Dark Matter Direct Detection

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EPS-HEP 2015
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Outline

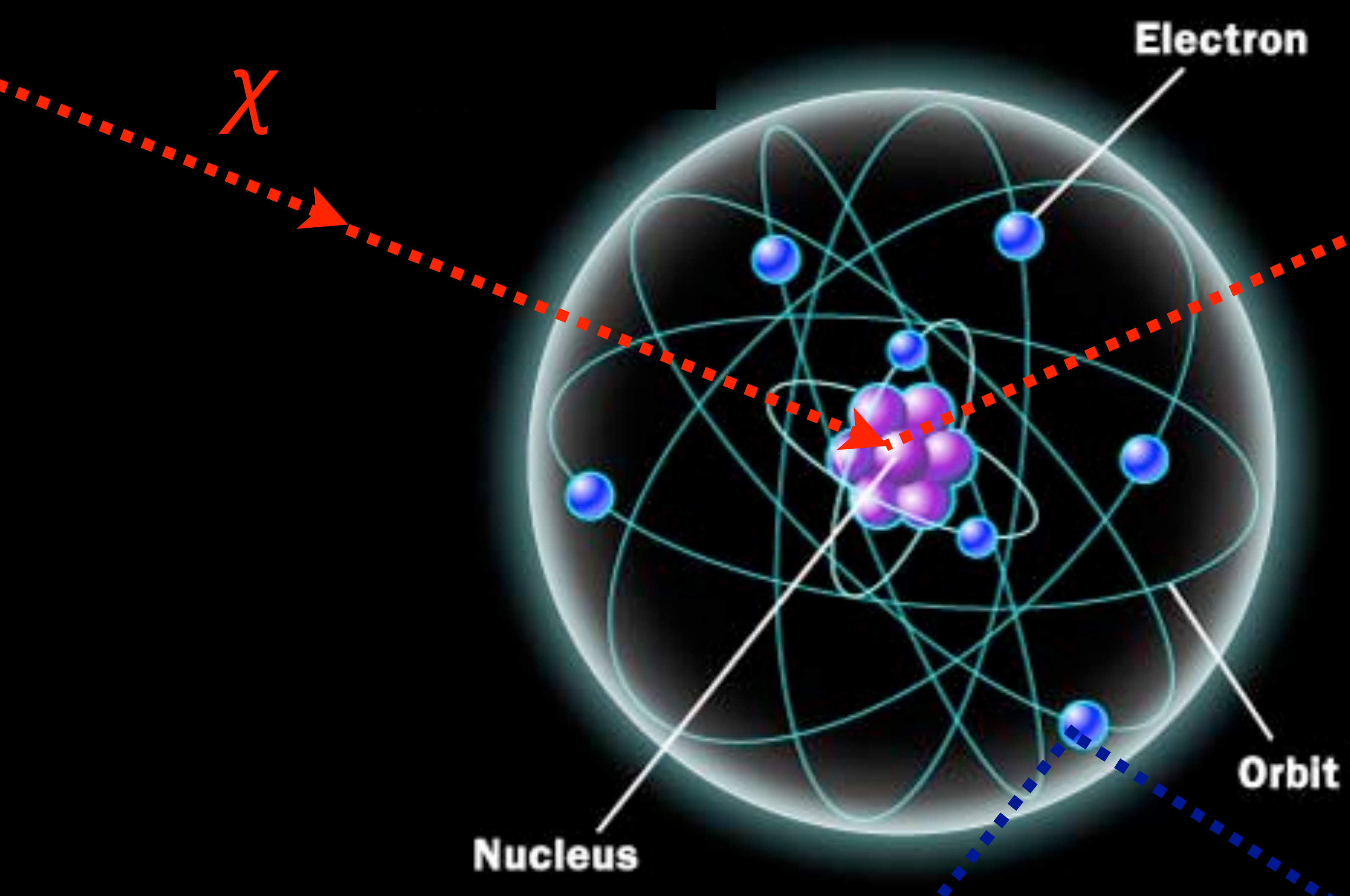
Experimental Considerations

Status and Prospects of Direct Detection Searches

Conclusions and Outlook

Dark Matter Direct Detection

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



Backgrounds:

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

$n\ N \rightarrow n\ N$

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

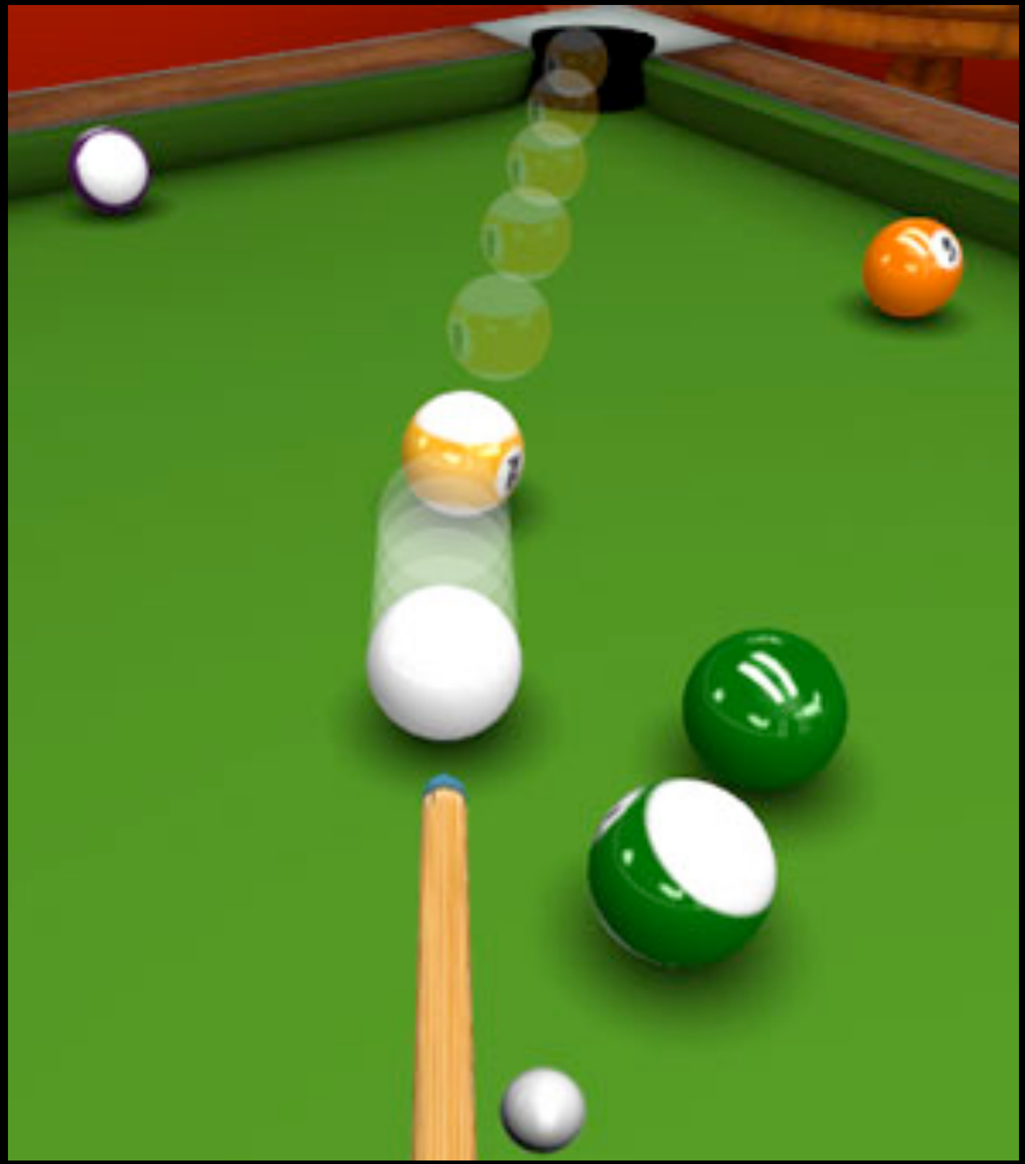
$\nu\ N \rightarrow \nu\ N$

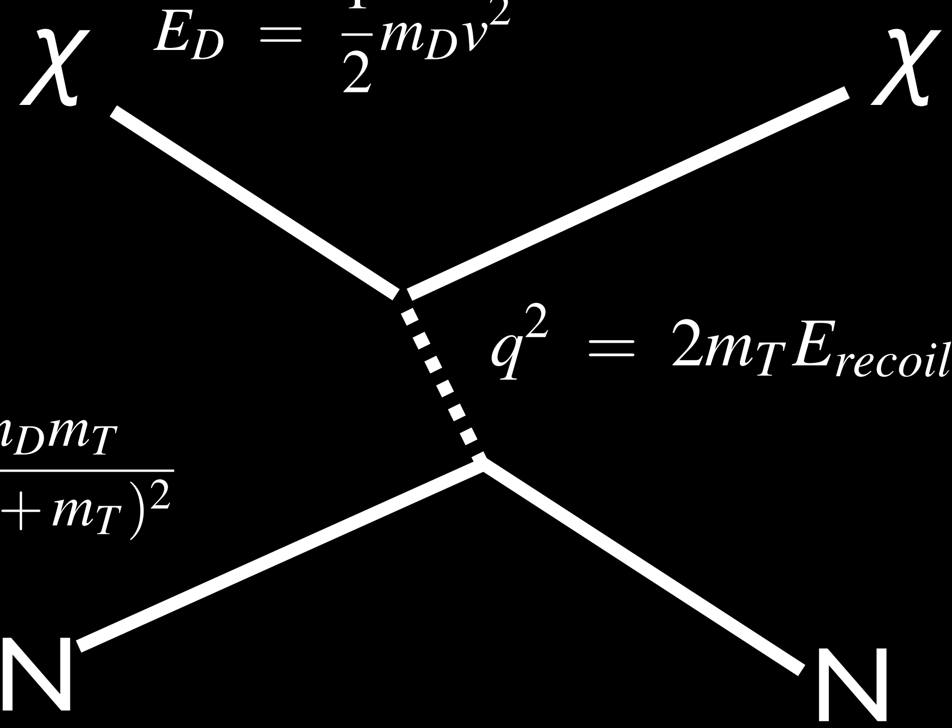
detector requirements: particle ID for recoil N, e-, alpha, n (multiple) final states

WIMP Scattering

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

recoil angle strongly correlated
with incoming WIMP direction





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

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

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

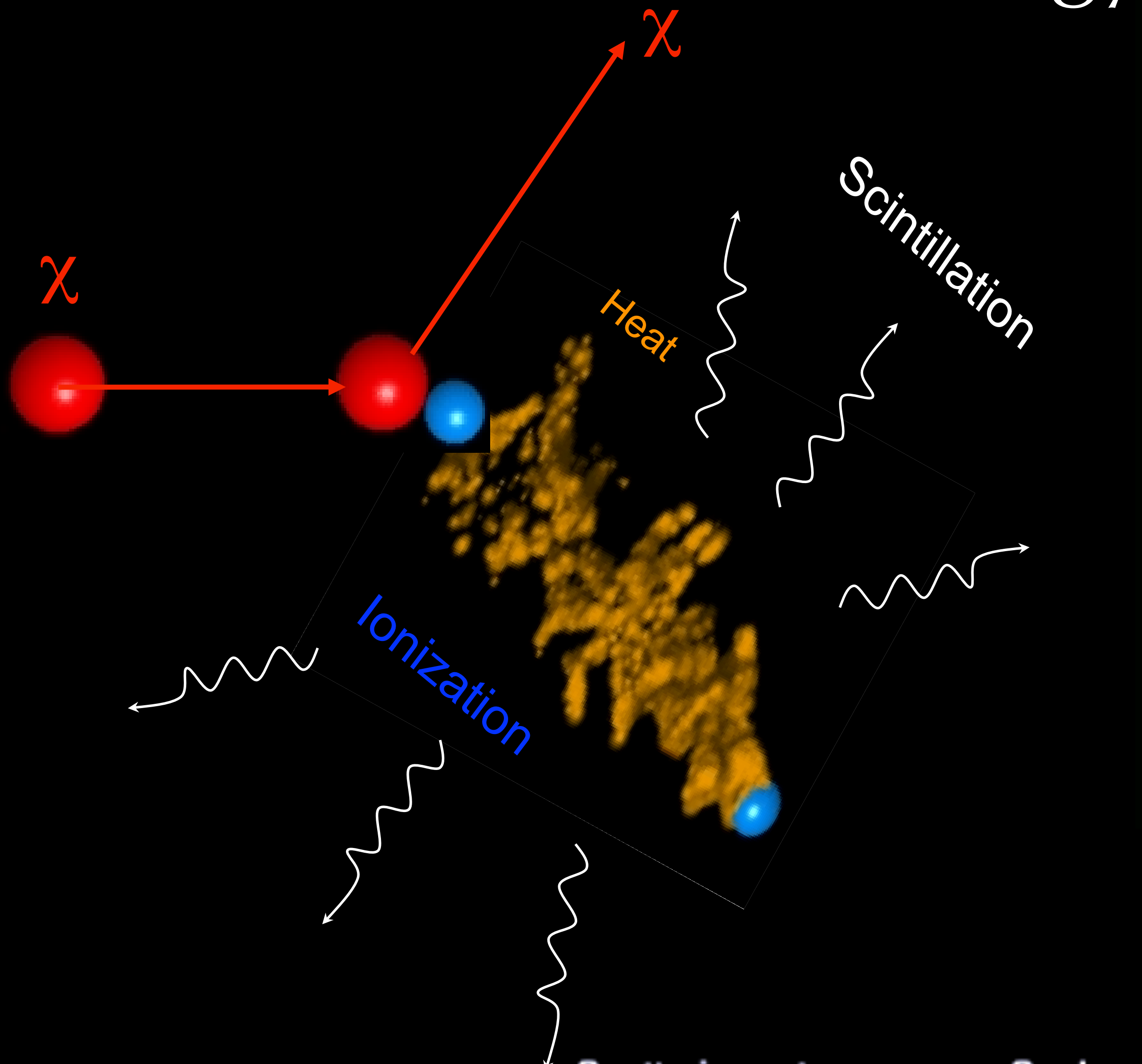
$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

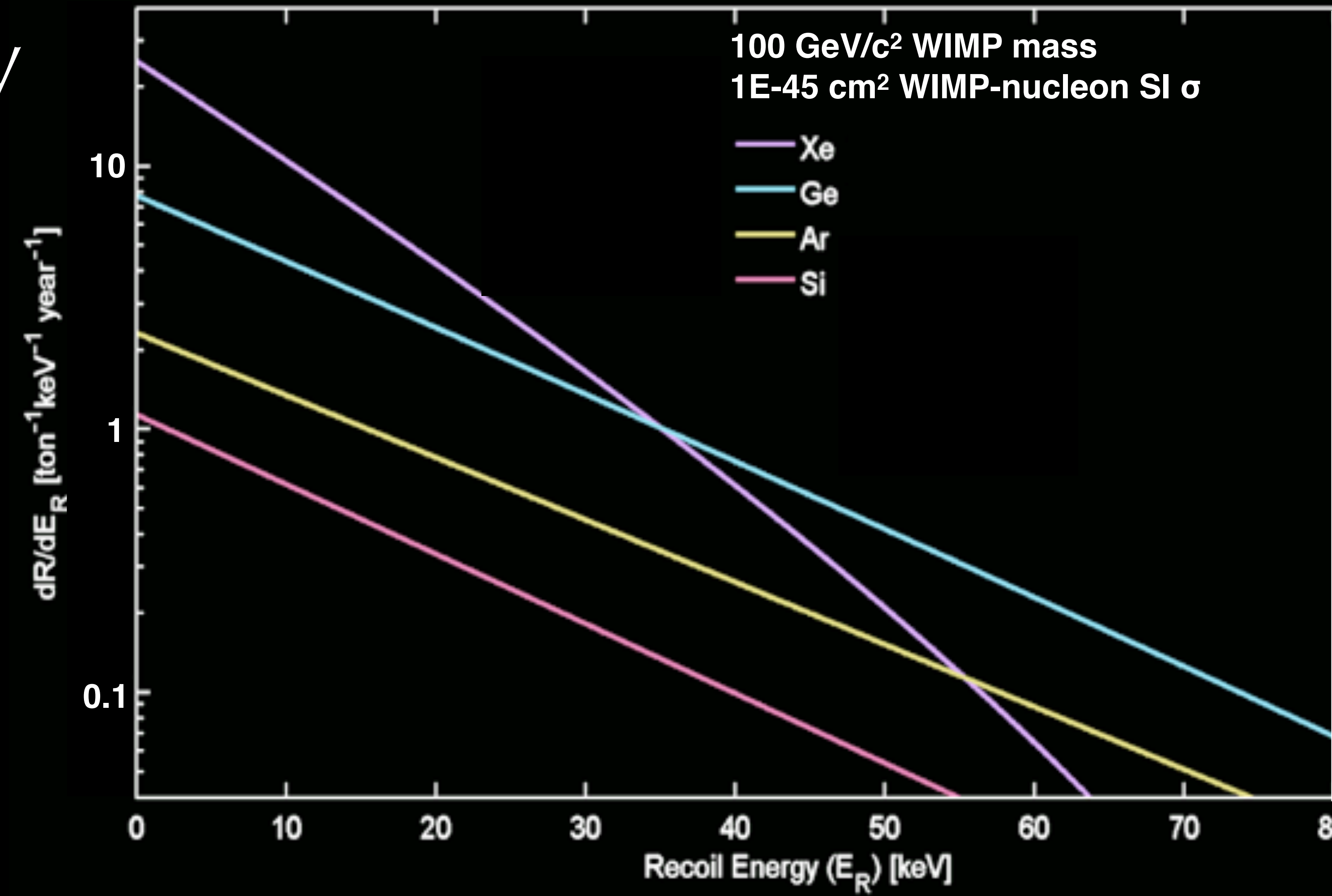
Spin Independent:
χ scatters coherently off of the entire nucleus A: σ~A^2
D. Z. Freedman, PRD 9, 1389 (1974)

Spin Dependent:
mainly unpaired nucleons contribute to scattering amplitude: σ~ *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

CDMS

DarcSide

EDELWEISS

LUX

CoGeNT

Panda-X

DMTPC

ANaIS

XMASS

DEAP/CLEAN

CRESST

KIMS

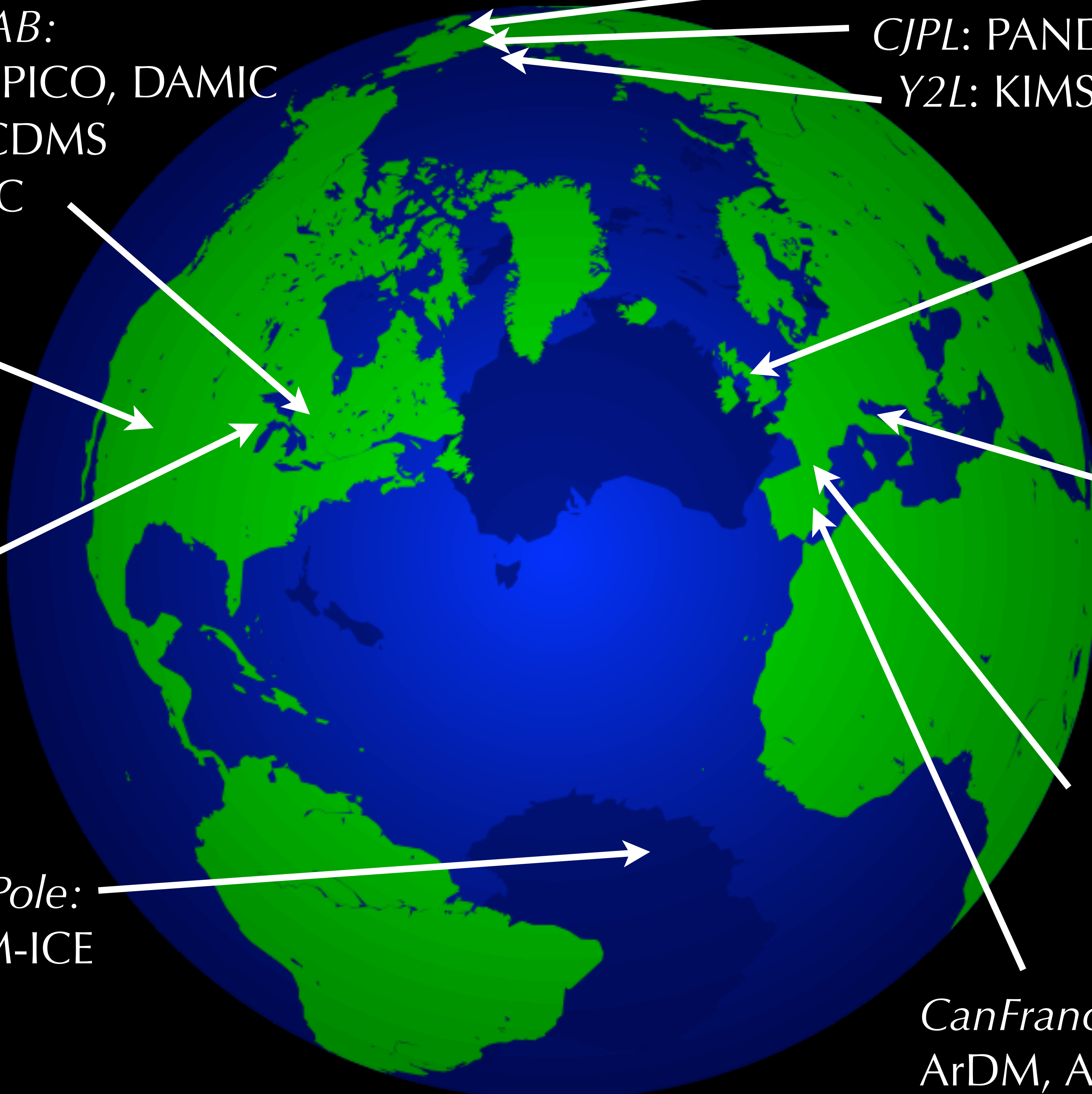
CRESSTII

Dama/LIBRA

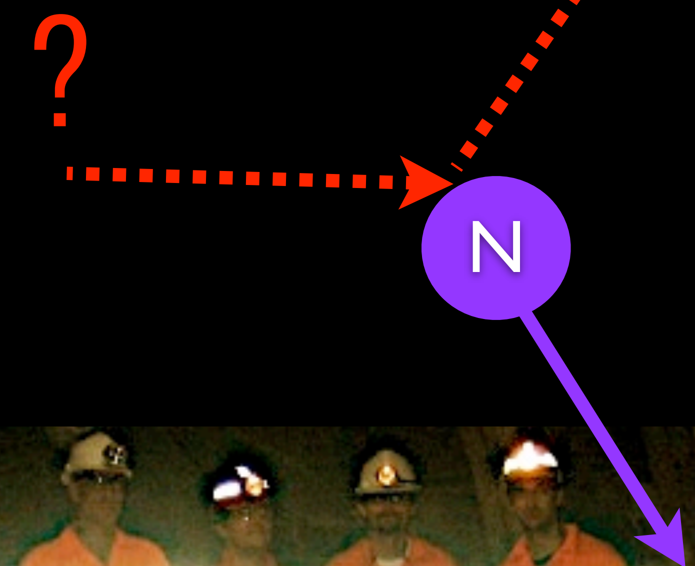
ROSEBUD

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

Around the World



Backgrounds



Gamma ray interactions:

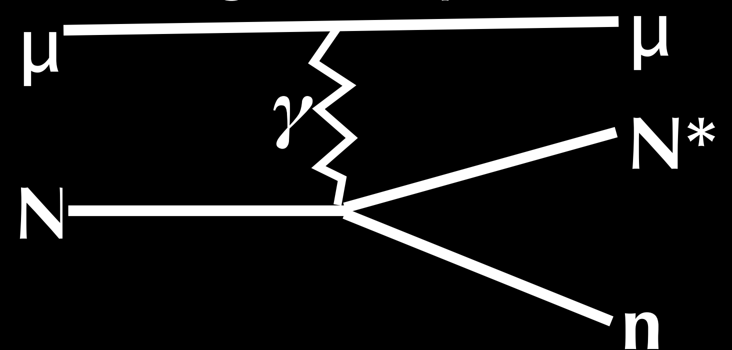
rate ~ N_e x (gamma flux), O(1E7) events/(kg day)

mis-identified electrons mimic nuclear recoils

Neutrons:

(alpha,n), U, Th fission,

cosmogenic spallation



nuclear recoil final state

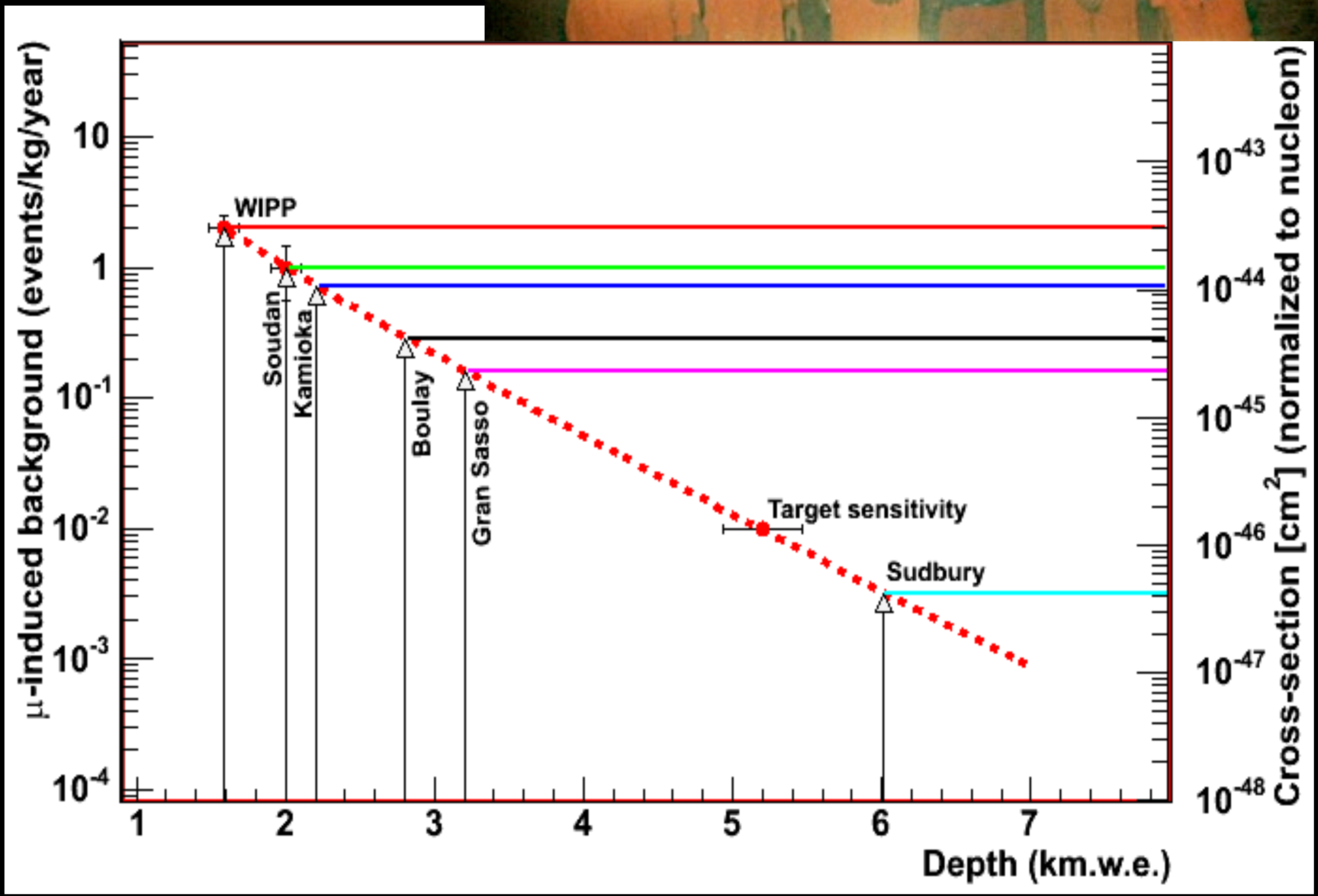
Contamination:

^{238}U and ^{232}Th decays,

recoiling progeny and

mis-identified alphas

mimic nuclear recoils

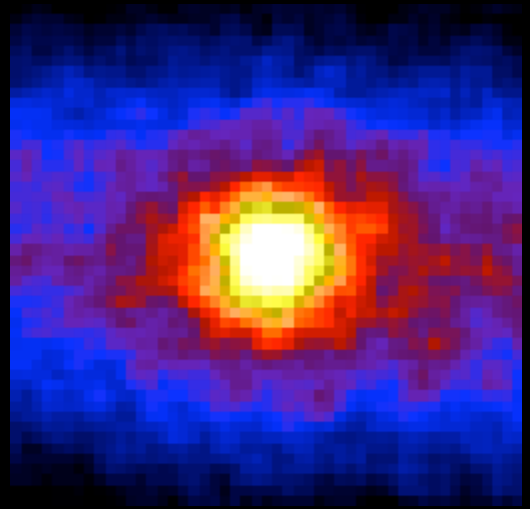


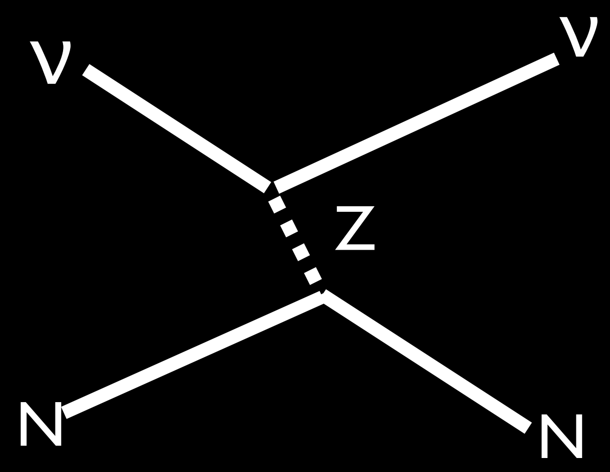
D.-M. Mei, A. Hime, PRD73:053004 (2006)

Irreducible Backgrounds

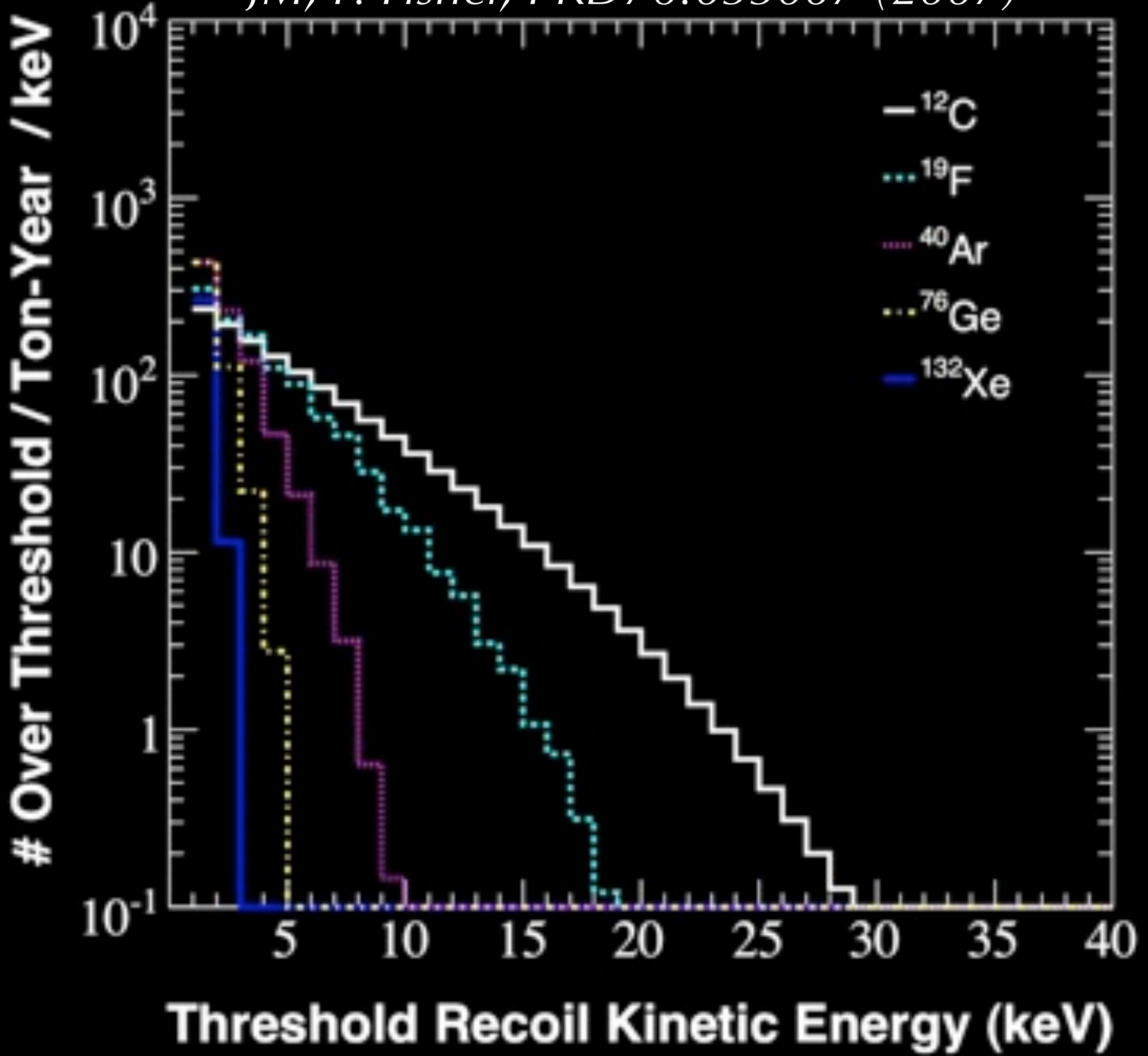
impossible to shield a detector from coherent neutrino scattering!

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





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



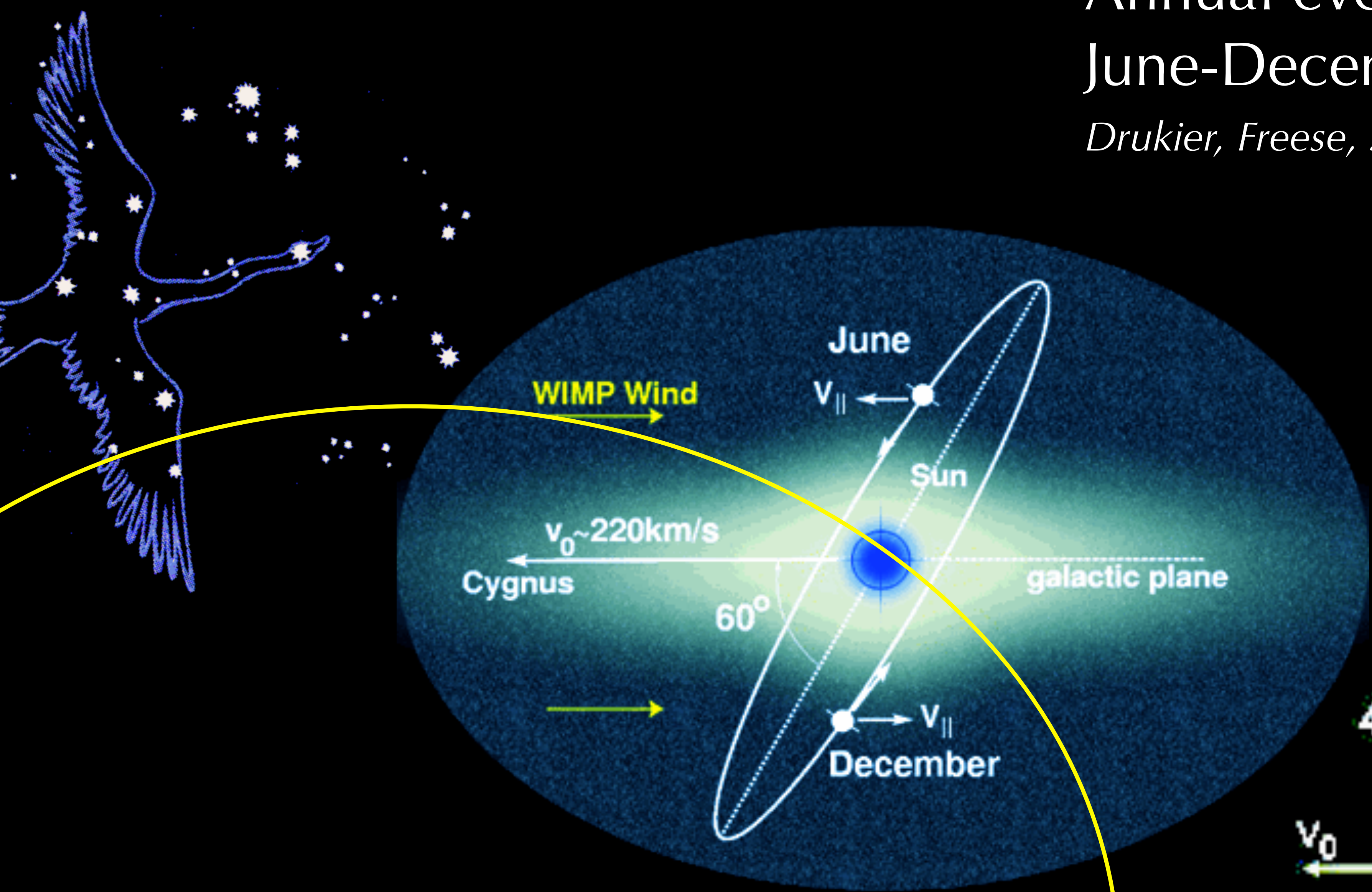
nuclear recoil final state
neutrino bound at 10^{-46}-10^{-48} cm^2
in zero-background paradigm

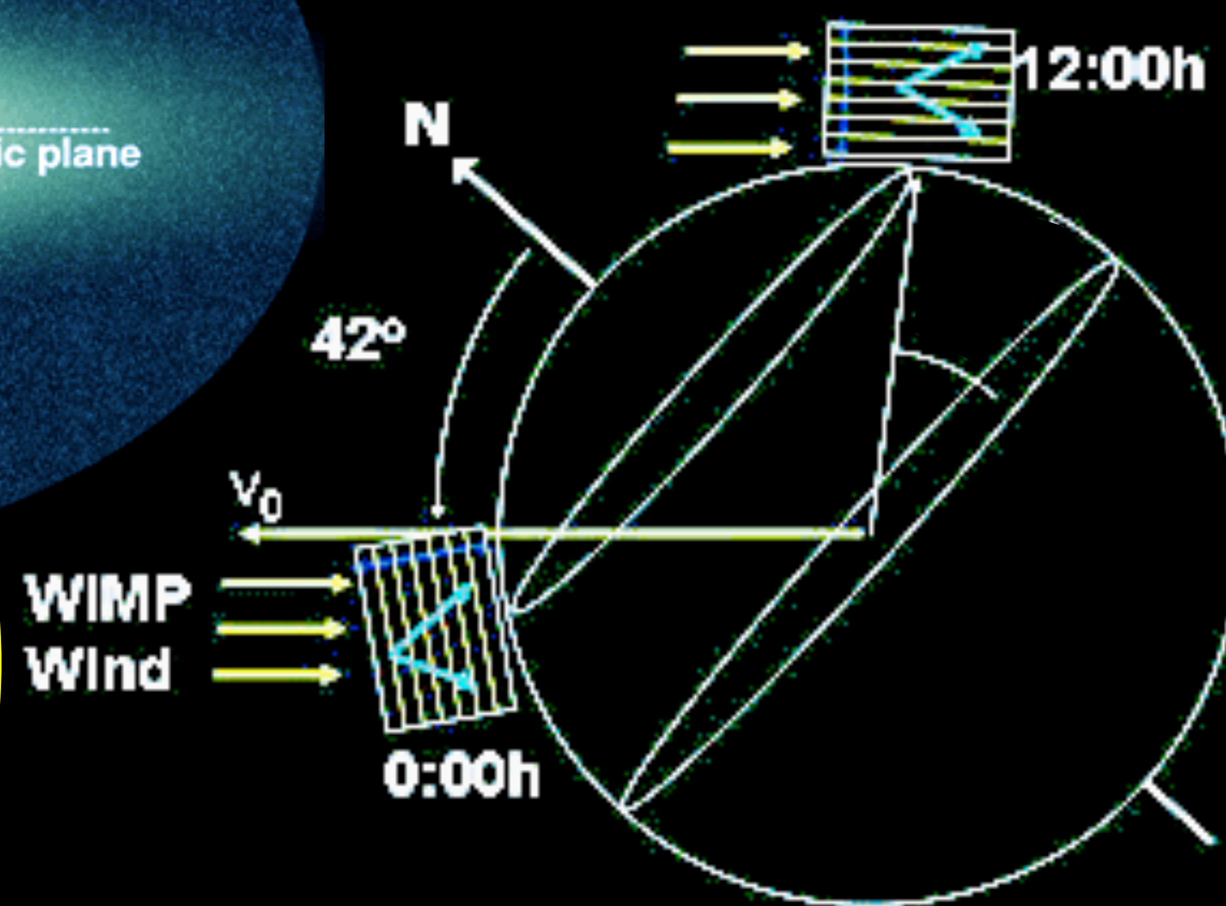
unless you measure
the direction!

