

Direct Dark Matter Detection - Part II

Julien Billard

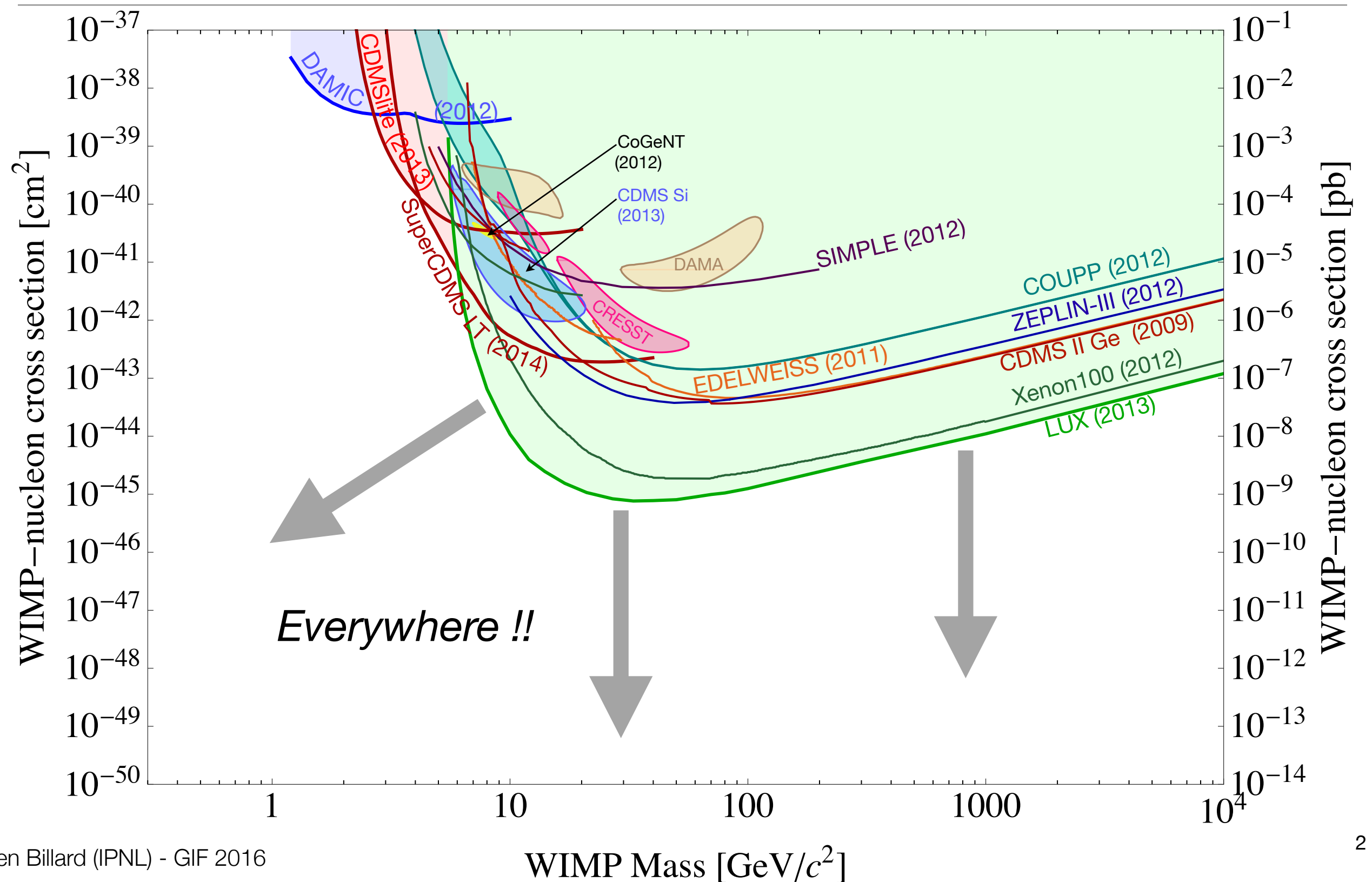
Institut de Physique Nucléaire de Lyon / CNRS / Université Lyon 1

Ecole de GIF

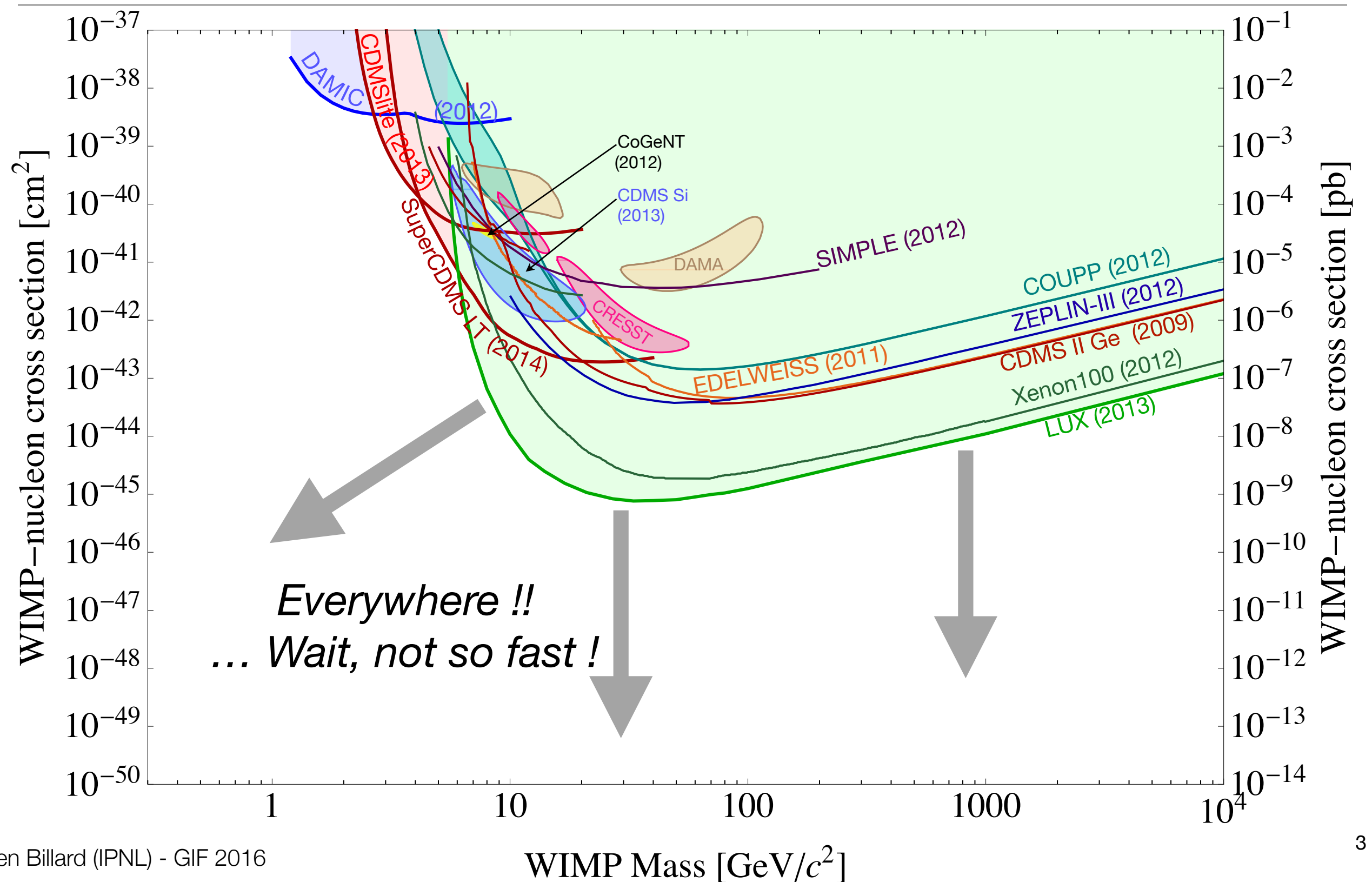
September 19-24, 2016



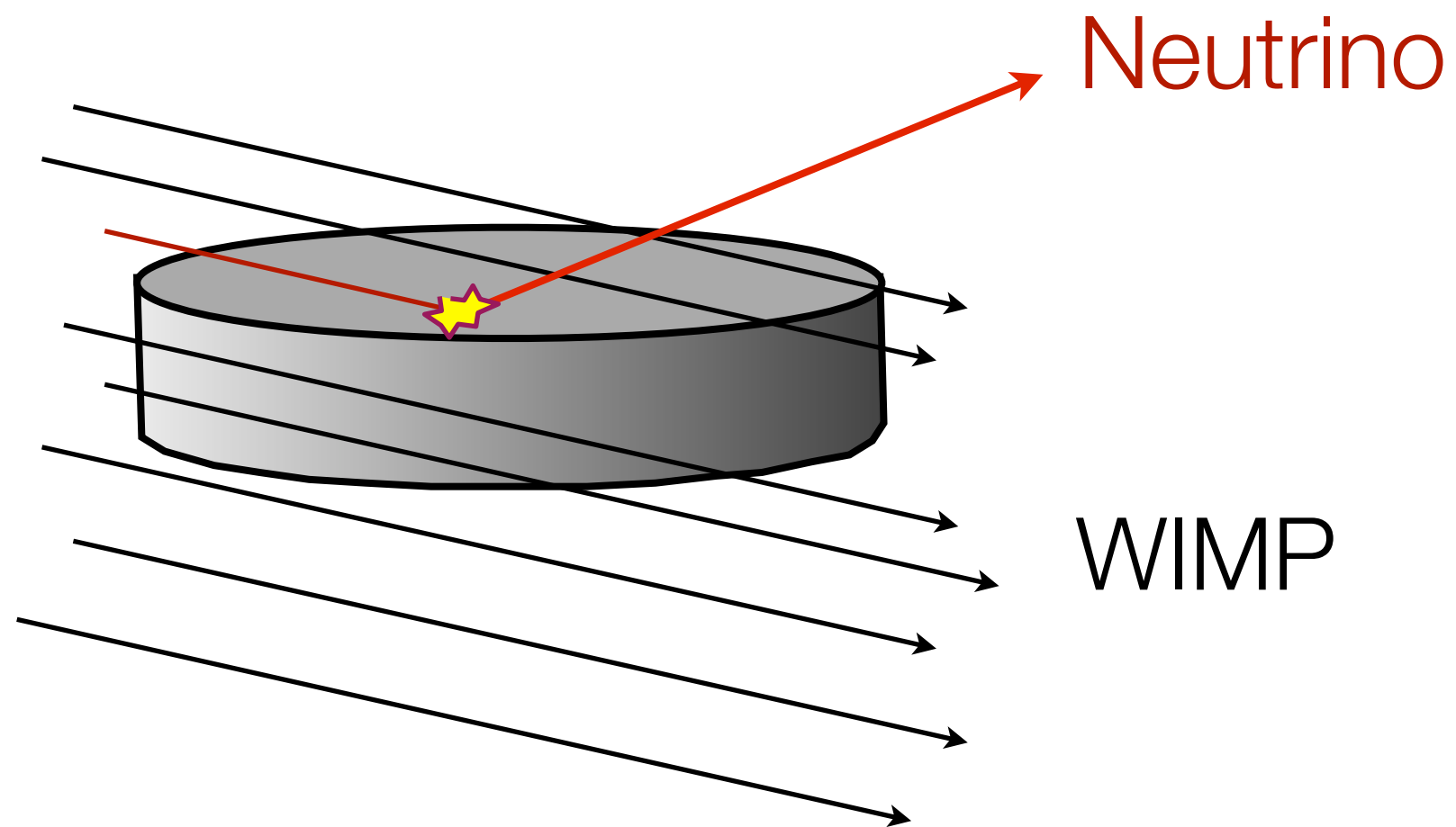
Where to look for Dark Matter?



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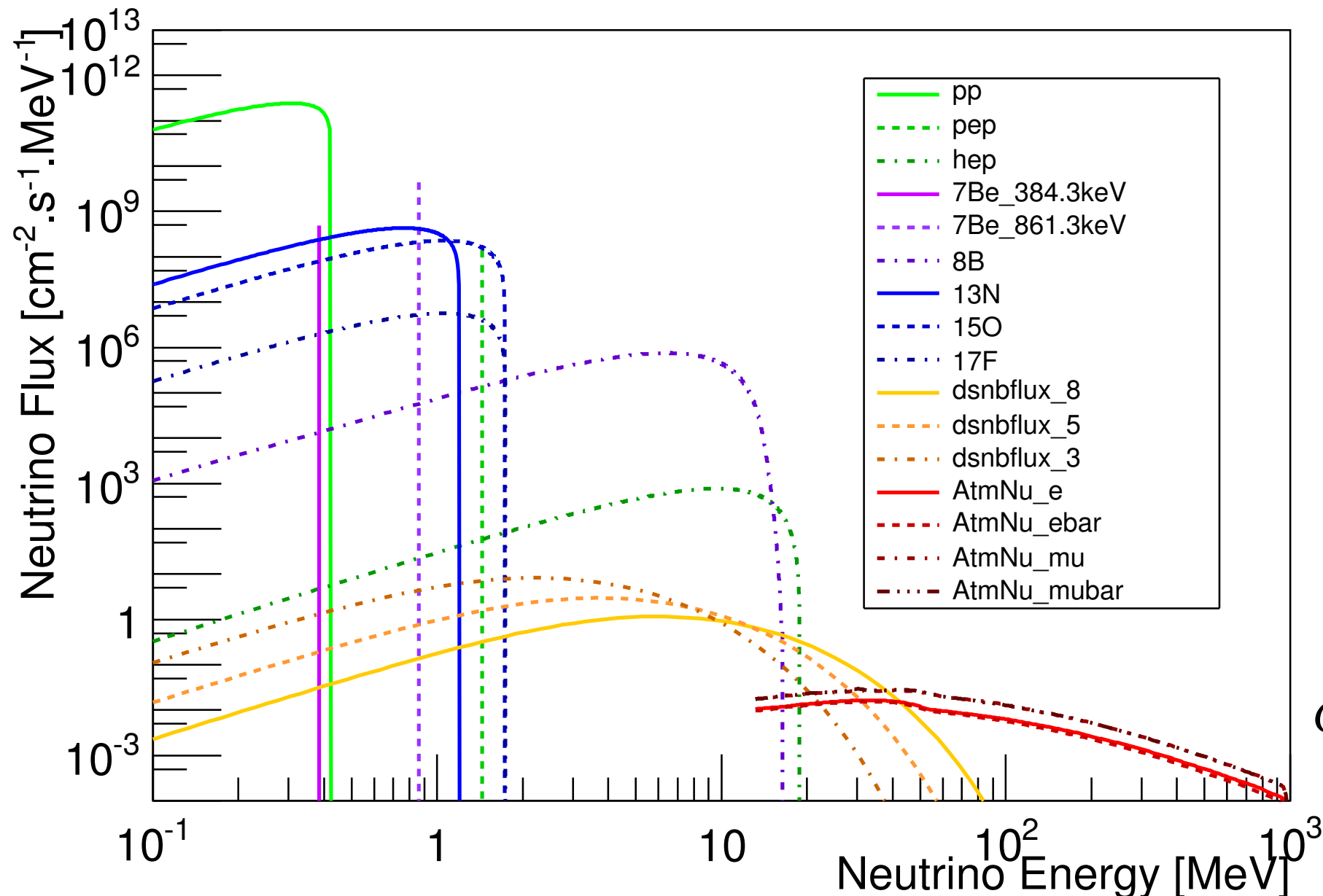
The neutrino background



- Based on:
- J. Billard, L. Strigari and E. Figueroa-Feliciano, PRD 89 (2014)
 - F. Ruppin, J. Billard, L. Strigari and E. Figueroa-Feliciano, PRD 90 (2014)
 - C. O'Hare, J. Billard, E. Figueroa-Feliciano, A. Green and L. Strigari, PRD 92 (2015)

The neutrino background

The neutrino flux at an Earth based detector:

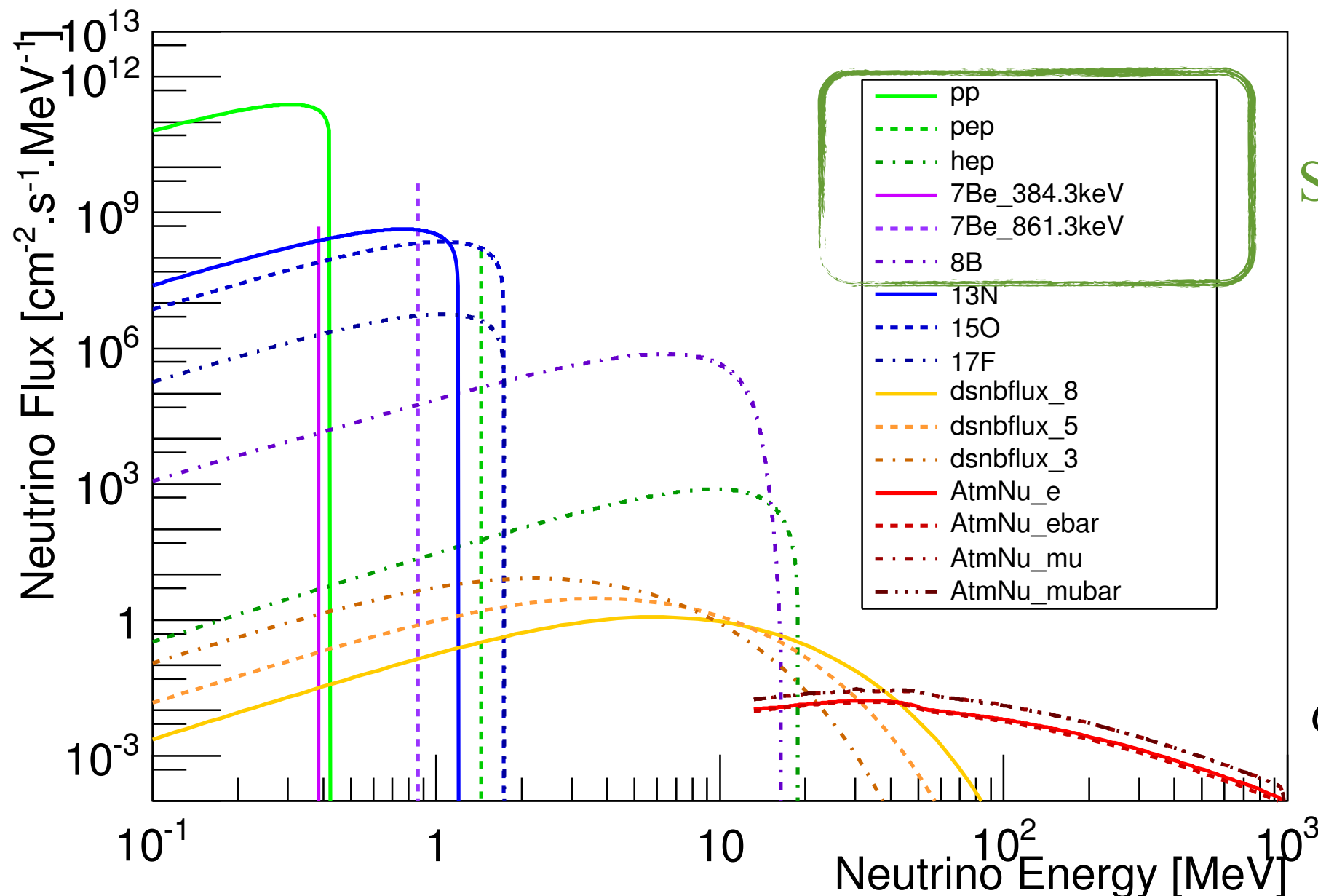


ν type	E_{ν}^{max} (MeV)	$E_{\text{rGe}}^{\text{max}}$ (keV)	ν flux ($\text{cm}^{-2} \cdot \text{s}^{-1}$)
pp	0.42341	5.30×10^{-3}	$5.99 \pm 0.06 \times 10^{10}$
${}^7\text{Be}$	0.861	0.0219	$4.84 \pm 0.48 \times 10^9$
pep	1.440	0.0613	$1.42 \pm 0.04 \times 10^8$
${}^{15}\text{O}$	1.732	0.0887	$2.33 \pm 0.72 \times 10^8$
${}^8\text{B}$	16.360	7.91	$5.69 \pm 0.91 \times 10^6$
hep	18.784	10.42	$7.93 \pm 1.27 \times 10^3$
DSNB	91.201	245	85.5 ± 42.7
Atm.	981.748	27.7×10^3	10.5 ± 2.1

Geo neutrinos are negligible

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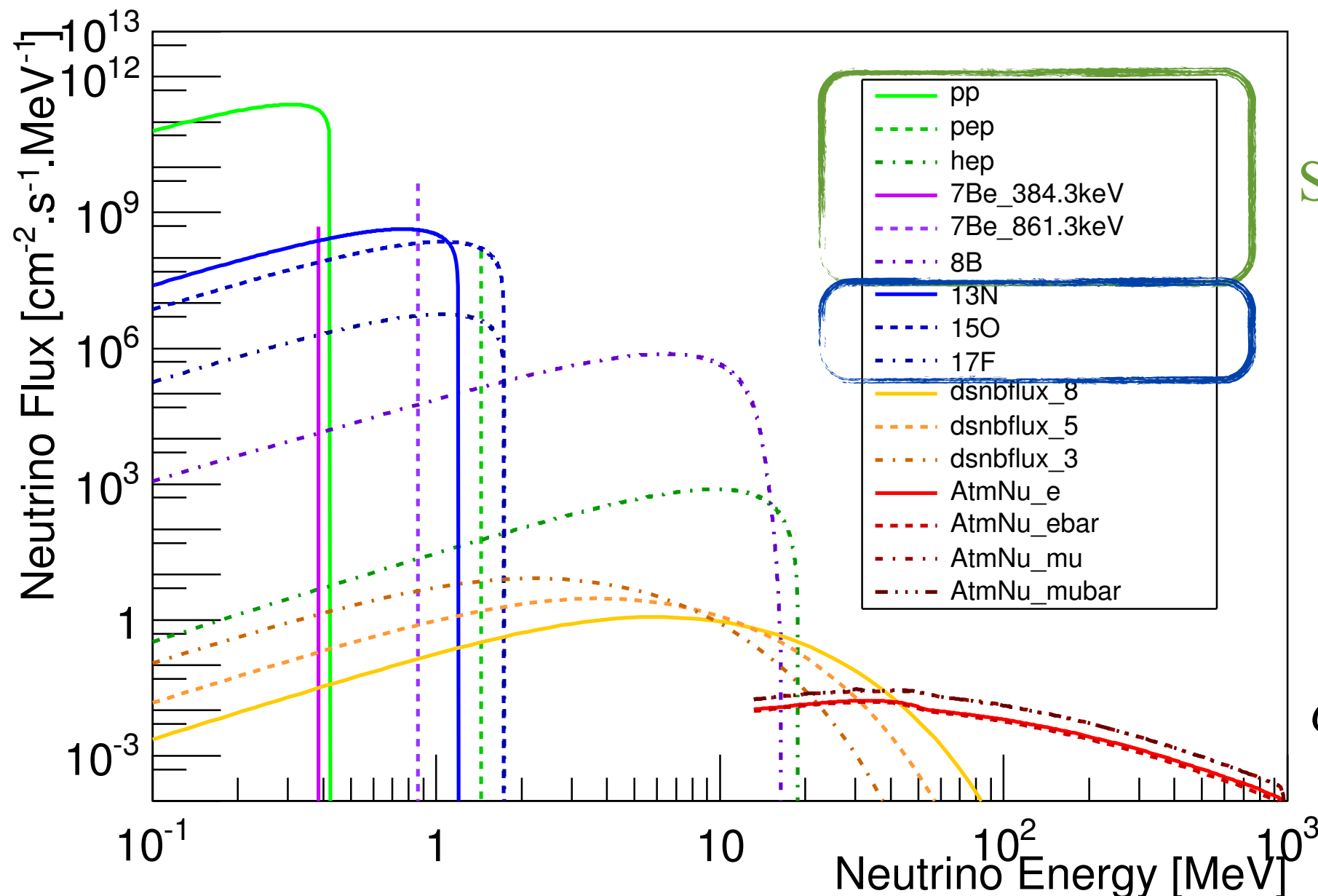
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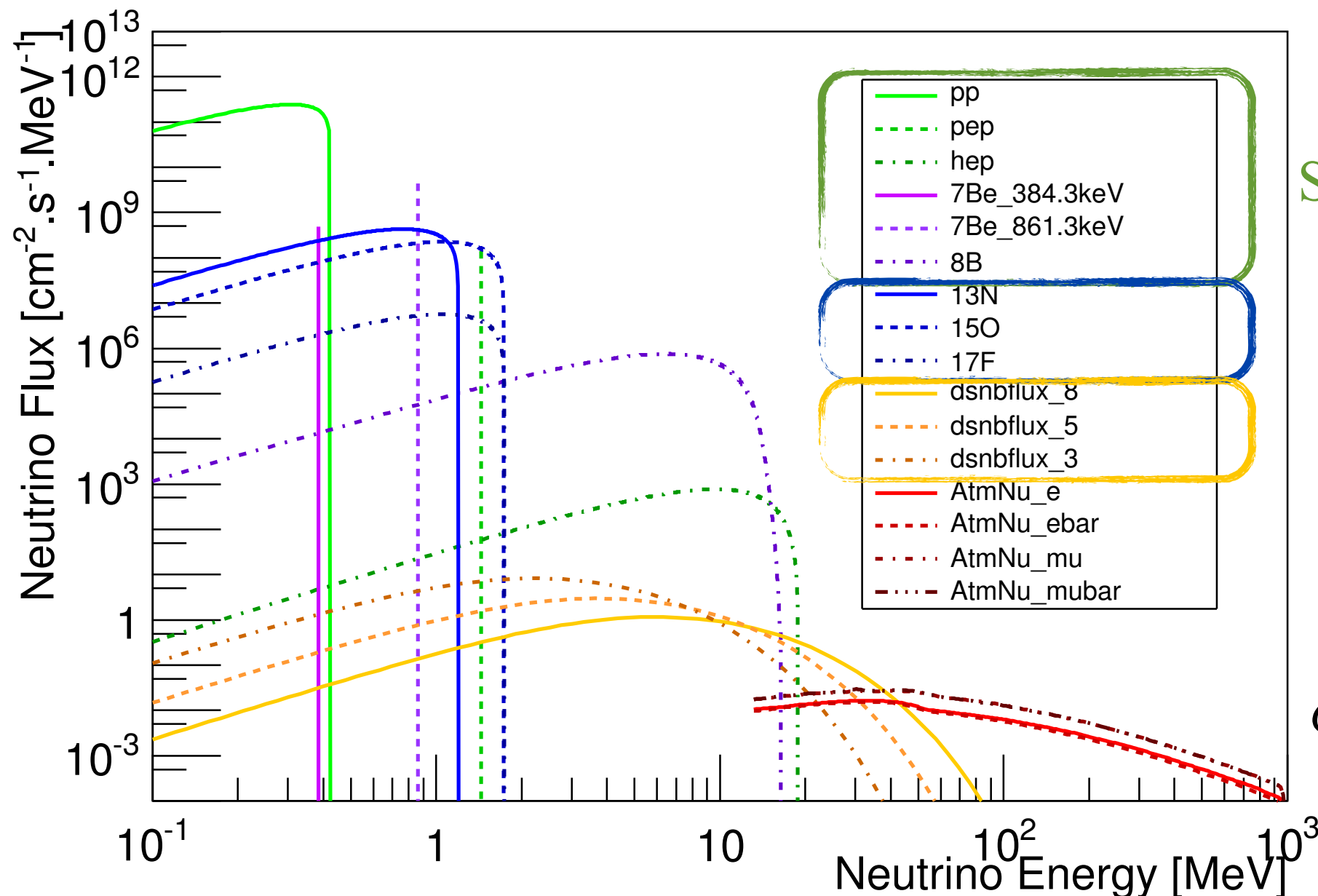
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Solar neutrinos: CNO

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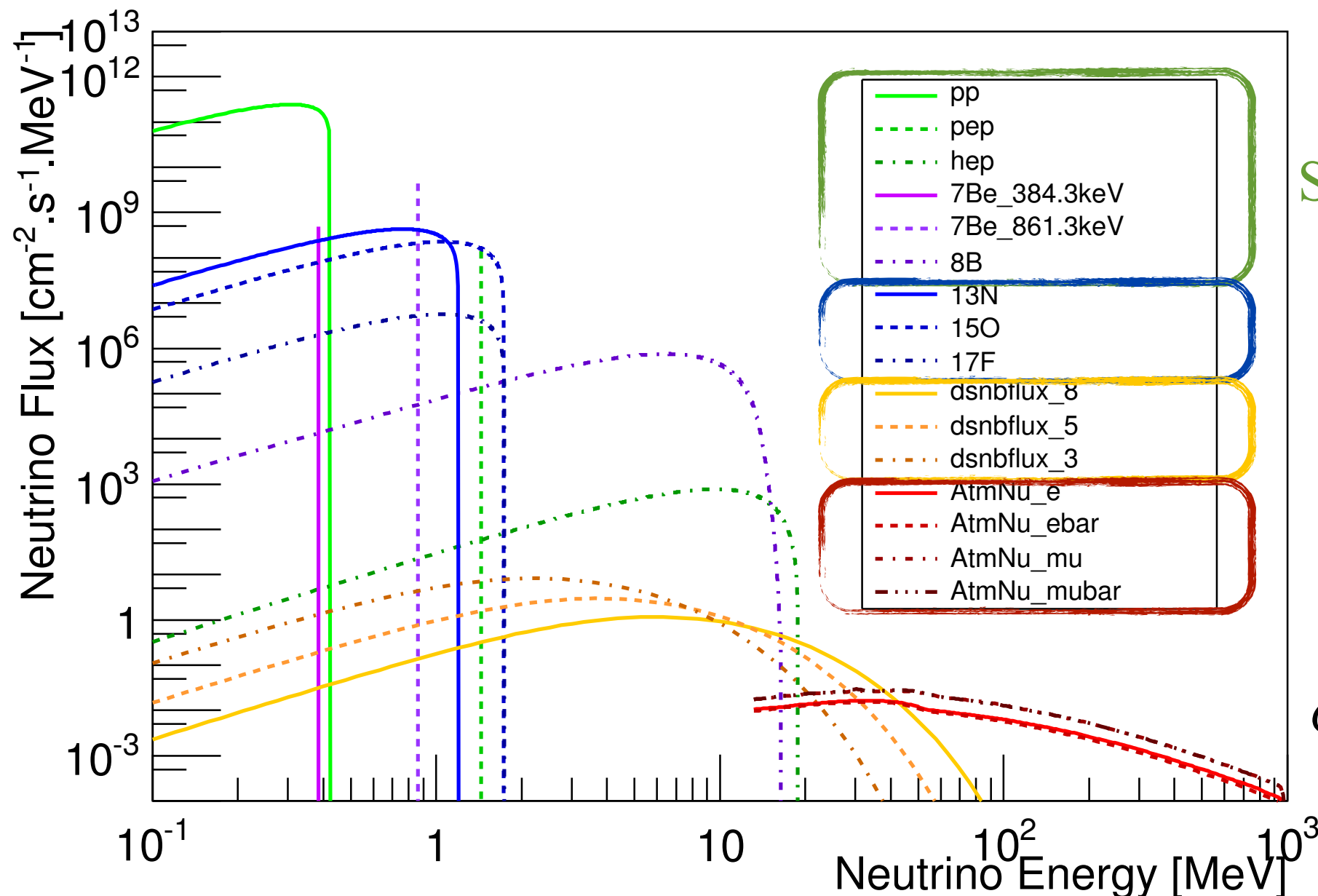
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DSNB neutrinos

Atm. neutrinos

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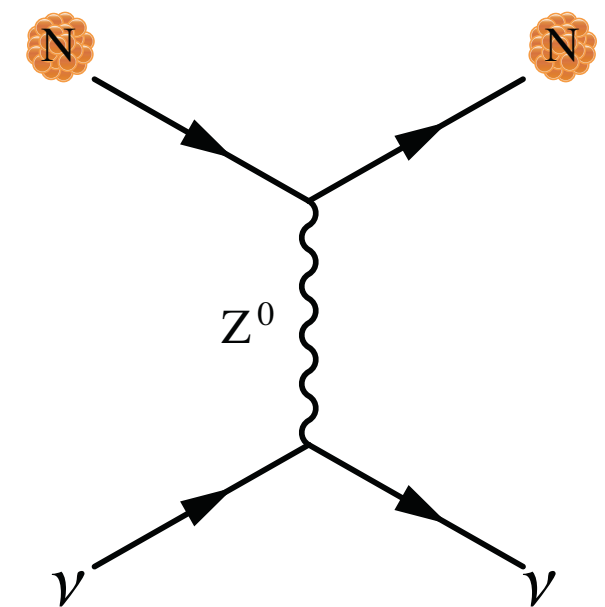
Neutrino interactions with Dark Matter experiment target material

- Coherent neutrino-nucleus elastic scattering (CNS):

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2} \right) F^2(E_r)$$

- σ : Cross Section
- E_r : Recoil Energy
- E_ν : Neutrino Energy
- G_f : Fermi Constant
- Q_w : Weak Charge $\sim A$
- m_N : Atomic Mass

Nuclear recoil



Neutral current

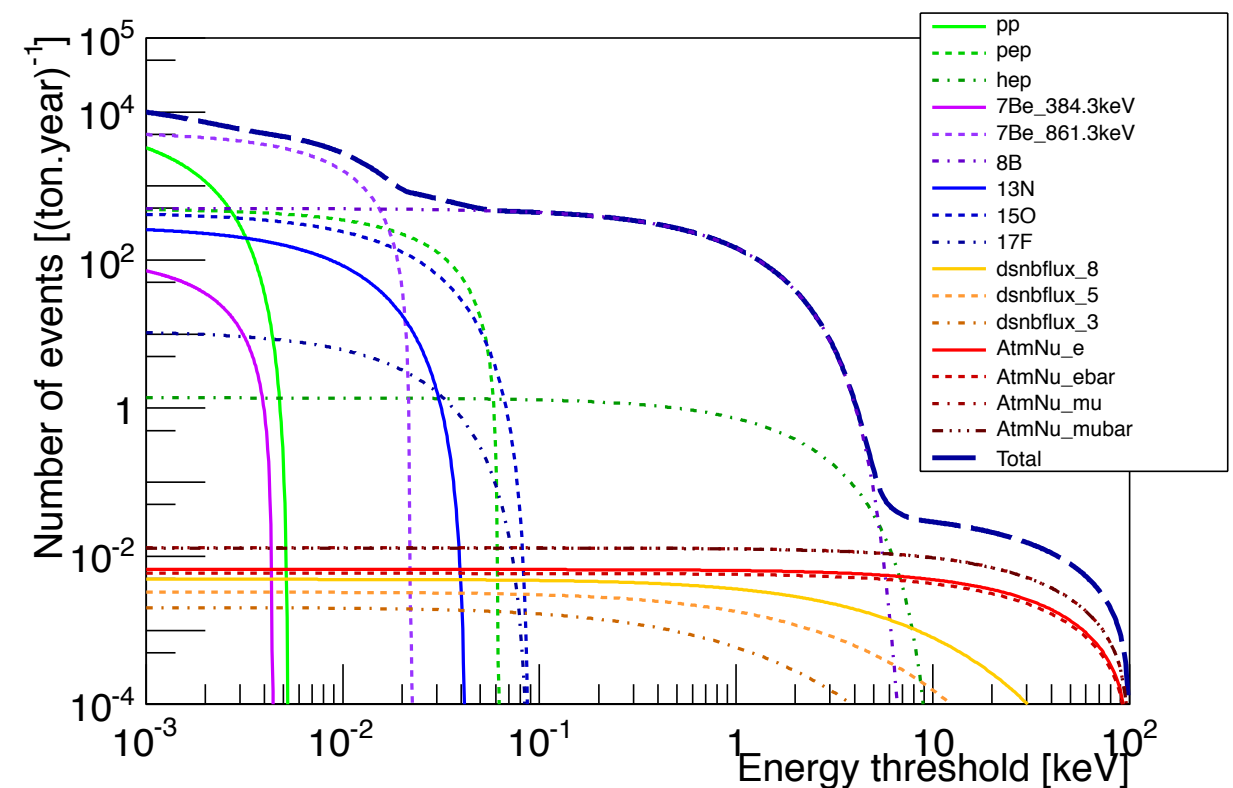
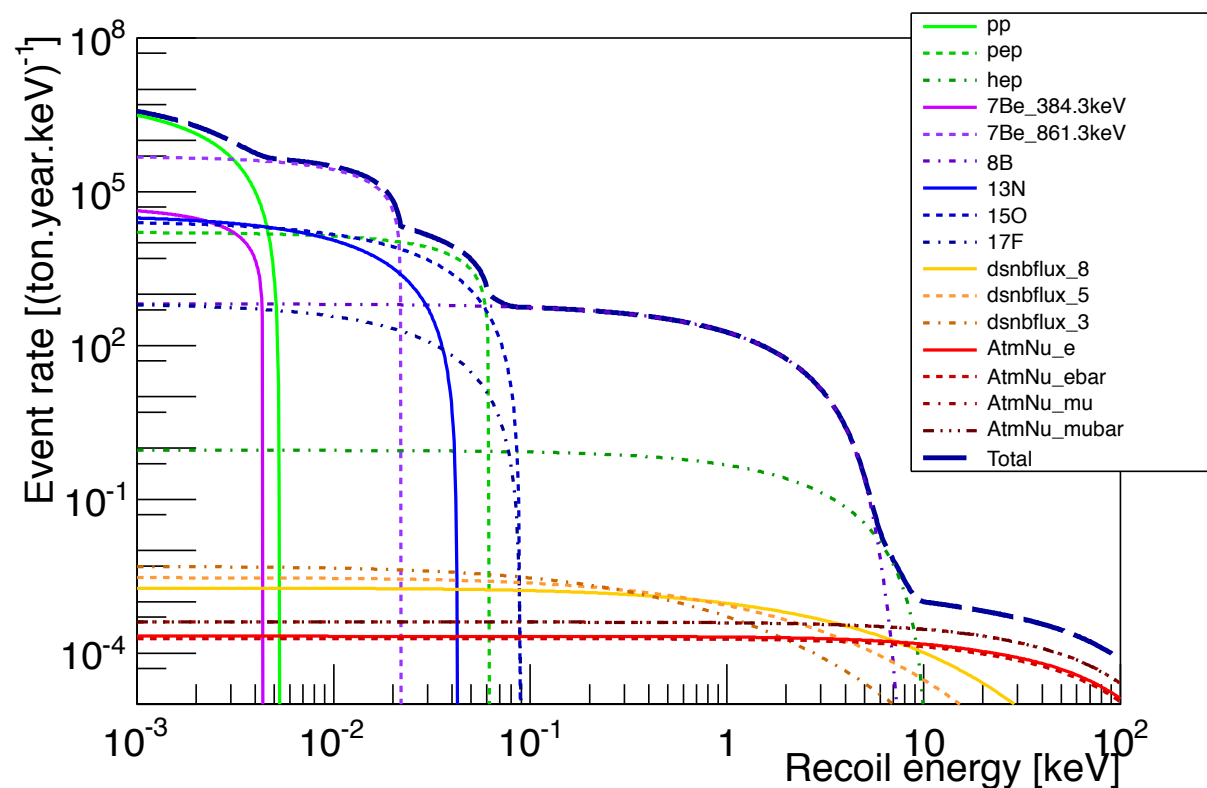
No flavor-specific terms!!!
Same rate for ν_e , ν_μ , and ν_τ

Ultimate background to direct detection

The neutrino background

Neutrino interactions with Dark Matter experiment target material

- Coherent neutrino-nucleus elastic scattering (CNS):

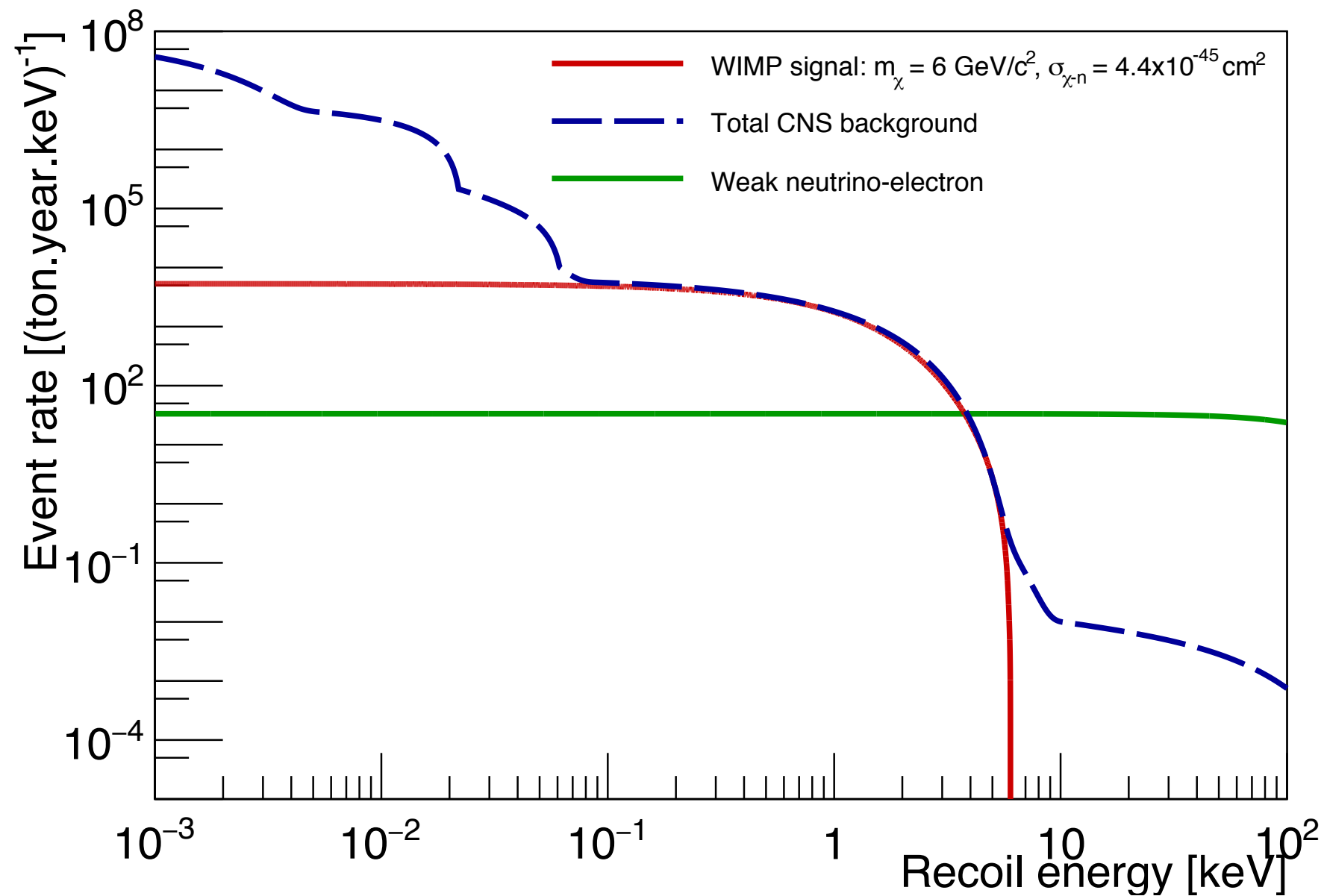


Depending on the Energy threshold, the CNS background can be very high!

- 1 keV threshold -> 100 evt/ton/year on Ge detector

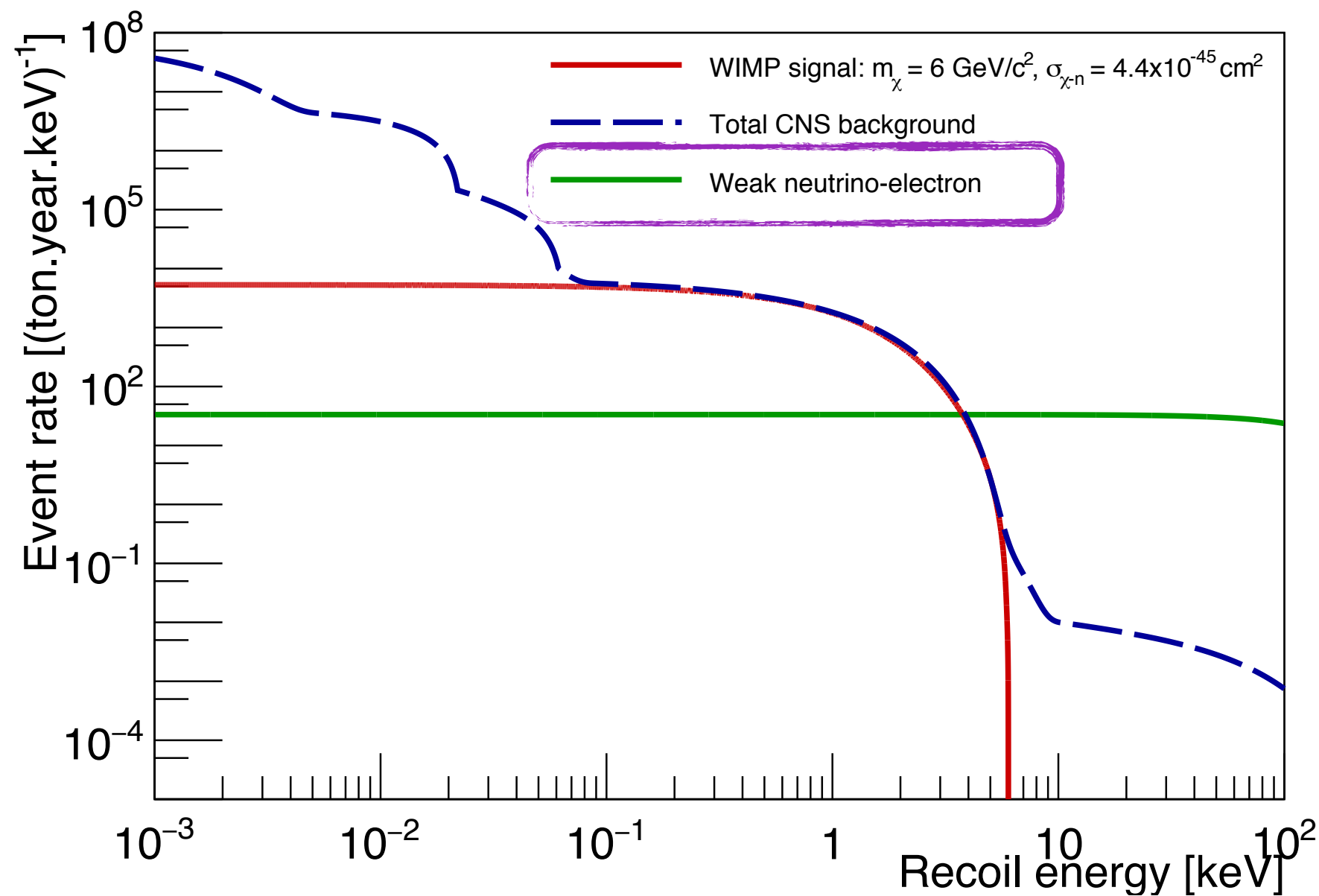
The neutrino background

Neutrino interactions with Dark Matter experiment target material



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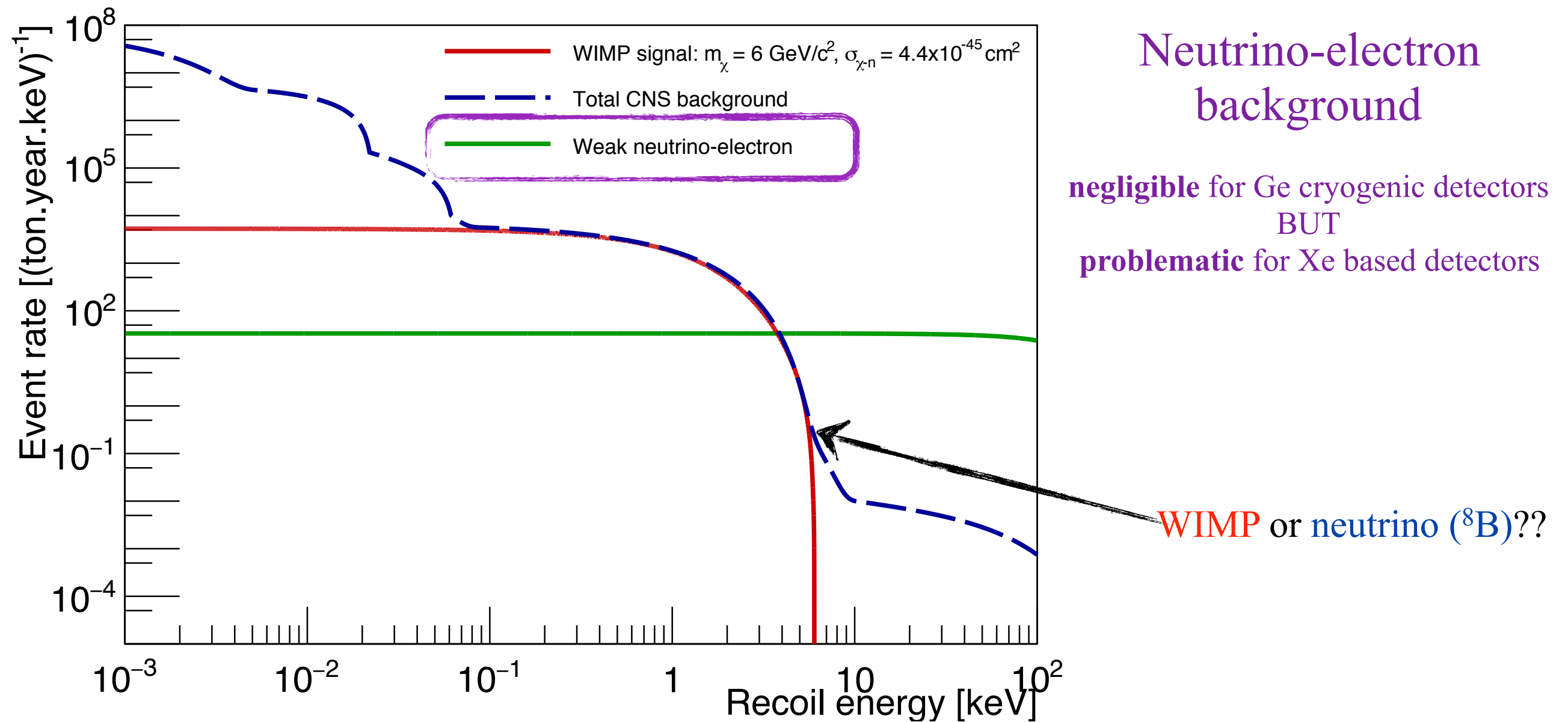


