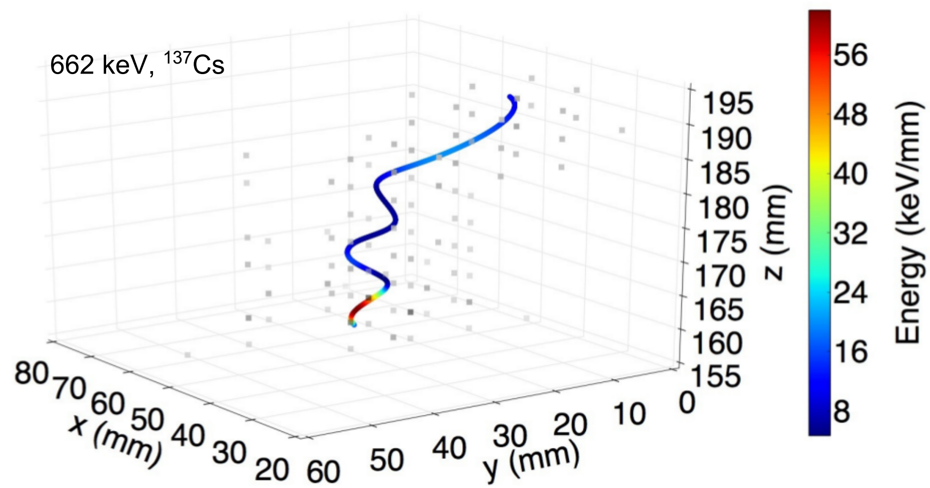
γ-Background topological suppression

Gaseous phase

- 0.05 g/cm^3 @ 10 bar, room temperature
- 1.25 MeV e$^-$ tracks about 15 cm long (70 keV/cm)
- > 200 keV en. deposition at the end of each track
- "Spaghetti with two meatballs" signature
- Backgrounds with only one "meatball"
- Topological signature (not available in liquid)

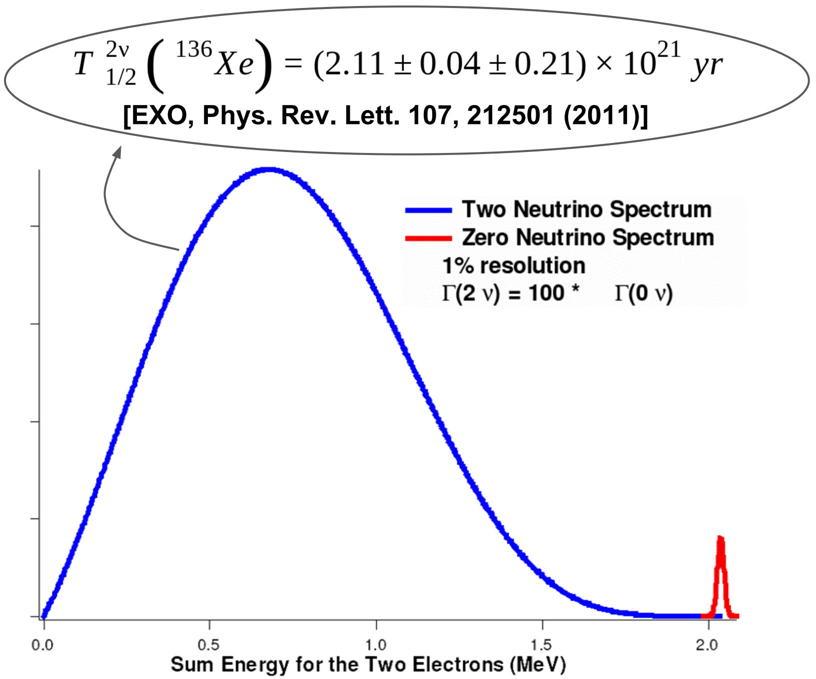


Extra handle in background suppression: topological signature recognition



2νββ decay as background

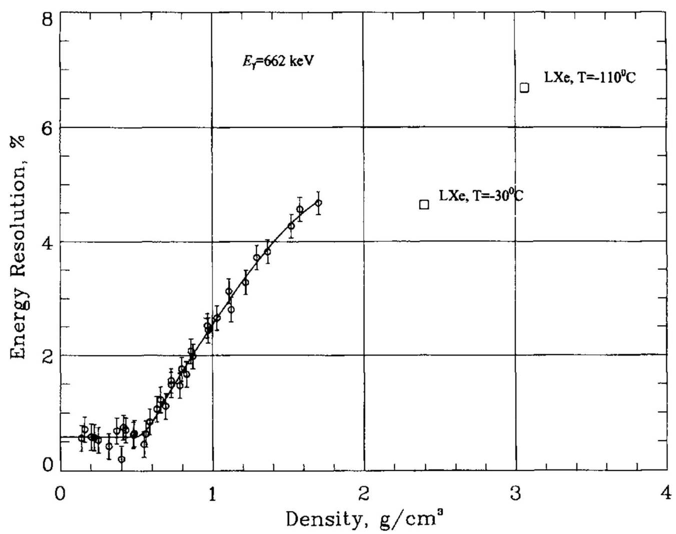
Topologically, 2νββ and 0νββ look the same

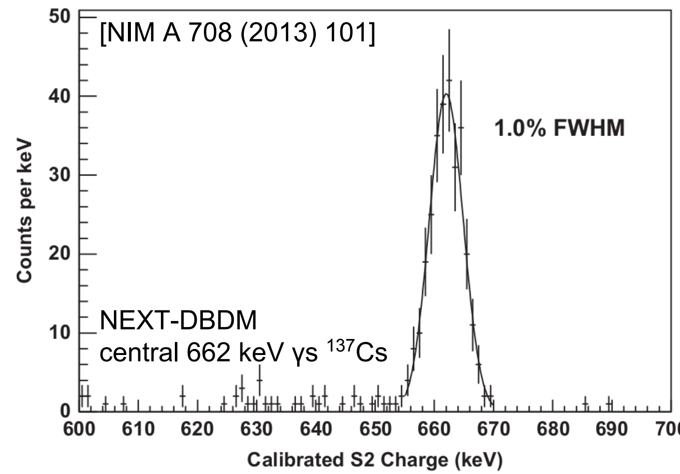


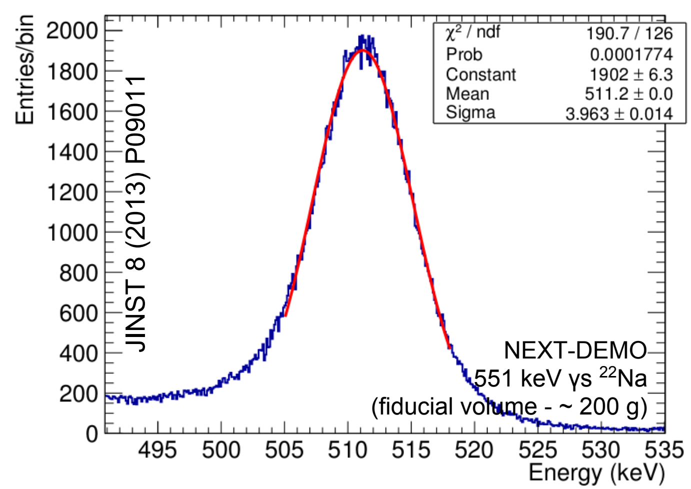
Energy resolution is a key ingredient in 0νββ decay searches!

Energy resolution in HPGXe

$$R_{\mathrm{E}} = 2.35\sqrt{\frac{F}{\overline{N}_{\mathrm{e}}} + \frac{1}{\overline{N}_{\mathrm{e}}}\left(\frac{J}{\overline{N}_{\mathrm{EL}}}\right) + \frac{2}{\overline{N}_{\mathrm{ep}}}}$$





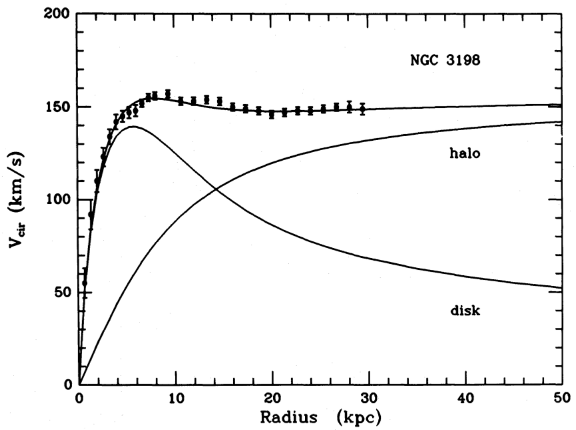


1.0 % @ 662 keV extrapolates to 0.57 % @ $Q_{\beta\beta}$

1.82 % @ 511 keV extrapolates to 0.83% @ $Q_{\beta\beta}$

EL in HPGXe allows outstanding energy resolution!

Dark Matter

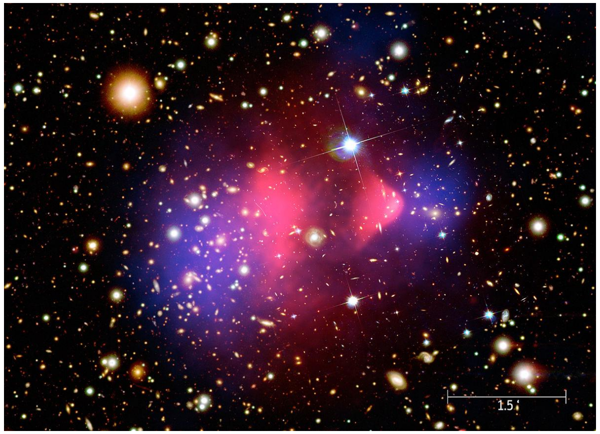


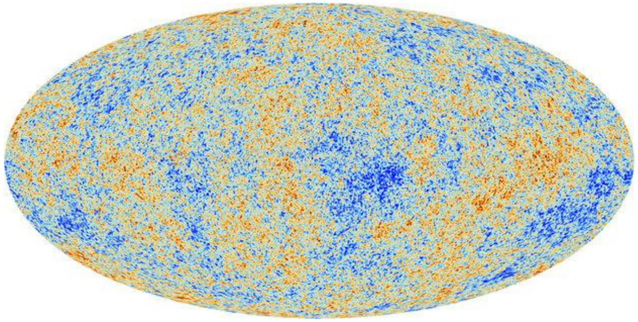
Evidence for DM comes from

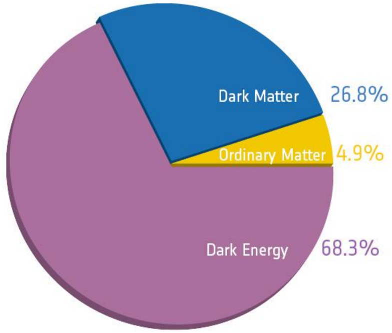
- Flat velocity distributions of spiral galaxies
- Gravitational lensing observations
- Fluctuations in the CMB

DM makes up 26.8 % of the Universe

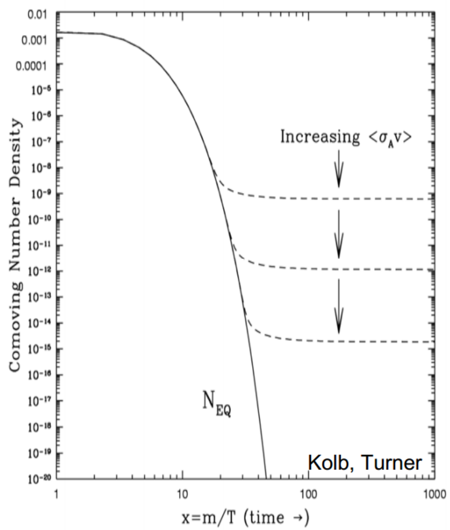
- 84.5 % of the matter

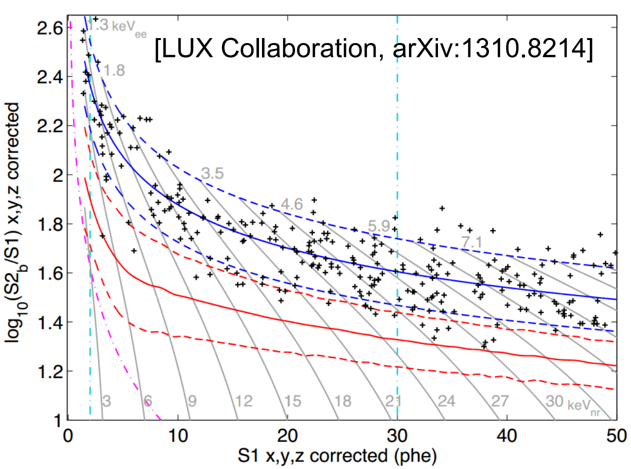






WIMPs





WIMPs are DM candidates

- Interact only through Weak and Gravitational Forces
- Their relic density matches the current DM density (0.3 GeV/cm^3)

Nuclear recoils induced by WIMPS

- Direct detection searches
- Low energy nuclear recoils
- Overlap with lots of background (mainly γs)
- S_2/S_1: distinguish between nuclear & electron recoils (may be better in HPGXe because lower F)
- Neutron induced events still a problem

S_2/S_1 discrimination may be better in HPGXe! It protects against γs but not against neutrons.

