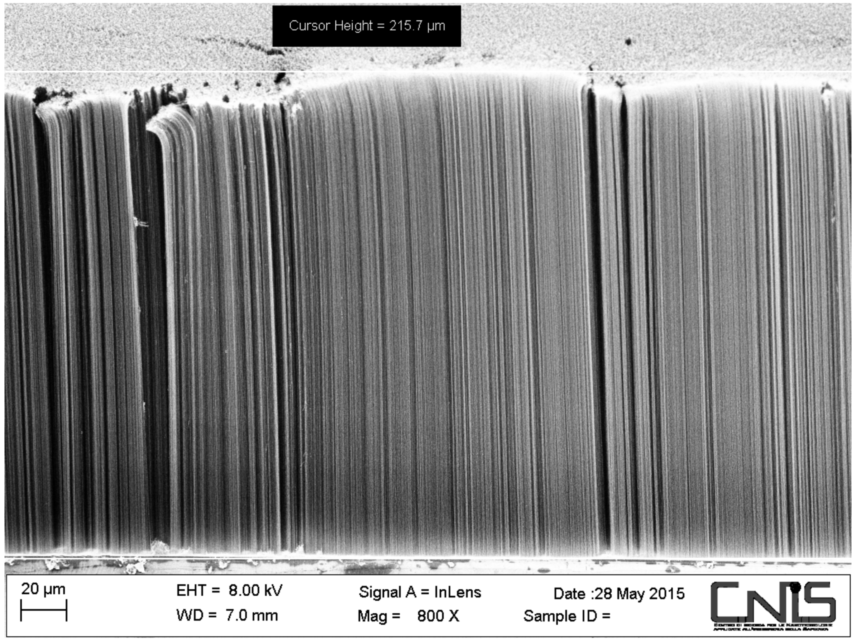


Outlook on direct dark matter searches

Gianluca Cavoto Sapienza Univ. Roma

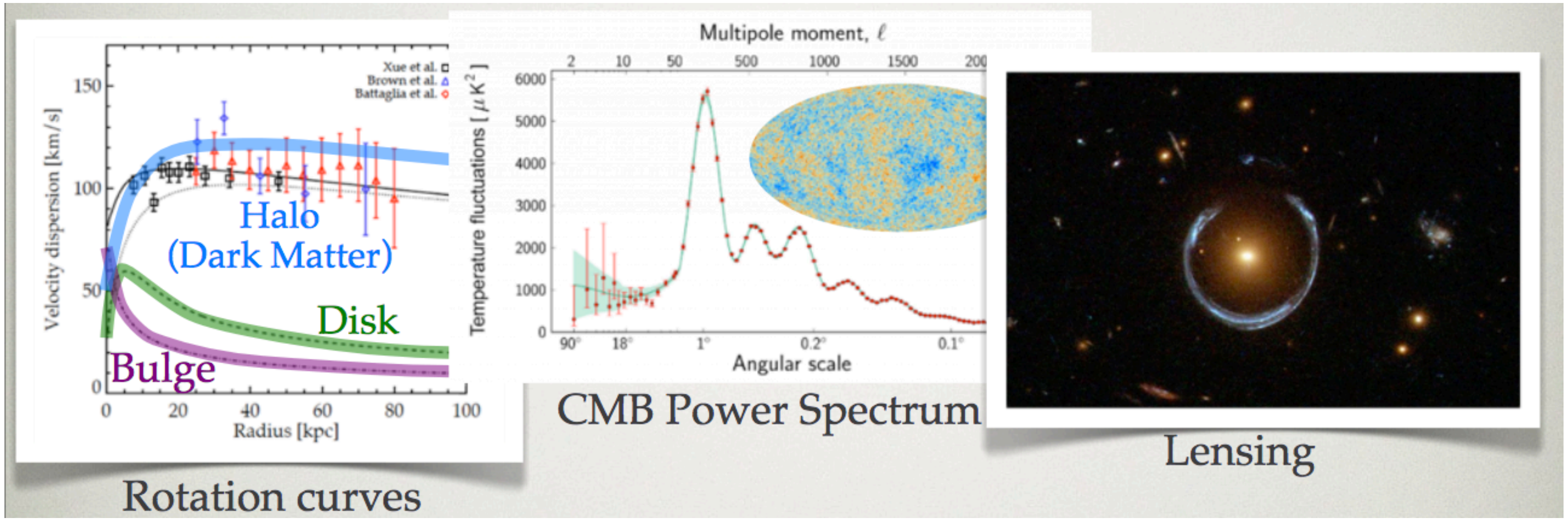
23 Nov 2017

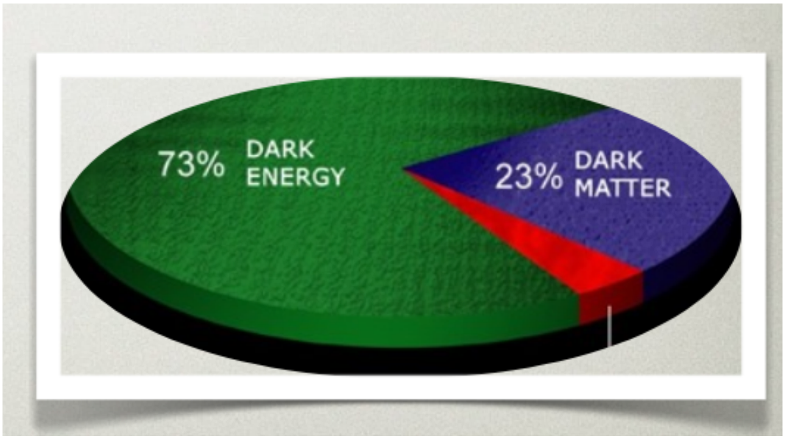
Outline

- ***Not a review, a (very) personal view on the future with a strong bias on the activity here in Rome***
- **WIMP** and detectors with ton-year exposures
- **Directionality** - a tool to reject background
  - Low pressure gas detector (CYGNUS), anisotropic targets (CNT)
- **Sub-GeV** dark matter
  - Detecting electrons
  - PTOLEMY and dark matter
- A comment on anti-particles in the cosmic rays
  - Hadronic cross sections at accelerators

Astrophysics and cosmology, evidences

- At very different scales, a robust evidence

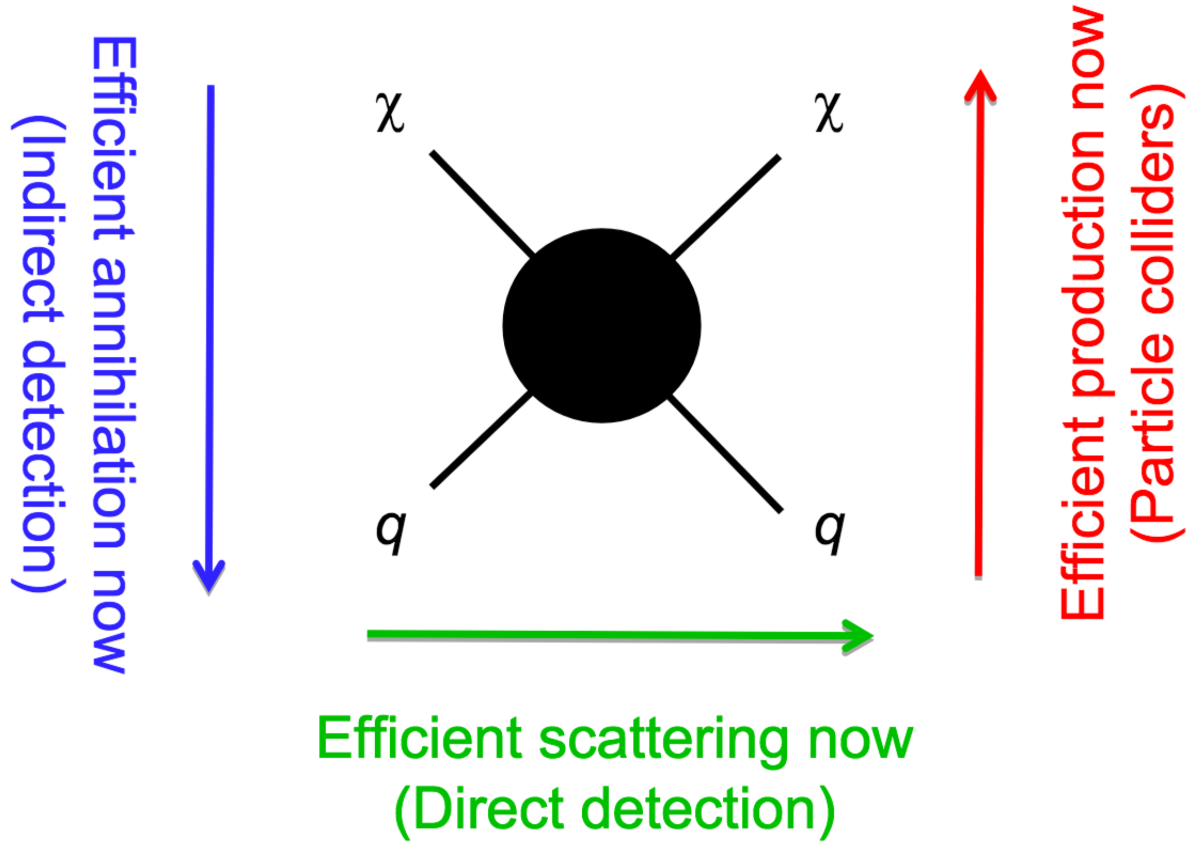




Strategies

DM particles in our galaxy annihilate:

a signal in cosmic ray incompatible with known sources



DM particles are produces in a lab (LHC)

Dark sector particles (mediator?)

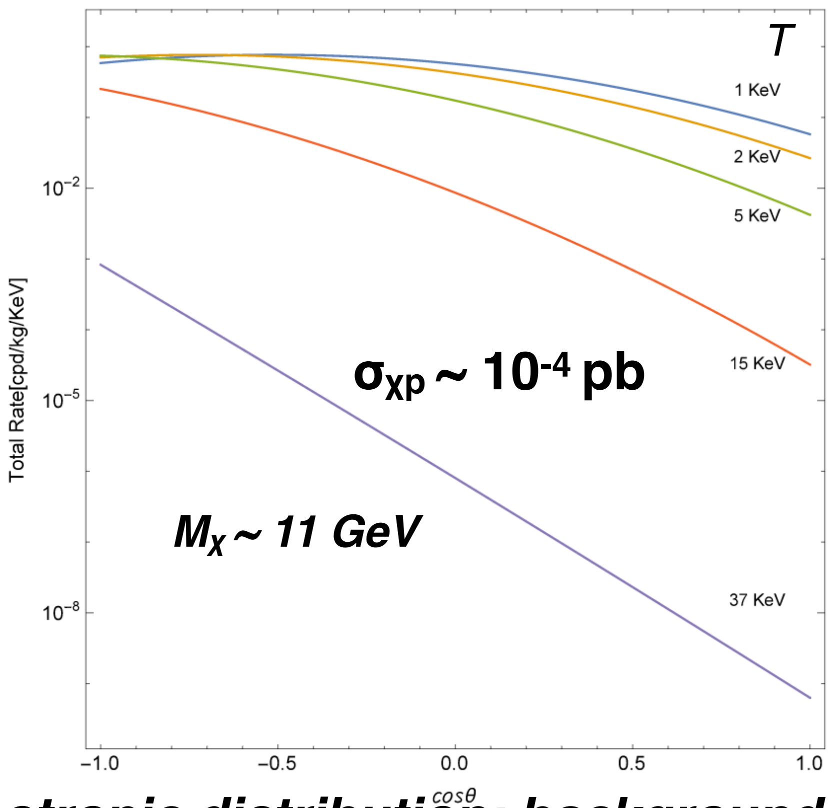
DM is around us, scatter on conventional matter (nuclei, nucleons, electrons)

Direct detection: the name of the game

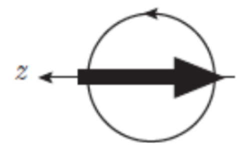
- No-one knows ***what*** a dark matter particle is
- **WIMP** model: non relativistic 10-1000 GeV particles with cross section much larger than solar neutrino weak cross section

ELASTIC scattering
of a WIMP χ
on a C ion

Decreasing experimental threshold



We ***move*** with the Sun in a galactic halo of DM particles

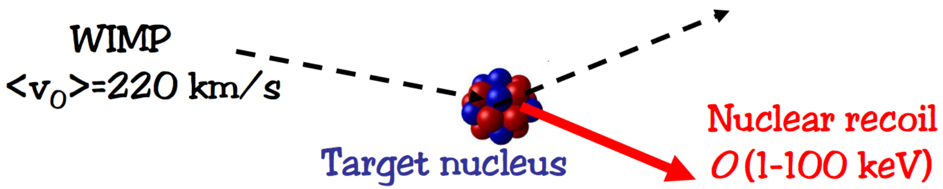


θ = π
WIMP "wind"

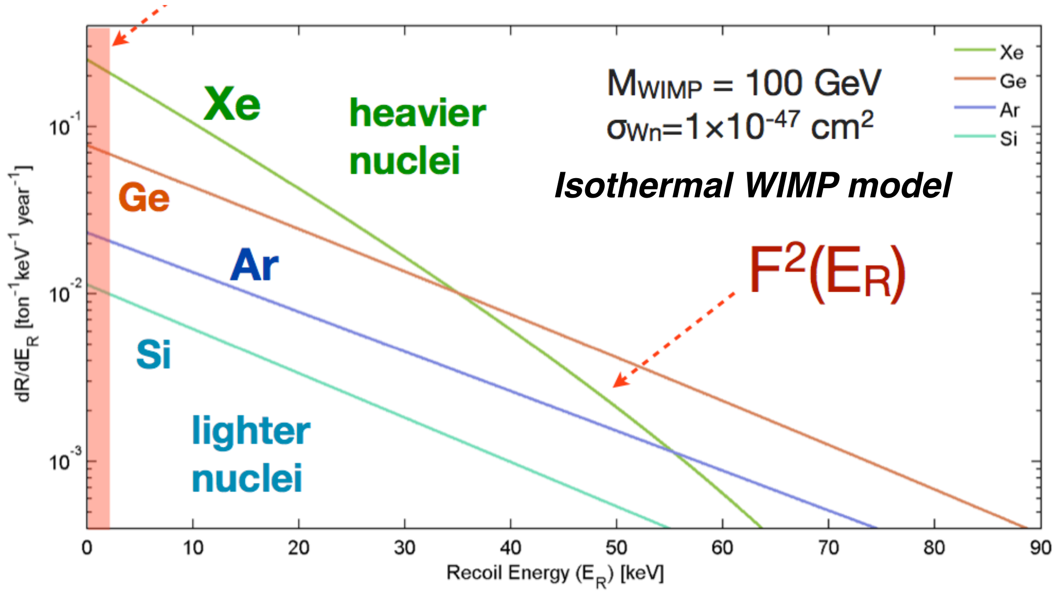
Anisotropic distribution: background rejection

INFN Istituto Nazionale di Fisica Nucleare

Response to elastic scattering



- WIMP (and neutrinos) interact **coherently** with a nucleus
- Energy release is **tiny**
- Rate is **few** events/Kg/year

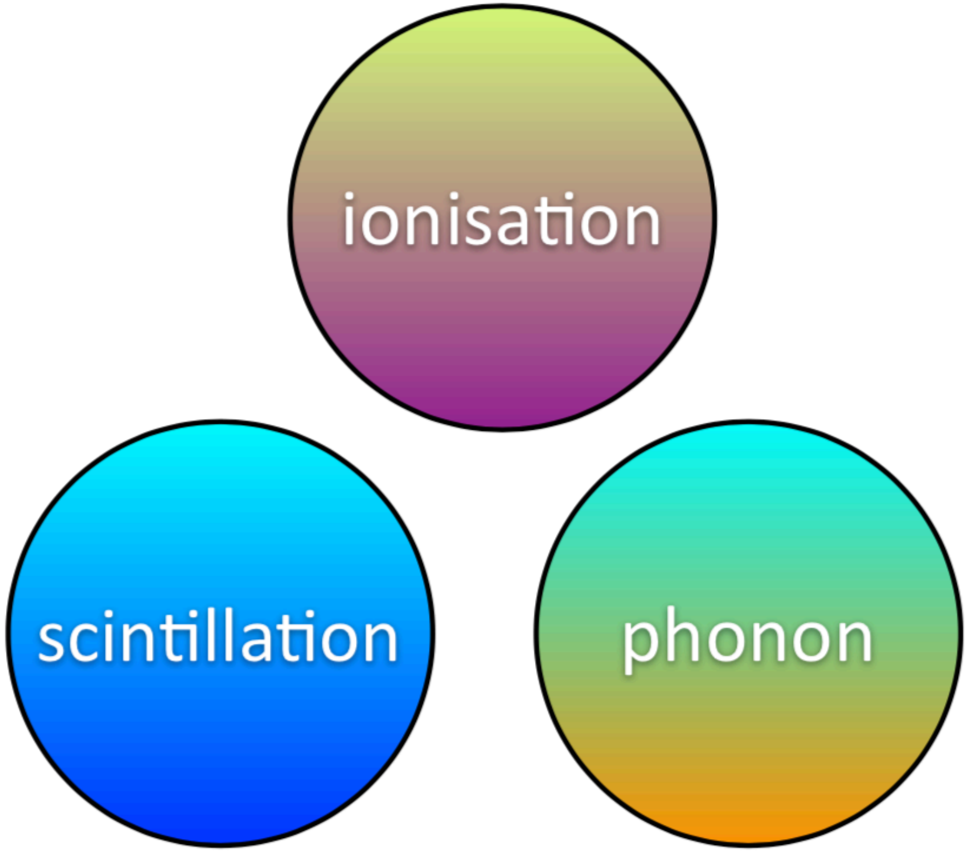


- Interaction might be **spin**-*independent* or spin-*dependent* (not all the nuclei are equivalent)
- Some effect of the **nuclear form factor**

*But other scheme are possible, interaction with **electron**, **inelastic** interaction…*

Multiple experimental signatures for signal

- Low threshold means (often) **low temperature**
- Scalability to **large mass**
- Use more than one carrier of information!
  - Rejection of electron background



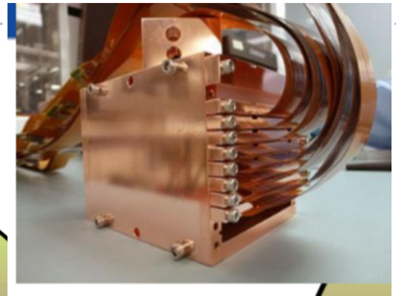
Large masses

Low threshold (very cold!)

