# Dark Matter Direct Detection: Experiment, Prospects for WIMPs and Beyond…

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# Outline

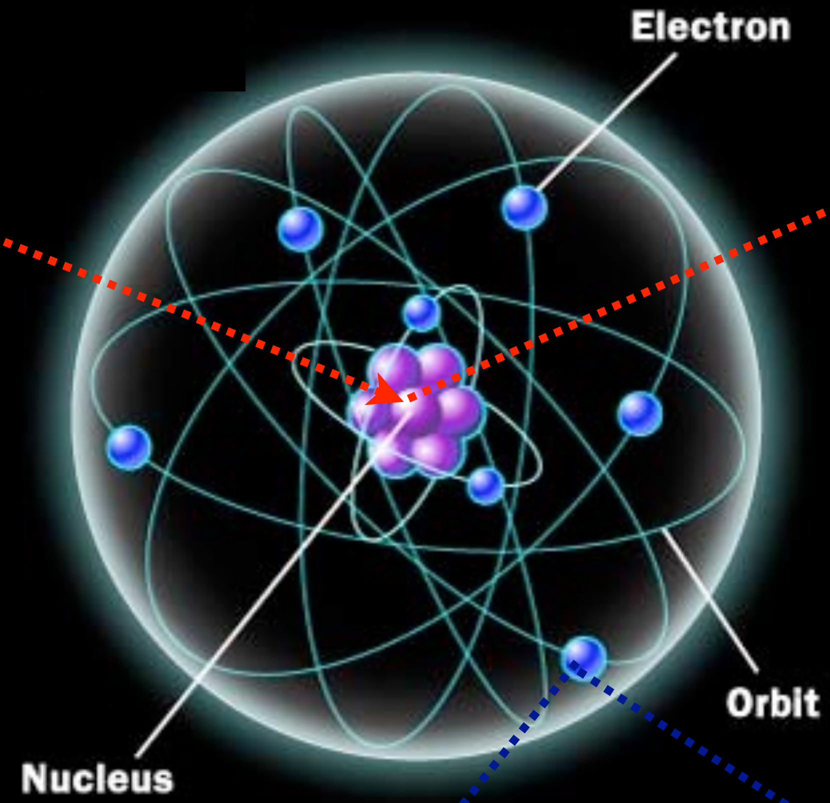
**Experimental Considerations in Direct Detection Searches**

Status and Prospects of Experiments

Beyond WIMP Dark Matter in Direct Detection Experiments

# Dark Matter Direct Detection

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




Backgrounds:

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

$n\, N \rightarrow n\, N$

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

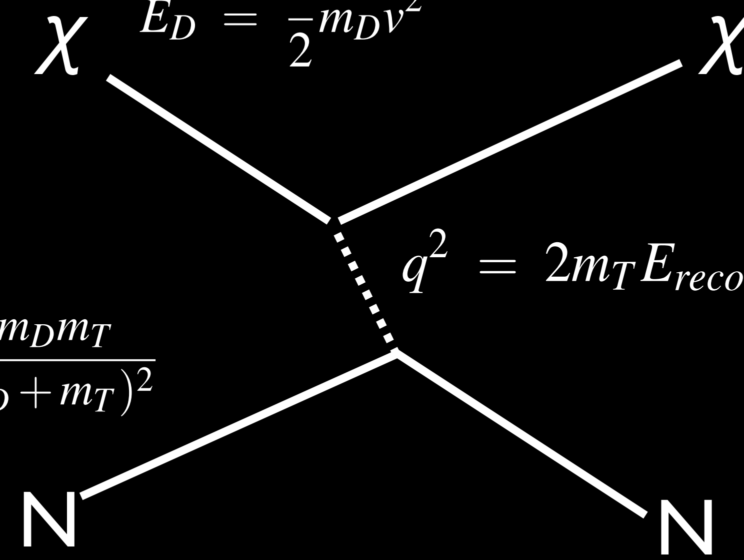
$\nu\, N \rightarrow \nu\, N$

*detector requirements: particle ID for recoil N, e-, alpha, n (multiple) final states*

# WIMP Scattering

kinematics: *v/c ~ 8E-4!*

recoil angle strongly correlated
with incoming WIMP direction




$$E_D = \frac{1}{2} m_D v^2$$

$$q^2 = 2 m_T E_{recoil}$$

$$r = \frac{4 m_D m_T}{(m_D + m_T)^2}$$

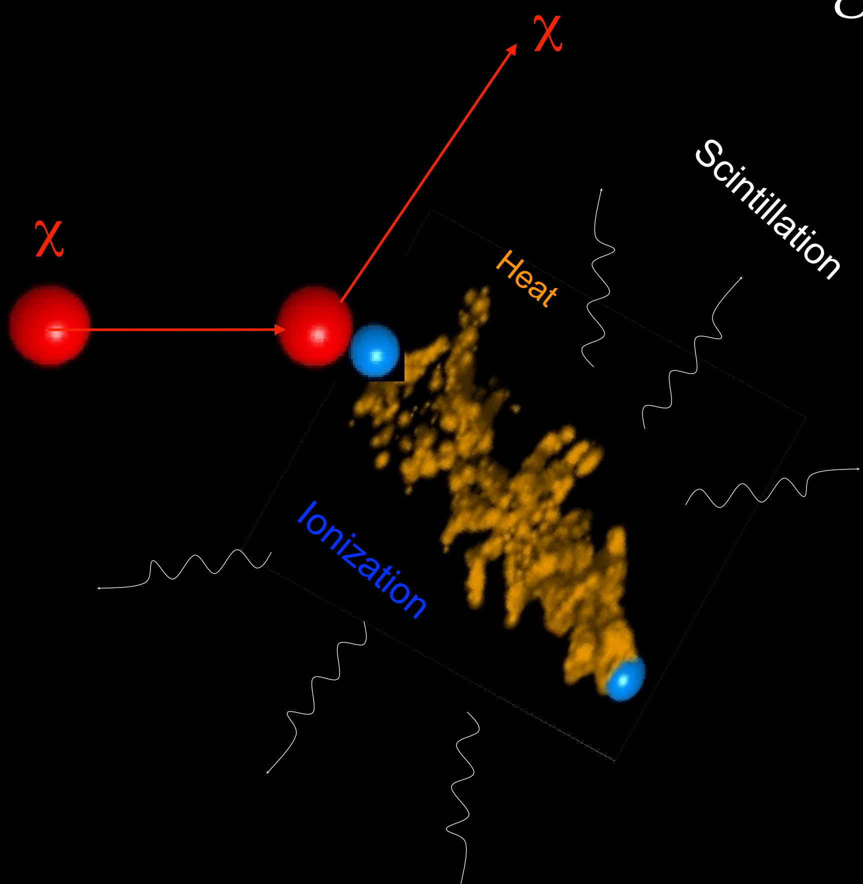
$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

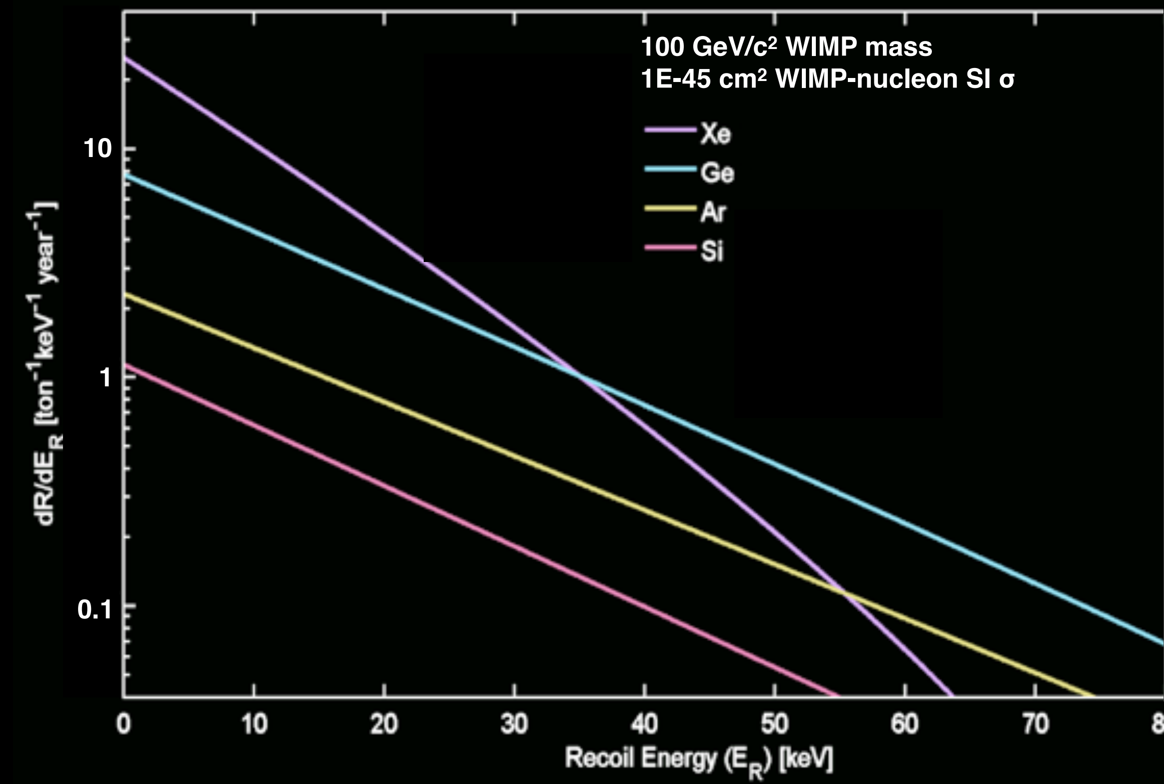
<u>Spin Independent:</u>
$\chi$ scatters coherently off of the entire nucleus A: $\sigma$~A$^2$
*D. Z. Freedman, PRD 9, 1389 (1974)*

<u>Spin Dependent:</u>
mainly unpaired nucleons contribute to scattering amplitude: $\sigma$~ *J(J+1)*

*detector requirements: measure recoil energy, time, +angle*

# Observable: Recoil Energy




Scattering rate — Sun's velocity around the galaxy — WIMP velocity distribution

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

WIMP energy density, 0.3 GeV/cm³ — Form factor

*detector requirements: ~1-10s of keV energy threshold, very low backgrounds*

# Detection Signature

PICO

Cogent COUPP

Picasso

Newage

DRIFT

ArDM

Xenon100

DarcSide

CDMS

EDELWEISS

CoGeNT

LUX

Panda-X

DMTPC


ANaIS

XMASS

DEAP/CLEAN

CRESST

KIMS

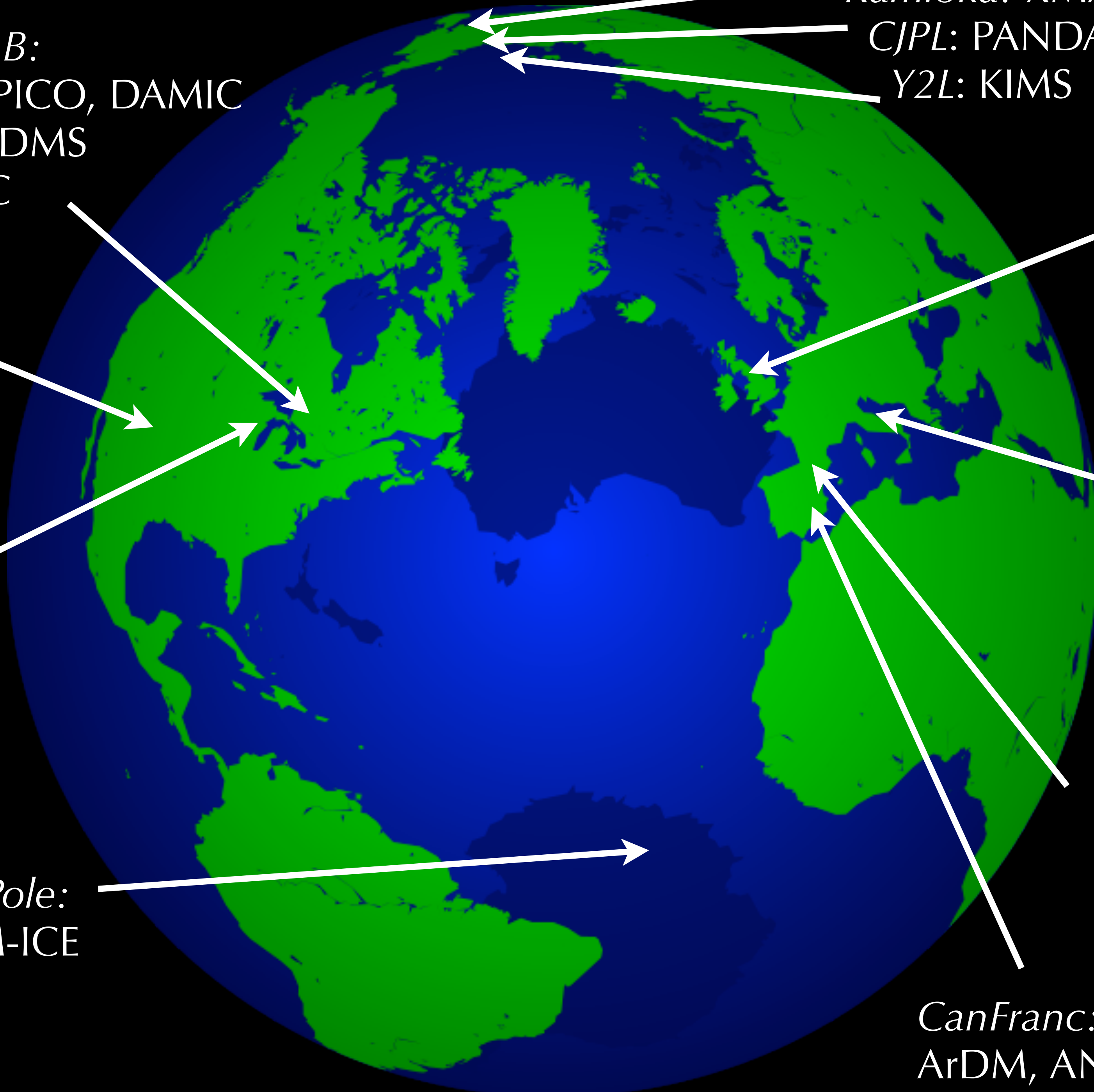
Dama/LIBRA

CRESSTII

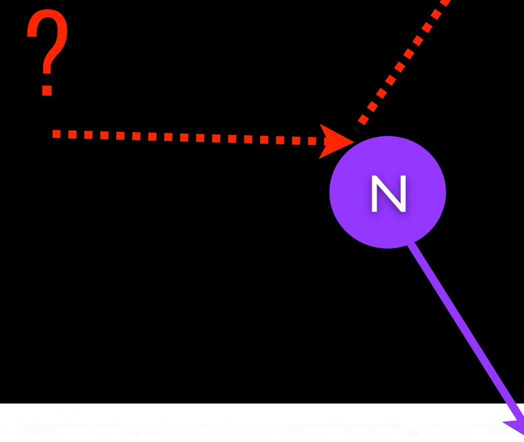
ROSEBUD

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

# Around the World



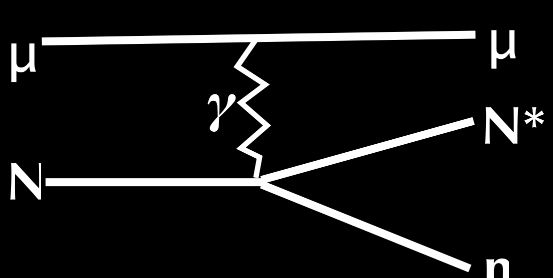
# Backgrounds

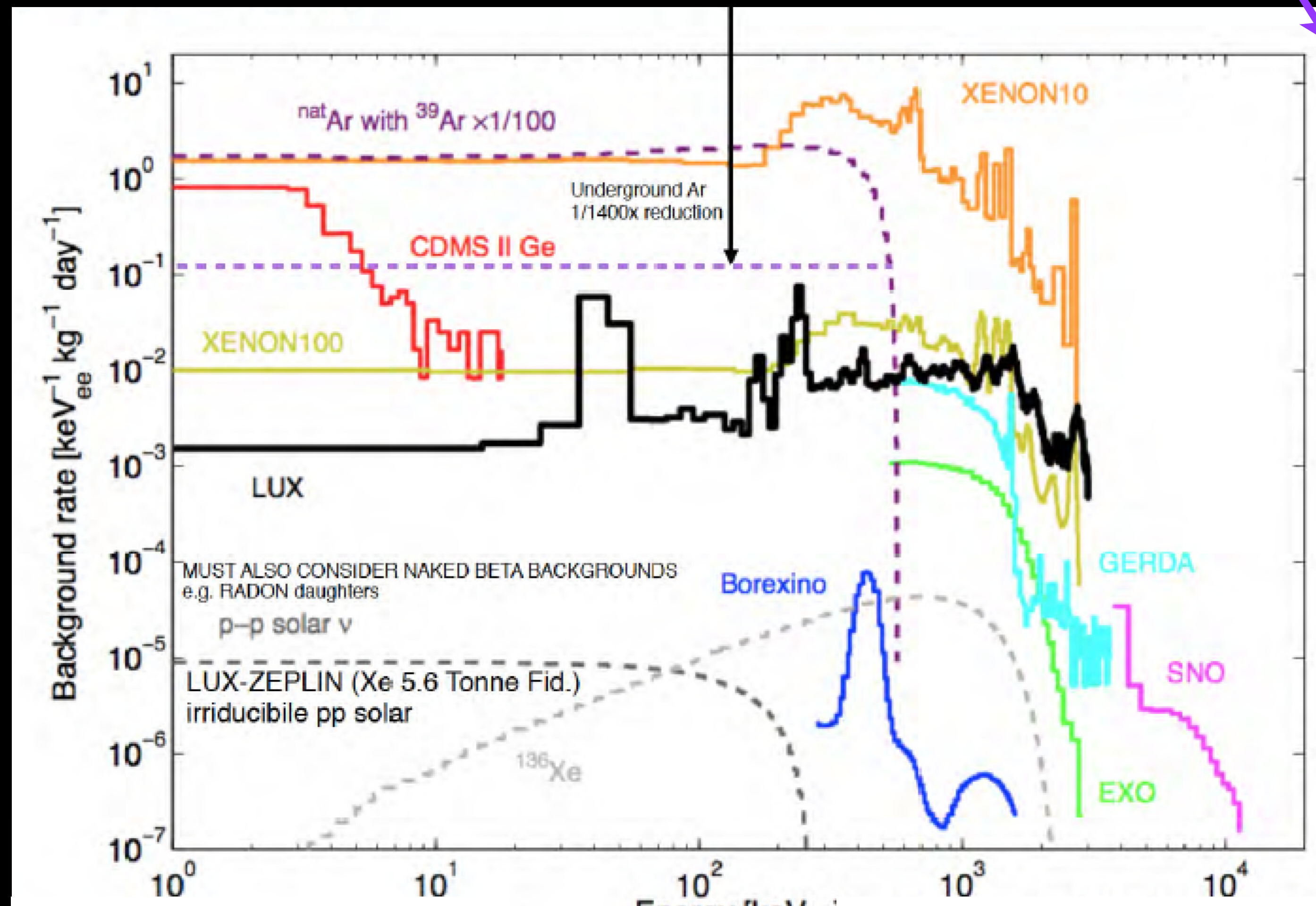



*Gamma ray interactions:* electron recoil final states
rate ~ $N_e$ x (gamma flux), O(1E7) events/(kg day)
mis-identified electrons mimic nuclear recoils

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

*Neutrons:*
Nuclear recoil final state.
(alpha,n), U, Th fission, cosmogenic spallation

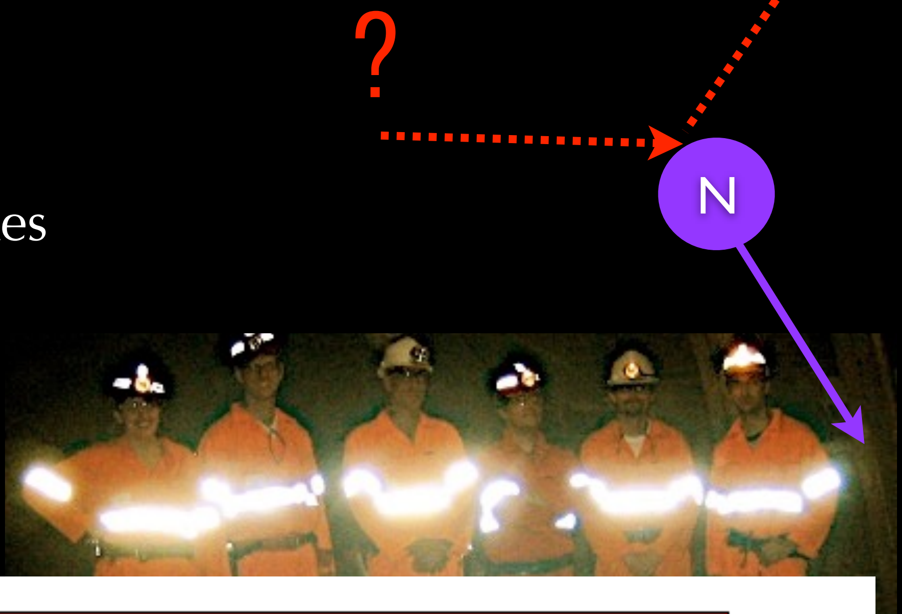



*D. Malling, UCLA DM'16*

*+ discrimination between e$^-$ vs. N*

# Backgrounds

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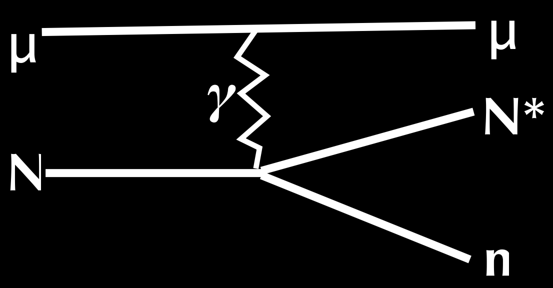
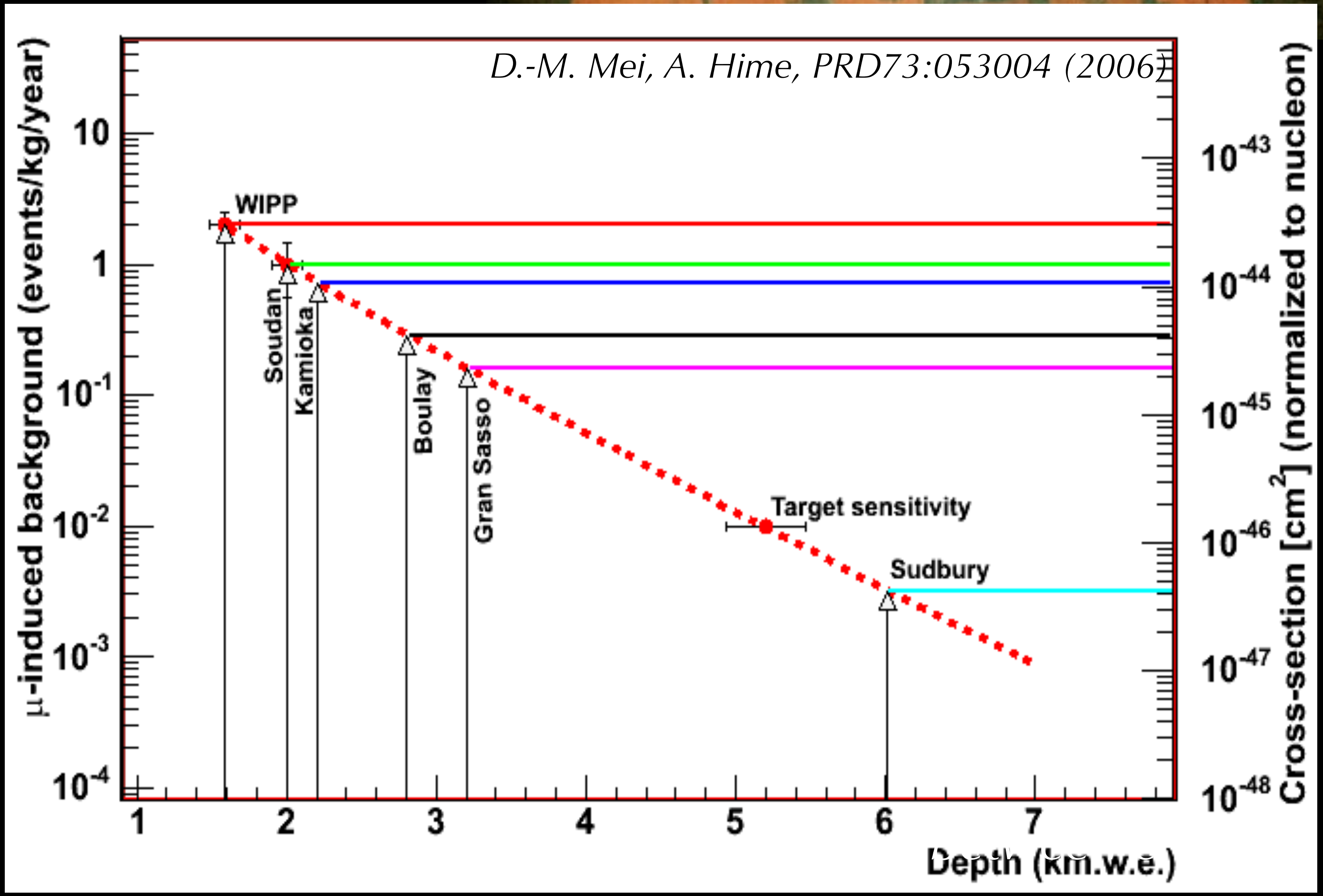
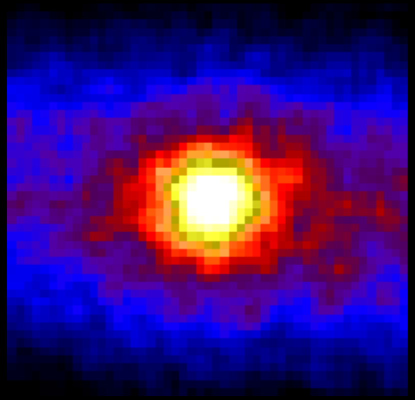


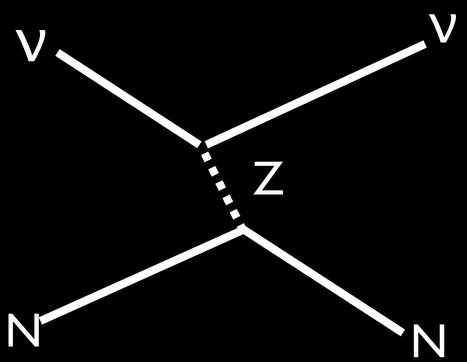

*+ large, active neutron shielding*

# Irreducible Backgrounds

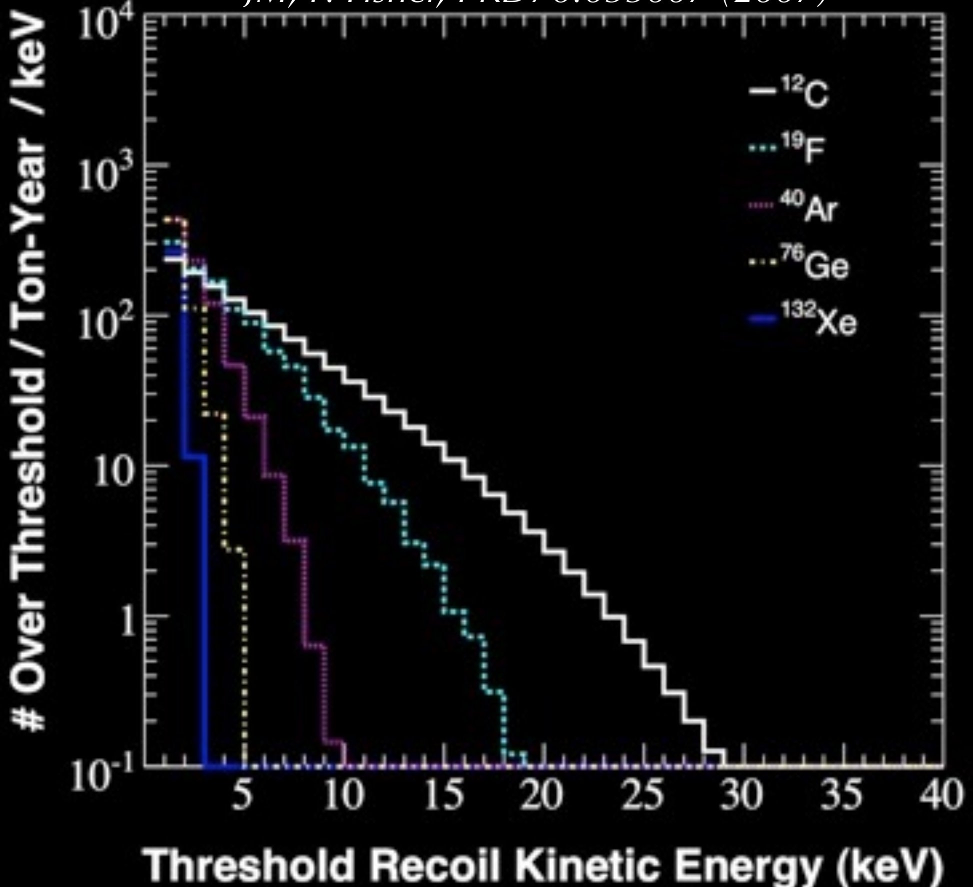


impossible to shield a detector from coherent neutrino scattering!

$\Phi$(solar $B^8$) = 5.86 x $10^6$ $cm^{-2}$ $s^{-1}$




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




nuclear recoil final state
neutrino bound at $10^{-46}$-$10^{-48}$ $cm^2$
in zero-background paradigm

*unless you measure the direction!*

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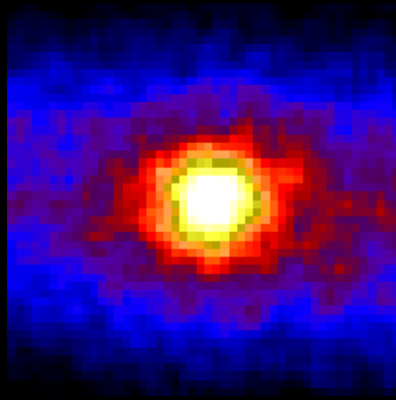

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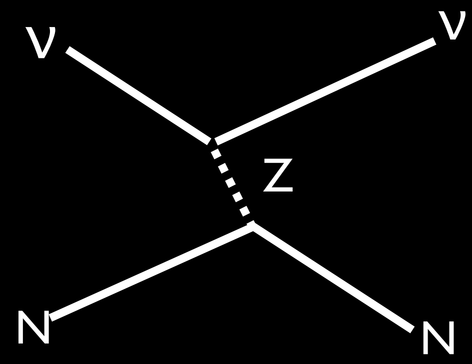
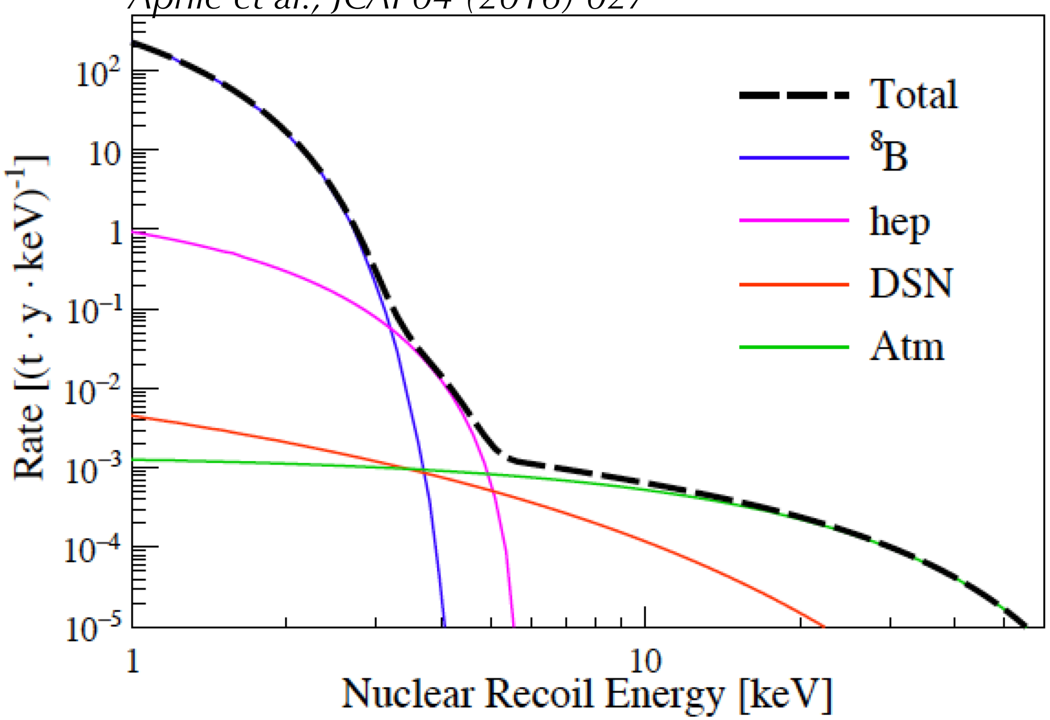
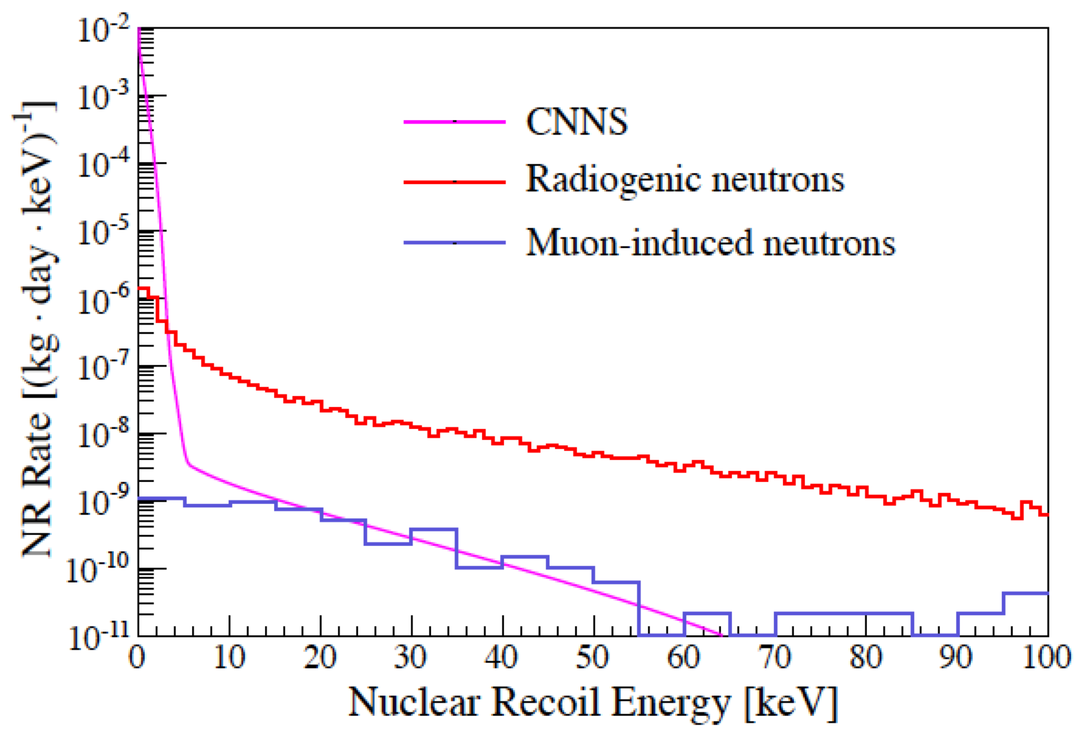
neutrino backgrounds from $^8B$ becoming important in current experiments!




