Experimental Techniques in Dark Matter and Neutrino Physics
Rare Event Searches

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Invisibles School 2023
Bad Honnef, DE

Outline

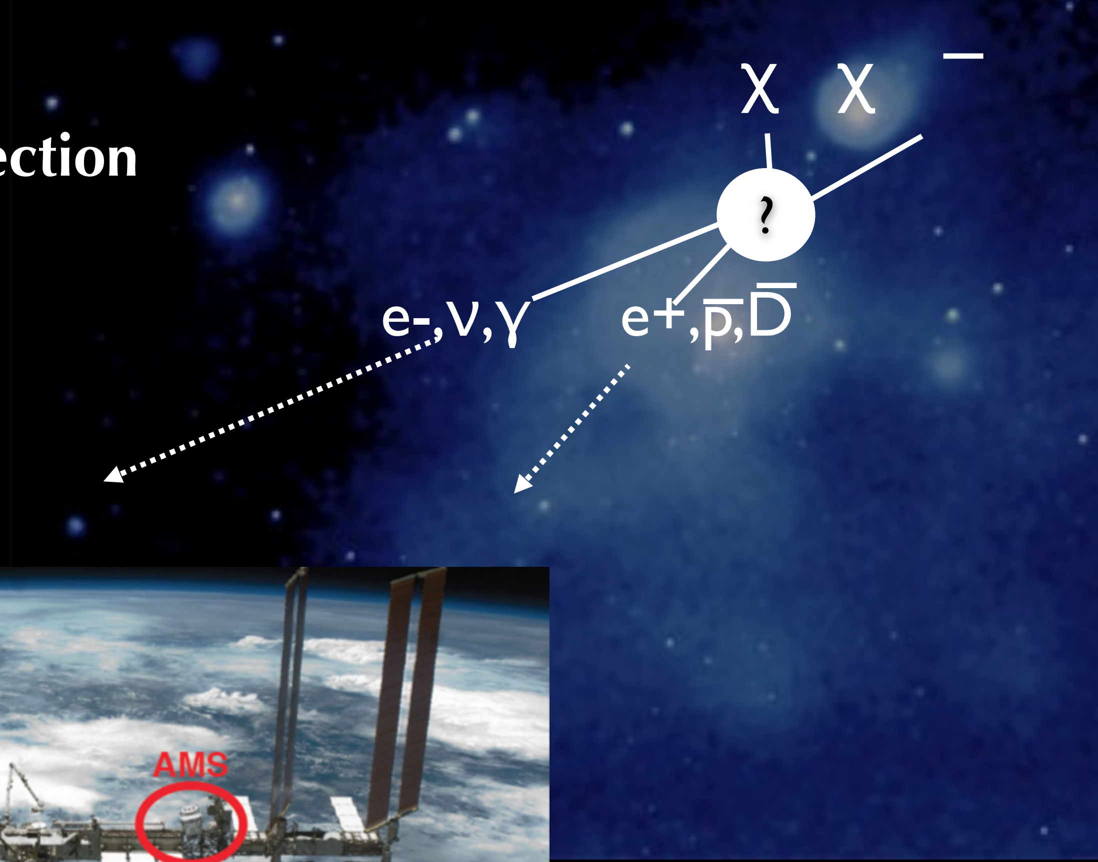
1. The Evidence for Dark Matter

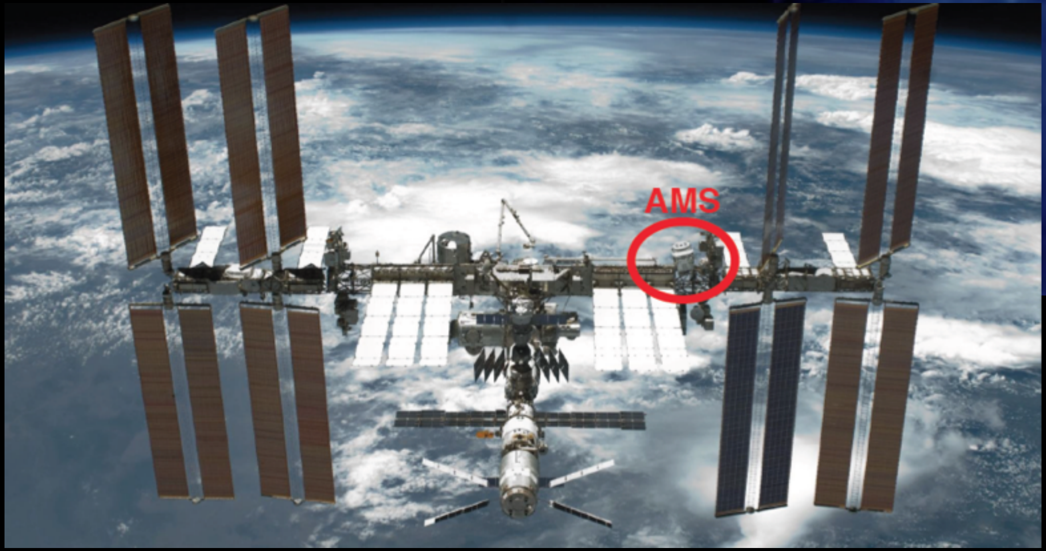
2. Dark Matter Detection Experimental Techniques

3. Dark Matter Search Status and Prospects

4. Neutrino Physics in Dark Matter Detectors

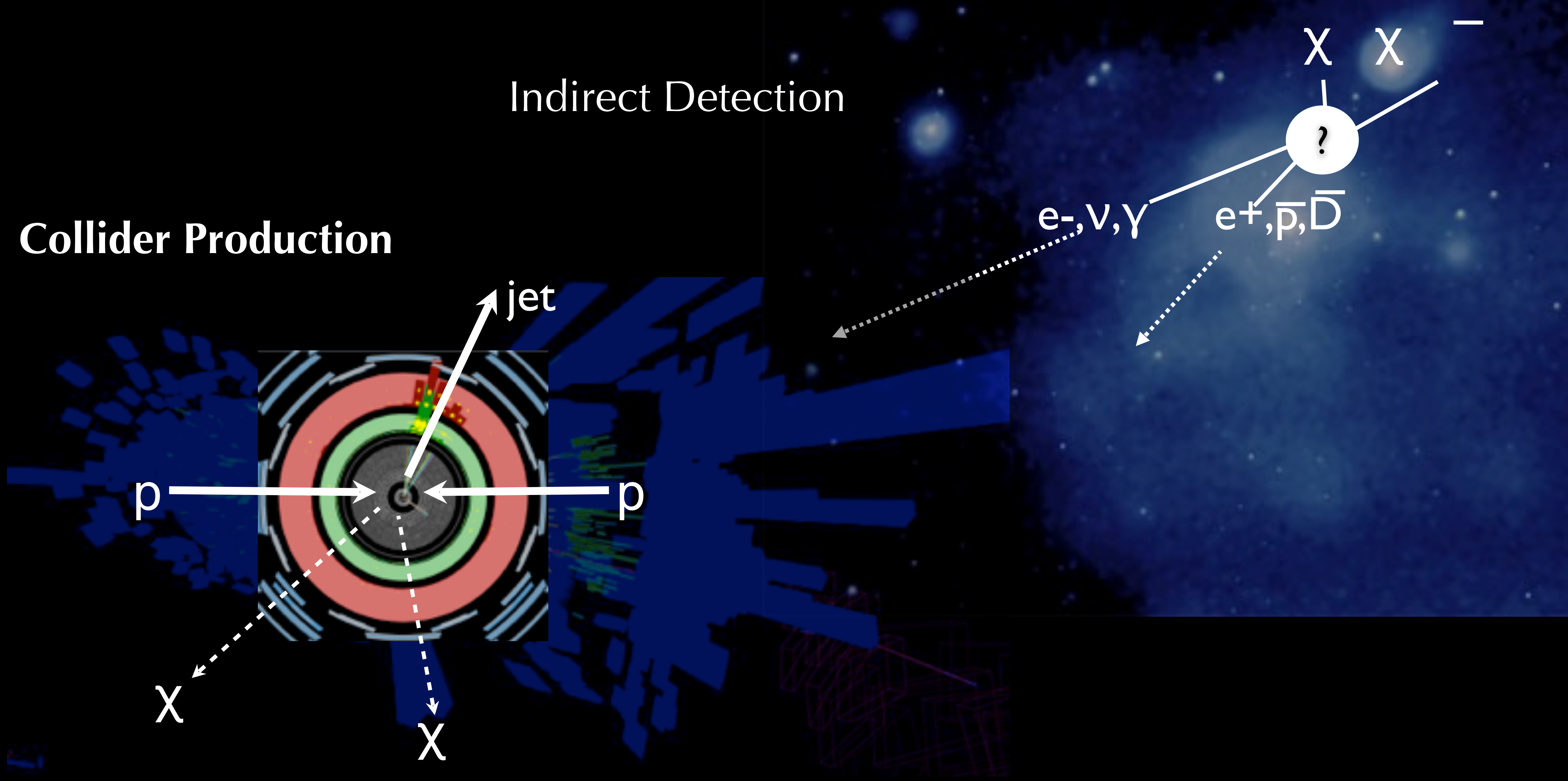
Indirect Detection

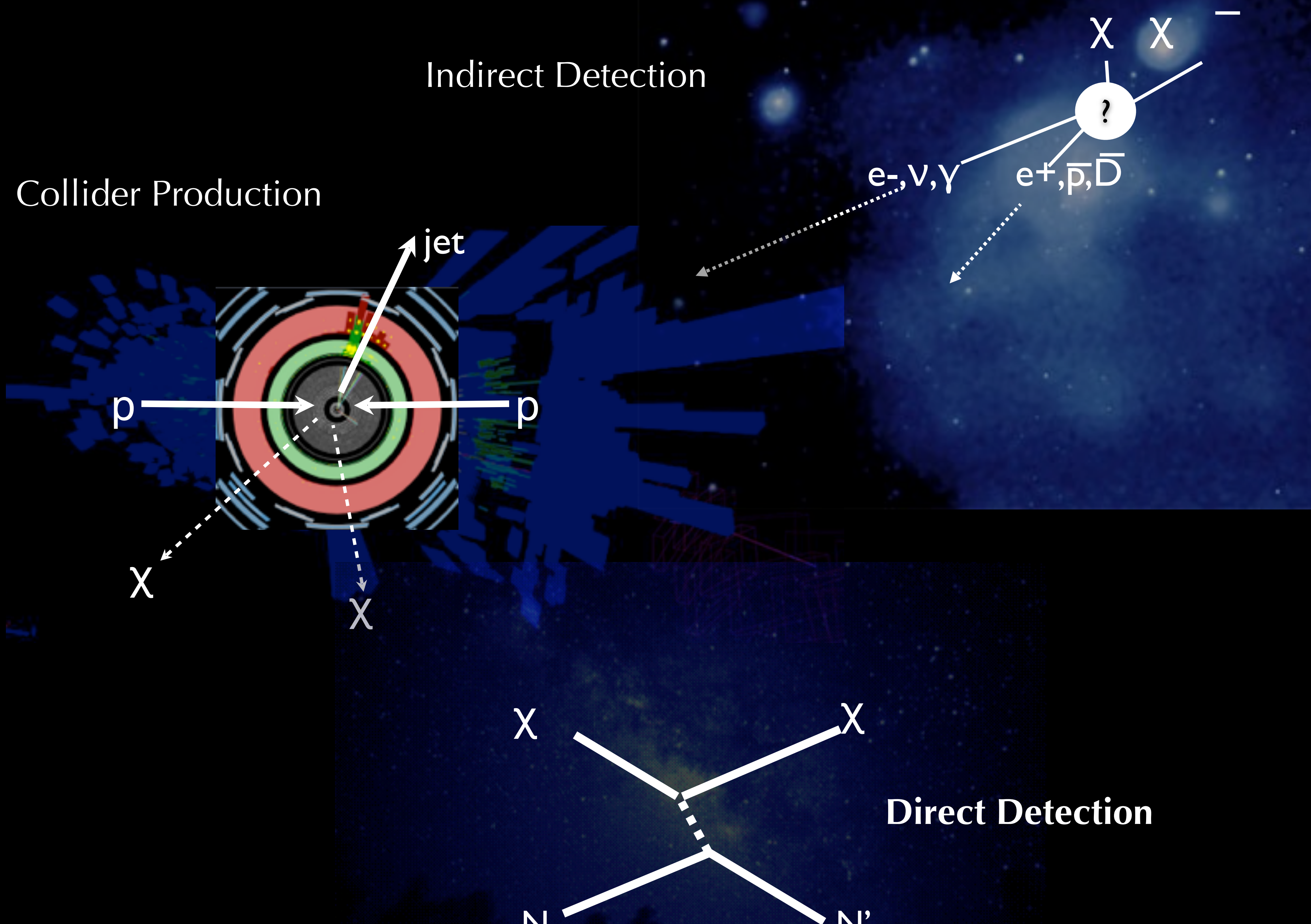




Indirect Detection

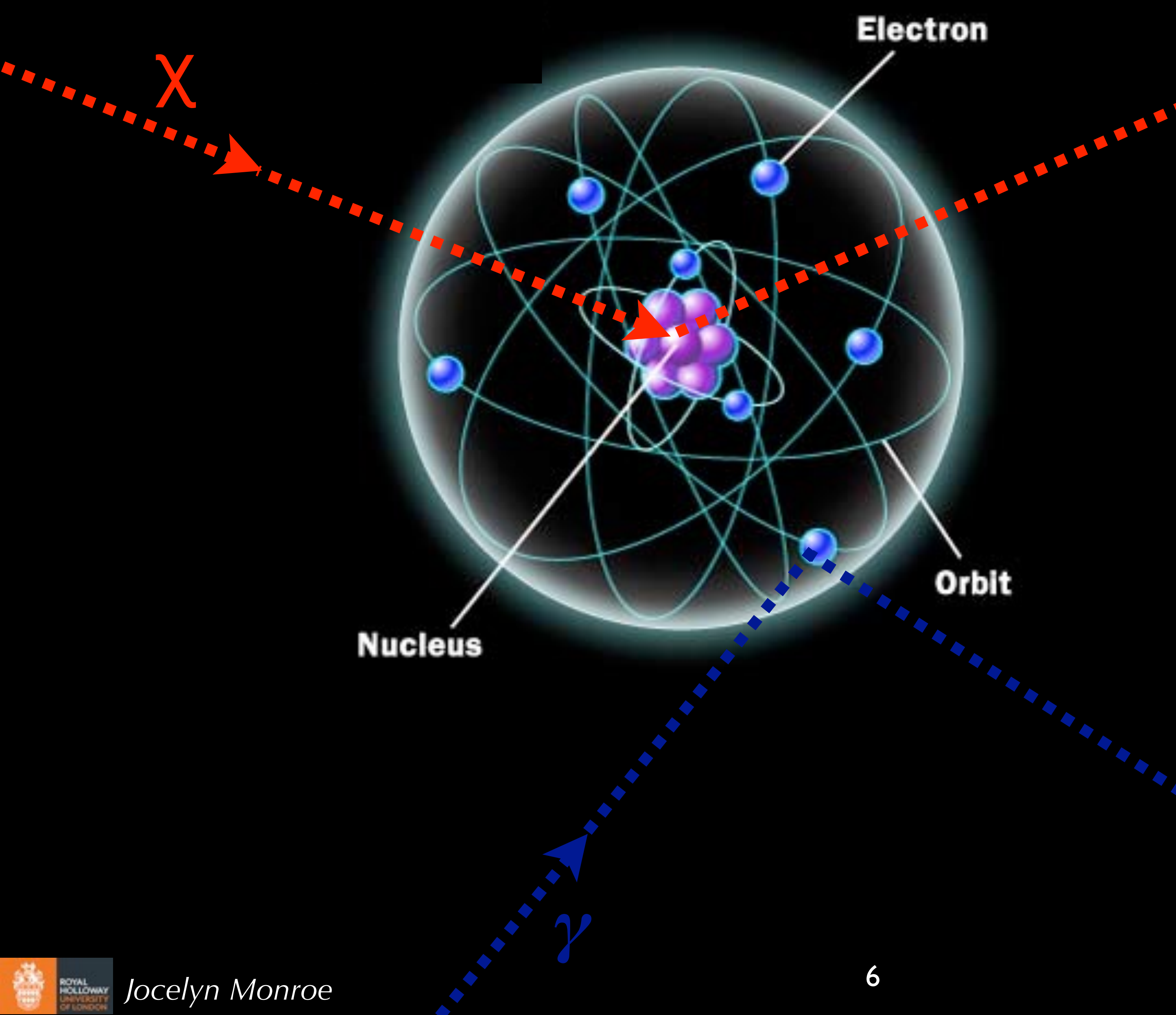
Collider Production




Indirect Detection
χ χ̄
?
e-,ν,γ
e+,p̄,D̄
Collider Production
jet
p
p
χ
χ
χ
χ
N
N'
Direct Detection

Direct Detection

Signal: $\chi N \rightarrow \chi N$



Backgrounds:

$\gamma\ e^- \rightarrow \gamma\ e^-$

$n\ N \rightarrow n\ N$

$N \rightarrow N' + \alpha, e^-$

$\nu\ N \rightarrow \nu\ N$

Detection

Number of Events = (Flux) x (Cross Section) x (Exposure)

(how much dark matter)

(how likely it is to interact)

(how long you look)

How Much?

10 WIMPs
(if mass=60 x proton)
inside, on average

flux = density x velocity = number of particles per unit area per unit time

Flux Estimate

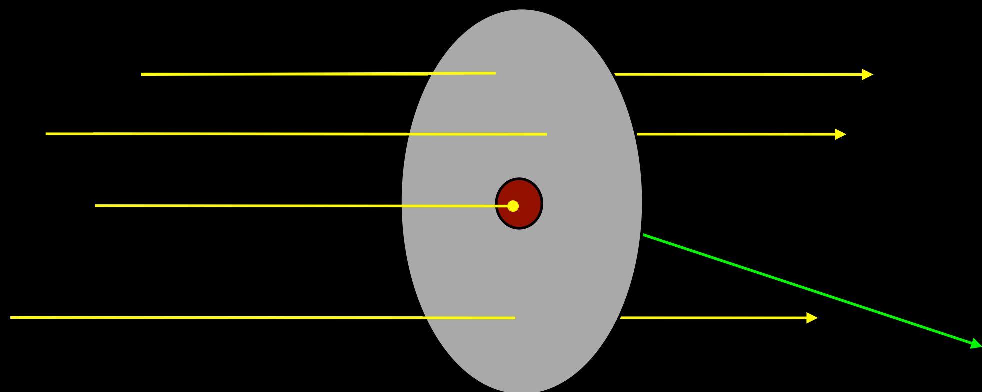
$$\Phi \;=\; \rho\, v \;=\; (0.3 GeV\, cm^{-3}/M[GeV])\; v \;\sim\; 0.3\frac{v}{M}\; cm^{-2}\; s^{-1}$$

where the WIMP mass M is in GeV. For M = 100 GeV,

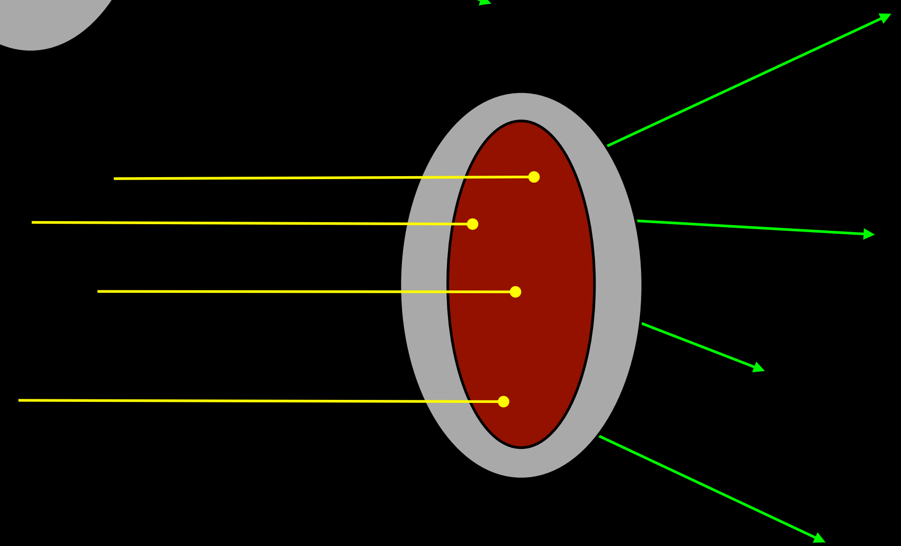
$$\Phi = \frac{0.3\ GeV\ cm^{-3}}{100\ GeV} \times (100\ km\ s^{-1}) \times (10^{-5}\ cm\ km^{-1}) \;=\; 3 \times 10^{-6}\ cm^{-2}\ s^{-1}.$$

Cross Section

probability of interaction per unit target area



WIMP - proton
interaction cross section
$\sigma(X\text{p}) < 1\text{E-}45\ \text{cm}^2$



proton - proton
interaction cross section
$\sigma(\text{pp}) \sim 1\text{E-}25\ \text{cm}^2$

Cross Section Estimate

Starting from Fermi's Second Golden Rule:

$$\frac{d\sigma}{d\Omega}(a+b\rightarrow c+d) \sim |T_{if}|^2 \frac{p_f^2}{v_i v_f}$$

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and working in the CMS frame, this is

$$\frac{d\sigma}{d\Omega}\sim G_F^2\frac{p_*^2}{v_r^2}$$

where v_r is the relative velocity of WIMP and nucleus, which is $v = p_*/\mu$ in this case. So

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$$\frac{d\sigma}{d\Omega} \sim G_F^2 \mu^2$$

since the non-relativistic elastic scattering cross section is isotropic in the CMS frame, $\sigma \sim G_F^2 \mu^2$.

$G_F \sim 10^{-5}\ GeV^{-2}$ and when $M_N = M = 100\ GeV$,

$$\mu = M_N M/(M_N + M) = M/2 = 50\ GeV$$

, and so

$$\sigma \sim (10^{-5}\ GeV^{-2})^2\ (50\ GeV)^2 = 2.5\times 10^{-7}\ GeV^{-2} \sim 2\times 10^{-35}\ cm^2,$$

III. Dark Matter Direct Detection

detect recoiling nucleus after χ scatters in detector. Find E_R:

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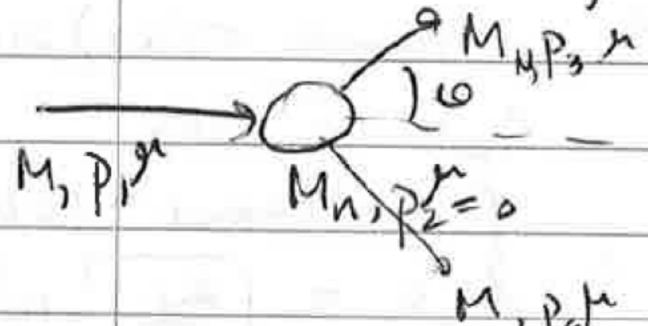

(i) $S = (p_1^\mu + p_2^\mu)^2$ (LAB) initial state

$$= p_1^{\mu\,2} + p_2^{\mu\,2} + 2 p_1^\mu p_2^\mu$$

$$= M^2 + M_N^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)$$ ($\vec{p}_2 \to 0$)

$E_1 = M + E_0$, $E_2 = M_N$

$$= M^2 + M_N^2 + 2E_0 M_N + 2MM_N$$

$$= (M + M_N)^2 + 2E_0 M_N$$

$$= E_{cm}^2$$

(E_0:) Kinetic energy of

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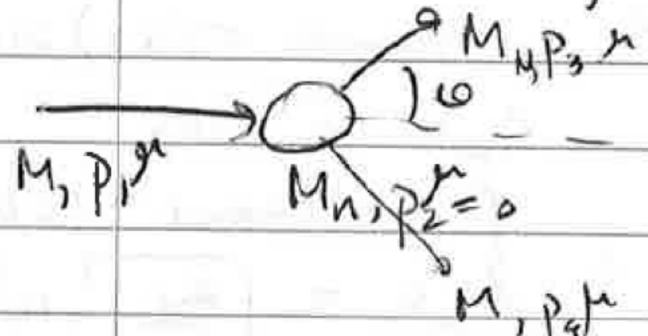

M_N, p_3^μ (E_R = recoil energy)

(i) (LAB) initial state

$$s = (p_1^\mu + p_2^\mu)^2$$
$$= p_1^{\mu 2} + p_2^{\mu 2} + 2 p_1^\mu p_2^\mu$$
$$= M^2 + M_N^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2) \quad (\vec{p}_2 = 0)$$
$$= M^2 + M_N^2 + 2E_0 M_N + 2 M M_N$$
$$= (M + M_N)^2 + 2 E_0 M_N$$
$$= E_{cm}^2$$

$E_1 = M + E_0$, $E_2 = M_N$

(E_0 = kinetic energy of DM $= \frac{1}{2} M v^2$)

(ii) evaluate final state in CMS: $\vec{p}_3 = -\vec{p}_4$

$$E_{cm} = E_3 + E_4$$
$$E_{cm} = \left(M_N + \frac{p^{*2}}{2M_N}\right) + \left(M + \frac{p^{*2}}{2M}\right)$$

(i): since non-relativistic, $E_0 \ll M, M_N$

so, $E_{CM}^2 = (M+M_N)^2 + 2E_0 M_N$

$$= (M+M_N)^2 \left[1 + \frac{2E_0 M_N}{(M+M_N)^2}\right]$$

$$E_{CM} = (M+M_N)\left[1 + \frac{2E_0 M_N}{(M+M_N)^2}\right]^{1/2}$$ & Taylor expand in $x = \frac{2E_0 M_N}{(M+M_N)^2}$

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$$(M+M_N)\left[1 + \frac{E_0 M_N}{(M+M_N)^2}\right]$$

set (i) = (ii), solve for $p^* = 2\mu^2 E/M$, $\mu = \frac{M_N M}{(M_N + M)}$

Since $E_0 = \frac{1}{2} M v^2$, we have recovered familiar result in elastic scattering that $p^{*2} = \mu^2 v^2$ $\left(\mu = \frac{M_N M}{M_N + M}\right)$

E_R^{max} when p^* is reversed in collision: $p_{lab} = 2p^*$

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$$E_R^{max} = \frac{p_{max}^2}{2M_N} = \frac{1}{2M_N}(2p^*)^2 = \frac{2\mu^2 v^2}{M_N}$$

if $M_X = M_N$ then $E_R^{max} = \frac{1}{2} M_N v^2$

if $M_X >> M_N$ then $E_R^{max} = 2v^2 M_N$

E_R^{max} when p^* is reversed in collision: $p_{lab} = 2p^*$

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if $M_X = M_N$ then $E_R^{max} = \frac{1}{2} M_N v^2$

if $M_X \gg M_N$ then $E_R^{max} = 2v^2 M_N$

with $v = 220\,km/s \cong 10^{-3}c$, $M_N = A \cdot GeV$ (A = atomic mass number of nucleus)

find $E_R^{max} = A \cdot keV$

Scattering rate

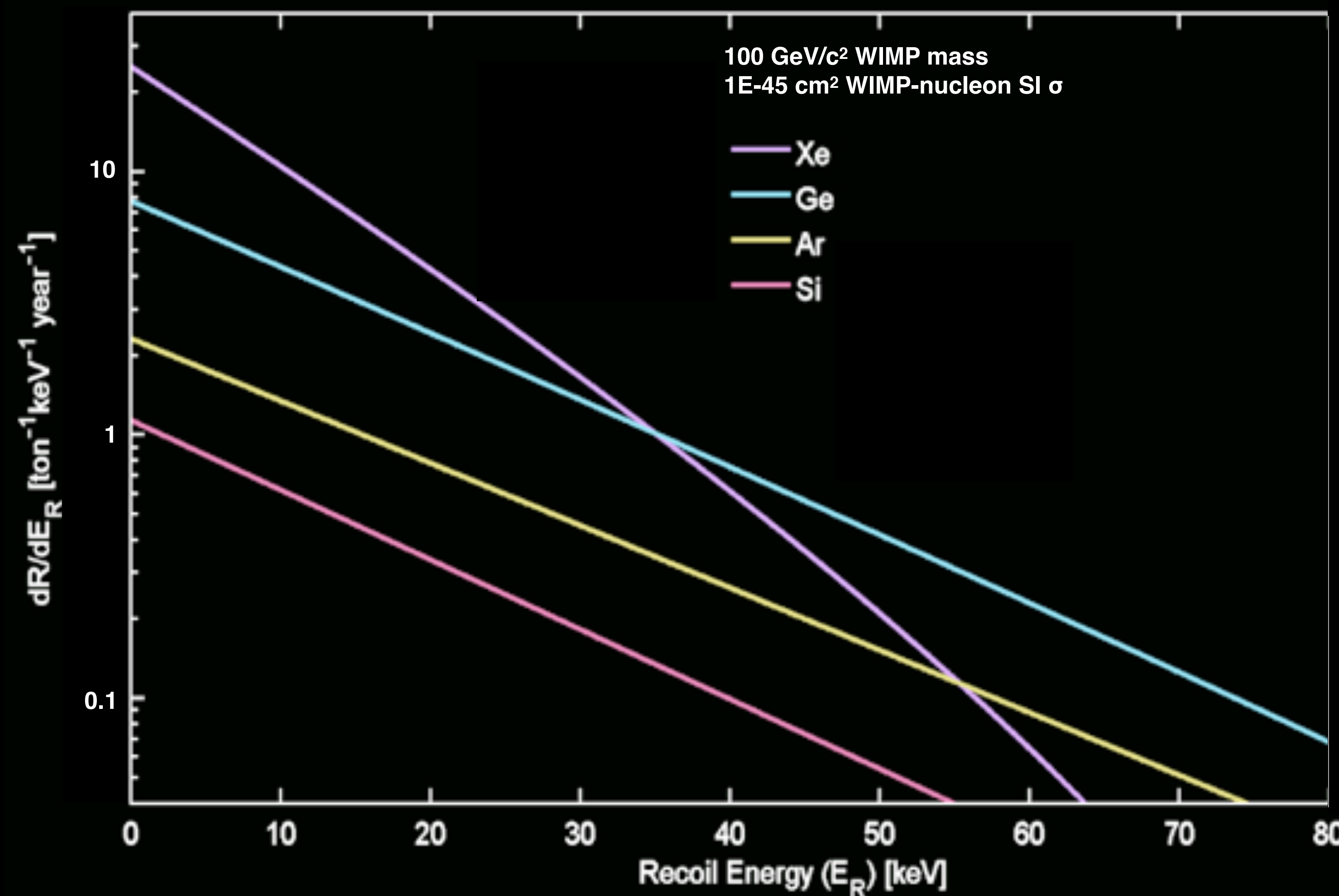
Sun's velocity around the galaxy

WIMP velocity distribution

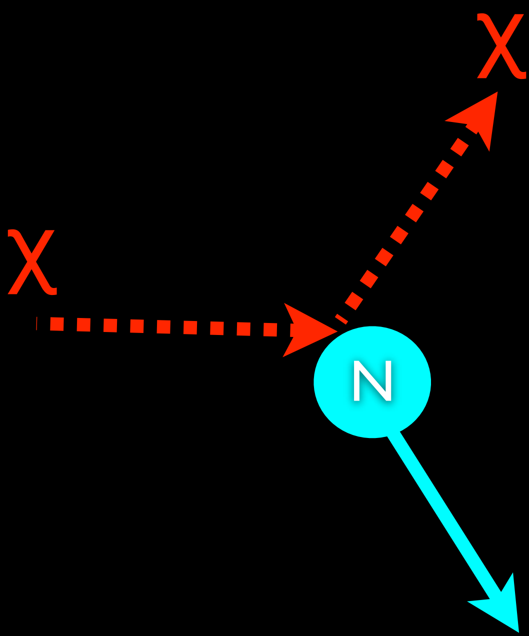
$$dR/dQ = (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0 m_\chi m_r^2)\, F^2(Q)\, T(Q)$$

