Outlook on direct dark matter searches

Gianluca Cavoto - Sapienza Univ. Roma and INFN
ARAP workshop
25 gennaio 2023

Outline

- ***Not a review, a (very) personal view on the future with a strong bias on the activity here in Rome***
- ***For a young researcher audience***

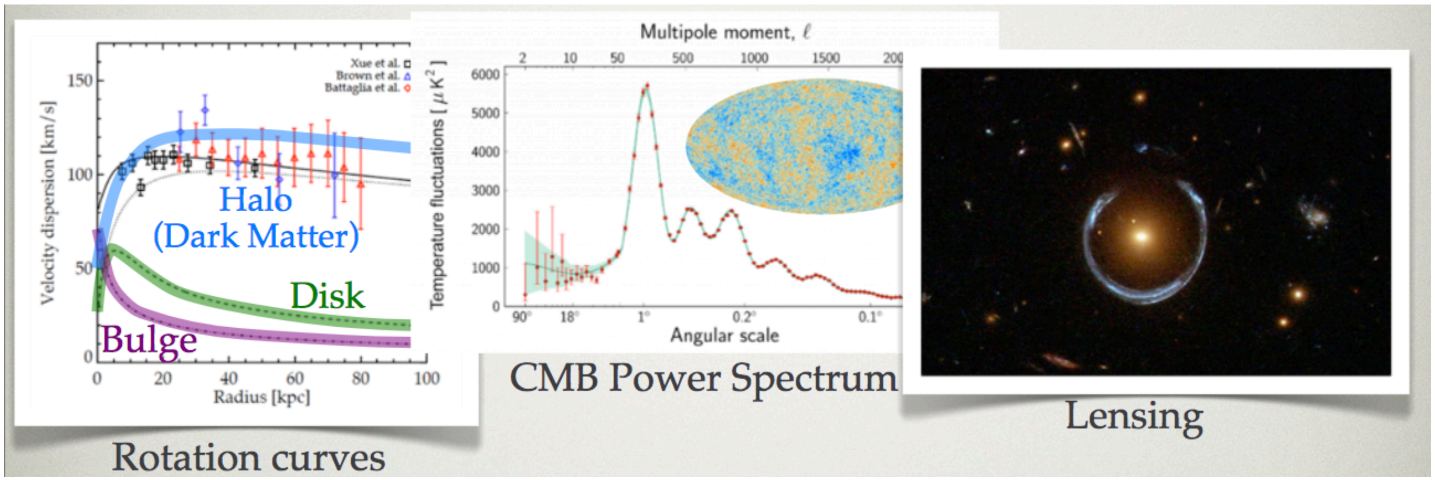
- **WIMP** and detectors with ton-year exposures

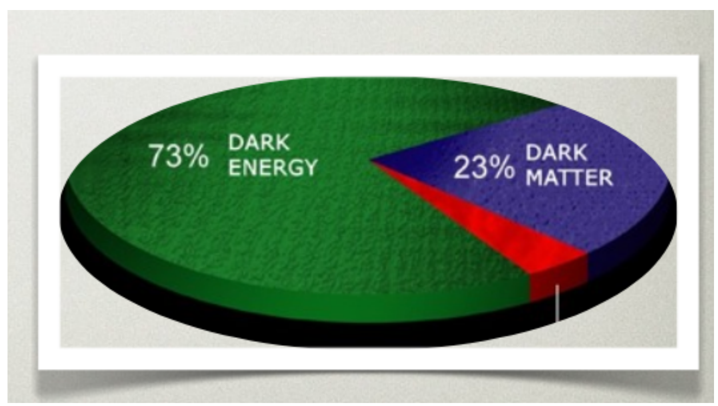
- **Directionality** - a tool to reject background
  - Low pressure gas detector (CYGNUS)
  - Anisotropic targets (CNT)

- **Sub-GeV** dark matter
  - Detecting electrons

Astrophysics and cosmology, evidences

- At very different scales, a robust evidence

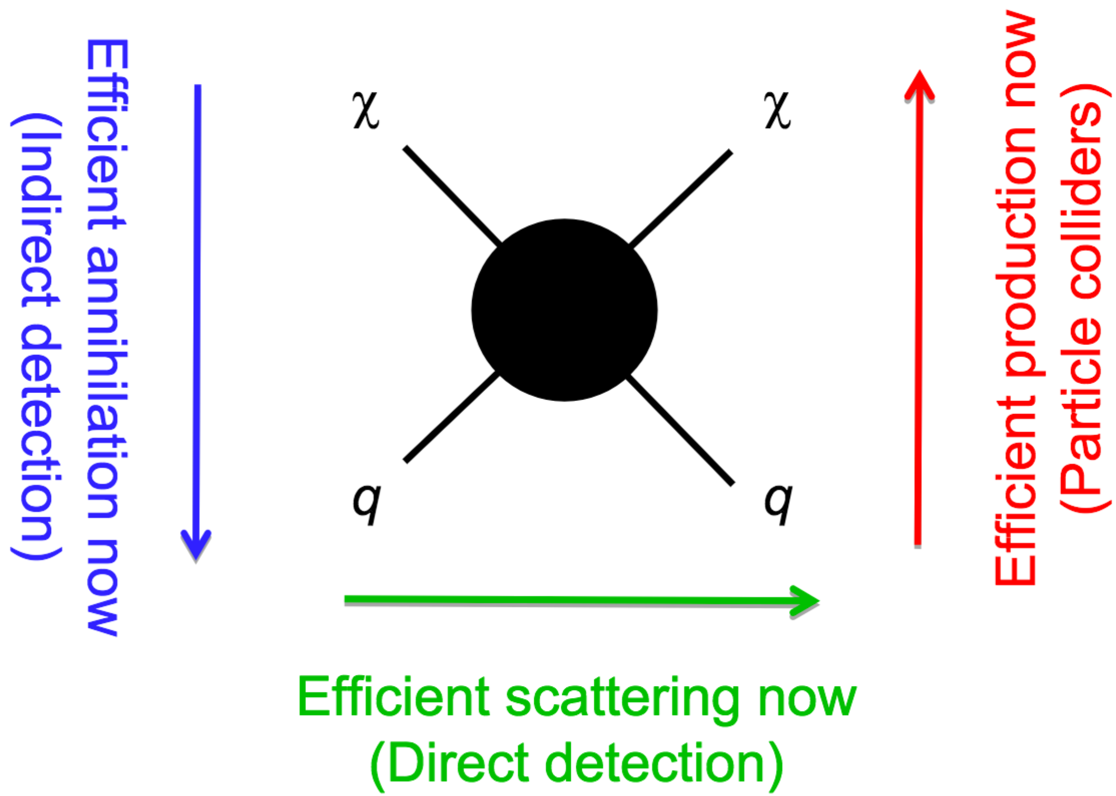




Strategies

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?)

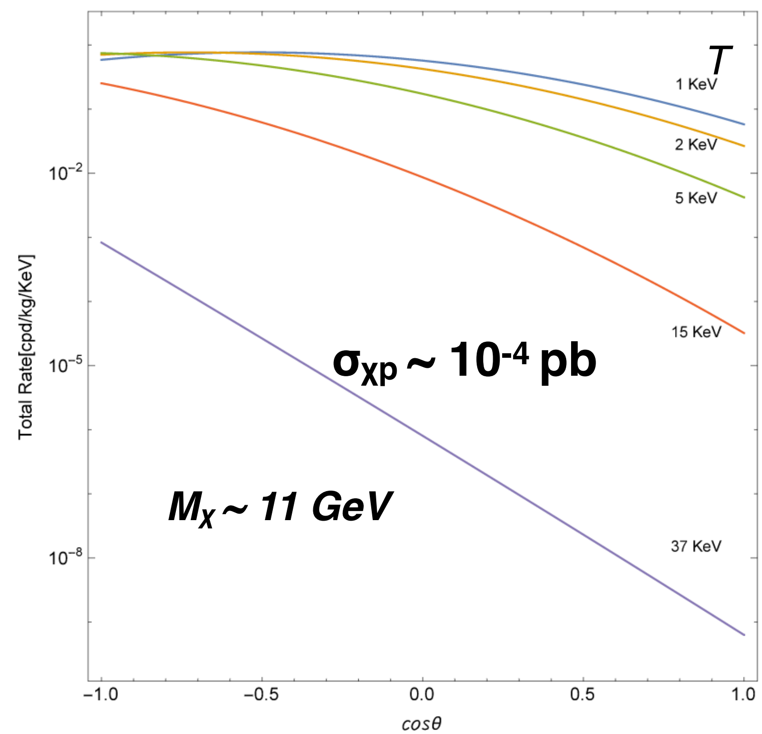
DM is around us, scatter on conventional matter (nuclei, nucleons, electrons)

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

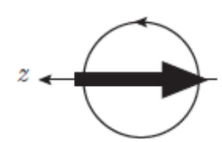
ELASTIC scattering of a WIMP χ on a C ion

Decreasing experimental threshold



C kinetic energy

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



θ = π

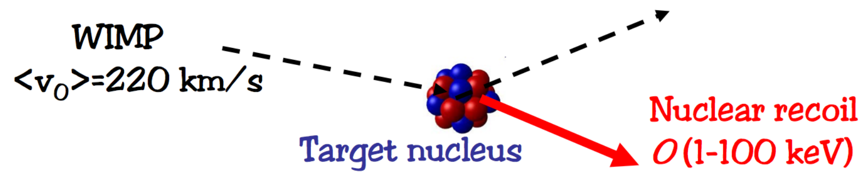
WIMP “wind”

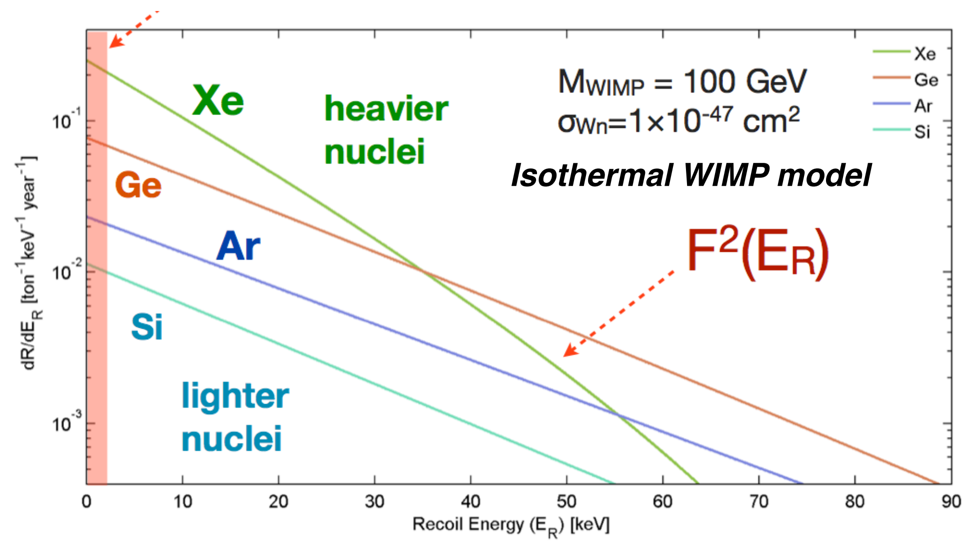
Anisotropic distribution: background rejection?

Response to elastic scattering

- WIMP (and neutrinos) interact **coherently** with a nucleus: **nuclear recoil (NR)**
- Energy release is **tiny**
- Rate is **few** events/kg/year

- Interaction might be **spin**-*independent* or spin-*dependent* (not all the nuclei are equivalent)
- Rate affected by the **nuclear form factor**

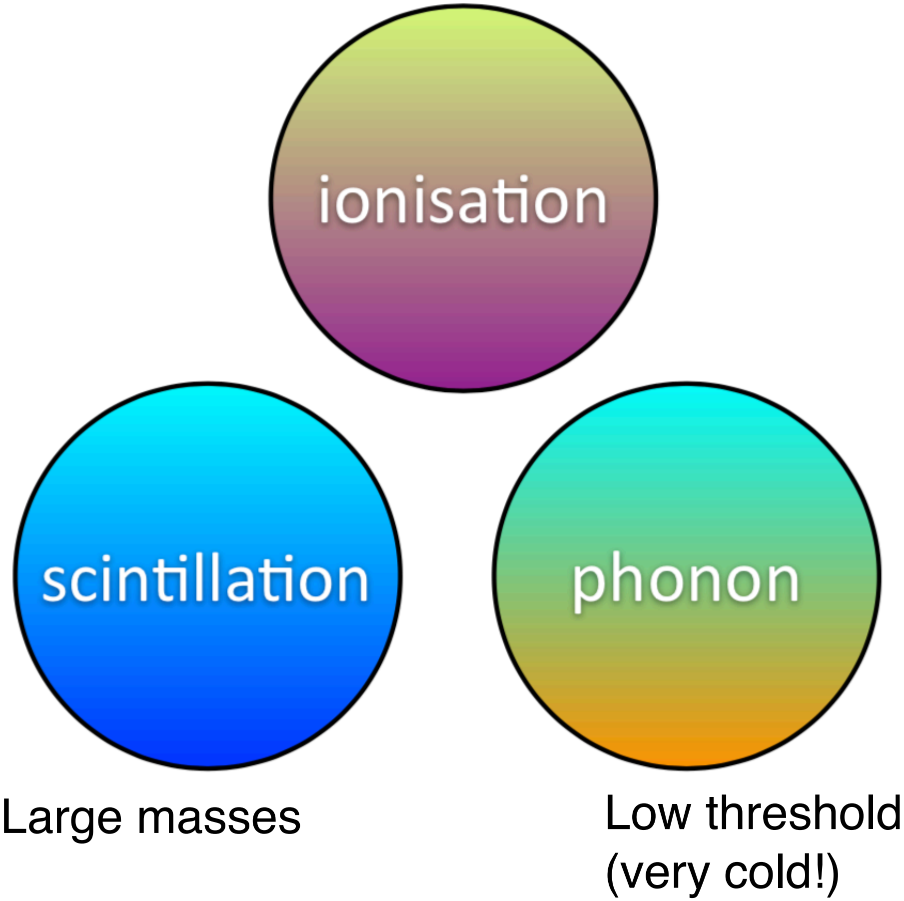




But other scheme are possible, interaction with **electrons**, **inelastic** interaction…

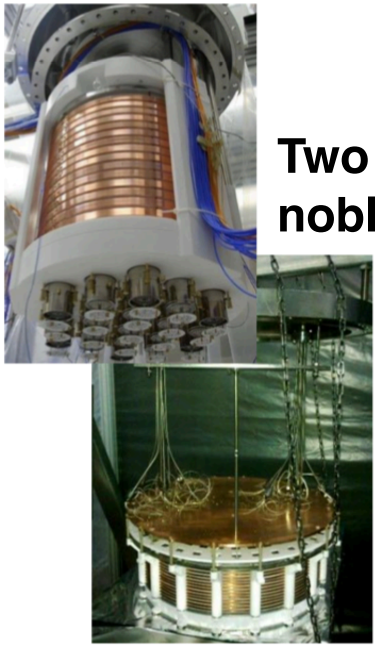
Multiple experimental signatures for signal

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

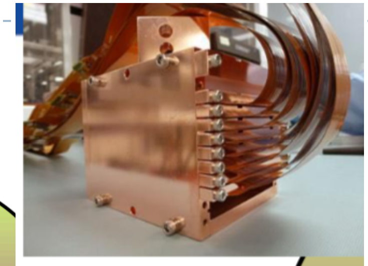


*One key element is to **calibrate** the energy scale of nuclear recoils (**quenching factors** for ionisation and scintillation)*

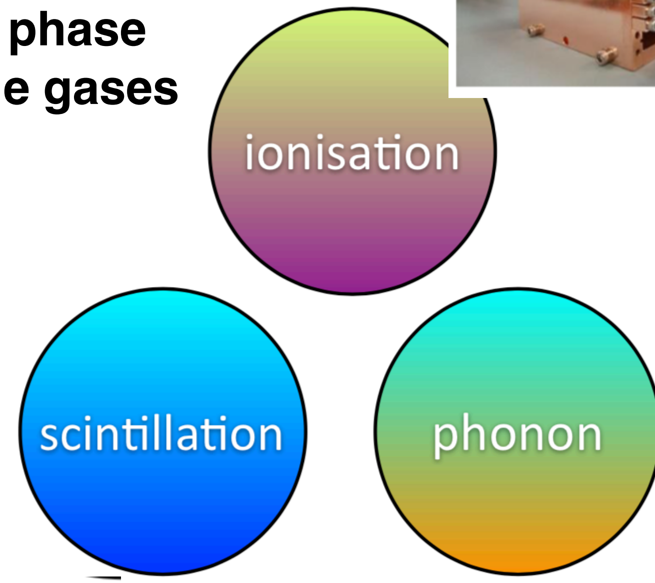
Multiple strategy for signal



Two phase noble gases



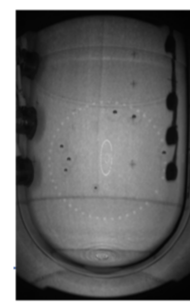
CCD



Cryogenic Bolometers

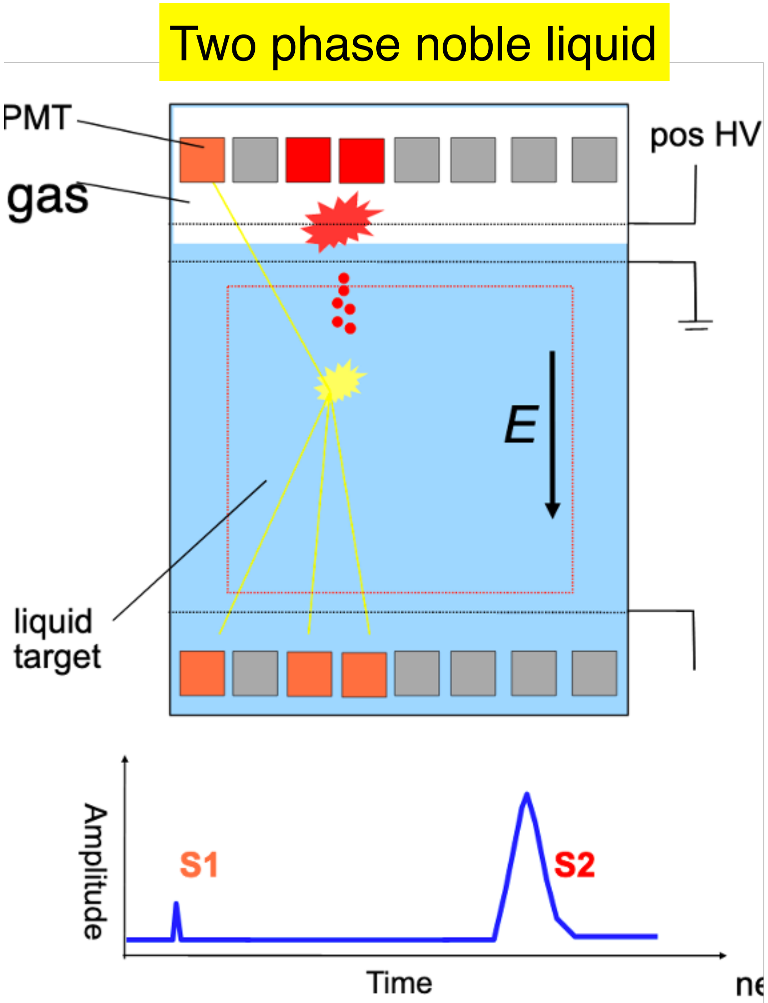
Inorganic Scintillators

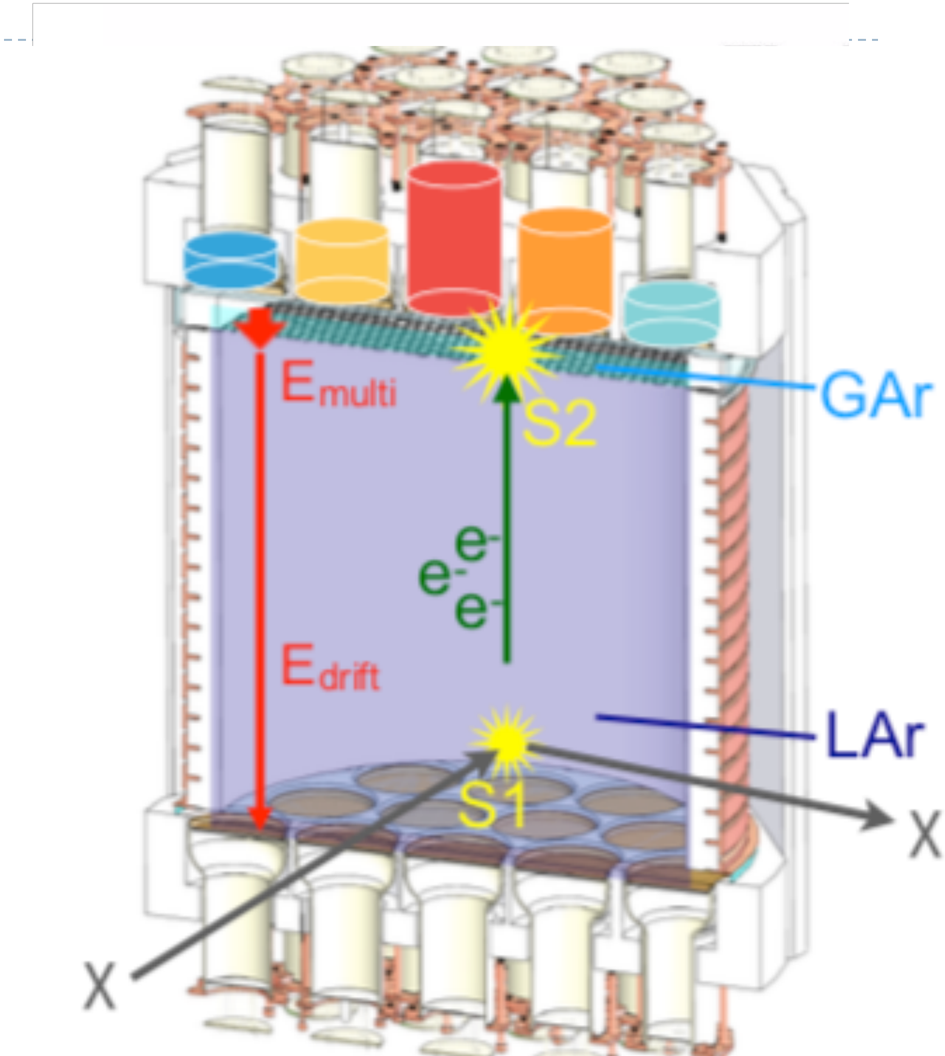
Cryogenic Scintillators



Bubble chambers

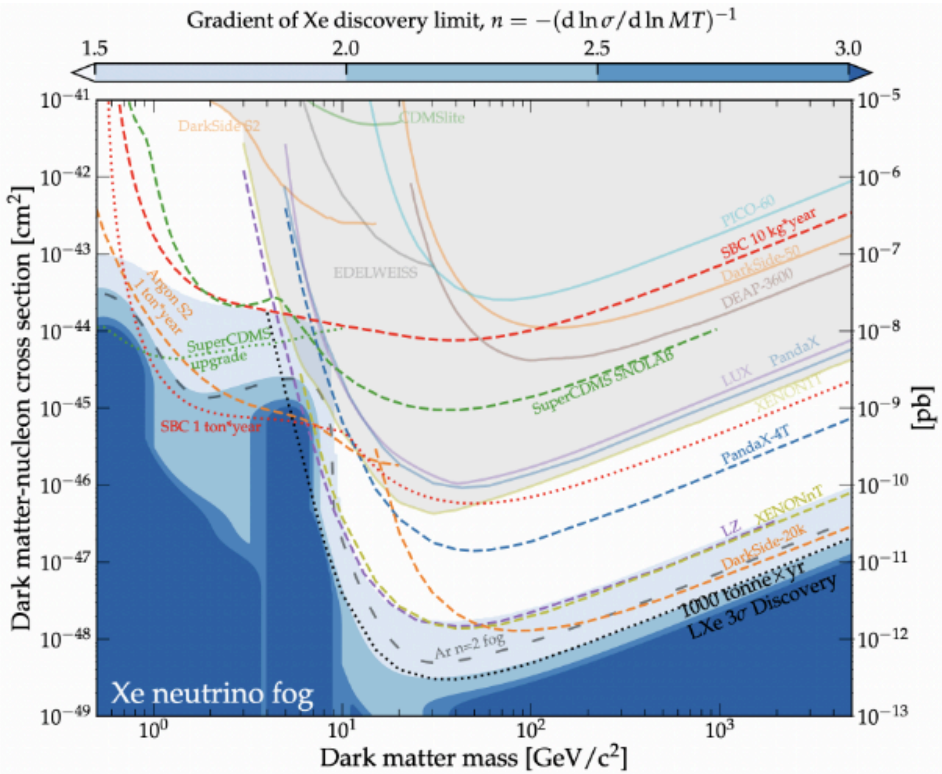
Double phase Time Projection Chamber (TPC)





Running on the frontline

Last results from noble liquid



Rick Gaitskell & [2203.08084]

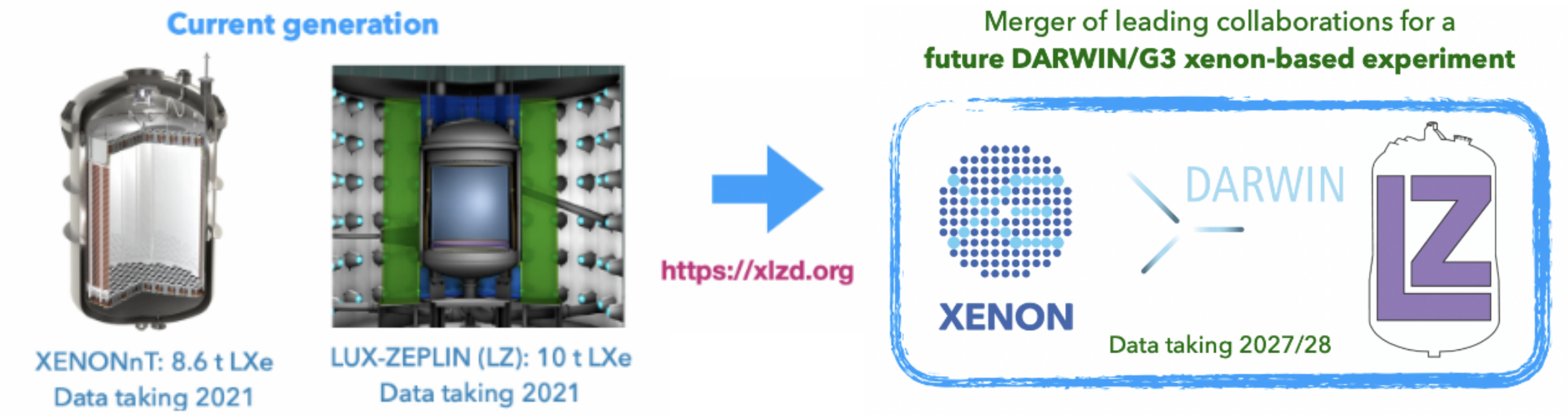
- **Xenon** is the big player (**LZ**, **XENONnT**)
- Cross section excluded in Xe target down to $\sigma_{Xp} \sim 10^{-10}$ pb (at 40 GeV)
- Close to the neutrino ***background*** limit (neutrino from the Sun): the **fog**
- Reduced mass sensitivity below 10 GeV: affected by threshold (and resolution)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