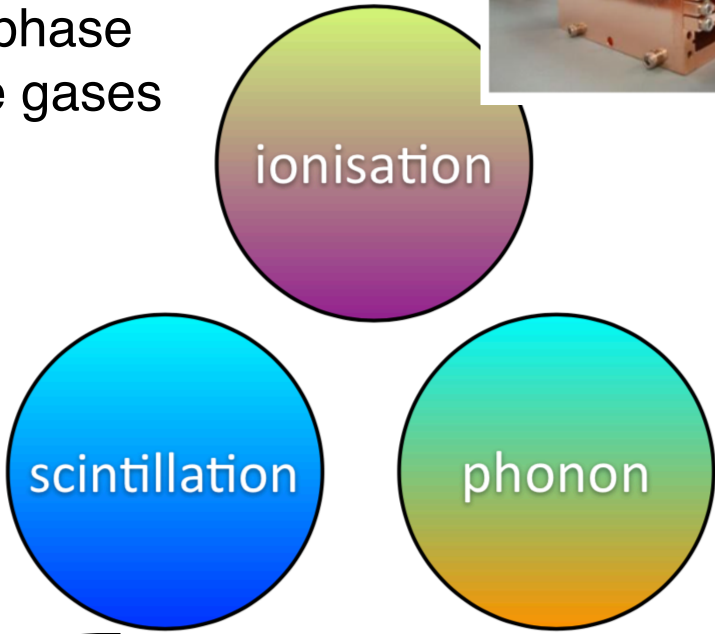
*One key element is to calibrate the energy scale of nuclear recoils (**quenching factors for ionisation and scintillation**)*

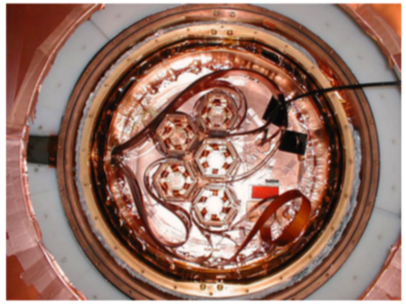
Multiple strategy for signal

Two phase noble gases



CCD

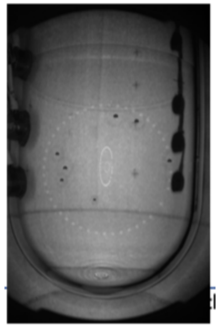




Cryogenic Bolometers

Inorganic Scintillators

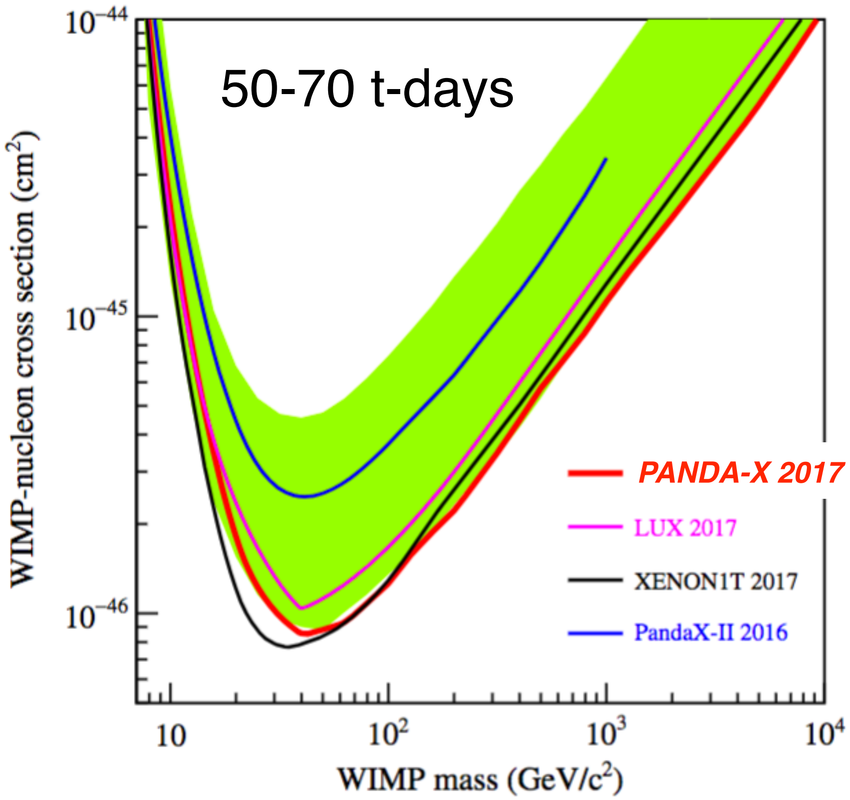
Cryogenic Scintillators



Bubble chambers

PANDA-X and XENON-1T results

Two phase noble liquid



- Cross section excluded in Xe target down to $\sigma_{\chi p} \sim 10^{-10}$ pb (at 40 GeV)
- Close to the neutrino ***background*** limit (neutrino from the Sun)
- Reduced mass sensitivity below 10 GeV: affected by threshold (and resolution) at low energy recoils

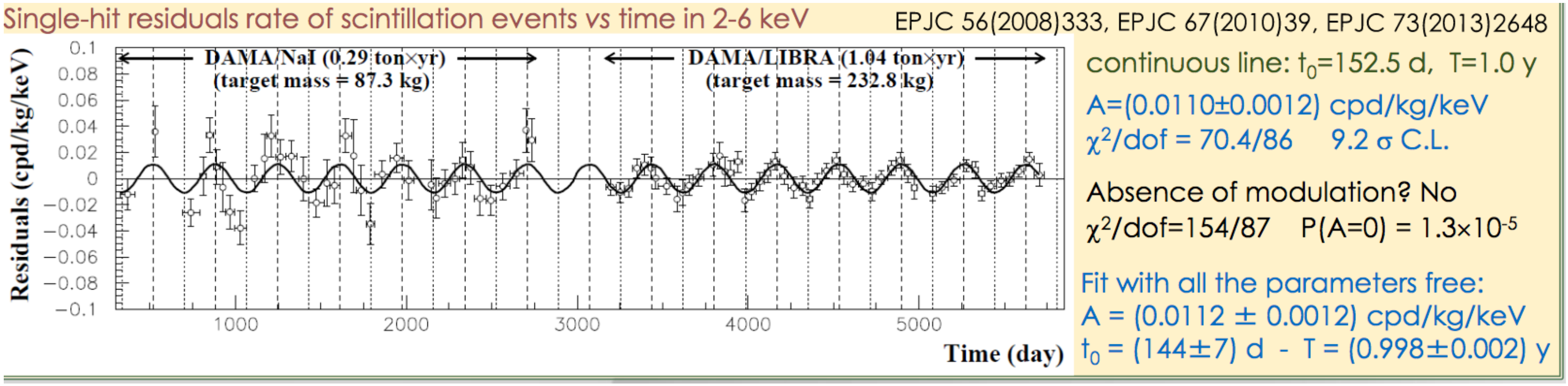
X. Cui et al. (PandaX-II Collaboration), Phys. Rev. Lett. 119, 181302 (2017).

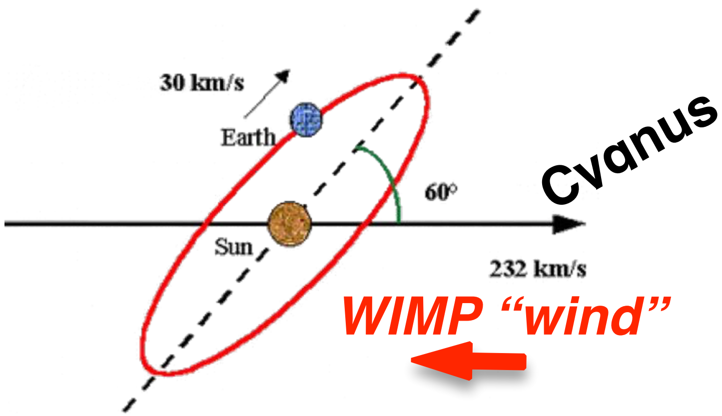
E. Aprile et al. (XENON Collaboration), Phys. Rev. Lett. 119, 181301 (2017).

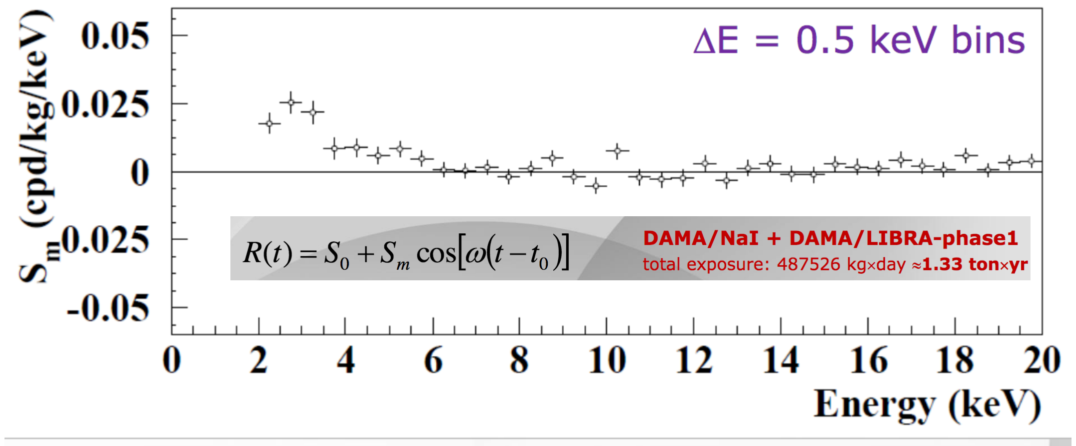
DAMA/Libra results

Scintillator

- Year-modulated signal in NaI **crystal** target (ton-y exposure)
- All the interpretation in terms of background not convincing so far.

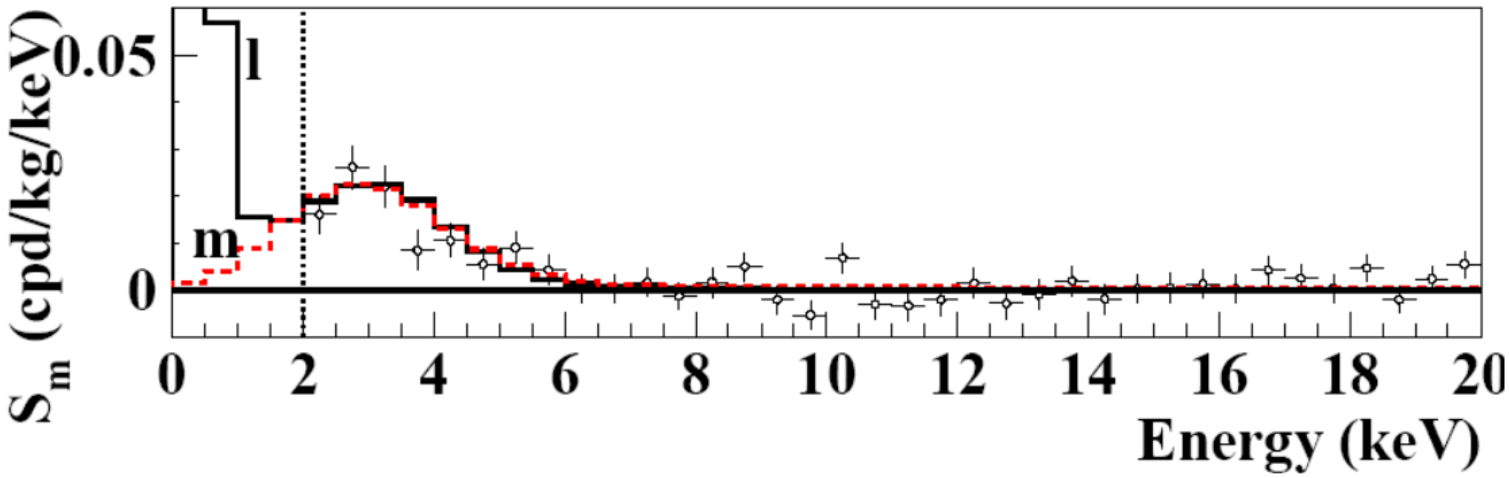






Preferred values for $\sigma_{\chi p} \sim 10^{-40}$ - 10^{-41} cm^2 with $M_\chi \sim$ 10 - 100 GeV

Lowering PMT threshold



- **Lowering** PMT threshold (higher Q.E. PMT) can shed light on **different models** of the WIMP distributions (halo, stream, etc.)
- Diurnal modulation might be investigated (large exposure)

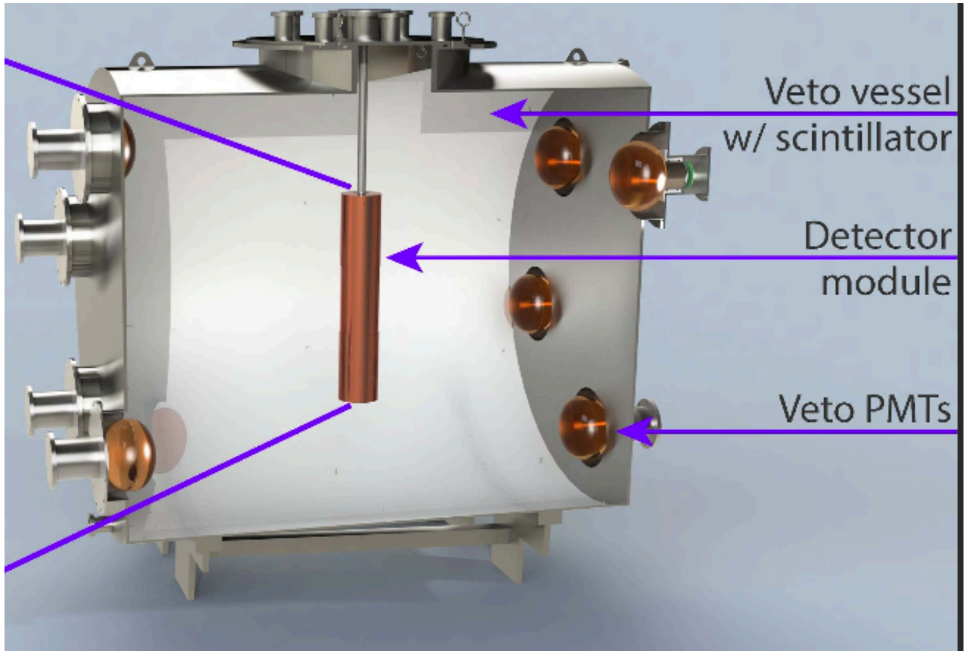
If an anisotropic scintillation crystal is found(**ZnWO**?), measure the WIMP direction! See later.