*XENON 1T example:*

*Aprile et al., JCAP04 (2016) 027*

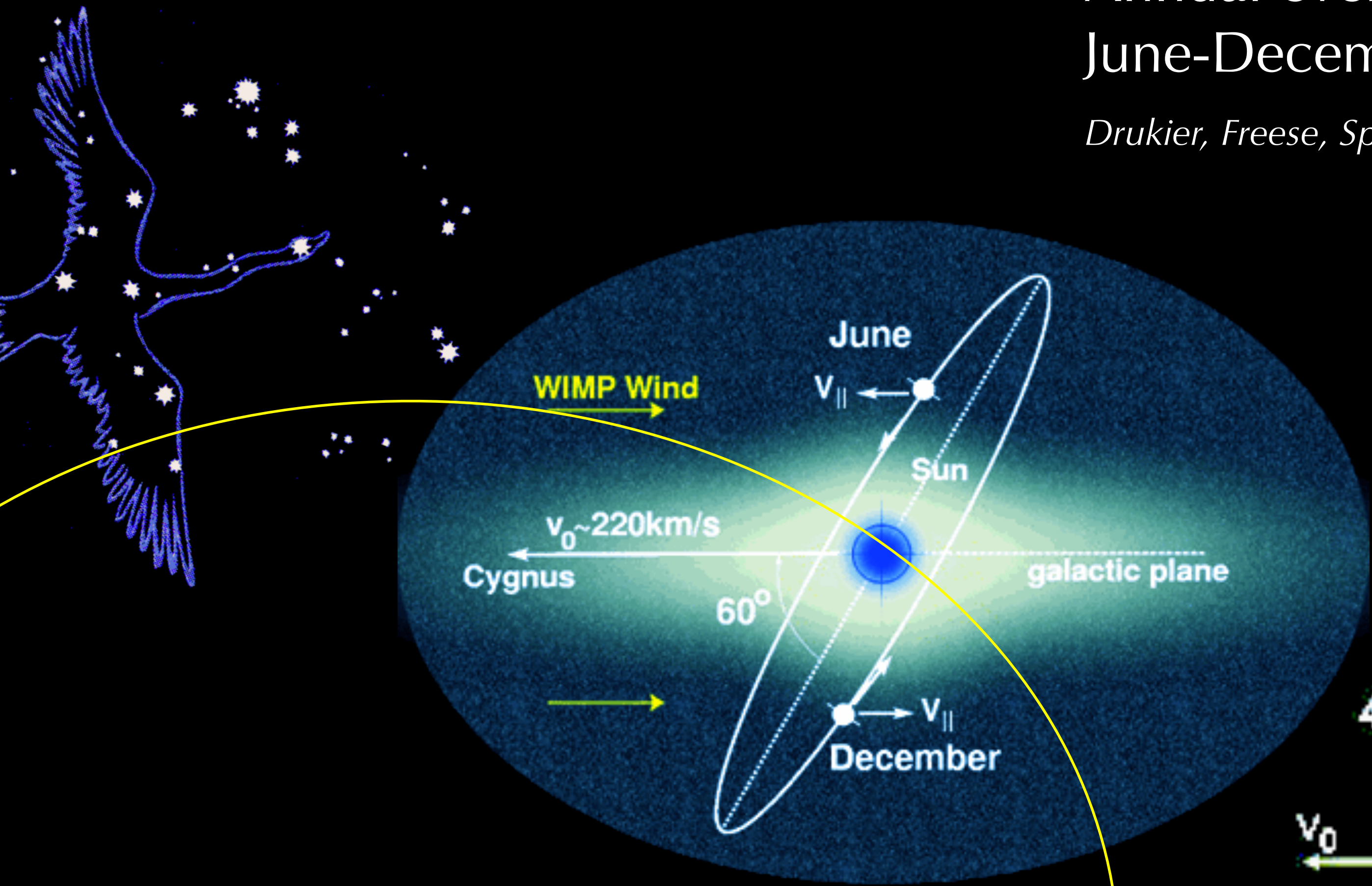


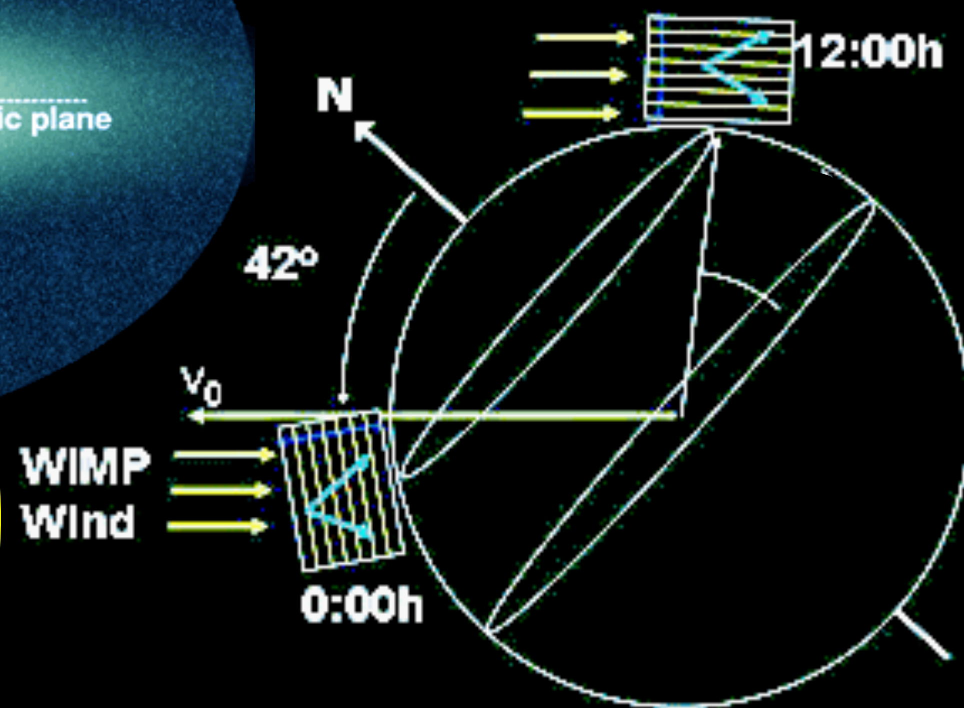



# Modulation Signatures

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!*

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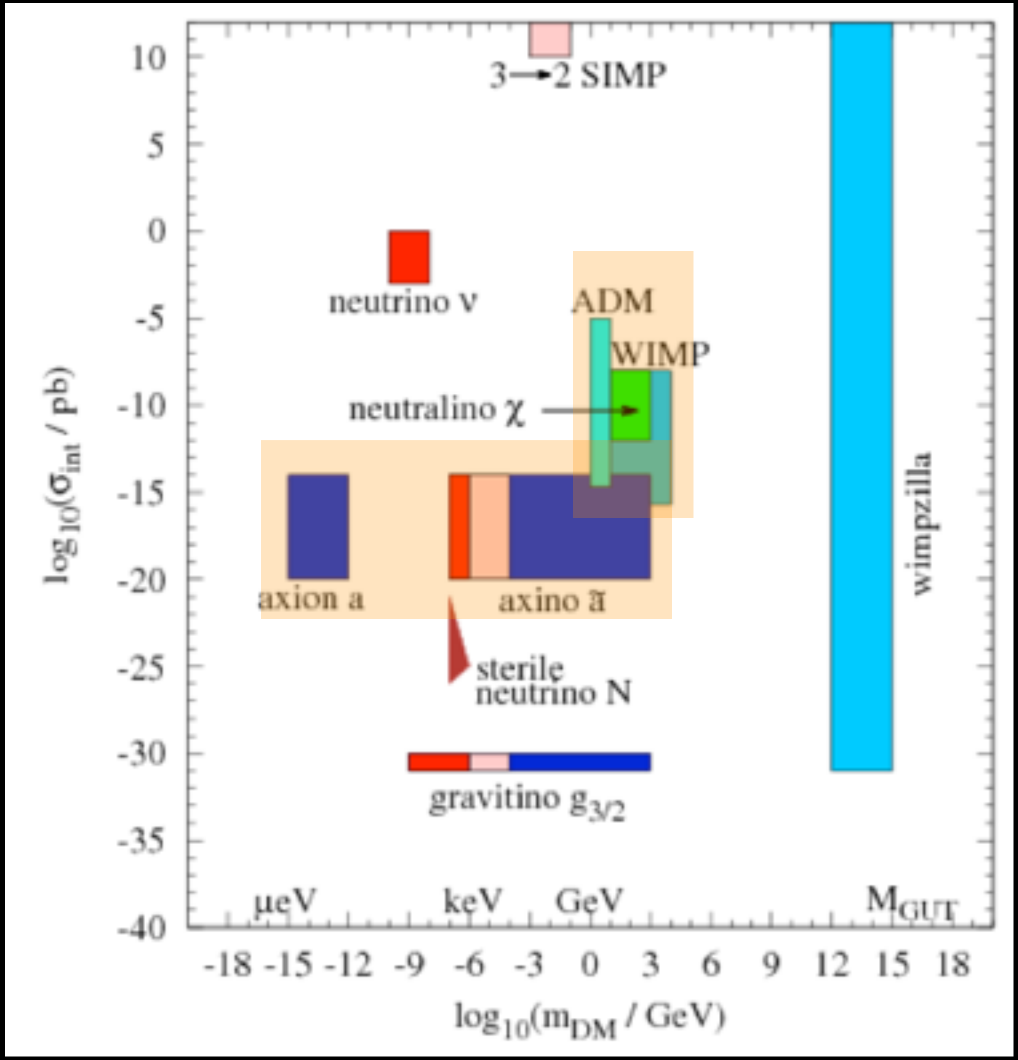
Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity…




*Baer et al., arXiv:1407.0017*

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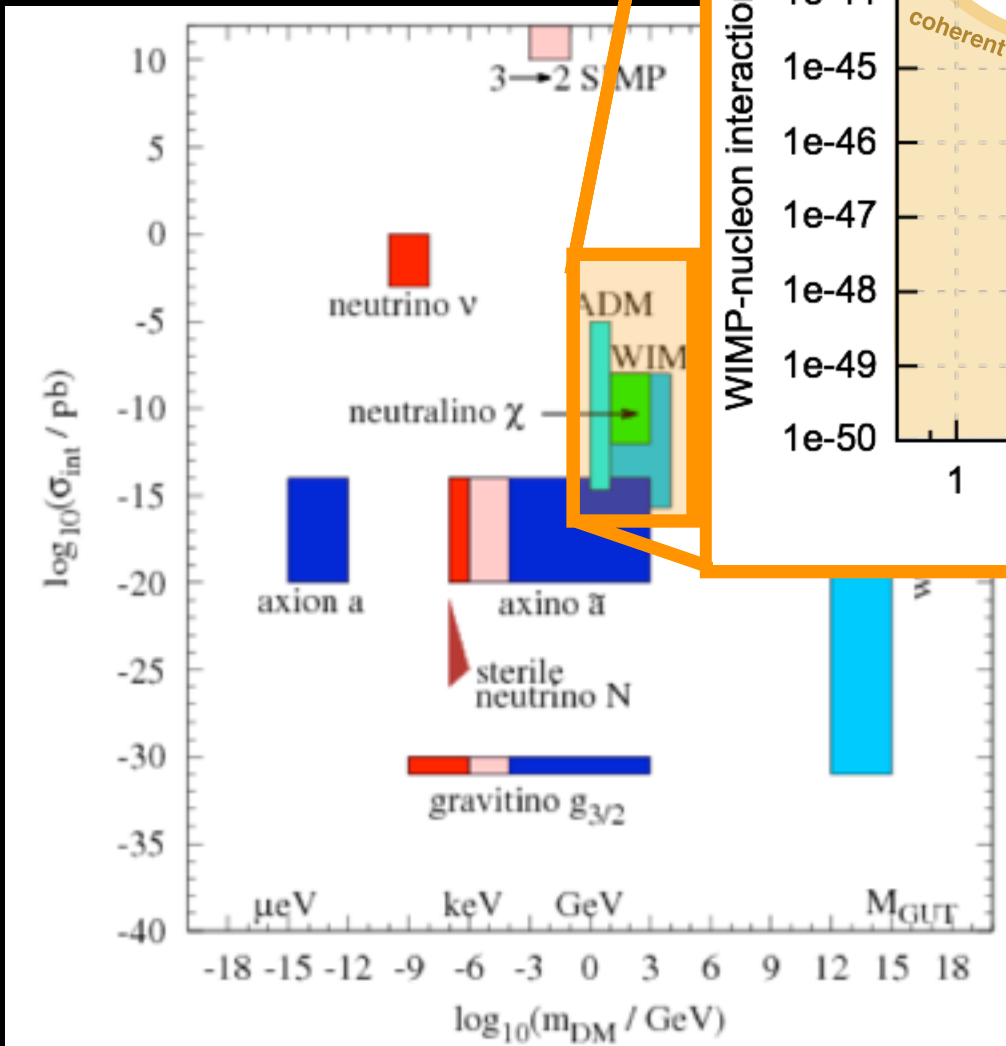


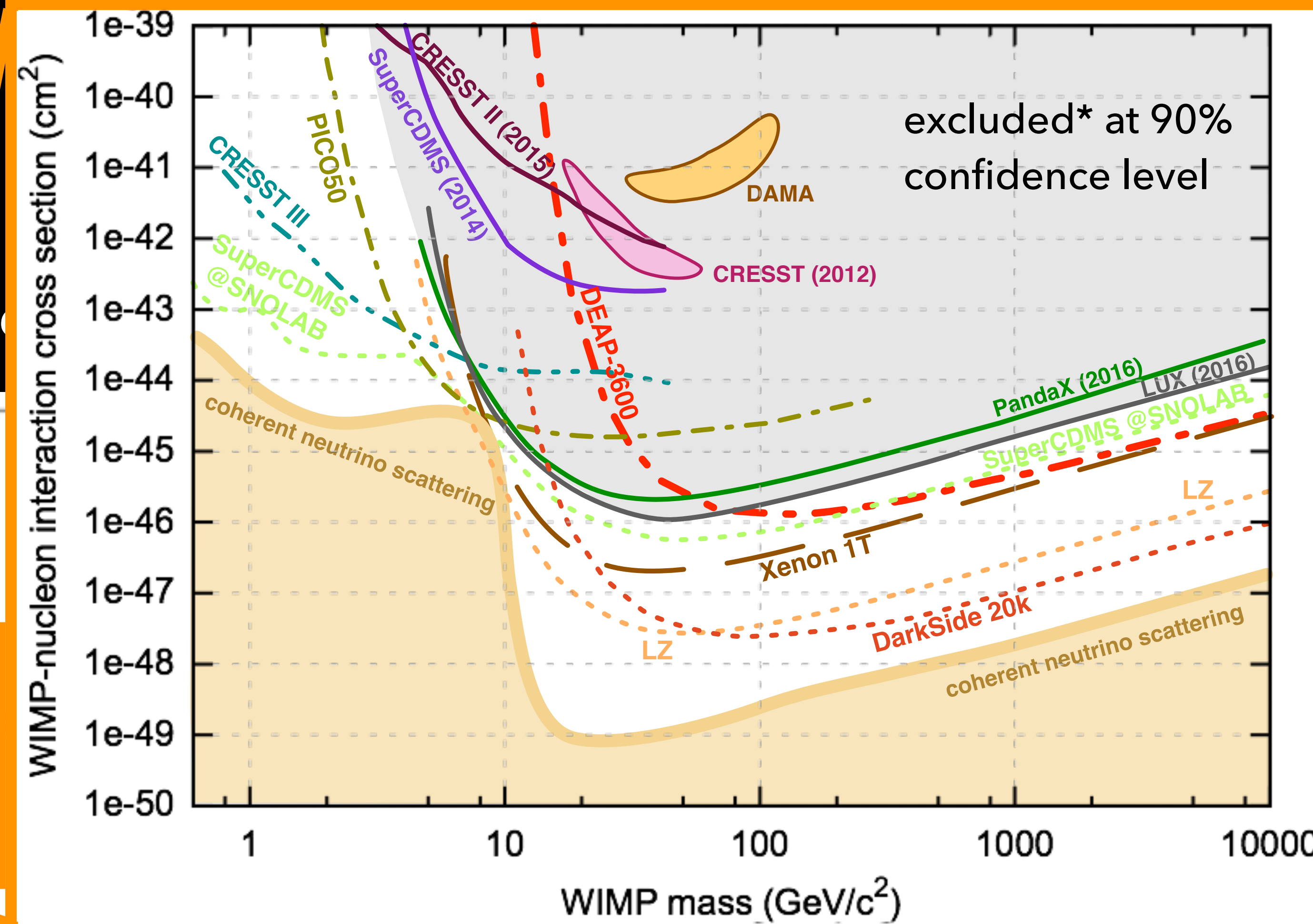


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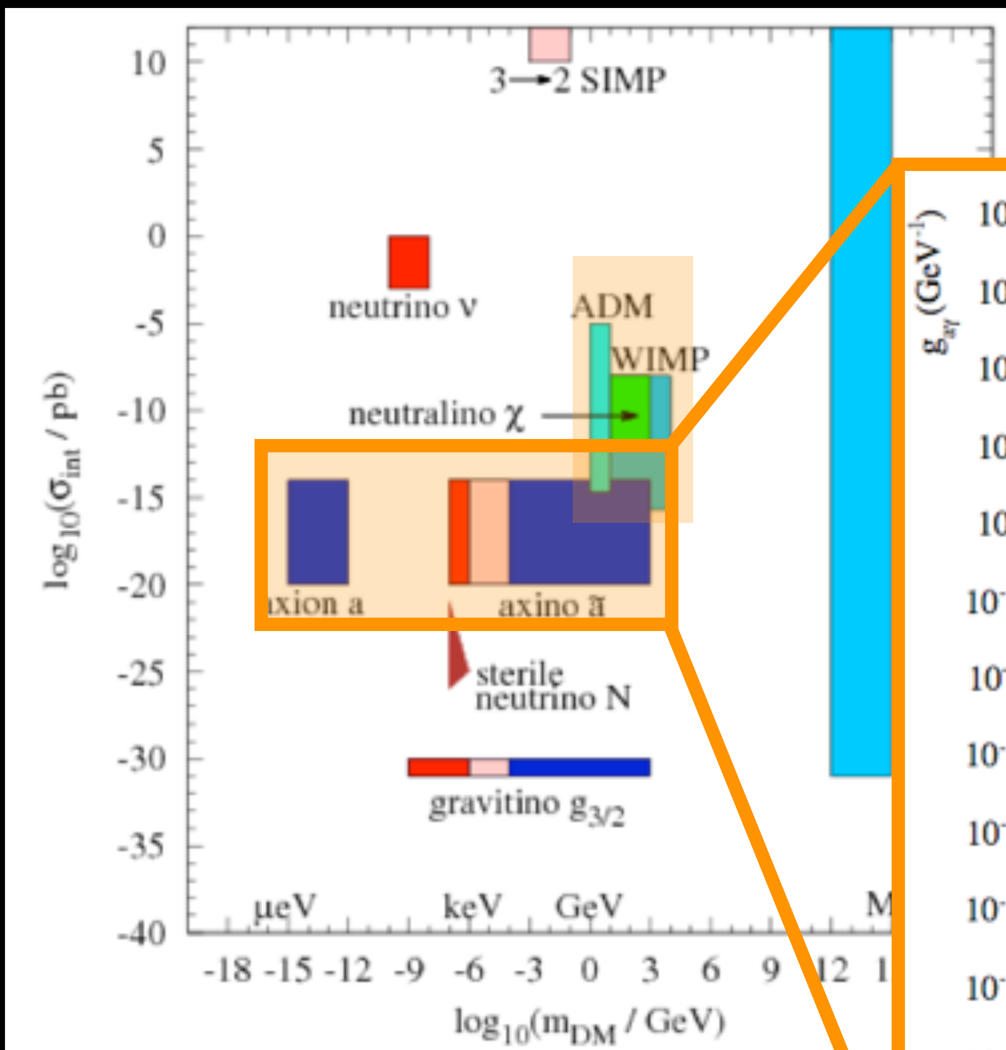
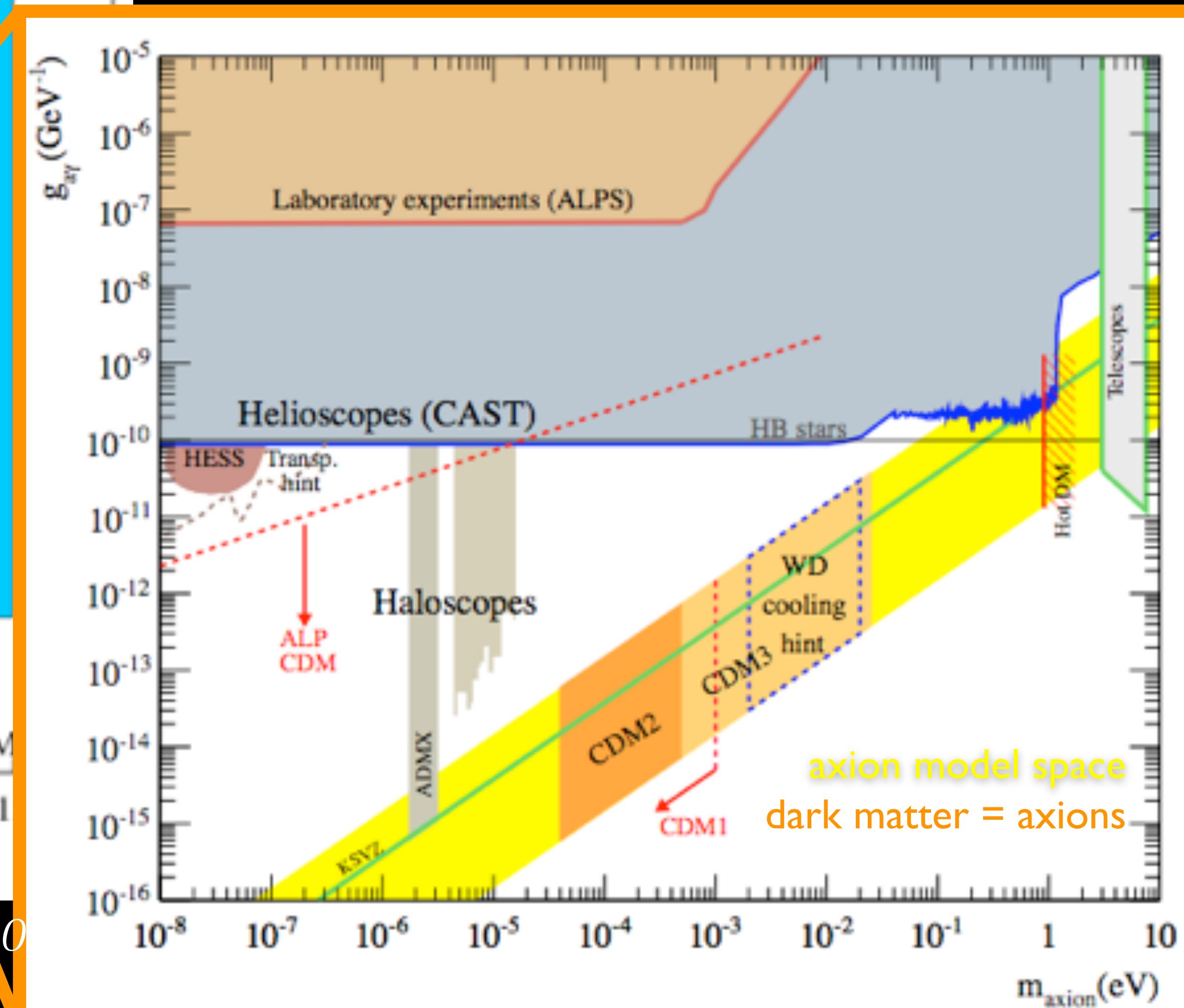
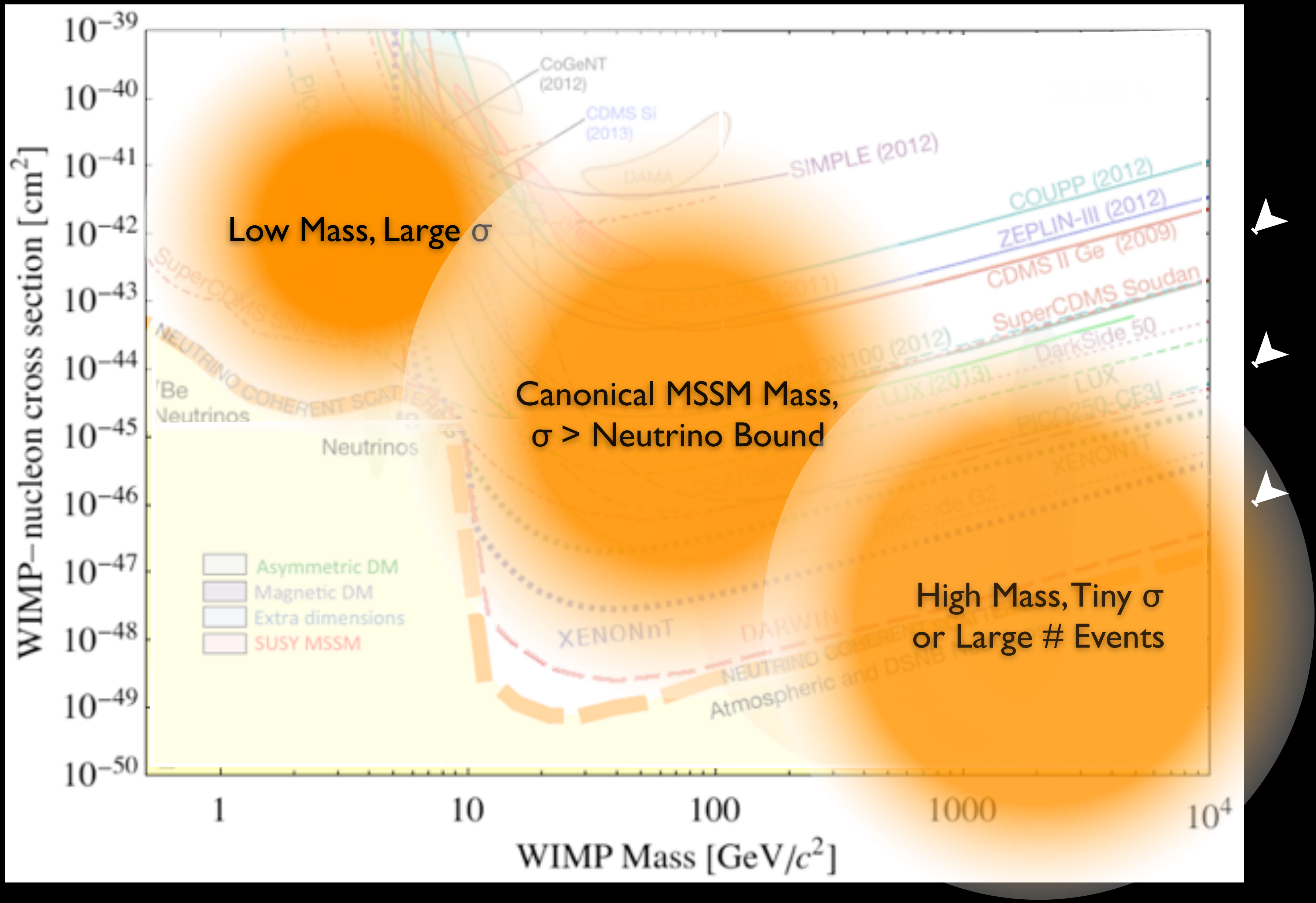



but starting to look for axions/ALPs too!




*Baer et al., arXiv:1407.00*

# The Low-Background Frontier: Prospects




1 event/ kg/day

1 event/ kg/year

1 event/ kg/century

so far: ~3 years / order of magnitude

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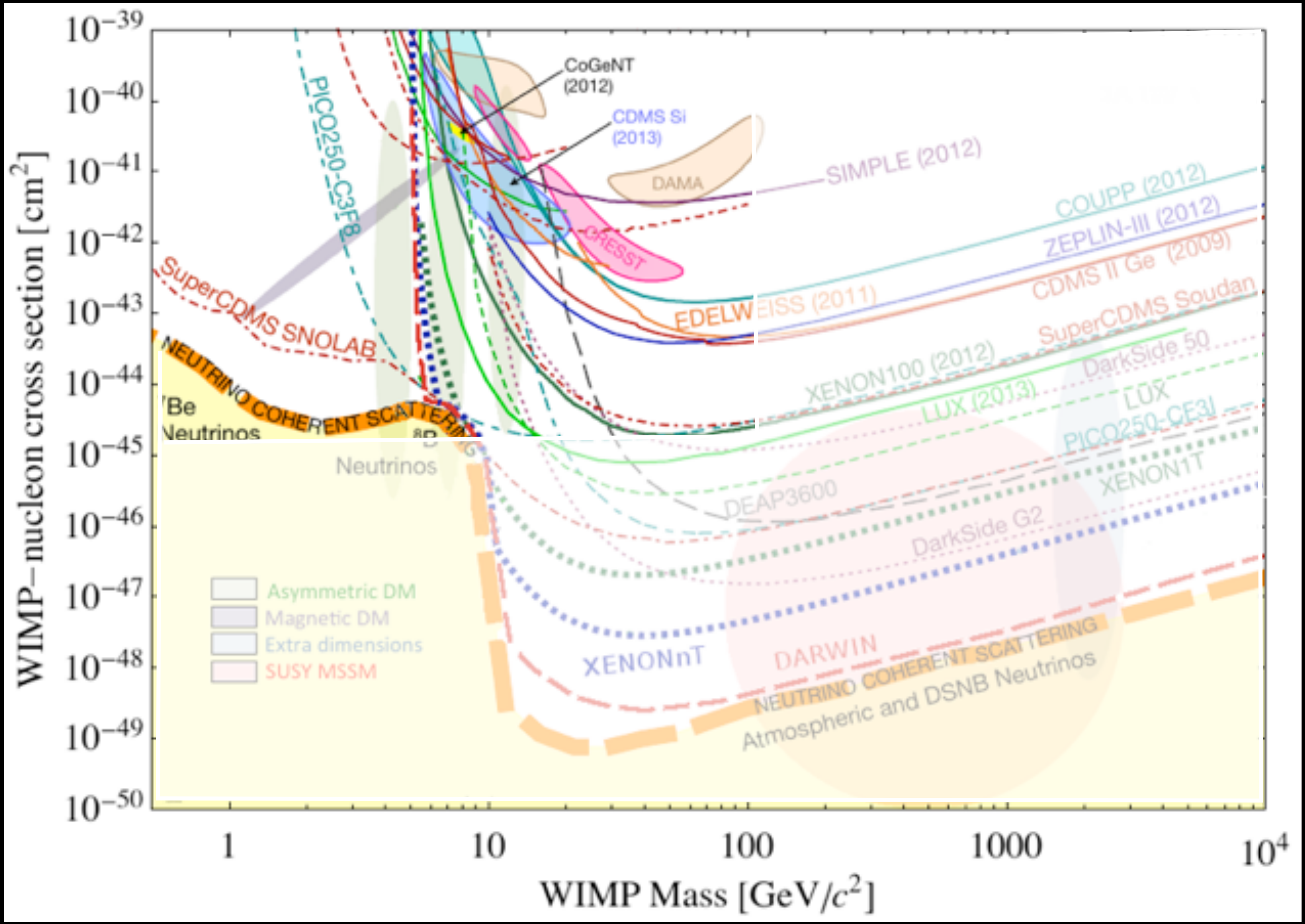


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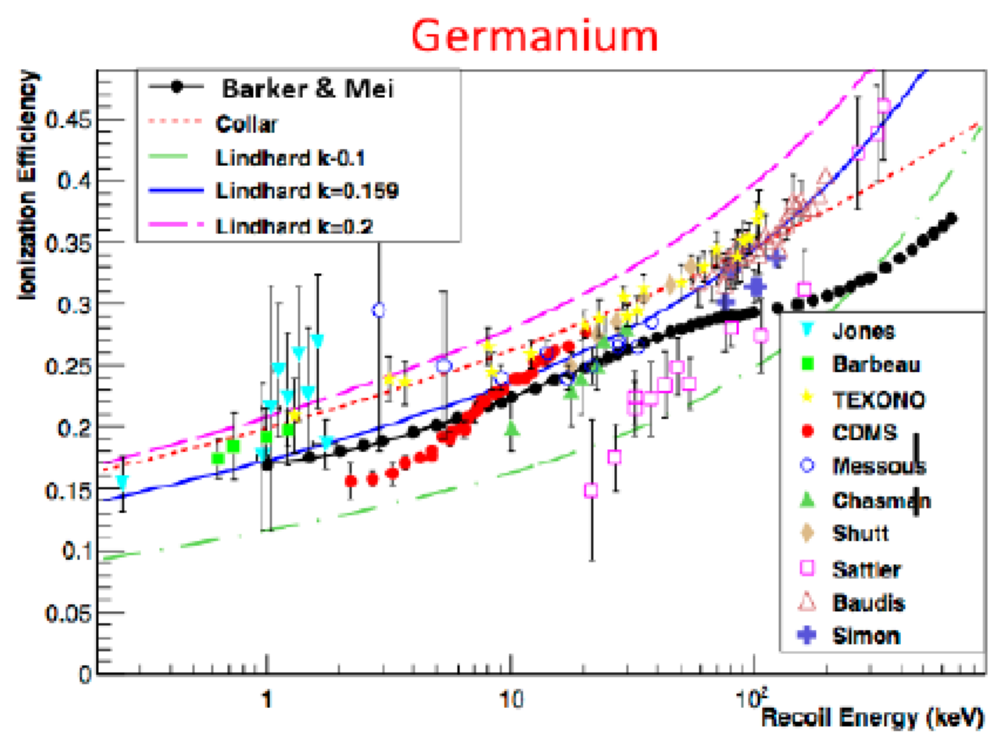
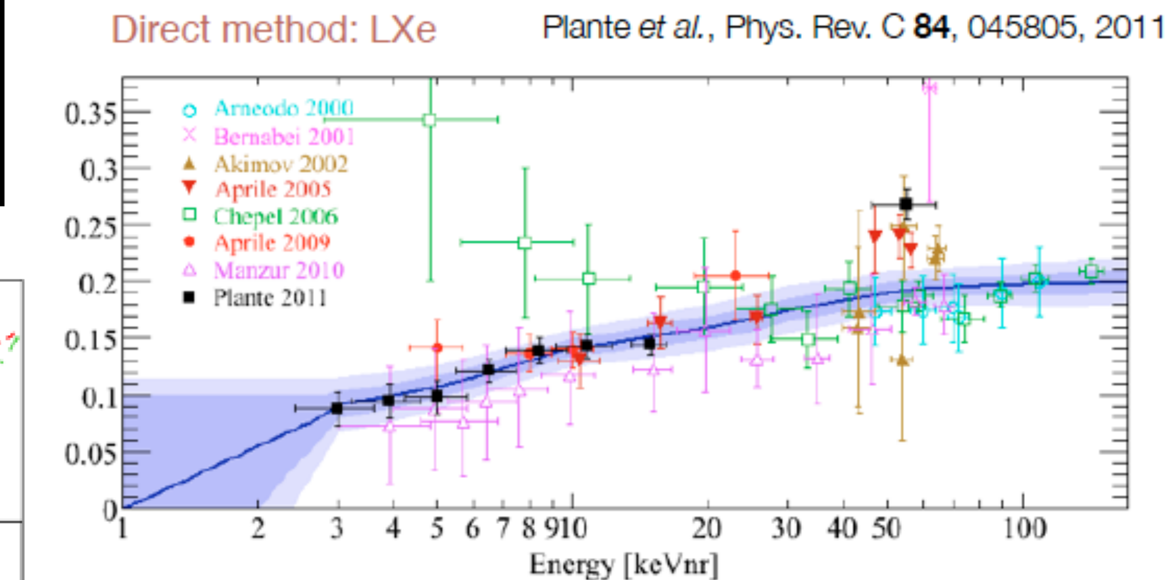
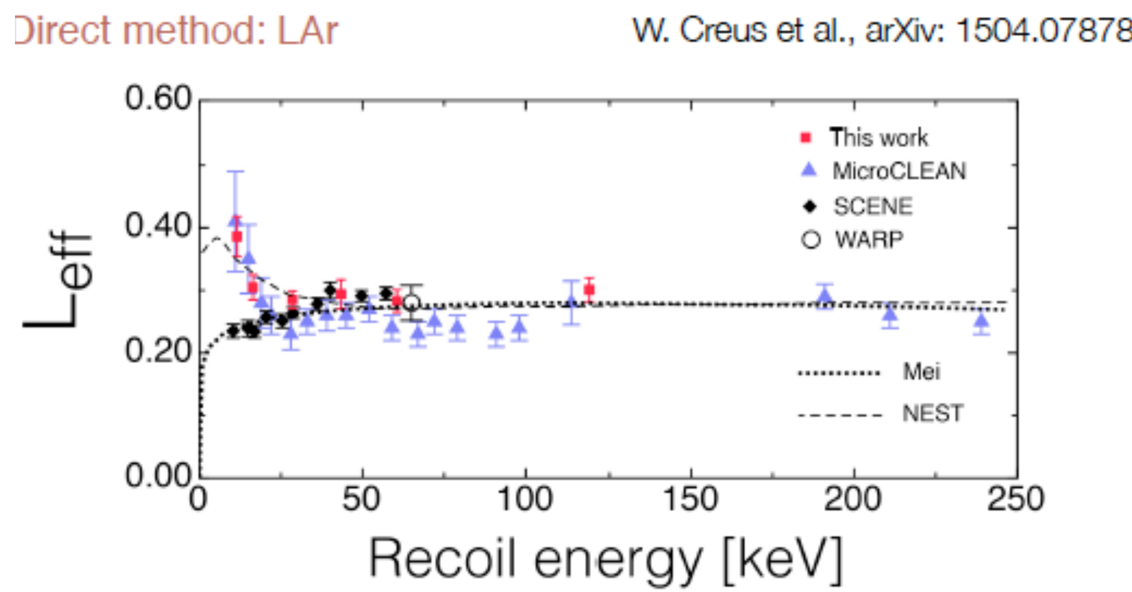
# Key Experimental Consideration: Quenching

*(material courtesy L. Baudis)*

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*

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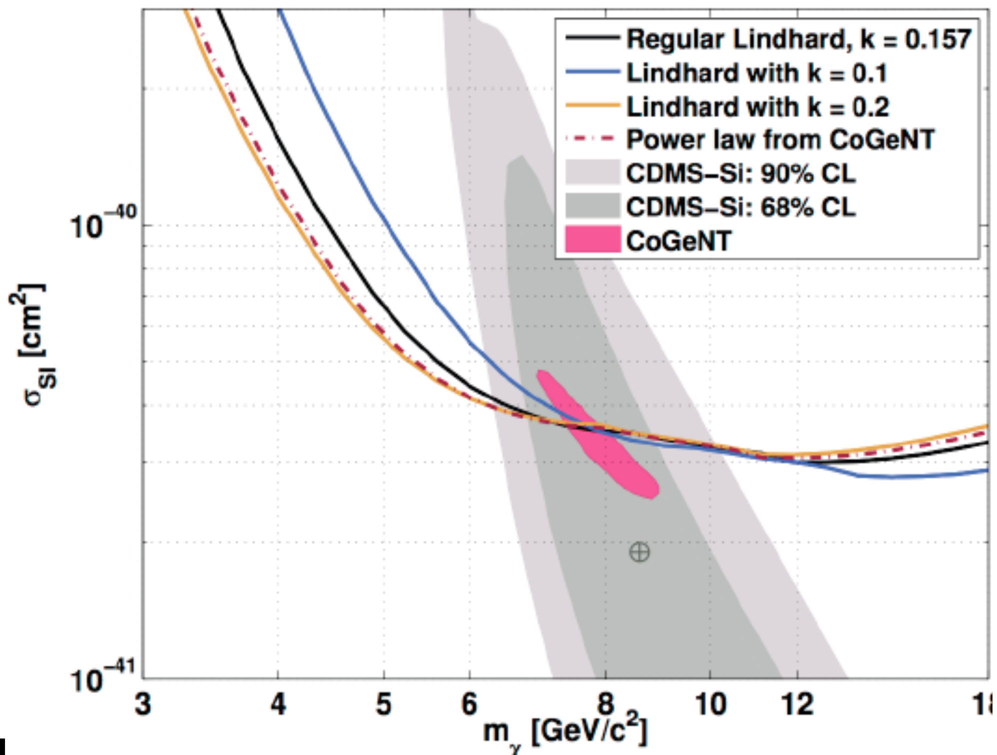
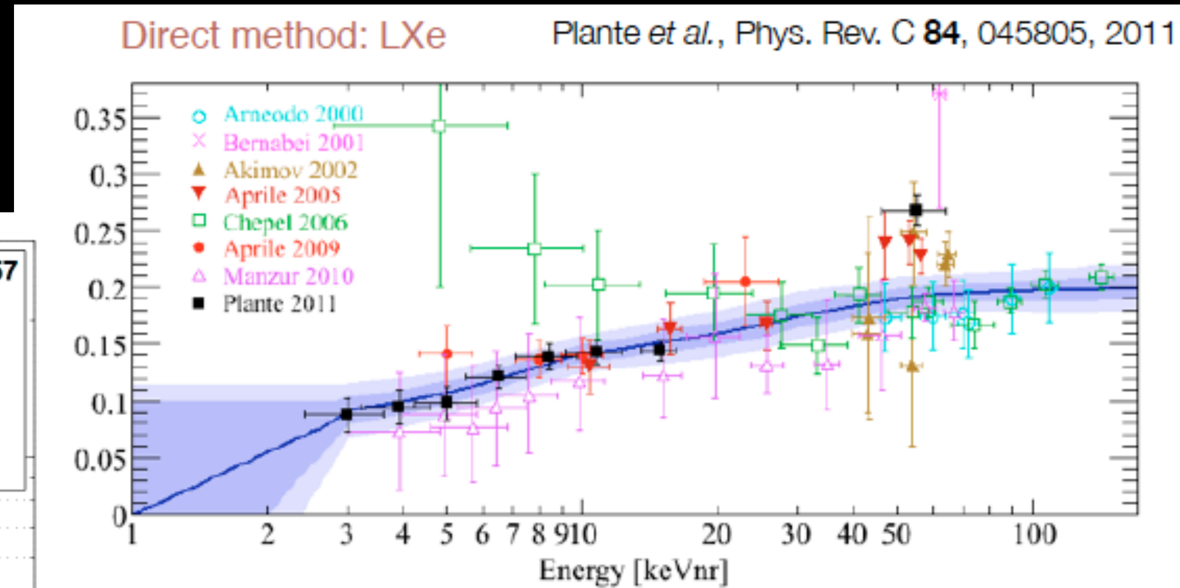
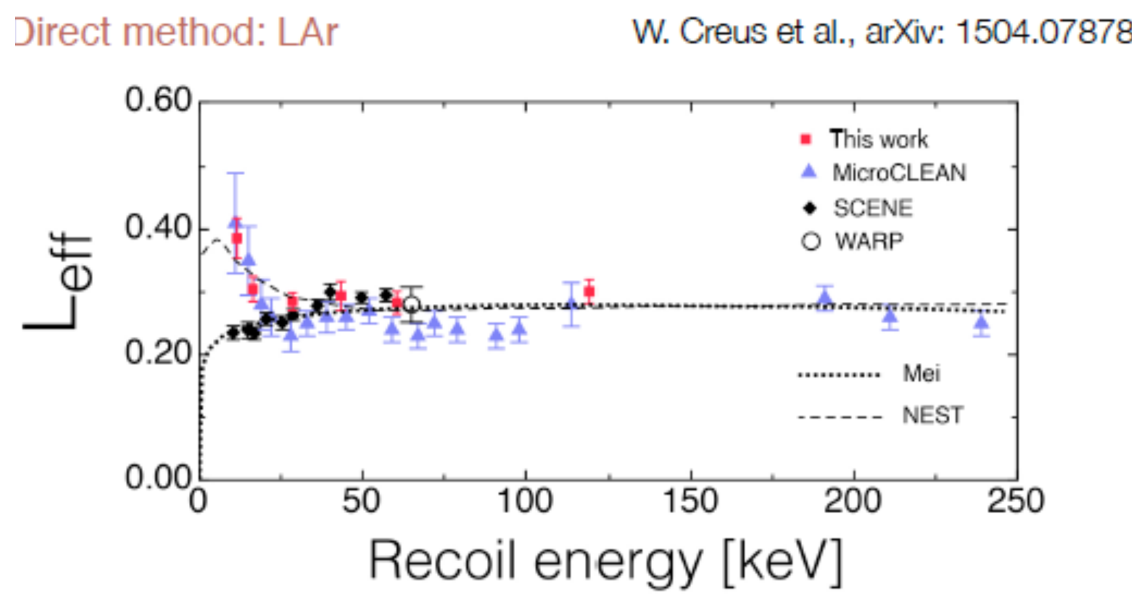



Impact of uncertainties up to x5-10 in dark matter limits, particularly at low mass!

