Measurement of scintillation and ionization yield with high-pressure gaseous mixtures of Xe and TMA

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RD51 Mini-Week

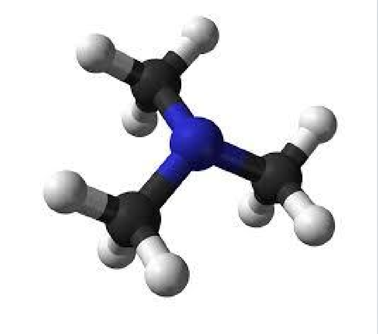
Outline

- Introduction
- The TEA-Pot: a test ionization chamber at LBNL
- Improved measurement of scintillation light yield
- Summary

Xe TPCs for rare event searches

- Xe TPCs are widely used for neutrinoless double beta decay searches and WIMP dark mater searches
  - Double beta decay: EXO (liquid), NEXT (gas)
  - Dark matter: LUX, LZ, XENON
- Two applications of our interest using high-pressure gaseous Xe TPC:
  - Search for neutrinoless double beta decay: the NEXT experiment.
  - Search for dark matter with directional sensitivity using Columnar recombination.

Performance improvements with TMA

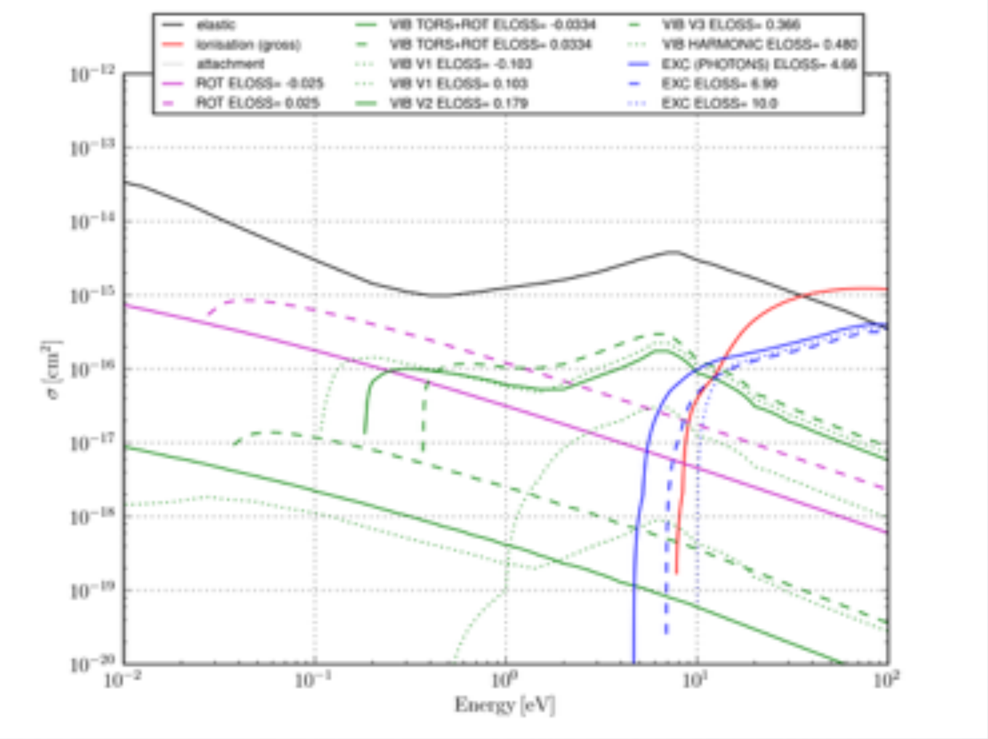


- Large inelastic cross section for efficient electron cooling
  - Many vibration and rotation modes
- Enhance ionization (which contribute to columnar recombination)

  Penning effect : $Xe^* + TMA \longrightarrow Xe + TMA^+ + e$

  Charge exchange: $Xe^+ + TMA \longrightarrow Xe + TMA^+$
- Scintillates at λ~300 nm, much more PMT-friendly than Xe (170nm)

TMA + e cross section



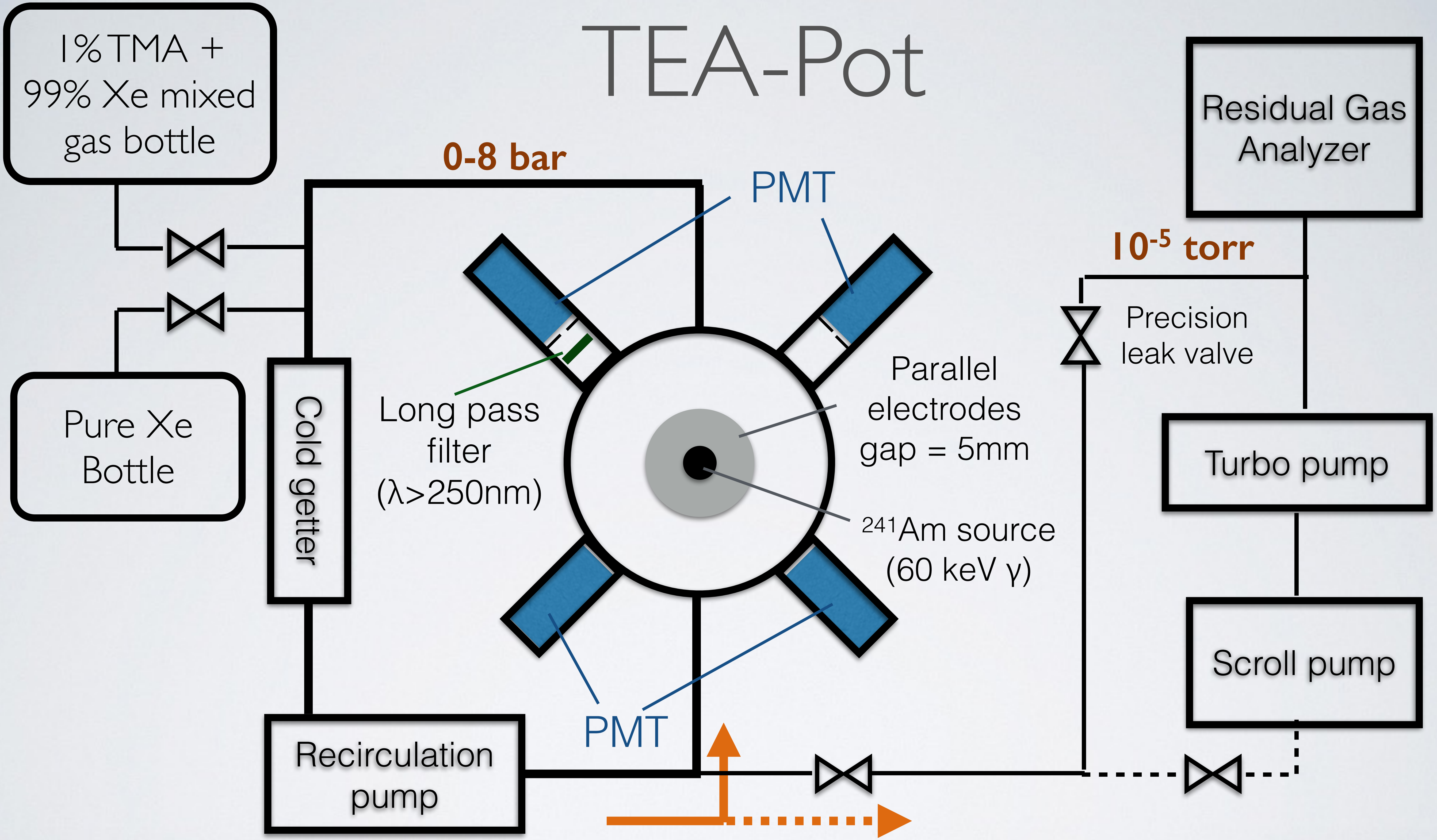
Better tracking for neutrinoless double beta decay searches
Enhance columnar recombination for directional dark matter searches
Even better energy resolution (?)

TEA-Pot

A test ionization chamber to measure Penning efficiency and light yield of Xe+TMA mixture

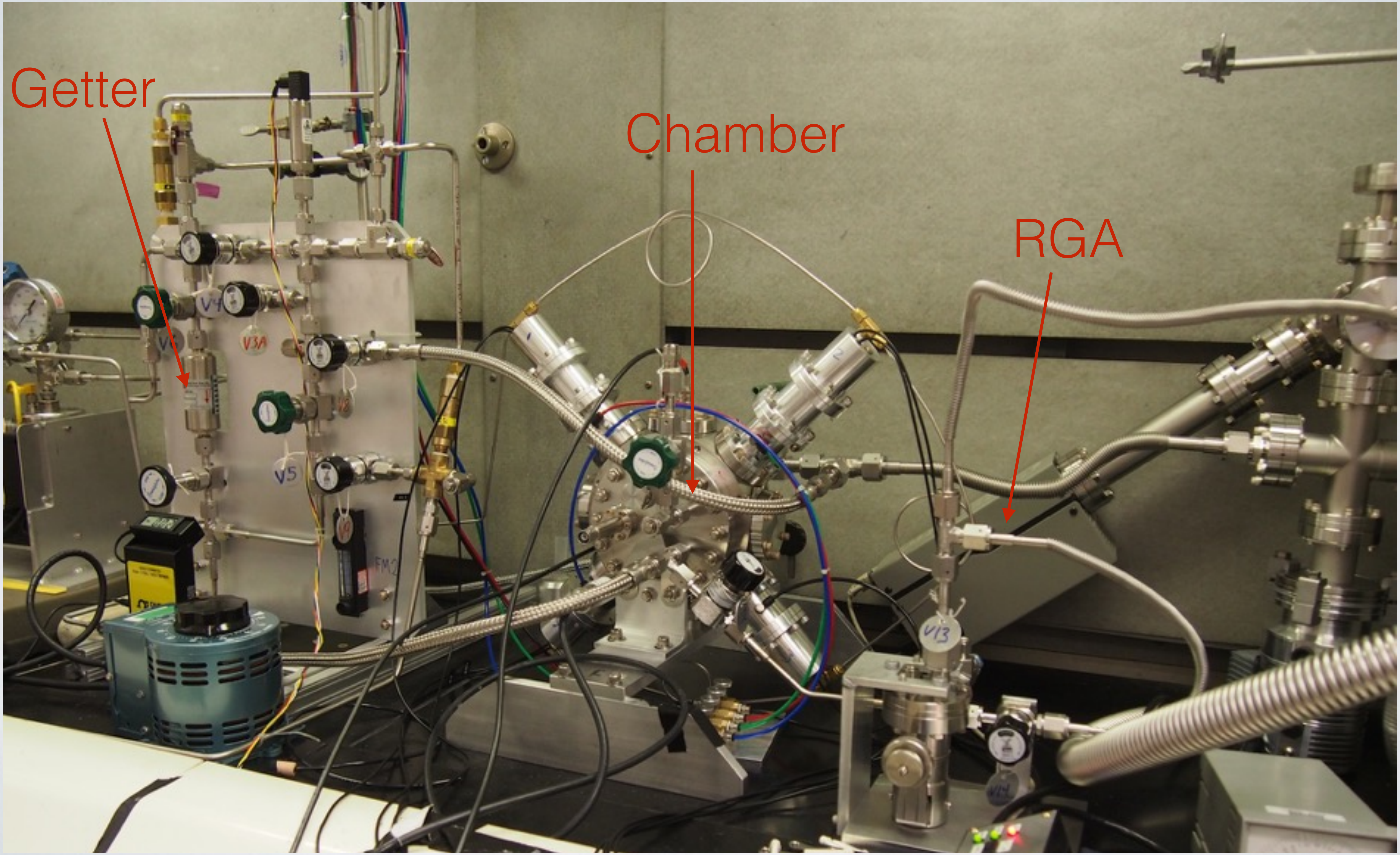
Tom Miller
Tom Webber
Joshua Renner
Azriel Goldschmidt
David Nygren
Yasuhiro Nakajima
Carlos Oliveira

