Optical TPC: current and future developments

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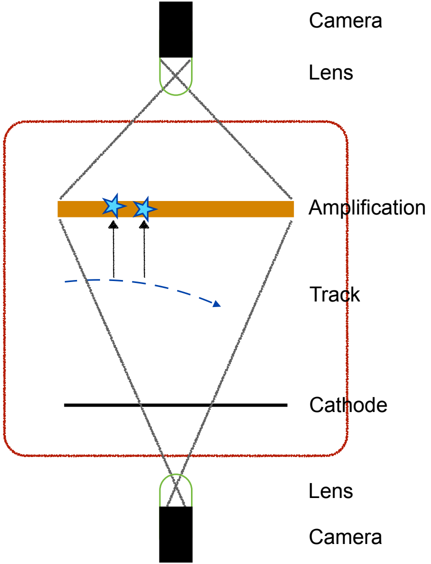
Optical Time Projection Chamber

- The general idea
- Comments on imaging
- Gas choices
- Current TPCs
- The next steps

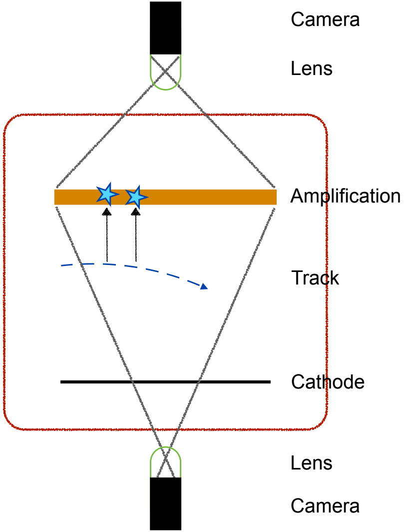
Tracks in the NIRNS heavy liquid bubble chamber.

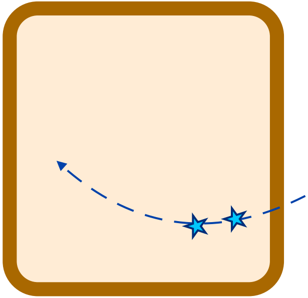
The concept

- A normal time projection chamber with either a transparent anode or no anode
- A camera is / cameras are focused on the gas amplification plane
- Said cameras image the scintillation light produced by the avalanche
- Depending on the gas and the wavelength of the scintillation light, a wavelength shifter may be needed
- I will focus on gas TPCs, but most of the concepts apply to the optical readout of a dual phase TPC



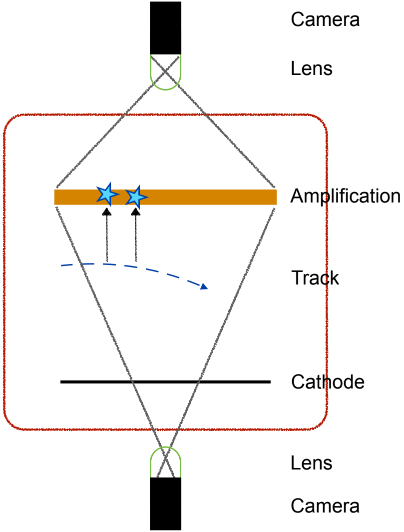
The concept, continued



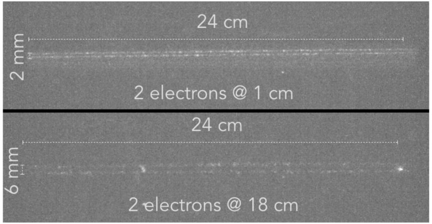


Camera view

The concept, continued

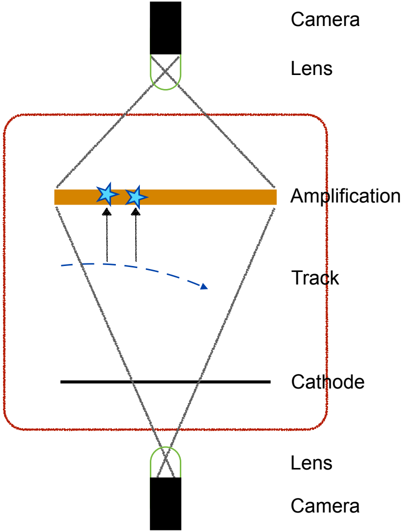


A real-world example:



Electron tracks in the LEMOn TPC, He-CF_4 (60-40), CYGNUS, arXiv 2005.12272

The concept, continued



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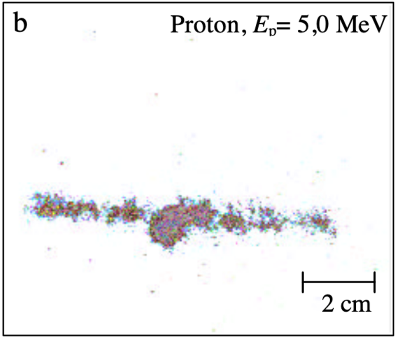
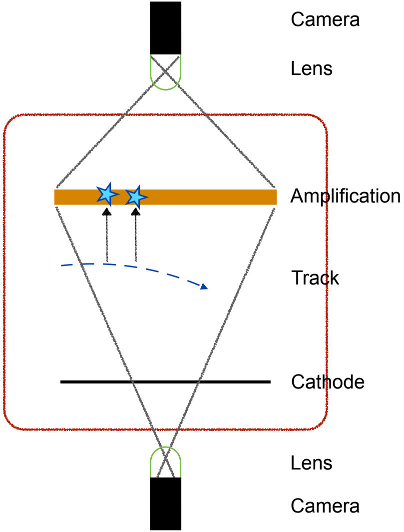


Proton track in the OPAC, $(H_5C_2)_3N$ (TEA) 7.5 Torr, arXiv physics/0410258

The concept, continued



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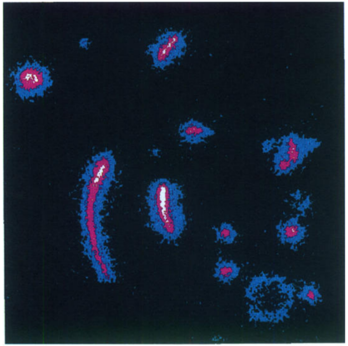
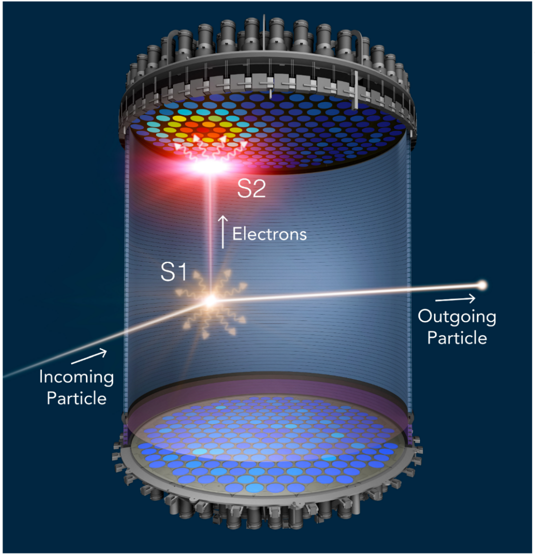
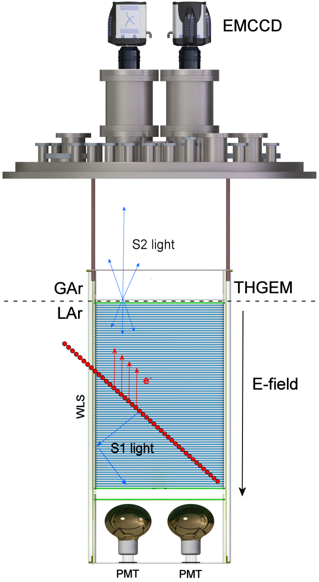


PPAC recoils from a neutron source, (CH_4+TEA or P10+TEA 20 to 50 Torr, Phys. Rev. Lett. 73, 1067 (1994)





LZ (arXiv 1703.09144) and Ariadne (`http://hep.ph.liv.ac.uk/ariadne/`)

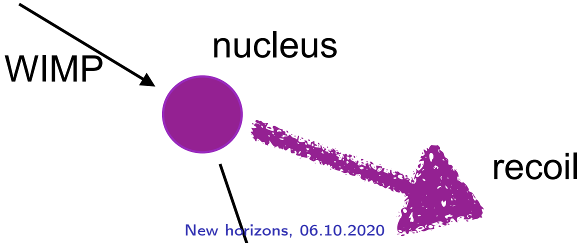
Advantages and challenges

- High granularity readout of large areas possible, since lenses allow to map large detector region of interest onto a small chip
- Decouple the readout fully from the gas volume
  - Less gas contamination from out-gassing
  - Less radioactive emissions from detector materials in the gas
  - Allows intervention on the readout without affecting the gas volume

  These makes optical readout particularly well suited for Dark Matter (DM) searches or cryogenic experiments
- A lens system attenuates the number of photons reaching a chip, requiring larger gain
- The wavelength of the scintillation light needs to match the camera's sensitivity: Only certain gas mixtures possible or wavelength shifting required
- Camera readout is only 2D – the third (z) coordinate needs to be obtained differently
  - Hybrid charge readout, PMTs, z measurements by diffusion