Neutrino-electron
background

negligible for Ge cryogenic detectors
BUT
problematic for Xe based detectors

The neutrino background

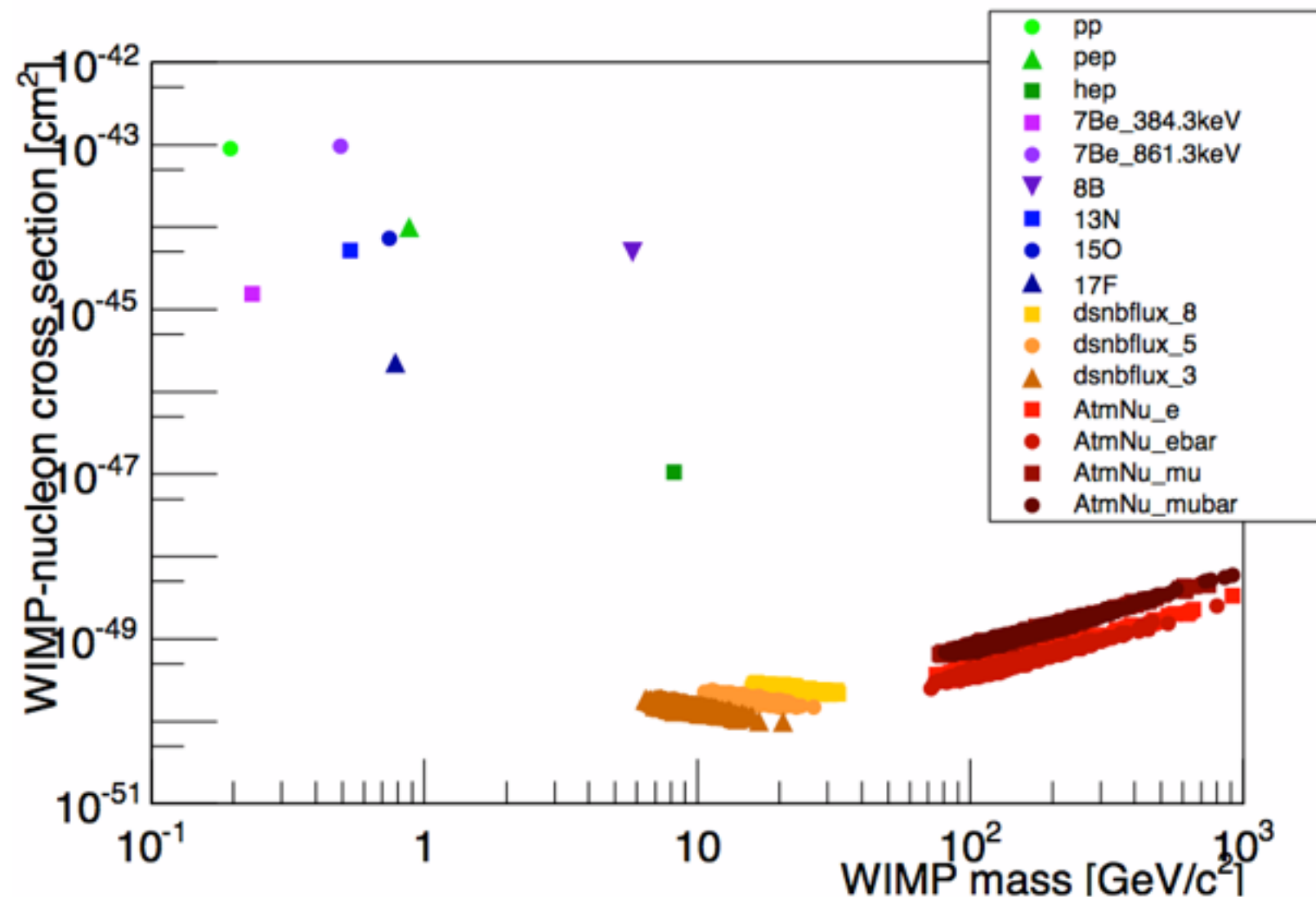
Neutrino interactions with Dark Matter experiment target material



The neutrino background

WIMP and neutrino equivalence:

- ➔ Using a maximum likelihood analysis where we fit a WIMP hypothesis to the different neutrino components we can determine the *WIMP-neutrino equivalent models*



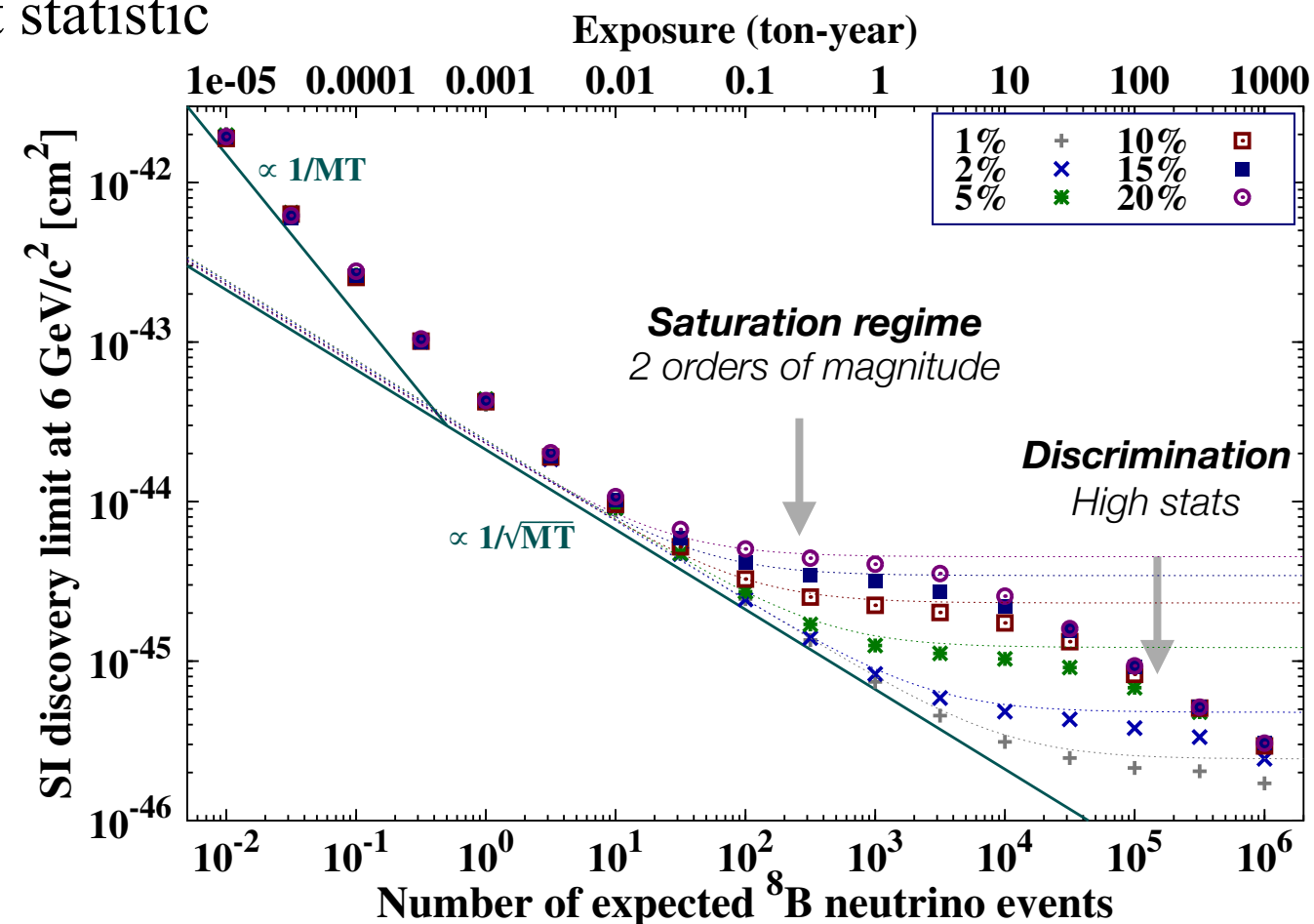
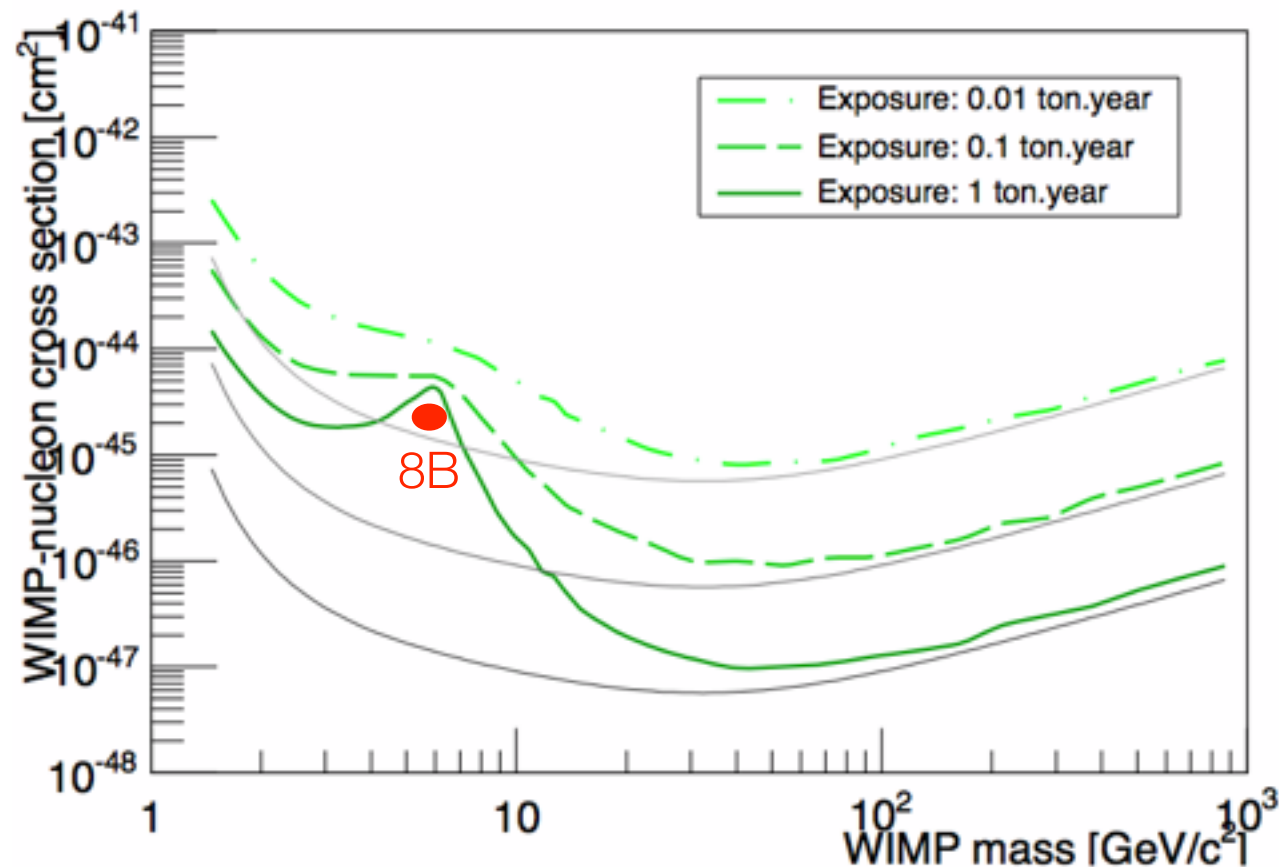
Xe target, no energy threshold, perfect energy resolution

The neutrino background

(F. Ruppin et al., PRD 90 (2014))

WIMP discovery potential:

- 90% probability to get a 3 sigma or more WIMP discovery significance
- Computed using a profile likelihood ratio test statistic

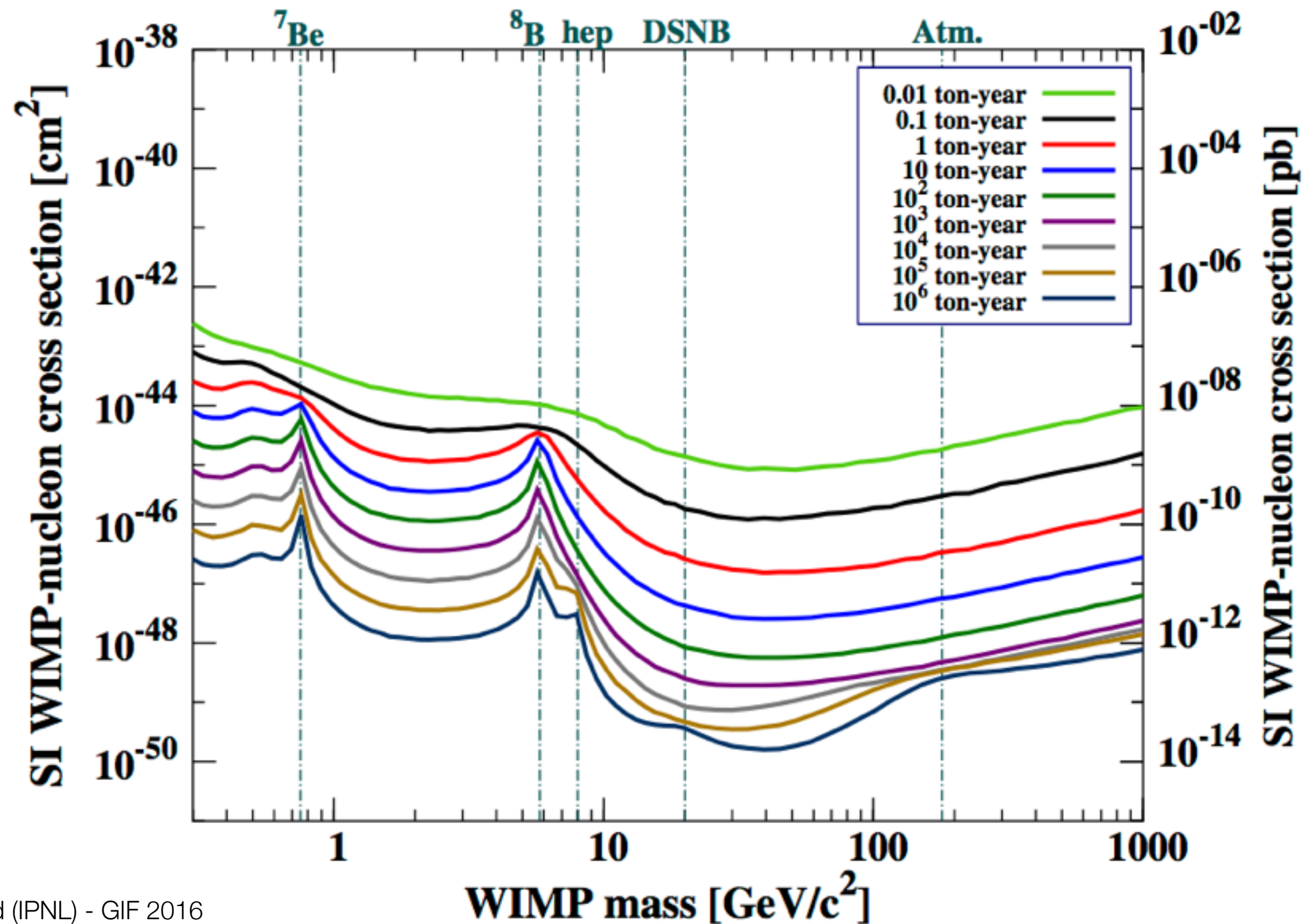


In the case of a **perfect spectral matching**, we expect the sensitivity to scale as:

$$\sigma_{90\%} \propto \frac{\sqrt{N_\nu + \xi^2(N_\nu)^2}}{N_\nu} = \sqrt{\frac{1 + \xi^2 N_\nu}{N_\nu}},$$

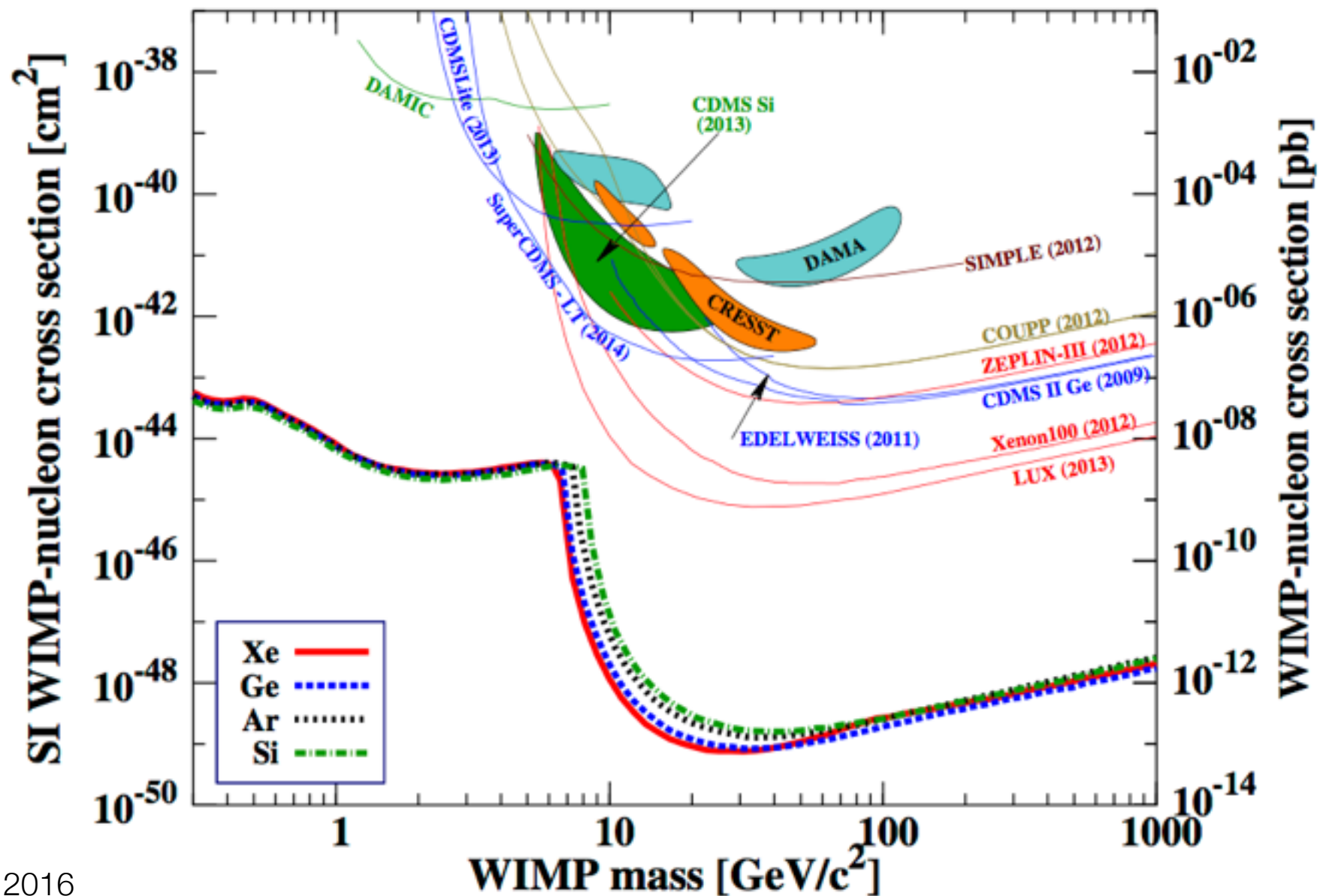
The neutrino background

(F. Ruppin et al., PRD 90 (2014))



The neutrino background

Target	Sample Experiment	E_{th}^{low} (eV)	E_{th}^{high} (keV)	Exposure ^{low} (ton-yr)	Exposure ^{high} ($\times 10^3$ ton-yr)
Xe	LZ/XENON1T	3	4	0.19	9.3
Ge	SuperCDMS/CoGeNT	5.3	7.9	0.38	15.6
Si	SuperCDMS/DAMIC	14	20	1.26	73.1
Ar	DEAP/DarkSide	9.6	14.4	0.72	32.5
CaWO ₄	CRESST	25	35	1.48	24.4
C ₃ F ₈	PICO	33	47.7	2.02	25.1
CF ₄	MIMAC/DMTPC	33	47.7	2.39	22.9
CF ₃ I	PICO/COUPP	33	47.7	2.42	23.8



The neutrino background

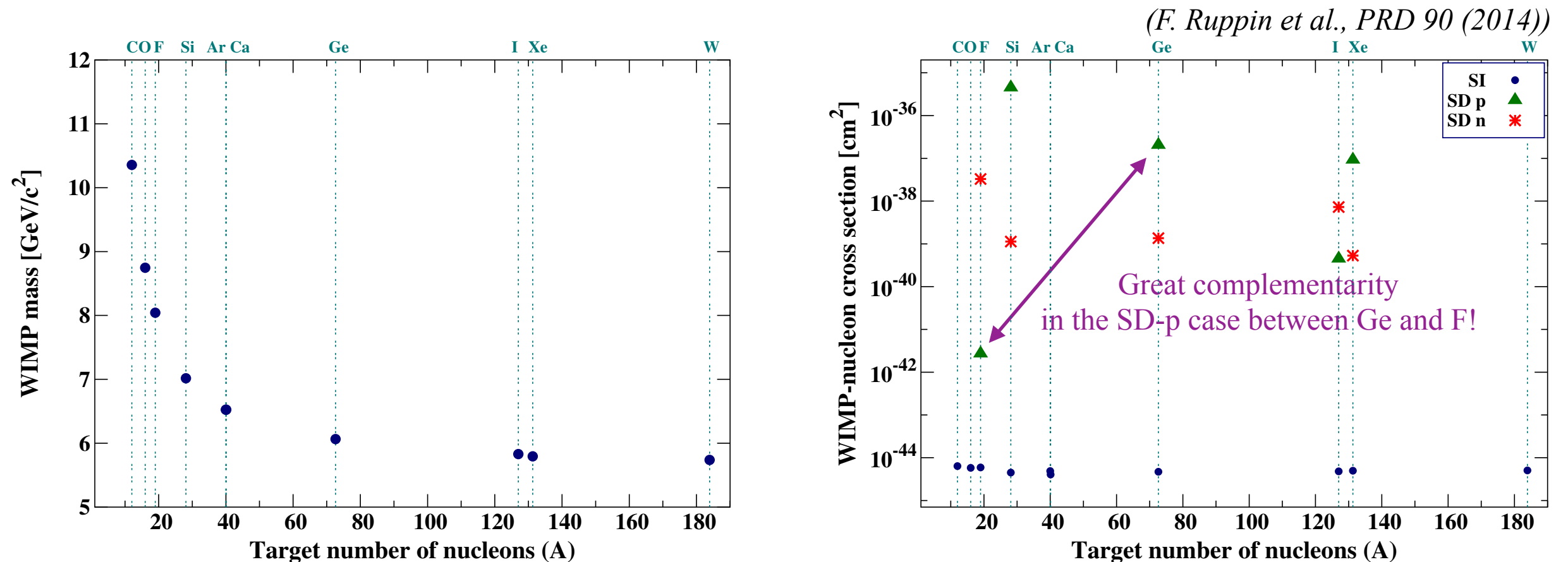
How to bypass this neutrino-induced saturation of the sensitivity?

1. **Reducing the systematic uncertainties on neutrino fluxes** $\sigma_{90\%} \propto \frac{\sqrt{N_\nu + \xi^2(N_\nu)^2}}{N_\nu} = \sqrt{\frac{1 + \xi^2 N_\nu}{N_\nu}},$
2. **Annual modulation** (first studied in J. H. Davis, JCAP 2015)
3. **Directional detection** (first studied in P. Grothaus et al., PRD 2014)
4. **Target complementarity:** combining data from several experiments, (F. Ruppin et al., PRD 2014)

The neutrino background

Considering target complementarity from different experiments

- ➔ The additional discrimination power brought by using different targets is related by how different are the WIMP-neutrino equivalent models



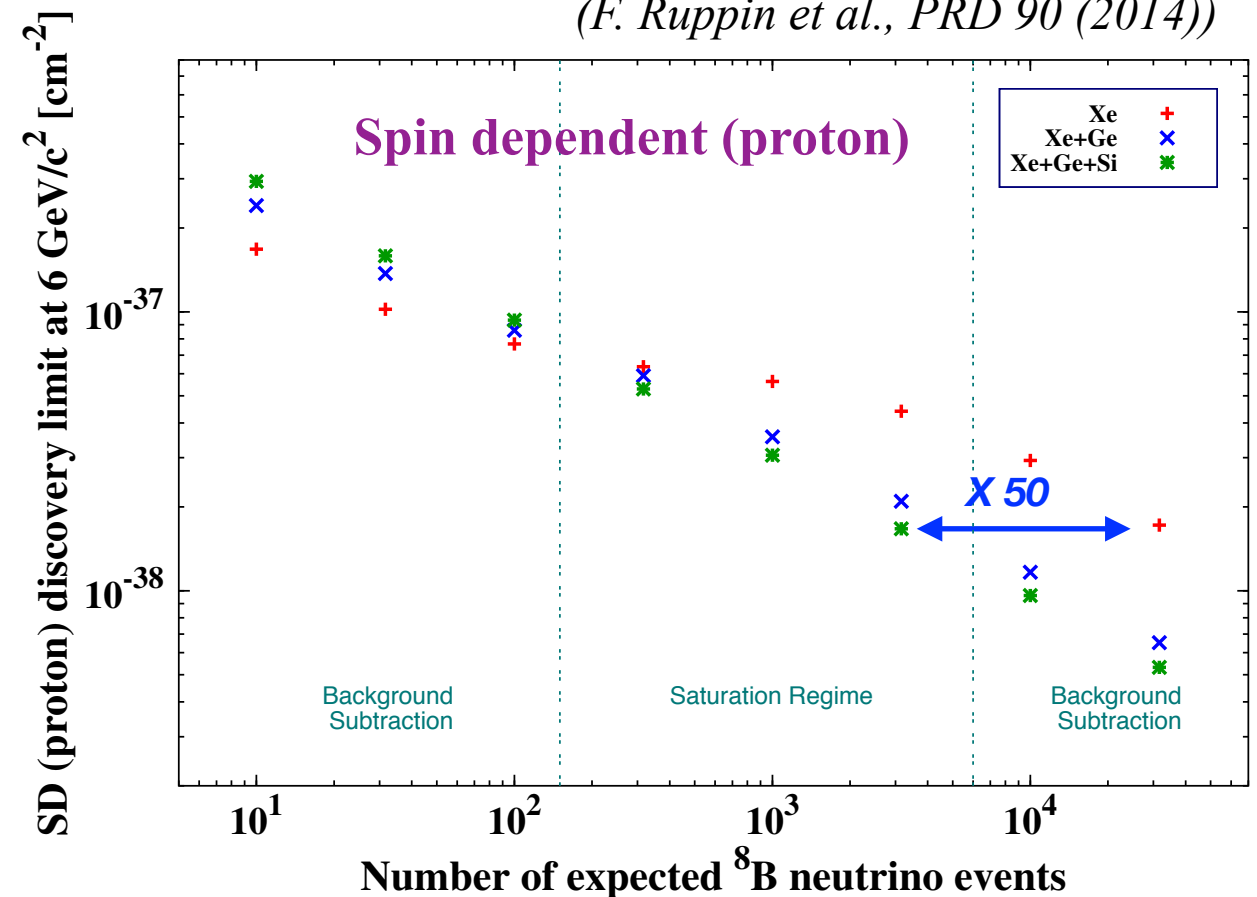
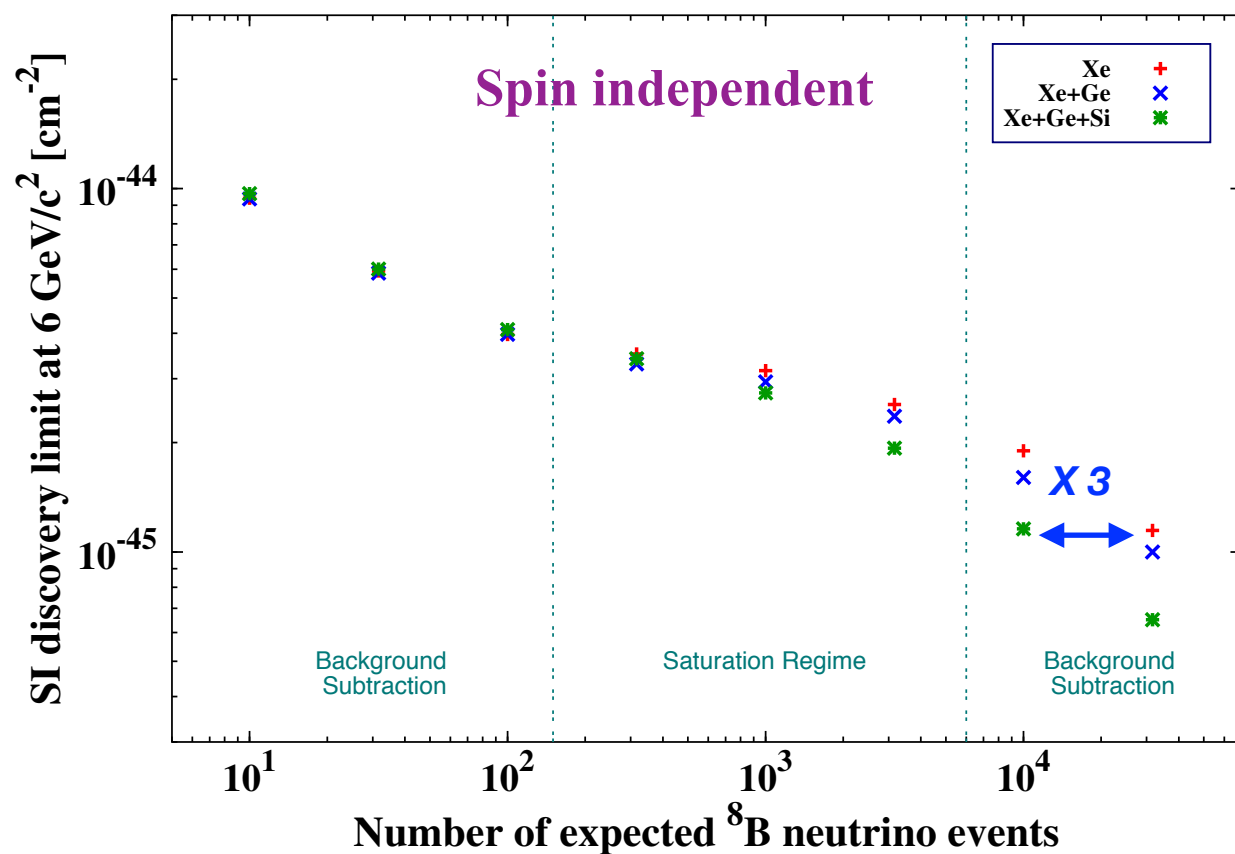
- Moderate differences in the WIMP mass and in the SI cross sections (SI and CNS are coherent)
- Huge differences in the SD case -> *WIMP hypothesis can't fit all experiments*

The neutrino background

Results from target complementarity

- Considering a 6 GeV WIMP mass and a fixed systematic of 16% for ^8B neutrinos
- Total number of neutrinos equally distributed amongst each target nuclei

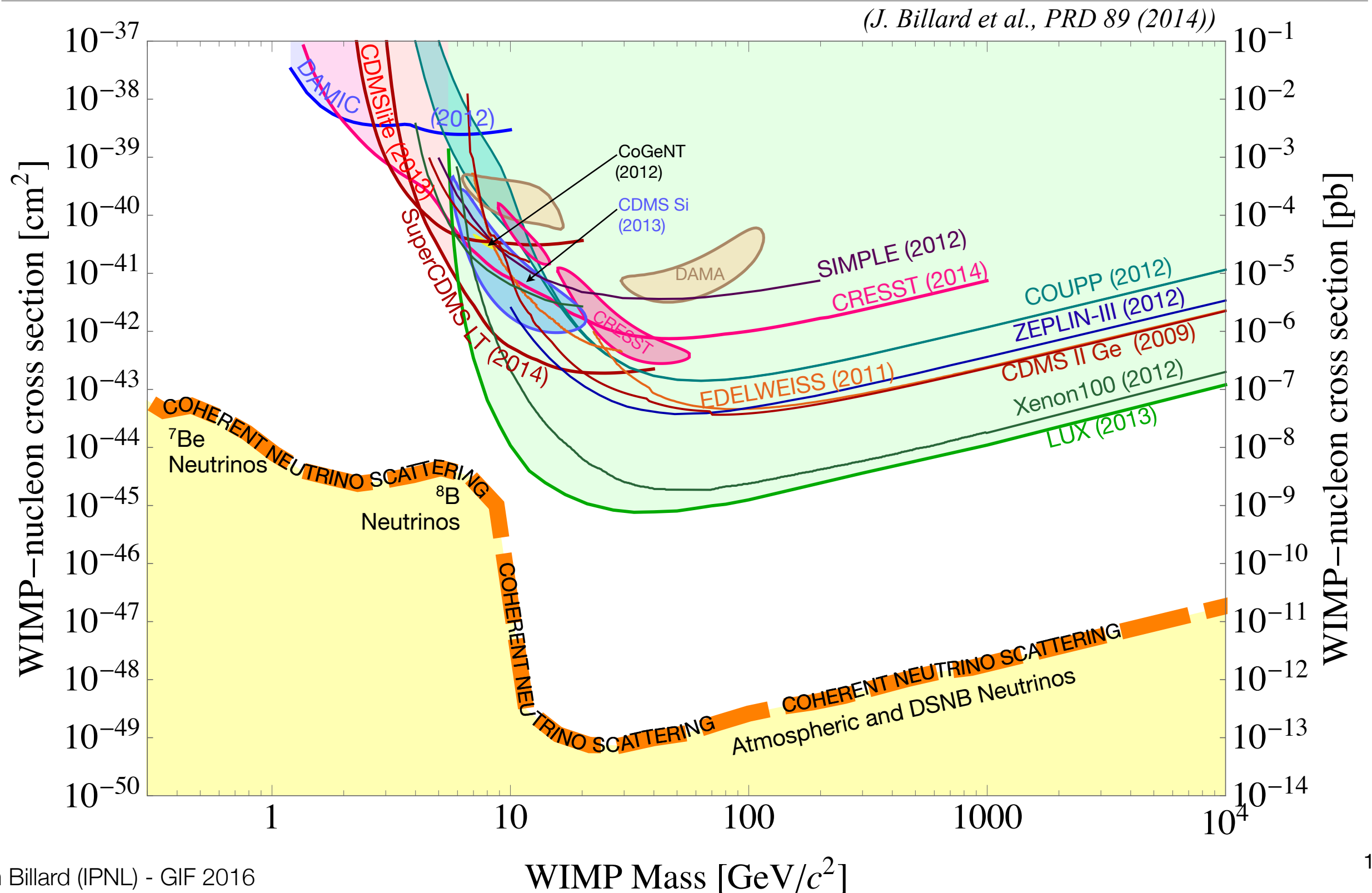
(F. Ruppin et al., PRD 90 (2014))



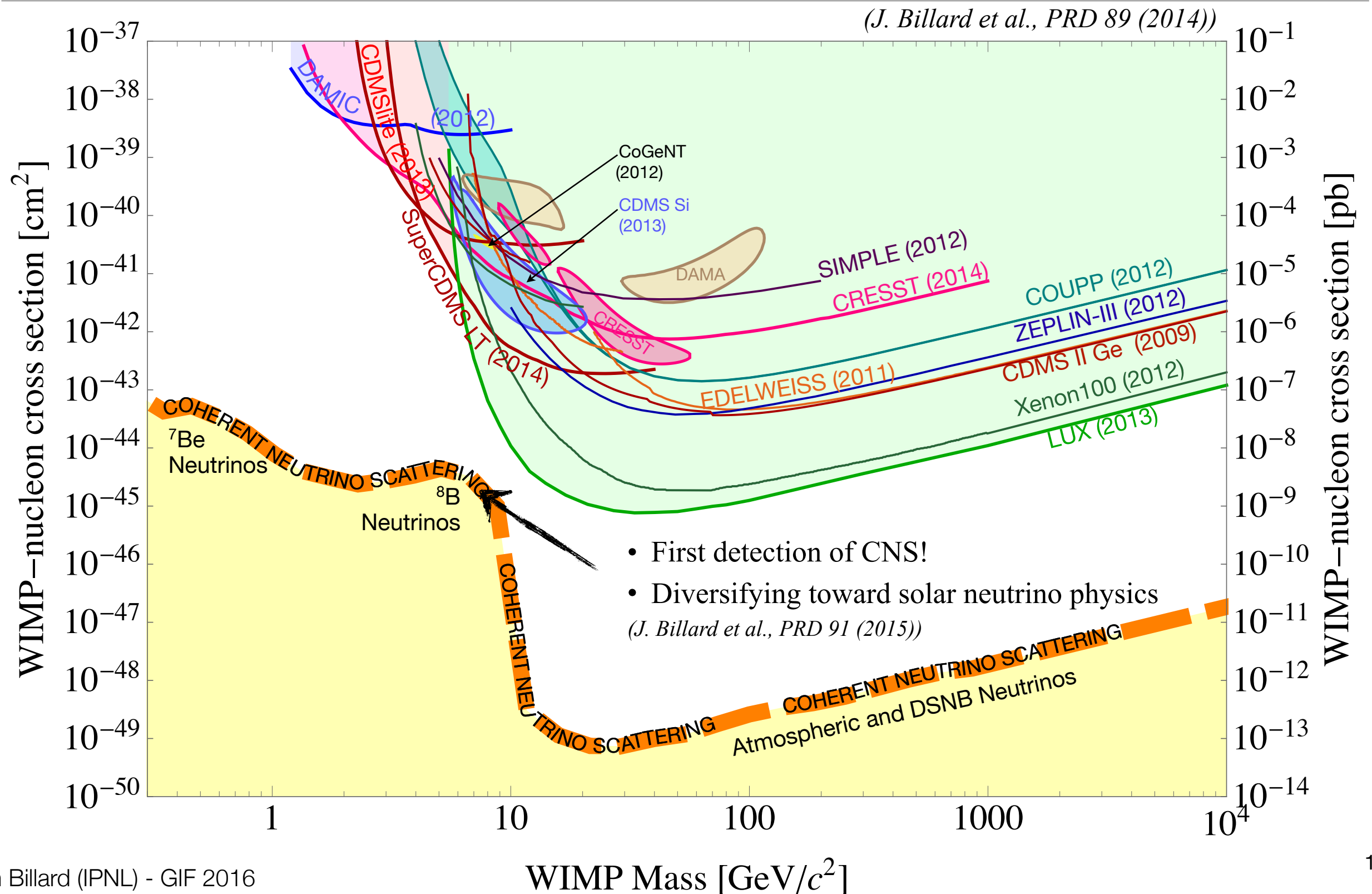
- No more saturation regime in the SD-p case with Xe+Ge+Si -> *no waste in exposure!*

Upcoming experiments should combine their data

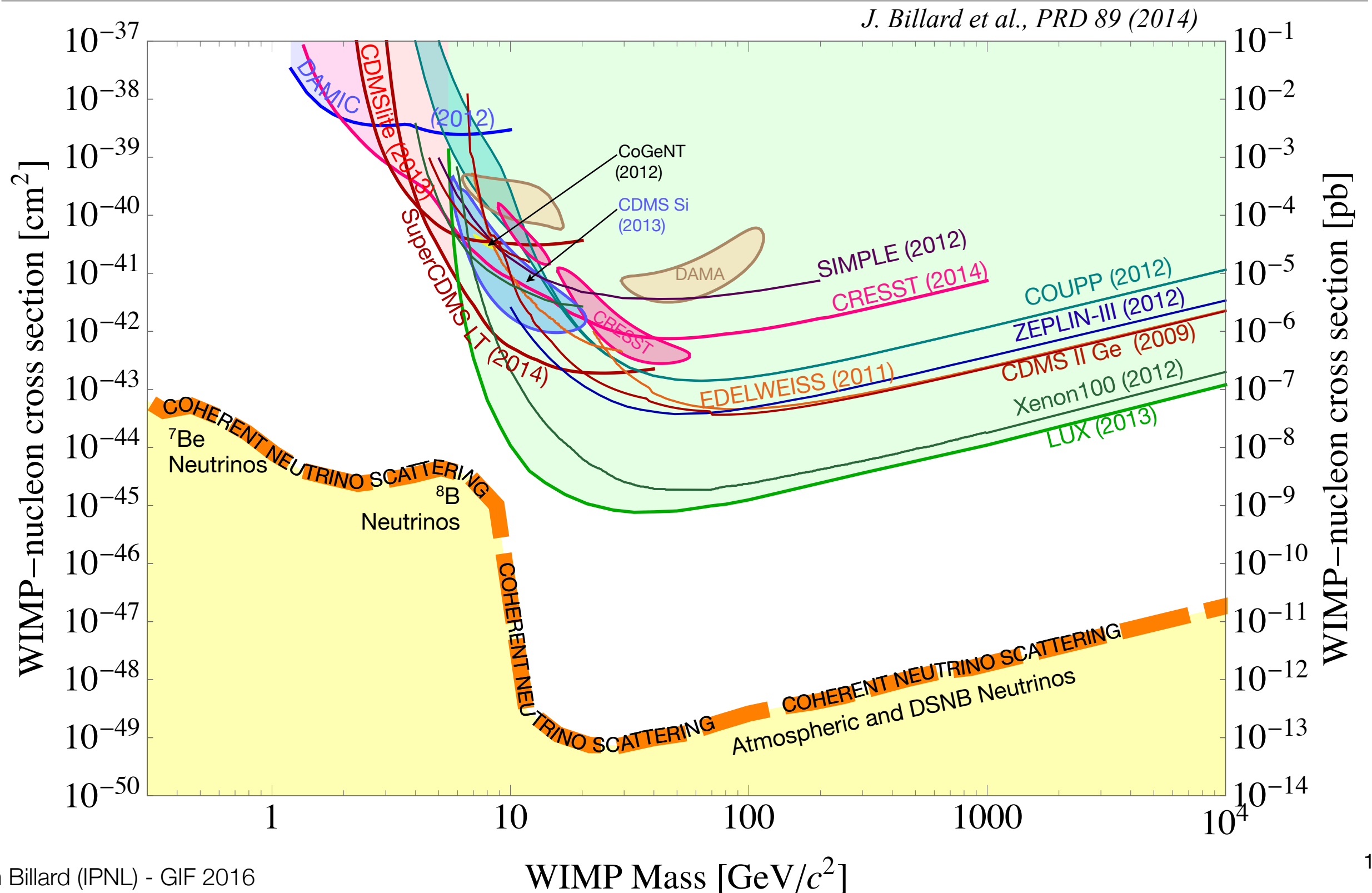
The neutrino background



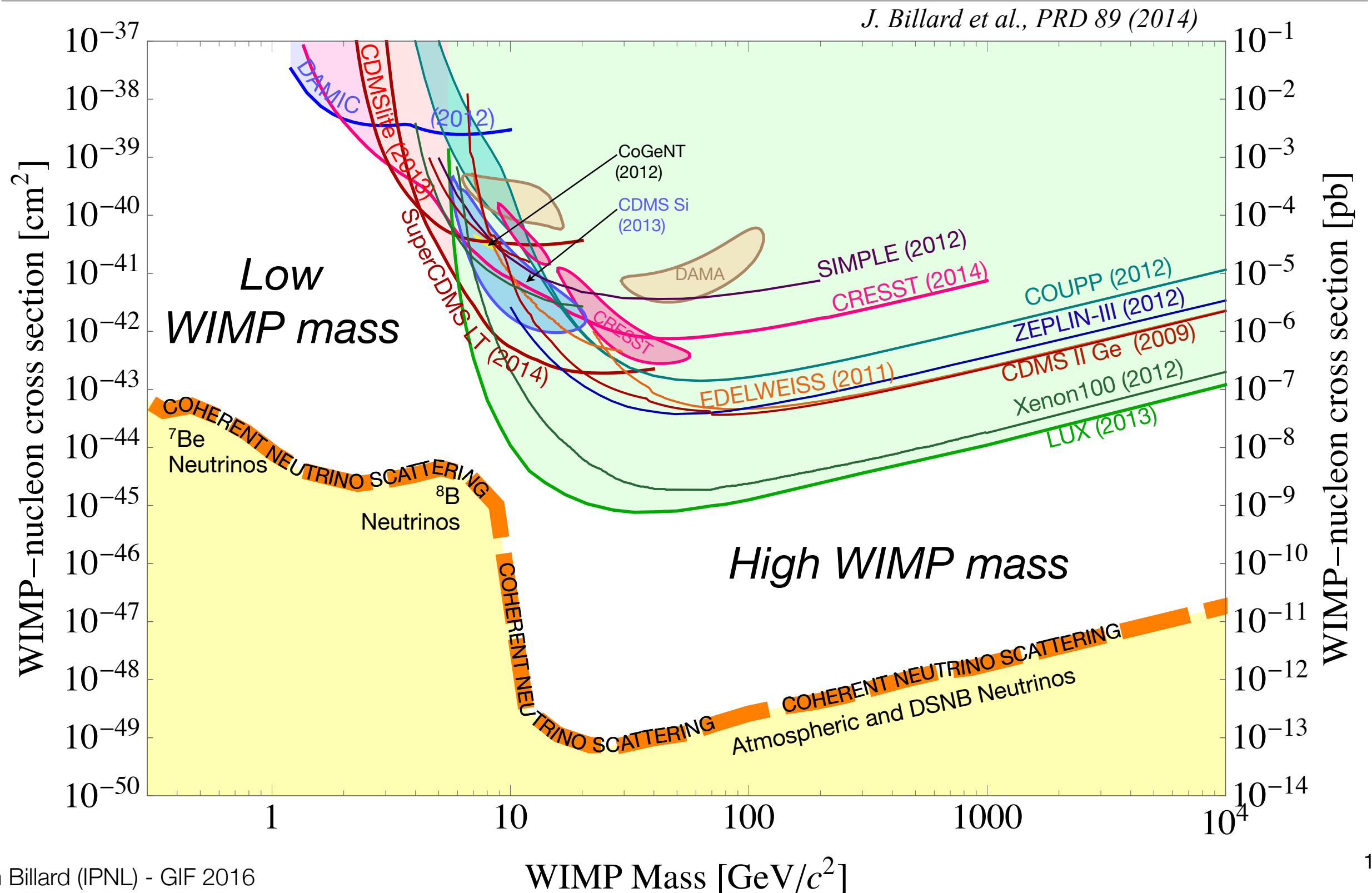
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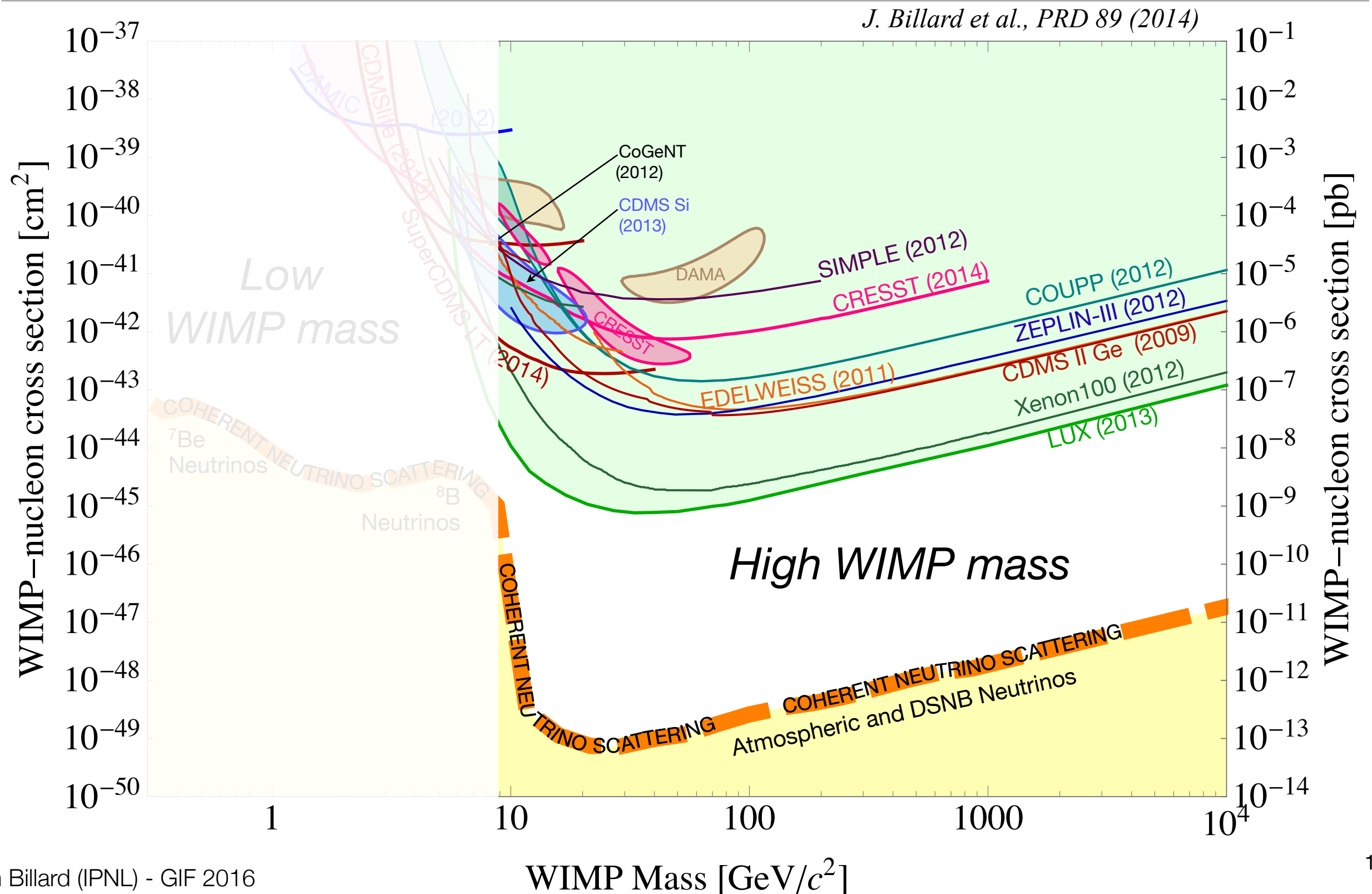
The neutrino background



The neutrino background



High WIMP mass region (10 GeV - 1 TeV)



Basics of direct detection

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

- **Low** and **controlled** backgrounds (*so that they can be subtracted*)
- **Discrimination** between signal and background (*to further reduce the background*)
- **Large exposure** (*few events per ton-year*)
- **Low energy threshold** (*the lower, the better, especially for low WIMP mass*)

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High WIMP mass region (10 GeV - 1 TeV)

Courtesy M. Schumann

Target	LXe	LAr	LNe
Atomic Number	54	18	10
Atomic mass	131.3	40.0	20.2
Boiling Point T_b [K]	165.0	87.3	27.1
Liq. Density @ T_b [g/cm ³]	2.94	1.40	1.21
Fraction in Atmosphere	0.09	9340	18.2
Price	\$\$\$\$	\$	\$\$
Scintillator	✓ 178nm	✓ 128nm	✓ 77nm
Ionizer	✓	✓	✗
W (E to generate e-ion pair) [eV]	15.6	23.6	
Dark Matter Projects [active collaborations]	~5	~3	1/2

18	
2	2
He	
Helium	
4.002602	
10	2
Ne	8
Neon	
20.1797	
18	2
Ar	8
Argon	
39.948	
36	2
Kr	18
Krypton	
83.798	
54	2
Xe	18
Xenon	
131.293	
86	2
Rn	18
Radon	
(222.0176)	

- Liquid above LN2 (77K): **easy cryogenics**
- **Good scintillators** (do not absorb its own light), and **good electron lifetime**
- Allow for **active discrimination**: scintillation and ionization (+ pulse shape in Ar)
- Can be purified to remove radioactive contaminants such as ³⁷Ar, ⁸⁵Kr, ¹²⁷Xe, ³⁹Ar

• « **Easy** » to scale to tons of detector material

High WIMP mass region (10 GeV - 1 TeV)

Single phase liquid only



DEAP
MiniCLEAN

Dual phase TPC liquid/gas



DarkSide
ArDM



XMASS

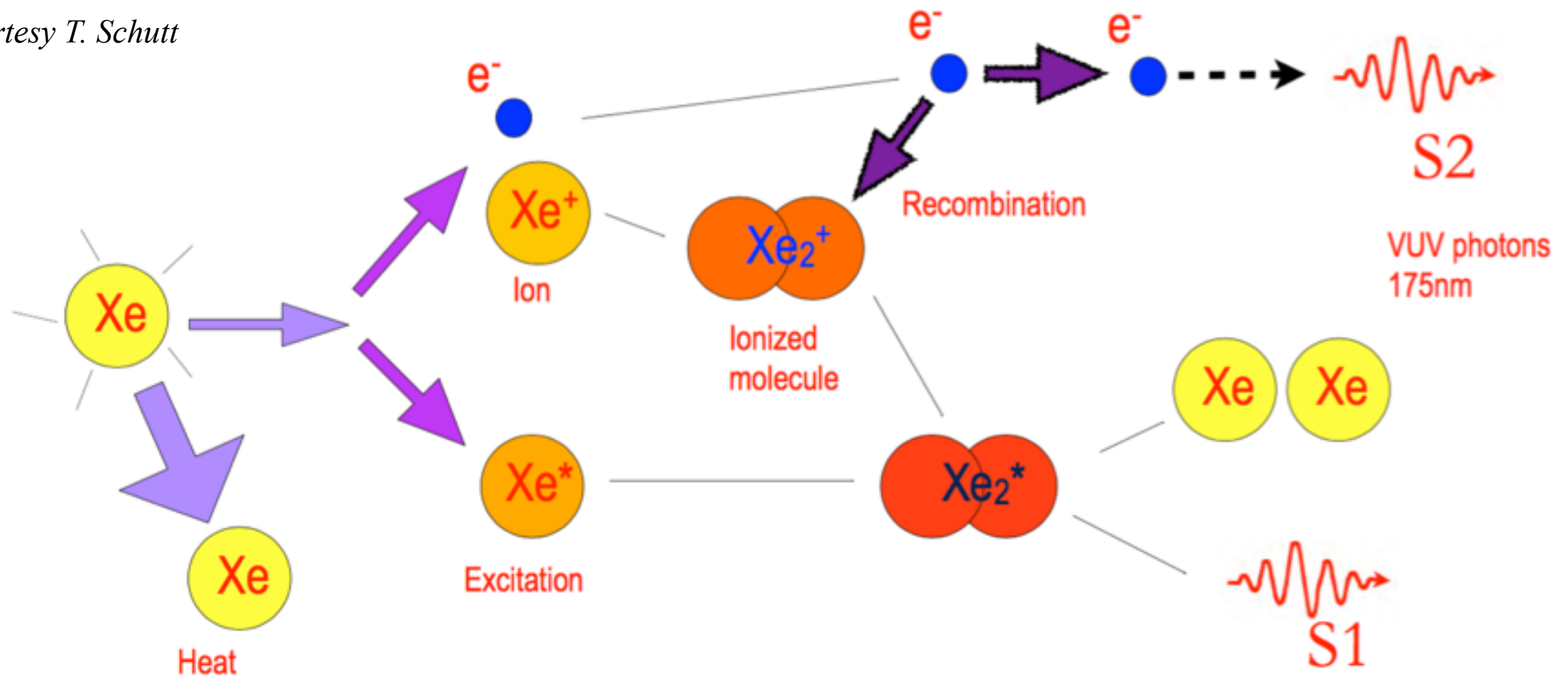


XENON-1T,nT
LUX
LZ
PANDAX

High WIMP mass region (10 GeV - 1 TeV)

How is the energy released in a Xe-based experiment?

