Dark Matter Direct Detection

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PPAP Town Meeting, Imperial College London
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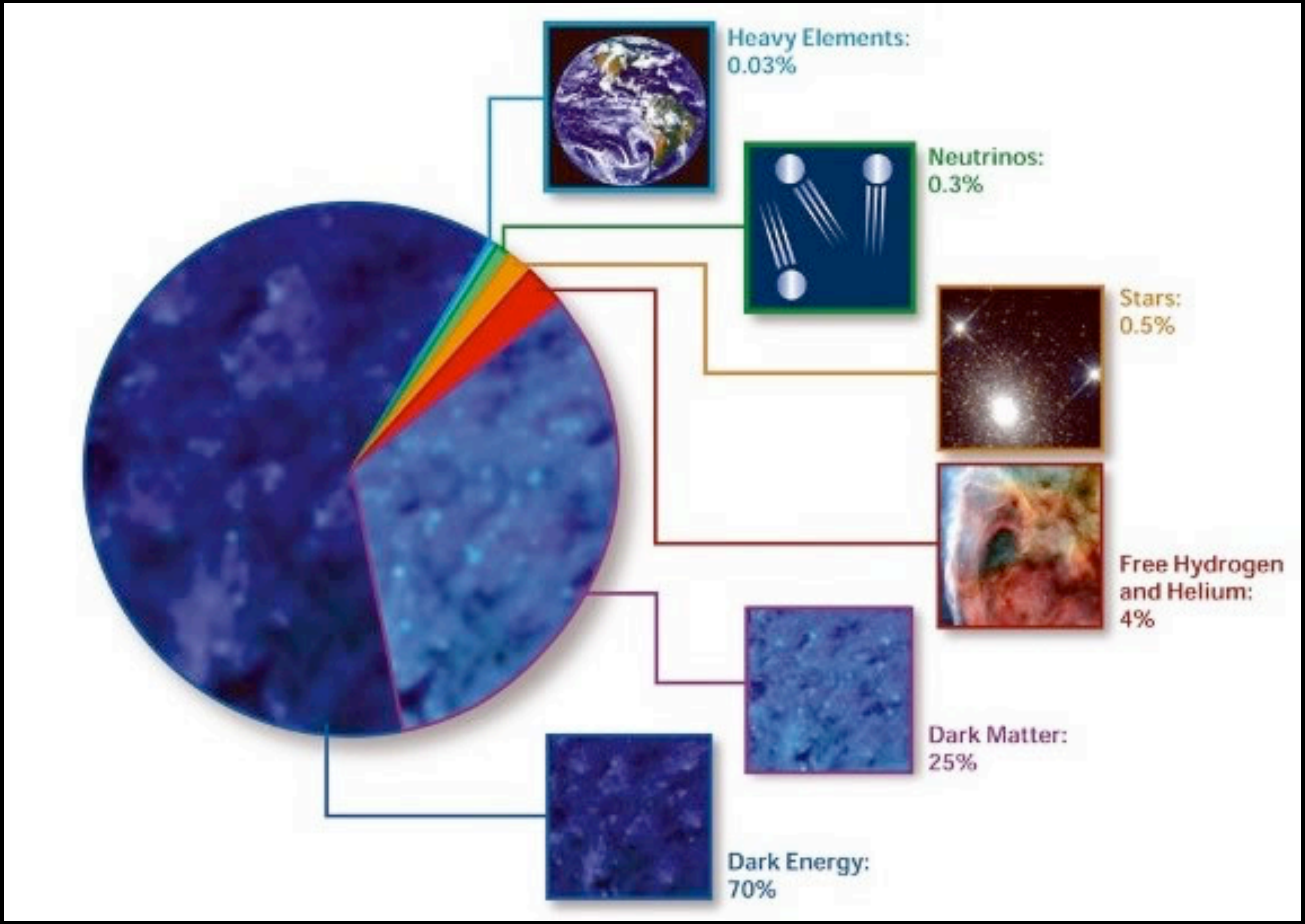
Outline

Introduction to Dark Matter Searches

Status and Prospects of Direct Detection Experiments

Outlook

Standard Model of Cosmology

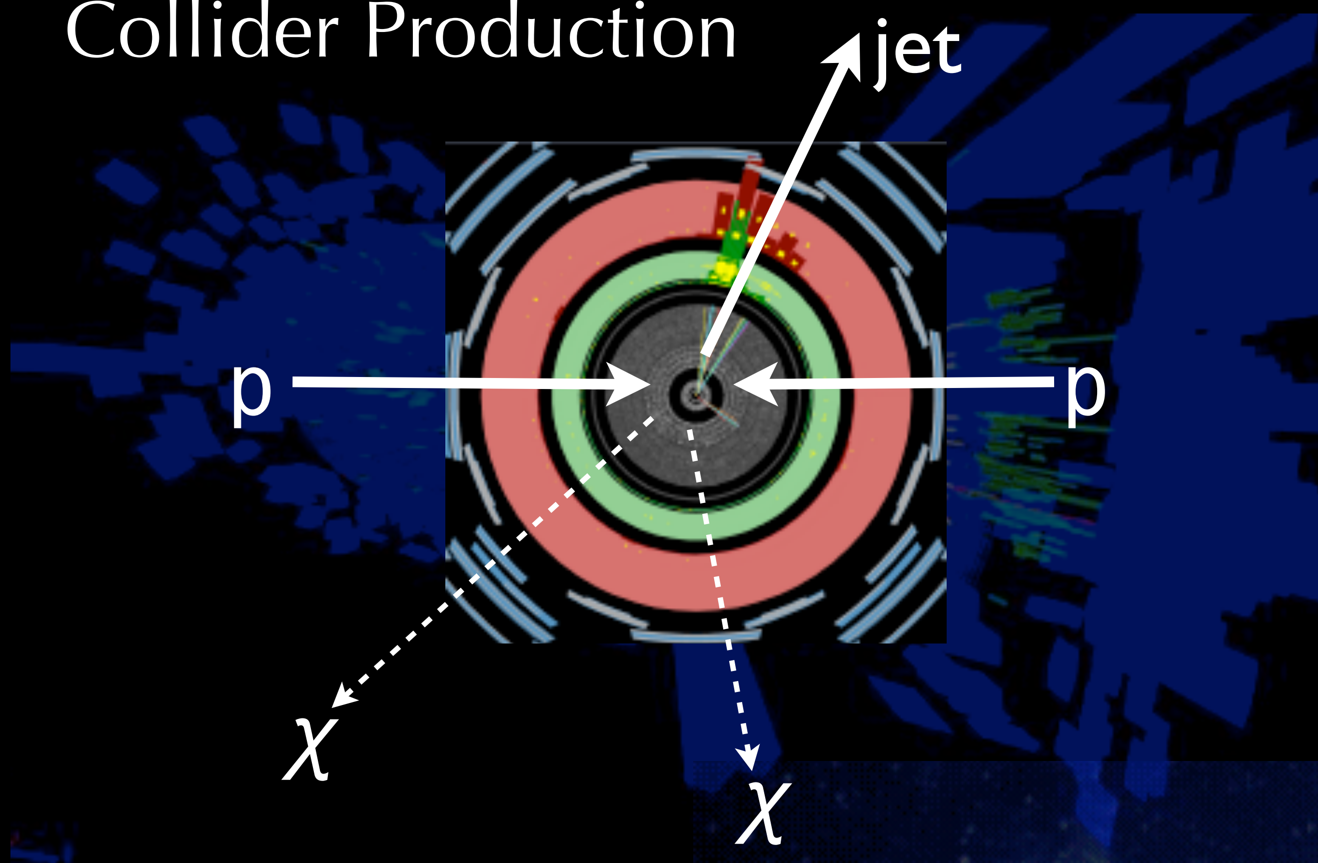


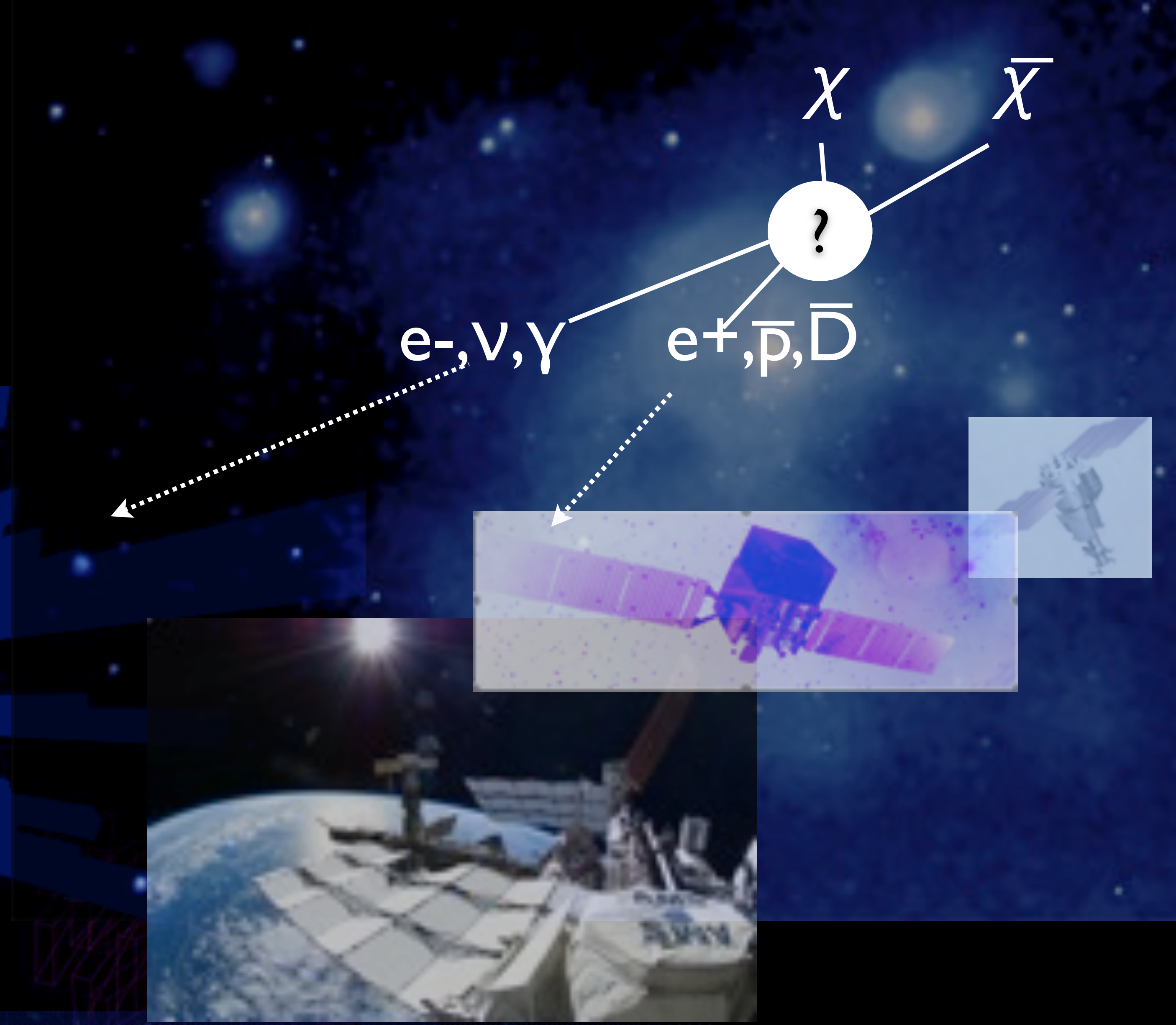
Dark Matter is ~30% of the energy density of the universe.

Searches for Dark Matter

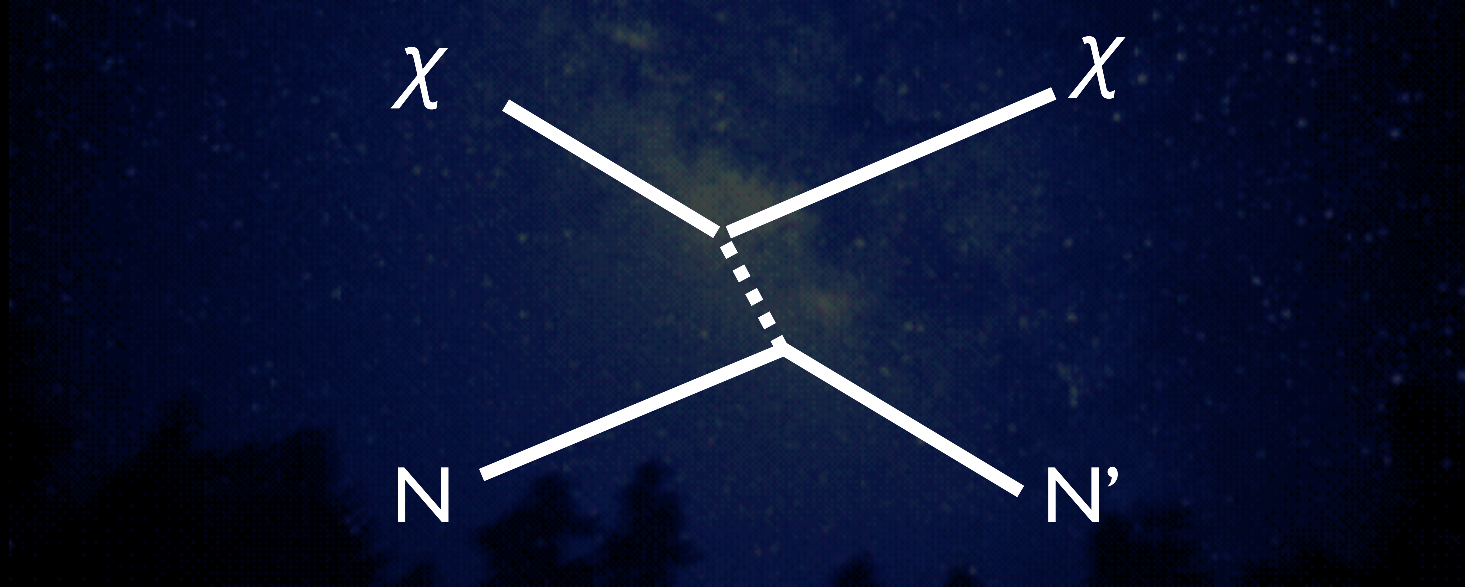
Indirect Detection

Collider Production



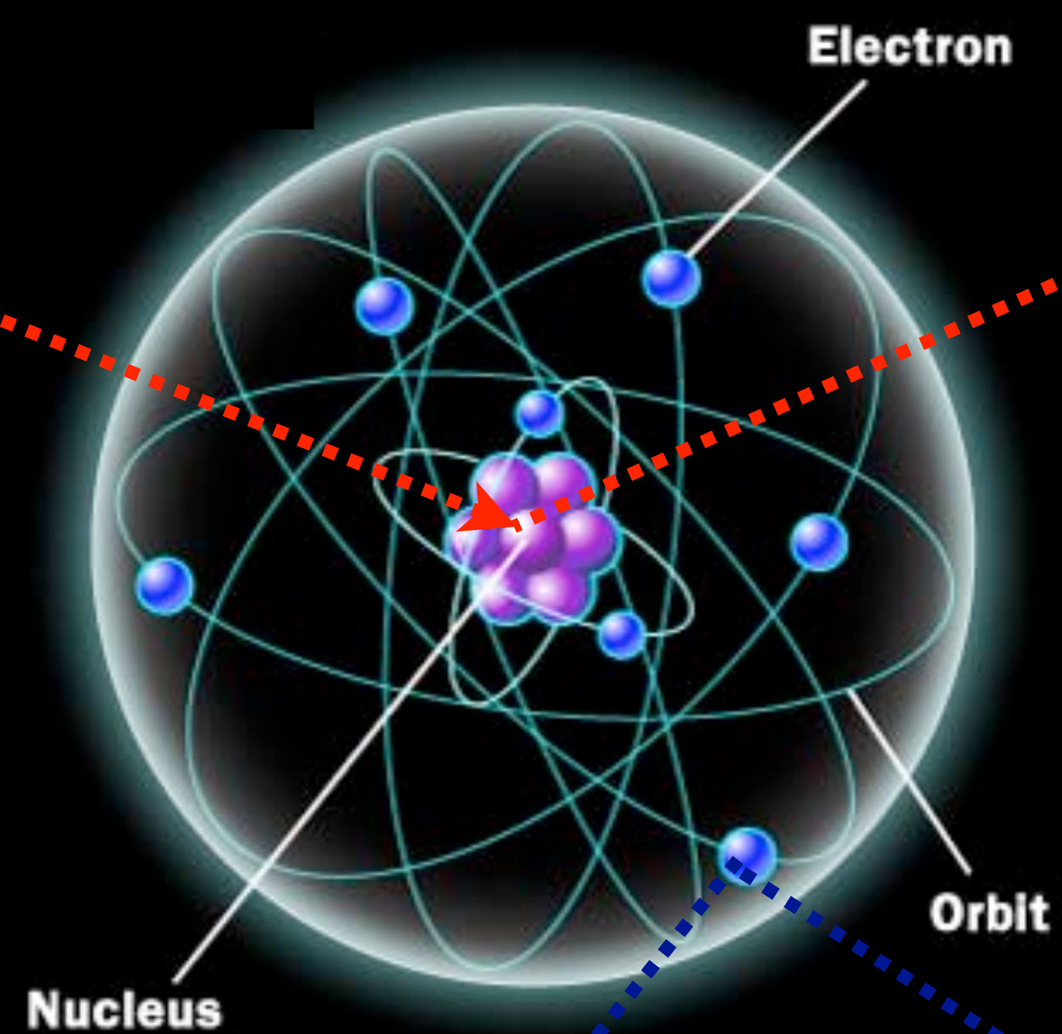


Direct Detection



Dark Matter Direct Detection

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



Backgrounds:

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

$n\ N \rightarrow n\ N$

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

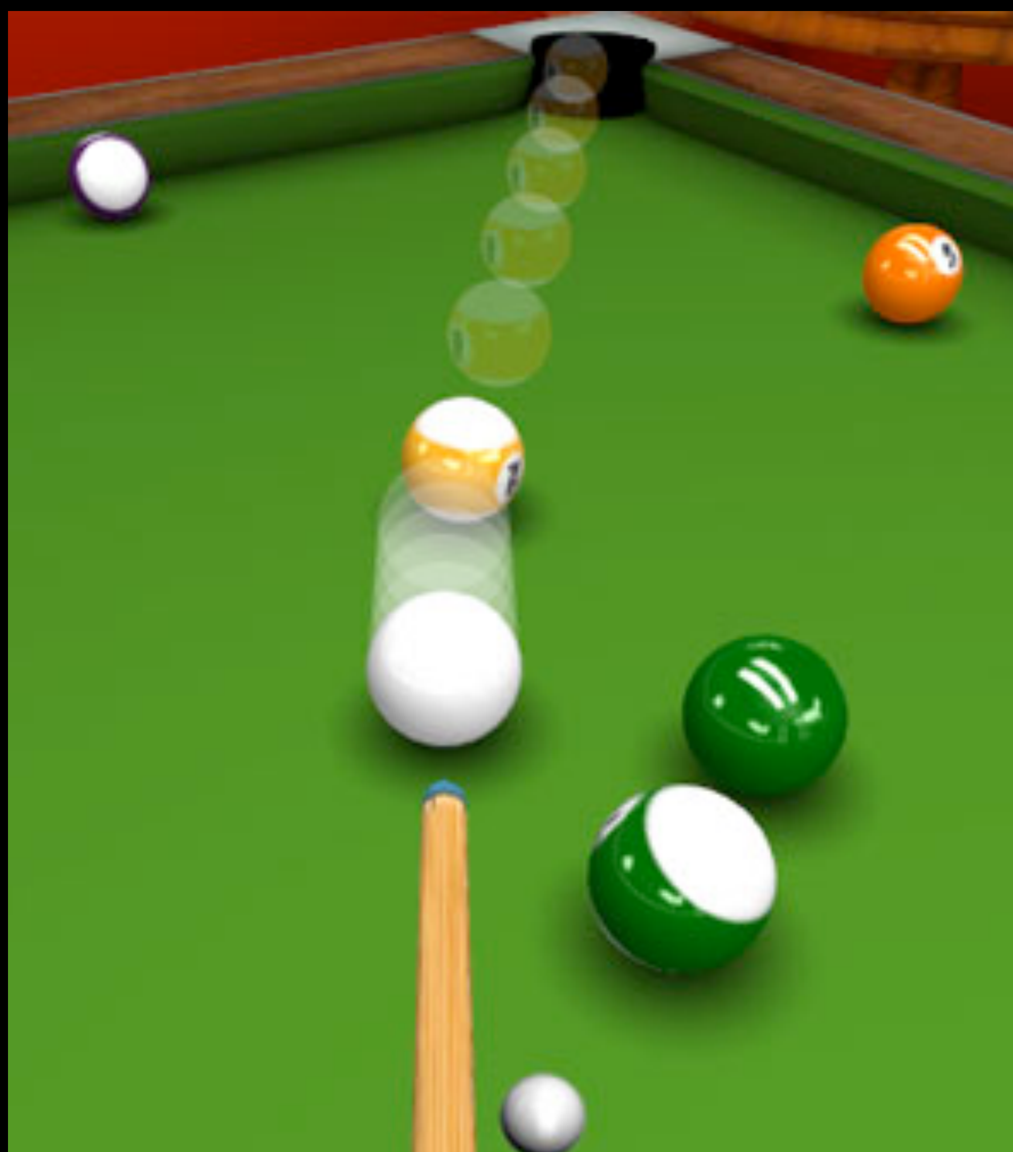
$\nu\ N \rightarrow \nu\ N$

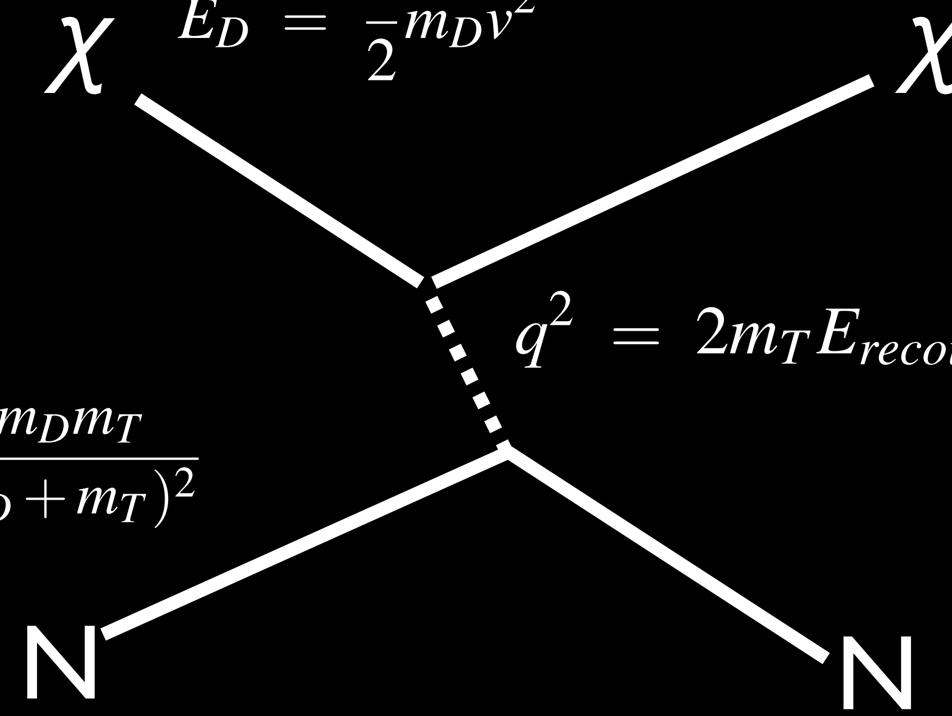
detector requirements: particle ID for recoil N, e-, alpha, n (multiple) final states

WIMP Scattering

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

recoil angle strongly correlated
with incoming WIMP direction





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

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

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

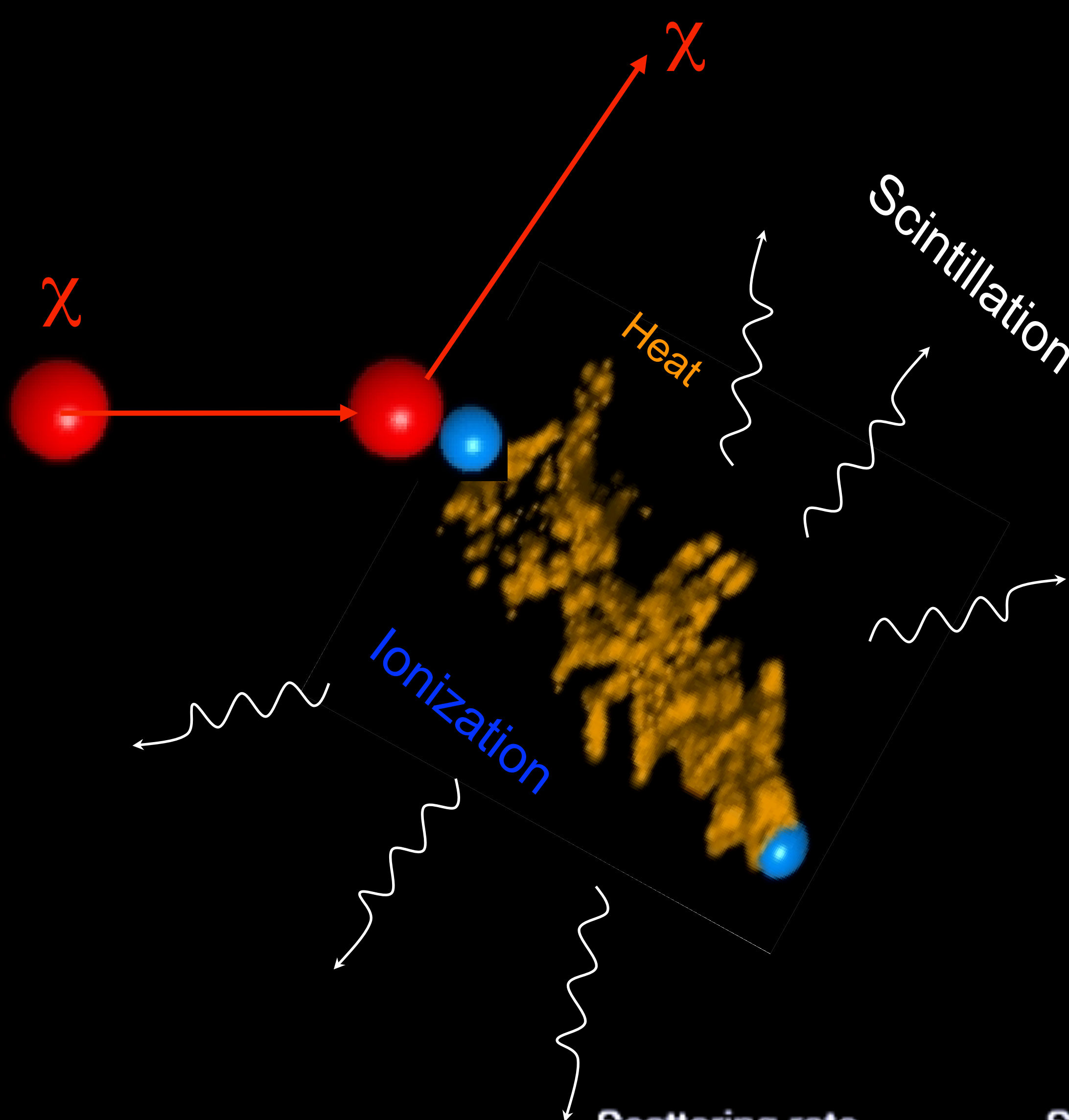
$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

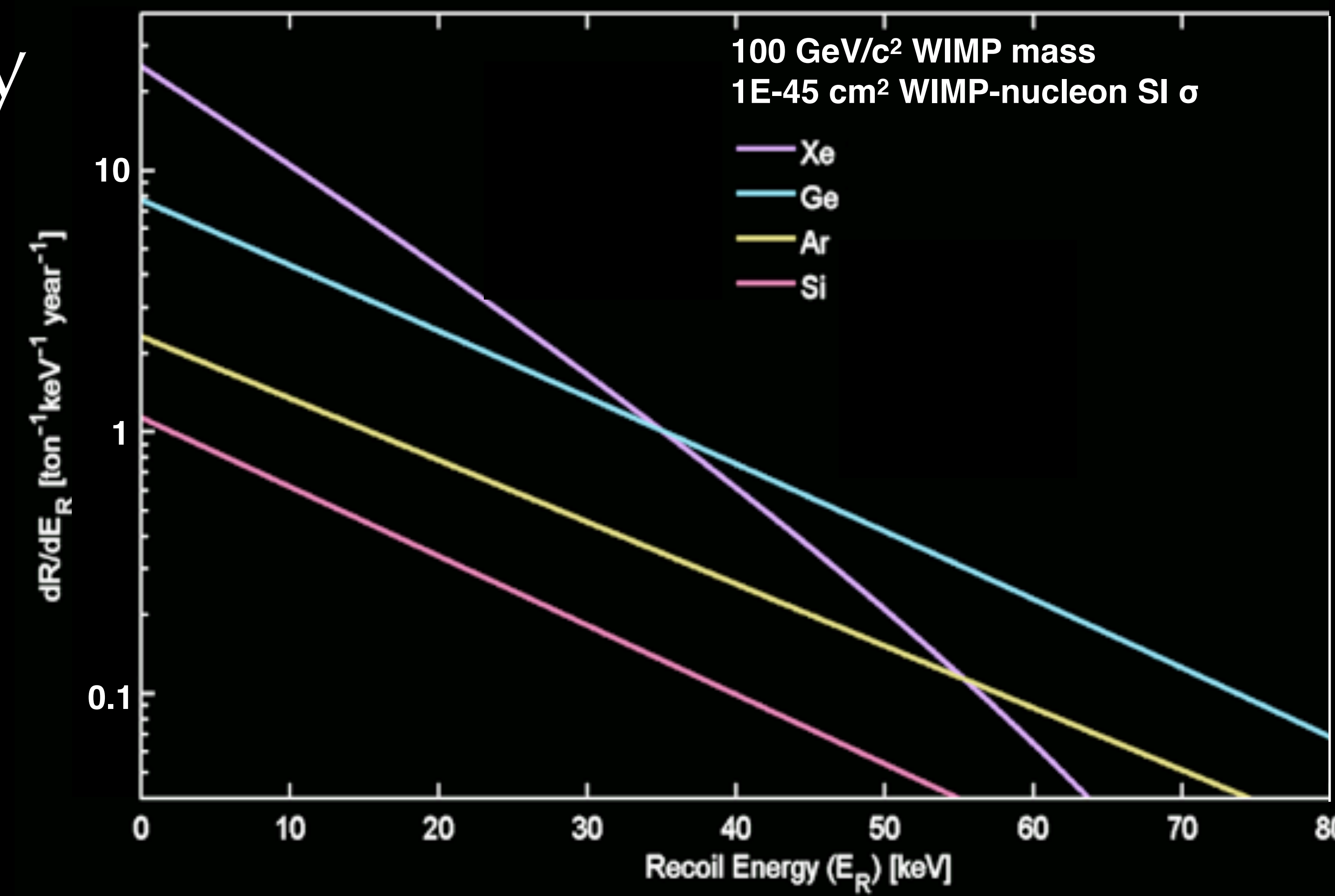
Spin Independent:
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$
D. Z. Freedman, PRD 9, 1389 (1974)

Spin Dependent:
mainly unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

detector requirements: measure recoil energy, time, +angle

Observable: Recoil Energy





Scattering rate

Sun's velocity around the galaxy

WIMP velocity distribution

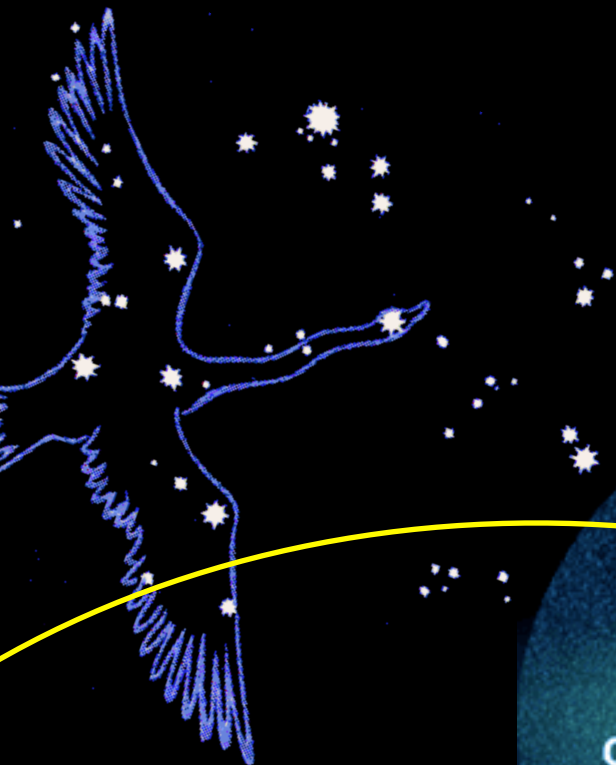
$$dR/dQ \sim (\sigma_0 \rho_0 /\sqrt{\pi}\, v_0\, m_\chi\, m_r^2)\, F^2(Q)\, T(Q)$$