WIMP energy density, 0.3 GeV/cm^3

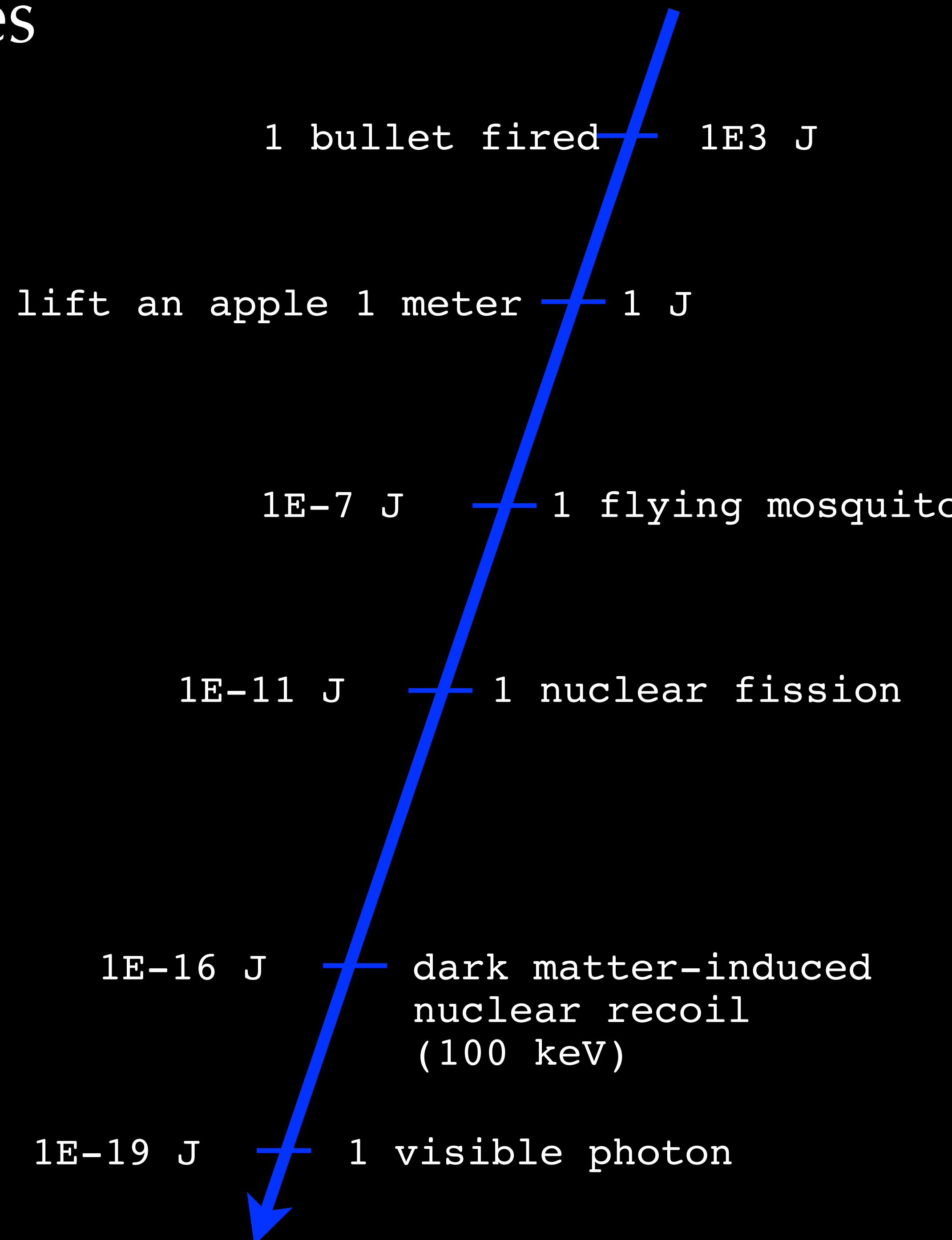
Form factor



Observable: Small Energies



Recoil Nucleus Kinetic Energy



Measurement

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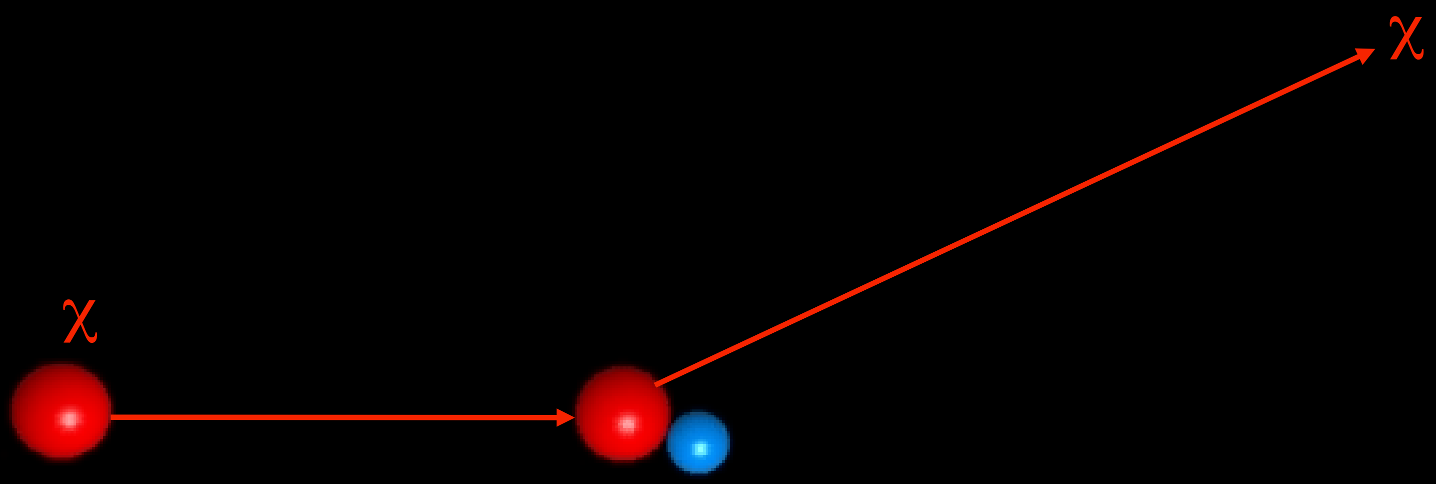

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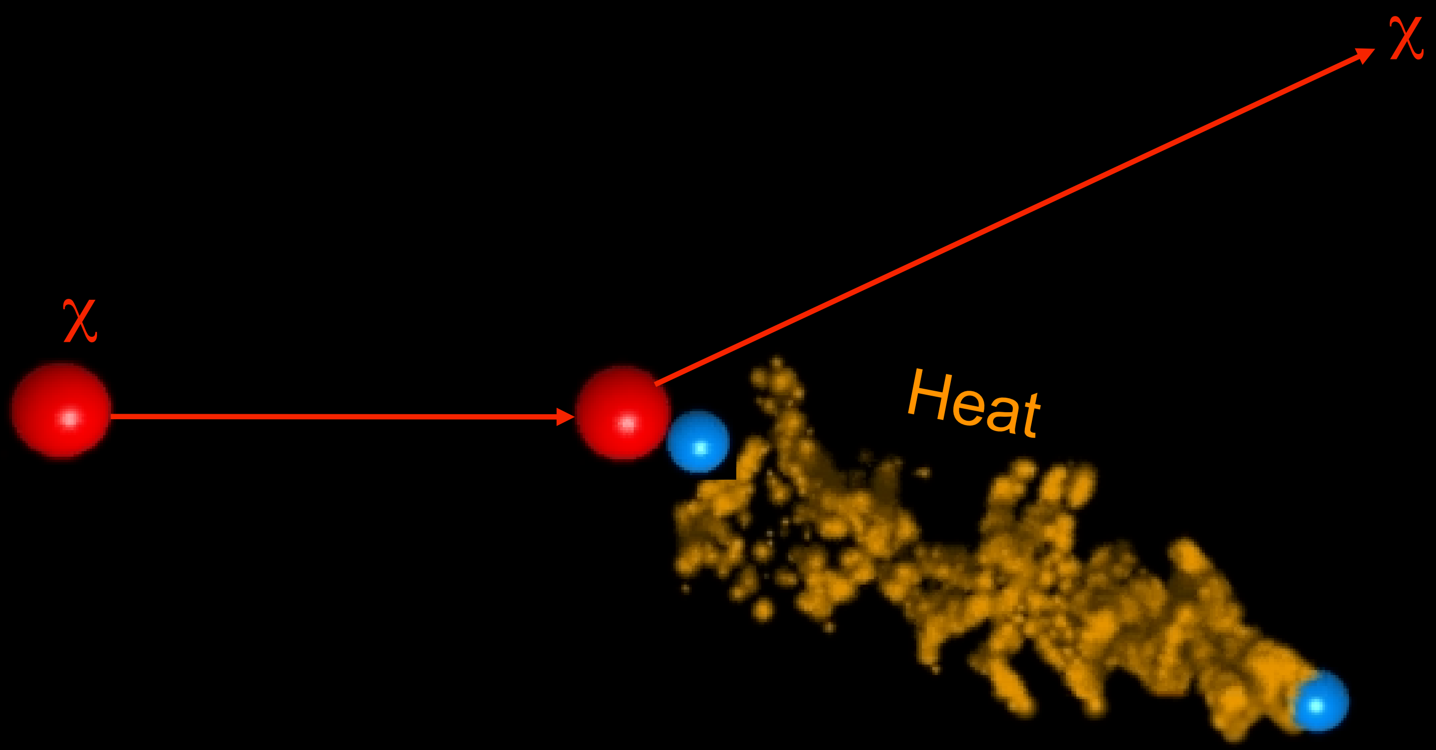

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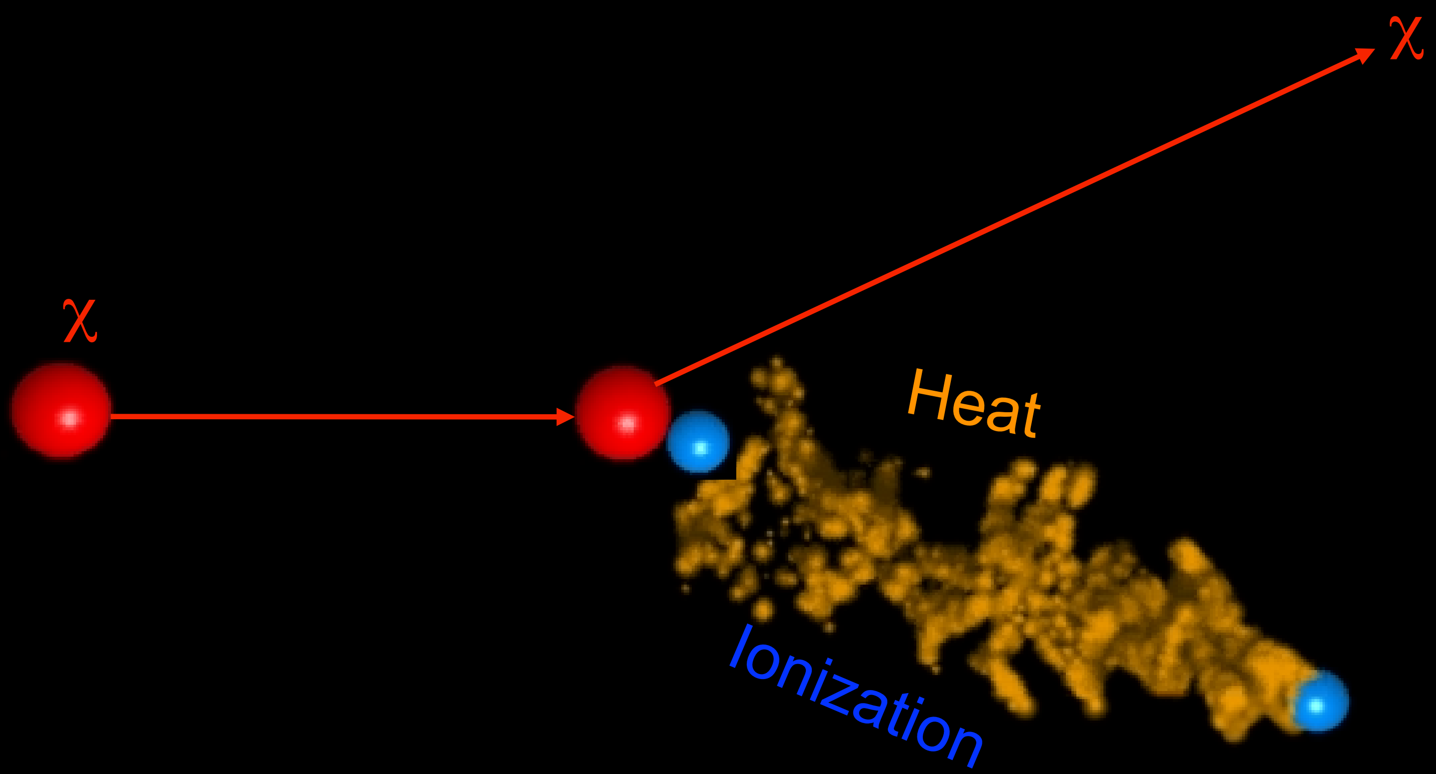

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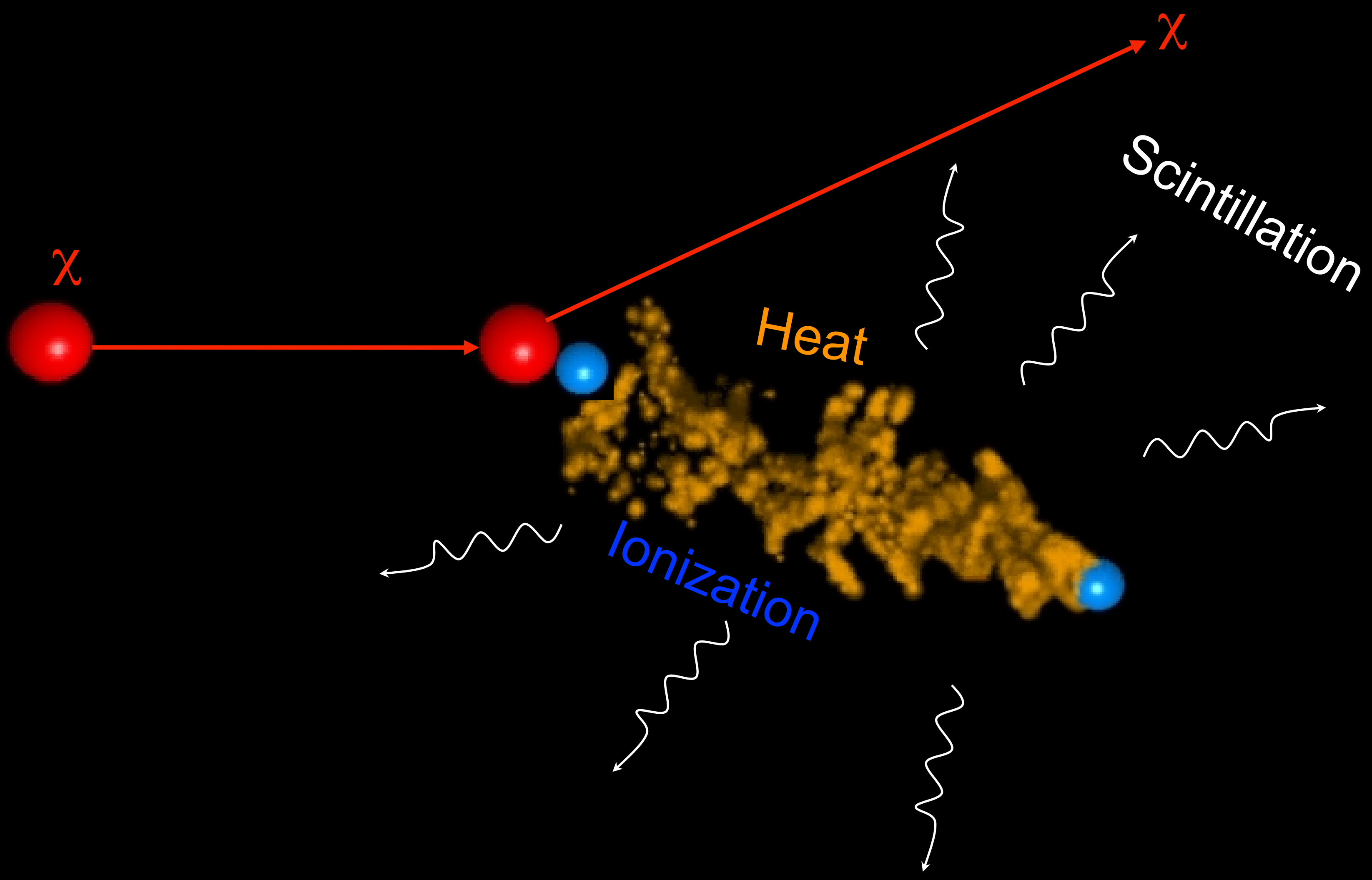
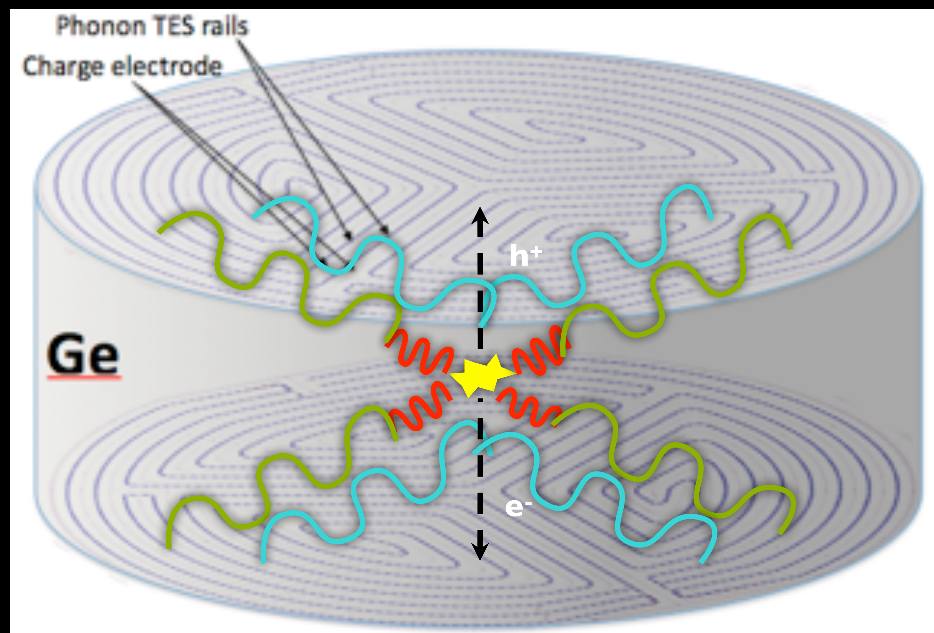


Detector Technologies for Small Energies

Cryogenic Bolometers

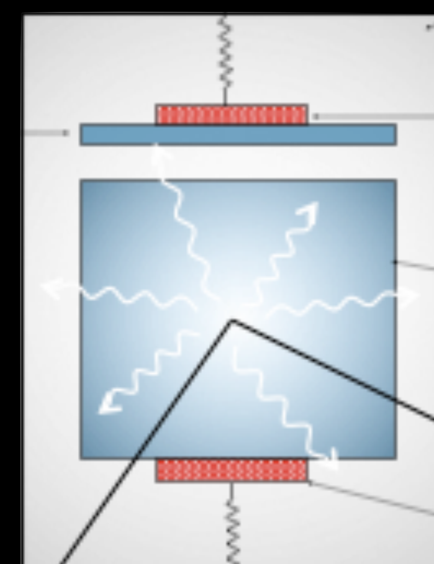
phonon, ionisation or scintillation readout of crystals at O(10 mK), using Ge, Si, $CaWO_4$

Phonon sensors: transition edge sensor measures E_{recoil} & R (timing)



Charge electrodes: biased at +/- 2V, measure E_{recoil}, configured to reject surface events

Scintillation side:
Si absorber + 300 gm $CaWO_4$, TES readout for particle ID



Phonon side: measure E_{recoil}l

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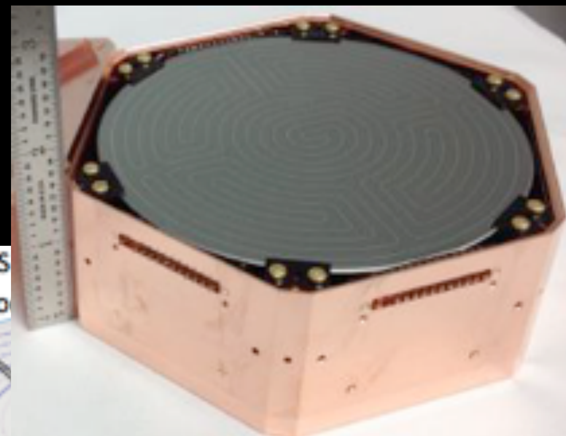

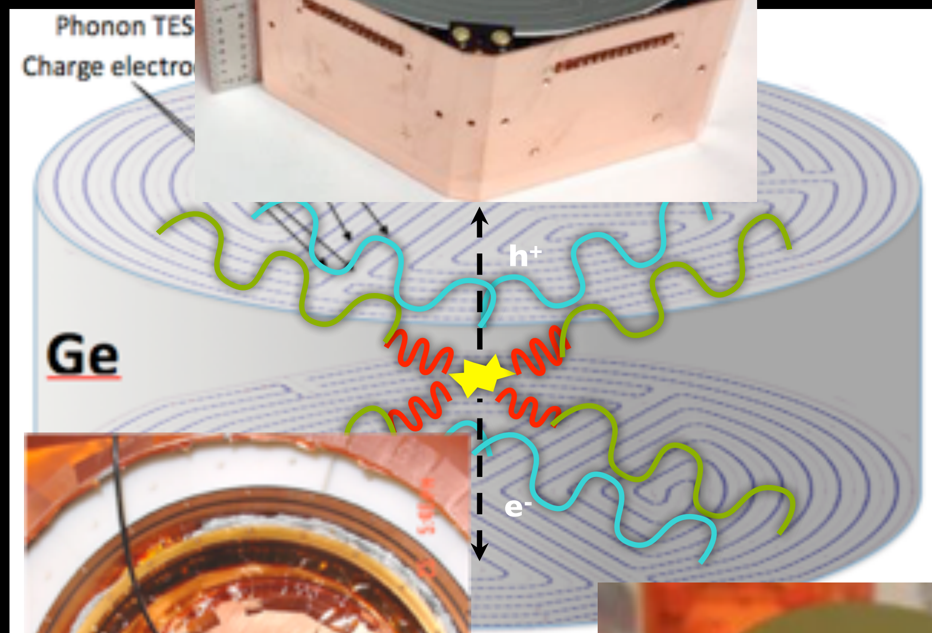

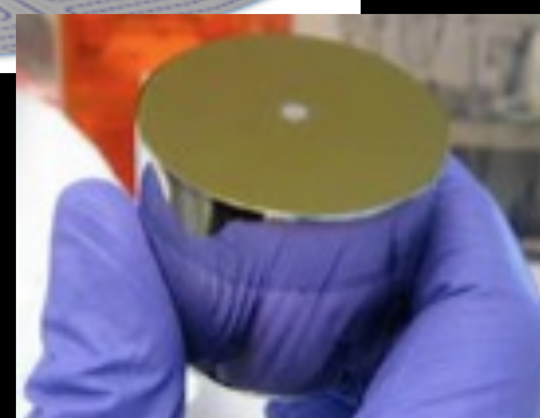

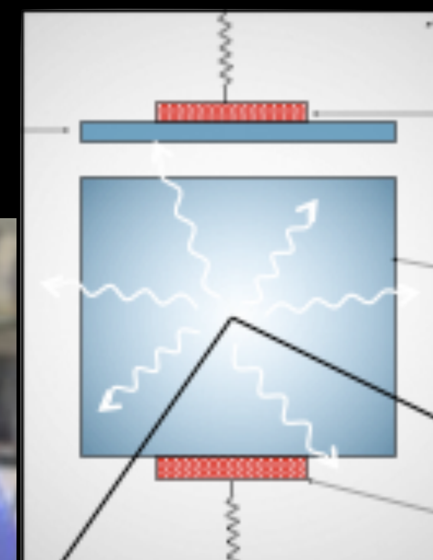

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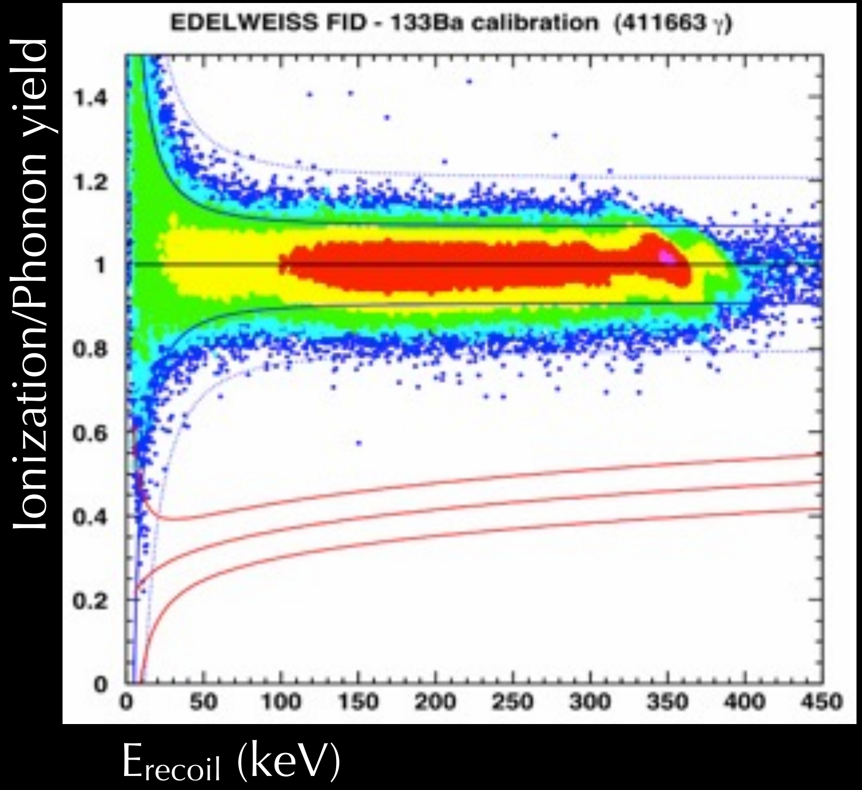
phonon, ionisation or scintillation readout of crystals at O(10 mK), using Ge, Si, $CaWO_4$

Dark Matter: rejects surface backgrounds by $x10^5$



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Gravitational Wave Search Experiments

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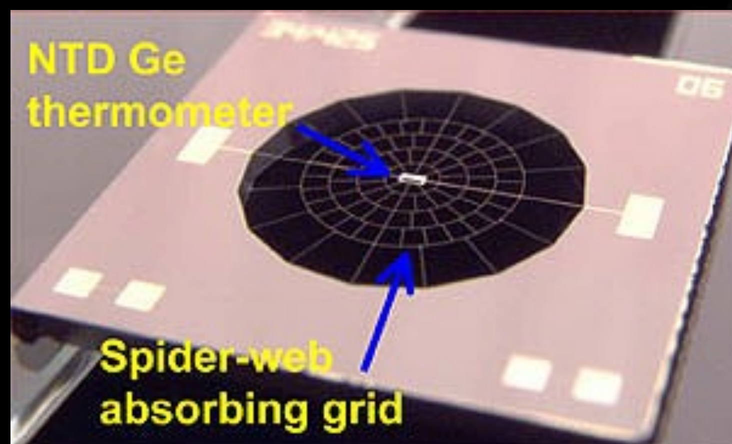
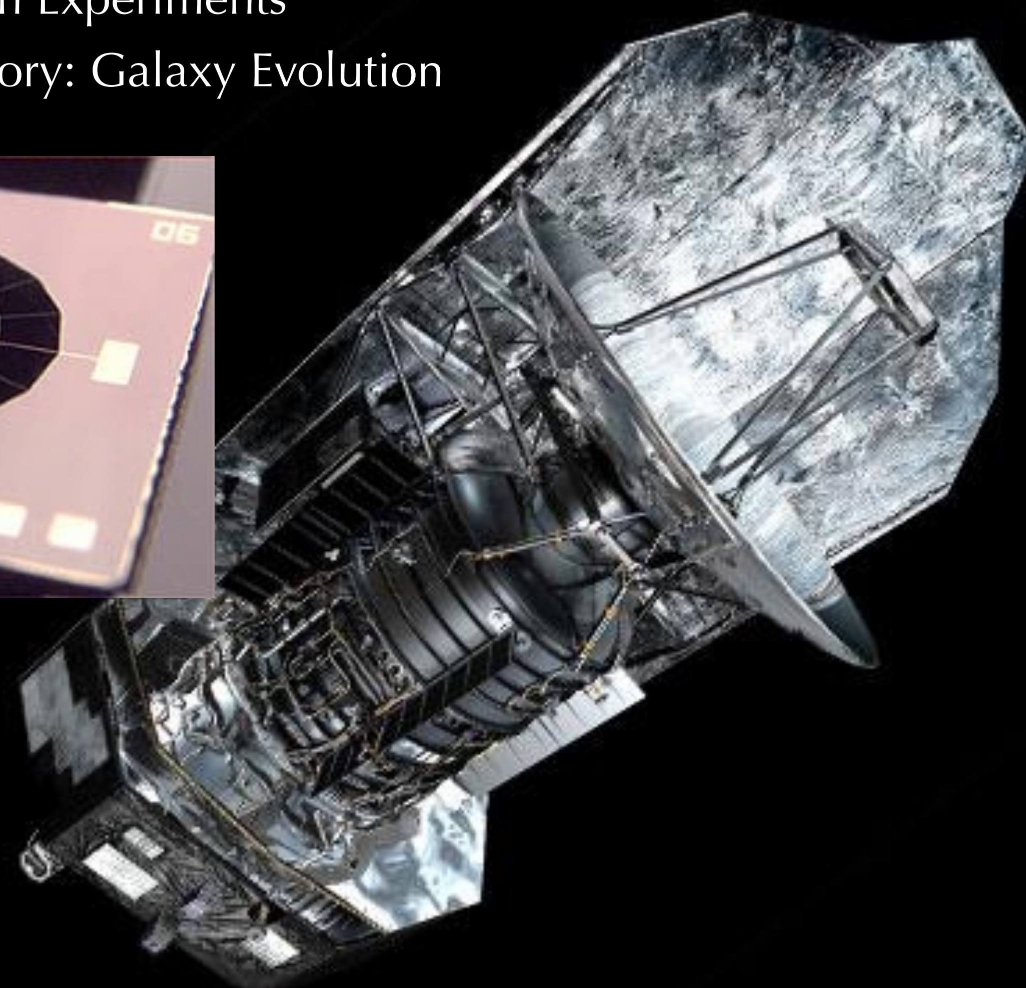
Gravitational Wave Search Experiments

Herschel Space Observatory: Galaxy Evolution





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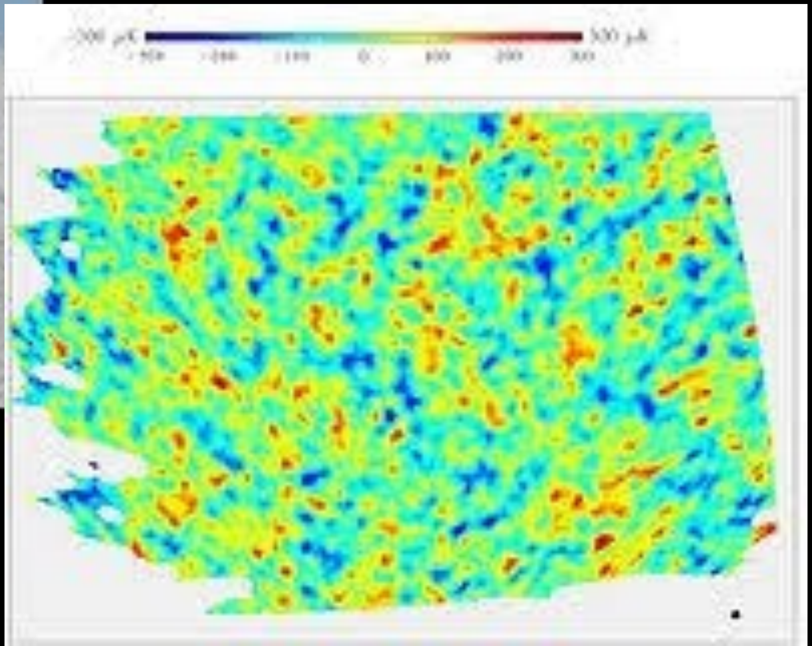
Cosmology, Curvature of Space Time: Boomerang



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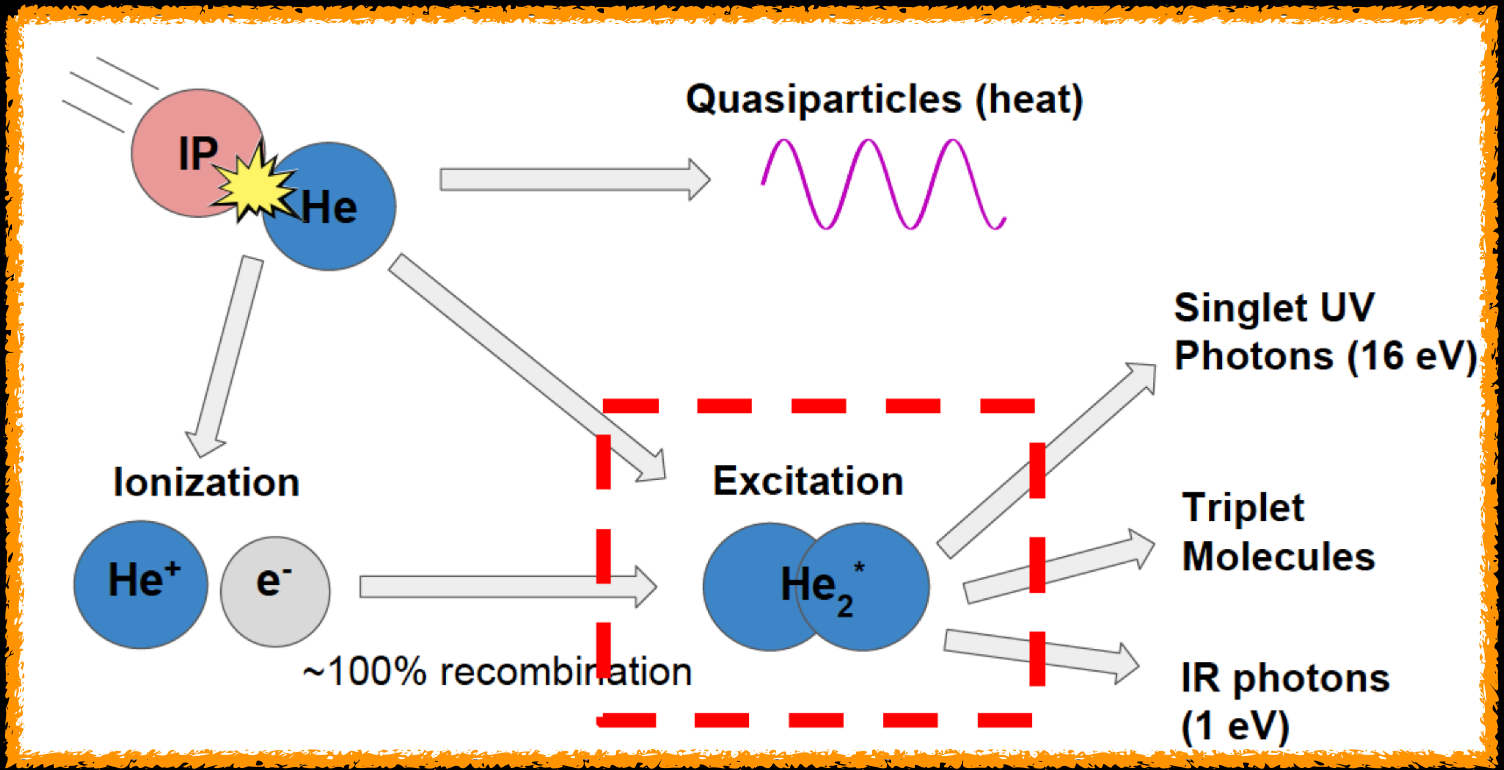
(Thanks: S. Hertel, D. McKinsey)

Liquid Nobles

He example



identify, reject electronic backgrounds via
(i) ionization vs. scintillation (Xe)
(ii) + pulse shape vs. time difference (Ar)

