Single photo-electron background in LArTPC

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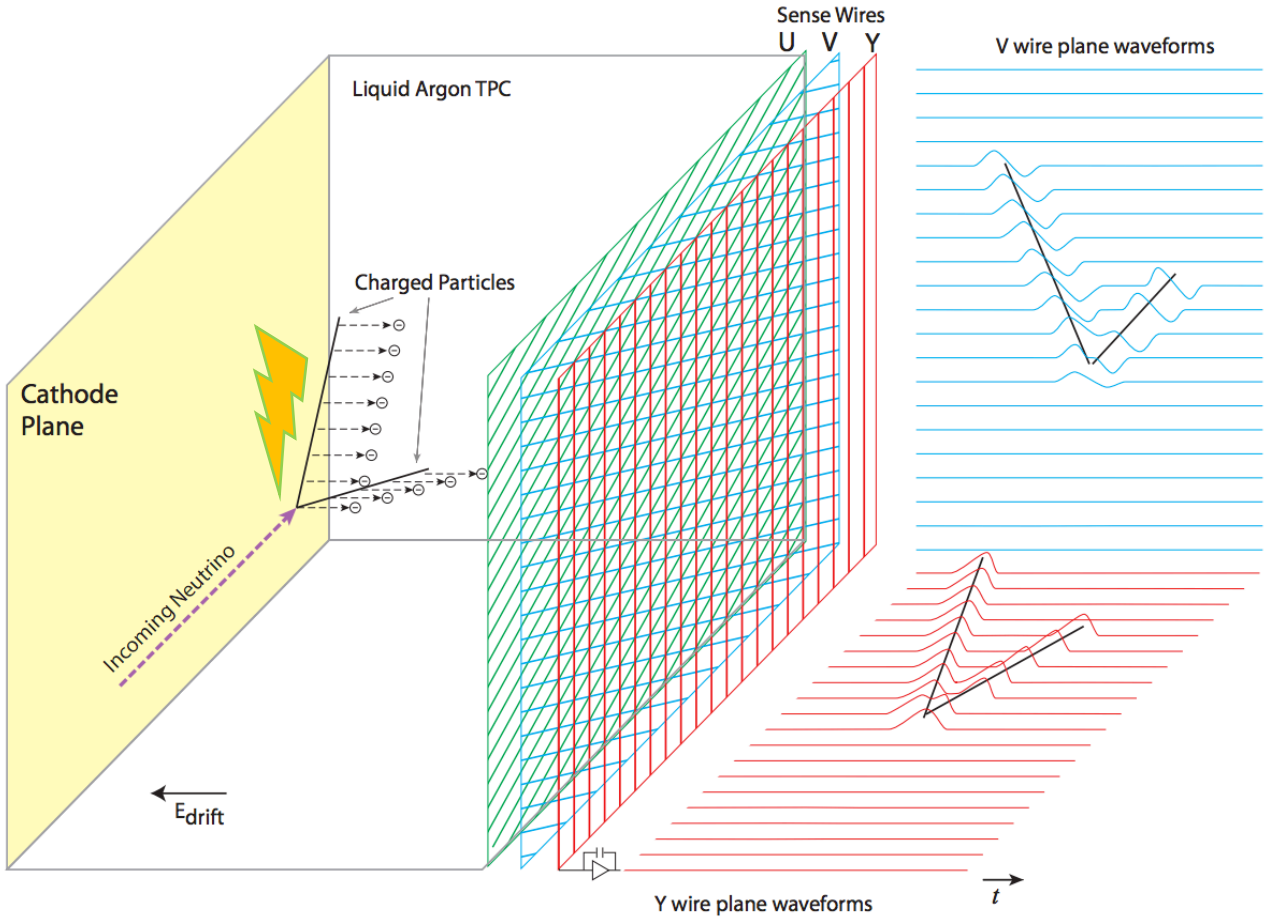
LArTPC ν experiments use light to trigger

LArTPC signals:

- Slow (~ms): Ionization charges collected at the anode.
- Fast (ns-us): Ar Scintillation light collected by light sensors (PMT).

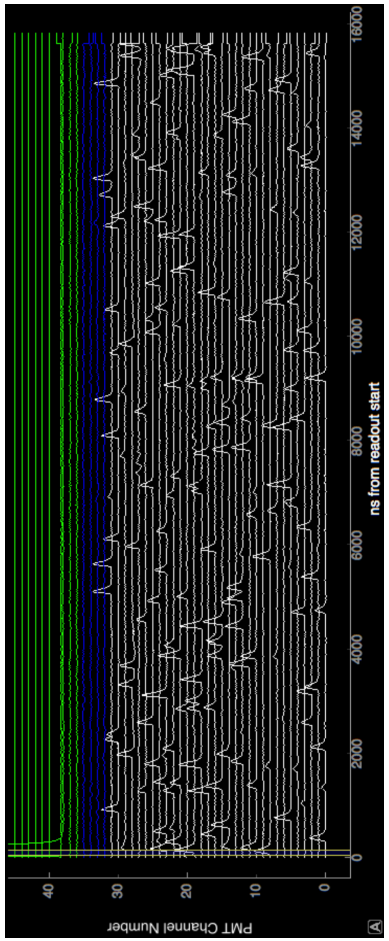
Fast light is often used to:

- define T0
- Improve calorimetry and PID
- **Trigger** (e.g. only ~0.2% beam spills in MicroBooNE have ν interactions)

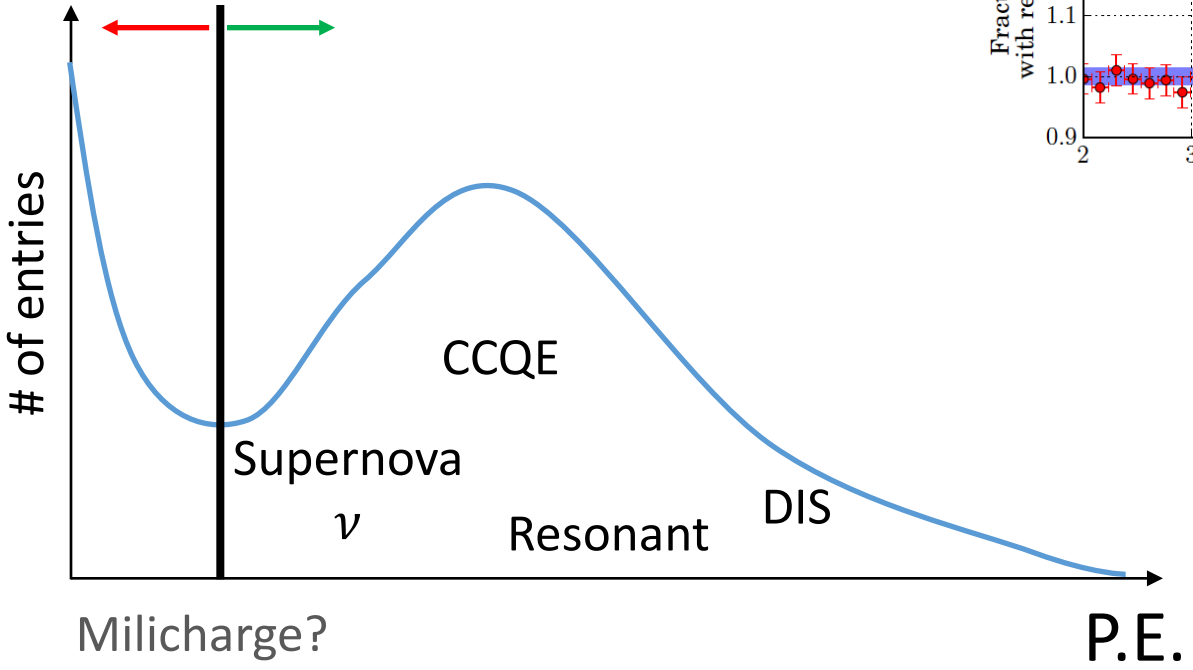


Light trigger

Background



Signals

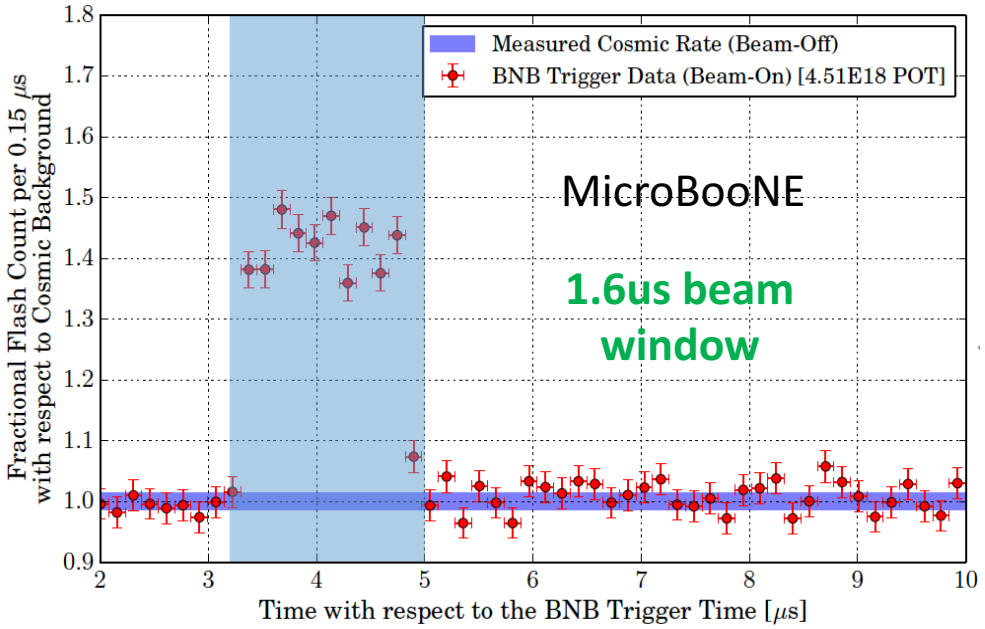


Milicharge?

