Calorimetric Energy Estimate for Supernova Neutrinos using the DUNE Photon Detection System

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The DUNE Experiment

❑ DUNE will be a 40 kt liquid argon TPC:

- 1300 km downstream of a neutrino beam produced at Fermilab
- With 4300 mwe of overburden, cosmic backgrounds are dramatically reduced allowing for rare event searches

❑ The experiment will

- Precisely measure neutrino oscillations
- Search for nucleon decay
- Search for bursts of neutrinos generated by a supernova

❑ A Photon Detection System (PDS) is needed in conjunction with the TPC to achieve each of these goals

A Supernova Neutrino Burst (SNB)

❑ When a massive star explodes, ≈99% of its gravitational energy is released in a burst of neutrinos

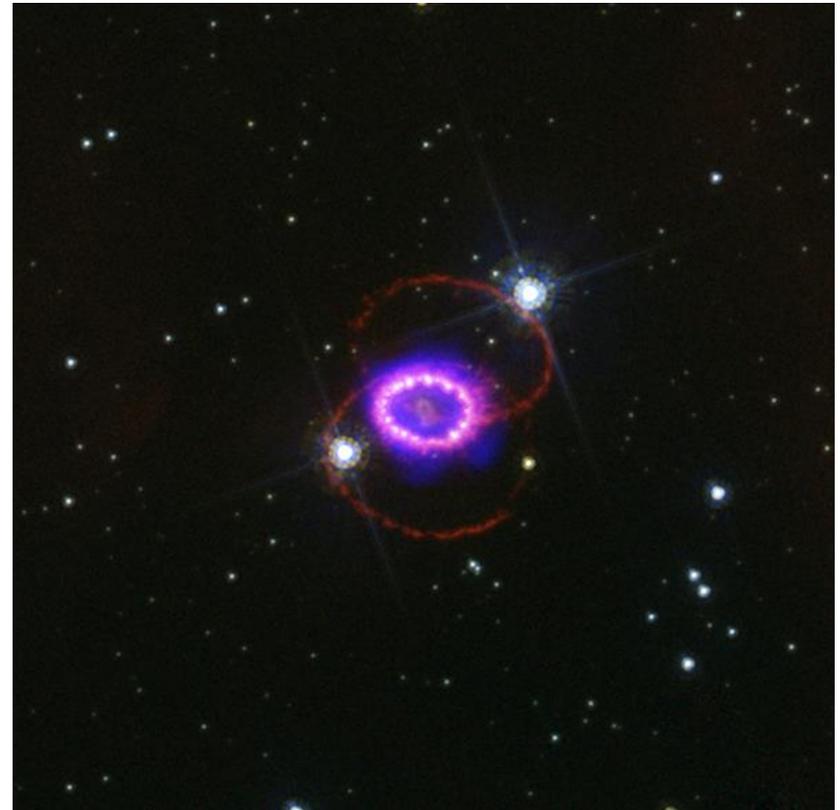- Typical energies are 5-30 MeV
- Burst lasts a few seconds

SN 1987a remnant in 2007, imaged in x-ray and optical

NASA/CXC/PSU/S. Park & D. Burrows
NASA/STScl/CfA/P. Chalis

❑ A burst of neutrinos were detected in 1987, associated with the death of a star in the Large Magellanic Cloud

- ≈20 $\bar{\nu}_e$ events detected in Kamiokande, IMB, and Baksan

Physics from Supernova Neutrinos

❑ **Neutrino physics**

- Absolute neutrino mass
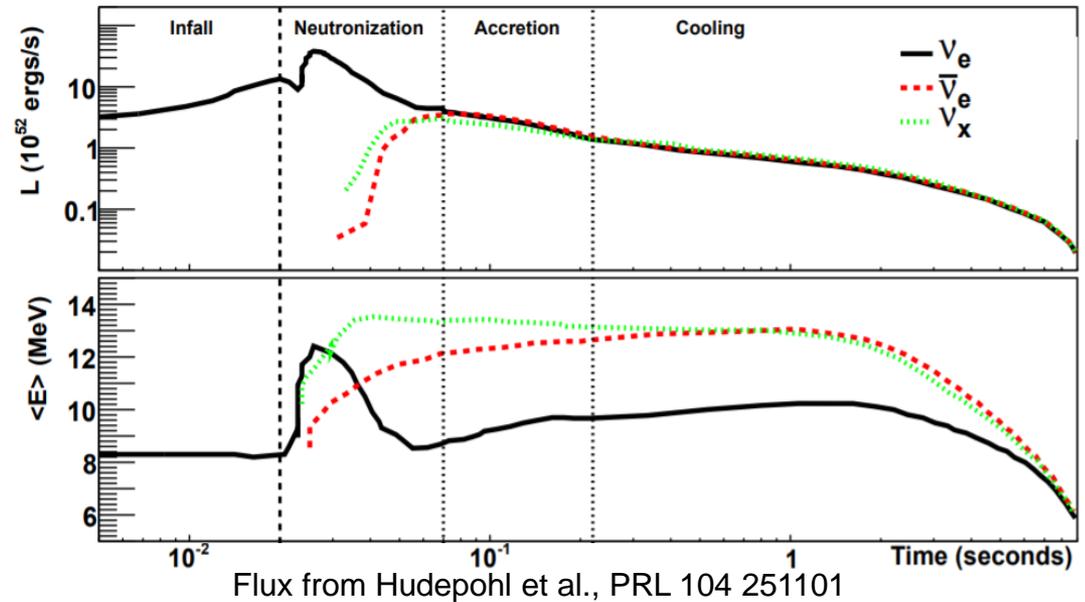- Neutrino Magnetic Moment
- Tests of neutrino oscillation

