Directional Dark Matter Detectors

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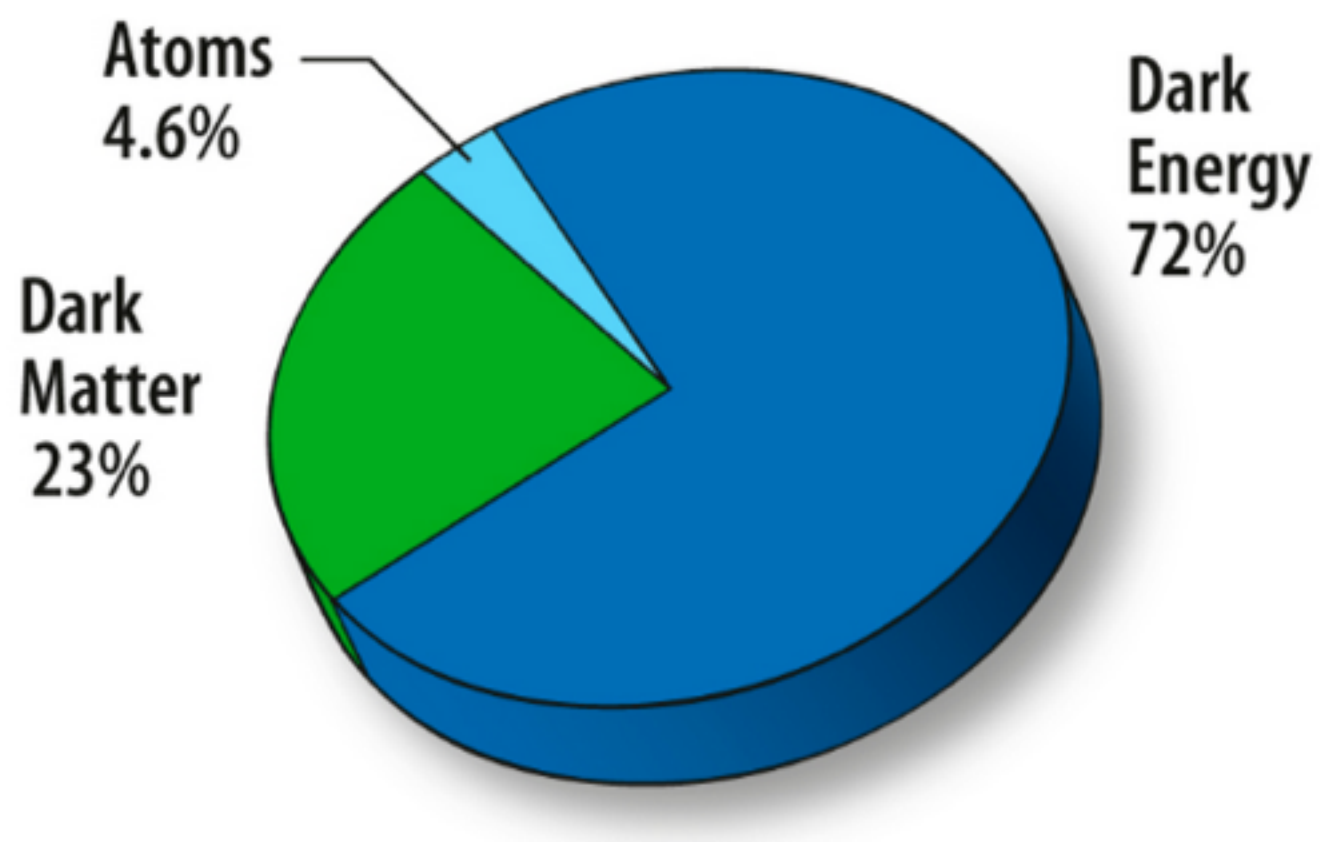
Oct. 6, 2015

Two views of dark matter

Astronomer

We know how much dark matter there is.

We know how it makes the universe look the way it does and how it created large-scale structure.



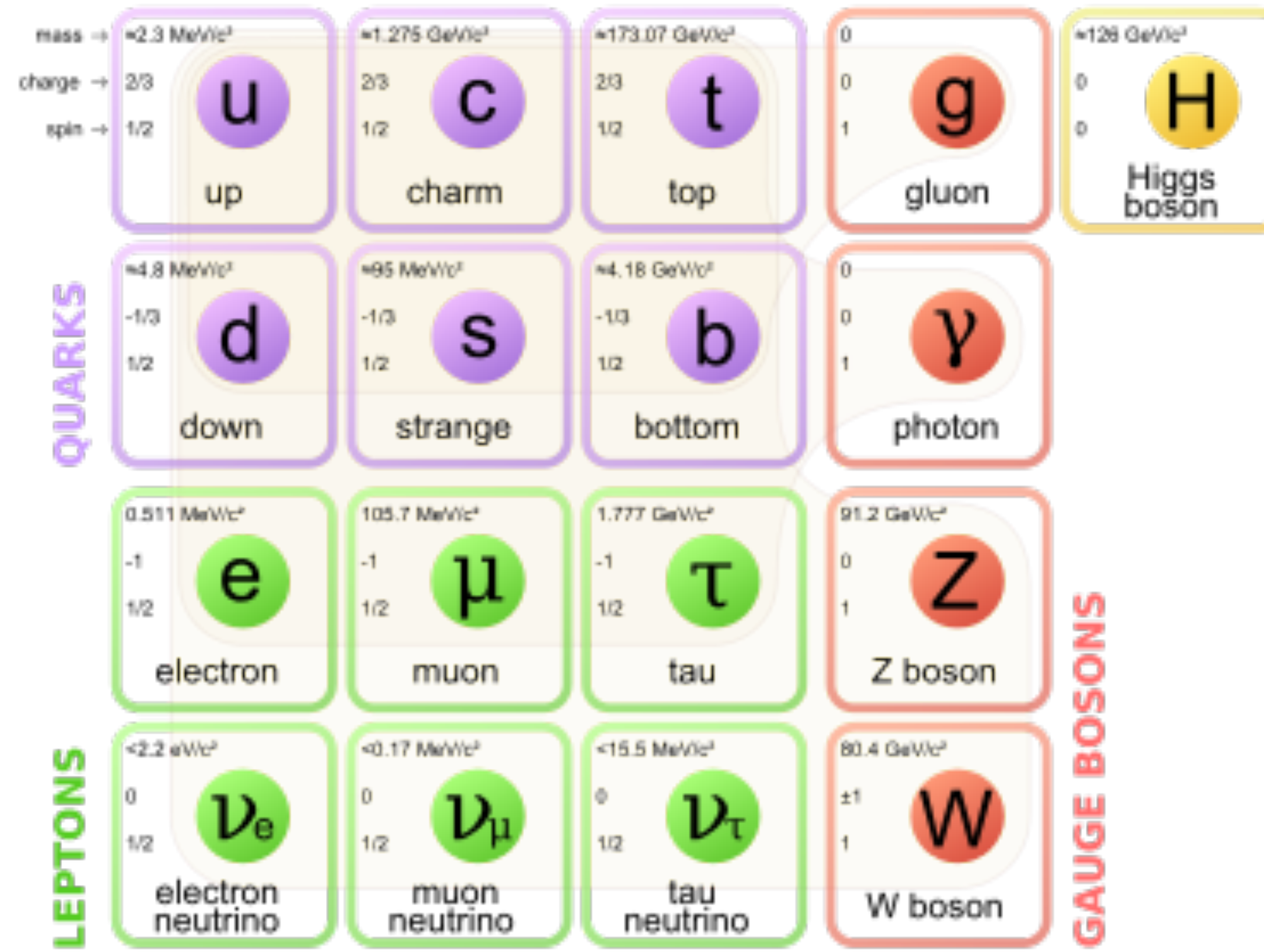
We have measured gravitational lensing and galactic rotation curves influenced by dark matter.

The dark matter density at Earth is 0.39 ± 0.03 GeV/cm^3.

Particle Physicist

We have a much better idea of what dark matter is not, than what it is.

It is not made up of Standard Model particles.



We do not know what dark matter is.

Main modes of access

1. ‘Direct’ detection: nuclear or photon recoil
   - e.g. CDMS, LUX, ADMX ...
2. ‘Indirect’ detection: annihilation leading to observable decay products
   - e.g. AMS, Fermi, HESS, IceCube
3. Production in the laboratory
   - e.g. LHC

Opinion

Not all three methods can definitively observe dark matter

The most compelling would be an observation of nuclear recoils 5σ above background

> But remember the solar neutrino problem ... it took correlation with an astrophysical phenomenon from directional measurements to seal the deal

What does this mean for indirect experiments or for the LHC?

DM Scattering Rate on nuclei

$\rho_{DM} = 0.4\ GeV/cm^3$ from Milky Way measurement

$M_{DM} = 100\ GeV/c^2 \Rightarrow n_{DM} = 4\times10^{-3}/cm^3$

$v = 10^{-3}c$, DM is cold, given by potential at Earth

$\sigma_{DM,N} = 10^{-45}\ cm^2$

Target is 1 kg of 100 GeV/c^2 nuclei (A=100)