TEA-Pot



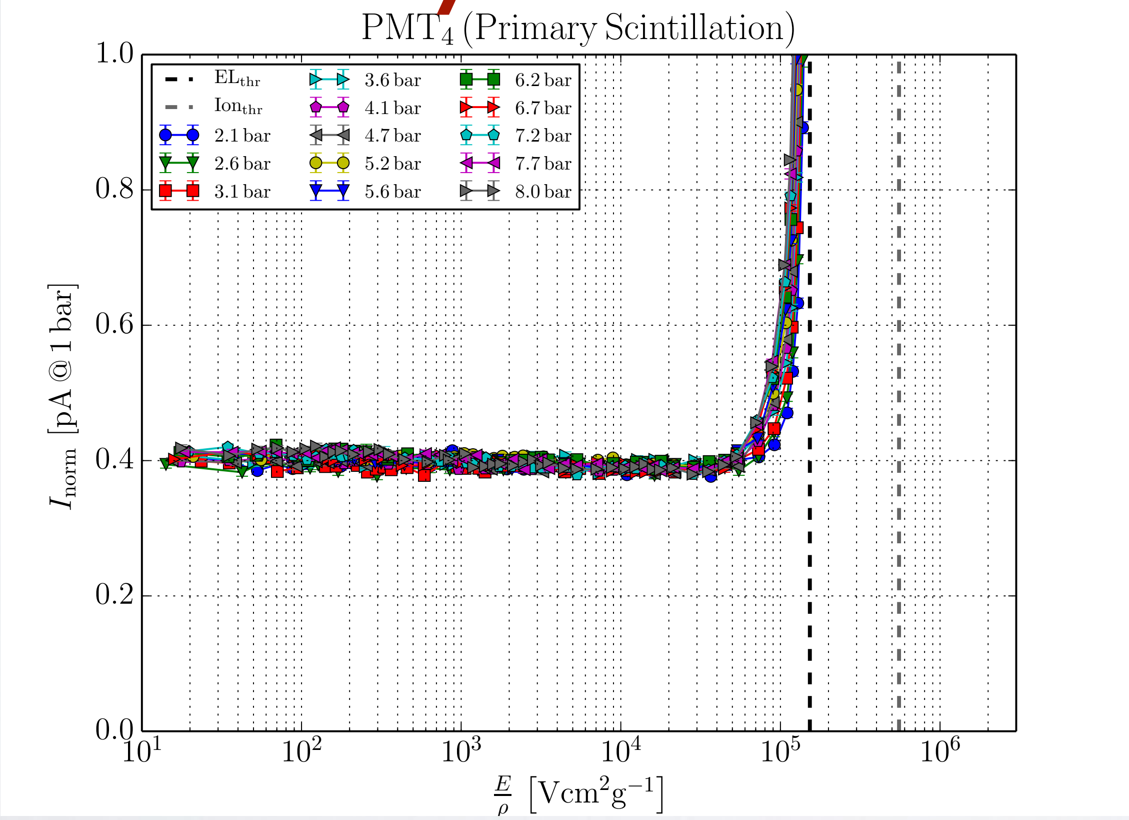
- Measures scintillation and ionization yield from pressurized gas (up to 8 bar) at various electric fields.
- In-situ measurement of the gas composition with the RGA

Setup at LBNL

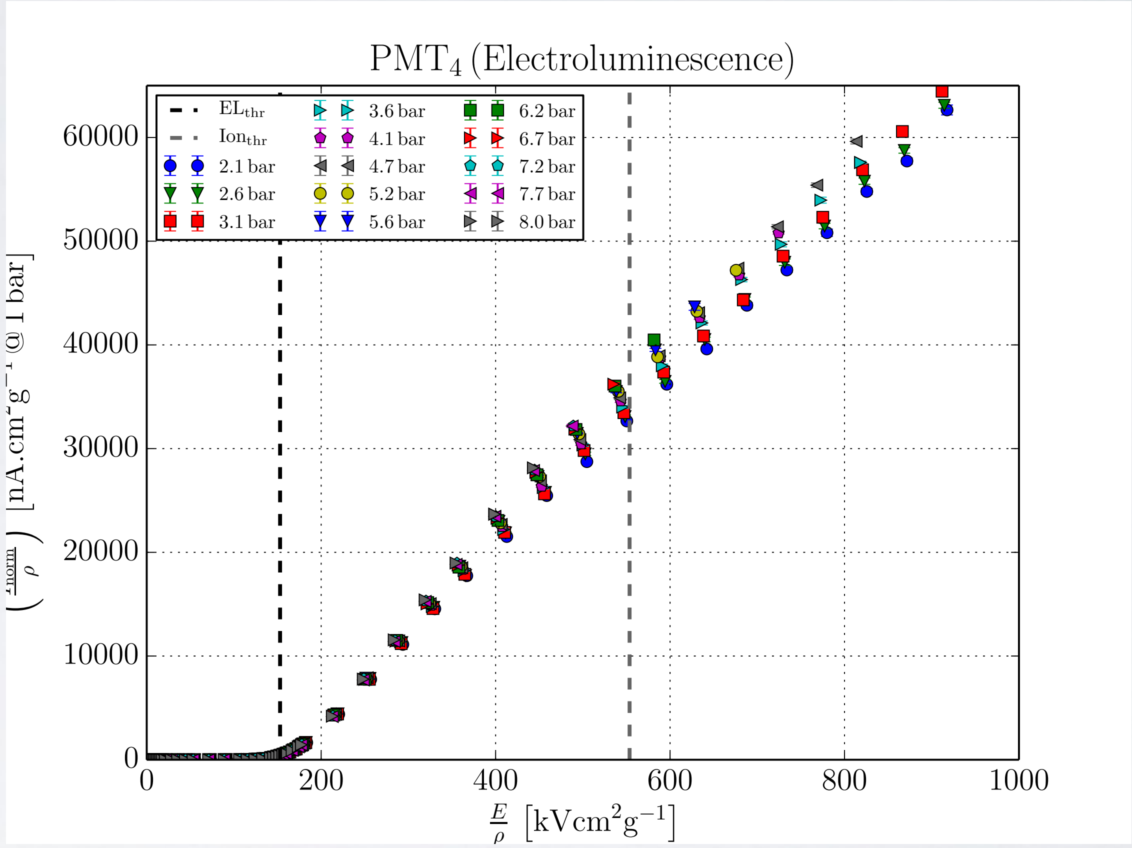


Measurement with pure Xe

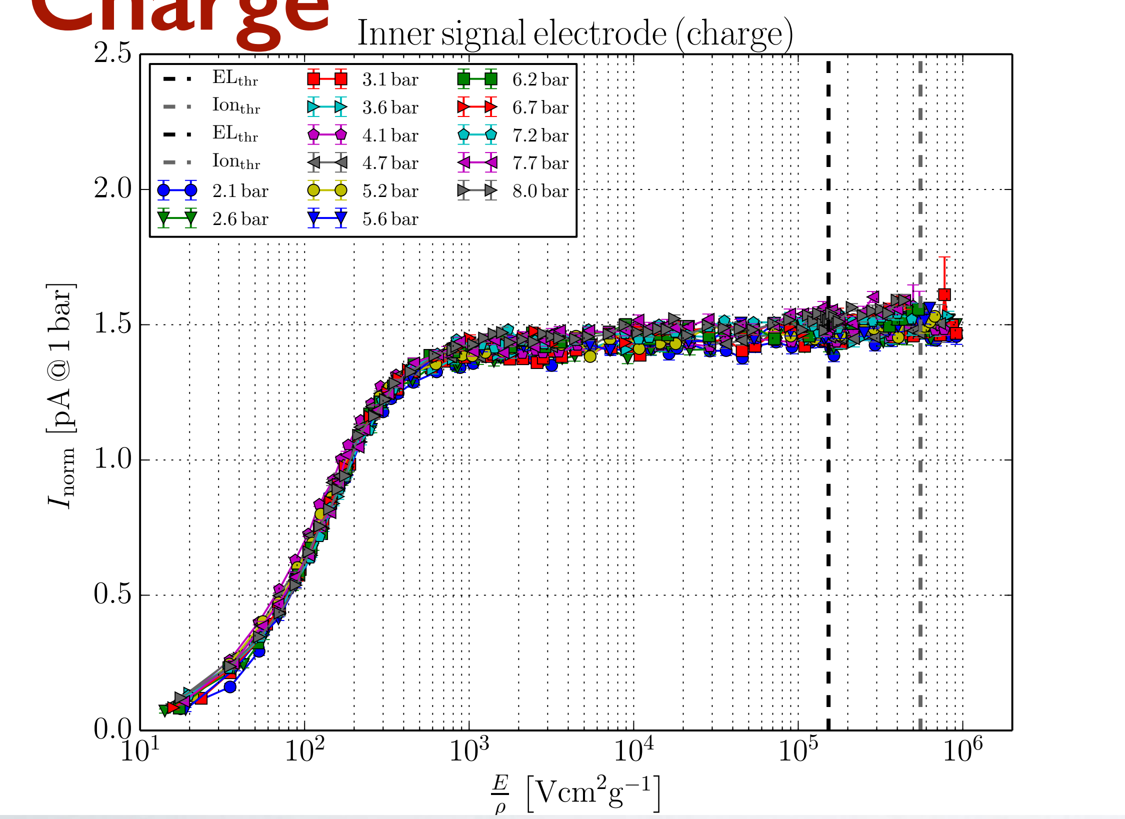
Primary scintillation



Electroluminescence



Charge

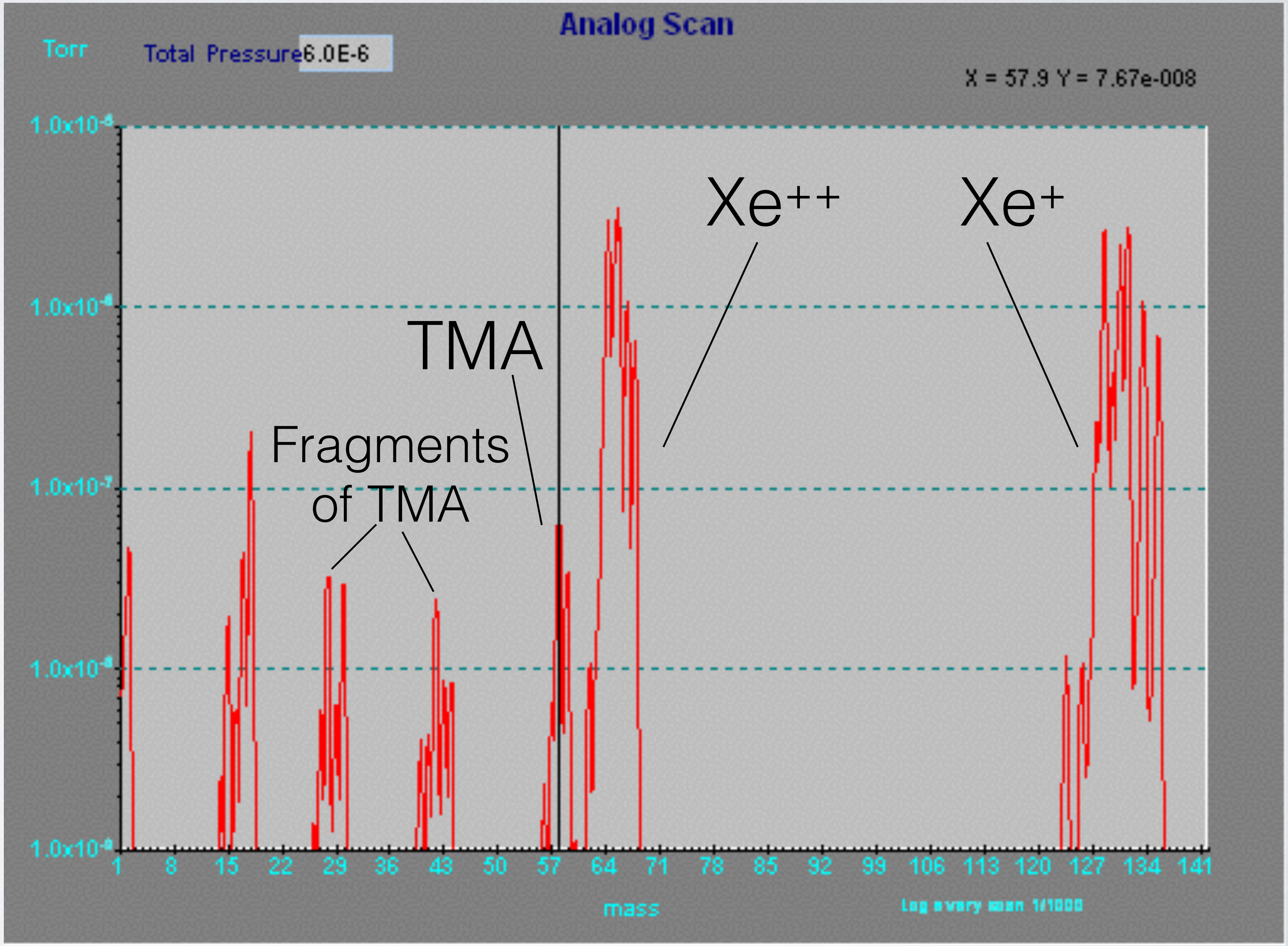


- Very high quality data, consistent between different pressures
- Difference of energy deposition in the active region is corrected using Geant4 simulation