WIMP energy density, 0.3 GeV/cm³

Form factor

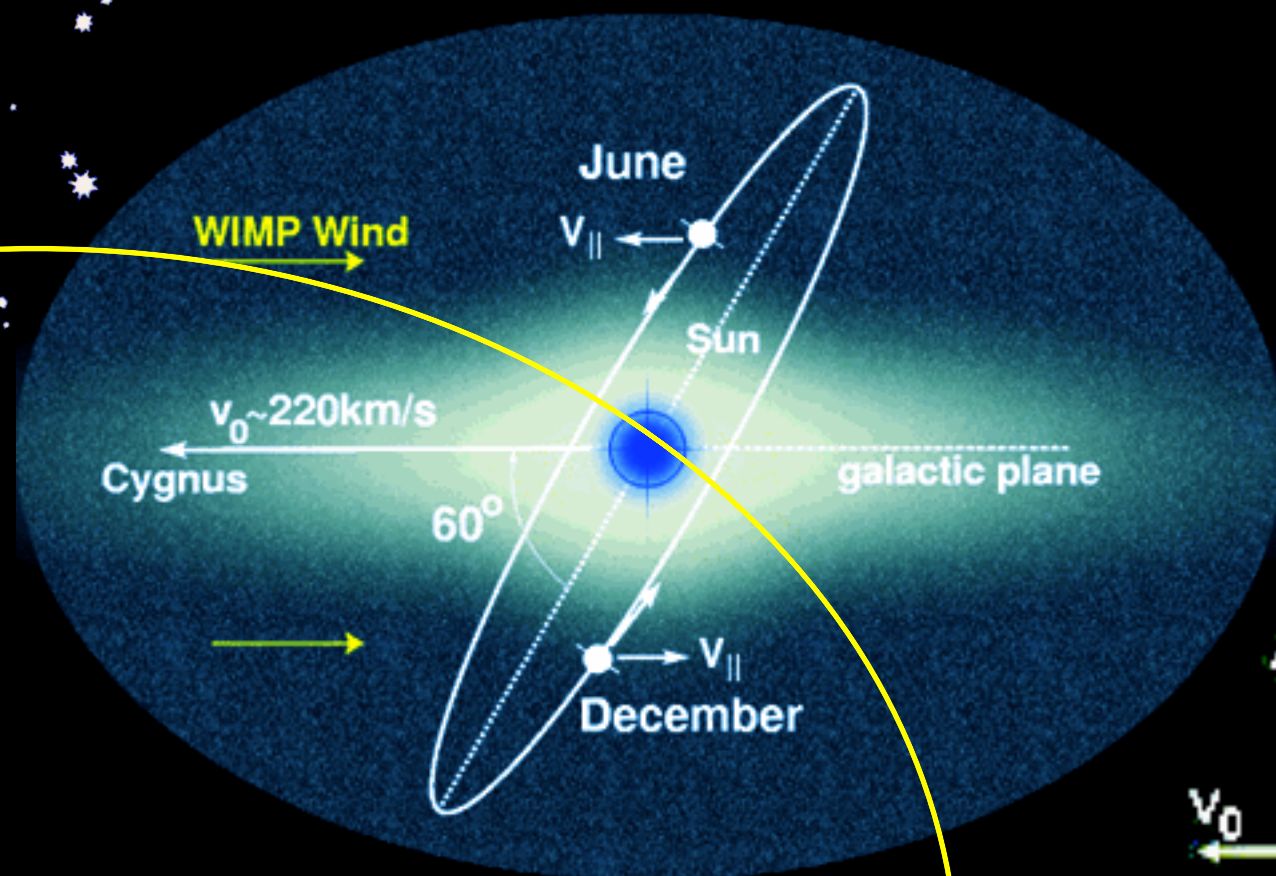
detector requirements: ~1-10s of keV energy threshold, very low backgrounds

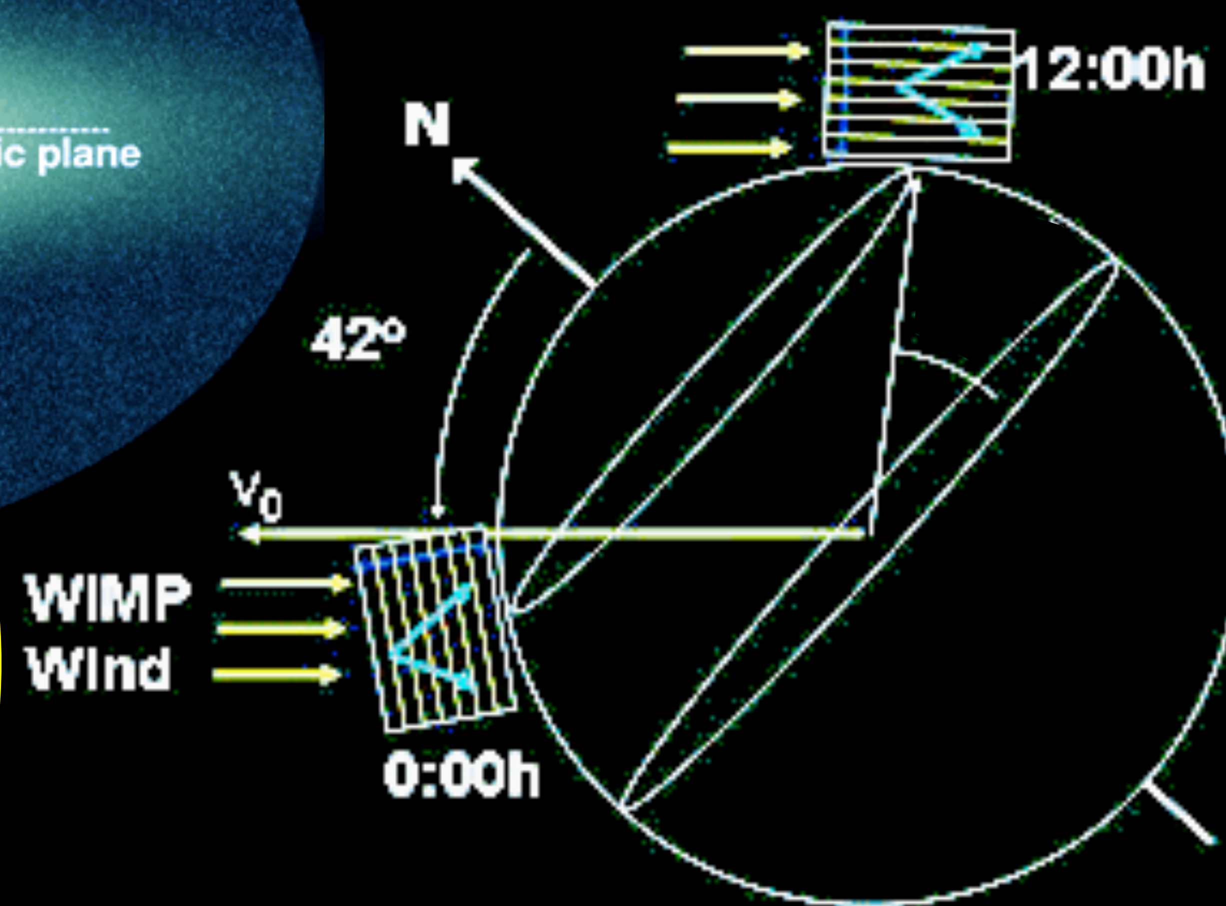
Modulation Signatures



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)

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Introduction to Dark Matter Searches

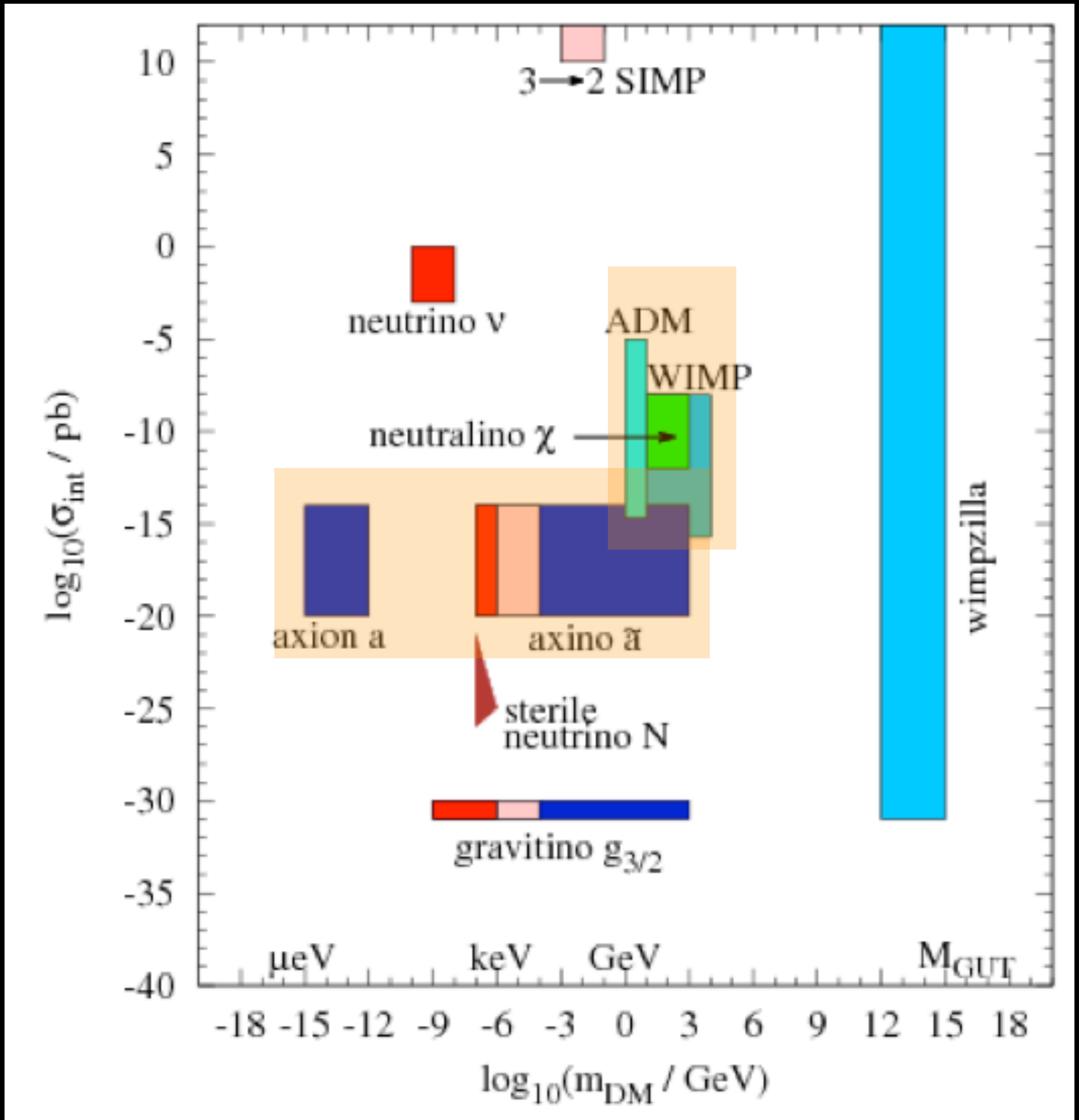
Status and Prospects of Direct Detection Experiments

Conclusions and Outlook

Model Space

Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity...

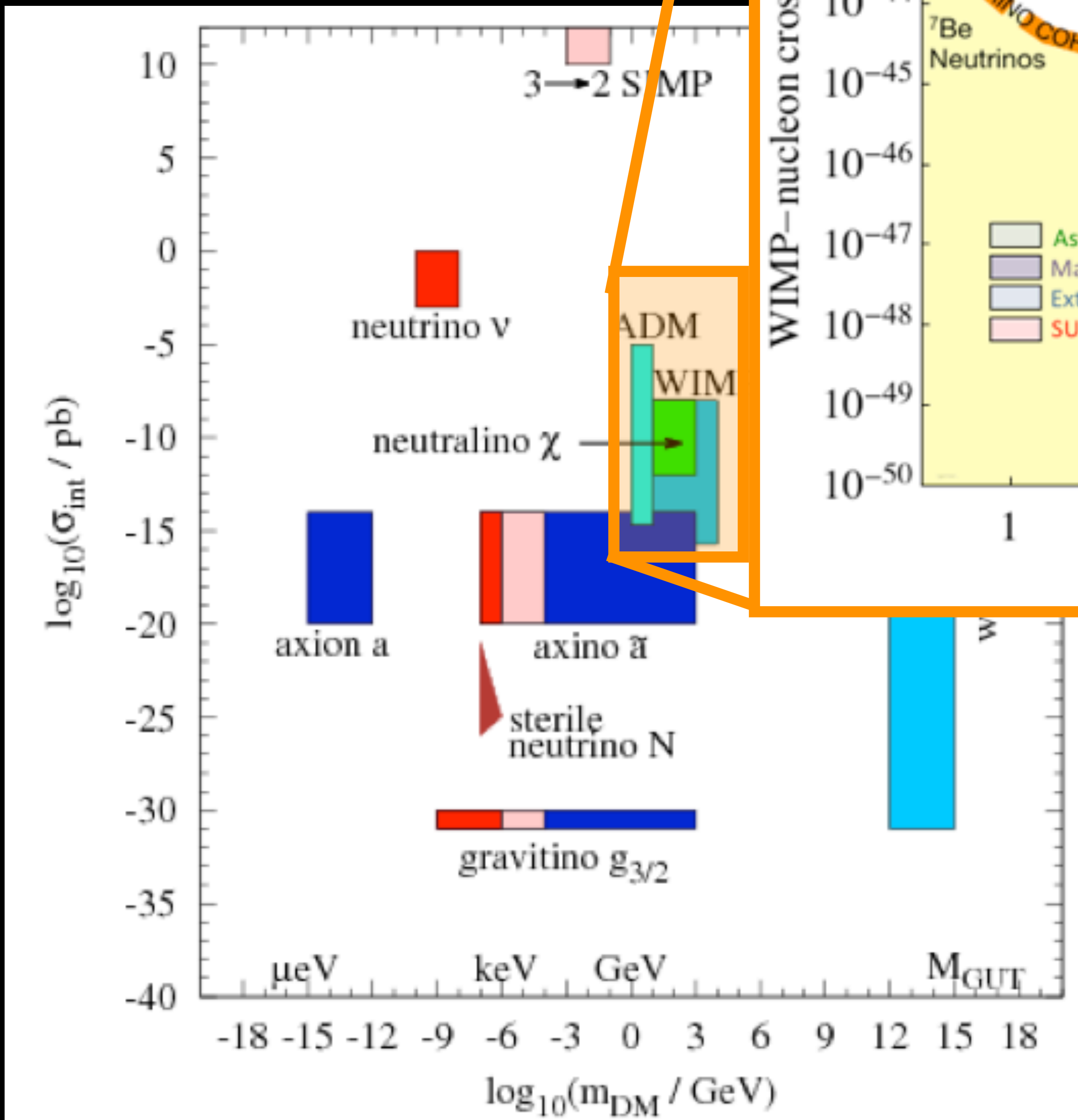


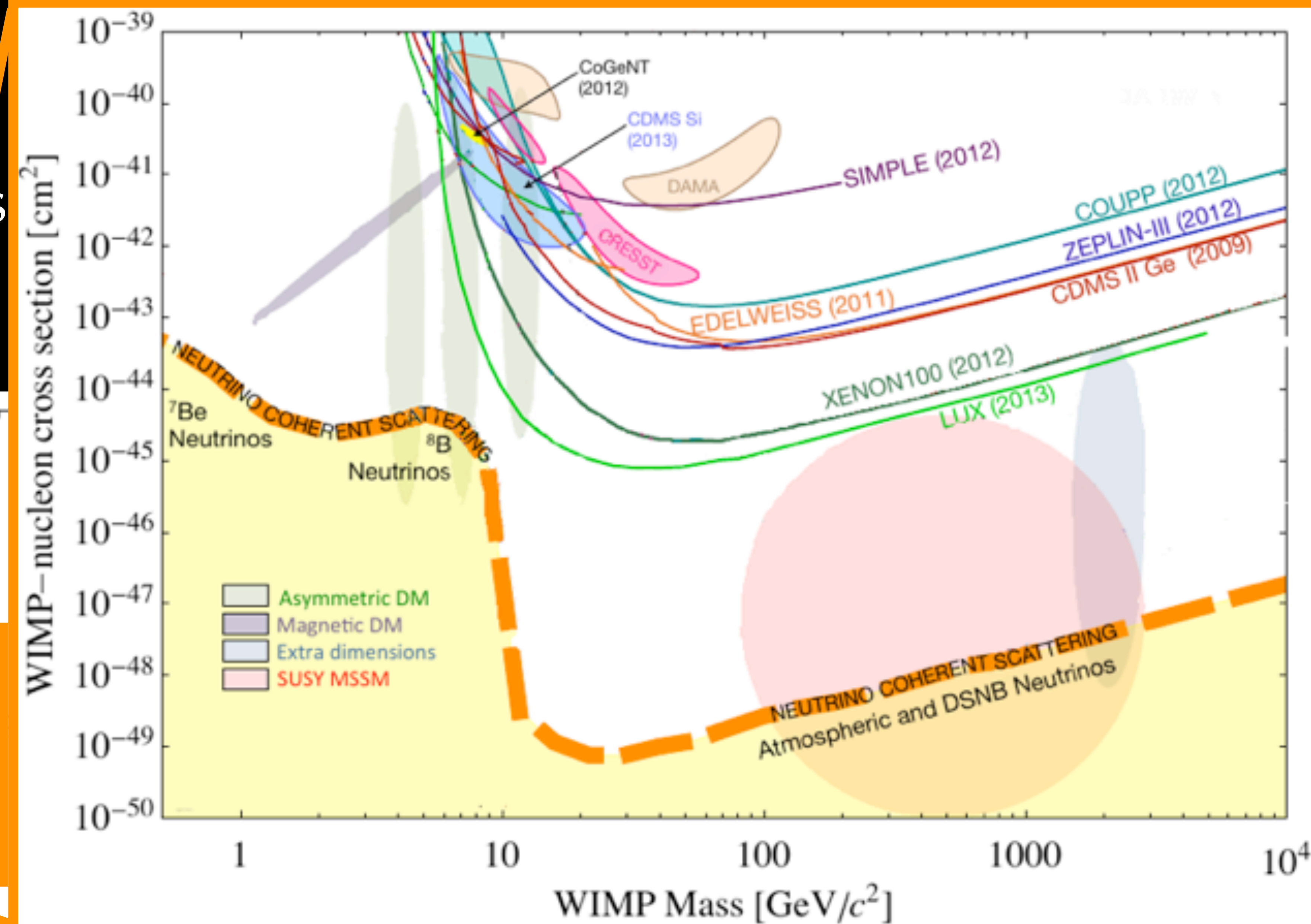
Baer et al., arXiv:1407.0017

Model Space

Wide range of parameters

Direct detection searches





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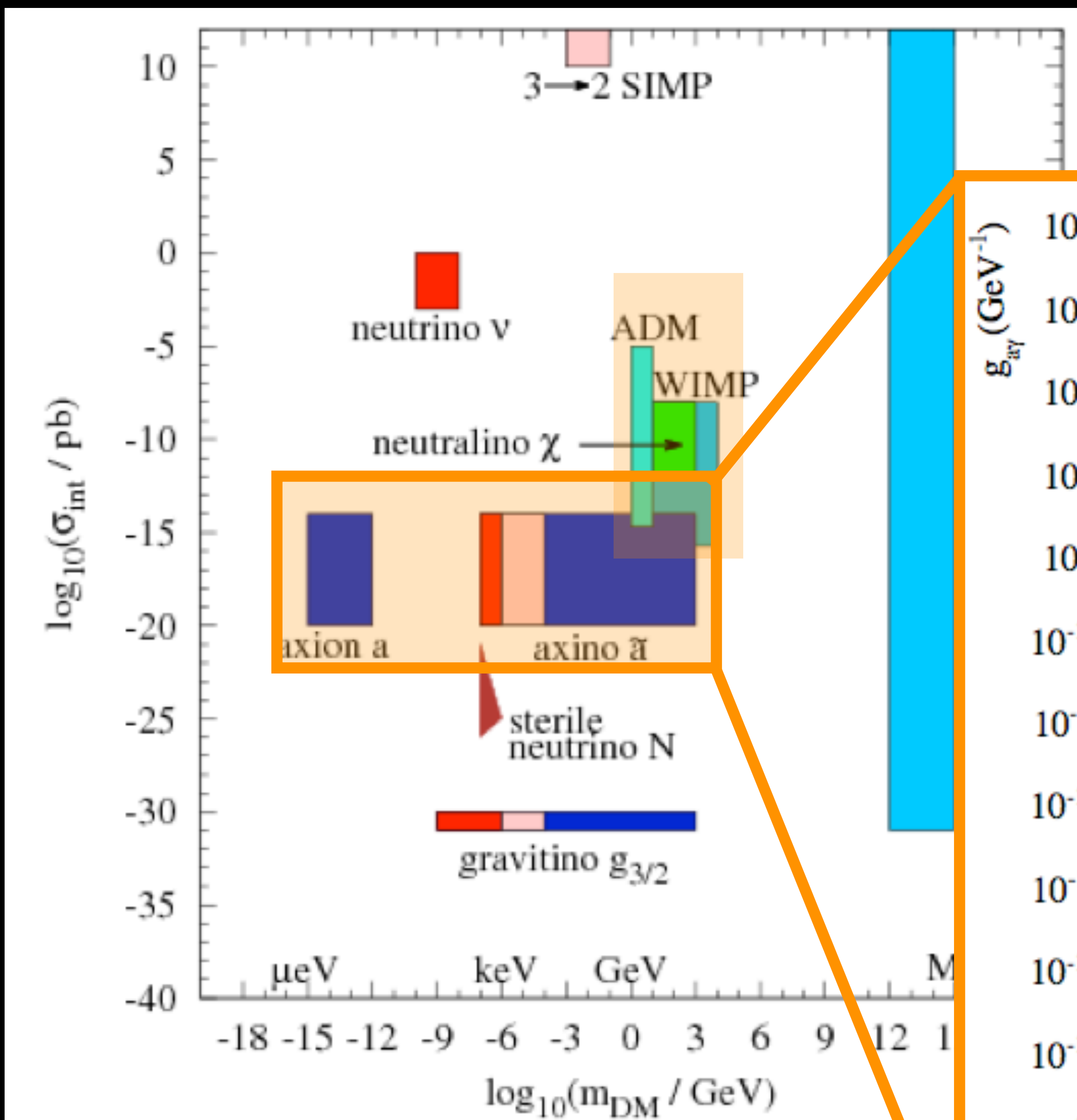
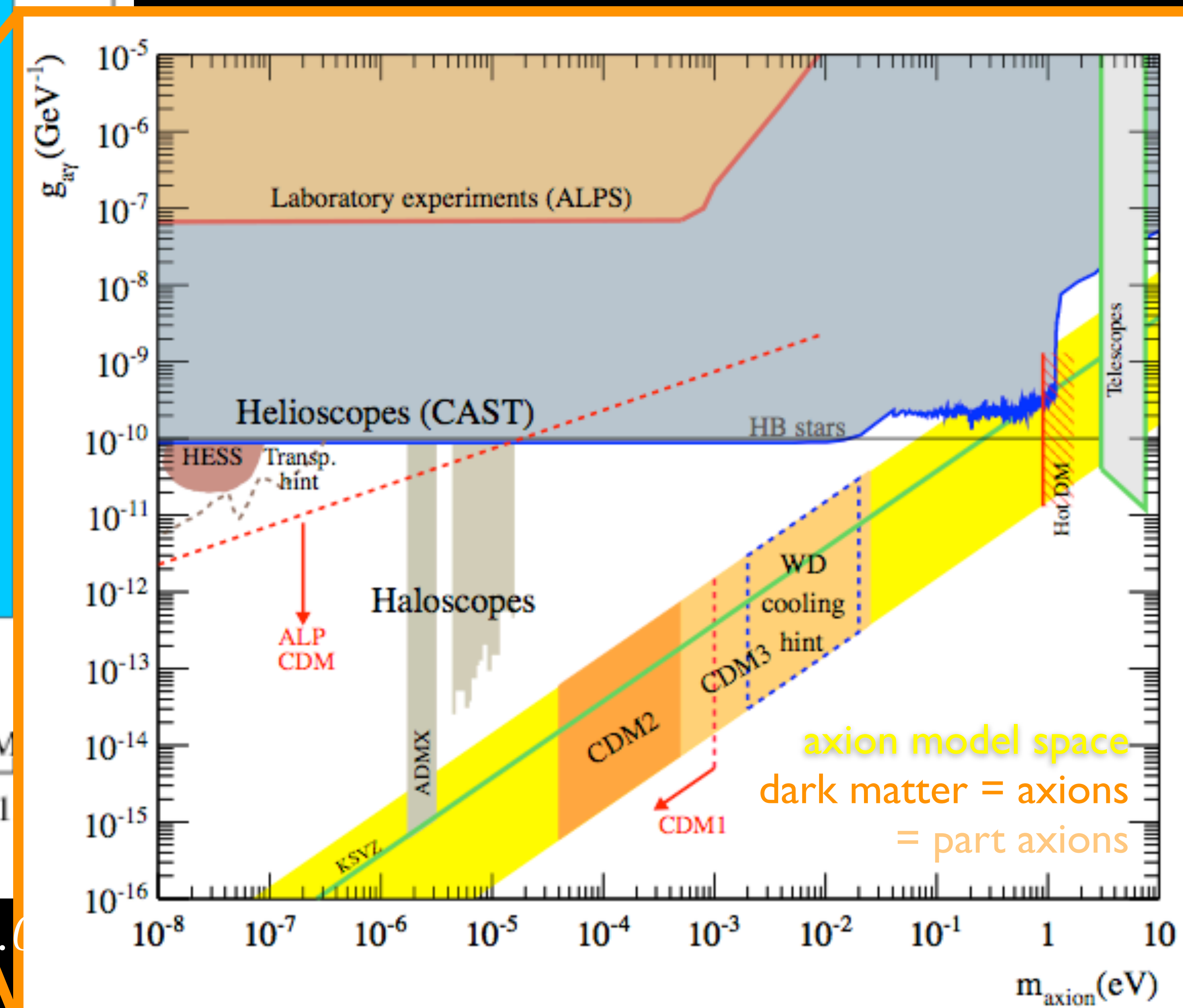
Model Space

Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity...

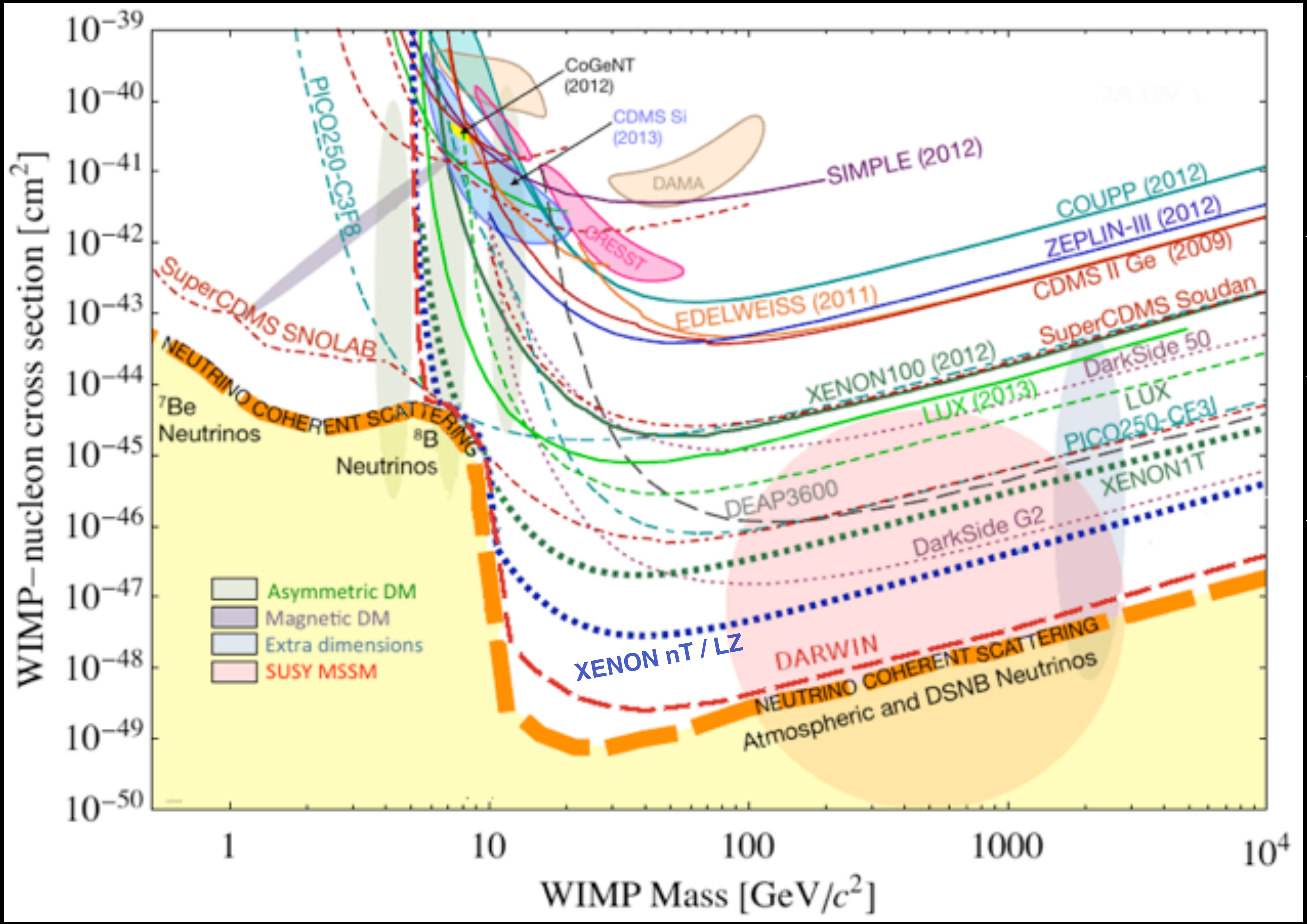


but starting to look for axions too!



Baer et al., arXiv:1407.0

The Low-Background Frontier: Prospects



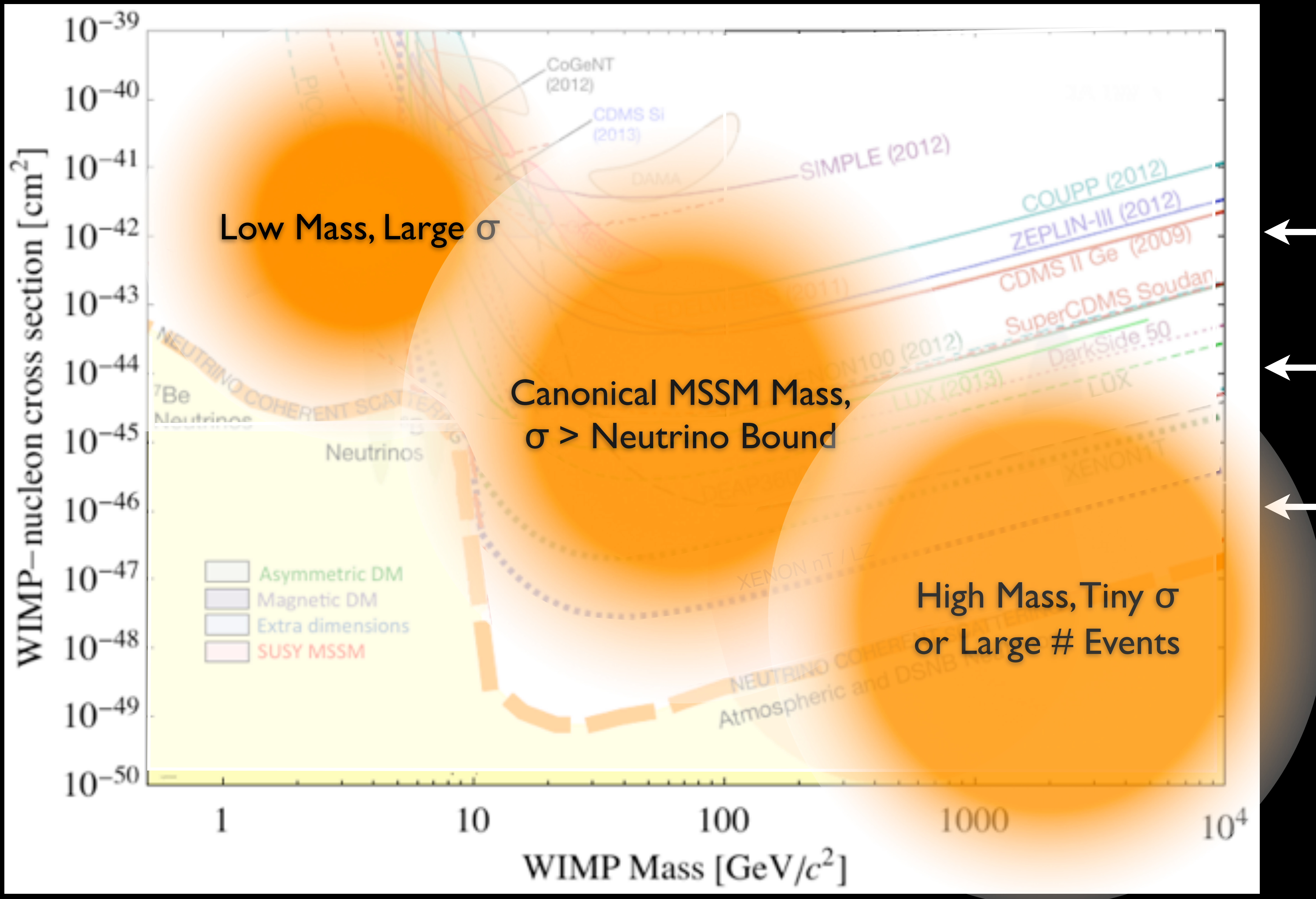
← 1 event/ kg/day

← 1 event/ 100kg/day

← 1 event/ 100 kg/ 100 days

so far: ~3 years / order of magnitude

The Low-Background Frontier: Overview



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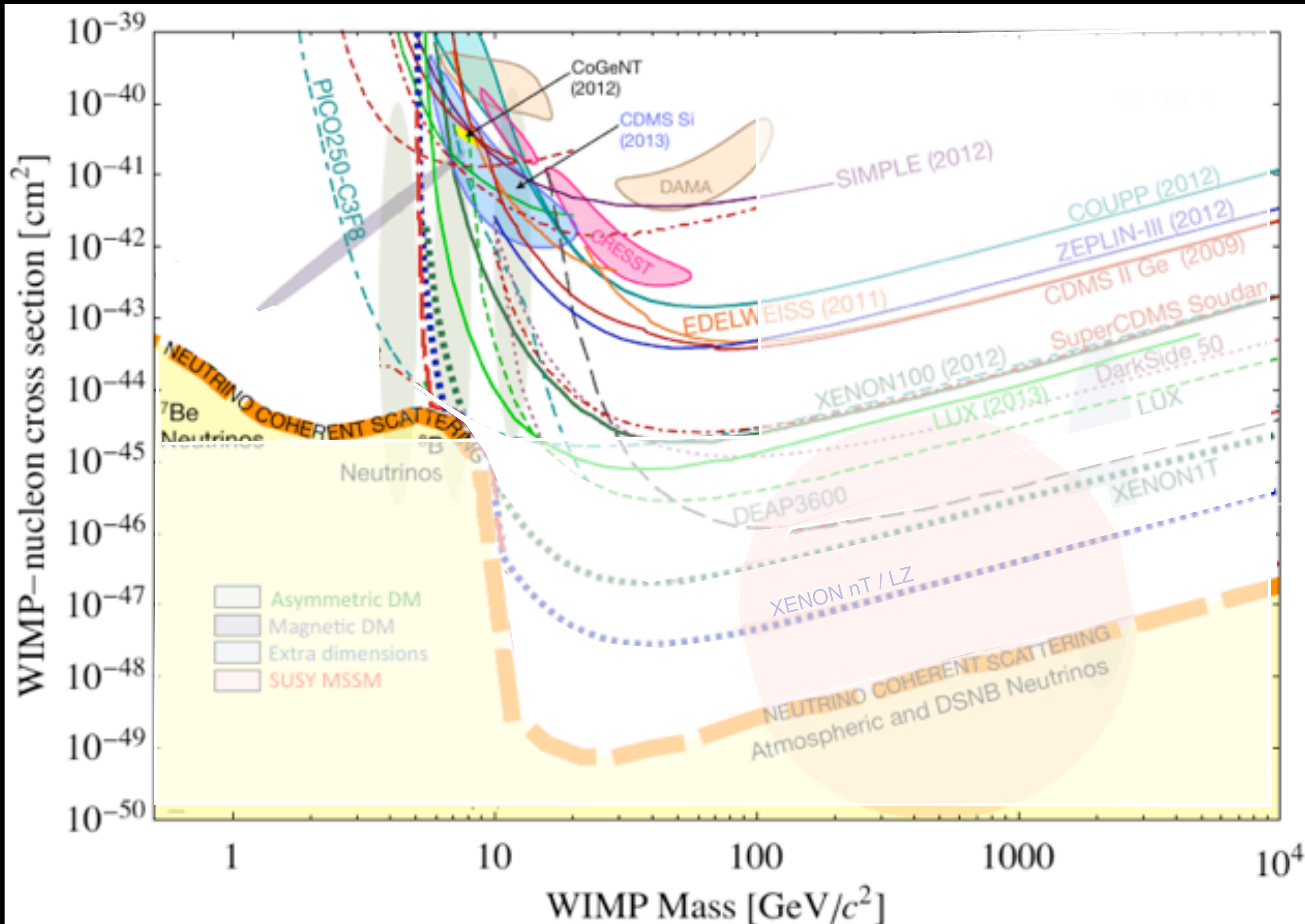
1 event/ 100 kg/ 100 days

