Direct Dark Matter Detection - Part IV

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From previous lecture…

From precision cosmology 23% of the Universe is made of Cold Non-Baryonic Dark Matter that could be be directly detected from an Earth-based experiment

We reviewed the two « main stream experimental strategies »

- *High WIMP mass:* ***Noble gas***
- *Low WIMP mass:* ***Cryogenic solid state detectors***

But isn't there other exciting ideas out there?

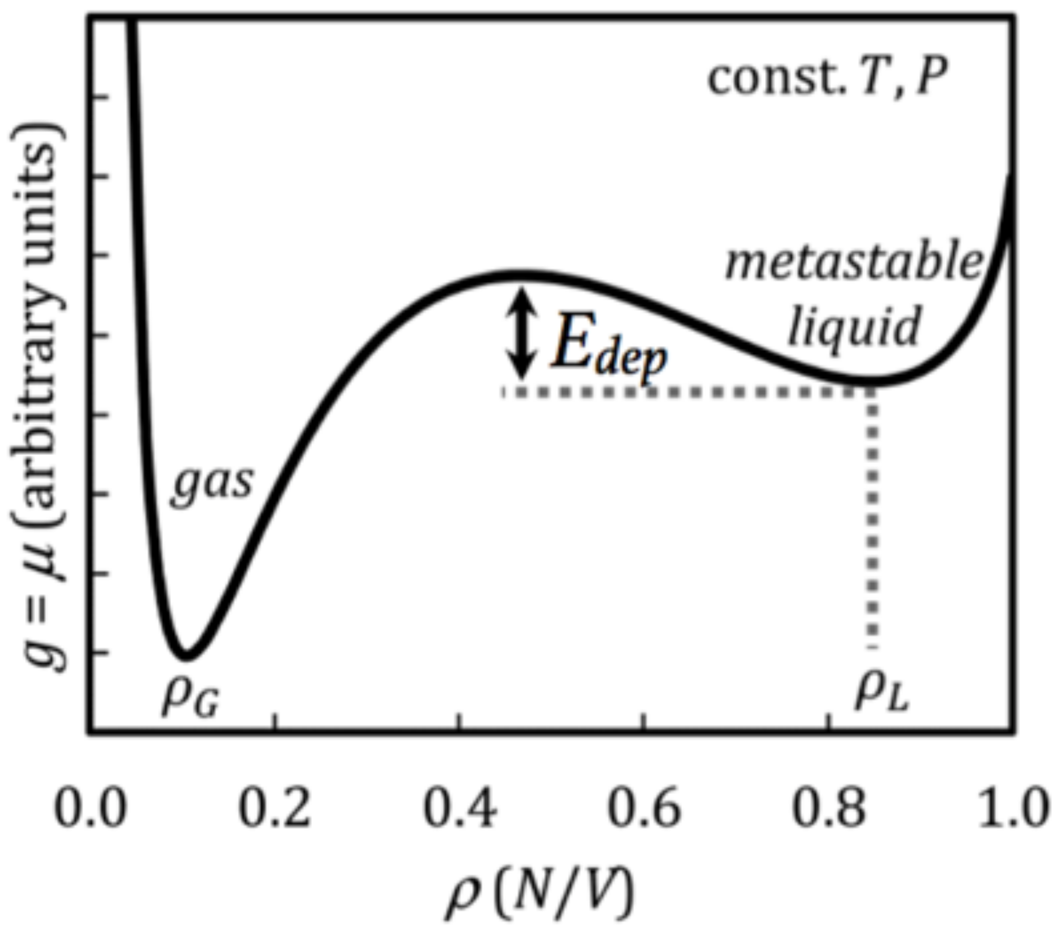
What should be the ultimate WIMP detector?

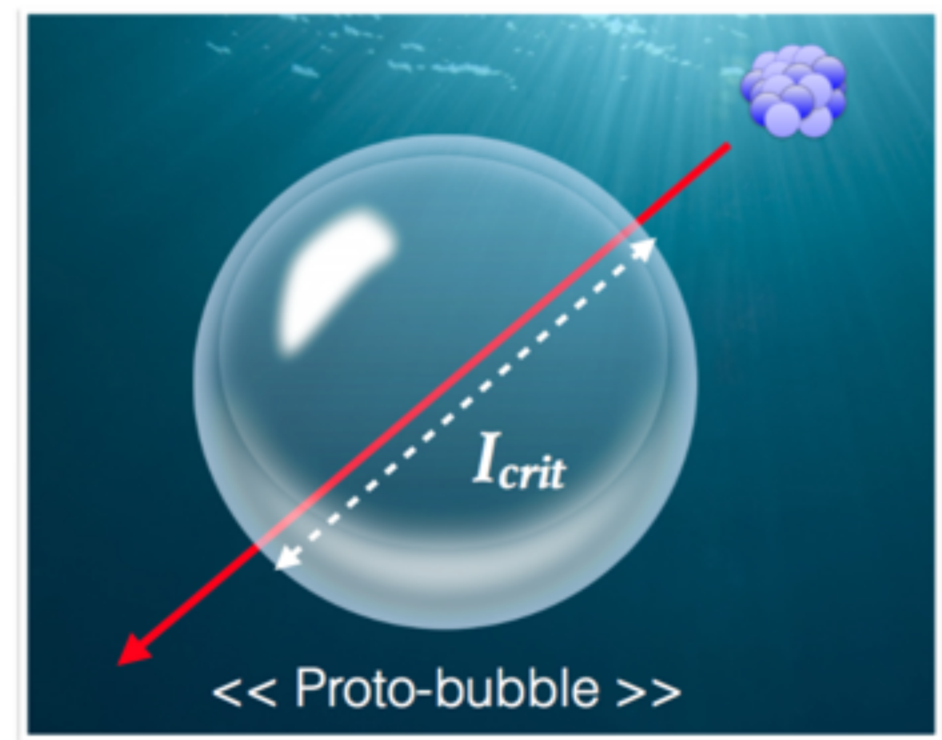
And what if Dark Matter is lighter than the GeV scale?

PICO experiment

C. Amole et al., Phys. Rev. D 93, 061101 (2016)

Nuclear recoil - only mechanism: superheated droplets





$$E_{dep} = \frac{dE}{dx} I_{crit} \geq E_{min}$$

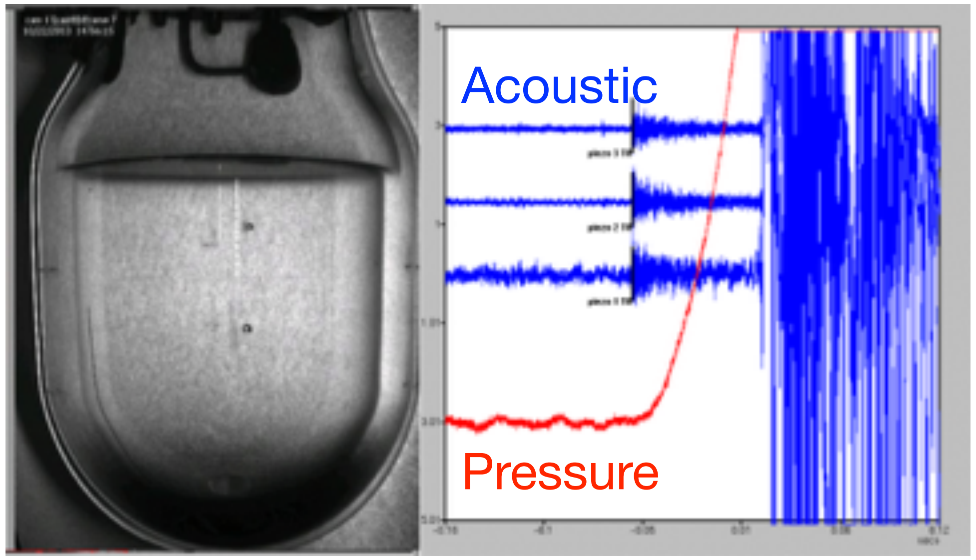
- By slowly changing the pressure or the temperature of a liquid, one can set it to a metastable state such as: ***superheated liquid***
- For a high enough energy density (dE/dx), such as a WIMP induced nuclear recoil, the system goes from superheated liquid to gas under the form of a bubble
- ***It is a threshold experiment, no energy measurement !***

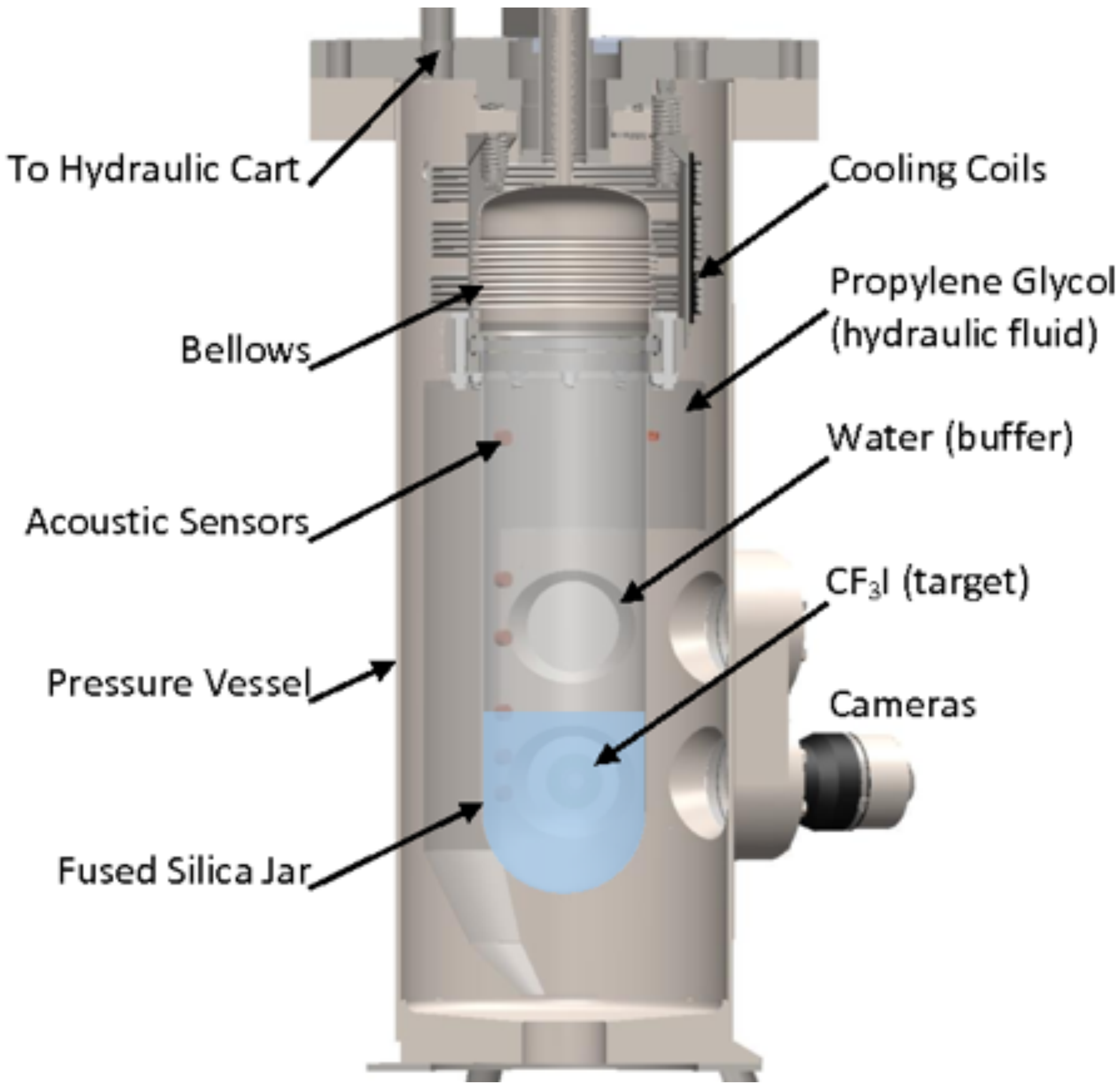
PICO experiment

C. Amole et al., Phys. Rev. D 93, 061101 (2016)

Nuclear recoil - only mechanism: superheated droplets

- The PICO experiment is installed in SNOLAB underground laboratory with lead and poly shields
- An active volume of a 2.9 L of CF3I target or C3F8
- It is sensitive to spin independent interaction (I) and spin dependent interaction (F)
- Acoustics sensors and fast pressure transducers to measure the bubble nucleation behavior
- A 100 fps video camera to observe the bubbles: **fiducialization** !

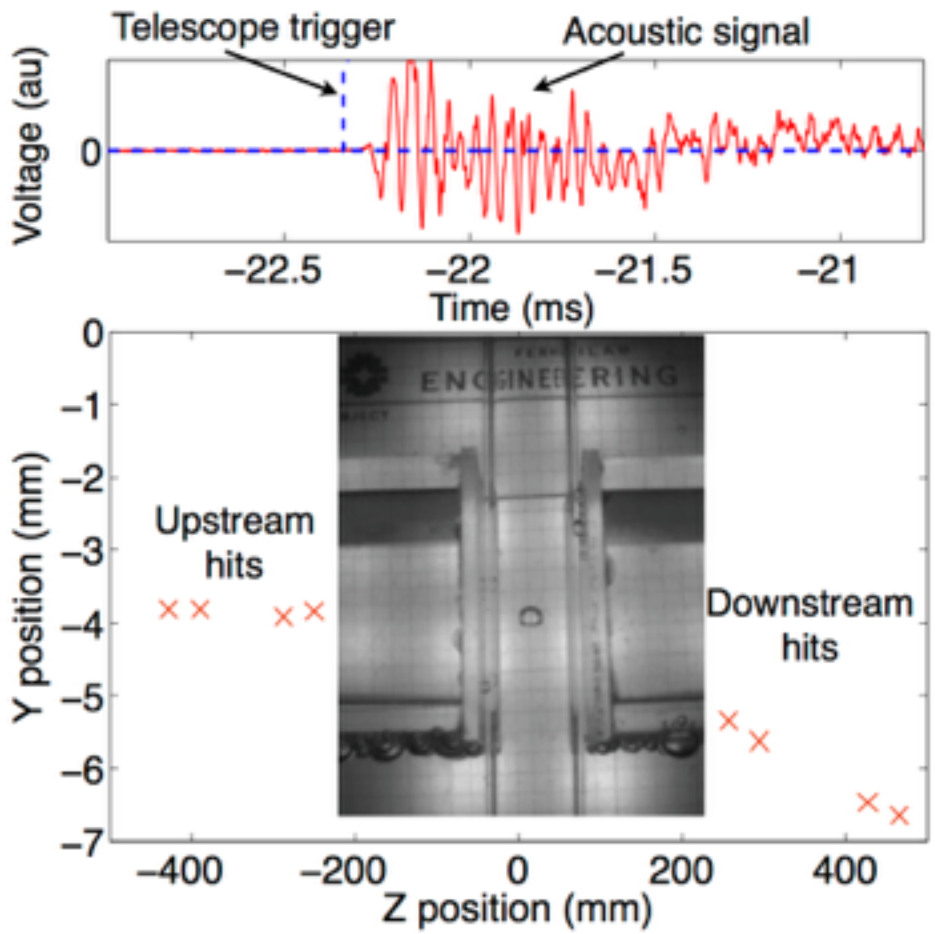


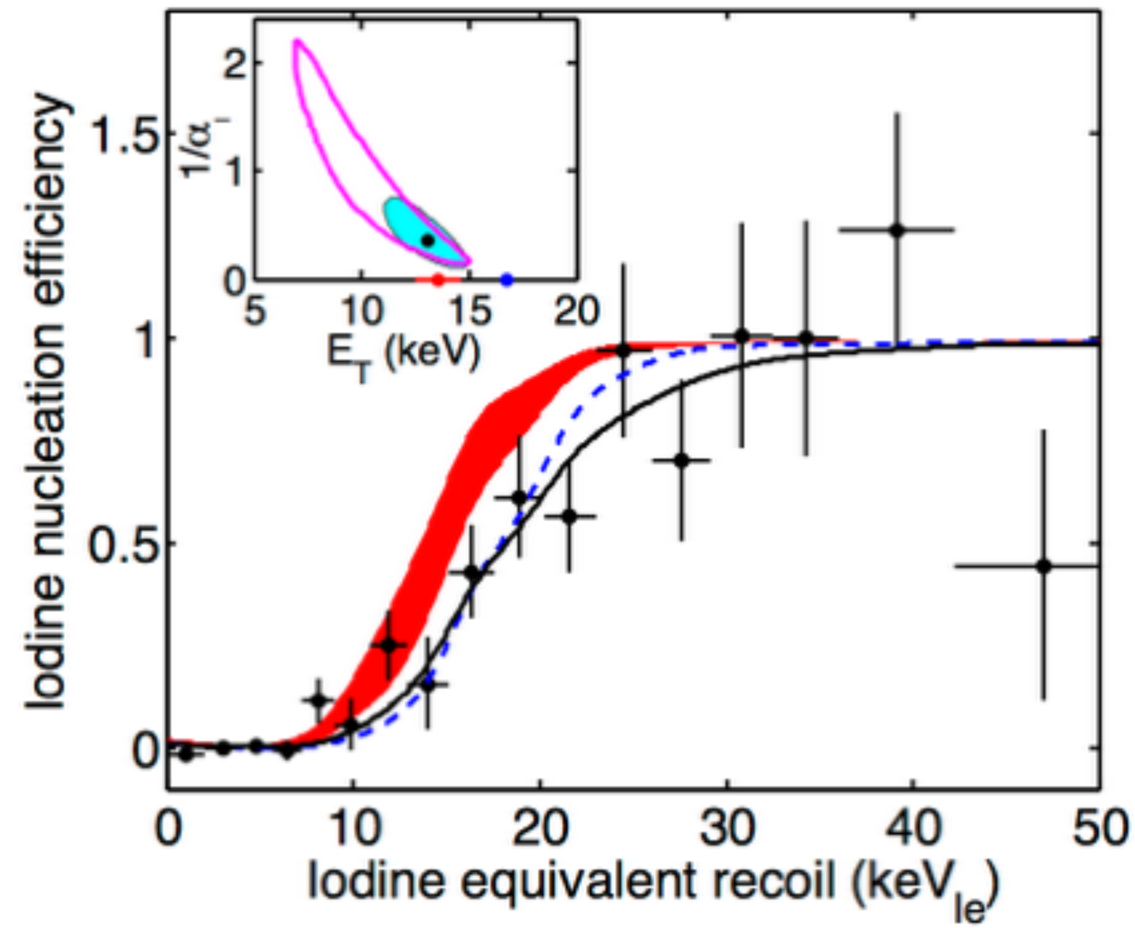


PICO experiment

C. Amole et al., Phys. Rev. D 93, 061101 (2016)

Calibration of the threshold energy?



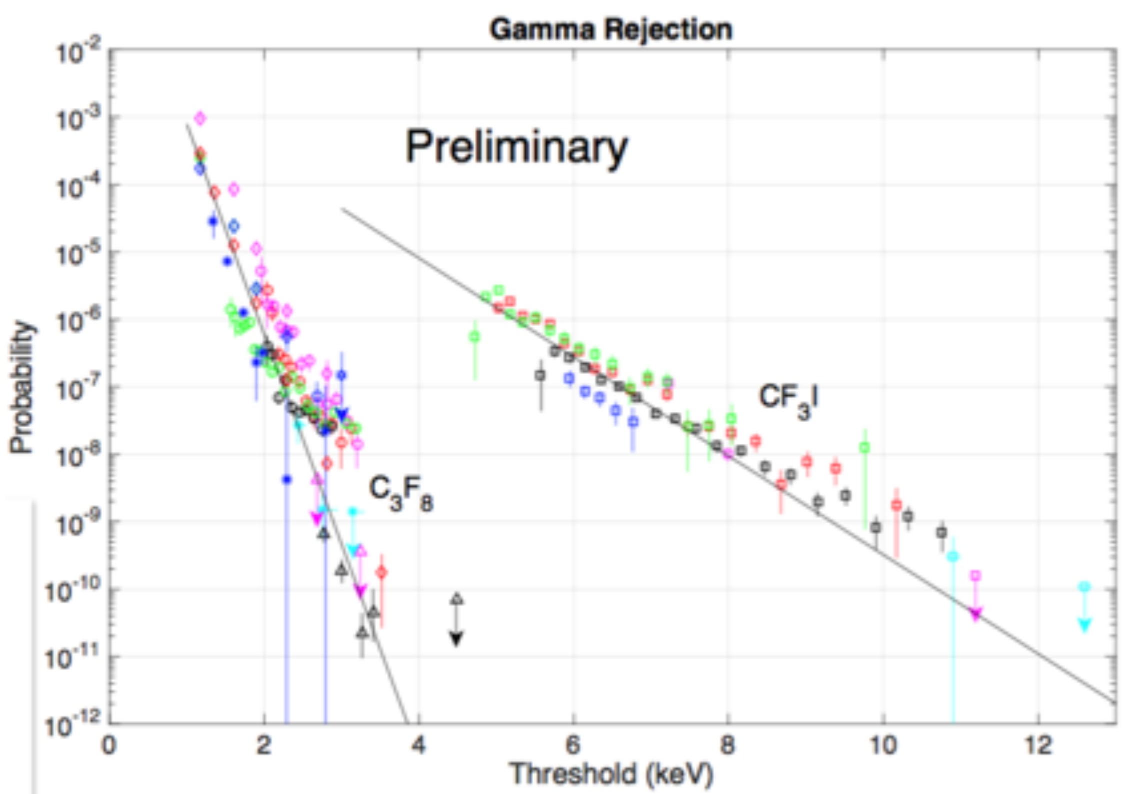


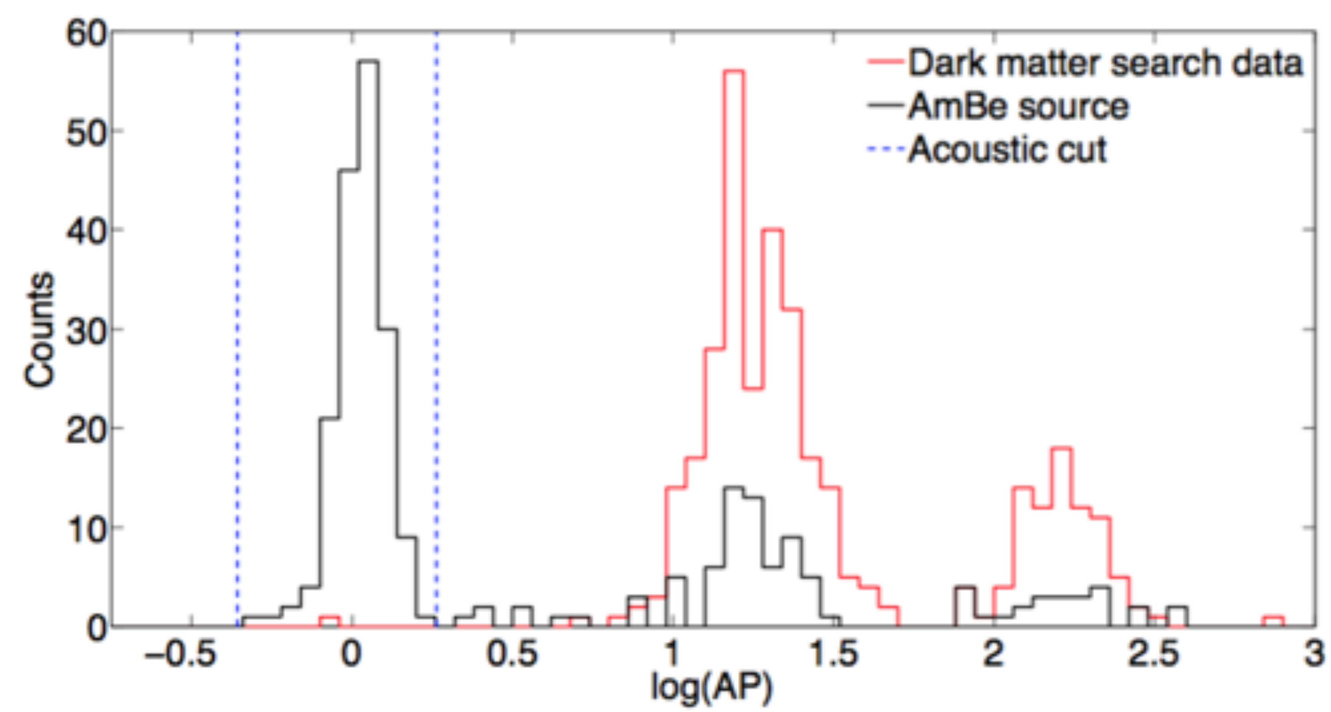
- Dedicated experiment using a 12 GeV/c negative pion beam to calibrate the energy threshold of Iodine nuclear recoil thanks to kinematics where the pion track is measured using 4 upstream and 4 downstream Si pixel telescope.
- They found a threshold of 13.2 keV in agreement with the Seitz model traditionally used
    - **Scanning over P and T allows to vary the threshold of the experiment**

PICO experiment

C. Amole et al., Phys. Rev. D 93, 061101 (2016)

Backgrounds?



