Micro-physics simulations of columnar recombination along nuclear recoil tracks in high-pressure Xe gas for directional dark matter searches

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Dec. 15, 2014

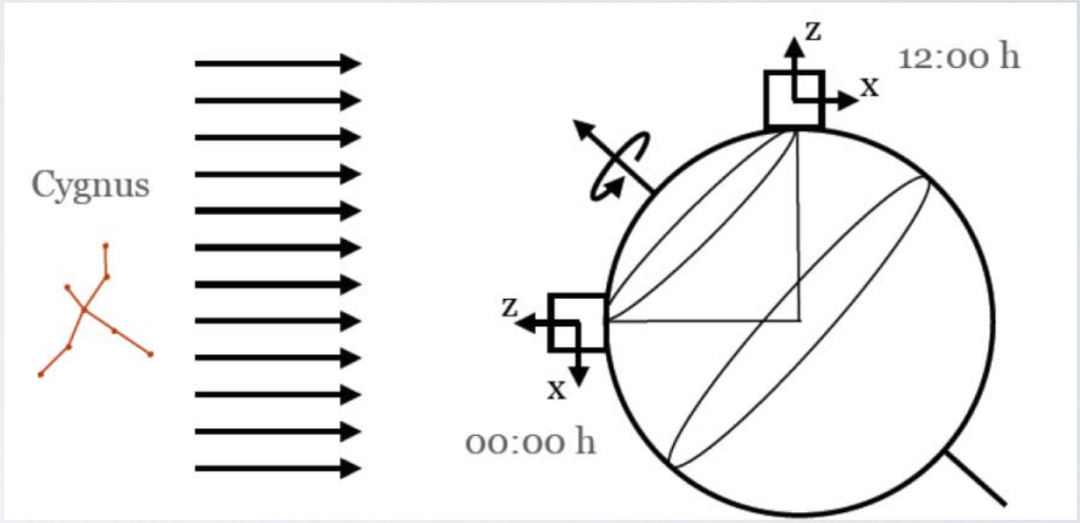
7th symposium on large TPCs for low-energy rare event detection

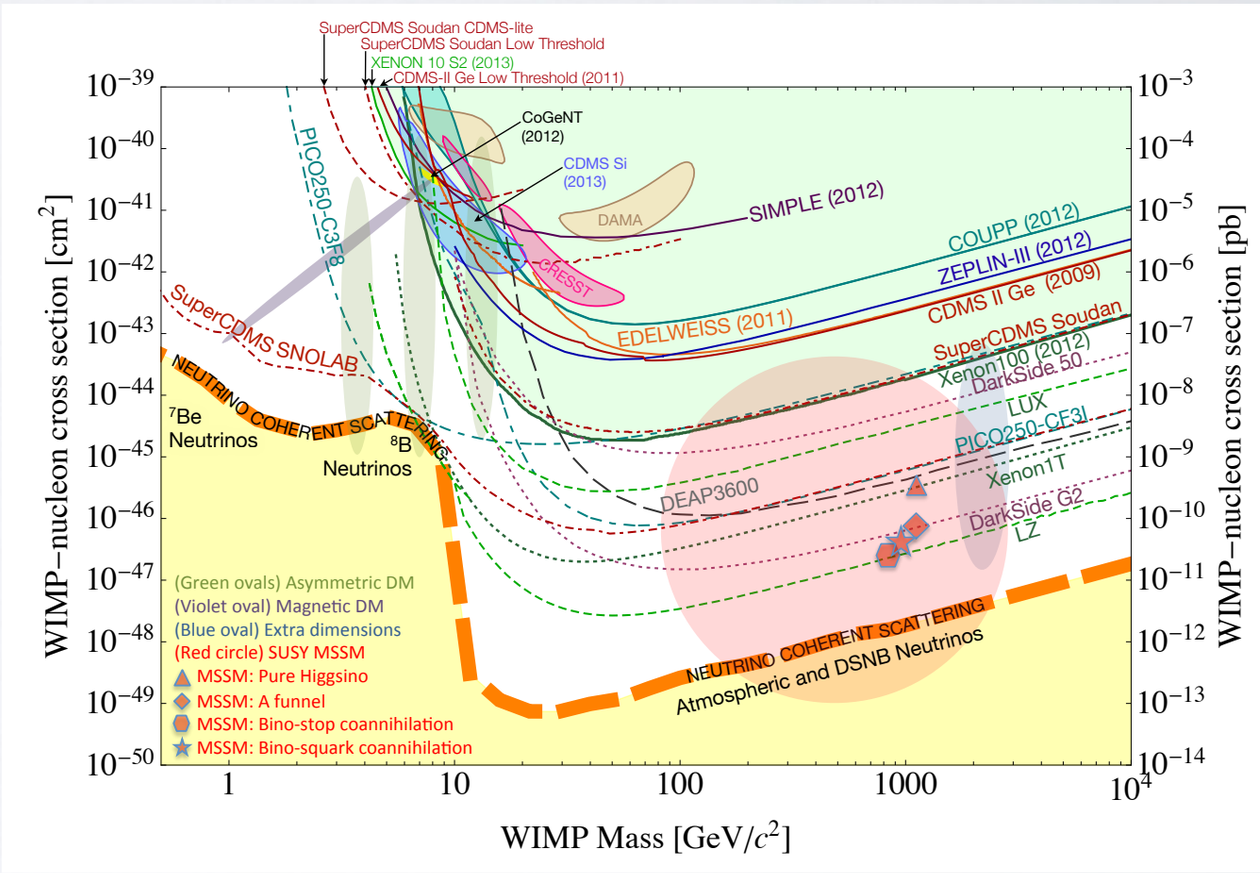
Outline

- Introduction
- Directional sensitivity with columnar recombination
- Micro-physics simulation of recombinations
- Summay

Search for WIMP dark matter

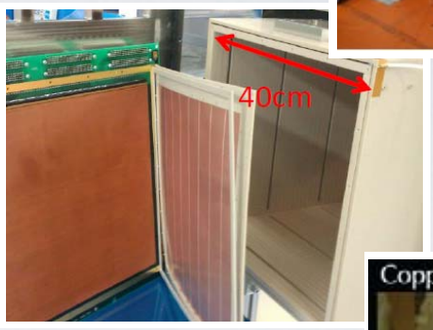
- If the dark matter is the WIMPs, Earth is moving through the "WIMP halo" at v~230km/s
- If interacted with the matter on Earth, makes a low-energy nuclear recoil (a few tens of keV), with a preferred direction of the "WIMP wind" from Cygnus.
- Currently most sensitive experiments manly using the energy information only.
- In order to build more confidence and reduce backgrounds further, detecting the directionality is a key.