The Low-Background Frontier: Overview



1 event/ kg/day

1 event/ 100kg/day

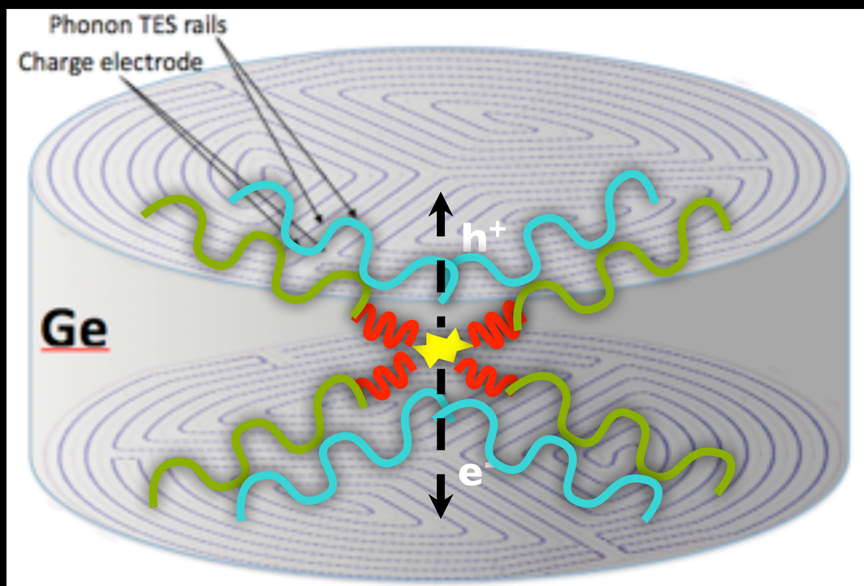
1 event/ 100 kg/ 100 days

Bolometers

phonon, ionisation or scintillation readout of crystals with Transition Edge Sensors at O(10 mK)

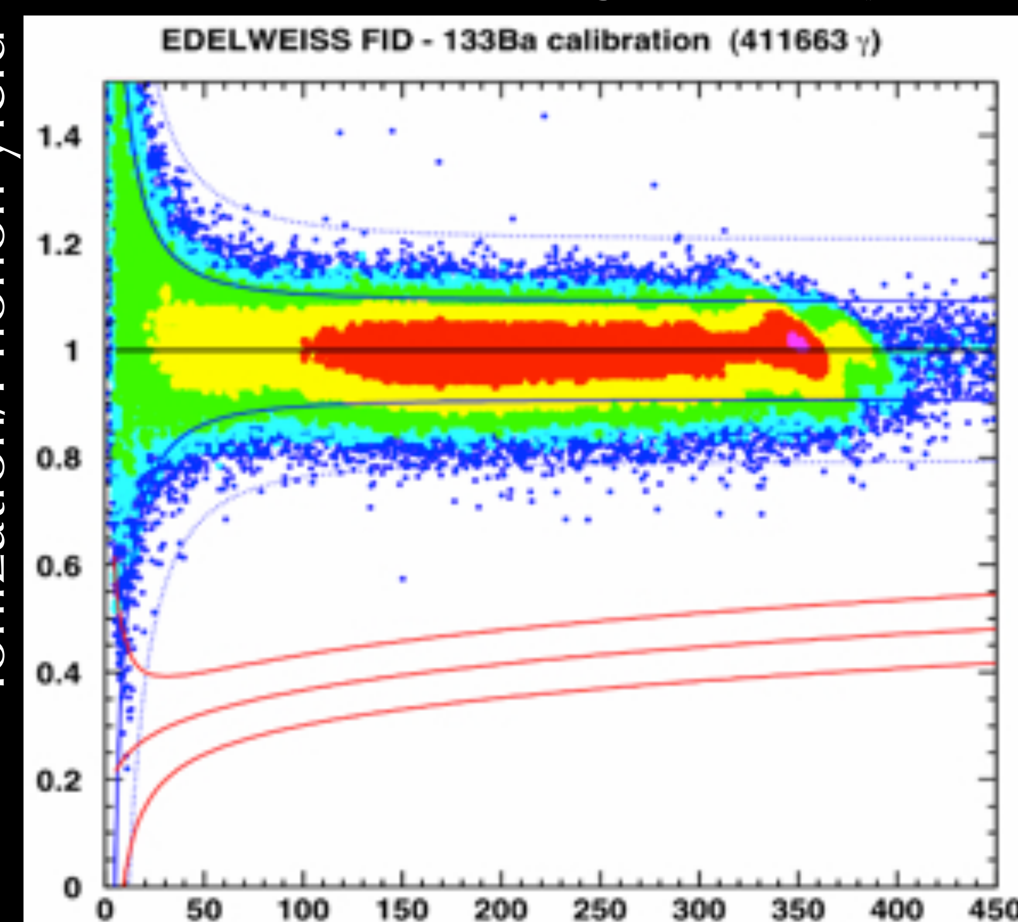
targets: Ge (SuperCDMS, EDELWEISS, COGENT, CDEX), Si (SuperCDMS), $CaWO_4$ (CRESST)

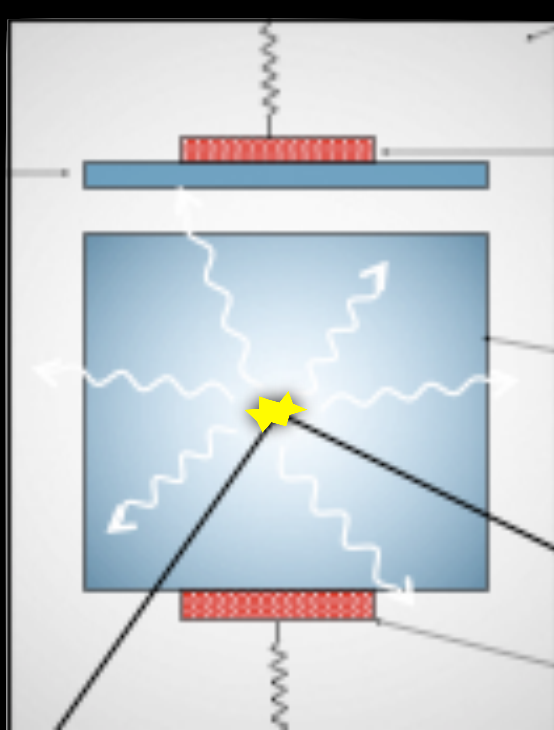
Phonon rails: 600 gm (SuperCDMS) or 800 gm (EDELWEISS) Ge, TES for E_{recoil} & R (timing)



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

EDELWEISS: interleaved electrodes reduce surface backgrounds by x10^5

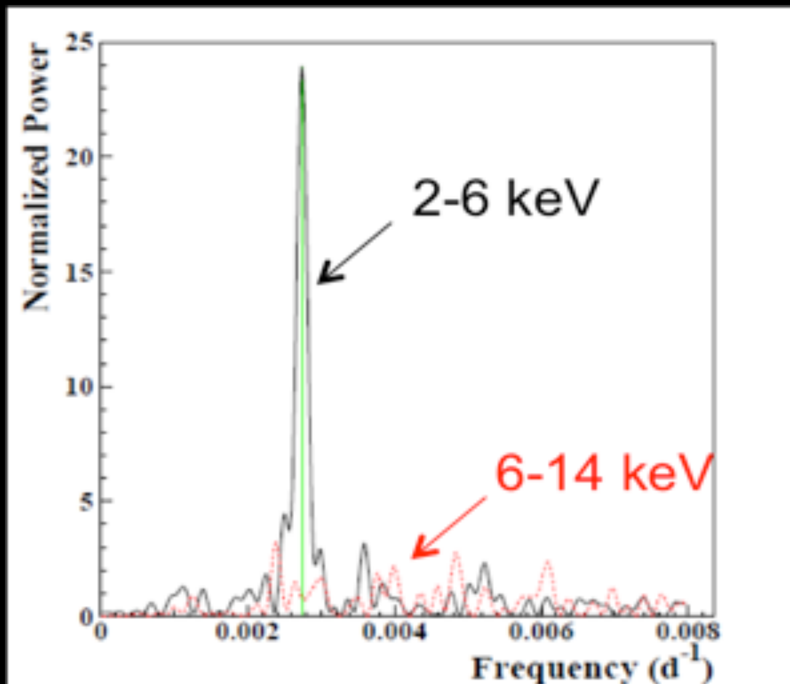


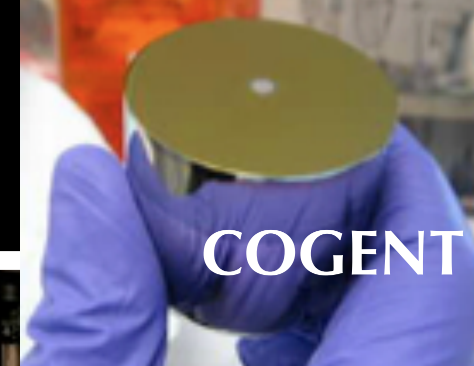


Scintillation side:
Si absorber on 300 gm $CaWO_4$, tungsten TES readout for particle ID

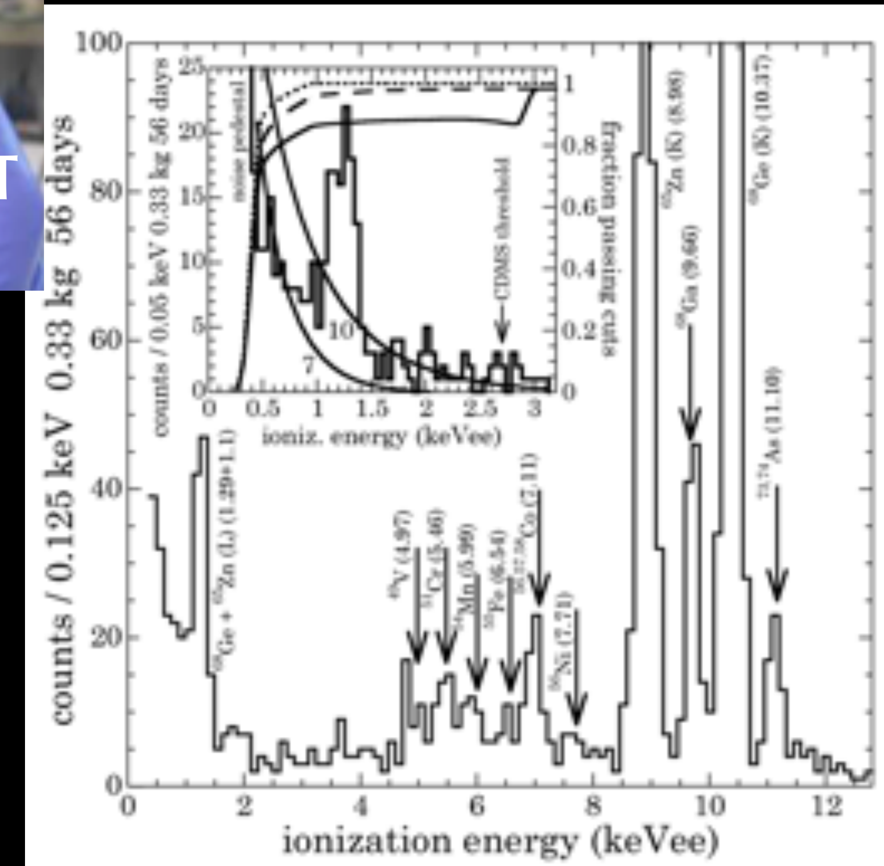
Phonon side:
TES readout to measure E_{recoil}

Dark Matter Signals?





arXiv:1002.4703



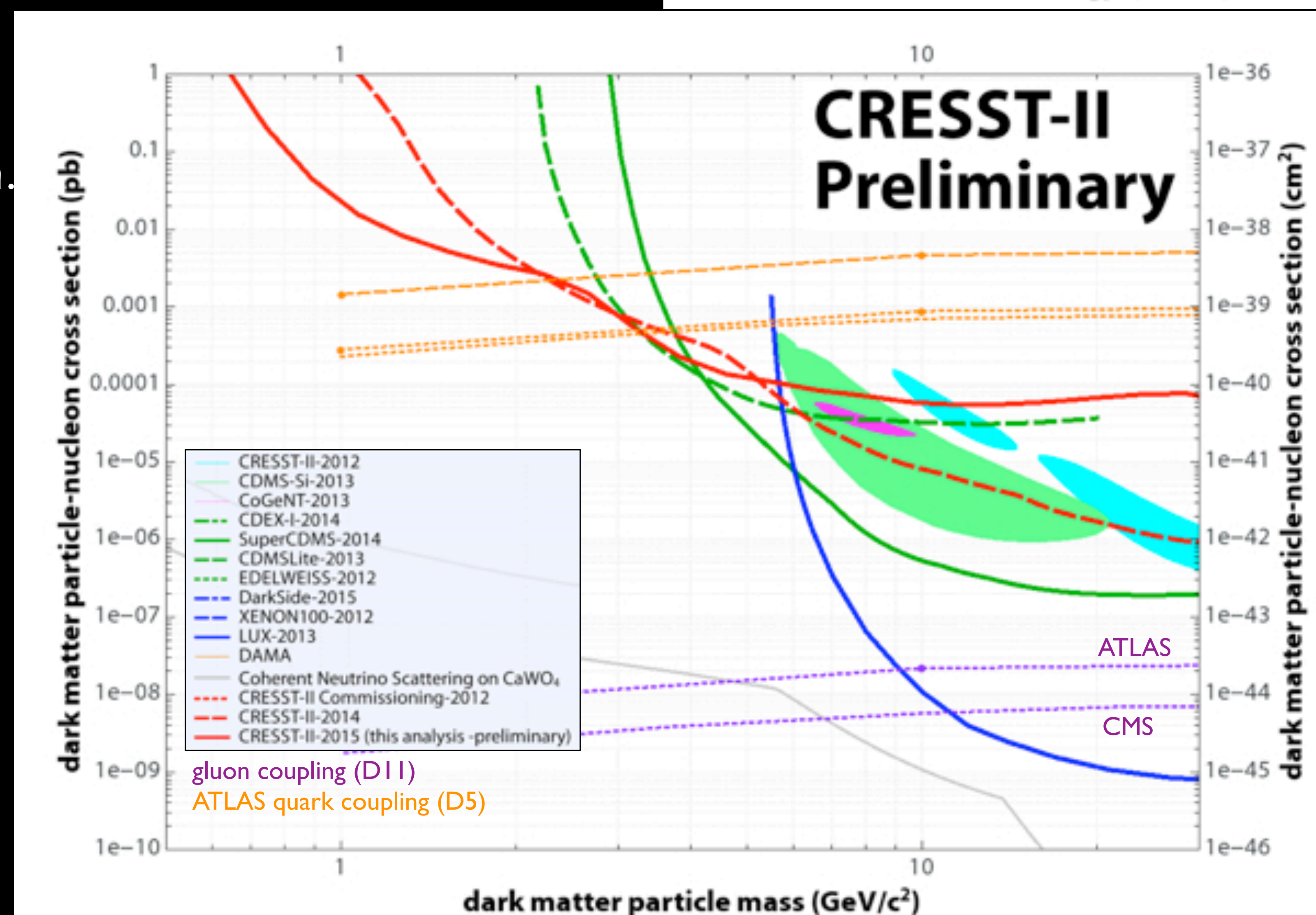
DAMA/LIBRA: 9.2**σ** excess in 2-6 keV, 1.33 ton-yr NaI data set, with modulation.

COGENT: excess in 0.5-3 keVee in 145 kg-day data set with Ge detector.

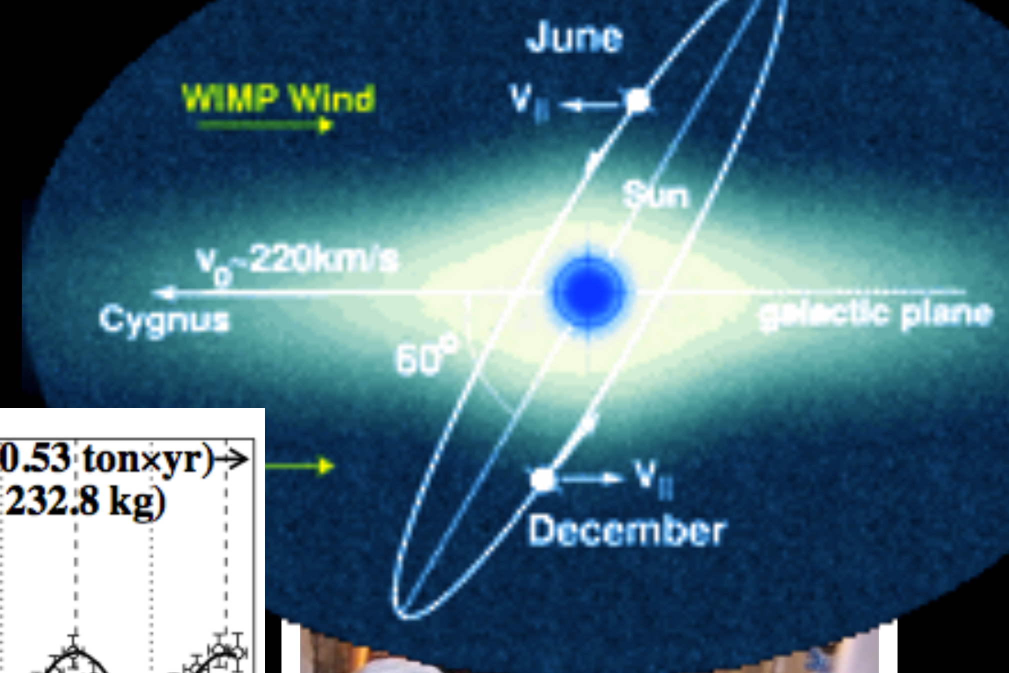
SuperCDMS: CDMS Si reported excess, SuperCDMS Ge excludes it.

CRESST-II: excess reported in phase-1, phase-2 excludes it. *(Oxford)*

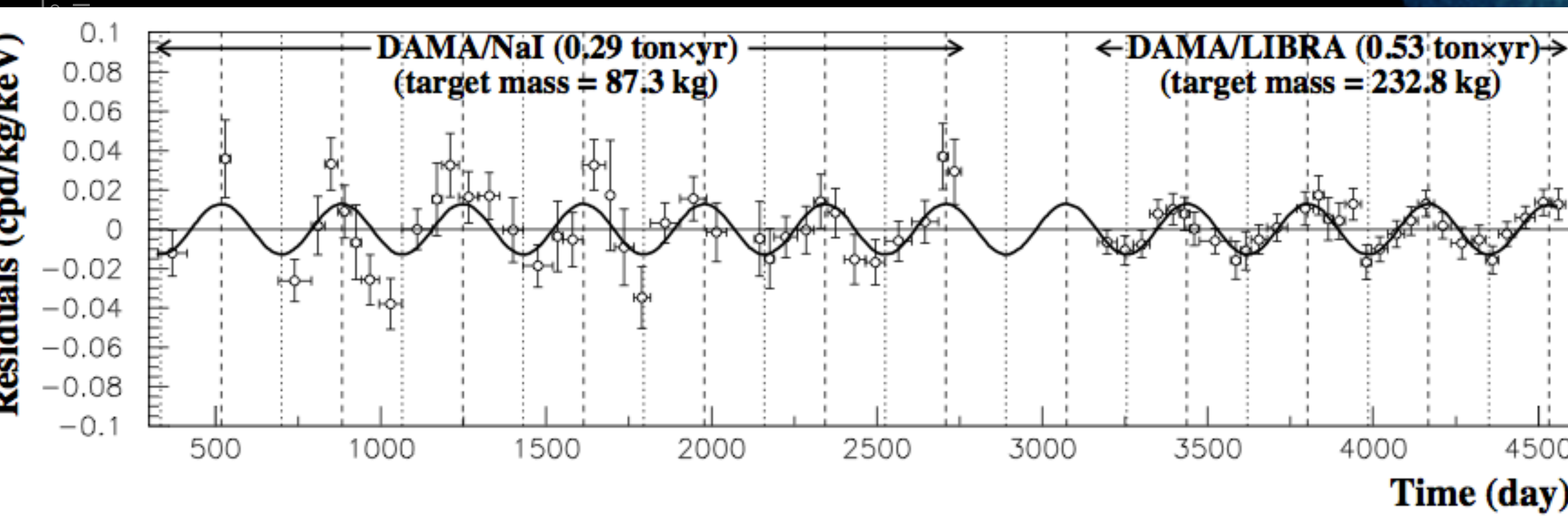
New results! 7 kg-day, 0.3 keV threshold.



Annual Modulation Tests



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



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

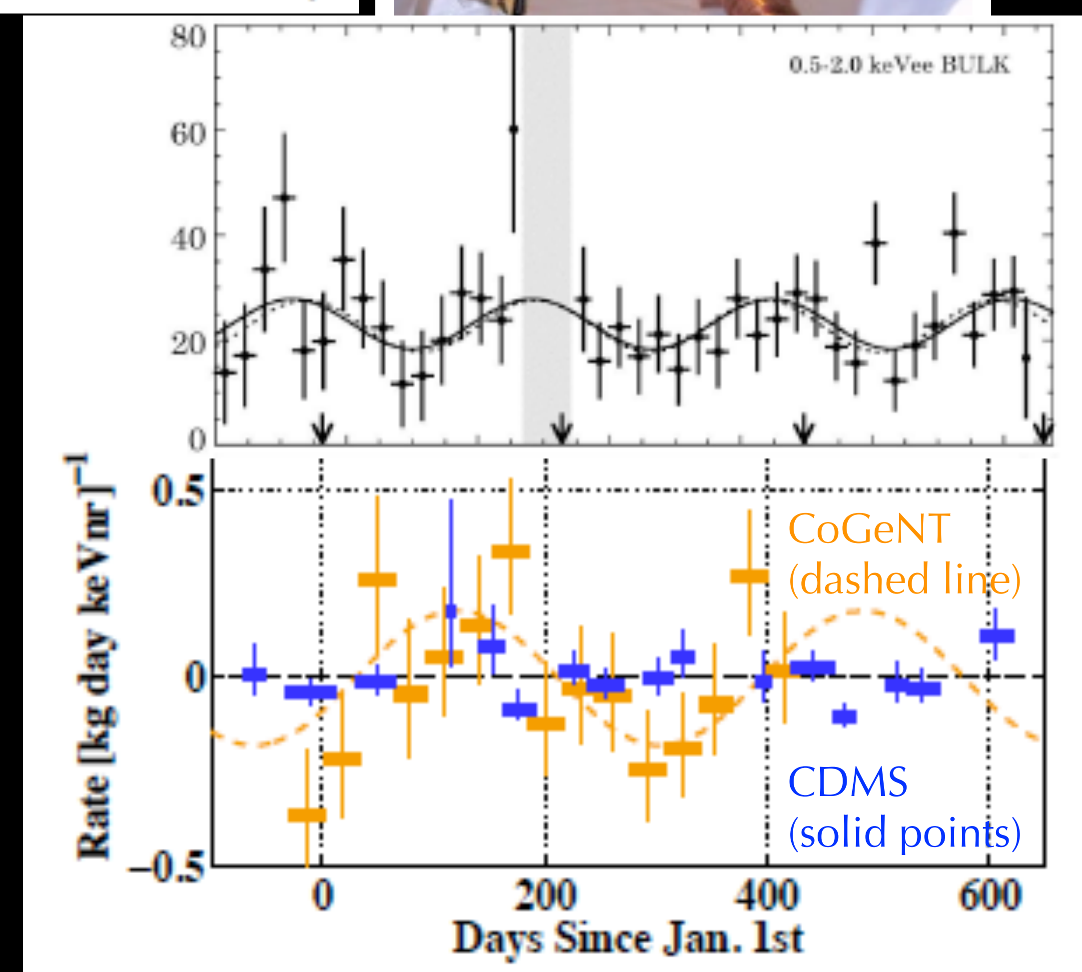
COGENT: Ge, ~2σ modulation reported. *arXiv:1401.3295*

MALBEK: Ge, no excess reported. *J. Wilkerson UCLADM'14*

CDMS: Ge, no modulation, at 98.3% CL, *arXiv:1203.1309*

KIMS: CsI, no modulation. *J.Phys.Conf.Ser. 384 (2012) 012020*

XENON100: Xe, 4.8σ exclusion of DAMA.
arXiv:1507.07748



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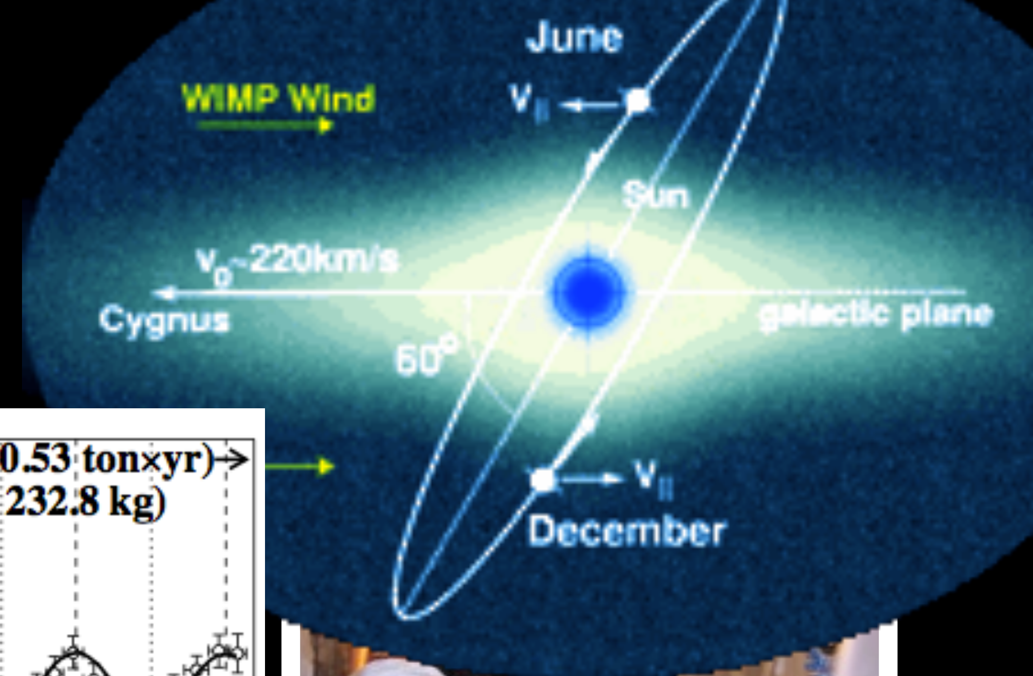

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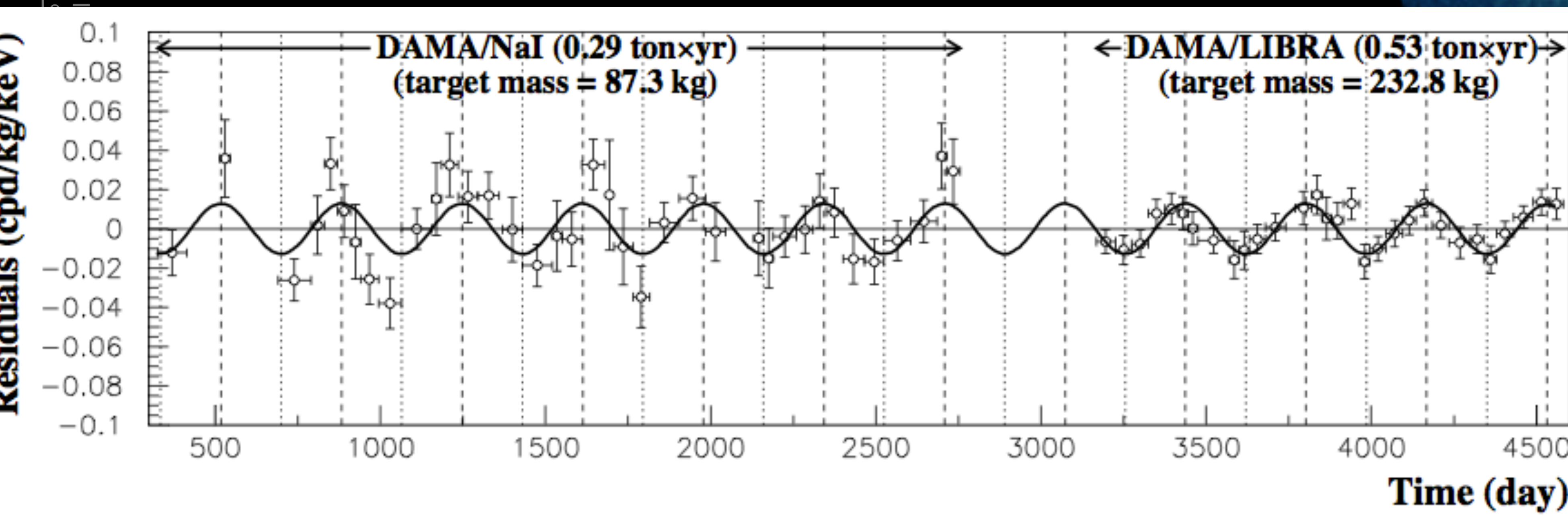

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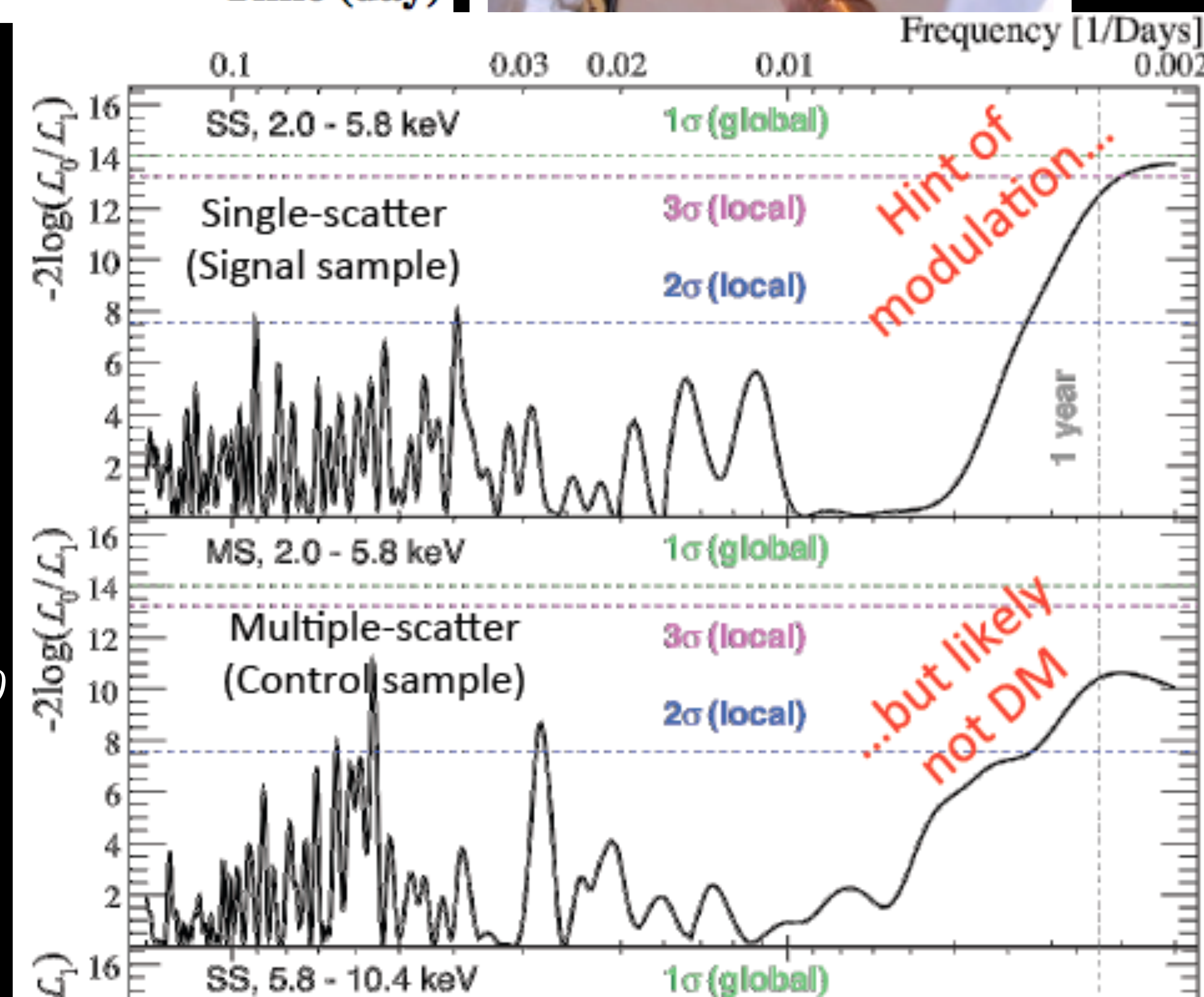
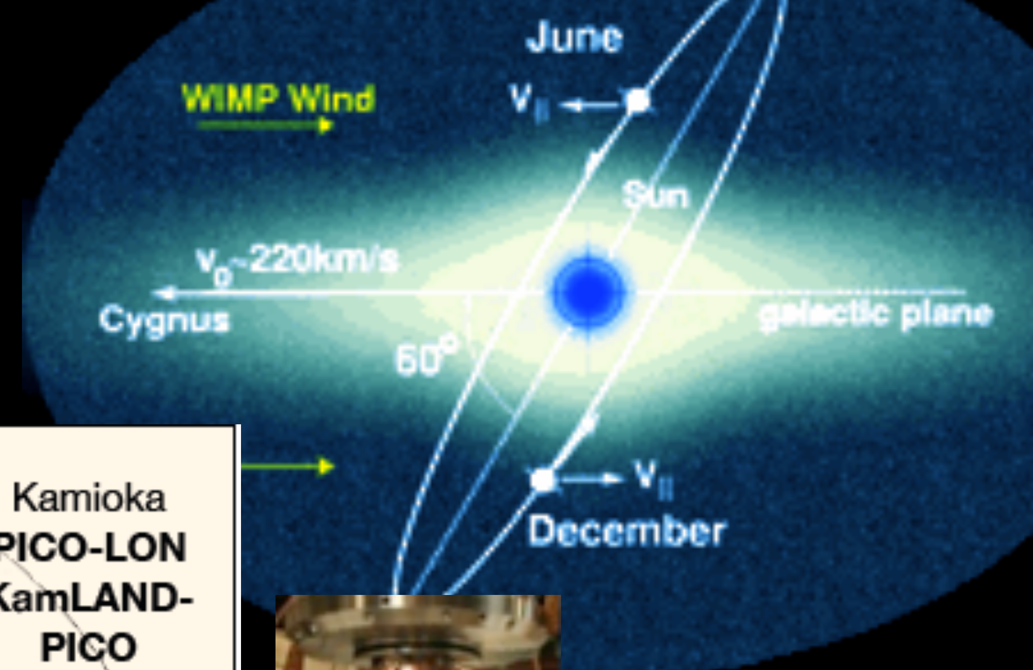
XENON100: Xe, 4.8σ exclusion of DAMA. ***New result!***
arXiv:1507.07748



