Innovative avenues for dark matter and neutrinos detection

Gianluca Cavoto - *Sapienza Univ Roma and INFN Roma*

Symposium on Low Energy Experimental Particle Physics -MPI

July 14-15 2022

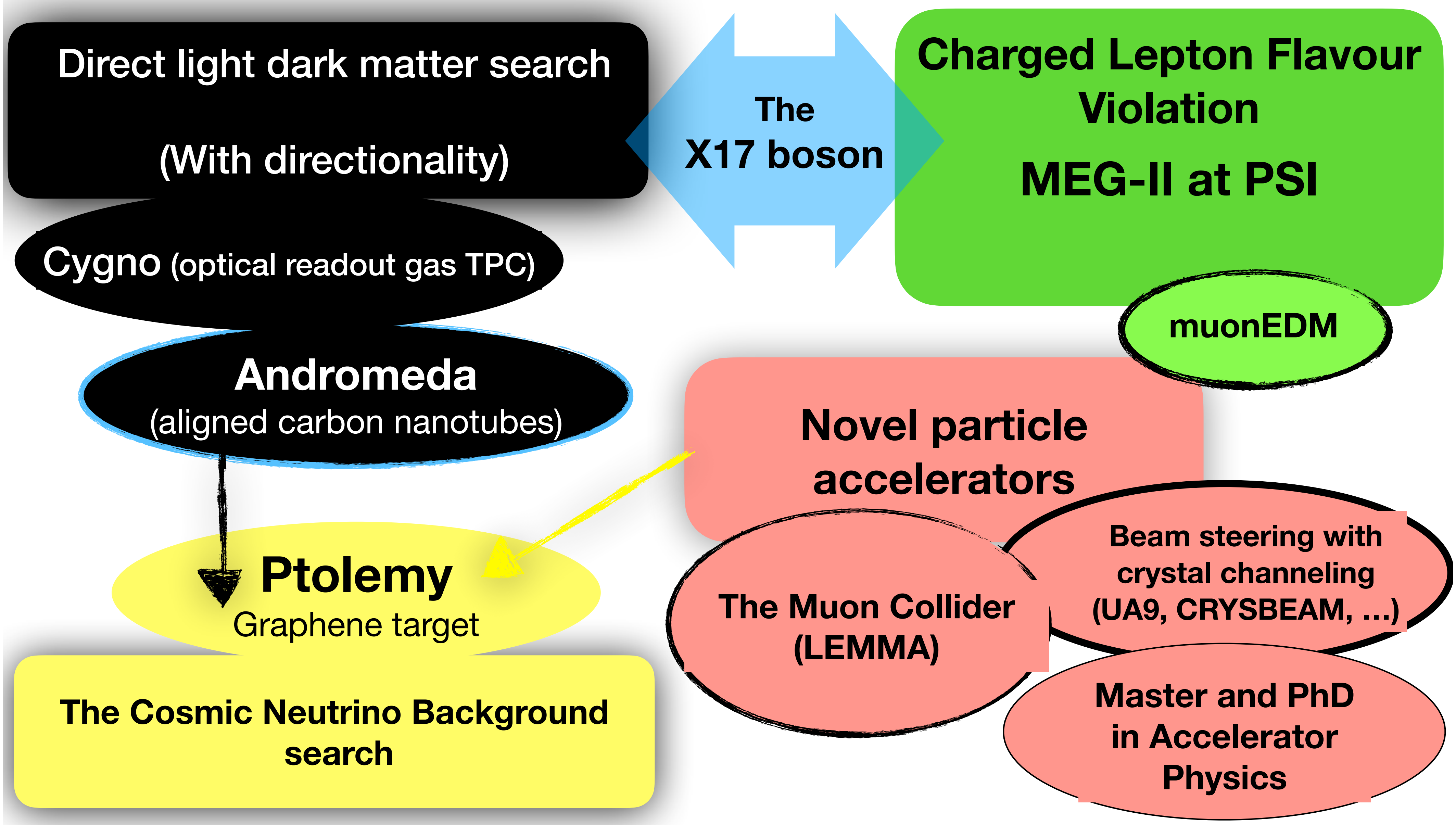
Outline

- Low energy experimental particle physics,
  - from my **personal perspective**

- **Innovative** detectors
  - **Ordered matter**, coherent interactions, nanostructure

- Two examples:
  - The search for **light dark matter**
  - The search for **cosmic neutrino background**

My recent and future projects



Direct light dark matter search

(With directionality)

Cygno (optical readout gas TPC)

Andromeda
(aligned carbon nanotubes)

Ptolemy
Graphene target

The Cosmic Neutrino Background search

The X17 boson

Charged Lepton Flavour Violation

MEG-II at PSI

muonEDM

Novel particle accelerators

The Muon Collider (LEMMA)

Beam steering with crystal channeling (UA9, CRYSBEAM, …)

Master and PhD in Accelerator Physics

My **recent** and future projects

The
X17 boson

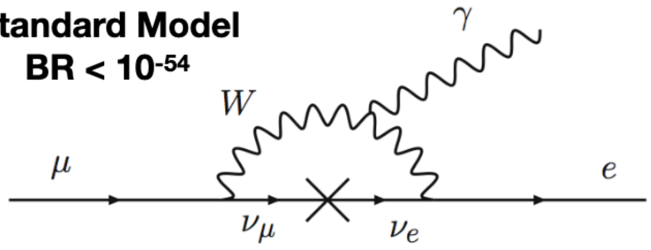
Charged Lepton Flavour Violation

MEG-II at PSI

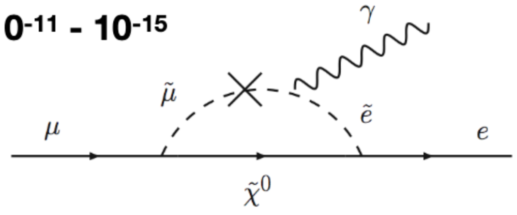
Charged lepton flavour violation

- Decay **μ into electron and γ** clear sign of New Physics

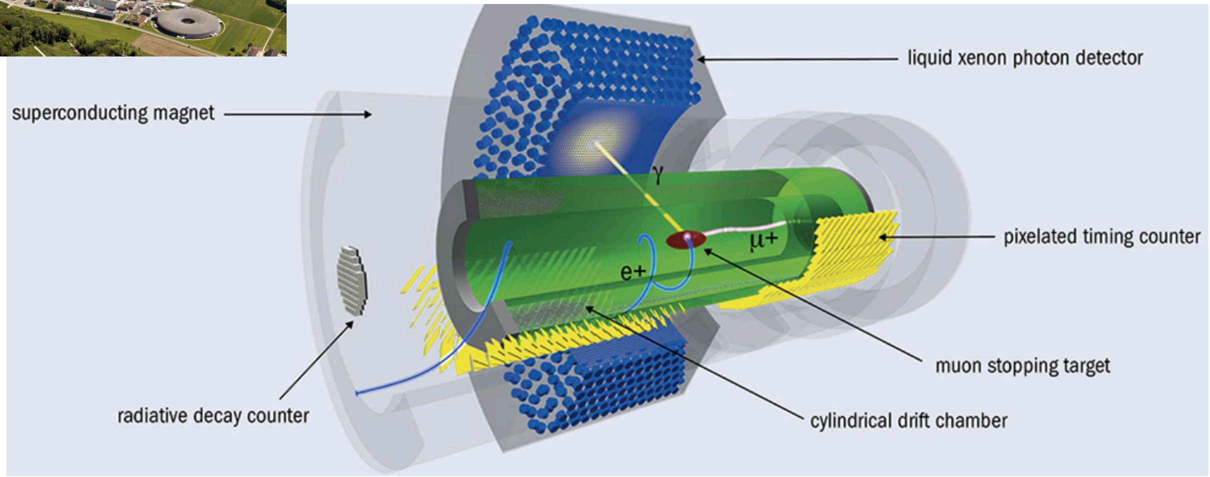
Standard Model
BR < 10^{-54}



SUSY
BR ~ 10^{-11} - 10^{-15}

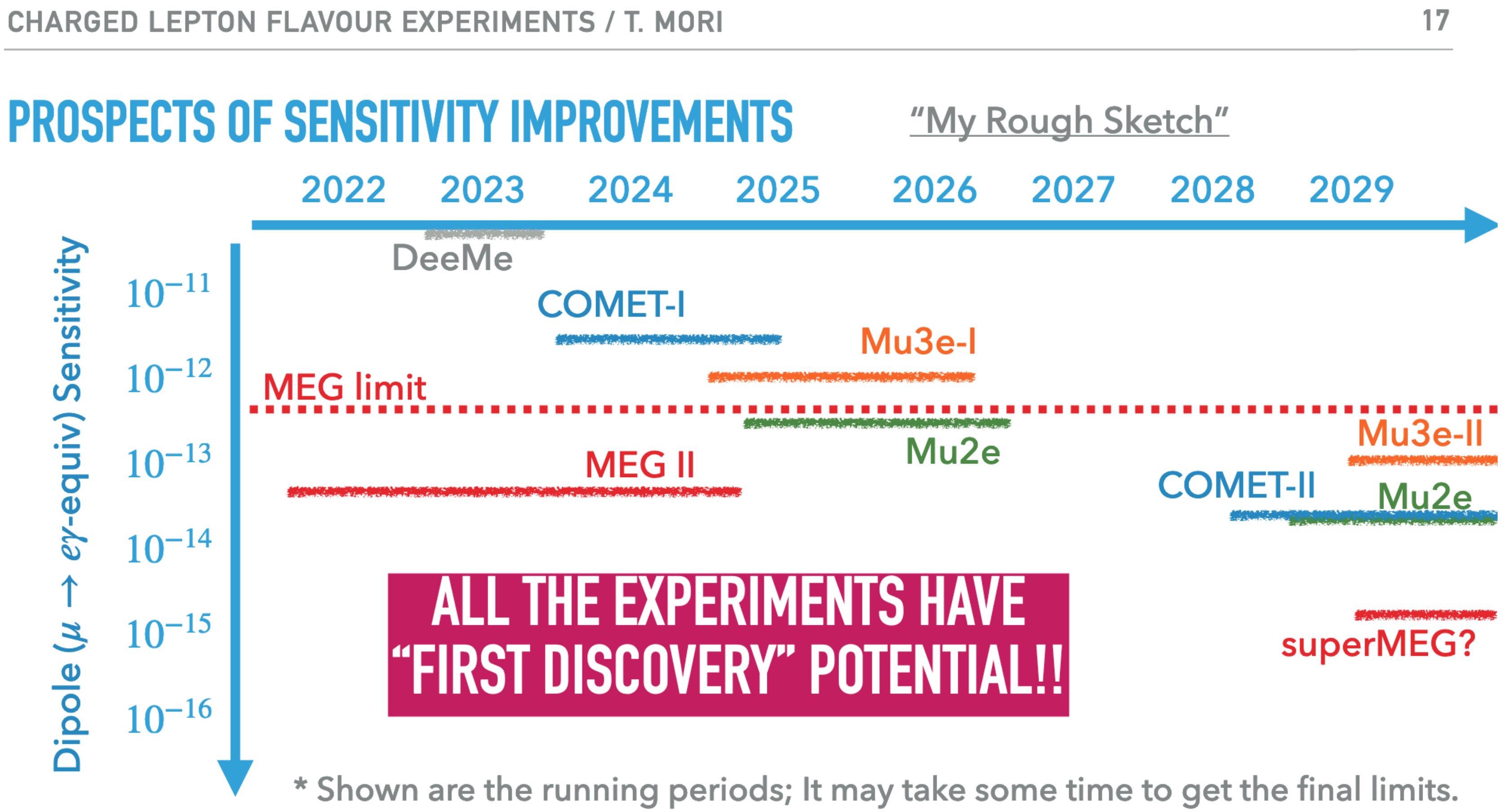


- MEG-II data-taking in full swing now
- Upgraded detector (drift chamber)
- Aiming at BF sensitivity **6 10^{-14}** in 3 years (x10 better than MEG)



Next on CLFV

- From ICHEP 2022 plenary talk



CHARGED LEPTON FLAVOUR EXPERIMENTS / T. MORI 17

PROSPECTS OF SENSITIVITY IMPROVEMENTS

“My Rough Sketch”

ALL THE EXPERIMENTS HAVE “FIRST DISCOVERY” POTENTIAL!!

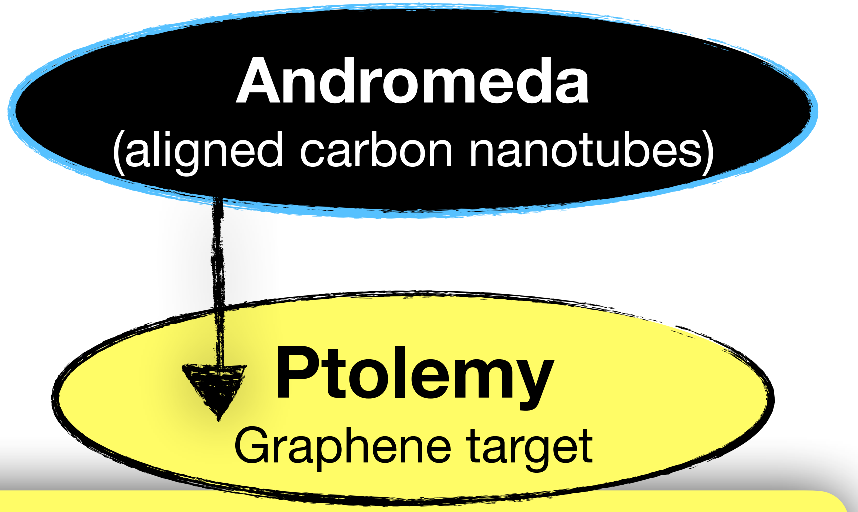
* Shown are the running periods; It may take some time to get the final limits.

- Cutting edge, complementary experiments for New Physics searches

My recent and **future** projects

Direct light dark matter search

(With directionality)



Andromeda

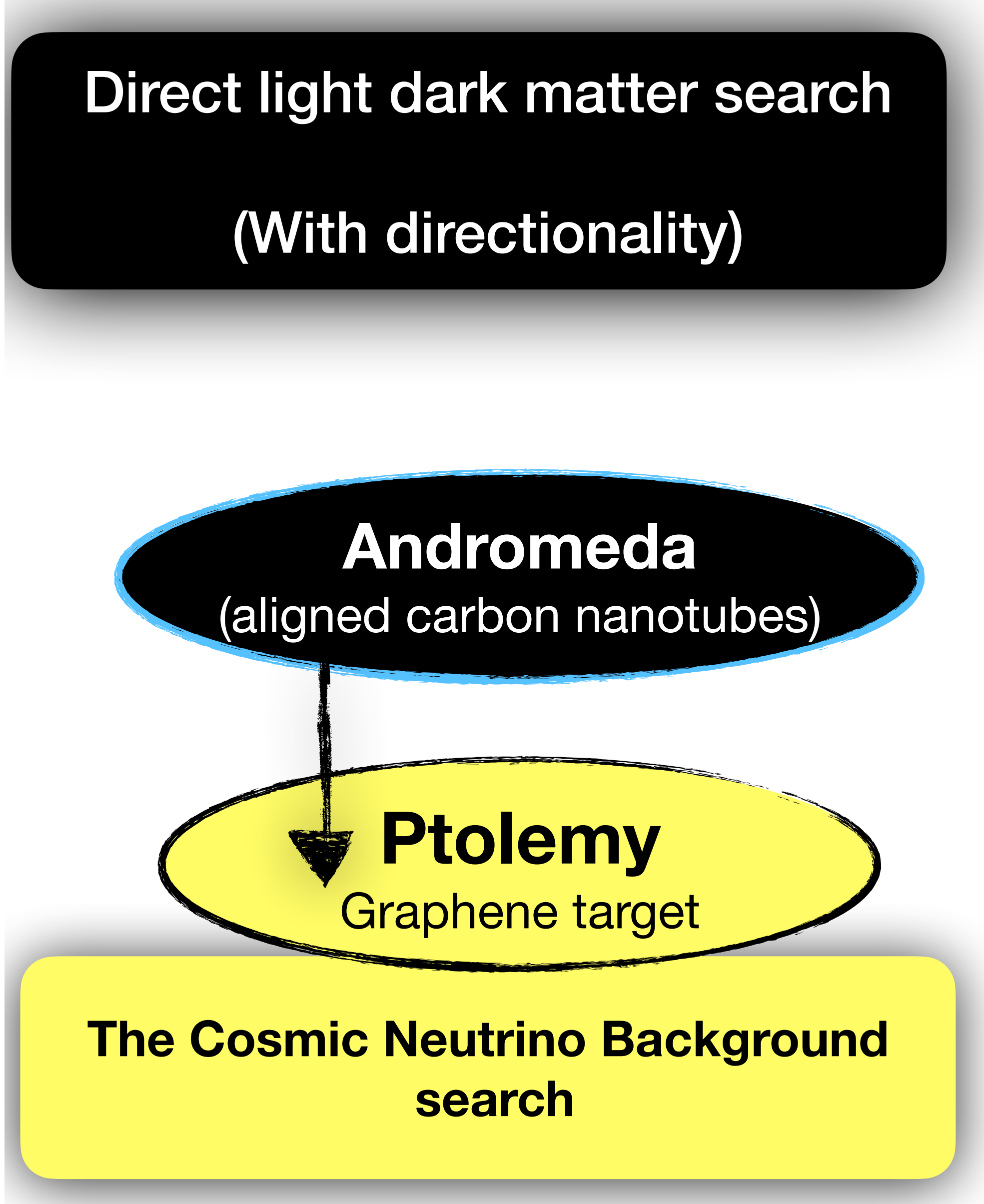
(aligned carbon nanotubes)

Ptolemy

Graphene target

The Cosmic Neutrino Background search

My recent and **future** projects



Direct light dark matter search

(With directionality)

Andromeda
(aligned carbon nanotubes)

Ptolemy
Graphene target

The Cosmic Neutrino Background search

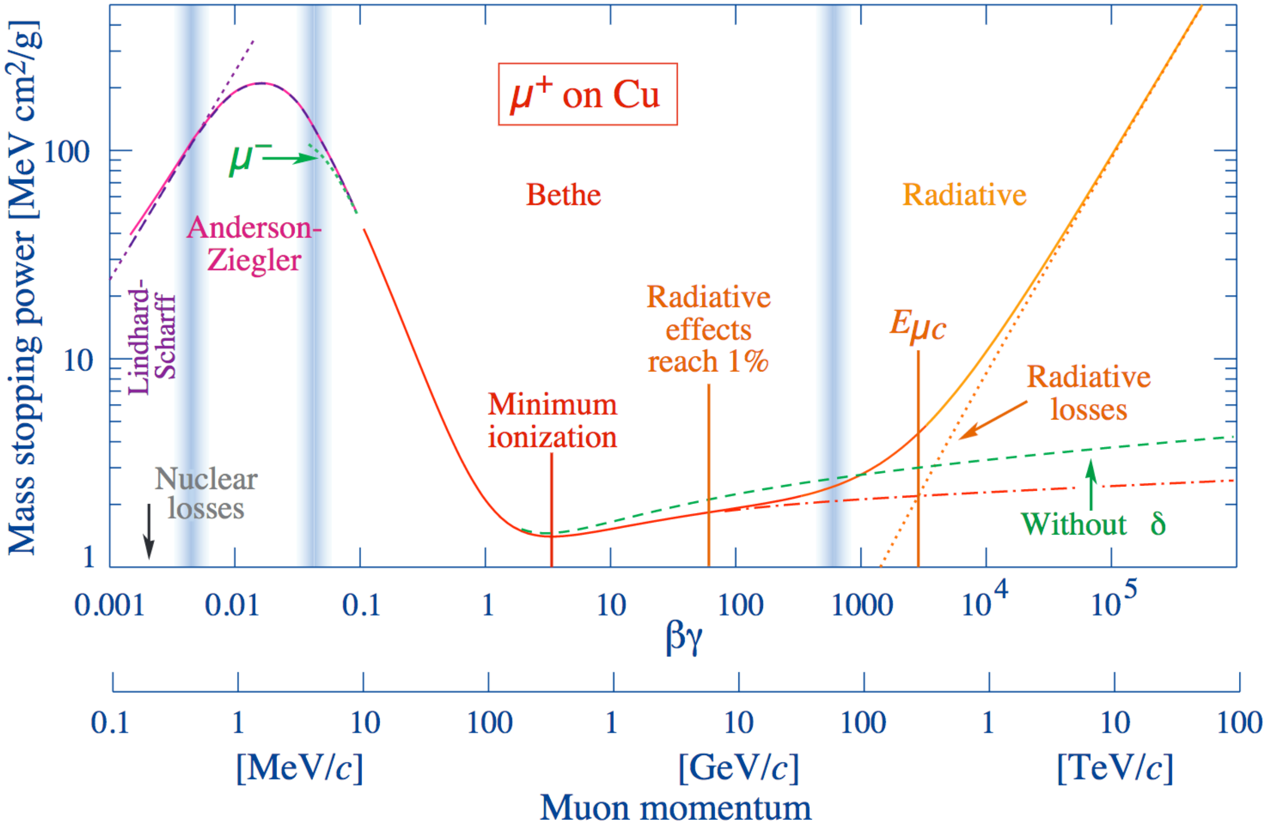
I will concentrate on the physics of these projects as an example