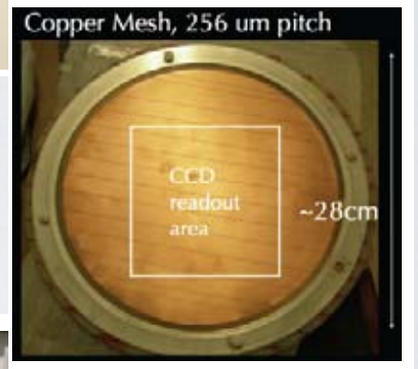




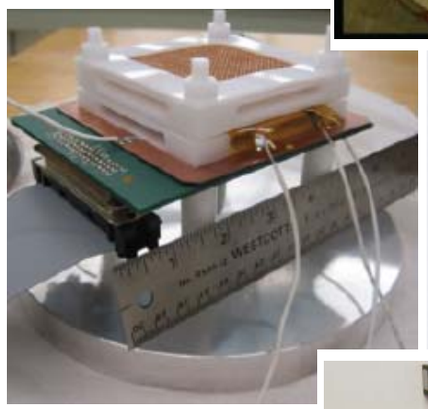
Dark matter searches with directional sensitivity

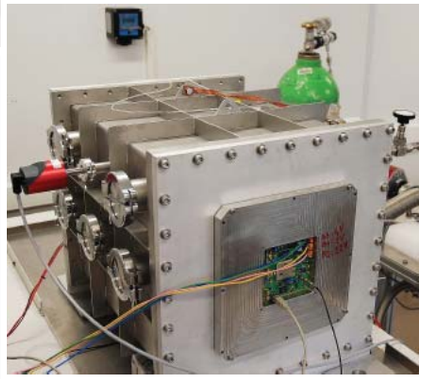
- Many dark matter searches with directional sensitivity
  - DRIFT, NEWAGE, MIMAC, DMTPC, D^3..
  - Detecting ~1mm track in low-pressure (~100 torr) gas.
  - Large target mass with directional sensitivity is a challenge



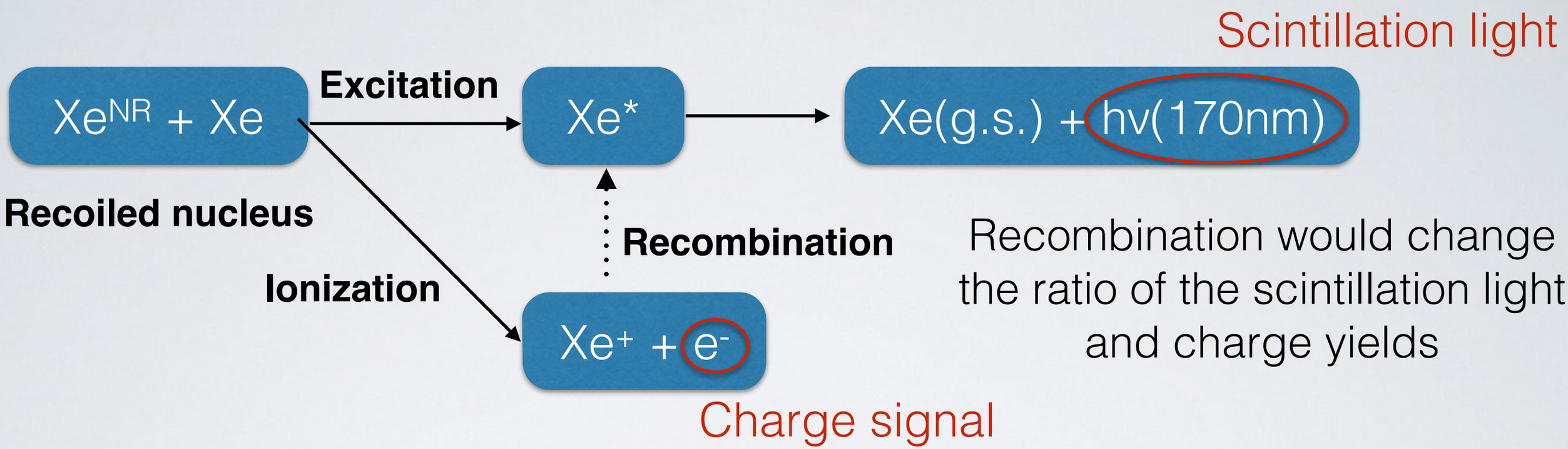


- We are exploring a new method of detecting directionality using Columnar Recombination
  - Idea first proposed by Dave Nygren
  - Might be capable of detecting **a few μm** tracks in <u>a hight-pressure (~10 bar) gas</u>. (**x100 denser!**)
  - No need of (can be expensive) positioning devices



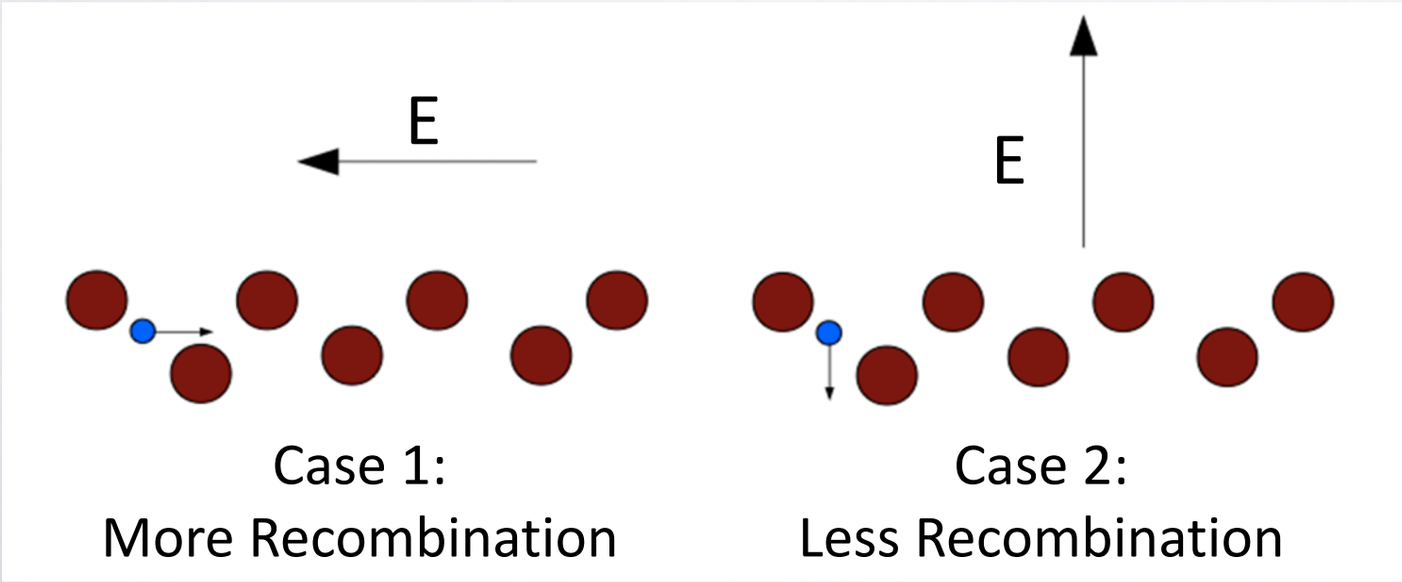


Directionality with columnar recombination



Recombination would change the ratio of the scintillation light and charge yields

Columnar Recombination



Recombination probability depends on the angle between the track and the external electric field.