Addition of TMA

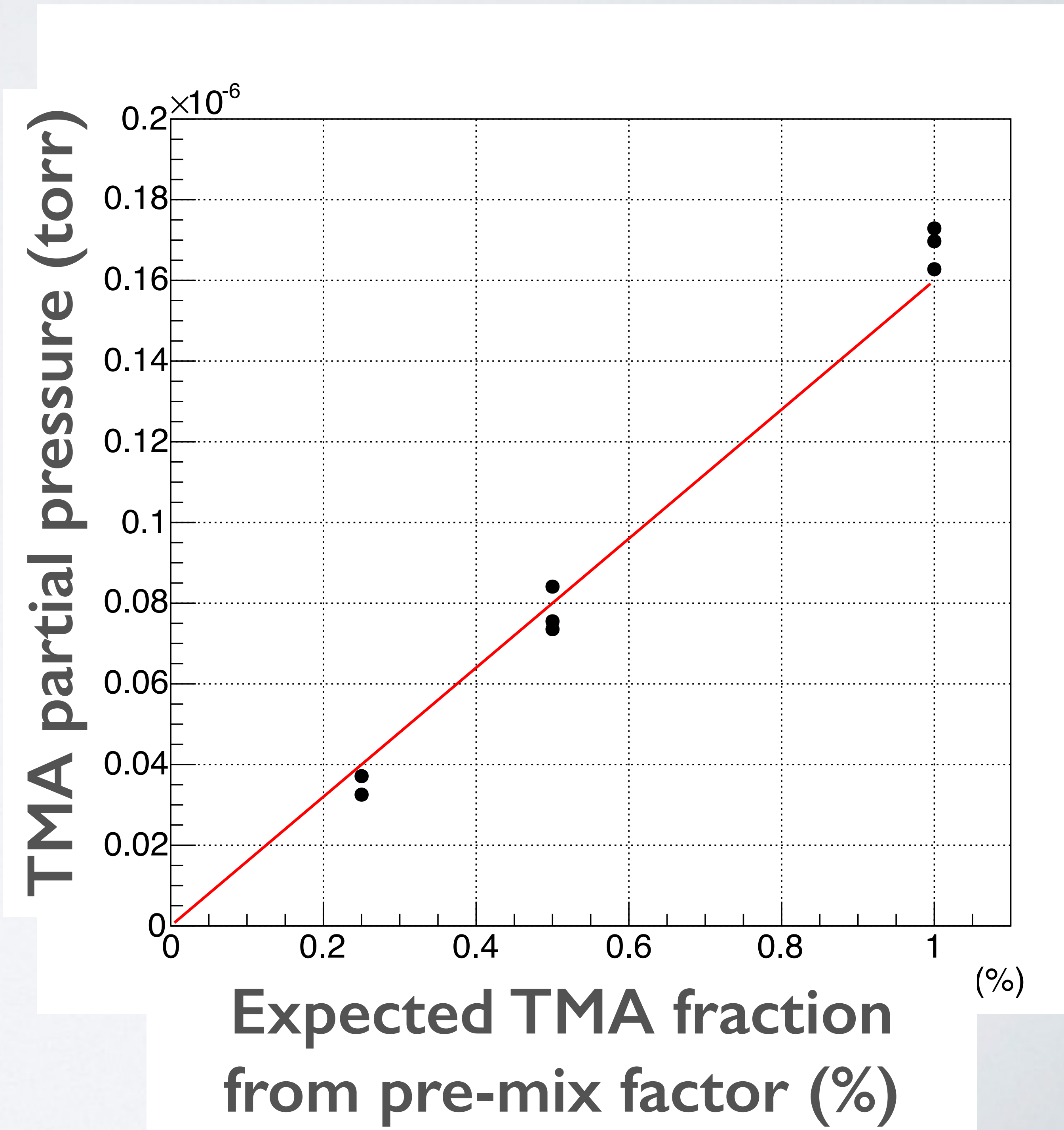
- TMA was introduced from a manufacturer pre-mixed 1% TMA + 99% Xe bottle.
- Found the getter (SAES, MC50-702F) quickly takes TMA from the gas in ~ an hour, then stabilize
- Continuously monitored TMA fraction using RGA

Typical RGA output



TMA concentration measurements

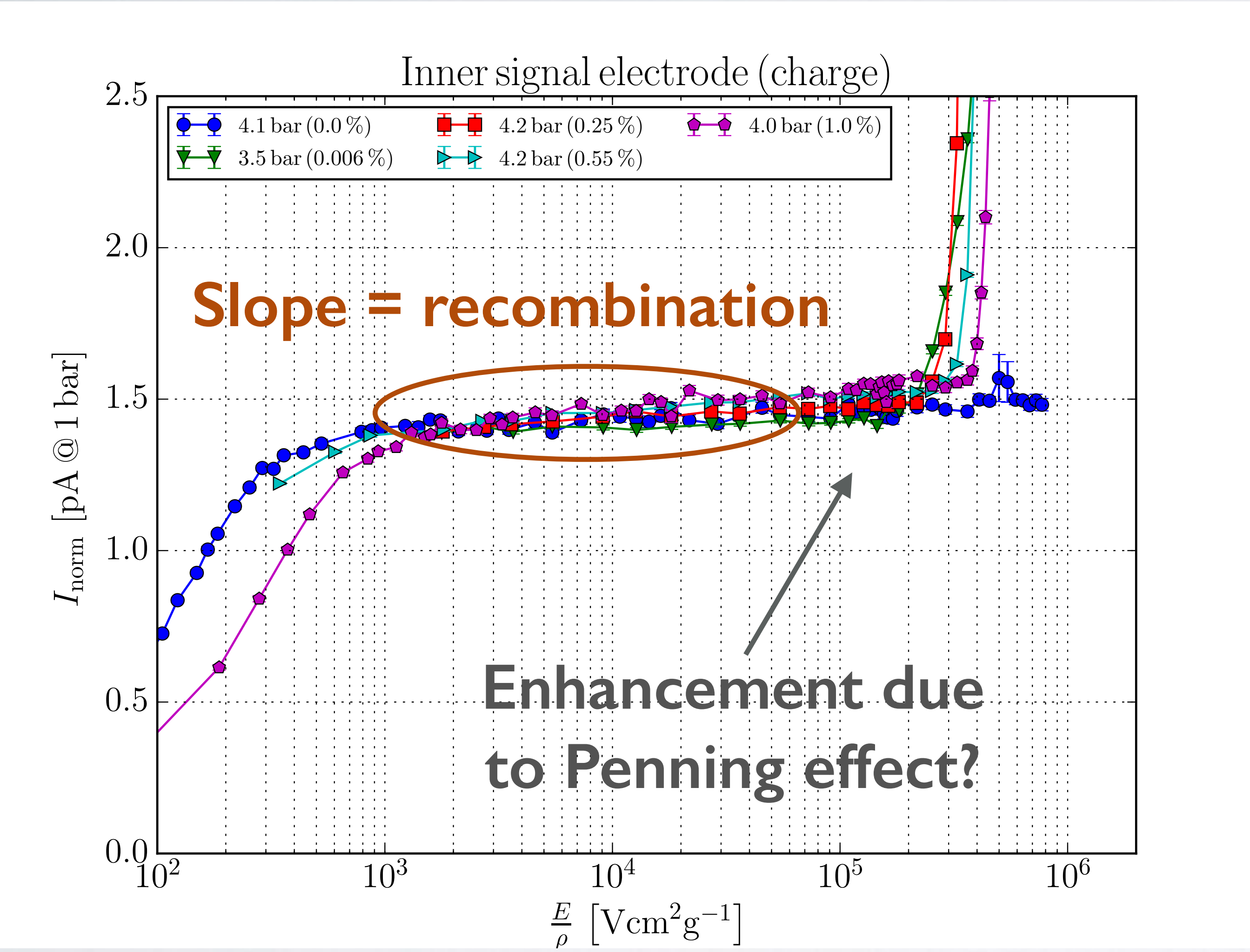
- Tested the system by measured TMA partial pressure for various pre-mixed Xe+TMA gas, without using filter.
- Monitored relative amount of TMA and Xe.
- TMA fraction measured at ~10% relative precision.



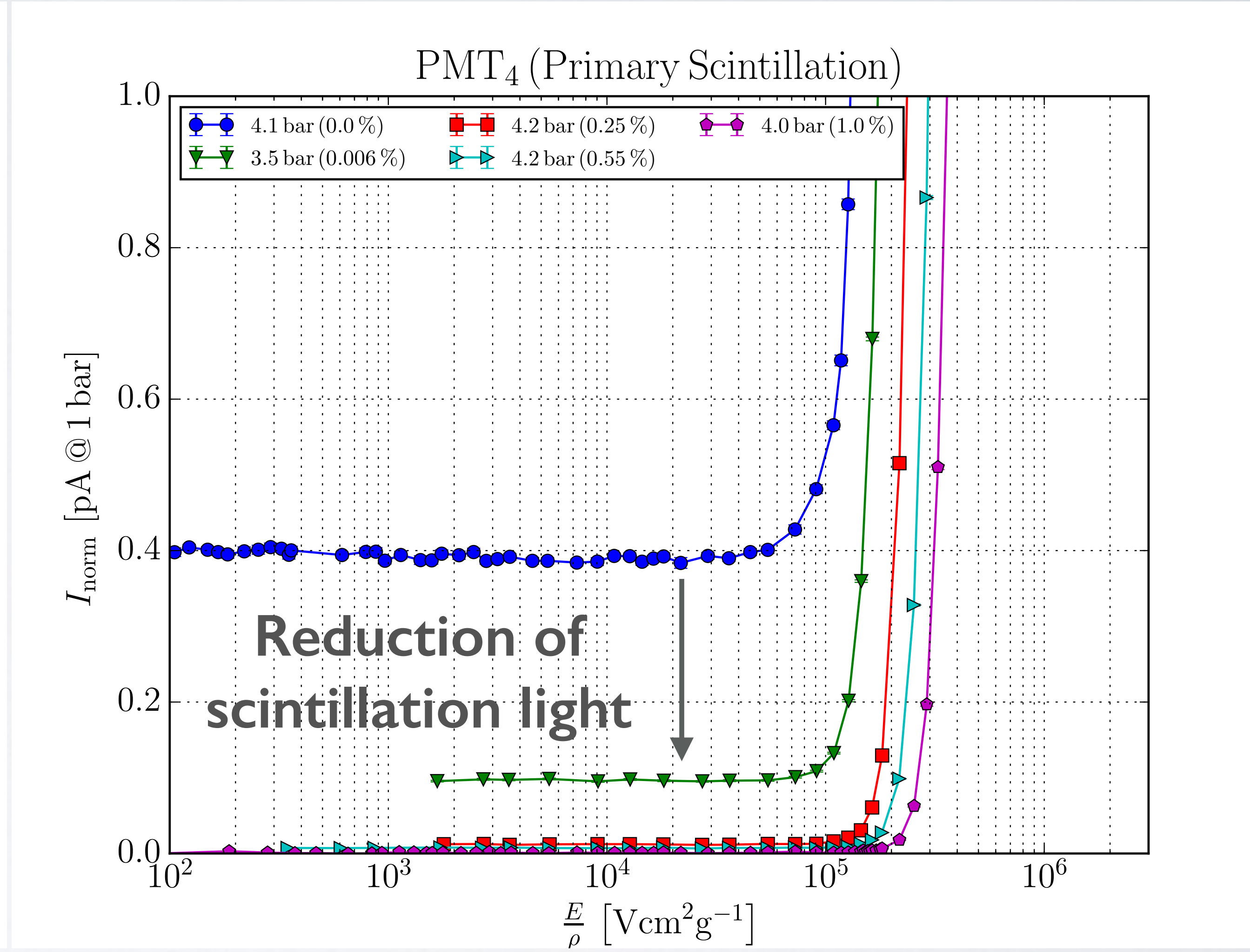
Result with TMA

arXiv:1505.03585

Charge signal



Light yield



- Enhanced recombination and slight hint of Penning effect (will come back later)
- Charge multiplication happens at lower field due to lower ionization energy of TMA and the Penning effect
- Big reduction of scintillation light. (a few % of pure Xe)