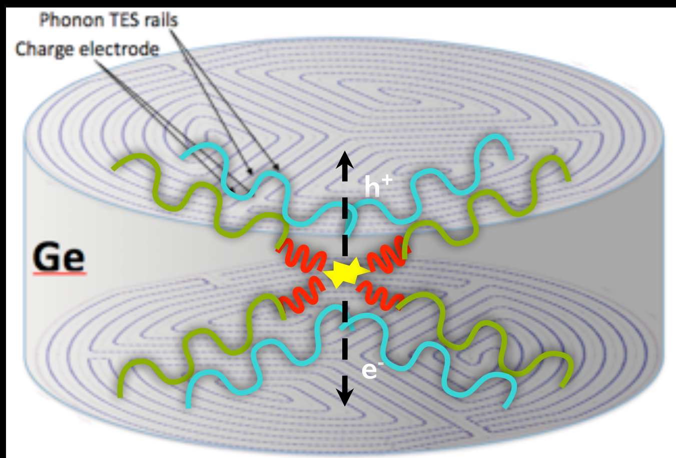
*measurement in the experiment energy region of interest required*

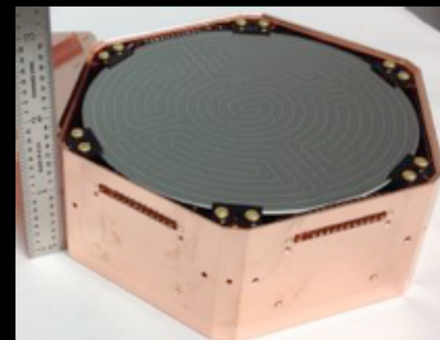
Low Mass, Large σ

# Bolometers

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

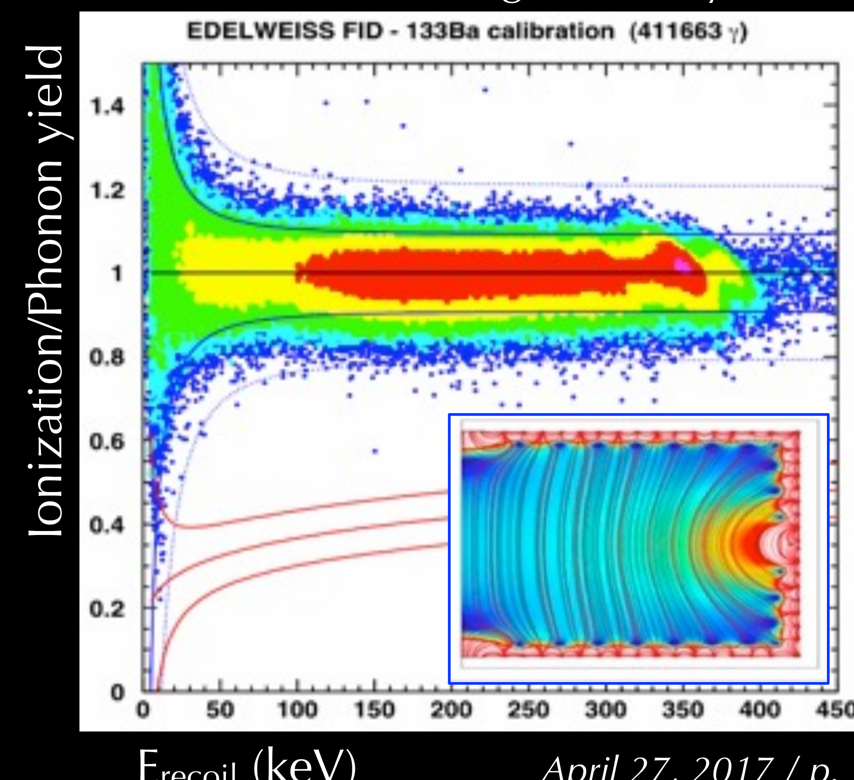
**Phonon rails**: 1400 gm (SuperCDMS) or 800 gm (EDELWEISS) Ge, TES for $E_{recoil}$ & R (timing)

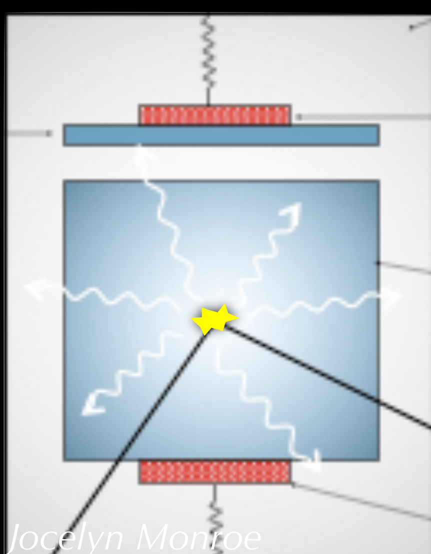


**Charge electrodes**: biased at +/- 2V, measure $E_{recoil}$, configuration optimised to reject surface events

EDELWEISS: interleaved electrodes reduce surface backgrounds by x$10^5$



**Scintillation side:**
Si absorber on 300 gm $CaWO_4$, tungsten TES
readout for particle ID

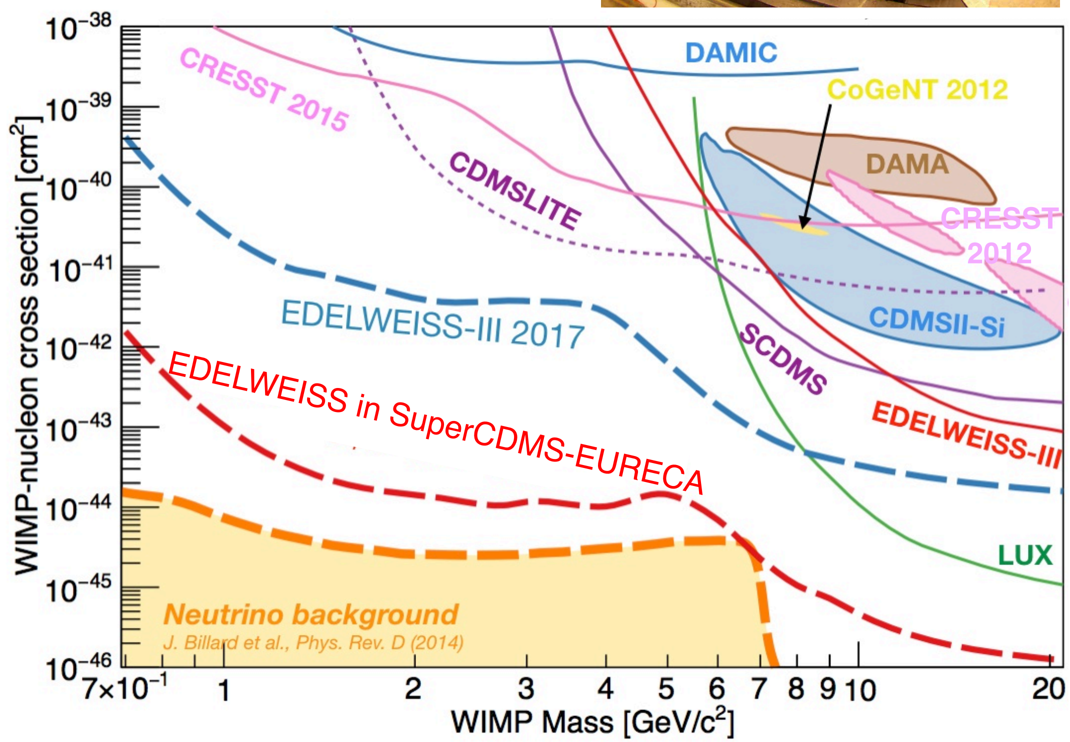
**Phonon side:**
TES readout to measure $E_{recoil}$l

# EDELWEISS

- Largest operating cryogenic Ge array (20 kg) for Direct DM search
- Latest results: arXiv:1603.05120

- 2017 goal @ LSM: optimizing sensitivity to 1-10 GeV WIMPs

- Beyond: completing the exploration of the low-WIMP mass region with a ~100 kg array of EDELWEISS detectors would require the environment projected for EURECA/ SuperCDMS



Low Mass, Large σ

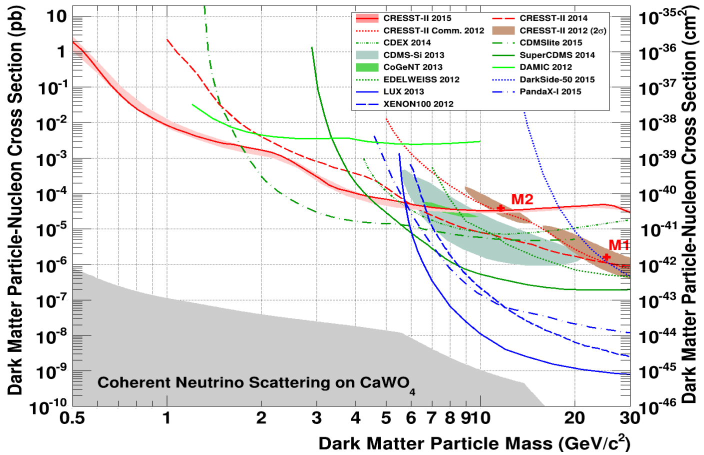
# CRESST

(thanks to F. Petricca)

## CRESST- II

300g scintillating $CaWO_4$ crystals
Measured nuclear recoil threshold ~300eV

- Leading sensitivity in low mass region
- Explore masses in the sub-GeV/$c^2$ range

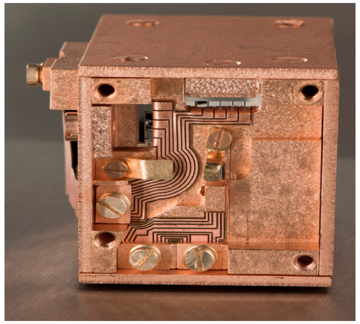


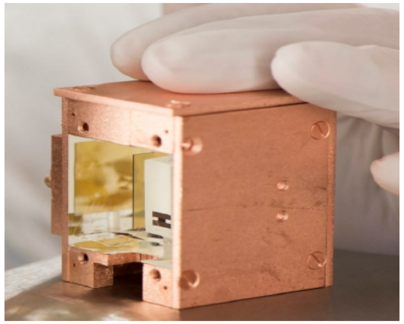

## CRESST – III arXiv:1503.08065

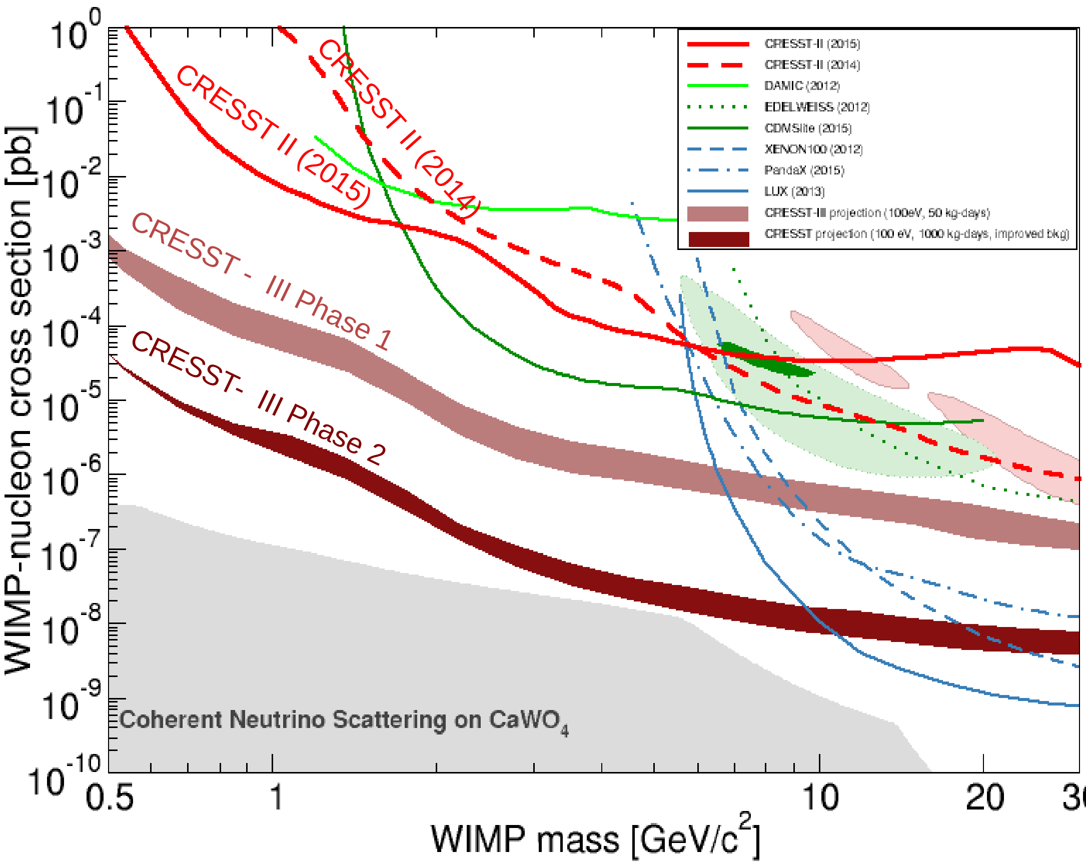
25g $CaWO_4$ crystals
Optimized for nuclear recoil threshold <100eV

### Phase 1

- Mounting of 10 modules completed
- Cool down in 2016
- 1 year of running ~50 kg days (2017)








### Phase 2

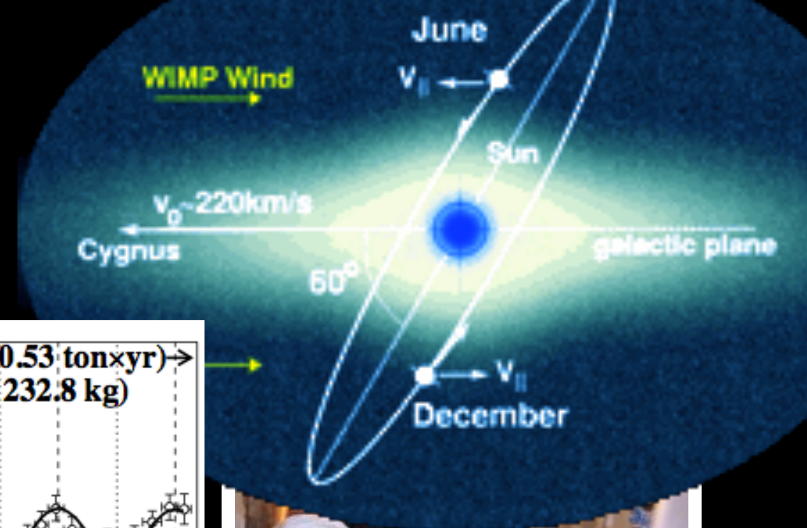
- 100 modules with improved background to approach the neutrino floor in the LNGS setup

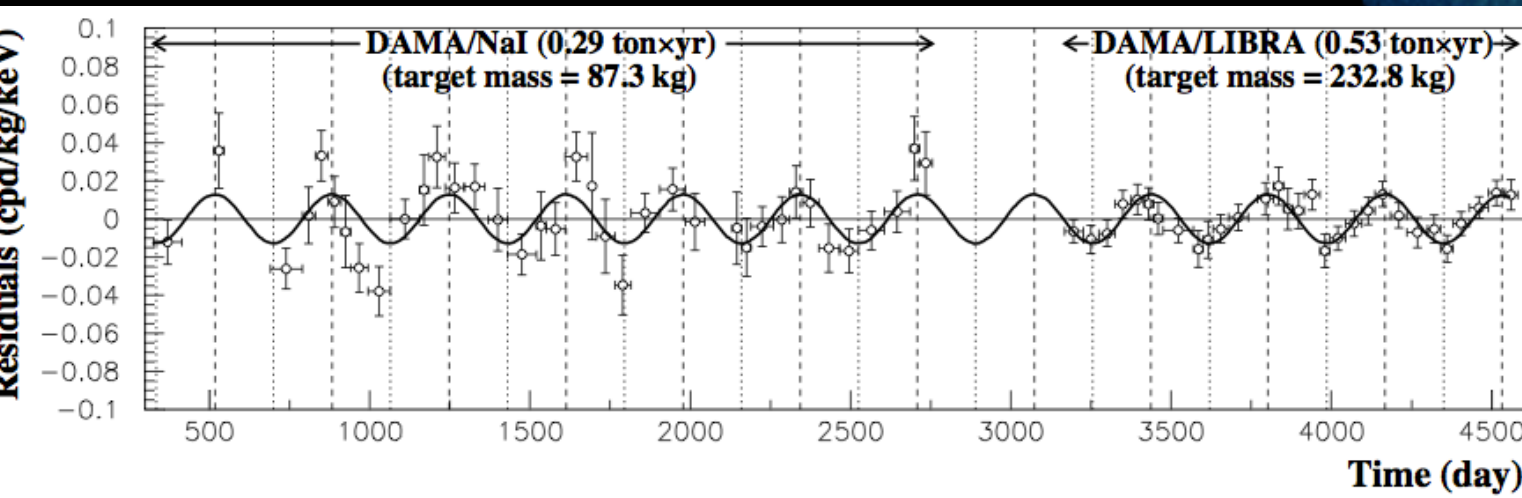
Low Mass, Large σ

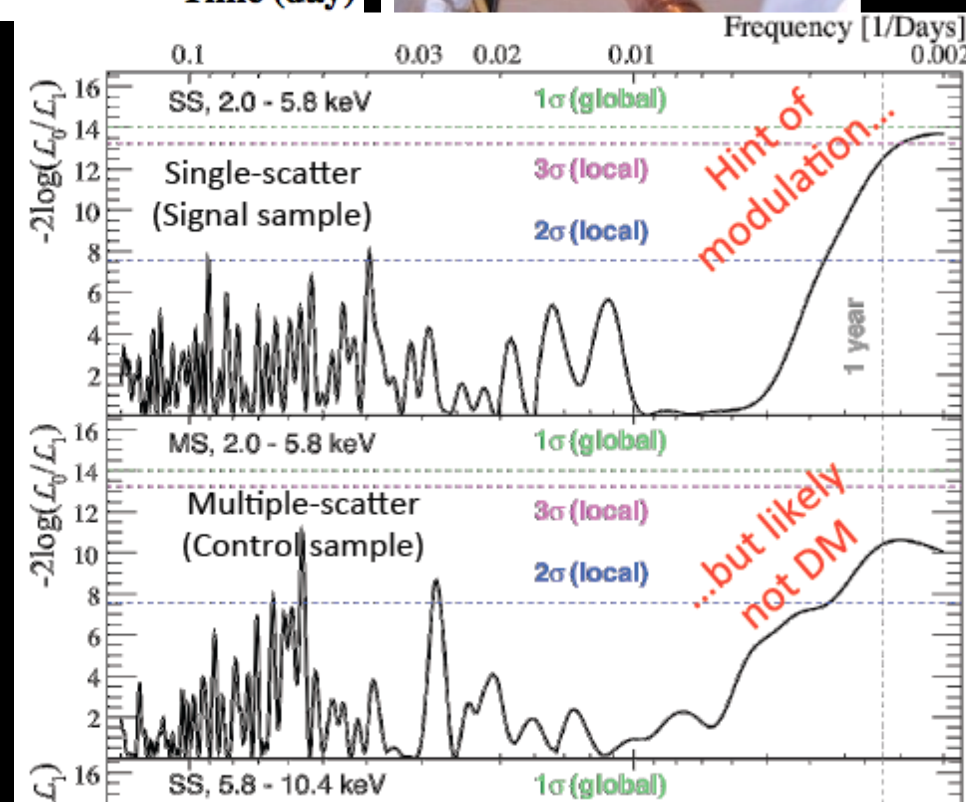
# Annual Modulation Tests

predicted modulation A~0.02-0.1, $t_0$=152.5 days

$t_0$ =




**DAMA/LIBRA:** measure (0.0112±0.0012) cpd/kg/keV, $t_0$ = (144±7) d in 1.33 T-yr.

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*arXiv:1507.07748*

**XMASS:** Xe, 833 kg in Kamioka, model-independent analysis modulation result reported
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Low Mass, Large σ

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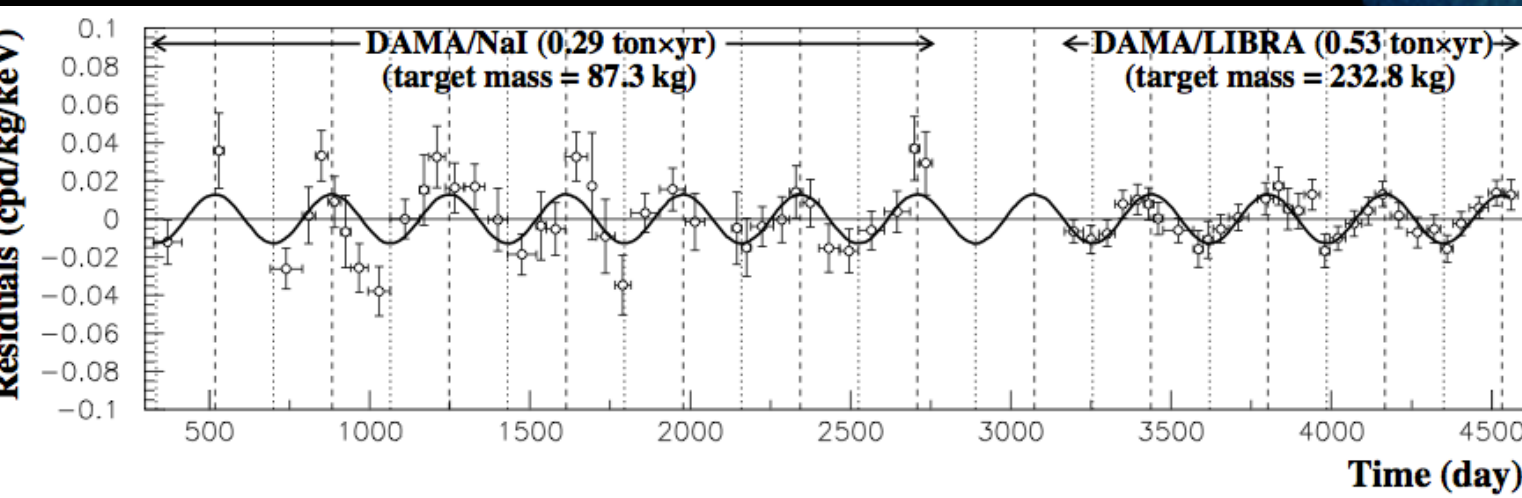


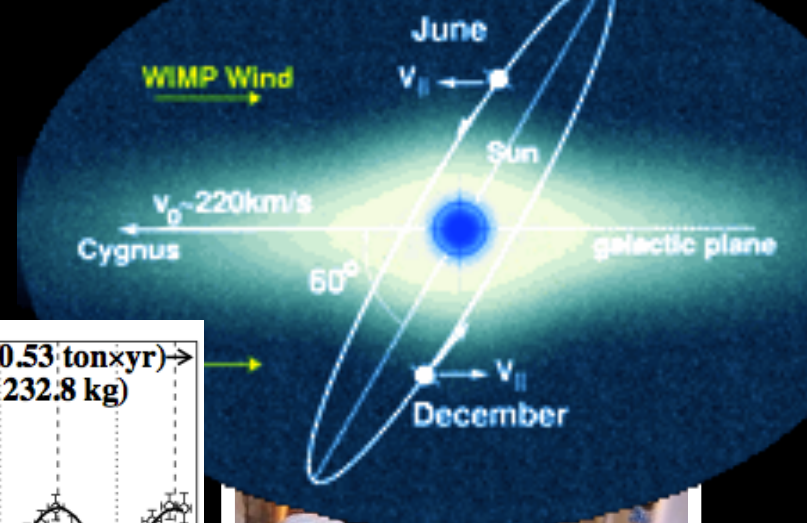


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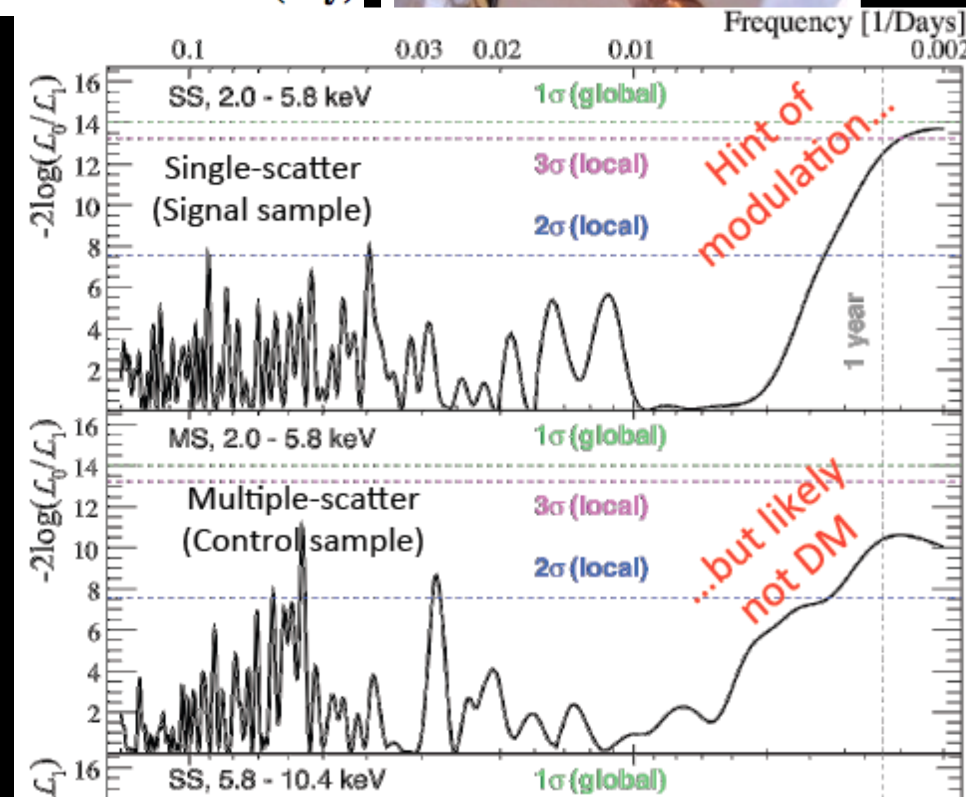


*Jocelyn Monroe*

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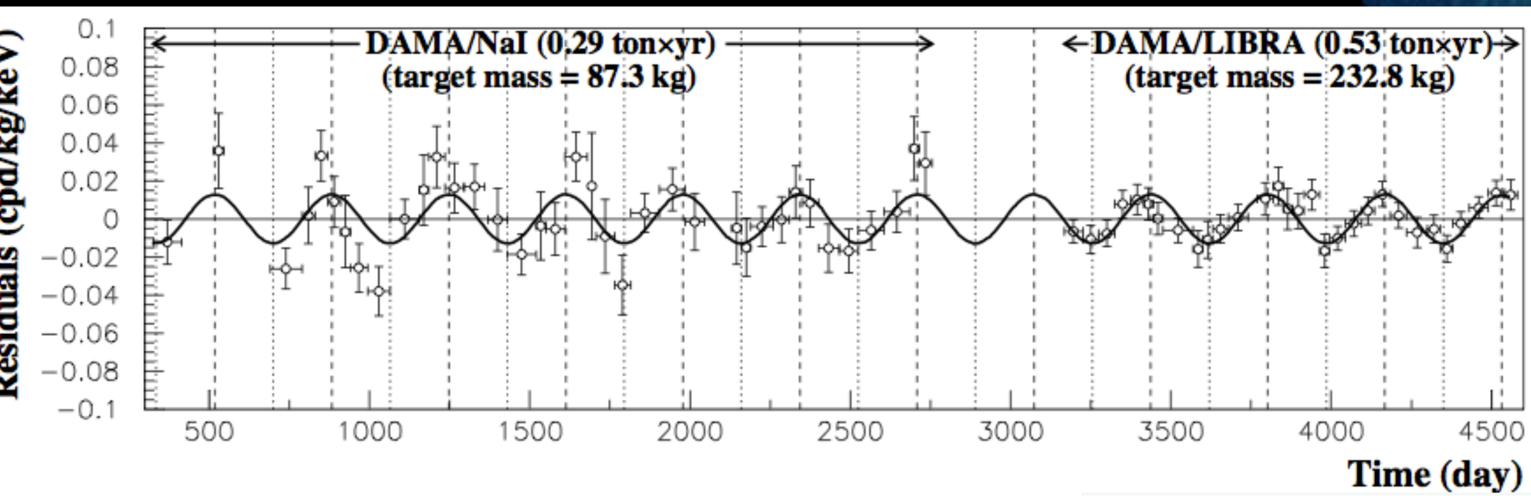


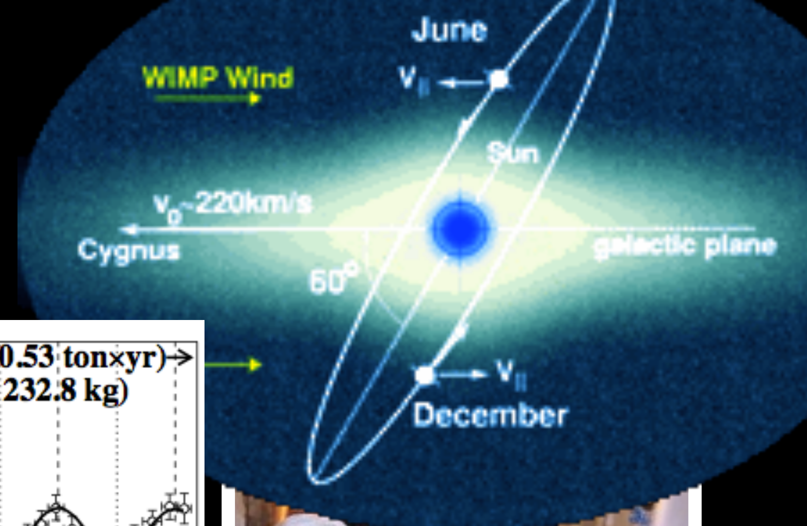


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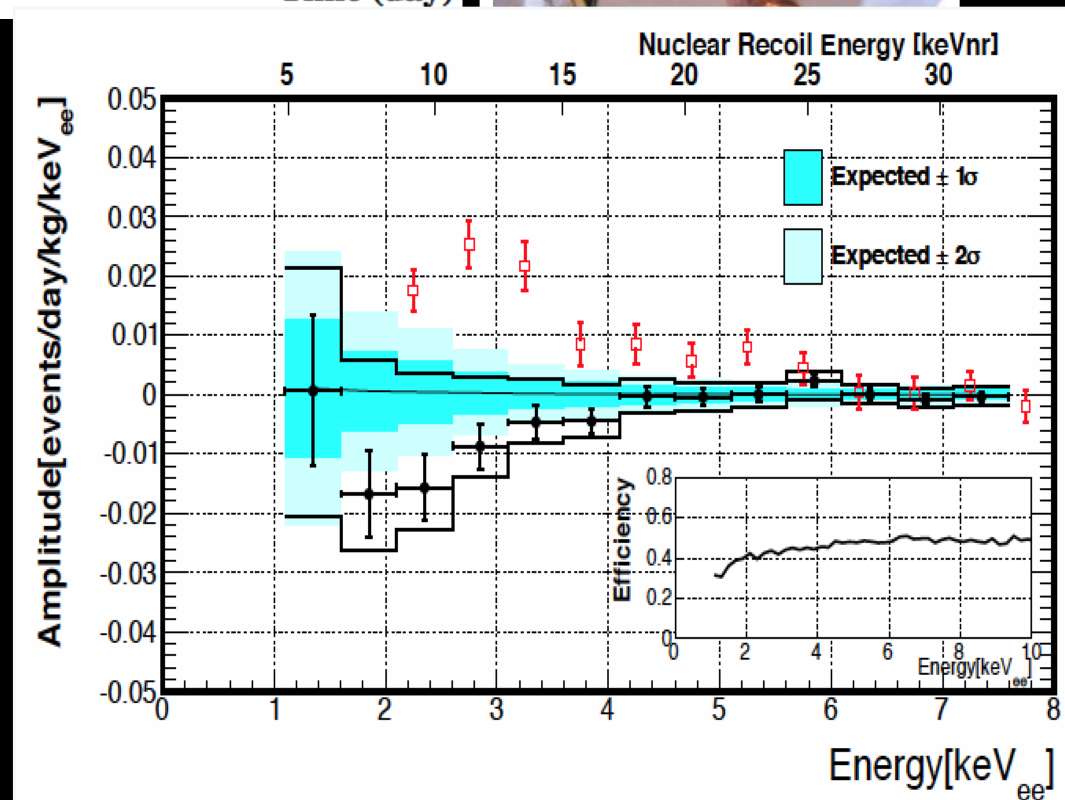


Low Mass, Large σ

# Annual Modulation Prospects

*(thanks to J. Villar)*

+**ANAIS** (Canfranc), **DM-Ice+KIMS** = **COSINE** (YangYang), **SABRE** (AU)

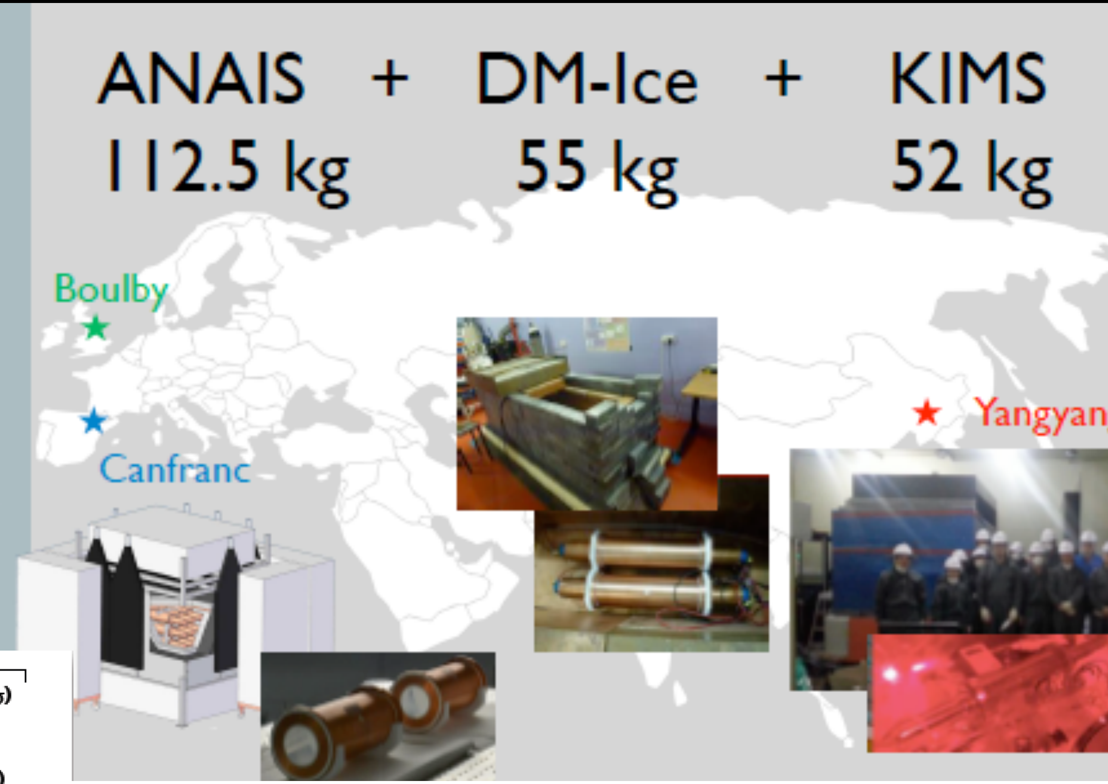
INTERNATIONAL NaI(Tl) COLLABORATIVE EFFORT

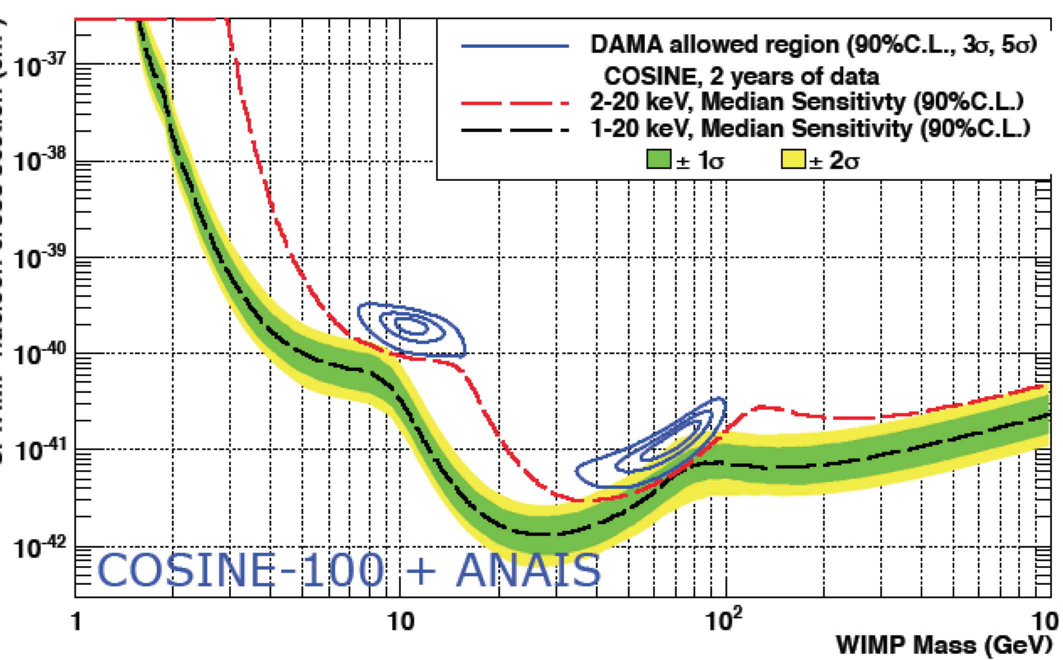
**COMBINED ANALYSIS of 220 kg NaI(Tl) with present background levels**

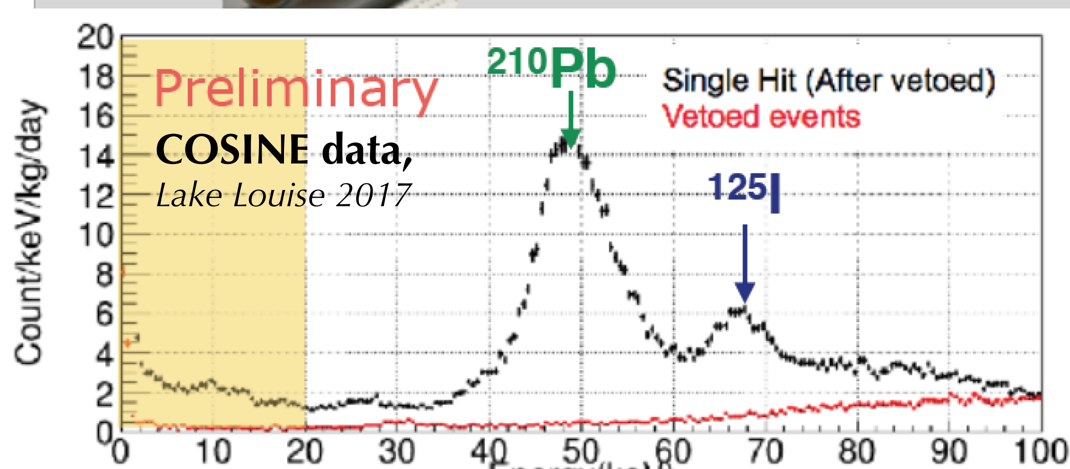
112.5 kg at Canfranc, Spain

+

107 kg at Yangyang, South Corea



Low Mass, Large σ

# Low-Mass Region Prospects

Goal: reach the neutrino bound!