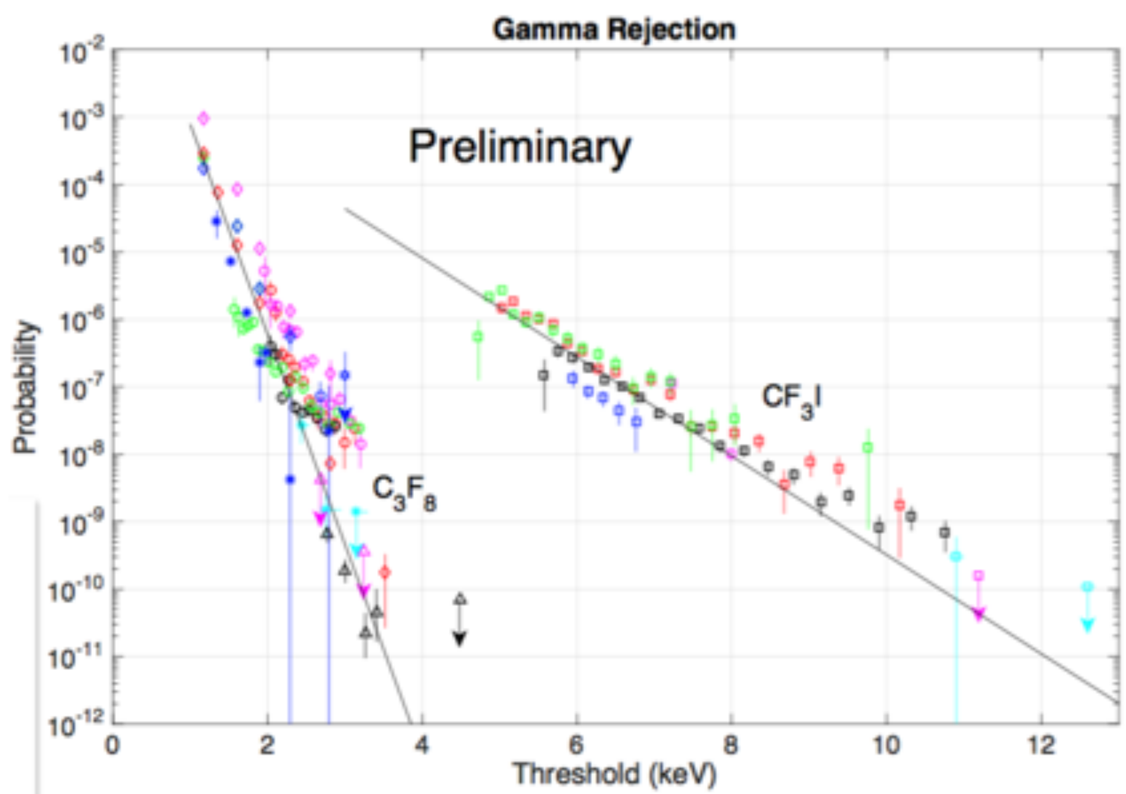


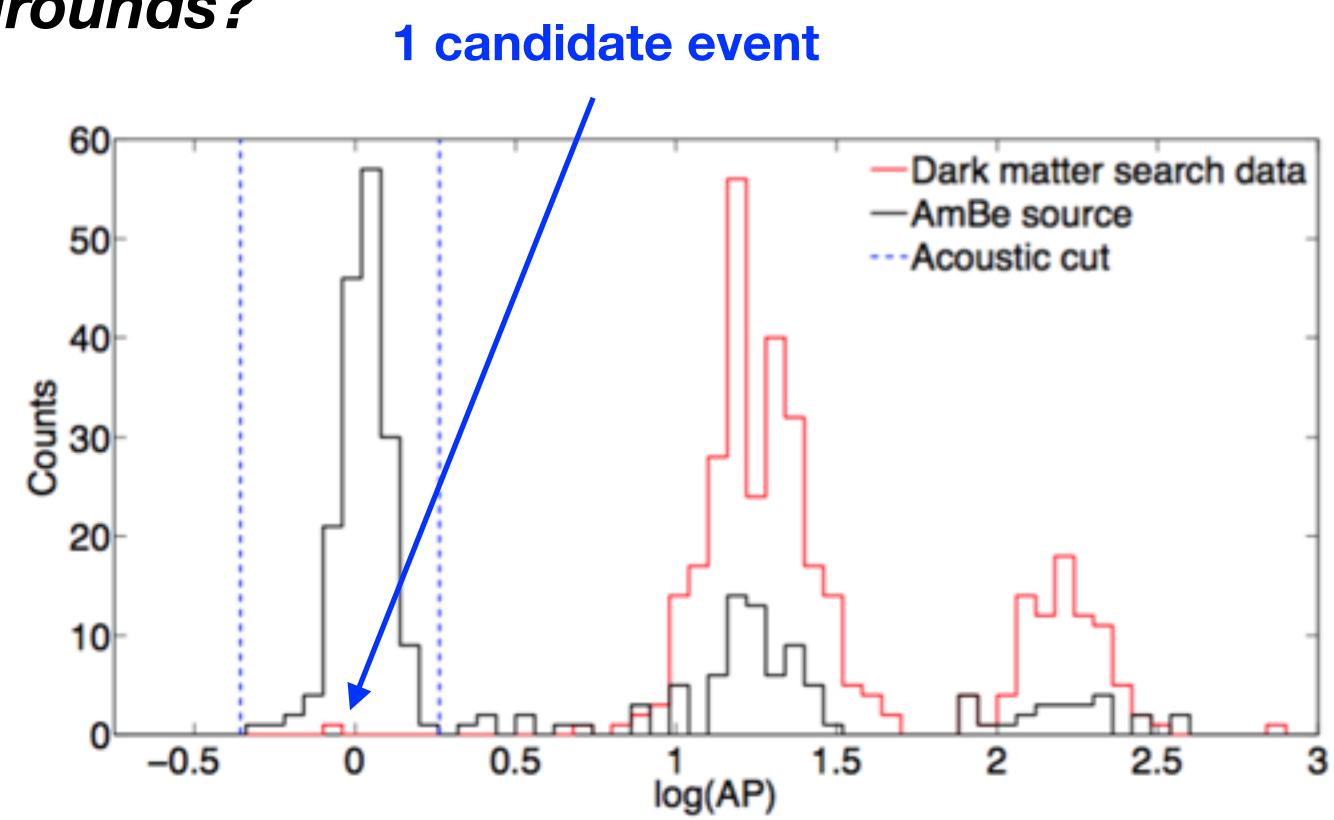
- This experiment is highly insensitive to gamma and beta as they have low dE/dx (minimum ionizing). C3F8 is even better, with a rejection factor of 10^6 at a threshold of 2 keV
- The most problematic backgrounds are alpha from alpha decays as they have similar dE/dx as nuclear recoils. However, their range is much longer so the bubbles sound differently
- Rejection of alpha is about 99.4% and 67% acceptance
- Neutrons can be rejected from multiplicity thanks to the 100 Hz cameras

PICO experiment

C. Amole et al., Phys. Rev. D 93, 061101 (2016)

Backgrounds?





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PICO experiment

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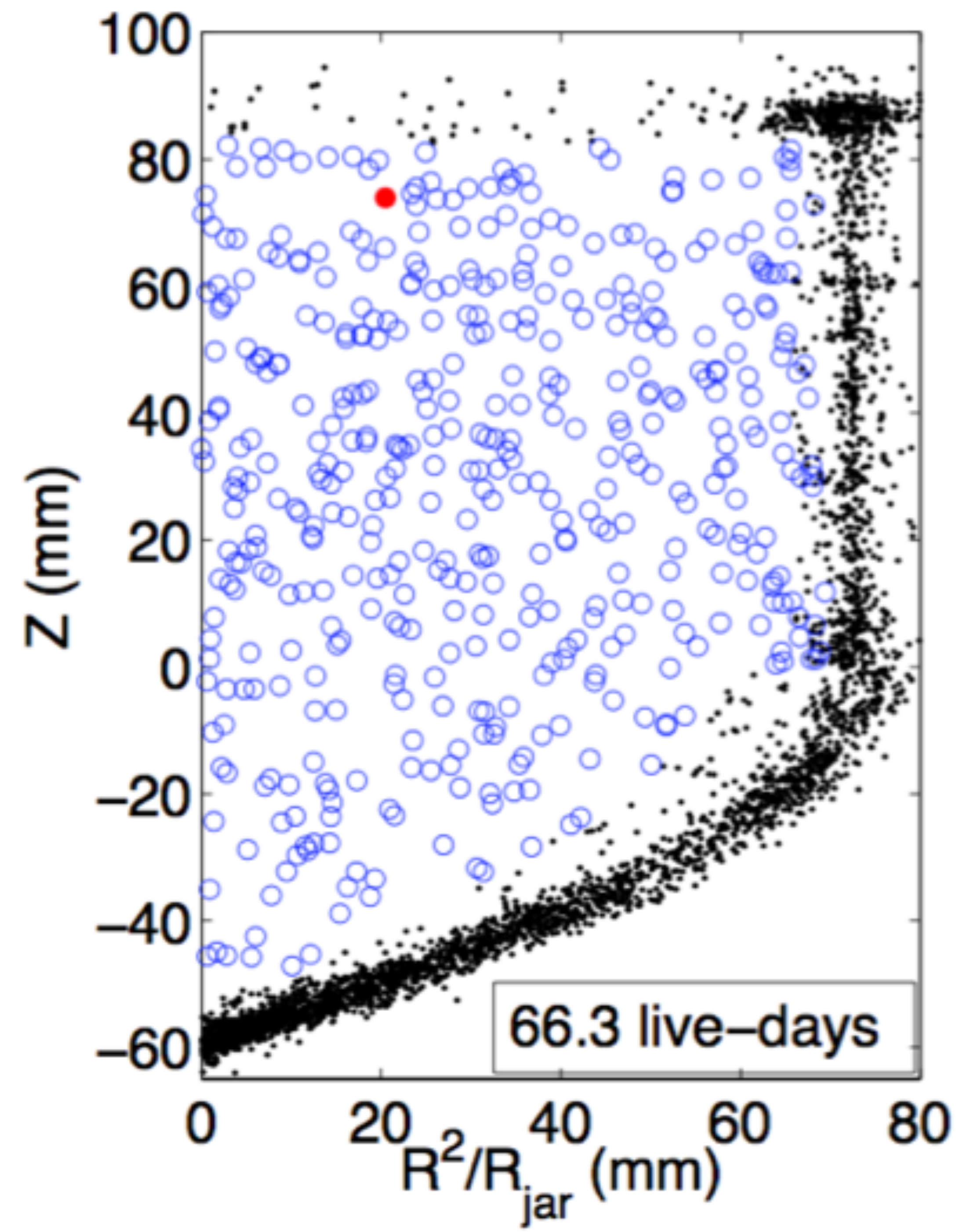
Results from PICO-2L

- RUN 1, corresponding to 74.8 kg-days of C3F8 with a 3 keV threshold has suffered from particulate contamination that nucleated bubbles and therefore unexpected backgrounds: 9 candidate events

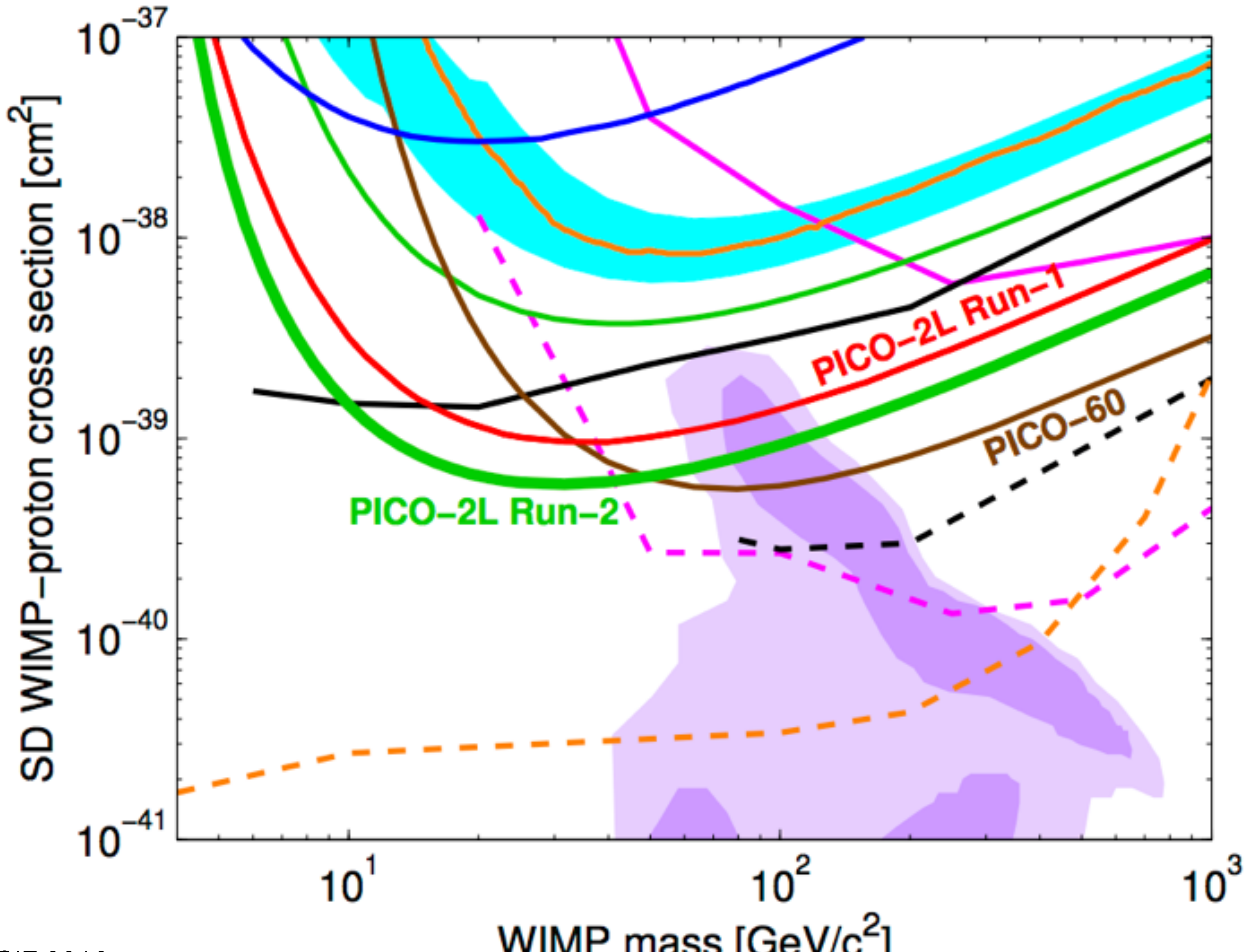
- For RUN 2, shown here, they cleaned the surfaces of the chamber and reduced the thermal gradient: 1 candidate event is 129.3 kg-days of C3F8 @ 3 keV



PICO experiment

C. Amole et al., Phys. Rev. D 93, 061101 (2016)

World leading limit in Spin-Dependent searches thanks to F !

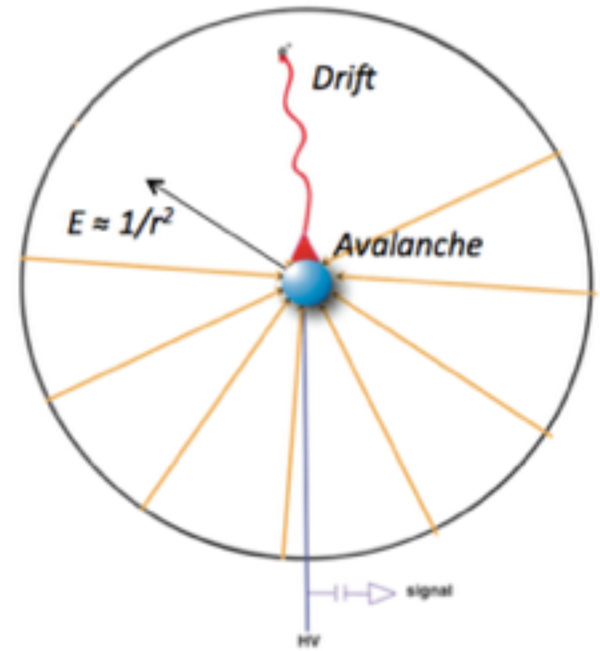


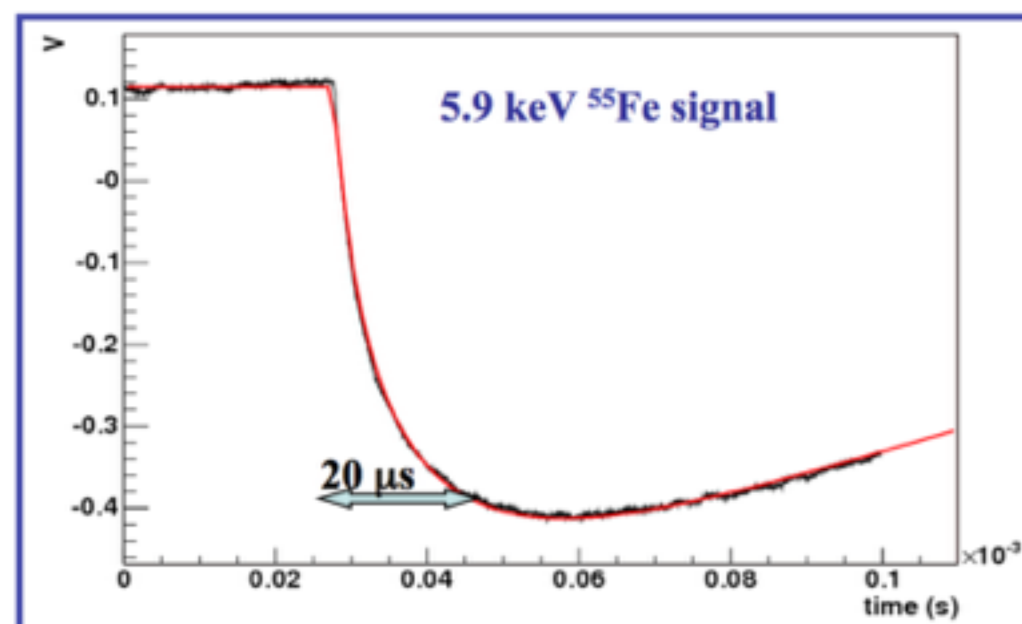
NEWS experiment

G. Gerbier at al., arXiv:1401.7902

Very-low threshold: spherical TPC

- New Experiment With a Sphere is installed in Modane (LSM) and is designed to reach very low threshold
- It is a gaseous Time Projection Chamber that can work with H, He, Ne, Xe from mbar pressures to 10 bars
- The primary ionization electrons drift toward the inner ball where the E-field is sufficiently intense to produce an avalanche
- The spherical electric field is from the outer shell to a few mm inner ball leading to a capacitance < 1 pF and therefore exquisite energy resolution and low threshold



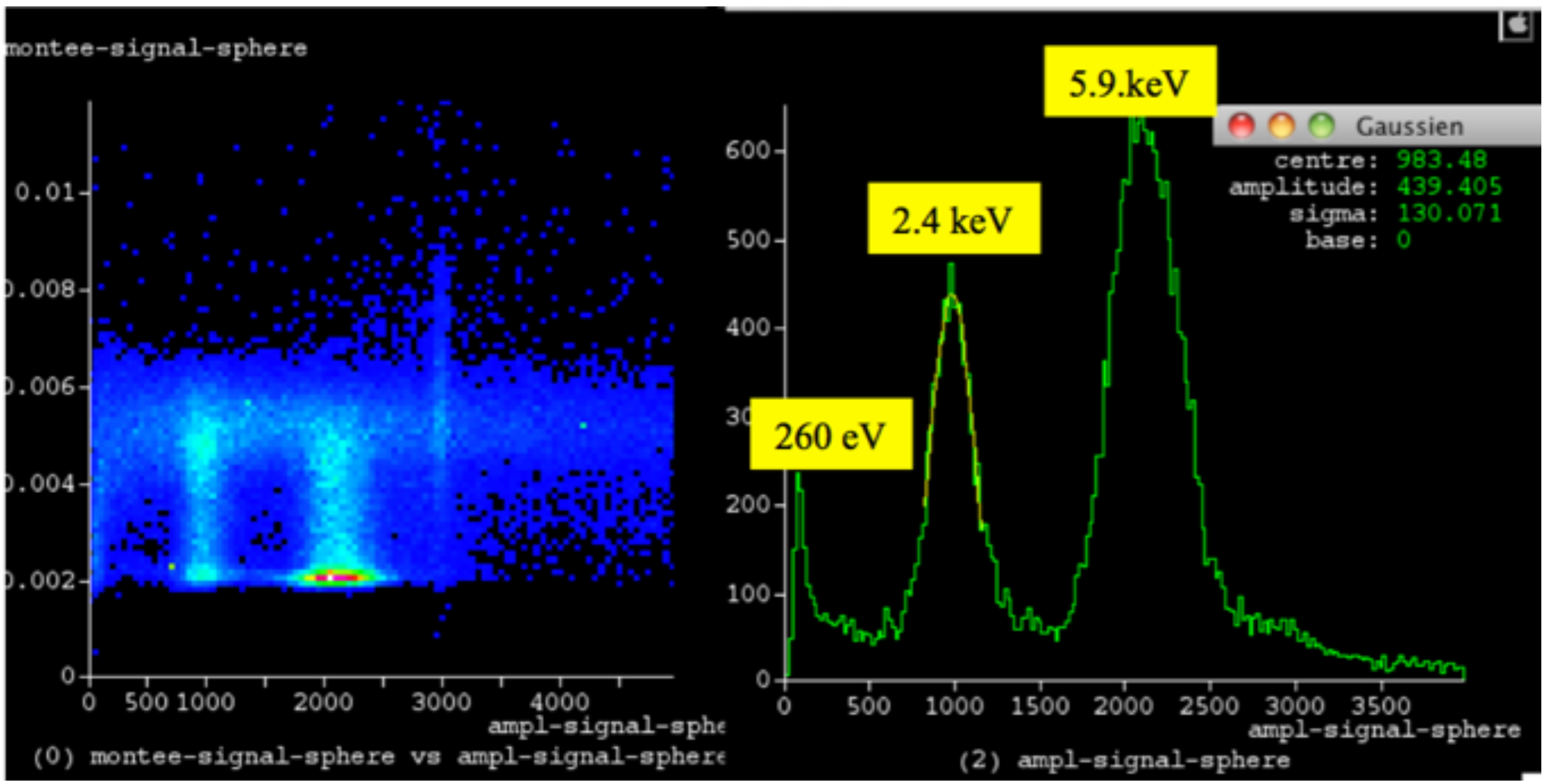


NEWS experiment

G. Gerbier at al., arXiv:1401.7902

Very-low threshold: spherical TPC

- The rise time of the pulse is proportional to the distance of the event from the inner ball as the primary ionization electrons will diffuse more
- Therefore, by measuring the rise time, surface events can be rejected: fiducialization
- Calibration example with: 37-Ar @ 250 mbar —> 260 eV peak well resolved



NEWS experiment

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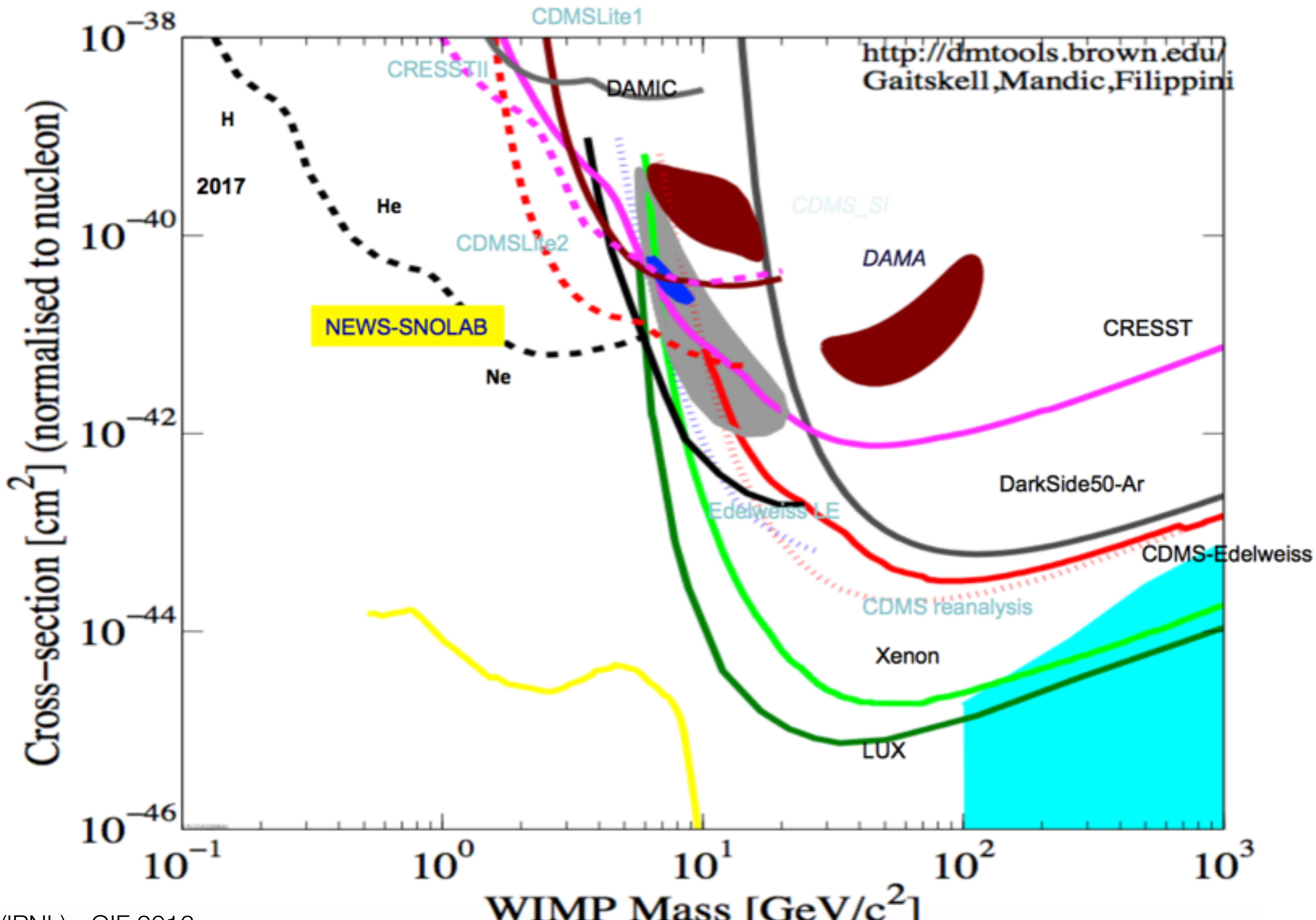
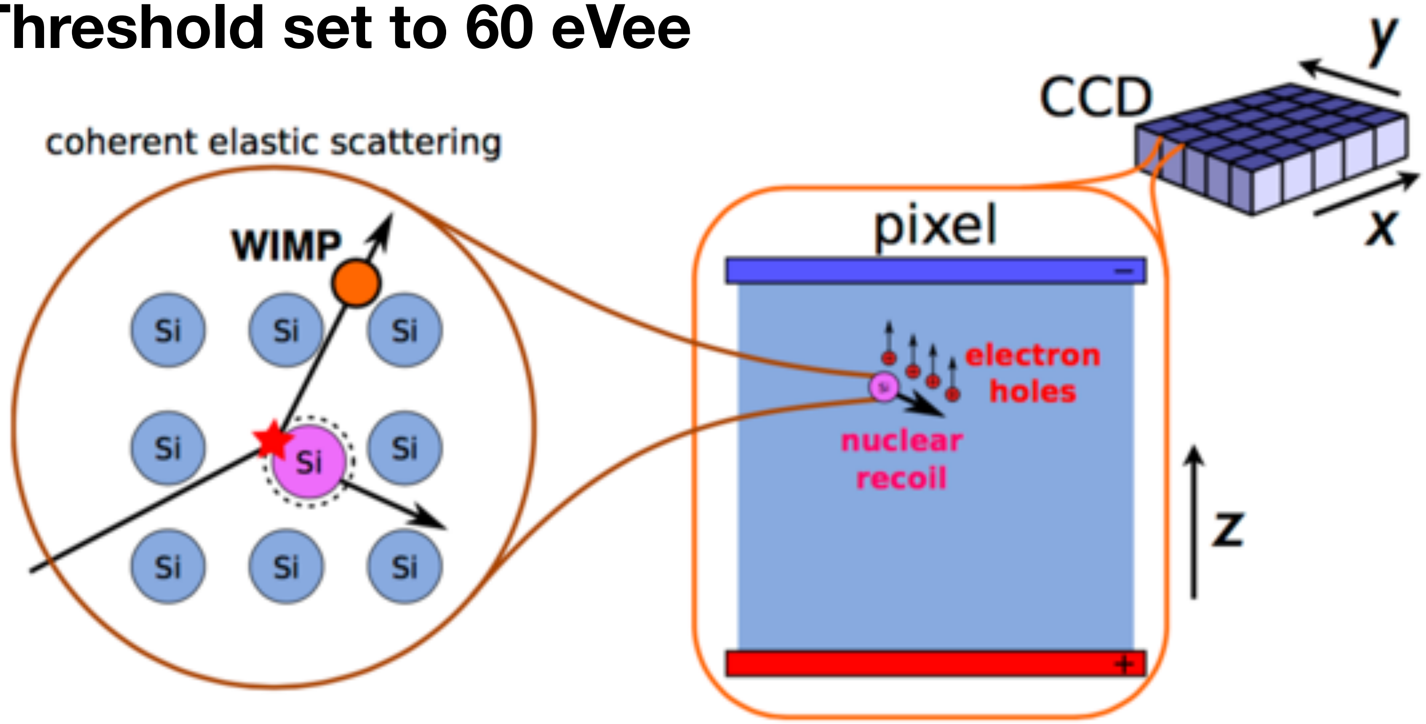


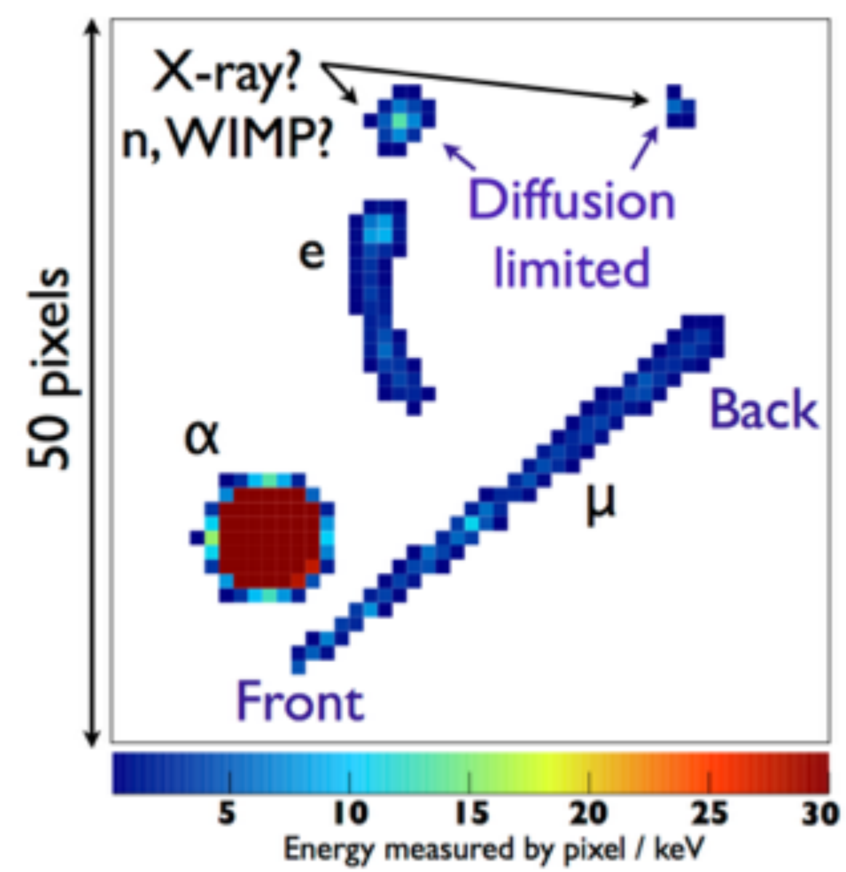
DAMIC experiment

DAMIC collaboration, arXiv:1510.02126

Very-low threshold: CCD

- DAMIC is looking for WIMP-nucleus scattering in Si CCD
- The primary ionization electrons are then drifted to the anode and we can measure the track topology and its energy
- The electronics reads out the charges collected « very slowly », by extracting them pixel-by-pixel, such that the overall capacitance of the system is minimal ~0.05 pF
- Additionally, the CCD is readout only every 8 hours to minimize injected noise
- Overall, this leads to a 2e- (~7 eV) noise RMS
- **Threshold set to 60 eVee**