Penning effect

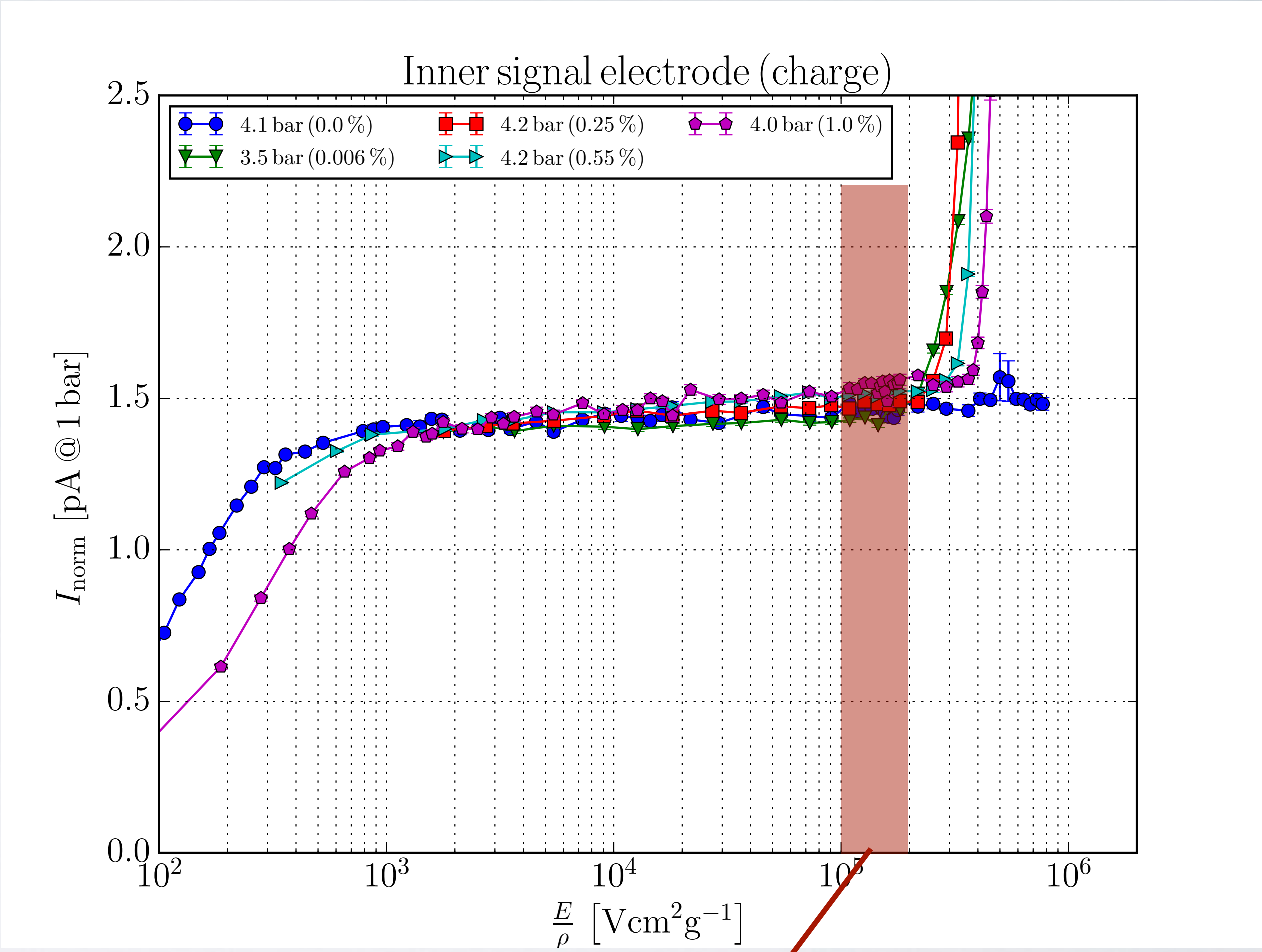
- Observed higher charge yield at higher TMA concentration: Penning effect.

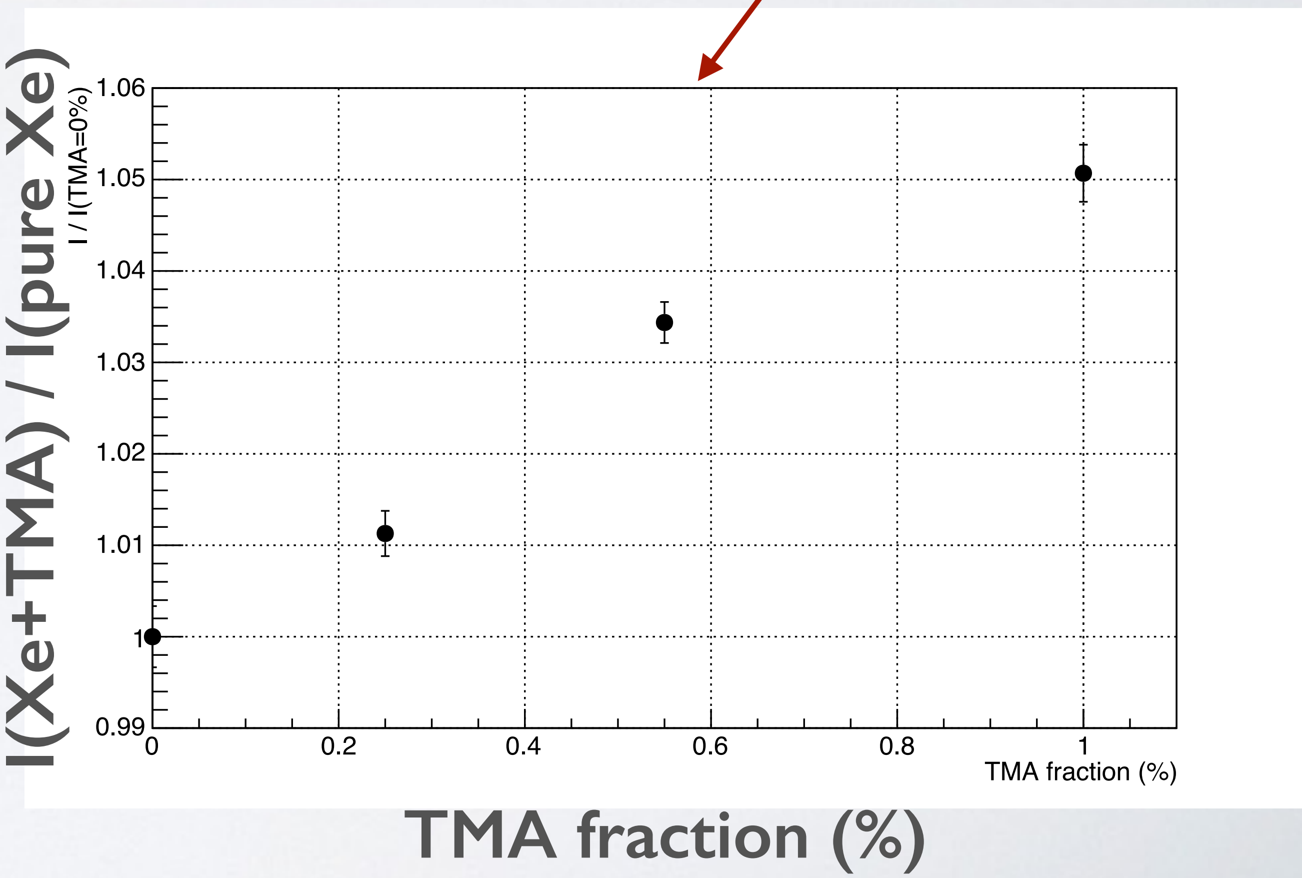
Xe* + TMA —> Xe + TMA⁺ + e

- (#Scintillation):(#Ionization) = 1/Wsc : 1/Wi ~ 1 : 2.5 [arXiv: 1409.2853]

$$\epsilon(\mathbf{Penning}) = \frac{W_{sc}}{W_i}\left(\frac{I(Xe + TMA)}{I(pureXe)} - 1\right)$$

- ~5% increase of the charge signal at 1% TMA ➜ 10-15% of Penning efficiency.





Recent updates

- Improved measurement of primary scintillation light.
  - Improved signal-to-background ratio with increased PMT gain (~x4) and better monitoring baseline drift
  - More focused on low total pressure region.
  - Investigating the nature of the light production mechanism.
- (Work in progress) Quantification of the Penning transfer efficiency with more data.

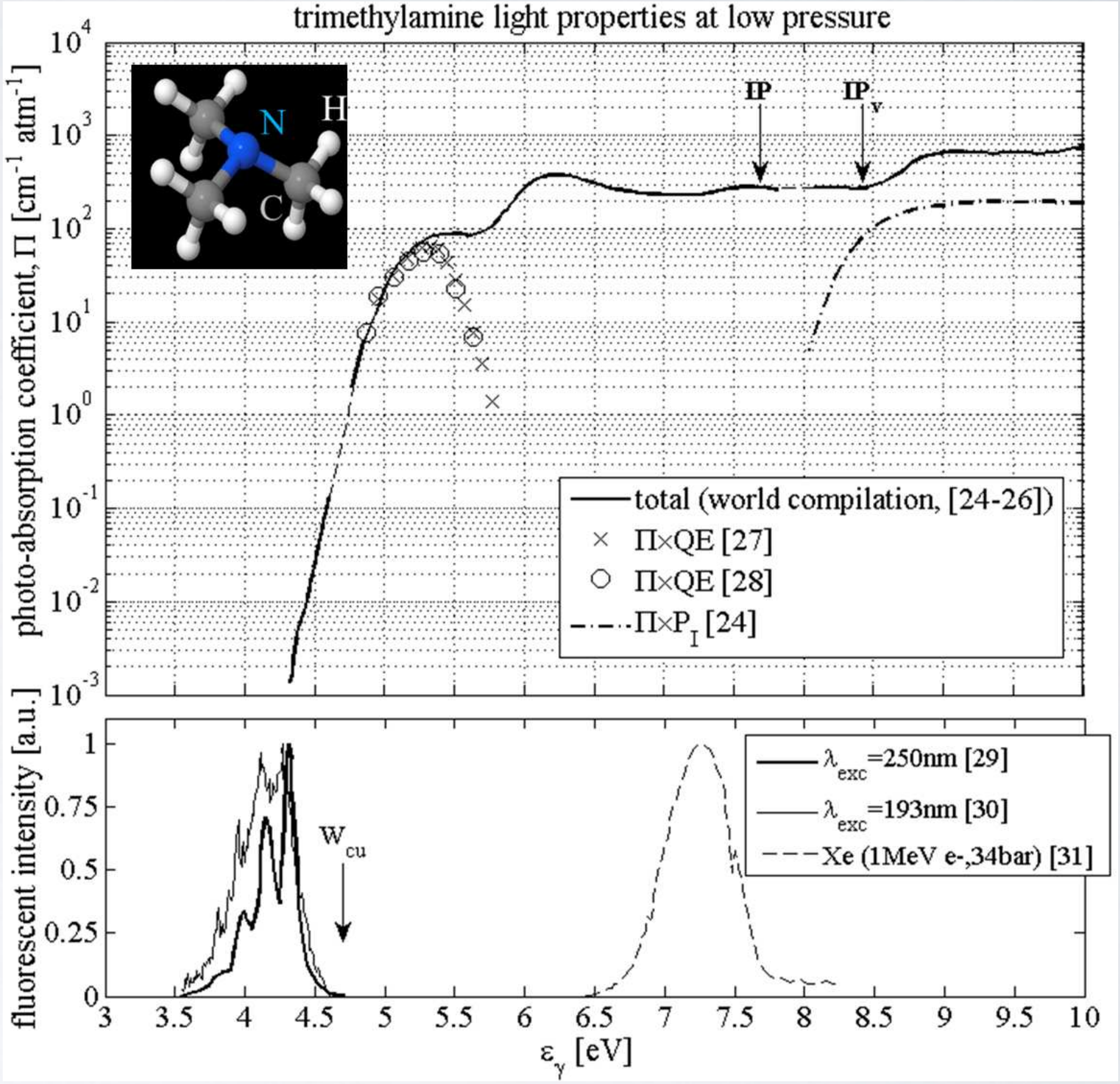
Improved measurement of primary scintillation light

Modeling primary scintillation light

arXiv: 1504.03678

- TMA is opaque to Xe light(λ=170nm), but transparent to its own light (λ=300nm)
  - Only fluorescence light from TMA de-excitation could reach the PMTs
- Energy transfer from Xe
  - Xe* + TMA → Xe + TMA*
  - TMA produce no visible light when excited at λ < 220 mm at low pressure
  - Enhanced light with additional gasses (including TMA itself)

    Obi et al (1980), Cureton et al (1981)
- Direct excitation of TMA
  - Incoming particle should excite TMA as well
  - Similar suppression/enhancements to excitation by UV lights?