**EDELWEISS-III:** new FIDs with <0.3 keV FWHM for low mass search, with lower-background clamps.

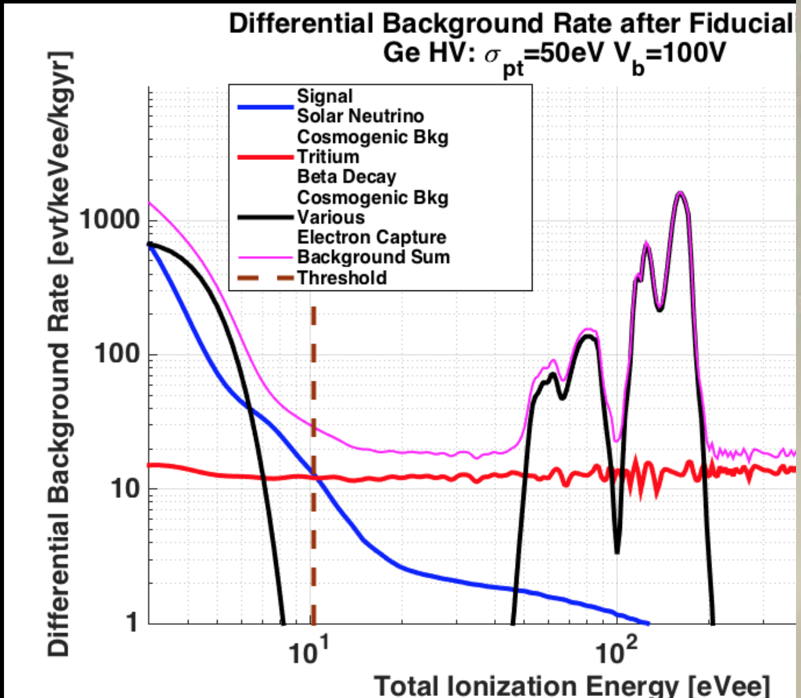
**CRESST:** R&D towards 0.1 keV threshold, with smaller crystals, lower background (3.5 ev/keV/kg/day).

**SuperCDMS:** 50 kg of 1.4 kg Ge (and Si) detectors, construction at SNOLAB 2018. Can operate in HV mode, for 0.9 keV threshold. *PRL 112 (2014) 041302)*

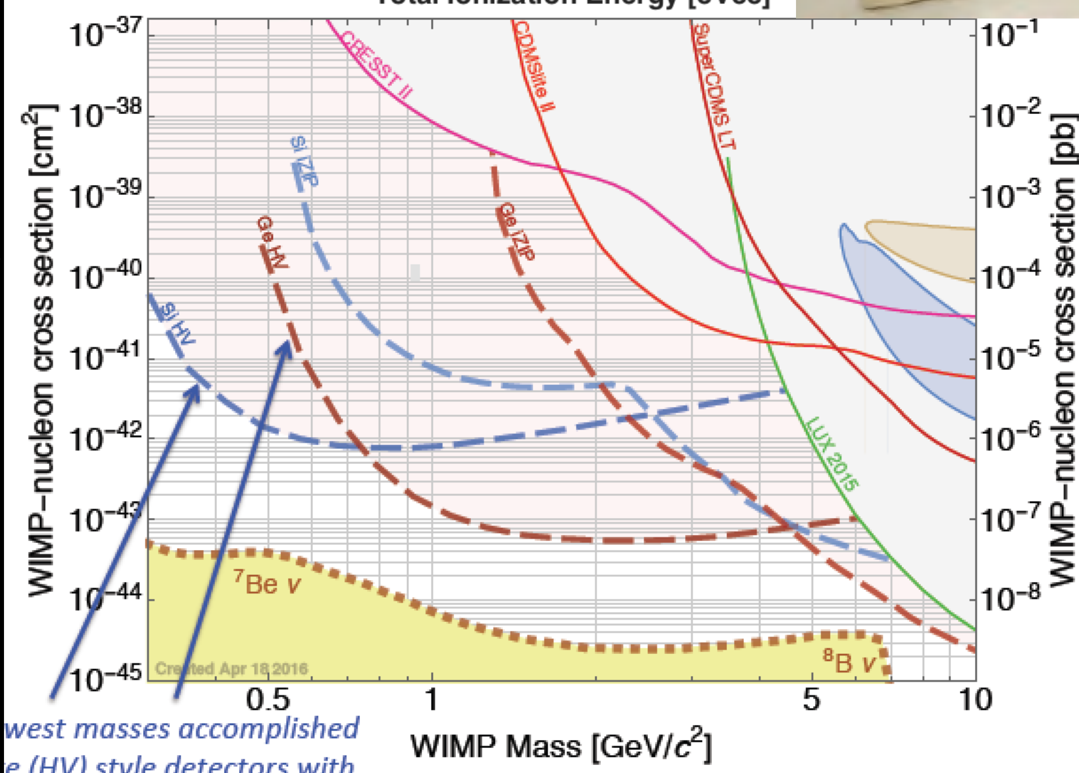
**EURECA:** collaboration of all of the above, to reach neutrino floor. SuperCDMS cryostat sized for ~400 kg.

**DAMIC:** search for WIMP interactions in CCD Si, 36 gm now operating at SNOLAB, with 5 ev/keV/kg/day. Aim for 1E-5 pb sensitivity, with 1 keV threshold. *arXiv:1506.02562*

**NEWS:** spherical, high pressure gas detector with 0.1 keV threshold, under construction at SNOLAB, aim for 1E-5 pb sensitivity with Ar, Ne targets.








*Jocelyn Monroe*

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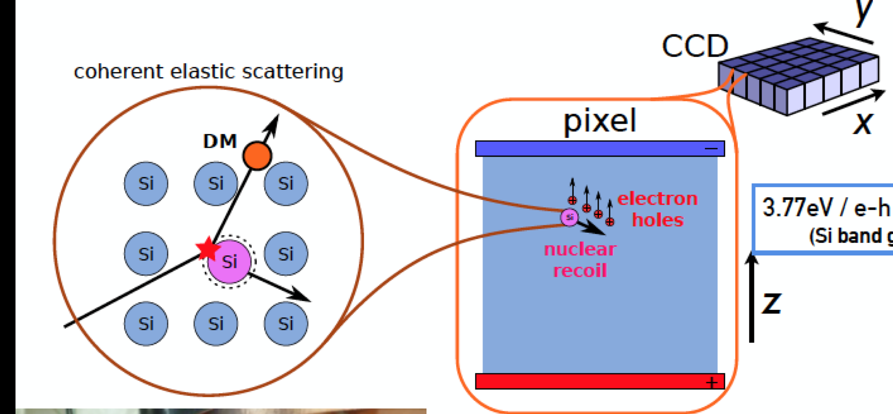
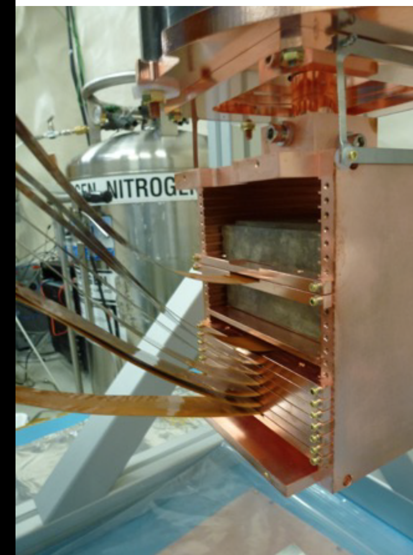
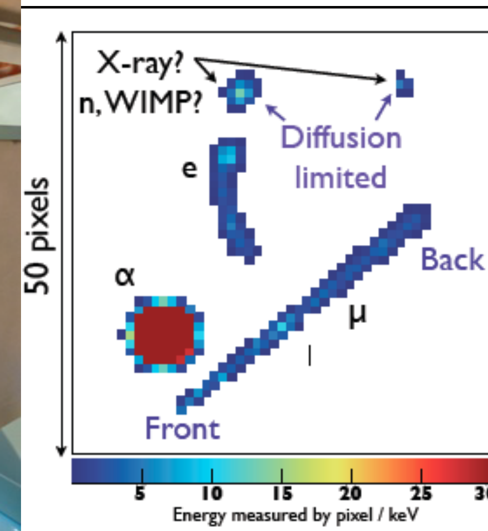
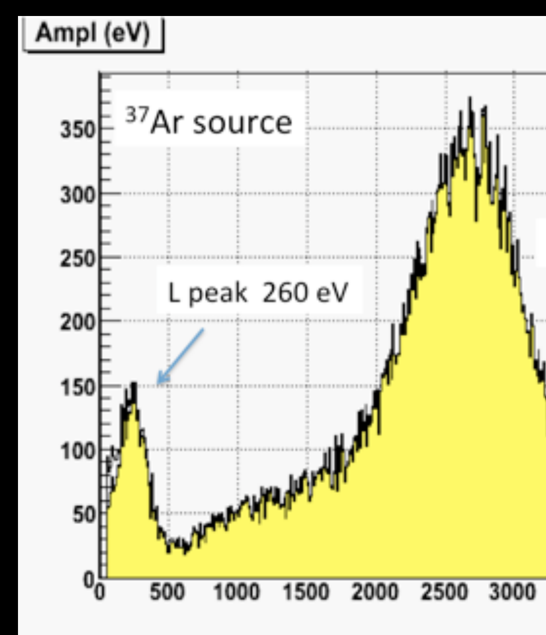
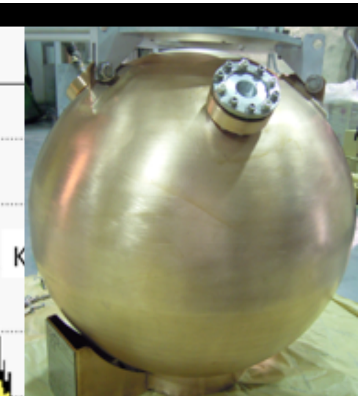


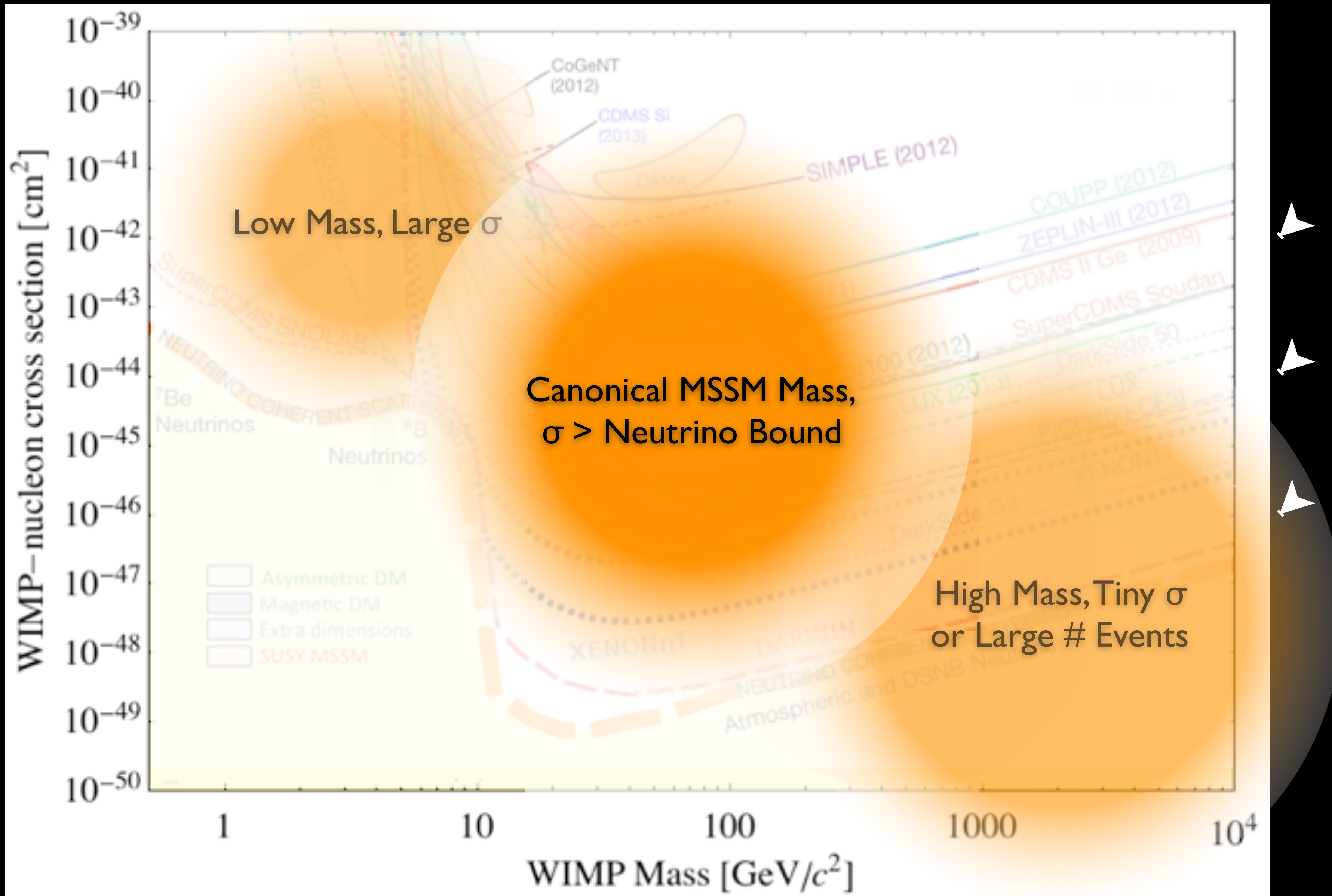



# The Low-Background Frontier: Prospects




1 event/ kg/day

1 event/ kg/year

1 event/ kg/century

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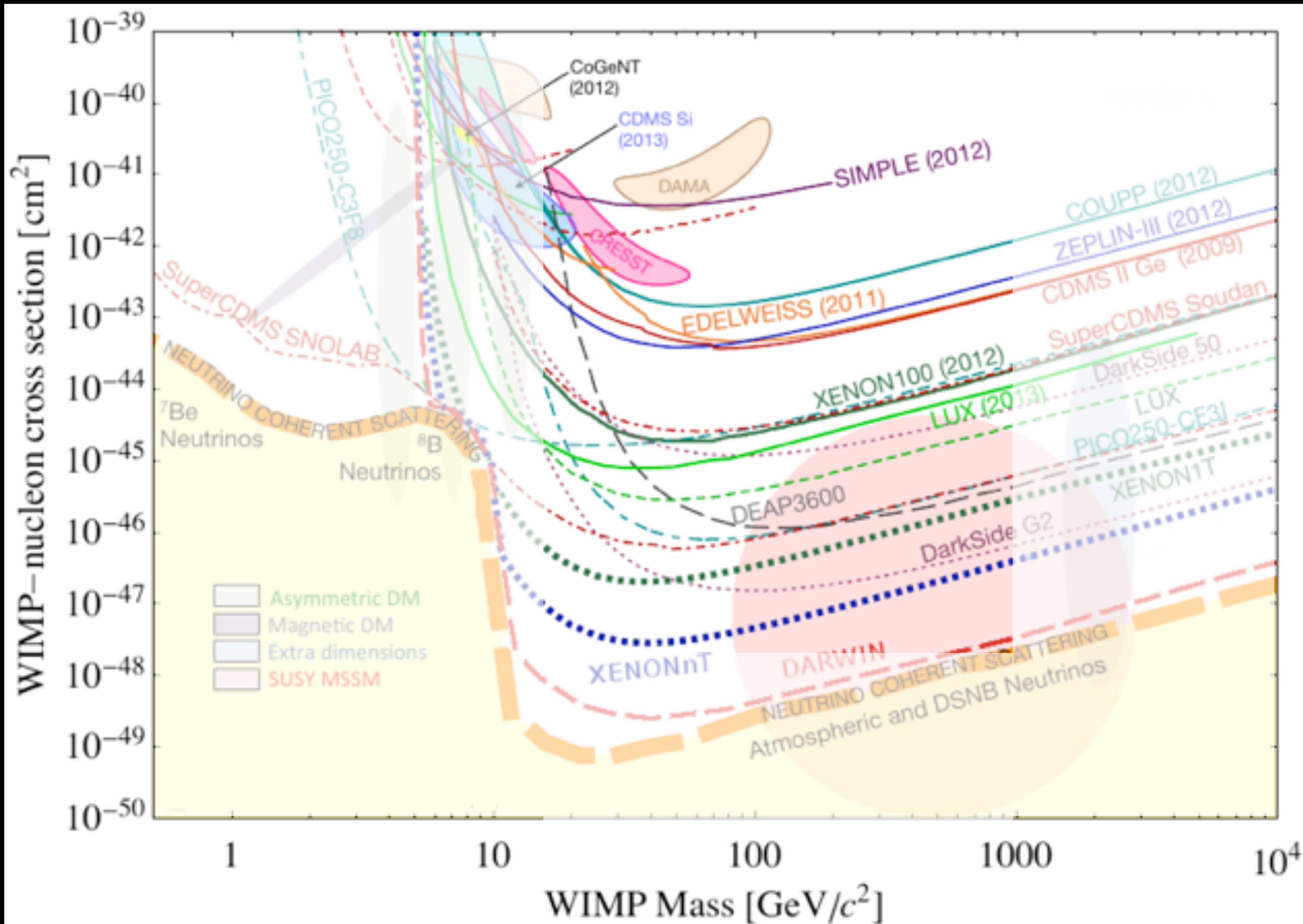


1 event/ kg/day

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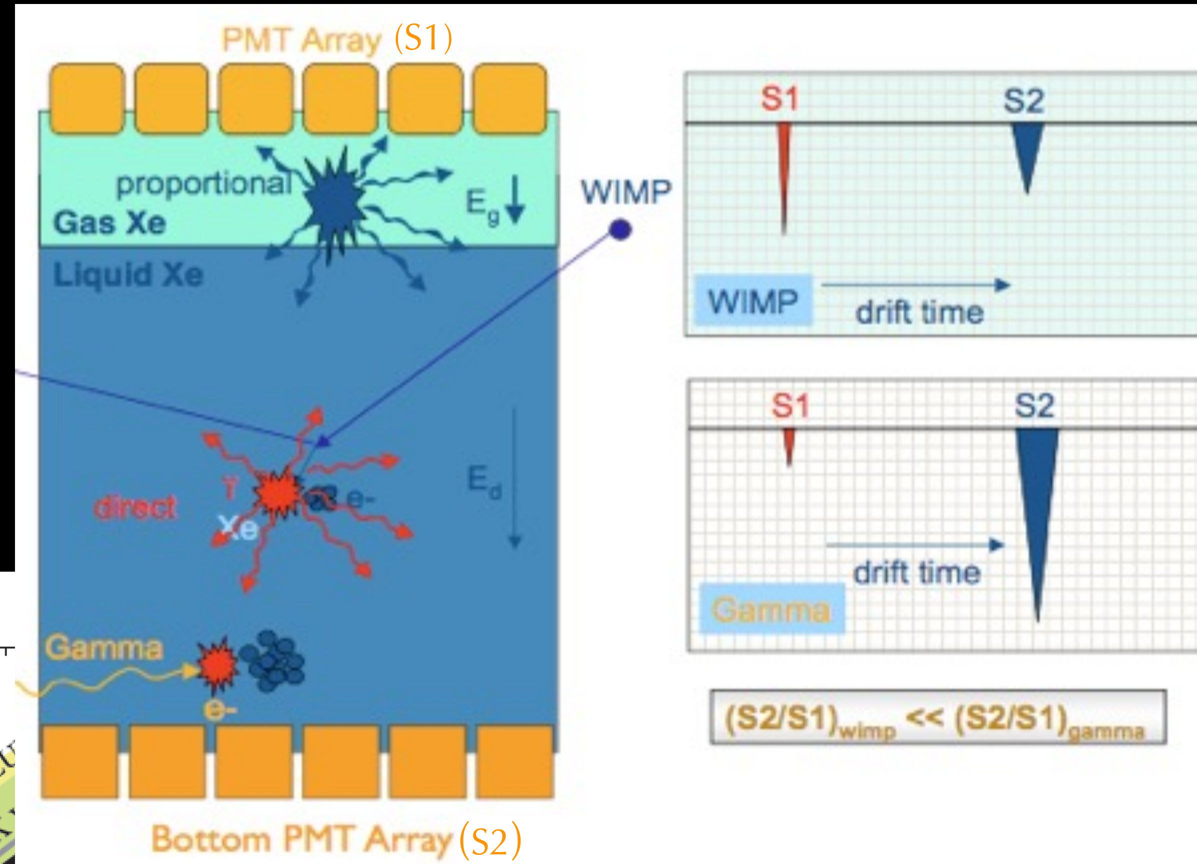
1 event/ kg/century

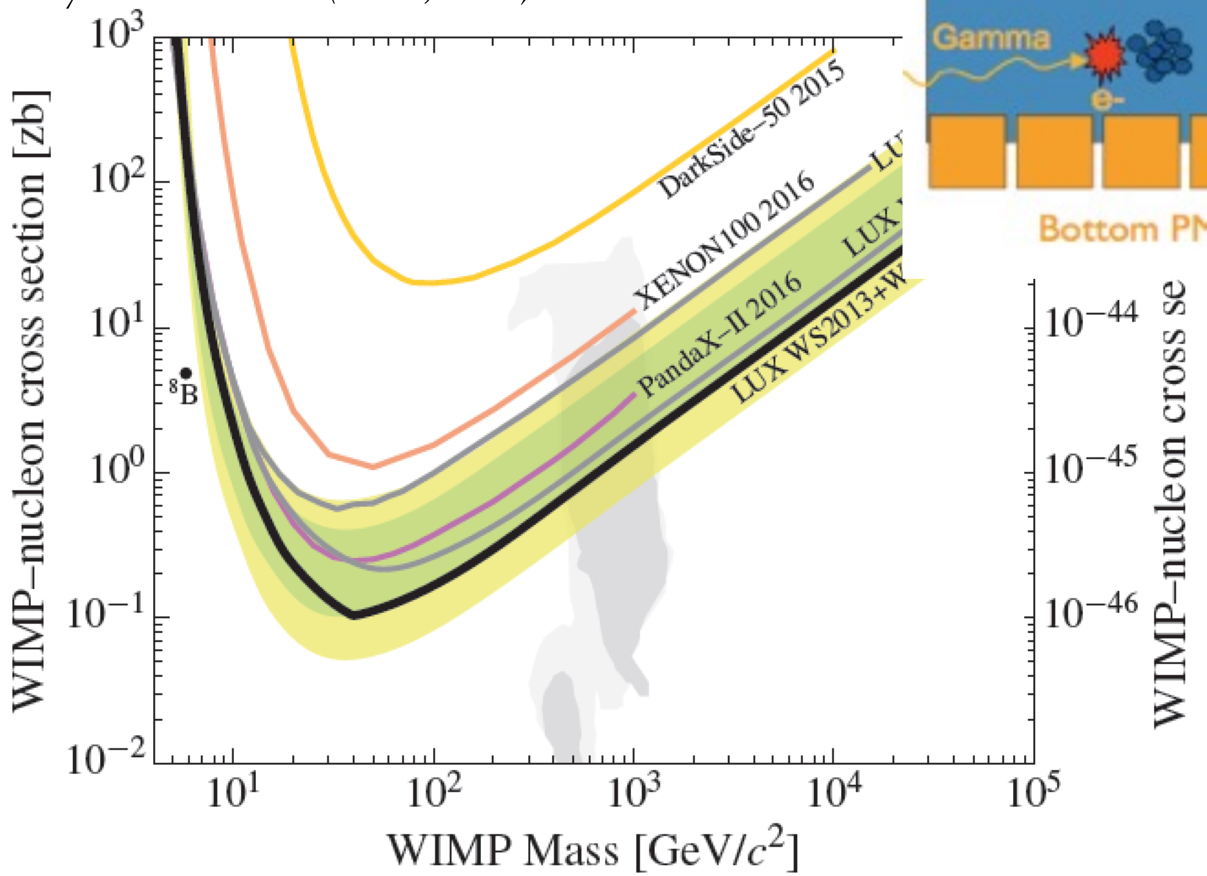
# 2-Phase Xe TPCs

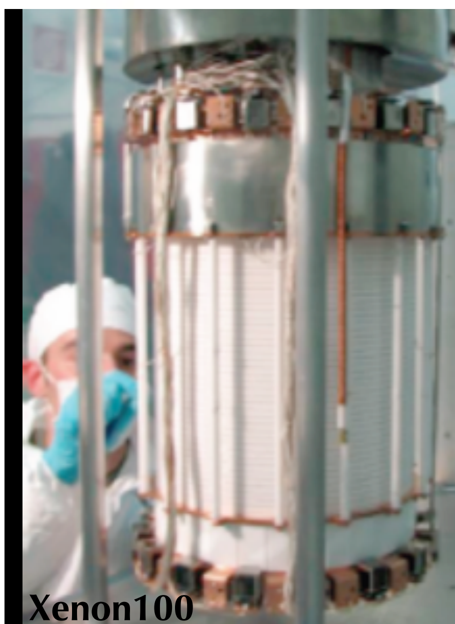
MSSM Mass,
σ > ν bound

target viewed by PMTs:
**“S1”:** amplified, drifted ionization signal
**“S2”:** primary scintillation




*Phys.Rev.Lett. 118 (2017) no.2, 021303*




**XENON-10** (kg)
**XENON-100** (kg)
**XENON-1T**
**LUX** (250 kg),
**PANDA-X** (120kg, 500 kg)

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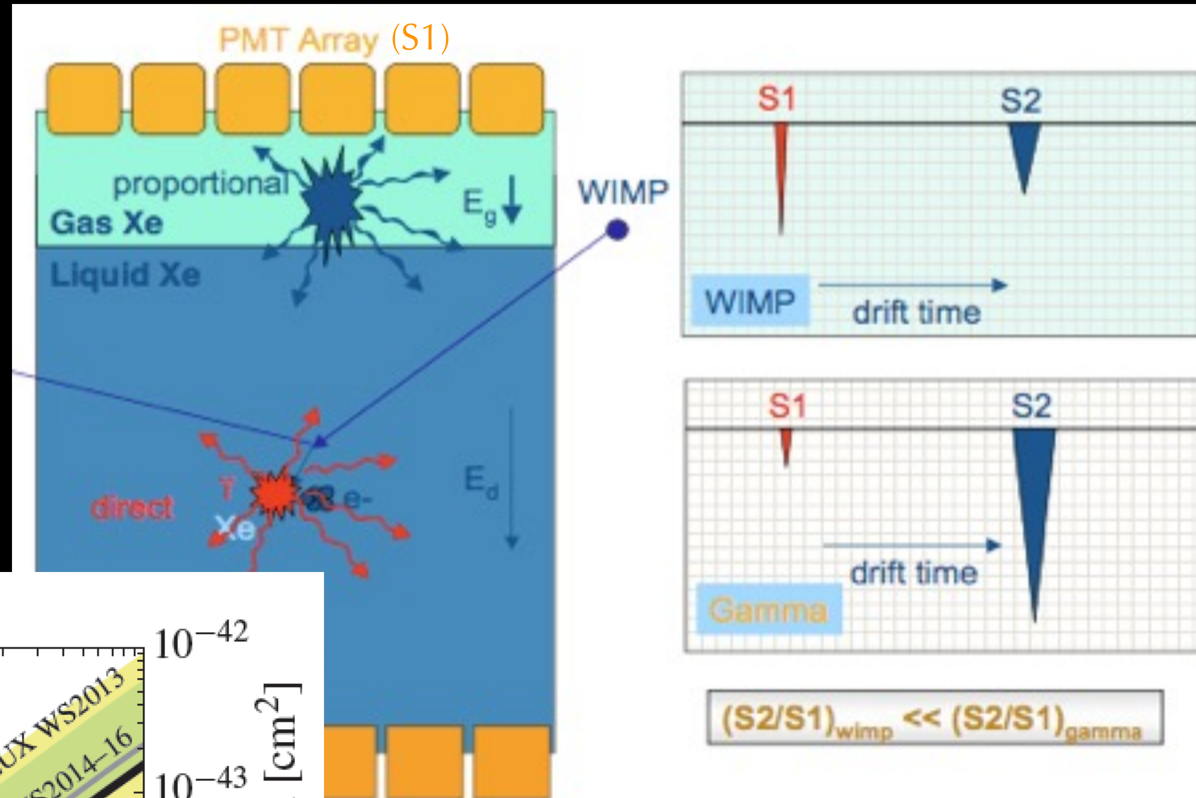
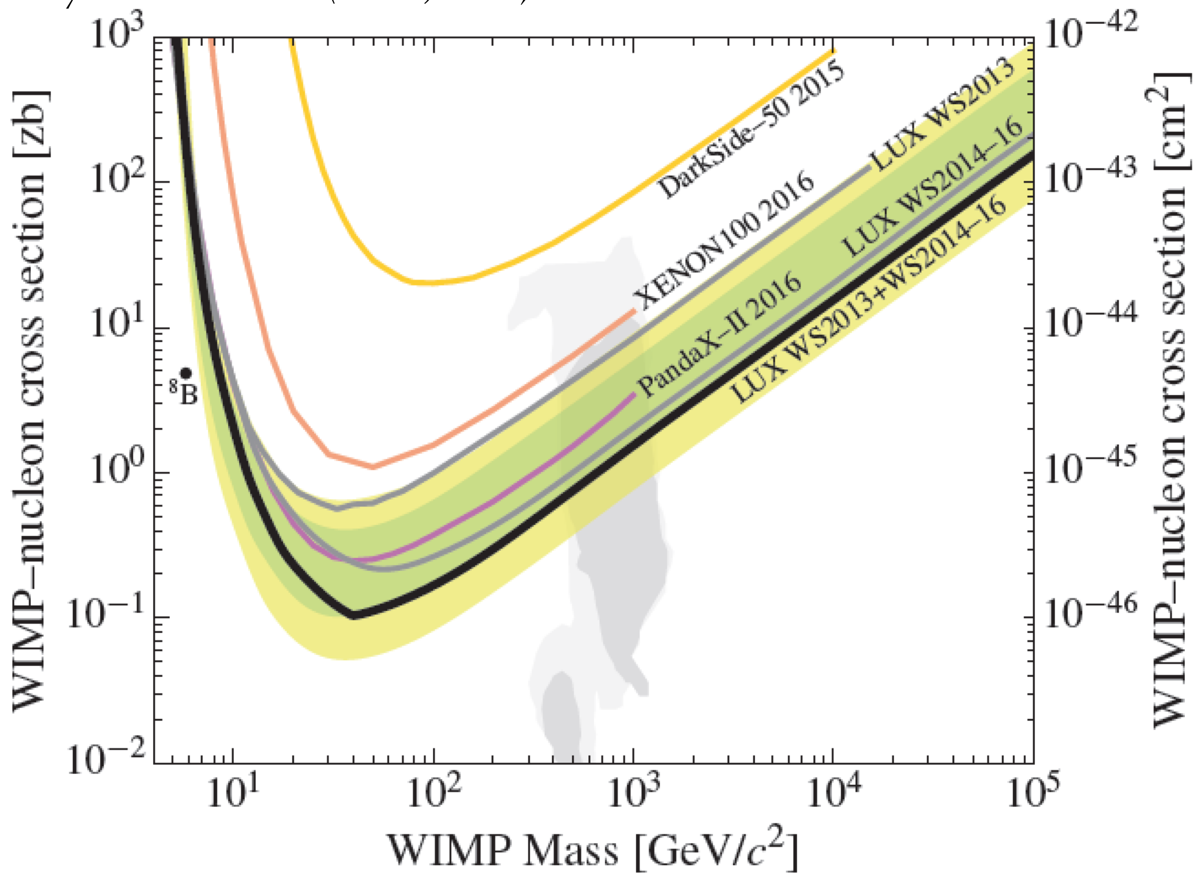



*Phys.Rev.Lett. 118 (2017) no.2, 021303*





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**XENON-1T**

**LUX** (250 kg),

**PANDA-X** (120kg, 500 kg)

MSSM Mass,
σ > ν bound

# 2-Phase Xe TPCs: Prospects

Goal: zeptobarn -> yoctobarn!