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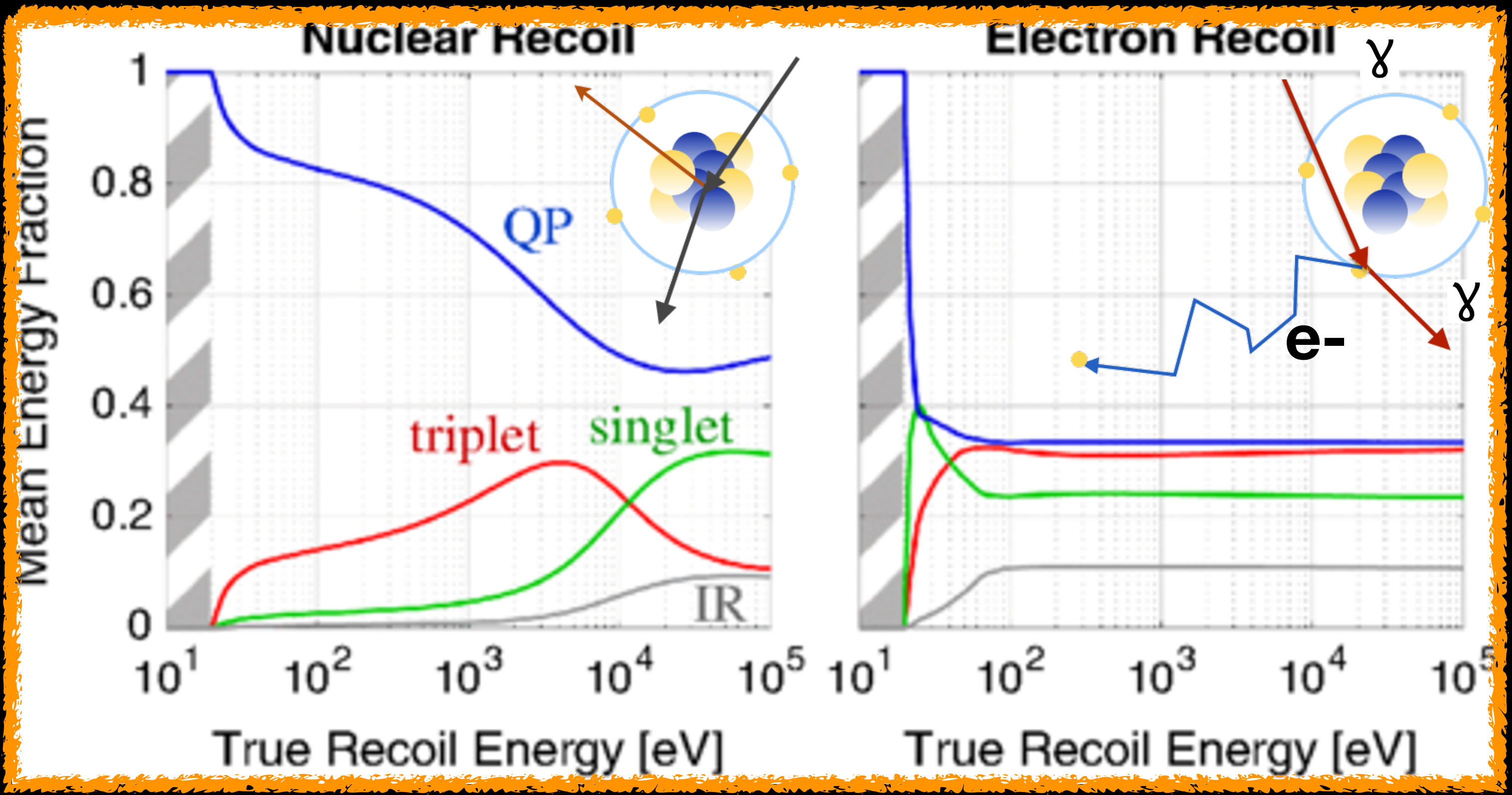

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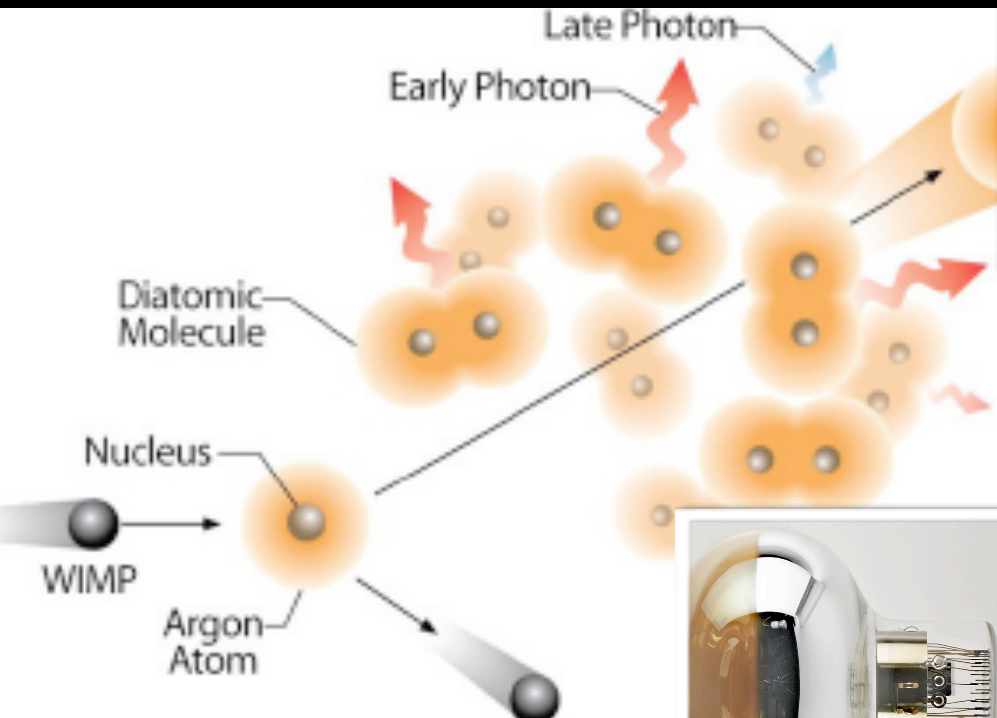
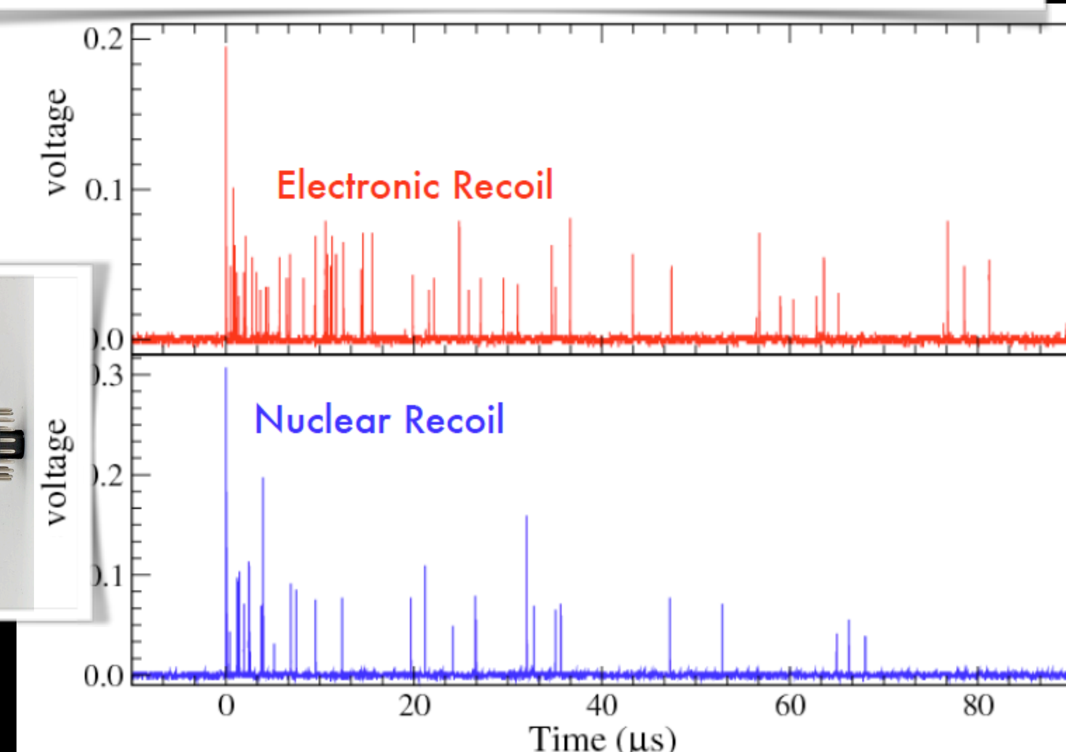
Ionization Partition

particle identification:
light vs. time depends on ionization density.

Table 3: Scintillation parameters for liquid neon, argon, and xenon.

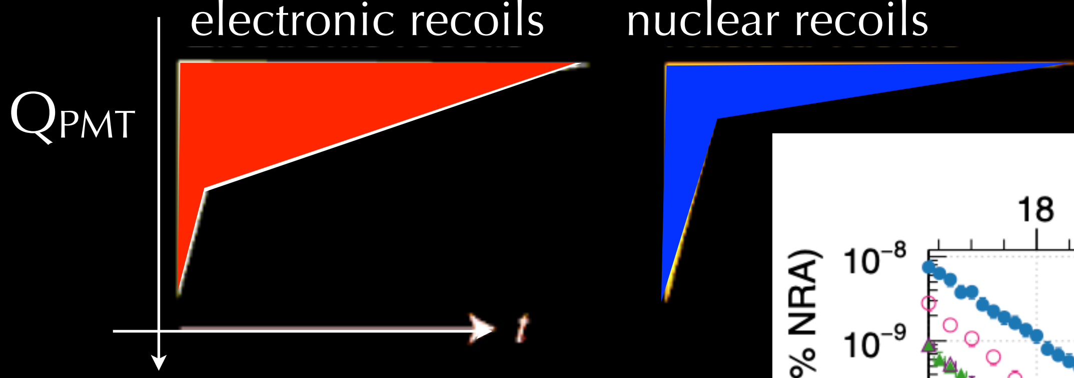
Parameter	Ne	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant τ_1 (ns)	2.2	6	2.2
late time constant τ_3	15 μs	1.59 μs	21 ns
I_1/I_3 for electrons	0.12	0.3	0.3
I_1/I_3 for nuclear recoils	0.56	3	1.6
λ(peak) (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30





Lippincott et al., Phys.Rev.C 78: 035801 (2008)

Pulse Shape Discrimination in Liquid Argon



Adhikari et al, Eur. Phys. J. C 80, 303 (2020)

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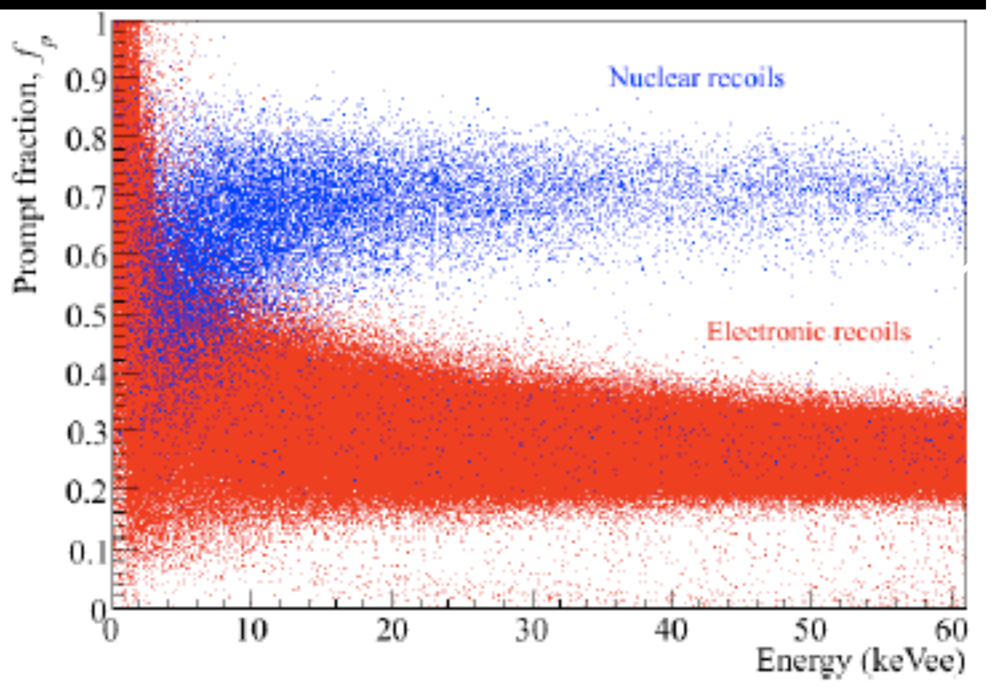

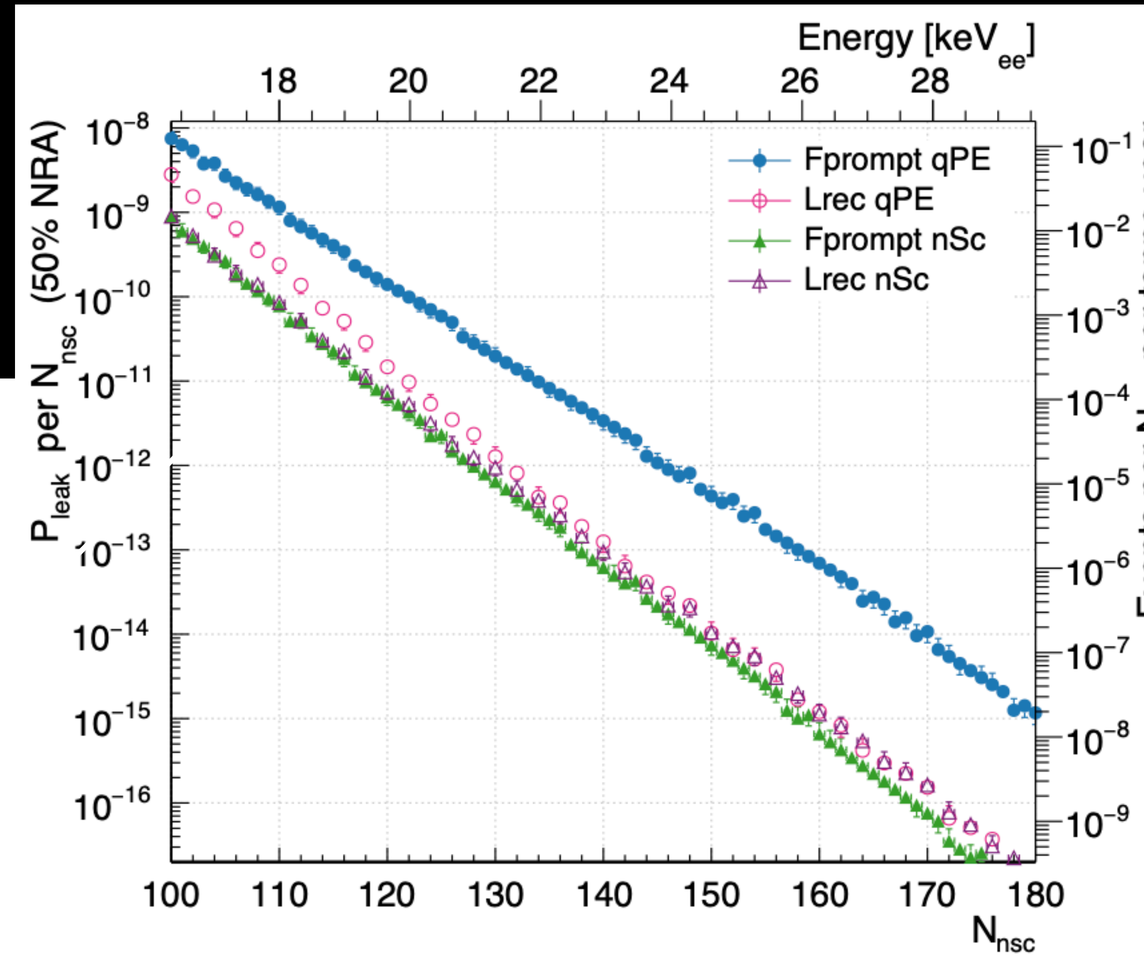

identify, reject electronic backgrounds via pulse shape vs. time difference at parts-per-billion level

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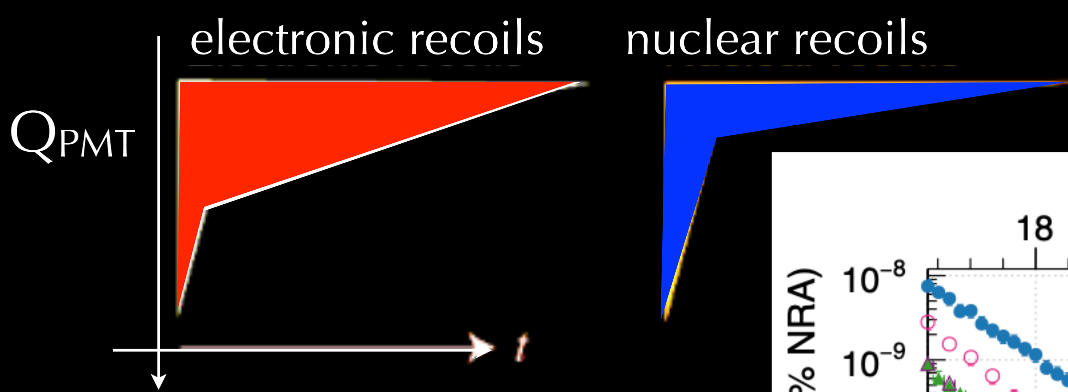

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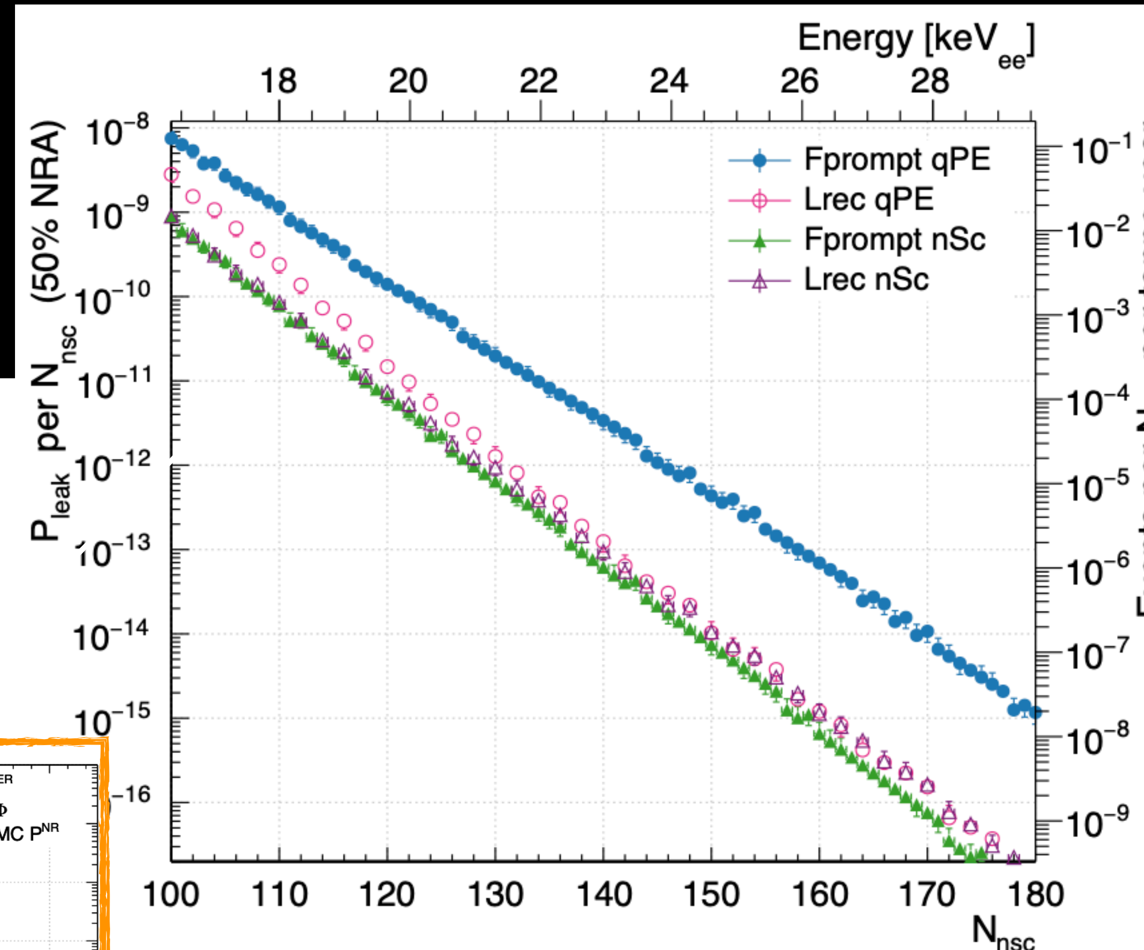

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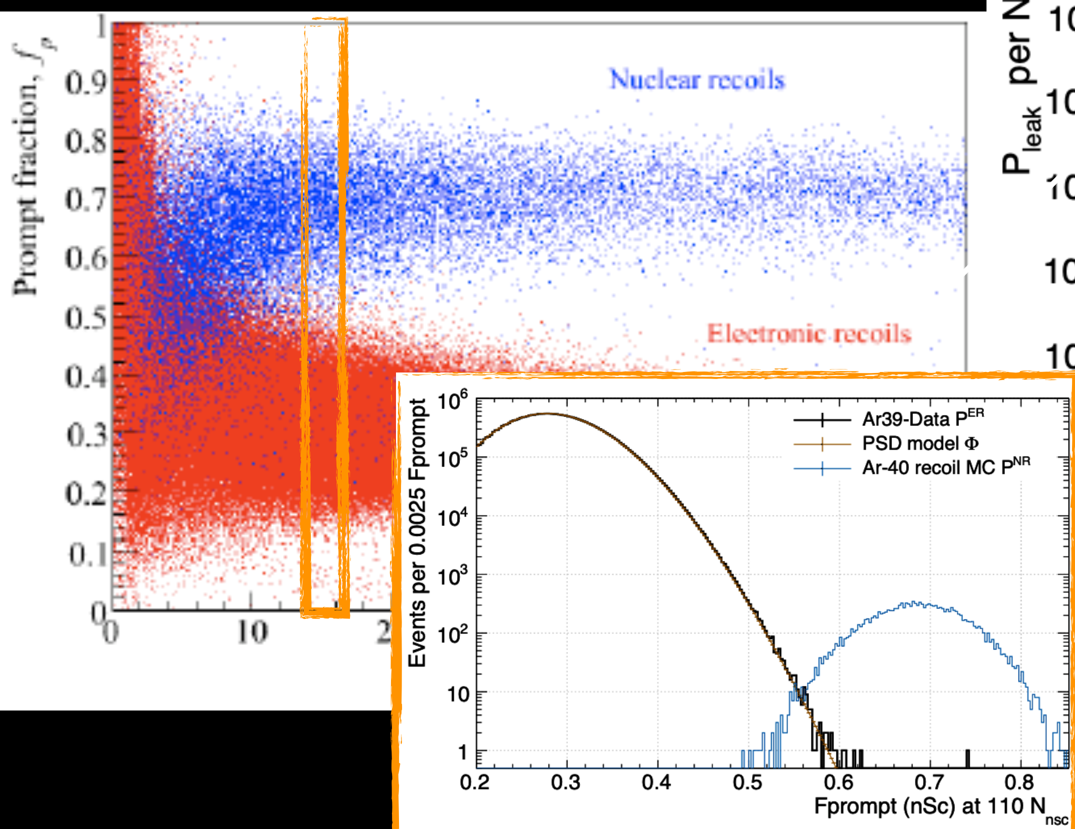

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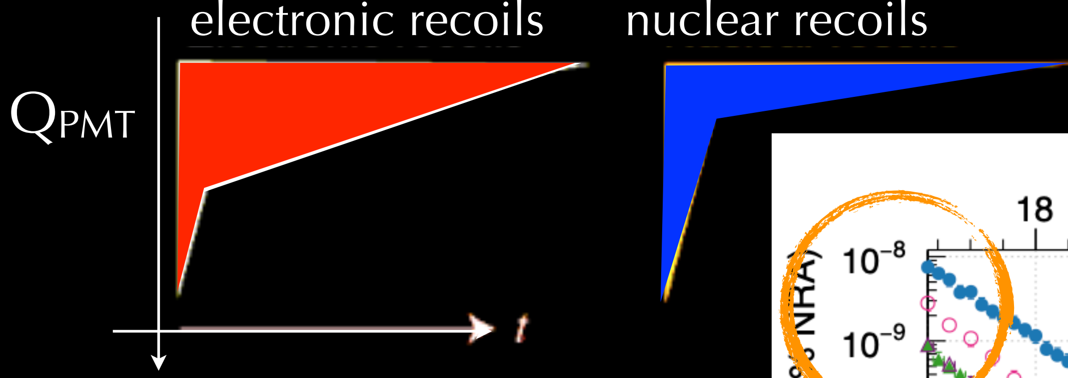

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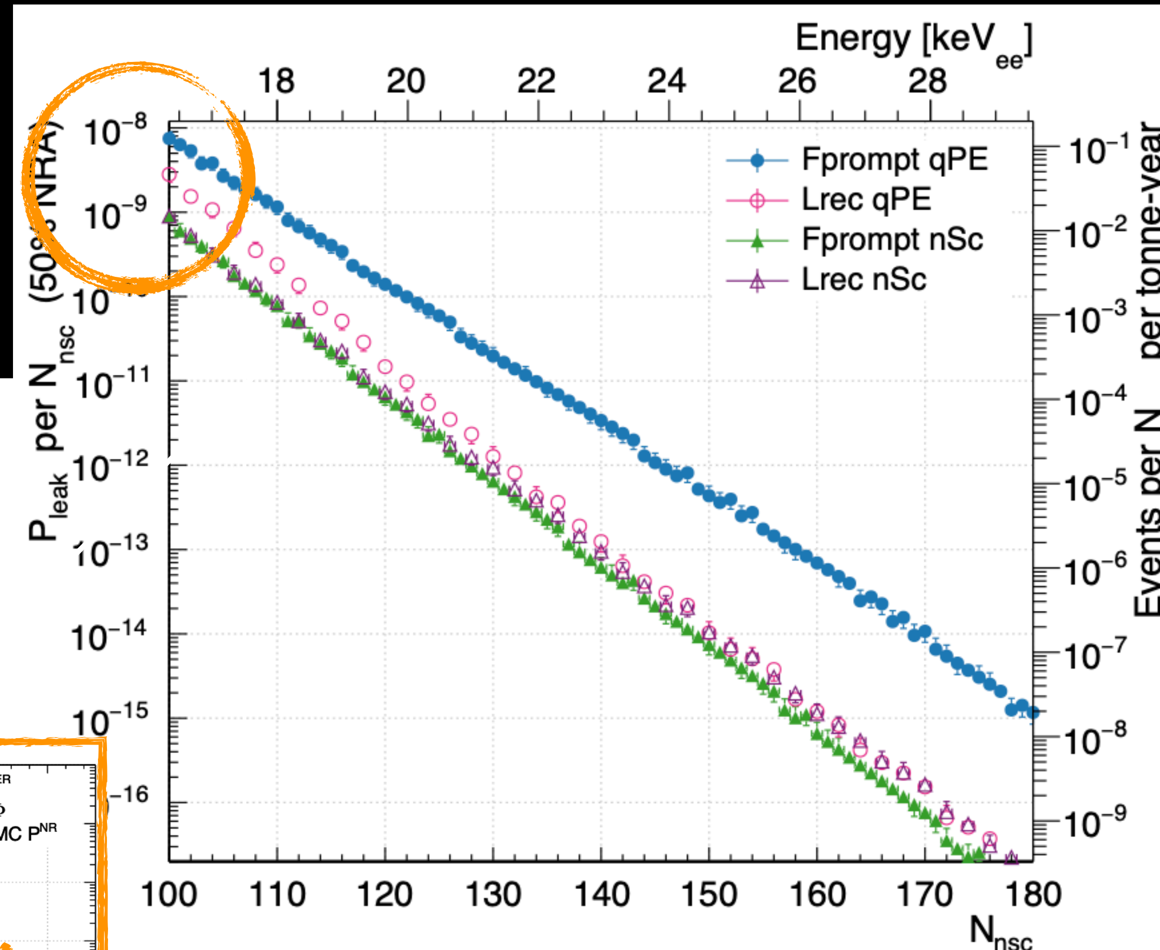

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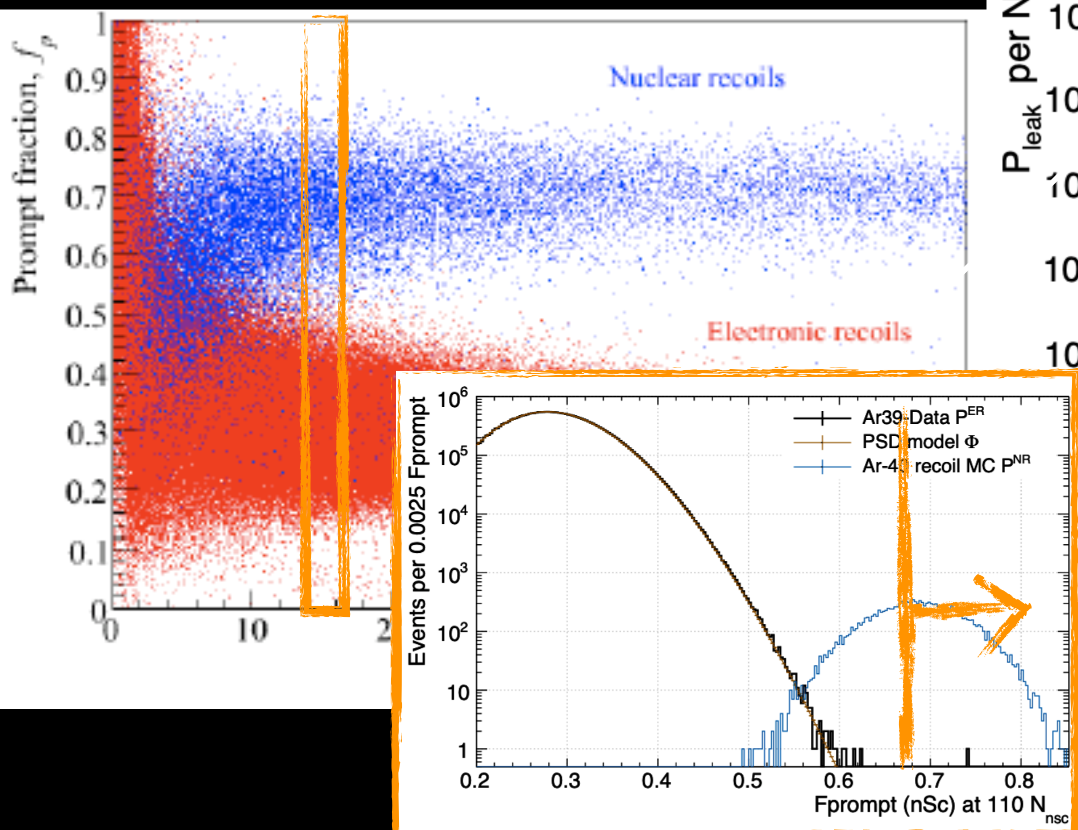

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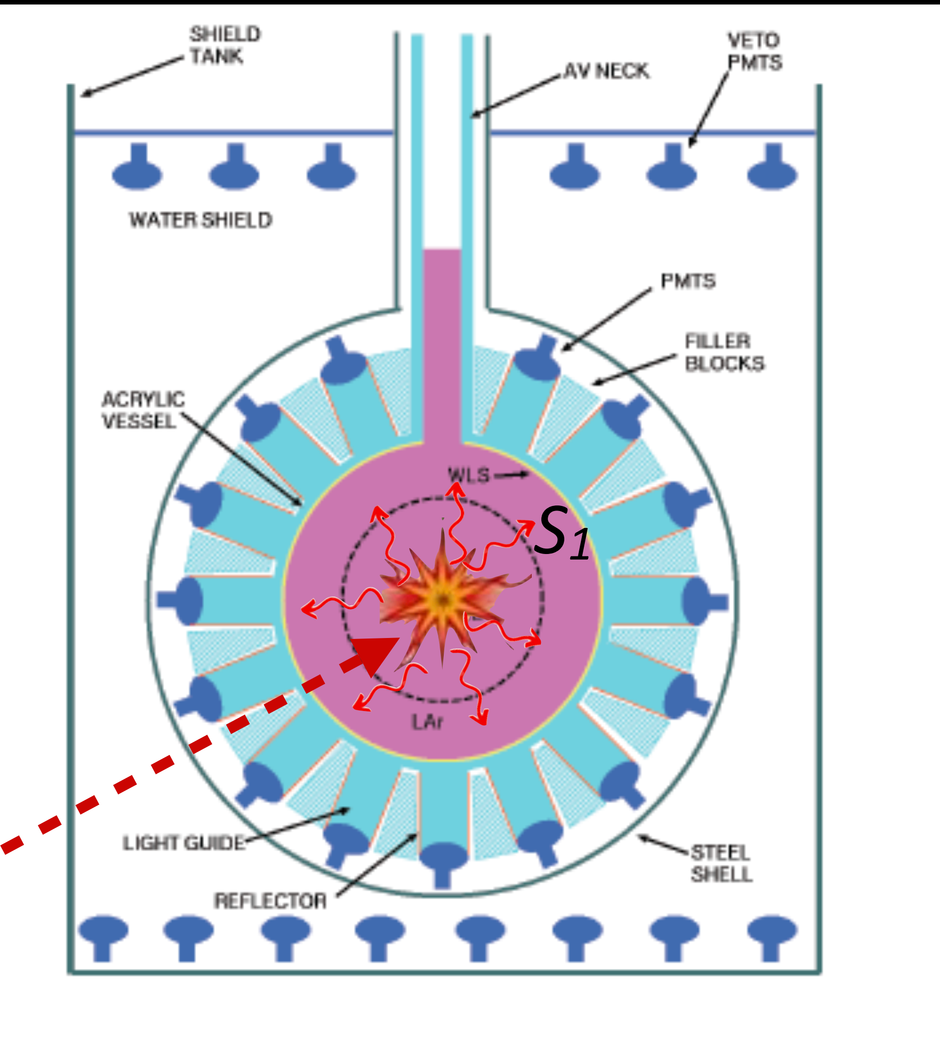
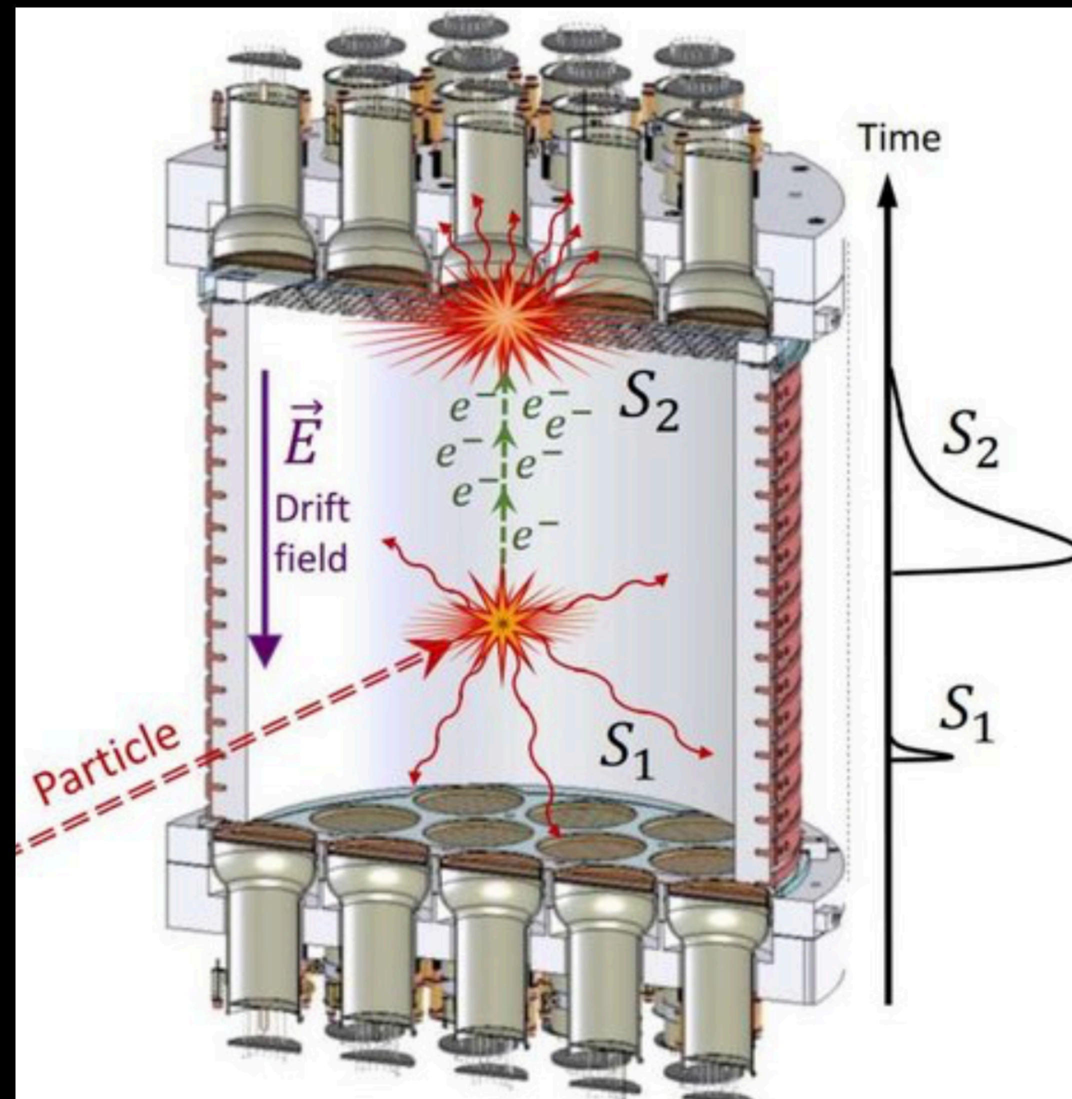
Liquid Noble Detectors