WIMP directionality

WIMP halo → WIMP wind

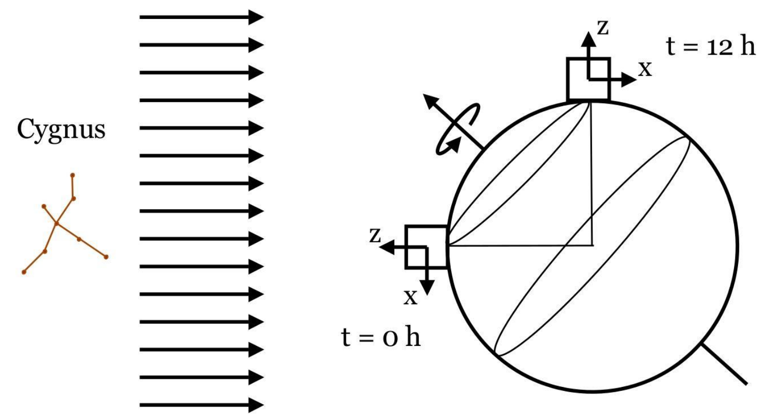
- Solar system orbit (~230 km/s)

Annual rate modulation

- Earth orbit (±30 km/s, few % effect)
- Background 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.

Experimental challenges (0νββ & DM)

Low density, extended tracks (0νββ)

- Topological signature recognition

Low Fano factor

- Energy Resolution (0νββ)
- S_2/S_1 Electron / Nuclear recoils (DM)

Columnar recombination, molecular additives

- Nuclear recoil directionality sensitivity (DM), as proposed by David Nygren
- The additive would also be benefit for previous points

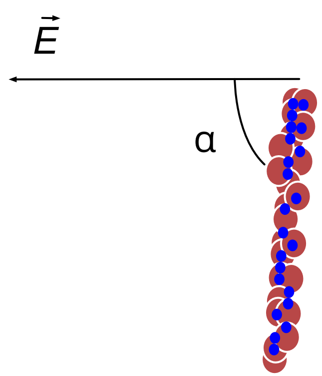
Columnar recombination (NR - DM)

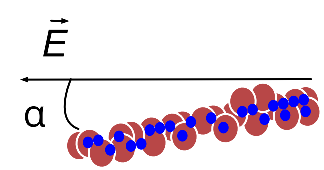
Columnar Recombination (CR) occurs when

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

For DM directionality:

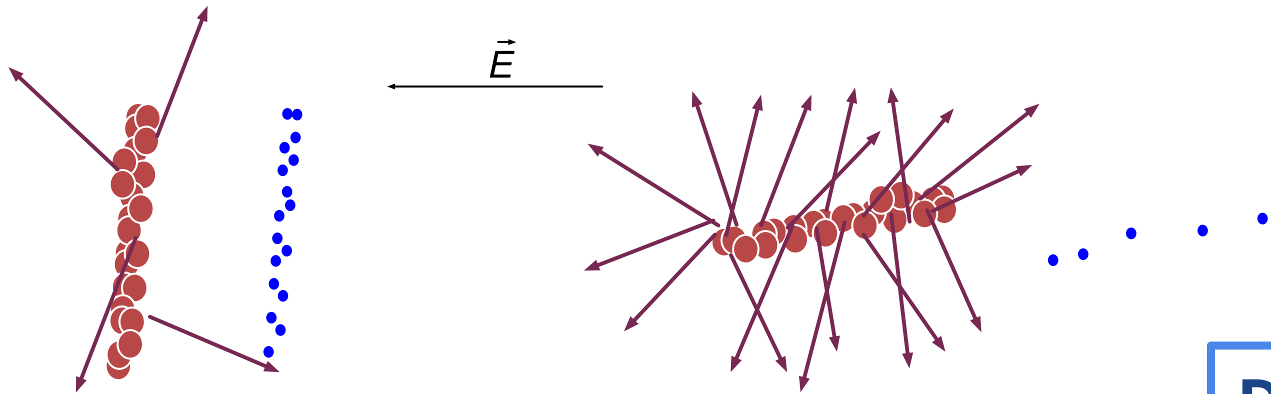
- Nuclear recoil tracks should show a linear shape
- alpha: angle between track and electric field vector





Columnar recombination (NR - DM)

CR increases as □ increases



Negligible CR

Substantial CR

D = R / I

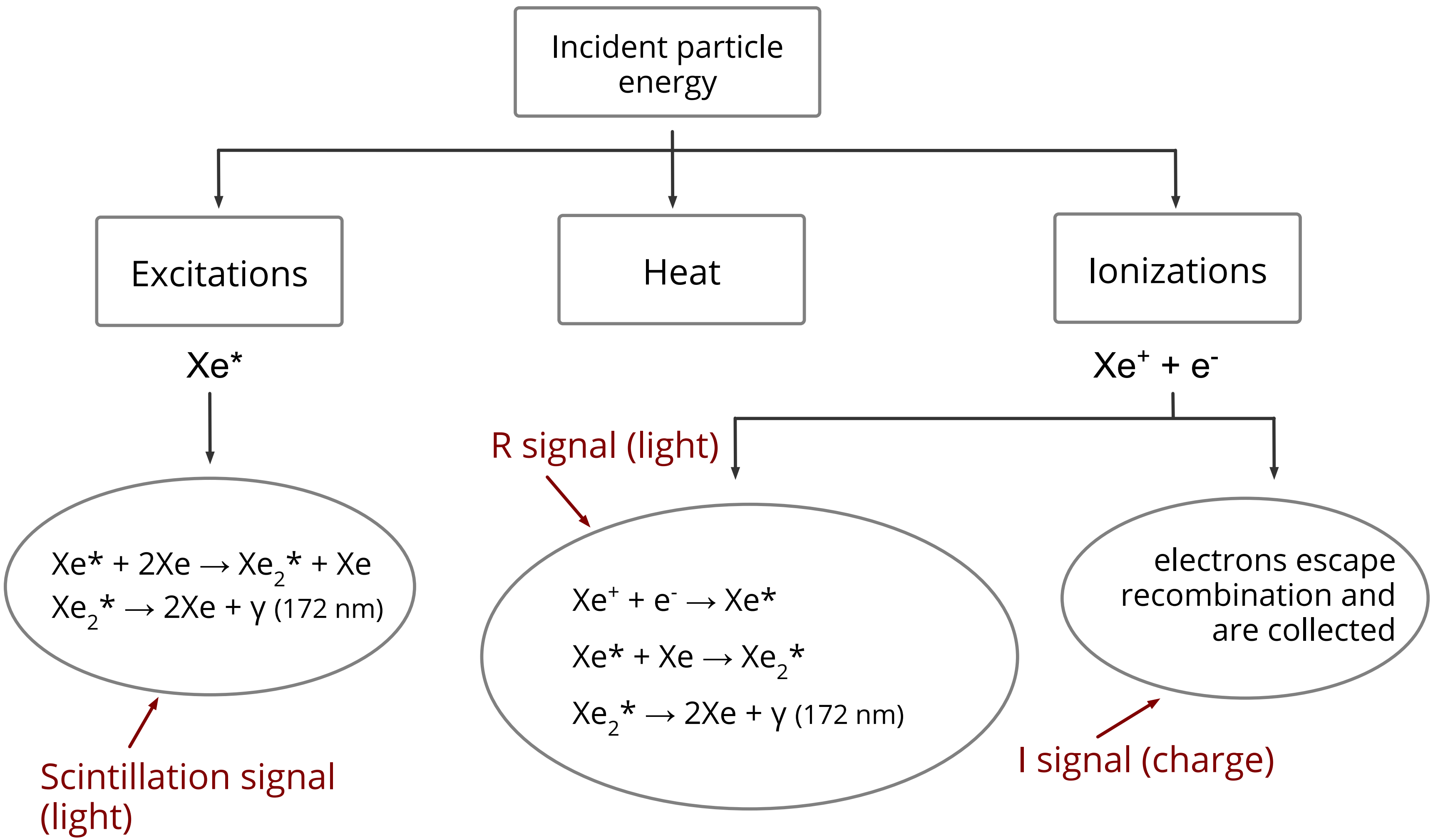
D – directionality signal
R – recombination signal
I – ionization signal

Sensing directionality:

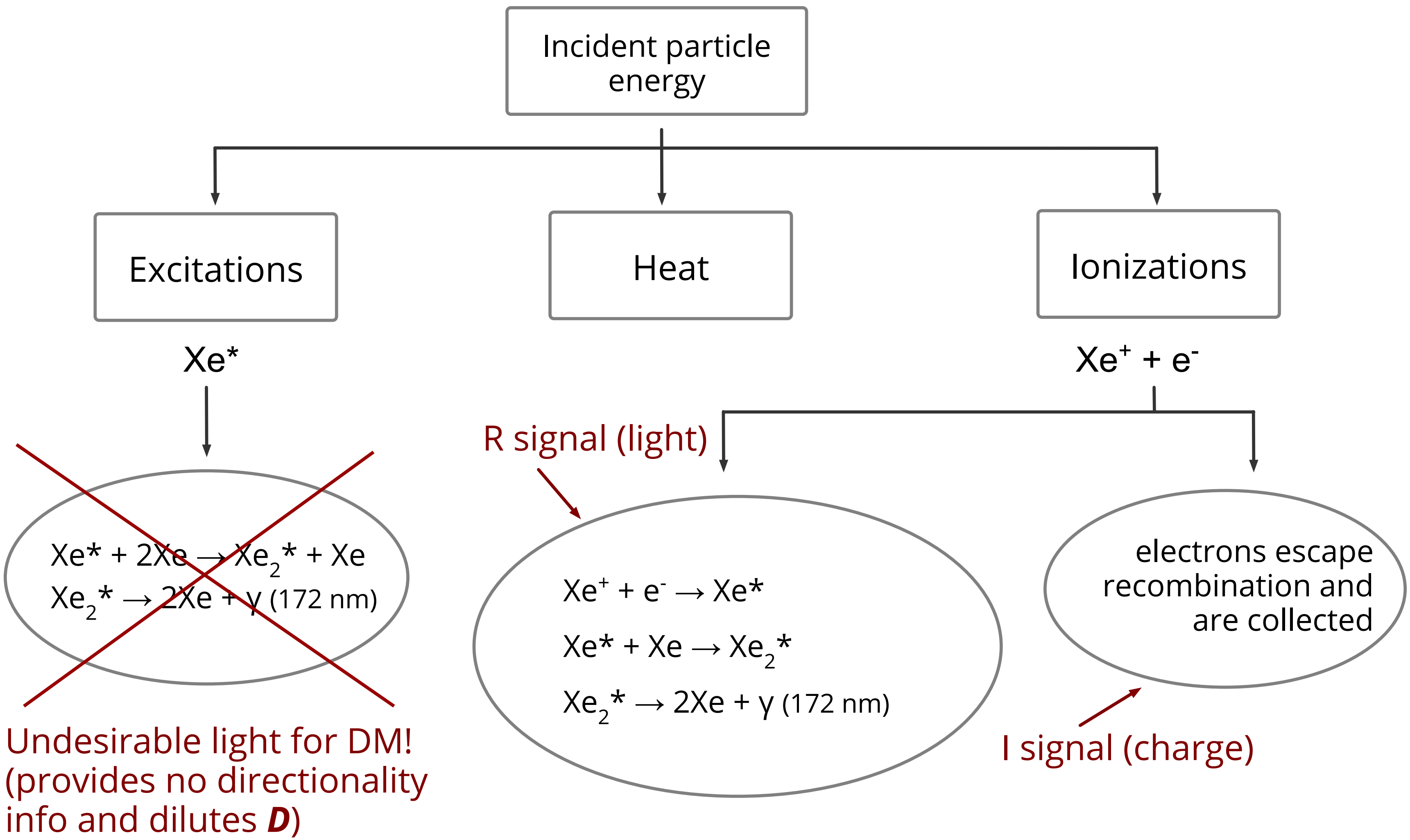
Determine *D* in a event-by-event basis

Diffusion doesn't degrade *D* (information extracted before drift of electrons)

NR & ER in pure HPGXe

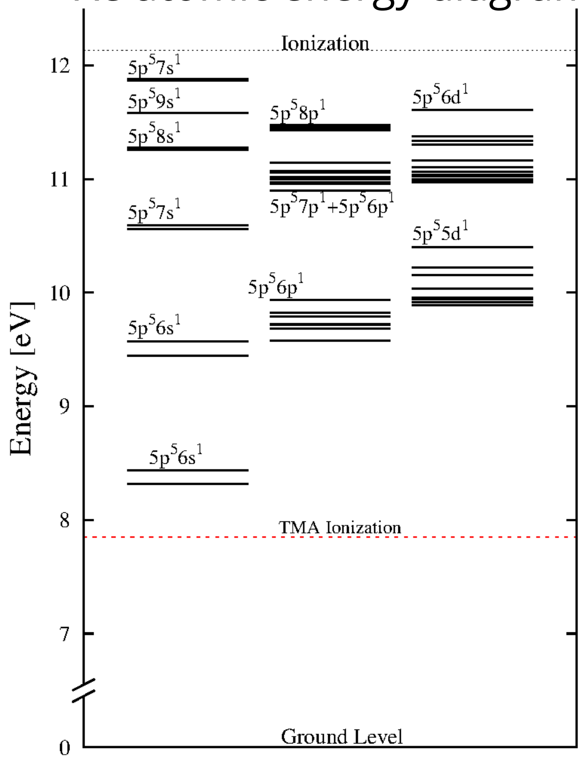


Excitations need to be converted into ionizations



Penning effect - TMA

Xe atomic energy diagram



Additive with lower IP

Excitation energy -> ionization

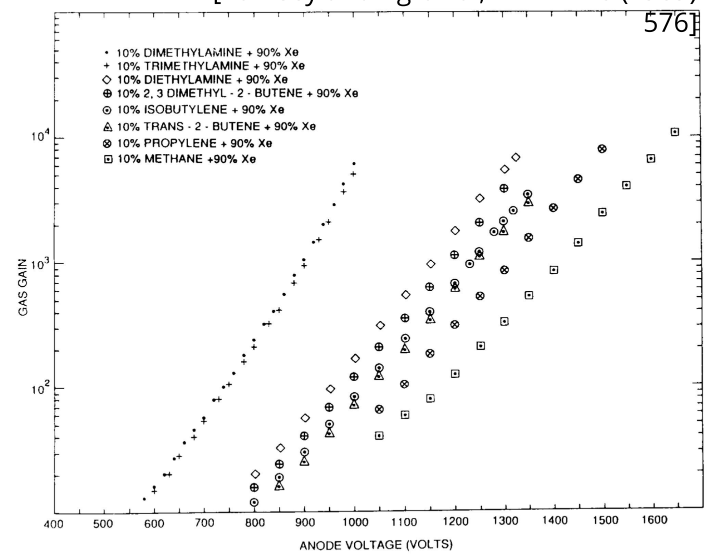
Indirect evidence from enhanced charge avalanche gain (Xe+TMA)