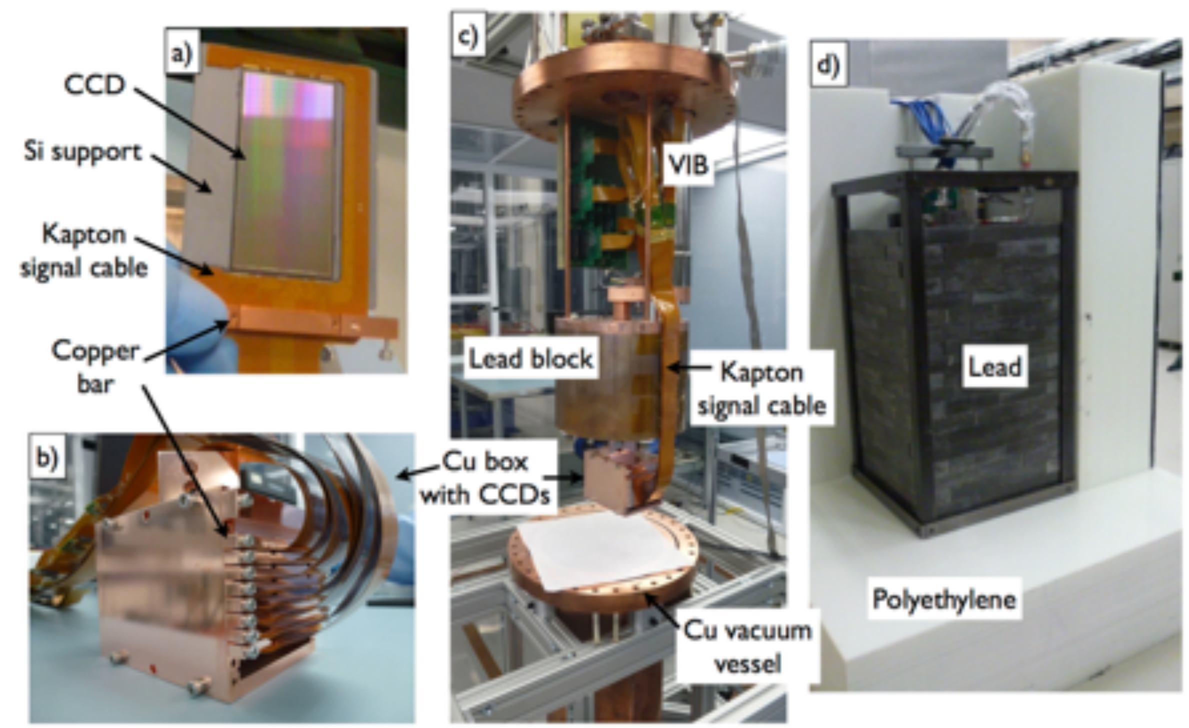


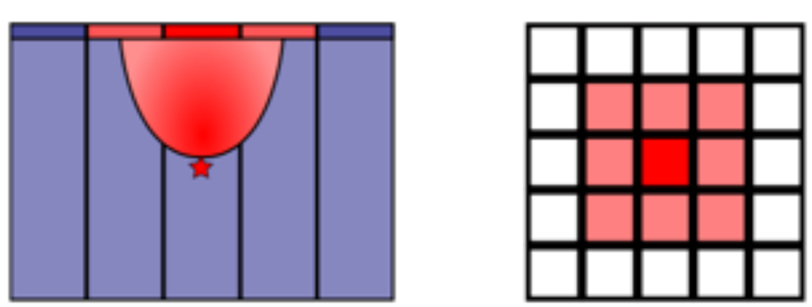
DAMIC experiment

DAMIC collaboration, arXiv:1510.02126

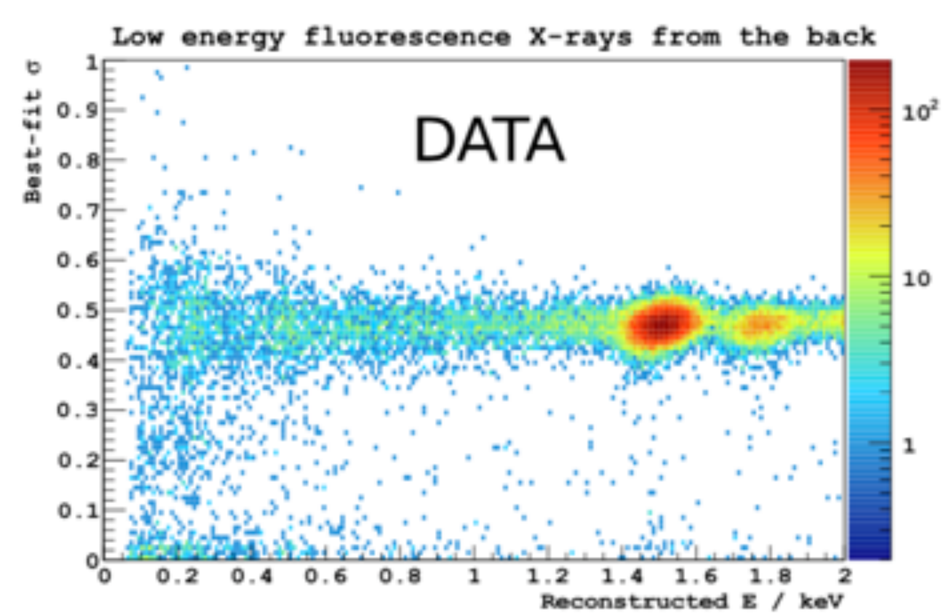
Very-low threshold: CCD

- DAMIC is installed in SNOLAB
- 16 Mpixel CCDs are 675 um thick with pixels of 15 um x 15 um for a total mass of 5.5 grams
- The current phase of the project is DAMIC100 with a total target mass of 100 grams of Si
- The CCDs are cooled down to 140 K to limit dark current (<0.1 e/pix/day)
- From charge diffusion -> fiducialization !
- 18 cm of Lead and 21 cm of Polyethylene shields





The charge diffuses towards the CCD pixels gates. Depth can be reconstrected from diffusion.



Bottom

Bulk

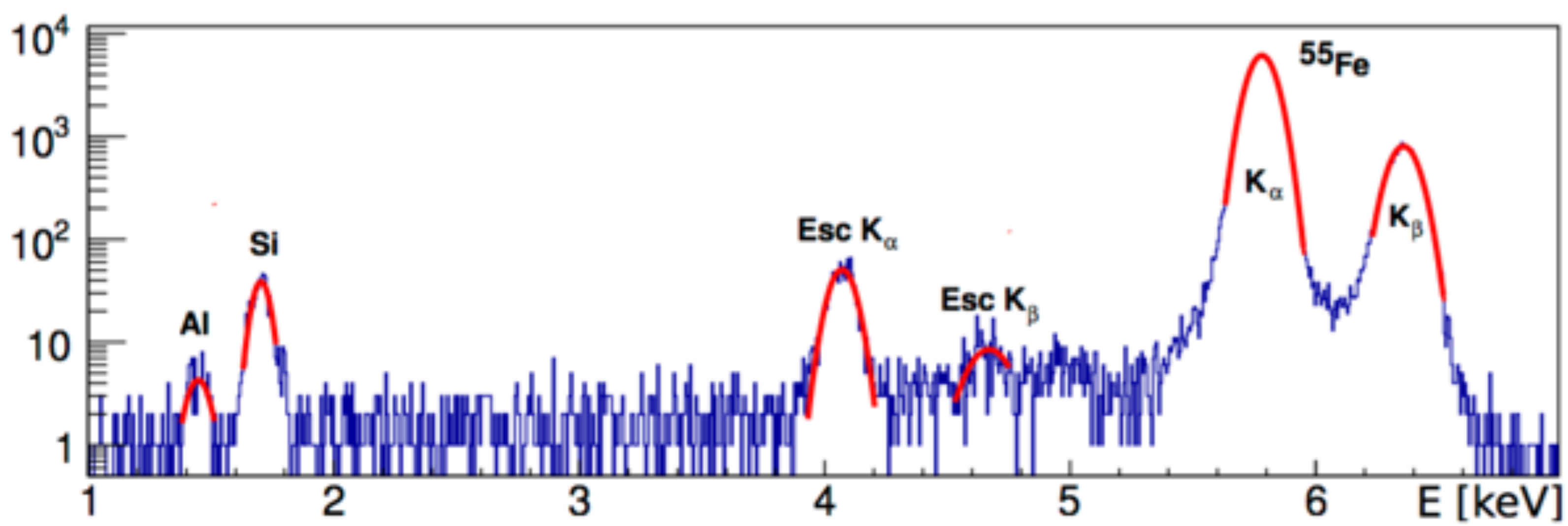
Top

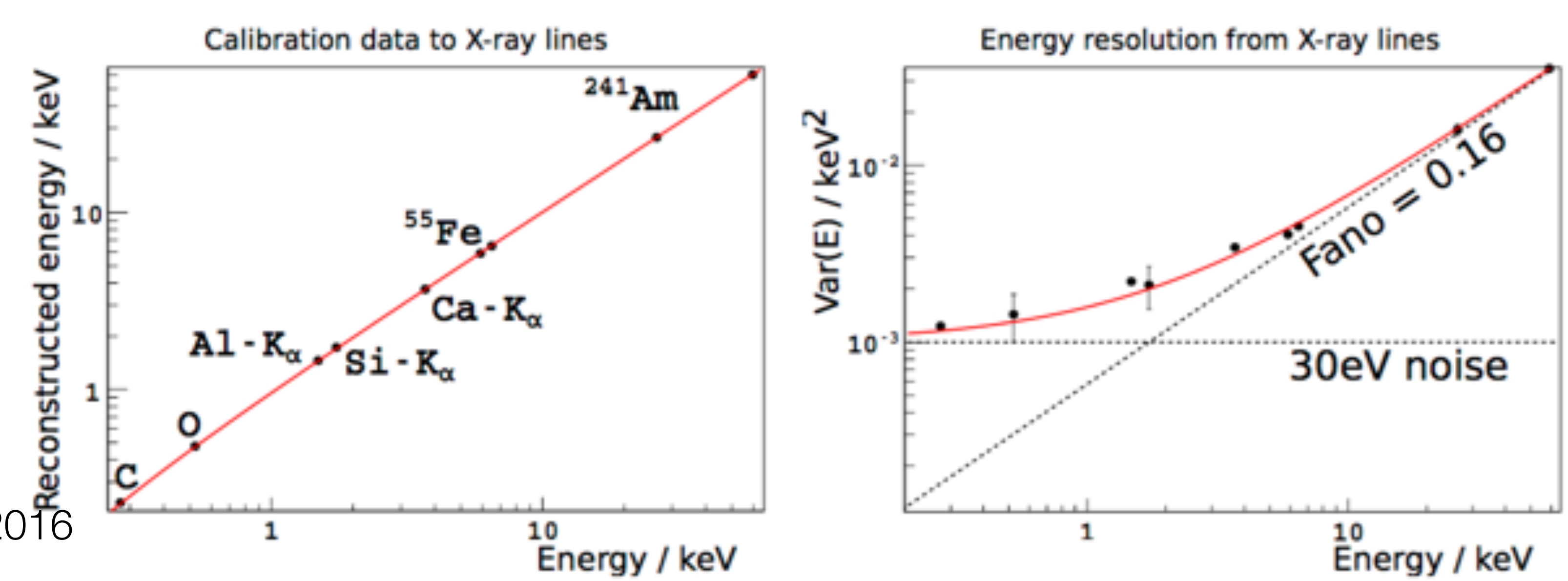
DAMIC experiment

DAMIC collaboration, arXiv:1510.02126

Very-low threshold: CCD

- Ionization energy calibration using X-ray sources (55Fe and 241Am) which additionally induce fluorescence X-ray lines from materials of the CCD (Al and Kapton).
- Excellent linearity and energy resolution (30 eVee)
- Measurement of the Fano factor of Si that drives the fluctuations in charge created



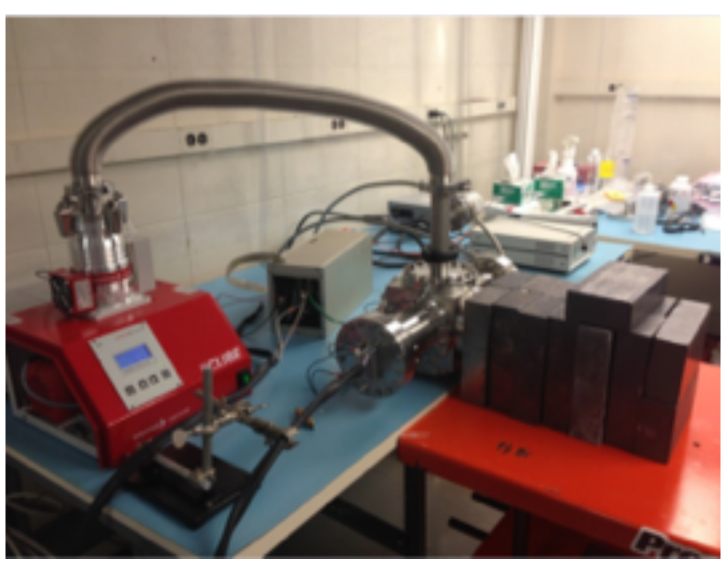


DAMIC experiment

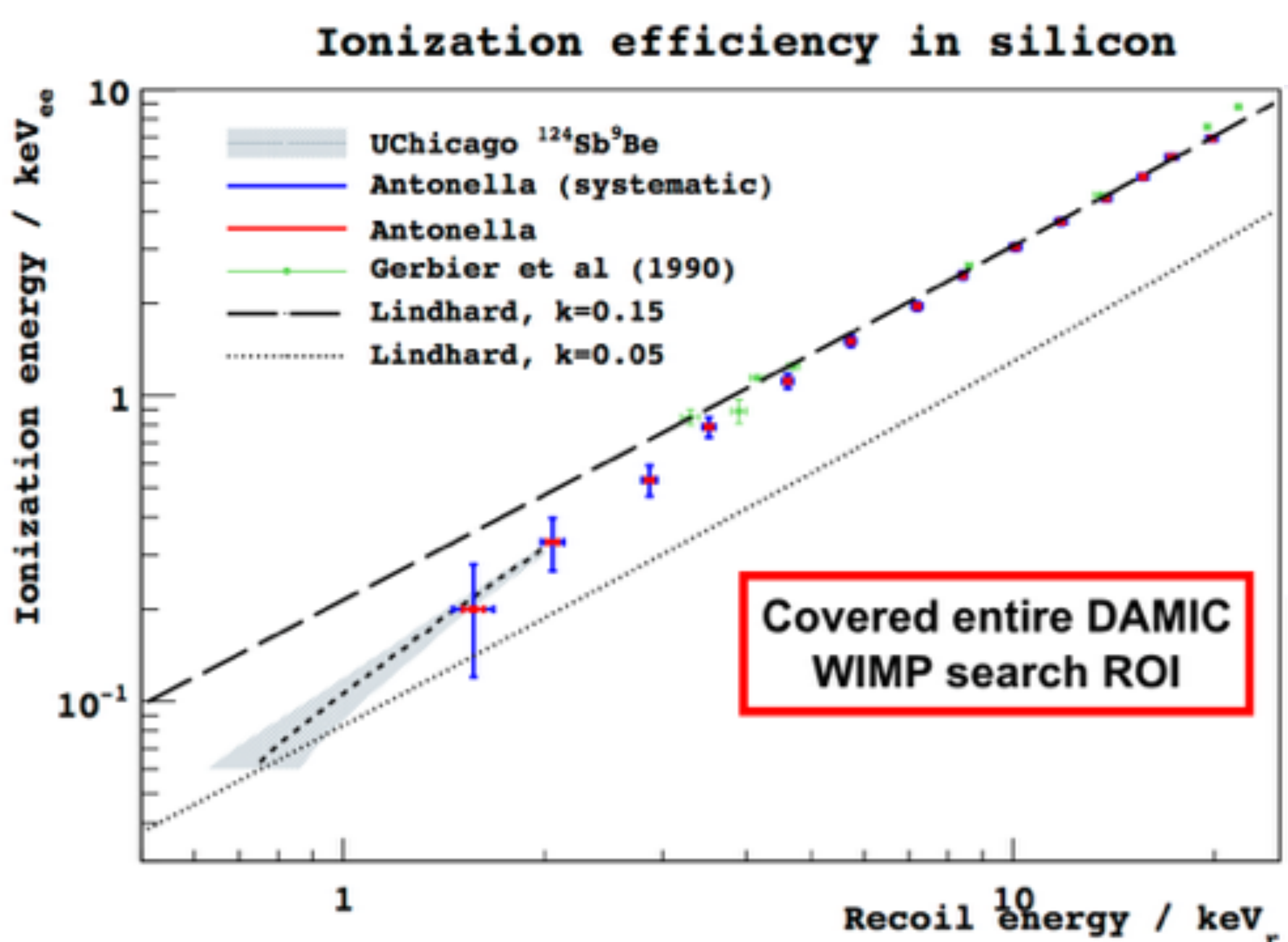
DAMIC collaboration, arXiv:1510.02126

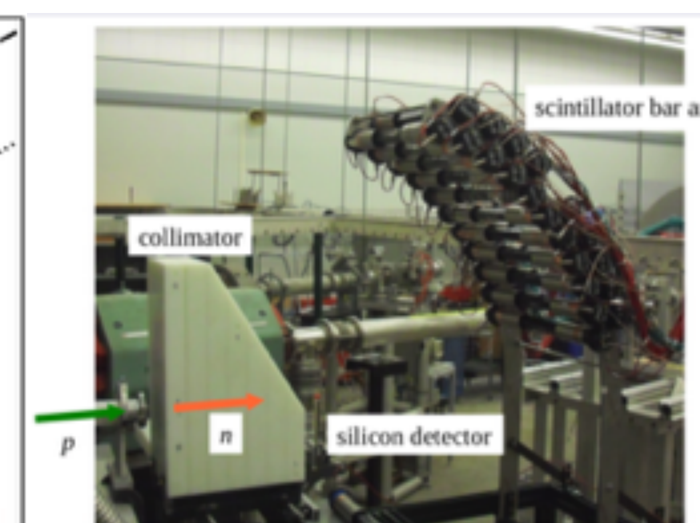
Very-low threshold: CCD

- DAMIC collaboration has performed a very thorough nuclear recoil energy scale calibration
- From the photo-production of neutrons from Y/Be (152 keV) the neutron beam at Notre Dame, they measured the ionization yield from 0.7 keVnr up to 20 keVnr (entire ROI covered)
- They have demonstrated that the Lindhard model usually assumed is over-optimistic !!!



- Photo-production of neutrons with Y/Be
- 0.7 to 2 keVnr

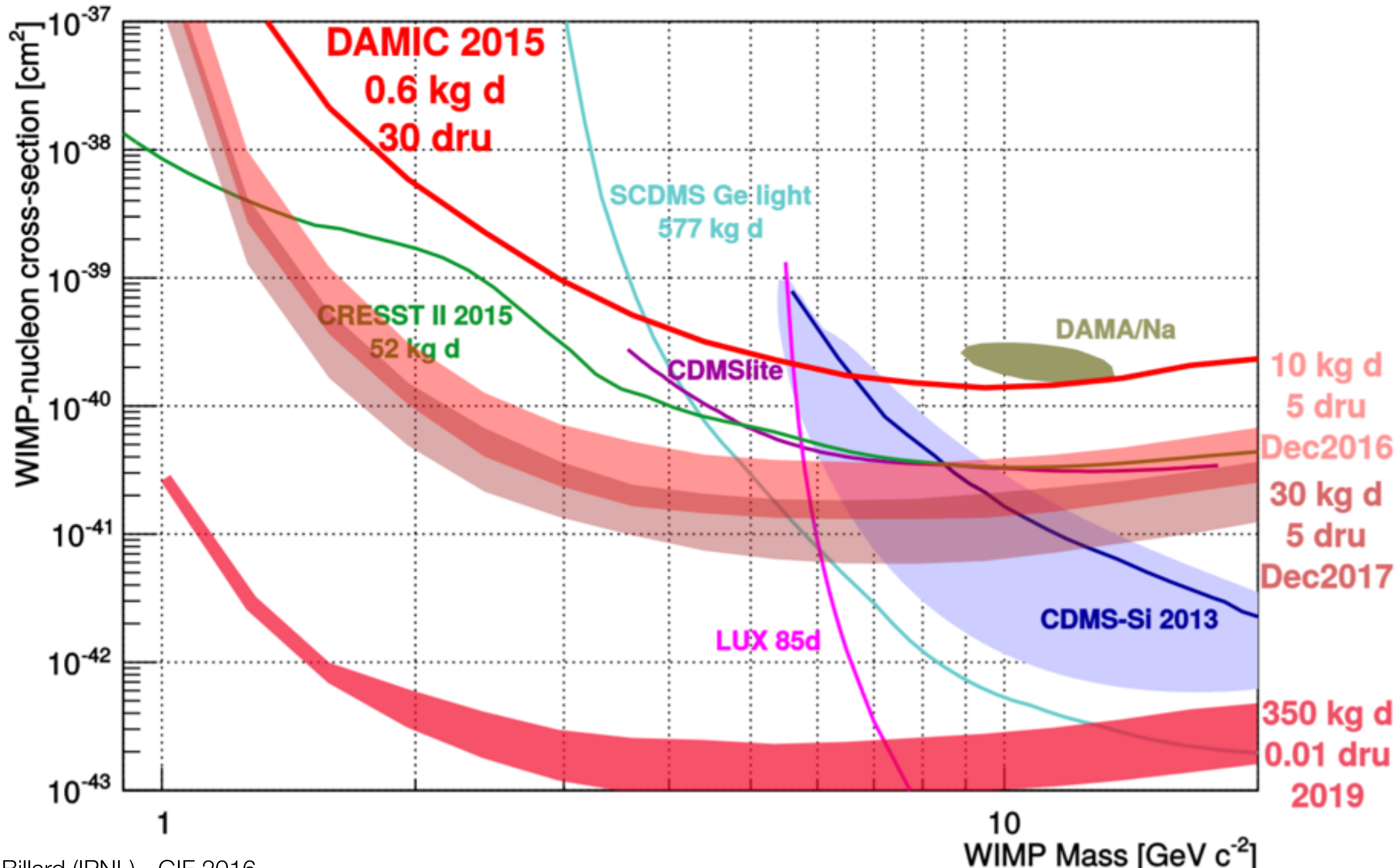




- Neutron beam and scintillators
- 2 to 20 keVnr

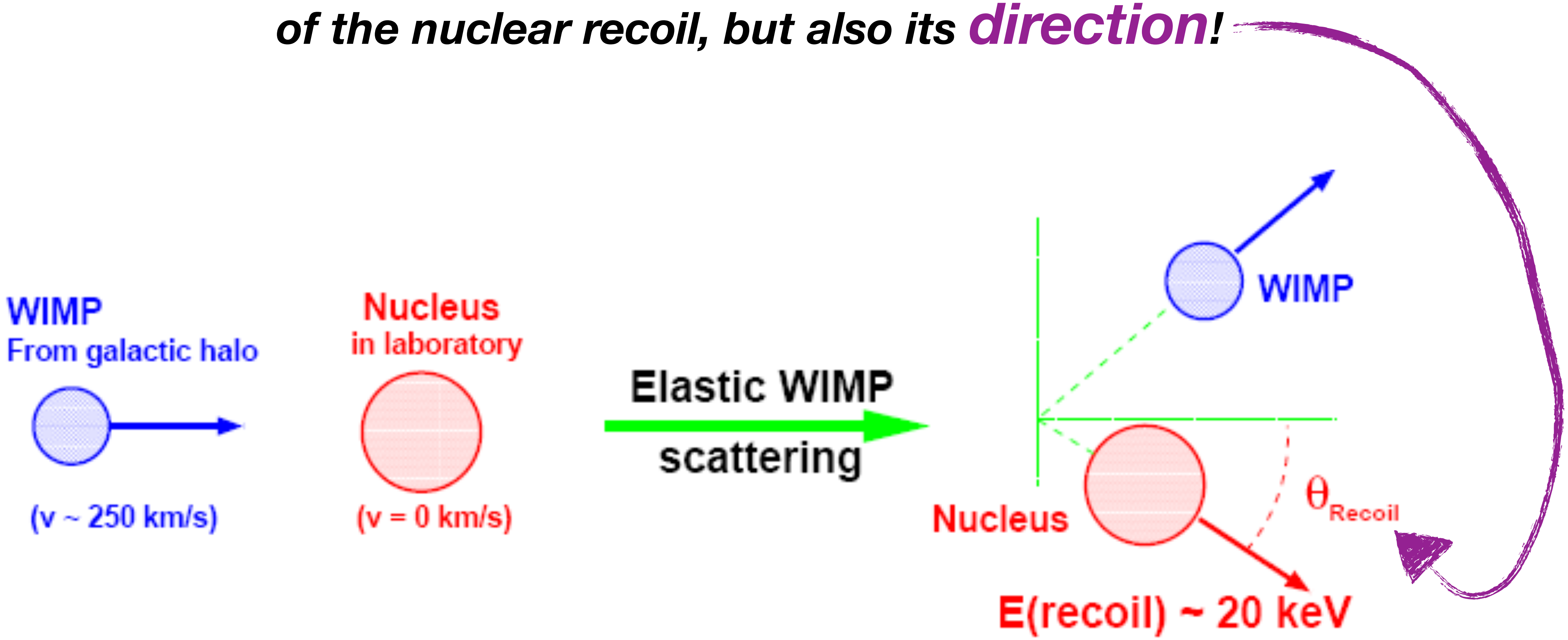
DAMIC experiment

DAMIC collaboration, arXiv:1510.02126



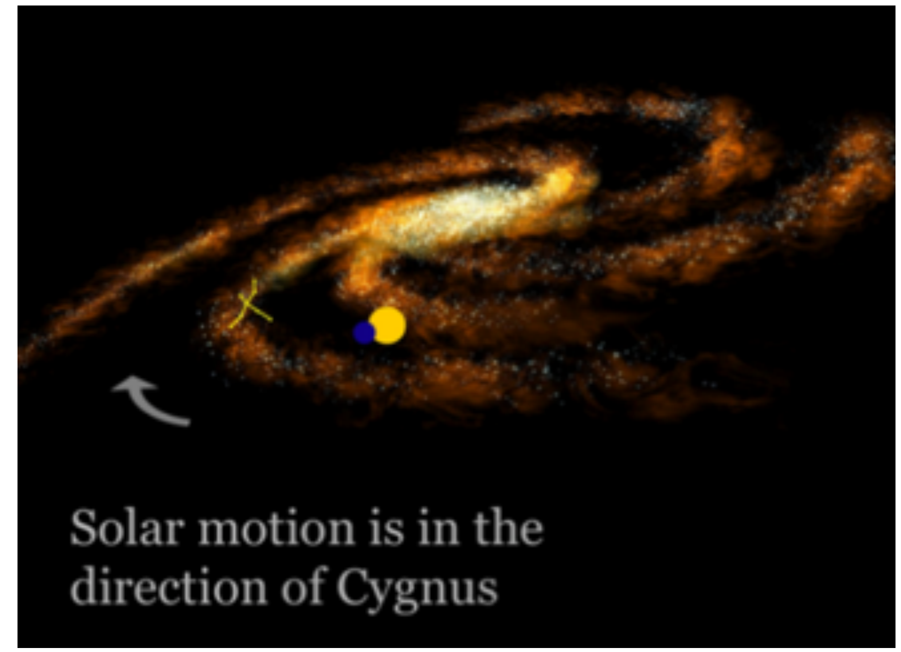
Directional detection

The ultimate detector should be able to measure not only the energy of the nuclear recoil, but also its direction!