They are intended as a scheme that can be replicated

Particle - matter interactions

The standard view

- Energy loss due to interaction with **electrons** (mostly)



From

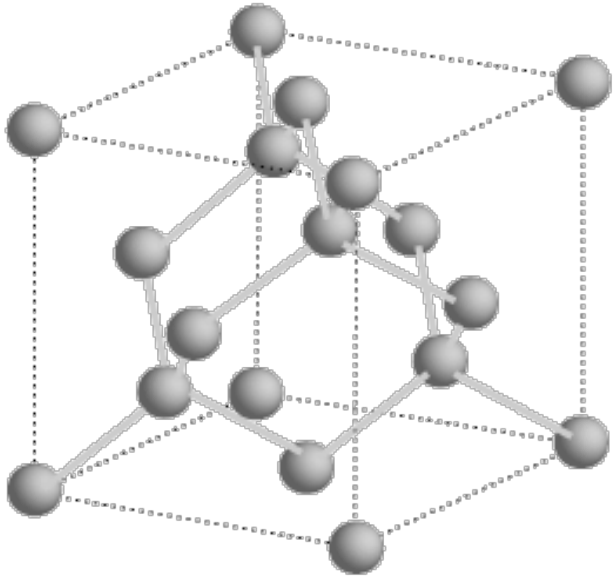
Particle Data Group

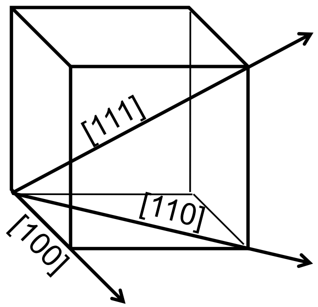
Book

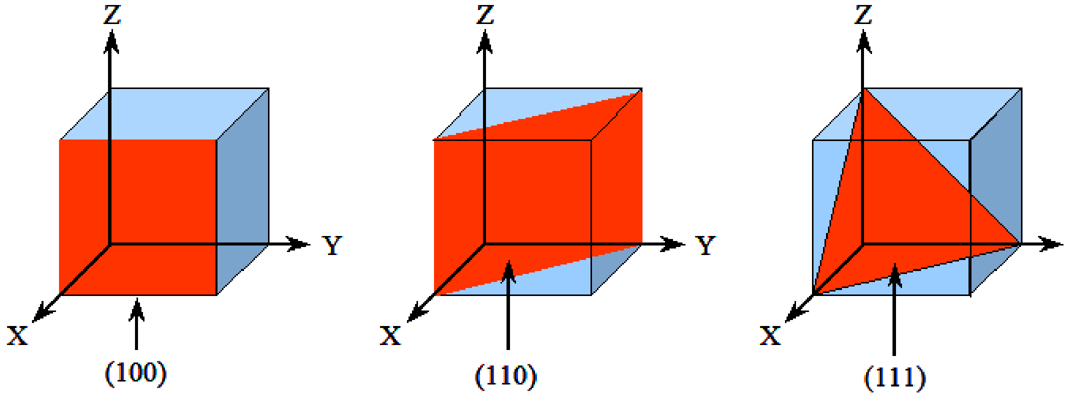
- Here the target is an “**amorphous**” material with **no ordering (collisions are uncorrelated)**

Crystals - ordered structure

- **Silicon**: two Face Centered Cubic Cells
- **Symmetry**: axial and planar





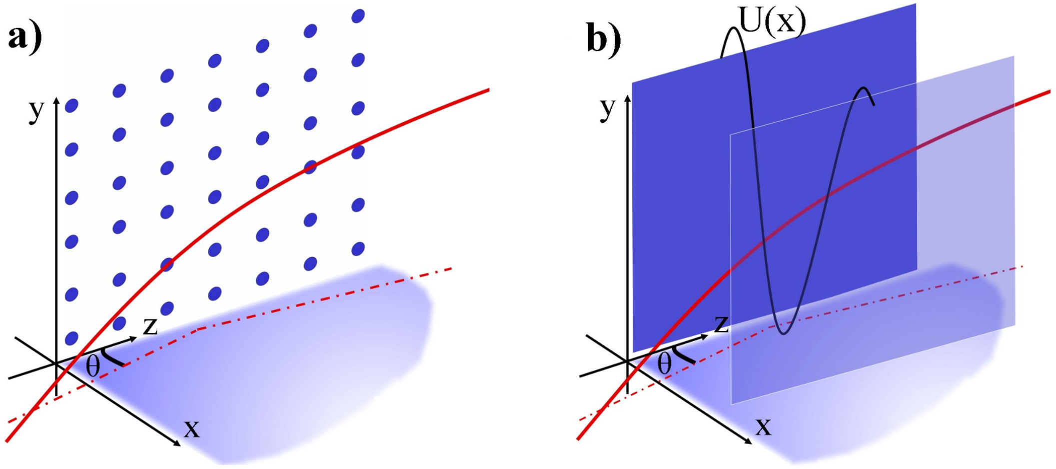


- If a charged particle is “**aligned**” with respect a plane or an axis, the macroscopic description of its interaction is changing.

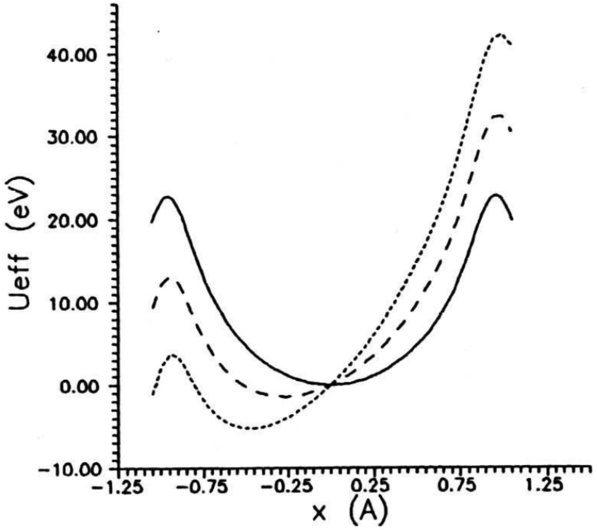
  - **Collision are correlated!**

Crystal channelling and bent crystals

- **Crystal channeling**, trapping (charged) particles within the lattice potential well

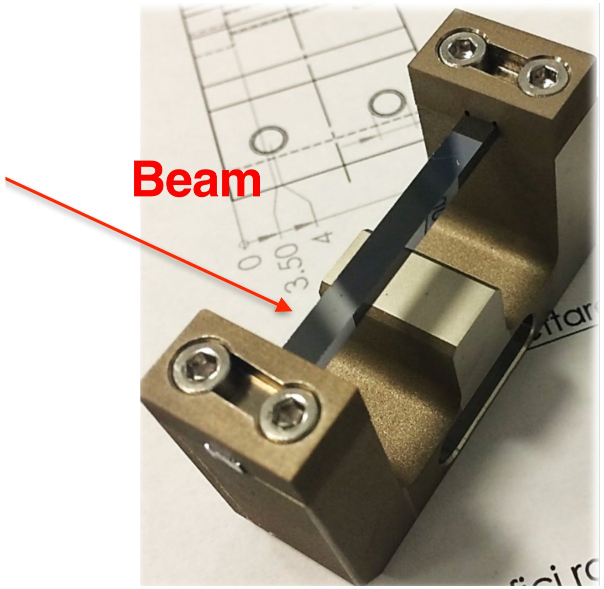


Decreasing curavture radius
(up to a **critical radius**)

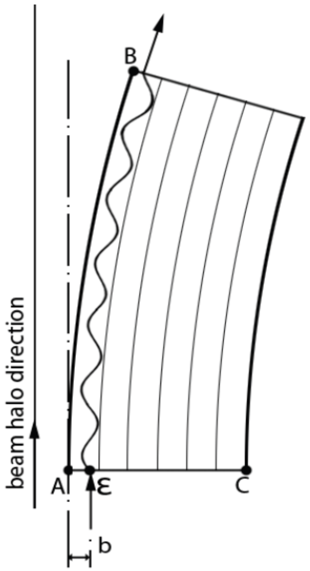


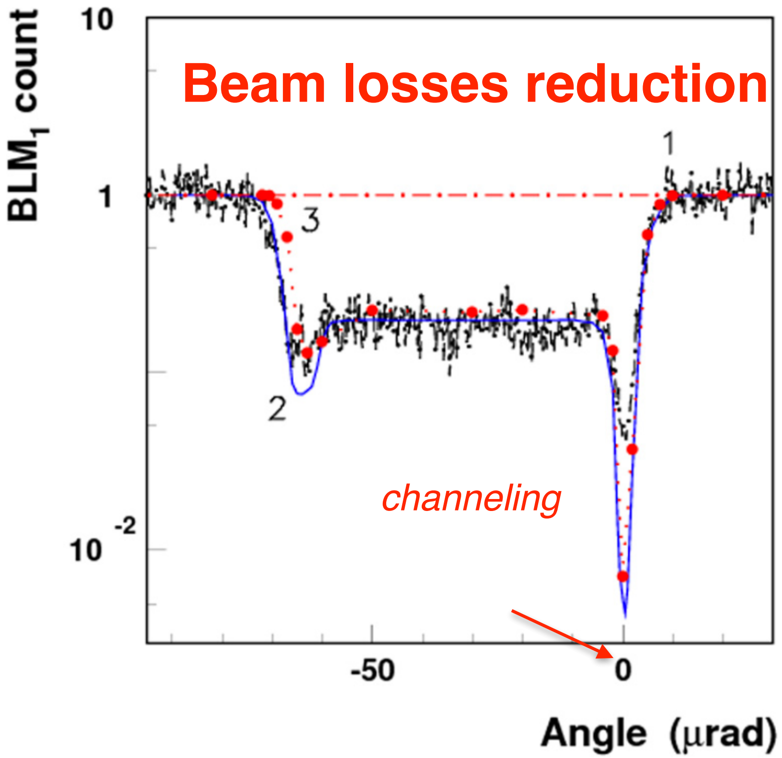
- Bending the crystal lattice planes is equivalent to adding a centrifugal force

Crystal collimation



Phys.Lett. B758 (2016) 129-133





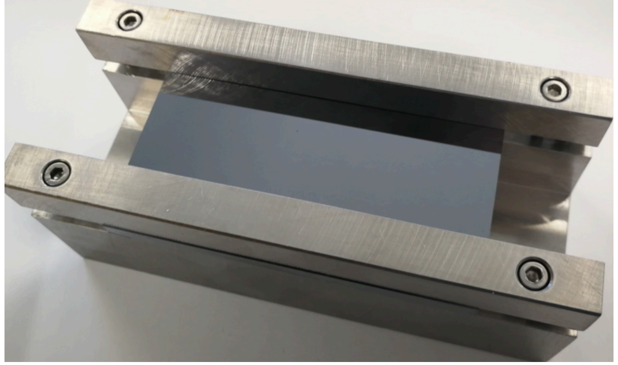
- Particles can be **trapped** in channeling **and bent**!
- Like in a **magnetic** field

- Bent crystal installed on the LHC (CERN UA9) as **collimators**

Building bridges

- Study of coherent interaction in crystal need a **collaboration** among **particle** physics and **condensed matter** physics
  Successful** physics program for crystal channeling at **ultra relativistic energy.

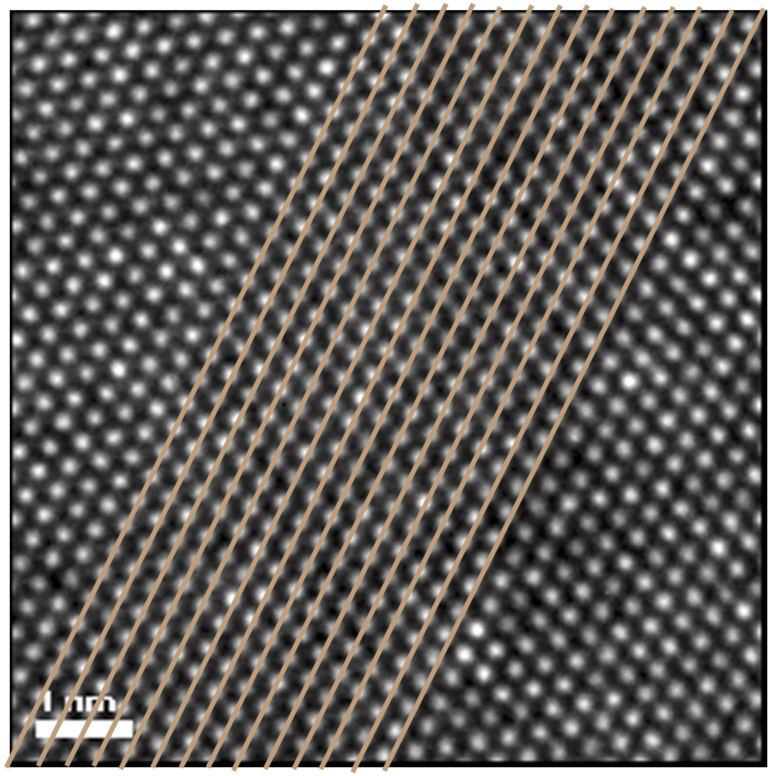
- **Impact:**
  - extracted LHC beam for **fixed target** physics program (ALICE, CRYSBEAM)
  - Measurement of magnetic and electric **dipole moments** of **baryons** (SELDOM)



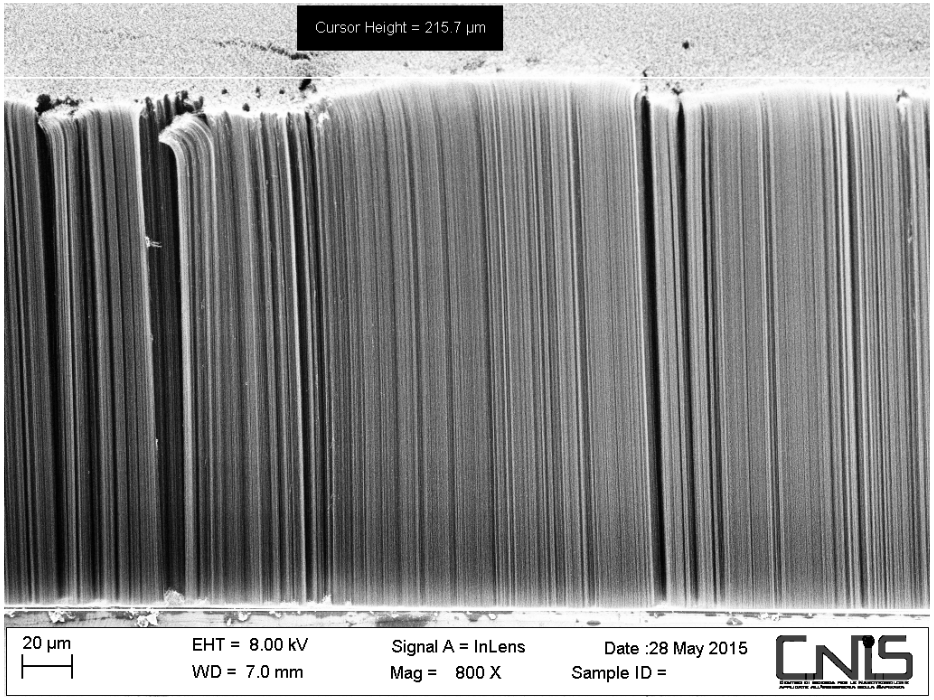
- The challenge is to implement this **bridge** for a much **lower** energy - in the range of few keV to few eV

- **Detection of the dark matter (*unknown*) interaction with matter**

Atom strings and carbon nanotubes



Ki-Bum Kim, SPIE Newsroom, DOI: 10.1117/2.1200812.1396



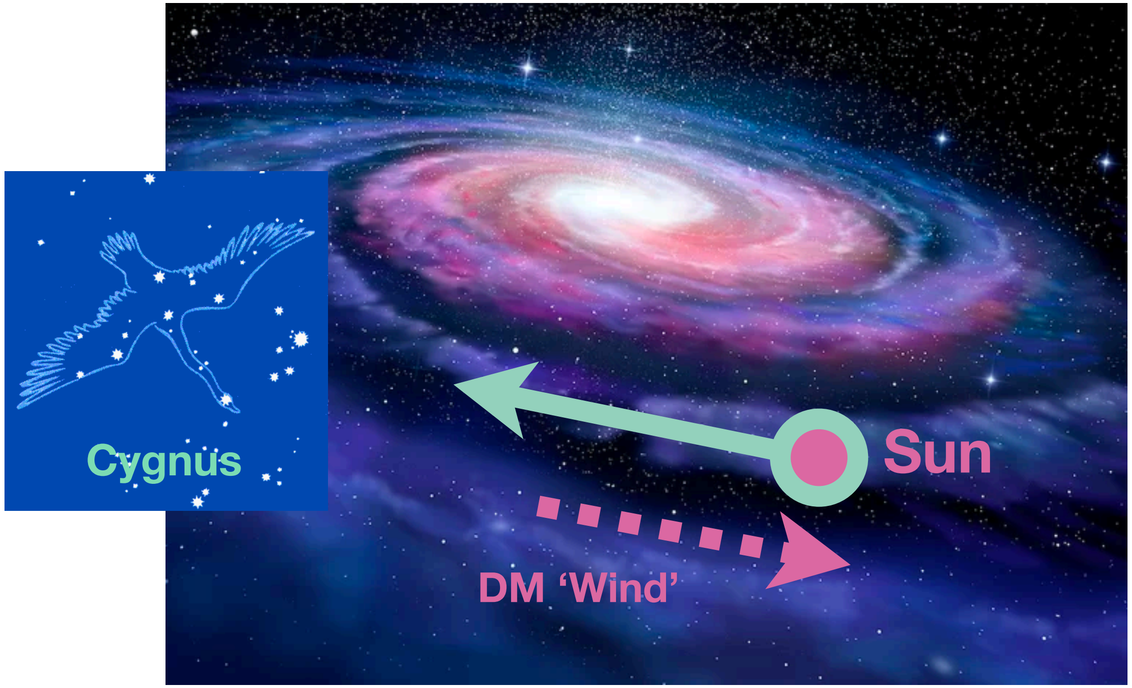
- Ordered structure, similar effective potential

Dark matter searches

Looking for Dark Matter in the Galaxy

- Finding DM particles in our Galaxy still an outstanding issue.
- Earth based experiments looking for DM scattering on matter ("**direct**" searches).

