Directional detection: status and challenges

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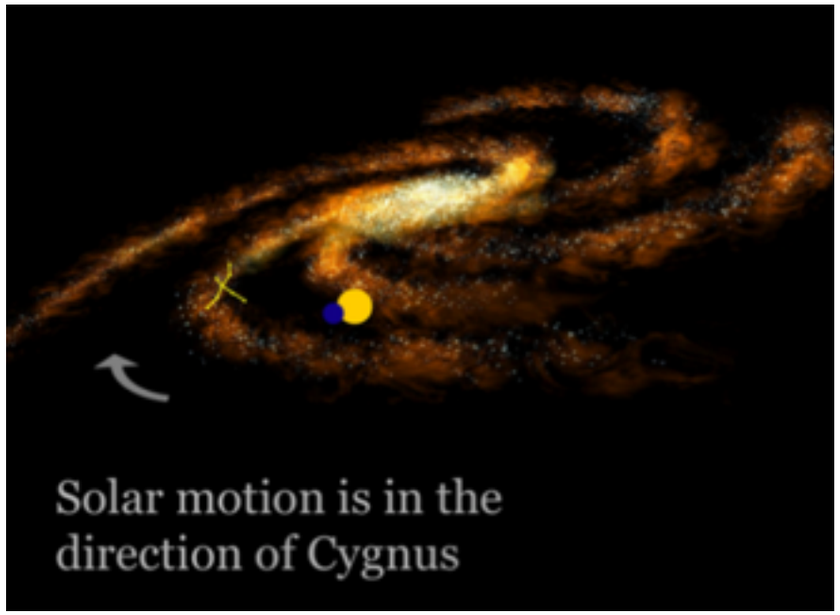
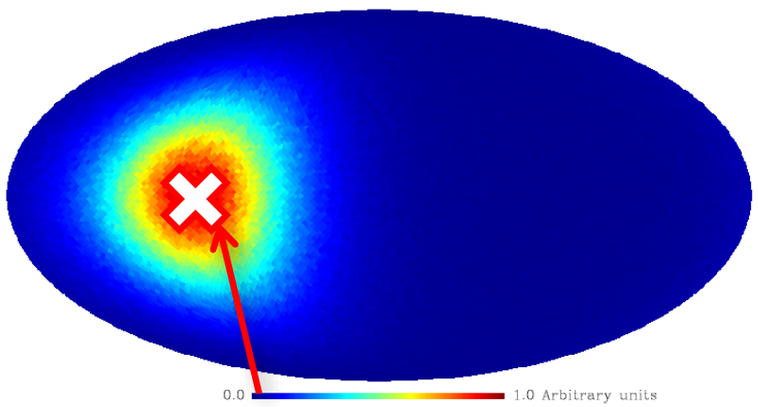
Directional detection: *introduction*

- 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

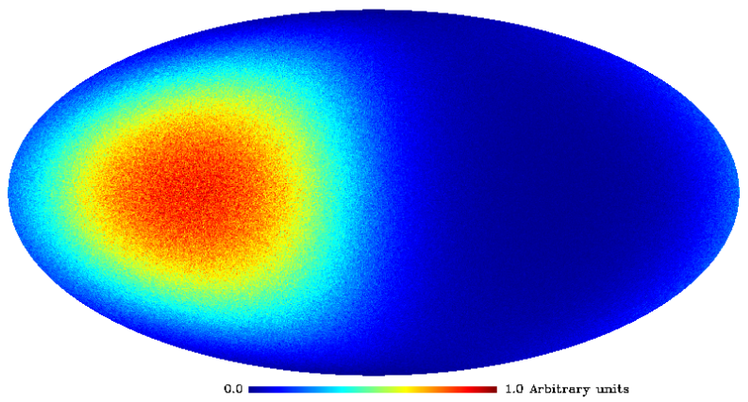


Cygnus Constellation $(l = 90^\circ, b = 0^\circ)$

After scattering

$m_{WIMP} = 100\ GeV/c^2$

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



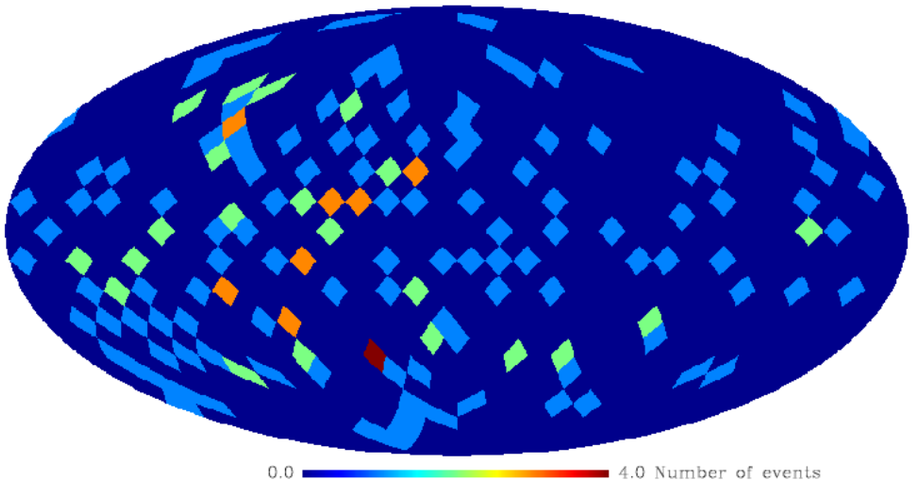
Expected WIMP signal

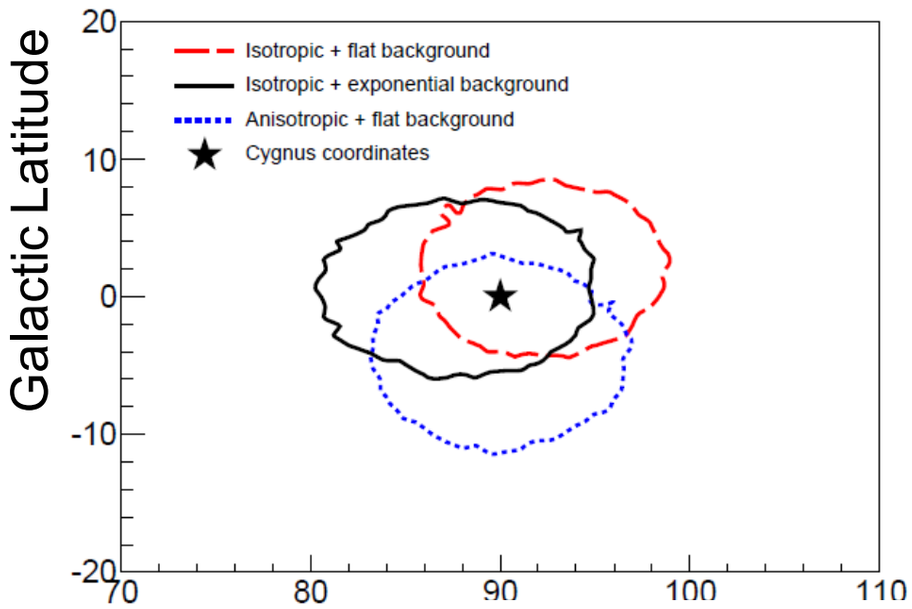
Directional detection: *smoking gun*

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

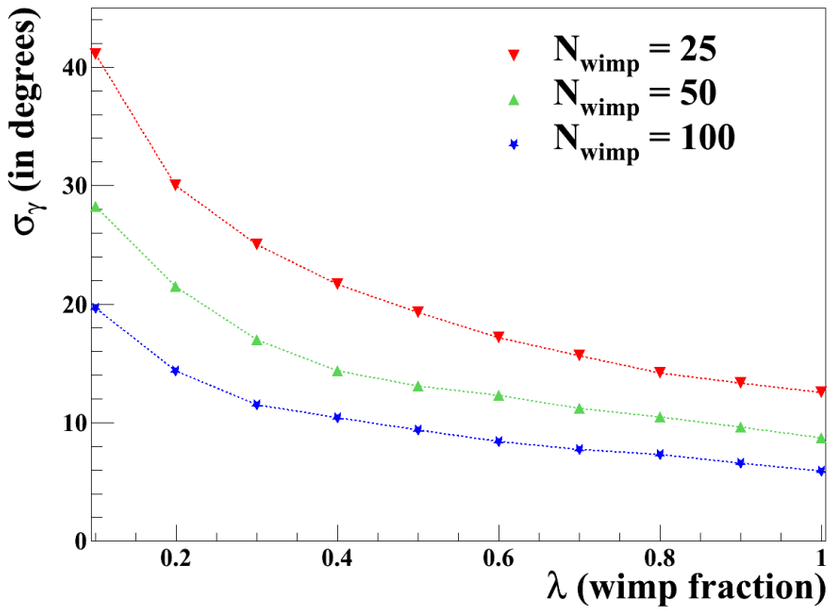
Directional detection as a tool for a definitive discovery