TMA seems to be ideal

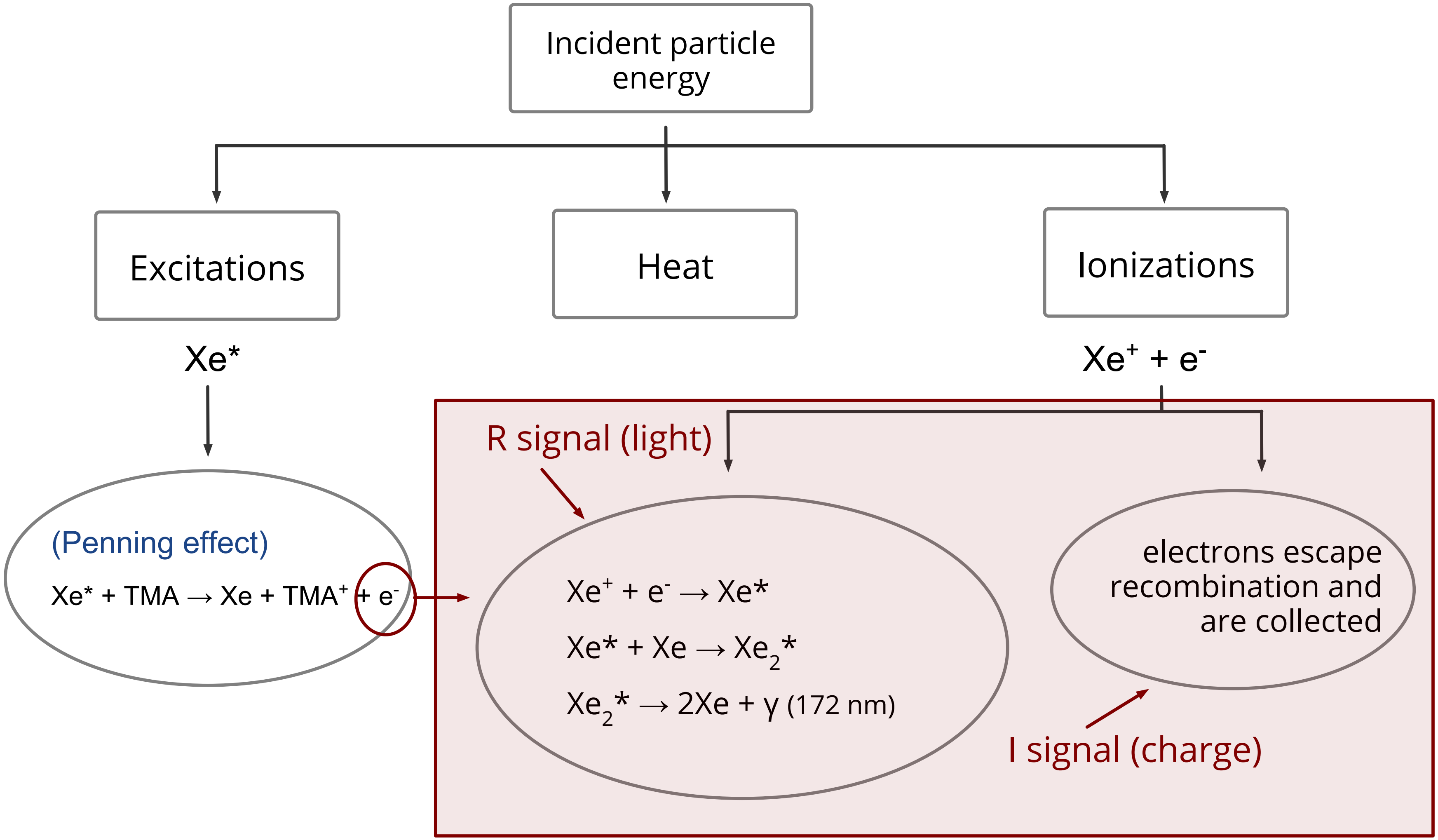
But other molecules might work as well: DMB, TEA, …?

Penning allows to convert excitation into ionization signal

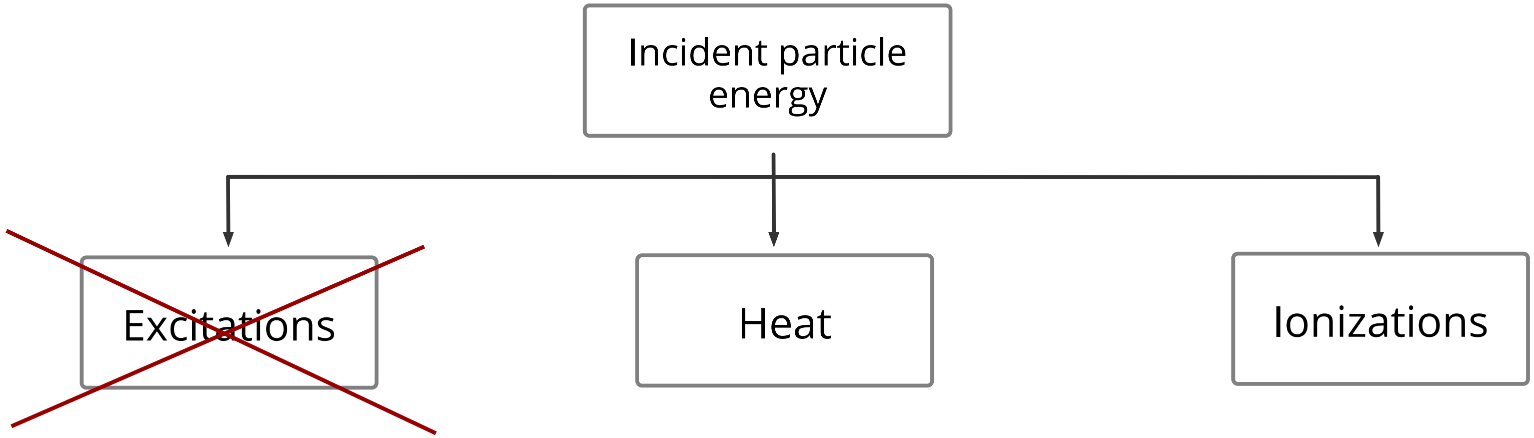
[Ramsey and Agrawal, NIMA 278 (1989) 576]



Penning effect - TMA



Penning | Better energy resolution

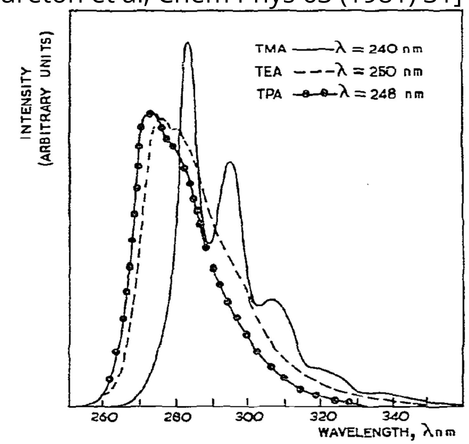


Penning supposedly improves intrinsic energy resolution and S_2/S_1 NR/ER discrimination.

Charge exchange & TMA fluorescence

TMA may shift recombination light to 300 nm, easier to detect!

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



4π light collection coverage (15 % overall DE) seems possible using WLS plastic bars

(Penning effect)

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

R signal (light)

(charge exchange)

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

(recombination)

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

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

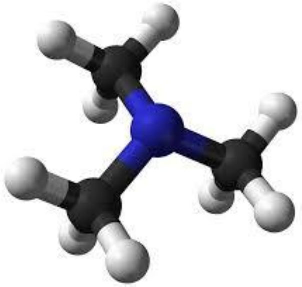
electrons escape recombination and are collected

I signal (charge)

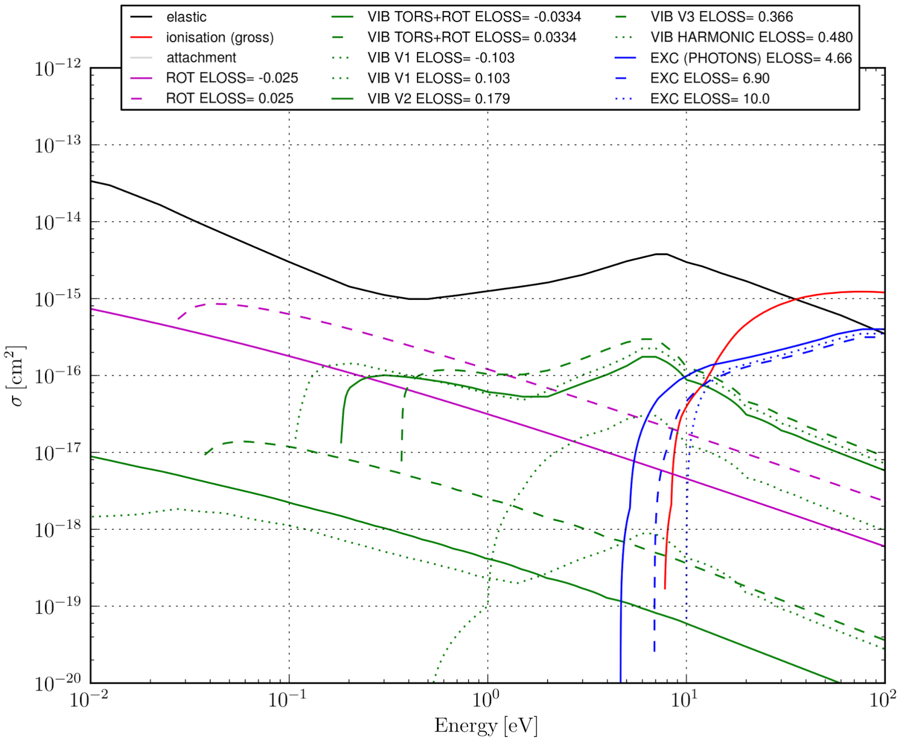
TMA cools down electrons

Many rotational and vibrational modes

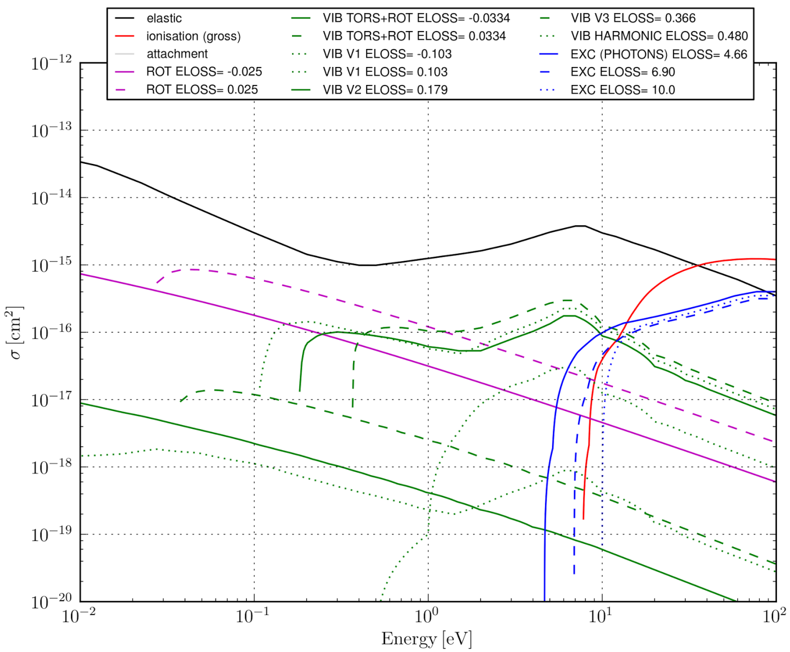
- Electrons are cooled down
- CR should be enhanced (better chance of e^-s recombining)
- Diffusion may be suppressed (better tracking)
- Electron drift velocity increases

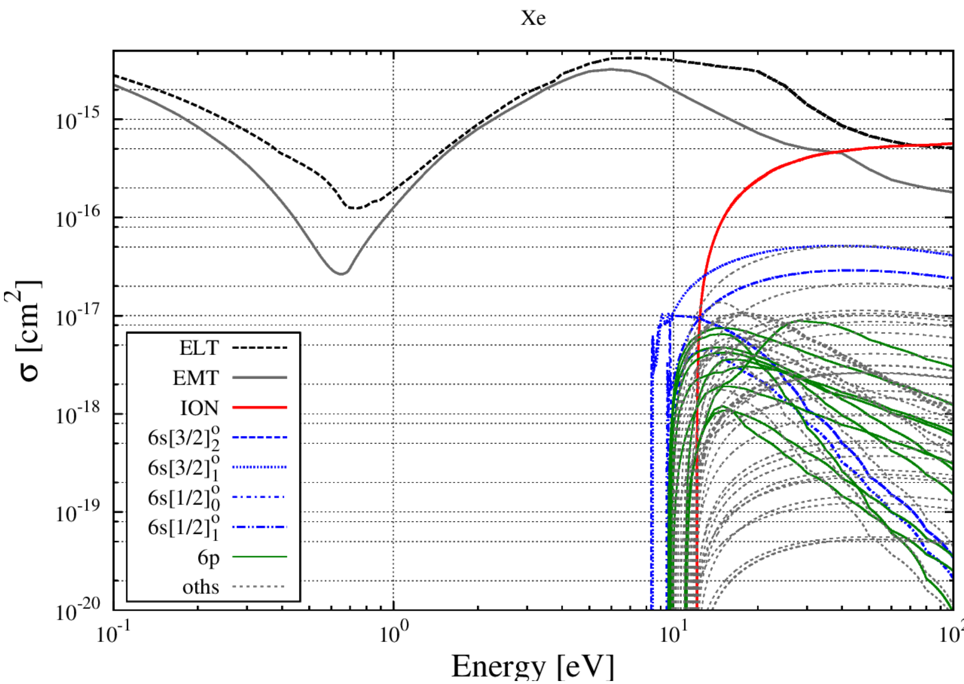


TMA may enhance CR and improve tracking!