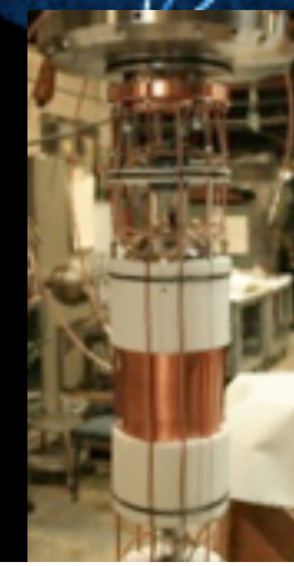
Annual Modulation Prospects

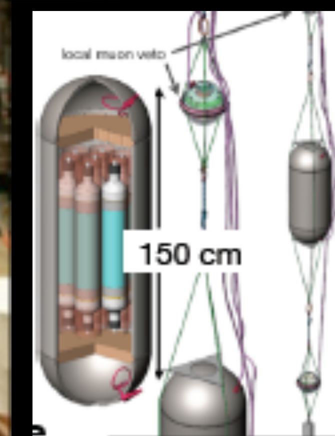
predicted annual modulation A~0.02-0.1, t_0 = 152.5 days

t_0 =



Northern Hemisphere	Gran Sasso **DAMA/Libra** 250kg running	Gran Sasso **SaBRE**	Canfranc **ANAIS**	Y2L **KIMS**	Boulby **DM-Ice North**	Kamioka **PICO-LON KamLAND-PICO**
Southern Hemisphere		Stawell **SaBRE** Lab completion 2017			South Pole **DM-Ice** 17 kg running 250 kg Projected	rock ice

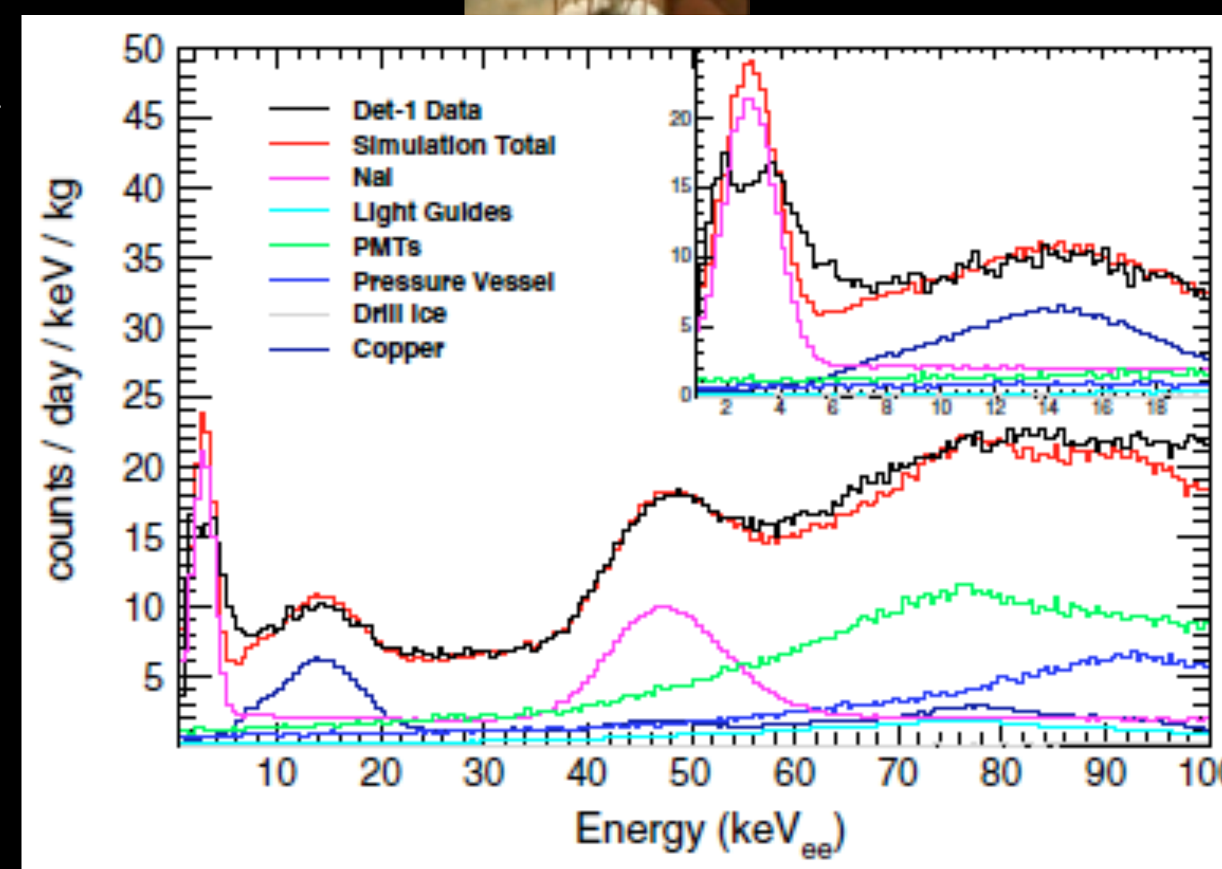




DAMA/LIBRA: phase-2 upgrade to lower energy threshold, took place in 2011, results not yet reported.

LXe: XMASS plans 5T, XENON1T -> nT.

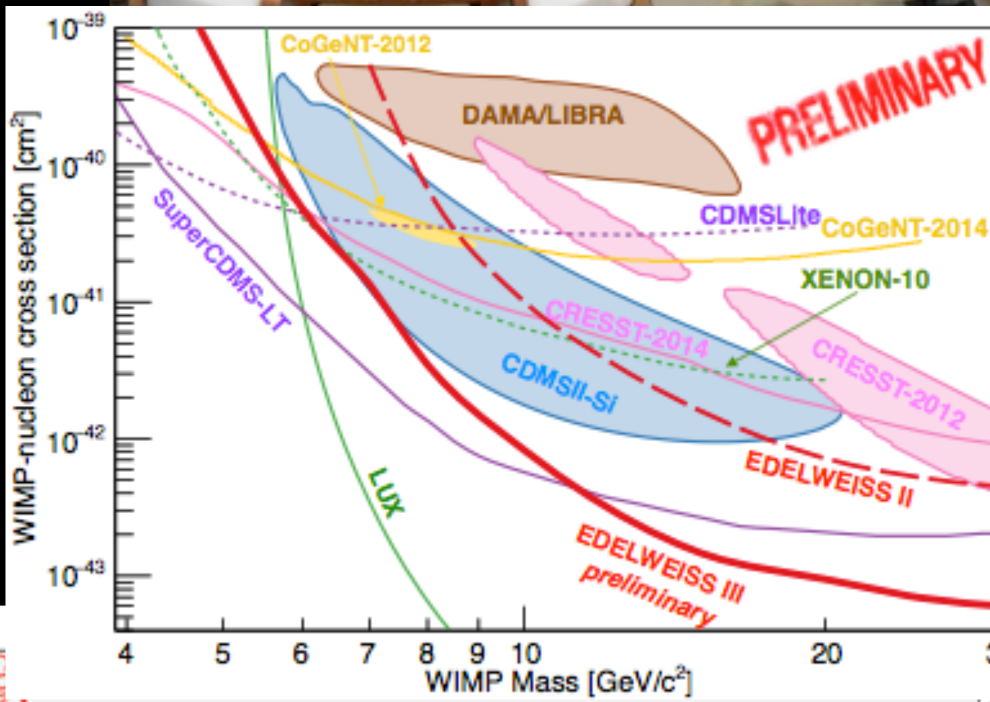
DM-ICE: NaI, 17 kg deployed in S. Pole ice, 37 kg at Boulby, background 7.9/(keV kg day) *PRD 90 092005 (2014)* plan 250 kg NaI scale up (need crystal radio-purity gains) *(Sheffield, Boulby Laboratory)*



Low-Mass Region Prospects

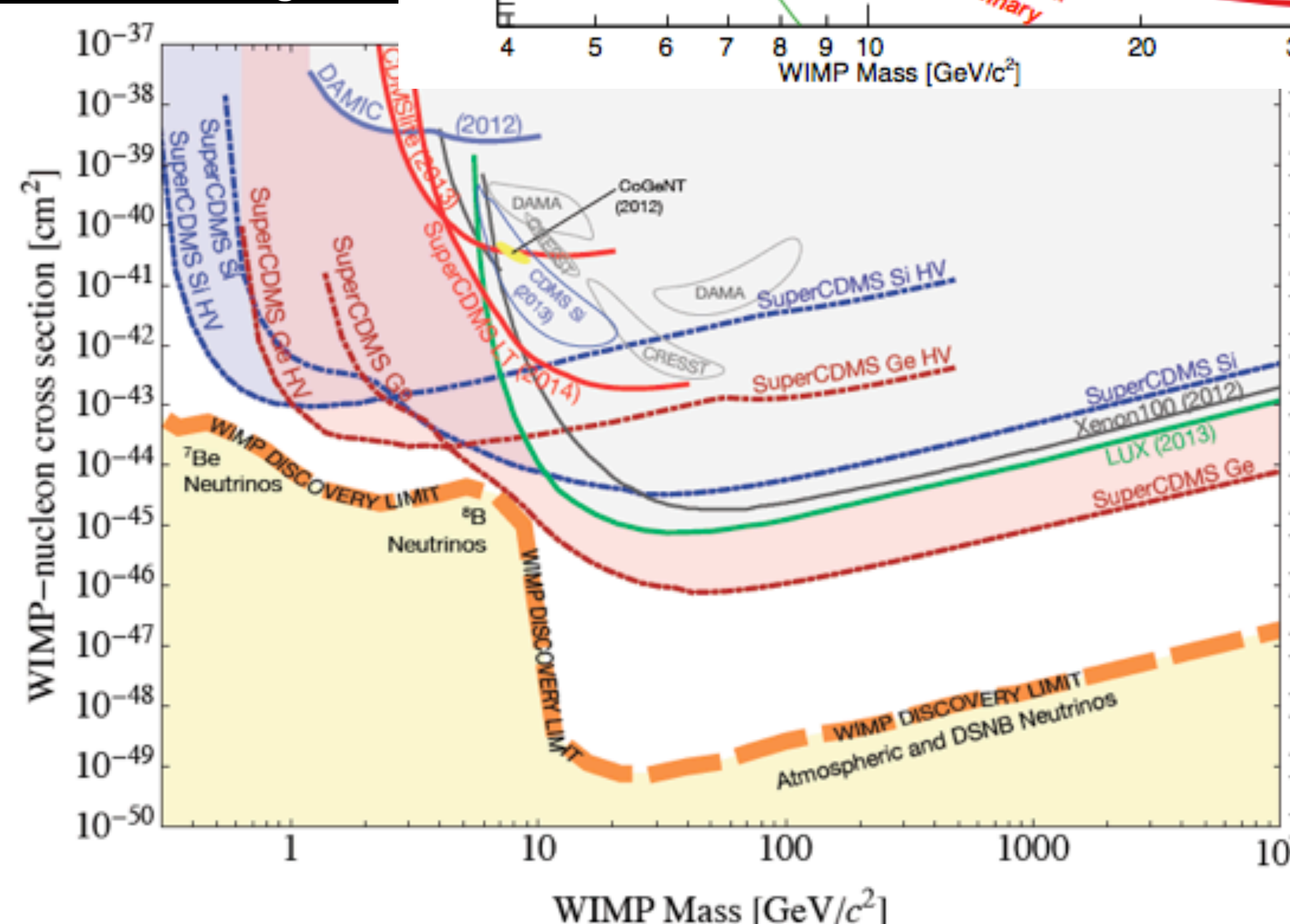
Goal: reach the neutrino bound!

CRESST: R&D towards 0.1 keV threshold, with smaller crystals, lower background for 1-6 GeV WIMPs search.



EDELWEISS-III: 24 x 800gm cryogenic Ge detectors in LSM. energy threshold reduced to 2.4 keV. UK: cabling, backgrounds. Detector development with SuperCDMS for low mass WIMPs. *(Oxford, Sheffield)*

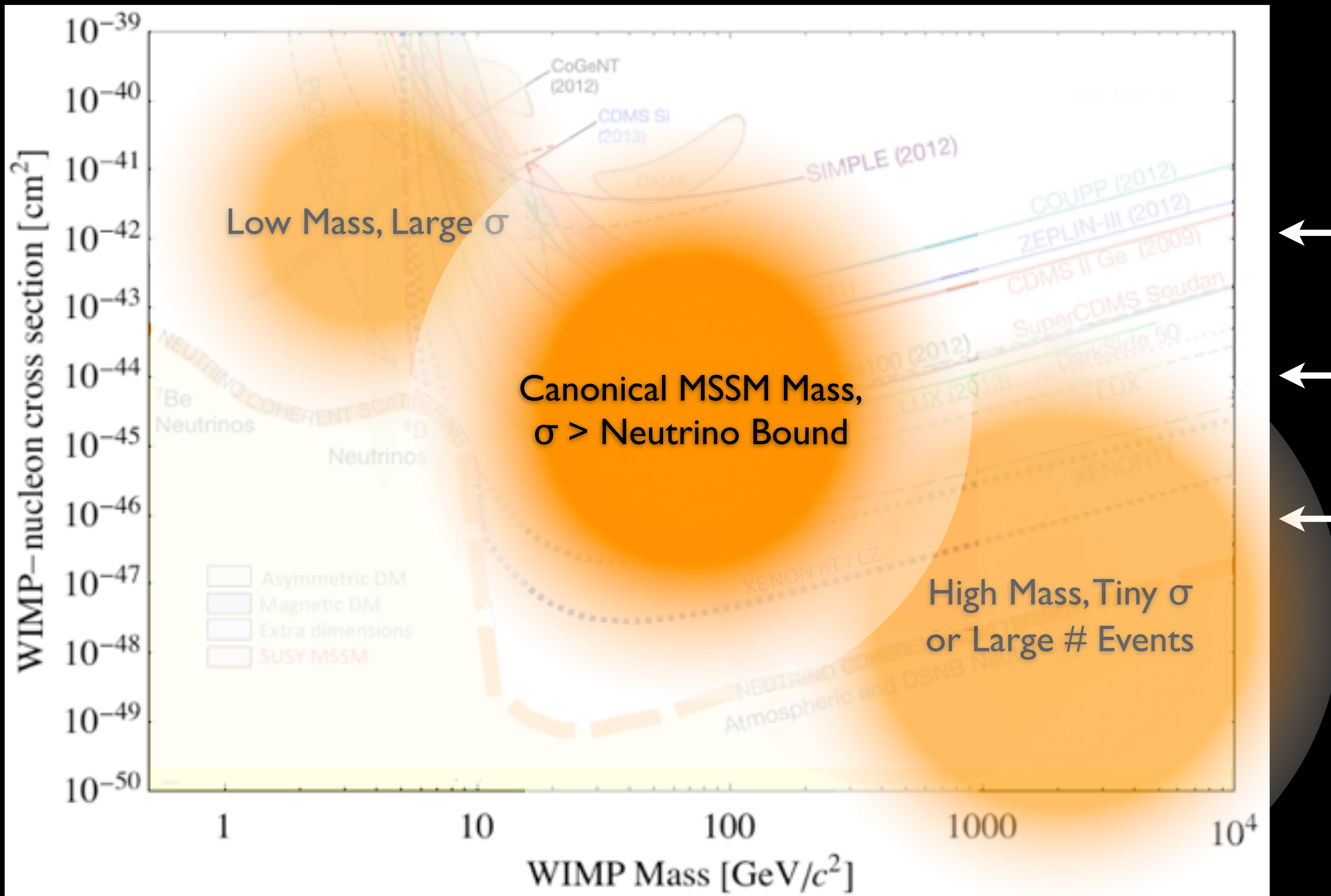
SuperCDMS: Focus on 0.3-10 GeV/c^2 WIMP masses with 50 kg of Ge (and Si) detectors at SNOLAB, from 2017. Operate in HV mode, for 0.9 keV threshold.



R&D towards very, very low mass:
DAMIC: search for WIMP interactions in CCDs, 100g to operate at SNOLAB. aim: 1E-5 pb with 1 keV threshold.

NEWS: spherical, high pressure gas detector with 0.1 keV threshold, at SNOLAB from 2017, aim: 1E-5 pb sensitivity with Ar, Ne targets.

The Low-Background Frontier: Prospects



1 event/ kg/day

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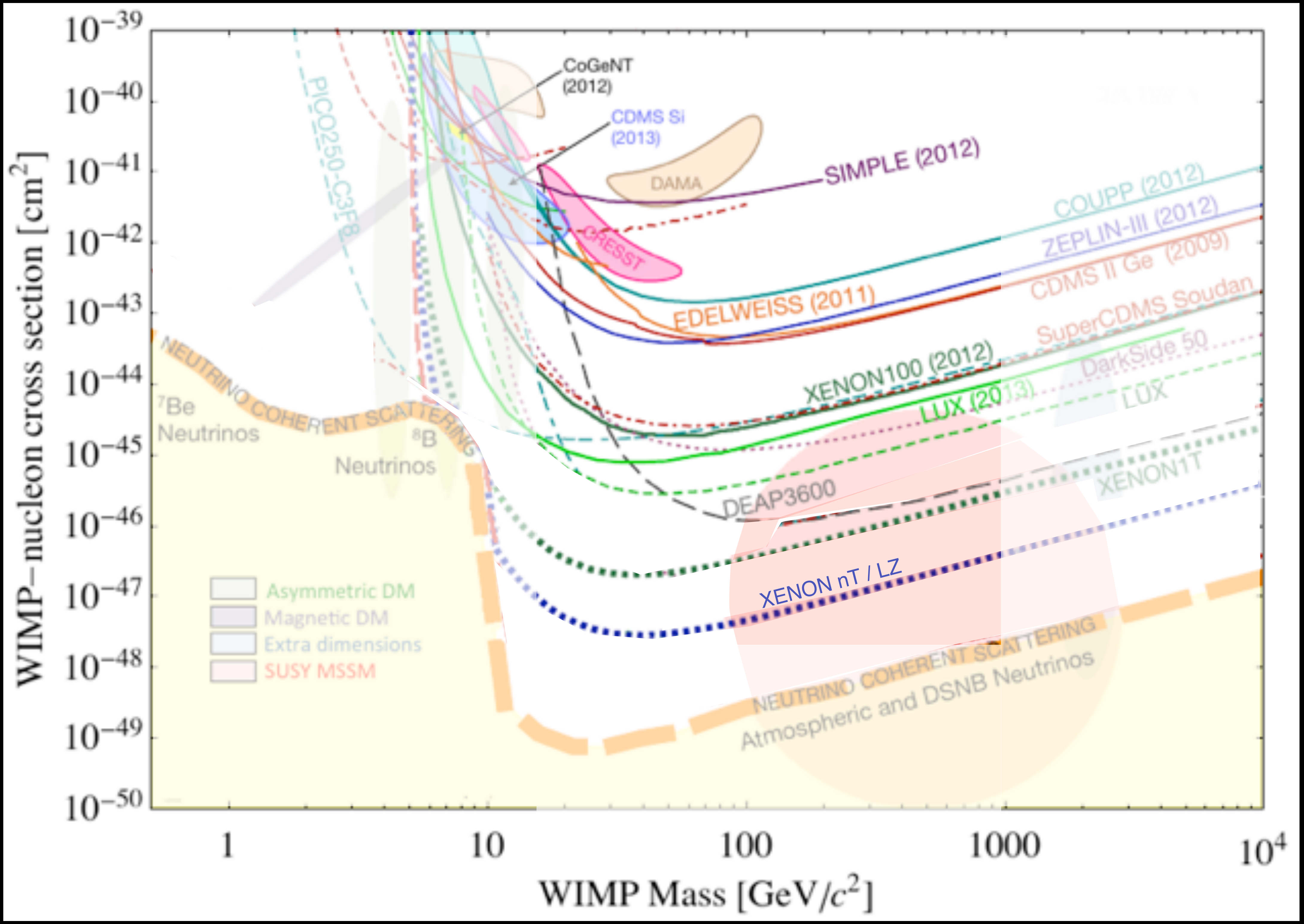

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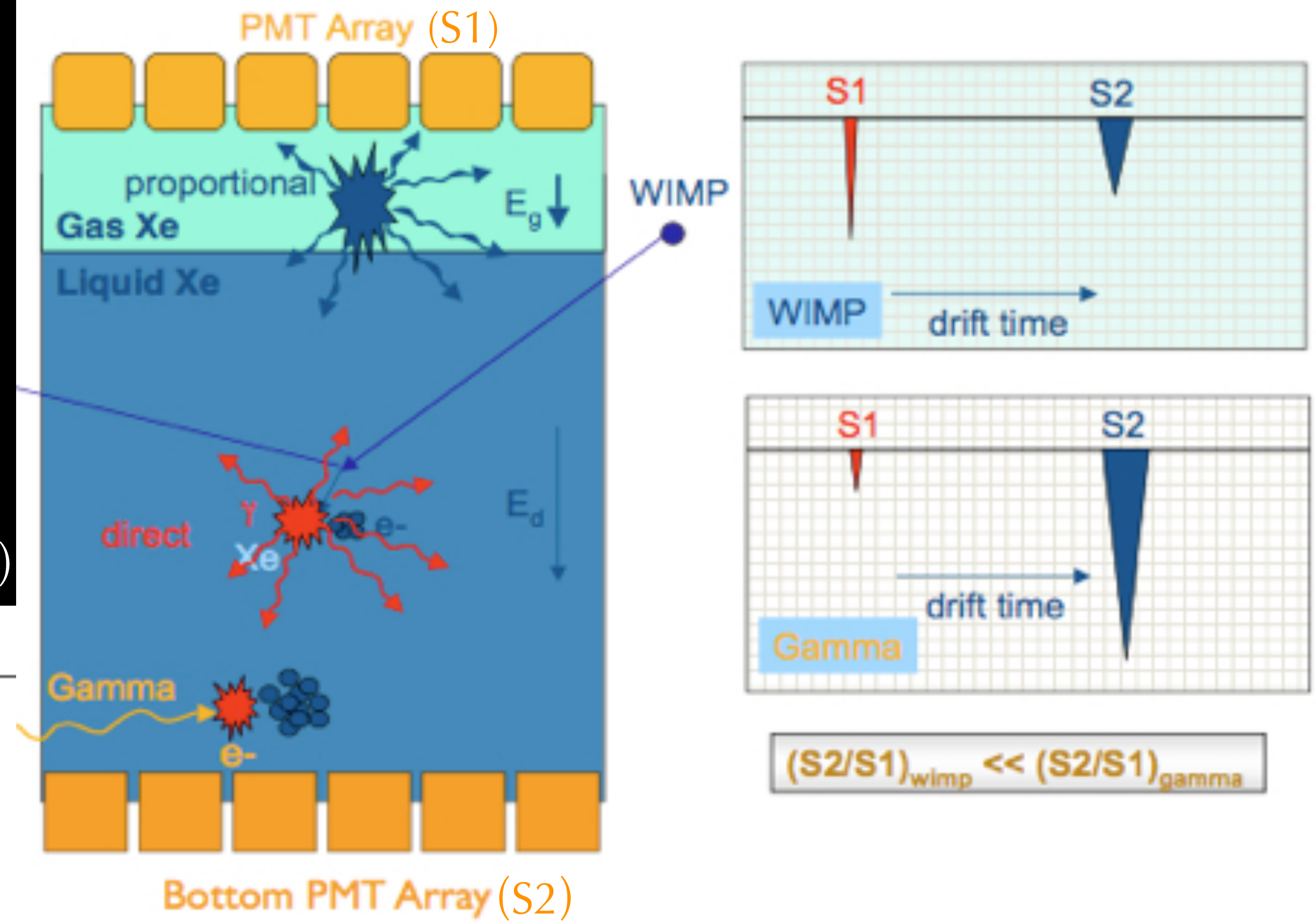
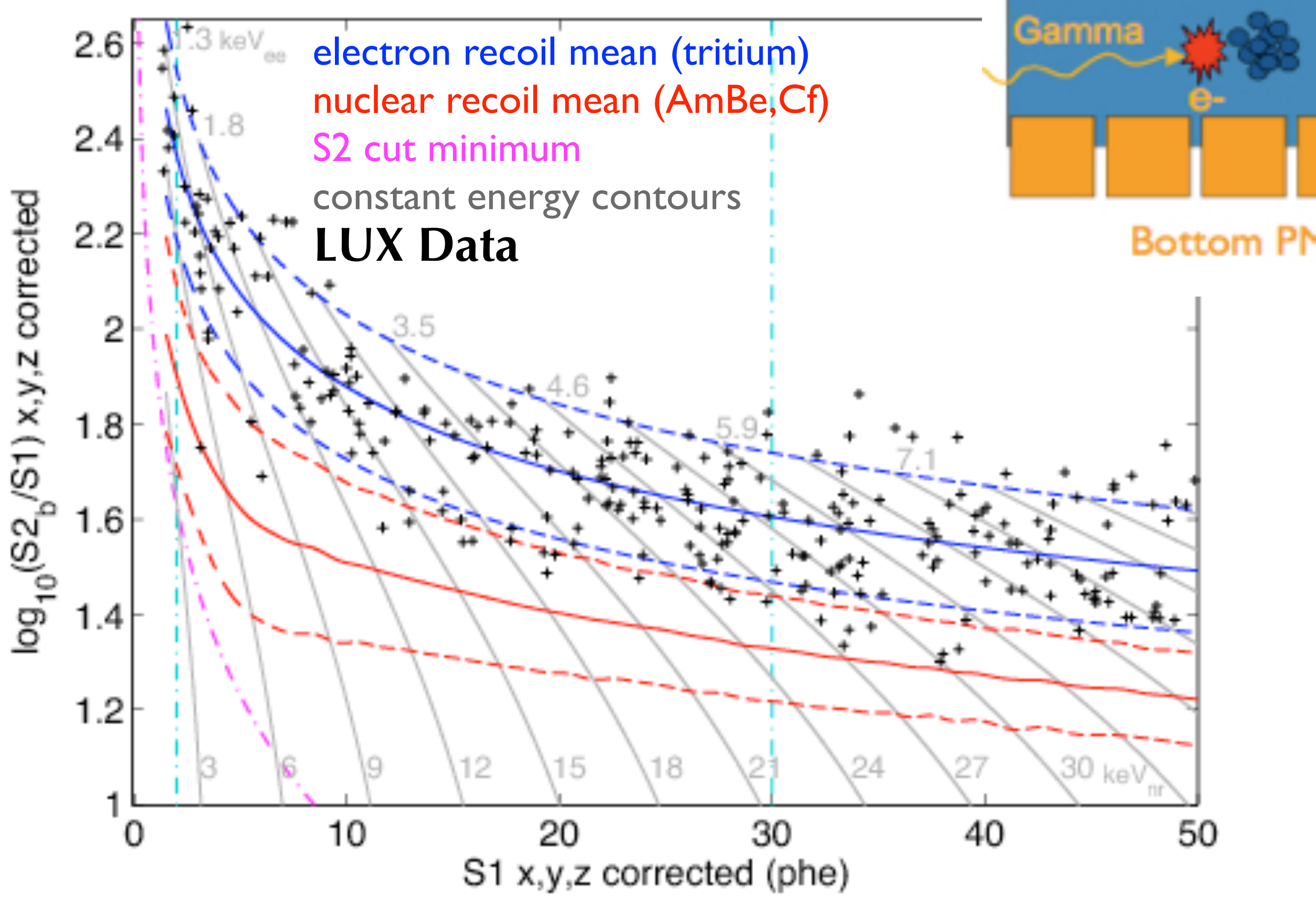
Two-Phase Xenon TPCs

target volume viewed by PMT arrays:
"S1": amplified, drifted
ionization signal
"S2": primary scintillation

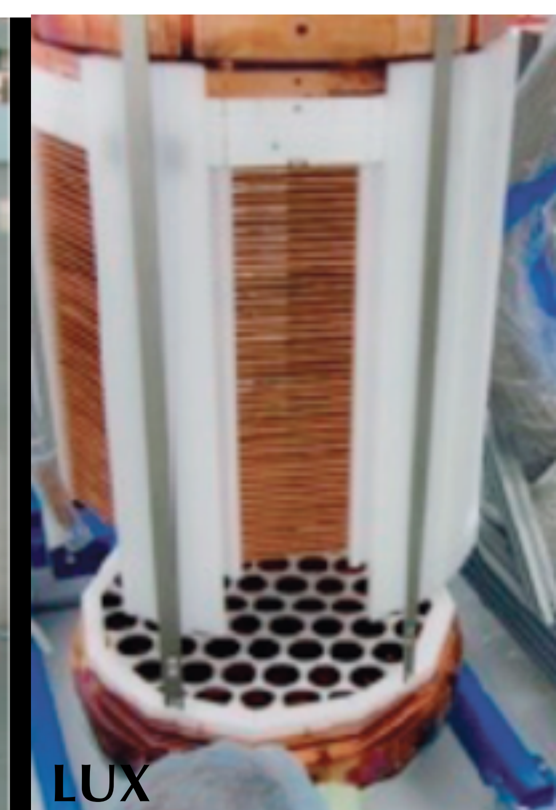
Xenon 10 kg, 100 kg, 1Tonne

LUX (250 kg), PANDA-X (120kg, 500 kg)



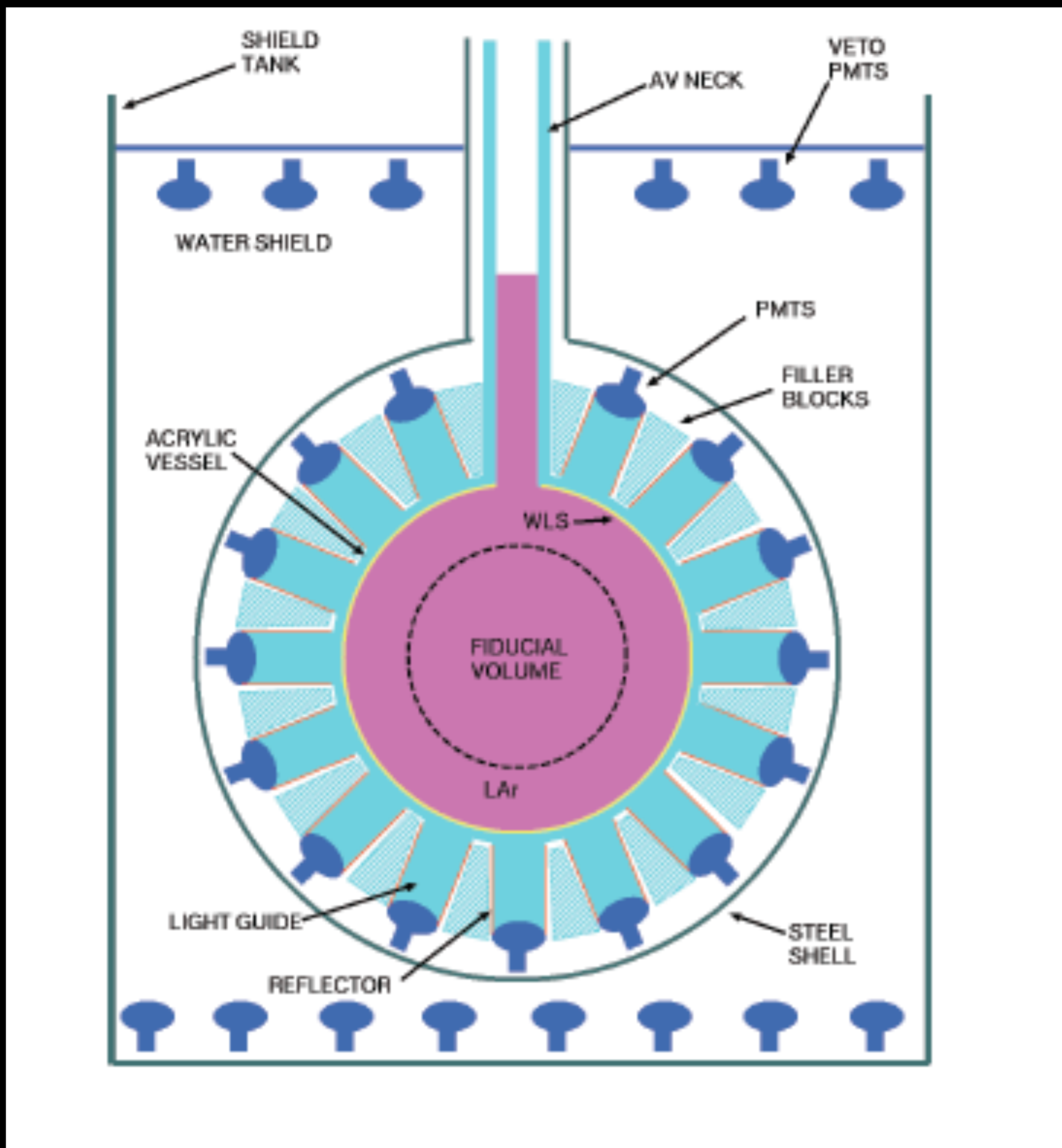


Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



Single Phase Liquid Nobles, a la Neutrinos

high light yield from 4π PMT coverage, self-shielding of liquid target, only detect scintillation



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

DEAP3600: 3600 kg LAr at SNOLAB, commissioning now, design like SNO to reduce backgrounds, future 50T detector.