Exotic dark matter models?

Solar neutrinos?

....



Want capable light detectors to provide:

1. Smaller background signal size -> lower threshold
2. Lower background rates-> lower contamination.

Good light triggers need

1. Smaller background signal size
-> lower threshold, more physics

2. Lower background rates->
high signal efficiency/purity

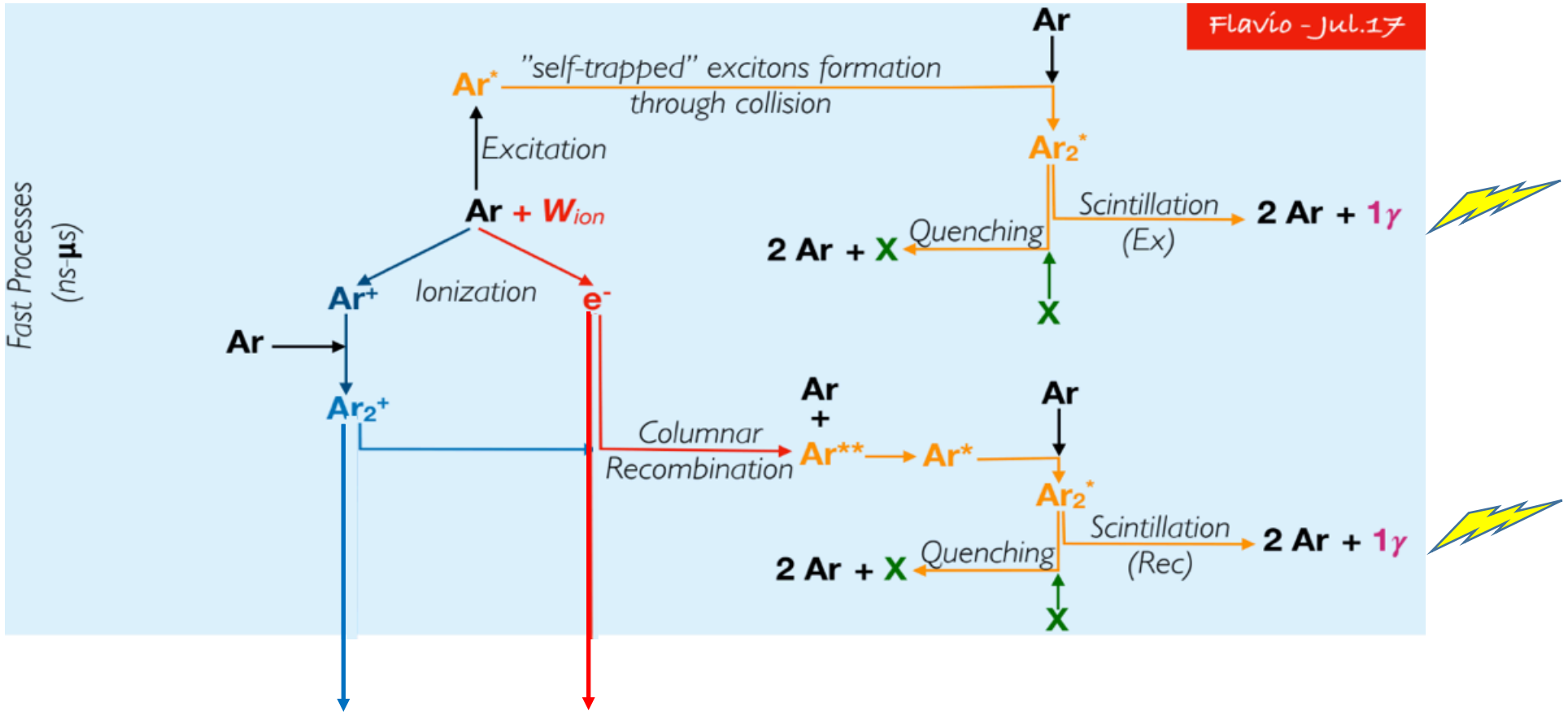
Focus on single PE (SPE) constant background:

- What mechanism could cause it?
  A model is proposed
- How to reduce its rate?
  Rate dependence on various detector parameters.
- What's the impact to low energy physics sensitivity?
  A ~1MeV physics example

Typical event display for surface LArTPC

Ionization charges induced by cosmic rays

Fast process in LAr

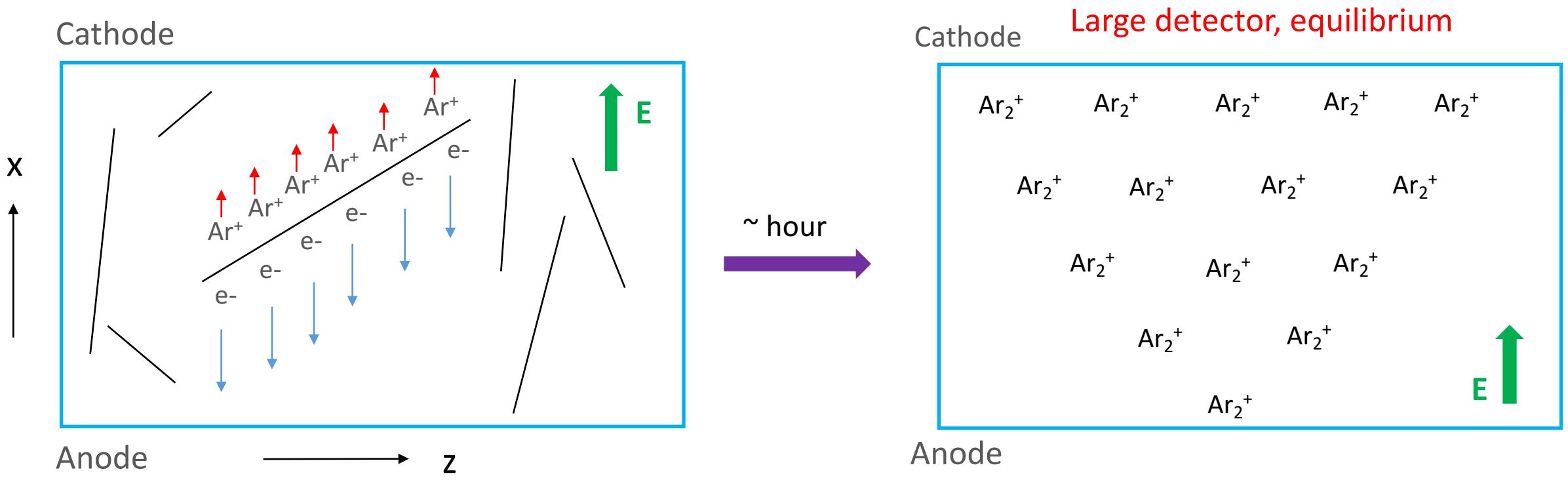


Ion+
to cathode

e-
to Anode

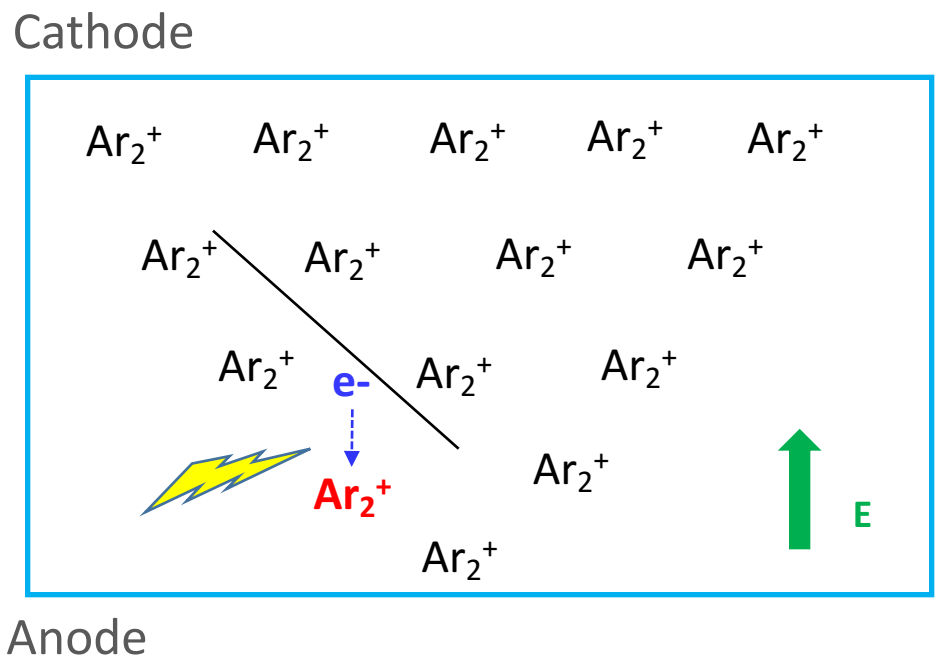
Well understood processes

The story starts with ions (space charge)...



- Ionization source (surface LArTPC): Cosmic rays ionize the argon and create e^-/ Ar^+ pairs along their trajectories.
- e^- drifts 100,000 faster than Ar_2^+. (e.g. It takes **20 mins** for Ar_2^+ drift from anode to cathode in MicroBooNE!)
- At equilibrium Ar_2^+ is roughly linearly distributed in X with maximum density at cathode.

