Dark Matter Direct Detection

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Department of Physics

NExT Workshop, Southampton
May 4, 2011

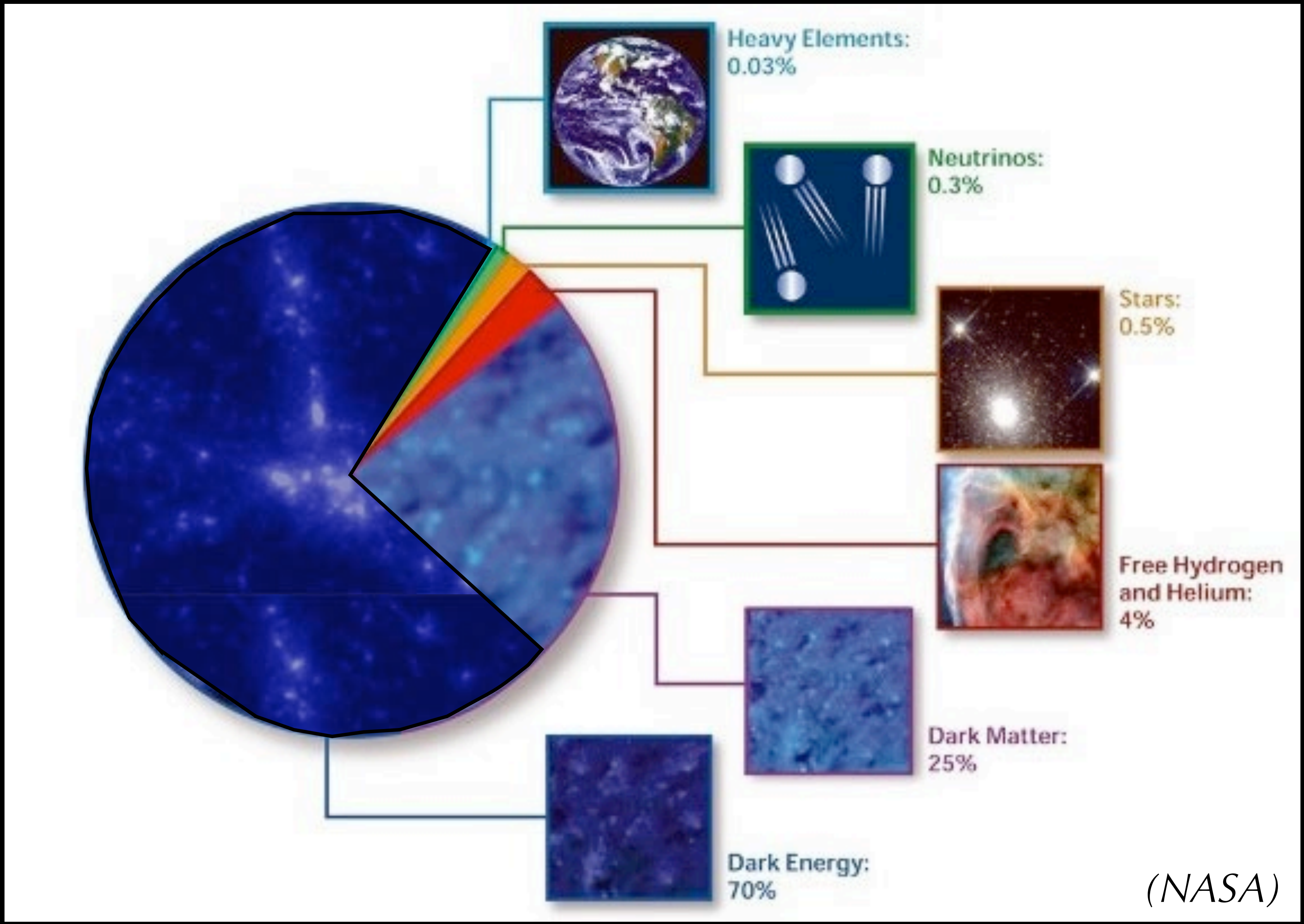
Outline

1. Dark Matter Direct Detection Overview

2. Review of Spin-Independent Results

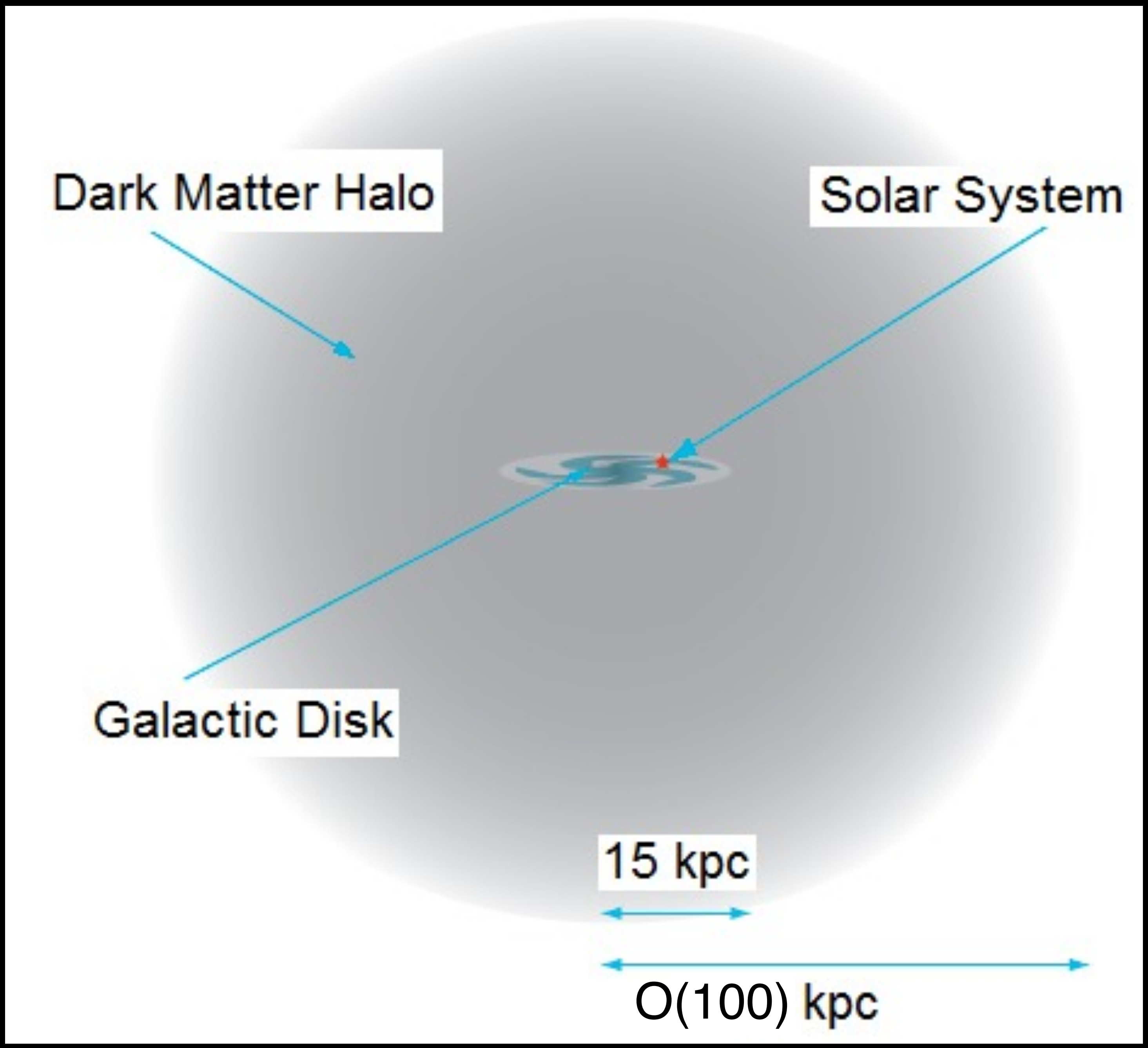
3. Review of Spin-Dependent Results

Standard Model of Cosmology



We only understand 4% of the universe.

What do we know about Dark Matter?



optically dark

density ~ 0.3 GeV/cm^3

dark matter particle mass: unknown

interactions: very weak

Dark Matter Candidates

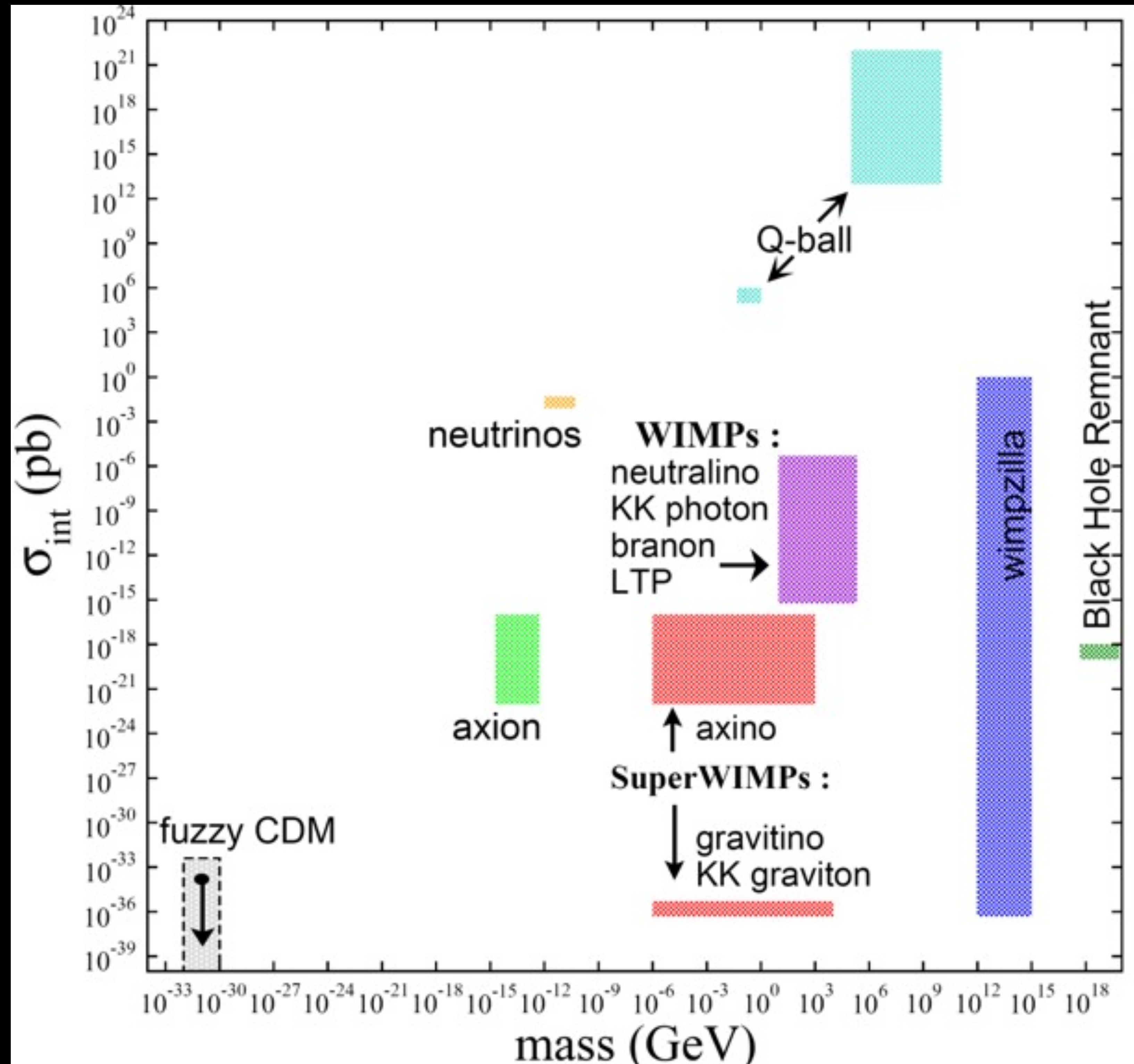
strong

e.m.

weak

gravity

interaction strengths



HEPAP/AAAC DMSAG Subpanel (2007)

masses

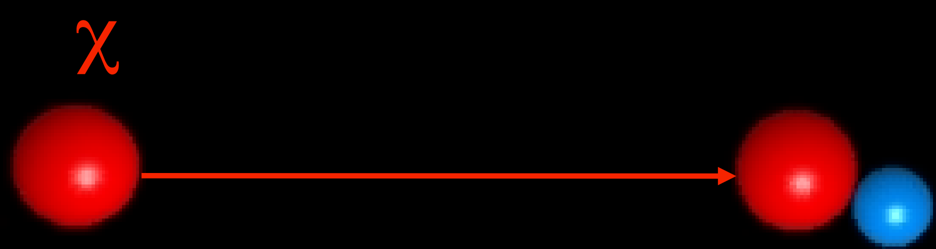
neutrino?