TMA fluoresces…





EL possible in TMA without charge avalanche?

- 1st Xe excited state: 8.3 eV
- IP of Xe: 12.12 eV
- Excited state of TMA: 4.6 eV
- IP of TMA: 7.9 eV

TMA EL may allow to keep improved intrinsic Energy Resolution.

Open questions (for both CM and $0\nu\beta\beta$)

What do Xe NR tracks look like in HPGXe?

How does CR happen microscopically

Penning efficiency? Time scale?

Does VUV Xe light break TMA chemical bonds?

Charge exchange efficiency? Time scale?

TMA fluorescence efficiency (after recombination)?

WLS efficiency?

Best geometry for light collection / transport?

Optimum fraction of TMA, pressure, drift field for CR?

Electric field range for linear EL amplification?

The "TEA-Pot"

Tom Miller

Tom Weber

Josh Renner

Howard Matis

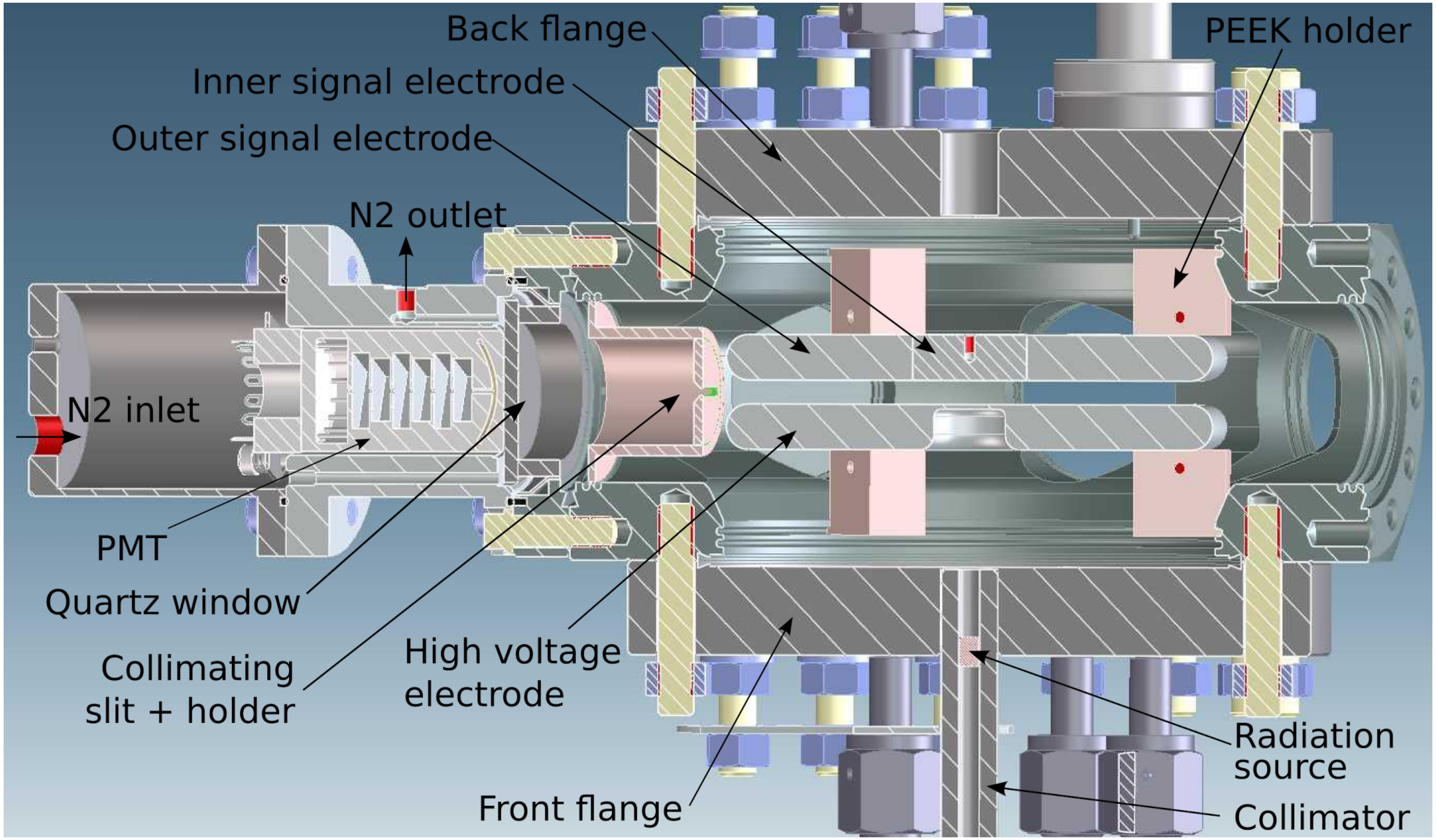
Azriel Goldschmidt

David Nygren

Yasuhiro Nakajima

TEA-Pot

Parallel plate ionization/scintillation chamber



TEA-Pot

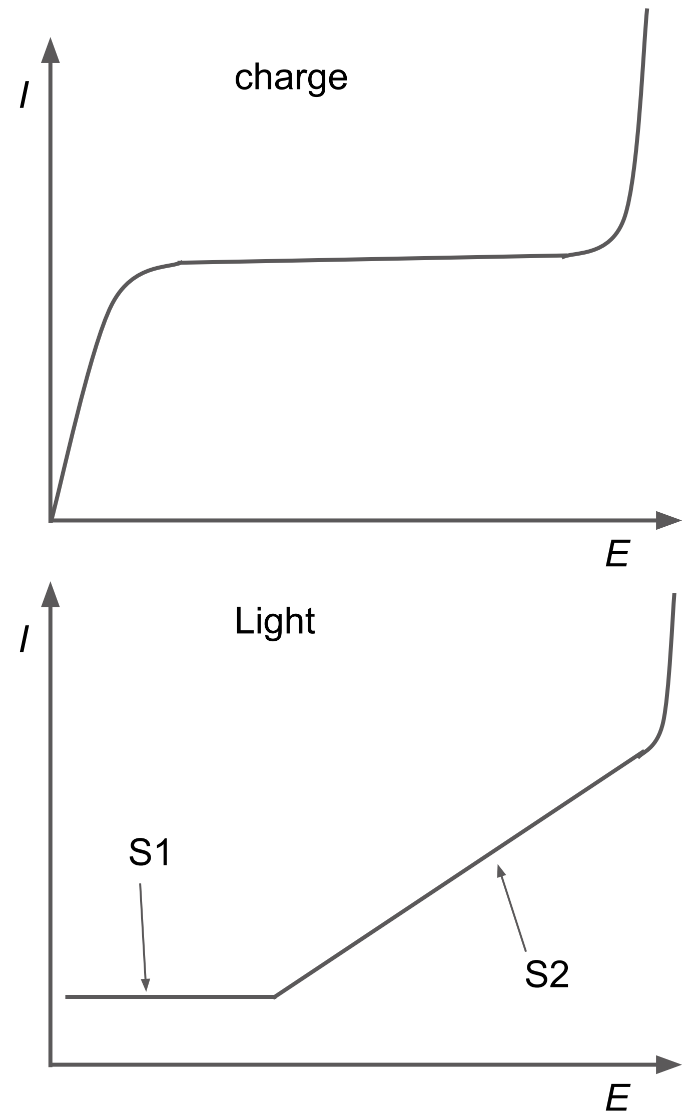
Charge and light signals

measured in DC mode

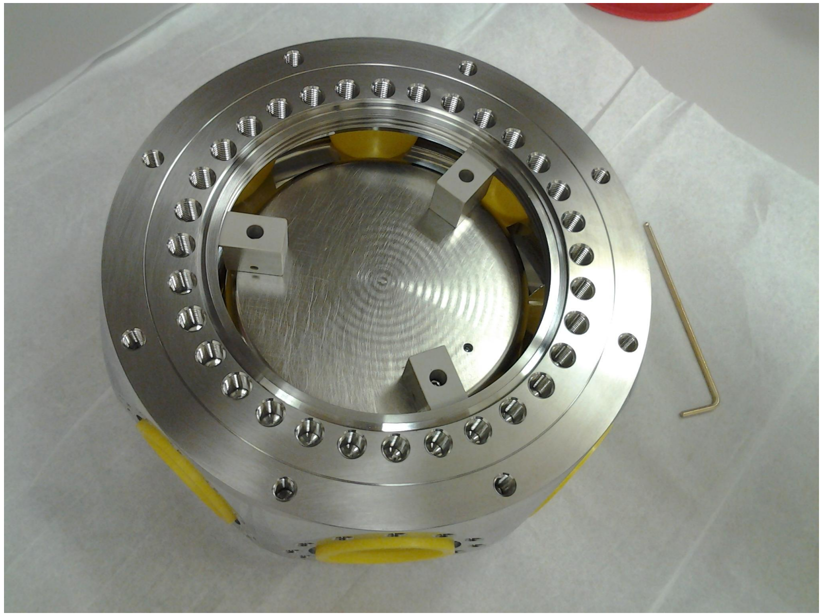