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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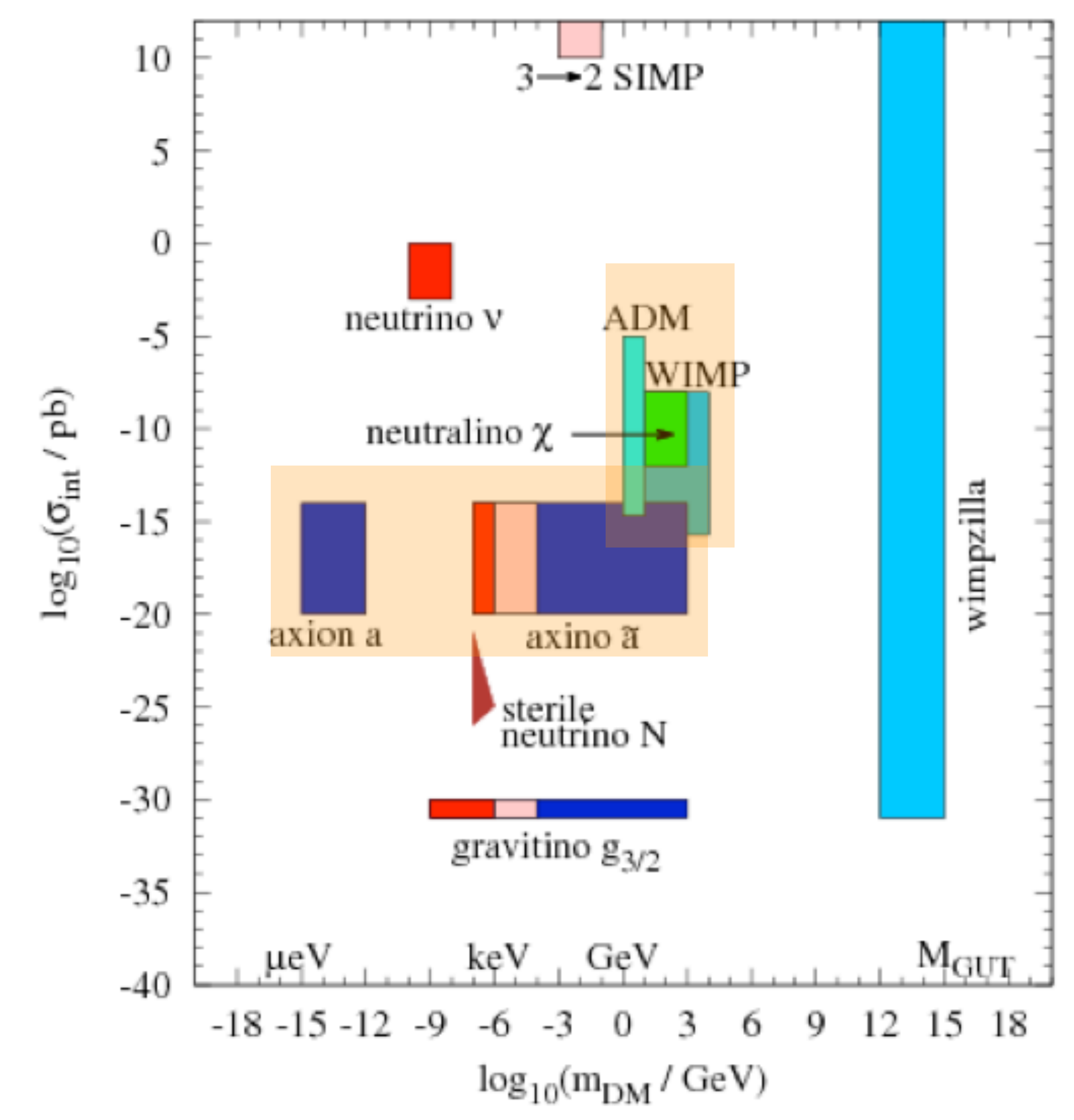
Model Space

Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity…

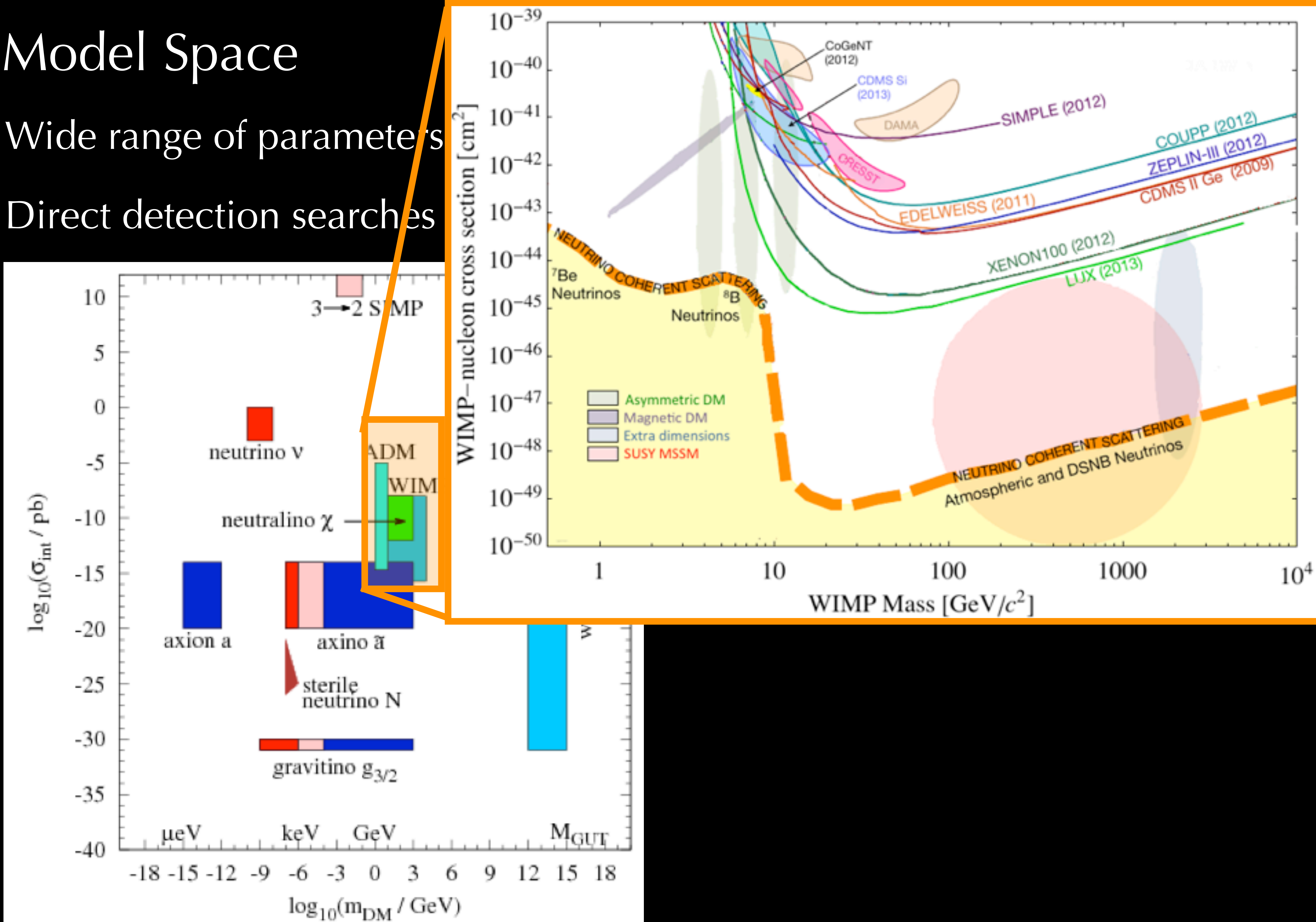


Baer et al., arXiv:1407.0017

Model Space

Wide range of parameters

Direct detection searches



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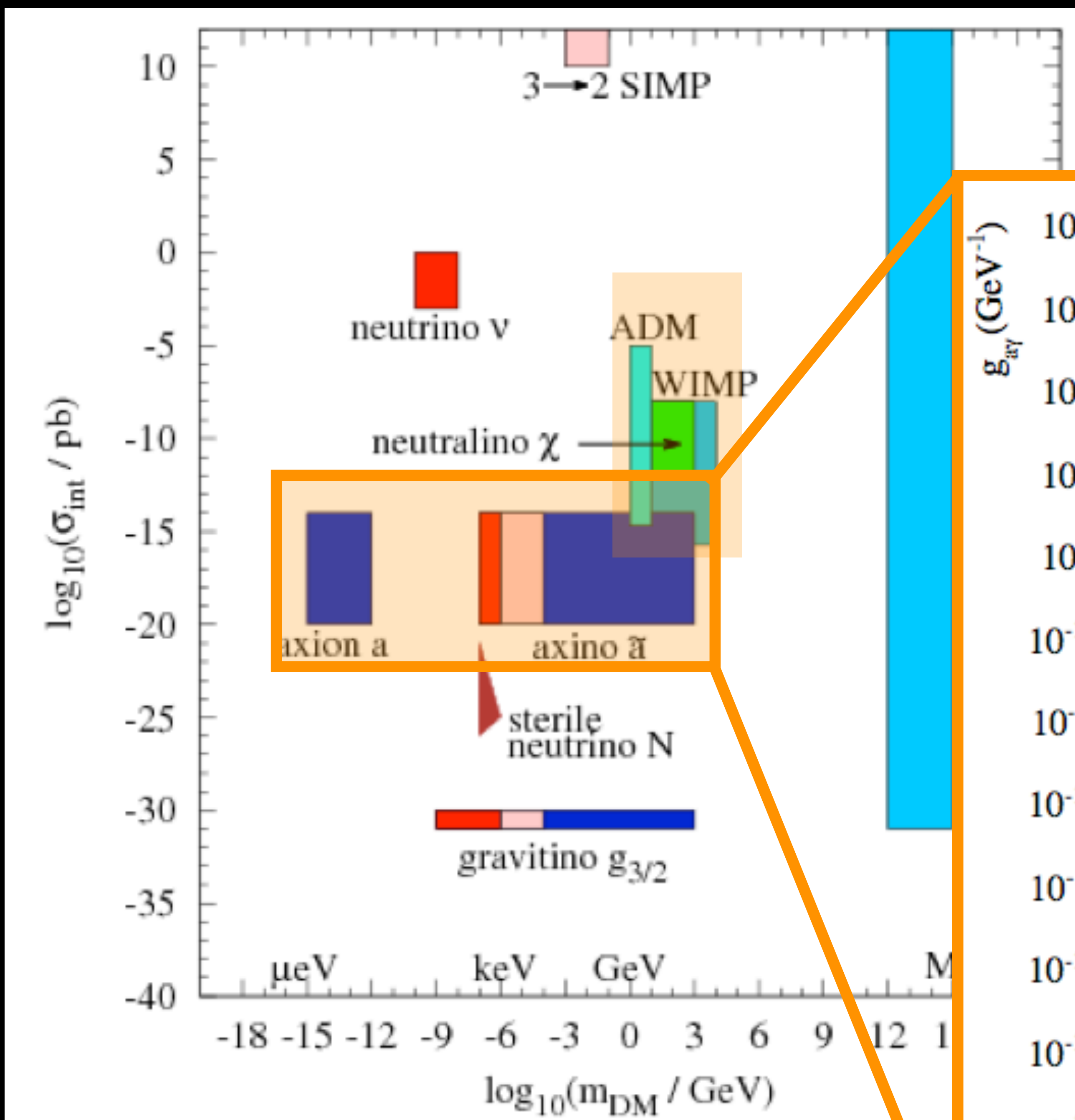
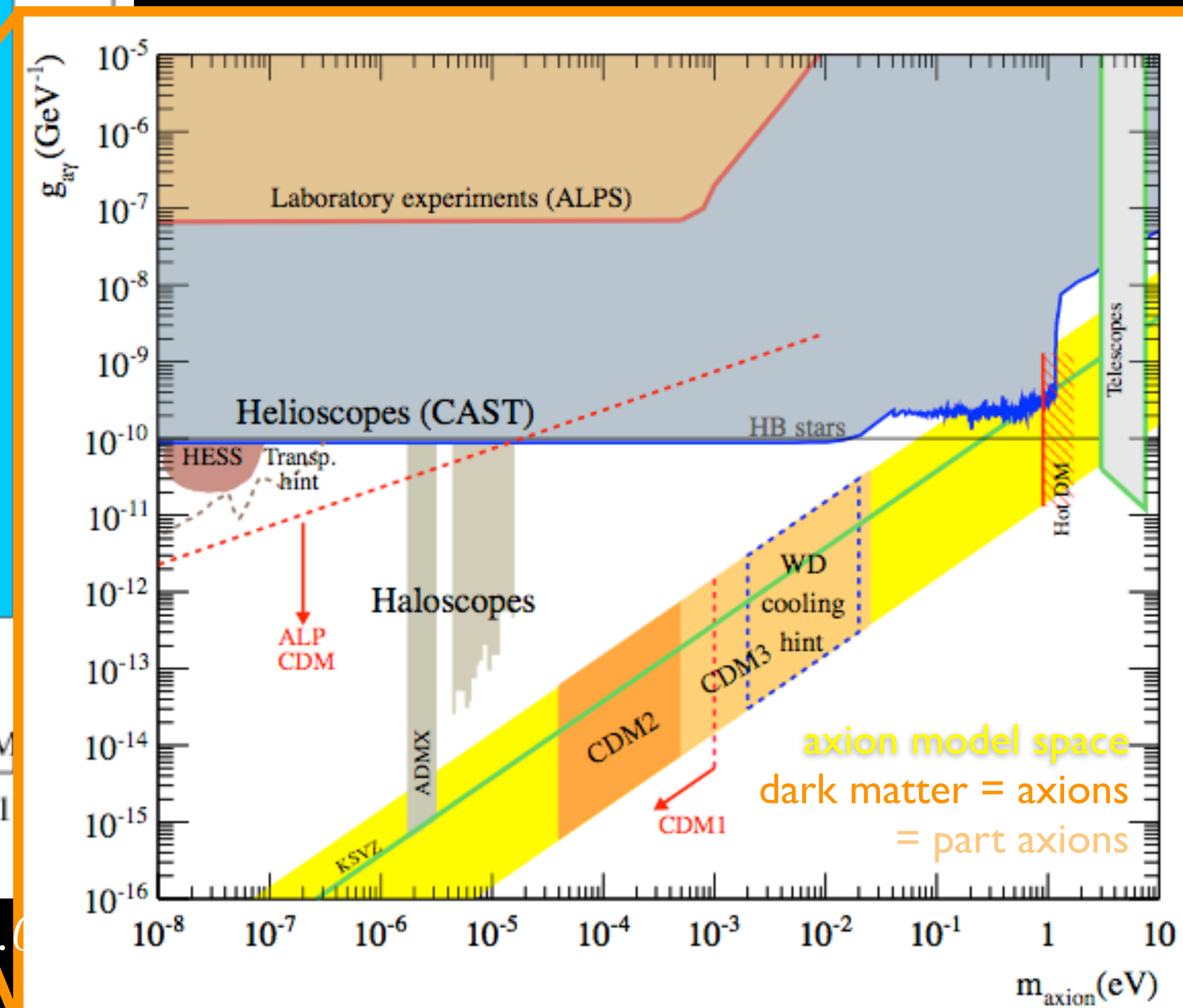
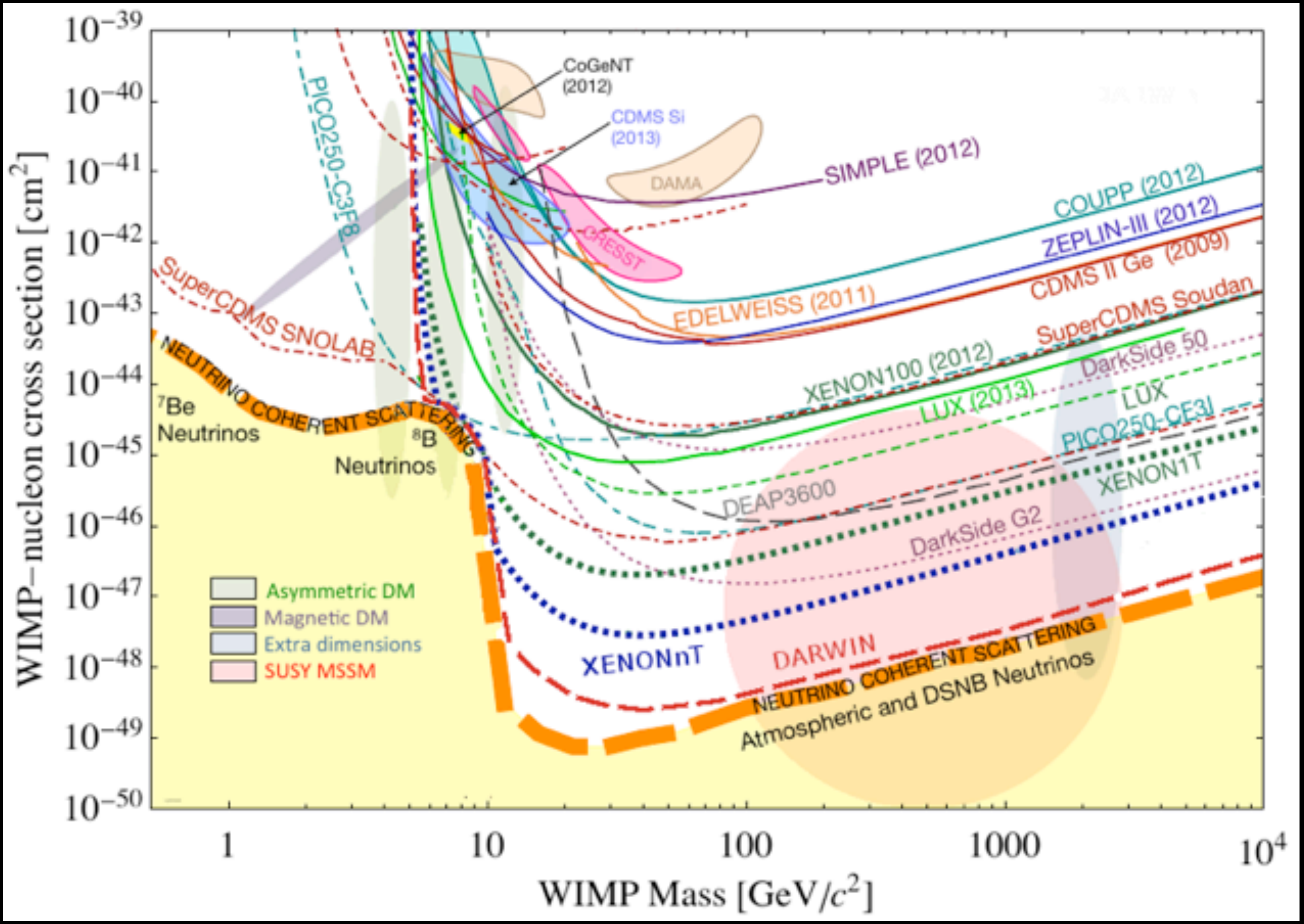


but starting to look for axions too!



Baer et al., arXiv:1407.

The Low-Background Frontier: Prospects



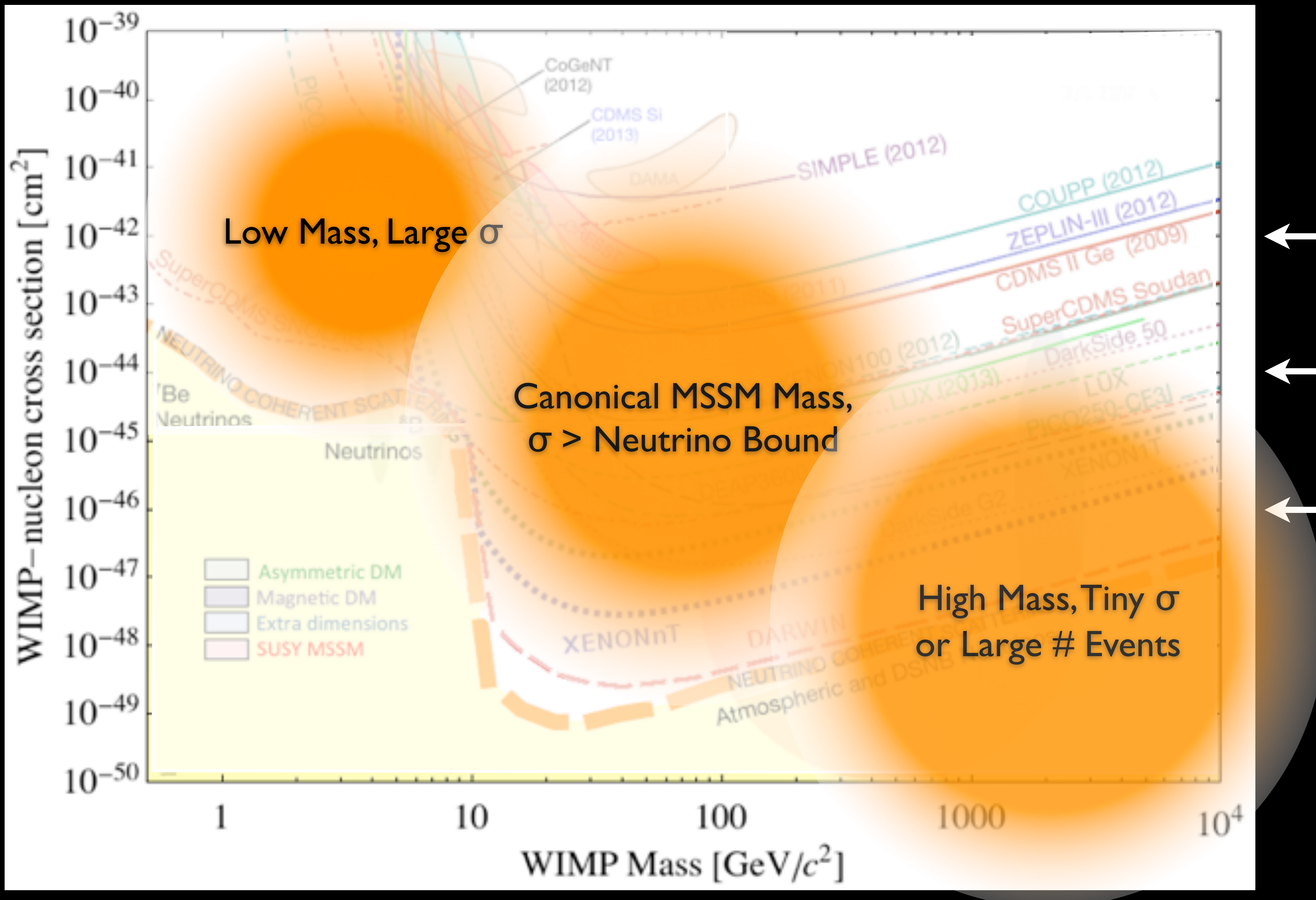
← 1 event/ kg/day

← 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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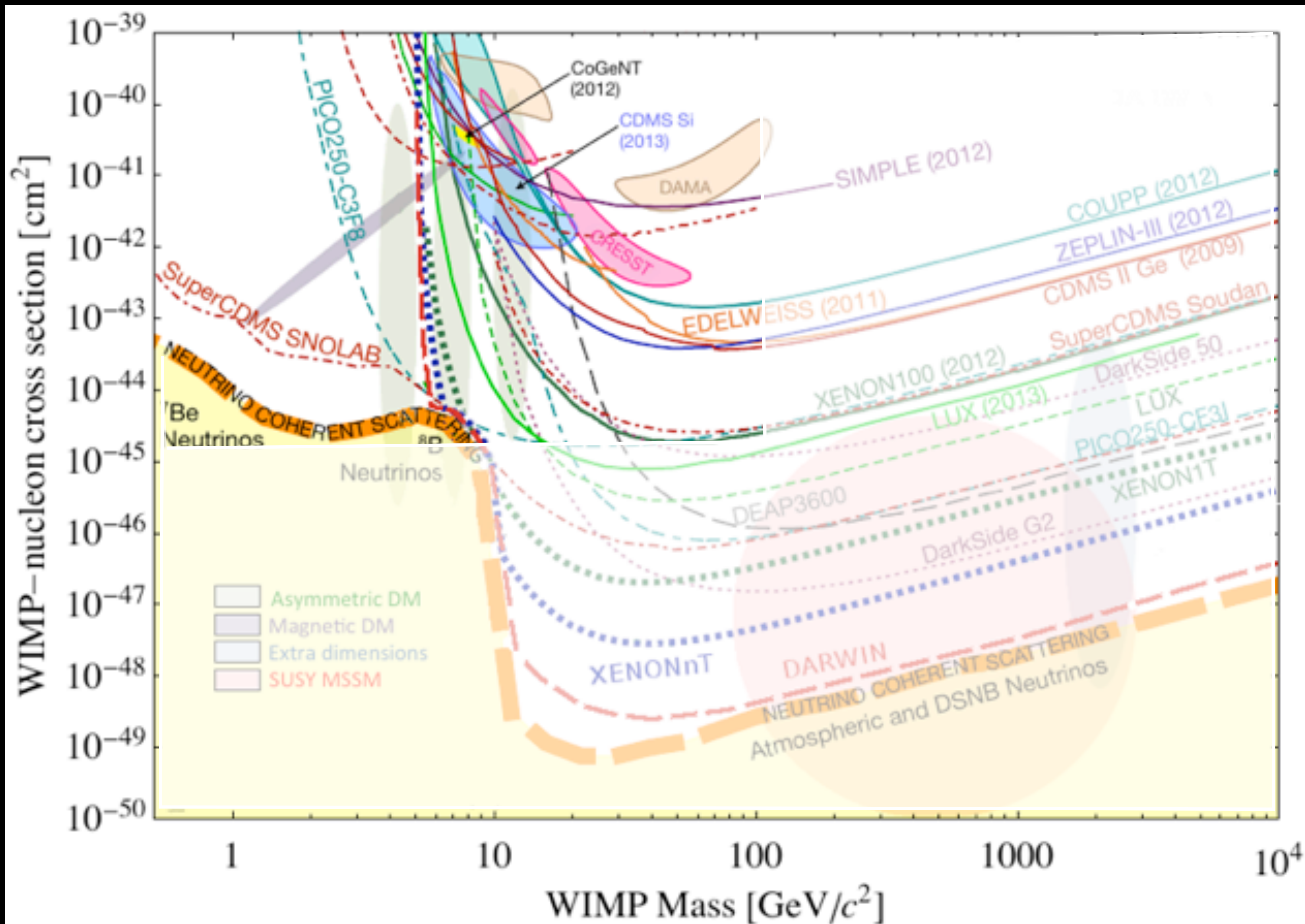

← 1 event/ kg/day

← 1 event/ 100kg/day

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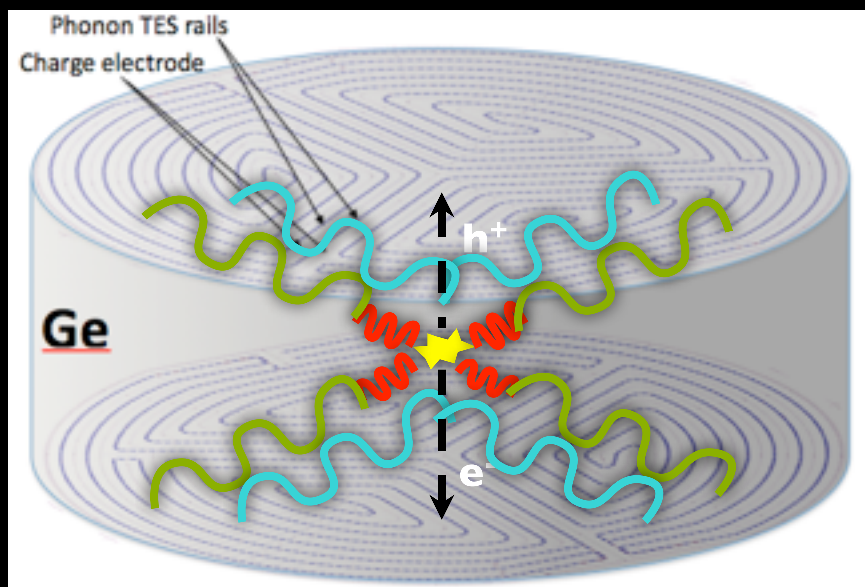
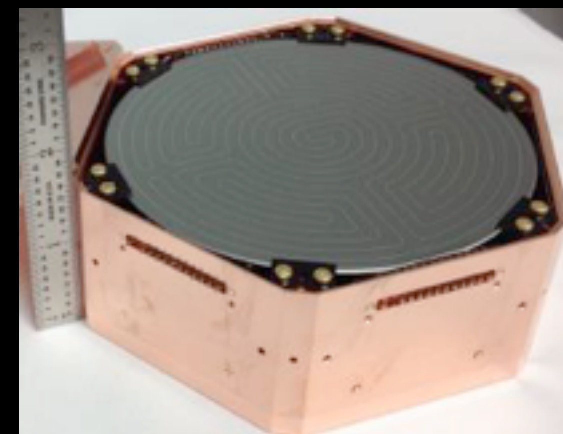
Bolometers

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

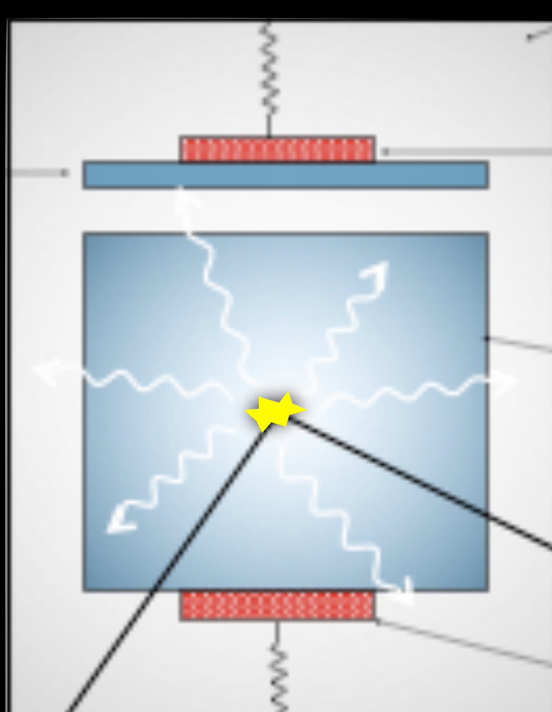
targets: Ge (SuperCDMS, EDELWEISS, COGENT, CDEX), Si (SuperCDMS), $CaWO_4$ (CRESST)

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

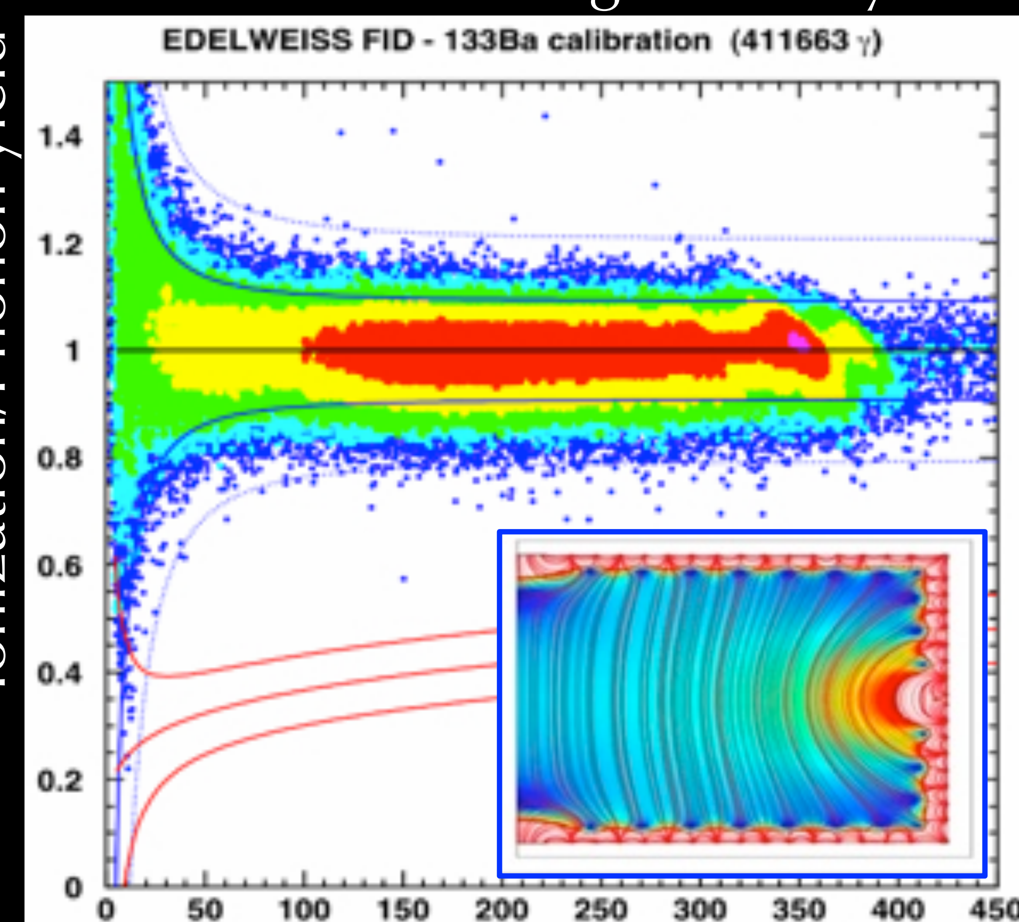


Scintillation side:
Si absorber on 300 gm $CaWO_4$, tungsten TES readout for particle ID

Phonon side:
TES readout to measure E_{recoil}

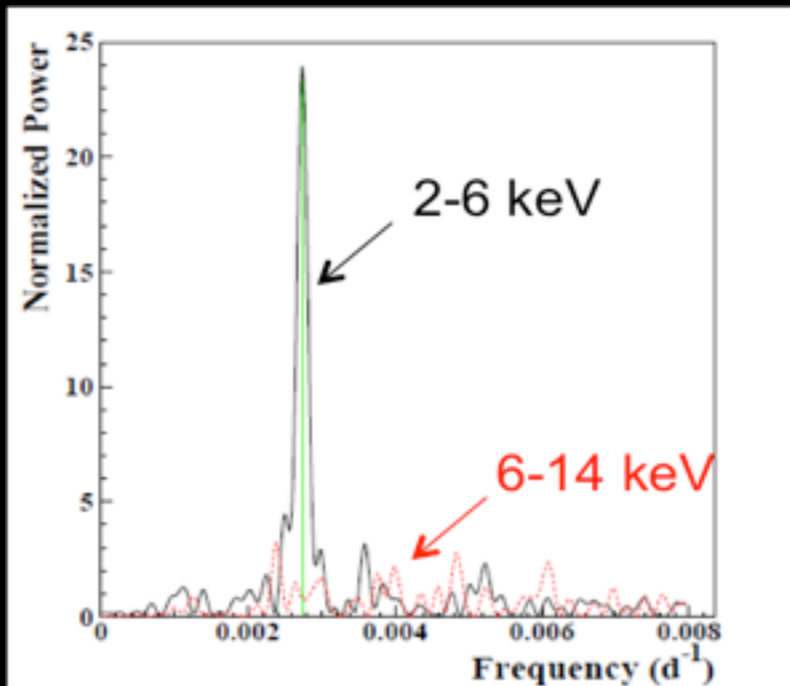
EDELWEISS: interleaved electrodes reduce surface backgrounds by $\times 10^5$

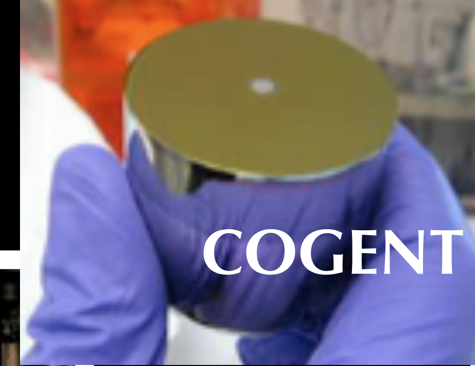
Ionization/Phonon yield



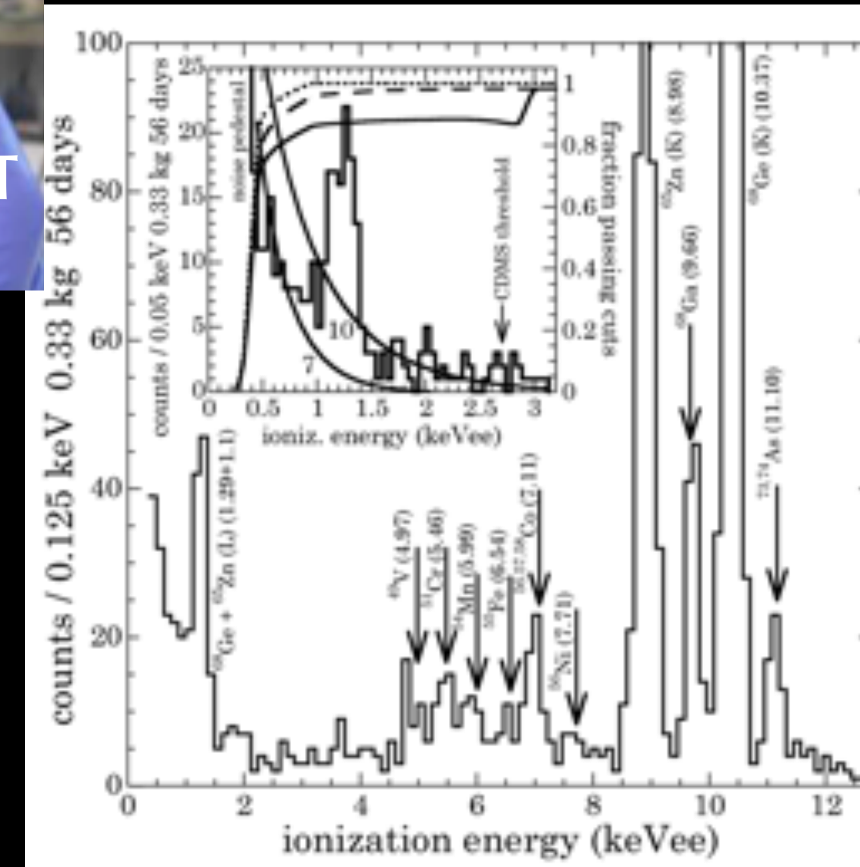
E_{recoil} (keV)

Dark Matter Signals?





arXiv:1002.4703

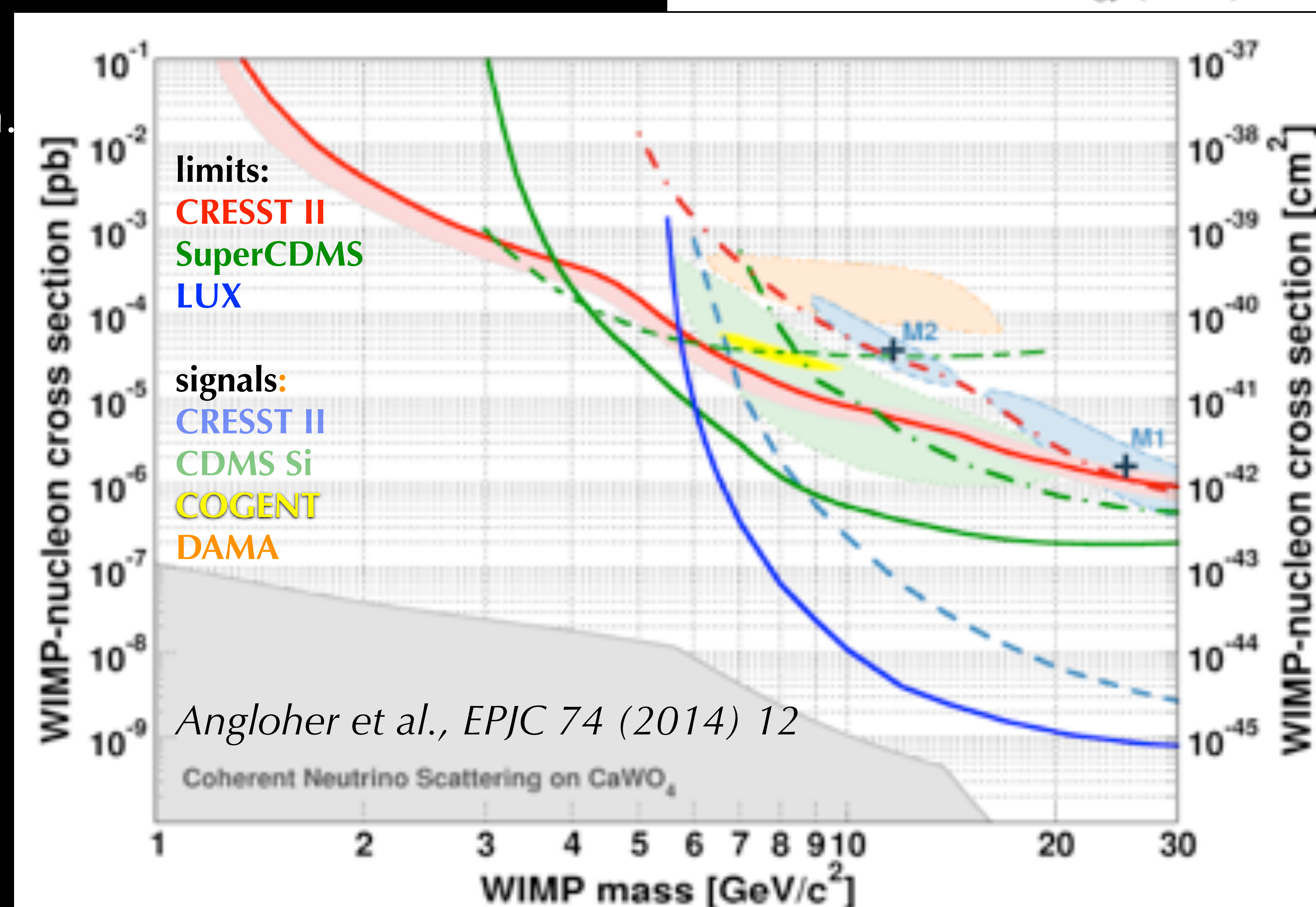


DAMA/LIBRA: 9.2**σ** excess in 2-6 keV, 1.33 ton-yr NaI data set, with modulation.

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 in 577 kg-day, 1.6 keVr threshold run.

CRESST-II: excess reported in phase-1, phase-2 excludes it in 29.4 kg-day, 0.6 keV threshold run.