DEAP data, event display

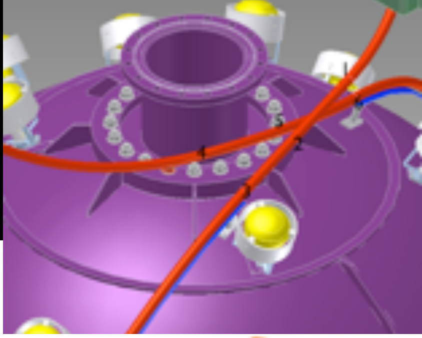
no electric fields = scale to O(kT) mass
1) no recombination in E field
2) no pile-up from ms-scale electron drift in TPC
but background discrimination from scintillation only!

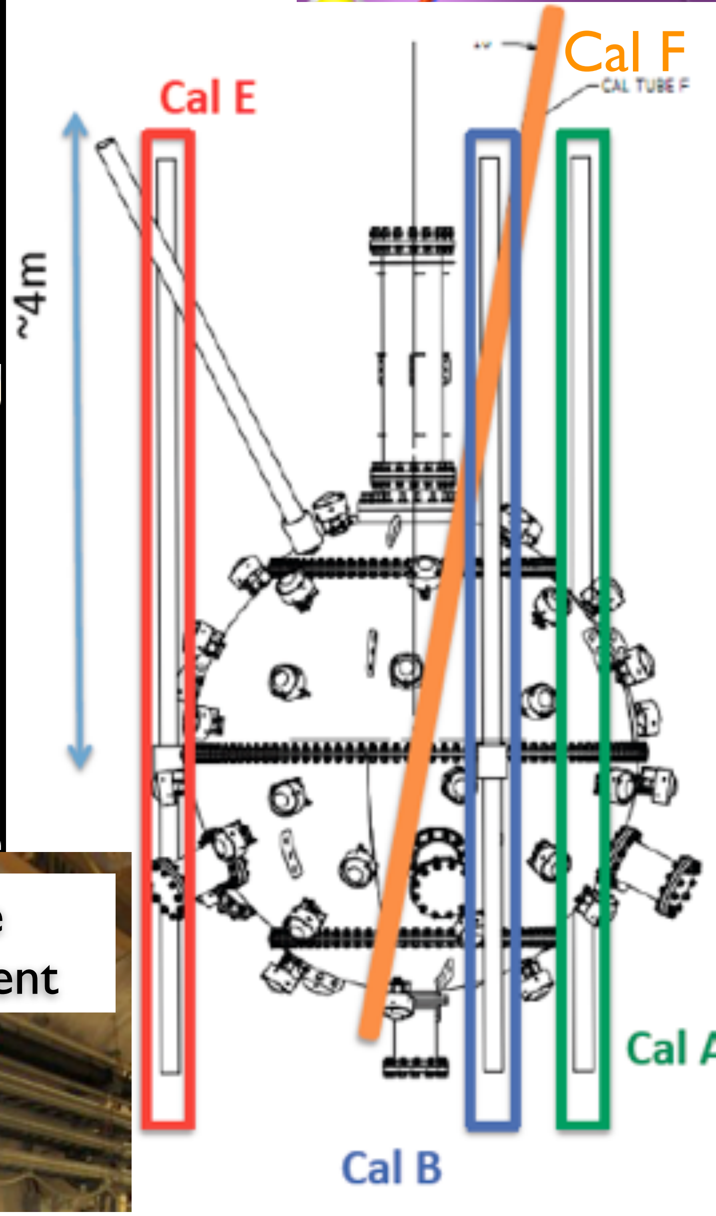
DEAP-3600 Commissioning

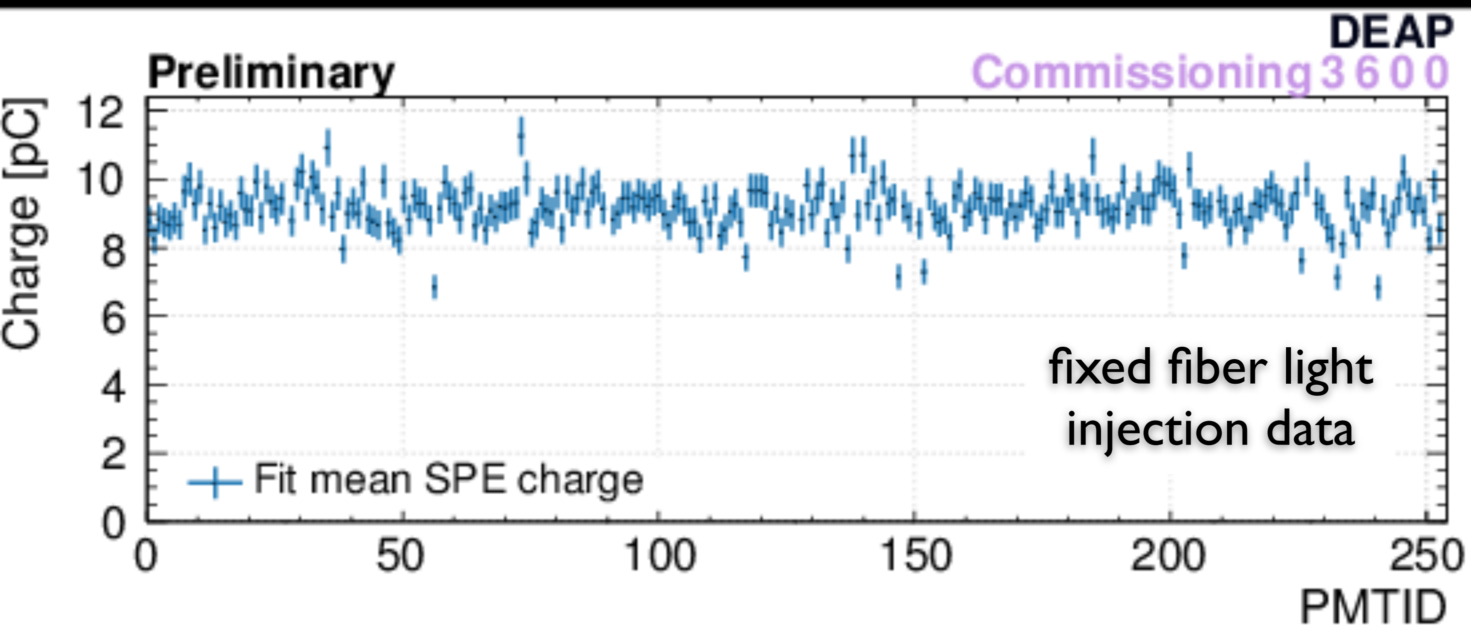
UK delivery of calibration systems (STFC PRD):

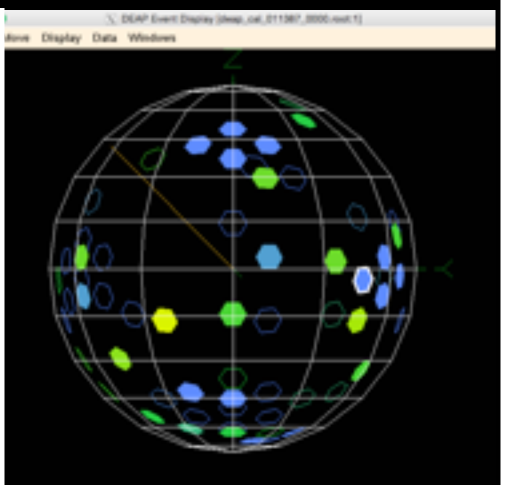
- tagged Na-22 source Cal A,B,E pipes, Cal F racetrack (*RAL*)
- tagged AmBe source in Cal A,B,E (*RHUL*)
- optical calibration sources, in-situ fixed fibers and multi-wavelength, deployable laser flask *(Sussex, RHUL)*

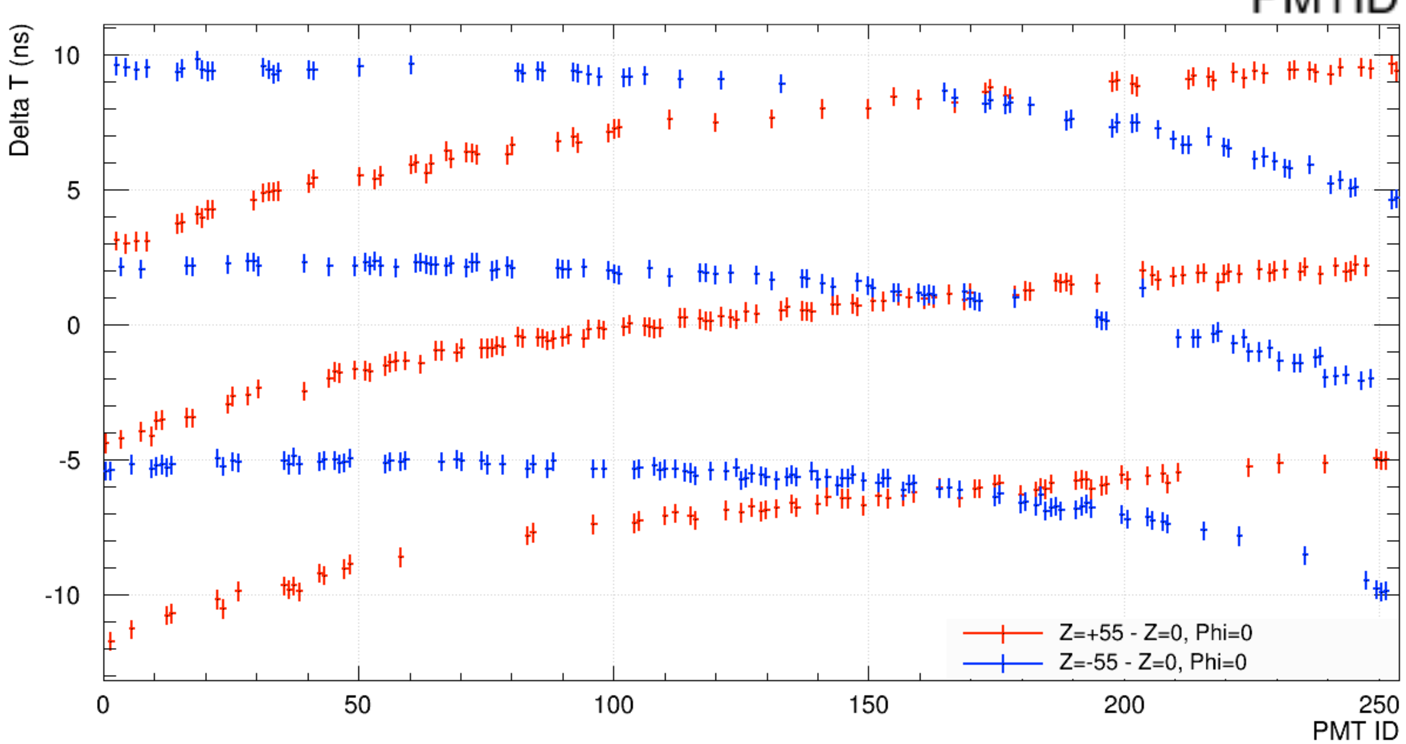
calibration campaigns now routine, PMT response well-understood.

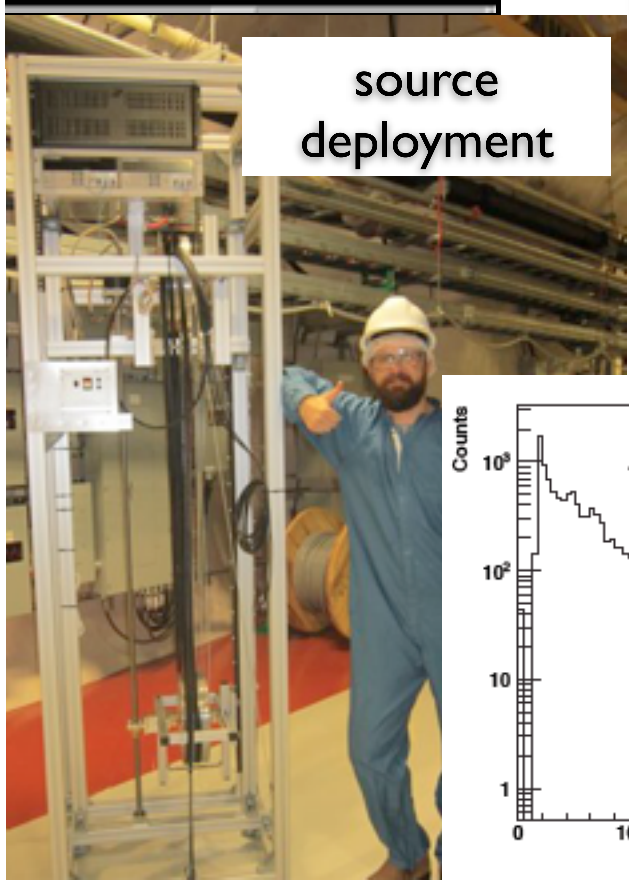


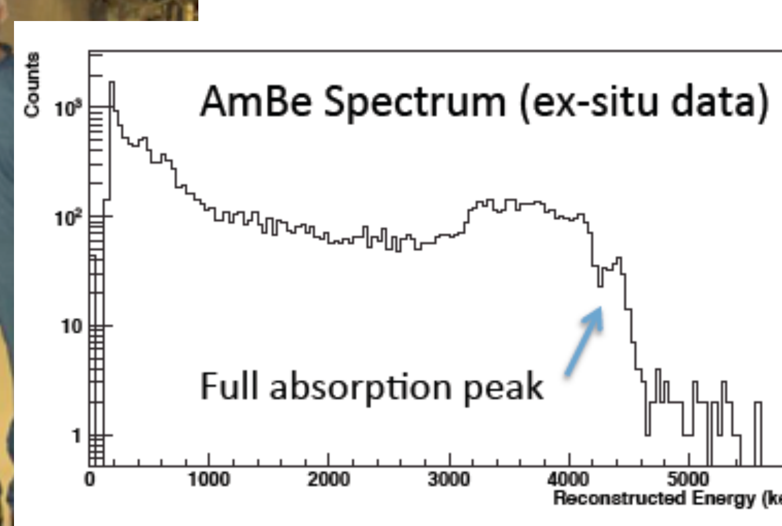












5-Year Future, Prospects

Goal: cover favored MSSM parameter space

LUX: calibrations to lower energy threshold, re-analysis of published data set soon. *(ICL, Edinburgh, UCL)*

PANDA-X: 500 kg LXe, construction & commissioning.

DEAP: 3.6T LAr, commissioning. Sensitivity: 1E-46 cm^2 at 100 GeV/c2 WIMP mass. *(RAL, RHUL, Sussex)*

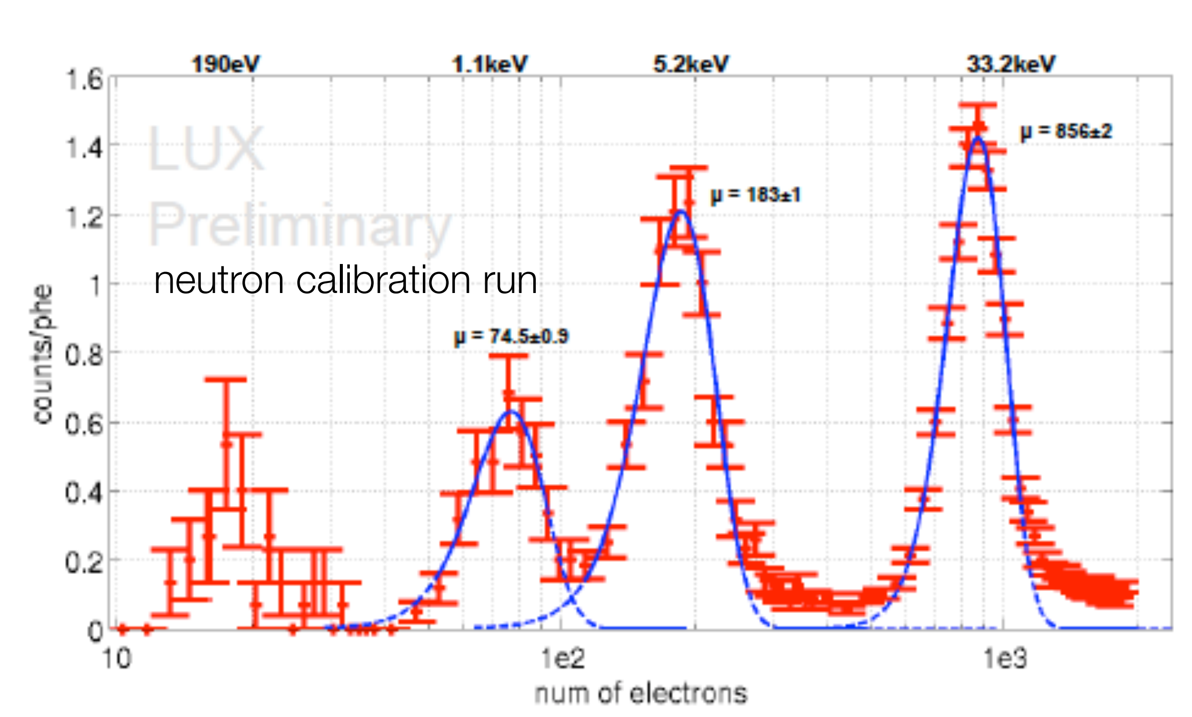
XENON-1T: 3.3T LXe, construction at LNGS. run from 2016. Sensitivity: 1E-47 cm^2.

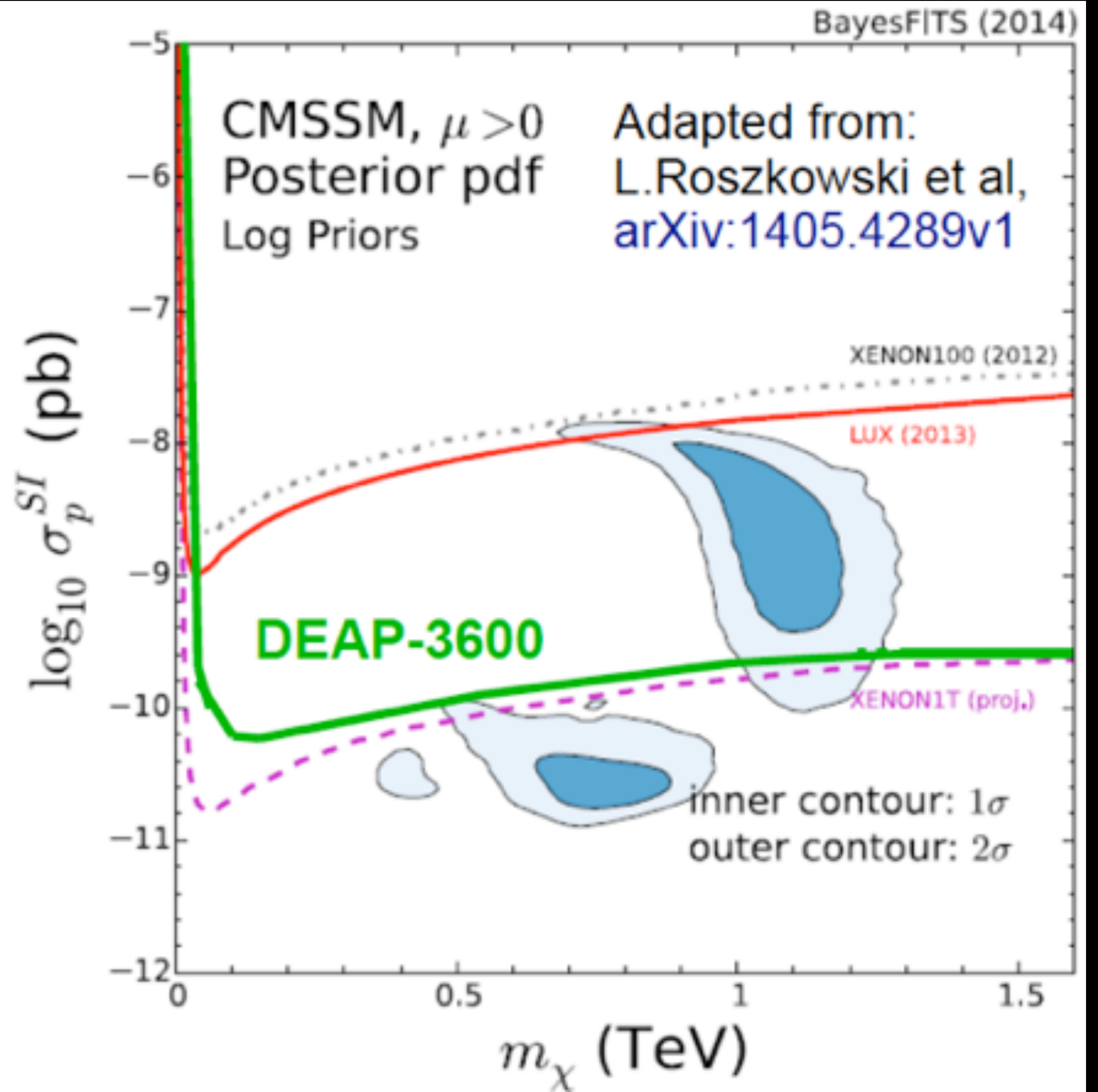
XENON-nT: upgrade to Xenon-1T to 7T Tonnes LXe, using same LNGS infrastructure + new TPC. From 2018.

LZ: follow-on to LUX, 7 Tonnes LXe, using same SURF infrastructure as LUX. Commissioning from 2019. *(Edinburgh, ICL, Liverpool, Oxford, RAL, Sheffield, UCL)*

- DOE-led project in CD process, CD-1/3a April 2015
- CDR: *1509.02910*
- procurement (cryostat, PMTs) underway in UK

Sensitivity: 2E-48 cm^2 + 0**νββ**, solar **ν** physics.





5-Year Future, Prospects

Goal: cover favored MSSM parameter space

LUX: calibrations to lower energy threshold, re-analysis of published data set soon. *(ICL, Edinburgh, UCL)*

PANDA-X: 500 kg LXe, construction & commissioning.

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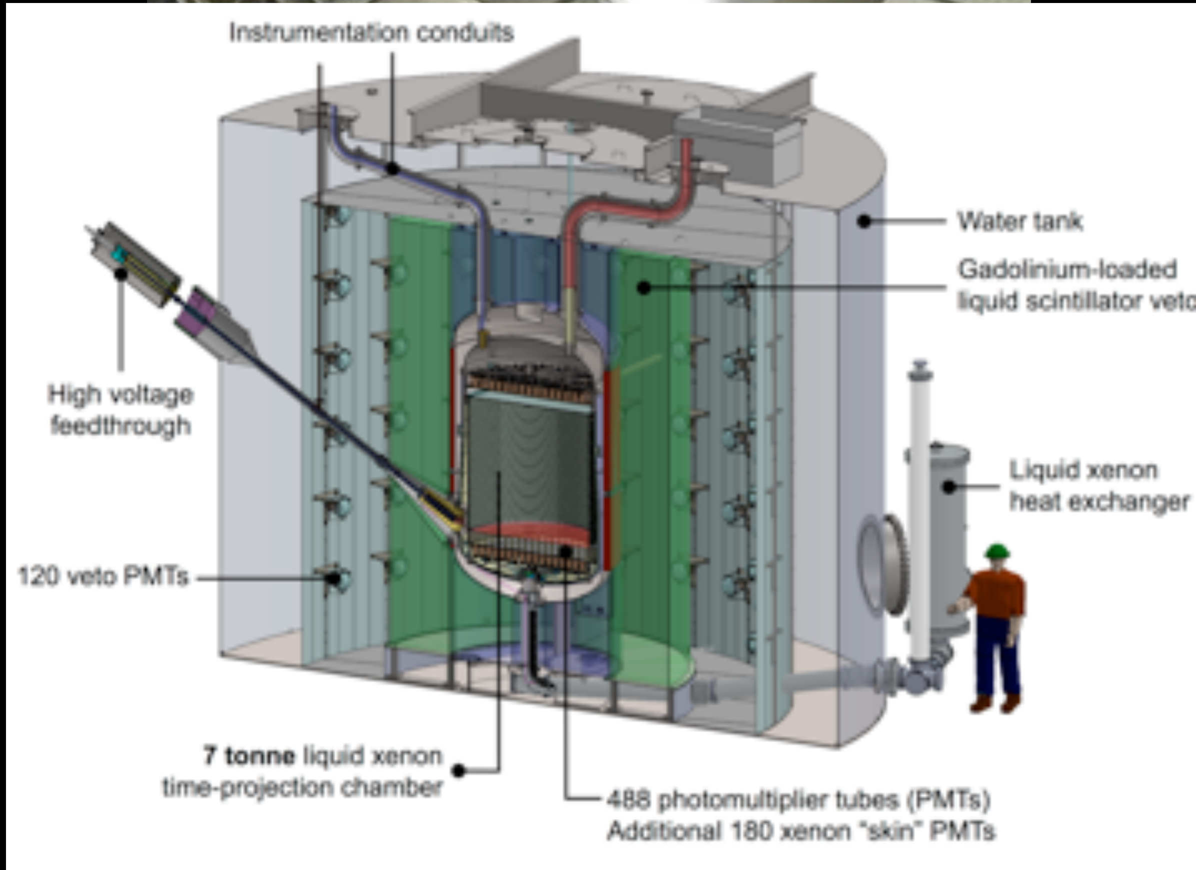
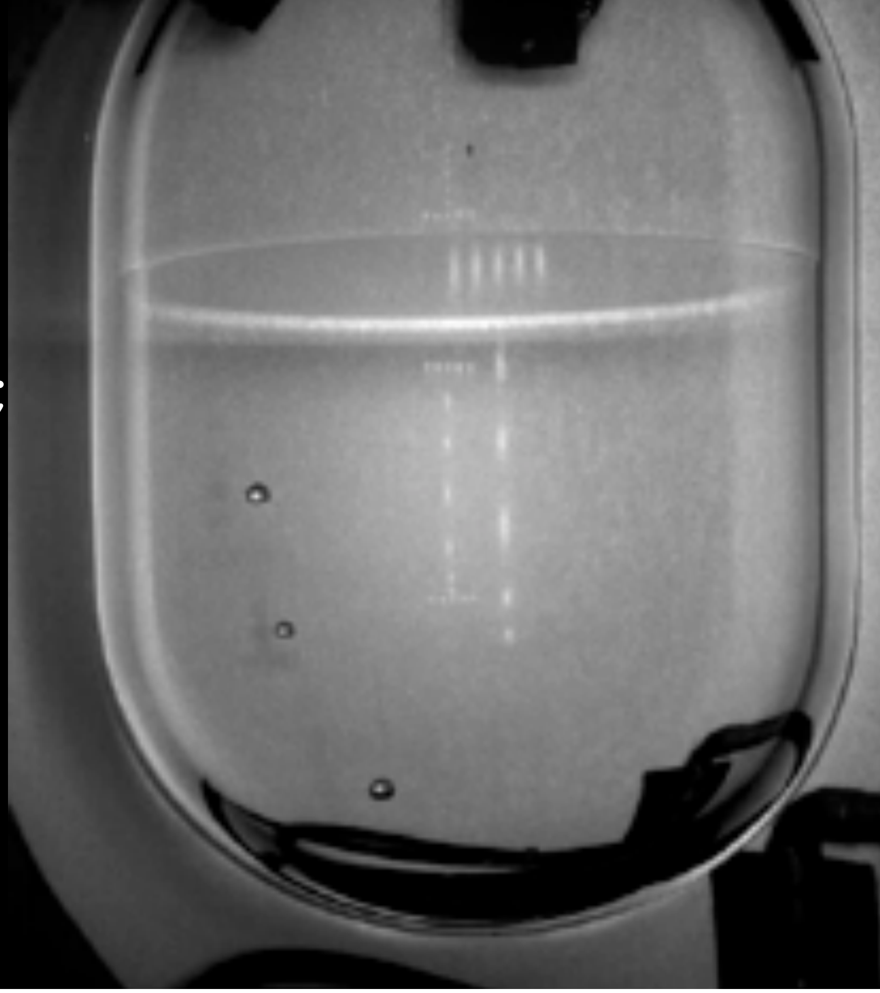


Bubble Chambers

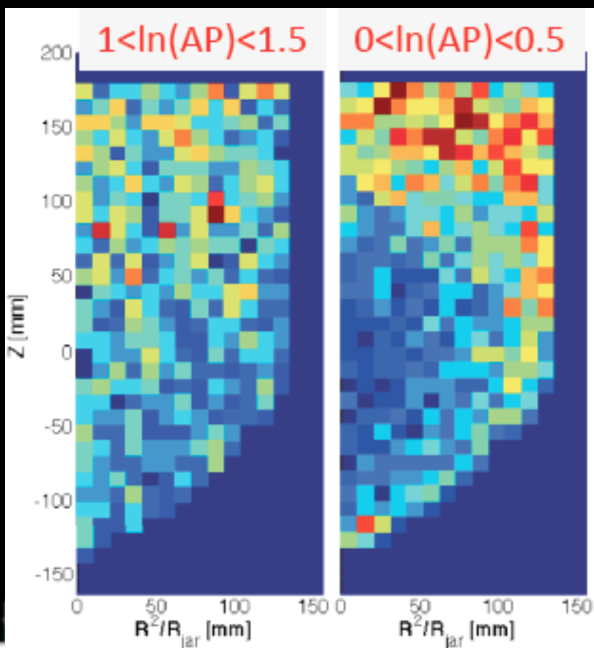


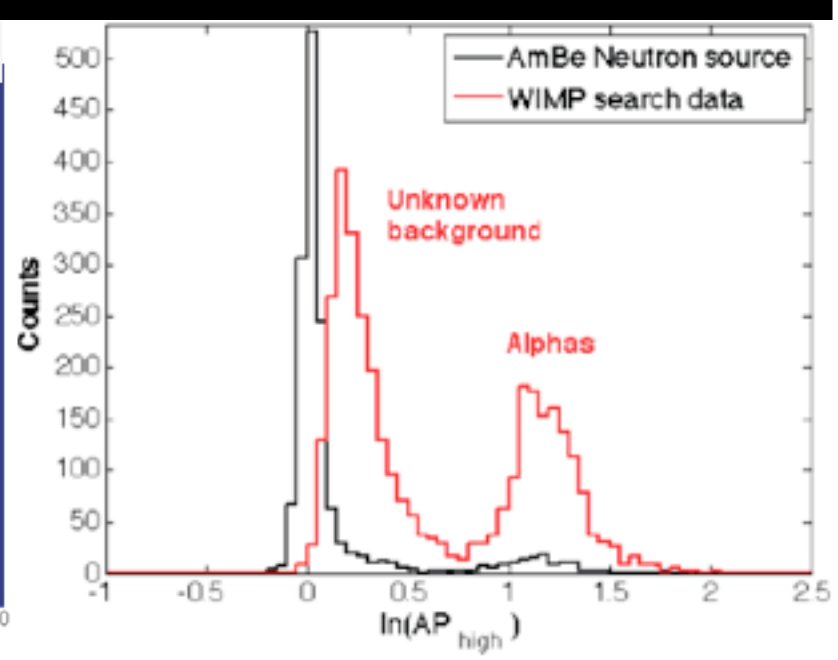
superheated CF_3I target, with camera and acoustic readout
measure integral counts above threshold when dE/dx > nucleation;
leading spin-dependent WIMP scattering sensitivity

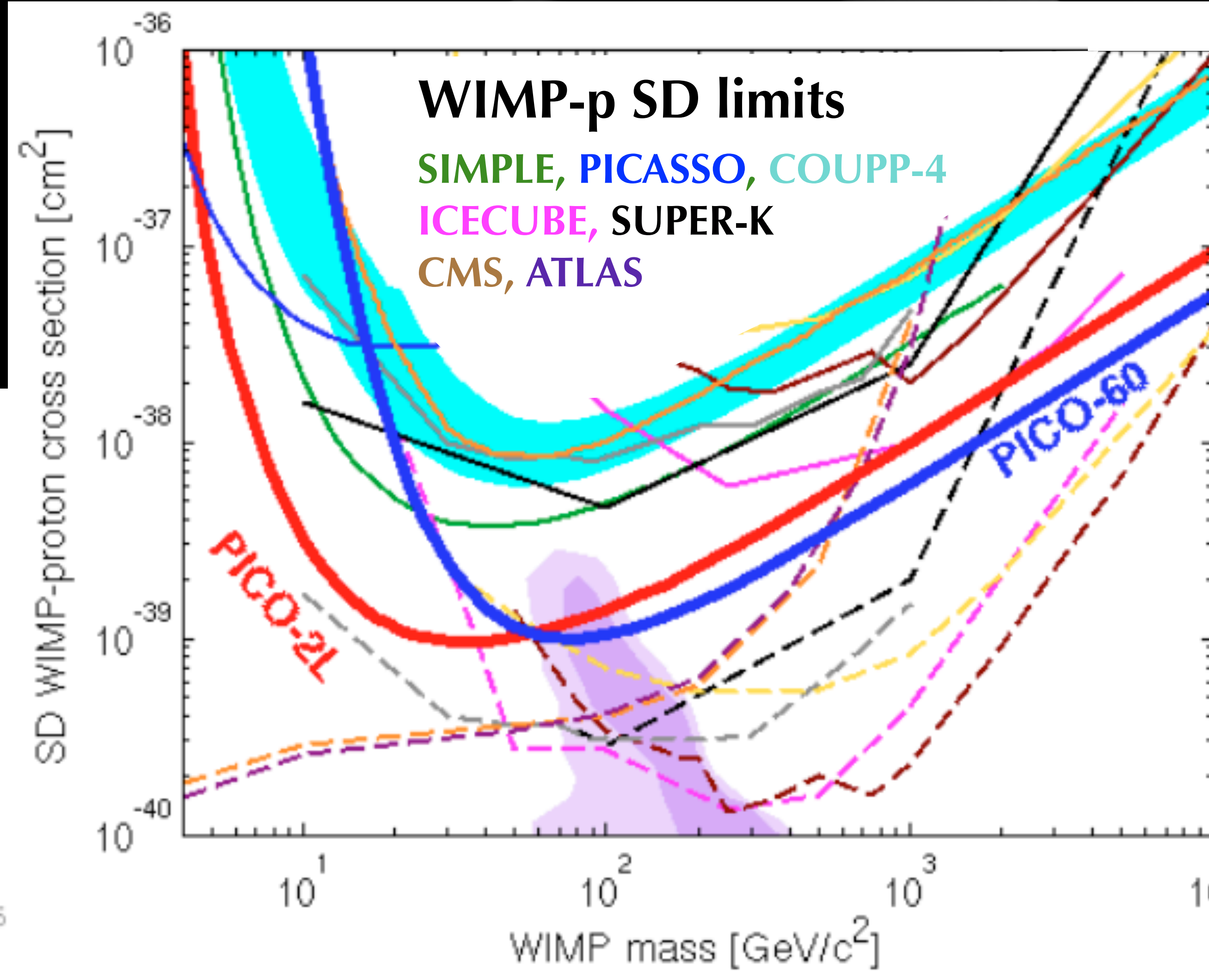
SIMPLE (Canfranc), PICASSO, COUPP, PICO (SNOLAB)