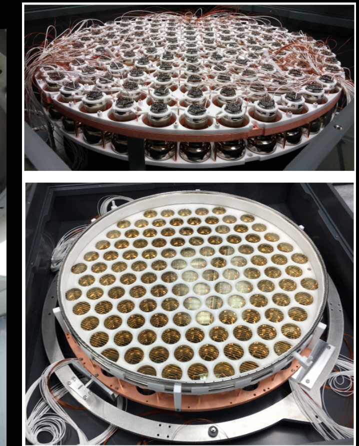
(and cover favored MSSM parameter space)

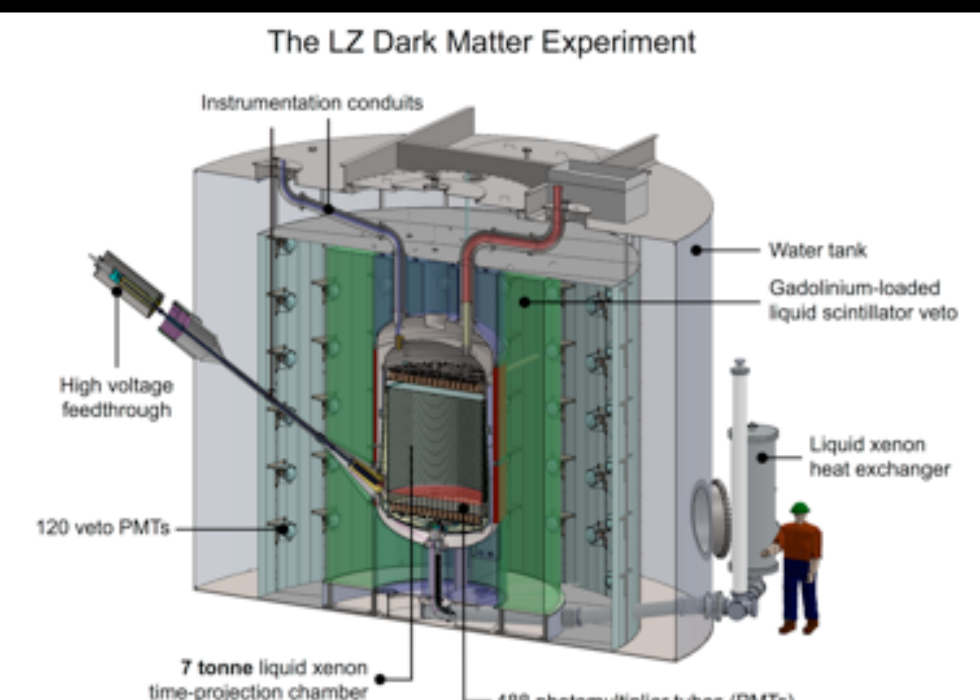
**PANDA-X:** low-mass WIMP results and 100 kg-year results from 400kg detector (active), plan 2 year run (*PRL 117, 121303 (2016)*.

**XENON-1T:** 3300 kg LXe (1000 kg fiducial), running at LNGS now. Sensitivity reach 1E-47 cm$^2$ after 2 Tonne-years.

**XENON-nT:** upgrade to 6000 kg LXe (active), using same infrastructure + new TPC, inner cryostat. Planned from 2018.

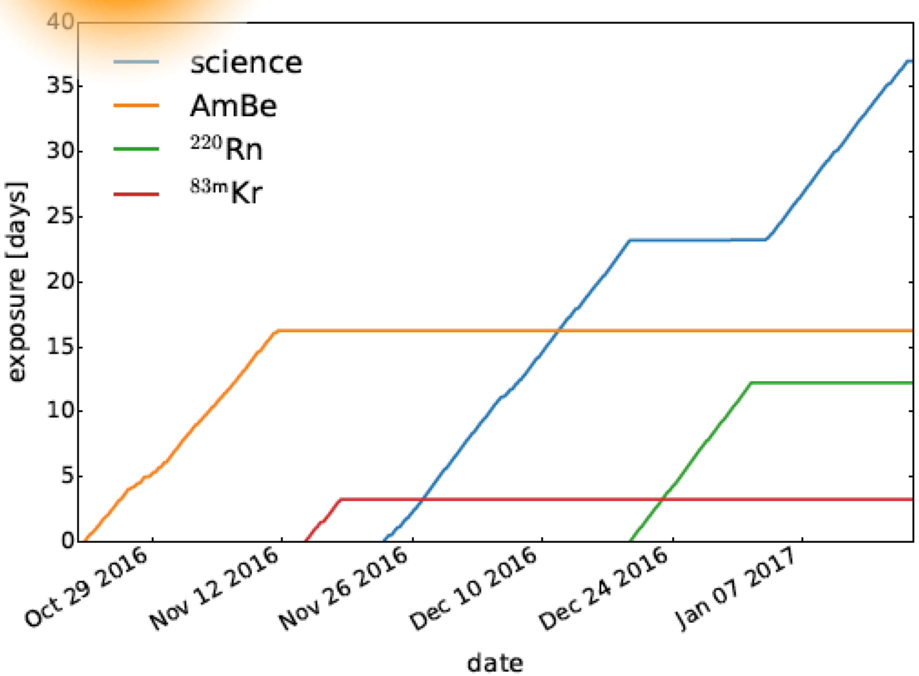
**LZ**: follow-on to LUX, 7000 kg LXe (active), at SURF, operation from 2020. Sensitivity reach to 2E-48 cm$^2$.






# XENON-1T Status

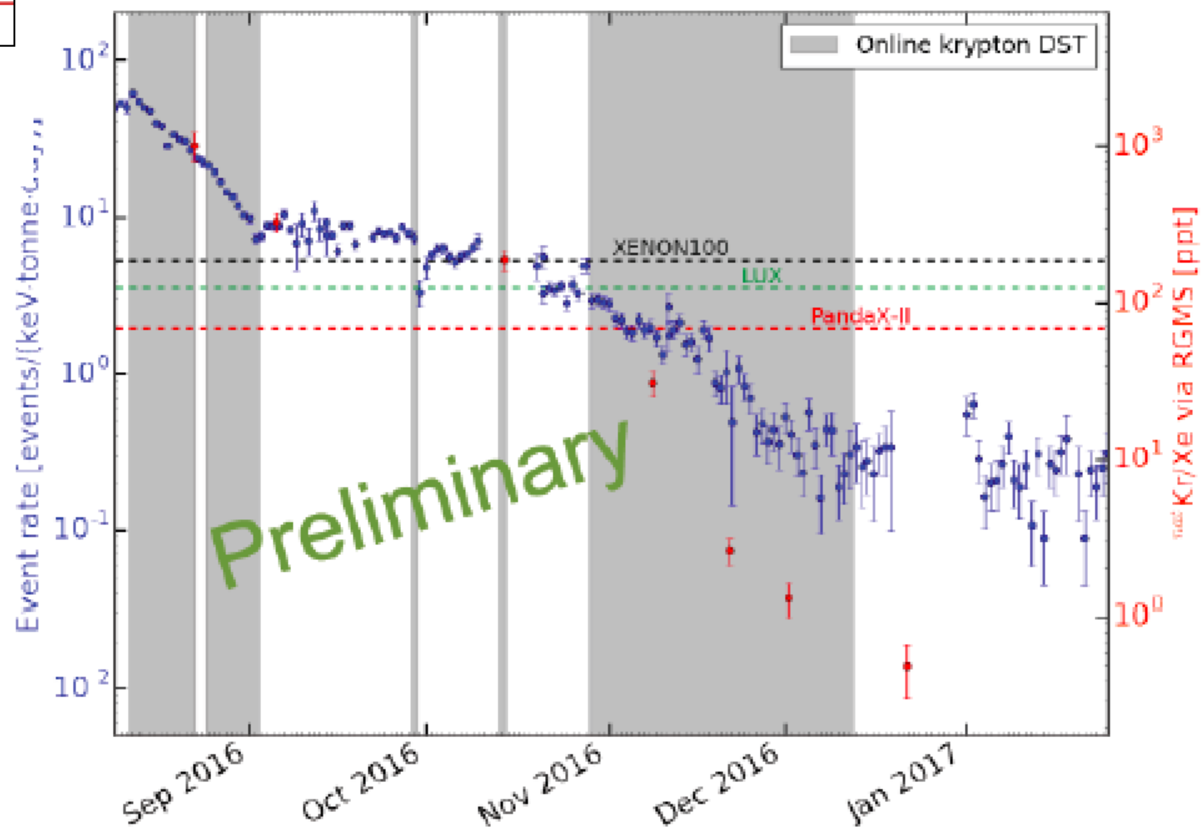
*(T. Marrodan, La Thuile '17)*




- New and improved analysis software
- Calibration campaign started in autumn 2016
- Continuous data taking since then

- Lowest background level of all LXe experiments
- Krypton background reduced by online cryogenic distillation XENON1T, arXiv:1612.04284
- Krypton level measured independently by RGMS

Eur. Phys. J. C 74 (2014) 2746



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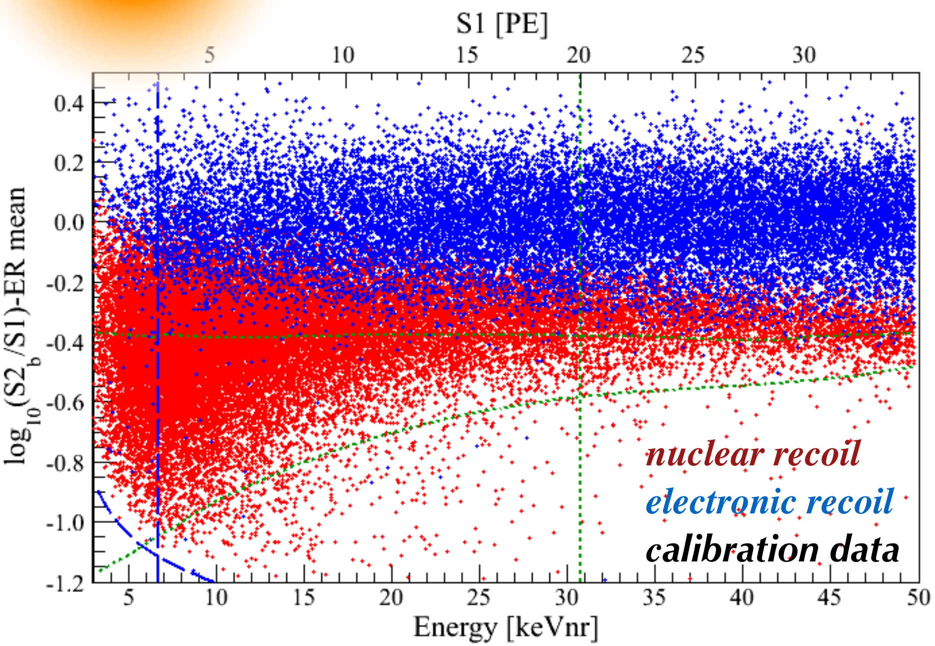


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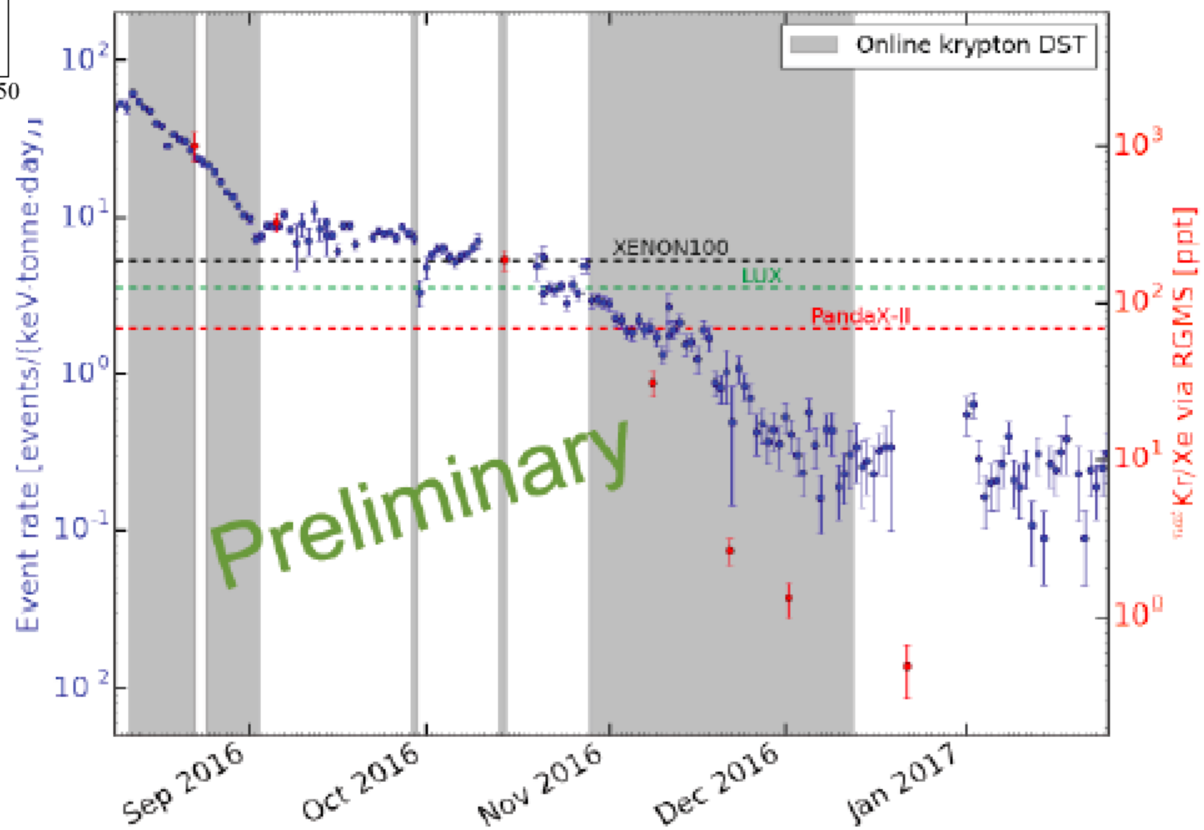
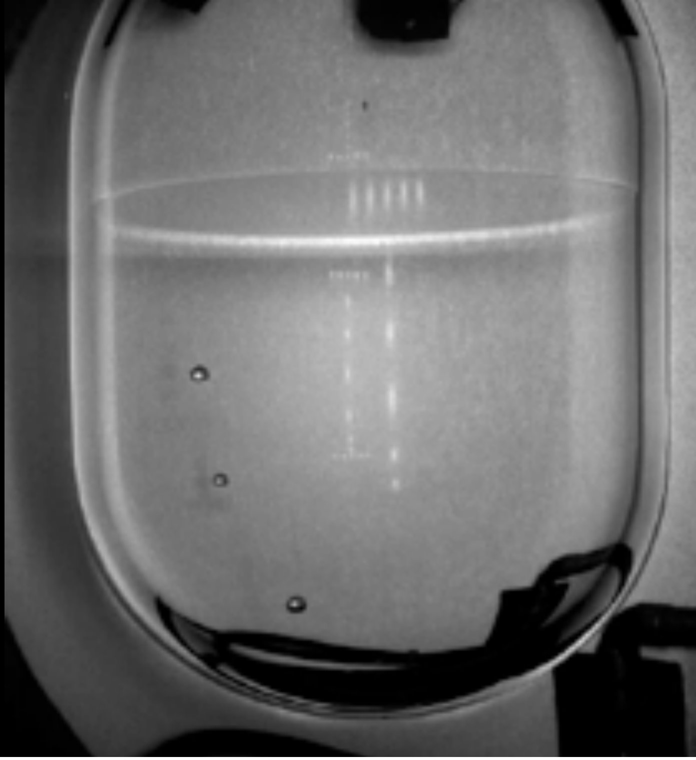


MSSM Mass, σ > ν bound

# Bubble Chambers

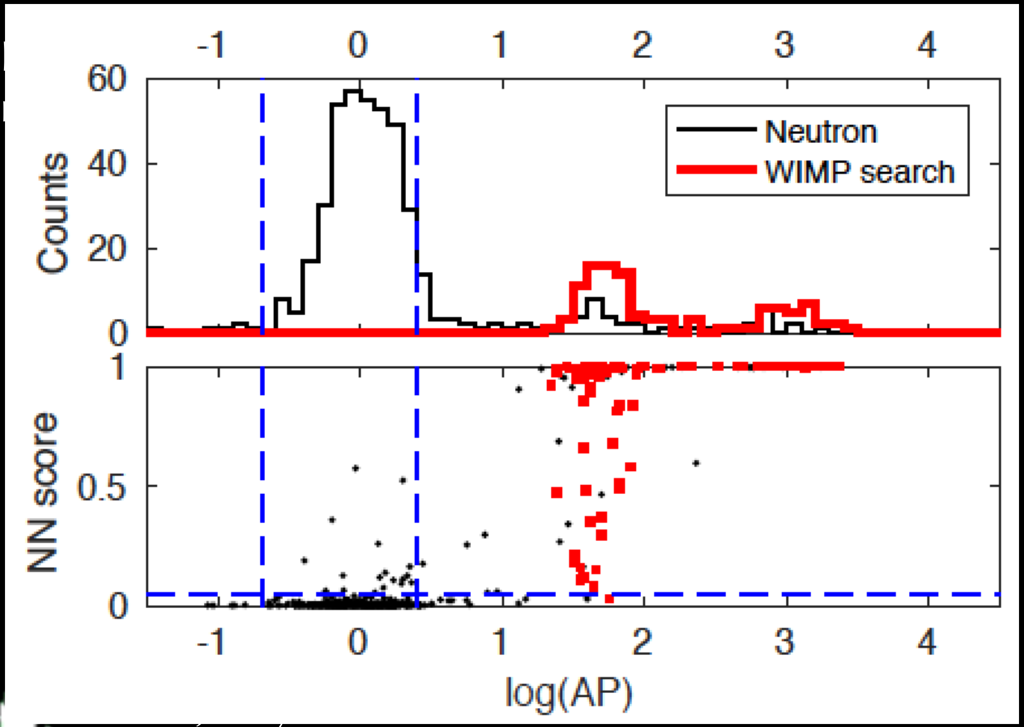
**SIMPLE** (GESA), **PICASSO+COUPP** = **PICO** (SNOLAB)



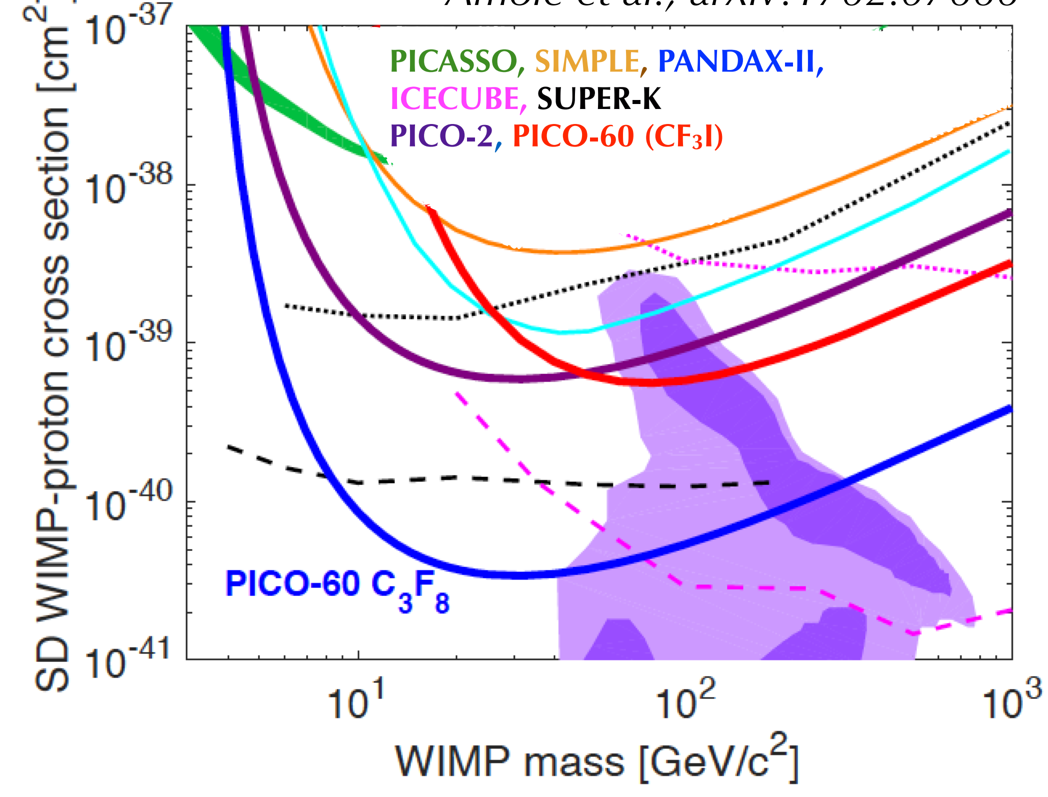
superheated target ($CF_3I$ +), camera and piezo (acoustic) readout
measure integral counts above threshold when dE/dx > nucleation

gamma rejection >1E-10, neutron discrimination from multiples,
1E-2 alpha rejection from acoustic readout

**PICO-60: (PICASSO+COUPP)** running since 2013 with $CF_3I$ target
upgraded in 2016 to $C_4F_8$ target prototyped in PICO-2L.
Best SD WIMP-proton limit (1167 kg-days, $E_{th}$ = 3.3 keV)




*Amole et al., arXiv:1702.07666*



MSSM Mass, σ > ν bound

# Spin-Dependent Cross Section Status

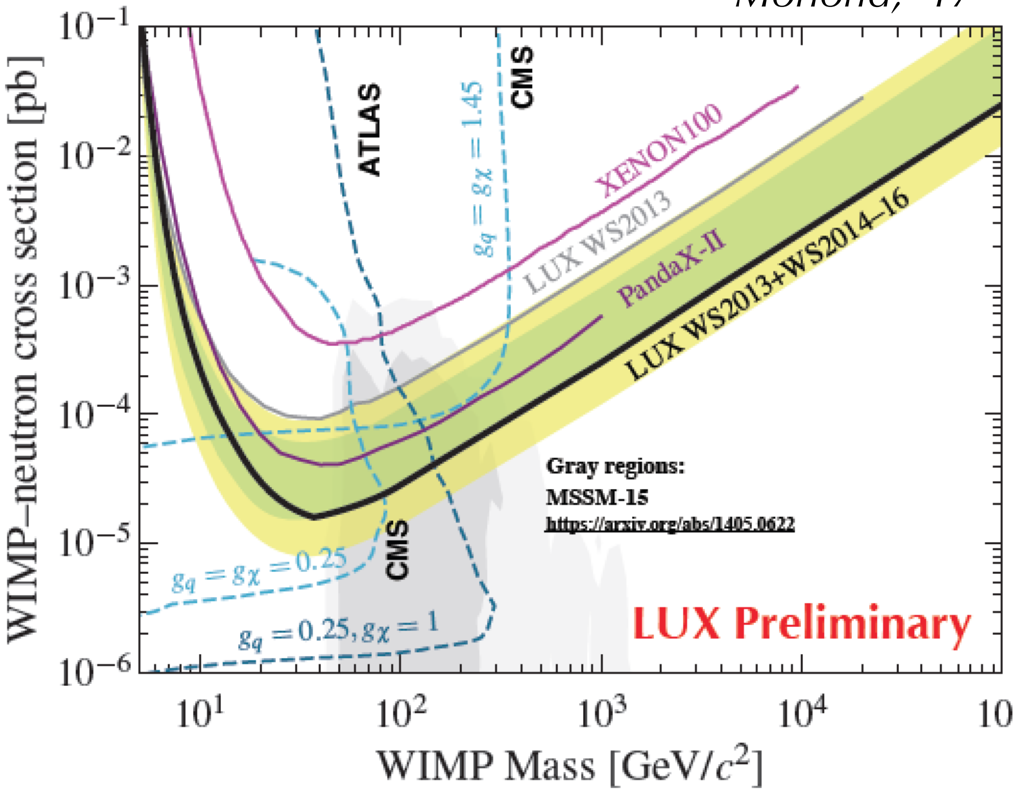
Direct detection limits strongest for now in WIMP-proton spin-dependent cross section below 100 GeV scale, but only just!

Collider limits comparable (caveat: model dependence) for WIMP-neutron SD cross section.

Progress in learning how to compare with each other…

PICO reports exclusion limits in WIMP mass vs. mediator mass plane using simplified model framework employed to interpret collider searches.

*Moriond, '17*

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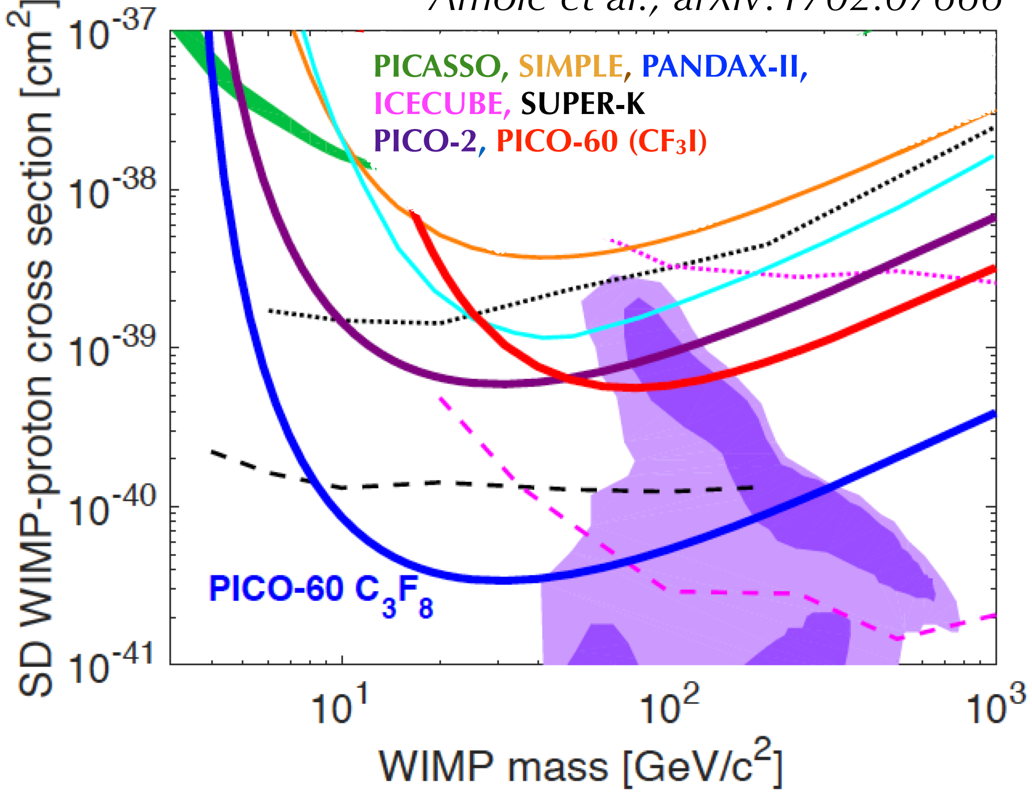

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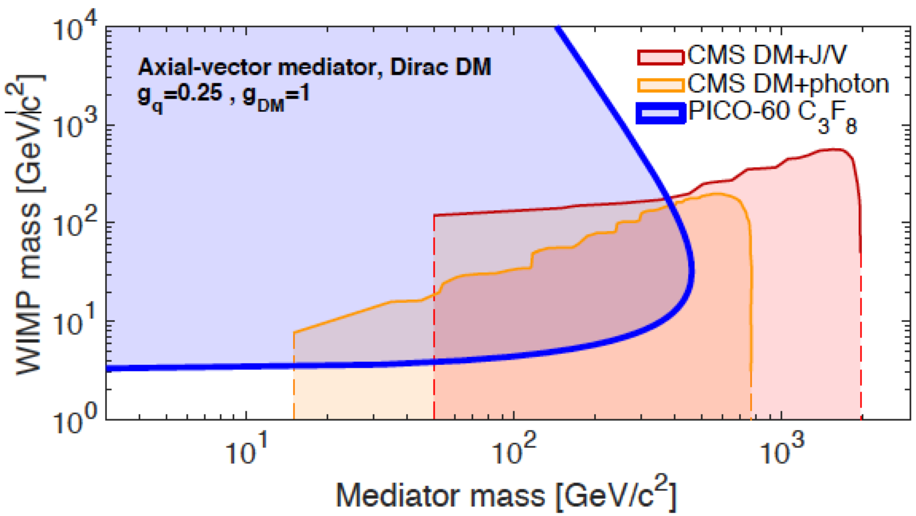
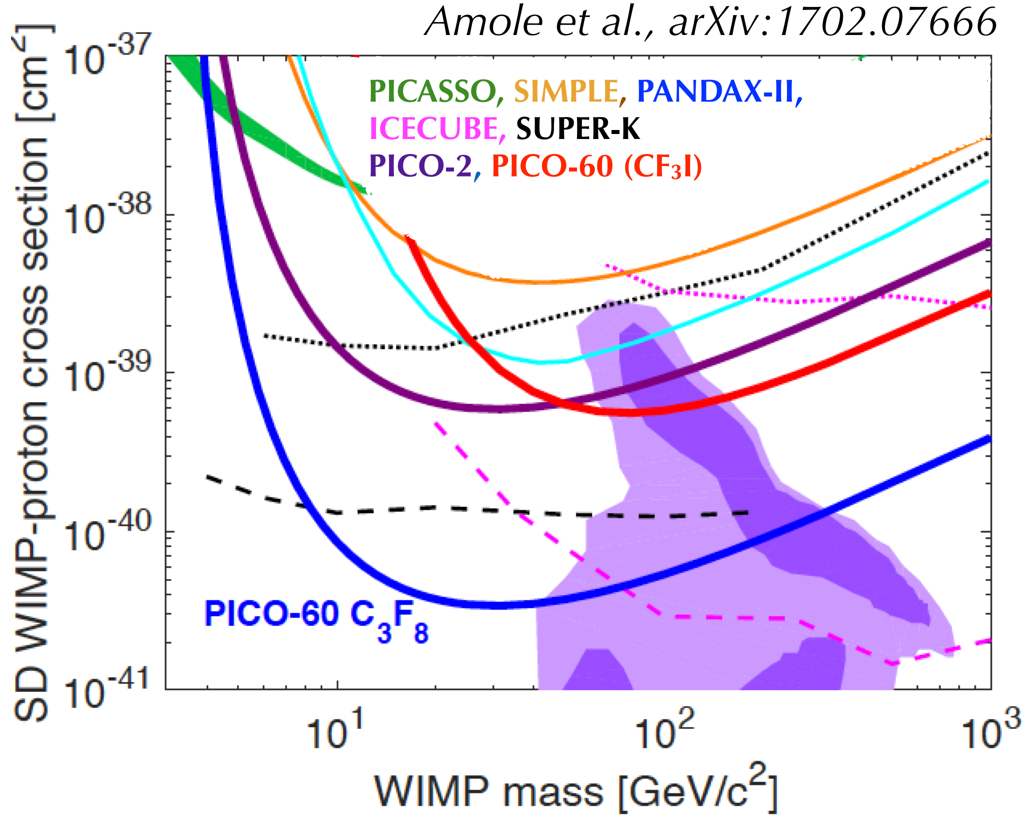



FIG. 6. Exclusion limits at 95% C.L. in the $m_{DM} - m_{med}$ plane. PICO-60 constraints (thick blue) are compared against collider constraints from CMS for an axial-vector mediator using the monojet/mono-V (red) [32] and mono-photon (orange) [33] channels. A similar analysis by ATLAS can be found in [52]

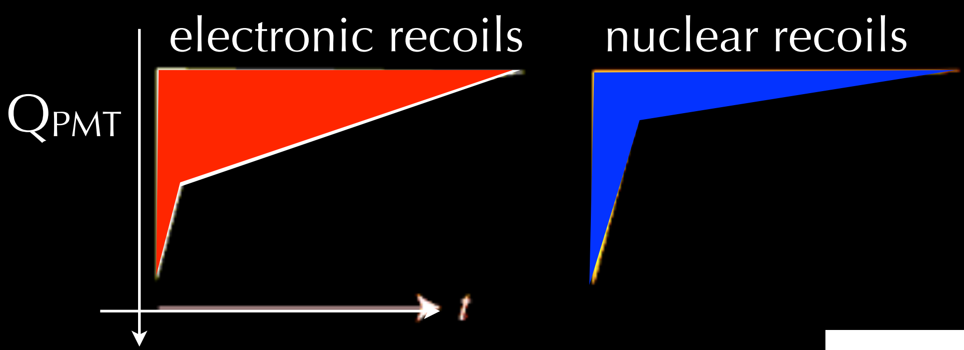
*Amole et al., arXiv:1702.07666*



MSSM Mass,
σ > ν bound

# Argon Detectors

Why? Liquid noble benefits, +Ar costs 0.001x Xe, so kTonne-scale detectors feasible!




pulse shape discrimination (PSD) for particle ID: x250 difference in scintillation time constants between electronic vs. nuclear recoils in Ar.

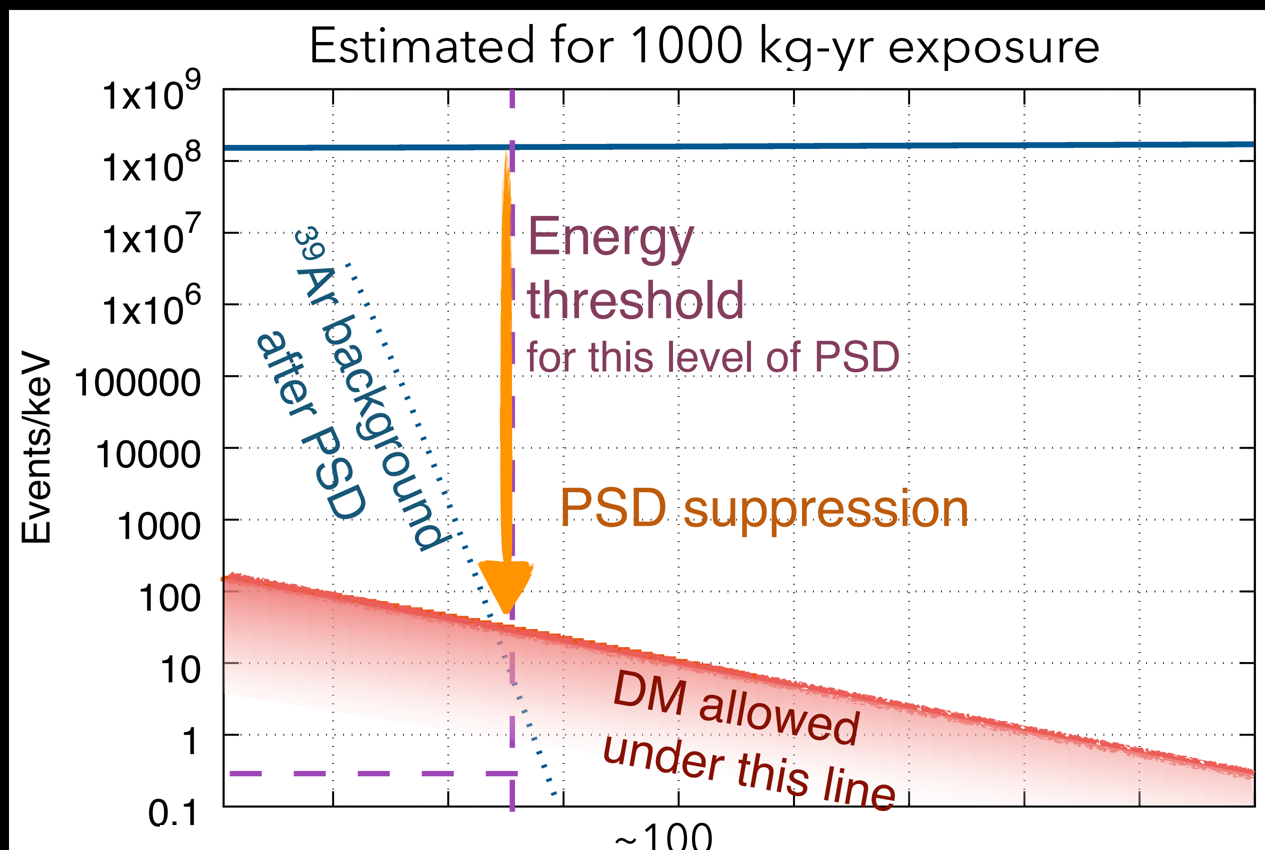
naturat Ar has Ar-39 beta-decay,1 Bq/kg, Q~550 keV.

**DarkSide-50:** 50 kg 2-phase TPC in LNGS, zero background limit *(arXiv:1510.00702)*, demonstrated depleted underground Ar.

**ArDM:** 850 kg 2-phase TPC in Canfranc, will test depleted UAr samples with 100x sensitivity. *(arXiv:1510.00702)*

**DEAP-3600:** 3600 kg single-phase detector running in SNOLAB, demonstrated PSD to 1E-8 level *(arXiv:0904.2930)*

**DarkSide-20k:** Coordination of all LAr experiments, on 20,000 kg detector at LNGS



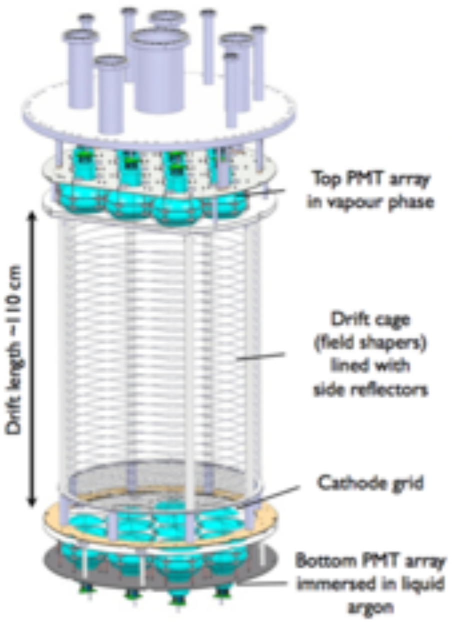

*(T. Pollmann)*

MSSM Mass, σ > ν bound

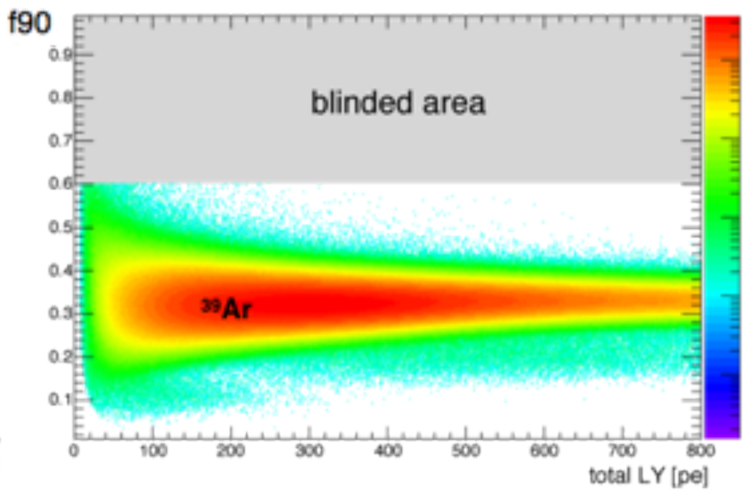
# ArDM-1t


*(thanks to C. Regenfus)*

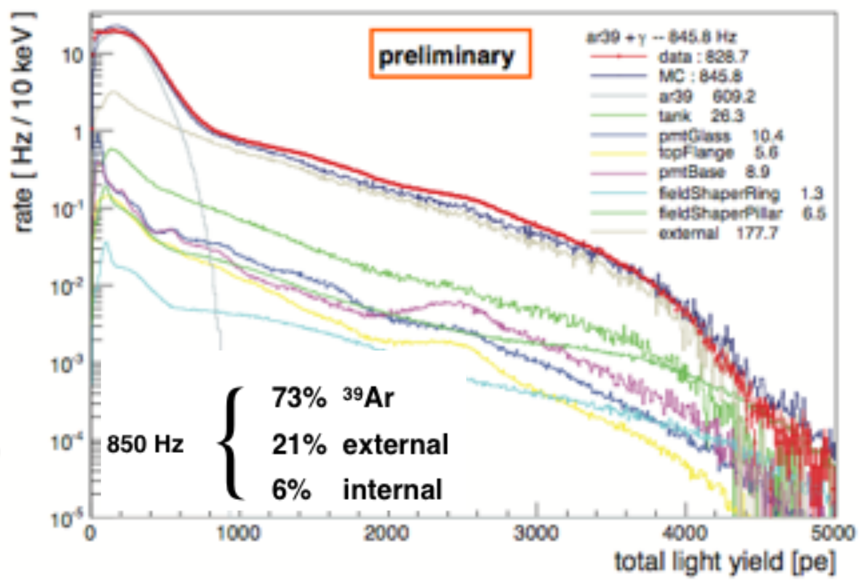
- Ton-scale LAr TPC at Canfranc @ 2500 m.w.e.
- 850 kg active mass, 24 8” PMTs, low background
- 1st 6-month run in single phase in 2015: to explore features of LAr for DM@ton-scale
- Detector upgrades in 2016 for double phase Run II in 2017 for verification of sensitivity and neutron backgrounds.
- 2018 and beyond: depleted argon studies with sensitivity down to $10^{-5}$. Demonstration at the ton-scale is a necessary step towards 10-tons and beyond.