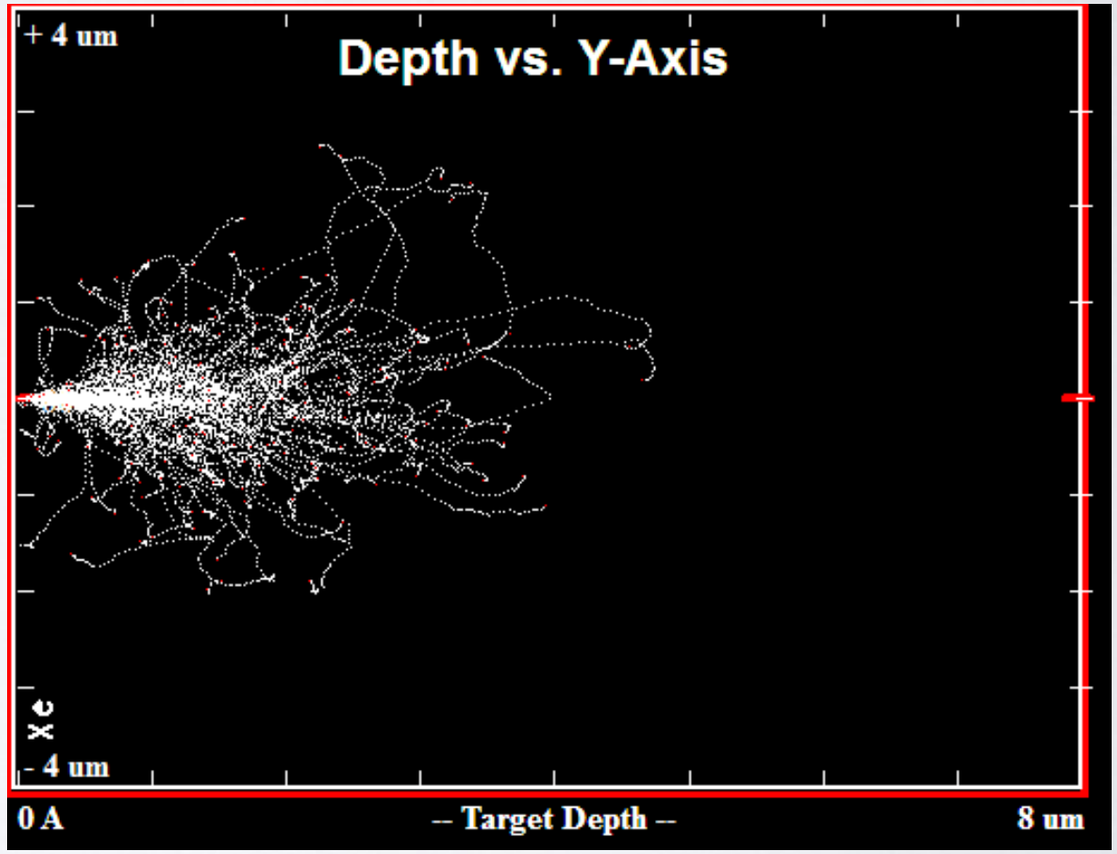
Observed phenomena for α-particles. Can we also see for (much shorter) nuclear recoils?

Conditions for columnar recombination (for ions)

- Distribution of Xe ions should hold the directional information

- Averaged track length: ~2 μm for 30 keV nuclear recoil in 10-bar Xe gas

Xe tracks from SRIM simulation (Injected 200 Xe ions at 30 keV)



Can ionized electrons "see" it by EM interaction?

Conditions for columnar recombination (for ions)

- Size of ions seen by electrons: Onsager radius (r_0):
  - The distance which thermal energy of a electron is equal to the Coulomb potential of an ion.

$$r_0 = \frac{e^2}{\epsilon k_B T}$$

- In liquid Xe, r_0 is on the same order of track length
- The track length would be much longer than r_0 in high-pressure gaseous Xe

	Density	Track length (30 keV, NR)	Onsager radius (r_0)	Volume for 1t detector
Liquid Xe	3.1 g/cm^3	~50 nm	~50 nm	~0.3 m^3
Gas Xe (10 bar, 300K)	**0.05 g/cm^3**	**~2 μm**	**~70 nm**	**~20 m^3**

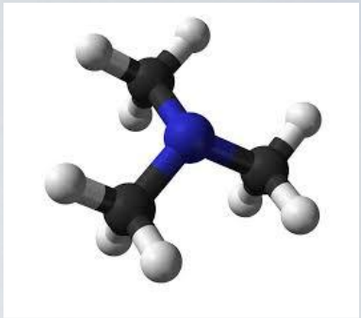
<u>Should be seen as a "track" in high-pressure Xe</u>

Condition for columnar recombination (for electrons)

- Need to keep thermalized electrons near the ions.
  - Total energy of electron-ion pair need to be negative.
- Pure Xe would not satisfy this due to lack of inelastic scattering below 7 eV.
  - Takes long time to thermalize
  - Large diffusion
- Need to add molecular additives with large inelastic cross sections

