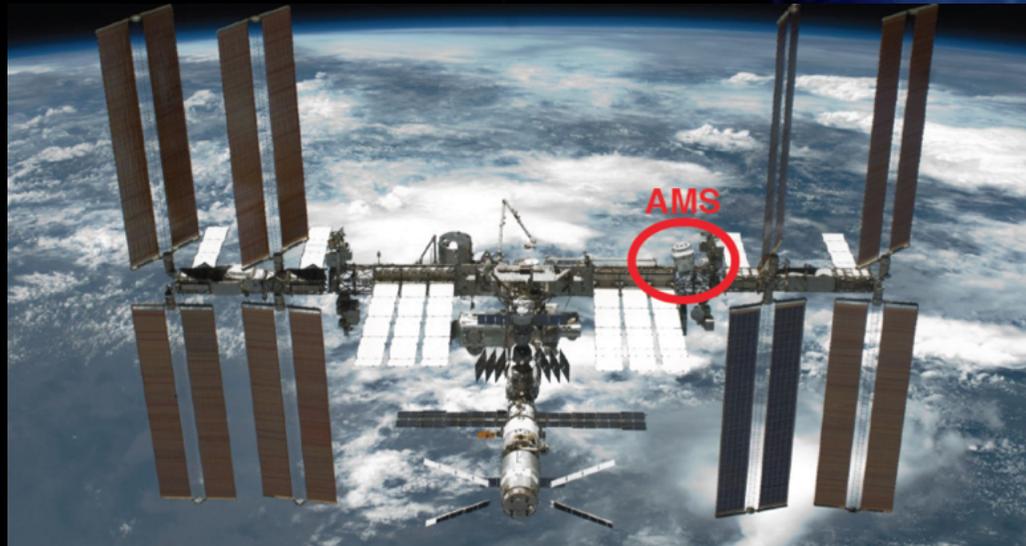
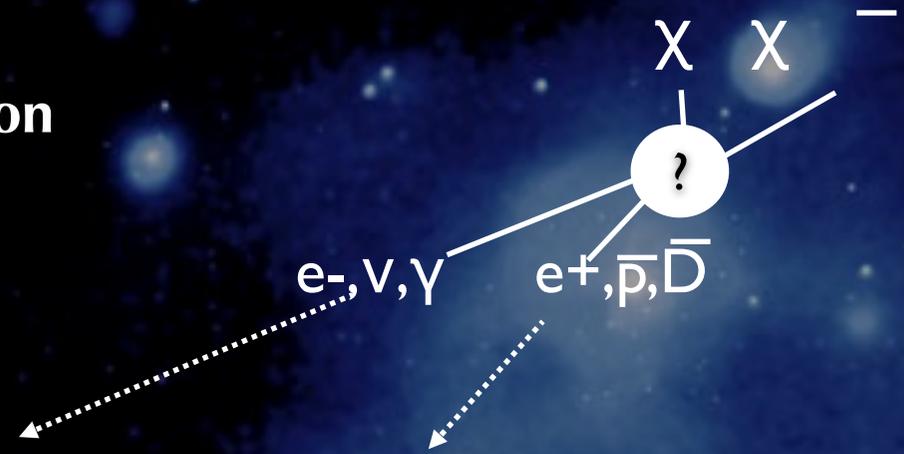


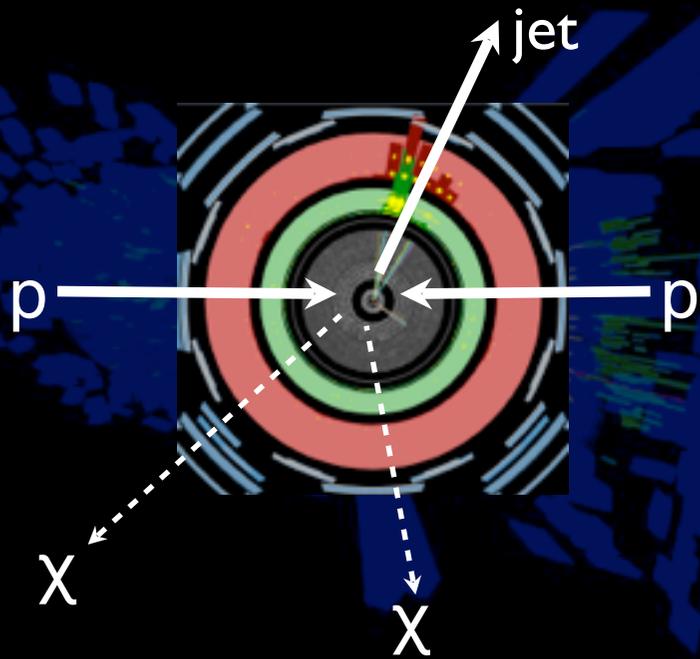
# Outline

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

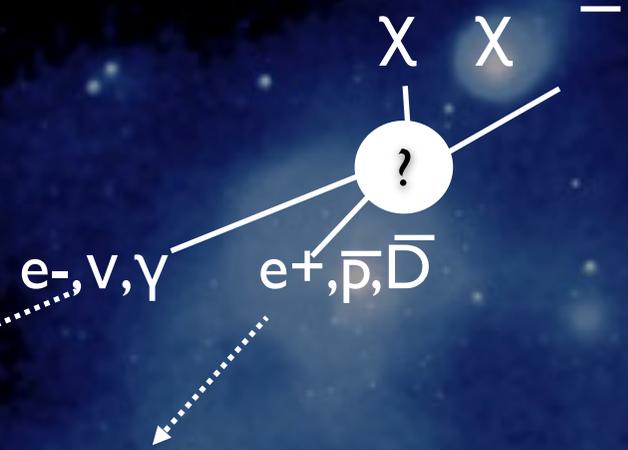
# Indirect Detection



# Collider Production

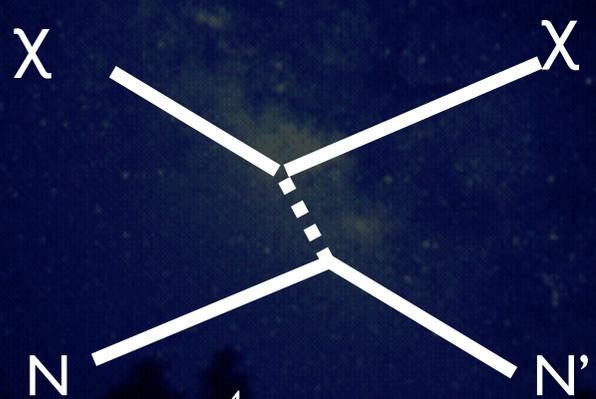
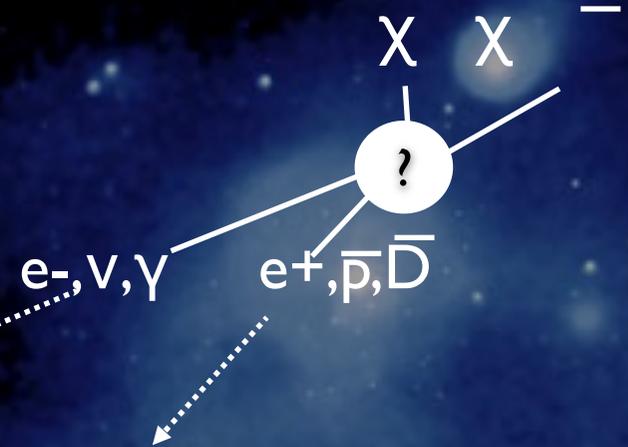
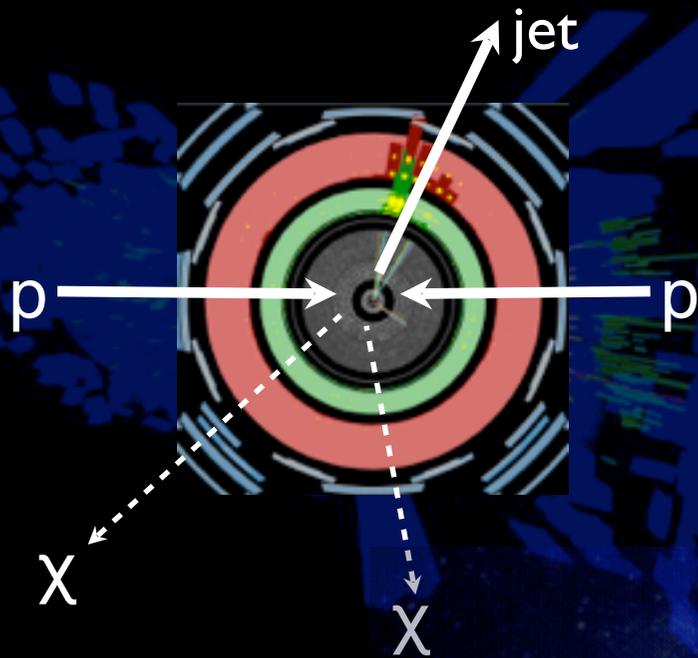


# Indirect Detection



# Indirect Detection

## Collider Production

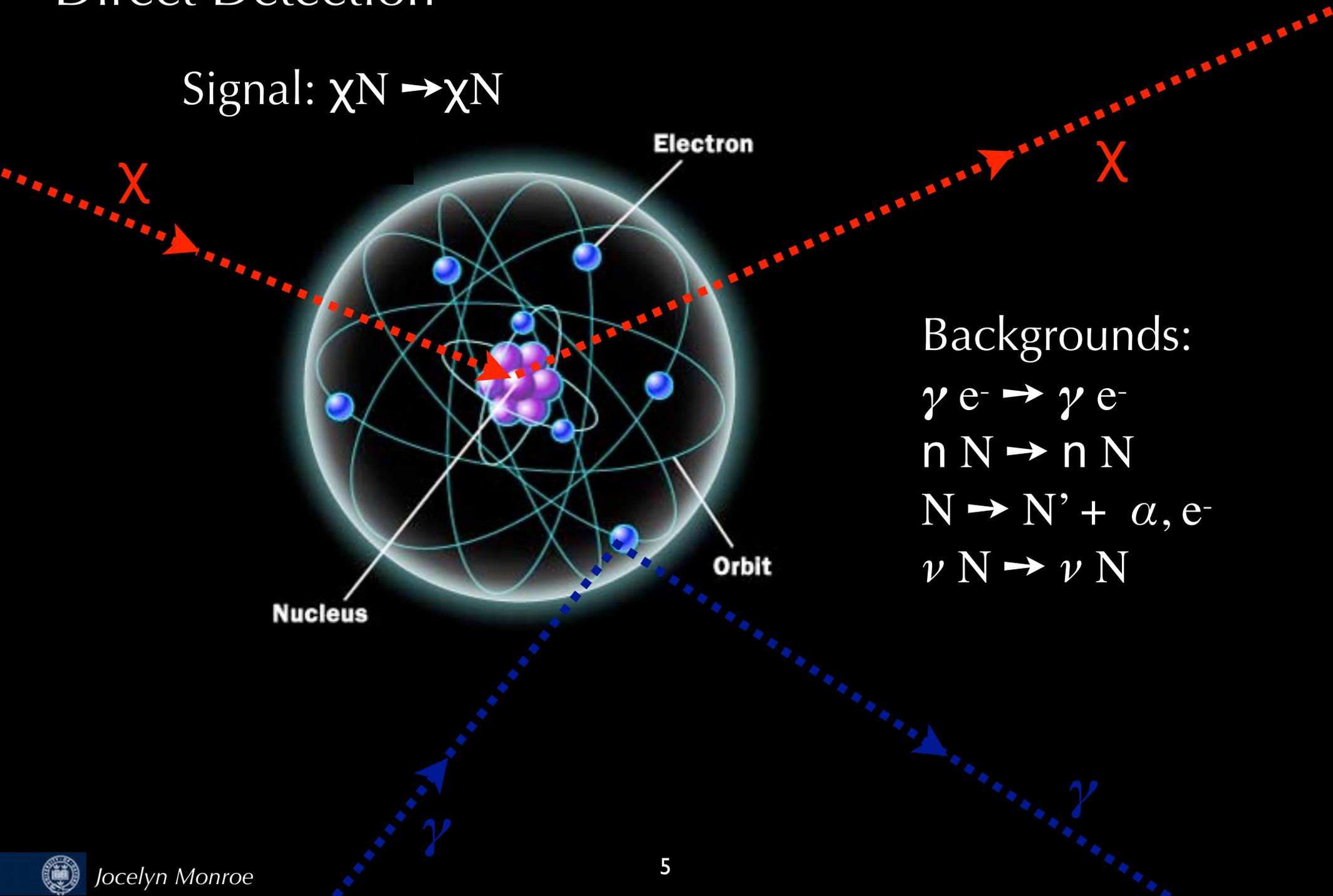


## Direct Detection



# 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

$$\text{Number of Events} = (\text{Flux}) \times (\text{Cross Section}) \times (\text{Exposure})$$

*(how much dark matter)*



*(how likely it is to interact)*



*(how long you look)*



# Flux Estimate

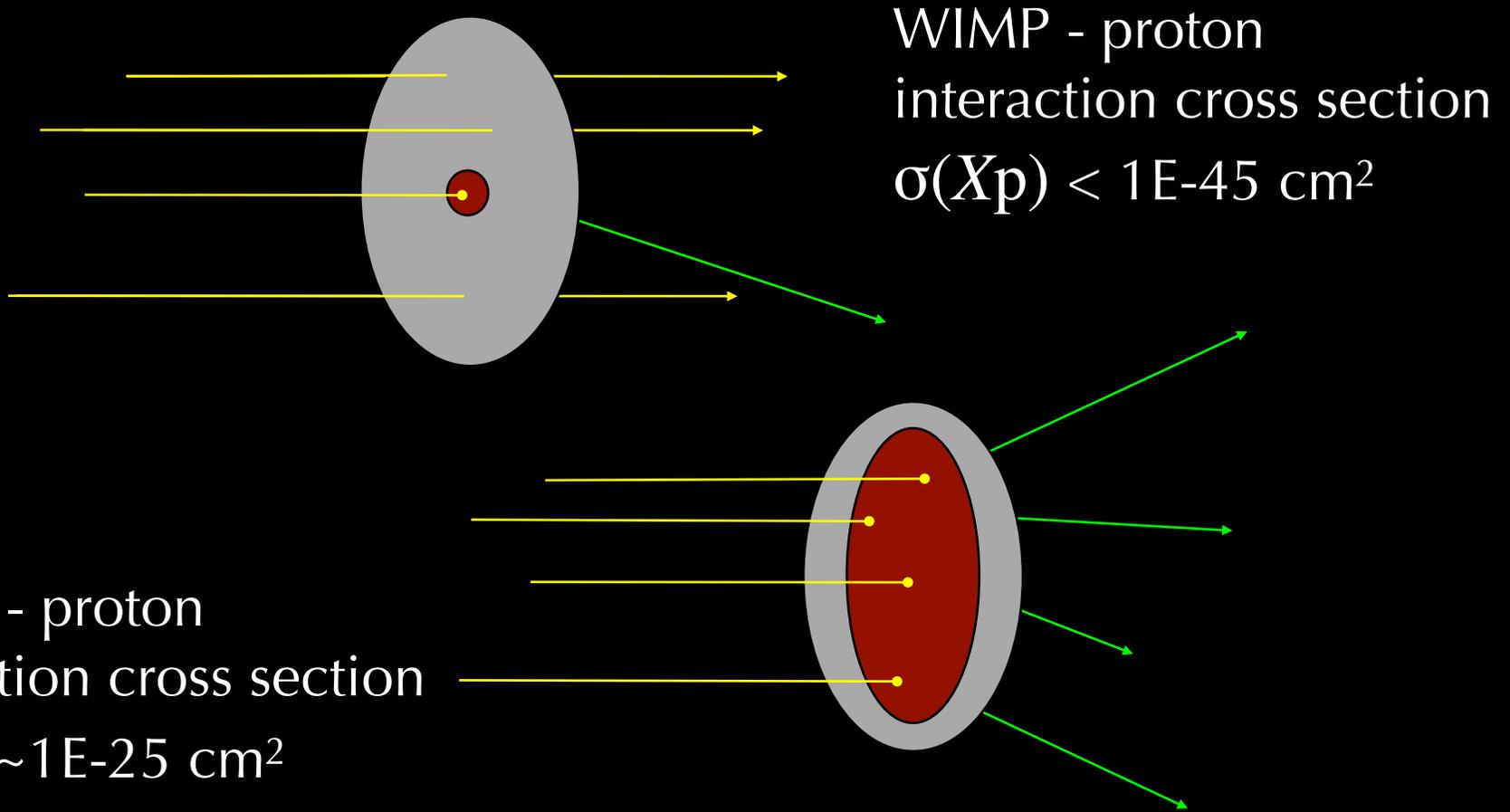
$$\Phi = \rho v = (0.3 \text{ GeV cm}^{-3} / M [\text{GeV}]) v \sim 0.3 \frac{v}{M} \text{ cm}^{-2} \text{ s}^{-1}$$

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

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

# Cross Section

*probability of interaction per unit target area*



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

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



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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,  $\sigma \sim G_F^2 \mu^2$ .

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

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

, and so

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

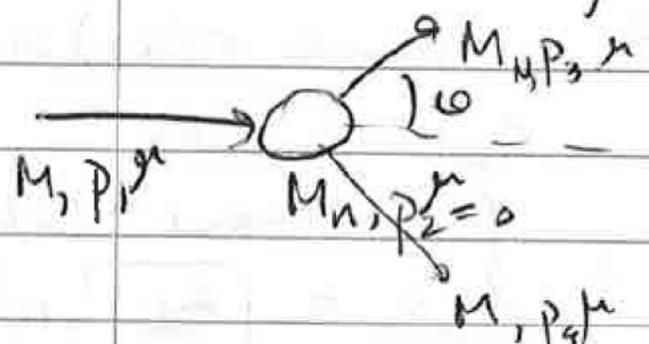


### III. Dark Matter Direct Detection

detect recoiling nucleus after  $\chi$  scatters in detector. Find  $E_p$ :  
elastic scattering:  $\chi N \rightarrow \chi N'$        $N = \text{nucleus}$ .

### III. Dark Matter Direct Detection

detect recoiling nucleus after  $\chi$  scatters in detector. Find  $E_R$ :  
 elastic scattering:  $\chi N \rightarrow \chi N'$   $N = \text{nucleus}$ .



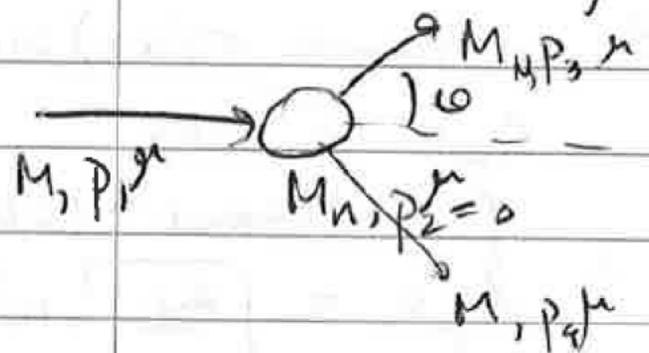
$$E_1 = M + E_0, \quad E_2 = M_N$$

↑  
 kinetic energy of

$$\begin{aligned}
 (i) \quad S &= (p_1^\mu + p_2^\mu)^2 && \text{(LAB) initial state} \\
 &= p_1^\mu{}^2 + p_2^\mu{}^2 + 2p_1^\mu p_2^\mu \\
 &= M^2 + M_N^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2) \\
 &= M^2 + M_N^2 + 2E_0 M_N + 2MM_N \\
 &= (M + M_N)^2 + 2E_0 M_N \\
 &= E_{CM}^2
 \end{aligned}$$

### III. Dark Matter Direct Detection

detected recoiling nucleus after  $\chi$  scatters in detector. Find  $E_R$ :  
 elastic scattering:  $\chi N \rightarrow \chi N'$   $N = \text{nucleus}$ .



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

kinetic energy of DM

$$= \frac{1}{2} M v^2$$

(ii) evaluate final state in CMS:

$$\vec{p}_3 = -\vec{p}_4$$

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

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

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

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

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

$$= E_{CM}^2$$

$$E_{CM} = E_3 + E_4$$

$$E_{CM} = \left( M_N + \frac{p_4^{\mu 2}}{2M_N} \right) +$$

$$\left( M + \frac{p_3^{\mu 2}}{2M} \right)$$

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

$$\text{so, } E_{CM}^2 = (M + M_N)^2 + 2E_0 M_N \\ = (M + M_N)^2 \left[ 1 + \frac{2E_0 M_N}{(M + M_N)^2} \right]$$

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

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

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

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



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

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

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

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

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

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

with  $v = 220 \text{ km/s} \approx 10^{-3} c$ ,  $M_N = A \cdot \text{GeV}$  ( $A = \text{atomic}$

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

mass  
number of  
nucleus)

Scattering rate

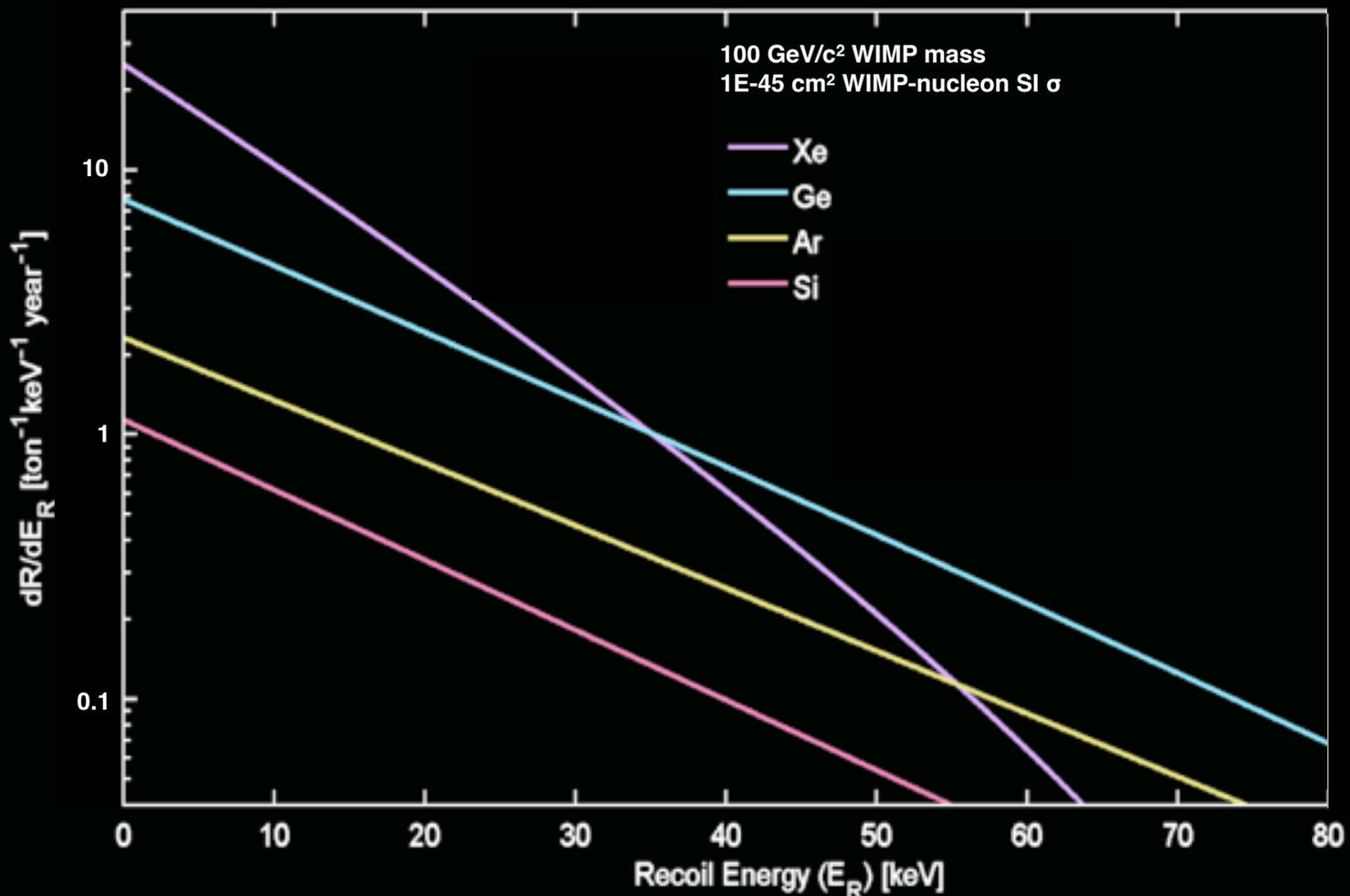
Sun's velocity around the galaxy

WIMP velocity distribution

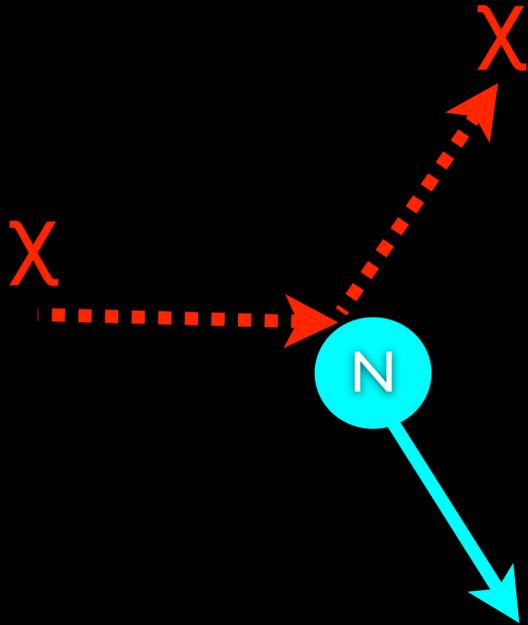
$$dR/dQ = (\sigma_0 \rho_0 / \sqrt{\pi} v_0 m_\chi m_T^2) F^2(Q) T(Q)$$

