Pulse Shape Discrimination in a Liquid Argon Time Projection Chamber

Application in DarkSide 20k

Congrès des Doctorant.es 2026
Janna Machts, 31/03/2026

Outline

Dark Matter

- ➔ Evidence
- ➔ General Knowledge & WIMP Dark Matter

Time Projection Chambers (TPCs)

- ➔ Set-up & Functionality
- ➔ Application to Dark Matter searches: Signal & Background

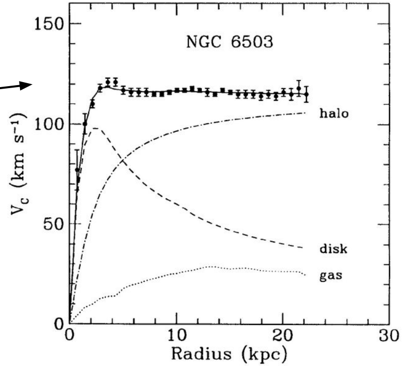
Pulse Shape Discrimination (PSD) in Liquid Argon TPCs

- ➔ Background & Usage
- ➔ Challenges
- ➔ Example Application

Dark Matter - Motivation and Current Status

Accumulating, independent evidence for missing matter:

1930s (Zwicky): Velocity dispersions in galaxy clusters
1970s (Rubin): Galactic rotation curves



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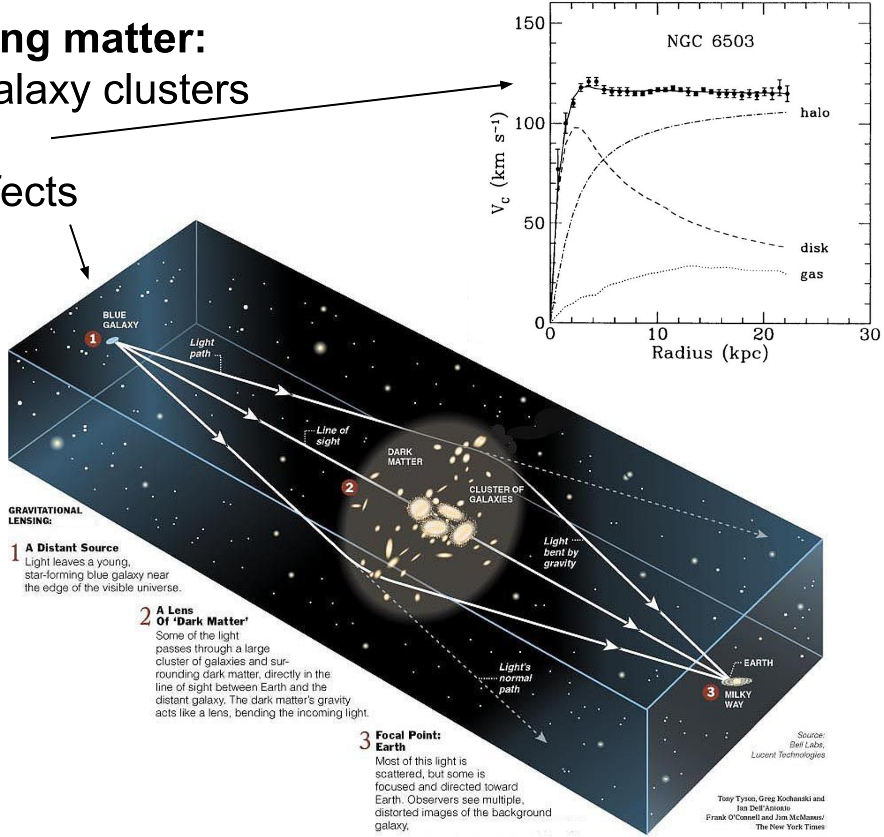