Pulse shape discrimination

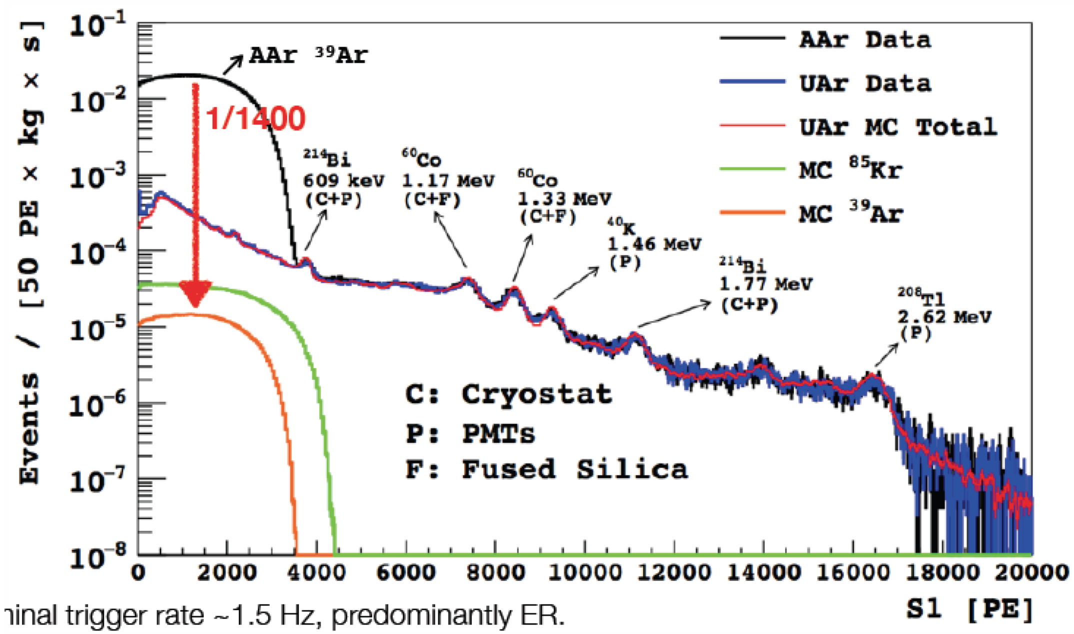


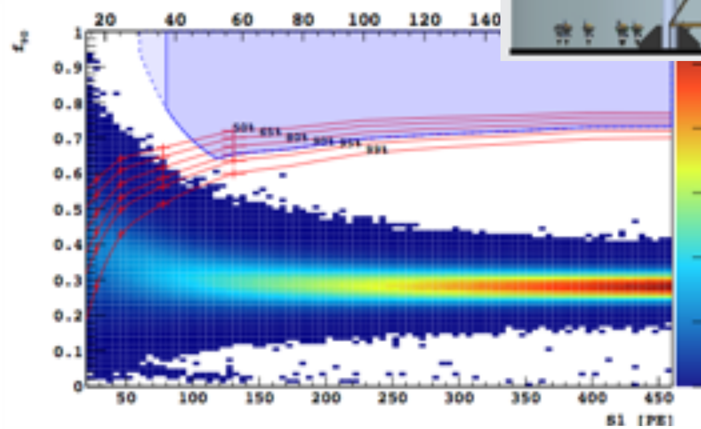

Low BG studies

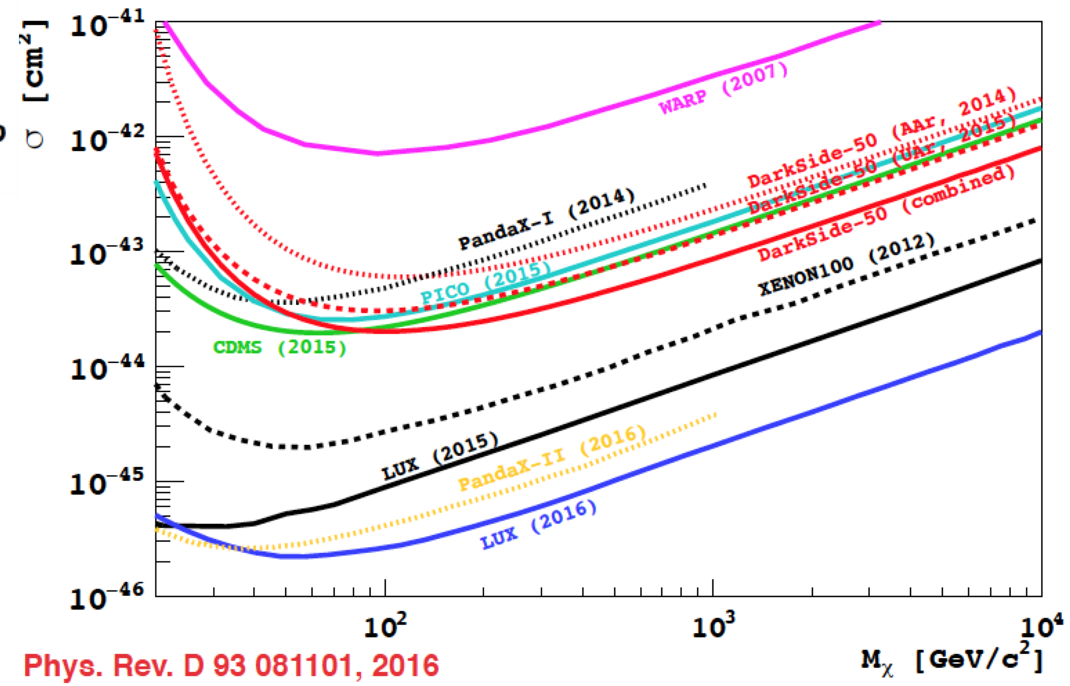


# DarkSide-50


- LArTPC (50 kg active, 150kg total) 38 3” PMTs at LNGS
- Liquid scintillator veto (30T) 110 PMTs + water veto (1 kT) 80 PMTs
- Development of argon depleted in Ar-39 (UAr)




Phys. Rev. D 93 081101, 2016

Demonstrated:

- β/γ rejection capability better than 1÷10$^7$ with Ar
- high-performance vetoing scheme and $^{39}$Ar suppression in underground argon by x1,400
- zero-background limits from AAr and UAr

MSSM Mass, σ > ν bound

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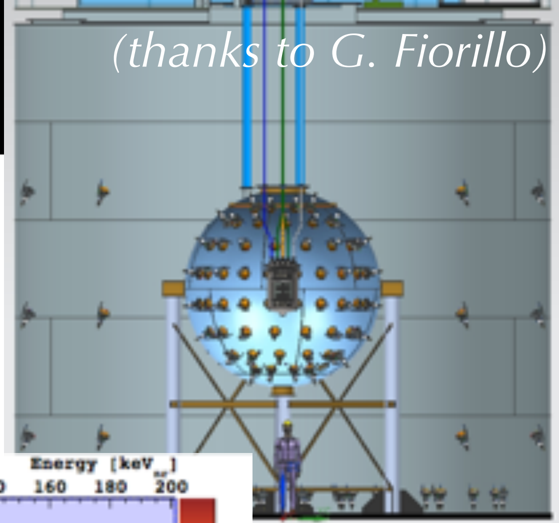


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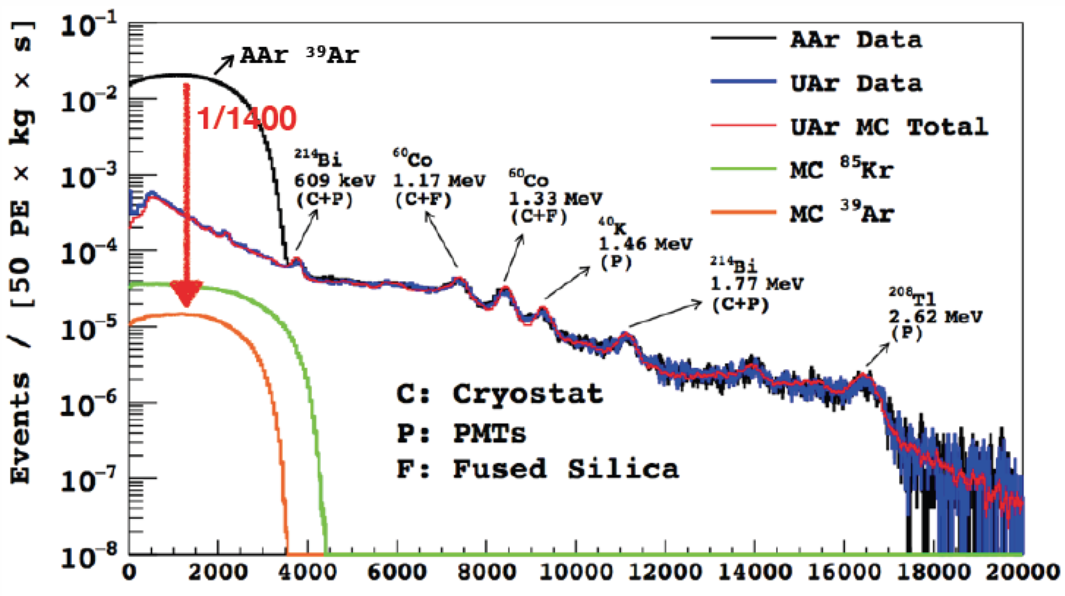


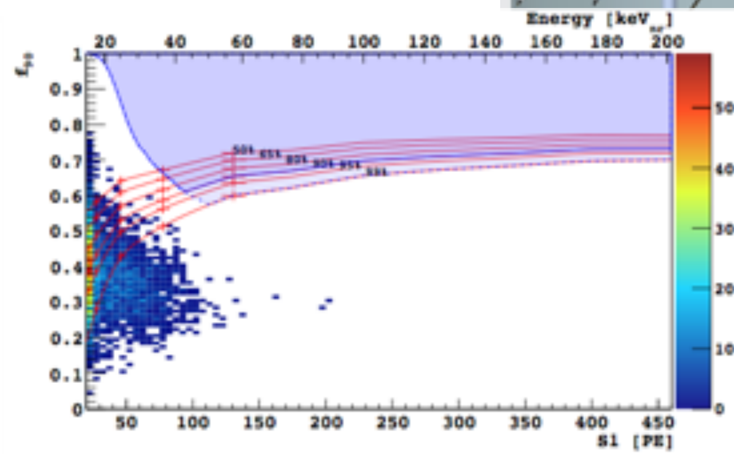


...inal trigger rate ~1.5 Hz, predominantly ER.

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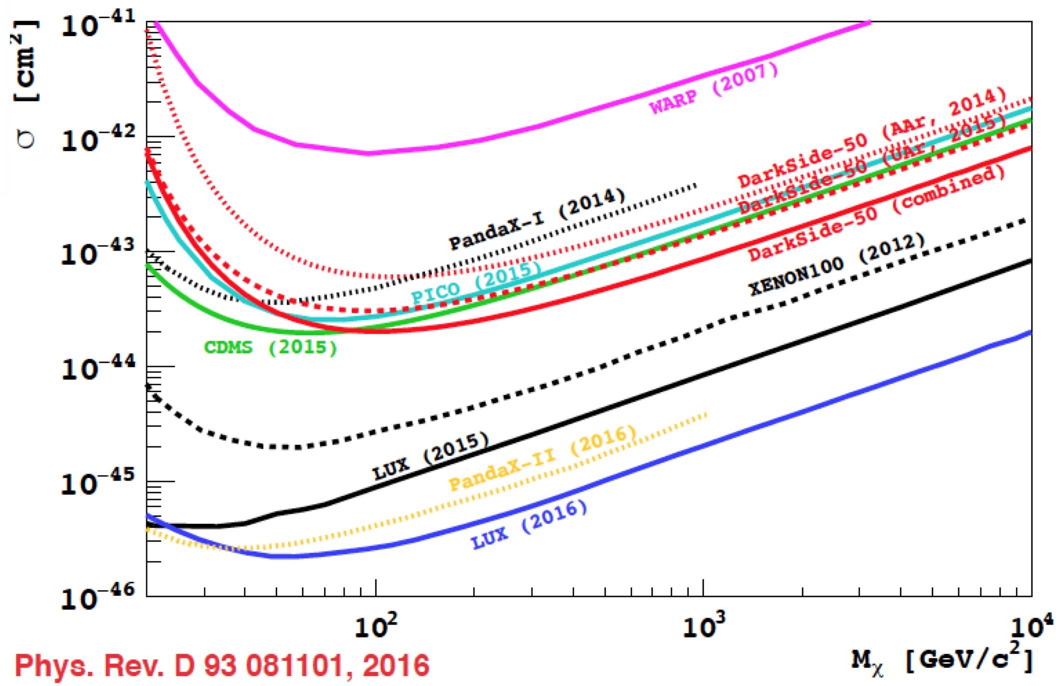
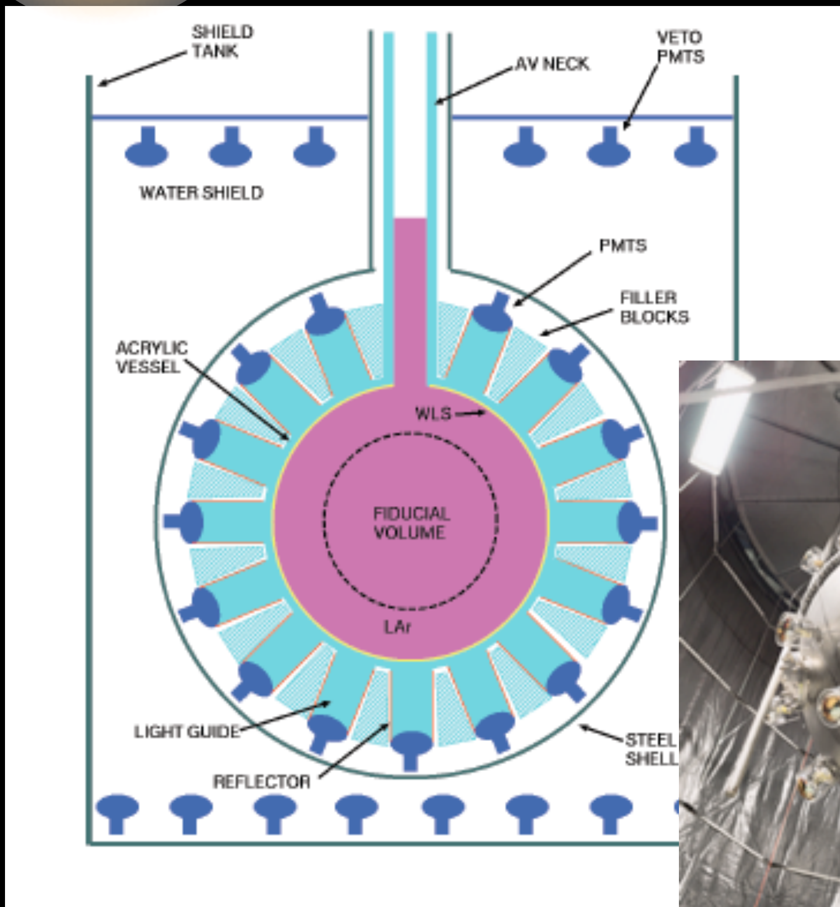


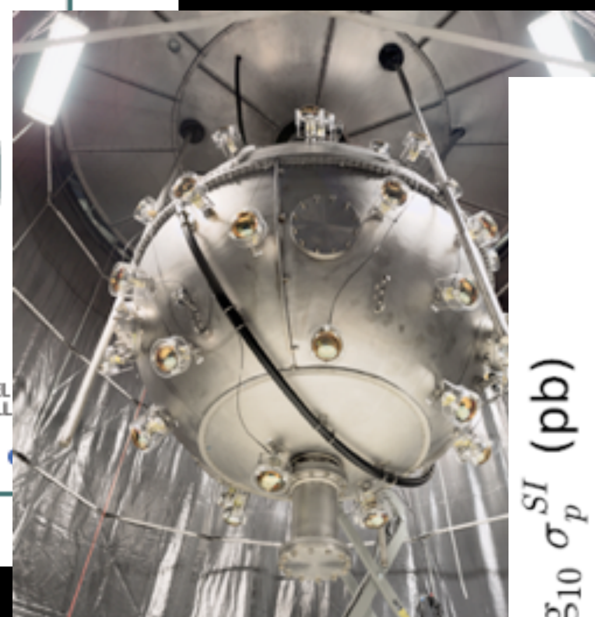

Phys. Rev. D 93 081101, 2016

MSSM Mass, $\sigma > \nu$ bound

# Single Phase Liquid Nobles, a la Neutrinos

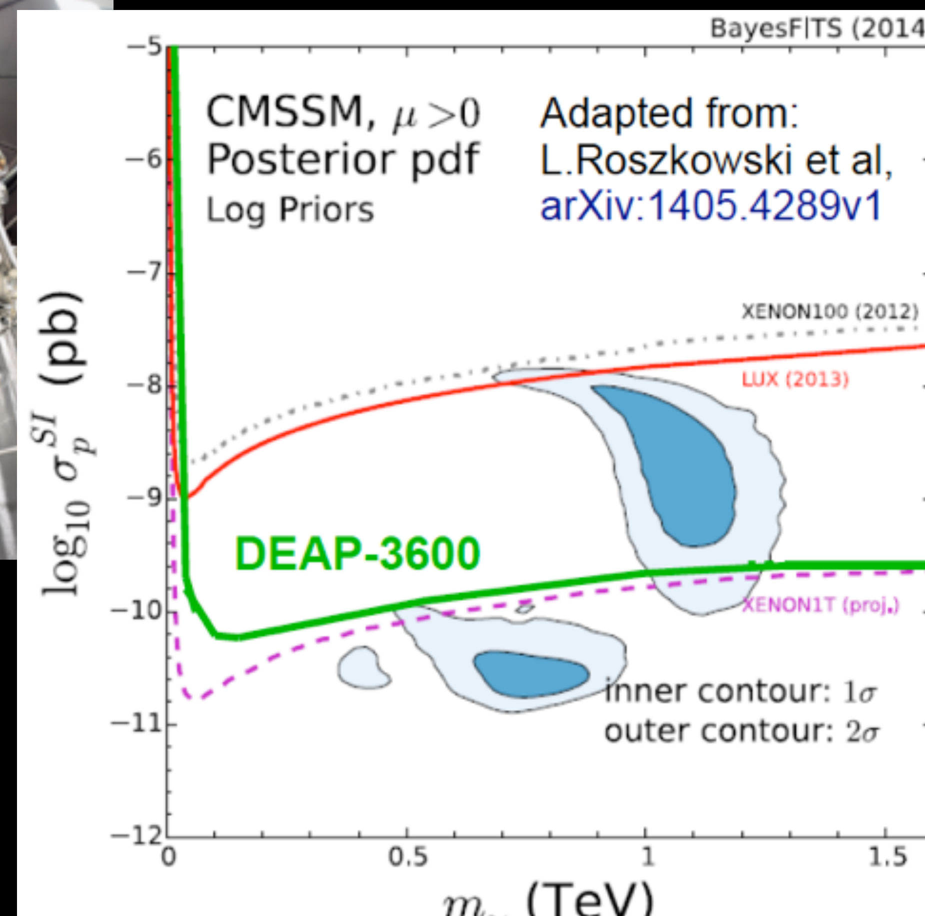
maximize light yield from 4**π** PMT coverage, target self-shields, only detect scintillation



**XMASS:** 832 kg LXe detector at Kamioka, running from 2013, upgrading PMTs to reduce backgrounds, future 5T detector.

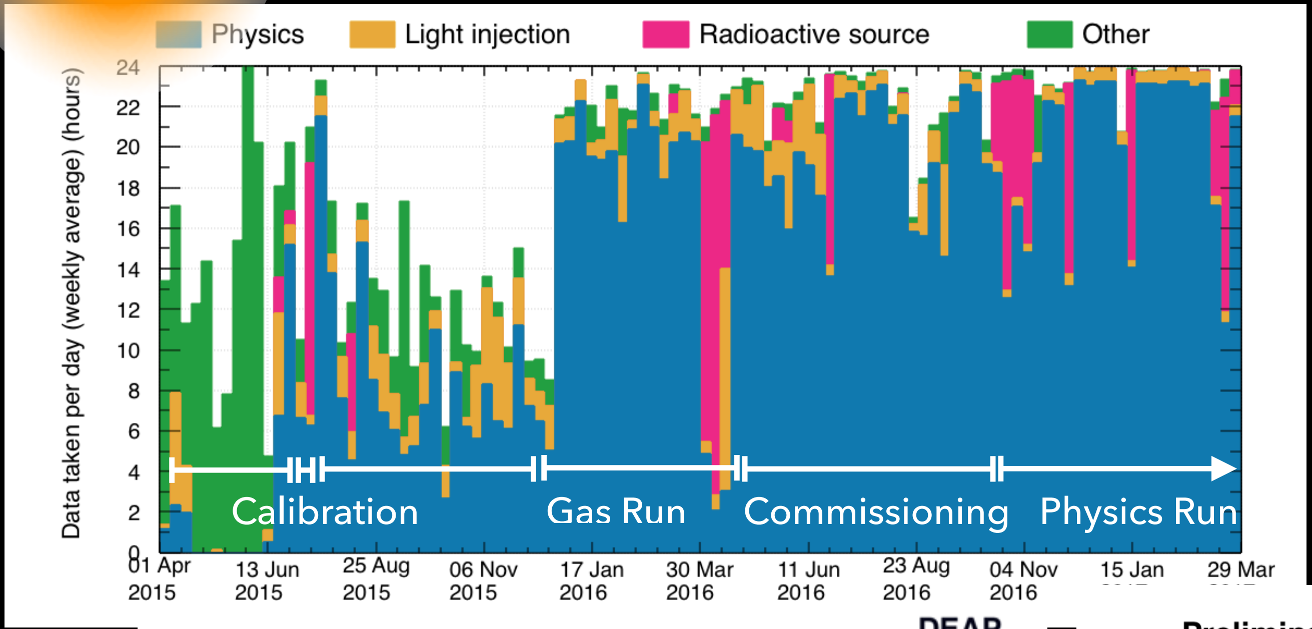
**DEAP-3600:** LAr at SNOLAB. 3600 kg target, with few PE threshold. detector commissioning now, physics start 2016, project <0.6 background/3000 kg-days, to reach 1E-46 cm² sensitivity




no electric fields = scale to large mass (O(100 T))
1) no pile-up from ms-scale electron drift in TPC
2) no recombination in E field
but background discrimination from scintillation only!

MSSM Mass, σ > ν bound

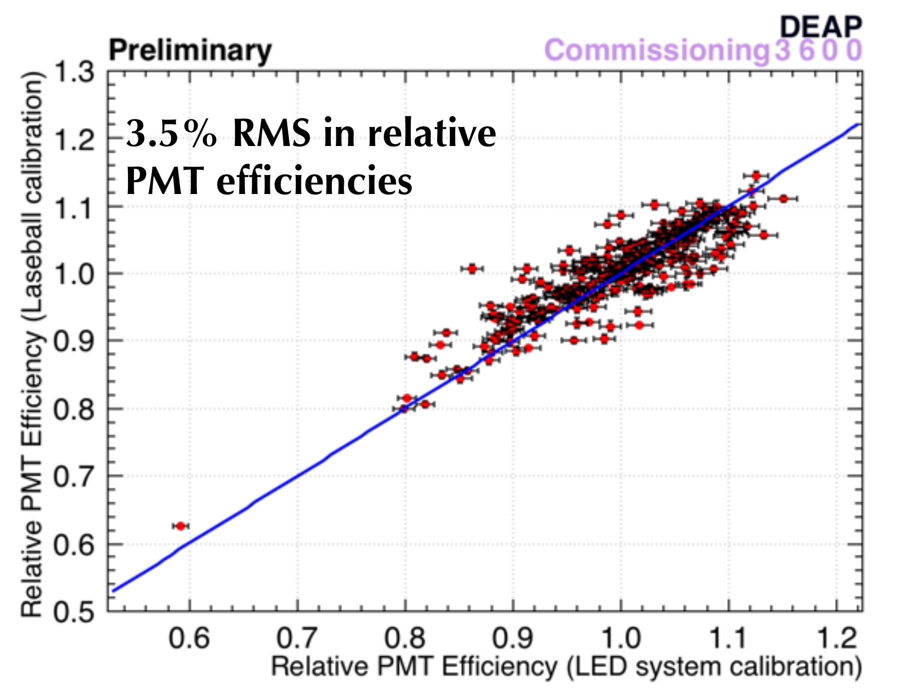
# DEAP-3600 Status

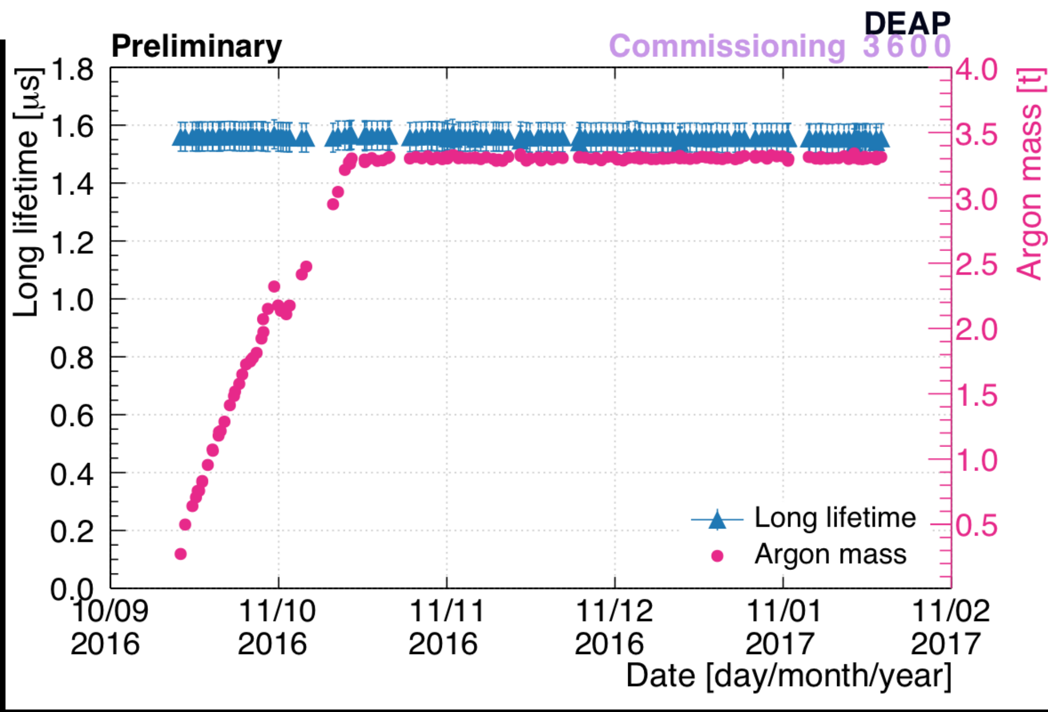



collected 500,000 kg-days raw exposure since Physics run start 11/16

PMT response well understood, detector stability measured with Argon triplet lifetime

first physics results planned for Summer 2017, stay tuned!



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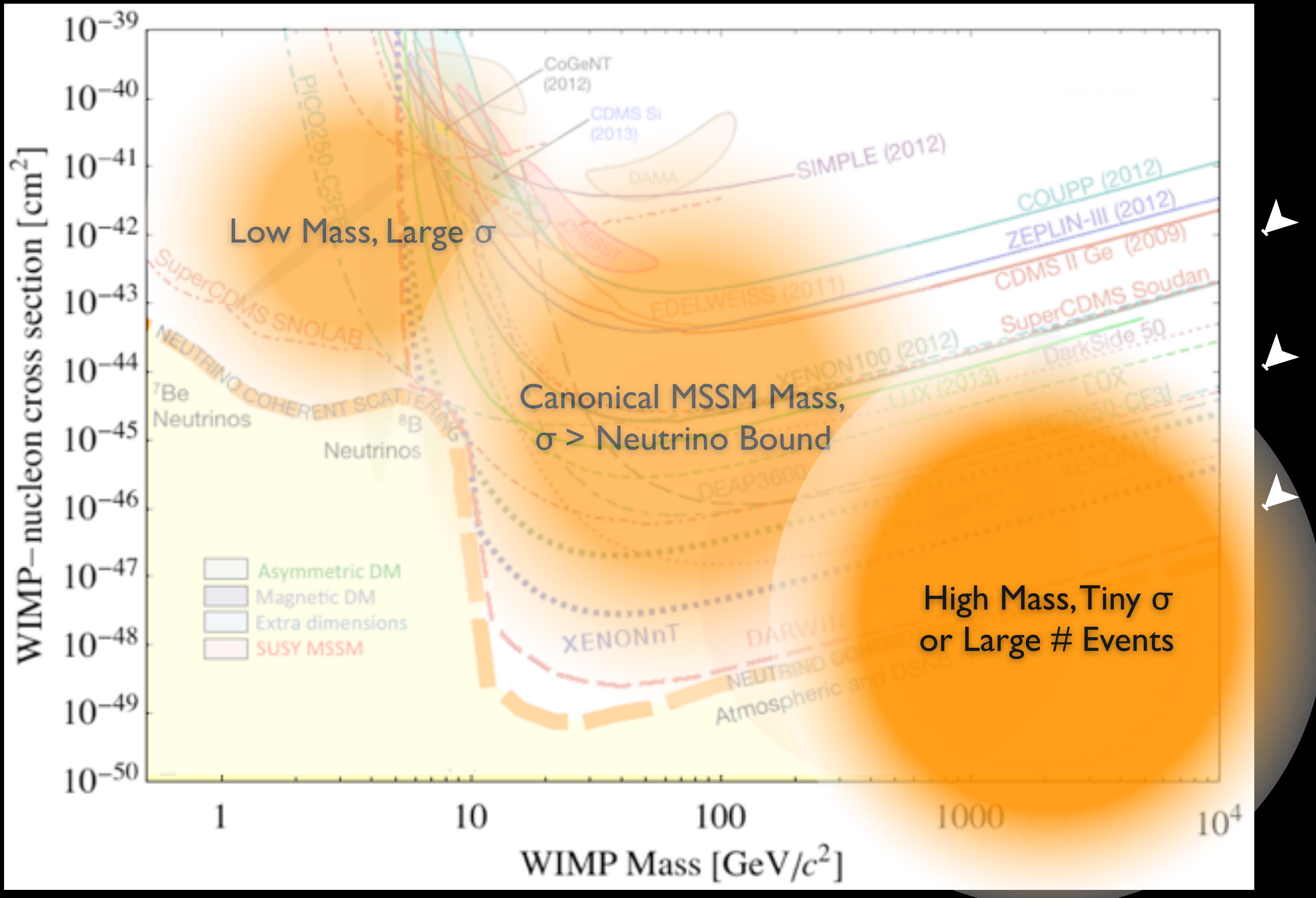



1 event/ kg/day

1 event/ kg/year

1 event/ kg/century

so far: ~3 years / order of magnitude

High Mass, Large # Events σ < ν bound

# DarkSide-20k

*(thanks to C. Galbiati)*

## An Integrated Program for the Ultimate DM Search with $^{39}$Ar-suppressed Argon TPCs

**ArDM-1t (now)**

**DarkSide-50 (now)**

**DEAP-3600 (now)**

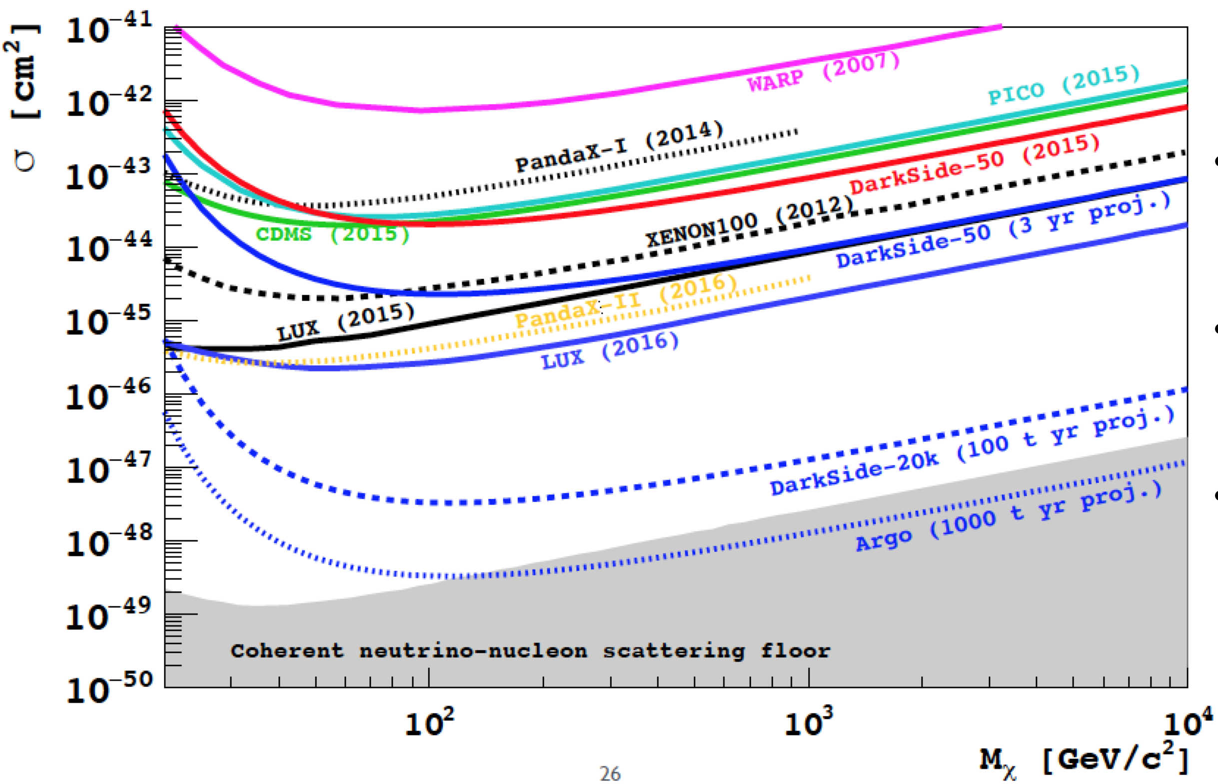
**MiniCLEAN (now)**

**DarkSide-20k (2021)**

100 T-yr background-free search

**Argo (mid-2020s)**

- 1,000 T-yr background-free search to *reach the "neutrino floor"*
- precision low-energy solar neutrino measurements




- Ultimate search requires1E6 kg-yr **background-free exposure**
- $^{39}$Ar-suppressed Ar TPC can deliver due to β/γ suppression
- complementary with LHC: exploration of very high masses with direct detection search