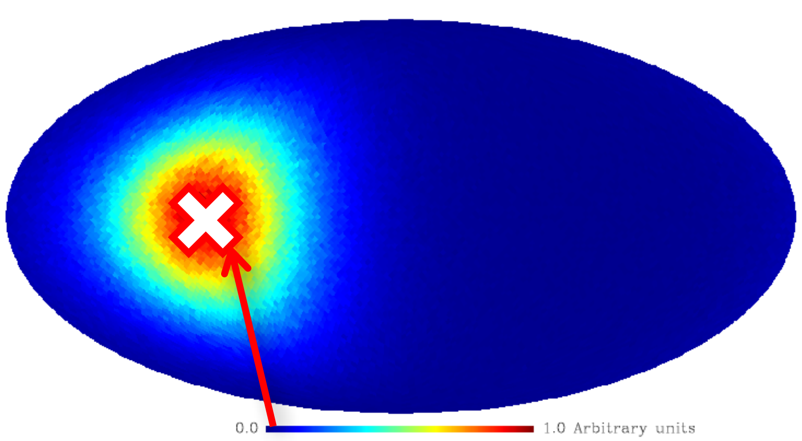


Directional detection: *theory*

- Thanks to the rotation of the Solar System around the galactic center, we expect a « wind of WIMP » coming from constellation Cygnus at l=90 and b=0
- The expected WIMP signal has a strong dipole feature which cannot be mimicked by any backgrounds
- ***Unambiguous dark matter signature !***



WIMP flux entering a terrestrial detector represented in galactic coordinates

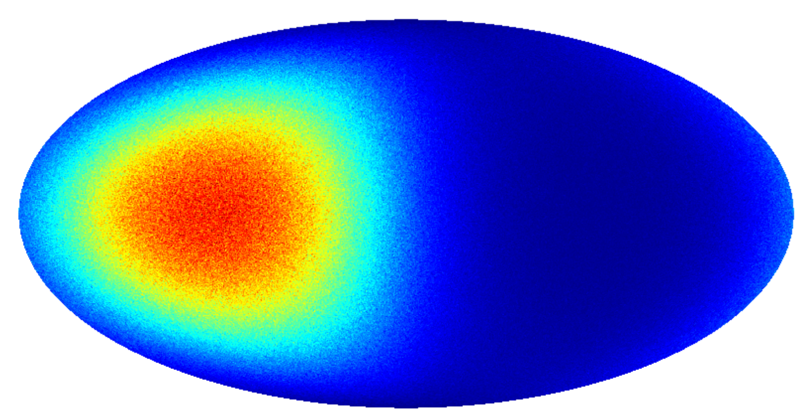


Cygnus Constellation $(l = 90^\circ, b = 0^\circ)$

After scattering

m_{WIMP} = 100 GeV/c^2

Angular distribution of nuclear recoils
^{19}F [5;50] keV



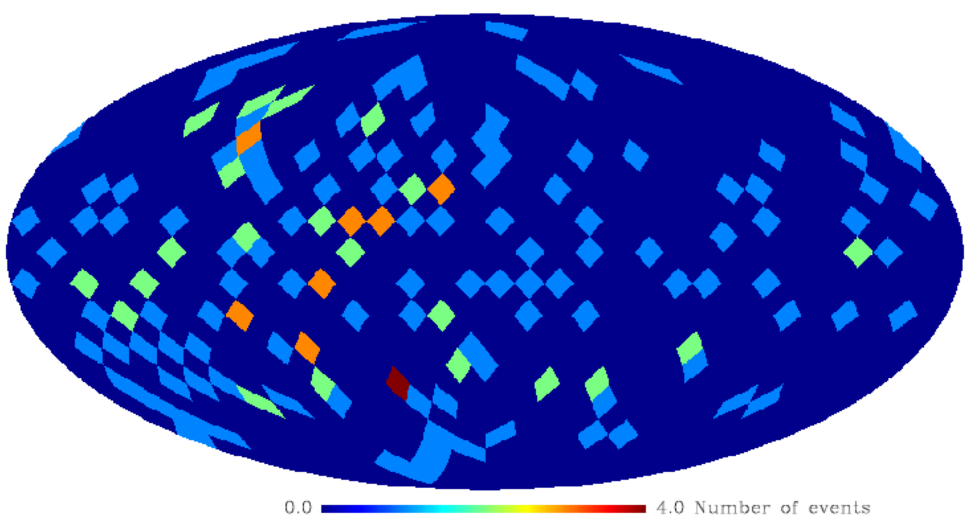
Expected WIMP signal

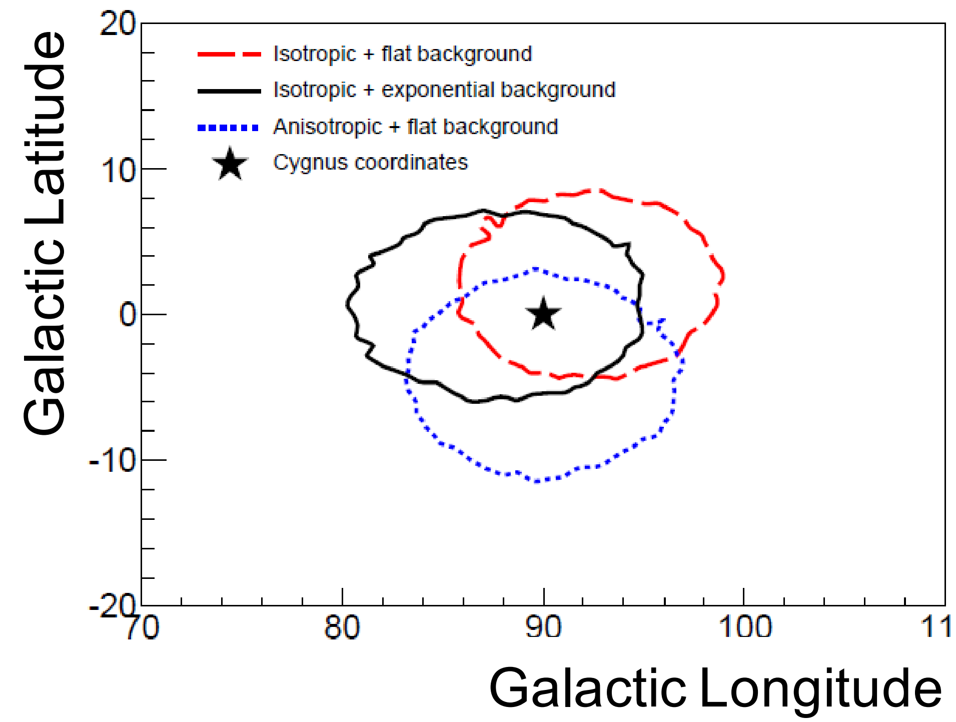
Directional detection: *theory*

J. Billard, F. Mayet and D. Santos, PLB 2009

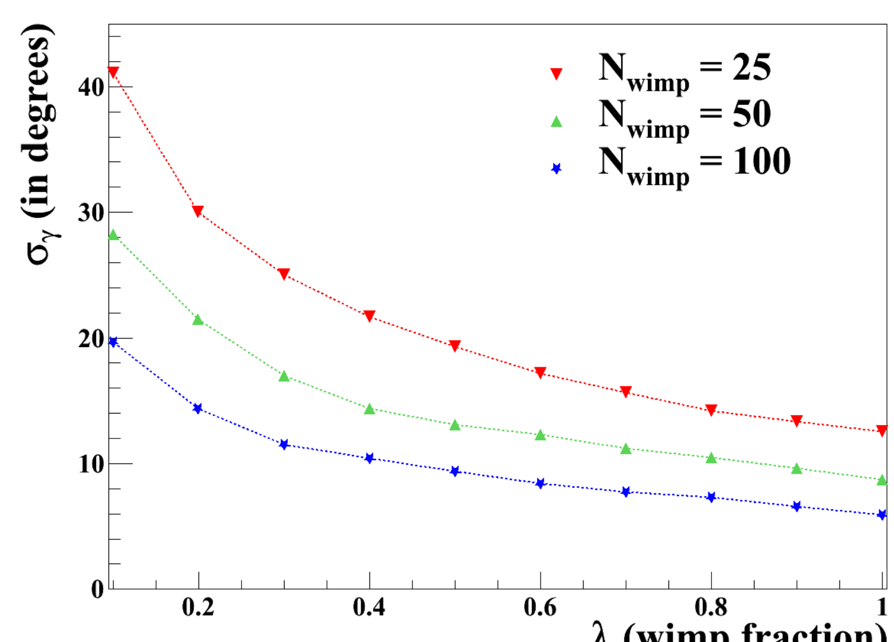
Directional detection as a tool for a definitive discovery

100 WIMP and 100 background events





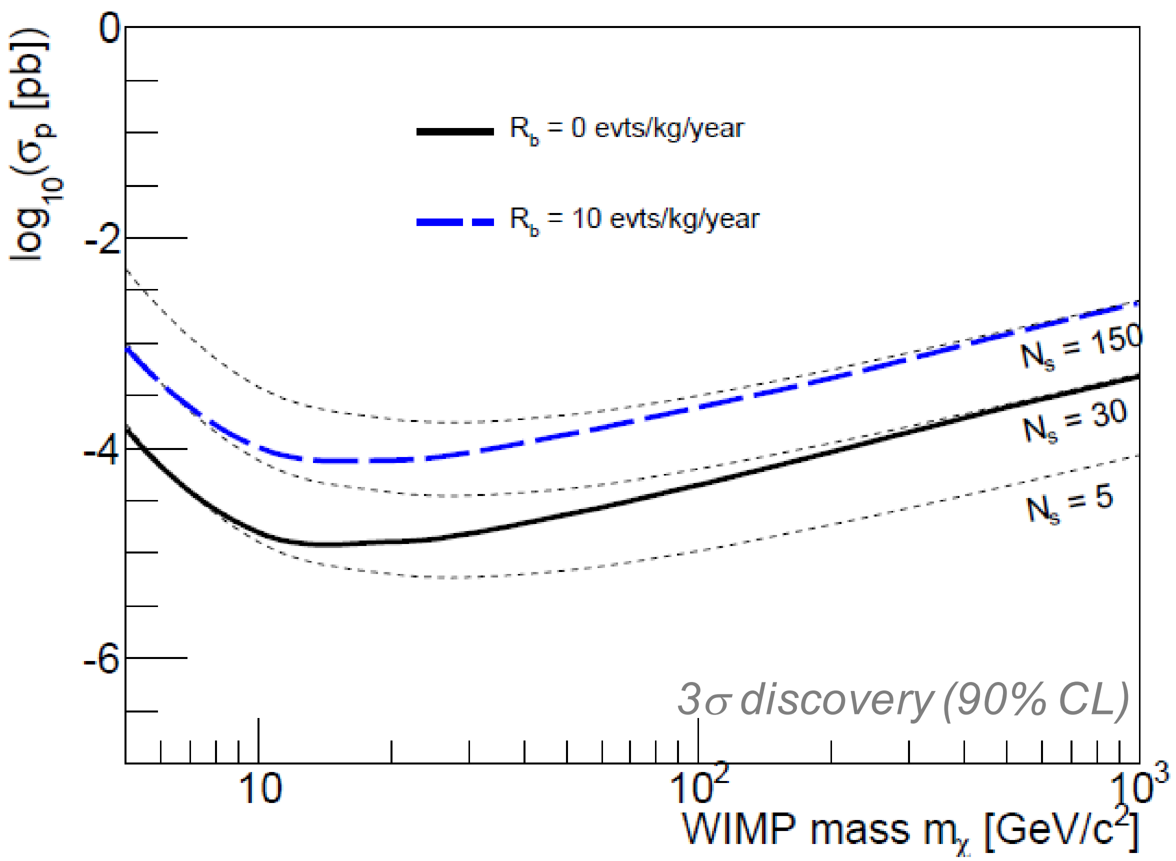
- With only a few tens of events and large background contamination, we can recover the galactic origin of the signal
- Recovering the main direction of the recoils is robust against halo uncertainties
- A 3 sigma discovery can be achieved with as few as ~10 WIMP and background events



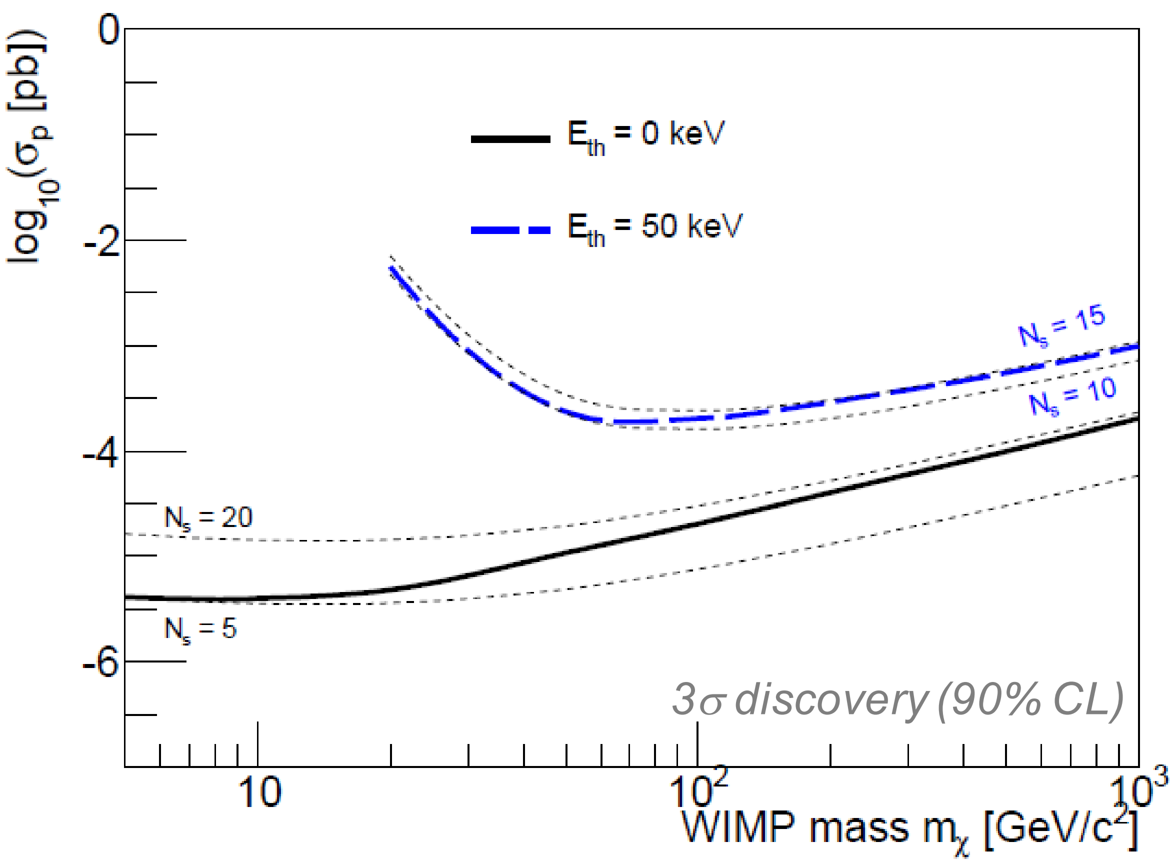
Directional detection: *theory*

J. Billard *et al.*, PRD 2012

Residual Background



Energy Threshold



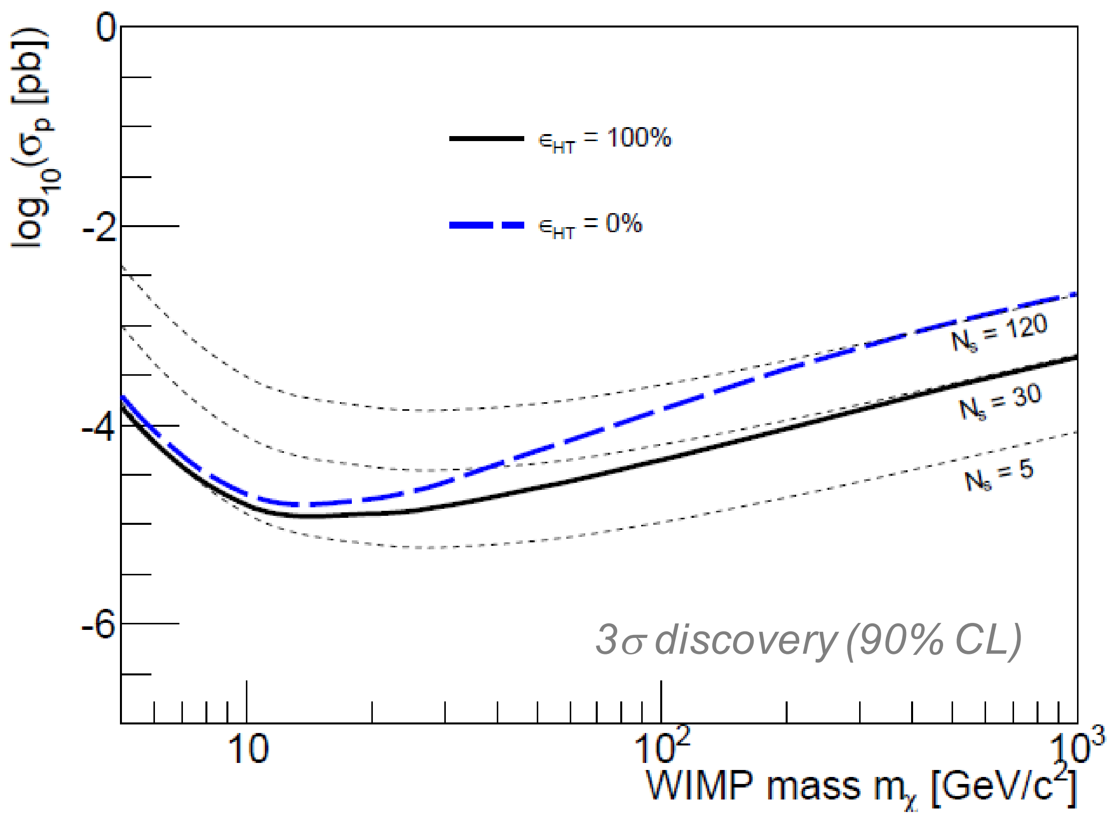
→ One order of magnitude loss
(from 0 to 10 events/kg/year)

→ The lower the better.
→ Goal: *well below 50 keV (recoil)*

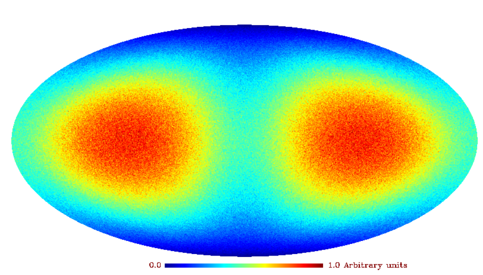
Directional detection: *theory*

J. Billard *et al.*, PRD 2012

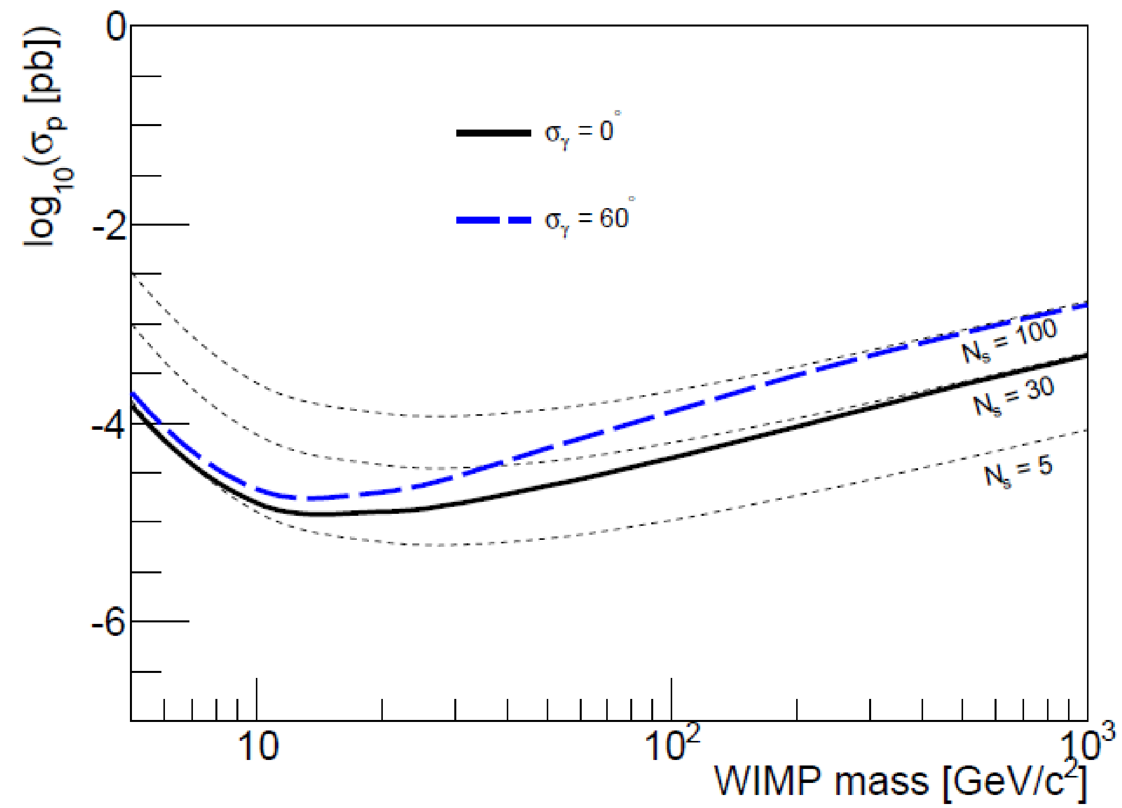
Sense recognition



→ No effect at low WIMP mass
→ Factor five above 100 GeV



Angular resolution



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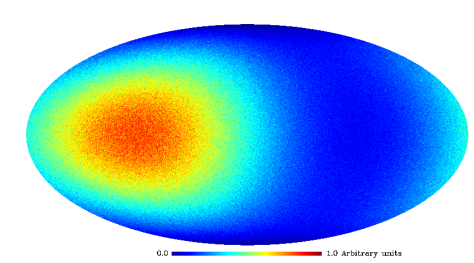
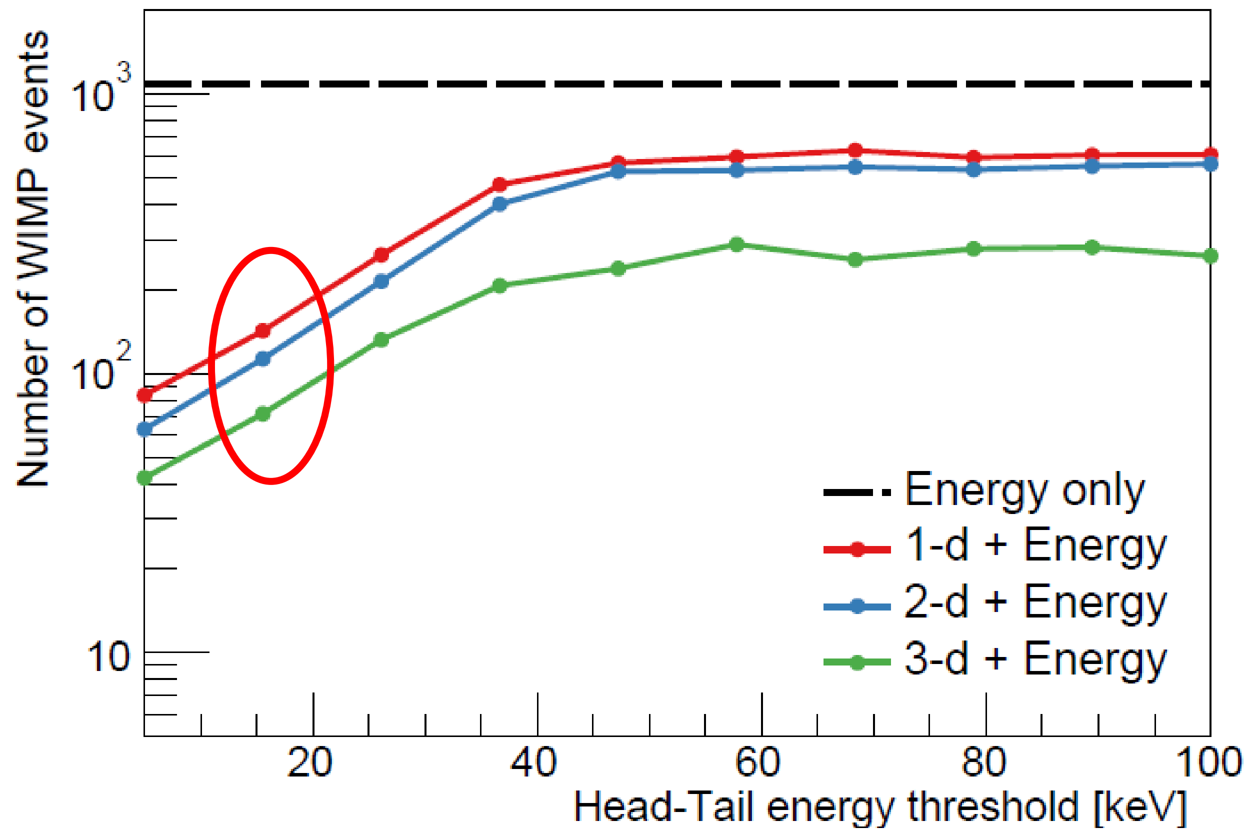


σ_Θ = 45 °

Directional detection: *theory*

J. Billard, PRD 2015

→ Number of events required to get a 3σ discovery (in 90% of experiments)
Non-directional (Energy only) & directional (1d, 2d, 3d)



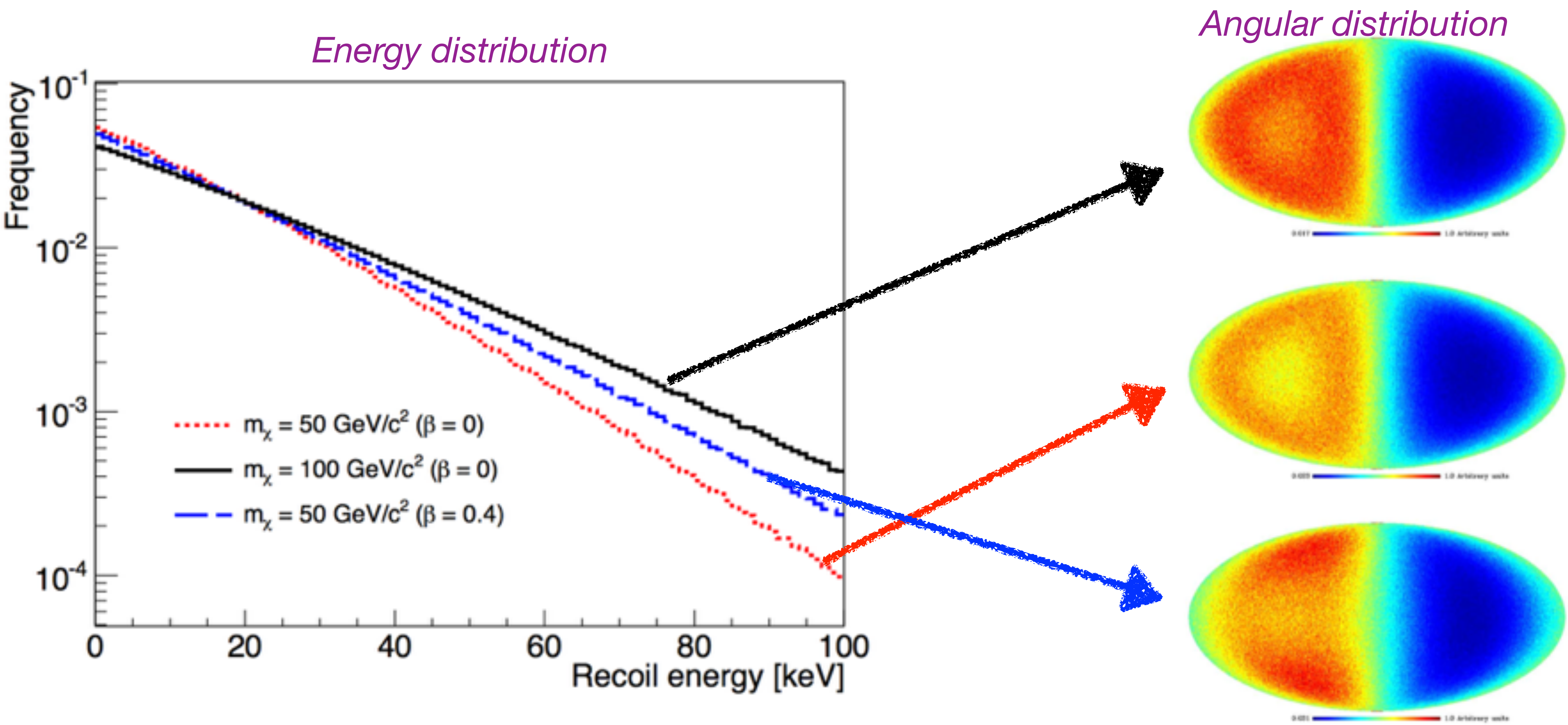
Xe detector +40 % background, 5-50 keV, 50 GeV WIMP