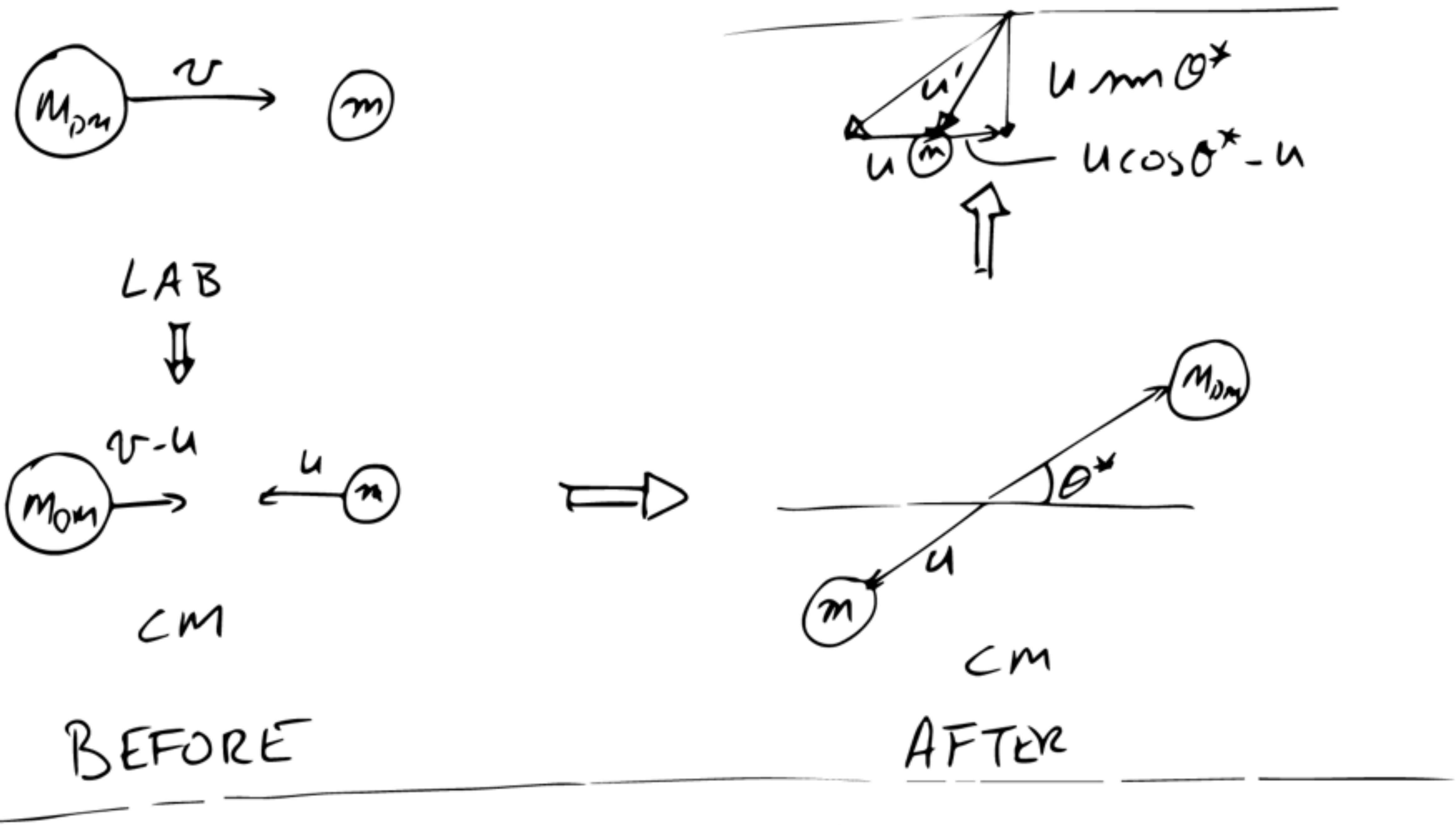
$\Rightarrow n_t = 6\times10^{24}$

$\Rightarrow$ Scattering rate $R = n_t n_{DM} (\sigma A^3) v$

$= 0.02/kg\text{-}y$

$\Rightarrow$ Need 100 kg detectors for this cross section

Energy Transfer



$$KE = \frac{1}{2} m u'^2 = \mu v^2 (1 - \cos\theta^*)$$

$$100\,\frac{\text{GeV}}{c^2} \quad (10^{-3} c)^2 \sim 100\ \text{keV}$$

Nuclear Recoil Experiments

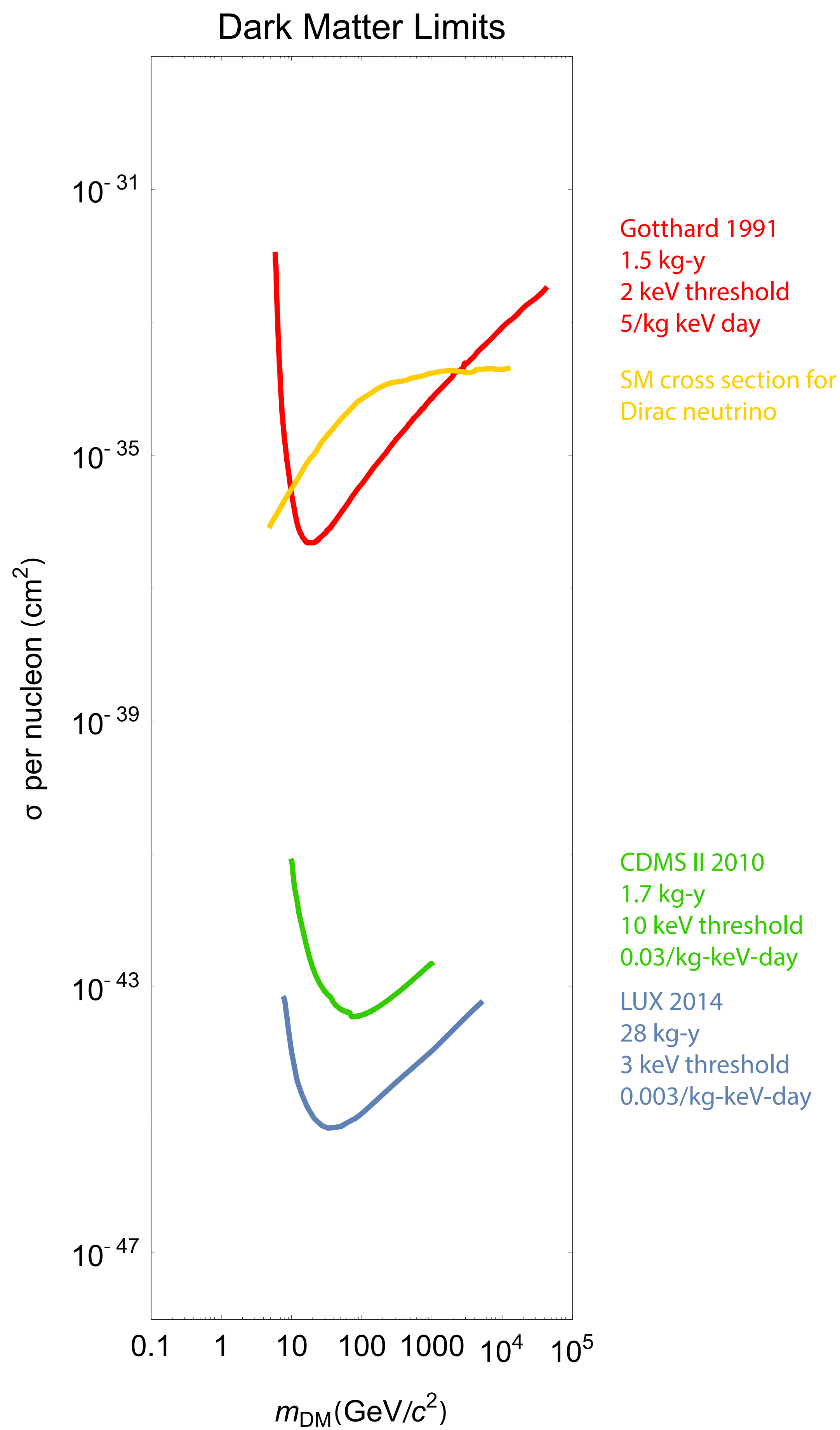
... are the most direct test of dark matter

There has been incredible progress in the last 2.5 decades:

Either cross section is smaller than 10^{-46} cm^2 or DM is heavier than 10 TeV

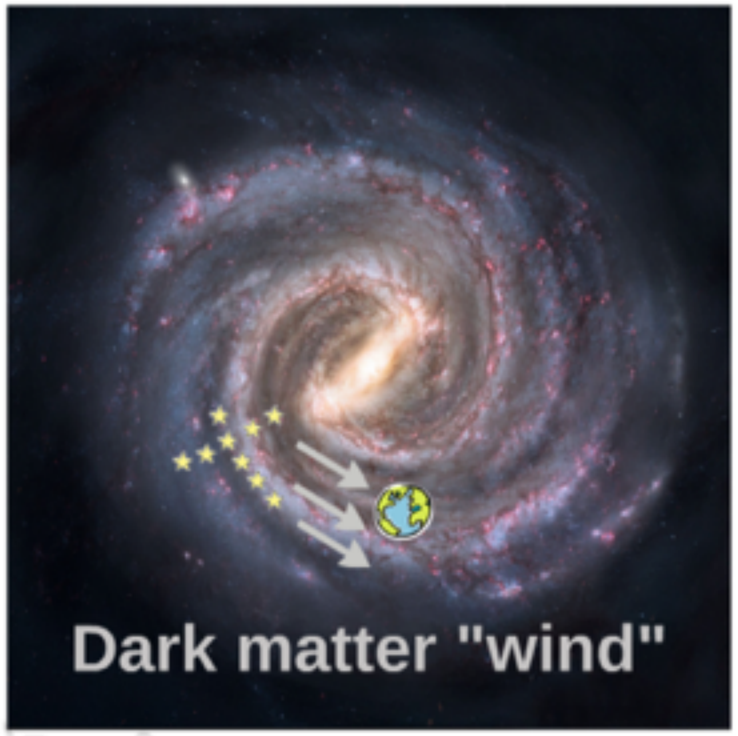
—> we are looking for a particle with an interaction strength 10 billion times smaller than a neutrino!

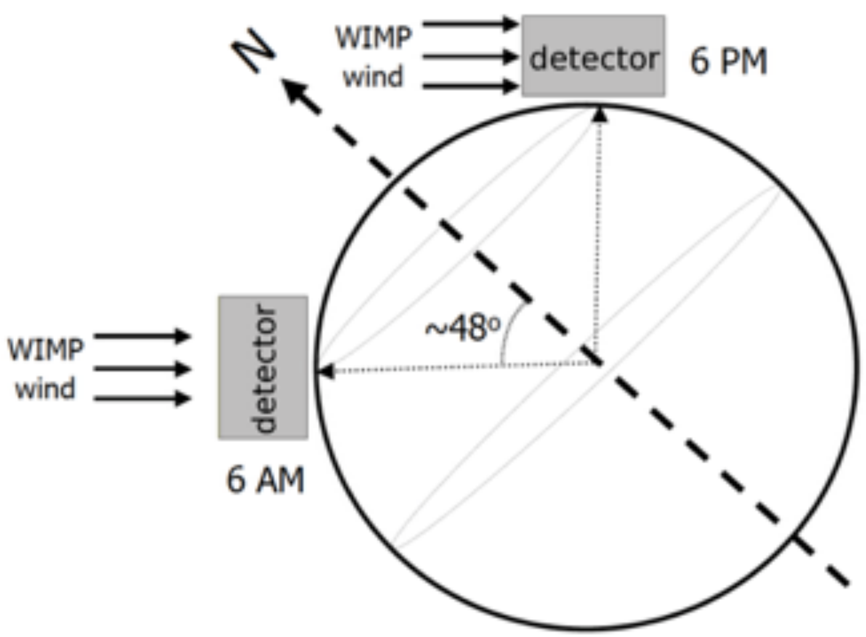
Neutrino backgrounds become important at 10^{-47} cm^2



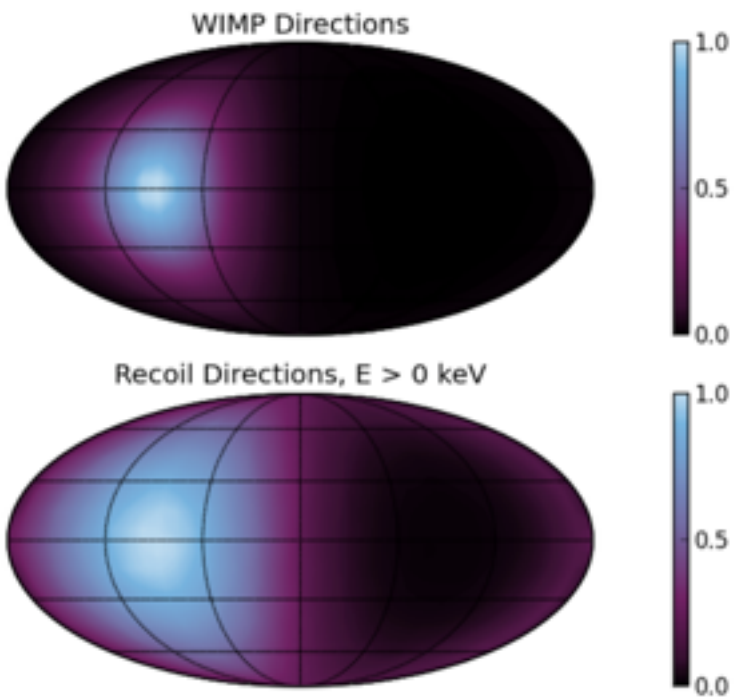
Directional detection

WIMPS have a preferred direction in galactic coordinates





Sidereal modulation in direction up to 10x annual modulation



A correlated signal would be unambiguous proof

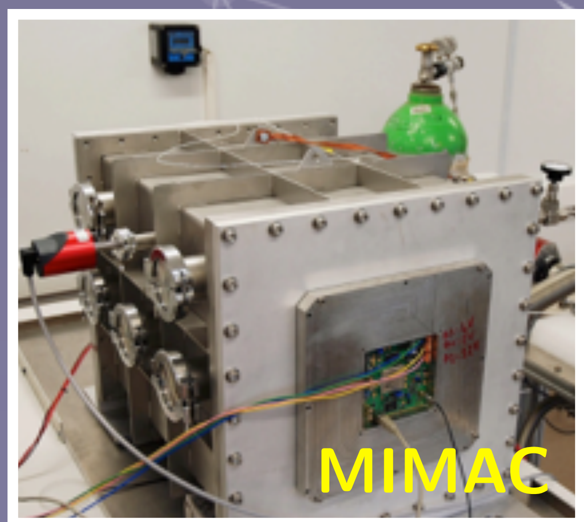
Directional optimization study

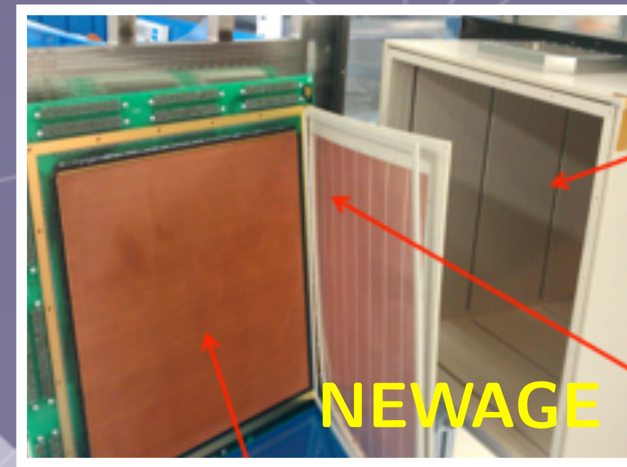
Baseline: E_T = 20 keV, S/N = ∞, 3D vector readout