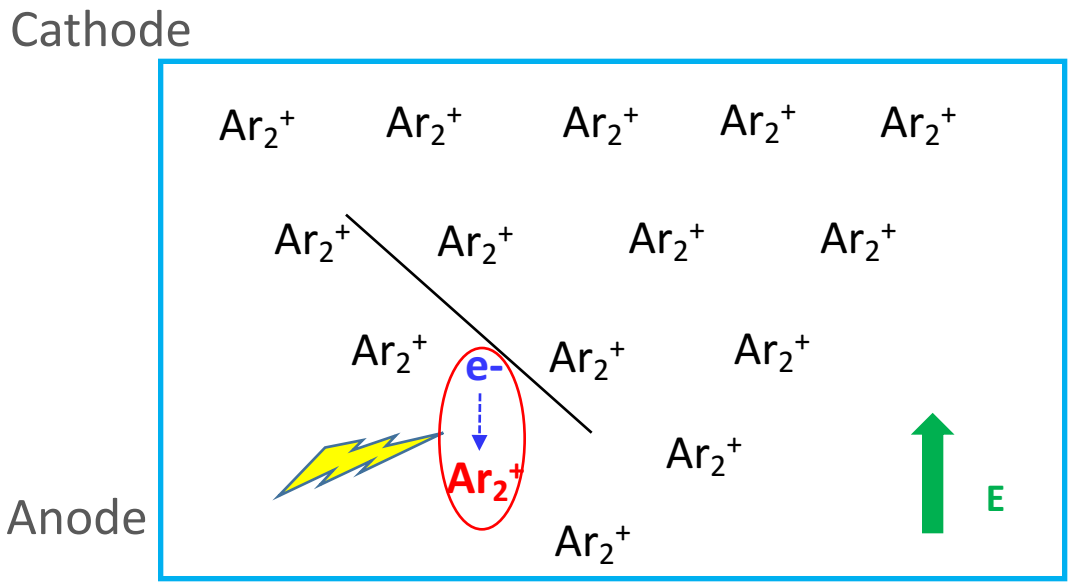
Photon production

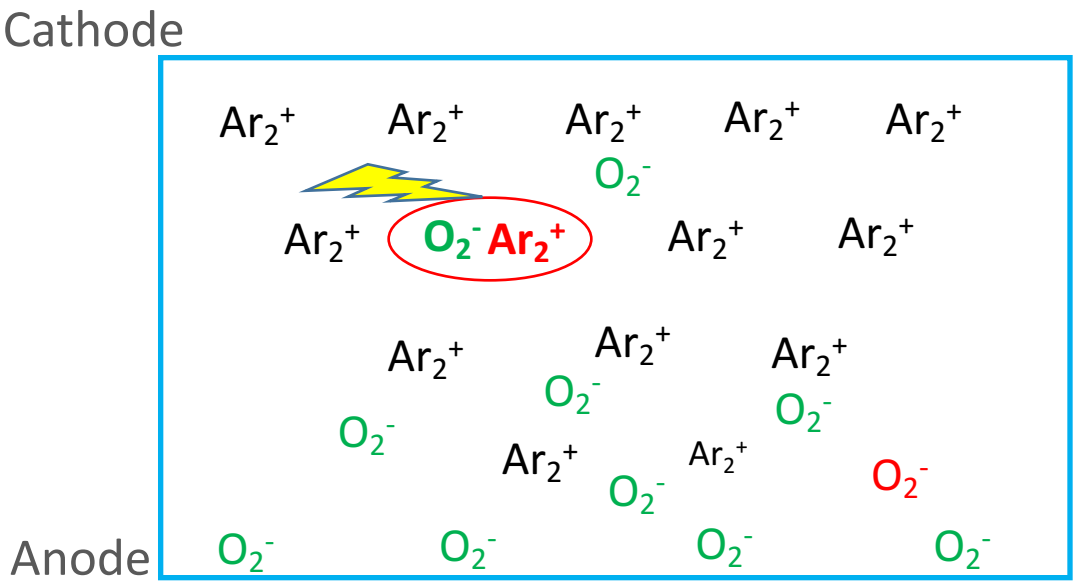


(1) Volume Recombination (VR)

$$Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$$

Photon production





(1) Volume Recombination (VR)

$$Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$$

Light from slow ions

Impurity (O_2, H_2O...) attachment:

$$e^- + O_2 \rightarrow O_2^-$$

(2) Mutual Neutralization (MN)

$$Ar_2^+ + O_2^- \rightarrow Ar_2^* + O_2 \rightarrow 2Ar + \gamma + O_2$$

LArTPC – lively ecosystem

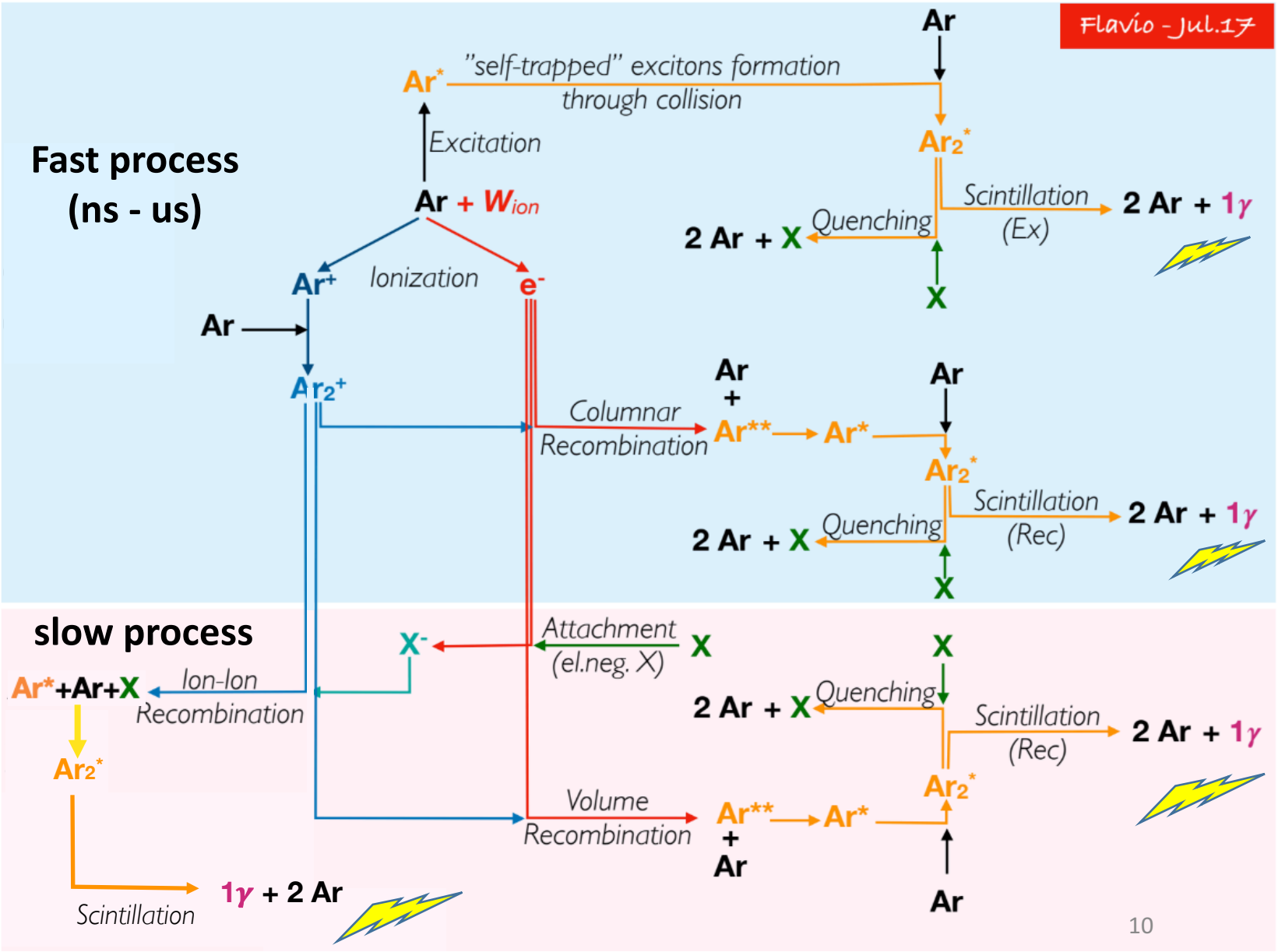
Differential Equations

Input parameters:

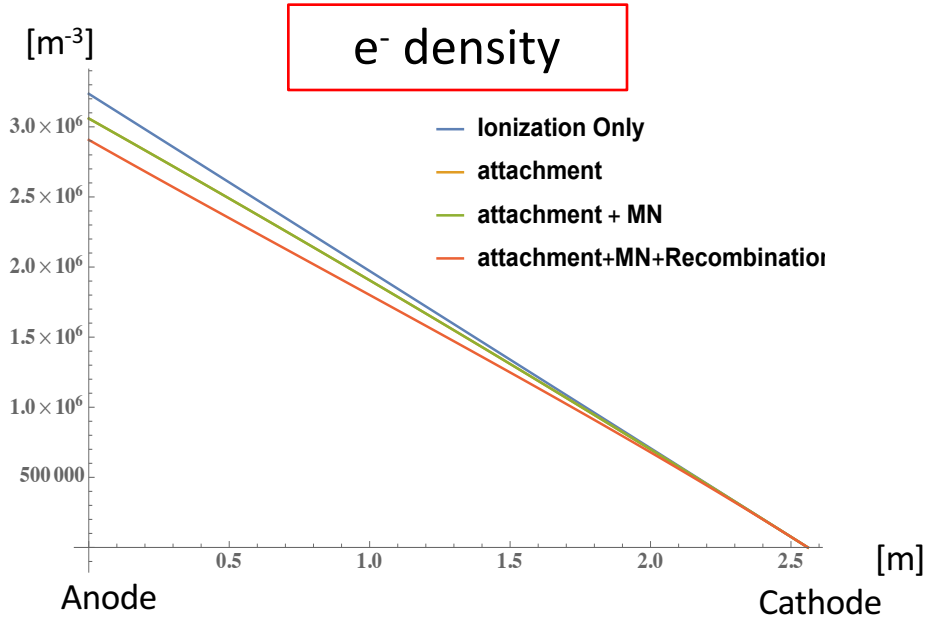
- Cosmic flux (provide ΔE)
- Rates of Volume Recombination.
- Rates of Mutual Neutralization.
- Impurity concentration.
- Drift distance
- E field: drift velocities.