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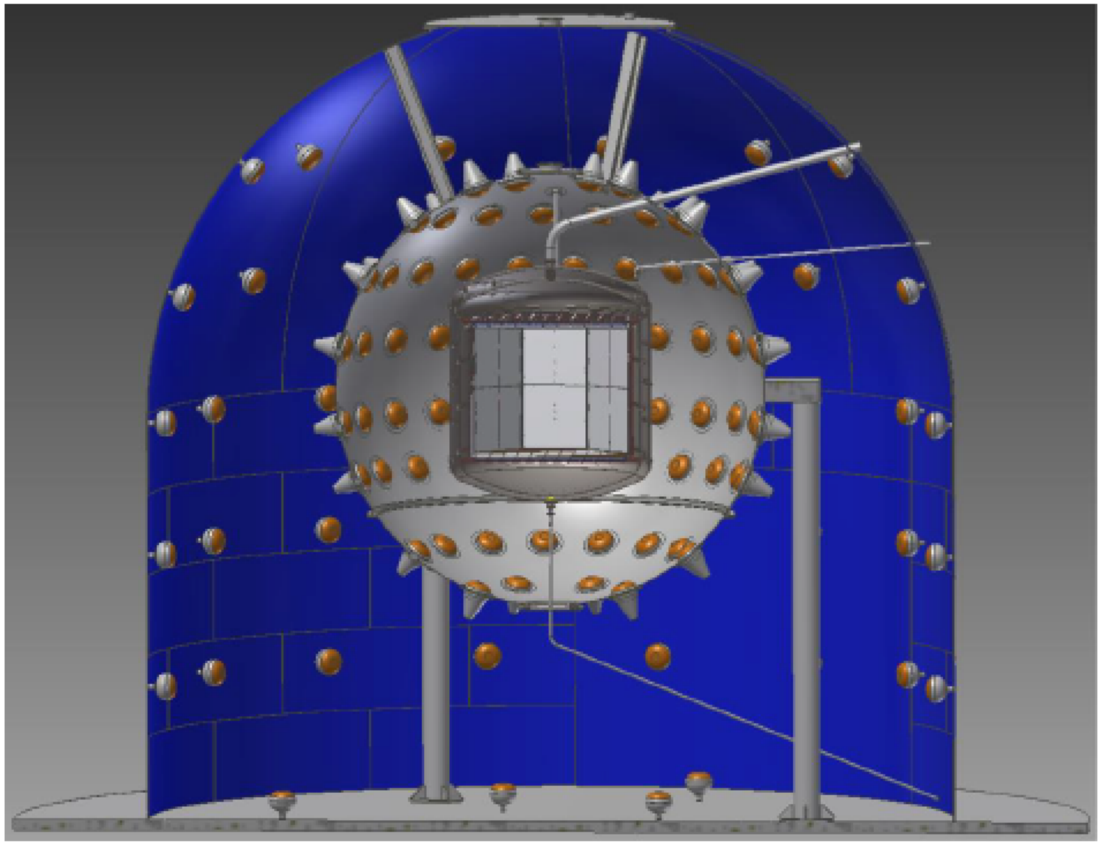
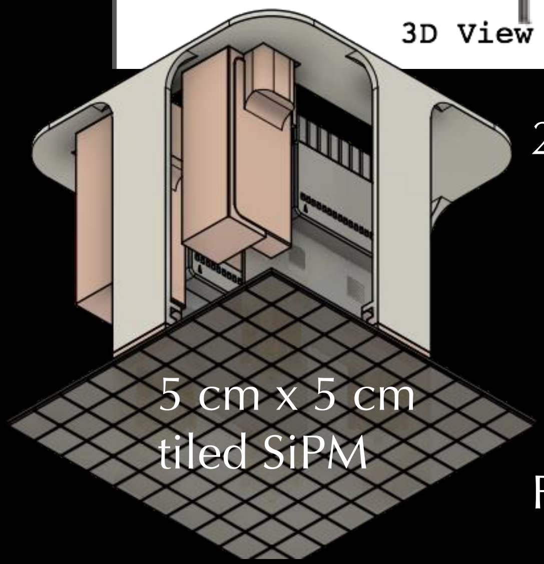
# DarkSide-20k

High Mass,
Large # Events
$\sigma < \nu$ bound




2-phase TPC at LNGS, designed for 20,000 kg fiducial mass of UAr

Key enabling technologies R&D funded and ongoing:

- Urania: 100 kg/d procurement of UAr
- Aria: active isotopic separation of $^{39}$Ar via cryogenic distillation
- Cryogenic, large-area SiPMs

First large-scale use of large-area cryogenic SiPMs for light readout

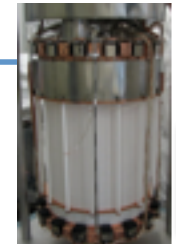
- 45% PDE and 0.1 Hz/mm$^2$ noise performance goals achieved in March'17

# DARWIN

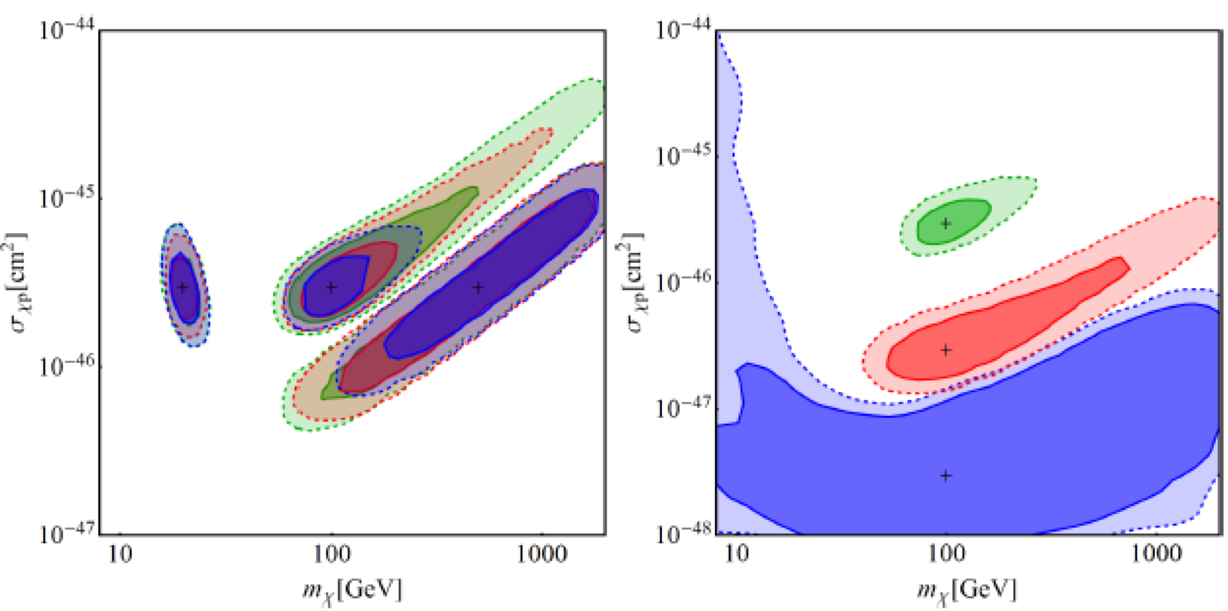
*(thanks to L. Baudis)*

## Ultimate LXe TPC at LGNS.

- ✓ 50 t (40 t) Lxe in total (in the TPC)
- ✓ ~$10^3$ photosensors
- ✓ 2.6 m drift length, 2.6 m diameter TPC
- ✓ Background: dominated by neutrinos
- ✓ WIMP spectroscopy, search + non-WIMP science: axion / ALP search, solar neutrinos, supernova neutrinos, sterile neutrinos, coherent neutrino – nucleus scattering, 0v2β decay of $^{136}$Xe.



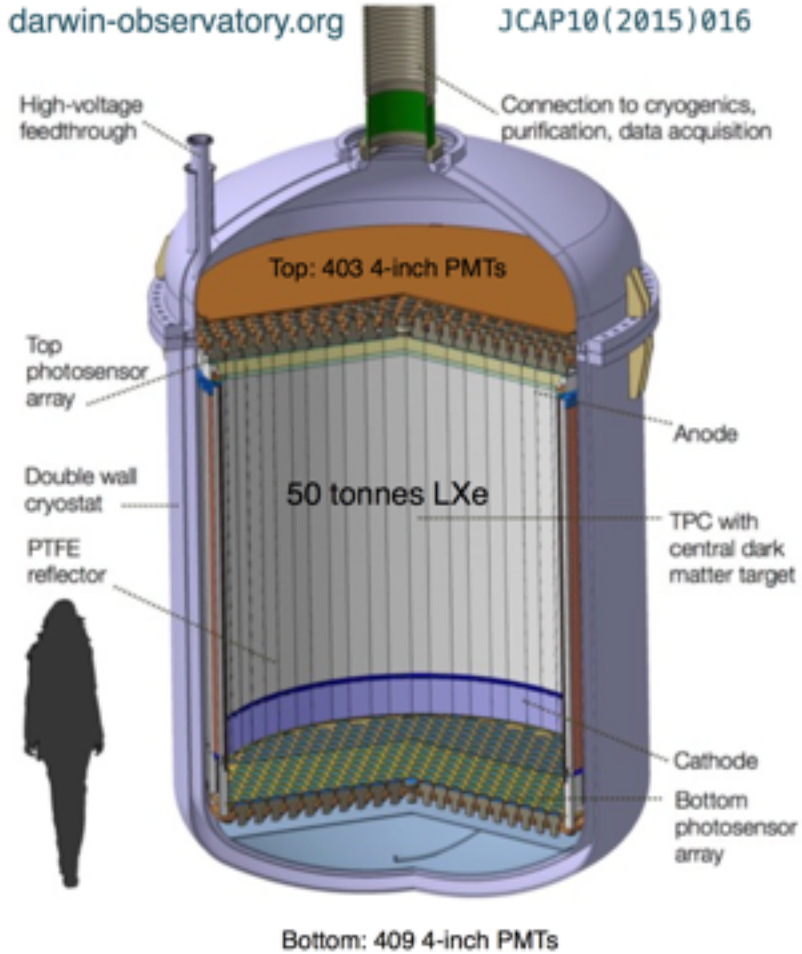

JCAP10 (2015) 016




Newstead et al., PRD D 88, 076011 (2013)

darwin-observatory.org

JCAP10(2015)016

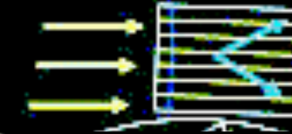


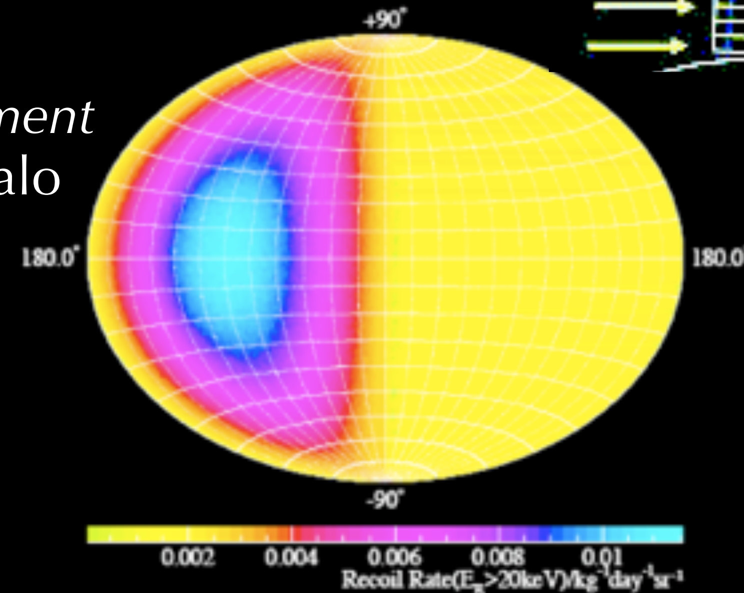
dark matter identification, σ > ν bound

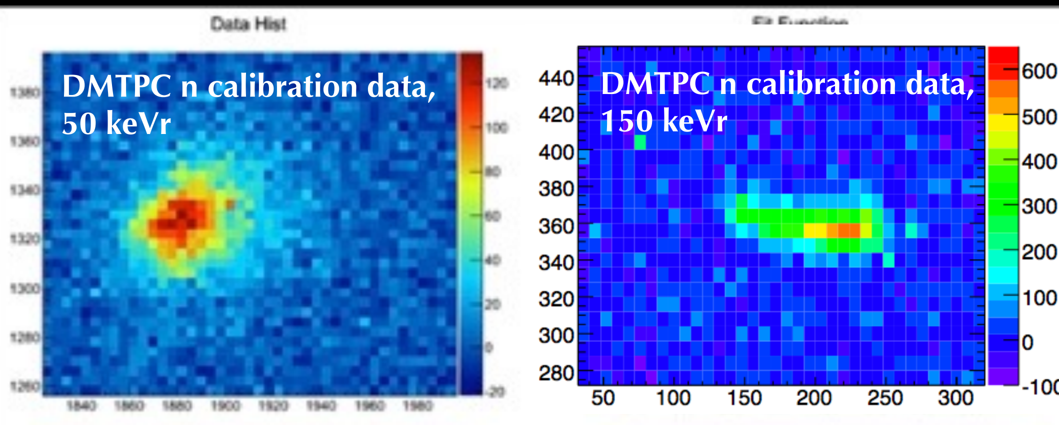
# Directional Detection

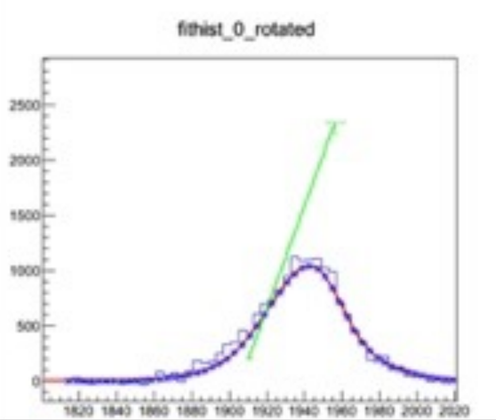
R&D towards recoil *direction measurement* to correlate a signal with the galactic halo

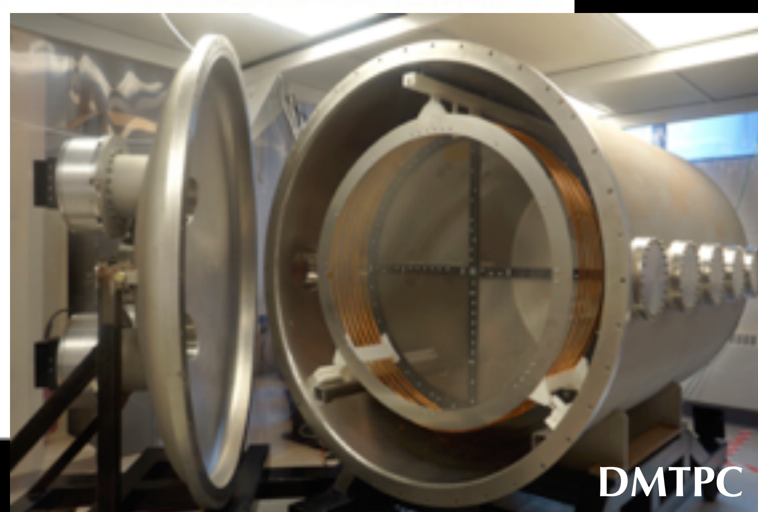
*Physics Reports 2016, arXiv:1602.03781*






**DRIFT:** 1m$^3$ MWPC, in Boulby since 2001

**DMTPC:** optical (CCD) and charge readout of $CF_4$; commissioning 1m$^3$ module.

**MIMAC:** micromegas, in LSM. Low E focus.

**NEWS:** fine-grained emulsions

**R&D:** Carbon nanotubes, DNA ++

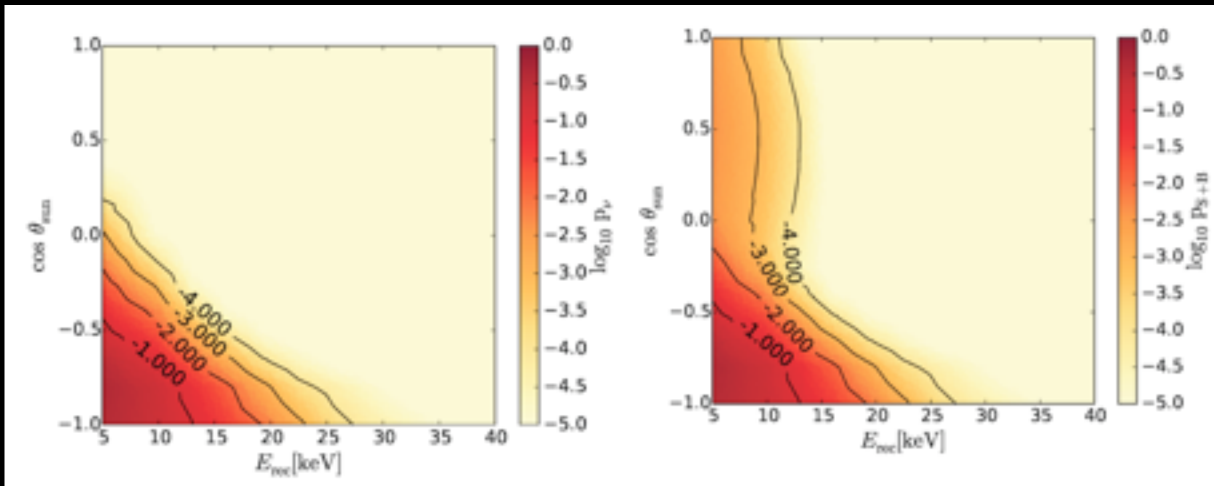
**CYGNUS:** global coordination towards a physics-scale directional experiment.

*huge experimental challenge to measure direction of recoil tracks of O(10 keV): <mm length!*

# Beyond the Neutrino Bound

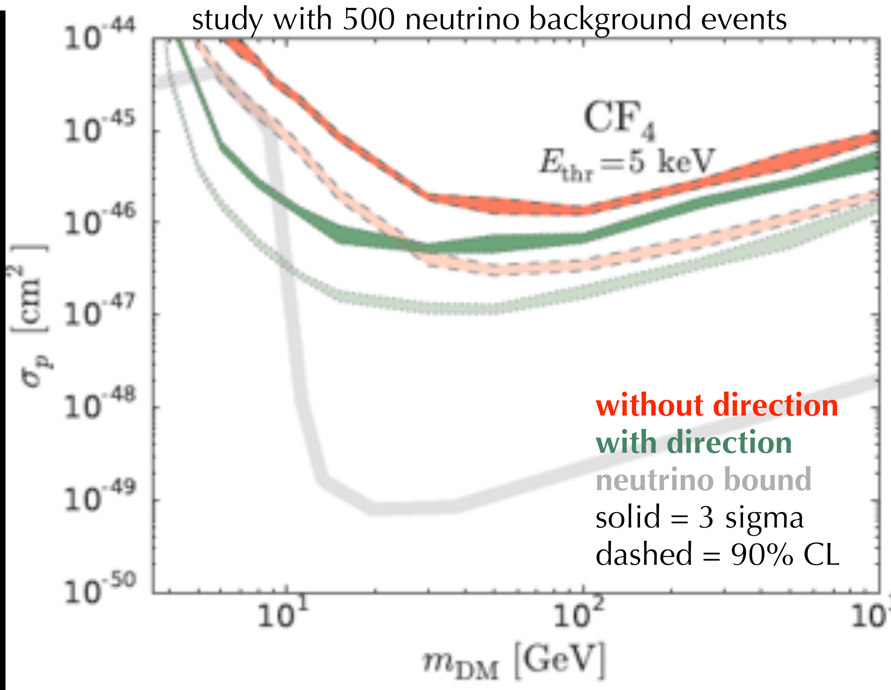
*Grothaus, Fairbairn, JM*
*Phys.Rev.D90 (2014) 055018*

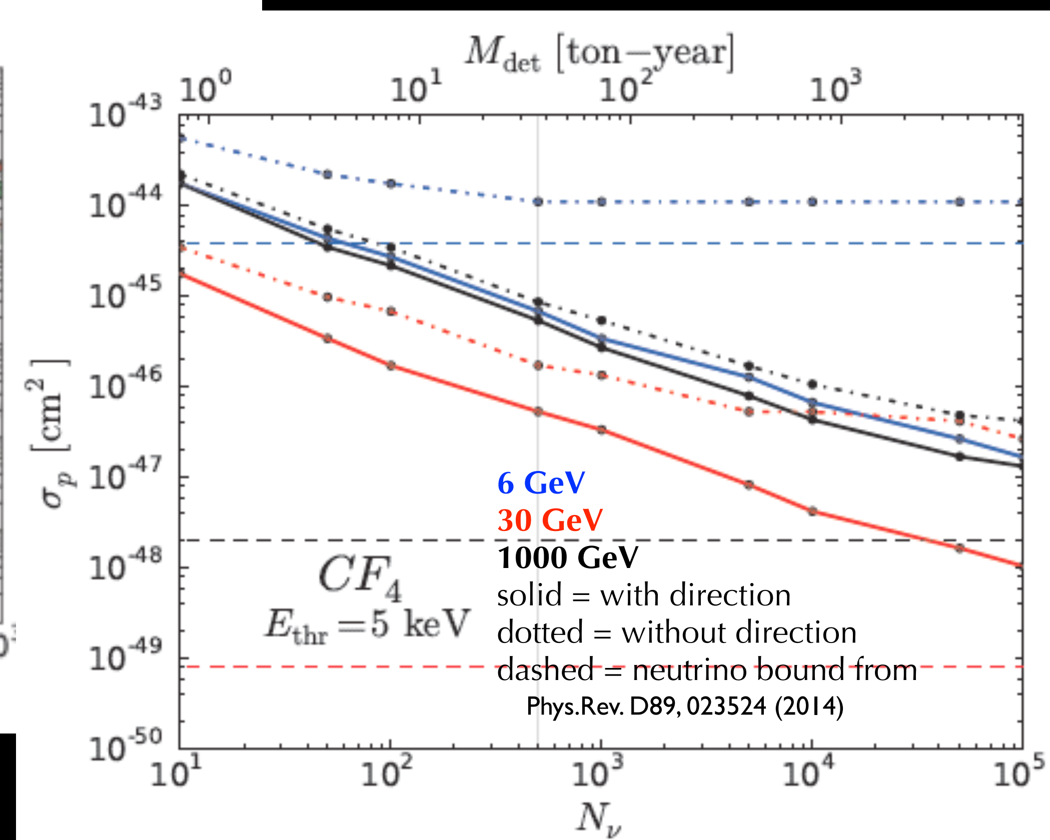
PDFs in (energy, angle, time) of event for coherent solar nu background vs. background+signal show significant differences, including 35° resolution:



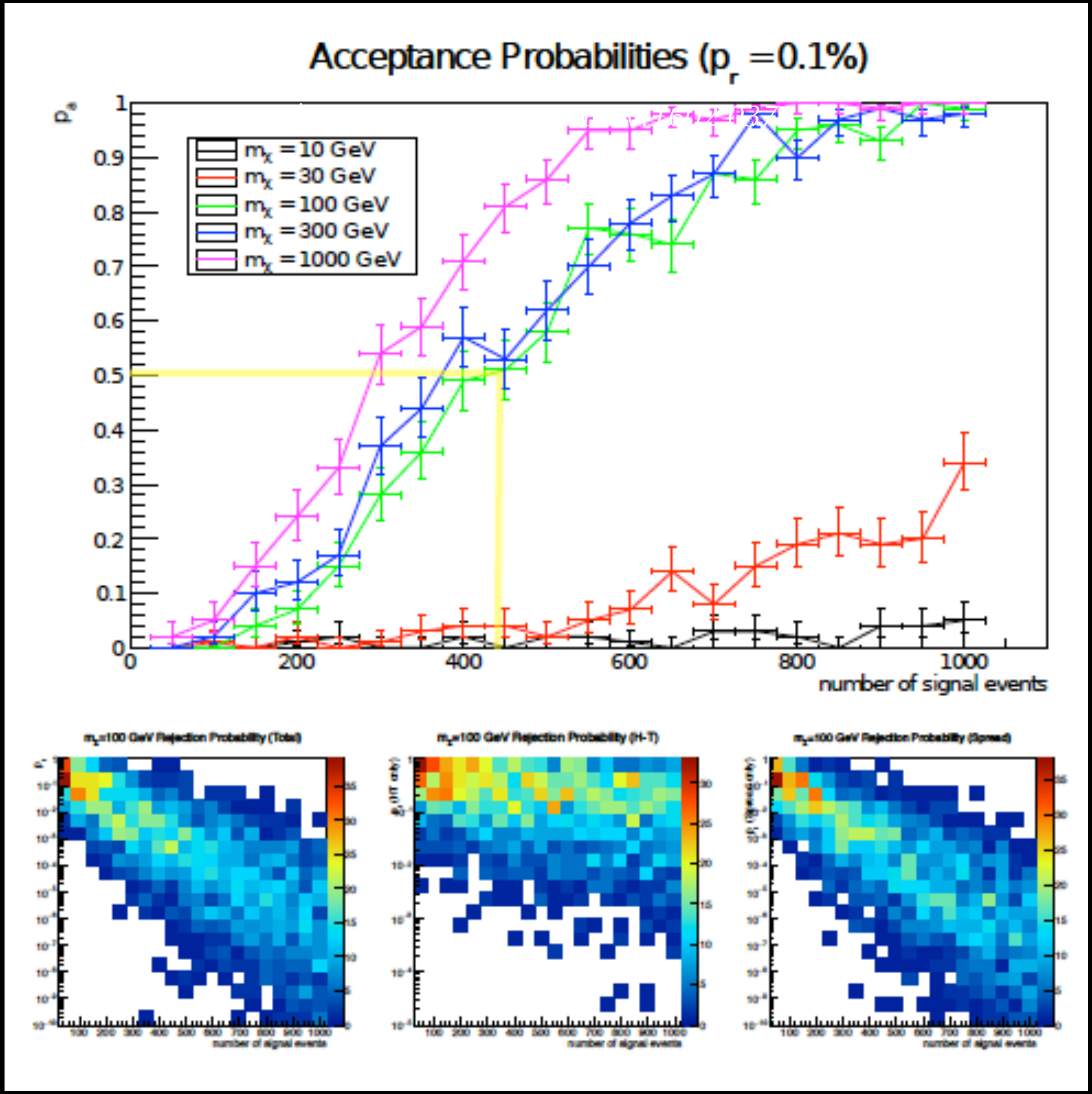

statistical test (CLs) shows

- directionality gains 10x in sensitivity with background
- no neutrino bound for directional detectors!



# Directional Detection Signal Sensitivity




<u>Analysis assumptions</u>

- Use physics model tuned on DMTPC calibration data
- simulate *n* experiments, compute forward fraction and axial spread per bin
- calculate *p* of obtaining these values from isotropic distribution, and combine bins using Fisher's method
- Result: need 450 events to measure anisotropy at $3\sigma$ in >50% of experiments.

*P. Fisher, JM et al., accepted to Phys. Rev. D*

# Outline

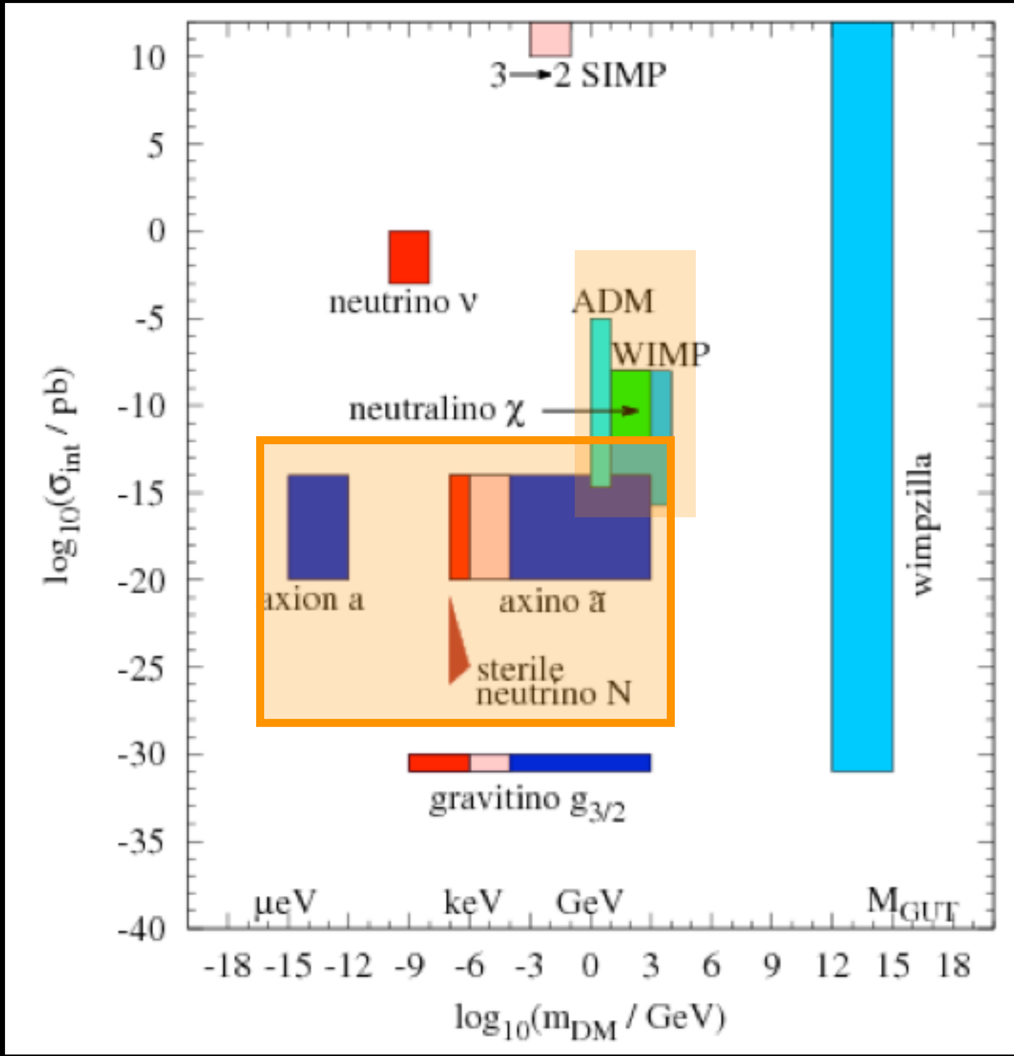
Experimental Considerations in Direct Detection Searches

Status and Prospects of Experiments

**Beyond WIMP Dark Matter in Direct Detection Experiments**

# Model Space

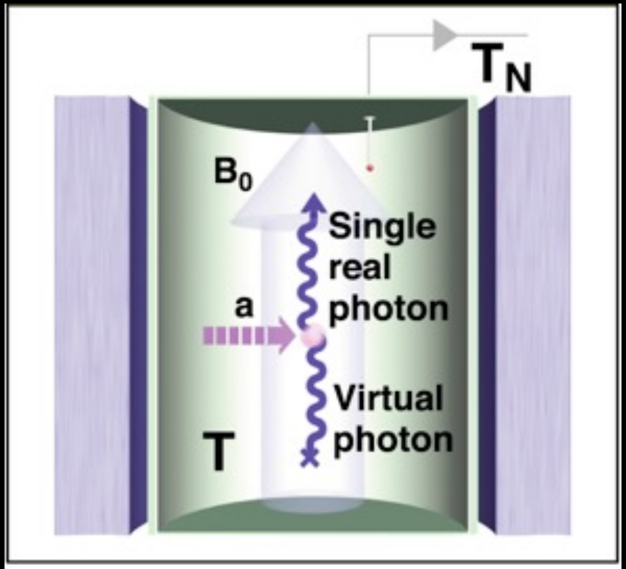
WIMPs aren't the only possibility!




*Baer et al., arXiv:1407.0017*

## Axion and ALP detection:

Primakoff conversion searches:
**ADMX**, **CAST** (direction modulation)




constraints from direct detection:
**EDELWEISS**, **XENON100**, **XMASS**

search for axio-electric effect:

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha_{em}\,{m_e}^2}\left(1-\frac{\beta_A^{2/3}}{3}\right),$$

observable: peak in electron recoil spectrum at axion mass. Analysis: bump hunt.

# Axions: Status and Prospects

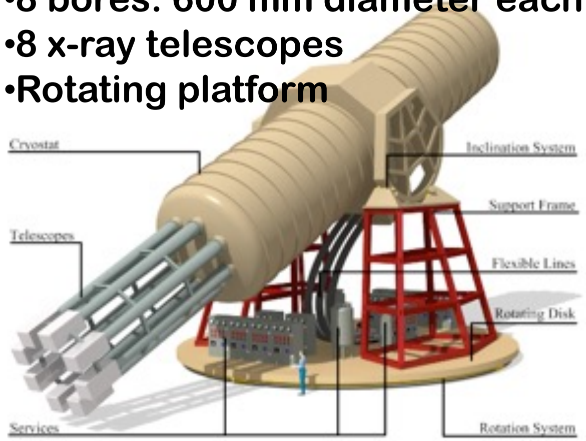
Primakoff conversion searches:

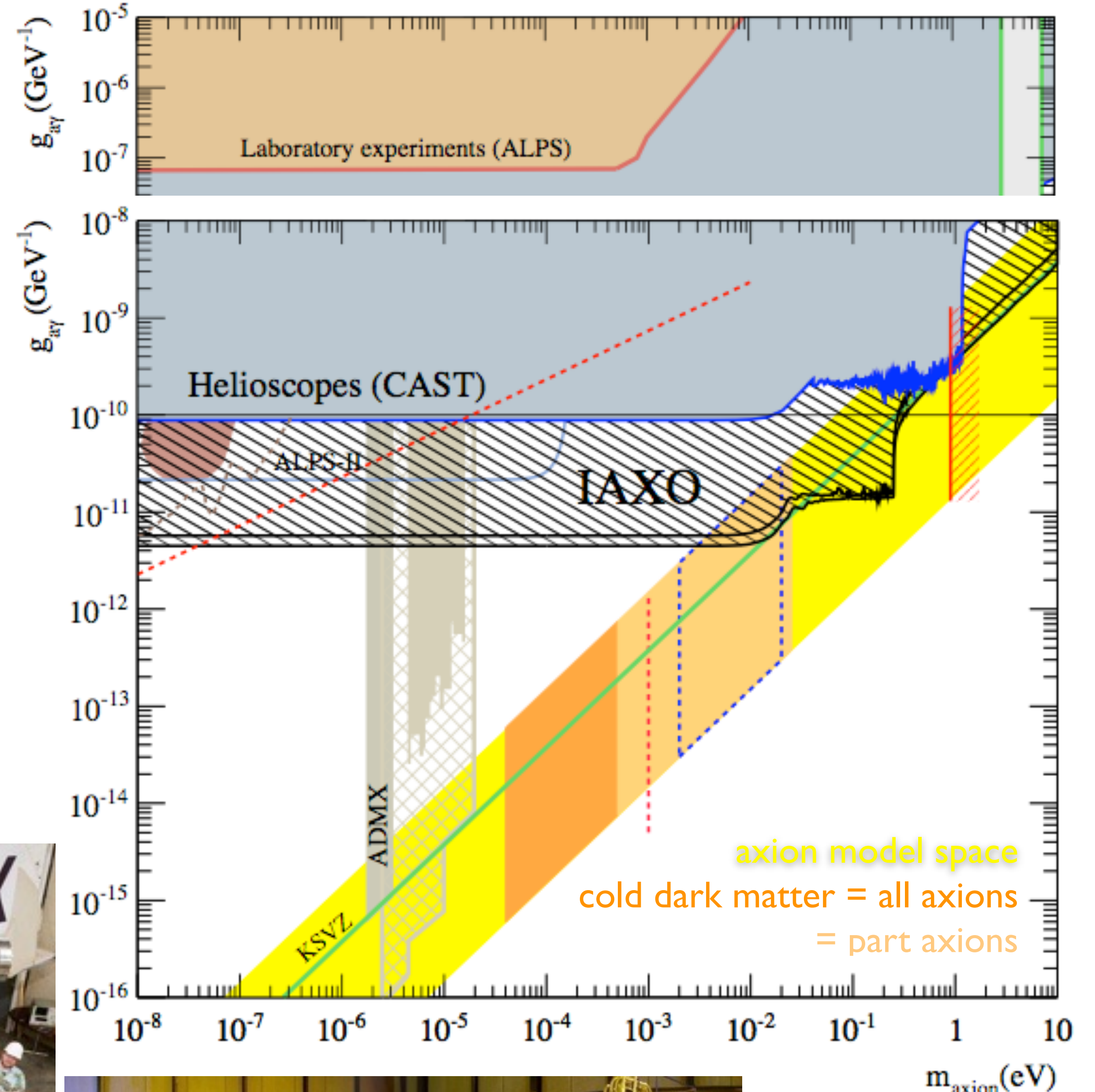
**CAST:** helioscope searching for solar axion conversion in an LHC magnet tracking the sun, micromegas readout

**ADMX**: halo axion conversion in resonant cavity with B field, scanning in frequency. Run 2 started 2016.

**IAXO**: international proposed axion helioscope at CERN, *(SPSC 1-242)*

- 20m long toroid 8-coil magnet
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes
- Rotating platform




*+many new ideas at smaller scales!*

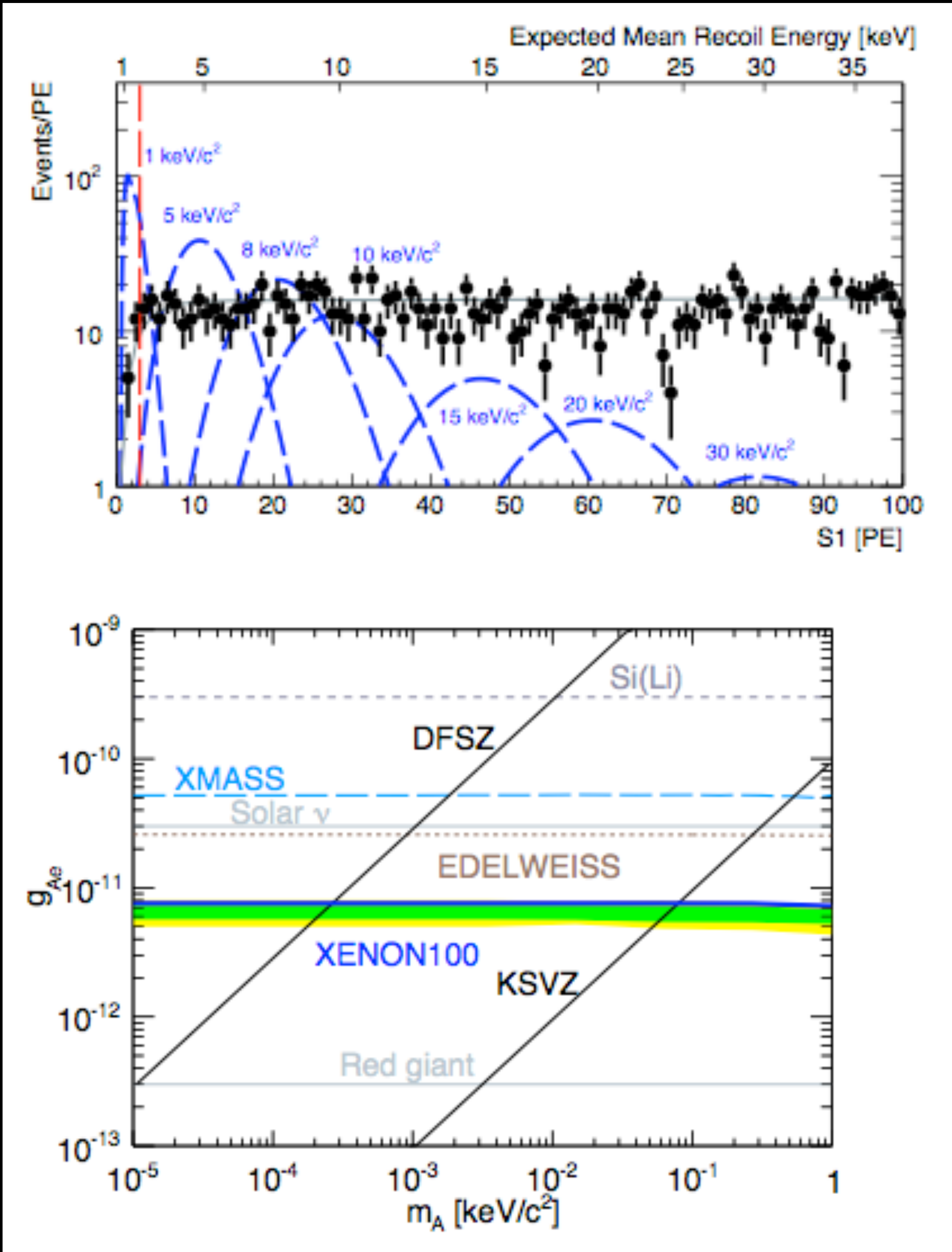
# Axion/ALPs in Direct Detection: Bump Hunts