WIMP energy density, 0.3 GeV/cm<sup>3</sup>

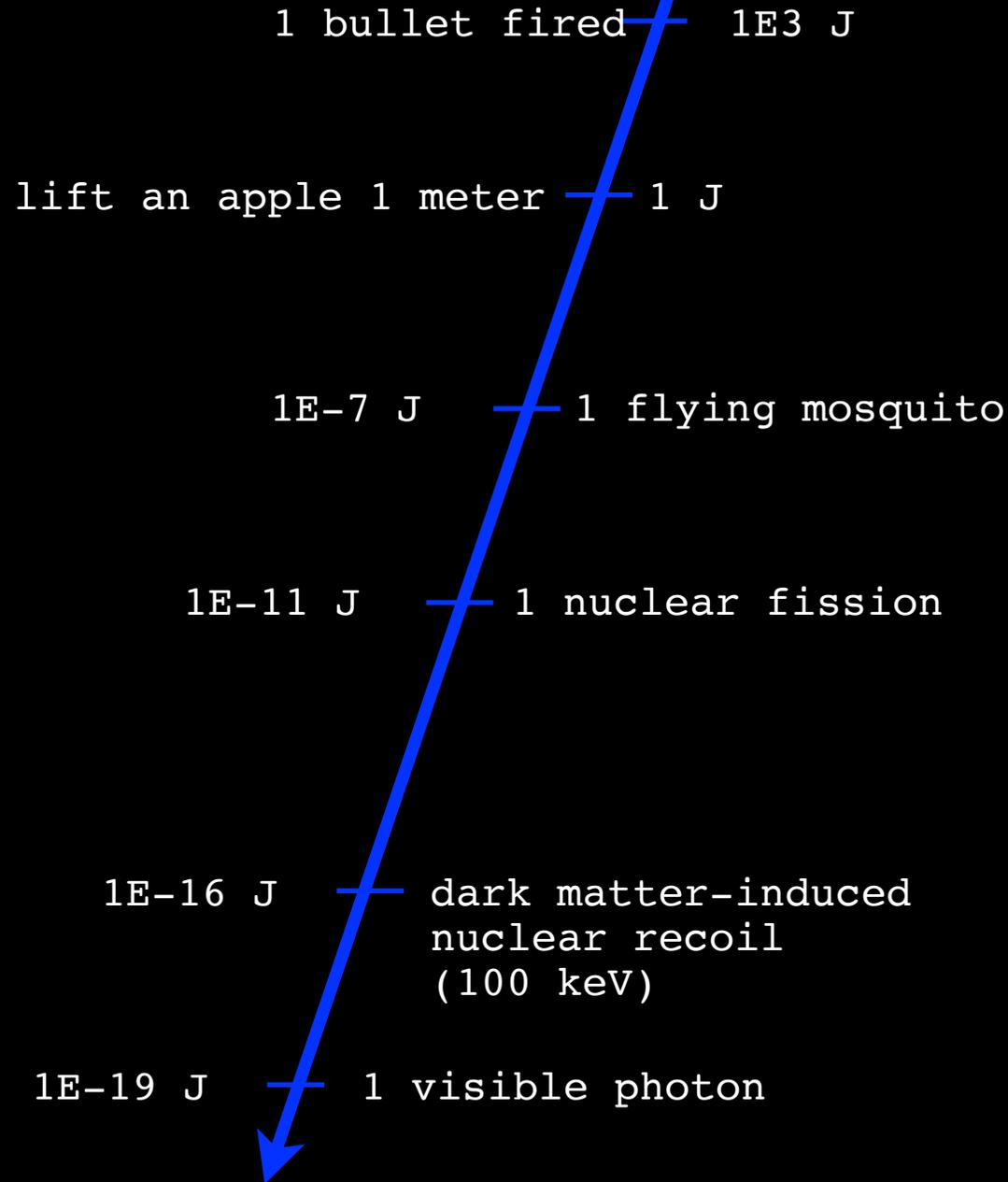
Form factor



# Observable: Small Energies



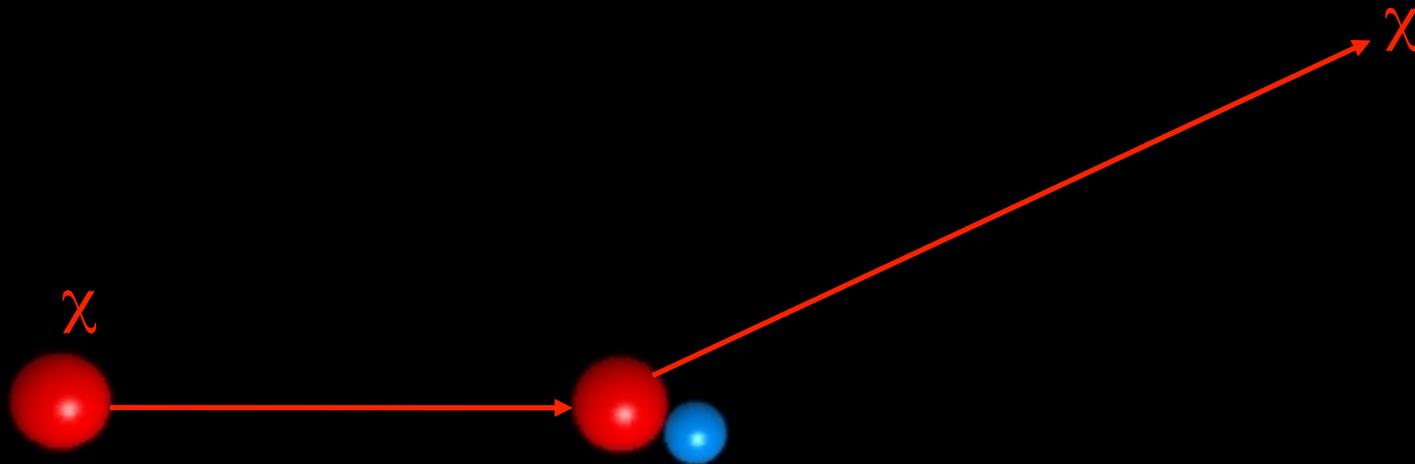
*Recoil Nucleus Kinetic Energy*



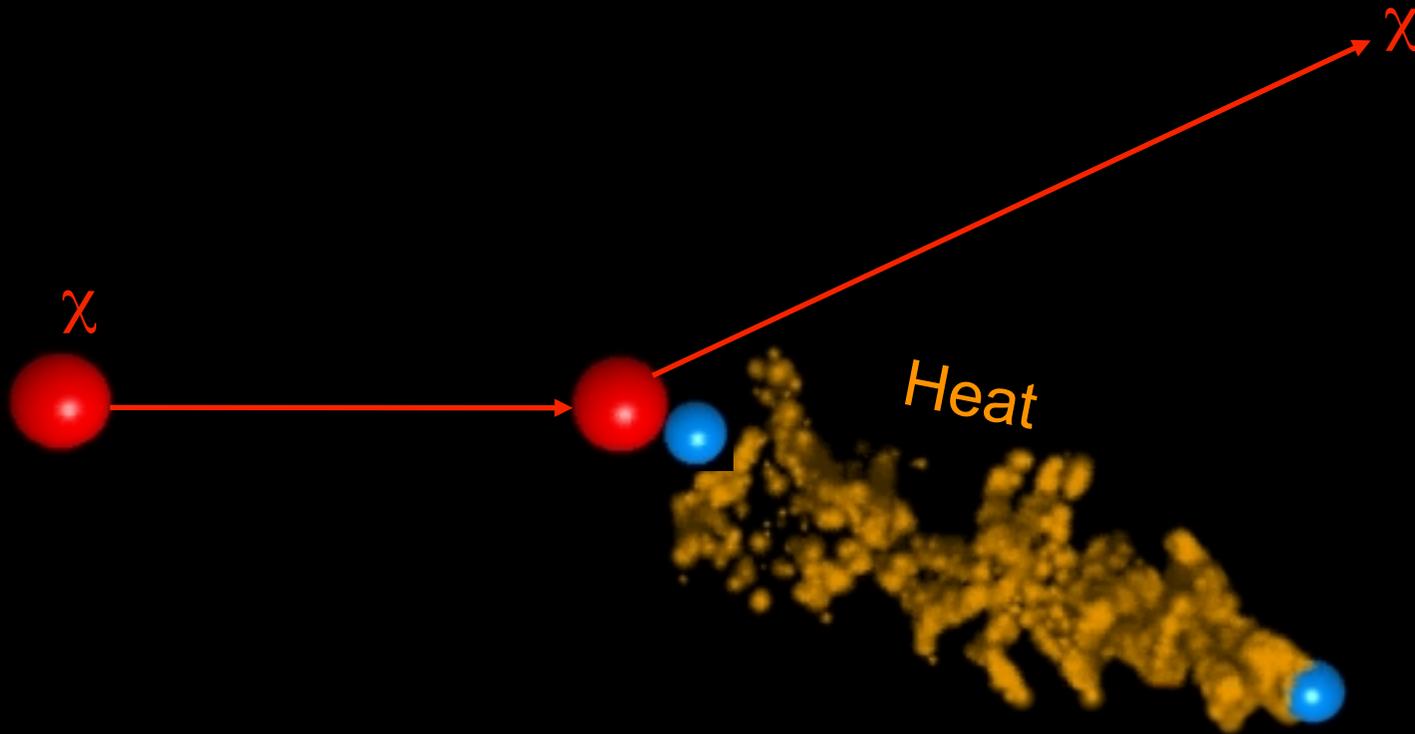
# Measurement



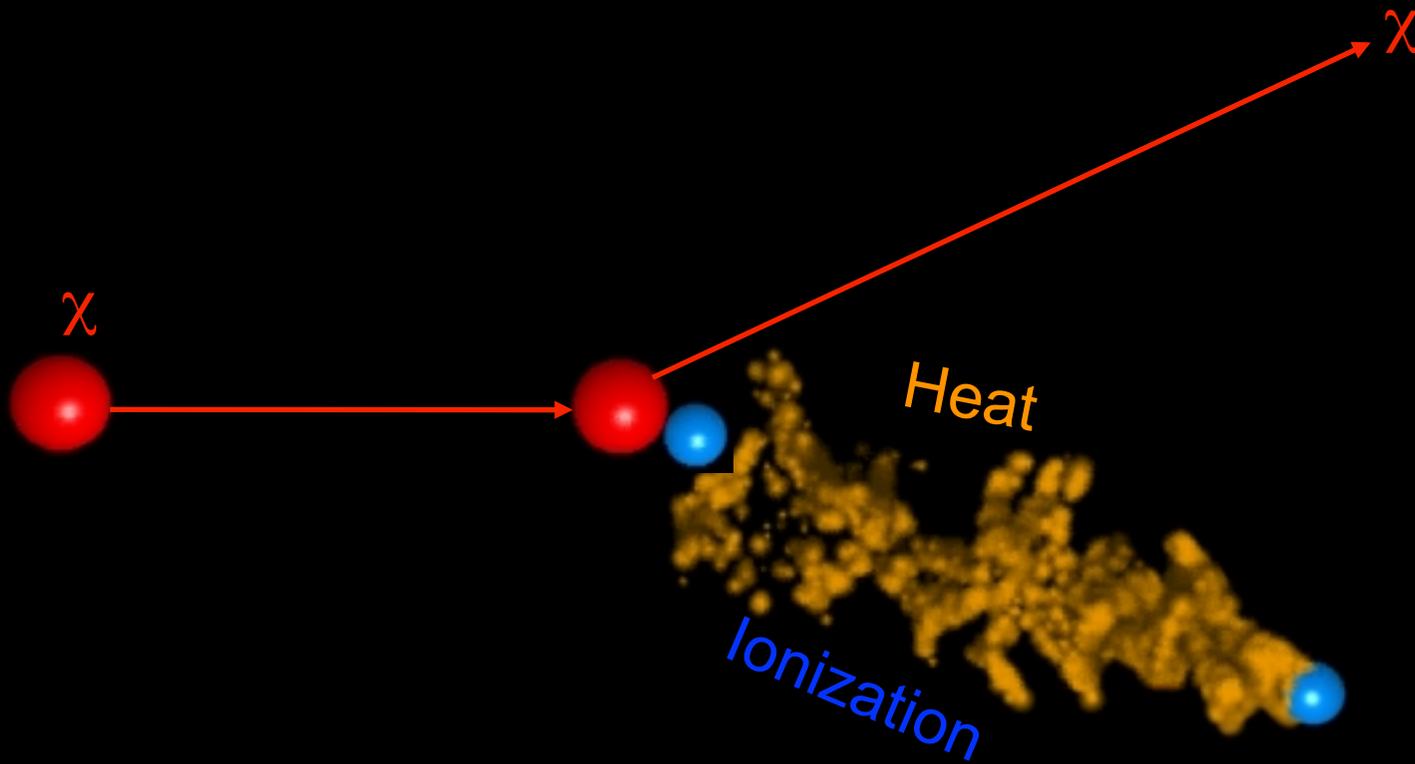
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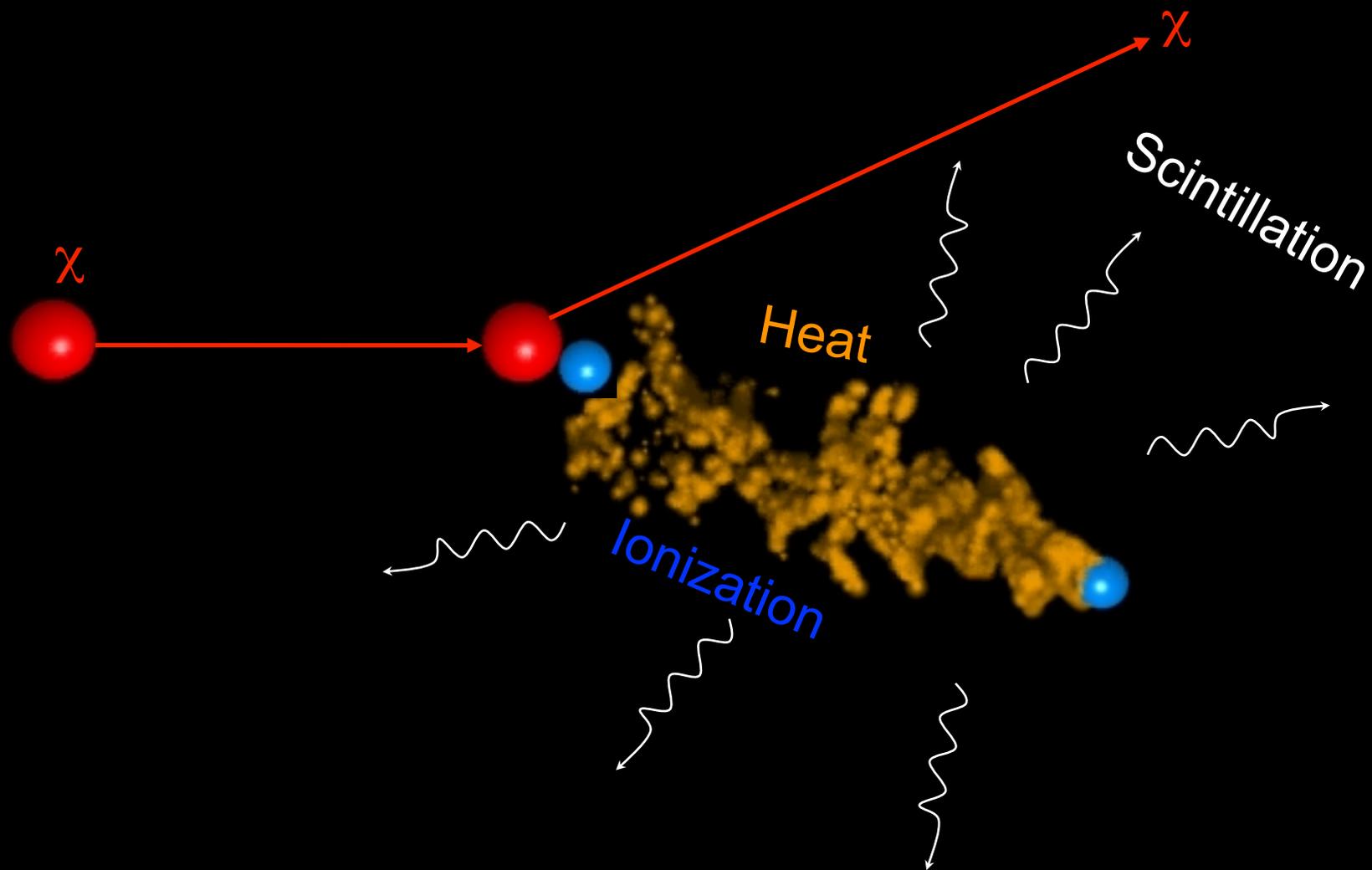
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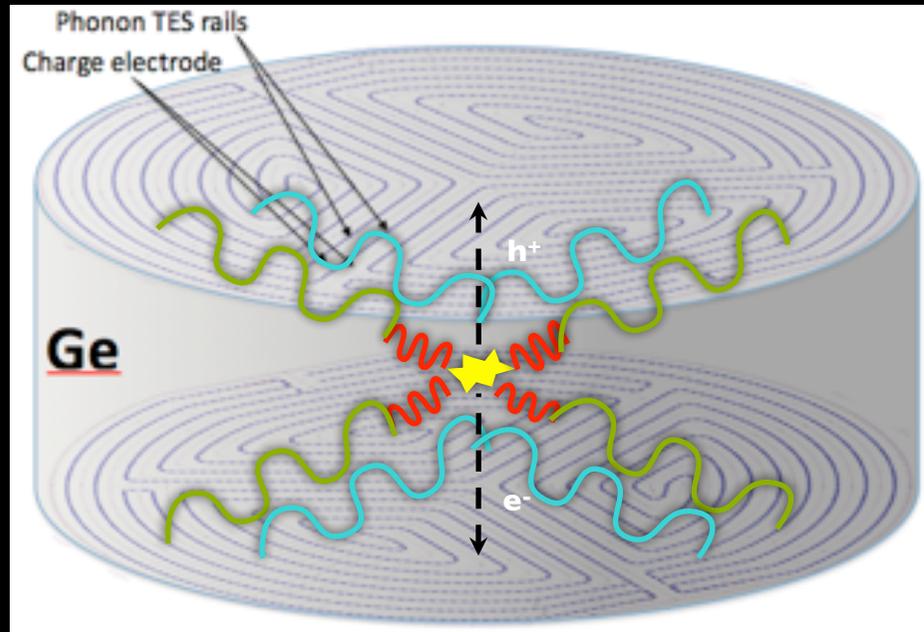


# Detector Technologies for Small Energies

# Cryogenic Bolometers

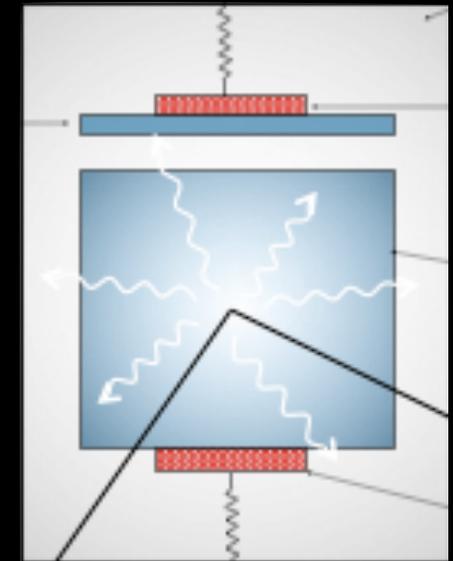
phonon, ionisation or scintillation readout of crystals at O(10 mK), using Ge, Si, CaWO<sub>4</sub>

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



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

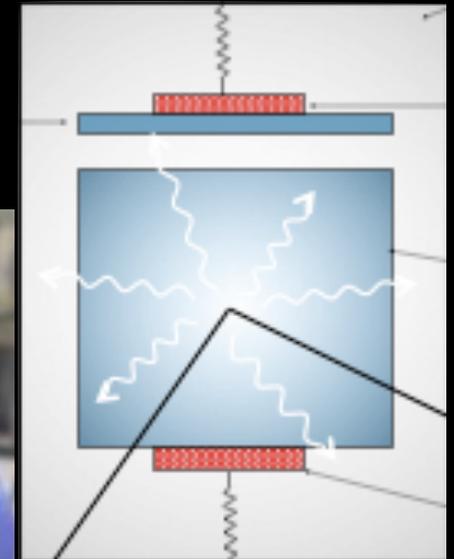
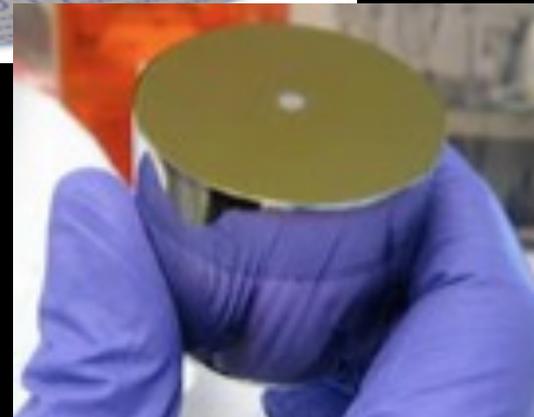
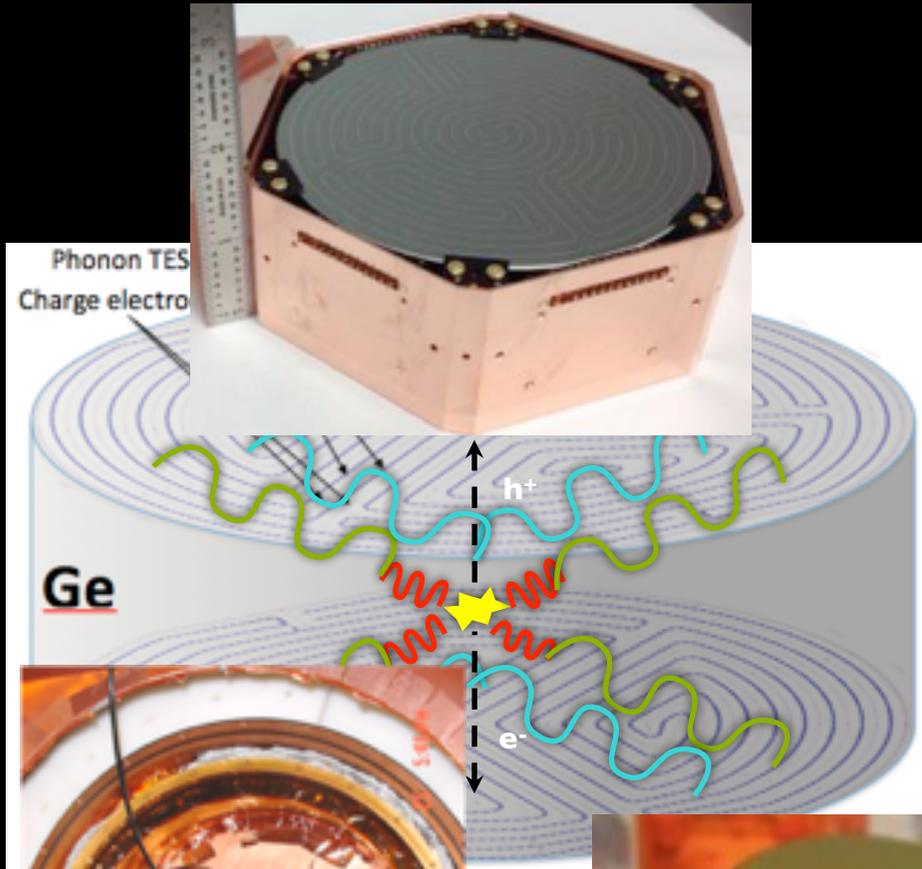
**Scintillation side:**  
Si absorber + 300 gm  
CaWO<sub>4</sub>, TES readout  
for particle ID



**Phonon side:** measure  $E_{\text{recoil}}$

# Cryogenic Bolometers

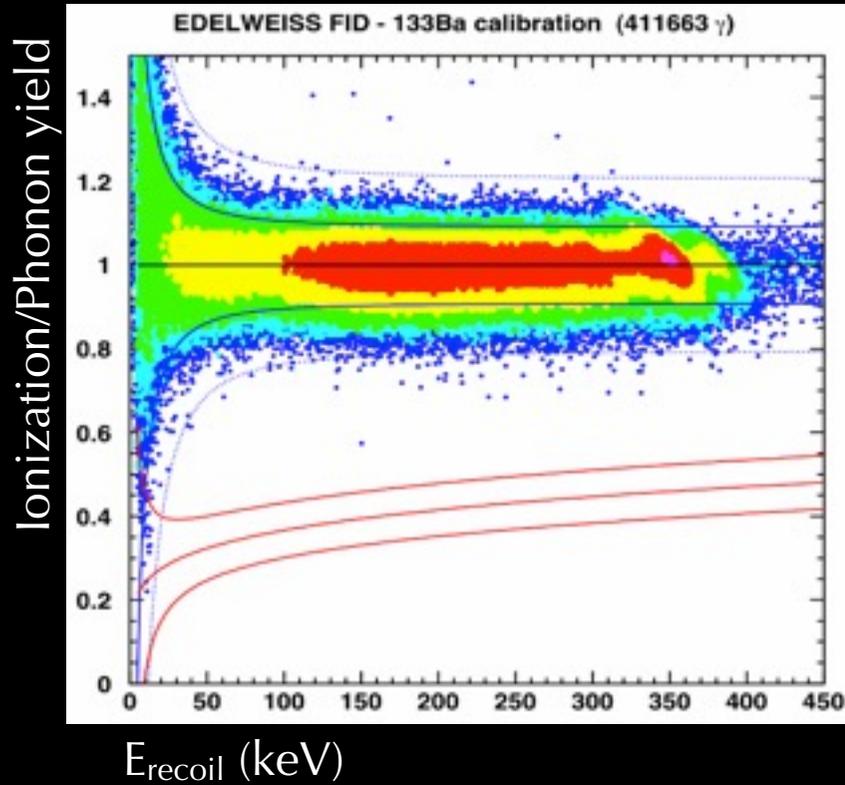
phonon, ionisation or scintillation readout of crystals at O(10 mK), using Ge, Si, CaWO<sub>4</sub>



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Dark Matter: rejects surface backgrounds by  $\times 10^5$



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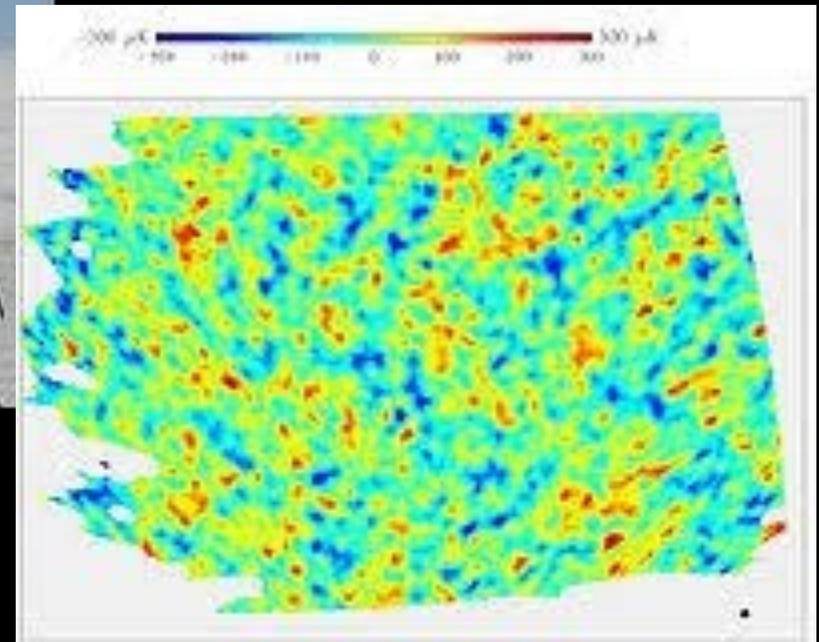
Gravitational Wave Search Experiments

Herschel Space Observatory: Galaxy Evolution

Cosmology, Curvature of Space Time: Boomerang

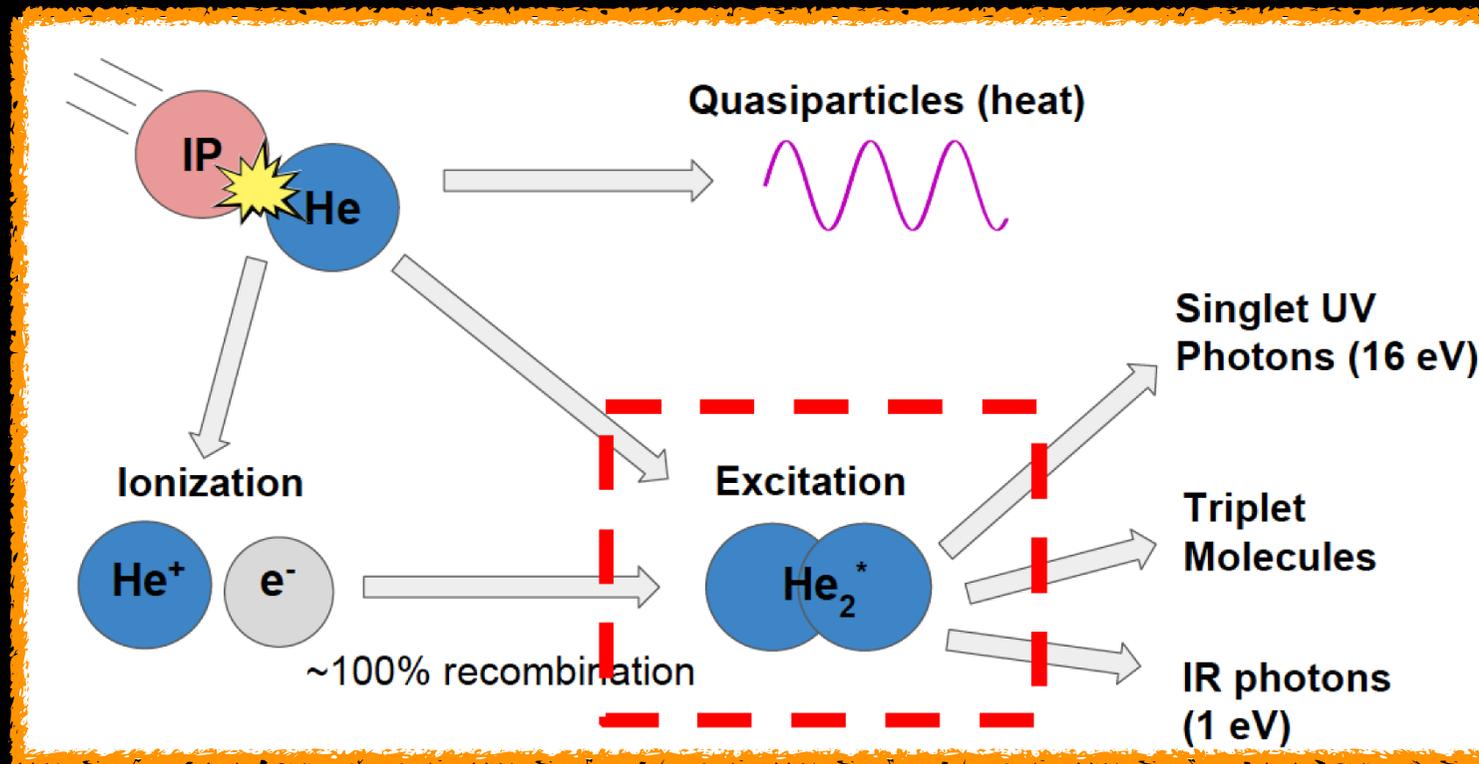


....