One of the candidate additives: **Trimethylamine (TMA)**

TMA



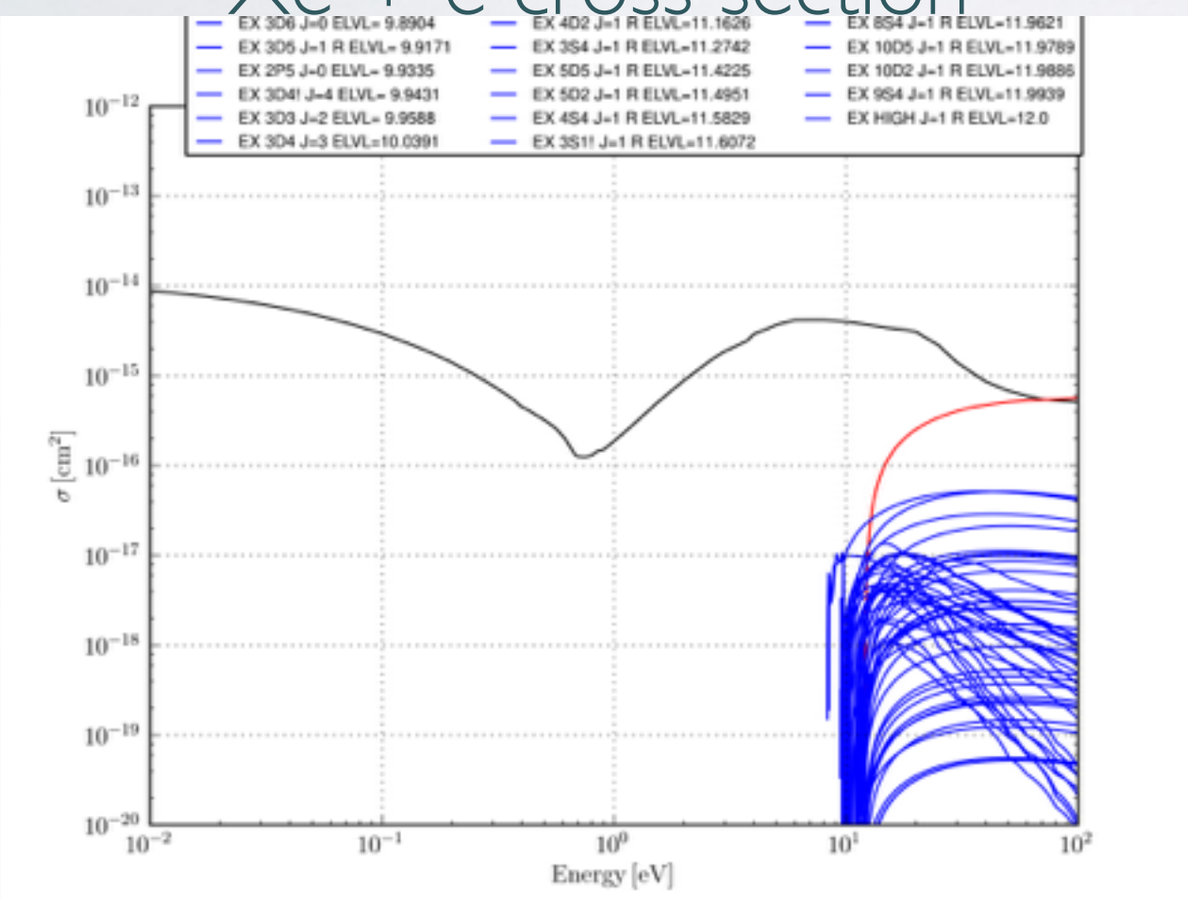
$N(CH_3)_3$

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

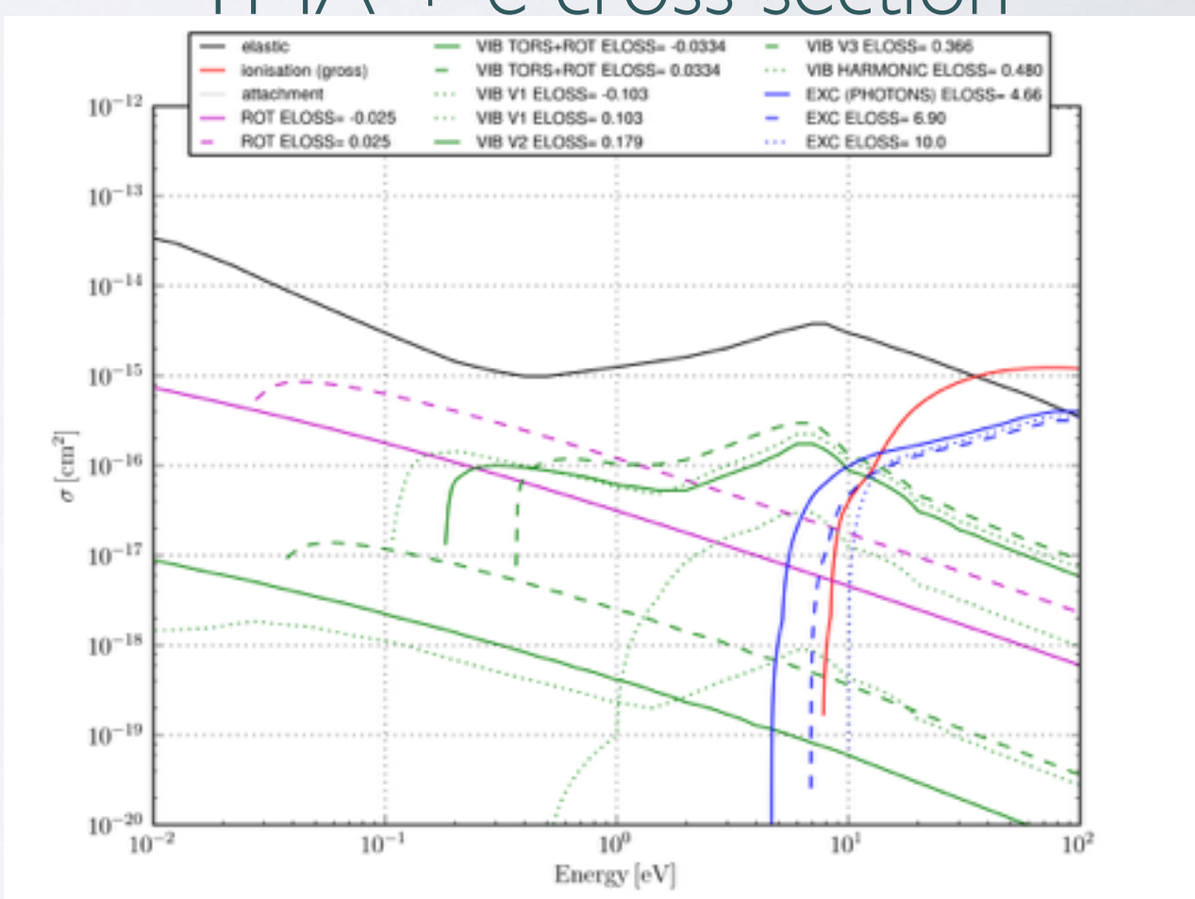
  Penning effect : $Xe^* + TMA \longrightarrow Xe + TMA^+ + e^-$