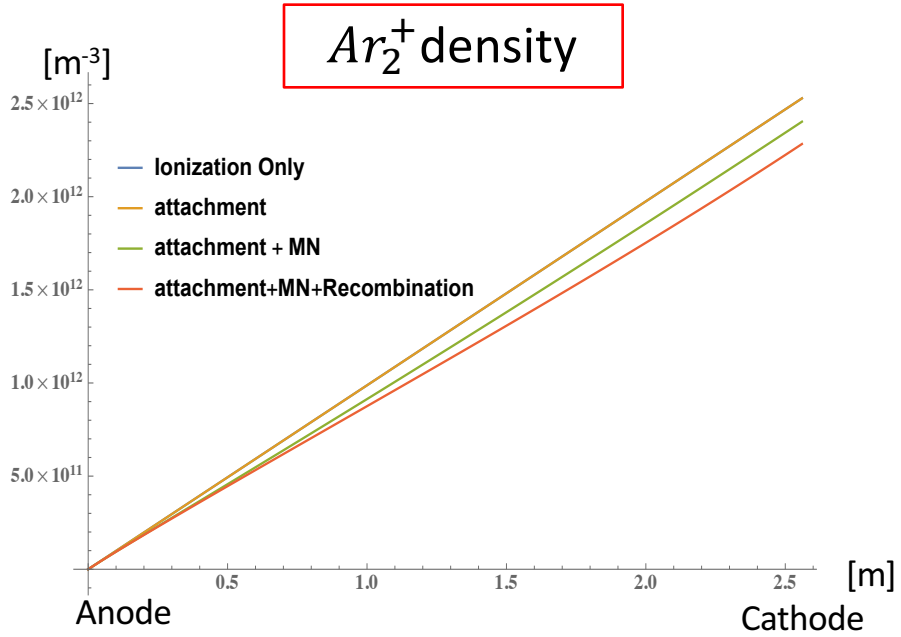
Solve:

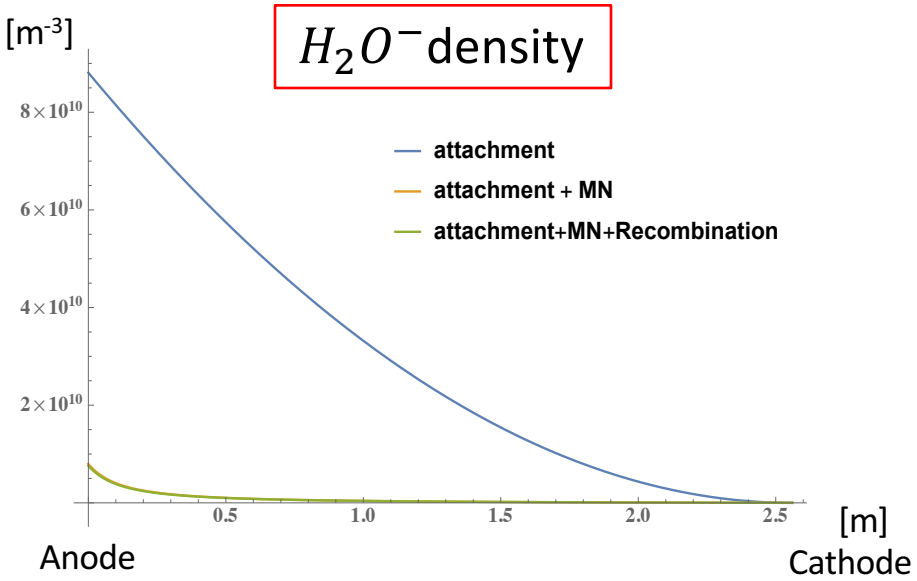
- Density distributions of ions
- Photon production rate

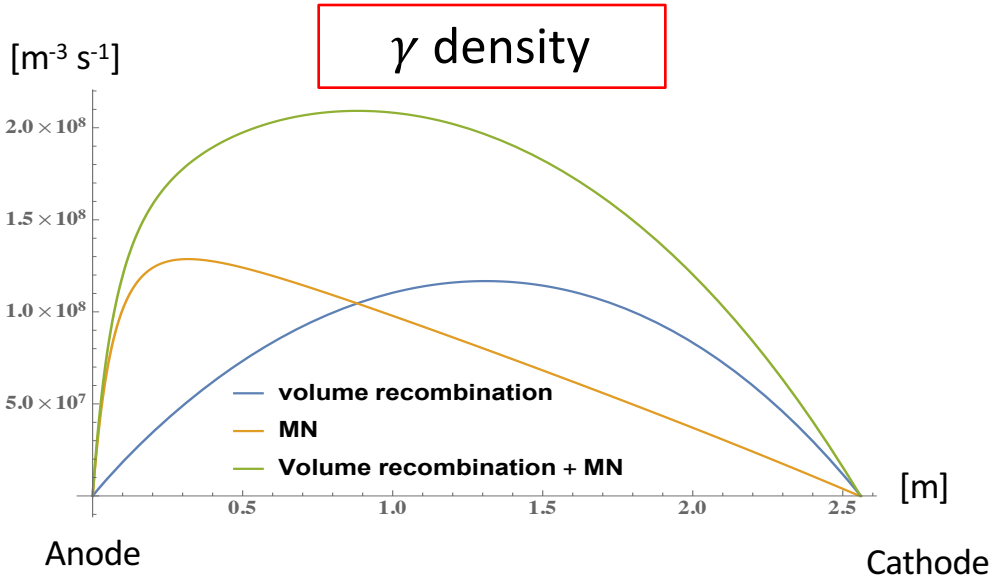


Solutions of differential eq. at equilibrium









What does the photon production rate depends on?

How to reduce this photon background?

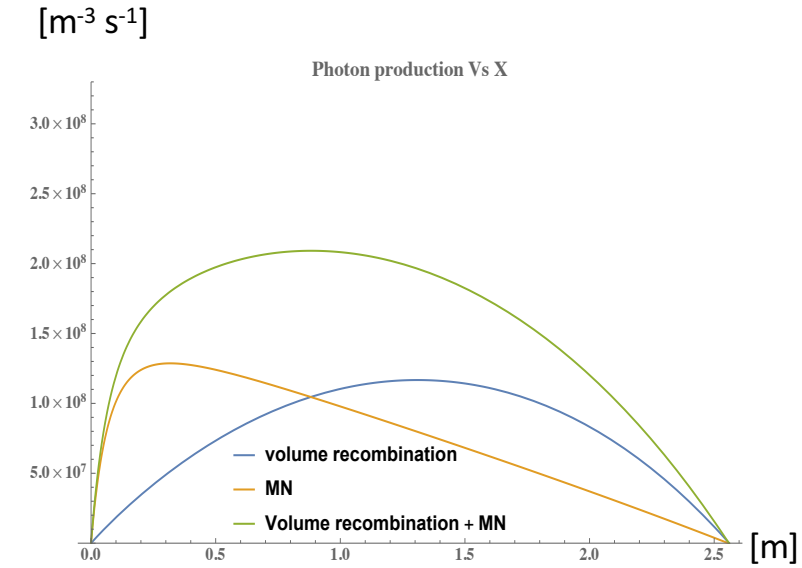
Ionization source (ΔE) dependence

- For surface LArTPC, cosmic ray is the primary source that originated this chain effect.
- To 0th order, the γ rate $\propto$ (cosmic flux)^{2}, need to go underground.
- 100m rock could suppress the cosmic flux by O(100).
- Ar39 is another ΔE source (1Bq/kg). ~1/100 of cosmic at surface, dominant ion producer underground.

