Dark Matter Direct Detection: Paradigm Confirmation or Shift?

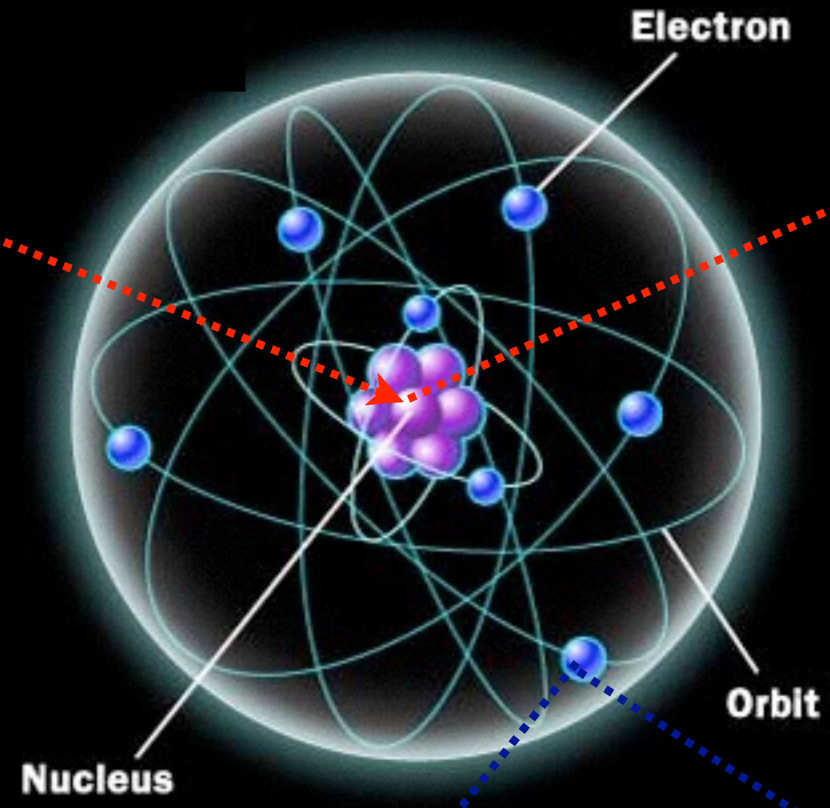
(Part 1: why you need background rejection for discovery)

Jocelyn Monroe,
Royal Holloway, University of London

Dark matter detection and detectability:
paradigm confirmation or shift?
KITP, Santa Barbara
May 3, 2018

Dark Matter Direct Detection

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



Backgrounds:

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

$n\; N \rightarrow n\; N$

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

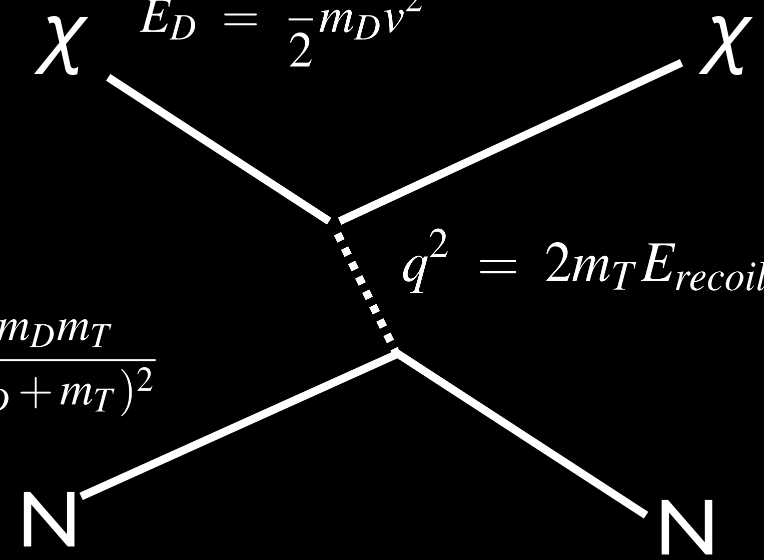
$\nu\; N \rightarrow \nu\; N$

experimental 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



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

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

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

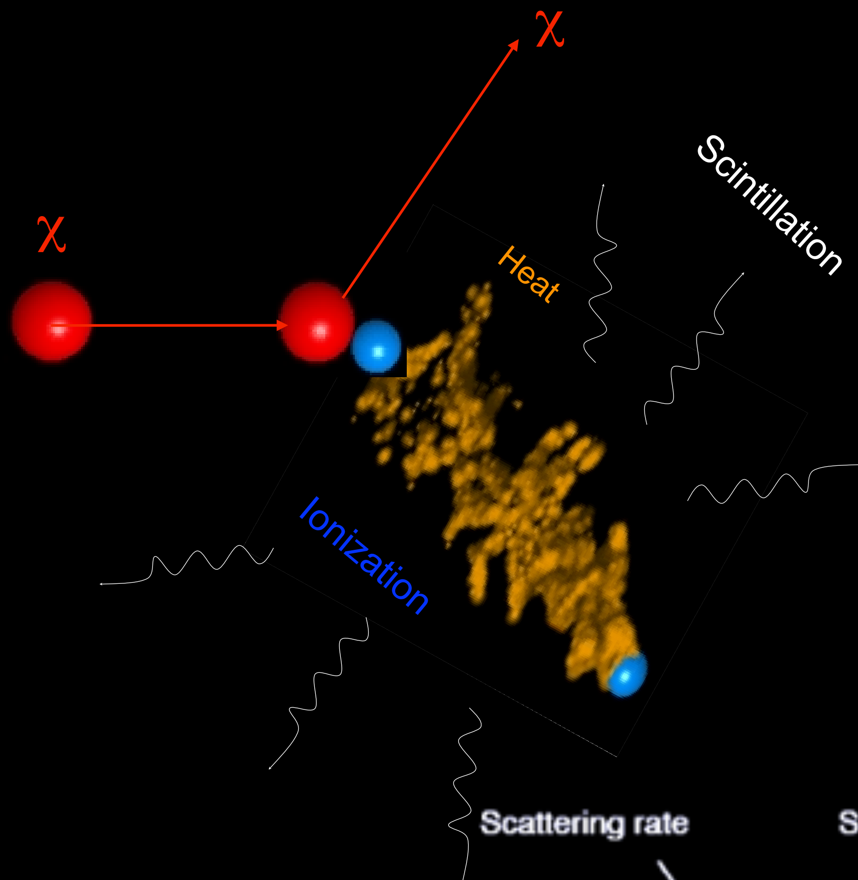
$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

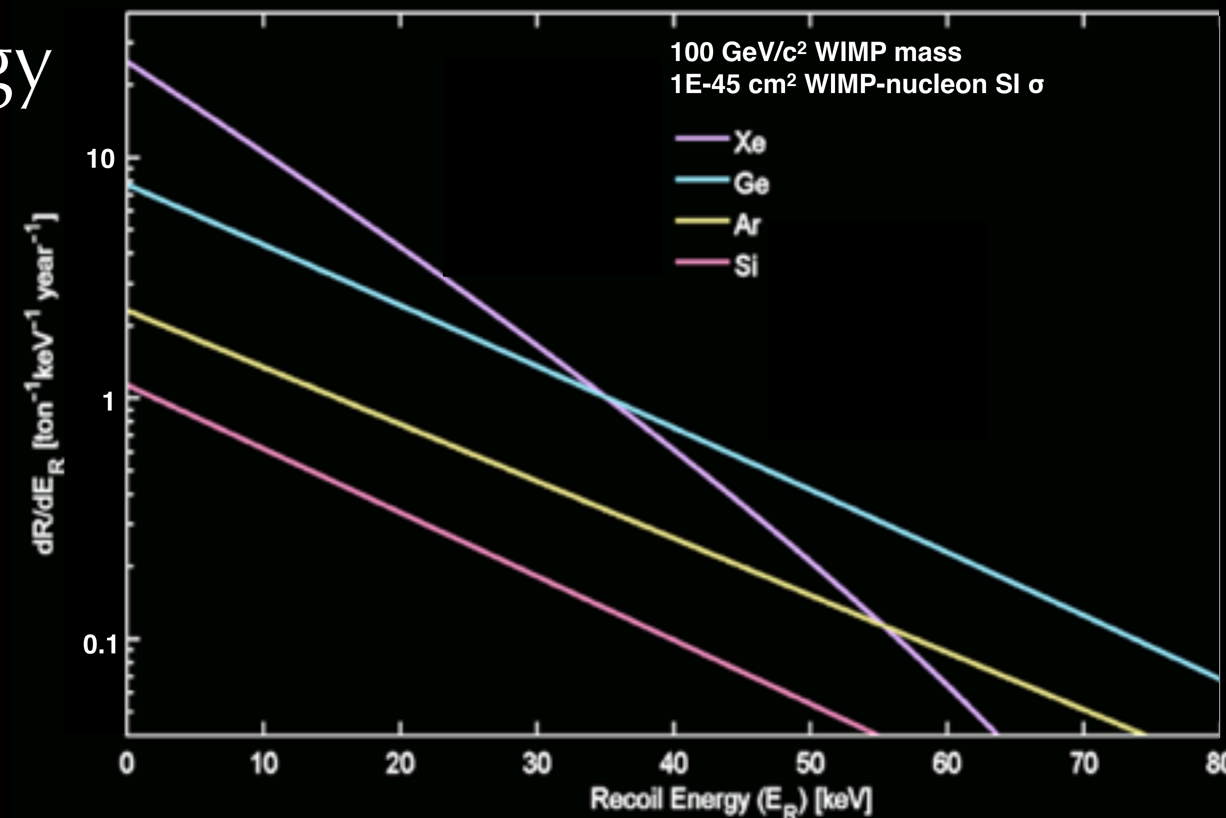
Spin Independent:
χ scatters coherently off of the entire nucleus A: σ~A^2
D. Z. Freedman, PRD 9, 1389 (1974)

Spin Dependent:
mainly unpaired nucleons contribute to scattering amplitude: σ~ *J(J+1)*

experimental requirements: measure recoil energy, time, +angle

Observable: Recoil Energy





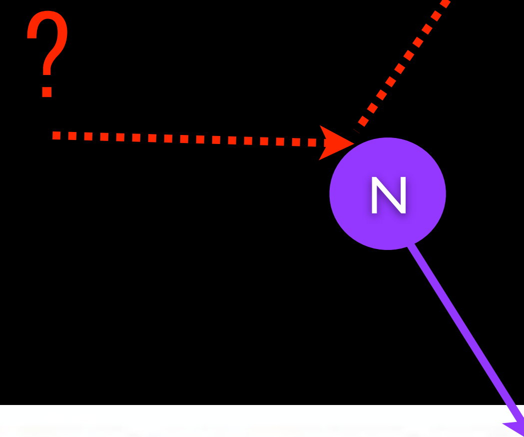
Scattering rate — Sun's velocity around the galaxy — WIMP velocity distribution

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

WIMP energy density, 0.3 GeV/cm³ — Form factor

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

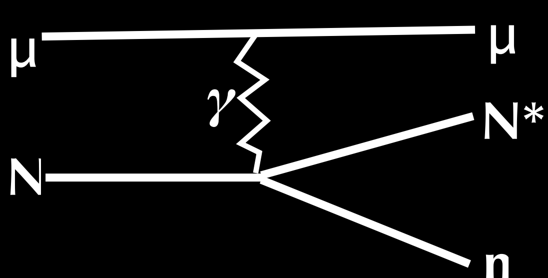
Backgrounds

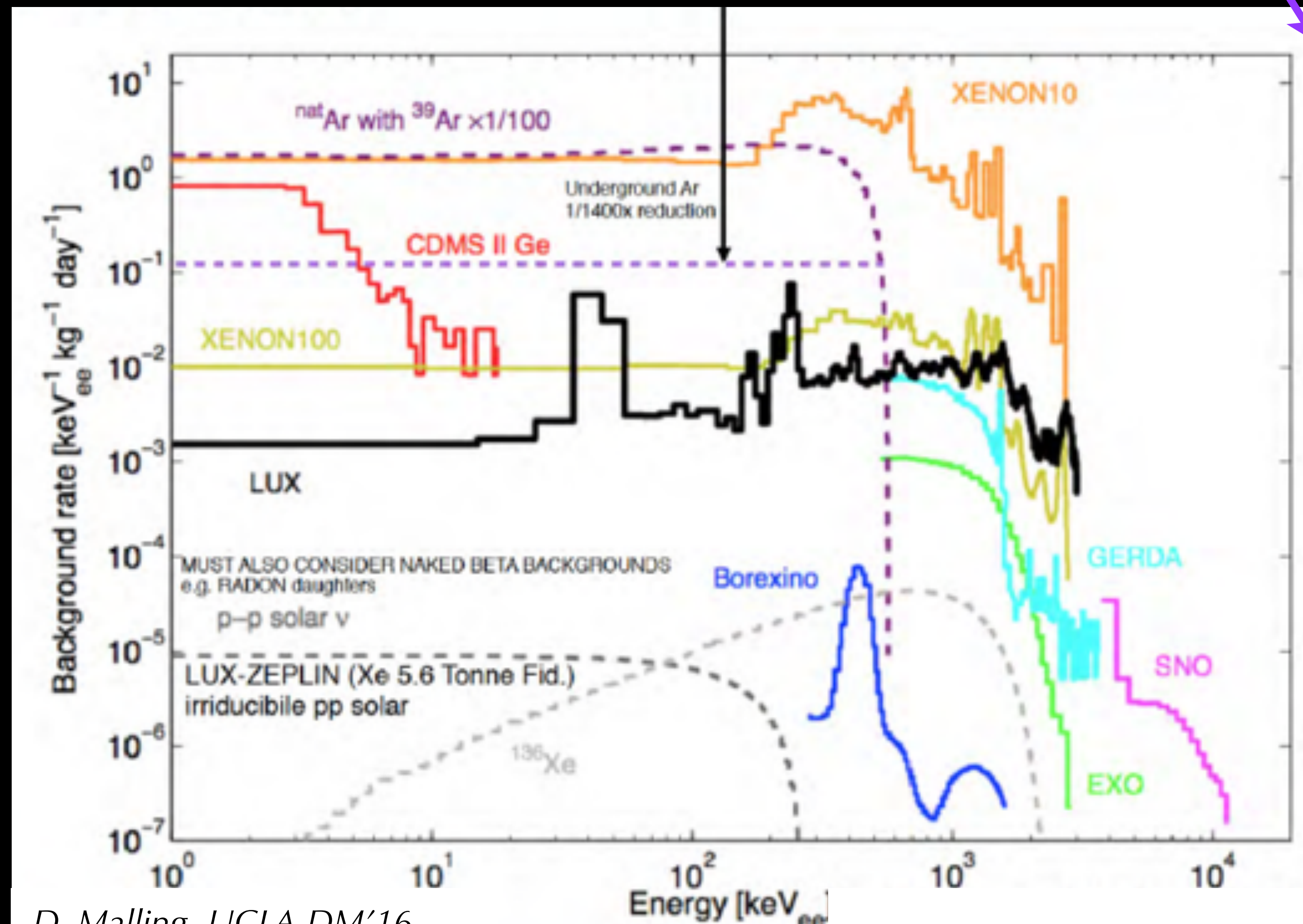


Gamma ray interactions: electron recoil final states
rate ~ N_e x (gamma flux), O(1E7) events/(kg day)
mis-identified electrons mimic nuclear recoils

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

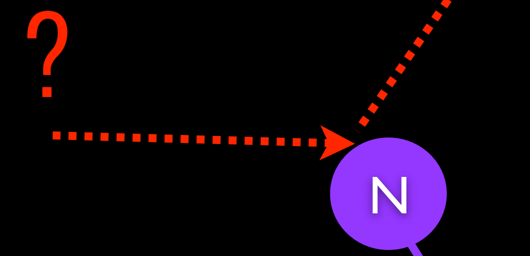




D. Malling, UCLA DM'16

+ discrimination between e⁻ vs. N

Backgrounds



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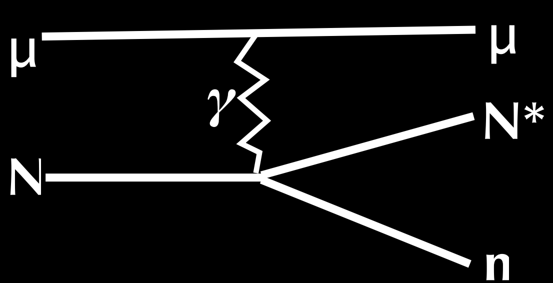

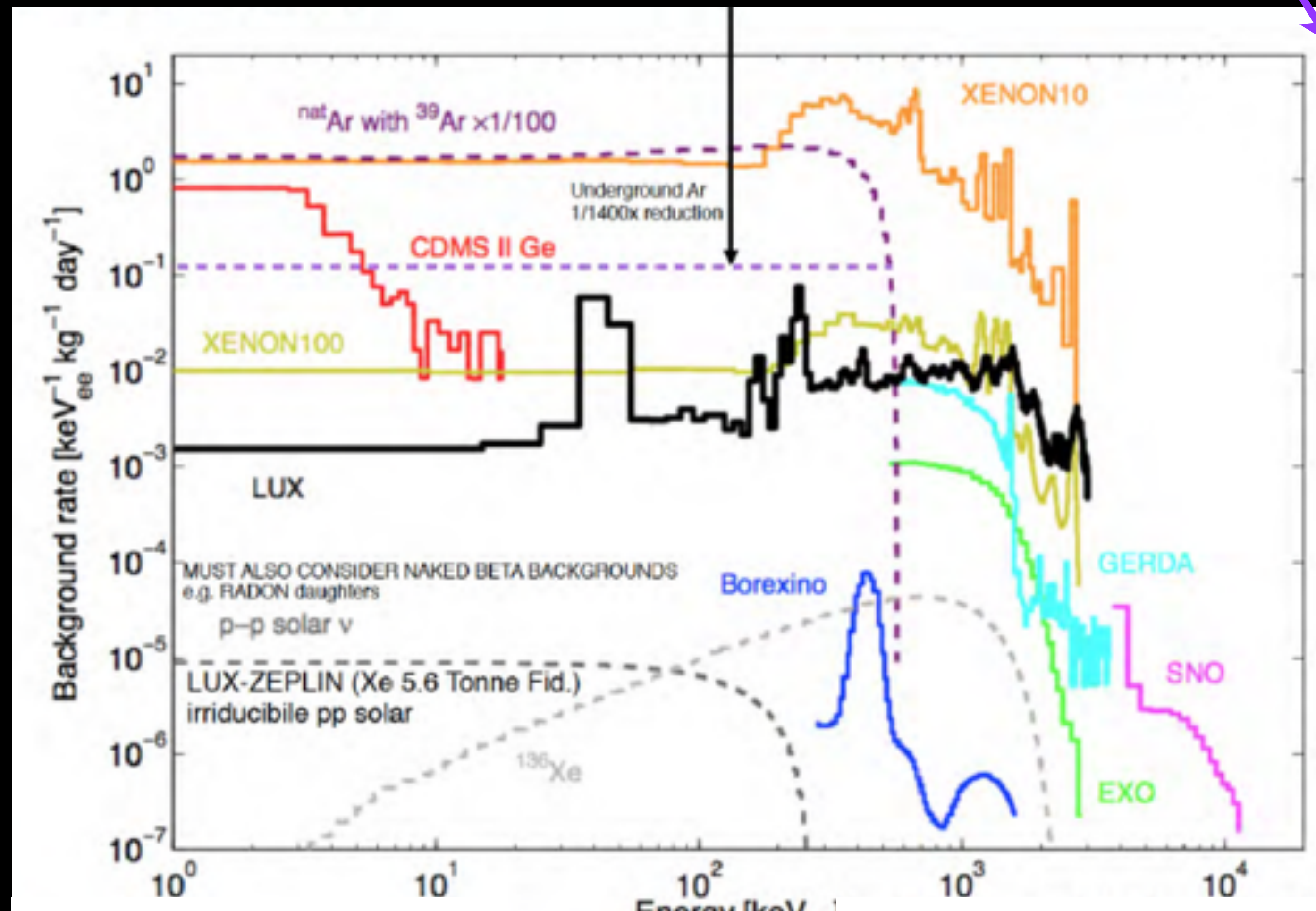

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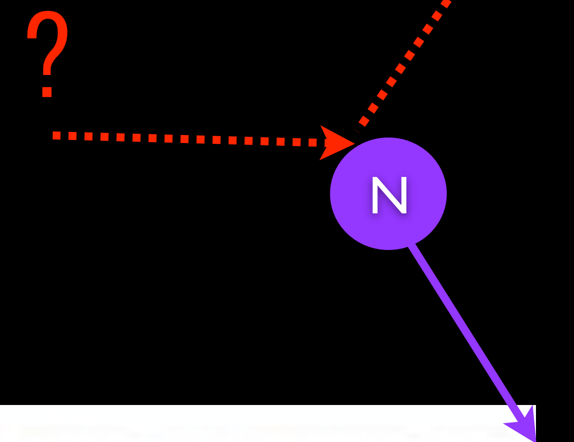