→ Directional detection allows for a great improvement wrt to energy-only
→ 1d less effective than 3d by a factor 3 *only* …
… that could be *easily* compensated by the exposure (solid-state/liquid detector)
e.g. Columnar recombination in dual-phase Xe or Ar TPC

Directional detection: *theory*

J. Billard, F. Mayet and D. Santos, PRD (83) 2011

Unique possibility to probe the nature of Dark Matter

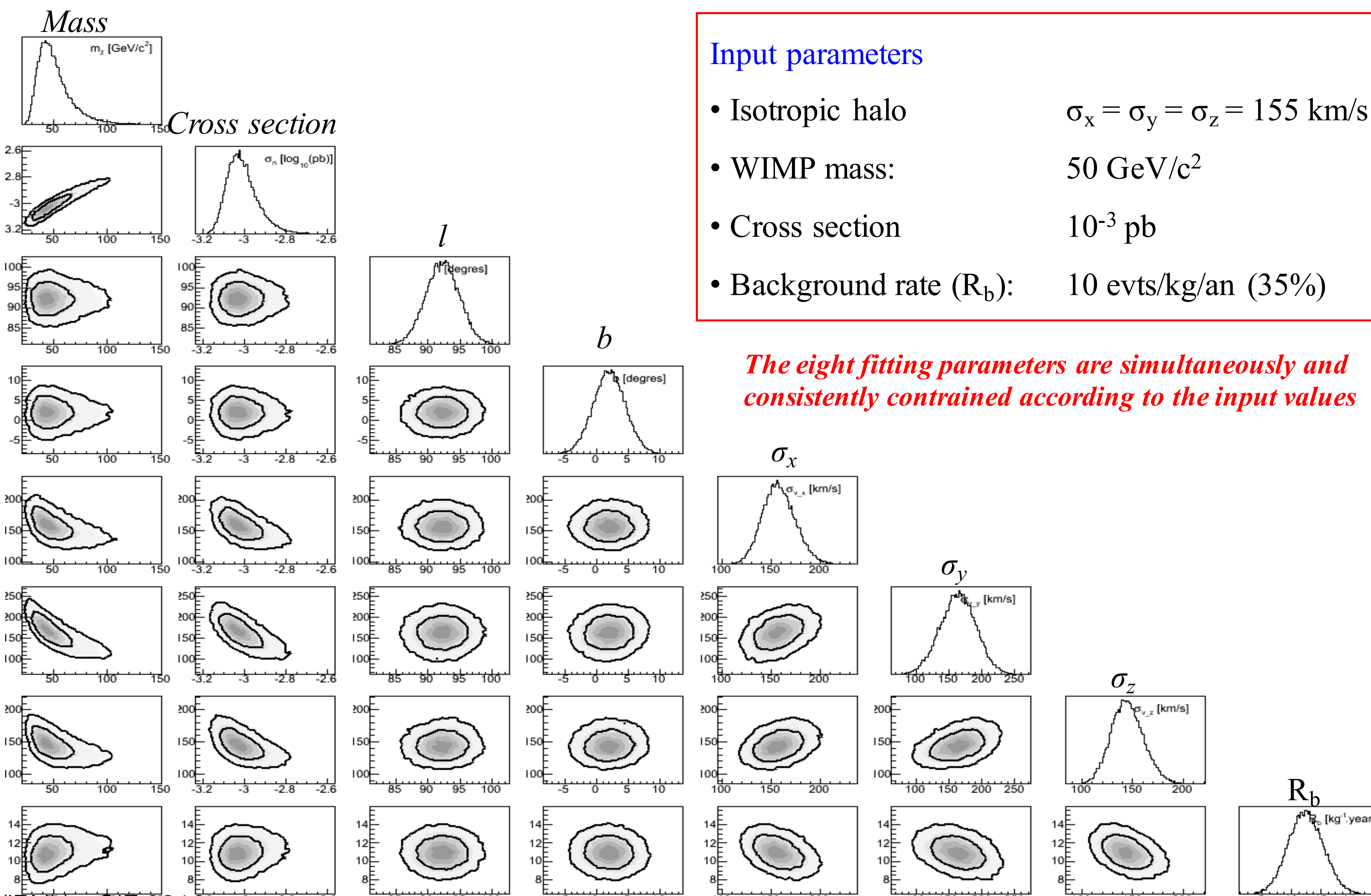


- By measuring both the energy spectrum and the angular distribution we can alleviate the degeneracies between the halo and the particle properties

Directional detection: *theory*

J. Billard, F. Mayet and D. Santos, PRD (83) 2011

Unique possibility to probe the nature of Dark Matter



Input parameters

- Isotropic halo: $\sigma_x = \sigma_y = \sigma_z = 155$ km/s
- WIMP mass: 50 GeV/c^2
- Cross section: 10^{-3} pb
- Background rate (R_b): 10 evts/kg/an (35%)

The eight fitting parameters are simultaneously and consistently contrained according to the input values

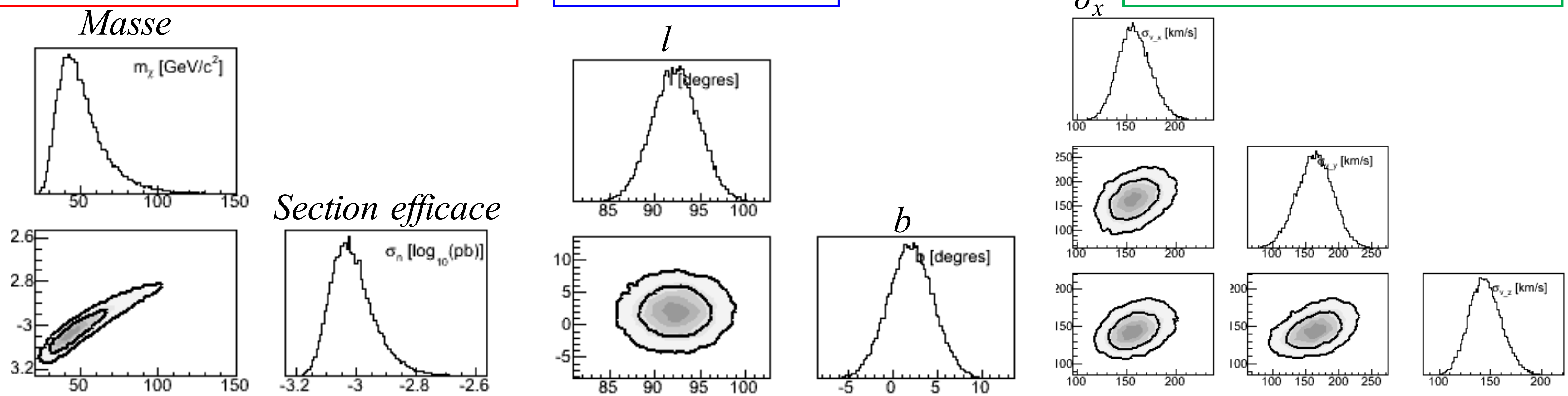
Directional detection: *theory*

J. Billard, F. Mayet and D. Santos, PRD (83) 2011

Unique possibility to probe the nature of Dark Matter

- With a single experiment of 30 kg-years we can measure both the halo and WIMP properties

WIMP mass Vs cross section | *Discovery proof* | *WIMP velocity distribution*

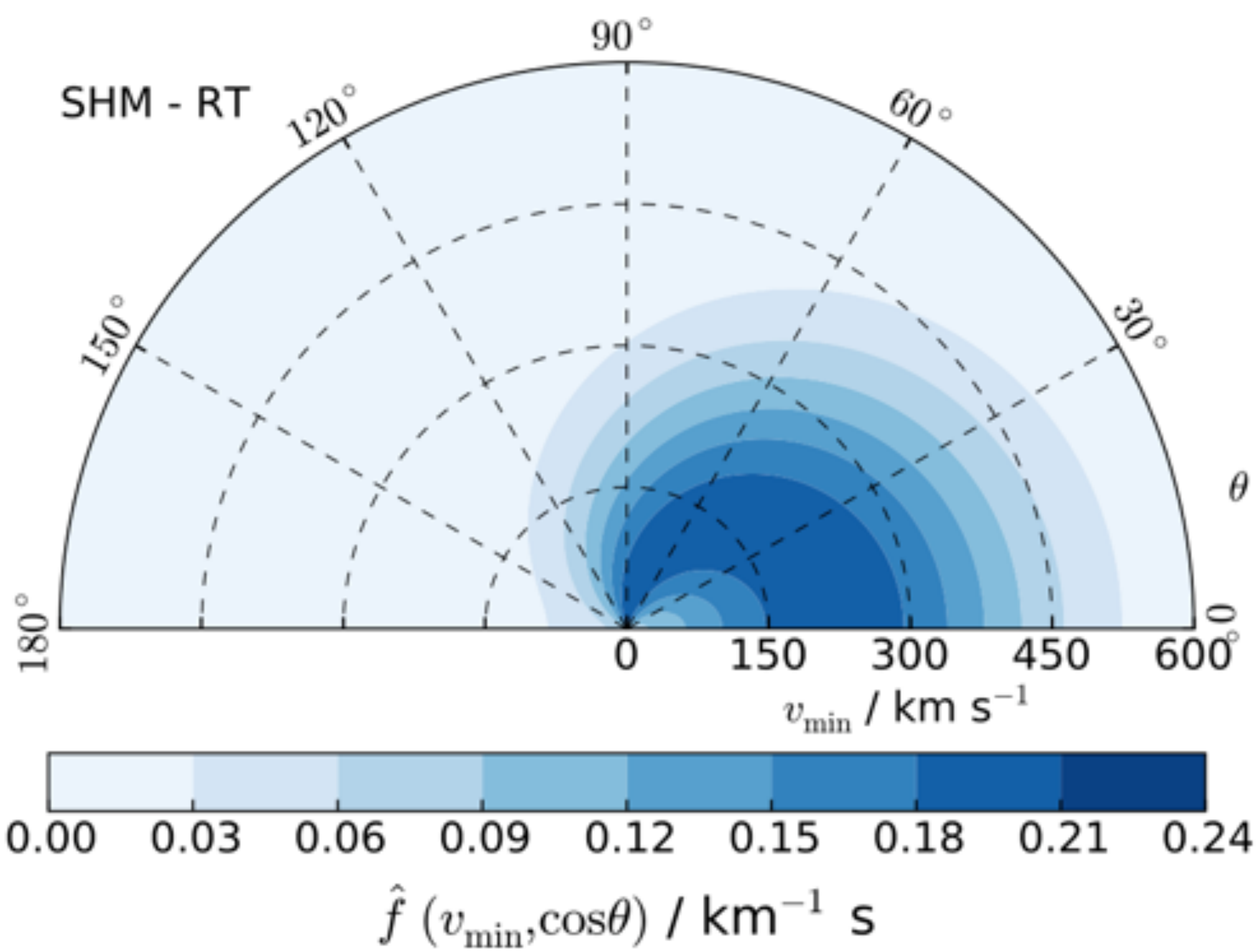


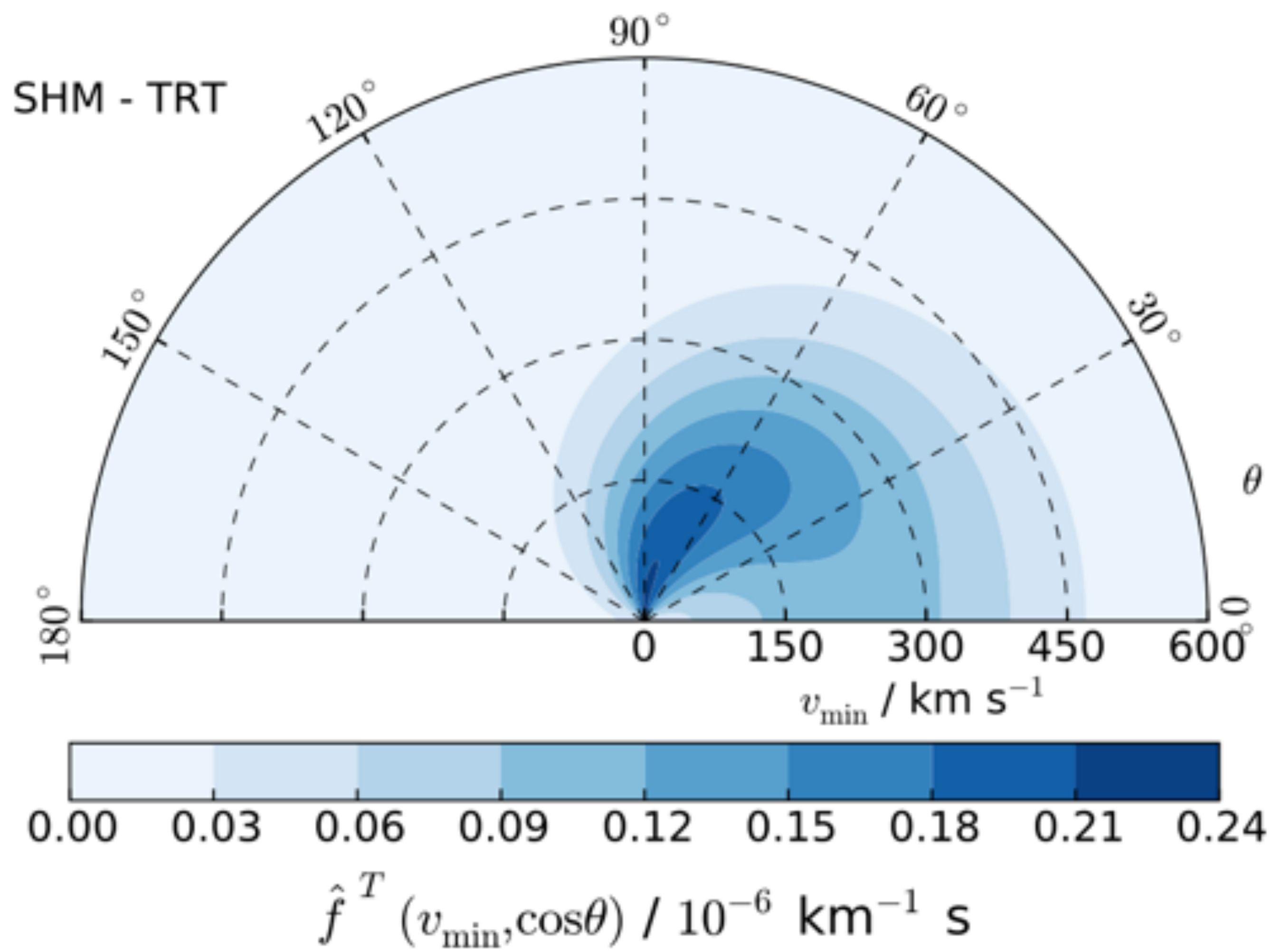
	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb))	$\ell_\odot$ (°)	$b_\odot$ (°)	σ_x (km.s^{-1})	σ_y (km.s^{-1})	σ_z (km.s^{-1})	β	R_b (kg^{-1}year^{-1})
Input	50	-3	90	0	155	155	155	0	10
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$	$92.2^{+2.5}_{-2.5}$	$2.0^{+2.5}_{-2.5}$	158^{+15}_{-17}	164^{+27}_{-26}	145^{+14}_{-17}	$-0.073^{+0.29}_{-0.18}$	10.97 ± 1.2

Directional detection: *theory*

B. Kavanagh, Phys. Rev. D 92, 023513 (2015)

Unique possibility to probe the nature of Dark Matter





- Going beyond the standard SI and SD interactions with Non-Relativistic Effect Field Theory Operators, we should expect some differences in the angular distribution of the WIMP induced events **if the transverse velocity is involved**
- Only a **few tens of events** are required to authenticate a non-standard operator

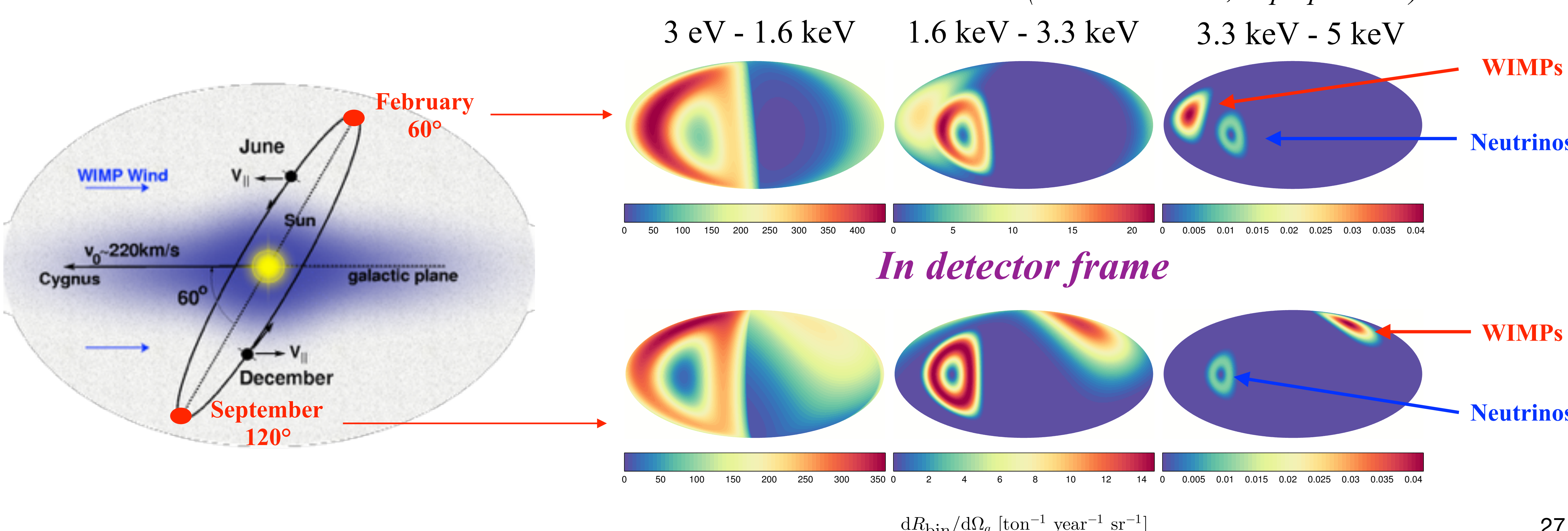
Directional detection: *theory*

C. O'Hare, et al., PRD 92 (2015)

Directional detection: beyond the neutrino floor

- The only non-isotropic background is coming from Solar neutrinos:
  - WIMPs are coming from **Cygnus**
  - Solar neutrinos are coming from … the **Sun**
- The angular separation between solar neutrinos and WIMP is of 60 (120) minimum (maximum)

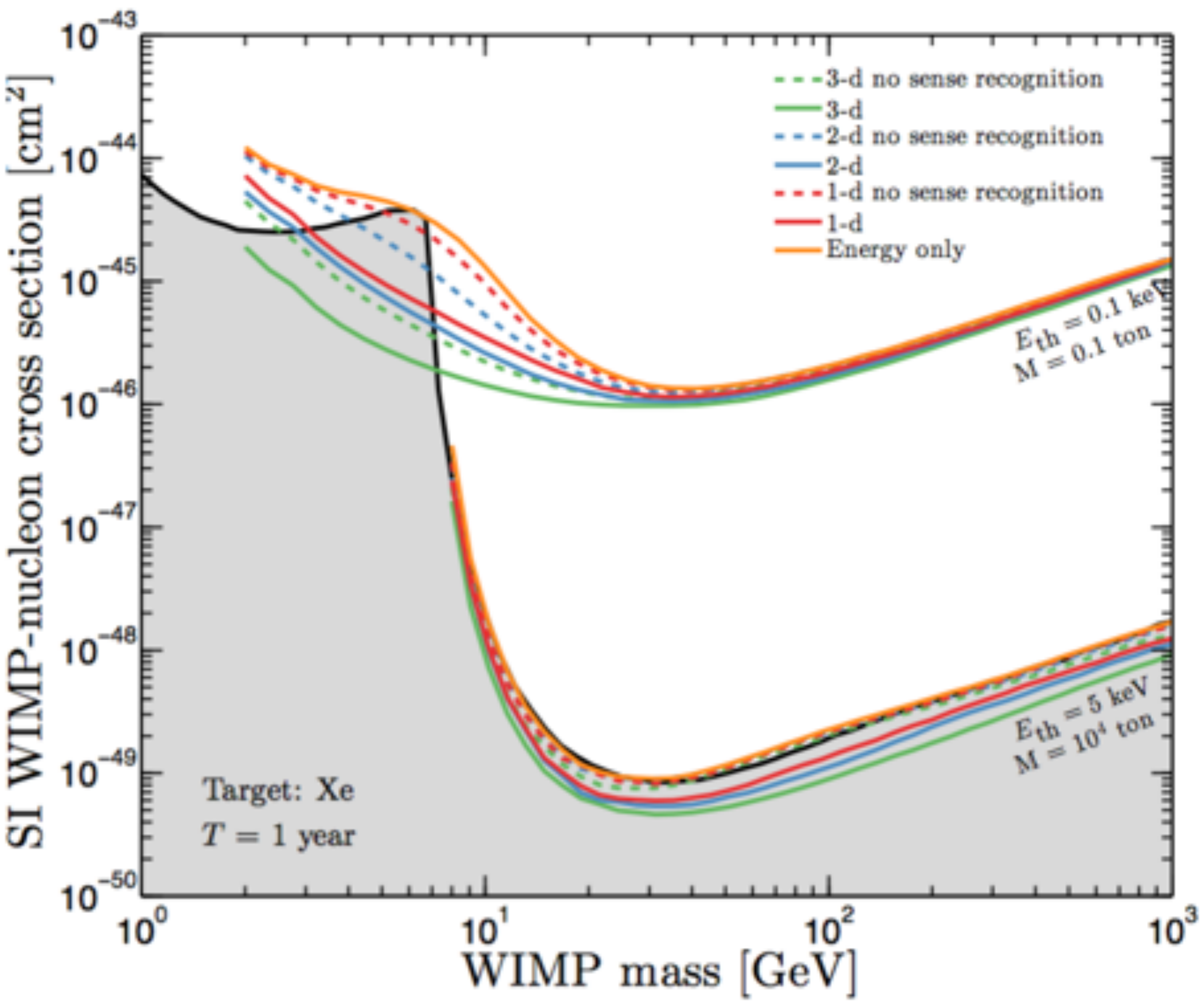
(C. O'Hare et al., in preparation)

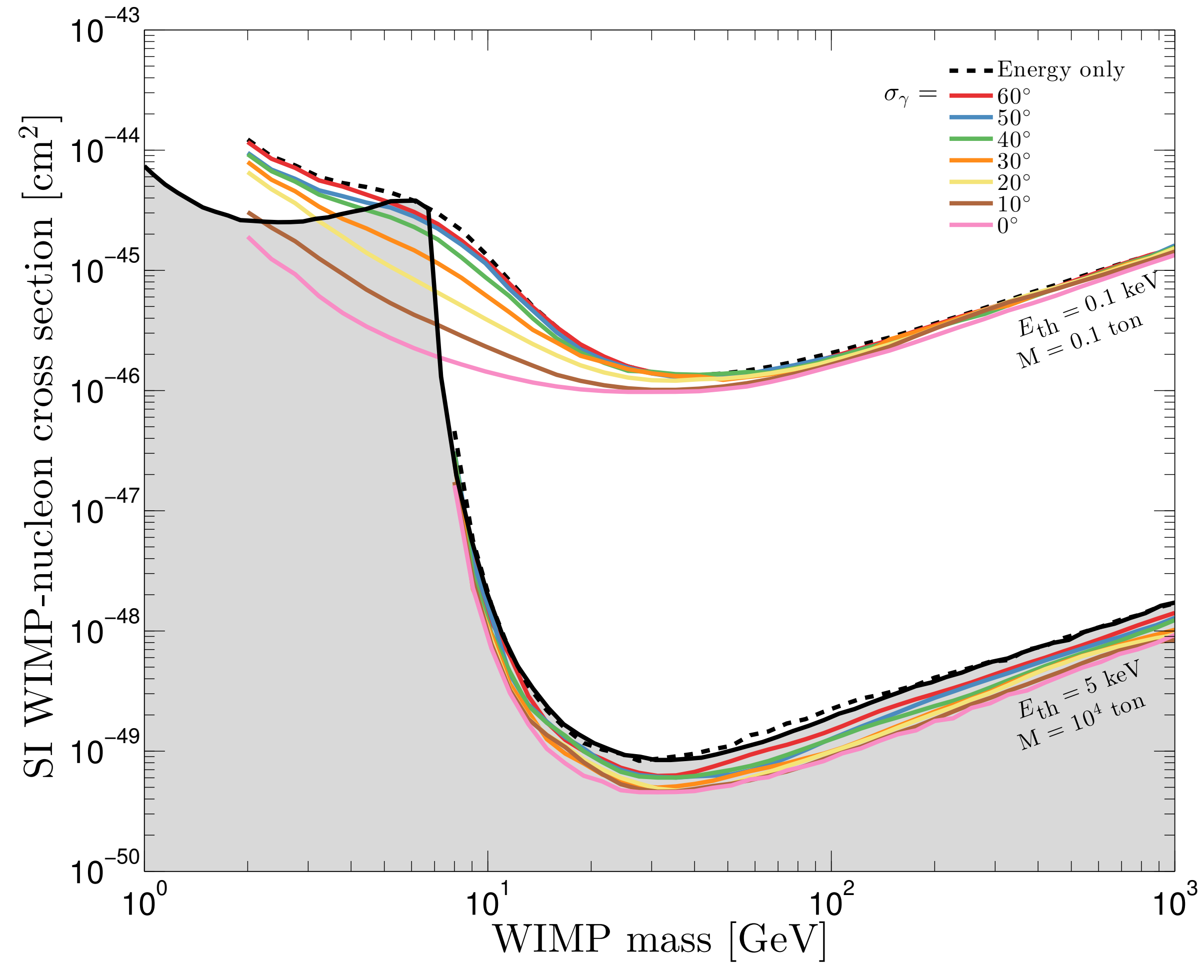


Directional detection: *theory*

C. O'Hare, et al., PRD 92 (2015)

Directional detection: beyond the neutrino floor





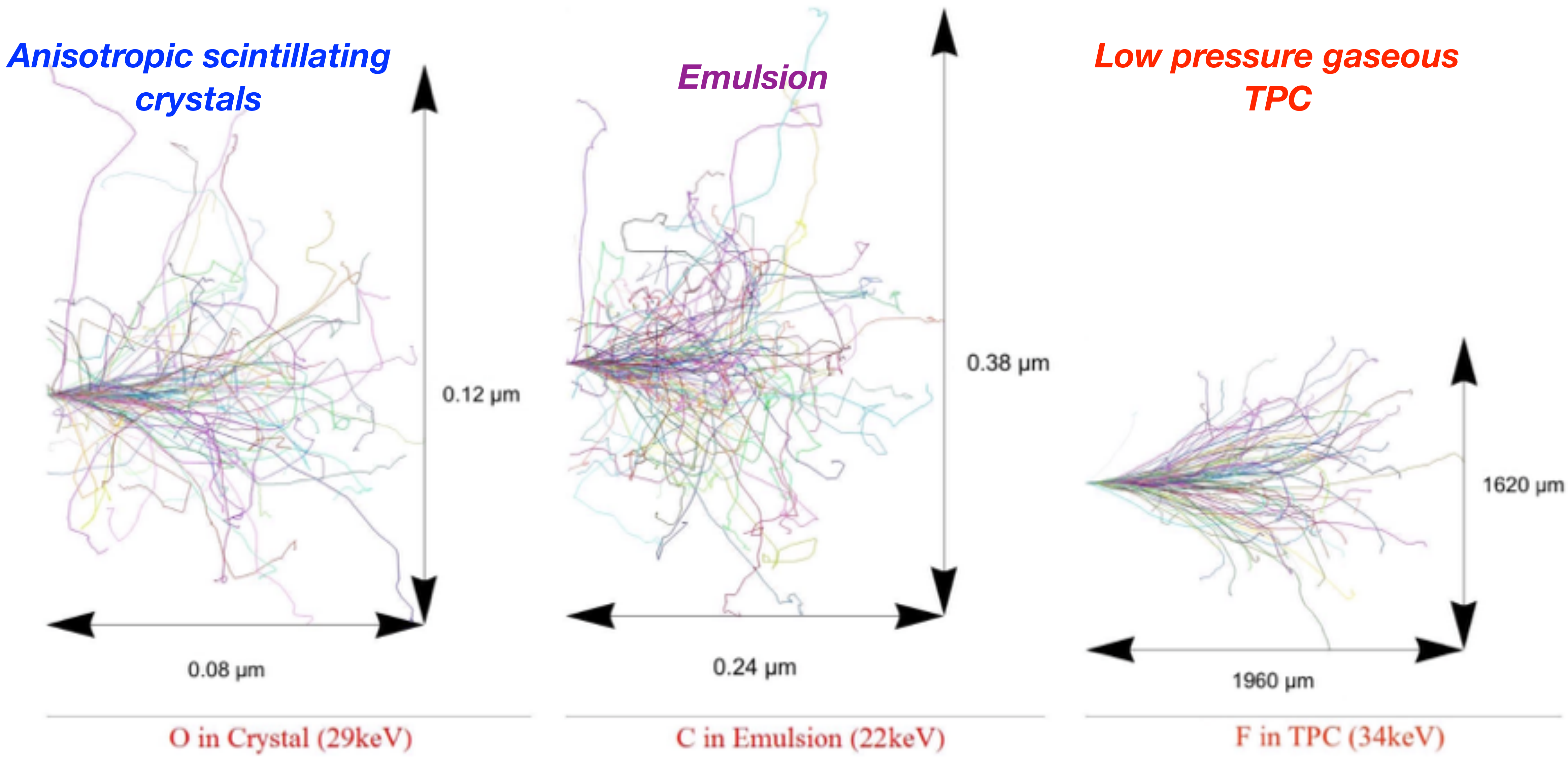
- Depending on track reconstruction capabilities (angular resolution and 1D/2D/3D readout) the irreducible neutrino background can be largely subtracted
- This works particularly well for solar neutrinos as atmospheric ones are isotropic …
    - ***This is a great motivation to build a ton-scale directional experiment !***