SABRE

Scintillator

- Radio-pure new NaI crystals
  - Goal is 10x better than DAMA/LIBRA
- Active veto (scintillator, 3x rejection) + additional shielding
  - Eventually expose the same target in the southern emisphere (Stawell gold mine, Australia)

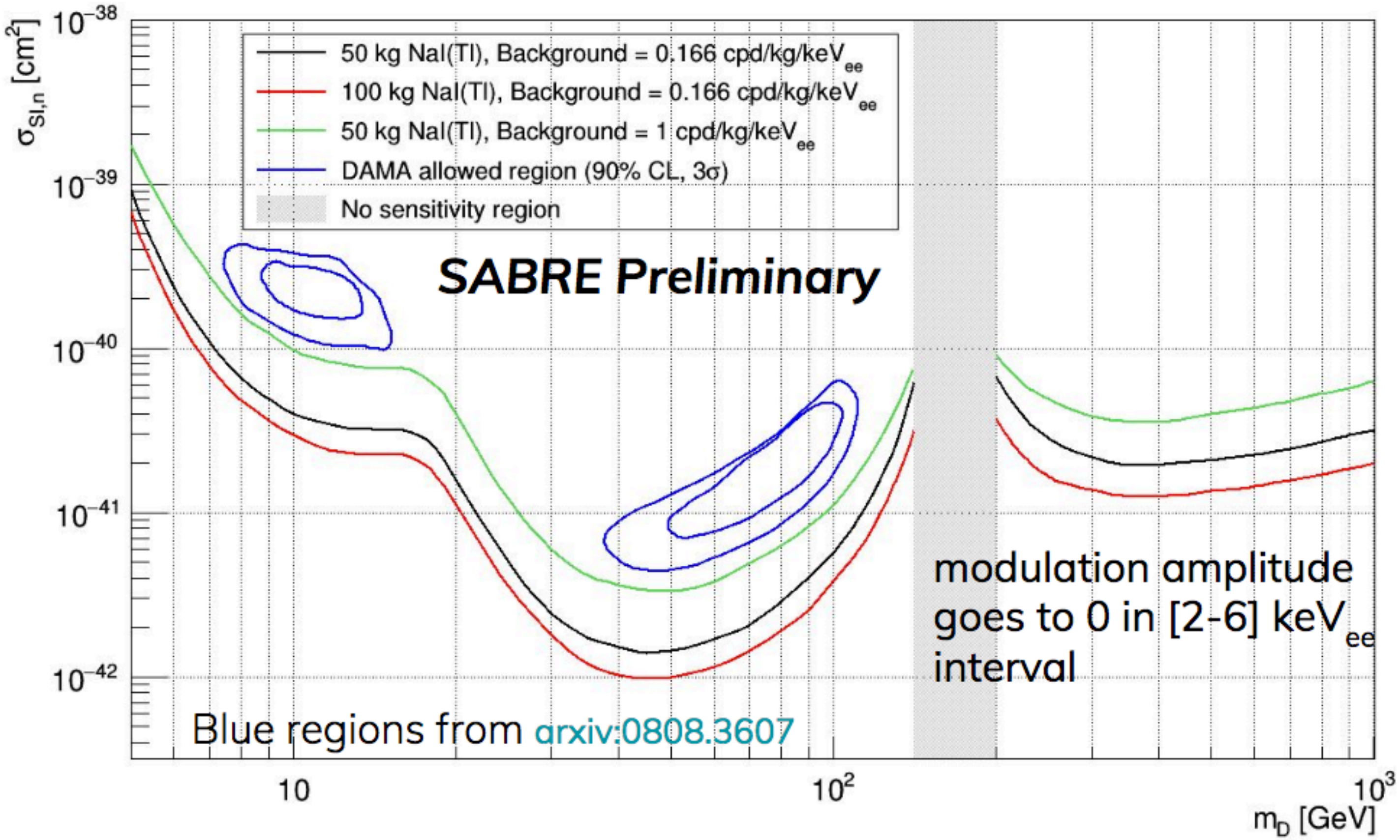
If same effect seen as in DAMA/LIBRA, confirm modulation measuring it in a different location (otherwise local systematics effect)



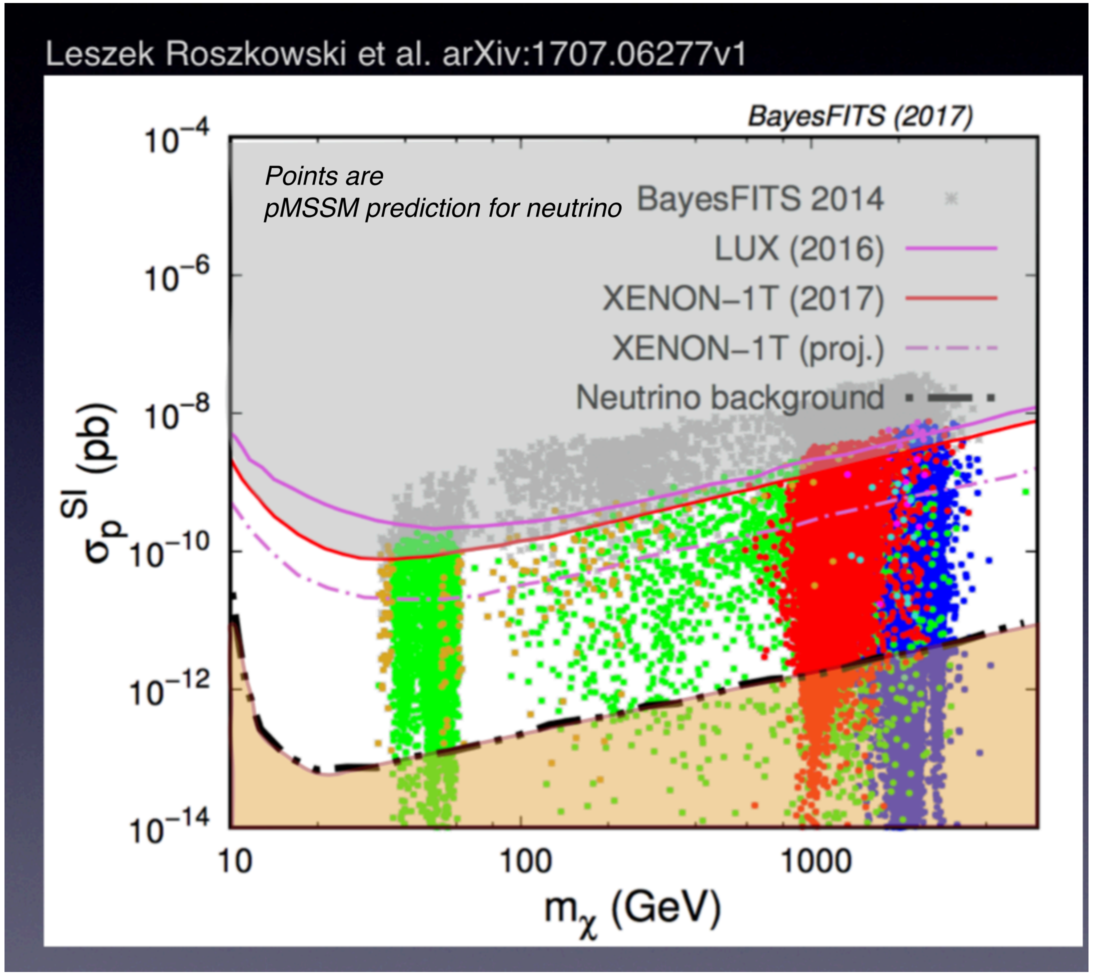
Prospect for SABRE

- Reproduce DAMA-LIBRA results

Exposure: 150 Kg y



Where are we aiming to ?

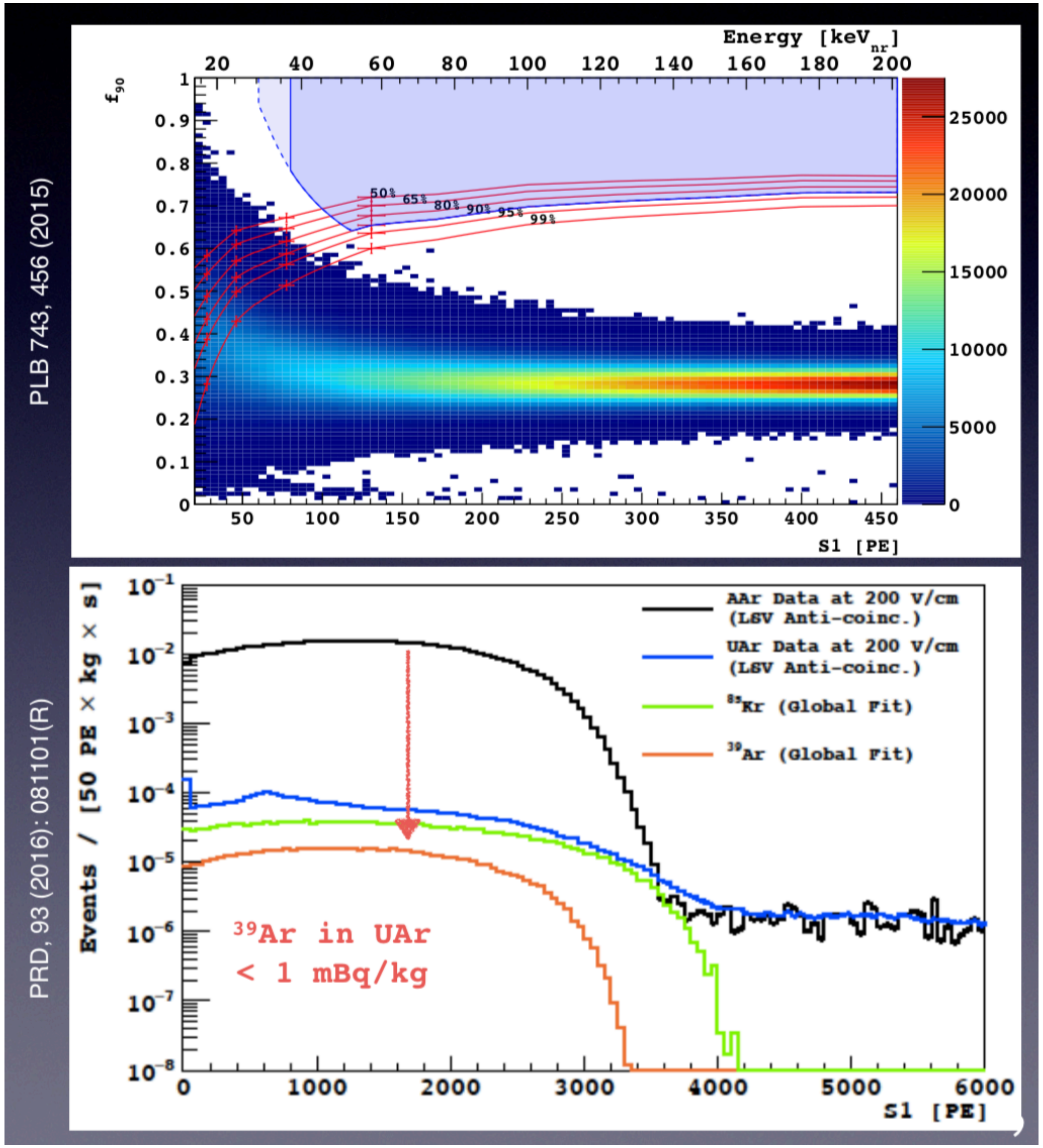


- Need multi-ton mass
- Need several years data-taking
- Is the solar neutrino background the end of the story ?

DARKSIDE

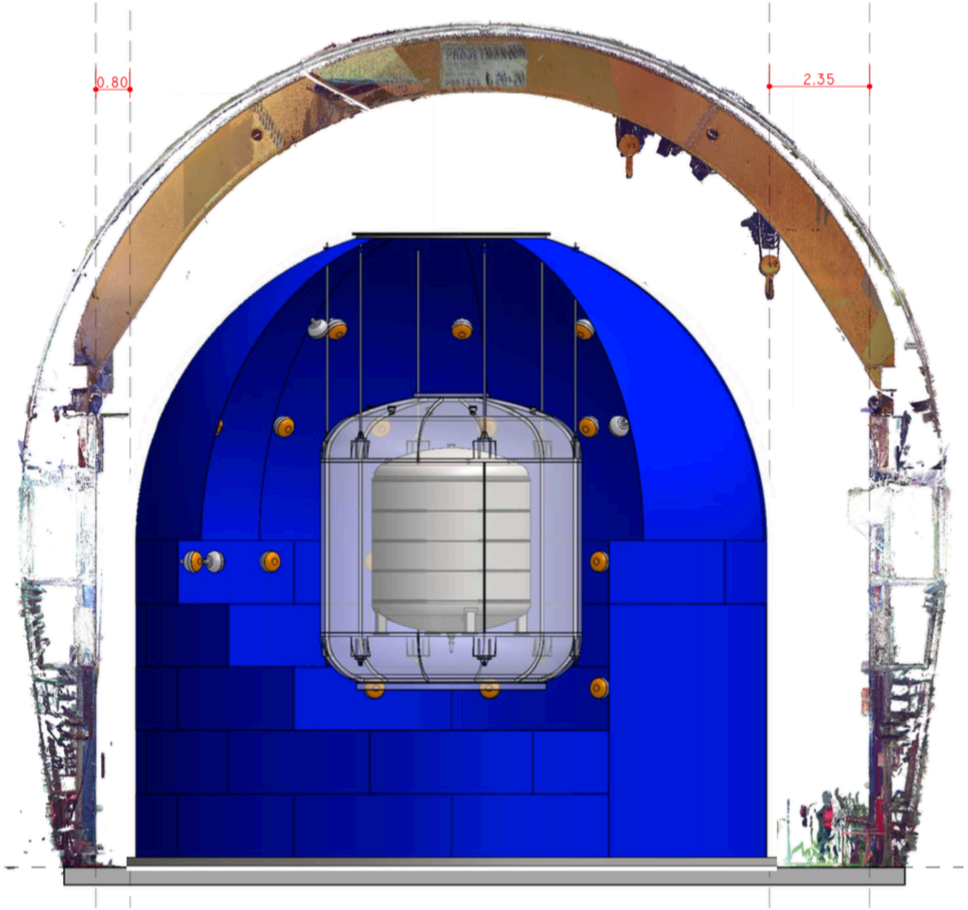
Two phase noble liquid

- Good for high energy recoils
- ***Ar***: pulse shape discrimination between electron and nuclear recoil
- Scint: 40 ph./keV light yield
- Ionization 20 eV/e
- BUT:
  - Need to remove radioactive ^{39}Ar



20 K Ar TPC

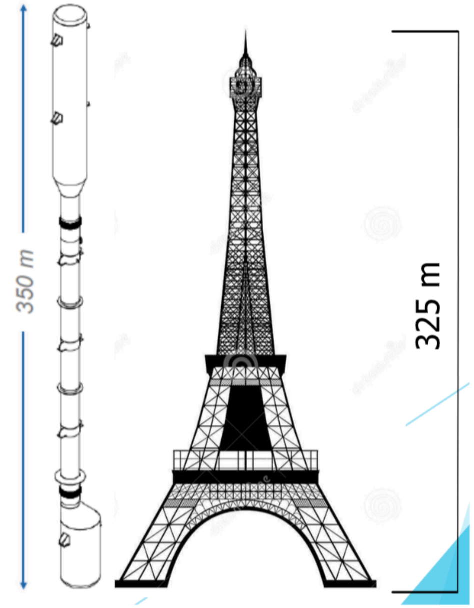
- 30 ton total, 20 ton fiducial, dual phase TPC, underground argon
- inside a liquid scintillator active neutron veto
- inside a 15m diameter 16m tall water tank, as active muon veto
- 15m^2 SiPM sensors (radiopure, increased LY, essential to keep PSD threshold low)
- Scalable design for application to larger scale detector
- Start of operation in 2021



100 ton yr background-free exposure

A big enterprises

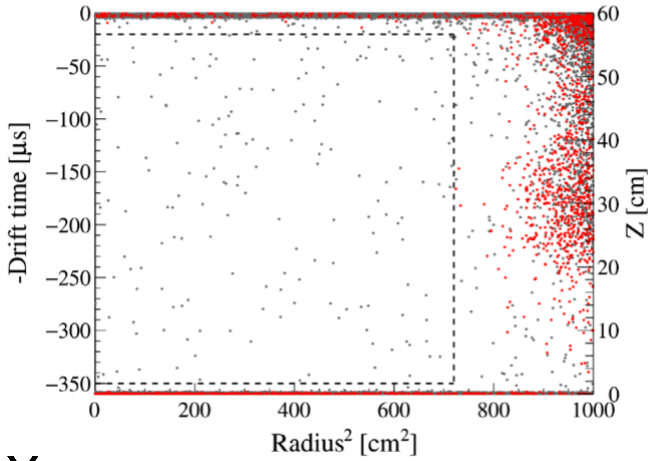
- Extract underground Ar and then purify it (ARIA project)
- Refurbishing of a Sardinia coal mine to host distillation tower



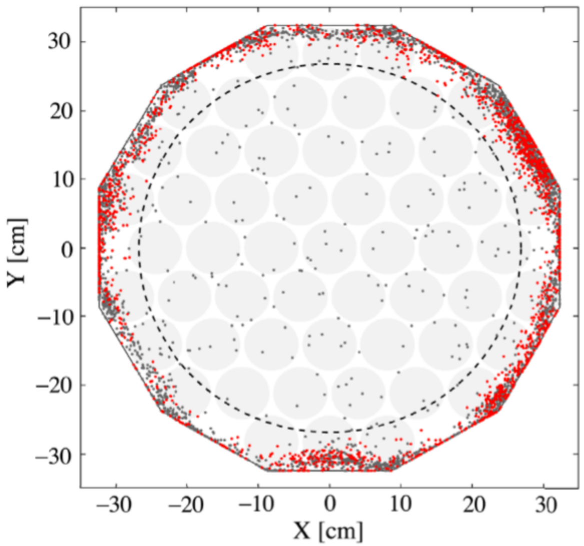
- In collaboration with local authorities
- Construction at CERN
- Potential of a broader technological impact

Fiducialization

Panda-X



(a) The r^2-z distribution.