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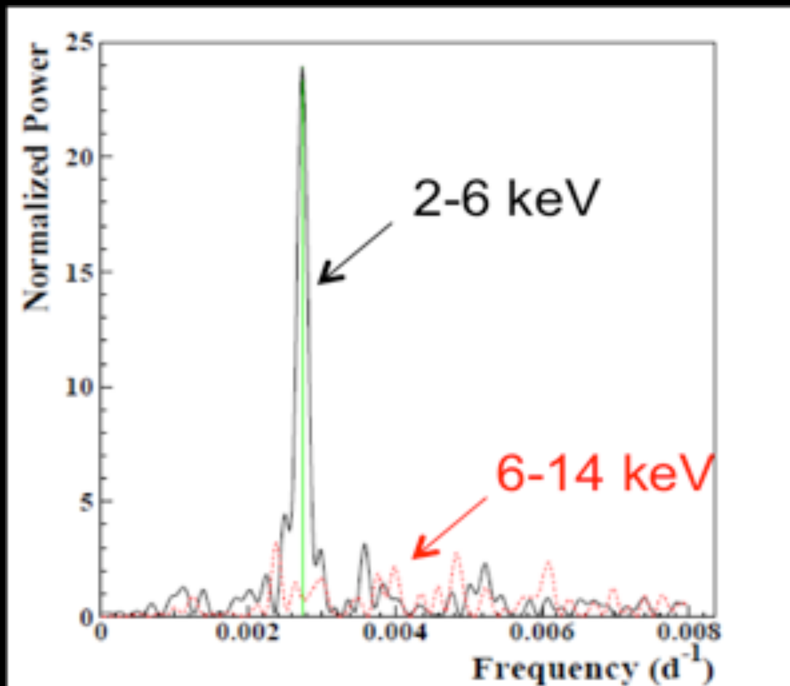

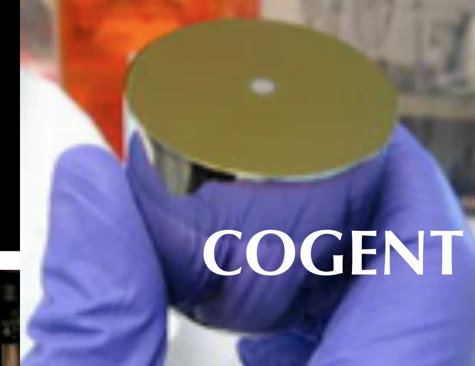

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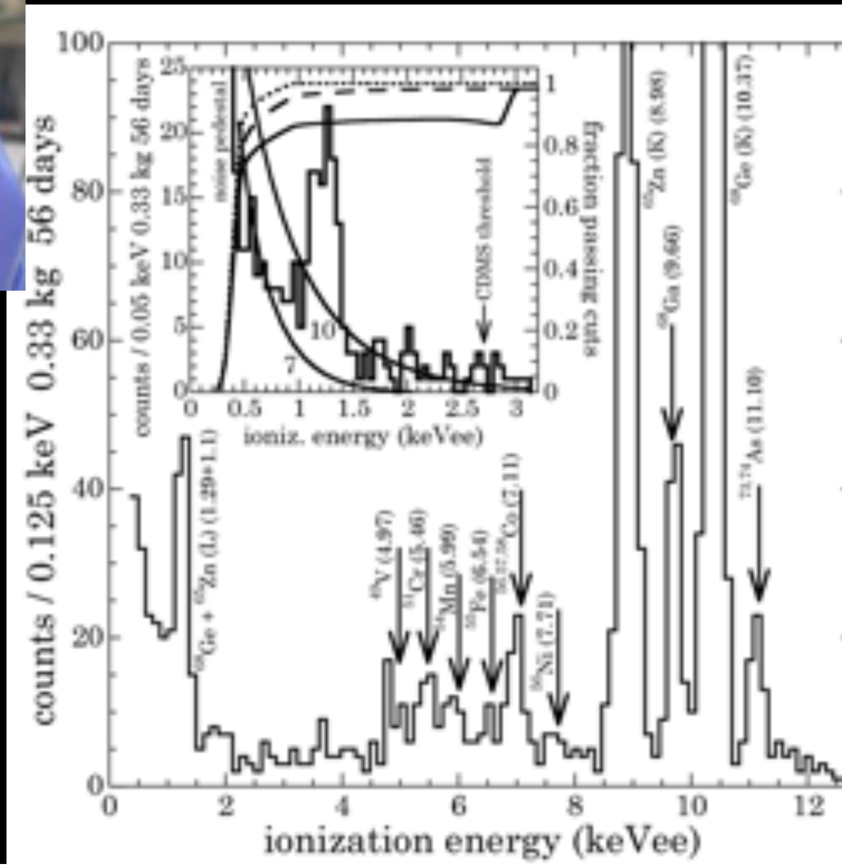

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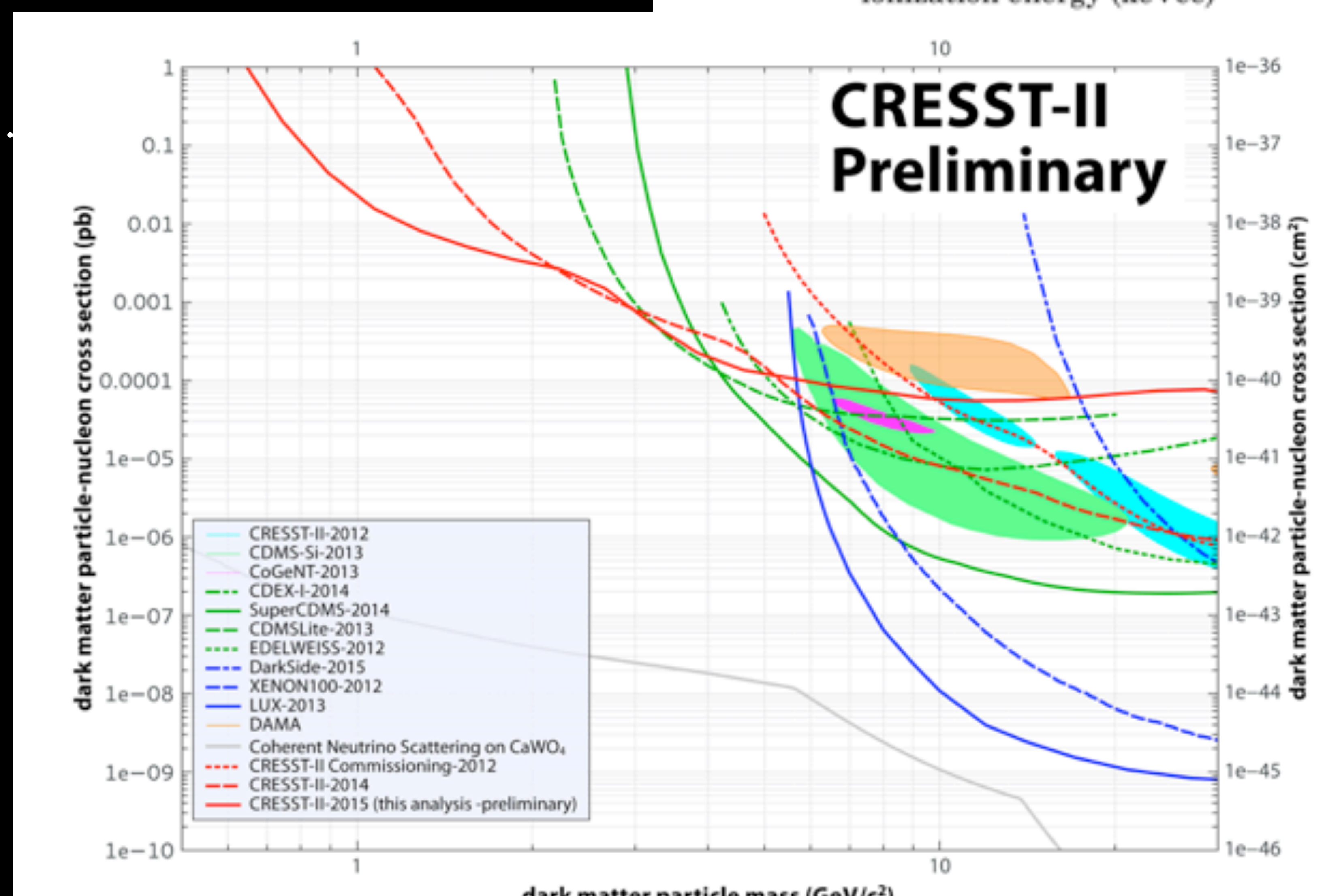
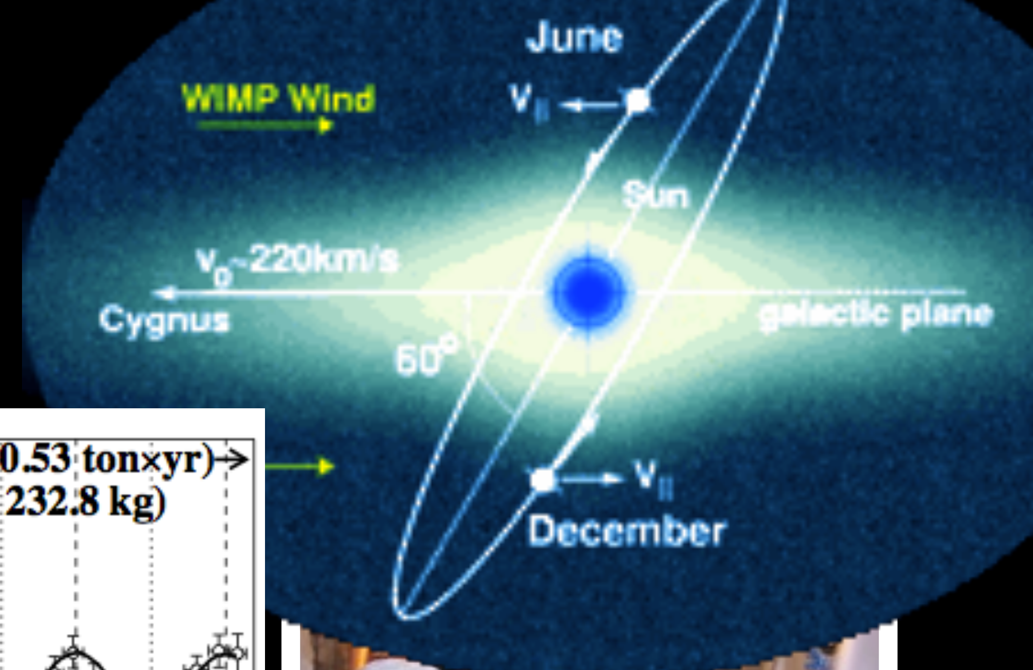
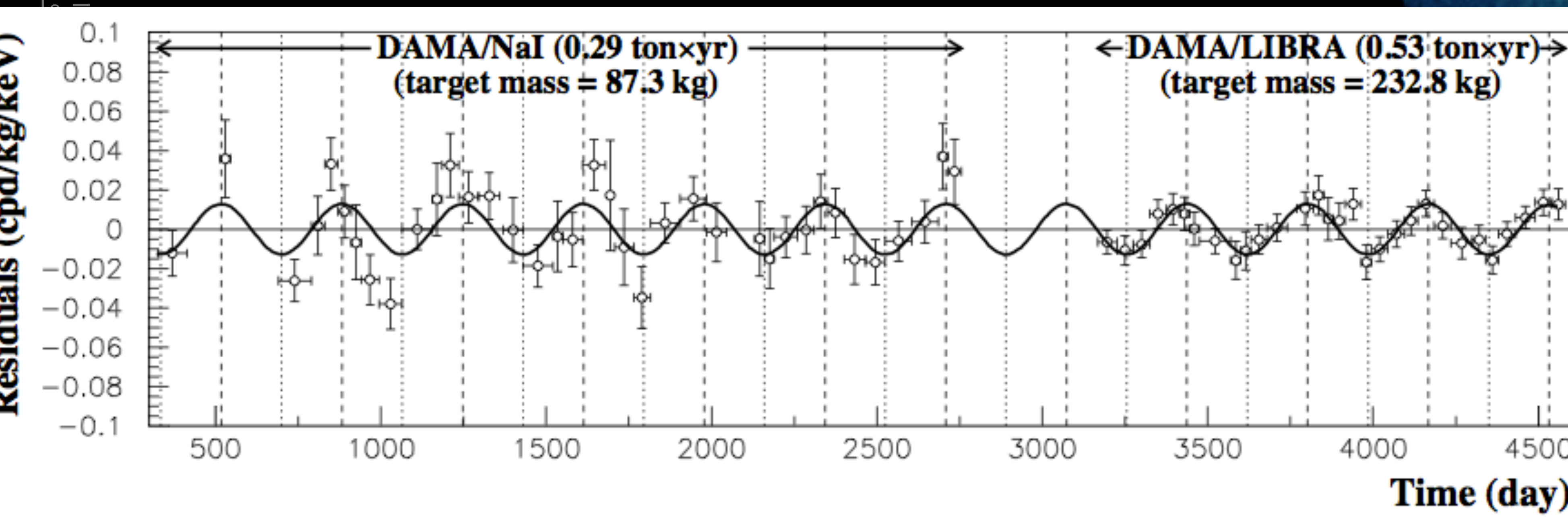
New results! 7 kg-day, 0.3 keV threshold.



Annual Modulation Tests

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





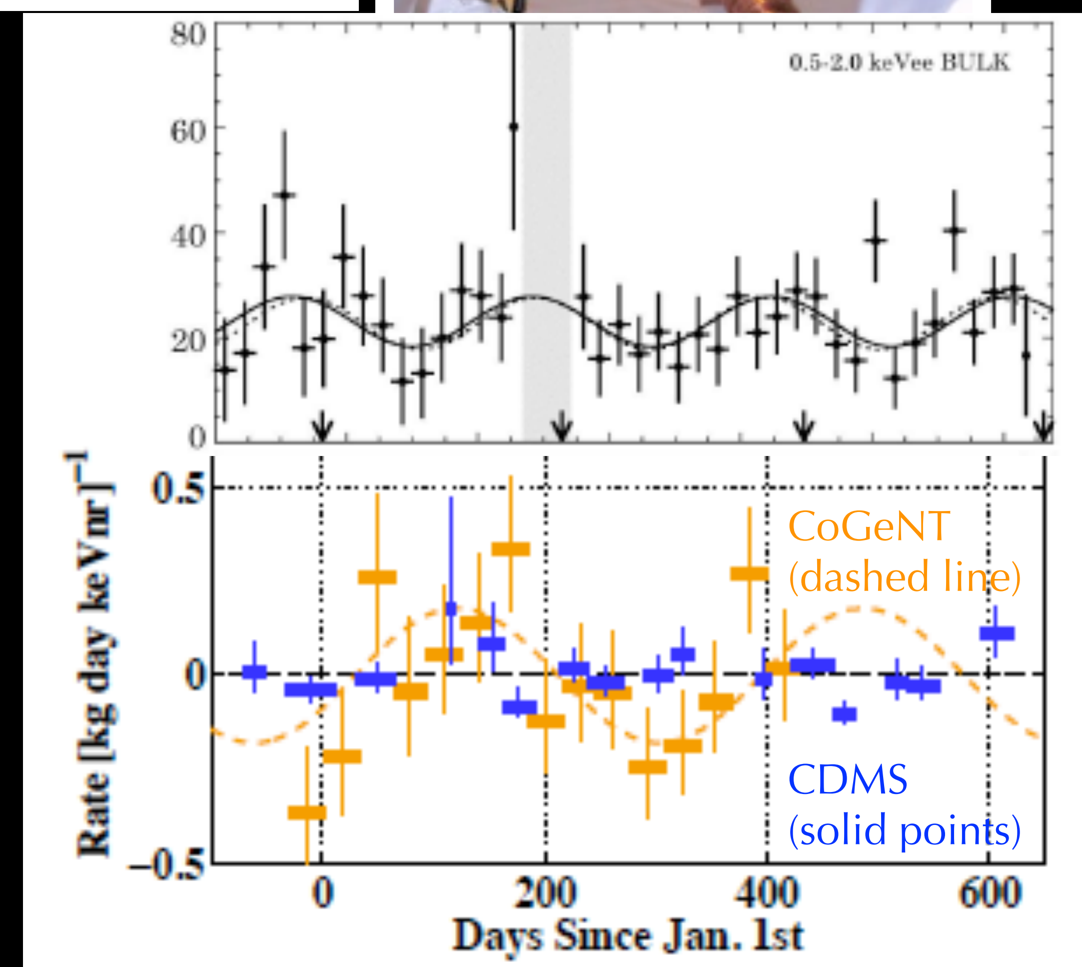
DAMA/LIBRA: measure (0.0112±0.0012) cpd/kg/keV, t_0 = (144±7) d in 1.33 T-yr.

COGENT: Ge, ~2σ modulation reported. *arXiv:1401.3295*
C-4 experiment follow-up.

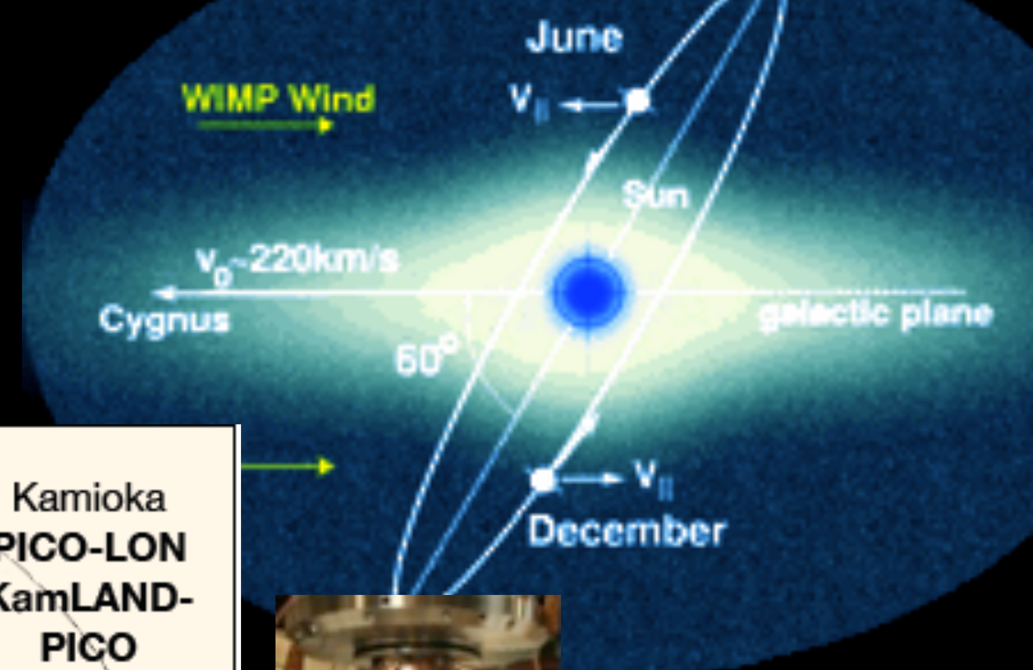
MALBEK: Ge, no excess reported. *J. Wilkerson UCLADM'14*

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

KIMS: CsI (104.3 kg at YangYang), no modulation observed. *J.Phys.Conf.Ser. 384 (2012) 012020*



Annual Modulation Prospects



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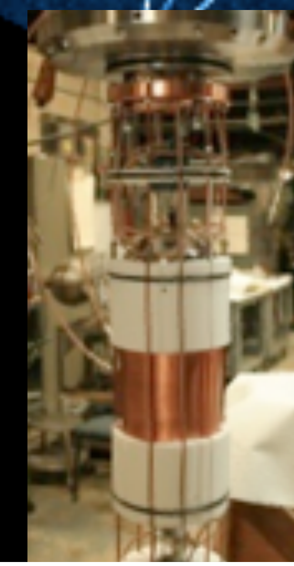
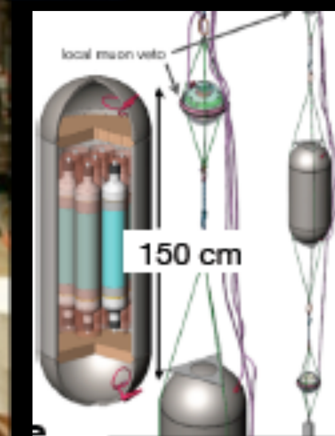
t_0 =

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



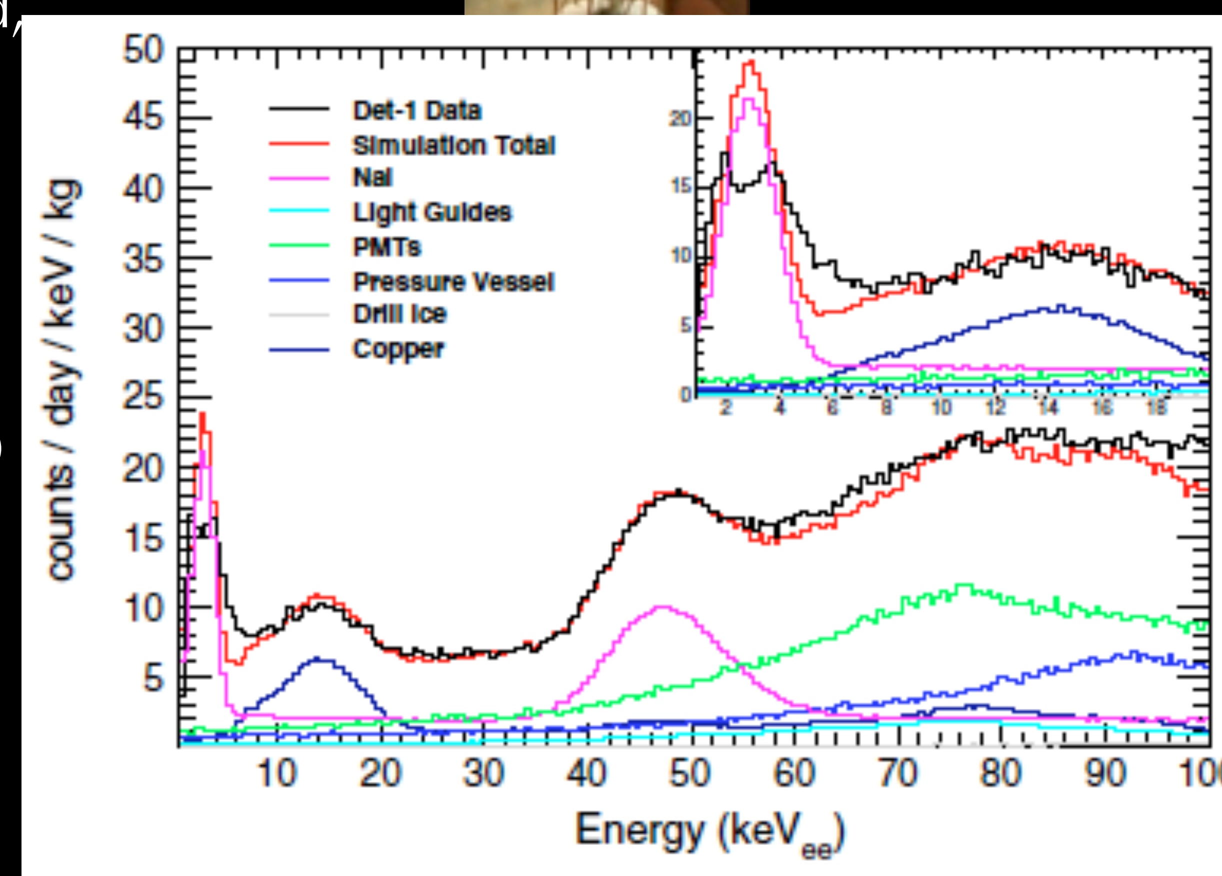


DAMA/LIBRA: phase-2 upgrade to lower energy threshold, took place in 2011, results not yet reported.

COGENT: C-4 experiment follow-up.

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)

XMASS: liquid Xe, 833 kg deployed in Kamioka, modulation results with 0.3 keVee threshold July 31!



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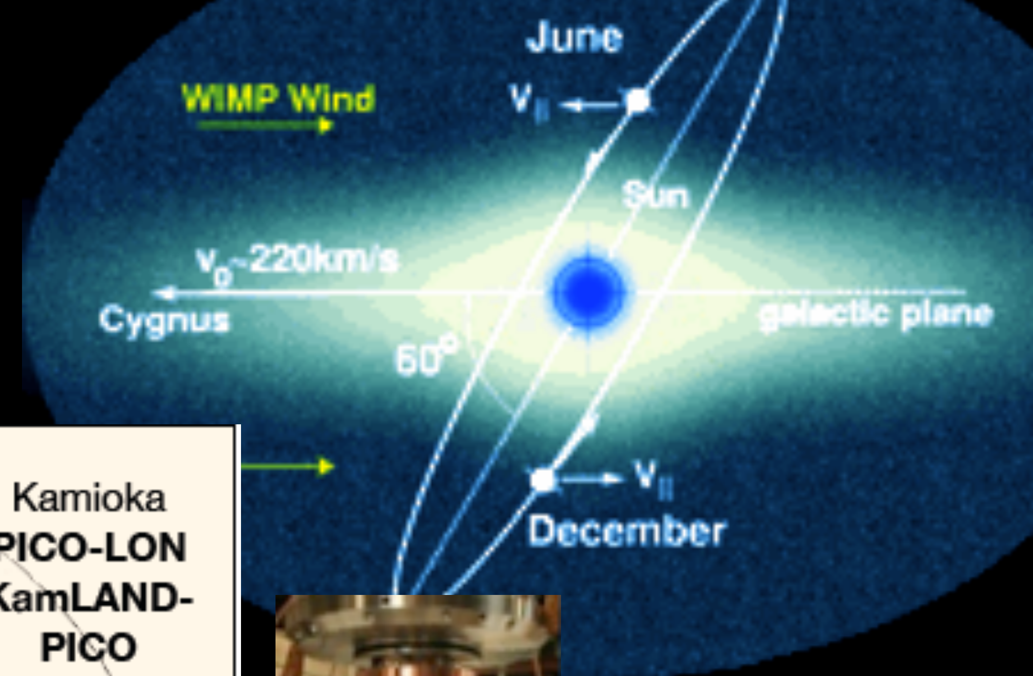

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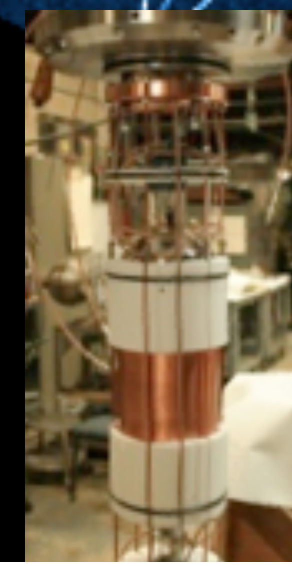

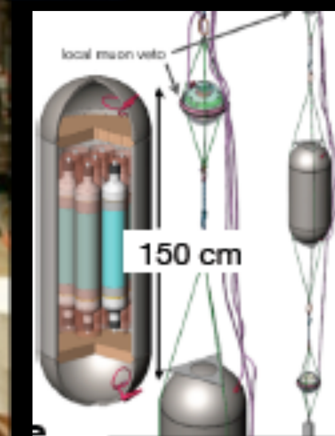

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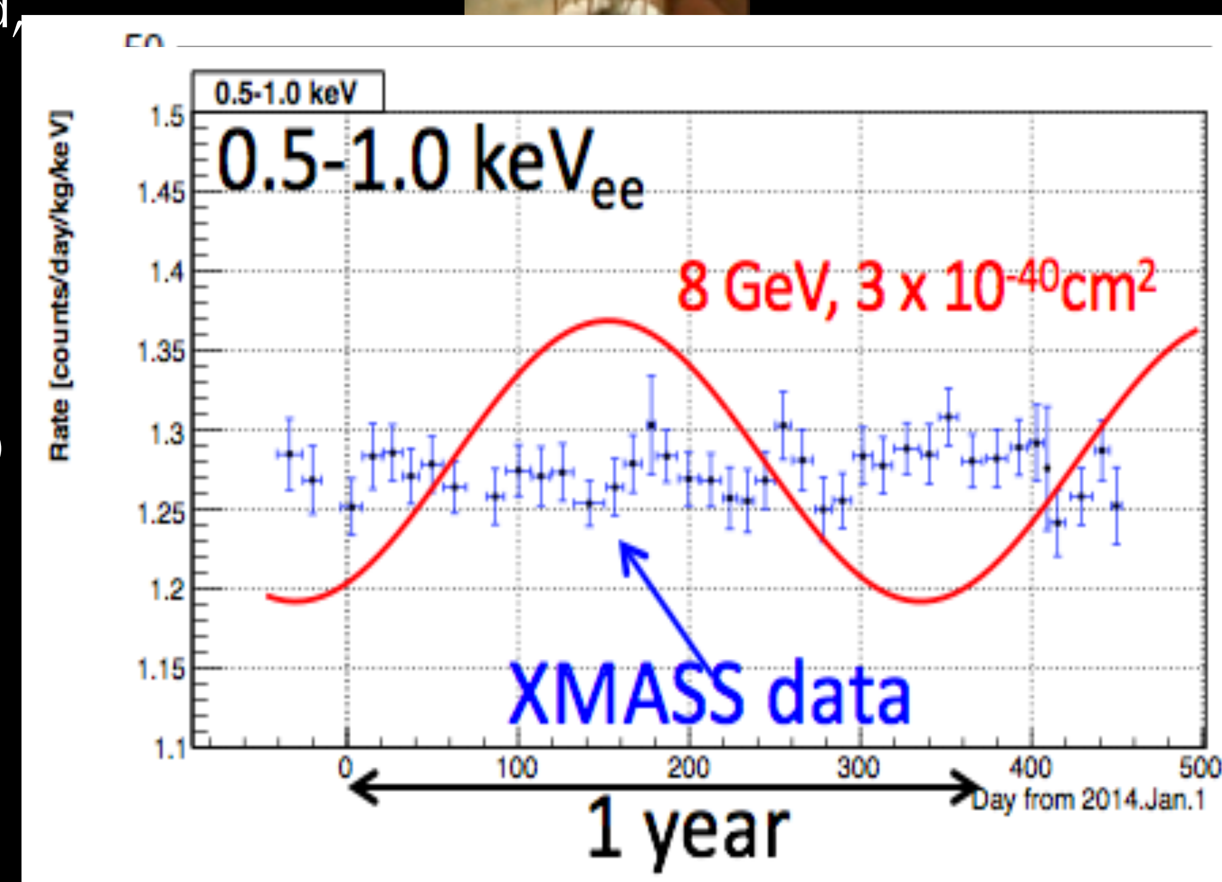


Low-Mass Region Prospects

Goal: reach the neutrino bound!

EDELWEISS-III: 36 FID-800 detectors at LSM, with >600 kg-days. Installing new FIDs with <0.3 keV FWHM for low mass search. 35 kg-day, 3.6 keVr threshold unblinded *arXiv:1504.00820*

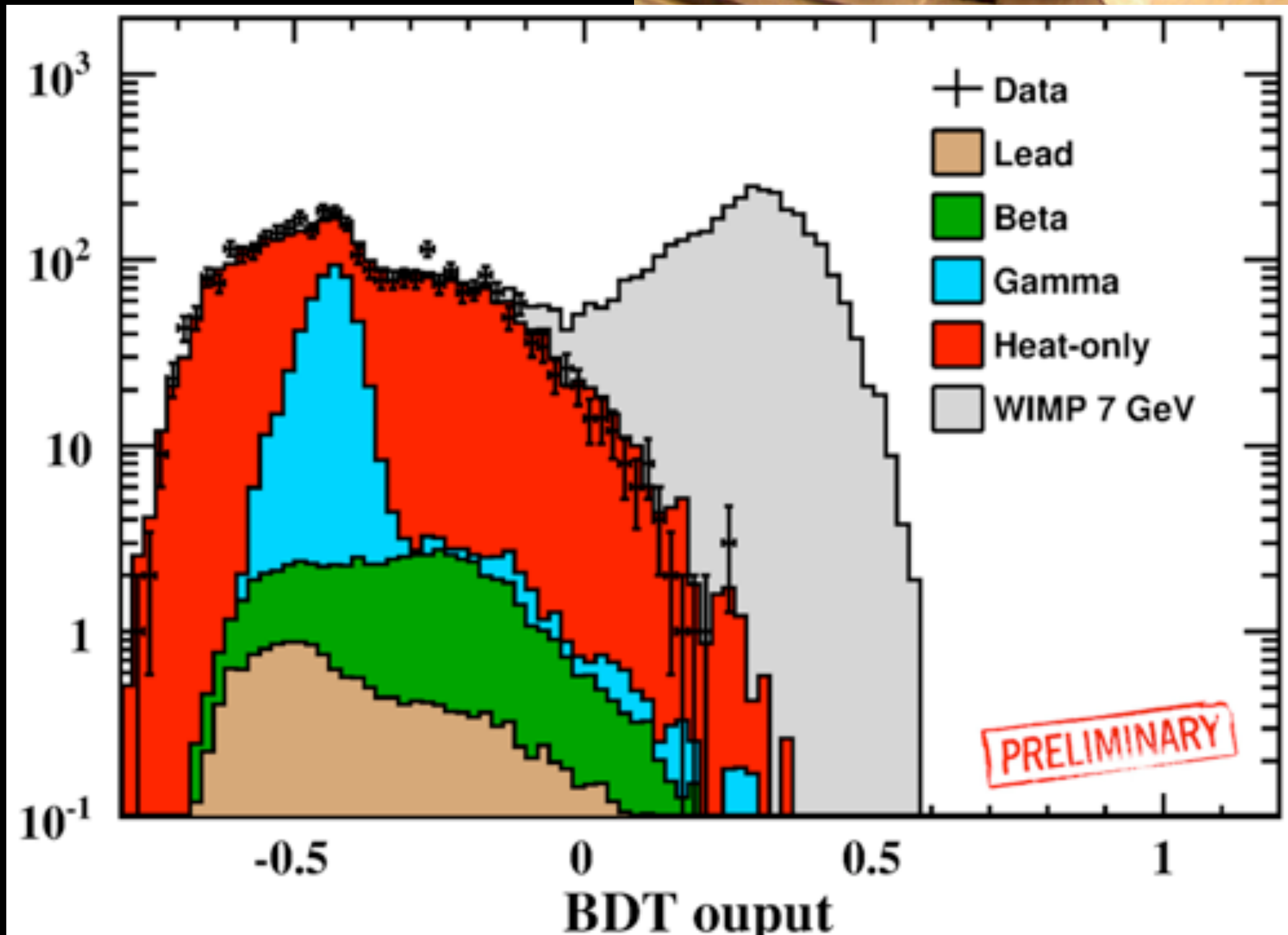
CRESST: 50 kg-day, low E threshold results for Fall'15. R&D towards 0.1 keV threshold, with smaller crystals (24 gm), lower background (3.5/keV kg day), for 1-6 GeV WIMP search.

SuperCDMS: Focus on 0.3-10 GeV/c^2 WIMP masses 50 kg of 1.4 kg Ge (and Si) detectors at SNOLAB, from 2017. Can operate in HV mode, for 0.9 keV threshold. *PRL 112 (2014) 041302.)*

EURECA: collaboration of CRESST + EDELWEISS ++, coordinate with SuperCDMS, cryostat for 400 kg).

DAMIC: search for WIMP interactions in CCD Si, 100g to operate at SNOLAB. 1E-5 pb sensitivity with 1 keV threshold at 2 GeV/c^2 *arXiv:1506.02562*

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



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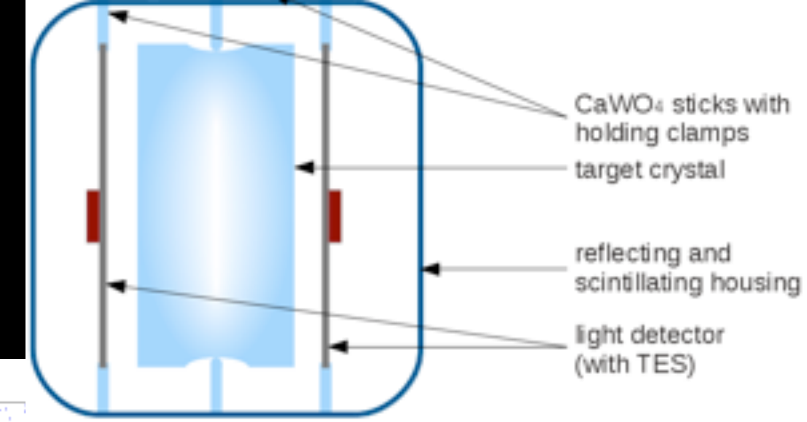

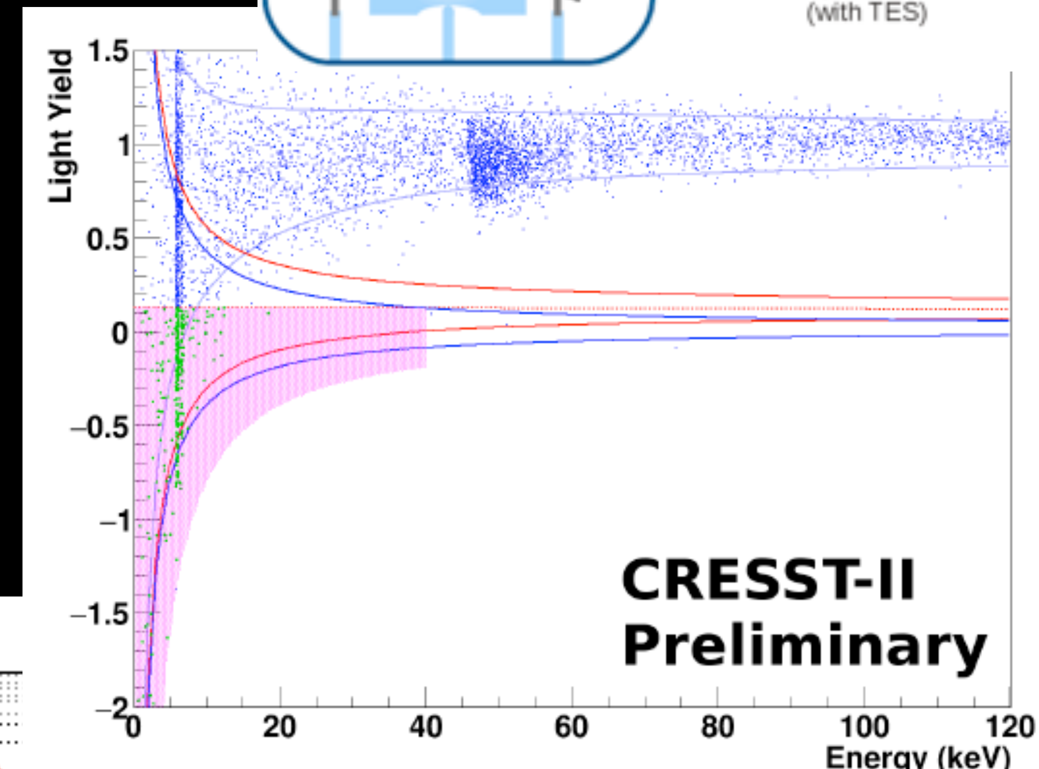

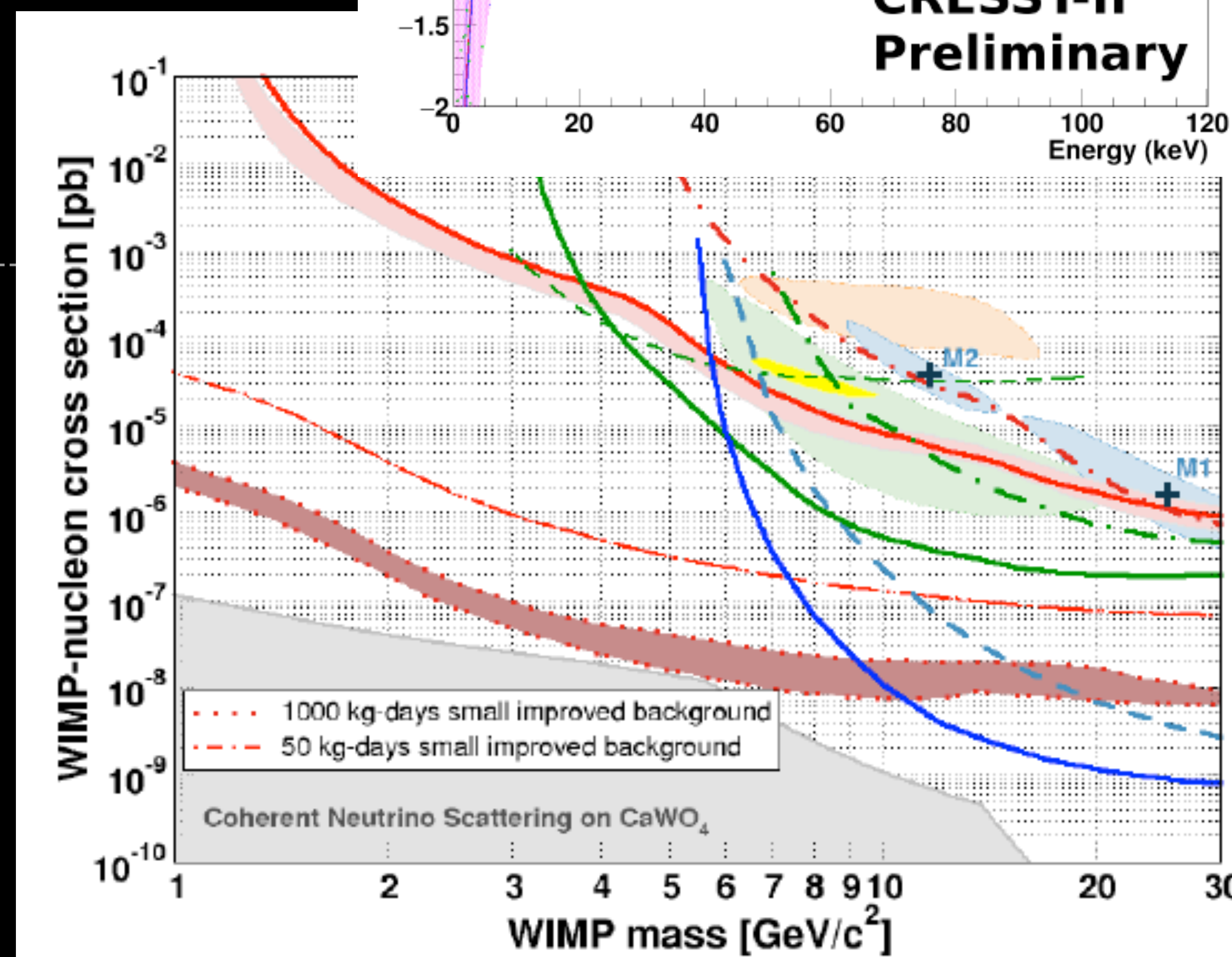

Low-Mass Region Prospects

Goal: reach the neutrino bound!