electron

t-quark

Direct Detection

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



Backgrounds:

$n\ N \rightarrow n\ N'$

$\gamma\ e^- \rightarrow \gamma\ e^{-\prime}$

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

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

Direct Detection

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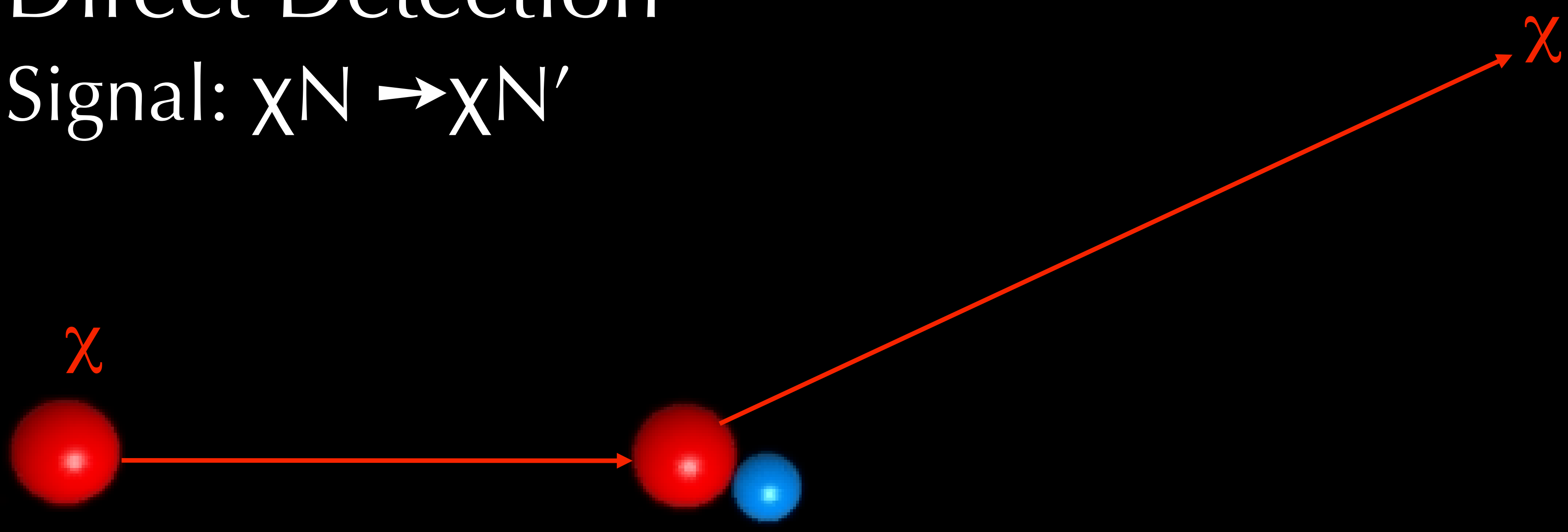

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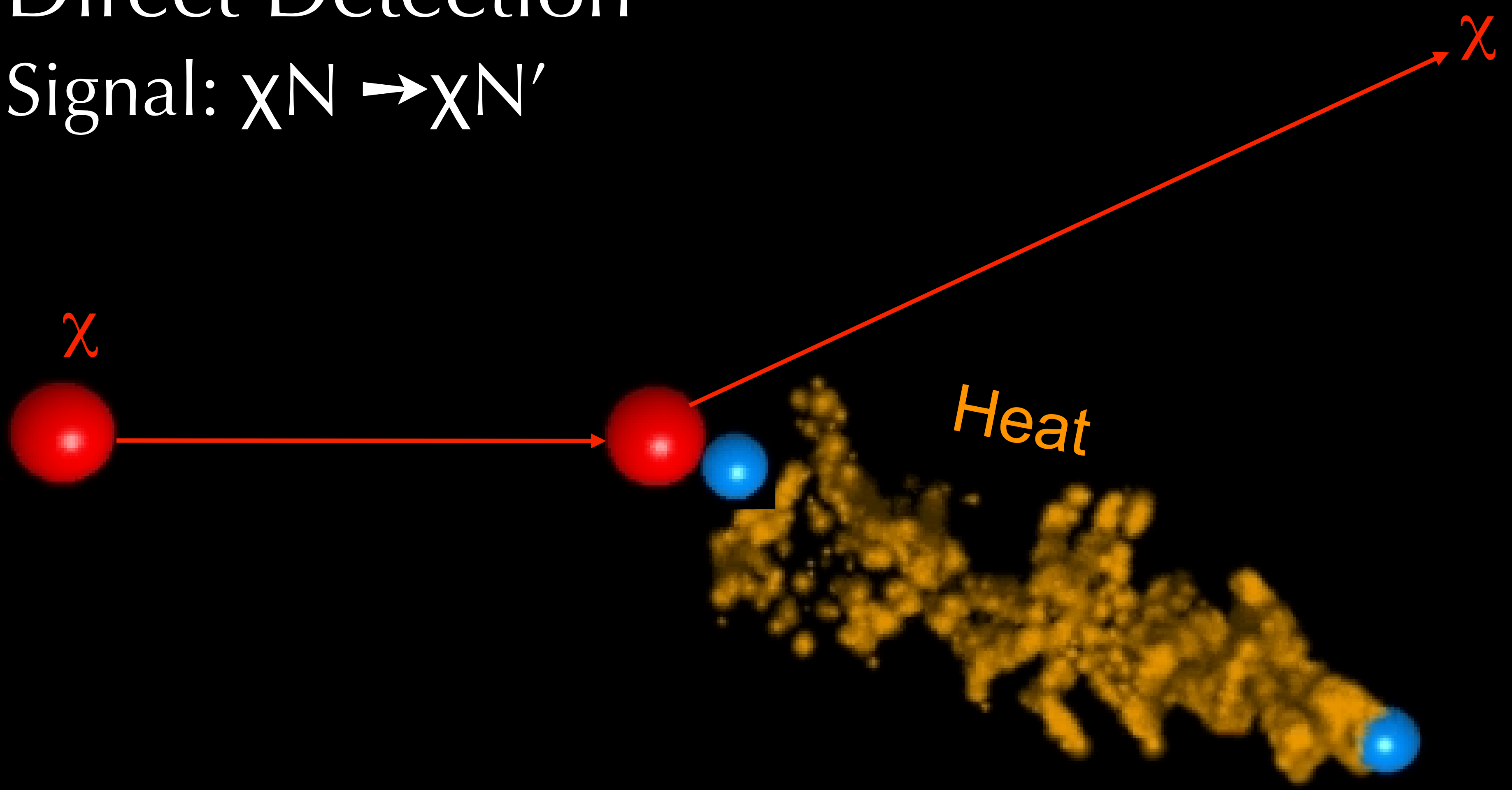

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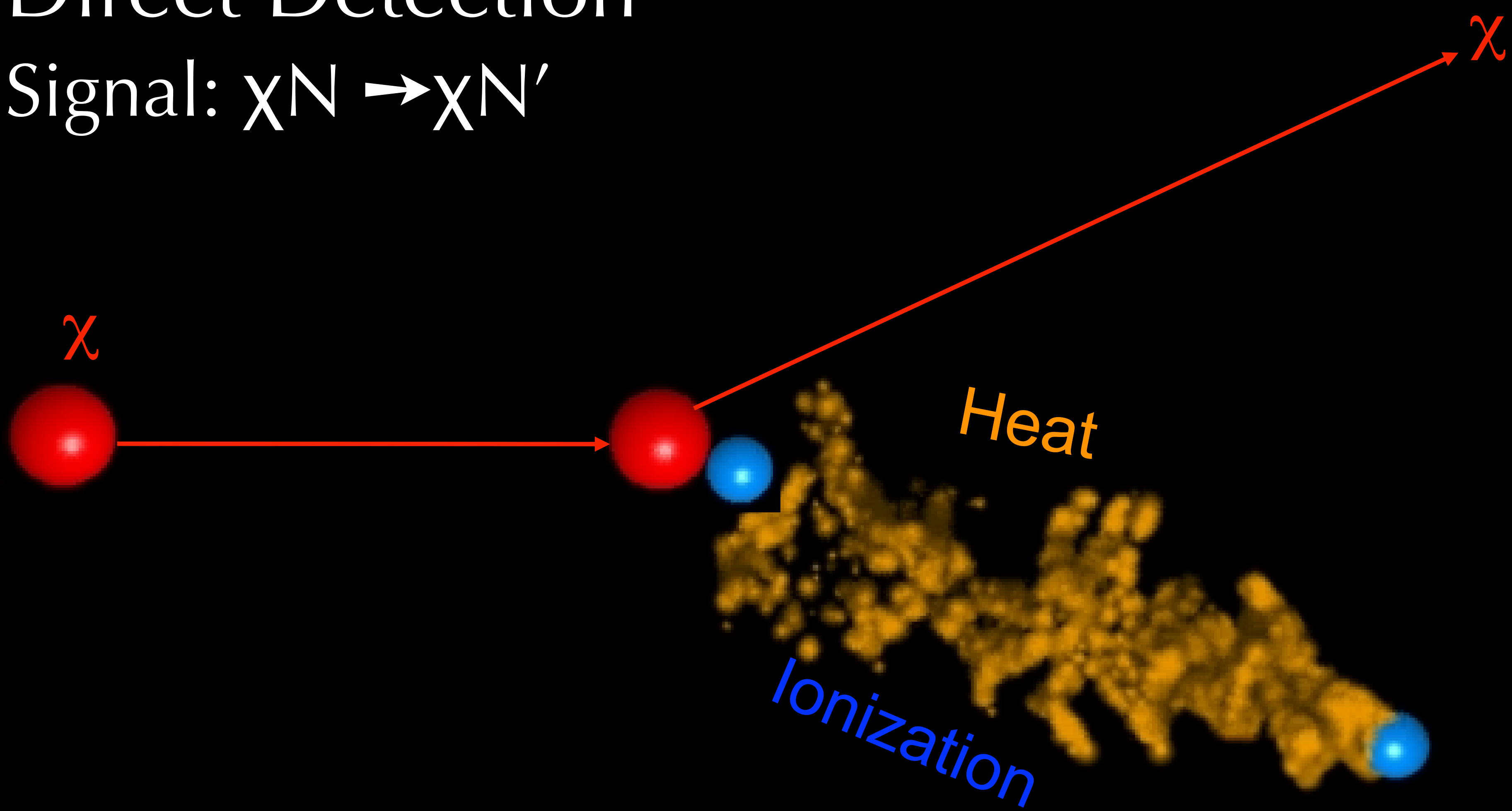