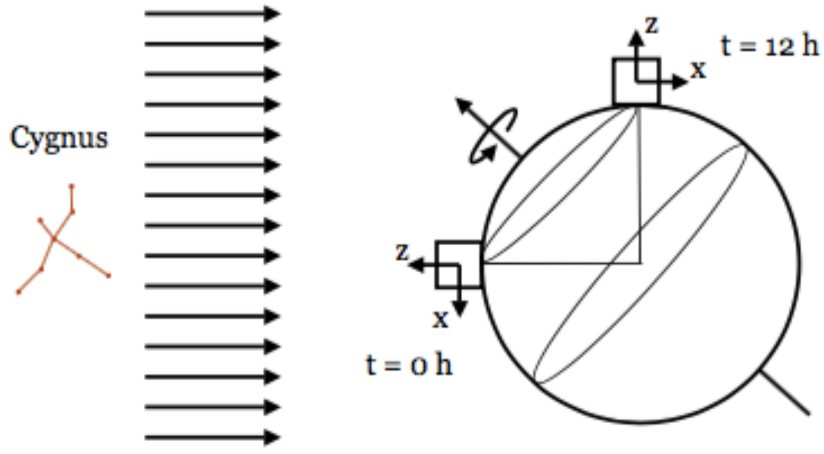


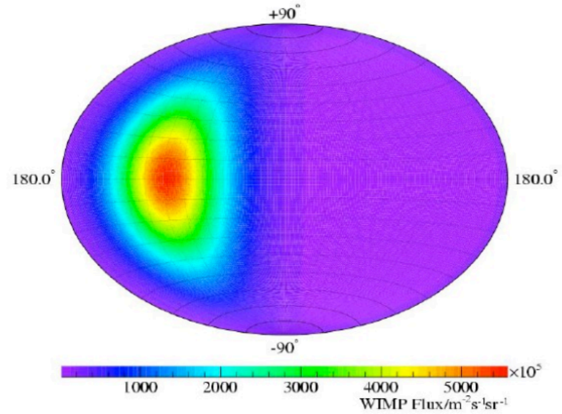
(b) The x-y distribution.

- The box containing the target material is radioactive
- Position sensitive detectors
  - Fiducial volume can be half of the total target mass.

Directionality

- **WIMP** must appear as coming from **CYGNUS**
- Nuclear recoils must reflect this feature (*dipole* distribution)
- Radioactive background is isotropic
- Solar **neutrinos** comes from the **Sun**!

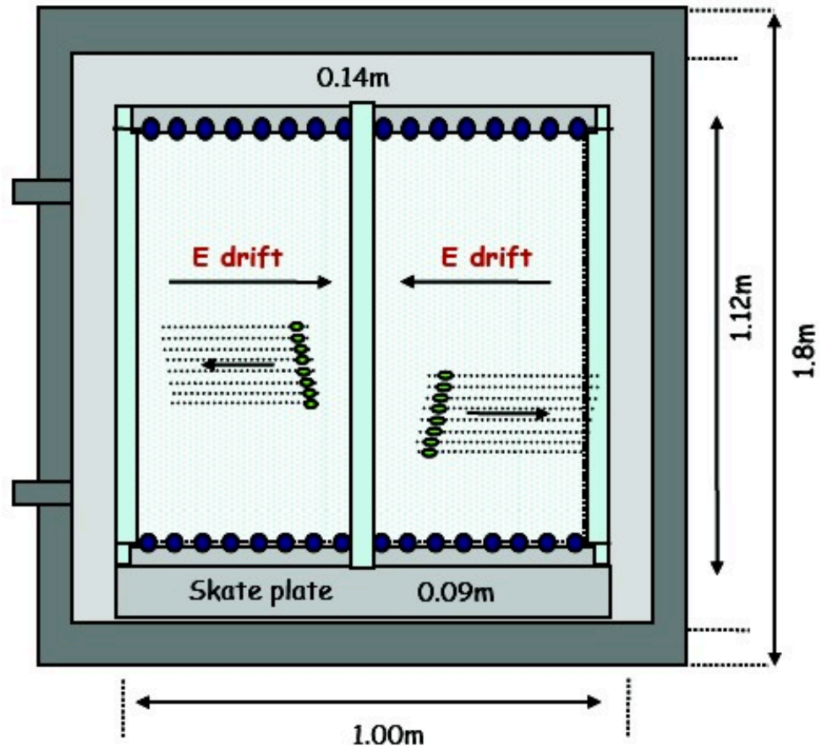


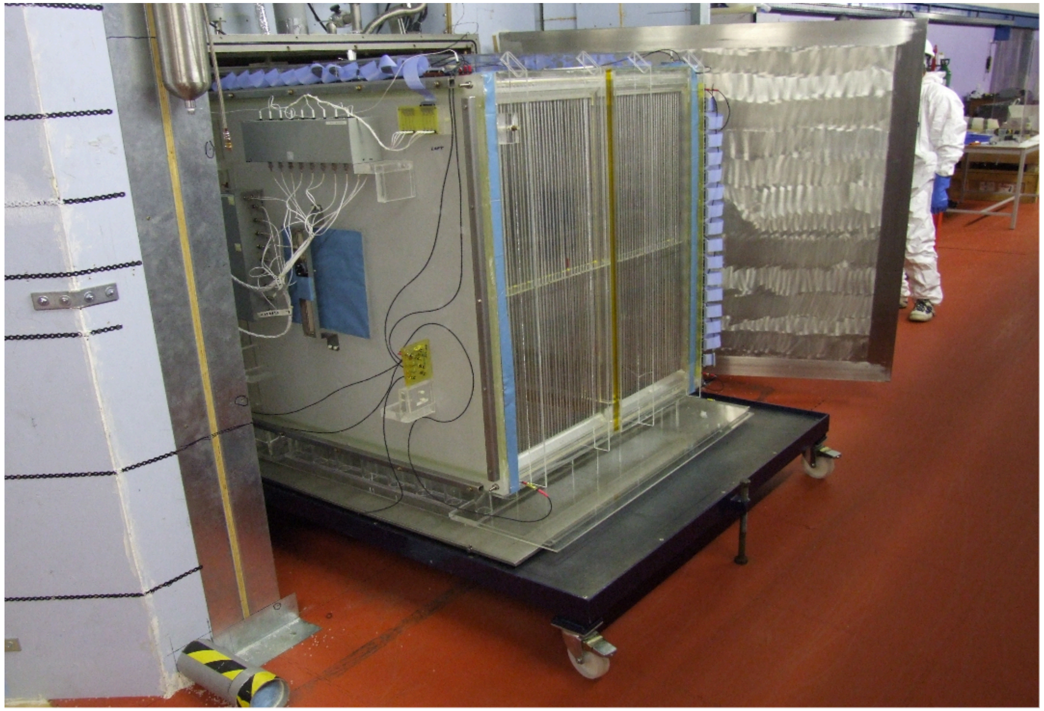


One m^3 low pressure gas TPC

Astropart.Phys. 91 (2017) 65-74

- The DRIFT detector (Boulby)

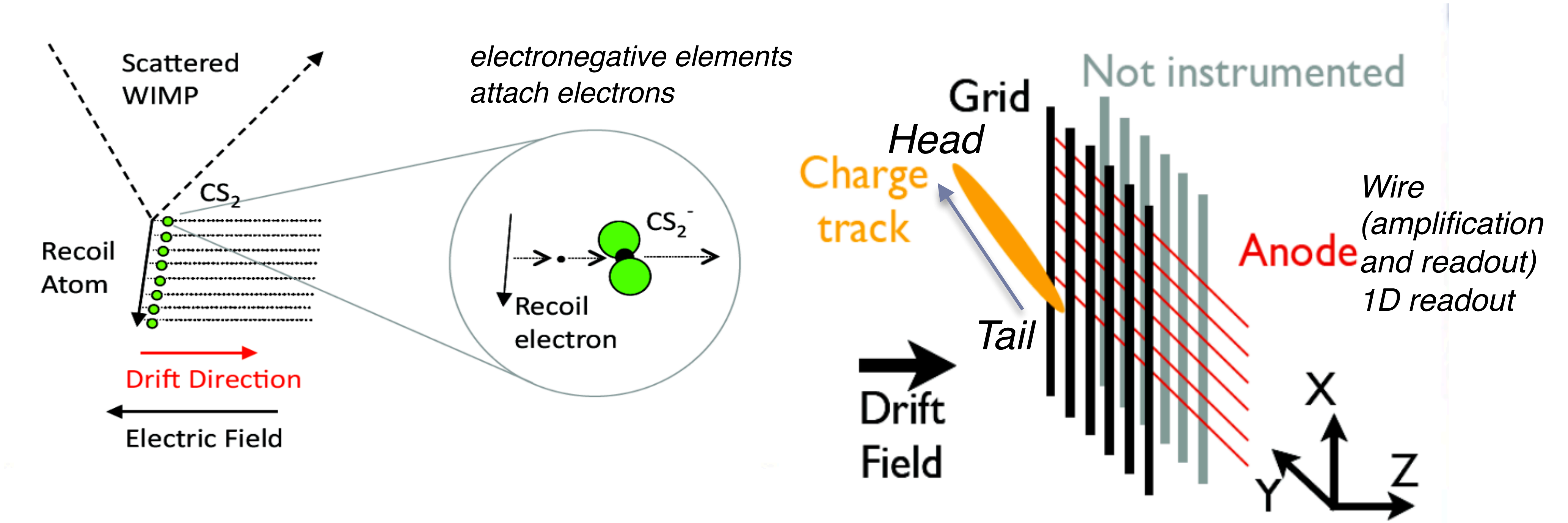




- Very small mass: gas mixture CS_2 : CF_4 : O_2 (30-10-1 torr)
- Full electron rejection up to 30 KeV_{ee}

Gas TPC

DRIFT: negative ion drift TPC

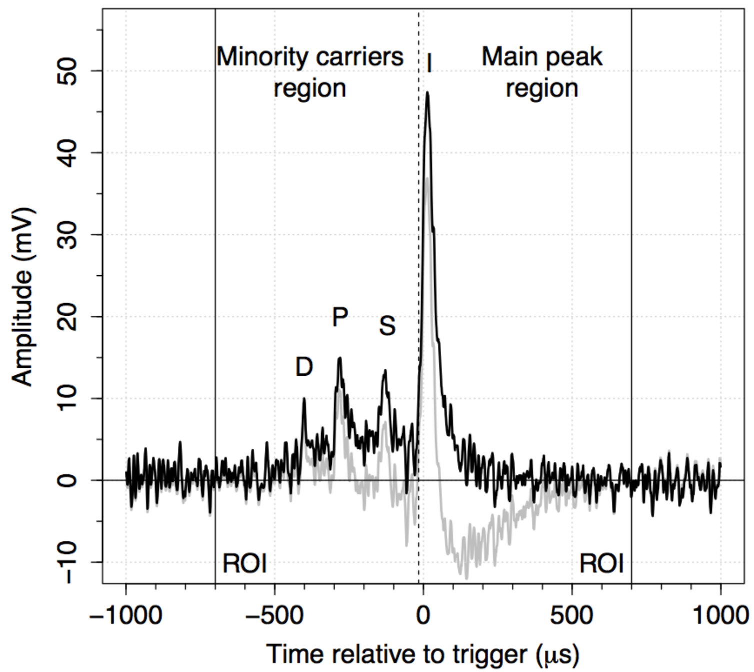


- Limited diffusion ever over long drift distance (<0.5mm on 0.5m)
- If anode segmented, a “ion recoil track” can be reconstructed: **direction**
- **Head-tail** information is valuable as well (might be enough for discrimination)

DRIFT fiducialization

- TPC with no external trigger.
  - Multiple negative ions drifting!

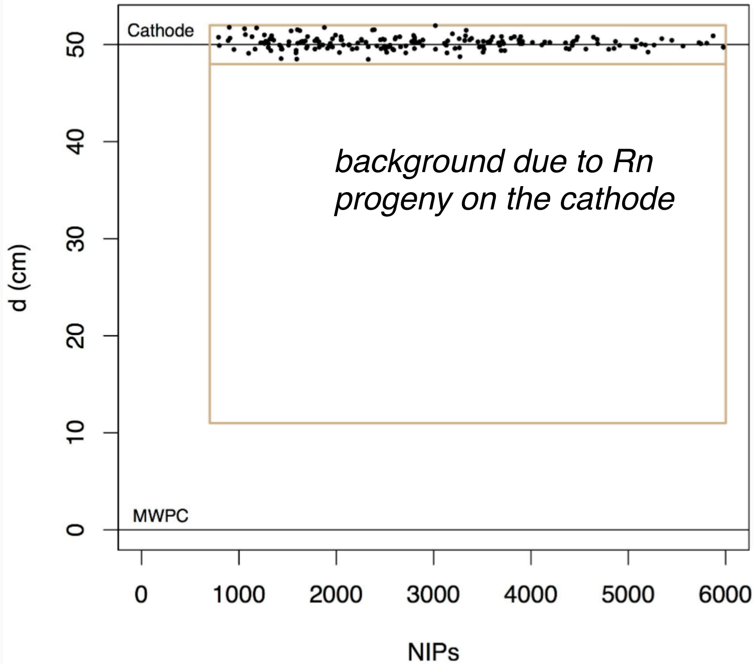
Signal on one wire



$$v_d = \left(\frac{1}{m} + \frac{1}{M}\right)^{1/2} \left(\frac{1}{3kT}\right)^{1/2} \frac{eE}{N\sigma},$$

ion ***gas***

Astropart.Phys. 91 (2017) 65-74



Z position measurement

$$z = (t_m - t_p)\frac{v^m_{drift} v^p_{drift}}{v^m_{drift} - v^p_{drift}}$$

A multi-site, ton observatory for WIMPs

- CYGNUS-TPC proto-collaboration
  - R&D effort with different technologies around the globe, hope to find the best one
- A White paper in preparation to find the optimal technology
  - It can be very simple, 1D + head-tail

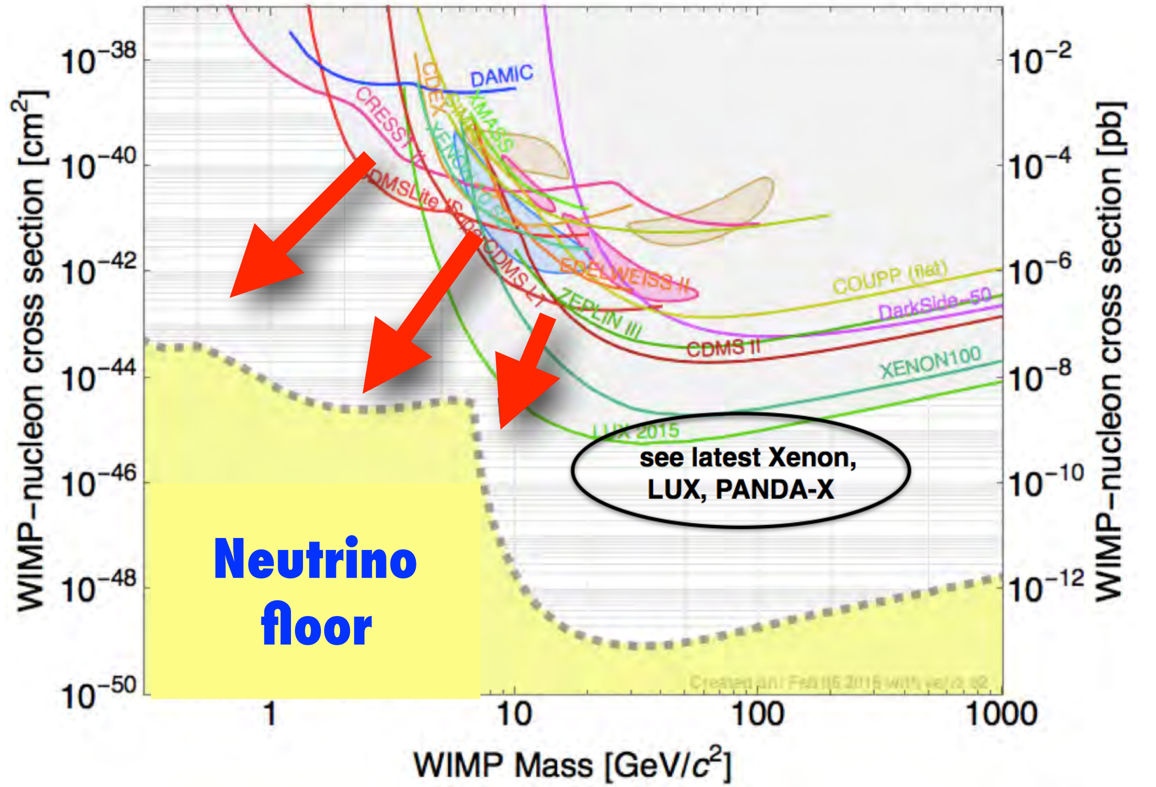
Directionality benefit from multiple sites at different latitude

CYGNUS-TPC key elements:

- Recoil sensitive TPCs with negative ions drift
- SF_6 gas mixture
  (possibly with He @ atmospheric pressure)
- Fiducialization with minority carriers
- Multiple underground sites

Low mass WIMP

- Lowering **threshold** in cryogenic detectors
- Lowering **mass** of the target nucleus
- **Gamma rejection difficult at low WIMP masses: new techniques ?**

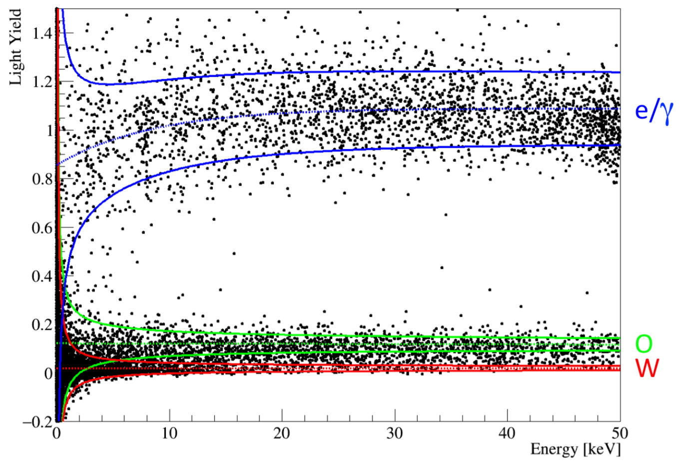


CRESST_III

Cryogenic scintillator

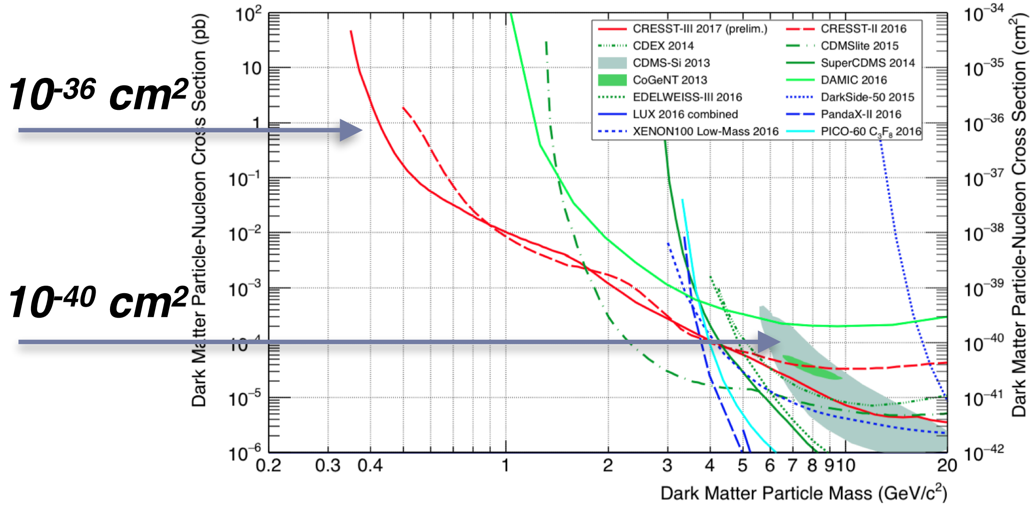
- Scintillation + phonon (TES) in $CaWO_4$ crystals (15 mK)
  - A 100 eV threshold, non-zero background though!