# Liquid Nobles

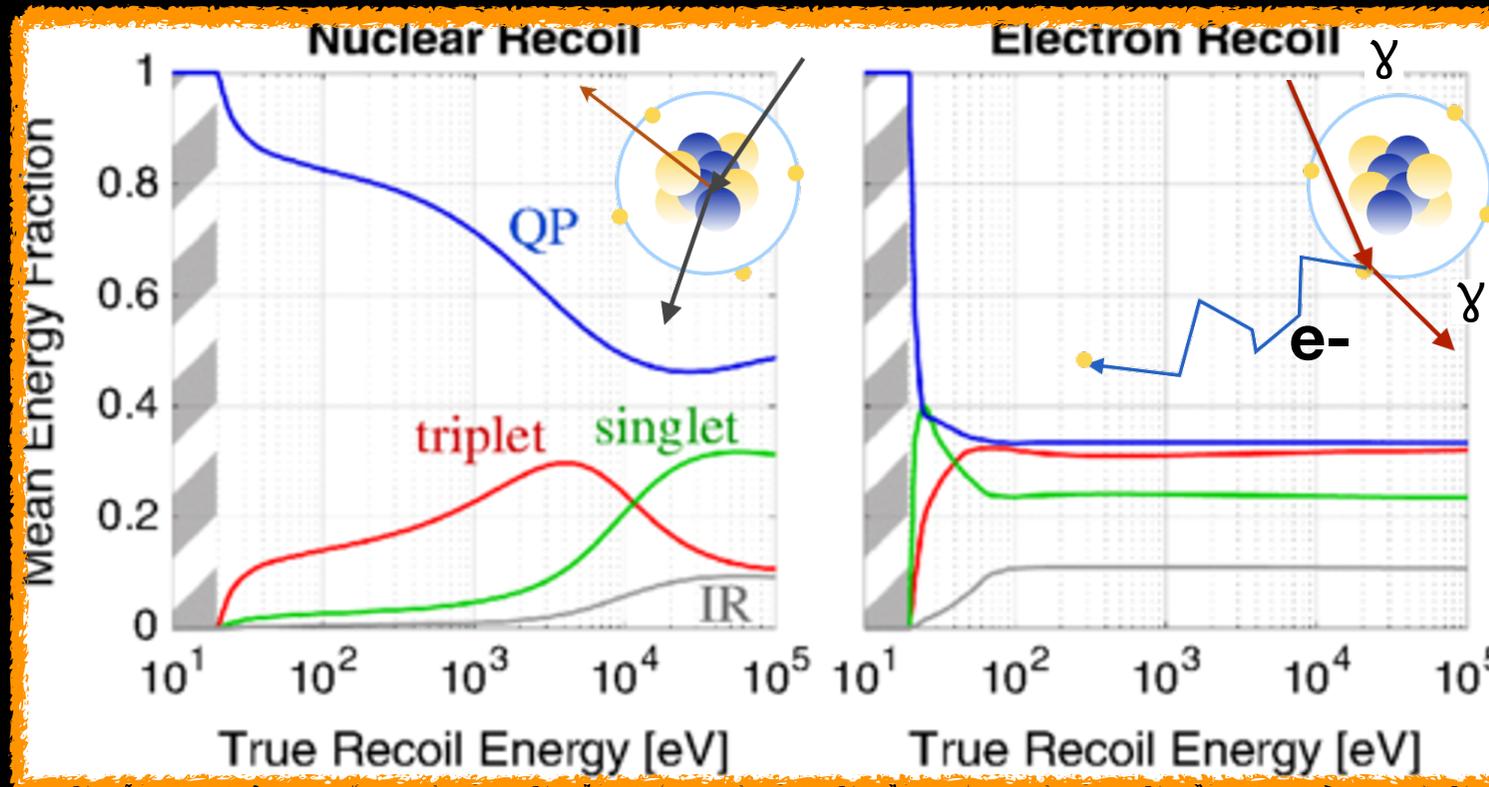
He example



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

# Liquid Nobles

He example



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

# Ionization Partition

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

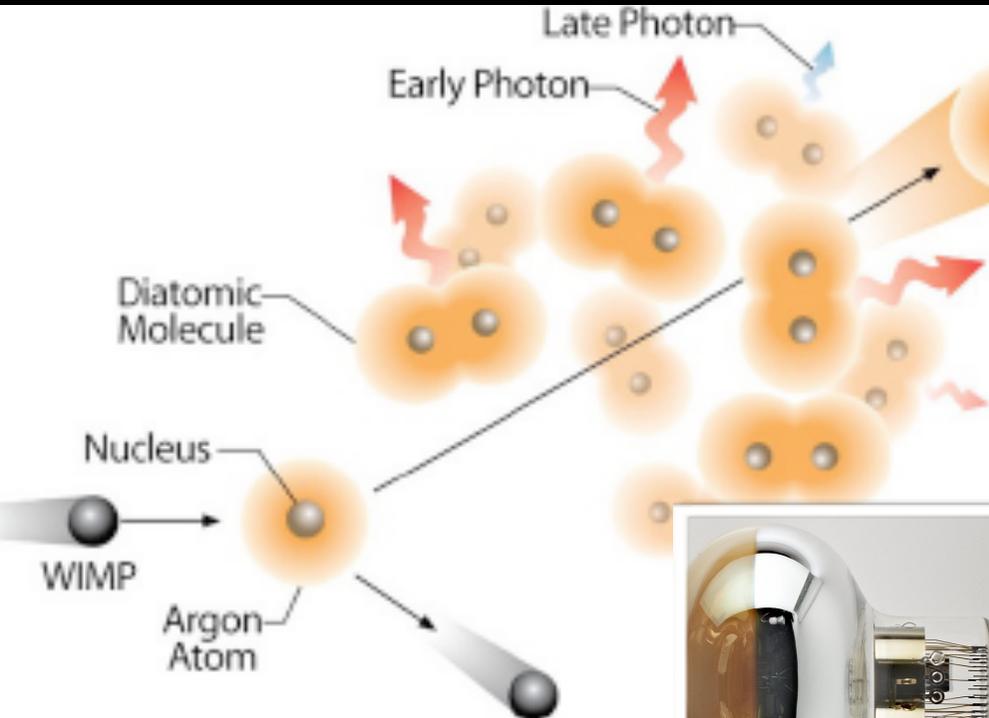
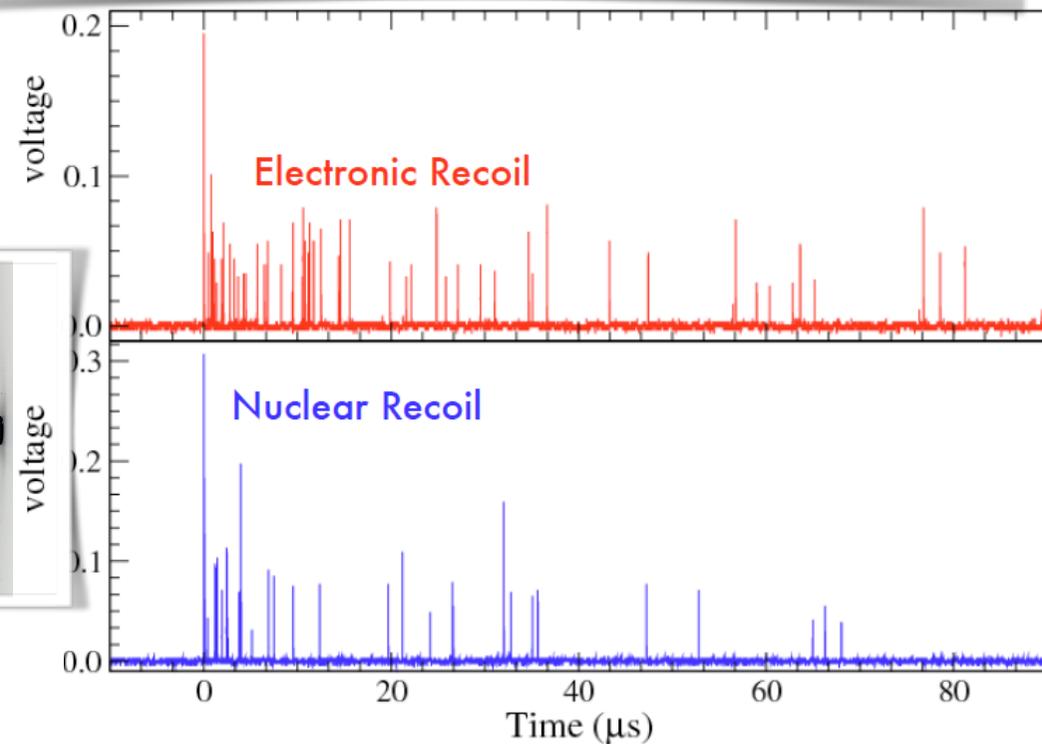


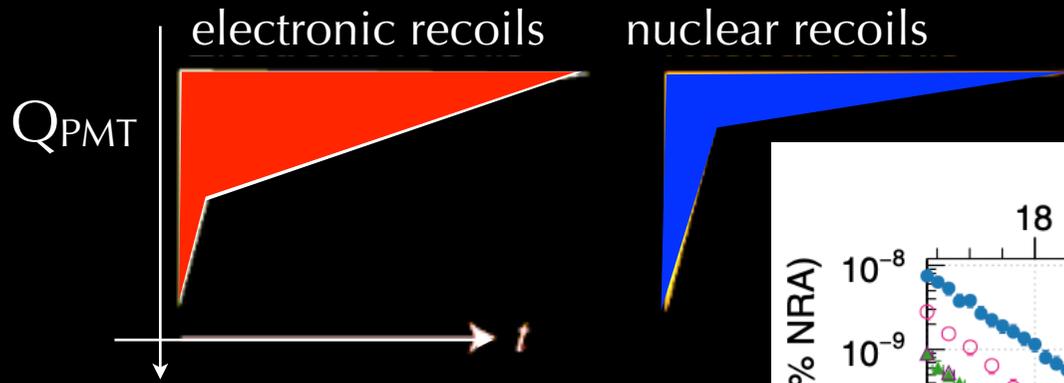
Table 3: Scintillation parameters for liquid neon, argon, and xenon.

Parameter	Ne	Ar	Xe
Yield ( $\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant $\tau_1$ (ns)	2.2	6	2.2
late time constant $\tau_3$	$15 \mu\text{s}$	$1.59 \mu\text{s}$	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
$\lambda(\text{peak})$ (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30



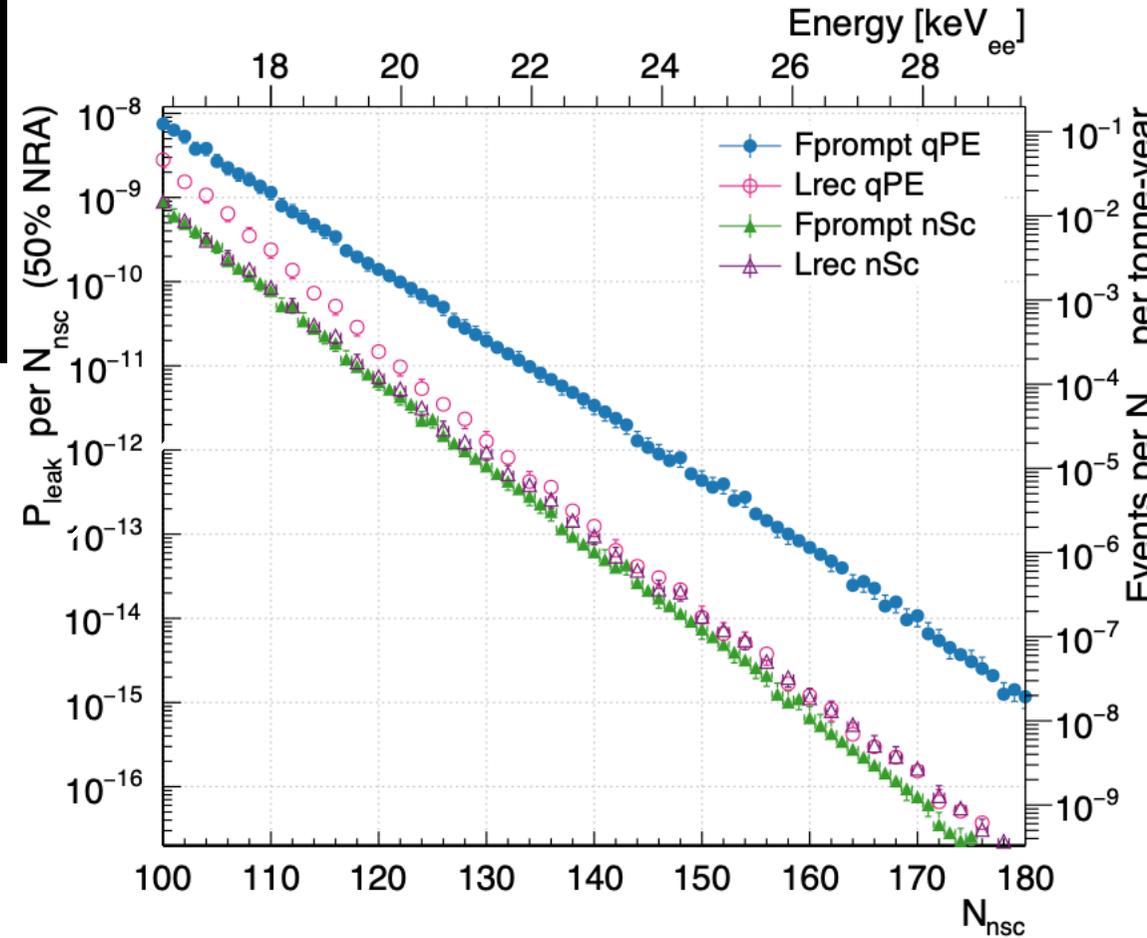
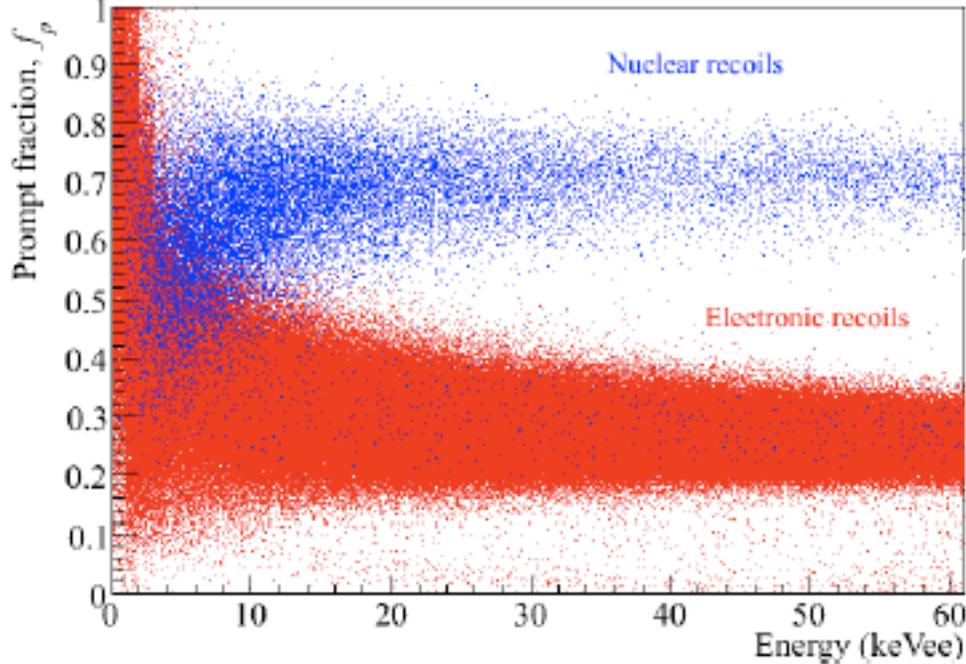
Lippincott et al., *Phys.Rev.C* 78: 035801 (2008)

# Pulse Shape Discrimination in Liquid Argon



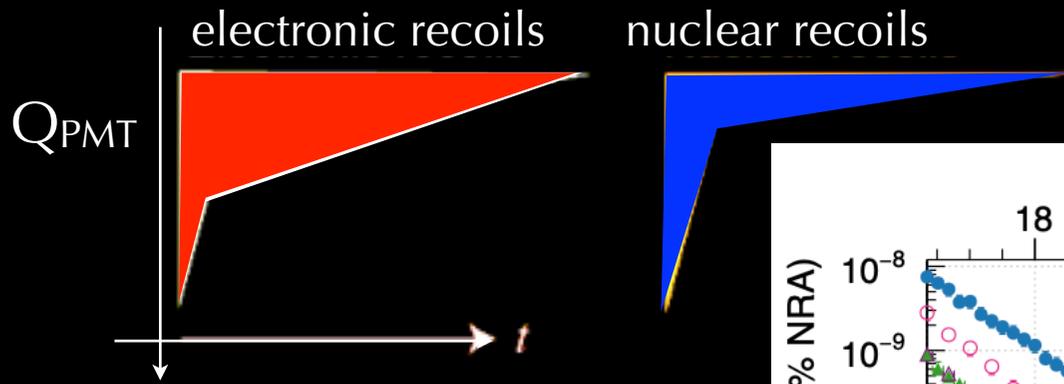
Adhikari et al, Eur. Phys. J. C 80, 303 (2020)

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



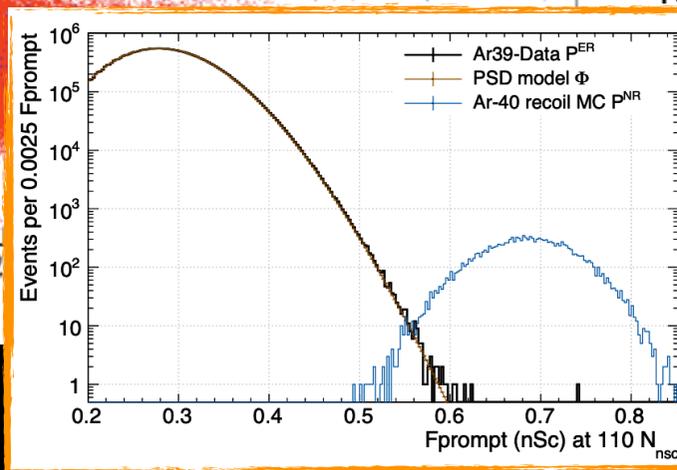
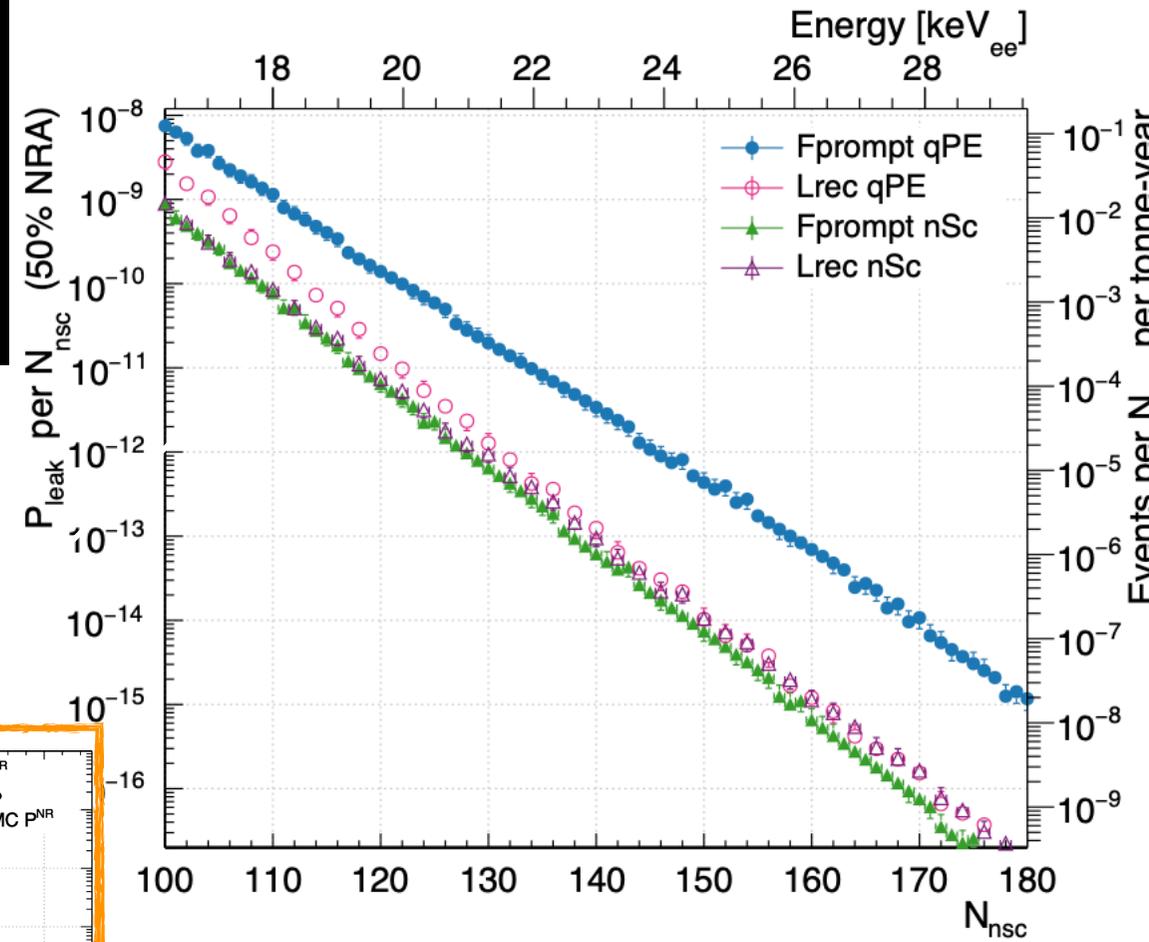
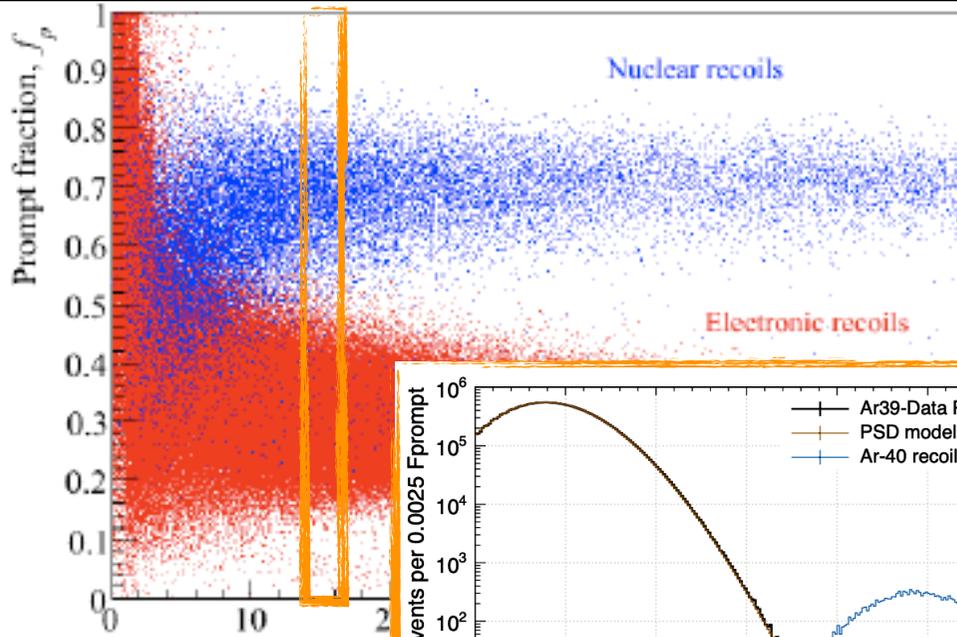
identify, reject electronic backgrounds via pulse shape vs. time difference at parts-per-billion level