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

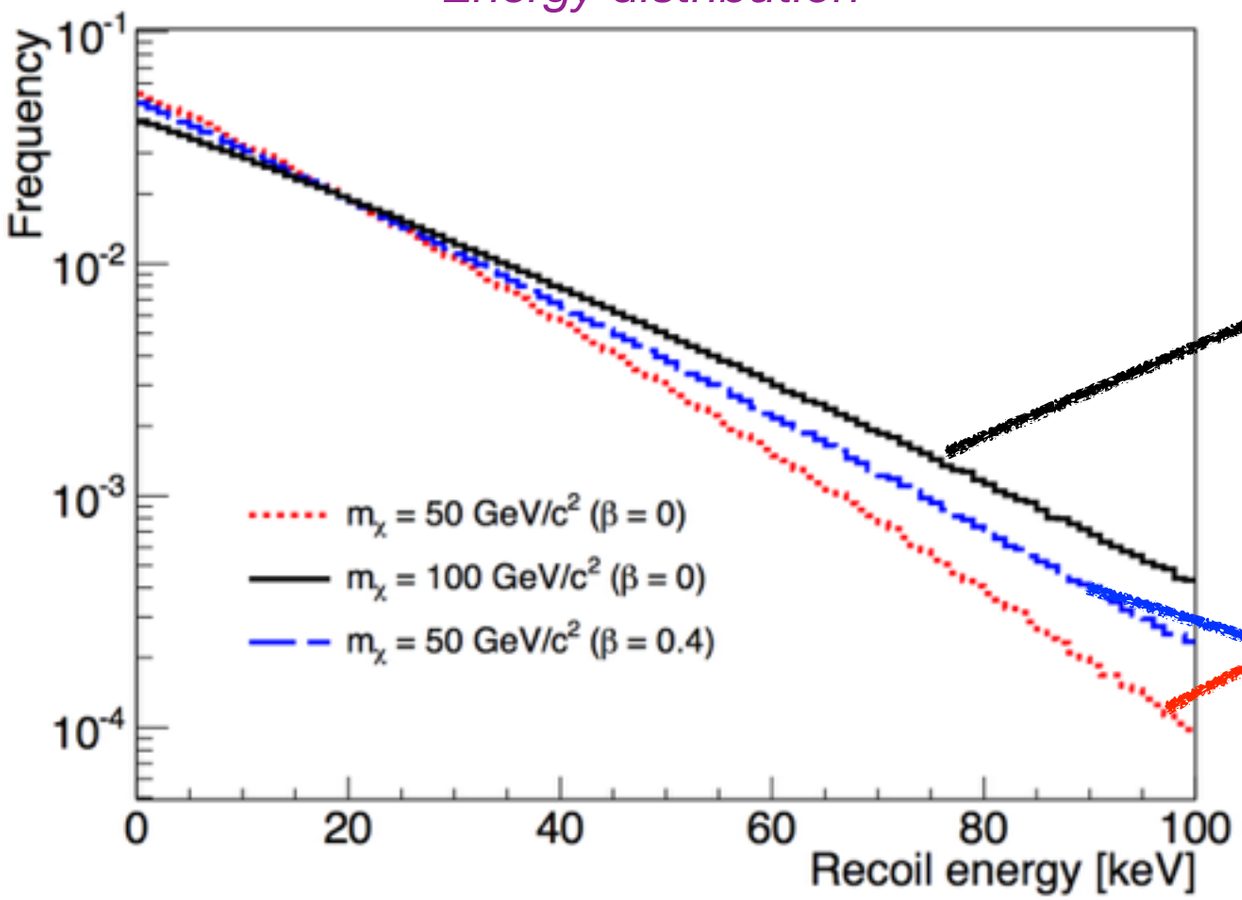


Directional detection: *WIMP astronomy*

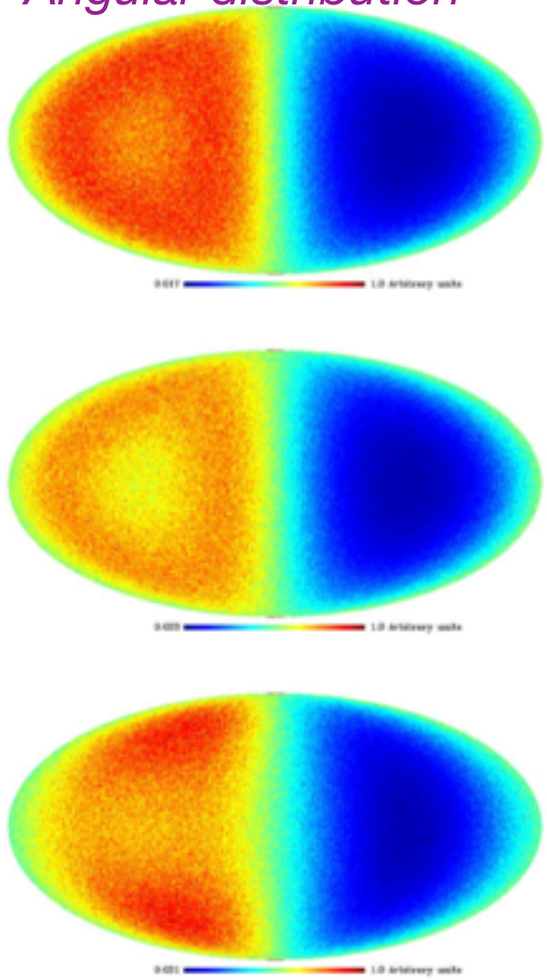
J. Billard, F. Mayet and D. Santos, PRD (83) 2011

Unique possibility to probe the nature of Dark Matter

Energy distribution



Angular distribution



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

Directional detection: *WIMP astronomy*

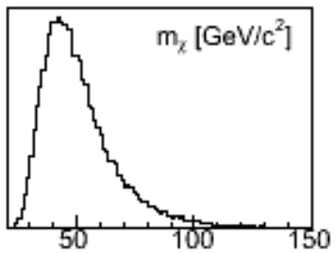
J. Billard, F. Mayet and D. Santos, PRD (83) 2011

Unique possibility to probe the nature of Dark Matter

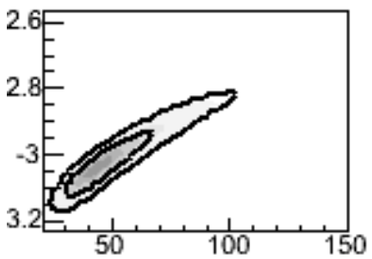
- With a single experiment of 30 kg-years we can measure both the halo and WIMP properties

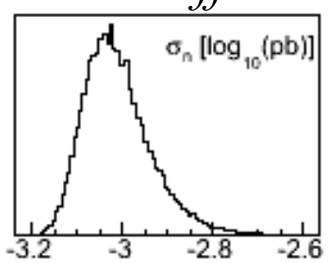
WIMP mass Vs cross section

Masse



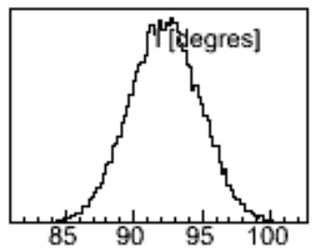
Section efficace

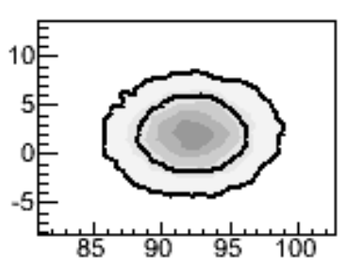




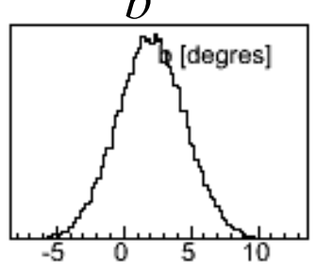
Discovery proof

l



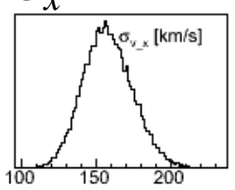


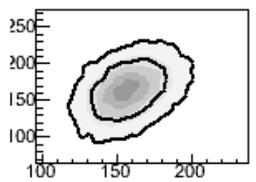
b

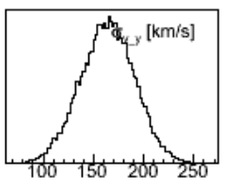


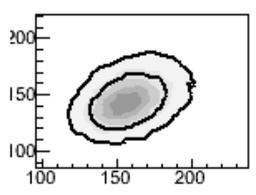
WIMP velocity distribution

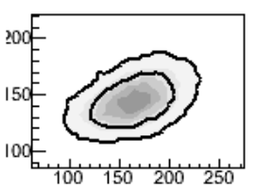
σ_x

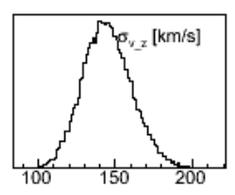












	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb)	$\ell_\odot$ (°)	$b_\odot$ (°)	σ_x (km.s^{-1})	σ_y (km.s^{-1})	σ_z (km.s^{-1})	β	R_b (kg^{-1}year^{-1})
Input	50	-3	90	0	155	155	155	0	10
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$	$92.2^{+2.5}_{-2.5}$	$2.0^{+2.5}_{-2.5}$	158^{+15}_{-17}	164^{+27}_{-26}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

Directional detection: *WIMP astronomy*

V. Belokurov, Astrophys. J **642** (2006)

- *Dark Matter streams:*

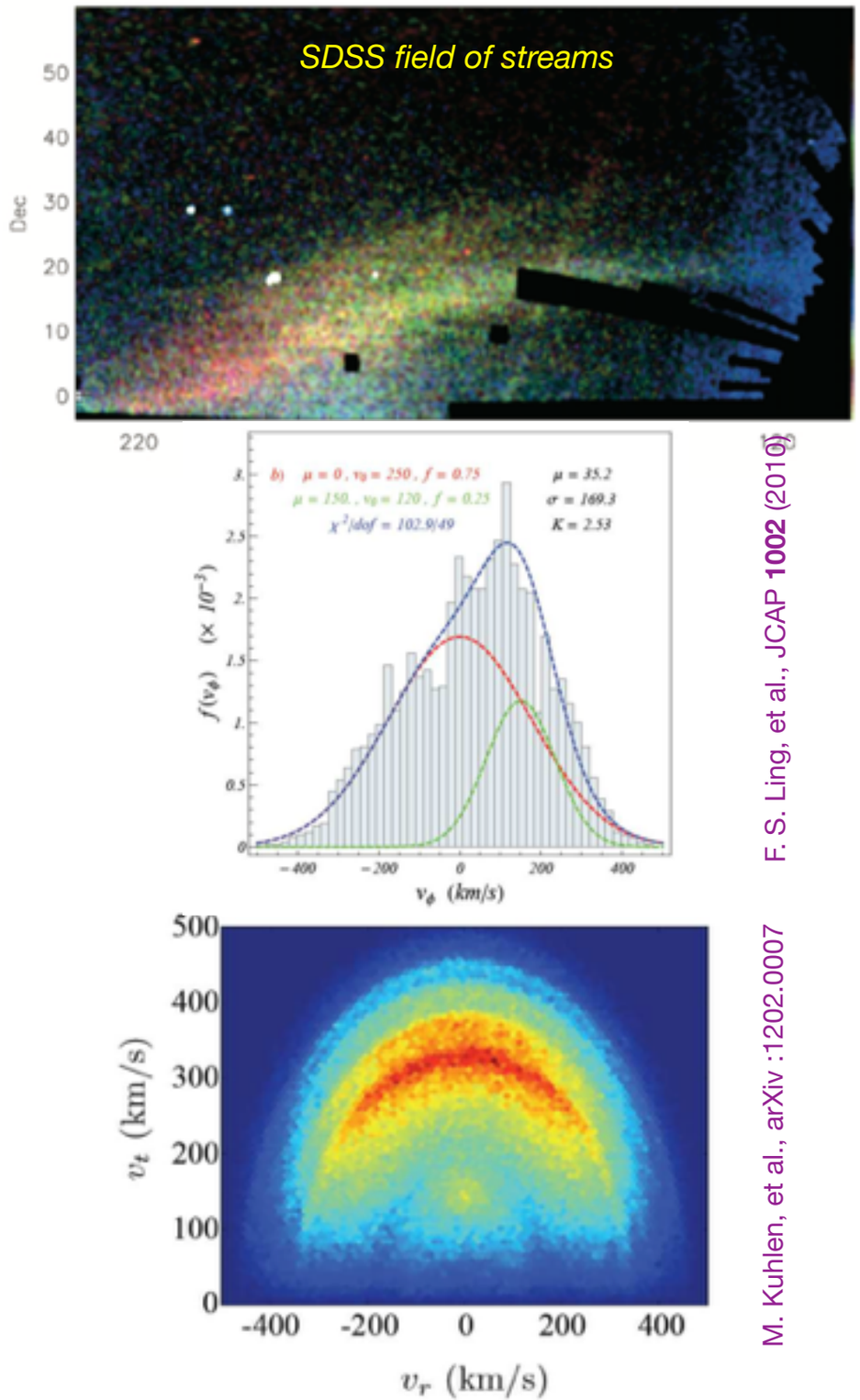
They are induced by infalling sub halos. Even though they are very likely, **their contribution to the local density should be less than 1%**

- *Dark disk:*

They may form if sub halos are dragged through and disrupted by the baryonic disk. Generally it is **co-rotating** with a **lag speed of 50 km/s**, is rather **cold** (~80 km/s) and could **contribute significantly to the local DM density**

- *Debris Flow:*

It is the sum of the total tidal streams, shells and plumes of debris from orbiting and infalling sub halos. From the Via Lactea simulations, these dark matter particles are found to be **spatially homogeneous but are isotropic** with a common speed of 340 km/s and **might significantly contribute to the DM density.**



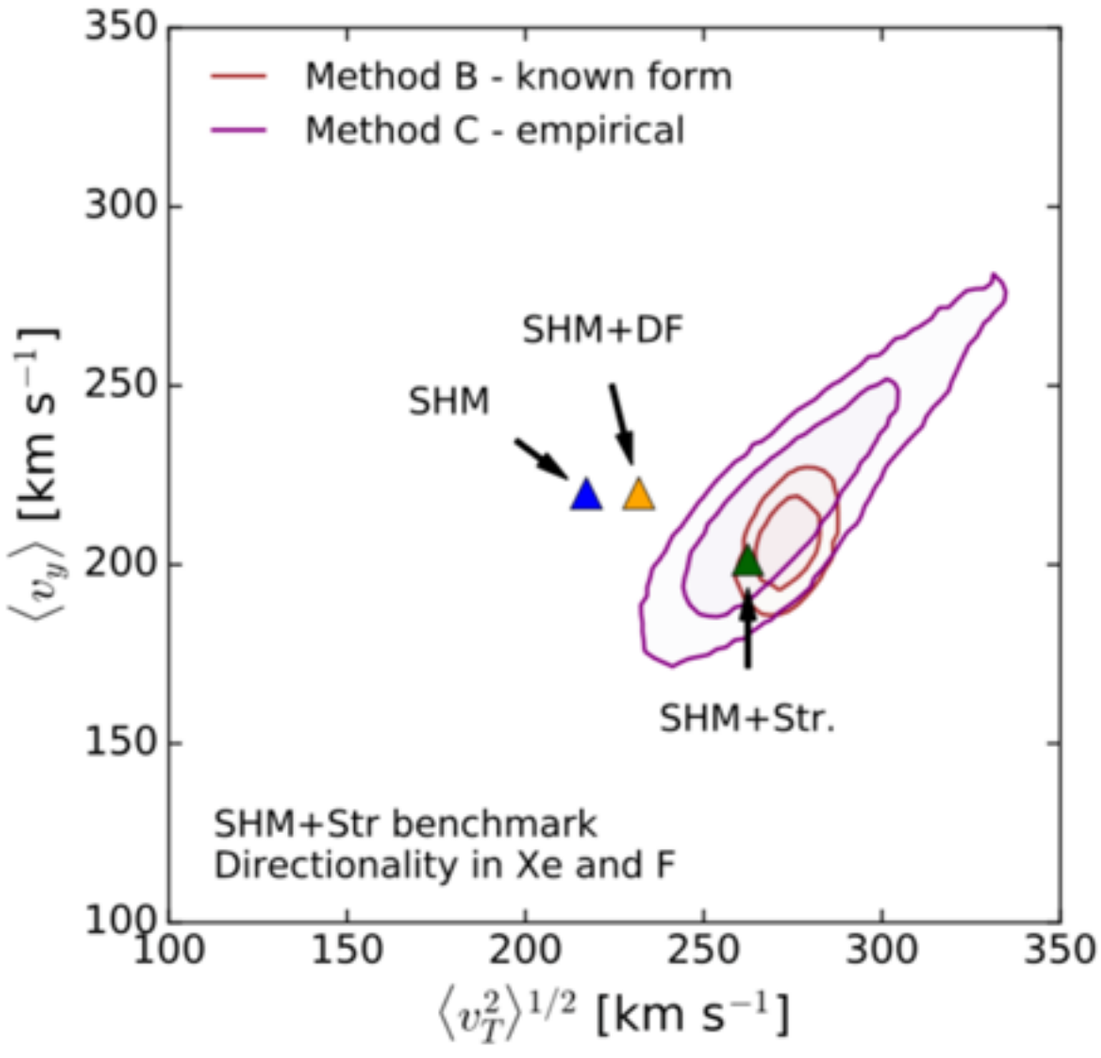
F. S. Ling, et al., JCAP **1002** (2010)