Detector A – neutron calibration



Detector A – 100eV threshold analysis

The exclusion limit



He based detector: UNDER

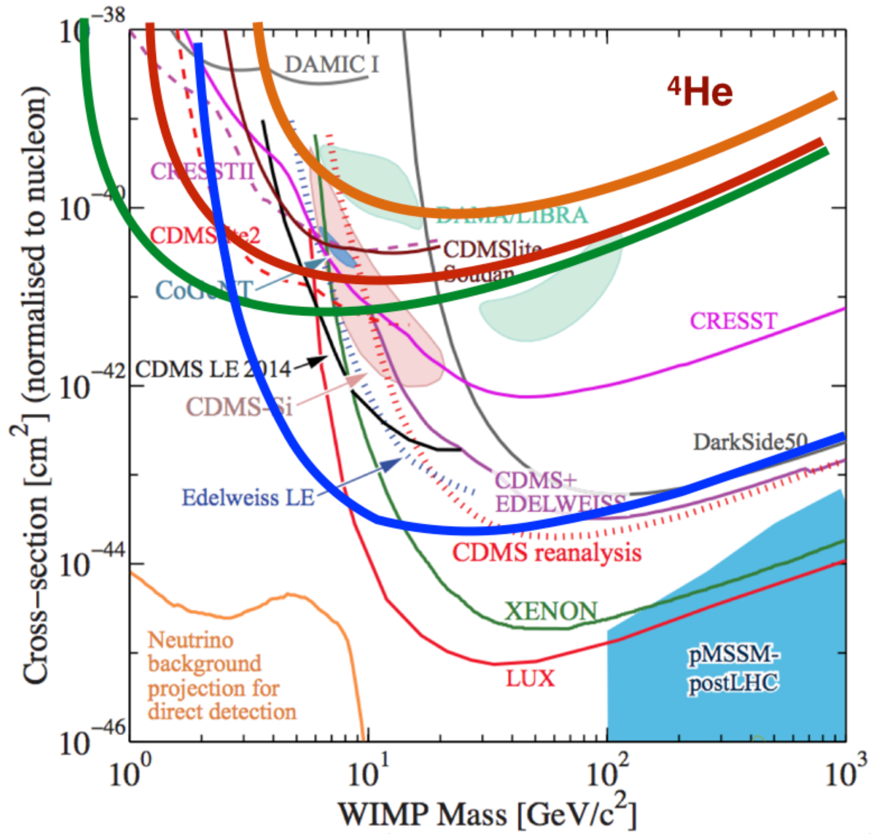
Gas TPC

- Proposal for ***LNGS***
  - With NO shielding it can primarily serve as a good **monitor for fast neutrons**
- With the addition of ^{3}*He* can be made sensitive to **thermal neutron**.
- **With** proper (neutron) **shielding** and low threshold can be a prototype for low mass **DM detector**

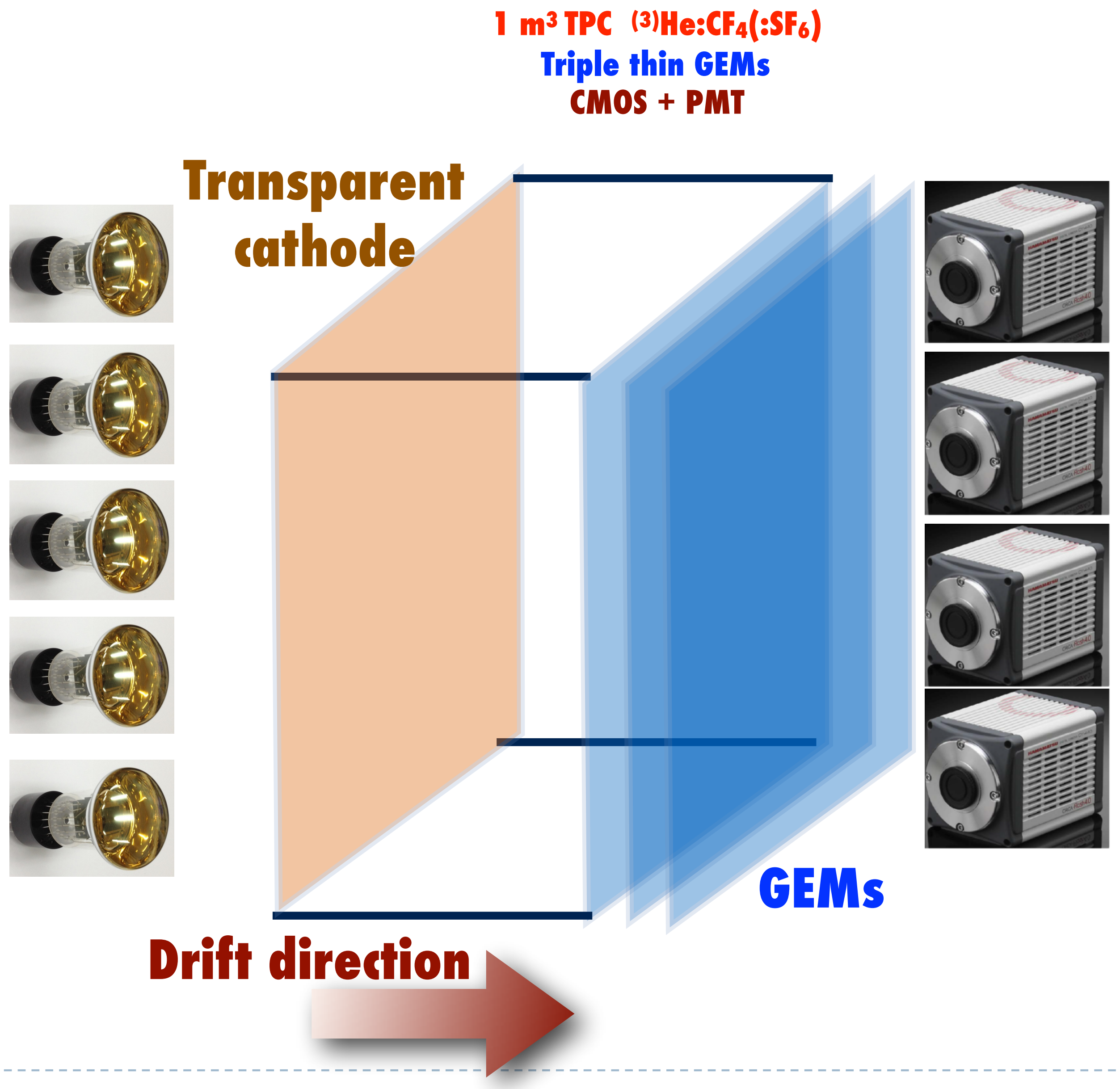
$^4He:SF_6$ 600:200 Torr
1 m^3 x 3 yrs
Zero background

E_{th} = 10 keVr
E_{th} = 3 keVr
E_{th} = 1 keVr

^{4}He recoils



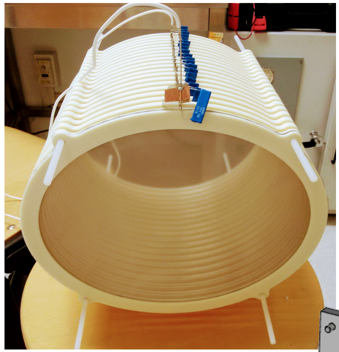
UNDER detector concept



- Gas pressure close to **1bar**
- Use GEM amplification at anode, read the **light from the GEM** discharge with a low noise **CMOS camera**
  - 2D X-Y resolution at 100 µm
  - No interference with gas
- ***Fiducialization to be addressed (CYGNYS_RD)***
  - negative ions drift of SF6 minority carriers
  - electron drift: diffusion
  - primary scintillation

R&D, CYGNUS

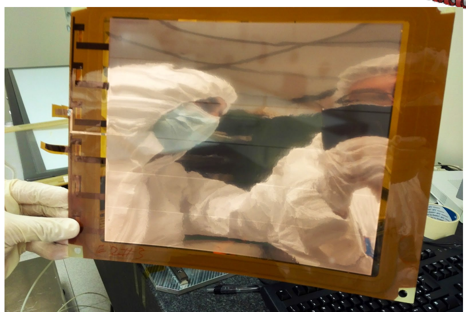
PMT



Field cage with
semi-transparent
cathode (20 cm drift space)

Optical bellow

CMOS camera



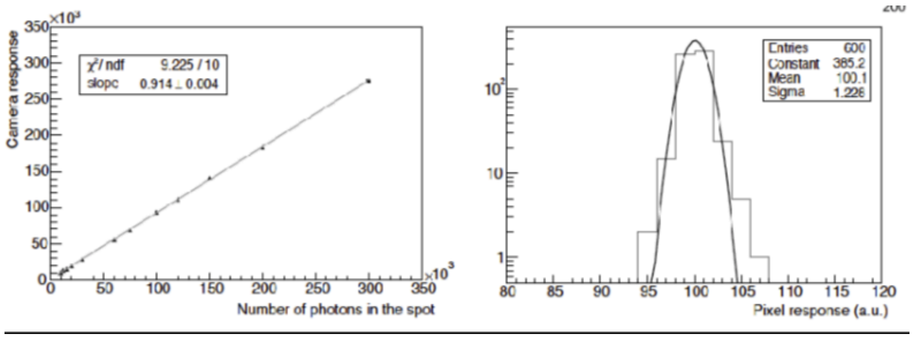
GEM

24x20 cm² GEMs (70 μm/140 μm)

Light readout

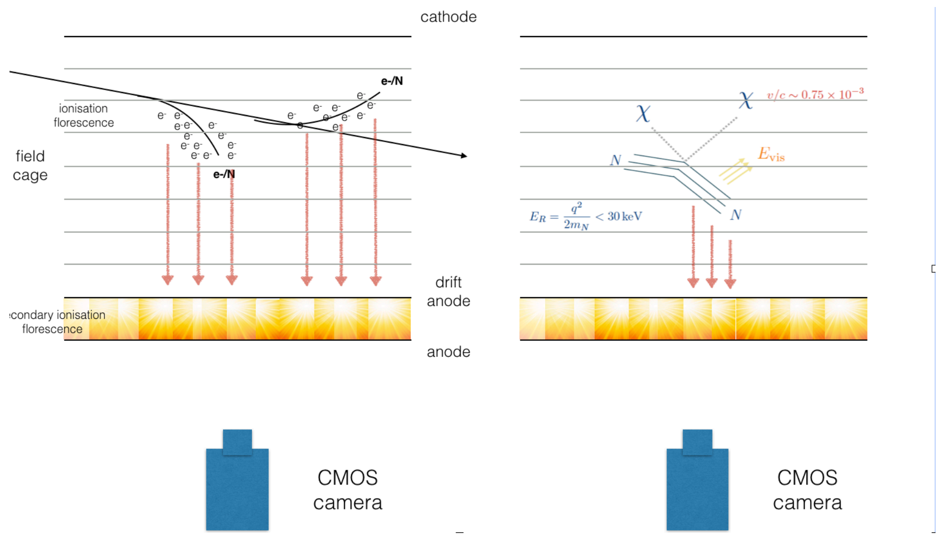
- Light production in a GEM discharge readout with low noise CMOS camera

For a m.i.p. track we predict (Garfield) ~ 7e⁻/mm (primary ionisation electrons)
For a m.i.p. track we **measure** ~ 1000 photons/mm
that means
~150 photons/primary electron



Camera calibration, pedestal is less than ***2*** photon per pixel (***"photon" noise equivalent***)

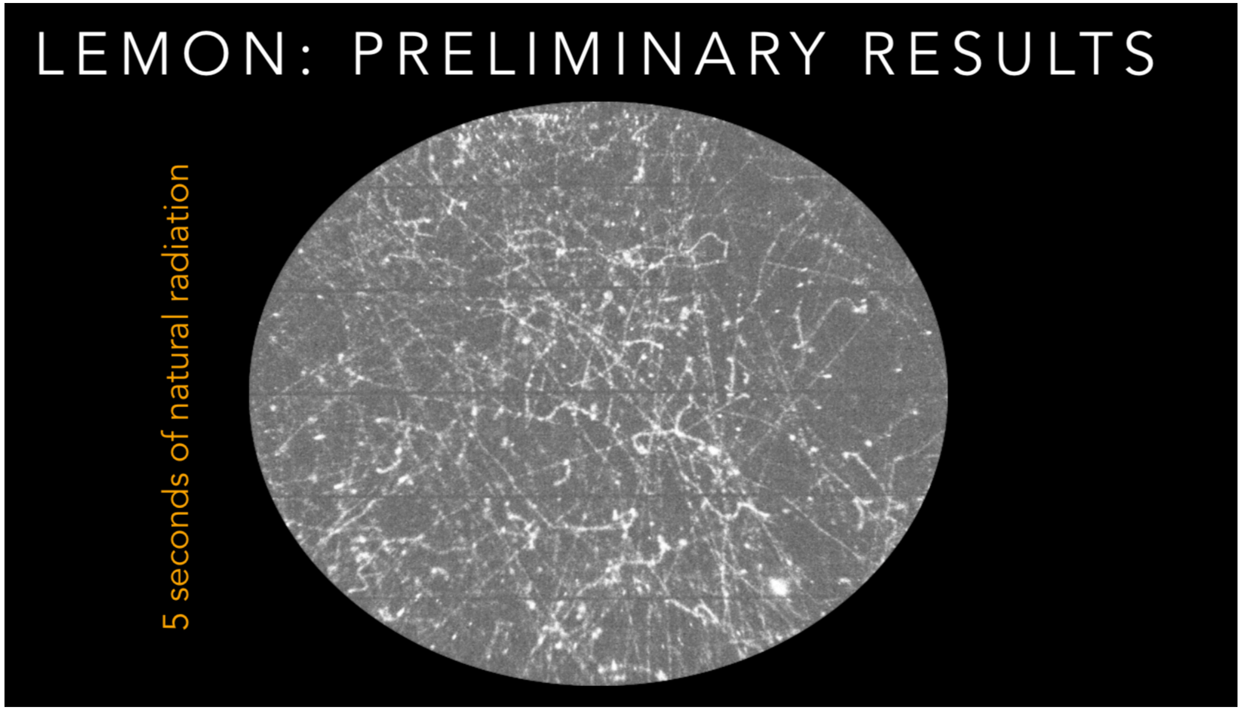
- Very good signal to noise ratio!