- Exploiting the "***directionality***": the **DM wind** from Cygnus constellation.



The WIMP as cold DM particle

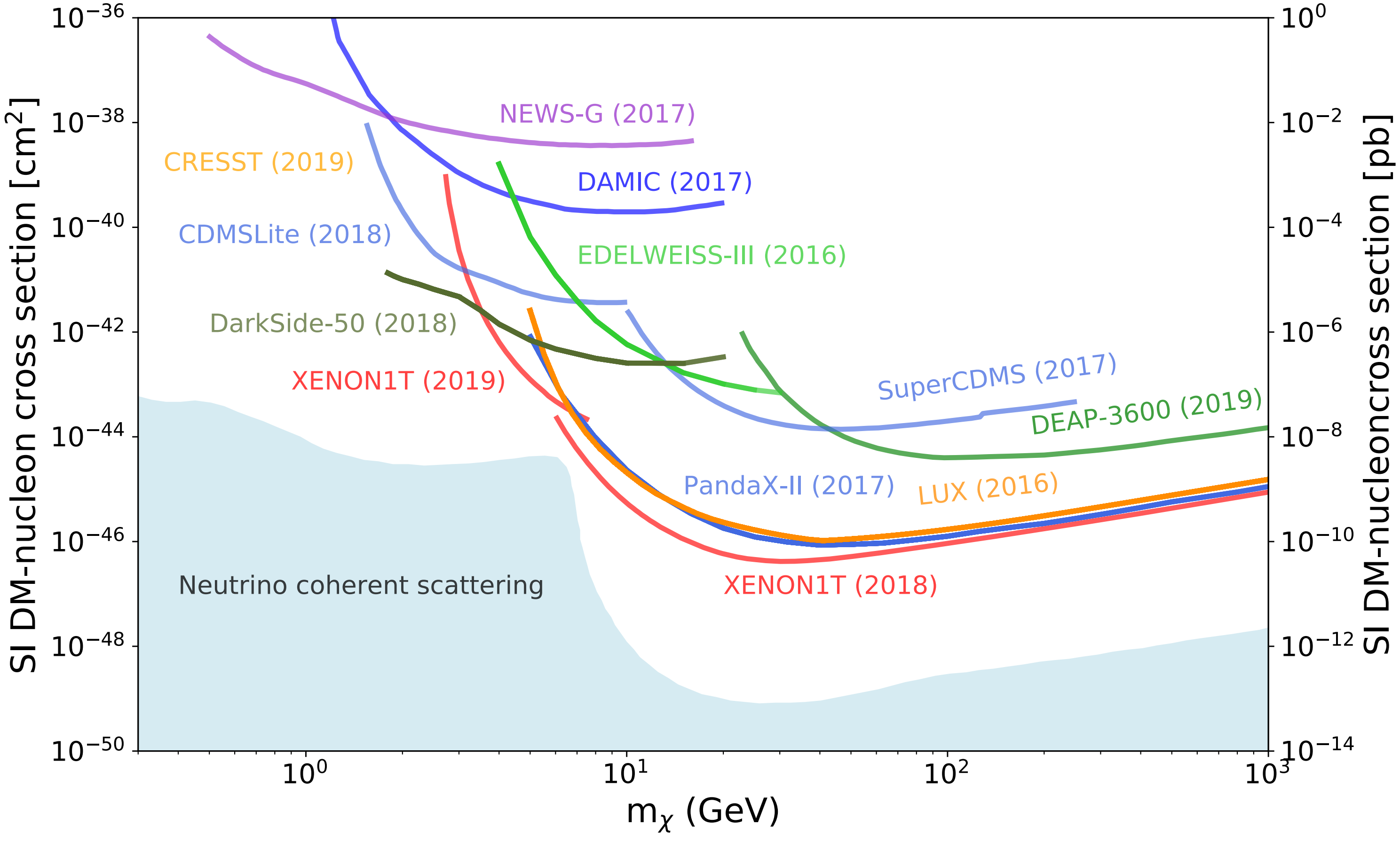
- In **ΛCDM**, dark matter is:
  - Massive
  - Electrically neutral
  - Not self-interacting (‘cold’)
  - Gravitationally interacting with ordinary matter
- Primordial **fluctuations** in DM density → virial wells
  - ‘Seeds’ for galaxies
- **Non-relativistic speed** (v_{DM} ~ 10^{-3} c)

- **WIMP** paradigm dark matter :
  - Massive **(M ~ 100 GeV)**
  - Electrically neutral
  - Not self-interacting (‘cold’)
  - Gravitationally interacting with ordinary matter

✓ **Weakly** interacting with ordinary matter

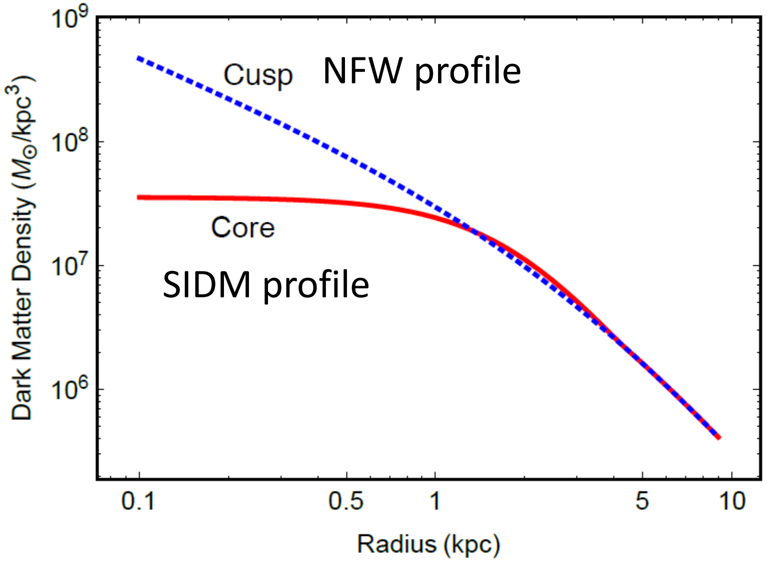
However, WIMPs are still hiding

- Exclusion regions from “direct” searches
- The “**neutrino floor**” is approaching (~10 GeV)



Cusp-core problem with WIMP ?

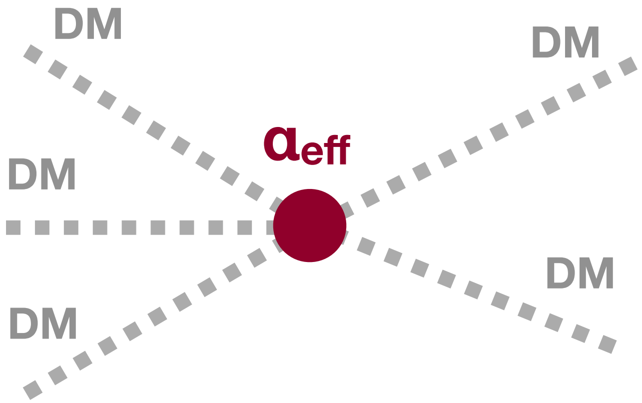
- ΛCDM successful in describing large scales structures from horizons (15000 Mpc) to intergalaxy distances (1 Mpc)
  - However sub-galactic structures (<1 Mpc) seems to be problematic (cusp-core, missing satellites, …)
  - Cold DM predicts galactic halos with ***high*** central **density**
  - Disagree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



Looking elsewhere (with a reason)

Hochberg et al., PRL 113 (2014) 171301

- The Strongly Interacting Massive Particles (SIMP)



$\alpha_{eff} \sim 1$

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

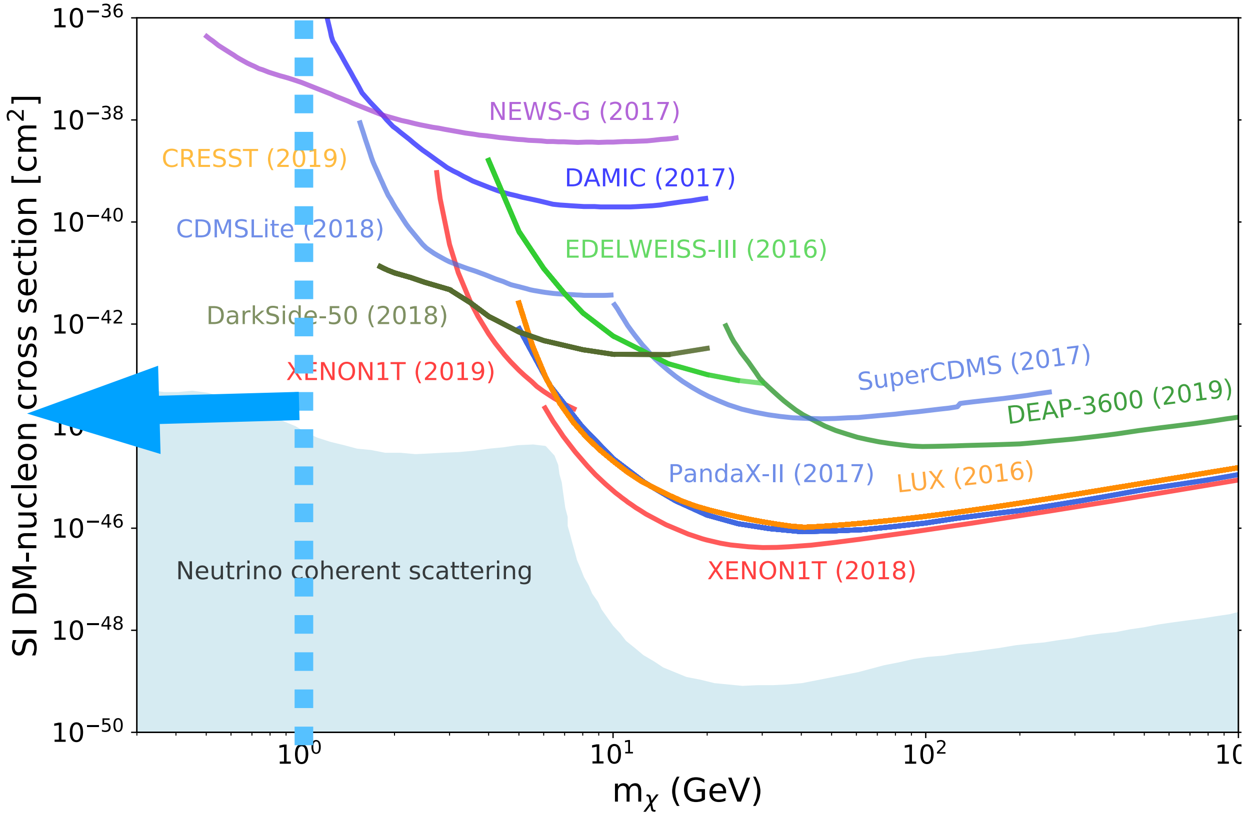
- SIMP predicts sub-GeV m_{DM}

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

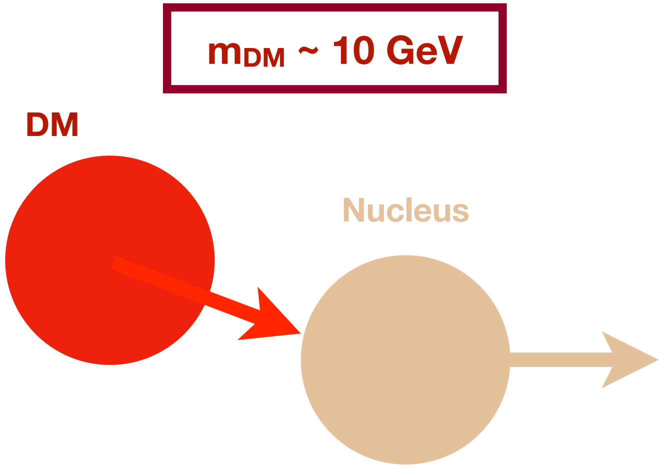
  (e.g. $\alpha_{eff} = 1 \rightarrow m_{DM} = 100$ MeV)

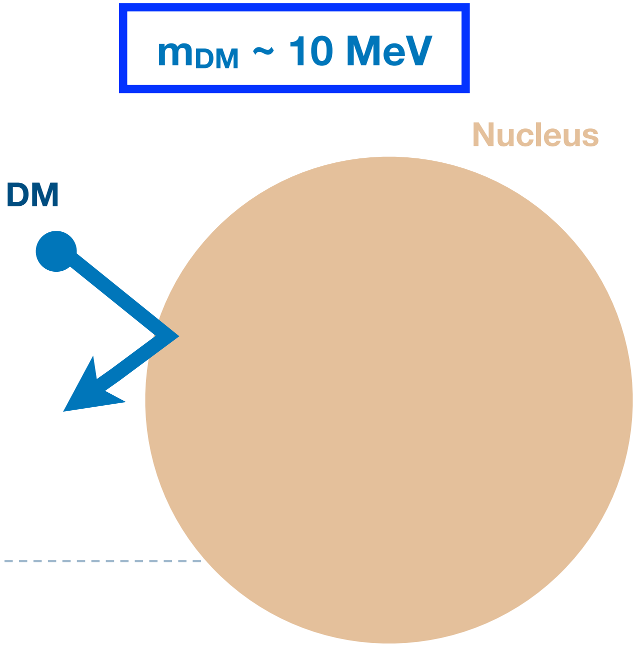
New mass range, new experiments

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

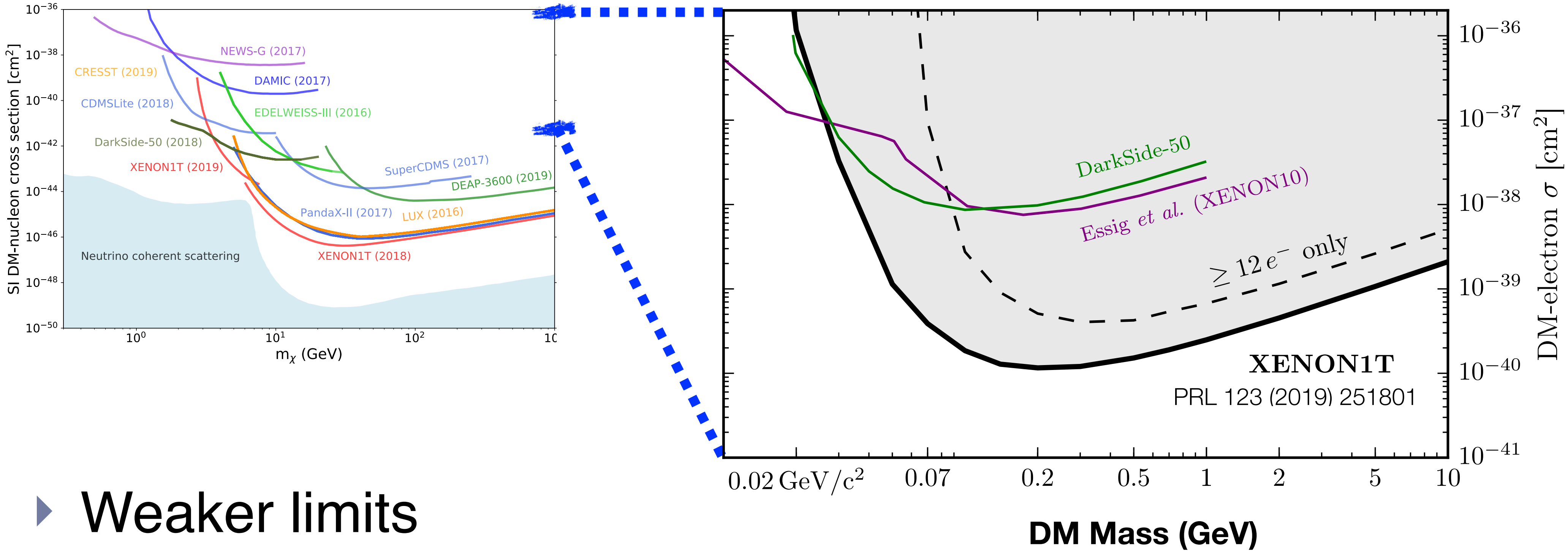


"light" DM


m_{DM} ~ 10 GeV


m_{DM} ~ 10 MeV

Electron recoils are (much) better

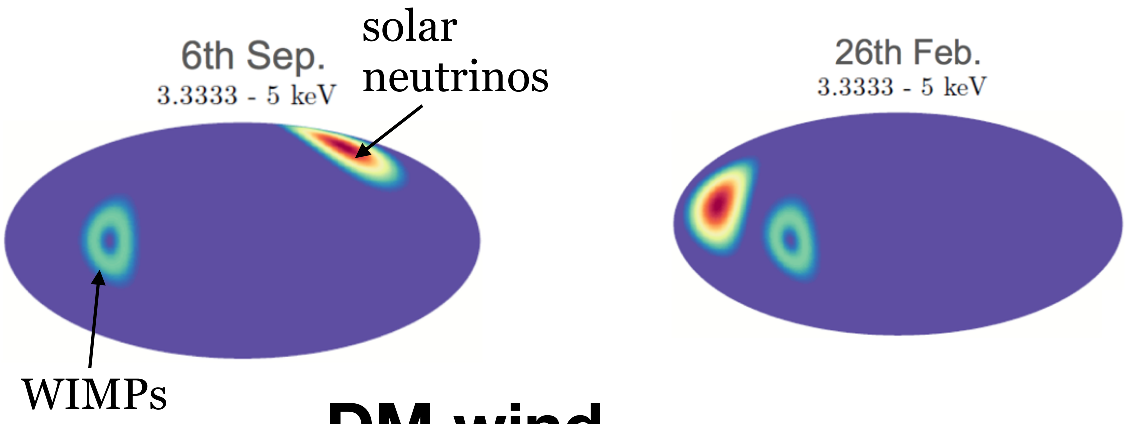


- Weaker limits
  - $m_{DM} < 100$ MeV very poor limits

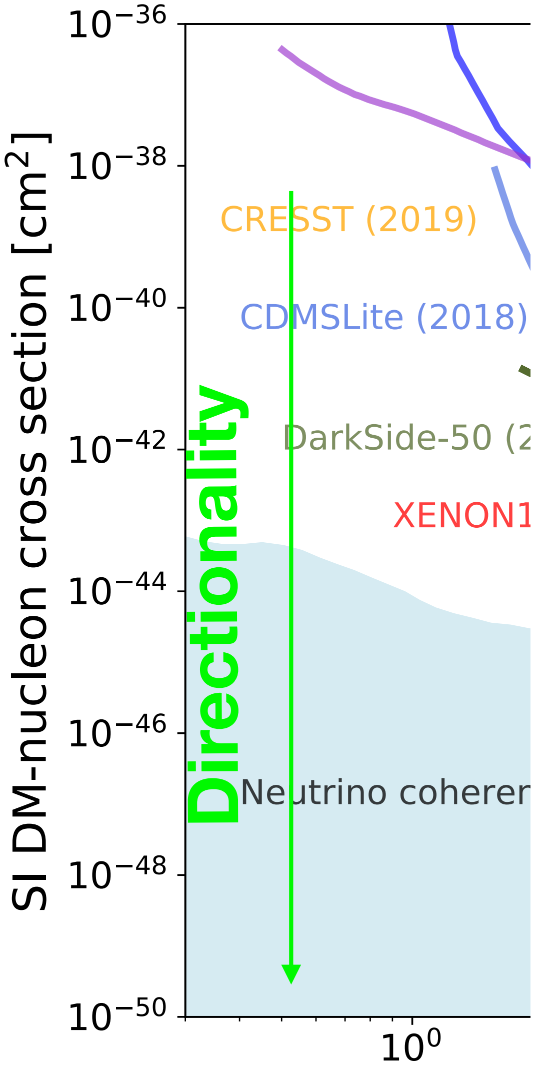
Window of opportunity for gram sized targets ?