A simple model

P_F: Fluorescent transfer prob
c: TMA concentration
P_{tot}: Total pressure

Energy transfer from Xe — **Direct excitation**

$$S_1(Xe+TMA) = E_{dep} \cdot \left[\frac{(1-c)P_F}{W_{sc,Xe}} + \frac{c}{W_{sc,TMA}}\right] \cdot f_{SQ}(c \cdot P_{tot}) \cdot \epsilon_{det} \cdot \epsilon_{QE}(300nm)$$

Fixed self-quenching factor
Based on Cureton et al (1981)

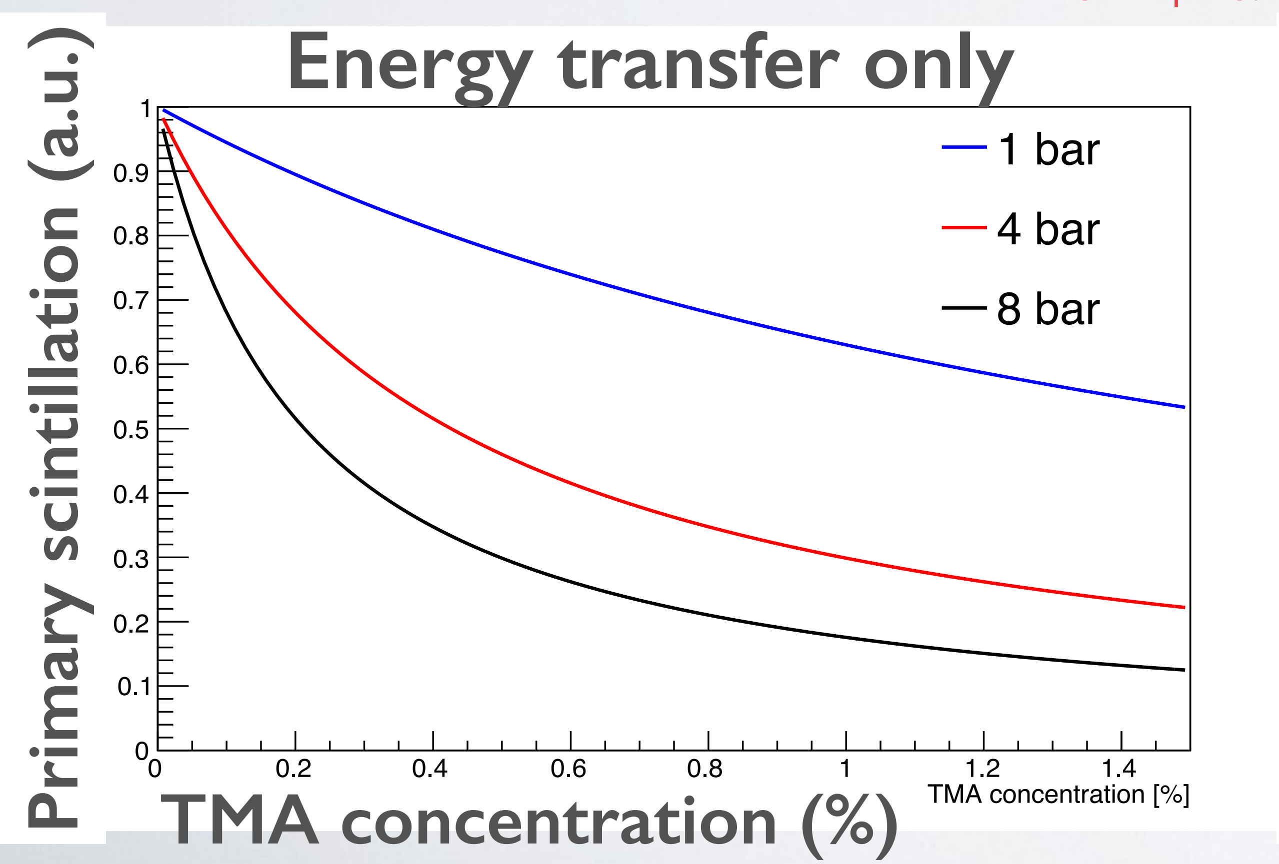
$$S_1(Xe) = E_{dep} \cdot \frac{1}{W_{sc,Xe}} \cdot \epsilon_{det} \cdot \epsilon_{QE}(170nm)$$

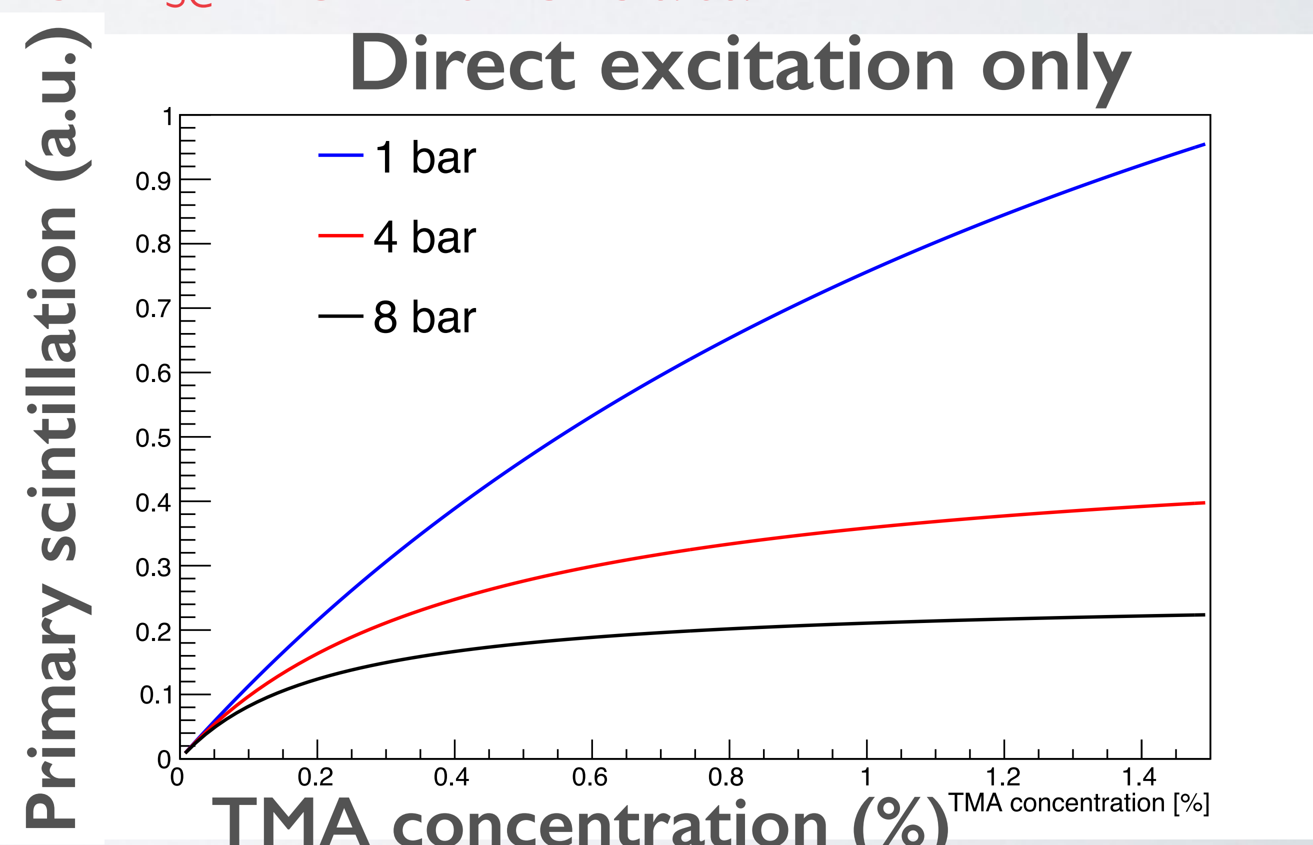
$$\frac{S_1(Xe+TMA)}{S_1(Xe)} = [(1-c)P_F + c \cdot R_{sc}] \cdot f_{SQ}(c \cdot P_{tot}) \cdot \frac{\epsilon_{QE}(300nm)}{\epsilon_{QE}(170nm)},$$

$$\text{where } R_{sc} = \frac{W_{sc,Xe}}{W_{sc,TMA}}$$

~2 (Fixed in the fit)

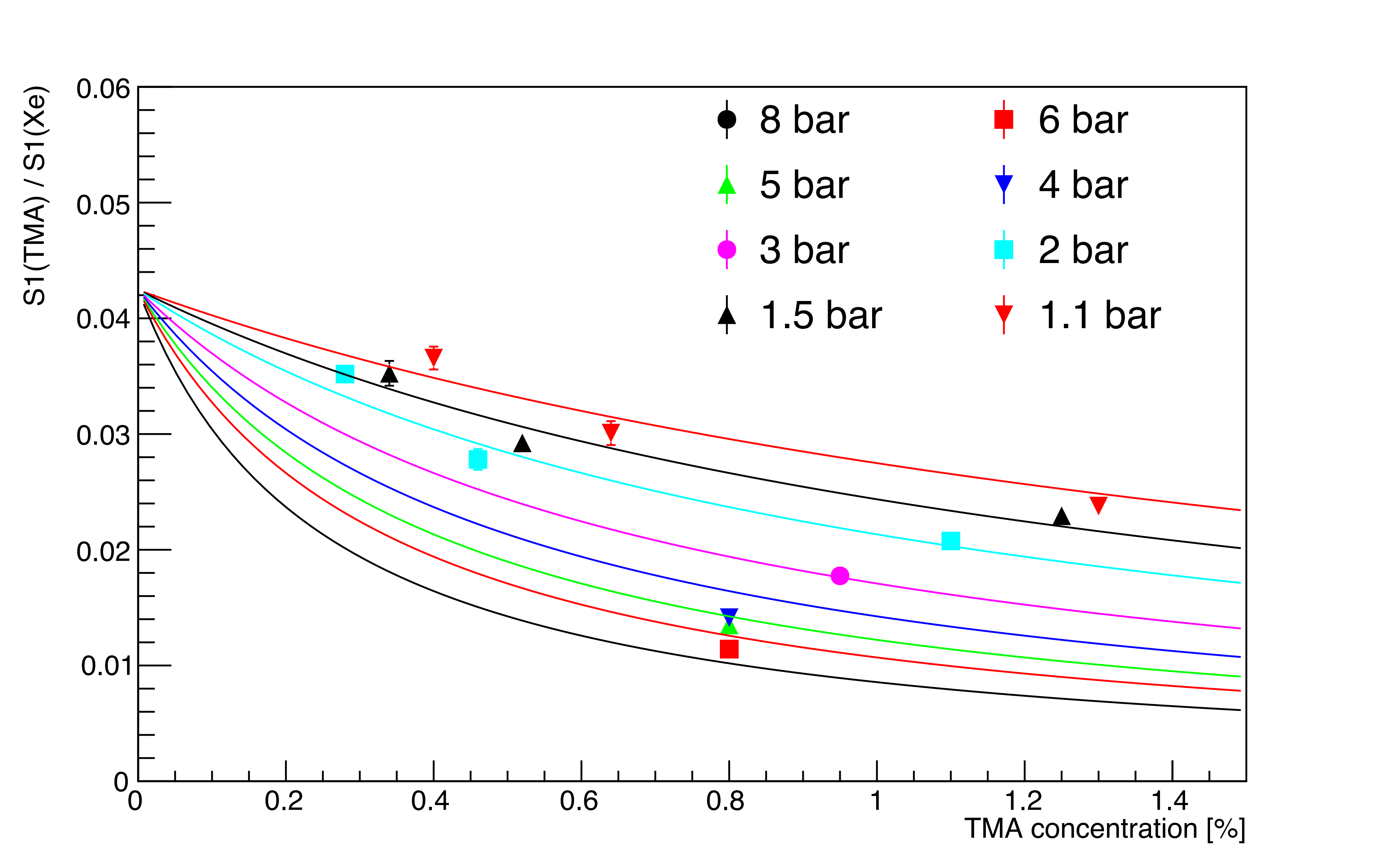
Fit P_F and R_{sc} from the data





Observed data

P_F: Energy transfer probability
R_{SC}: Relative direct excitation



Best fit:

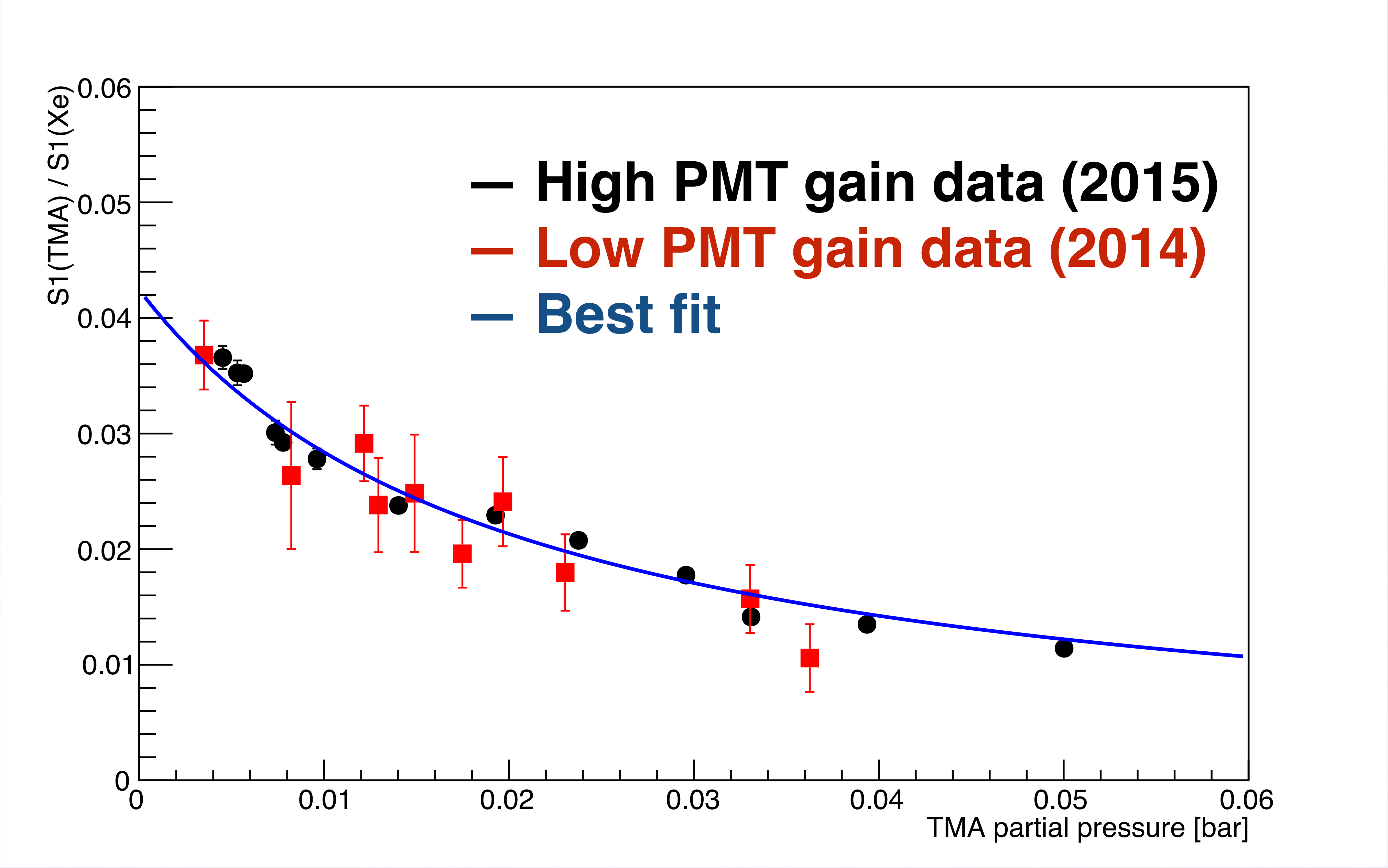
$P_F = 0.02$

$R_{SC} = 0.0$

Full systematic uncertainty not yet included

- The data suggests that **the most of the light are from energy transfer from Xe* (Xe*+TMA → Xe + TMA*)**
- Quantification systematic uncertainty underway.

Observed data



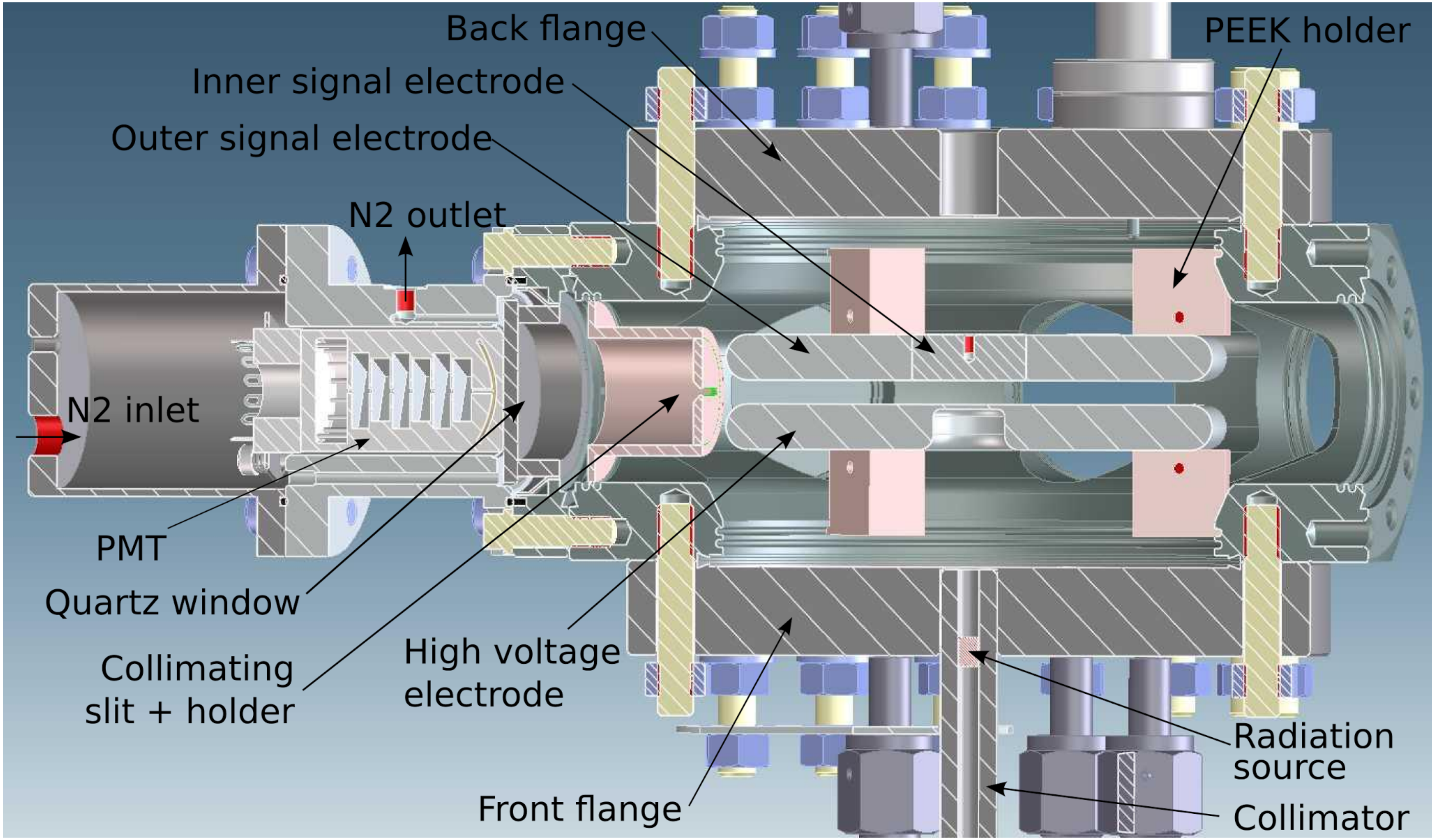
- Assuming all the light are from energy transfer, the light yield scales with the TMA partial pressure (= cP_{tot})

Summary

- Successfully measured basic quantities of scintillation and ionization yield for Xe+TMA gas mixture at various electric field.
- Made detailed investigation of primary scintillation light.
  - The data suggests majority of the light is from energy transfer from Xe* to TMA (Xe* + TMA ➔ Xe + TMA*)
- Improved quantification of penning transfer efficiency with more data in progress.
- Many thanks Diego Gonzalez Diaz for helpful discussions and suggestions.