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

Xe + e cross section



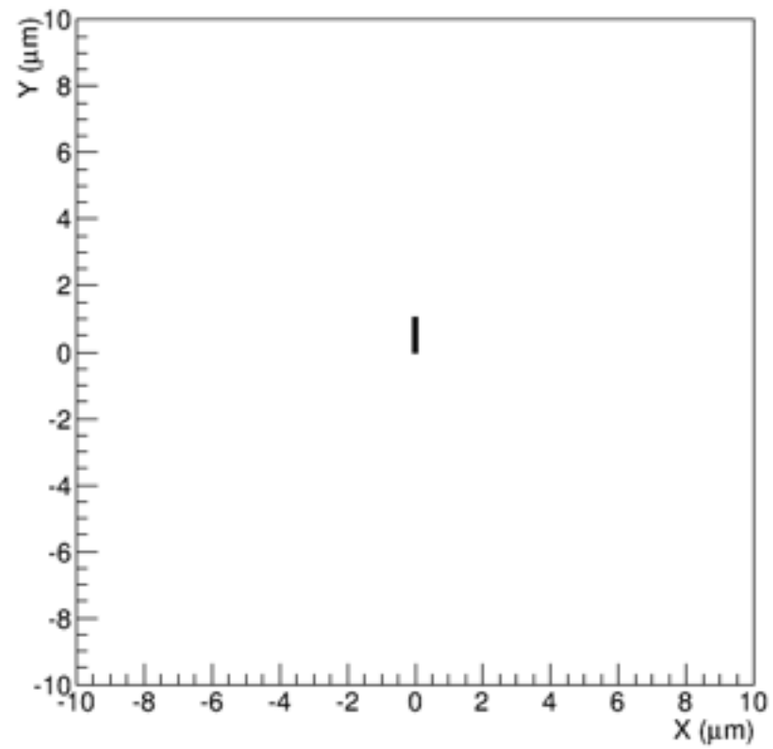
TMA + e cross section

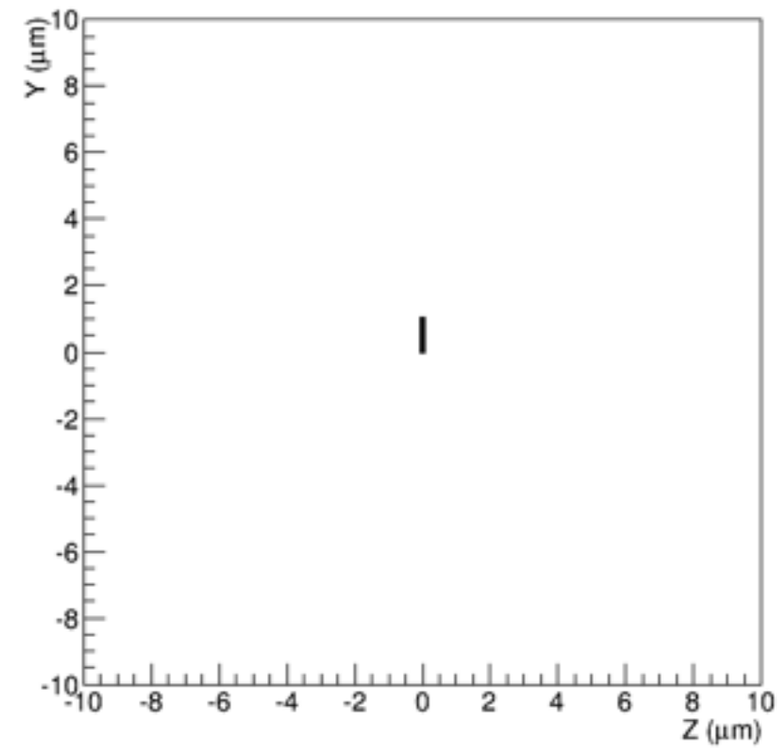


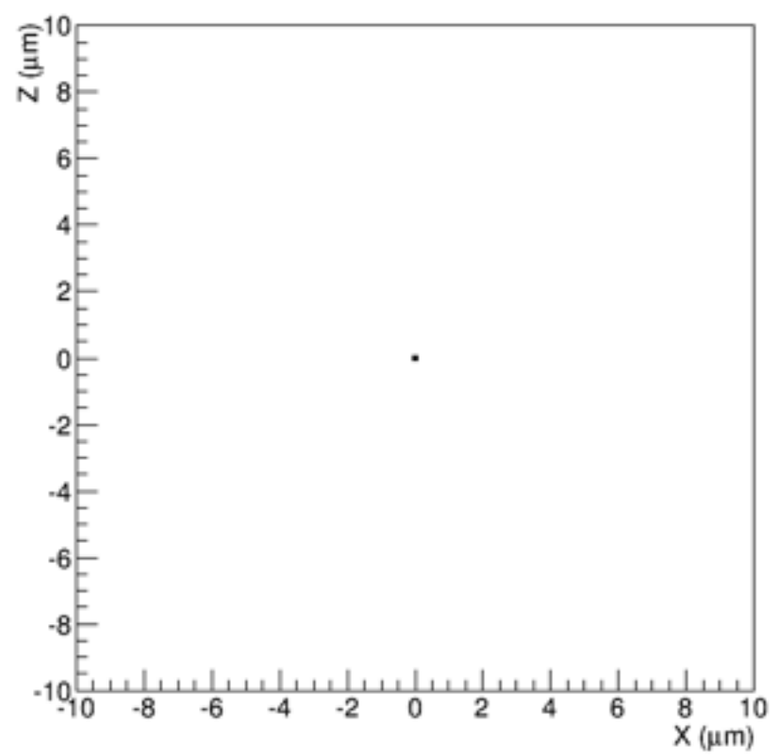
Recombination simulation

- Multi-body simulation of election-ion transport, based on **Garfield++**
- TMA is introduced as a "coolant" (Penning effect and Charge exchange are not simulated at this moment)
- Electrons "recombine" if the distance to an ion is within a de Broglie wave length.

Code primarily developed by Megan Long (Former UC Berkeley student) and Azriel Goldschmidt

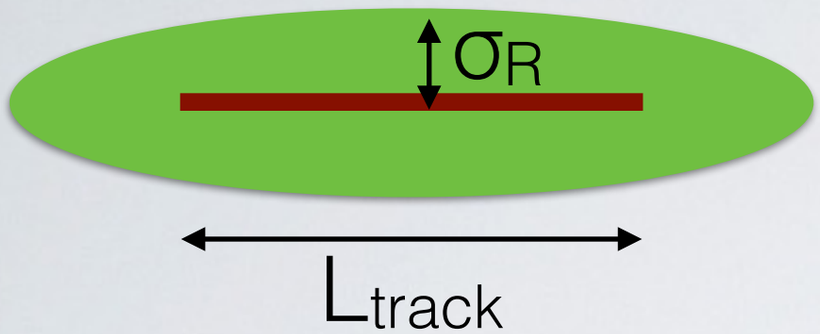






- 10 bar
- 10%TMA+90%Xe gas mixture
- Electric field along the Y-axis, 1000V/cm
- Simulate transport of 100 ion and electron pairs
- Movie of the first 1 nsec