Flat surfaces

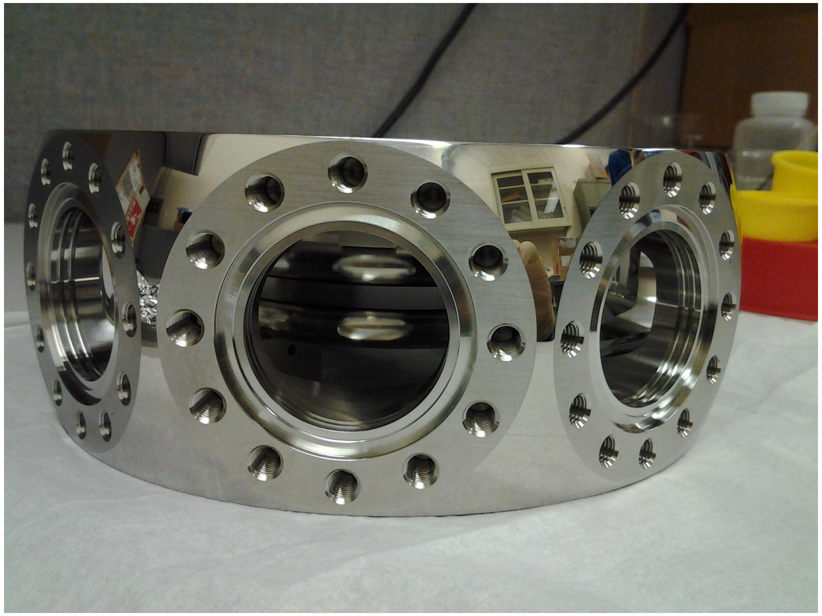
no avalanche due to field concentration

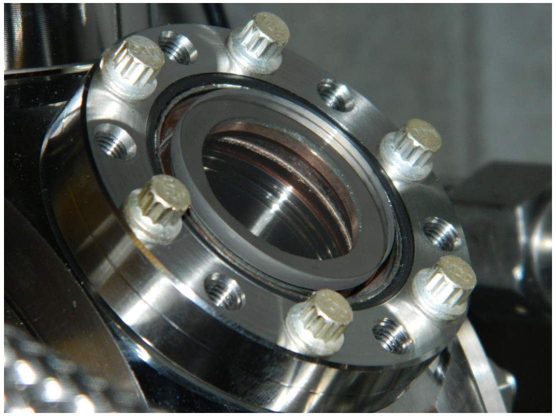
60 keV Gamma-rays used so far



TEA-Pot - details





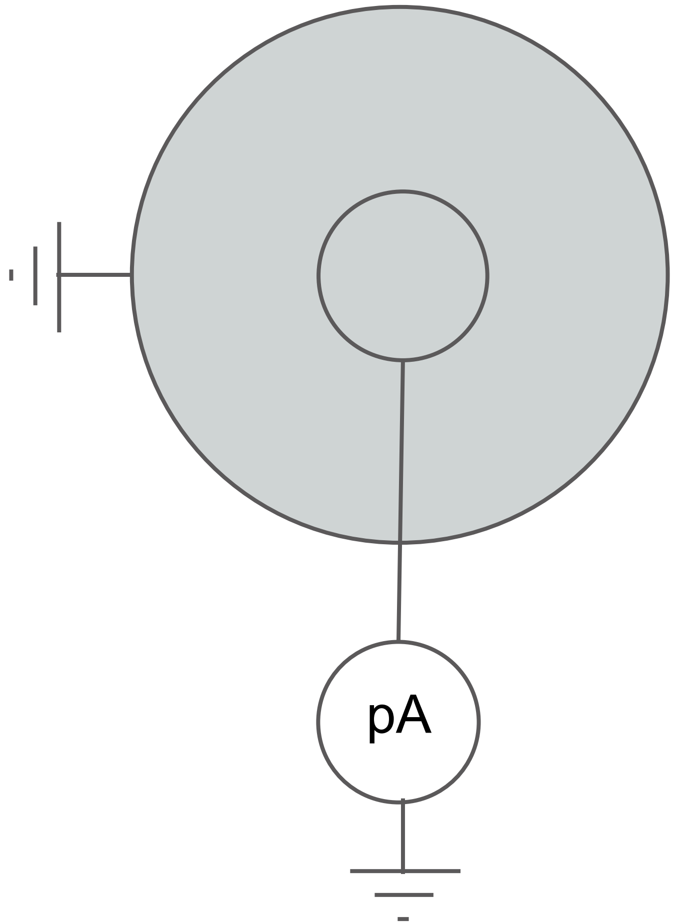


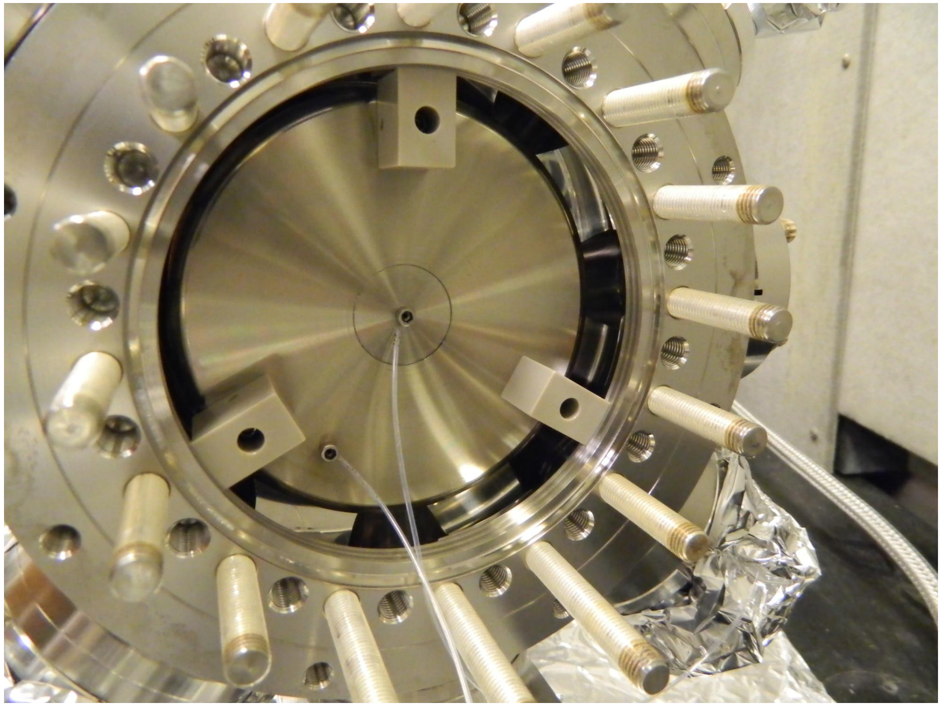
Minimum amount of plastics

High vacuum techniques

CF

TEA-Pot - Signal Electrode

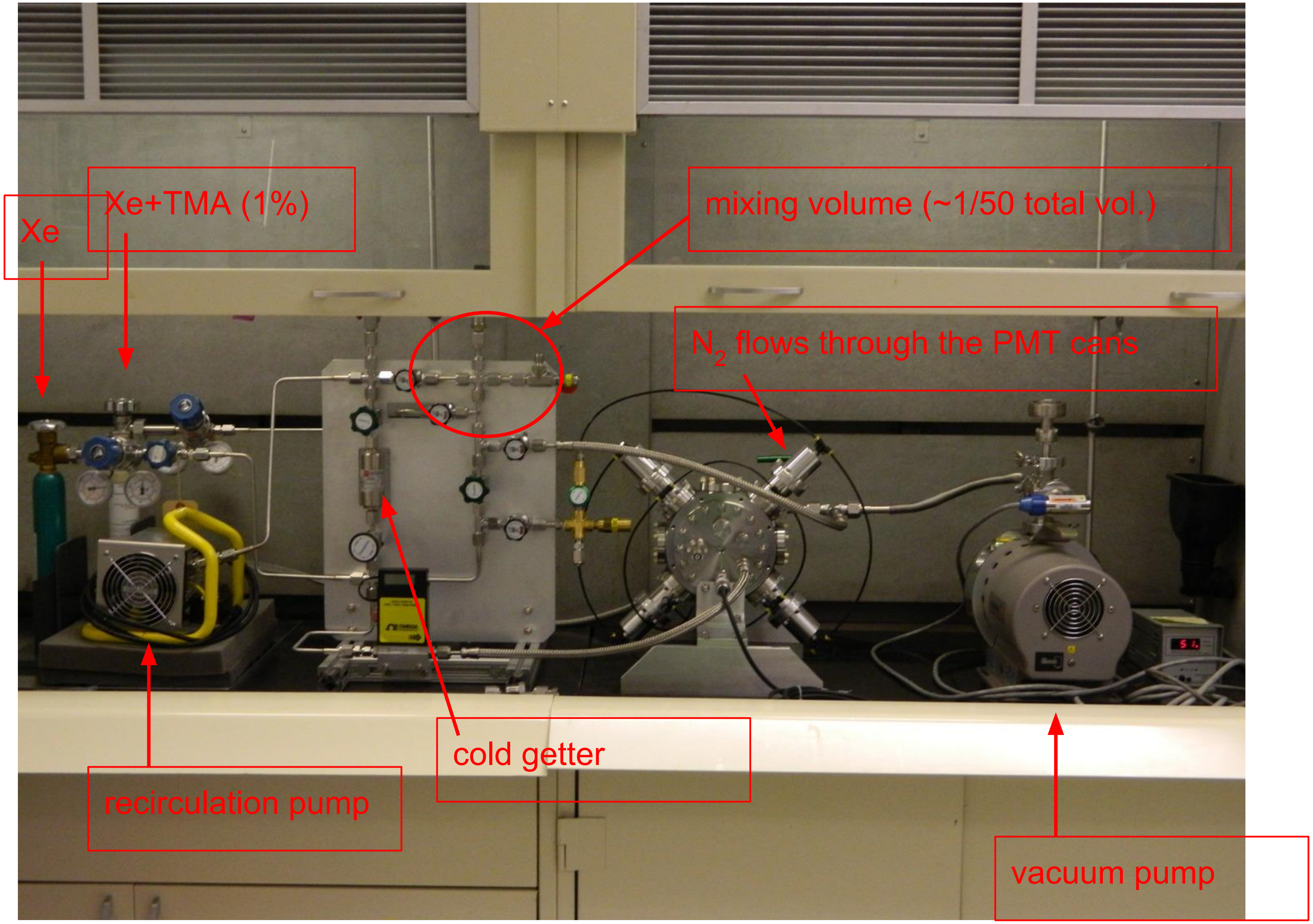




1” diameter inner disc

50 um thick foil of Teflon as insulator

TEA-Pot

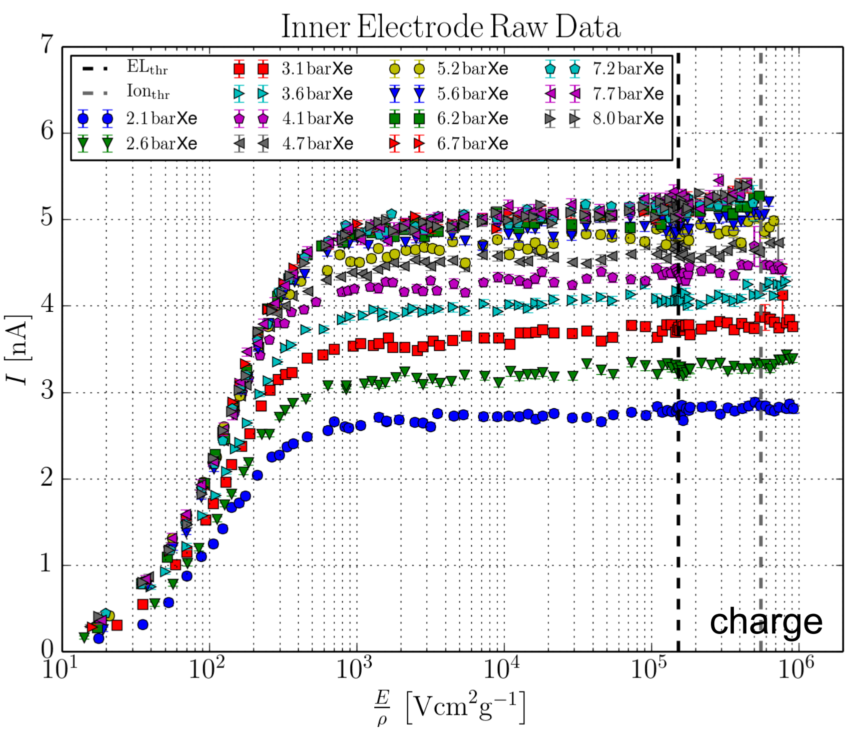


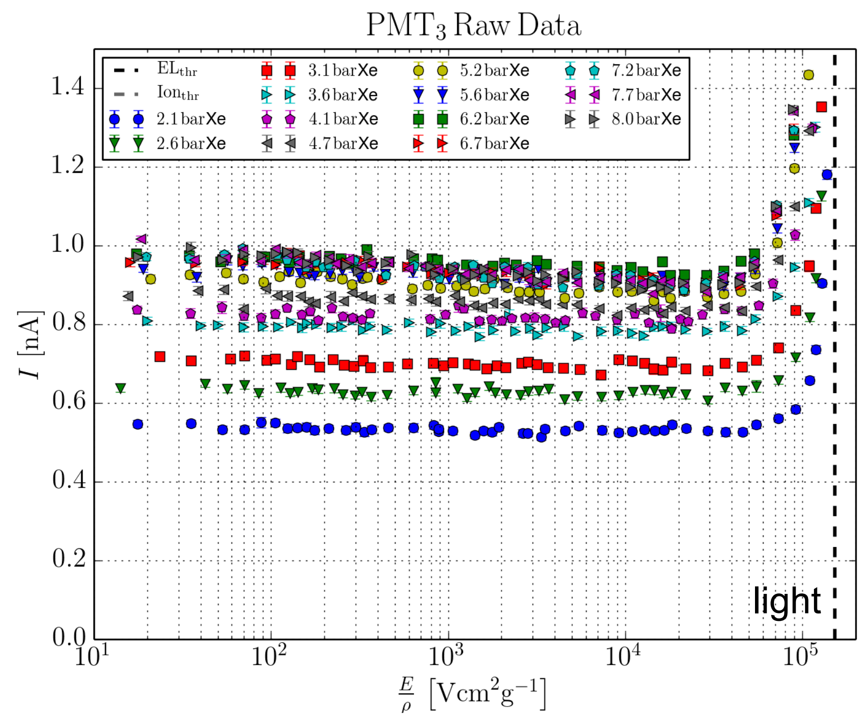
Xe
Xe+TMA (1%)
mixing volume (~1/50 total vol.)
N2 flows through the PMT cans
recirculation pump
cold getter
vacuum pump

Baseline (pure Xe) - Raw data

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

Set up a baseline for comparison with Xe+TMA mixtures





Energy deposited in the interaction gap is dependent on pressure.

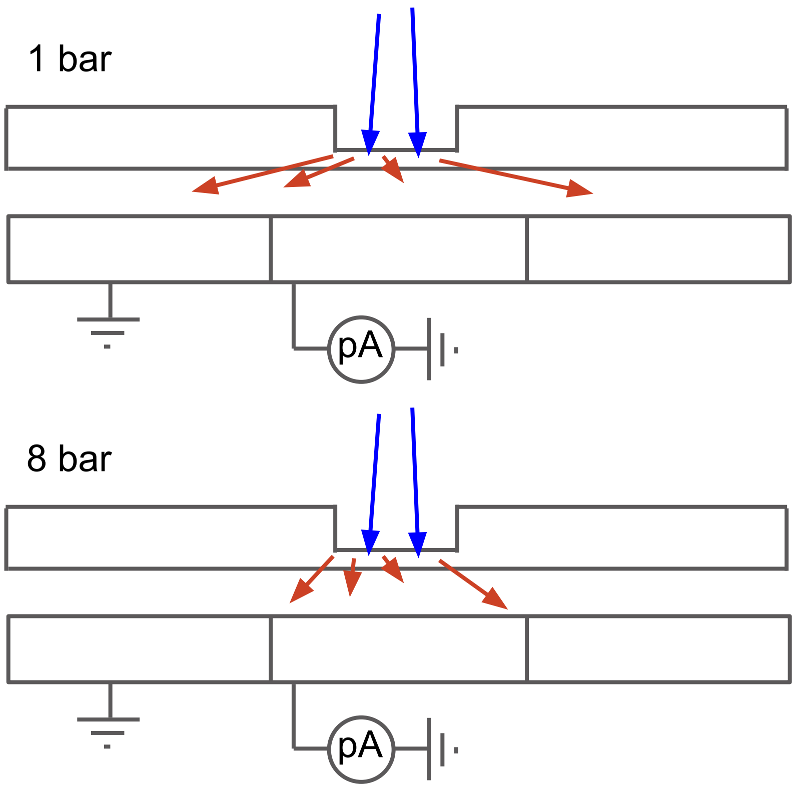
Attenuation corrections

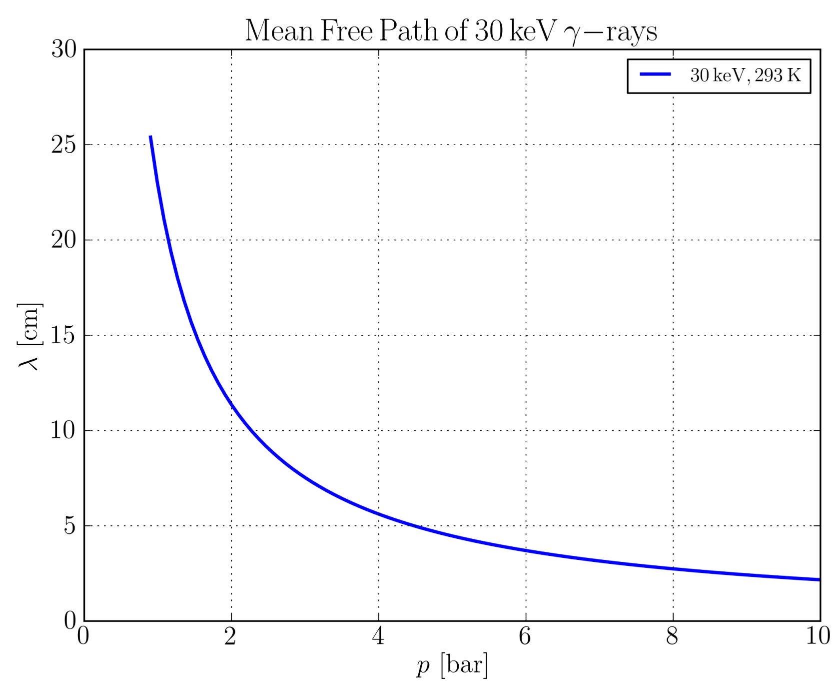
of X-rays interacting in the central gap:

Attenuation of 60 keV γs by the chamber materials

Fluorescent (30 keV) and Compton X-rays may escape the inner electrode region

Both effects vary with pressure



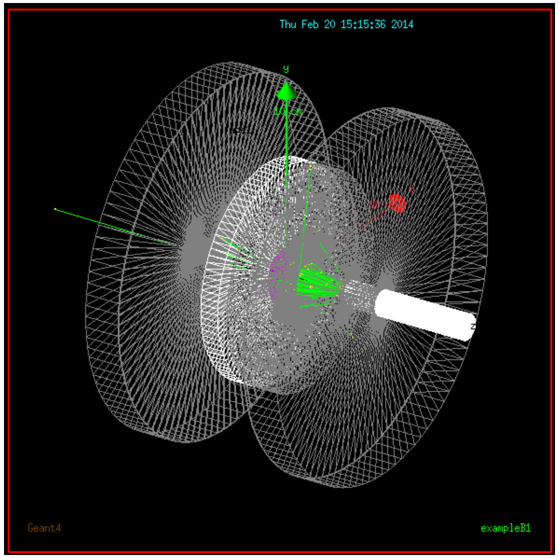


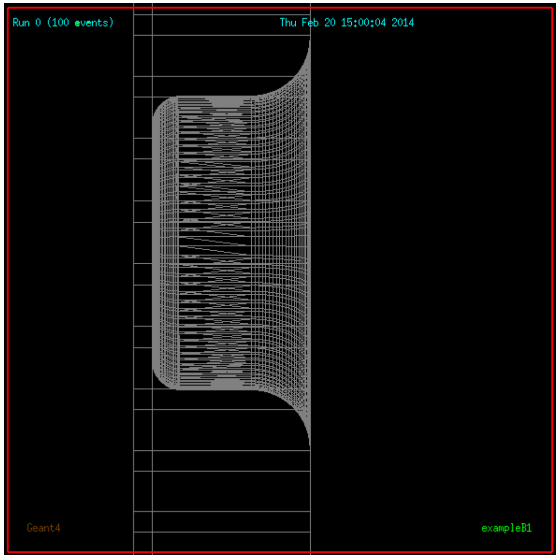
Attenuation normalization

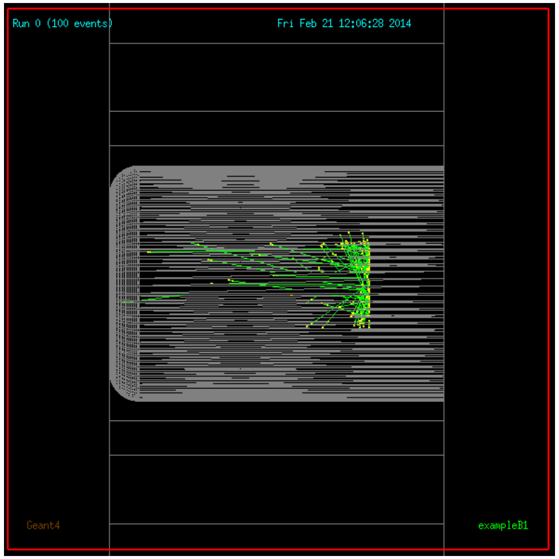
GEANT4 Monte Carlo simulation of 60 keV Gammas interaction in the chamber

Detailed geometry in the center of the chamber

Correction considers attenuation in the Xe volume between flange & HV electrode, in the HV electrode material and in the central gap



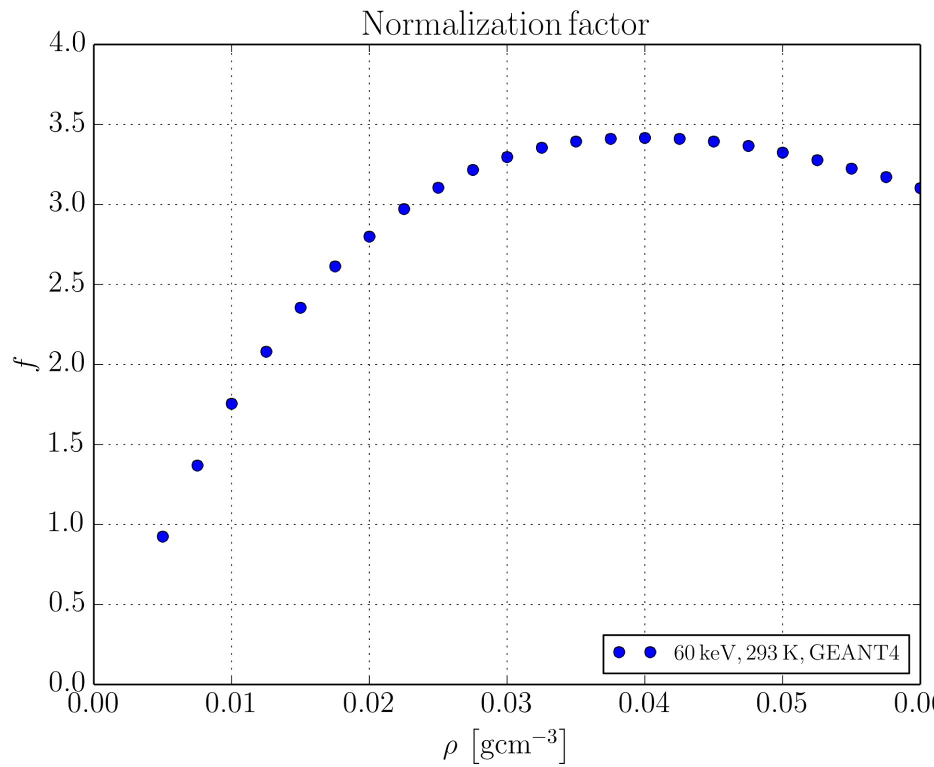




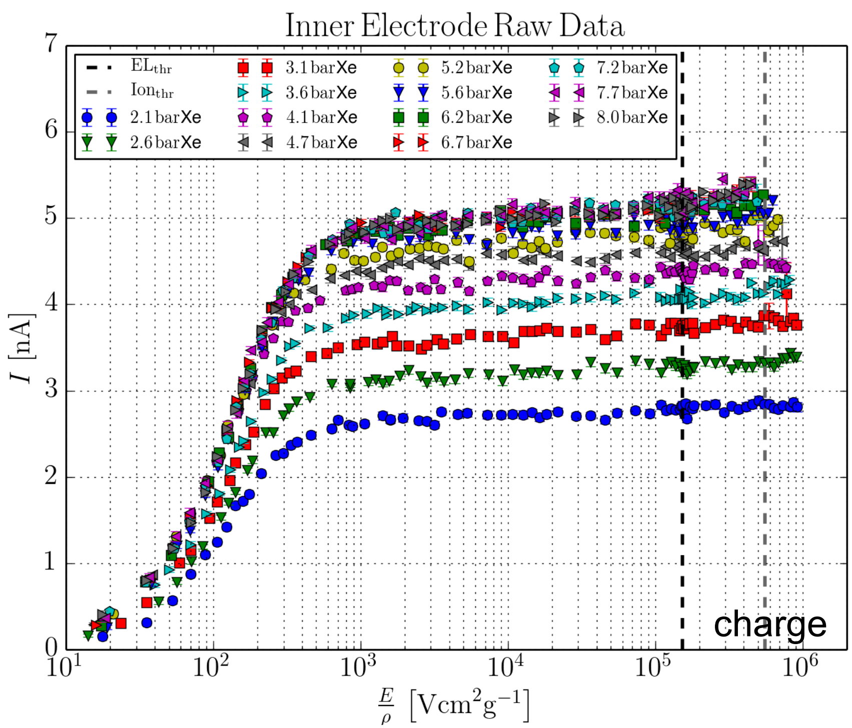
Normalization factors

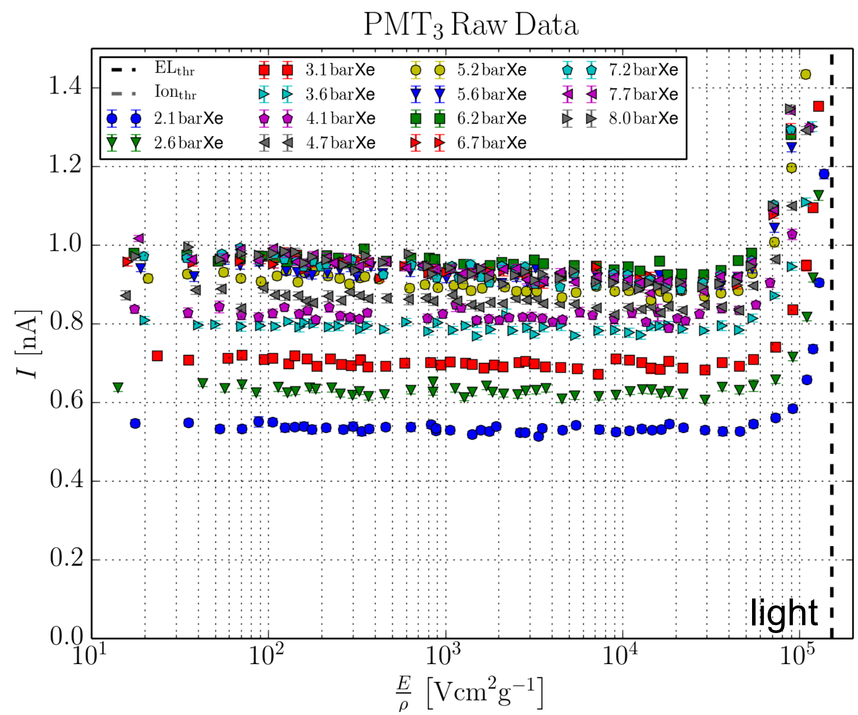
$$I_{norm} = I_{raw} \frac{E_{center}(\rho_{1bar})}{E_{center}(\rho)}$$

$$\frac{1}{f}$$



Baseline (pure Xe) - Raw data

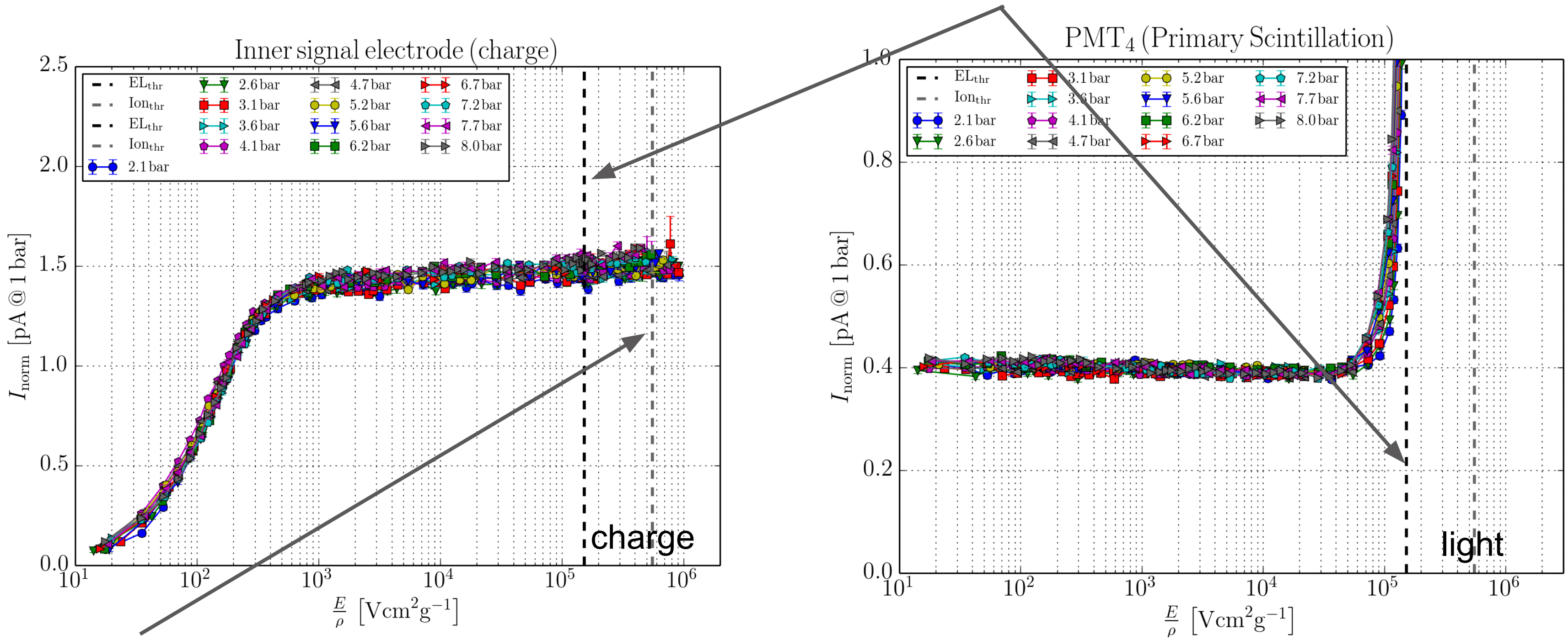




$$I_{norm} = I_{raw} \frac{E_{center}(\rho_{1bar})}{E_{center}(\rho)}$$

Baseline (pure Xe) - Normalized data

EL threshold [C. M. B. Monteiro et al, JINST 2 (2007) P05001]