Single Phase Detector:
no electric fields… S1 only,
but, no recombination in E field

Dual Phase Detector:
Primary scintillation (S1) and proportional gas scintillation from drifted electrons (S2)



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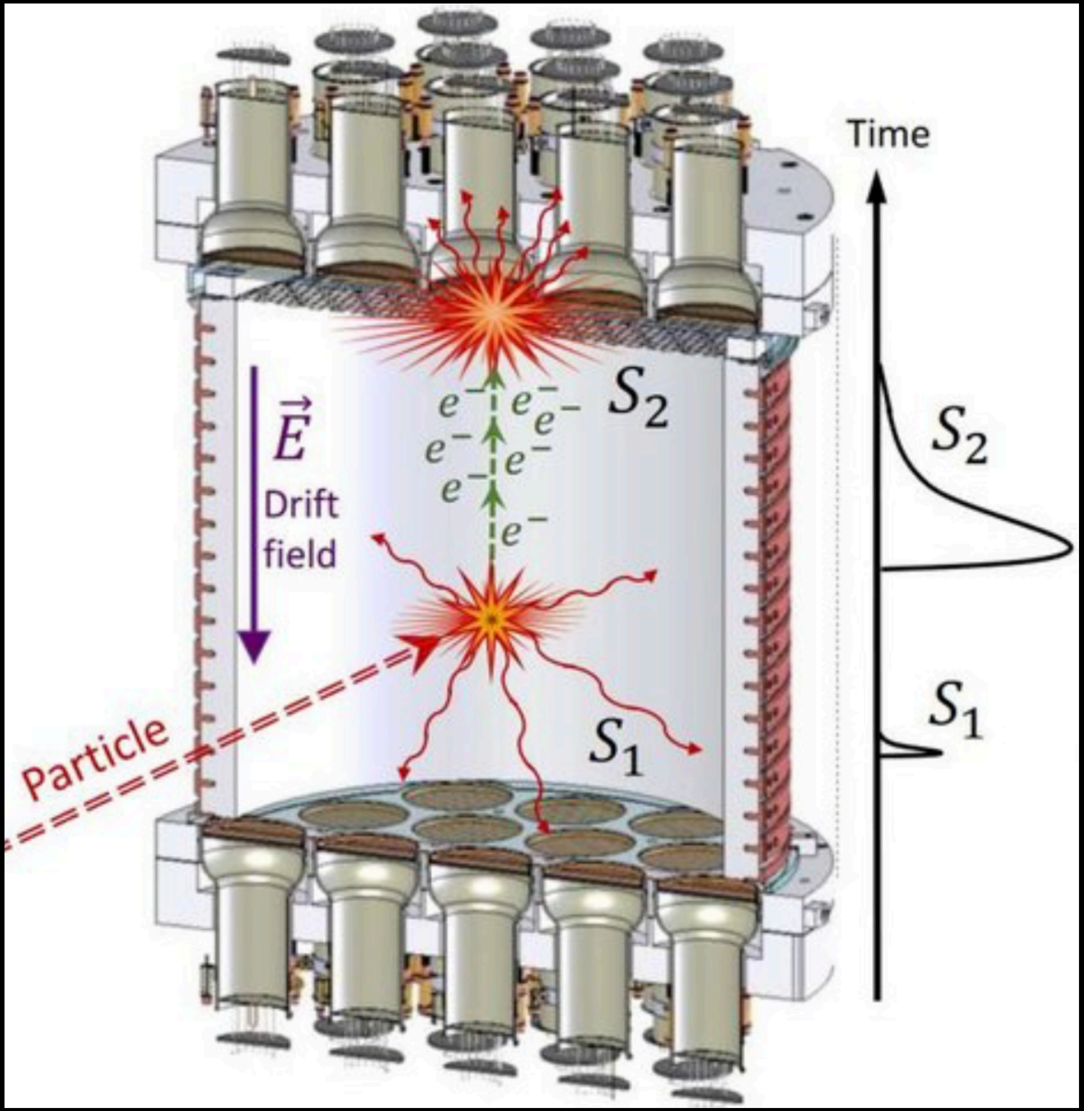
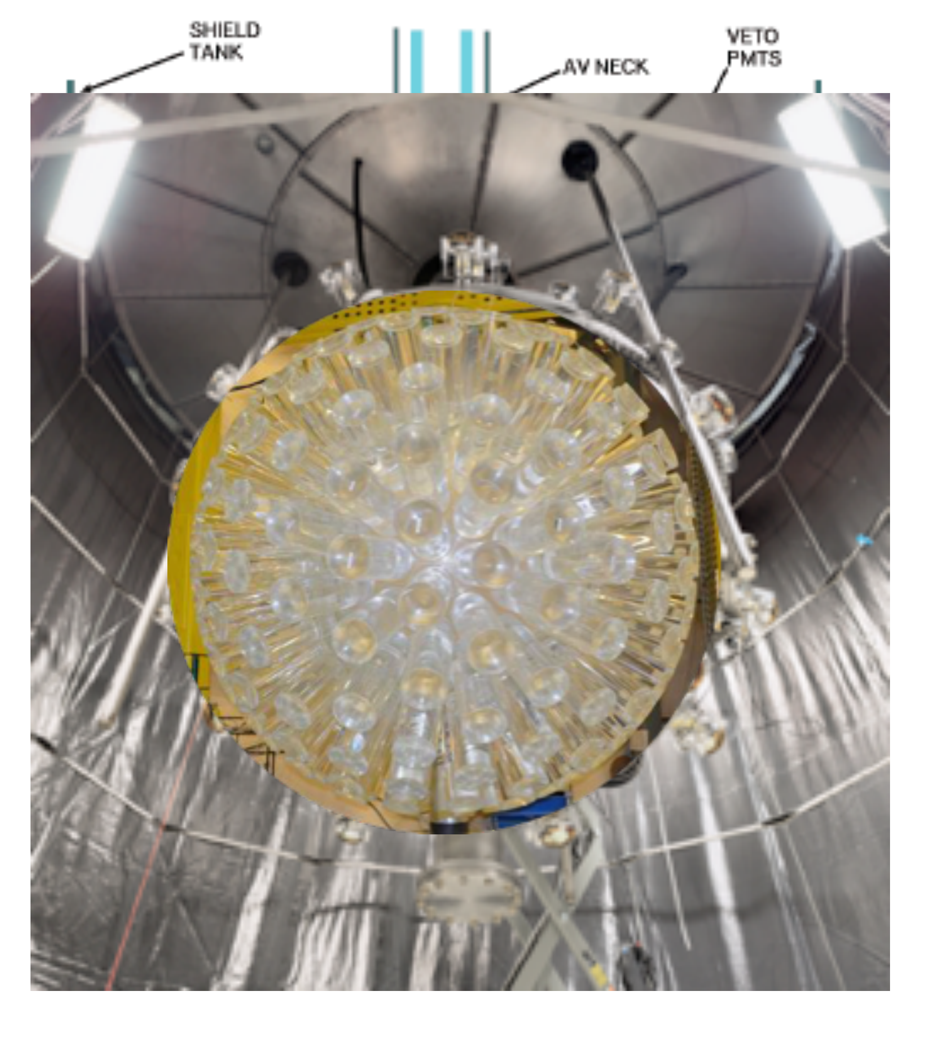
Dual Phase Detector:
Primary scintillation (S1) and proportional gas scintillation from drifted electrons (S2)



Liquid Noble Detectors



Single Phase Detector:
no electric fields… S1 only,
but, no recombination in E field

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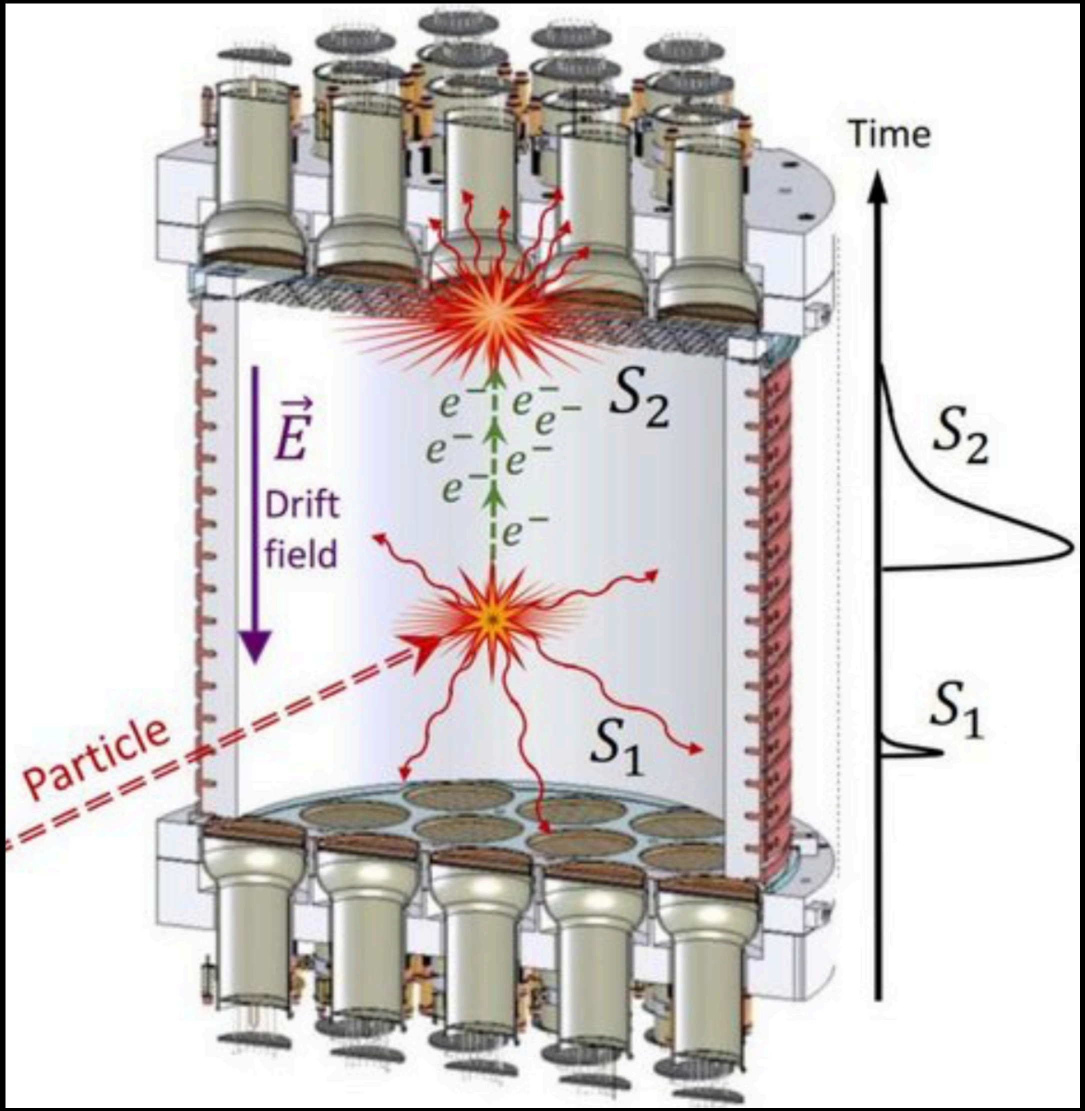
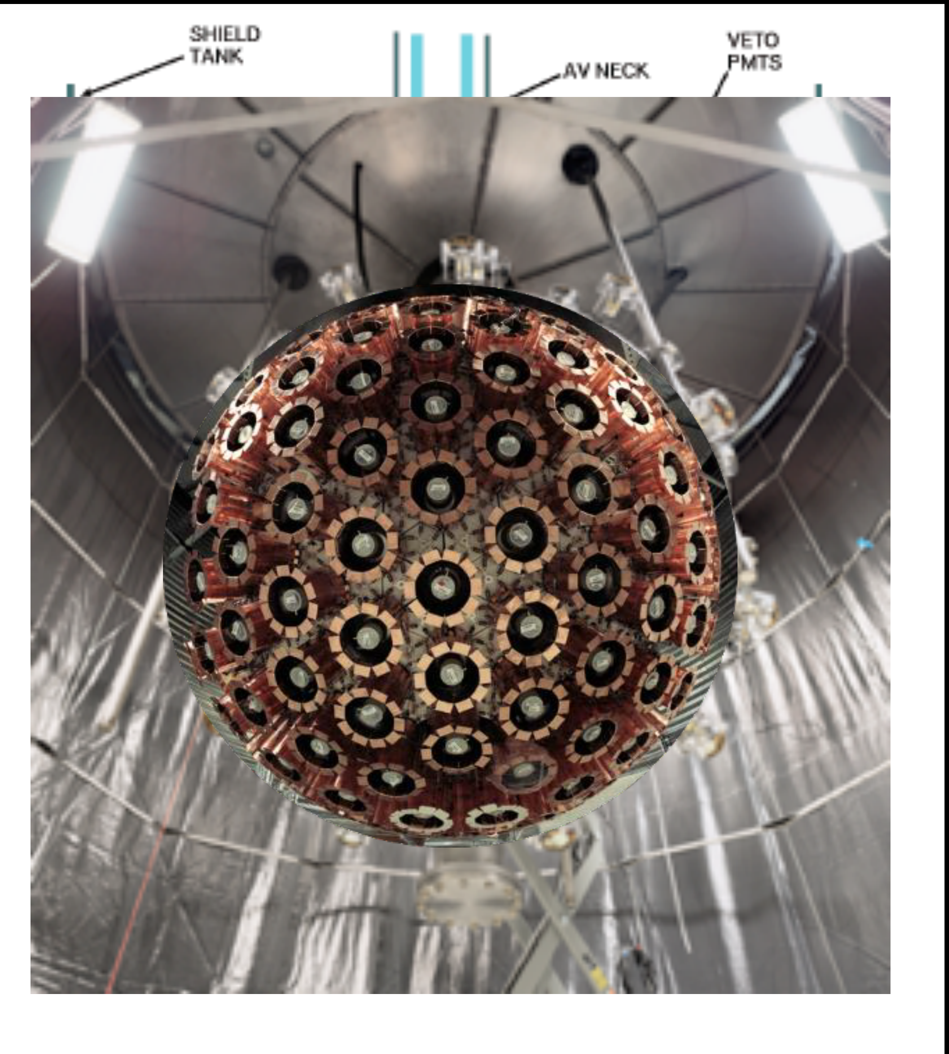
Primary scintillation (S1) and proportional gas scintillation from drifted electrons (S2)



Liquid Noble Detectors



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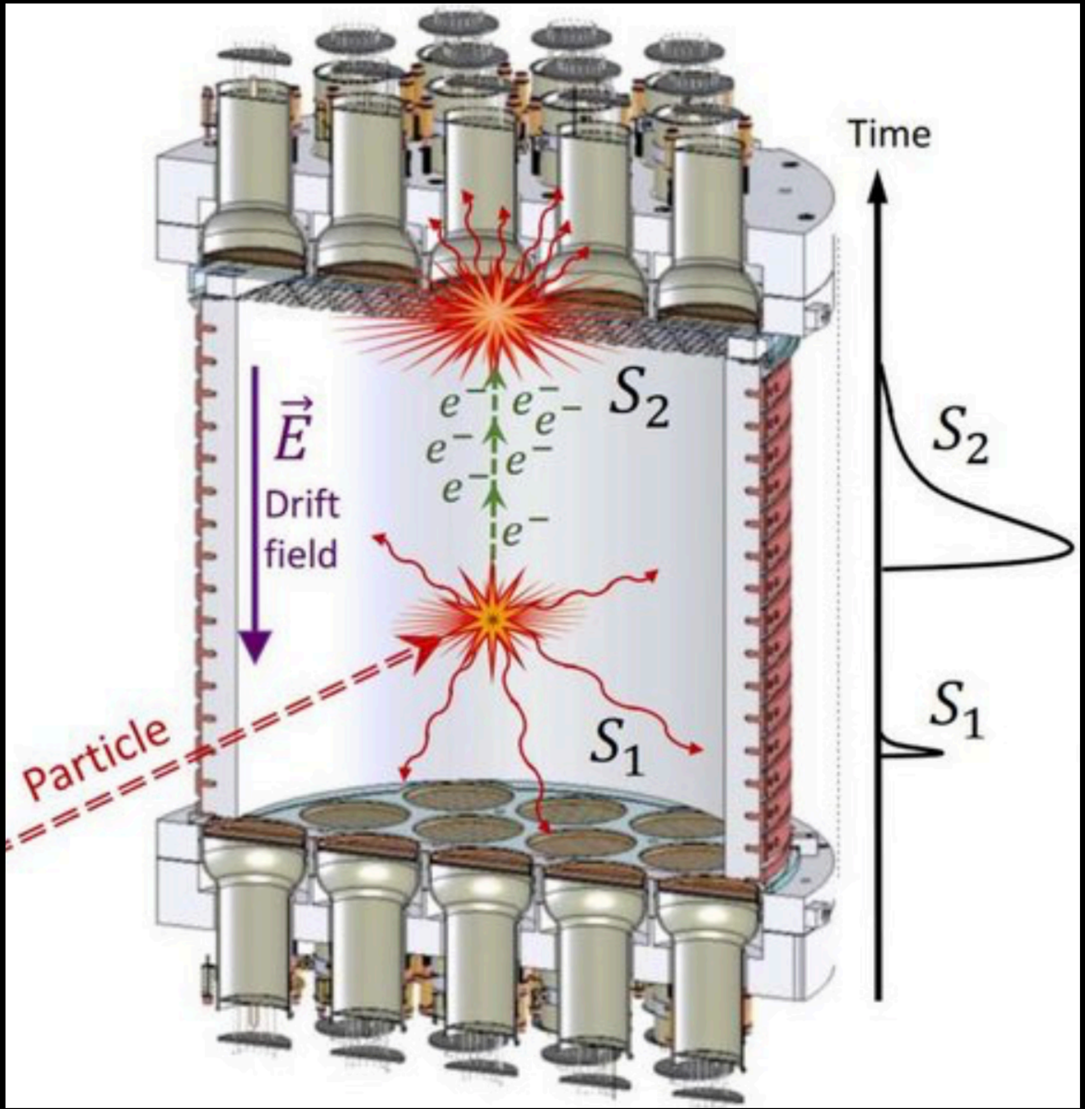
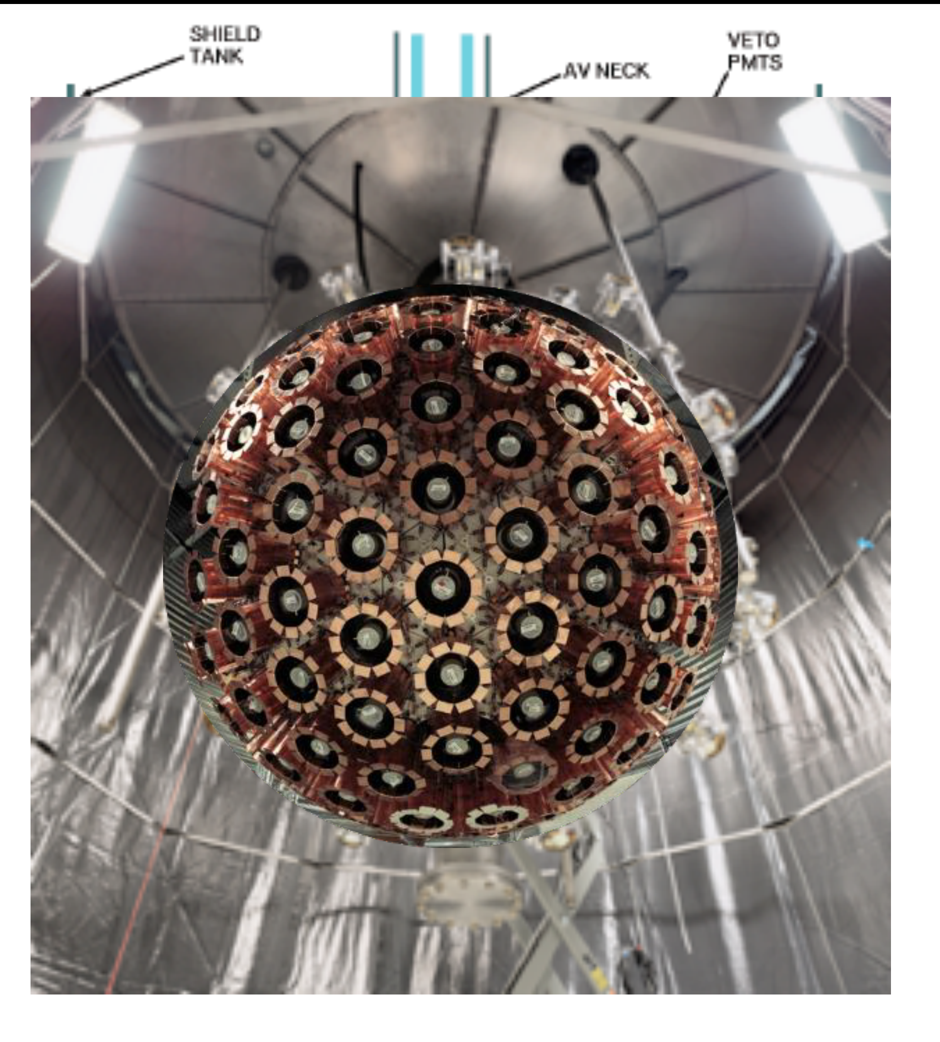


Liquid Noble Detectors



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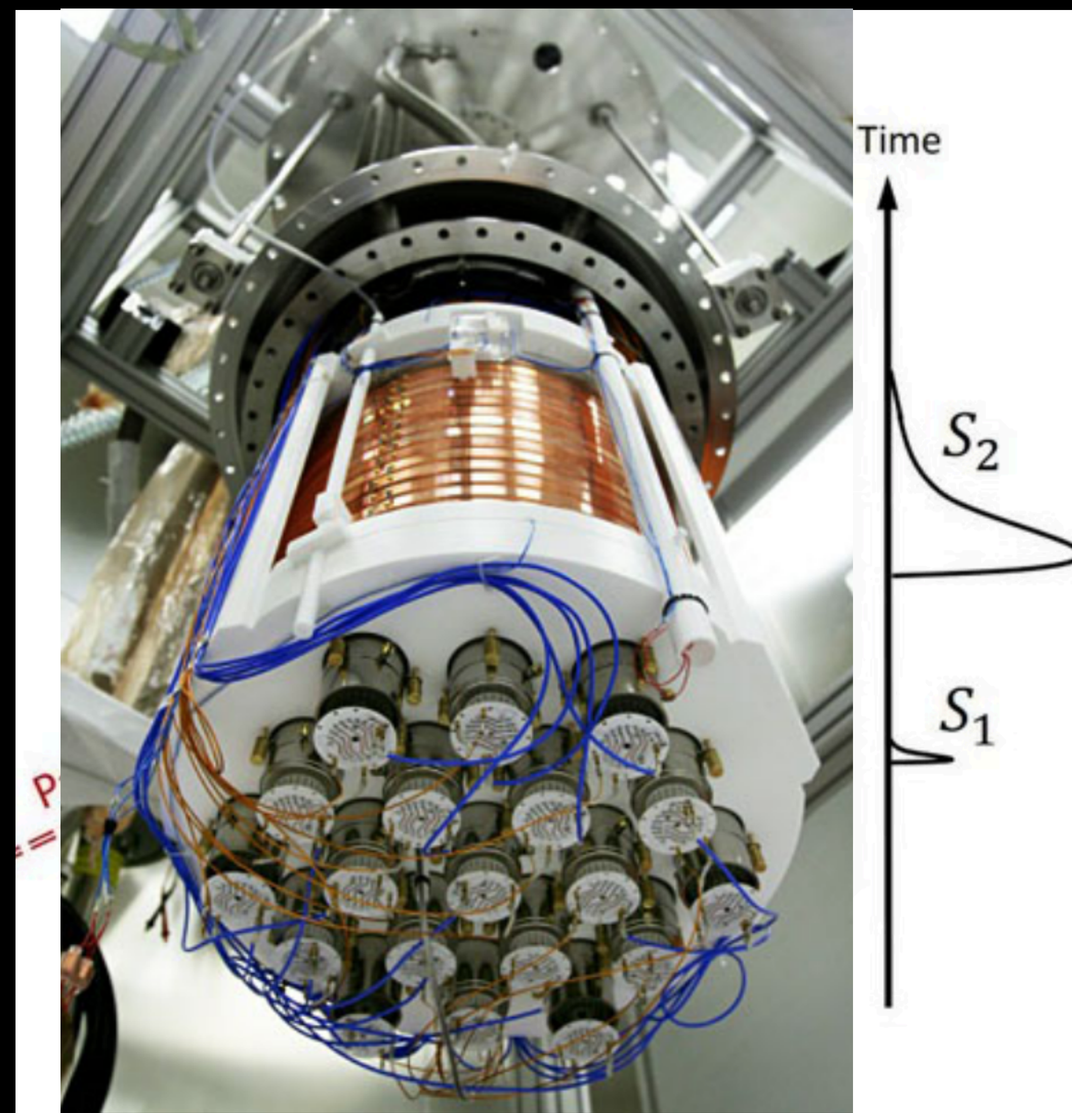
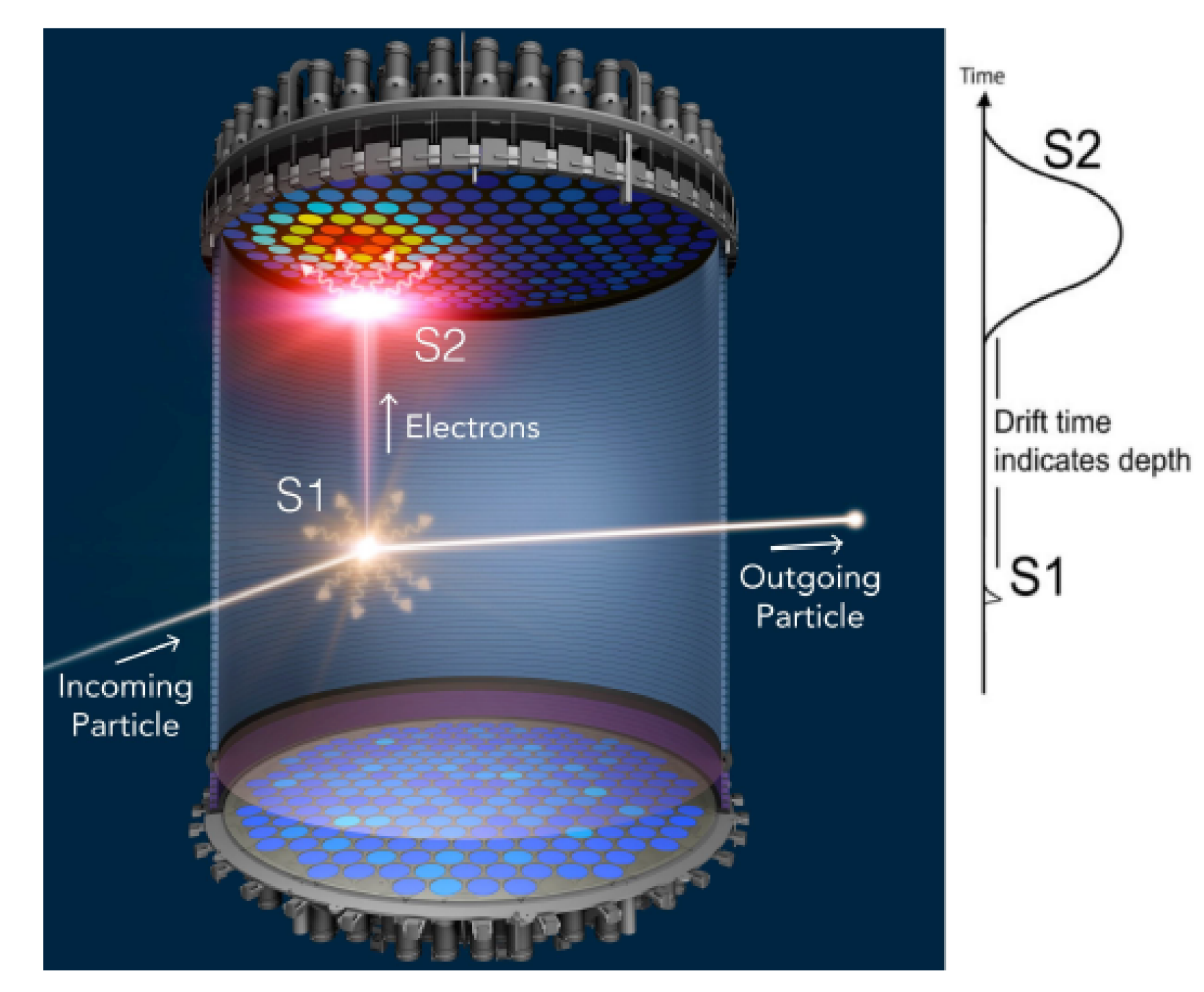


Charge + Light



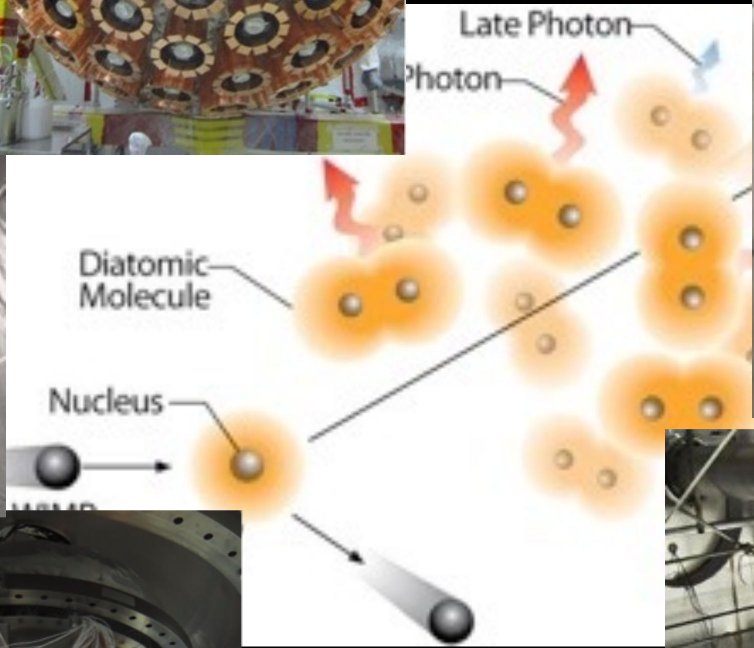
https://lz.slac.stanford.edu/our-research/lz-research

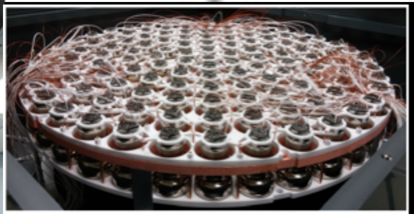
Detector Technology:
dual-phase
Time Projection
Chambers
with multi-tonne
liquid Xe, Ar targets

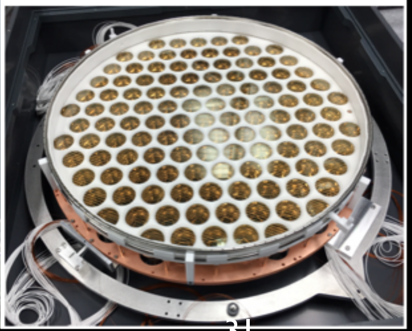
read out primary
scintillation: "S1" +
proportional gas
scintillation from
drifted electrons: "S2"

Goal: reach the
neutrino floor!