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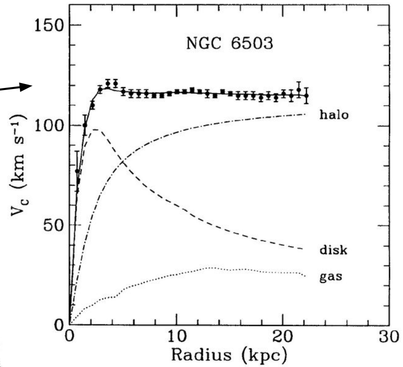
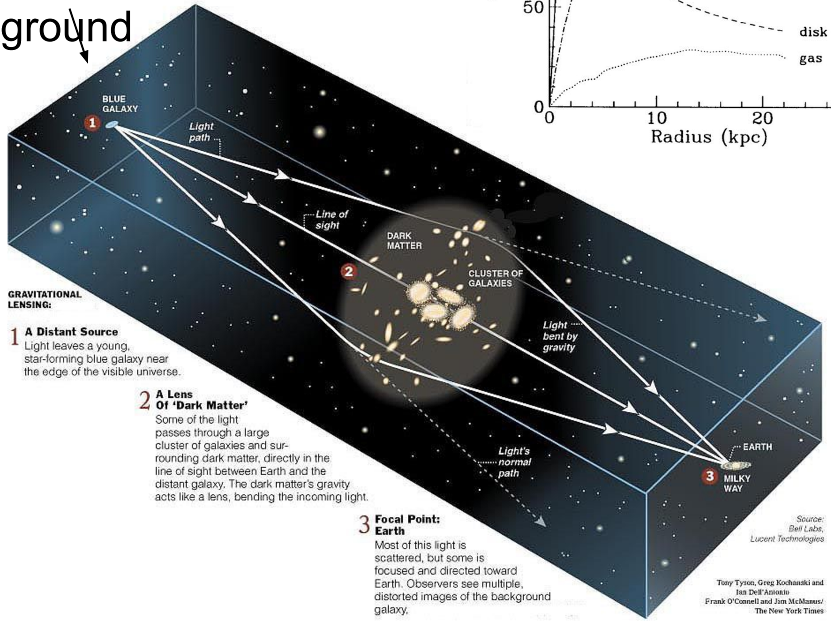
21st century:	Cosmic Microwave Background





GRAVITATIONAL LENSING:

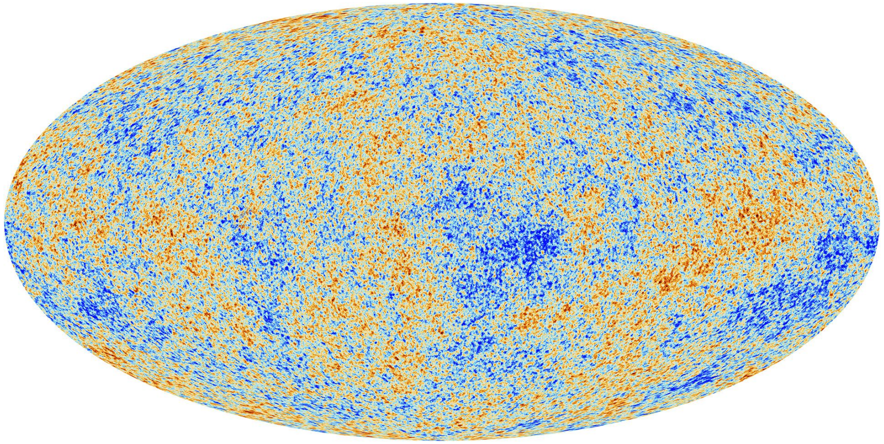
1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times



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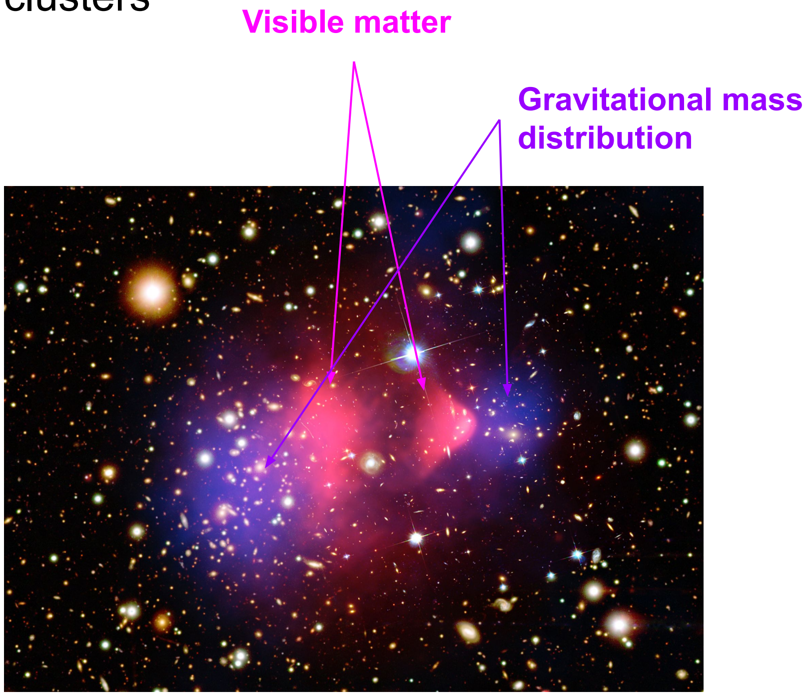
21st century:	CMB power spectrum

Known properties:

- Massive - interacts gravitationally
- No electromagnetic interaction
- No strong interaction
- Low self-interaction

Bullet cluster:
Colliding galaxies



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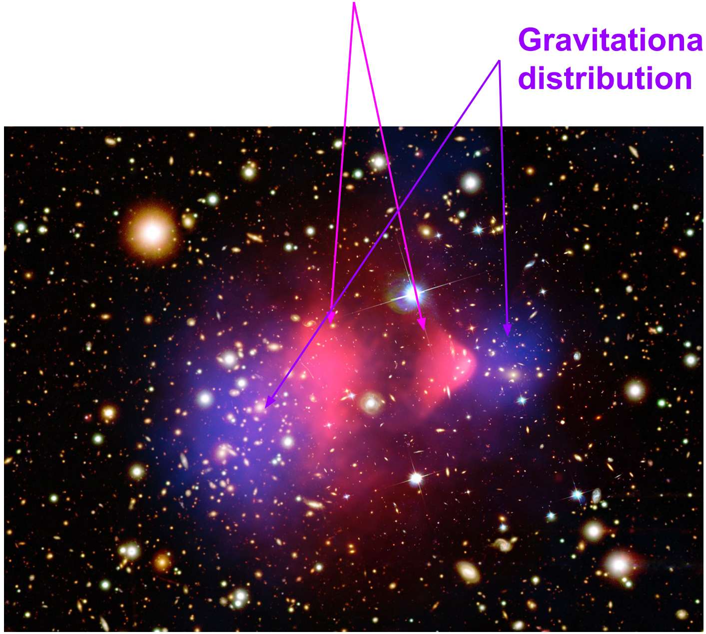
- Low self-interaction → **Bullet cluster: Colliding galaxies**
- Potential weak interaction
  ⇒ **W**eakly **I**nteracting **M**assive **P**articles (WIMPs)
  Detection through **interaction with ordinary matter**



Visible matter

Gravitational mass distribution

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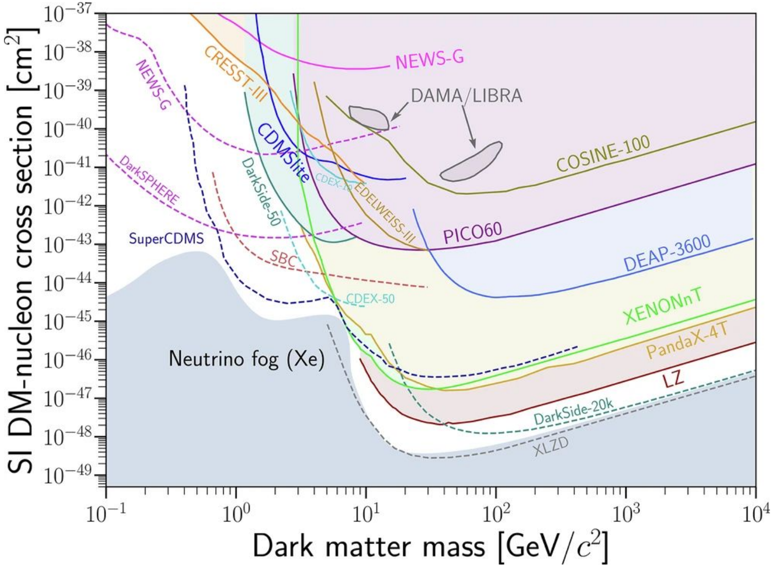
  Detection through **interaction with ordinary matter**
- Many other theories, e.g. axions, dark photons, primordial black holes, MOND, …

Exclusion Plot

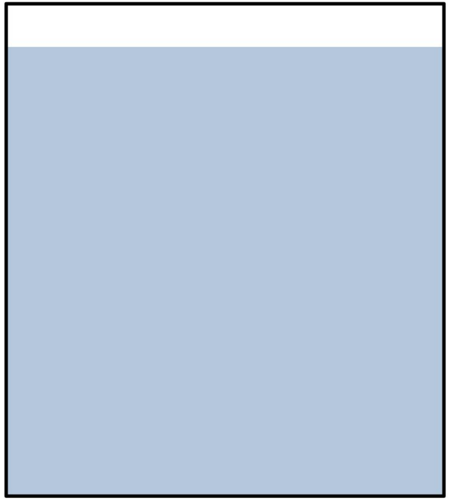


Xia, Q., Canonica, L. : **Progress and prospects in the underground laboratories' search for dark matter.** *Commun Phys* 9, 105 (2026). https://doi.org/10.1038/s42005-026-02563-1

Dual-Phase Time Projection Chambers

Basic Set-Up

- Target: active detector volume filled with liquid noble gas
- Small gas pocket at the top