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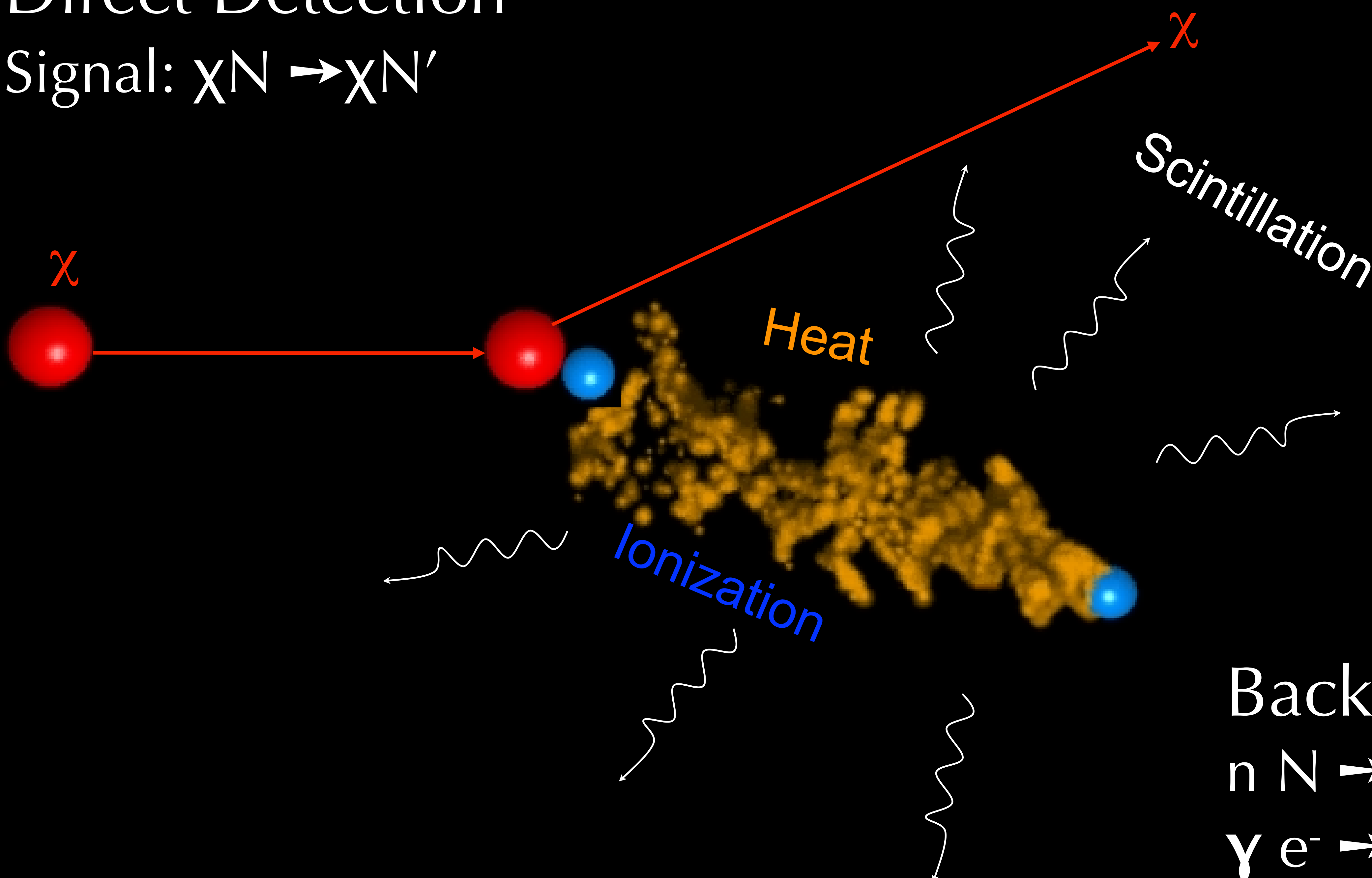

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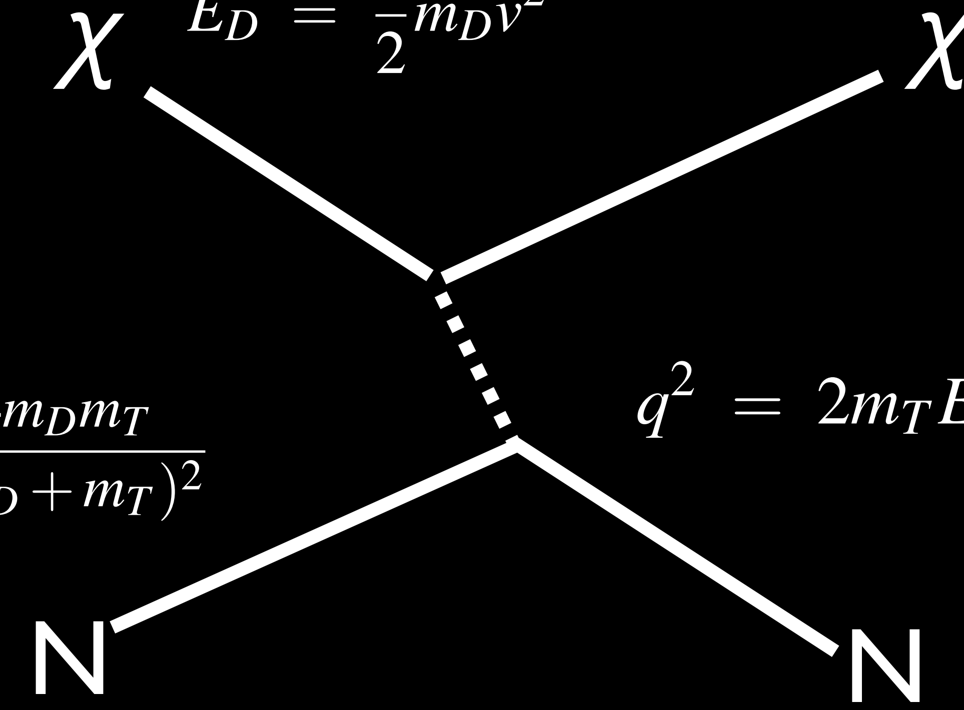
WIMP Scattering

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



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

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

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

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

<u>Spin Independent:</u>

χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$

D. Z. Freedman, PRD 9, 1389 (1974)

<u>Spin Dependent:</u>

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

SI vs. SD

Savage et al., arXiv:0808.3607

$$\sigma = \sigma_{\rm SI} + \sigma_{\rm SD};$$

$$\sigma_{0,\rm SI} = \frac{4\mu^2}{\pi}[Z f_{\rm p} + (A - Z) f_{\rm n}]^2 \, .$$

$$\sigma_{SD}(q) = \frac{32\mu^2 G_F^2}{2J+1}\left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q)\right] .$$

Many of the parameters that factor into the expected recoil rates for a scattering detector are unknown, including the WIMP mass, four WIMP-nucleon couplings (SI and SD couplings to each of protons and neutrons), the local WIMP density, and the WIMP velocity distribution in the halo. In this paper, we shall fix the halo model to the SHM and the local density to 0.3 GeV/cm^3. In addition, we shall take $f_{\rm p} = f_{\rm n}$ (equal SI couplings) so that there are only three independent scattering couplings; the SI coupling will be given in terms of the SI scattering cross-section off the proton, $\sigma_{\rm p,SI}$. The parameter space we examine will then consist of the four parameters m, $\sigma_{\rm p,SI}$, $a_{\rm p}$, and $a_{\rm n}$.

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Nuclear physics uncertainties are important!

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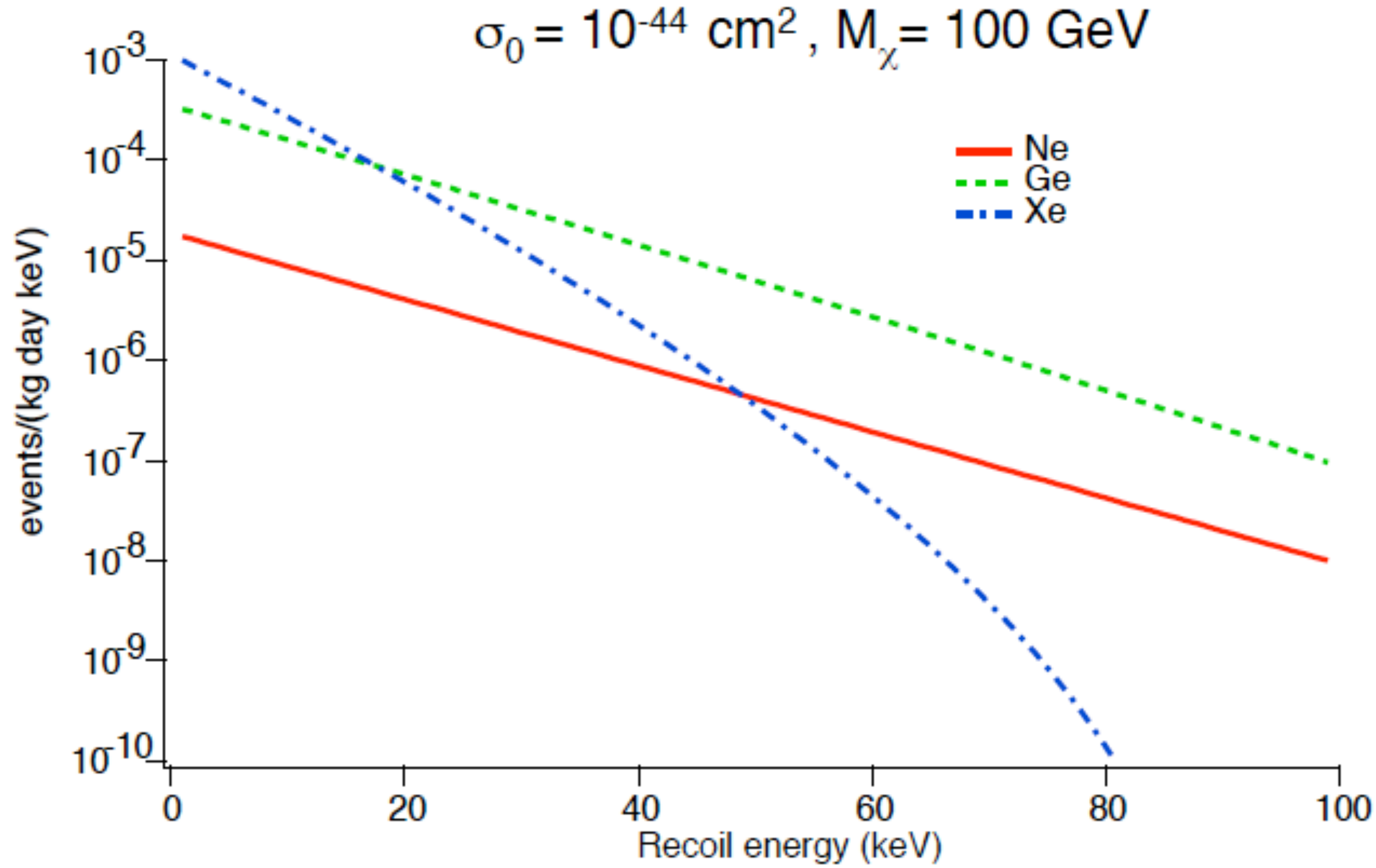
Nuclear physics uncertainties are important!

Measurement

energy of recoiling nucleus

expected signal rate (per unit detector mass per unit time):



$$R(t) = \int_{E_1/Q}^{E_2/Q} \mathrm{d}E \, \epsilon(QE) \frac{\rho}{2m\mu^2} \sigma(q) \, \eta(E,t).$$

energy range of the experiment

detection efficiency

dark matter density

integral over dark matter velocity distribution

interaction cross section

quenching Q = dE_ionization/dE_total

dark matter & target particle masses

DRIFT

IGEX

Picasso

WARP

Newage

ArDM

COUPP

ZeplinIII

CDMS

Edelweiss

Xenon100

LUX

CoGeNT

DMTPC

ANaIS

DEAP/CLEAN

XMASS

KIMS

Dama/LIBRA

CRESST

CRESSTII

ROSEBUD

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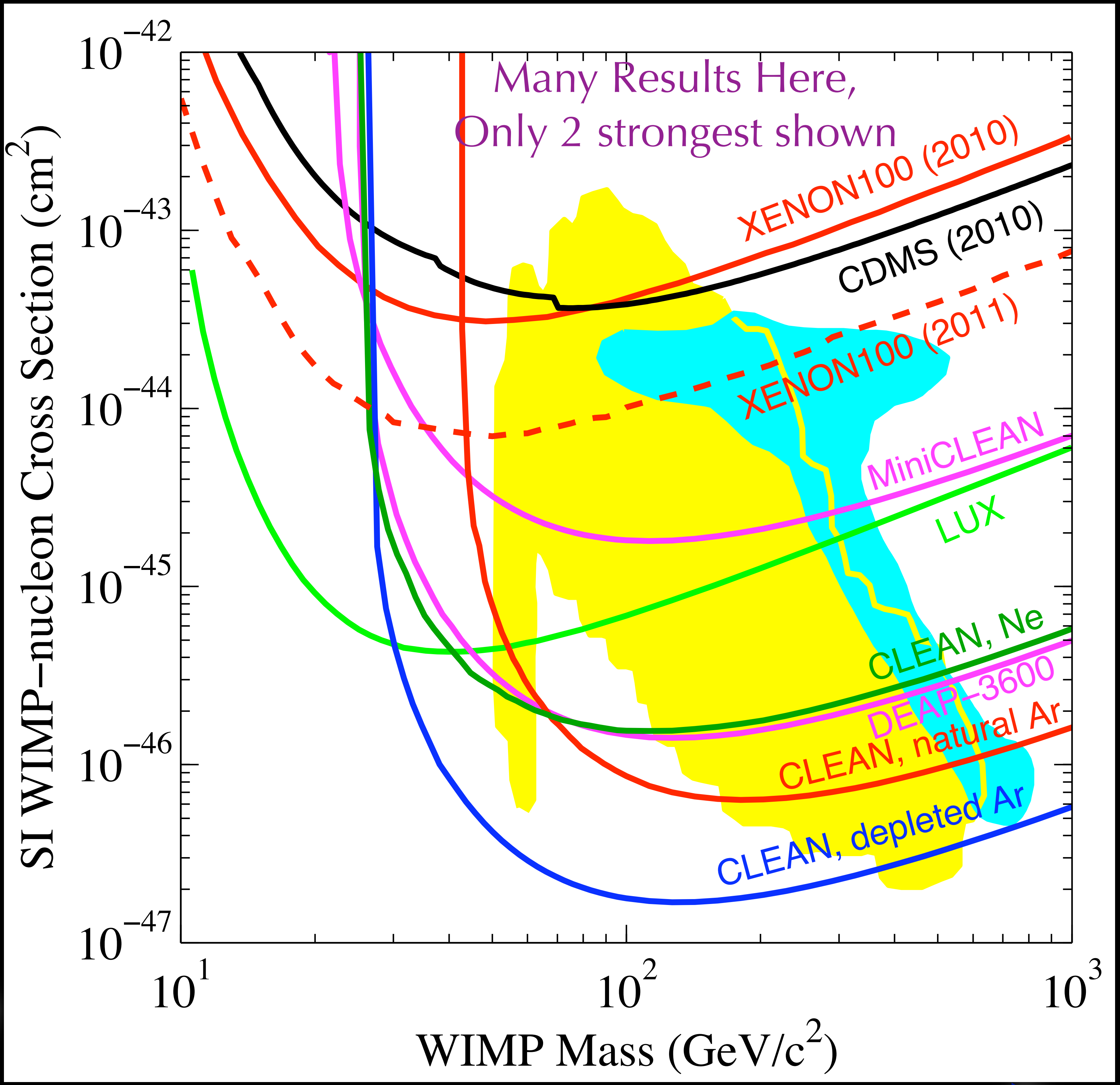
Spin-Independent Cross Section Limits



Scalability of Detector Technology

← 1 event/ kg/day

← 1 event/ 100 kg/day

← 1 event/ 100 kg/ 100 days

New Techniques for Backgrounds

Complementary with High-Energy Frontier

need 100-1000 dark matter events to measure mass, cross section

A Long Way to Go...