Simulation results



σ_R: standard deviation of the distance from the track

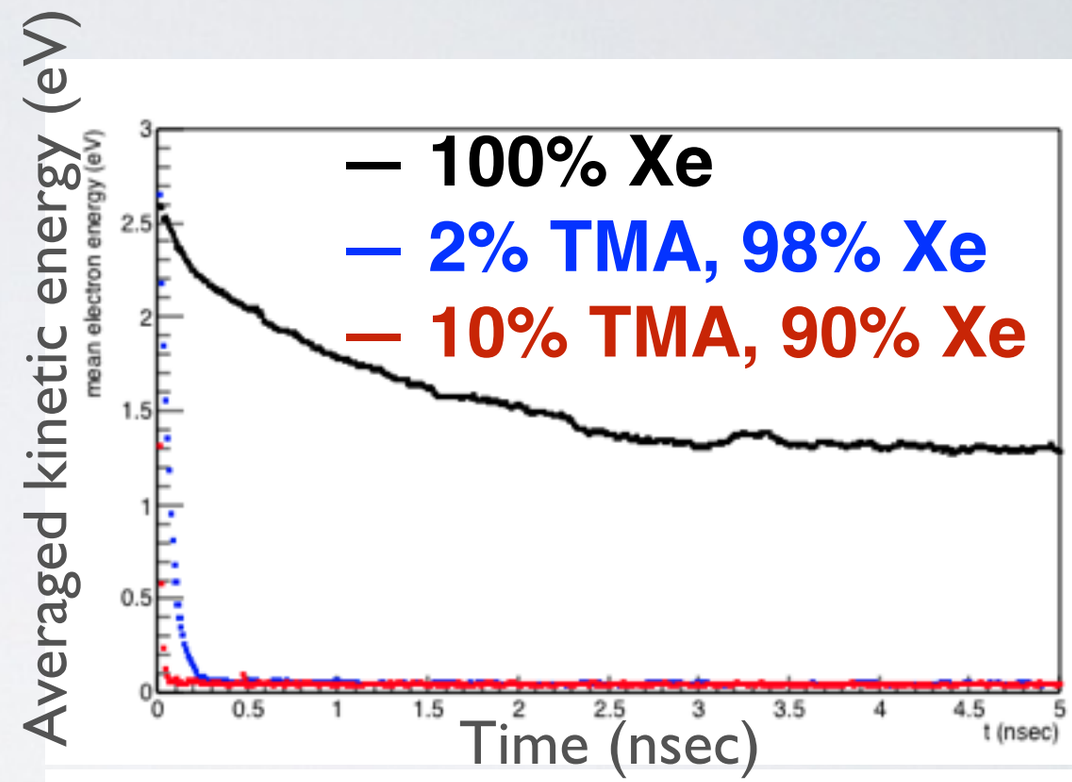
- Need to keep $\sigma R < L_{track}$ in order to retain directionality.

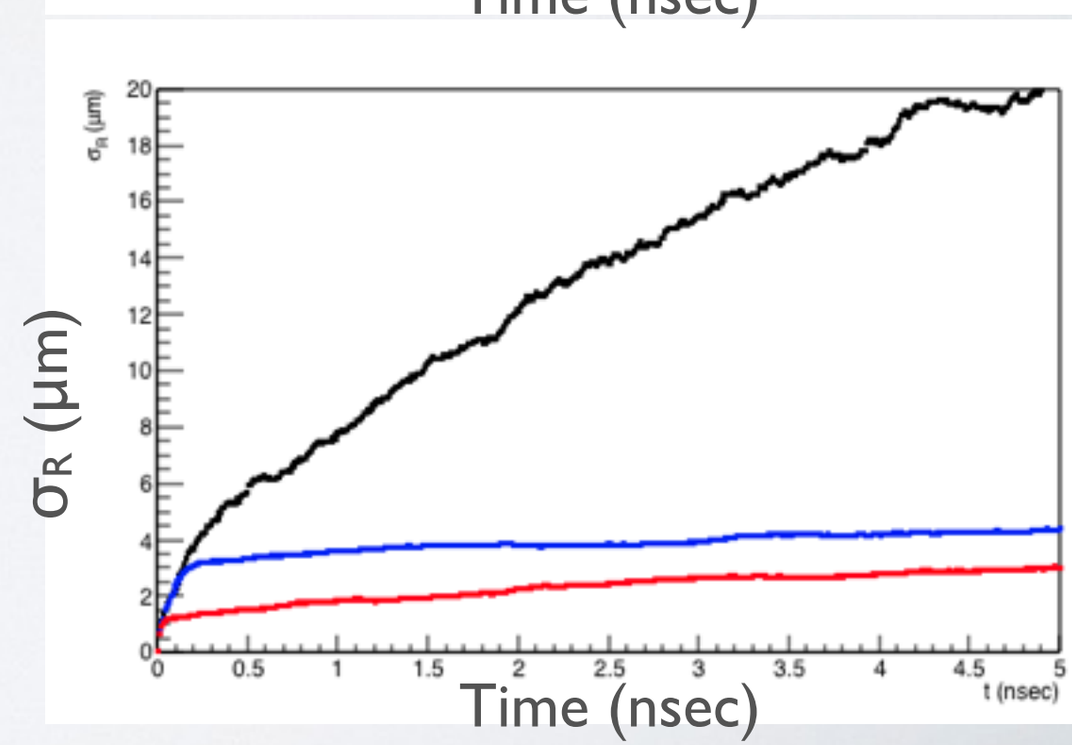
- Ions and electrons from an 1-μm track overlap for O(nsec) at typical drift velocity of 1 μm/nsec.