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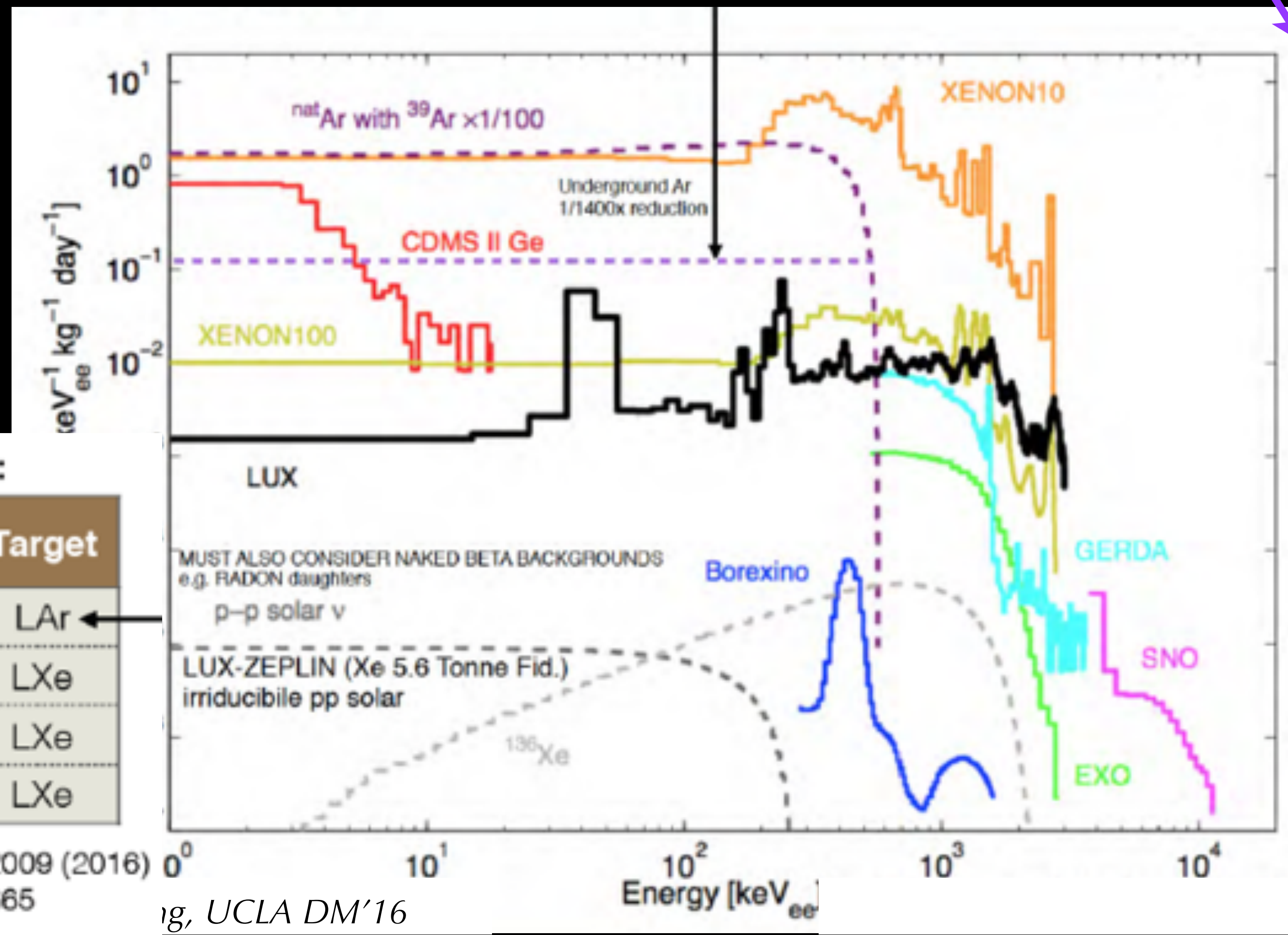


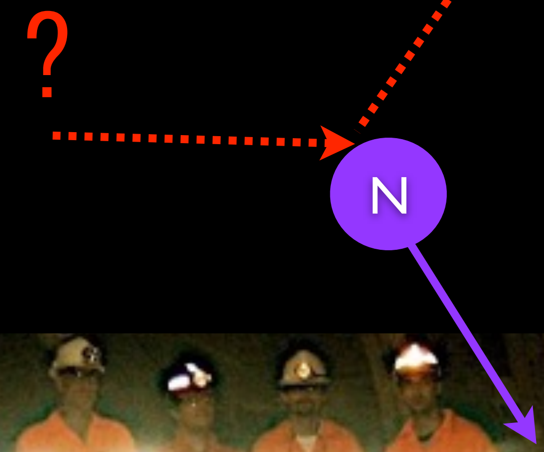
^{222}Rn in Dark Matter experiments:

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

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

+ discrimination between e^- vs. N

Backgrounds



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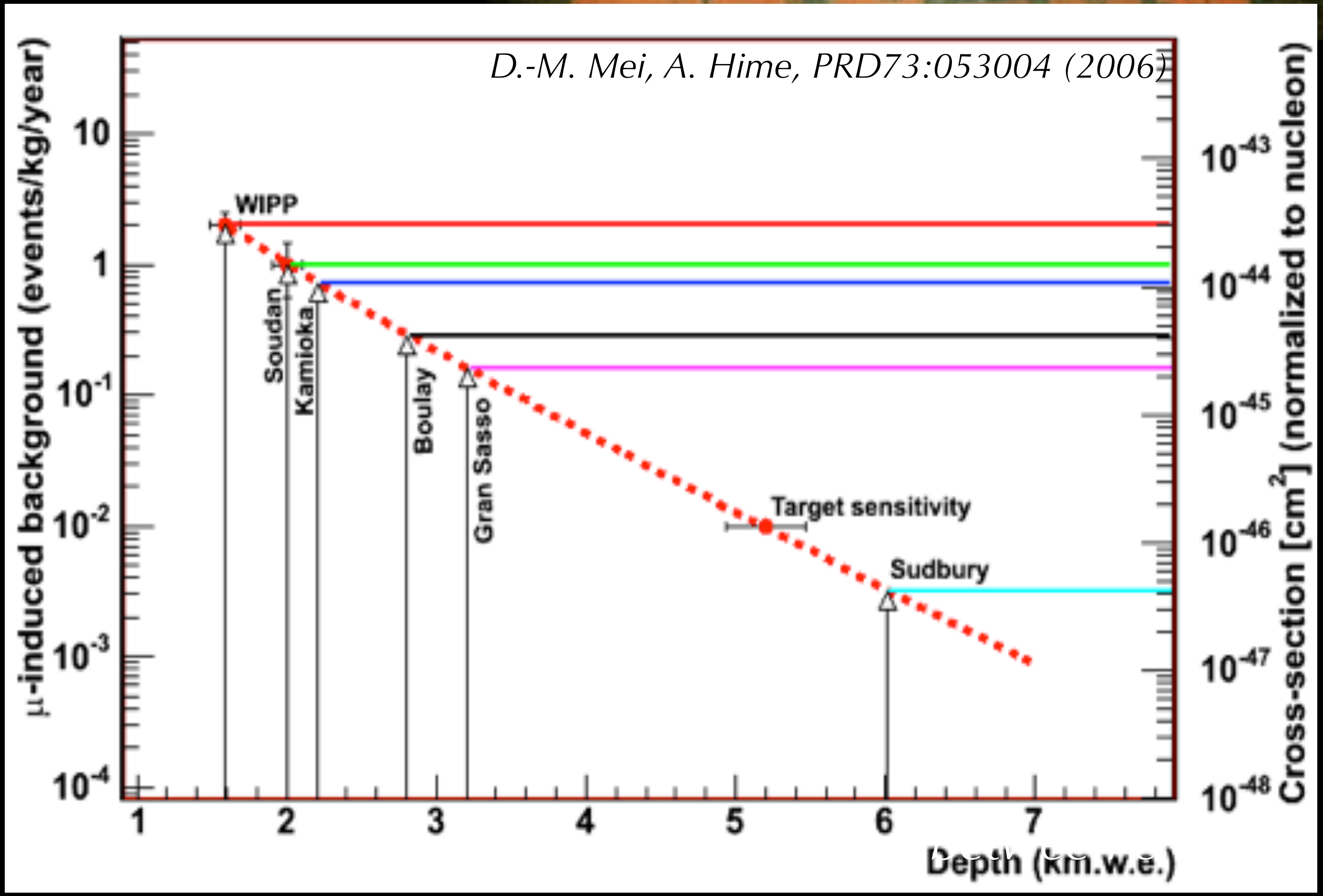

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Nuclear recoil final state.
(alpha,n), U, Th fission,
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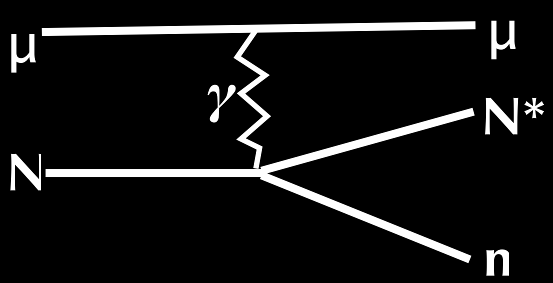
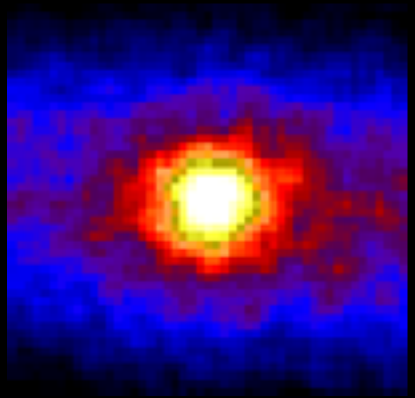


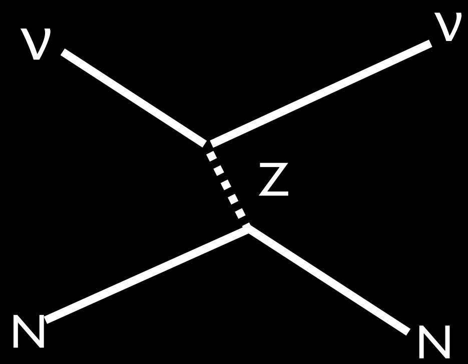
+ large, active neutron shielding

Irreducible Backgrounds

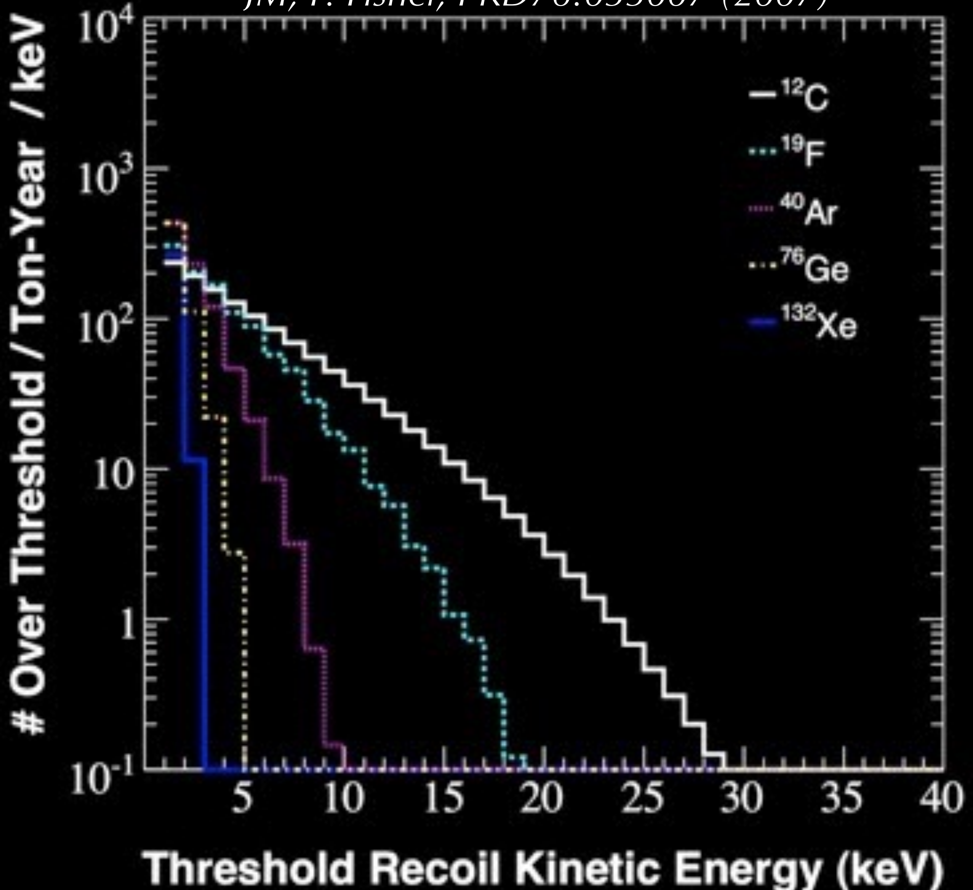


impossible to shield a detector from coherent neutrino scattering!

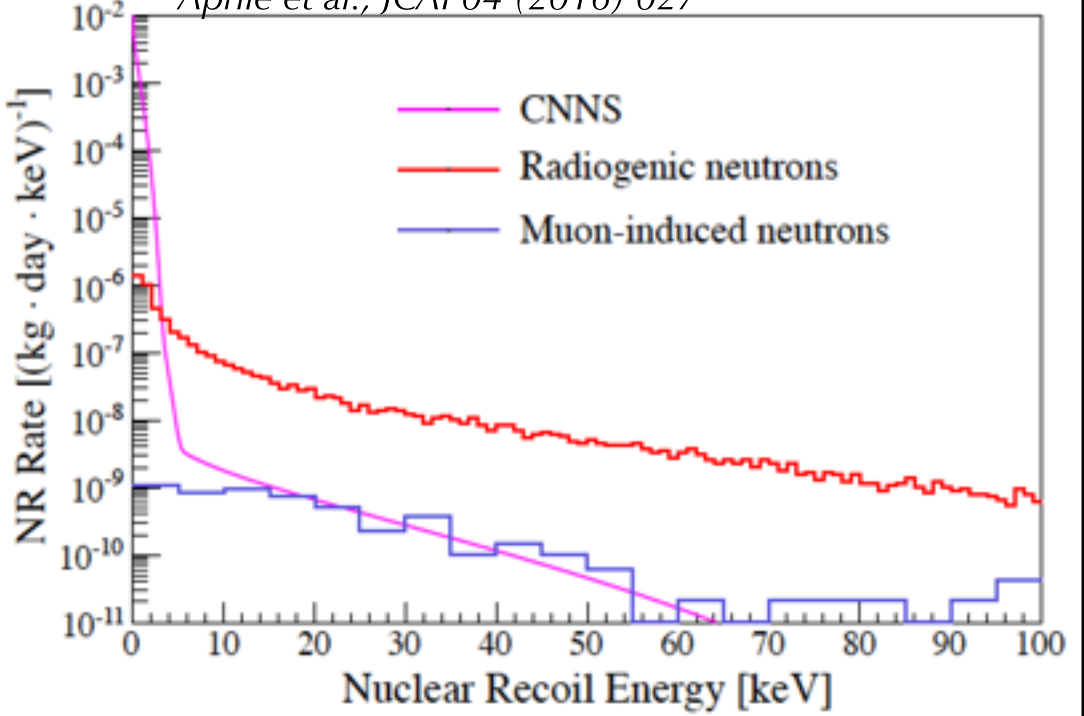
Φ(solar B^8) = 5.86 x 10^6 cm^{-2} s^{-1}



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



Aprile et al., JCAP04 (2016) 027



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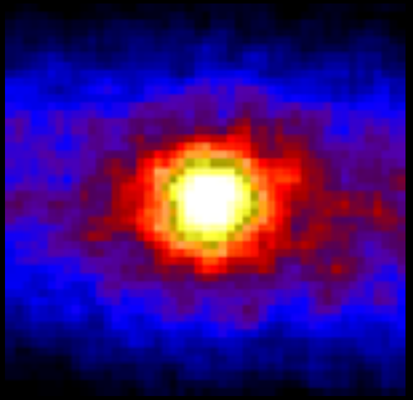

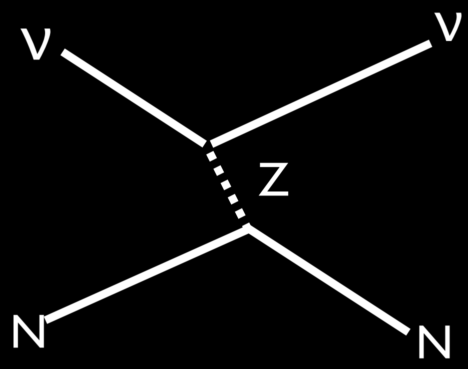

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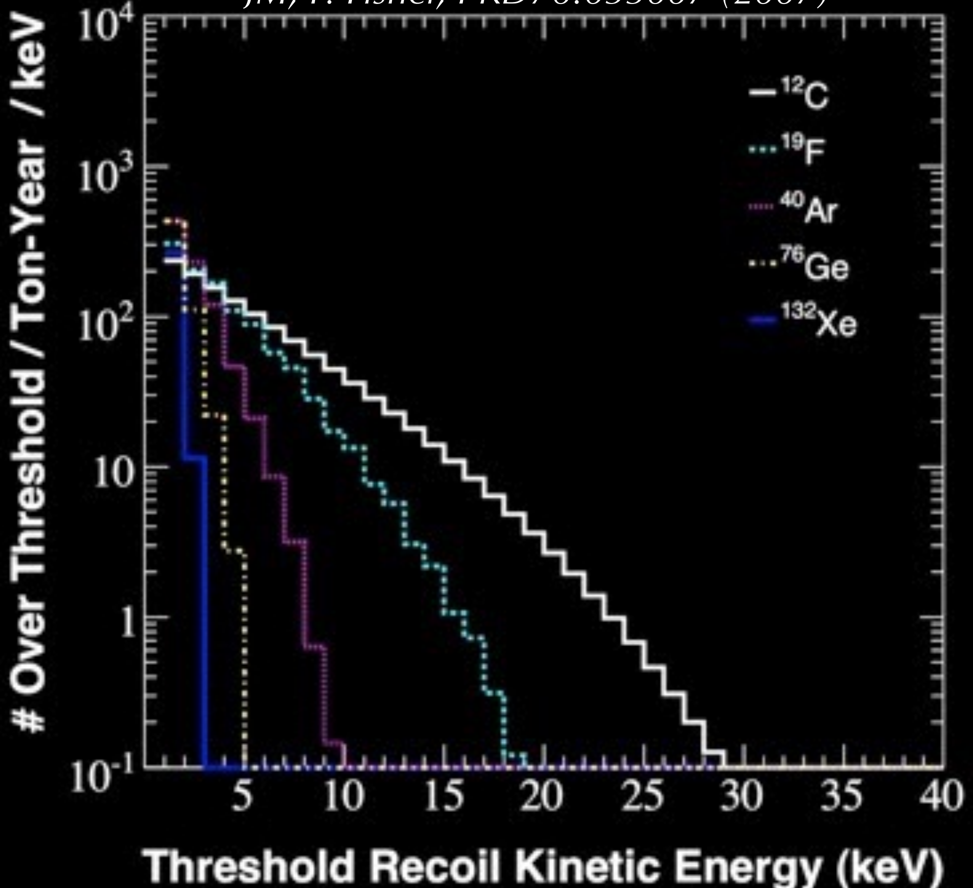


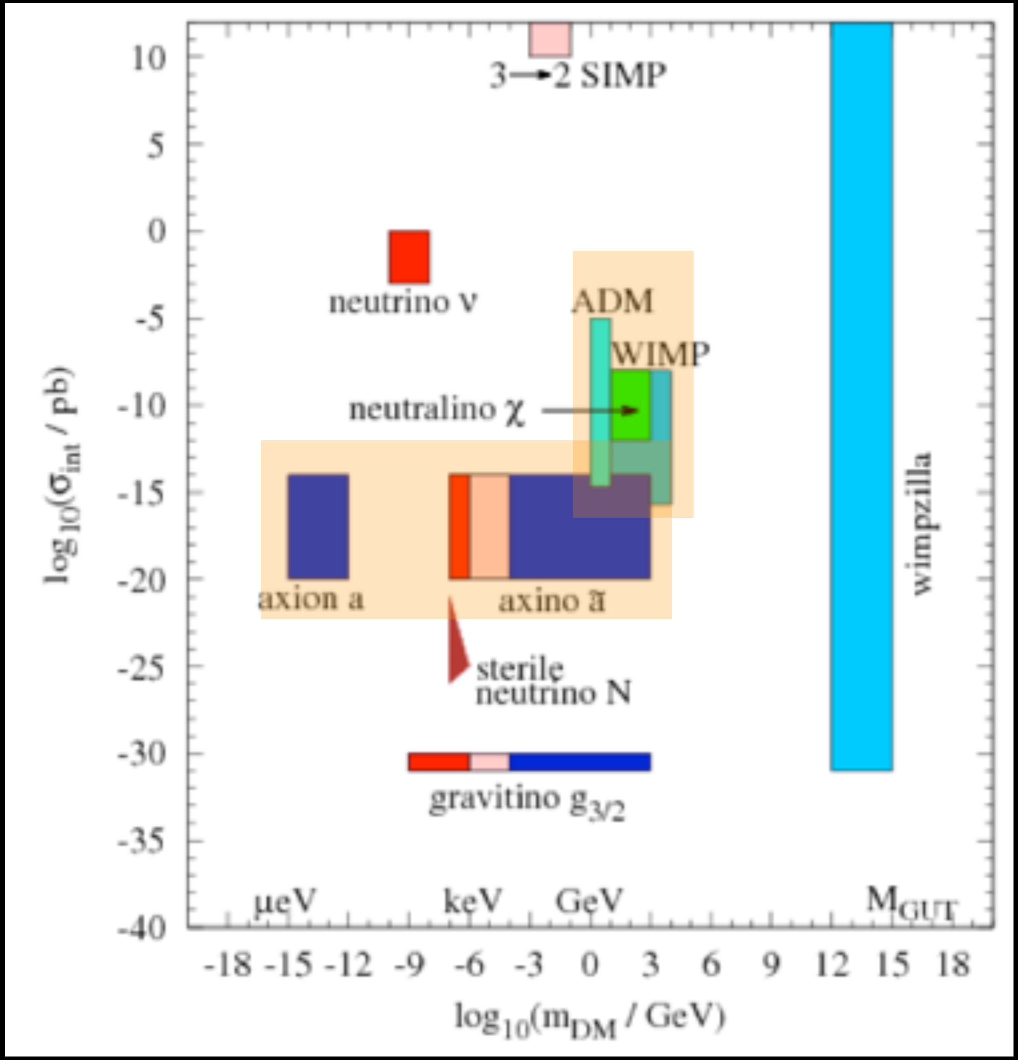
nuclear recoil final state
neutrino bound at 10^{-46}-10^{-48} cm^2
in zero-background paradigm

unless you measure the direction!