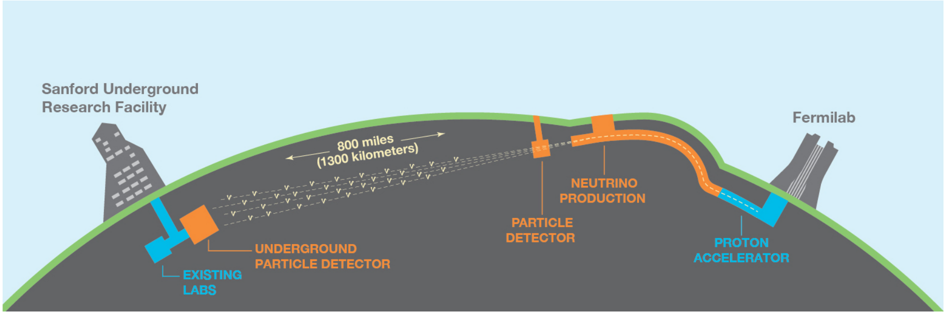
Gas filled TPCs for dark matter searches

- TPCs are used to search for a signal from direct detection of potential dark matter
  - ∗ A WIMP scatters with a gas atom
  - ∗ The nucleus recoils for a few mm,
  - ∗ Energy deposit in the gas: Less than a fraction of 100 keV
- Gas filled TPCs can not only measure that there was a recoil, but also resolve the track of the recoiled nucleus provided the spatial resolution is high enough → optical readout
- Ultra pure detectors with low background are needed, low event rates expected
- The gas target in a TPC is a very low density target – on the other hand: TPCs are scalable



Neutrino-nucleus scattering measured with a Time Projection Chamber

- TPCs act as target for ν-nucleus scattering as well as detection medium for the interaction's final state particles
- Advantage: Coverage of the full solid angle and low momentum threshold for particle detection
- Disadvantage: Low interaction probability for weakly interacting particles
  $\rightarrow$ High pressure gas, higher target density and event rate



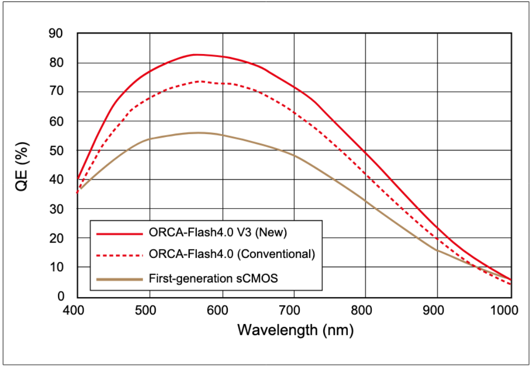
Cameras and optics

- **A lens system attenuates the number of photons reaching a chip, requiring larger gain**
- The wavelength of the scintillation light needs to match the camera's sensitivity: Only certain gas mixtures possible or wavelength shifting required
- Camera readout is only 2D – the third (z) coordinate needs to be obtained differently

Cameras

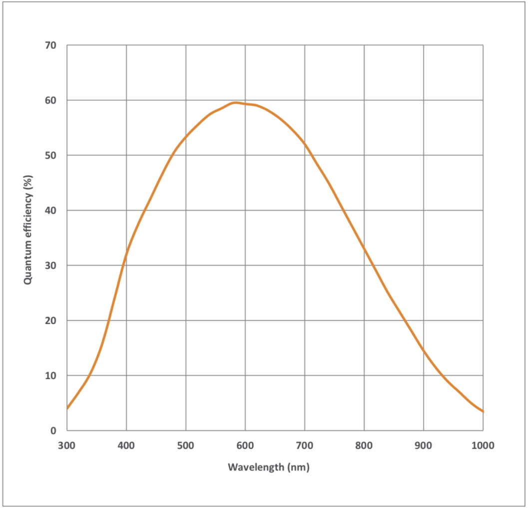
- The continued progress in the development of CCD cameras and the development of scientific CMOS (sCMOS) cameras is clearly aiding the current efforts of optical TPC development
- Scientific CMOS cameras are (almost) as low noise as CCD cameras and are more sensitive to light while retaining their original advantage of being fast
- To give a few numbers:
  - ∗ Usually about $\sim$2000 $\times$ 2000 pixels and a readout rate of $\sim$100 frames per second (for a limited number of time)
  - ∗ Low median readout noise of $\lesssim 1e^-$
  - ∗ High end: More than 3000 frames per second at relatively high resolution (PHANTOM cameras)