Neutrino floor exploration

O'Hare et al, Phys. Rev. D 92, 063518 (2015)



DM wind



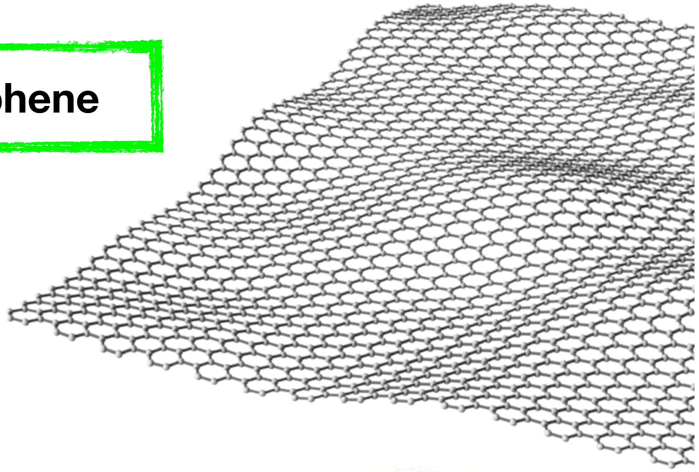
- Solar neutrinos direction never overlaps with DM wind
- In general a powerful tool to suppress any background (radioactivity)

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

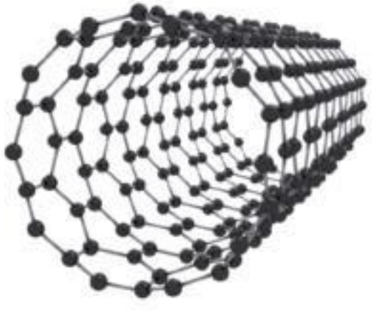
Solid state targets: 2D materials

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

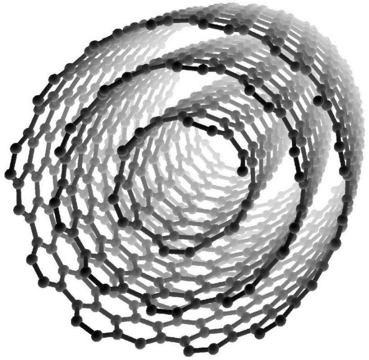
Graphene



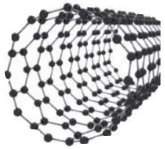
Single-wall nanotube



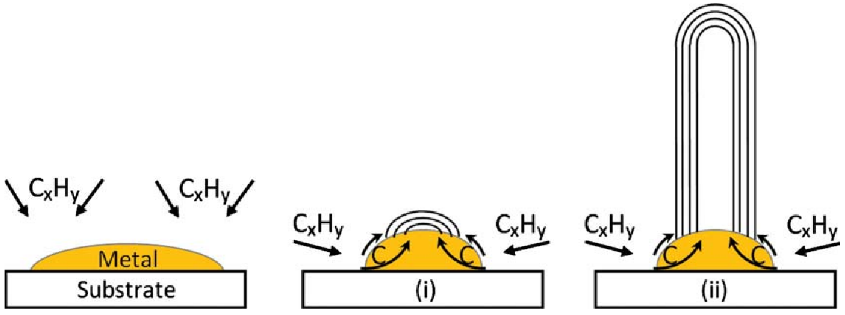
Multi-wall nanotube

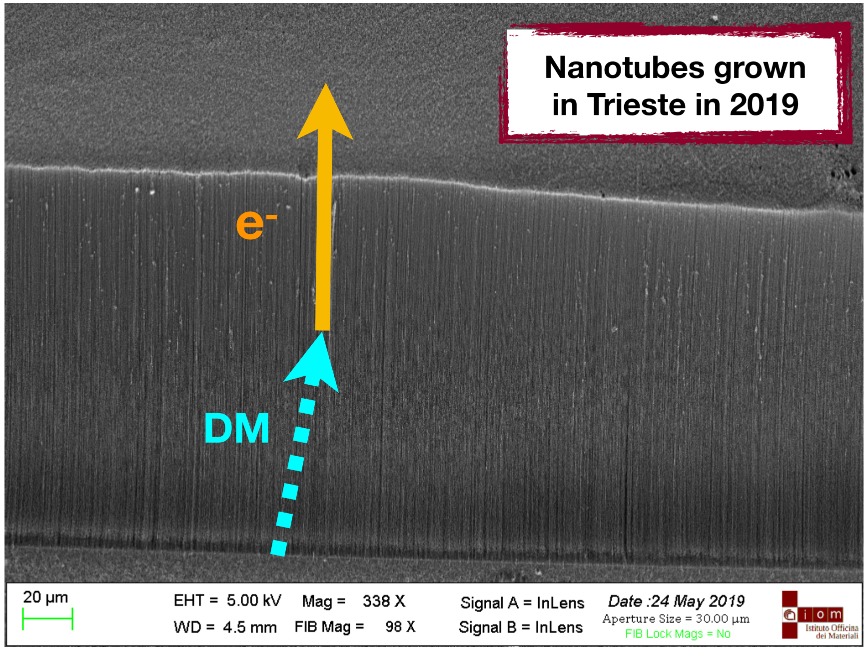


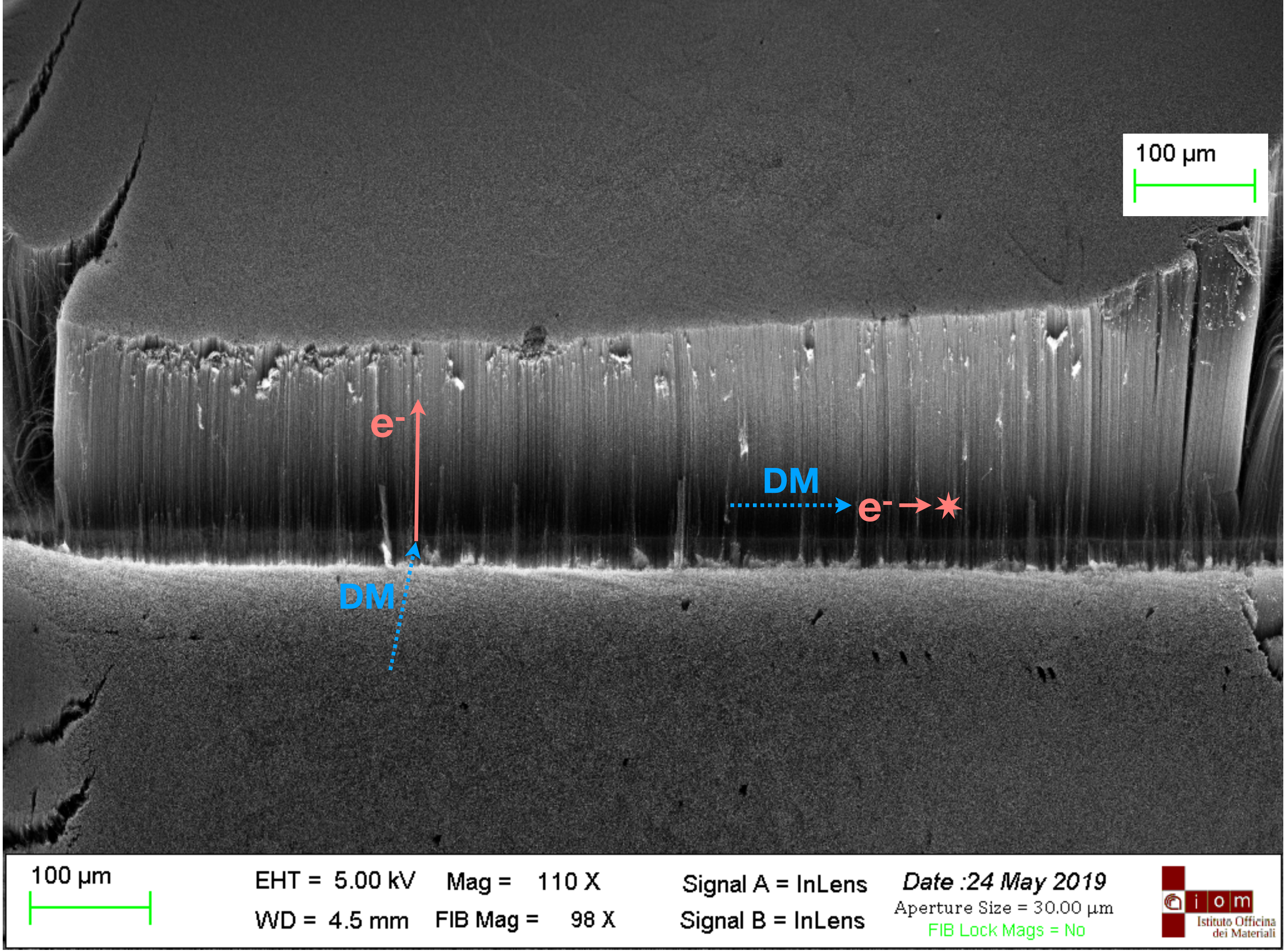
Growing vertically aligned CNT



- **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




Nanotubes grown in Trieste in 2019

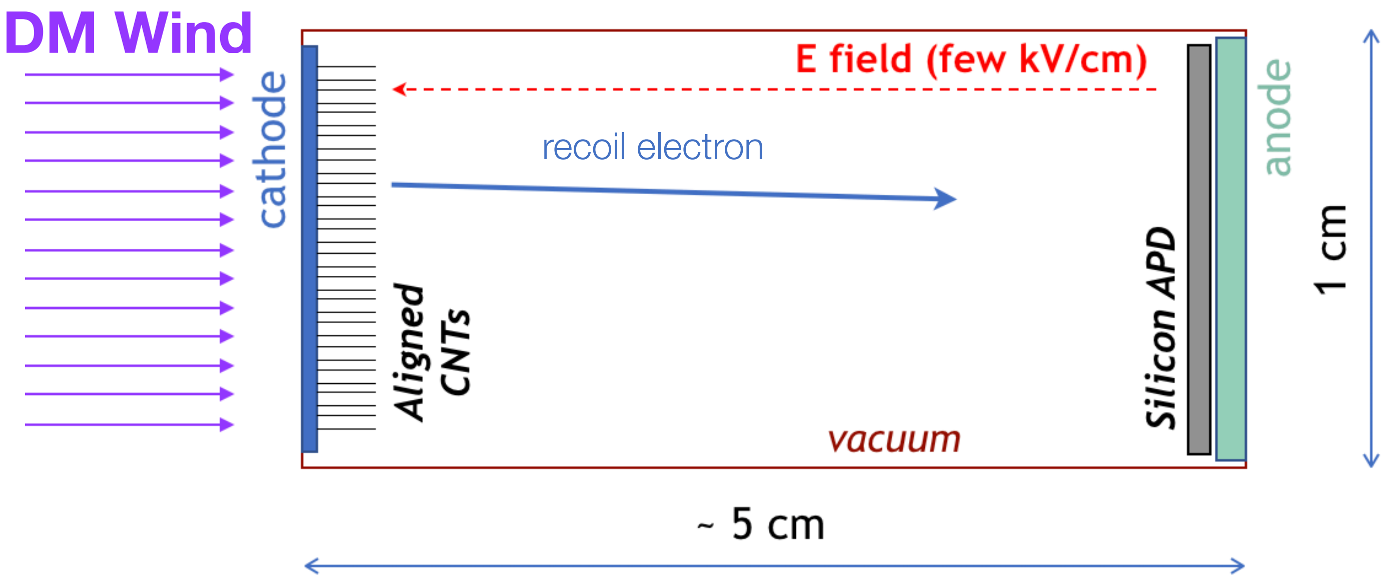

100 µm
e⁻
DM
e⁻
DM
100 µm
EHT = 5.00 kV
WD = 4.5 mm
Mag = 110 X
FIB Mag = 98 X
Signal A = InLens
Signal B = InLens
Date :24 May 2019
Aperture Size = 30.00 µm
FIB Lock Mags = No
iom
Istituto Officina dei Materiali

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

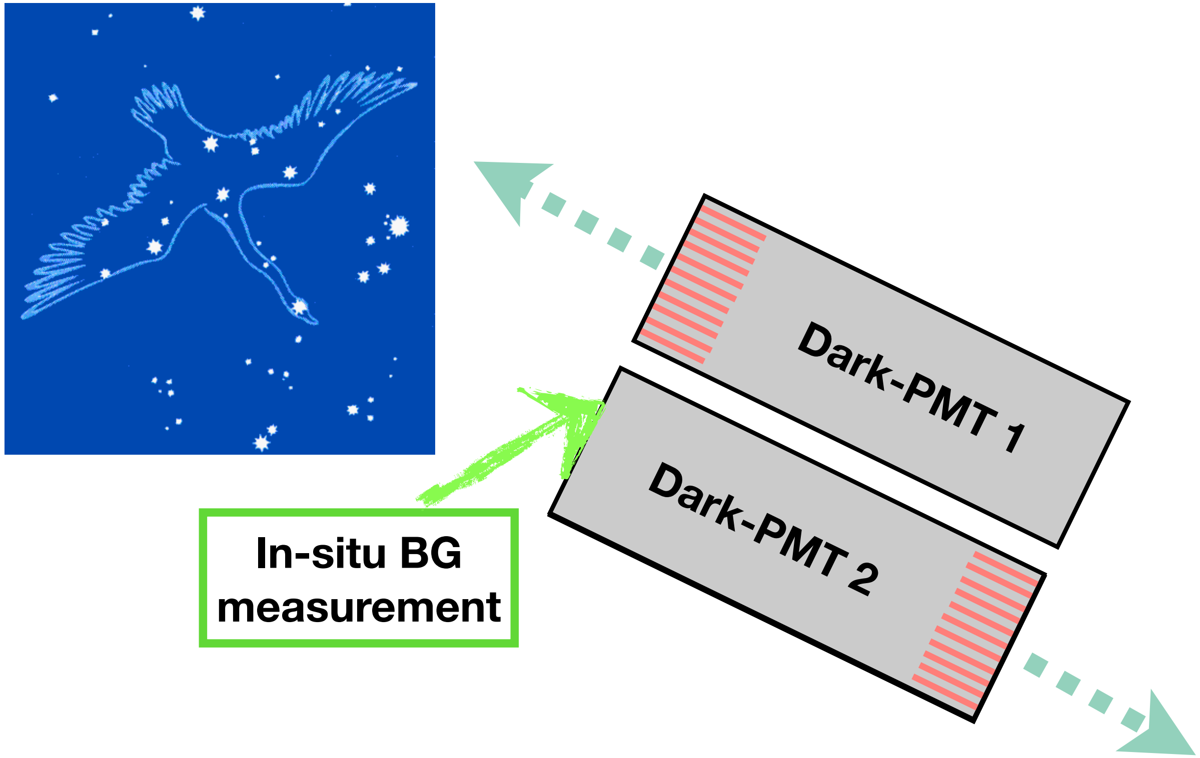


- ‘Dark-photocathode’ of aligned **nanotubes**
  - Ejected e^- accelerated by electric field
  - Detected by solid state **e^- counter**

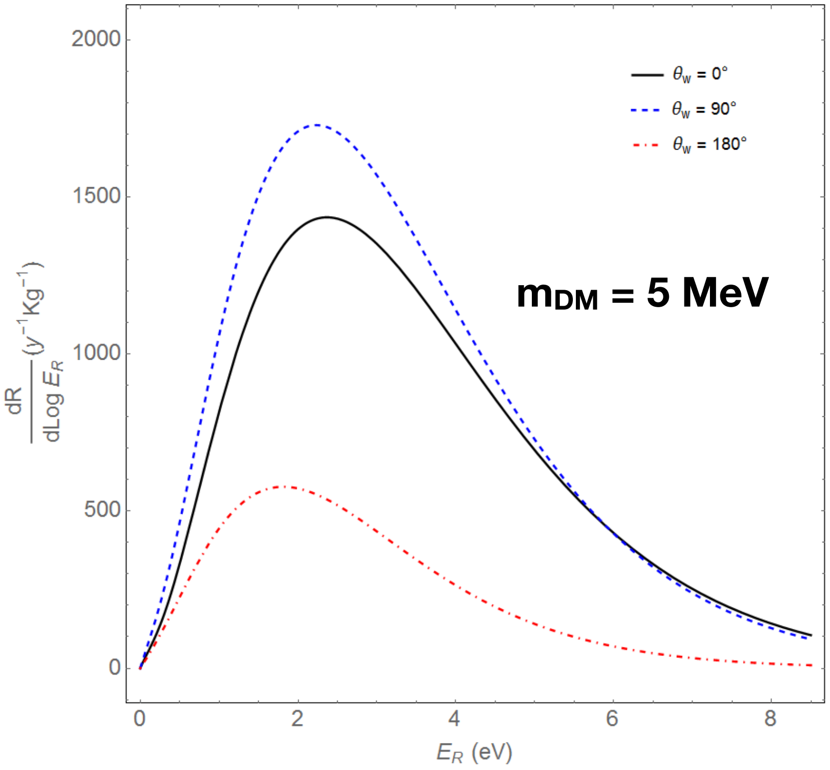
Dark-PMT features:

- **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

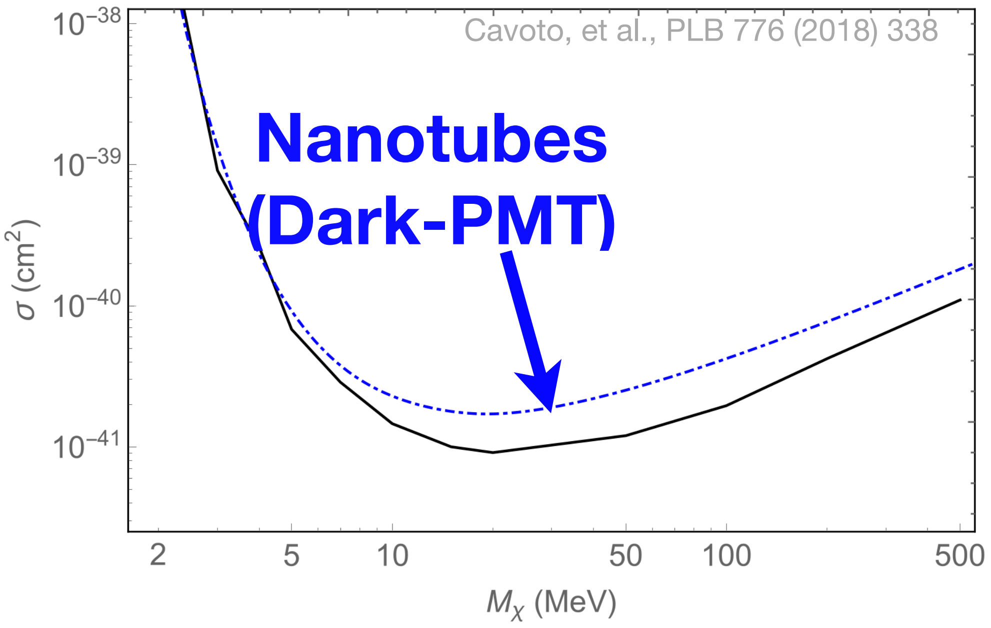


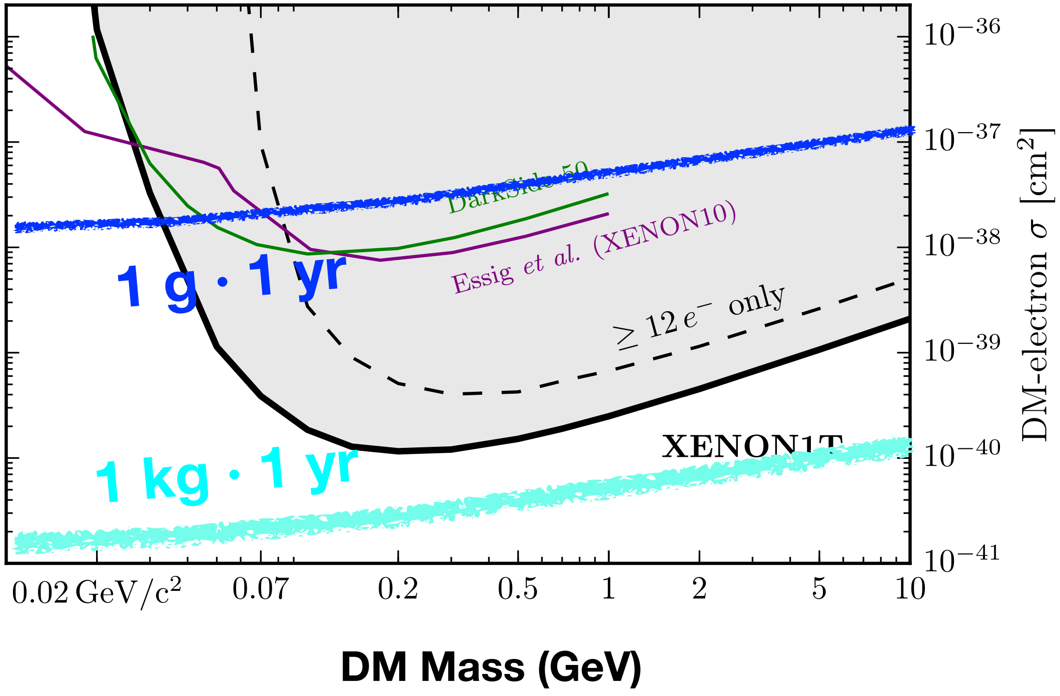
- **Two** sets of detectors: pointing towards Cygnus, and in **orthogonal** direction
  - Search variable: N_1-N_2

In principle sensitive to eV electrons!