EDELWEISS-III: 36 FID-800 detectors at LSM, with >600 kg-days. Installing new FIDs with <0.3 keV FWHM for low mass search. 35 kg-day, 3.6 keVr threshold unblinded *arXiv:1504.00820*

CRESST: 50 kg-day, low E threshold results for Fall'15. R&D towards 0.1 keV threshold, with smaller crystals (24 gm), lower background (3.5/keV kg day), for 1-6 GeV WIMP search.

SuperCDMS: Focus on 0.3-10 GeV/c^2 WIMP masses 50 kg of 1.4 kg Ge (and Si) detectors at SNOLAB, from 2017. Can operate in HV mode, for 0.9 keV threshold. *PRL 112 (2014) 041302.)*

EURECA: collaboration of CRESST + EDELWEISS + coordinate with SuperCDMS, cryostat for 400 kg).

DAMIC: search for WIMP interactions in CCD Si, 100g to operate at SNOLAB. 1E-5 pb sensitivity with 1 keV threshold at 2 GeV/c^2 *arXiv:1506.02562*

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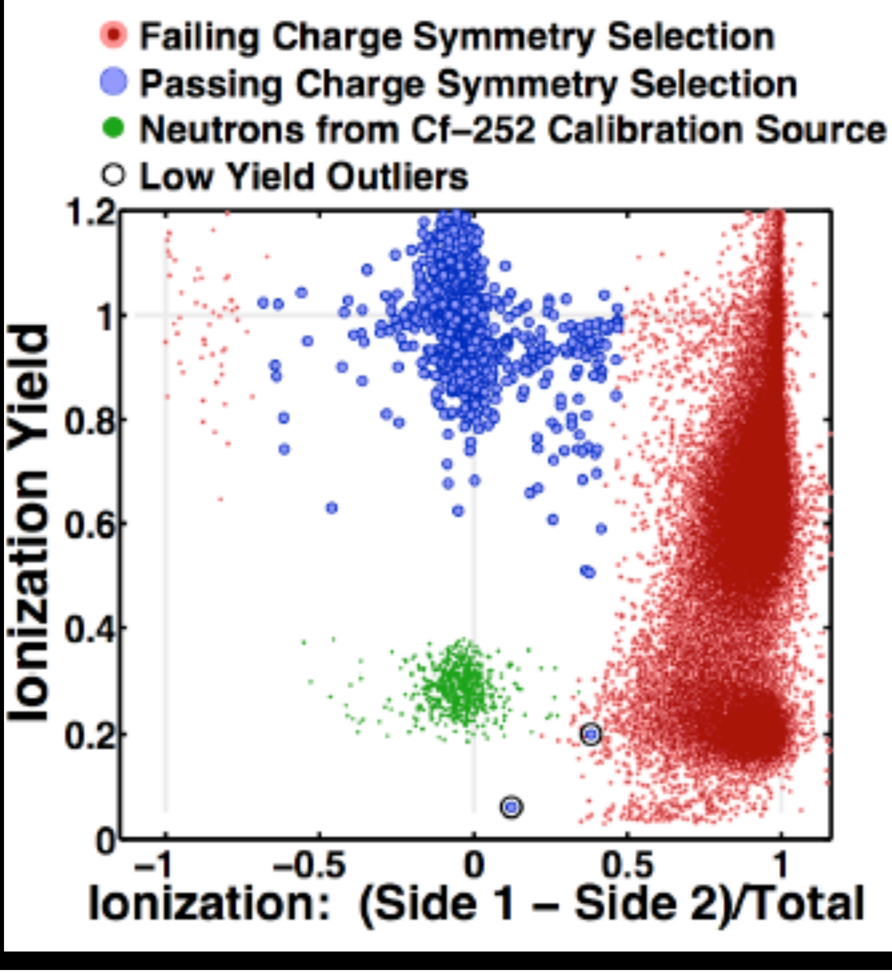

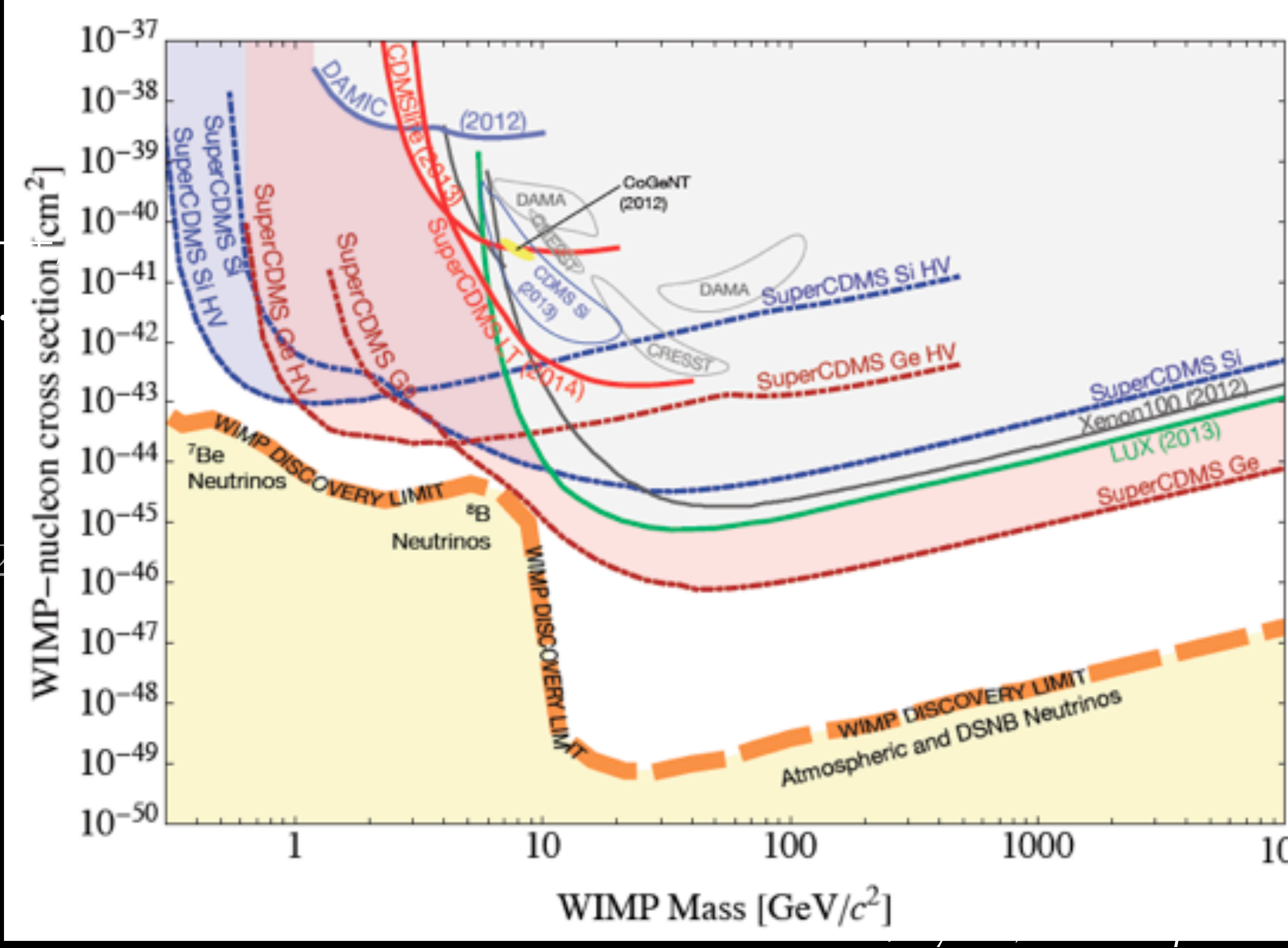

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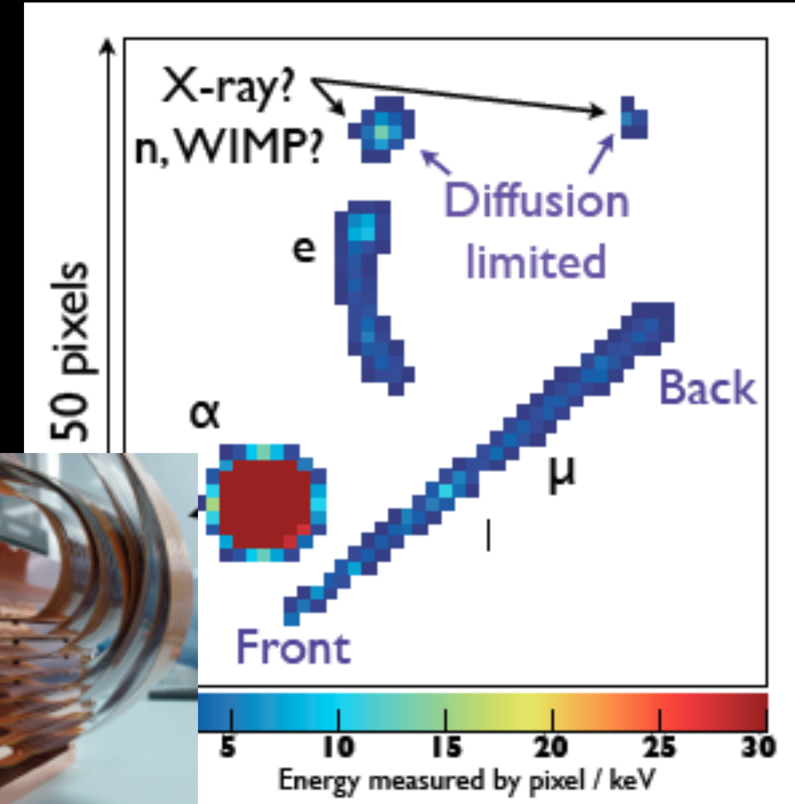
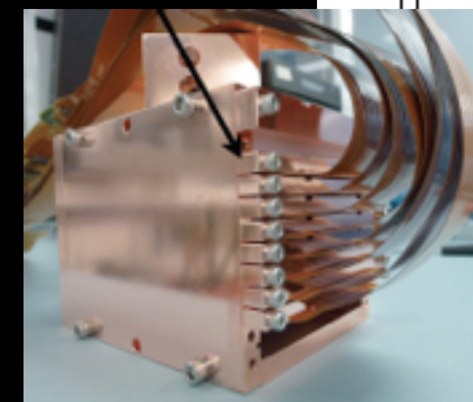
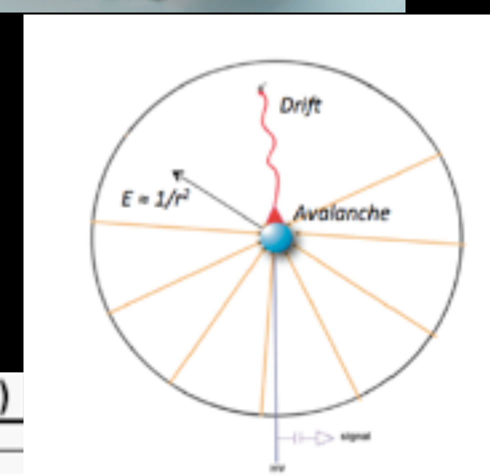
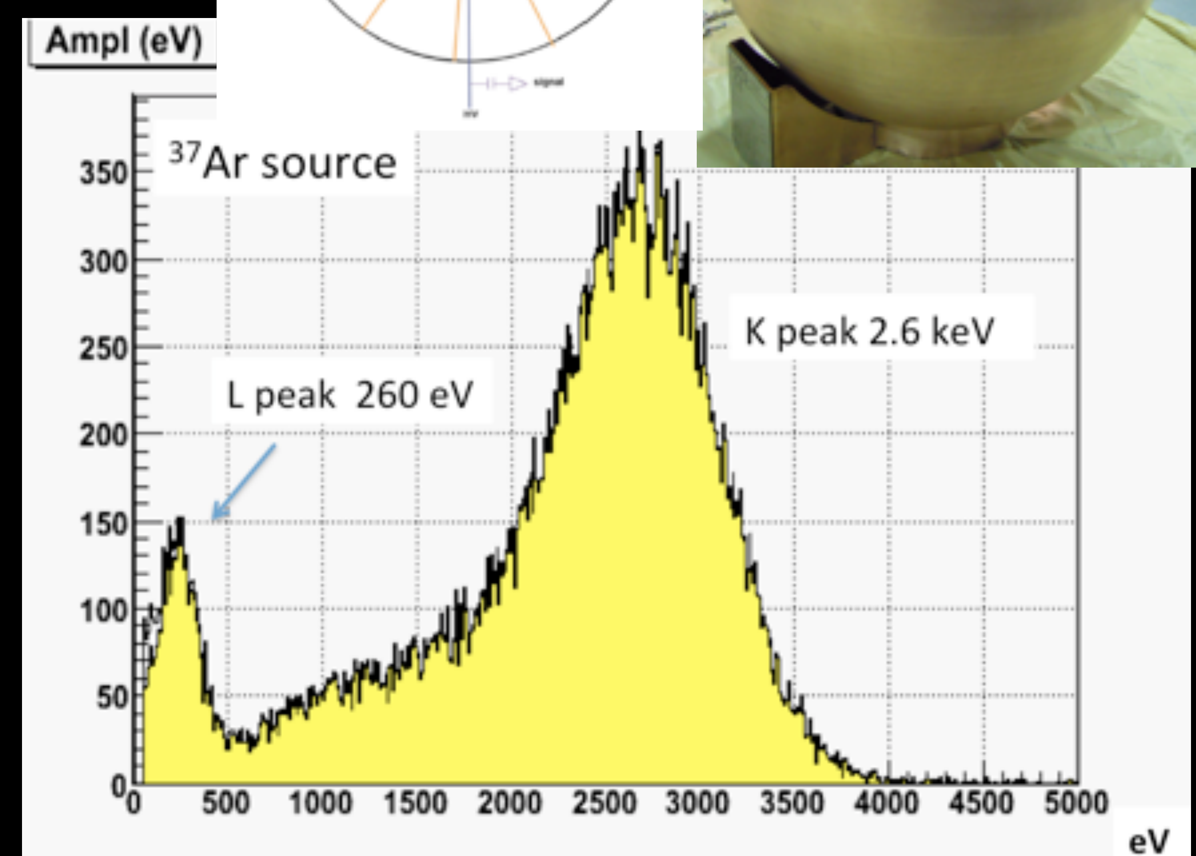
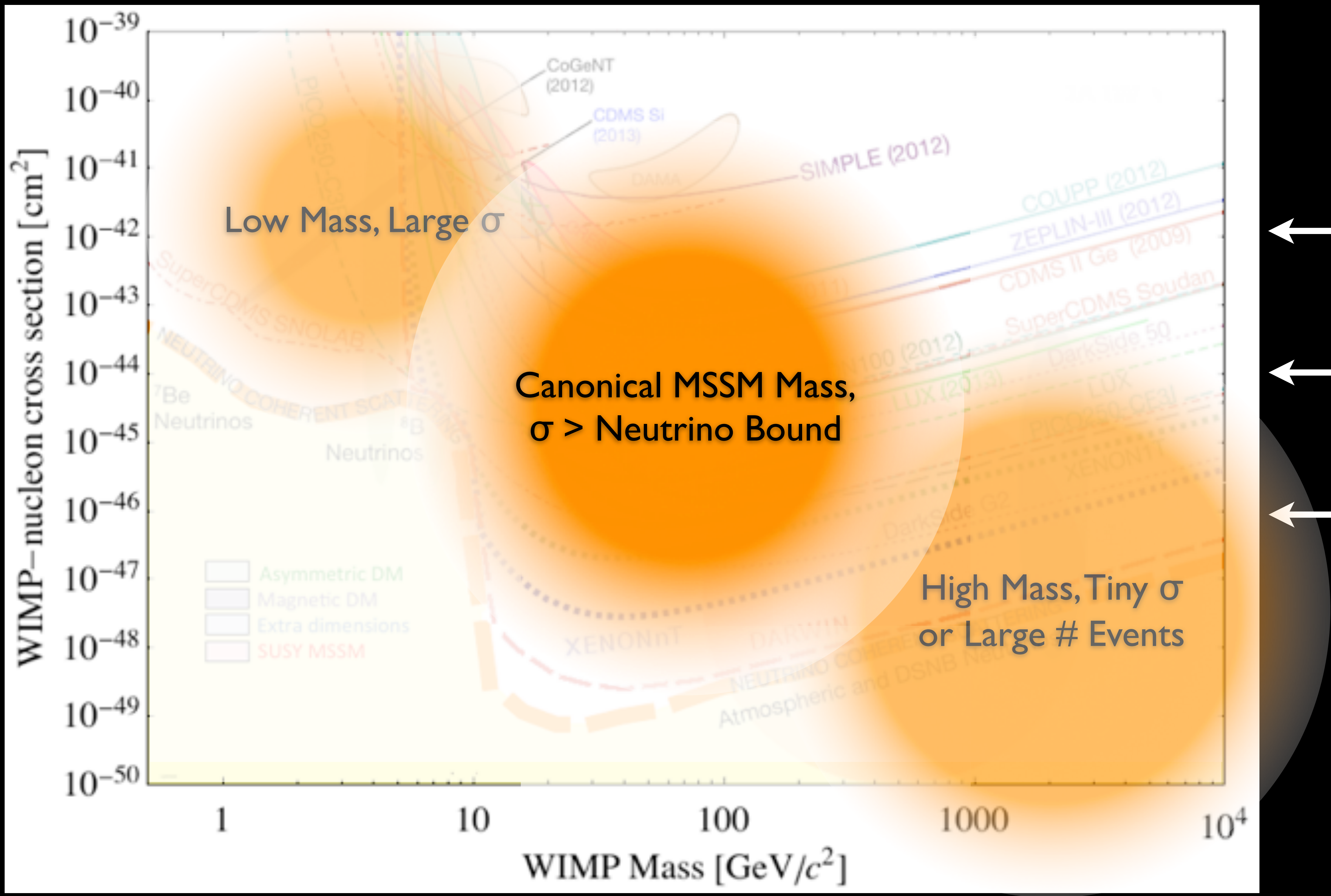








The Low-Background Frontier: Prospects



1 event/ kg/day

1 event/ 100kg/day

1 event/ 100 kg/ 100 days

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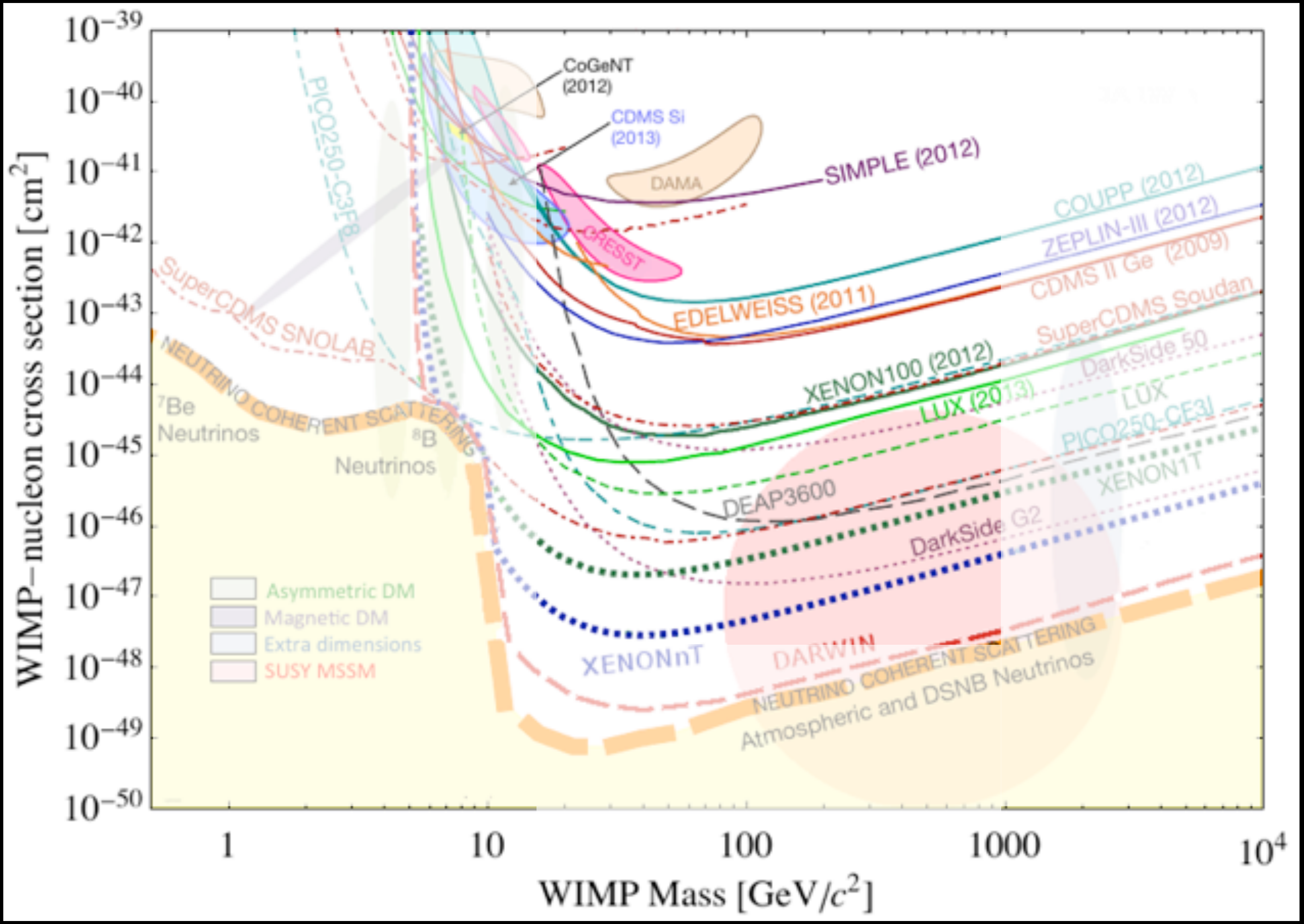

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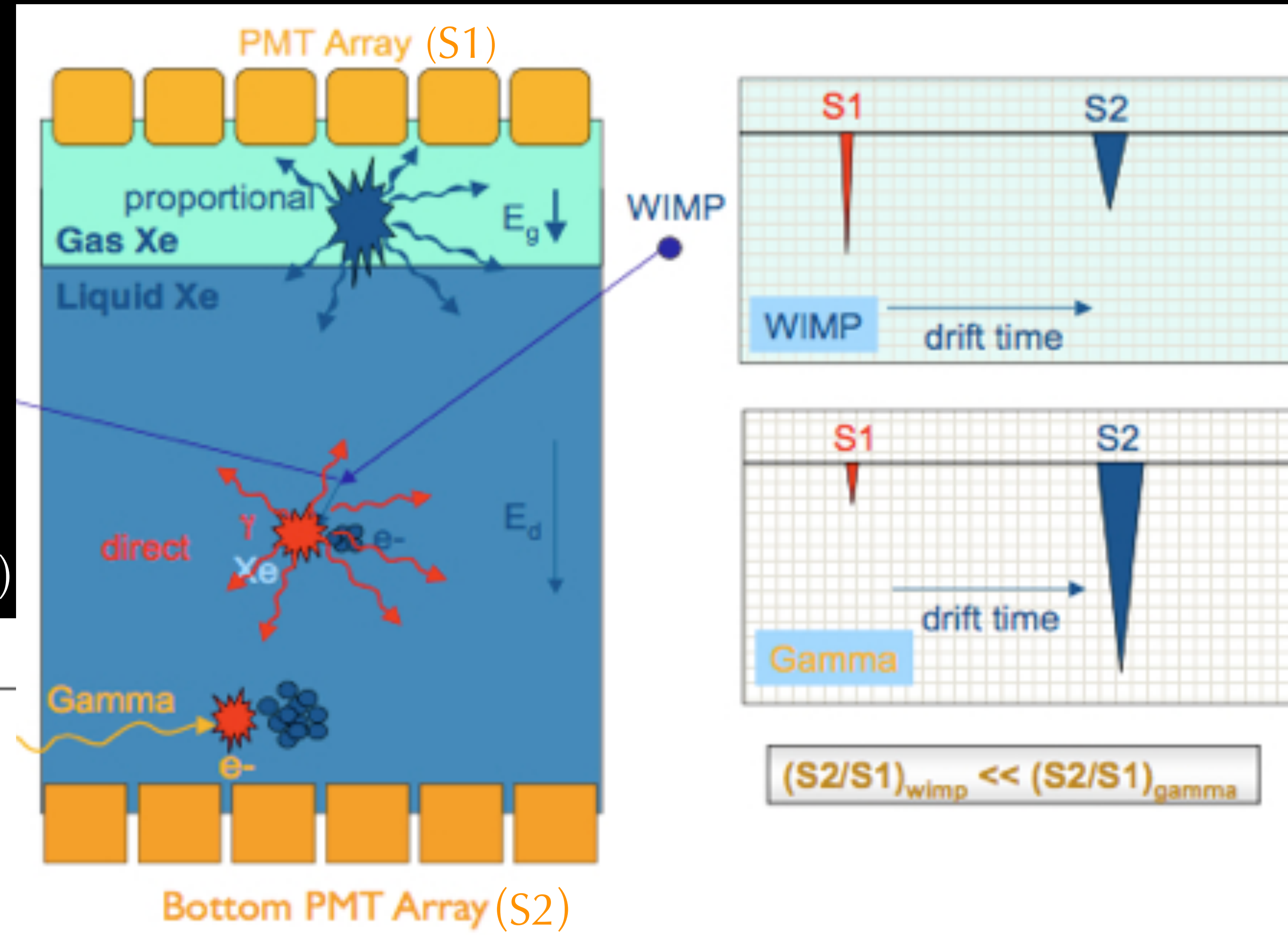
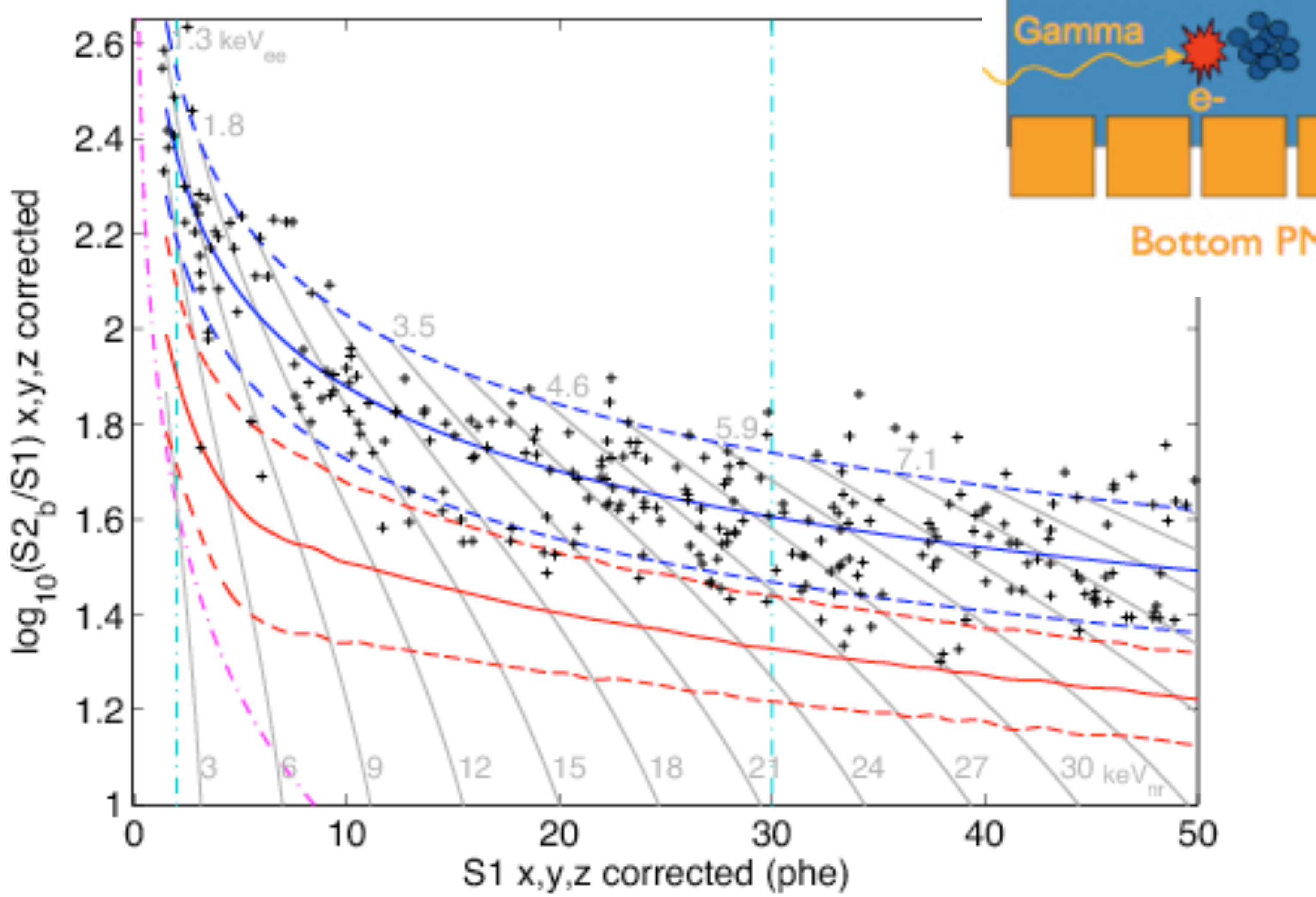
Two-Phase Xenon TPCs

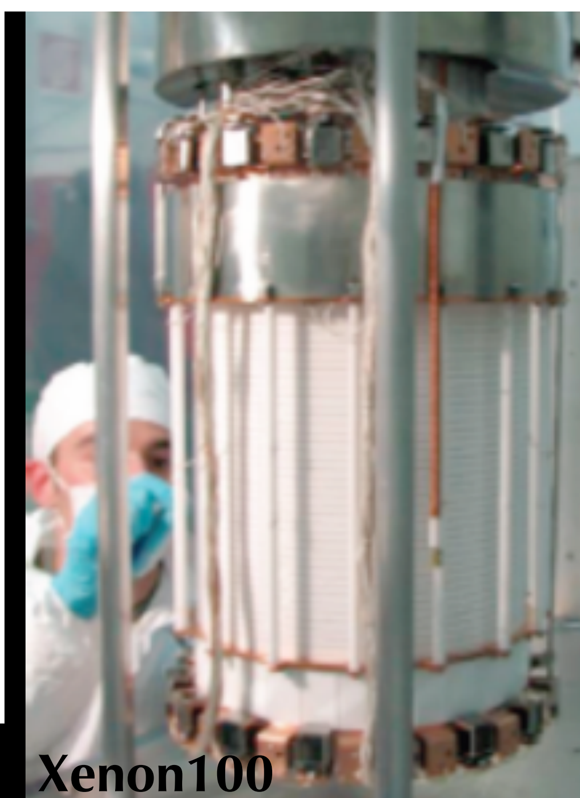
target volume viewed by PMT arrays:
“S1”: amplified, drifted
ionization signal
“S2”: primary scintillation

Xenon 10 kg, 100 kg, 1Tonne
LUX (250 kg), PANDA-X (120kg, 500 kg)



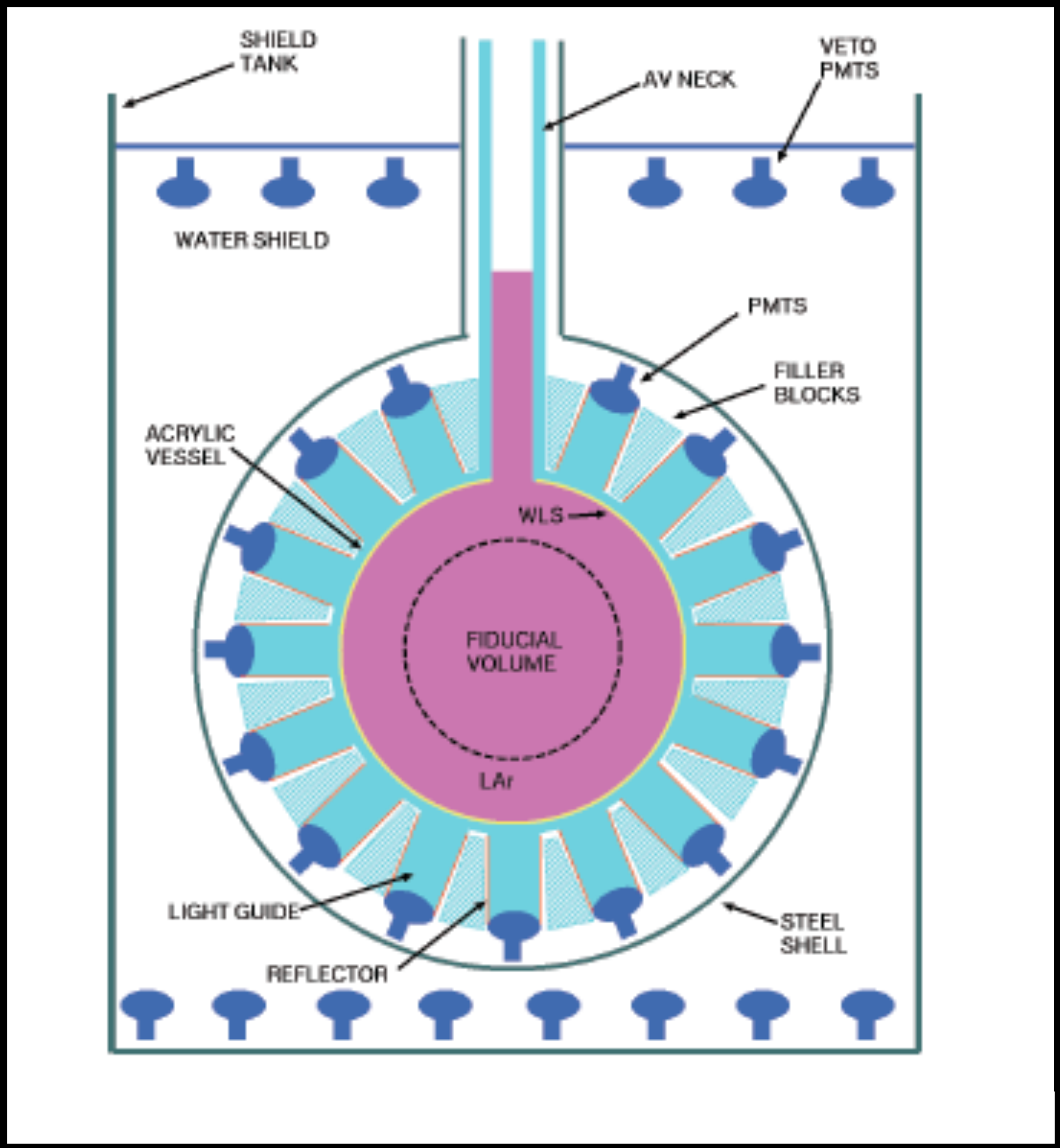


Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



Single Phase Liquid Nobles, a la Neutrinos

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



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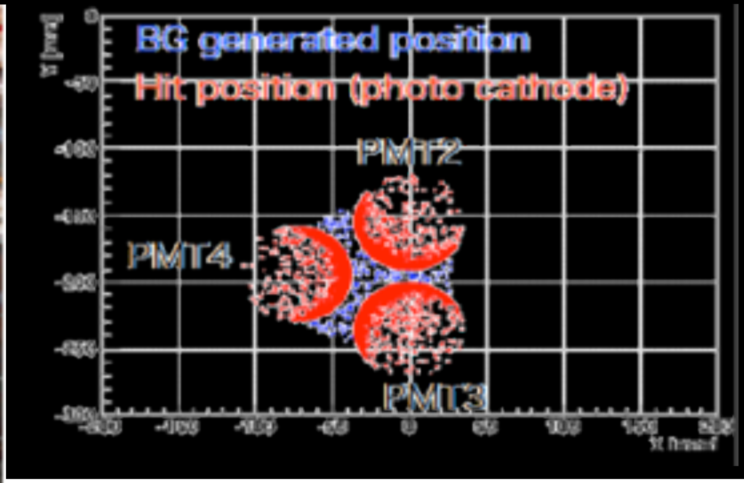
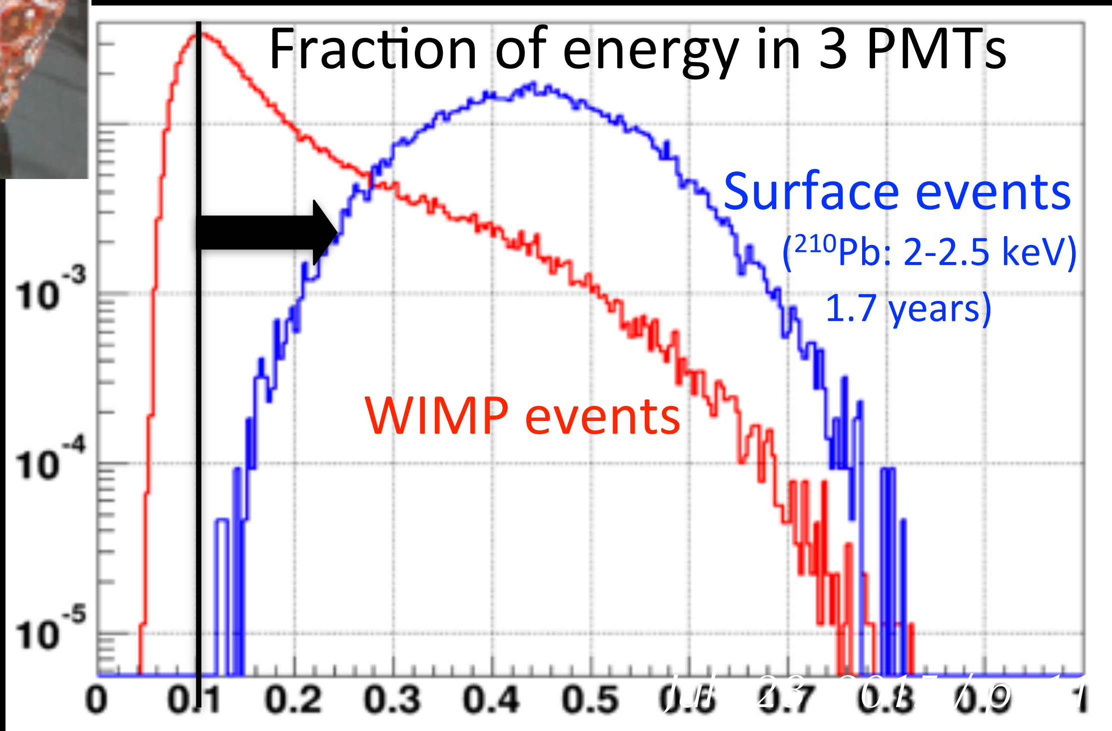
DEAP-3600: 3.6T LAr detector at SNOLAB, commissioning now, physics Fall 2015, project <0.6 background/3000 kg-days 1E-46 cm² sensitivity





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

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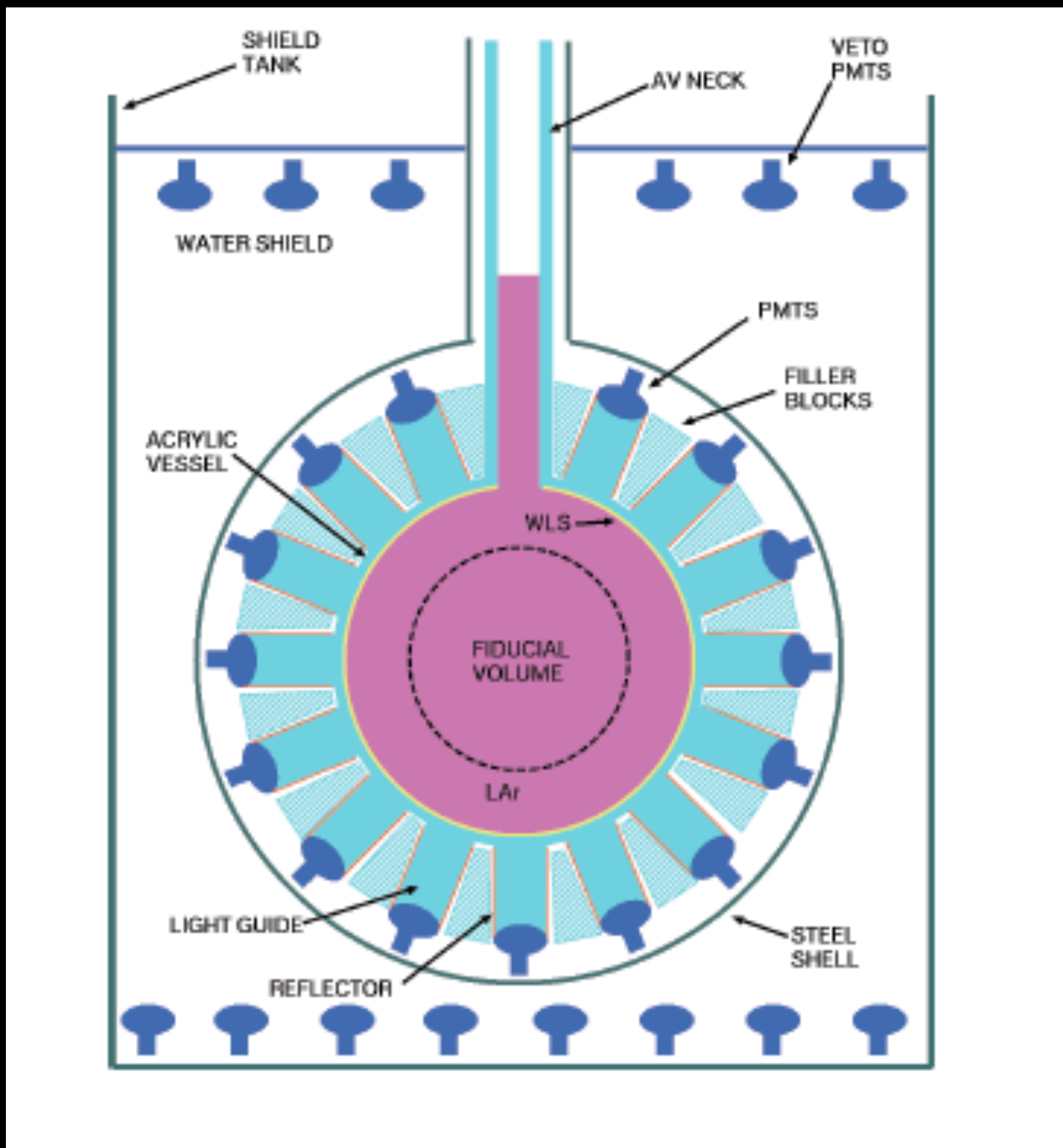