❑ **Stellar Astrophysics**

- Time-evolution of neutrino burst
- Neutron star cooling
- Black hole formation

Flux from Hudepohl et al., PRL 104 251101

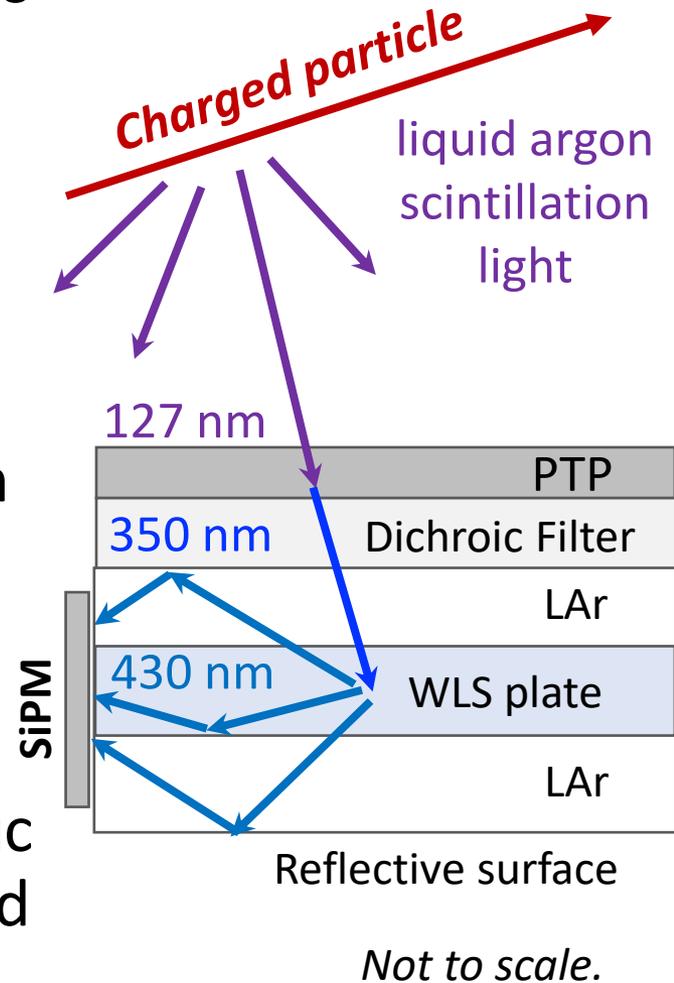❑ **DUNE would see** ≈3000 events from a galactic supernova, mostly from $^{40}Ar(\nu_e, e)$ interactions

PDS Goals for DUNE

❑ Reconstruct the timing of each event to resolve the position ambiguity along the drift direction

- Allows for detector fiducialization and rejection of in-coming background
- Corrects for the attenuation of drift electrons by impurities in the argon

❑ Trigger in the case of a supernova neutrino burst (SNB)

- Redundancy between TPC and PDS triggers increases DUNE's efficiency for recording valuable SNB data