Ionization onset [C. A. B. Oliveira, PLB 703 (2011) 217]

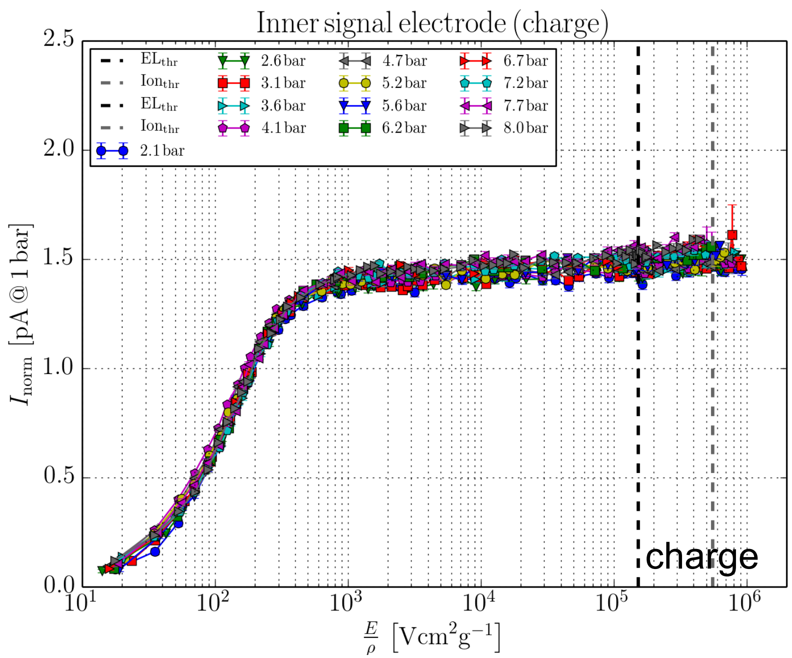
GEANT4 is able to normalize the data correctly (within 10 % error)

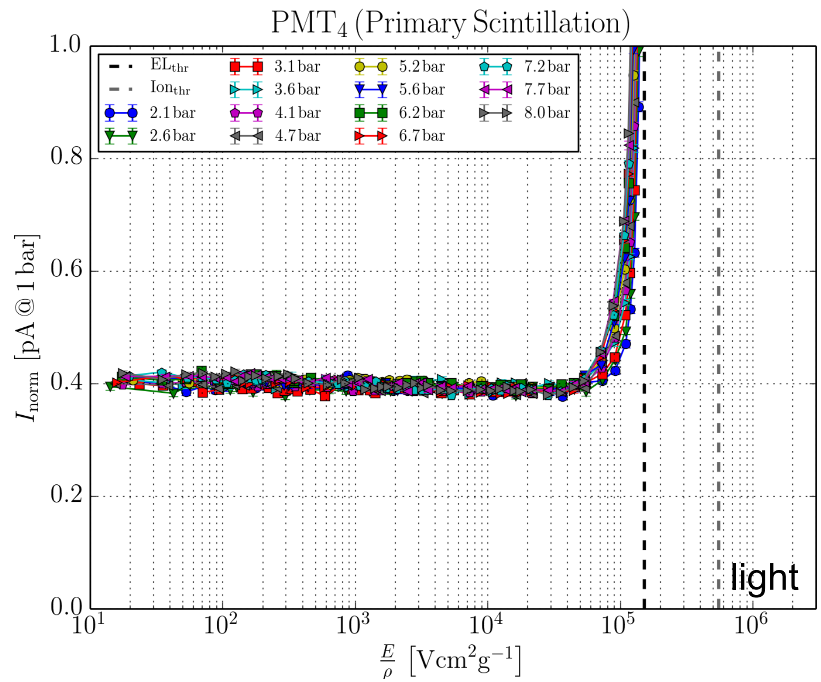
Change in dynamics of charge drift visible at low fields low fields

EL and ionization onsets in agreement with previous measurements

Textbook quality data!

Baseline (pure Xe) - Normalized data



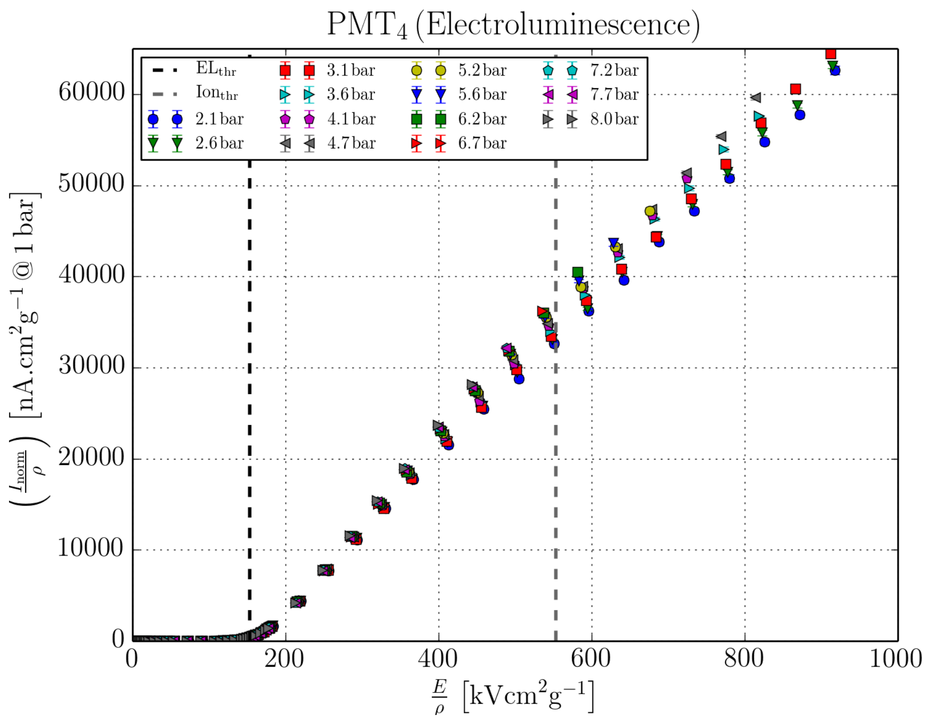


Anti-correlated variation in the charge and VUV light when scanning electric field (6 % in amplitude)

No pressure dependence observed

Evidence for slight recombination suppression by electric field in γ-rays

Baseline (pure Xe) - Normalized data



EL keeps linear behavior even after the ionization threshold

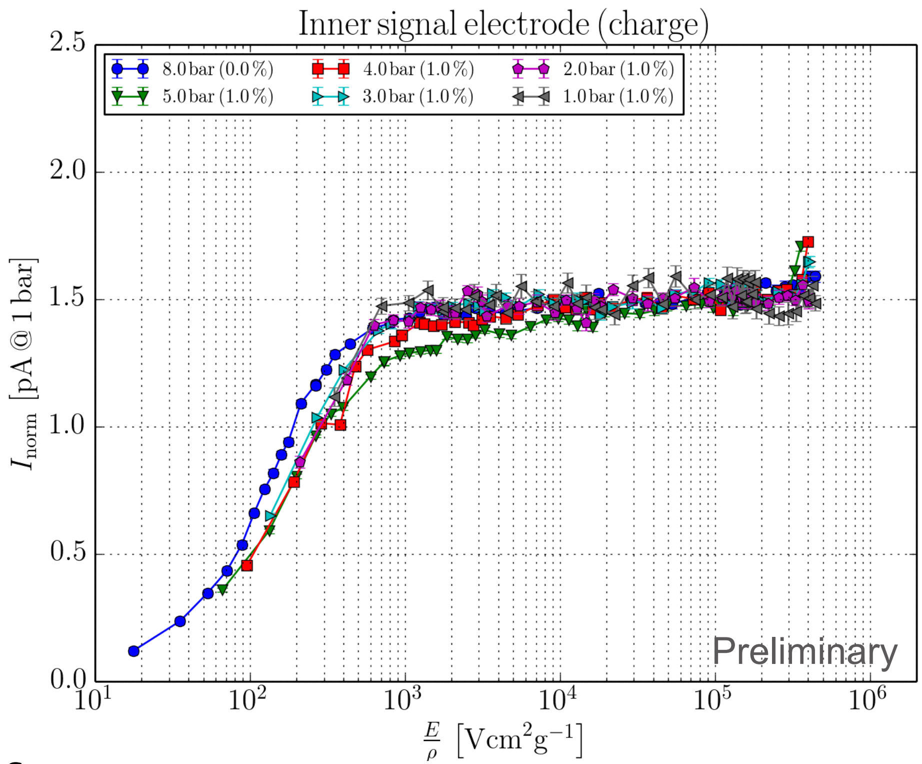
ioniz. coef.: ~ 0.01 se /pe / cm

Observed expected linear behavior of Xe VUV EL

Baseline (pure Xe)

Good understanding of the detector. Robust baseline for comparison with Xe+TMA mixtures!

Xe+TMA data - 1 % nominal

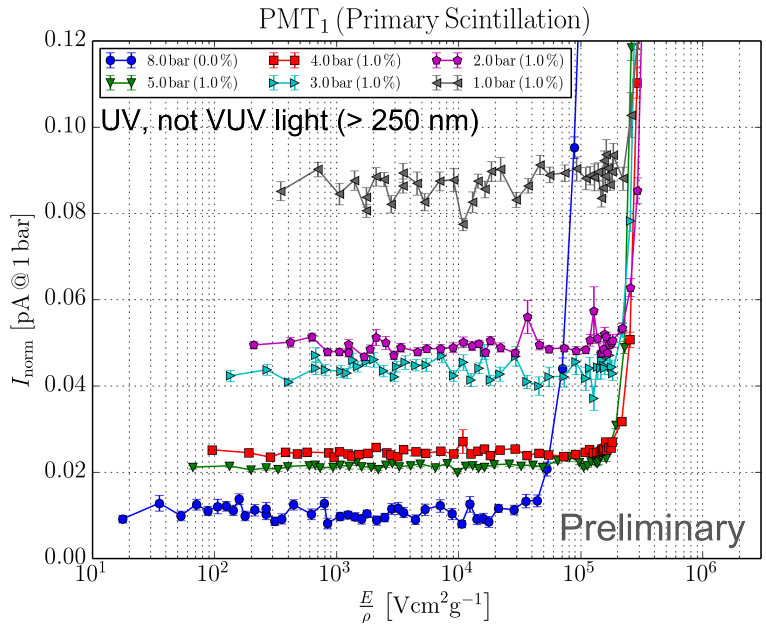


No evidence for Penning!!

- Previous evidence was indirect
- Excimer formation too fast? < 70 ns at 1 bar. Decrease quadratically with p
- Lower pressures? Higher TMA concentrations?

Hint for recombination enhancement

Xe+TMA data - 1 % nominal



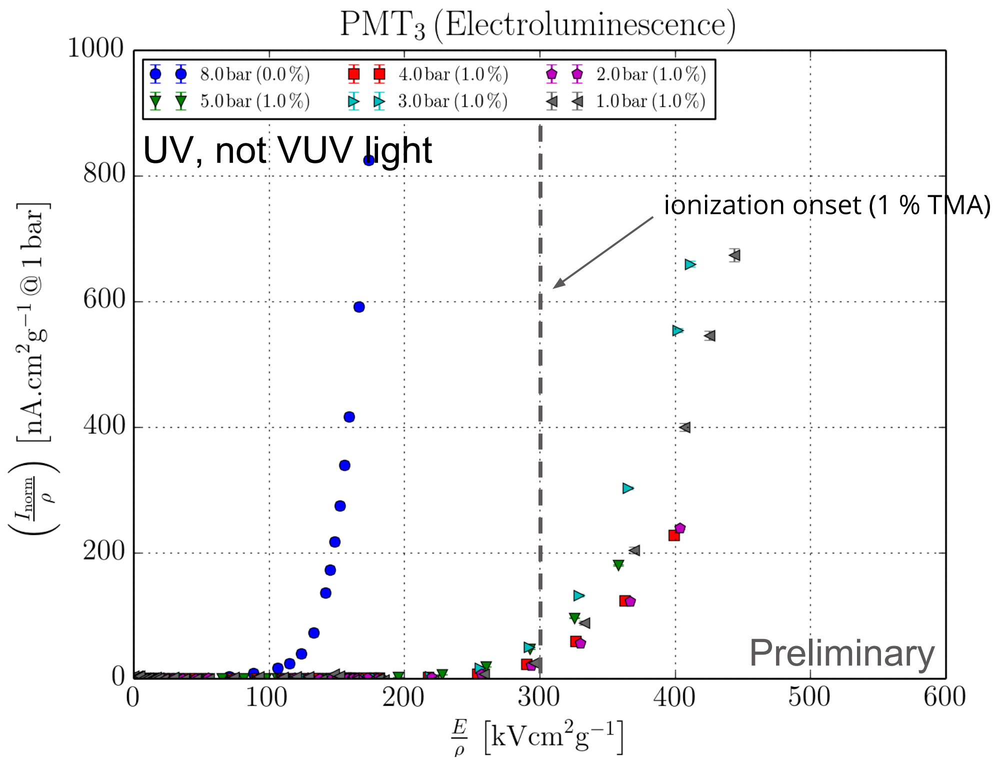
TMA light is present

TMA absorbing its own light?

Evidence for electron cooling

Recombination not leading to TMA light?