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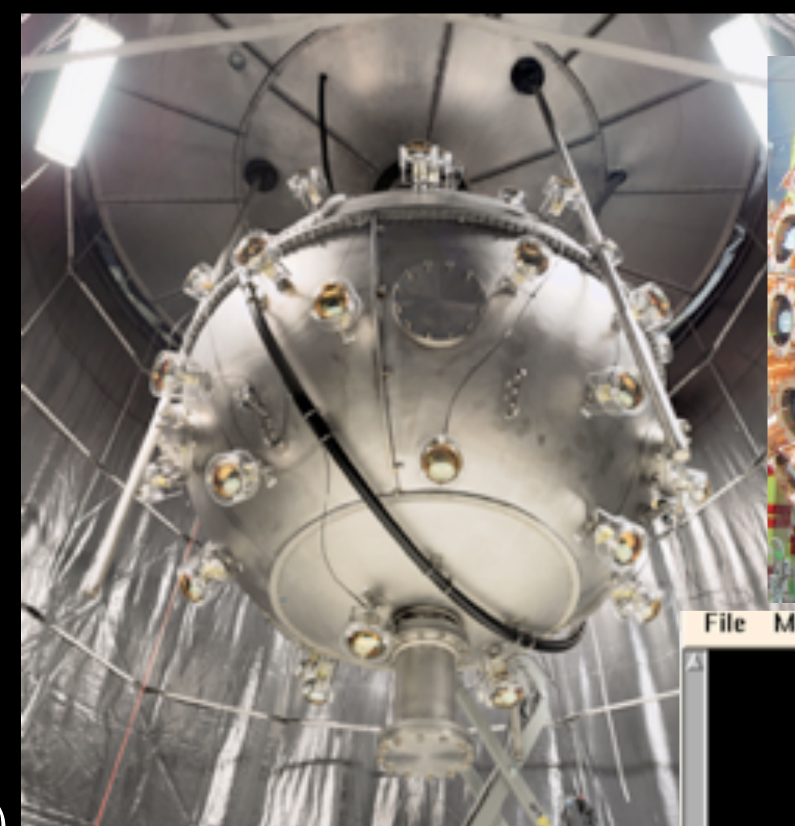

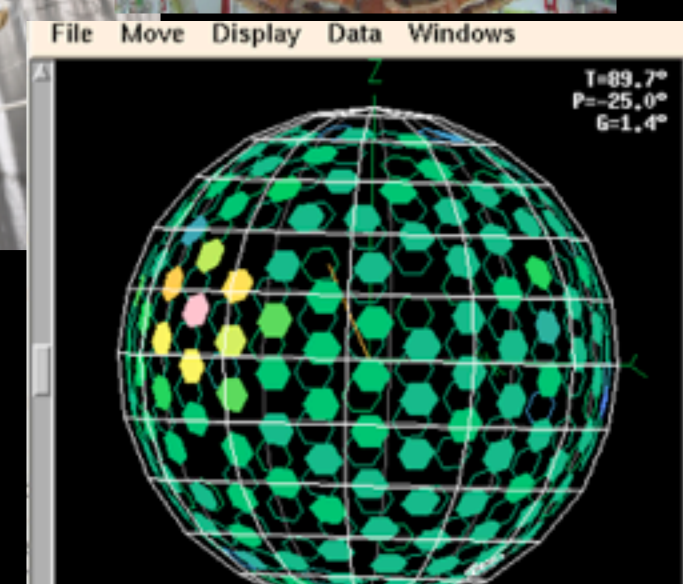

DEAP data, event display

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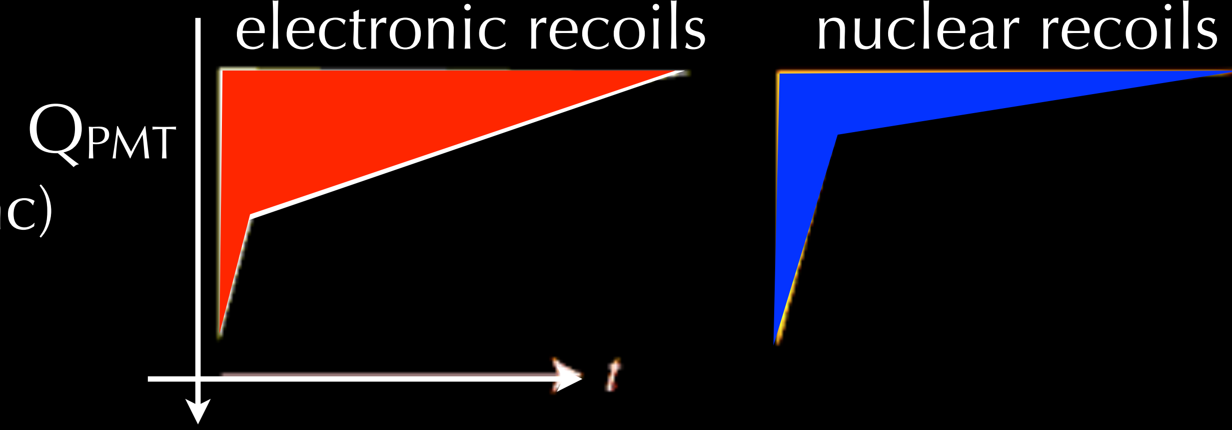
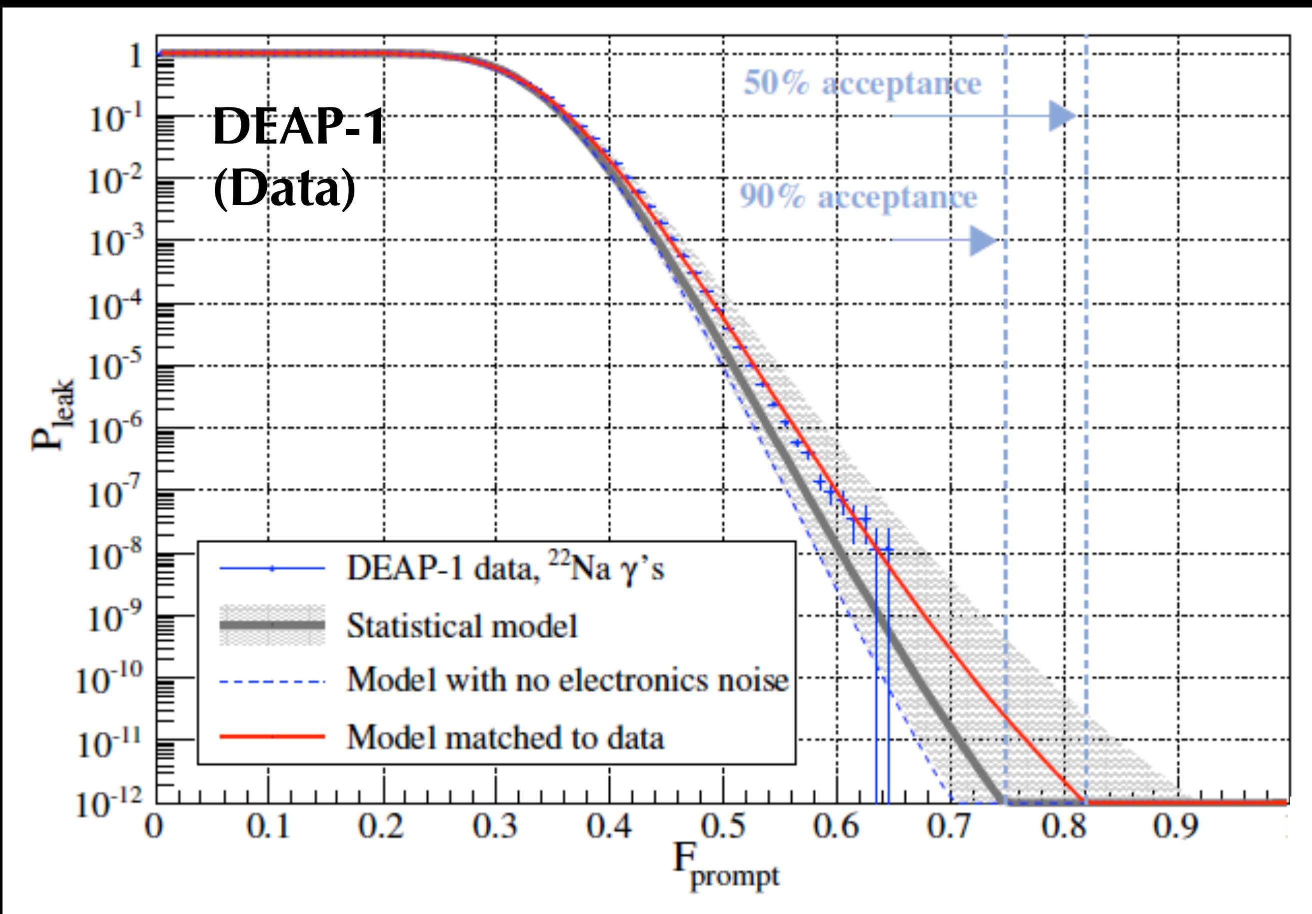
single phase: DEAP-3600 (SNOLAB)
two-phase: DarkSide-50 (LNGS), ArDM (Canfranc)

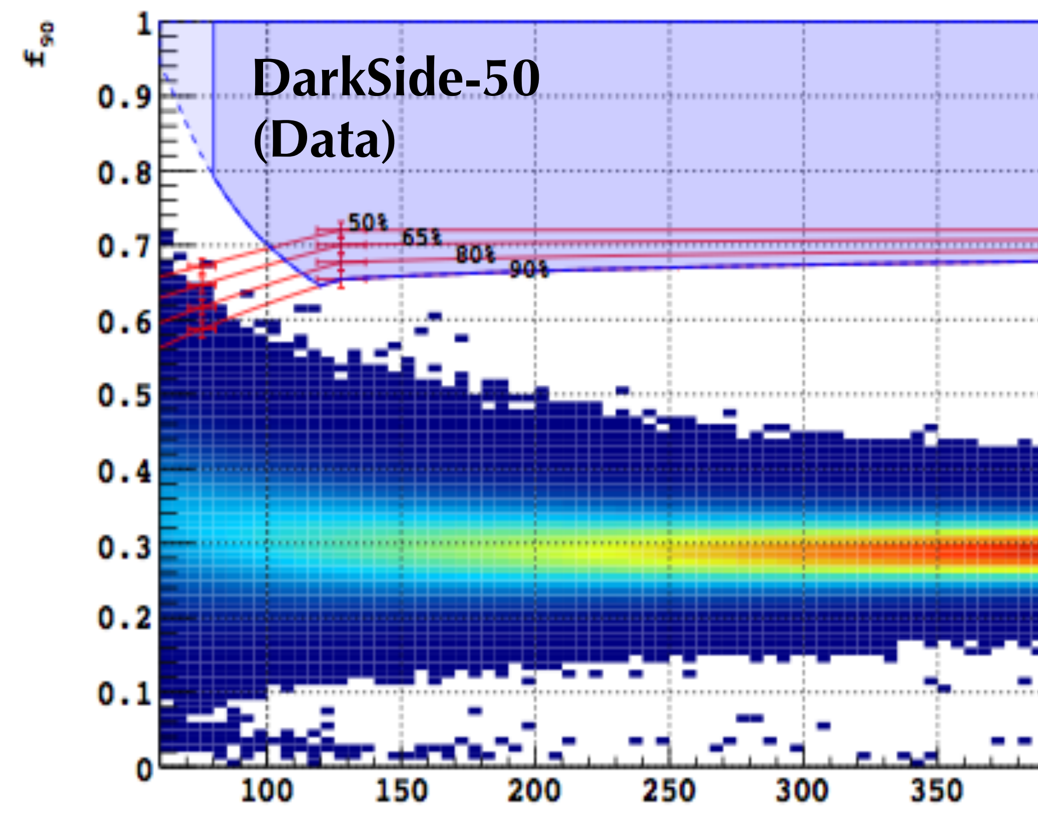


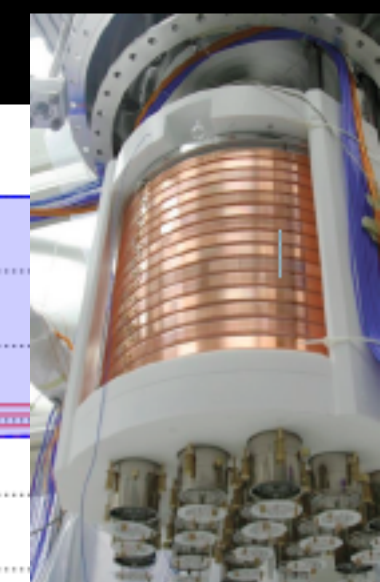
pulse shape discrimination (PSD):
x250 difference in scintillation time constants between electronic vs. nuclear recoils in Ar.

naturat Ar has Ar-39 beta-decay background of 1 Bq/kg, with 550 keV endpoint.

Discrimination measured to be 3E-8, predicted to exceed 1E-10. *(arXiv:0904.2930)*







DarkSide-50: published limit with natural Ar, now operating with 50 kg depleted Ar, measure depletion >300x *(C. Galbiati, LNGS-2020)*

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ARGO: Coordination of LAr detectors, ArDM will test depleted UAr samples with 100x sensitivity.

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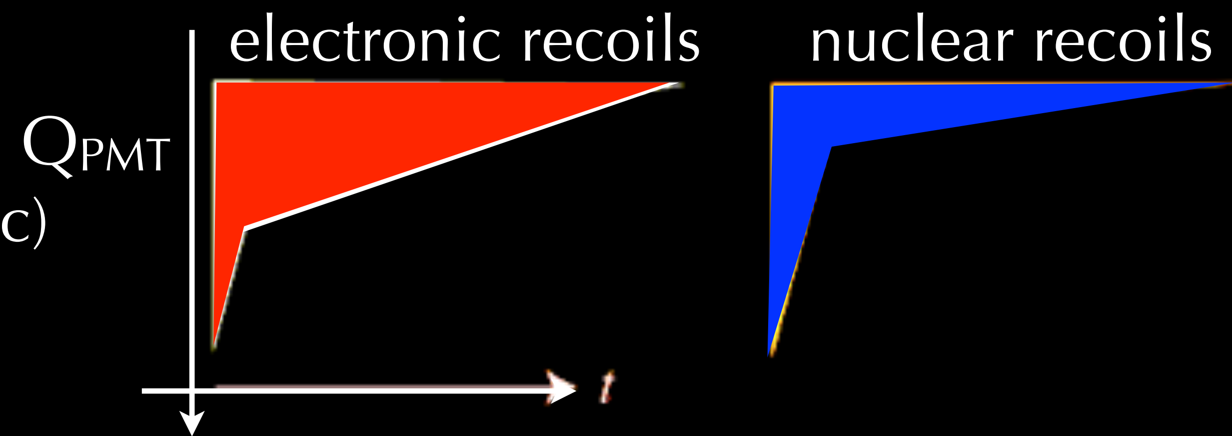

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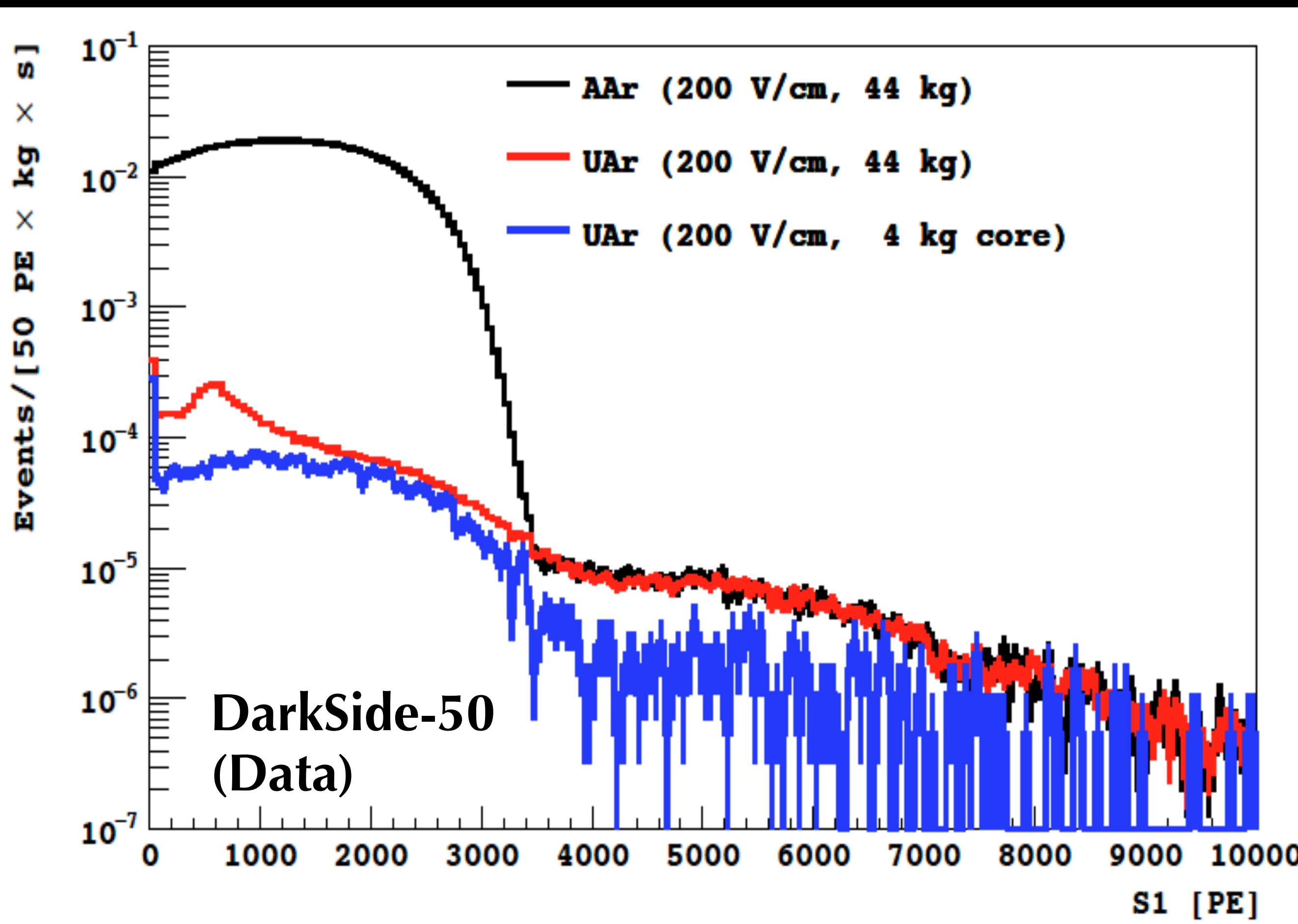

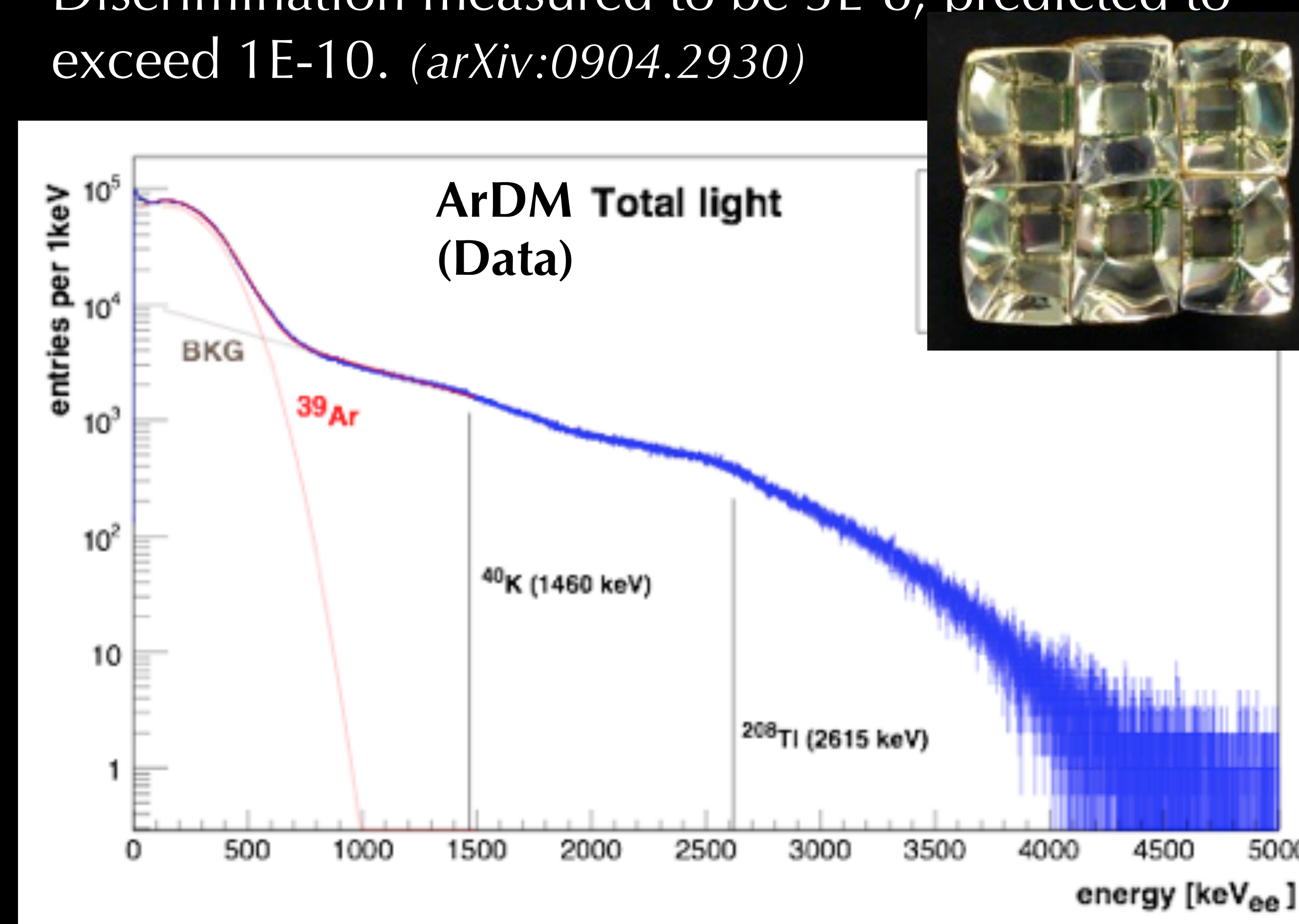

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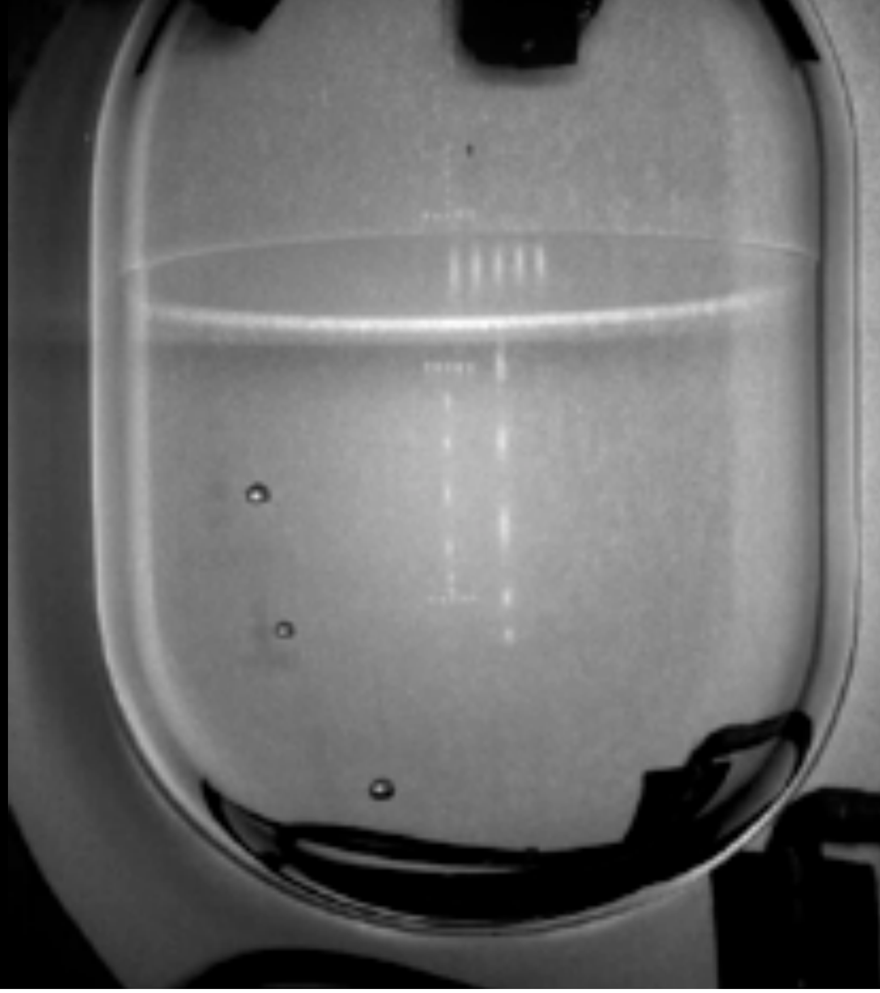
Bubble Chambers



superheated CF_3I target, with 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

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
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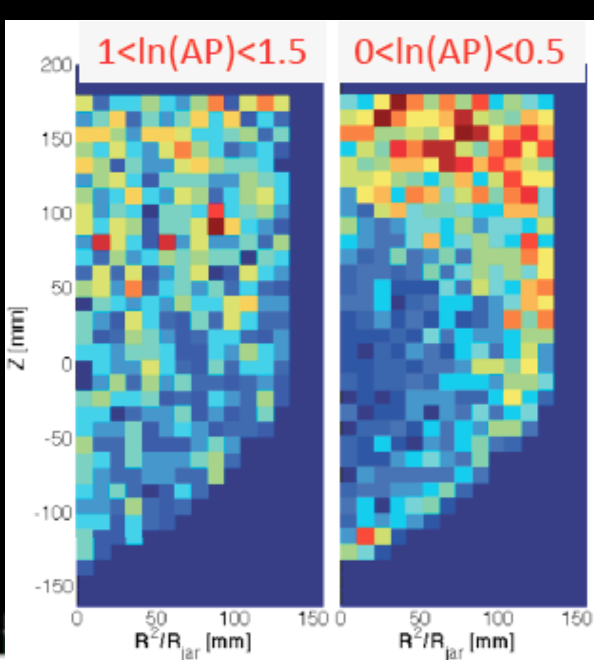
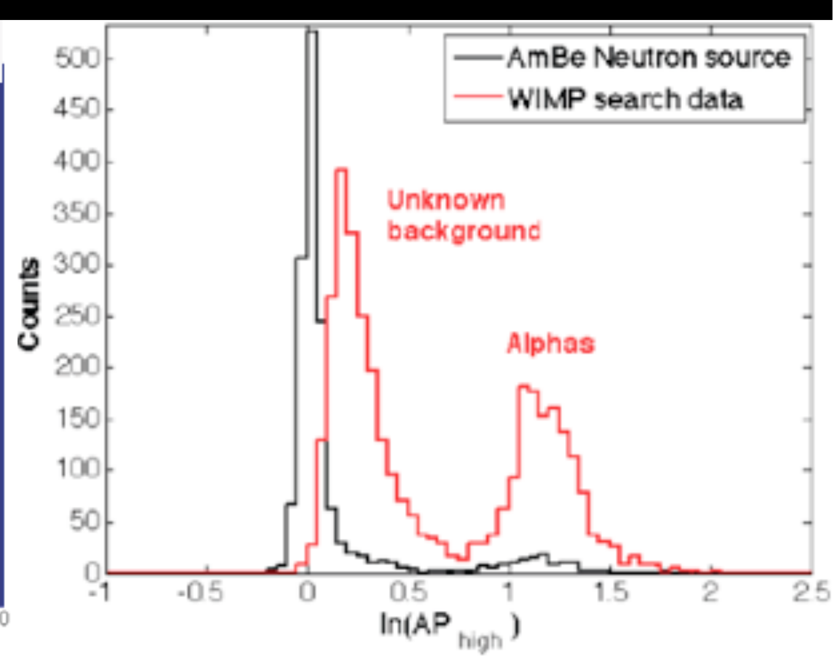
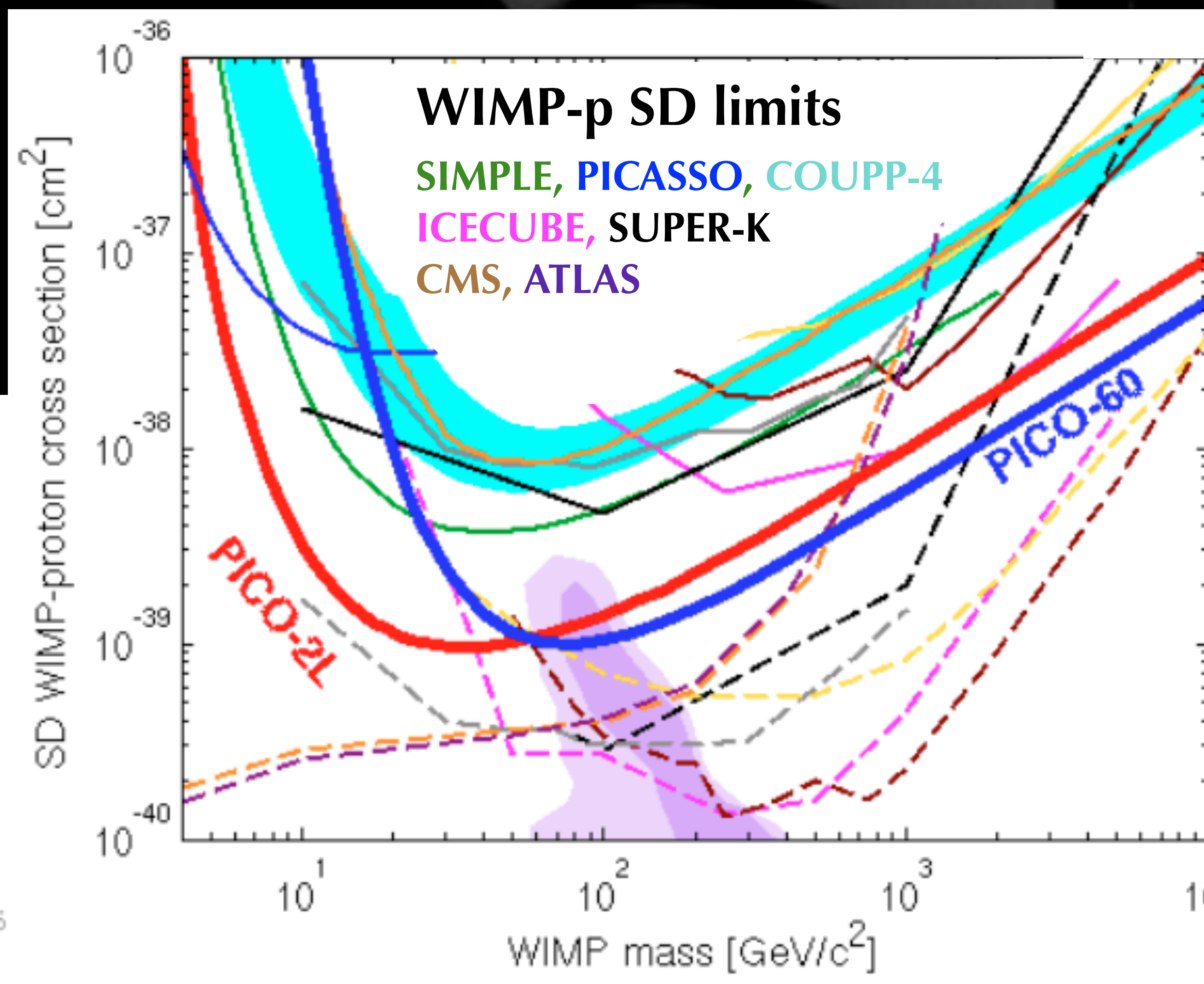
target upgrade of PICO-60 planned Fall 2015







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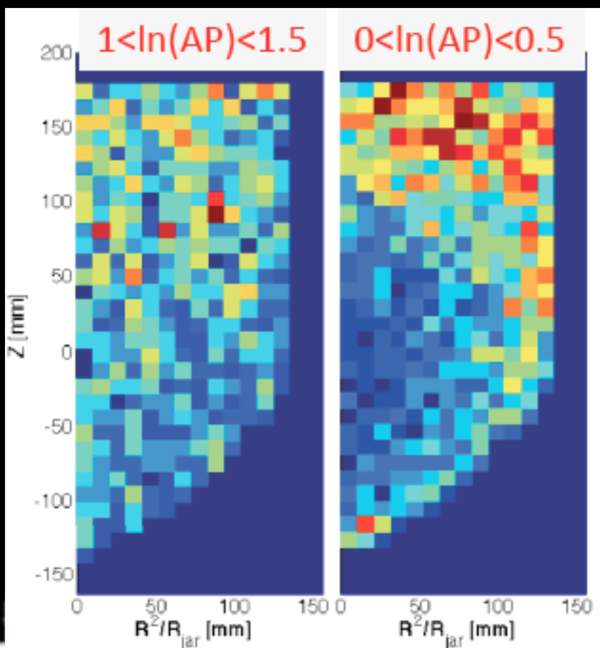

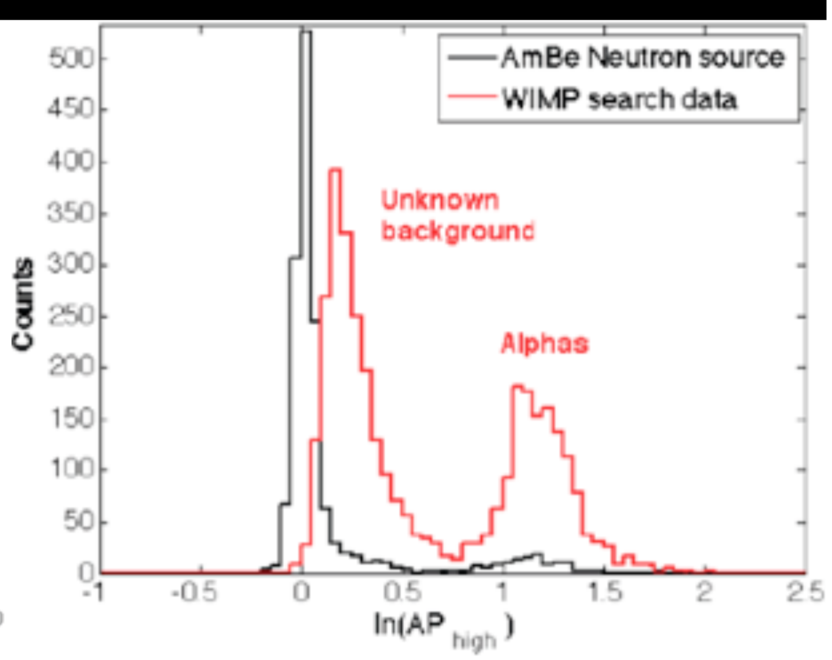

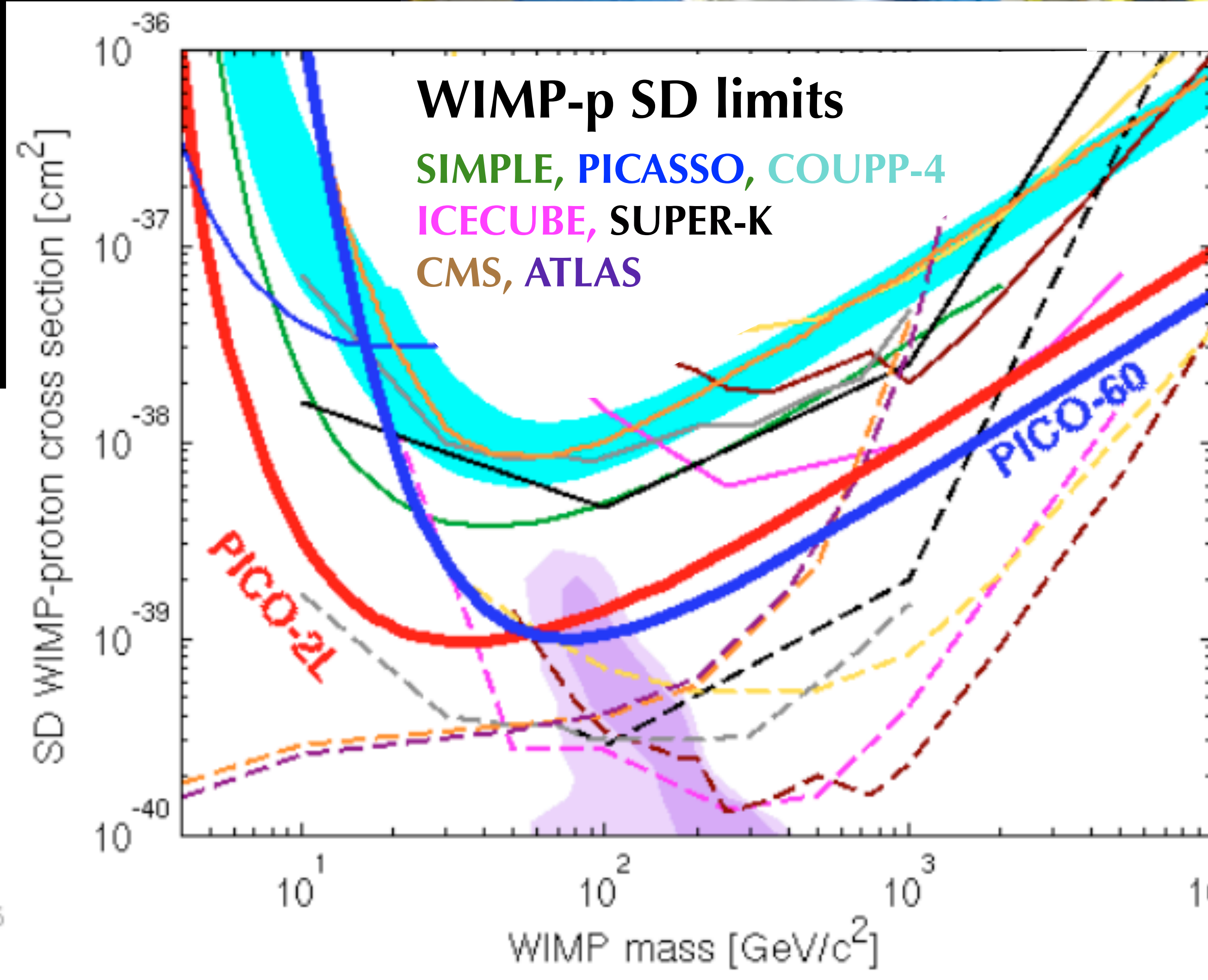

Two-Phase Xenon TPCs: Prospects

Goal: cover favored MSSM parameter space

XENON-100: annual modulation search with 153 live days close to unblinding, search for inelastic scattering on Xe-129, low energy calibrations underway for low-mass WIMP search, test facility for x10 Rn mitigation upgrade in Xenon-1T

LUX: calibrations to lower energy threshold, re-analysis of published data set results planned for late Summer 2015

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XENON-1T: 3300 kg LXe (1000 kg fiducial), construction at LNGS. Detector services completed, TPC installation Fall 2015. Sensitivity reach 1E-47 cm^2 after 2 Tonne-years.