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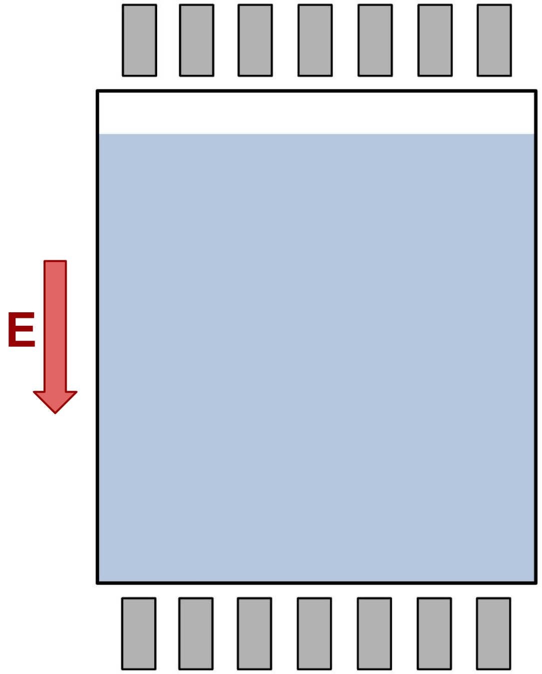

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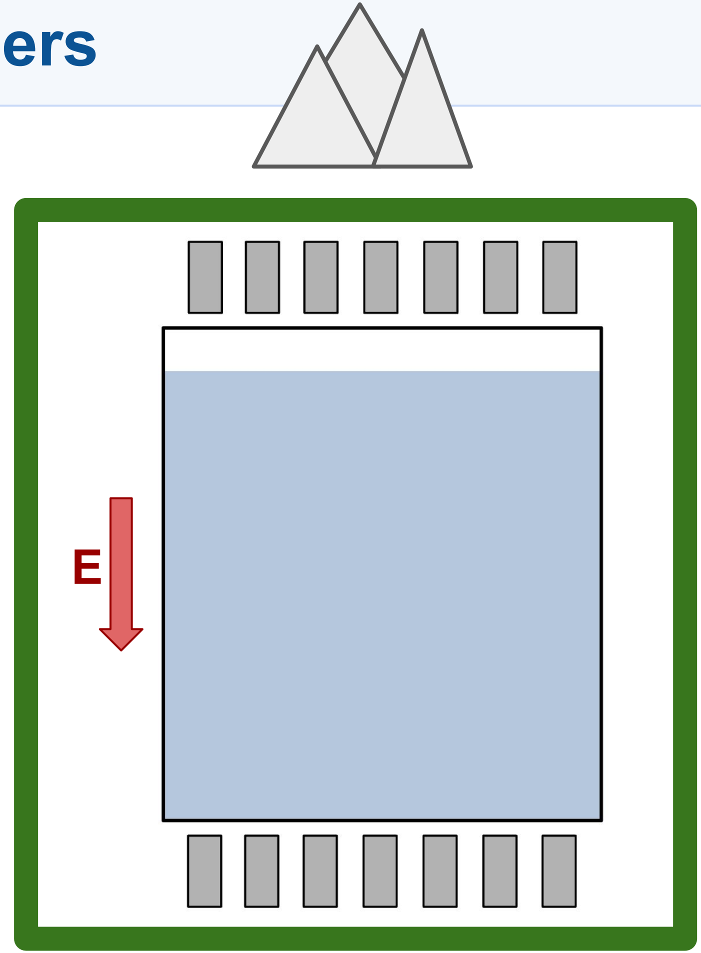

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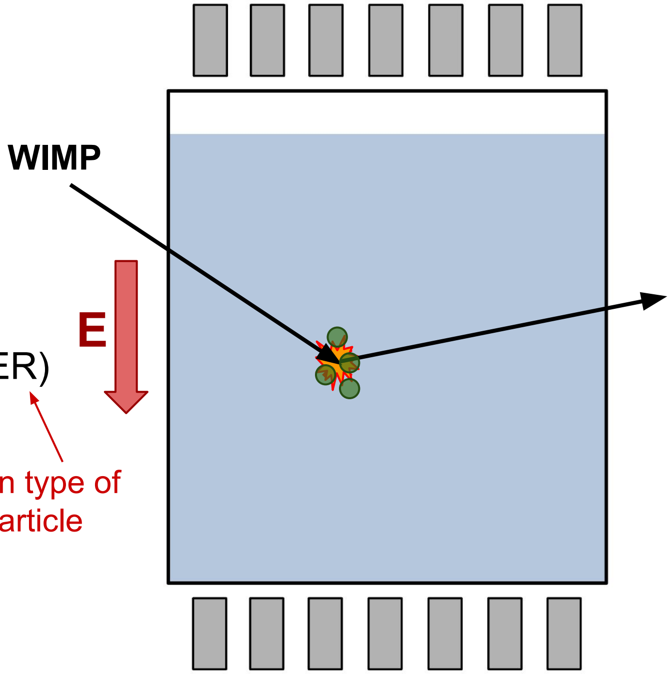
Functionality for DM searches