A snapshot of radioactivity

TPC with electron drift in He-CF_4 (60-40) gas mixture

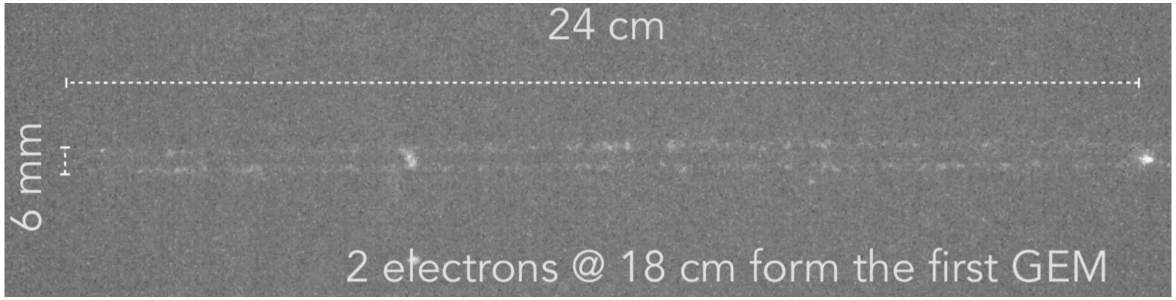
- Use 2D projection to separate *electron recoils* from *nuclear recoil* (specific ionisation)
- directional information



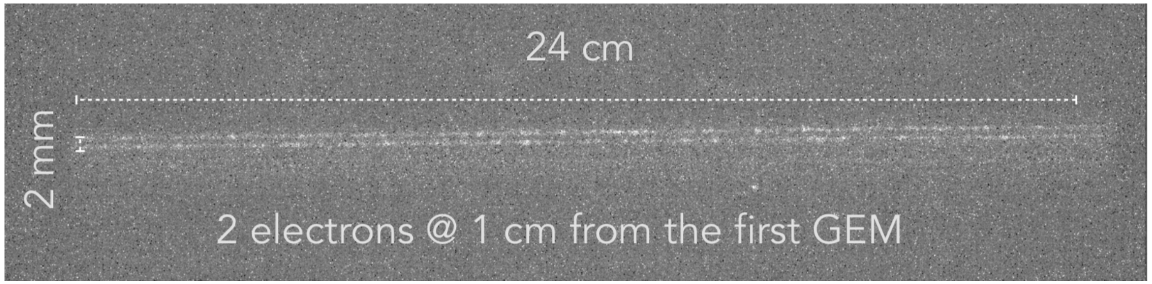
Electron tracks

- *450 MeV electron tracks producing ionisation cluster, drifting to GEM, flash of lights during GEM discharge*

$HeCF_4$(60/40)
by Garfield simulation



dE/dx @ 400 MeV = 0.23 keV/mm
about ~ 7 primary e^- / mm
V_{drift} = 4.5 cm/μs @ 640 V/cm



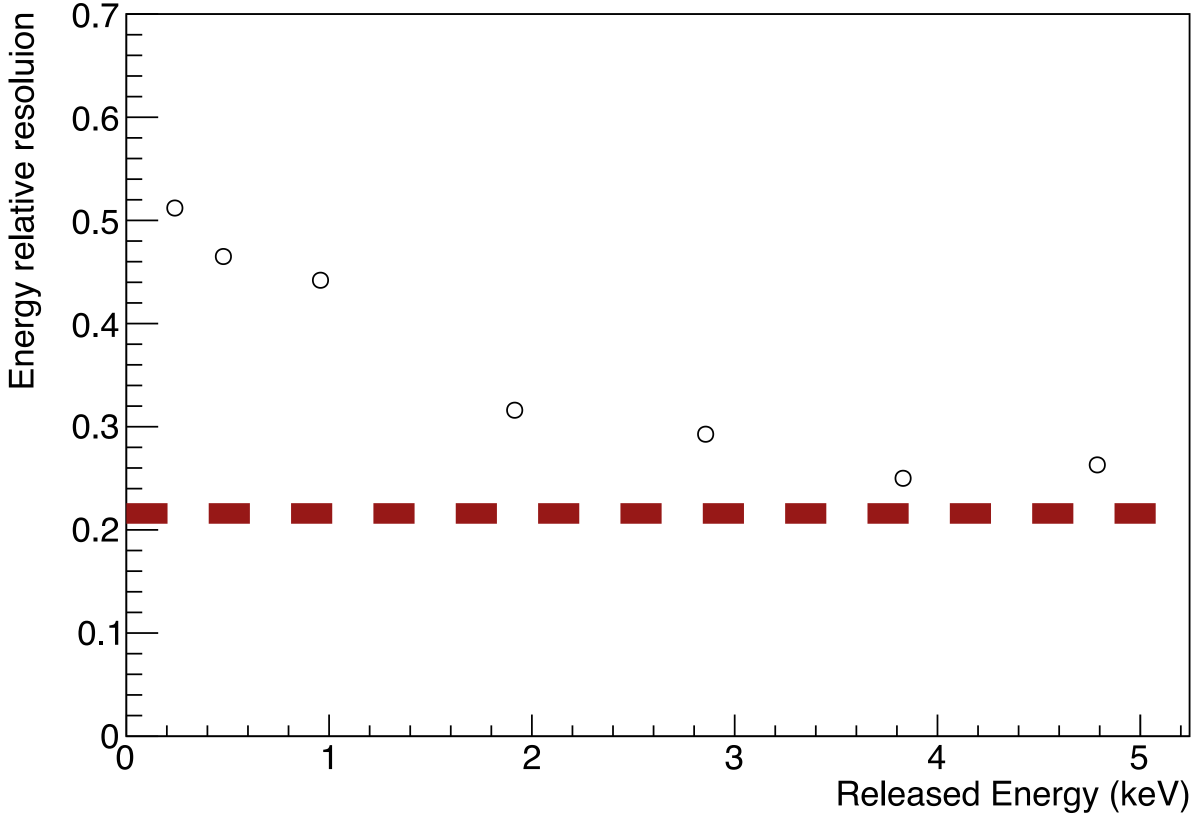
Resolution for a high energy electron track is 30-60 μm

Energy resolution

By studying the distribution of collected light in slices of different widths, the energy resolution behaviour was evaluated.

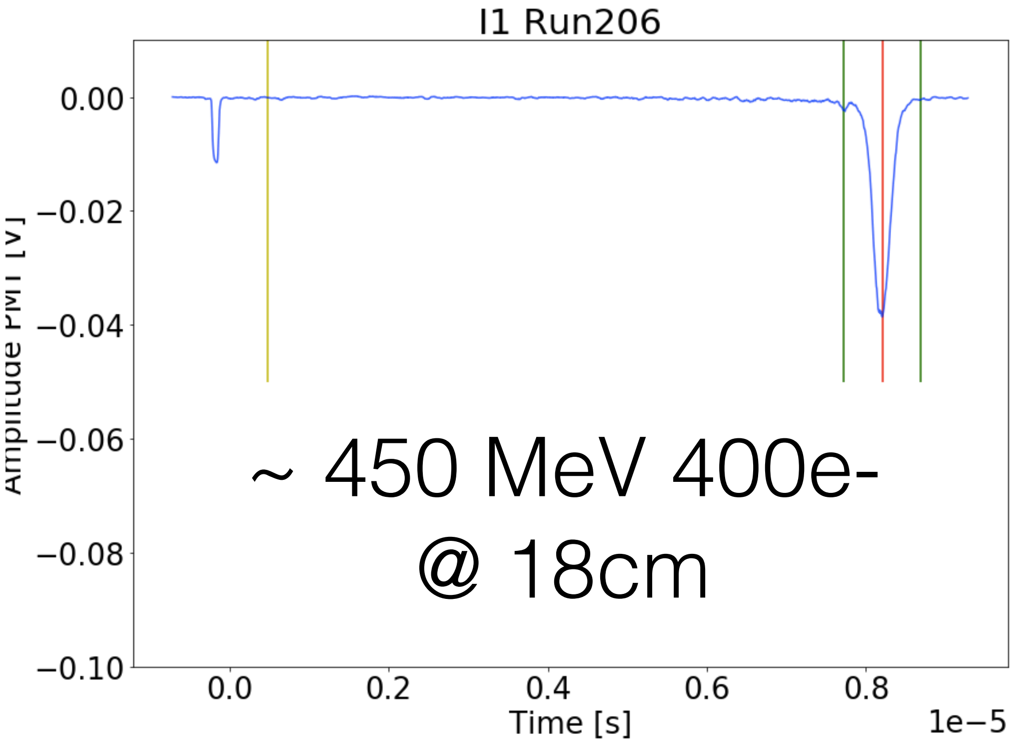
Promising results for reaching a low energy threshold

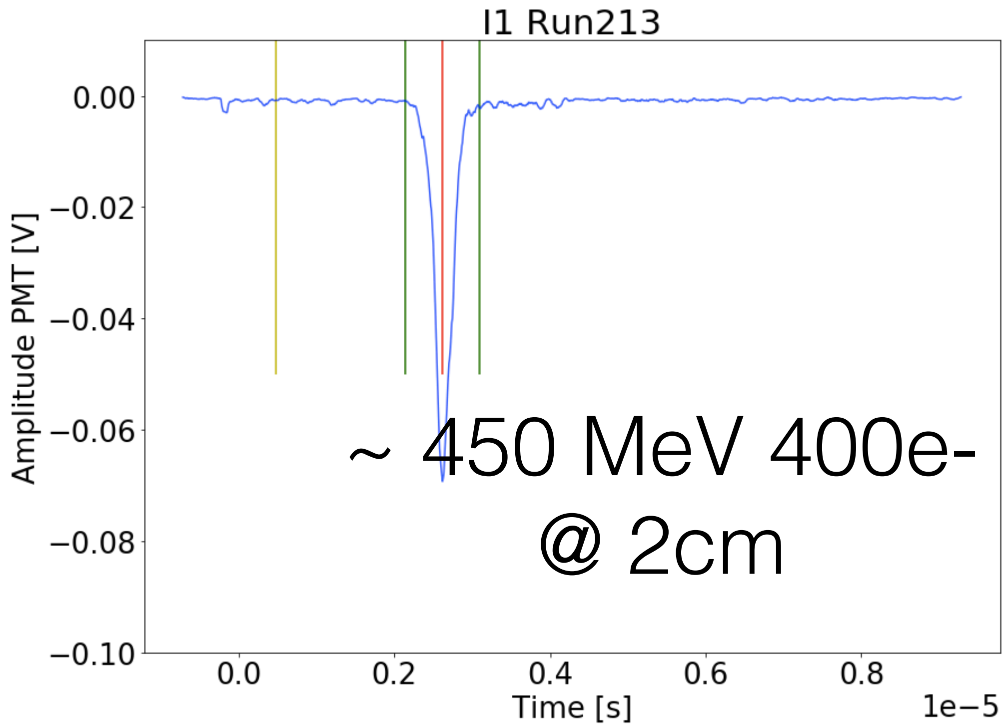
Resolution limited by intrinsic gain fluctuation



Primary light

Primary (from e track) and secondary (first GEM) light signals

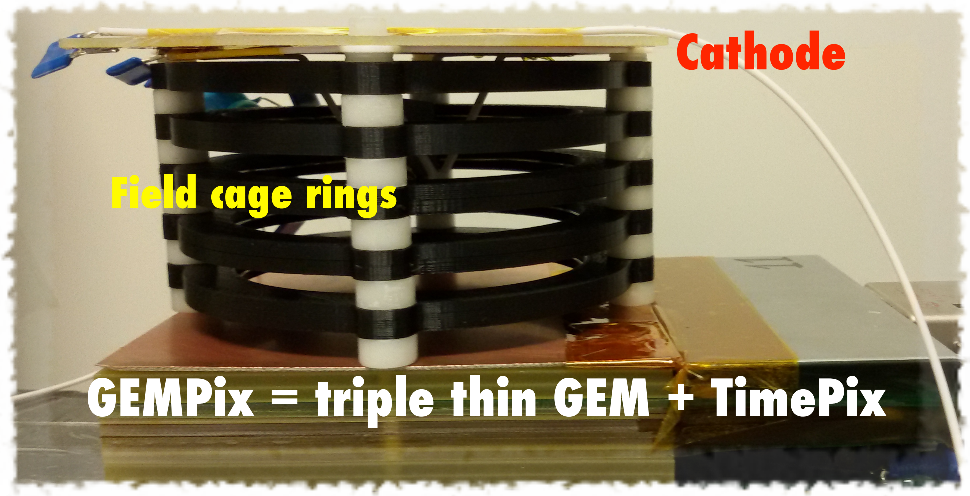




Still very far from being useful for full fiducialization
(but we used sub-optimal Q.E. PMT and limited light collection)
It might be good to reject cathode events anyway!

R&D NITEC

NITEC: Negative Ion Time Expansion Chamber

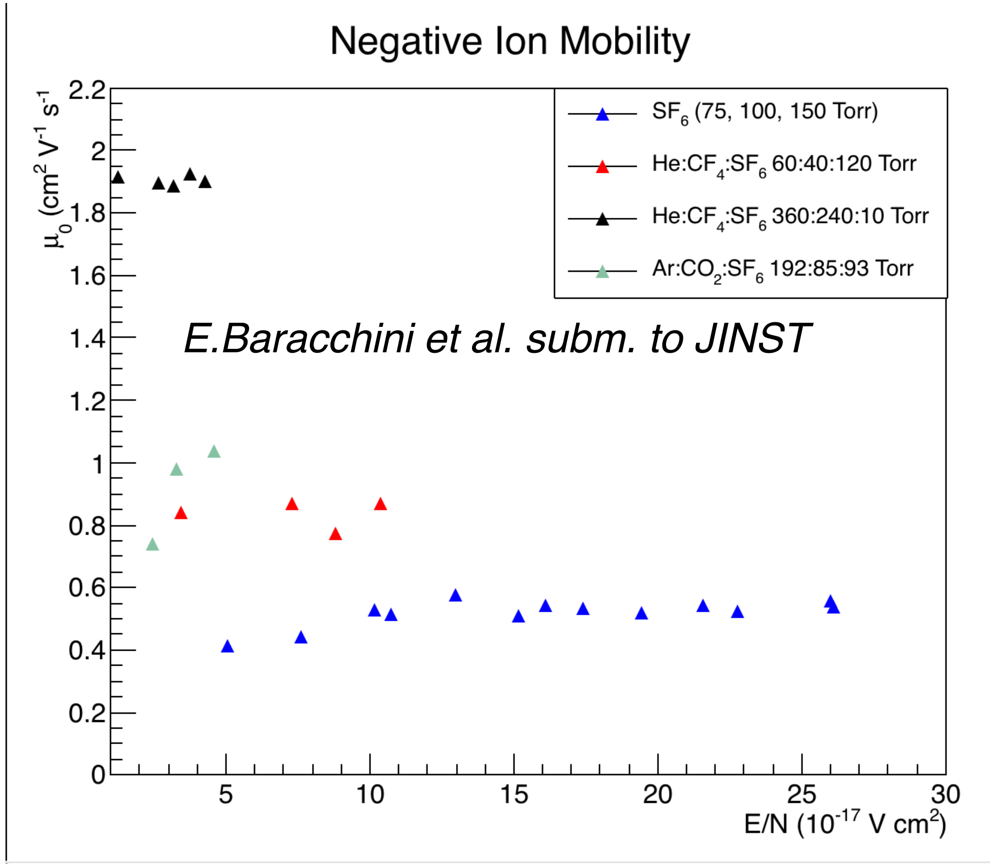


3 x 3 x 5 cm^3
0.045 Liters
Triple thin GEMs
Timepix pixel charge readout

- Small gas volume to study gas properties
- Operation in pure SF_6 at low pressure
- Operation with gas mixture
- GEM pixelated charge readout

SF_6 negative ion drift

- Measured ion mobility in SF_6 based gas mixture at 600 torr.
  (from drift velocity of negative ions generated by the 45 MeV BTF electron beam)

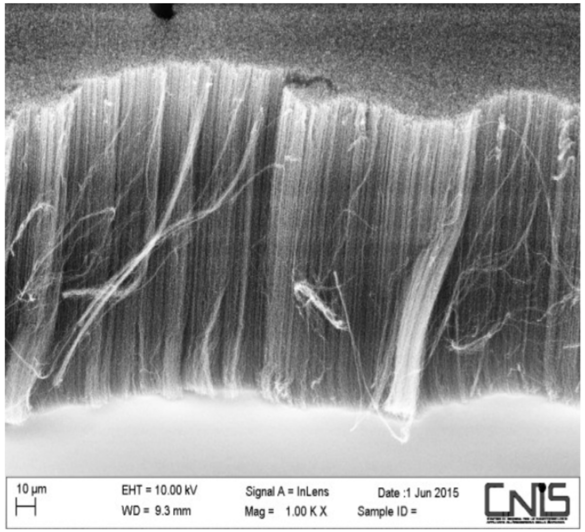


- Need to understand the "**light**" **gain** of gas mixture with SF_6
- Hope to see signal of **minority** carriers (SF_5, SF_4, etc.)