Sensitivity down to 2 MeV DM

Exposure = 1 kg · 1 year

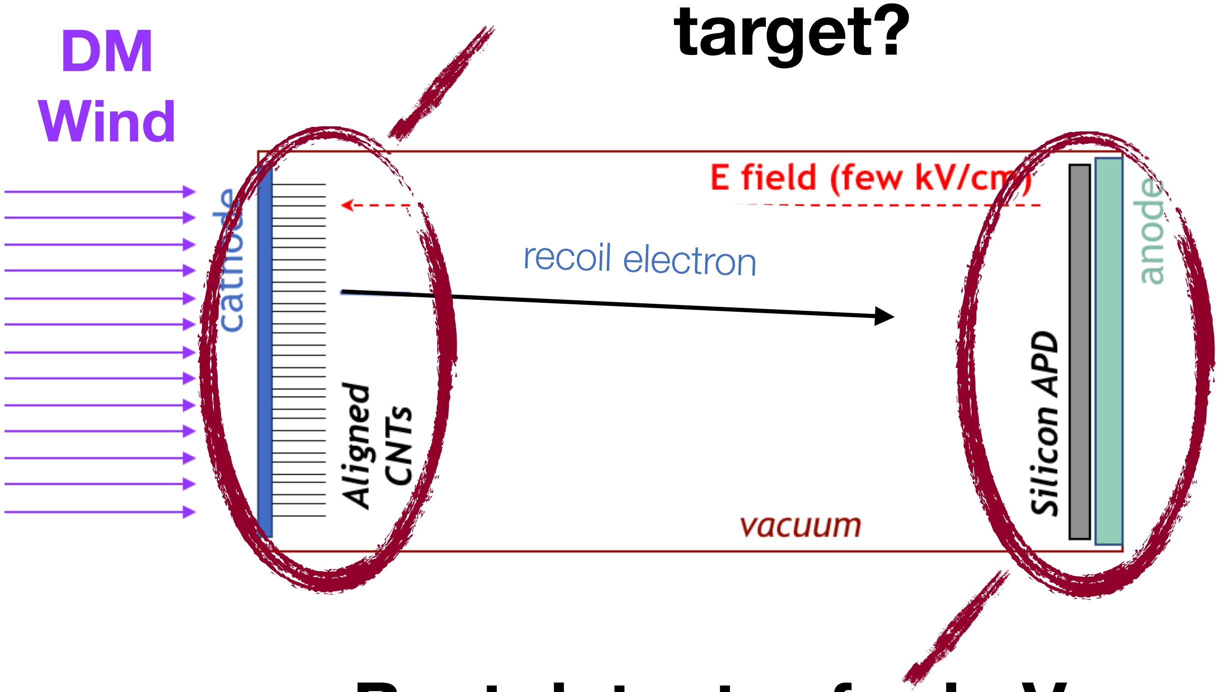




- Competitive searches with gram target mass.

The Andromeda project

- **Main objective:** have a working dark-PMT protoype by end of project (3 years)
  - Challenges on **both sides** of detector

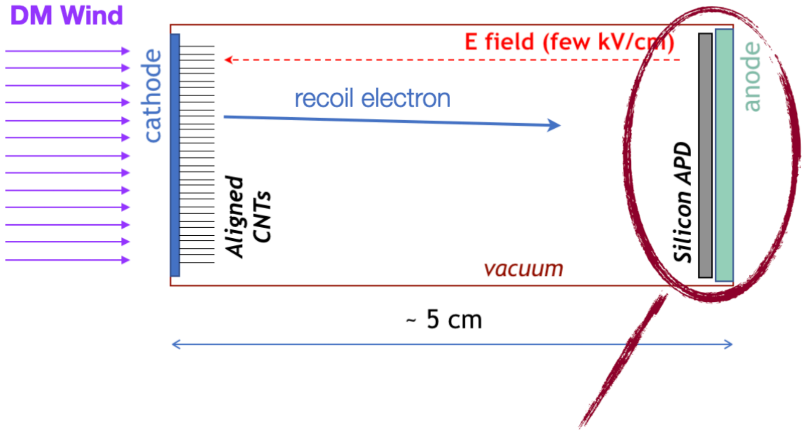


Ideal nanotubes for DM target?

Best detector for keV electrons?

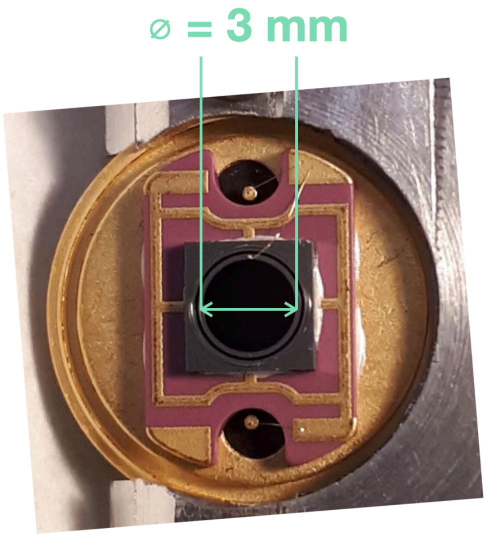
Silicon detectors for keV electrons

APDs and SDDs ‘born’ as photon detectors

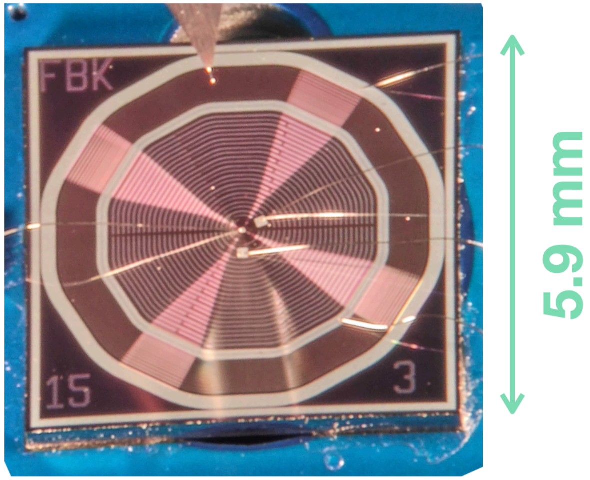


Challenge: detect keV electrons (with high efficiency)

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

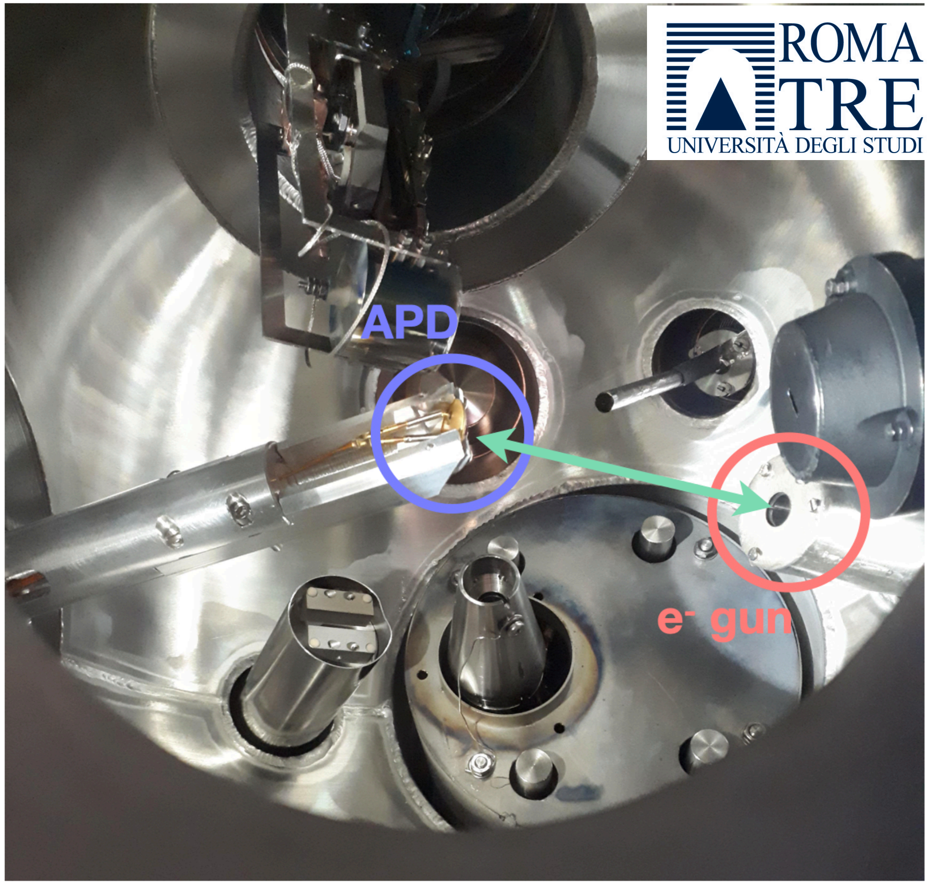


- Possible upgrade: **Silicon Drift Detectors**
  - Ultimate resolution
  - FBK (SDD) + PoliMi (electronics)



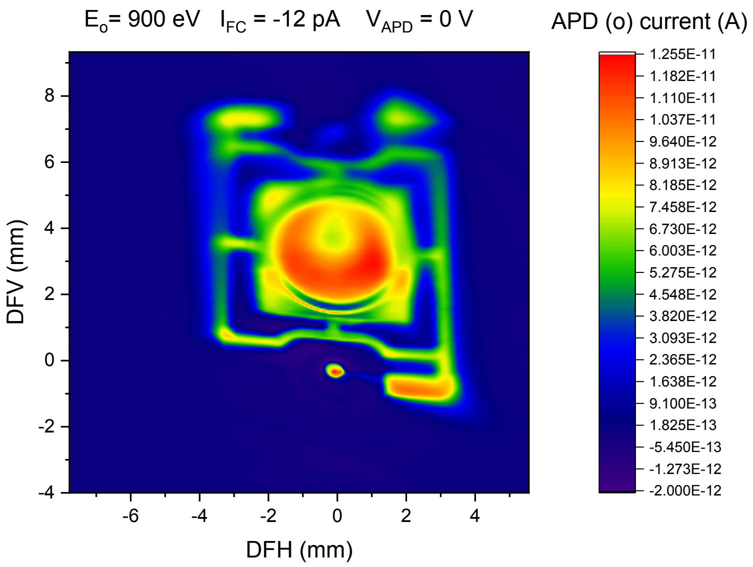
APD Characterization

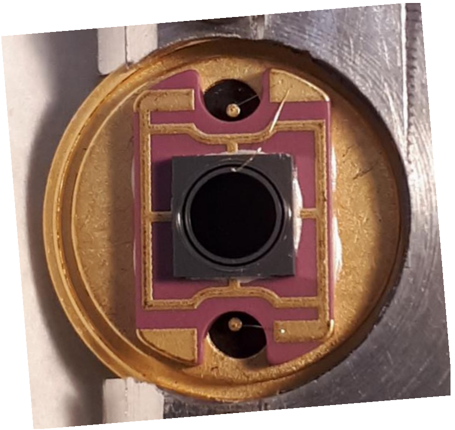
- State-of-the-art e$^-$ gun @ LASEC Labs (Roma Tre)
  - Electron **energy**: 30 < E < 1000 eV
  - Energy uncertainty < 0.05 eV
- Gun **current** as low as a few fA
  - i.e. electrons at ~10 kHz (not bunched)
  - Can probe **single-electron** regime
- Beam profile ~ 0.5 mm
  - Completely **contained** on APD (⌀ = 3 mm)

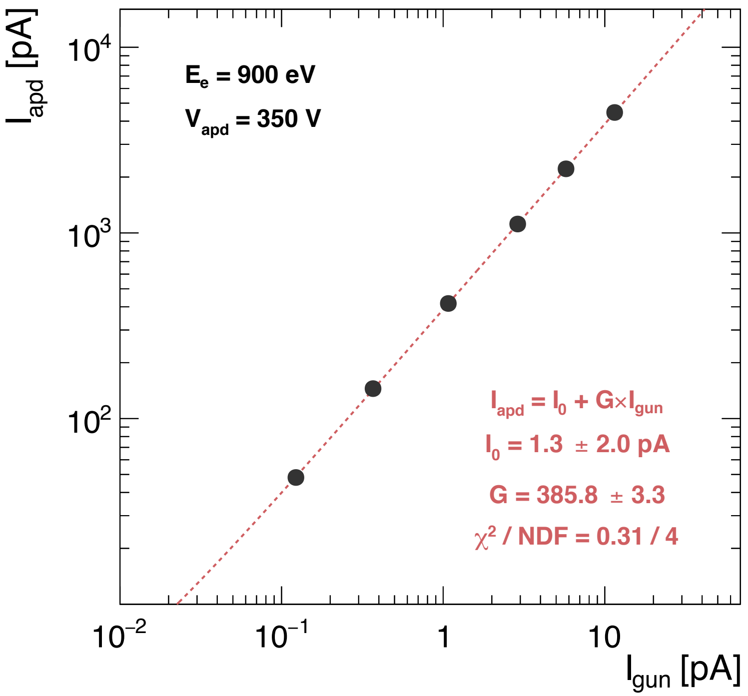


APD and 900 eV electrons

A. Apponi et al 2020 JINST 15 P11015

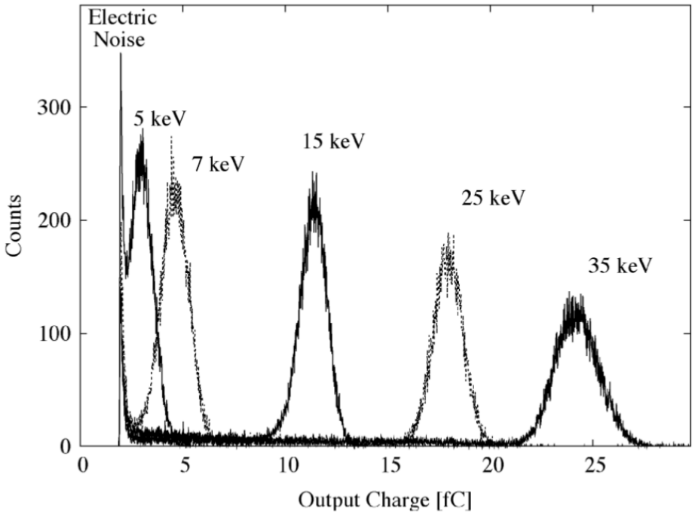




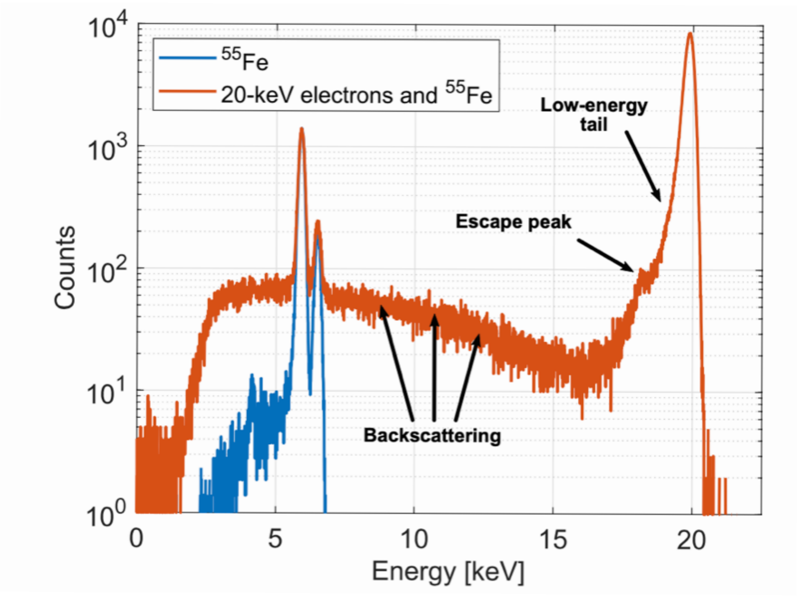


- Reading APD bias current when shooting gun on it
  - $V_{apd} = 0$: electronic ‘image’ of APD
  - $V_{apd} = 350$ V: I_{apd} **proportional** to I_{gun}

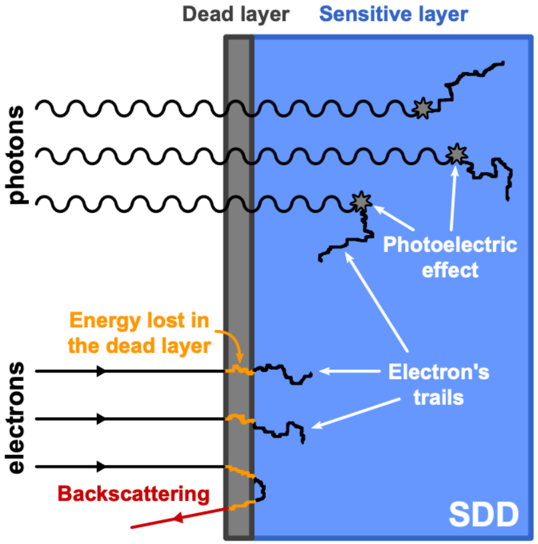
Single electron detection with silicon detectors