Model Space

Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity…



Baer et al., arXiv:1407.0017

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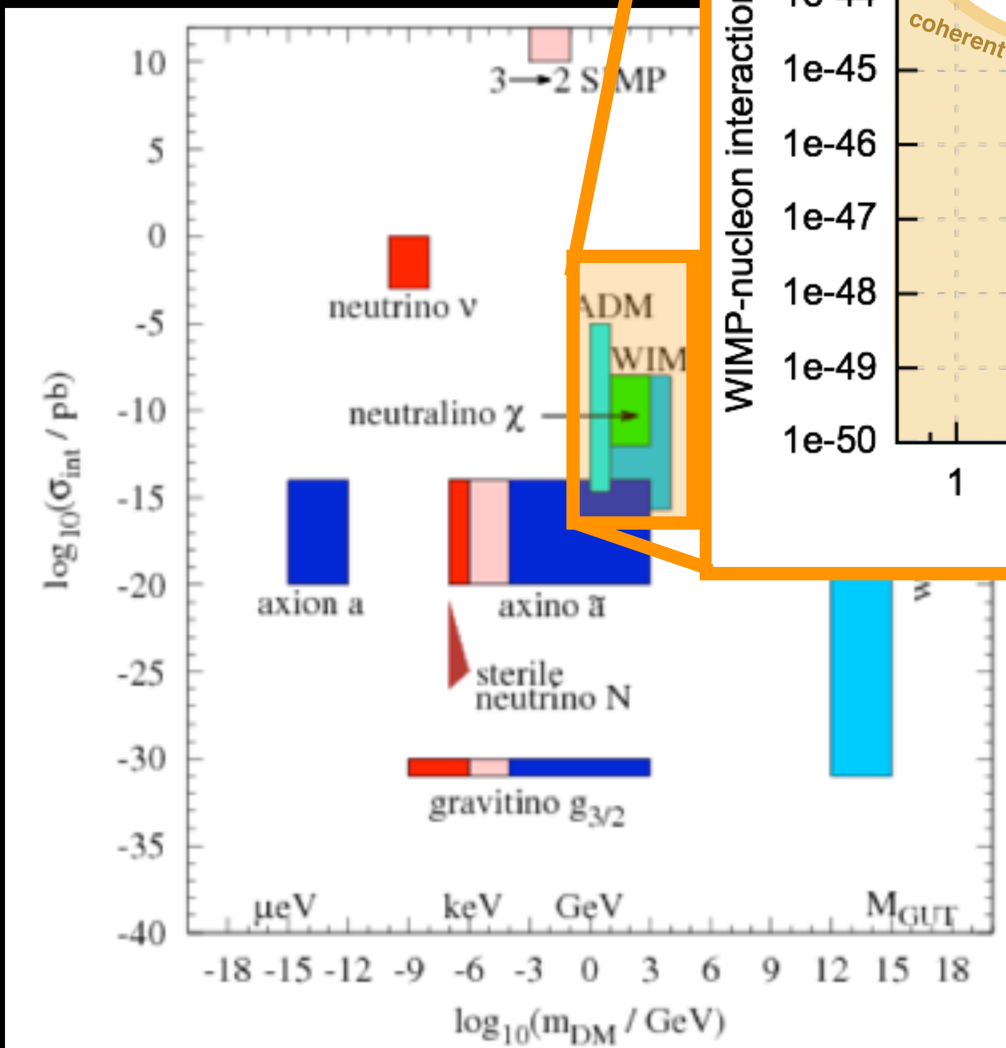
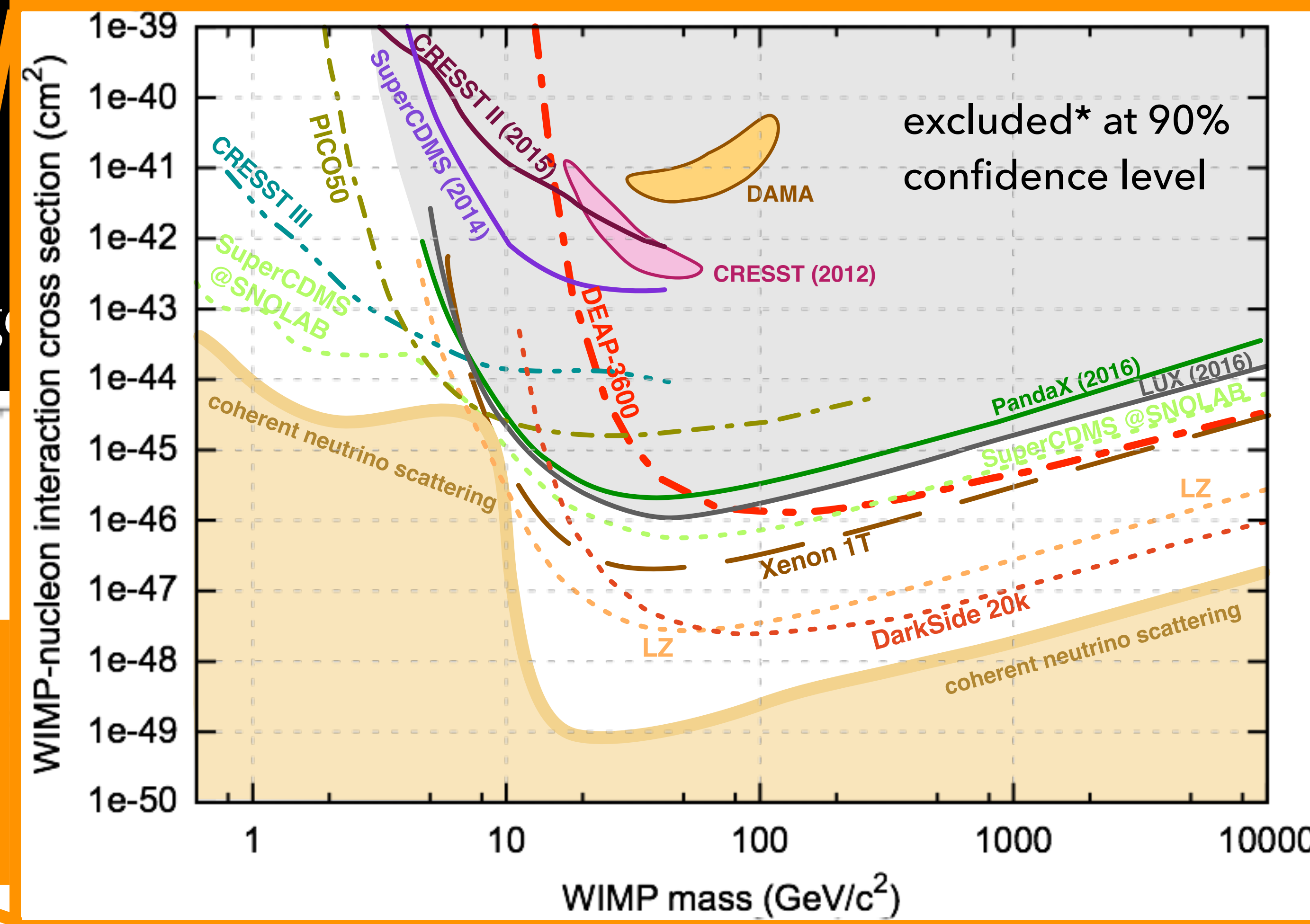
Direct detection searches g





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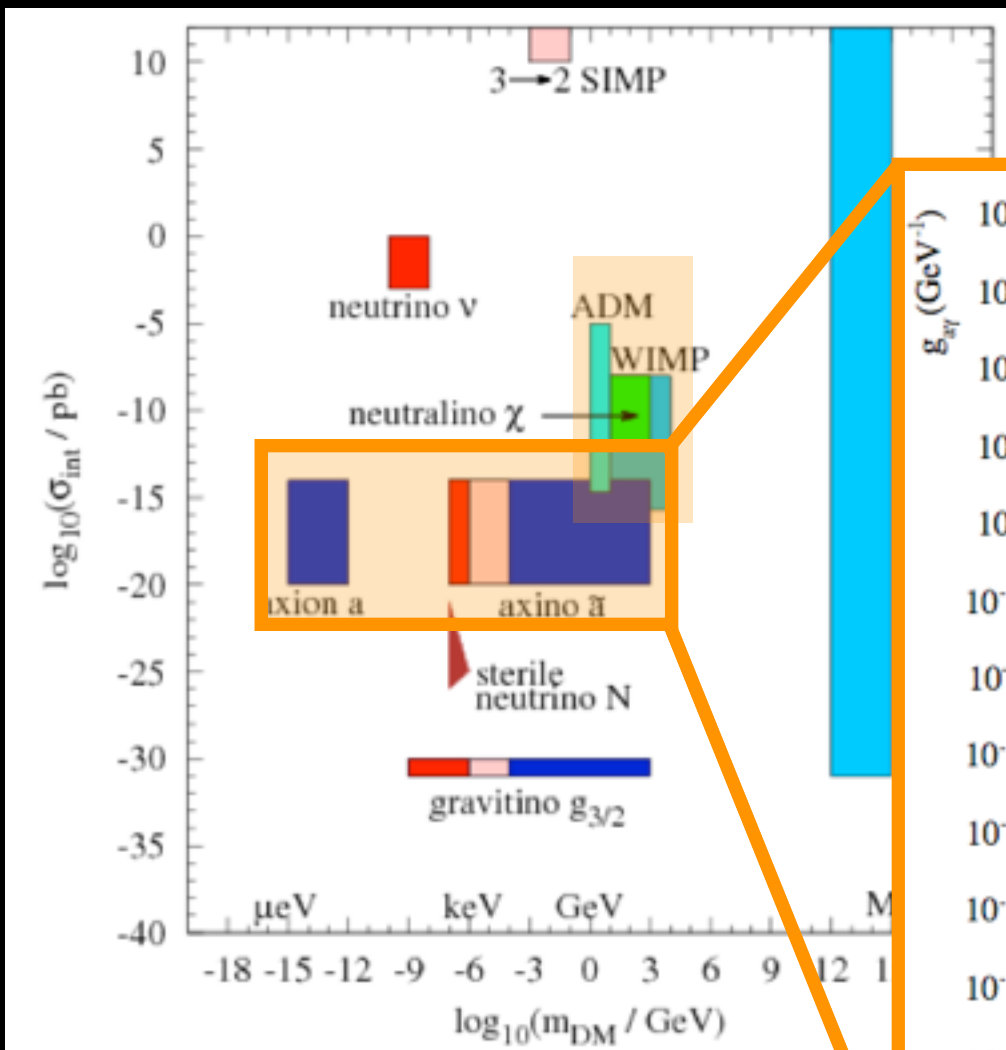
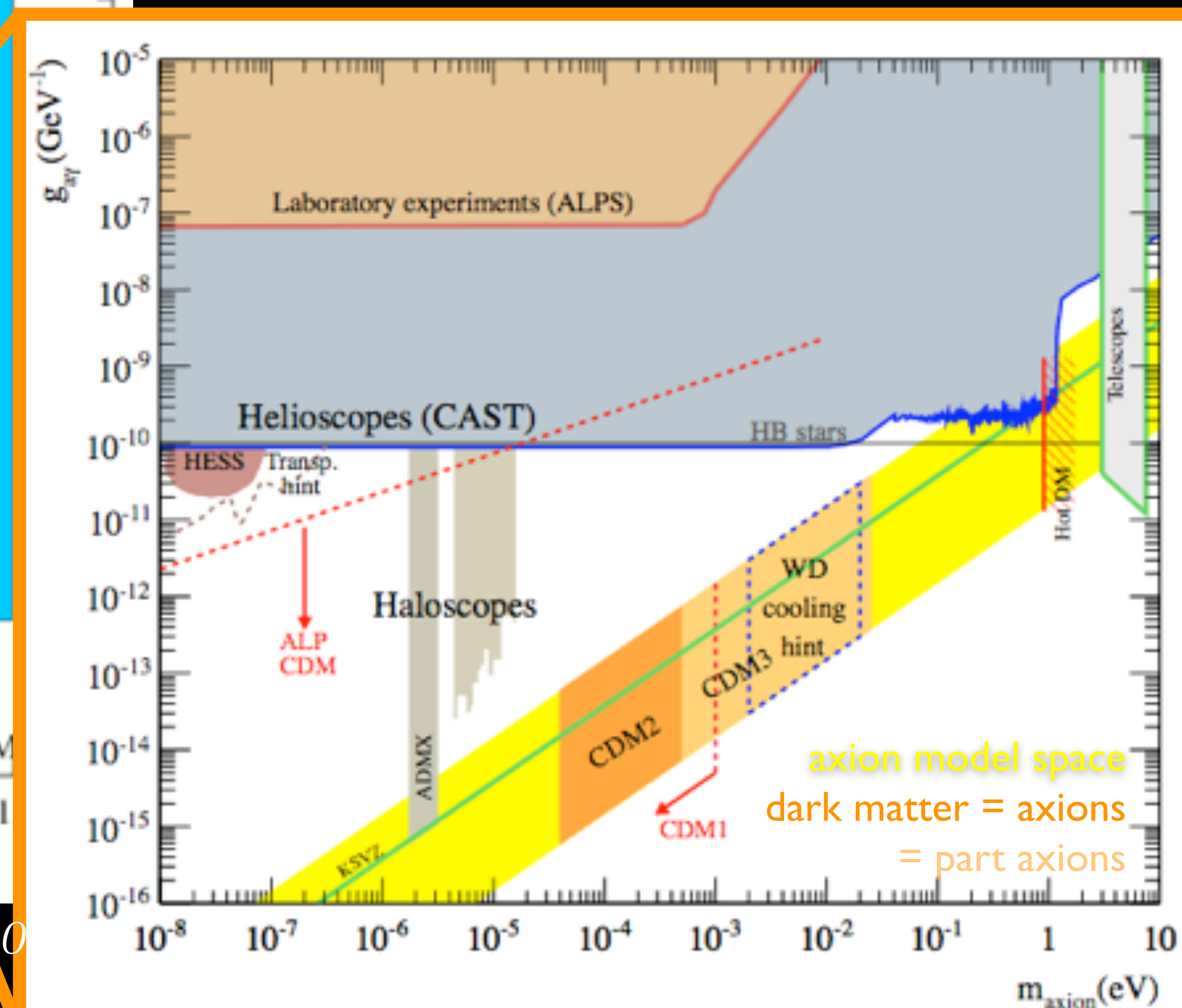


but starting to look for axions/ALPs too!



Baer et al., arXiv:1407.00

Points for Discussion

1) How will we know if we've found dark matter?

2) How important is background discrimination?

3) How high/low should we go, in mass?

4) How low should we go in cross section?

5) Should one draw limits from direct, indirect, and collider searches on the same plot?

6) What (or where) else should we look in direct detection experiments?

Points for Discussion

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2) How import

3) How high/lo

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5) Should one … llider searches on the same plot?

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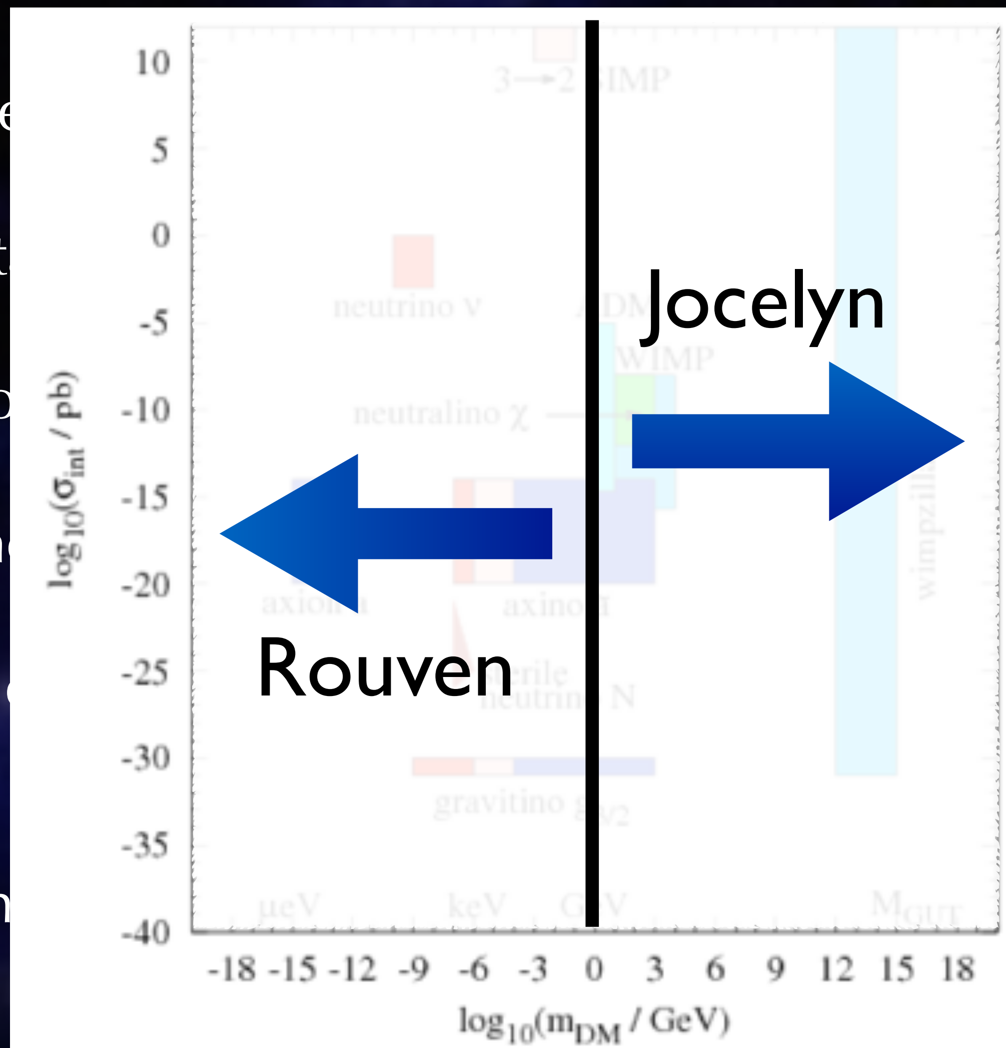


How Will We Know ~~If~~ When We Find Dark Matter?

Detection Signature

PICO

Cogent COUPP

Picasso

Newage

DRIFT

ArDM

Xenon1T

DarkSide

CDMS

EDELWEISS

CoGeNT

LUX

LZ

Panda-X

DMTPC

ANaIS

XMASS

DEAP3600

CRESST

COSINE

Dama/LIBRA

CRESSTII

ROSEBUD

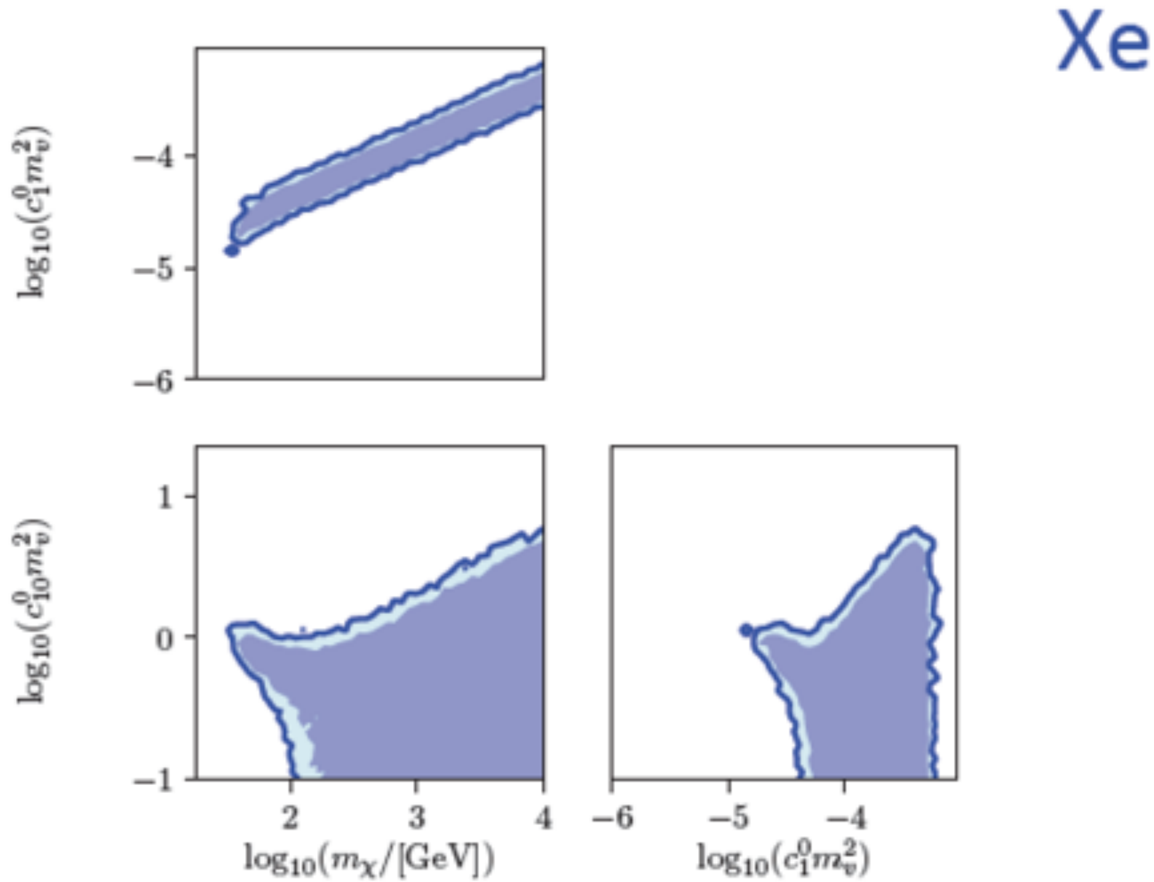
existing detectors: many targets (Xe, Ge, Ar, NaI, CsI, $CaWO_4$, CF_3I, C_3F_8, F ...)