PICO-60: (PICASSO+COUPP) running since 2013 with CF_3I target
background population observed, preliminary limit (E_{th} = 7 keV)
Iodine target: expect 49 recoils above 22 keV in DAMA region, observe <4.1 @ 90% CL *(D. Jeter, CIPANP'15)*

PICO-2L: C_3F_8 target, SD WIMP-proton limit
(212 kg-days, E_{th} = 3.2 keV) *arXiv:1503.00008 (PRL)*
target upgrade of PICO-60 planned Fall 2015







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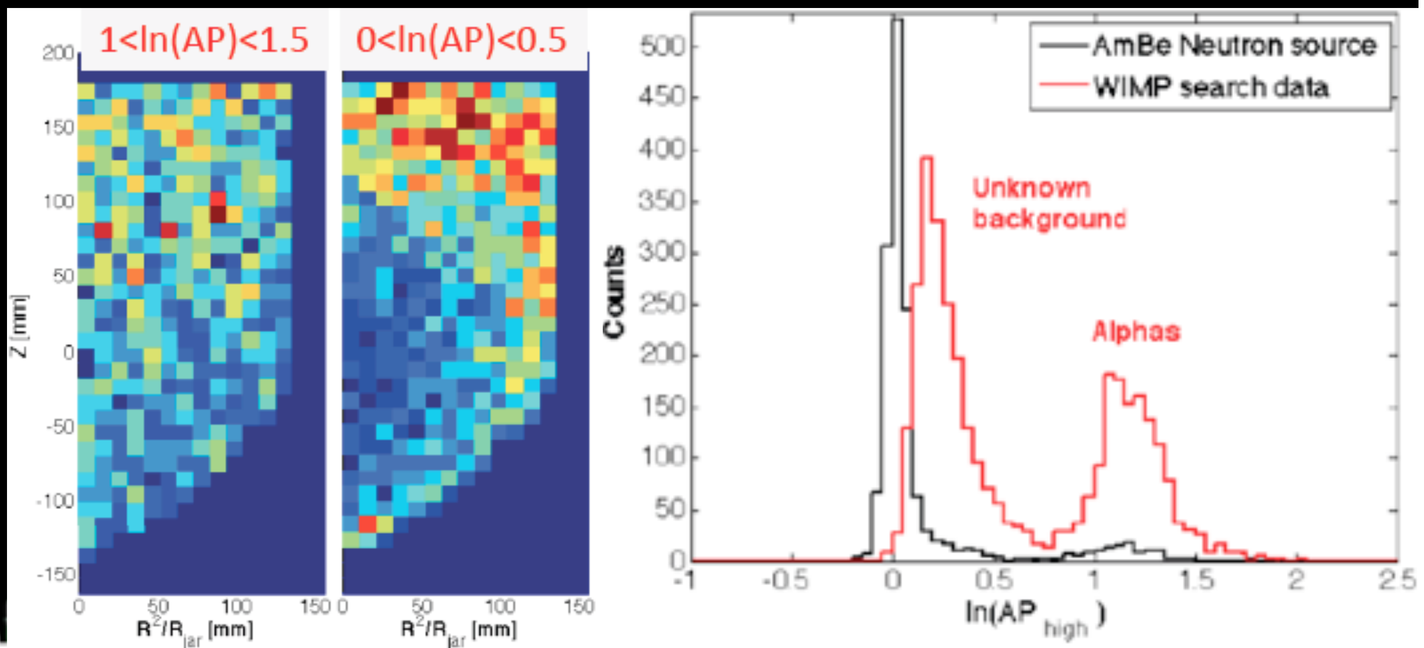
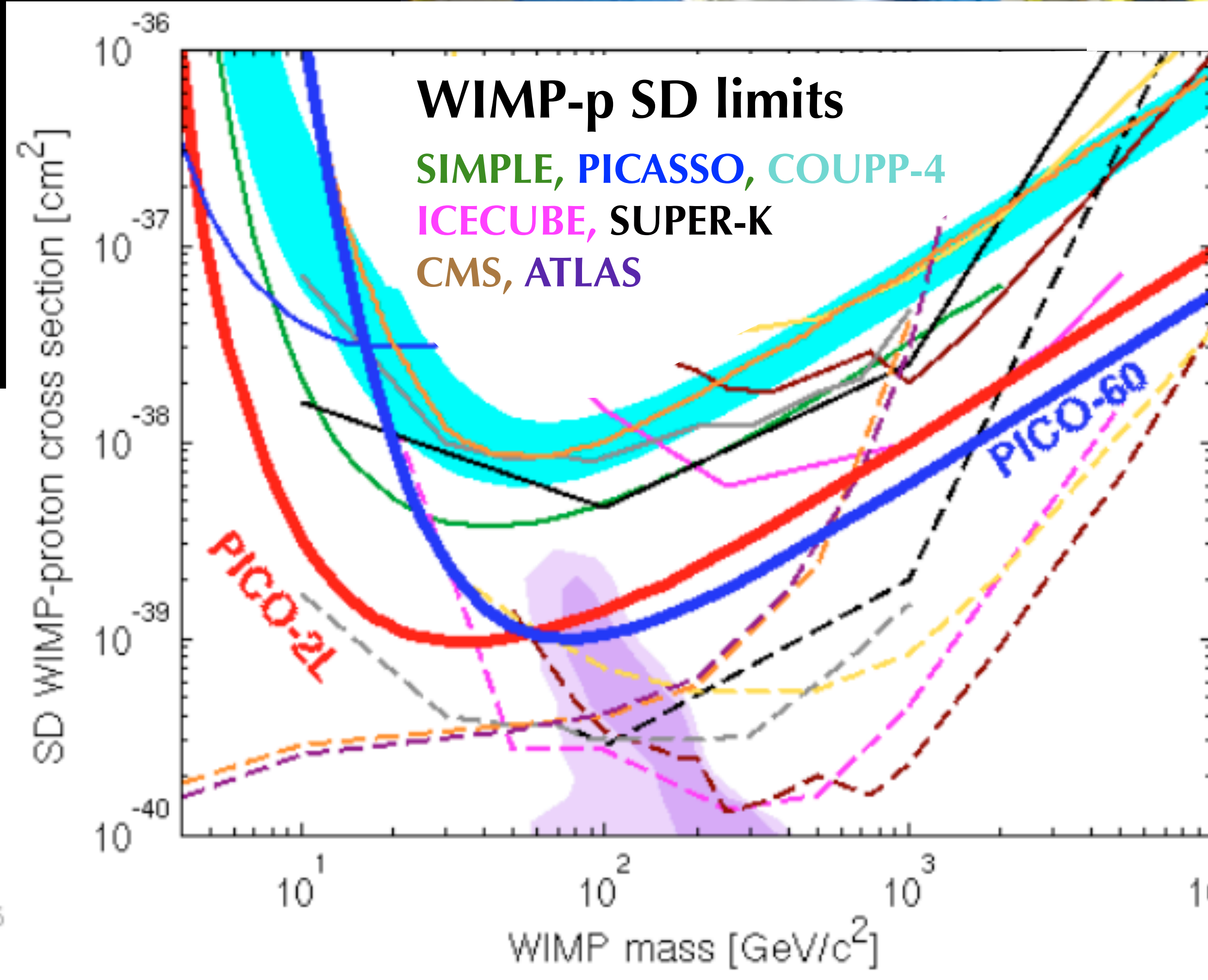
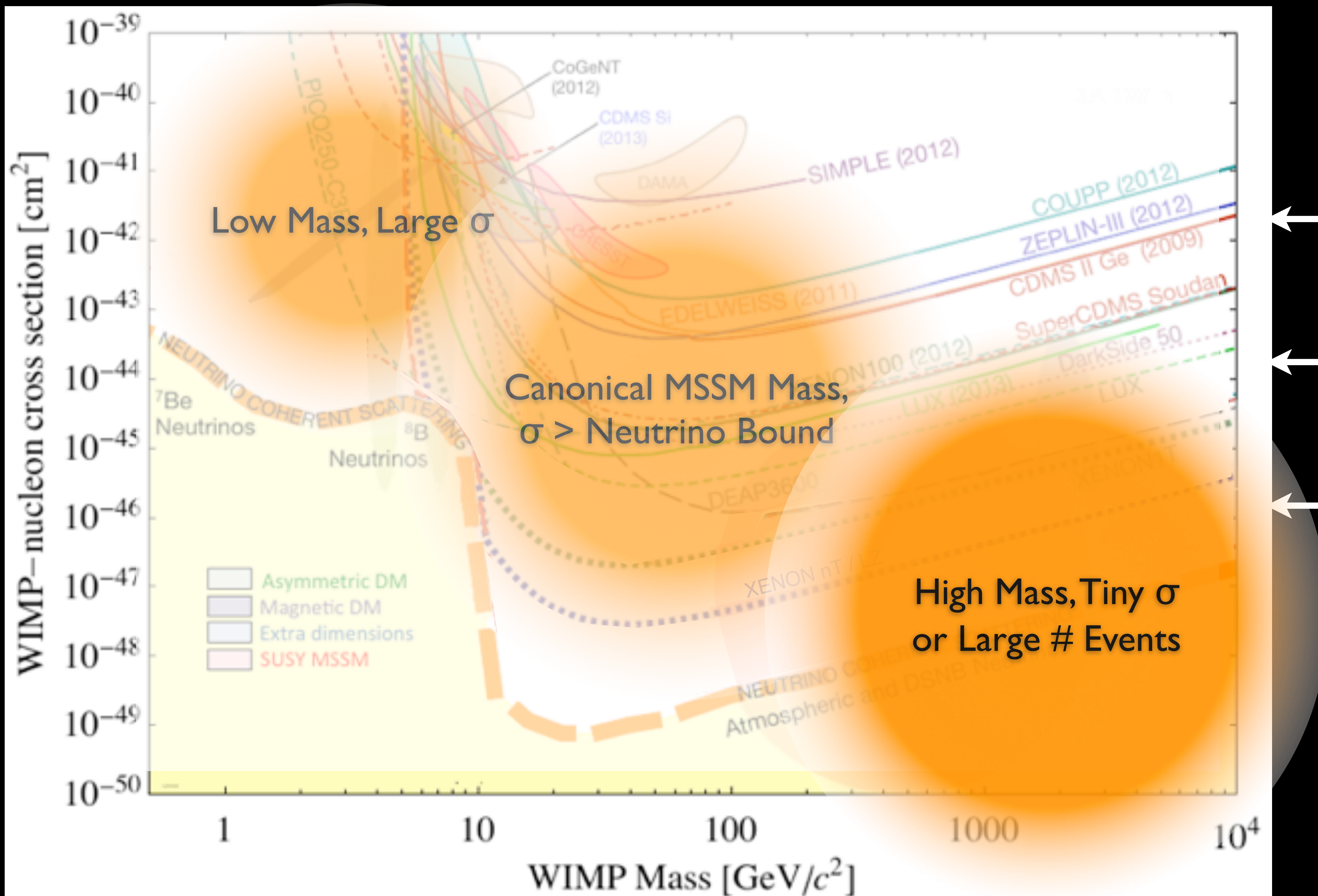




The Low-Background Frontier: Prospects



1 event/ kg/day

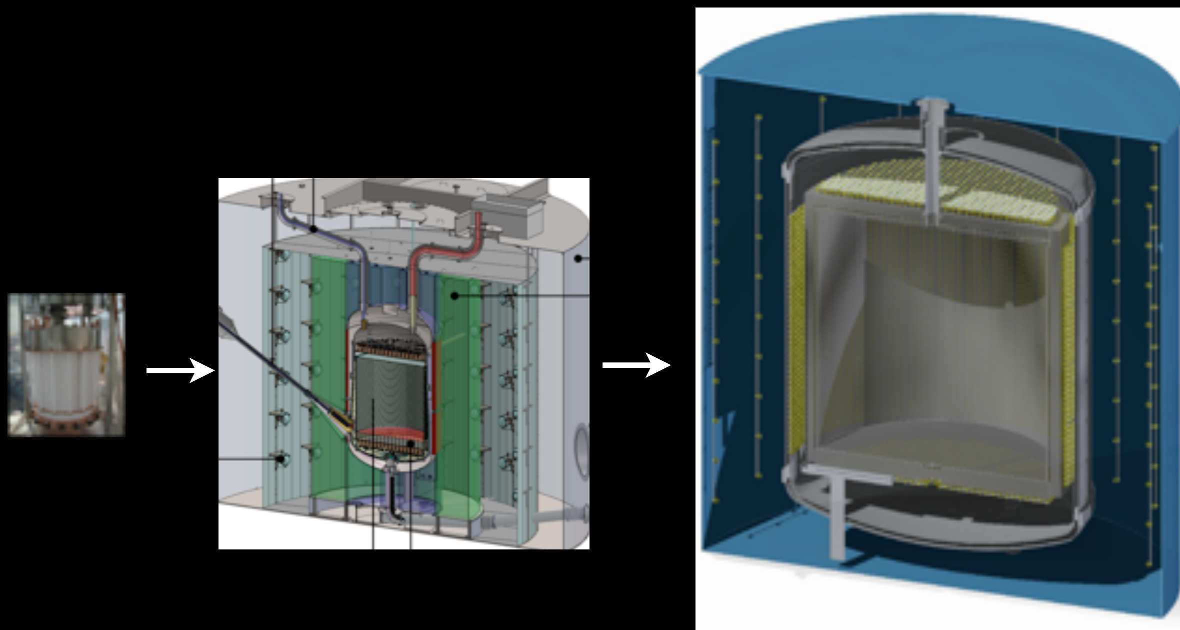
1 event/ 100kg/day

1 event/ 100 kg/ 100 days

so far: ~3 years / order of magnitude

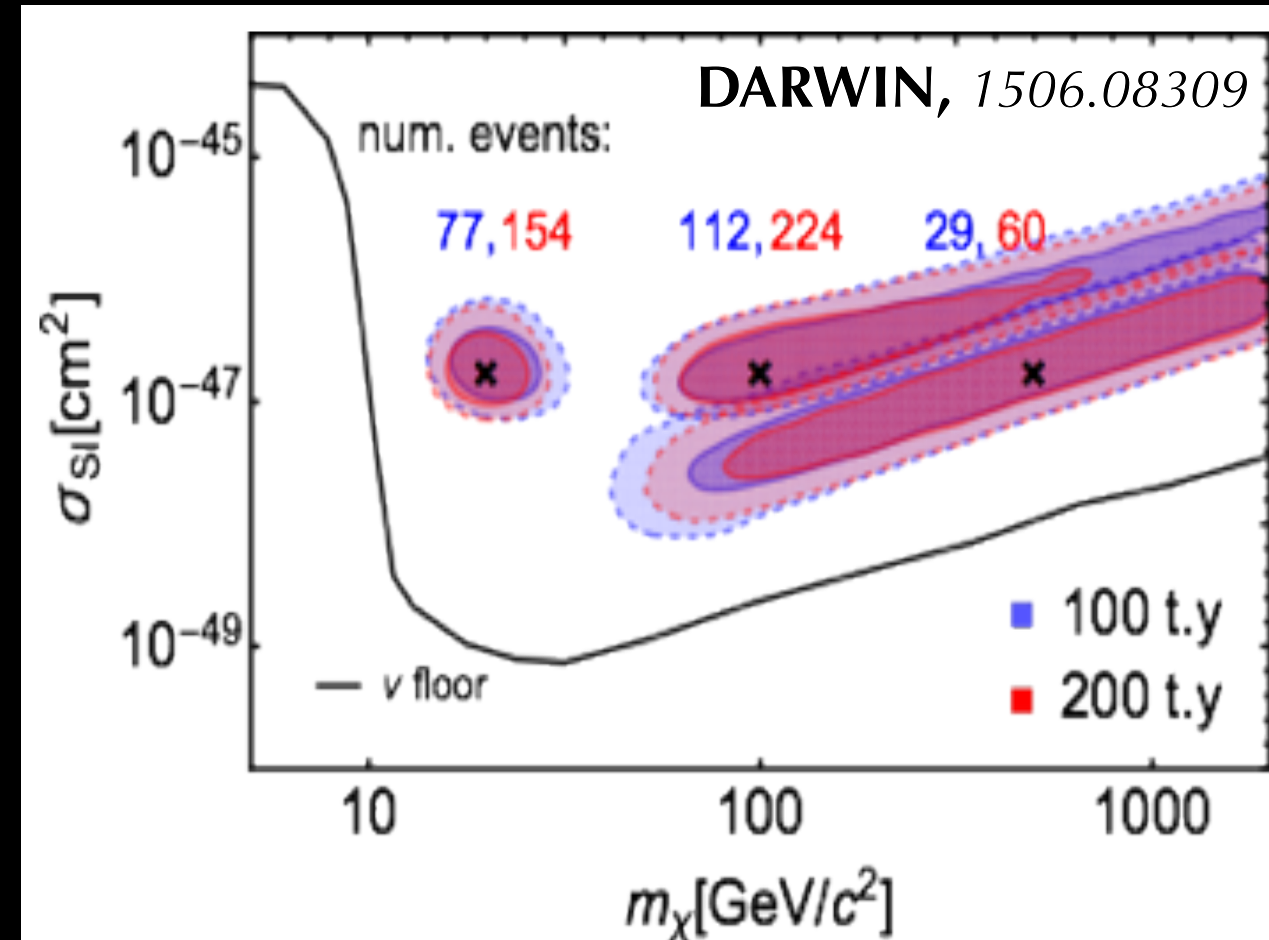
Beyond the Neutrino Bound

Goal: WIMP spectroscopy!



Experiment	σ(1 TeV)	σ(10 TeV)
DarkSide-50	2E-43	2E-42
XENON-100	2E-44	2E-43
DEAP-3600	5E-46	5E-45
XENON-1T	3E-46	3E-45
LZ (7T)	5E-47	5E-46
1 Neutrino	2E-48	2E-47
DEAP-50T	3E-48	3E-47
ARGO-300T	9E-49	9E-48

adapted from C. Galbiati



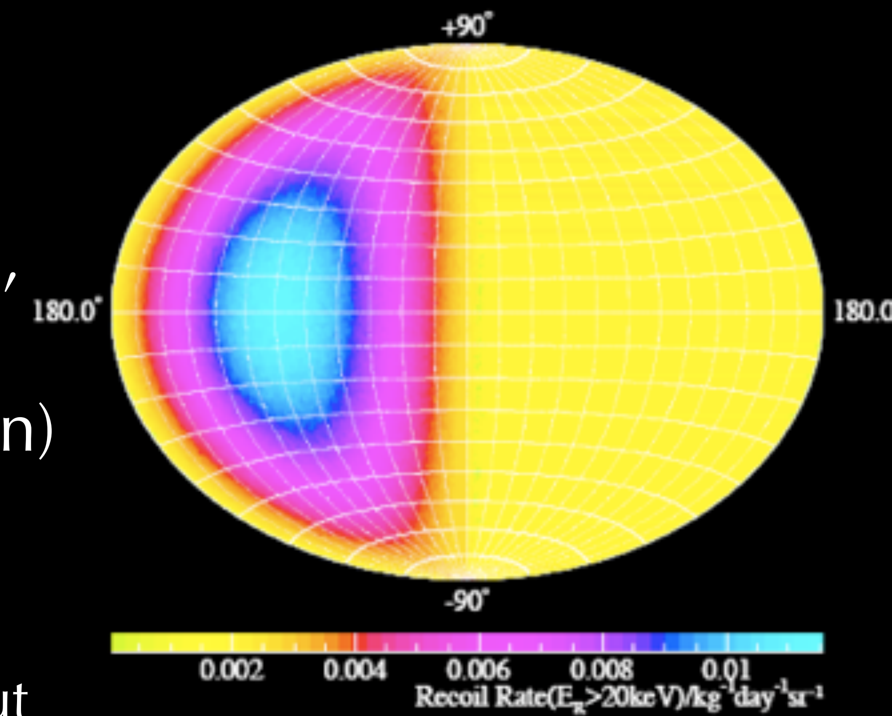
DARWIN: design study for 50-80T two-phase LXe Size: >2m length x diameter. Background dominated by solar **ν**-e scattering.

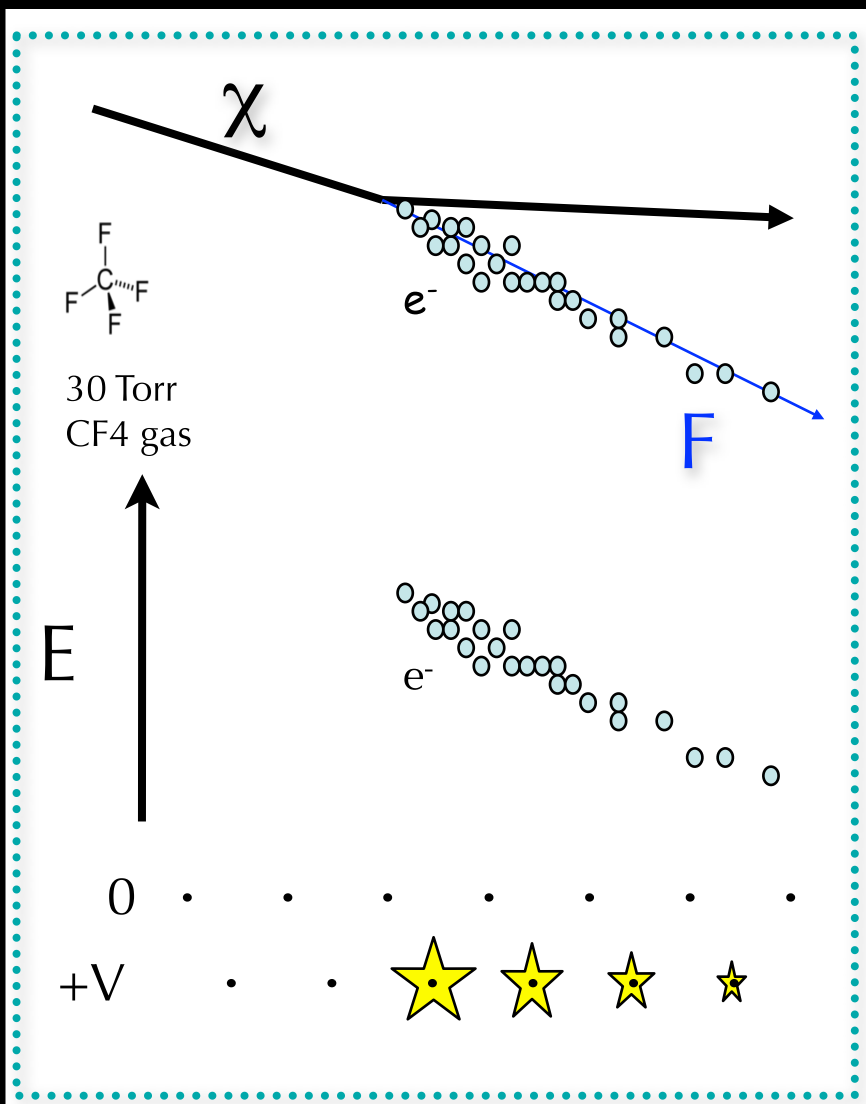
Emphasis on high-mass sensitivity:
DEAP-50: design for 50T single-phase LAr. Size: 7m diameter x tall. Background tolerances much easier than DEAP-3.6, a la SNO.

ARGO: design for 300T depleted LAr detector. LOI to LNGS for 20T prototype stage. Global coordination of LAr experiments.

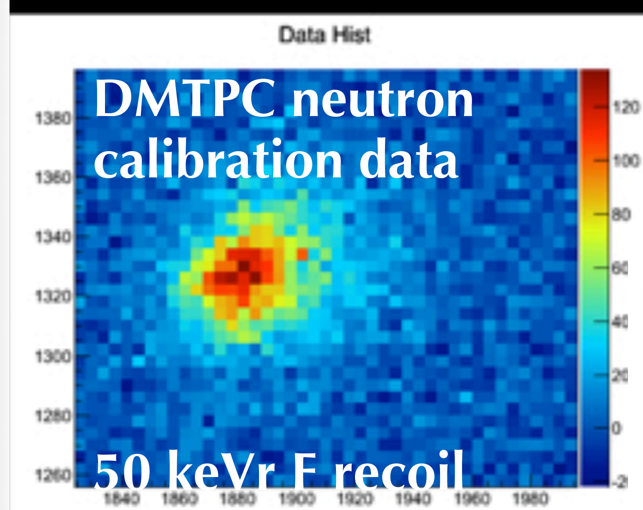
Directional Detection

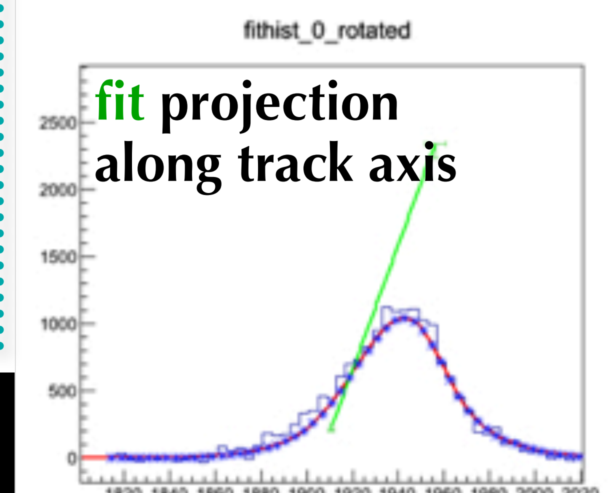
R&D towards dark matter recoil tracking, in low background, scalable detectors to positively identify a candidate signal with the galactic dark matter halo (need ~35º resolution)

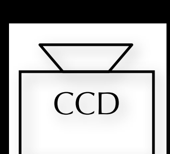




strategy: low pressure CF-4 gas in TPCs with high resolution readout

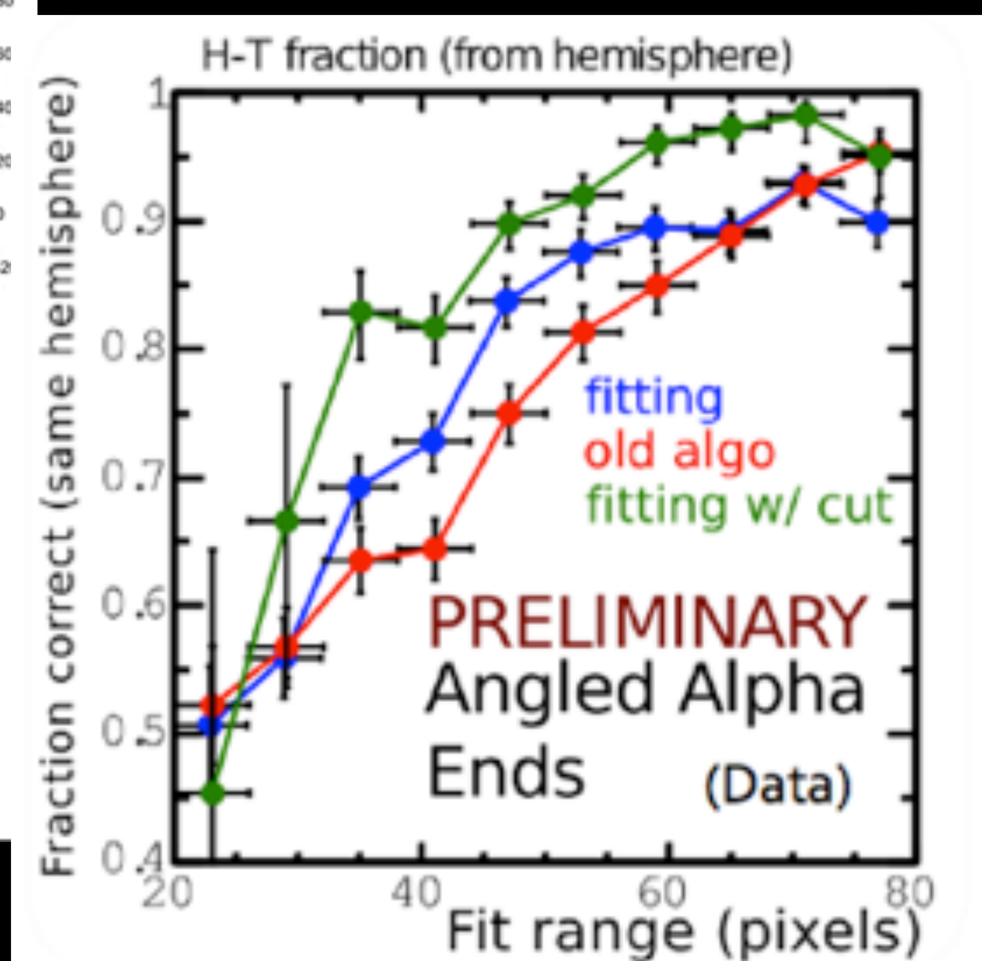






optical+ charge readout

DMTPC example: use dE/dx along track to fit for vector direction



Energy range equivalent ~50-200 keV

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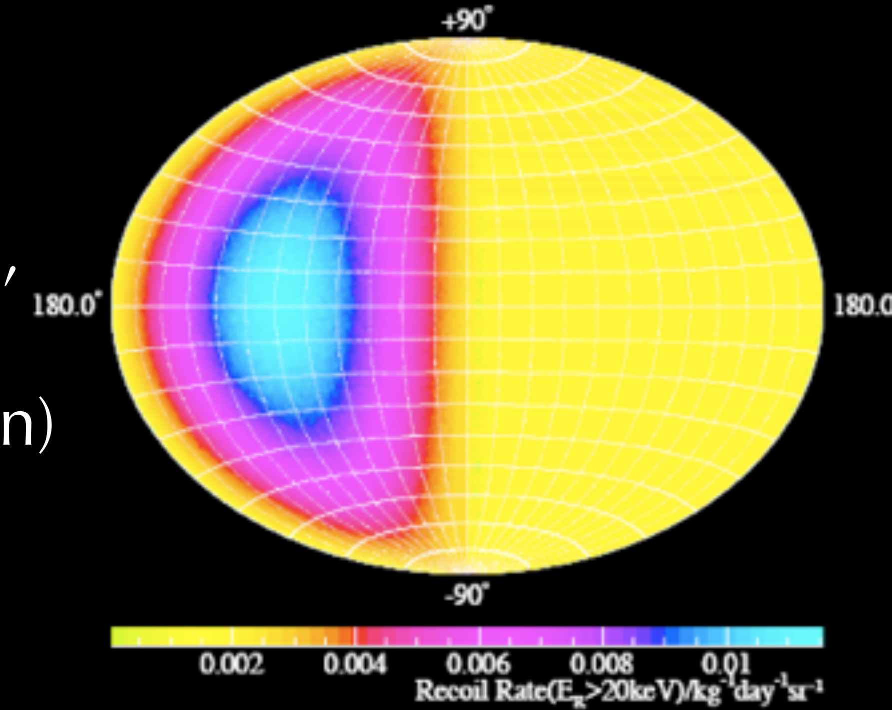
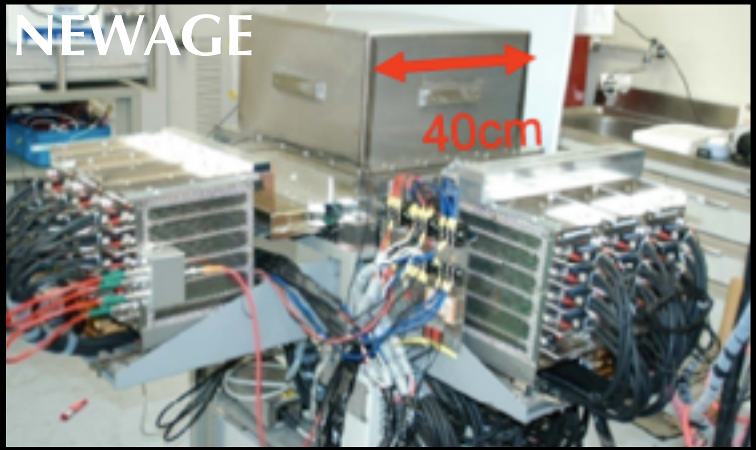
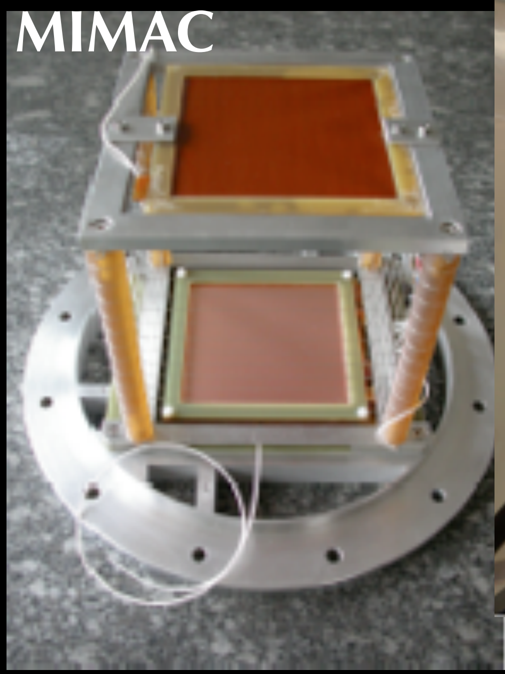
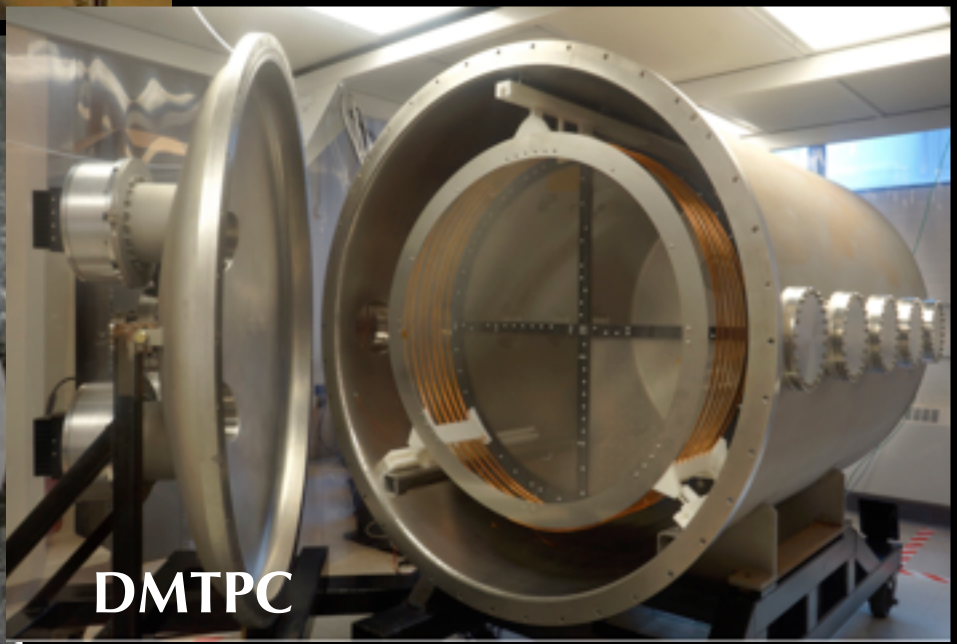








DMTPC: CCD and charge readout of CF_4; measure 40° resolution, commissioning 1m^3 module for SNOLAB. *(RHUL)*

DRIFT: MWPC readout, operating 0.8m^3 detector in Boulby since 2001. Negative ion drift of CS_2+CF_4. *(Sheffield, Edinburgh)*

MIMAC: micromegas readout of CF_4 target, in Modane. Focus on low energy.