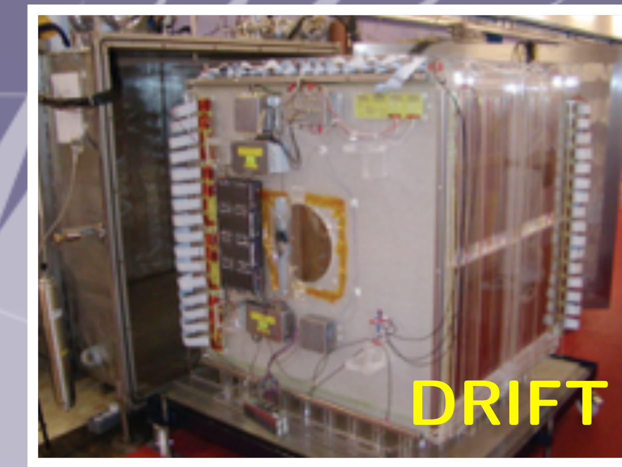
difference from baseline configuration	N_{90}	N_{95}
none	7	11
$E_T = 0$ keV	13	21
no recoil reconstruction uncertainty	5	9
$E_T = 50$ keV	5	7
$E_T = 100$ keV	3	5
$S/N = 10$	8	14
$S/N = 1$	17	27
$S/N = 0.1$	99	170
3-d axial read-out	81	130
2-d vector read-out in optimal plane, raw angles	18	26
2-d axial read-out in optimal plane, raw angles	1100	1600
2-d vector read-out in optimal plane, reduced angles	12	18
2-d axial read-out in optimal plane, reduced angles	190	270

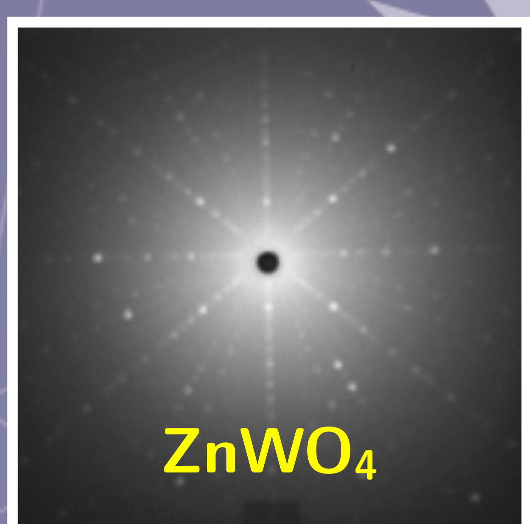
Astropart. Phys. 27:142-149 (2007)

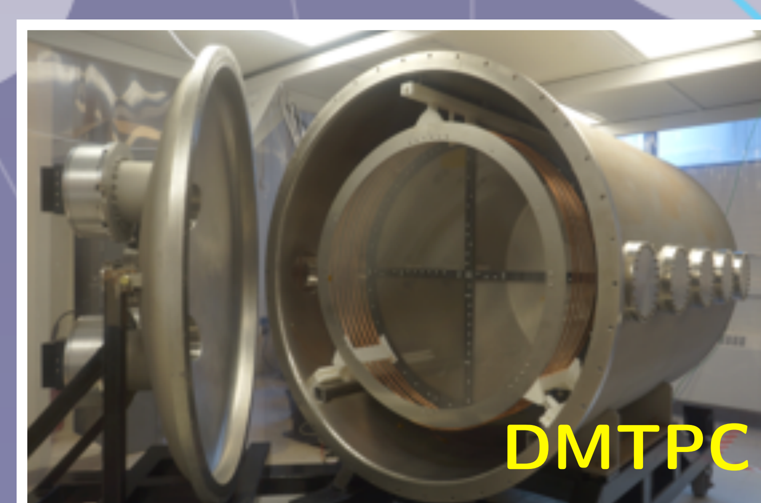
CYGNUS









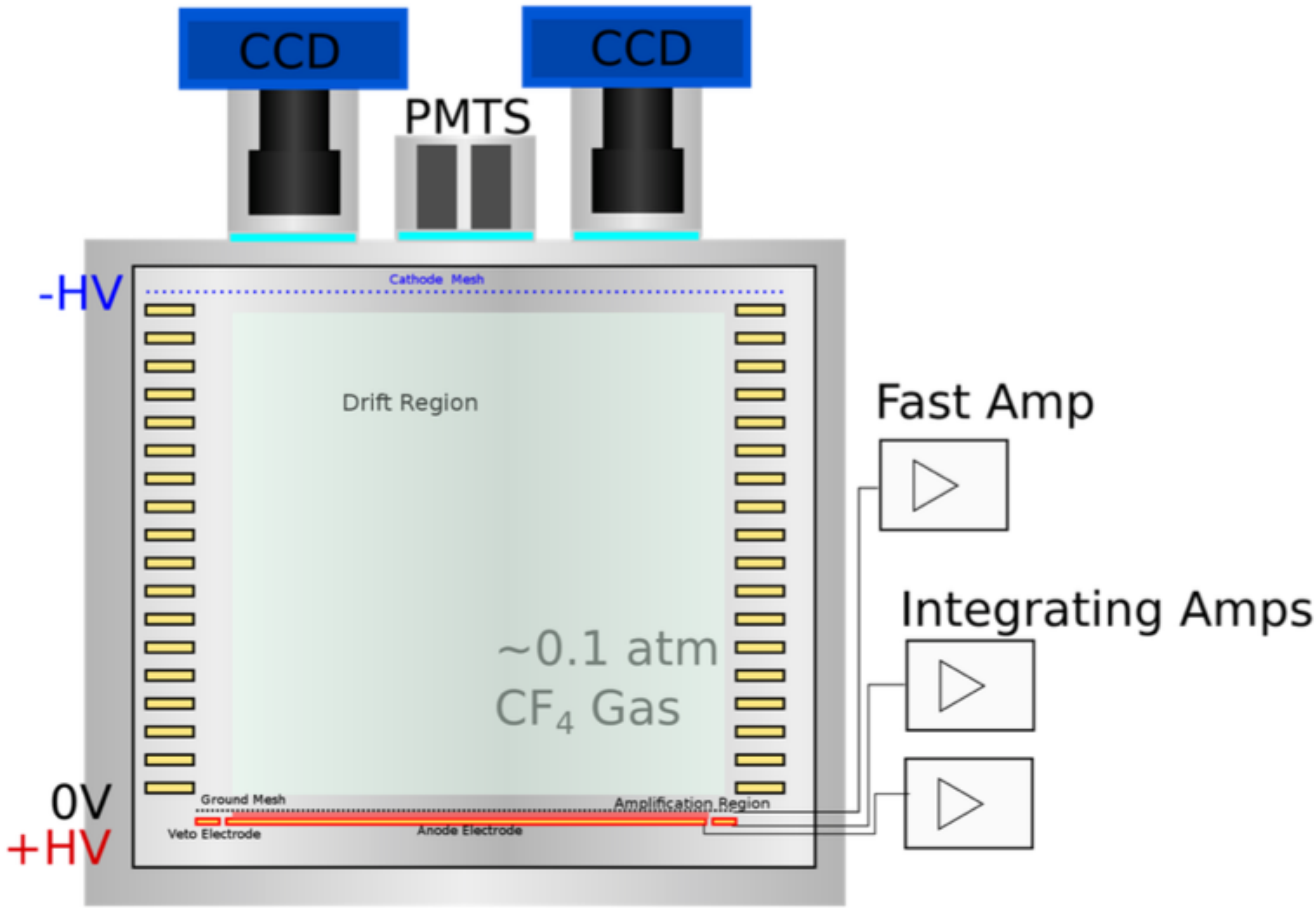


Some existing directional experiments

Collaboration	Technology	Target	Readout	Volume (m^3)	Angular resolution	Head-tail
DRIFT	NITPC	$CS_2 + CF_4$	MWPC 2D + z	0.8		yes?
DMTPC	TPC	CF_4	Optical (CCD) 2D + charge + timing	0.02, 1	$< 15^\circ$ @ 100 keV	yes
NEWAGE	TPC	CF_4	μPIC 2D + timing	0.036	40° @ 50 keV	no
MIMAC	TPC	$CF_4 + CHF_3$	MicroMegas 2D + timing	0.006	70° @ 60 keV	yes
D^3	TPC	$HeCO_2$	Si pixel 2D + z	6E-05	$< 1^\circ$ @ 1 MeV	
Emulsions	emulsions	AgBr	Optical (microscope) 2D	n/a	20° @ 60 keV	no

All are sensitive to both SI and SD interactions

Case example: DMTPC



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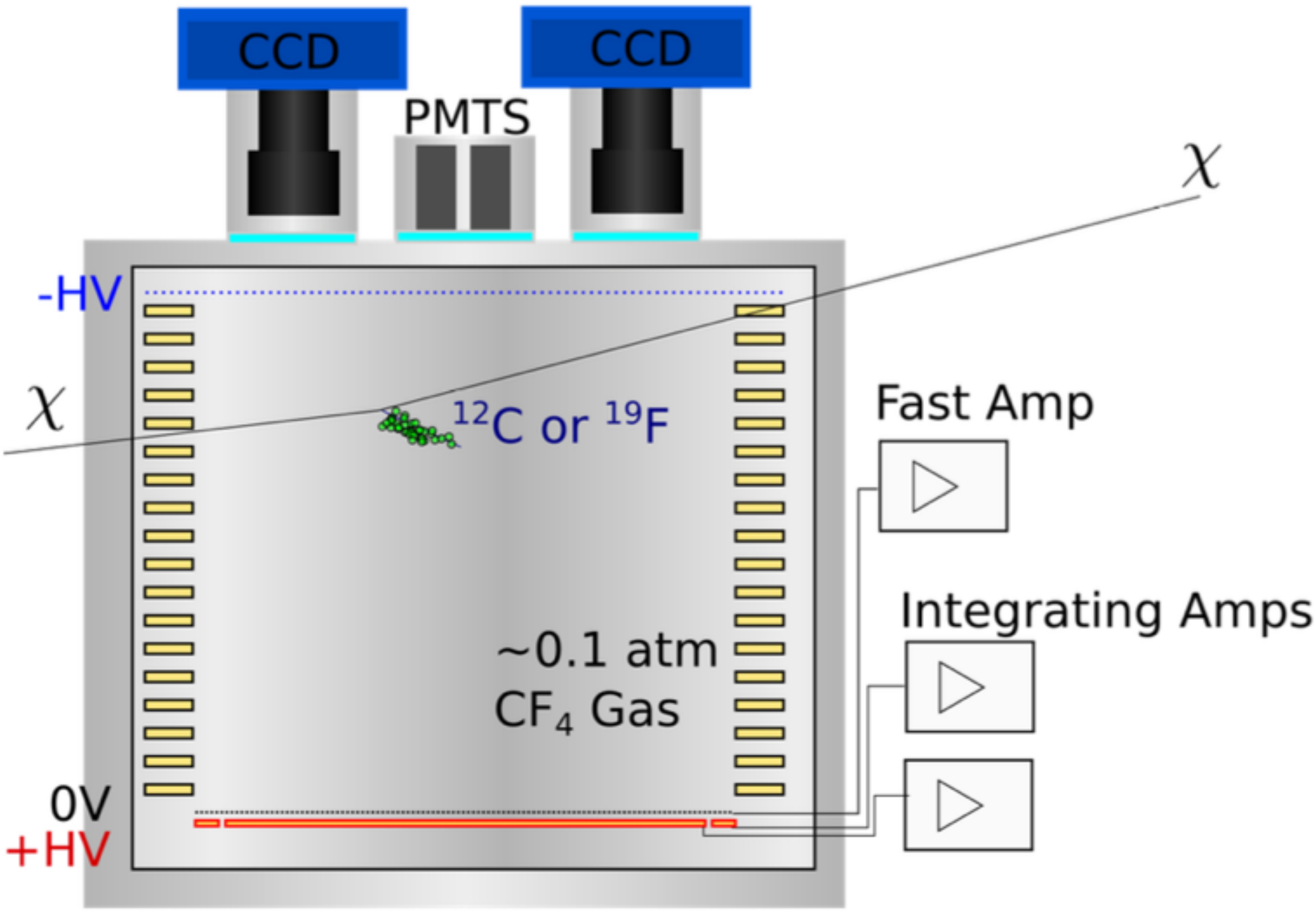