❑ Assist in event reconstruction and particle identification

- Explored further in this talk

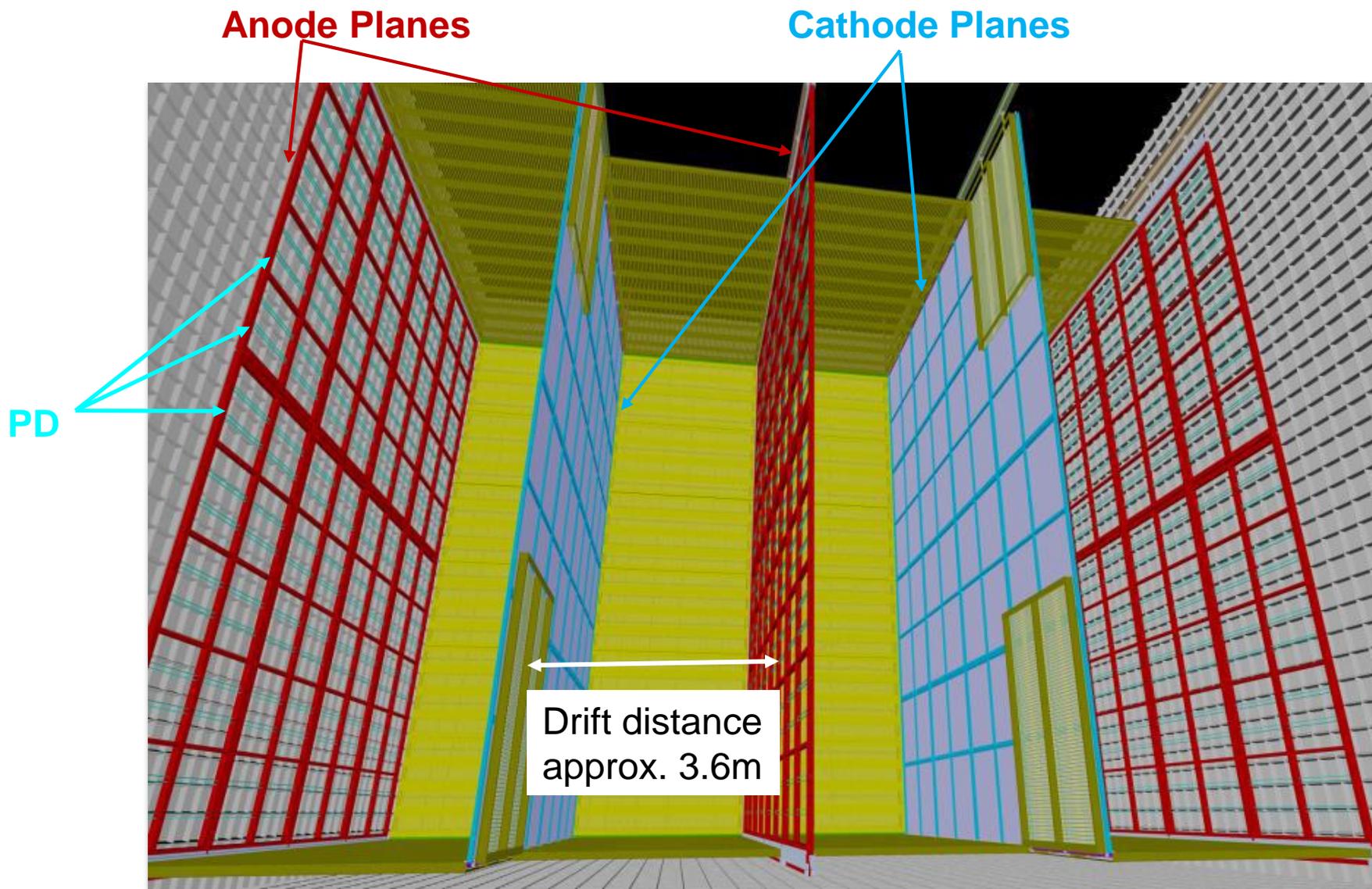❑ Further topics, such as Michel electron identification, are also being considered

Collecting Scintillation Light with PDS

☐ ARAPUCA[1] photon detectors developed to enhance light yield in DUNE by trapping photons of a certain wavelength

☐ PD is coated in PTP which shifts photon wavelengths to 330-400 nm

☐ A dichroic filter just below is transparent to photons at wavelengths below 400 nm but reflective at longer wavelengths

☐ Below, a second wavelength shifter adjusts the wavelength to 430 nm

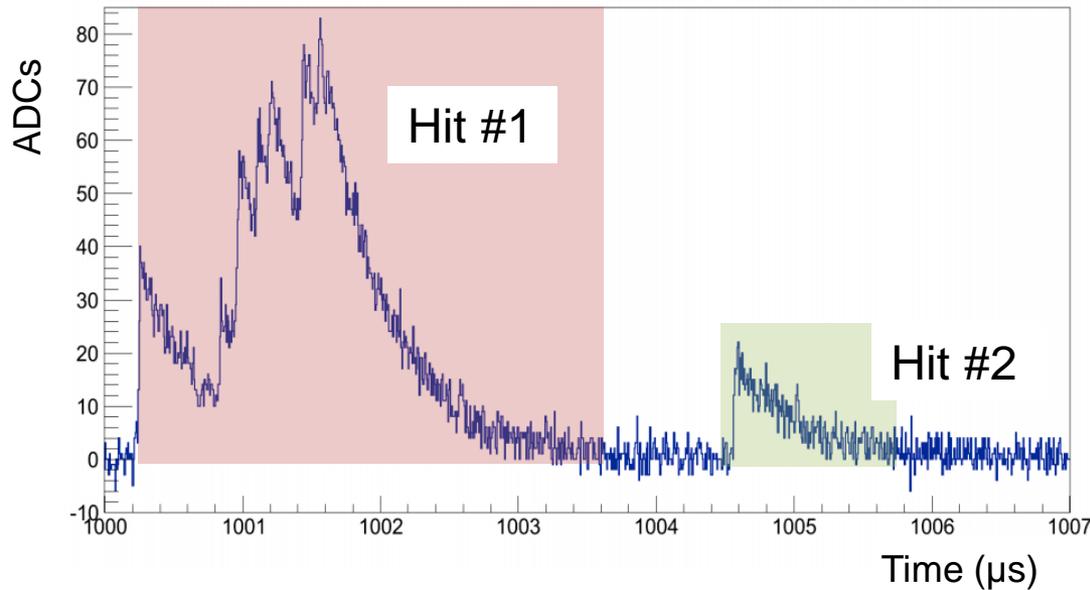☐ Light is thus trapped between the dichroic filter and the reflective wall until captured by a SiPM

Charged particle

liquid argon scintillation light

127 nm

	PTP
350 nm	Dichroic Filter
	LAr
430 nm	WLS plate
	LAr

SiPM

Reflective surface

Not to scale.