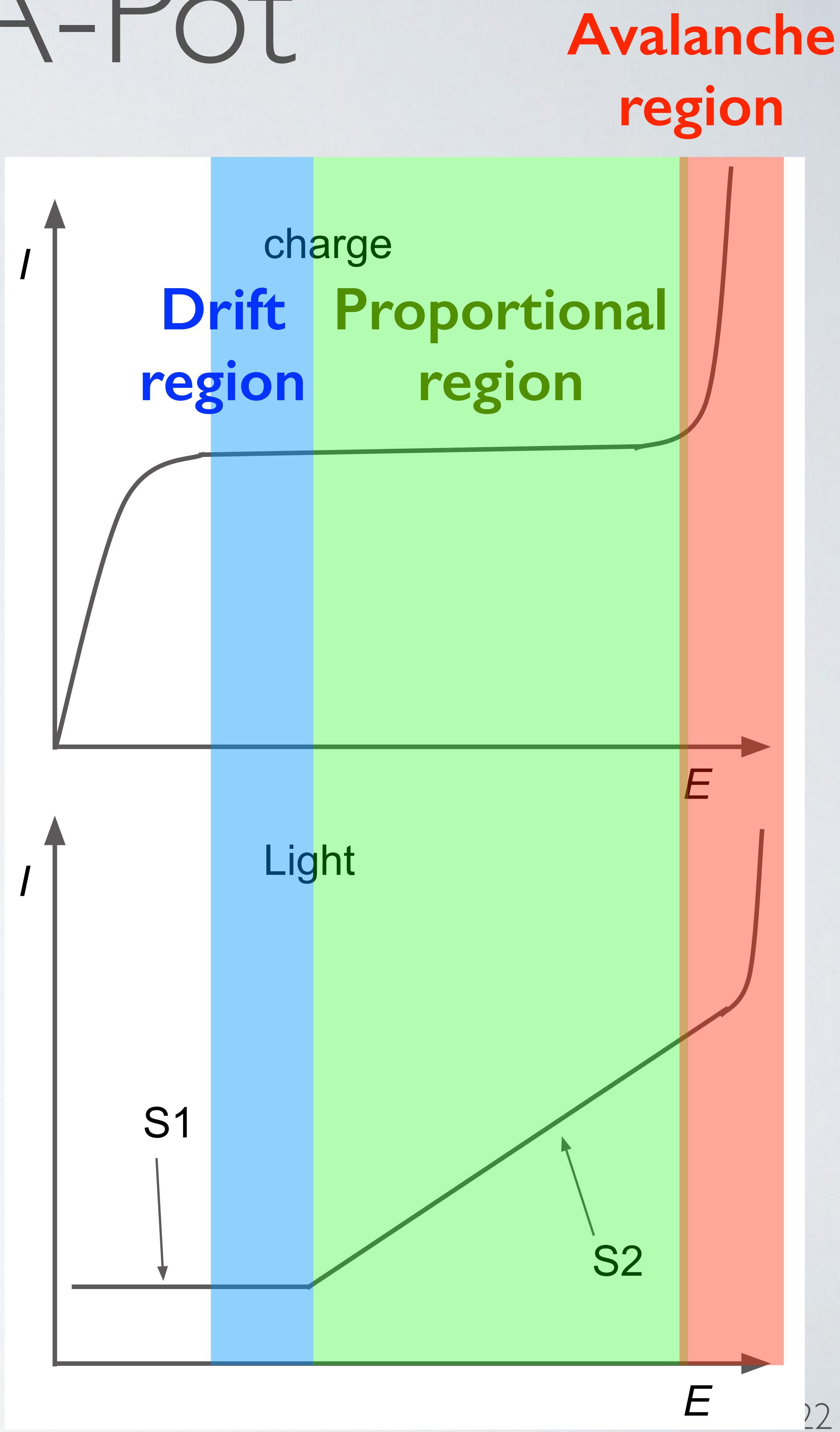
Backup slides

Structure details



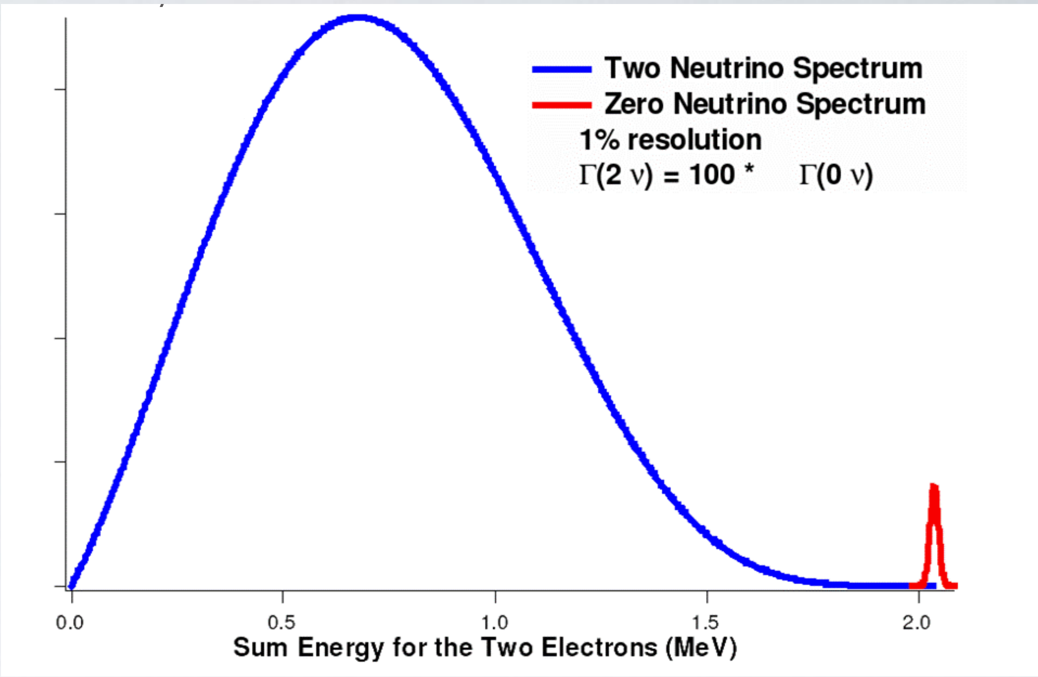
Data from TEA-Pot

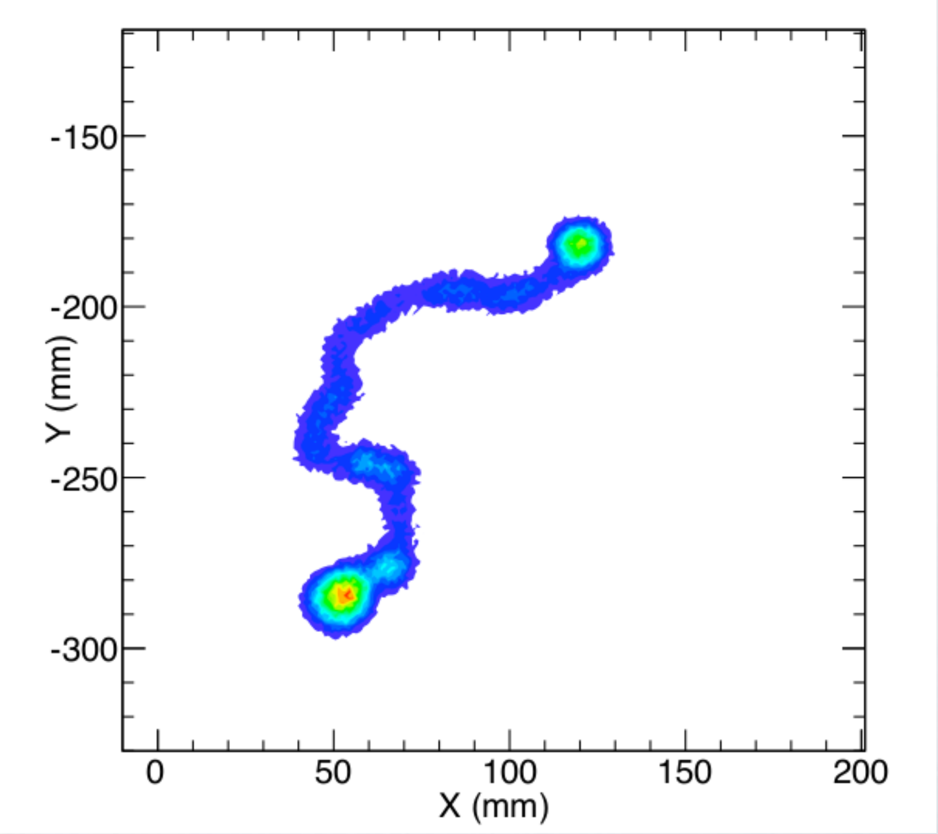
- Measure current from PMTs and electrodes in the DC mode.
- 60 keV gamma-ray from ^{241}Am source is used
- Scan wide range of the electric field from the drift region to the avalanche region.



Neutrinoless double beta decay search

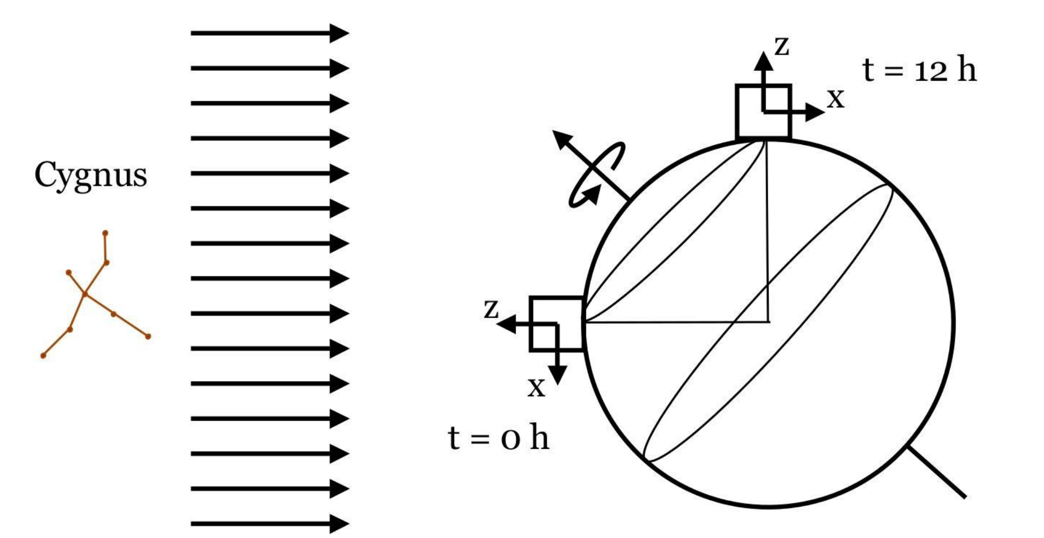
- NEXT experiment:
  - Search for neutrinoless double beta decay from ^{136}Xe with high-pressure gaseous Xe TPC
  - Extra handle by tracking two electrons
- Higher energy and tracking resolutions are keys to improve the sensitivity
- See Diego Gonzalez-Diaz's talk(s)



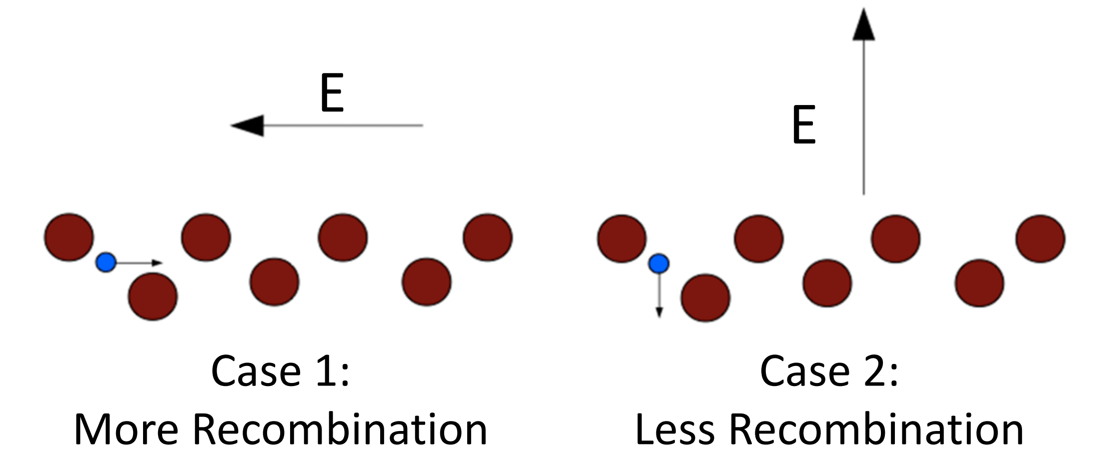


Directional dark matter search with columnar recombination

- Directionality of short-nuclear recoil from WIMP scattering can be obtained by utilizing Columnar Recombination
- Keys to realize this idea:
    - Efficient cooling of electrons
    - Make as much as electron-ion pair
- See my talk given yesterday

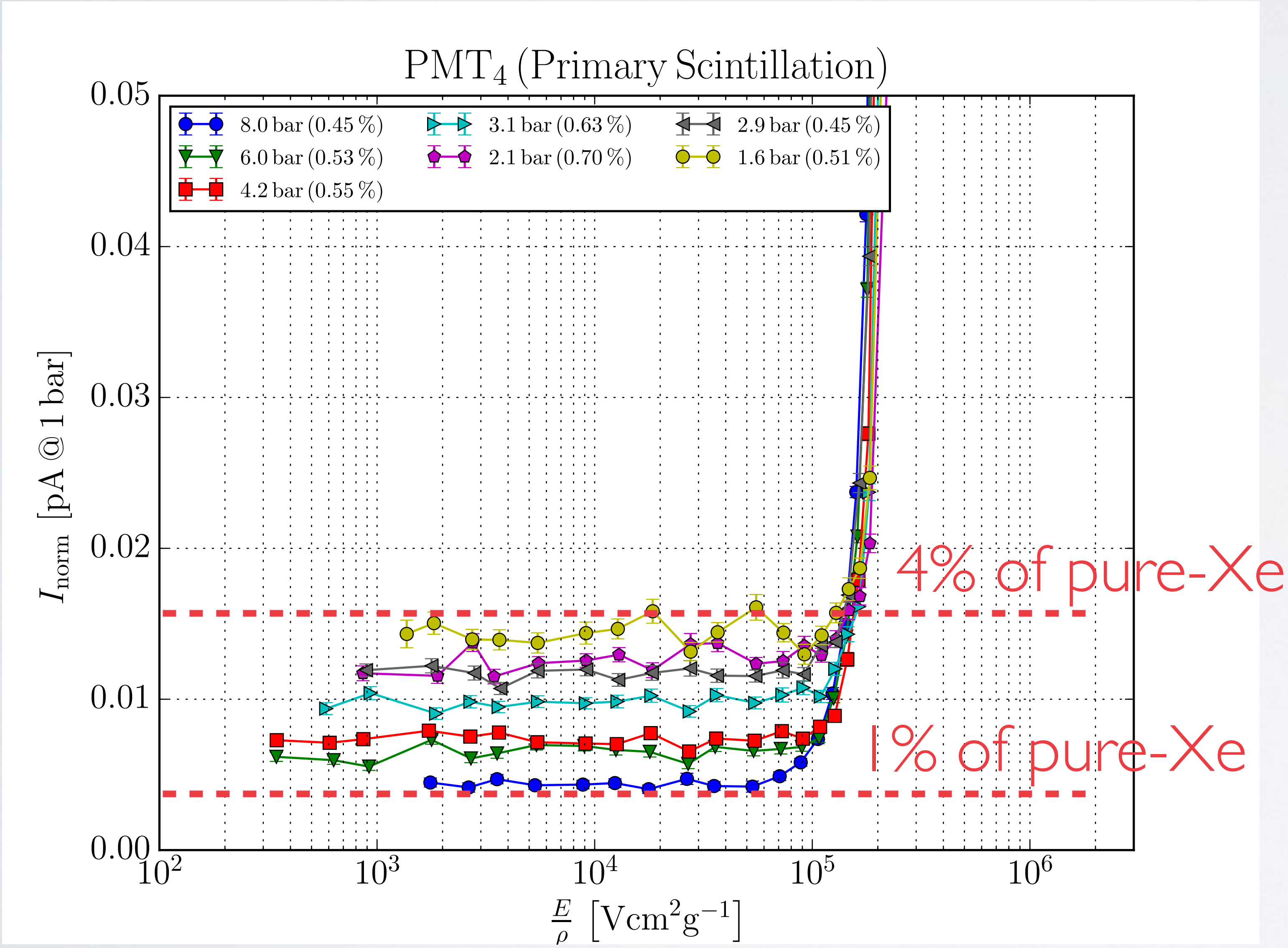


[S. Ahlen et al, Int. J. Mod. Phys. 25 (2010) 1]