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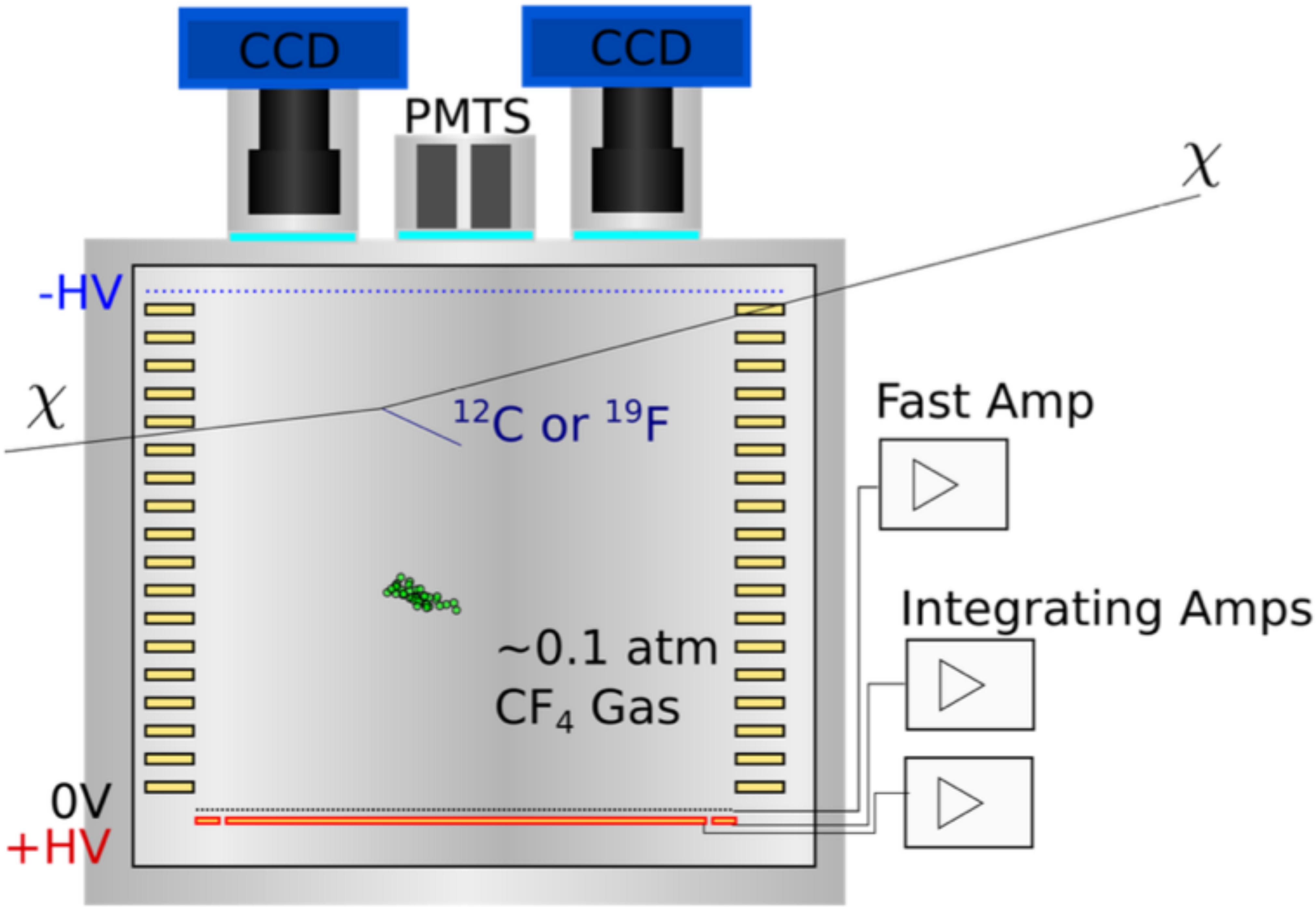

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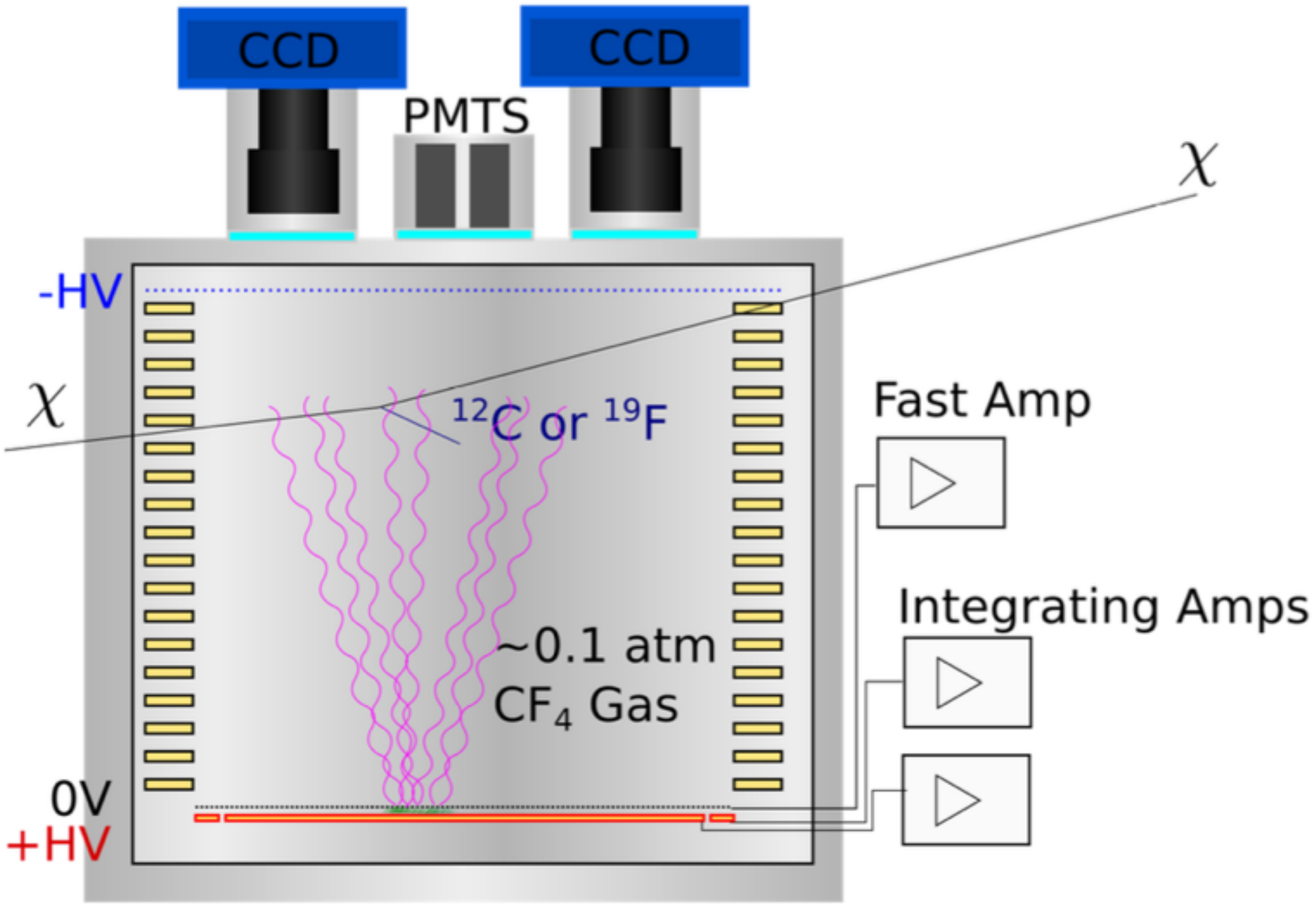