- Incoming particles collide with nucleons (NR) or electrons (ER) and deposit energy (elastic collision)
  ⇒ Scintillation + Ionization of noble gas atoms

Depends on type of incoming particle



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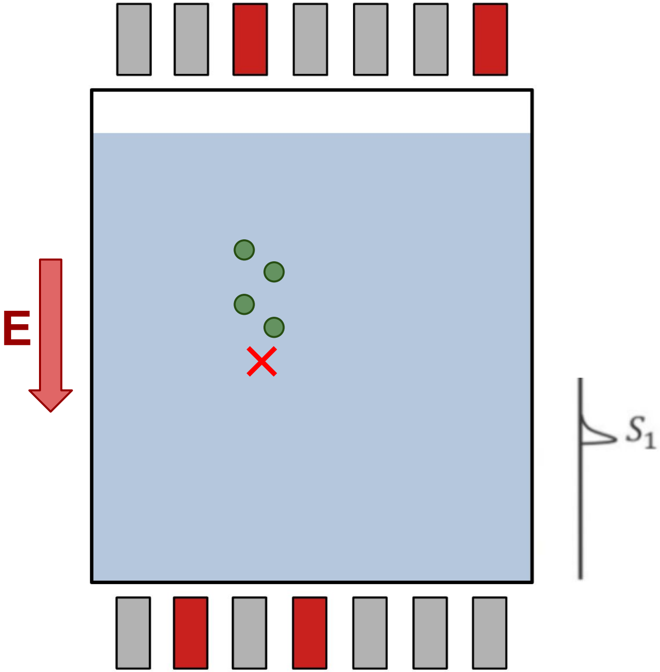

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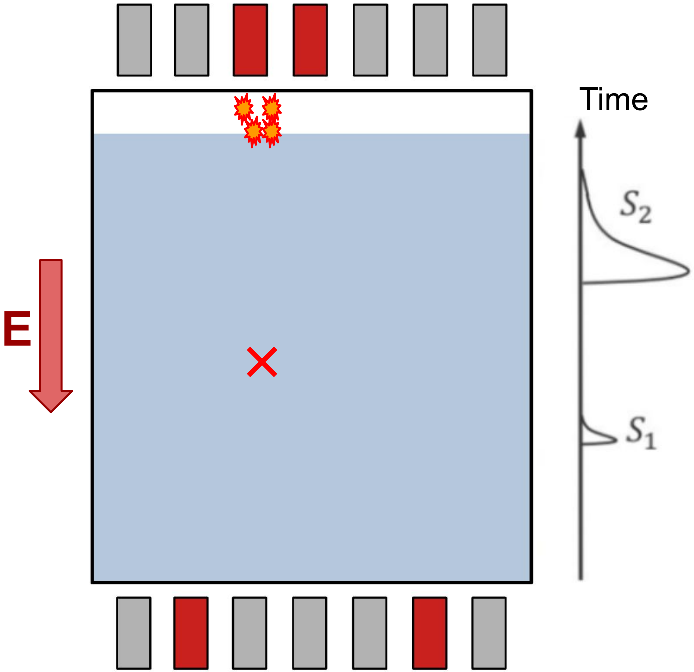

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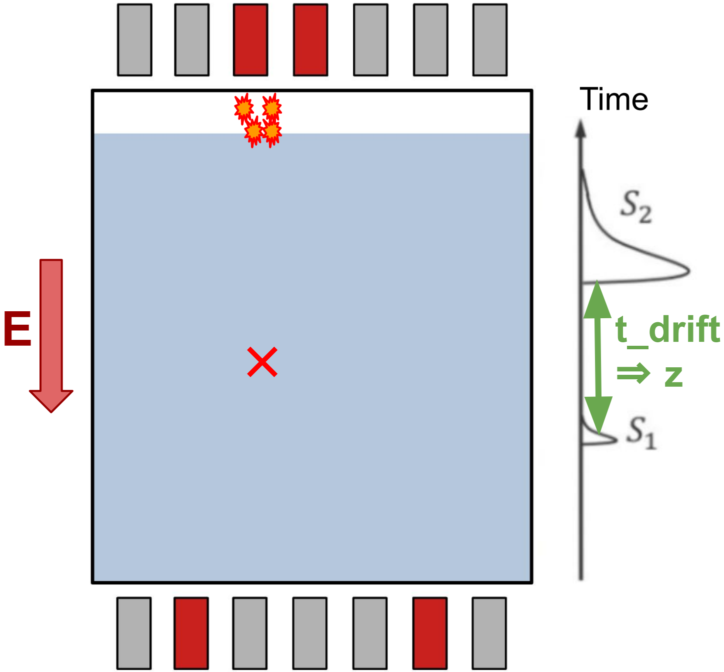