Quantum efficiency



ORCA-Flash4.0 V3

Andor Neo sCMOS 5.5 →



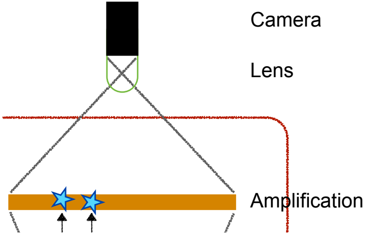
Photon attenuation, geometrical considerations

Using lenses will reduce the number of photons reaching a camera chip by a factor η:

$$\eta = \frac{1}{16}\left(\frac{1}{f_{\#}}\right)^2\left(\frac{1}{1+m}\right)^2$$

- $f_{\#}$ The “f-stop” number, determining the depth of view and the intensity (for constant exposure time)
- m De-magnification, *i.e.* the ratio of the object size to its size in the image or the ration of the object distance to the focal length

Their are other factors at play like *e.g.* the transmission of the windows to which the cameras are bolted



For example:

	m	η	area / pixel	full area
LEMOn TPC (CYGNUS)	$50.6/2.5 = 20.24$	1.0×10^{-4}	$125 \times 125\,\mu m^2$	$25.6 \times 25.6\,cm^2$
Dark Matter TPC (DMTPC) 10 L	$56.7/8.5 = 6.67$	7.4×10^{-4}	$156 \times 156\,\mu m^2$	$15 \times 15\,cm^2$
HPTPC	$110/5 = 22$	0.82×10^{-4}	$230 \times 230\,\mu m^2$	$71 \times 71\,cm^2$

- $\eta \sim 10^{-4}$ typical, this needs to be compensated by the gas gain
- The typical area / readout pixel may be larger, because pixels are often binned together to reduce the noise (*e.g* 4×4)

arXiv 2005.12272 (LEMOn TPC) and NIM A 755 (2014) 6–19 (Dark Matter TPC)

The counting gas: scintillation properties

- ☑ A lens system attenuates the number of photons reaching a chip, requiring larger gain
- ☐ **The wavelength of the scintillation light needs to match the camera's sensitivity: Only certain gas mixtures possible or wavelength shifting required**
- ☐ Camera readout is only 2D – the third (z) coordinate needs to be obtained differently

Gas choice

- First things first: The physics requirements for your TPC may not leave you much of a choice.
  - Neutrino beam characterisation: It is advantageous for the principal component of your gas to be matched to the far detector (*e.g.* Ar in the case of DUNE)
  - Dark matter searches: To probe certain models, the target gas nuclei need to have a given isospin
- Cameras are most efficient at optical wavelengths, also the transmission of the windows is high at these values
  - Select a gas with high scintillation light yield
  - Coat the windows with wavelength shifter, *e.g.* tetra-phenyl butadiene (TPB), emission maximum at 430 nm or p-terphenyl, emission maximum at 350 nm
  - Add a gas to the mixture, which works as wavelength shifter
- A topic for its own talk
- In the following I focus on light emission in the visible / near infra-red

Ne

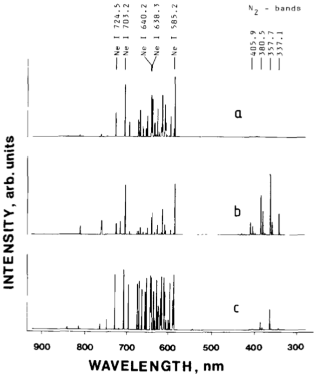


Fig. 2. (a) Scintillation spectrum (direct, beam-excited) of Ne recorded at 1000 nA beam current and 120 kPa pressure. (b) Field enhanced scintillation spectrum of Ne recorded with a wire potential of +1500 V, at 20 nA beam current and 120 kPa pressure. (c) Field enhanced scintillation spectrum of Ne recorded with a wire potential of −1500 V, at 8 nA beam current and 120 kPa pressure.

Ar

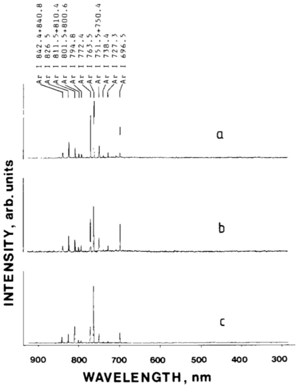


Fig. 3. (a) Scintillation spectrum (direct, beam-excited) of Ar recorded at 100 nA beam current and 200 kPa pressure. (b) Field enhanced scintillation spectrum of Ar recorded with a wire potential of +1600 V, at 80 nA beam current and 200 kPa pressure. (c) Field enhanced scintillation spectrum of Ar recorded with a wire potential of −1600 V, at 1.3 nA beam current and 200 kPa pressure.