Not to Scale

10^{-24} cm^2: σ(neutron-A elastic scattering)

10^{-28} cm^2: σ(total inelastic pp at TeVatron)

10^{-35} cm^2: σ(gg → H) at LHC (Standard Model)

10^{-37} cm^2: σ(gg → H) at TeVatron (Standard Model)

10^{-39} cm^2: σ(single top) at TeVatron

10^{-40} cm^2: σ(ν QE) at T2K

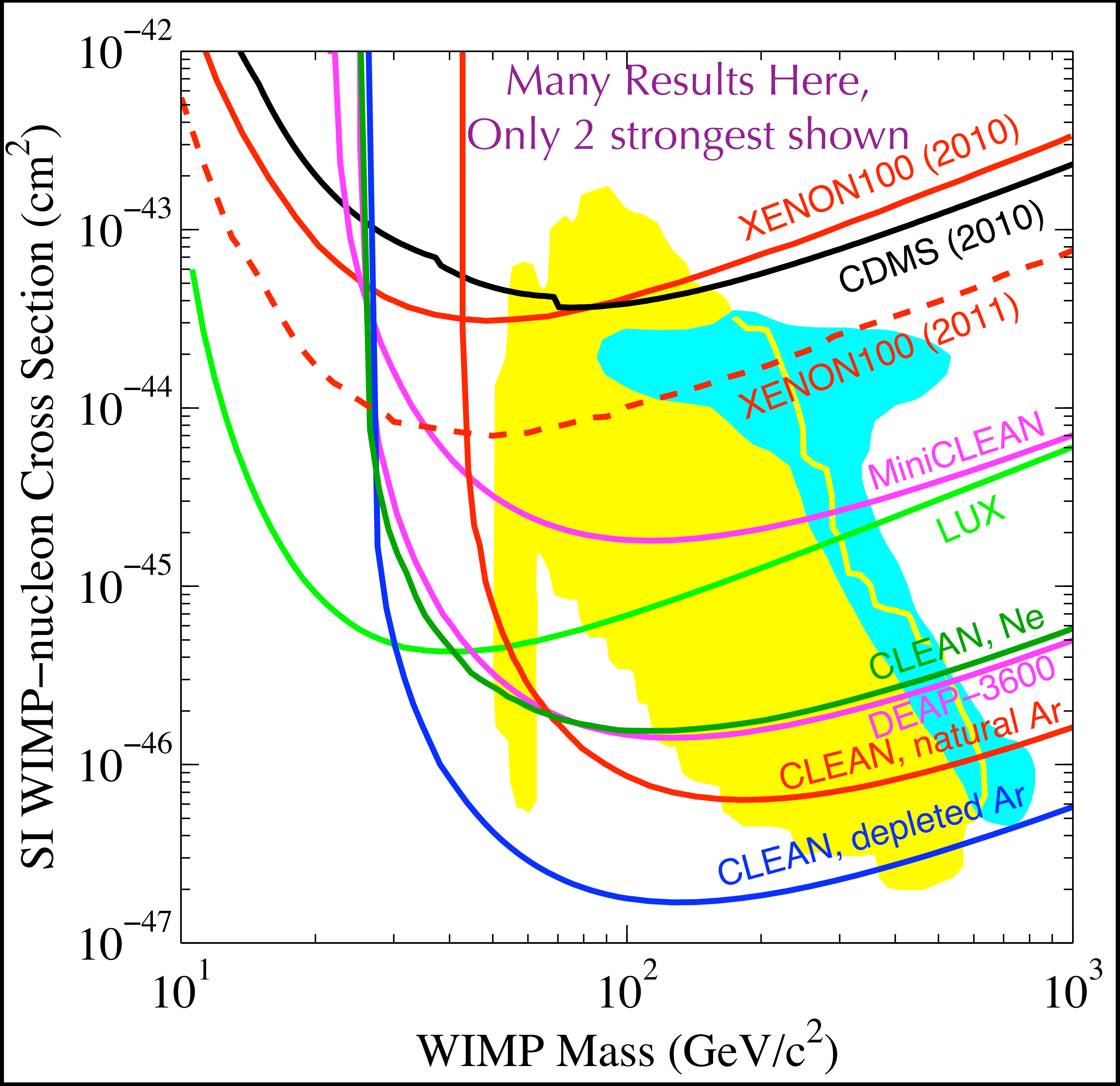
10^{-43} cm^2: σ(ν NC Elastic) for geo-ν

10^{-45} cm^2: σ(ν-e Elastic) for solar ν

σ(DM coherent scattering)? 10^{-47} cm^2

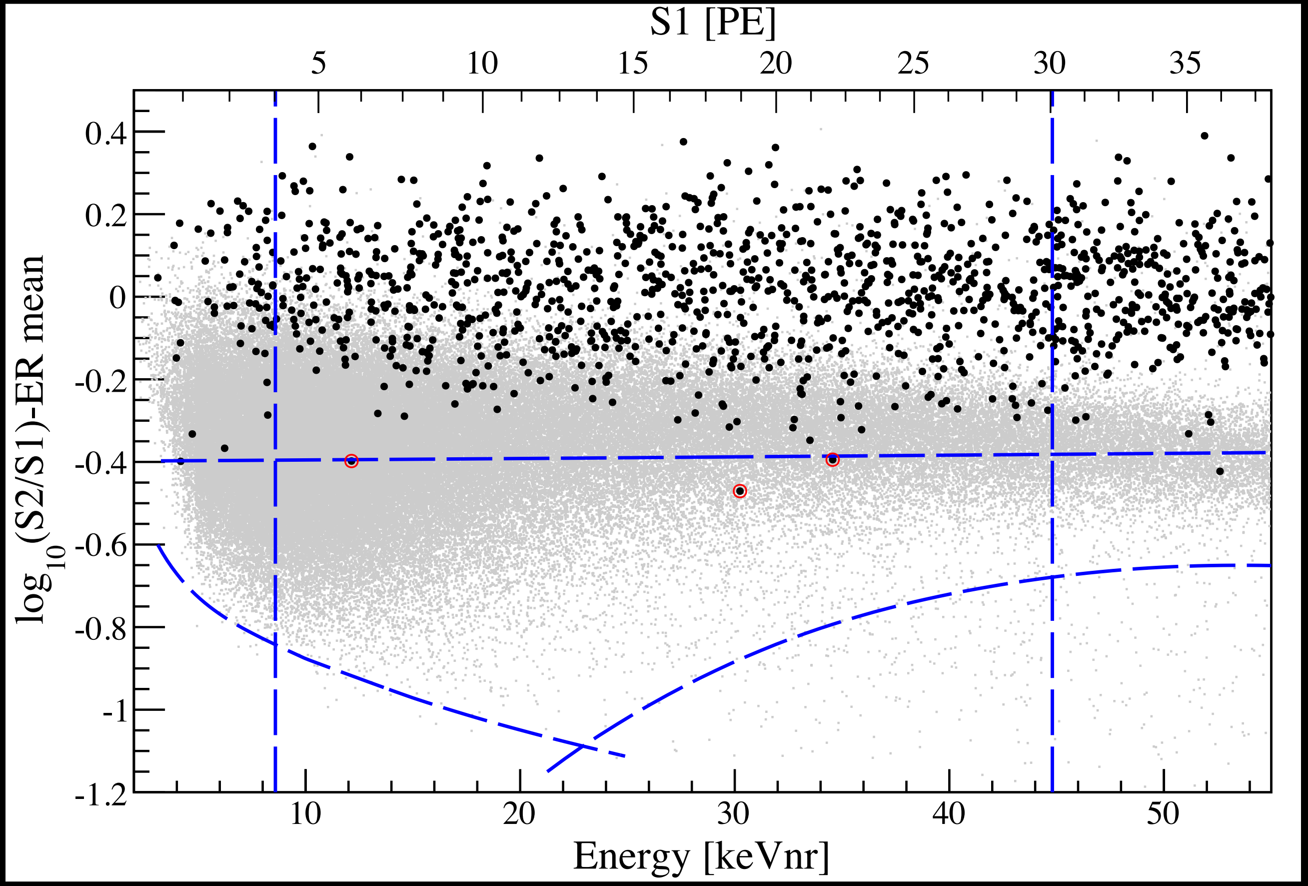
Spin-Independent Cross Section Limits

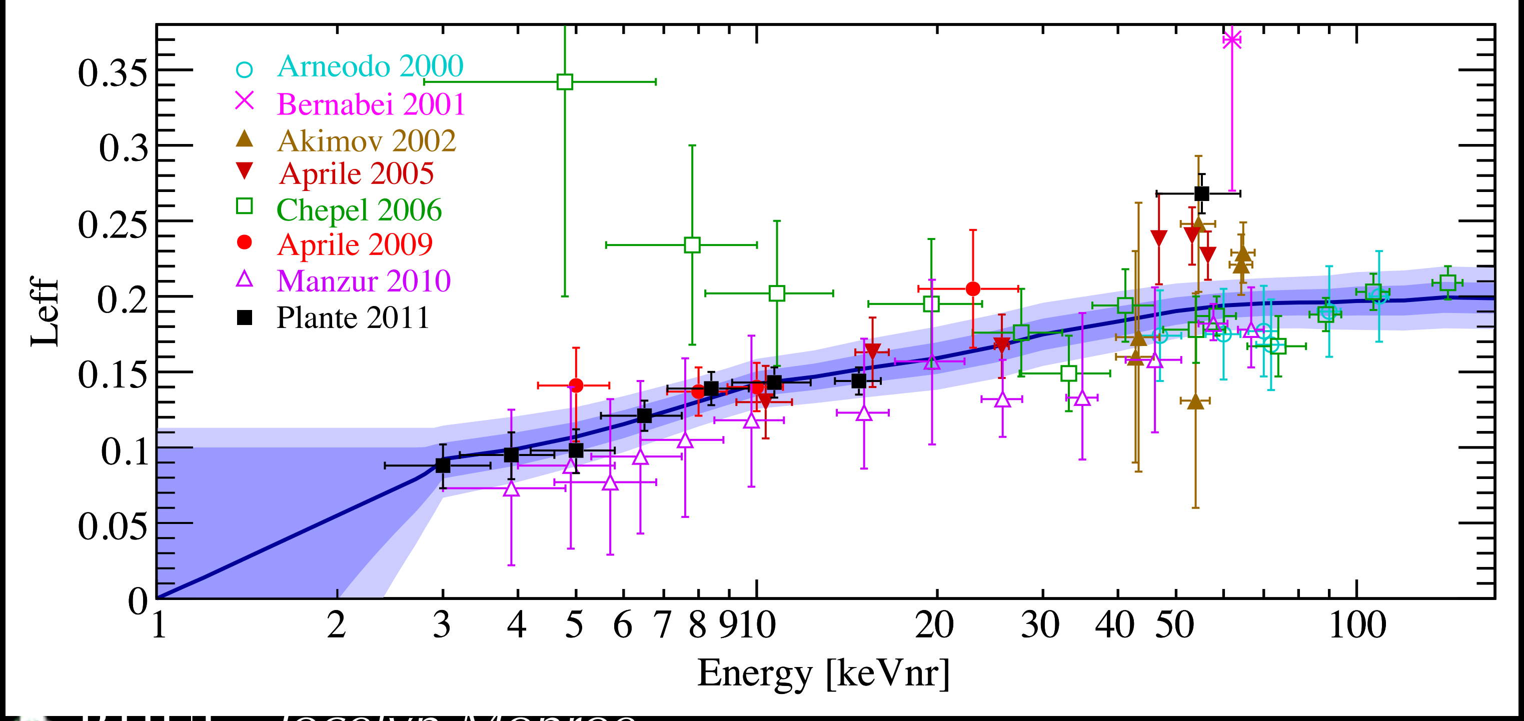
1. **Null Results**
2. Near-Future Searches
3. Signals?