[1]Marinho, Paulucci, Machado, Segreto; arXiv 1804.03764

PDS Distribution in DUNE

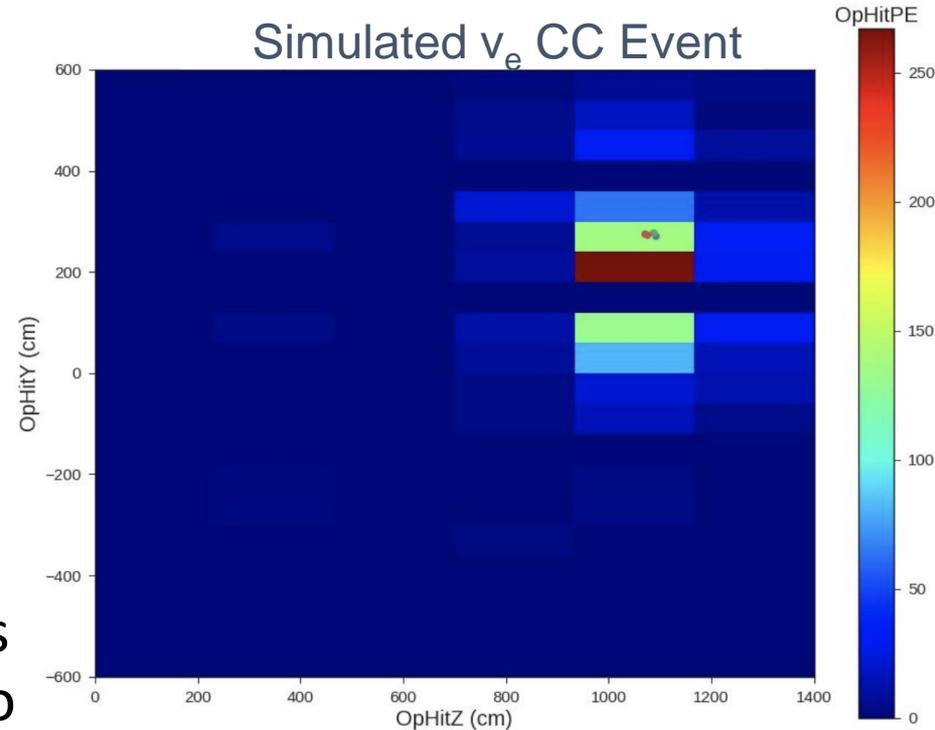Anode Planes

Cathode Planes

PD

Drift distance approx. 3.6m

Identifying Activity in the PDS

❑Hits in the PDS are recorded when SiPM voltage increases above threshold and continue until the trace returns to baseline

- Hit time given by first sample over the threshold
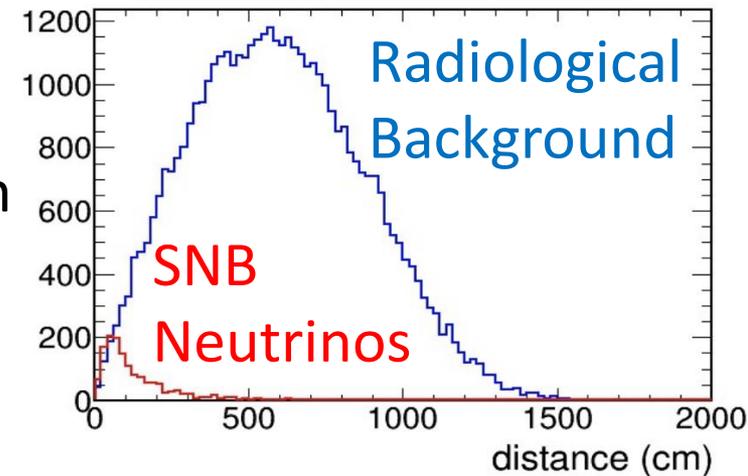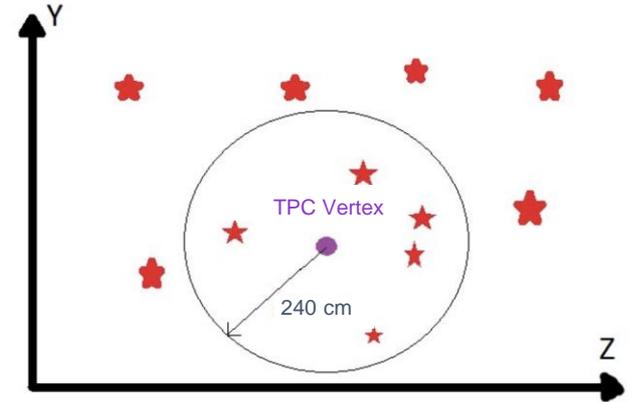- We convert to Photo-Electrons (PEs) using the integral of the voltage trace

Clustering PDS Hits into Flashes

❑ If multiple nearby hits are identified within a 0.5 μs window, a flash is reconstructed