Drift distance dependence

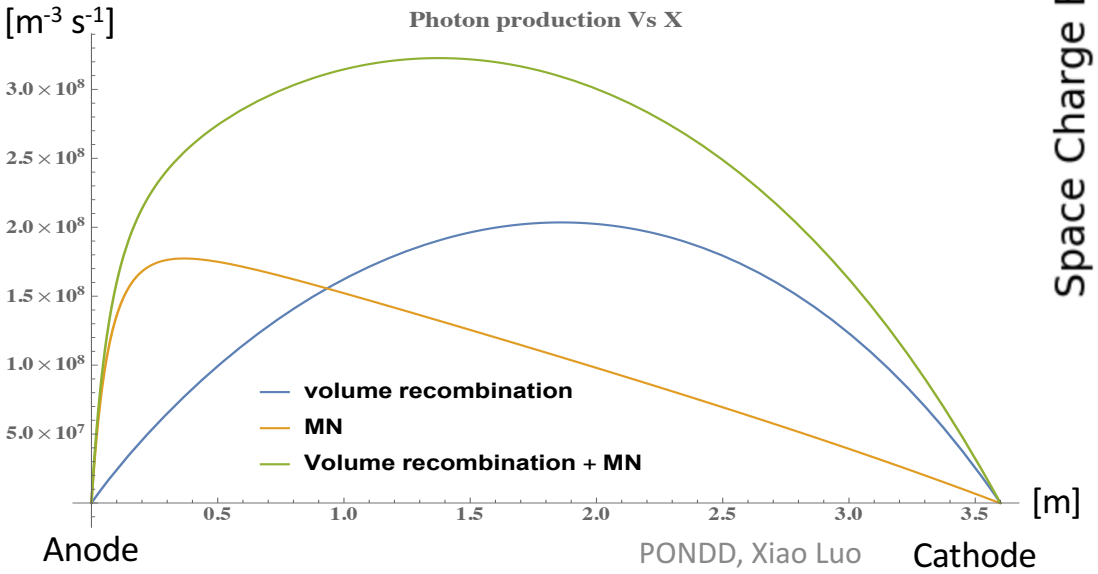
Drift distance ↑ , γ rate ↑

MicroBooNE
2.56m Drift

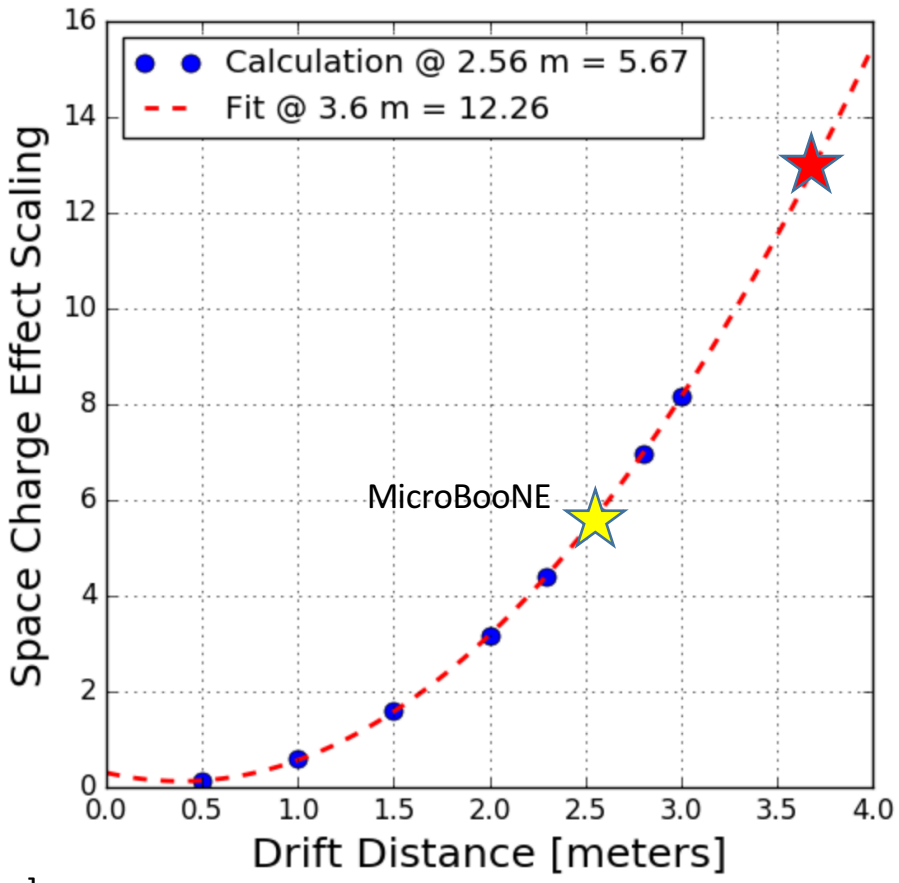


ProtoDUNE
3.6m Drift

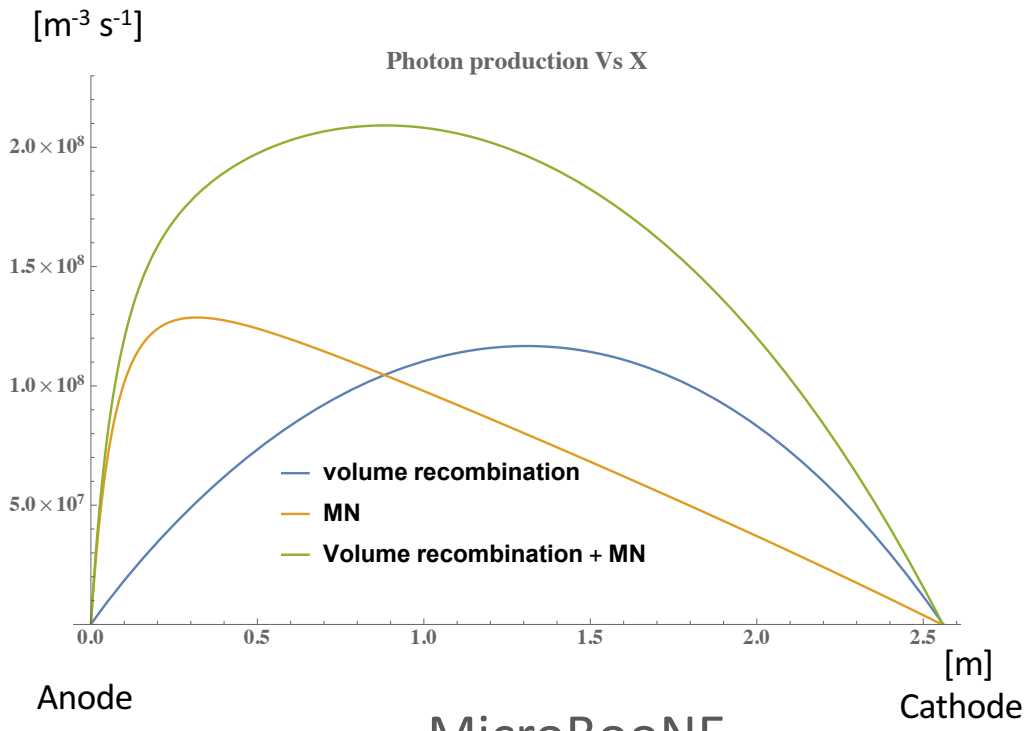
X 2.2 γ rate



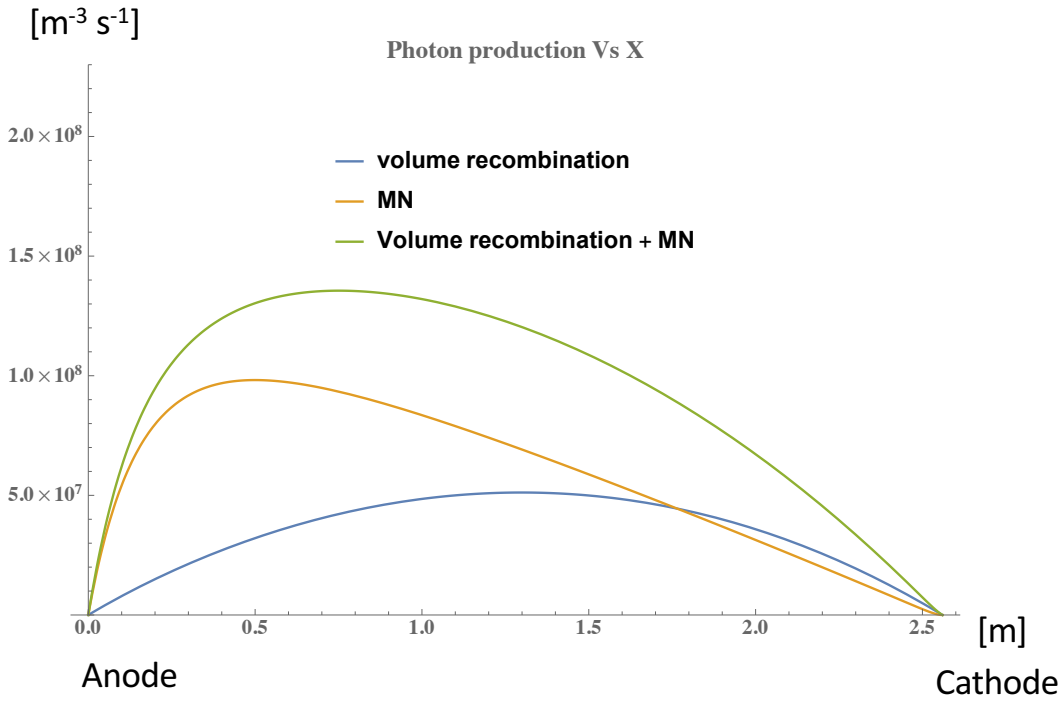
SPE rate scaling with TPC drift distance