Xe

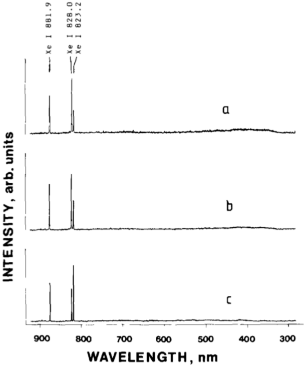


Fig. 5. (a) Scintillation spectrum (direct, beam-excited) of Xe recorded at 200 nA beam current and 160 kPa pressure. (b) Field enhanced scintillation spectrum of Xe recorded with a wire potential of +1600 V, at 260 nA beam current and 160 kPa pressure. (c) Field enhanced scintillation spectrum of Xe recorded with a wire potential of −1600 V, at 1.1 nA beam current and 160 kPa pressure.

NIM A 268 (1988) 204-208

CF_4

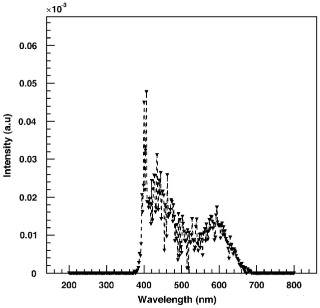


Fig. 6. Observed photon spectrum at the apparatus PMT in arbitrary units of intensity versus wavelength in nm. The scale of the intensity is the same as in Fig. 5. For clarity, error bars are not shown. Each bin is the product of the true CF_4 spectrum, the acrylic and quartz transmittance, and the PMT quantum efficiency.

NIM A 592 (2008) 63-72

He-CF_4 and Ar-CF_4

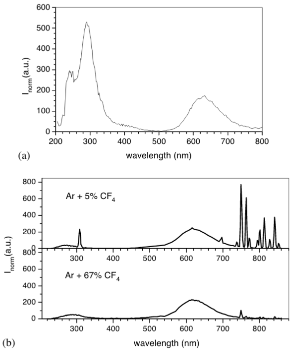


Fig. 2. Light intensity, normalised to the current, as a function of the wavelength for (a) He + 40%CF_4; (b) two Ar + CF_4 mixtures. Spectra were measured at charge gains of 170 for He + 40%CF_4 and 40 for both Ar + CF_4 mixtures. Above 400 nm, a long-pass colour glass filter with wavelength cut-off at 435 nm is used in order to avoid second-order diffraction effects.

NIM A 504 (2003) 88–92

Gas choice, Number of photons per electron

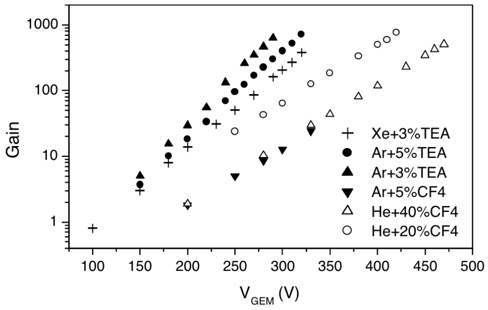


Fig. 1. Gain versus applied voltage for several gas mixtures.

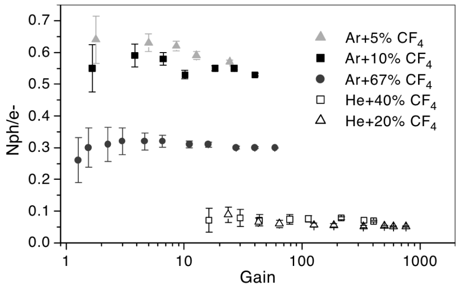
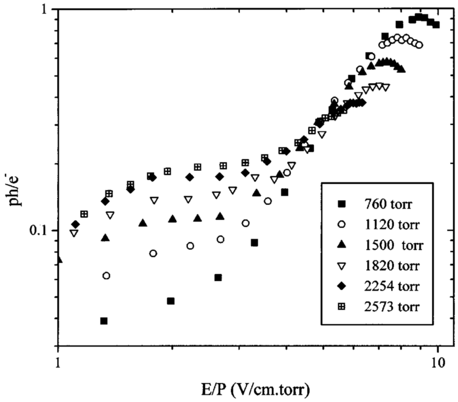


Fig. 3. Total number of photons emitted per secondary electron, above 400 nm, as a function of charge gain for several CF_4 mixtures. The systematic error is estimated to be less than 20%.