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

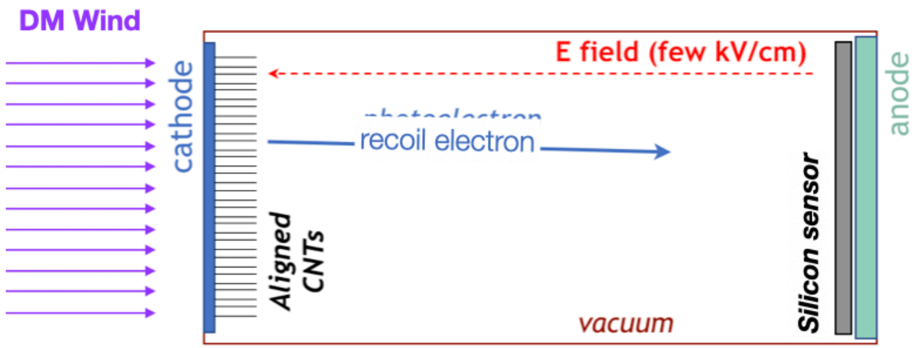


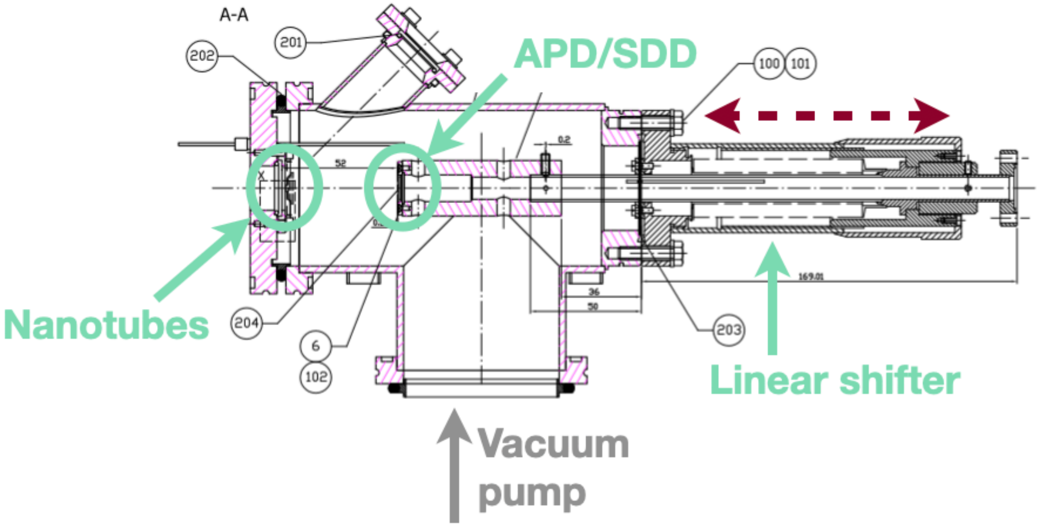
G.Gugiatti, et al.,
NIM A **979** (2020) 164474

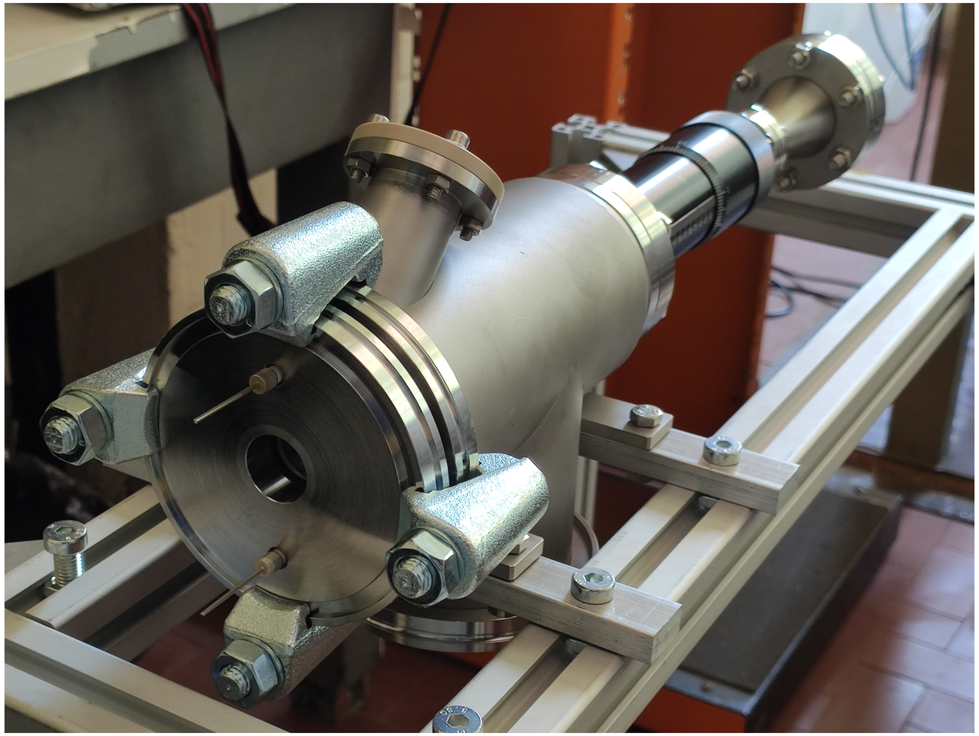


- APD can measure single e-
  - But only if $E_e > 5$ keV
- SDD: excellent resolution
  - But higher cost/complexity

Dark PMT prototype-0: Hyperion

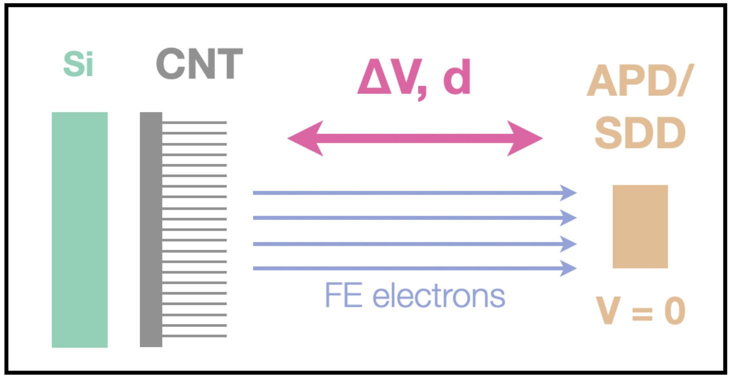




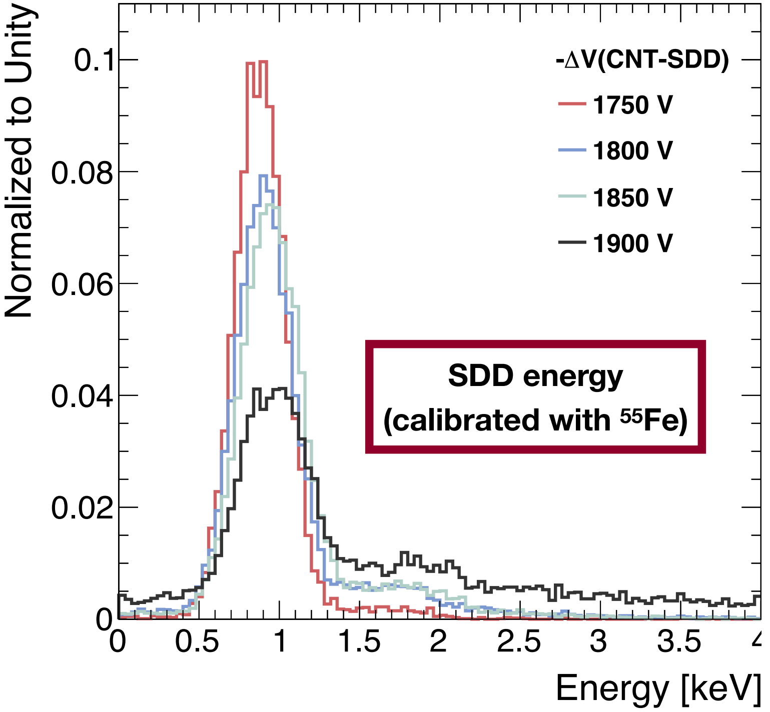


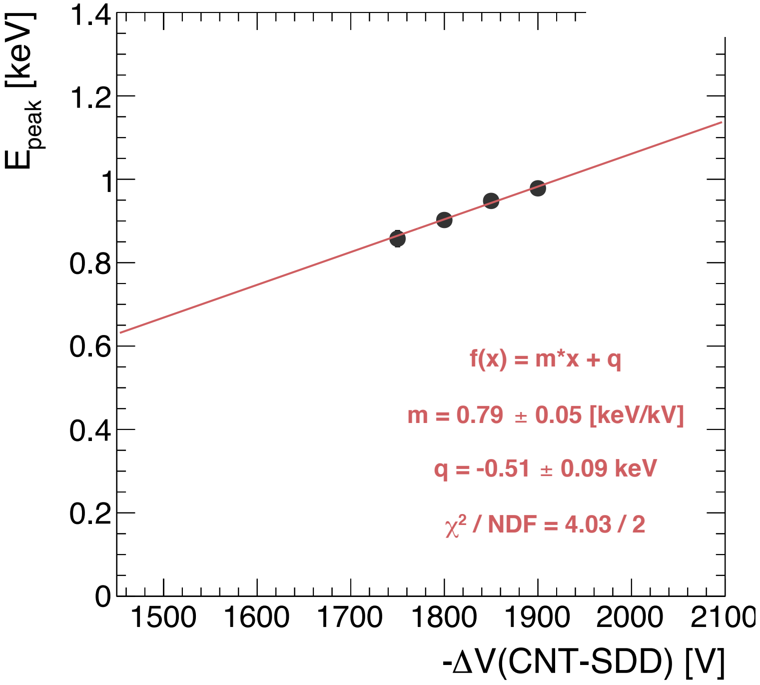
Field emission from CNT

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



Hyperion Prototype

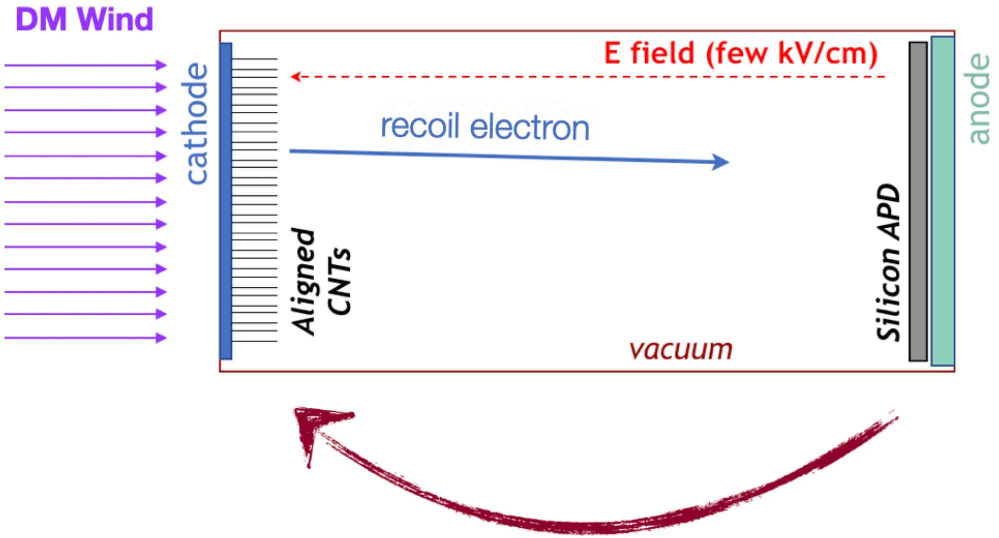




We can measure ~2 keV electrons emitted by CNTs

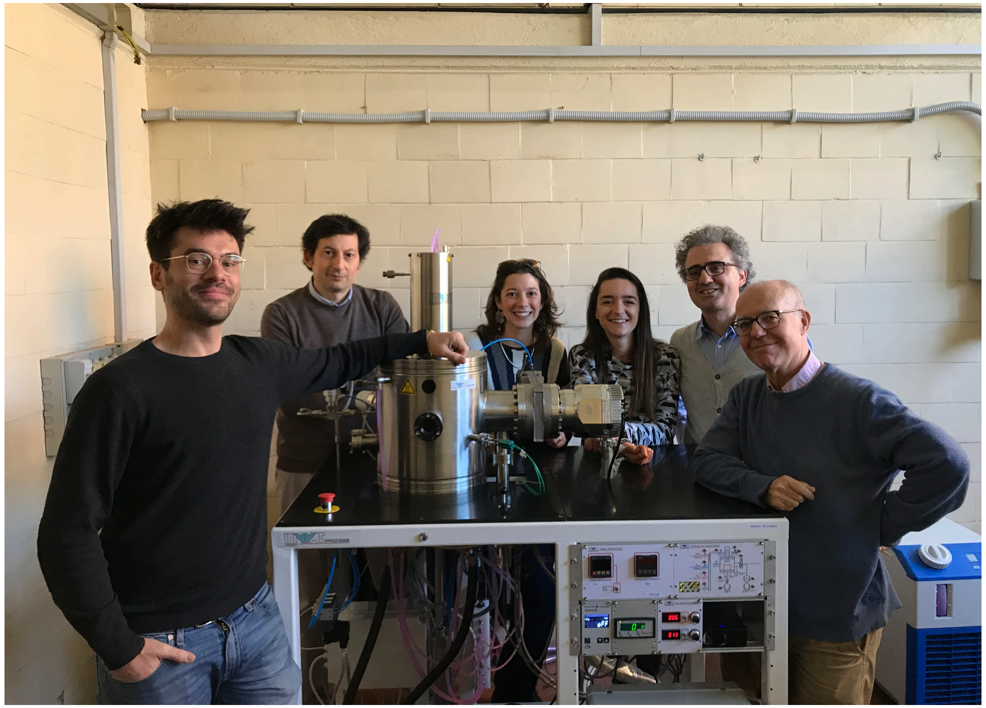
Controlling this effect critical to avoid background in DM searches

Switch to the other side: VA-CNT



Chemical Vapour Deposition chamber for CNT

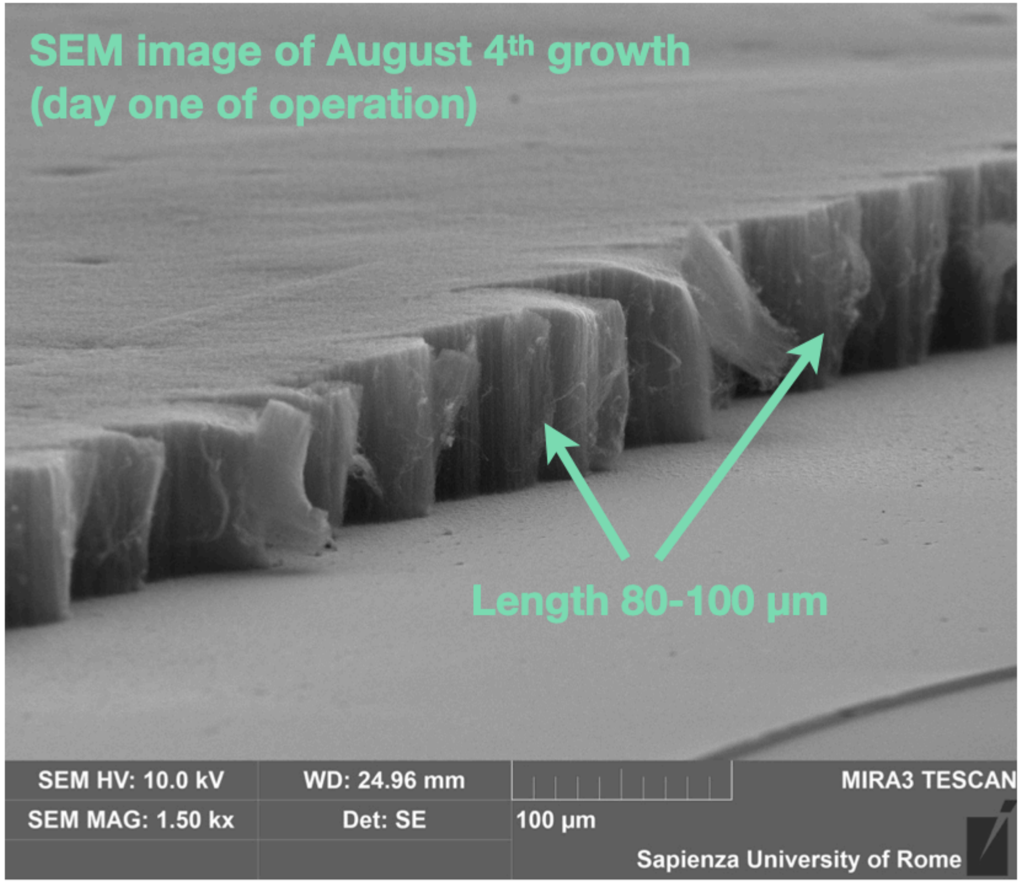
ATTRACT



- 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
- Being upgraded with metal evaporator

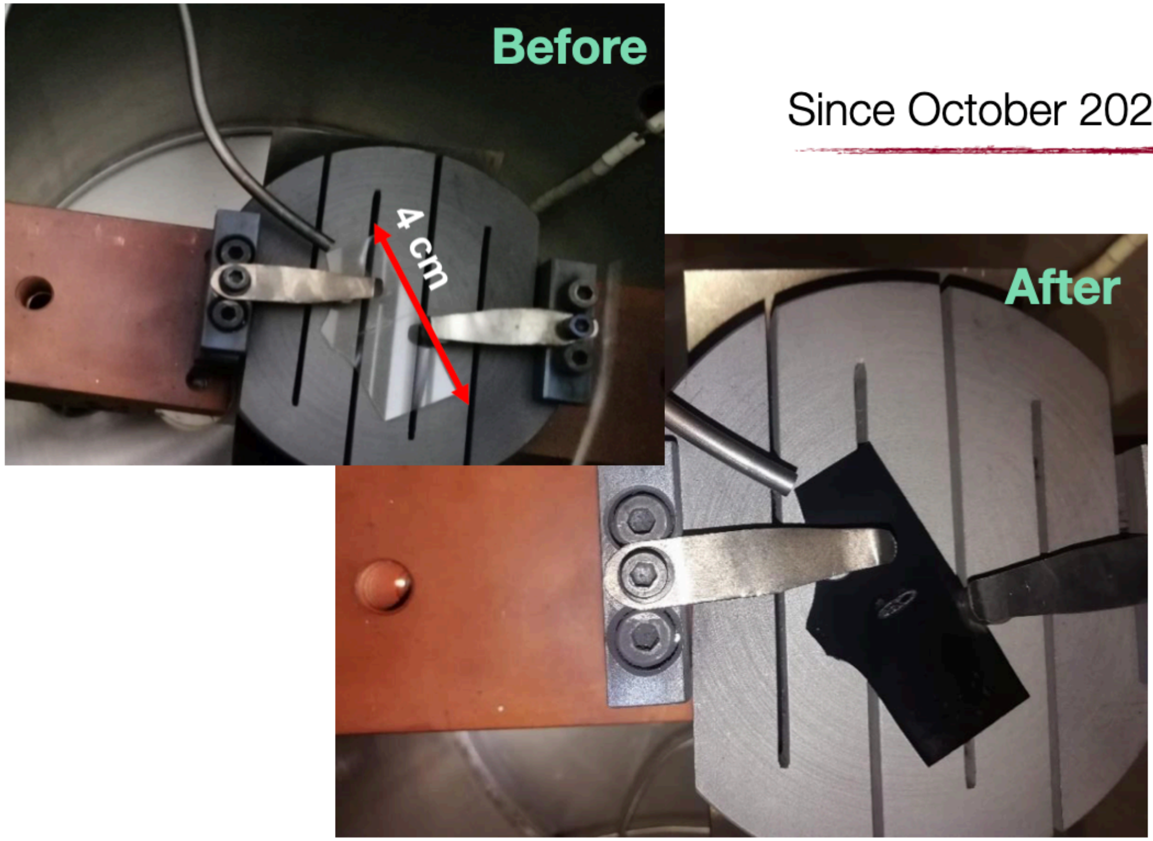
First successful growth of CNT



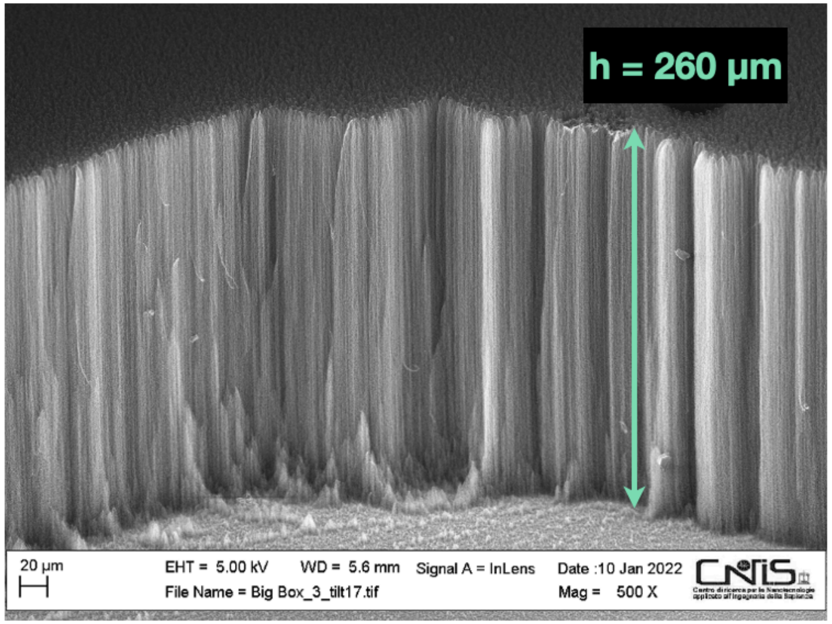
- Successfully synthetized multi-wall nanotubes
- Growing nanotubes on a **number** of subtrates:
  - ☑ Silicon
  - ☑ Fused silica
  - ☑ Basalt fibers
  - ☑ Quartz fibers
  - ☑ Carbon fibers
  - ☐ Metallic supports (Copper)