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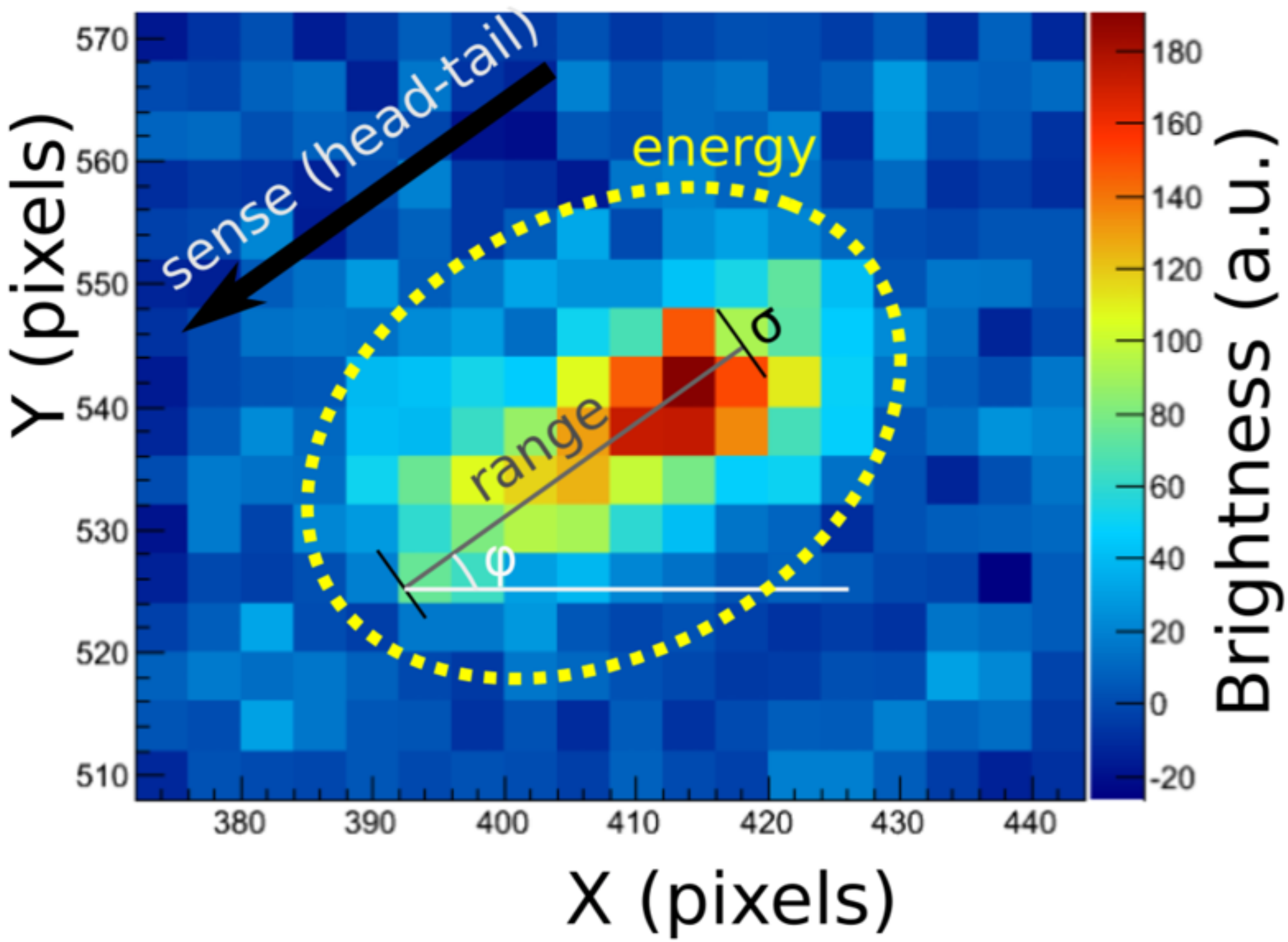
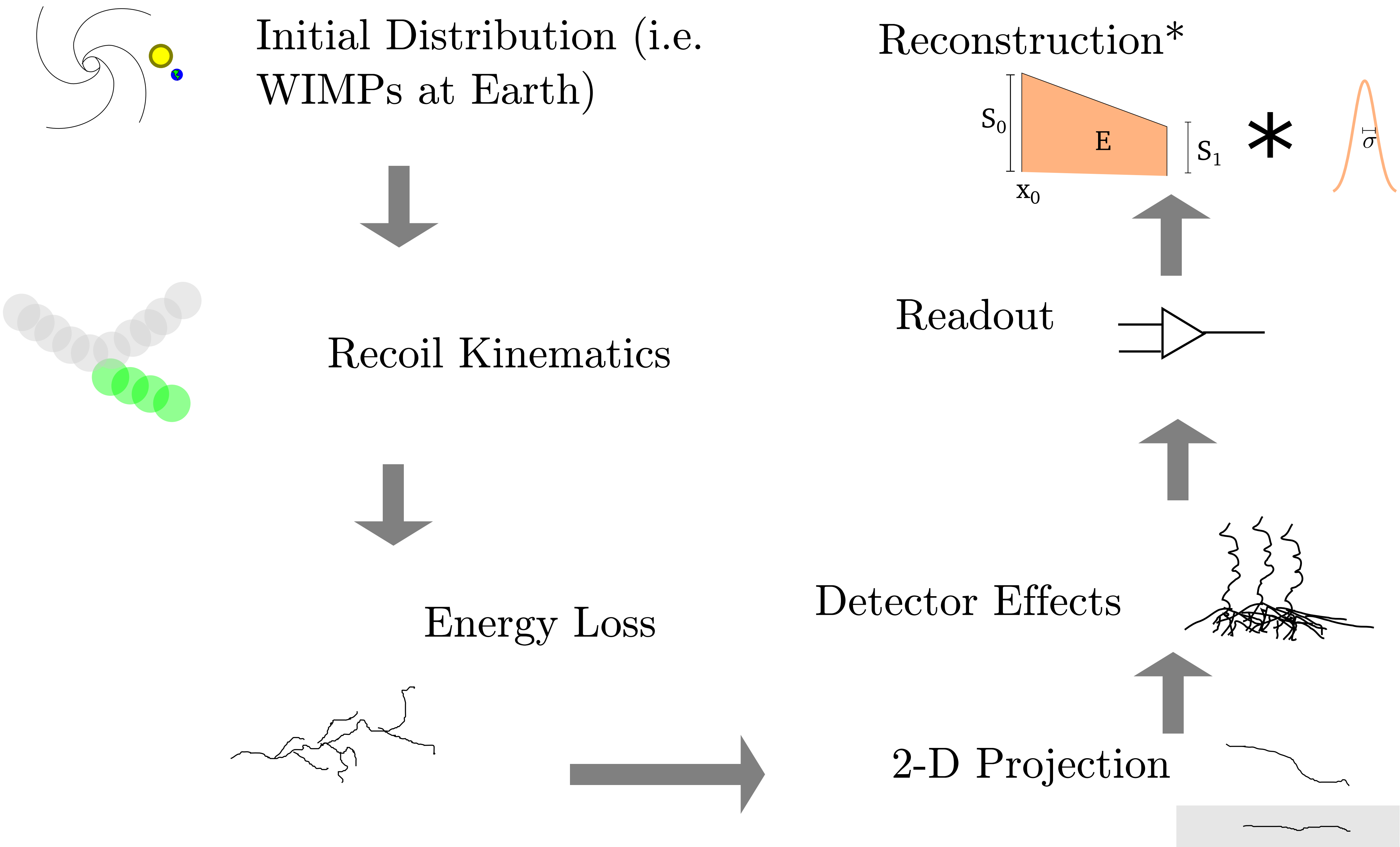
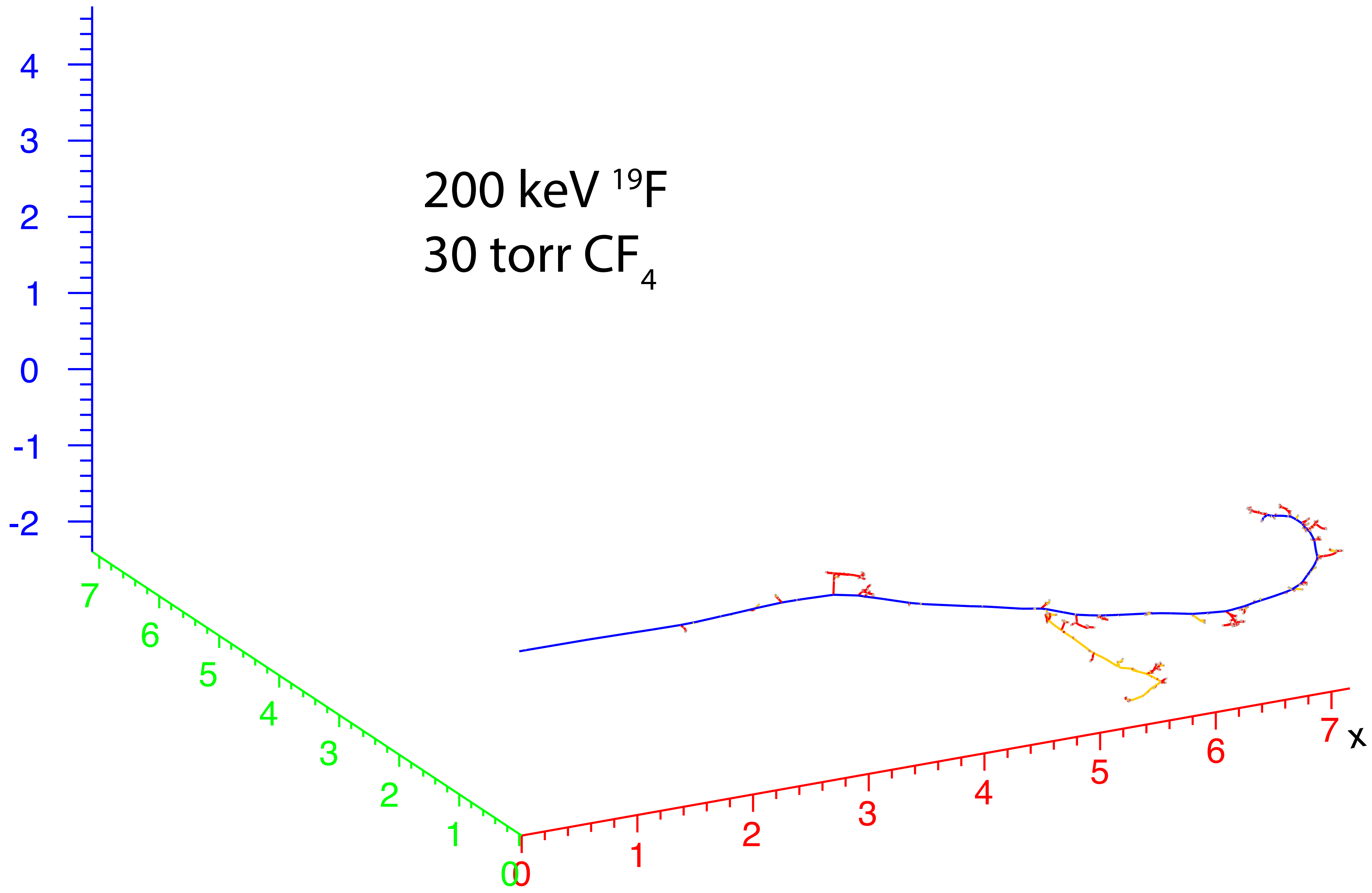


Signal Directionality Flowchart