❑ PDS channels are distributed over the anode plane

- Distribution of PE reconstructs the vertex of the event for two coordinates perpendicular to the drift direction
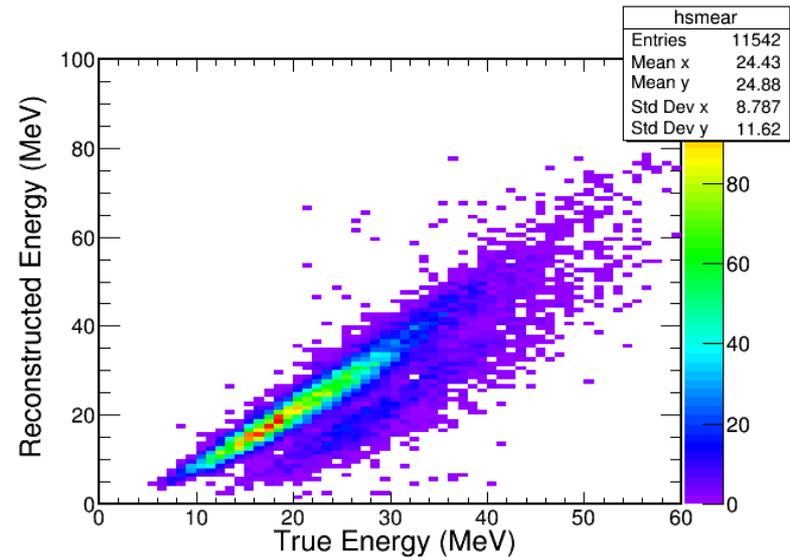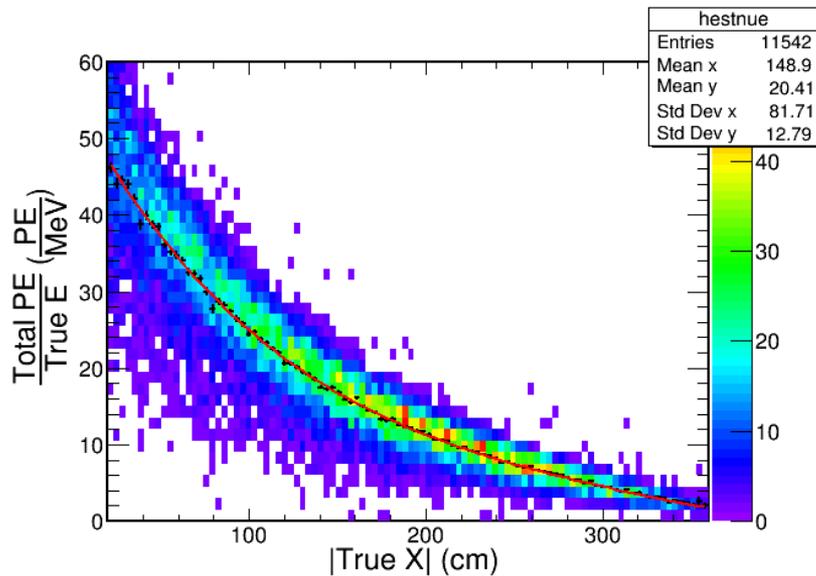

Simulated v_e CC Event

Matching PDS and TPC Activity

❑ Both PDS and TPC hits will give information on the coordinates perpendicular to the drift direction

❑ Requiring a coincidence between the PDS flash and TPC positions will reduce the rate of uncorrelated background in the two systems

- Vertex reconstruction is within 240 cm for PDS and TPC

- The time of the PDS flash precedes TPC activity, with the time delay no more than one drift time
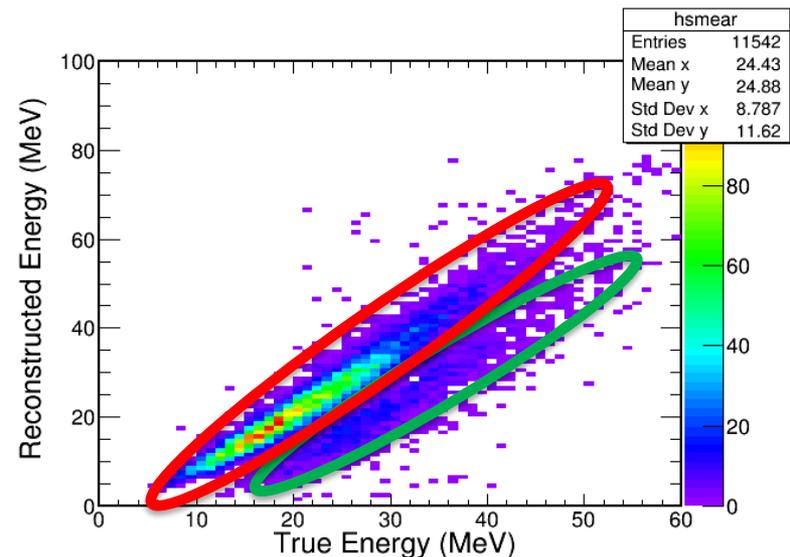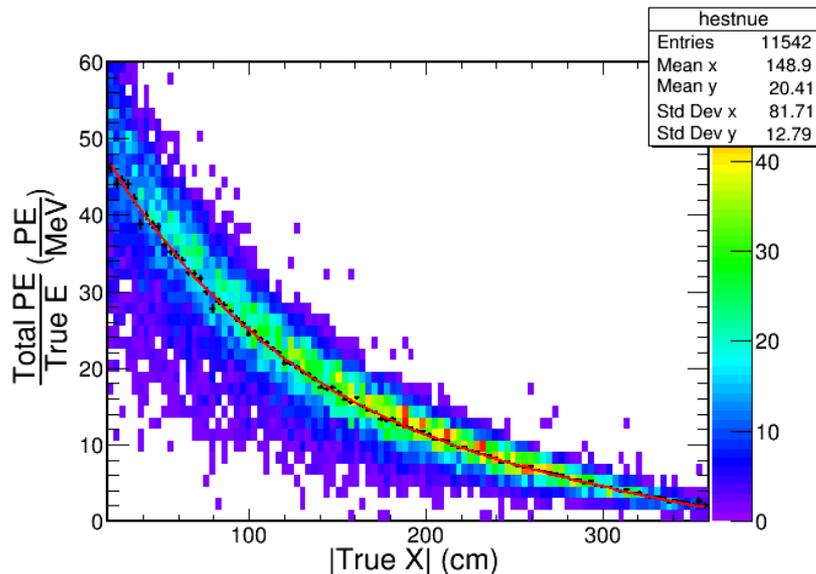
Reconstructing Neutrino Energy