Xenon100 Status and Outlook

arXiv:1104.2549v2
48 kg x 100 days





^{83}Kr background from air leak, taking new data after purification (since June 2010)

expected 1.8+/-0.6 events, saw 3 (28% background probability)

new quenching measurement

projected sensitivity: 1E-45 cm2

(E. Aprile)

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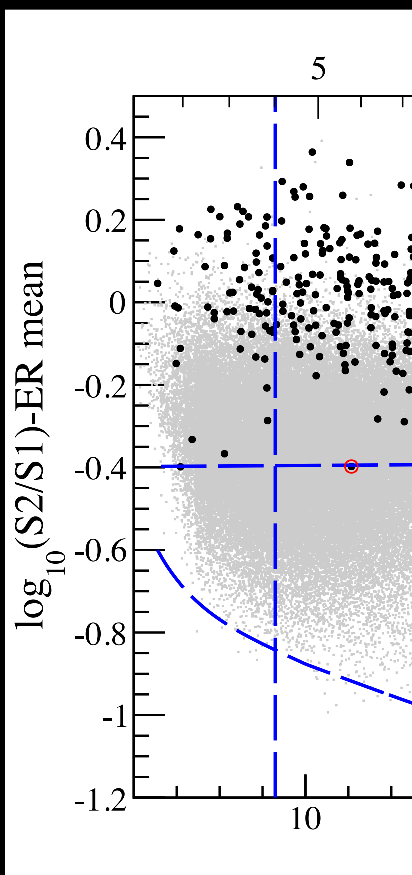

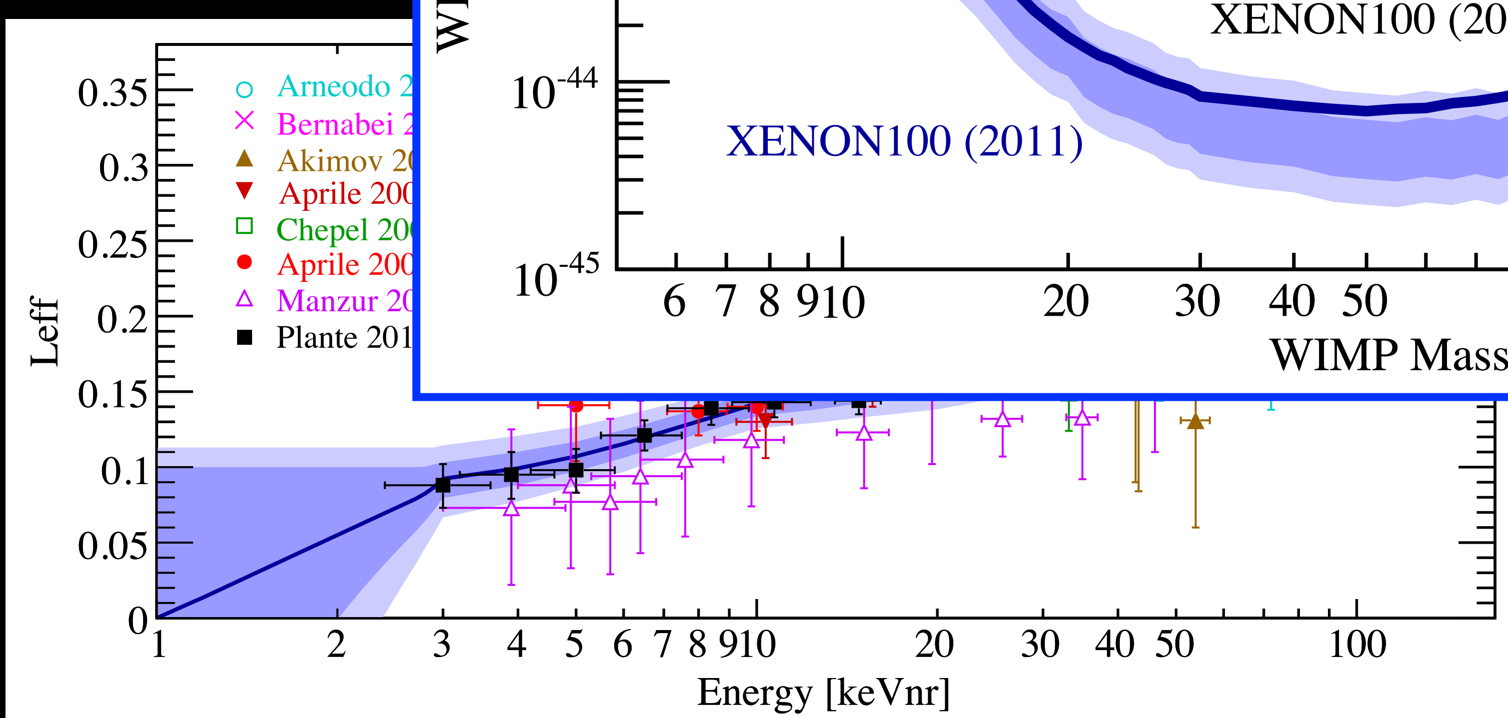

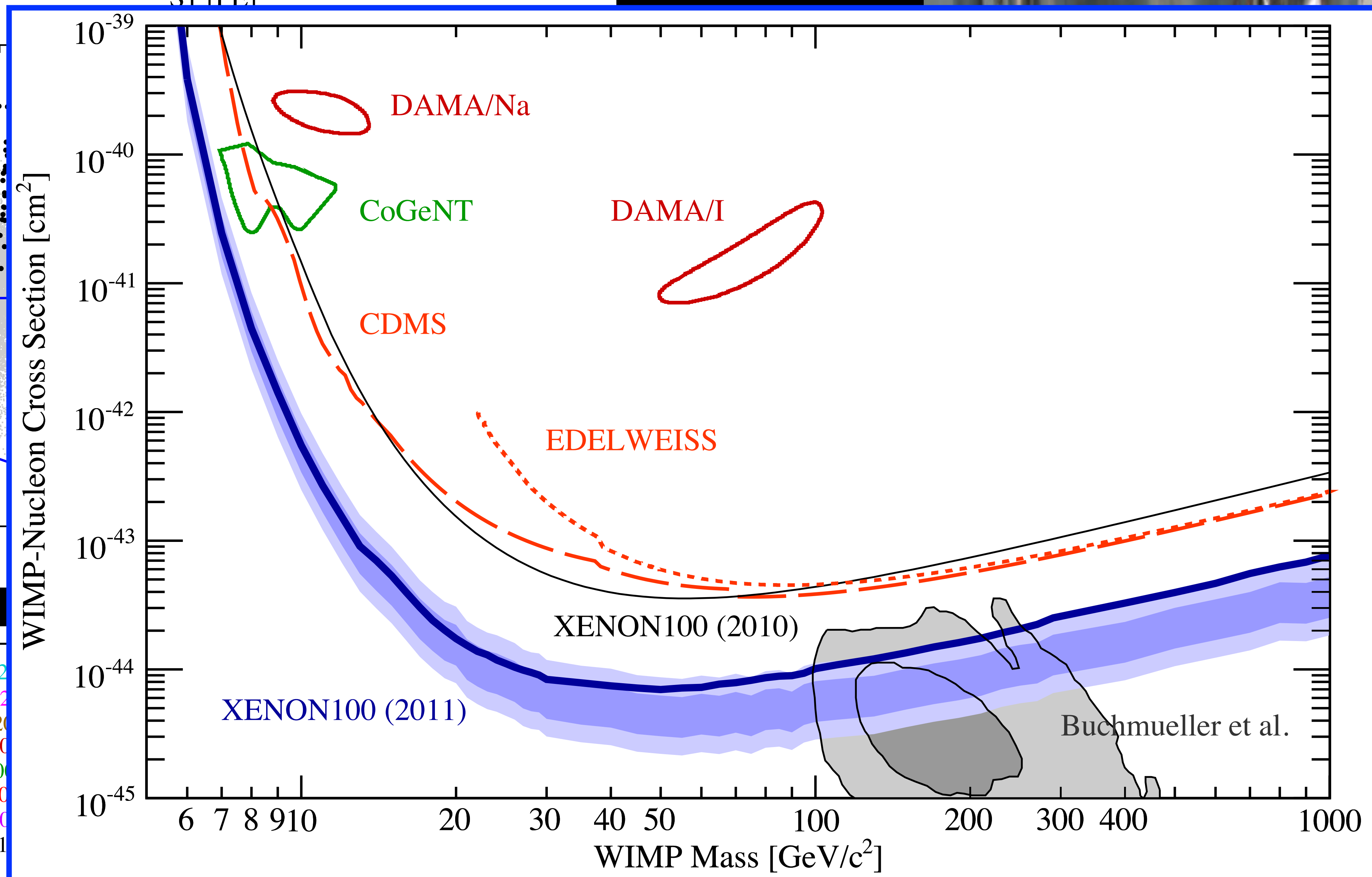

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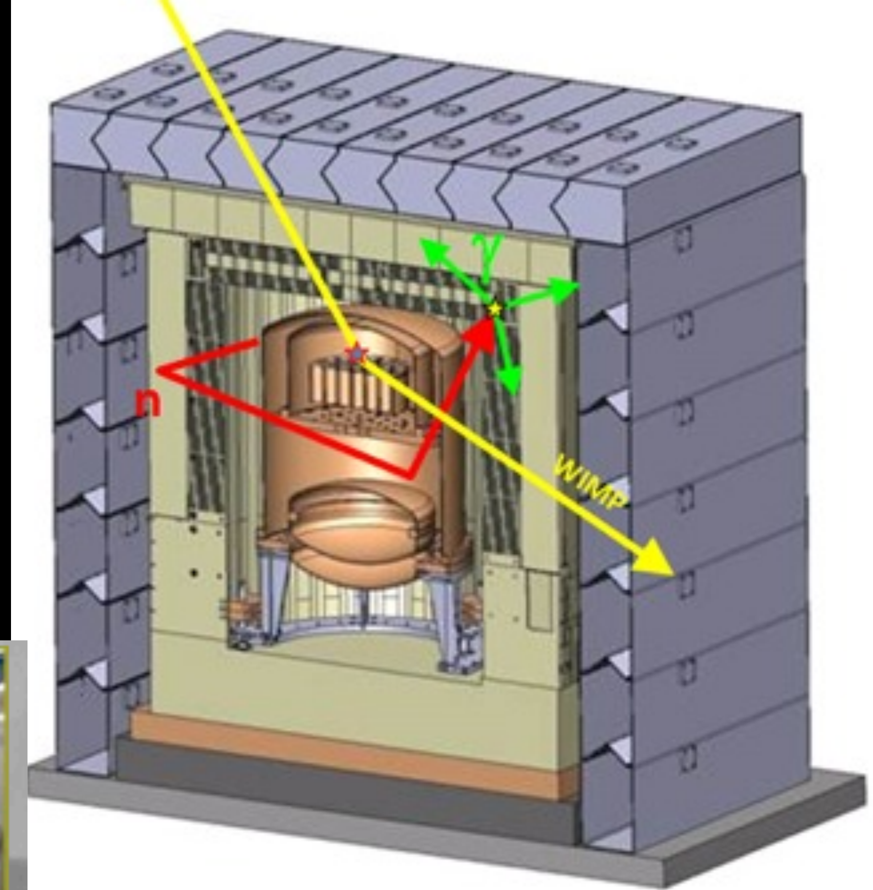
ZeplinIII Status and Outlook

Background expectation in 1-year dataset, in a/c with veto and realistic signal acceptance:
®**0.4±0.1 neutron scatters**
®**2.4±0.2 electron recoils**

- **Main challenge is to achieve the same**
- **discrimination power as in FSR with new**
- **phototubes (poorer optical performance)**