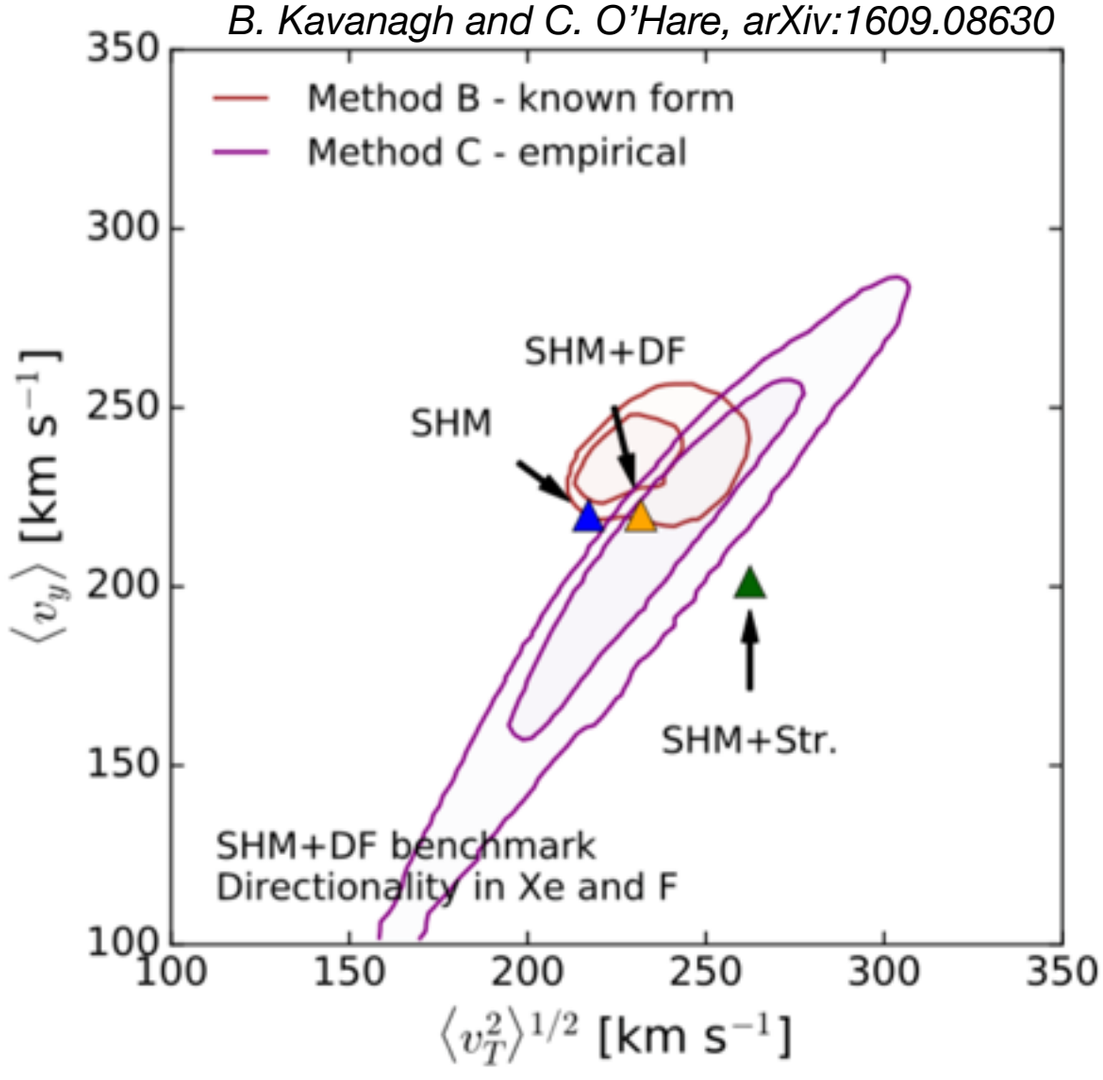
M. Kuhlen, et al., arXiv :1202.0007

Directional detection: *WIMP astronomy*

Unique possibility to probe the nature of Dark Matter

B. Kavanagh and C. O'Hare, arXiv:1609.08630



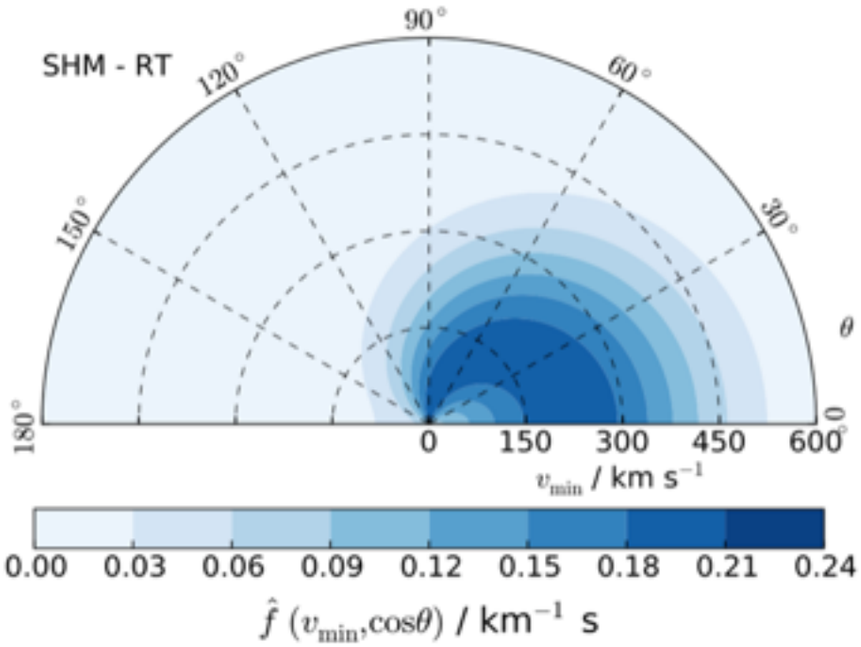


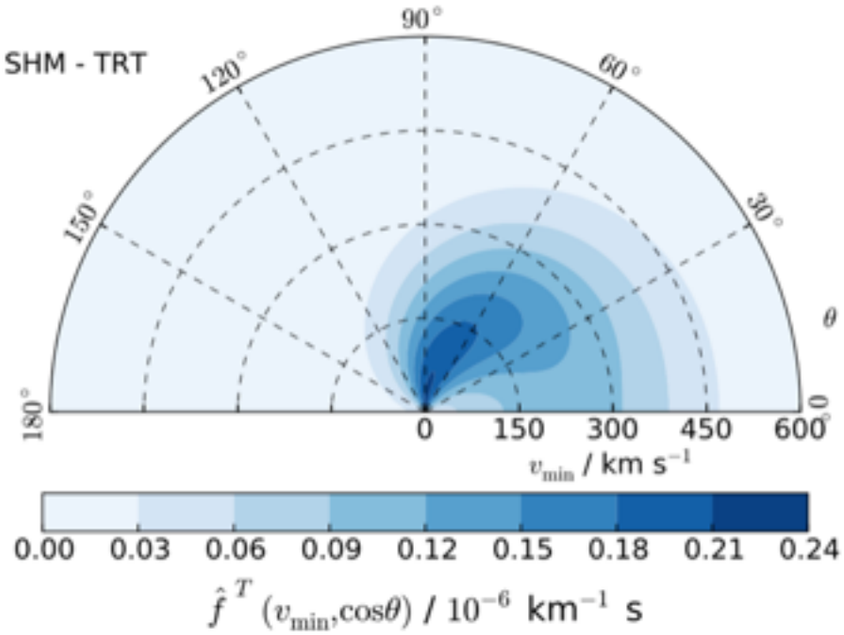
Directional detection will allow us to determine the ultra-local WIMP velocity distribution in a model independent approach

Directional detection: *WIMP astronomy*

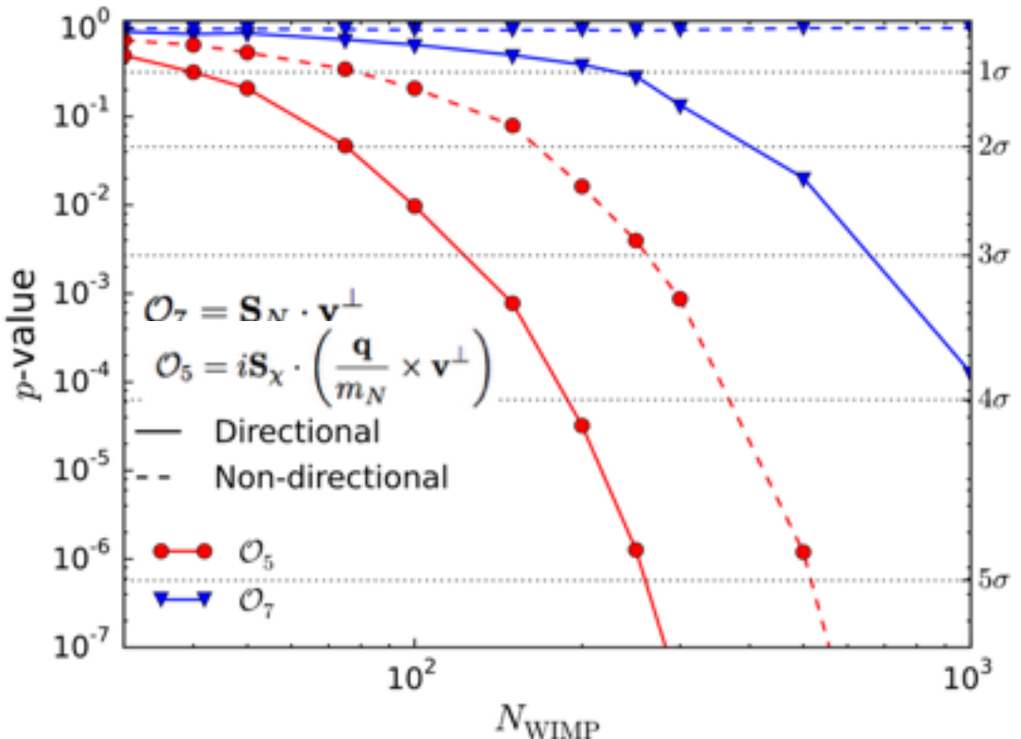
B. Kavanagh, Phys. Rev. D 92, 023513 (2015)

Unique possibility to probe the nature of Dark Matter





- Going beyond the standard SI and SD interactions with Non-Relativistic Effective Field Theory Operators
- We expect significant differences when transverse velocity is involved in the scattering process
- Only a **few tens of events** are required to authenticate a non-standard operator