❑ Rayleigh scattering attenuates the observed light yield as a function of the distance to the PDS detectors, exactly the drift time in the DUNE geometry

❑ After correcting for this attenuation, the PDS estimates neutrino energy calorimetrically
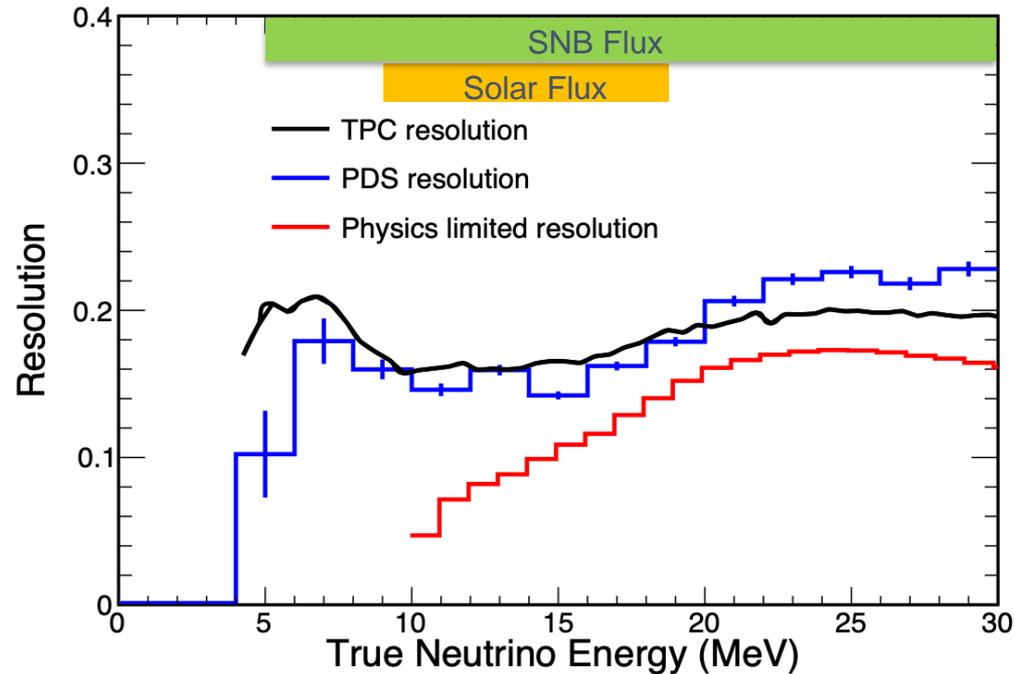
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- For low-energy ν_e CC interactions, two populations are apparent: events with and without neutron emission
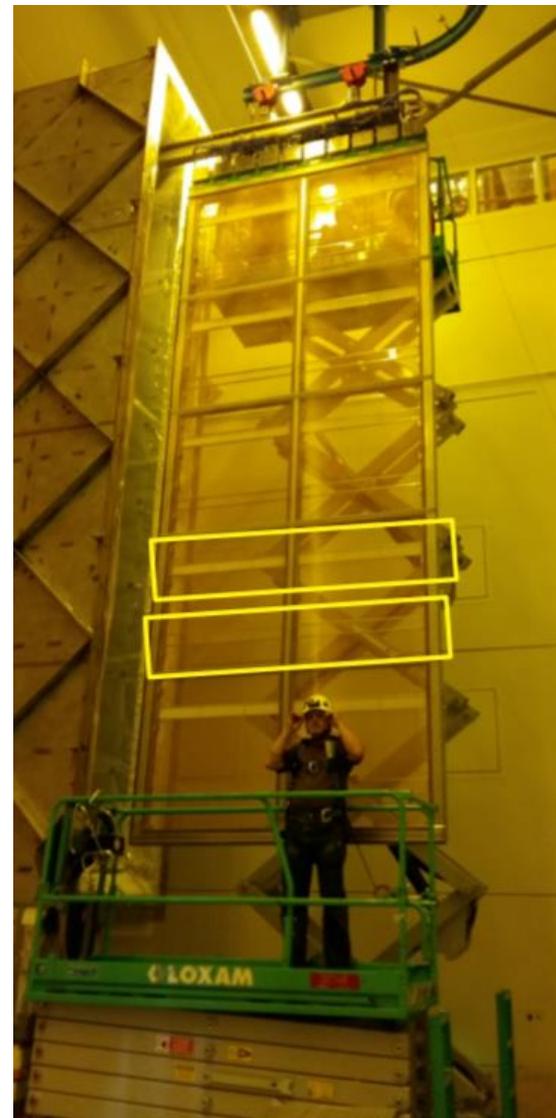
Energy Resolution for low-E ν_e CC