(H. Araujo, IOP)



First science run

- **First science run at Boulby: 83 days in 2008**

  Strong constraints on WIMP-nucleon scattering cross-sections
  - V. N. Lebedenko *et al.*, Phys. Rev. D 80: 052010 (2009)
    Scalar cross-section excluded above 8.1x10^{-8} pb (90% CL) at 60 GeV/c^2
  - V. N. Lebedenko *et al.*, Phys. Rev. Lett. 103: 151302 (2009)
    WIMP-neutron cross-section excluded above 1.9x10^{-2} pb (90% CL)
  - Akimov *et al.*, Phys. Lett. B 692: 180 (2010)
    Explanation of DAMA with inelastic DM model ruled out at 87% CL
- **Phase-II upgrades commissioned in 2009/10**
  - New photomultiplier array (low background)
  - New anti-coincidence veto (background reduction & diagnostic)
  - New calibration hardware (reduction of systematics)
  - System automation (underground effort, improved stability)
- **Second science run underway since Jun 2010**

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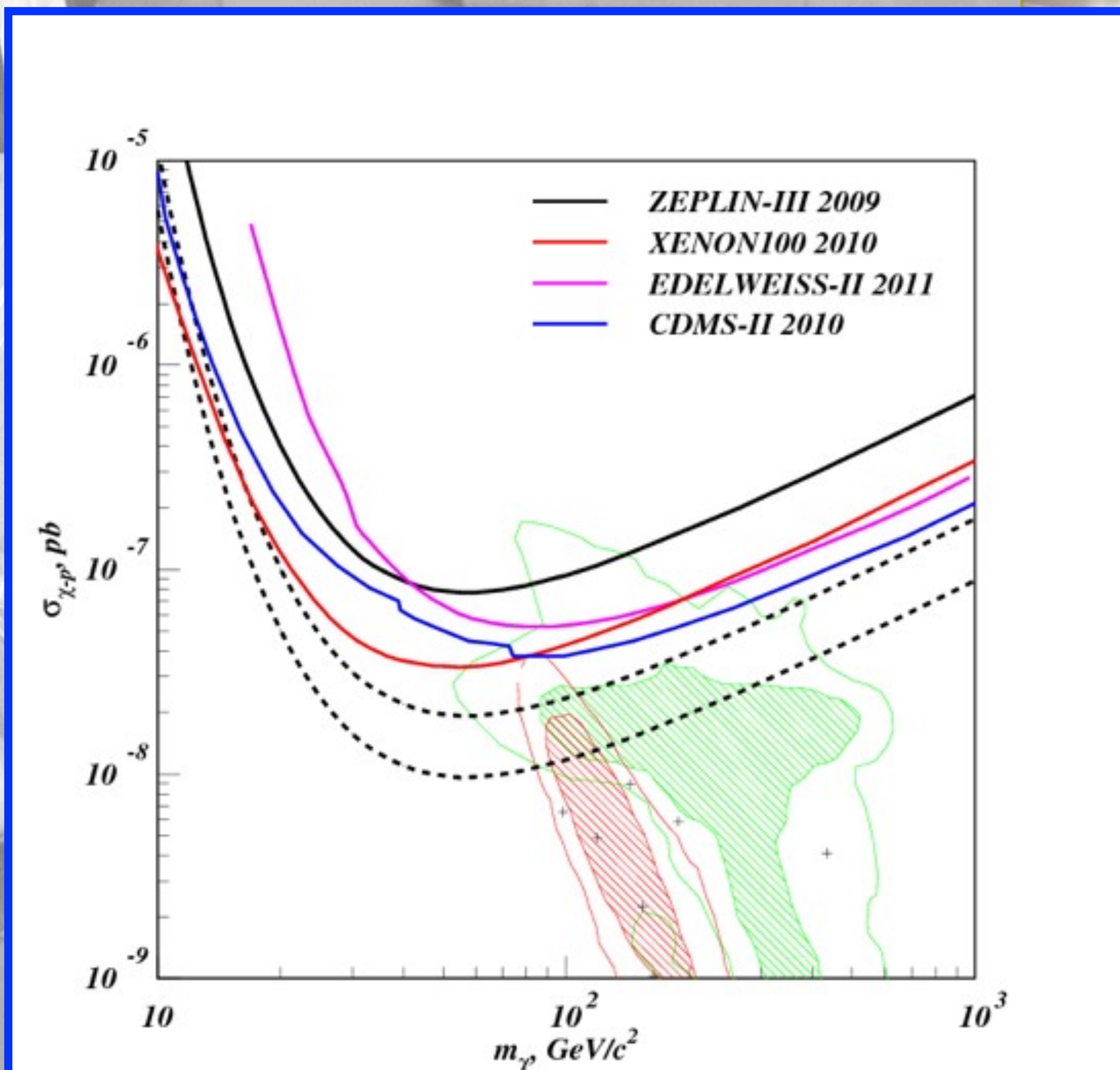
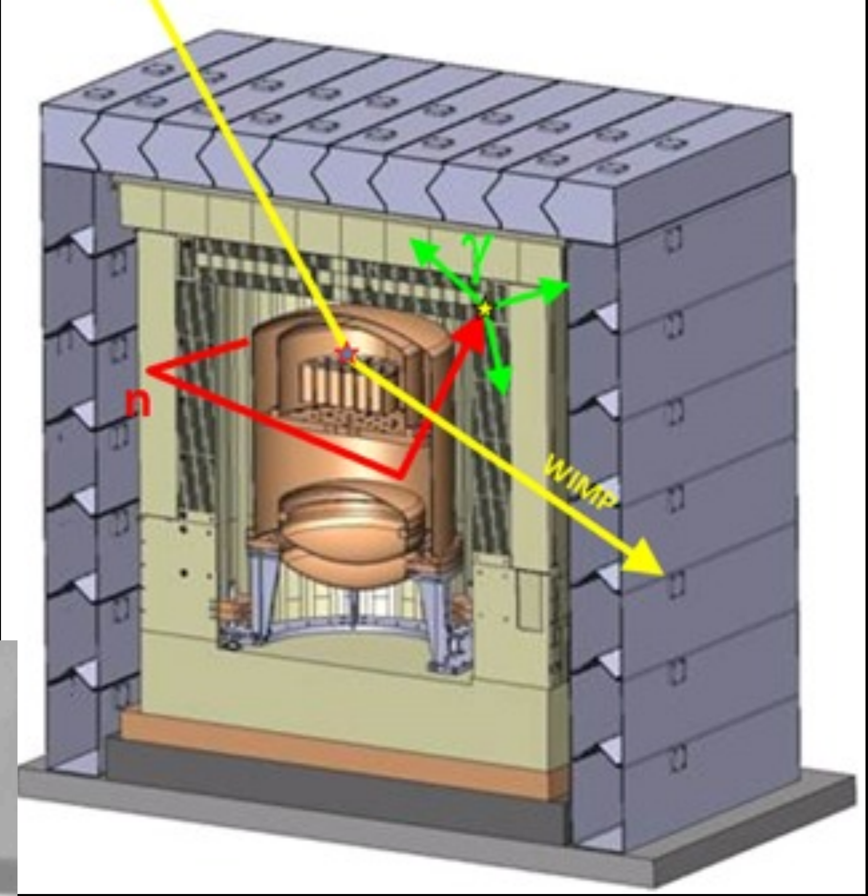




expected sensitivity matches Xenon100 current

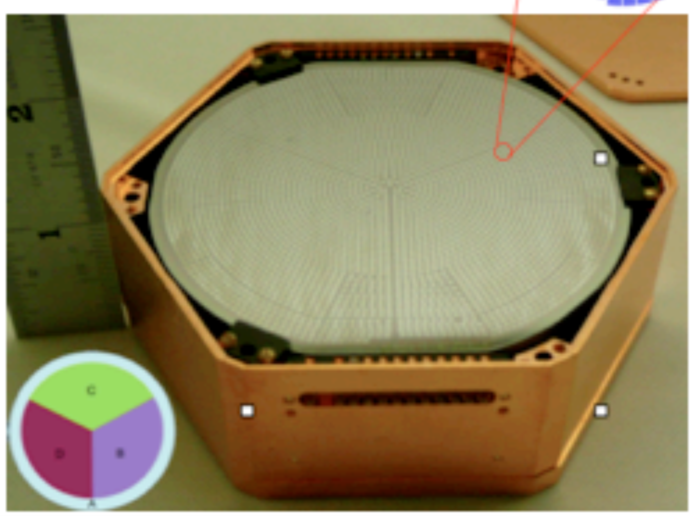
May 4, 2011

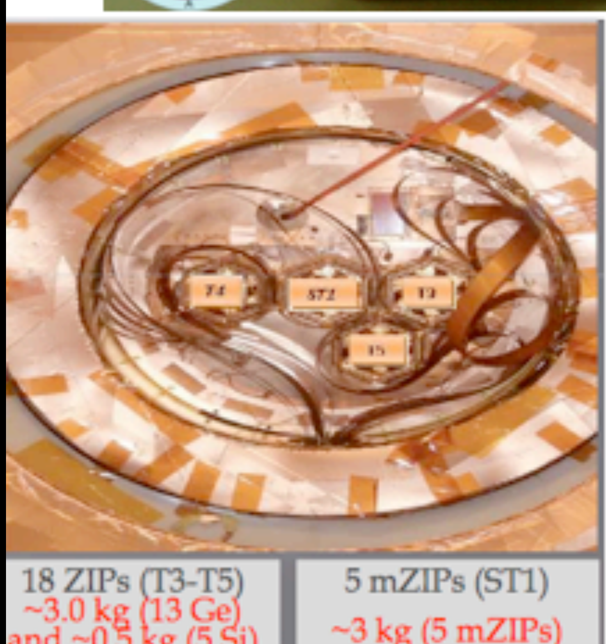
CDMS Status and Outlook

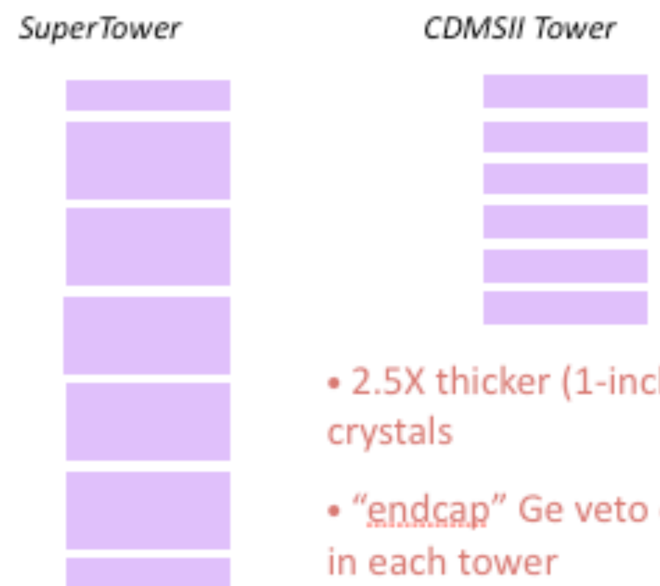
arXiv:0912.3592v1

- Two events observed
  - Consistent with 0.9 events expected from known backgrounds (surface + neutron)
  - Neither are golden events
    - Likelihood encourages suspicion about one event
    - Event reconstruction encourages suspicion about the other event
  - But: No obvious errors to exclude either event

SuperCDMS







- 2.5X thicker (1-inch) Ge crystals
- "endcap" Ge veto detectors in each tower
- modified Al fin layout, improves phonon collection efficiency
- cleaner, simplified, and streamlined production
- "mercedes" phonon sensor layout, outer phonon "guard"

15 kg of Ge at Soudan, arranged as 5 SuperTowers

arXiv:0907.1438v1
annual modulation analysis: 440 kg-day, 2-8 keVee, no evidence (disagrees with DAMA rate at 6.8 sigma, or, x2 at 90%CL on modulation amplitude)

(E. Figuroa)