Newstead et al., PRD D 88, 076011 (2013)
DARWIN, JCAP 10 (2015) 016

Complementarity

Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings



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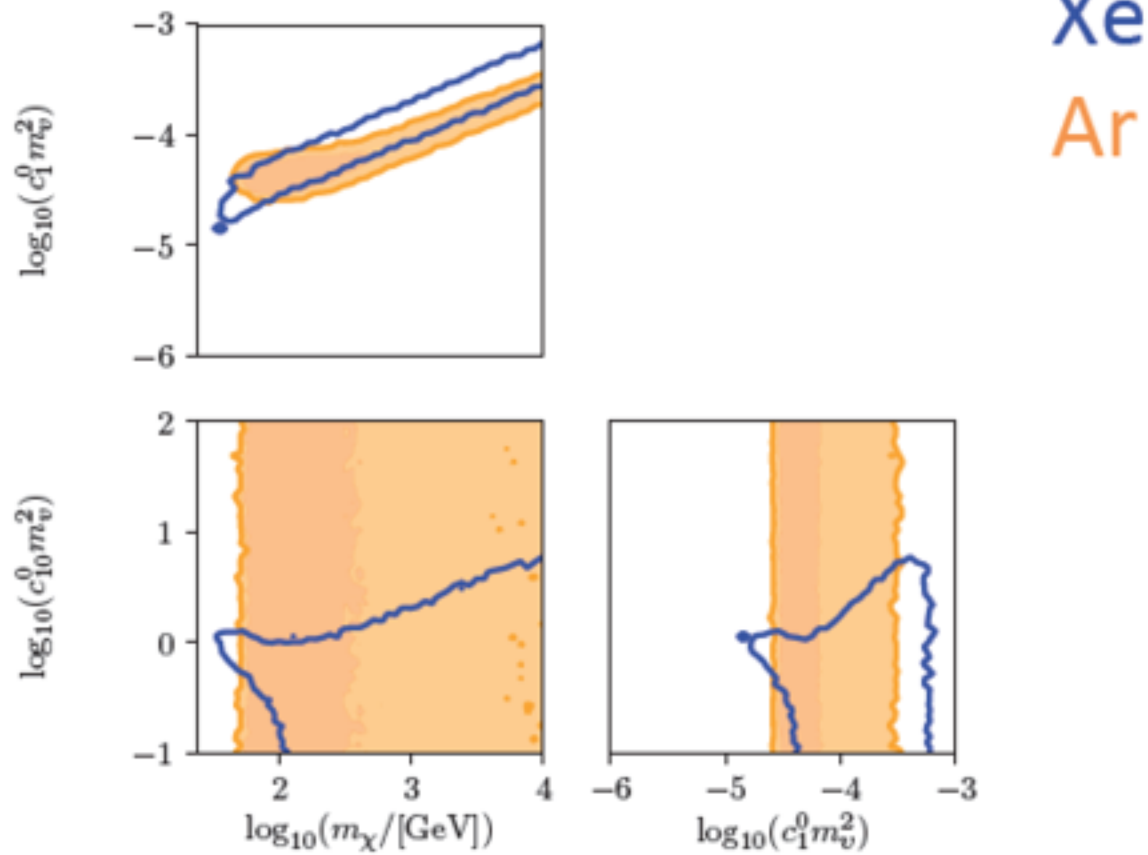

D. Cerdeno, IPPP April 2018

Complementarity

Example: Scalar DM – Scalar Mediator
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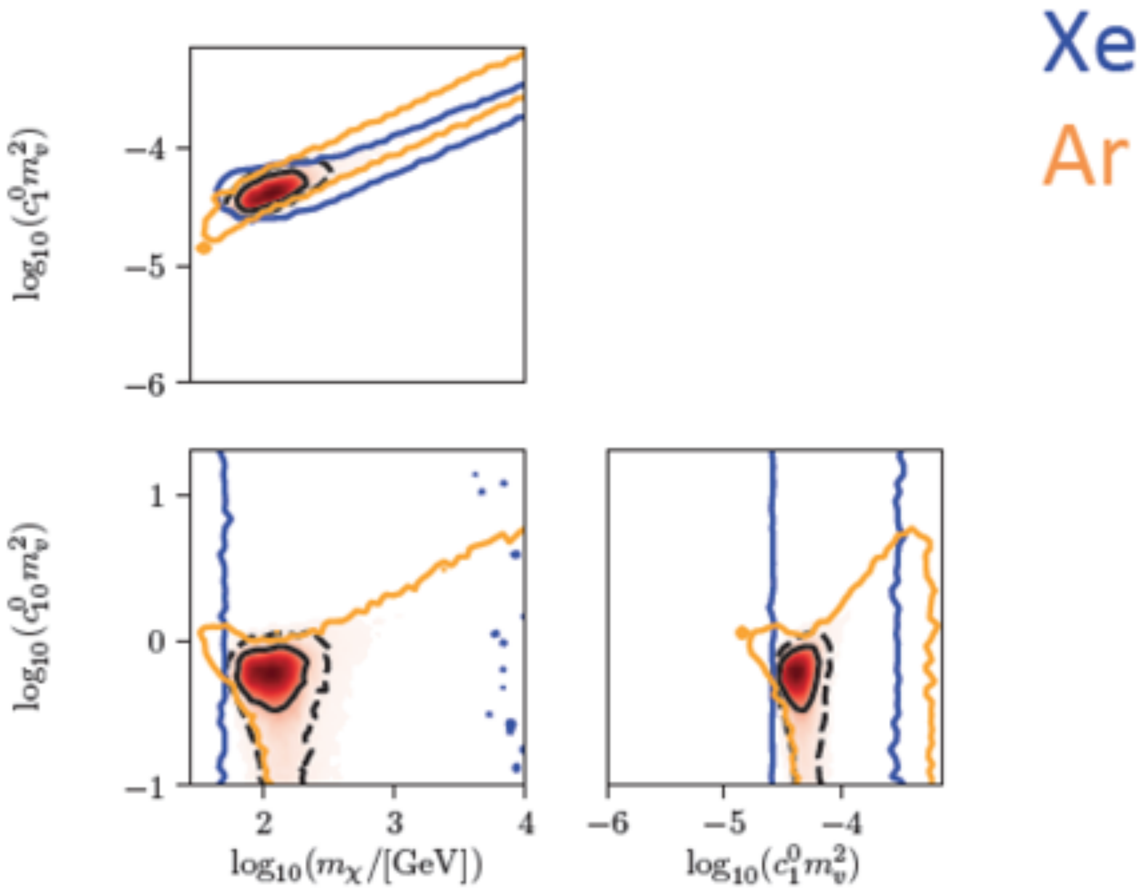
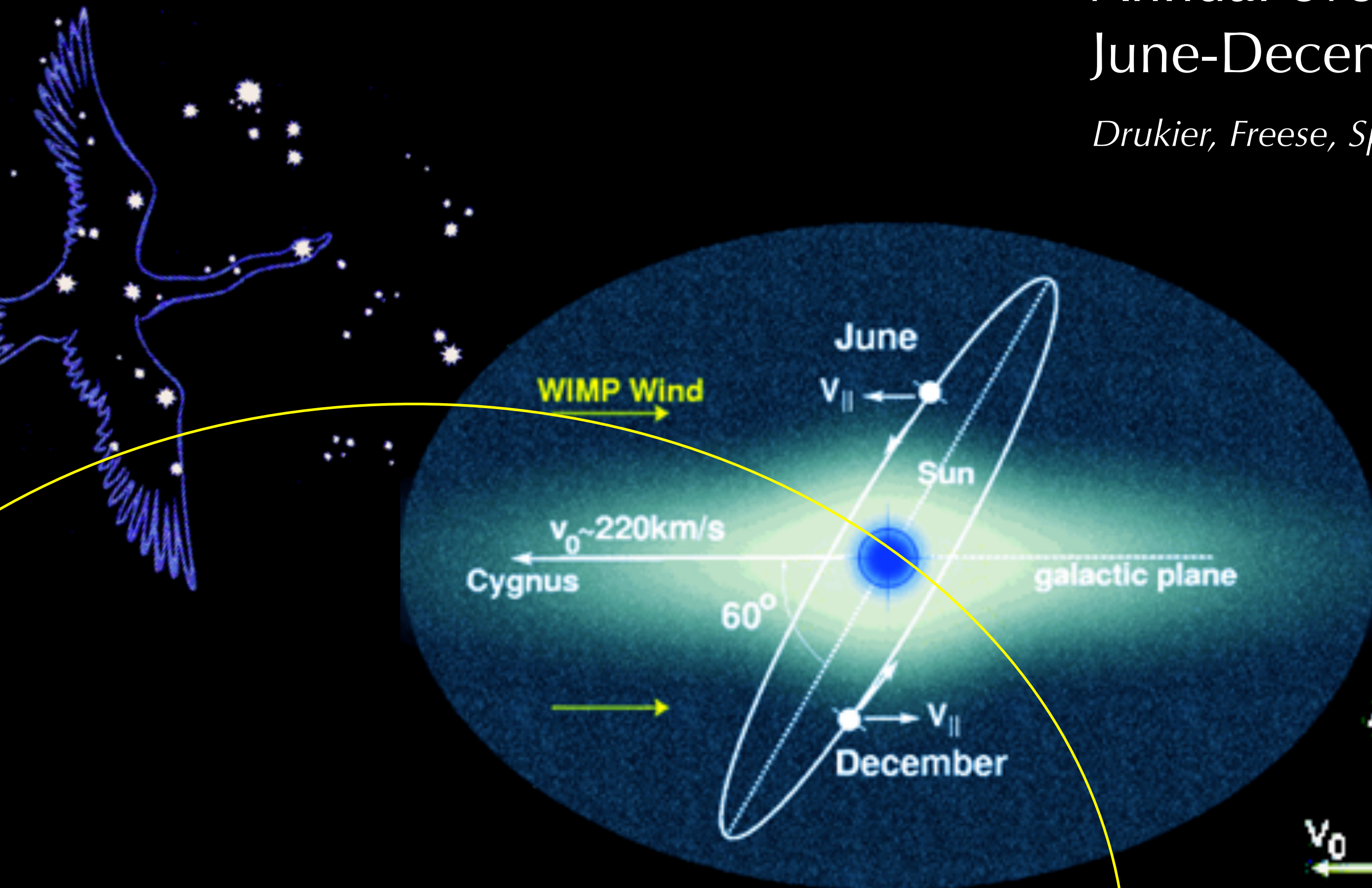
Combining data some degeneracies can be removed

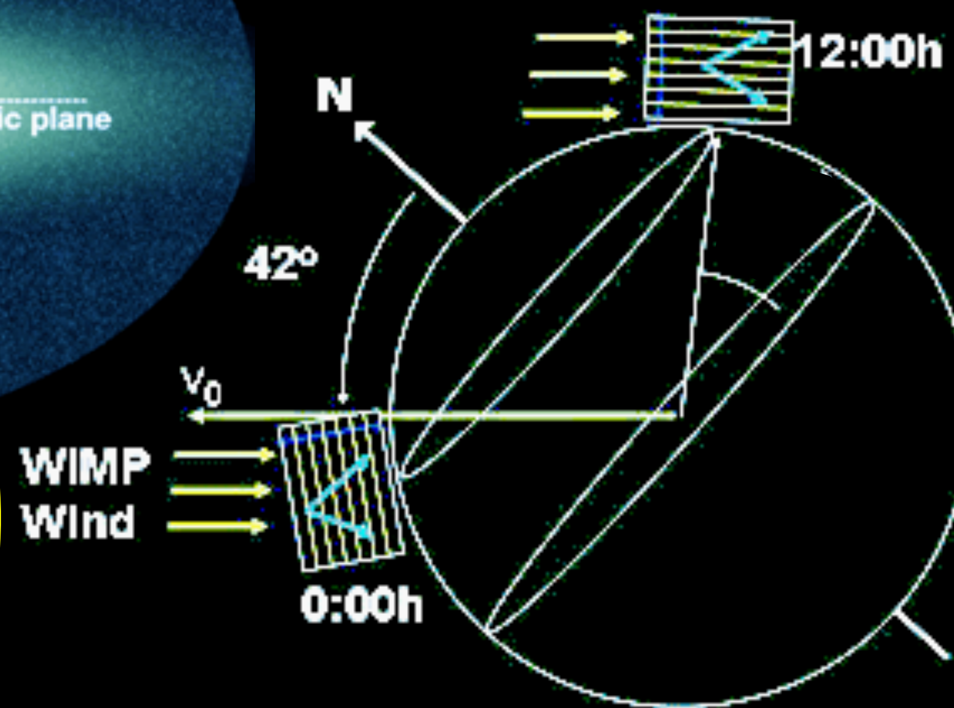


Modulation Signatures

Annual event rate modulation:
June-December asymmetry ~2-10%.

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





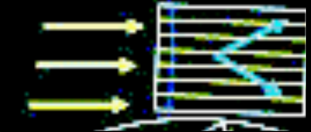
Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate.

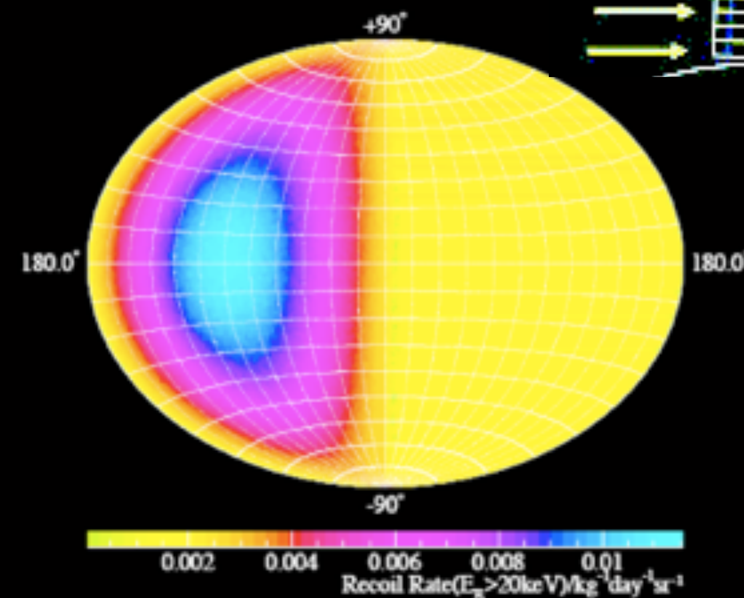
Spergel, Phys. Rev. D36:1353 (1988)

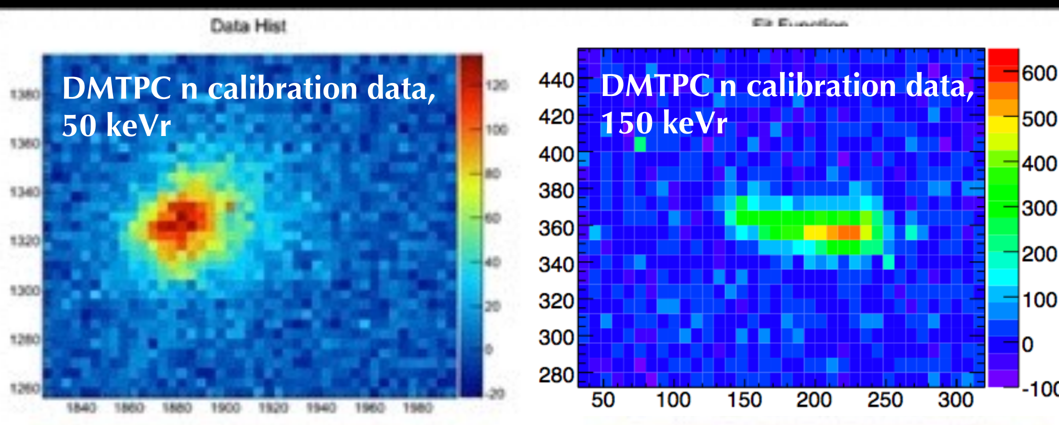
detector requirements: achieve + measure stability vs. time to a very high level!

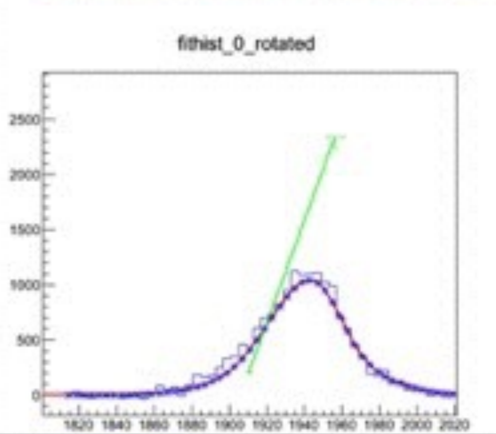
Directional Detection

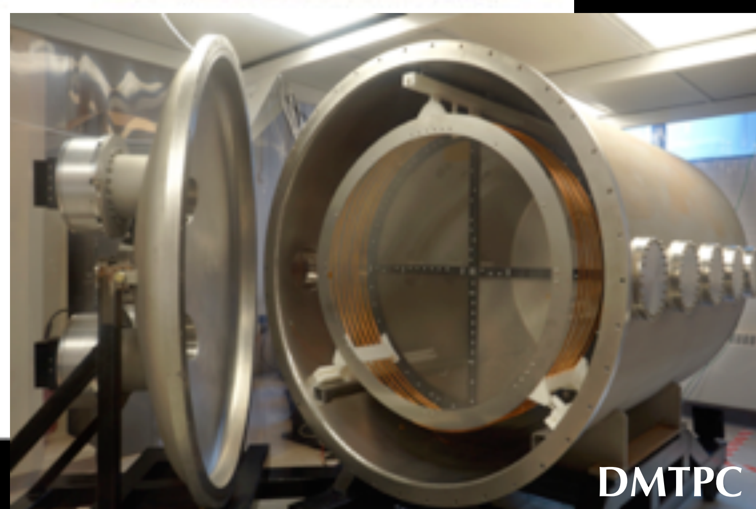
R&D towards recoil *direction measurement* to correlate a signal with the galactic halo











Many R&D efforts:
DRIFT, DMTPC, MIMAC, NEWS, RED etc.

largest are 1m^3 (O(100g) target).

Majority use CF_4 gas; NEWS uses emulsions.

CYGNUS: global coordination towards a physics-scale directional experiment.
Physics Reports 2016, arXiv:1602.03781

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

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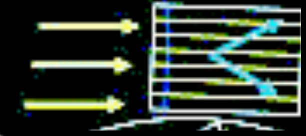
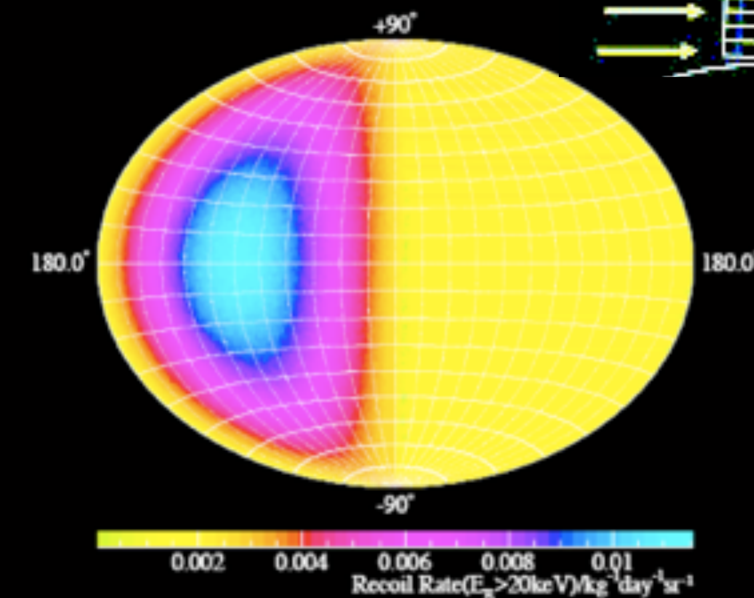
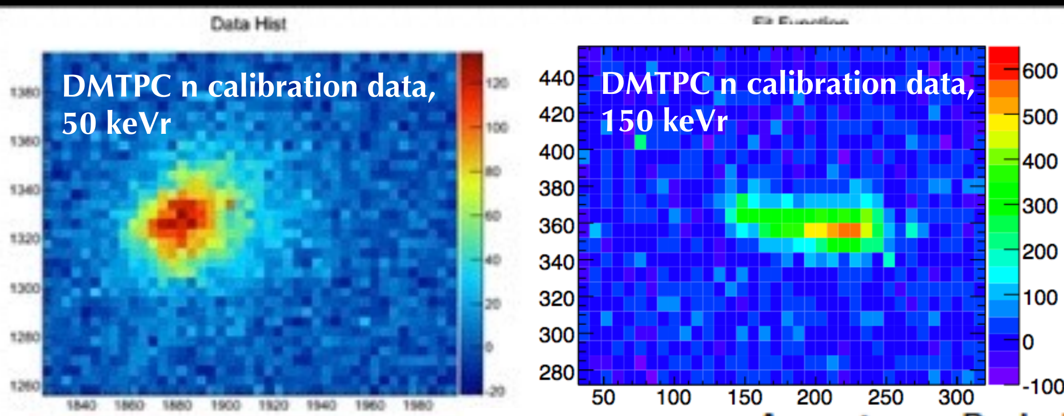
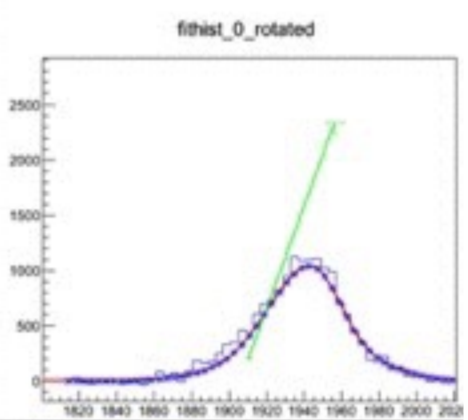
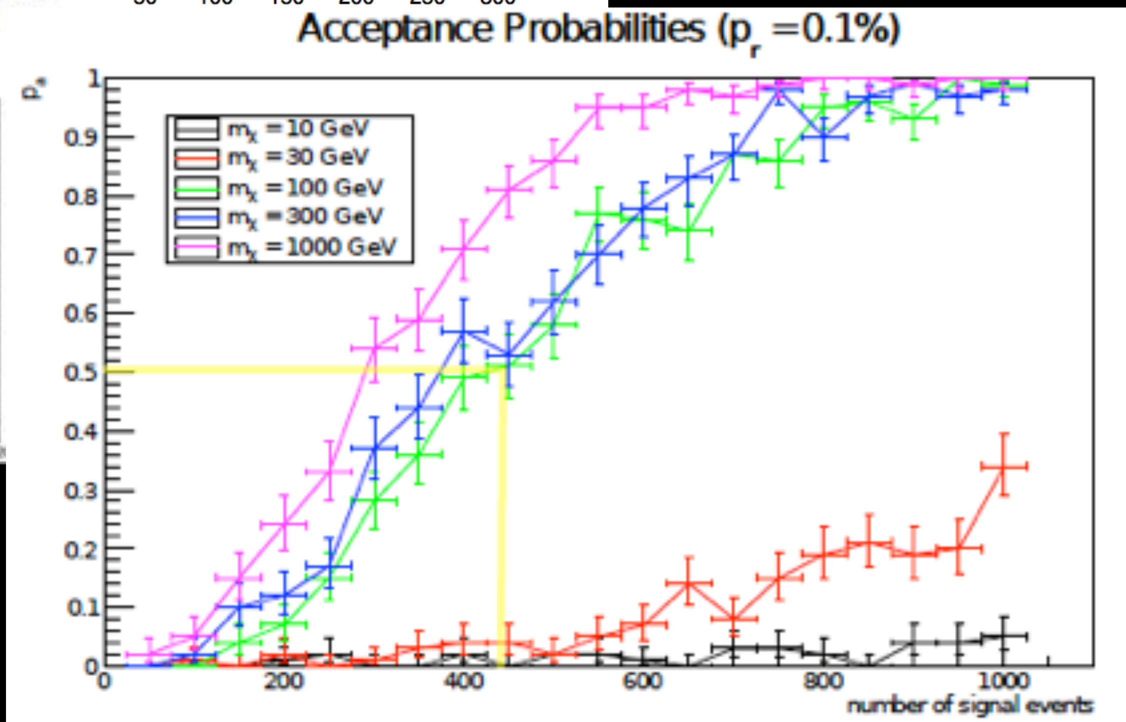










detectors achieve angular resolution of ~35° at 50 keVr

with current best direction reconstruction, need 200-400 events to measure anisotropy at 3σ significance

Phys.Rev.D95 (2017) 122002

How Important is Background Discrimination?