❑ TPC and PDS information give independent energy estimates

- Performance comparable for energies relevant for SNB and solar neutrinos
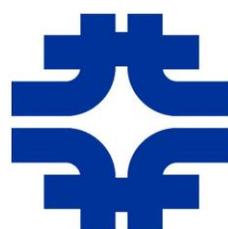
❑ Combined information will notably improve on current resolution

Summary

❑ DUNE will implement a PDS based on the ARAPUCA design to supplement the physics sensitivity of the TPC

❑ A full reconstruction of simulated scintillation photons suggests we can reconstruct drift time with PDS information even for low-energy neutrinos

❑ Preliminary studies show energy resolution is comparable to that achieved by the TPC for energies relevant for supernova and solar events

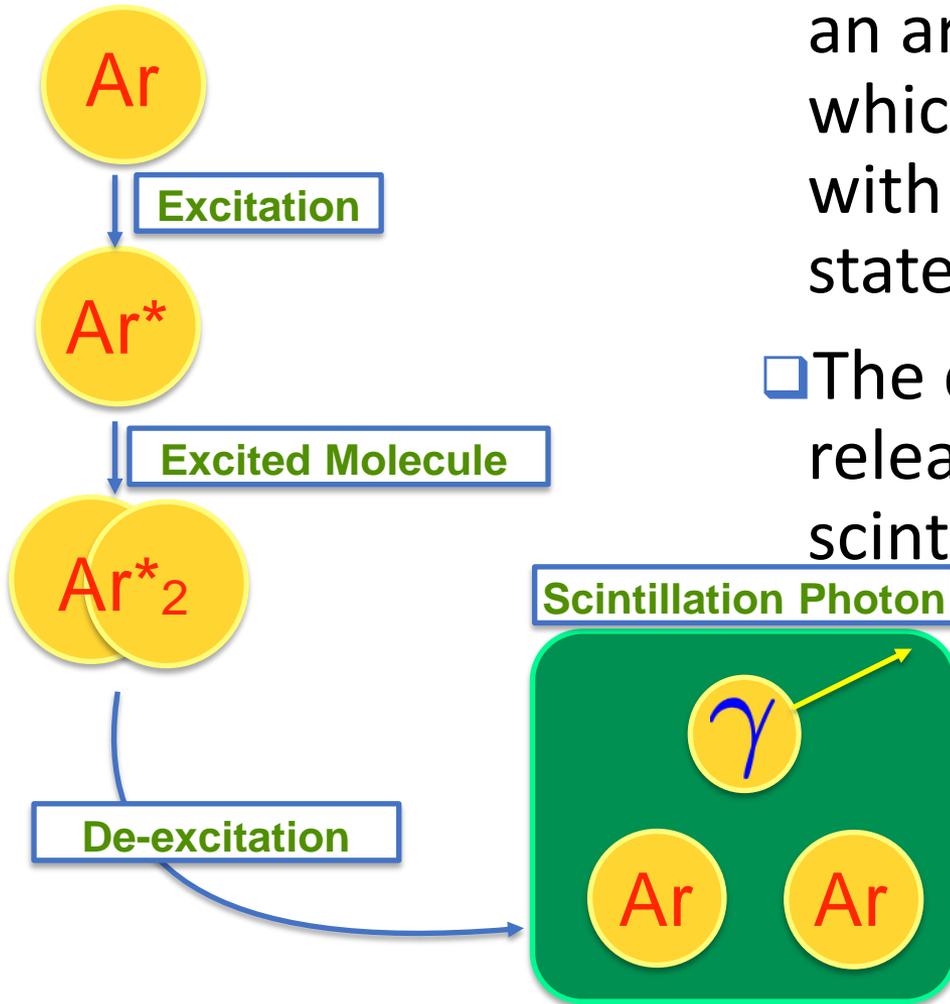❑ Thanks to B. Behera for several studies contributing to this talk

Thank You!