Directional detection: *experiment*

Directional detection: *experiment*

C. Couturier et al, arXiv:1607.08157

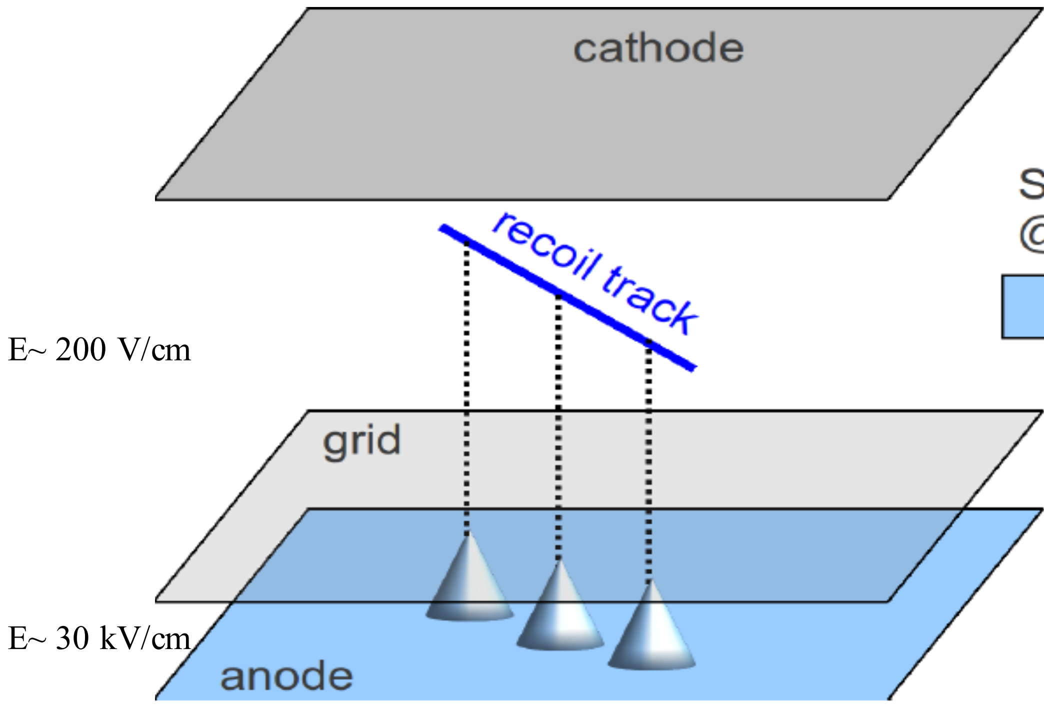
What detector material to use?



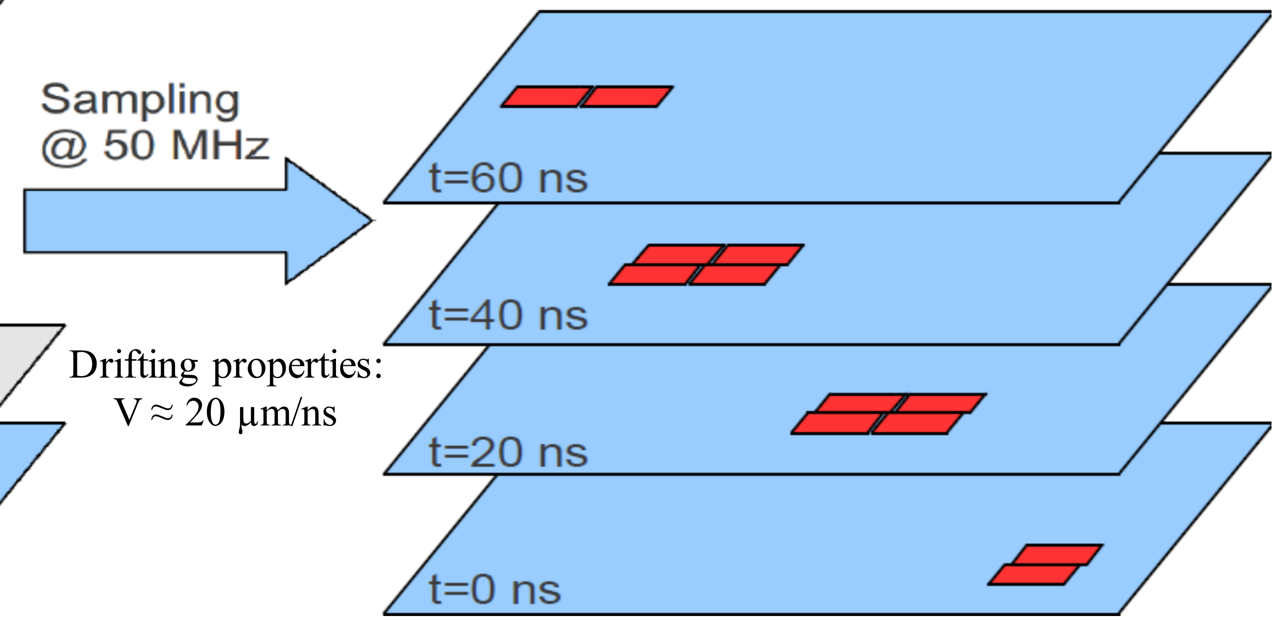
- Many ideas and R&D projects are ongoing to perform directional detection of Dark Matter
- Low pressure (few tens of mbar) gaseous TPC are intrinsically better suited for this purpose

Directional detection: *experiment (MIMAC)*

MIMAC detection strategy

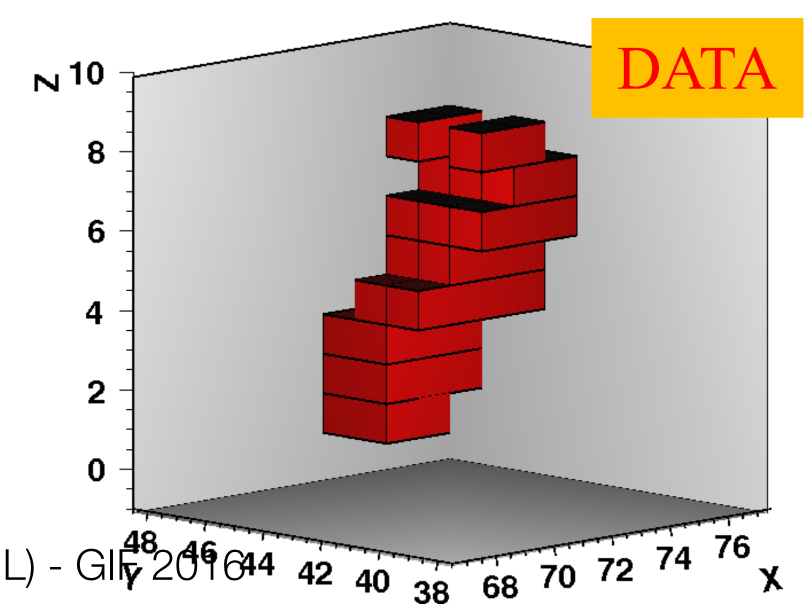


Scheme of a MIMAC μTPC



Evolution of the collected charges on the anode

Measurement of the ionization energy: Charge integrator connected to the grid



$70\ \%\ CF_4 + 28\%\ CHF_3 + 2\%\ C_4H_{10}$

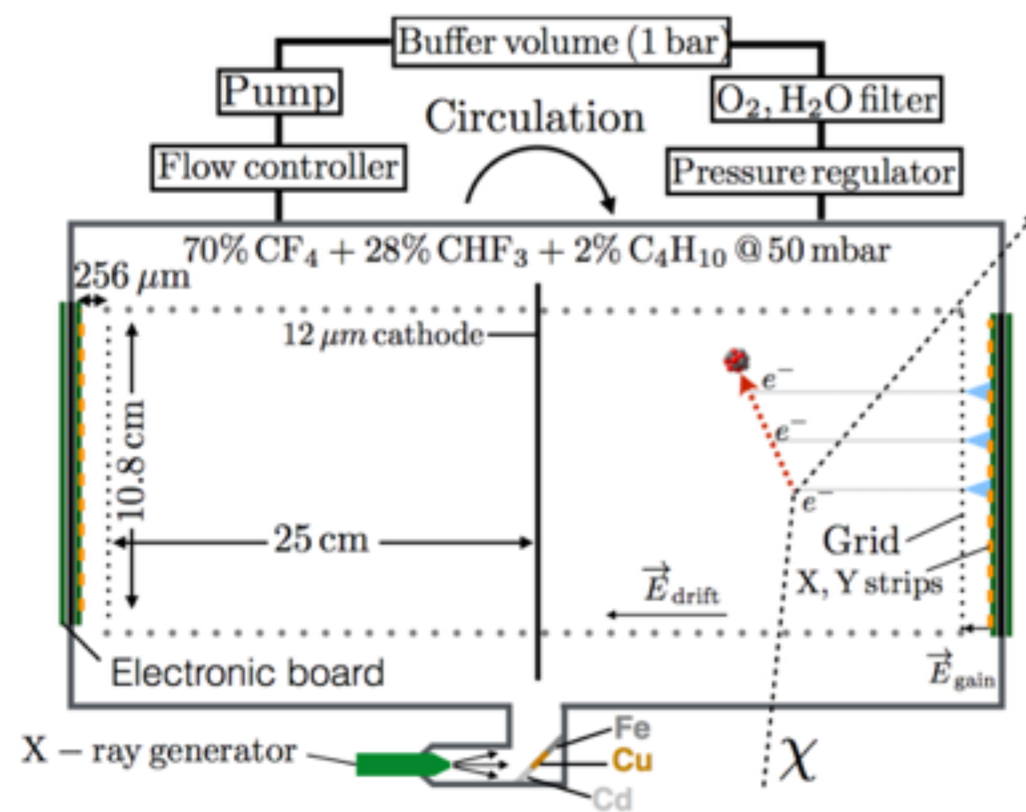
50 mbar,
170 V/cm

Fluorine candidate
@ 50 keV ionization

Directional detection: *experiment (MIMAC)*

The MIMAC experiment

- MIMAC is installed in LSM since 2012
- It now consists of a dual-chamber facing each other sharing a common cathode
- It is filled with CF4+CHF3+C4H10 at 50 mbar corresponding to a total target mass of a few grams
- In a permanent circulation mode to ensure high gas quality and purity, removing oxygen and water
- In-situ ionization energy calibration done twice a week thanks to an X-ray generator
    - ***Next phase is a 1m3 detector***

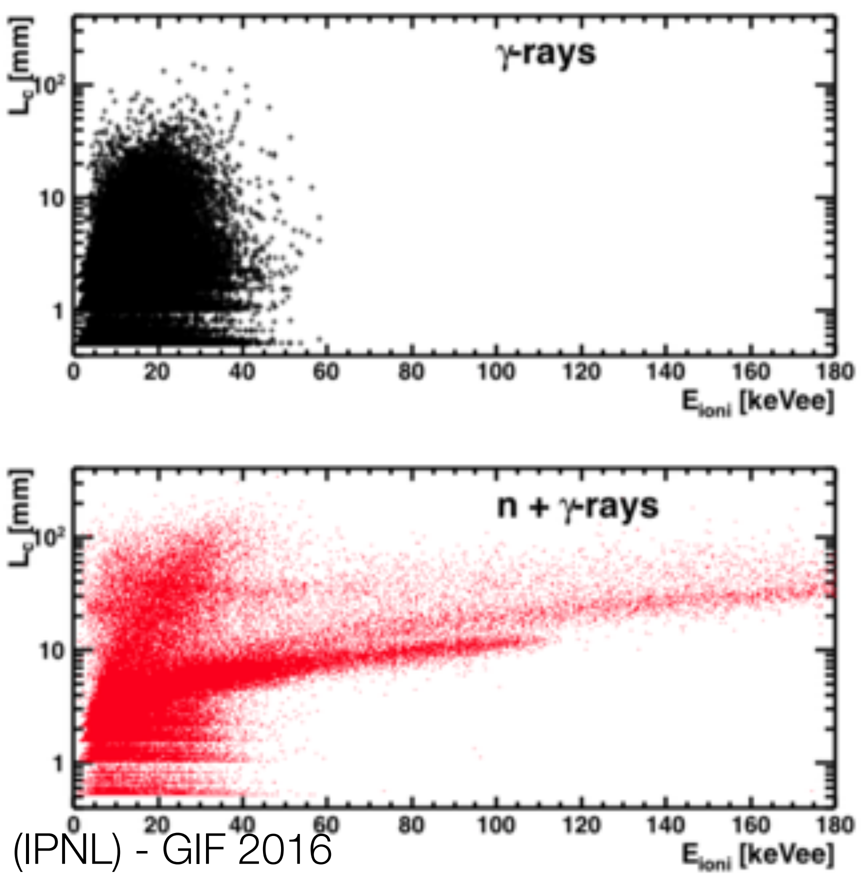


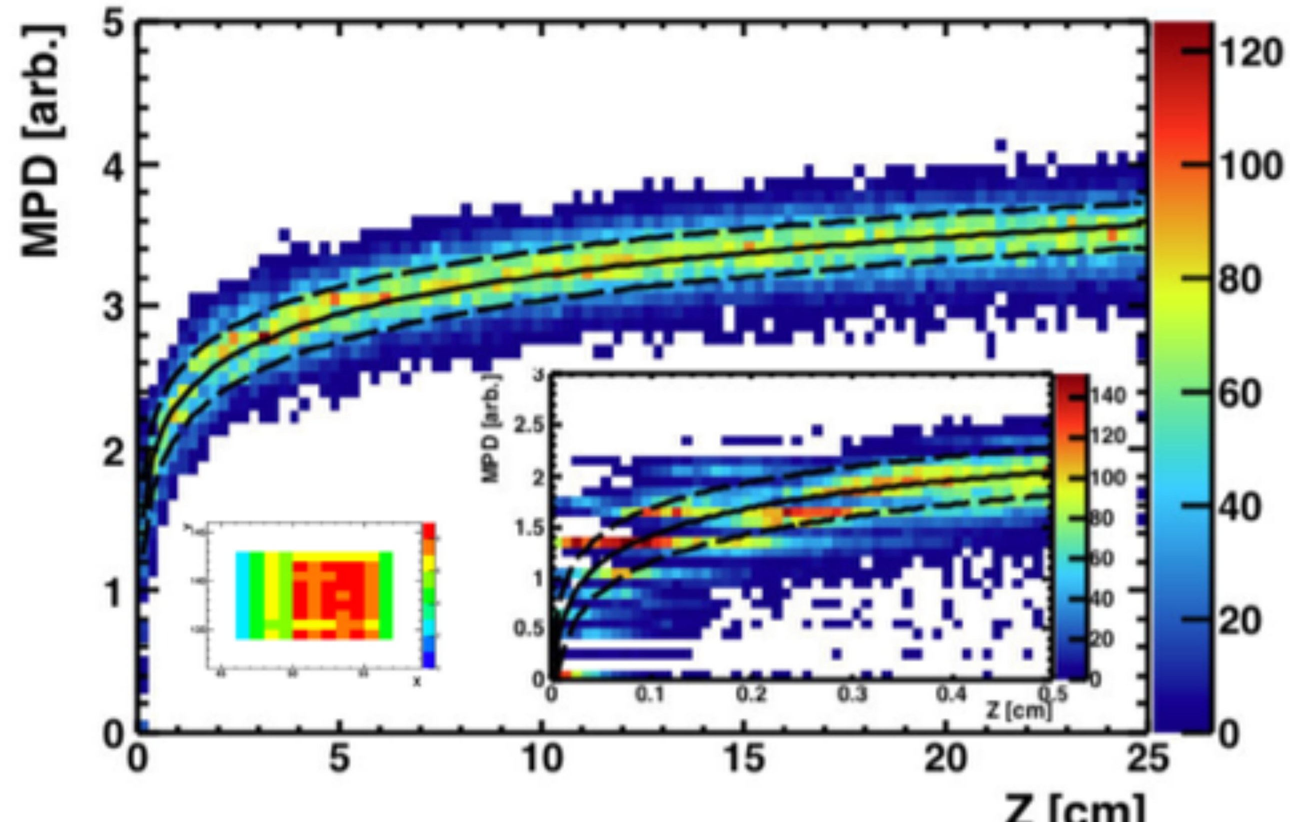
Directional detection: *experiment (MIMAC)*

Q. Riffard, PhD thesis (Grenoble) 2016

MIMAC strategy

- Electronic recoils have a much lower dE/dx than nuclear recoils so for a given recoil energy, ER tracks are much longer the NR tracks —> ***ER/NR discrimination***
- Because of diffusions of primary ionization electrons, surface events from the anode/cathode can be rejected and events from the side are rejected thanks to event location on the pixelized anode —> ***3D fiducialization***
- Furthermore, 210Pb alpha decay events are rejected from chamber 1/2 coincidences

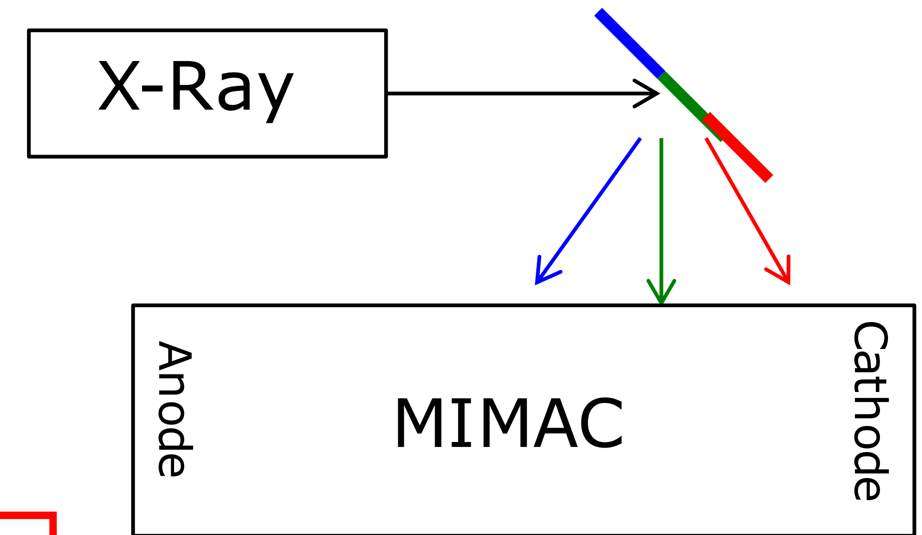




Directional detection: *experiment (MIMAC)*

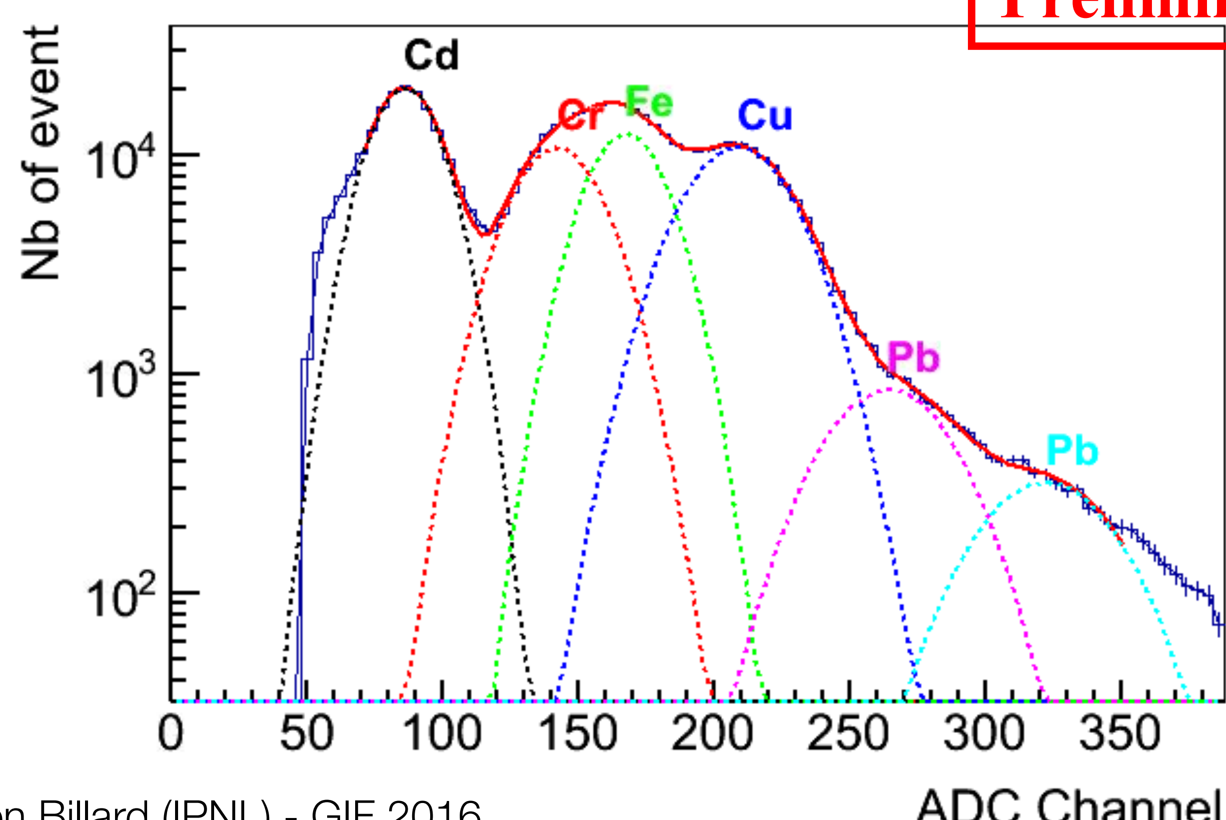
Ionization energy calibration

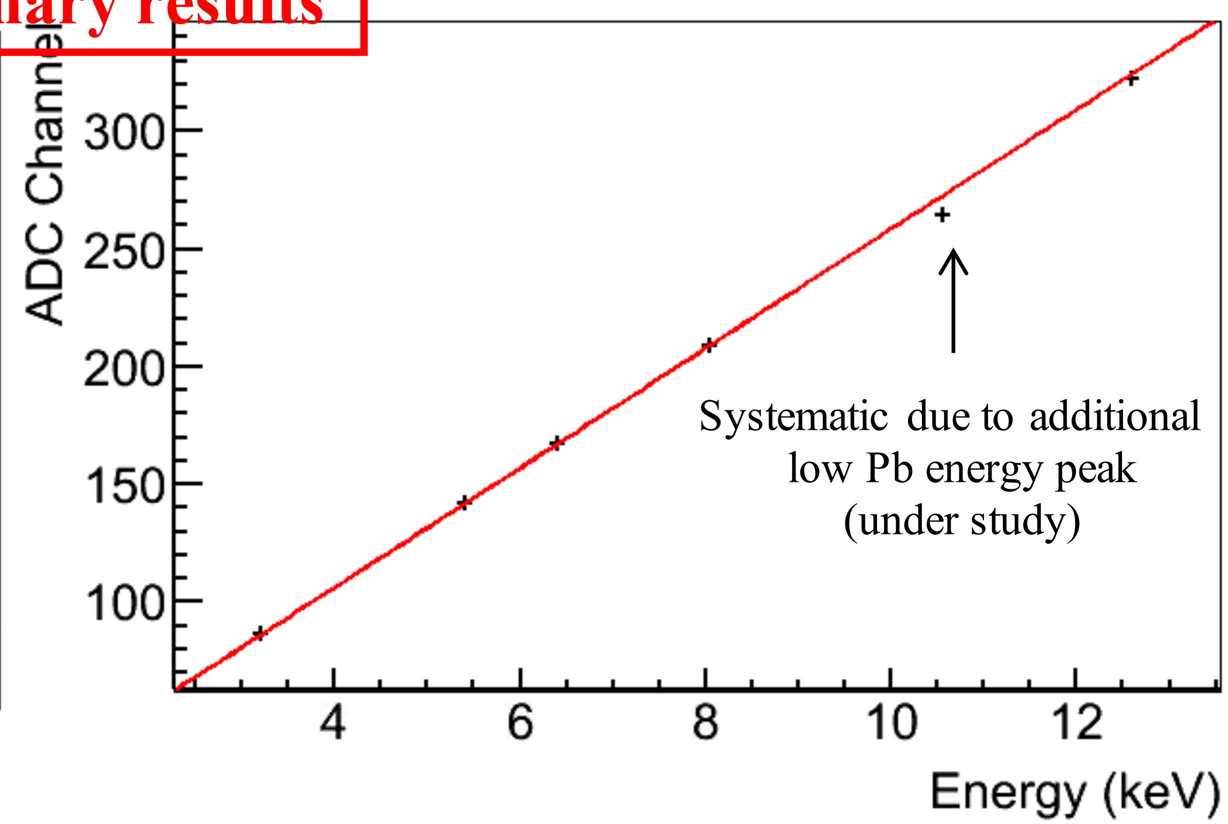
- X-Ray tube (Amptek)
- Foil of Cd, Cu, Pb (fluorescence)
- Cr and Fe lines from detector materials



J. Lamblin et al., in preparation

Preliminary results



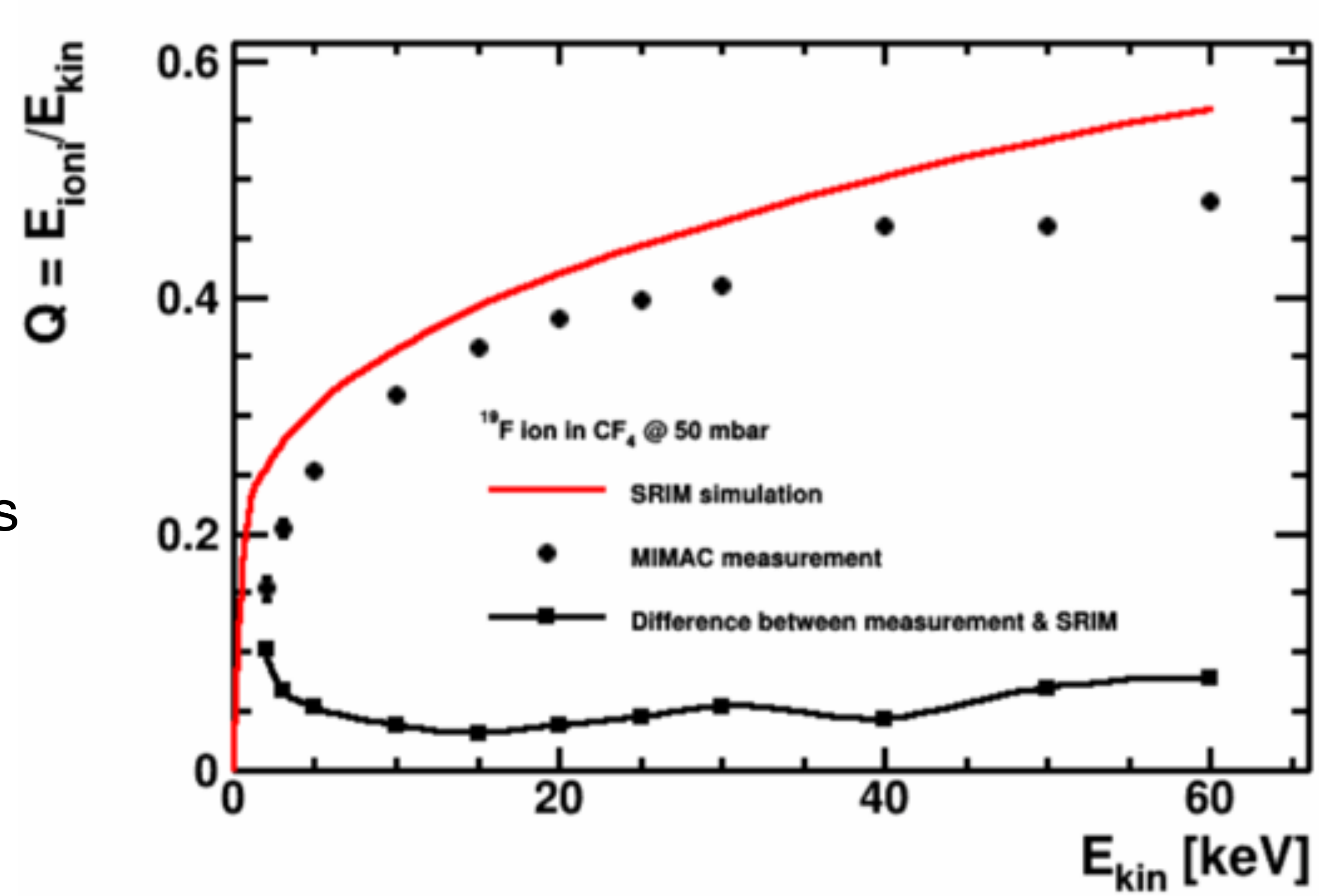


Directional detection: *experiment (MIMAC)*

Q. Riffard, PhD thesis (Grenoble) 2016

Calibration of the nuclear recoil energy scale

- The MIMAC collaboration has developed a low energy ion source to accurately measure the ionization yield of nuclear recoils
- They can measure the ionization yield for different ions in different gases and pressures
- Observe deviations from standard Lindhard predictions, like DAMIC in Si
- This is a very unique setup !