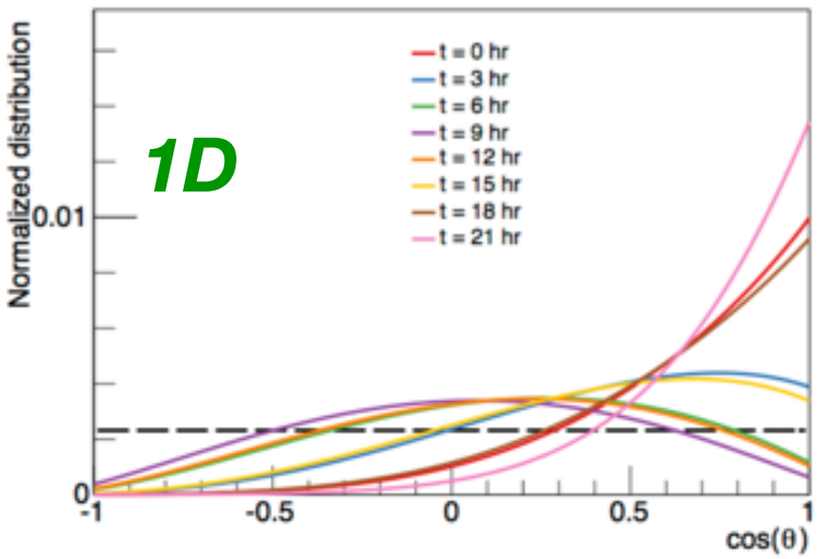


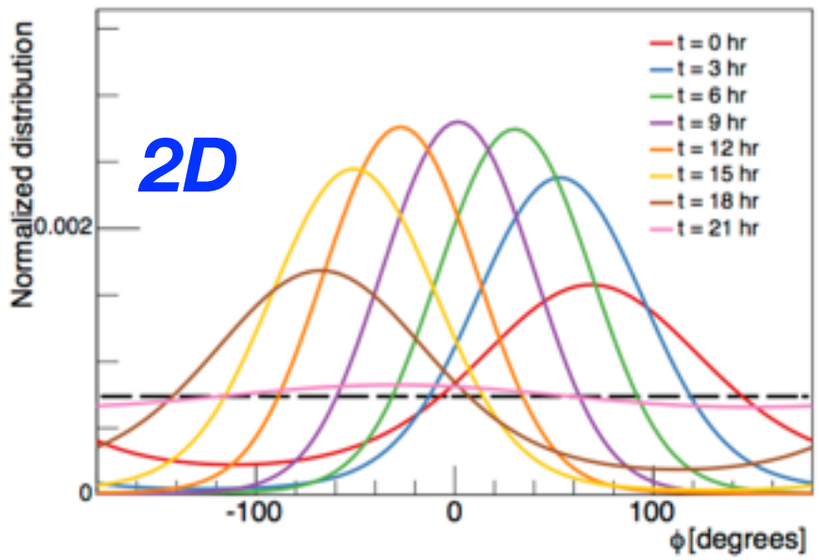
Directional detection: *Readouts*

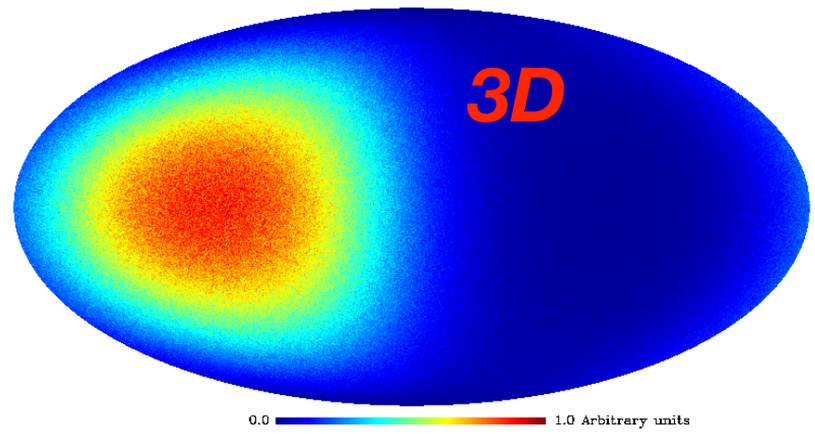
J. Billard, Phys. Rev. D 91 (2015)