Carbon target: CNT

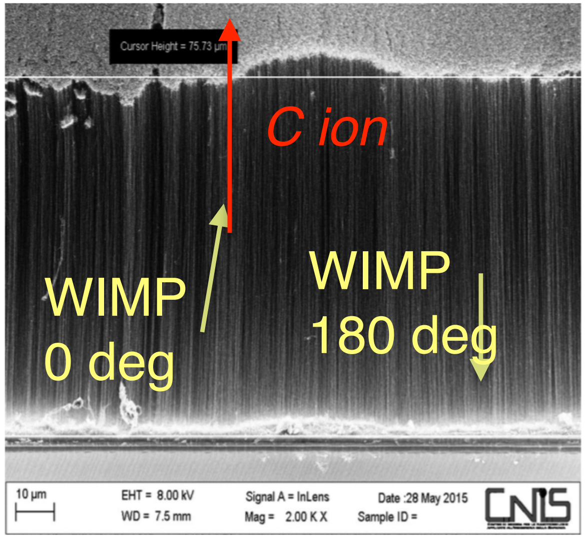
- Idea: WIMP scatters on a ***anisotropic*** target as ***aligned*** carbon nanotubes.
- Nuclear recoils are **exiting the target only** when they are along the CNT axis - otherwise absorbed

collaboration University of Mons, Belgium



length: ***100 μm (can be increased)***
ext. diameter: ***(20 ± 4) nm***
aspect ratio: ***5x10⁴***

commercial

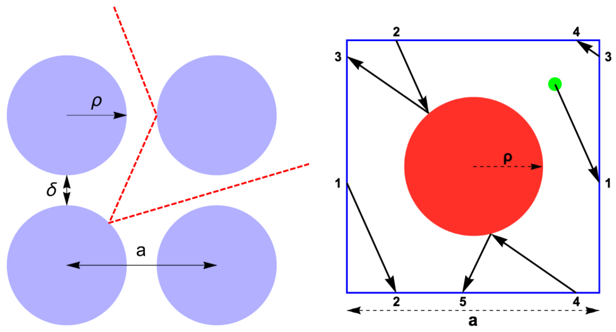


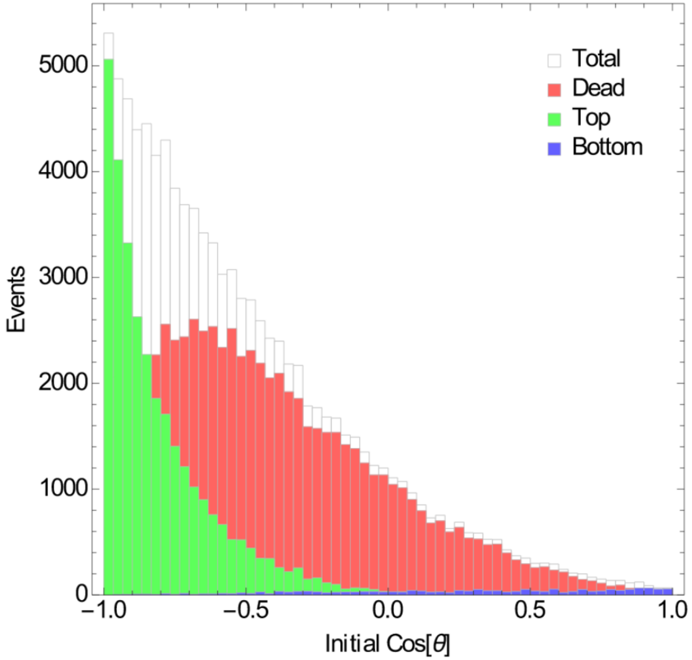
detector side

substrate (absorbing)

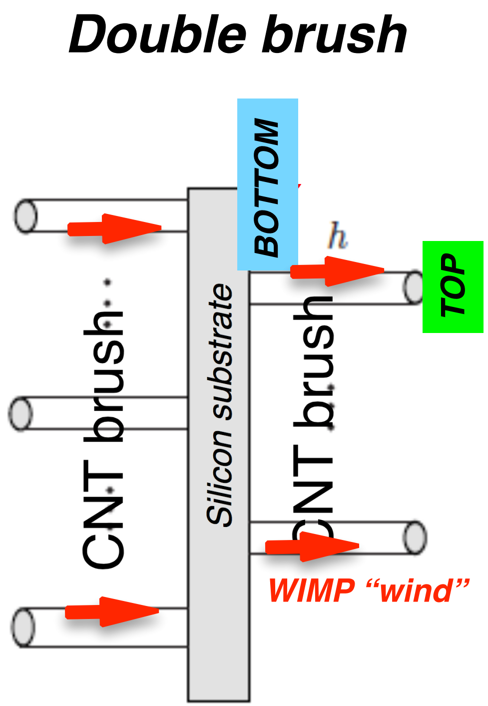
length: 75 ***μm***
ext. diameter: ***(13 ± 4) nm***
aspect ratio: 0.6 ***x10⁴***

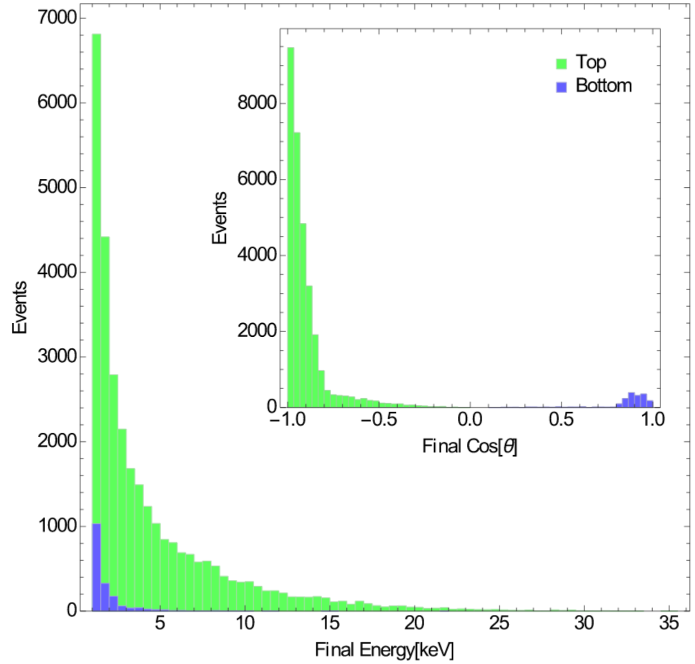
C ion moving within the array





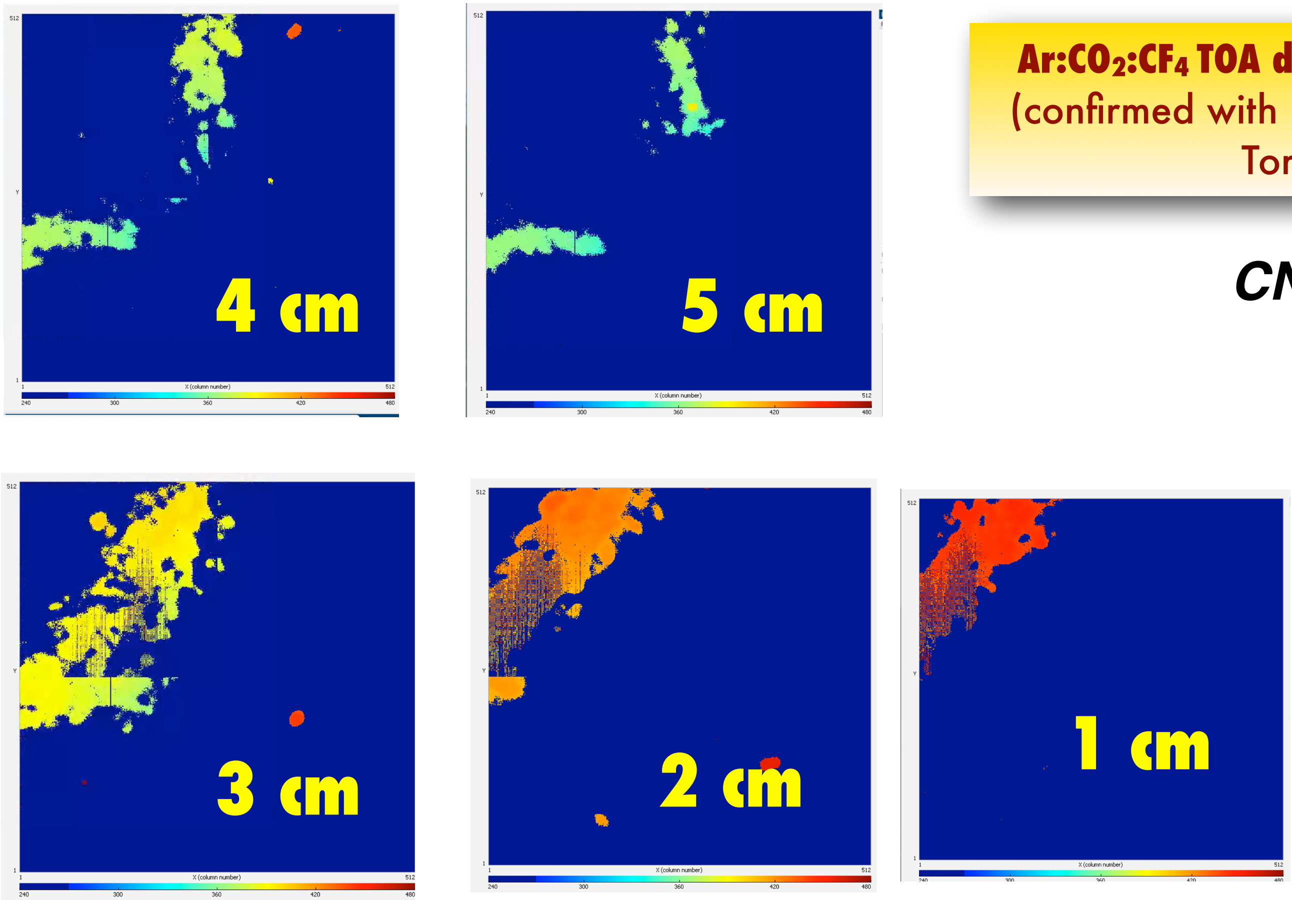
Initial C ion direction



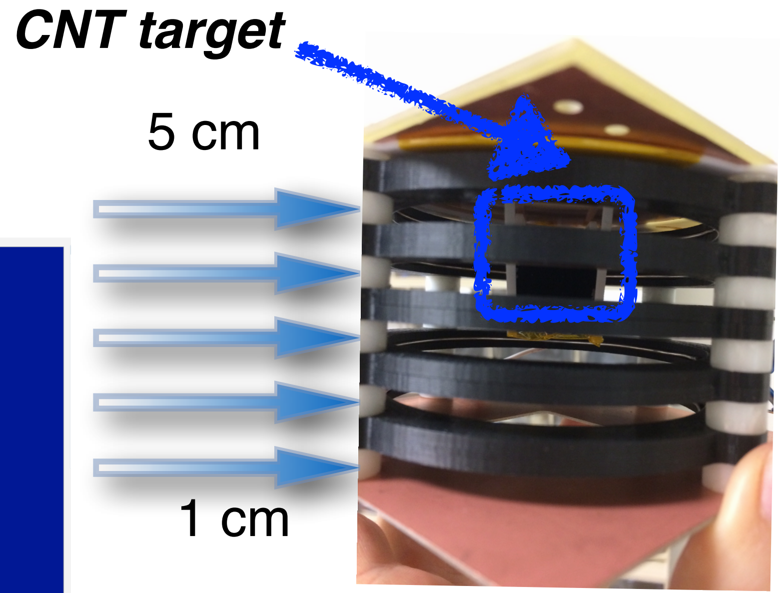


Final C ion energy and direction

First look at CNT



$Ar:CO_2:CF_4$ TOA data @ 300 Torr
(confirmed with pure SF_6 @ 150 Torr)

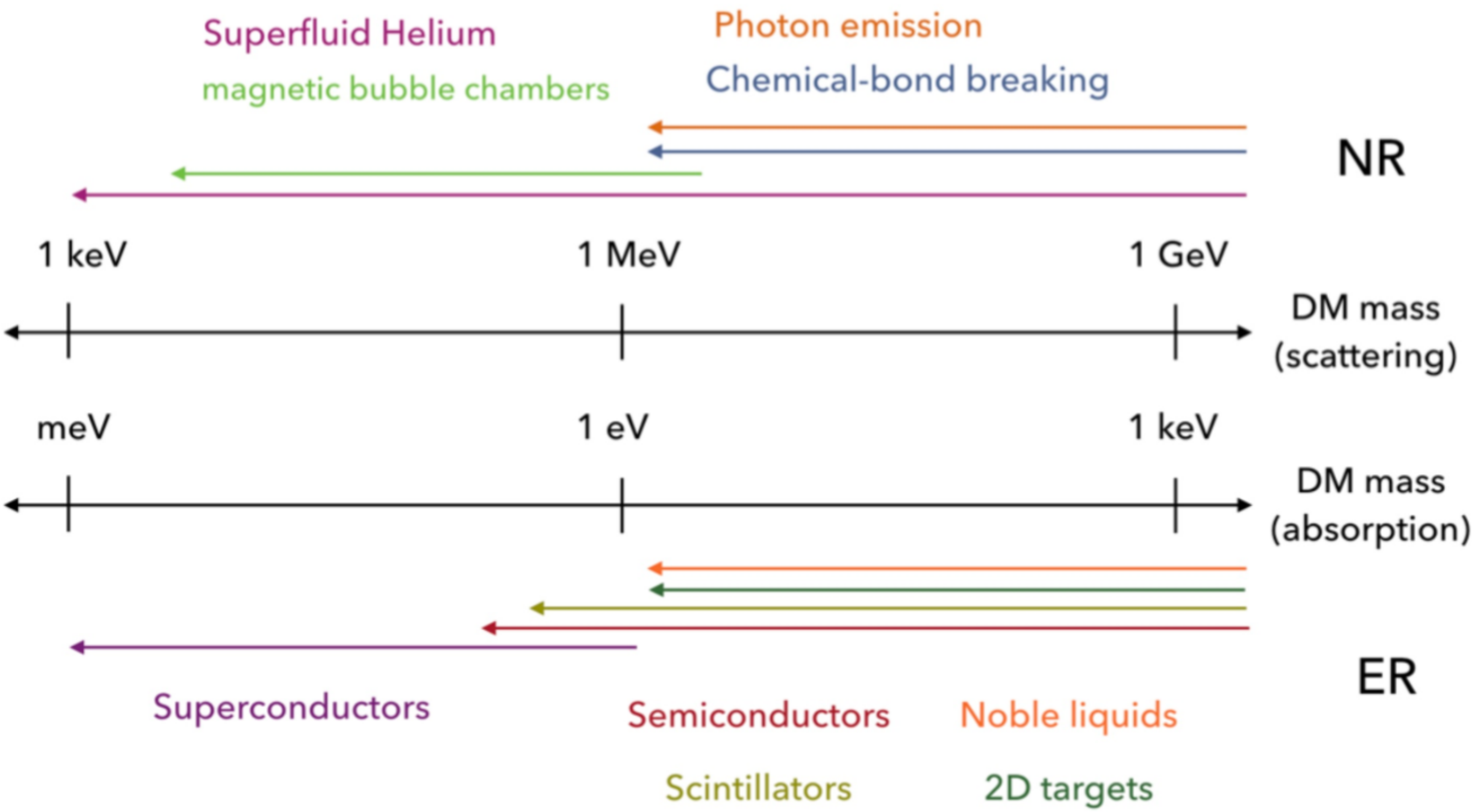


Color is drift time (along Z) for different Z position (X-Y projection)

CNT are good conductor, modifying the field cage electric field.
Different field configuration to be tried for the conceptual demonstration

- What if dark matter is not so massive ? Scattering over the target ***electrons***

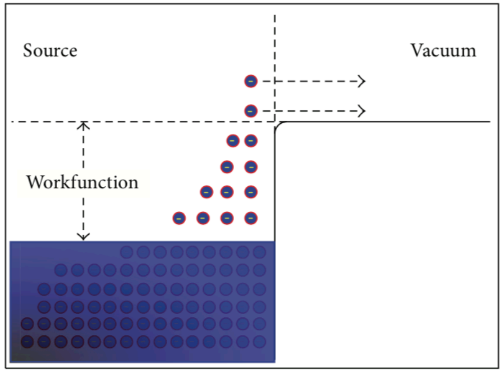
Sub-GeV dark matter



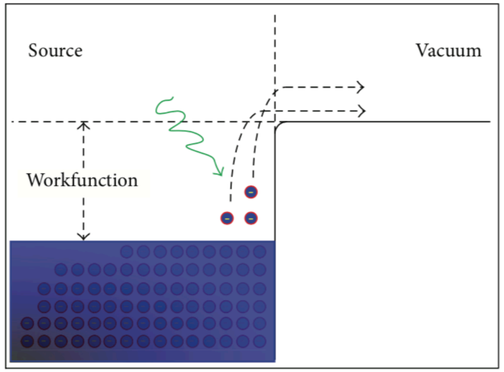
US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report : https://arxiv.org/abs/1707.04591

Electron emission from a cathode

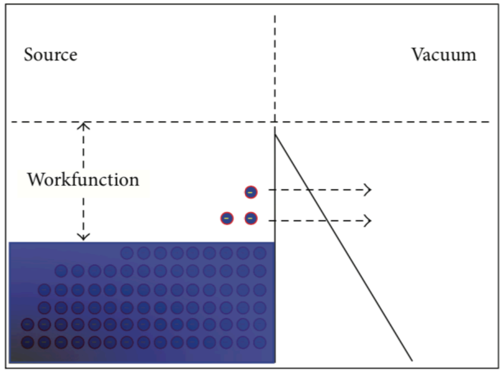
Thermoionic emission *Photoelectric emission*



(a)



(b)



(c)

Field emission

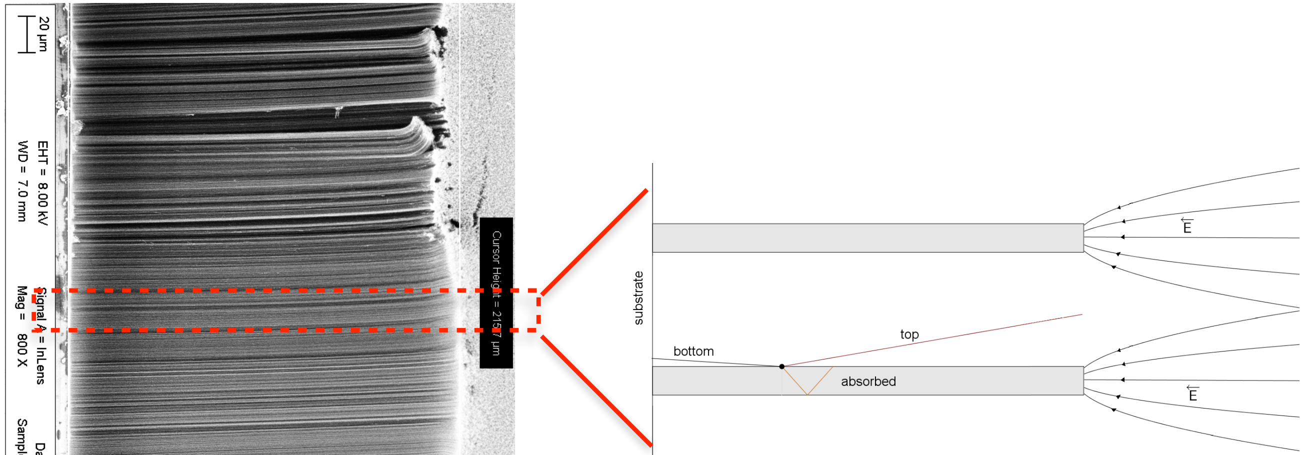
What about a DM particle scattering off an electron ? a ***dark-cathode*** *?*