Courtesy T. Schutt

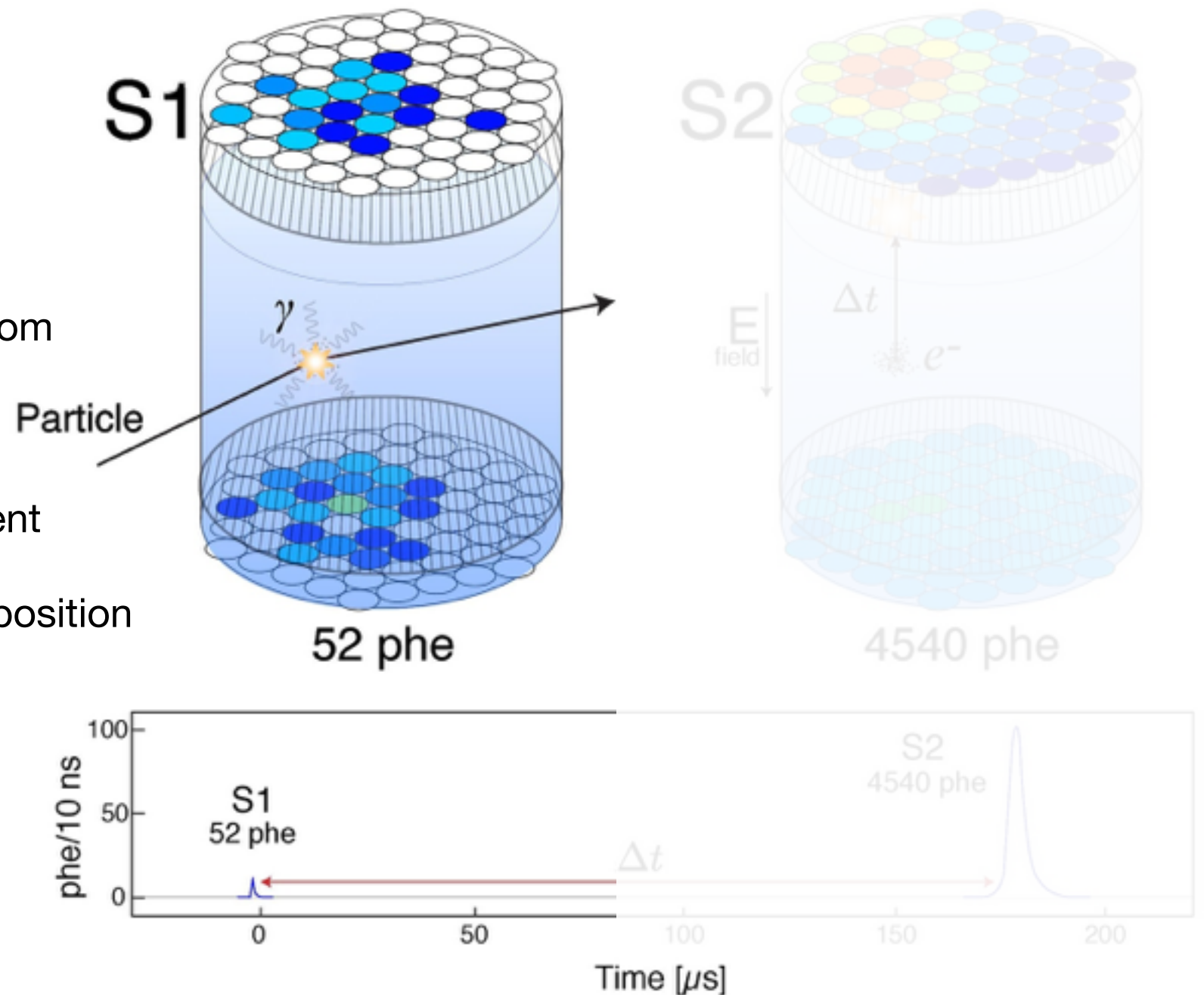


- The recoiling nucleus/electron releases its energy in heat/ionization/scintillation
- Electrons drifted to the gaseous phase undergo an avalanche process producing light (S2)
- Recovering the true nuclear recoil energy is not trivial !!!

High WIMP mass region (10 GeV - 1 TeV)

What is the detection strategy?

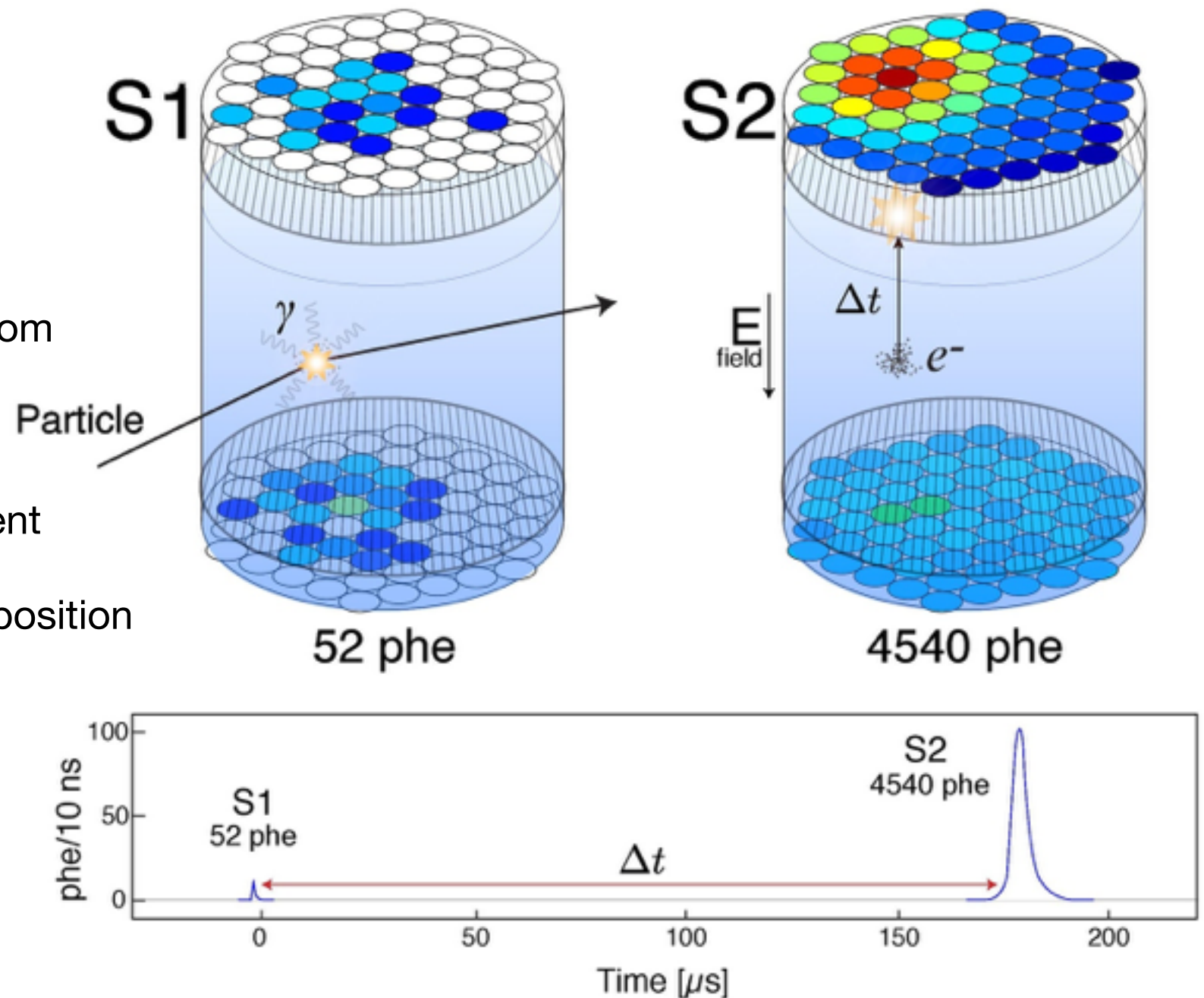
- Measure primary scintillation light (S1)
- Measure secondary scintillation light from ionization avalanche (S2)
- Drift time give the Z-position of the event
- PMTs give energy information and XY position



High WIMP mass region (10 GeV - 1 TeV)

What is the detection strategy?

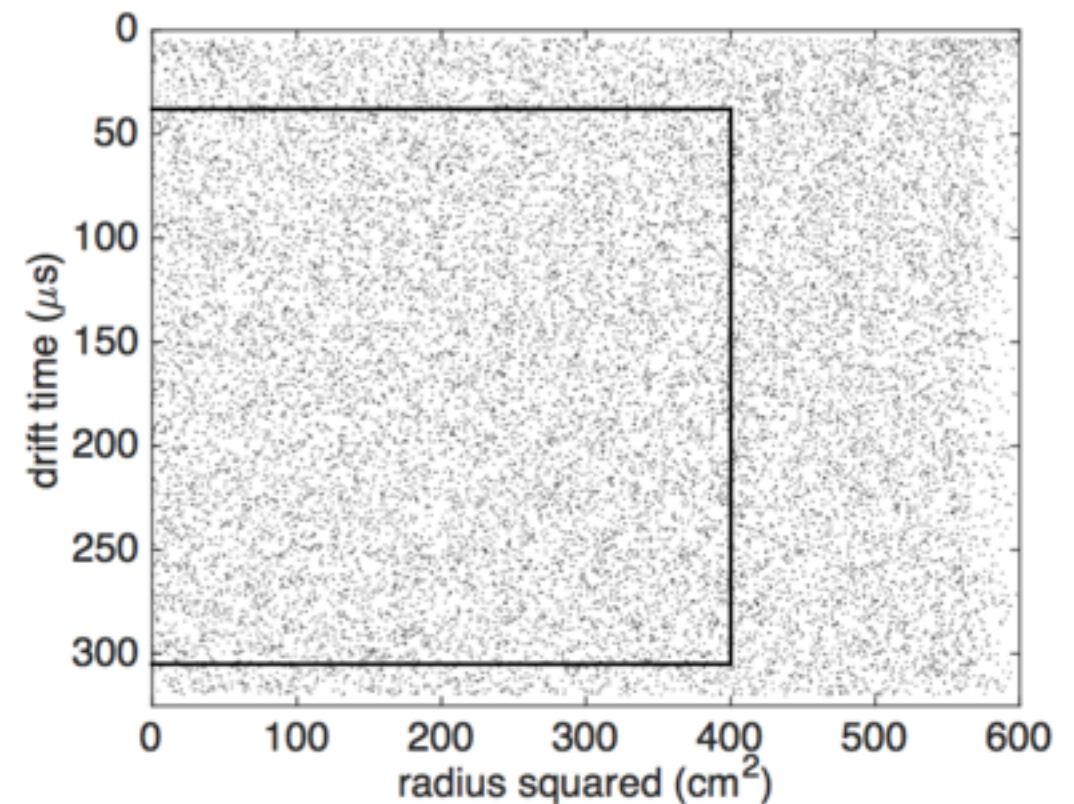
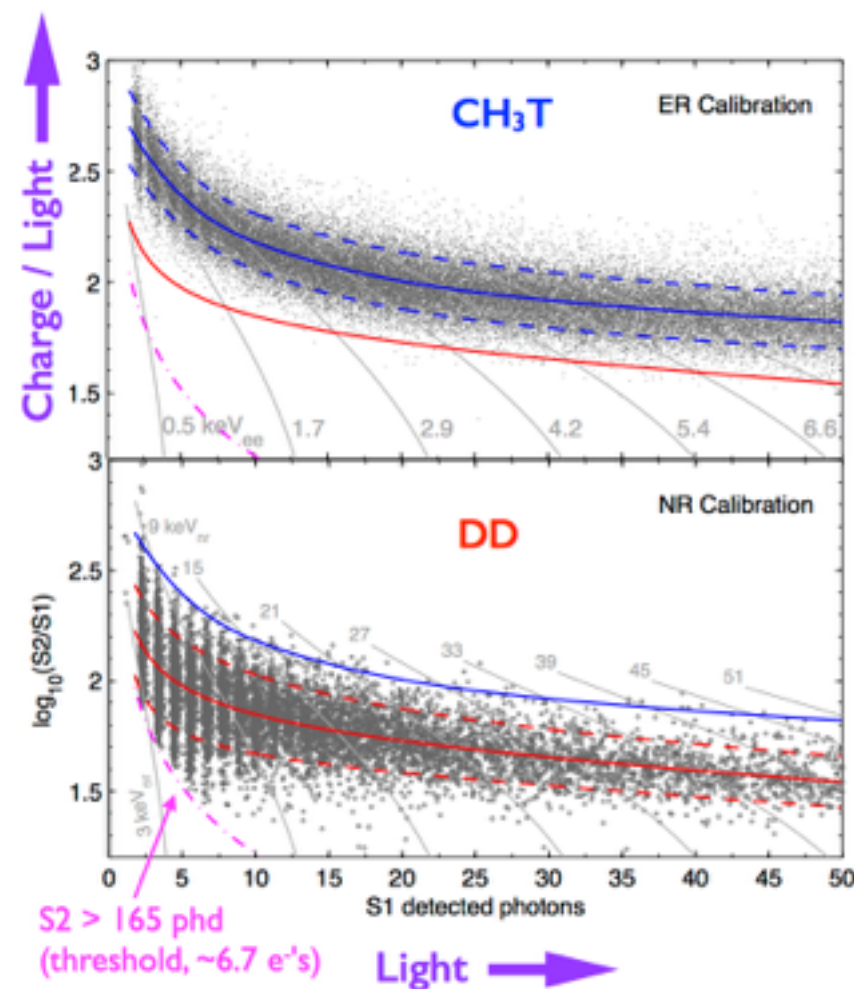
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High WIMP mass region (10 GeV - 1 TeV)

LUX, IDM2016

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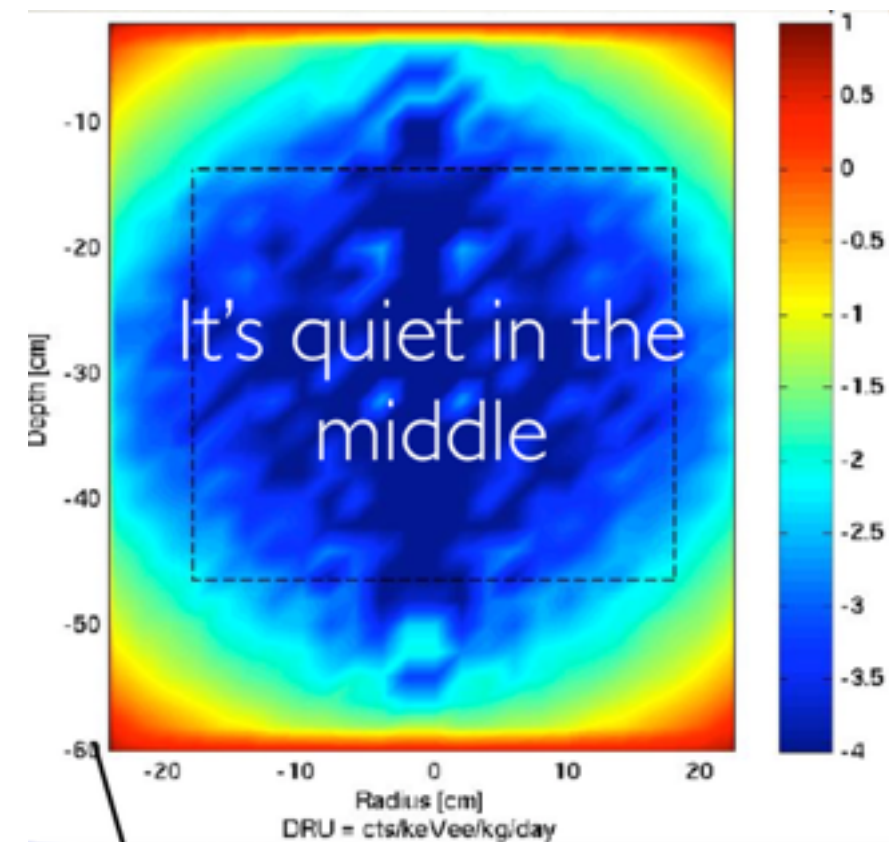
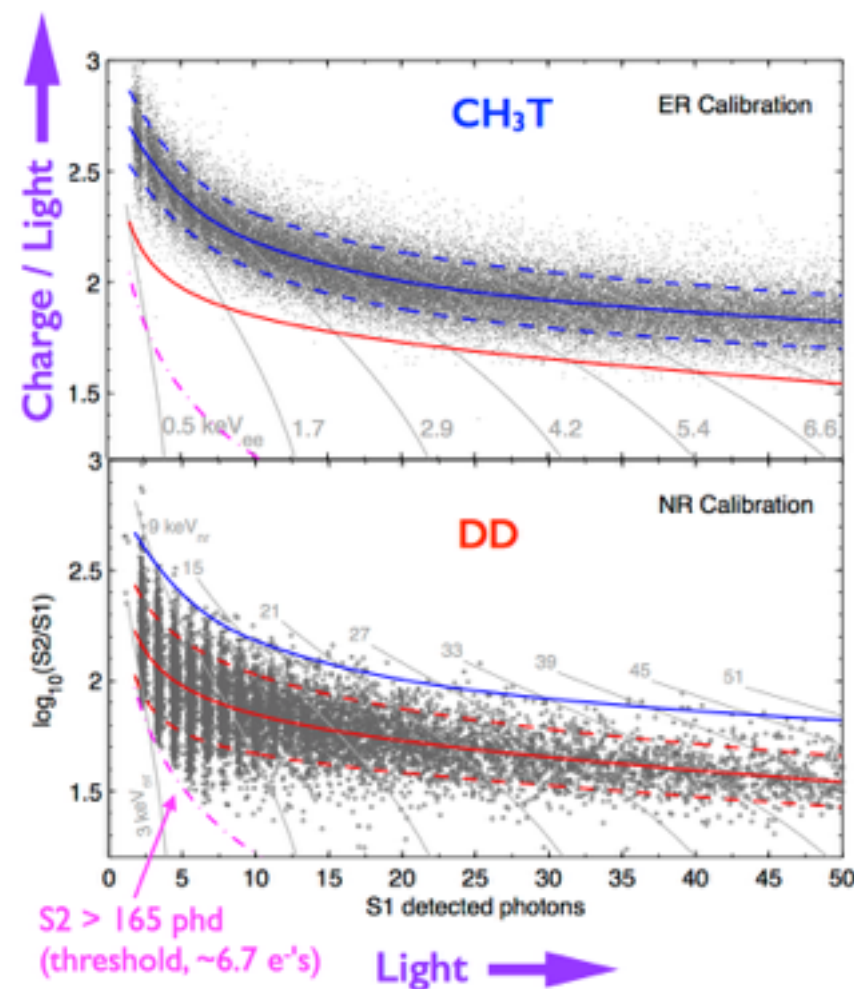


- S2 is larger for electronic recoils than for nuclear recoils (**discrimination**)
- However, rejection efficiency is about 99,5% for a 50% nuclear recoil acceptance
- Thanks to the XYZ positioning, we can select only events happening in the bulk of the detector (**fiducialization**)

High WIMP mass region (10 GeV - 1 TeV)

LUX, IDM2016

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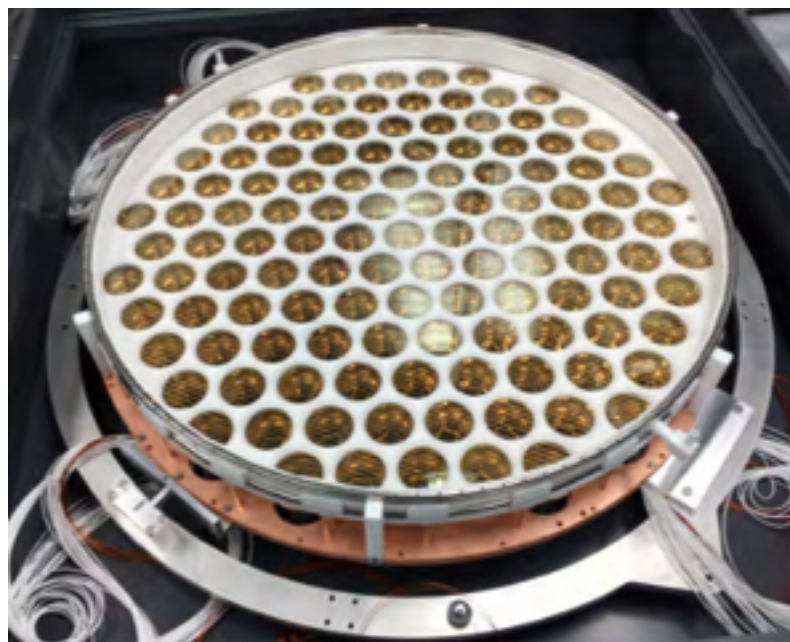


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- With a larger detector, we can get the bulk region even more quiet (**self-shielding**)

High WIMP mass region (10 GeV - 1 TeV)

XENON, IDM2016

How do we measure the light S1 and S2?



- High Quantum Efficiency at 175 nm (~24%)
- ~10 kV between anode and cathode, 180 V/cm (LXe) and 6 kV/cm (GXe) for extraction/amplification
- When going to larger scale TPC, the challenge is to conserve a good light collection. Need highly efficient PTFE coating

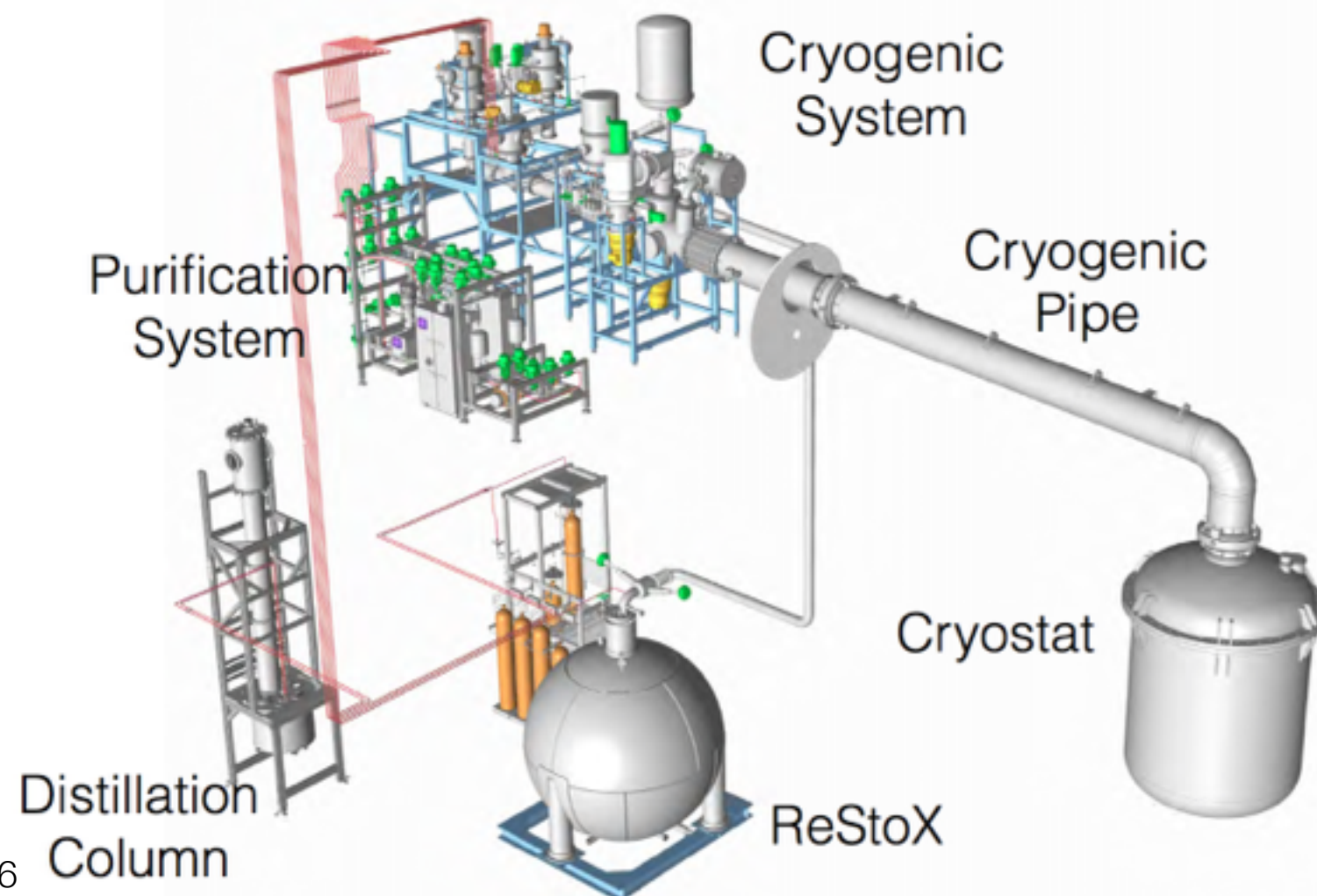


High WIMP mass region (10 GeV - 1 TeV)

- XENON-1T installation:

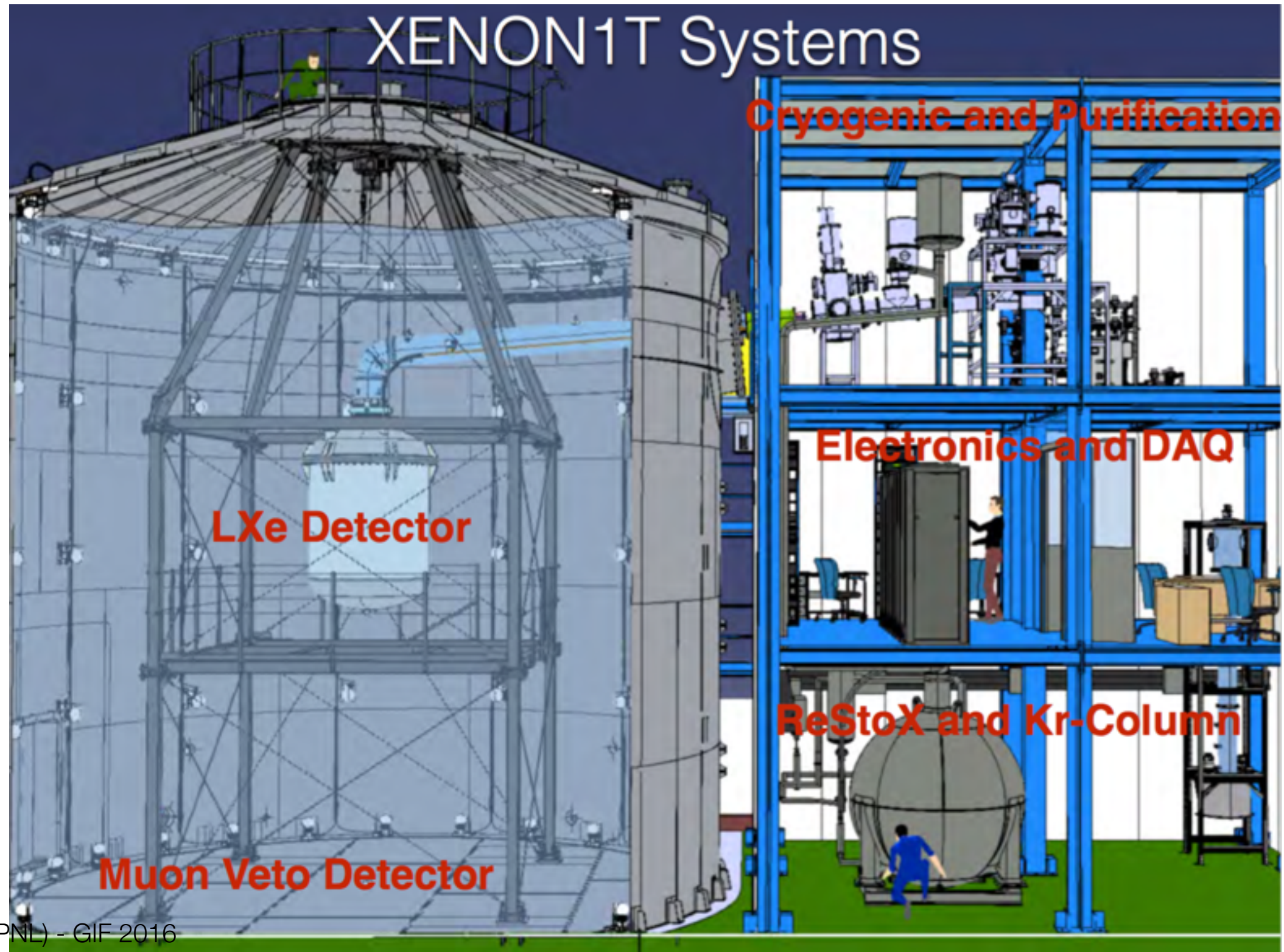
XENON, UCLA Dark Matter 2016

- Cryogenic system to cool the Xe to its liquid phase @ 165 K
- Highly complex feedthrough for cryogenics, detector cables and high voltages
- Purification column to remove radioactive ^{85}Kr from Xe
- Storage tank of 7600 kg of LXe
- Cryostat contains the TPC filled with LXe (~3.5 ton) immersed in a gigantic water shield



High WIMP mass region (10 GeV - 1 TeV)

XENON, UCLA Dark Matter 2016



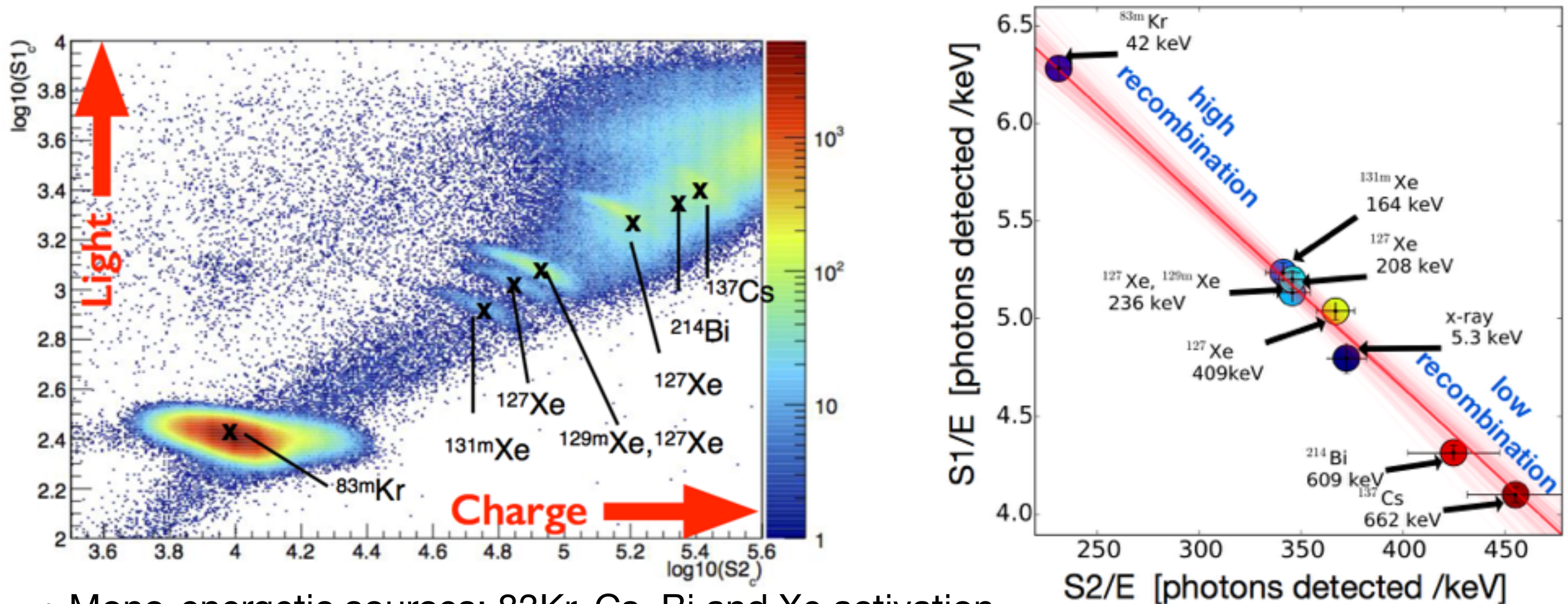
High WIMP mass region (10 GeV - 1 TeV)

XENON, UCLA Dark Matter 2016



High WIMP mass region (10 GeV - 1 TeV)

How do we measure the true electron recoil energy ? *LUX, IDM2016*



- Mono-energetic sources: ^{83}Kr , Cs, Bi and Xe activation
- Electron recoils all start with the same excitation/ionization ratio
- Energy-dependent **recombination** then moves quanta from one category to the other, 1-to-1

$$\frac{E}{W} = n_\gamma + n_e = \frac{S1}{g_1} + \frac{S2}{g_2}$$

*g1: light collection efficiency
x PMT quantum efficiency
~0.1 phd/photon*

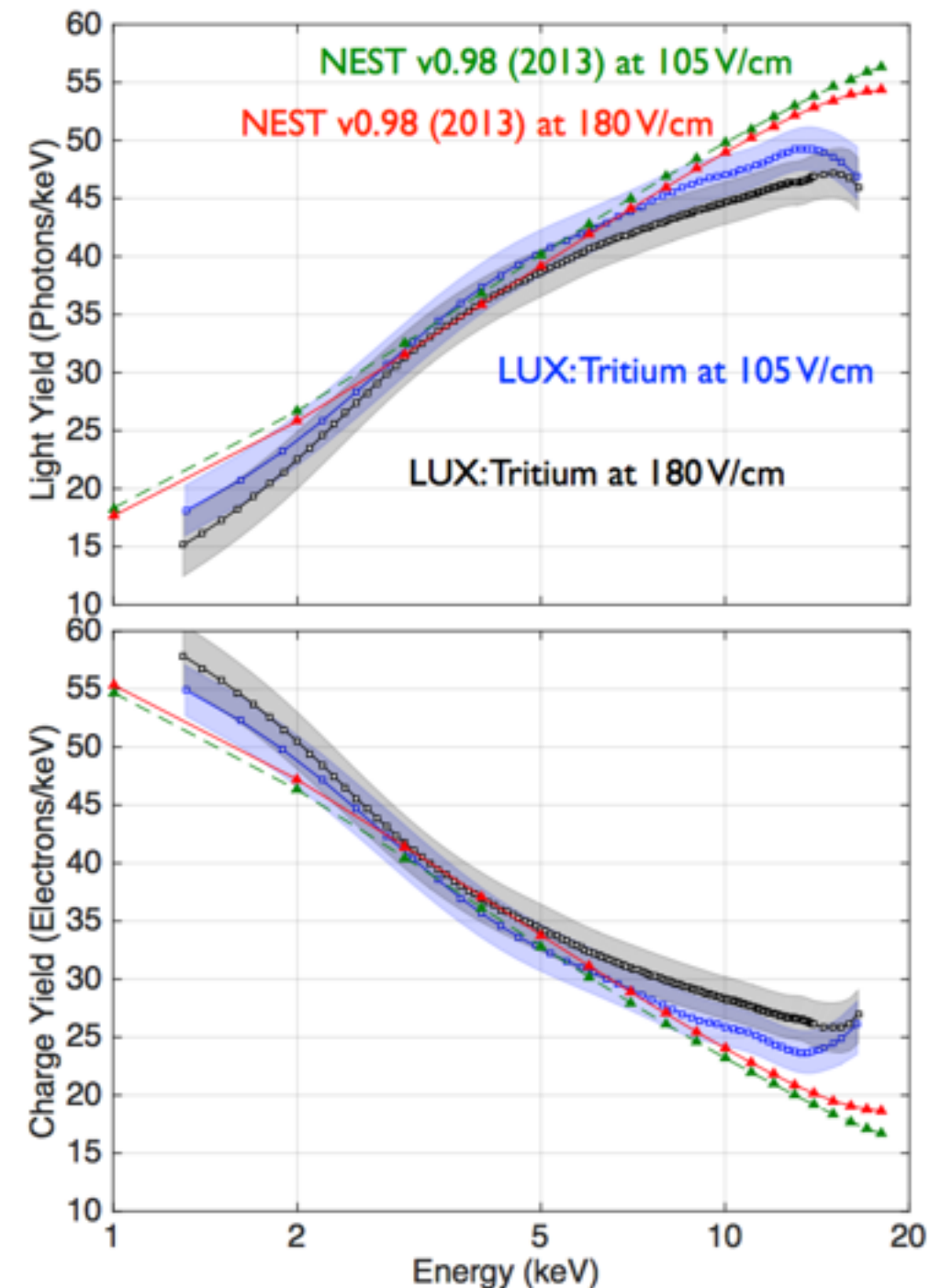
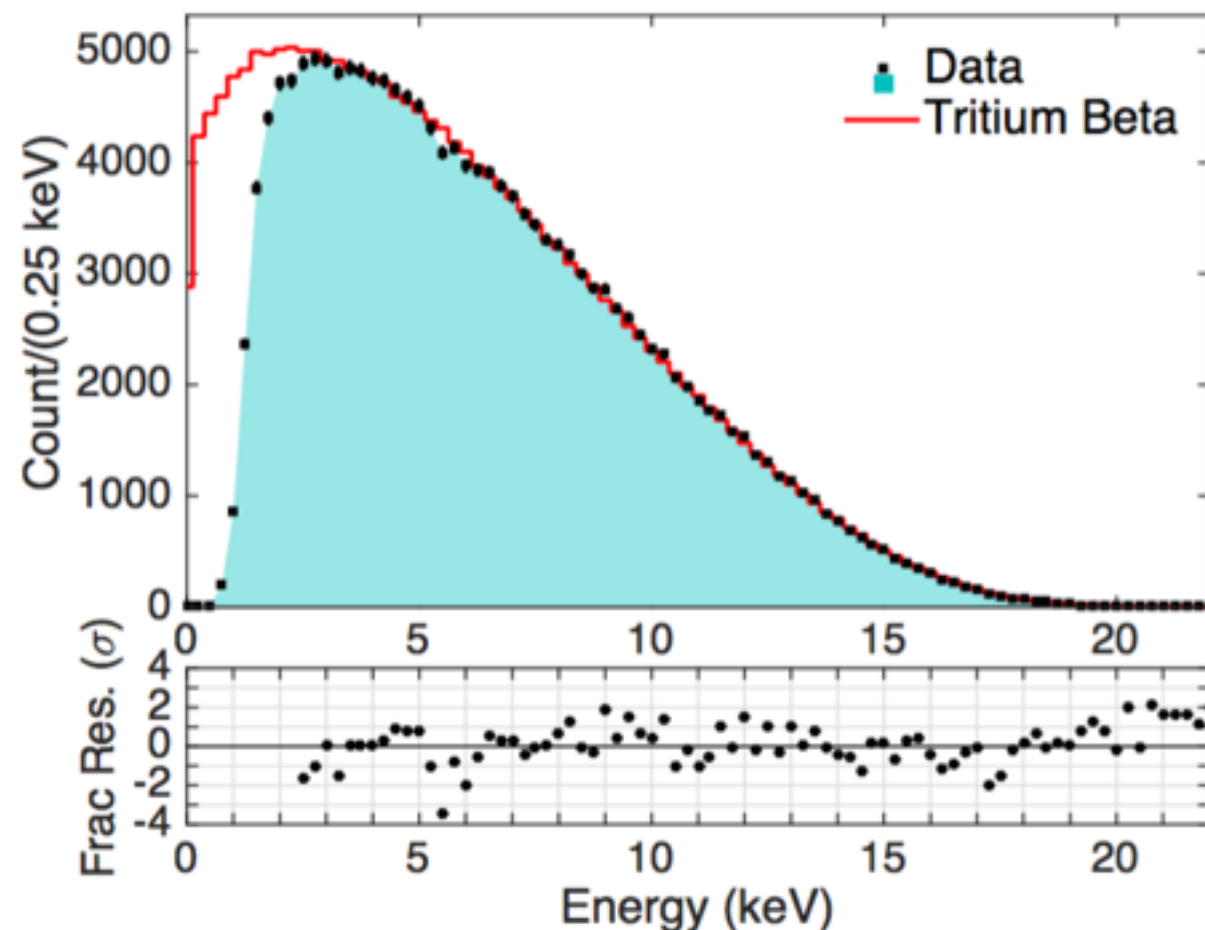
*g2: electron extraction efficiency
x single electron response
~12.1 phd/electron*

- W has been measured at 13.7 eV independently, g1 and g2 are derived from Doke plot

High WIMP mass region (10 GeV - 1 TeV)

How do we measure the true electron recoil energy ? ^{LUX, IDM2016}

- ER calibration and ER band definition up 18 keV using CH3T: uniform in detector volume (**needed for position correction**)
- Absolute Qy and Ly for electronic recoils by fitting the tritium beta decay spectrum

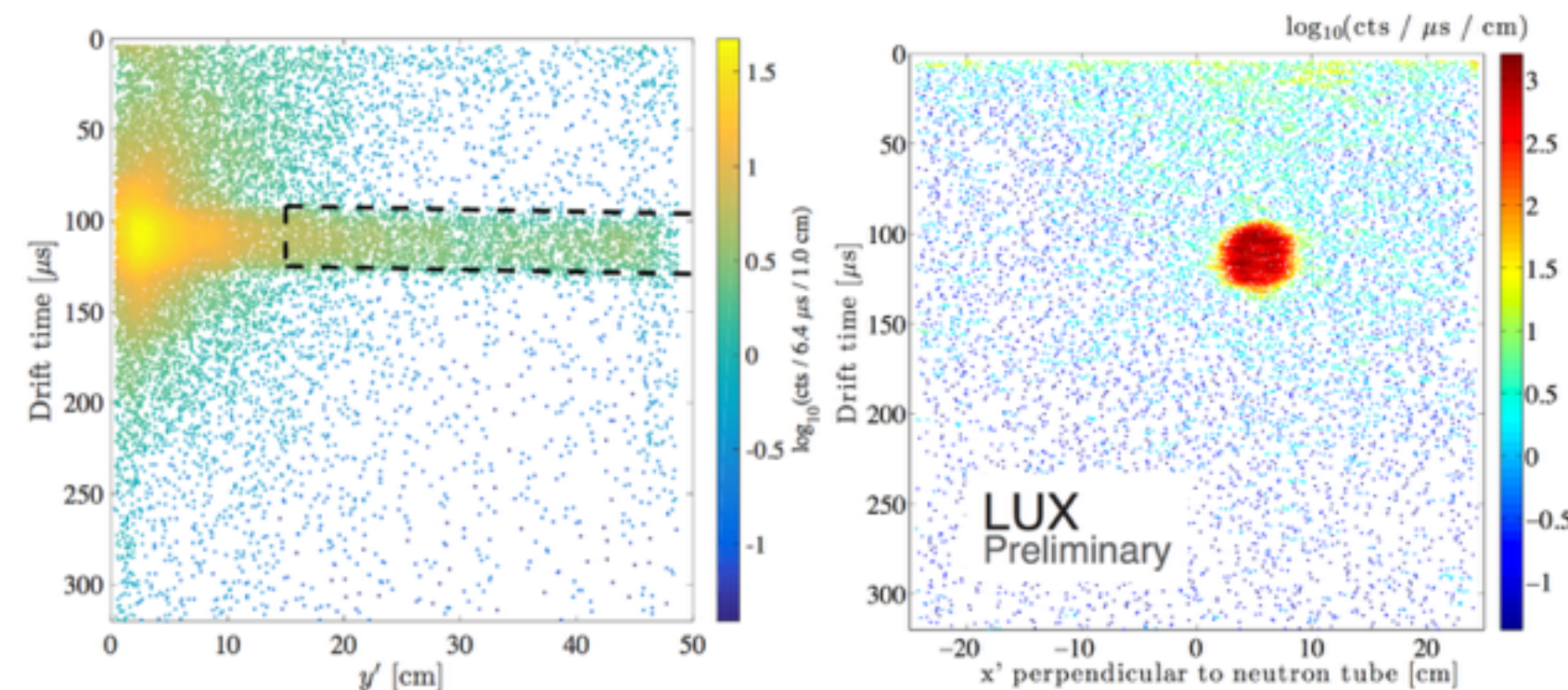
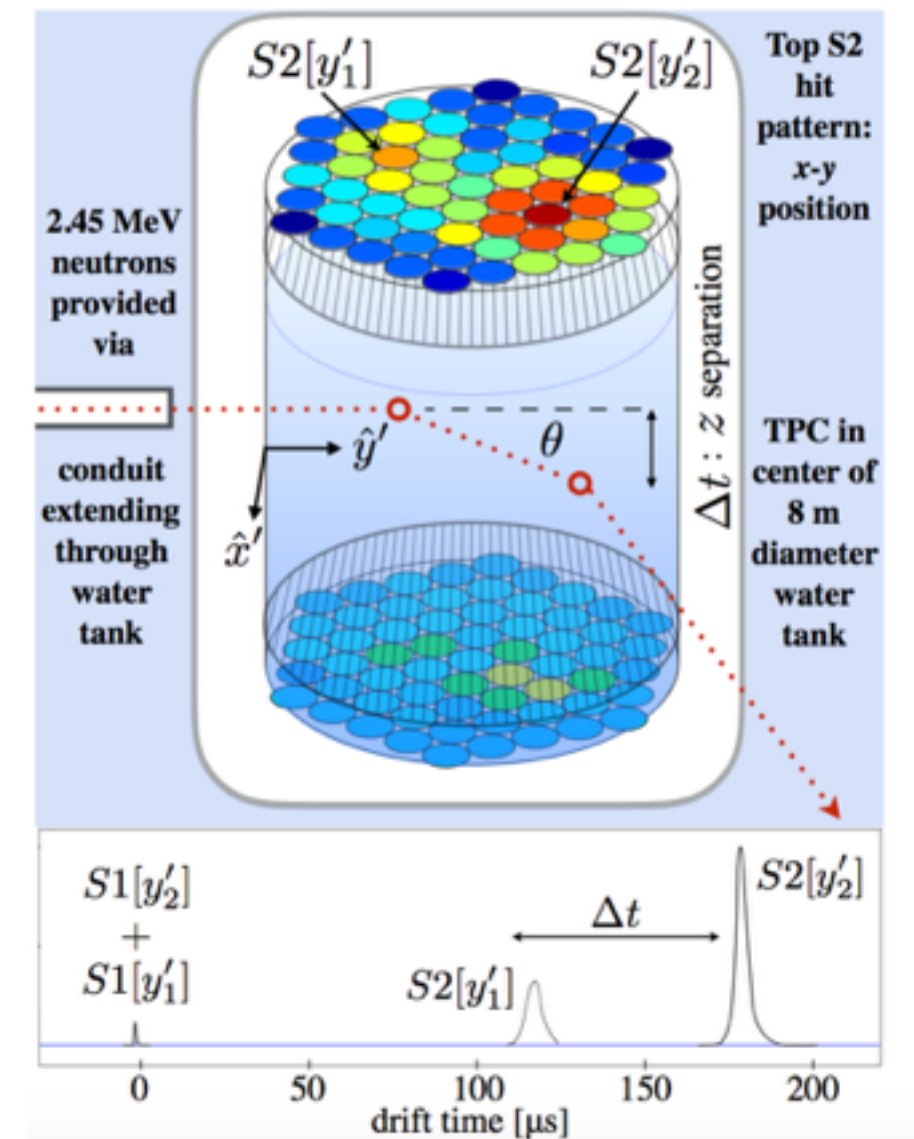


High WIMP mass region (10 GeV - 1 TeV)