NIM A 504 (2003) 88–92

- In addition to the scintillation light achieved, the gas gain and the number of photons per electron need to be considered

Light yield for different gas mixtures



IEEE, VOL. 48, NO. 3, JUNE 2001

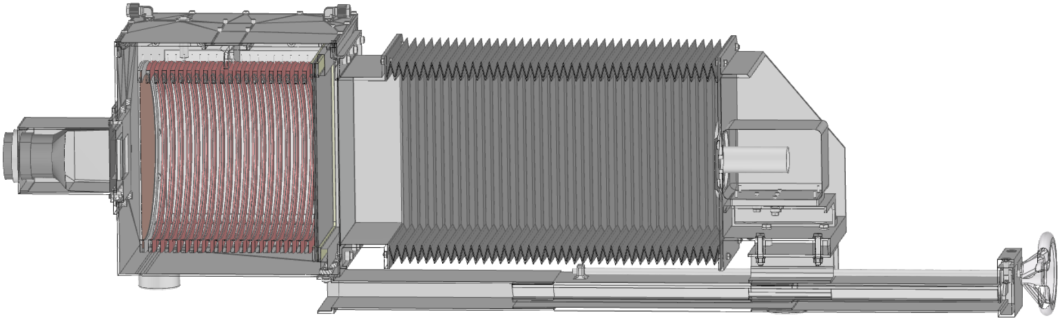
Figure: Pure Ar, various P

- Neutrino experiments require a high pressure gas to reach the necessary interaction rates in the TPC
- For DUNE, a mixture with Ar predominance is needed
- Measurements of the photon-to-electron ration in pure Argon and various mixtures with Argon pre-dominance in the near infra-red region 400 nm to 1000 nm
- At high electric fields the light emission levels off $\rightarrow$ transition to a purely ionising regime

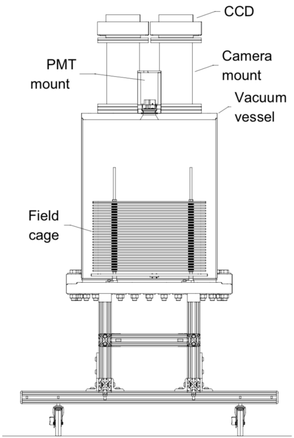
Current developments: The third coordinate

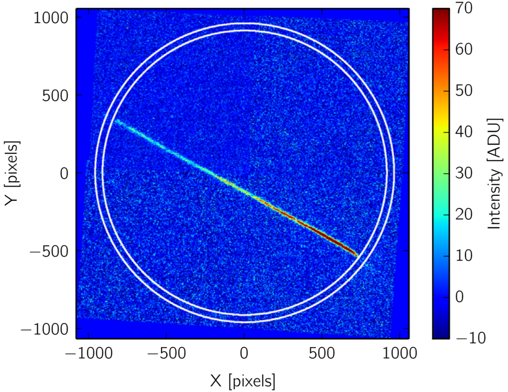
- ☑ A lens system attenuates the number of photons reaching a chip, requiring larger gain
- ☑ The wavelength of the scintillation light needs to match the camera's sensitivity: Only certain gas mixtures possible or wavelength shifting required
- ☐ **Camera readout is only 2D – the third (z) coordinate needs to be obtained differently**

LEMOn prototype TPC

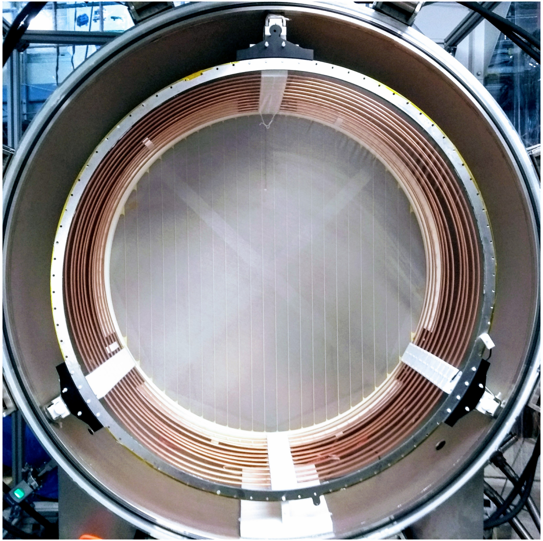


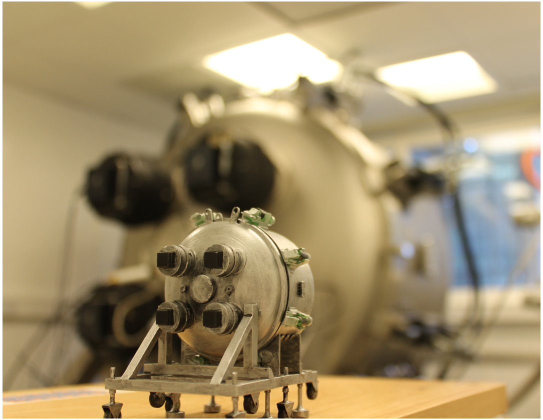
Dark Matter Time Projection Chamber 4Shooter