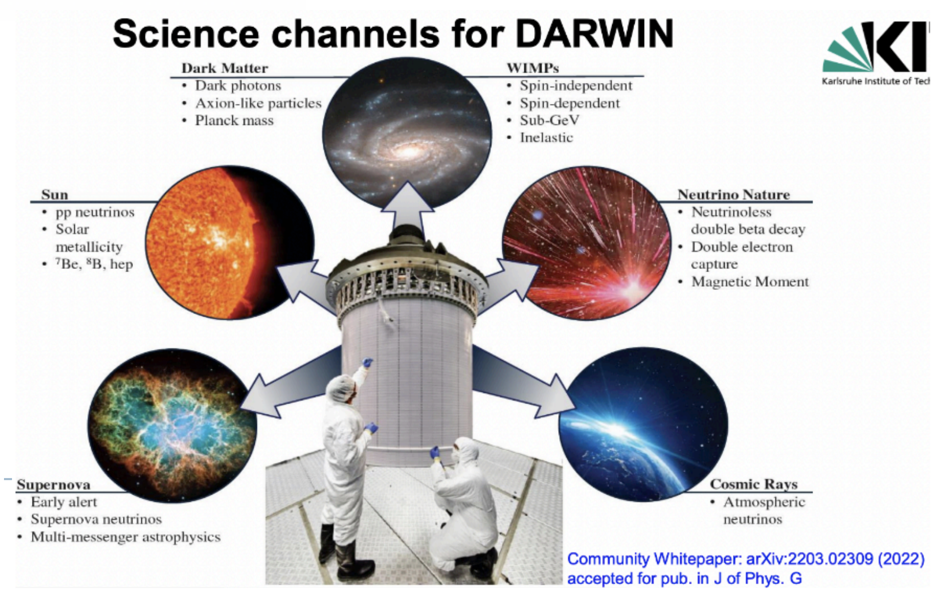
Large target mass (>> 1 ton) is critical for the discovery reach

Future for the LXe

C.O'Hare IDM 2022

- LZ + XENON + DARWIN, many tons LXe

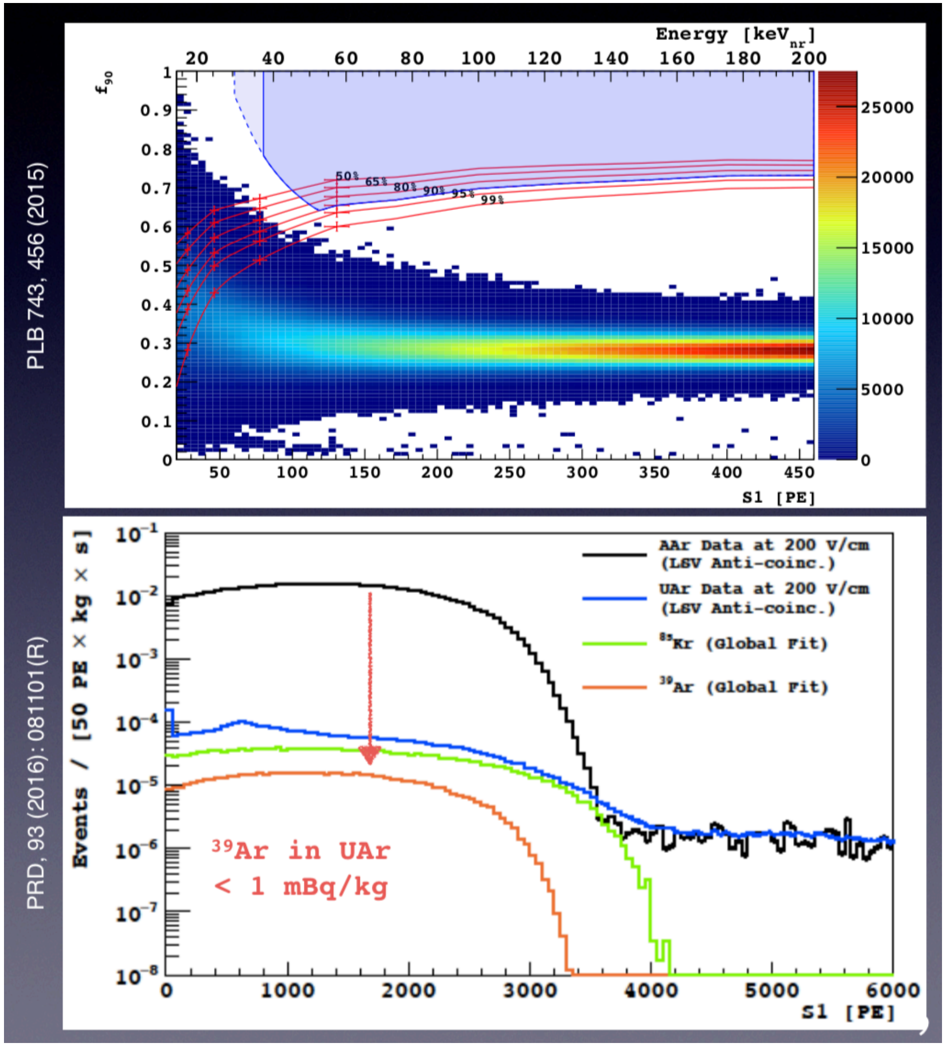




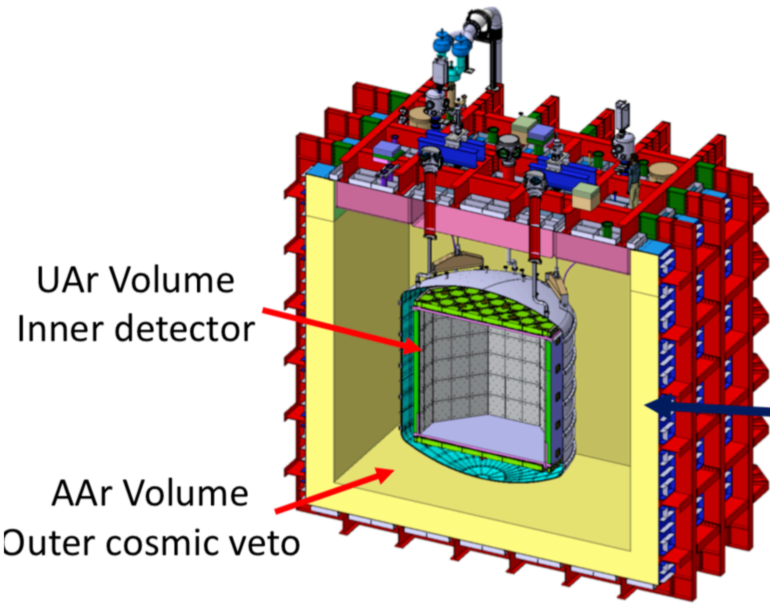
DarkSide

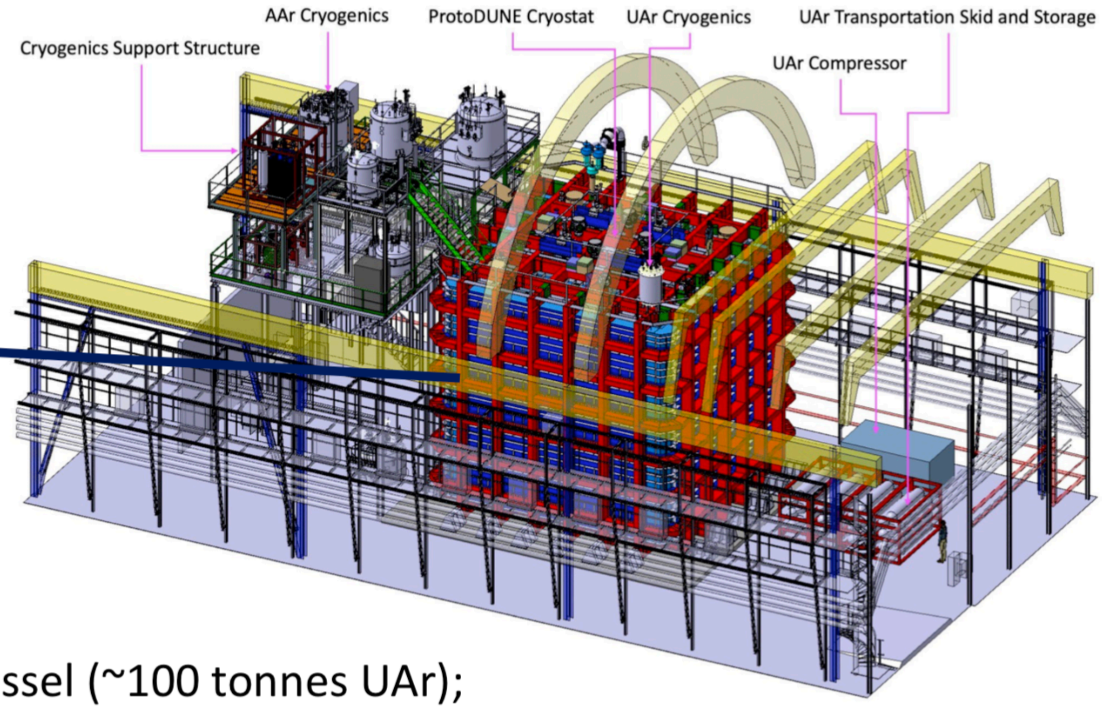
Two phase noble liquid

- Good for high energy recoils
- ***Ar***: pulse shape discrimination between ER and NR (S_1 - S_2)
  - Scintillation: 40 ph./keV
  - Ionization: 20 eV/e
- BUT:
  - Need to remove radioactive ^{39}Ar



The DarkSide-20 overview

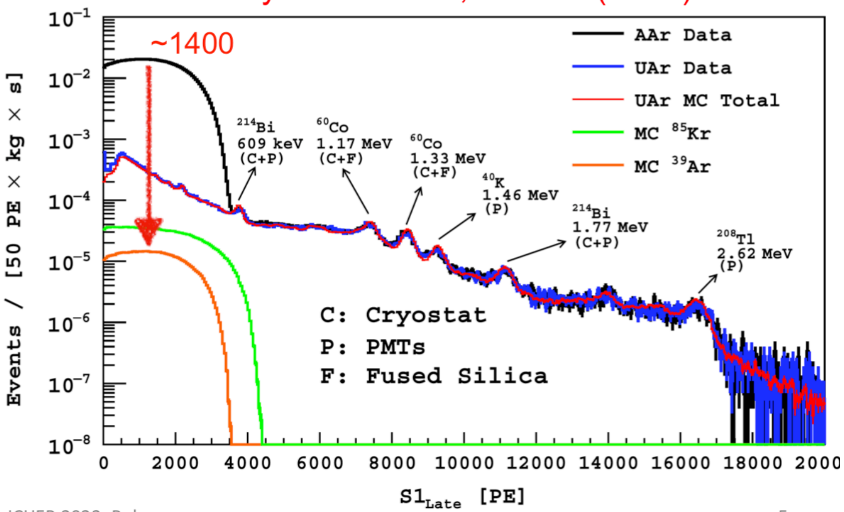




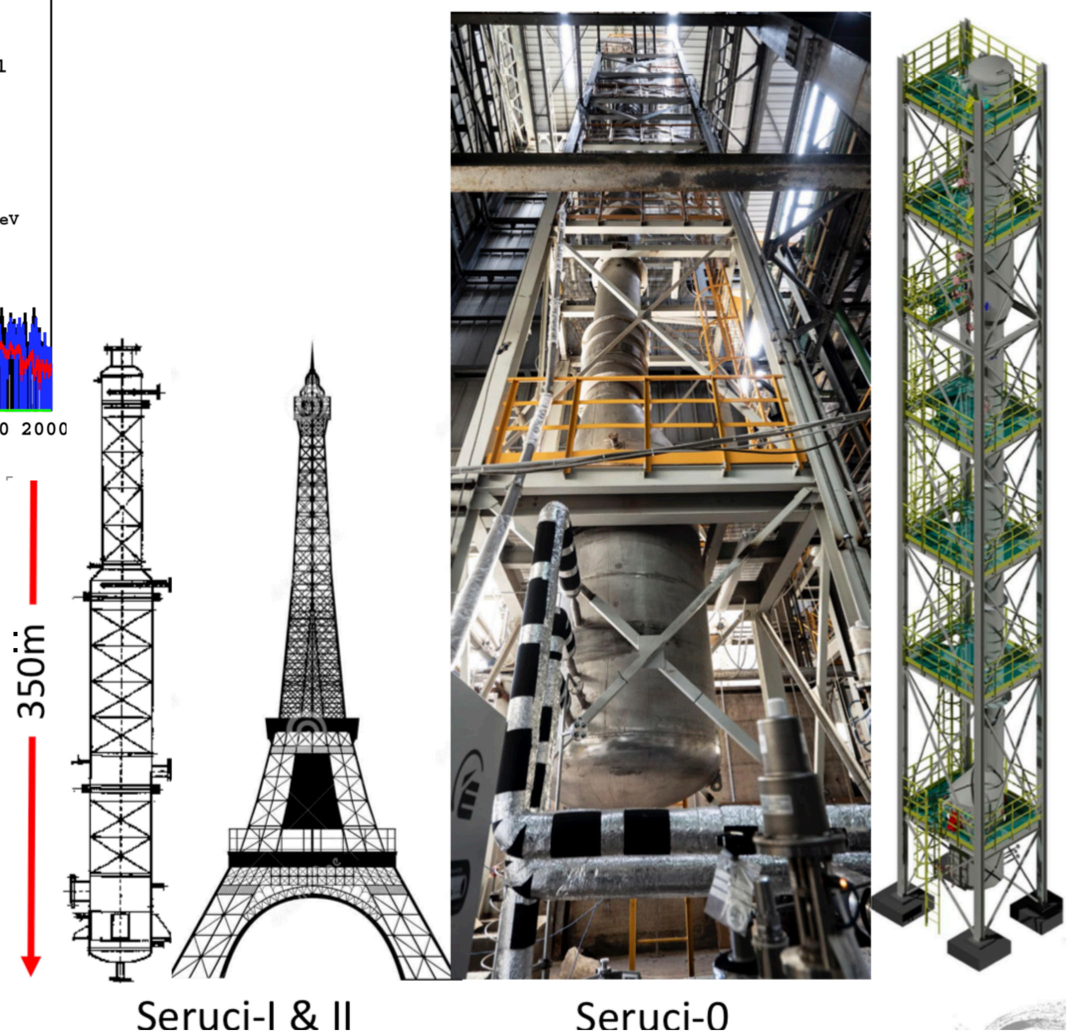
- @LNGS Hall C, Italy;
- Inner detector inside the Ti (or SS) vessel (~100 tonnes UAr);
- Immersed in the AAr bath (~700 tonnes) contained by a membrane cryostat.

UAr purification

Phys. Rev. D 93, 081101 (2016)

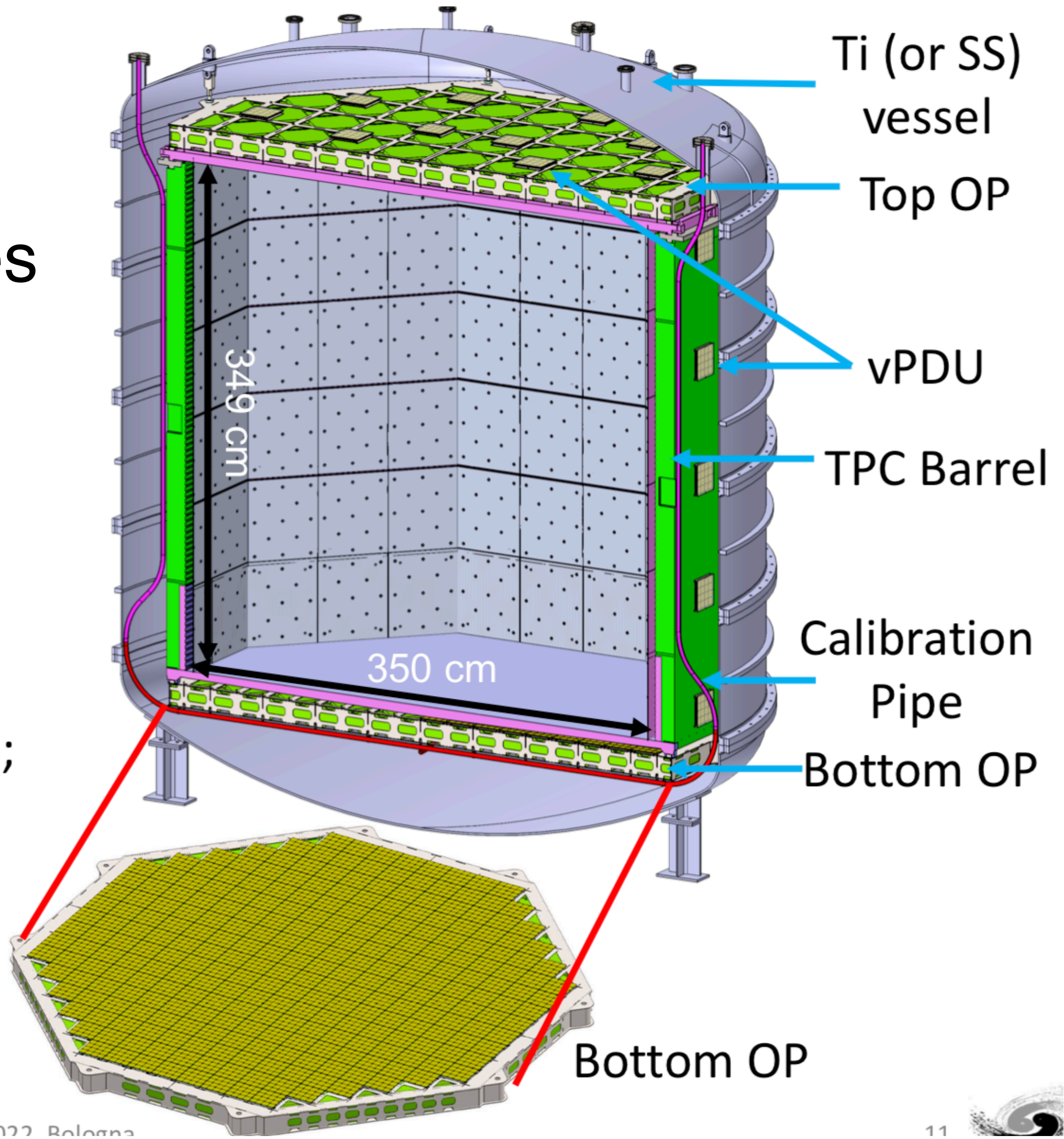


- Extract **underground Ar** in Colorado (USA) : already purer than **atmospheric Ar**
- then purify it (ARIA project) to 99.999%
- Refurbished Sardinia's coal mine
- Ready to start purification



The inner detector

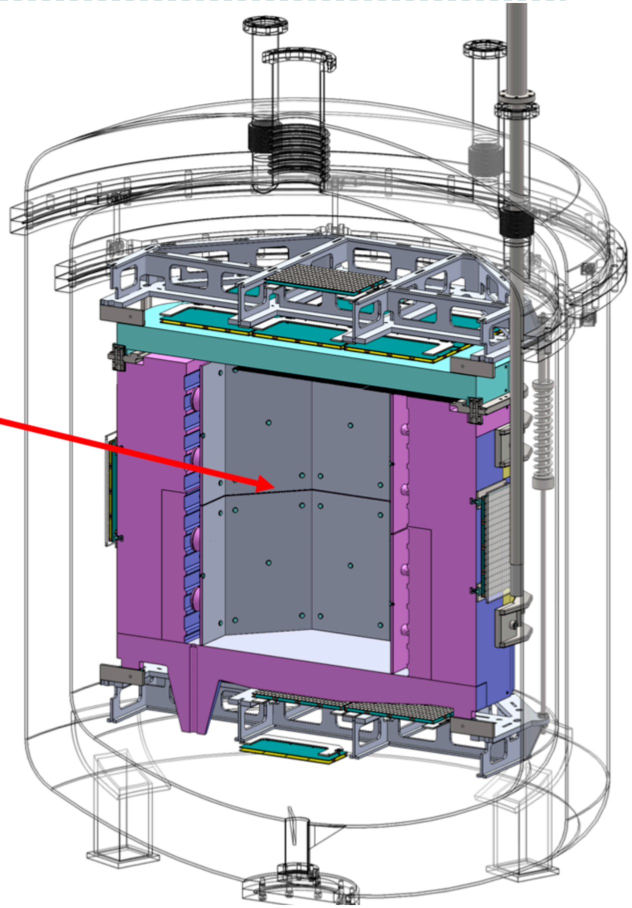
- Fiducial UAr 20.2 tonnes
- Then active veto (UAr) to reject neutrons



- Cryogenic **SiPM** (FBK) m;
- 10x10cm^2 detection units
- > 2000 channels !

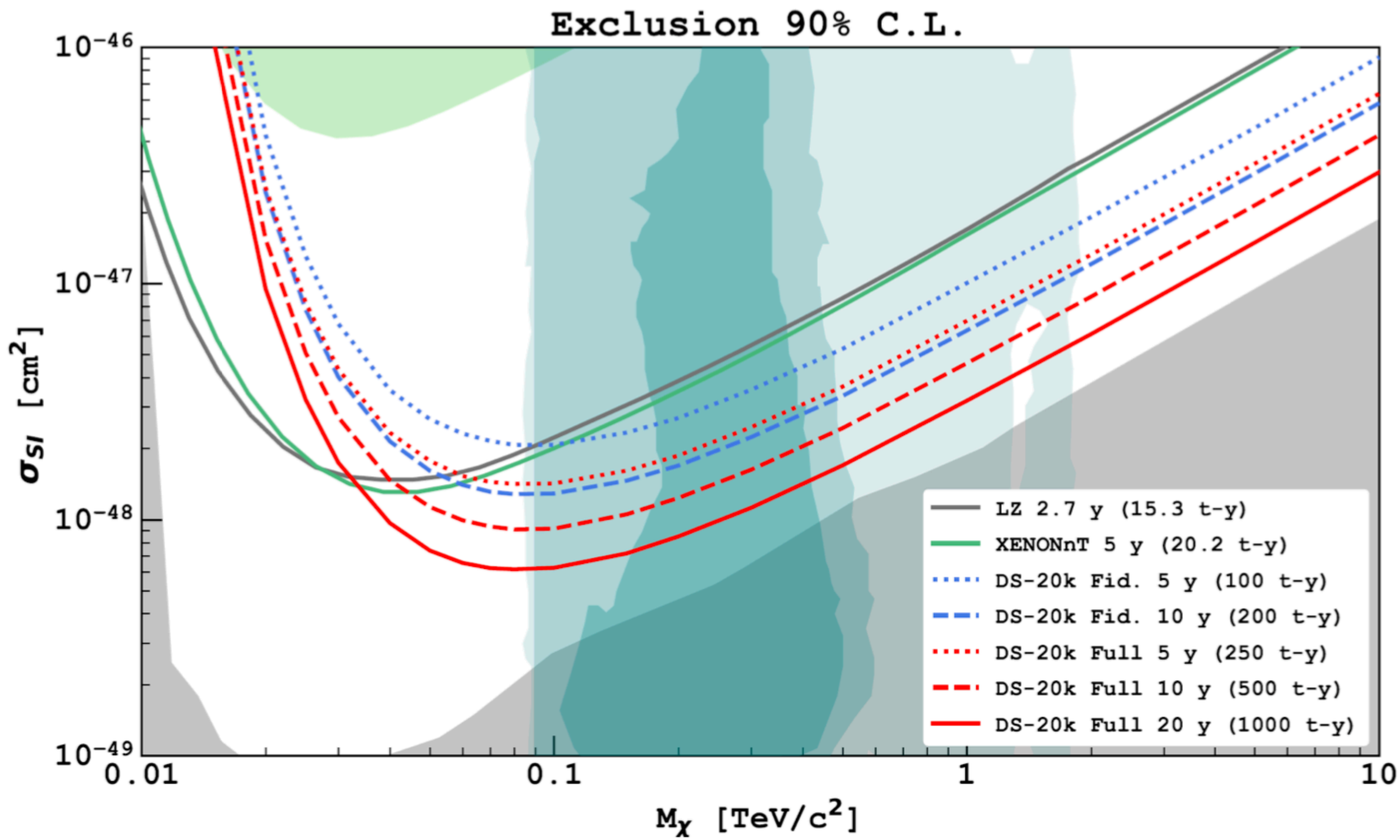
Entering the construction phase

- Inner detector mock-up planned before the final fabrication;
- A down-scaled version of the DS-20k TPC barrel;
  - Mechanical validation in liquid argon;
  - HHV test;
  - …



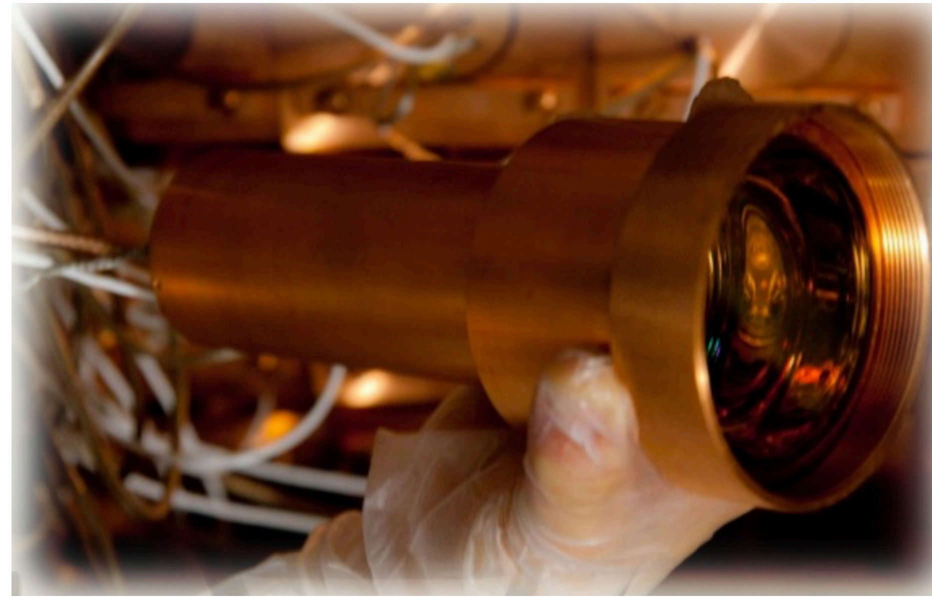
- TPC assembly @LNGS NOA CR2;
- Detector installation and integration @LNGS Hall C;
- Construction start from 2023, UAr to be filled in 2026.