# Pulse Shape Discrimination in Liquid Argon



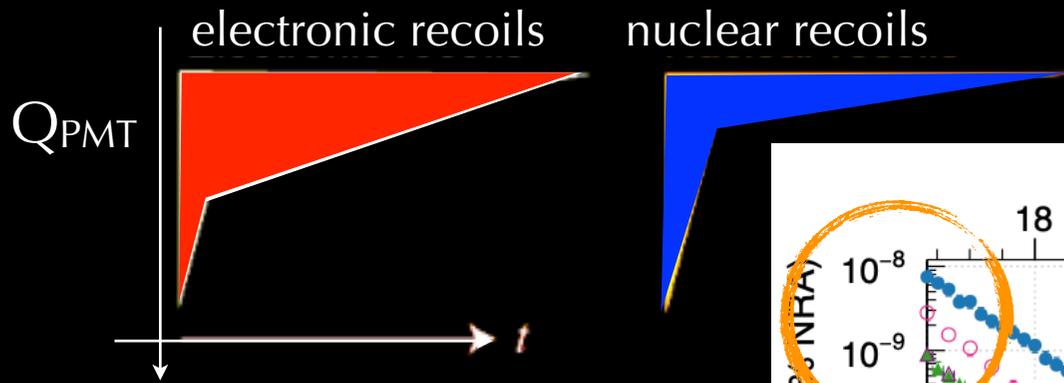
Adhikari et al, Eur. Phys. J. C 80, 303 (2020)

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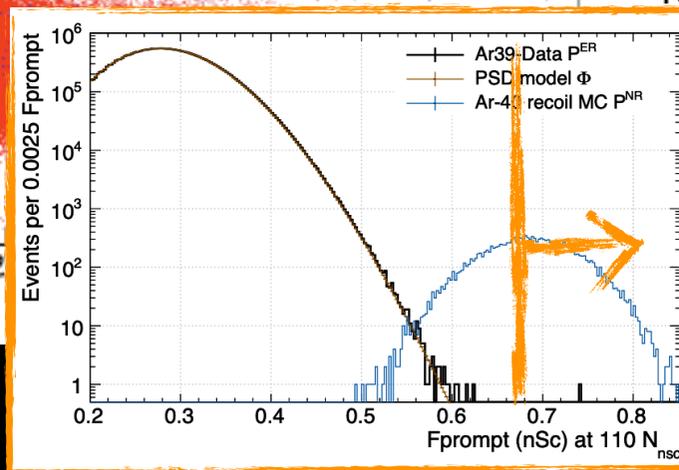
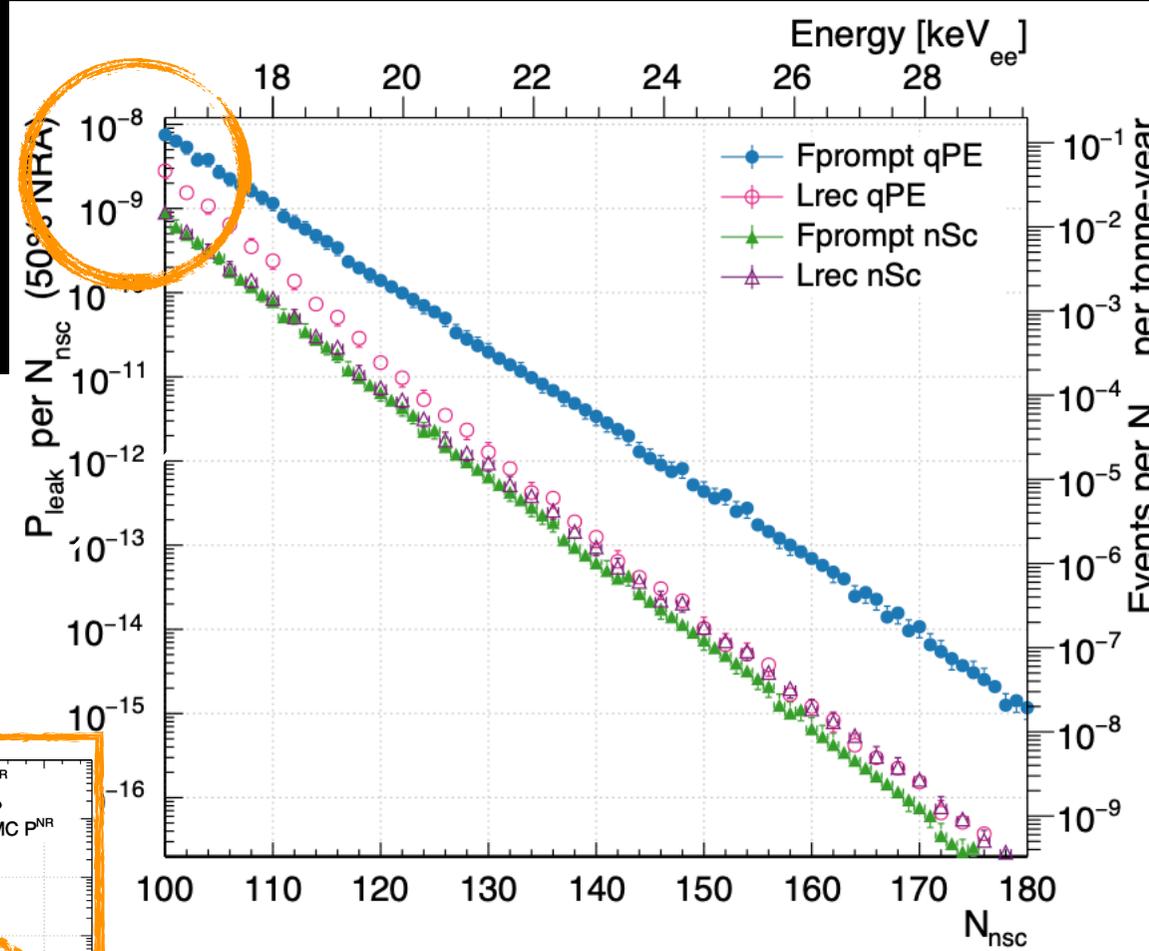
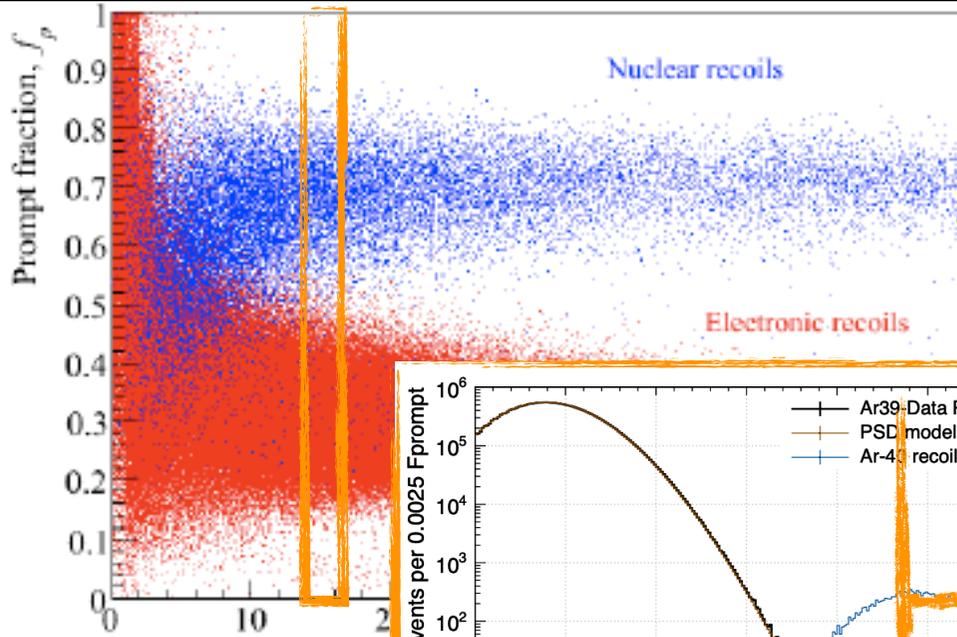
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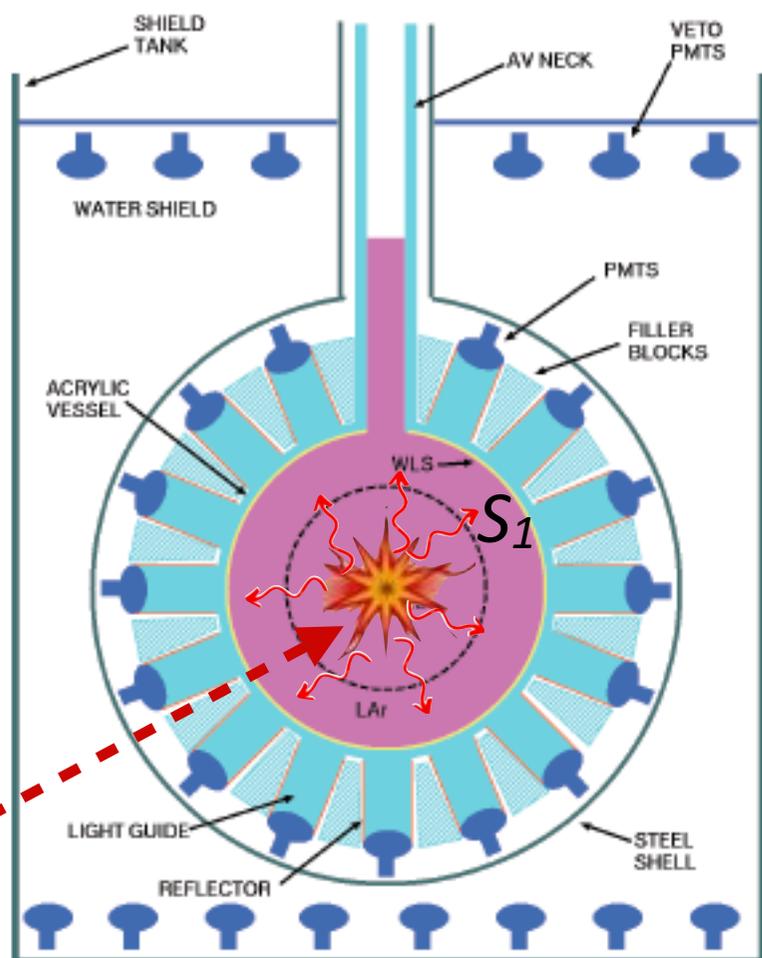
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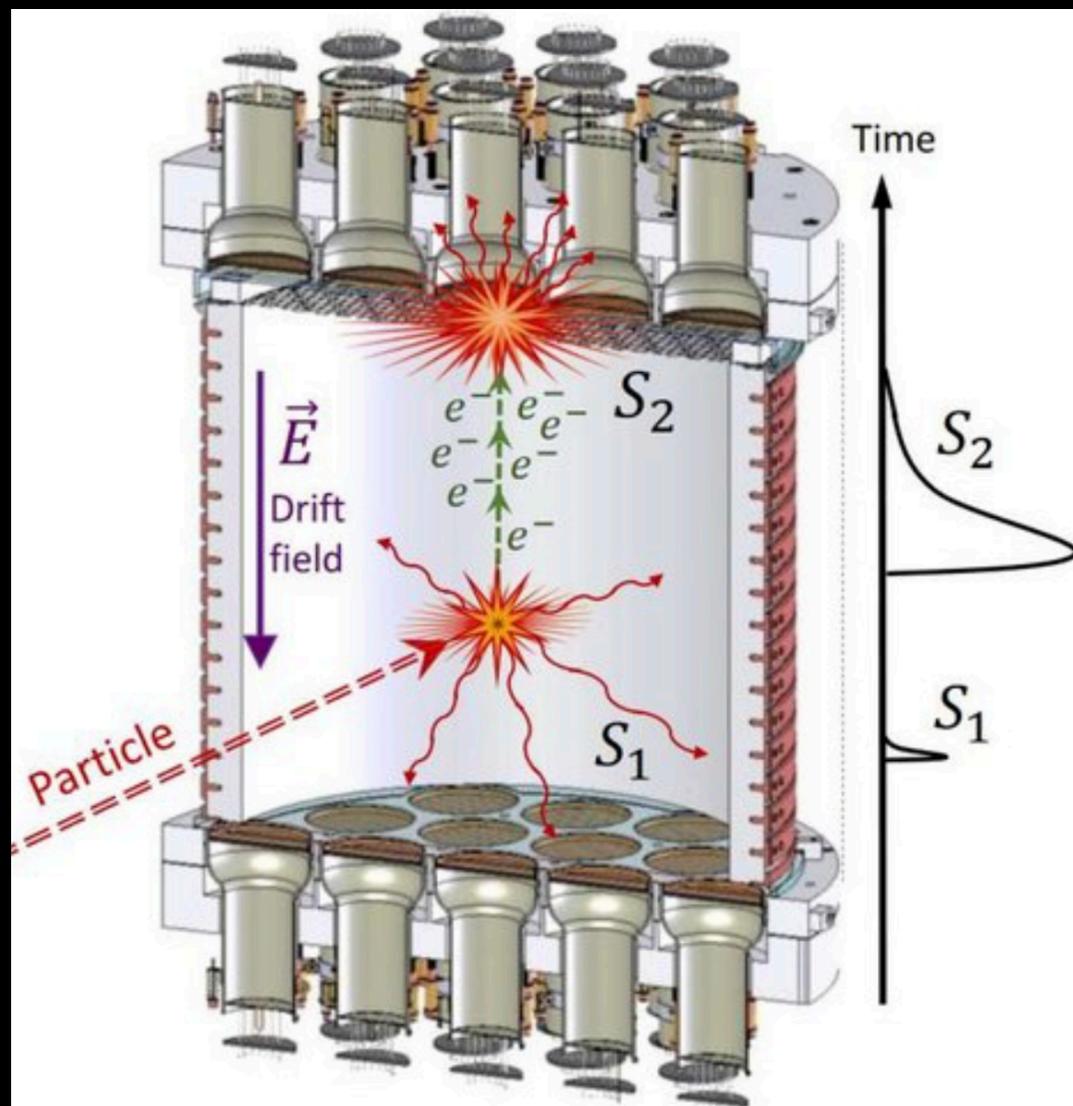
# Liquid Noble Detectors



**Single Phase Detector:**  
no electric fields...  $S_1$  only,  
but, no recombination in E field

## Dual Phase Detector:

Primary scintillation ( $S_1$ ) and proportional gas scintillation from drifted electrons ( $S_2$ )



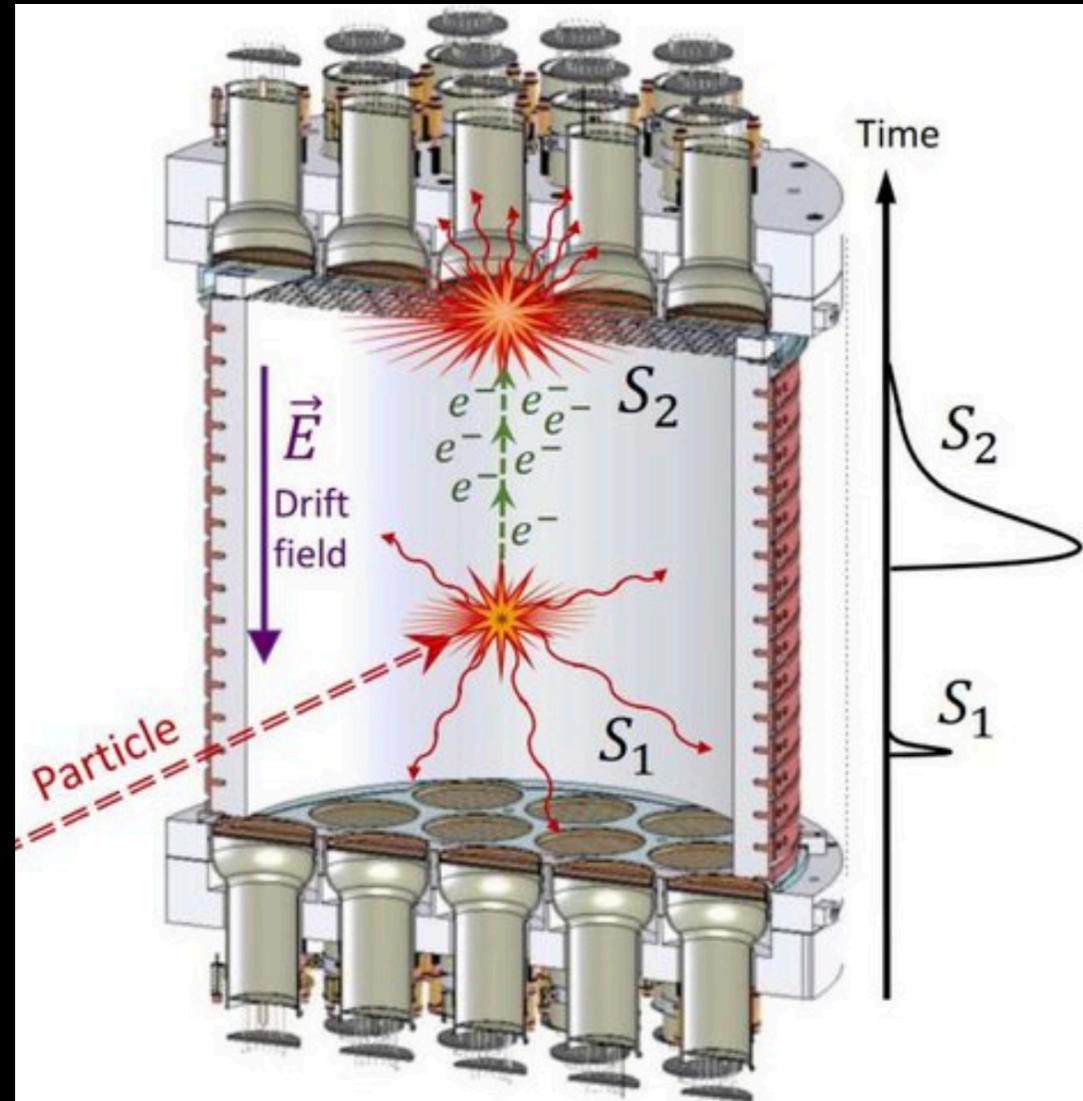
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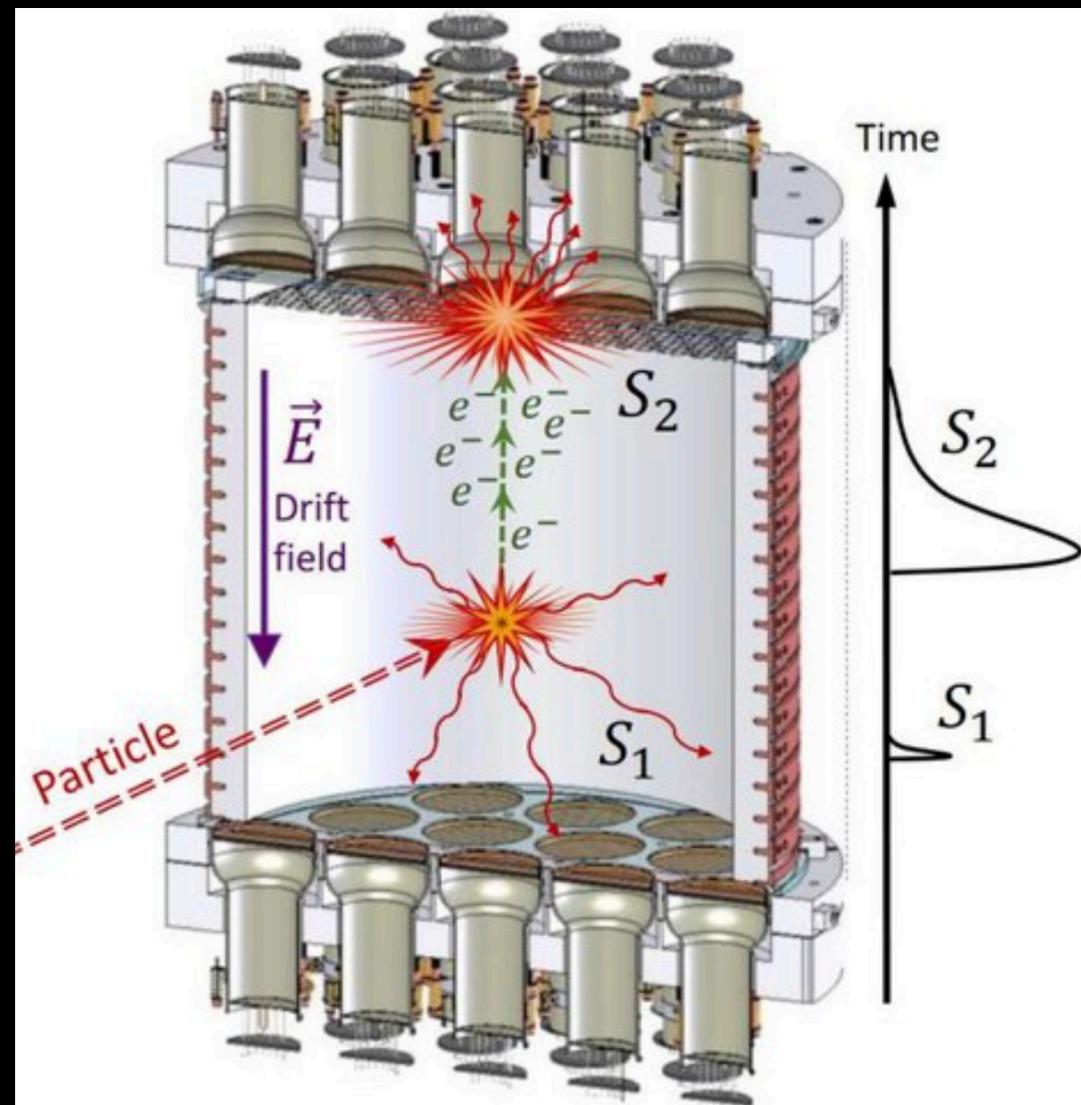
# Liquid Noble Detectors



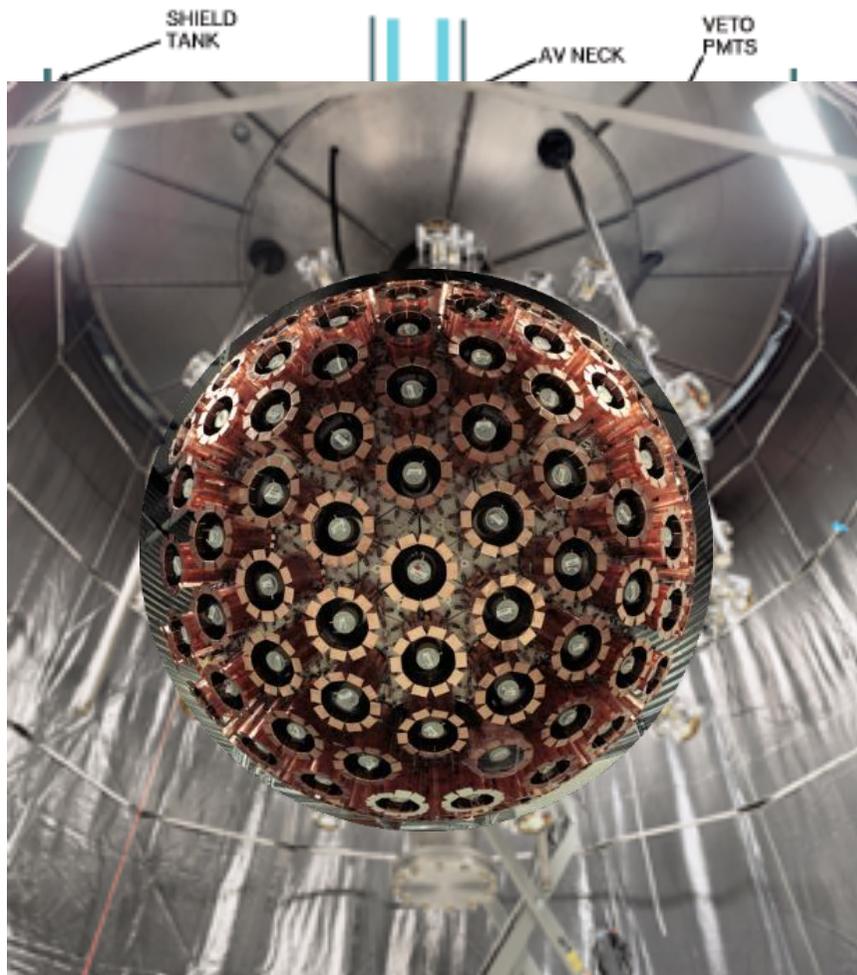
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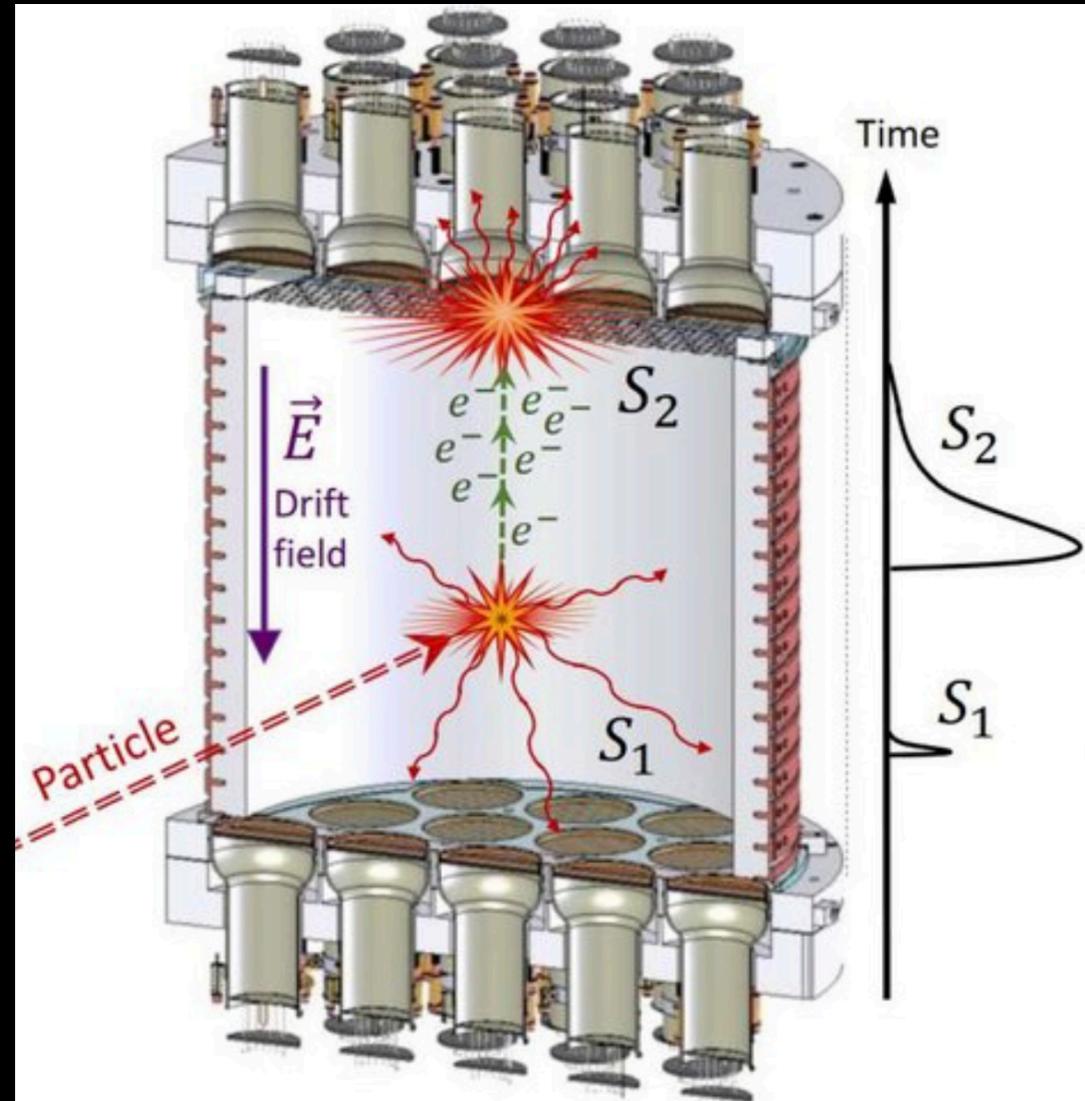
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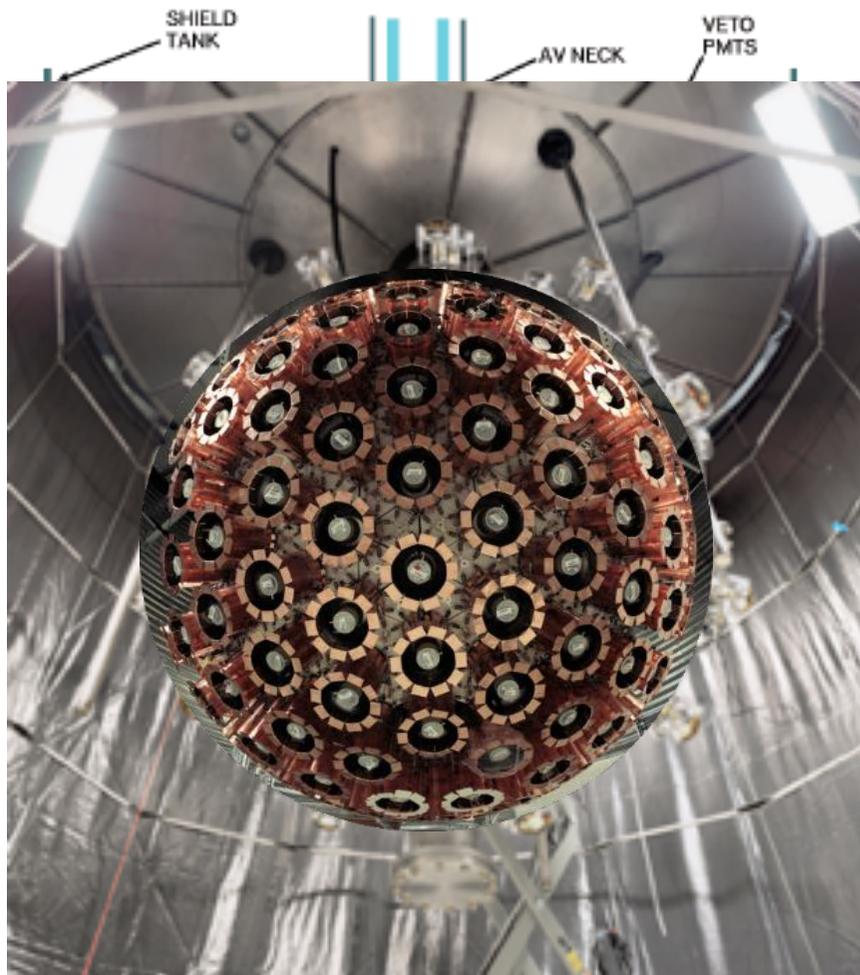
**Single Phase Detector:**  
no electric fields... S1 only,  
but, no recombination in E field