How do we measure the true nuclear recoil energy ? *LUX, IDM2016*

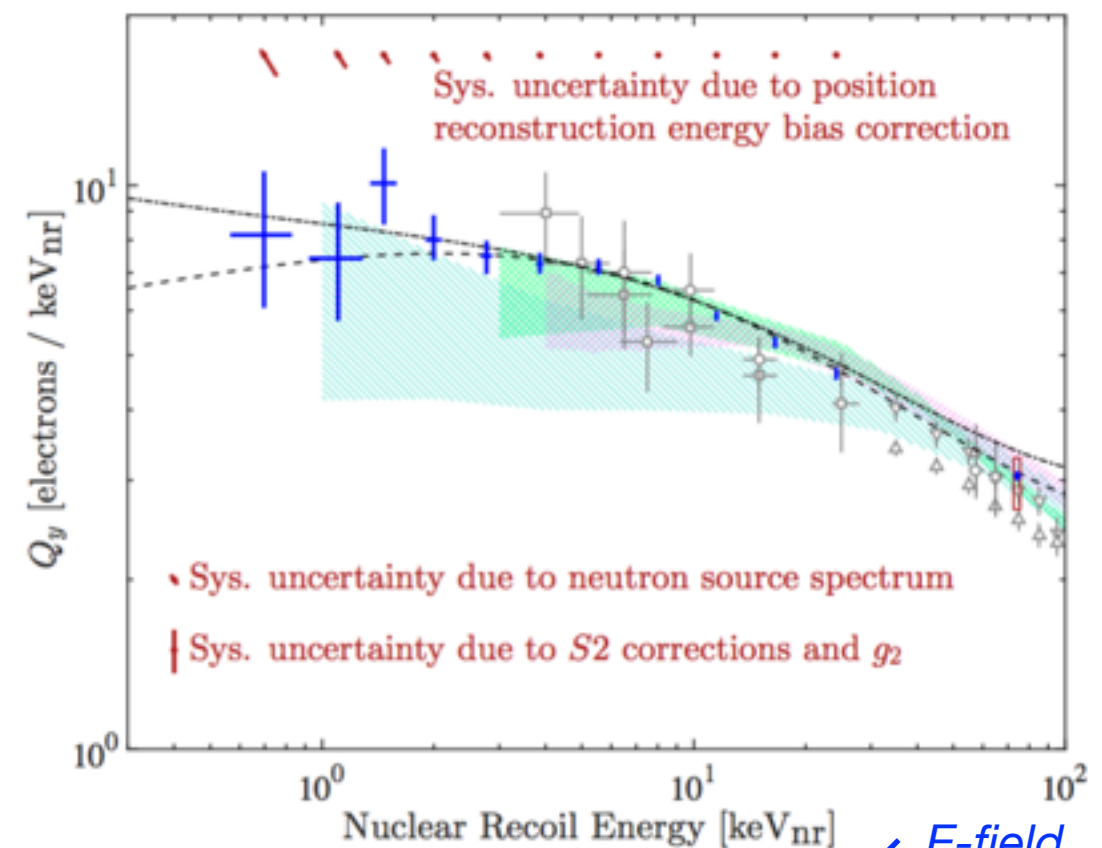
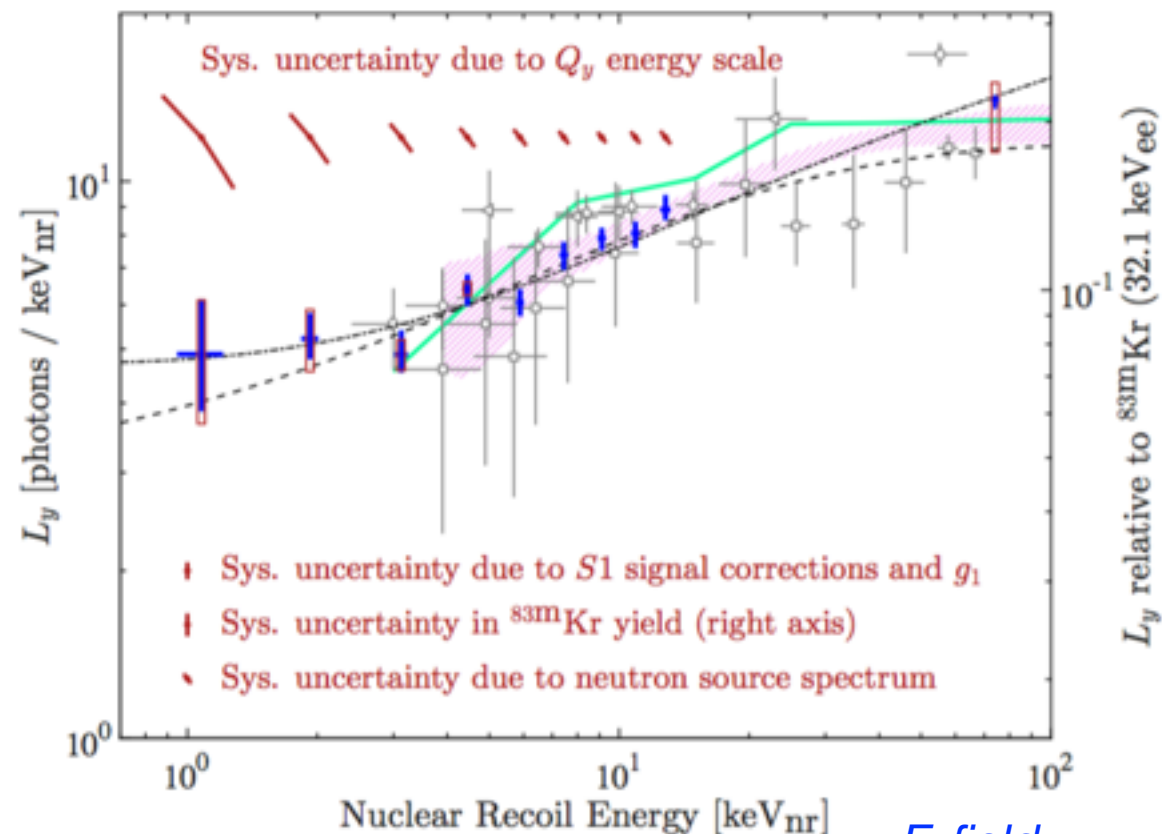
- LUX performed the first in-situ nuclear recoil energy calibration using a DD mono-energetic source (2.45 MeV) and their ability to recover interaction vertices

$$E_r = E \frac{4m_\chi m_N}{(m_\chi + m_N)^2} \cos^2 \theta_r$$



High WIMP mass region (10 GeV - 1 TeV)

How do we measure the true nuclear recoil energy ? LUX, IDM2016



$$S1 = E_{nr} L_y(E_{nr}, \mathcal{E}) g_1$$

$$S2 = E_{nr} Q_y(E_{nr}, \mathcal{E}) g_2$$

Absolute light yield

light collection efficiency
times
PMT quantum efficiency
~0.1 phd/photon

Absolute charge yield

electron extraction efficiency
times
single electron response
~12.1 phd/electron

2 keV nuclear recoil: S1 = 1 phd, S2 = 200 phd

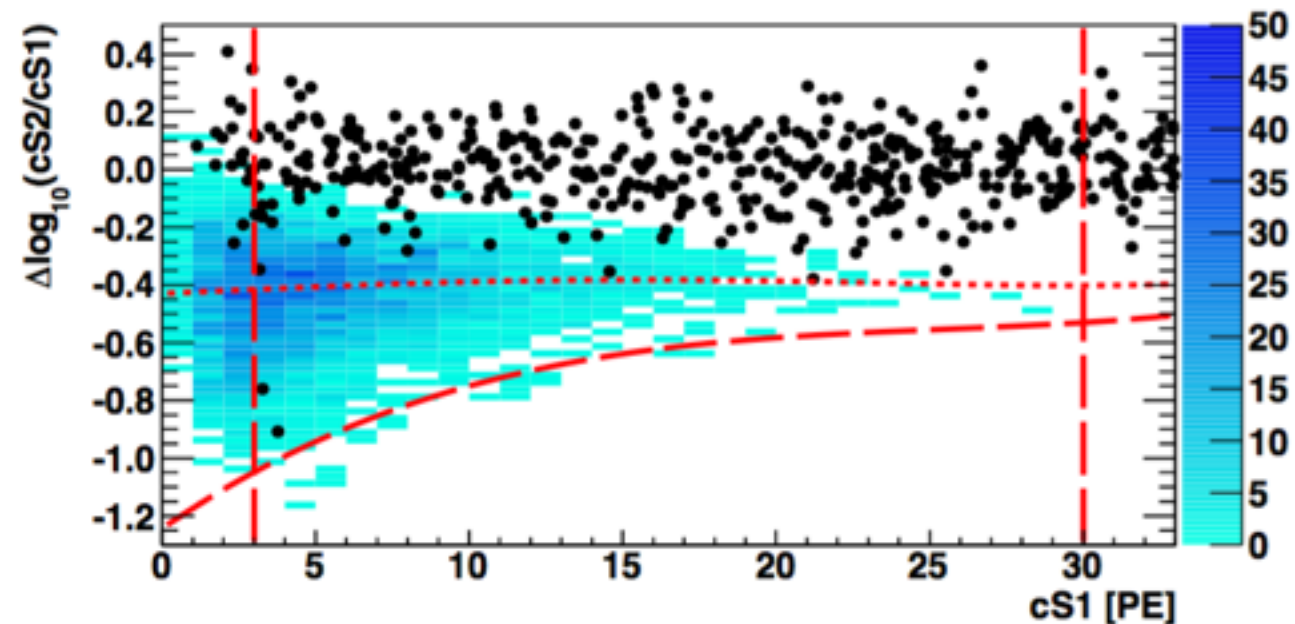
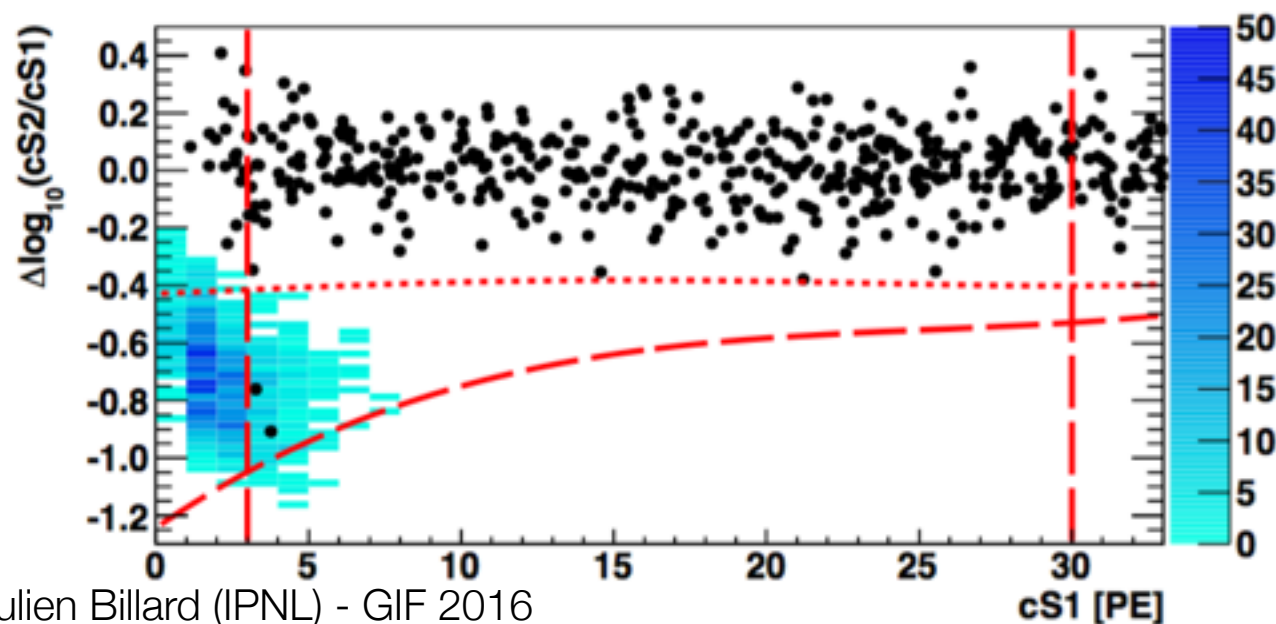
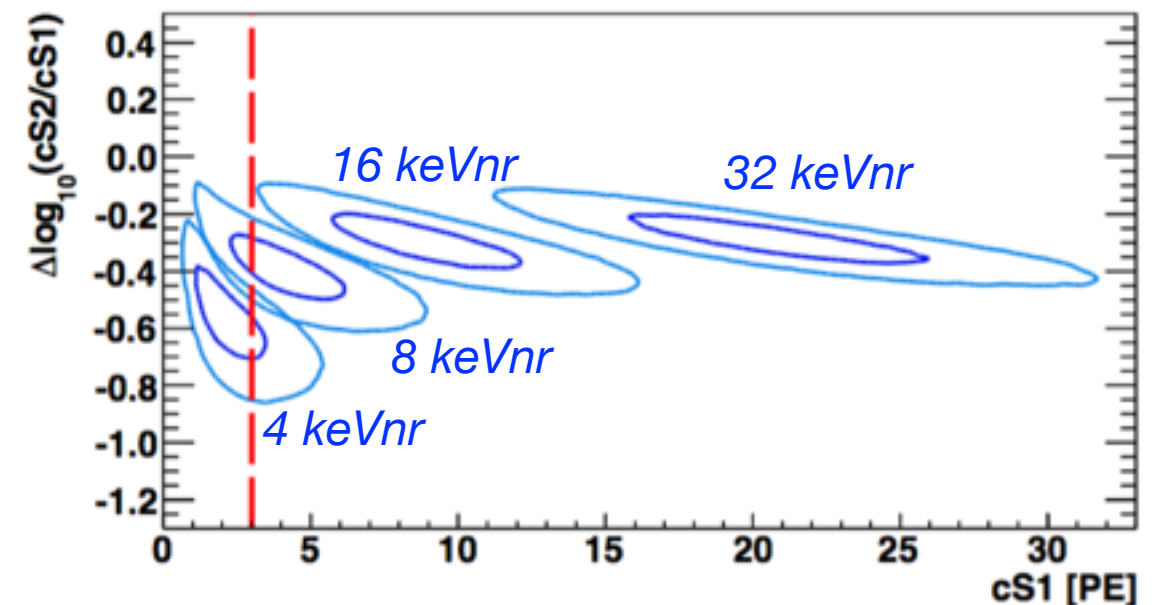
2 keV electronic recoil: S1 = 5 phd, S2=1000 phd

High WIMP mass region (10 GeV - 1 TeV)

XENON, IDM2016

How does a WIMP signal look like

- A WIMP signal would be **uniformly distributed in the detector volume**
- Plot on the right show simulations of mono-energetic nuclear recoil
 - We see the strong anti-correlation S2/S1
 - We appreciate how bad is the energy resolution in such experiments !!
- Plots below show a 8 GeV (left) and 25 GeV (right) WIMP signal in the S1/S2 plane



High WIMP mass region (10 GeV - 1 TeV)

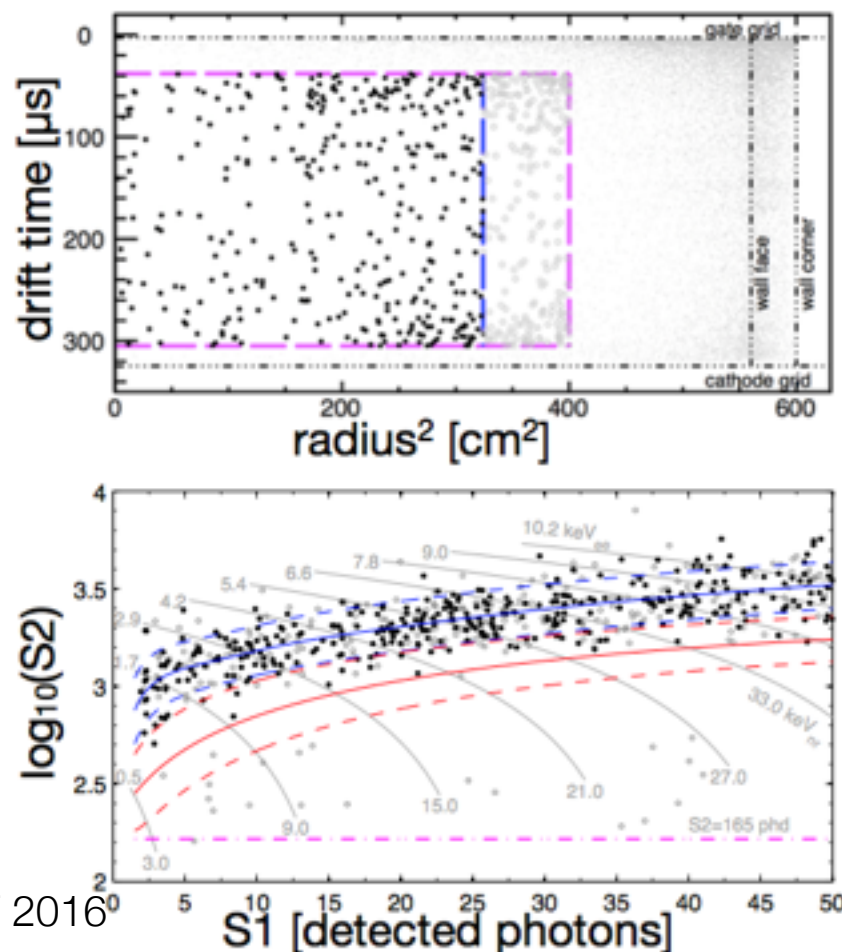
LUX, UCLA Dark Matter 2016

LUX analysis scheme

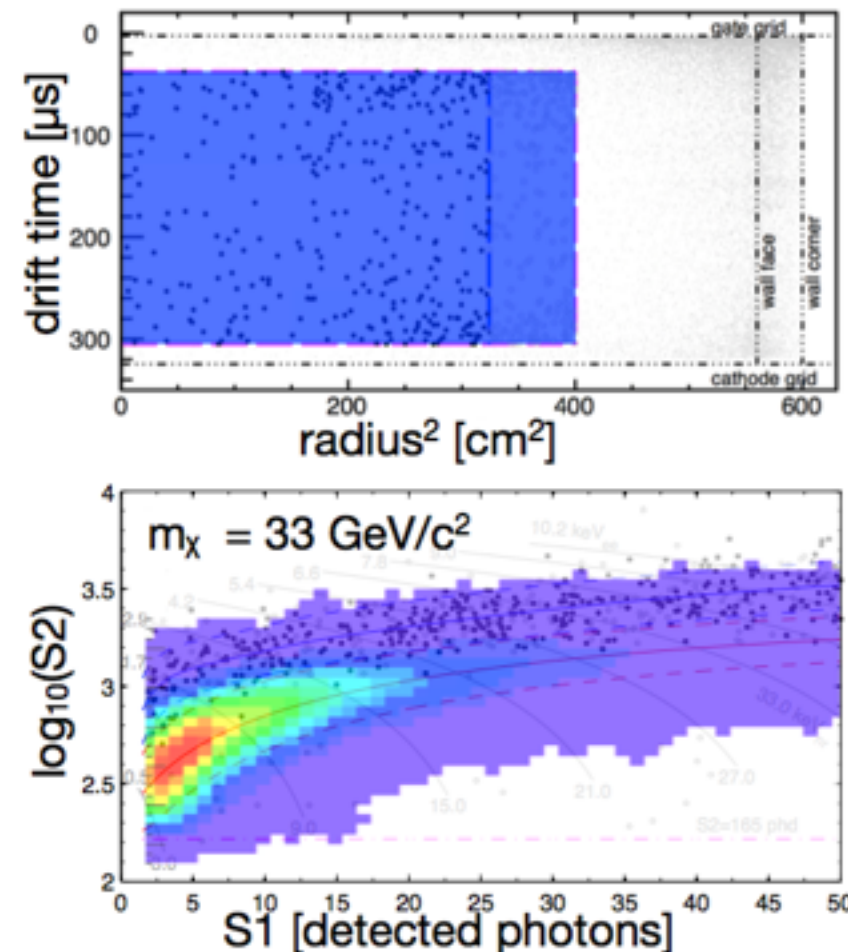
- Profile likelihood analysis of the new LUX result
- Fiducial cut to benefit from self-shielding
- Data-driven background model accounts for activated Ar and Xe, wall events, remaining gammas and betas
- WIMP signal model relies on robust calibration and efficiency estimates

	Parameter	Constraint	Fit value
	Lindhard k	0.174 ± 0.006	-
	S2 gain ratio: $g_{2,DD}/g_{2,WS}$	0.94 ± 0.04	-
background rates	Low- z -origin γ counts: $\mu_{\gamma, \text{bottom}}$	172 ± 74	165 ± 16
	Other γ counts: $\mu_{\gamma, \text{rest}}$	247 ± 106	228 ± 19
	β counts: μ_{β}	55 ± 22	84 ± 15
	^{127}Xe counts: $\mu_{\text{Xe-127}}$	91 ± 27	78 ± 12
	^{37}Ar counts: $\mu_{\text{Ar-37}}$	-	12 ± 8
	Wall counts: μ_{wall}	24 ± 7	22 ± 4

Exposure Events



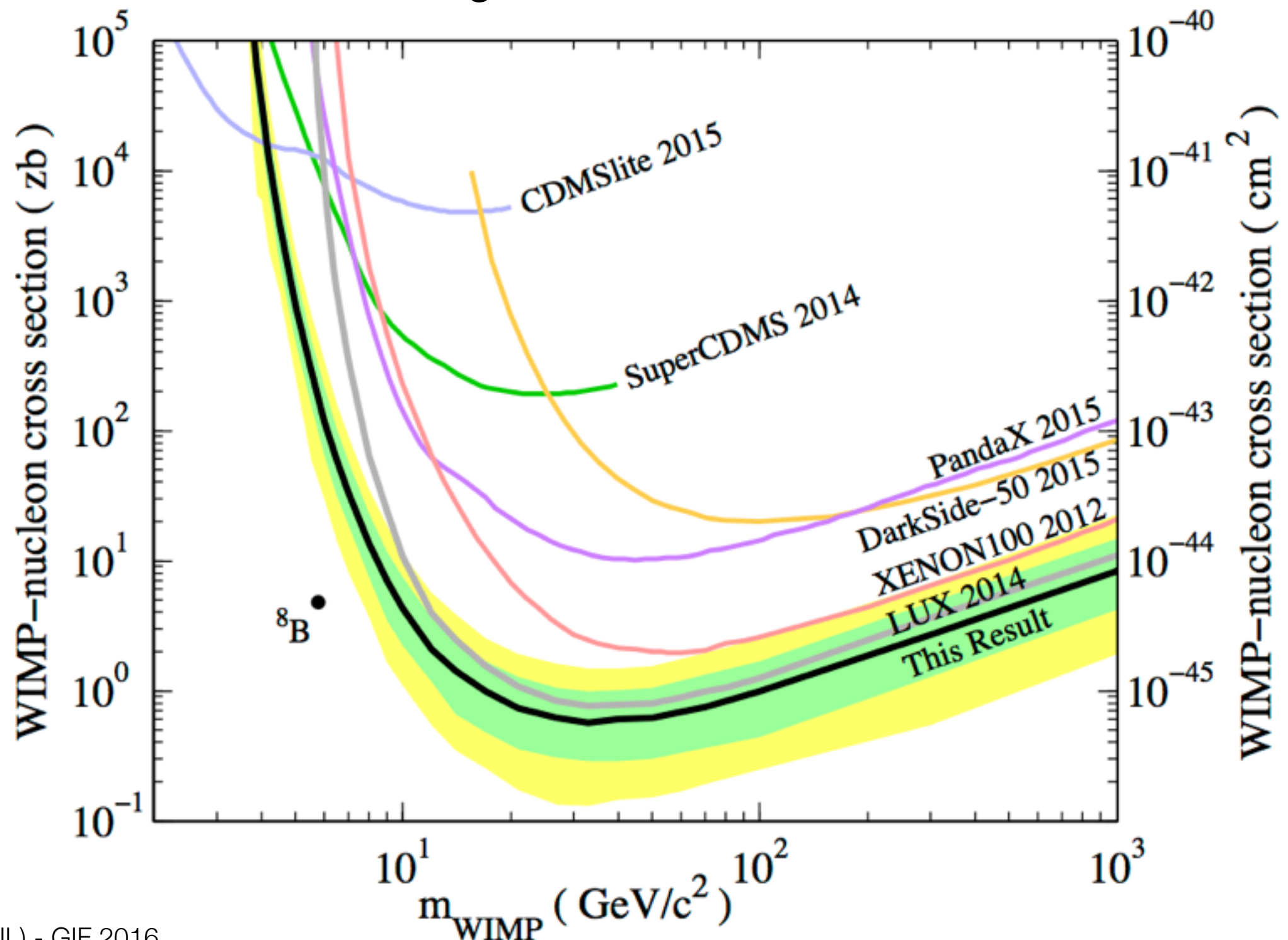
Example WIMP Model



High WIMP mass region (10 GeV - 1 TeV)

LUX, UCLA Dark Matter 2016

World leading limit for standard WIMP searches



High WIMP mass region (10 GeV - 1 TeV)

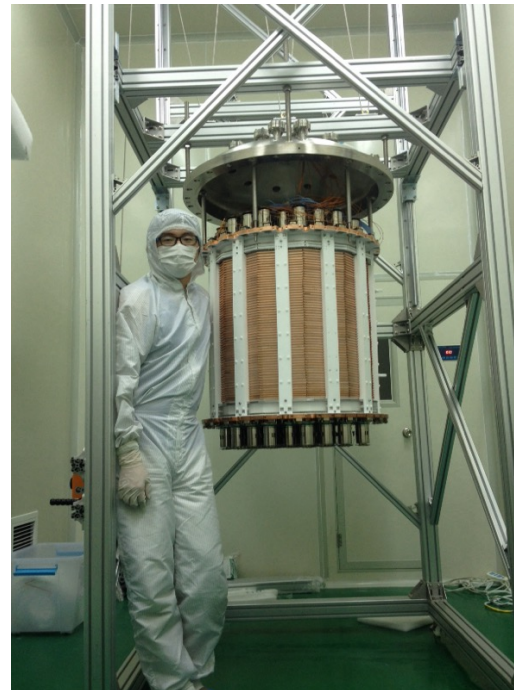
IDM2016

Ongoing Xe dual phase TPC direct detection experiments



LUX:

- 259 kg of LXe (48 cm drift)
- 61 PMT on top and bottom
- Purified Xenon (low Kr)
- Water veto (muons, neutrons)
- Sanford Lab
- 33500 kg-days
- leading limit 0.2 zb @ 50 GeV



PANDAX-II:

- 500 kg of LXe (60 cm drift)
- 55 PMT on top and bottom
- Purified Xenon (low Kr)
- CJPL Lab
- 33000 kg-days
- co-leading limit 0.2 zb @ 50 GeV



XENON-1T

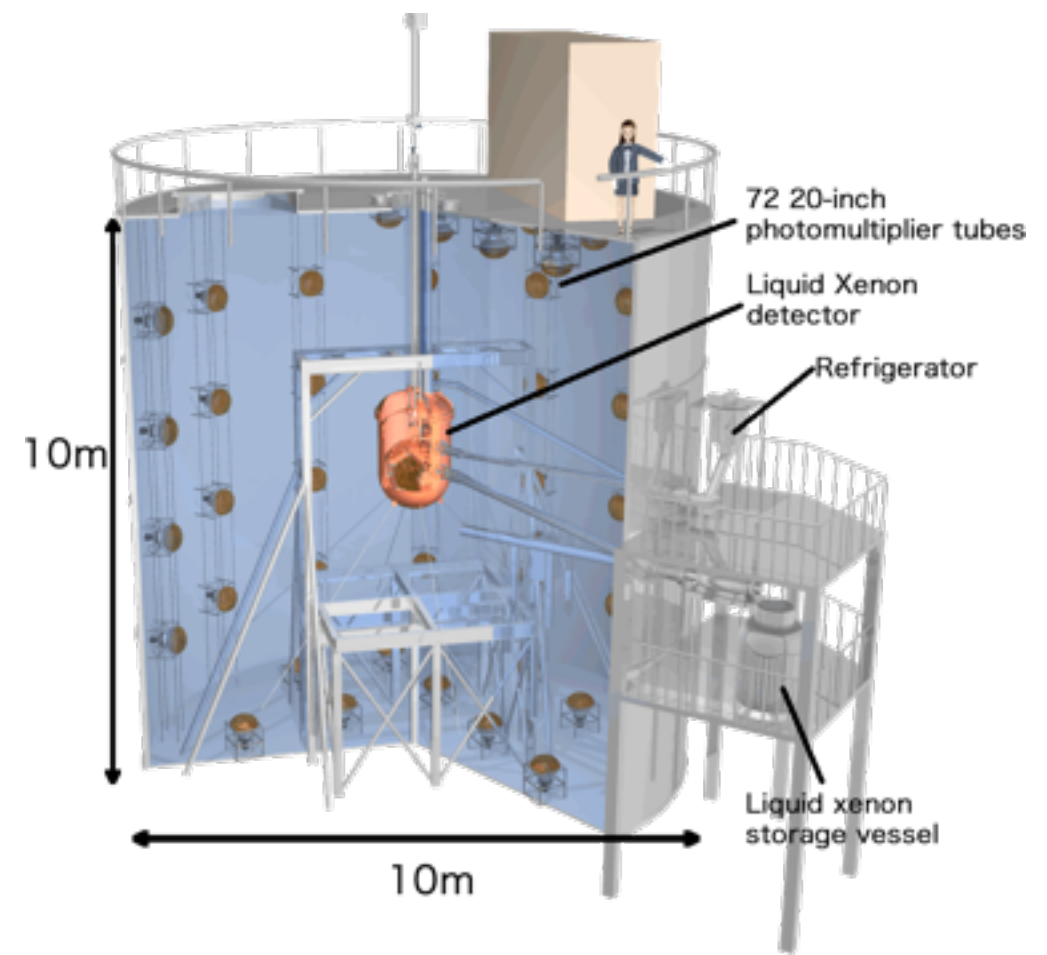
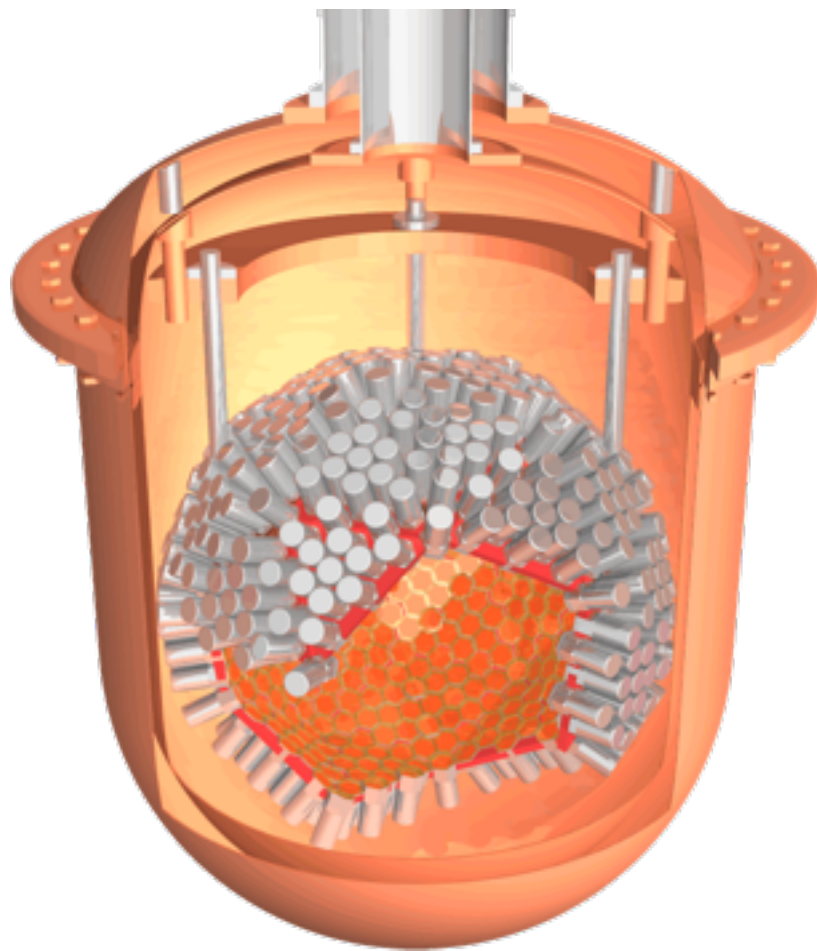
- 3500 kg of LXe (1m drift)
- 120 PMT on top and bottom
- Purified Xenon (low Kr)
- LNGS (Gran Sasso)
- cooling down
- **expect 0.01 zb @ 50 GeV (2017)**

High WIMP mass region (10 GeV - 1 TeV)

XMASS, IDM2016

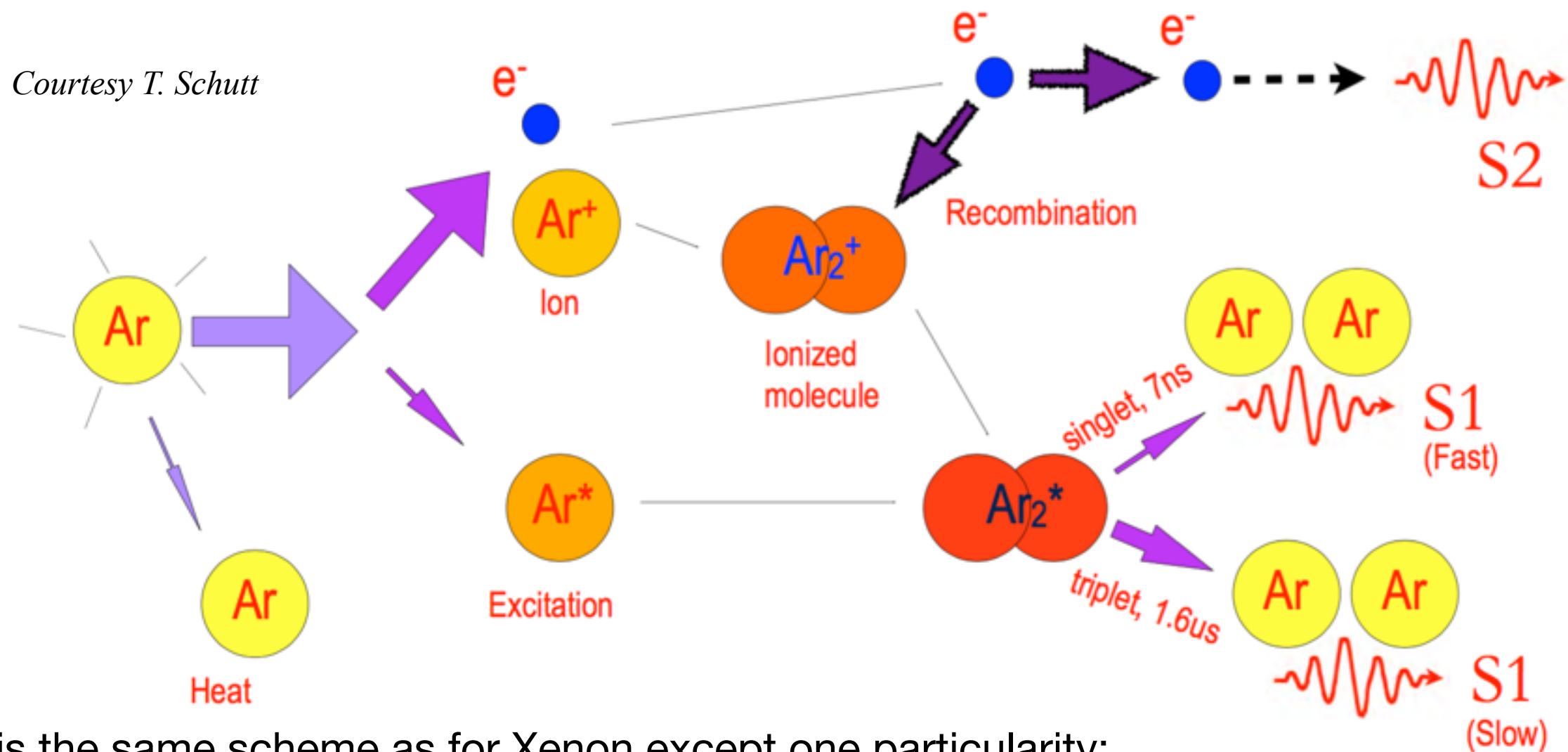
XMASS: single phase LXe dark matter detector

- In Kamioka underground lab
- The detector is filled with 1 ton of LXe
- 62% coverage with 642 low-radioactivity PMTs —> S1 scintillation only (no discrimination)
- Strategy: maximal exploit self-shielding with strong fiducial cut (100 kg FV) + water veto
- Results: 10^{-43} cm^2 at 20 GeV



High WIMP mass region (10 GeV - 1 TeV)

How is the energy released in a Ar-based experiment?



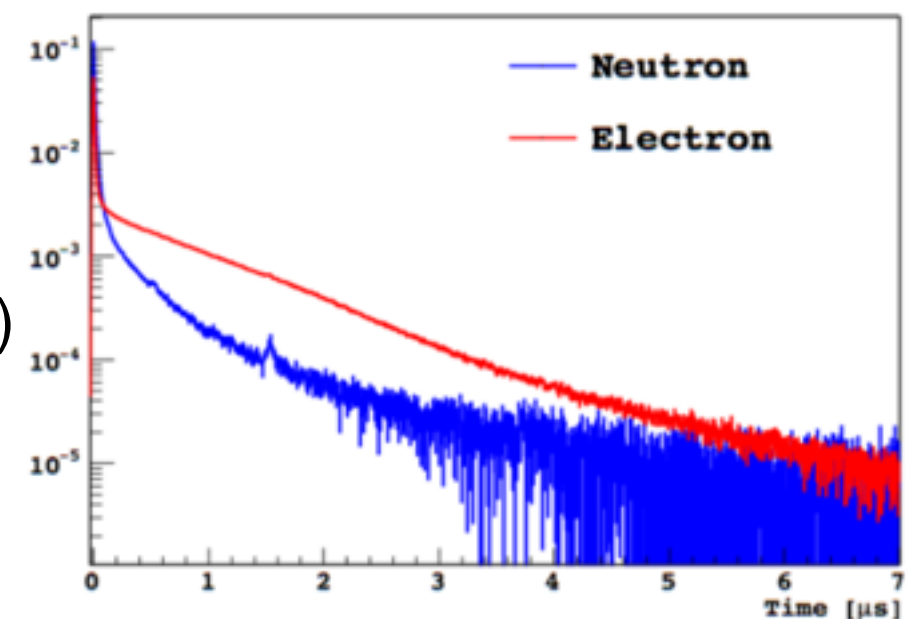
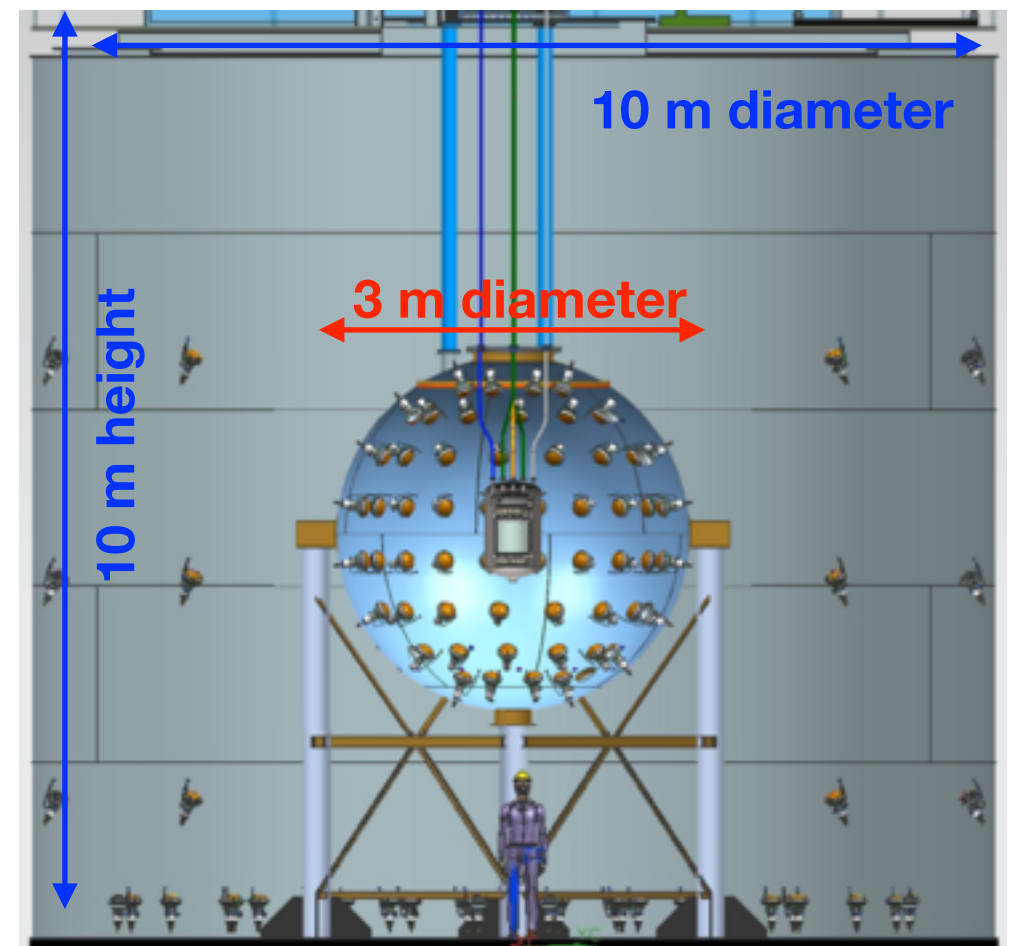
- It is the same scheme as for Xenon except one particularity:
 - There is two excited states that de-excite emitting scintillation light with different time constants
 - Nuclear recoil lead to a larger singlet/triplet ratio than electronic recoil
 - Nuclear recoil pulses are faster than electronic ones —> **pulse shape discrimination**

High WIMP mass region (10 GeV - 1 TeV)

DarkSide, IDM2016

What is the detection strategy?

- Similar detection principle as Dual-phase Xe TPC
- Primary scintillation (S1) and ionization (S2)
- Cheap, easy to scale and self-shielding !
- Can discriminate Electronic recoils from:
 - S1 Vs S2 discrimination
 - Pulse Shape Discrimination (f_{90})
- Current phase: DarkSide-50
 - 153 kg of Underground Argon (UAr)
 - 50 kg fiducial mass
- 38 PMT on bottom and top planes
- 30-ton B-loaded doped Liquid Scintillator Veto (neutrons)
- 1-ton Water Cherenkov Veto (muons and neutrons)
- Installed in LNGS (Gran Sasso)

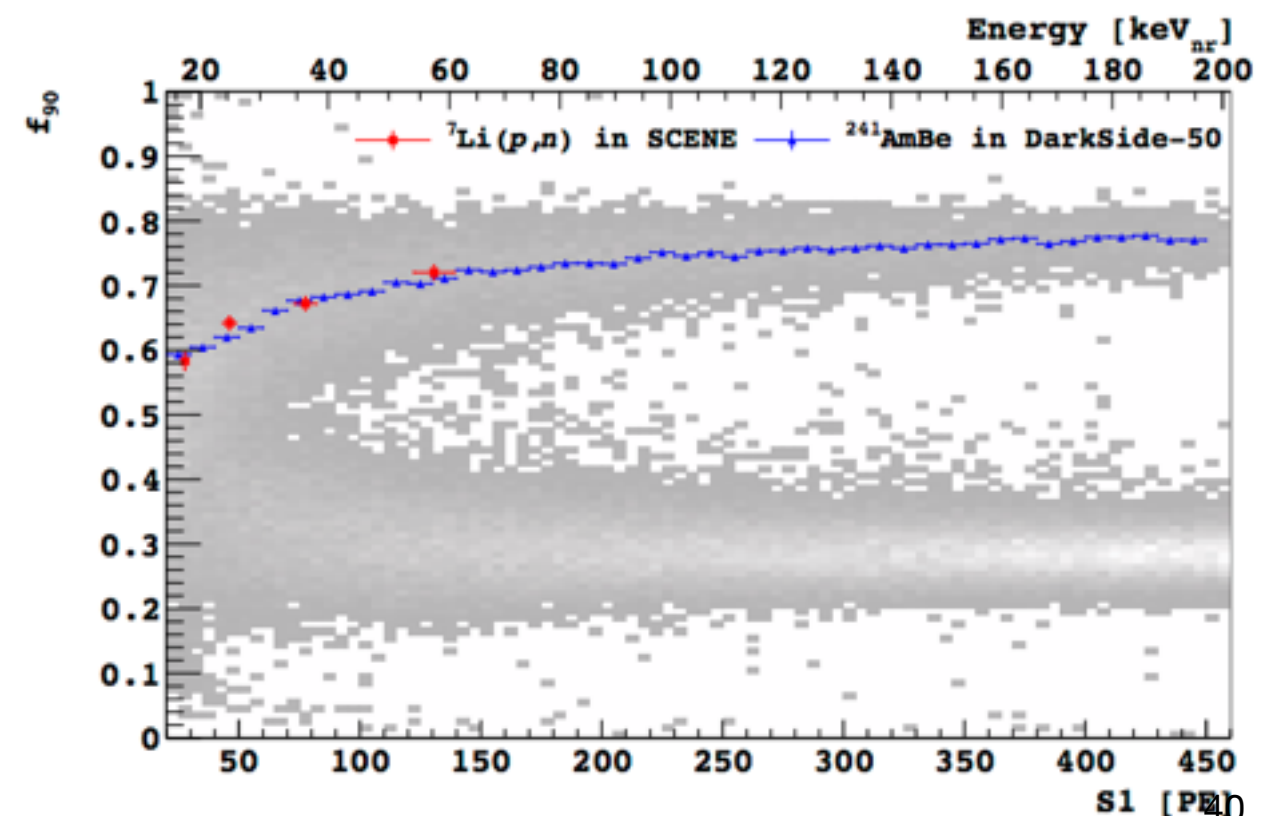
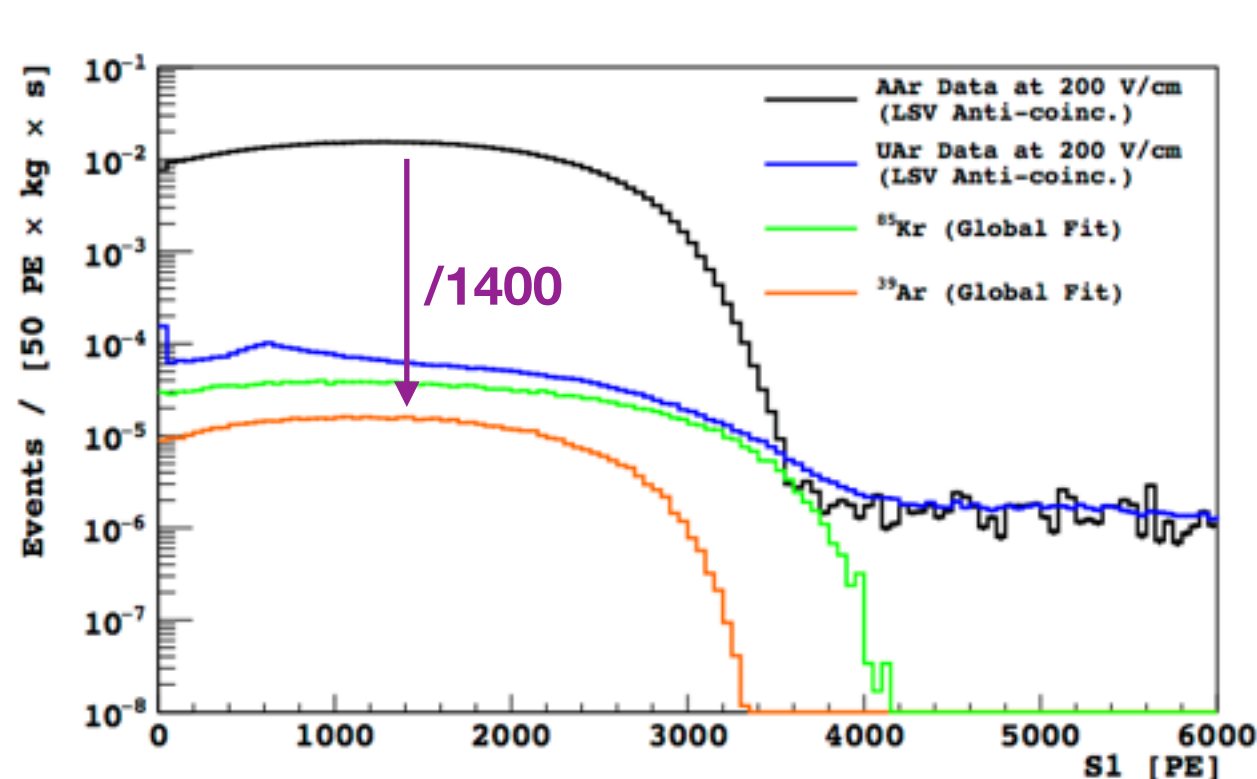


High WIMP mass region (10 GeV - 1 TeV)

DarkSide, IDM2016

What is the detection strategy?