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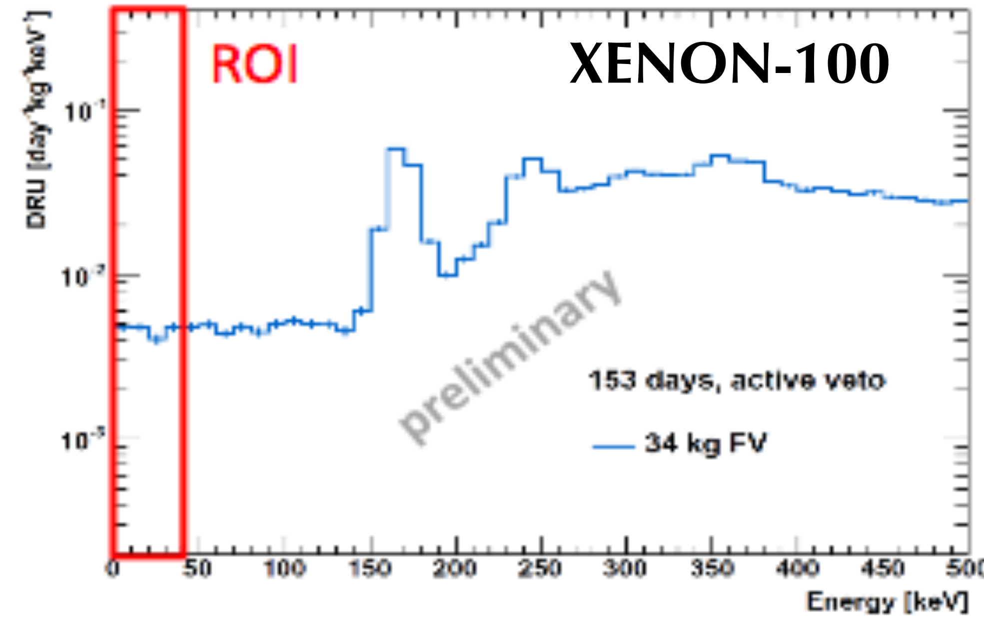

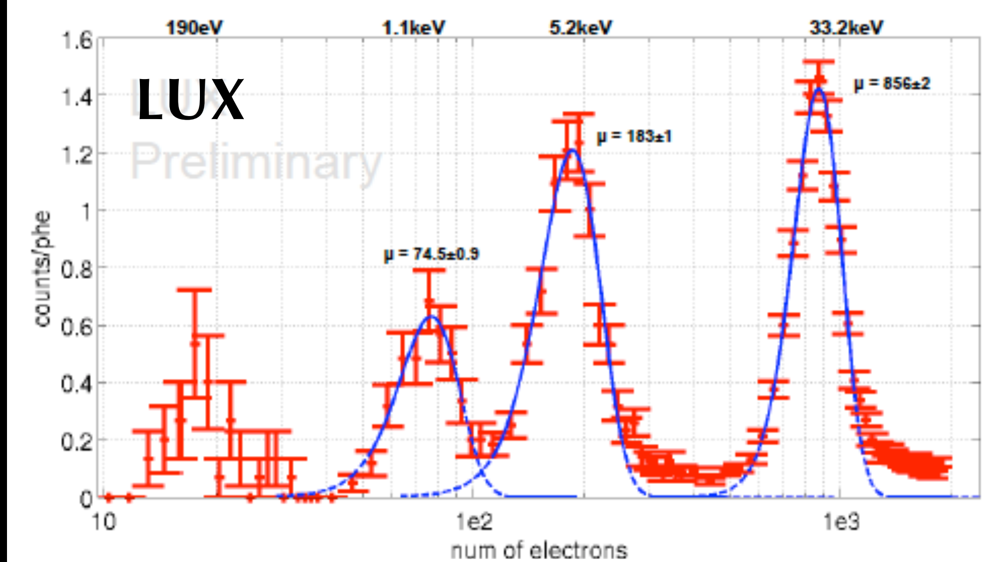

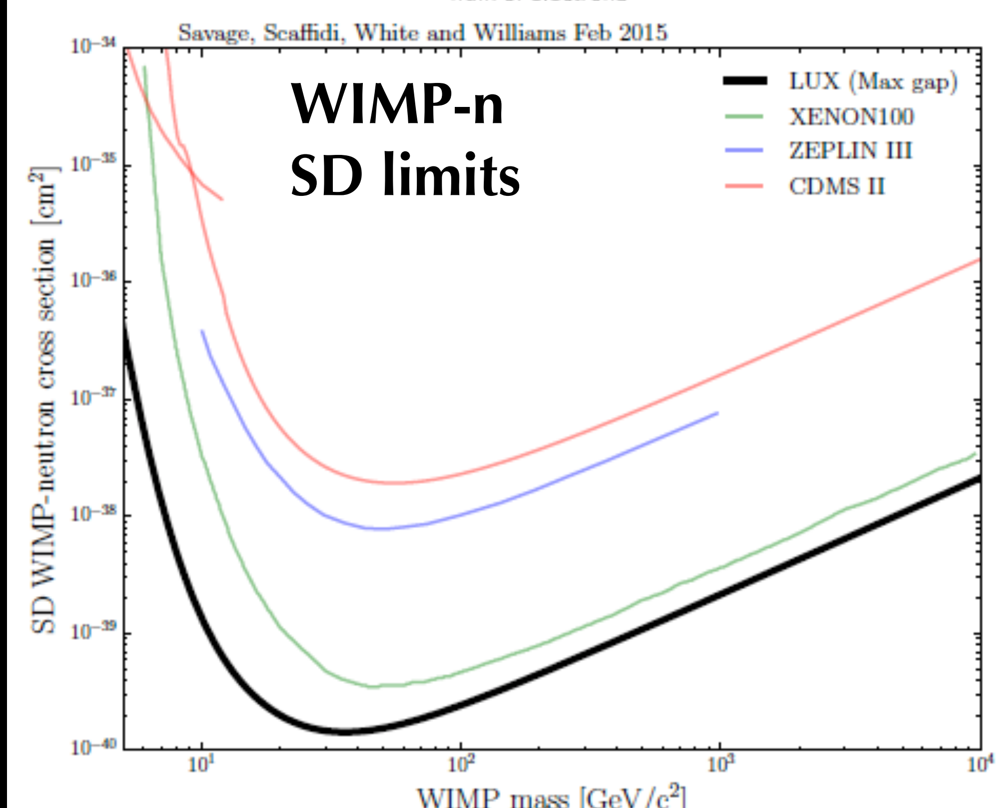

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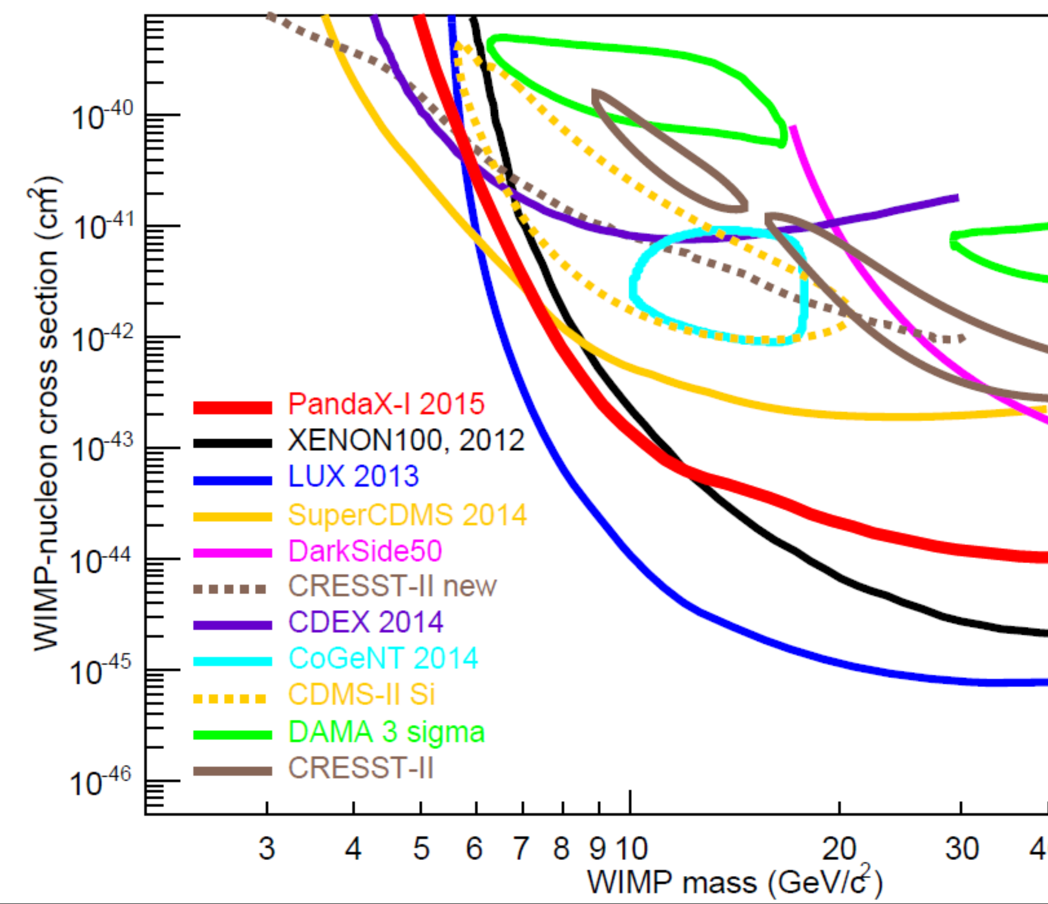

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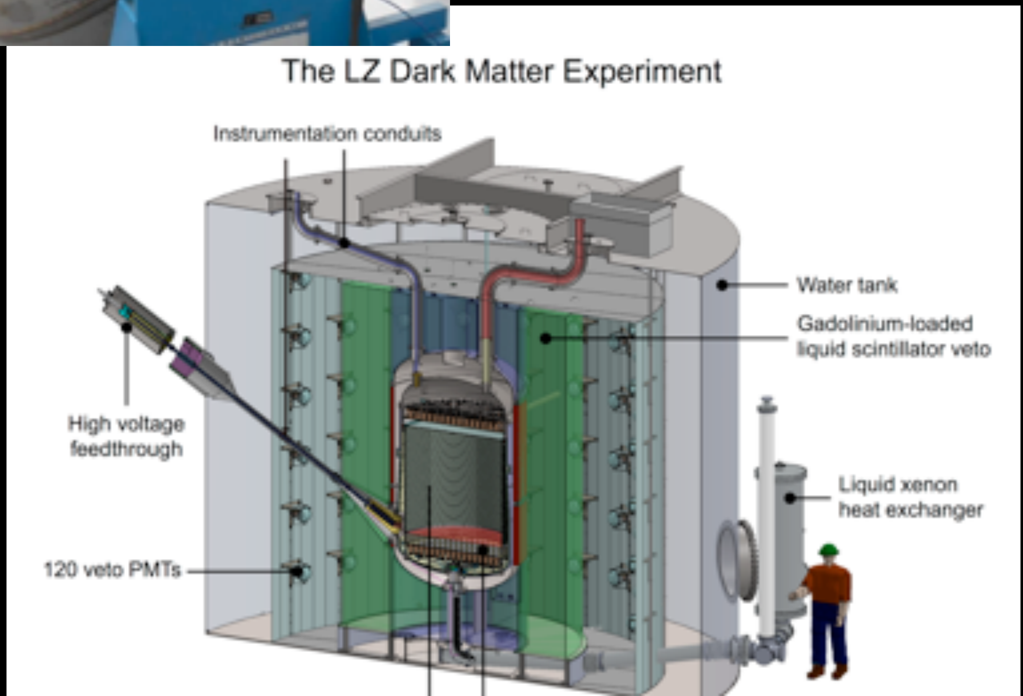

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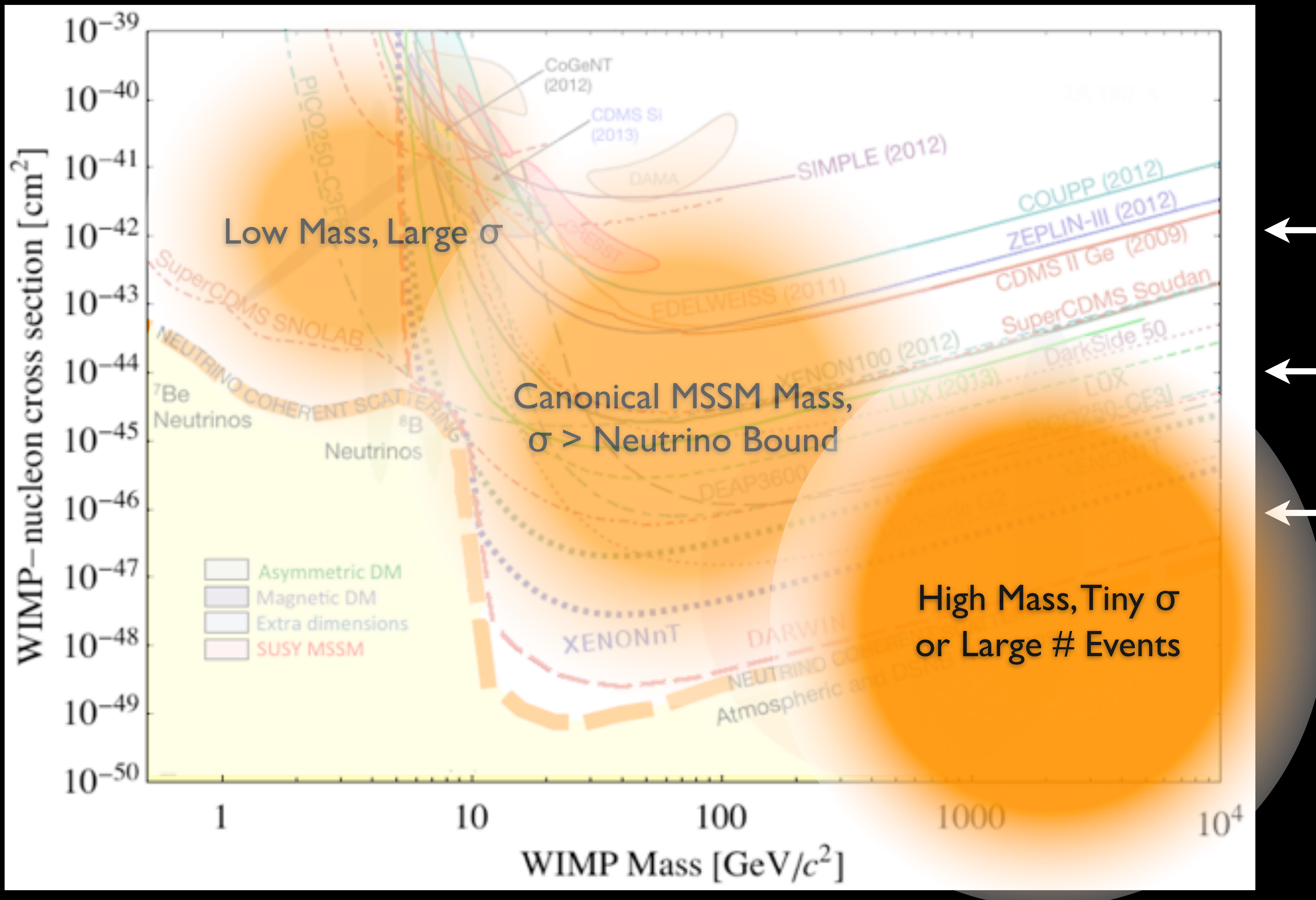

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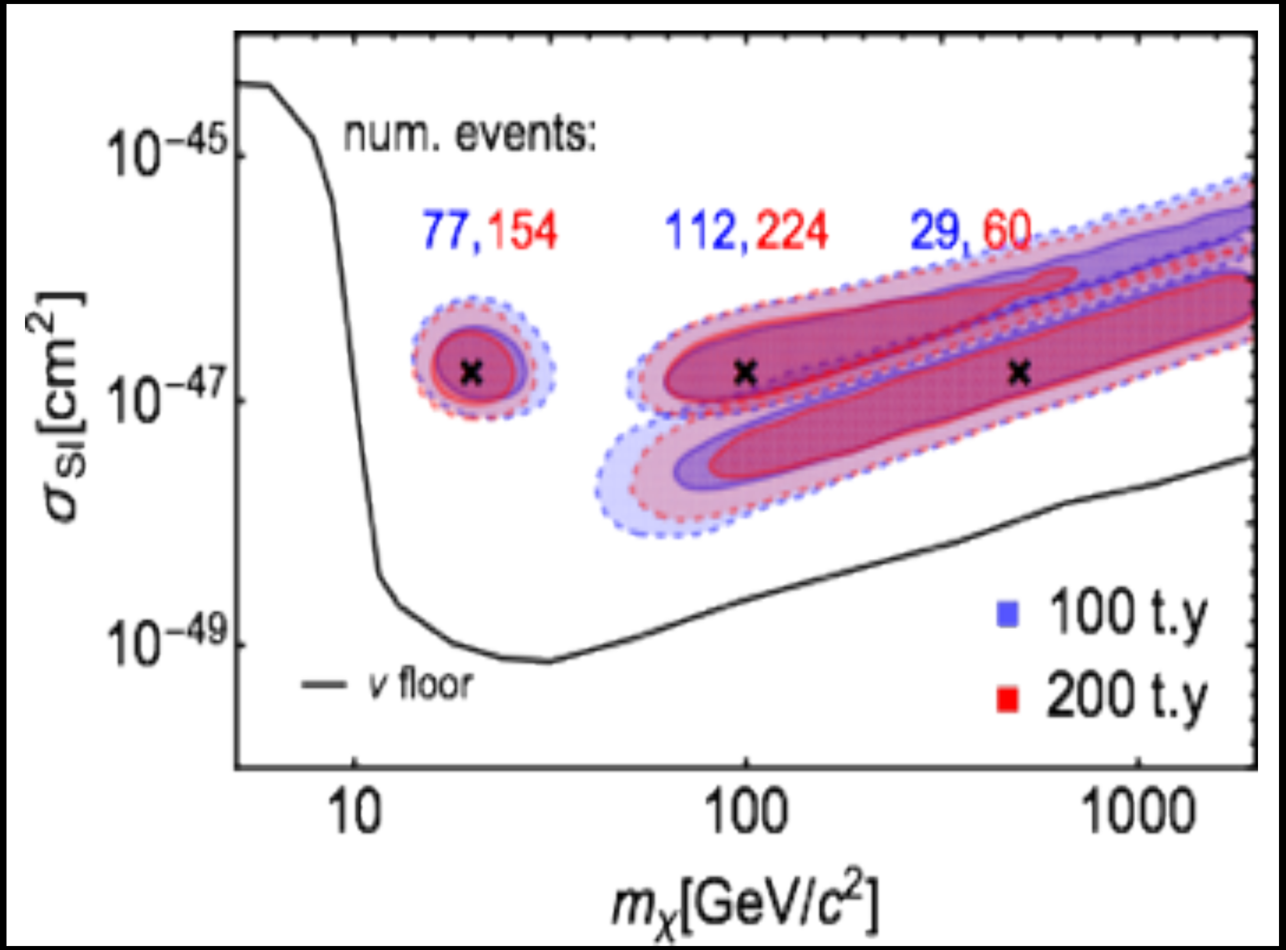
so far: ~3 years / order of magnitude

Beyond the Neutrino Bound

Goal: WIMP spectroscopy!



DARWIN: design study for 50-80T two-phase LXe detector. Size: >2m length, >2m diameter, few k photosensors. Background dominated by neutrinos. *arXiv:1506.08309*

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DEAP-50: design for 150T single-phase LAr detector. Size: 7m diameter x tall. Background tolerances easier than DEAP-3.6. Need depleted LAr for >50T. *(M. Kuzniak, PASCOS)*

Beyond the Neutrino Bound

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Experiment	σ(1 TeV)	σ(10 TeV)
LUX	1.1×10^{-44}	1.2×10^{-43}
XENON	1.9×10^{-44}	1.9×10^{-43}
DS-50	2.3×10^{-43}	2.1×10^{-42}
ArDM	8×10^{-45}	7×10^{-44}
DEAP-3600	5×10^{-46}	5×10^{-45}
XENON-1ton [2]	3×10^{-46}	3×10^{-45}
LZ [1]	5×10^{-47}	5×10^{-46}
DS-20k	9×10^{-48}	9×10^{-47}
1 Neutrino	2×10^{-48}	2×10^{-47}
ARGO	9×10^{-49}	9×10^{-48}

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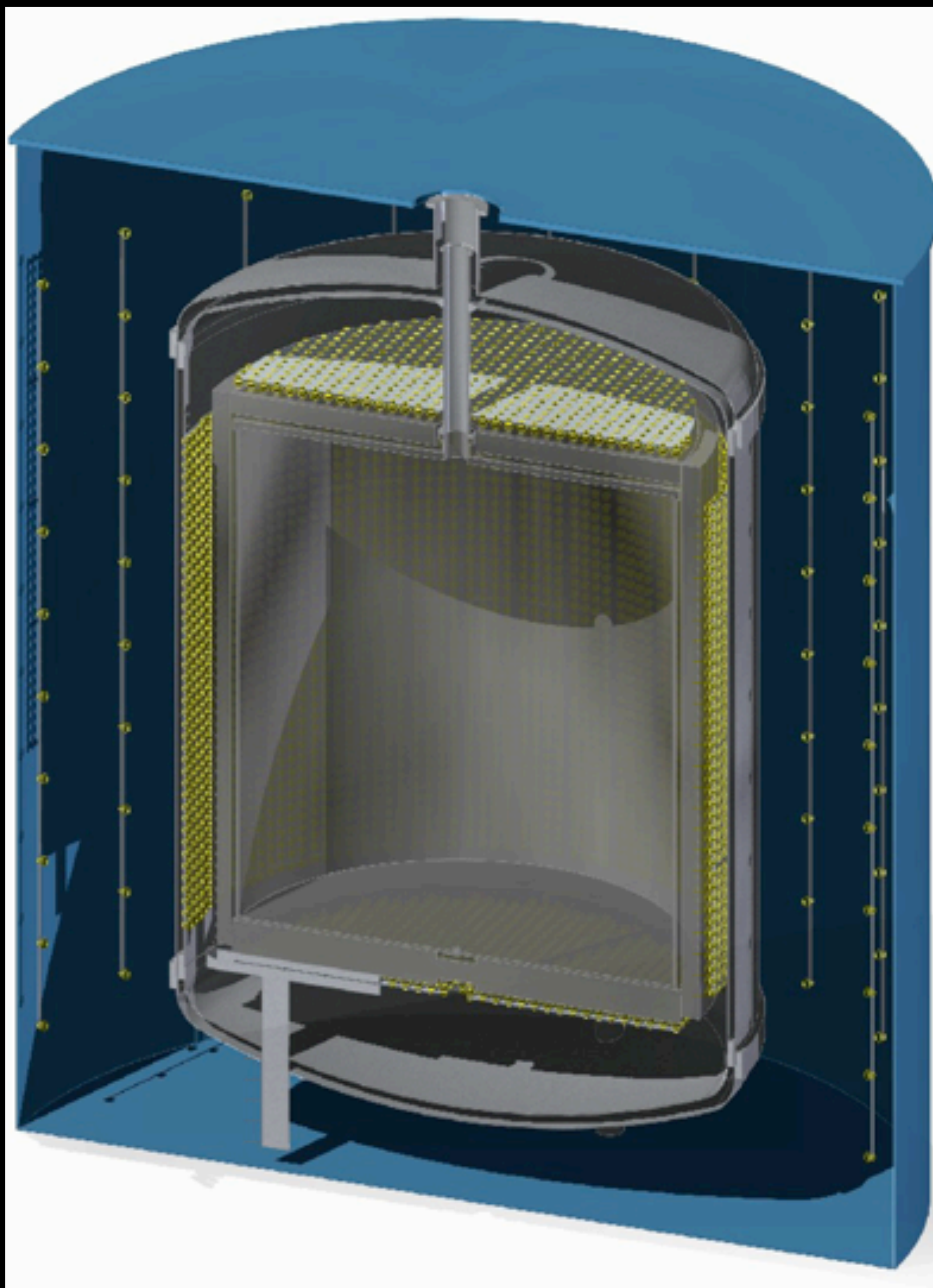

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ArDM	8×10^{-45}	7×10^{-44}
DEAP-3600	5×10^{-46}	5×10^{-45}
XENON-1ton [2]	3×10^{-46}	3×10^{-45}
LZ [1]	5×10^{-47}	5×10^{-46}
DS-20k	9×10^{-48}	9×10^{-47}
1 Neutrino	2×10^{-48}	2×10^{-47}
ARGO	9×10^{-49}	9×10^{-48}

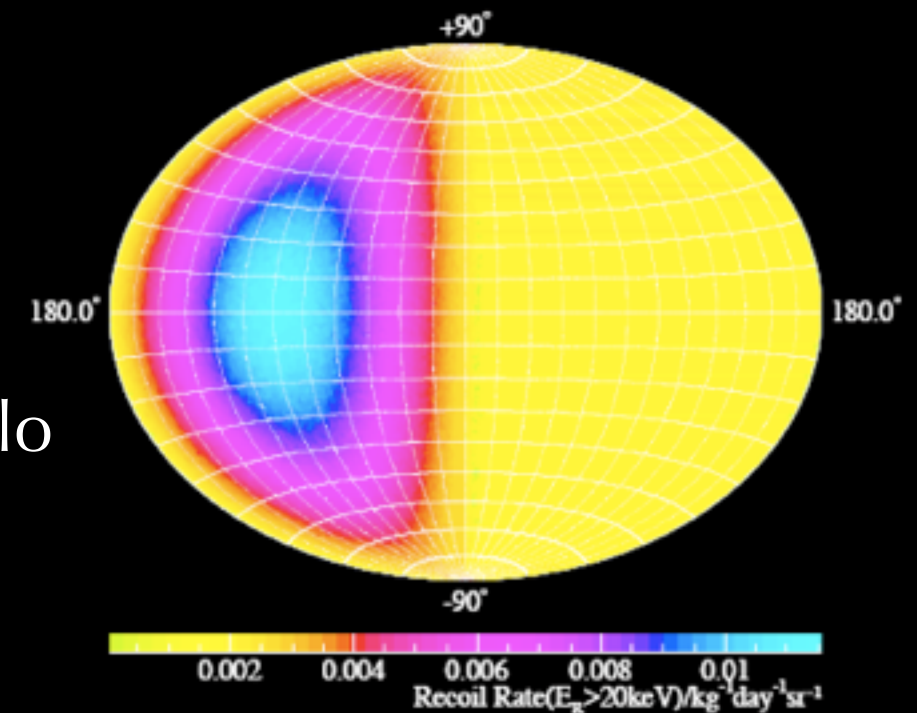
DARWIN: design study for 50-80T two-phase LXe detector. Size: >2m length, >2m diameter, few k photosensors. Background dominated by neutrinos. *arXiv:1506.08309*

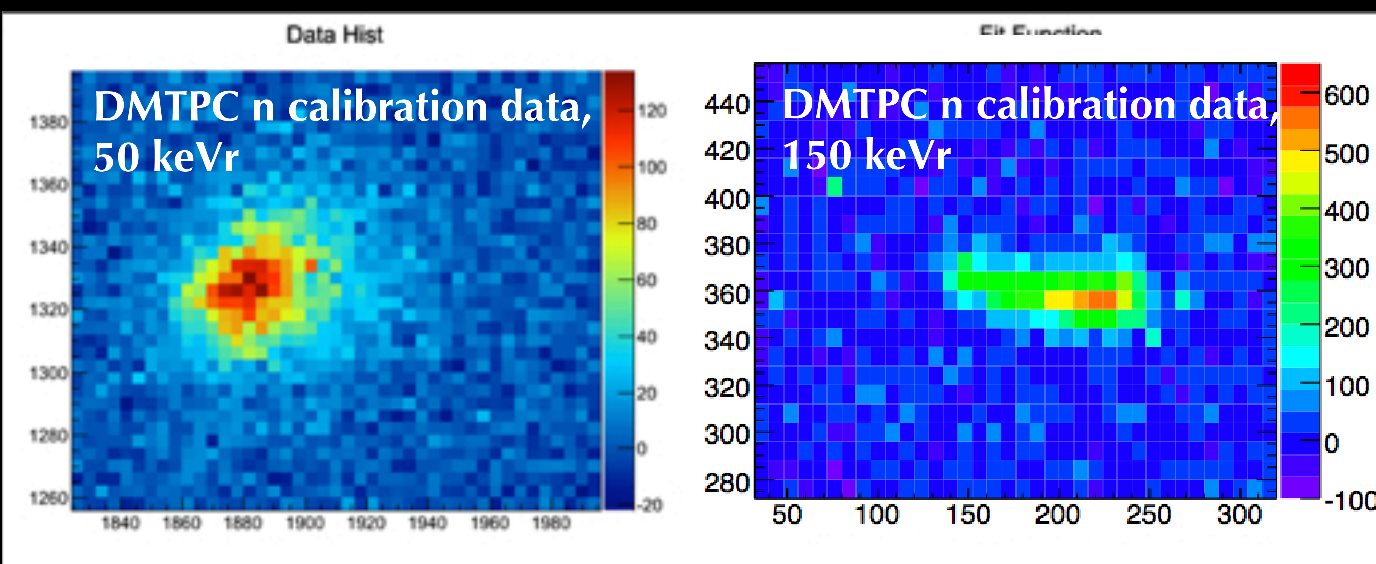
ARGO: LOI for 300T depleted LAr detector at LNGS. Prototype 20T stage (DarkSide-20k). Emphasis on high-mass sensitivity. *(C. Galbiati, LNGS 2020)*

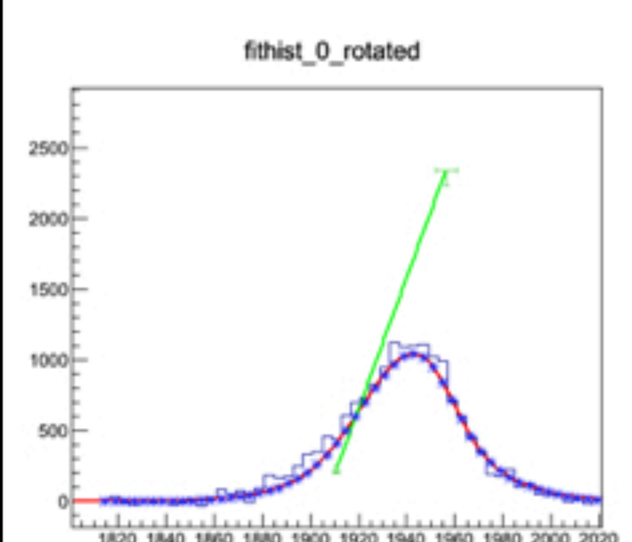
DEAP-50: design for 150T single-phase LAr detector. Size: 7m diameter x tall. Background tolerances easier than DEAP-3.6. Need depleted LAr for >50T. *(M. Kuzniak, PASCOS)*

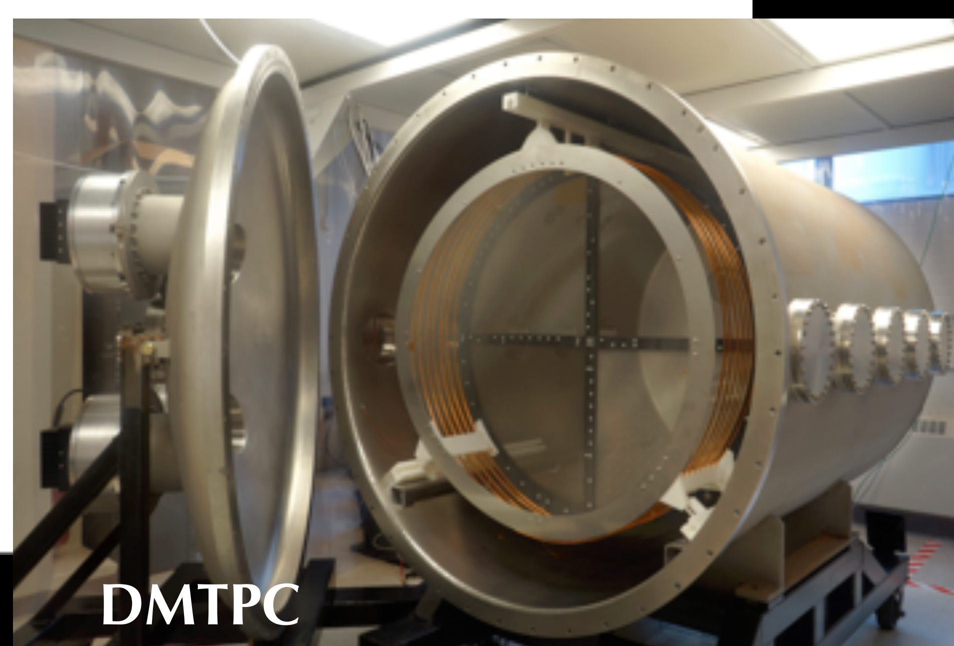
Directional Detection

R&D towards ~30º resolution, low background, scalable detector to positively identify a candidate dark matter recoil signal as coming from the galactic dark matter halo









DMTPC: optical (CCD) and charge readout of CF_4 target; measure 40º resolution, commissioning 1m^3 module.

DRIFT: MWPC readout, operating 1m^3 detector in Boulby since 2001. Negative ion drift of CS_2+CF_4.

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

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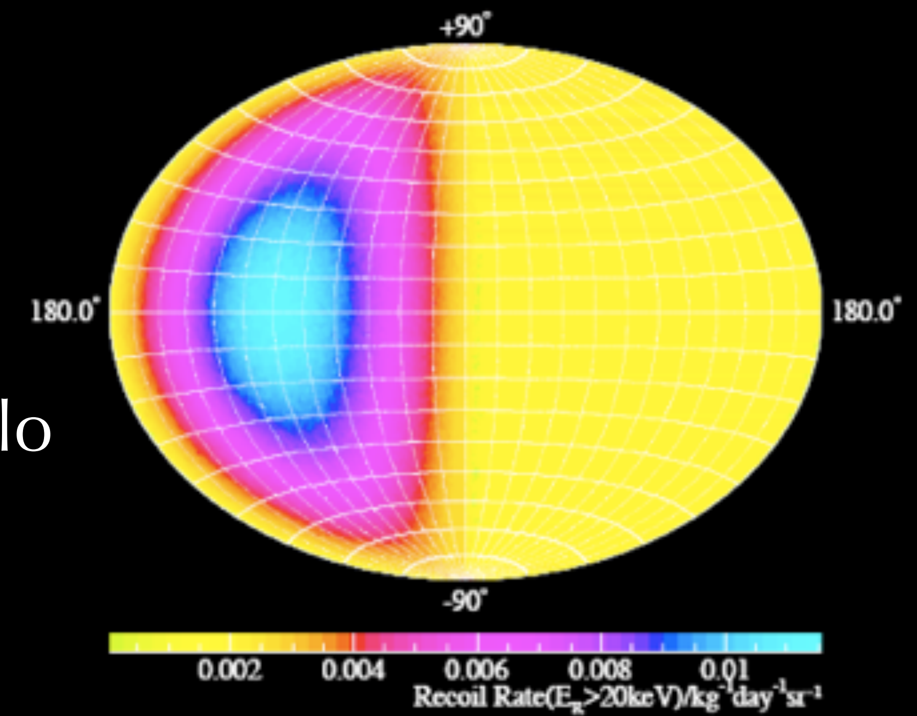

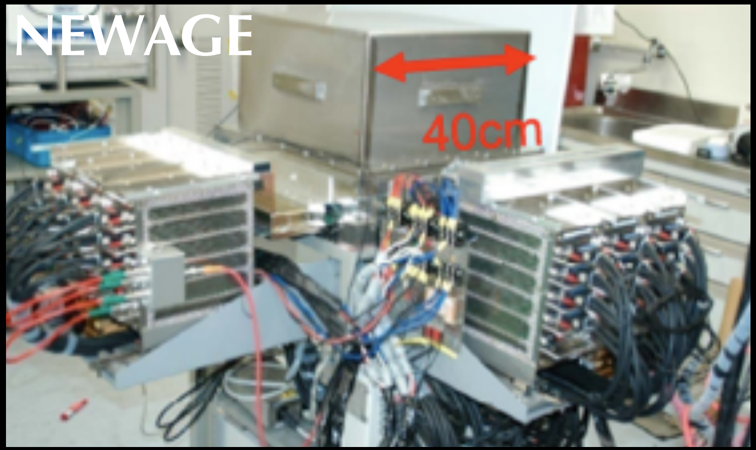

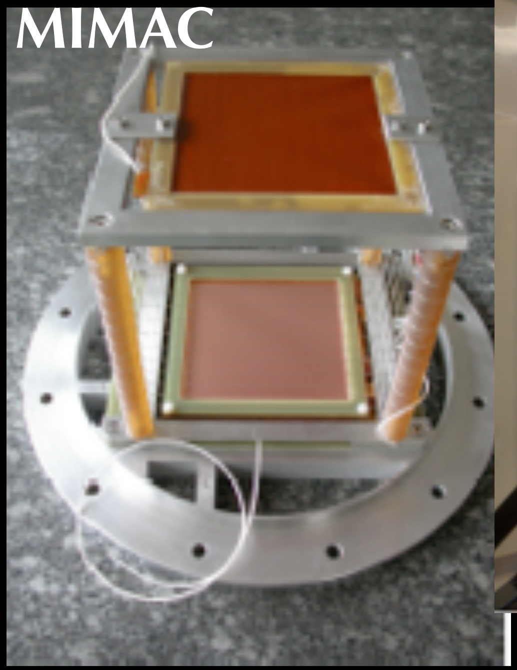

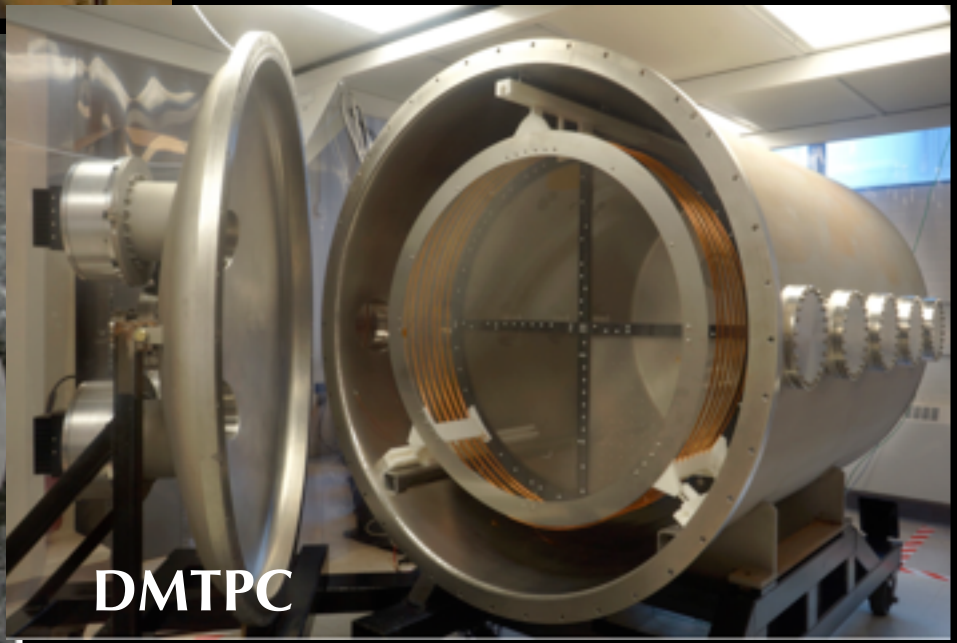

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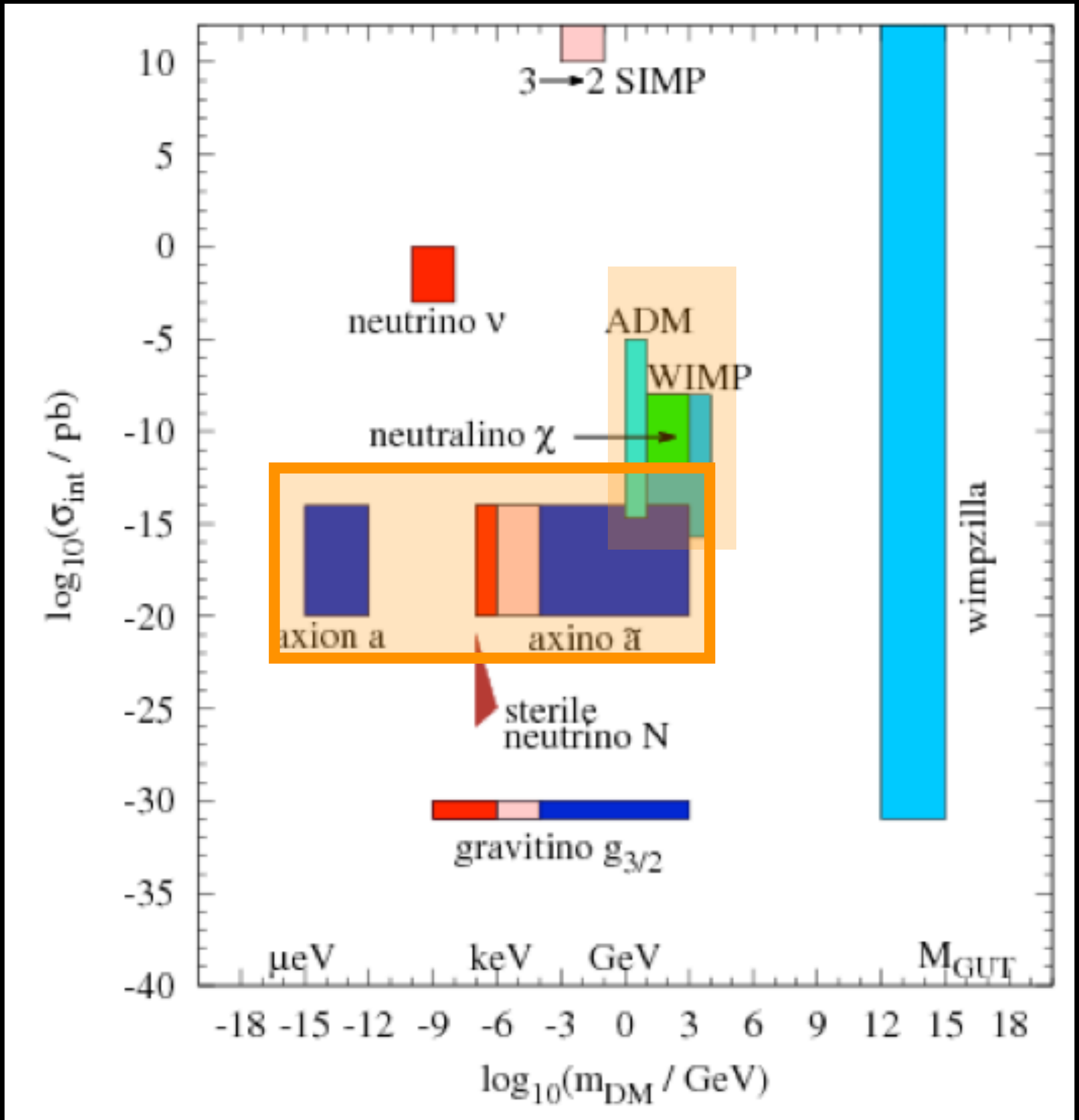
plus R&D on fine-grained emulsions, pixel chips, high P gas, biological detectors, C nanotubes, ++

Model Space

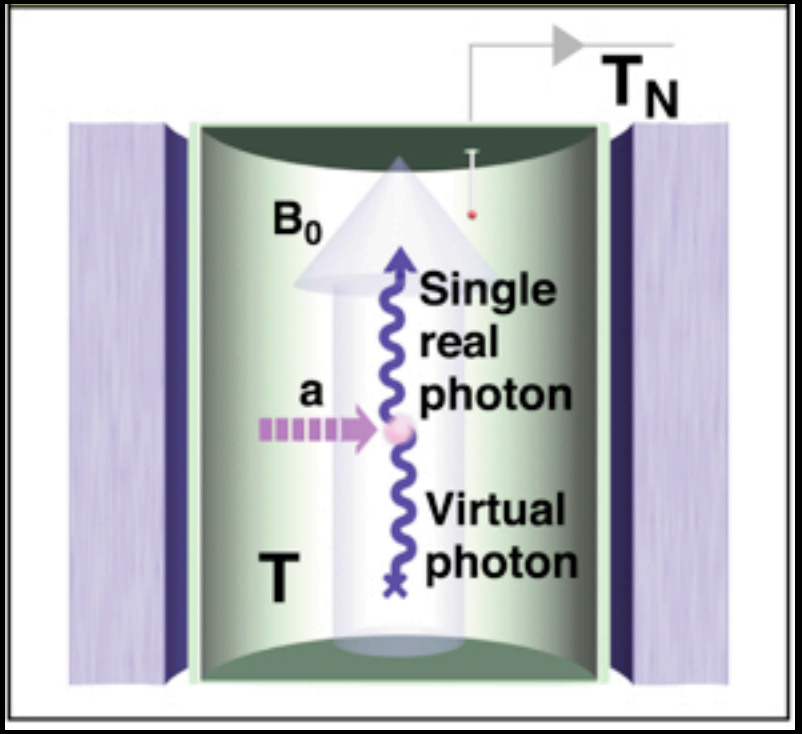
WIMPs aren't the only possibility!