Backup

Producing Scintillation in Liquid Ar

Self trapped excitation luminescence

Ar

Excitation

Ar*

Excited Molecule

Ar*$_2$

De-excitation

Scintillation Photon

γ

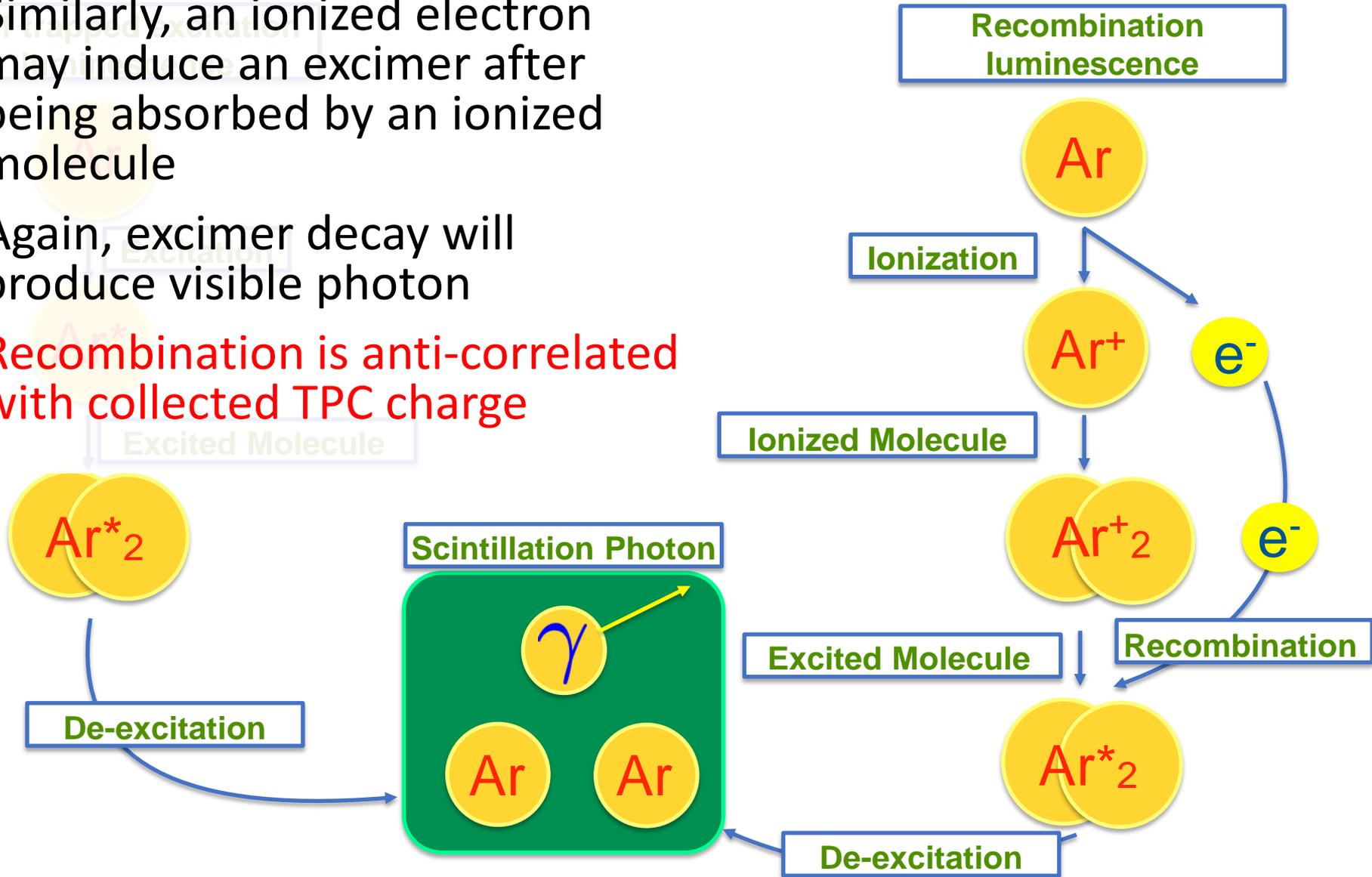Ar   Ar

❑ A charged particle may excite an argon atom as it passes by, which quickly forms an excimer with nearby atom in the ground state

❑ The decay of this excimer releases a detectable scintillation photon

Producing Scintillation in Liquid Ar

- Similarly, an ionized electron may induce an excimer after being absorbed by an ionized molecule

- Again, excimer decay will produce visible photon

- Recombination is anti-correlated with collected TPC charge

Recombination luminescence

Ar

Ionization

Ar$^+$ e$^-$

Ionized Molecule

Ar$^+_2$ e$^-$

Excited Molecule   Recombination

Scintillation Photon

γ

Ar   Ar

De-excitation

Ar$^*_2$

De-excitation

Ar$^*_2$

Producing Scintillation in Liquid Ar

Self trapped excitation luminescence

Ar → (Excitation) → Ar* → (Excited Molecule) → Ar*₂ → (De-excitation) → Scintillation Photon

Recombination luminescence

Ar → (Ionization) → Ar⁺ + e⁻ → (Ionized Molecule) → Ar⁺₂, e⁻ → (Recombination) → (Excited Molecule) → Ar*₂ → (De-excitation) → Scintillation Photon (γ, Ar, Ar)

Resolution vs PDS Performance

❑ The energy resolution is determined from the widths of the distribution of (reconstructed - true)/true neutrino energy for simulated events.