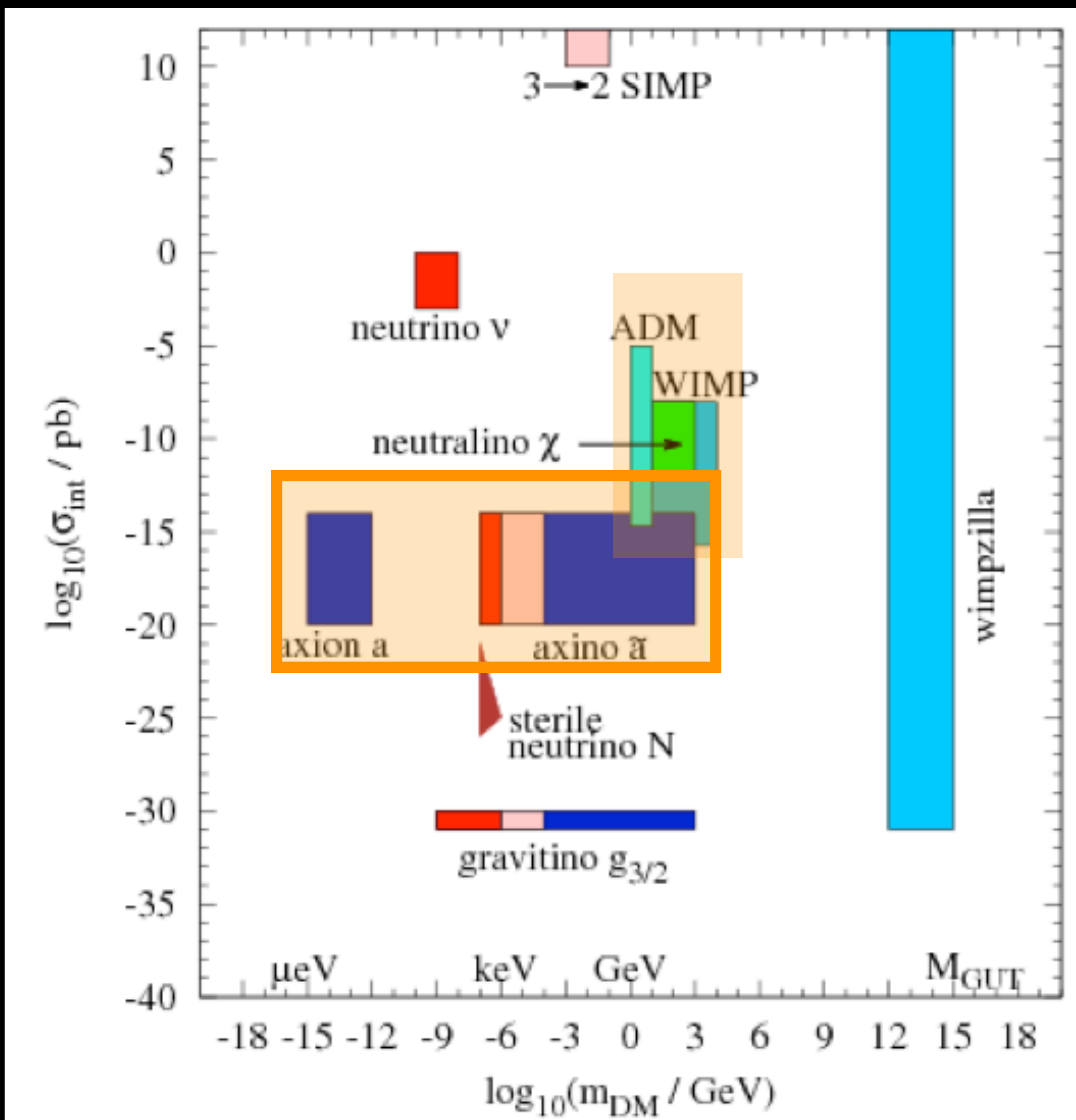
NEWAGE: mu-PIX readout of CF_4 target, in Kamioka. First directional limit.

CYGNUS: coordination of directional R&D

plus R&D on fine-grained emulsions, pixel chips, high P gas, biological detectors, C nanotubes, ++

Model Space

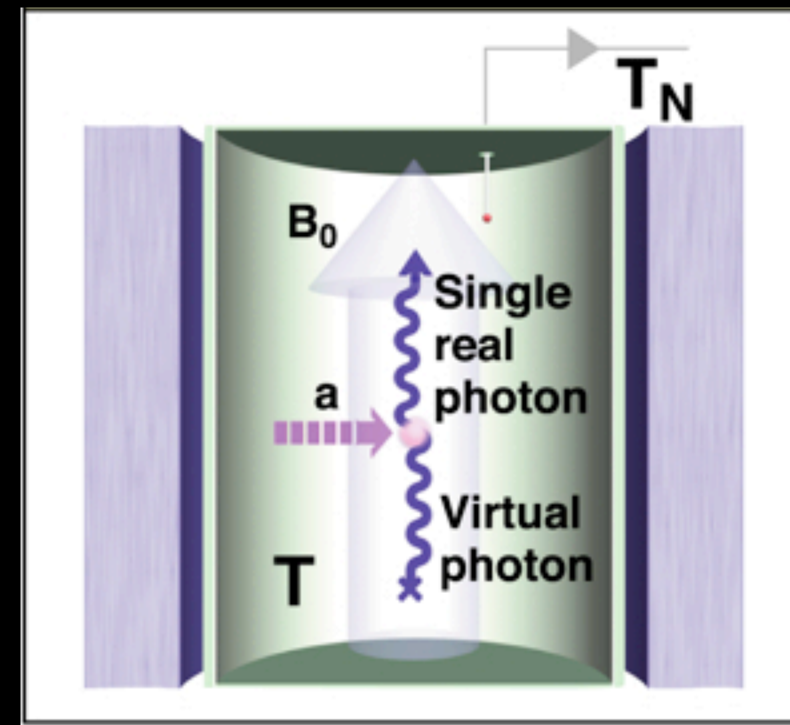
WIMPs aren't the only possibility!



Baer et al., arXiv:1407.0017

Axion and ALP detection:

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



new 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.

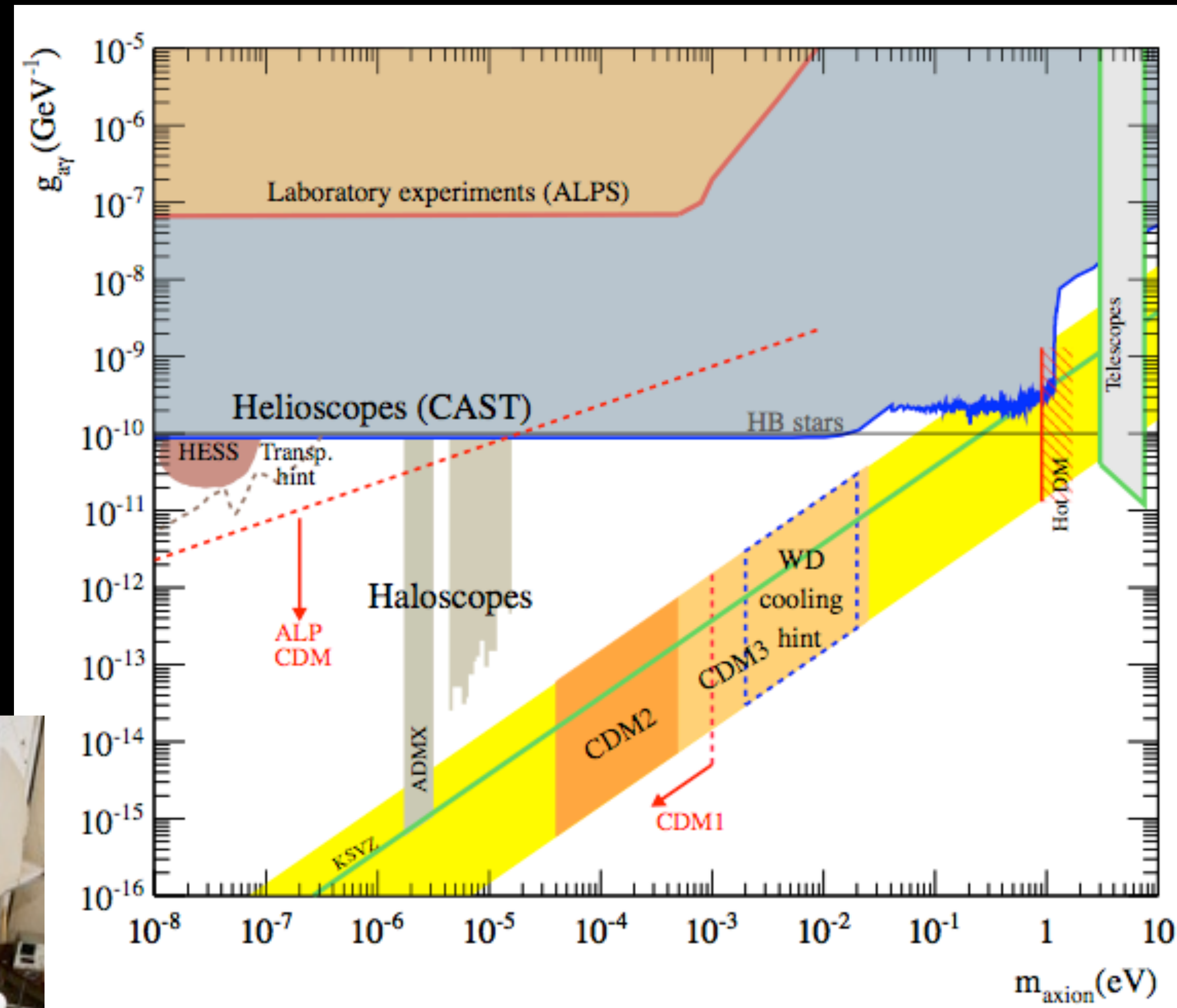
Axions: Status and Prospects

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 just started! *(Sheffield, Lancaster)*

•aim to develop active cavity resonators to improve mass scan rate, and reach



IAXO: coordination of axion searches, proposal for helioscope at CERN, *(SPSC 1-242)*

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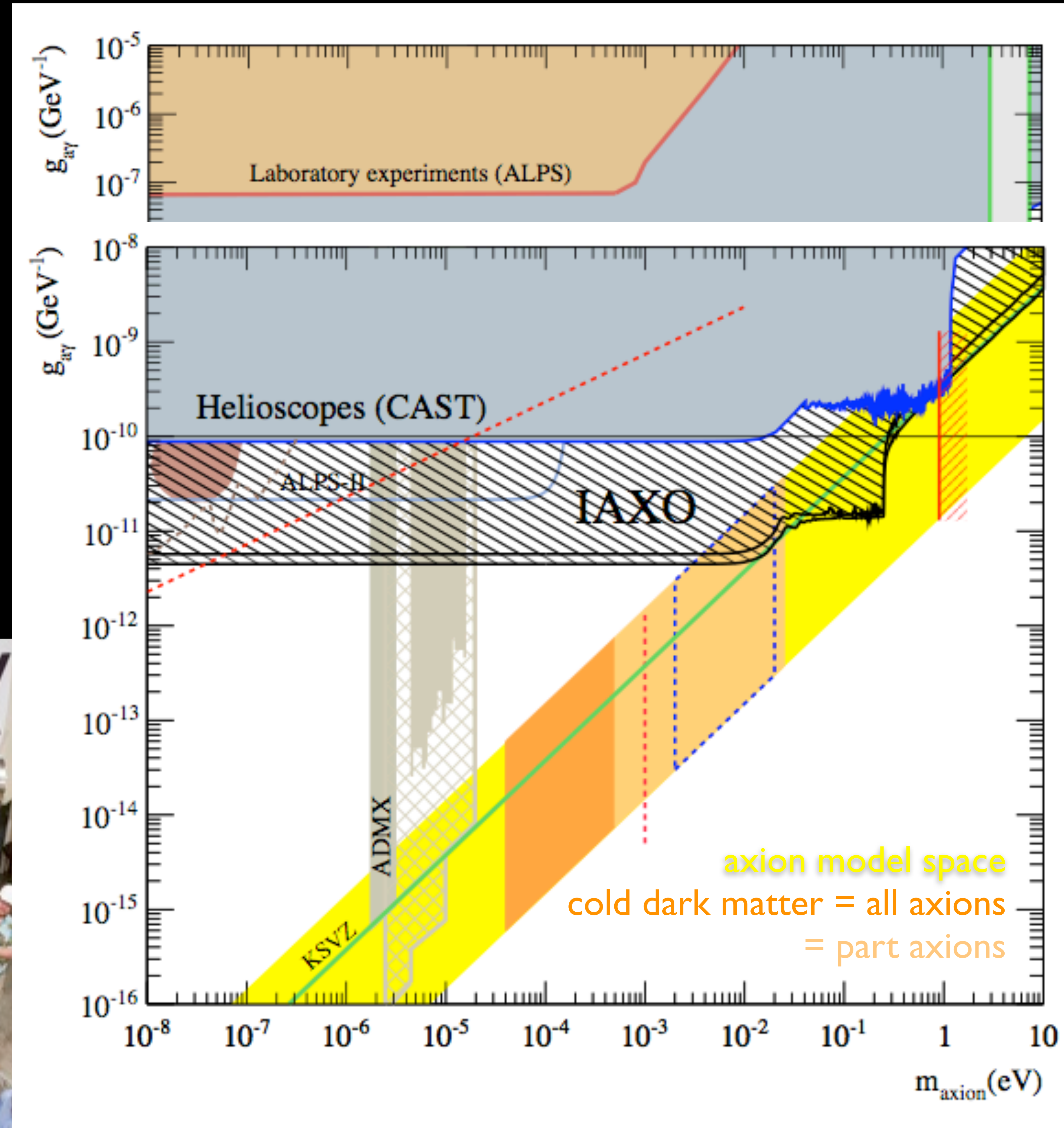


Conclusions & Outlook

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, ...)

Experiments with UK involvement that are running or funded will improve reach by 3 orders of magnitude over next decade.

This is a field where the structure of the STFC funding is difficult: exploitation support is critical, need a mechanism to bid for this (successfully) in projects where STFC does not provide significant capital. Adding breadth through CG only is very, very hard for small experiments.

Thanks to E. Daw, H. Kraus, H. Araujo, N. Spooner for input.

Extra

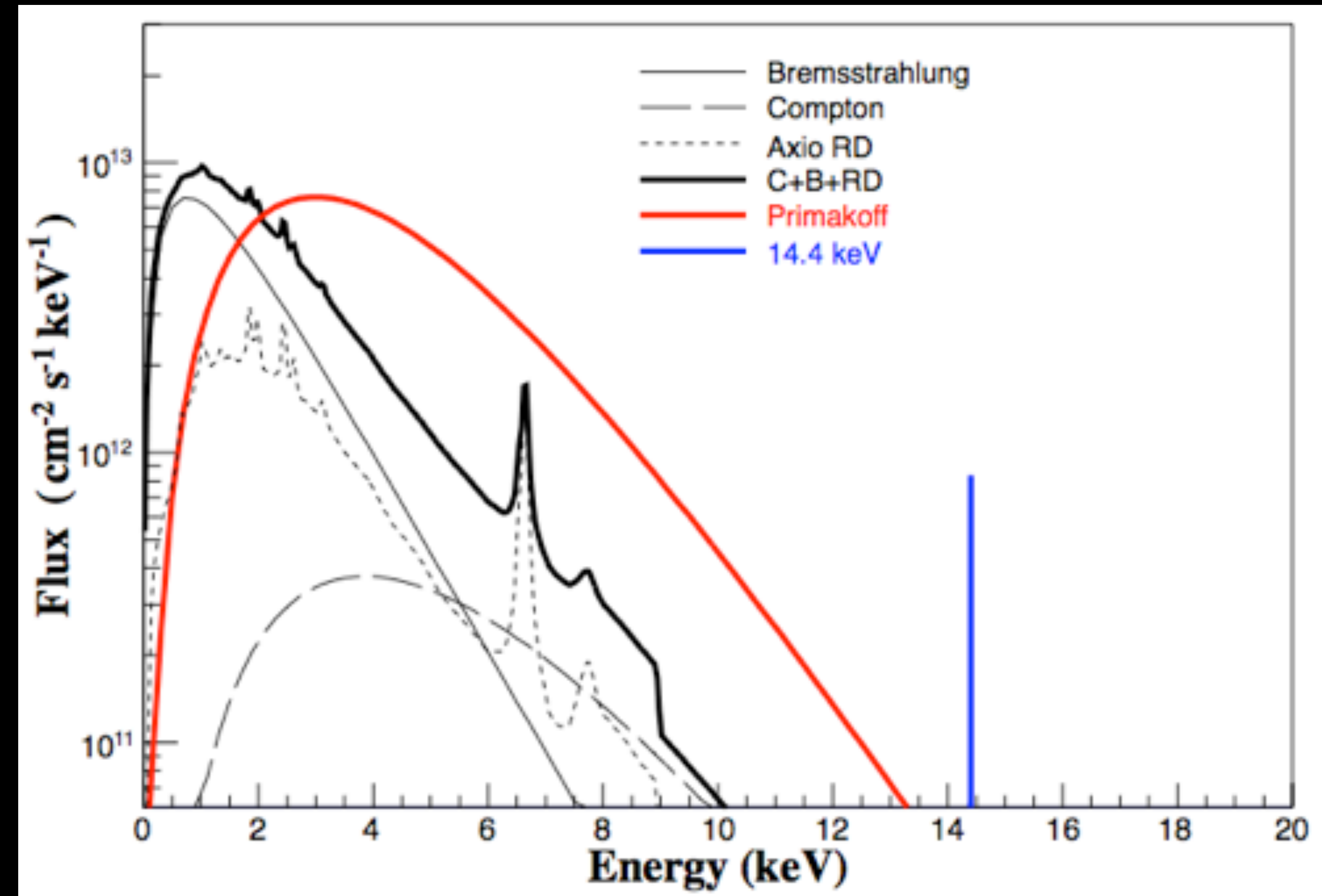
Axion/ALPs in Direct Detection

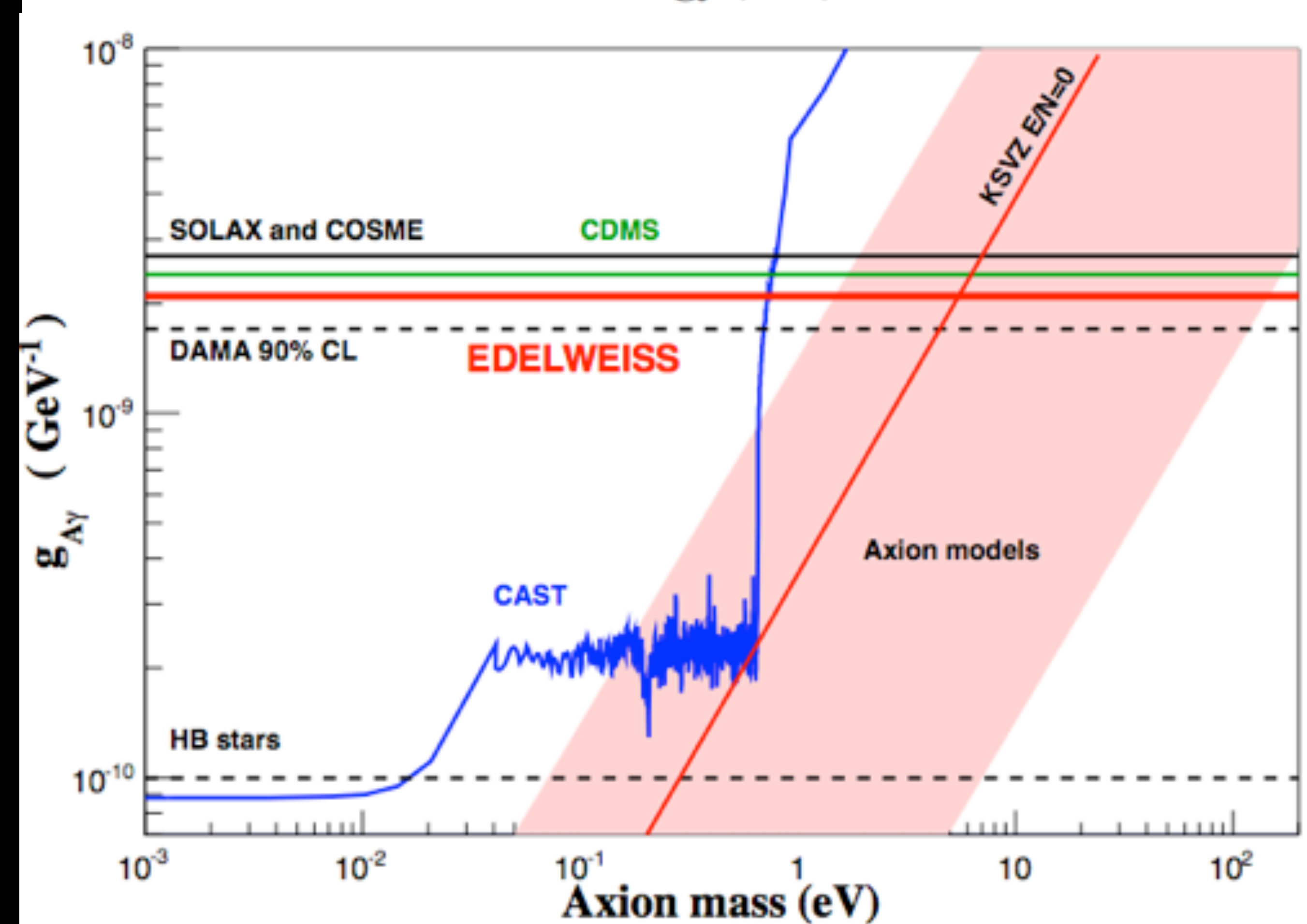
EDELWEISS: search for axion conversion to photons, 357 kg-day exposure, >2.5 keVee, uses time modulation and Primakoff spectrum to reduce backgrounds x100. *(arXiv:1307.1488)*

XMASS: search for vector or pseudo-scalar bosons with 132 live day x 41 kg fiducial mass, >40 keV. Background is O(1E-4)/(keV kg day) *(arXiv:1406.0502)*

XENON100: searches for axions and ALPS in 34 kg x 224.6 days, >2 keVee, with background of 1E-4/(keV kg day). *(arXiv:1404.1455)*

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





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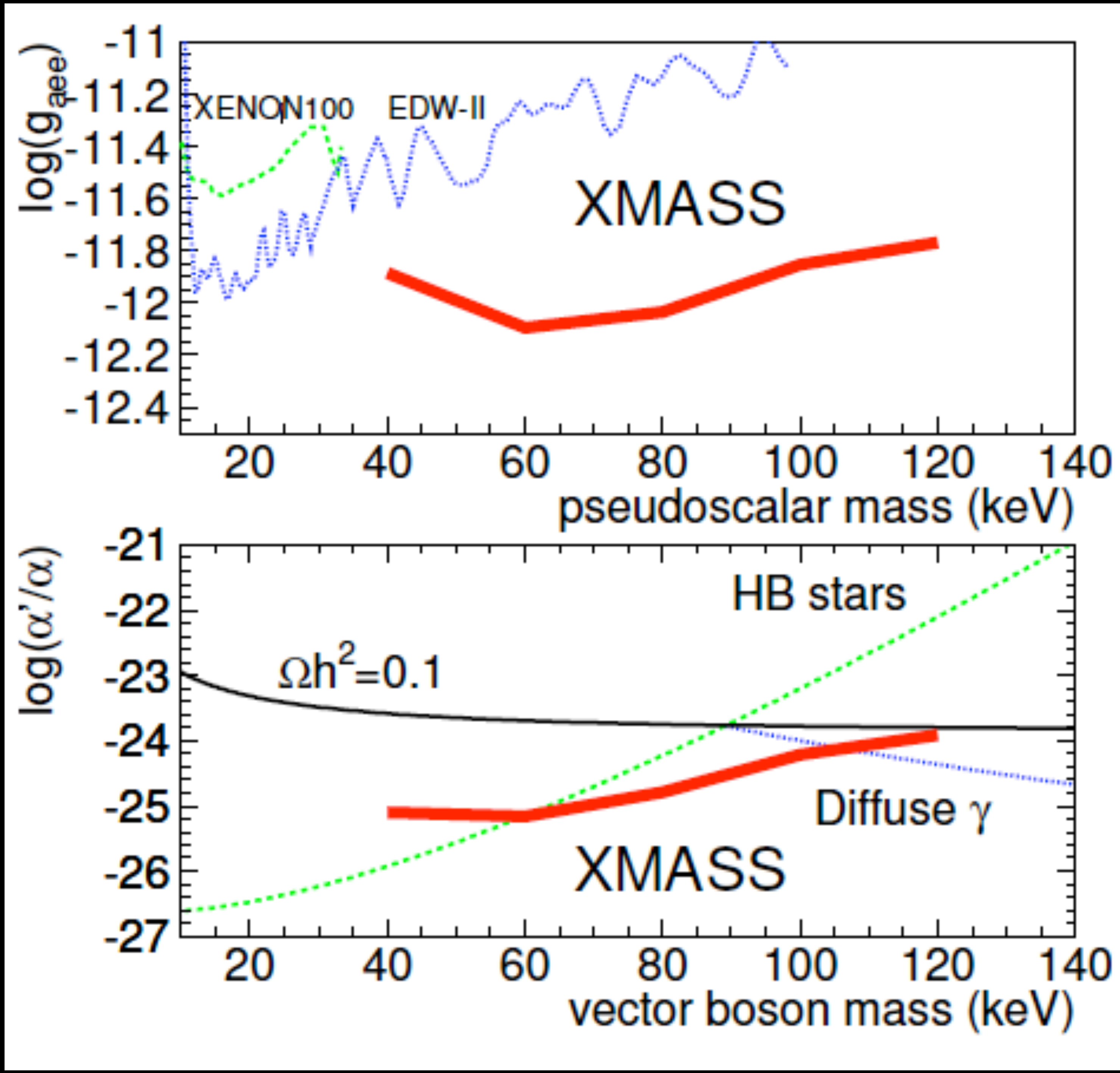

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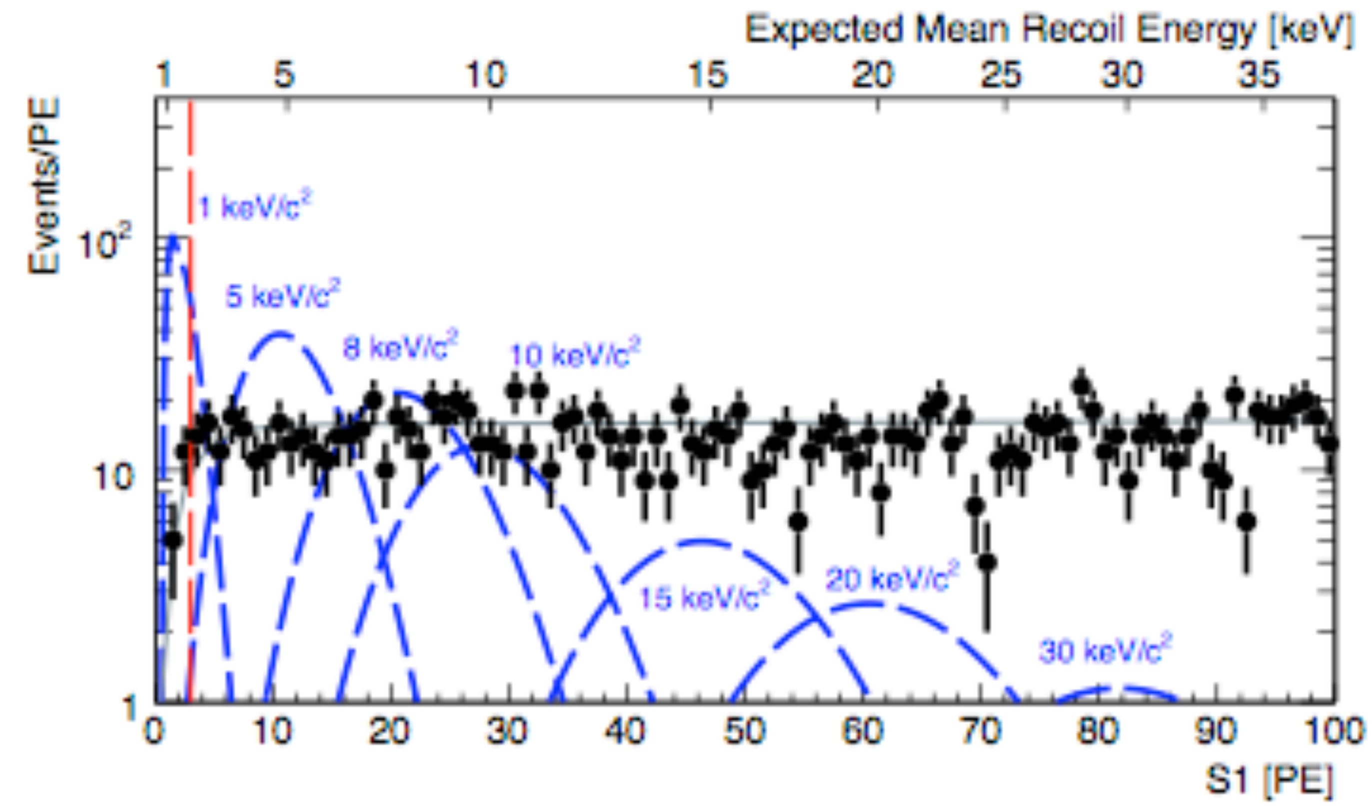

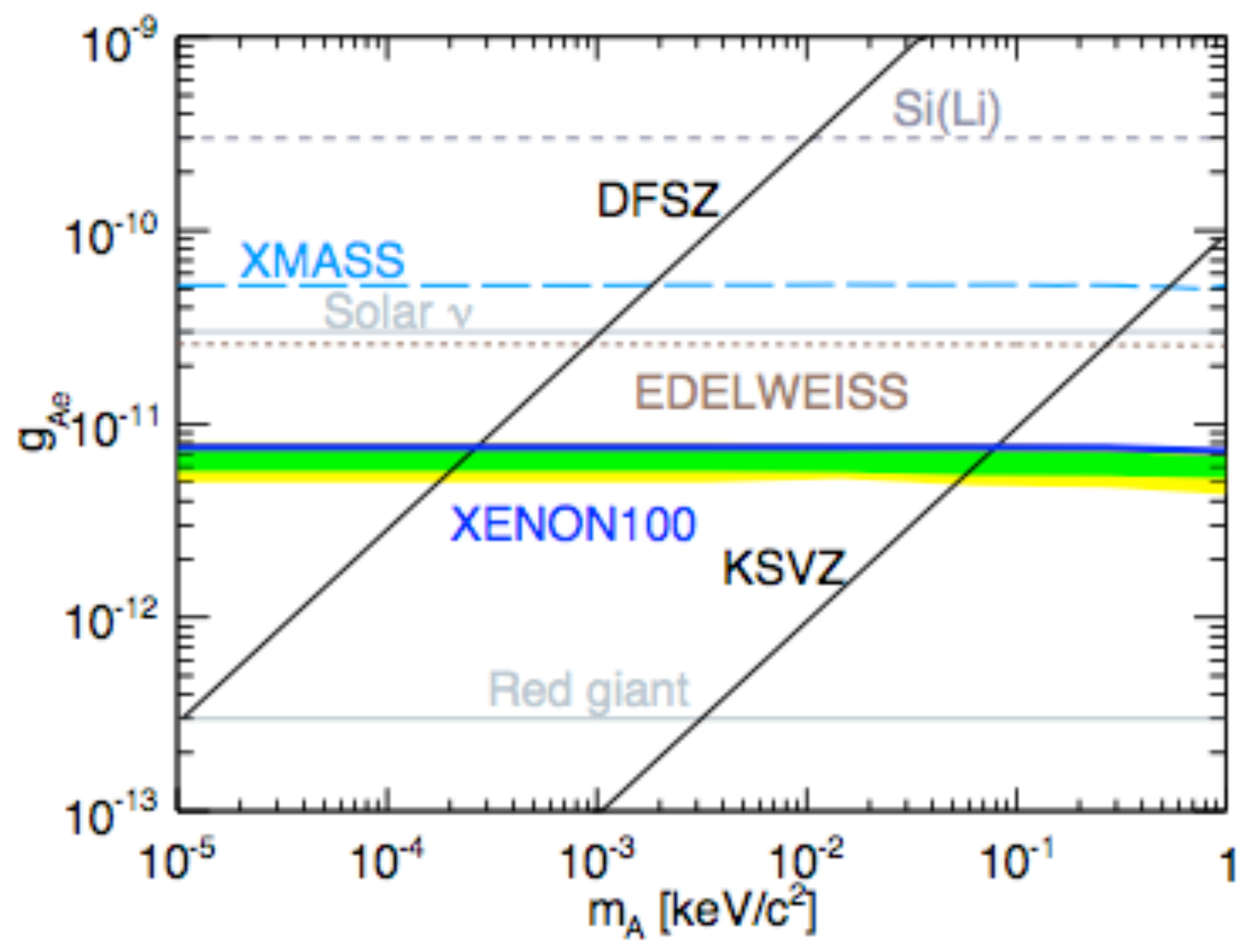

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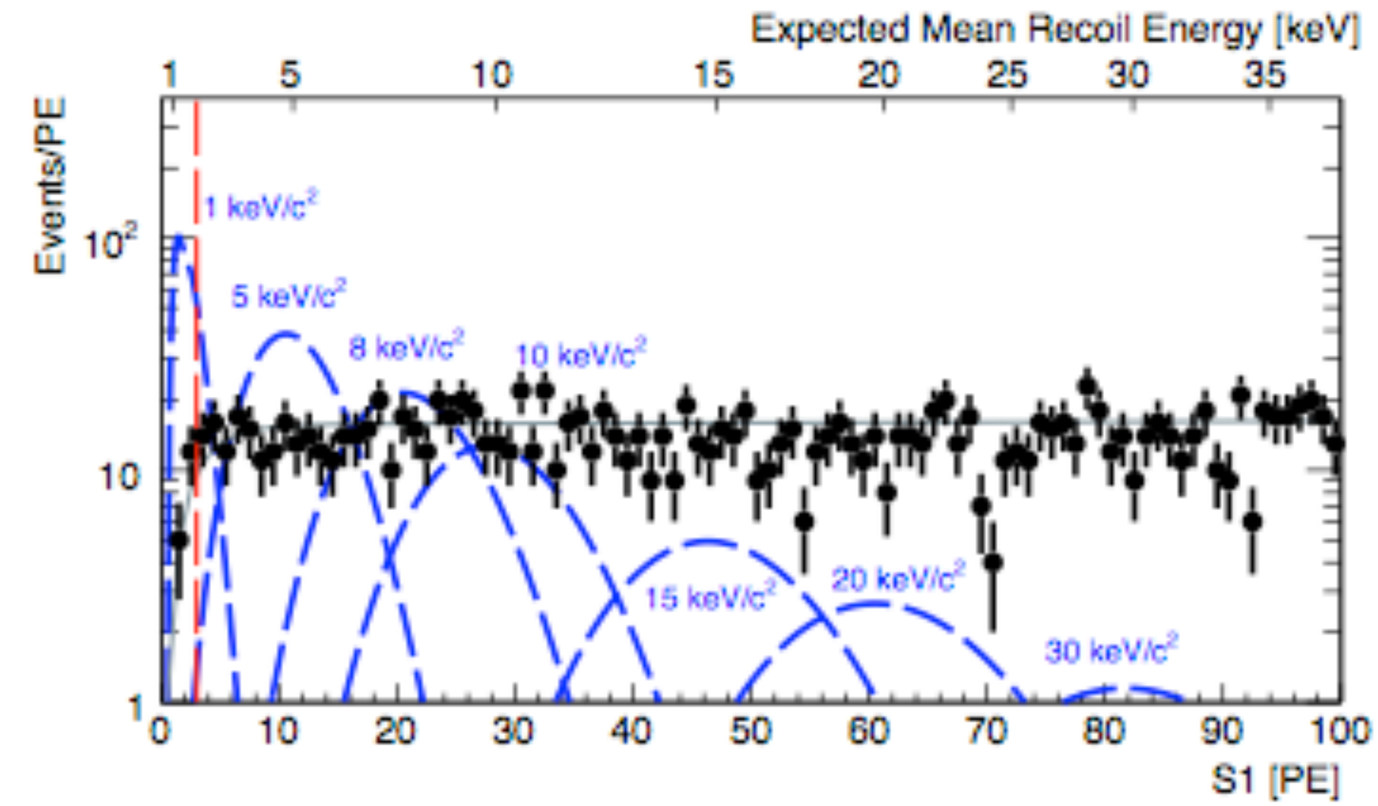