Closer look at primary scintillation light

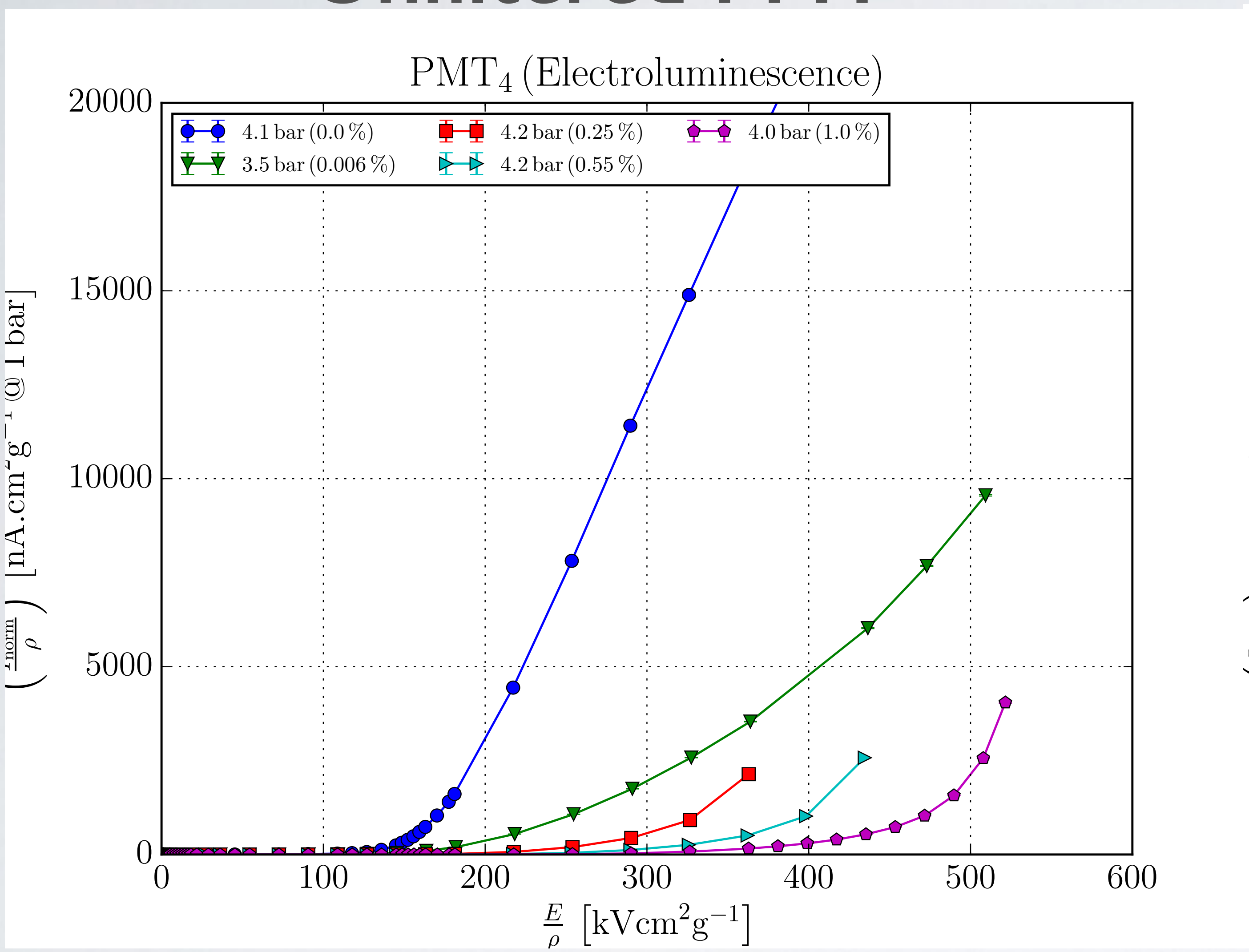
Unfiltered PMT



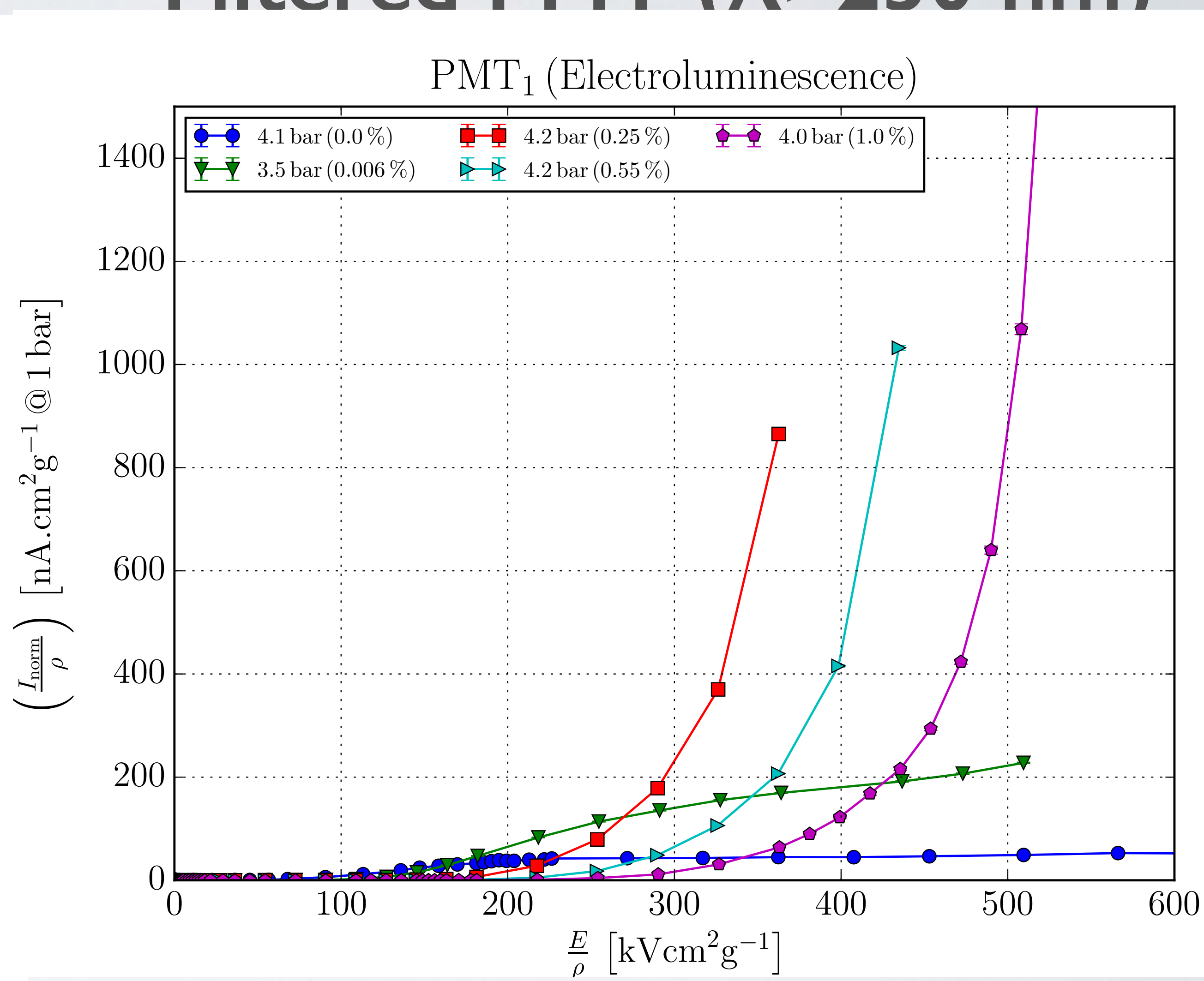
- Small amount of primary scintillation light observed at 1-4% level of the pure Xe case.
- Filtered PMT (λ>250nm) observed consistent light yield.
- Consistent with the light just coming from the direct excitation of the TMA
- Pressure dependence consistent with the known self-quenching of the TMA
- No significant additional scintillation light (from TMA recombination, energy transfer from Xe etc) observed.

Electroluminescence light

Unfiltered PMT



Filtered PMT (λ>250 nm)



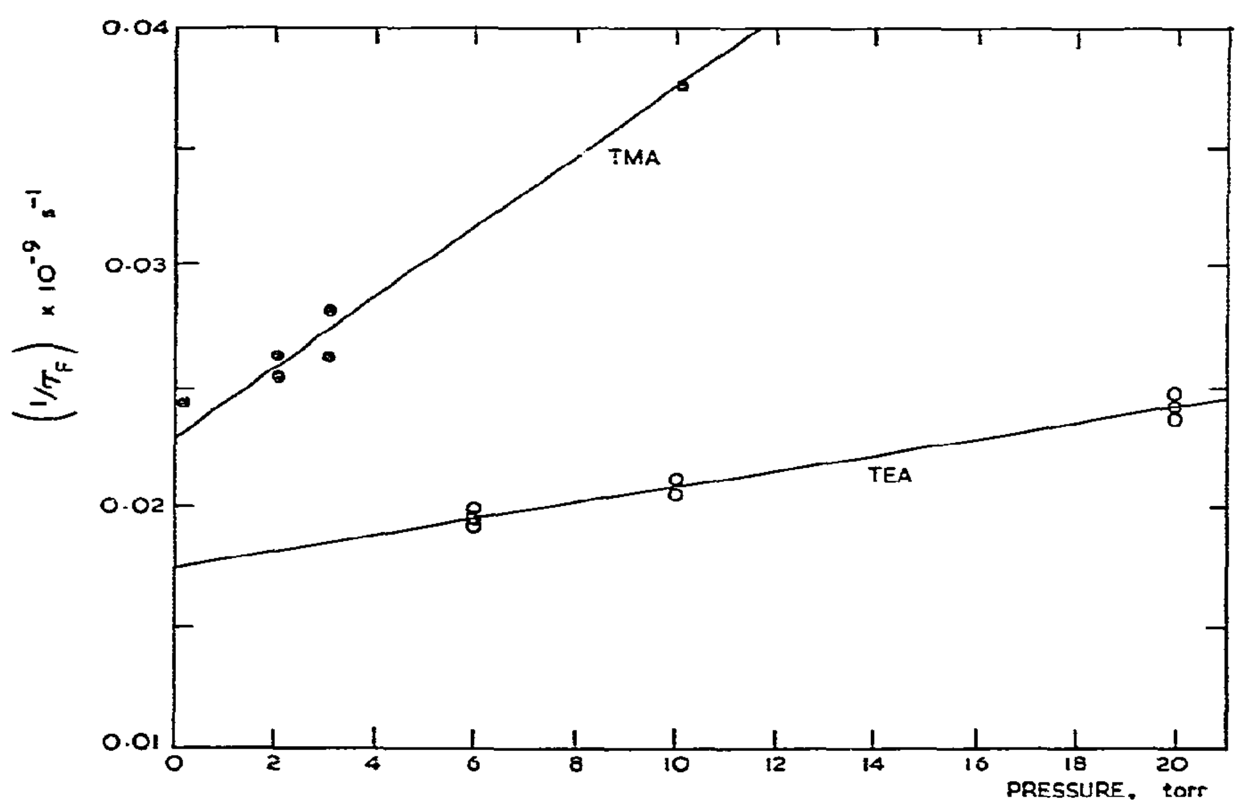
- Observed clear signal of the electroluminescence light from TMA
- Higher threshold at higher TMA concentration, due to electron cooling by TMA.

TMA self-quenching

- Reported by Cureton et al (1981)
- Extracted by the light emission time constant
- In terms of the light yield, the effect should be proportional to:

$$\propto \frac{1/\tau_0}{1/\tau_0 + k_{SQ} c P_{tot}}$$

c: TMA concentration
P_{tot}: total pressure
k_{SQ}: self-quenching constant
τ_0: Time constant for radiative TMA decay



k_{sq} = 1.125 x 10^9 [$bar^{-1}sec^{-1}$]
τ_0 = 44 nsec

Results from filtered PMT

Filtered PMT