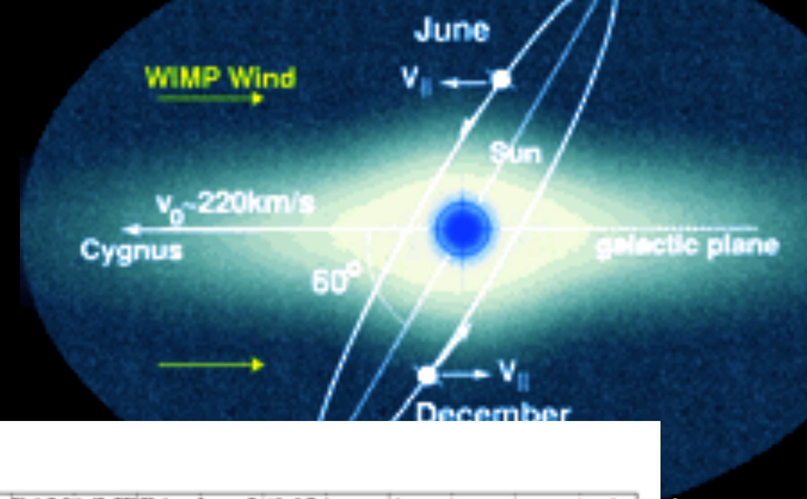
How Important is
Background Discrimination?

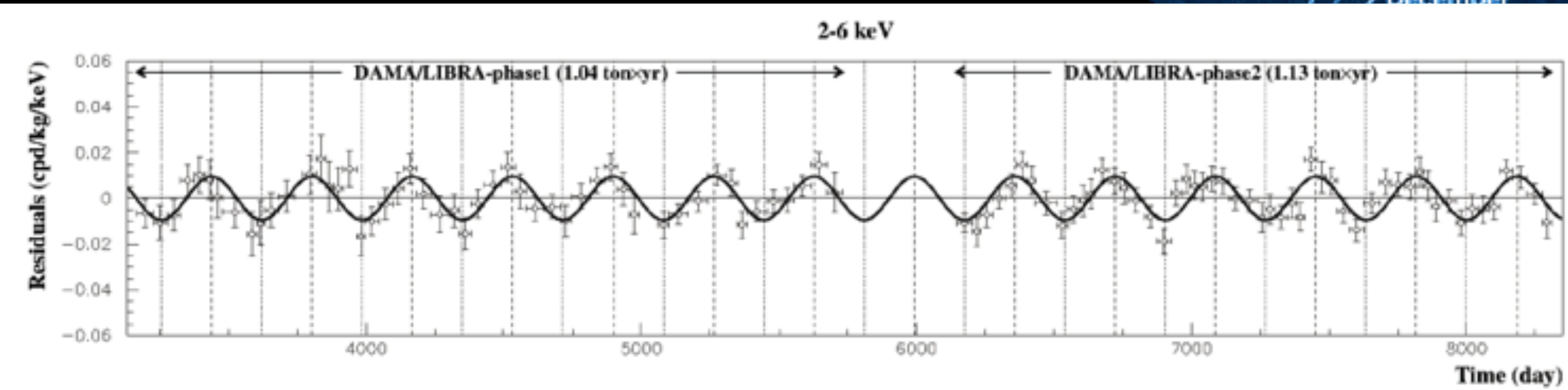
It is essential.

Annual Modulation Tests

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

DAMA/LIBRA: measure (0.0095±0.0008) cpd/kg/keV, t_0 = (145±5) d in 2.17 tonne-yr.



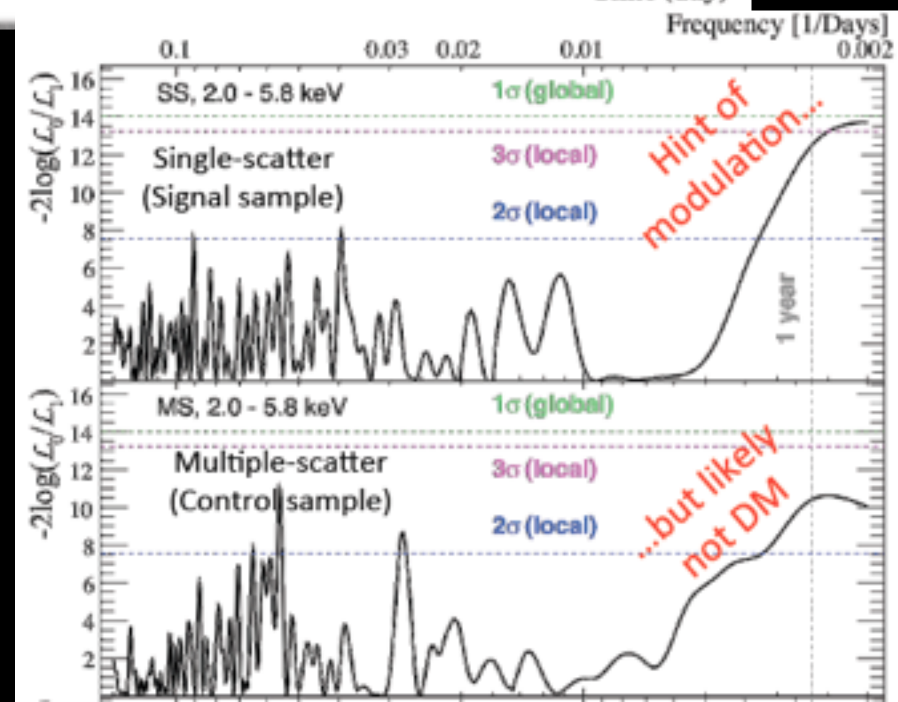


CSLNGS, March 2018

many other searches, on Ge, CsI, Xe, etc. observe no evidence of signal modulation.

In the same underground laboratory:
XENON100: Xe, 4.8σ exclusion of DAMA, test of leptophilic dark matter *arXiv:1507.07748*

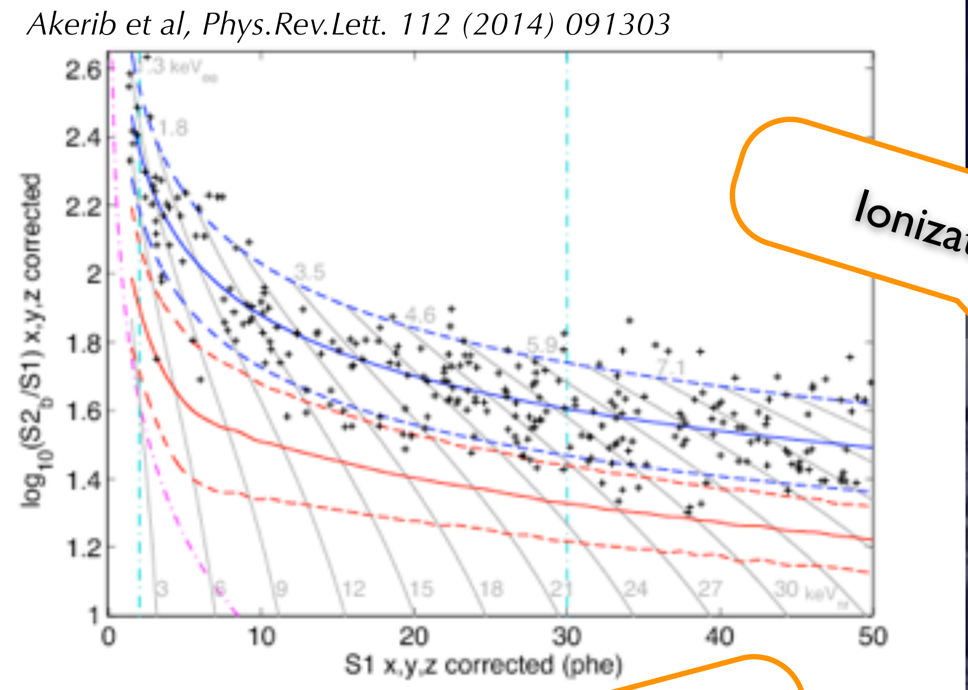
with the same target:
COSINE: NaI in S. Korea, 2-year run ongoing
Eur.Phys.J. C 78 107 (2018)



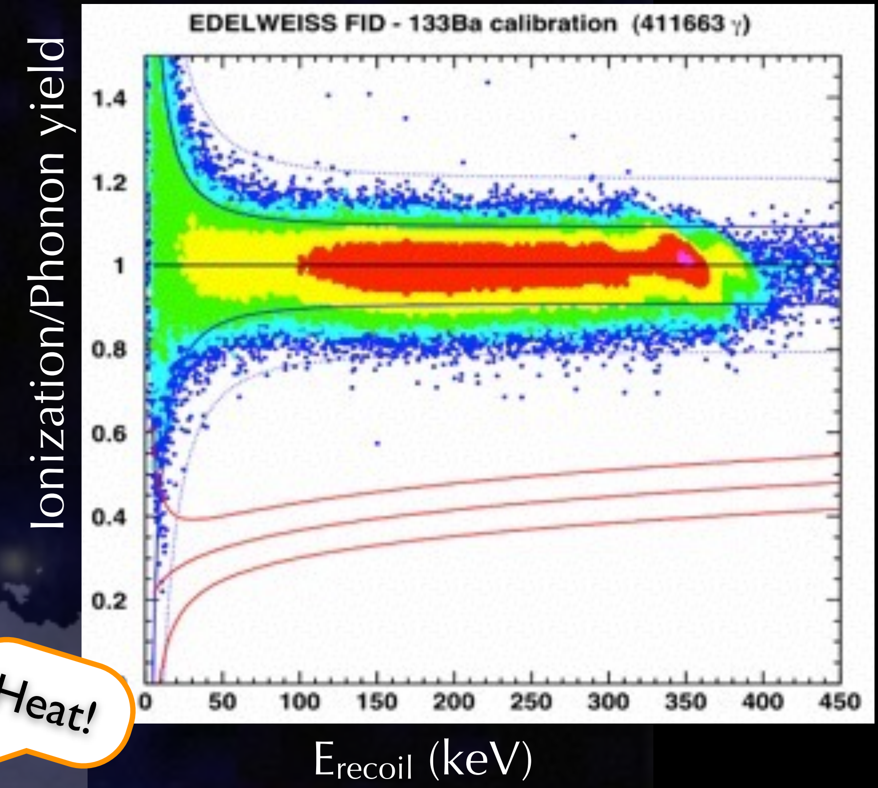
Jocelyn Monroe

Background Discrimination Strategies

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



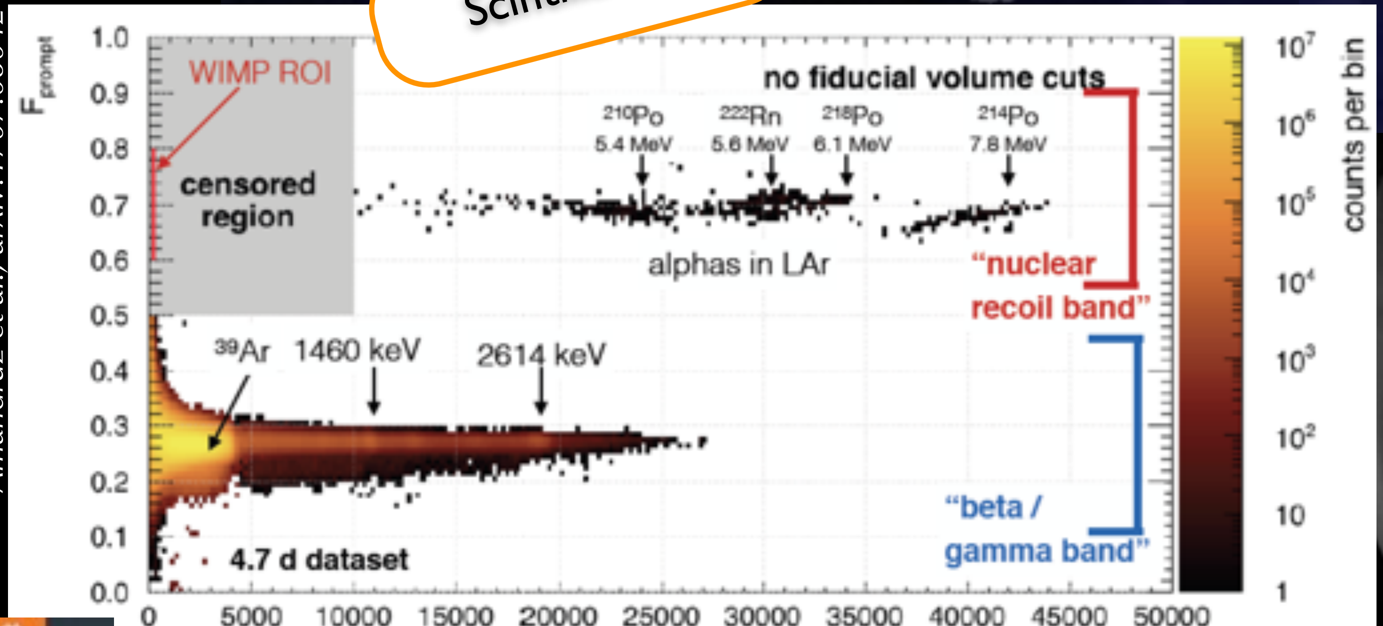
Ionization!

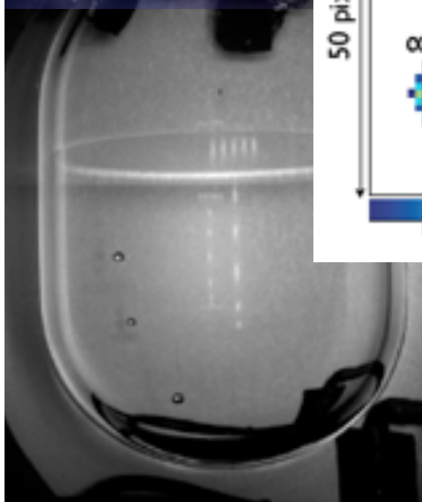


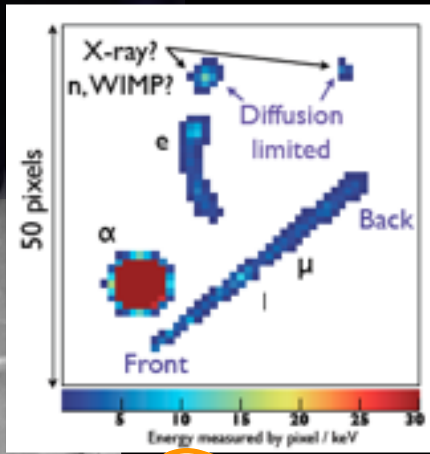
Heat!

Scintillation!