- Main challenge comes from ^{39}Ar background from:
 - Naturally present in Atmospheric Argon (1 Bq/kg)
 - Supported by cosmogenic activation
 - Need to go underground and use depleted Argon (>1400 reduction)
- Pulse Shape Discrimination is powerful and even more efficient than S1/S2

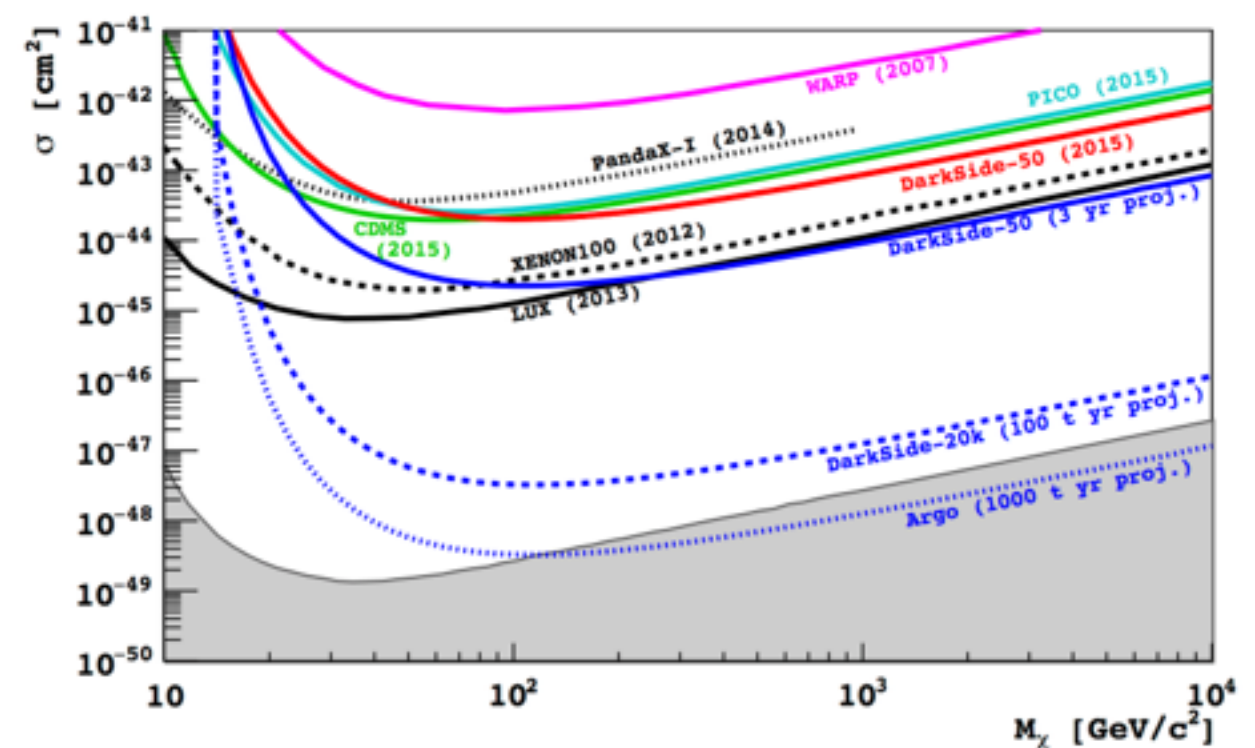
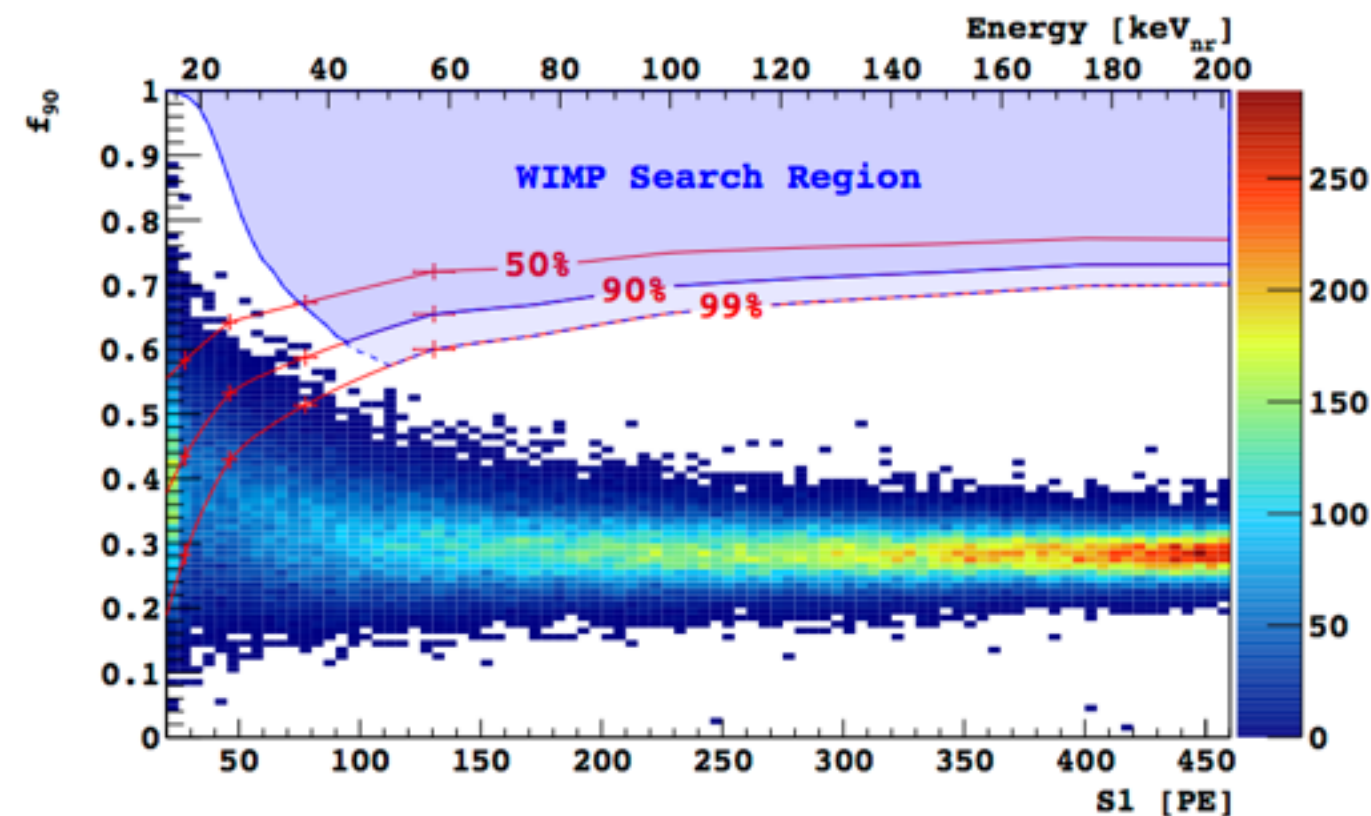


High WIMP mass region (10 GeV - 1 TeV)

DarkSide, IDM2016

DarkSide-50 results

- Combining AAr and UAr runs (5900 kg-days)
- Zero-background strategy enforces high energy threshold (~ 30 keV_{nr}, 50% eff.)
- Pulse Shape Discrimination is powerful and even more efficient than S1/S2 (not used)
- Best Ar-based limit: 10^{-44} cm² @ 100 GeV
- Next step is DarkSide-20k (20-tons) with DAr (Distillation of UAr with 350 m tall column)

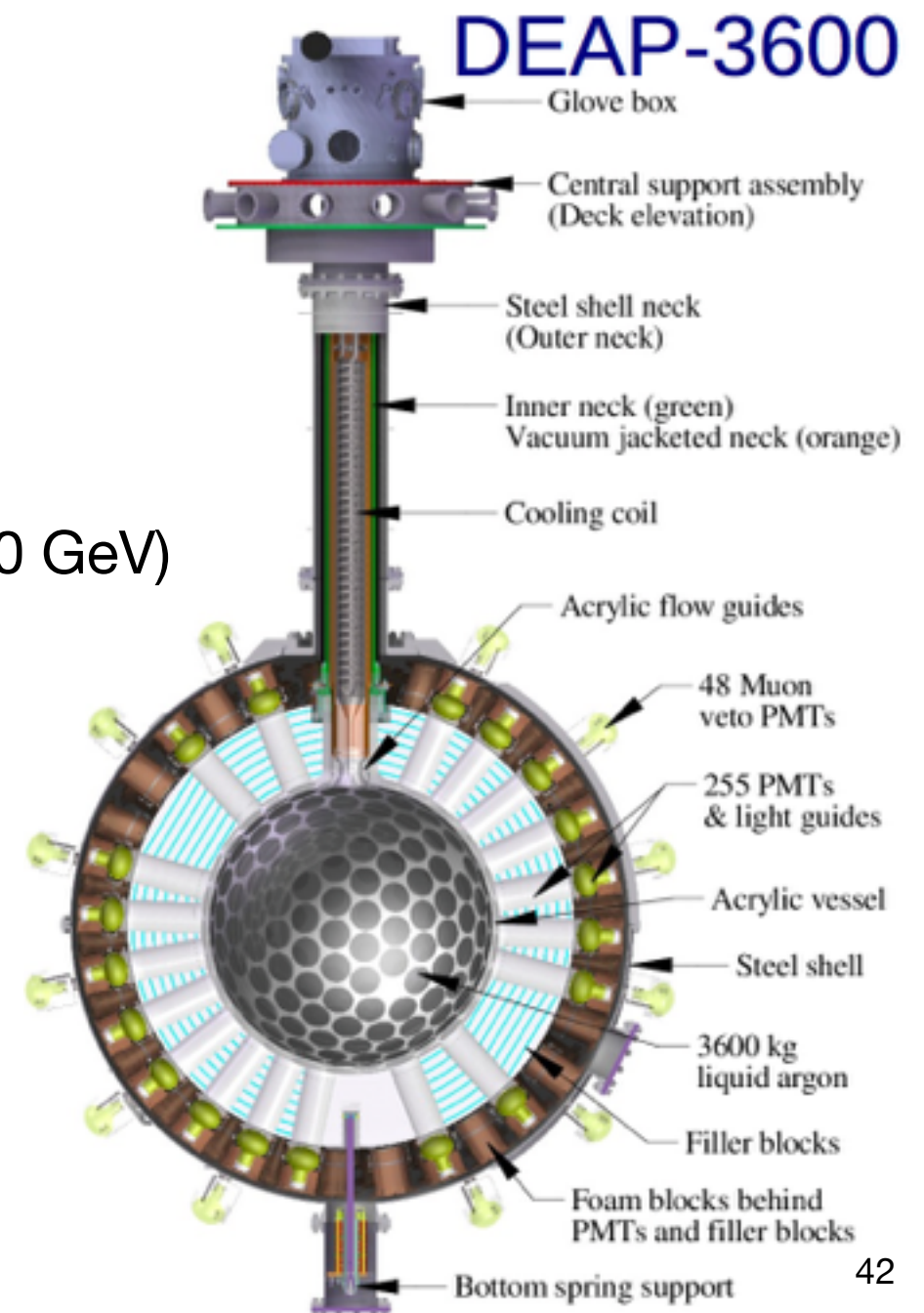
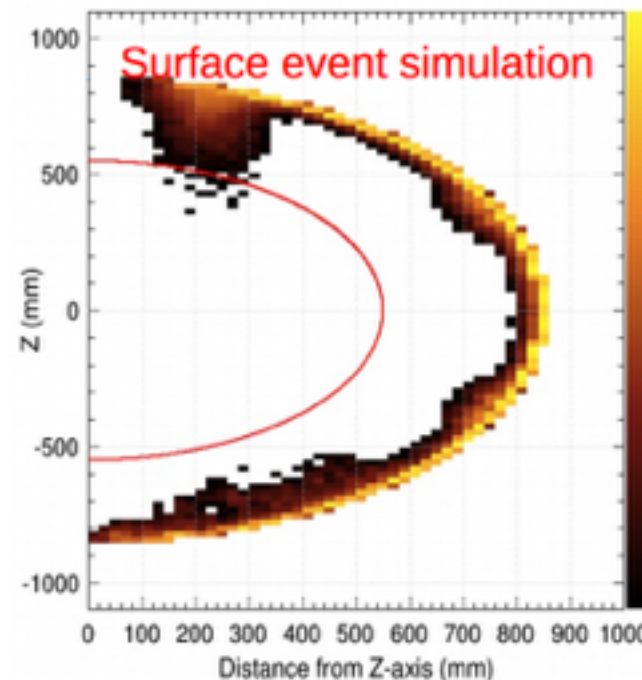
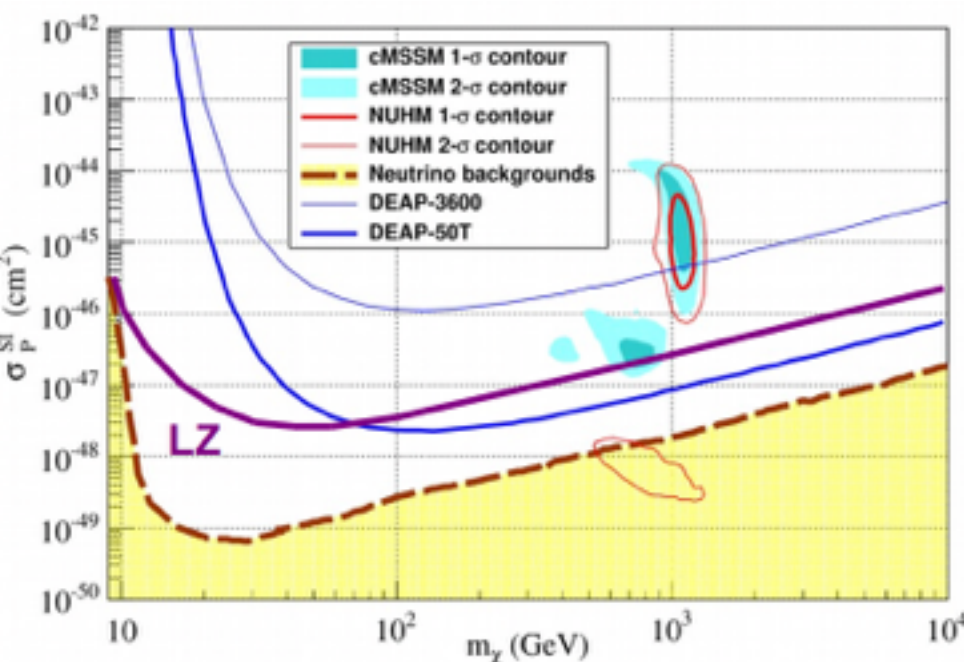


High WIMP mass region (10 GeV - 1 TeV)

DEAP, IDM2016

DEAP-3600: single phase LAr dark matter detector

- In SNOLAB underground lab
- The detector is filled with 3.6 ton of LAr
- 255 low-background PMTs (32% QE, 75% coverage)
- Resurfaced « in-situ » to remove Rn contamination
- Immersed in 8m of water shield with 48 PMTs
- Strategy: self-shielding, fiducialization and PSD $\sim 10^{-10}$
- Results expected: physics run just started ($10^{-46} \text{ cm}^2 @ 100 \text{ GeV}$)

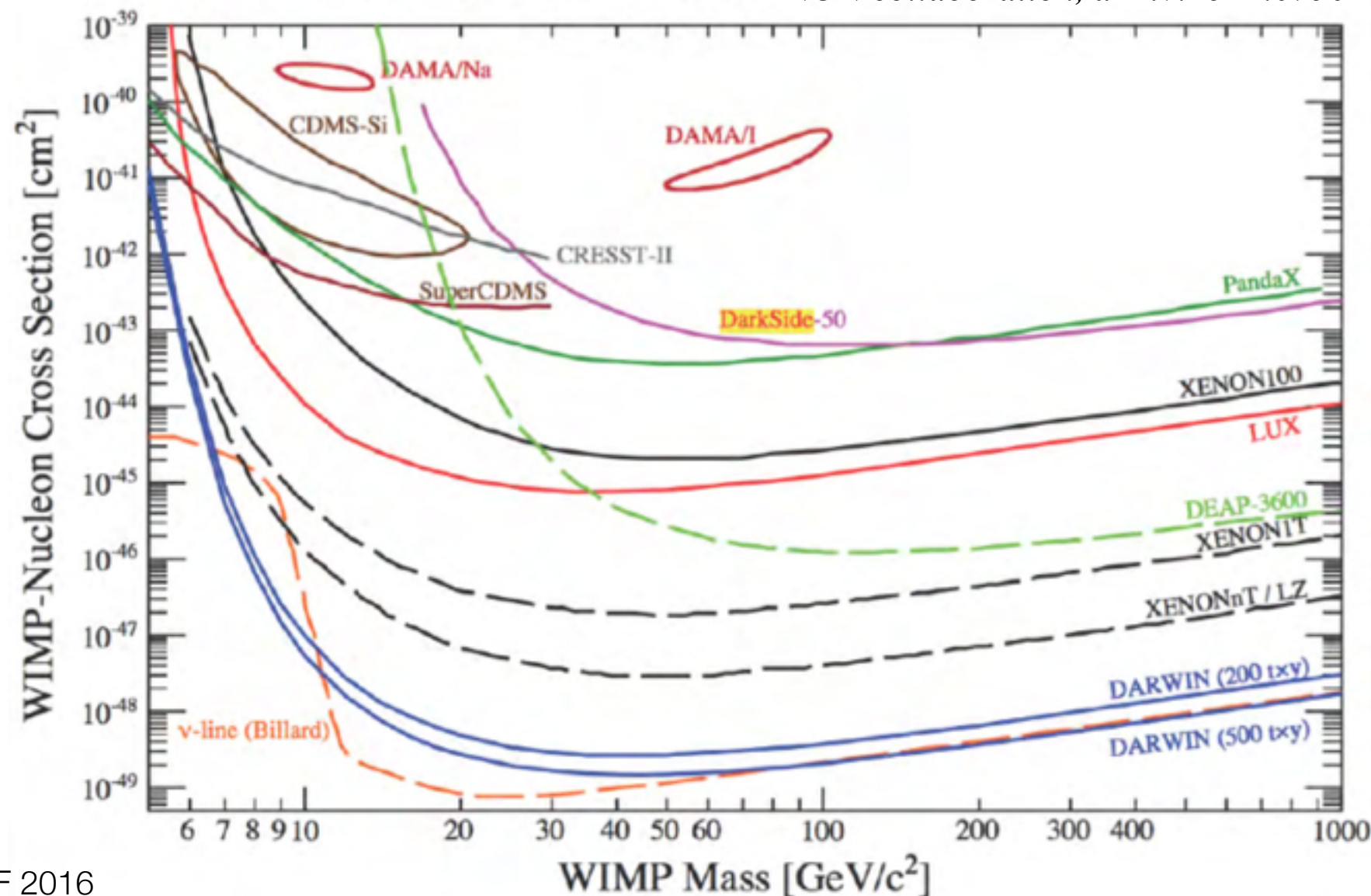


High WIMP mass region (10 GeV - 1 TeV)

Darwin, IDM2016

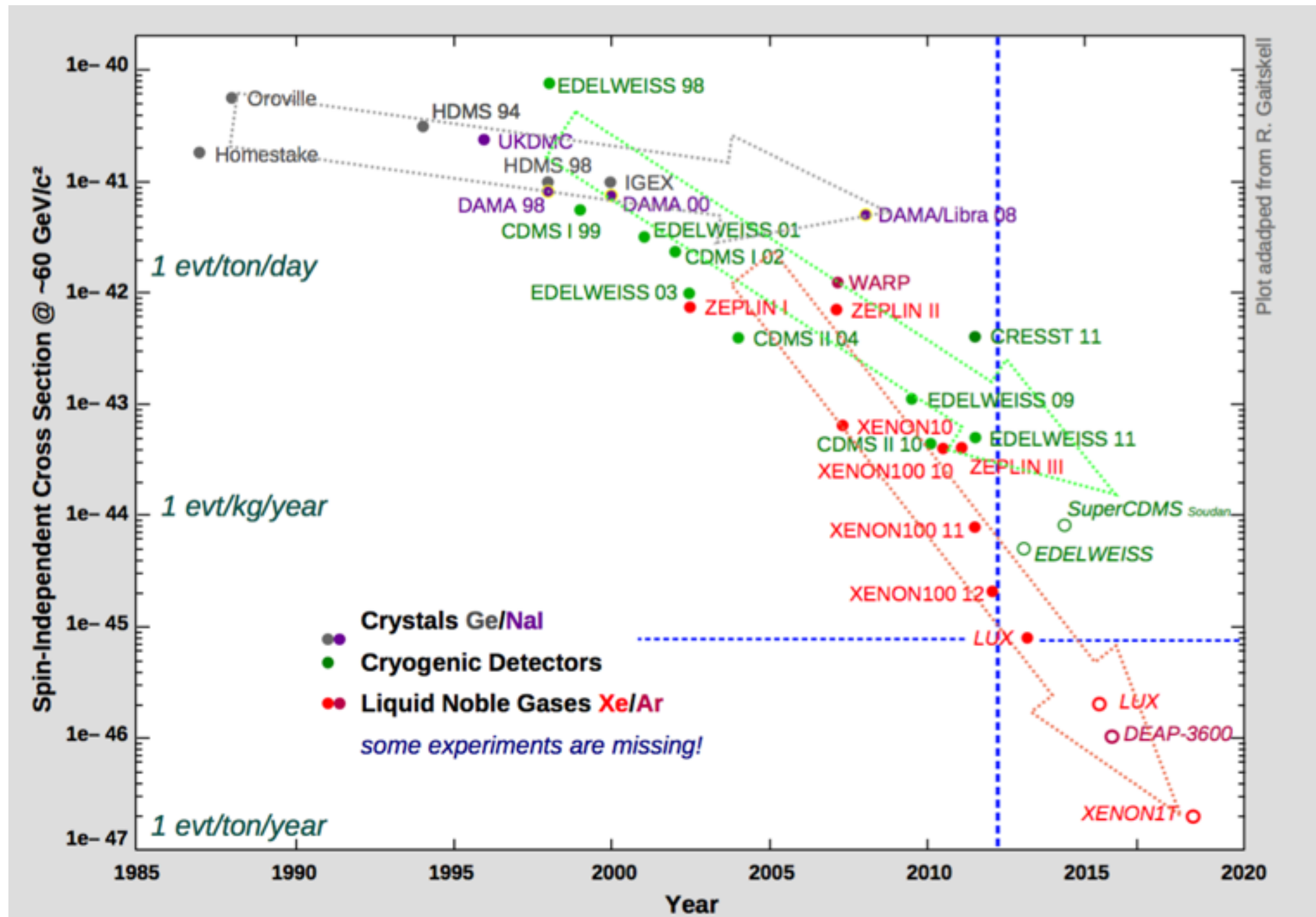
- Results coming soon from G2 experiments: **XENON1T** (Xe) and **DEAP** (Ar)
- G3 experiments aim at reaching the neutrino floor induced by atmospheric neutrinos
- Limited sensitivity to light (below 10 GeV) WIMP

XENON collaboration, arXiv:1512.07501

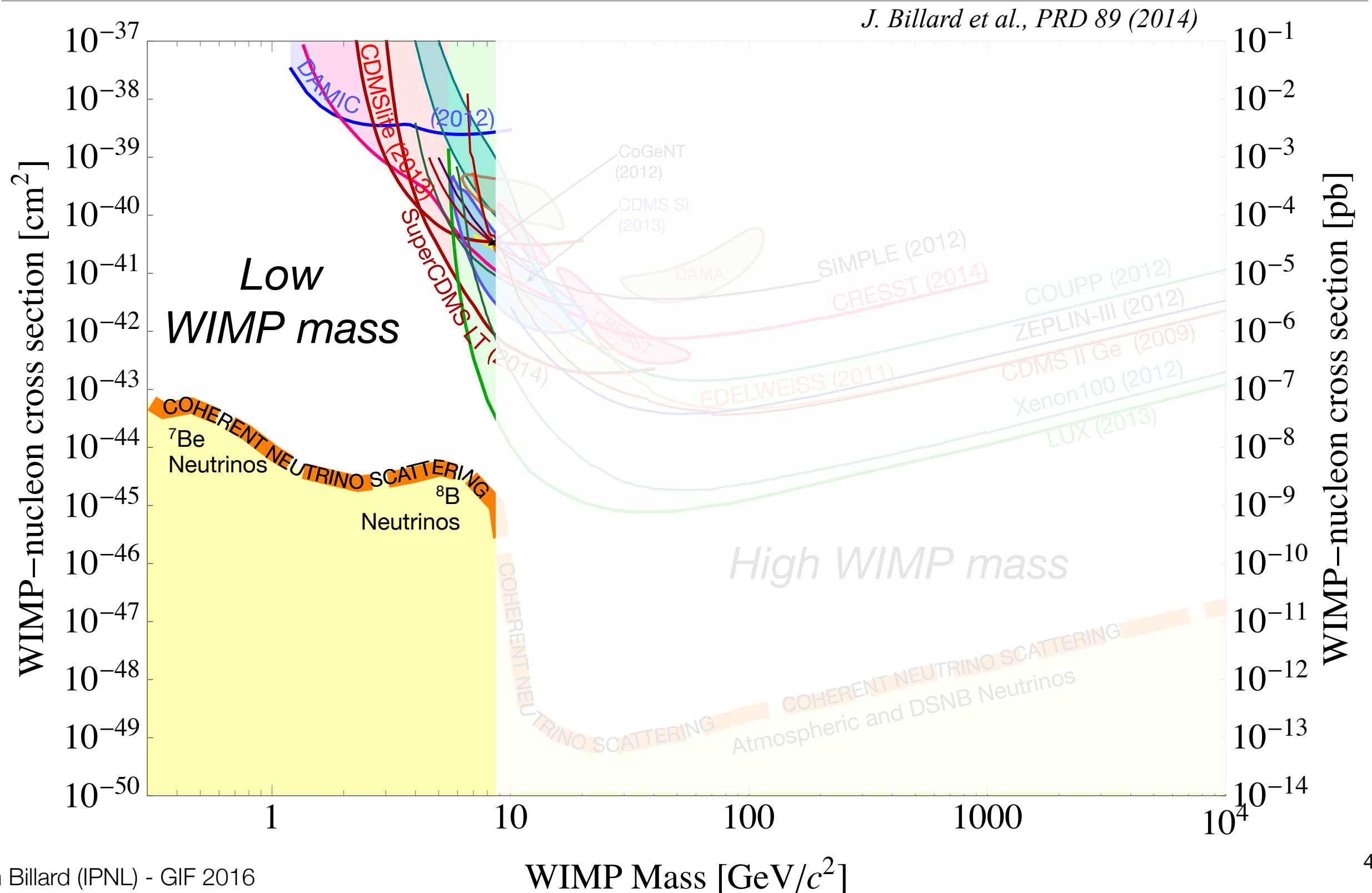


High WIMP mass region (10 GeV - 1 TeV)

Courtesy R. Gaitskell



Low WIMP mass region (1 GeV - 10 GeV)



Basics of direct detection

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

- **Low** and **controlled** backgrounds (*so that they can be subtracted*)
- **Discrimination** between signal and background (*to further reduce the background*)
- **Large exposure** (*few events per ton-year*)
- **Low energy threshold** (*the lower, the better, especially for low WIMP mass*)

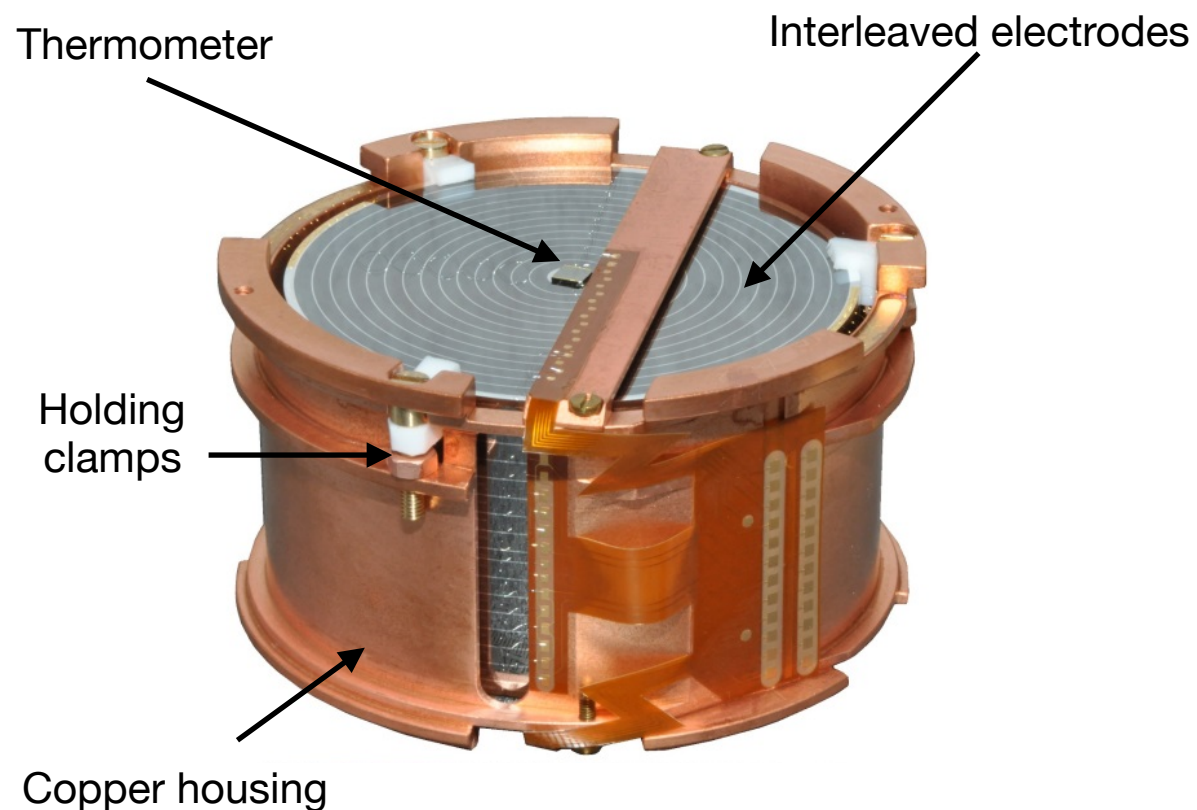
Basics of direct detection

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Low WIMP mass region (1 GeV - 10 GeV)

Heat + ionization

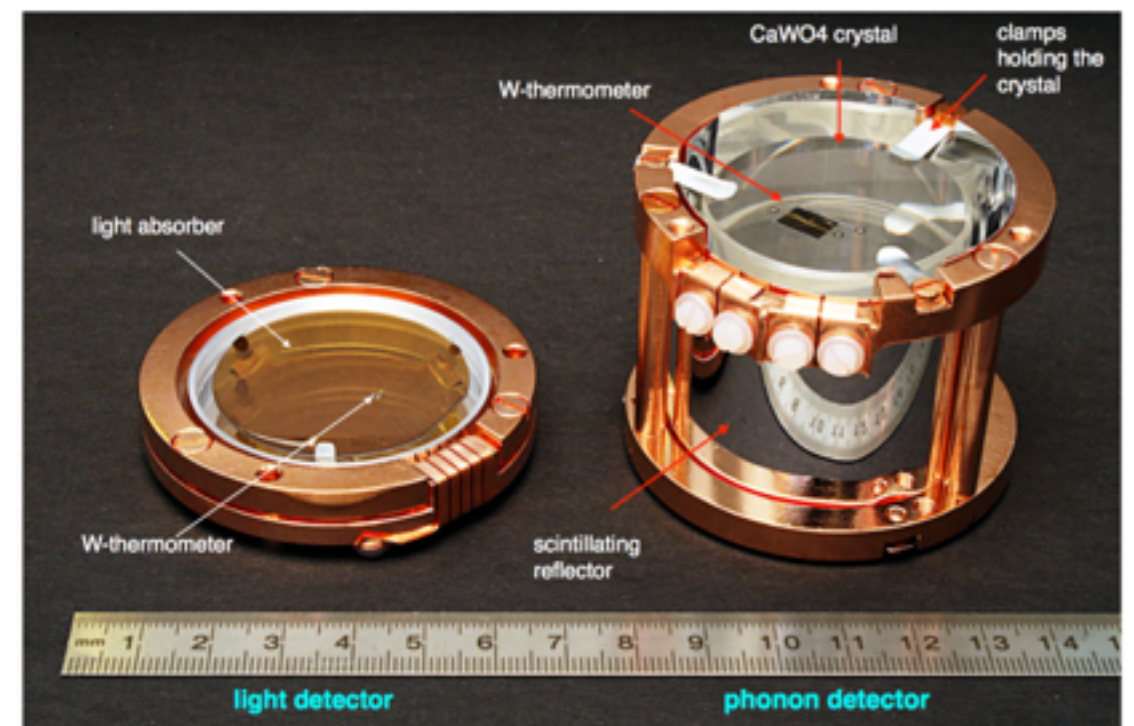


EDELWEISS (18 mK)

SuperCDMS (50 mK)

Ge target

Heat + scintillation



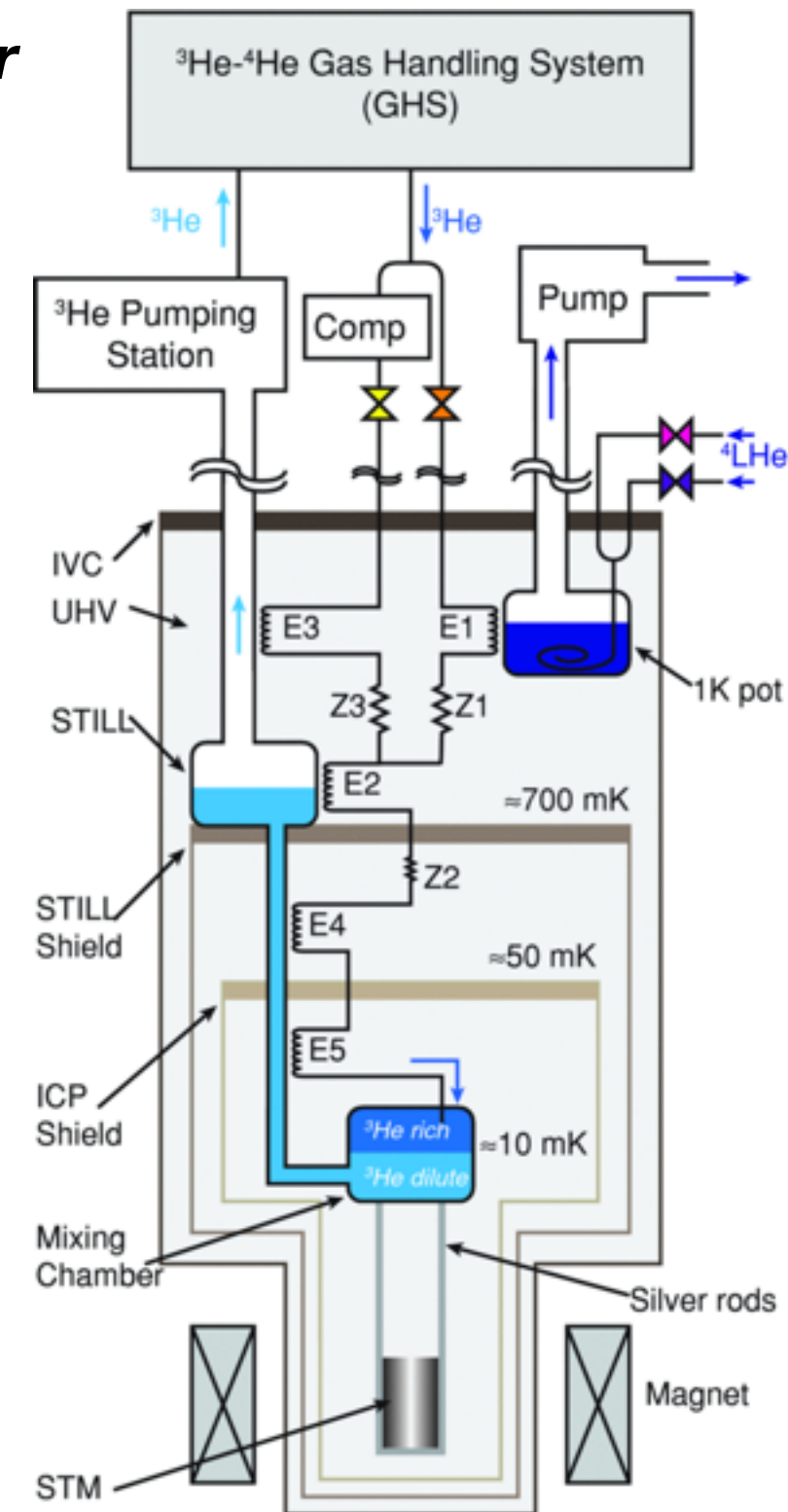
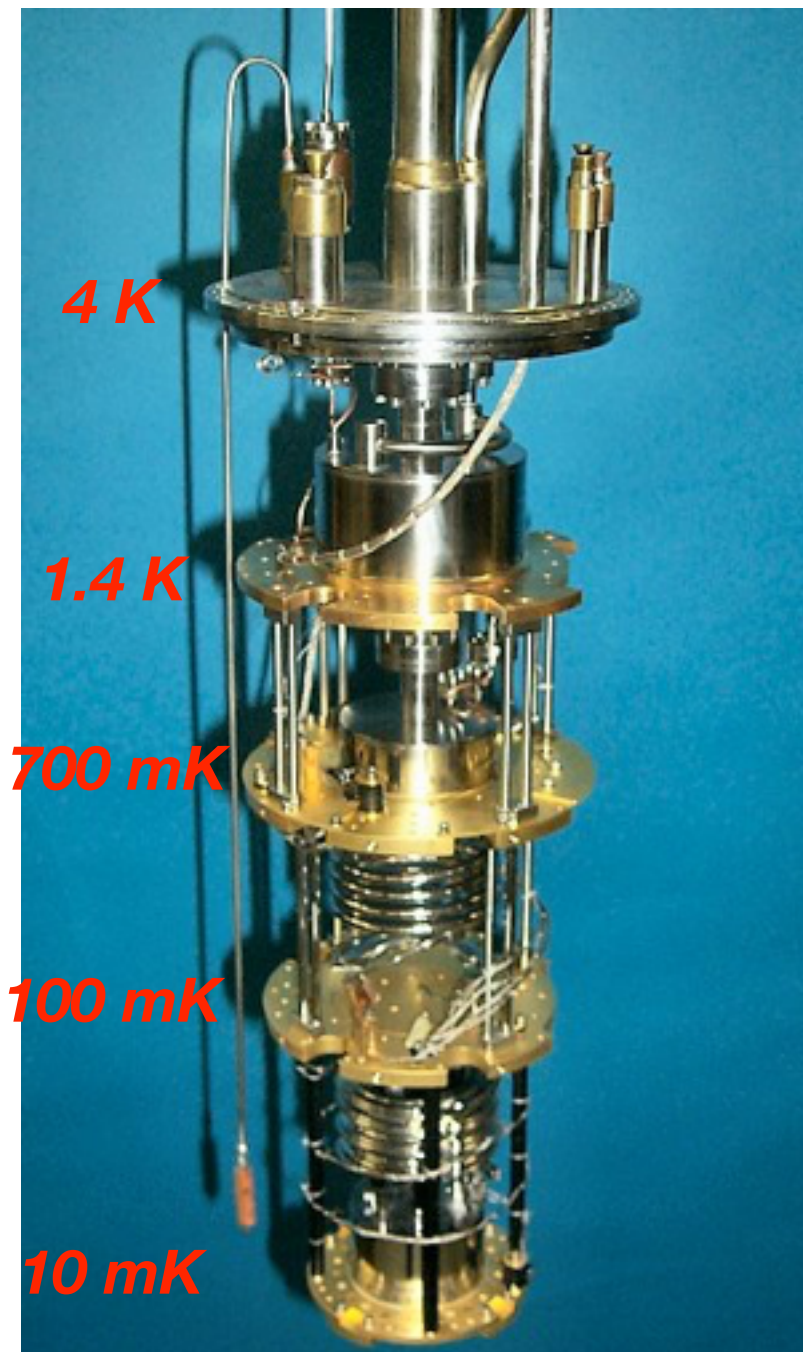
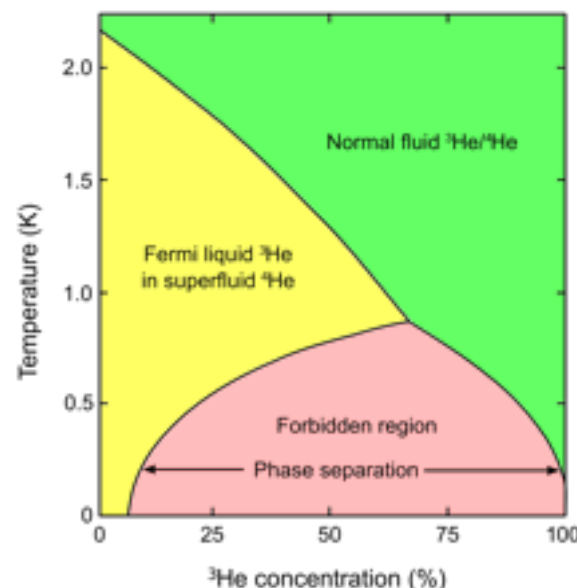
CRESST (18 mK)

CaWO₄ target

Low WIMP mass region (1 GeV - 10 GeV)

To reach 10 mK we need to use He3/He4 dilution refrigerator

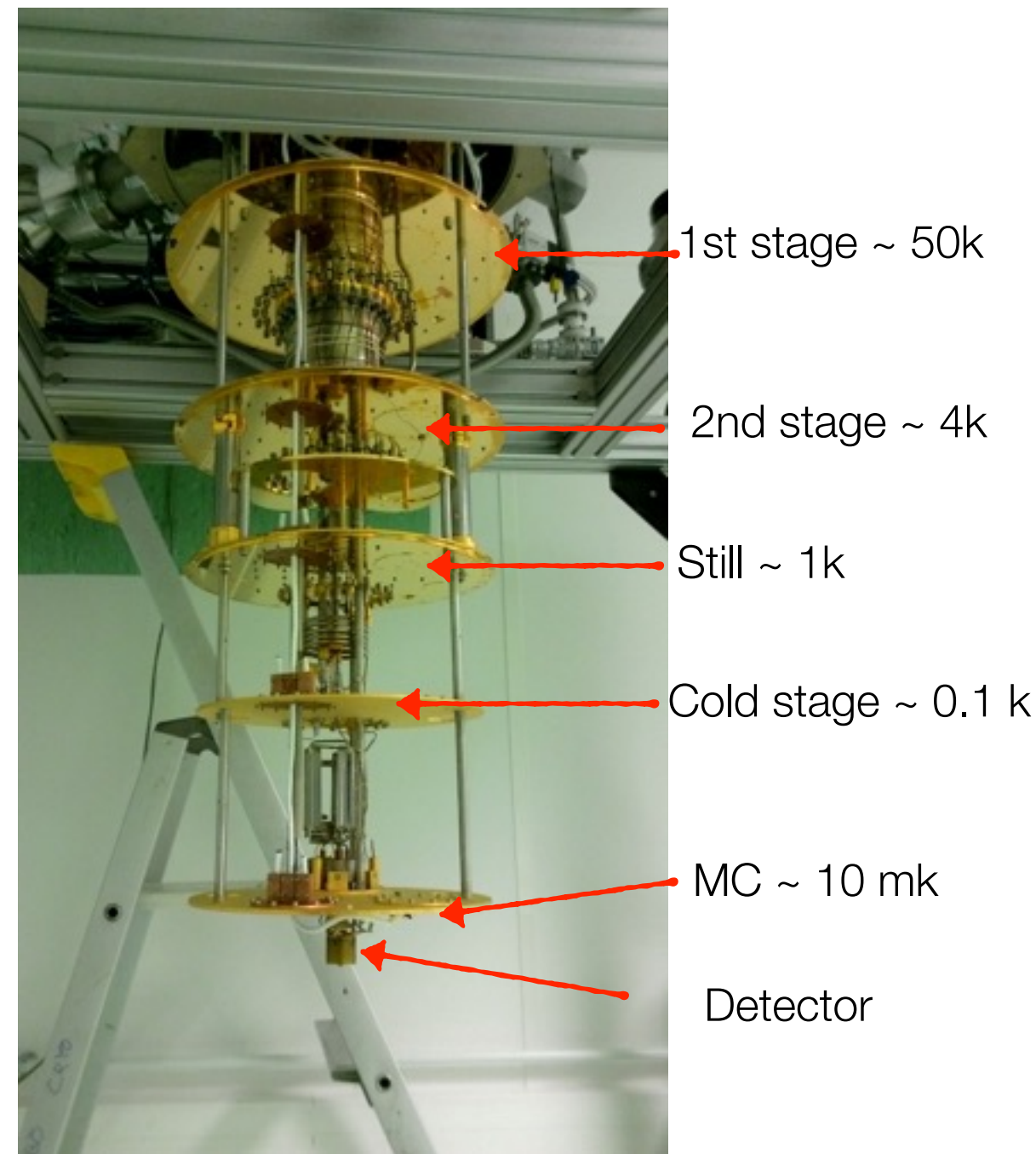
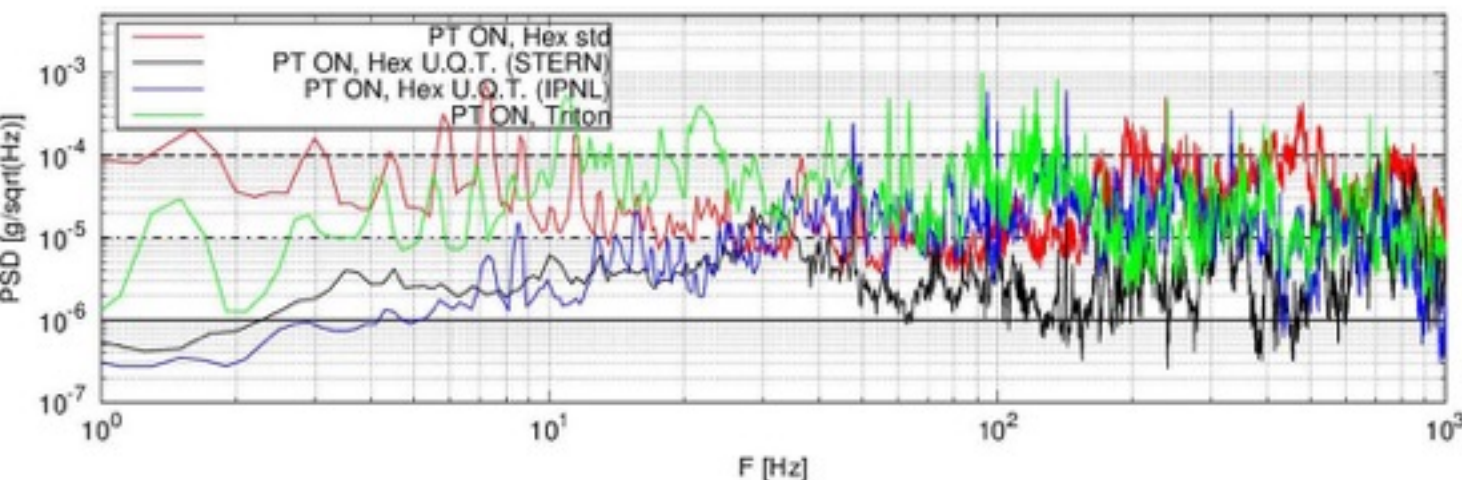
- **Cool down to 4K:**
 - thanks to pre-cooling LN2 and LHe
- **Reach 1 K thanks to evaporative cooling**
 - Done by pumping on LHe in 1K pot
- **Condense the He3/He4 mix**
- **Reach 700 mK thanks to Joule-Thompson**
- **Below 800 mK: phase separation (rich/poor)**
- **10 mK thanks to He3/He4 dilution**
 - Forcing He3 through poor phase is endothermic
 - Done by pumping on dilute phase (poor)



Low WIMP mass region (1 GeV - 10 GeV)

- **Standard « wet » cryostats are expensive**
 - LHe cost is ~1000 euros for a week
- **Cryofree fridges are the future**
 - Pulse tube to reach 4 K
 - But they vibrate !!!
- **Pulse tube have to be de-coupled mechanically**
 - ~ 1 micro-g/sqrt(Hz) level achieved
 - <100 nm (RMS) !!

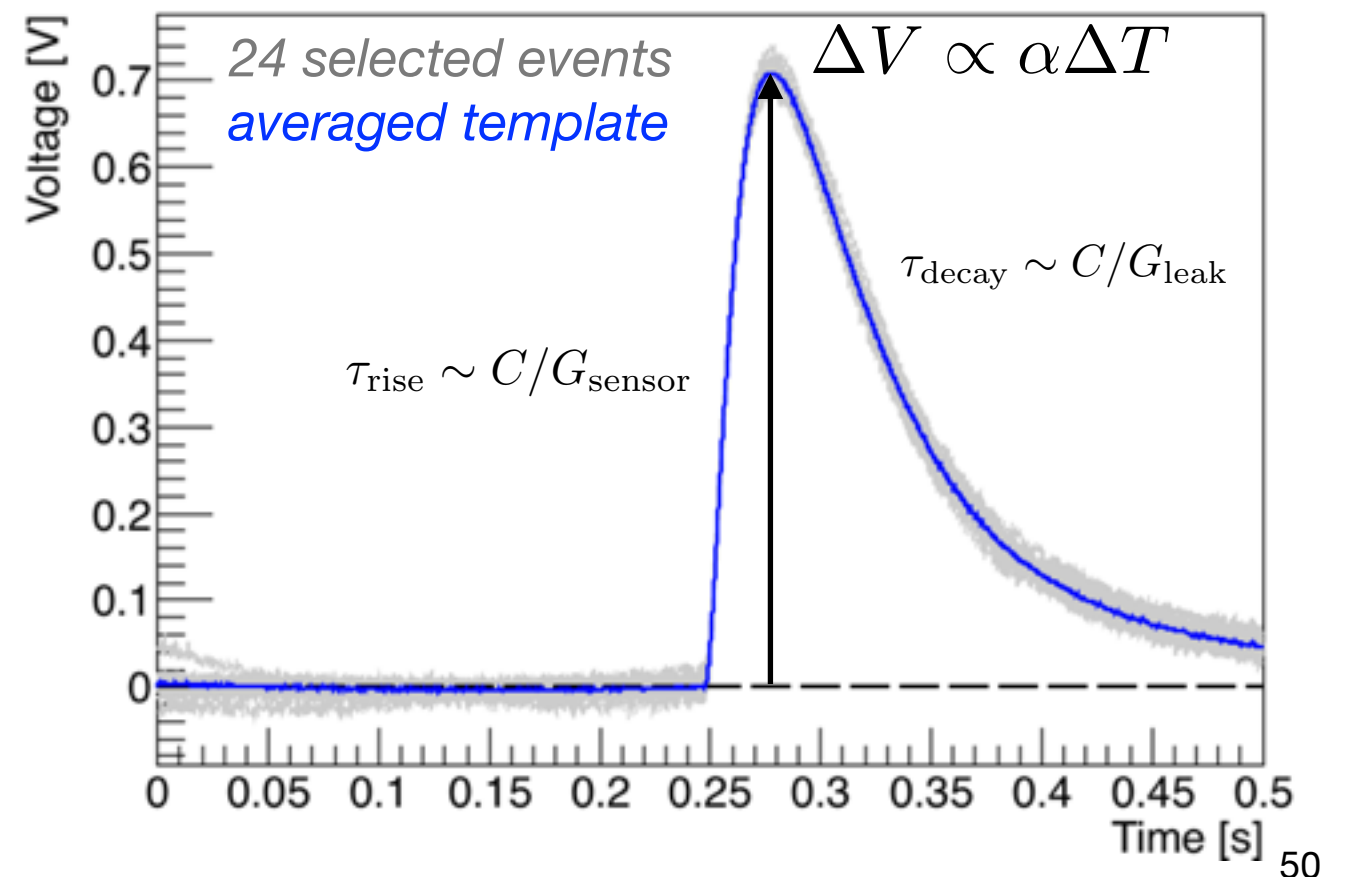
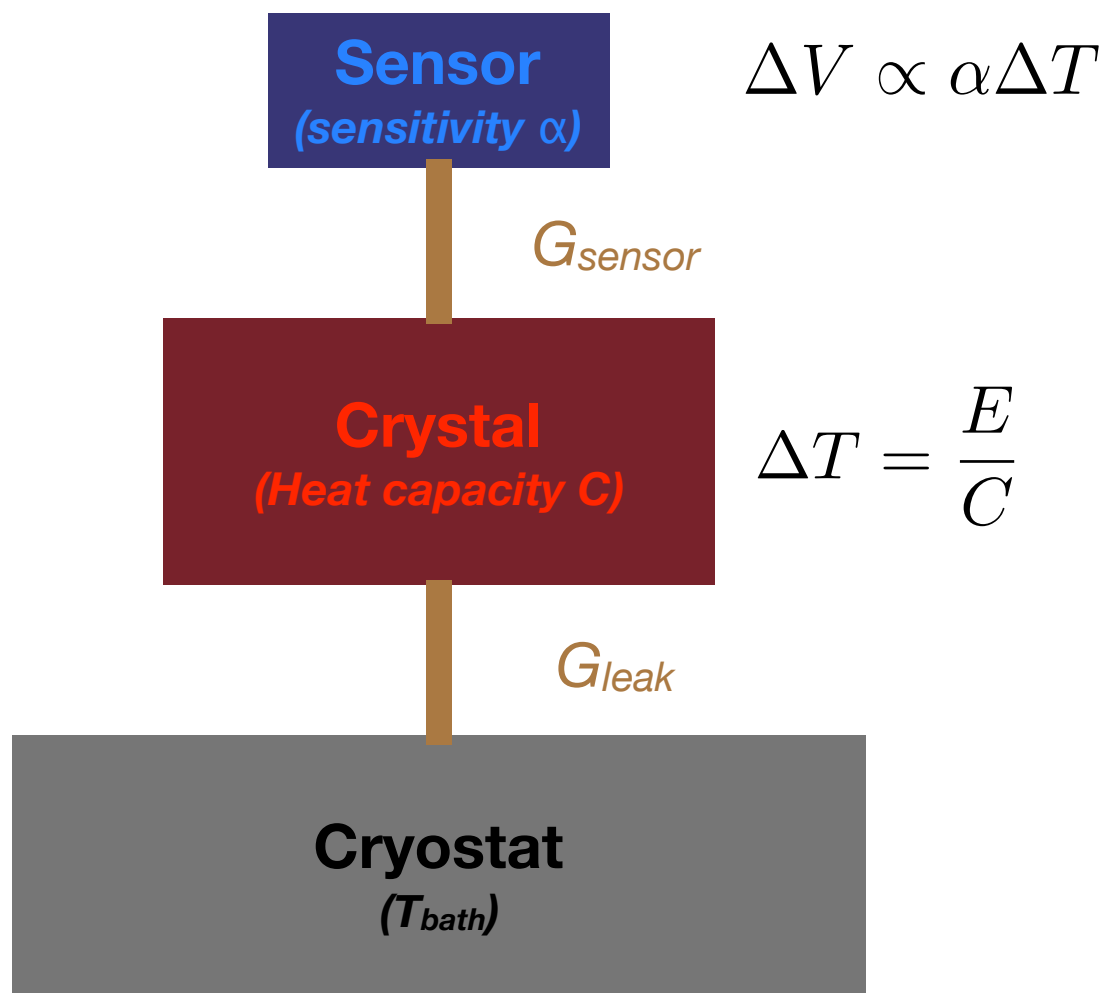
E. Olivieri, J. Billard and M. De Jesus, to be submitted



Low WIMP mass region (1 GeV - 10 GeV)

How do we measure heat (phonons)?