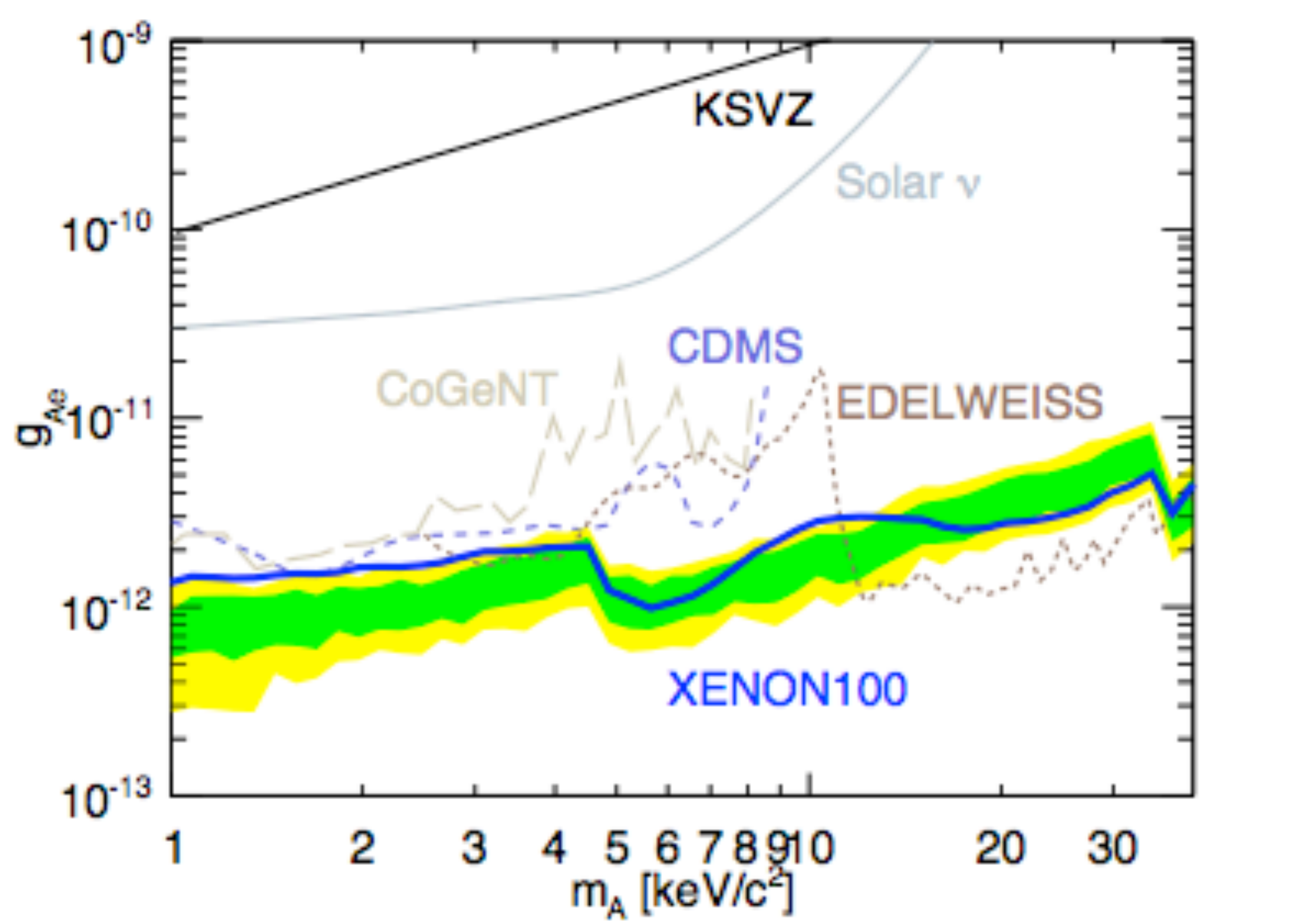

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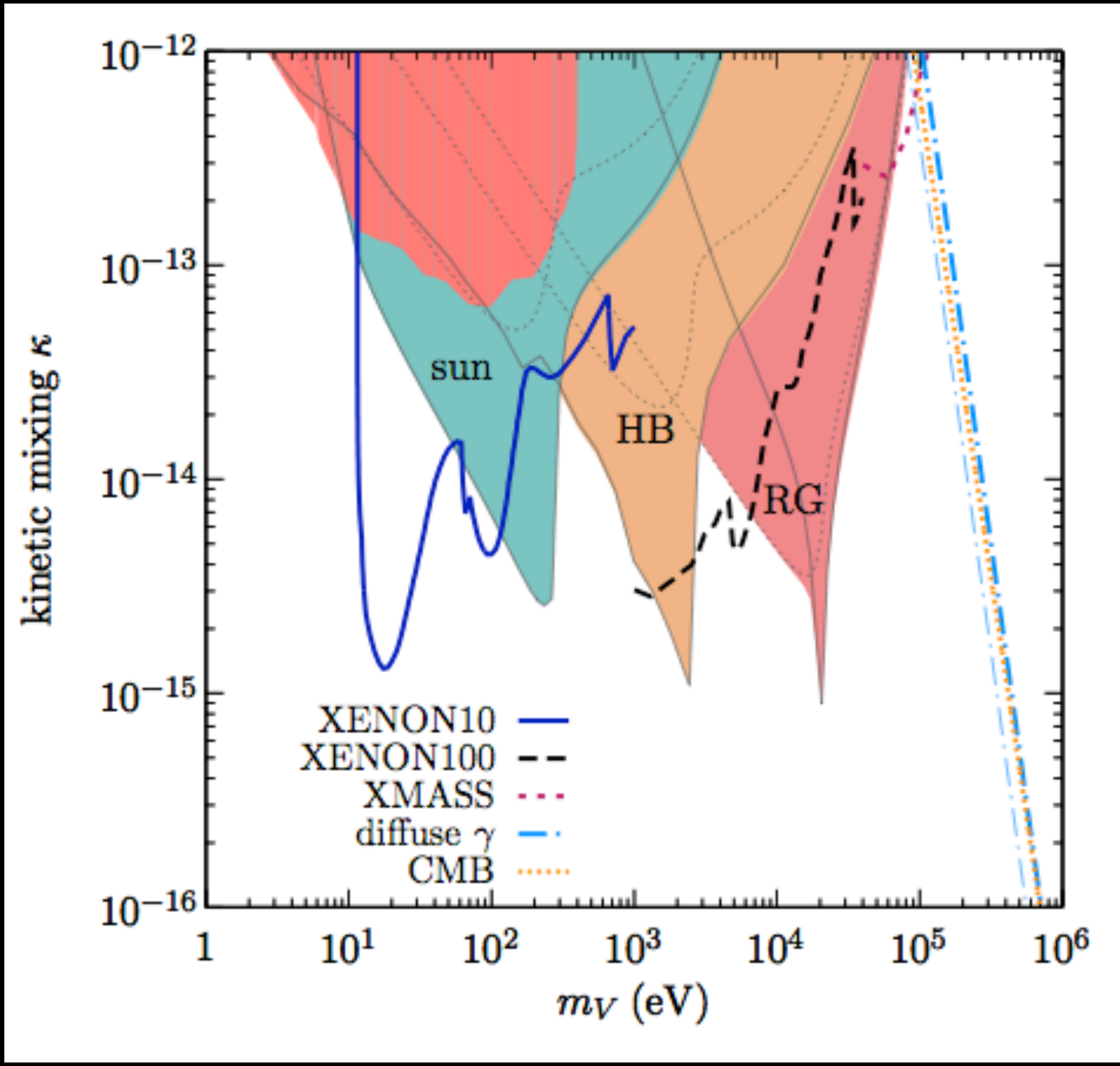
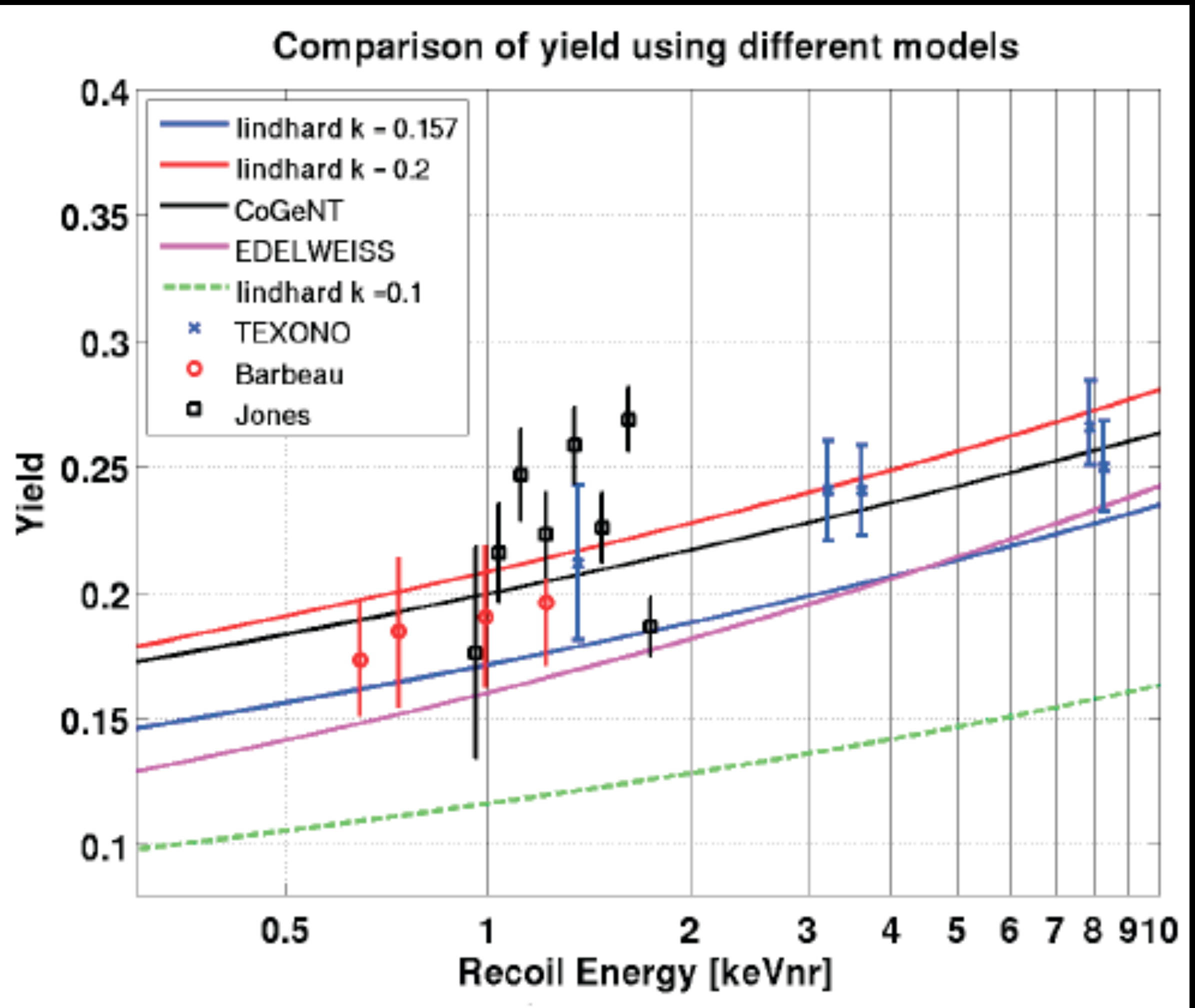
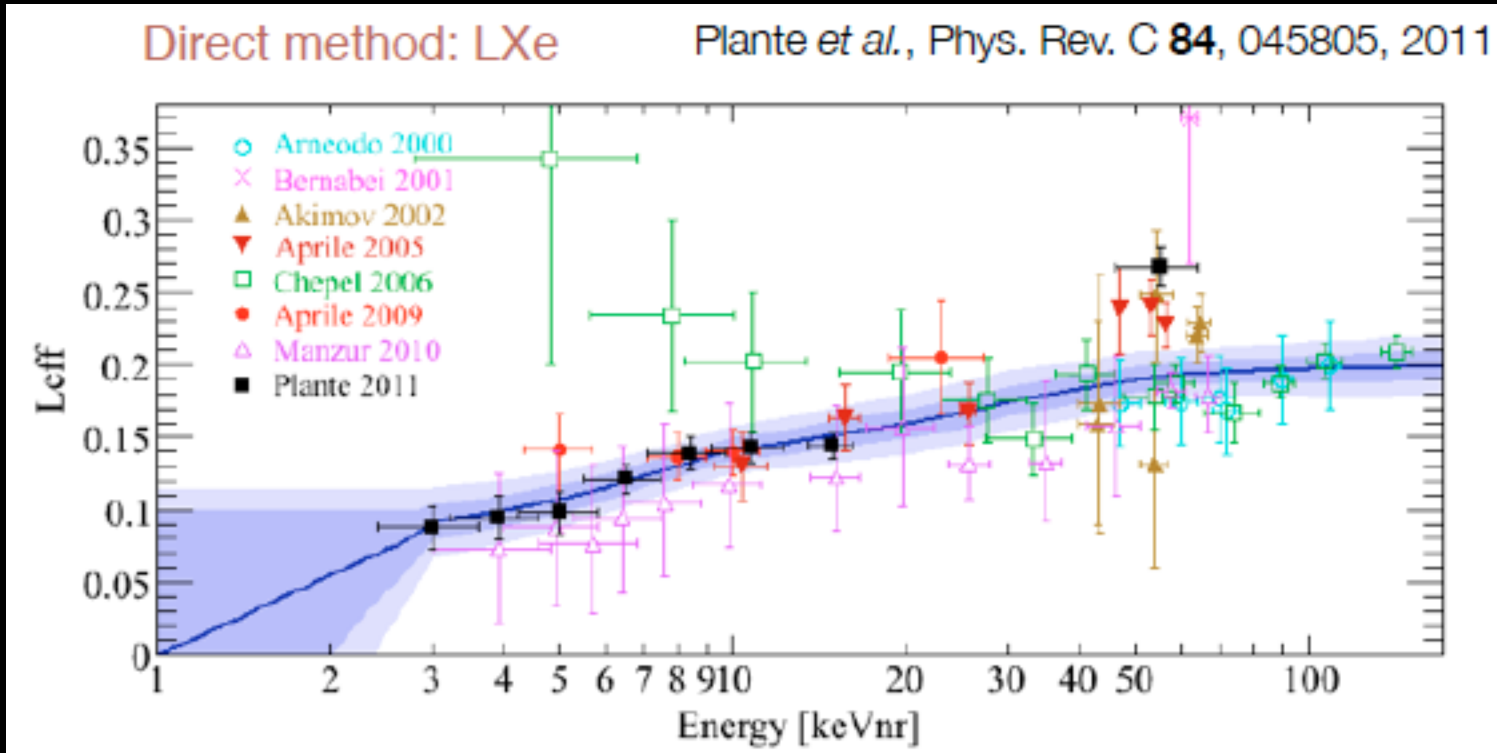


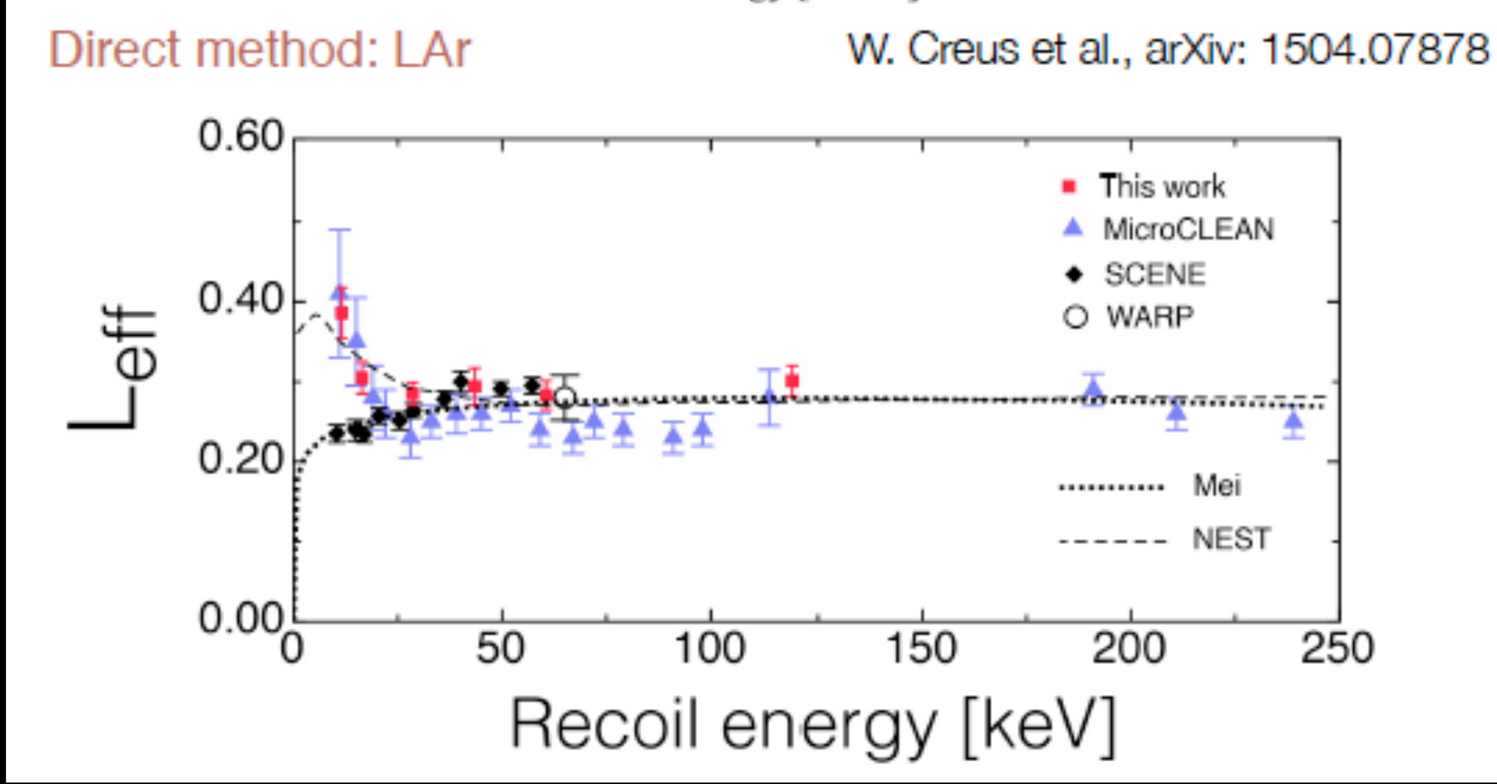
Quenching

(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!

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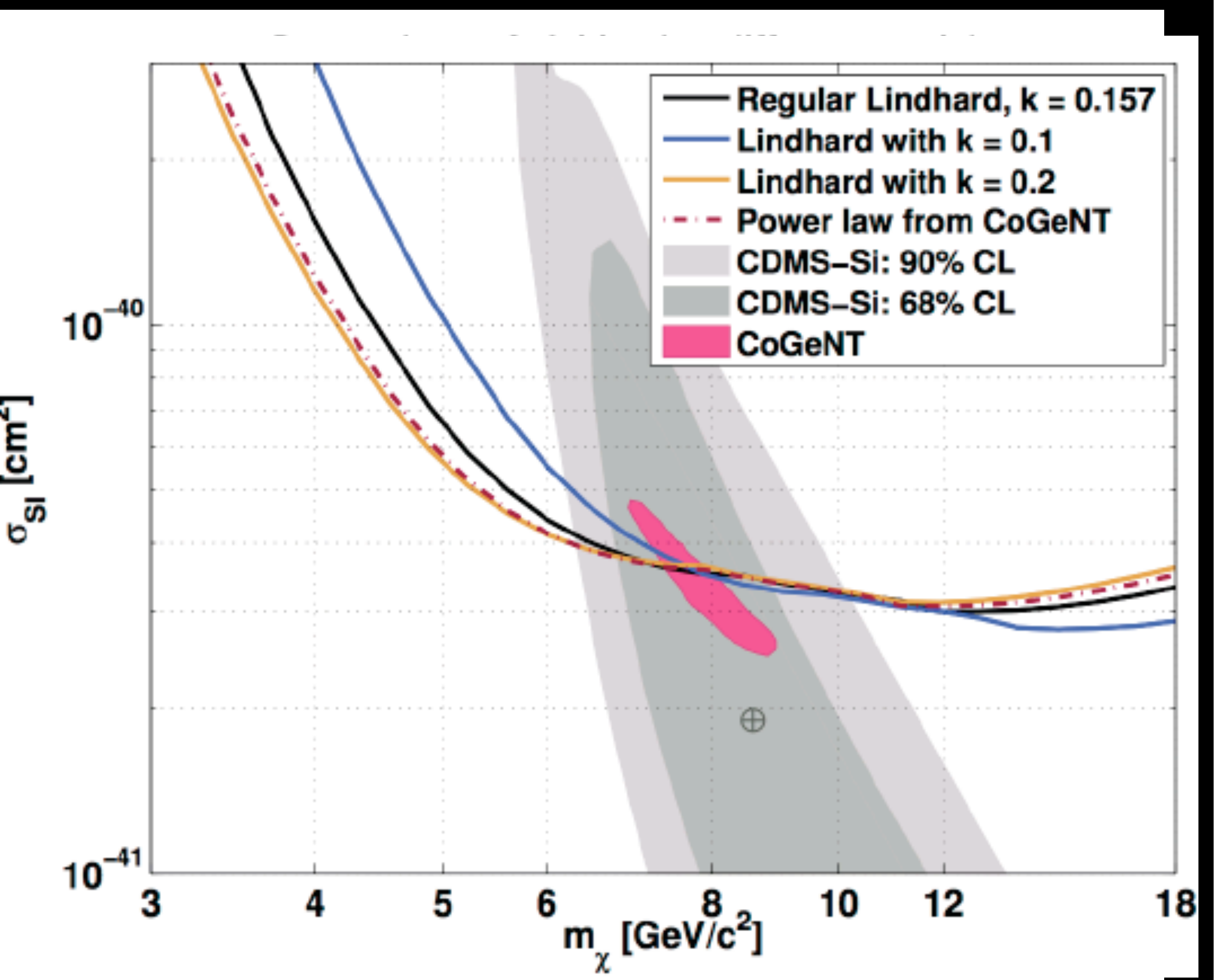

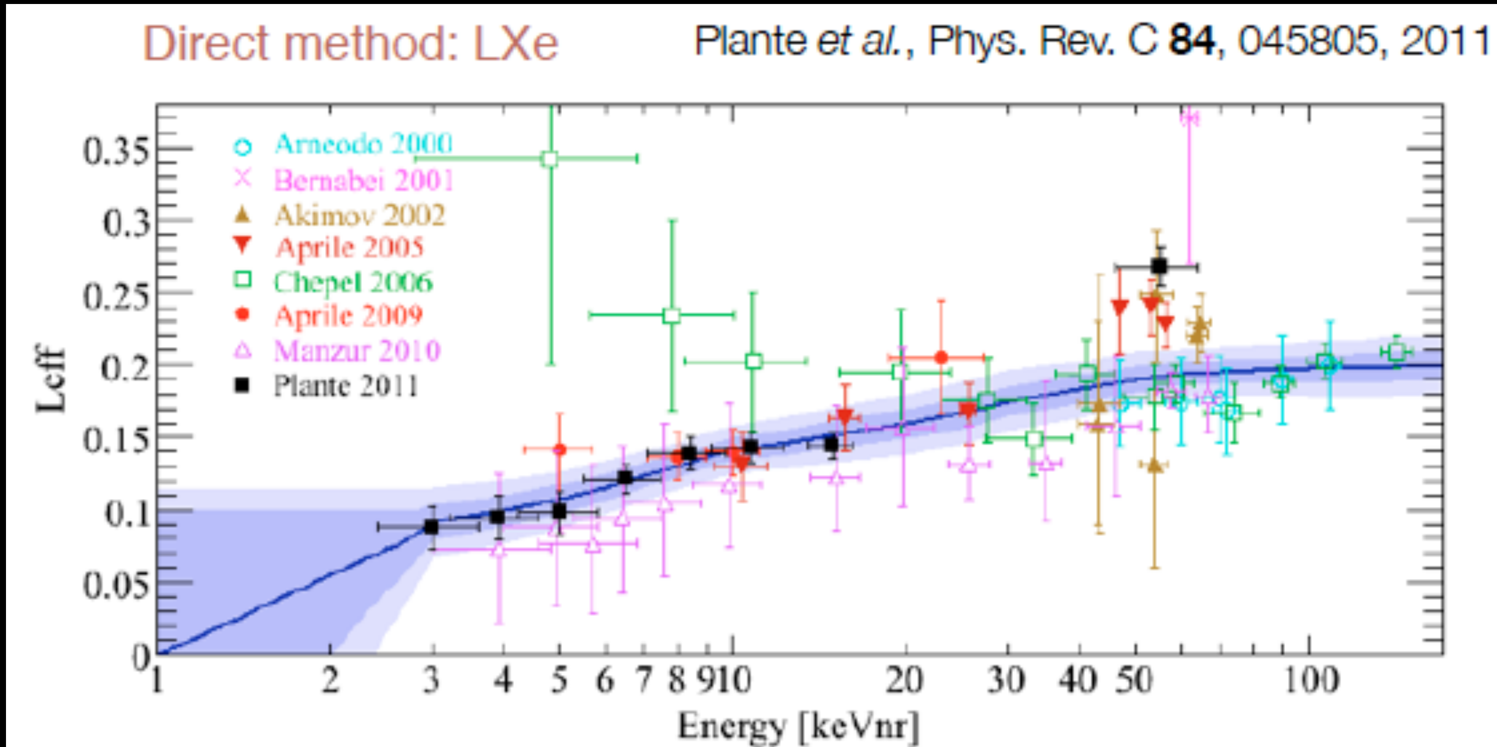

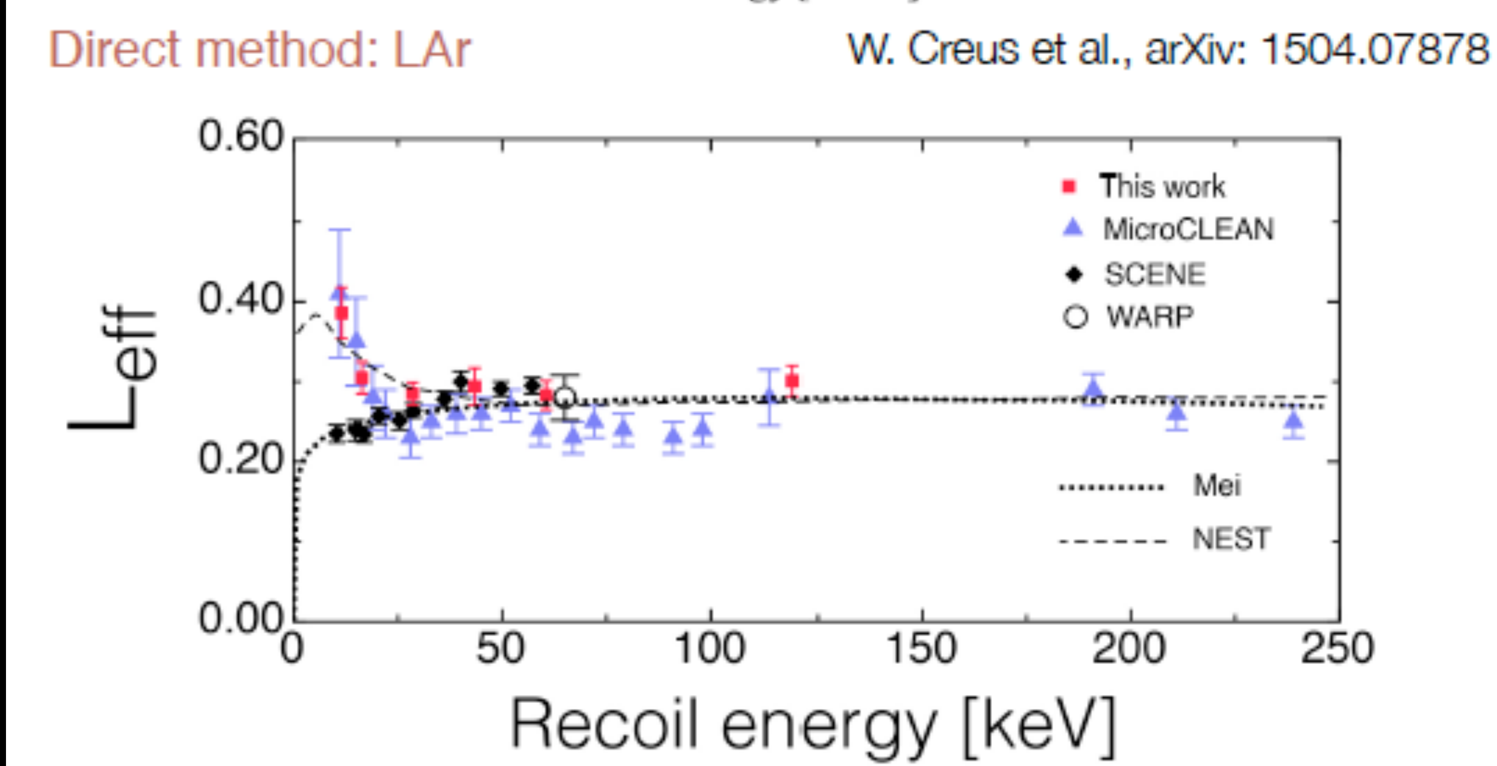

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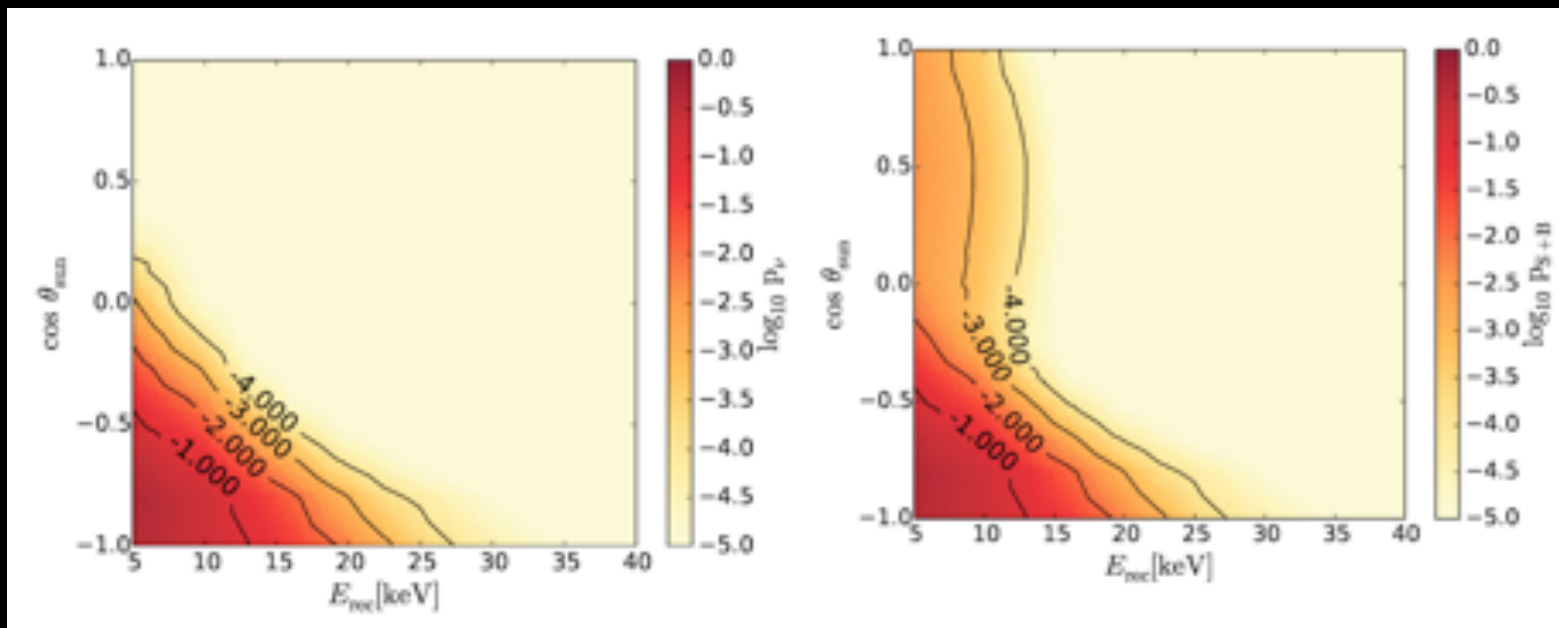
Beyond the Neutrino Bound

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!