Very fast process, growing 10 mg over ~1x1 cm^2 support in ~10 m
100 cm^2 detector for 1 gram

Optimizing CNT growth process

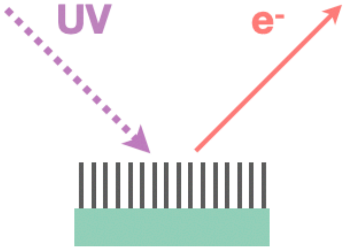


Since October 2020 achieving **uniform** growths over 4x2 cm^2

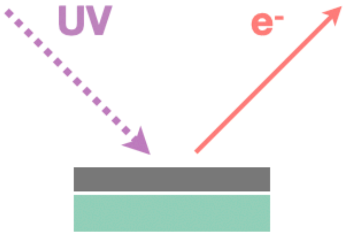


CNT characterisation with photons and electrons

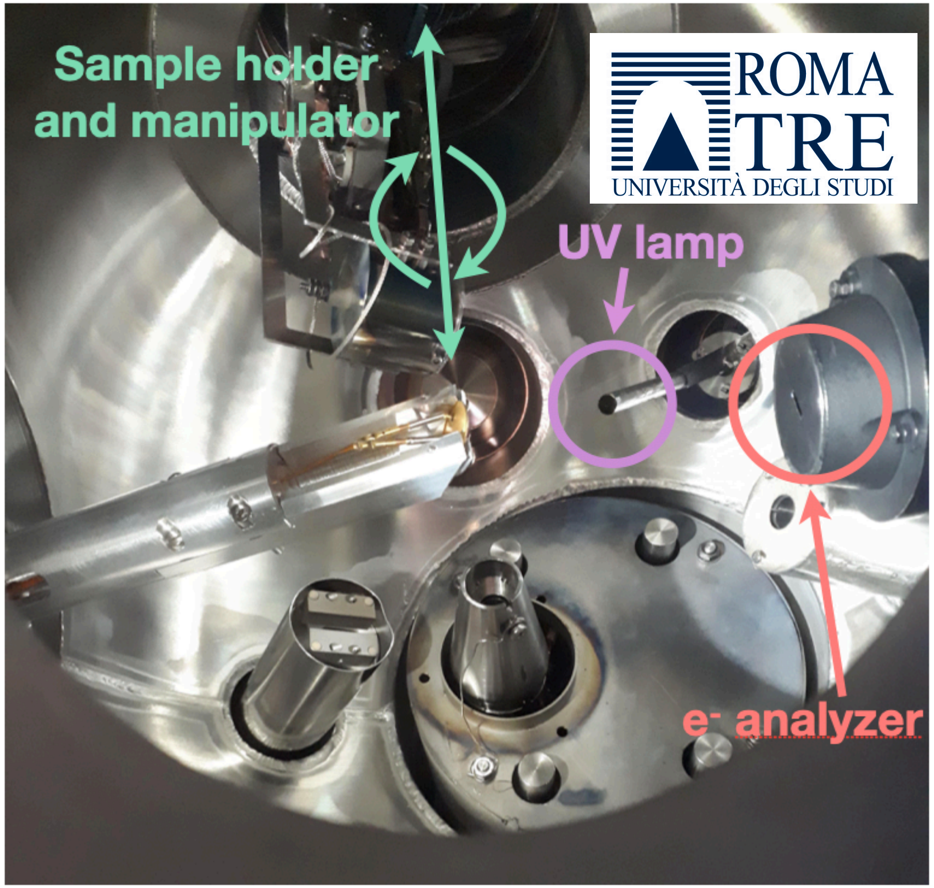
- Large UHV chamber at Roma Tre LASEC labs
  - Equipped with UPS, XPS, e^- energy loss analysis
- Performed UPS characterization of **nanotubes**
  - And compared them to **amorphous carbon**



Nanotubes

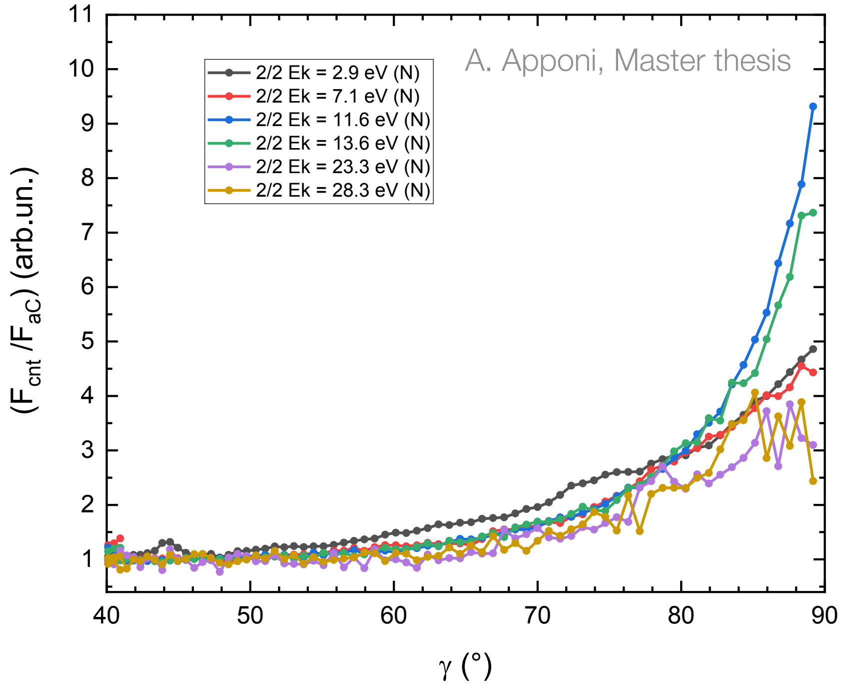


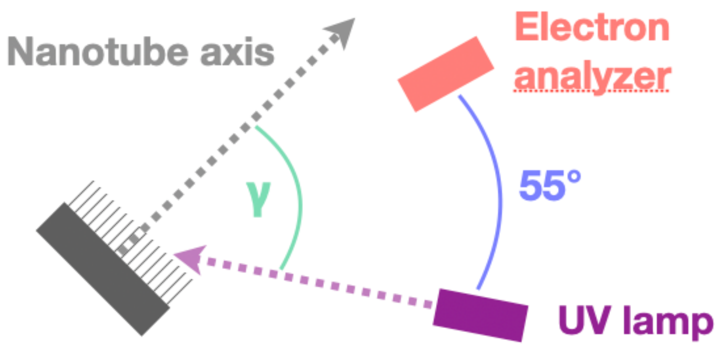
Amorphous carbon



Anisotropic electron emission (?)

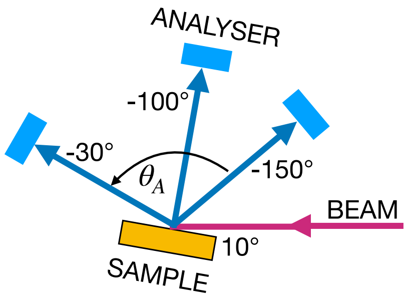
- Using He (I+II) UV lamp
    - hν = 21.2 eV and 40.8 eV
- Studied electron flux ratio F_{cnt}/F_{aC}
    - vs angle γ between nanotube axis and UV light
    - Normalized so that $F_{cnt}/F_{aC} = 1$ @ γ = 40°
    - CNT variation **up to 10x larger** than aC @ γ = 90° (grazing angle)
    - Further proof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

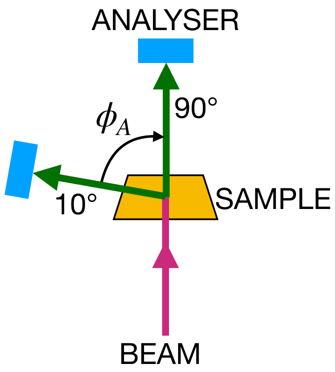


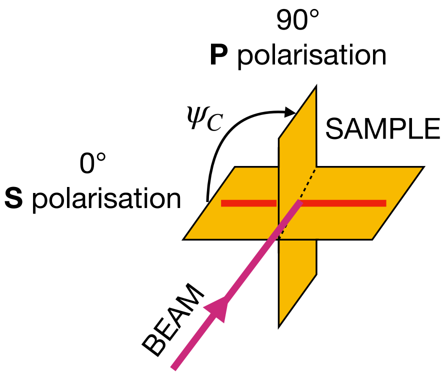


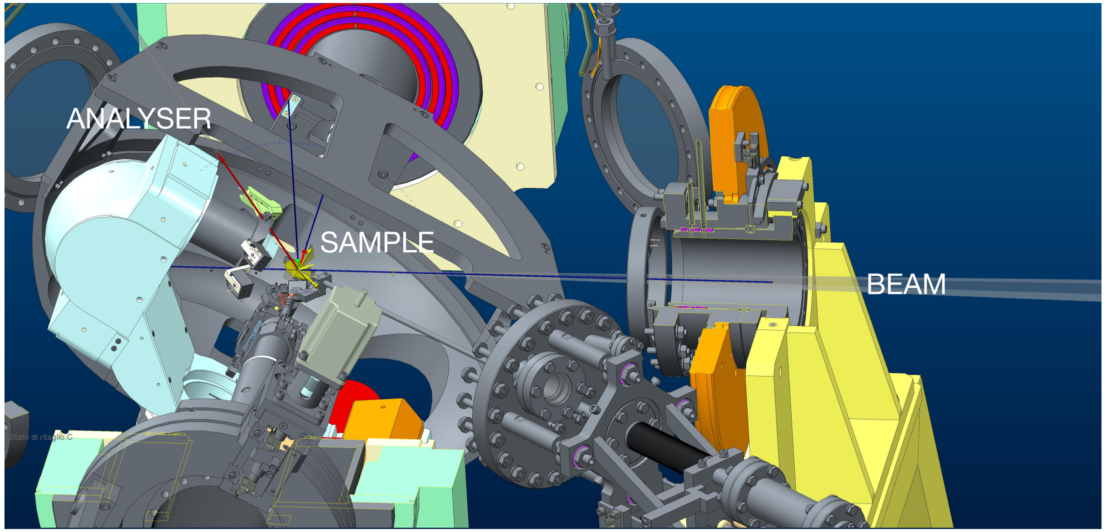
VA-CNT at synchrotron

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



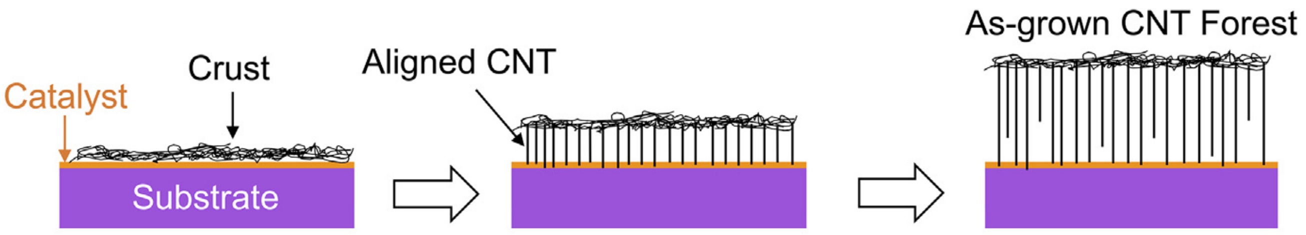


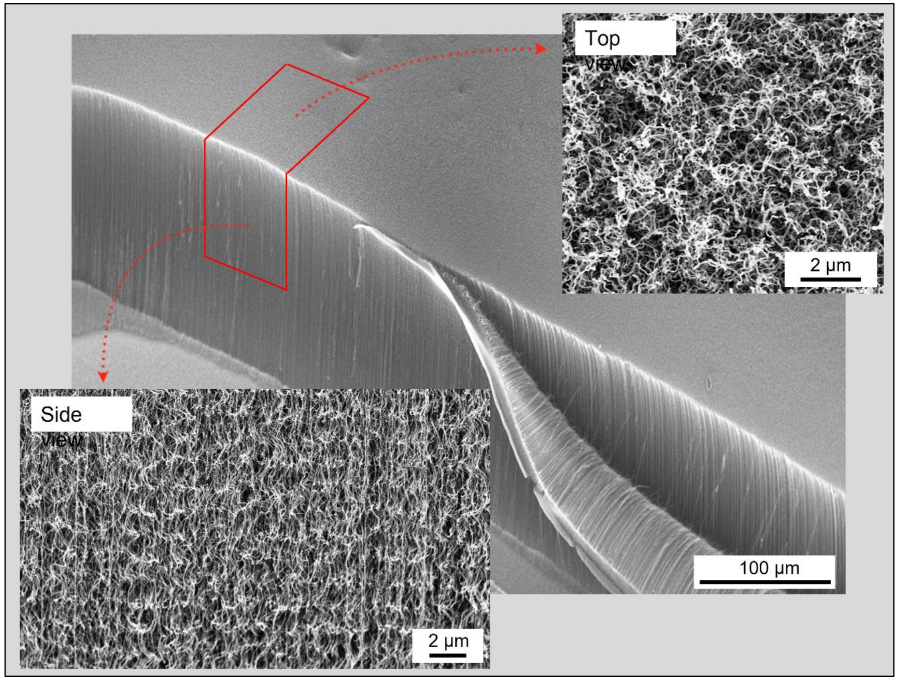




- **Rich** characterization program **underway**
  - Valence band analysis
  - Angular scans
  - Drain current analysis

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

Beyond DM

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

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

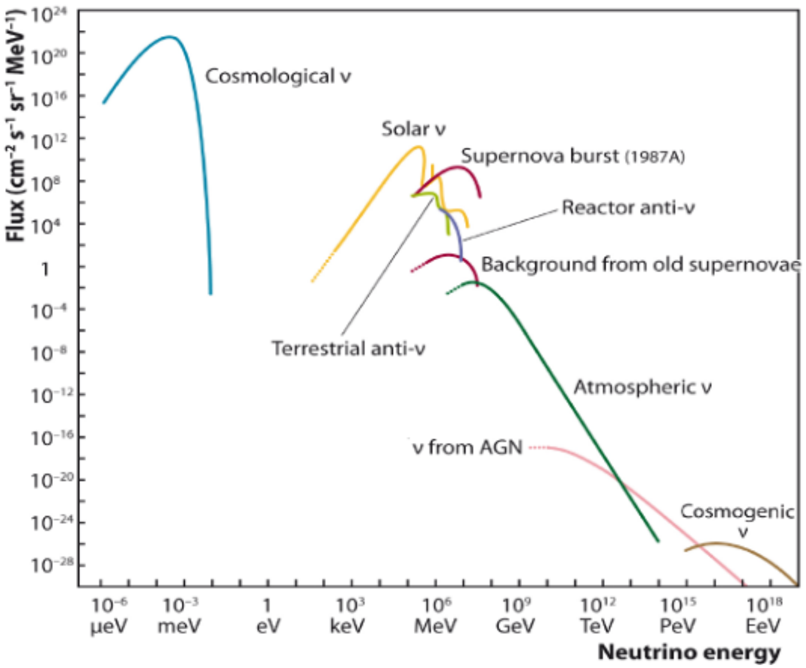
- CNT in novel **composite** materials
  - Add CNT to fibres (basalt)
  - Additive manufacturing, **patented** a new CNT based Cu powder

- Use of CNT to host tritium atoms for the **Ptolemy** target
  See https://arxiv.org/abs/2203.11228