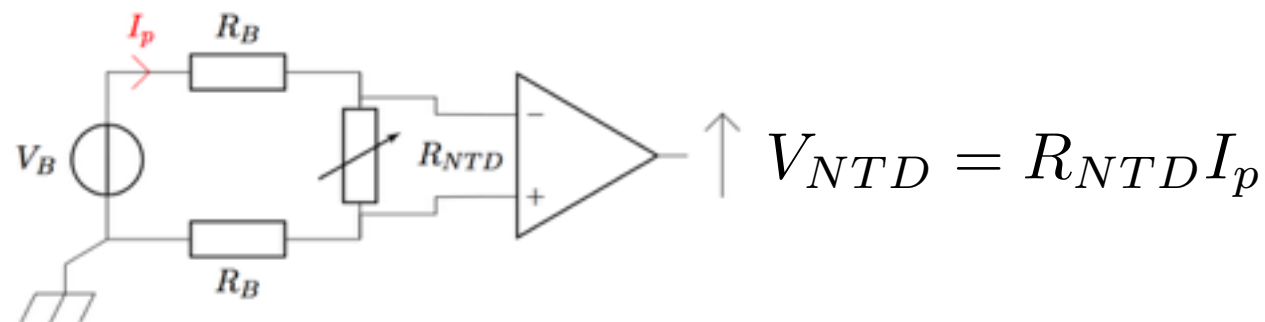
- **Basic principle:**
- Need to work at low temperature as **heat capacity goes as T^3**
- Need to have $G_{\text{sensor}} \gg G_{\text{leak}}$ such that sensor isothermal with crystal to maximize heat signal
- We want $C_{\text{sensor}} \ll C_{\text{crystal}}$ and largest possible α
- The time response of the detector is fixed by the total heat capacity and the leak to the bath
- Two types of sensors **NTD** (EDELWEISS) and **TES** (CDMS and CRESST)



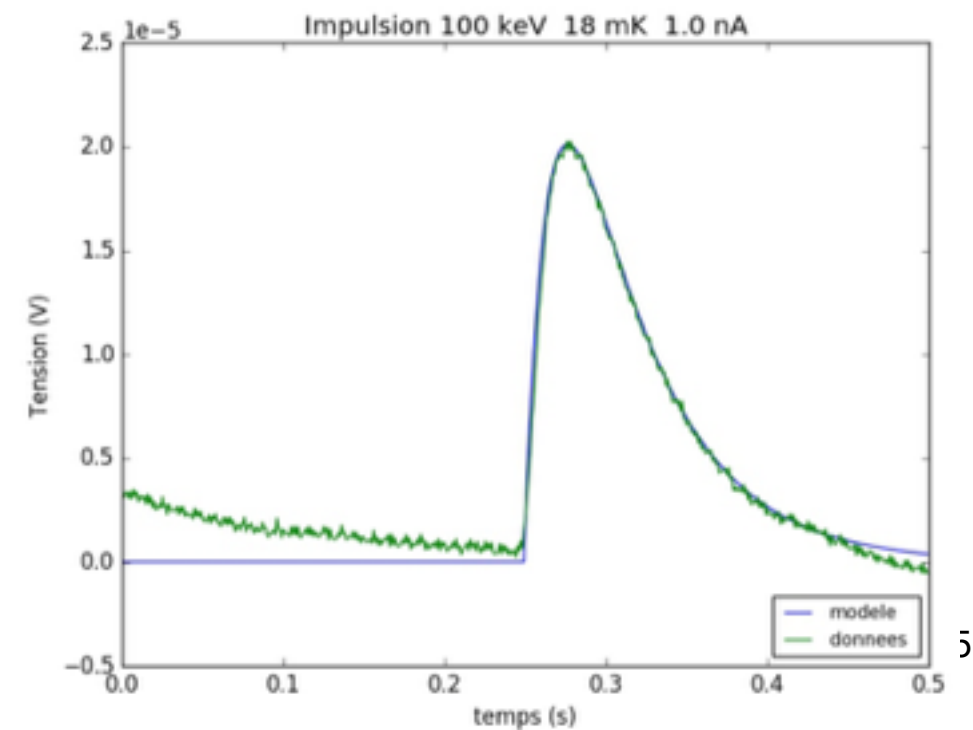
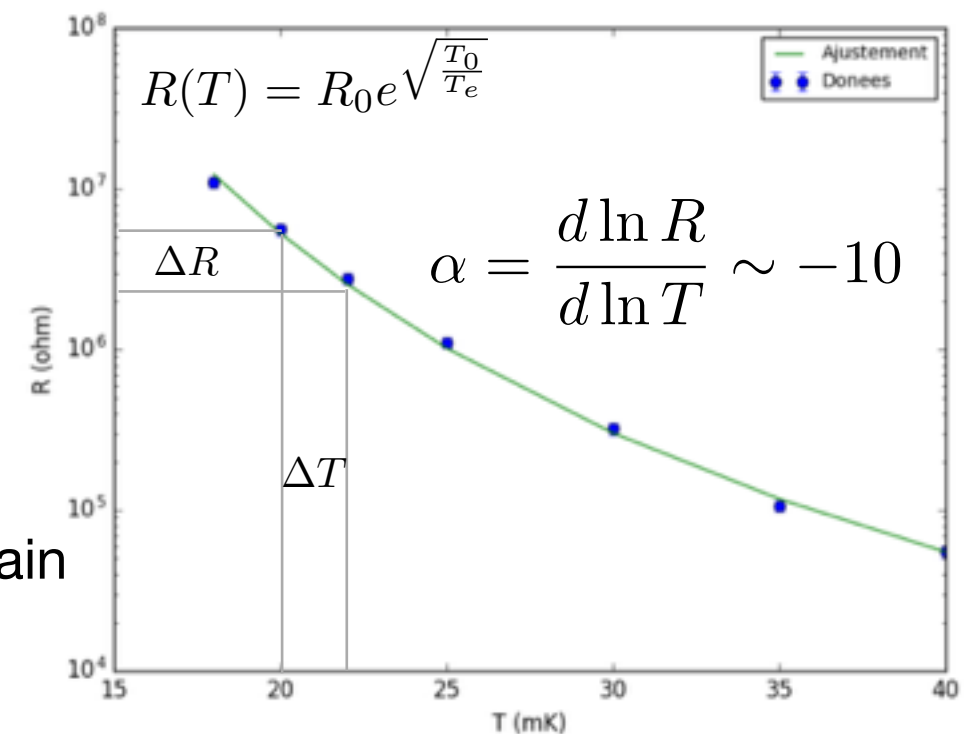
Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS heat sensor - NTD

- NTD: Neutron Transmutation Doped germanium
- Resistivity as a function of temperature follows Efros' law
- T_0 depends on the neutron dose, R_0 on the NTD geometry
- At working point, NTD resistance ~ 1 -100 M Ω
- Current biased ($\alpha < 0$) with big bias resistors ($R_b \sim 1$ G Ω)
- I_p has to be optimized: too big $\rightarrow$ heats up, too small $\rightarrow$ no gain



- NTD readout are cheap and simple
- Thermal measurement: they are slow (~ 500 ms) and limited by the heat capacity of the crystal
- High impedance: sensitive to microphonic noise
- Limited to 100 eV (RMS) resolution for 800 g Ge detector

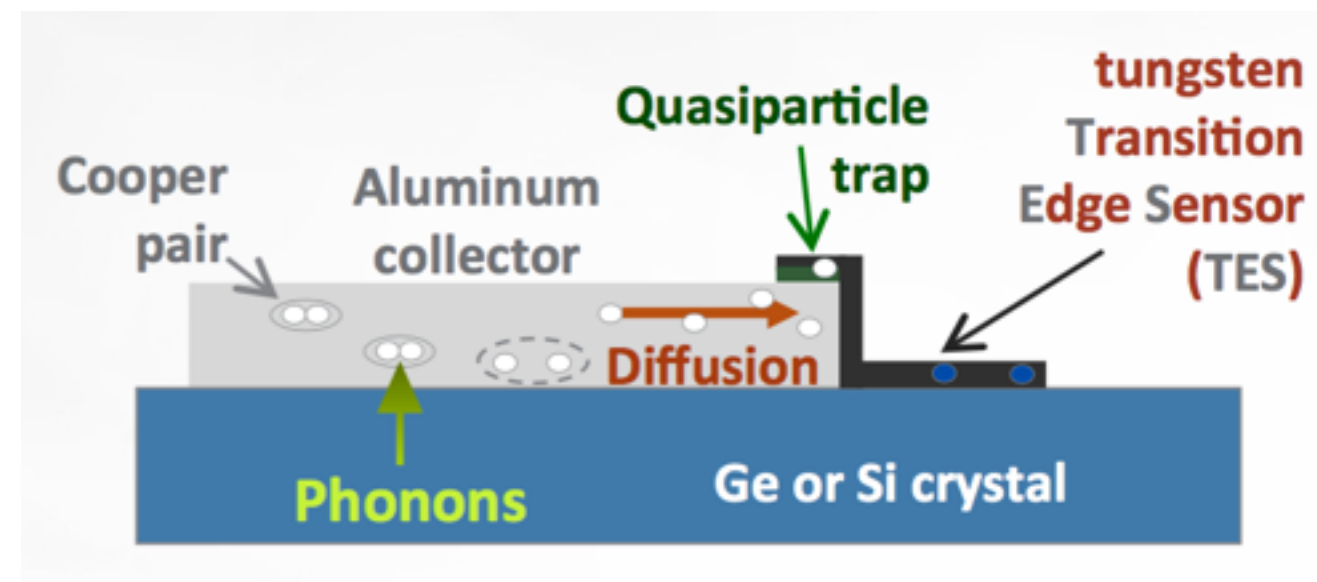
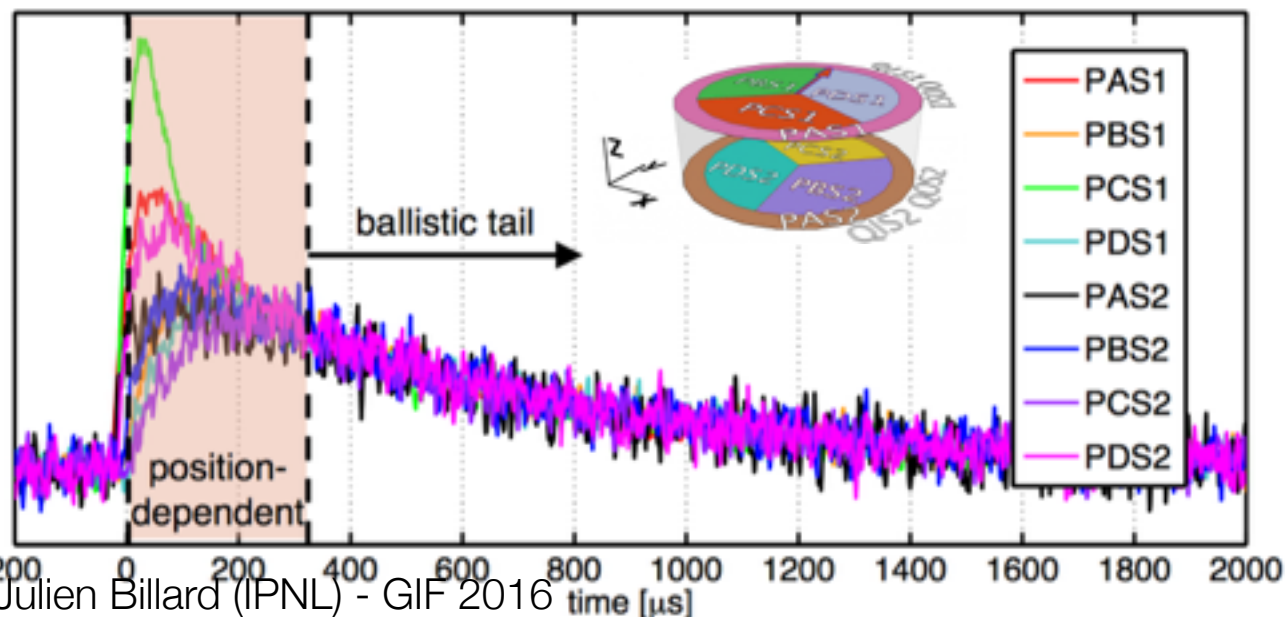
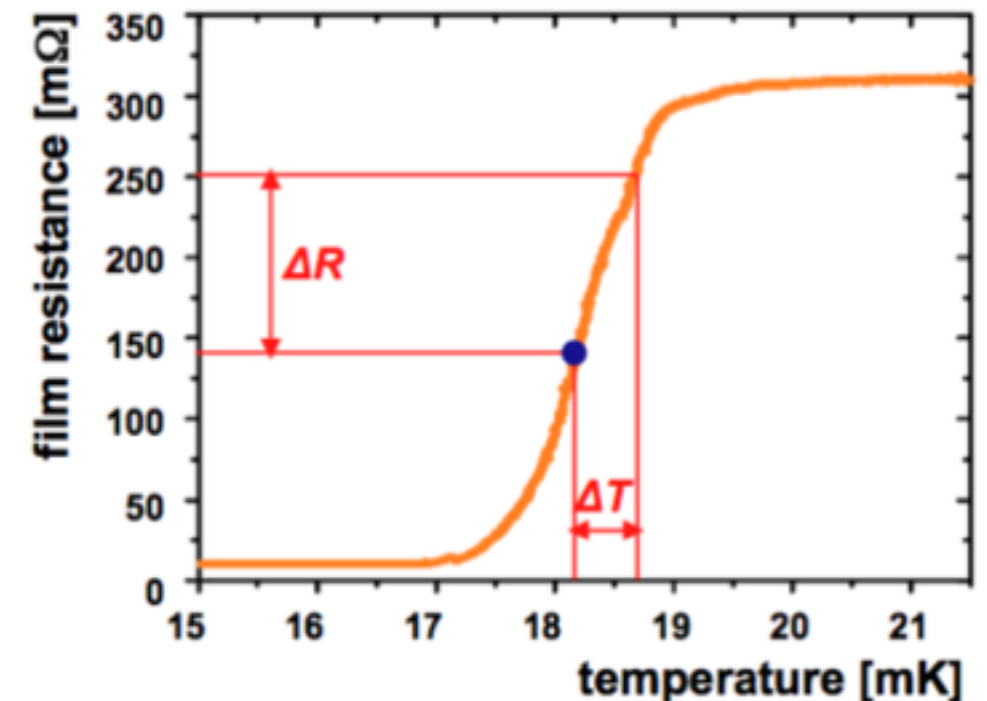


Low WIMP mass region (1 GeV - 10 GeV)

CRESST and CDMS heat sensor - TES

$$\alpha = \frac{d \ln R}{d \ln T} \sim 100$$

- TES: Transition Edge Sensor (in Tungsten)
- Sharp ($\alpha \sim 100$) transition supra/normal at T_c
- Sensitive to athermal phonons (above the Al gap $340 \mu\text{eV}$)
- Voltage biased ($\alpha > 0$), readout by SQUIDs amplifier
- Complex and expensive
- Very sensitive to EM pick ups
- At first order not limited by crystal heat capacity (decoupled)
- Very fast, position sensitive, could reach few eV resolution

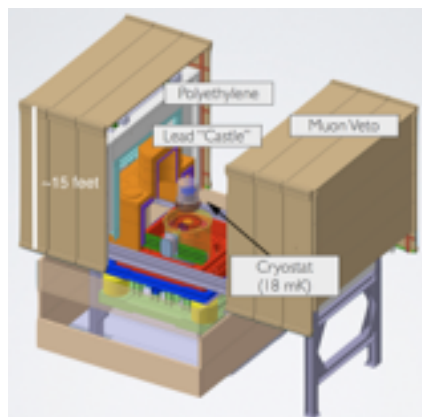


Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS strategy: heat + ionization

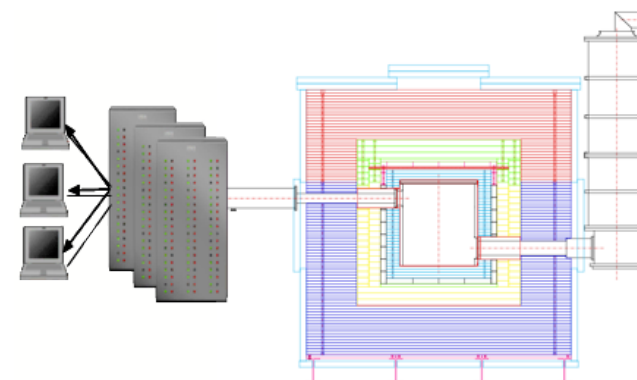
EDELWEISS

- In Modane Underground Laboratory
- Upgrade from EDELWEISS II, in continuous operation since summer 2014
- 850g Germanium detectors measure ionization and **thermal phonons**
- 36 detectors = 20 kg target mass (largest array)



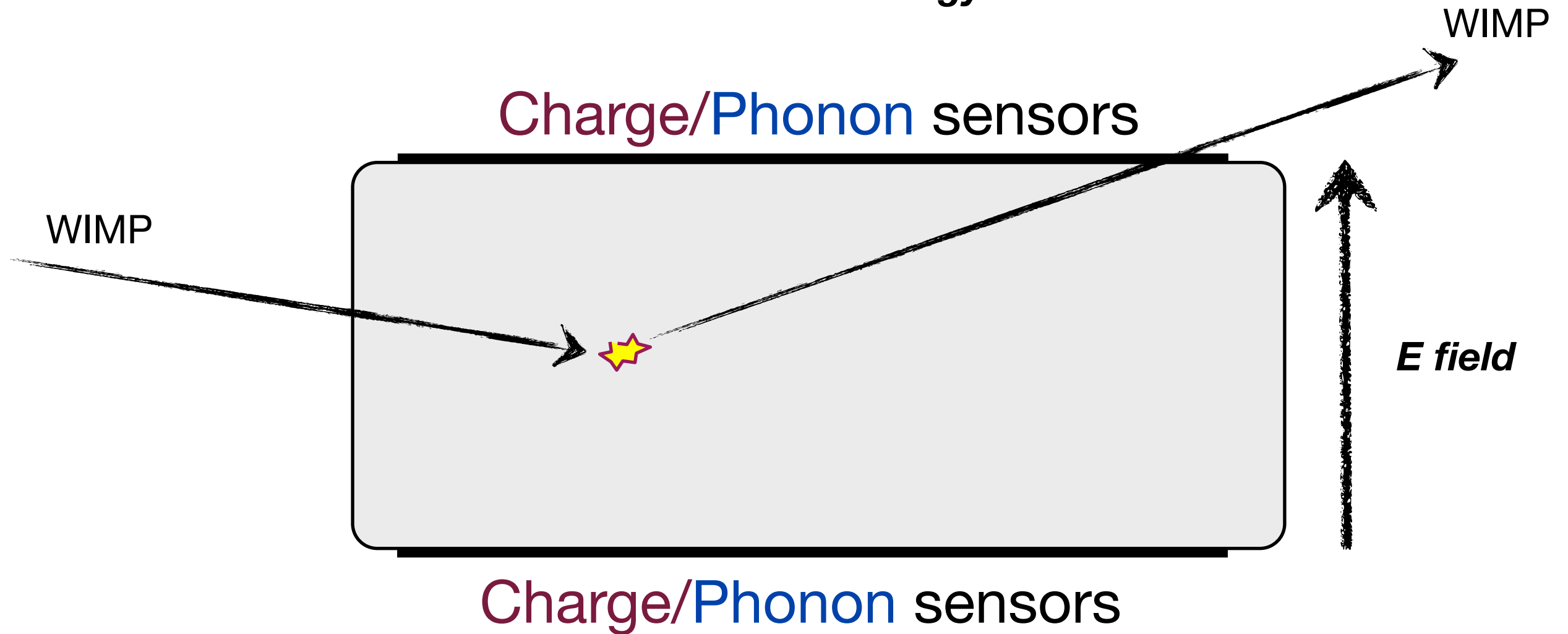
SuperCDMS

- In Soudan mine, but now being un-installed to be installed in SNOLAB
- Upgrade from CDMS II, in continuous operation since spring 2012, stopped in 2016
- 600g Germanium detectors measure ionization and **non-equilibrium phonons**
- 15 detectors = 9 kg target mass



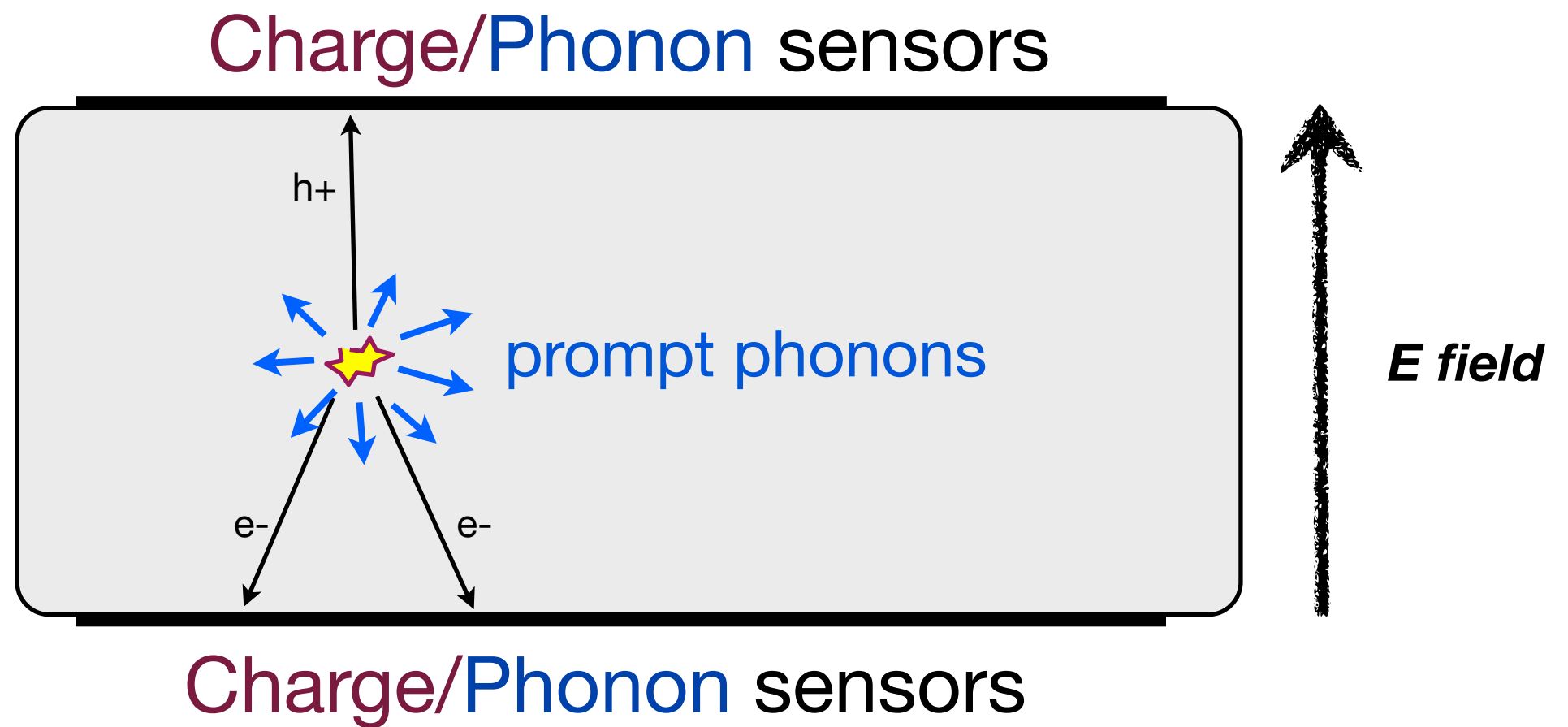
Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS strategy: heat + ionization



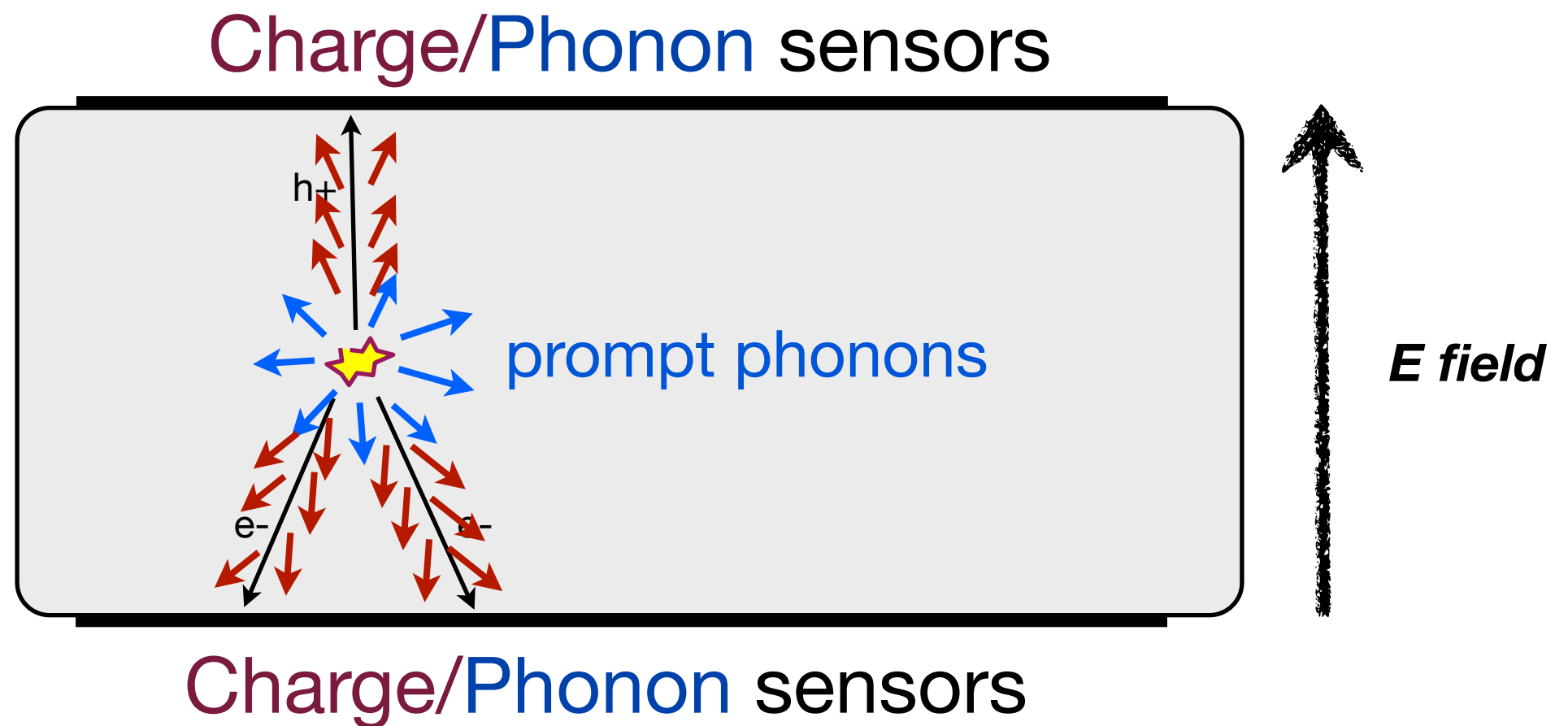
Low WIMP mass region (1 GeV - 10 GeV)

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Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS strategy: heat + ionization



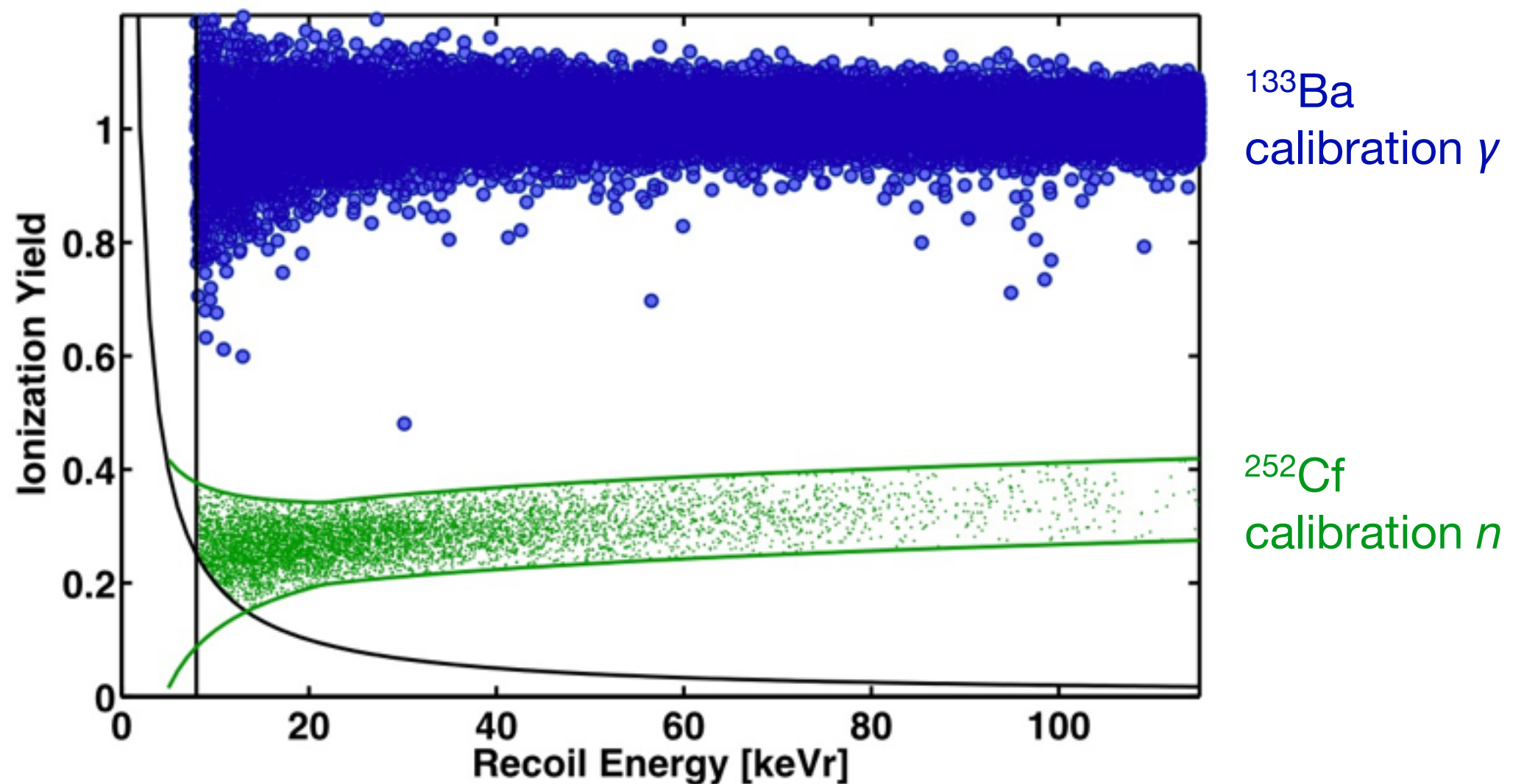
$$\begin{aligned} E_{total} &= E_{recoil} + E_{luke} \\ &= E_{recoil} + \frac{1}{3 \text{ eV}} E_{ion} \Delta V \end{aligned}$$

Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS strategy: heat + ionization

Electron recoils have a **higher ionization yield** than nuclear recoils

$$Y = E_q/E_r$$

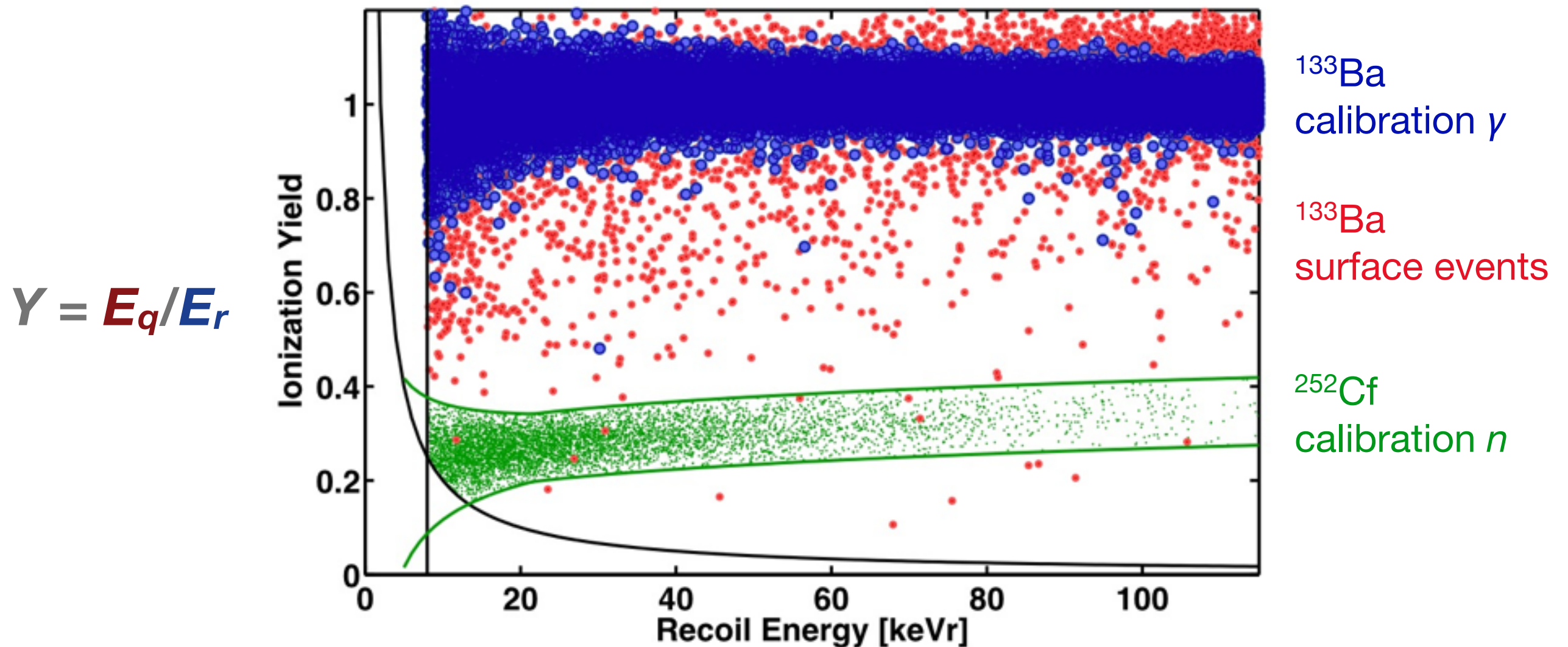


Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS strategy: heat + ionization

Electron recoils have a **higher ionization yield** than nuclear recoils

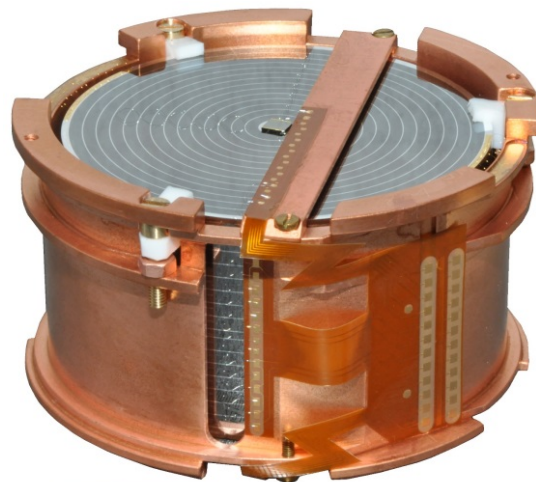
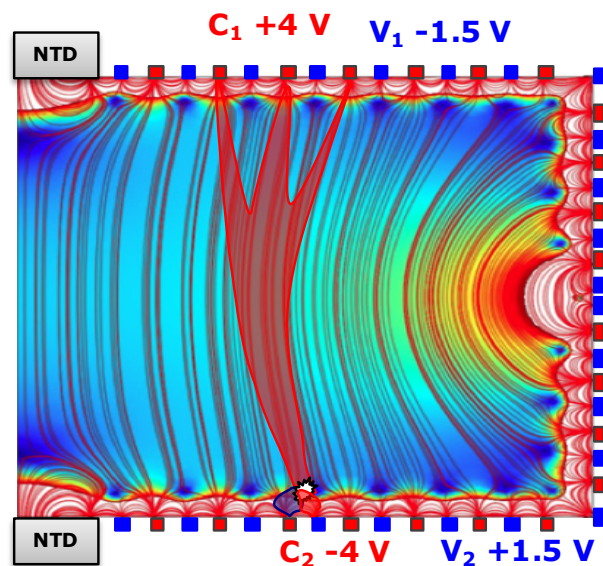
Surface events have a **reduced ionization yield** and can mimic nuclear recoils



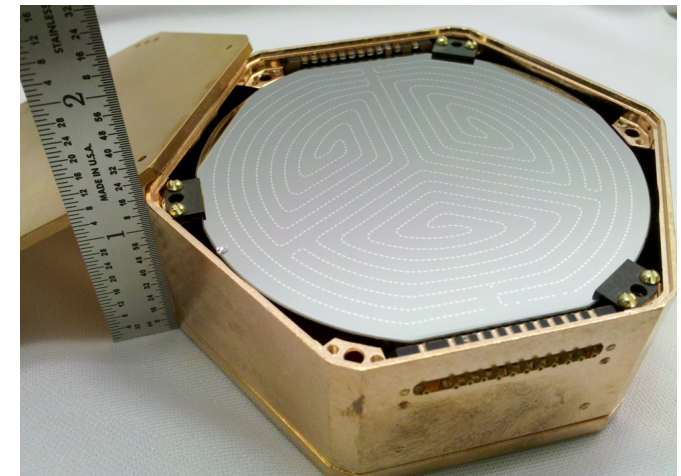
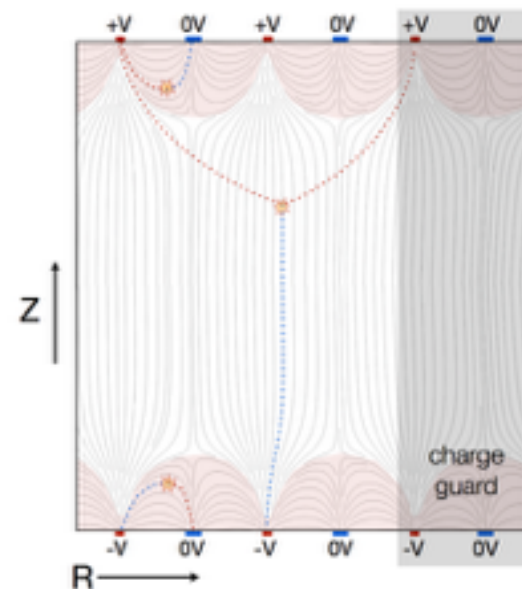
Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS strategy: heat + ionization

EDELWEISS FID800



SuperCDMS iZIP



- The two detector technologies have interleaved bias lines to trap charges created at the surfaces —> **Fiducialization !**
- This way surface event can be rejected by asking that non of the veto electrodes see a signal (EDELWEISS) or if there is a charge asymmetry between the top and bottom surfaces
- **Rejection power is over 10^5 while keeping a high NR acceptance down to a few keV**
- Only EDELWEISS has a full coverage and readouts all electrodes (best rejection)
- BUT, SuperCDMS iZIP detectors can perform event fiducialization using phonon information

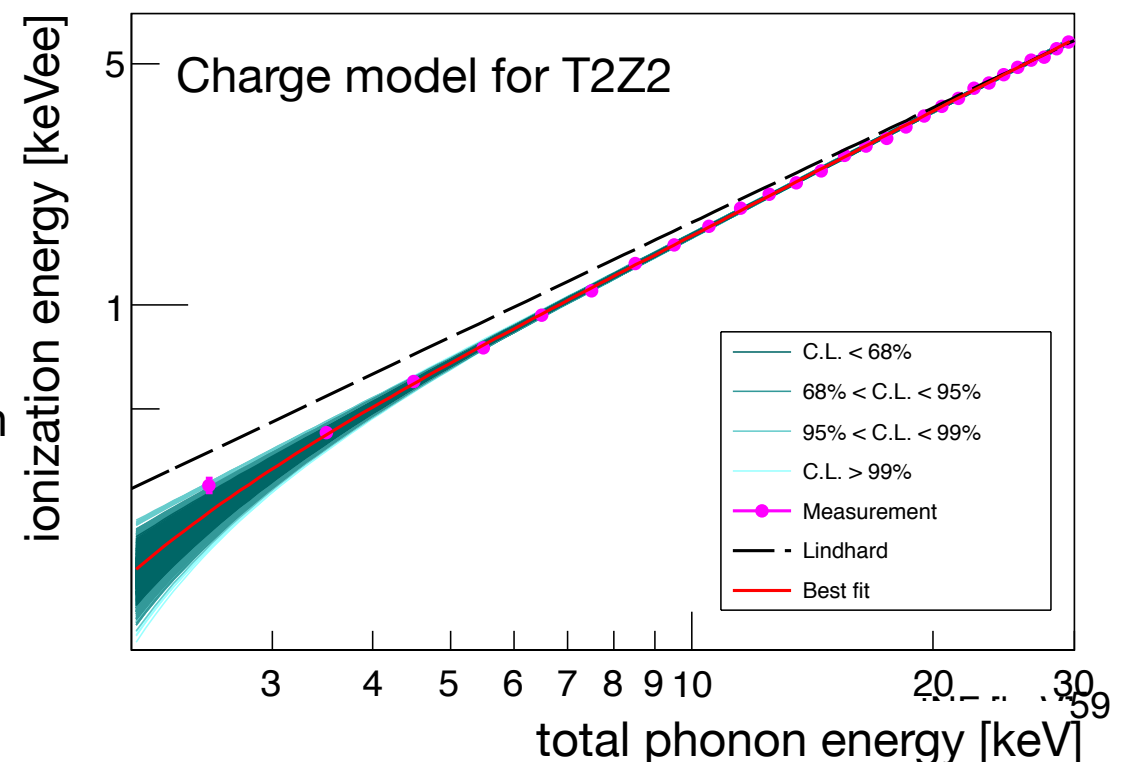
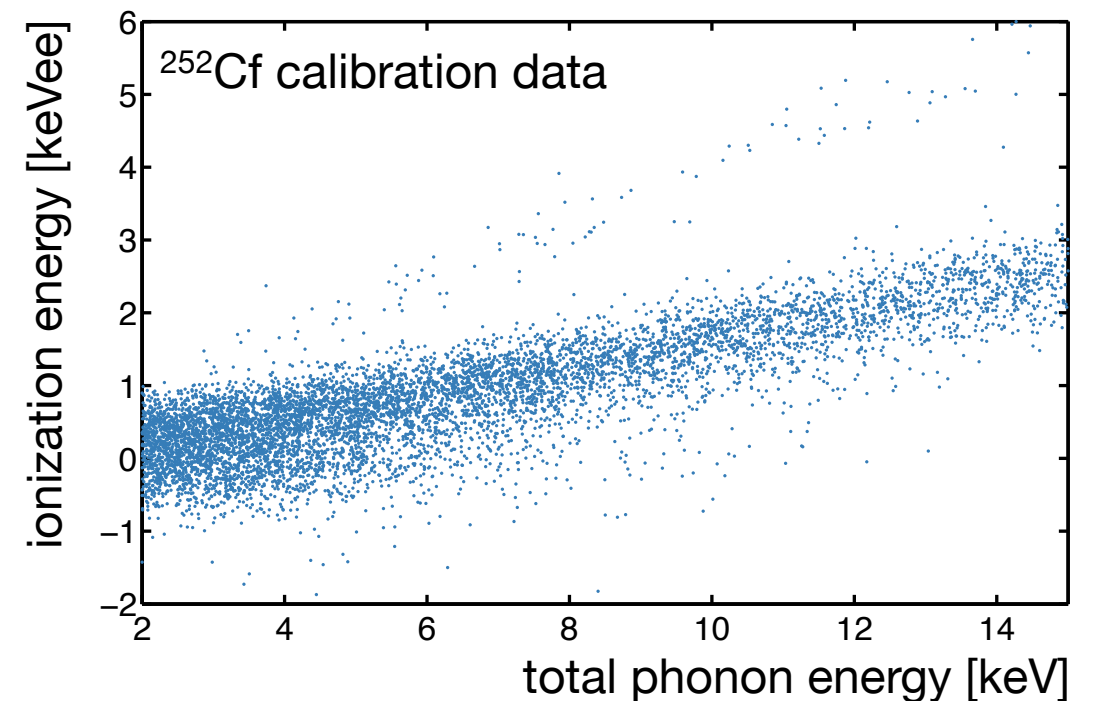
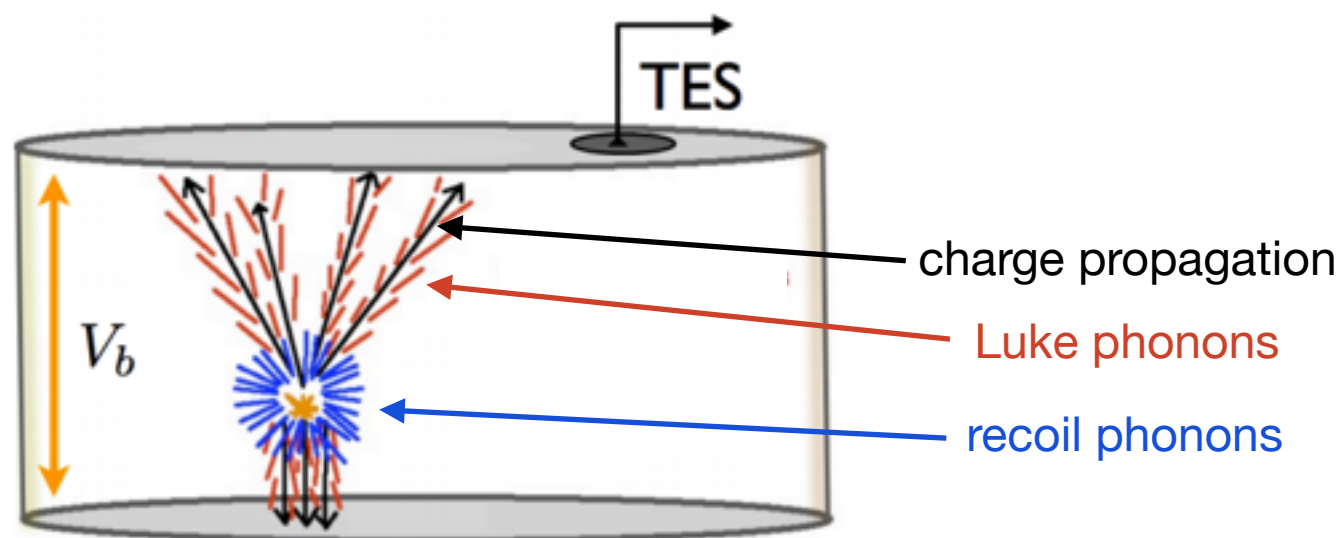
Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS strategy: heat + ionization

$$E_t = E_r + E_L$$

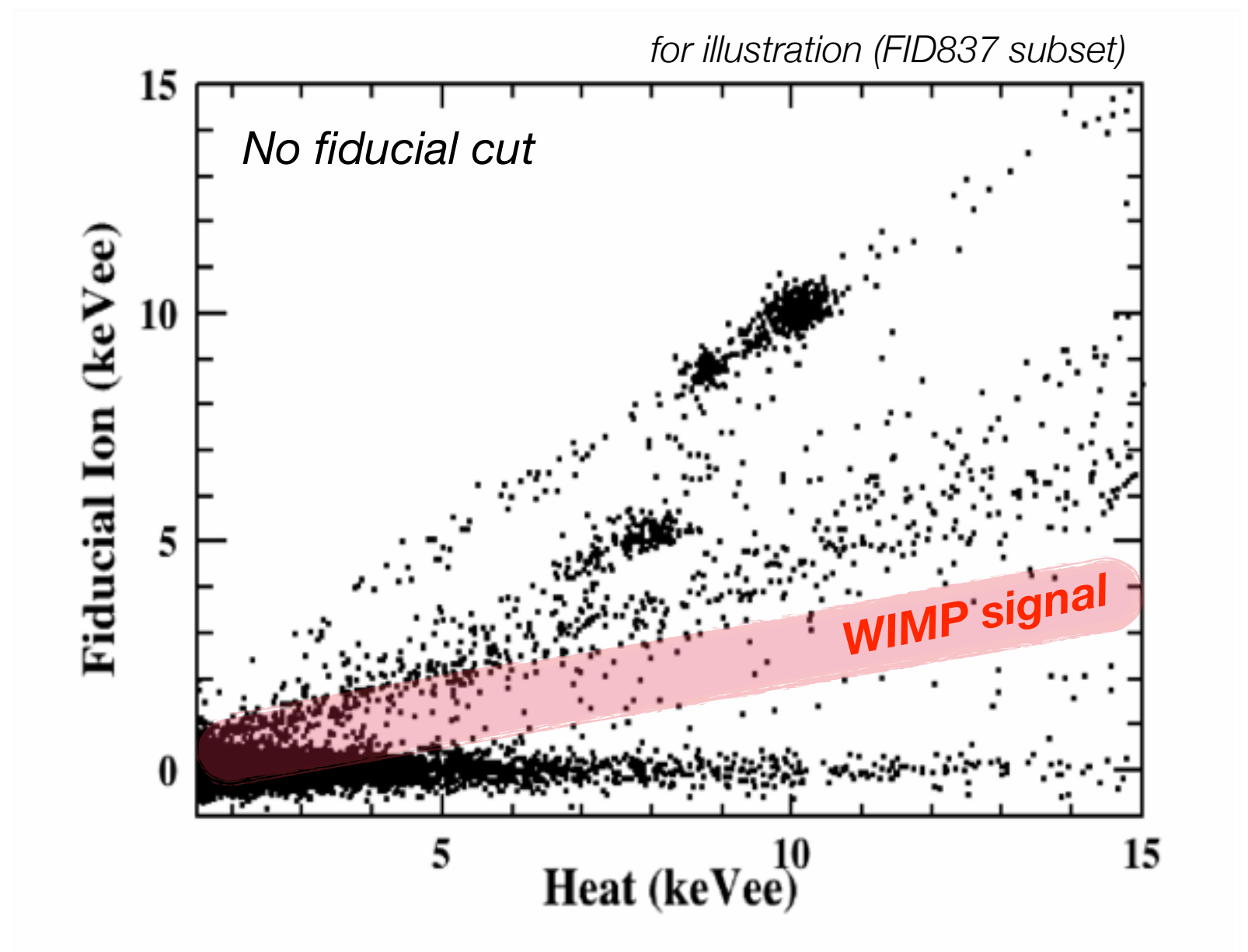
$$E_r = E_t - \frac{1}{3 \text{ eV}} E_Q(E_t) \Delta V$$