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- Energy reconstructed from total observed light

Direct Dark Matter Searches: Signal & Backgrounds

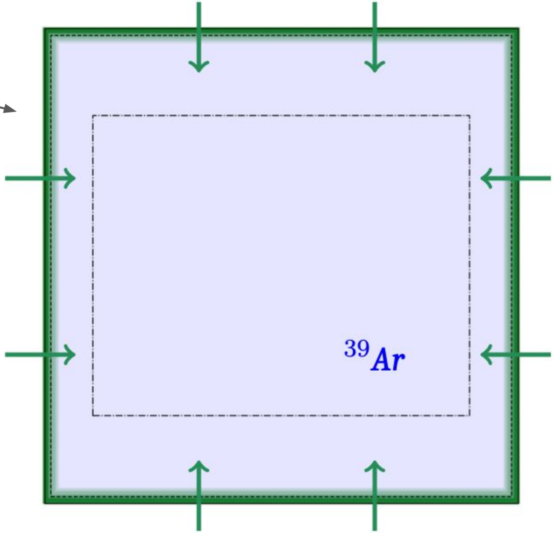
Very few expected signals ⇒ need “perfect” rejection of backgrounds

- Strategy: Use reconstructed event variables (e.g. position, energy, …) to identify background events
- Dangerous background: **Radioactive isotopes in liquid noble gas**

  ⇒ event parameters are the most similar

  ⇒ Argon: **Ar39 β-decay**

Fiducialisation not helpful



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Take advantage of different interaction types:

WIMPs: Weak interaction ⇒ Nuclear Recoils (**NR**)
e+/e- : electromagnetic ⇒ Electron Recoils (**ER**)

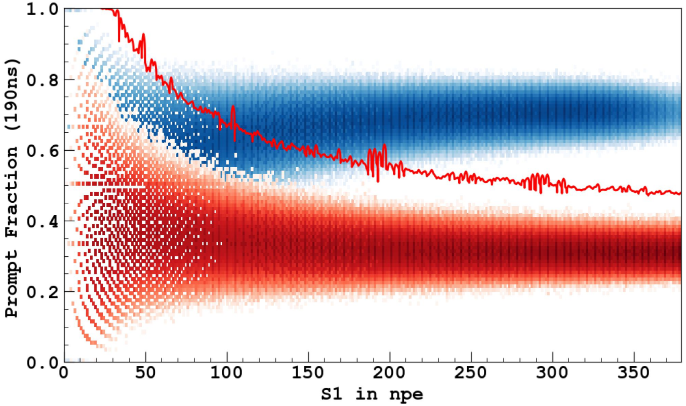
Argon: **Faster scintillation** from NR
⇒ Pulse Shape Discrimination
Separates NR & ER

Pulse Shape Discrimination in Liquid Argon - S1 Signal

Argon: **Faster scintillation** from NR

Define prompt fraction:

$$f_p = \frac{q_{prompt}}{Q_{Tot}}$$



NR

ER

Pulse Shape Discrimination in Liquid Argon - S1 Signal

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Acceptance Region
If done well: **background free**

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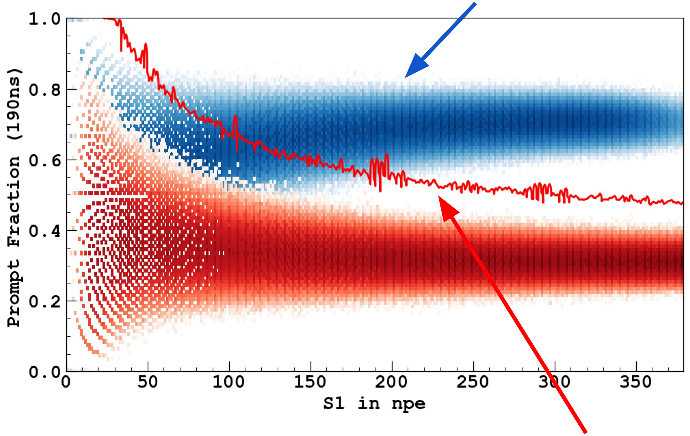