Dark matter (WIMP) sensitivity

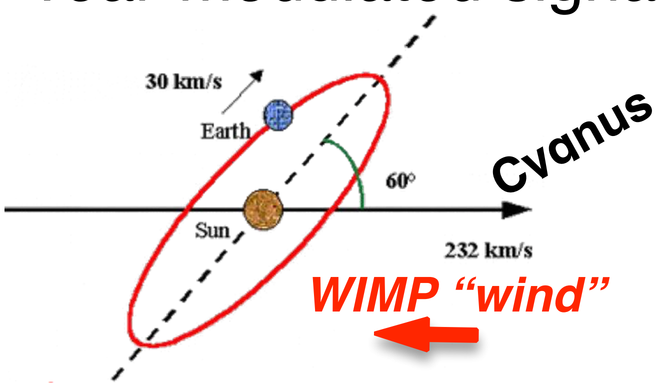


Extend the search down to < 10^{-12} pb

A (possible) signal of DM from NaI (DAMA/Libra)?



- Year-modulated signal in NaI **crystal** target (ton-y exposure)



$$R = S_0 + S_m \cos(\frac{2\pi}{T}(t - t_0))$$

T = 1 year

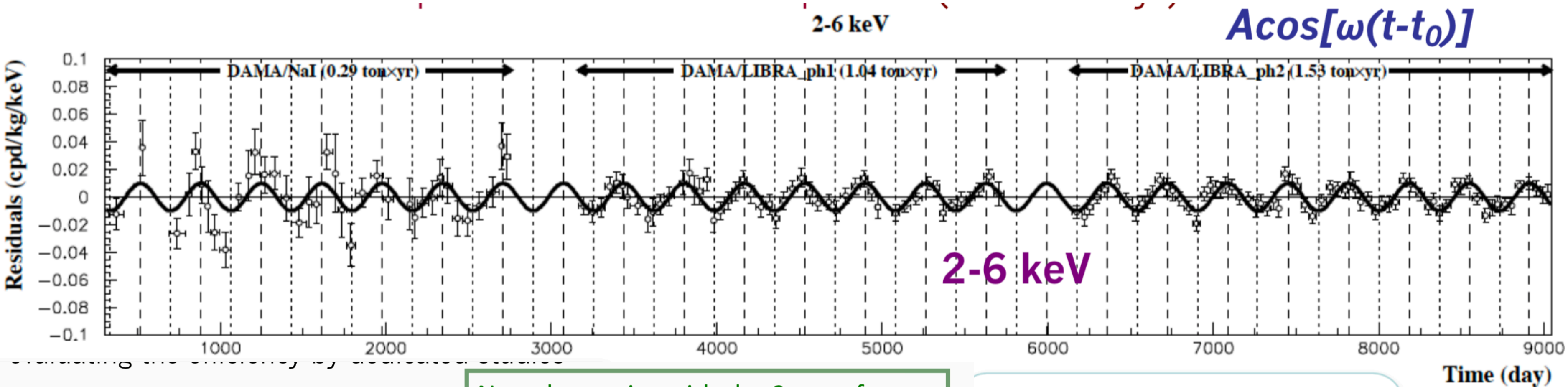
t_0 ~ beginning of June

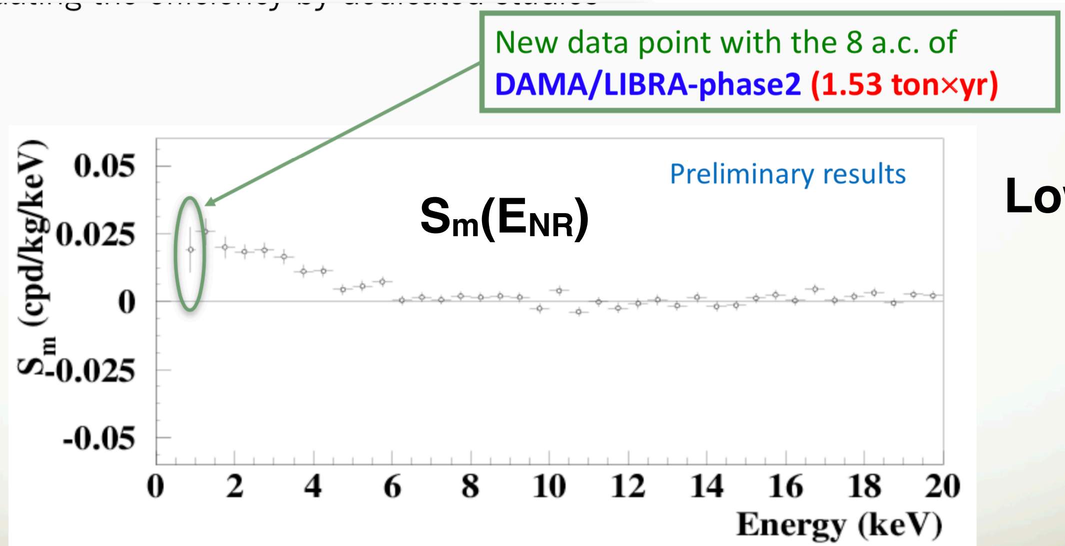
DAMA/Libra results

Scintillator

P.Belli at IDM 2022

- All the interpretation in terms of background not convincing so far.



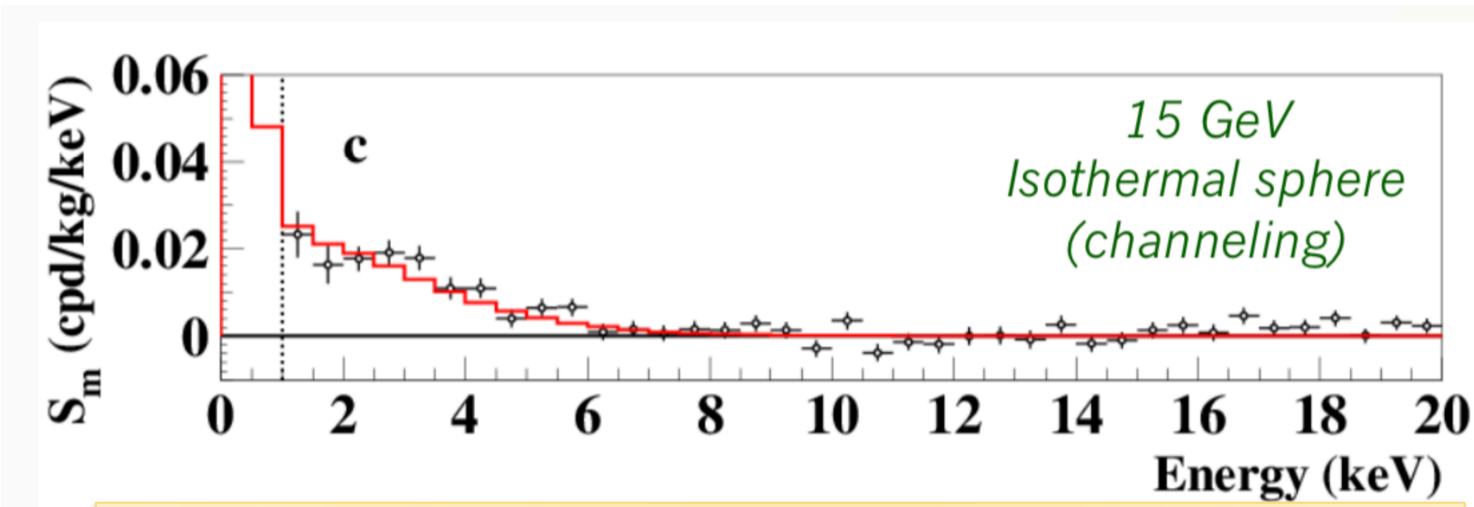


Lower PMT threshold (0.75 keV)

Preferred values for
$\sigma_{\chi p} \sim 10^{-4}$ - 10^{-5} pb and
$M_\chi \sim$ 10 - 100 GeV

Lowering PMT threshold with DAMA

- **Lowering** PMT threshold (higher Q.E. PMT) can shed light on **different models** of the WIMP distributions (halo, stream, etc.)



What about reproducing this result independently ? Several efforts in the world (COSINE, ANAIS, SABRE,…)

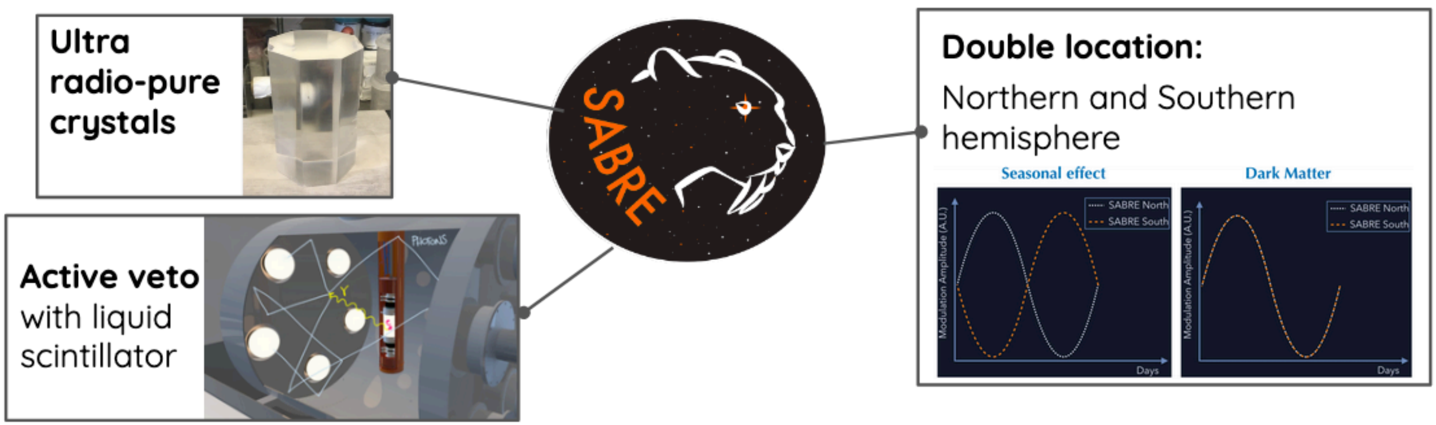
What about measuring the WIMP direction ?

SABRE, reproducing DAMA

Scintillator

Rate << 1 count/day/kg/keV

- **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 hemisphere (Stawell gold mine, Australia)

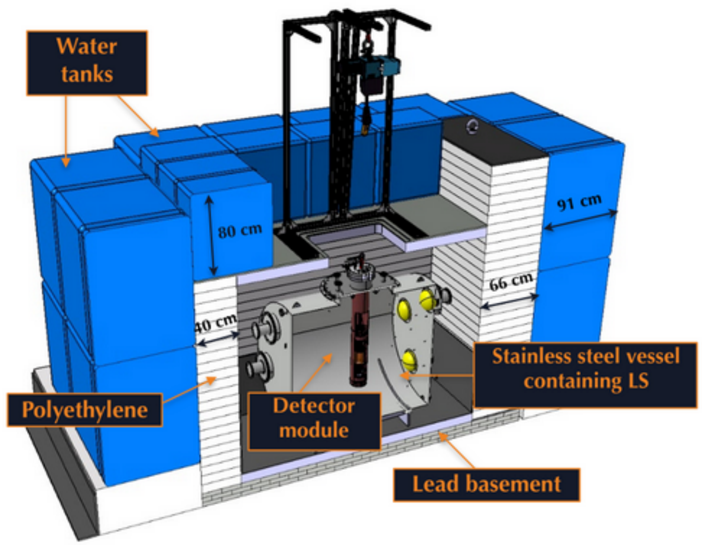


If same effect seen as
in DAMA/LIBRA, confirm modulation
measuring it in a different location
(*otherwise a local systematics effect?*)

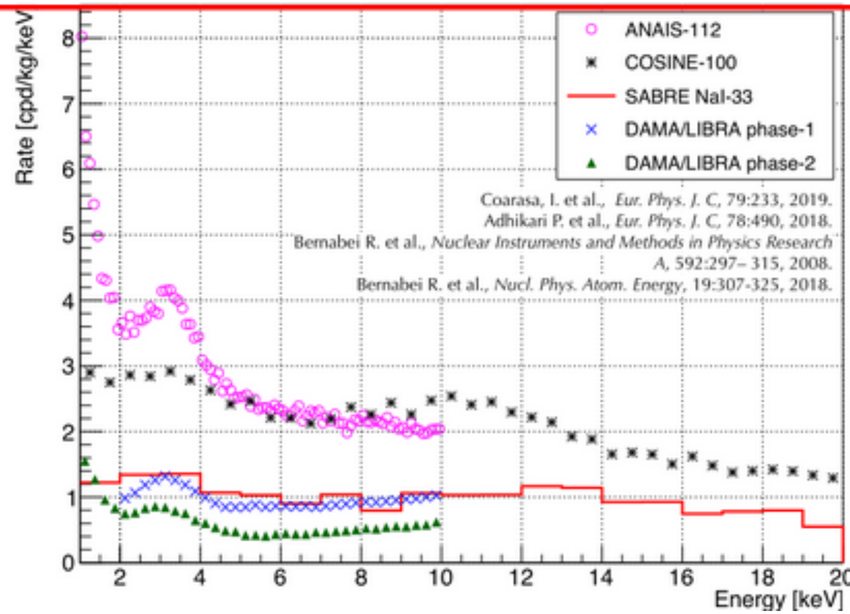
The Proof of Principle

- LNGS test-stand for single ultra pure crystals

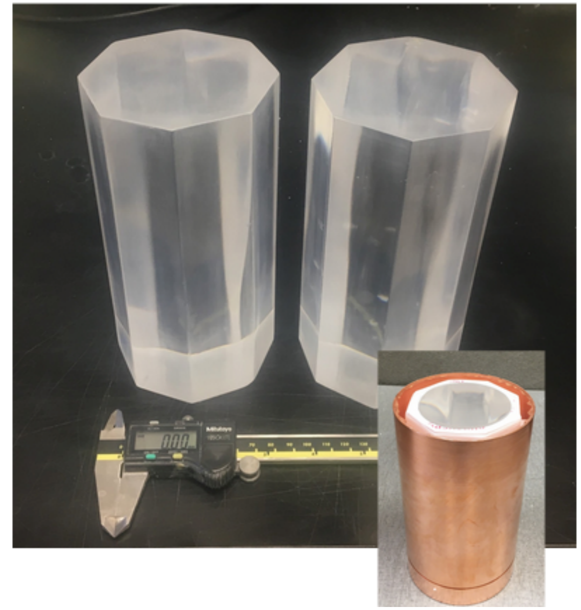
Measured Rate in 1 to 6 keV: 1.20 +/- 0.05 count/day/kg/keV



SABRE-PoP background reached the same background of DAMA/LIBRA phase 1



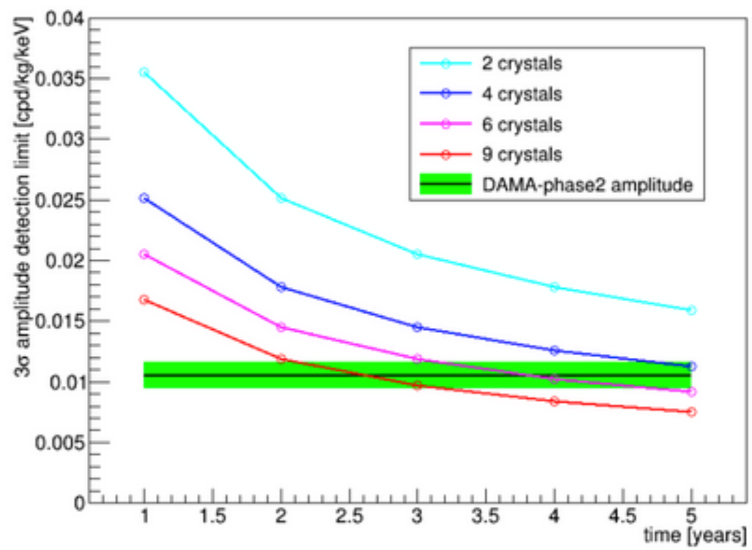
Prospect for SABRE



- Further R&D need to reduce the background
  - Contamination of the crystal reflector and crystal with 210 Pb

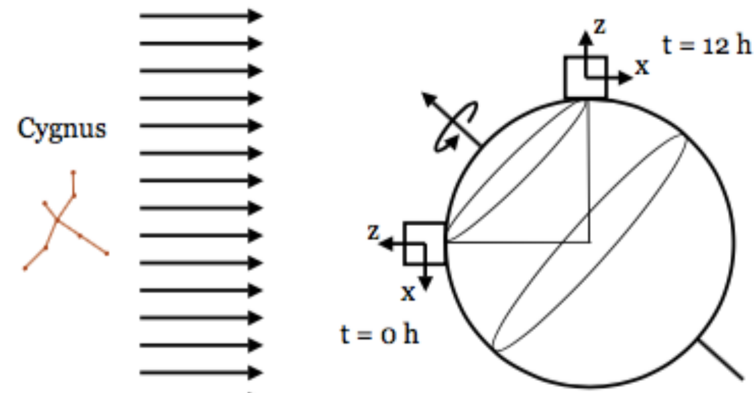
5 kg crystals

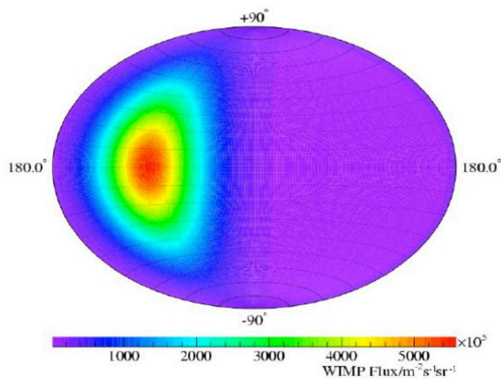
Annual modulation analysis: sensitive to DAMA results in 3 year with 0.3 cpd/keV/kg background



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**!

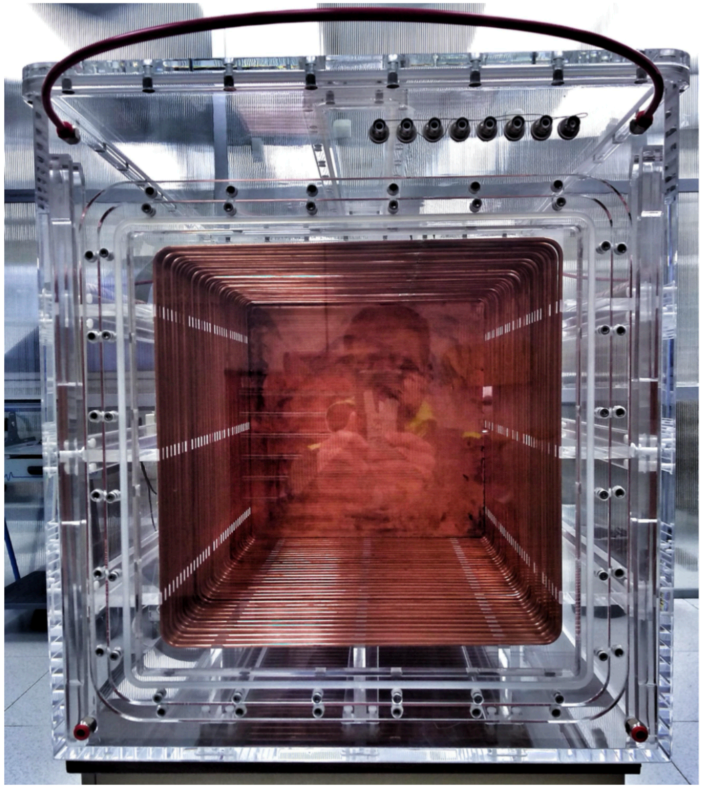




The gas TPC approach CYGNO

- **Reduce density** to have longer, **visible** nuclear recoils (NR)
- **Measure the NR direction, infer DM direction**
- Discriminate ER against NR (**dE/dx**)
- Challenge is to instrument **large volumes**.
  - Veto/shielding might be an issues
- **Scalable readout** to large surface is the name of the game

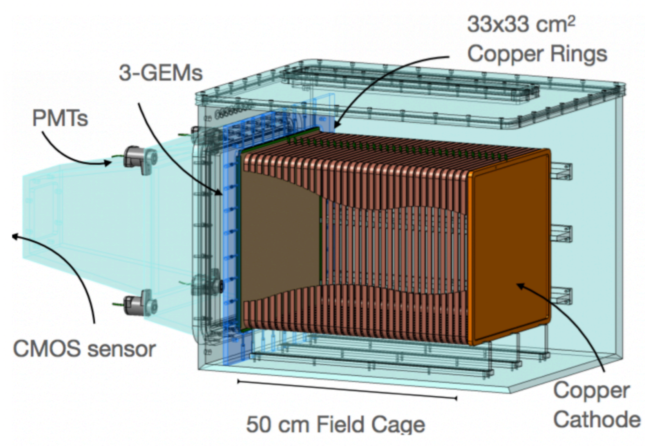
- **CYGNO**:
  - gas at atmospheric pressure
  - GEM amplification
  - Optical readout (CF_4 scintillation)
  - He (H) based mixtures
    - Low mass DM too!



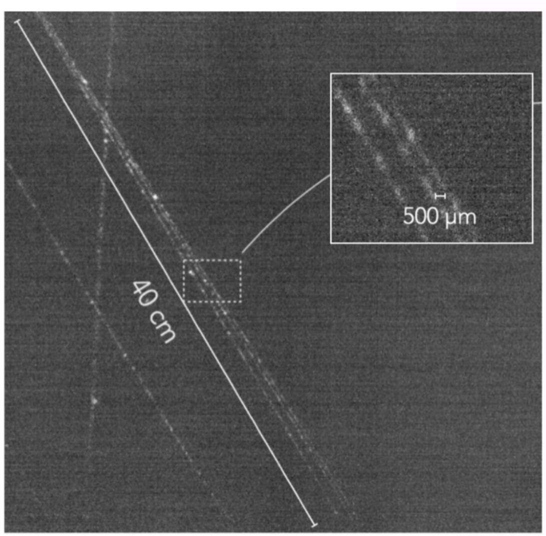
The optical readout of GEMs

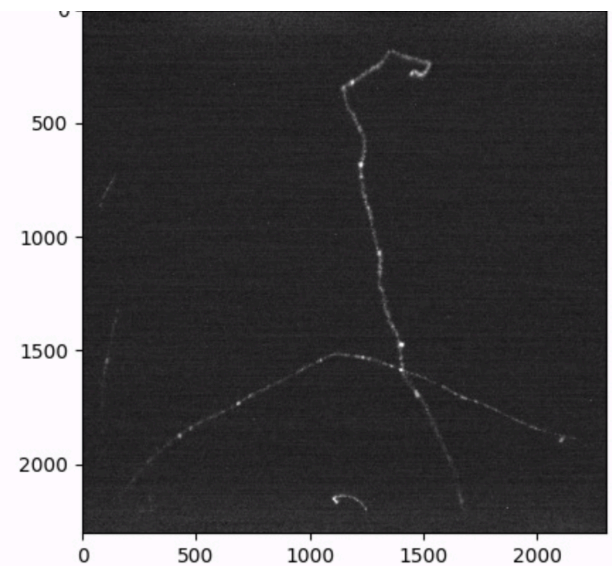
CYGNO

- First 50 liter prototype installed **underground** at LNGS (close to DAMA)



Cosmic rays (overground at LNF)



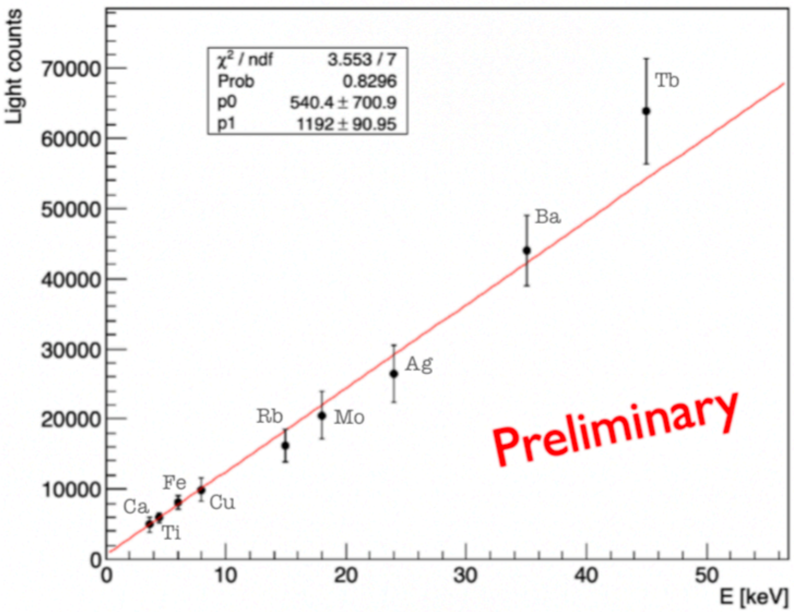


Electron Recoils from internal and external **radioactivity** (underground)

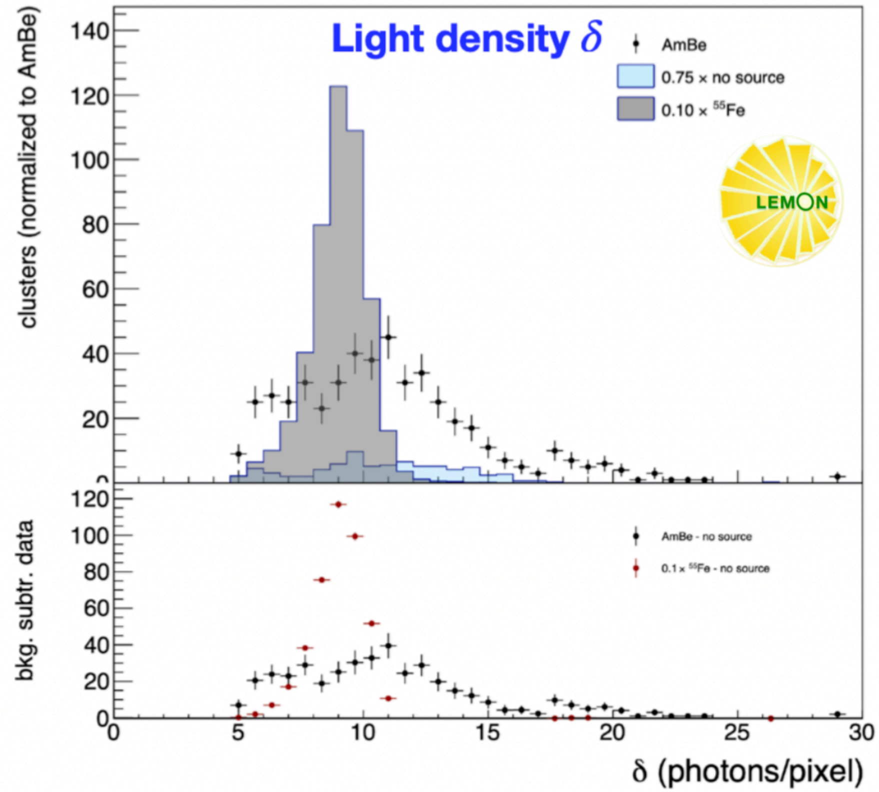
Calibration and NR/ER discrimination

CYGNO

Electronic recoil (ER) calibration:



- ~ **13% energy resolution**
- **good linearity** in the response



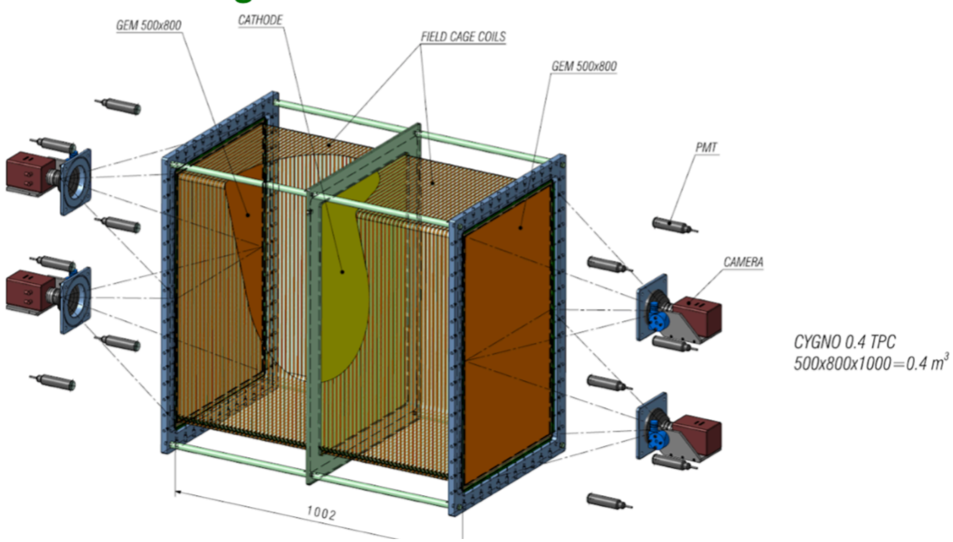
Neutrons from Am-Be source
40% NR efficiency with
4% ER contamination

Plans for CYGNO - Phase 1

- Build a **~0.5 m³** detector with low radioactivity components and passive shielding (Cu + water) for **Hall-F** at LNGS
- A **~1 kg** target mass aiming at a **sub keV** detection threshold
- Exploit **angular discrimination** of ER background (higher thr.)