Amandruz et al., arXiv:1707.08042



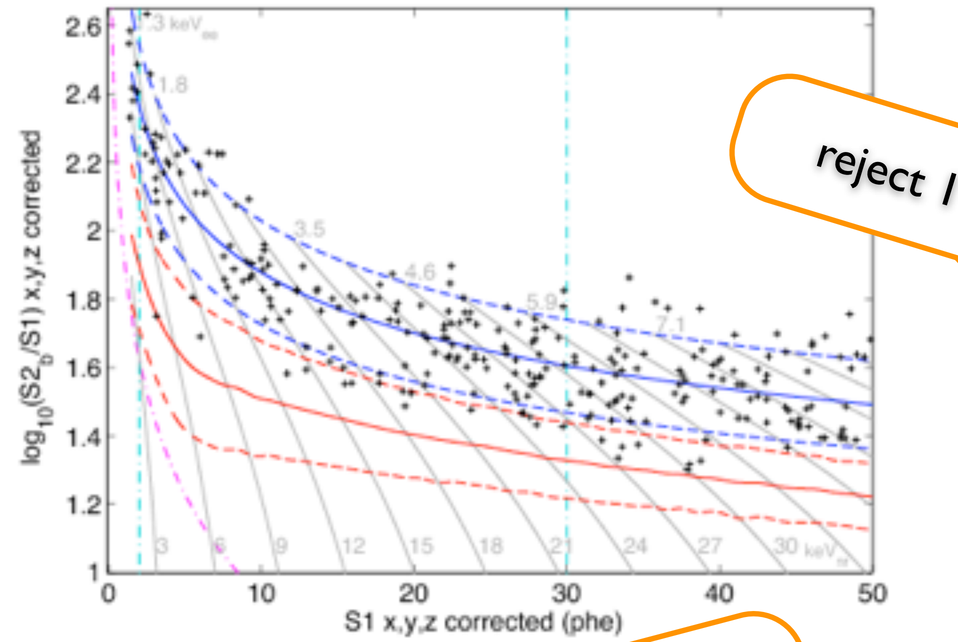




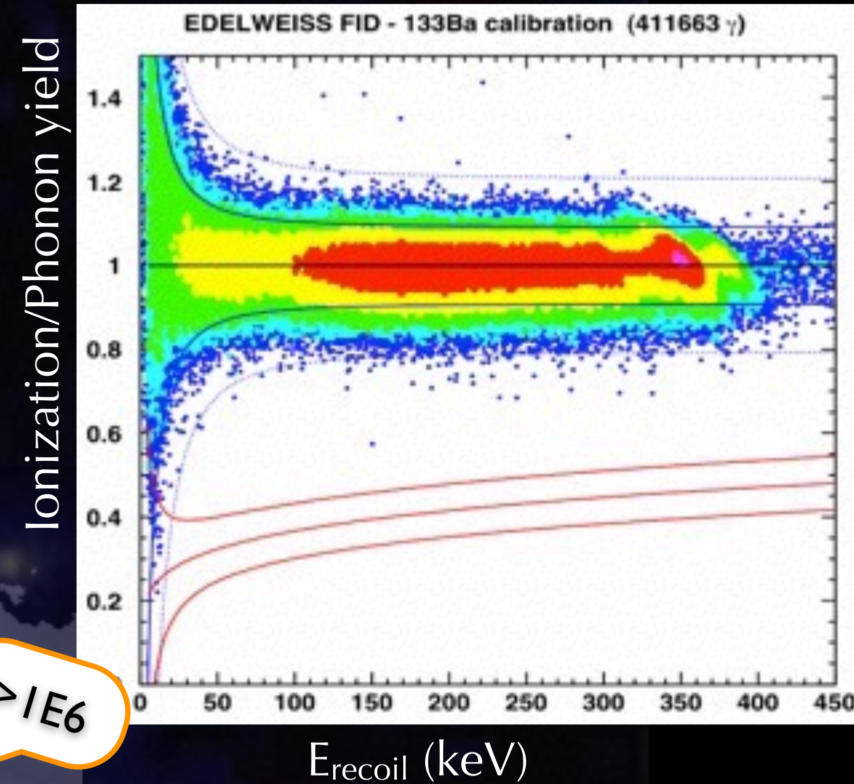
Topology

Background Discrimination Strategies

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



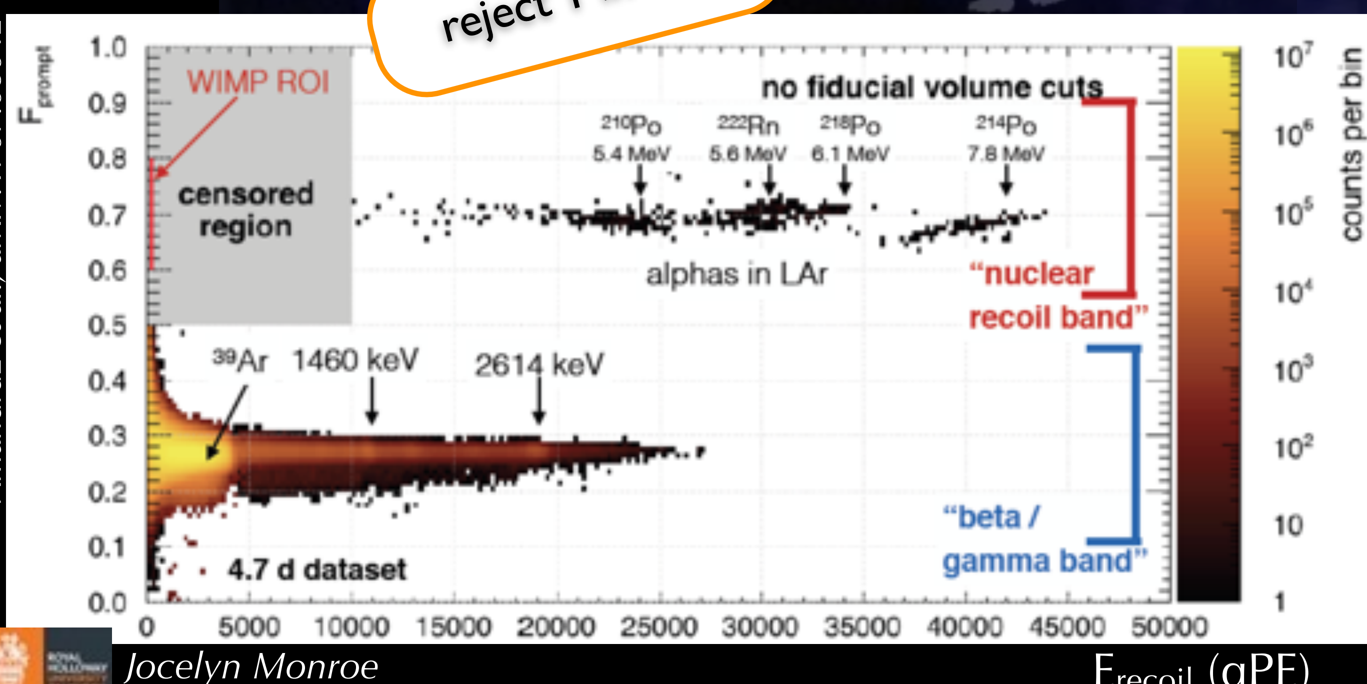
reject 1 in 1E3

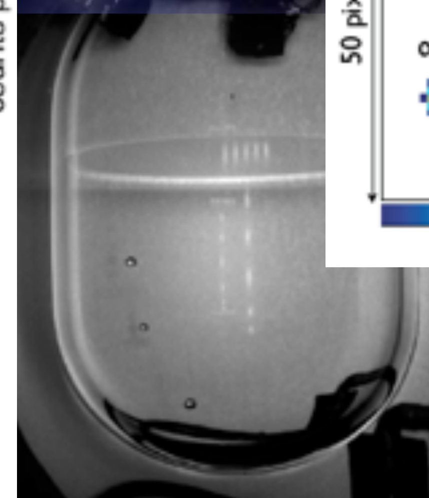


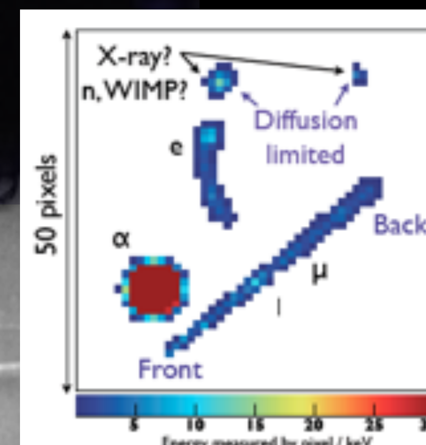
>1E6

reject 1 in 1E8

Amandruz et al., arXiv:1707.08042

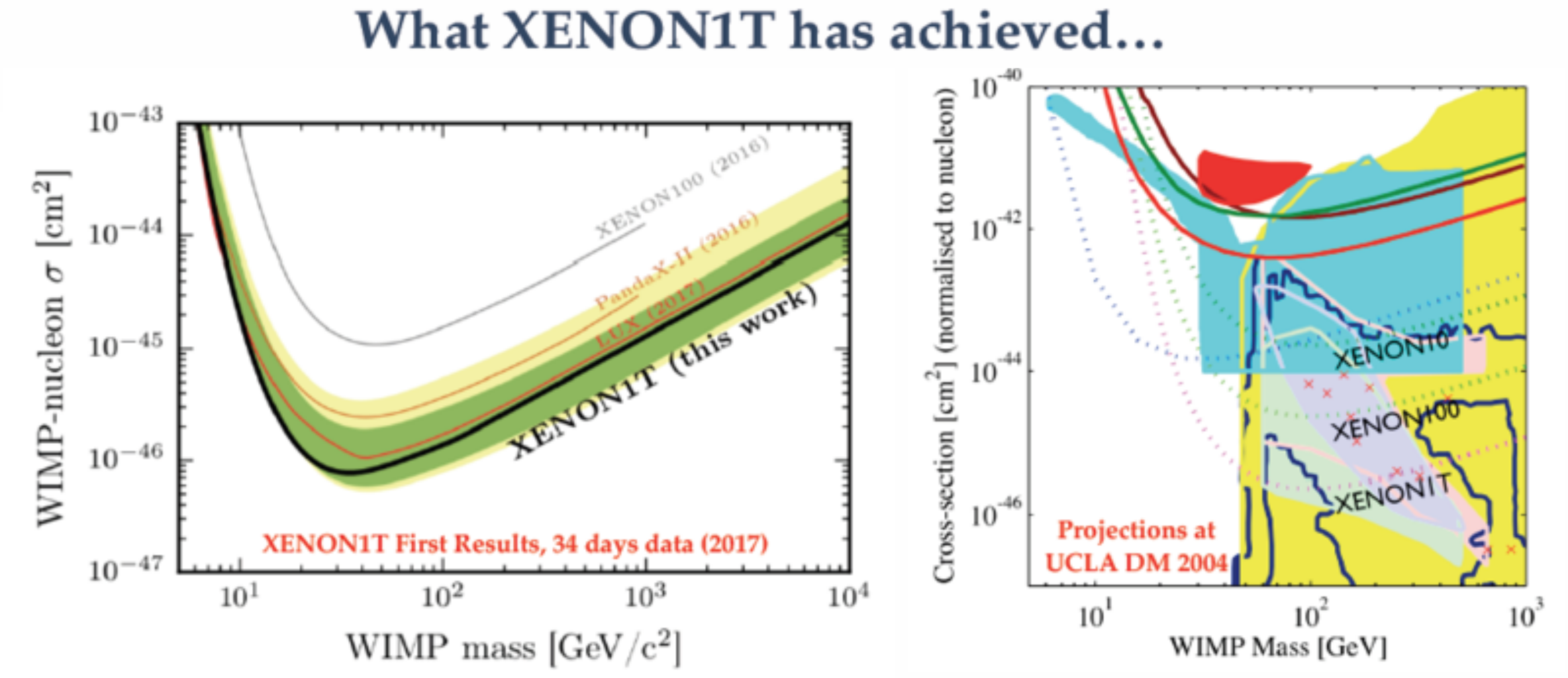






>1E2

Background Discrimination: Historical Optimism is Justified!



K. Ni, UCLA DM 2018

How High Should We Go?

Is High Mass Interesting?

Yes. >few hundred GeV is out of LHC reach, but accessible in direct detection experiments.

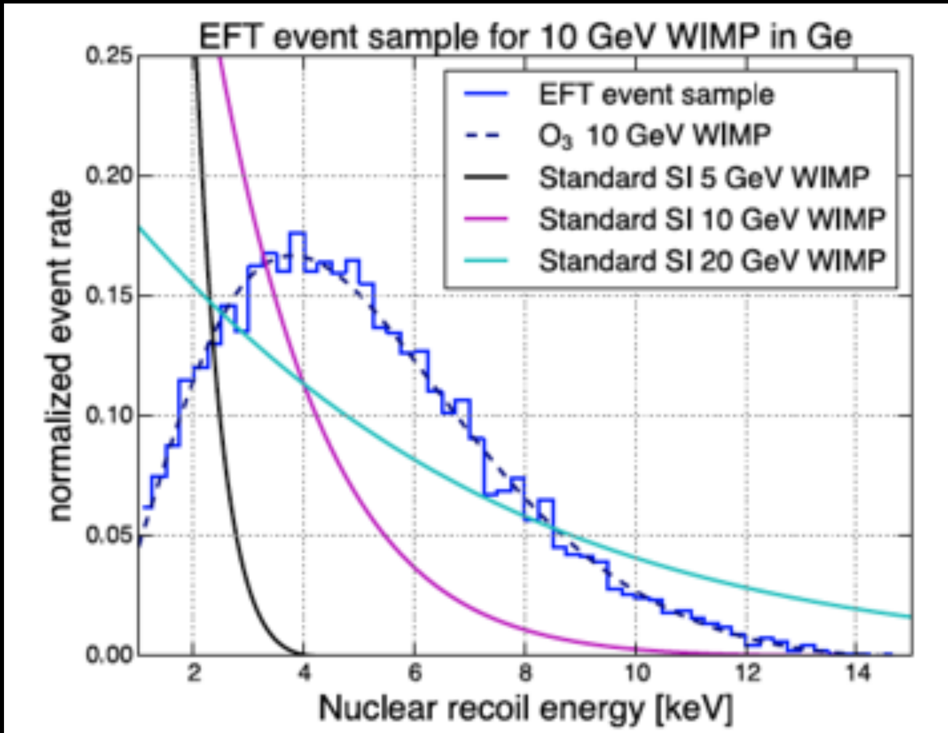
In EFT approach, the spectrum from possible interactions (e.g. momentum dependent) does not have the typical WIMP exponential.

Information isn't only at threshold!

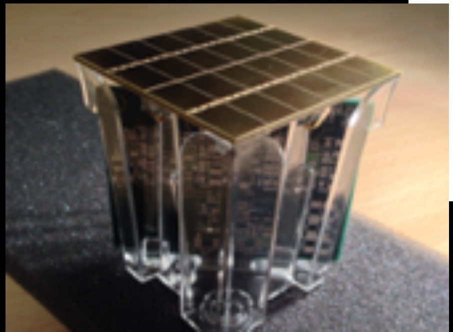
Beyond SUSY, variety of models can have DM candidates up to few TeV, e.g. little Higgs, warped extra dimensions, walking technicolor, …

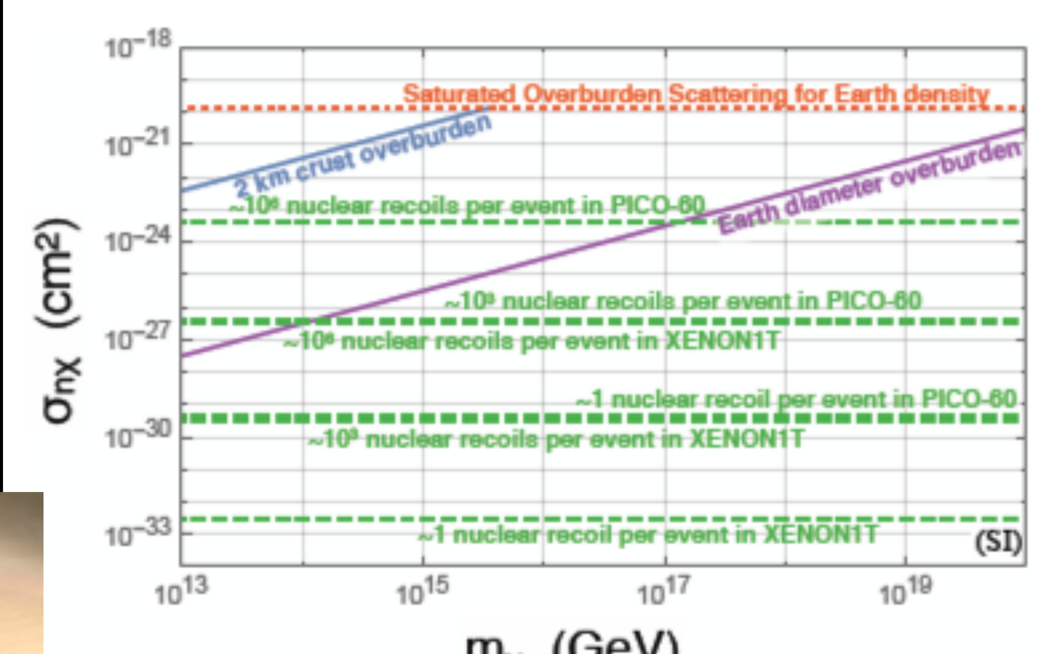
New ideas at higher masses:
- MIMPs
- composite states
- …

to be explored by DarkSide-20k, DARWIN, LZ, Xe-nT



25 cm² tiled SiPM





1803.08044

Aalseth et al, Eur.Phys.J.Plus 133 (2018) no.3, 131

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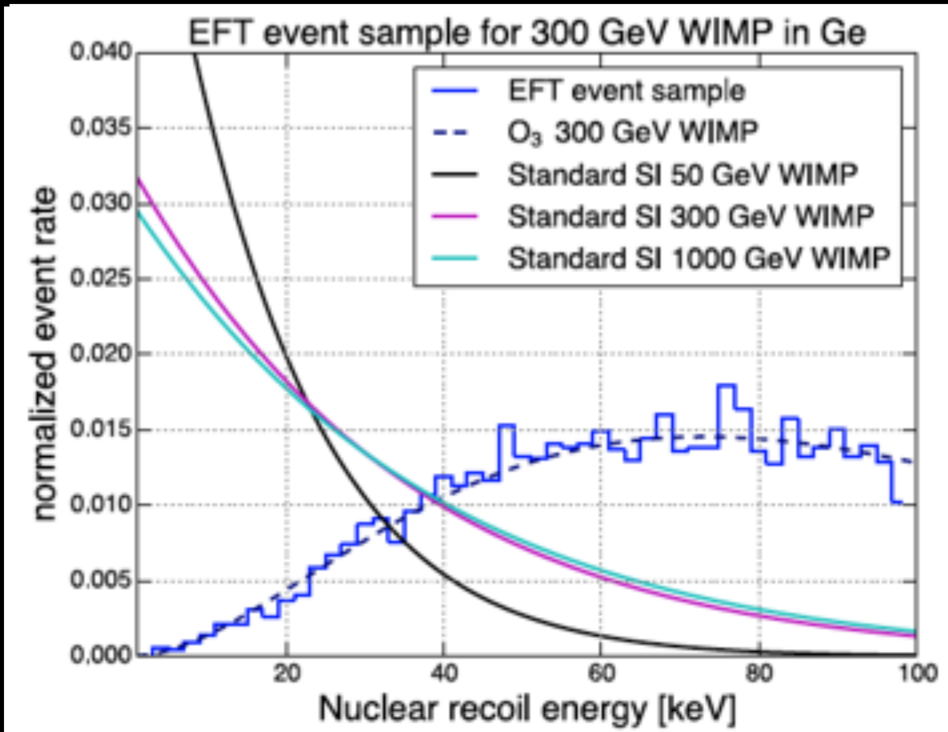
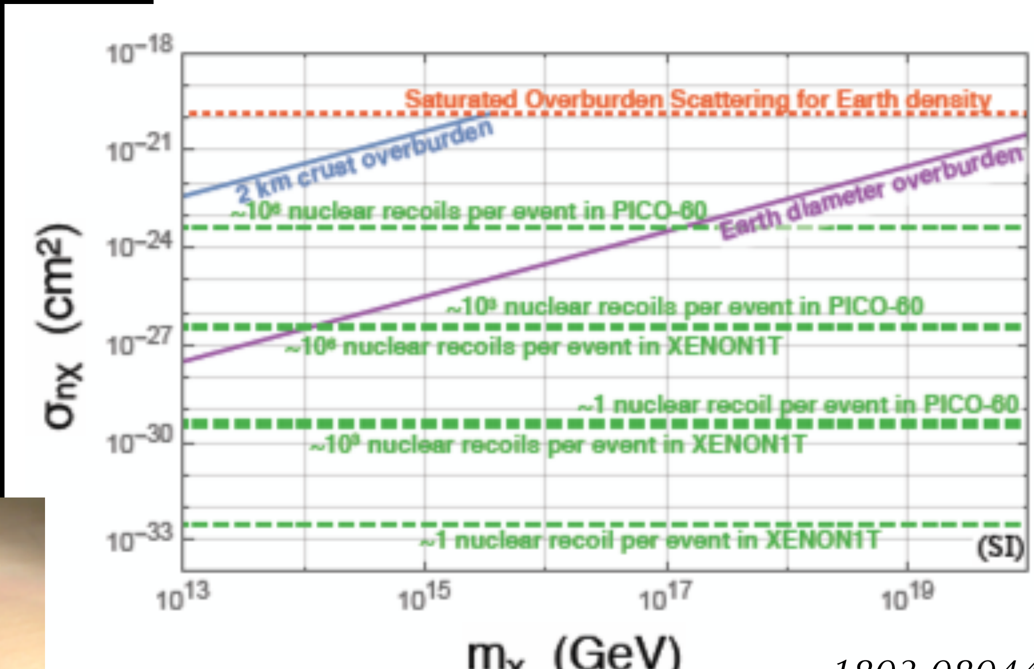


Aalseth et al, Eur.Phys.J.Plus 133 (2018) no.3, 131



1803.08044

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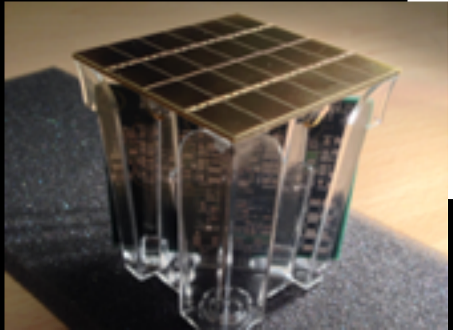
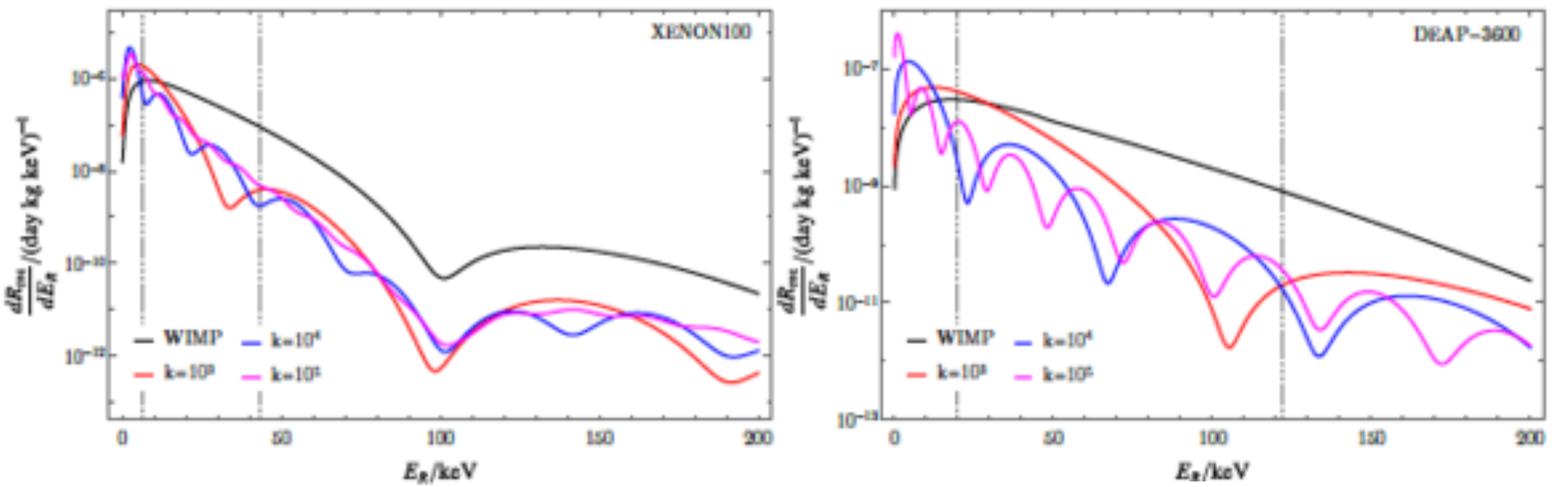


Spectral Distortion in Direct Detection, Prospects

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 light dark nucleons.

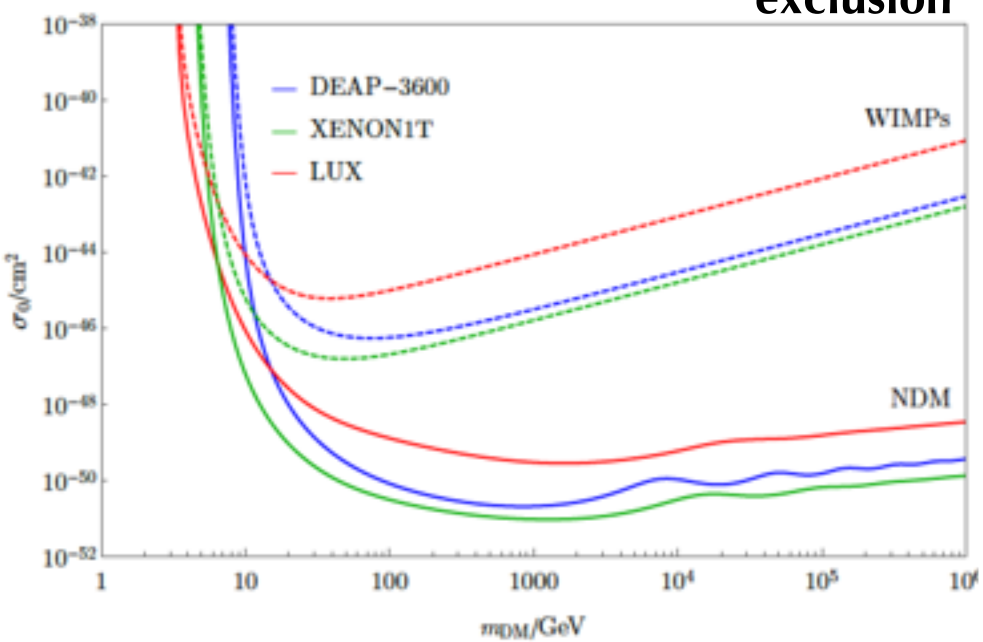
Scattering process now has a form factor from the nuclear dark matter and the target.



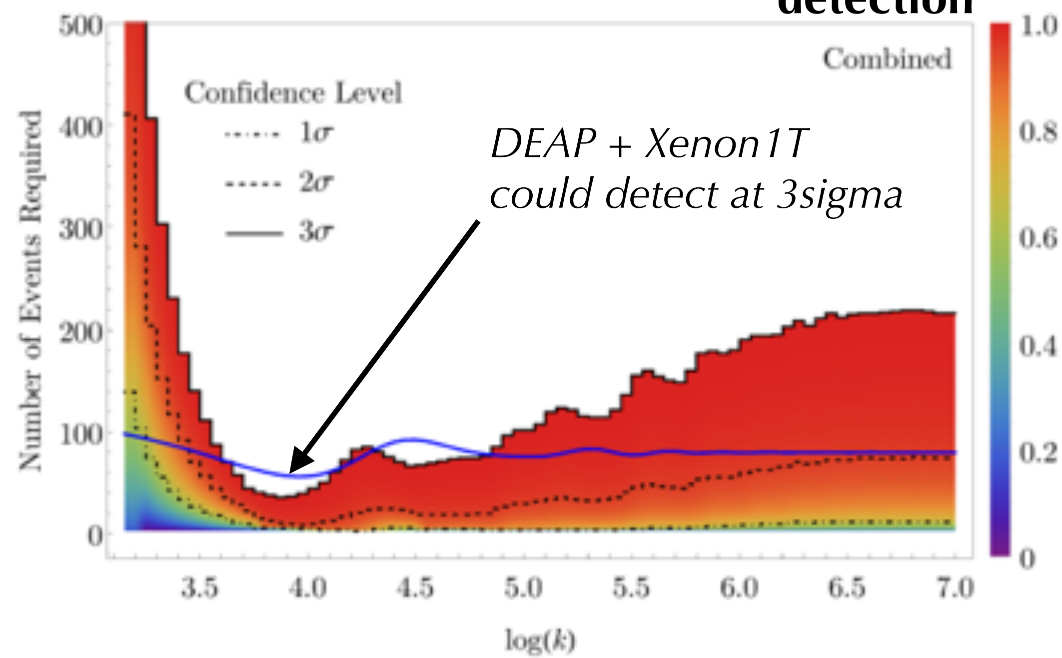
example: dark nucleon mass = 1 GeV, r = 1 fm, and per-SM nucleon xsec = 1E-46 cm^2.