NR

ER

Rejection Cut

Pulse Shape Discrimination in Liquid Argon - S1 Signal

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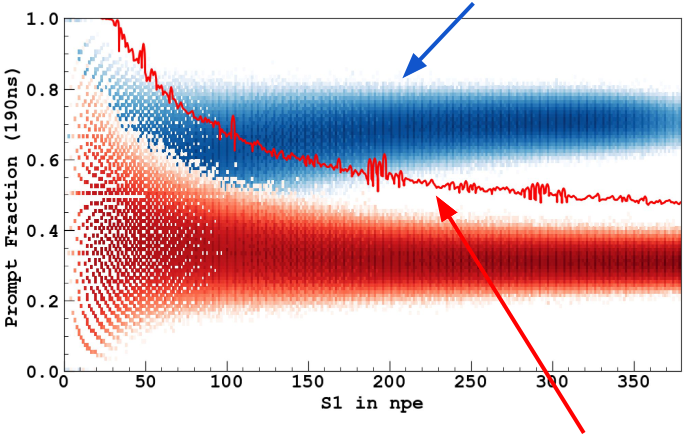


NR

ER

Rejection Cut

- Rejection cut determines acceptance probability for NR events
  ⇒ Needed for **sensitivity projection**
- Detector/electronics effects change the prompt fraction
  ⇒ Need to be aware of potential fluctuations & worst-case scenarios

Studying Pulse Shape Discrimination in DS20k

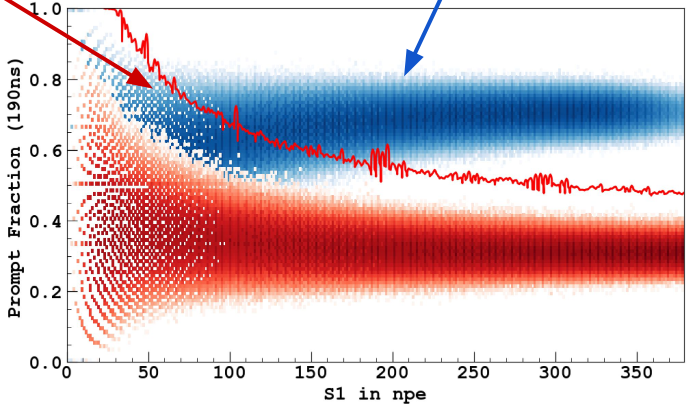
Challenges:

- Cut placed in low-statistics region ⇒ high-stats samples needed
- Large computation time ⇒ toy-Monte Carlo instead of full simulation

Trade-off

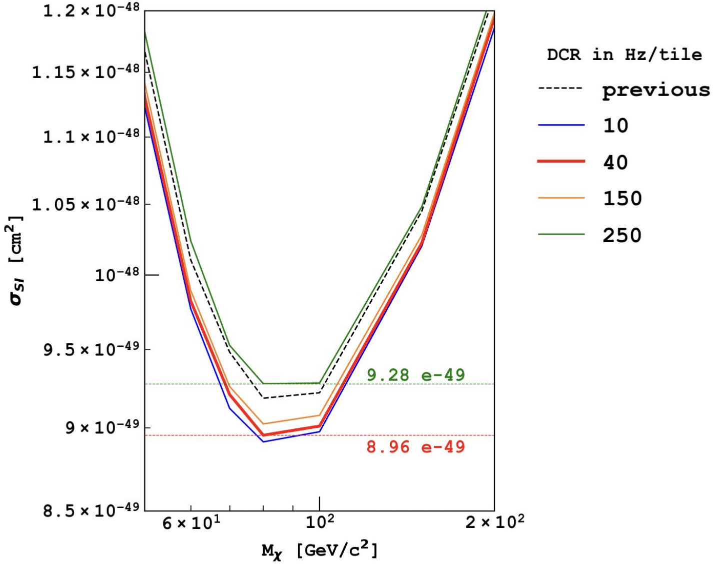
- Small changes can have a relevant effect
  ⇒ Requires careful investigation what to include