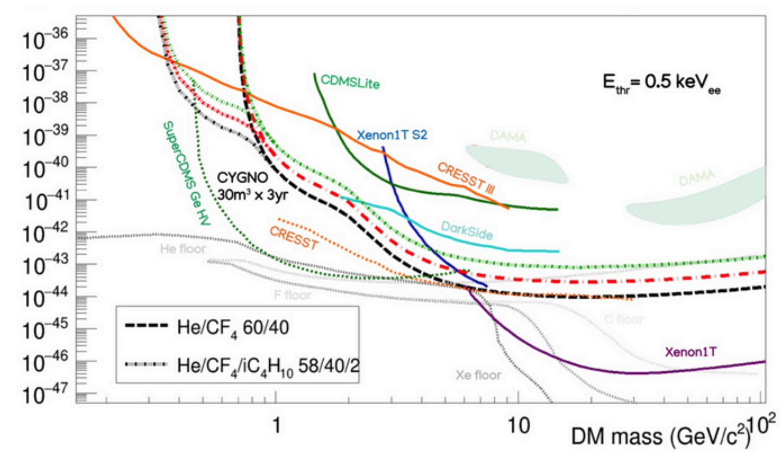
CYGNO Phase 1

Designed at LNF and to be installed at LNGS



https://www.mdpi.com/2410-390X/6/1/6

CYGNO Phase 2 (30 m³)

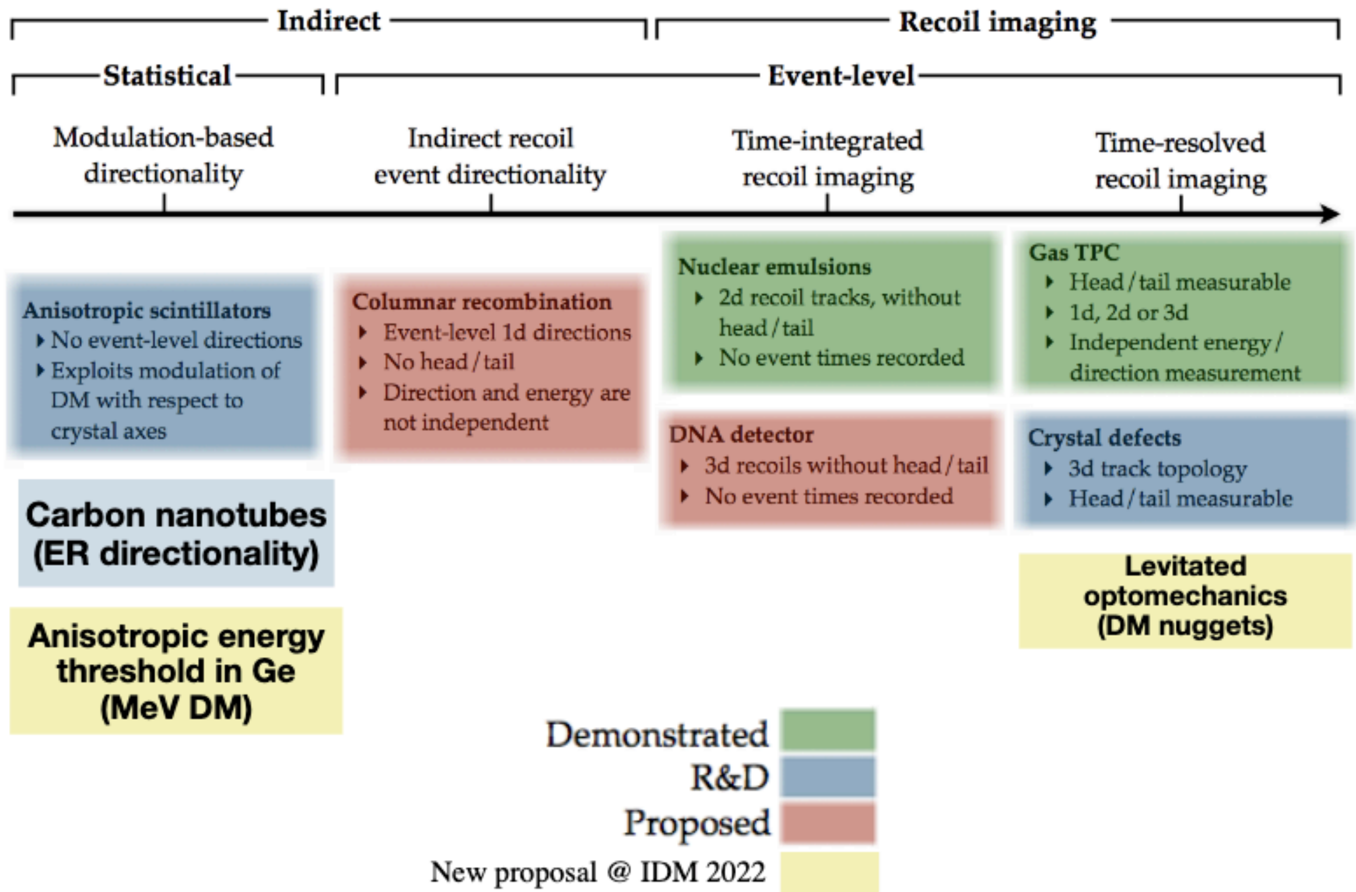


Very competitive for spin-dependent search (flourine)

Directional tools

E.Baracchini

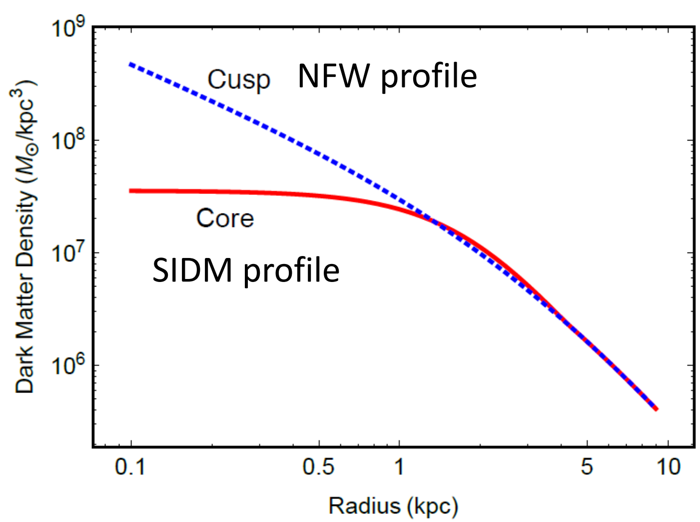
Liberally adapted from S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224



Also US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report :

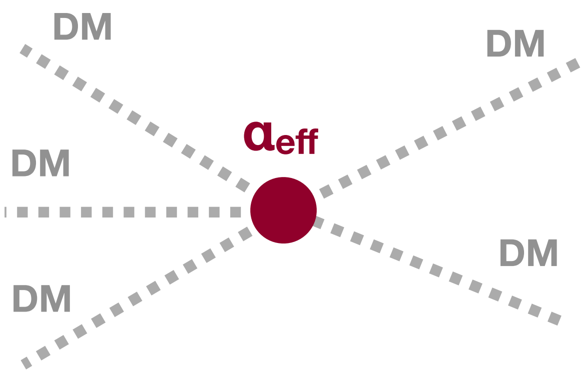
Cusp-core problem with WIMP ?

- ΛCDM successful in describing large scales structures from horizons (15000 Mpc) to intergalaxy distances (1 Mpc)
  - However sub-galactic structures (<1 Mpc) seems to be problematic (cusp-core, missing satellites, …)
  - Cold DM predicts galactic halos with ***high*** central **density**
  - Disagree with rotation curves at **small *r***



Looking elsewhere (with a reason)

- The Strongly Interacting Massive Particles (**SIMP**)



$\alpha_{eff} \sim 1$

- Self-interaction 3→2 heats up DM and lowers density in Galaxy formation

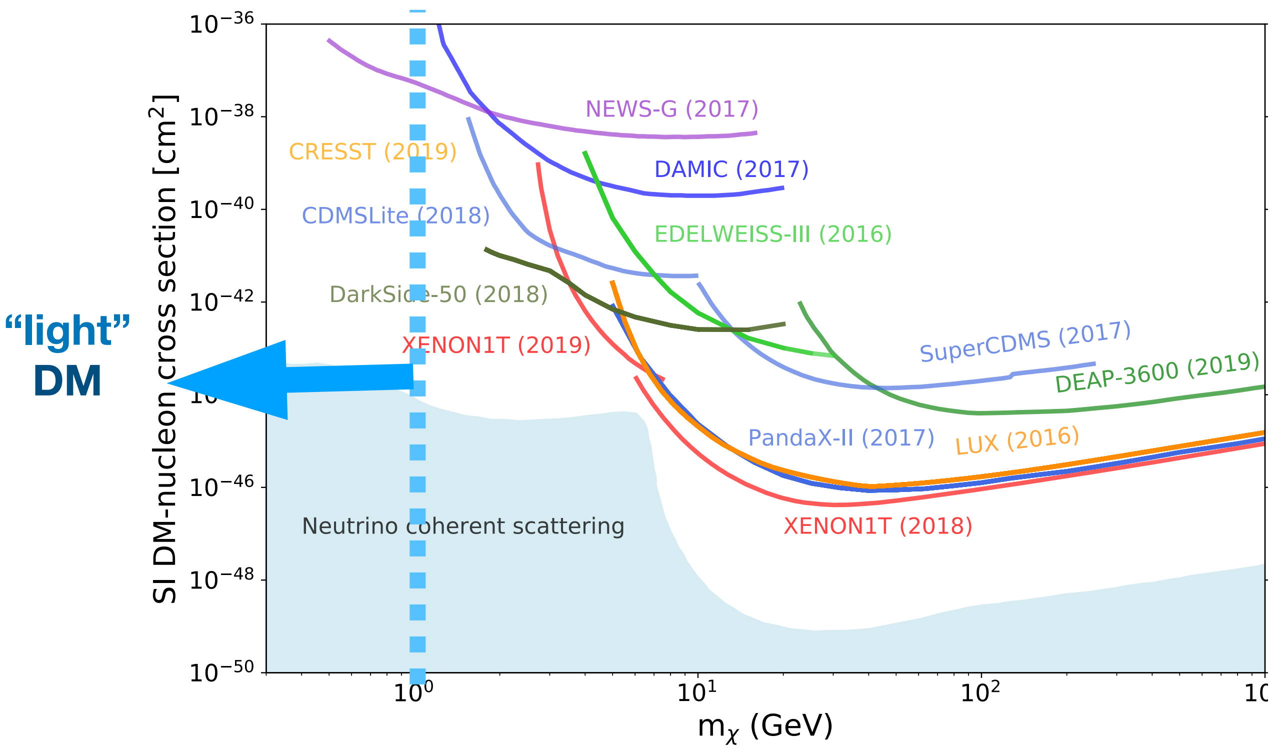
- SIMP predicts **sub-GeV m_{DM}**

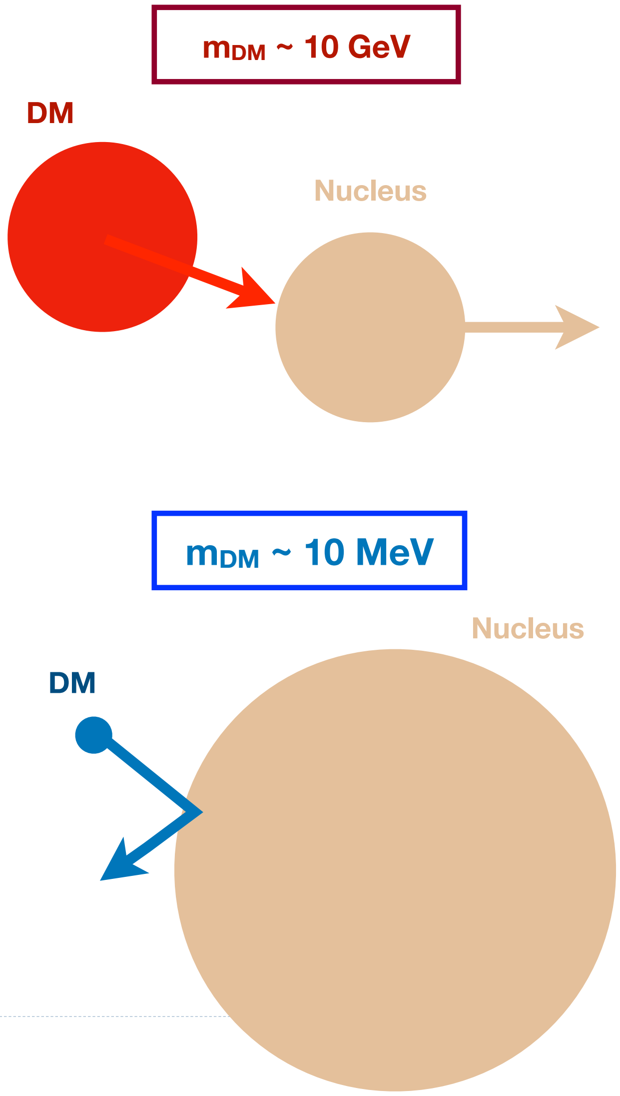
  $m_{DM} \sim \alpha_{eff} (T^2 M_{Pl})^{1/3}$

  (e.g. $\alpha_{eff} = 1 \rightarrow m_{DM} = 100$ MeV)

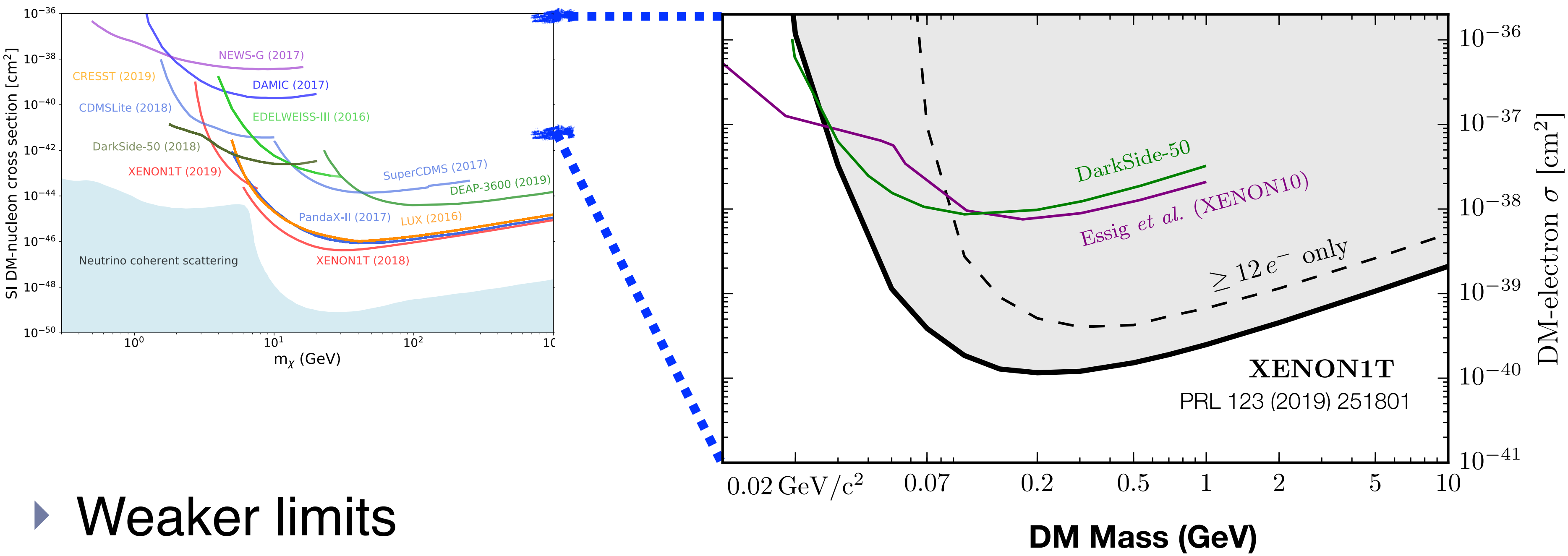
New mass range, new experiments

- Look for a single **recoiling** particle
  - Nuclei too heavy for light DM





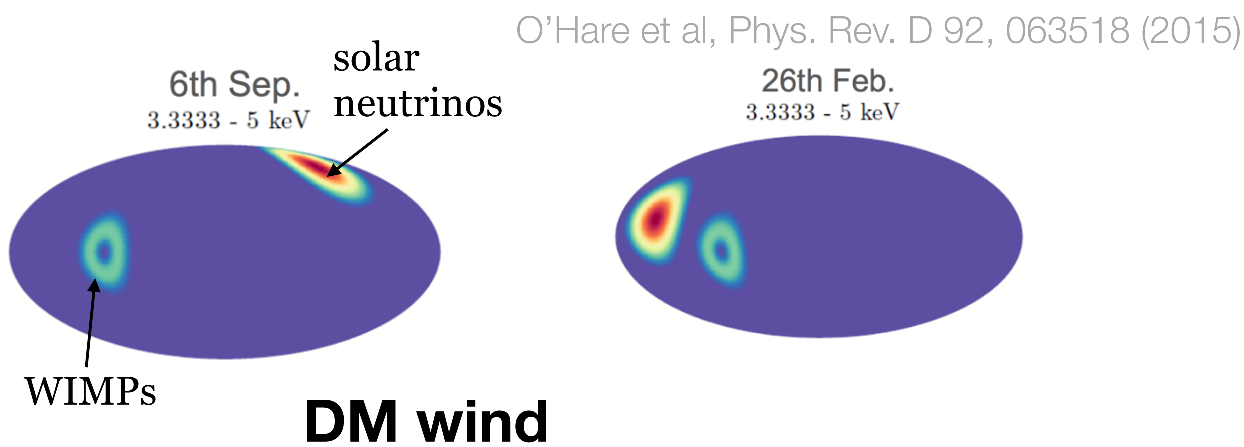
Electron recoils are (much) better

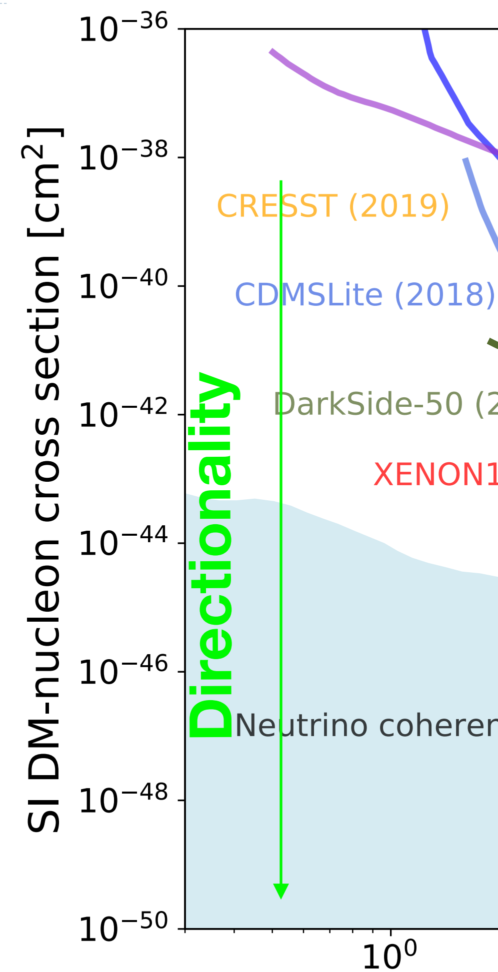


- Weaker limits
  - $m_{DM} < 100$ MeV very poor limits

Window of opportunity for gram sized targets ?

Neutrino floor exploration





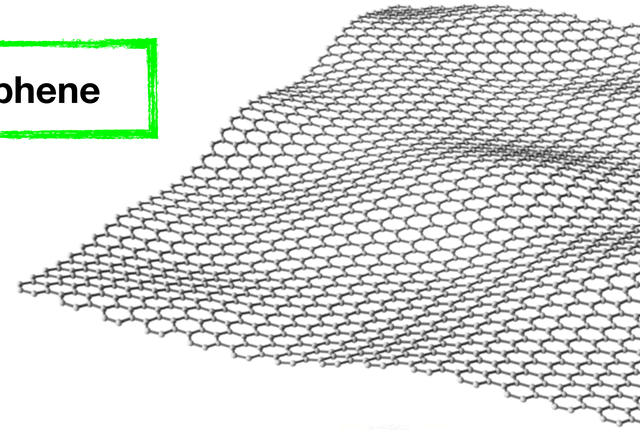
- Solar neutrinos direction never overlaps with DM wind
- In general a powerful tool to suppress any background (radioactivity)

A new detector: Light DM sensitivity and directionality in the same detector

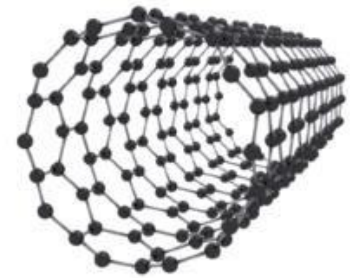
Solid state targets: 2D materials

- **Back of the envelope** calculation:
  K_{DM} = 5-50 eV (for m_{DM} = 10-100 MeV)
  - Assuming $v_{DM} \sim 300$ km/s
- **Enough** to extract an electron from carbon
  - $\Phi \sim 4.7$ eV (work function) so $K_e \sim 1$-50 eV
  - Extremely **short** range in matter!
- 2D materials: electrons ejected **directly** into vacuum
  - **Graphene** and **carbon nanotubes**