E field dependence



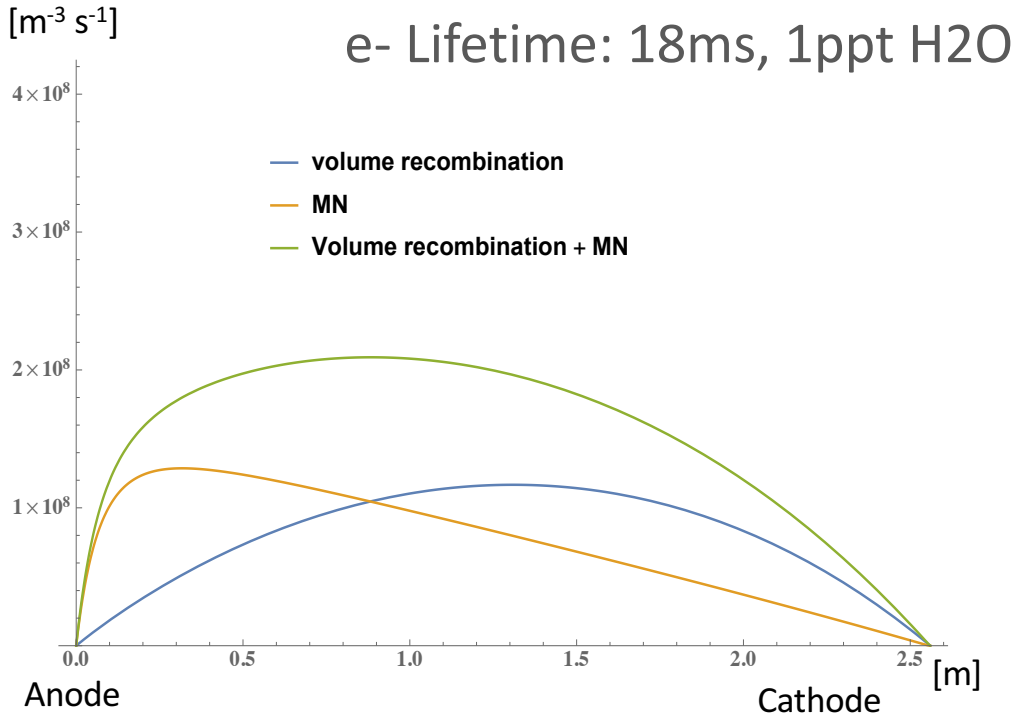
MicroBooNE
E field: 273 V/cm

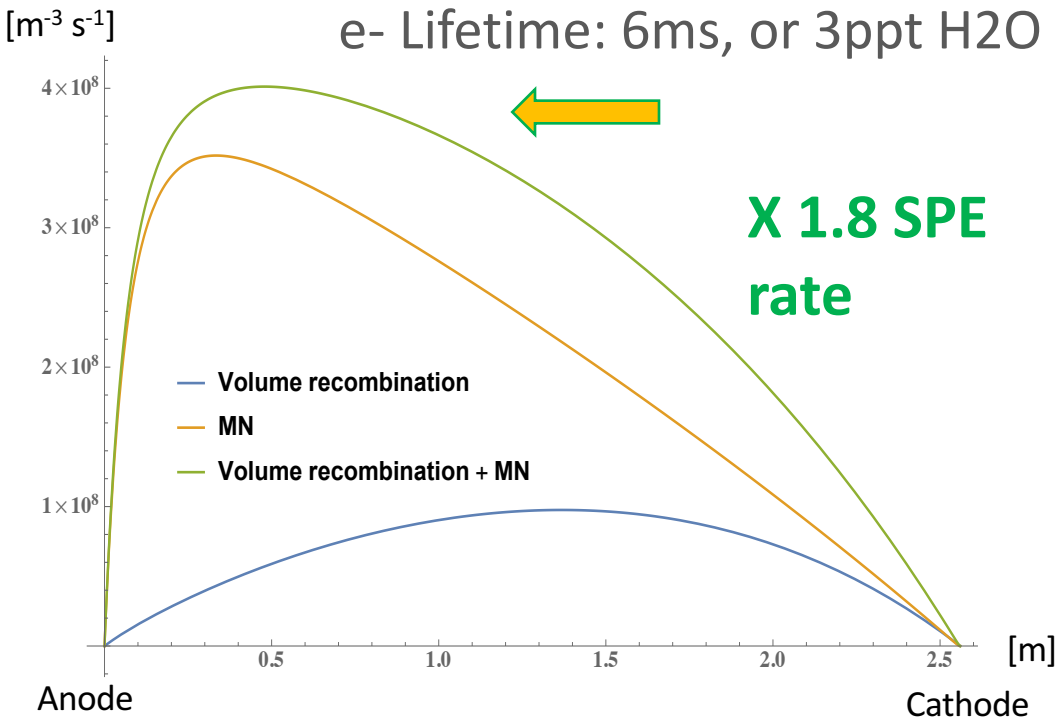


ProtoDUNE
E field: 500 V/cm

- Higher E field in protoDUNE leads to lower (**X 0.67** MicroBooNE) γ rate. E field ↑ SPE rate ↓
- Model is consistent with the experimental observation.

Impurity concentration dependence





- Impurity negative ion could potentially generate photons through Mutual Neutralization with positive Ar ion. Impurity concentration ↑, γ rate ↑
- However, impurity also absorb the light and quench the light detection.

Summary of the features of this light background

- Caused by slowly drifting ions. After equilibrium, appear as steady γ background.
- It's unclear if these γ have the same wavelength as "normal" Ar scintillation light (128nm).
- The rate of γ production depends on:
  - Source of the ionization (e.g. cosmic flux, Ar39). Want shielding.
  - TPC drift distance. Want shorter drift distance.
  - E field -> drift velocities of the electrons and ions. Want higher E field.
  - Impurity concentration. Complicated, need further study.
  - The rates of the γ production processes (very few references)
  - Varies in X (drift direction). This is another handle to experimentally test the model.

What’s the impact to low energy physics sensitivity?

A ~1MeV physics example

Let's be a bit quantitative

Detector specifics

Drift distance	E field	Cosmic induced ion pairs	Impurity
2.56m	273 V/cm	1.58×10^{9} $m^{-3}s^{-1}$	1ppt H_2O

Drift velocities

e- drfit velocity	Ar2+ drift velocity	H2O- drift velocity
1.25×10^{3} m/s	1.6×10^{-3} m/s	2.5×10^{-3} m/s

Rates

Impurity attachment	Volume Recombination	Mutual Neutralization
1.2×10^{-15} m^3/s	7×10^{-11} m^3/s *	2.8×10^{-13} m^3/s **

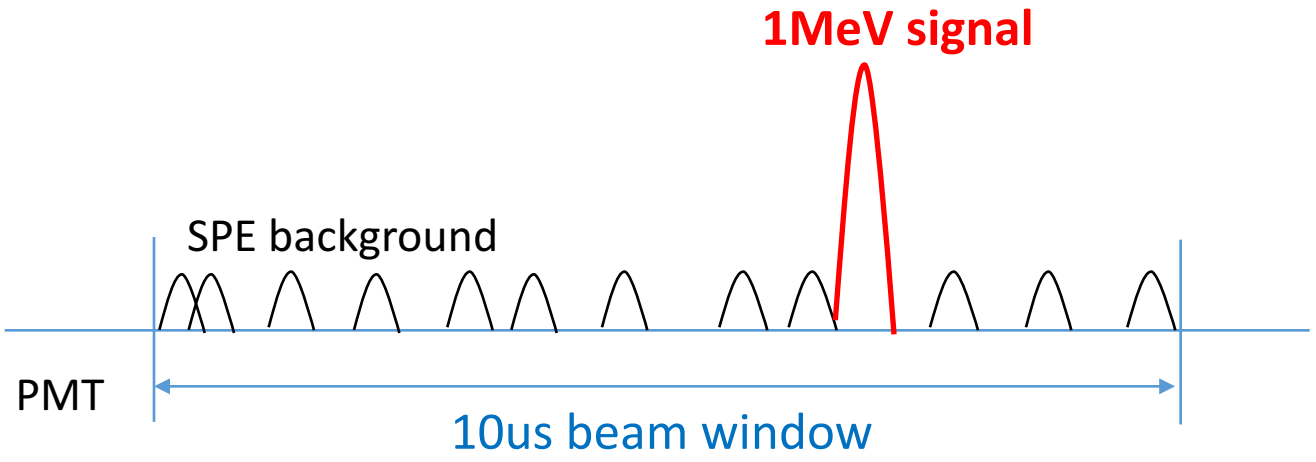
Background: γ production rate is **~ 1e10 Hz** in TPC volume.

Signal light yield: 1MeV ~40,000 γ

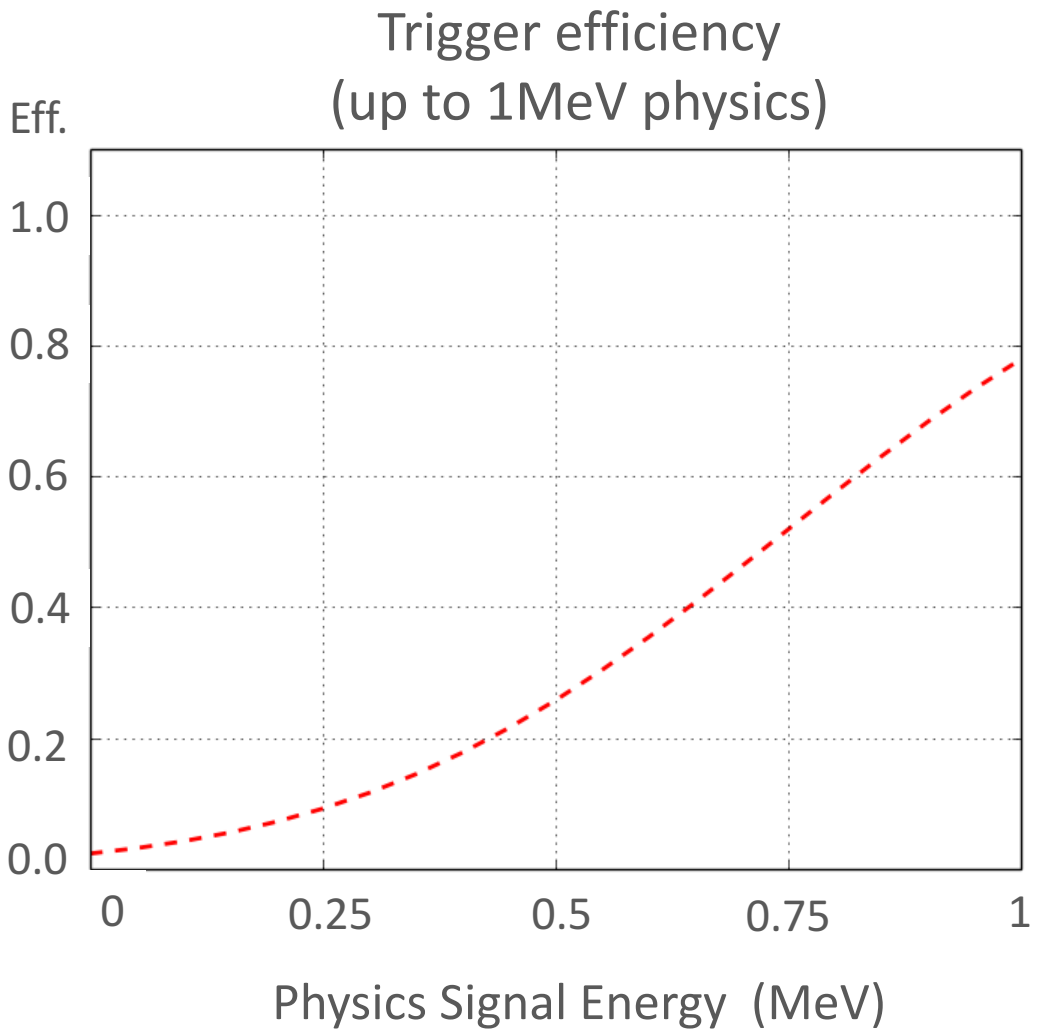
* Shinsaka et.al., J. Chem. Phys. **88**, 7529 (1988)