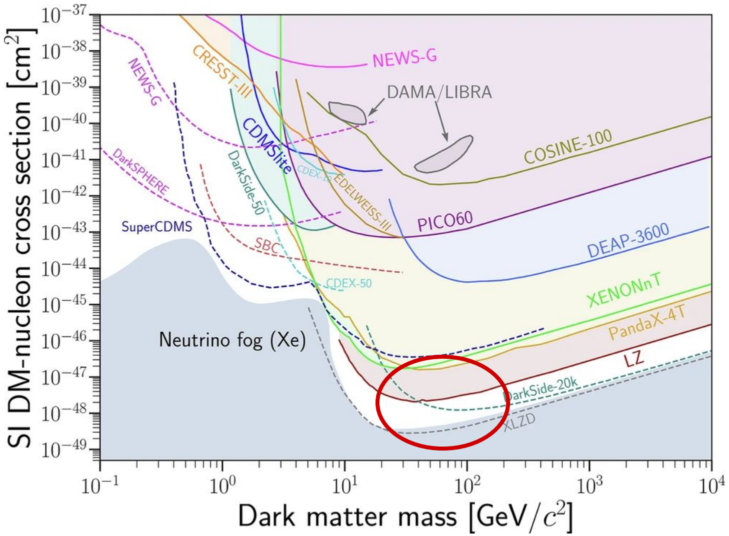
Potential Signals



Example: Influence of Dark Count Rate on DS20k sensitivity

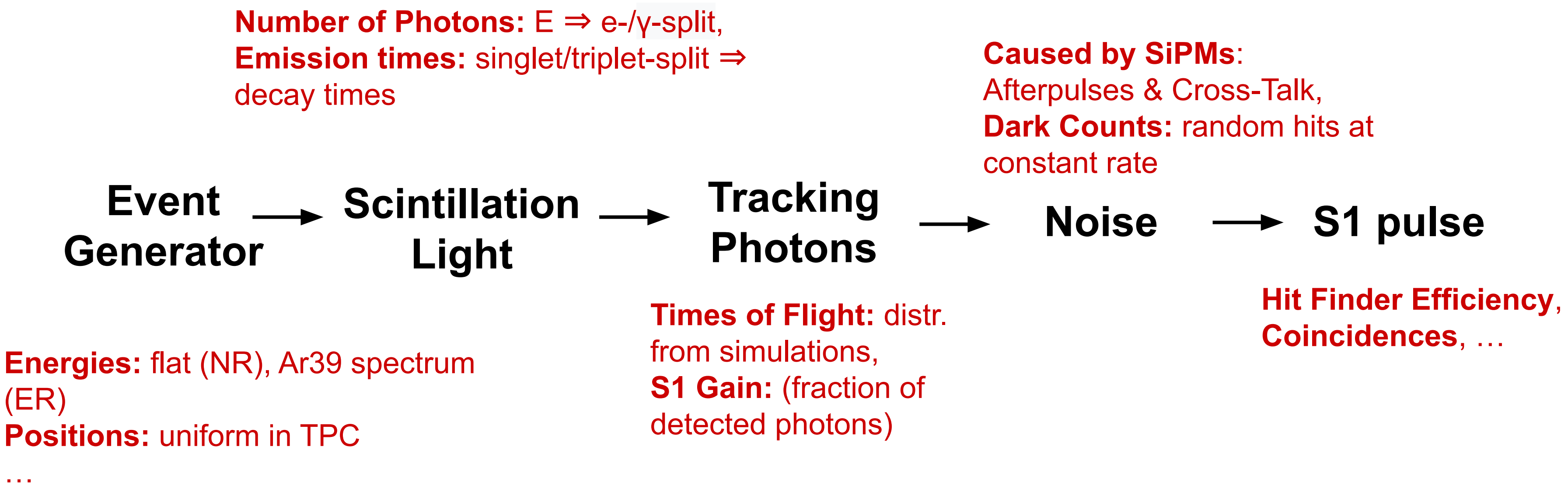
Randomly registered photoelectrons (unrelated to events)





Small effect in most sensitive region ⇒ shows robustness of the detector

Back-up: Brief Logic of the Toy MC



Event Generator → **Scintillation Light** → **Tracking Photons** → **Noise** → **S1 pulse**

Energies: flat (NR), Ar39 spectrum (ER)
Positions: uniform in TPC
…

Number of Photons: E ⇒ e-/γ-split,
Emission times: singlet/triplet-split ⇒ decay times

Times of Flight: distr. from simulations,
S1 Gain: (fraction of detected photons)

Caused by SiPMs:
Afterpulses & Cross-Talk,
Dark Counts: random hits at constant rate

Hit Finder Efficiency,
Coincidences, …

Backup: Pulse Shape Discrimination in Liquid Argon - S1 Signal

Scintillation in Noble Gases

- Light emitted through deexcitation of excited dimers

  Two lowest-lying states: singlet & triplet levels ⇒ **populated differently by NR & ER**

  $\tau = 6$ ns

  $\tau = 1600$ ns

  Argon: **vastly different lifetimes**

Define Prompt fraction:

$$f_p = \frac{q_{prompt}}{Q_{Tot}}$$

Photoelectrons observed within short **prompt window** (e.g. 190ns)

Photoelectrons observed over **whole gate** (e.g. 8µs)