Comparing readout strategies to directional detection

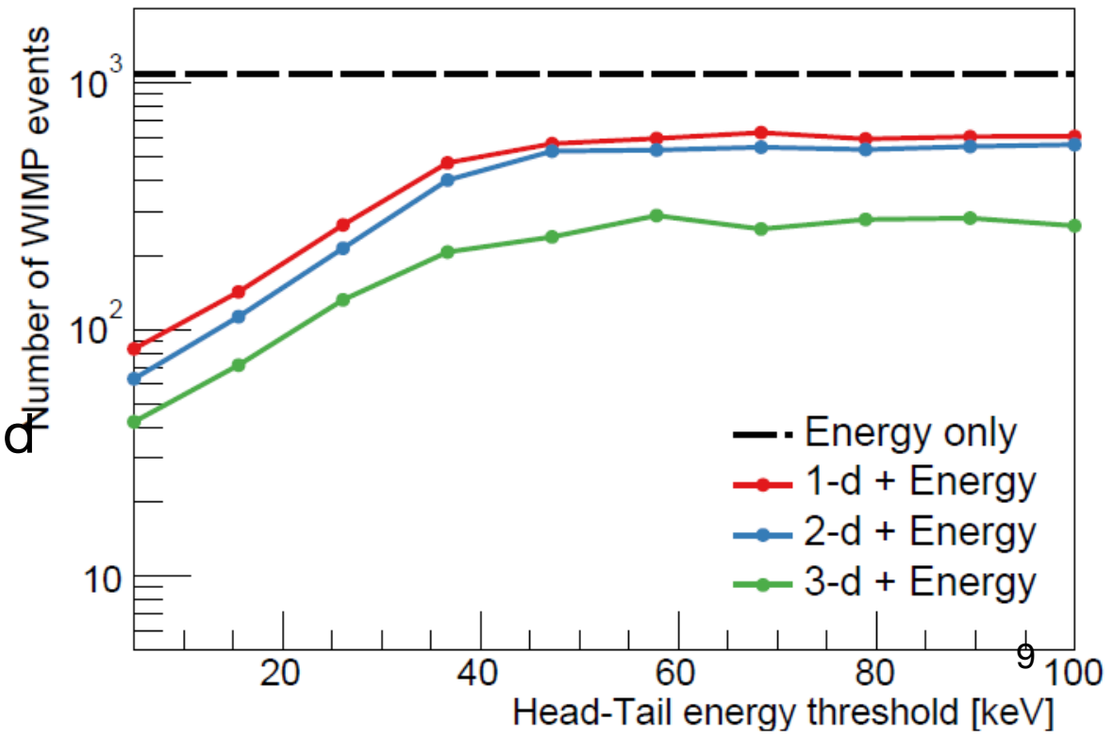
GOOD ***BEST***



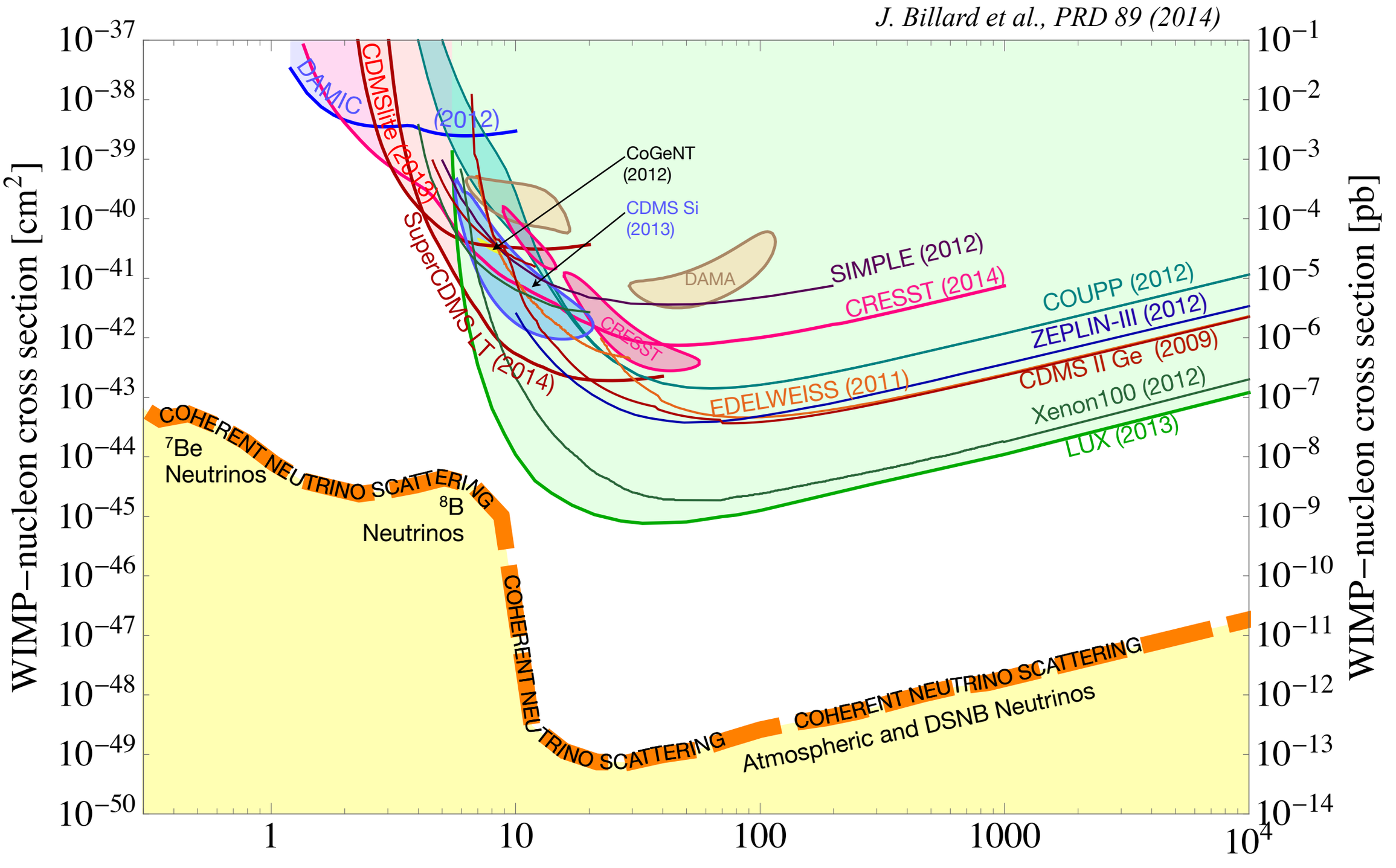




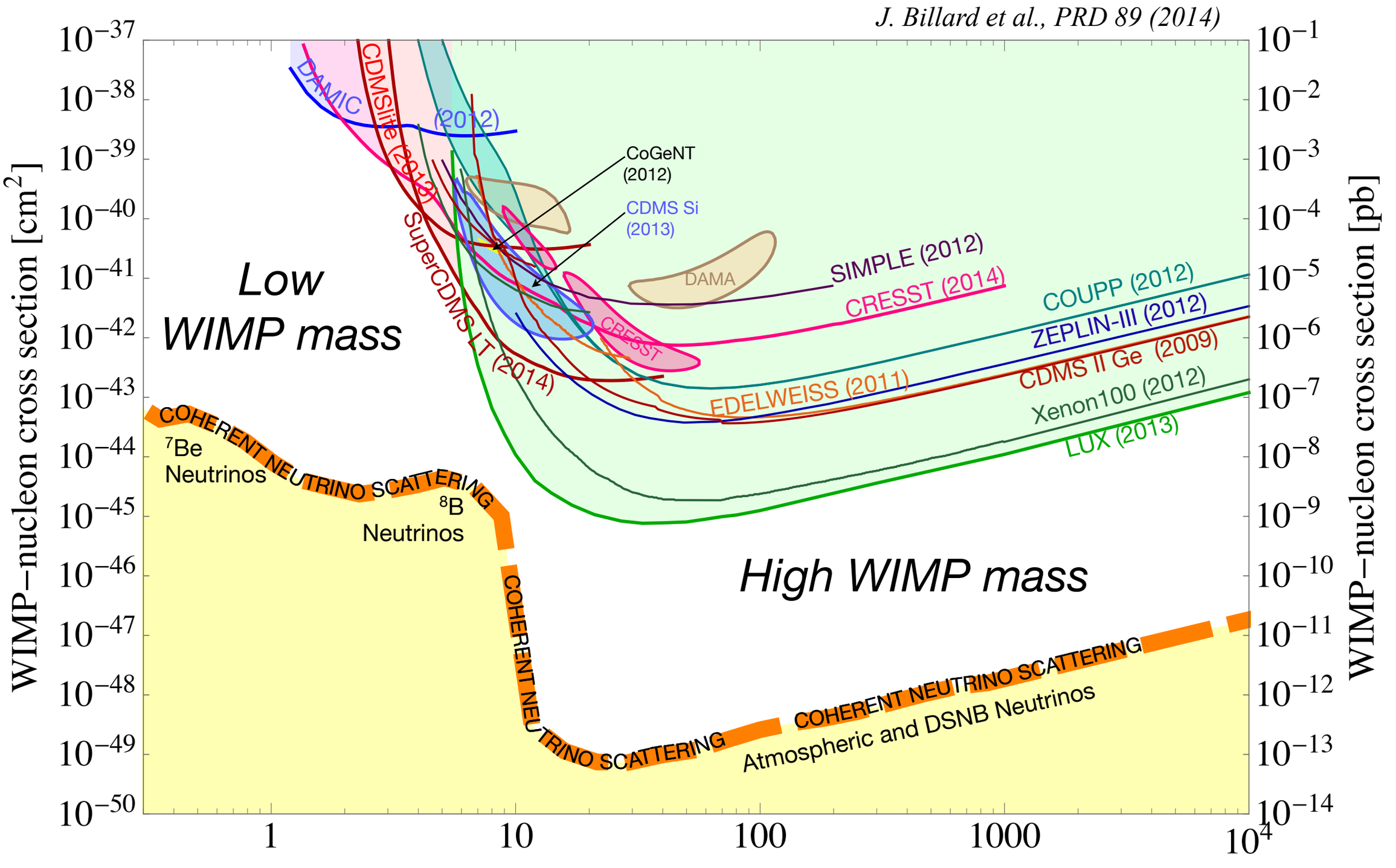
- Even lower directionality orders: 1D and 2D, offer great discrimination power against any isotropic background
- Sense recognition (head-tail) is a key experimental issue which dramatically impacts the discovery potential
- 1d less effective than 3d by a factor 3 *only which could easily be* compensated by the exposure (solid-state/liquid detector)
  - e.g. Columnar recombination in dual-phase Xe or Ar TPC, or anisotropic scintillation



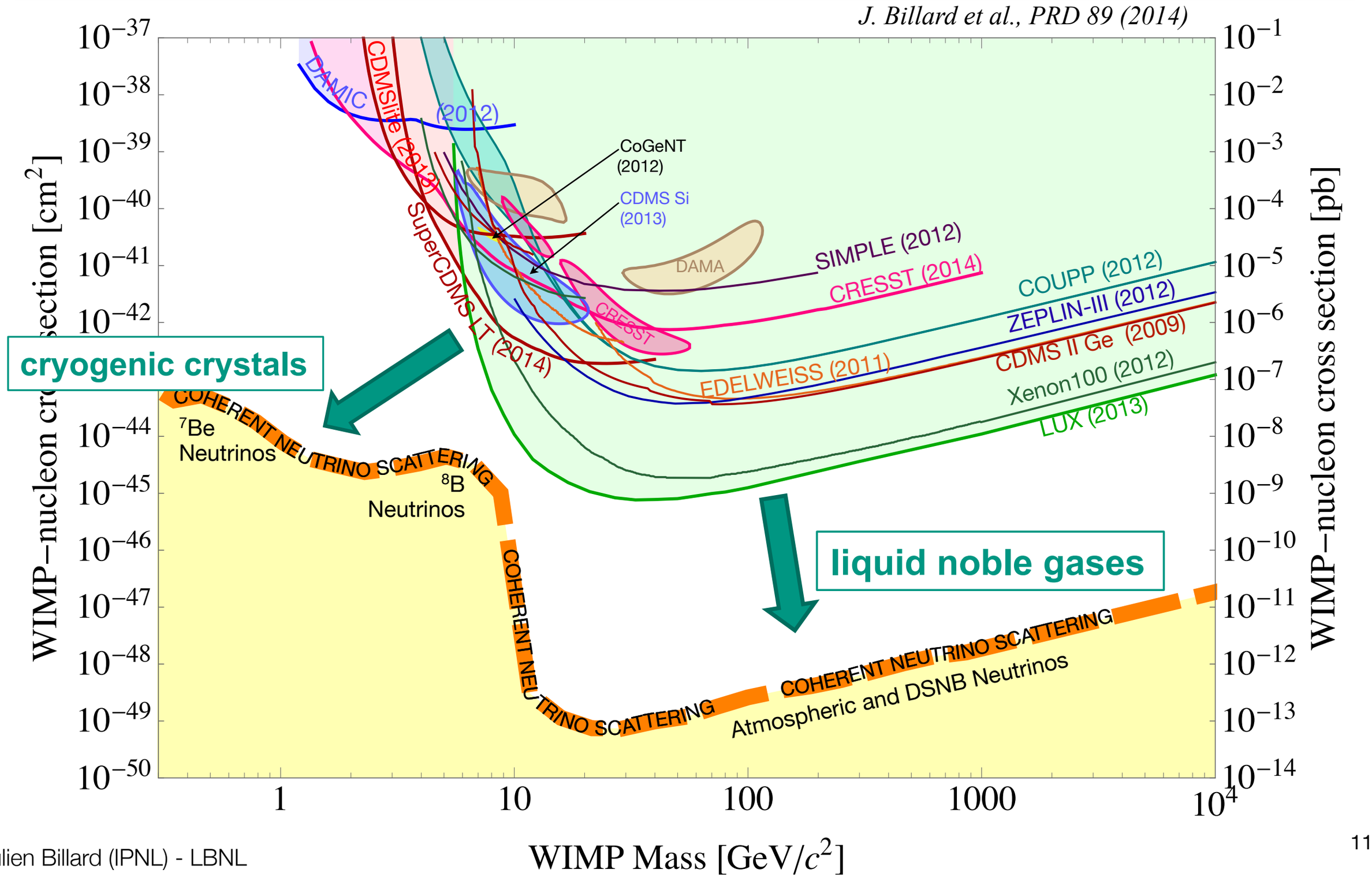
Directional detection: *The neutrino background*



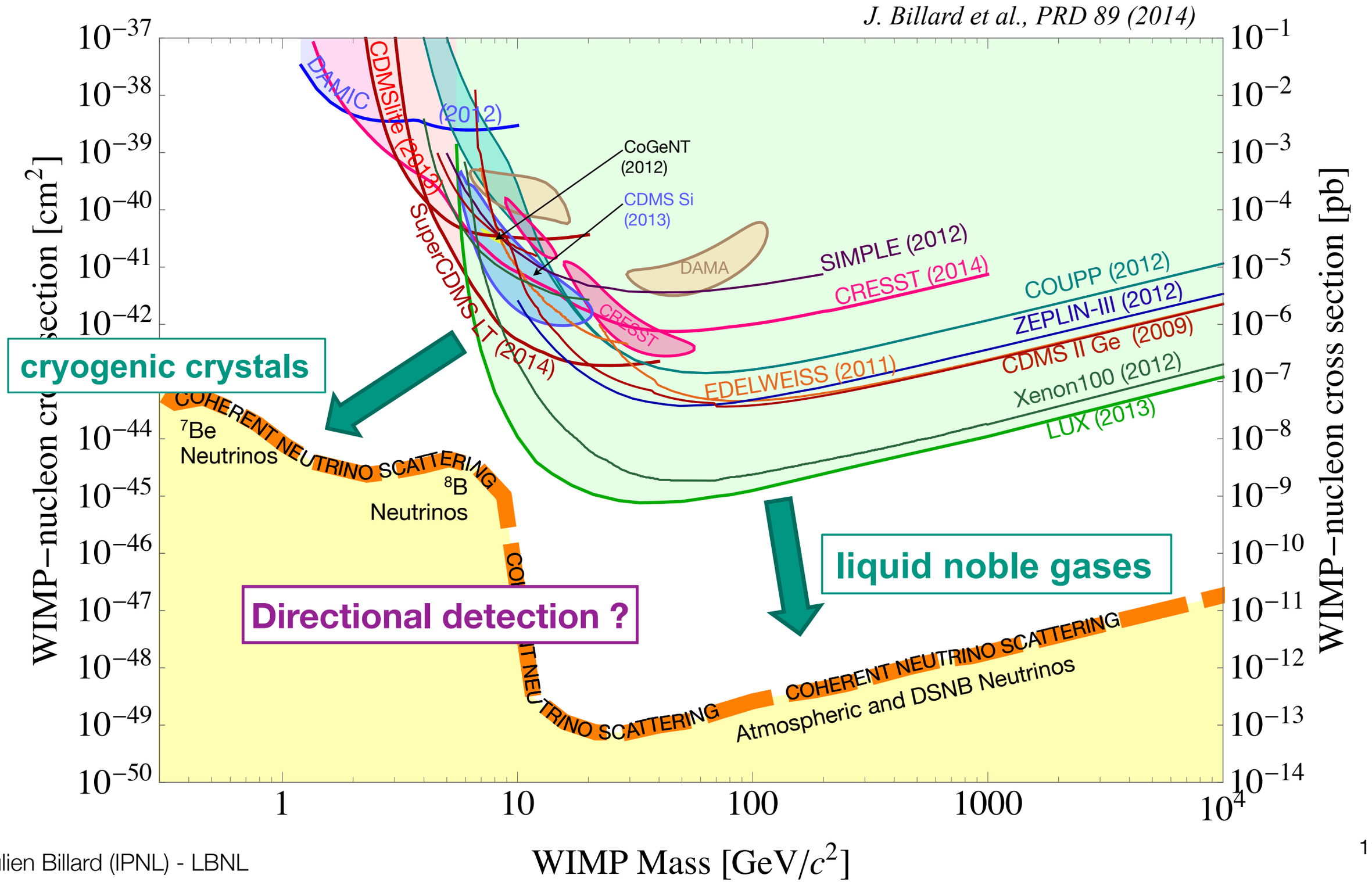
Directional detection: *The neutrino background*



Directional detection: *The neutrino background*



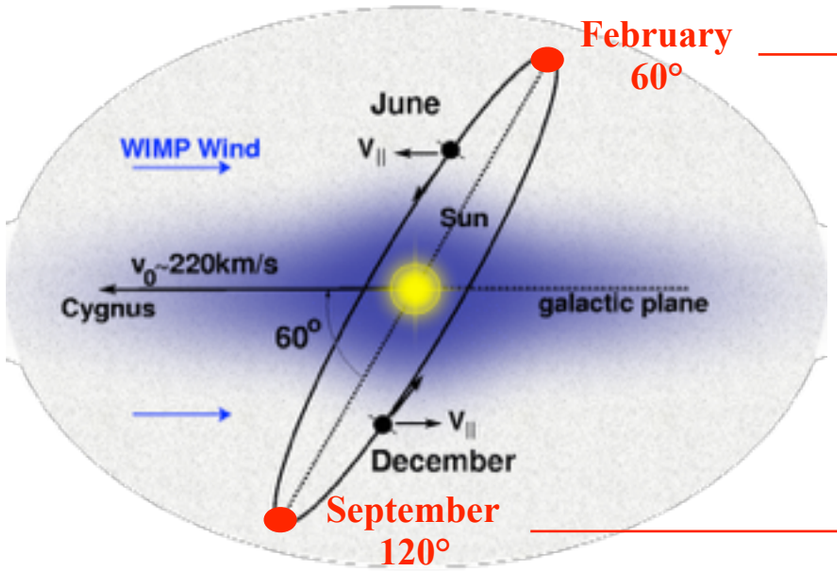
Directional detection: *The neutrino background*