High pressure TPC





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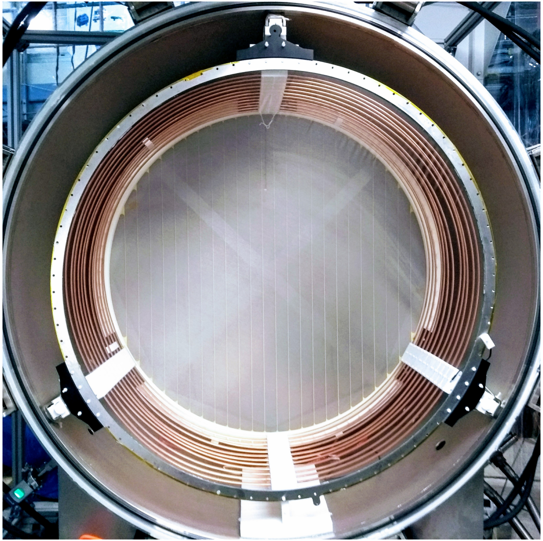
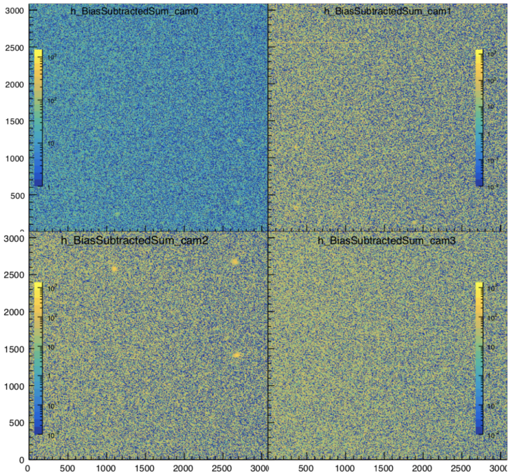
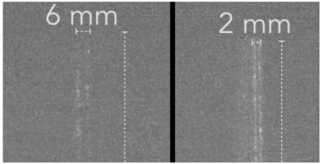
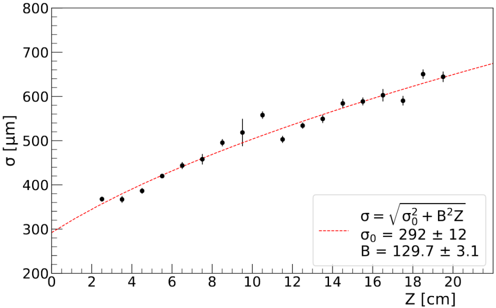




The third coordinate: Diffusion



- In this example the two images are made with the track position shifted by ∼180 mm
- A spread in space points can be seen by eye as well as quantified
- The z resolution possible is likely on the order of 1 cm



CYGNUS, arXiv 2005.12272

The third coordinate: Additional light measurement

In addition to the camera(s) a Photo Multiplier Tube (PMT) or Silicon Photon Multiplier (SiPM) measures light

- Provide a time stamp to the arrival of light form the gas amplification
- In case of a low track density and an external trigger → z measurement

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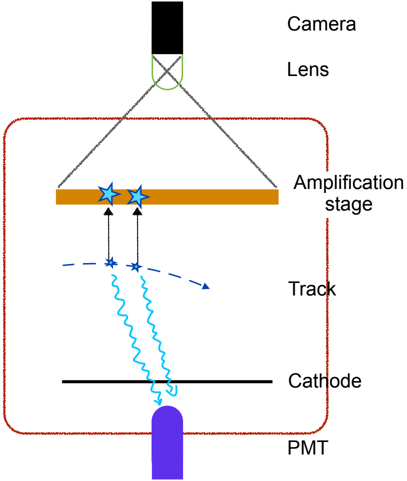
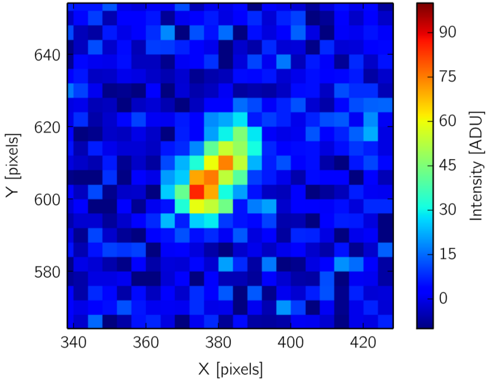
- If the scintillation light form the primary ionisation is strong such a measurement could provide t_0 for each event
- In case of a high track occupancy, the primary ionisation light may not allow to calculate z, but it could still serve as trigger