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.

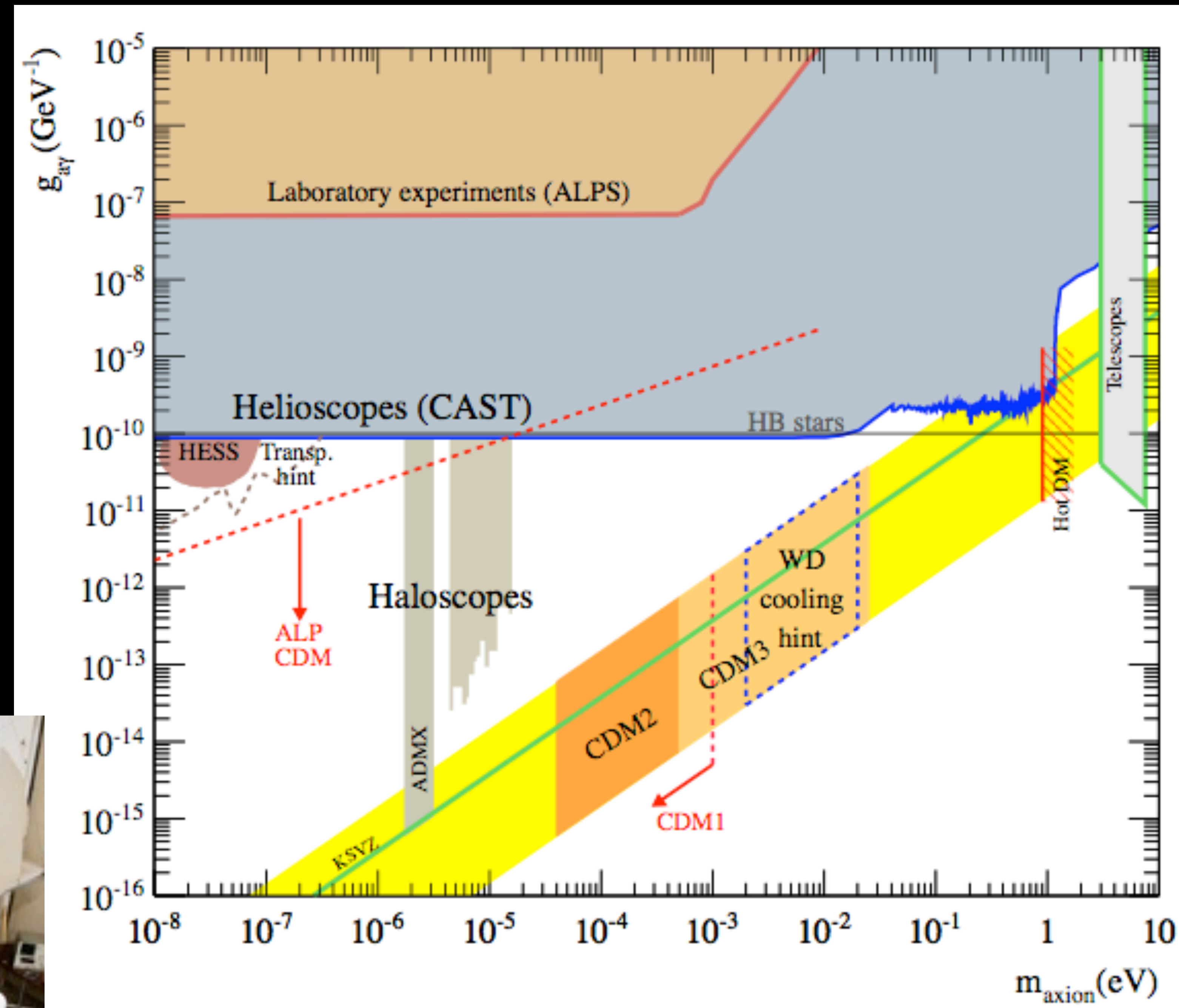
Axions: Status and Prospects

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!

IAXO: coordination of axion experiments, proposal for axion helioscope at CERN, dedicated magnet design. *(SPSC 1-242)*



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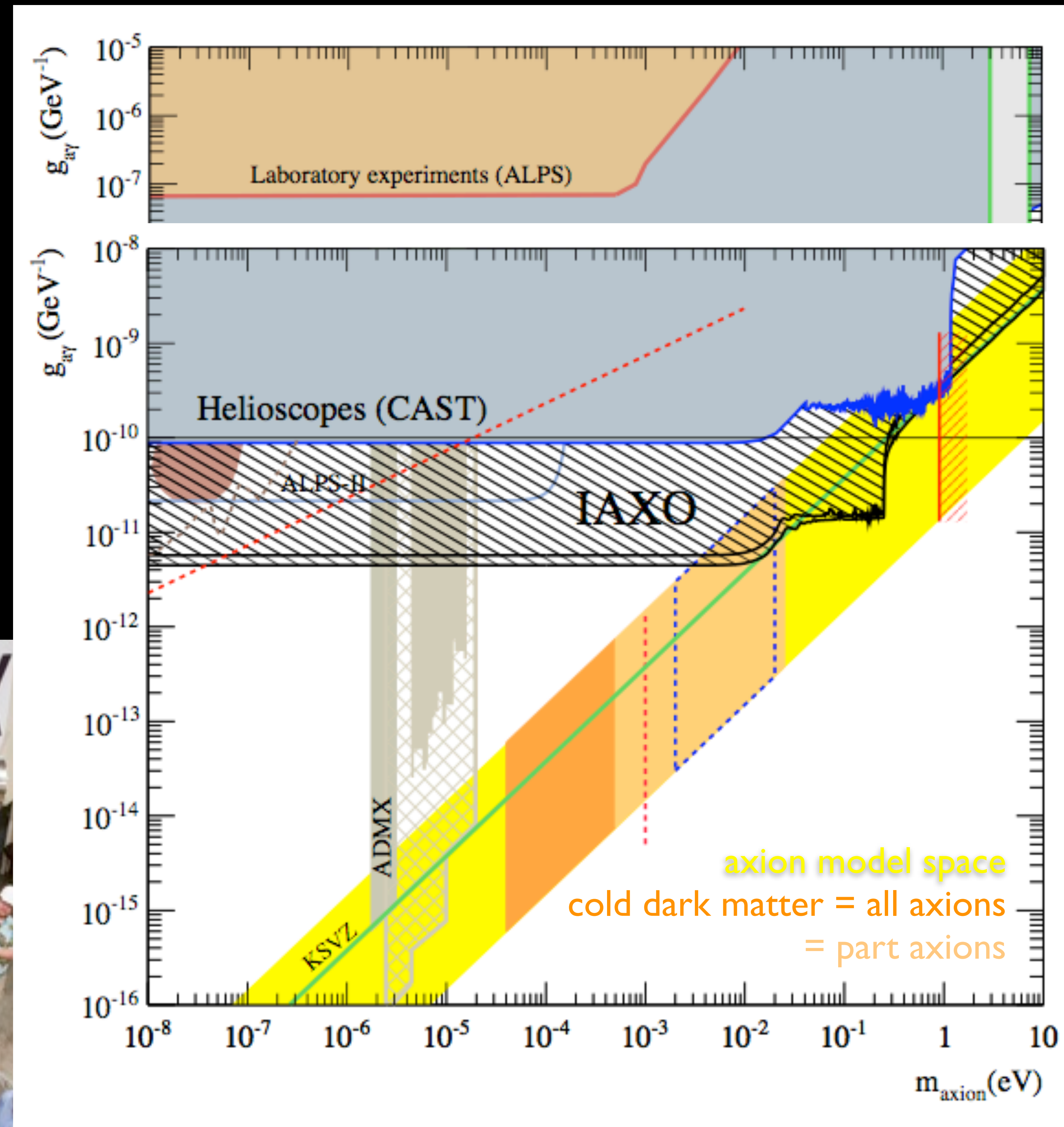

Axion/ALPs in Direct Detection

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)*

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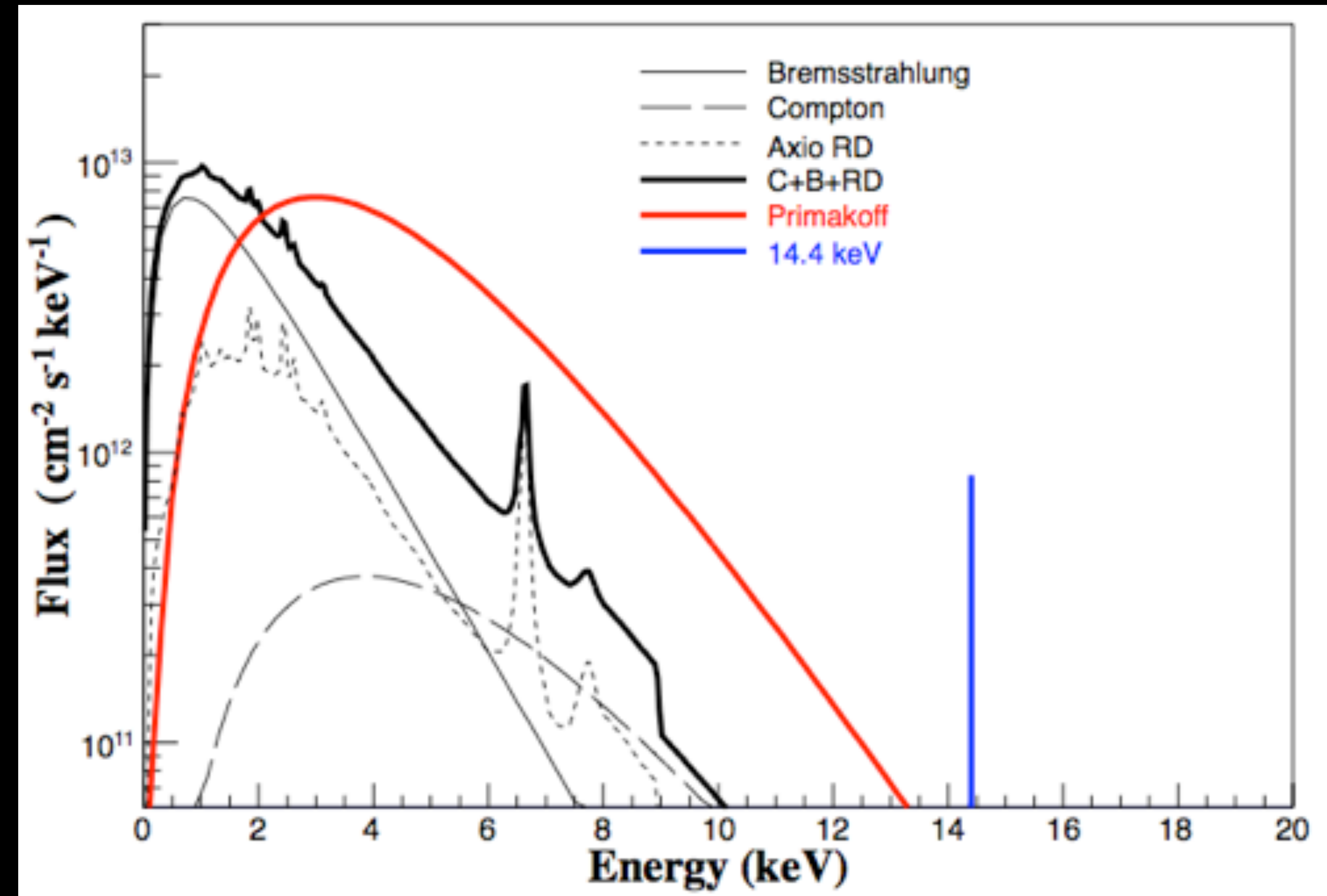

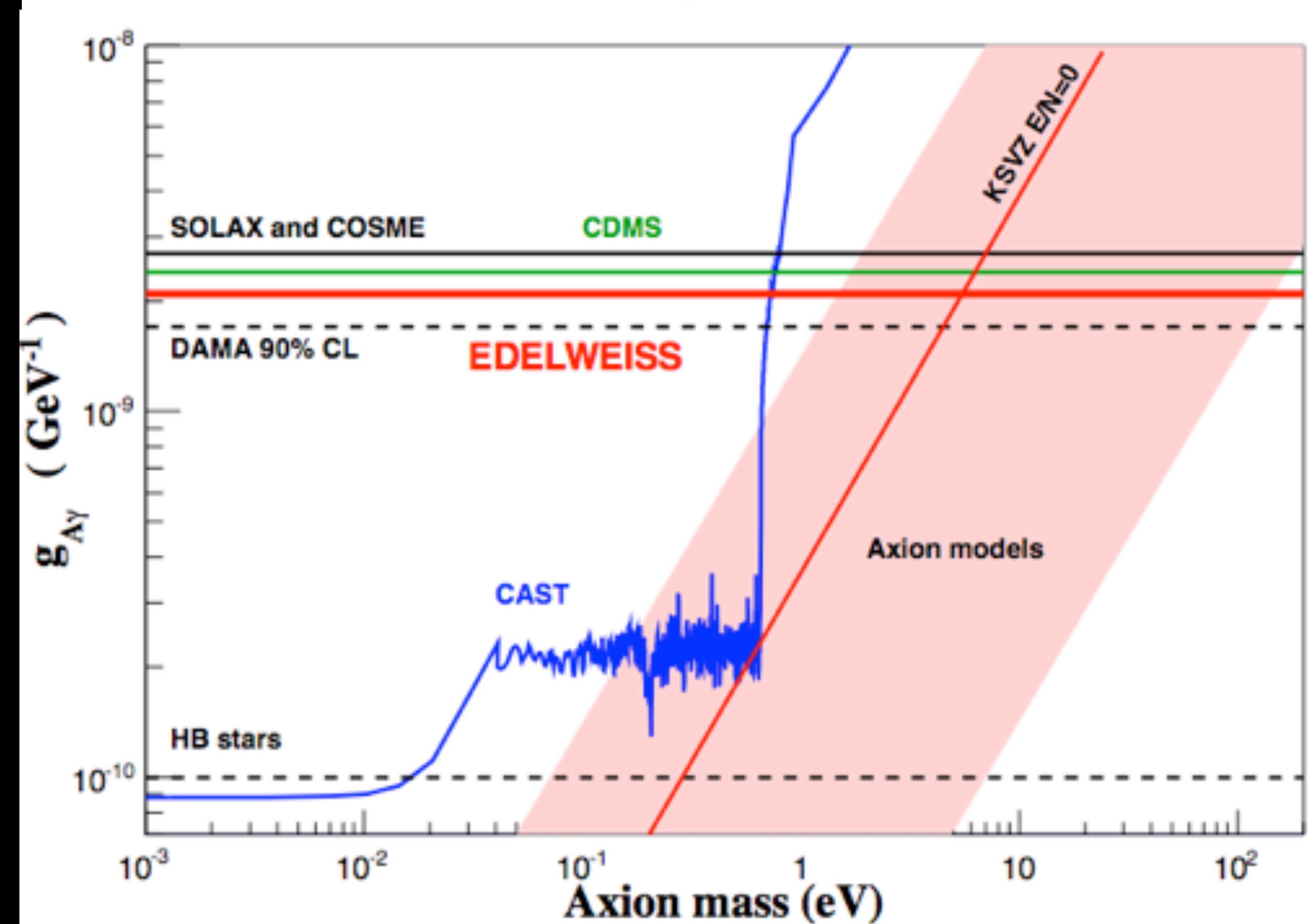

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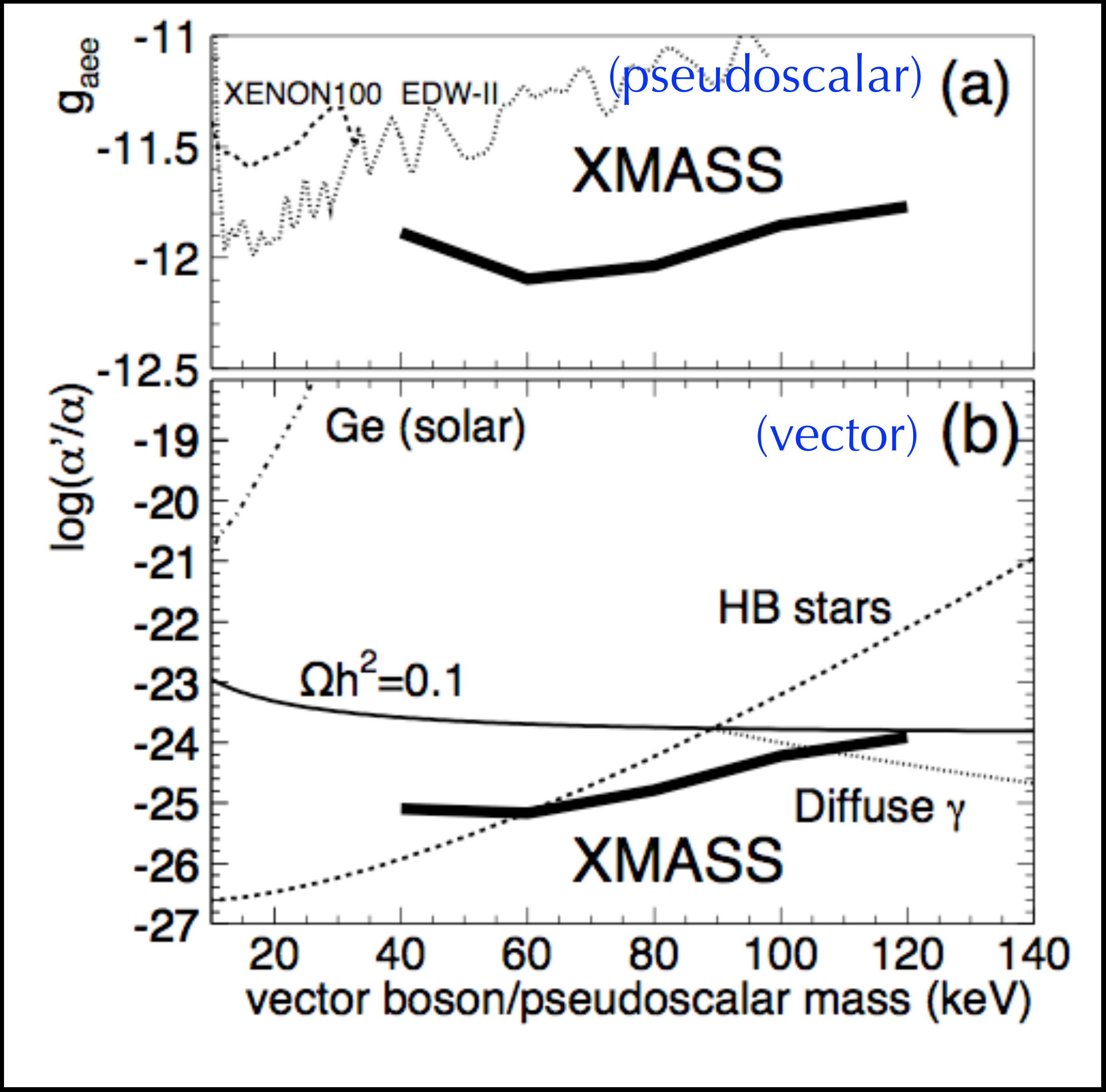

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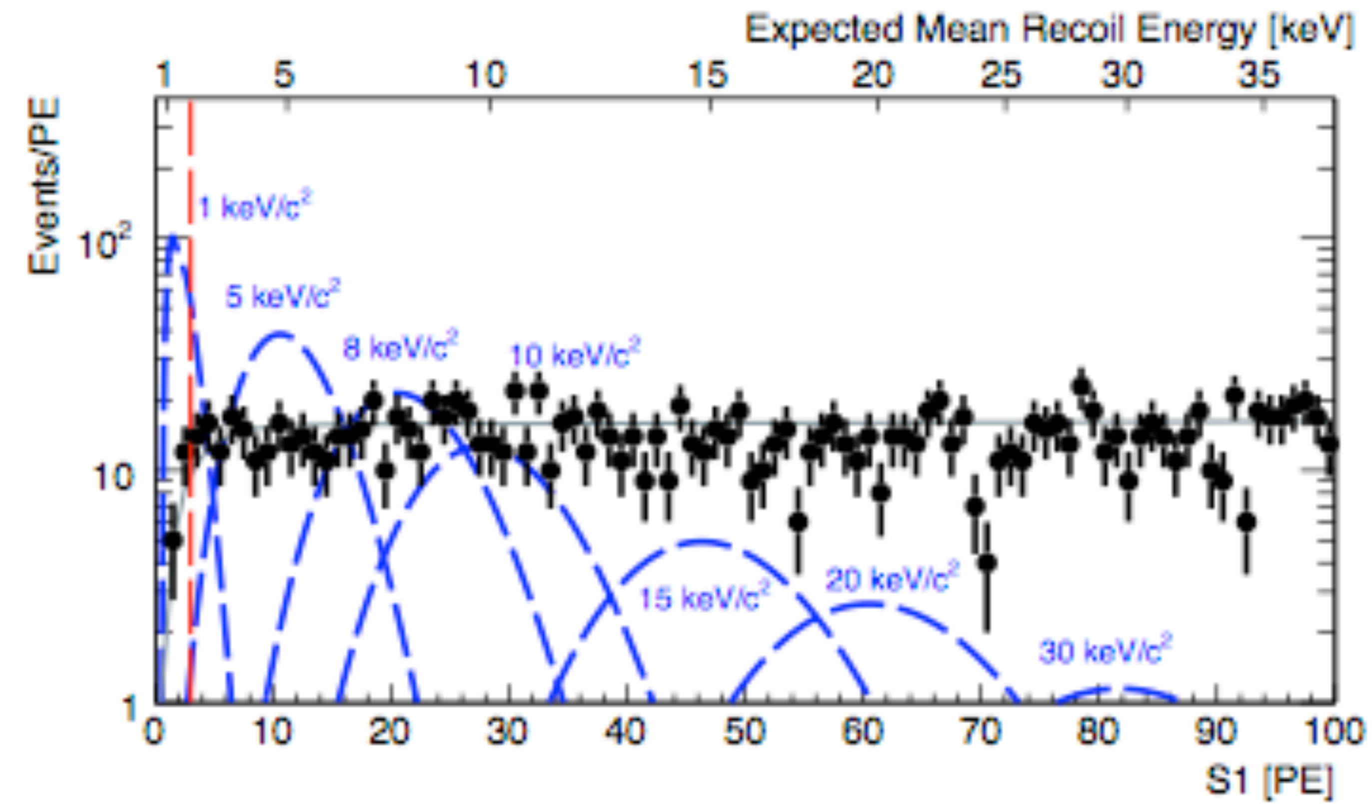

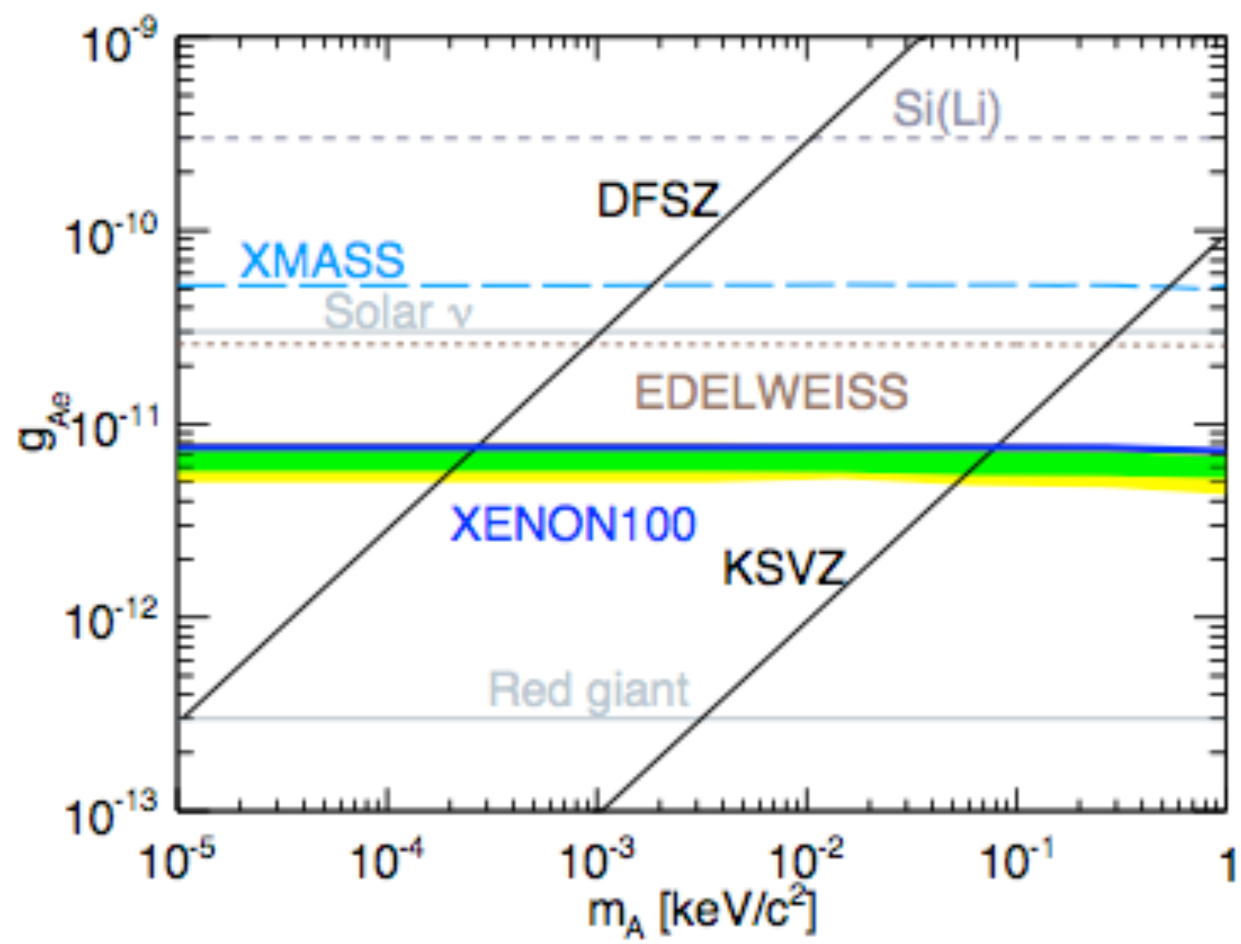

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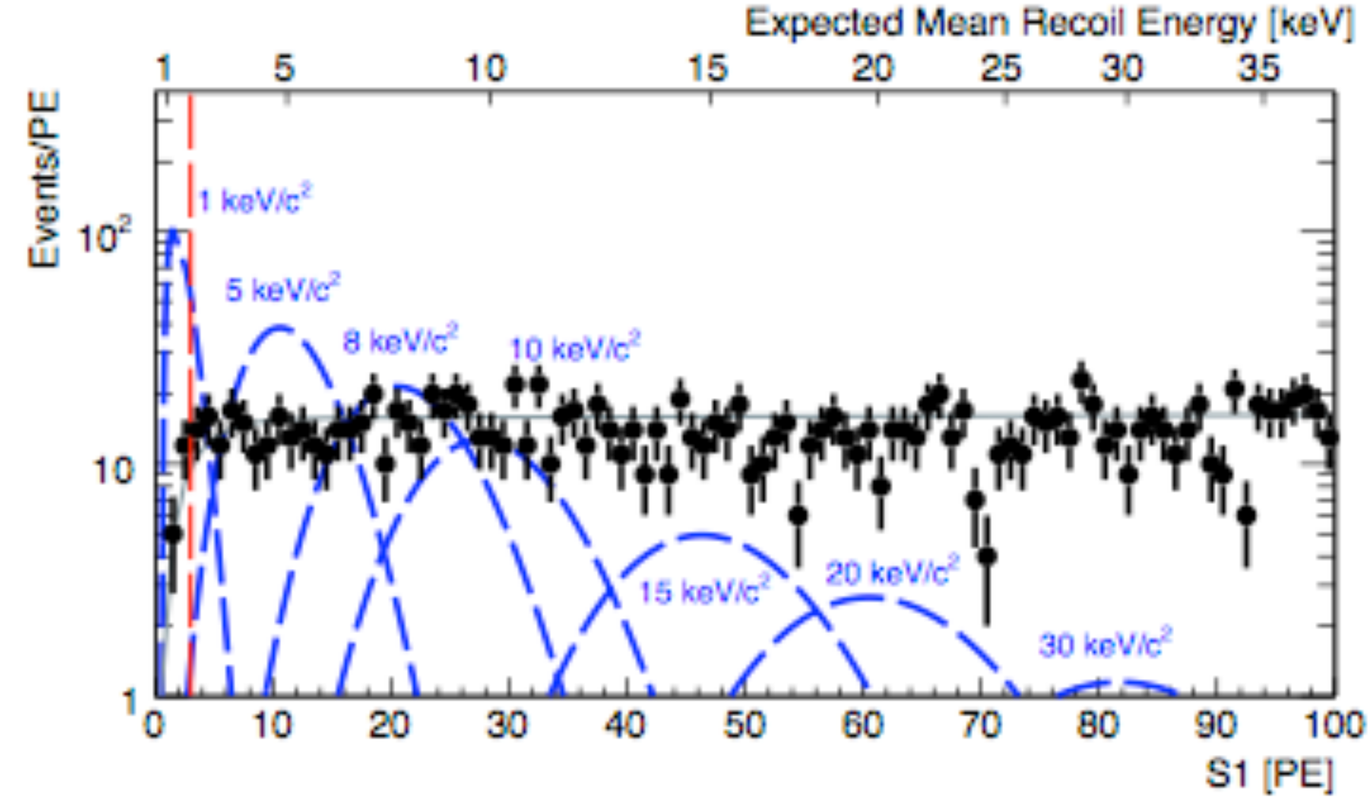
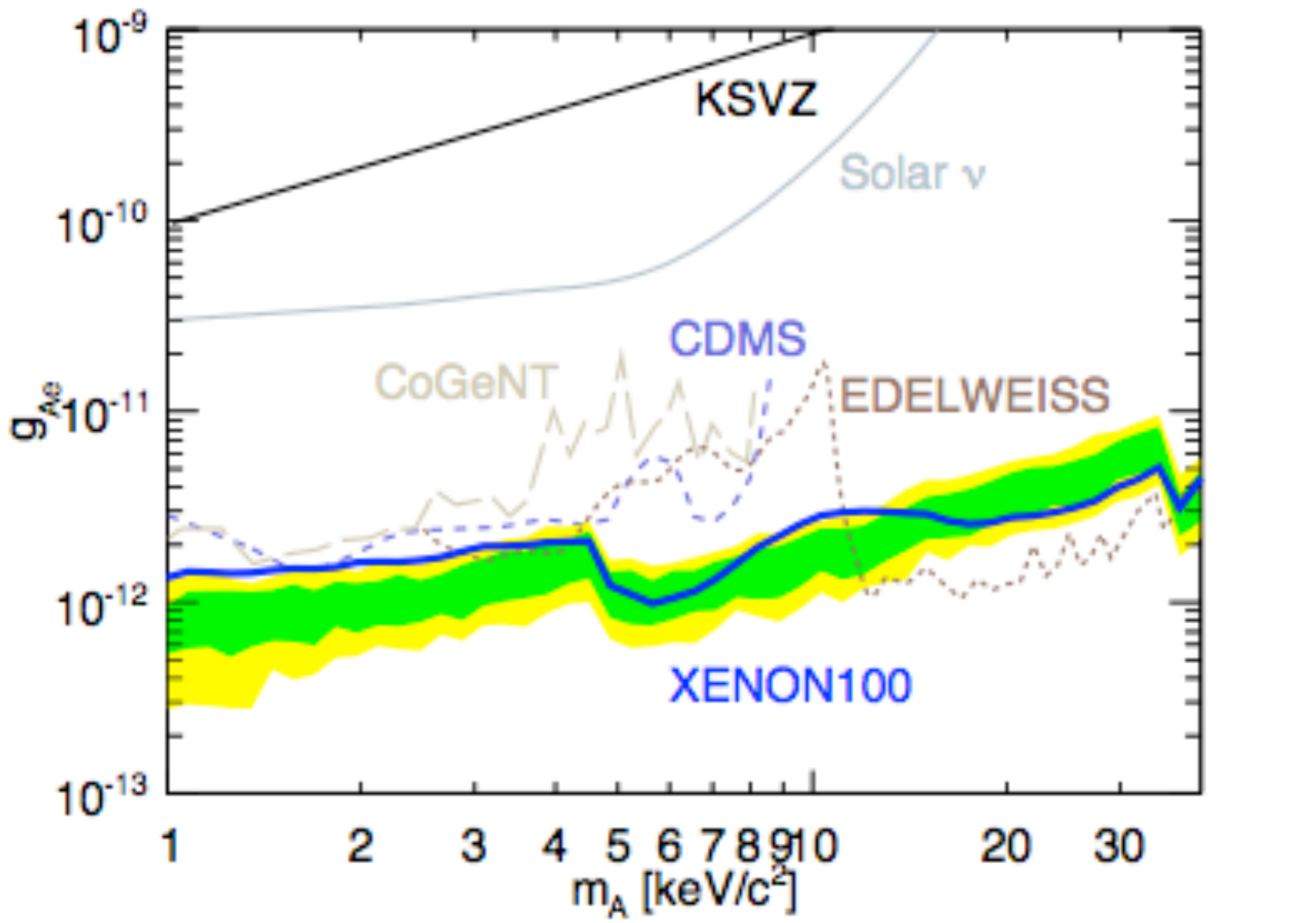




Conclusions & Outlook

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, ...)

Prospects for discovery in direct detection searches are good!

Experiments running now or under construction will improve sensitivity reach by 1-2 orders of magnitude in next few years.

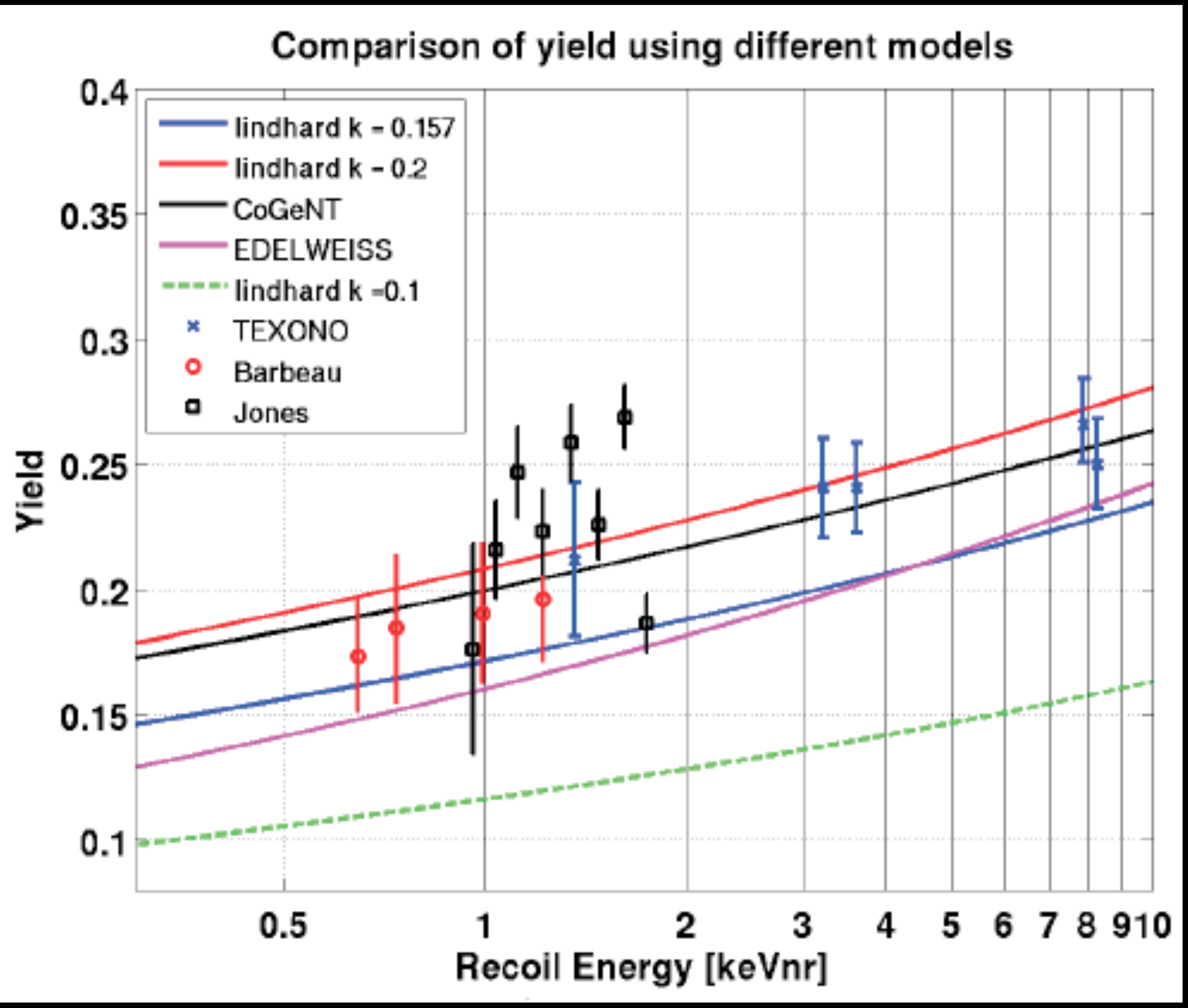
Experiments will reach the neutrino bound within the next decade.