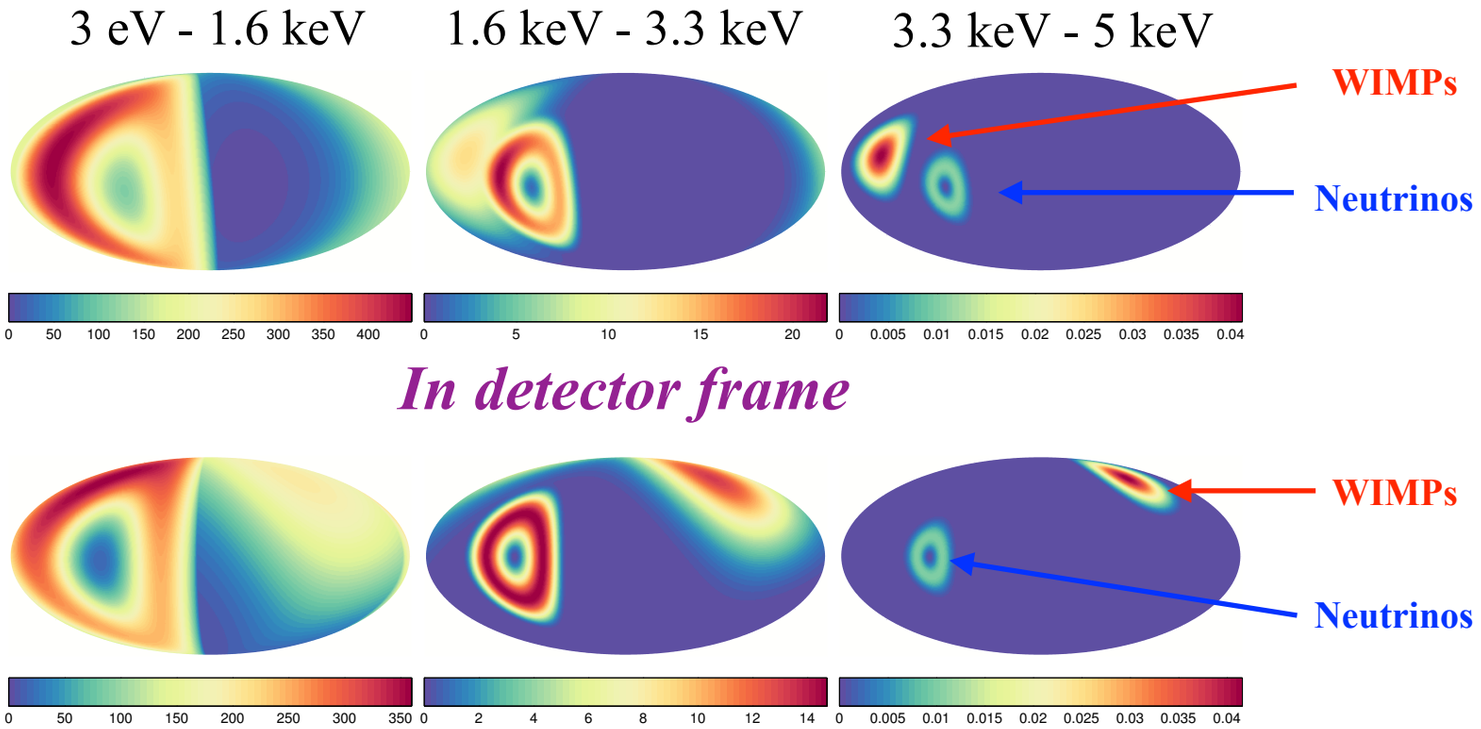
Directional detection: *The neutrino background*

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., PRD 92 (2015)

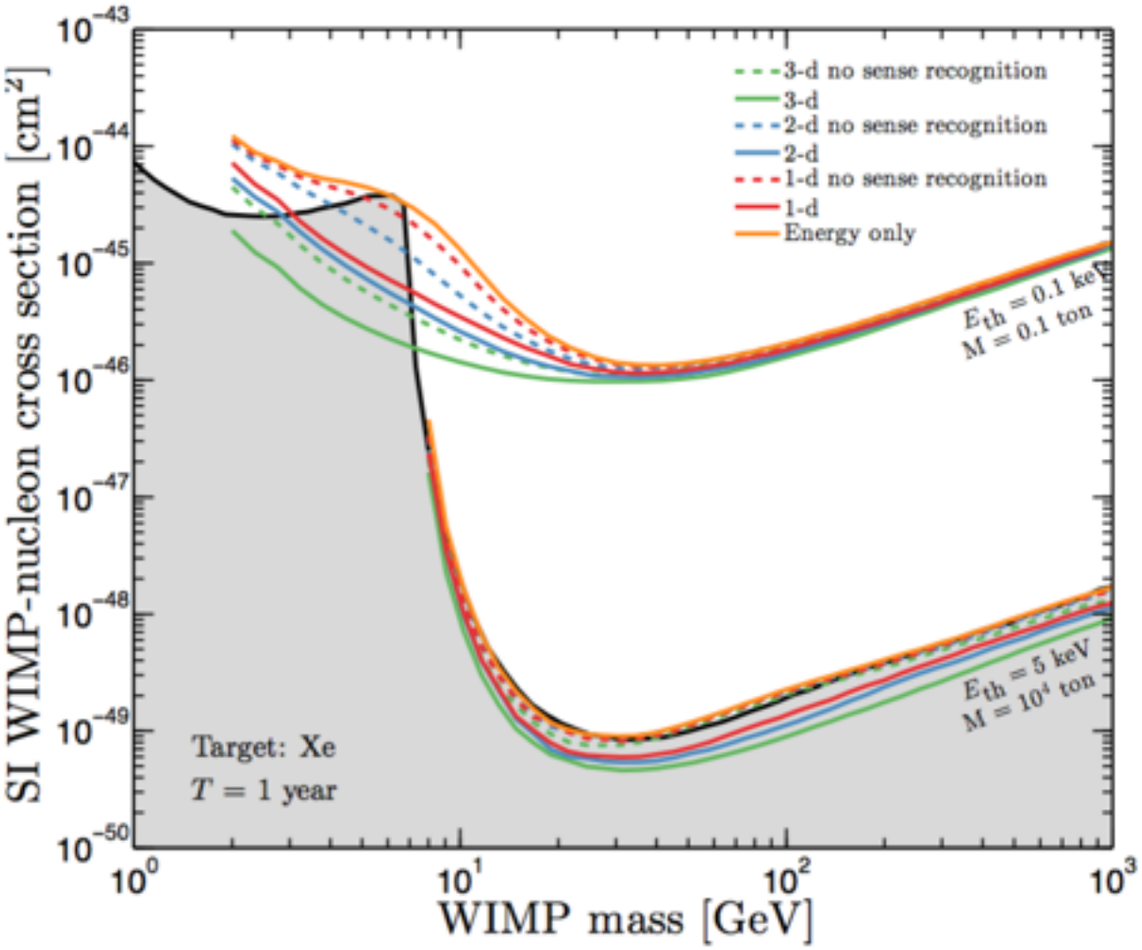


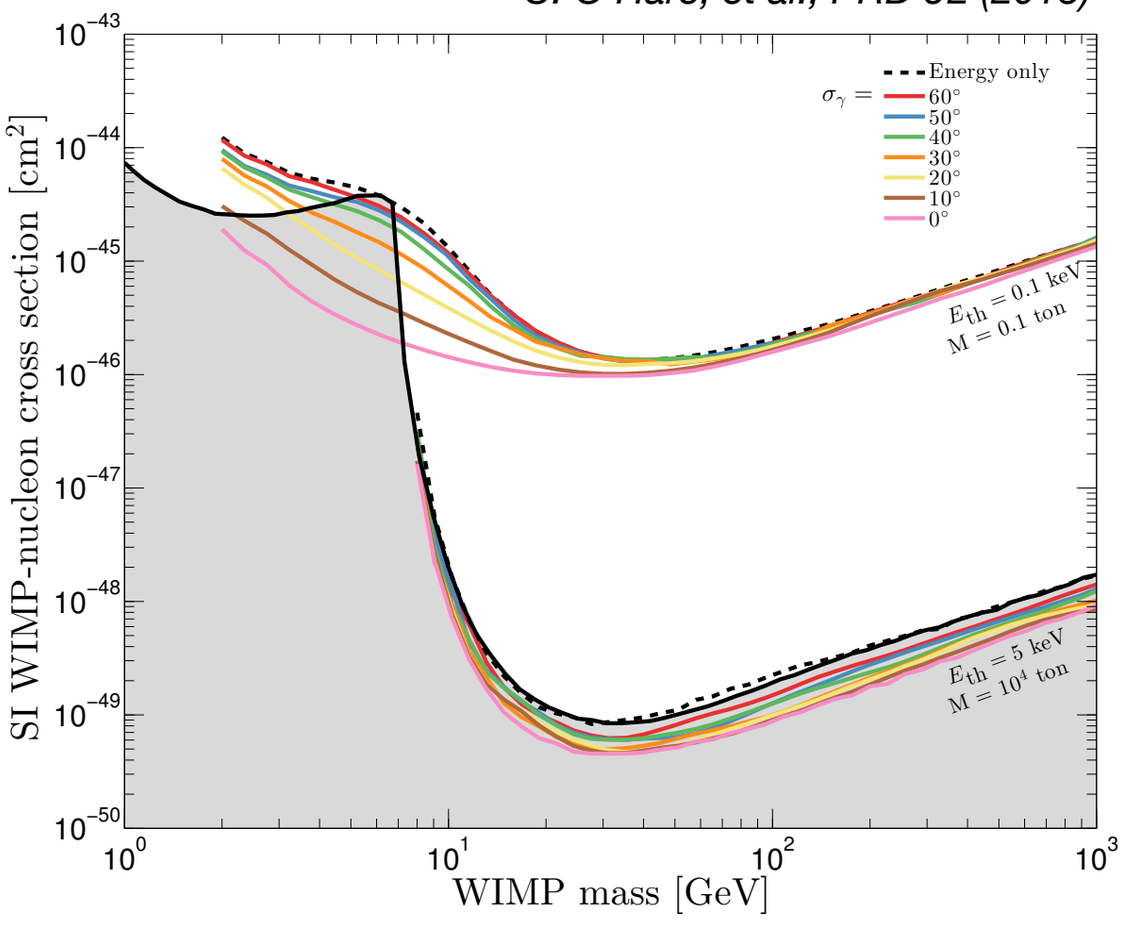
$\mathrm{d}R_{\mathrm{bin}}/\mathrm{d}\Omega_q\ [\mathrm{ton}^{-1}\ \mathrm{year}^{-1}\ \mathrm{sr}^{-1}]$

Directional detection: *The neutrino background*

Directional detection: beyond the neutrino floor

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





- 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*

The « wish list » for a directional direct detection experiment:

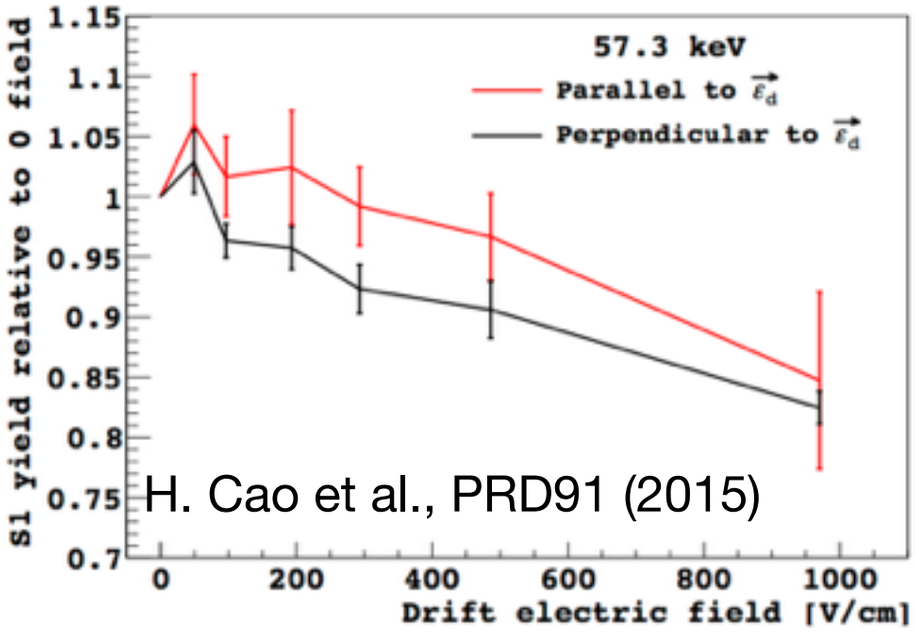
- **Low** and **controlled** backgrounds *(so that they can be subtracted)*
- **Discrimination** between signal and background *(to actively reject remaining backgrounds)*
- **Large exposure** (*few events per ton-year*)
- **Low energy threshold** *(the lower, the better, especially for low WIMP mass)*
- **Directional track reconstruction** *to authenticate the Galactic origin of the signal*
  - *Readout strategy: 1D, 2D or 3D*
  - *Angular resolution and threshold*
  - *Sense recognition*