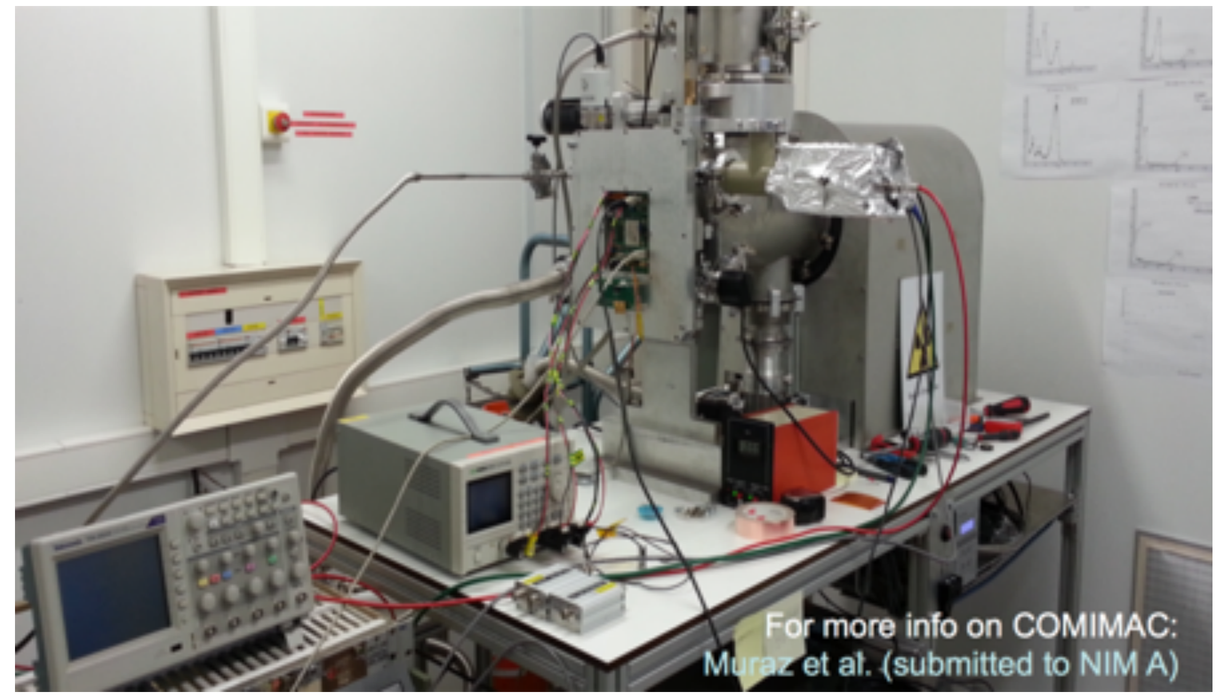


Directional detection: *experiment (MIMAC)*

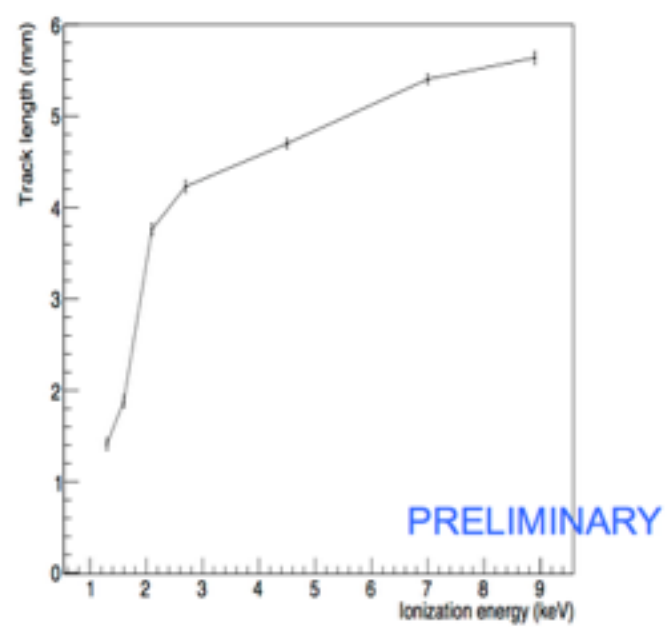
C. Couturier et al, in preparation

Studying the NR track properties

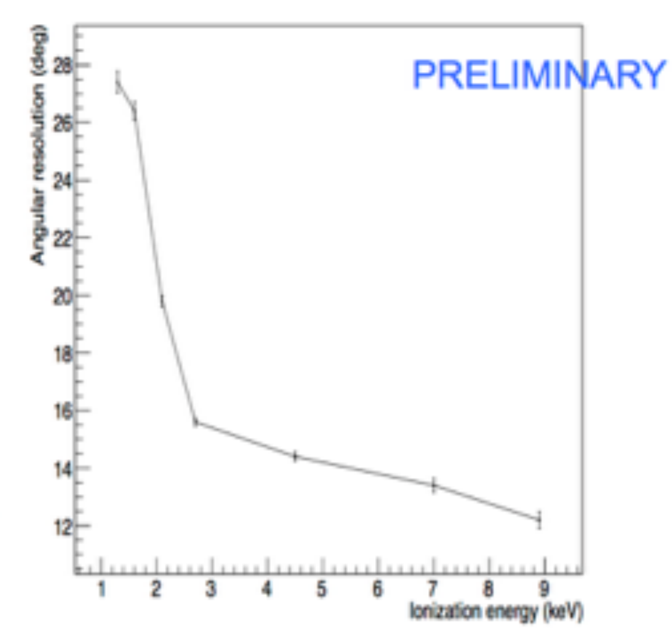
- The MIMAC collaboration has developed a ***small*** low energy ion source that can be coupled to a MIMAC prototype to study the nuclear recoil track properties
- They have been able to measure the track length (***few mm***) at various energies and also derive the angular resolution of the experiment
- For a few keVnr F recoil, they show an angular resolution of about ***20 degrees***, which is enough to perform an accurate directional detection of dark matter



- Track



- Angular resolution

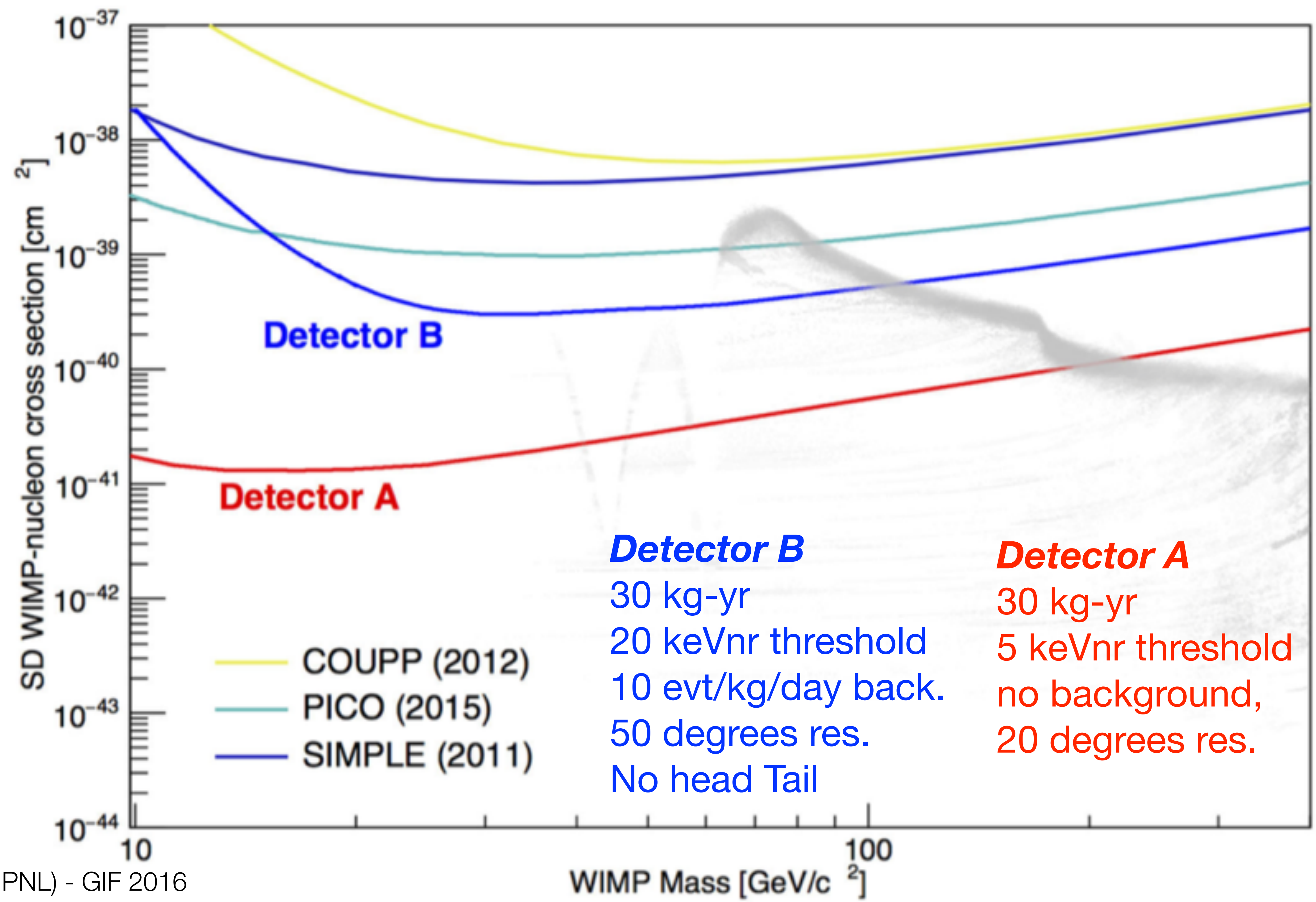


Couturier et al. (in preparation)

Directional detection: *experiment (MIMAC)*

Q. Riffard, PhD thesis (Grenoble) 2016

Future sensitivities



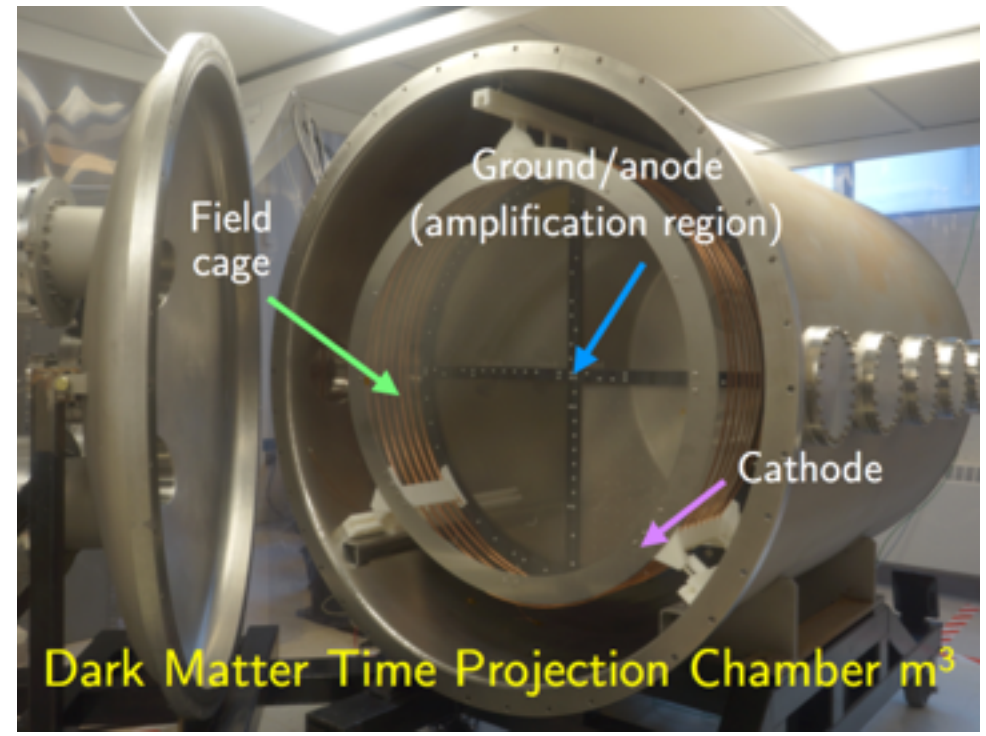
Detector B
30 kg-yr
20 keVnr threshold
10 evt/kg/day back.
50 degrees res.
No head Tail

Detector A
30 kg-yr
5 keVnr threshold
no background,
20 degrees res.

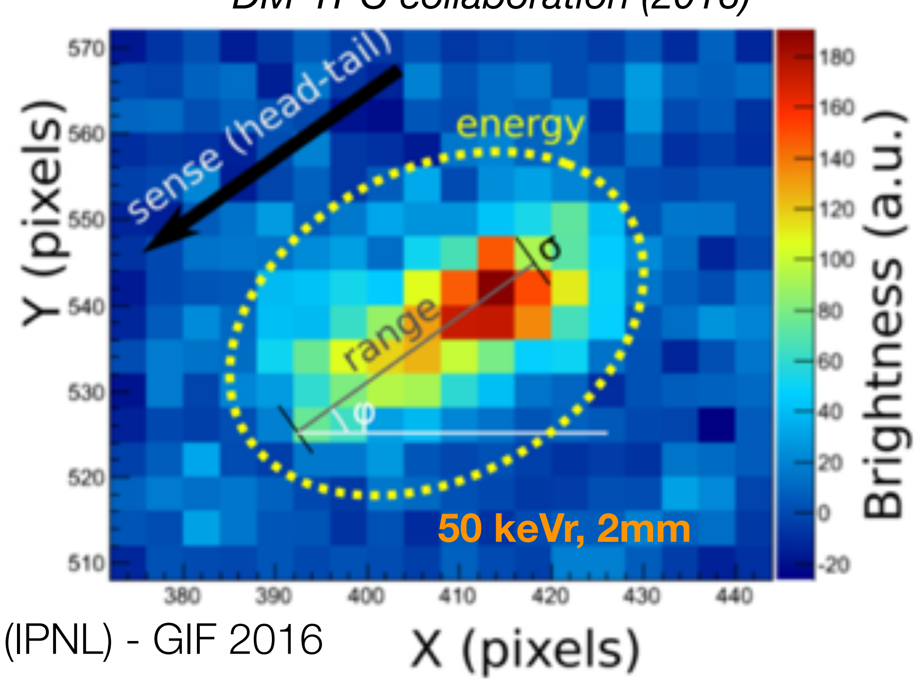
Directional detection: *experiment (DMTPC)*

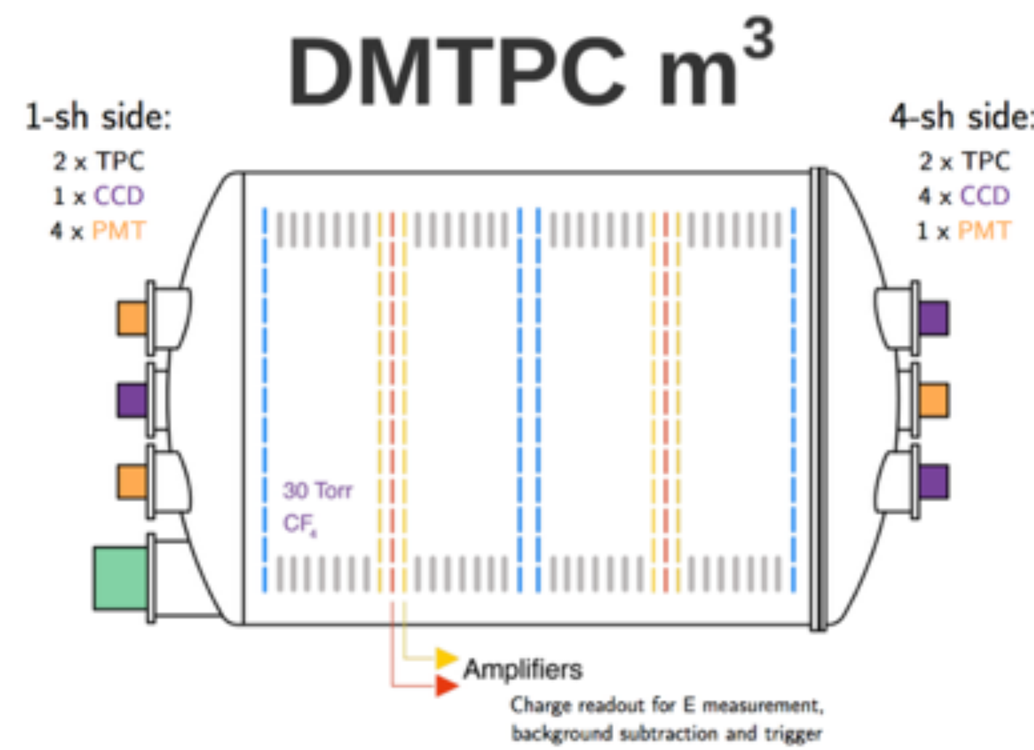
DMTPC, IDM2016

- DMTPC experiment measures the track information and energy from secondary scintillation using a CCD and CF4 gas at 50 mbar.
- PMTs are used for coincidence, energy measurement (and primary scintillation ?)
- Energy also readout by Charge Sensitive Preamplifier on the mesh
- 2D track readout, with projected-z reconstruction
- XYZ fiducialization ~ not sensitive to ER
- first 1m3 module to be installed in SNOLAB soon !



DM-TPC collaboration (2016)

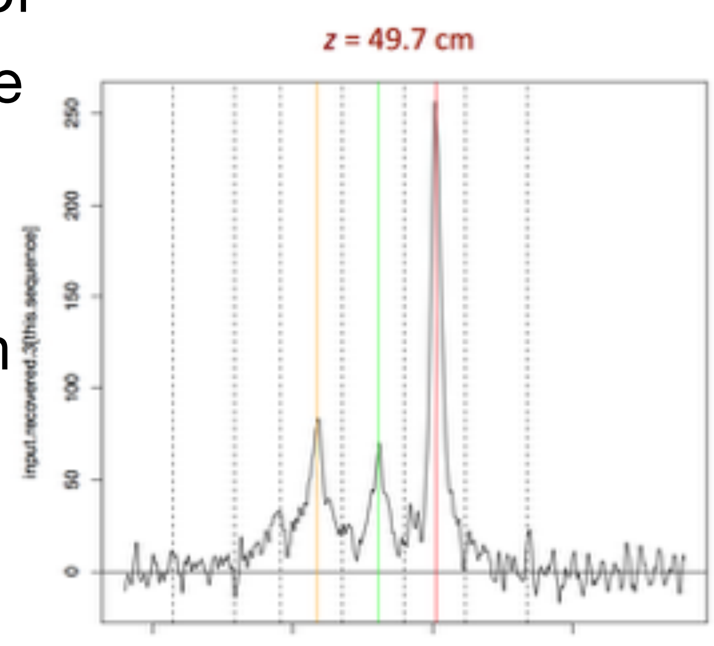


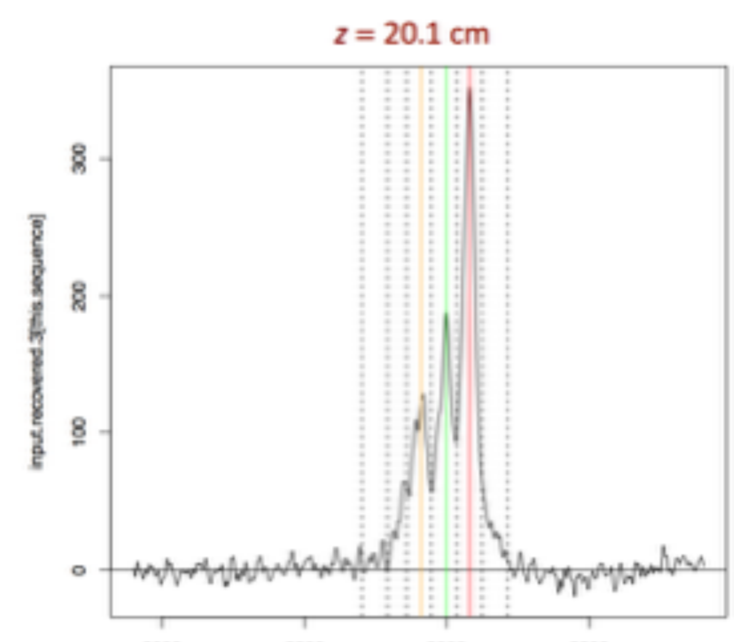


Directional detection: *experiment (DRIFT)*

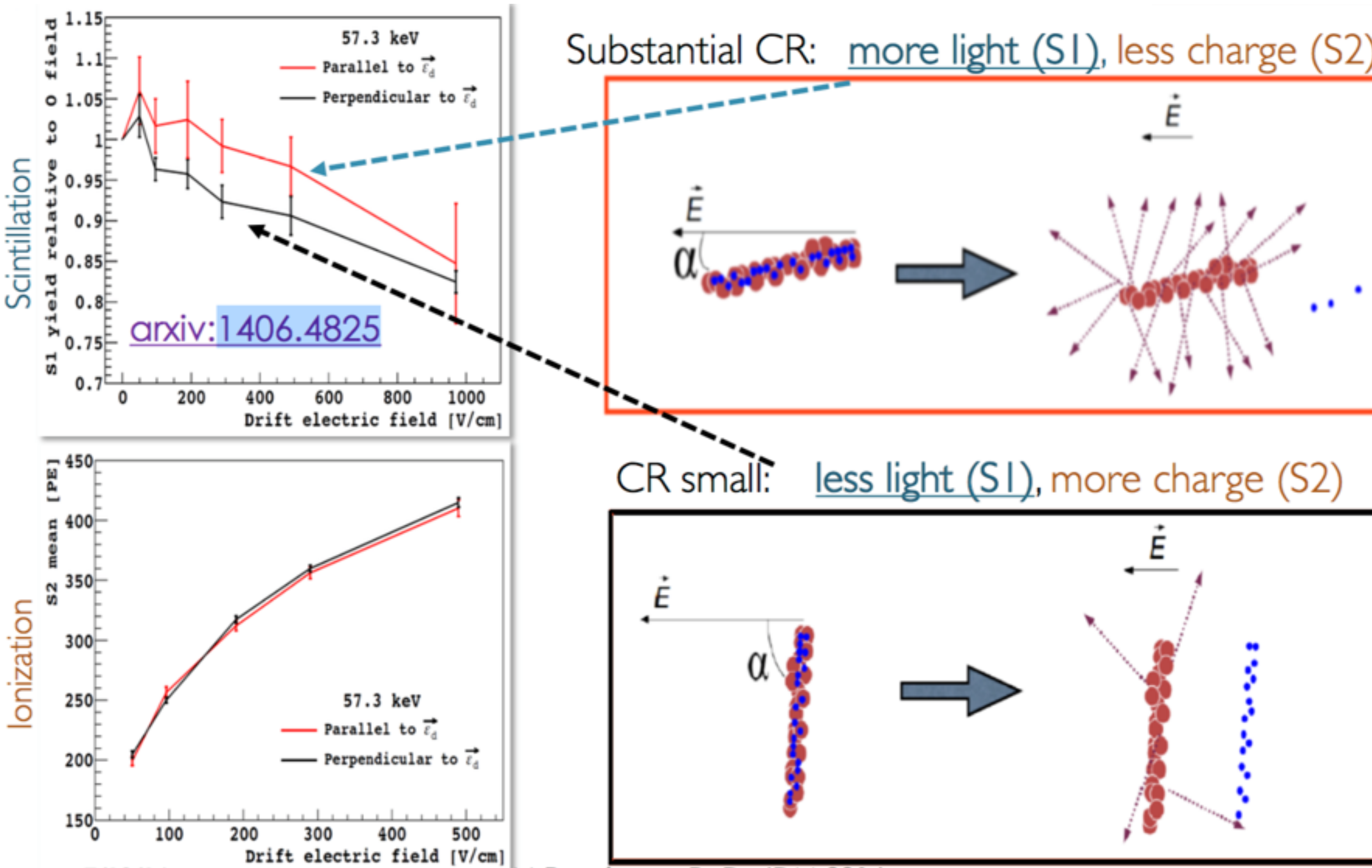
DRIFT, UCLA dark matter 2016

- Drift has pioneered the field of directional detection since 2001
- Using 1m3 detector filled with CS2 at ~50 mbar and MWPC
- Negative ion diffuse much less: longer drift distance
- They successfully got rid of Radon progeny thanks to 0.9 um texturized thin mylar cathode
- Very limited tracking resolution because of the pitch of 2 mm between wires but have good XY resolution
- Thanks to minority carriers from O2 contamination they recover the Z position
- ***They are now background free ! (for now…)***