## Dual Phase Detector:

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



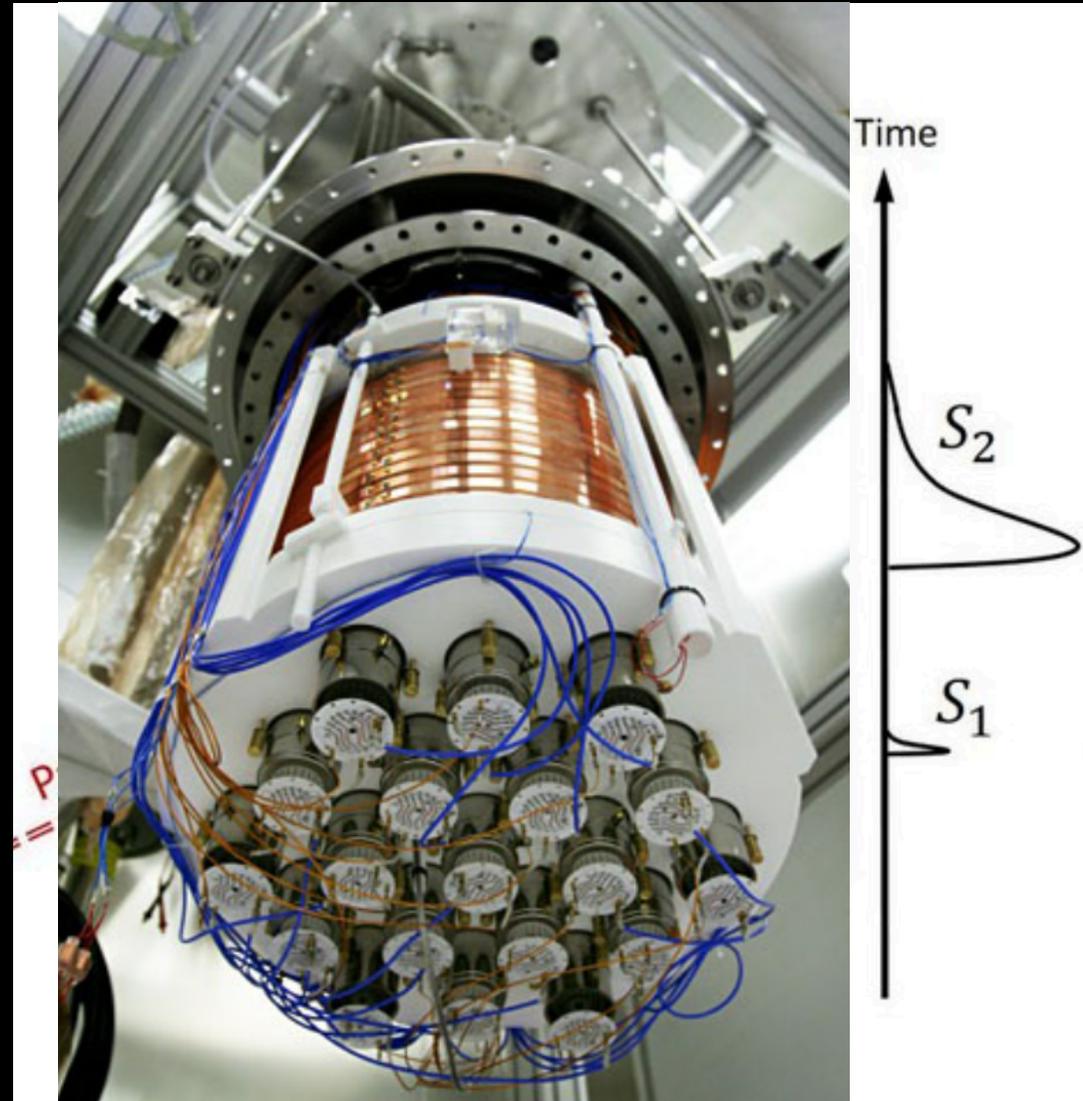
# Liquid Noble Detectors



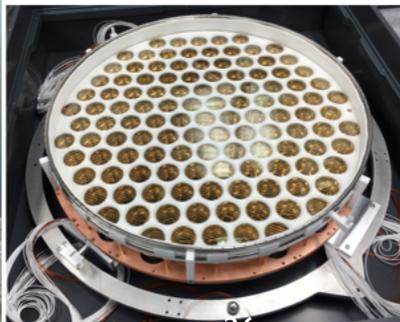
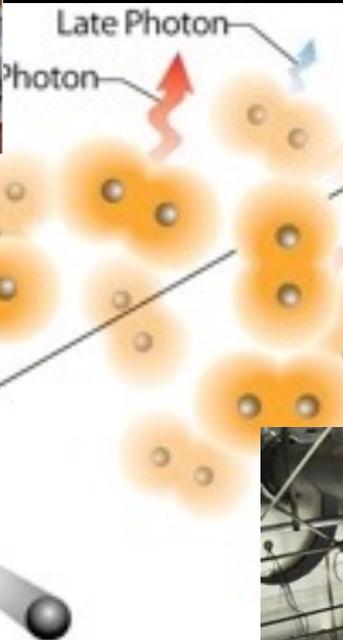
**Single Phase Detector:**  
no electric fields... S1 only,  
but, no recombination in E field

## Dual Phase Detector:

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



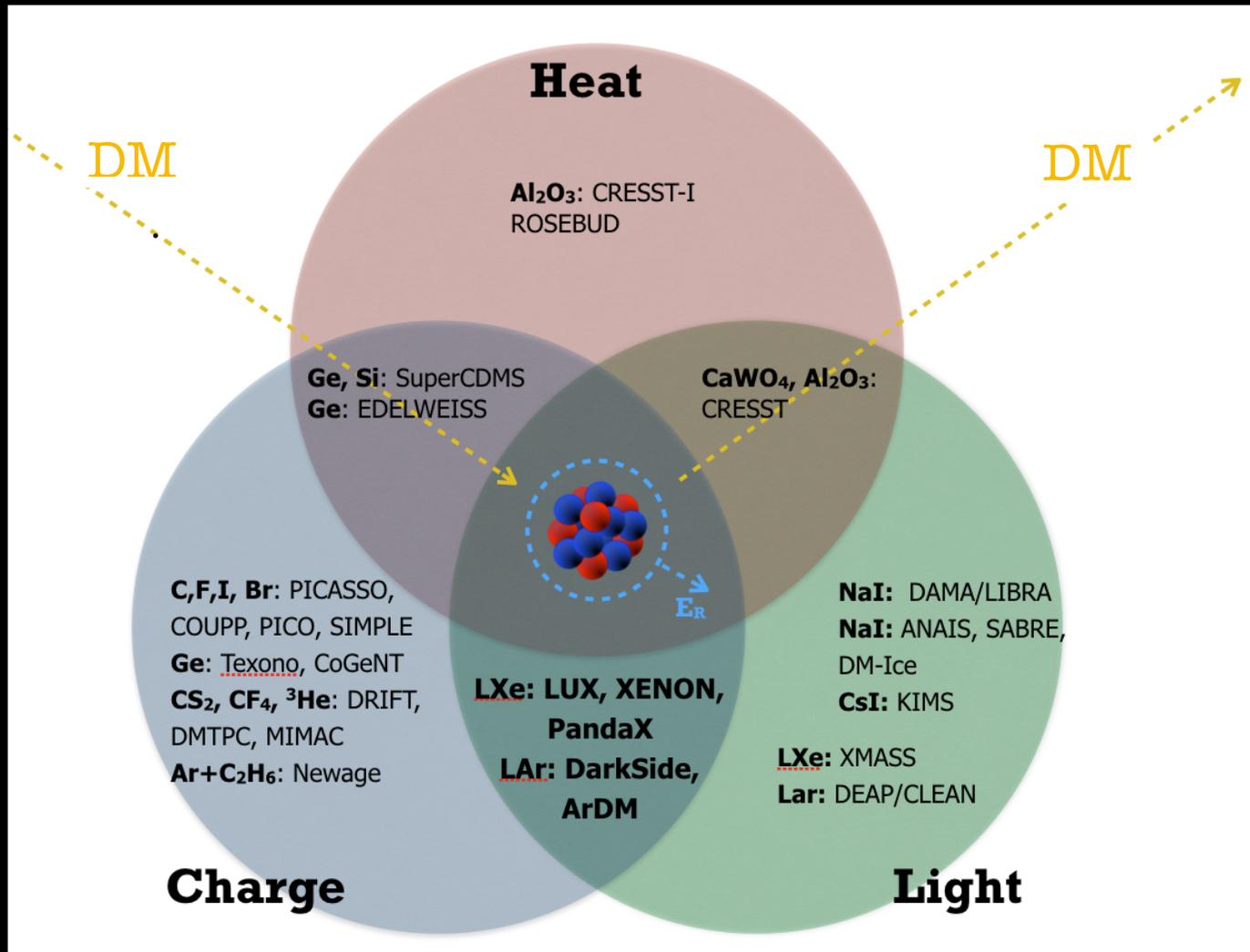
# Noble Liquids



# Energy Detection Strategies

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

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



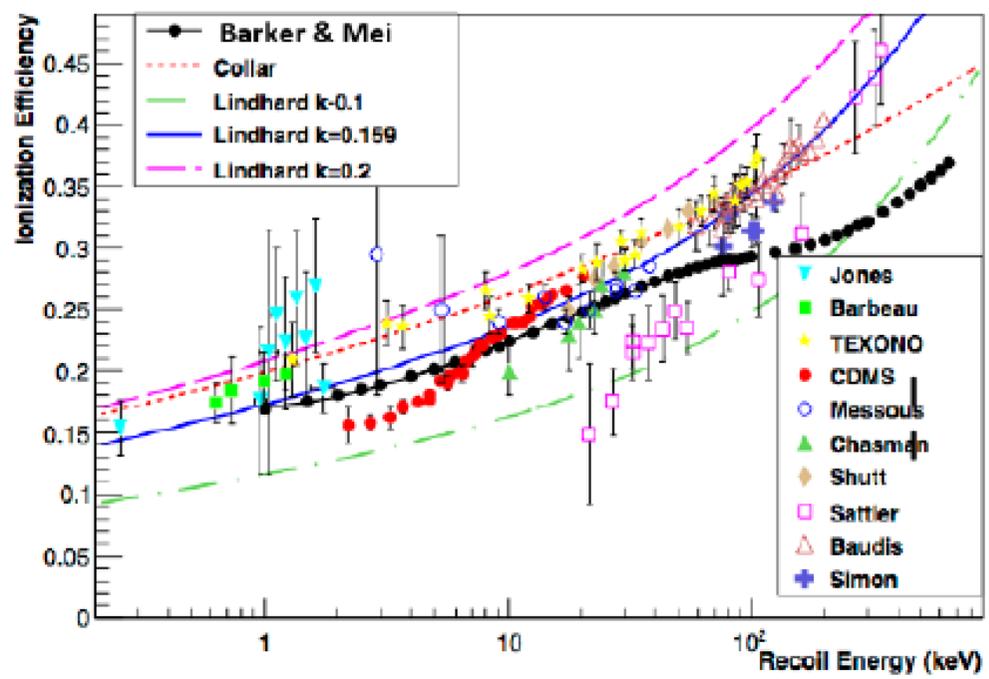
$E_R$  threshold now  $O(10\ eV)$ ,  
potential to reach  $eV$

$E_R$  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

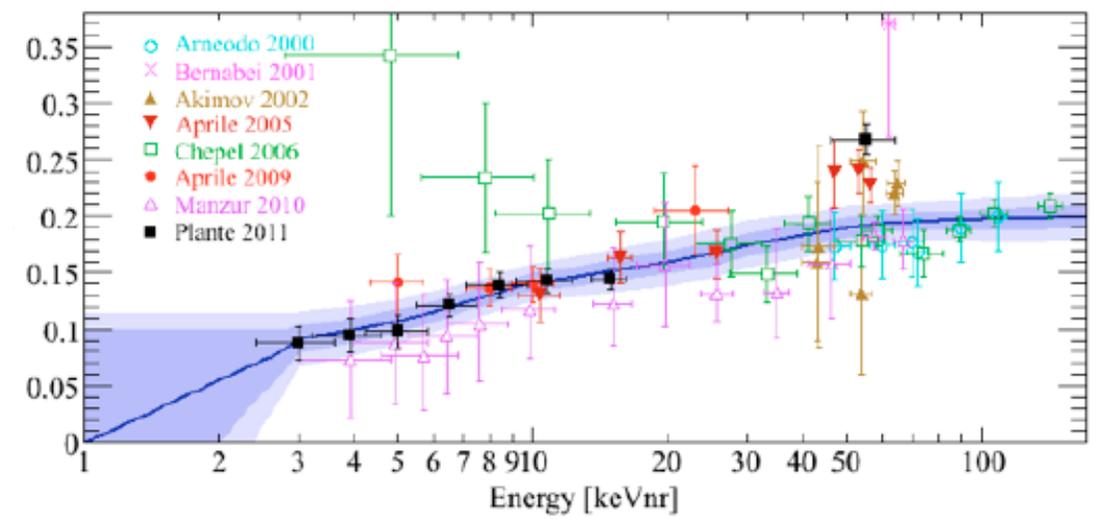
## Germanium



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

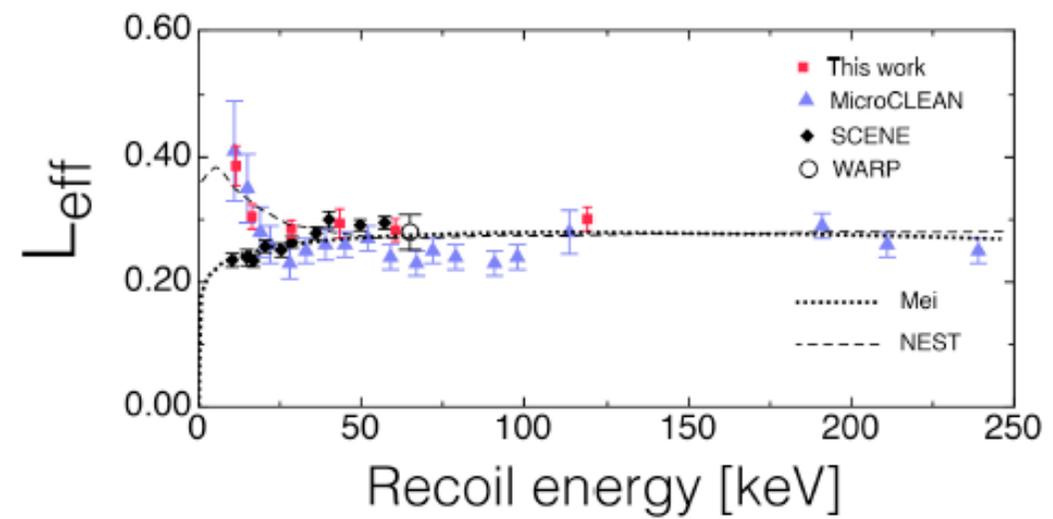
## Direct method: LXe

Plante et al., Phys. Rev. C **84**, 045805, 2011



## Direct method: LAr

W. Creus et al., arXiv: 1504.07878

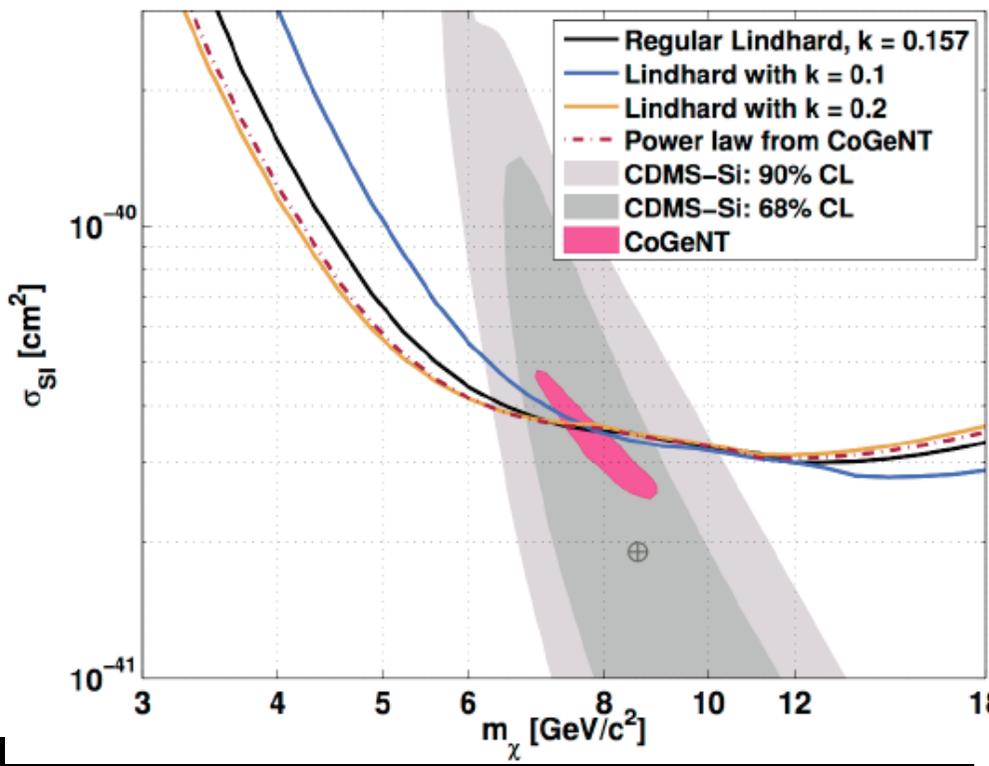


*measurement in the experiment energy region of interest required*

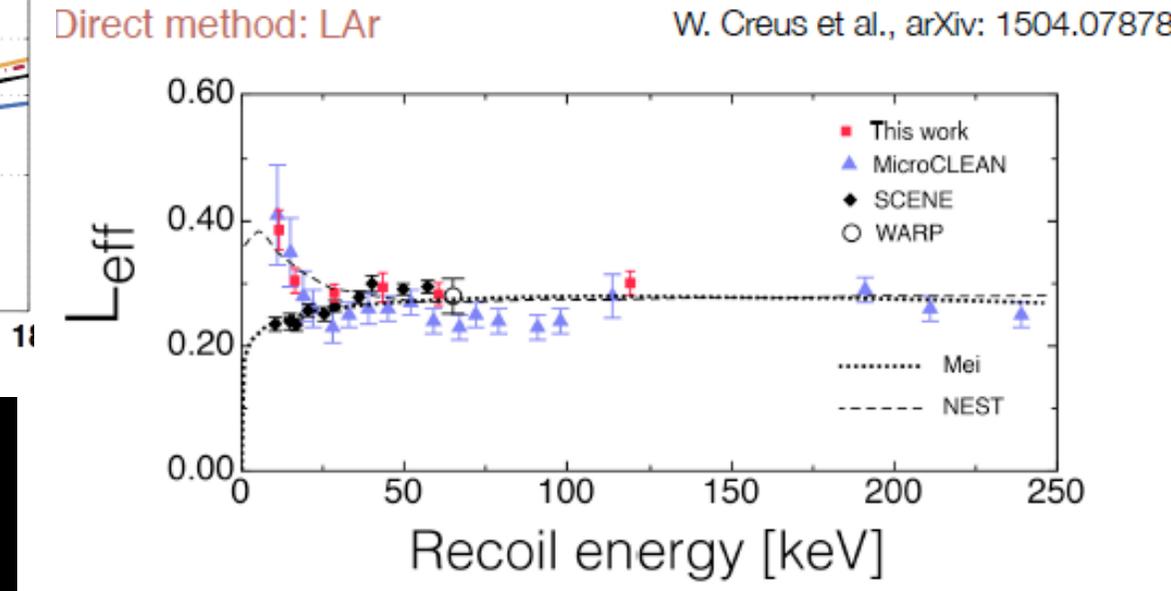
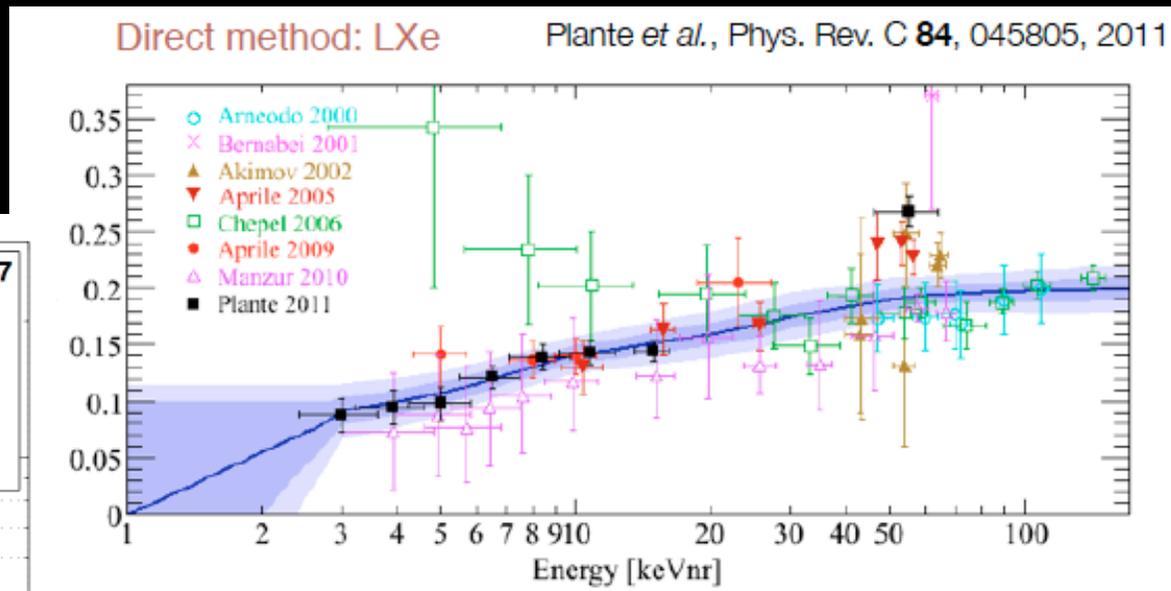