Directional detection: *experiment (few examples)*

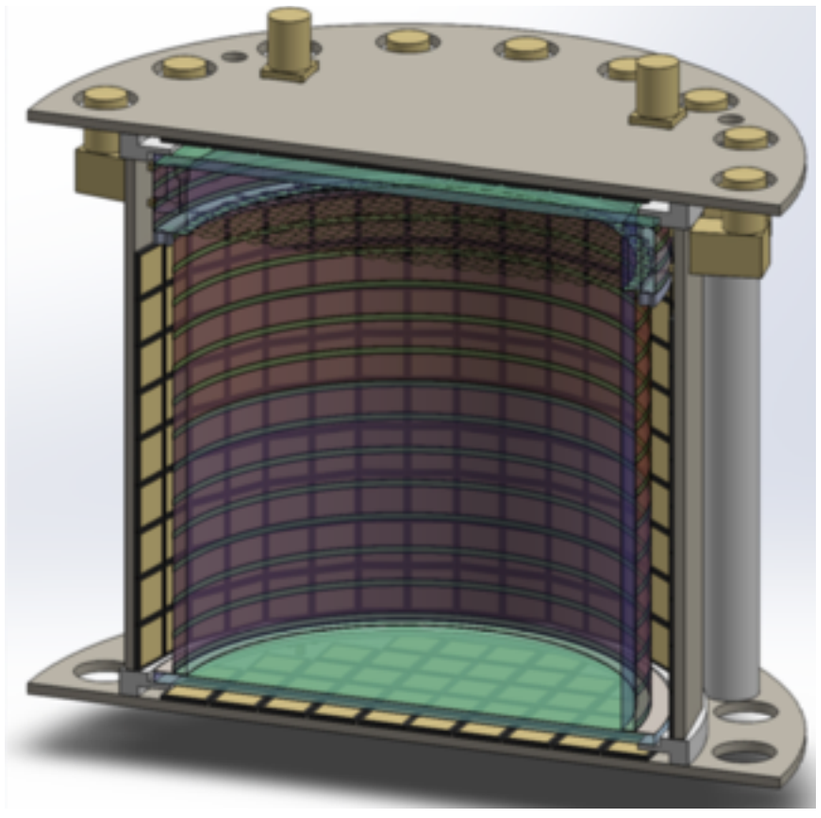
G. Fiorillo, CYGNUS 2016

Liquid state: 1D readout (RED)

- Columnar recombination possible if track is longer than the Onsager radius ~80 nm (~35 keV in LAr) [D. Nygren, 2013].
- 1D directional sensitivity from columnar recombination:
  - **perpendicular to E:** less S1, more S2
  - **parallel to E:** more S1, less S2
- First hint from the SCENE collaboration [H. Cao et al., 2015]
- RED project aims at improving on the previous SCENE measurements: Use of SIPM with 4Pi coverage, High spatial resolution (3-5 mm) to reject multiple scattering, Improved Light yield efficiency
- Add directional sensitivity to large LAr project as DarkSide-20K, in run by 2020



H. Cao et al., PRD91 (2015)

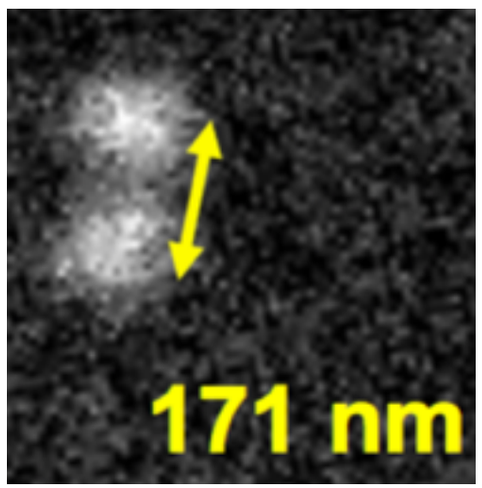


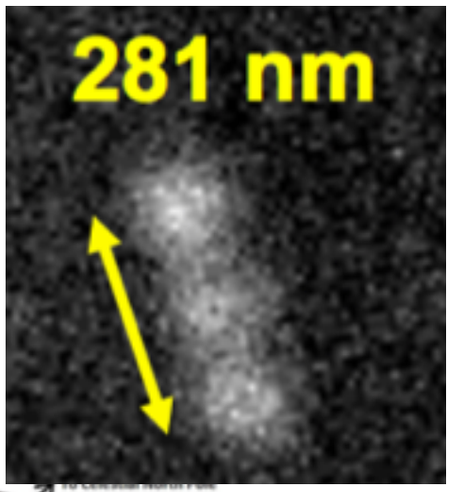
Directional detection: *experiment (few examples)*

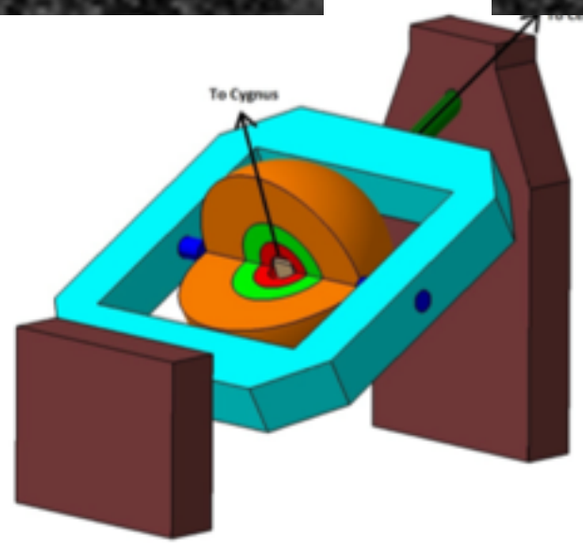
G. De Lellis, CYGNUS 2016

Solid state: 2D readout (NEWS)

- Use of emulsion films to enable WIMP induced nuclear recoil tracking
- Tracks produce line of silver grain
- Challenges:
  - small grains (<40 nm) and highly packed to reduce energy threshold (~20 keV)
  - 3 g/cc need several layers of emulsion
  - fast and efficient readout with optical microscope (10 nm) resolution
- To optimize directionality, the experiment will be mounted on gyroscope as there is no timing information available
- 1 kg R&D prototype funded at LNGS



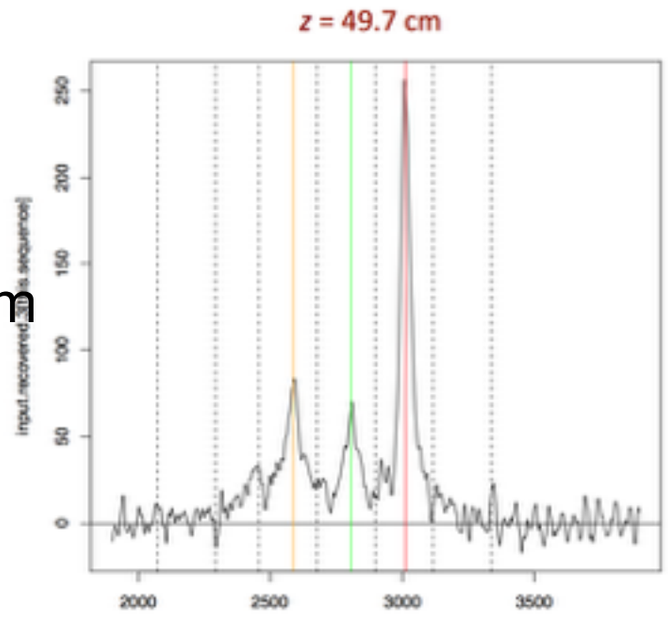


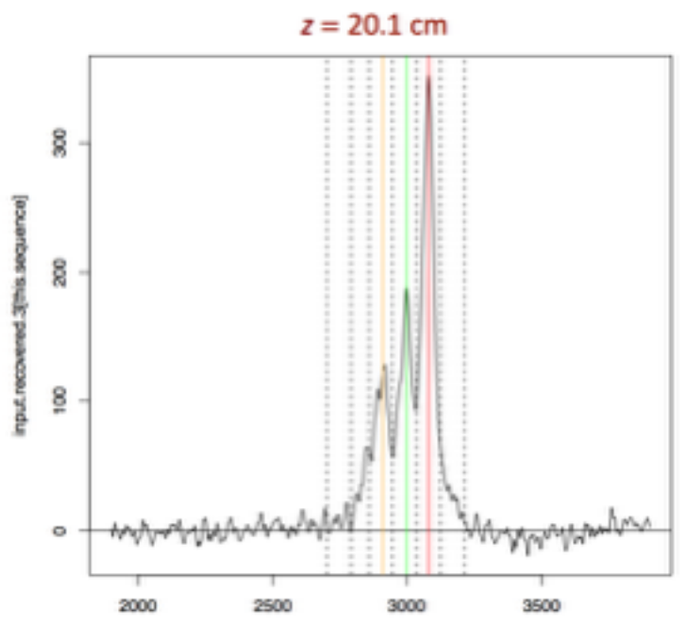


Directional detection: *experiment (few examples)*

Gas TPC: 2D readout (DRIFT)

- Drift has pioneered the field of directional detection since 2001
- Using 1m3 detector filled with CS2 (negative ion) at ~50 mbar and MWPC
- 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
- SF6 gas under investigation to benefit from low diffusion, z-fiducialization and SD sensitivity from F

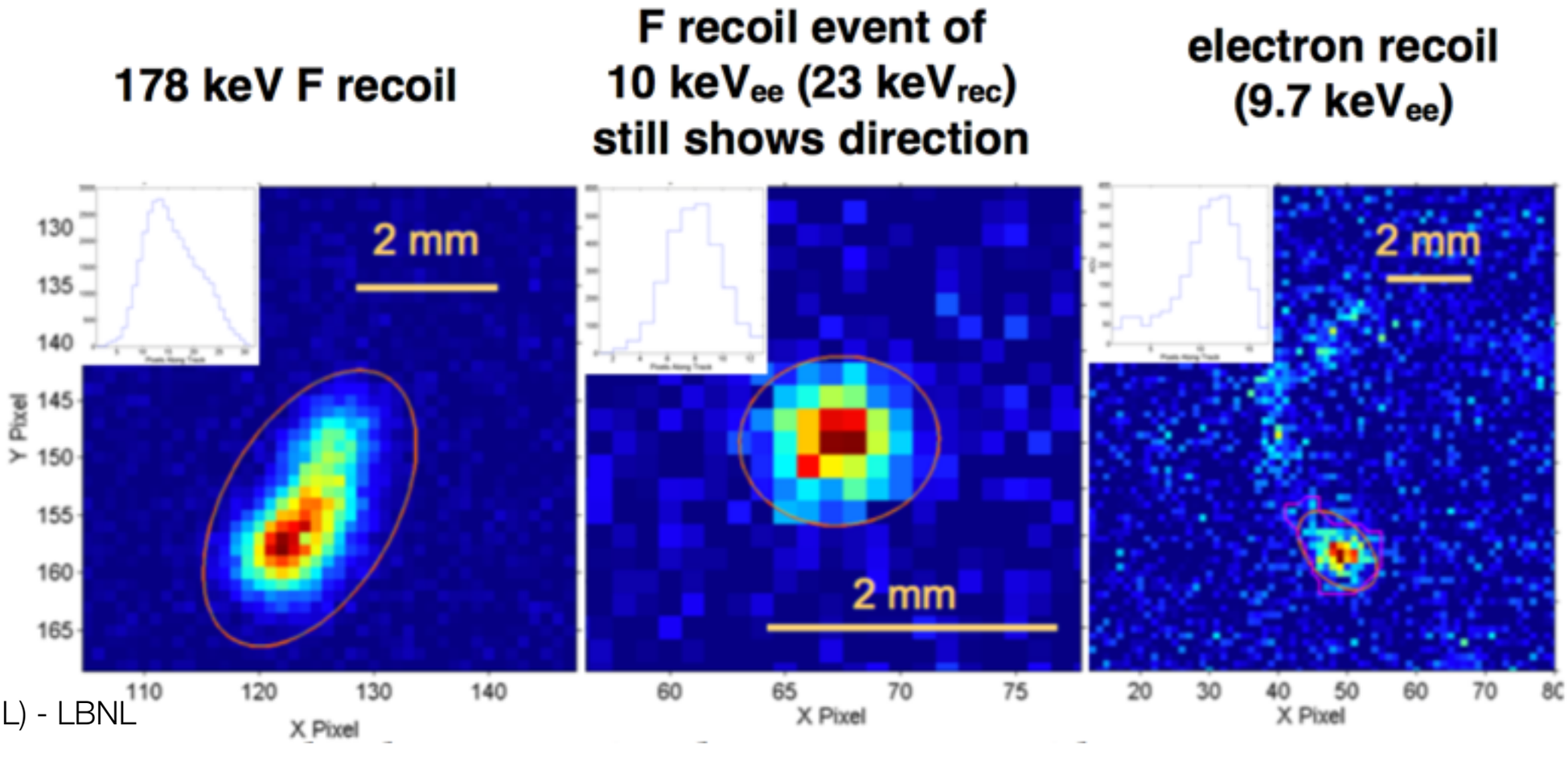




Directional detection: *experiment (few examples)*

Gas TPC:* *High resolution 2D readout R&D (UNM, DRIFT) *D. Loomba, CYGNUS 2016*

- CCD camera + 3 GEM in series to ensure high gain > 10000 but small drift volume (1 cm)
- Consider negative ion gas (e.g. CS2) instead of electron gas (e.g. CF4) to reduce diffusion
- For the first time, even 55-Fe electron tracks are resolved and can be rejected down to 5 keV
- Sense recognition possible down to few tens of keVee
- SF6 gas under investigation to benefit also from z-fiducialization and SD sensitivity from F