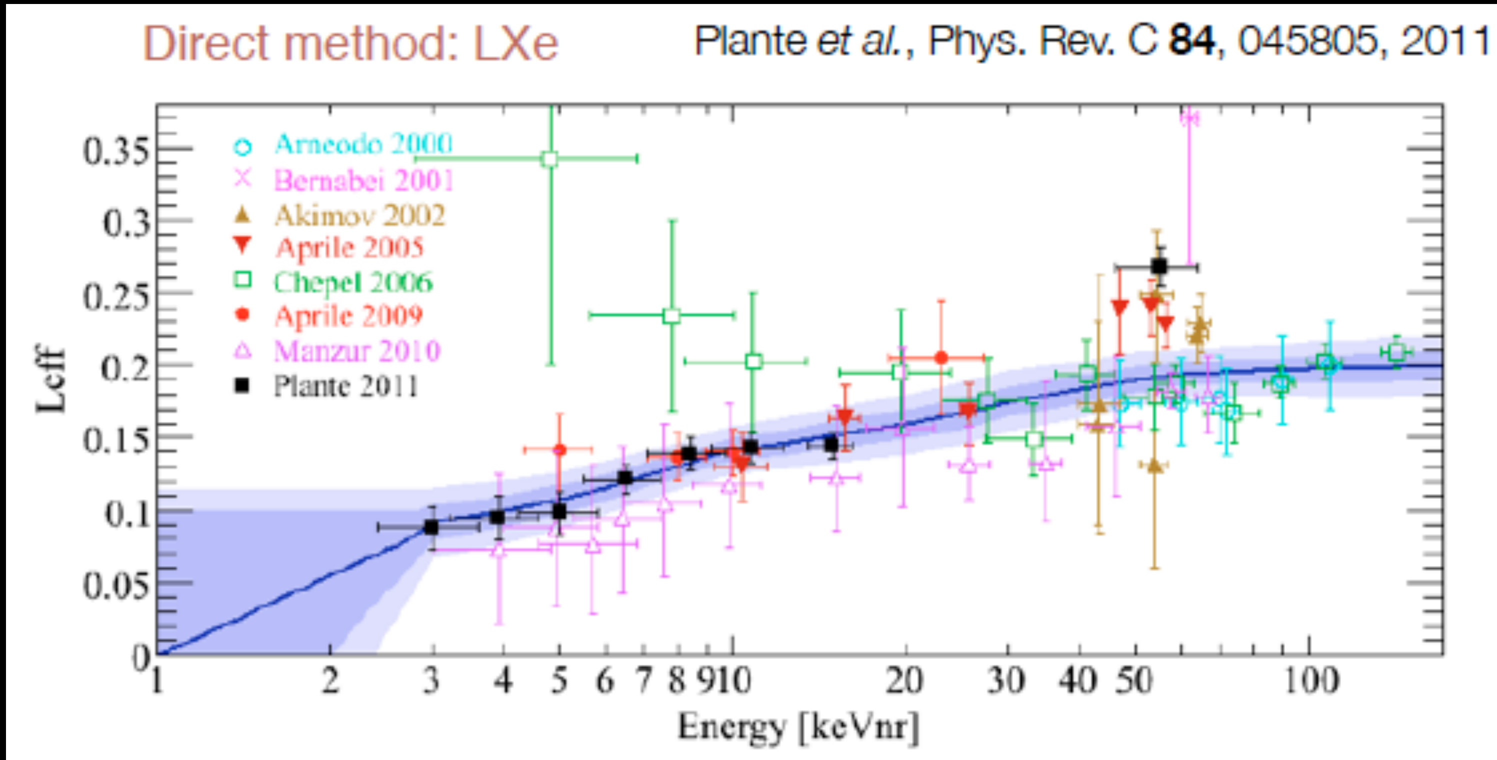
Extra

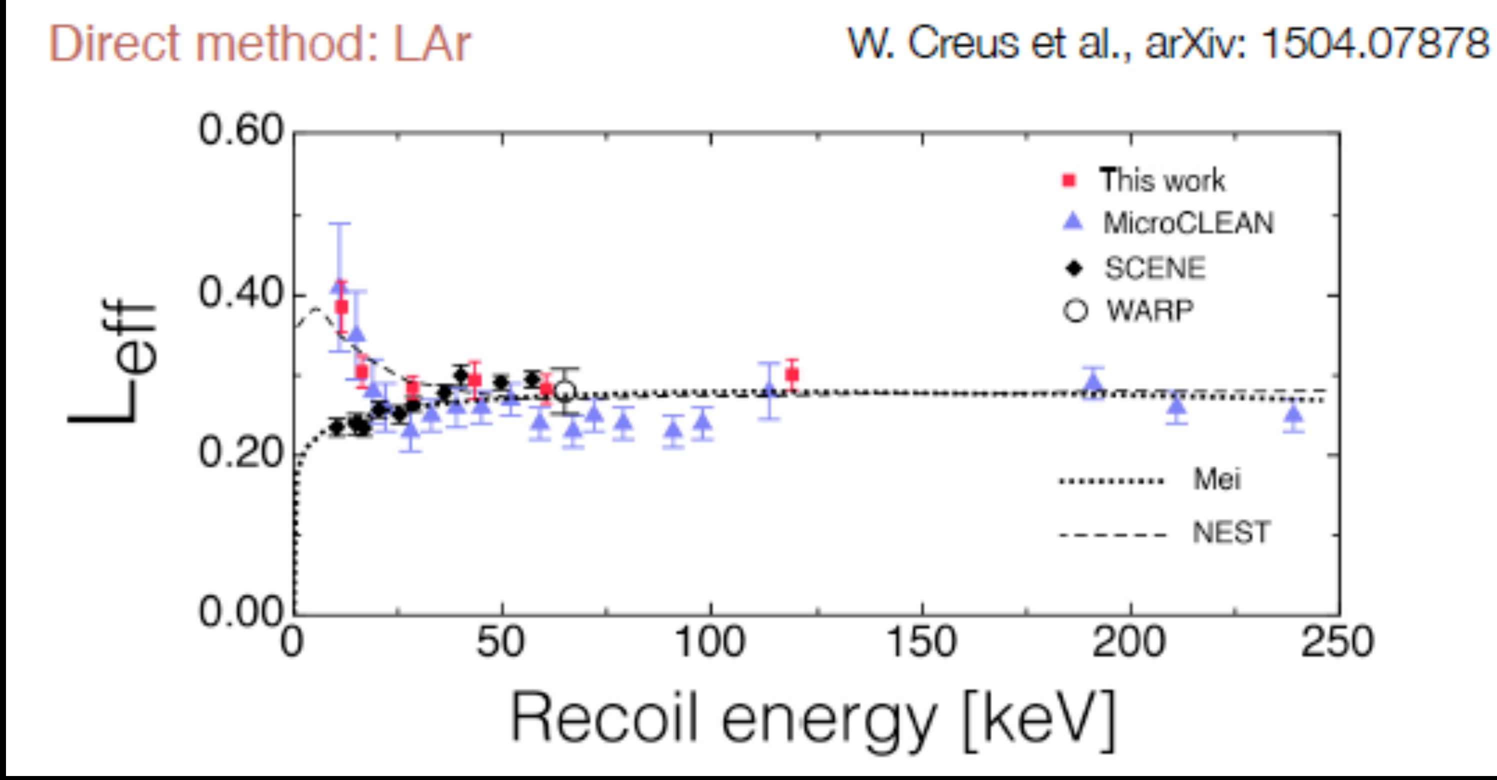
Quenching

(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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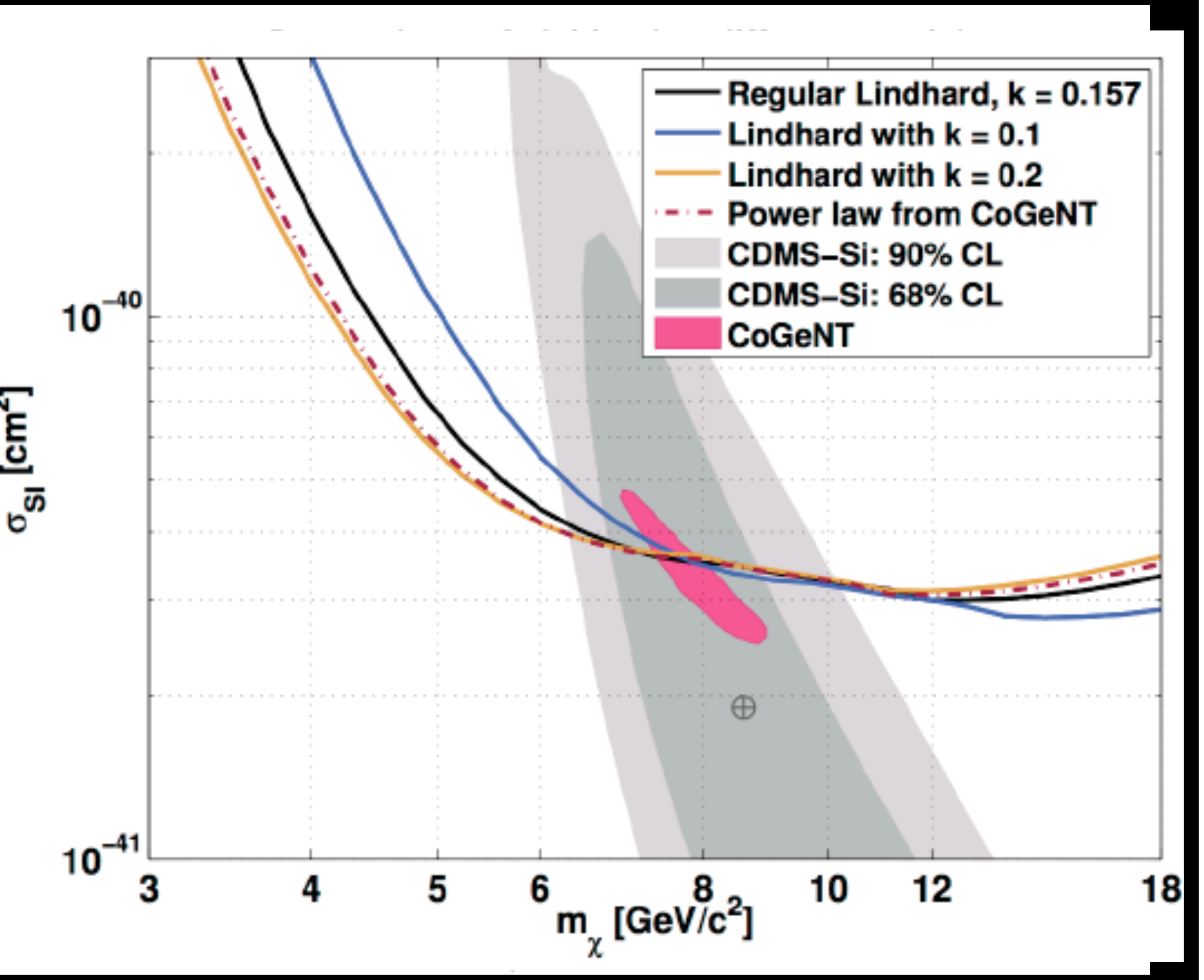

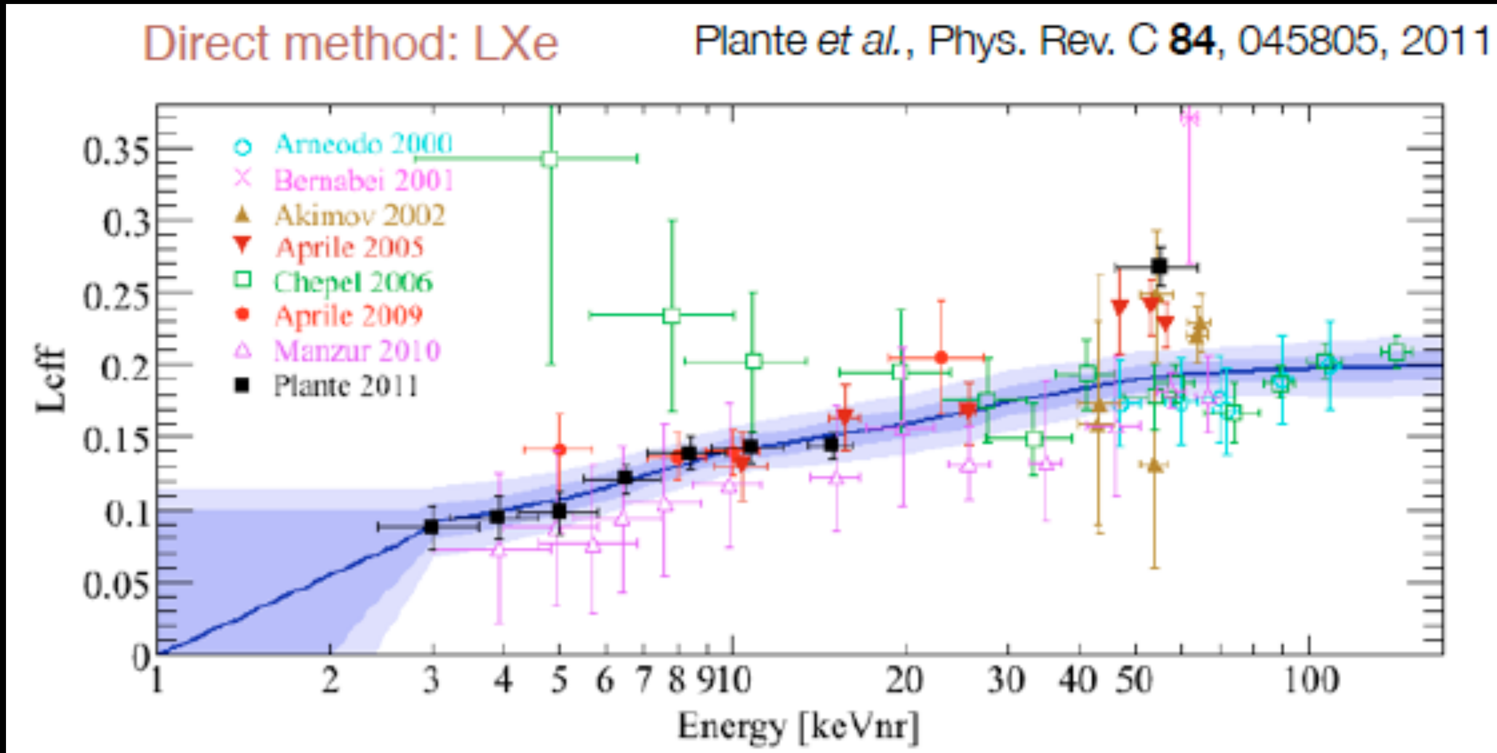

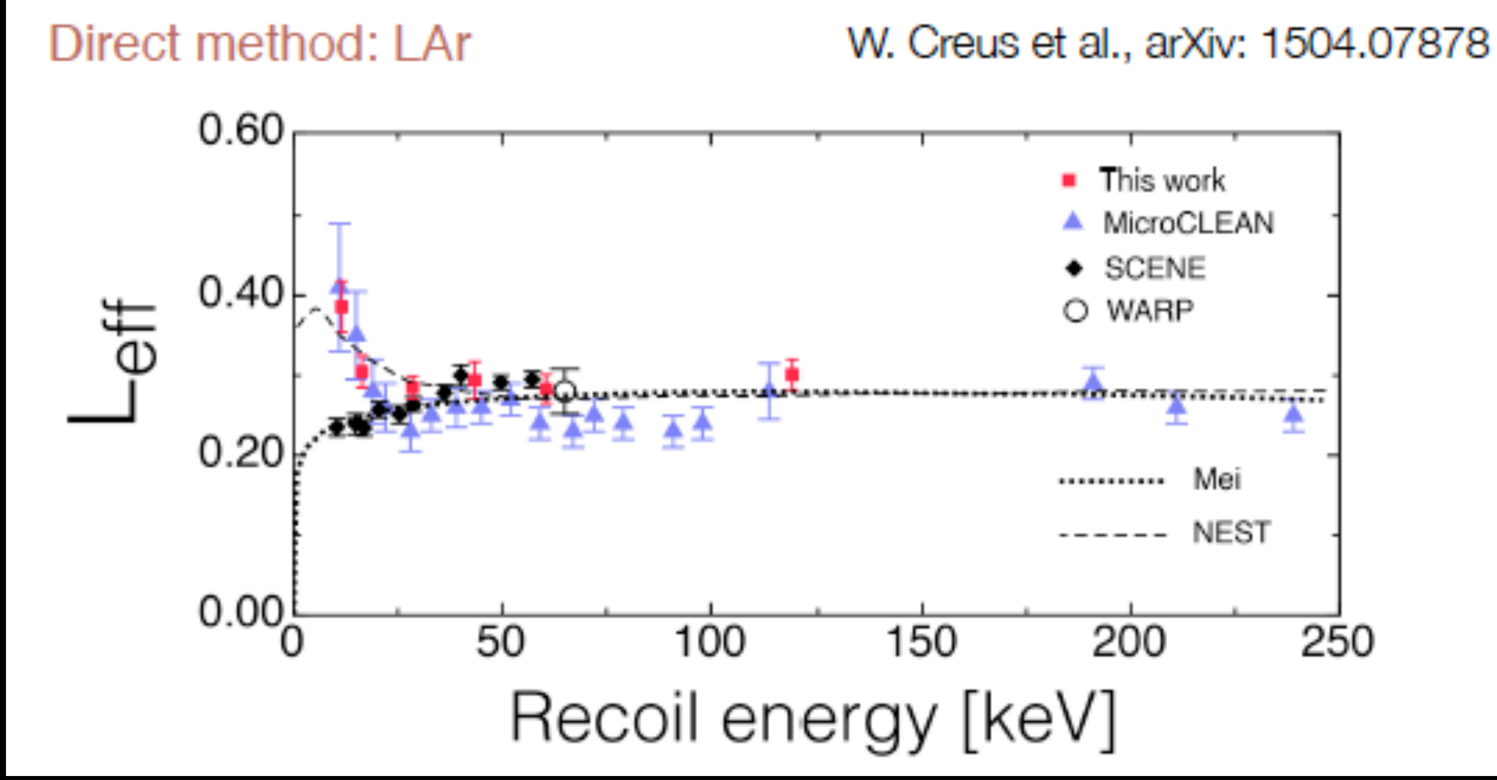

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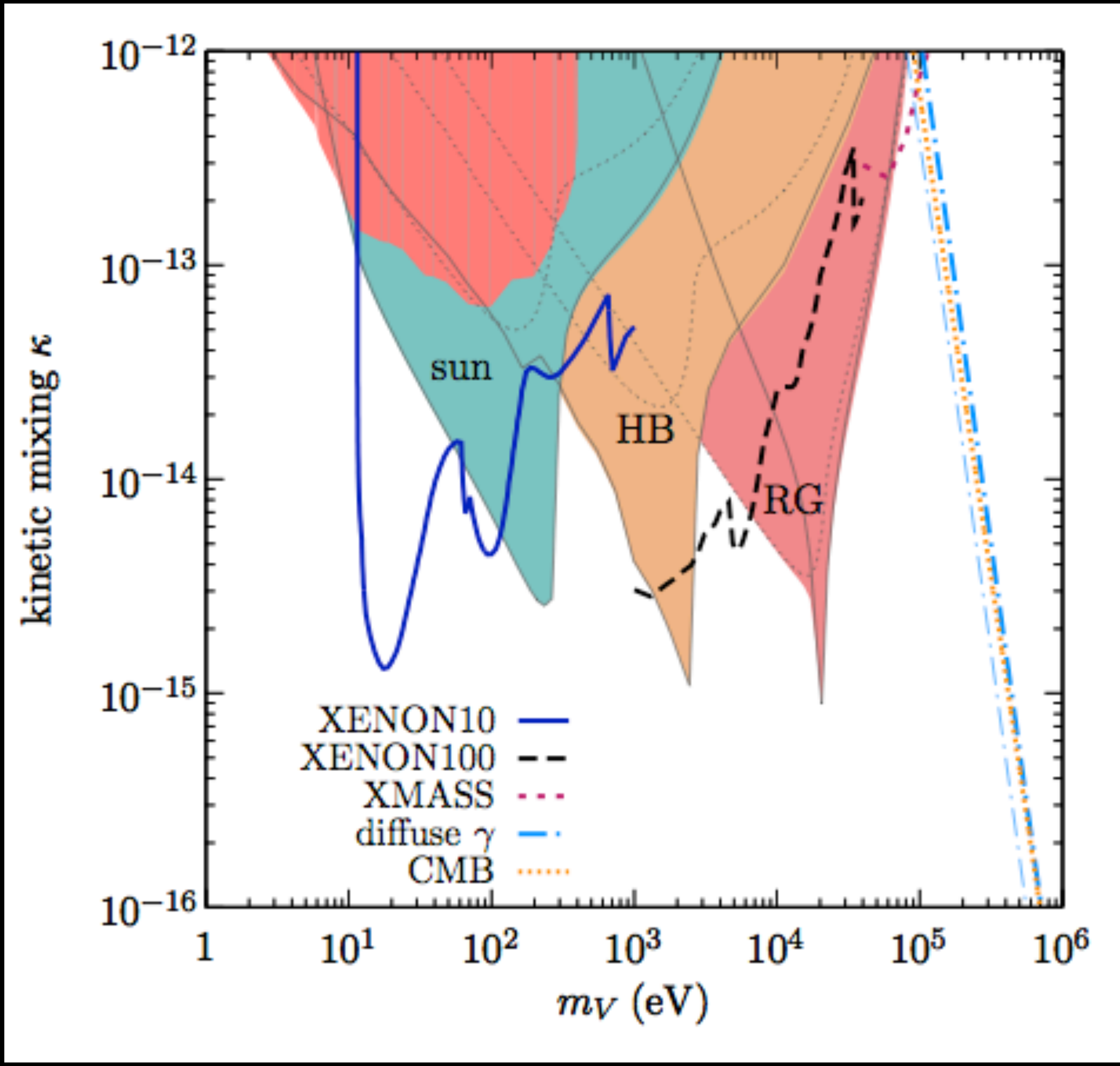
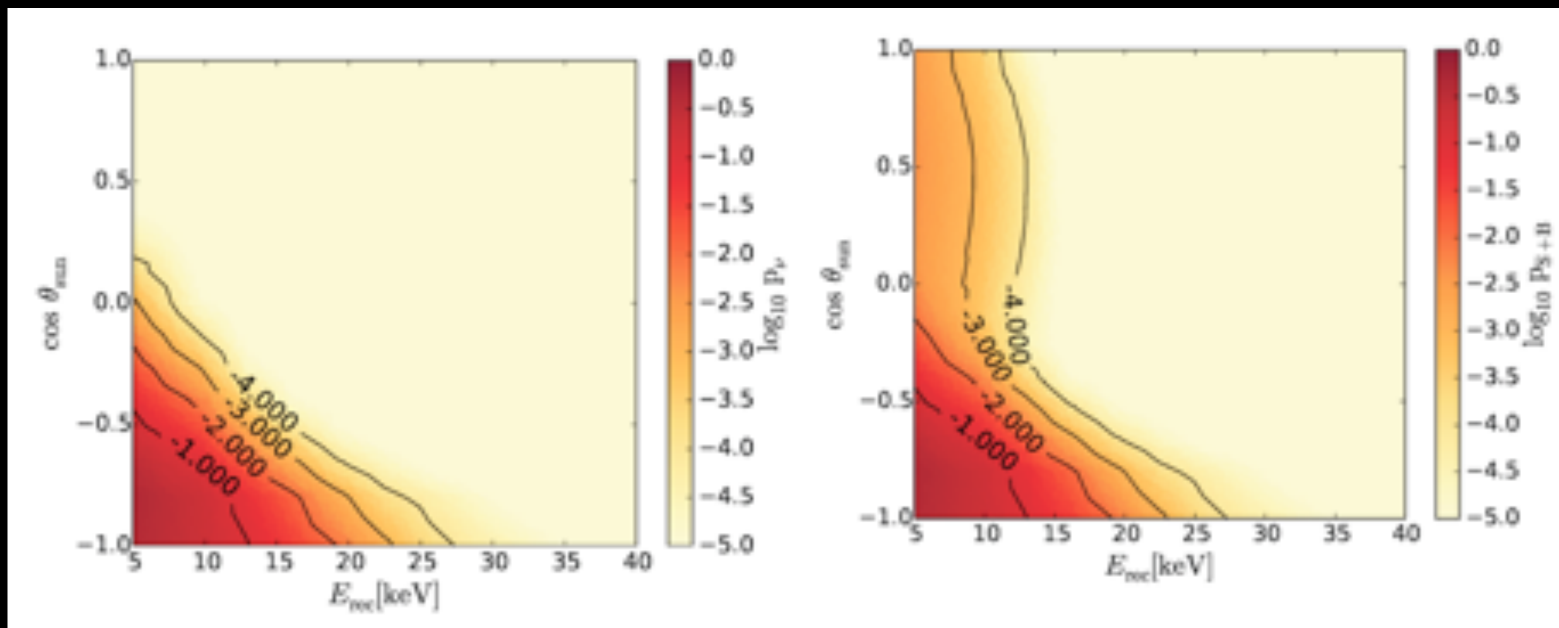


Beyond the Neutrino Bound

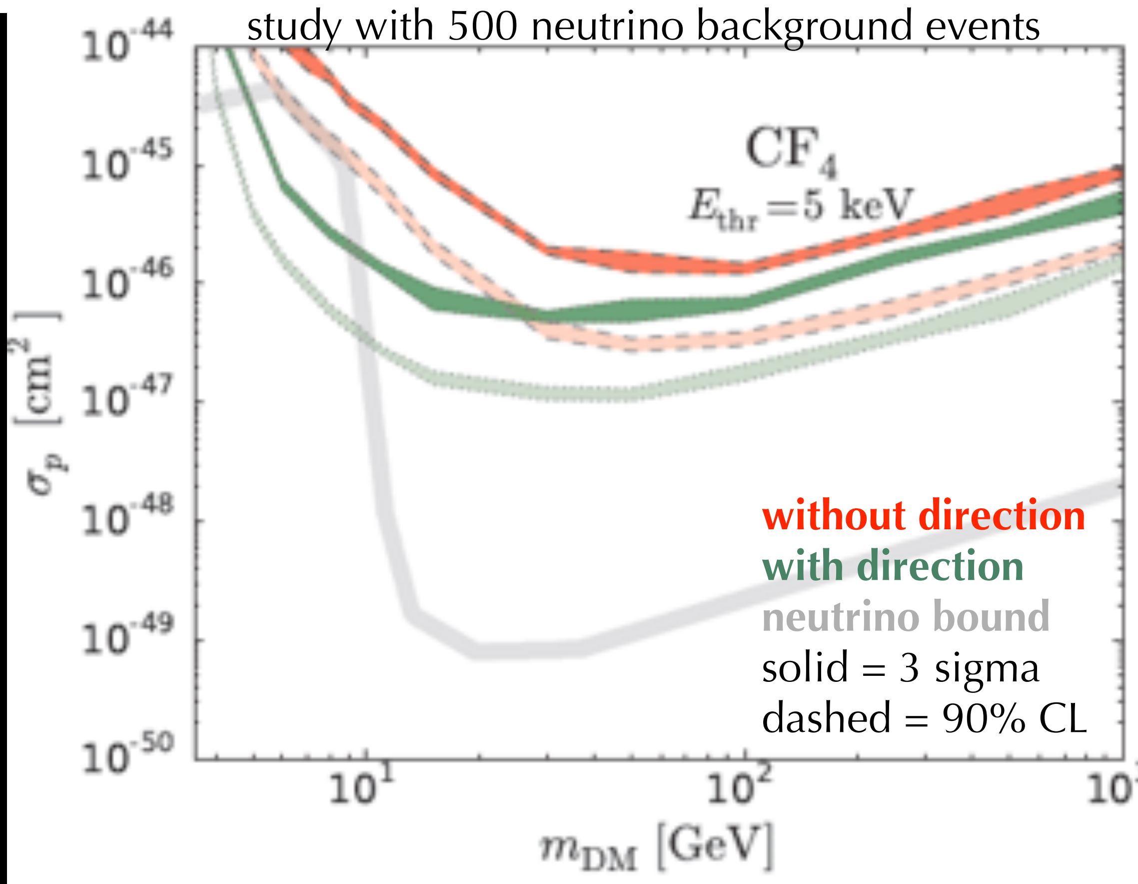
Grothaus, Fairbairn, JM
Phys.ReV.D90 (2014) 055018

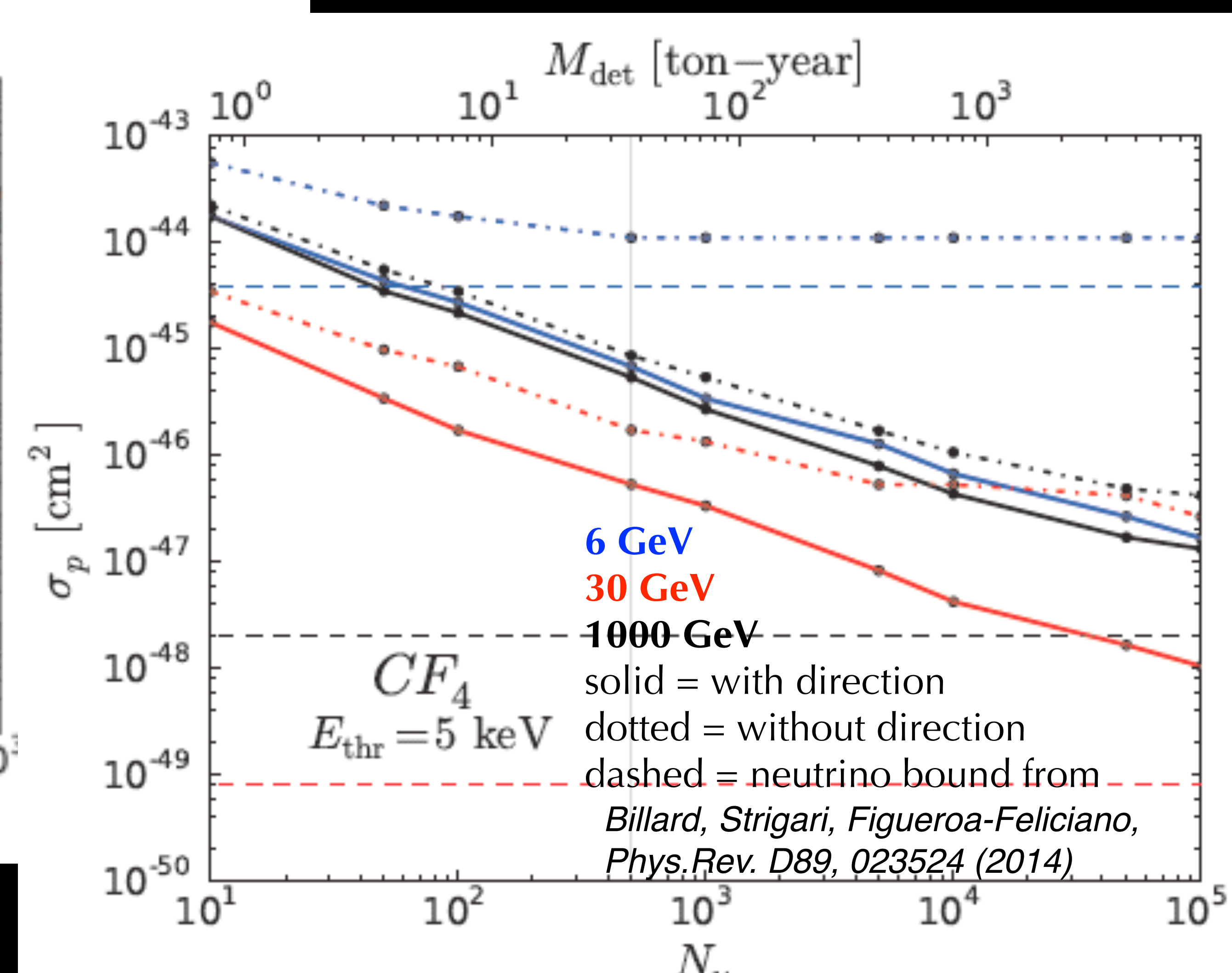
PDFs in (energy, angle, time) of event for coherent solar nu background vs. background+signal show significant differences, including 35º resolution:



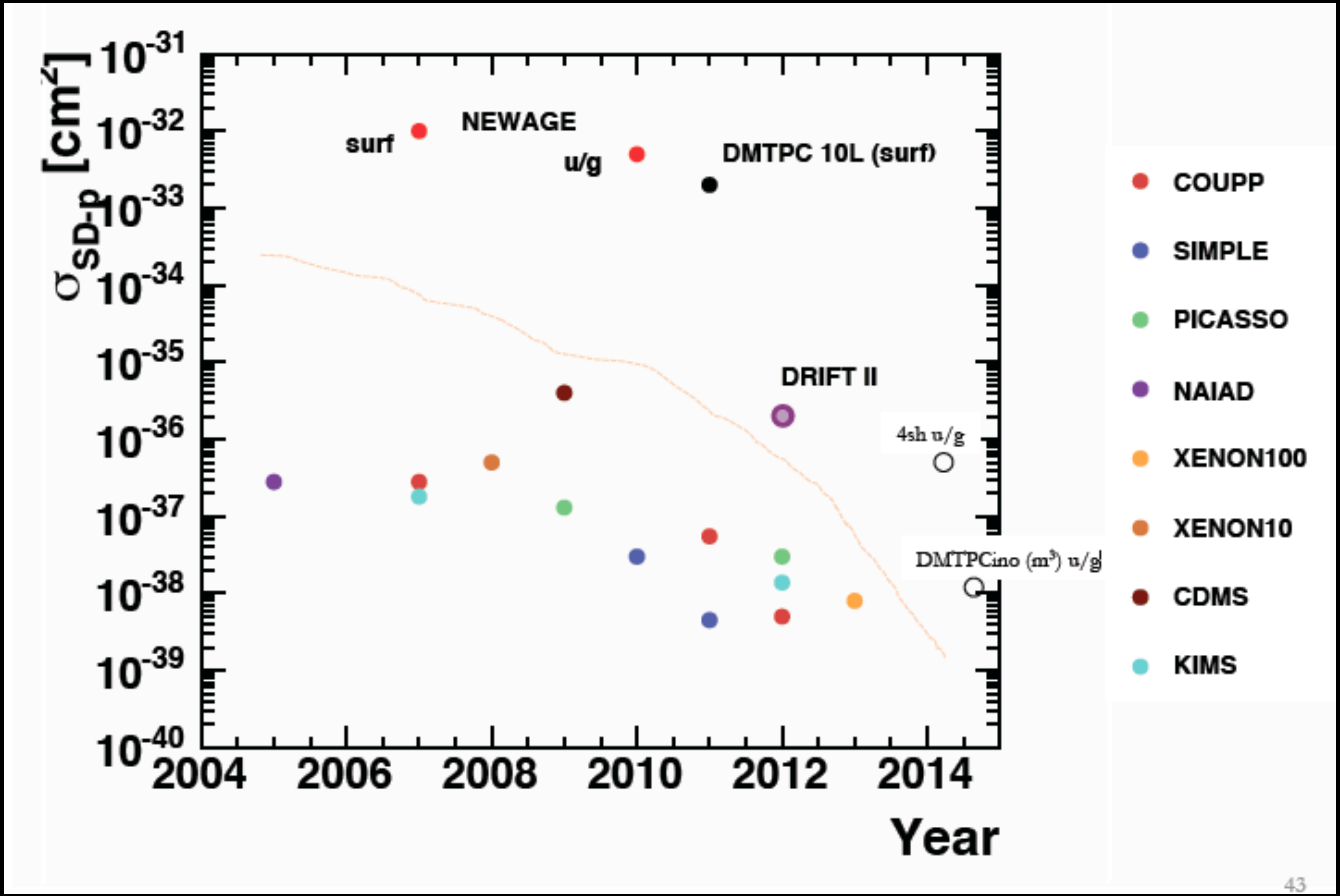
statistical test (CLs) shows

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





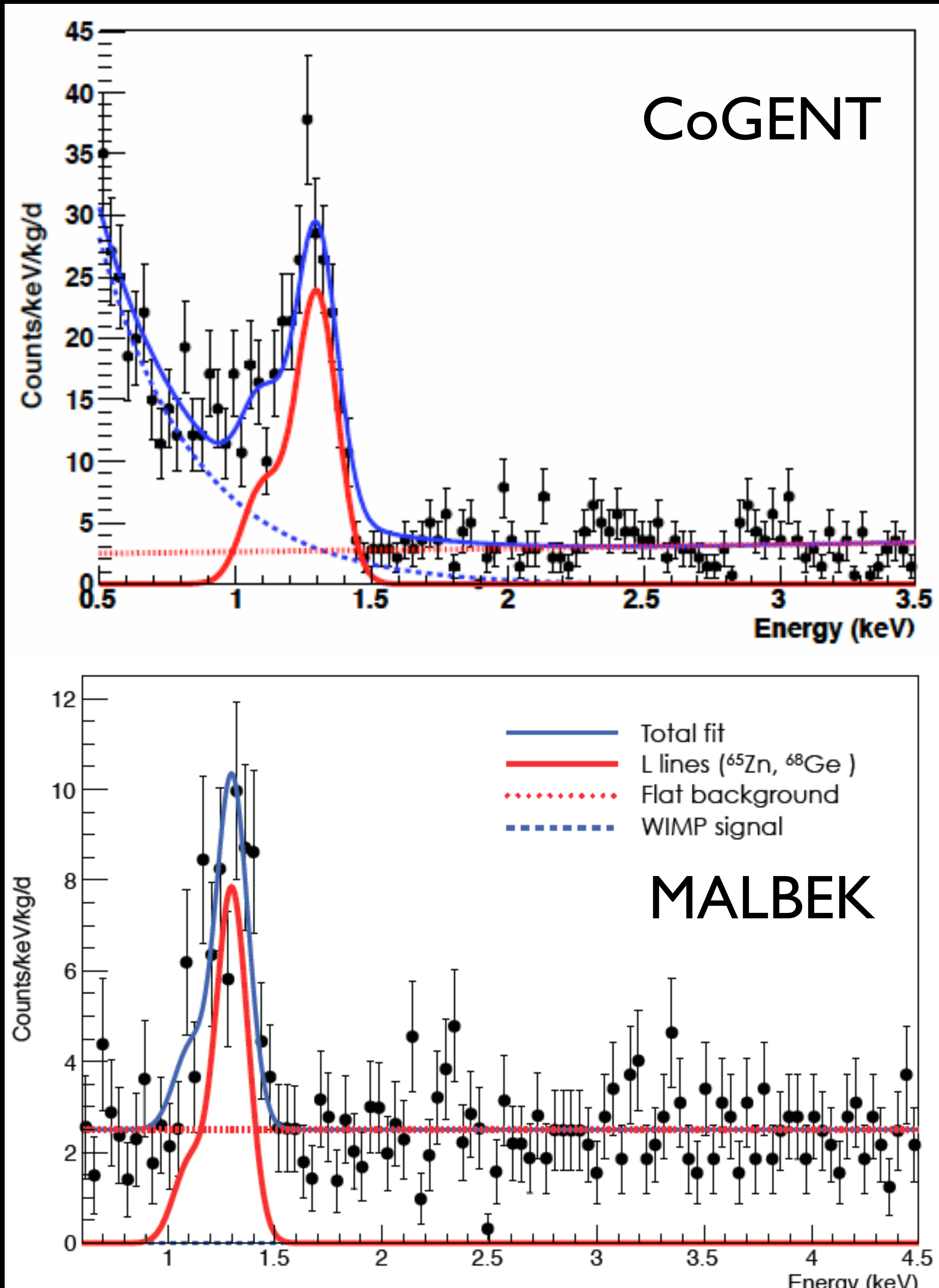
Directional Detection: Progress



O(1m^3) detector to be competitive with current non-directional SD searches

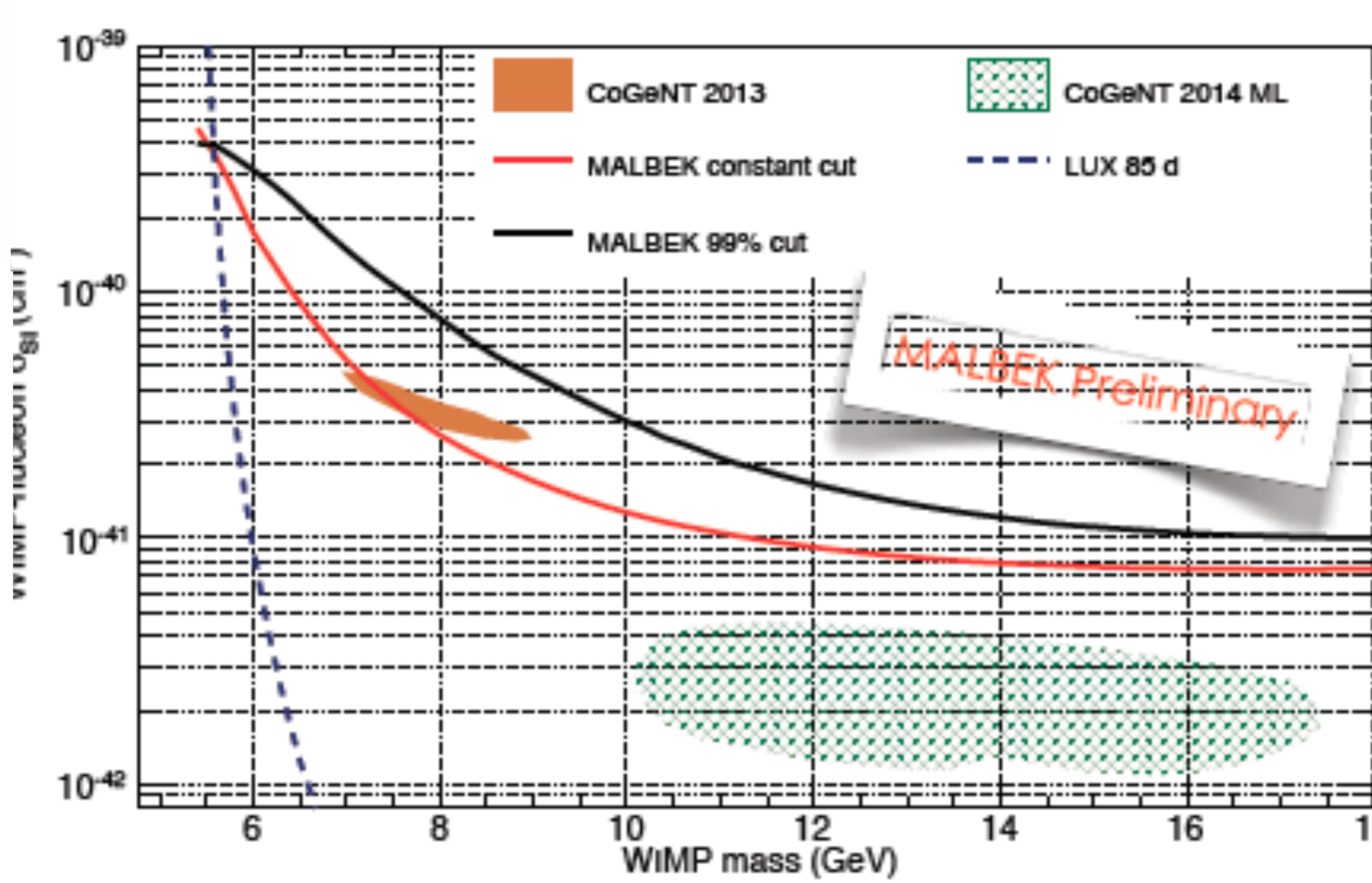
directionality is starting to catch up….

CoGENT and MALBEK



0.44 kg Ge detector, point contact

- 0.5 keV energy threshold
- COGENT: excess fit by 8 GeV WIMP
- MALBEK: similar detector, assayed detector components, found Pb-210 background from clam reran without them, best fit: no DM



- CoGENT 2013 allowed region excluded, CoGENT 2014 region allowed