For DMTPC-like detectors



TRIM track



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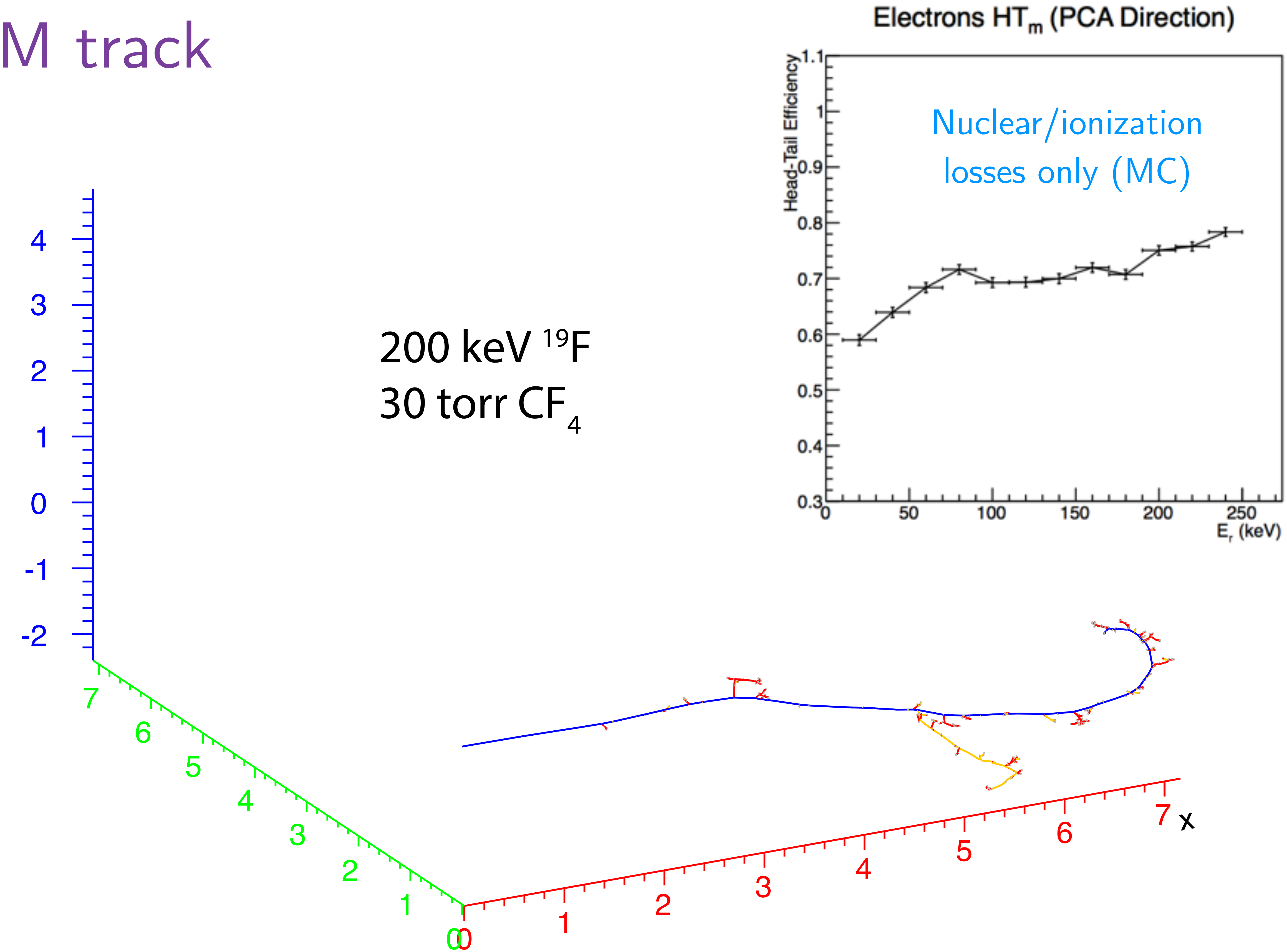
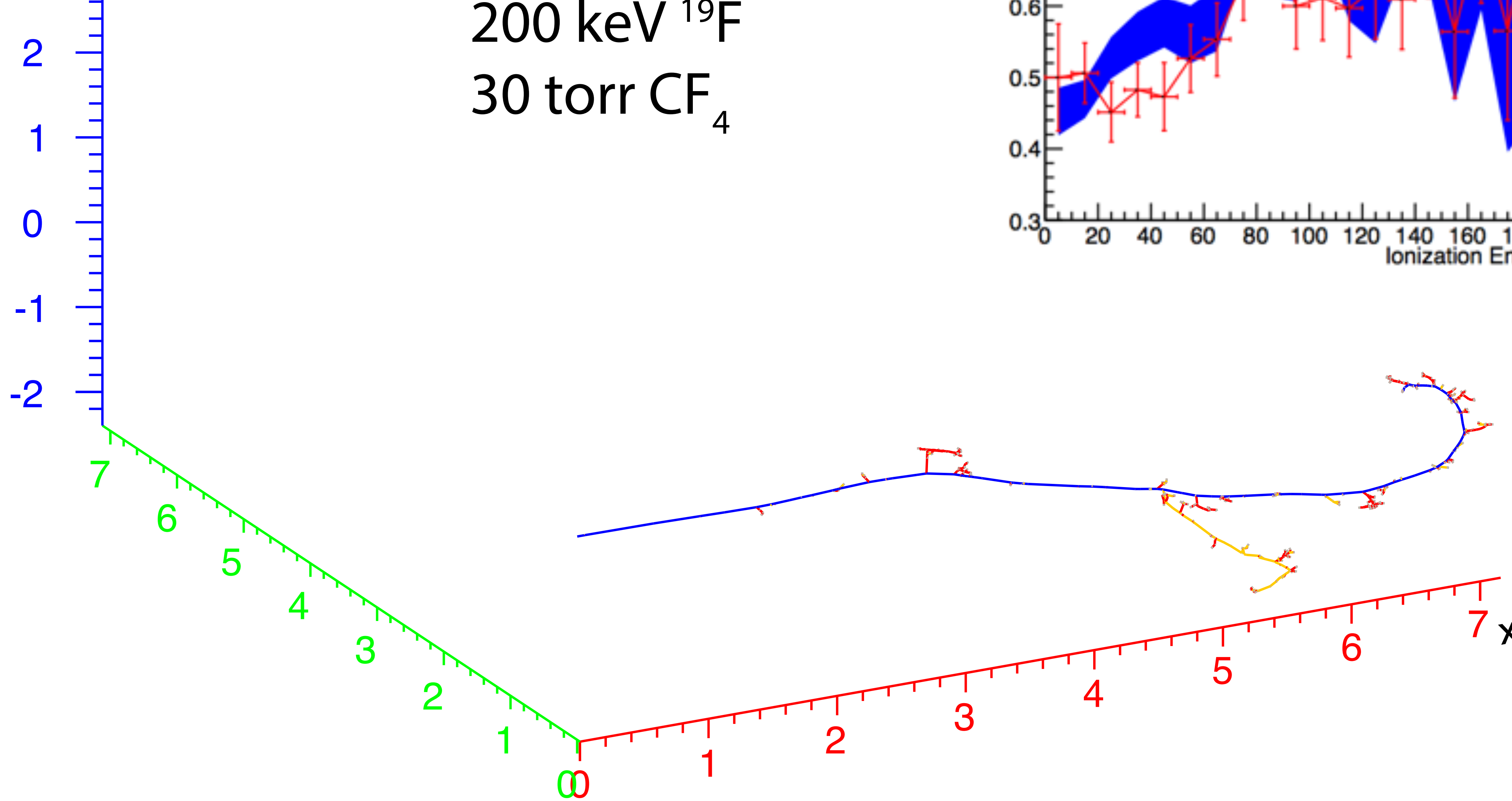
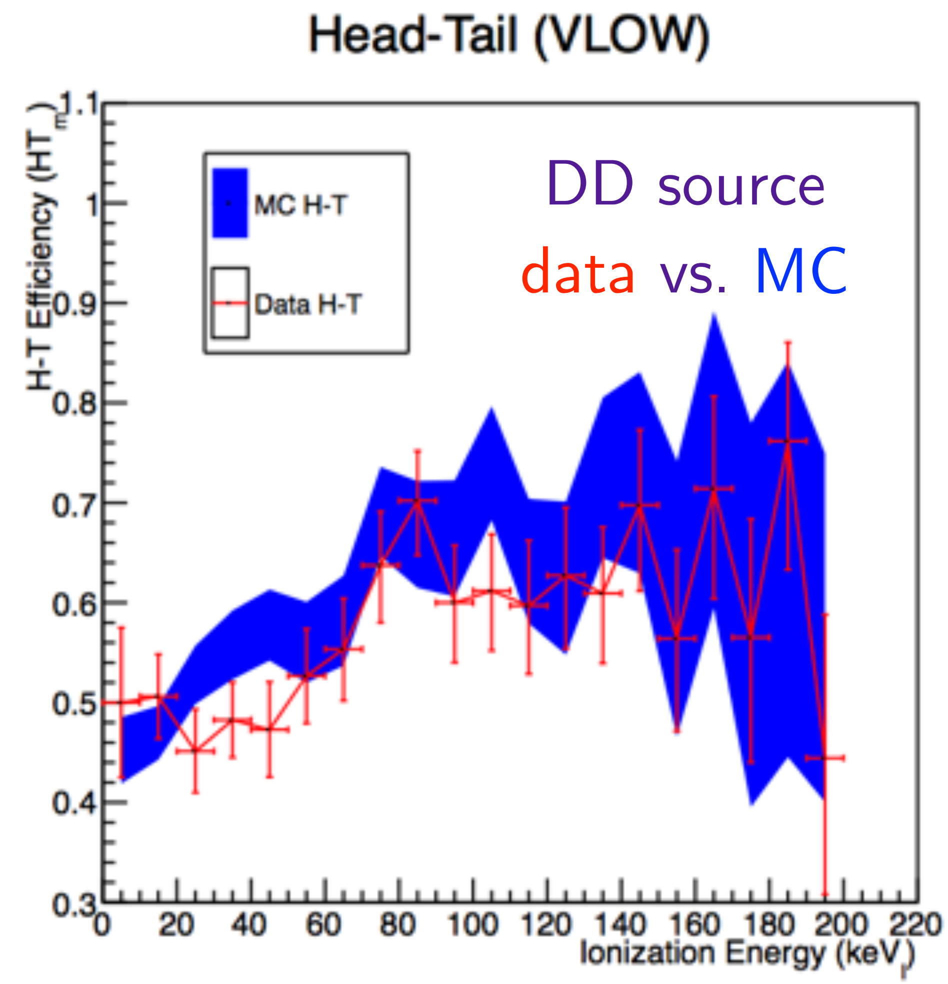