# Key Experimental Systematics: Quenching

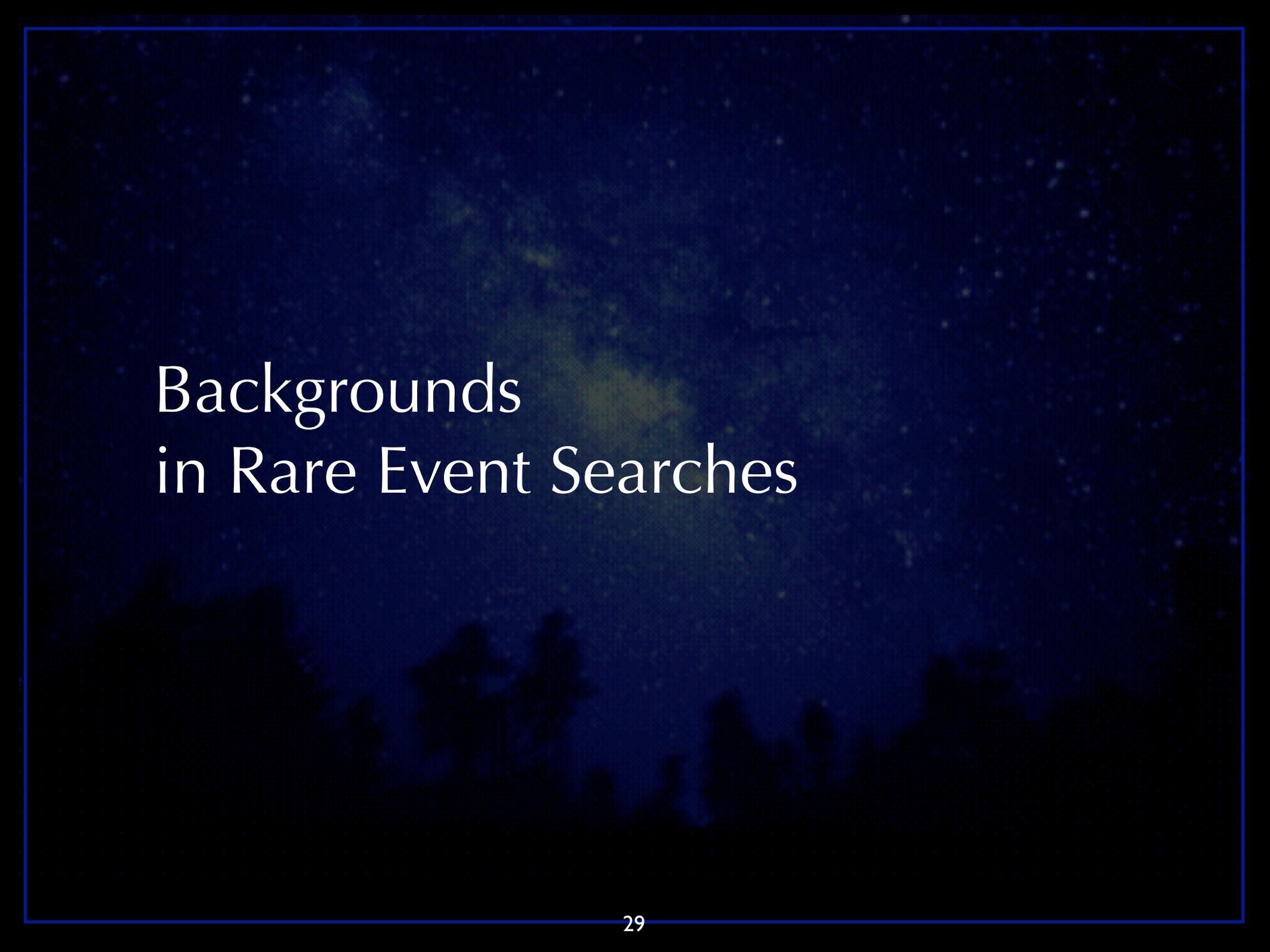
Current status of measurements of visible/recoil energy in -ionization on Ge -scintillation on Xe, Ar



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



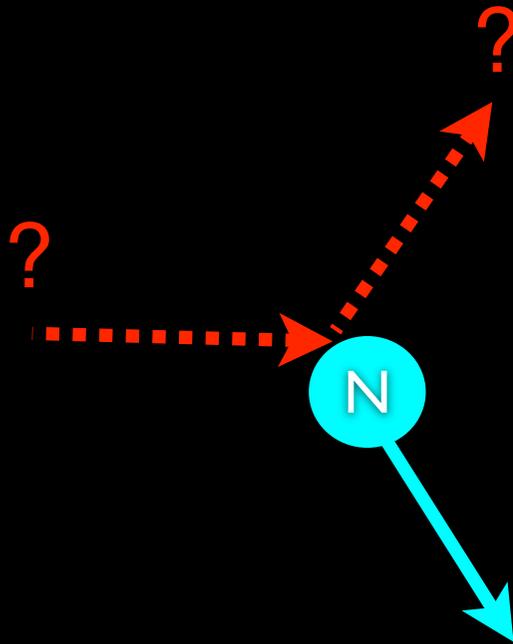
*measurement in the experiment energy region of interest required*



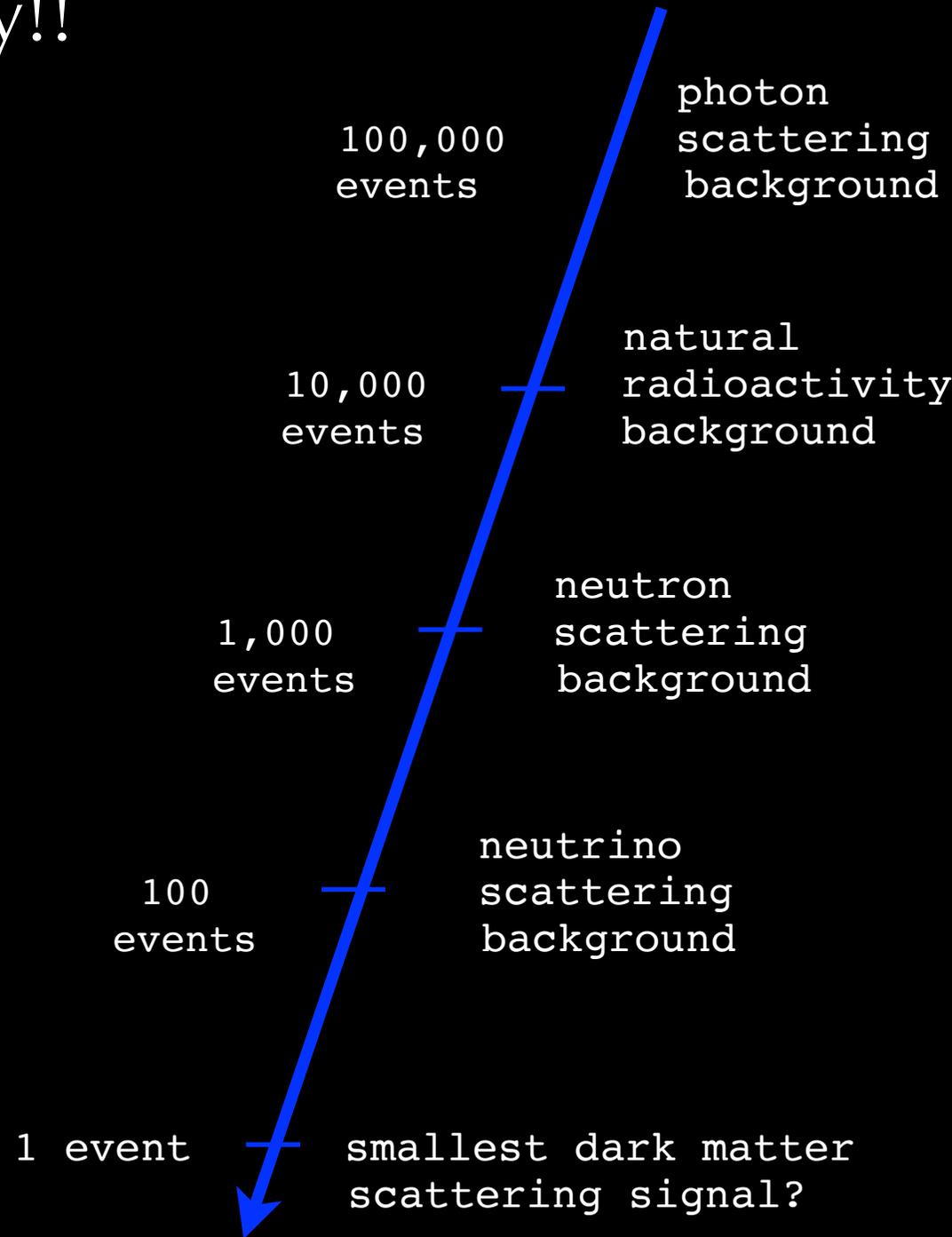
# Backgrounds in Rare Event Searches

# DM Interaction Rate is Tiny!!

*In dark matter experiments...*



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



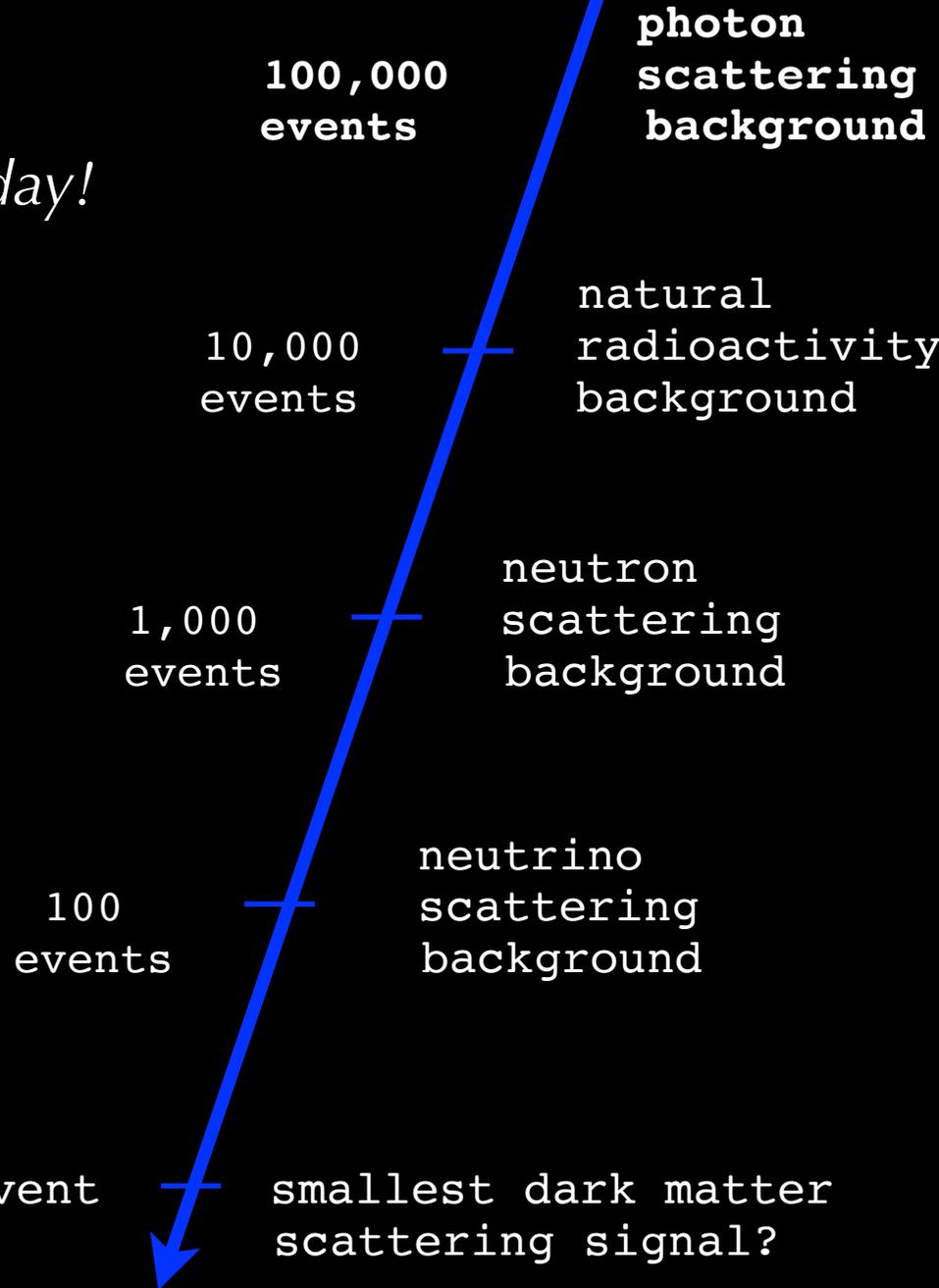


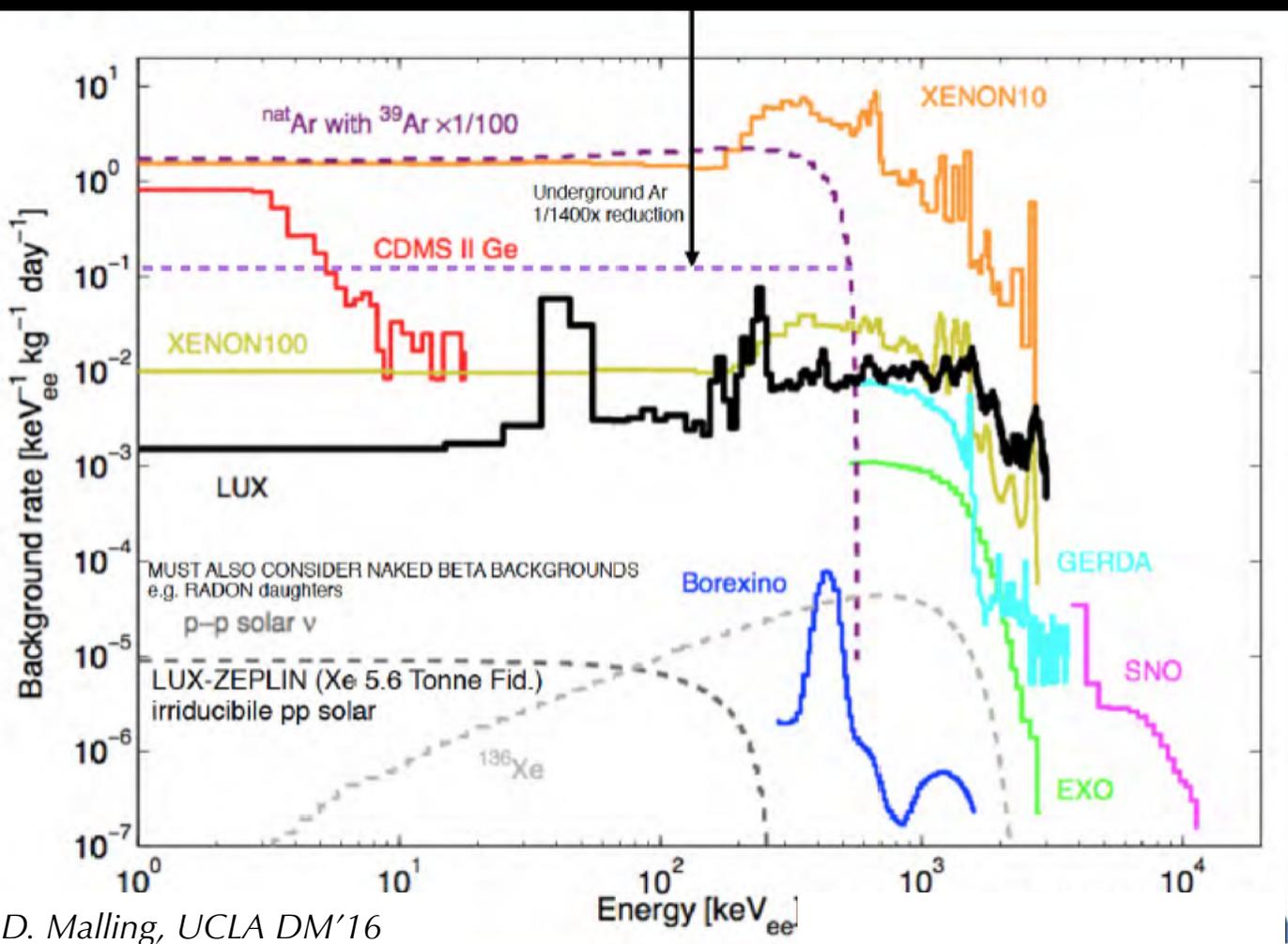
Geiger counter

*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

10,000 events — natural radioactivity background

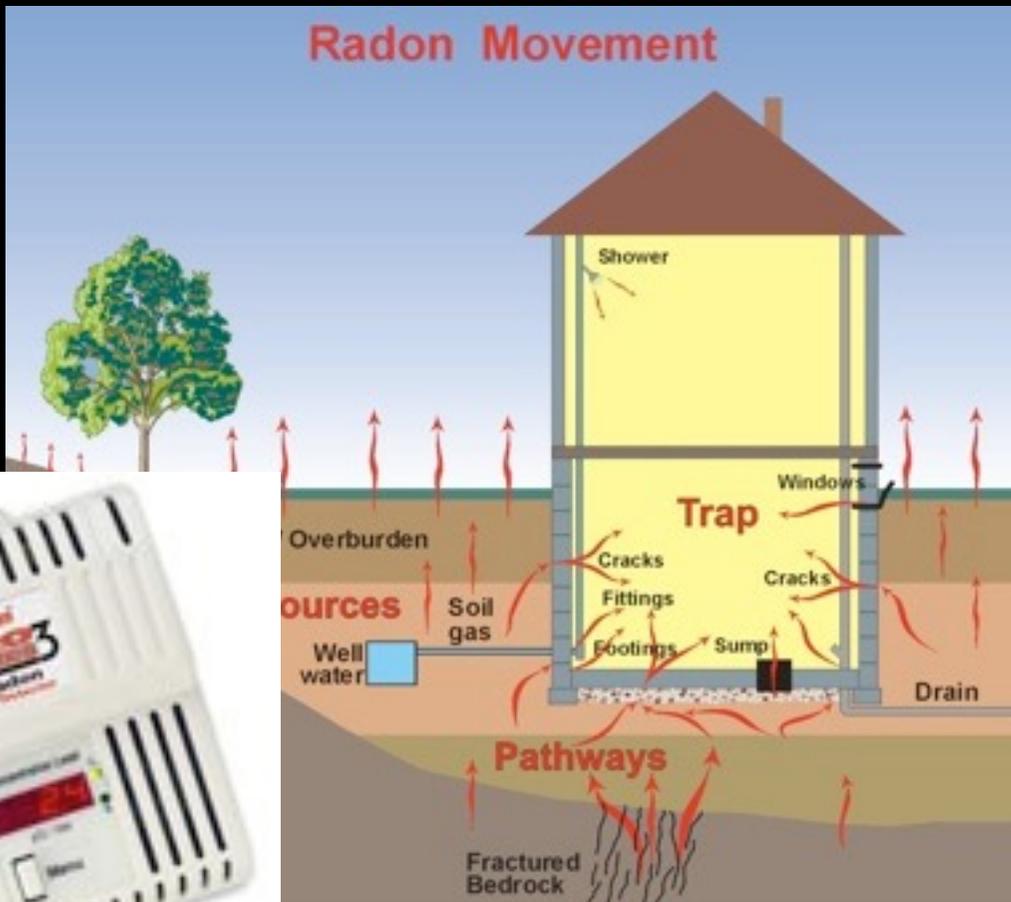
1000 events — neutron scattering background

1 event — neutrino scattering background

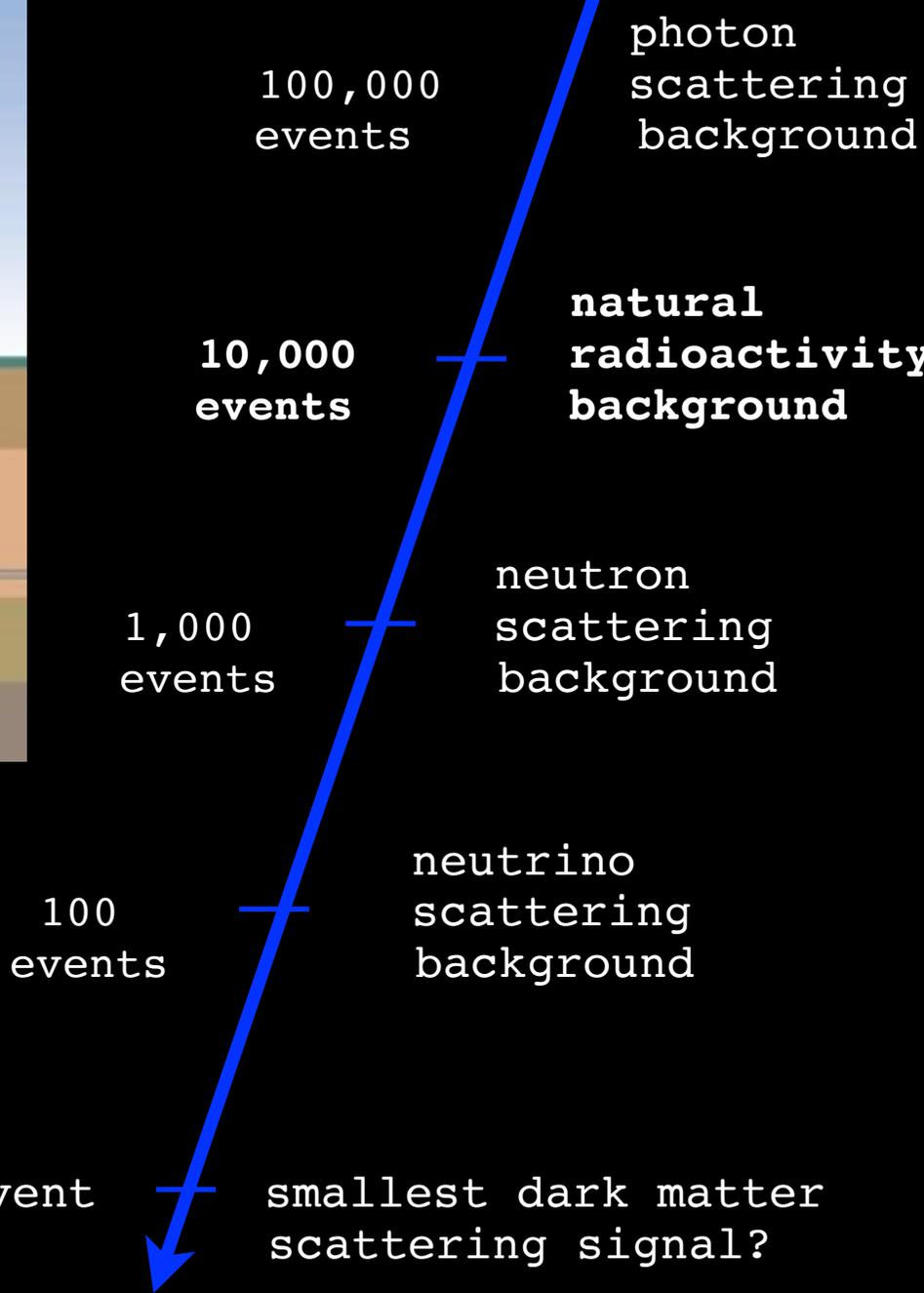
smallest dark matter scattering signal?



# Radon Movement

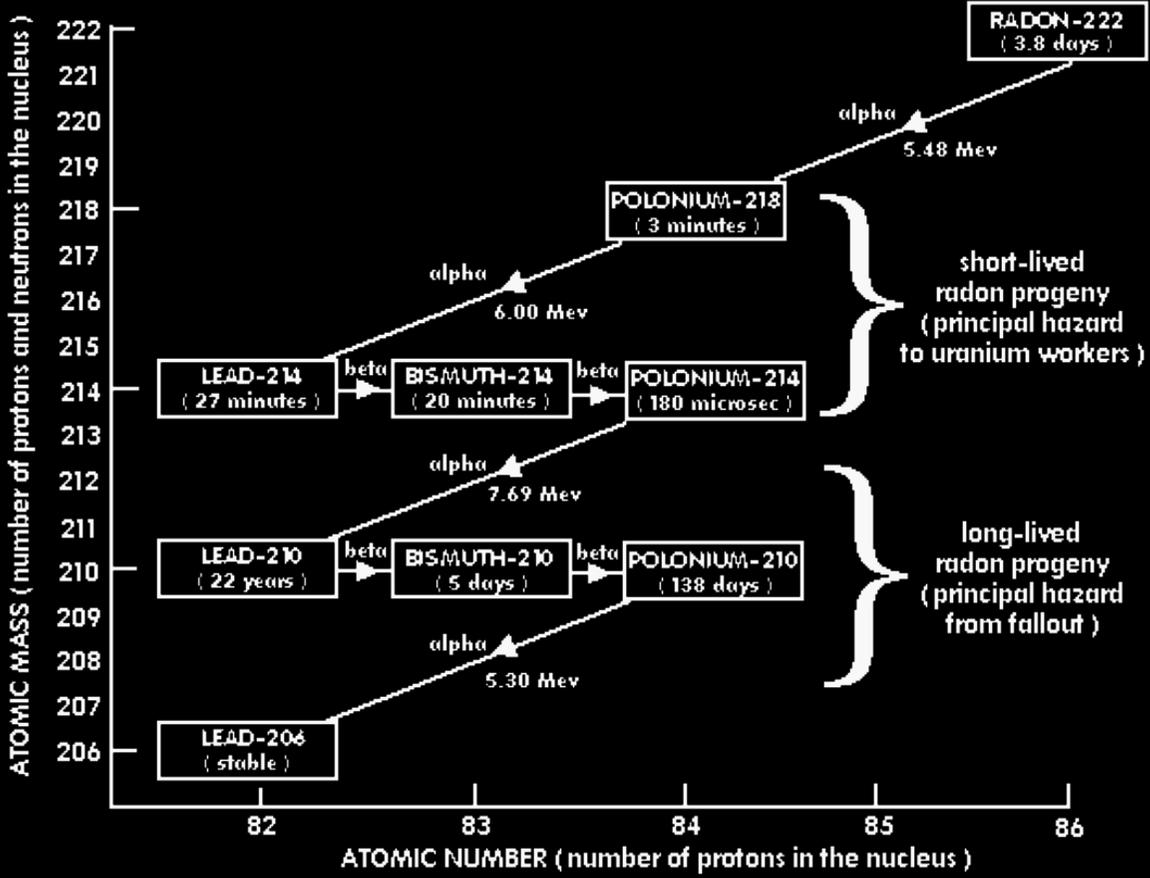


*In your basement: 200,000 radon decays/kg/day set off the alarm!  
experiments use high-purity materials  
to control radon concentrations*



# 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 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  $^{230}\text{Th}$  and  $^{226}\text{Ra}$  in the  $^{238}\text{U}$  decay chain.