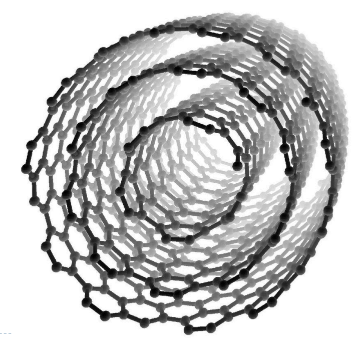
Graphene



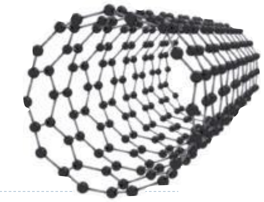
Single-wall nanotube



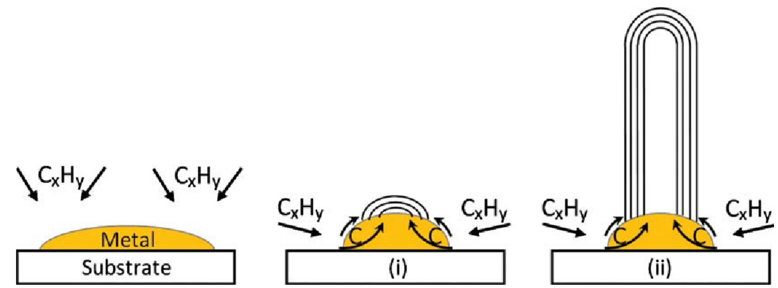
Multi-wall nanotube



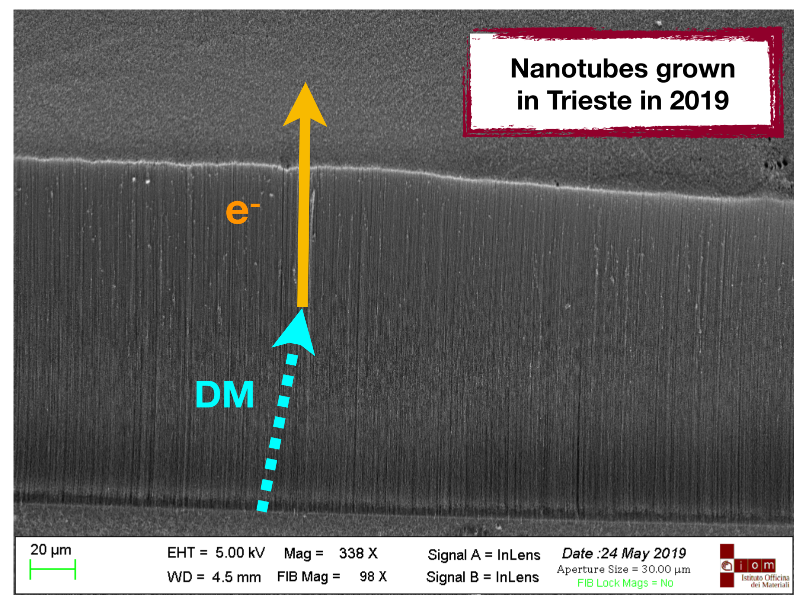
Growing vertically aligned CNT

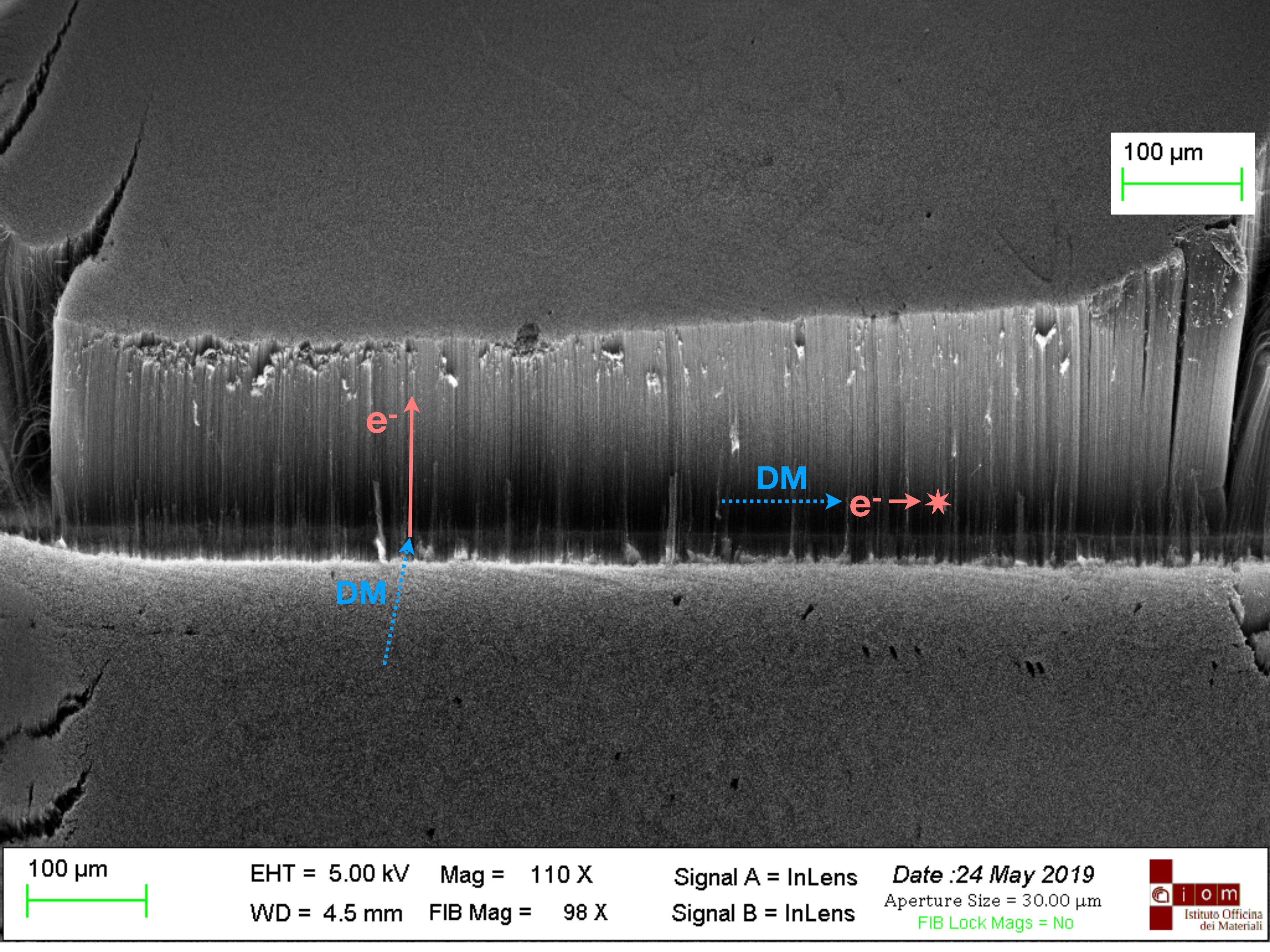


- **Carbon nanotubes** synthesized through Chemical Vapor Deposition (CVD)
  - Internal diameter ~5 nm, length up to 300 µm
  - Single- or multi-wall depending on growth **technique**



- Result: vertically-aligned nanotube 'forests' **(VA-CNT)**
  - **'Hollow'** in the direction of the tubes
  - Electrons can **escape** if **parallel** to tubes
  - Makes it an **ideal** light-DM target

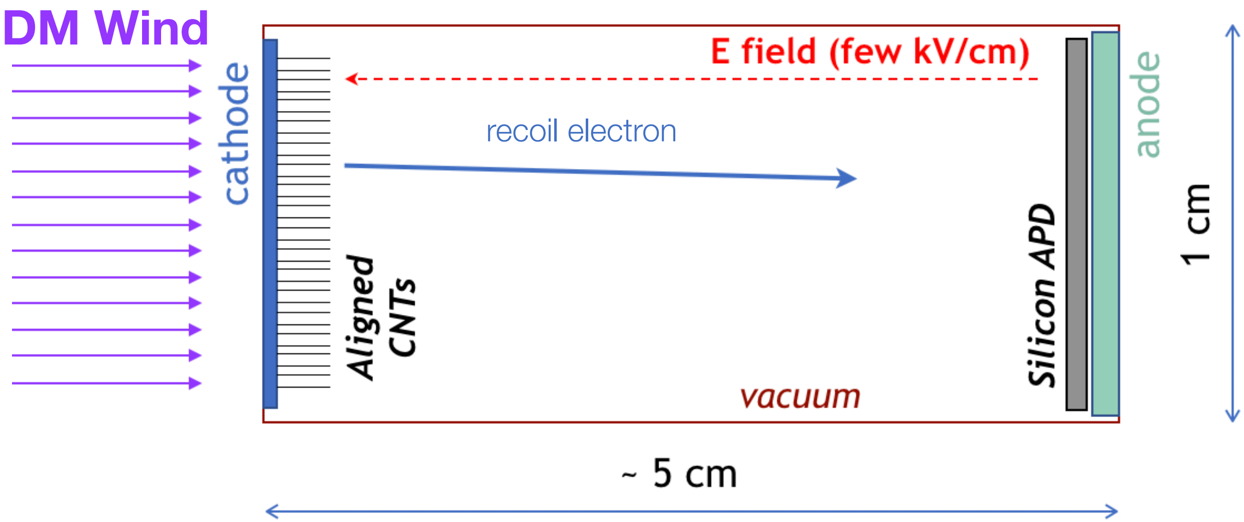




100 µm
e-
DM
e- → ✶
DM
100 µm
EHT = 5.00 kV
Mag = 110 X
WD = 4.5 mm
FIB Mag = 98 X
Signal A = InLens
Signal B = InLens
Date :24 May 2019
Aperture Size = 30.00 µm
FIB Lock Mags = No
Istituto Officina dei Materiali

The Dark PMT

L.M. Capparelli, et al., Phys. Dark Universe, 9-10 (2015) 24
G.Cavoto, et al., EPJC 76 (2016) 349
G. Cavoto, et al., PLB 776 (2018) 338



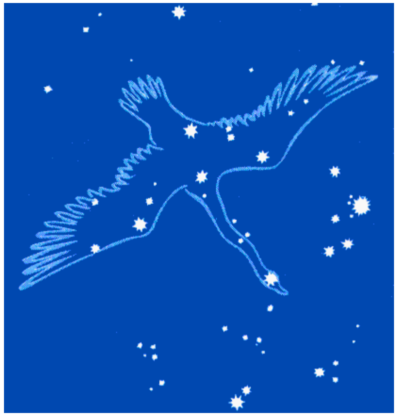
- ‘Dark-photocathode’ of aligned **nanotubes**
  - Ejected e^- accelerated by electric field
  - Detected by solid state **e^- counter**

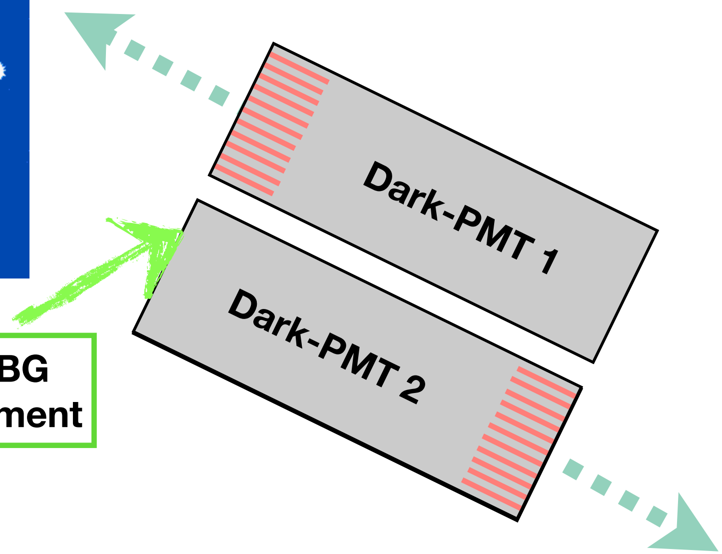
Dark-PMT features:

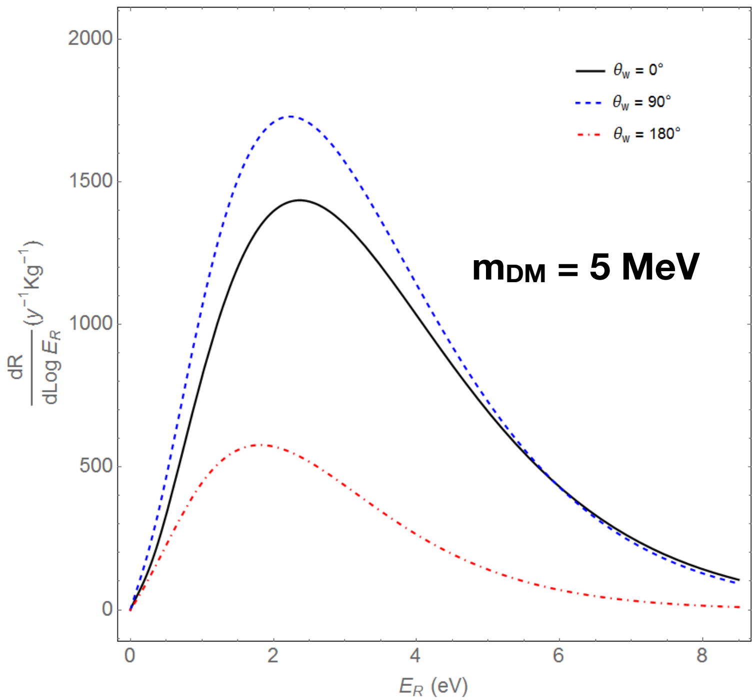
- **Portable, cheap, and easy to produce**
- **Unaffected by thermal noise (Φ_e = 4.7 eV)**
- **Directional sensitivity**

A telescope of dark PMT

G. Cavoto, et al., PLB 776 (2018) 338





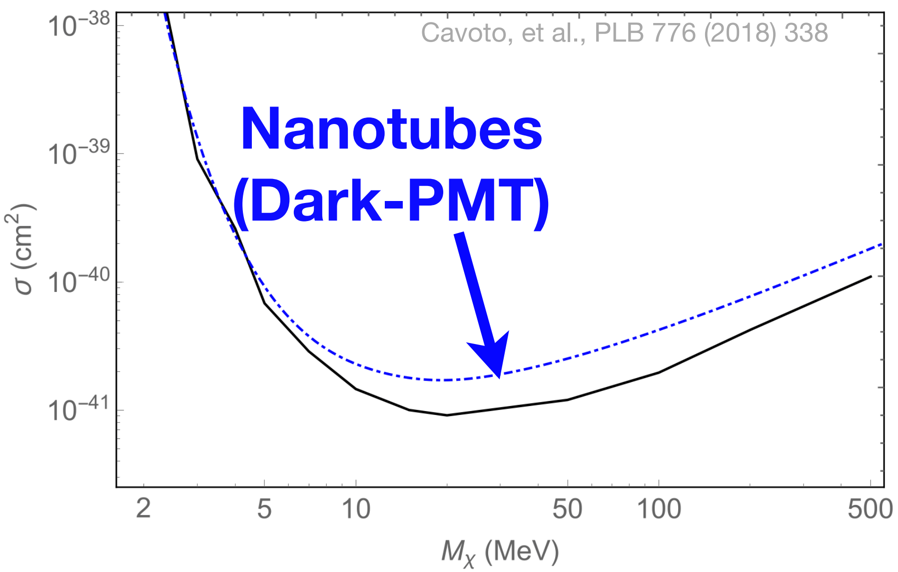


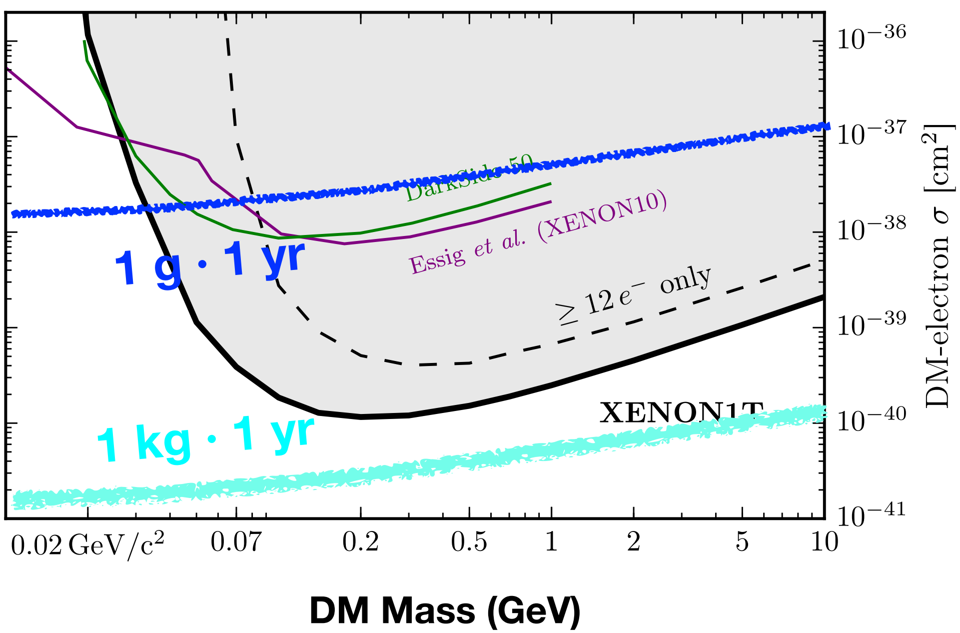
- **Two** sets of detectors: pointing towards Cygnus, and in **orthogonal** direction
  - Search variable: N_1-N_2

In principle sensitive to eV electrons!

Sensitivity down to 2 MeV DM

Exposure = 1 kg · 1 year



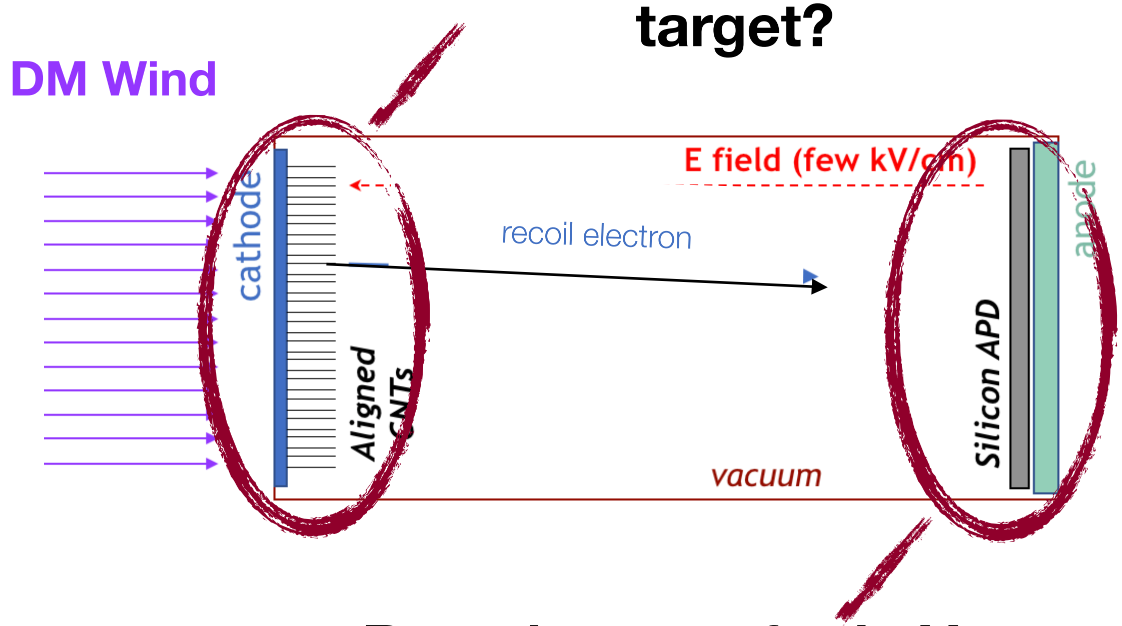


- Competitive searches with gram target mass.

The Andromeda project

- **Main objective:** have a working dark-PMT protoype by end of project
  - Challenges on **both sides** of detector

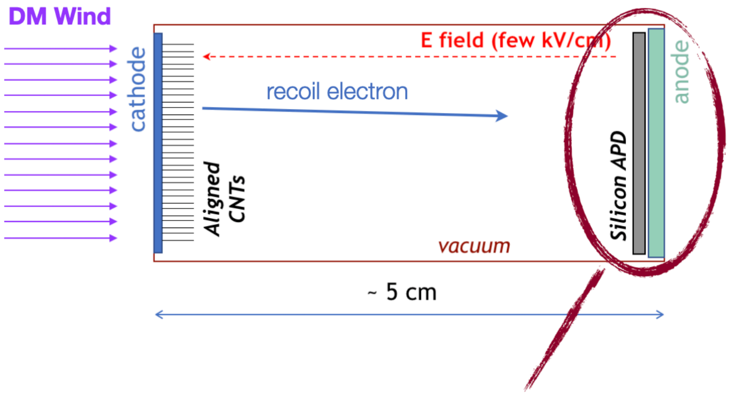
Ideal nanotubes for DM target?



Best detector for keV electrons?

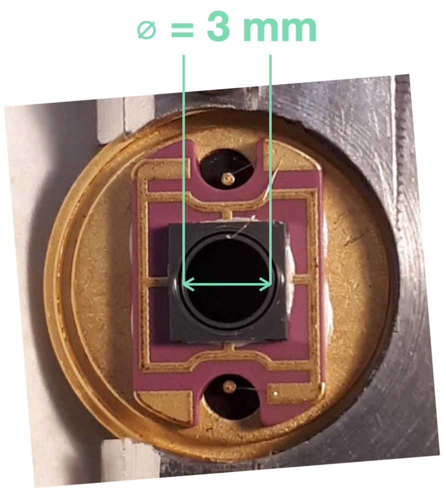
Silicon detectors for keV electrons

APDs and SDDs 'born' as photon detectors

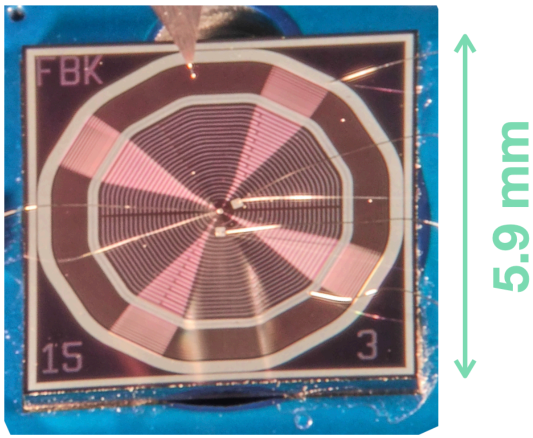


Challenge: detect keV electrons (with high efficiency)

- Benchmark: **Avalanche Photo-Diodes**
  - Simple, cost-effective
  - Hamamatsu windowless APD



- Possible upgrade: **Silicon Drift Detectors**
  - Ultimate resolution
  - FBK (SDD) + PoliMi (electronics)



APD Characterization

❖ State-of-the-art e^- gun @ LASEC Labs (Roma Tre)

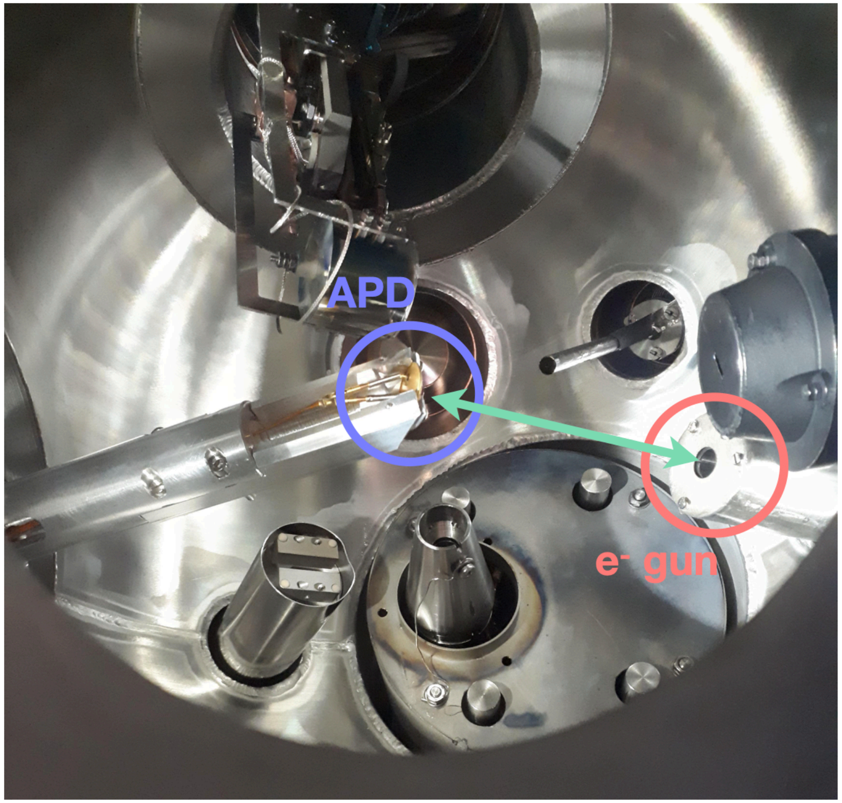
  - Electron **energy**: 30 < E < 1000 eV
  - Energy uncertainty < 0.05 eV

❖ Gun **current** as low as a <u>few fA</u>

  - i.e. electrons at ~10 kHz (not bunched)
  - Can probe **single-electron** regime

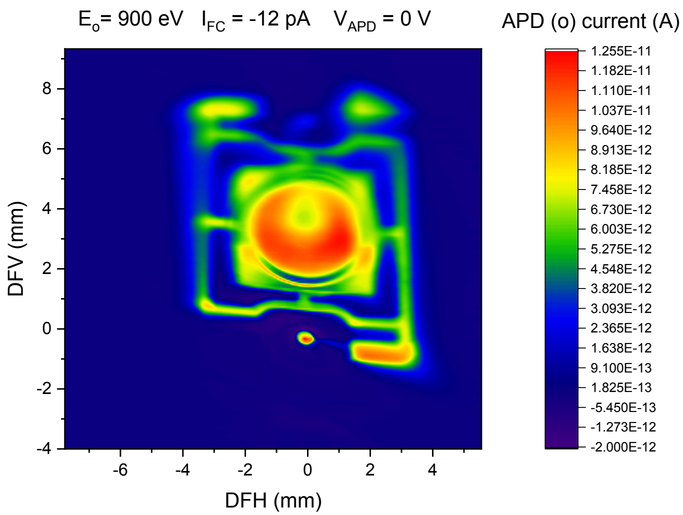
❖ Beam profile ~ 0.5 mm

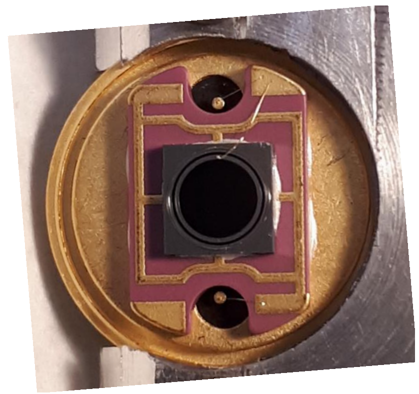
  - Completely **contained** on APD (⌀ = 3 mm)

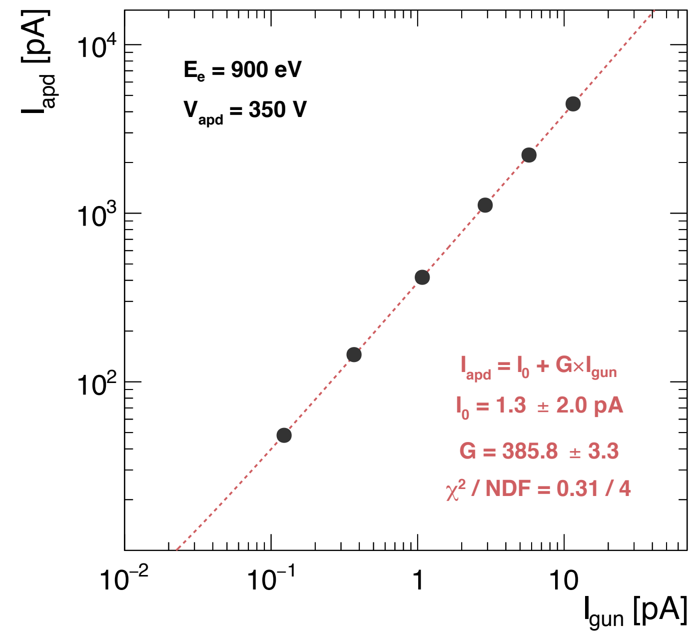


APD and 900 eV electrons

A. Apponi et al 2020 JINST **15** P11015



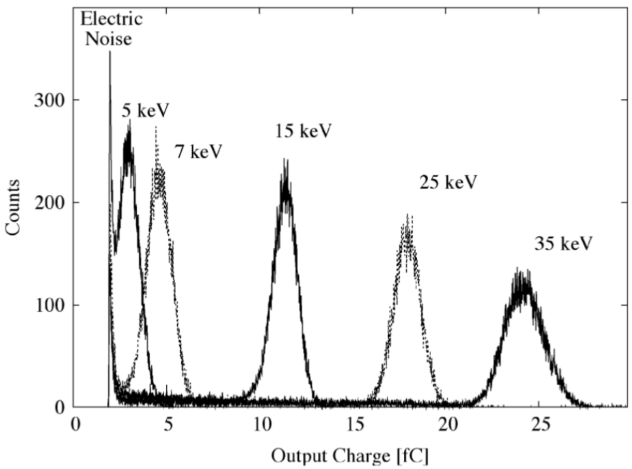




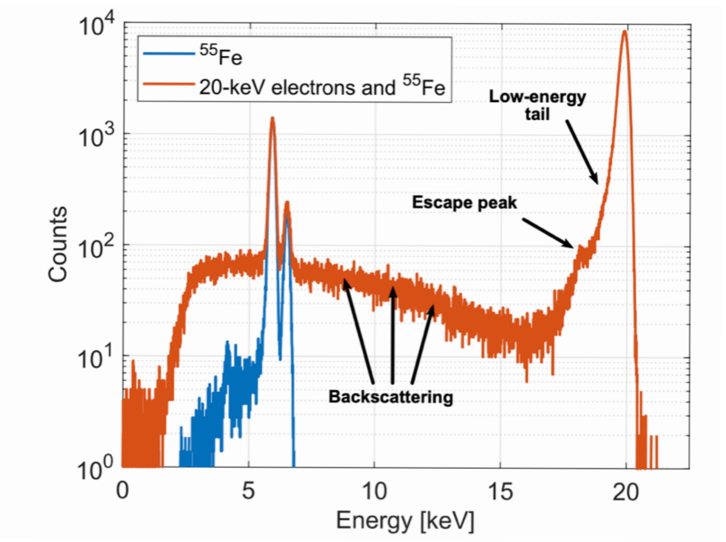
- Reading APD bias current when shooting gun on it
  - $V_{apd} = 0$: electronic ‘image’ of APD
  - V_{apd} = 350 V: I_{apd} **proportional** to I_{gun}