**XENON100**: searches for axions and ALPS >2 keVee, with background of 1E-4/(keV kg day). *(arXiv:1404.1455)*

**XMASS**: search for vector or pseudo-scalar bosons with mass>40 keV. Background is O(1E-4)/(keV kg day) *(arXiv:1406.0502)*

**Constraints from Theorists**: limits on kinetic mixing to hidden sector coupling extracted from XENON 10, 100, and XMASS spectra. *(arXiv:1412.8378)*

**DAMIC**: search for 1-30 eV axion absorption by electron in the Si, increasing the measured leakage current. *(accepted to PRL, 2017)*



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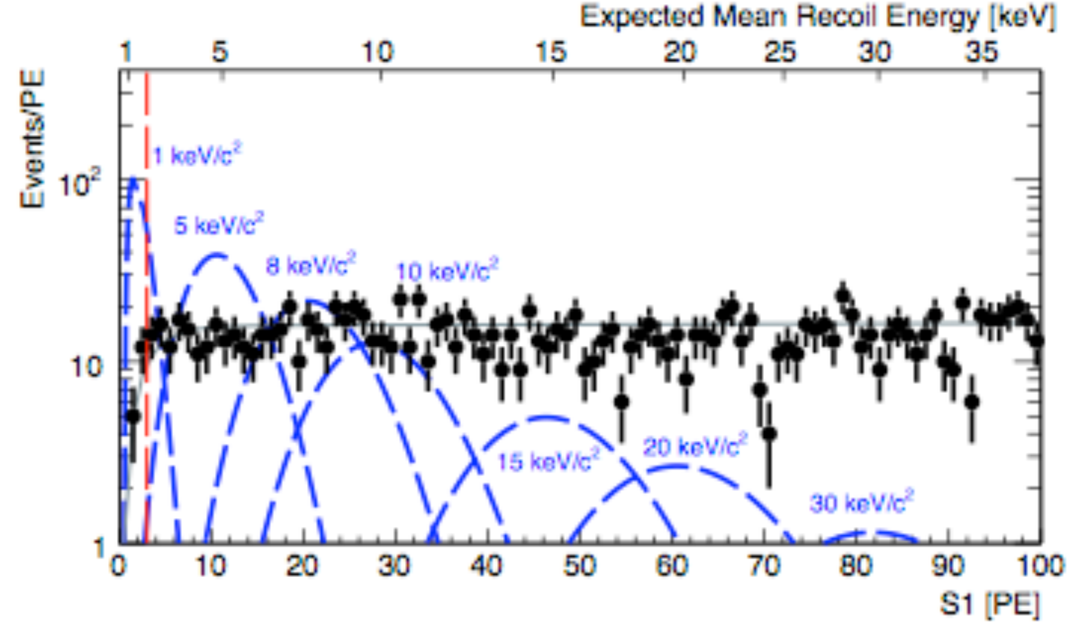


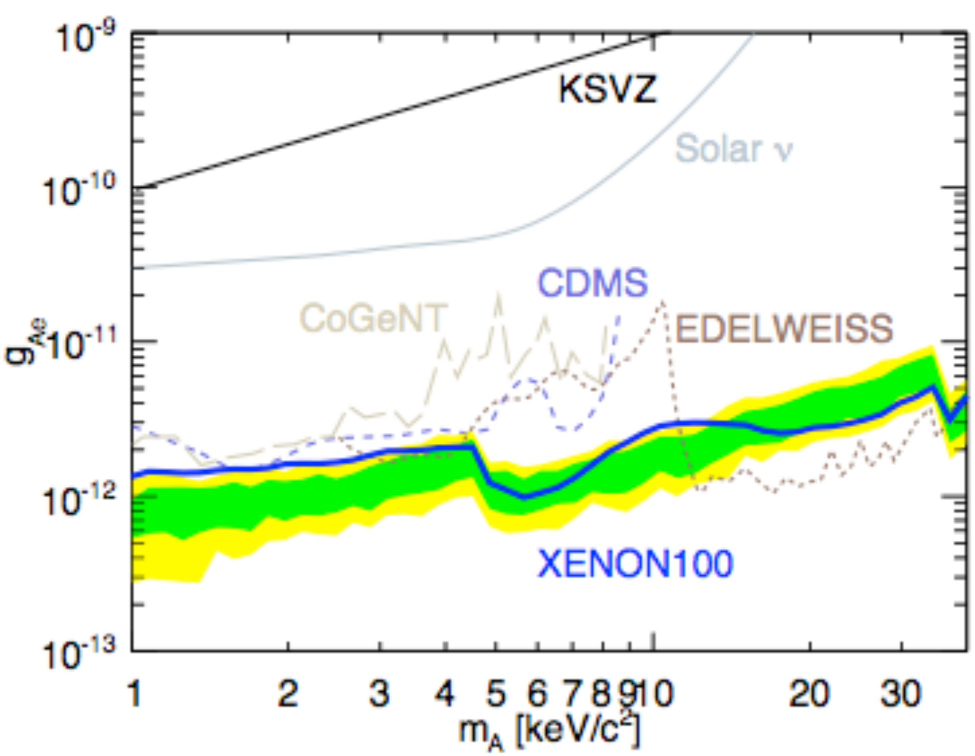

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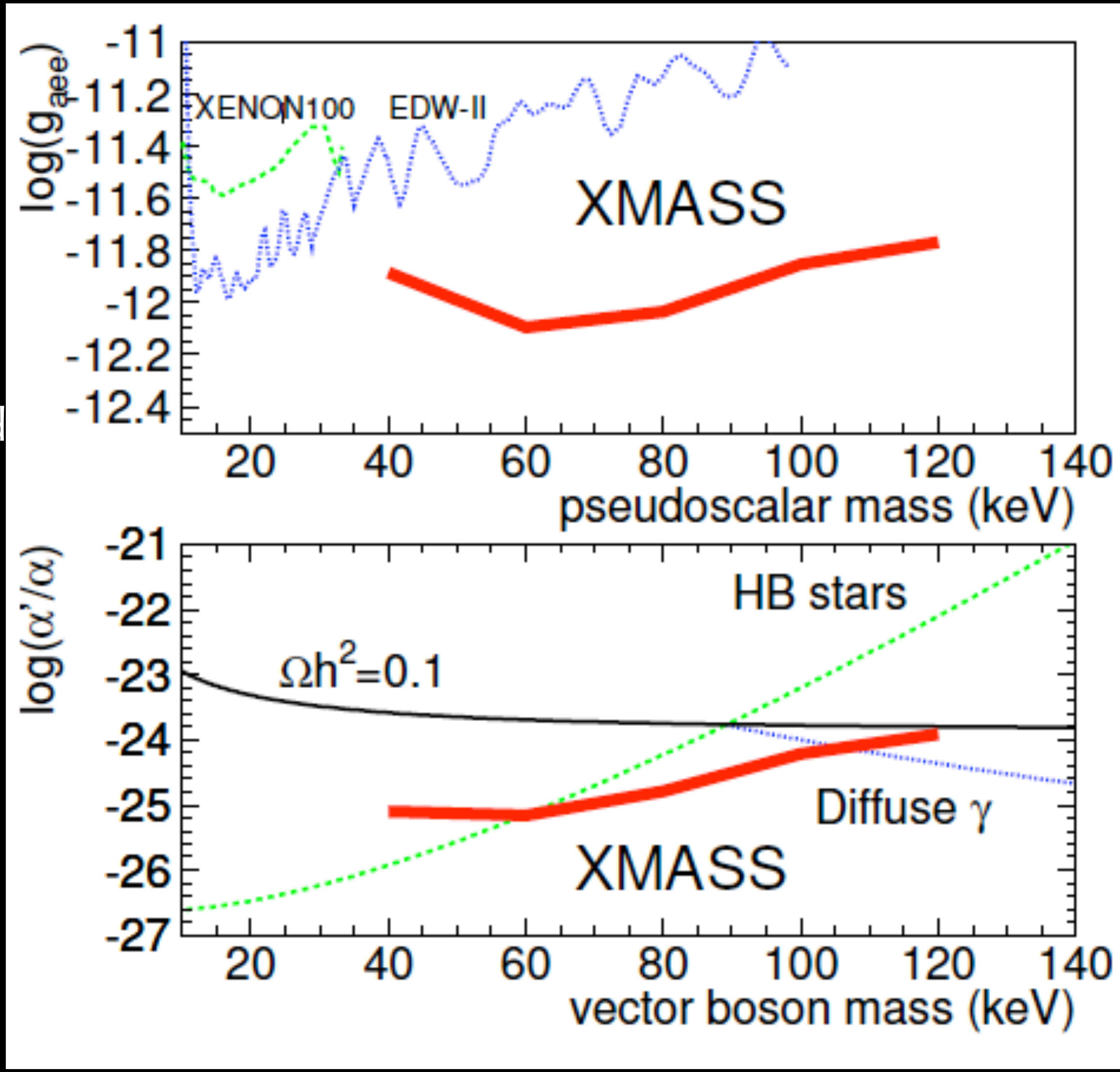

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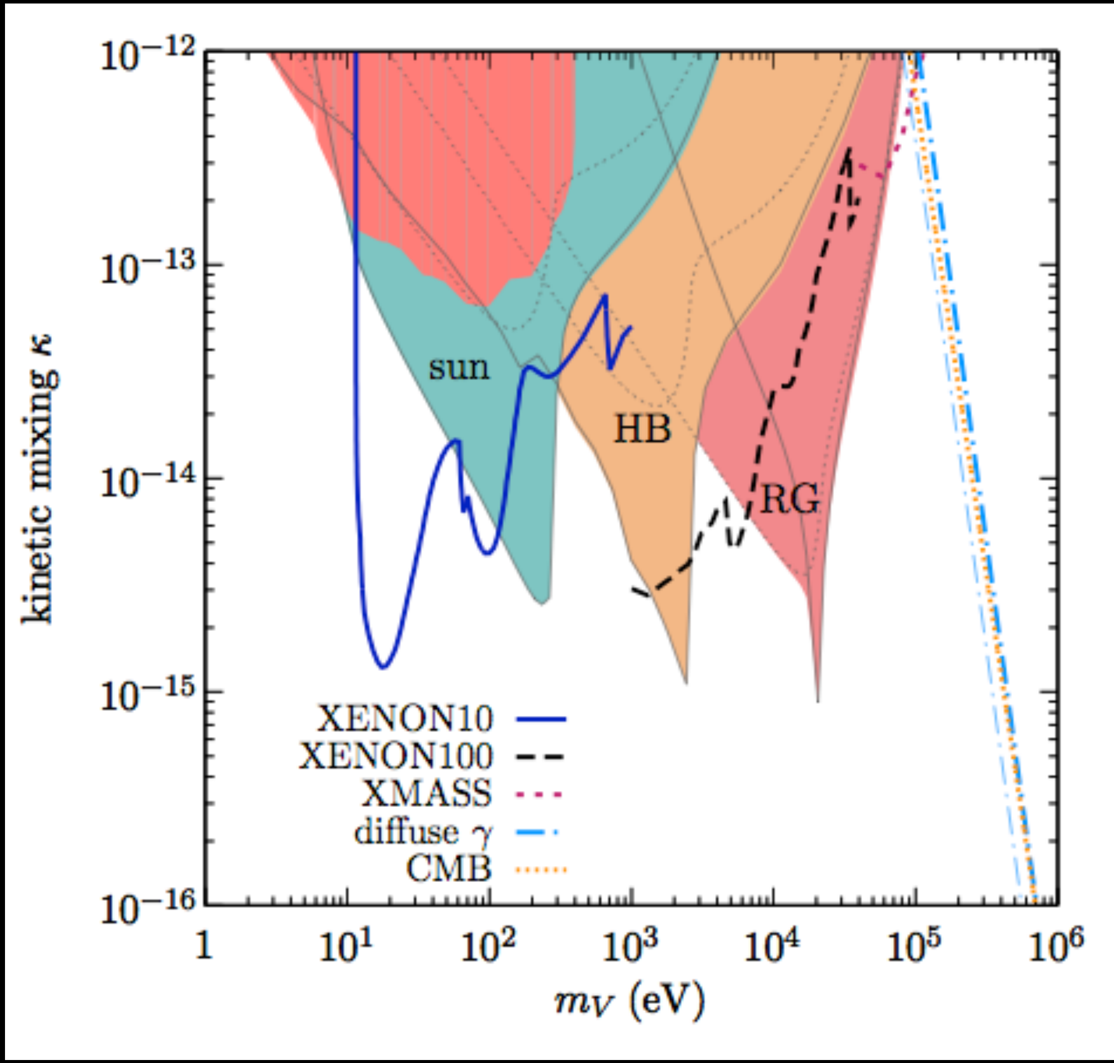

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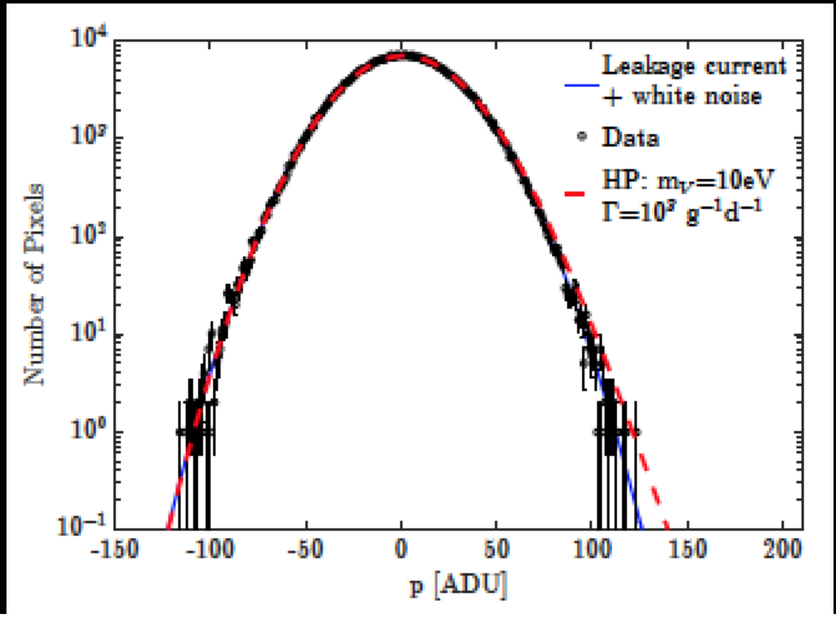


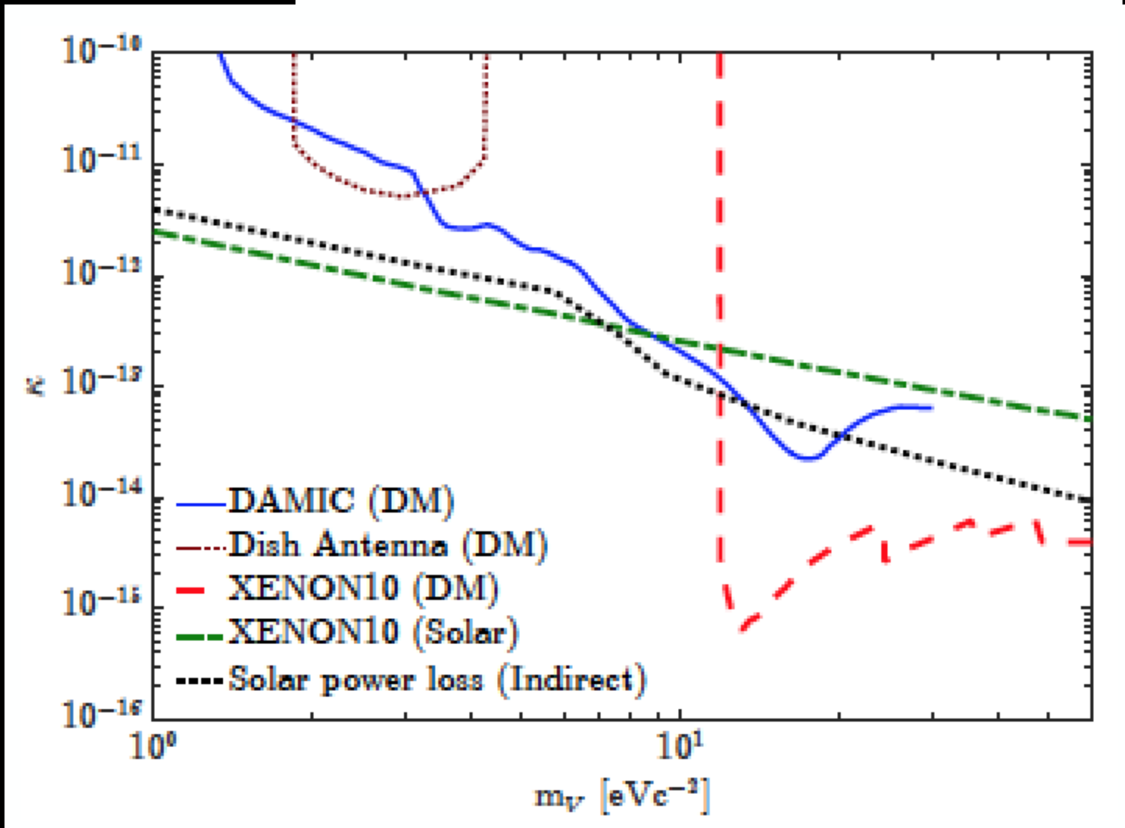

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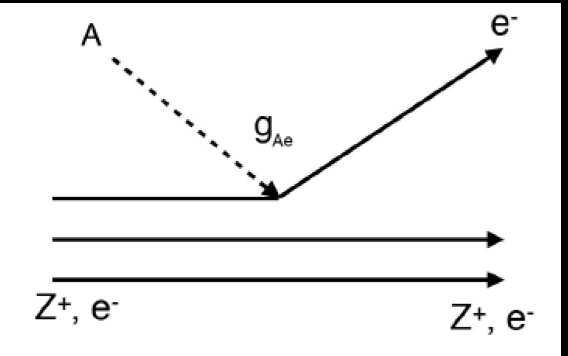
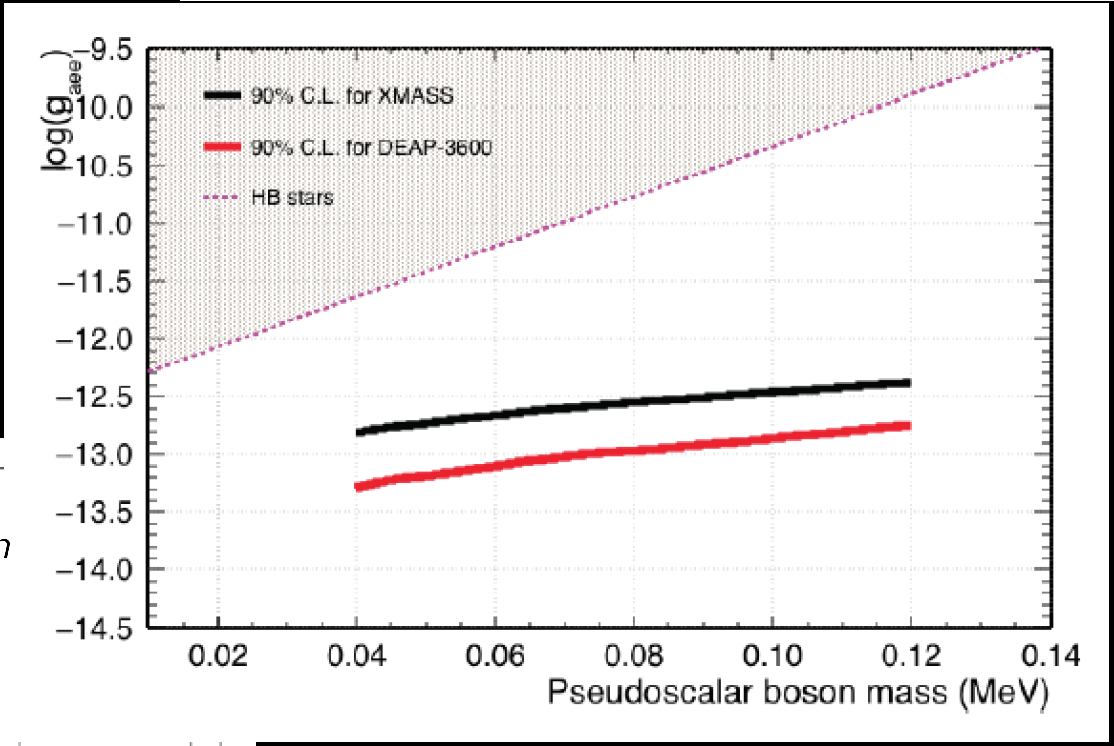



$$R \simeq \frac{1.2\text{x}10^{19}}{A} g_{aee}^2 \left(\frac{m_a}{\text{keV}}\right)\left(\frac{\sigma_{\text{photo}}}{\text{barn}}\right)\text{kg}^{-1}\text{day}^{-1}$$

**Future Prospects**:

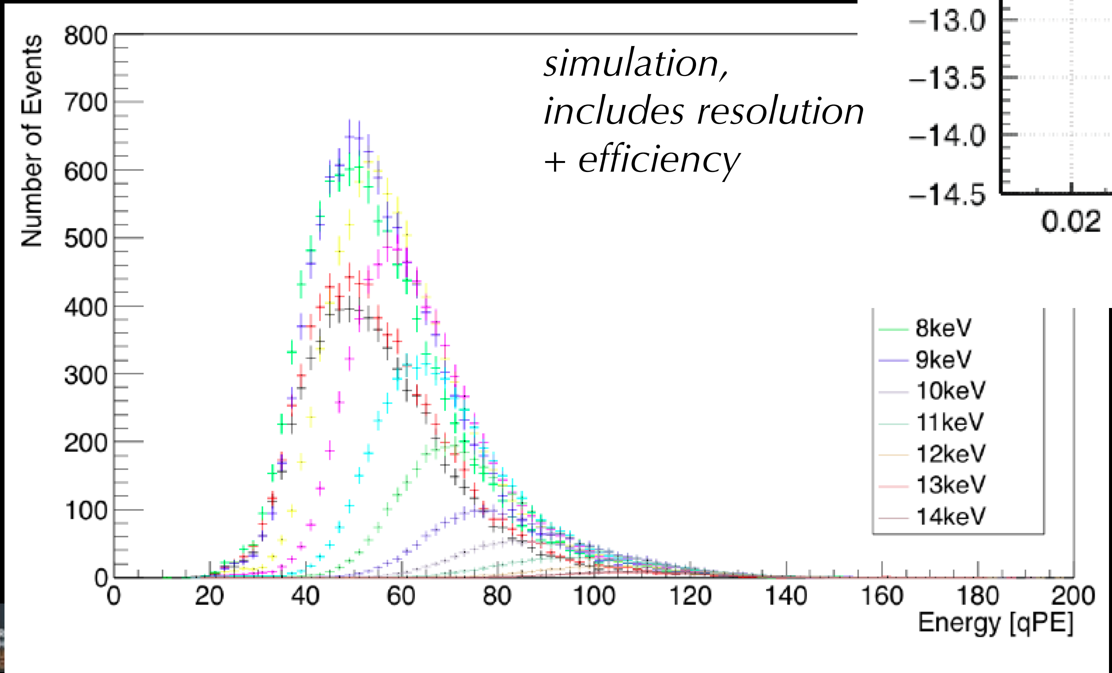
- example sensitivity to pseudo scalar bosons in DEAP-3600 with 3000 kg-yr exposure, increased by ~1/(atomic mass ratio)




- ALP bump hunts in Ar detectors have interesting potential:

-100s of events in DEAP at best-current limit from Xenon100

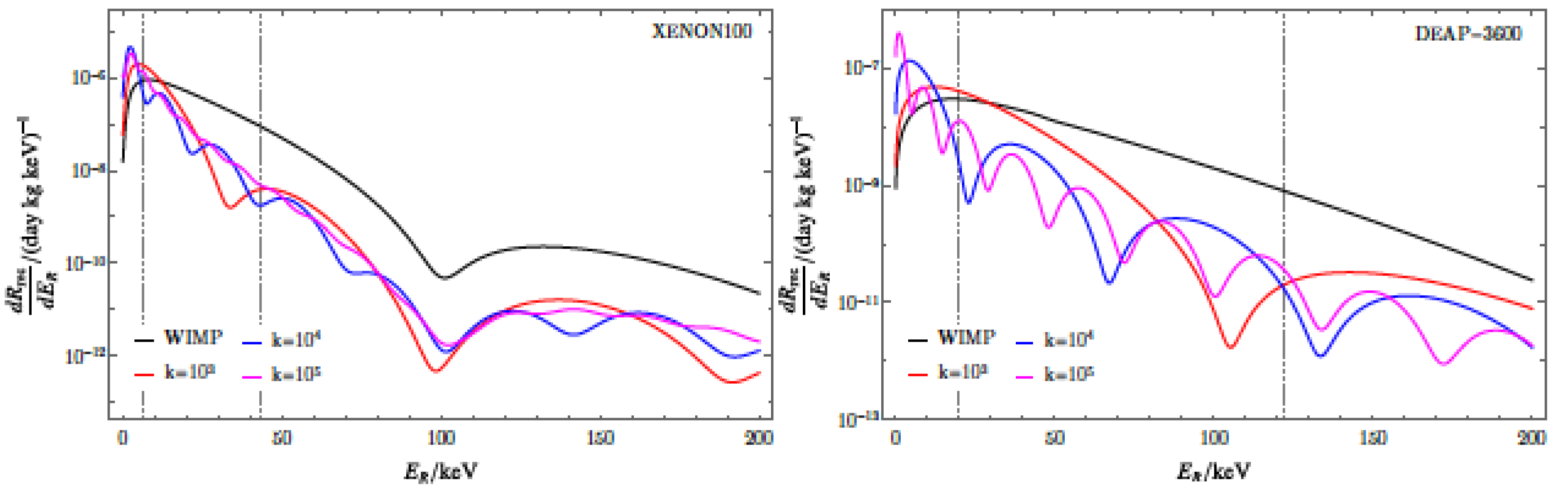
-sensitivity scales as sqrt(t) vs. t in the presence of Ar-39 backgrounds




- main experimental challenges are detailed understanding of efficiency at/below trigger threshold

# Spectral Distortion in Direct Detection, Prospects

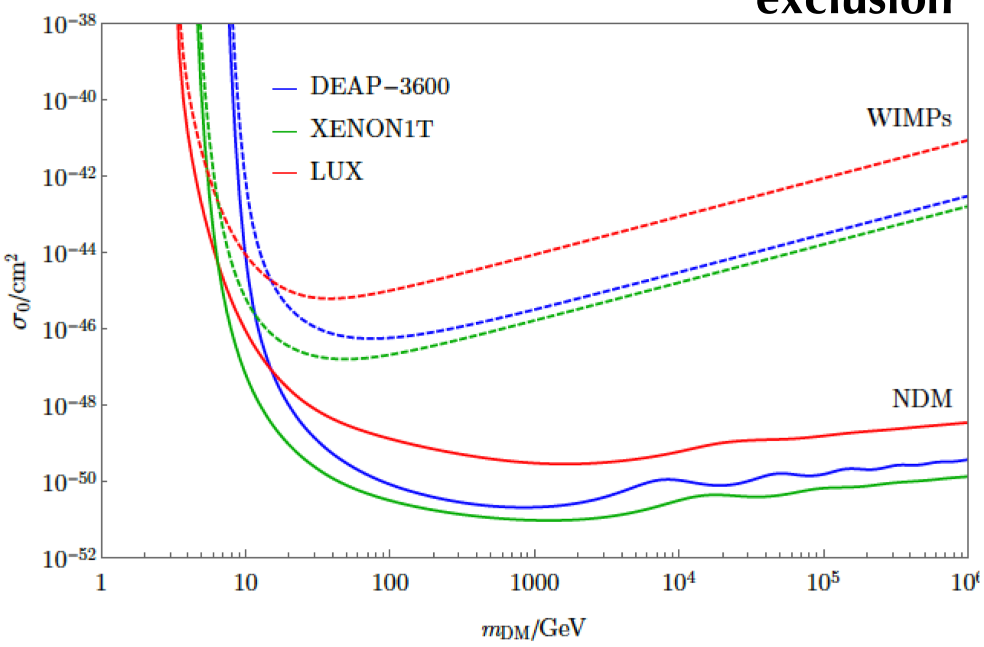
**DEAP-3600:** sensitivity to composite dark matter, e.g. *Hardy, Lazenby, March-Russell, West JHEP 07 (2015)*
dark nuclei, formed of *k* bound states of self-interacting dark nucleons.
Scattering process now has a form factor from the nuclear dark matter and the target.



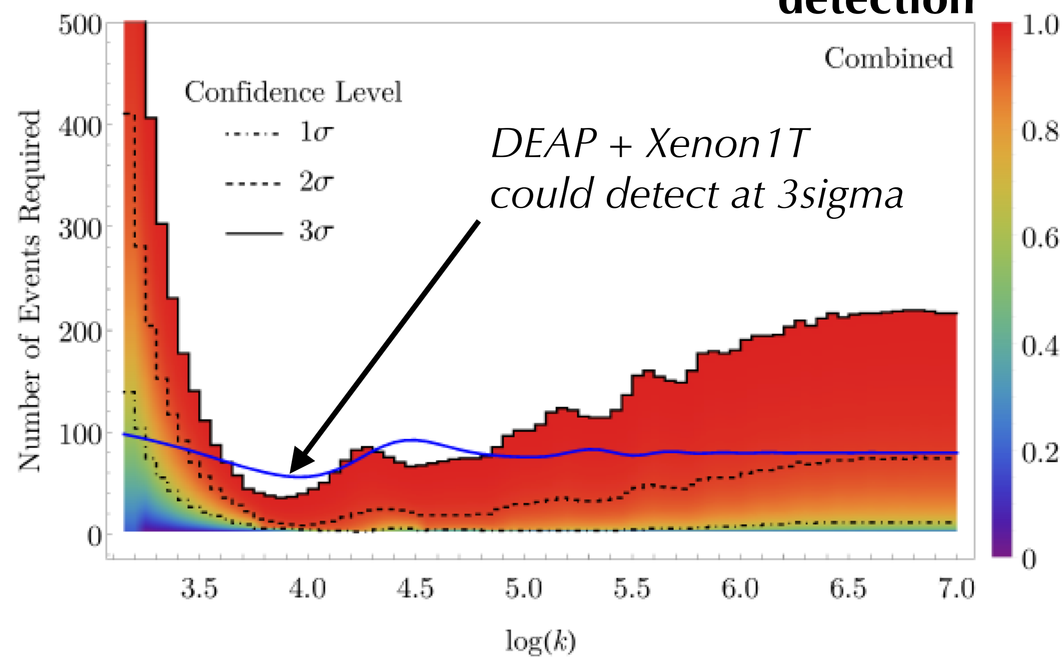

example: dark nucleon mass = 1 GeV, r = 1 fm, and per-SM nucleon xsec = 1E-46 cm$^2$.

*Kirk, Butcher, JM, West, arXiv:1610.01840*

**exclusion**




**detection**

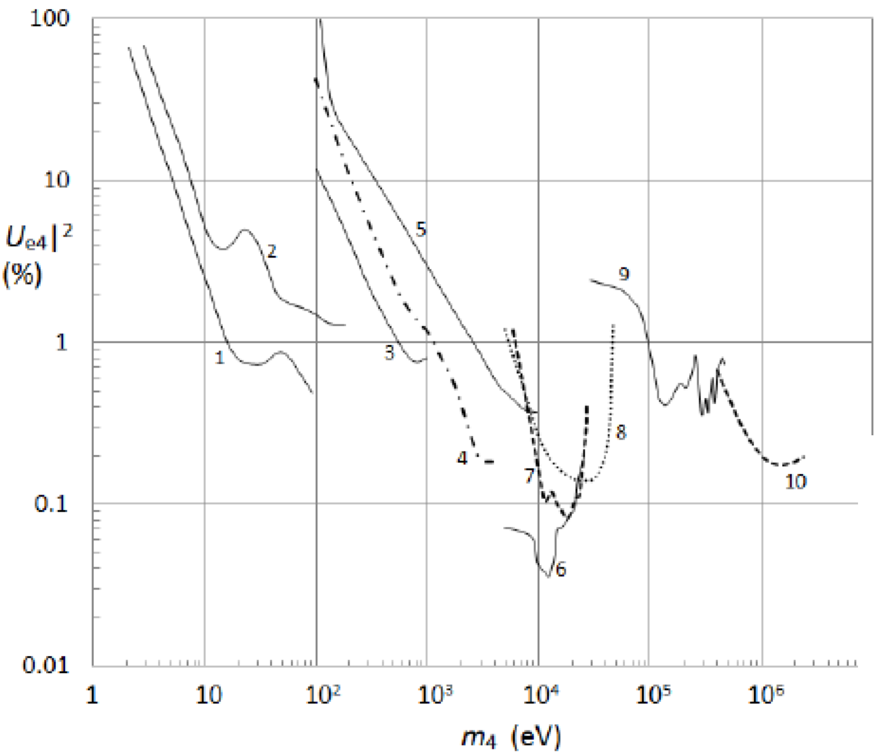


# Sterile Neutrino Dark Matter Sensitivity, Prospects

*(N. Fatemoghomi, JM, in preparation)*

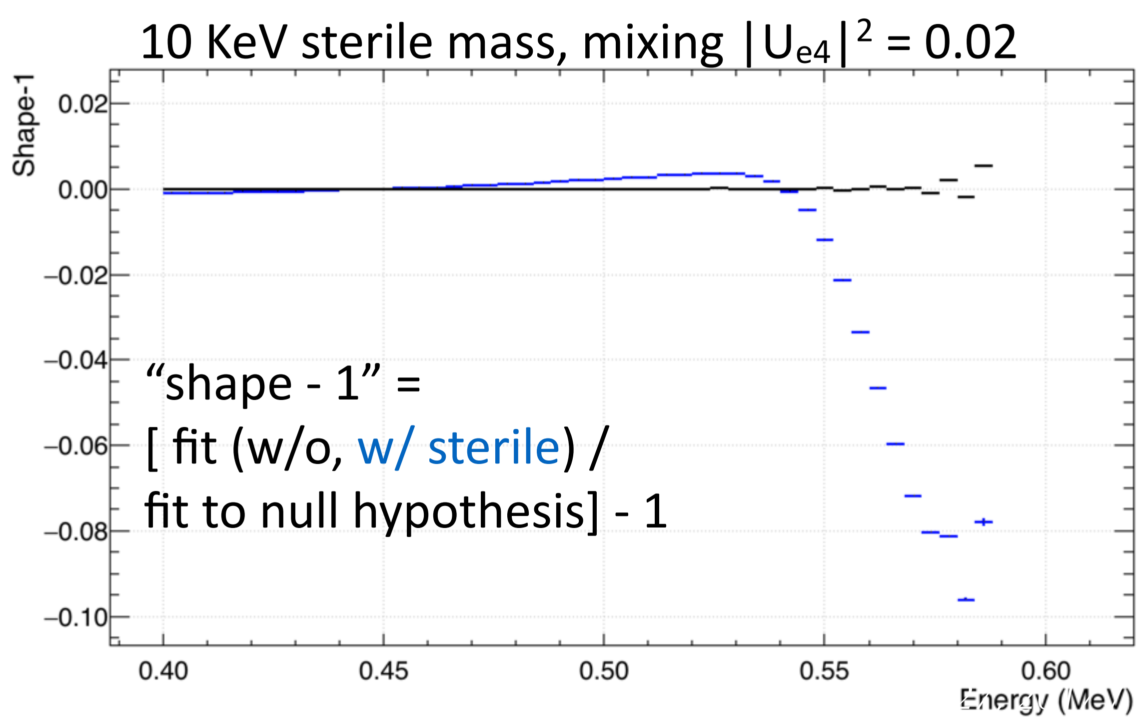
The beta decay energy spectrum is modified by neutrino mass and mixing:

$$\frac{dN}{dE} = A \cdot F(E, Z+1) \cdot p \cdot (E + m_e) \cdot \sum_i P_j \cdot (\varepsilon - V_j - m_i) \cdot \sum_i |U_{ei}|^2 \cdot \sqrt{(\varepsilon - V_j)^2 - m_i^2} \cdot \theta(\varepsilon - V_j - m_i)$$




upper limit on $|U_{e4}|^2$ at 10 keV mass ~ 0.02 at 90% CL *(arXiv:1503.07416)*

In DEAP-3600 with 3 years exposure, including energy resolution, the distortion produced in the Ar-39 beta spectrum at the endpoint would be large!




high statistics, high Q-value beta decays of background isotopes (e.g. Ar-39) in large detectors with good resolution potentially gives sensitivity to WDM.

# Conclusions & Outlook

Direct detection searches are rapidly expanding physics reach:

to lower cross sections, probing new parameter space,
to lower masses, testing new models,
to higher masses, complementary with the LHC,
to new particle candidates (axions, ALPS, ...)

Many new ideas for non-standard searches in direct detection!

Experiments running now or under construction will improve sensitivity reach by 1-2 orders of magnitude in next few years, aiming to continue to beat Moore's Law by 2x.

… and today's background may be tomorrow's signal. *(T. Kajita, 2015)*