- Fit mean ionization energy as a function of total phonon energy for nuclear recoils from ^{252}Cf or AmBe neutron calibration
- Most detectors consistent with or slightly below Lindhard theory



Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS low-energy backgrounds

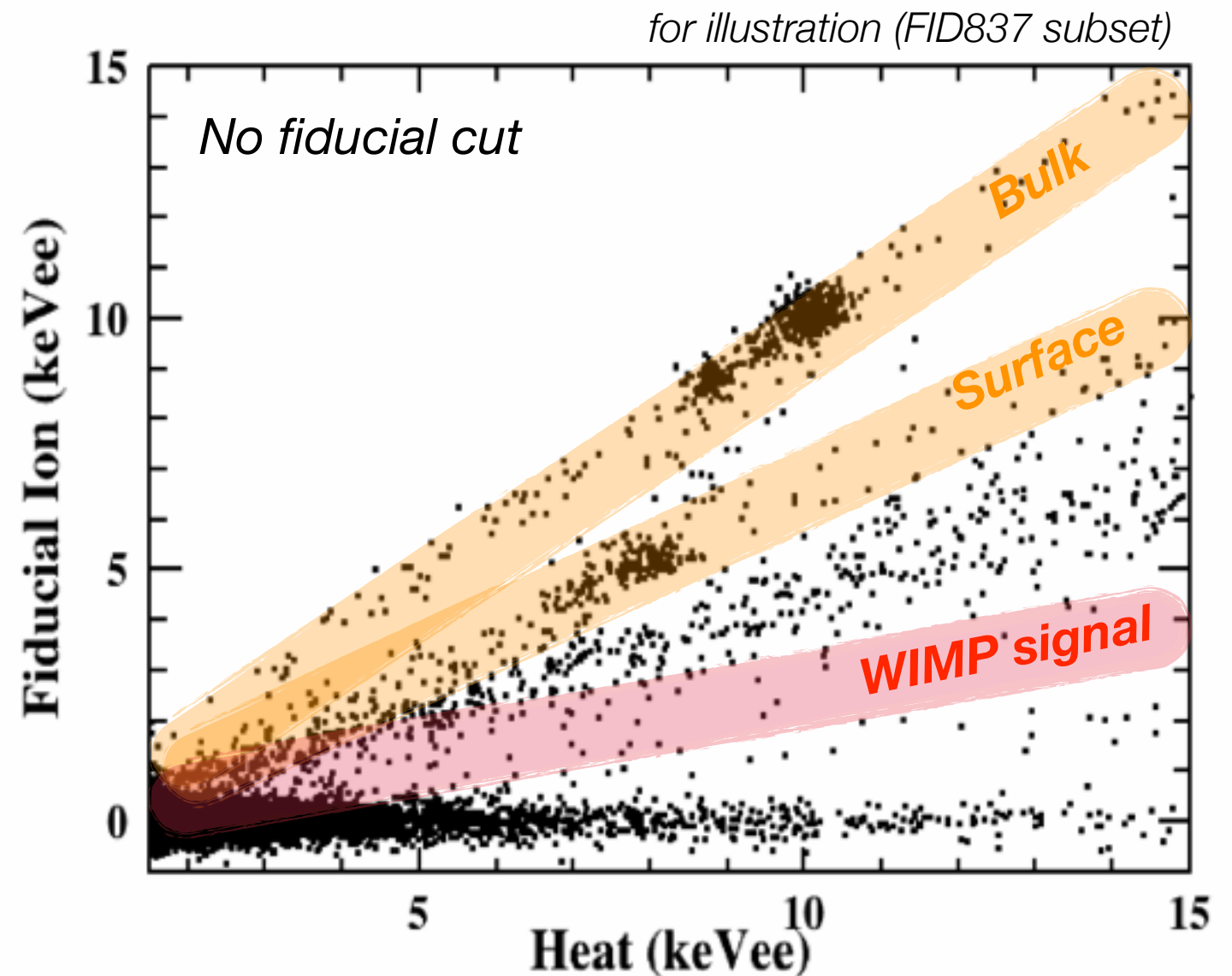


Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS low-energy backgrounds

Gamma + activation lines

- Internal radioactivity from shielding and cryostat
- Cosmogenic activation lines: K/L-shell capture from $^{68,71}\text{Ge}$, ^{65}Zn , ^{68}Ga

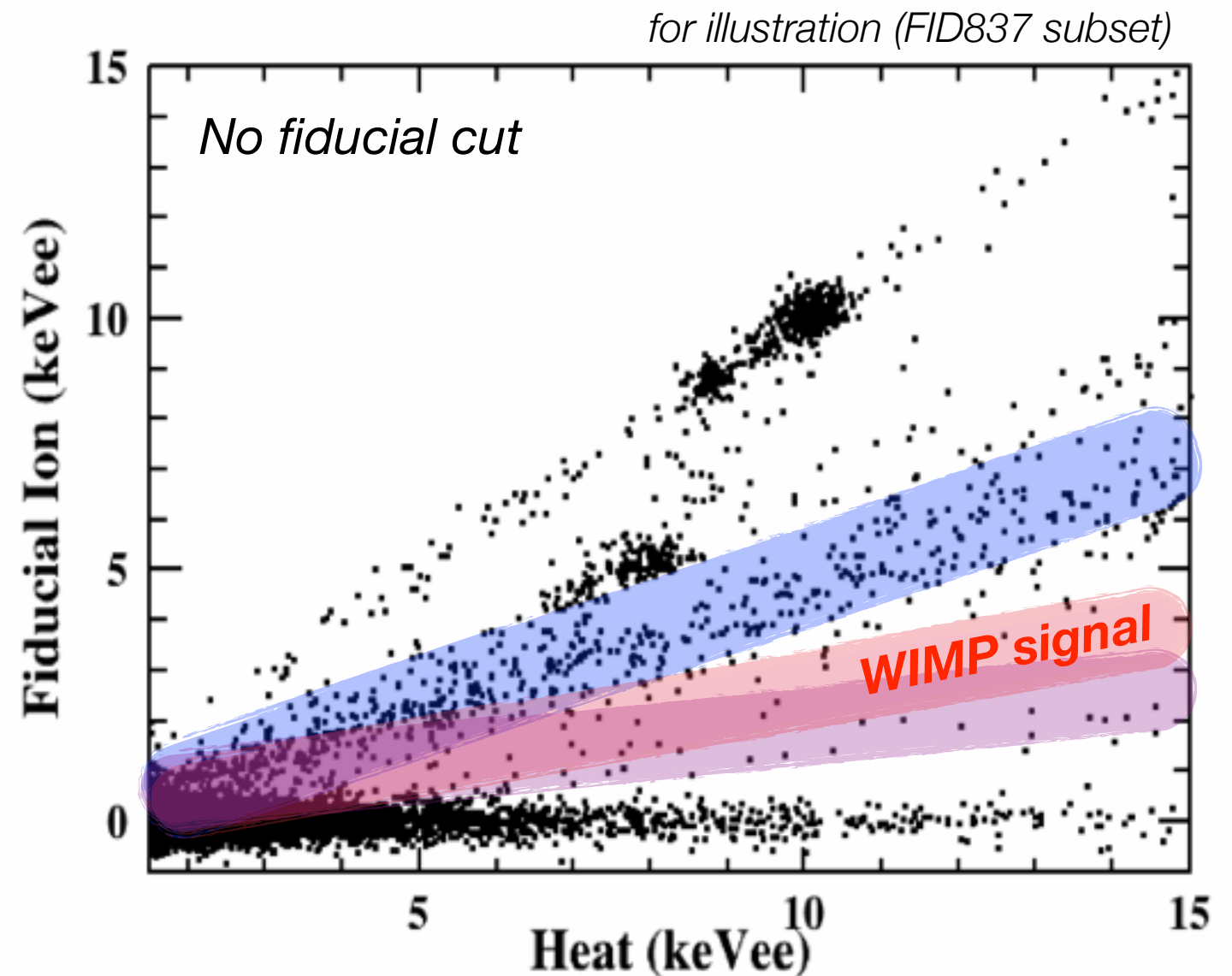
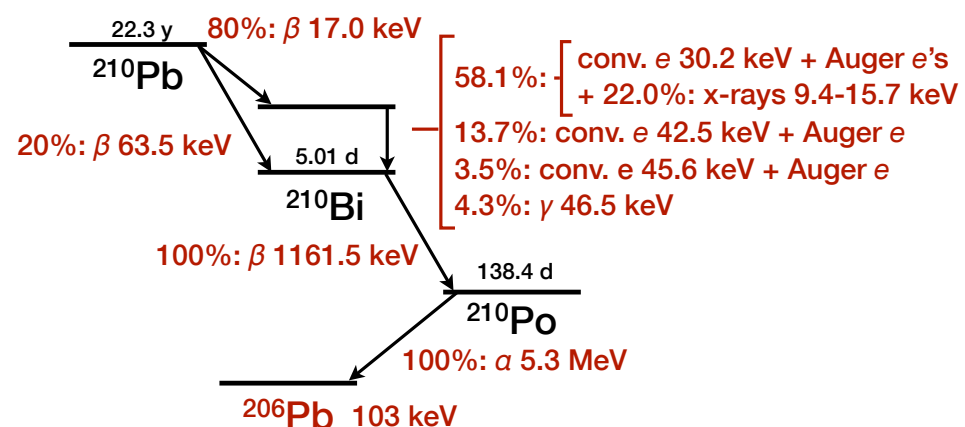


Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS low-energy backgrounds

^{210}Pb “surface events”

- betas and ^{206}Pb nuclei from ^{210}Pb decay chain
- events are located on detector face and sidewall **surfaces** from ^{222}Rn contamination

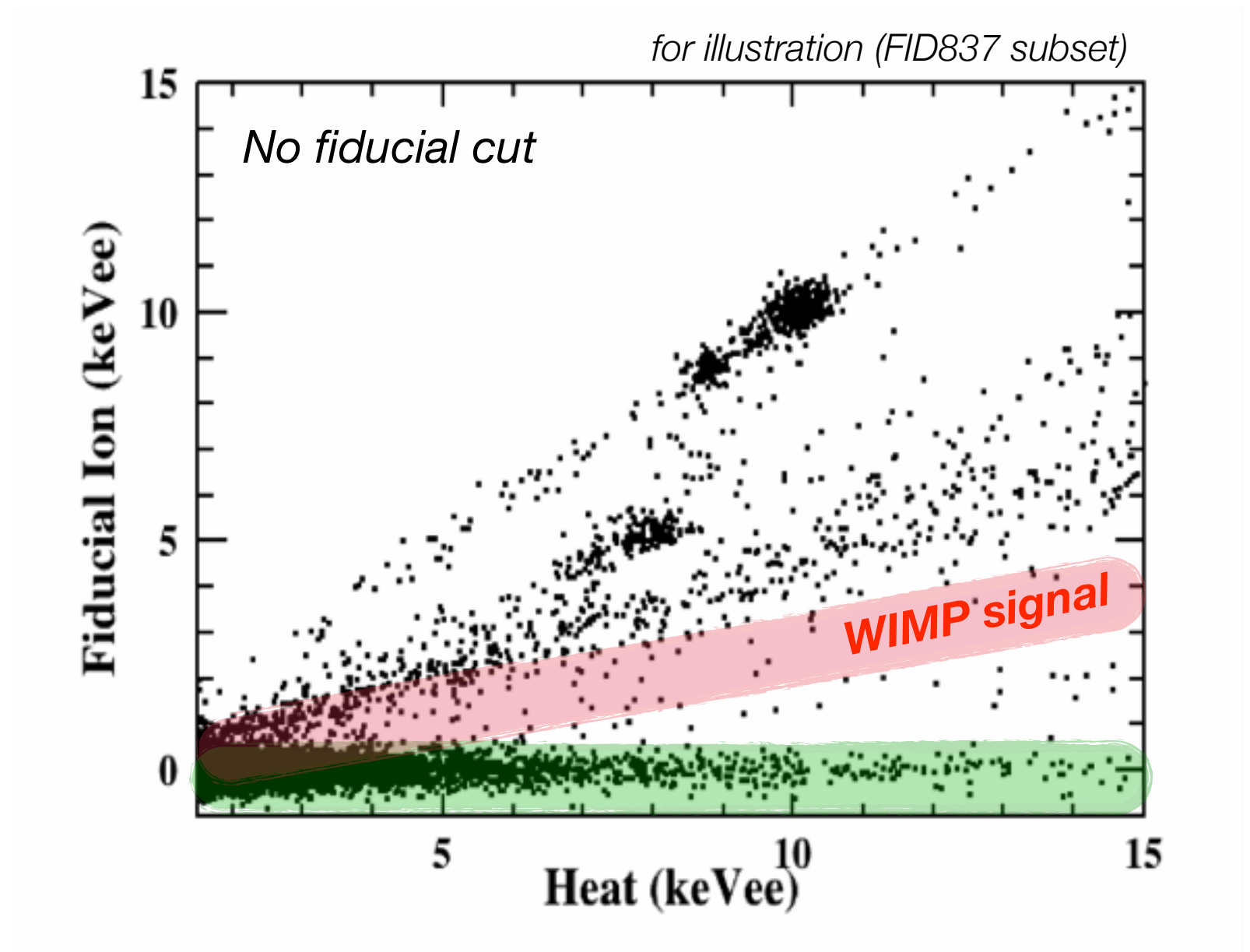


Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS low-energy backgrounds

Heat only

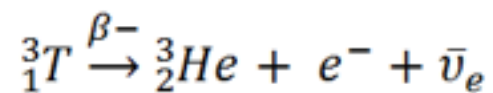
- Dominating background at low-energy
- Not seen in CDMS
- Origin under investigation
highest priority of the EDELWEISS collaboration



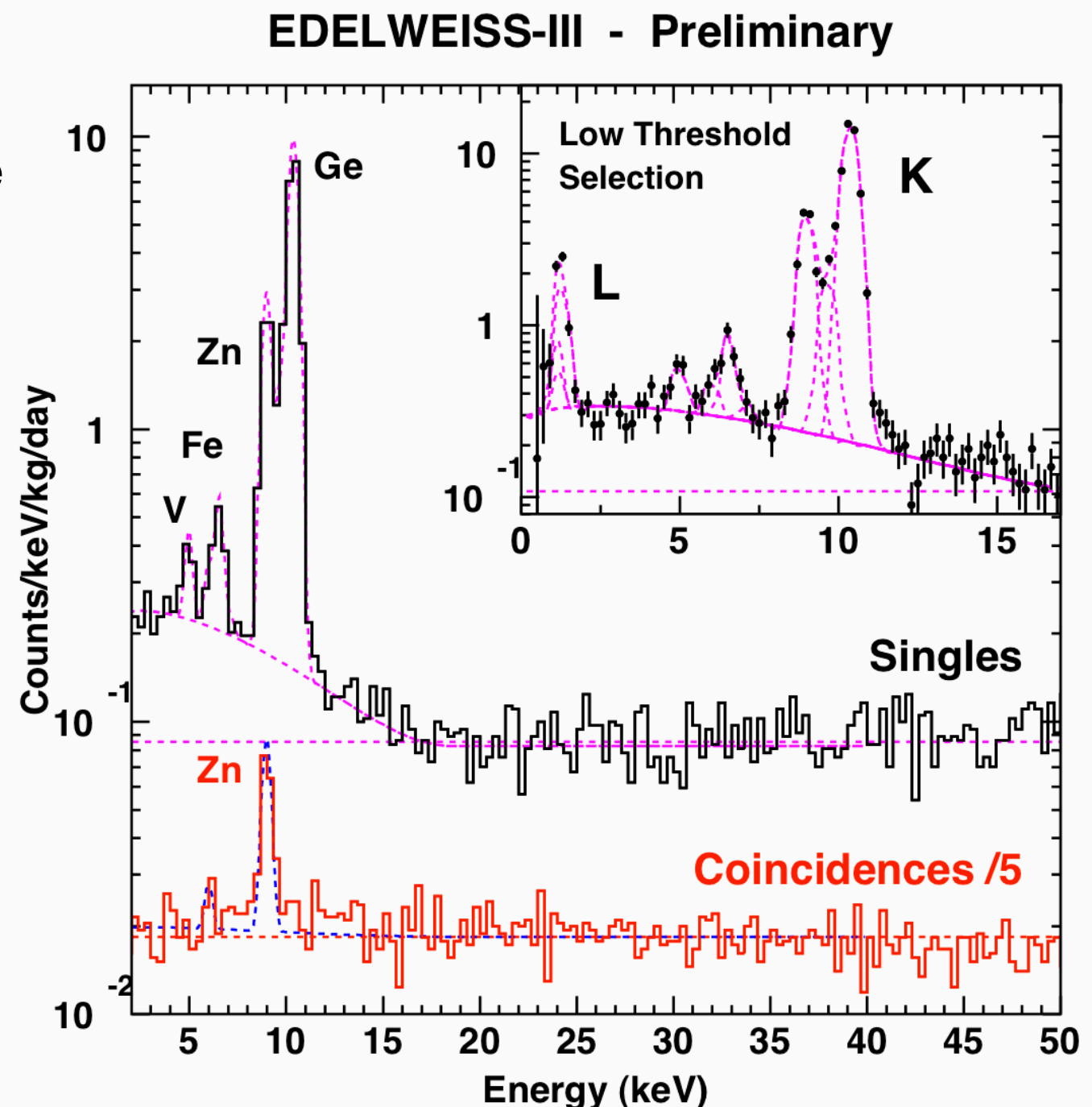
Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS Coll., arXiv:1607.04560

EDELWEISS and CDMS low-energy backgrounds

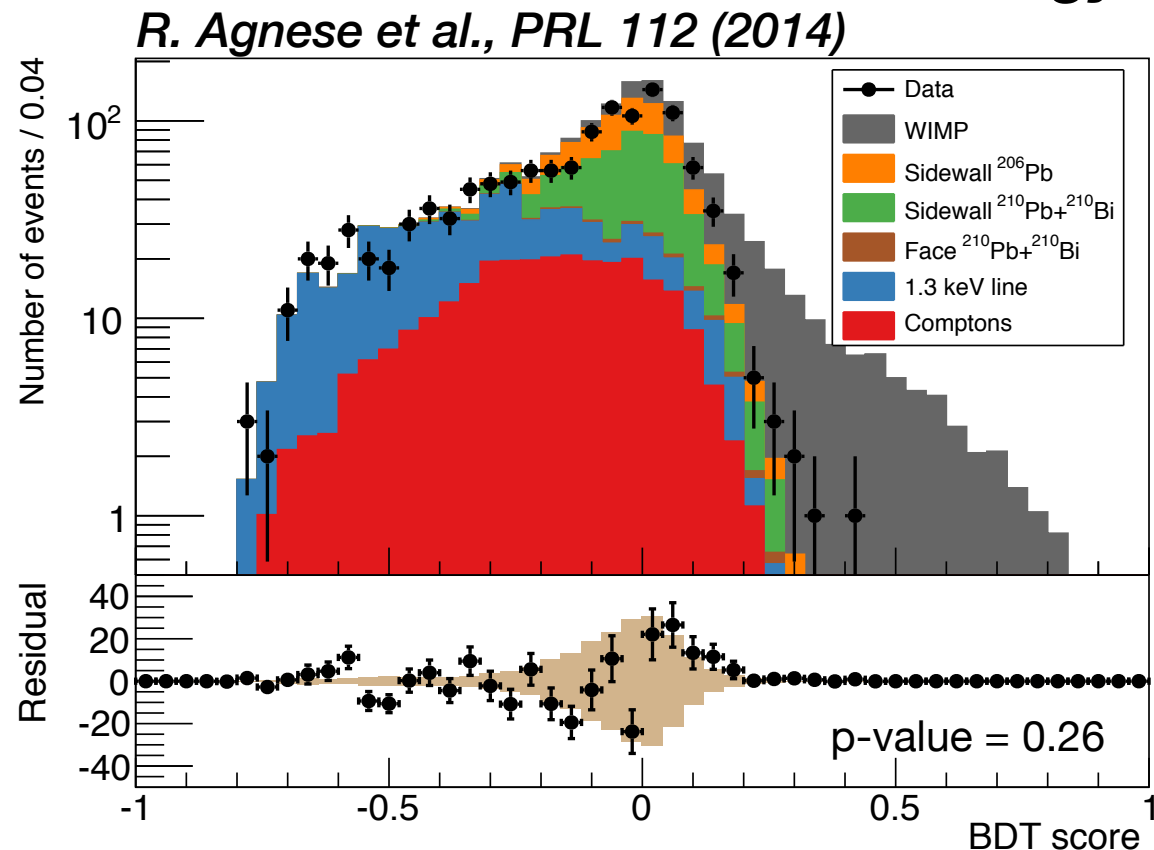


- Tritium beta decay will become one of the major background component for next generation Ge experiments
- Thanks to its impressively low gamma background (<0.1 DRU) and exquisite ionization energy resolution (200 eV RMS)
- EDELWEISS-III is the first Ge experiment to observe the intrinsic tritium beta background convincingly and measure its production rate



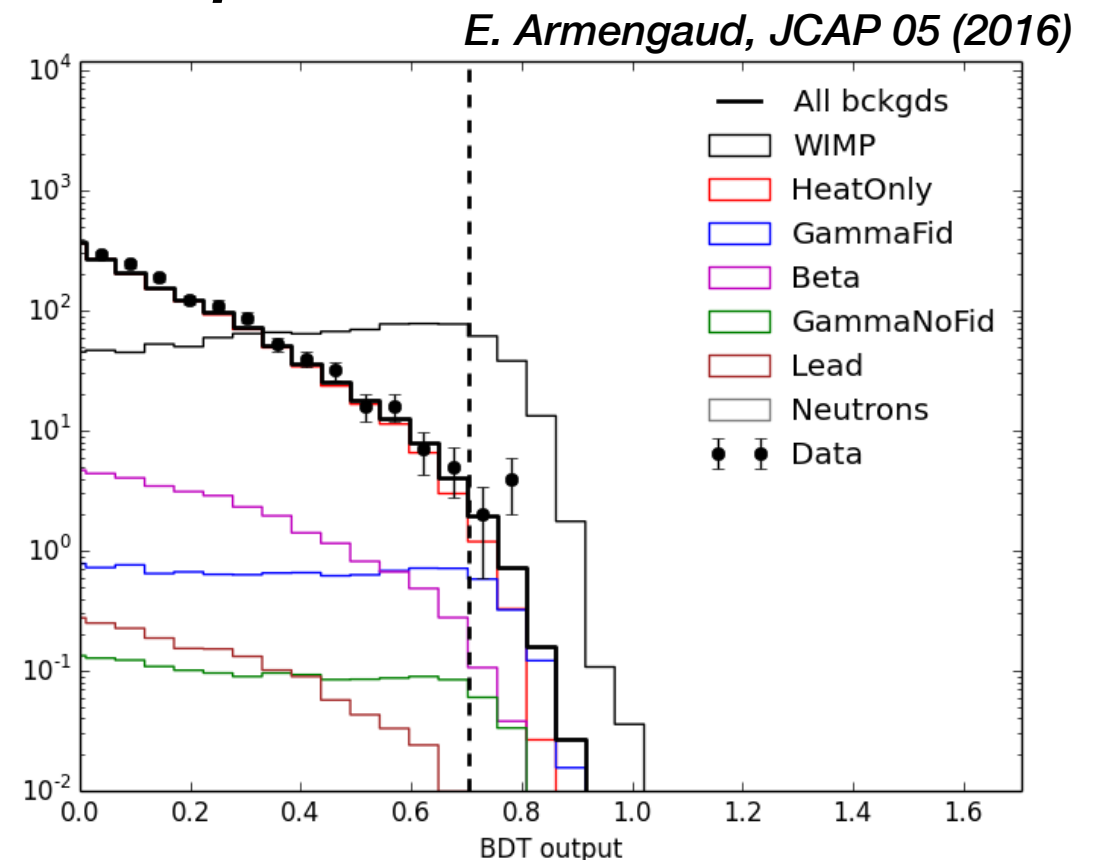
Low WIMP mass region (1 GeV - 10 GeV)

Low energy analysis techniques: *BDT*



SuperCDMS-LT

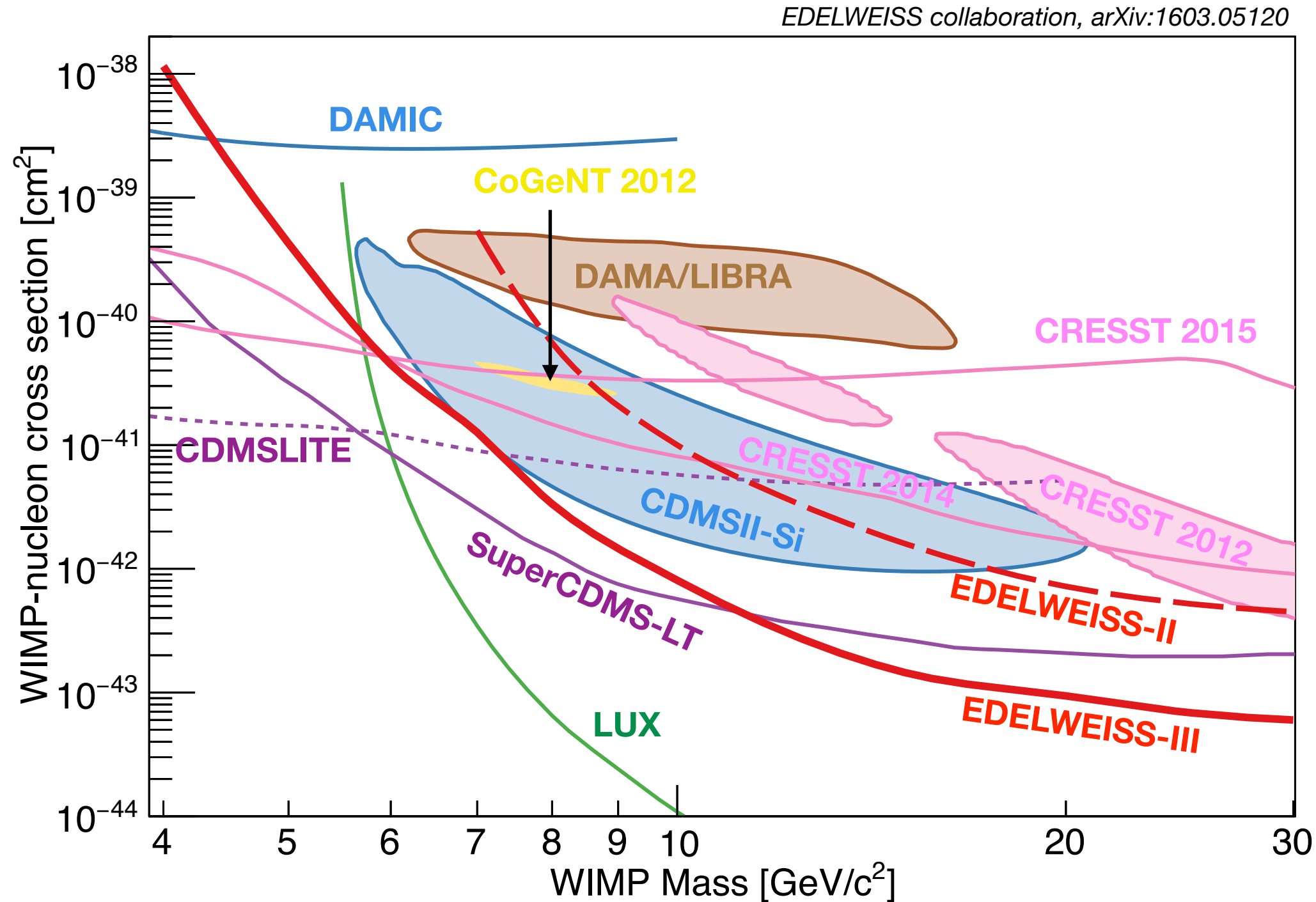
- 7 detectors with lowest thresholds: (1.6 keVnr - 5 keVnr)
- 577 kg-d of exposure
- BDT analysis with heat and ionization energies, radial and vertical phonon partition
- No significant excess over back. expect.



EDELWEISS-III

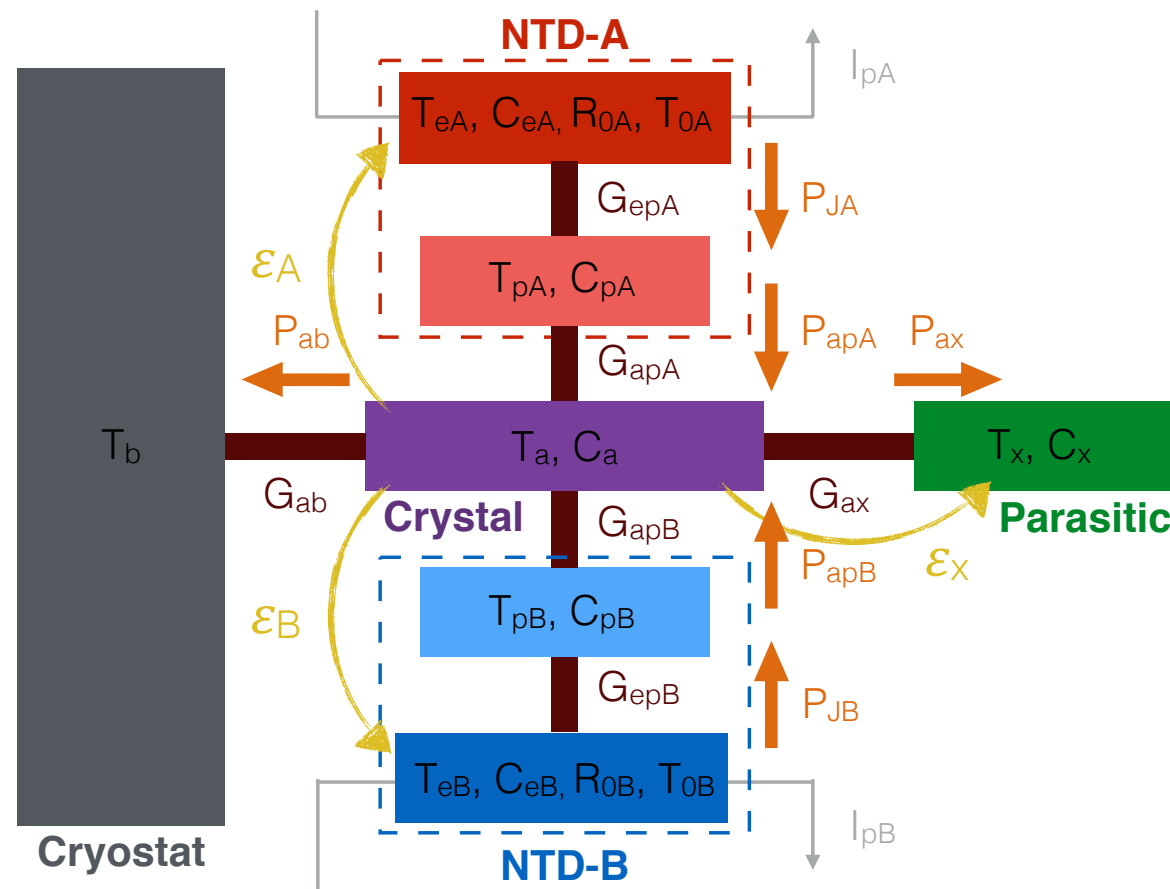
- 8 detectors with lowest thresholds: (2.4 keVnr - 3.6 keVnr)
- 582 kg-d of fiducial exposure
- BDT analysis with 4 electrodes, 2 heat sensors and heat only monitoring rate
- No significant excess over back. expect.

Low WIMP mass region (1 GeV - 10 GeV)

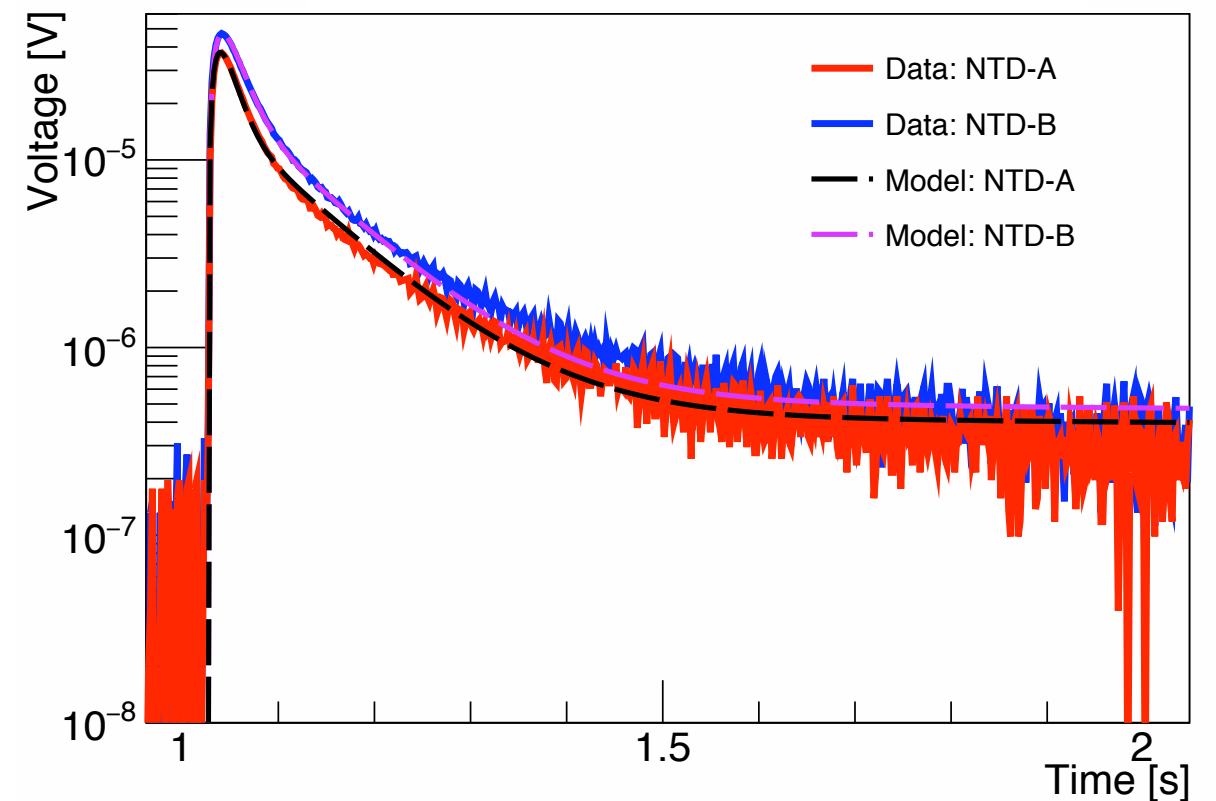


Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS towards lower thresholds



J. Billard et al., J. Low Temp. Phys. (2016)



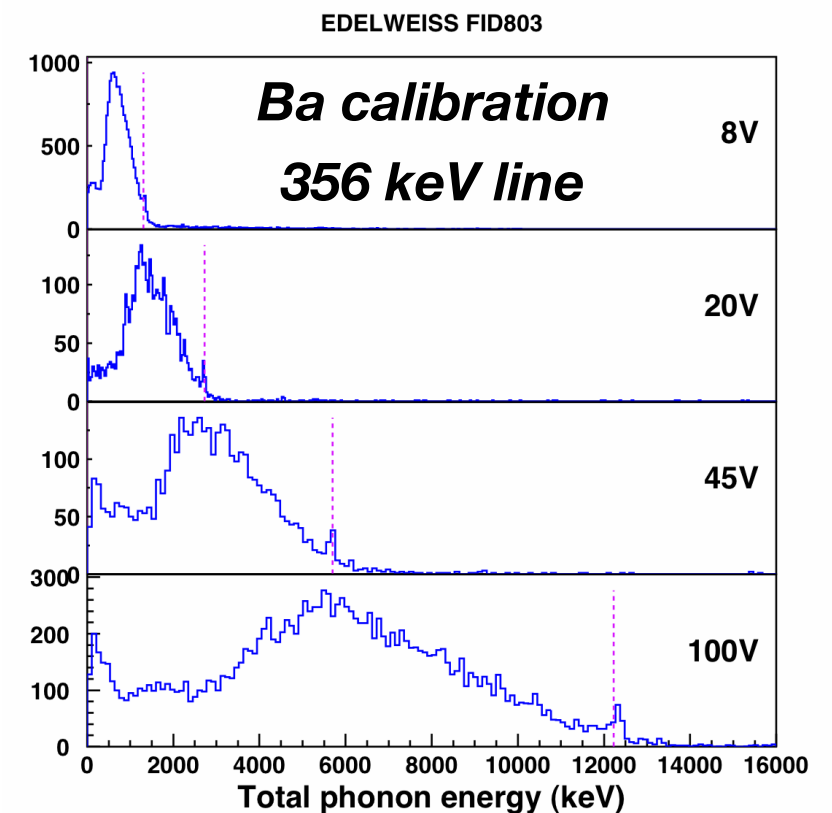
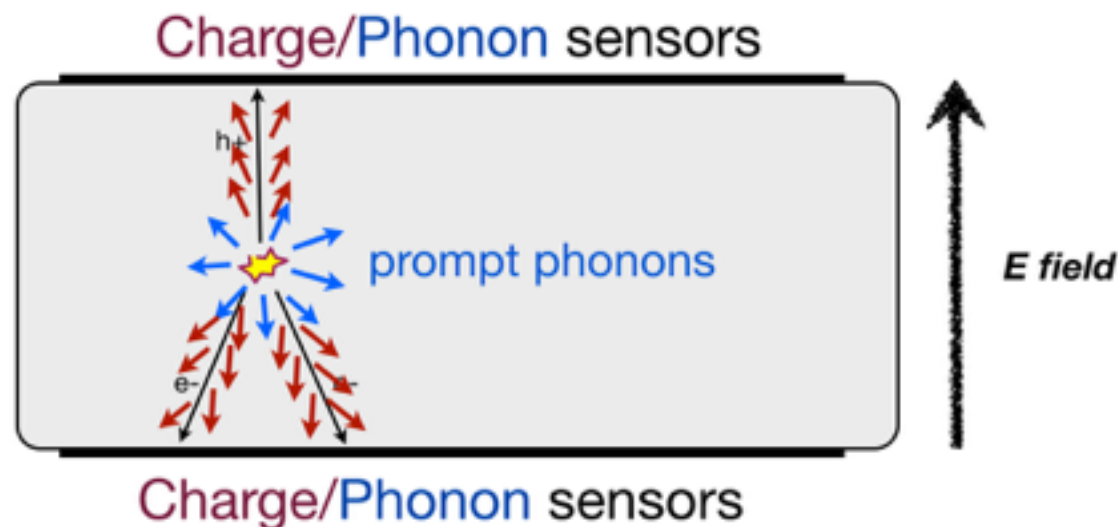
- We developed a detailed model of our heat signals that fits very well observed pulses
 - Sensitivity to ballistic phonons and presence of a parasitic heat capacity
 - Optimized sensors, to be tested this year, should reach 100 eV baseline resolution
- HEMT R&D for ionization signal also ongoing in collaboration with SuperCDMS to reach 100 eVee baseline resolution *A. Phipps et al., J. Low Temp. Phys. (2016)*

Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS towards lower thresholds

Luke-Neganov effect

$$E_t = E_r + \frac{1}{3 \text{ eV}} E_Q \Delta V$$



- Use the energy deposited in ionization to boost the total heat signal
- Loose ER/NR discrimination as heat $\sim$ ionization
- Working **up to 100 V** leading to a boost factor of ~ 35
- Lowest threshold achieved of **60 eVee (300 eVnr)** - achieved by both CDMS and EDELWEISS

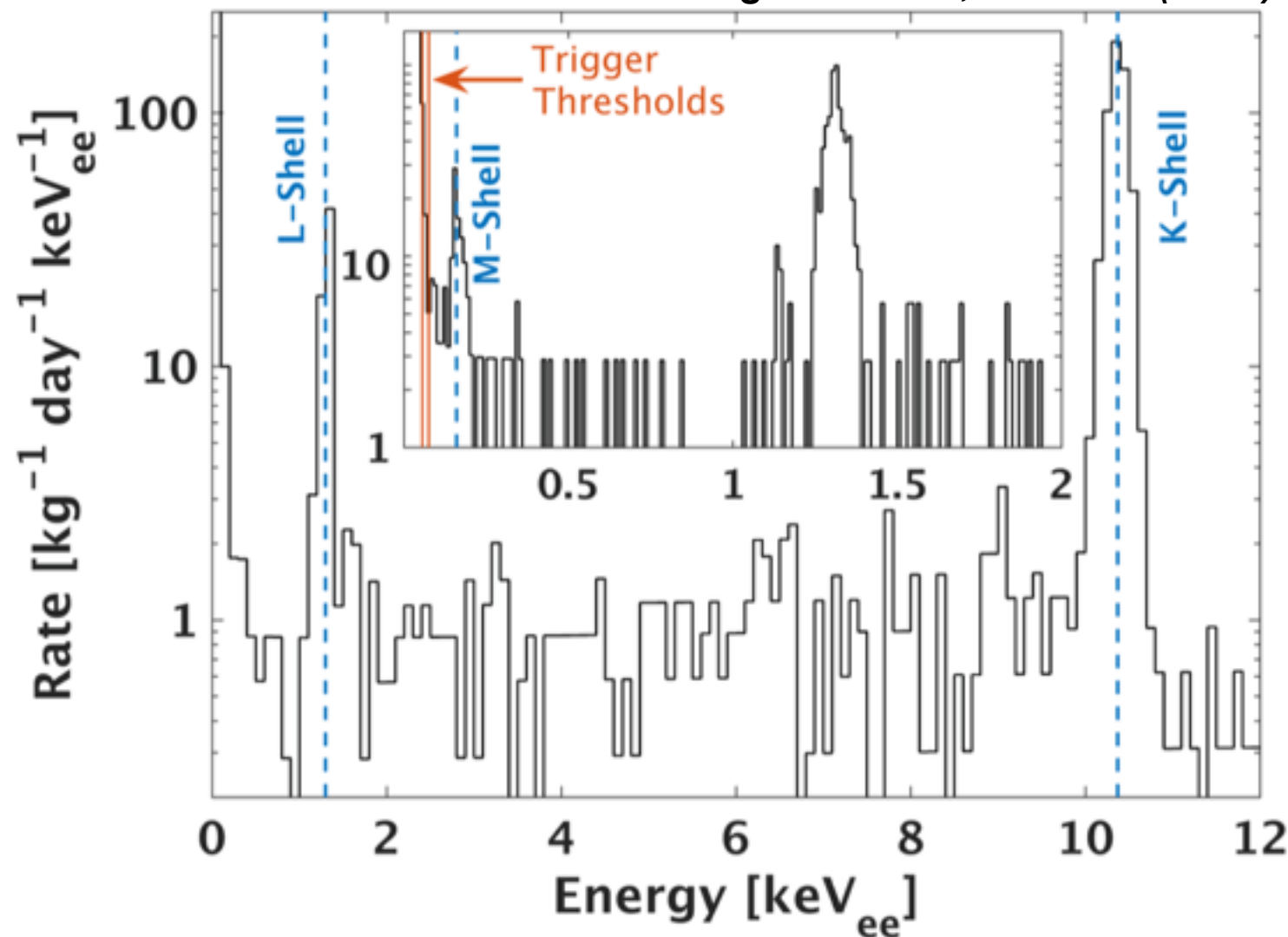
Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS towards lower thresholds

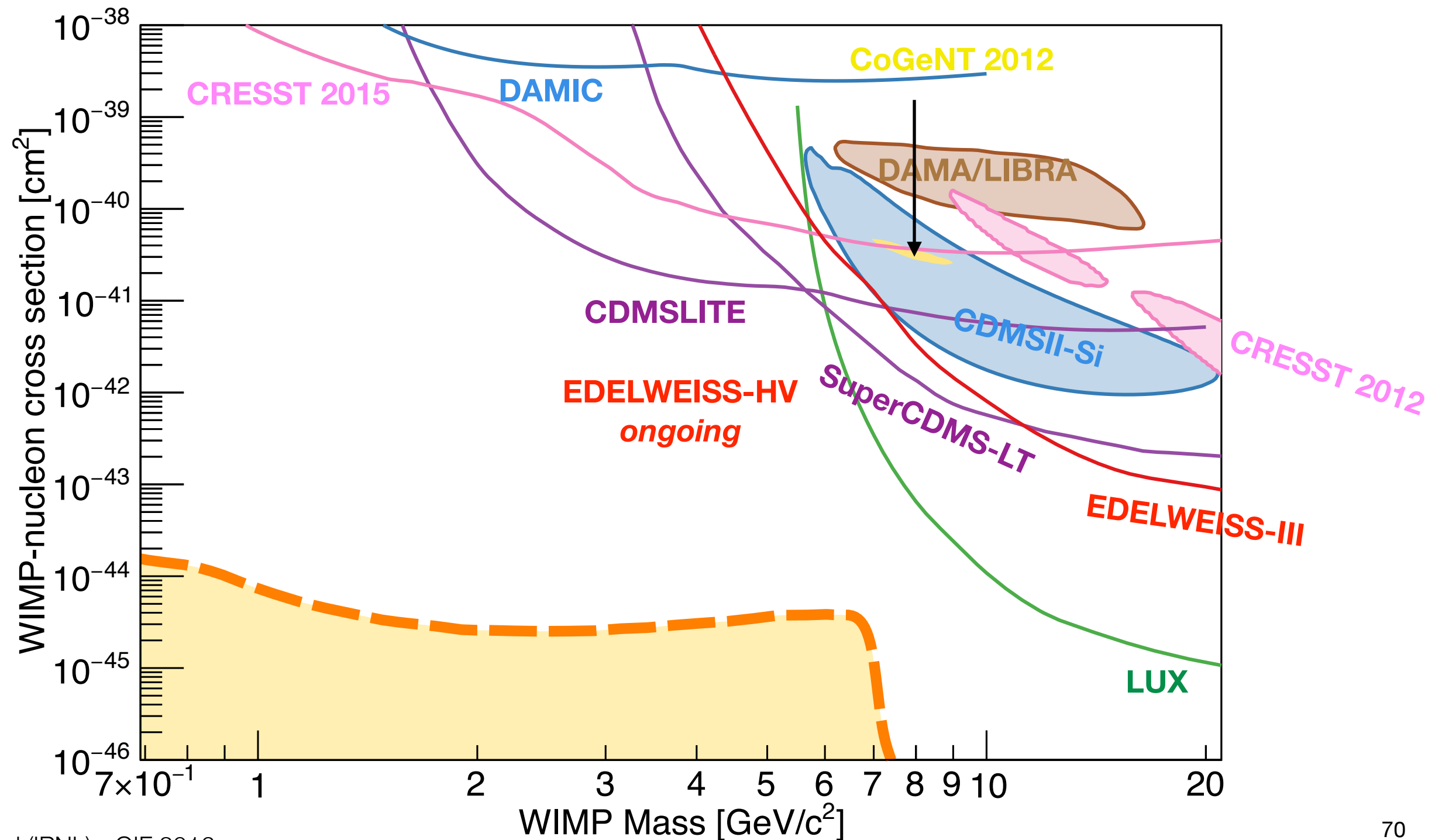
R. Agnese et al., PRL 116 (2016)

SuperCDMS - CDMSLite 2

- Operated stably at 70V or **24x** amplification (only 12x due to electronics limitations) for 2 months
- Acquired 70 kg-days
- Ionization energy calibration with EC lines at 1.3 keV_{ee} and 10.4 keV_{ee}
- Must assume NR energy scale
- 60 eV_{ee} threshold => 300 eV_{nr}
- No ER/NR discrimination but phonon fiducialization !