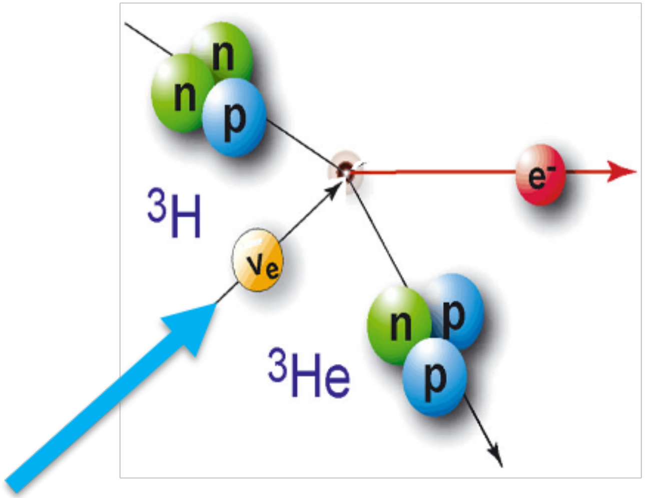
The cosmological neutrino background

- Messanger from 1s after the Big Bang

- Cold Matter (T ~ 1.9K)
- About 100/cm3 here and now



Neutrino capture on Tritium



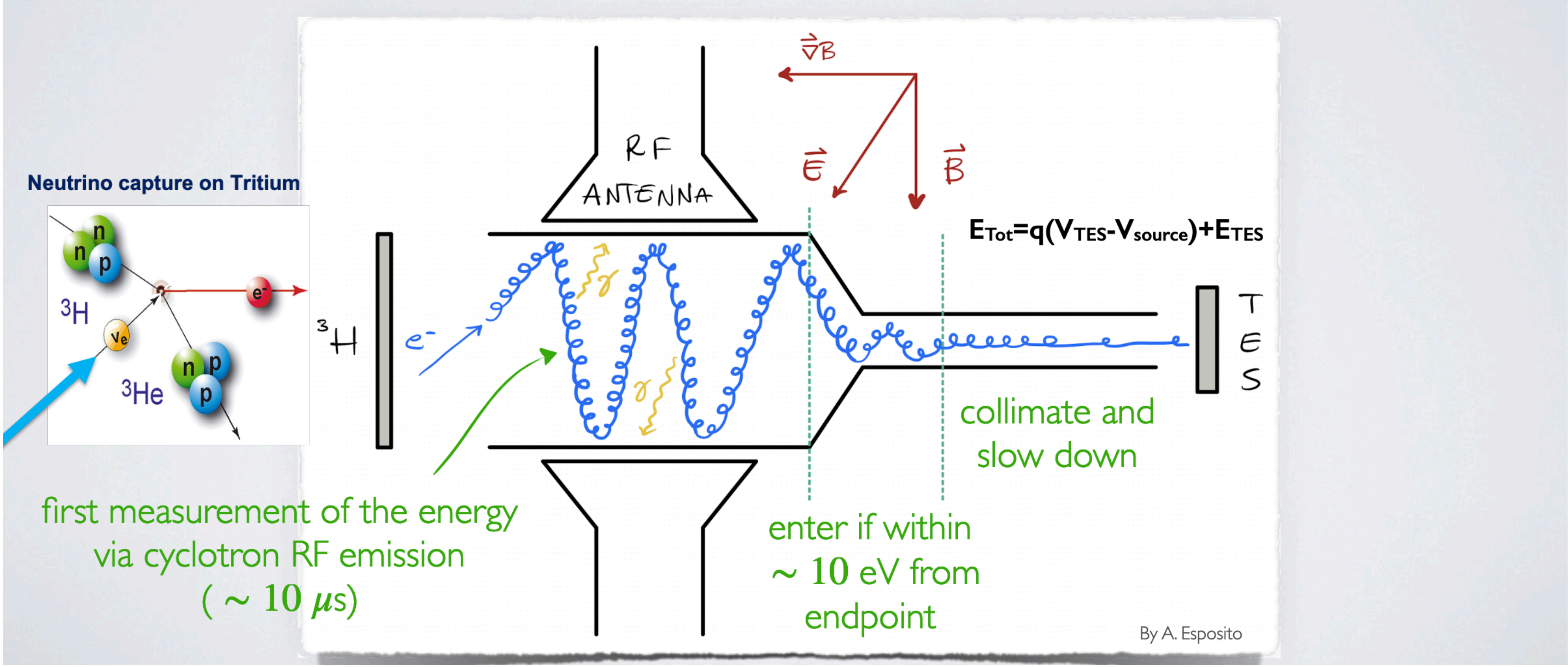
The Ptolemy project

M.G. Betti *et al* JCAP07(2019)047

The Ptolemy idea

M.G.Betti et al,
Progress in Particle and Nuclear Physics,
106, (2019) 120-131

- A new electromagnetic filter based on RF radiation detection (electron cyclotron motion) and dynamic E field setting



$E_{Tot}=q(V_{TES}-V_{source})+E_{TES}$

first measurement of the energy via cyclotron RF emission (~ 10 μs)

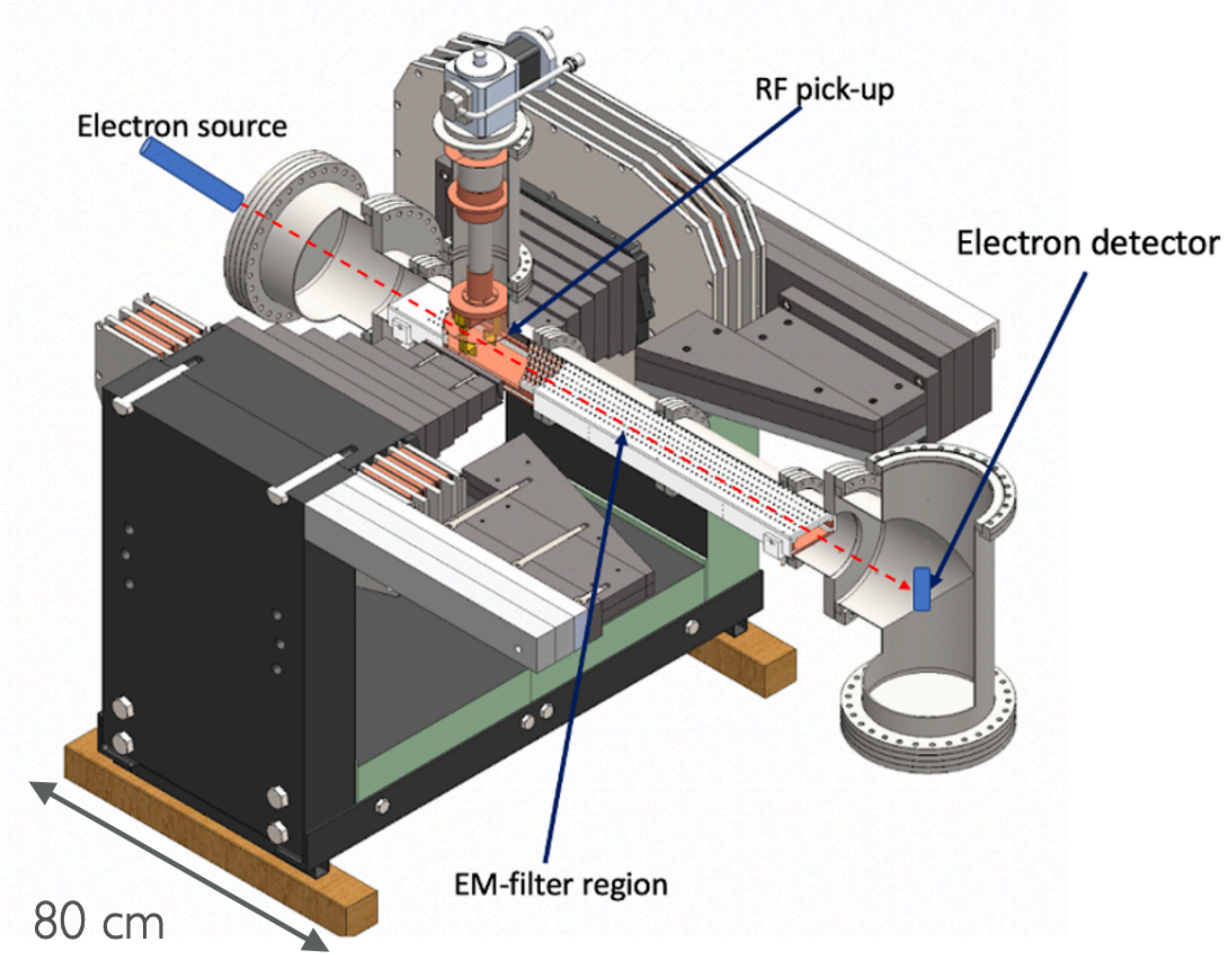
enter if within ~ 10 eV from endpoint

collimate and slow down

The demonstrator

A. Apponi et al 2022 JINST 17 P05021

- **Tritium on graphene**
- 27 GHz radiation detection
- Electromagnetic filter with 1ppm voltage precision
- Microcalorimeter TES



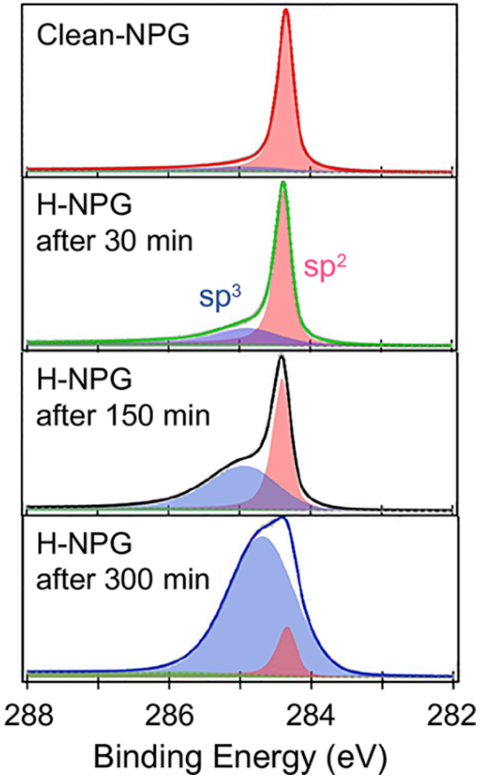
Aiming at 50 meV electron energy resolution

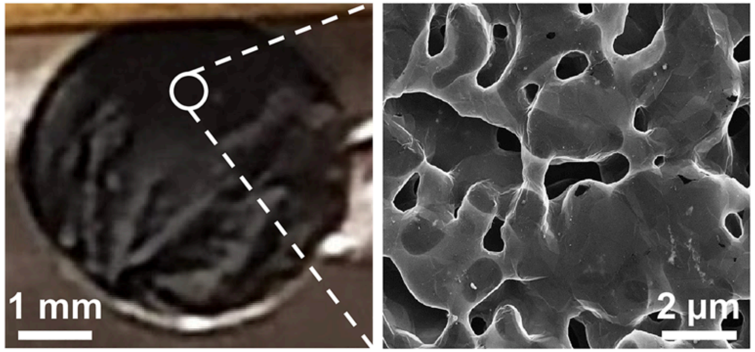
Flat graphene

- **Nanoporous graphene** used as support for tritium

- Bond atomic tritium to carbon atoms
  - Well defined potential
  - Store many atoms in small space

M.G.Betti et al, Nano Lett. 2022, 22, 7, 2971–2977



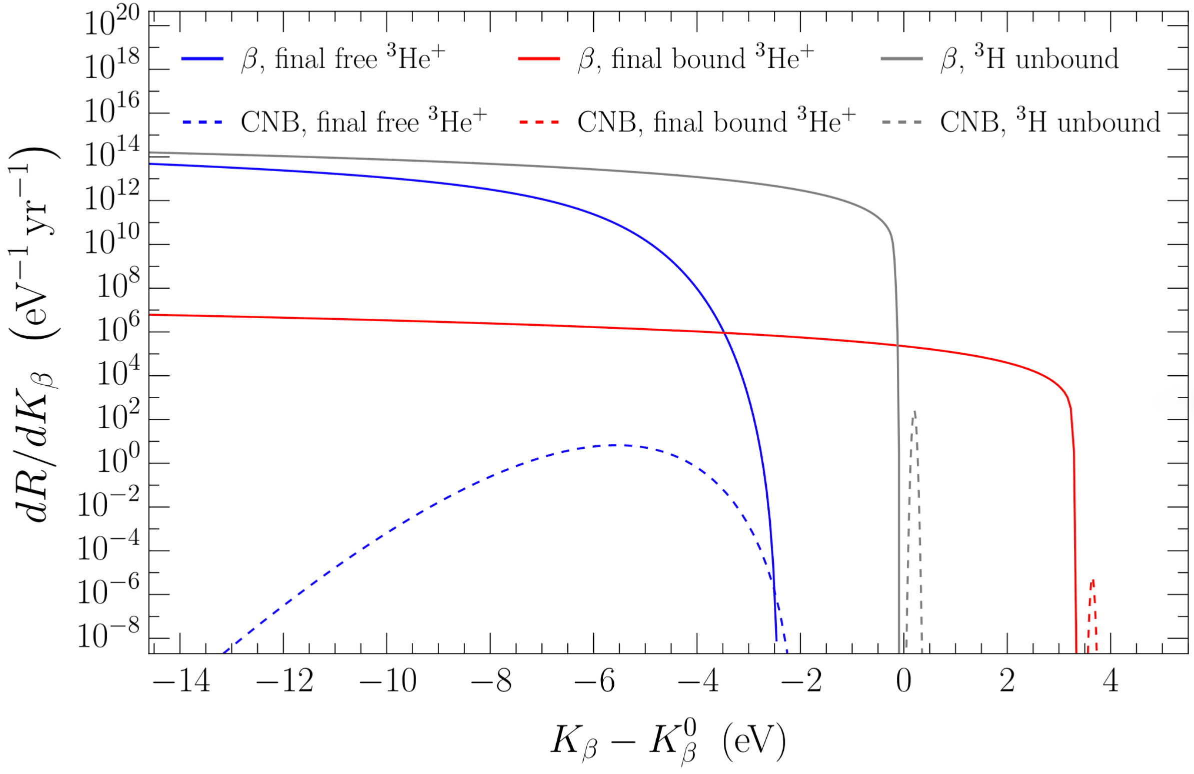


Reached >90% coverage with hydrogen

…hitting the Heisenberg limit??

- Spatially localised tritium (by covalent bond) implies an uncertainty on the tritium momentum

- Effect on the electron energy resolution: ~500 meV (!?!)

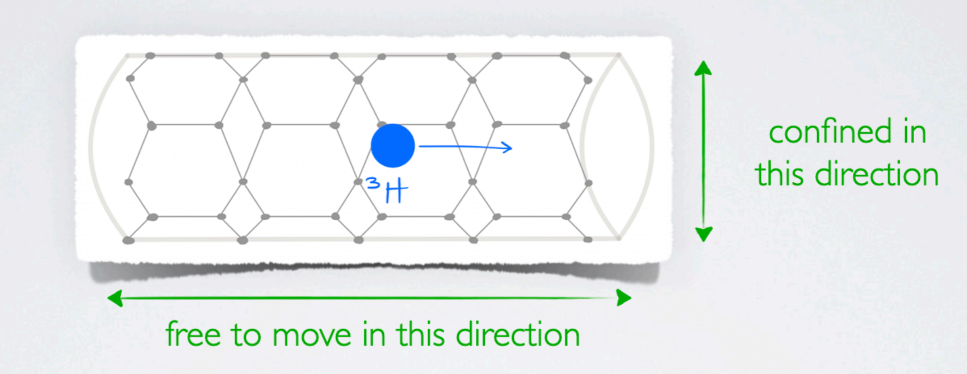


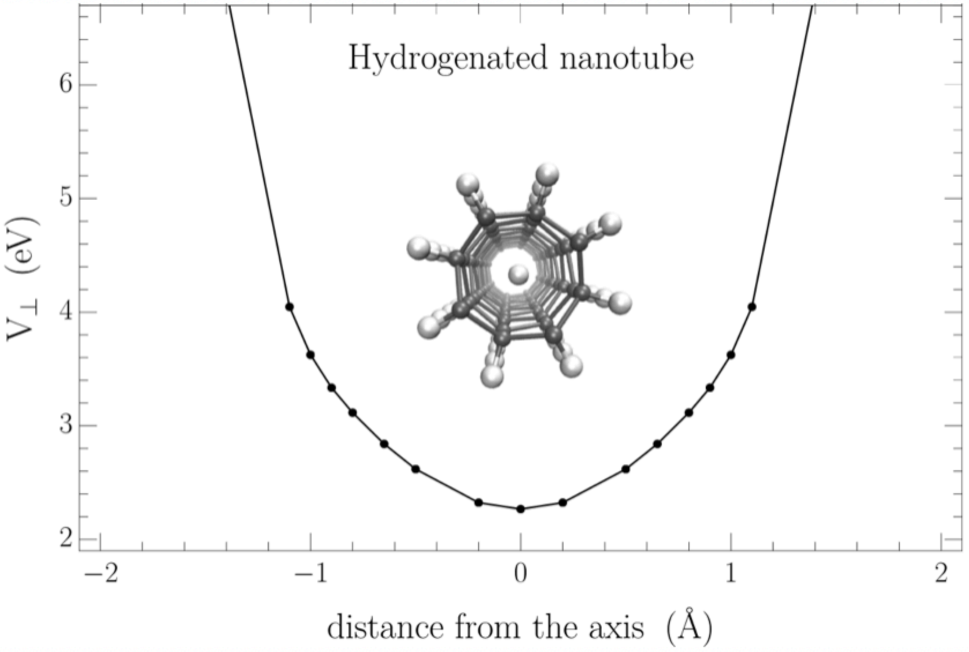
Critical for endpoint Analysis (neutrino mass)

Carbon nanotubes a solution?

A.Apponi et al., https://arxiv.org/abs/2203.11228

- Electric **Potential** binding tritium depends on the concavity of the surface !



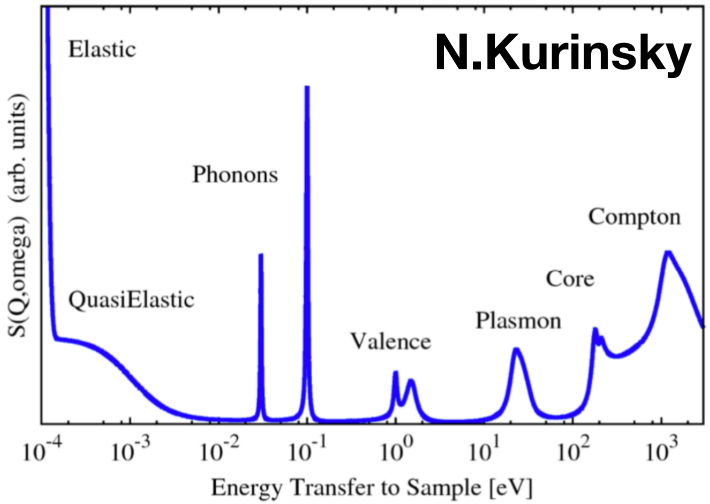


- “**Passivated**” CNT can host a tritium atom
- Prevent dimerization with **magnetic** field

Some final thoughts

Talk to the others

- Exchange between particle physics and condensed matter physics is a great opportunity in the realm of **new sensors** development.
- Especially true in the range of “low energy” particle physics
- Details of **physics at atomic/ subatomic scale necessary** to understand a particle detector



Interaction with **theorists** is of paramount importance
Sometime you get crazy (i.e. difficult to implement) ideas

But out of 10 (?) crazy ideas you get a **bright bold one**

The example of carbon nanostructure

- Expertise in **synthesis** is crucial
  - Need of a fast turnaround of **synthesis-characterisation-prototyping**
  - True in general for new fancy detectors!

- ***Carbon nanostructure*** *are attractive since can be grown to mascoscopic scale (* ***cm***$^{\boldsymbol{2}}$ *sized tiles or flakes)*
  - Reaching a similar quality as *crystals* might be important

- Application beyond particle physics are ubiquitous

Some sociology

- Particle physics experiments (also in the low energy domain) have a **long preparation** period
  - before taking data and publish a (single?) high impact result.

- R&D in collaboration with condensed matter physicists and theorists might fill the **gap** with high impact publications (although in a different “physics sector”)

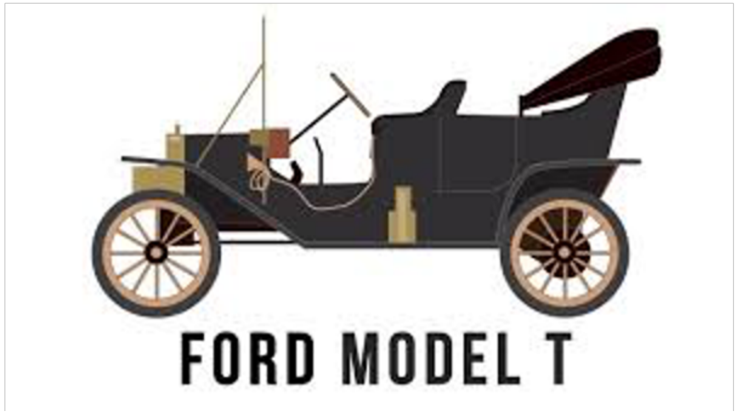
- Can open vast opportunities of **multi-disciplinary** projects.
  - Beyond physics (biology, health, mechanics,…)

- Can lead to important **technology transfer** to other researches: (e.g. particle accelerator, GW interferometer) or industry

Do not be afraid (to leave your comfort zone)

Looking for a game-changer for future experiments

When asked if he believed in asking customers what they want – Ford replied: **"If I had asked them what they had wanted, they would have said a faster horse."**



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AMALDI RESEARCH CENTER

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