Kirk, Butcher, JM, West, JCAP 1710 (2017) 10, 035

exclusion



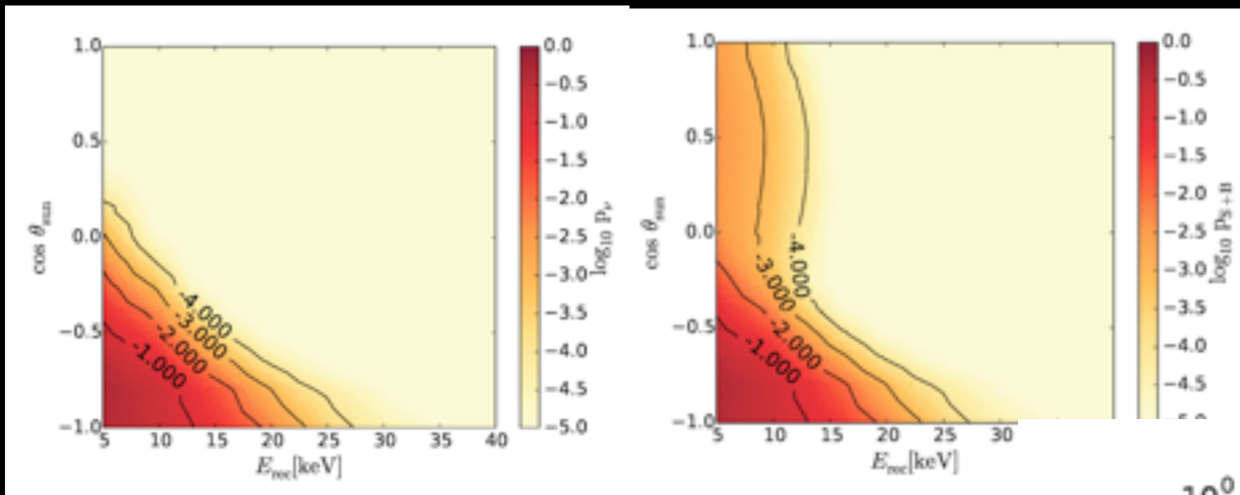
detection



How Low Should We Go (in Cross Section)?

Is the Neutrino Bound the End? No.

- sensitivity scales with sqrt(time) instead of linearly in time (with zero background)
- background systematics become crucial



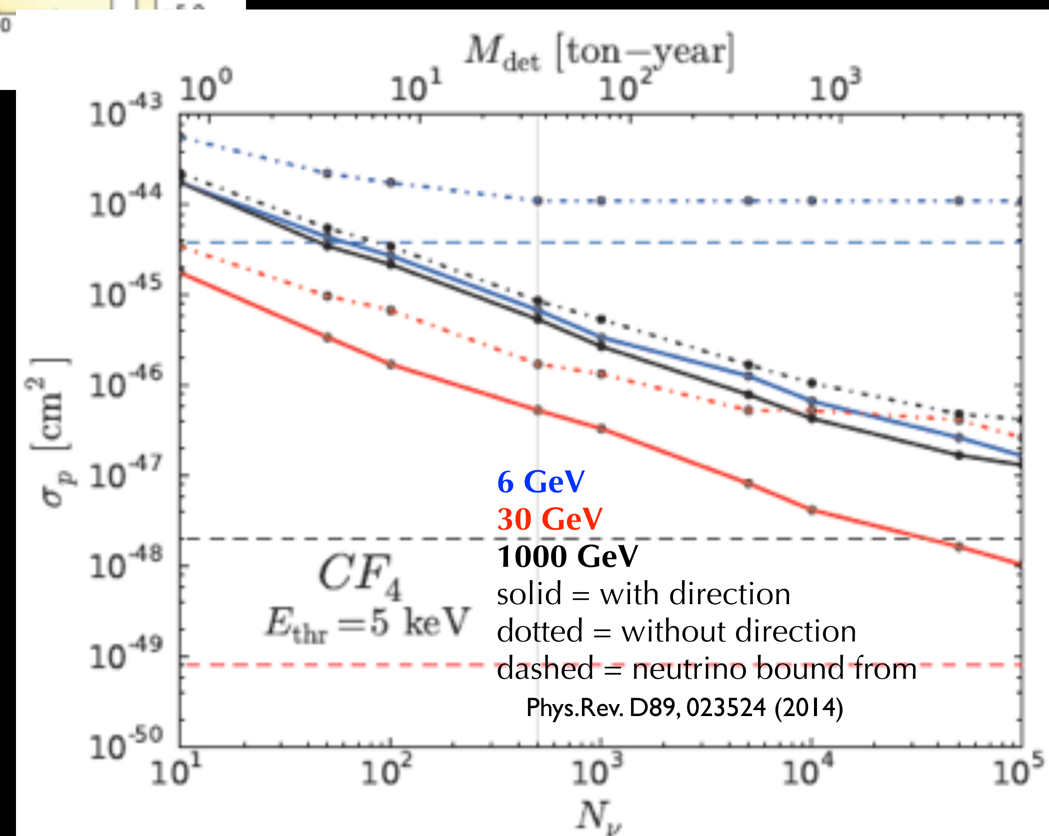
PDFs in (energy, angle, time) of event for coherent solar neutrino background vs. background + dark matter signal are different! (includes angular resolution)

- annual modulation still contains information

- directionality gains 10x in sensitivity in the presence of backgrounds

- no neutrino bound for directional detectors

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

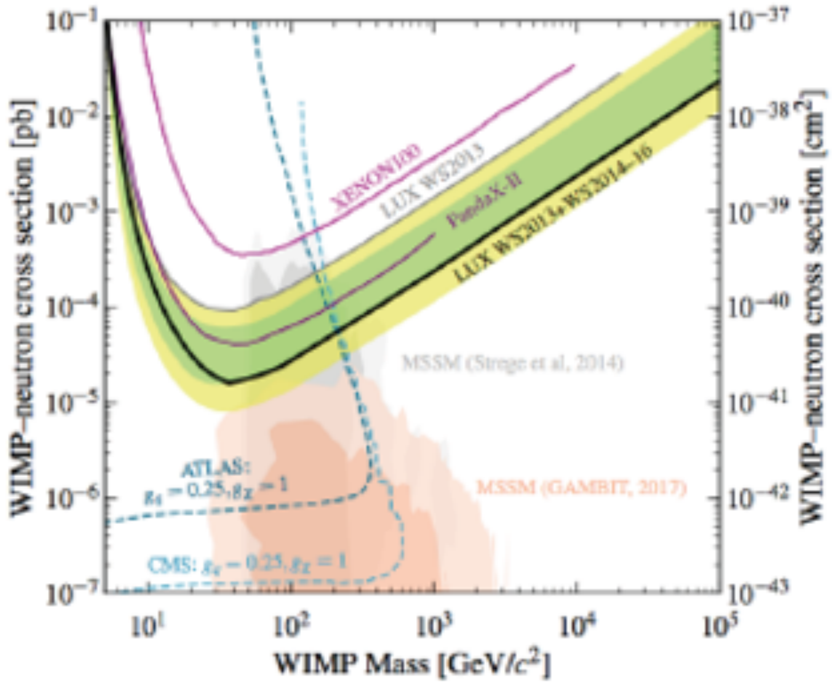


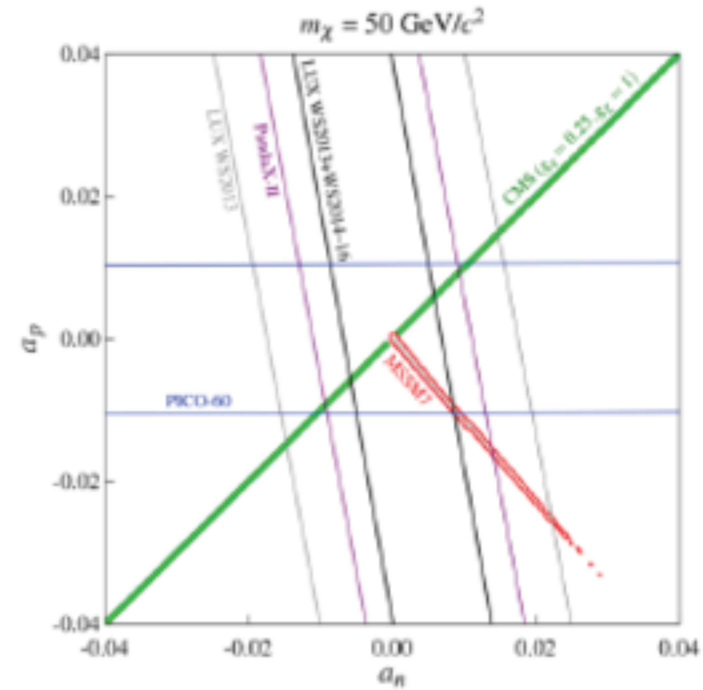
Is a fishing expedition at the 'low background frontier' intrinsically interesting?

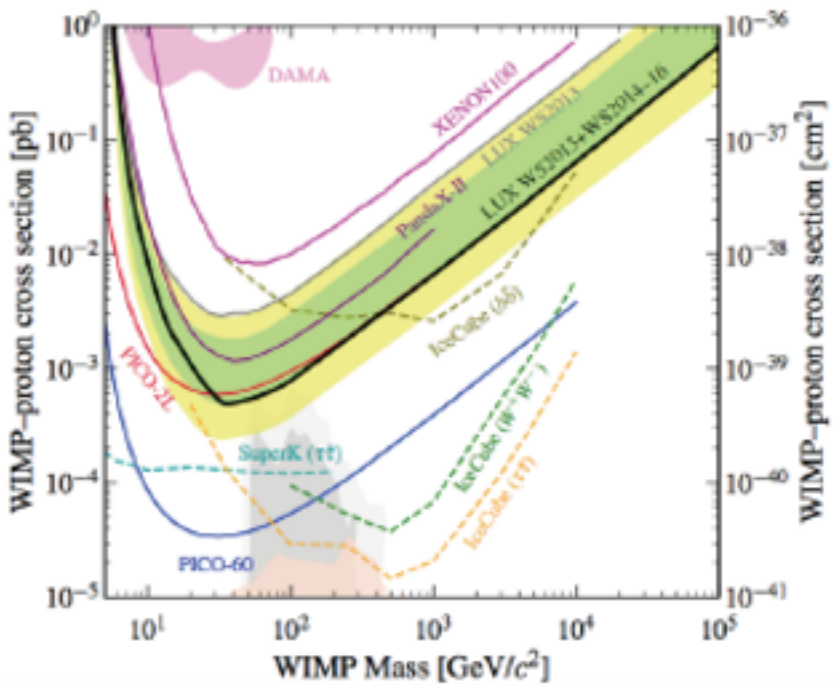
Do Limits from Direct/Indirect/Collider Searches Belong on the Same Plot?

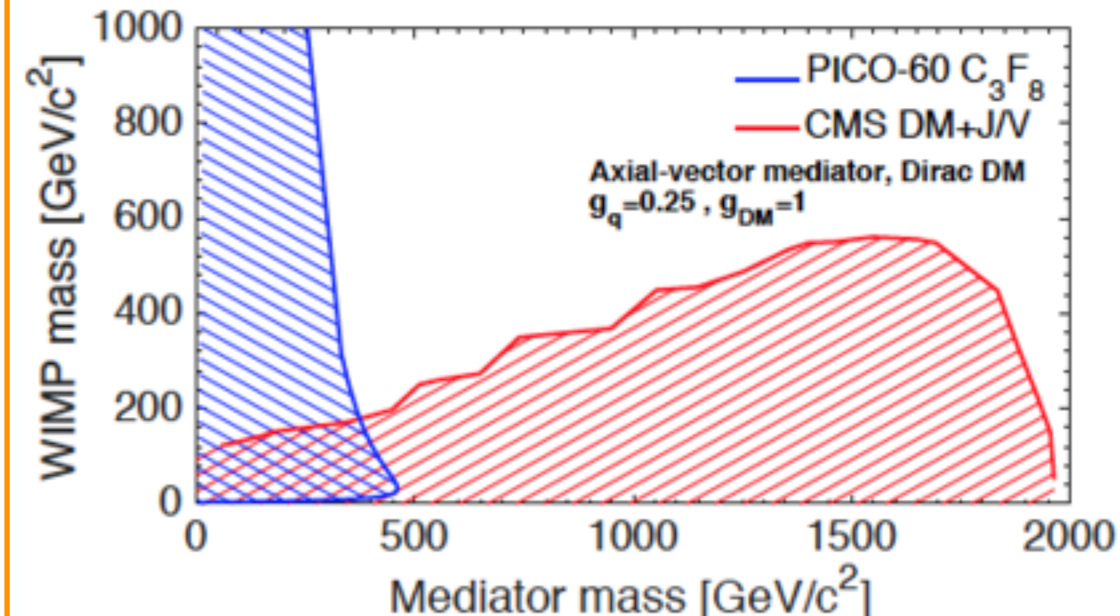
Example

Spin-Dependent Cross Section Constraints









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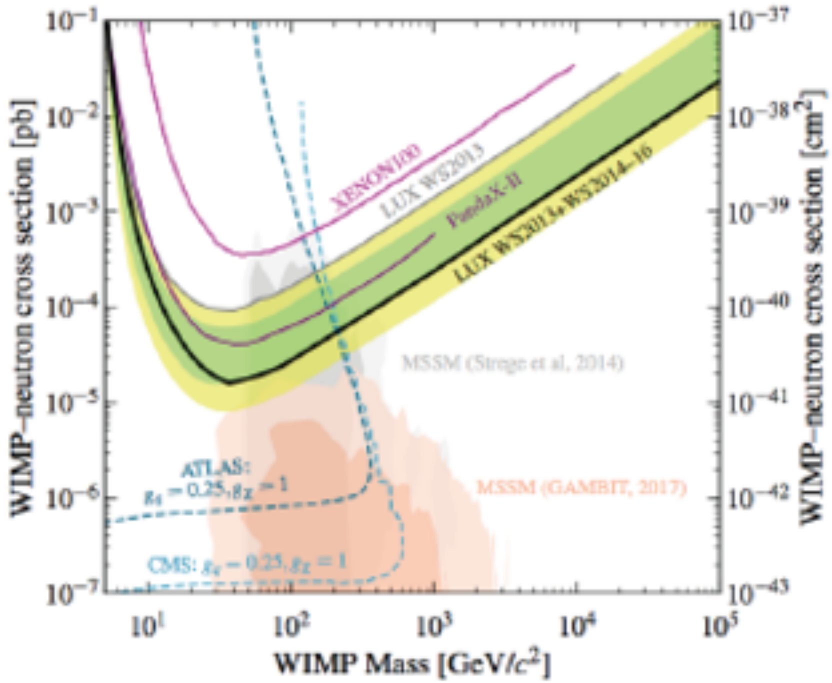
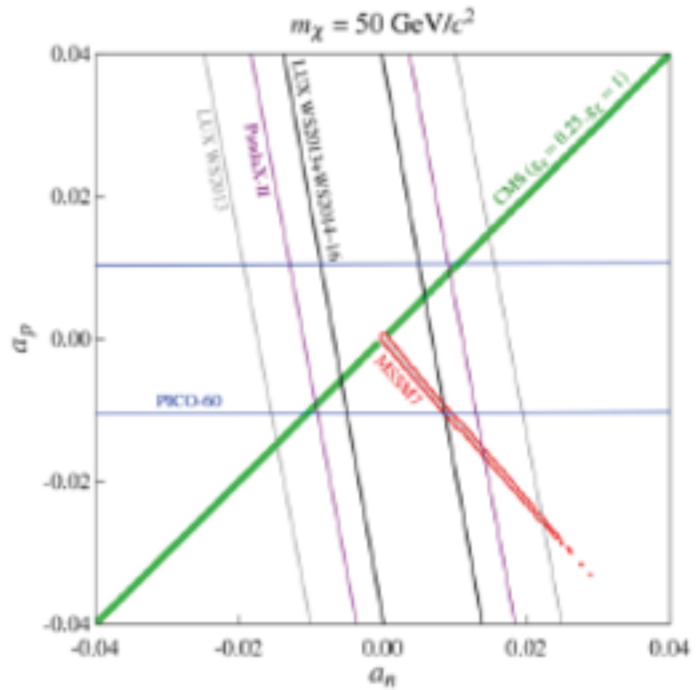
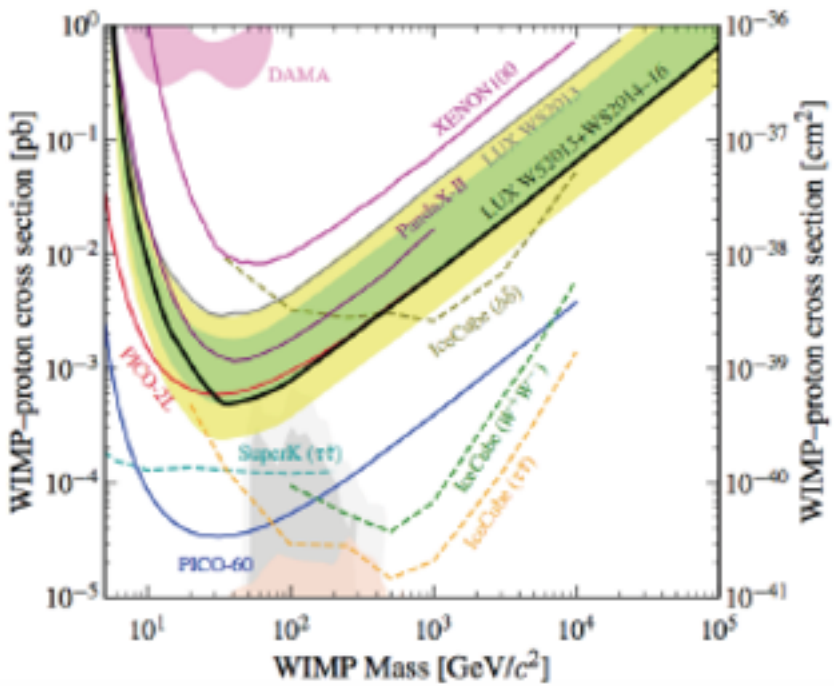
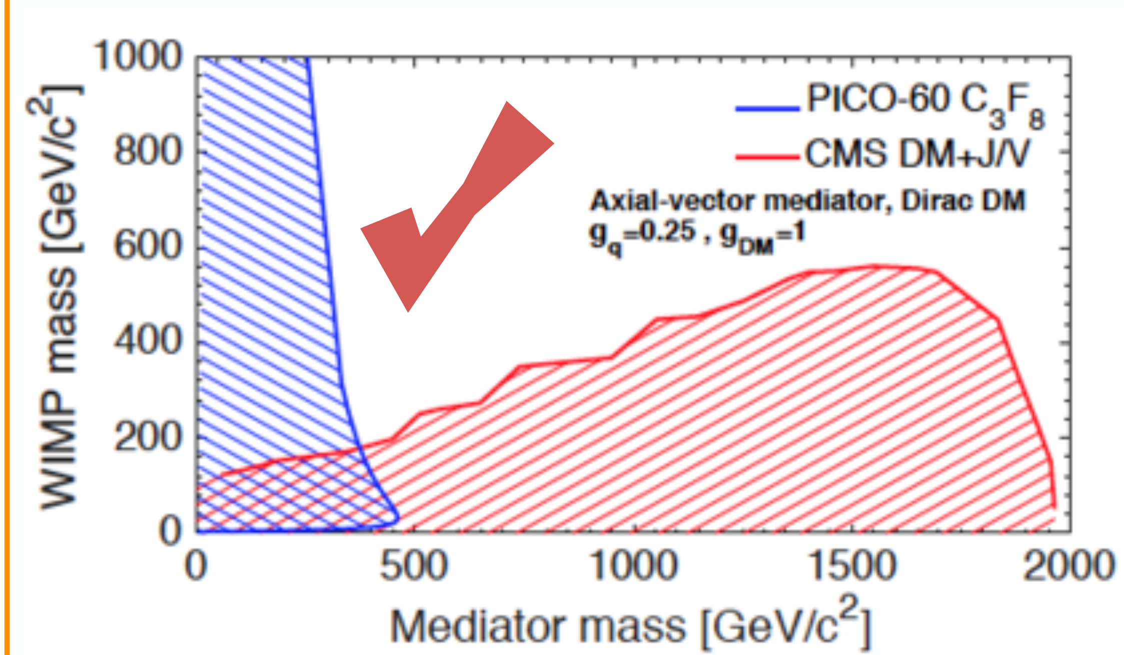


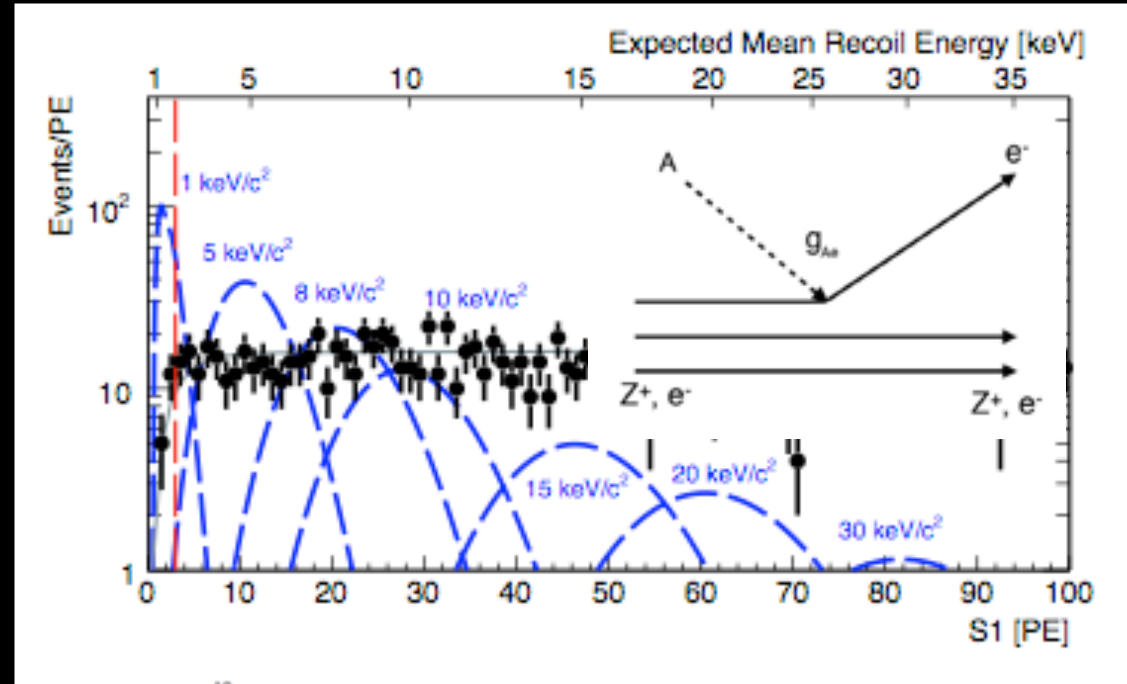






What Else Should We Be Looking For?
(in Direct Detection Experiments)

Bump Hunts in Direct Detection



search for axio-electric effect:

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

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

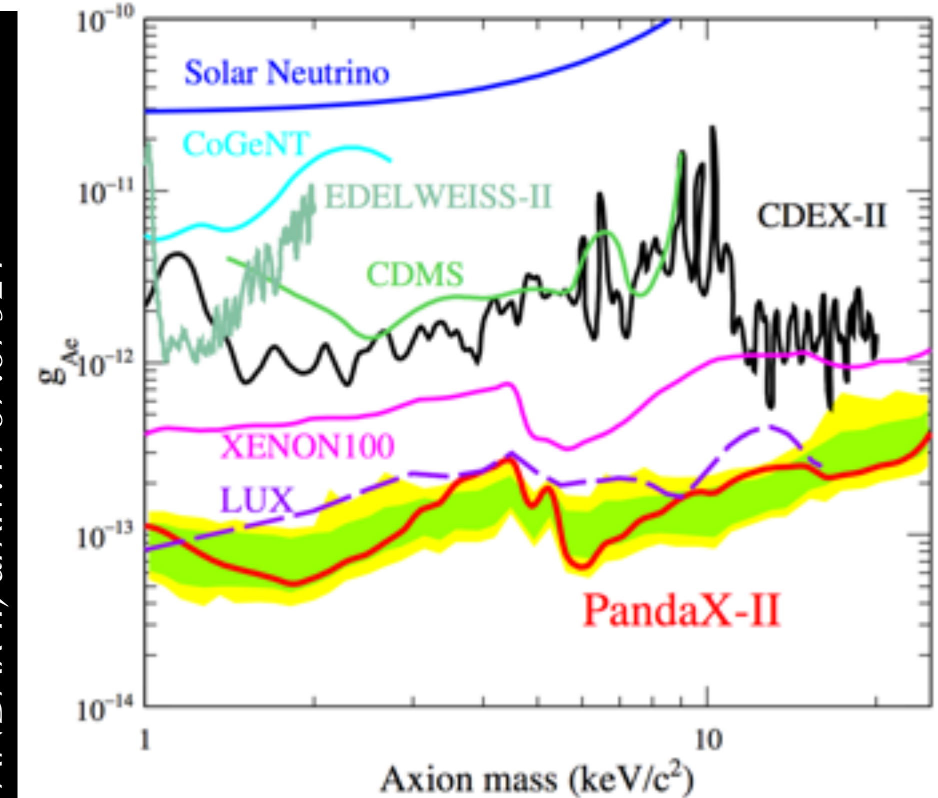
PANDAX-II: searches for ALPS >2 keVee, with background levels of 1E-4/(keV kg day).