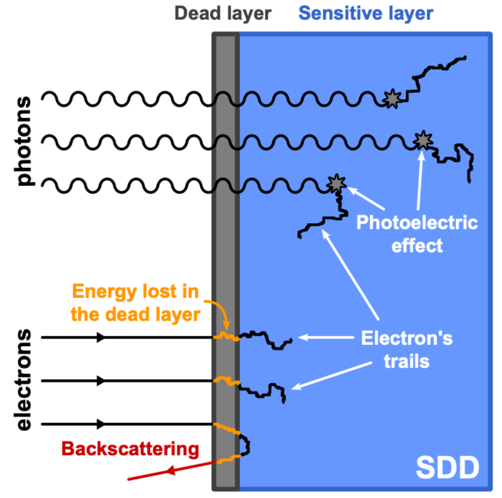
Single electron detection with silicon detectors

S. Kasahara, et al.,
IEEE Trans. Nucl. Sci. **57** (2010) 1549



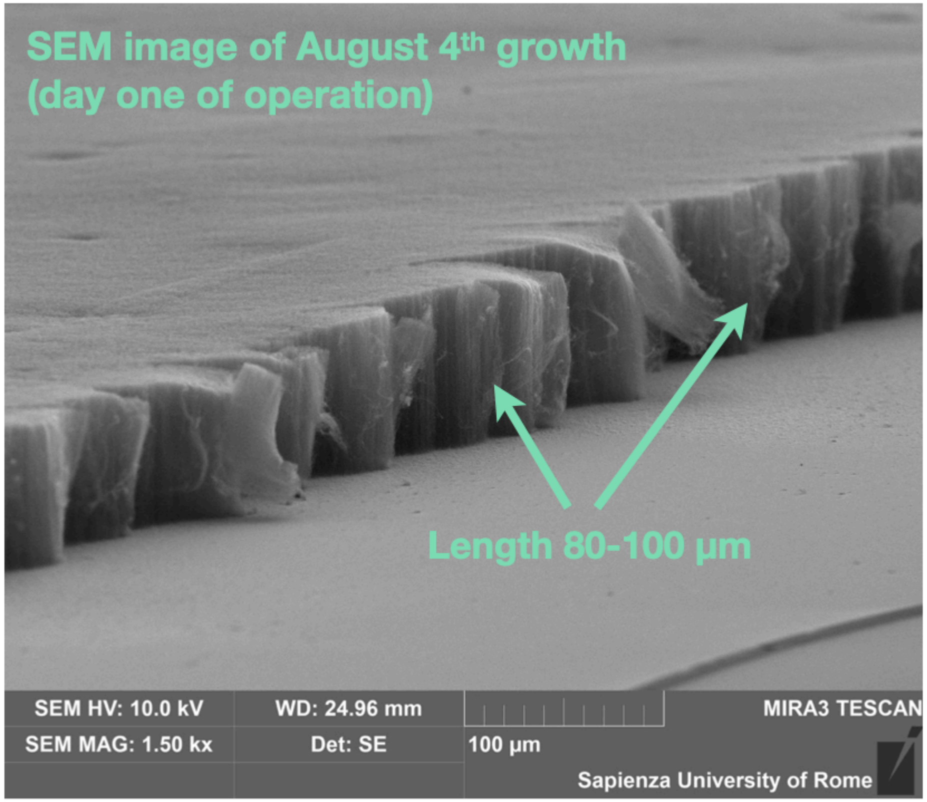
G.Gugiatti, et al.,
NIM A **979** (2020) 164474





- APD can measure single e-
  - But only if $E_e > 5$ keV
- SDD: excellent resolution
  - But higher cost/complexity

First successful growth of CNT

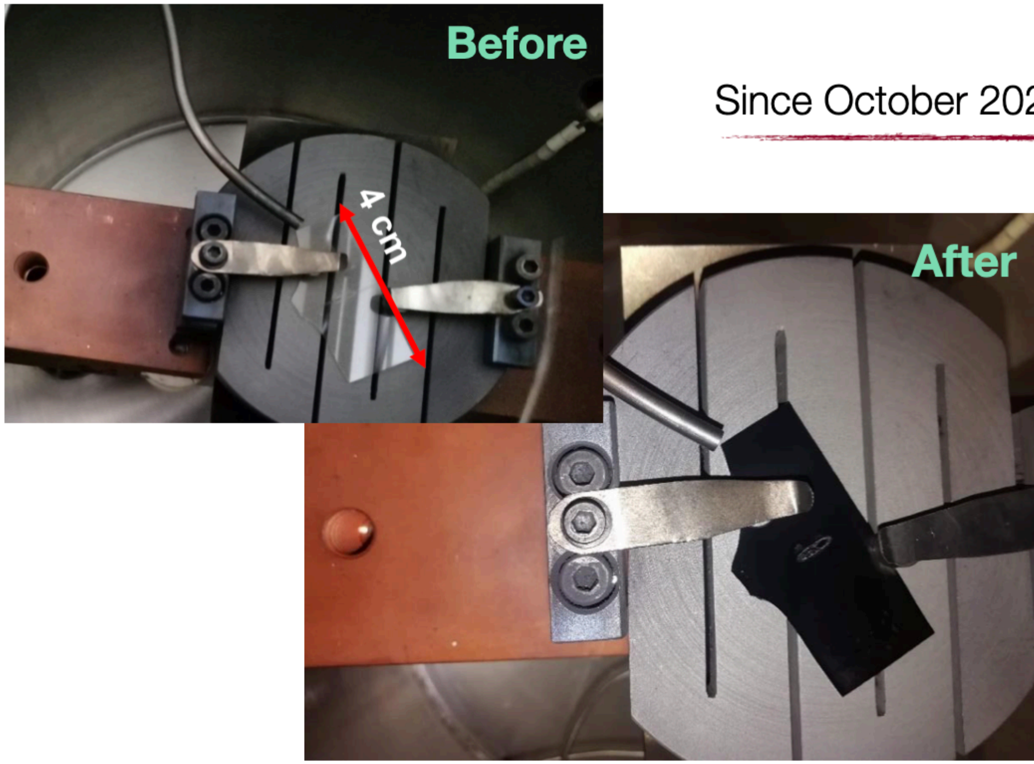


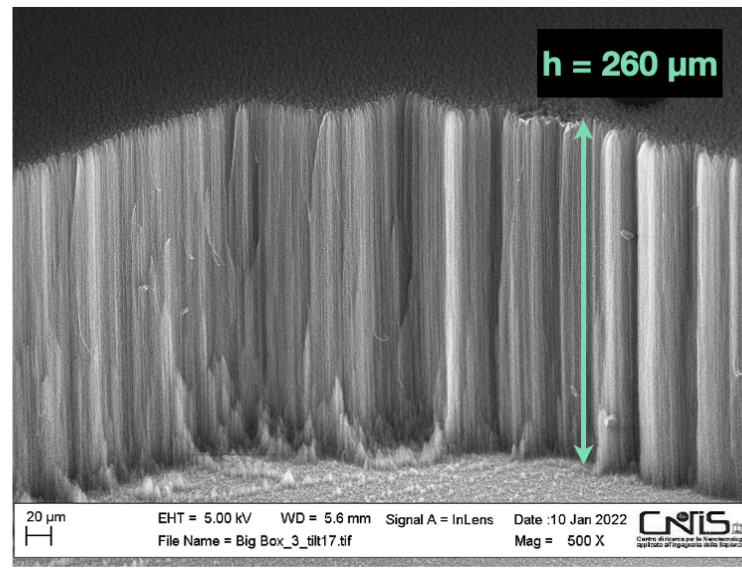
- Successfully synthetized multi-wall nanot
- Growing nanotubes on a **number** of subtr
  - ☑ Silicon
  - ☑ Fused silica
  - ☑ Basalt fibers
  - ☑ Quartz fibers
  - ☑ Carbon fibers
  - ☐ Metallic supports

Very fast process, growing 10 mg over ~1x1 cm² support in ~10 minutes
100 cm² detector for 1 gram

Optimizing CNT growth process

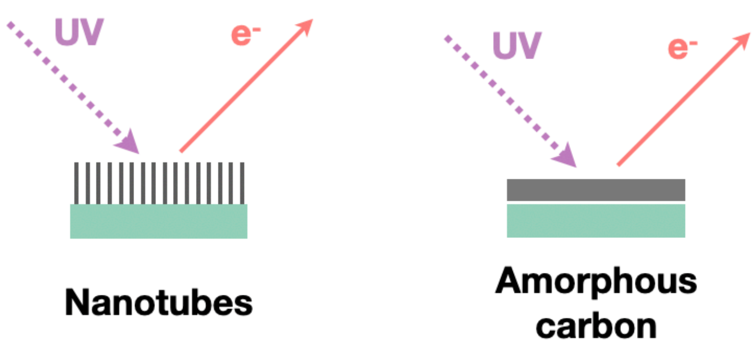
Since October 2020 achieving **uniform** growths over 4x2 cm^2

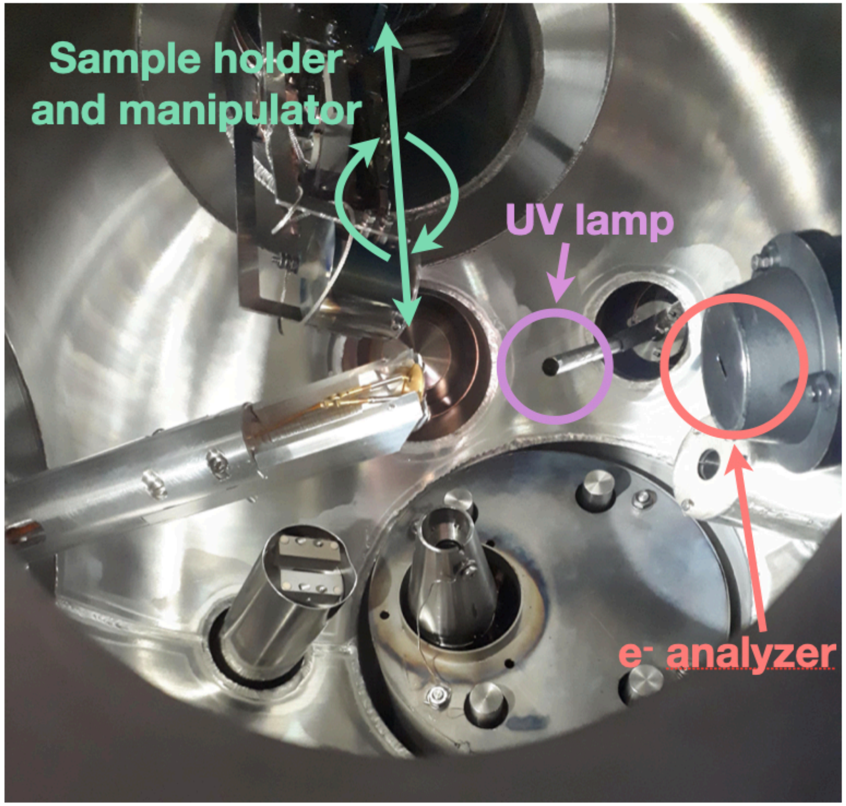




CNT characterisation with photons and electrons

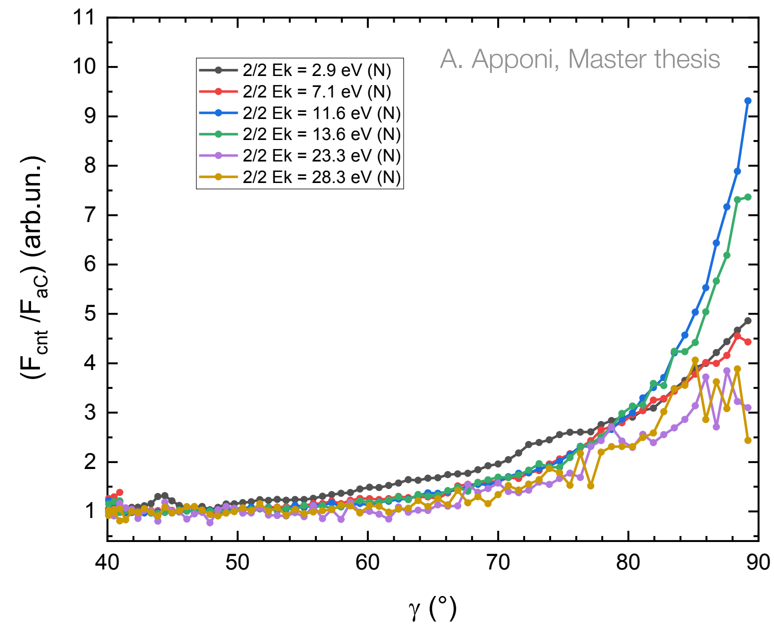
- Large UHV chamber at Roma Tre LASEC labs
  - Equipped with UPS, XPS, e^- energy loss analysis
- Performed UPS characterization of **nanotubes**
  - And compared them to **amorphous carbon**

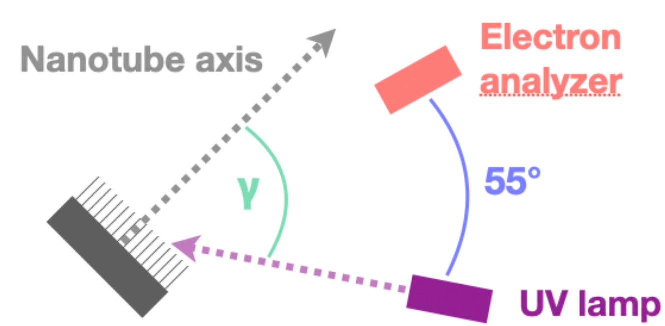




Anisotropic electron emission (?)

- Using He (I+II) UV lamp
  - $h\nu$ = 21.2 eV and 40.8 eV
- Studied electron flux ratio F_{cnt}/F_{aC}
  - vs angle γ between nanotube axis and UV light
  - Normalized so that $F_{cnt}/F_{aC} = 1$ @ γ = 40°
  - CNT variation **up to 10x larger** than aC @ γ = 90° (grazing angle)
  - Further proof of **anisotropy** of nanotubes

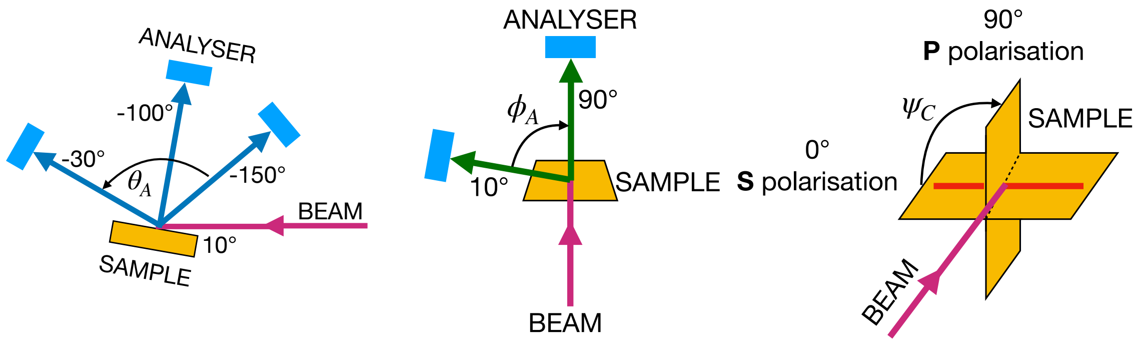


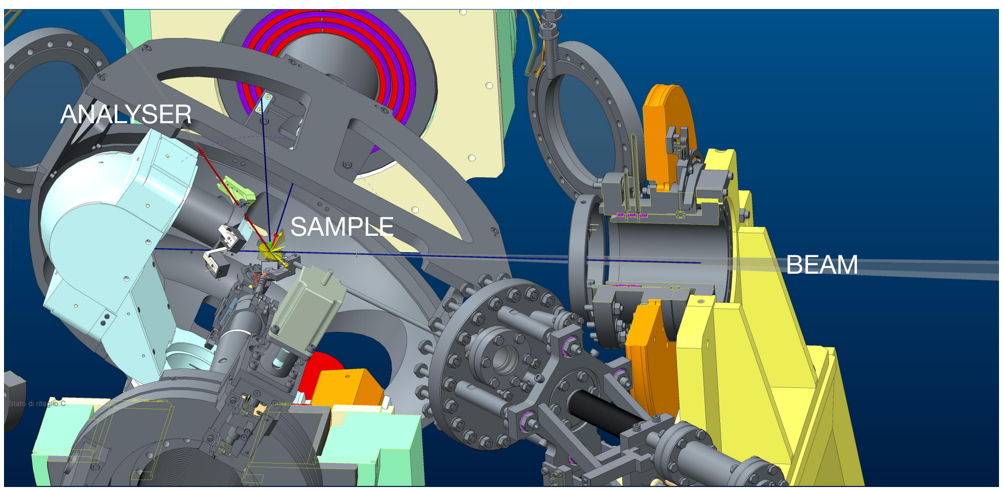


VA-CNT at synchrotron

Elettra Sincrotrone Trieste

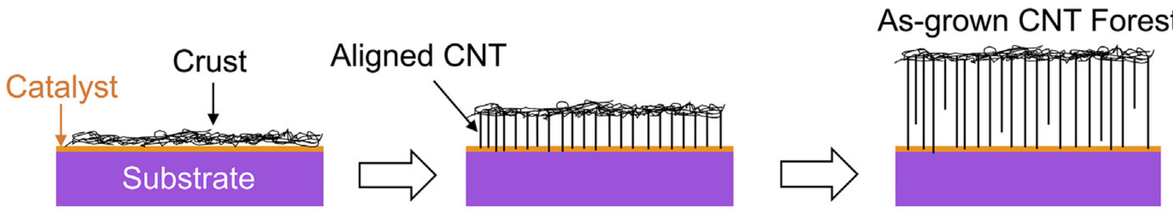
- BEAR beamline: 2.8-1600 eV photons
  - Selectable polarization
  - 'Everything' can rotate

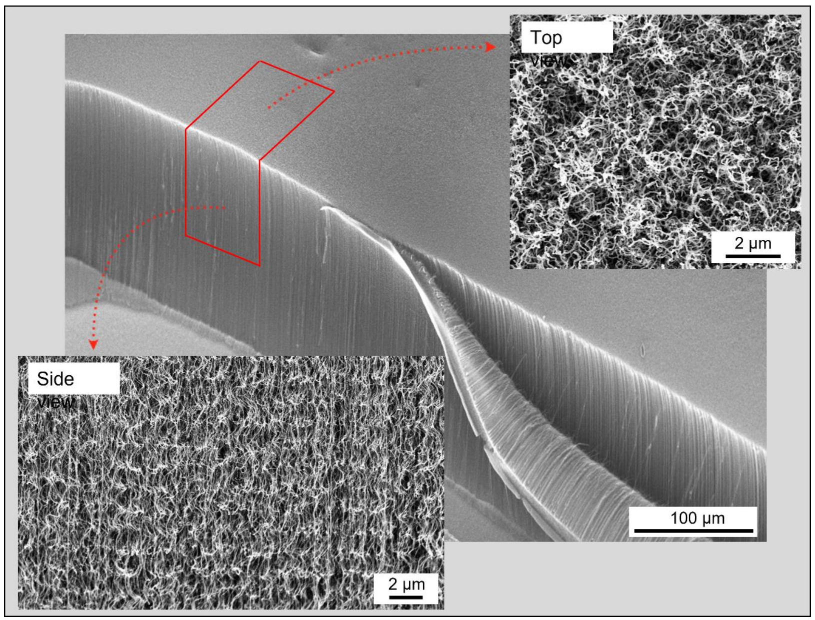




- **Rich** characterization program **underway**
  - Valence band analysis
  - Angular scans
  - Drain current analysis

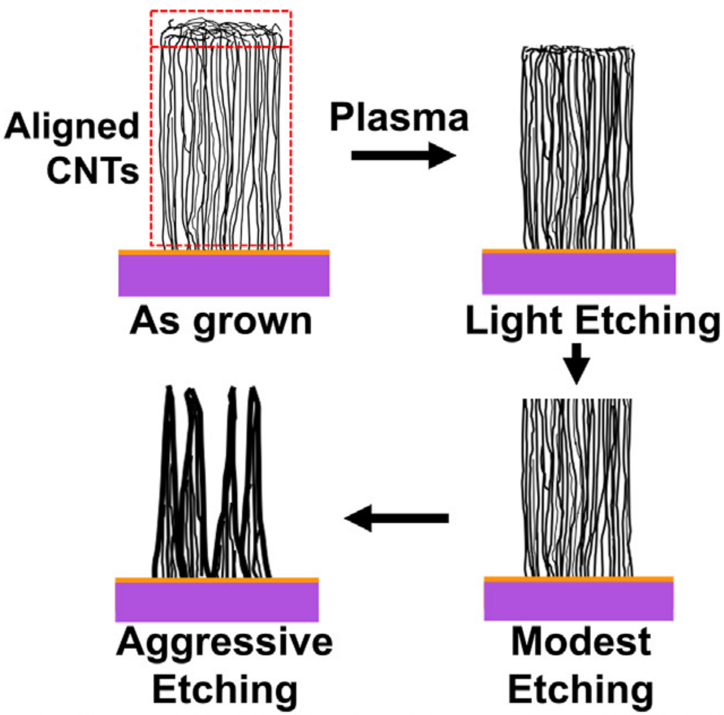
VA-CNT feature to be corrected

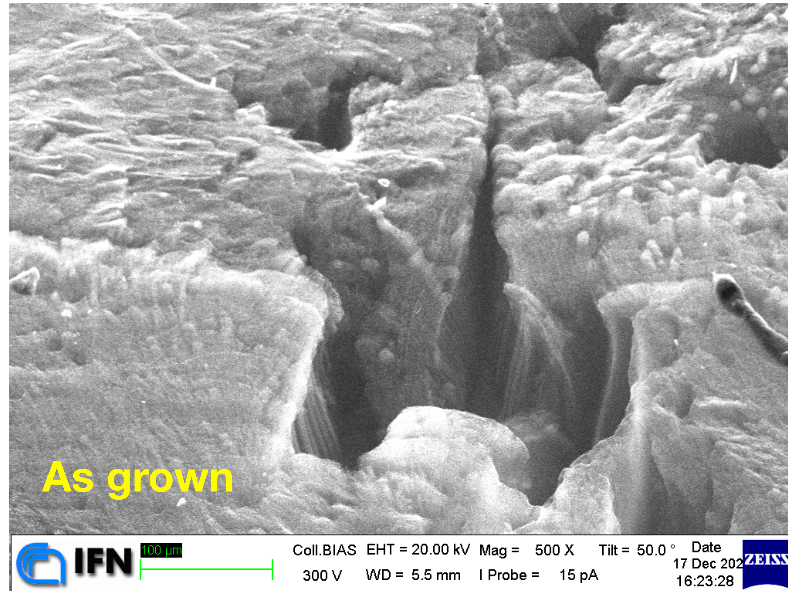


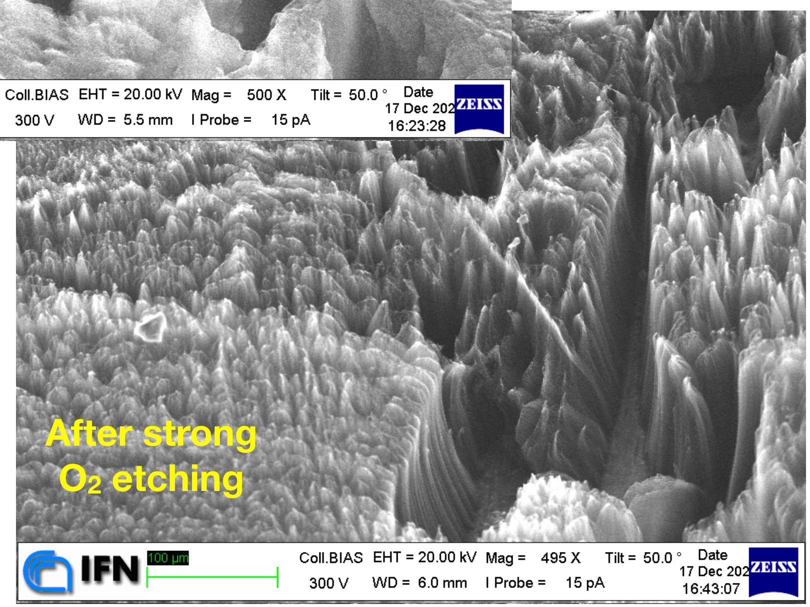


- **Traditional** CVD synthesis produces nanotubes straight at the µm-scale, but:
  - Non-aligned (spaghetti-like) **top layer**
  - Side **'waviness'** at the nanoscale
- **Both** hamper electron transmission
  - Need to **minimize** both effects for ideal DM target