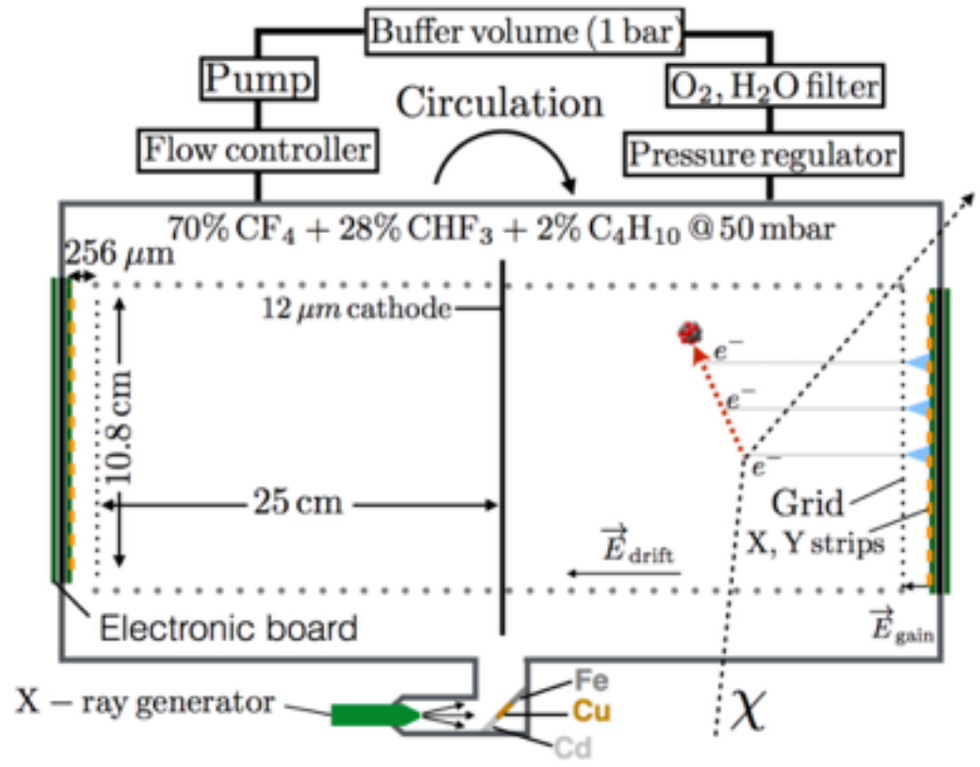


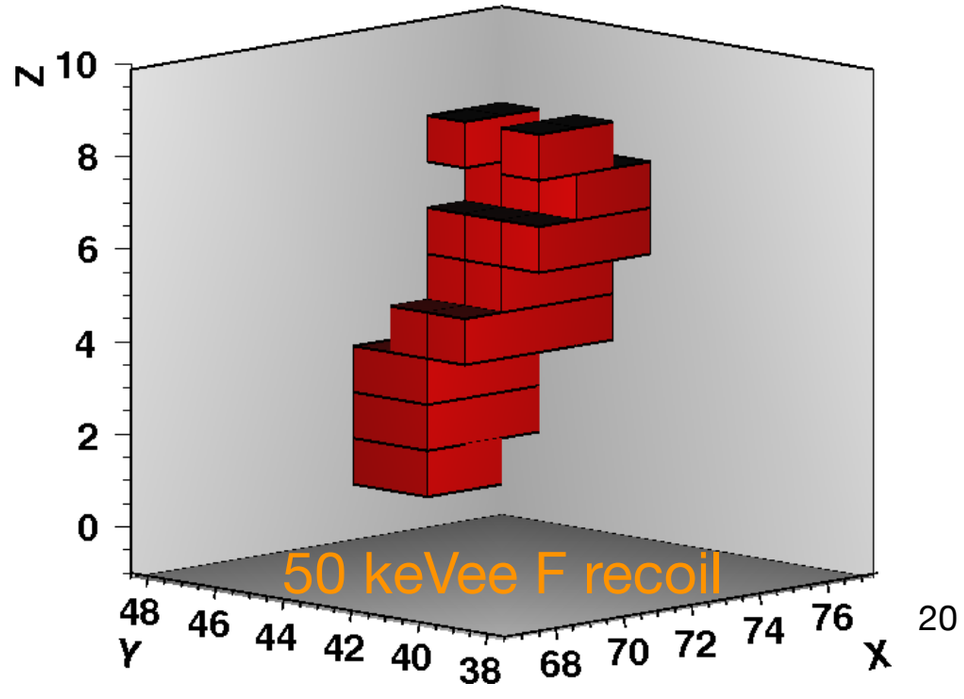
Directional detection: *experiment (few examples)*

D. Santos, CYGNUS 2016

Gas TPC: 3D readout (MIMAC)

- Dual-chamber instrumented with pixelized micromegas with self-triggered electronics
- It is filled with CF4+CHF3+C4H10 at 50 mbar corresponding to a total target mass of a few grams
- Track topology to discriminate ER/NR
- Use X,Y positioning and electron drift diffusion (Z) to fiducialize detector
- Angular resolution of 20 degrees (RMS) for a few keVee energy but no sense recognition (yet!)
- Energy threshold around 1 levee
- NR calibration thanks to ion source
- ***Other 3D includes: D3 and NEWAGE experiments***

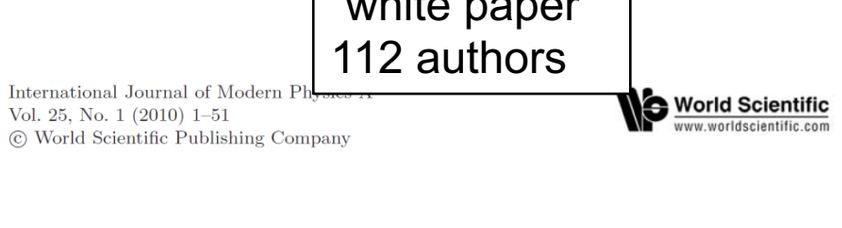




Directional detection: *CYGNUS*

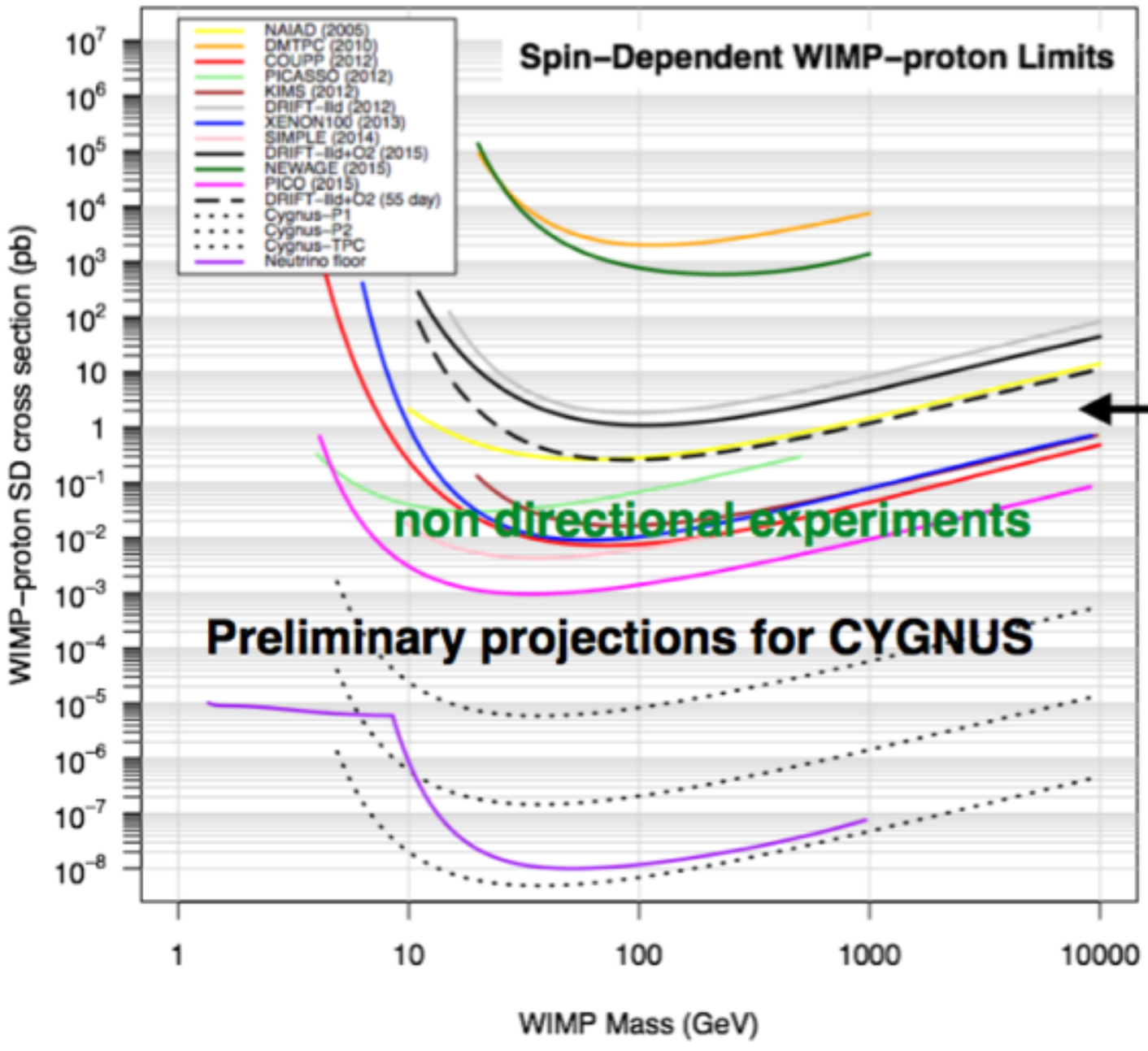
The CYGNUS Galactic Directional Nuclear Recoil Observatory

- From bi-annual workshops to a **collaborative effort**
- Three review papers have been produced about physics case and readout technologies (+ one in preparation)
- CYGNUS proto-collaboration agreement includes solid and gaseous TPC technologies to determine what is the best detection strategy for a large scale experiment
- 4 working groups with monthly meetings **dedicated at determining the optimal technology**
  - Engineering (N. Spooner, University of Sheffield)
  - Simulation (S. Vahsen, Hawaii University)
  - Background (E. Baracchini, INFN Frascati)
  - Gas R&D (K. Miuchi, Kobe University)



Directional detection: *CYGNUS*

N. Spooner, CYGNUS 2016



The Pathfinder Strategy

~Current directional experiment state

CYGNUS - Pathfinder 1

CYGNUS - Pathfinder 2

CYGNUS - TPC

Australia, China, France, Italy, Japan, UK, US

Conclusions

Take away points:

- Directional detection offers the unique opportunity to unambiguously discover Dark Matter and probe its nature from both particle and galactic halo physics

- It is the only way to efficiently probe dark matter models below the neutrino bound

- It is a very challenging detection techniques and many experiments and R&D projects are ongoing and continuously improving their directional capabilities in both 1D, 2D and 3D using solid, liquid and gaseous detector medium

- The CYGNUS proto-collaboration has recently formed to regroup most of ongoing projects in order to coordinate the construction of a futur large scale Galactic Directional Nuclear Recoil Observatory dedicated to both dark matter and neutrino physics