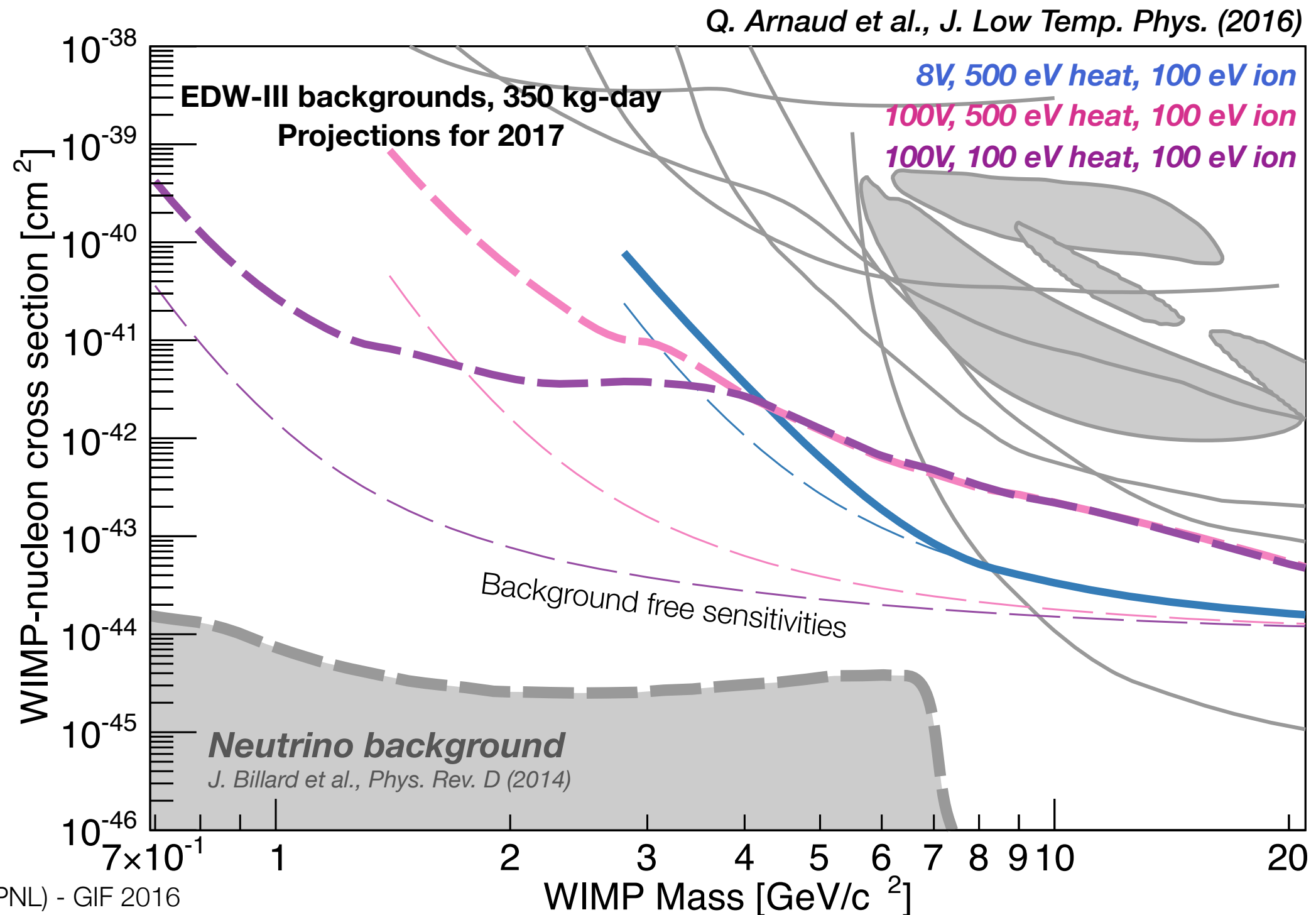


Low WIMP mass region (1 GeV - 10 GeV)



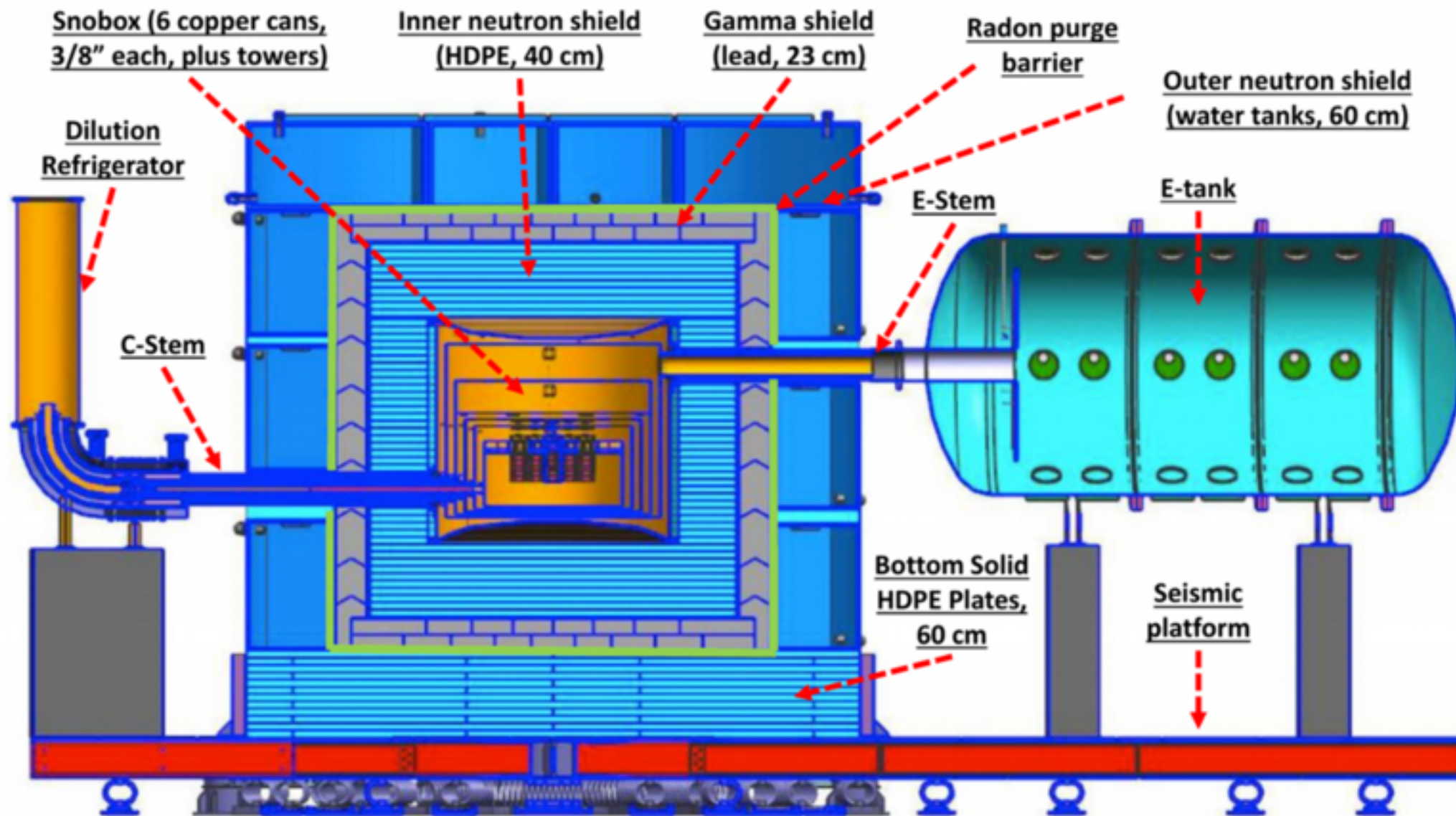
Low WIMP mass region (1 GeV - 10 GeV)

EDELWEISS and CDMS towards lower thresholds



Low WIMP mass region (1 GeV - 10 GeV)

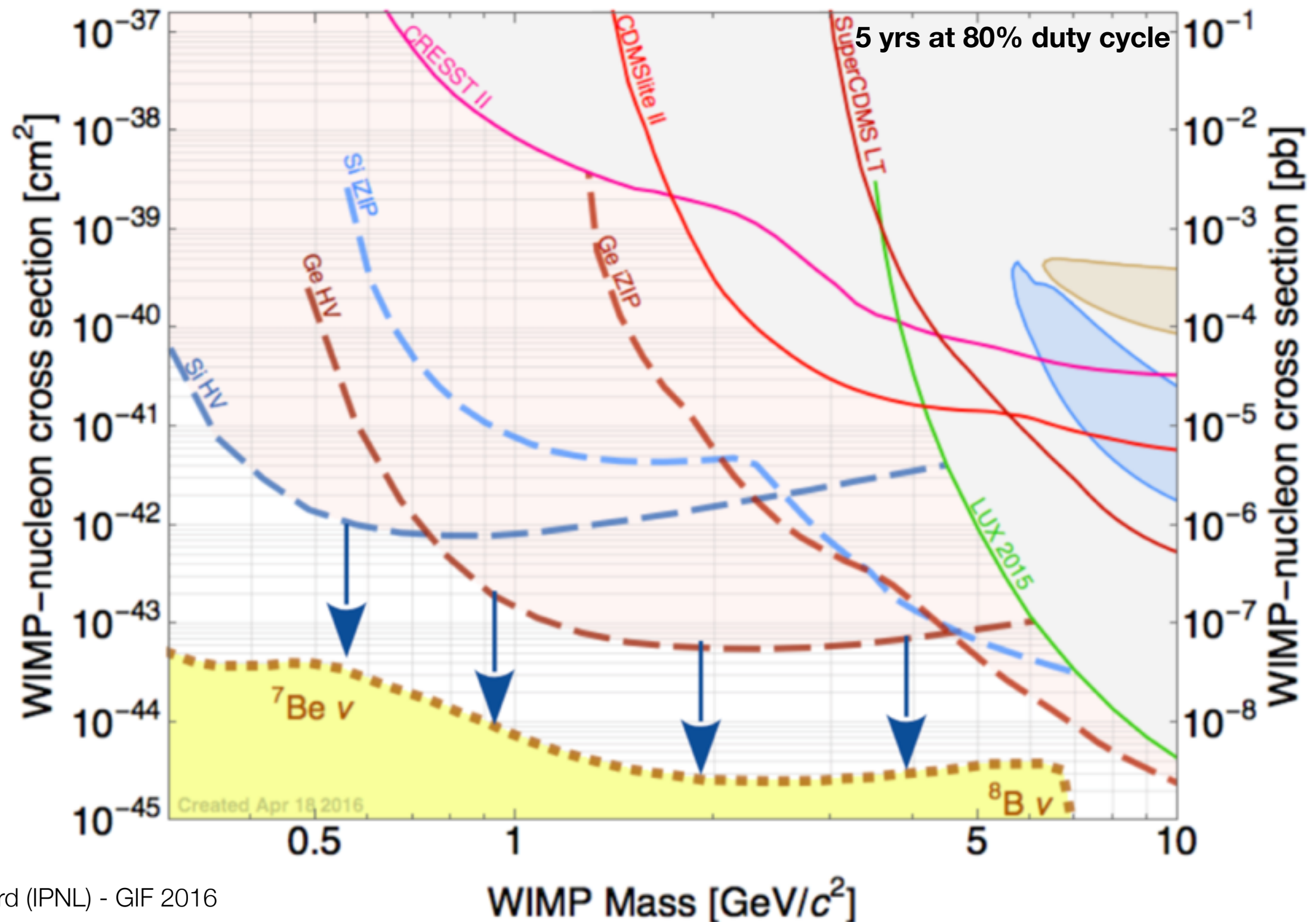
S. Golwala, UCLA Dark Matter (2016)



- Going to SNOLAB and to lower temperatures (20 mK)
- 3 Ge iZIP towers (50 kg)/ 1 Si iZIP tower (4 kg)
- 4 HV Ge (5.6 kg)/ 2 HV Si (1.4 kg)
- Construction planned for 2018 and data taking starts in 2020

Low WIMP mass region (1 GeV - 10 GeV)

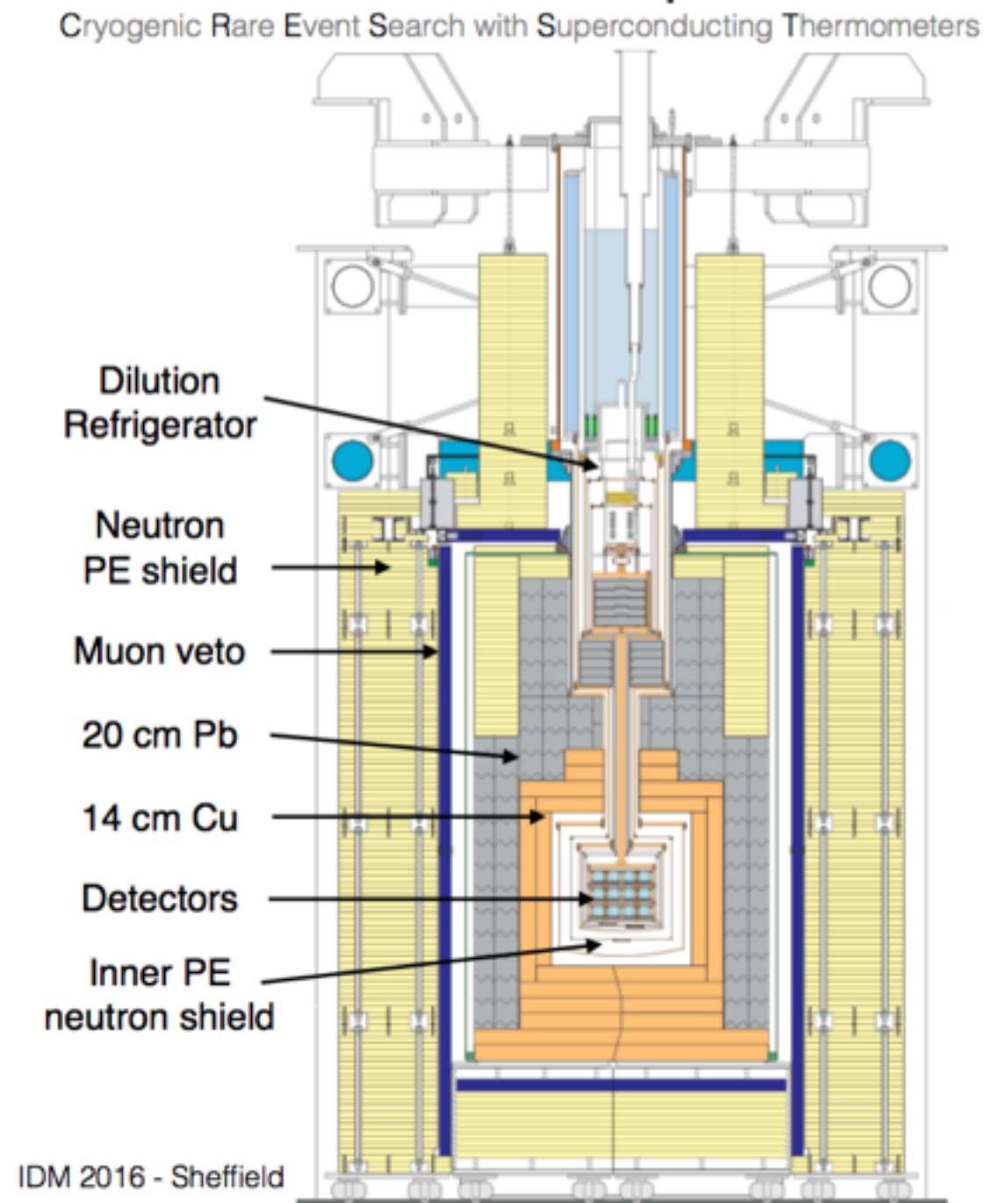
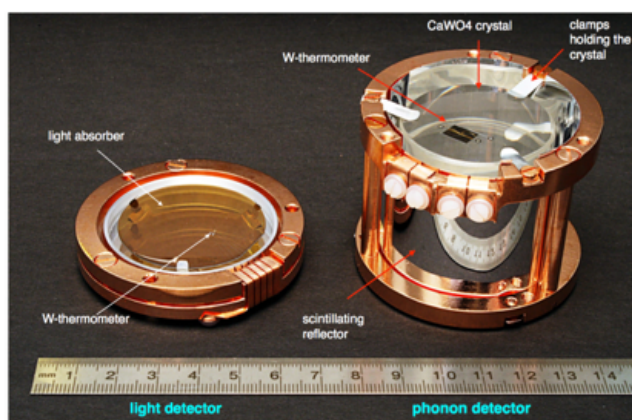
S. Golwala, UCLA Dark Matter (2016)



Low WIMP mass region (1 GeV - 10 GeV)

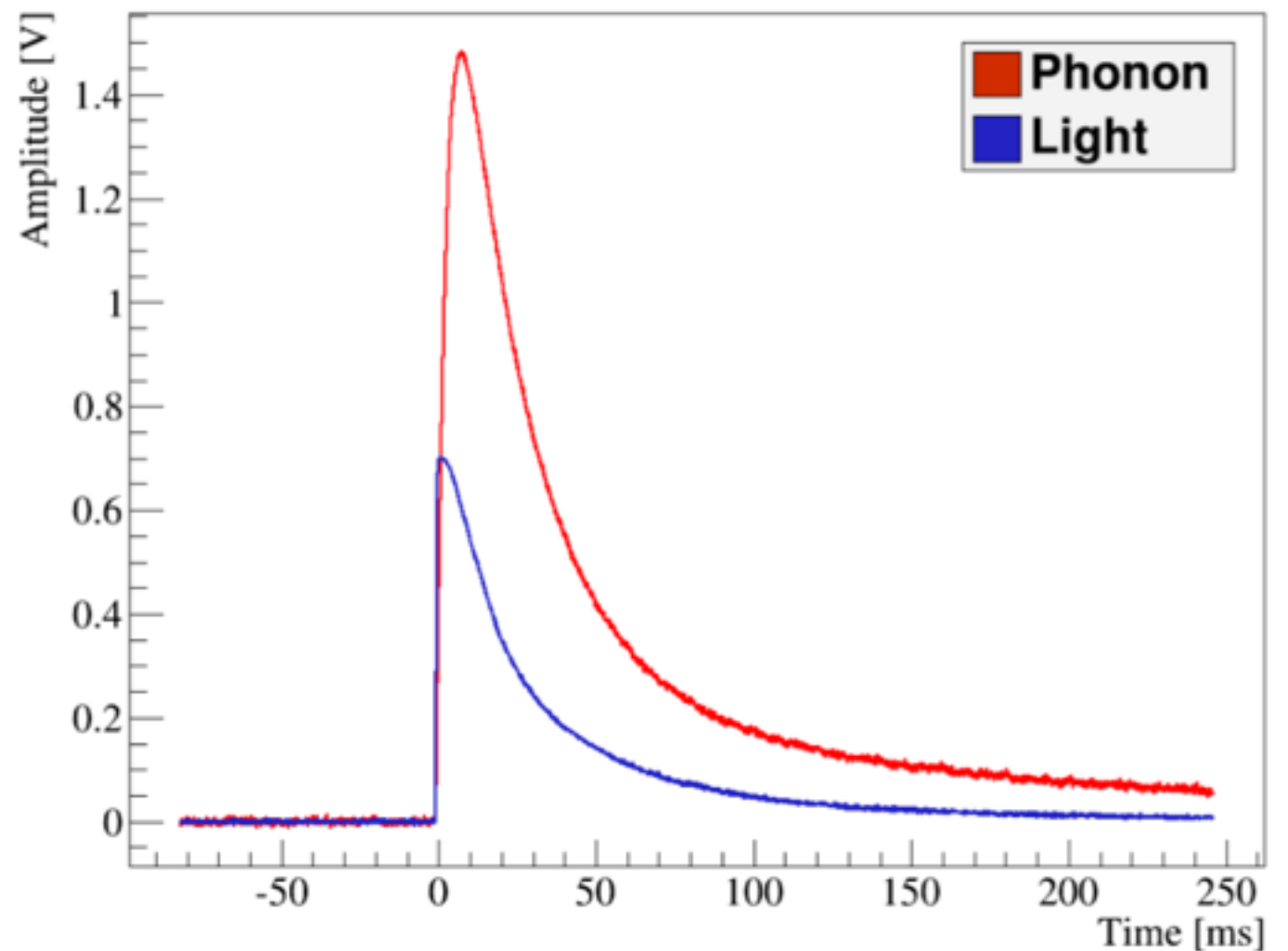
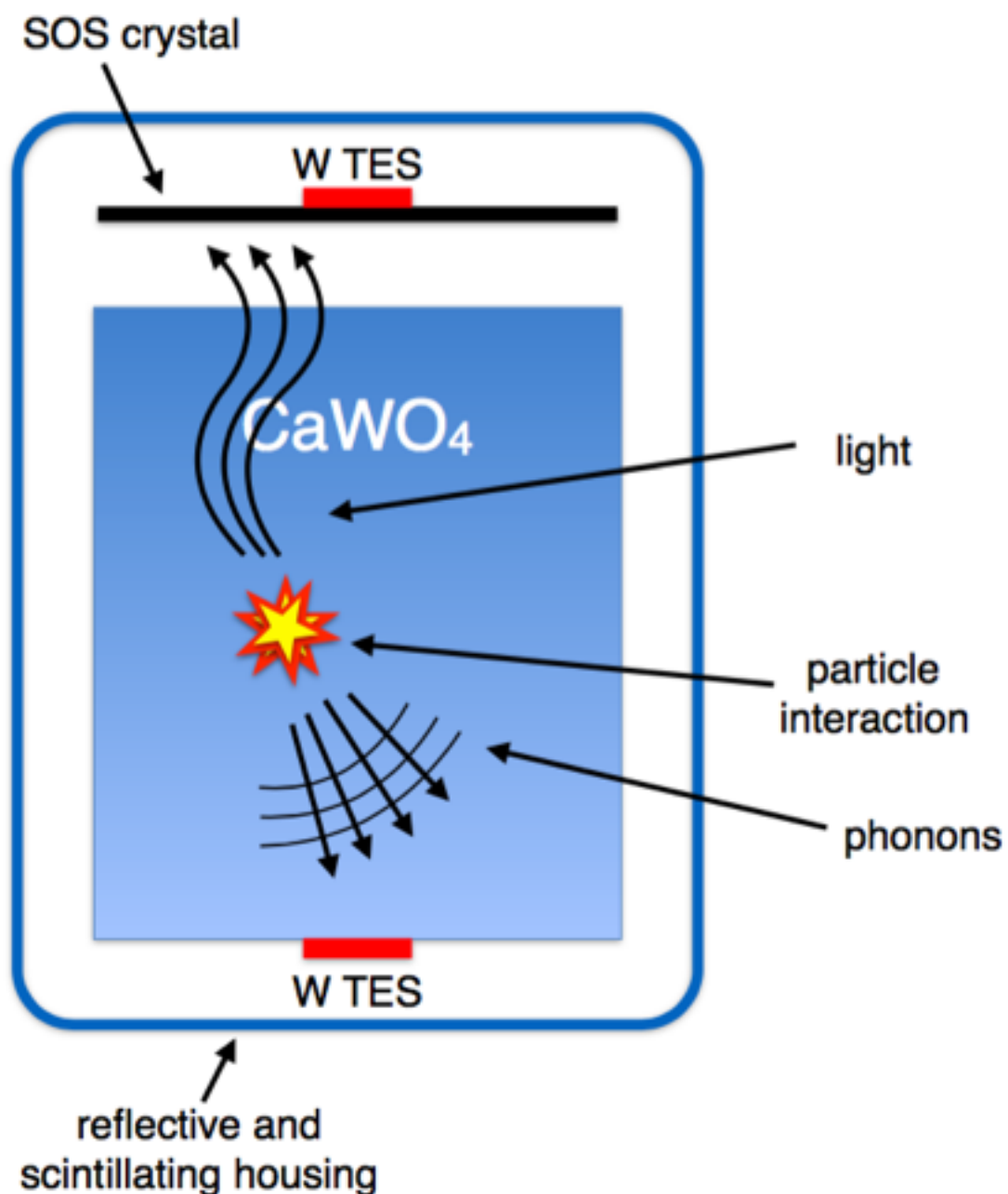
CRESST strategy: heat + scintillation

- CRESST is installed in LNGS.
- Low radioactivity environment with the usual Pb/poly/Cu shields and muon veto
- Phase two started in August 2015 with new scintillating clamps —> infamous DM hint
- 18 detector modules working at 14 mK corresponding to a total mass of 5 kg of CaWO₄ that can measure heat and light



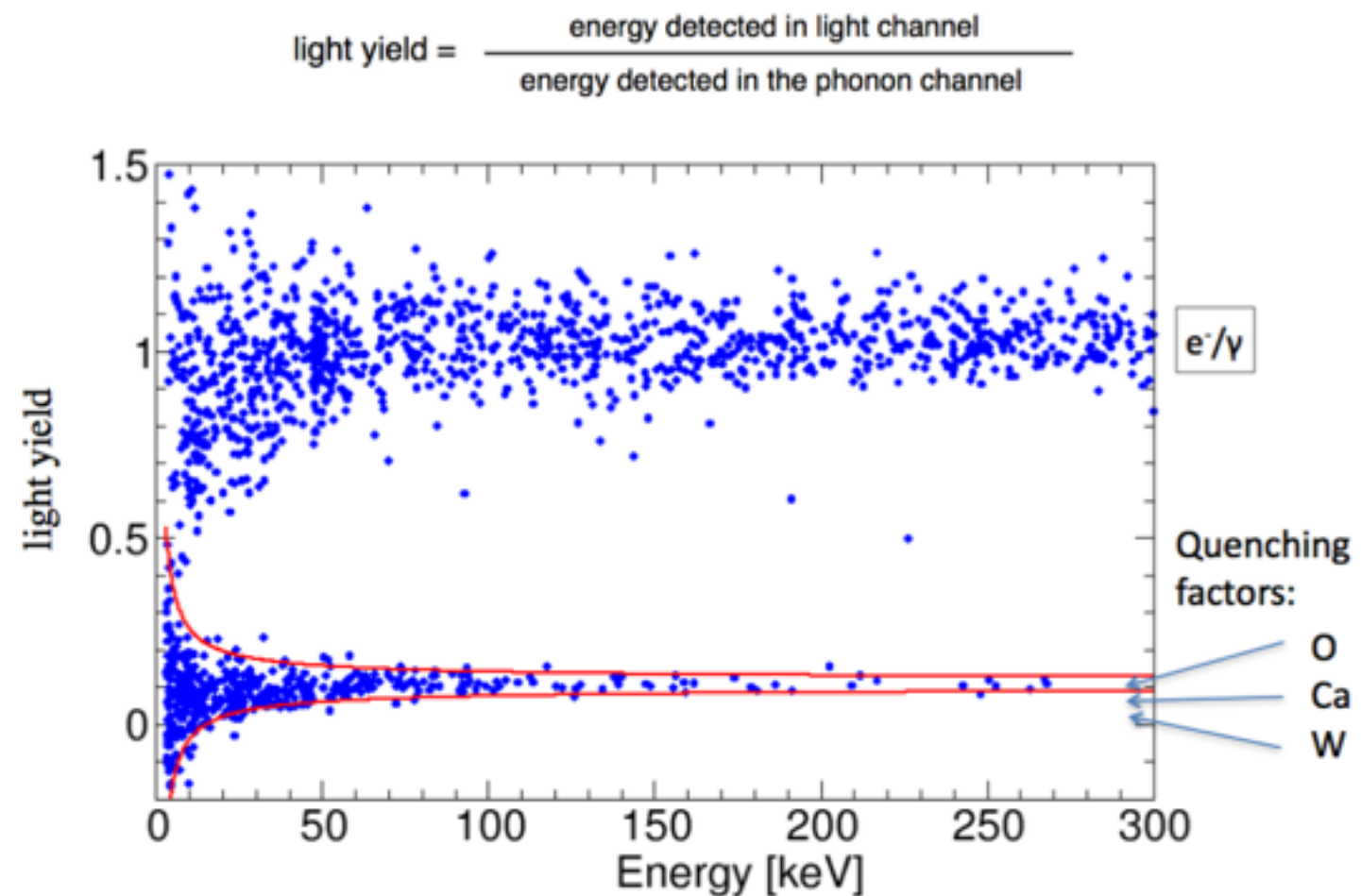
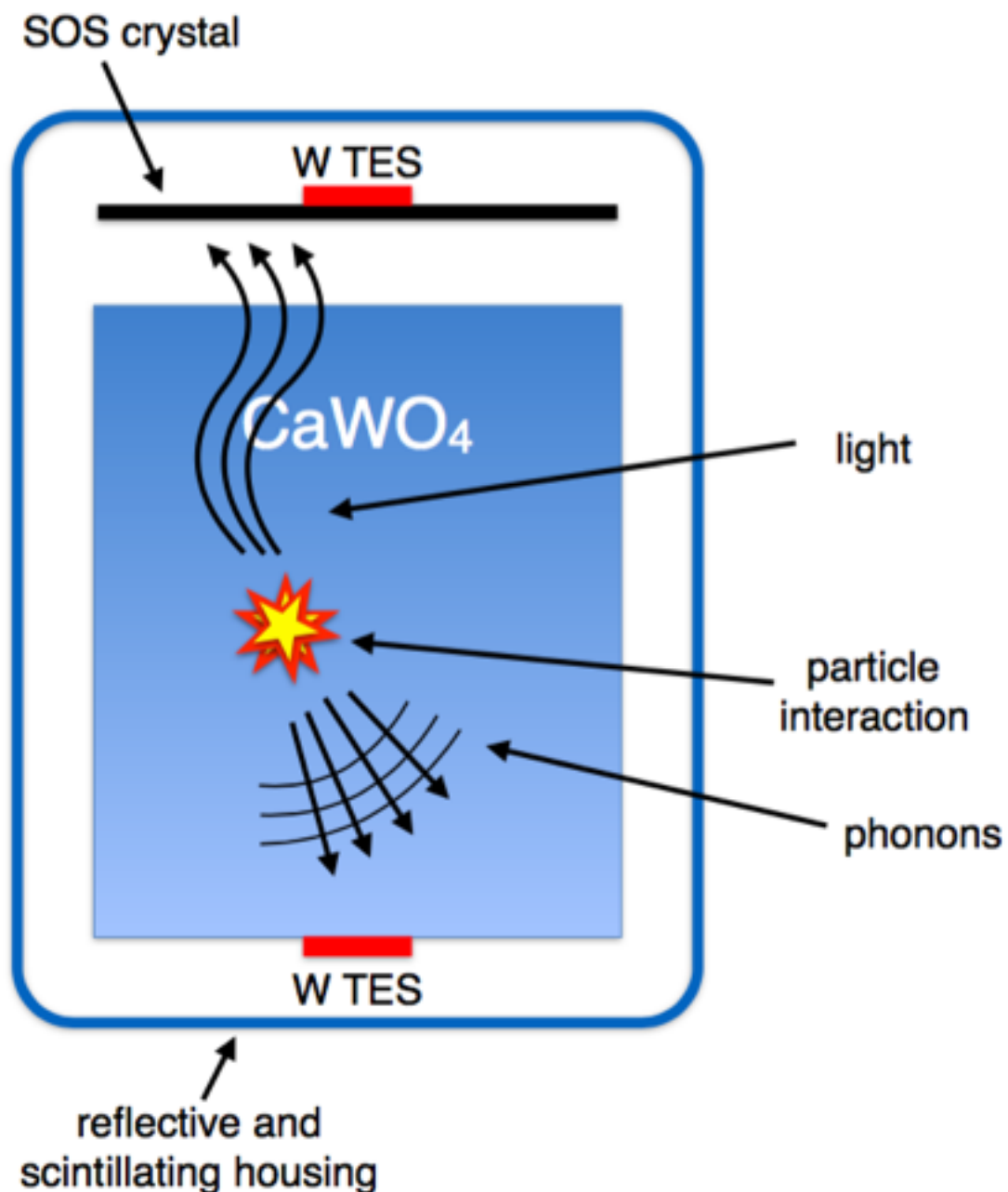
Low WIMP mass region (1 GeV - 10 GeV)

CRESST strategy: heat + scintillation



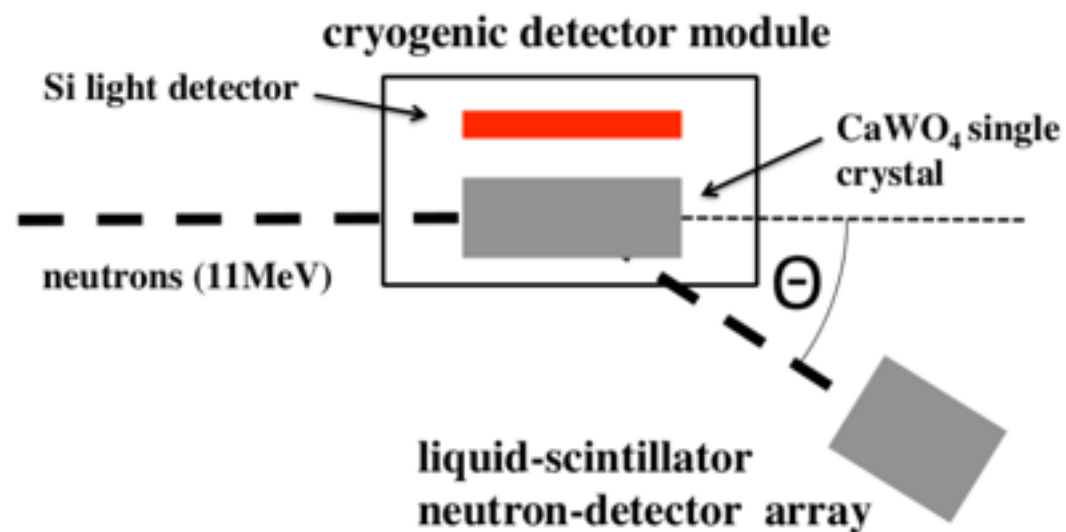
Low WIMP mass region (1 GeV - 10 GeV)

CRESST strategy: heat + scintillation

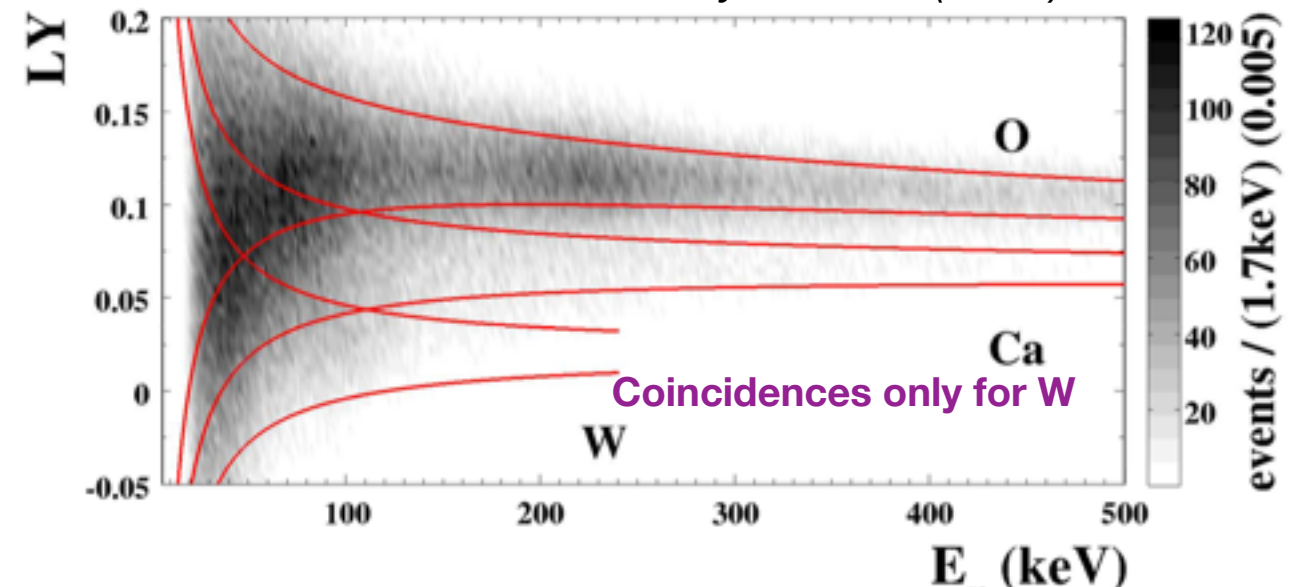


Low WIMP mass region (1 GeV - 10 GeV)

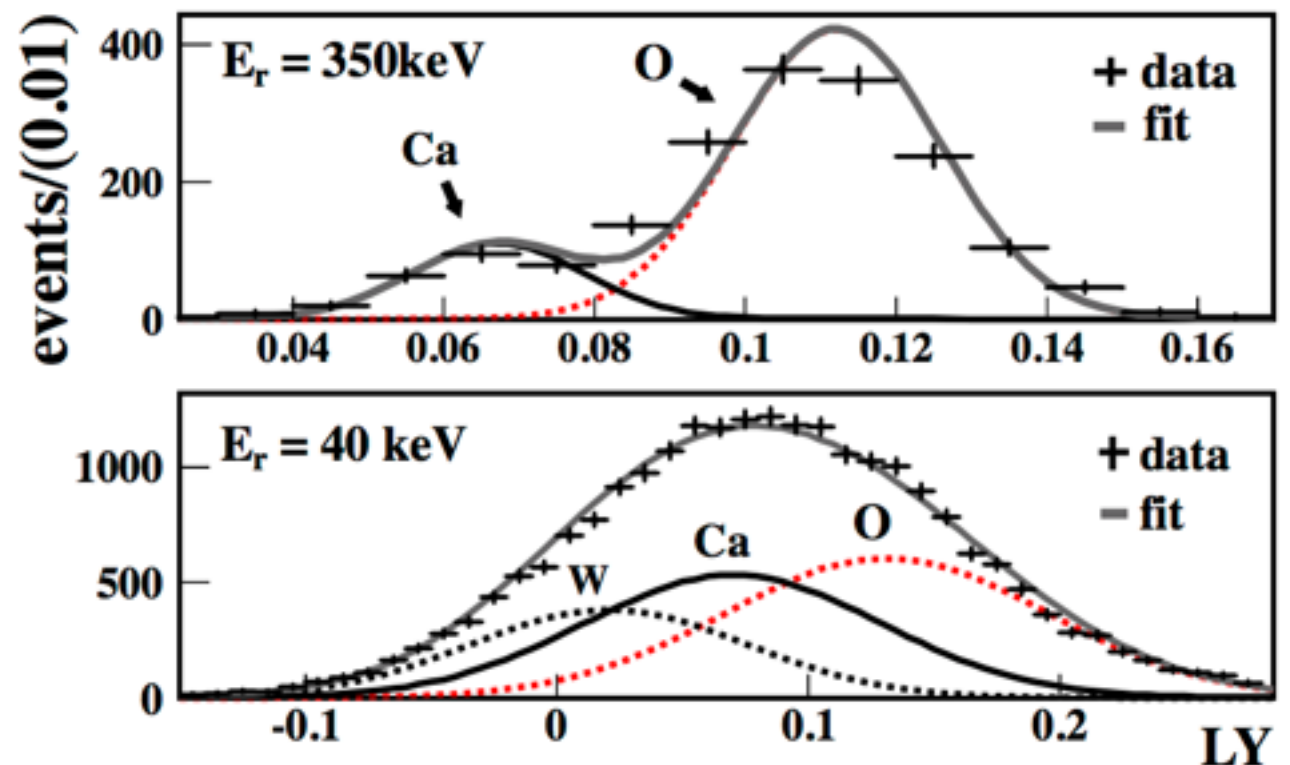
Light yield calibration



R. Strauss et al., Eur.Phys.J. C74 (2014) 2957



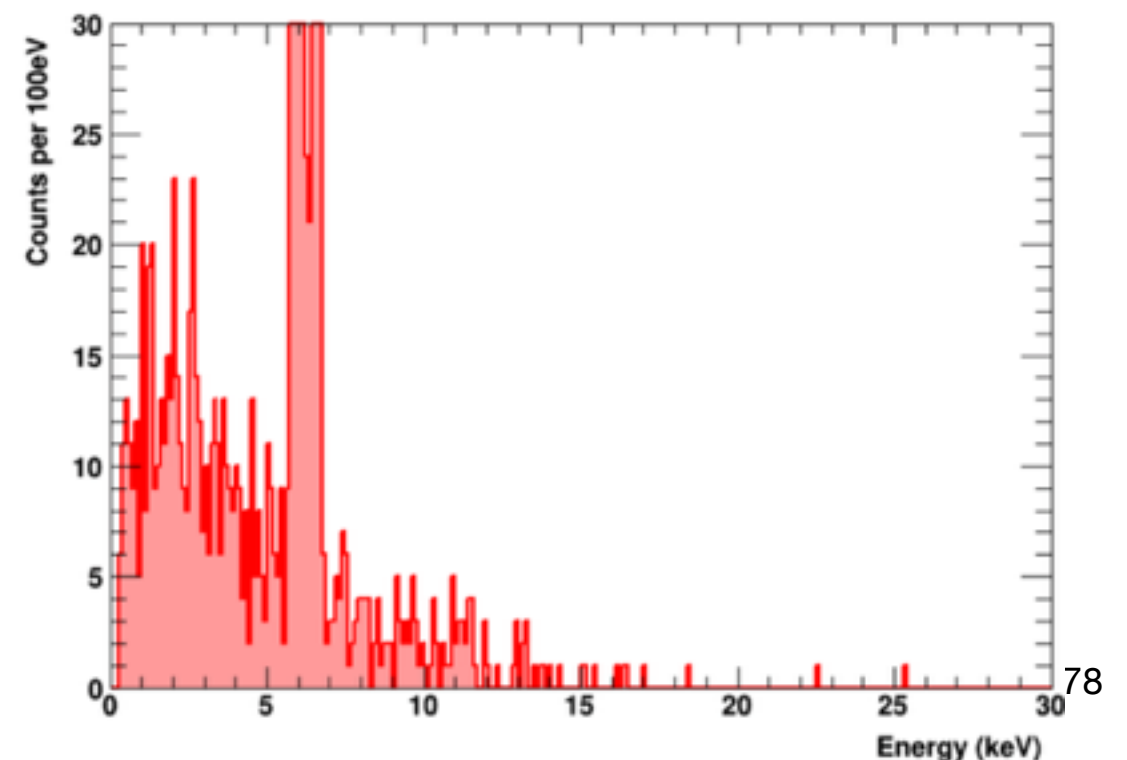
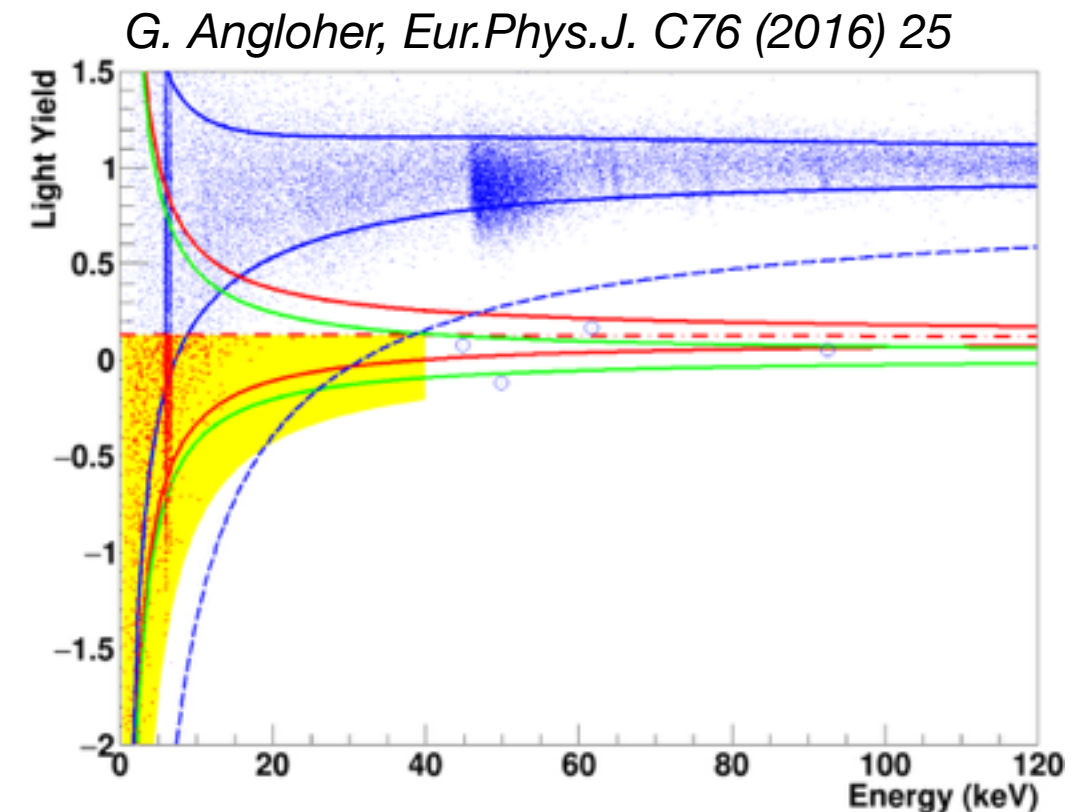
- To define the WIMP acceptance band, the CRESST collaboration did a detailed characterization of their detector's response to neutron induced nuclear recoils
- Information power is very low, large systematics at low energy
- But, scintillation is only a few percent so not really needed to recover E_r



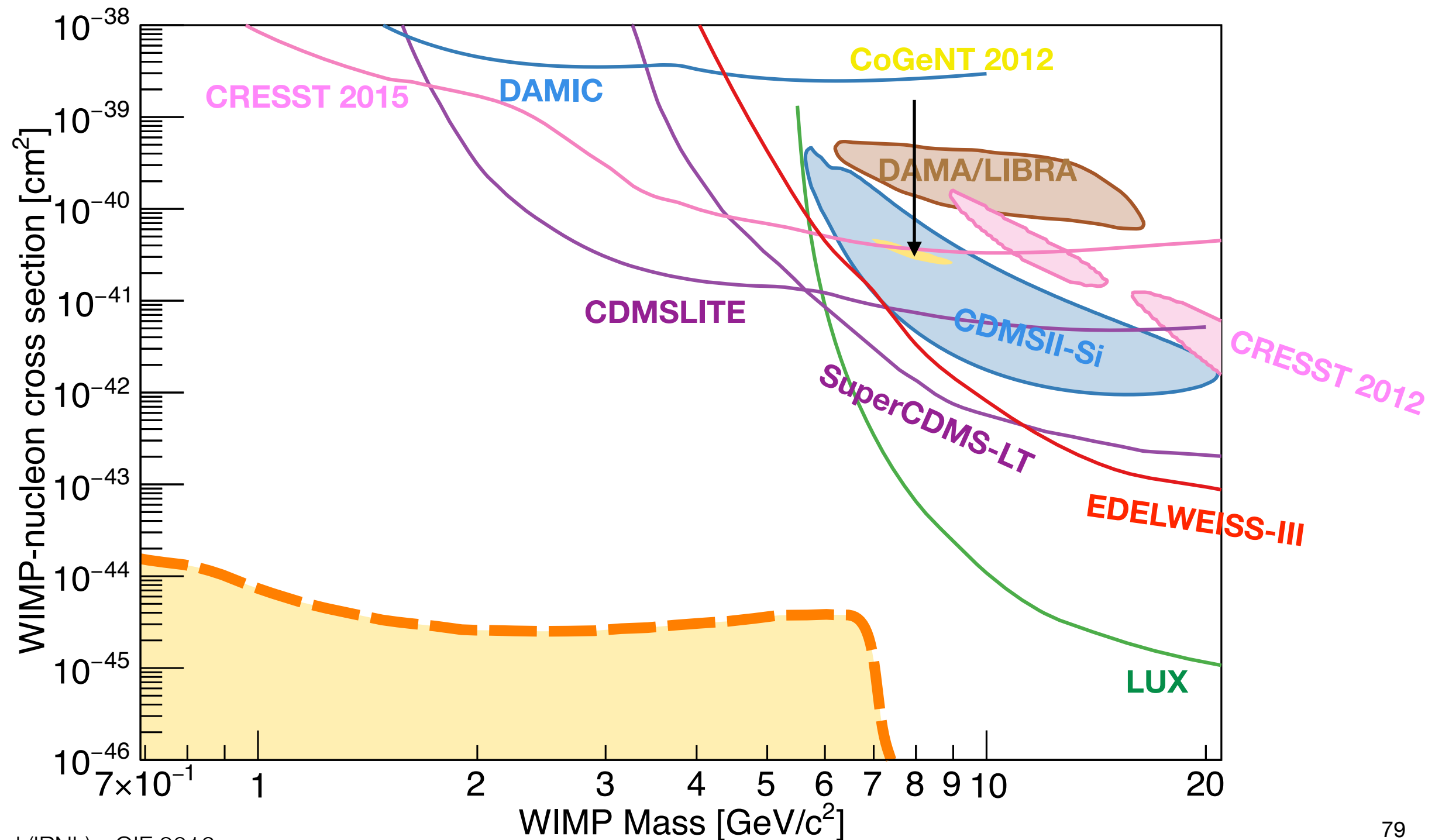
Low WIMP mass region (1 GeV - 10 GeV)

CRESST-II analysis

- Total of 52 kg-days of exposure with a single detector module (LISE) chosen for its lower energy threshold (307 eV).
- Acceptance band defined as everything below the median of the O recoils and up to W endpoint.
- Strong Fe line as a source was left on the module accidentally, but doesn't hurt the limit too much
- The limit has been derived thanks to optimal interval method, i.e. no background subtraction but signal-to-noise optimization



Low WIMP mass region (1 GeV - 10 GeV)

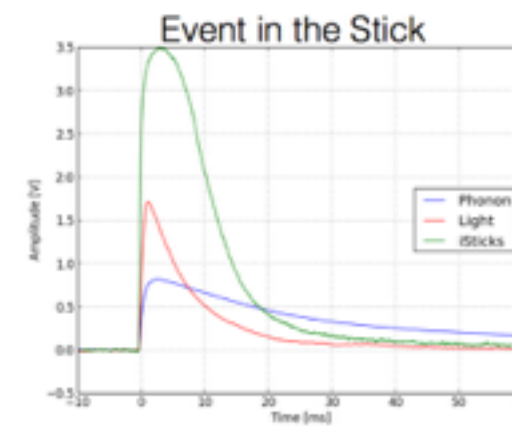
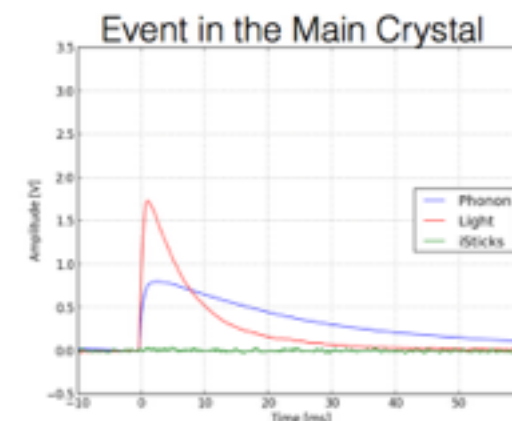
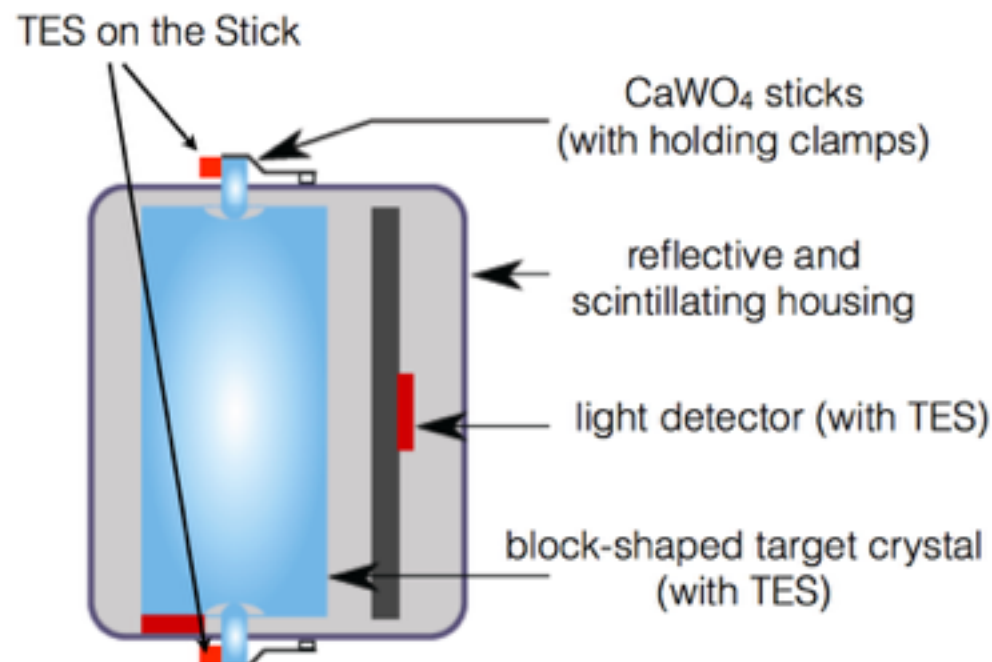


Low WIMP mass region (1 GeV - 10 GeV)

Next step?

CRESST collaboration, IDM 2016

- The CRESST collaboration is now fully dedicated to low-mass WIMPs
- They are lowering their threshold by reducing the size of the crystals 250 g $\rightarrow$ 24 g such that the threshold has gone from 500 eV to 100 eV as the athermal phonon collection efficiency gets larger and better match to the sensor bandwidth
- Reduce crystal contamination from radio active isotopes by ~ 10
- Actively reject events from the sticks: iStick
- New run ongoing with a target exposure of 50 kg-days with 10 modules



Low WIMP mass region (1 GeV - 10 GeV)