The third coordinate: Hybrid optical and charge readout

- Add a coarse charge readout to the TPC
- As a PMT/SiPM readout, the charge-readout gives the time of arrival at the amplification stage
- A detailed waveform analysis can give some information about the inclination of the track
- Again: In case of a low track density and an external trigger → z measurement
- If the charge readout is segmented, larger occupancies can be tolerated



NIM A 755 (2014) 6–19 (Dark Matter TPC)

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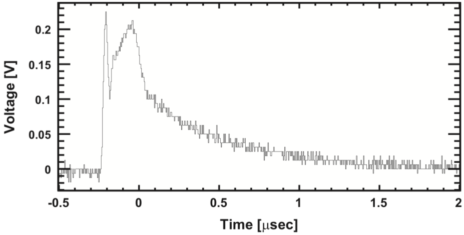
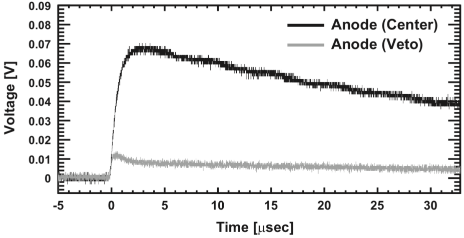
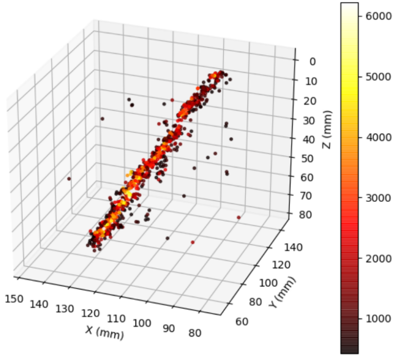




NIM A 755 (2014) 6–19 (Dark Matter TPC)

The third coordinate: Fast cameras

- Use a very fast camera to reconstruct the full 3D track from several images
- Example: Tests for Ariadne, CF_4 100 mbar
  - ∗ TimePix 3 camera coupled to a lens and an intensifier
  - ∗ The TimePix 3 camera can measure time of arrival of photons as well as intensity
  - ∗ To overcome the detection threshold of the chip a light intensifier is used in addition to the gas amplification in the detector (THGEM)
- Similar developments under-way in different labs, *e.g.* the RD51 lab at CERN



2019 JINST 14 P06001

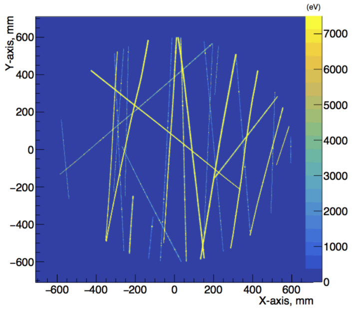
3D Ariadne measurement, see a video here: http://hep.ph.liv.ac.uk/ariadne/video/

Summary / Outlook

- ☑ A lens system attenuates the number of photons reaching a chip, requiring larger gain
- ☑ The wavelength of the scintillation light needs to match the camera's sensitivity: Only certain gas mixtures possible or wavelength shifting required
- ☑ Camera readout is only 2D – the third (z) coordinate needs to be obtained differently

Current status

- I have shown you several examples for TPCs with optical readout
- The concept is well established
- Challenges, currently addressed:
  - z coordinate reconstruction
  - Efficient readout and track finding



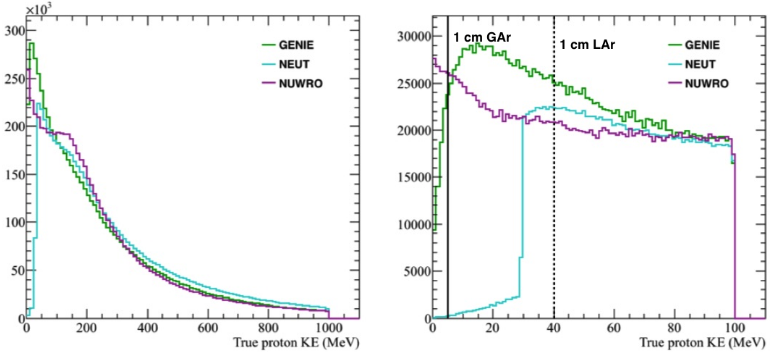
simulation

A future optical TPC...

- ... excellent 2D resolution
- ... t_0 from a primary scintillation measurement
- ... third coordinate reconstruction – by a fast camera or an hybrid readout

Backup

Model uncertainties in ν interaction generators



- Monte Carlo ν interaction generators disagree strongly in the low momentum region
- A gas filled TPC with excellent tracking performance can constrain these