- TMA quickly thermalize electrons and keep them within a few μm

Can be sensitive for tracks longer than a few μm

Simulation at 10 bar, 1000 V/cm

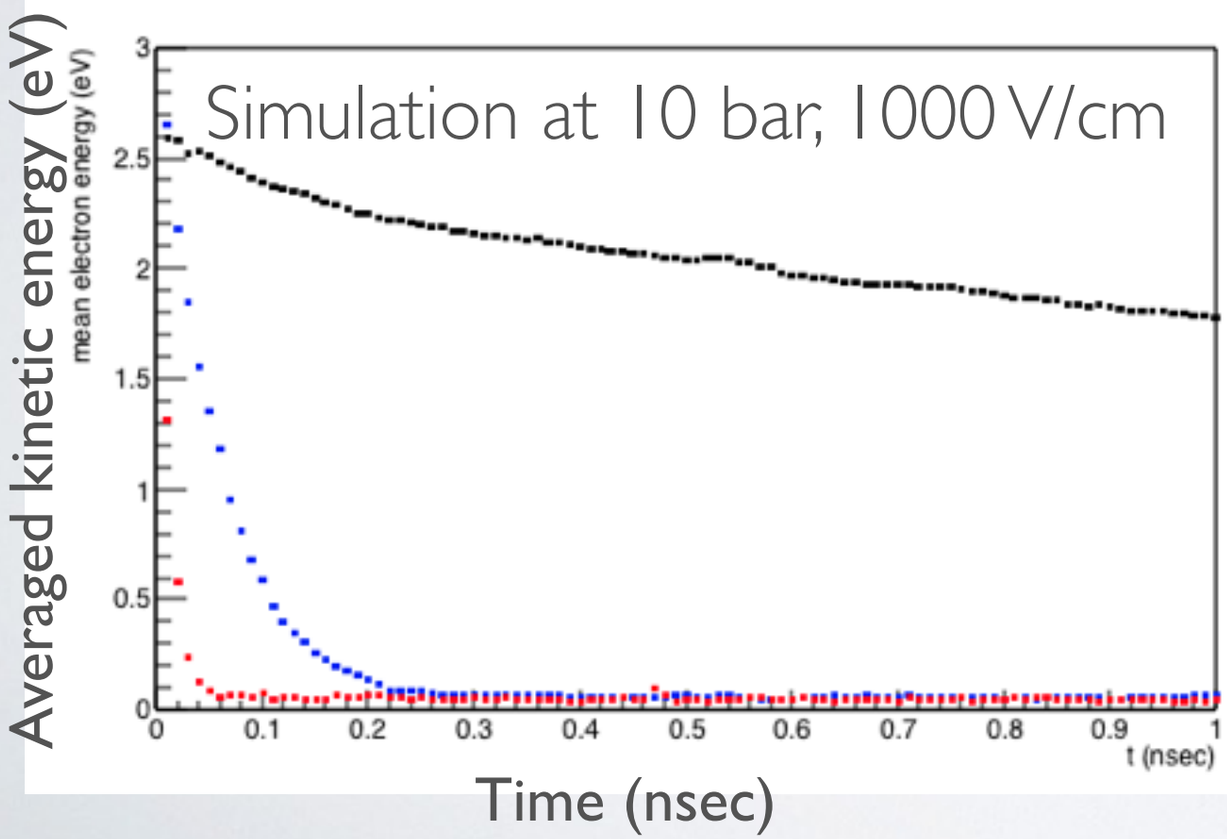


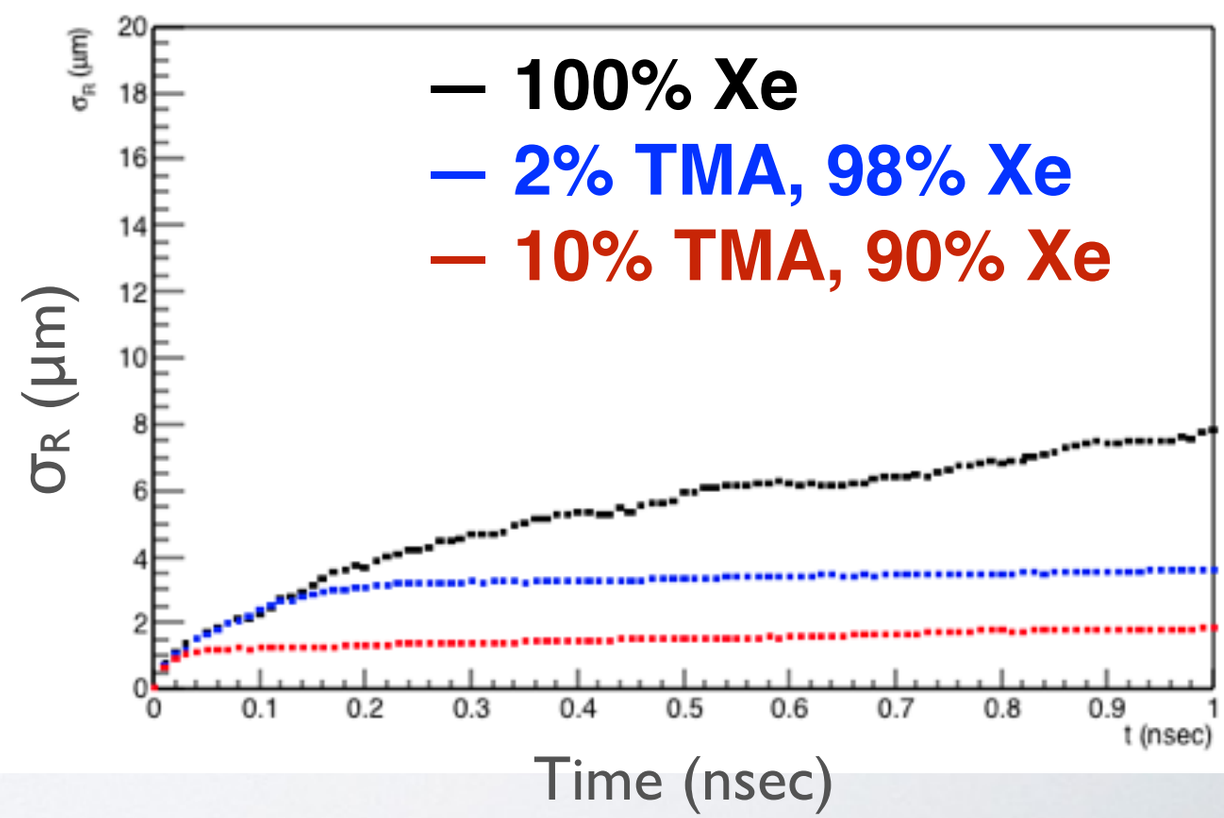


What determines the size of electron cloud?

- Initial explosion of electrons
  - 1 eV electron moves at v/c ~ 10^{-3}
  - Quickly grows the size of electron cloud to O(μm) in 10-100 psec

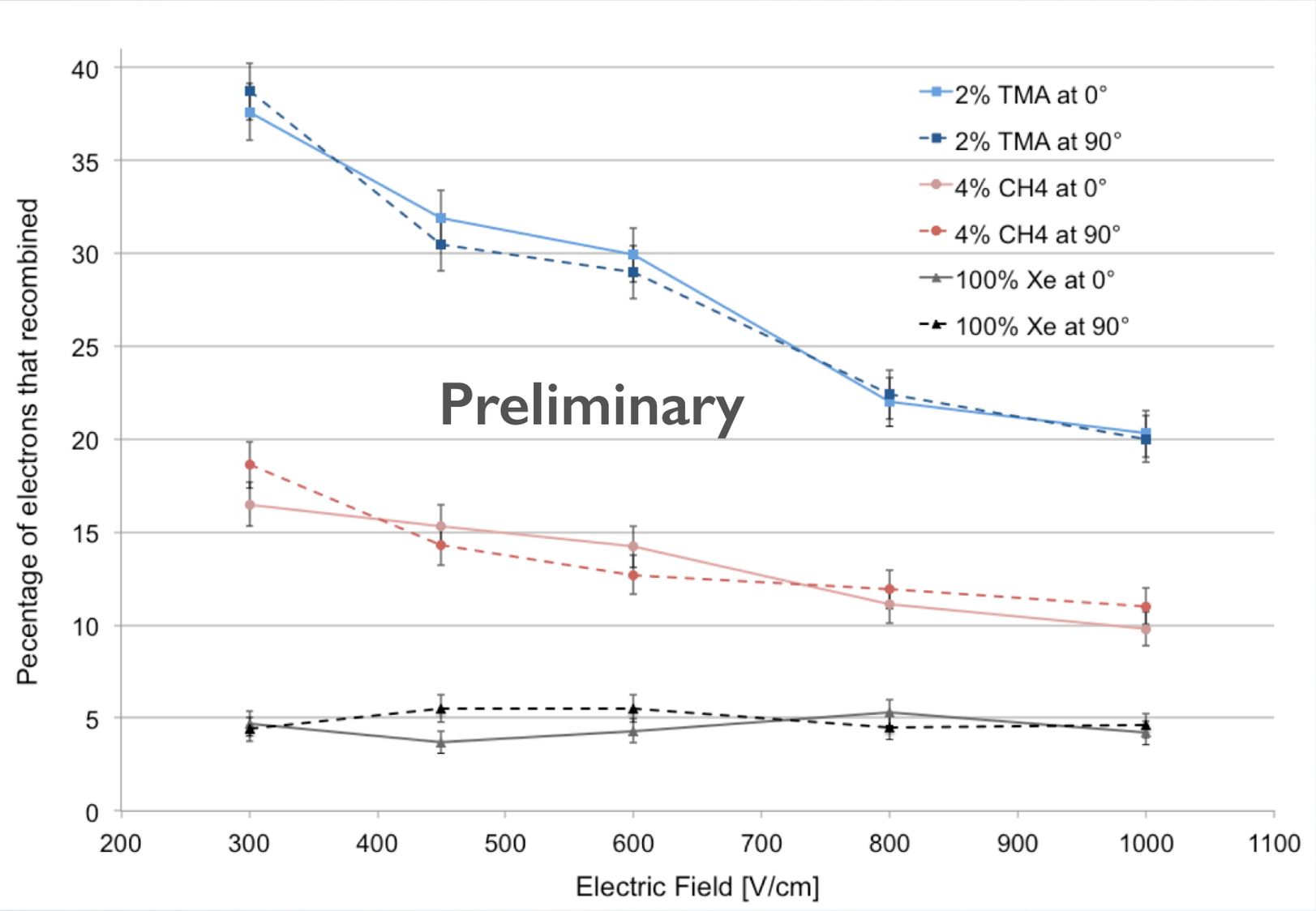
Higher TMA concentration helps quicker cooling and makes σ_R smaller