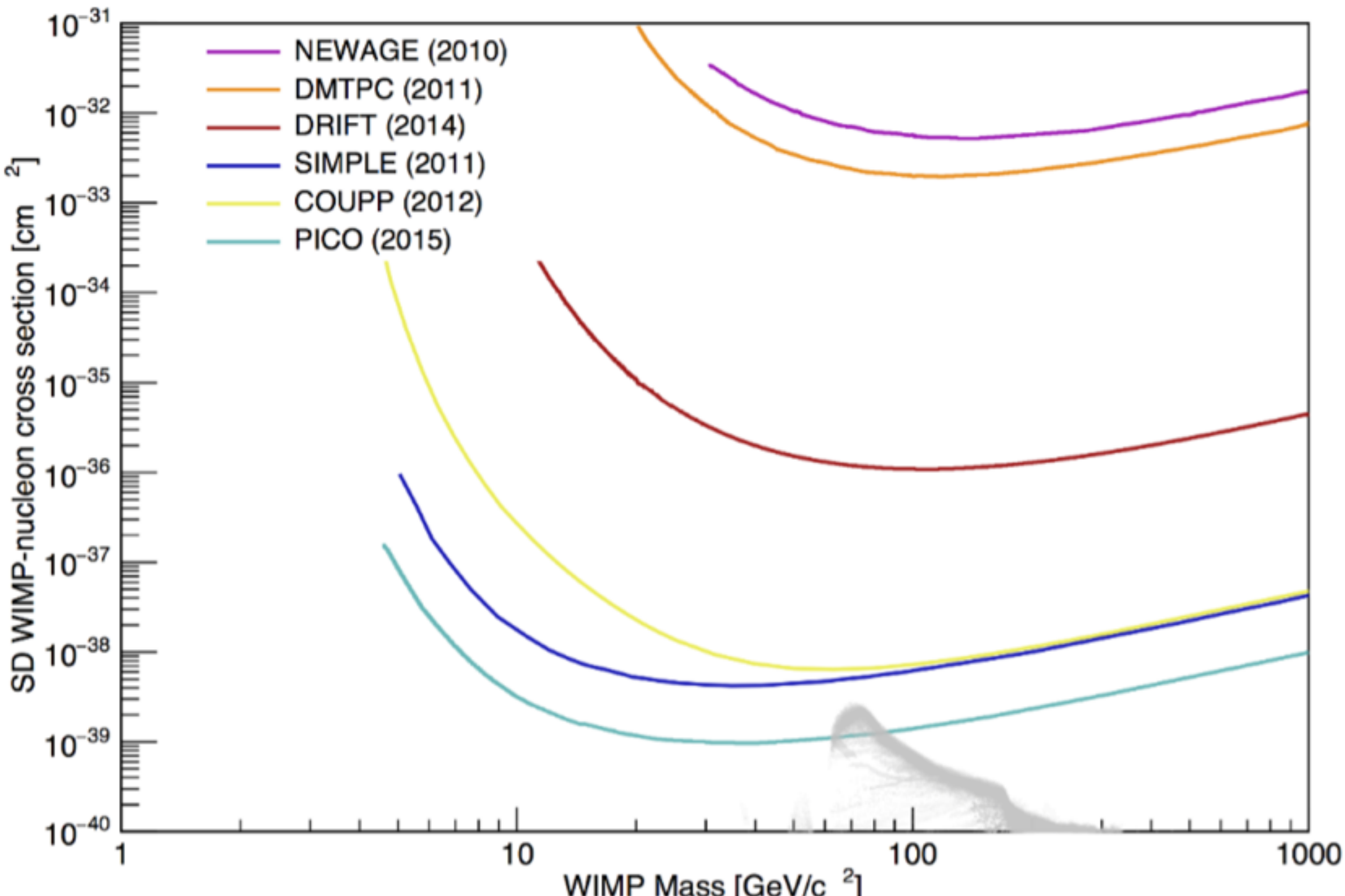
Directional detection: *Columnar Recombination?*



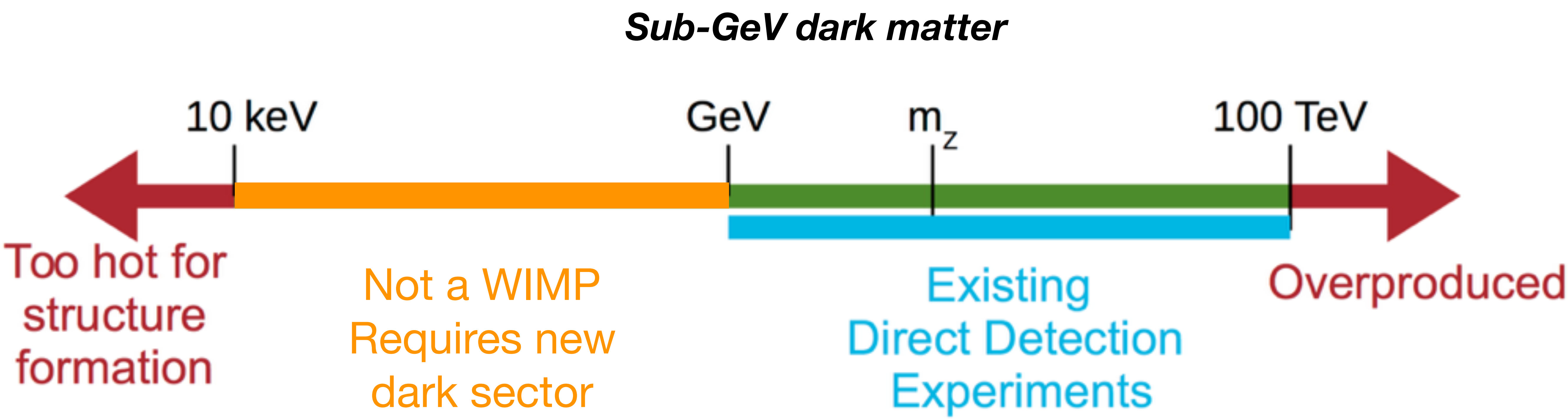
Courtesy M.Cadeddu (CA)

Directional detection: *other experiments*

Q. Riffard, PhD thesis (Grenoble) 2016

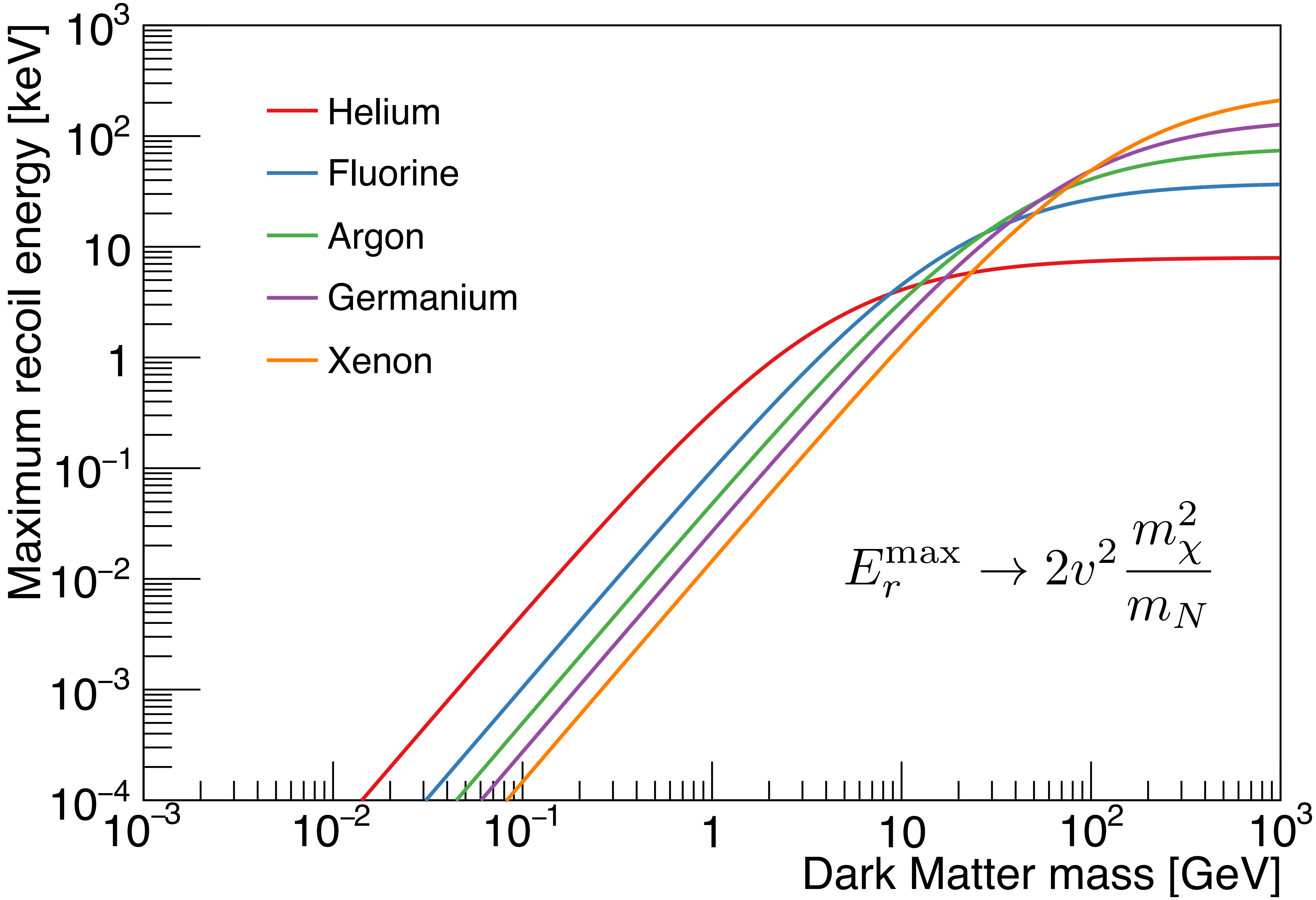


Light Dark Matter (1 MeV - 1 GeV)



- A WIMP candidate is limited to a few GeV (Lee-Weinberg limit)
- Light Dark Matter is however becoming motivated as no evidence of SUSY at LHC so more exotic models might be required
- To avoid the lower bound, one possibility is to postulate the existence of a new light bosons connecting the dark (hidden) sector to the Standard Model
- Increases annihilation cross section and reduces Dark Matter coupling to SM to satisfy accelerator constraints

Light Dark Matter (1 MeV - 1 GeV)

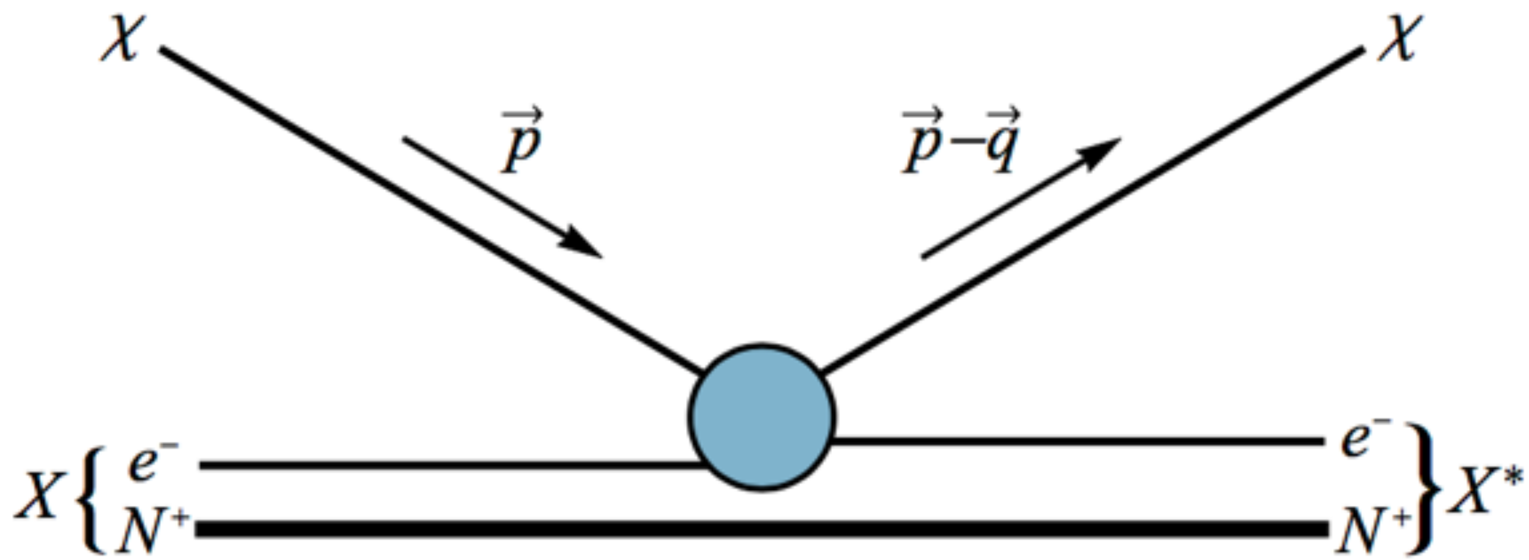


But direct detection of Sub-GeV dark matter via nuclear recoil is impossible !

Light Dark Matter (1 MeV - 1 GeV)

R. Essig et al., JHEP 1605 (2016)

Dark Matter - electron scattering



$$E_\chi + E_e + E_N = E'_\chi + E'_e + E'_N$$

$$\Delta E_e = -\Delta E_\chi - \Delta E_N \qquad (E_N = 0, E_e \neq 0)$$

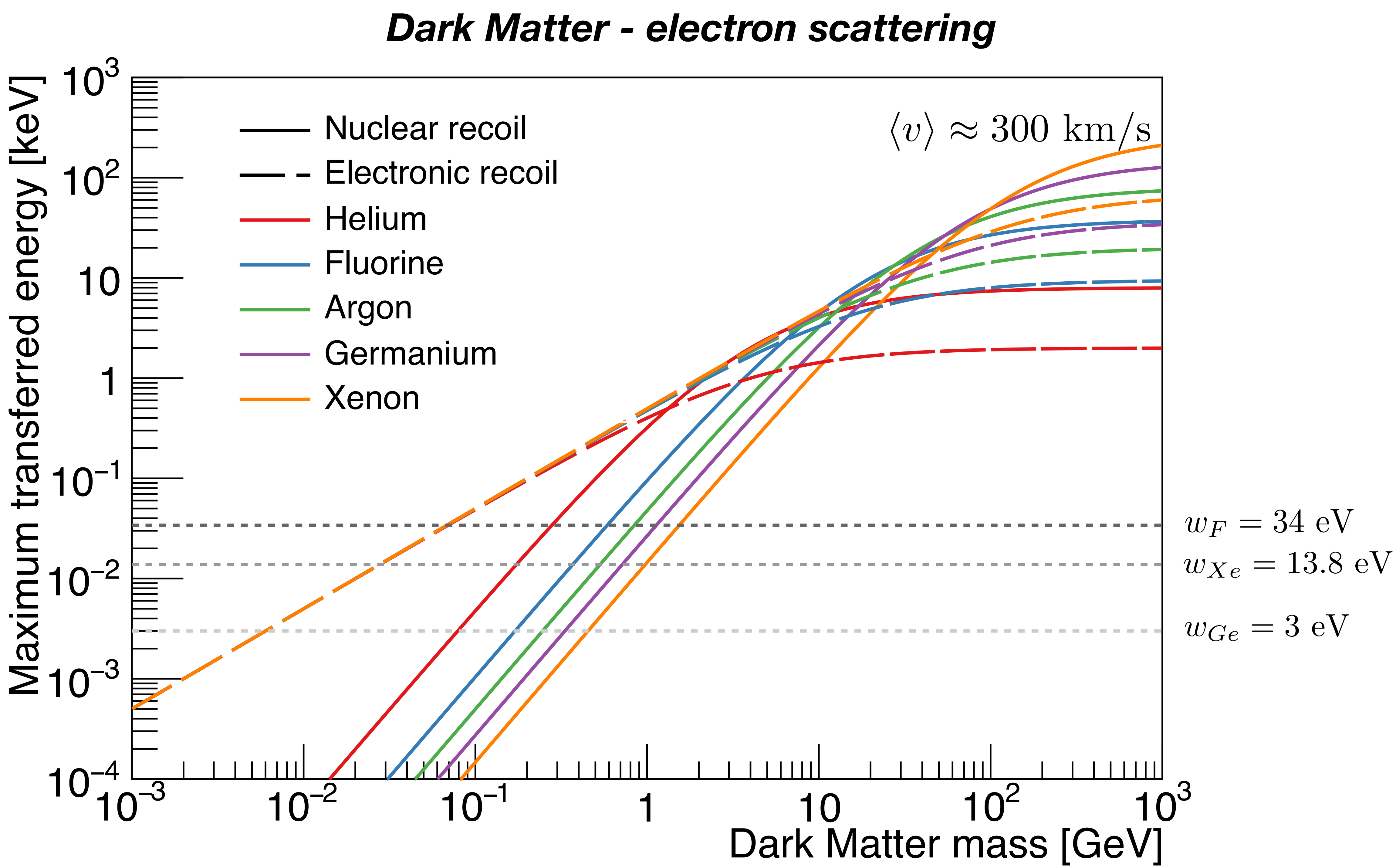
- We can then easily derive the ***transferred energy*** to the bound electron:

$$\Delta E_e = \frac{1}{2} m_\chi v^2 - \frac{|m_\chi \vec{v} - \vec{q}|}{2m_\chi} - \frac{q^2}{2m_N} = \vec{q}.\vec{v} - \frac{q^2}{2\mu_{\chi N}}$$

- The maximum transferred energy to the bound electron is equal to:

$$\Delta E_e^{\max} = \frac{1}{2}\mu_{\chi N} v^2 \qquad (\text{for } q = \mu_{\chi N} v)$$

Light Dark Matter (1 MeV - 1 GeV)



For DM masses below 1 GeV, only DM-electron scattering can potentially be considered

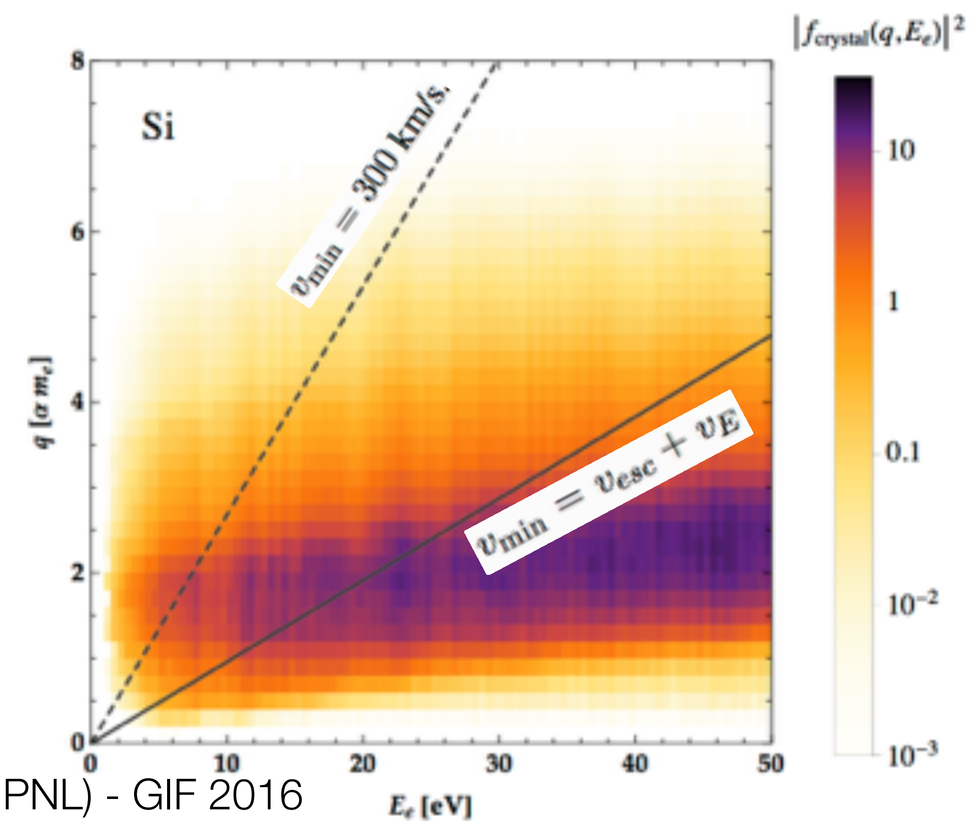
Light Dark Matter (1 MeV - 1 GeV)

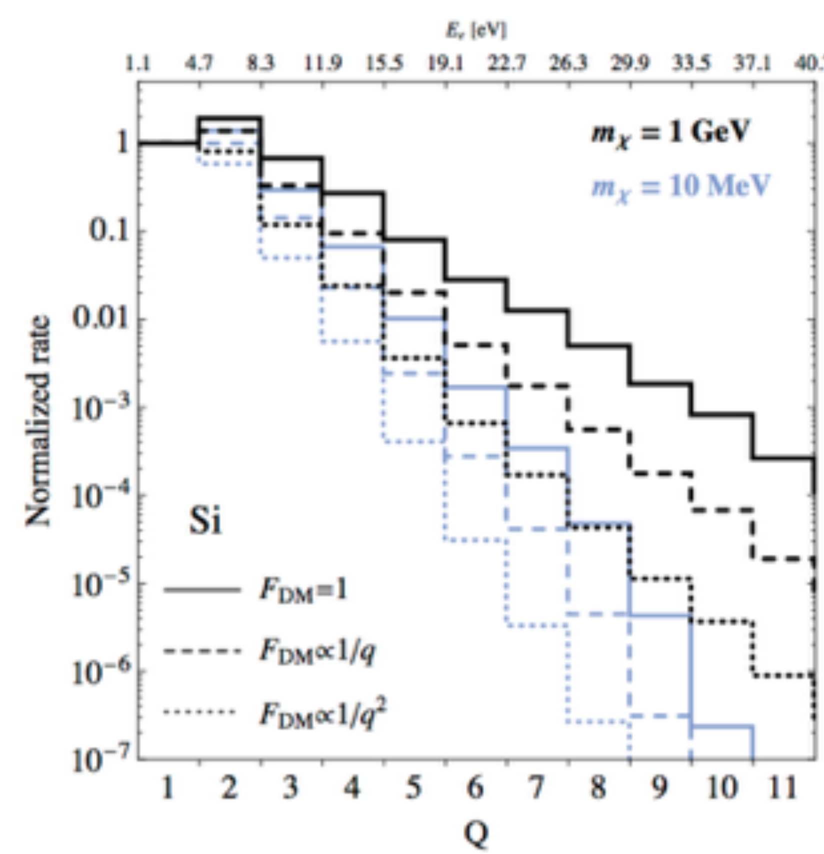
R. Essig et al., JHEP 1605 (2016)

Dark Matter - electron scattering

- The A' boson is kinetically mixed with the SM photon $\mathcal{L} \supset \frac{\epsilon}{2\cos\theta_W} F_Y^{\mu\nu} F'_{\mu\nu}$
- The cross section and form factors are then derived as: $\overline{\sigma}_e = \frac{16\pi\mu_{\chi e}^2 \alpha\epsilon^2\alpha_D}{(m_{A'}^2 + \alpha^2 m_e^2)^2}$ $F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2}$
- The differential event rate in the crystal is given by:

$$\frac{dR_{\text{crystal}}}{d\ln E_e} = \frac{\rho_\chi}{m_\chi} N_{\text{cell}}\overline{\sigma}_e\alpha \times \frac{m_e^2}{\mu_{\chi e}^2}\int d\ln q \left(\frac{E_e}{q}\eta(v_{\min}(q,E_e))\right) F_{\text{DM}}(q)^2 |f_{\text{crystal}}(q,E_e)|^2$$



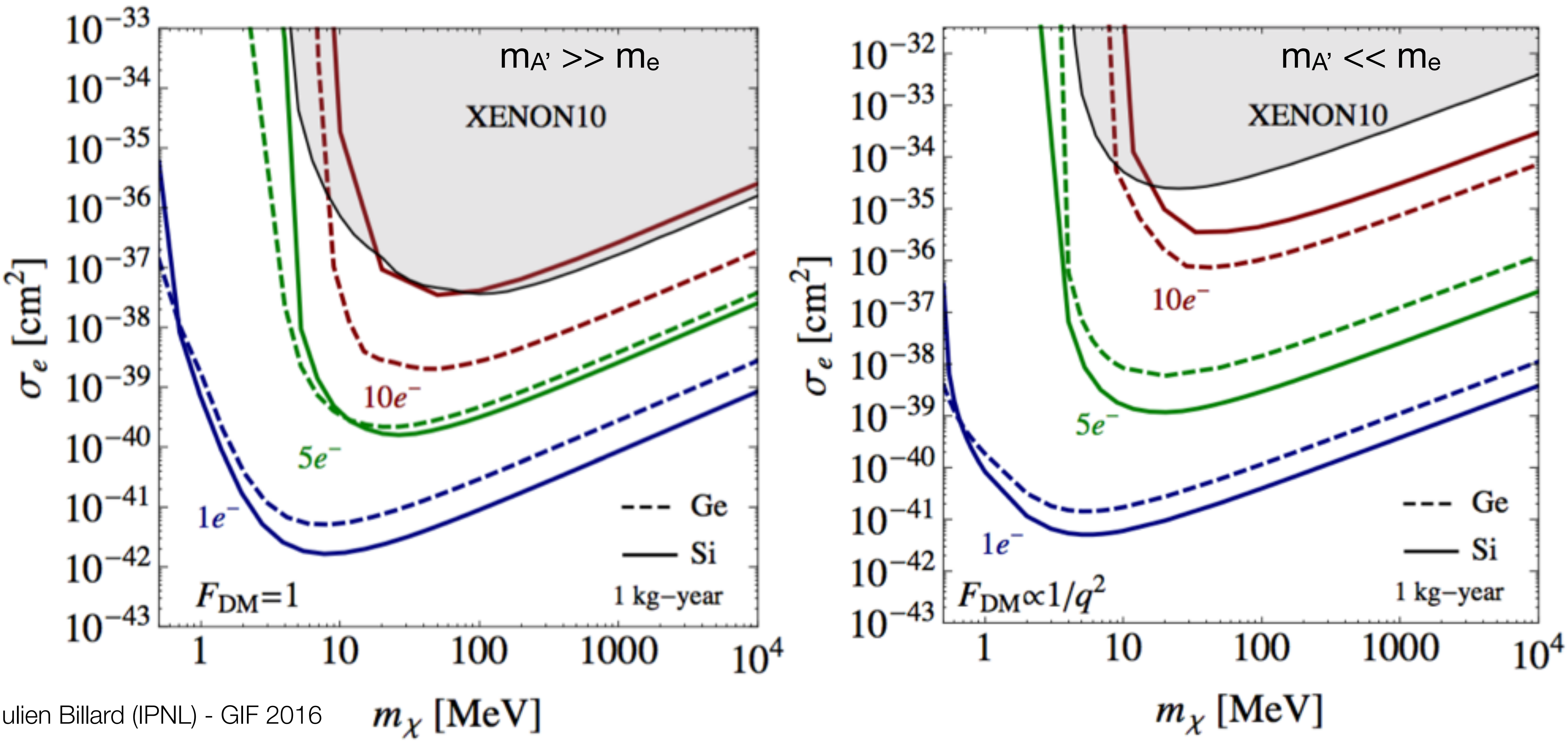


Light Dark Matter (1 MeV - 1 GeV)

R. Essig et al., PRL 109 (2012)

R. Essig et al., JHEP 1605 (2016)

- First experimental result from XENON 10 (2012) as sensitive to single electron
- No new S2 only analyses from LXe experiments because of large single-e⁻ background
- Most sensitive experiment in the future will be solid state detectors thanks to lower W-value



Conclusions

Take away points:

- Precision cosmology, including many probes (BAO, CMB, structure formation, BBN, …) suggest that the matter/energy budget of the Universe is made of 23% of cold dark matter

- Stellar kinematics suggests that our Milky Way is immersed in a dark matter halo which outweighs the baryonic disk by a factor of 10 suggesting that we can directly detect this new particle (WIMP?)

- Noble gas TPC is the leading search strategy above 10 GeV while solid state (cryogenic) experiments are particularly well suited for low WIMP mass

- Both strategies will soon encounter the ultimate neutrino background (first detection of CNS!)

- Directional detection is getting ready to probe the nature of Dark Matter in a « post-discovery » era

- Meanwhile we should keep an open mind and not be afraid of more exotic theoretical scenarios and experimental strategies