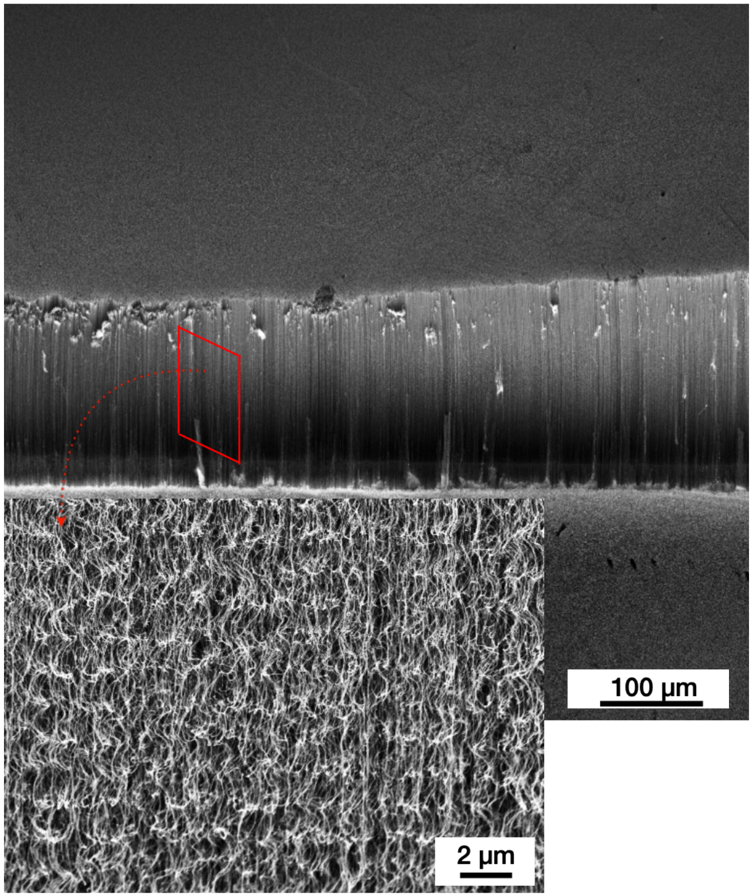
Plasma etching to remove crust



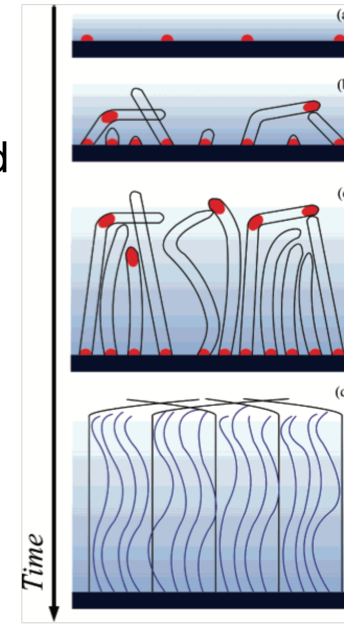




Aiming at ultimate parallelism at nanoscale

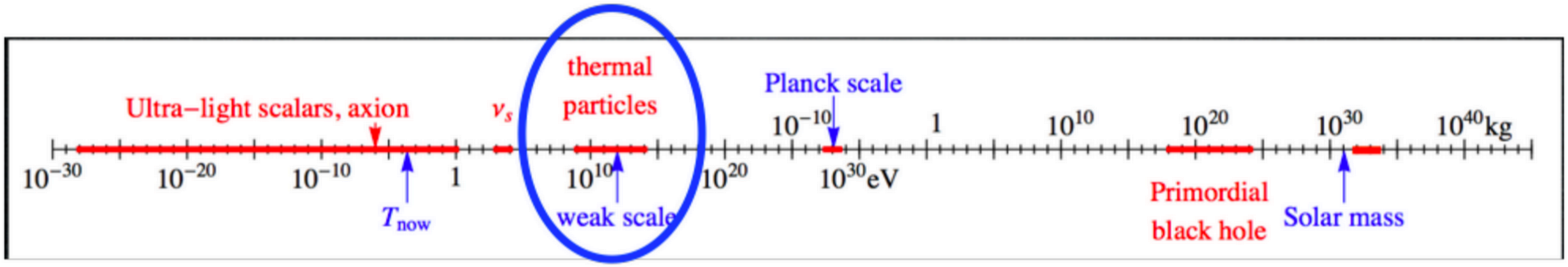


- Nanotube waviness caused by **two** factors:
  - Non-uniformity of catalyst seed **size**
  - Low **density** of seeds
- Seeds of different **size** grow nanotubes at different **rates**
  - Interaction between **fast and slow** lead to waviness
- Parallelism due to van der Waals **tube-tube interactions**
  - **Denser** seeds
    → stronger interaction
    → **straighter** tubes



	Current	Goal
Seed density (cm^{-2})	10^{10}-10^{11}	> 10^{12}
Seed size (nm)	15-30	5 (±20%)

A why not ? Approach



- Several possibility to solve the DM puzzle
  - Even primordial black holes
  - A lot of plausible theories
- Other candidates might be axion like particles (or the QCD axion itself)
  - Totally different experimental approach (cavity resonators)

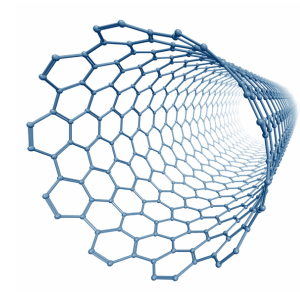
My conclusion (for direct searches)

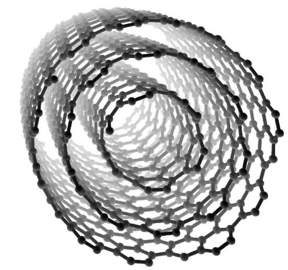
- “**Several ton-year** “is the new frontier in the high mass (> 10 GeV) region (**XENON**, **DarkSide**, future Ar and Xe big experiments
  - So far null results but keep digging.
- Need to prepare to dig into the **neutrino floor (or fog)**
  - **directional** tools need to be explored now (**CYGNO**) (anisotropic targets, low density large volume)
- **DAMA**/**Libra** result yet unconfirmed
  - Various attempts to **redo** an experiment with the same target (NaI)
    - Reduce background (low radioactivity - **Sabre**, ER discrimination)
- WIMP not the only candidate
- **Look in other mass range,** well below GeV
  - **electron** recoils (**Andromeda**)

Backup slides

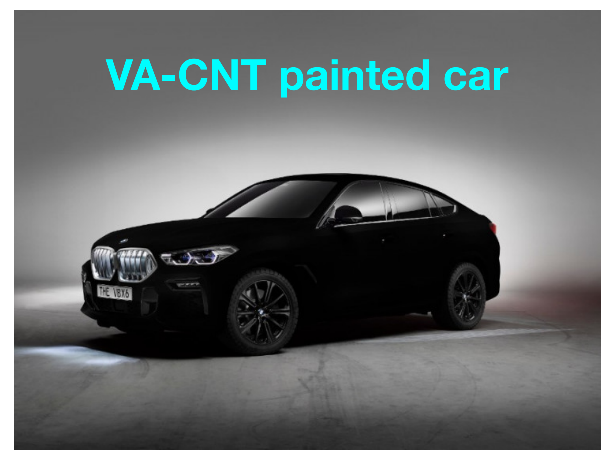
Conclusion and outlook

- **Light DM** direct detection prefers **electrons** as target
  - Hollow VA-CNT structures:
    - emission of ~eV electron into vacuum
    - Anisotropy: correlation with DM wind possible
  - **A light DM directional detector**





- Andromeda is exploring a **hybrid** configuration (CNT + silicon detectors)
  - Relying on keV electron detection
  - Easily scalable (in principle) to large mass.
    - Need an optimised synthesis and advanced characterisation of the target



CRESST_III

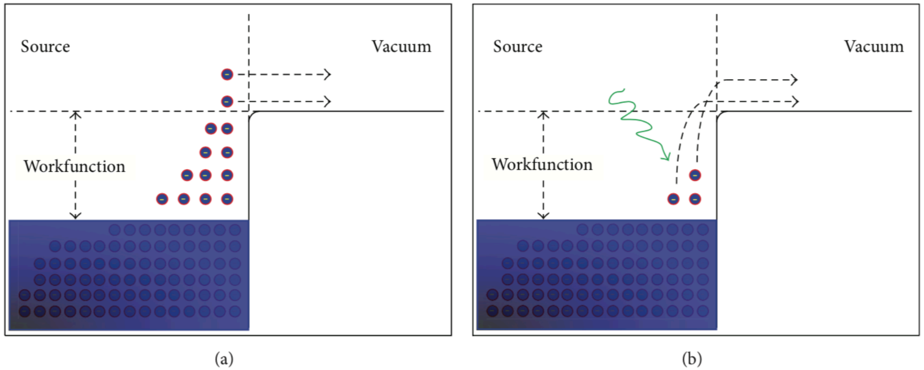
Cryogenic scintillator

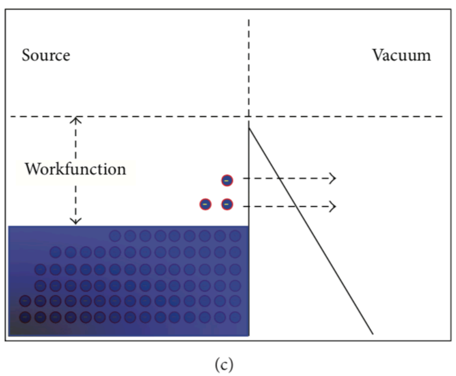
- Scintillation + phonon (TES) in $CaWO_4$ crystals (15 mK)
  - A 100 eV threshold, non-zero background though!

10^{-40} cm^2

Electron emission from a cathode

Thermoionic emission *Photoelectric emission*





Field emission

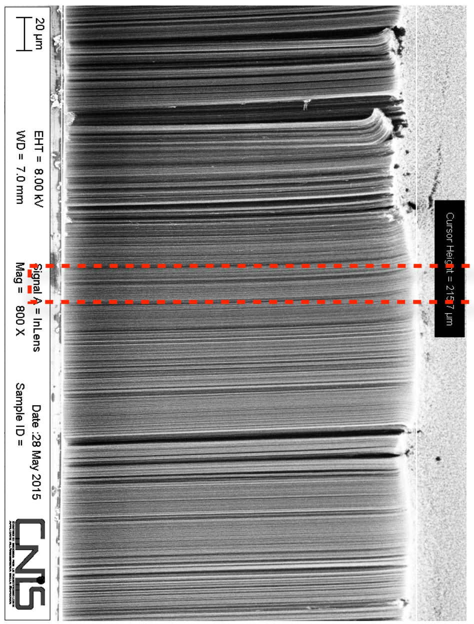
What about a DM particle scattering off an electron ?
*a **dark-cathode** ?*

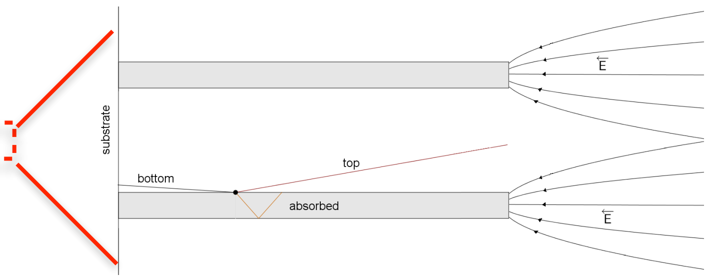
Work function of CNT is > 4 eV

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



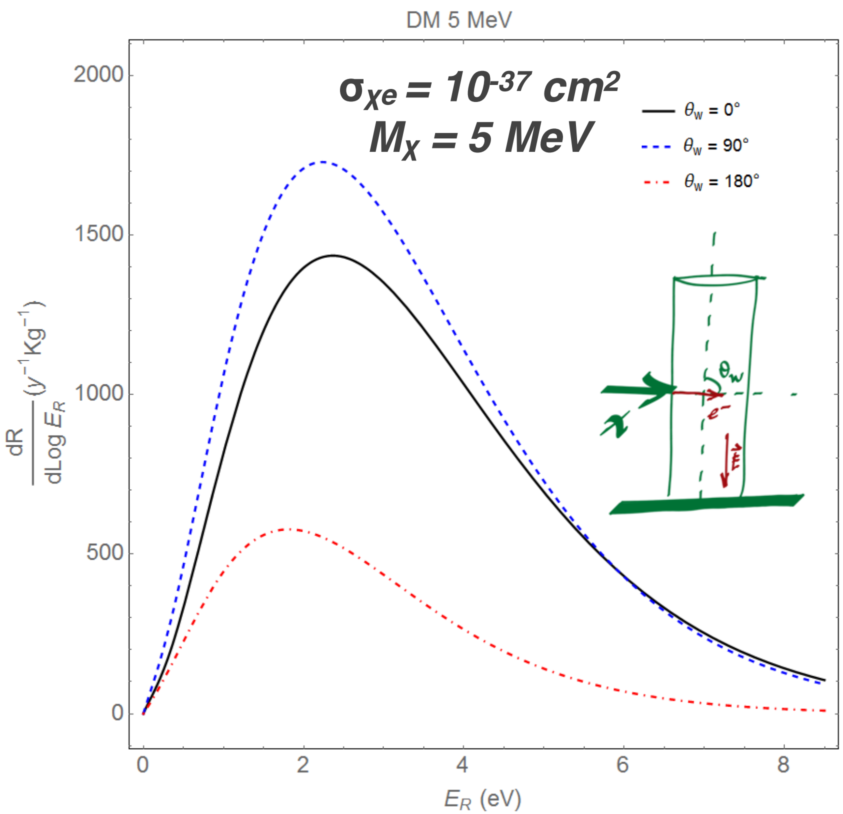


Electron collected by an external electric field ***E***

- **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



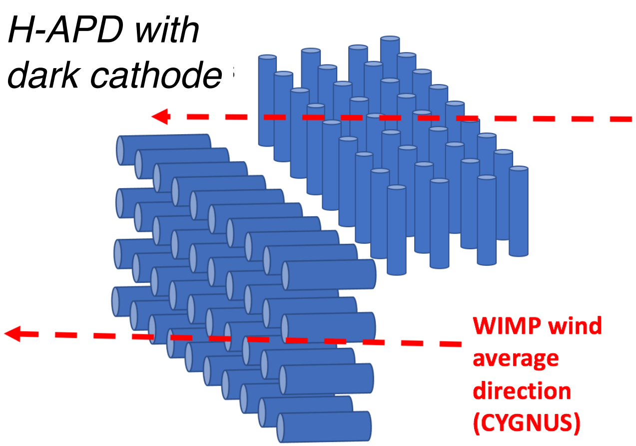
Different rate at different angles $\boldsymbol{\theta_w}$

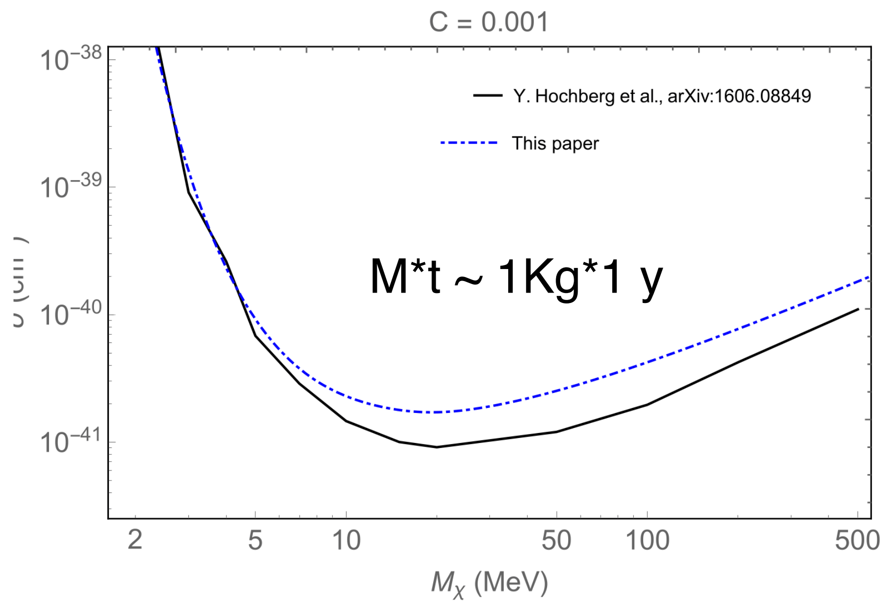
θ_w ~90 preferred by graphene electron wave function

- 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

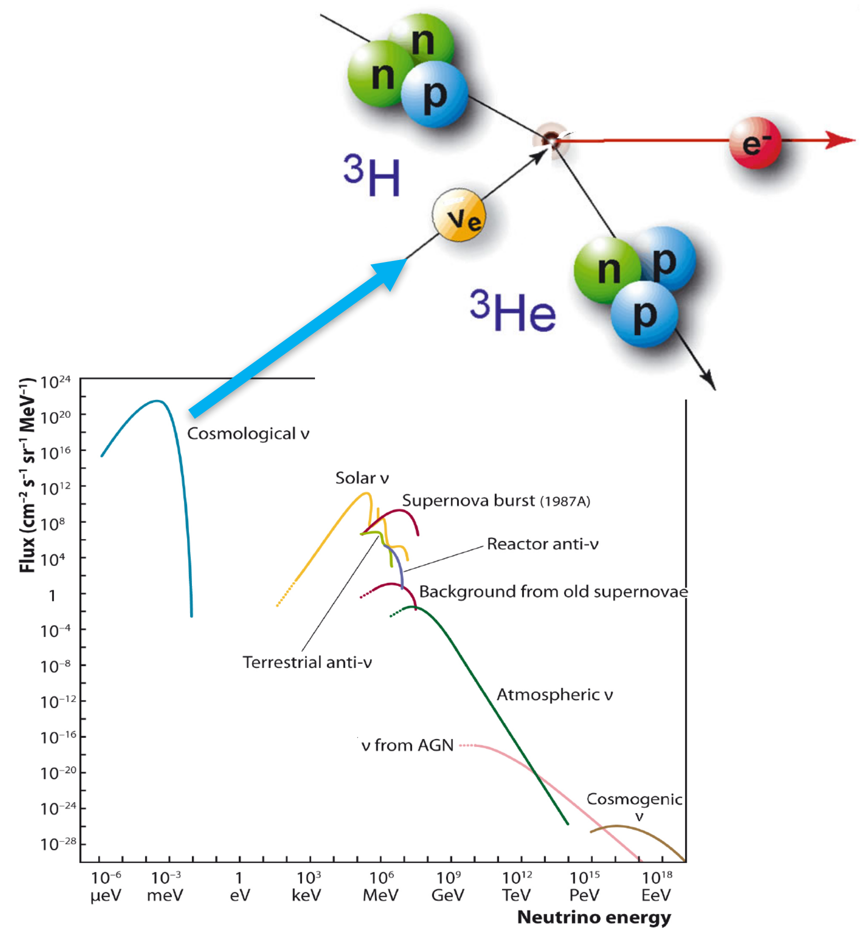




- Two arrays of *hybrid dark-photodiodes (~10^4 units, 10mg dark cathode mass each)*

PTOLEMY - graphene target

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

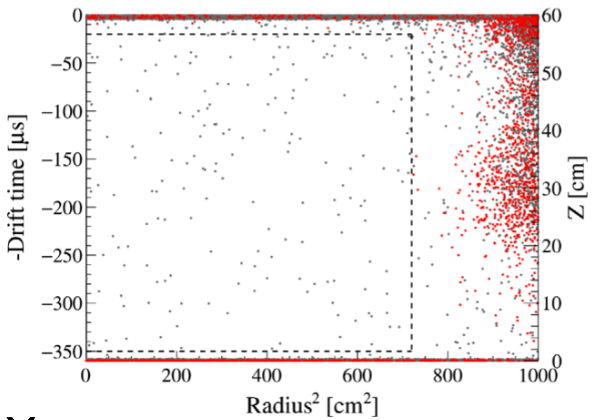


Detect electron of few eV kinetic energy

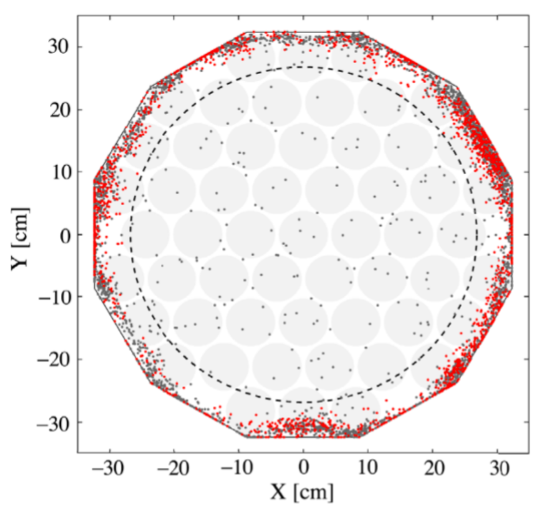
MAC-E filter technique to select the endpoint of the tritium

Fiducialization

Panda-X



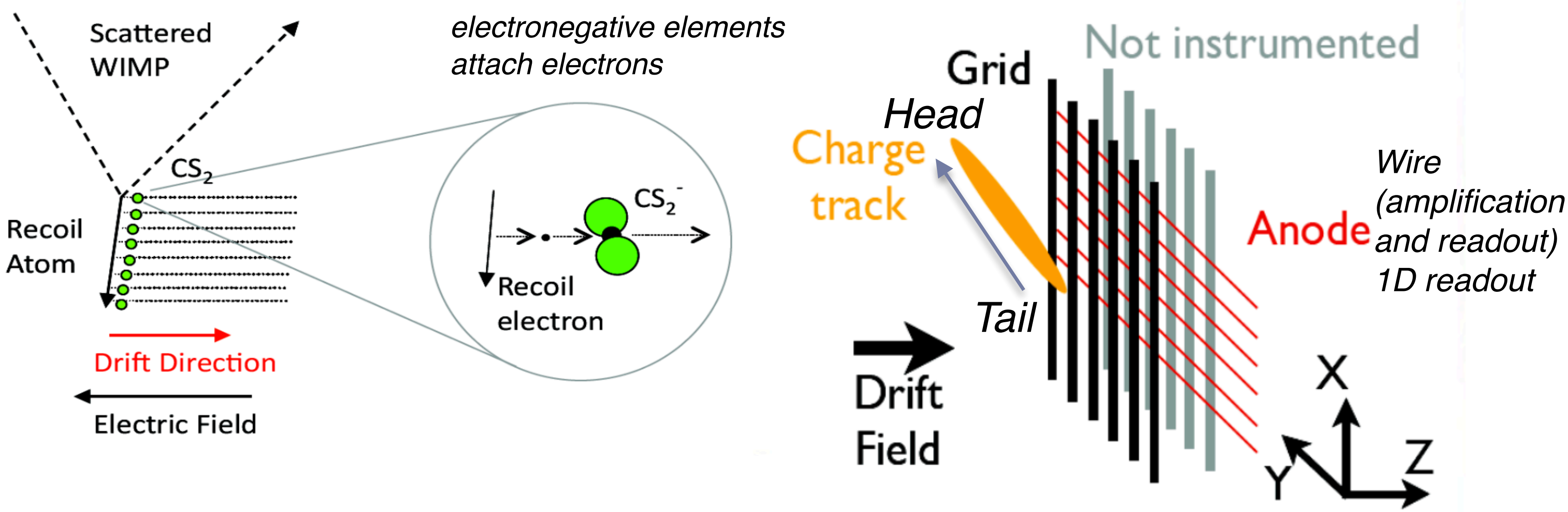
(a) The r^2-z distribution.



(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.