Xe+TMA data - 1 % nominal



Observed TMA EL

- No EL without charge avalanche for the concentration and pressure studied

Evidence for absorption of TMA by the getter

- Need to understand the purifier dynamics
- Need for TMA concentration measurement system

Summary

Not clear if atomic / molecular processes happening in Xe+TMA allows substantial signal for NR directionality sensitivity

At the studied conditions

- No evidence for Penning
- No evidence for recombination TMA fluorescence
- No evidence for EL without charge gain

In principle, still a large region of the parameter-space to explore

The TEA-Pot is working well and taking data!

- We have a good understanding of the detector behavior (pure Xenon)
- We should be able to learn about important microscopic processes

Future work

Implement system for measuring TMA concentration

- Seems feasible in real time with a turbo pump & RGA
- Higher control in the phase-space exploration

Try to understand the dynamics of the purifier

- Knowledge of TMA concentration in real time is key

Continue to explore different concentrations and pressures

Modify the chamber and implement pulse mode

- Study also NR using a thin ^{238}Pu deposited source
- Alpha tagged by a solid state detector

Explore other additives

- TEA, DMB, ...

Parallel work

Simulations of NR interactions in HPGXe

Azriel Goldschmidt adapting code from M. Foxe (LLNL, liquid Ar)

Simulations of collective charge effects in CR for NR & ER

Azriel Goldschmidt & Megan Long using Garfield++

No evidence for noticeable CR found in the explored phase-space. Other regions being explored (http://portal.nersc.gov/project/hpx/recombination/)

Experimental studies of CR with alpha particles

D. Herrera & D. González-Díaz (Zaragozza)

Evidence for directionality sensitivity at HP (up to 10 bar) Xe+TMA (few %) for alphas

Thank you!
Questions?

cabdoliveira@lbl.gov
carlos.oliveira.cacia@gmail.com
www.carlosoliveiraresearch.com

Backup slides

Optimization of R signal collection

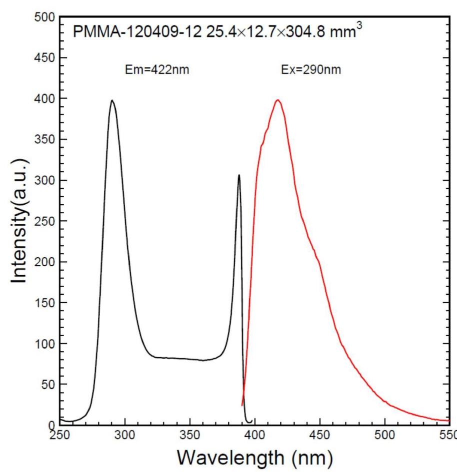
Impractical covering a large detector with PMTs

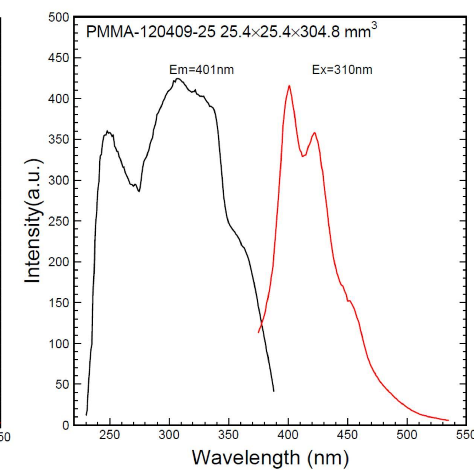
cost, radiopurity

Plastic bars for WLS

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

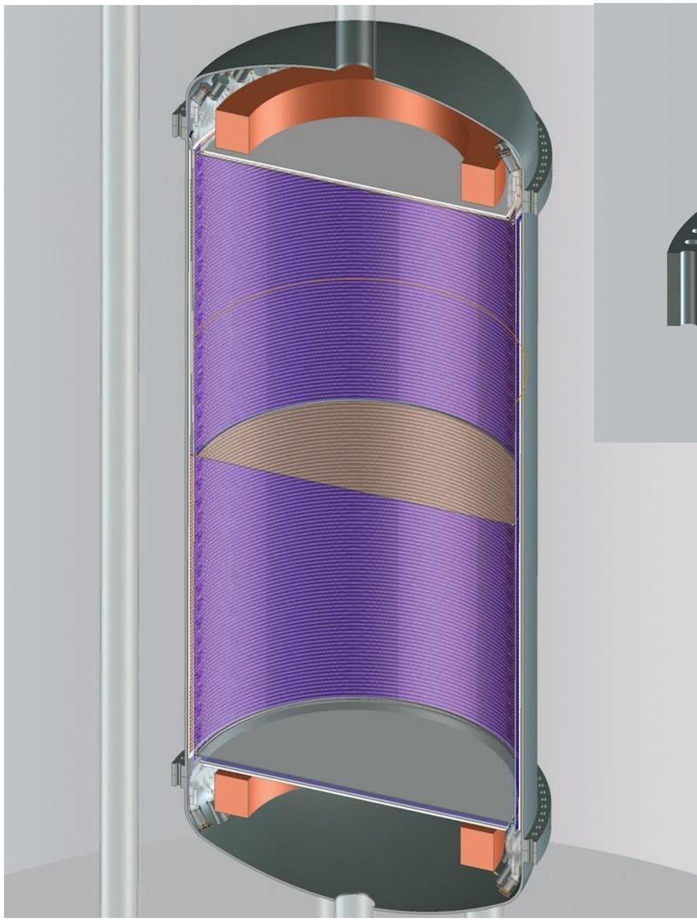
Providential WLS by commercial plastic bars.

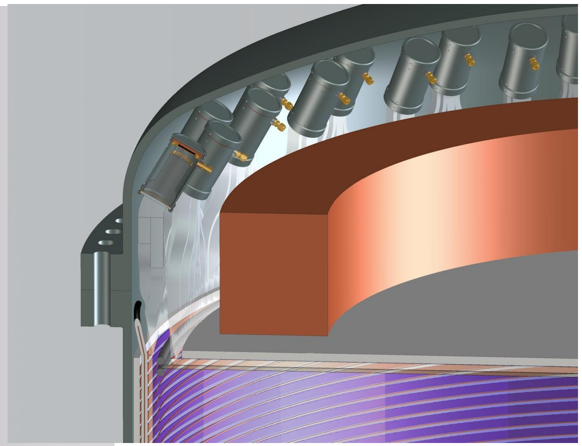




Optimization of R signal collection

Back





High optical coverage seems feasible!

Symmetric “ton-scale” HPGXe TPC

WLS plastic in all surfaces

Except HV cathode plane

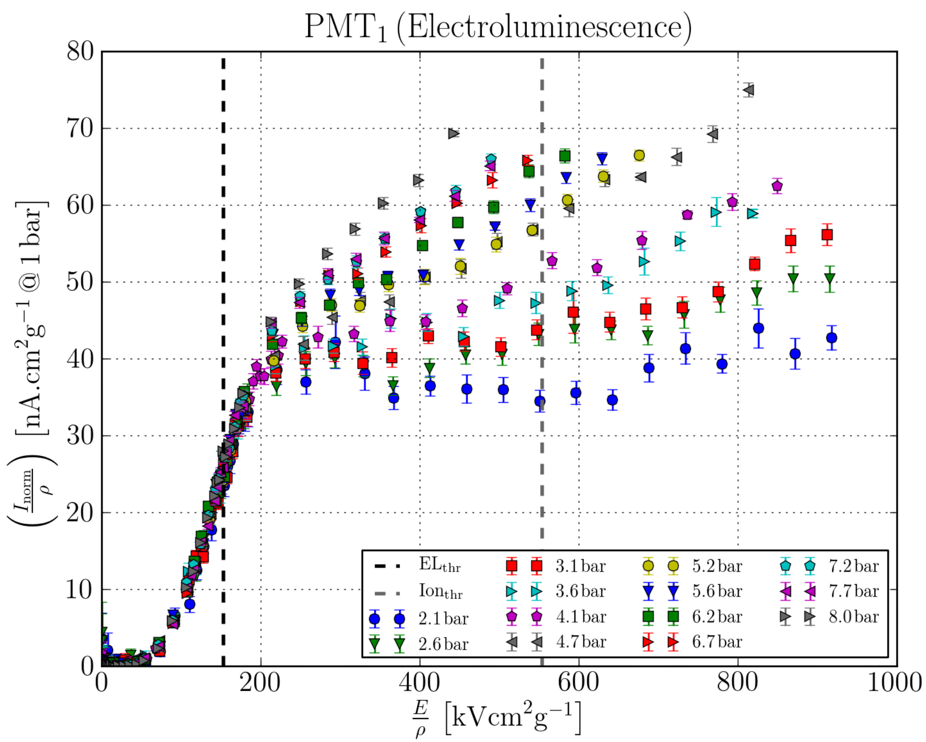
Light guides

Few PMTs shielded by copper rings

Preliminary GEANT4: 15 % overall DE

[Rodolfo Orellana, simple geometry]

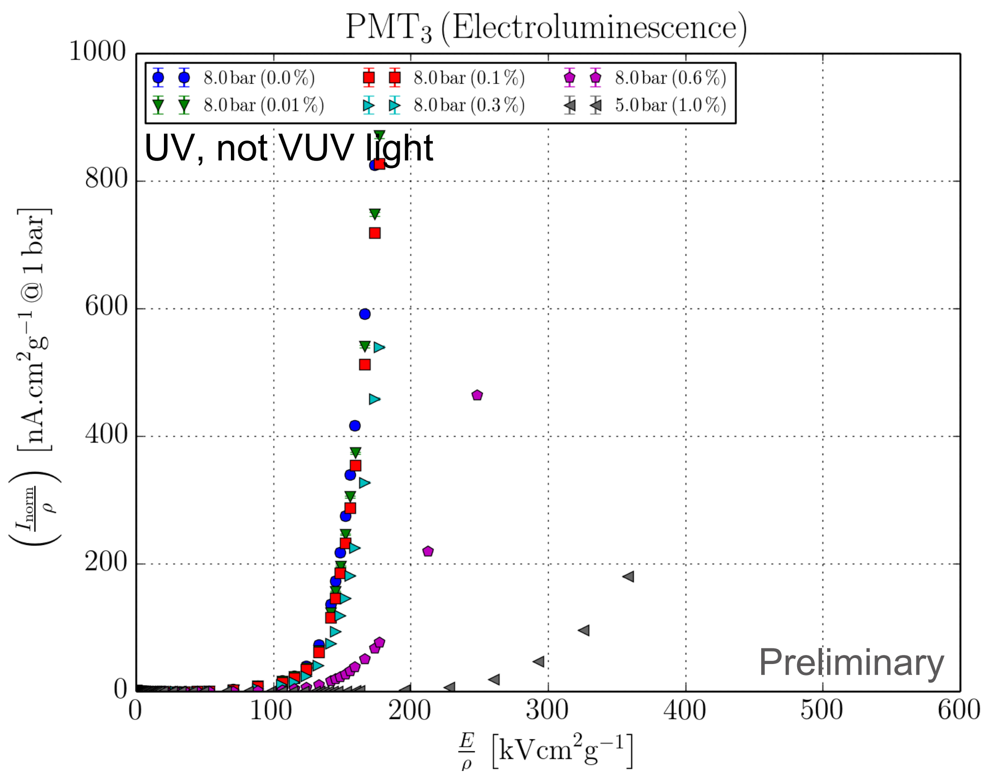
Baseline (pure Xe) - filtered PMT



Light >250 nm not expected to be observed!

- Impurity not removed by cold getter?
- About 800x less light than VUV

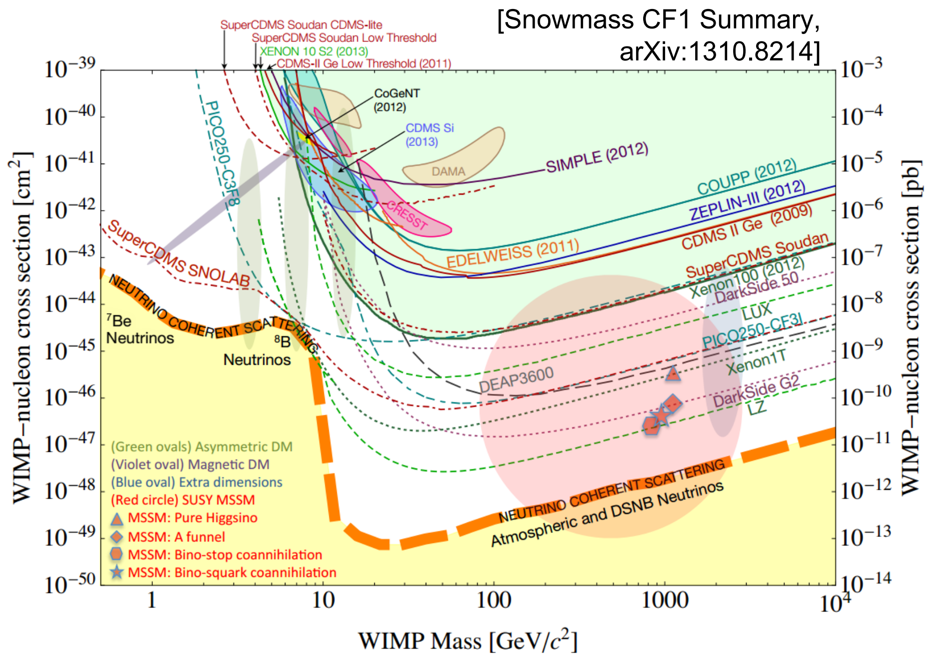
TMA absorbed by the getter



WIMPs

WIMPs not seen with xenon. Future experiments

- Lower cross section limits
- Neutrino Coherent Scattering limit (without directionality sensitivity)
- Even if a few events are seen, directionality might be key for a discovery



Directionality discrimination is of major importance!

Microscopic picture (DM directionality)