Would also be applicable for other directional dark-matter searches?

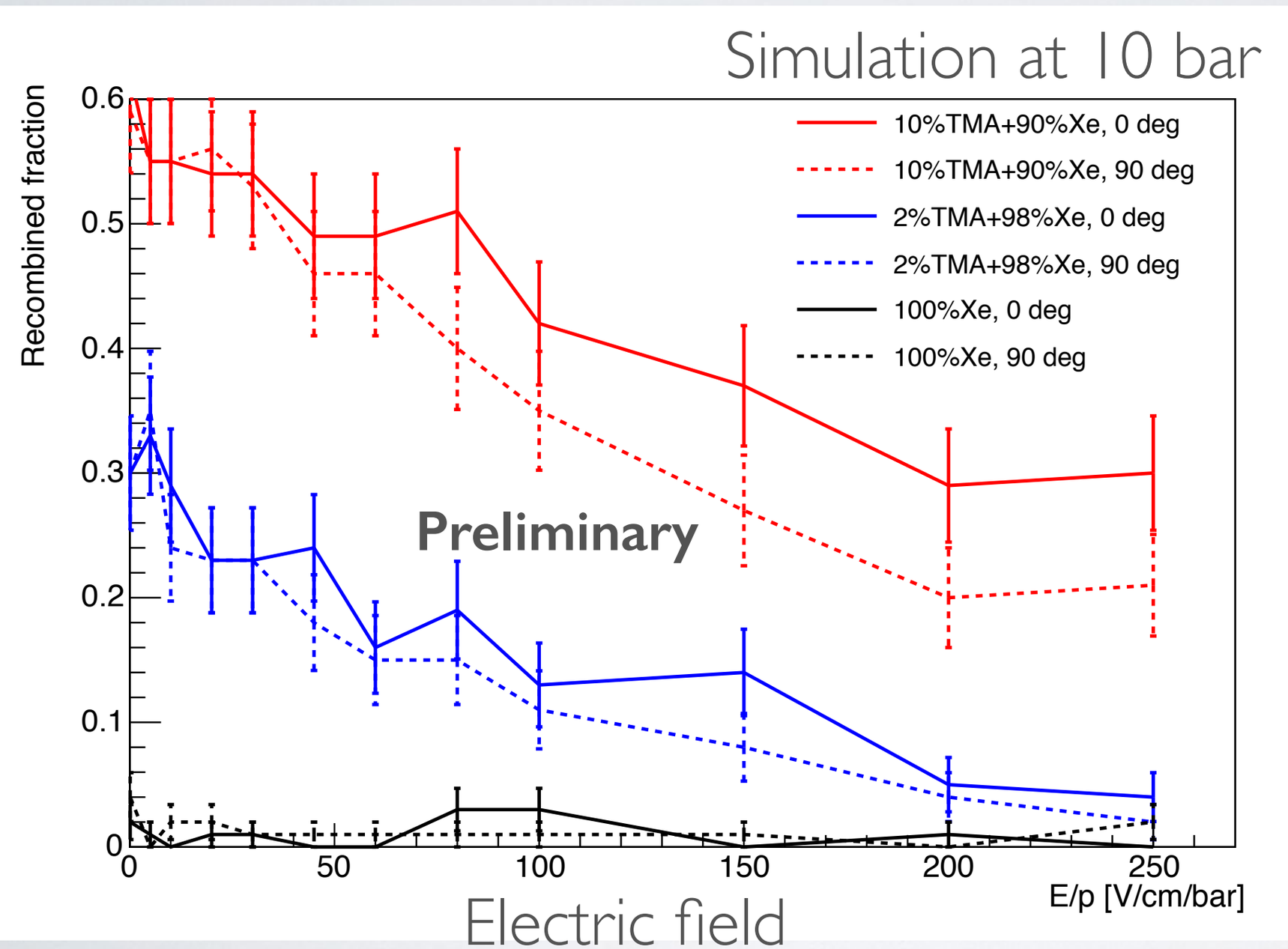
Directional sensitivity (1)



Megan Long

- Simulation of 100 electron-ion pairs from a 1 μm track. (density of α particles)
- Electrons and ions are uniformly distributed along a straight line.
- Big enhancement of recombination with TMA, but no sign of directionality at this condition.

Directional sensitivity (2)



- Stretched the track from 1 μm to 4μm

10% TMA: $\sigma_R \sim 2$ μm

2% TMA: $\sigma_R \sim 4$ μm

- Simulation predicts difference of recombination probability!

Still long way ahead…

- Need to implement realistic ionization density
  - Currently, uniform distribution on a straight line
- Need to evaluate sensitivity, including detection efficiency of recombination light (S1), and it's statistical fluctuation.
- Strong penning effect is necessary to maximize the sensitivity
  - What is the Penning transfer efficiency for TMA?
- Is 10% TMA concentration realistic? (Probably not)
  - TMA is known to have self-quenching, UV-light absorption, etc.
  - TMA is toxic

Summary

- Exploring a novel method of detecting short nuclear recoils utilizing columnar recombination
- With sufficient gas additives to cool the ionized electrons, recombination probability would change for a track longer than a few μm in high-pressure Xe gas.
- Many more study with more realistic assumptions are needed to evaluate directional sensitivity.
- Any inputs are welcome!