DRIFT: negative ion drift TPC

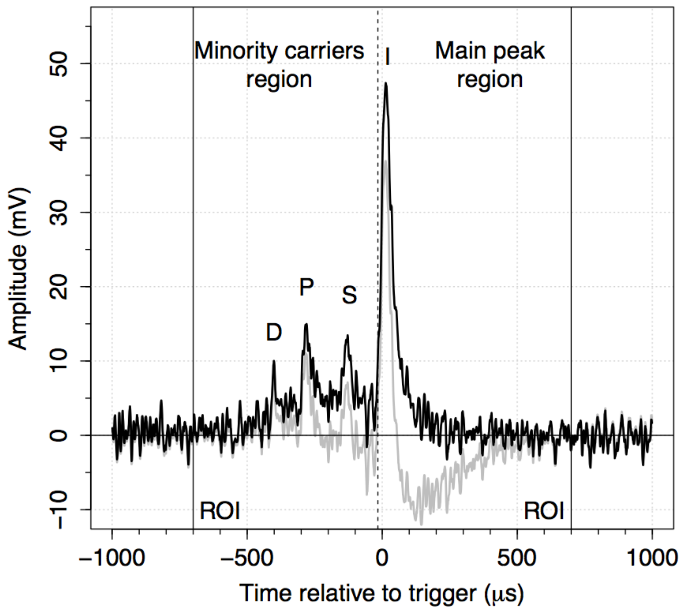


- Limited diffusion ever over long drift distance (<0.5mm on 0.5m)
- If anode segmented, a "ion recoil track" can be reconstructed: **direction**
- **Head-tail** information is valuable as well (might be enough for discrimination)

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***

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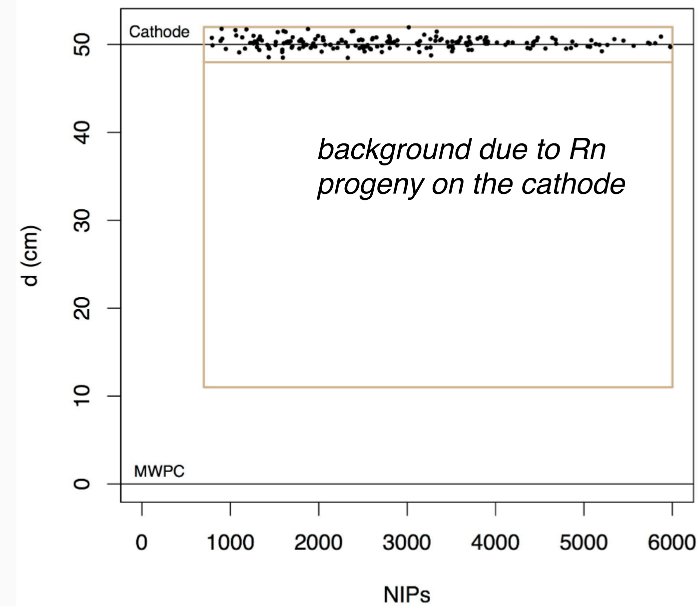
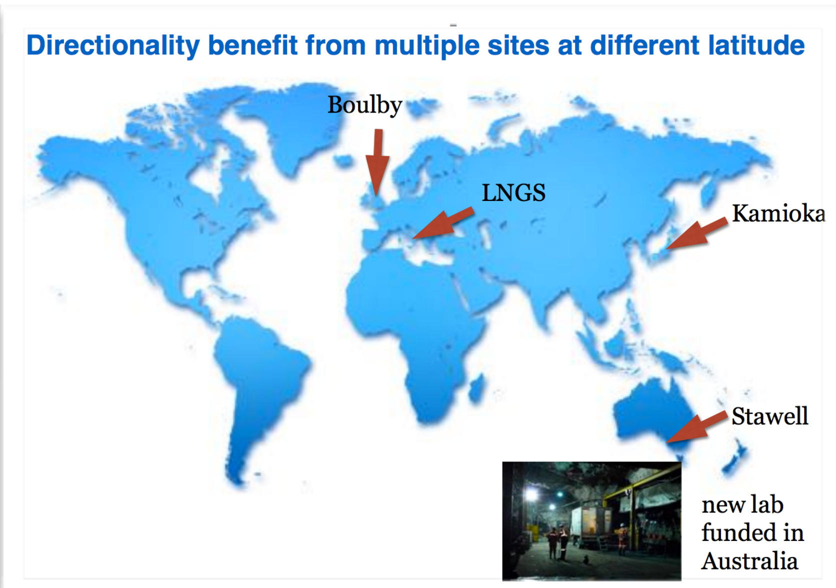


Z position measurement

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

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

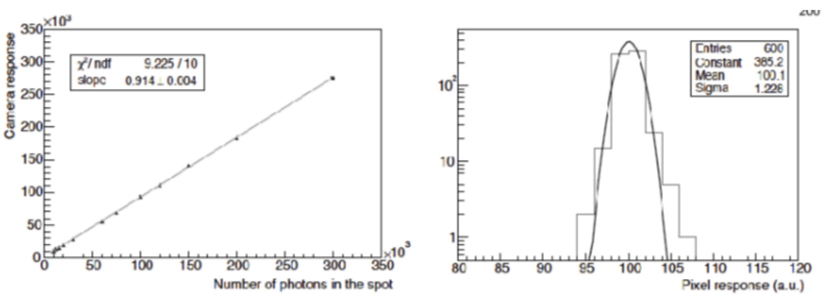


CYGNUS-TPC key elements:

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

Light readout

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



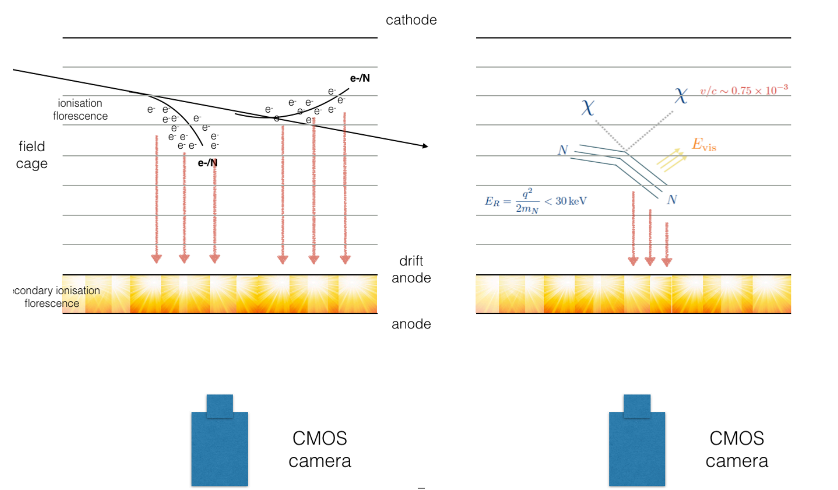
For a m.i.p. track we predict (Garfield) ~ 7e⁻/mm (primary ionisation electrons)

For a m.i.p. track we **measure** ~ 1000 photons/mm

that means

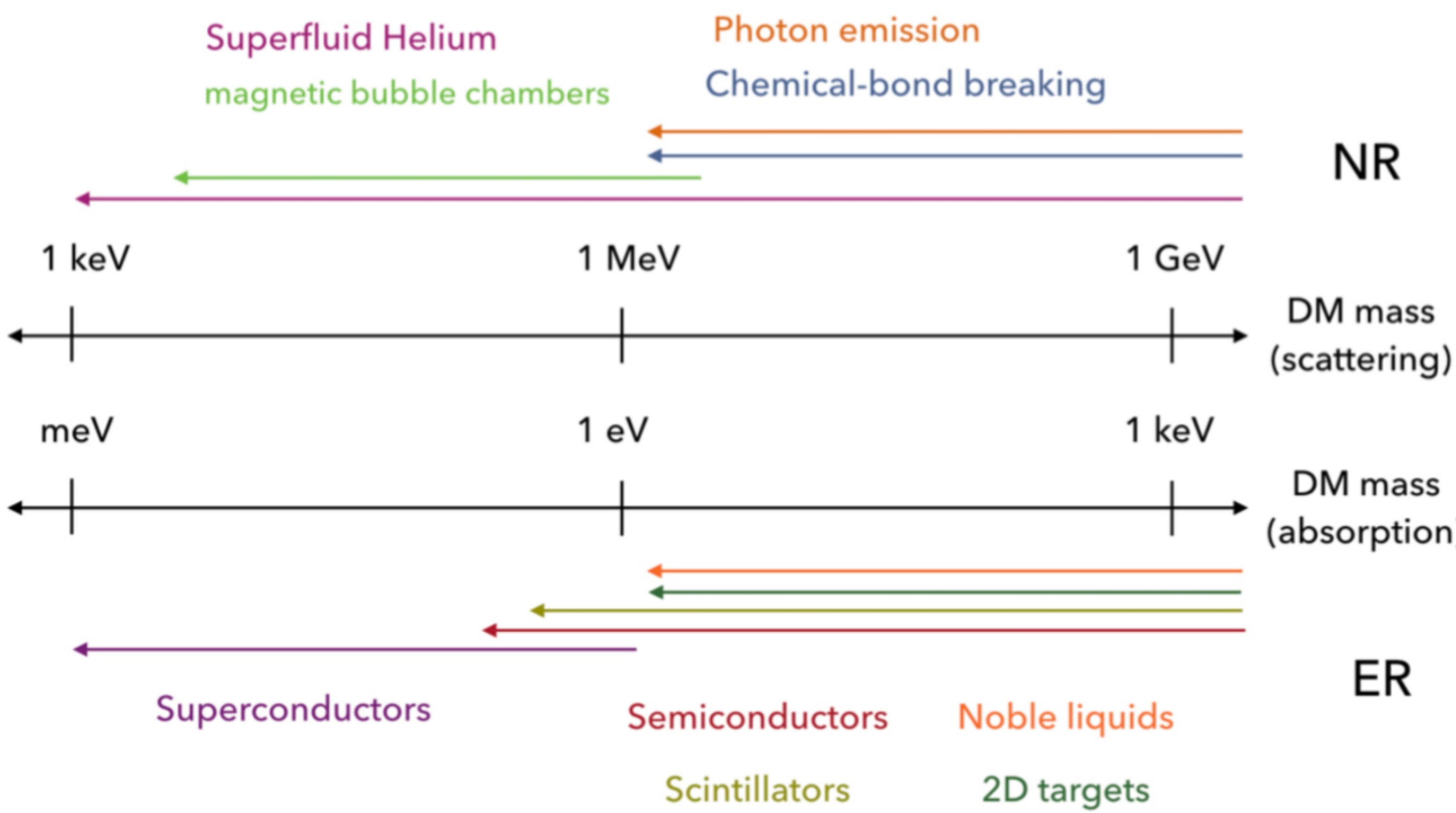
~150 photons/primary electron

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

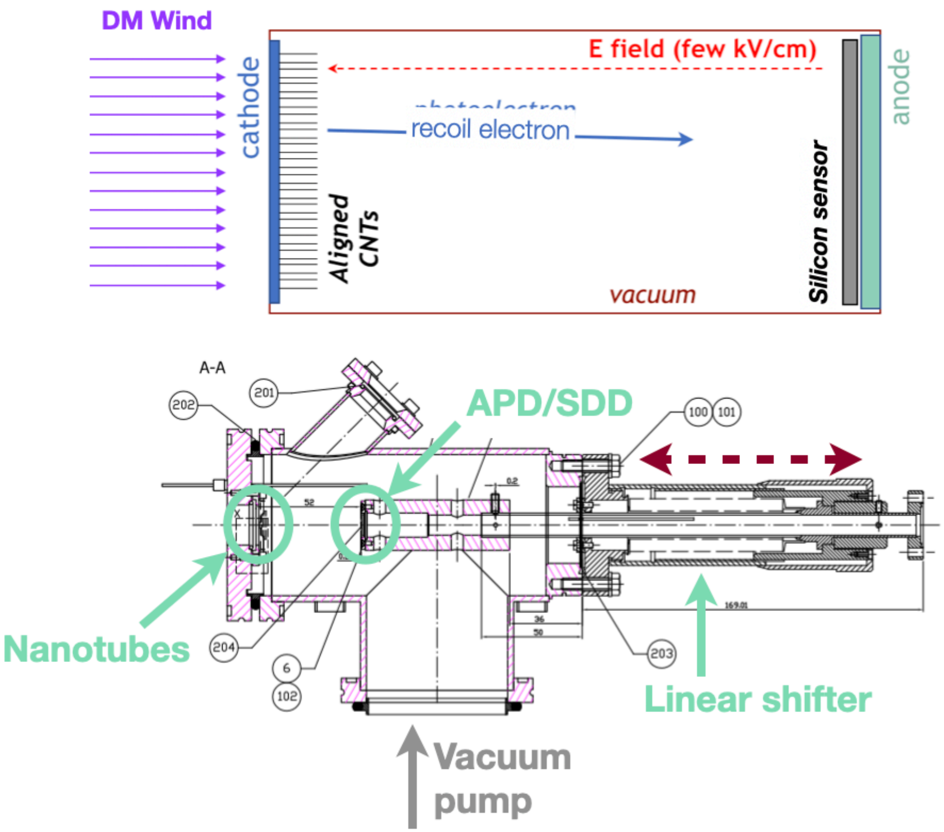


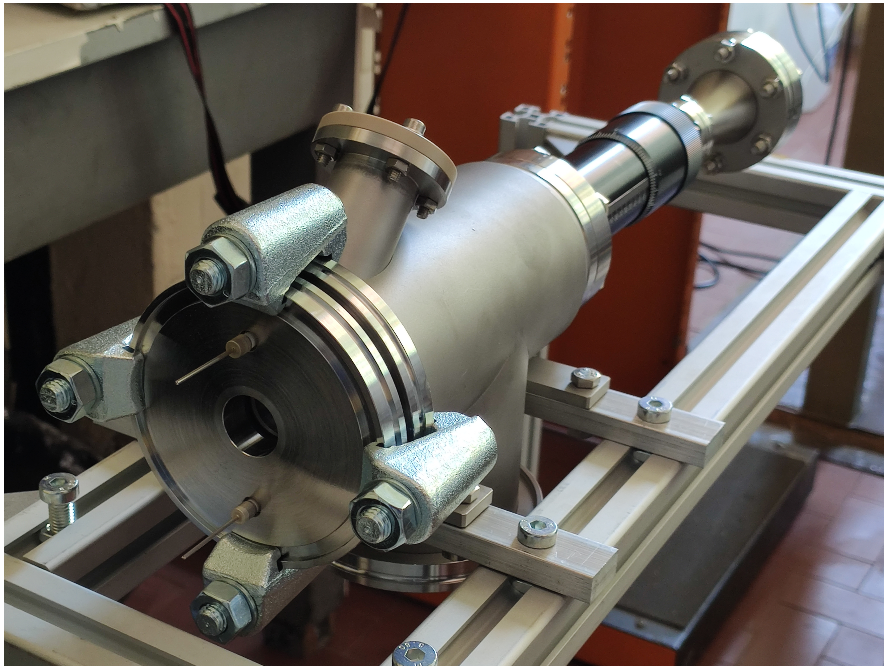
- Very good signal to noise ratio!

Sub-GeV dark matter



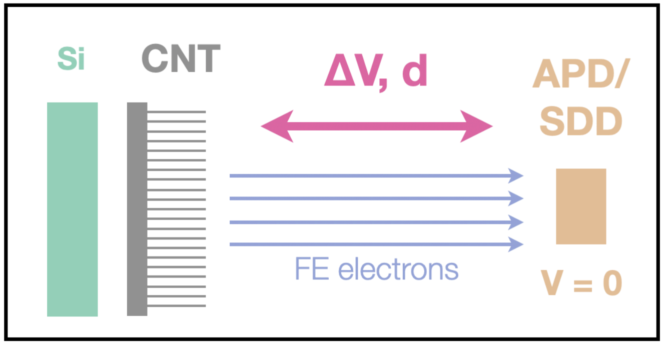
Dark PMT prototype-0: Hyperion



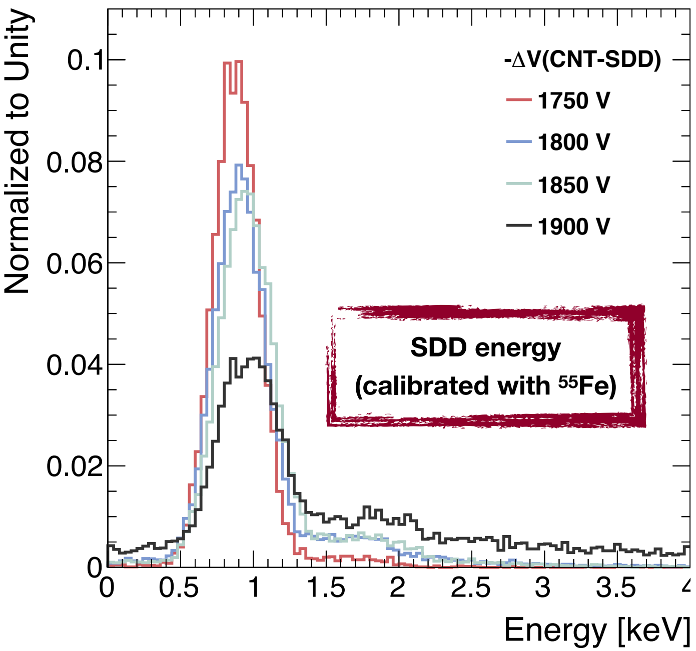


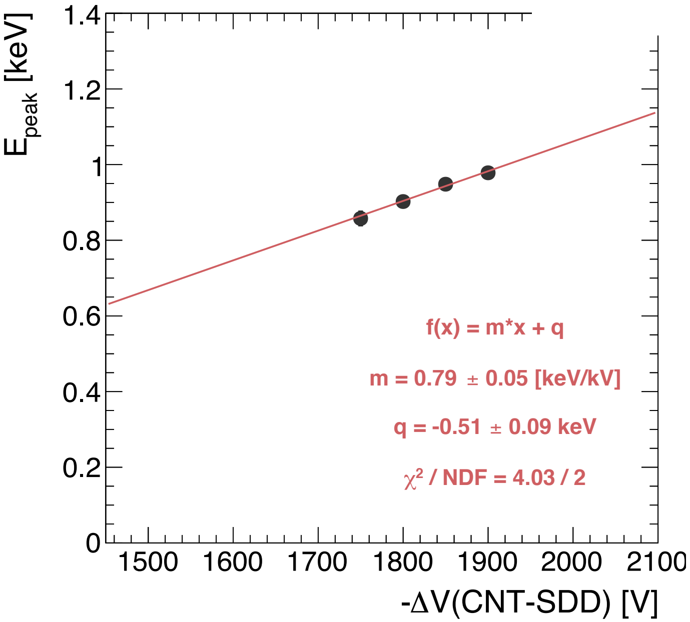
Field emission from CNT

- Observed **field electron emission** from CNTs
  - For high ΔV / small d(CNT-SDD)
  - Well-documented effect eg Carbon 45 (2007) 2957



Hyperion Prototype

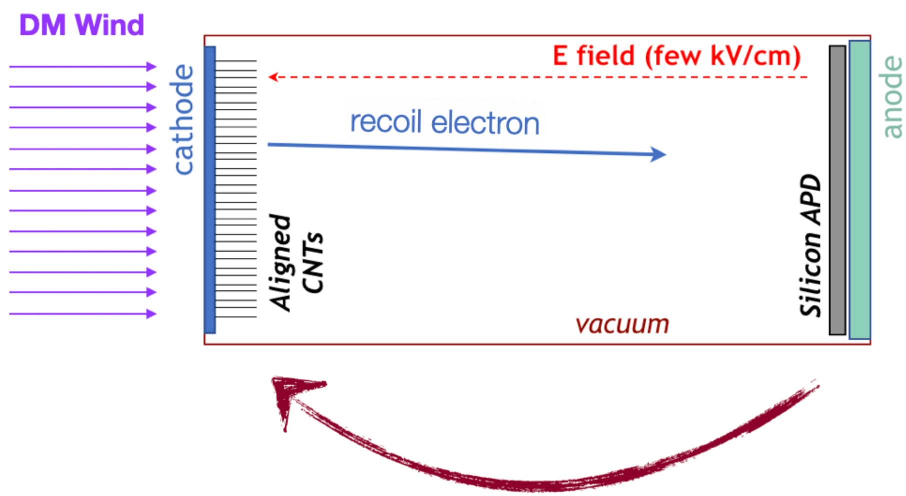




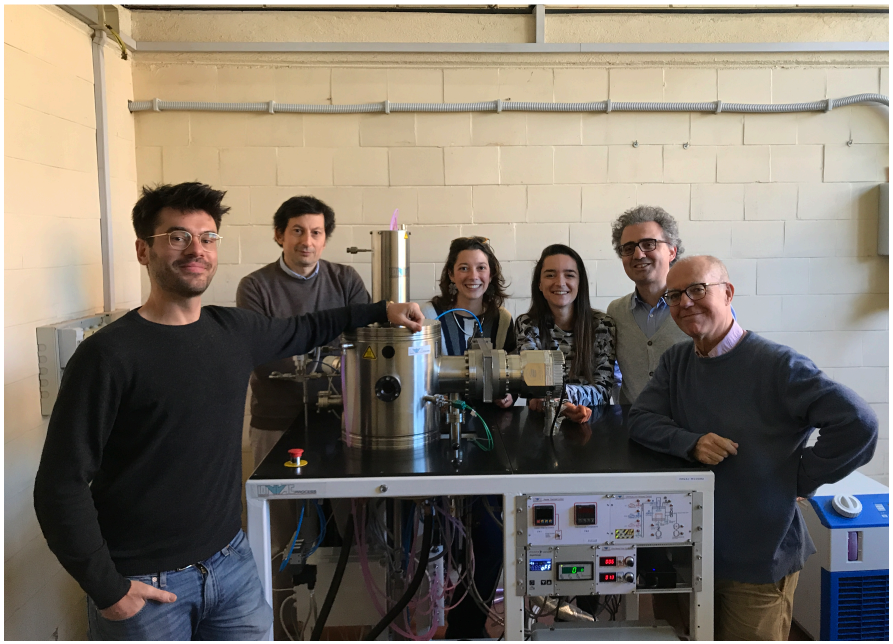
We can measure ~2 keV electrons emitted by CNTs

Controlling this effect critical to avoid background in DM searches

Switch to the other side: VA-CNT



Chemical Vapour Deposition chamber for CNT

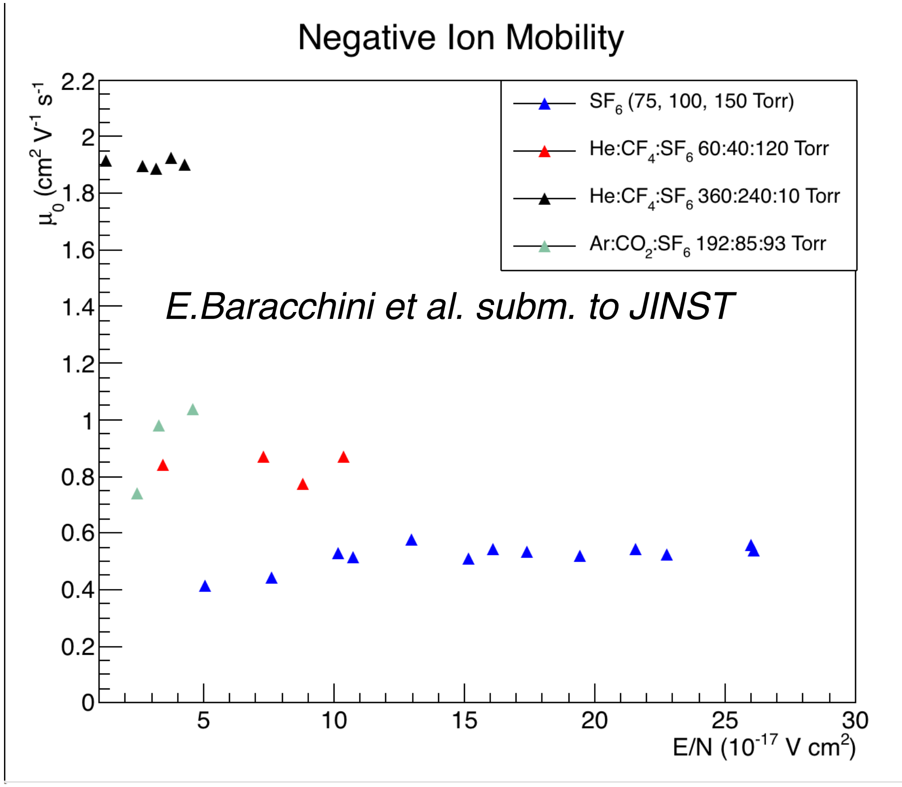


- Start to develop a novel **UV light** detector made with carbon nanotubes

- CVD chamber Equipped with **Plasma-Enhanced** technology
  - Capable of **single-wall** nanotubes
- **Operational** (in few weeks) since August 2020 (despite COVID)
- Being upgraded with metal evaporator

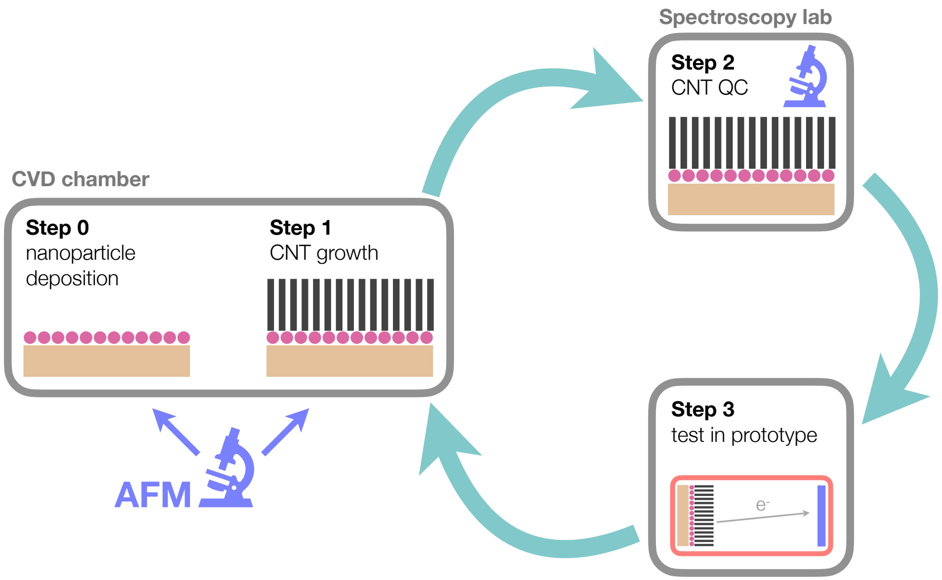
SF_6 negative ion drift

- 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.)

Planned upgrade of VA-CNT synthesis



- Seed deposition will be done in **same vacuum volume** as synthesis
  - **Control** over seed uniformity/density
  - **No oxidation**
- Atomic force microscope (AFM) will check nanoparticle density/uniformity
  - Quick feedback → quick optimization

Beyond DM

- **UV light** detector based on VA-CNT (NanoUV)
  The calibration technique for dark PMT, in fact

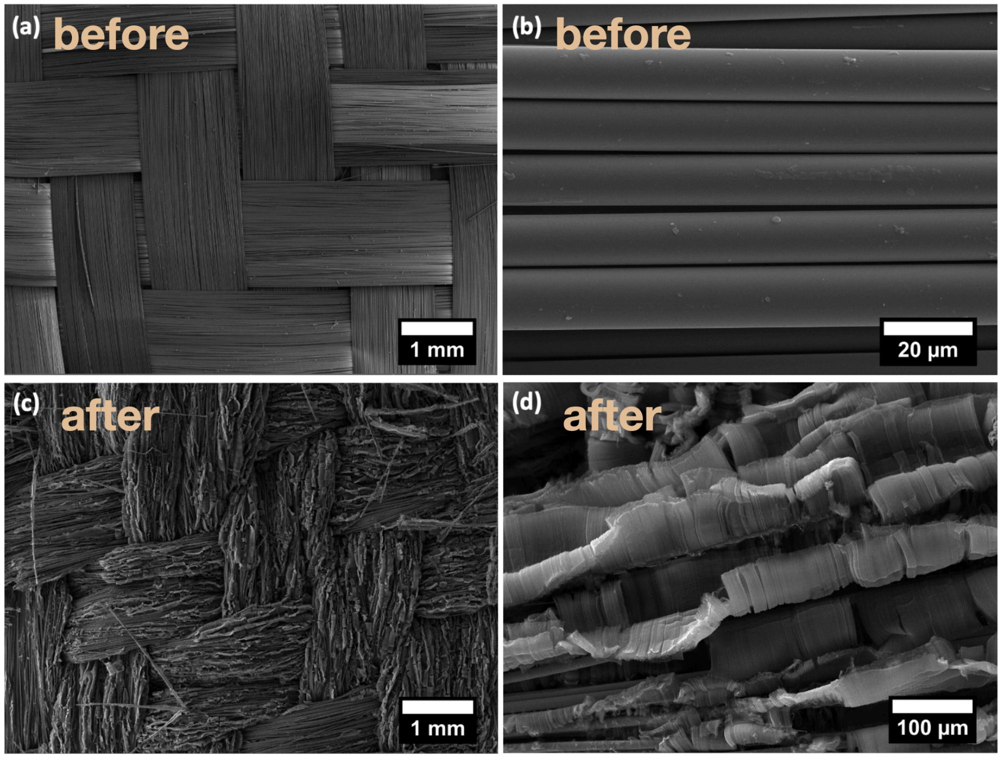
- VA-CNT for **bio**sensor or anti-microbial surfaces
  (collaboration with Biology department)

- CNT in novel **composite** materials
  Additive manufacturing

- Use of CNT to host tritium atoms for the Ptolemy target
  See hep/ph/…

Basalt fiber enhanced with CNT

in collaboration with Sapienza DICMA



Paper submitted to Nano Today

- **Basalt fibers**: exciting new 'green' material
  - **Excellent** mechanical properties
  - Much **cheaper** than carbon fibers
- We grew nanotubes **directly** on the fibers
  - **Without** catalyst (world first!)
- Fibers become **highly** conductive (>250 S/m)
  - (Normally basalt is insulator)
  - Applications: EM shielding, smart textiles