** Miller et.al. , The Journal of Chemical Physics 140, 044304 (2014); The Journal of Chemical Physics 136, 204306 (2012);

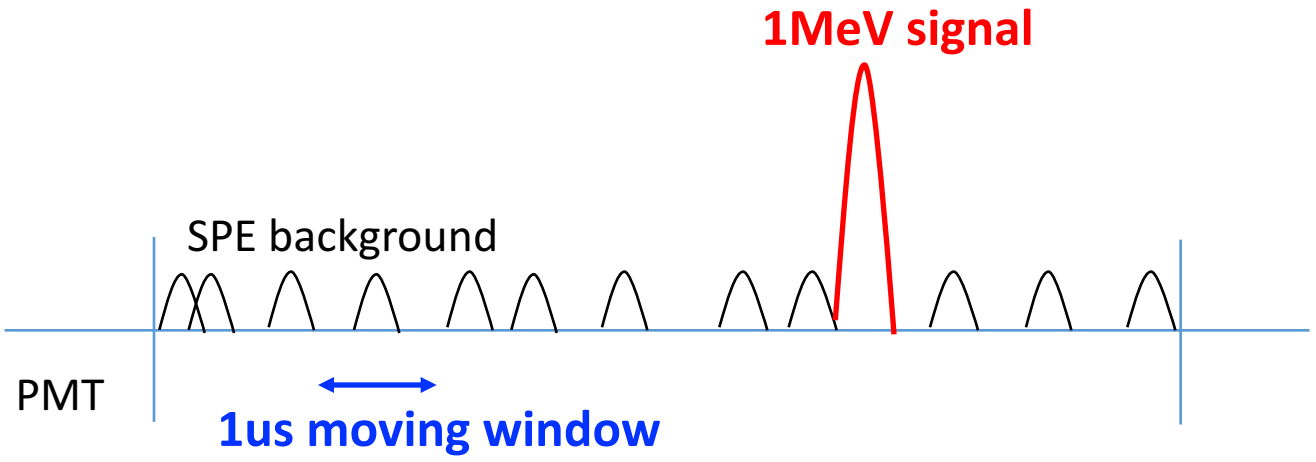
1MeV physics Case study – Baseline



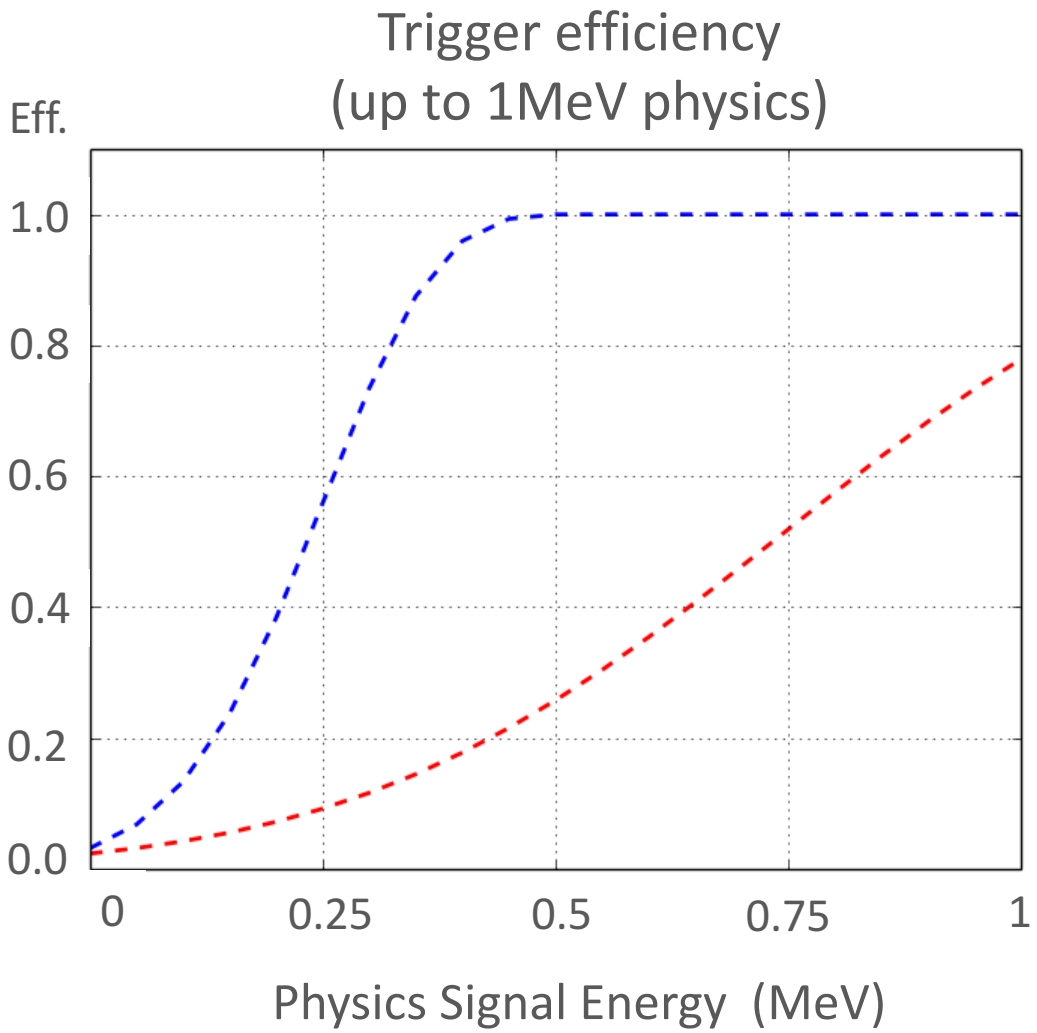
- **Bkg LY: 1e10Hz, Signal LY: 40,000 γ /MeV**
- Light detection efficiency ε = 0.0005
- Beam window is 10us.
- 1MeV Signal: Signal LY* ε = 20 PE detected.
- Steady SPE background: Poisson mean 50PE (Bkg LY * ε * 10us) in beam window.
- Dumb trigger: Set the threshold at 64PE (~3MeV) to remove 95% of background.



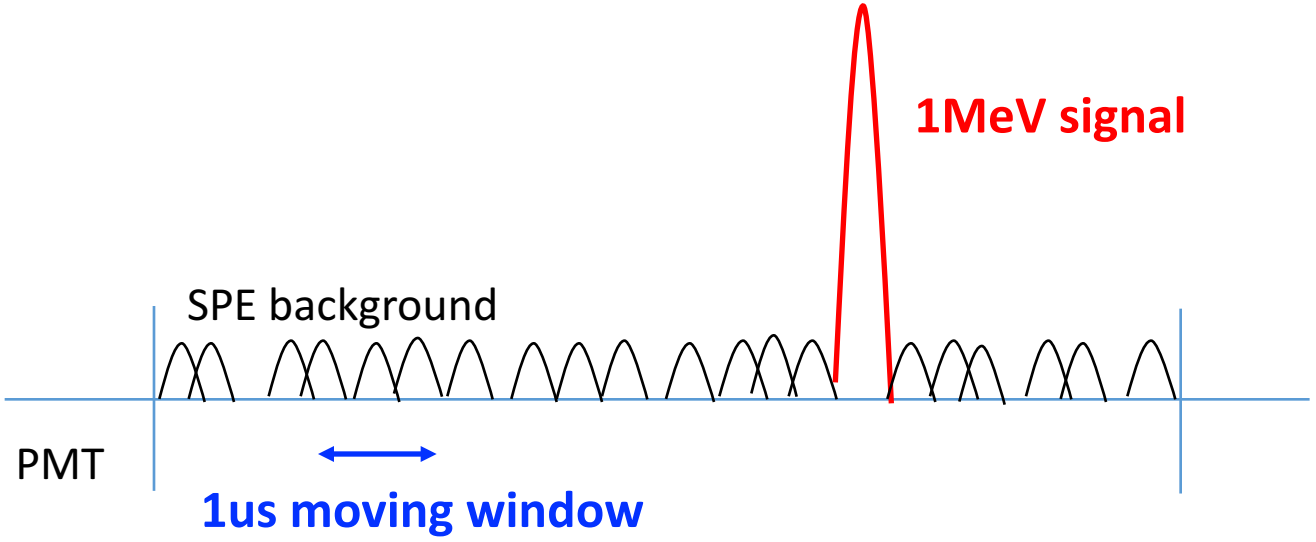
1MeV physics Case study – Smarter trigger