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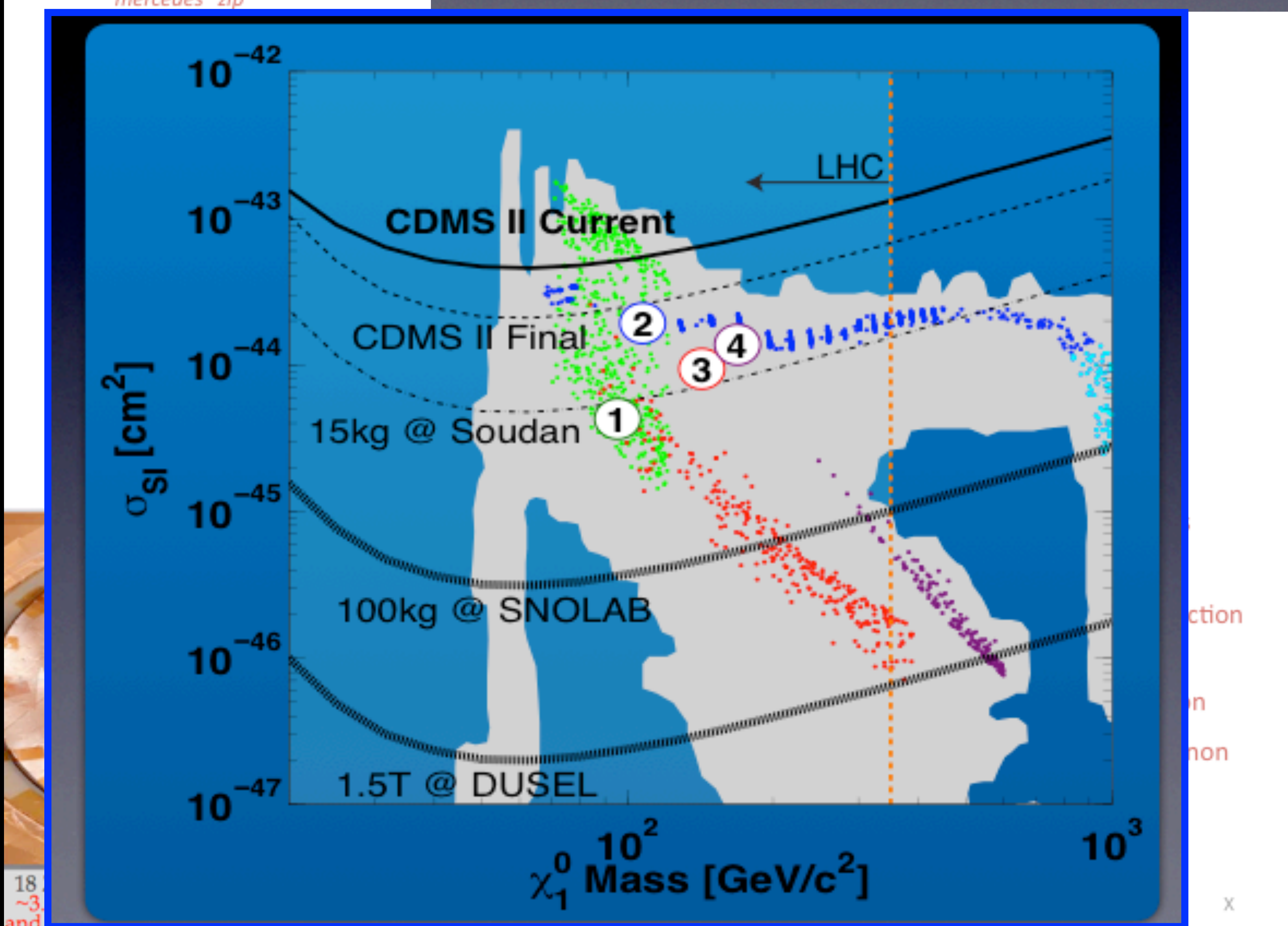

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projected 15kg@ SNOLab sensitivity matches Xenon100 projected

(E. Figuroa)

Spin-Independent Cross Section Limits

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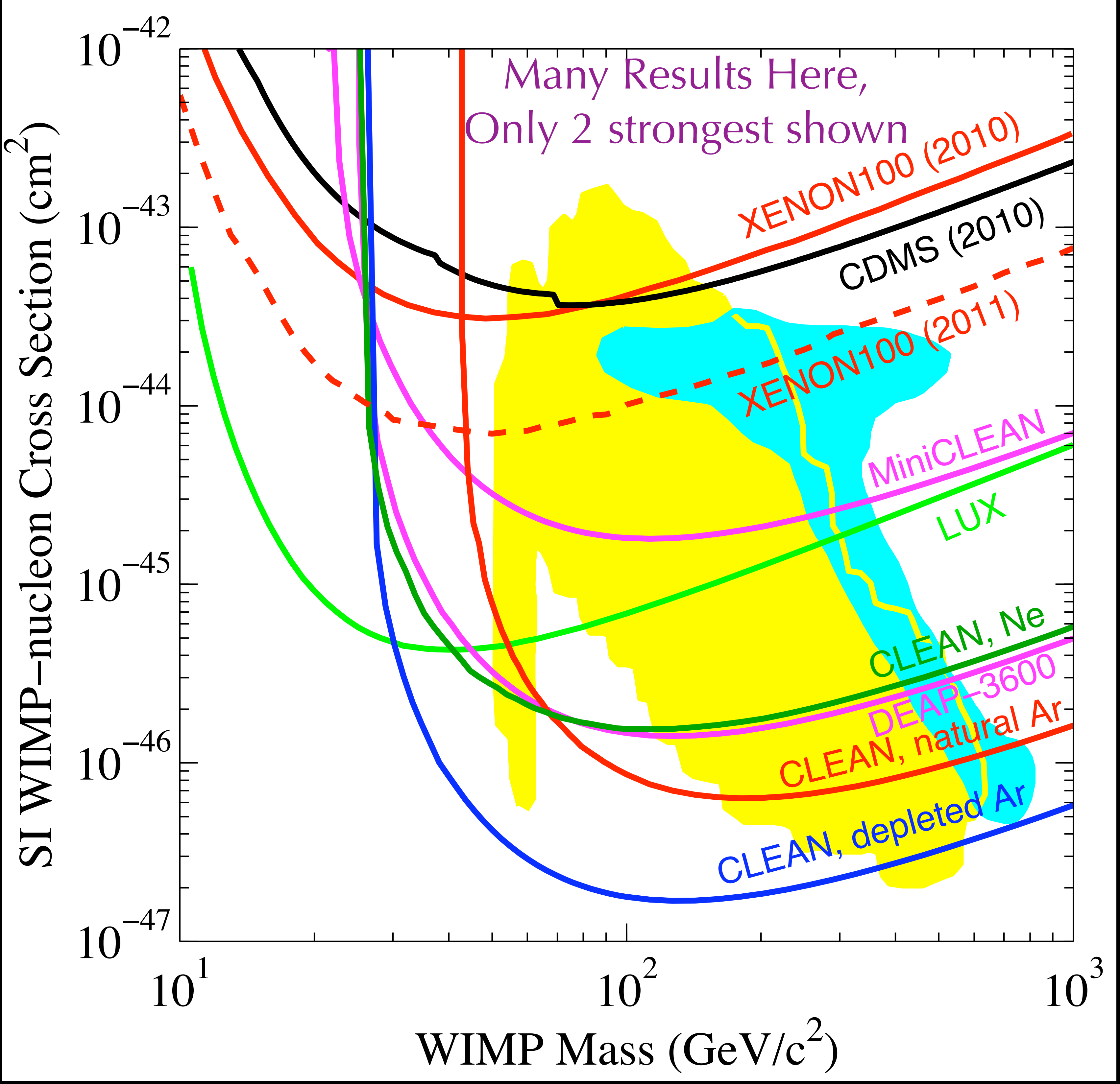
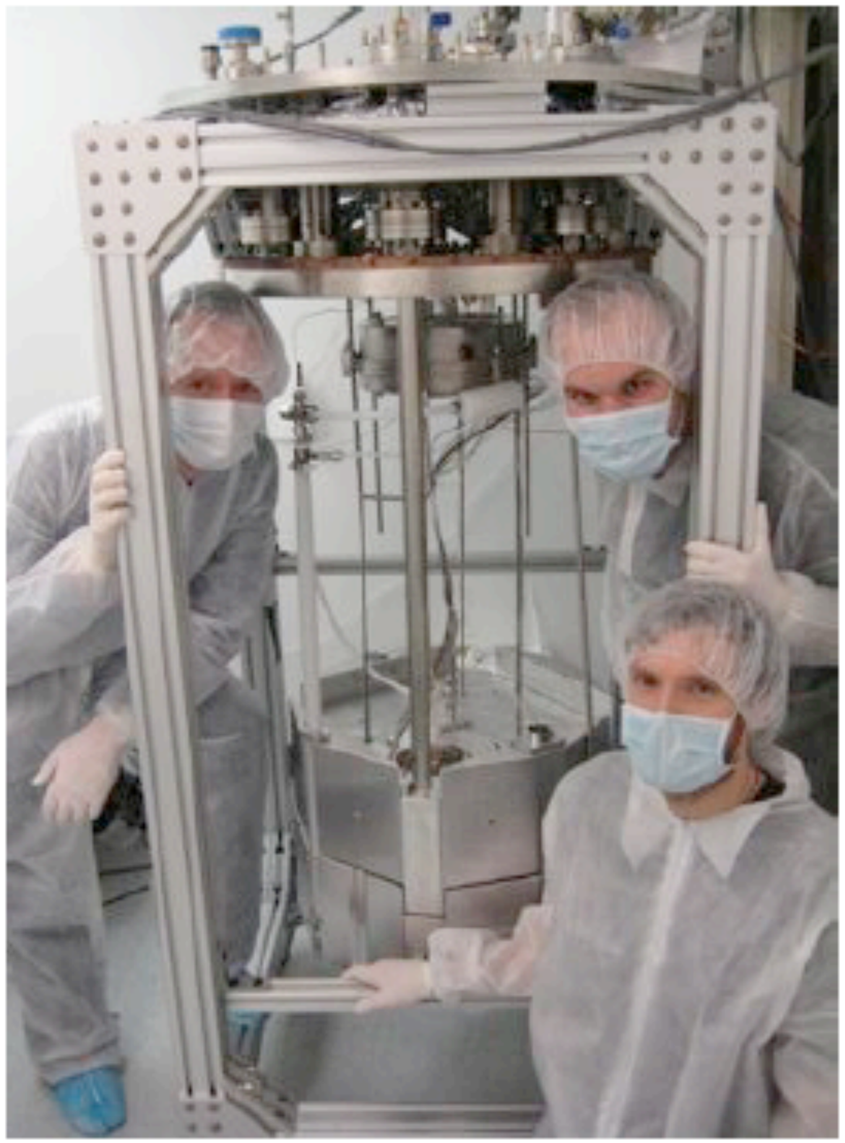