Noble Liquids

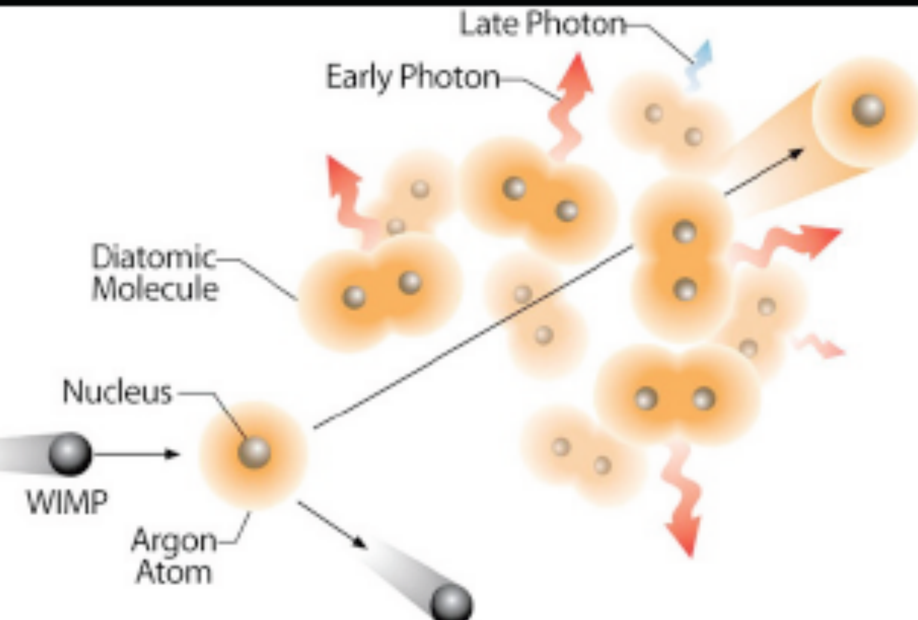


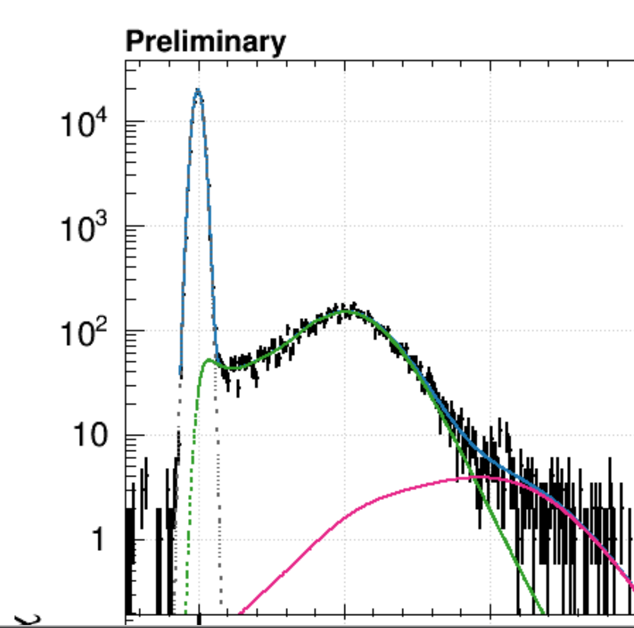




Energy Measurement

EUV Light | WLS | Visible Light | Charge



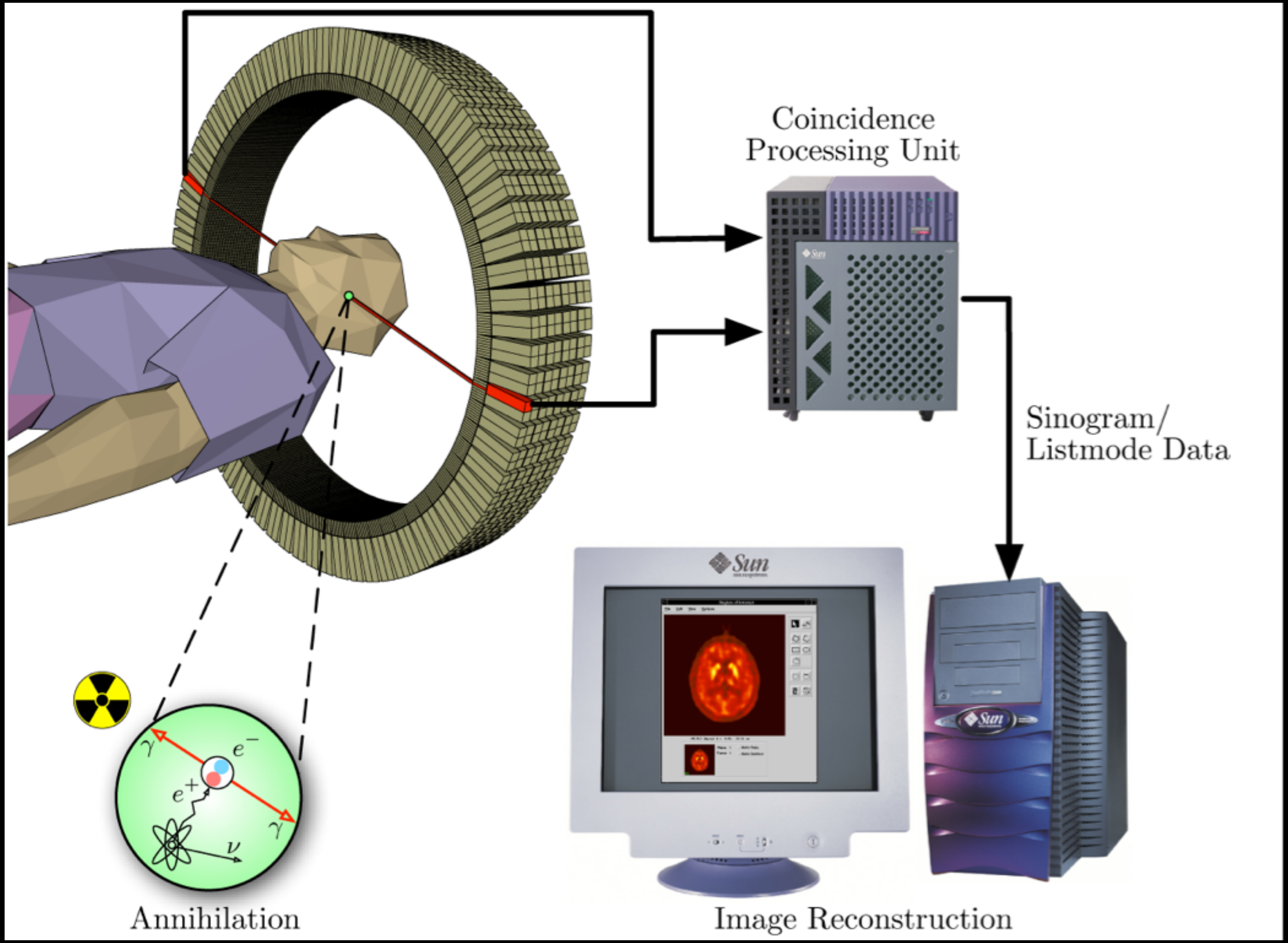


Argon/Neon | TPB | Acrylic/Ar/Ne | PMT

one photon at a time

Positron Emission Tomography

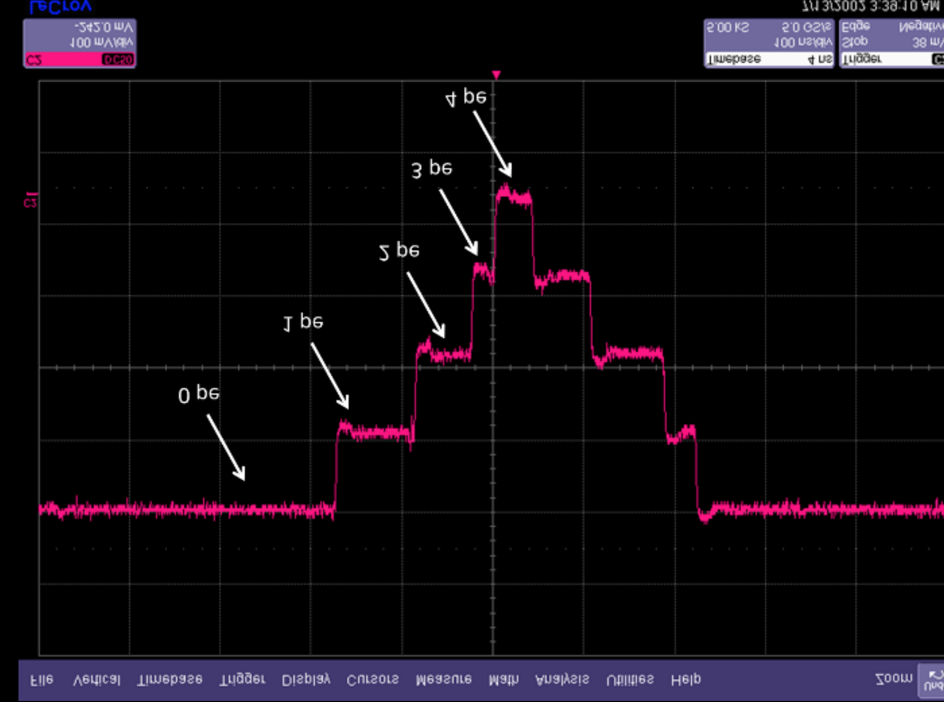
nuclear medicine functional imaging technique,
observes metabolism of a tracer taken by the patient in the body

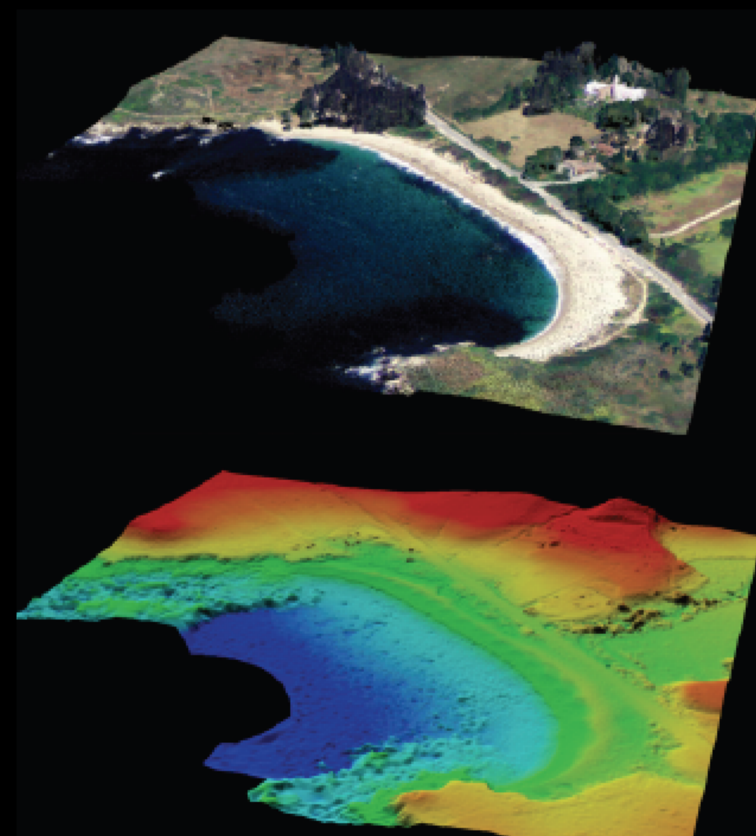


SiPMs, Digital SiPMs

TRIUMF

- TOF PET revolution
  - 10 ps ~ few mm
- Many particle physics applications
  - Plastic scintillator
  - Calorimeters with inorganic scintillators
- LiDAR
  - High precision (10ps~mm)
  - High rate
  - Possible imaging capabilities
  - Huge market: self driving cars, ...

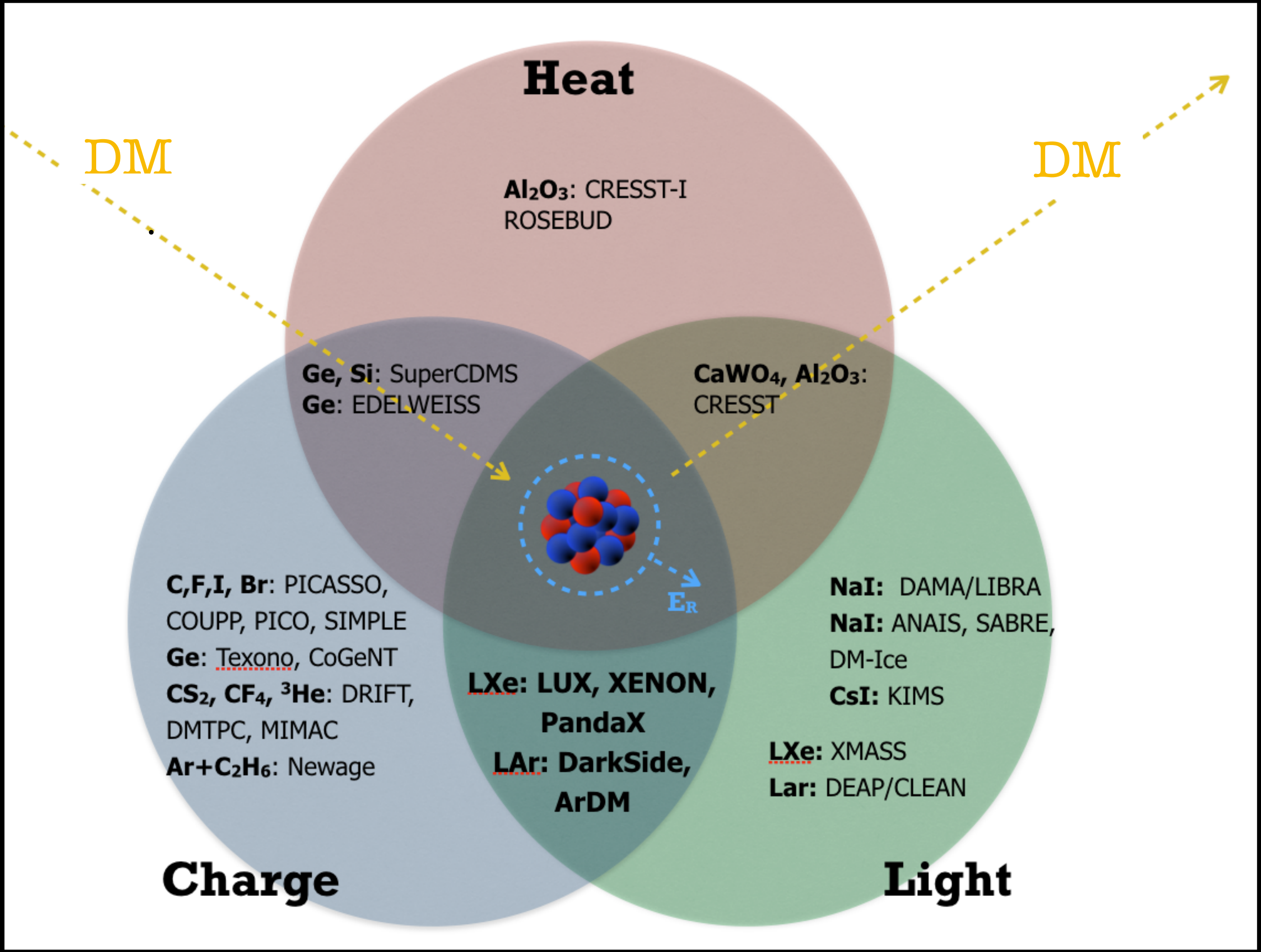




Energy Detection Strategies

Nuclear recoil $E_R \sim 1E\text{-}6 \times m_{DM}$

E_R threshold now O(10s eV), potential to reach meV



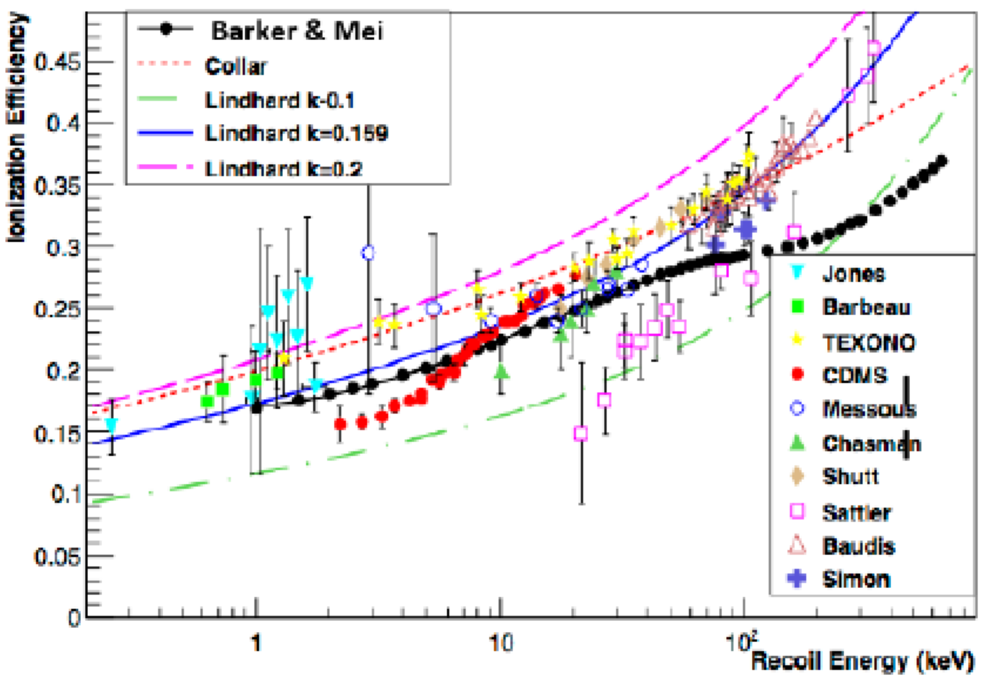
E_R threshold now O(10 eV), potential to reach eV

E_R threshold now O(keV), potential to reach 10 eV

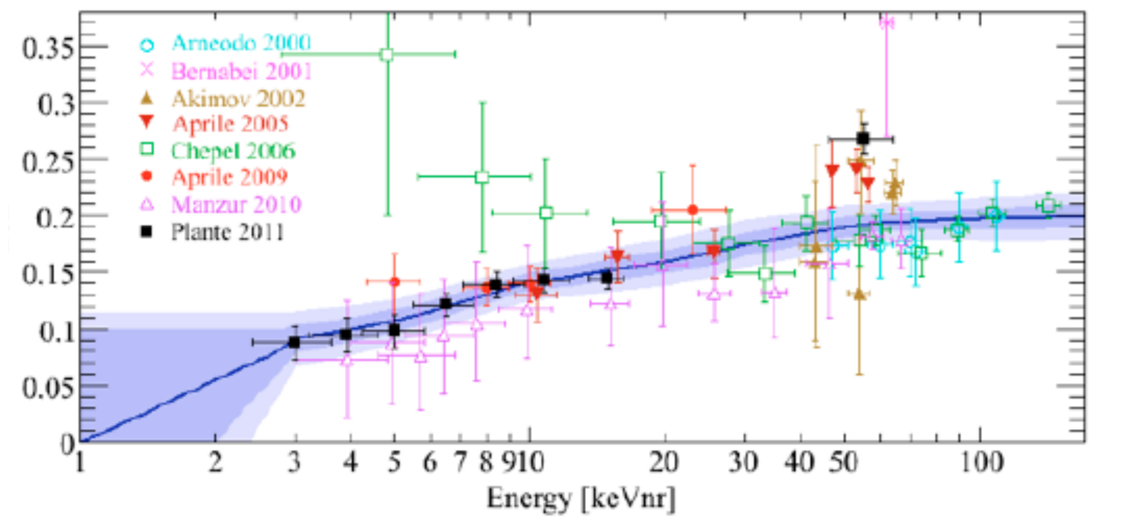
Key Experimental Systematics: Quenching

Current status of measurements of visible/recoil energy in
-ionization on Ge
-scintillation on Xe, Ar

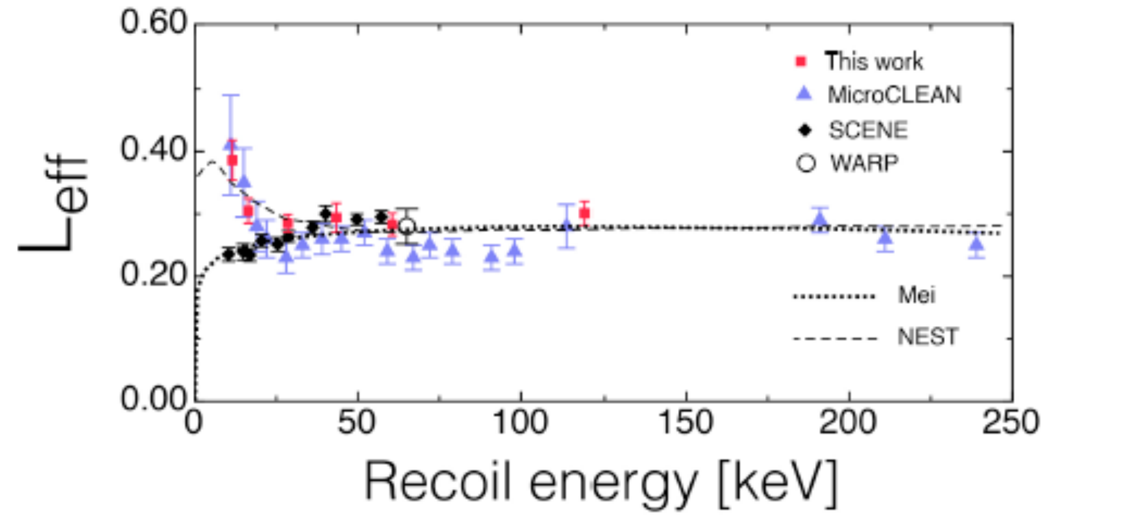
Germanium



Direct method: LXe   Plante *et al.*, Phys. Rev. C **84**, 045805, 2011



Direct method: LAr   W. Creus et al., arXiv: 1504.07878



Impact of uncertainties up to x5-10 in dark matter limits, particularly at low mass!

measurement in the experiment energy region of interest required

Key Experimental Systematics: Quenching

Current status of measurements of visible/recoil energy in
- -ionization on Ge
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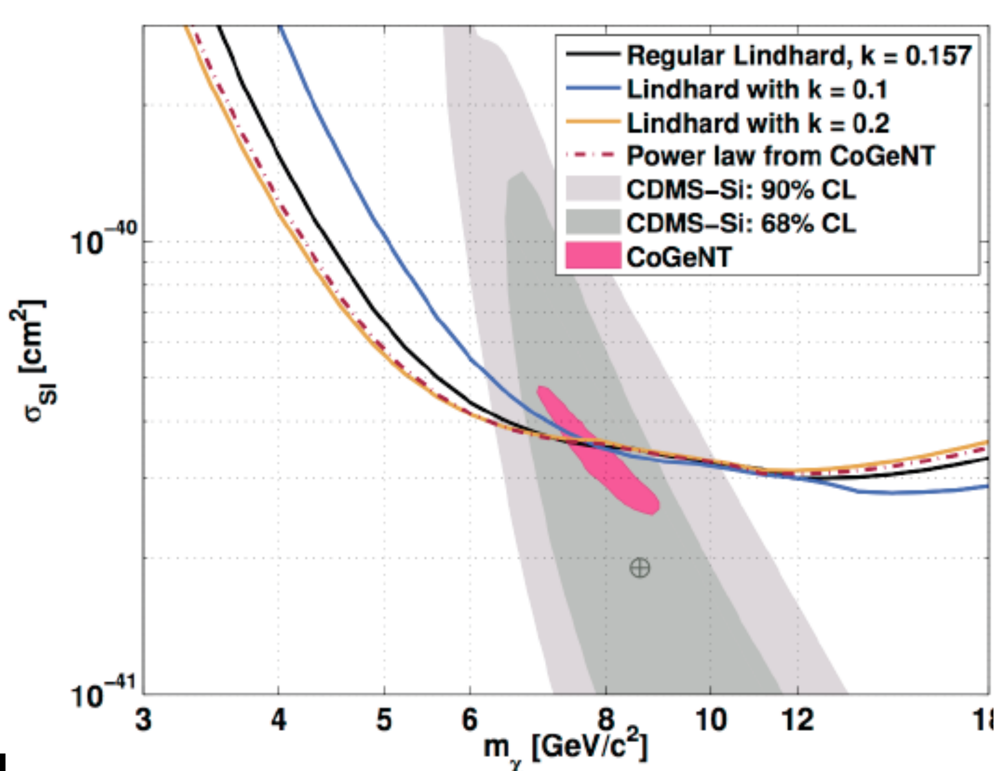

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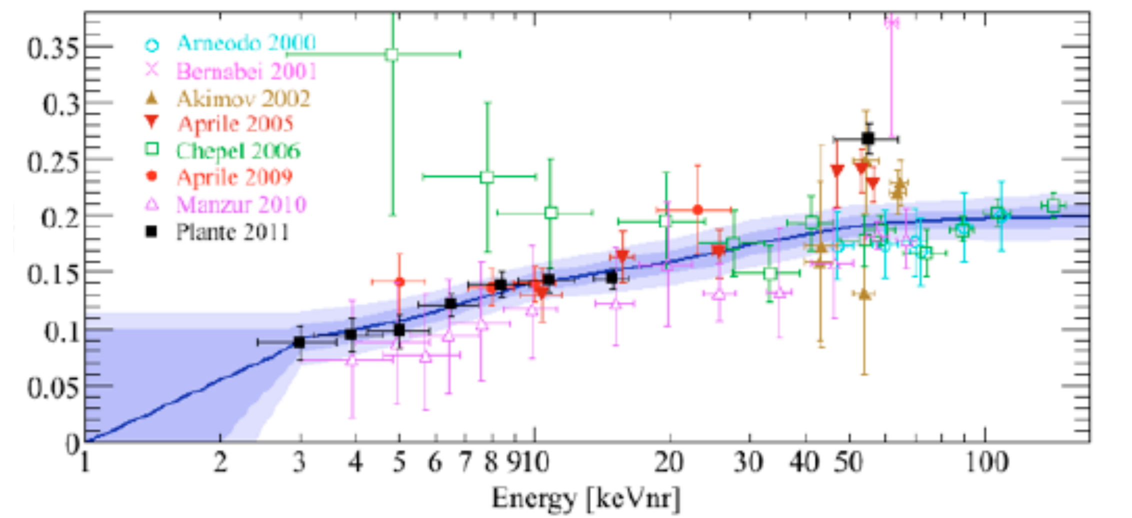

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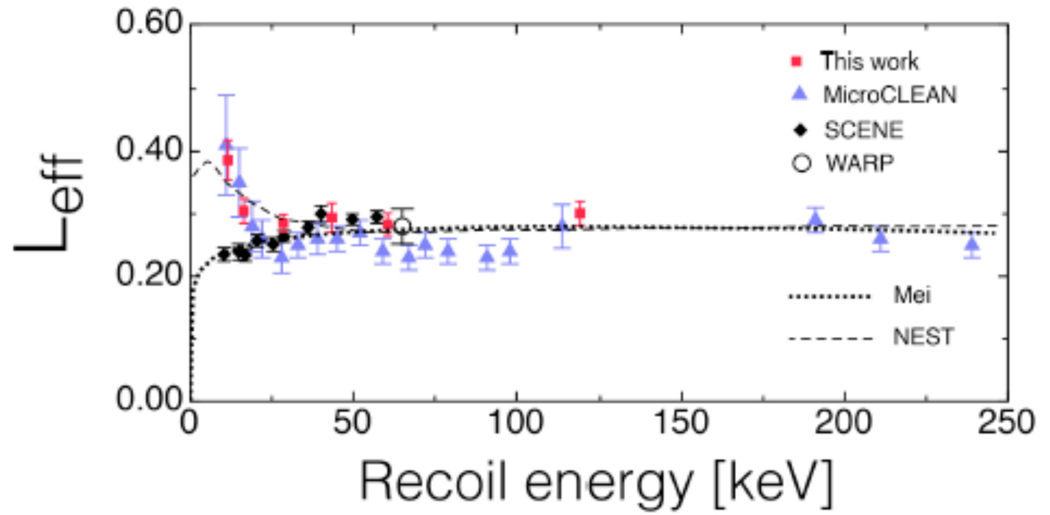


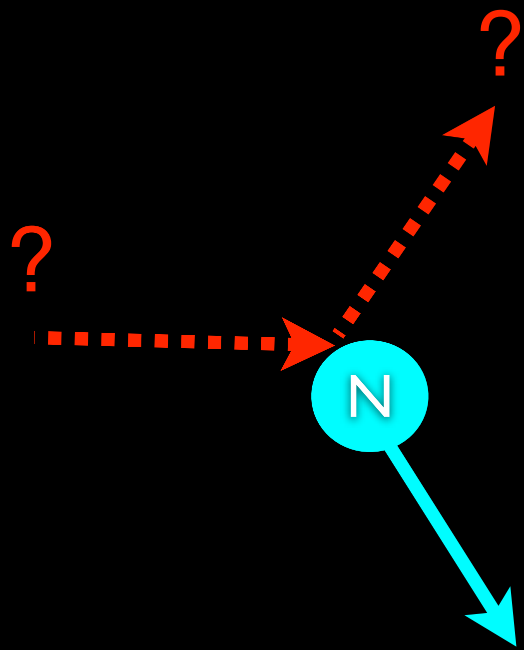
Impact of uncertainties up to x5-10 in dark matter limits, particularly at low mass!

measurement in the experiment energy region of interest required

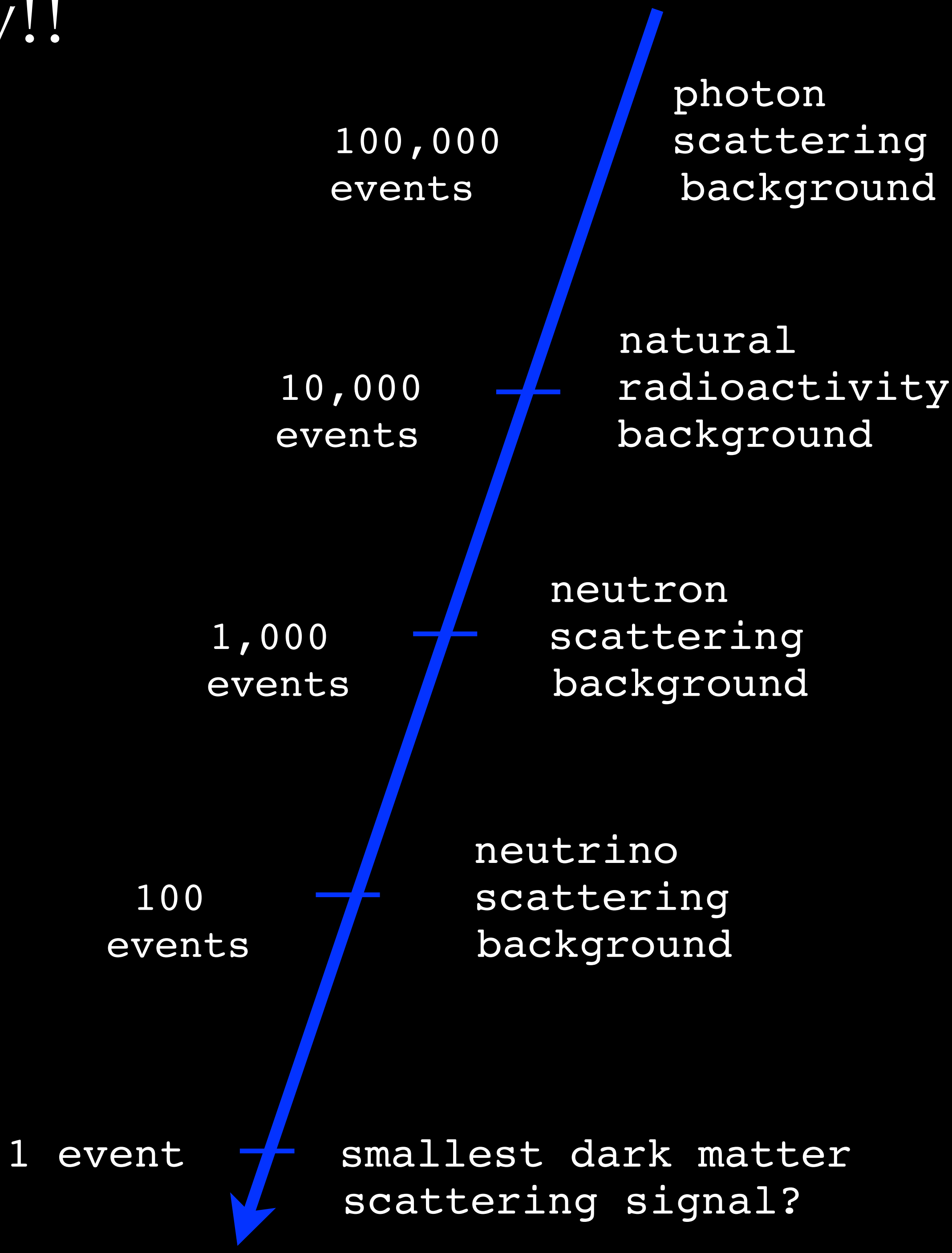
Backgrounds
in Rare Event Searches

DM Interaction Rate is Tiny!!

In dark matter experiments...