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

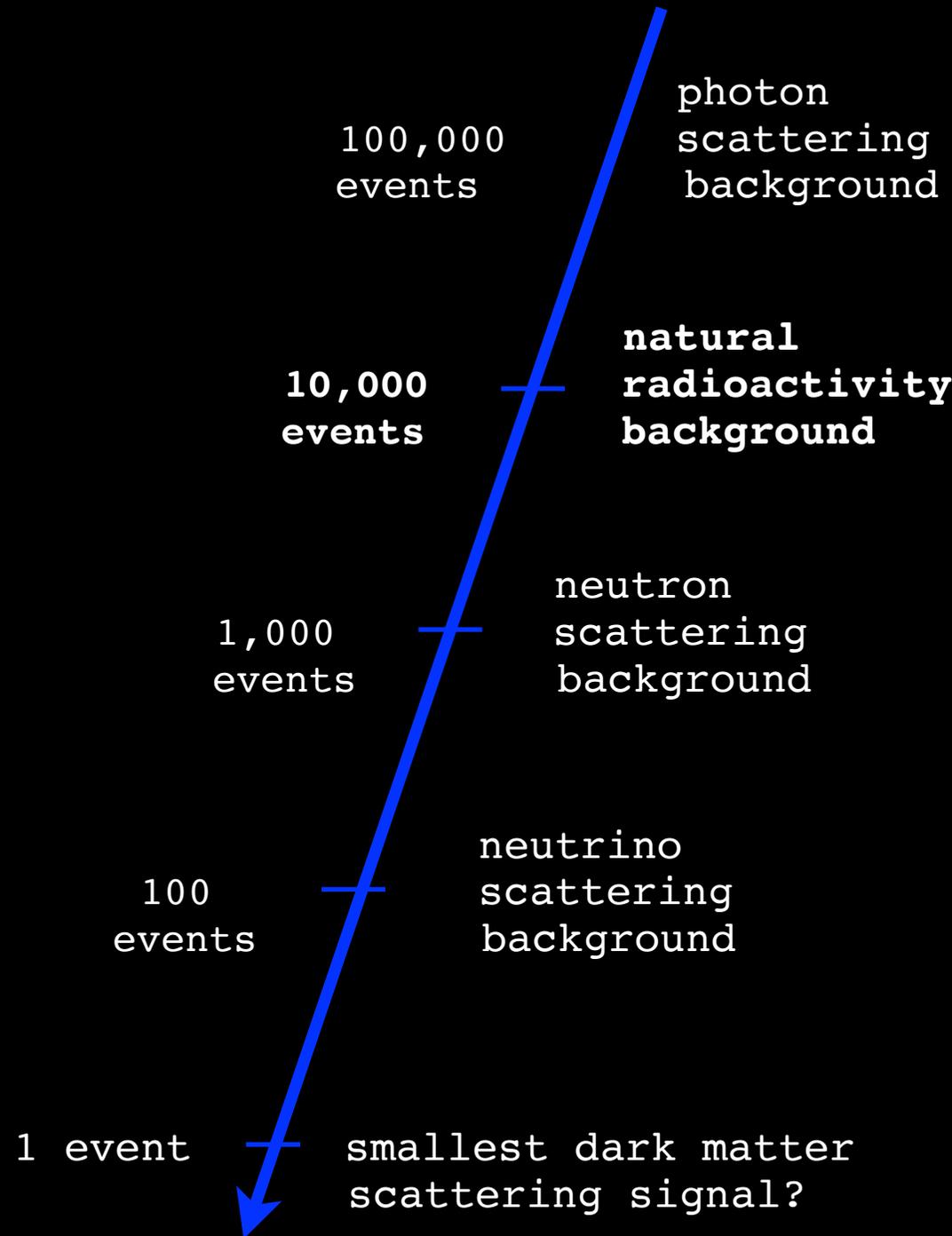
Component	$^{238}\text{U}_{\text{lower}}$	$^{238}\text{U}_{\text{upper}}$	$^{232}\text{Th}$	$^{235}\text{U}$
[mBq/kg]				
Methyl methacrylate monomer (LG bonding)	$1.4 \pm 1.0$	< 15	< 0.9	< 1.8
AV acrylic	< 0.1	< 2.2	< 0.5	< 0.2
Acrylic beads (RPT)	< 3.1	$16 \pm 15$	$0.8 \pm 0.3$	$0.6 \pm 0.5$
LG acrylic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

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

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



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



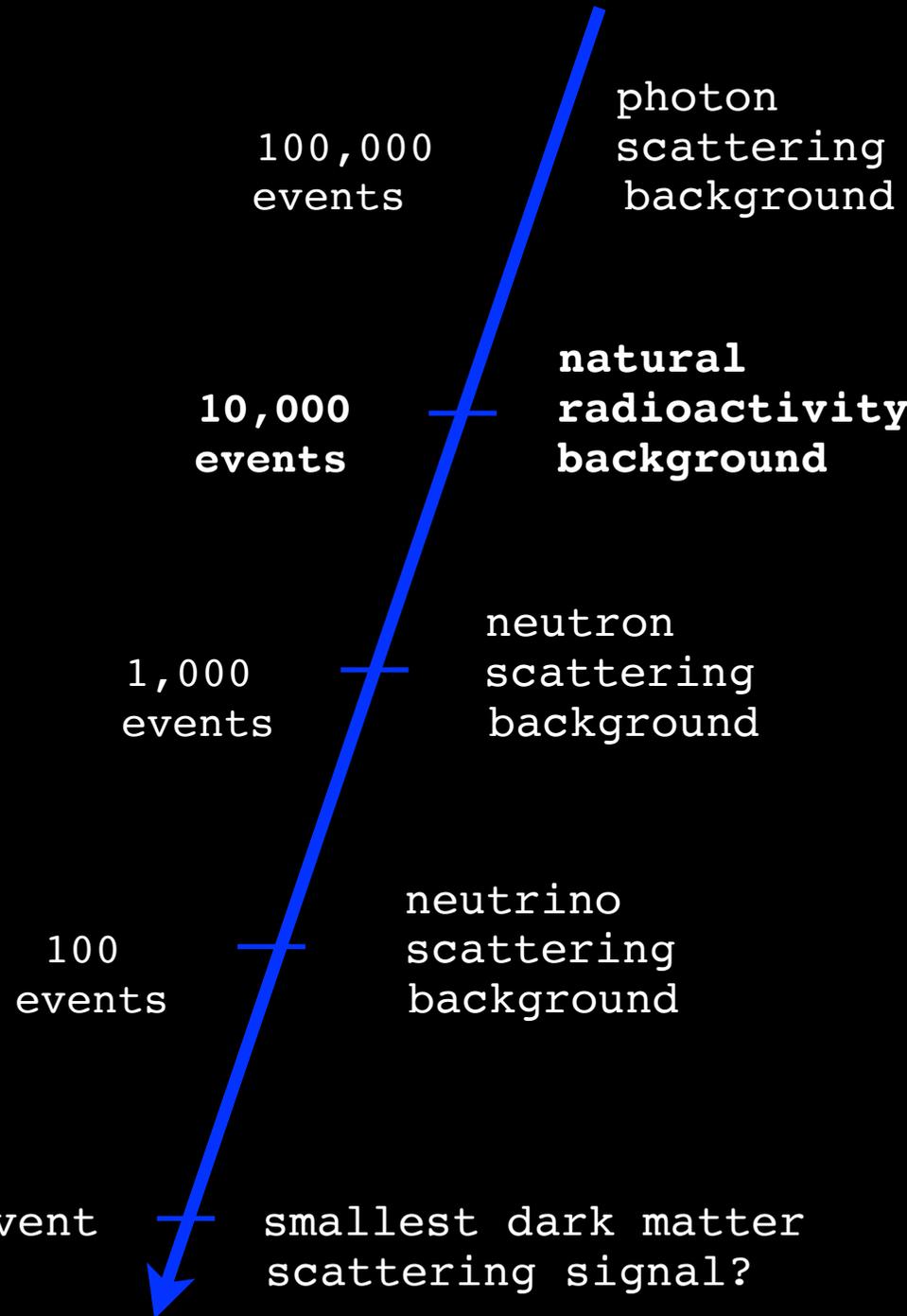
## <sup>222</sup>Rn in Dark Matter experiments:

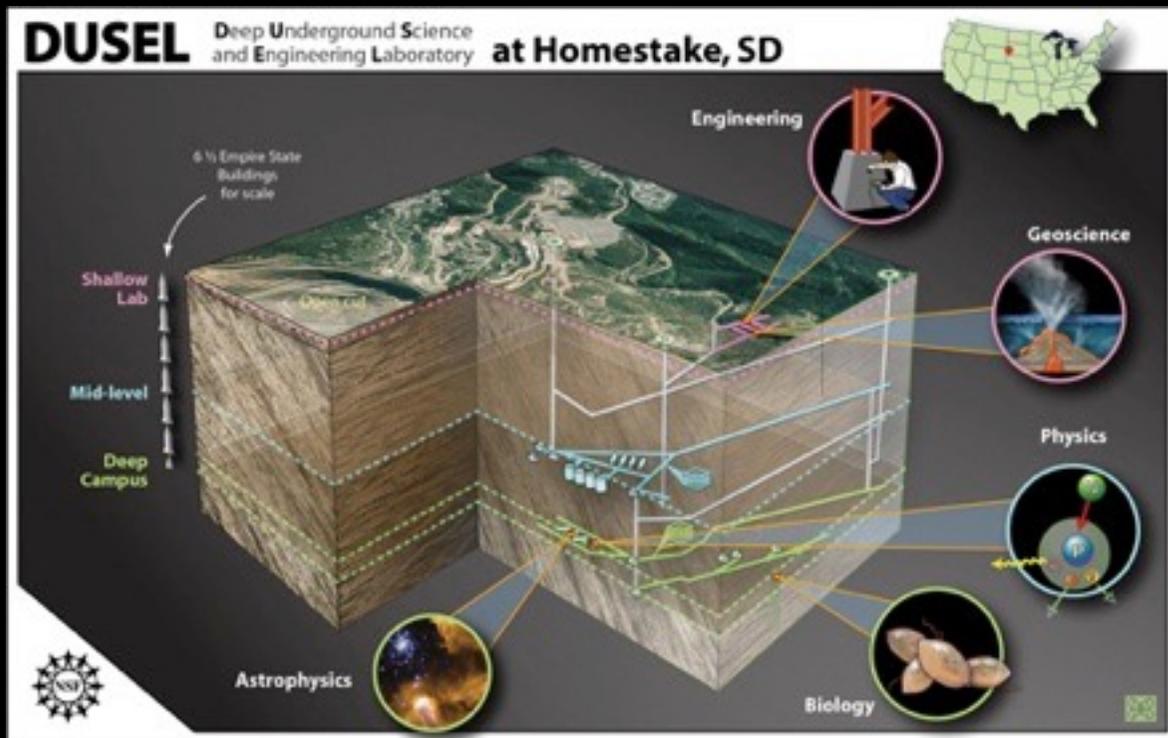
Experiment	Activity / rate	Target
DEAP-3600	≈0.2 μBq / kg	LAr ←
PandaX-II	6.6 μBq / kg	LXe
LUX	66 μHz / kg	LXe
XENON1T	10 μBq / kg	LXe

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

### *Control of Detector Contamination:*

<sup>238</sup>U and <sup>232</sup>Th decays, recoiling progeny and mis-identified alphas, betas mimic nuclear recoils





100,000 events

photon scattering background

10,000 events

natural radioactivity background

1,000 events

neutron scattering background

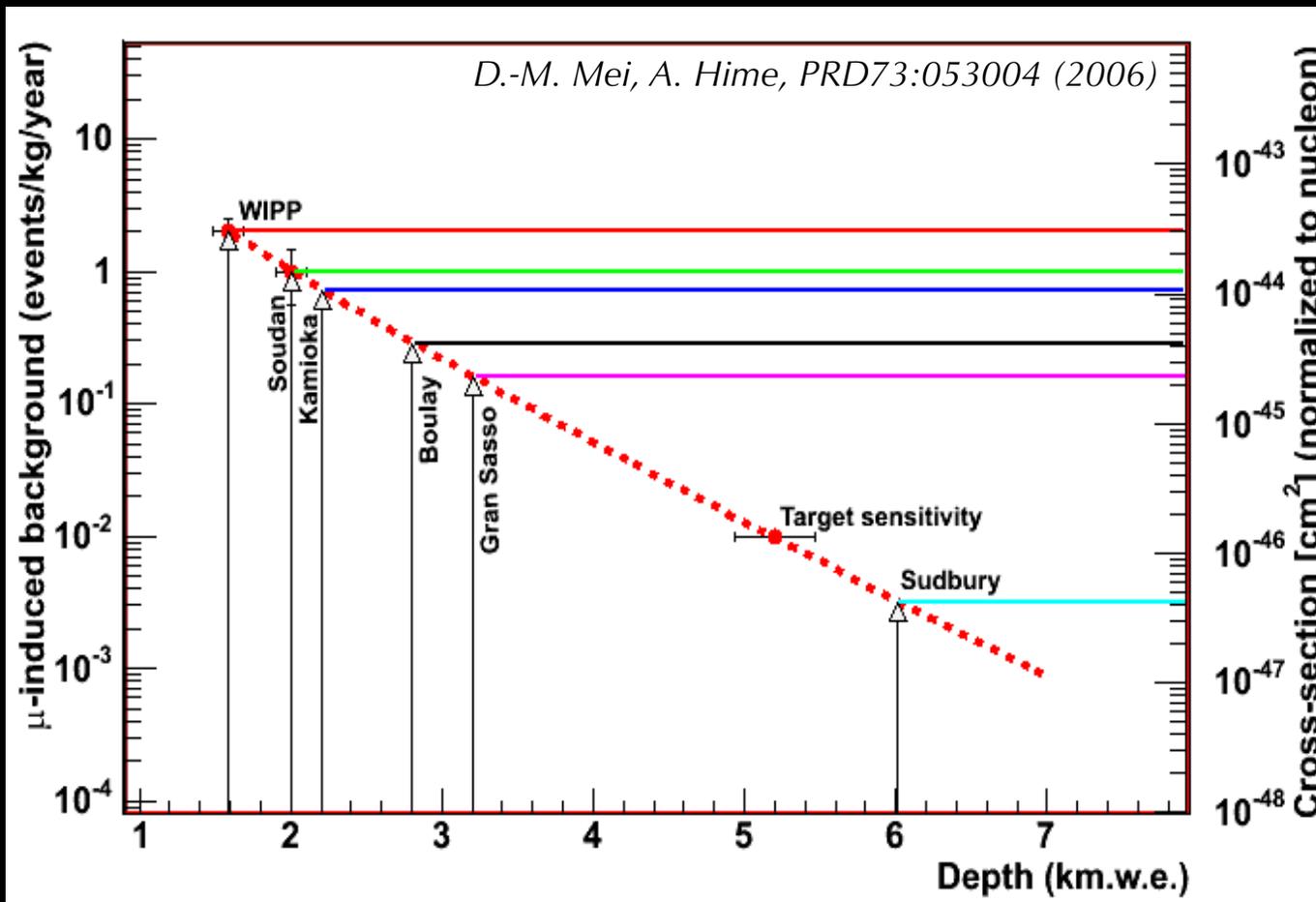
100 events

neutrino scattering background

1 event

smallest dark matter scattering signal?

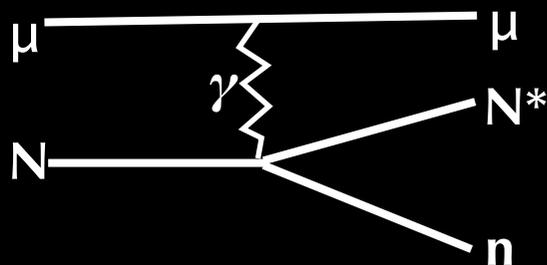
*experiments go 1-2 km underground to shield detectors from neutrons*



+ large, active neutron shielding

Nuclear recoil final state.

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



1 event

100,000 events  
photon scattering background

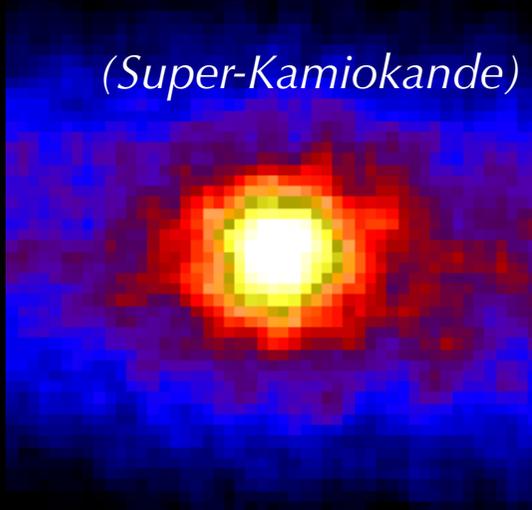
1000 events  
natural radioactivity background

neutron scattering background

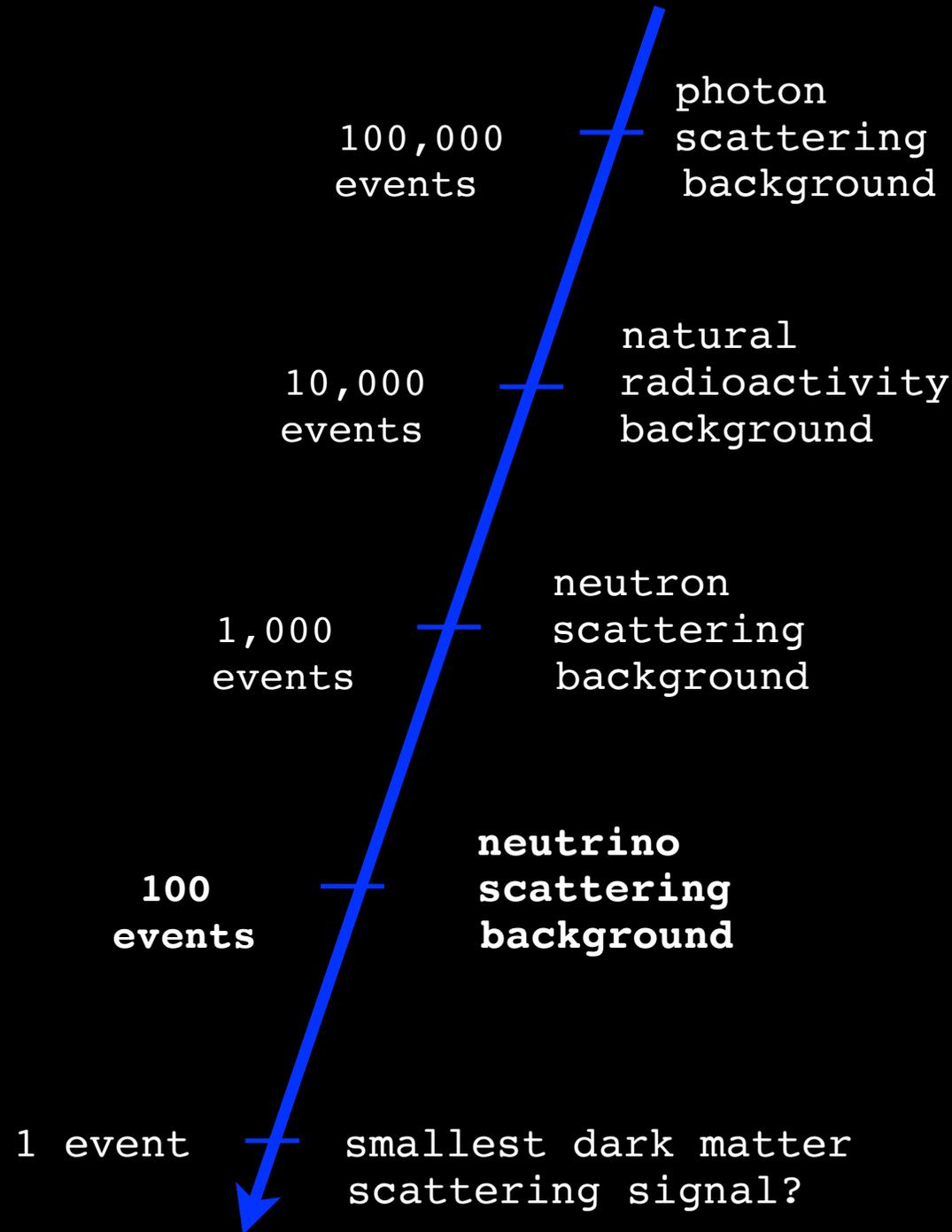
100 events  
neutrino scattering background

smallest dark matter scattering signal?

# Backgrounds



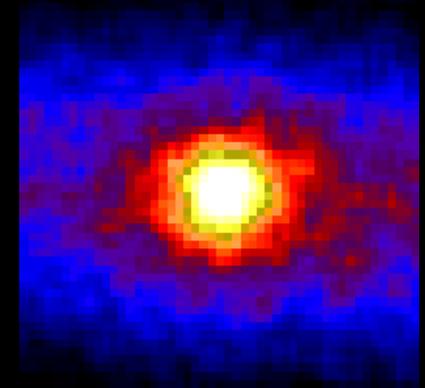
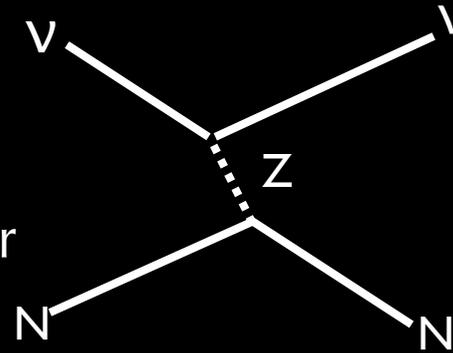
*The sun shines 100,000,000,000 neutrinos/cm<sup>2</sup>/s, 1 in a million events/kg/day are backgrounds to dark matter searches.*



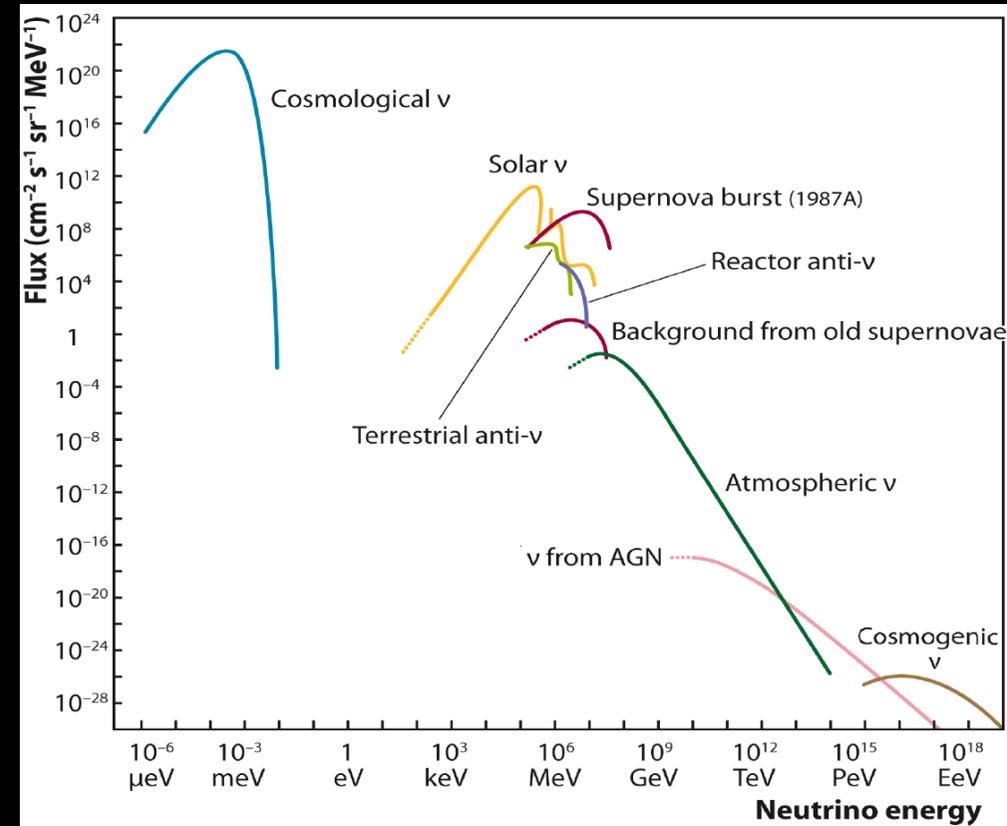
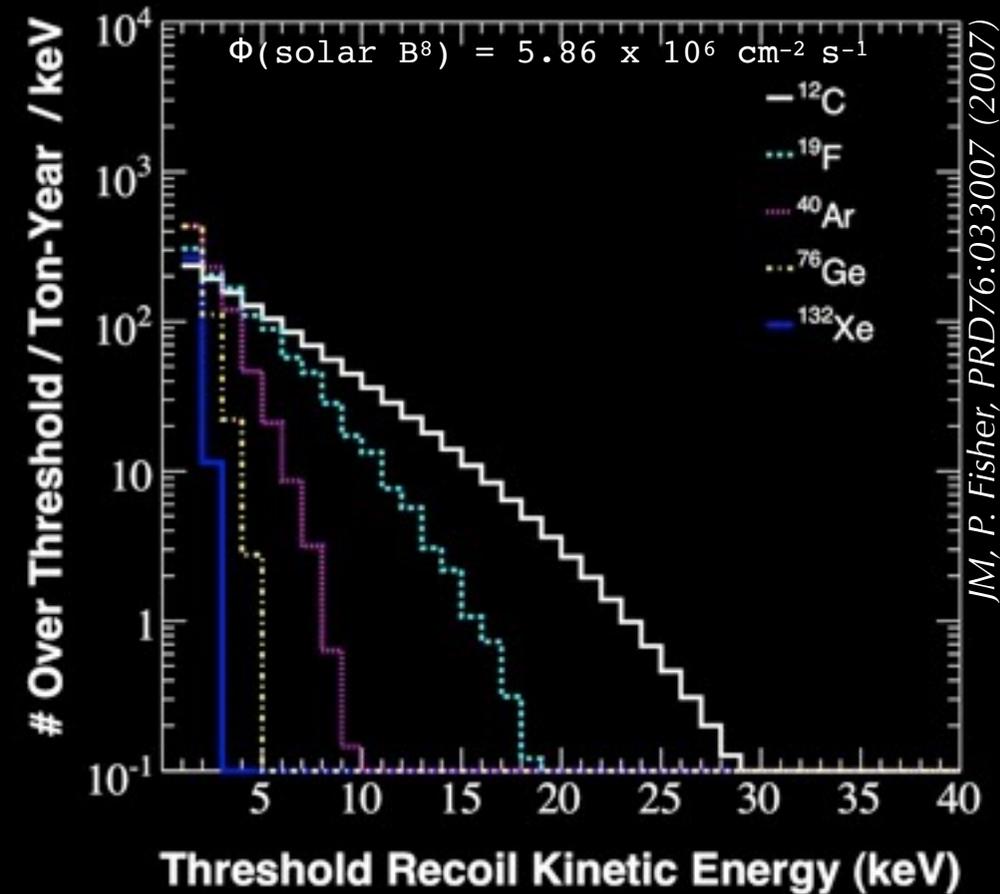
# Irreducible Backgrounds

impossible to shield a detector from coherent neutrino scattering!

A limiting background at the neutrino floor



...but also an *opportunity*.