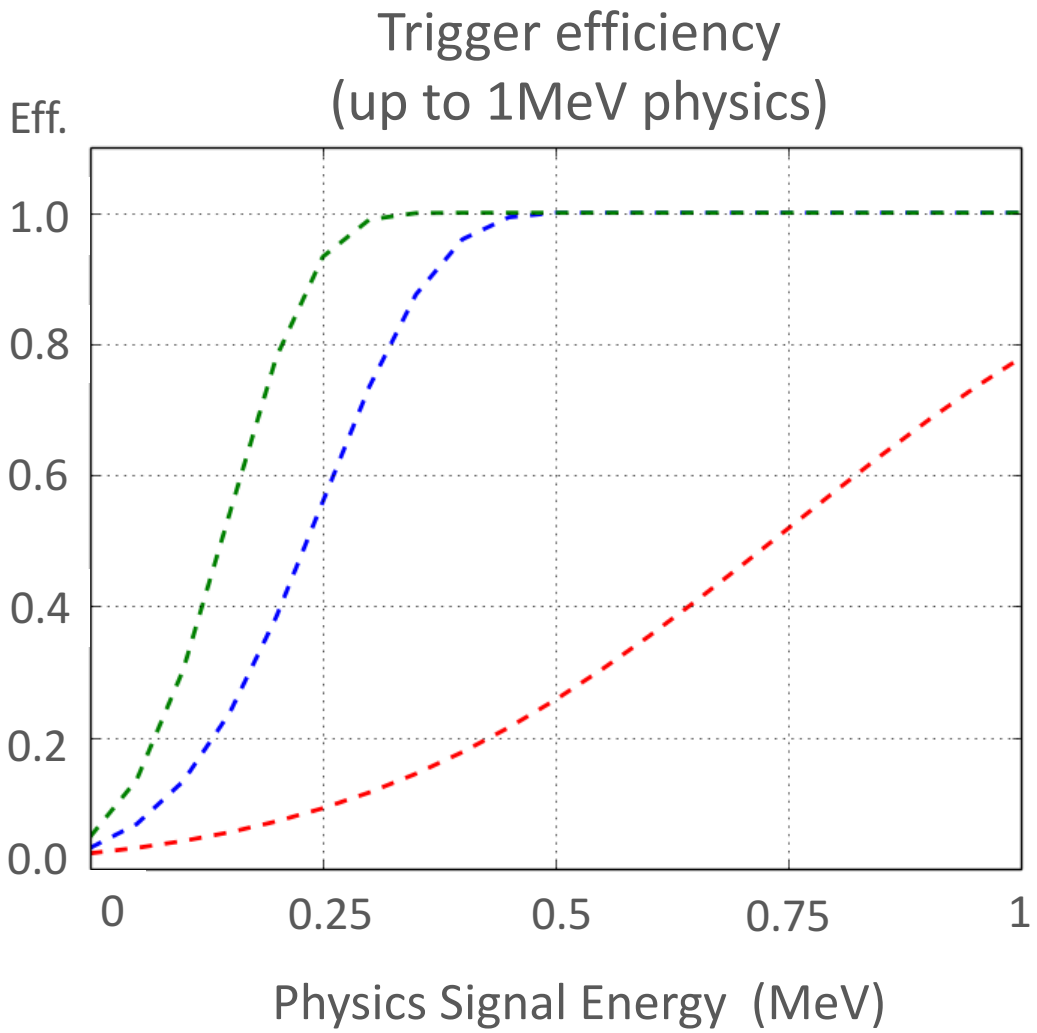
- **Bkg LY: 1e10Hz, Signal LY: 40,000 γ /MeV**
- Light detection efficiency ε = 0.0005
- **Beam window is 1us. (X0.1 smaller)**
- 1MeV Signal -> 20 PE detected.
- Steady SPE background -> Poisson mean **5PE** in 1us window.
- Smarter trigger: Set the threshold at **9PE** (~0.5MeV) to remove 95% of background.



1MeV physics Case study – Better light detection



- **Bkg LY: 1e10Hz, Signal LY: 40,000 γ /MeV**
- **Light detection efficiency ε = 0.001 (X2 better)**
- Beam window is 1us.
- 1MeV Signal -> **40 PE** detected.
- Steady SPE background -> Poisson mean 10PE 1us window.
- Better trigger: Set the threshold at **15PE** (0.38 MeV) to remove 95% of background.



Conclusion

- Light signal from LAr is used to form triggers for neutrino experiments. It's important to understand the light background.
- High rate of SPE background is observed from large surface LArTPCs. A model is developed to explain this background.
- Model needs to be tested with data. Optimize the detector design to reduce the SPE background.
- Smarter trigger, better light detector will enable interesting low energy physics.

Thank You!

backup

Mathematical form

(1) Volume Recombination (VM)

$$Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$$

(2) Mutual Neutralization (NM)

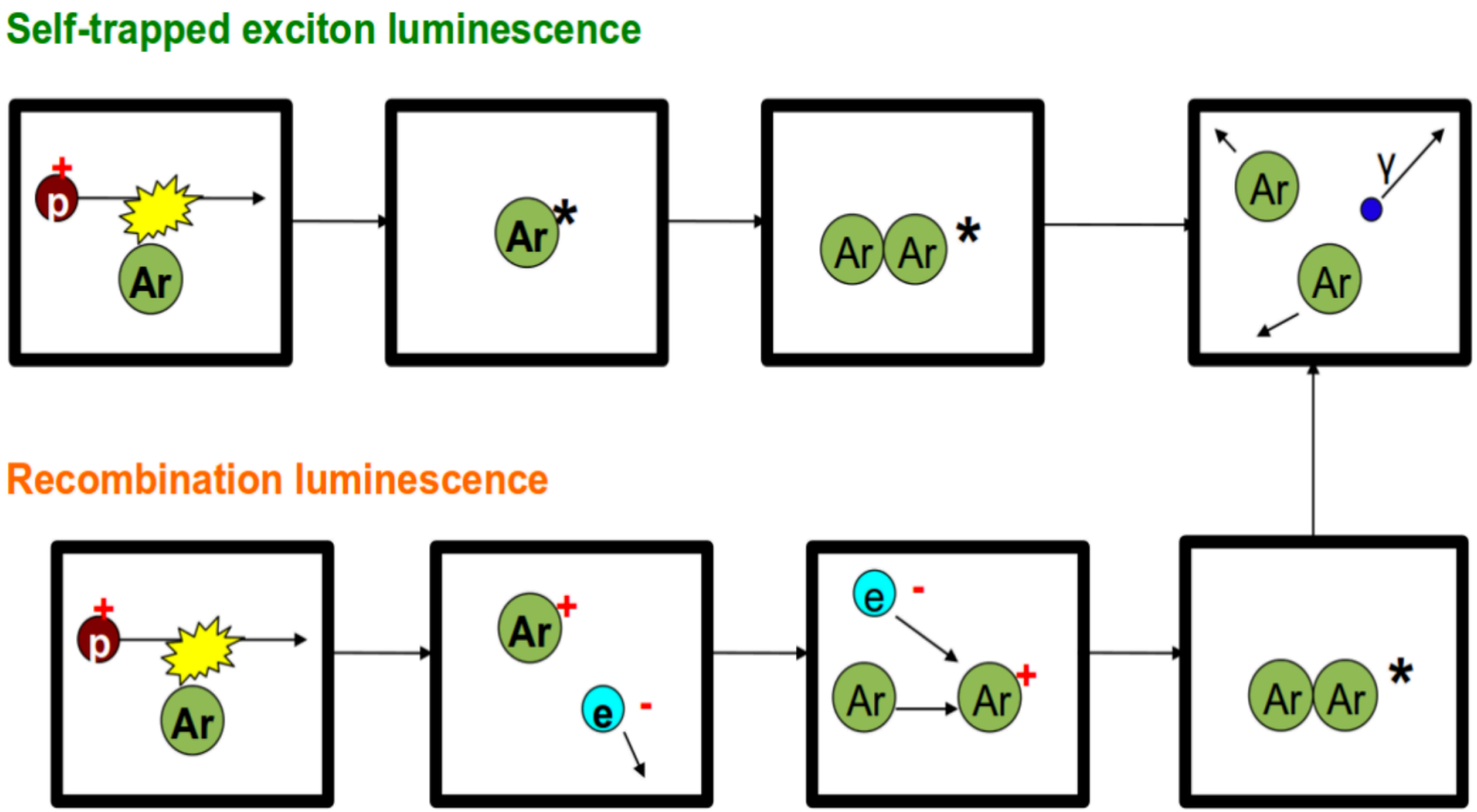
$$Ar_2^+ + O_2^- \rightarrow Ar_2^* + O_2 \rightarrow 2Ar + \gamma + O_2$$

With the two processes that can produce photons->a rate problem at equilibrium

Solve the differential equations.

$$\begin{cases} -v_d^e \cdot \frac{\partial n_e(x)}{\partial x} & = n_{pair} - k_A n_X n_e(x) - k_R n_+(x) n_e(x) \\ v_d^+ \cdot \frac{\partial n_+(x)}{\partial x} & = n_{pair} - k_{MN} n_-(x) n_+(X) - k_R n_+(x) n_e(x) \\ -v_d^- \cdot \frac{\partial n_-(x)}{\partial x} & = k_A n_X n_e(x) - k_{MN} n_-(x) n_+(X) \\ n_e(d) & = 0 \\ n_+(0) & = 0 \\ n_-(d) & = 0 \end{cases}$$

Light Signal from LAr - you are familiar with



- Two ArAr* excited states are created.
- De-excitation creates scintillation Argon light with two time constants: Fast light - **6ns,** Slow light - **1.6us**
- Photon energy: 9.7eV (128nm)
- Fast light signal gives the T0 for the charged particle entering LArTPC.

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