Work function of CNT is > 4 eV

All these effects are suppressed: room temperature is low enough, UV photon efficiently screened, E field < 100 V/μm

Electron emitted from aligned CNT

- Electron extracted by a DM scattering
  - ***Few eV energy*** electrons recoiling off

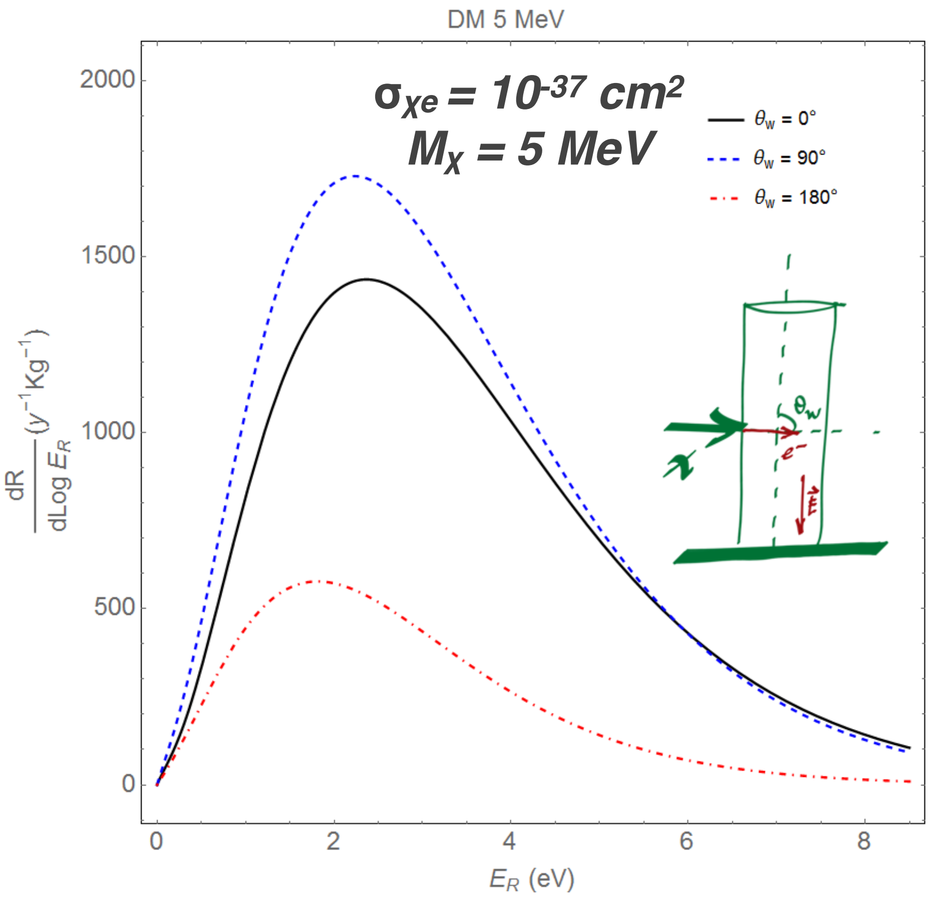


Electron collected by an external electric field ***E***

- **Inelastic** electron - graphene interactions are **suppressed** at this energy (compare ***e*** wavelength)

- electrons can be *transmitted*, *reflected absorbed* by a graphene sheet
- absorption ~ 10^{-3} (but no good data available)

Directionality



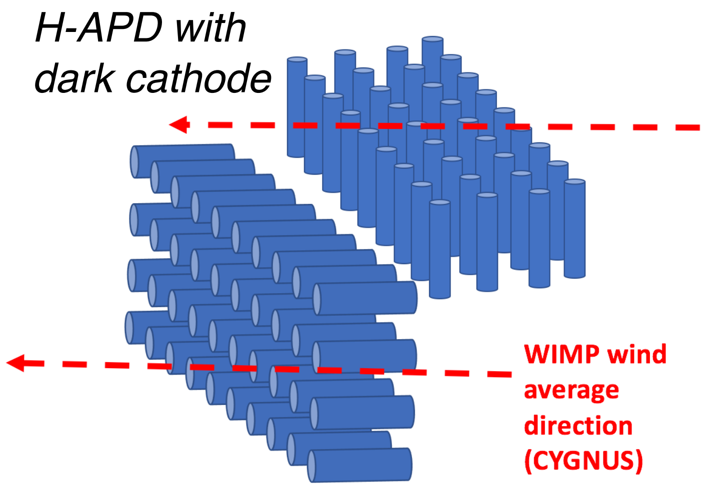
Different rate at different angles ***θ_w***

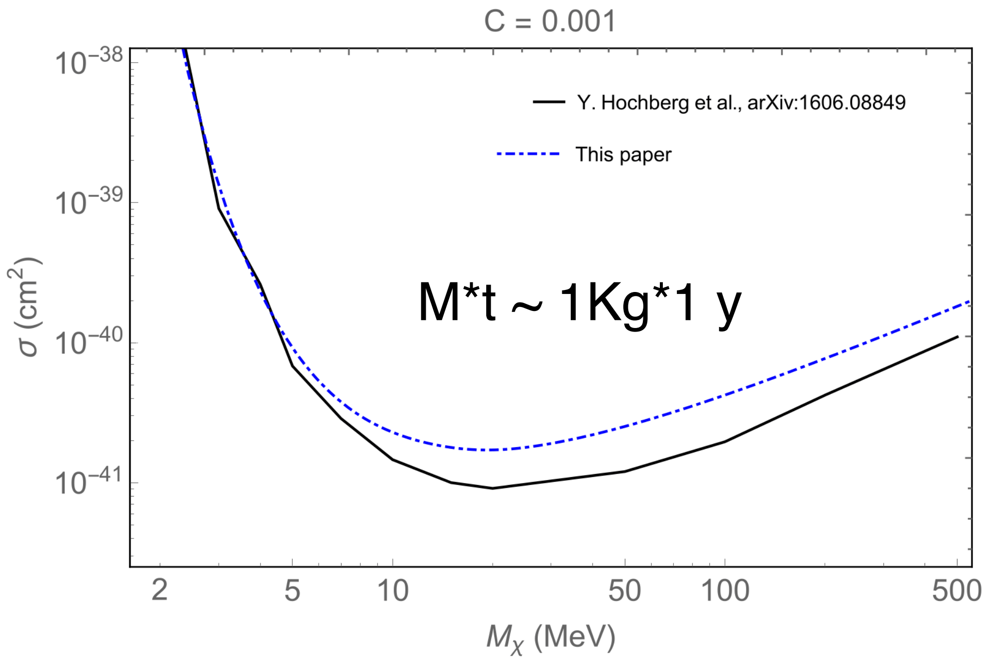
θ_W ~90 preferred by graphene electron wave function

- A rate **asymmetry** can be measured by comparing two CNT target orientation

With an exposure of 100g * 160 day a 5σ non null asymmetry can be measured

Sensitivity region





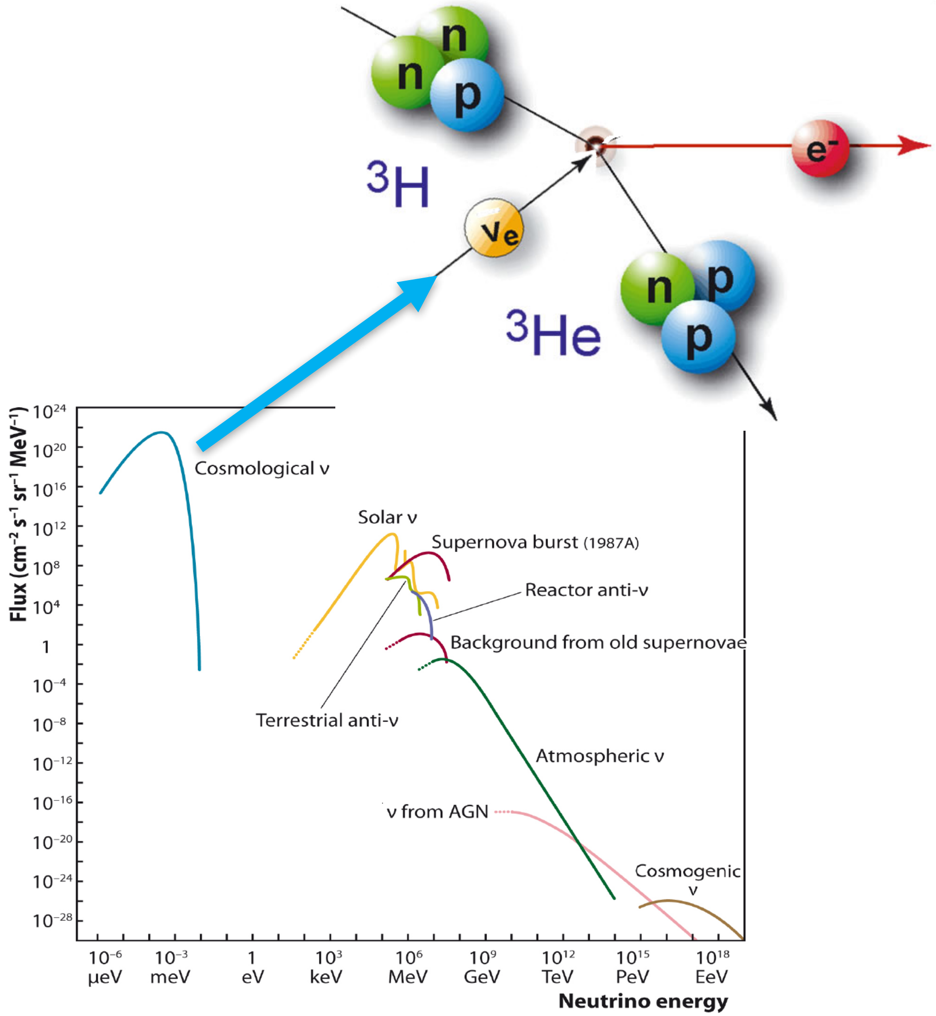
- Two arrays of *hybrid dark-photodiodes* *(~10^4 units, 10mg dark cathode mass each)*

PTOLEMY - graphene target

- PonTecorvo Observatory for Light Early universe Massive neutrino Yield.
  - **dope graphene sheets with ^3H:** target for relic neutrinos

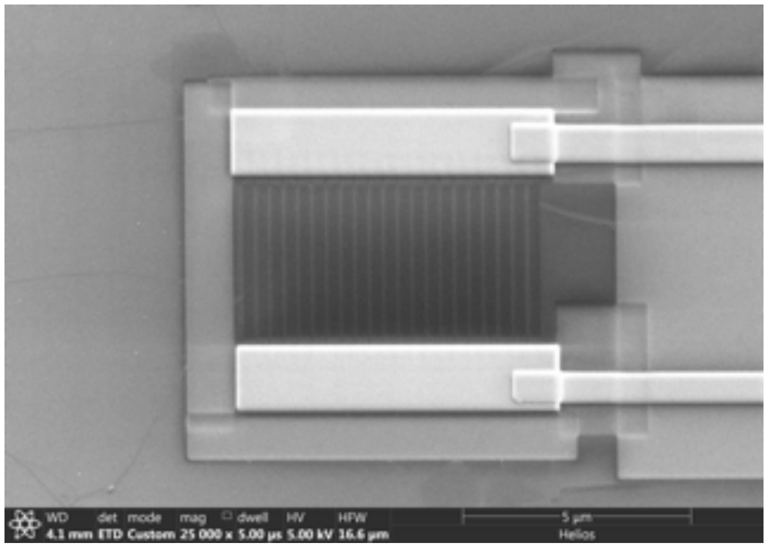
Detect electron of few eV kinetic energy

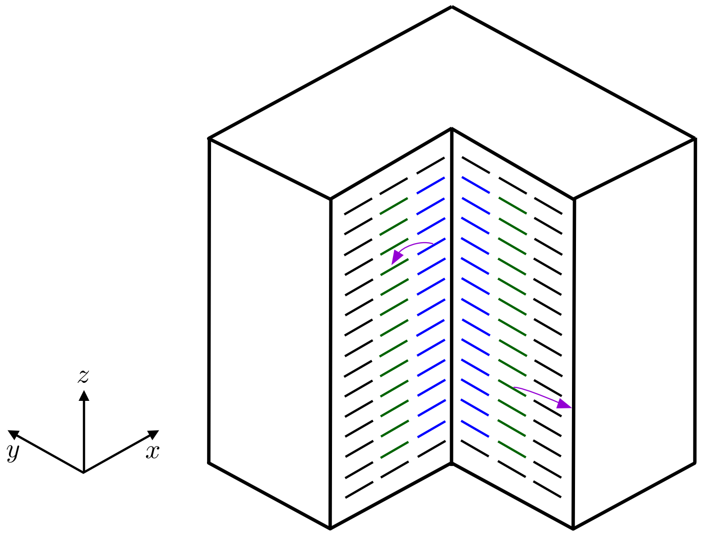
MAC-E filter technique to select the endpoint of the tritium



PTOLEMY G^3

- Null experiment with no tritium (prove radio-purity at the level of relic neutrino detection
- Compact arrangement of graphene sheets
  - G-FET (nano-ribbon, unable band gap



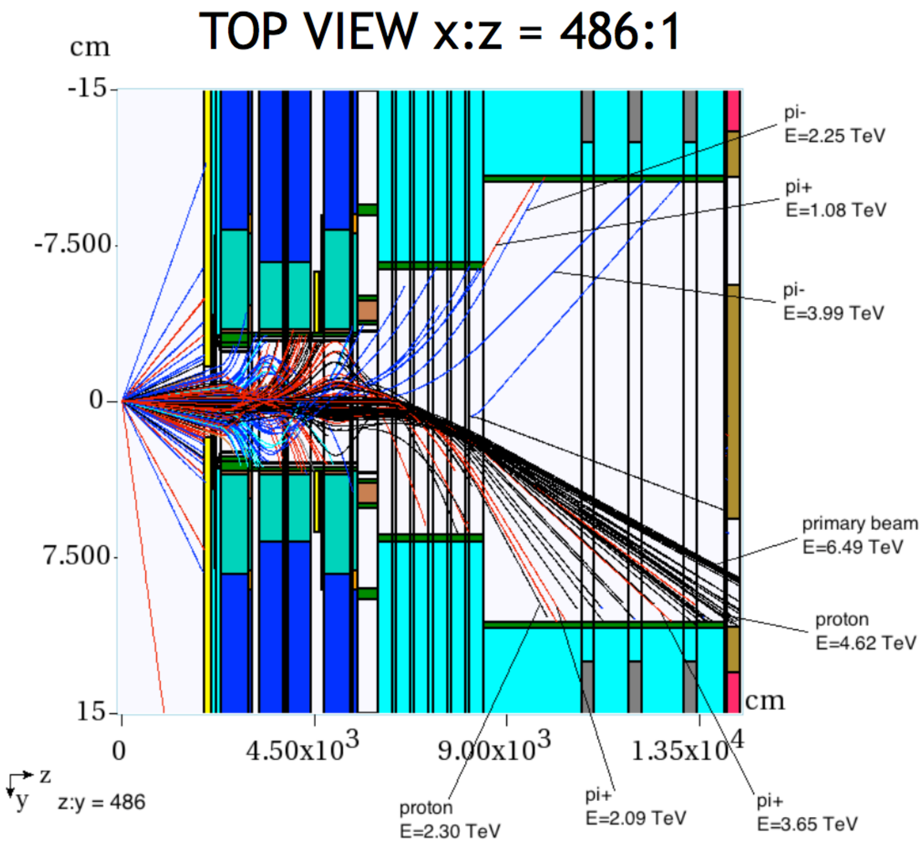


A last detour on indirect searches

Forward physics and cosmic rays

- Secondary particle production from IP at very small angle: calibration of MC for cosmic rays, <u>muon production</u>

$$\sqrt{s} = 13TeV \rightarrow E_p = 10^{17}eV$$



Small Angle Spectrometer

https://indico.cern.ch/event/435373/

LHC point 5 200 inelastic collisions

LHC magnets close to the IP deflect secondaries toward to the pipe

Use a bent crystal to <u>extract</u> those forward secondaries and count them!

Muon identification (charm)

My conclusion (for direct searches)

- **WIMP** is a **great** paradigm, but DAMA/LIBRA result yet **unconfirmed**.
- "**Several ton-year** "is the new frontier in the high mass (> 10 GeV) region, but so far null results are not very encouraging.
- Need to prepare to dig into the **neutrino floor**
  - directional tools need to be explored now (anisotropic targets, low density large volume)
- Look in other mass range, well below GeV
  - **electron** recoils

Besides brute force, we need some brave (experimental) idea
and - possibly - some luck
(since nobody really knows where exactly to look).