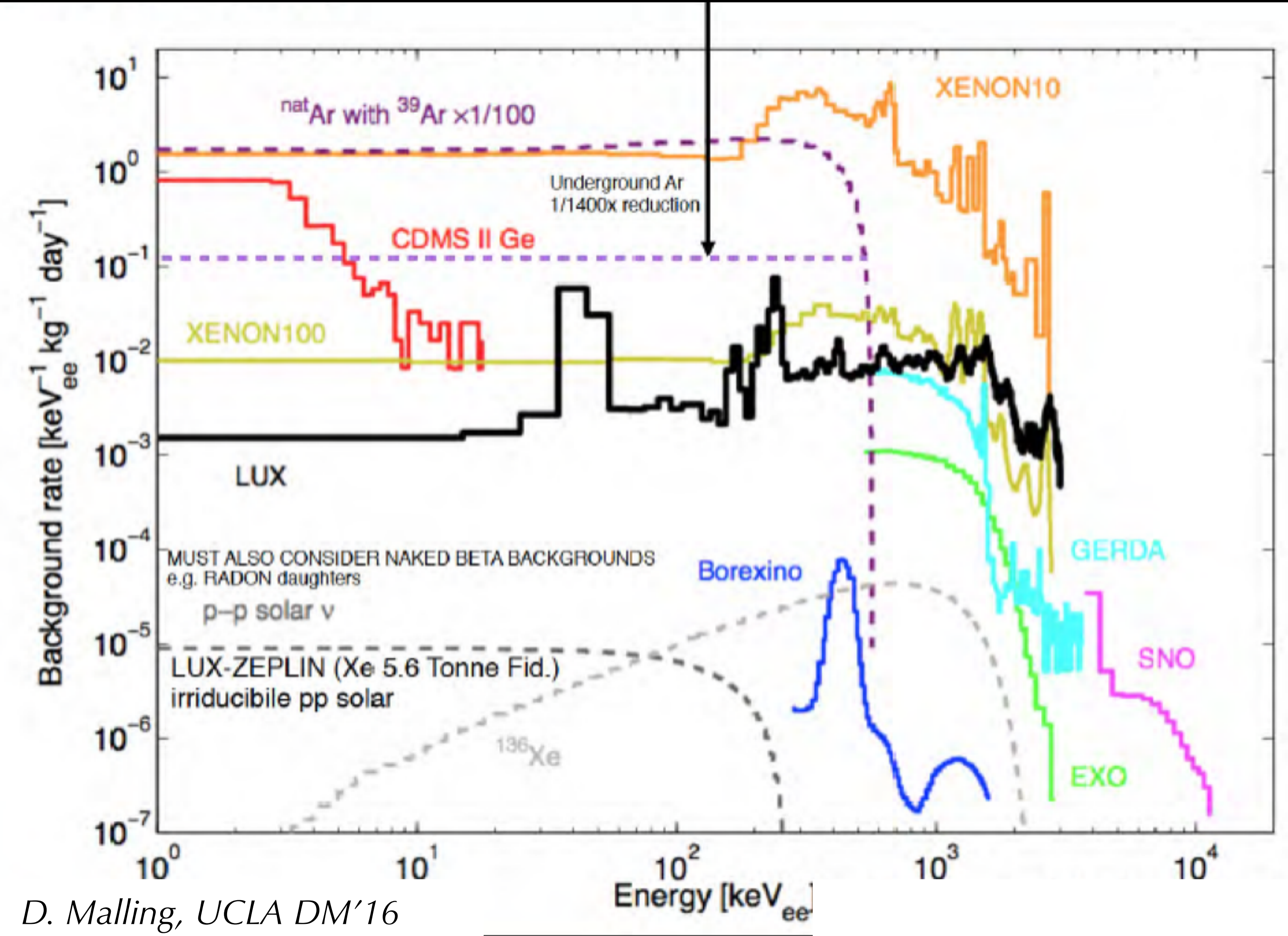
Anything else that does this
can mimic a dark matter signal!



Geiger counter

In this room:
10,000,000 photon scattering events/kg/day!

experiments use lead shielding to block photons



D. Malling, UCLA DM'16

+ *discrimination between e⁻ vs. N*

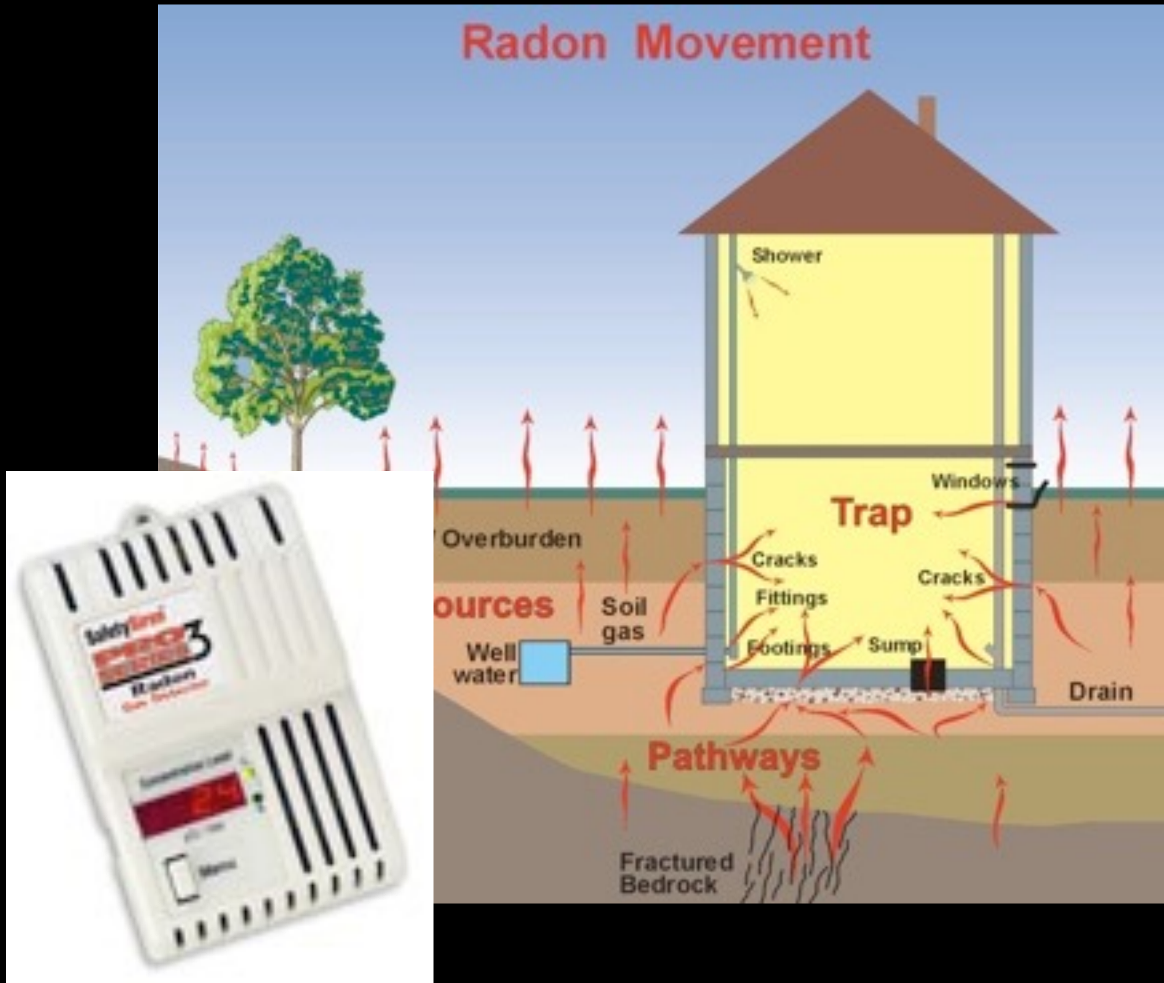
100,000 events — **photon scattering background**

0,000
vents — natural radioactivity background

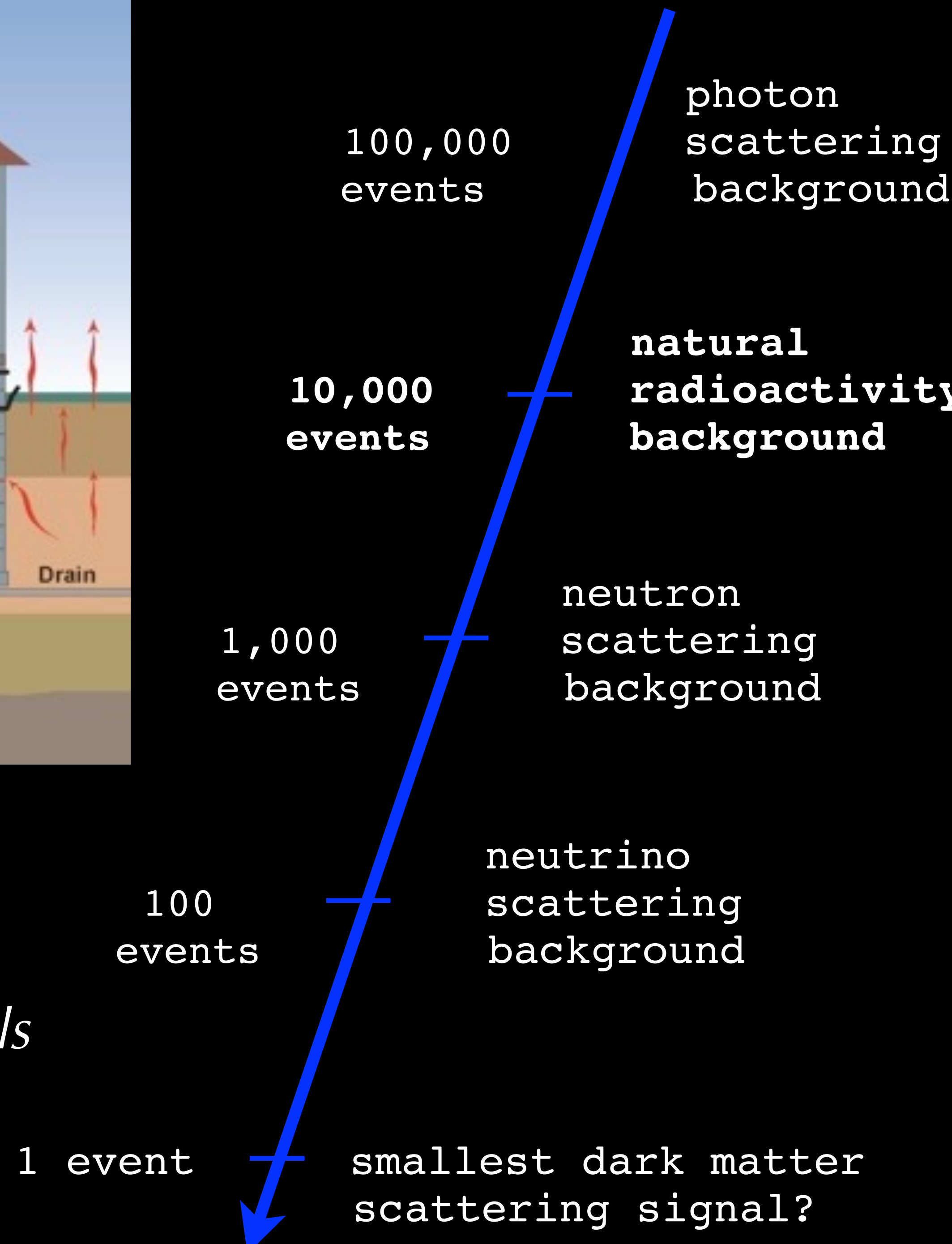
00
ts — neutron scattering background

neutrino scattering background

1 event — smallest dark matter scattering signal?

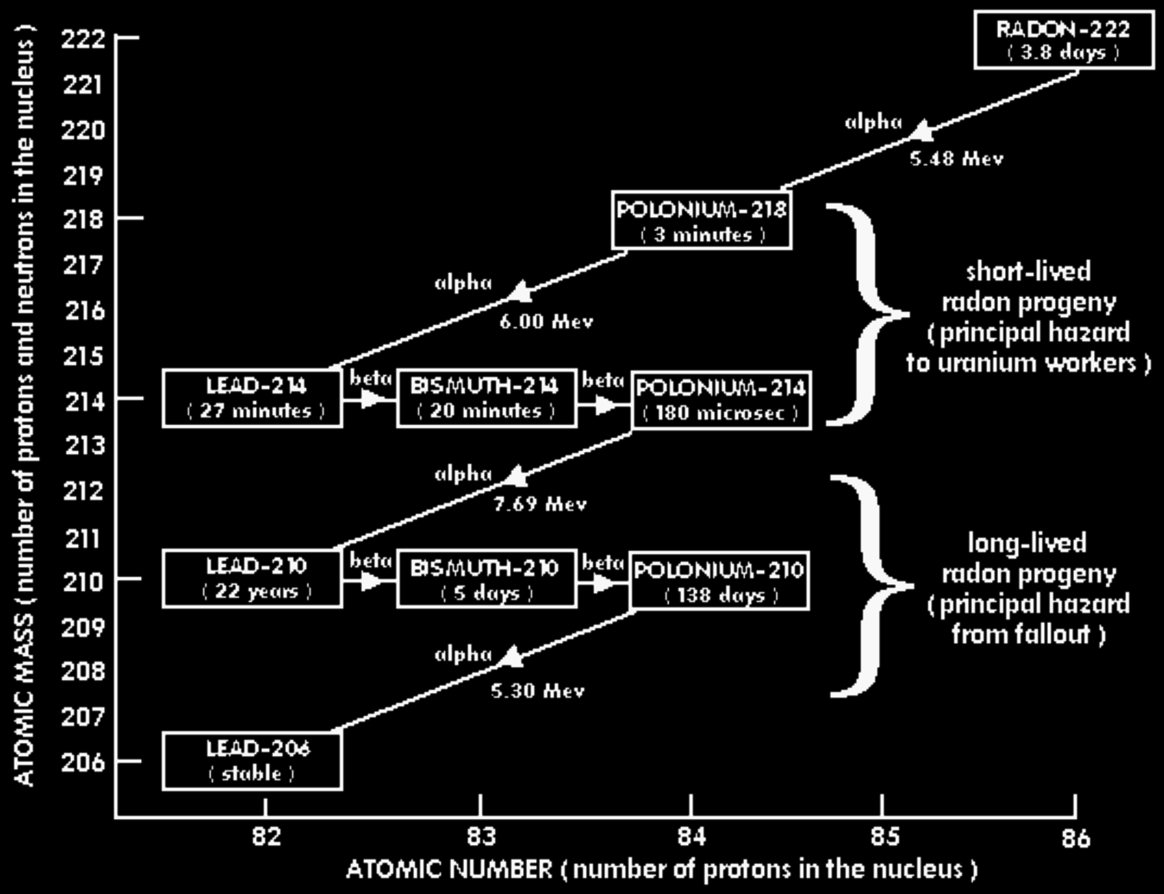


In your basement: 200,000 radon decays/kg/day set off the alarm! experiments use high-purity materials to control radon concentrations



Natural Radioactivity Backgrounds

Can't shield a detector from uranium and thorium present in trace amounts inside detector materials, however daughters and associated decay particles can mimic dark matter signals…



so dark matter experiments "screen" to identify low-radioactivity materials.

Material Screening, Example

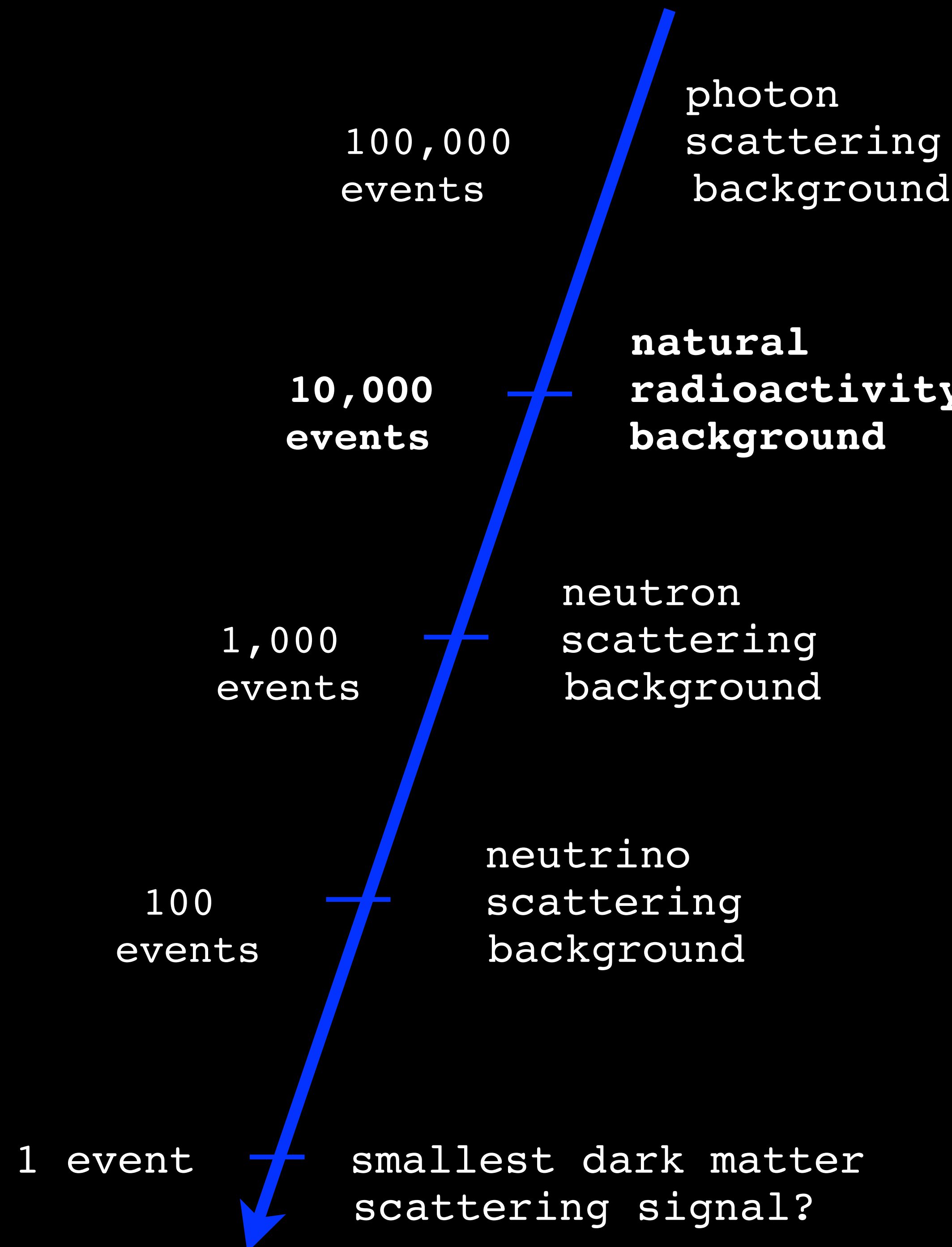
Table 8: ^{222}Rn emanation results for components used in the I
3600 detector contained within the stainless steel shell. A desc
for many of the components can be found in Section 4. Unc
ties arise from counting, sample emanation times, and detect
trapping efficiency.

Source	Emanation
	[mBq/m^2]
Filler blocks	1.6 ± 0.5
FINEMET PMT magnetic shielding [37]	0.8 ± 0.2
ESR film reflector [2]	< 2.2
Tyvek diffuse reflector	< 0.1
Black tyvek absorber	0.4 ± 0.2
PMT mount PVC (McMaster-Carr stock)	< 0.7
PMT polyethylene foam	< 0.9
Teflon sheets (McMaster-Carr stock)	0.4 ± 0.2
High density polyethylene pipe	3.5 ± 0.8
304 Stainless Steel (McMaster-Carr stock)	< 1.6
Carbon steel (McMaster-Carr stock)	0.6 ± 0.1
White PMT mount adhesive styrofoam sheet	< 1.5
Stycast 1266 A/B (Emerson & Cuming)	< 4.2
	[mBq/m]
RG59 PMT cable (Belden E82241)	0.026 ± 0.001
Steel shell EPDM O-ring	16.1 ± 1.8
Viton O-ring	1.3 ± 0.2
Buna 451 O-ring	17 ± 2
	[mBq/unit]
Hamamatsu R5912 PMTs	< 0.3
PMT mount O-ring	0.3 ± 0.1

Table 7: Gamma assay results for tooling used during construction and manufacture of detector components. Activities are reported with 1-sigma uncertainties. A 90% confidence limit is placed when the measurement is below the background sensitivity of the detector. It is assumed that secular equilibrium is broken between ^{230}Th and ^{226}Ra in the ^{238}U decay chain.

Component	^{238}U^{lower}	^{238}U^{upper}	^{232}Th	^{235}U
		[mBq/kg]		
Purification System Welding				
TIG weld sample	7.7 ± 5.7	< 27	25.2 ± 7.8	< 16
SMAW weld sample	< 23	< 1255	51.9 ± 12.2	< 13
Welding electrodes A (Blue Demon TE2C-116-10T)	221 ± 65	< 493	1890 ± 184	< 56
Welding electrodes B (Blue Demon TE2C-116-10T)	66.6 ± 42.6	< 1300	710 ± 103	< 138
Welding electrodes C (Blue Demon TE2C-116-10T)	86.1 ± 21.8	< 642	911 ± 73	< 108
Weld filler rods	< 4.8	< 157	3.0 ± 2.5	< 1.8
Inner AV Sanding				
Brazed diamond sanding pad (Superabrasives)	141 ± 24	< 845	49.8 ± 17.9	31 ± 19
Plated diamond sanding pad (Superabrasives)	4680 ± 283	< 4130	6180 ± 300	218 ± 64
3M 6002J flexible diamond pads	25.1 ± 15.4	< 785	< 10.8	< 33
Diamond sandpaper (Diamante Italia)	3120 ± 136	< 2300	3370 ± 125	157 ± 22
Red sandpaper (RPT)	48.7 ± 19.7	< 335	< 10.1	< 32
LG Acrylic Polishing				
Diamond lapping film (3M 661X)	142 ± 38	< 882	93.6 ± 35.0	< 31
Diamond lapping film (3M 661X)	94.0 ± 16.5	< 276	$105. \pm 18.1$	< 33

Component	^{238}U^{lower}	^{238}U^{upper}	^{232}Th	^{235}U
		[mBq/kg]		
Methyl methacrylate monomer (LG bonding)	1.4 ± 1.0	< 15	< 0.9	< 1.8
AV acrylic	< 0.1	< 2.2	< 0.5	< 0.2
Acrylic beads (RPT)	< 3.1	16 ± 15	0.8 ± 0.3	0.6 ± 0.5
LG acrylic	< 0.1	< 9.0	< 0.3	< 0.6
304 welded stainless steel (steel shell)	1.4 ± 1.1	< 5.0	4.7 ± 1.5	< 3.3
304 stainless steel stock (steel shell)	2.1 ± 1.1	40 ± 56	1.9 ± 1.1	< 5.4
316 stainless steel bolts (steel shell)	< 6.1	< 315	94 ± 9	< 17
Carbon steel (stock)	2.0 ± 0.7	111 ± 43	10.0 ± 1.0	8.6 ± 1.9
R5912 HQE PMT glass	921 ± 34	225 ± 114	139 ± 7	25 ± 3
R5912 HQE PMT ceramic	978 ± 56	15500 ± 2800	245 ± 28	503 ± 51
R5912 HQE PMT feedthrough pieces	1140 ± 60	2350 ± 1460	430 ± 32	38 ± 9
R5912 HQE PMT metal components	< 5.5	–	< 3.3	–
RG59 PMT cable (Belden E82241)	4.5 ± 1.3	91 ± 46	1.2 ± 0.9	3.4 ± 1.4
PMT mount PVC (Harvel)	72 ± 5	232 ± 130	18.6 ± 2.5	5.6 ± 1.5
PMT mount copper	< 0.5	< 10	< 0.8	< 1.3
Filler block polyethylene	0.4 ± 0.3	< 14	< 0.1	< 0.15
Filler block Styrofoam [39]	33.5 ± 3.4	115 ± 64	< 1.5	< 1.4
White Tyvek paper (diffuse reflector)	< 0.3	50 ± 37	1.3 ± 0.8	< 2.2
Black Tyvek paper (LG wrapping)	< 1.8	< 127	5.6 ± 2.3	< 3.8
Black polyethylene tube (upper neck)	13.7 ± 1.8	< 60	3.2 ± 1.1	2.6 ± 1.4
TPB (Sigma Aldrich)	< 3.9	–	< 8.7	–



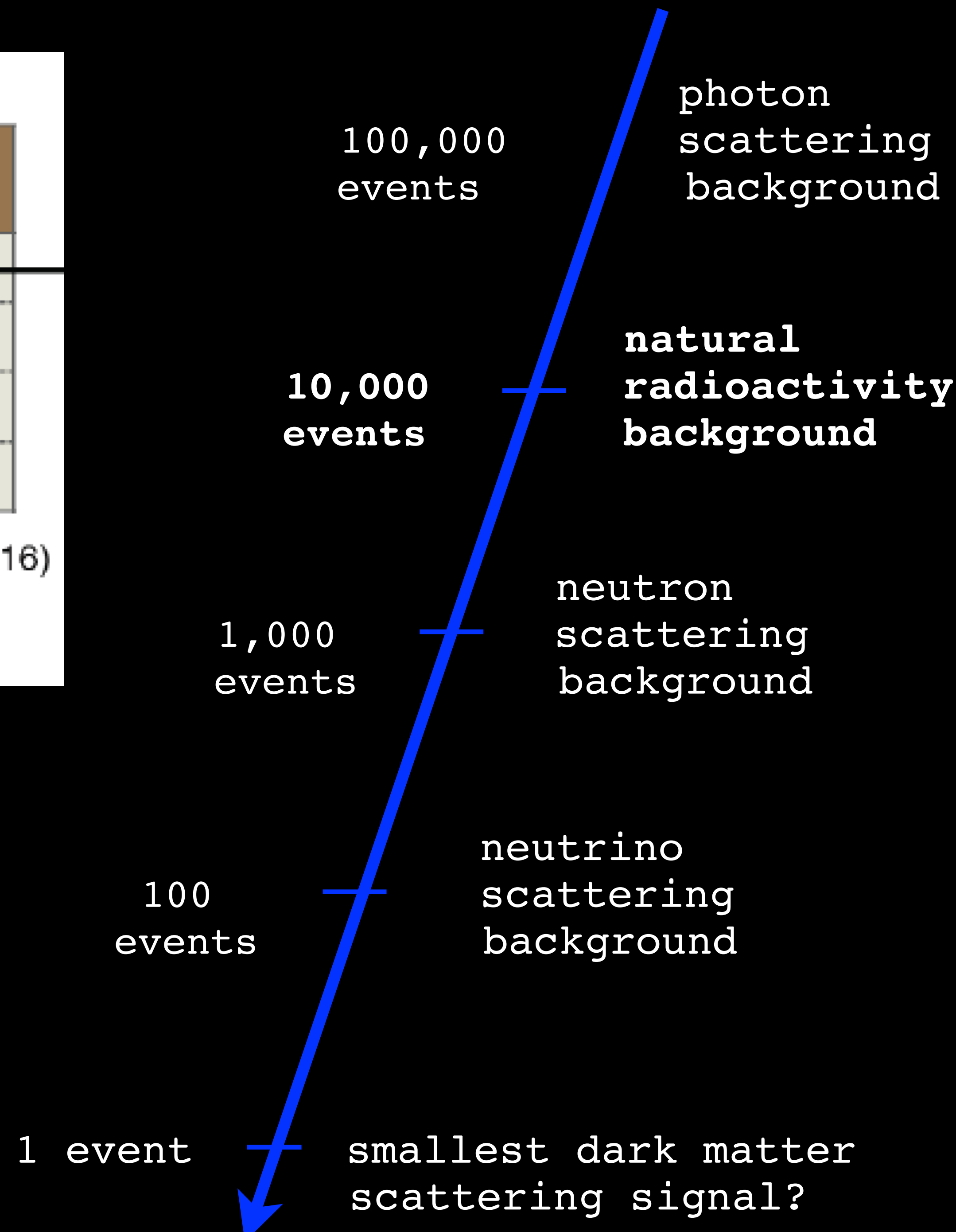
Control of Detector Contamination:
^{238}U and ^{232}Th decays, recoiling progeny and mis-identified alphas, betas mimic nuclear recoils

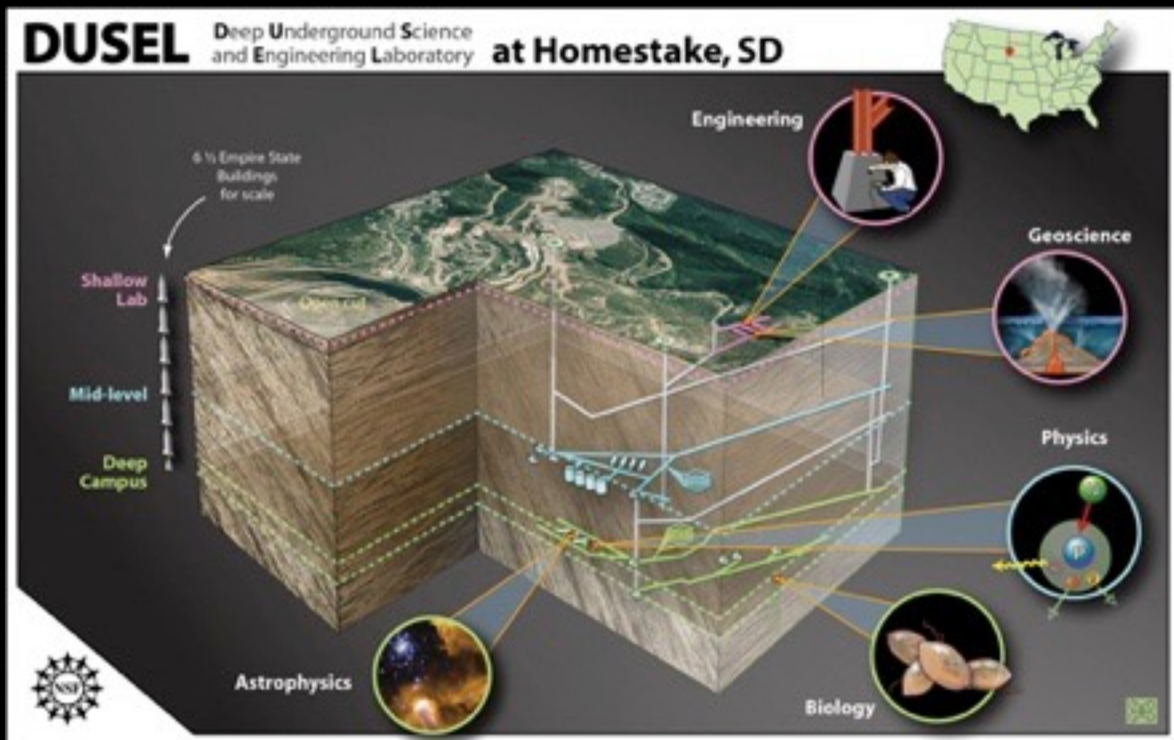
^{222}Rn in Dark Matter experiments:

Experiment	Activity / rate	Target
DEAP-3600	≈0.2 μBq / kg	LAr ←
PandaX-II	6.6 μBq / kg	LXe
LUX	66 μHz / kg	LXe
XENON1T	10 μBq / kg	LXe

- PandaX-II: PHYSICAL REVIEW D 93, 122009 (2016)
- LUX: Physics Procedia 61 (2015) 658 – 665
- XENON1T: XeSAT 2017 talk [link]

Control of Detector Contamination:
^{238}U and ^{232}Th decays, recoiling progeny and mis-identified alphas, betas mimic nuclear recoils





experiments go 1-2 km underground to shield detectors from neutrons

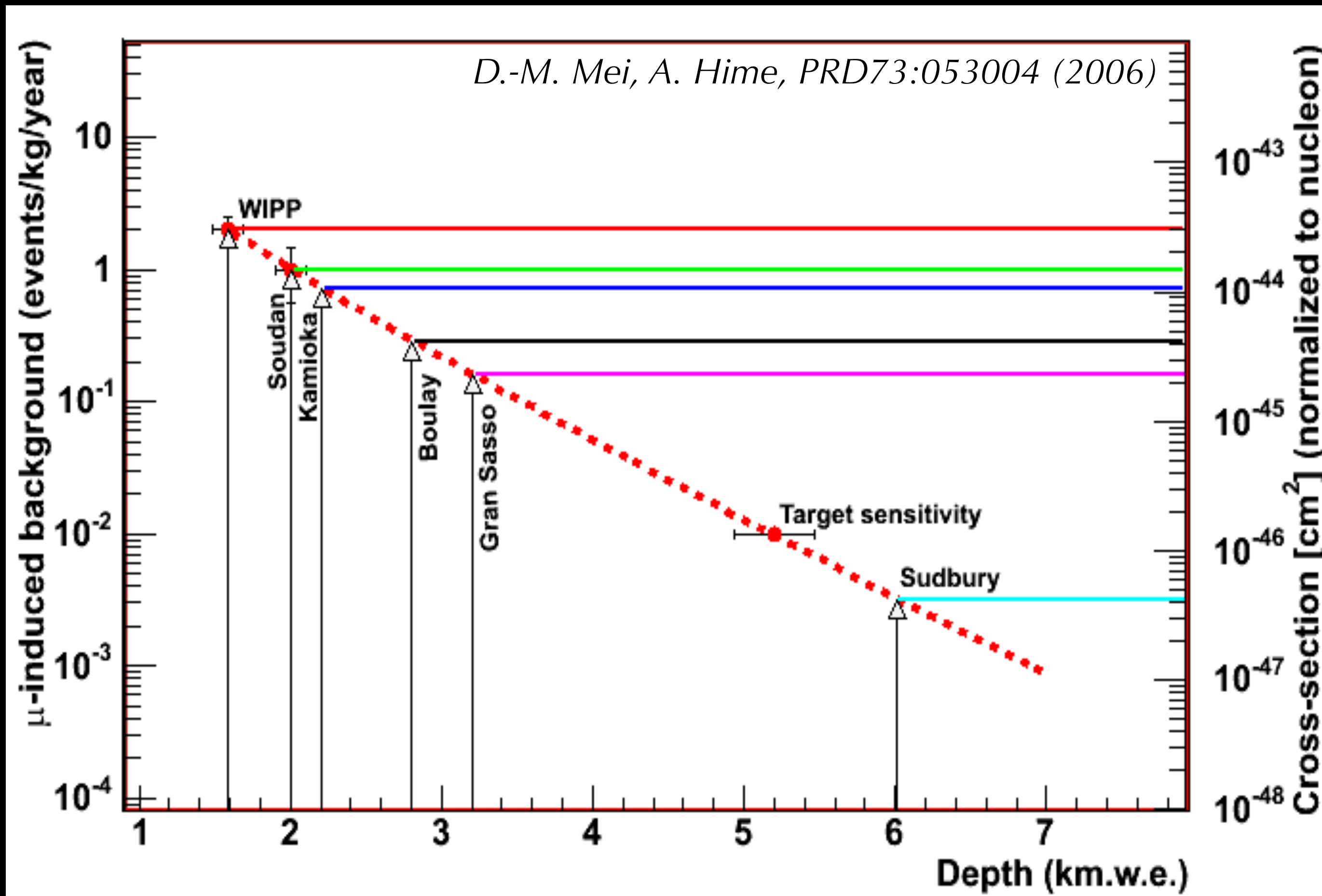
100,000 events — photon scattering background

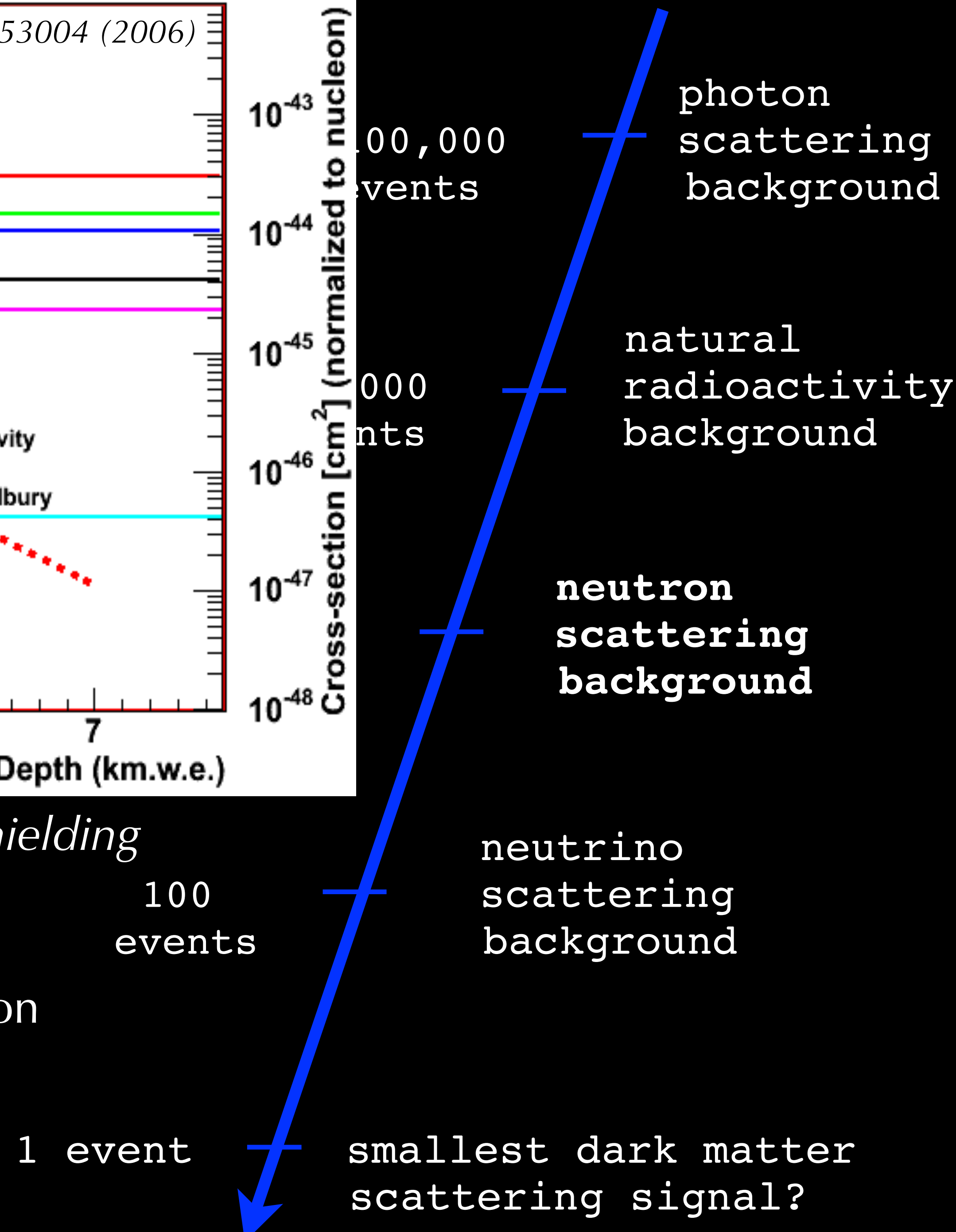
10,000 events — natural radioactivity background

1,000 events — neutron scattering background

0 ents — neutrino scattering background

1 event — smallest dark matter scattering signal?