200 keV ^{19}F
30 torr CF_4
Electrons HT_m (PCA Direction)
Head-Tail Efficiency
Nuclear/ionization losses only (MC)
E_r (keV)

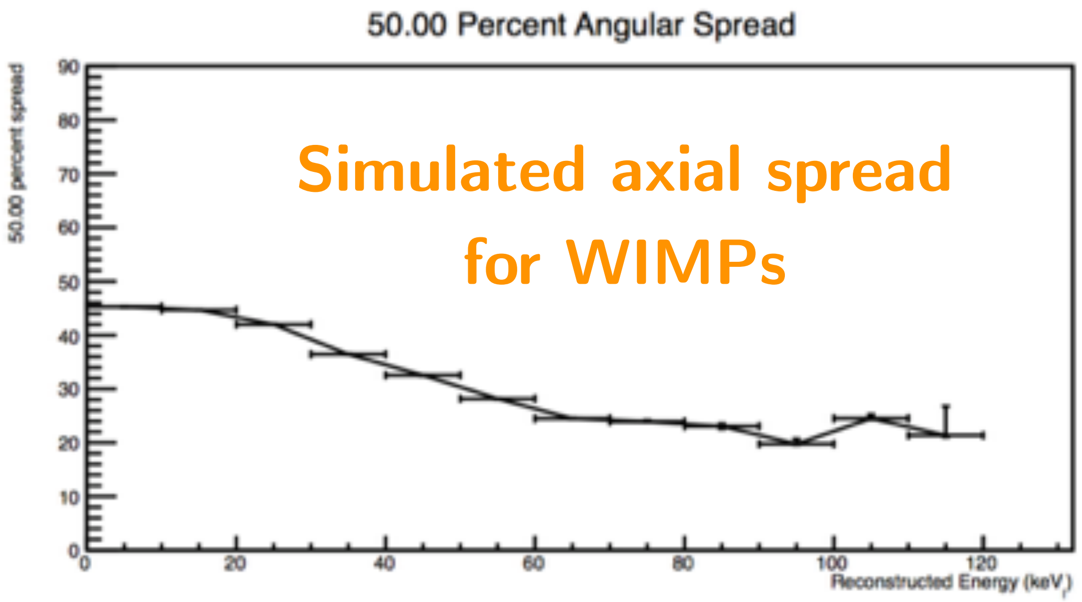
TRIM track

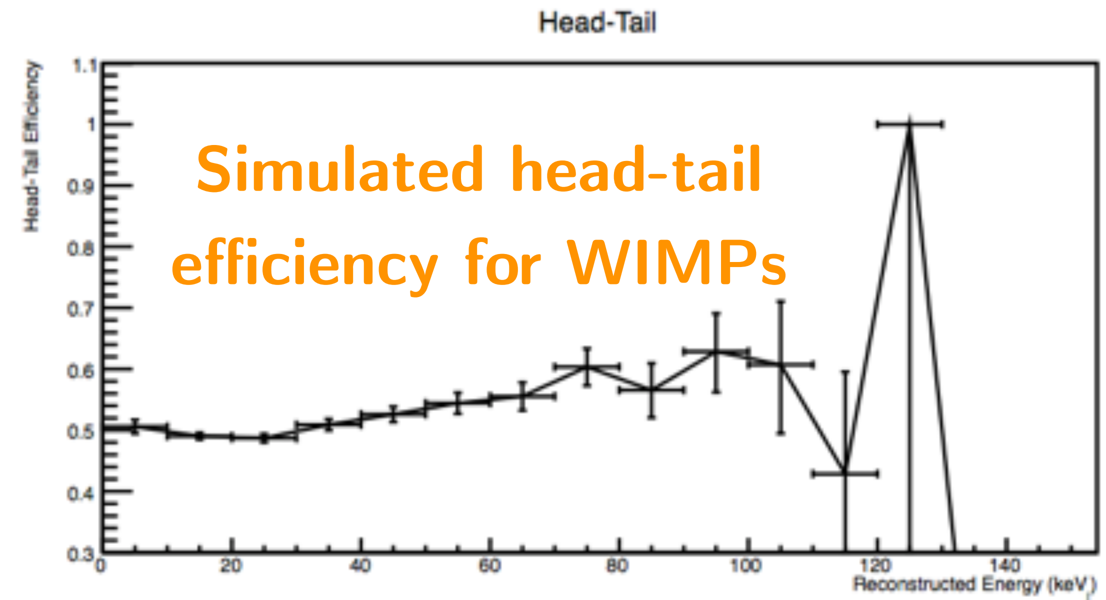
200 keV ^{19}F
30 torr CF_4

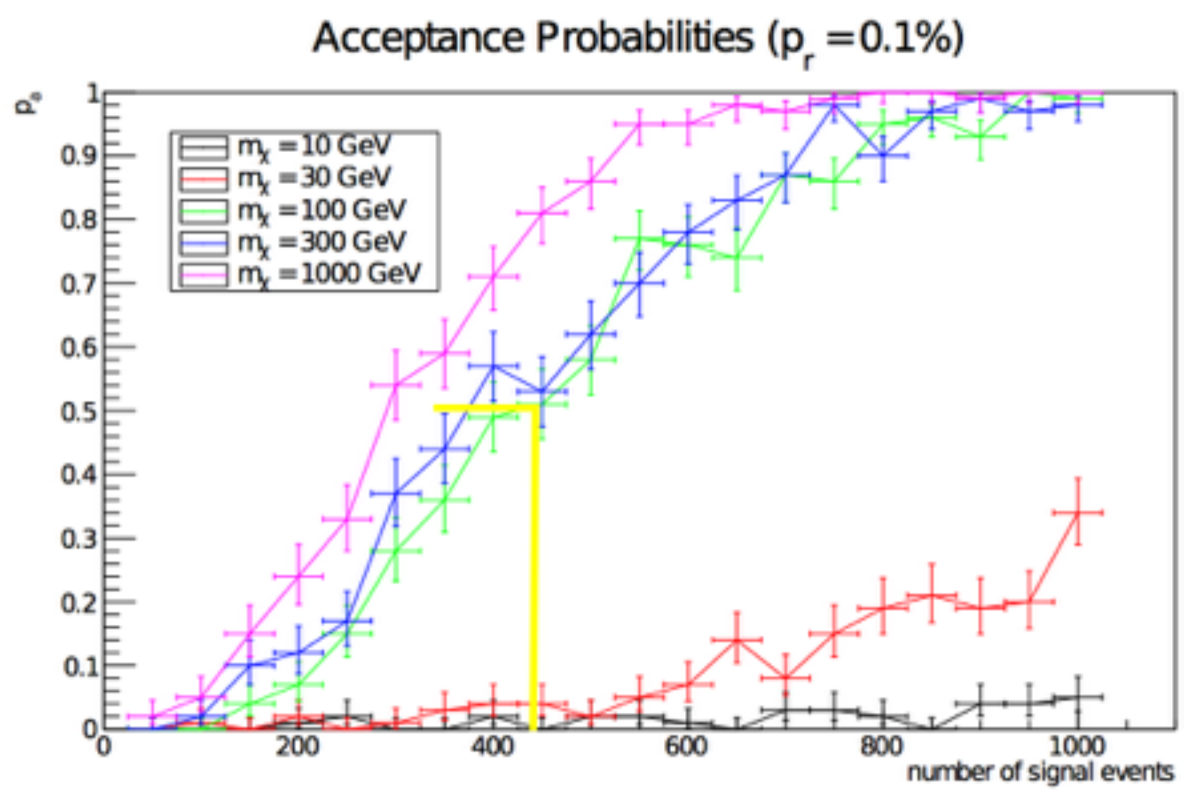




Projected directional sensitivity





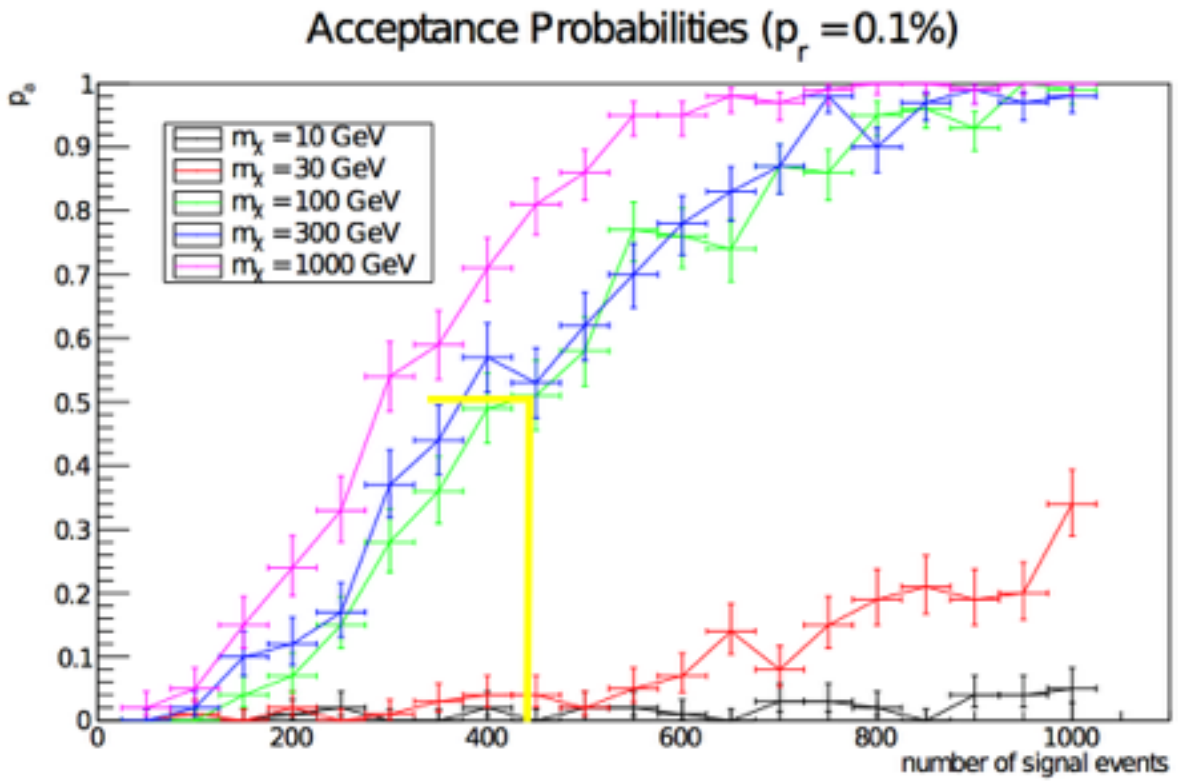


Probability of rejecting isotropy with *n* signal events

Projected directional sensitivity

—> Current level of sensitivity from counting experiments [$\sigma_p = 1$ fb] can be achieved with 300 (450) m^3-years, for a WIMP mass of 1000 (100) GeV.

=



Probability of rejecting isotropy with *n* signal events

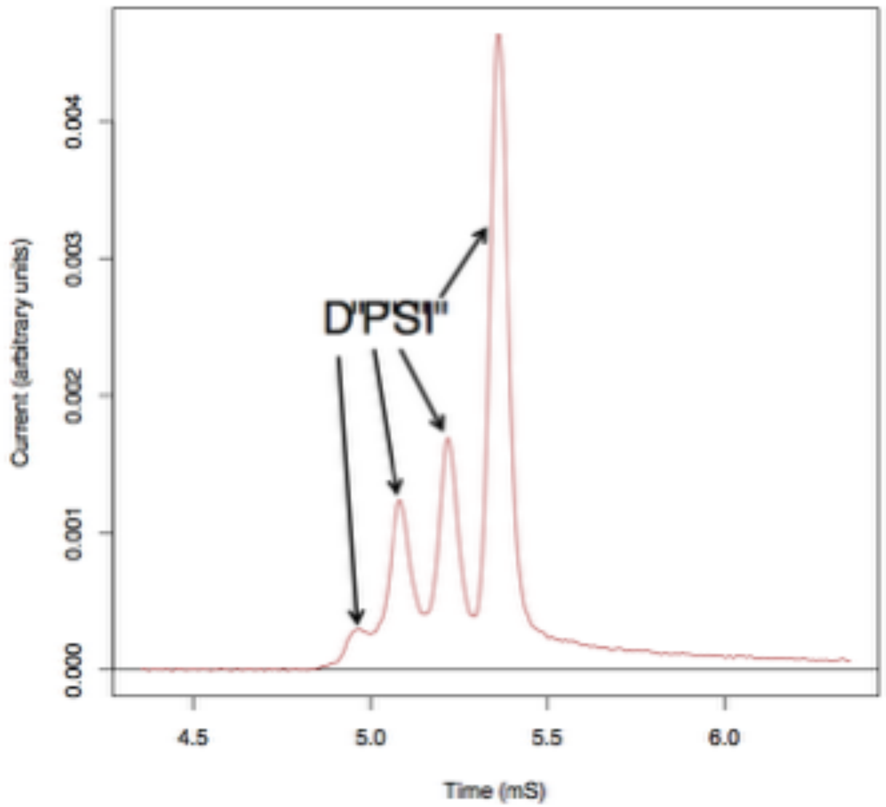
Projected directional sensitivity

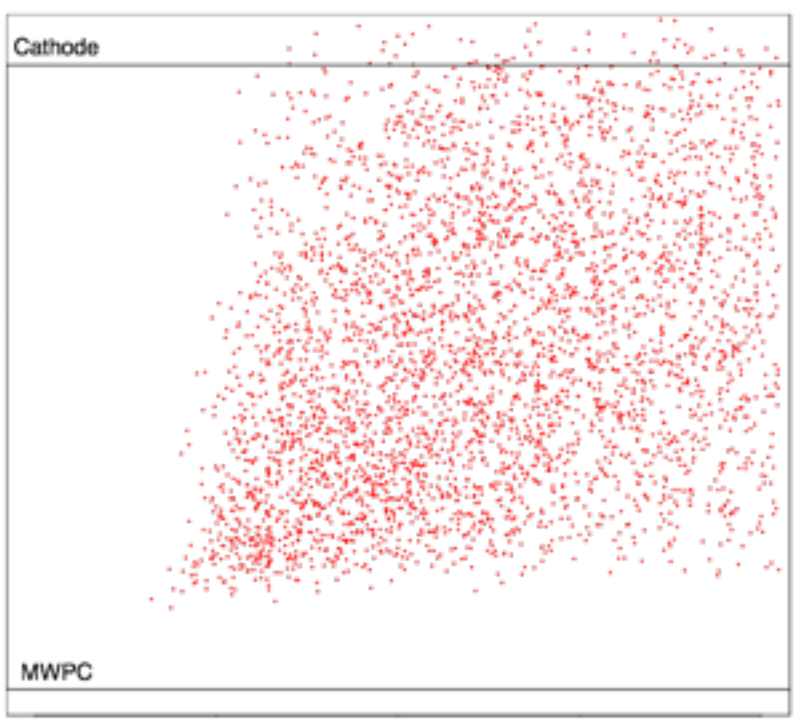
—> Current level of sensitivity from counting experiments [$\sigma_p = 1$ fb] can be achieved with 300 (450) m^3-years, for a WIMP mass of 1000 (100) GeV.

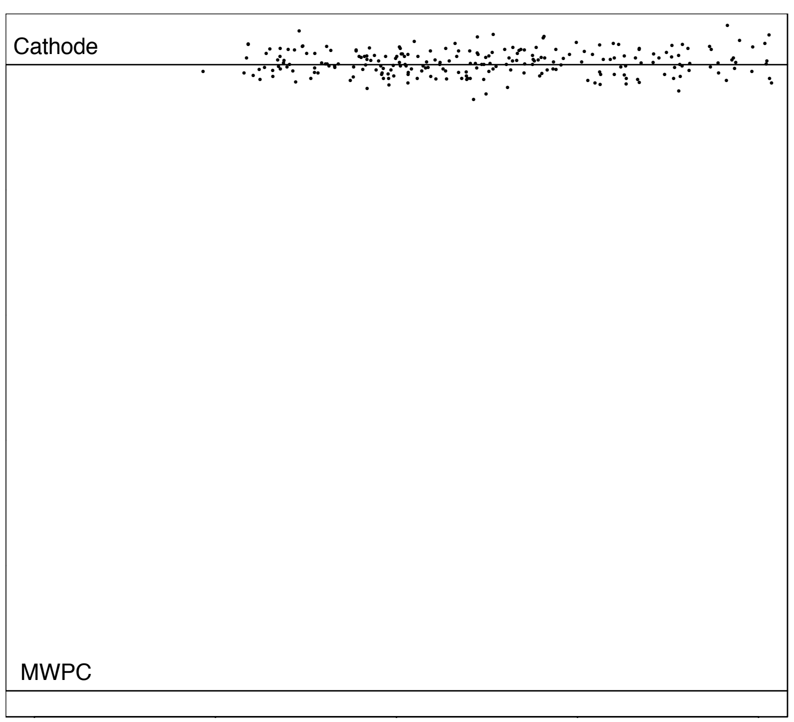
This is equivalent to 2.4 (3.6) 125-m^3-years

Background-free DRIFT IId

Adding O_2 to CS_2-CF_4 mixture produces minority peaks and allows for *z* fiducialization and background-free running







Where to go from here

Without reliable head-tail determination at low energies, axial information will dominate directional sensitivity for low-pressure TPC experiments

... when does it make more sense to increase pressure (target mass) and focus only on axial sensitivity?

Can novel gas mixtures enhance directional performance and sensitivity?

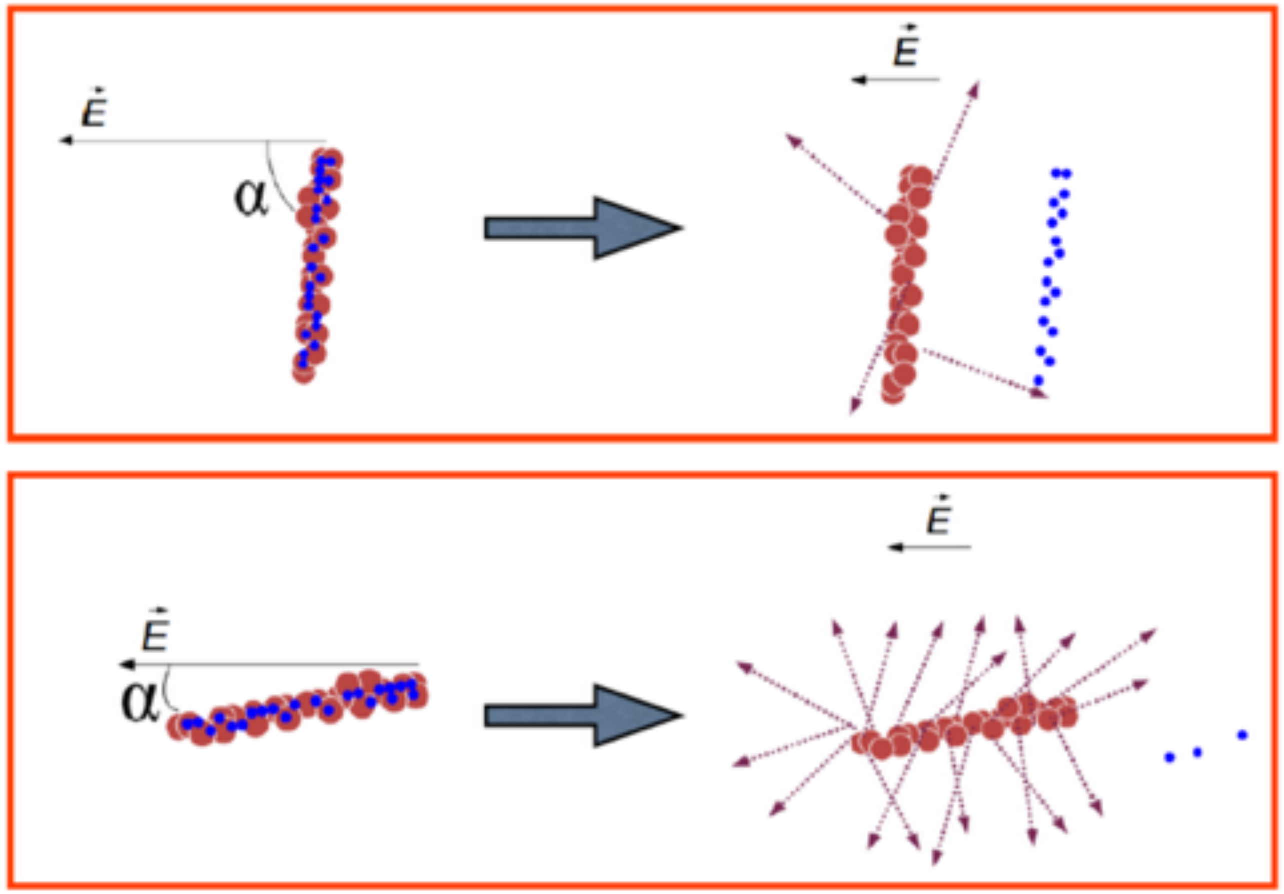
Light nuclei would experience less nuclear stopping, but energy spectrum suppressed by reduced mass

Adding light targets with spin-dependent cross section, e.g. H, ^{3}He, CH_4?