XENON-1T: search for vector or pseudo-scalar bosons with mass>8 keV. Background is O(1E-4)/(keV kg day).

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

Constraints from Theorists: limits on kinetic mixing to hidden sector coupling extracted from XENON, DAMIC. *(arXiv:1709.07882)*

PANDAX-II, arXiv:1707.07921



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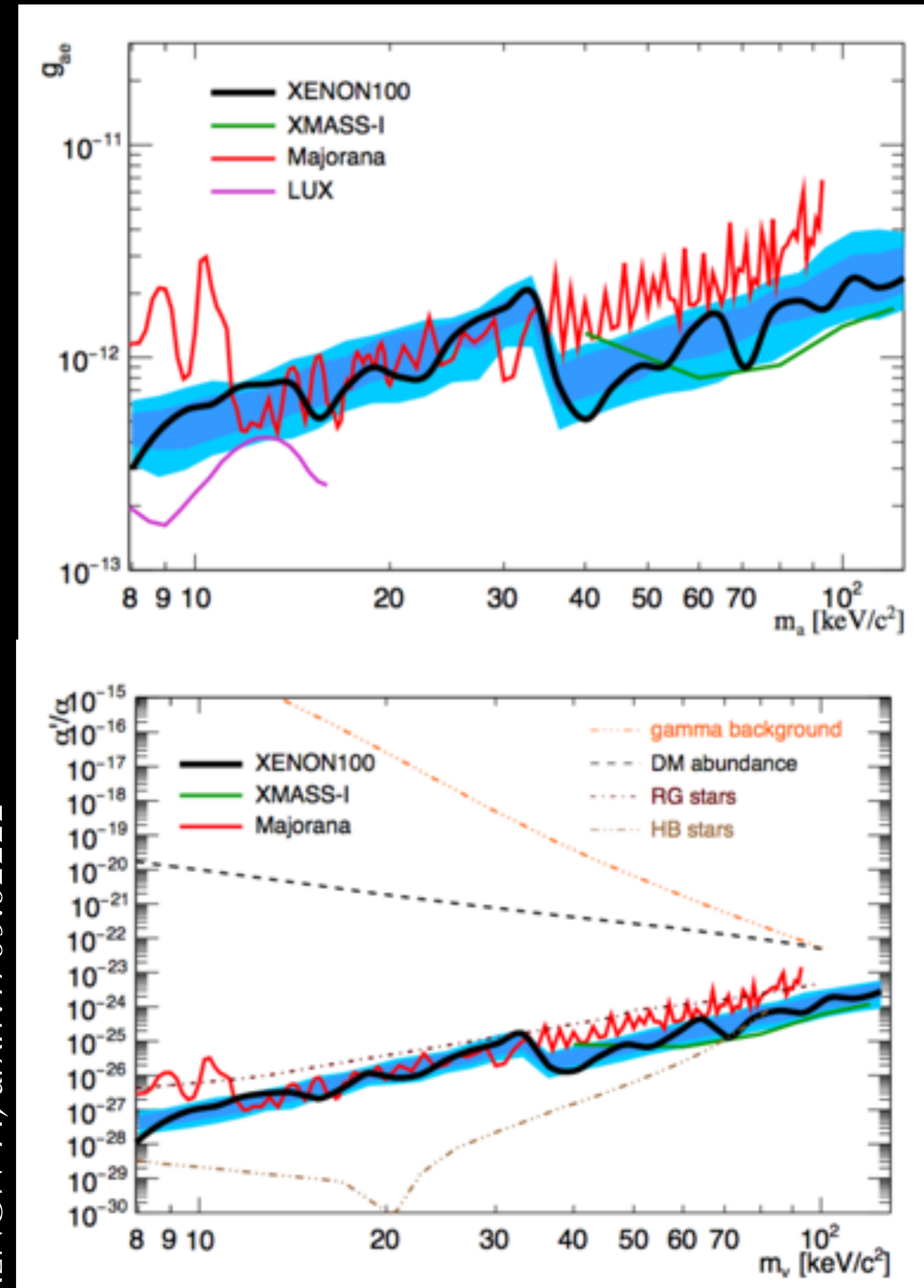


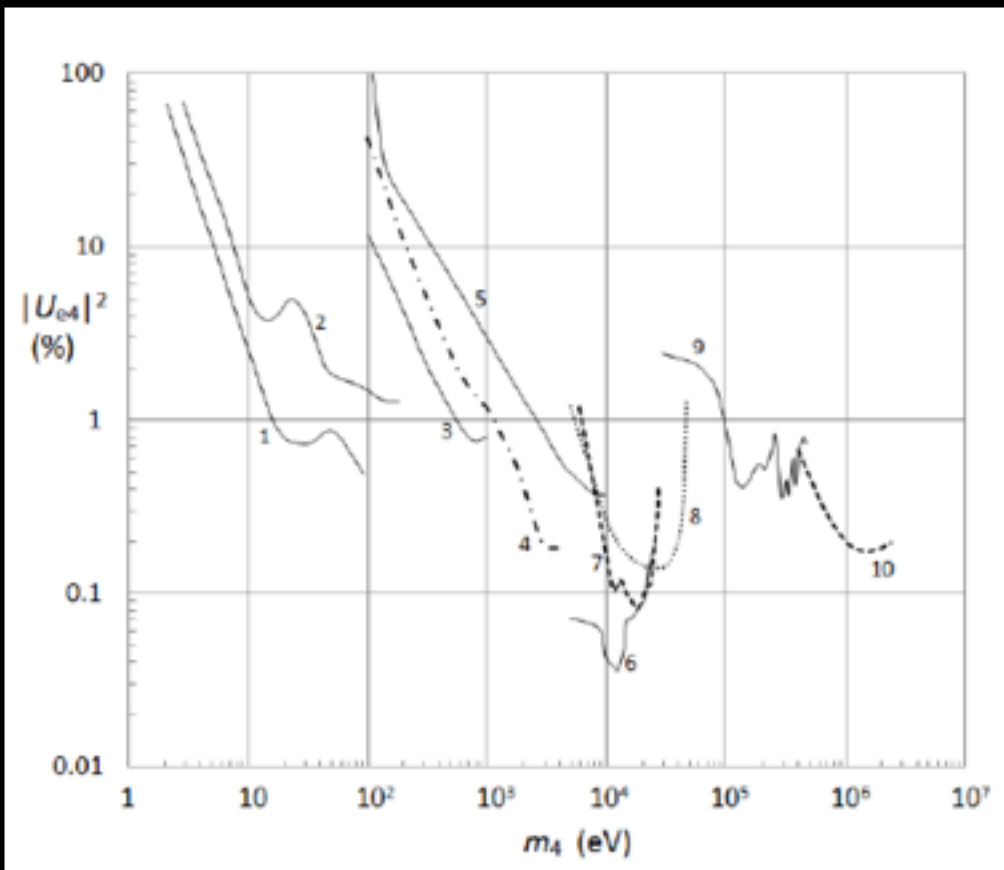
XENON-1T, arXiv:1709.02222

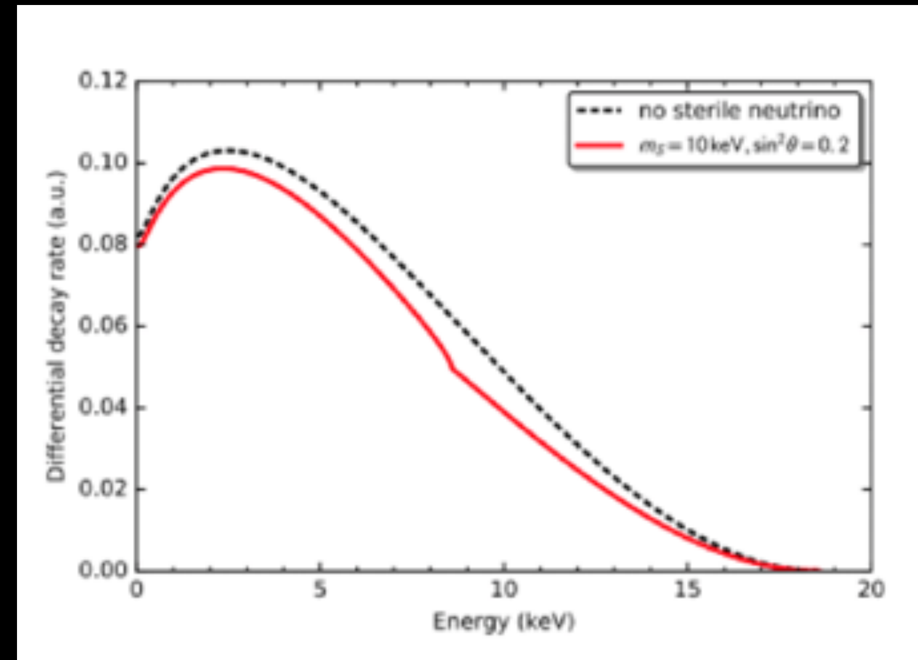
Sterile Neutrino Dark Matter Sensitivity, Prospects

(N. Fatemighomi, JM, in preparation)

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

Upper limit on $|U_{e4}|^2$ at 10 keV mass ~ 0.02 at 90% CL from beta decay experiments.
(arXiv:1503.07416)





High statistics, high Q-value beta decays of backgrounds (e.g. Ar-39) in large detectors with good energy resolution potentially has sensitivity to sterile neutrino dark matter at ~10-100 keV.

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

big challenge: nuclear physics uncertainties

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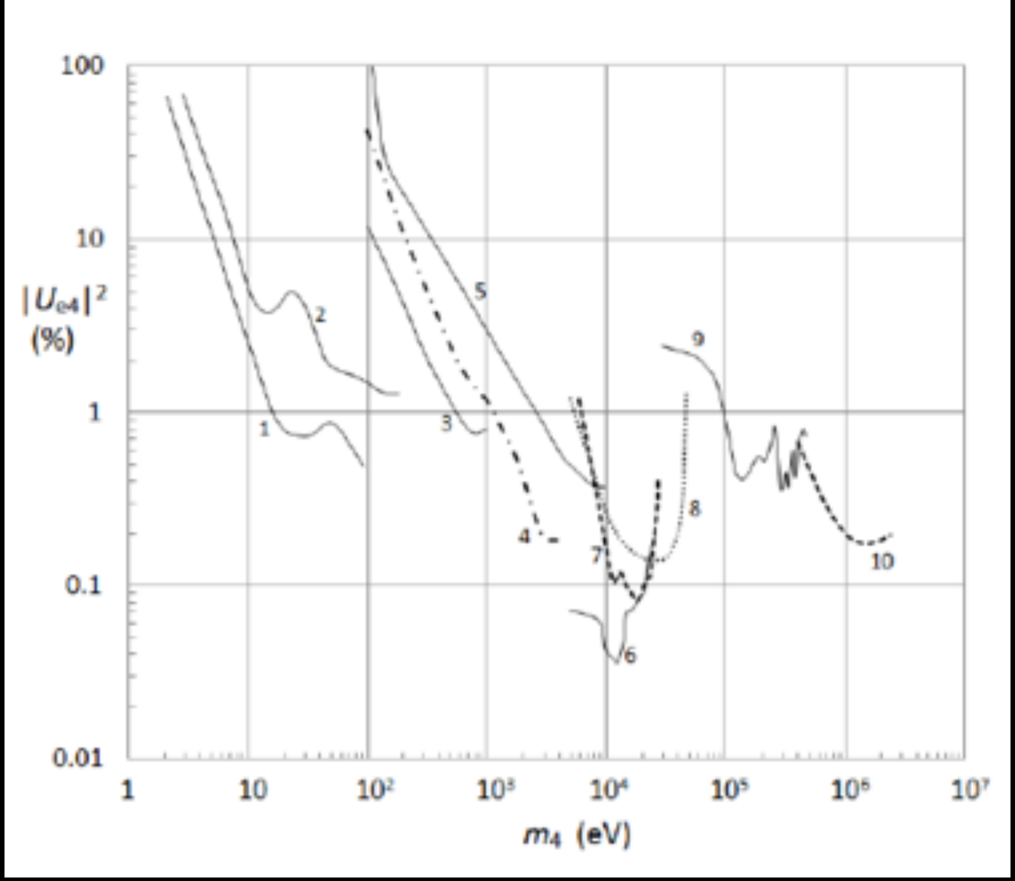

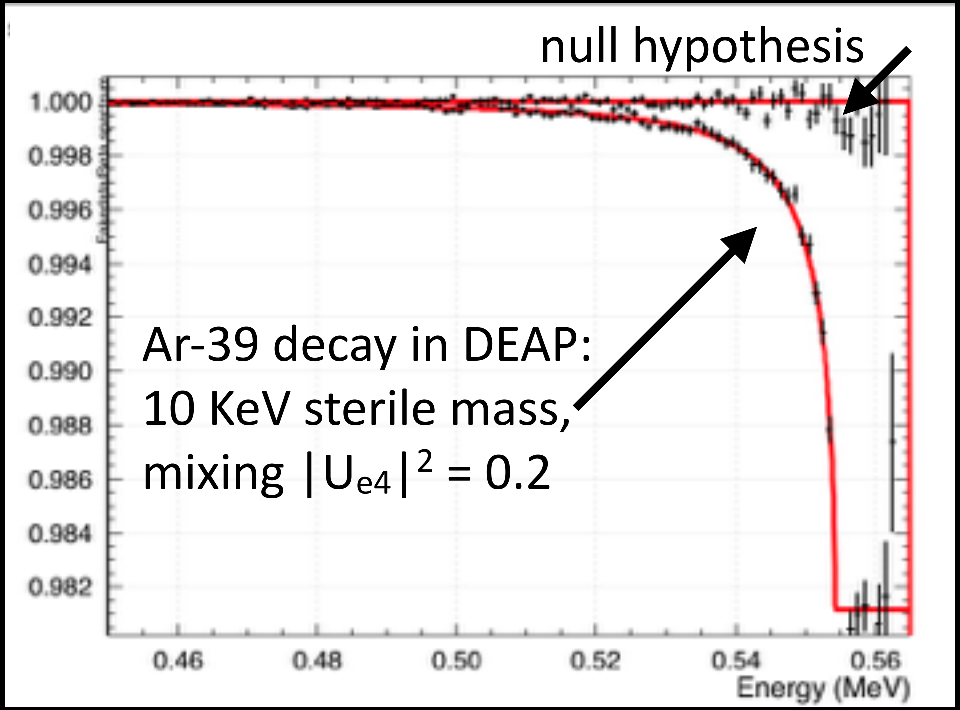

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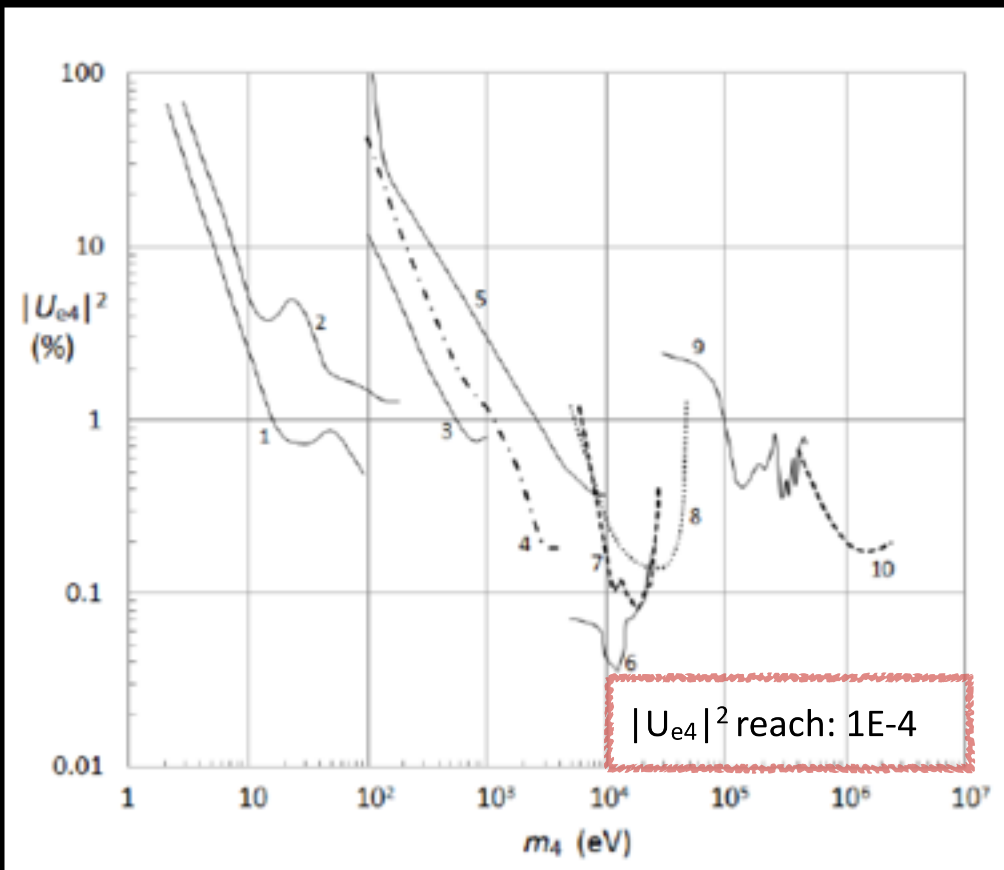

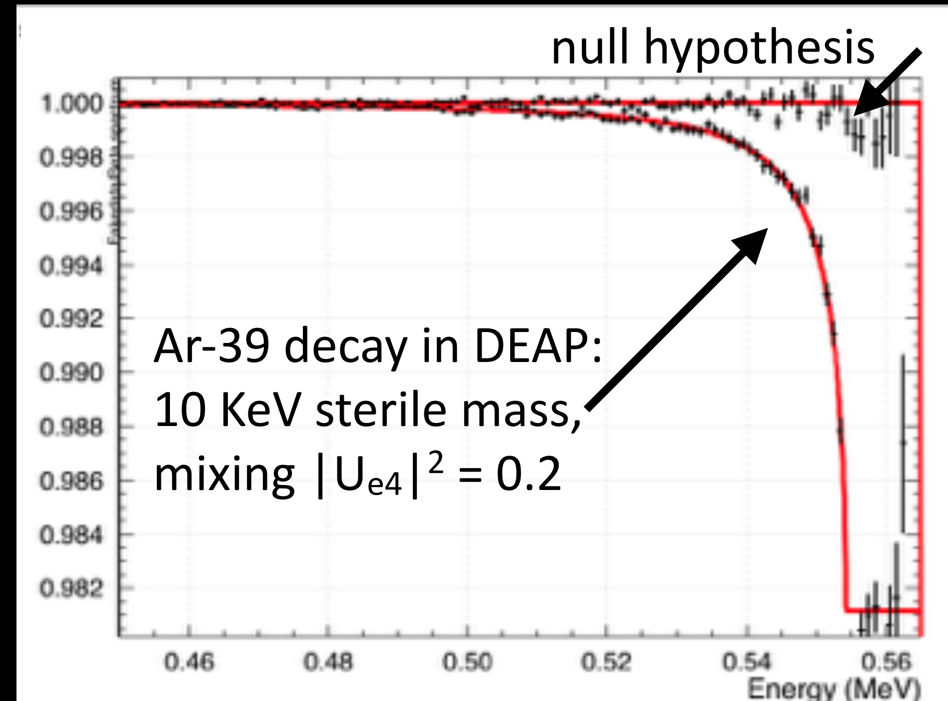

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Conclusions & Outlook

Is direct detection of dark matter beyond reach?

The only way to find out is to do the experiments.
But would we recognize a signal if we saw one?

What we should be looking for in direct detection is the next energy scale in particle physics!

Is there a no-lose theorem for direct detection (at the 100T or kT scale)?

Should we re-evaluate search strategies? Yes.

Many new ideas for non-standard searches in direct detection
… and today's background may be tomorrow's signal. *(T. Kajita, 2015)*