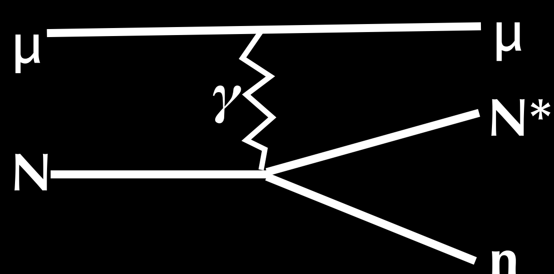




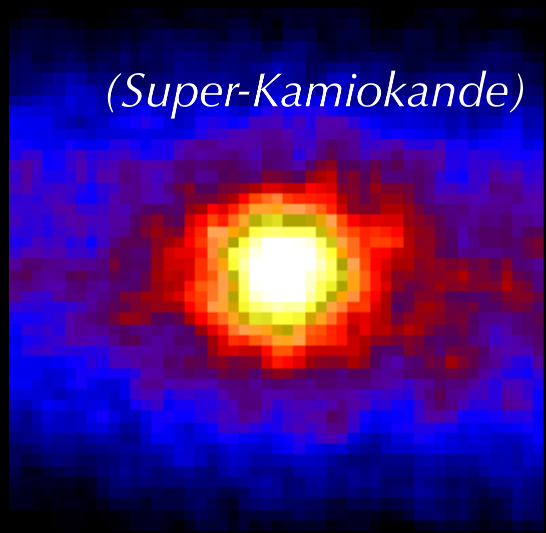
+ large, active neutron shielding

Nuclear recoil final state.

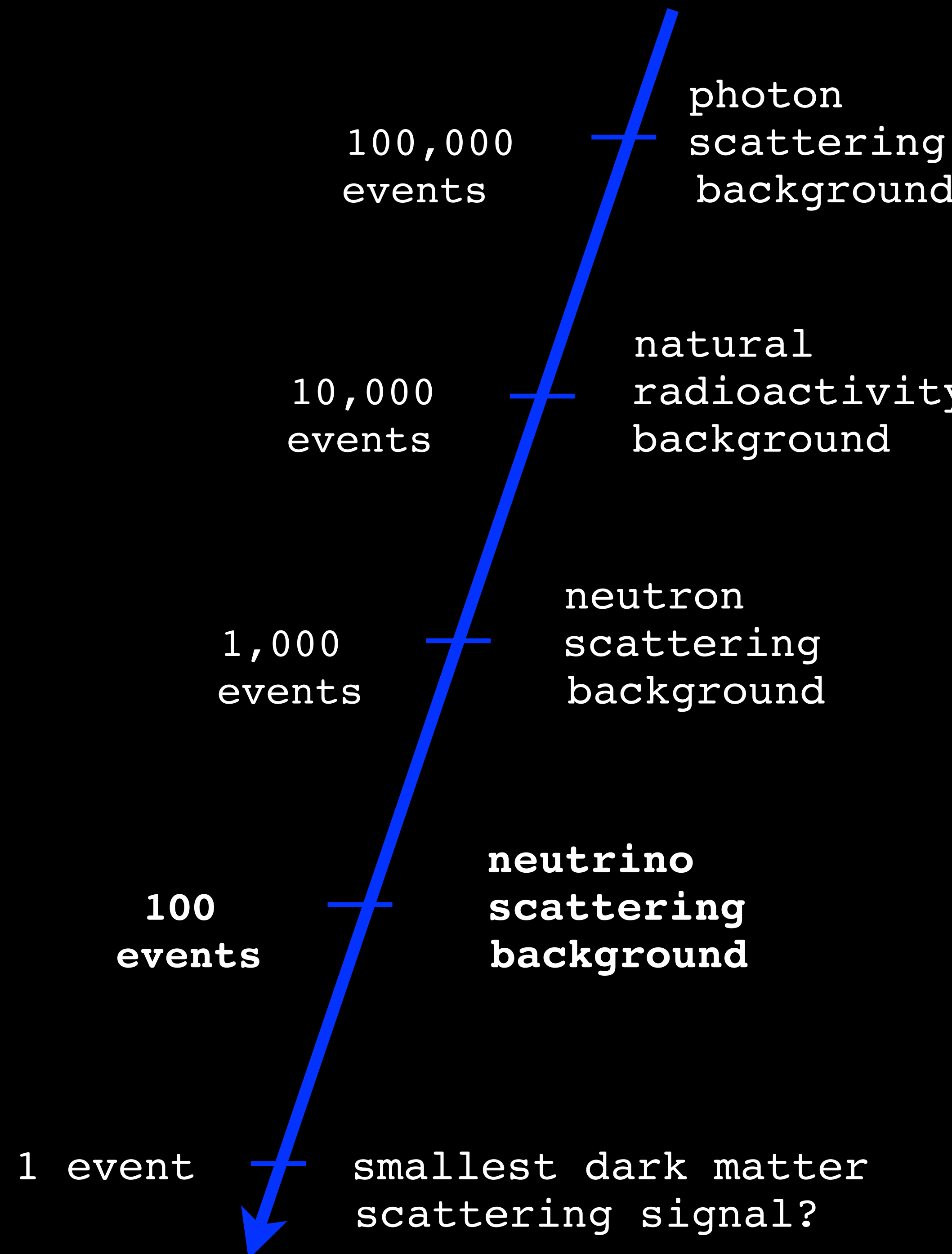
(alpha,n), U, Th fission, cosmogenic spallation



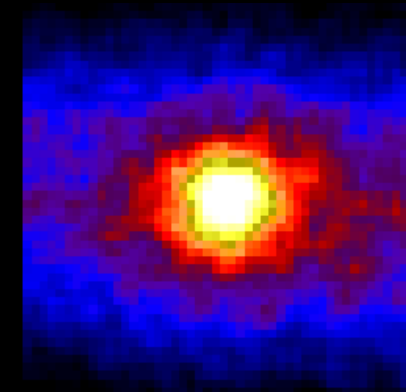
Backgrounds



The sun shines 100,000,000,000 neutrinos/cm^2/s, 1 in a million events/kg/day are backgrounds to dark matter searches.

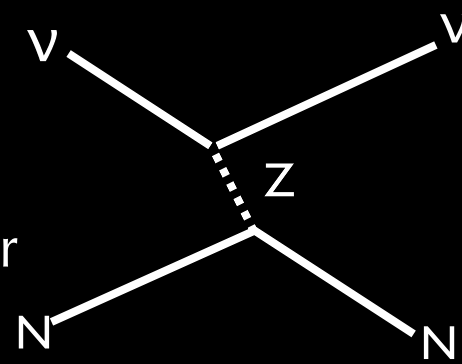


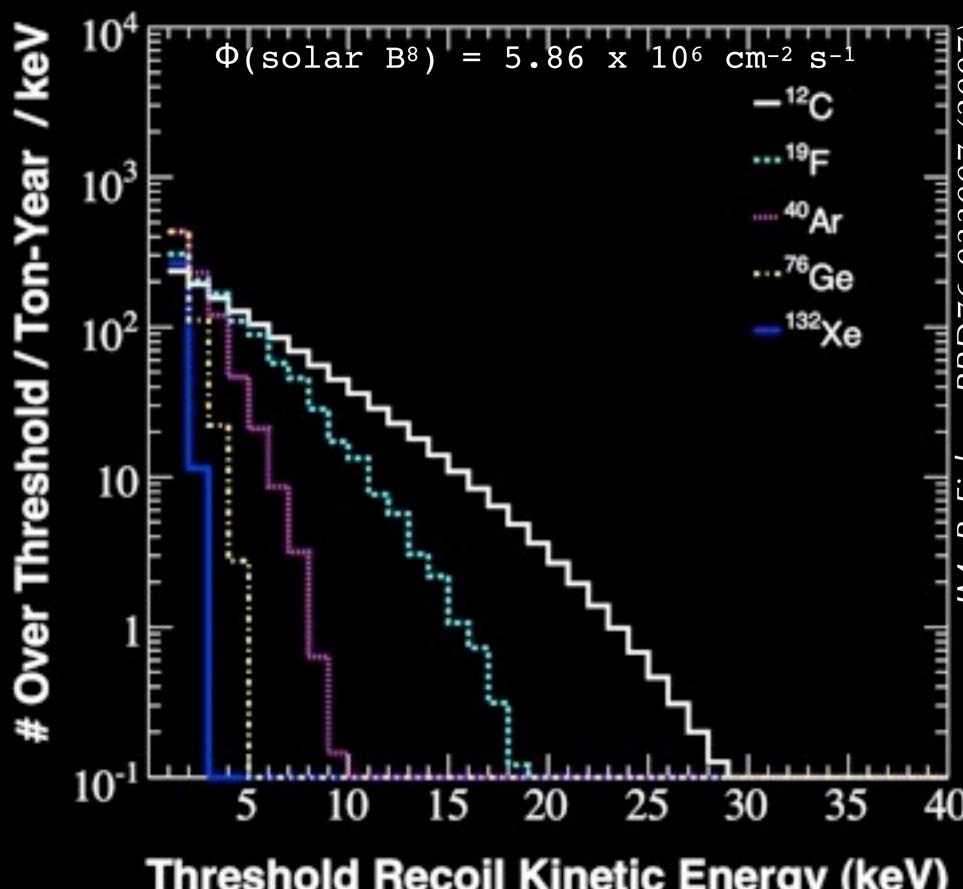
Irreducible Backgrounds



impossible to shield a detector from coherent neutrino scattering!

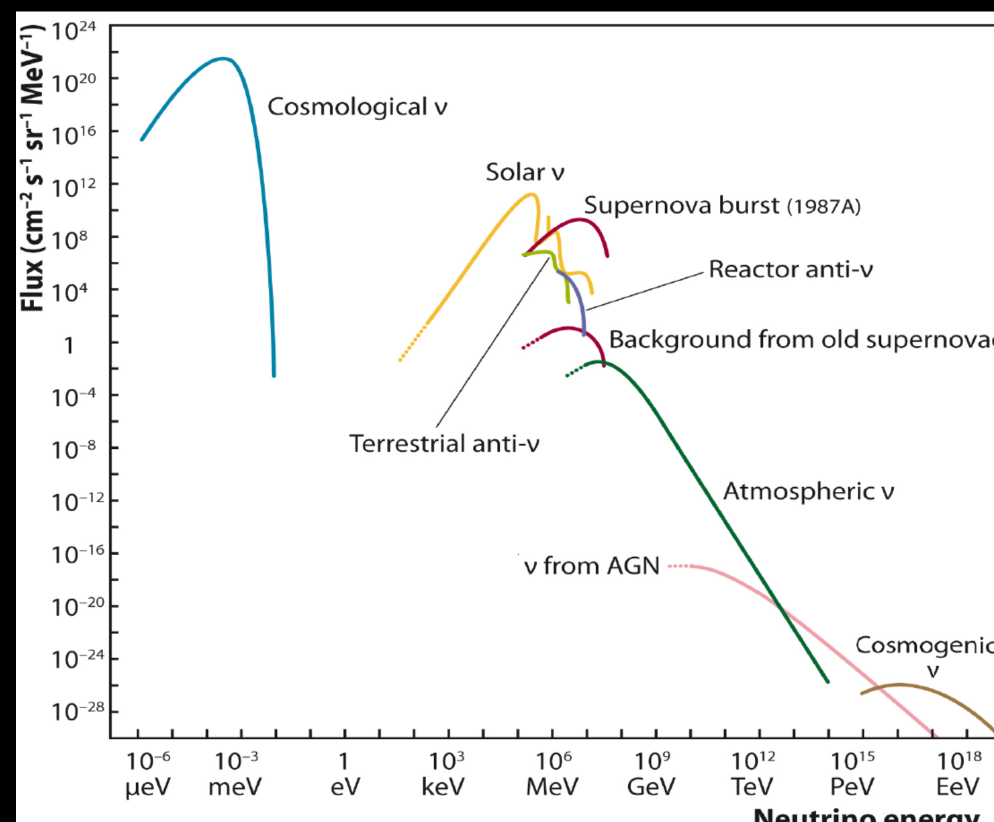
A limiting background at the neutrino floor





JM, P. Fisher, PRD76:033007 (2007)

…but also an *opportunity*.



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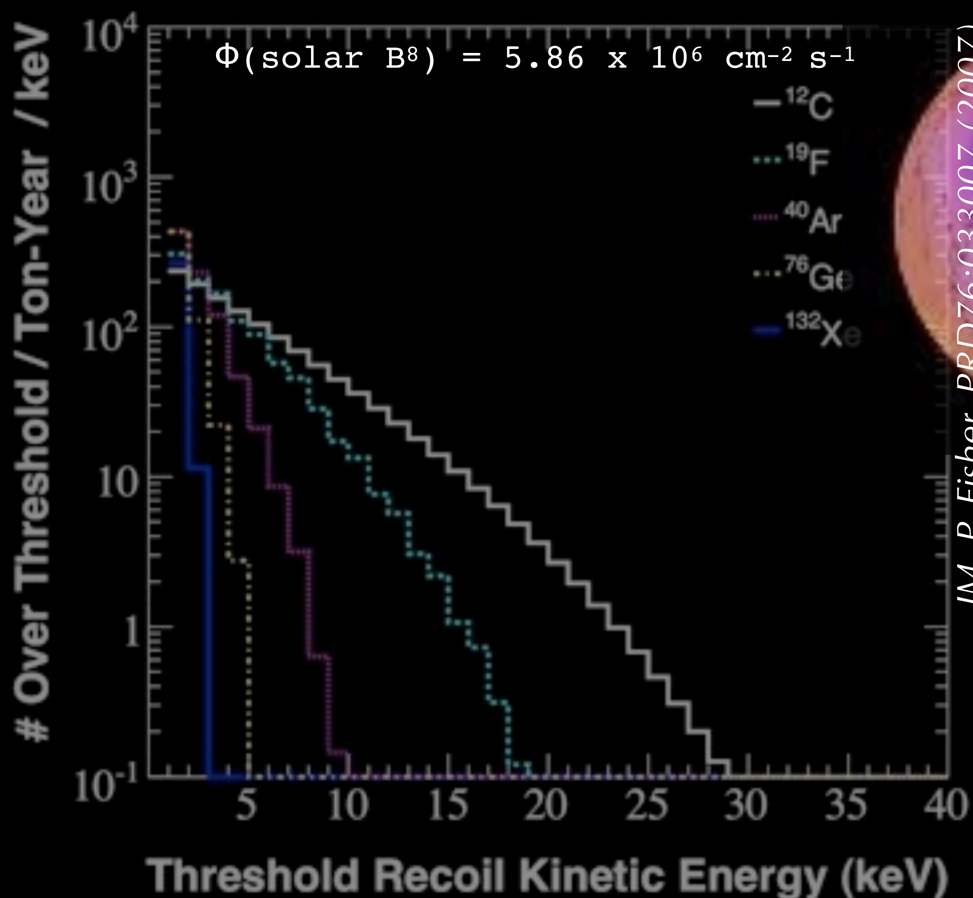

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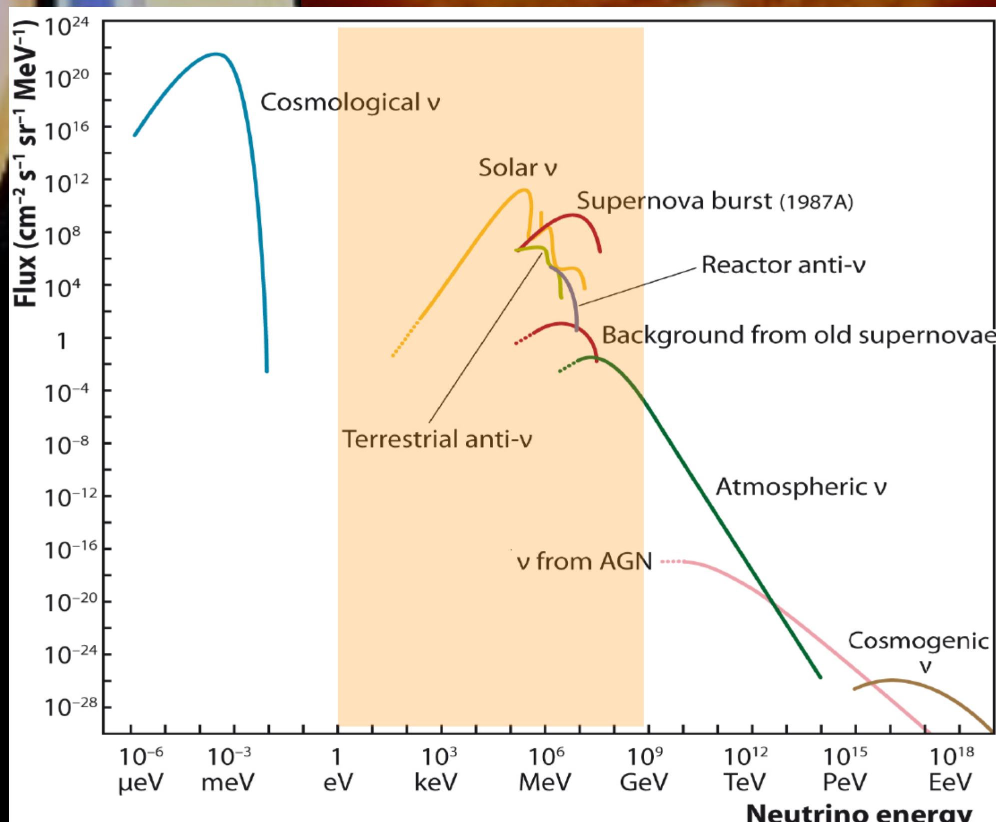
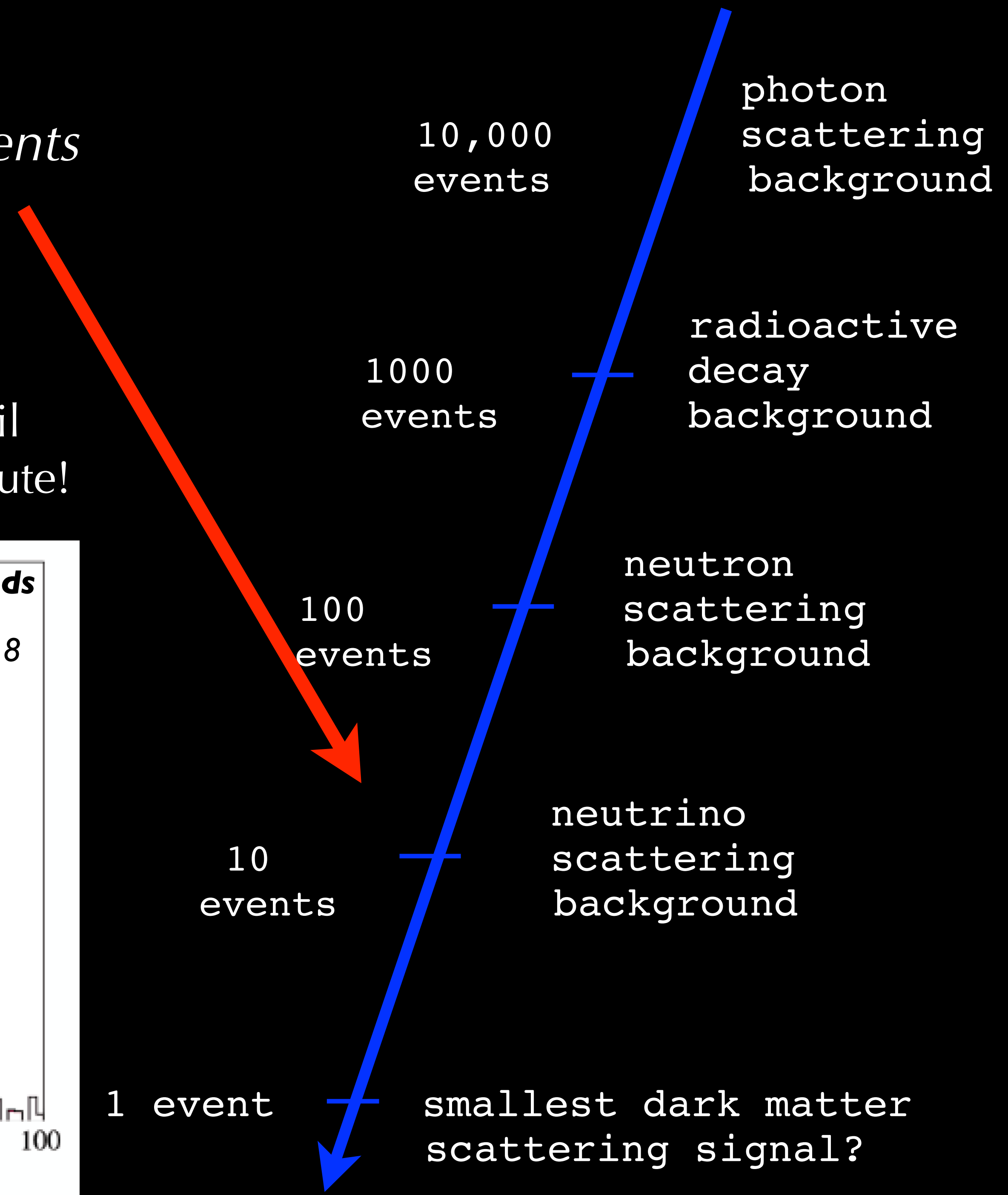
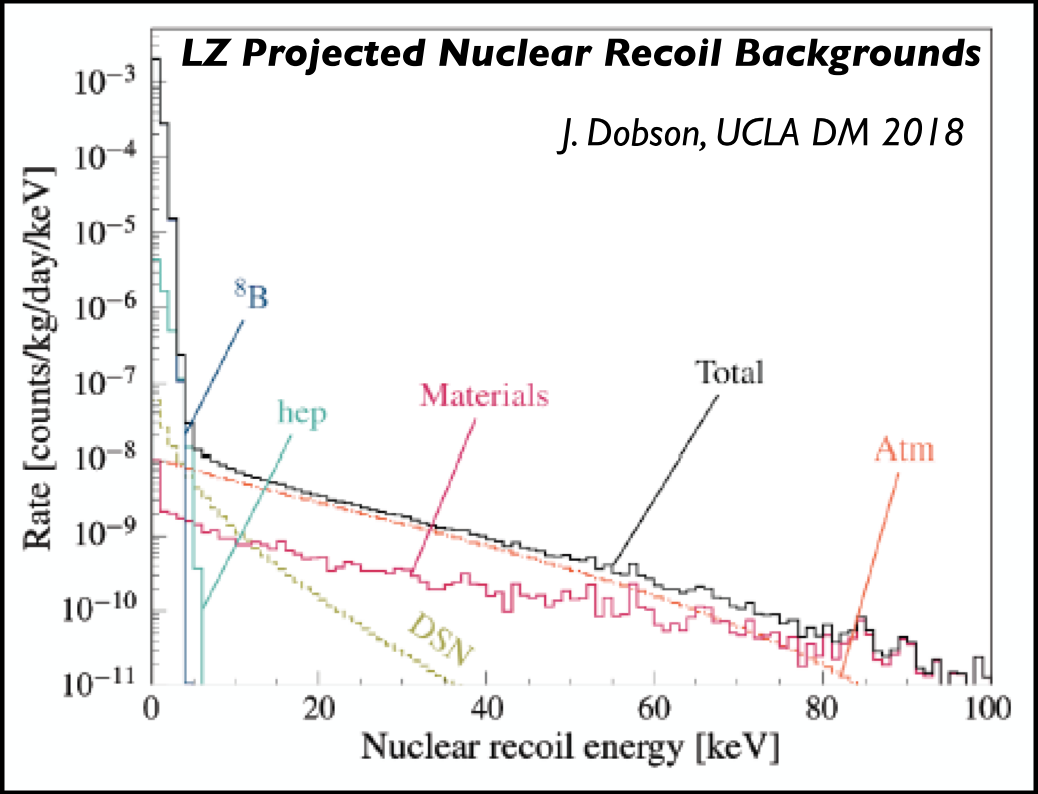


Background Sources

experiments are here



neutrino floor: depends on electron recoil discrimination, both ν-N and ν-e contribute!



Background Sources

experiments are here

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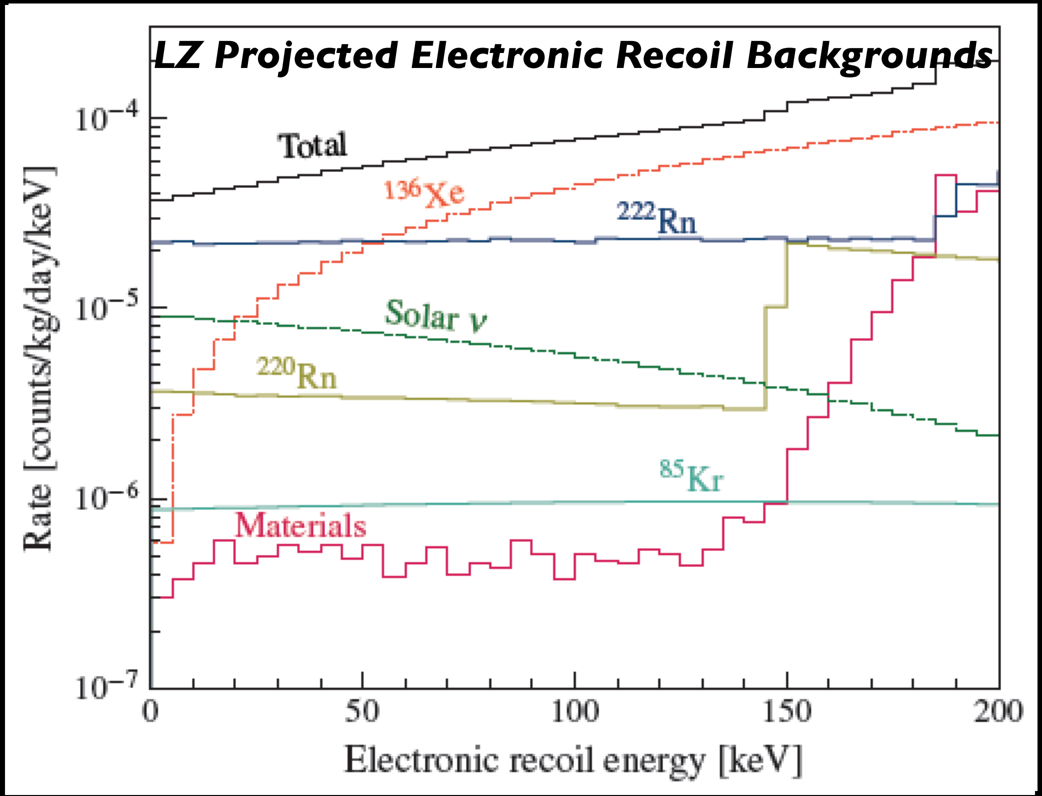
1000 events — radioactive decay background

100 events — neutron scattering background

10 events — neutrino scattering background

1 event — smallest dark matter scattering signal?

neutrino floor: depends on electron recoil discrimination, both ν-N and ν-e contribute!



Background Strategies

PICO

Sensei

Cogent

DAMIC

Xenon-nT

Newage

DRIFT

LZ

CDMS

DarkSide

EDELWEISS

Panda-X

CoGeNT

ANaIS

XMASS

DEAP3600

CRESST

COSINE

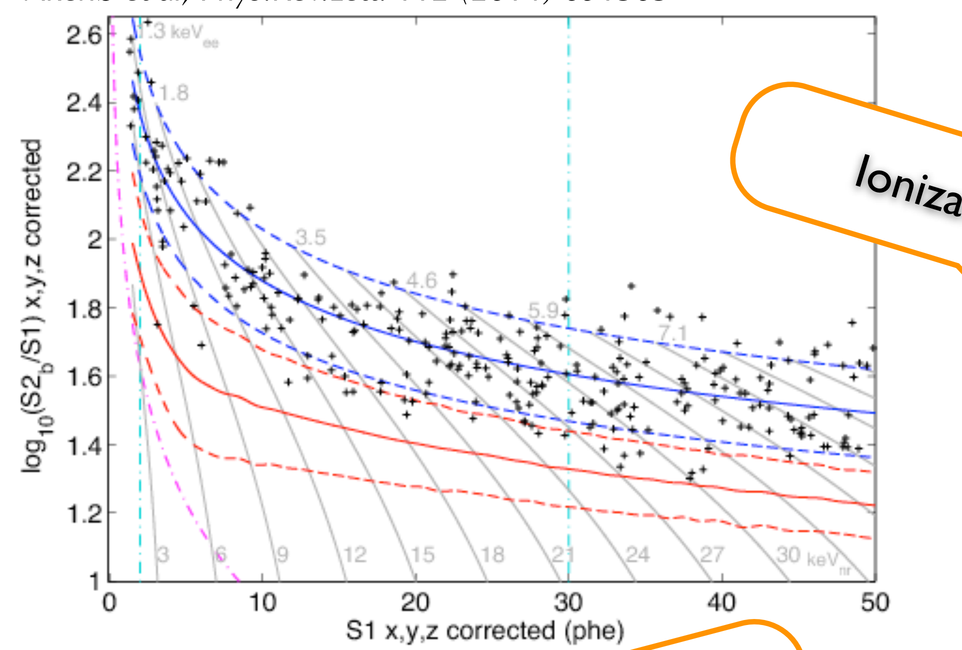
CRESSTII,III

Dama/LIBRA

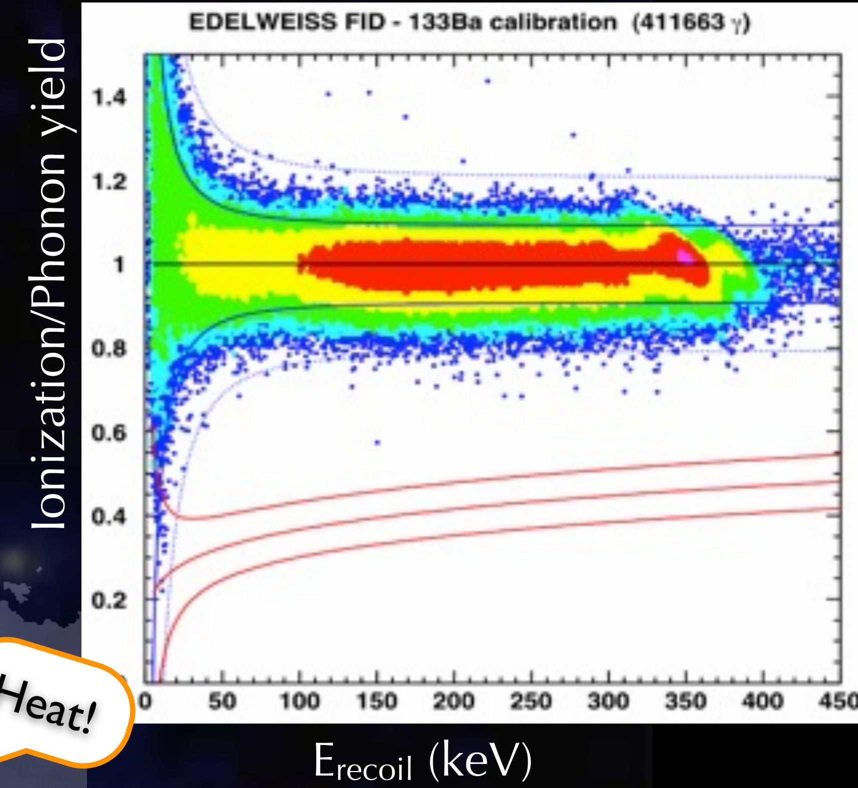
existing detectors: many targets (Xe, Ge, Ar, NaI, CsI, $CaWO_4$, CF_3I, C_3F_8, F ...)