# Background Sources

*experiments  
are here*

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

10,000  
events

photon  
scattering  
background

1000  
events

radioactive  
decay  
background

100  
events

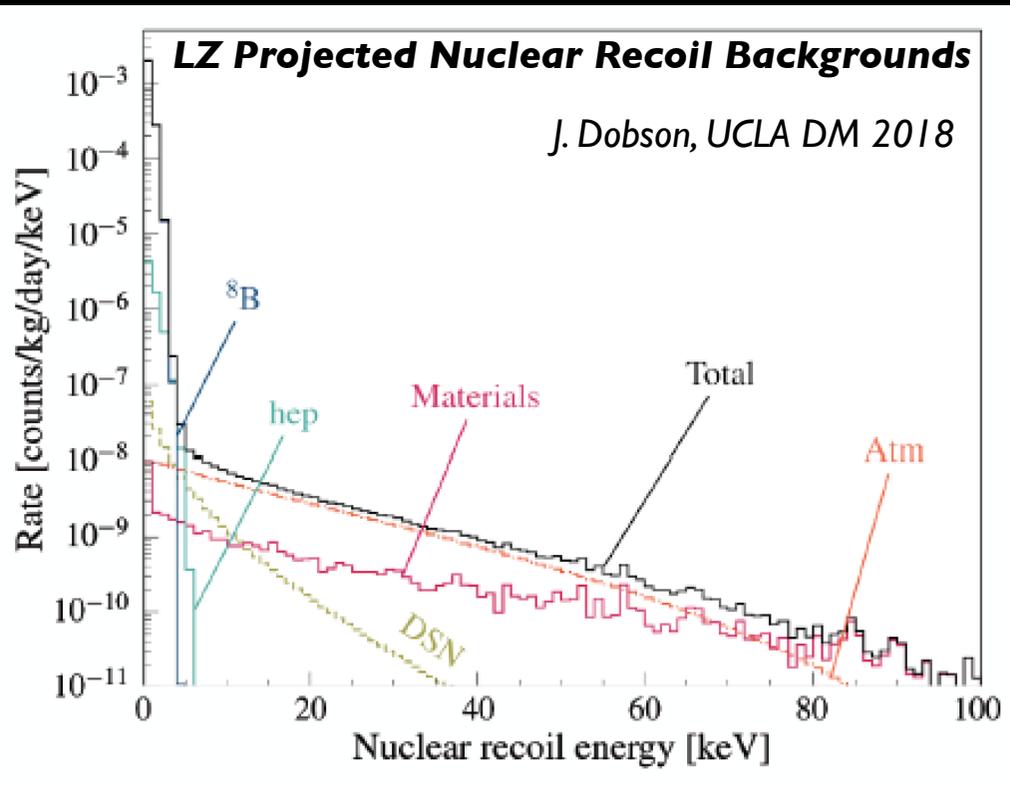
neutron  
scattering  
background

10  
events

neutrino  
scattering  
background

1 event

smallest dark matter  
scattering  
signal?



# Background Sources

*experiments  
are here*

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

10,000  
events

photon  
scattering  
background

1000  
events

radioactive  
decay  
background

100  
events

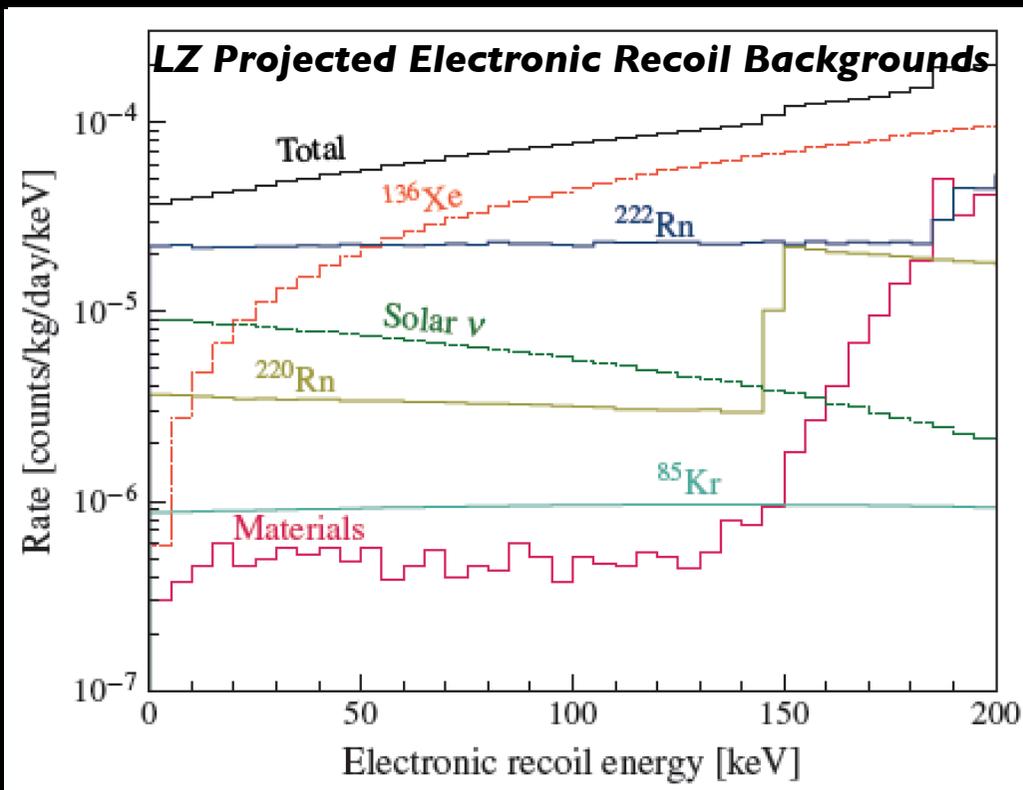
neutron  
scattering  
background

10  
events

neutrino  
scattering  
background

1 event

smallest dark matter  
scattering  
signal?



# Background Strategies

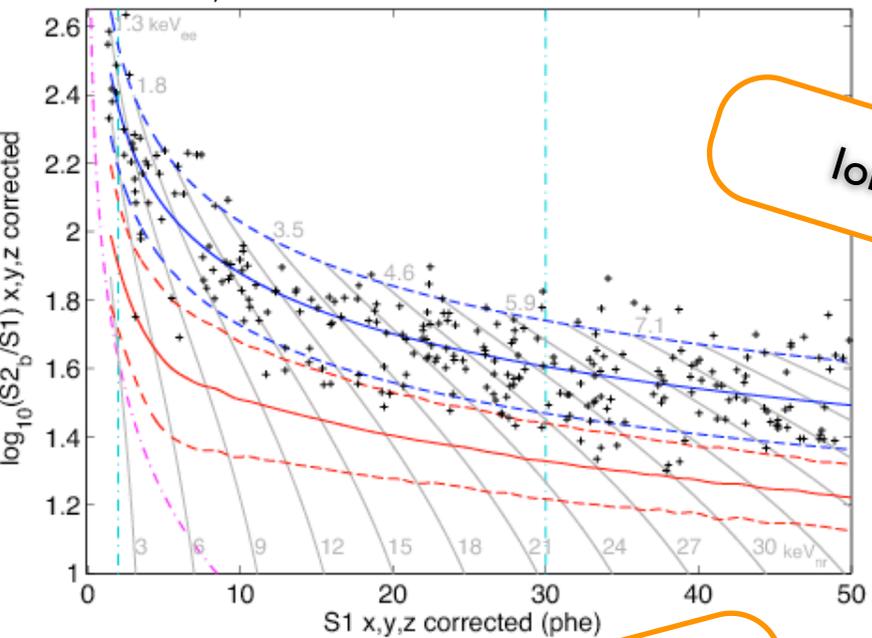


*existing detectors: many targets (Xe, Ge, Ar, NaI, CsI, CaWO<sub>4</sub>, CF<sub>3</sub>I, C<sub>3</sub>F<sub>8</sub>, F ...)*



# Background Strategies

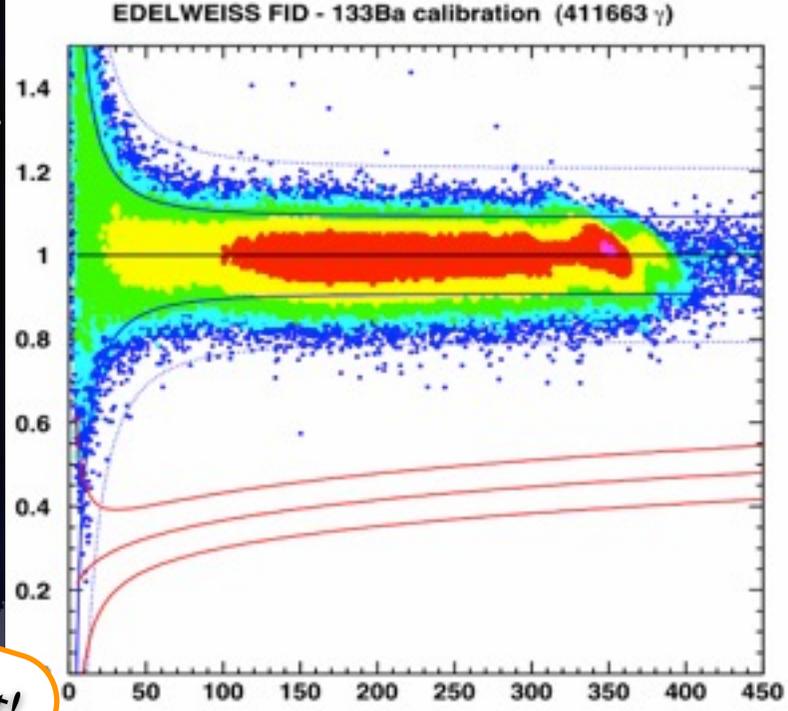
Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



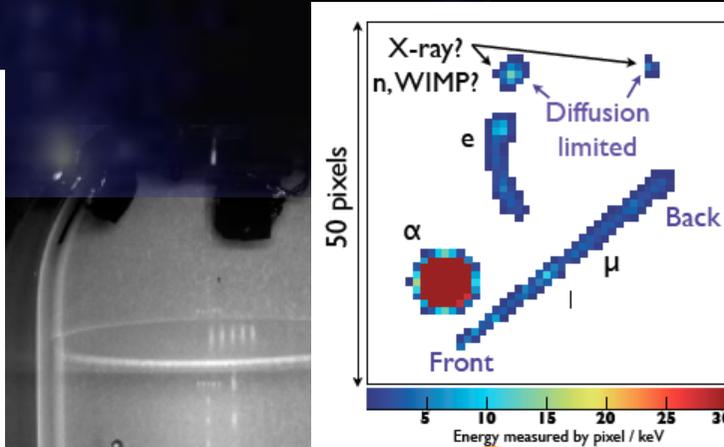
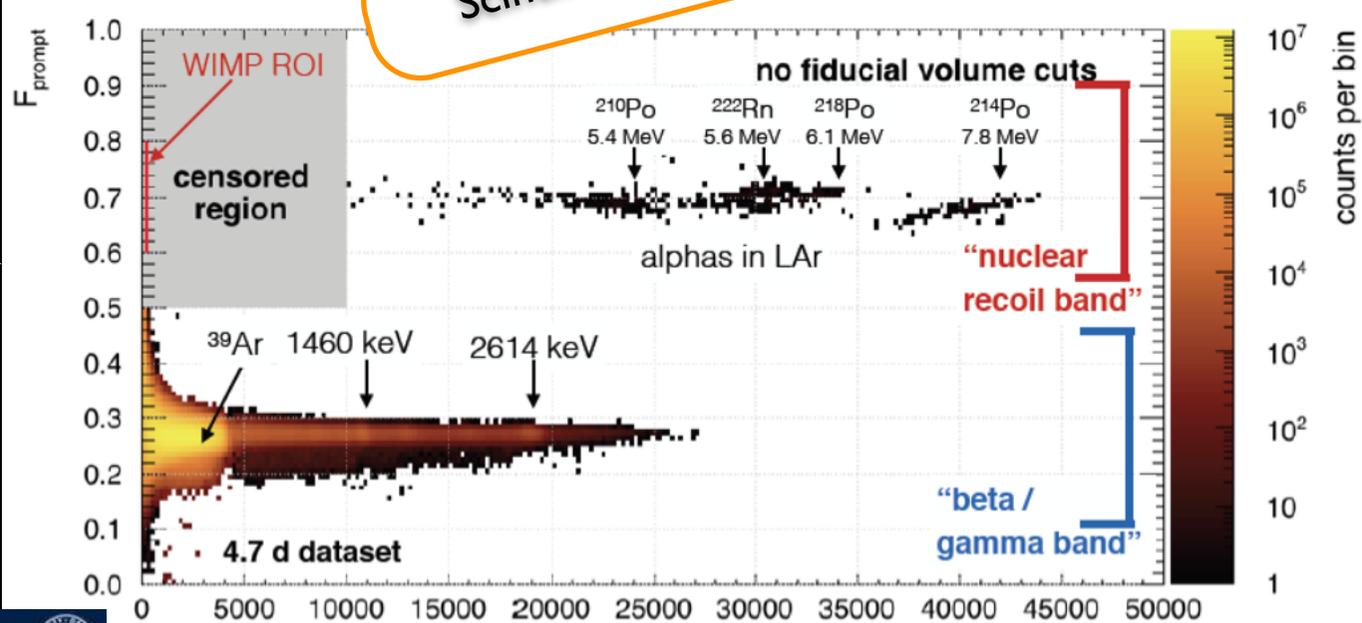
Ionization!

Heat!

Scintillation!



Erecoil (keV)



Topology

Amandruz et al., arXiv:1707.08042

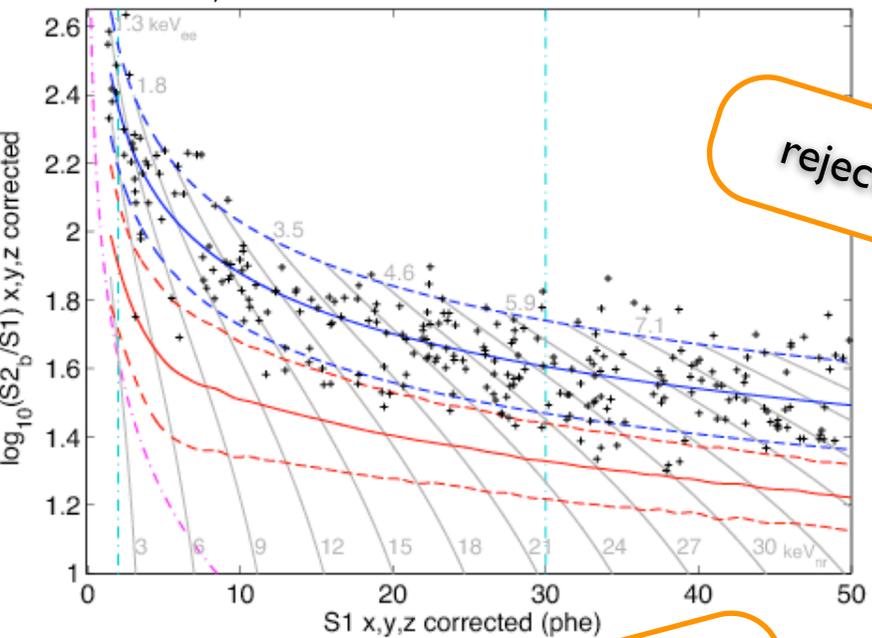


Jocelyn Monroe

$E_{\text{recoil}} \text{ (qPE)}$

# Background Strategies

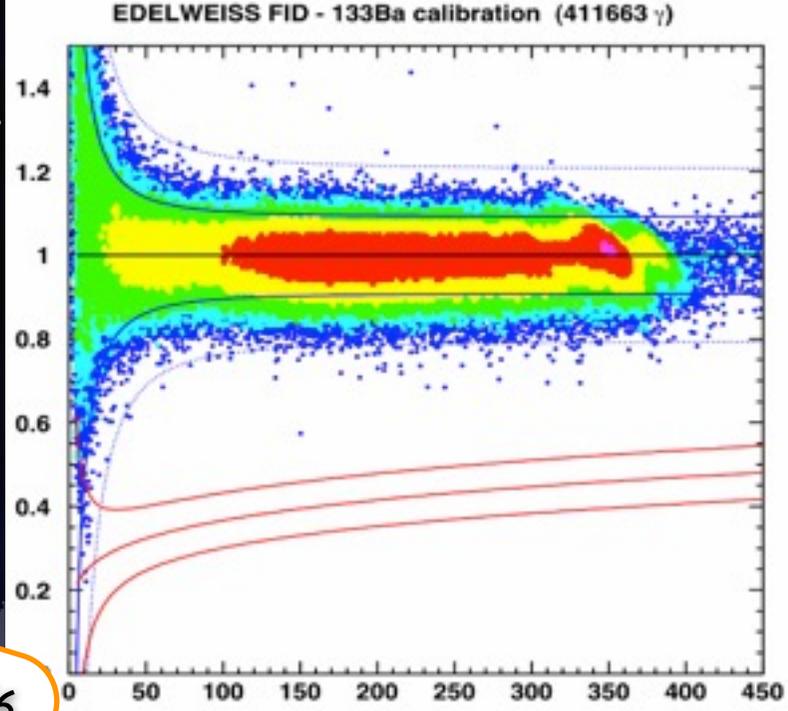
Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



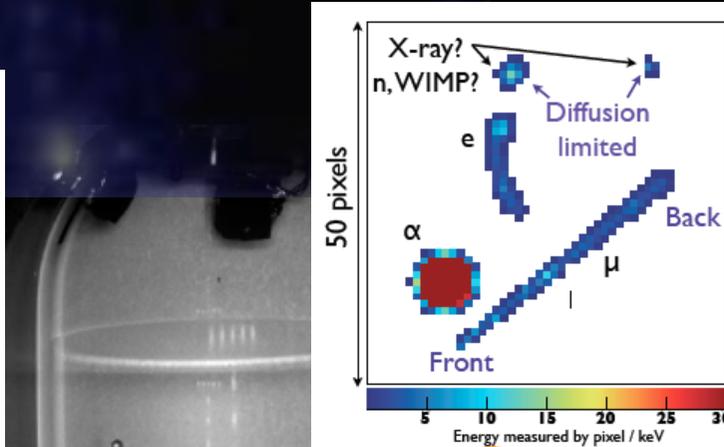
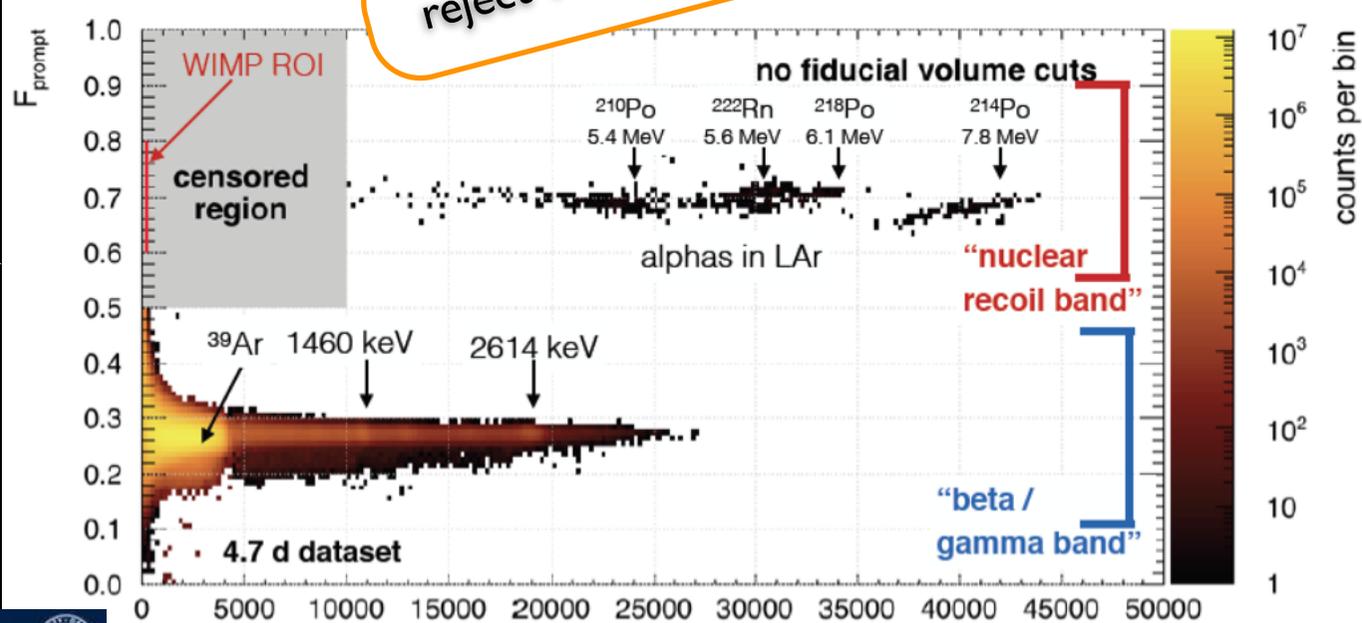
reject I in >IE3

>IE6

reject I in >IE9



Erecoil (keV)



>IE2

Amandruz et al., arXiv:1707.08042



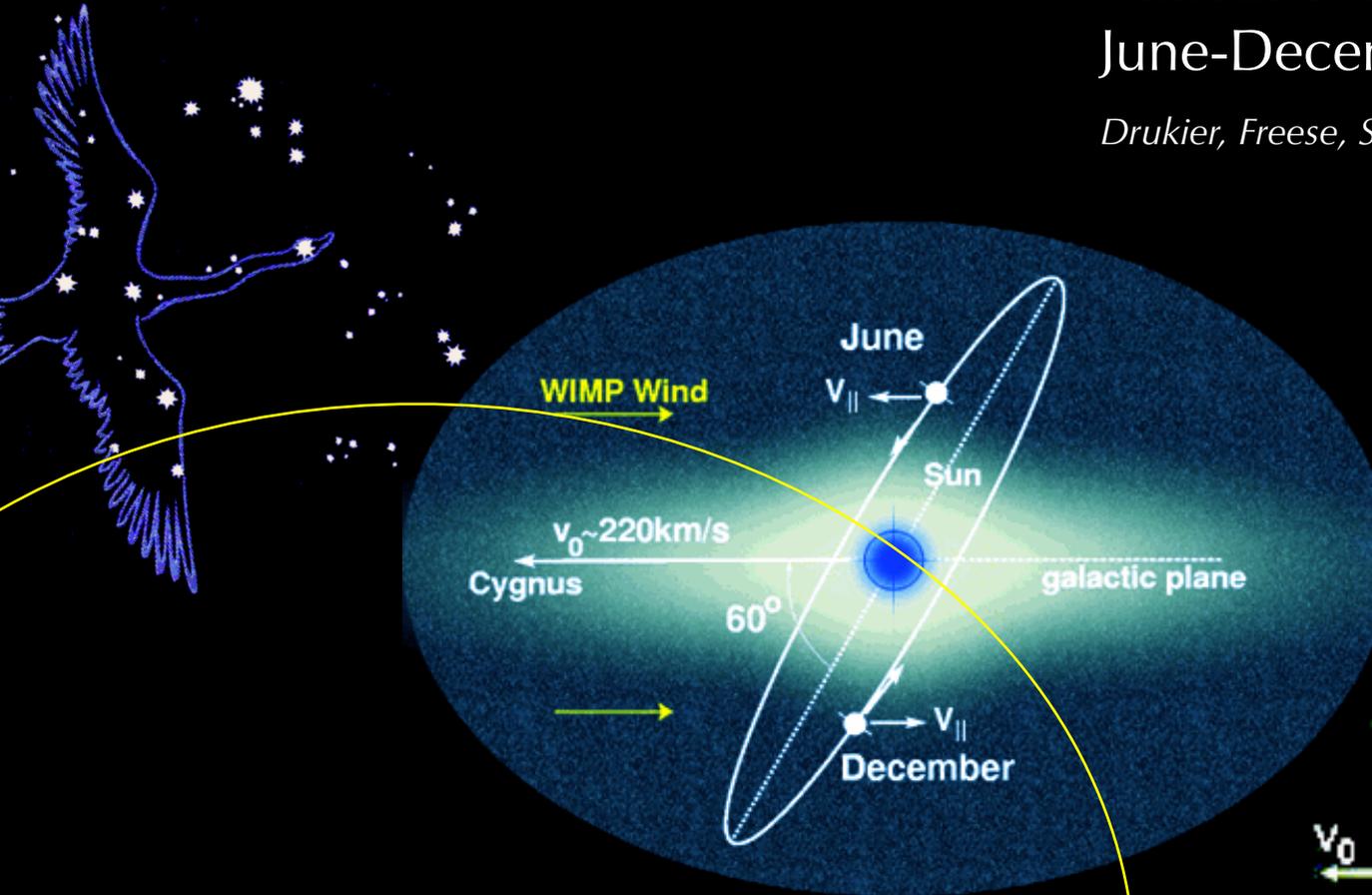
Jocelyn Monroe

Erecoil (qPE)

# Modulation Signatures

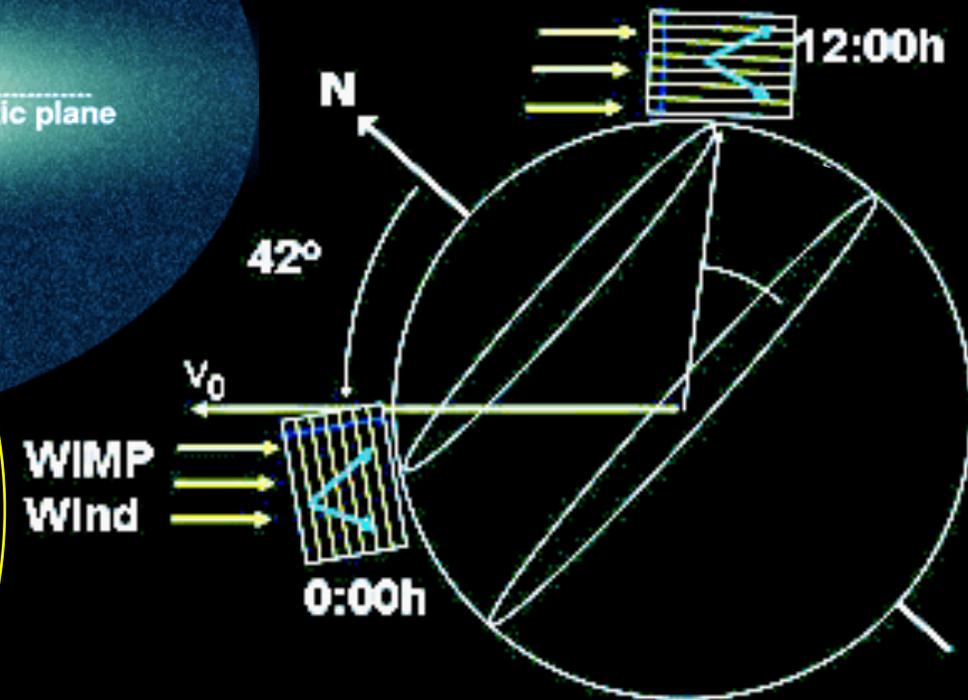
Annual event rate modulation:  
June-December asymmetry  $\sim 2-10\%$ .

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



Sidereal direction modulation:  
asymmetry  $\sim 20-100\%$  in  
forward-backward event rate.

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



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