Adding Ne to CF_4 to make Penning mixture? Other high-gain variants?

Can photon collection efficiency be improved with new(er) technologies, e.g. SiPM, MPPC?

Columnar Recombination



CR increases as angle α decreases

Directionality information obtained prior to drift

J. Phys. Conf. Ser. 460 012006

Current progress in CR

NICE (E. Baracchini et al.)

- Detect primary scintillation light (timing) using commercial SiPMs in energy plane
- Detect ionization (tracking) using GEMPix
- Need to find an appropriate capture agent for Xe
- Head-tail sensitivity?
- See E. Baracchini's talk at Cygnus 2015 directional workshop

TEA-Pot

- Preliminary studies with TMA report no detection of scintillation light, suggesting it might not be suitable
- See Y. Nakajima's talk at 7th Symposium on large TPCs

Polar angle CR detector

Detector type	space-fixed		Earth-fixed	
	Axial	Head-tail	Axial	Head-tail
General	62.30 ± 0.56	9.90 ± 0.09	193.2 ± 2.1	19.22 ± 0.19
Angular Only	231.4 ± 2.7	12.70 ± 0.13	767.0 ± 9.2	23.91 ± 0.25
Xenon, 30 GeV WIMP, 3 keV threshold	168.1 ± 1.6		535.6 ± 5.8	
Xenon, 30 GeV WIMP, 10 keV threshold	218.5 ± 2.0		702.7 ± 7.6	
Xenon, 50 GeV WIMP, 30 keV threshold	1318 ± 12		4087 ± 44	

Space-fixed polar detector in optimal orientation has roughly same performance as detector with full 3D tracking

For 5×10^{-46} cm^2 SI cross section and 30 GeV WIMP, an exposure of 770 (2480) kg-year with a space-fixed (Earth-fixed) axial polar detector and 10 keV threshold can reach a 3σ signal

Phys. Rev. D 92, 043523 (2015)

LHe

Low target mass means high sensitivity to light (1-10 GeV) WIMPs

Many signals to choose from: primary scintillation light (S1), ionization charge (S2), metastable triplet excimers (S3), rotons, phonons, electron bubbles

Directionality from rotons?

A Concept for A Dark Matter Detector Using Liquid Helium-4

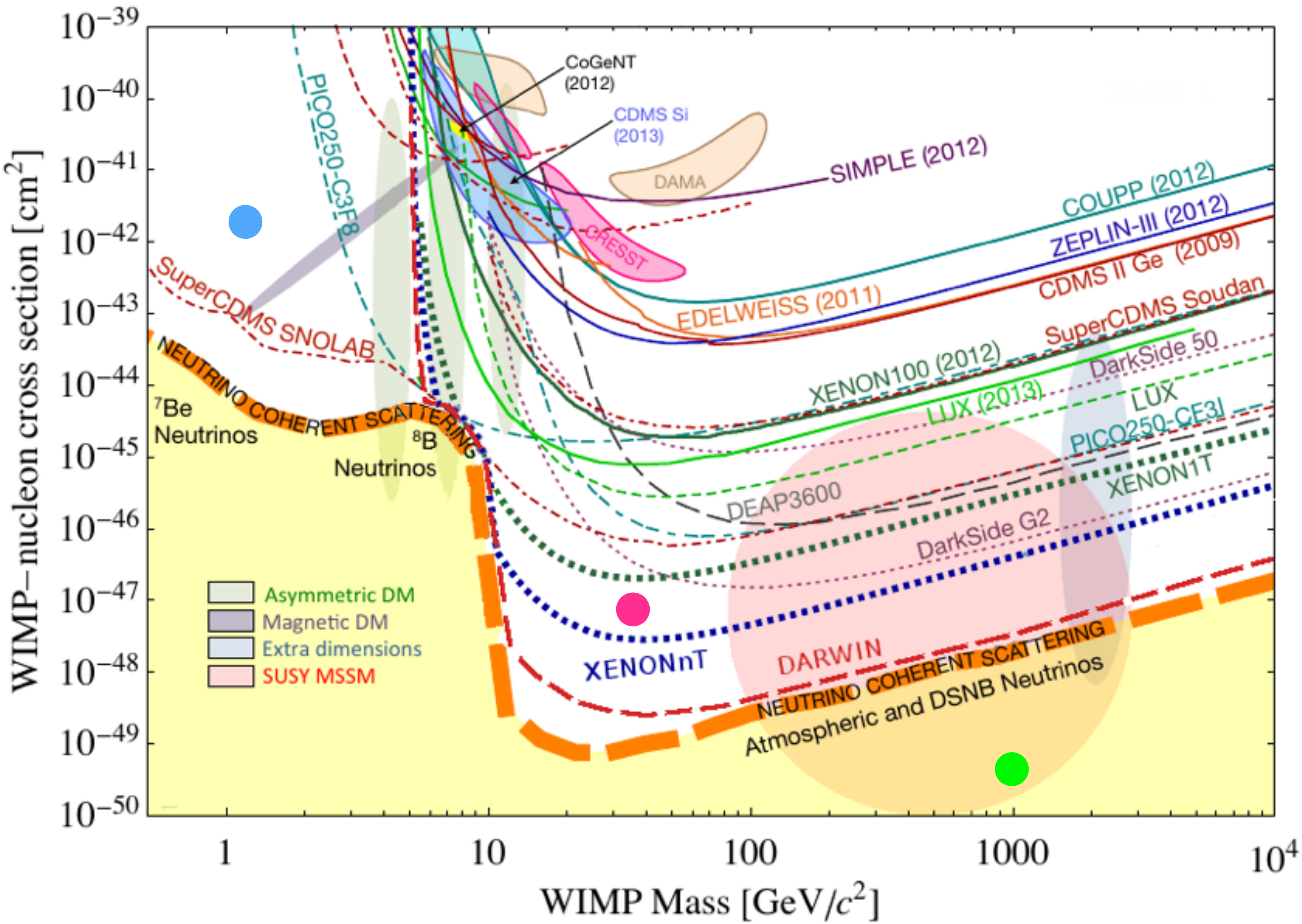
W. Guo*
Mechanical engineering department, Florida State University, Tallahassee, FL 32310, USA

D.N. McKinsey†
Physics department, Yale University, New Haven, CT 06520, USA
(Dated: February 20, 2013)

rings can be as low as on the order of 1 m/s [124]. However, it has been shown that at low temperatures when isotropically purified helium is pressurized to above 15 bar, electrons can be driven at a speed close to or higher than the Landau velocity (∼ 50 m/s). Instead of nucleating vortex rings, the electrons spontaneously emit roton pairs [125–127]. The rate of roton emission depends on the field strength. Furthermore, it has been shown that when the electron speed is not too much higher than the Landau velocity, the majority of the emitted rotons tend to have momentum aligned in the same direction with the electron velocity [128]. A roton beam is formed accompanying every extracted electrons. Note that rotons in the

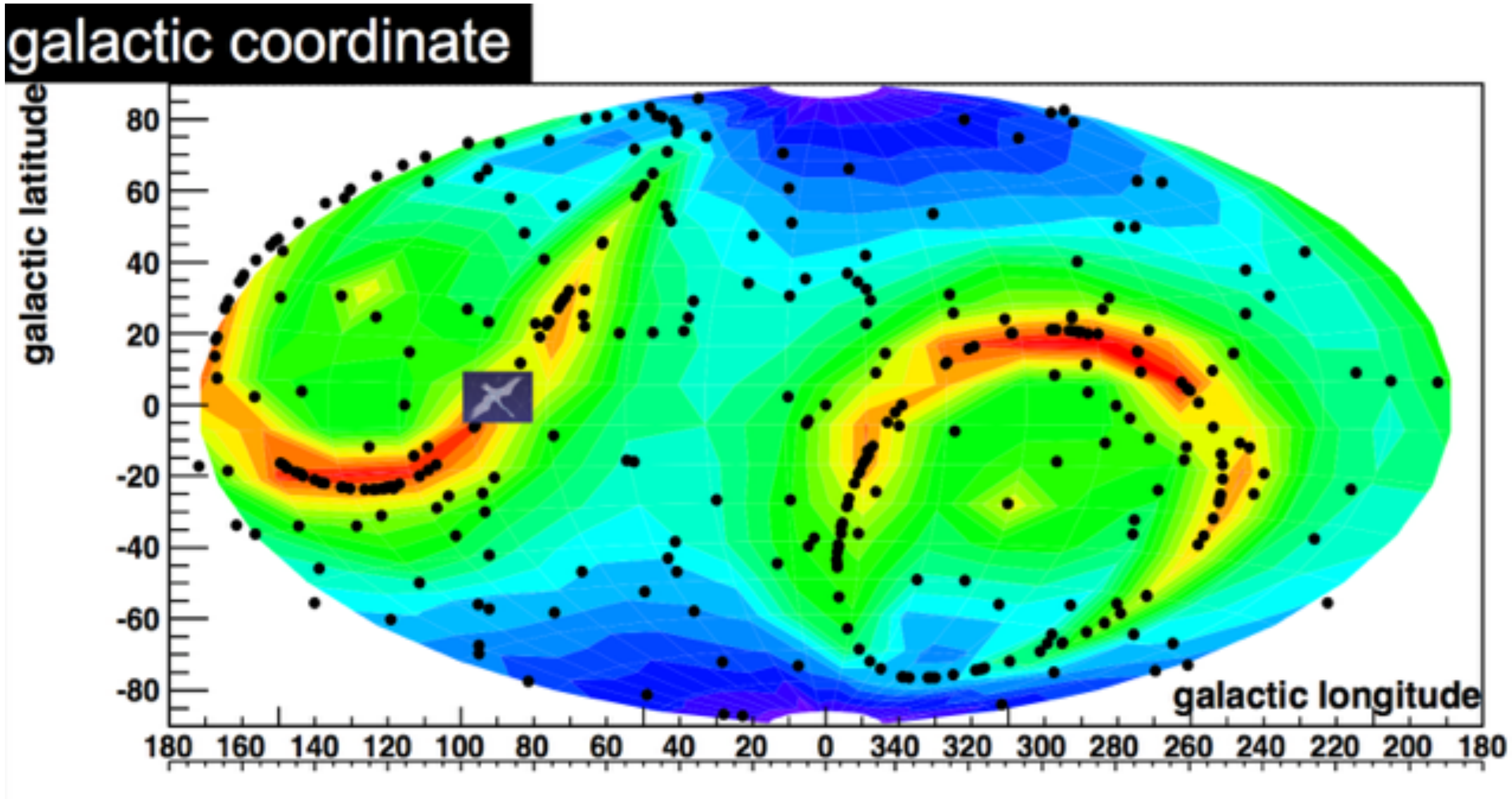
Phys. Rev. D 87:115001 (2013)

A few scenarios



Strategy for directional detectors

- Continue pushing directional R&D on multiple fronts
- Further investigation into fields of chemistry and material science can help identify optimal gas mixtures, scintillators, etc.
- Closer collaboration with non-directional experiments is highly desirable



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som detta år tillerkännes den som inom
fysikens område gjort den viktigaste
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med ena hälften gemensamt belöna

Raymond Davis Jr

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för banbrytande insatser inom astrofysiken, särskilt för detektion av kosmiska neutriner

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STOCKHOLM DEN 10 DECEMBER 2002

Erling Norrby

Some food for thought ...

How does the effort needed to build a large directional experiment balance against the confidence gained from an annual signal collected over several years?