Background Strategies

Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



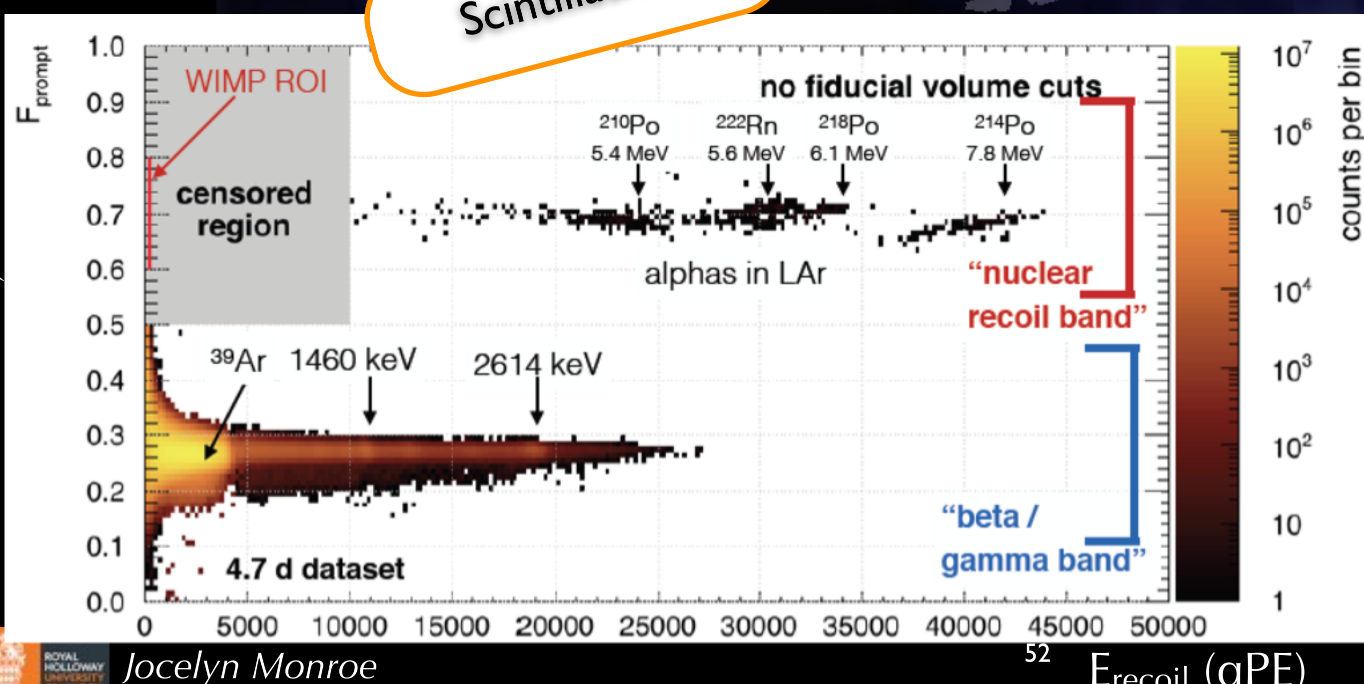
Ionization!

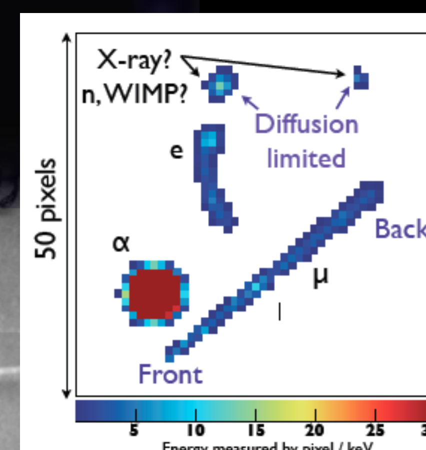


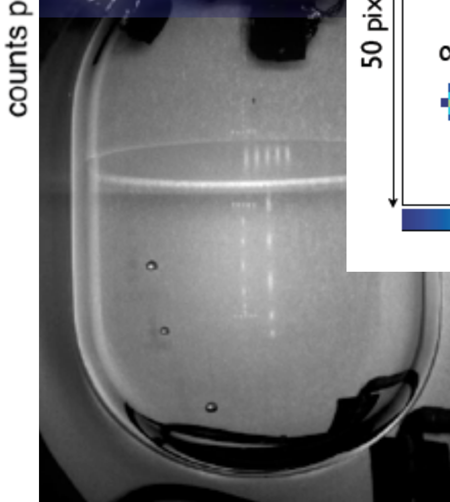
Heat!

Scintillation!

Amandruz et al., arXiv:1707.08042



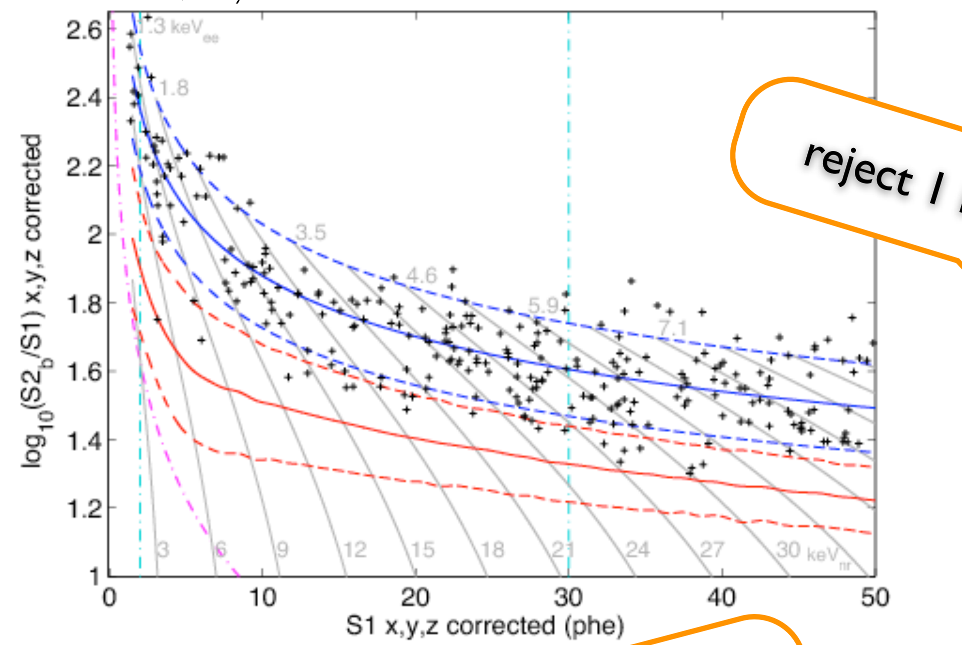




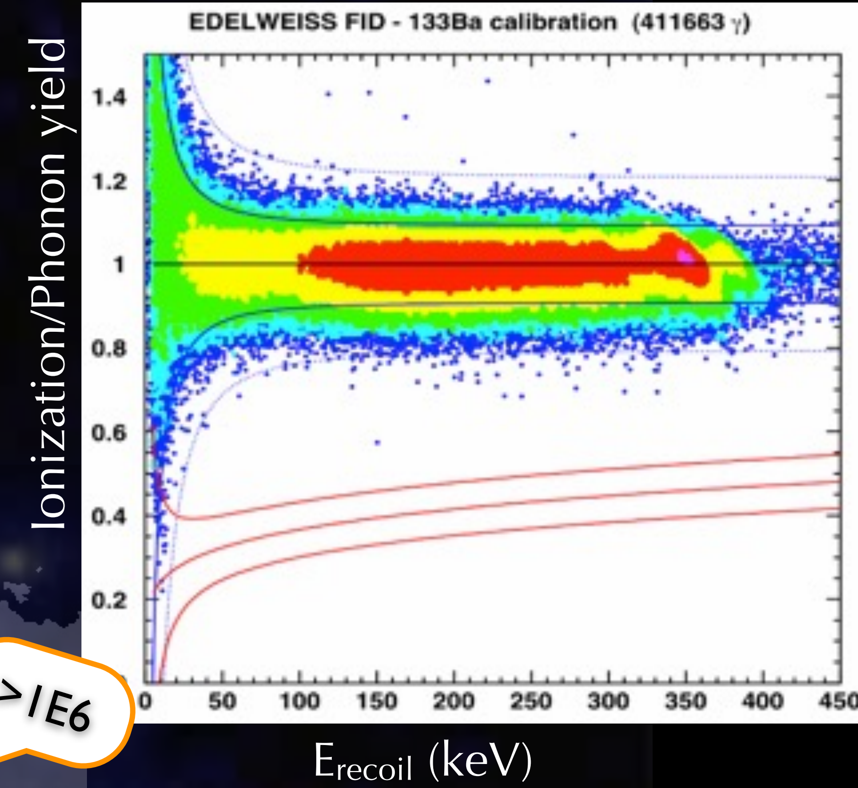
Topology

Background Strategies

Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



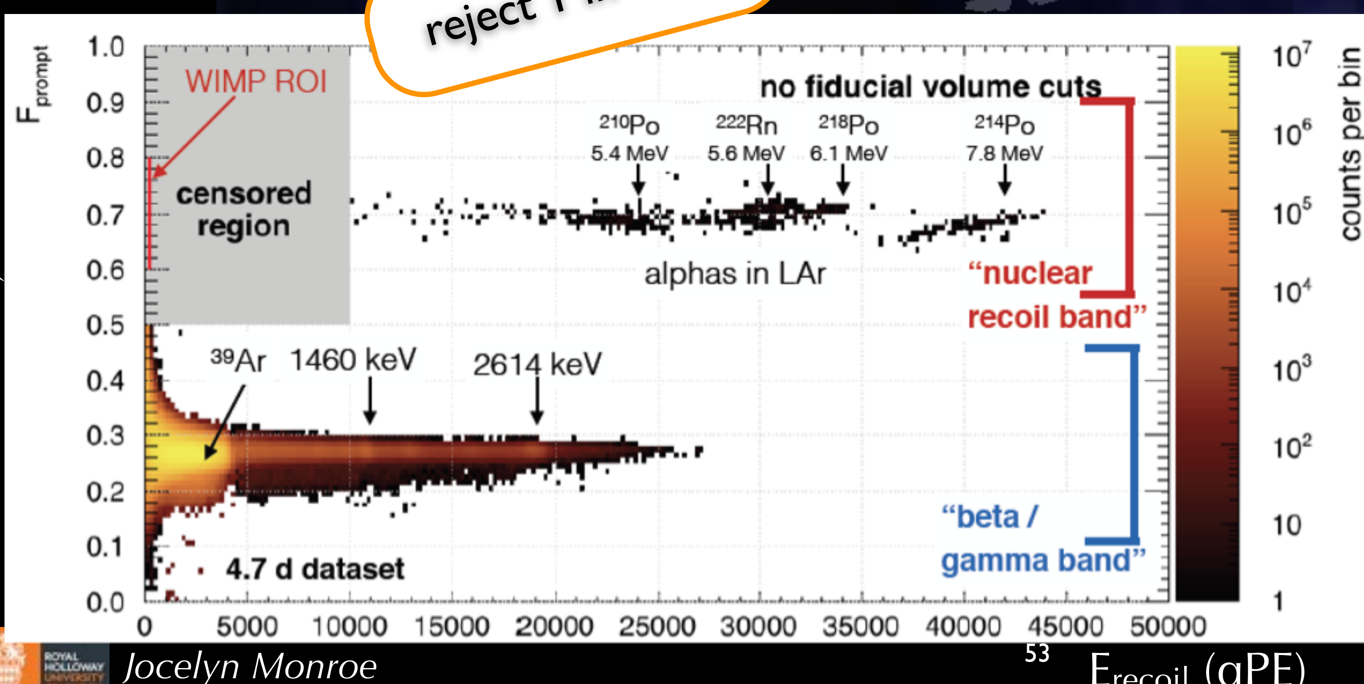
reject 1 in >1E3

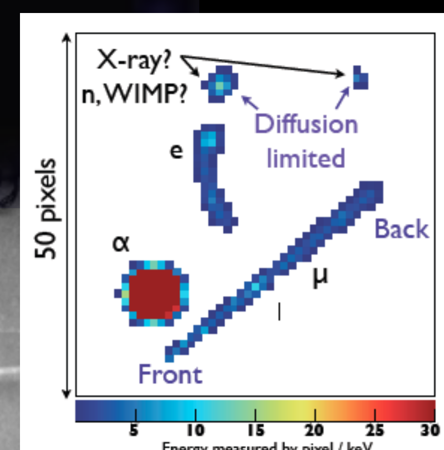


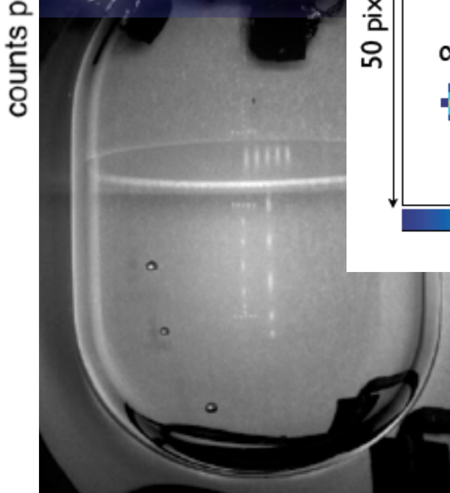
>1E6

reject 1 in >1E9

Amandruz et al., arXiv:1707.08042





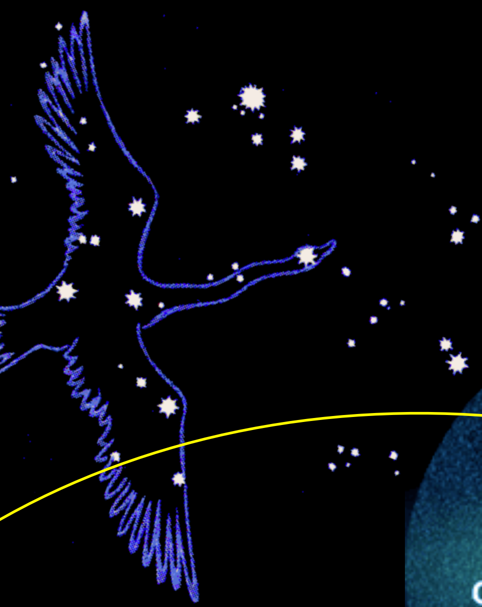


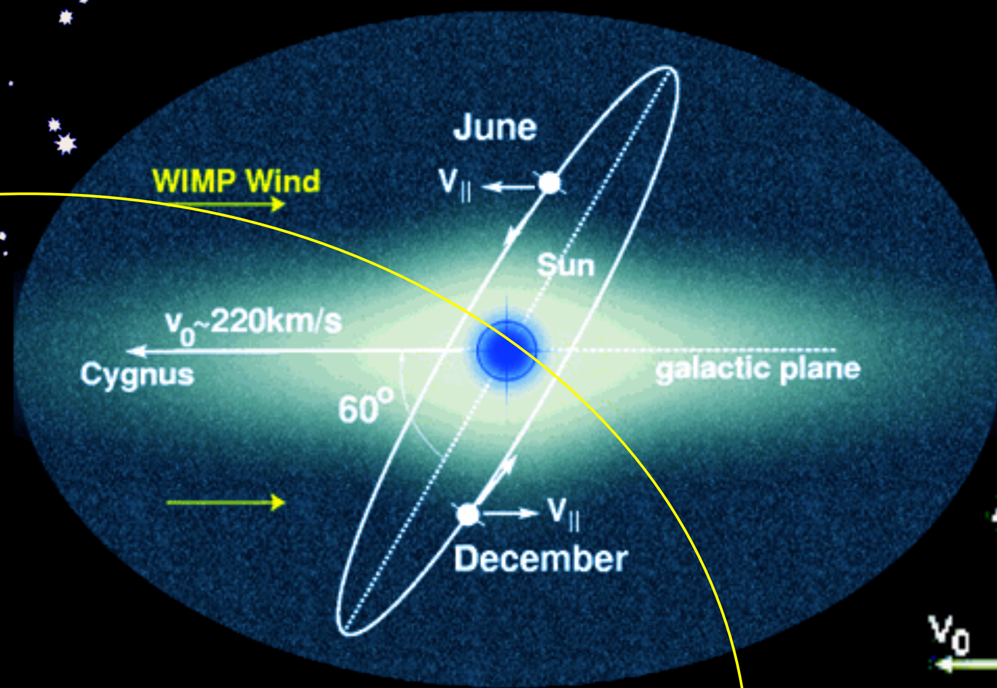
>1E2

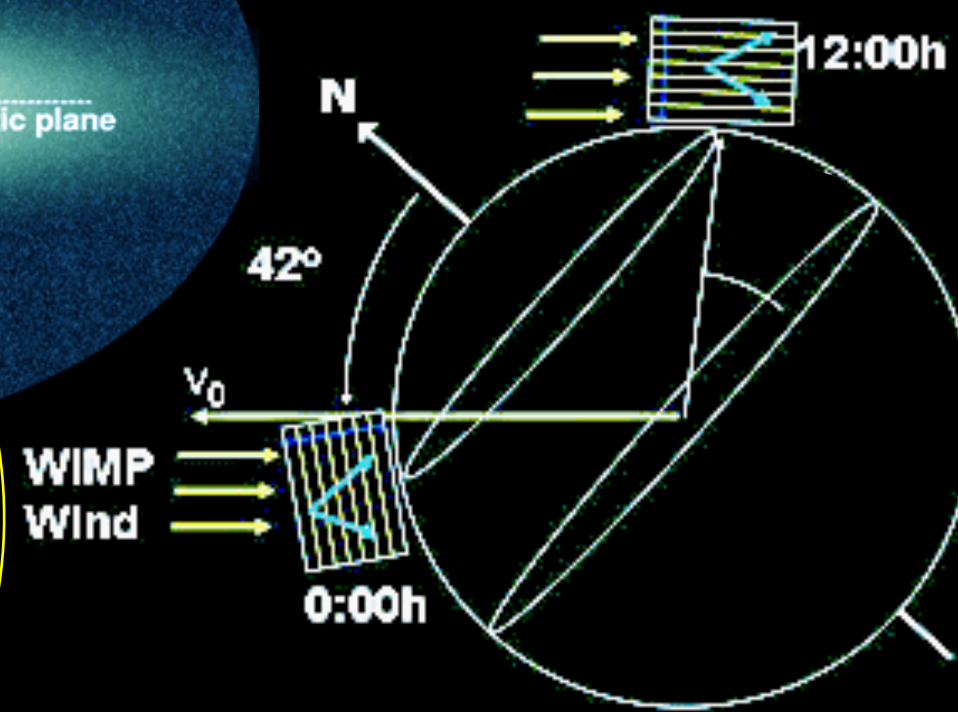
Modulation Signatures

Annual event rate modulation: June-December asymmetry ~2-10%.

Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)





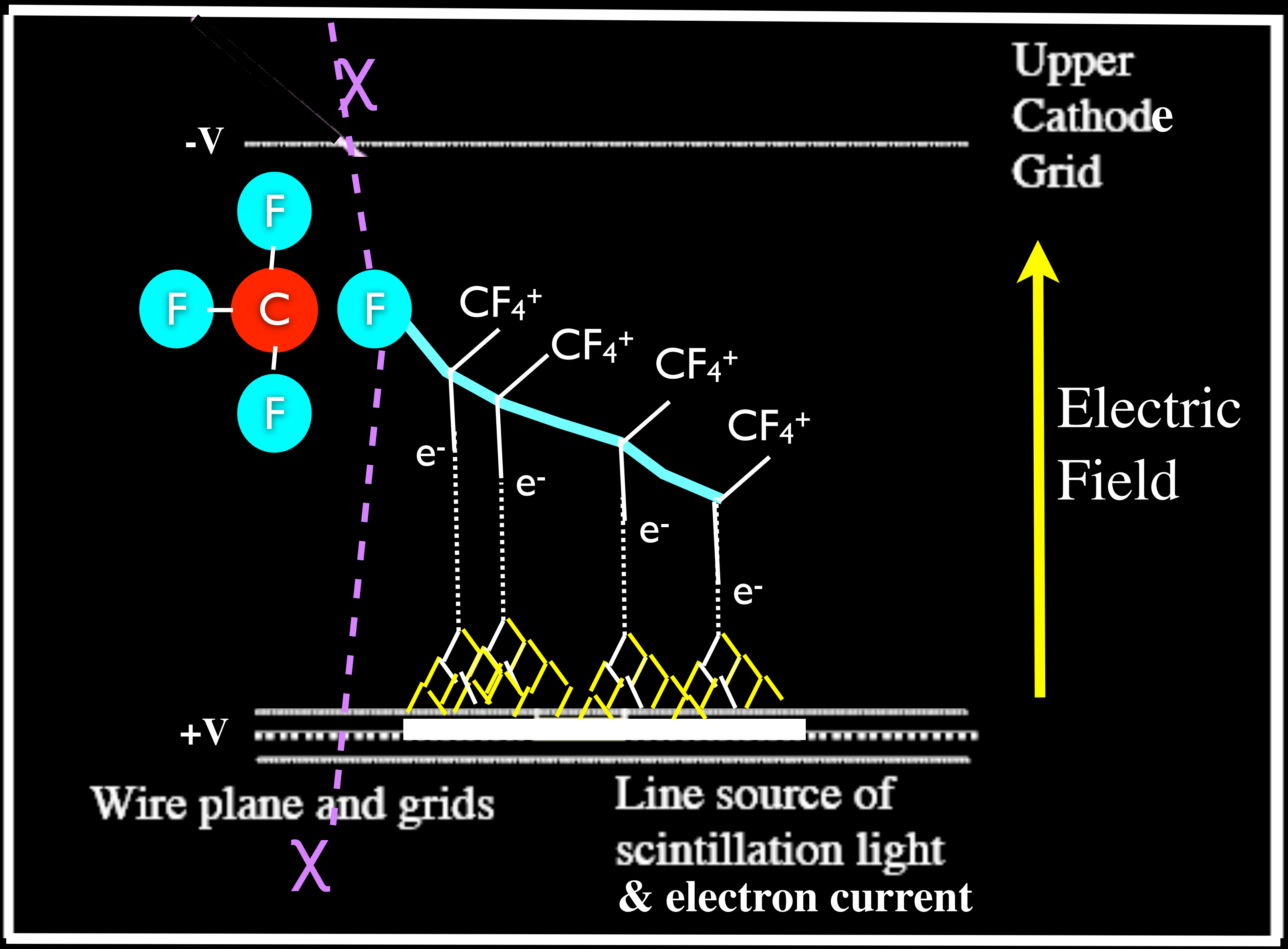


Sidereal direction modulation: asymmetry ~ 20-100% in forward-backward event rate.

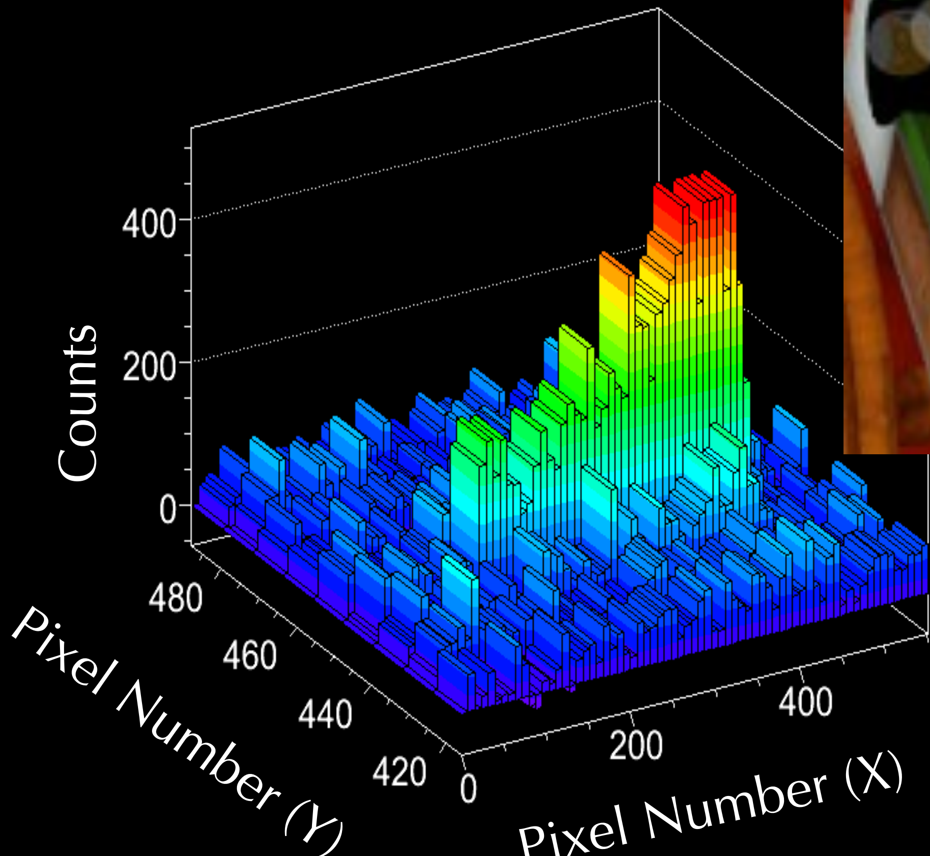
Spergel, Phys. Rev. D36:1353 (1988)

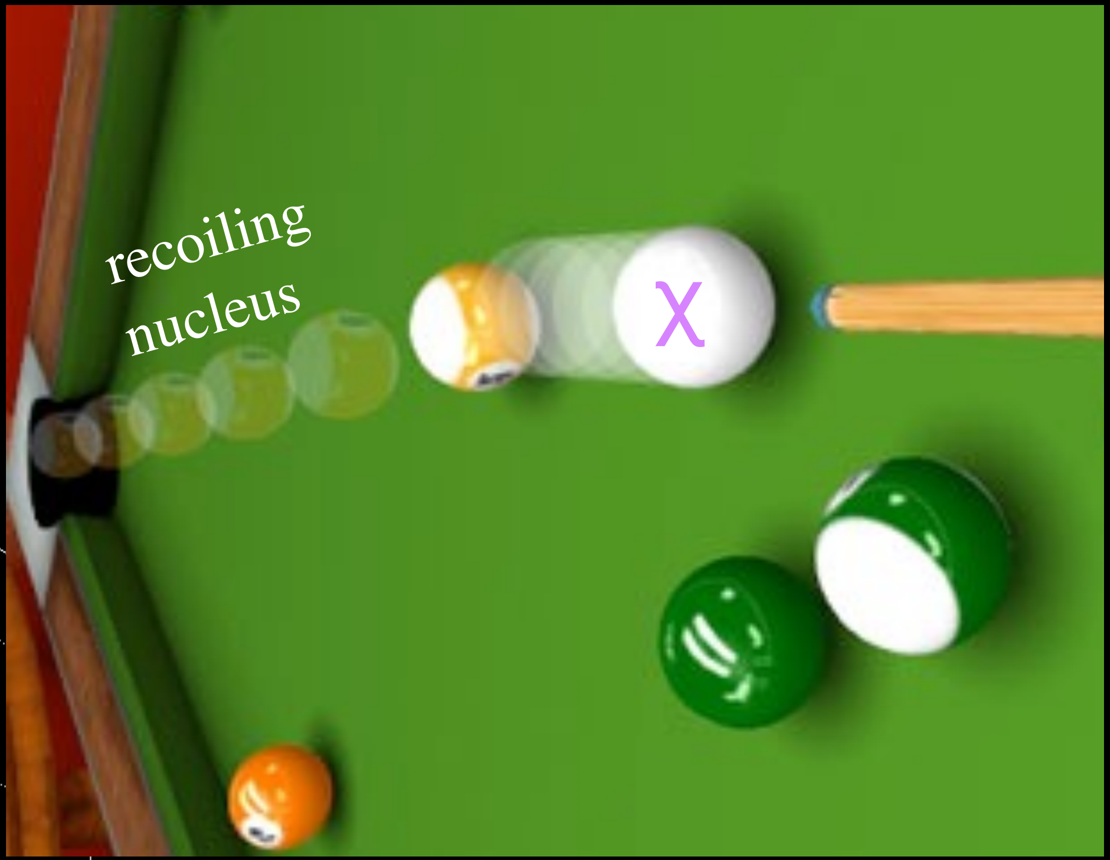
detector requirements: achieve + measure stability vs. time to a very high level!

Time Projection Chamber



Time Projection Chamber



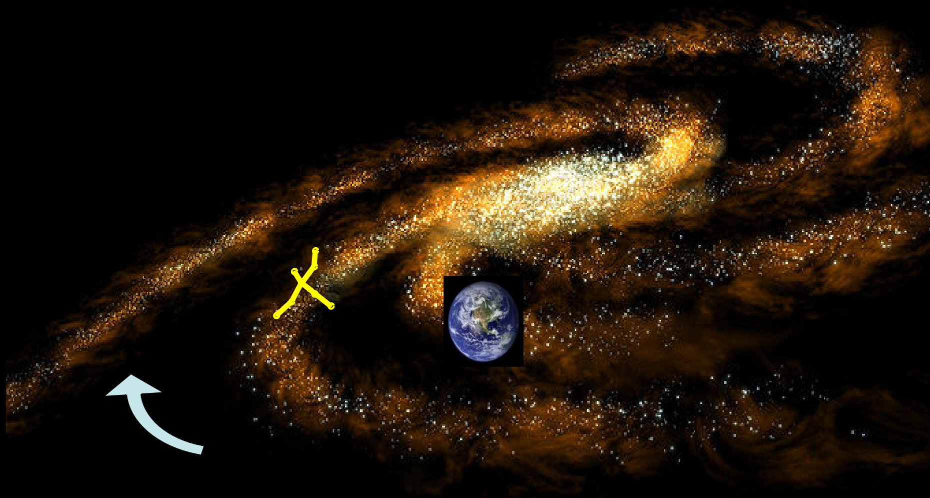


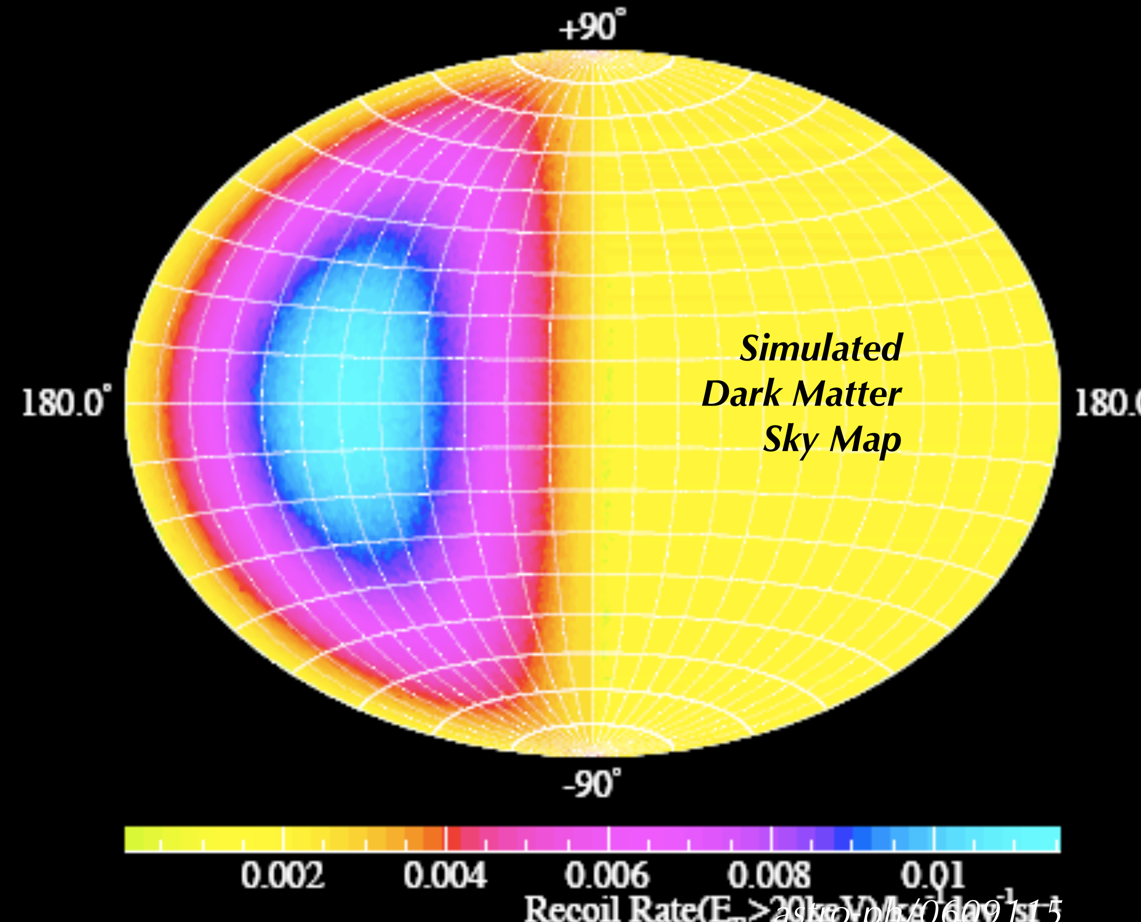
CCD data from DMTPC

Directional Detection

The Dark Matter Wind "blows" from Cygnus

search for a dark matter source





simulated reconstructed dark matter sky map: search for anisotropy

Unambiguous proof:
Correlation of WIMP-induced nuclear recoil signal with galactic motion