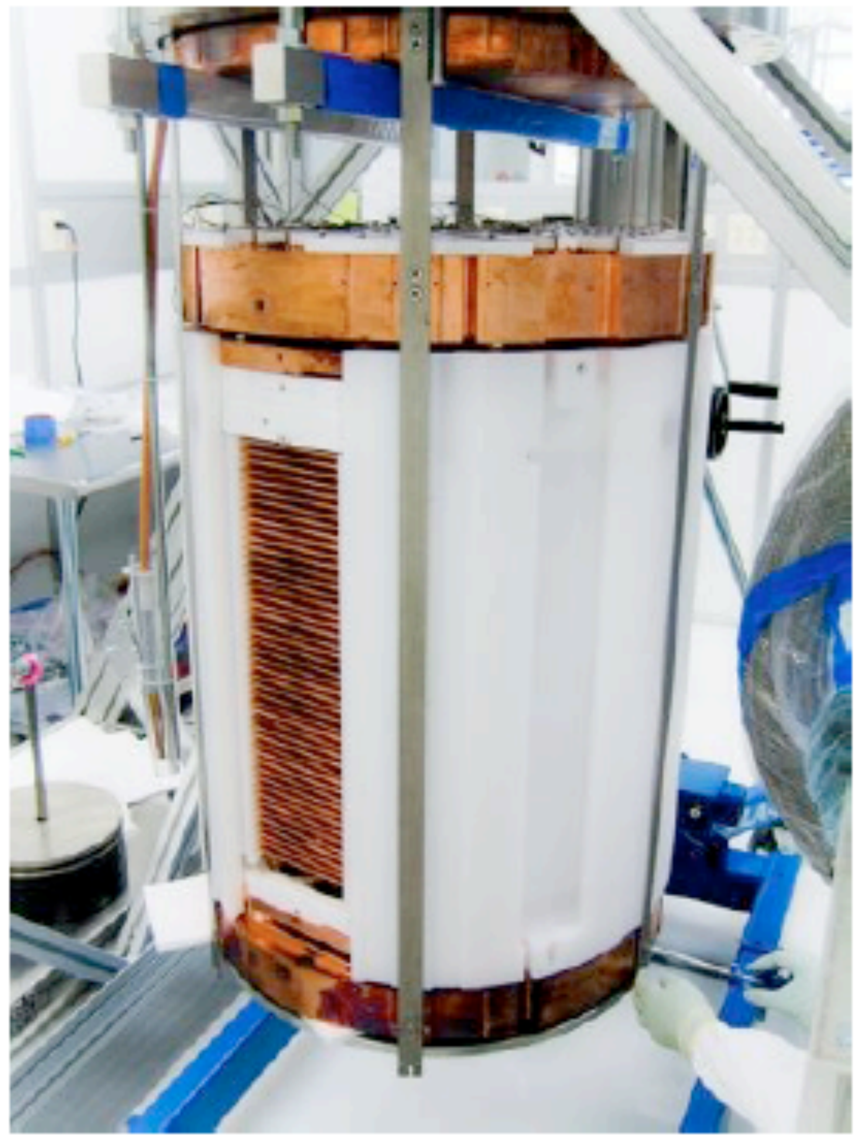
The LUX Program

LUX0.1 - CWRU



2007-2009

LUX - Surface



2010-2011

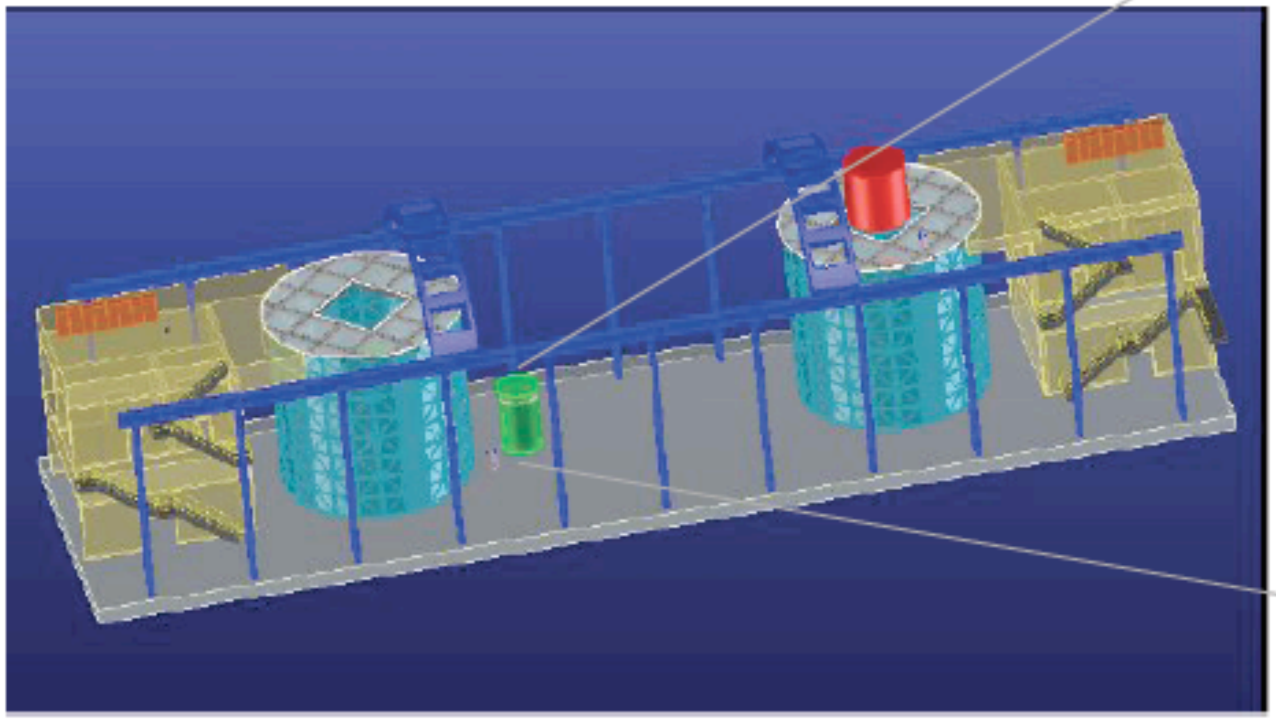
Right now

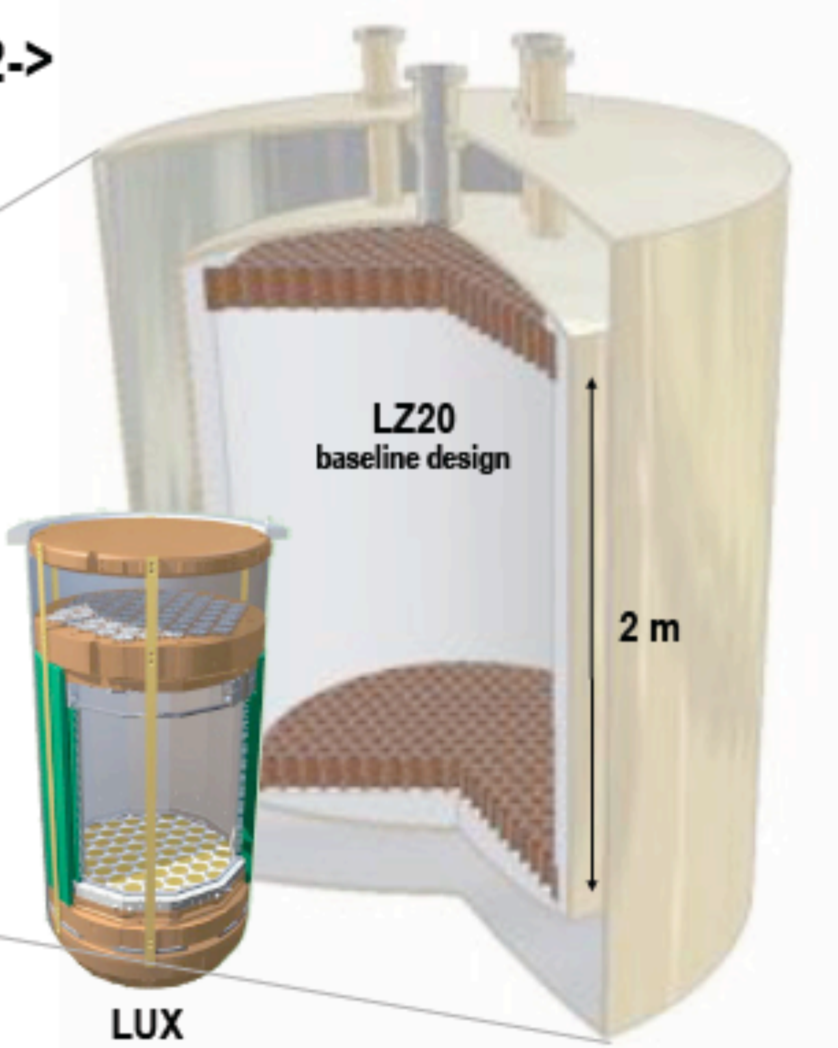
LUX - Underground

2011+

Future LUX-ZEPLIN III (LZ) Program

- New collaborators from Zeplin III and US institutions
  - Imperial College, London
  - STFC Rutherford Appleton Lab
  - ITEP, Moscow
  - Moscow Engineering Physics Institute
  - LIP, Coimbra
  - University of Edimburgh
  - UC Santa Barbara
  - LBNL
- Several phases: 3 tonne at Sanford Lab, SUSEL, 2012-> and 20 tonne at DUSEL from 2014 → 2018+
- DUSEL Program at Homestake 4850L and 7400L





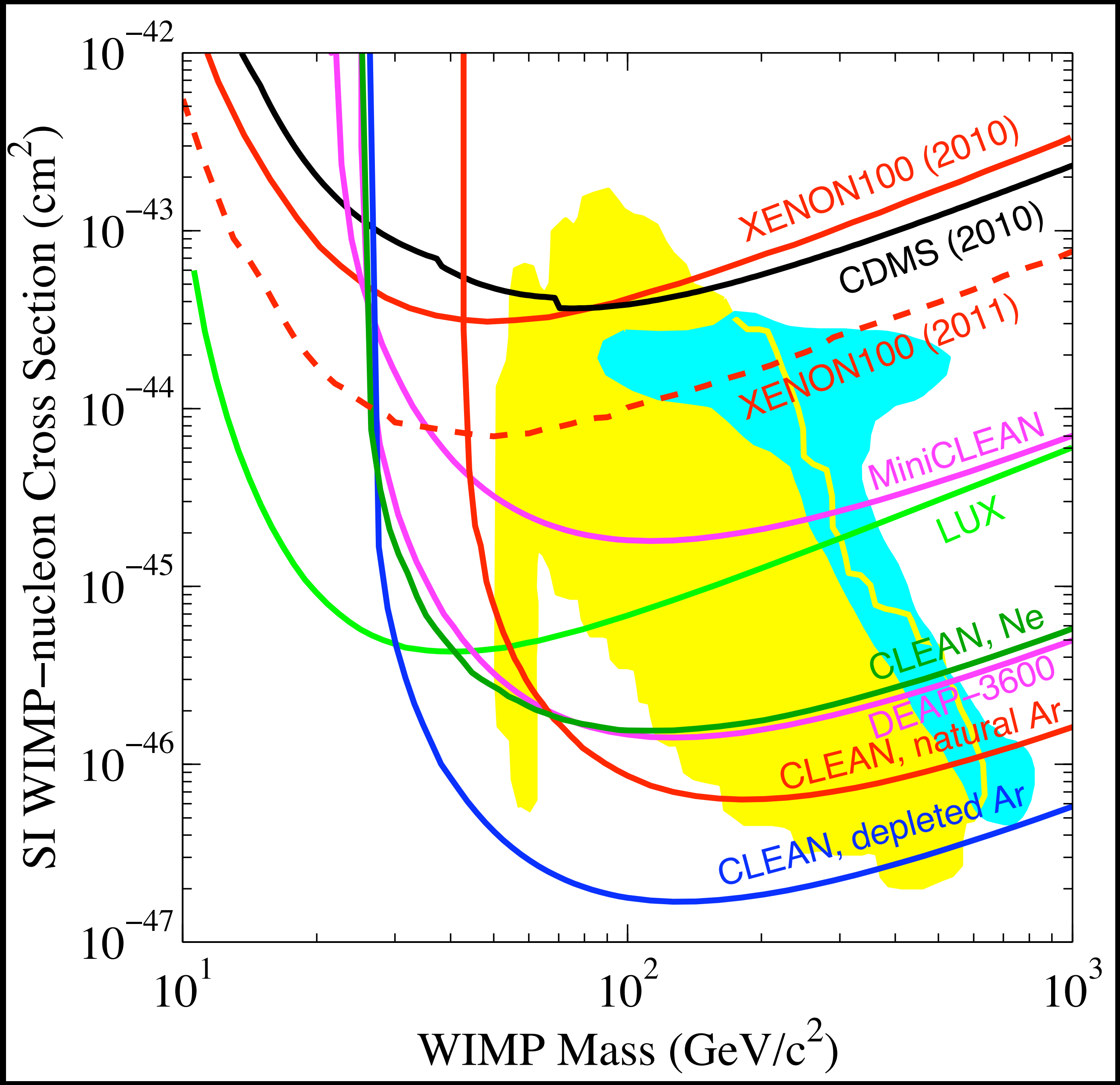
LUX Experiment / Rick Gaitskell / Brown University

DUSEL timeline uncertain now, planned LUX 300 kg detector installation underground in 2012

DEAP/CLEAN (Single Phase Detector Program)

DEAP-1 (7 kg) µCLEAN (4 kg) MiniCLEAN (300 kg) DEAP-3600 (3600 kg) CLEAN(100T)

2006 2007 2011 2014 2018



current experiments

MiniCLEAN (150 kg fiducial)

construction: 2010-2011

run: 2012-2014

DEAP-3600 (1 tonne fiducial)

construction: 2011-2013

run: 2014-2019

CLEAN (10 tonne fiducial)

proposal: 2016

*DEAP-3600: **first** tonne-scale detector, great dark matter discovery potential!*

DEAP/CLEAN Collaboration

BOSTON UNIVERSITY

VE RI TAS HARVARD

Queen's UNIVERSITY

UNIVERSITY OF ALBERTA

THE UNIVERSITY of NEW MEXICO

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

THE UNIVERSITY OF SOUTH DAKOTA VERITAS 1862

Massachusetts Institute of Technology

LUX ET VERITAS

Penn UNIVERSITY of PENNSYLVANIA

NIST

SYRACUSE UNIVERSITY SUOS CULTORES SCIENTIA CORONAT FOUNDED A·D·1870

Carleton UNIVERSITY

TRIUMF

SNOLAB MINING FOR KNOWLEDGE CREUSER POUR TROUVER... L'EXCELLENCE

Los Alamos NATIONAL LABORATORY EST.1943

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Royal Holloway University of London

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Los Alamos NATIONAL LABORATORY EST.1943

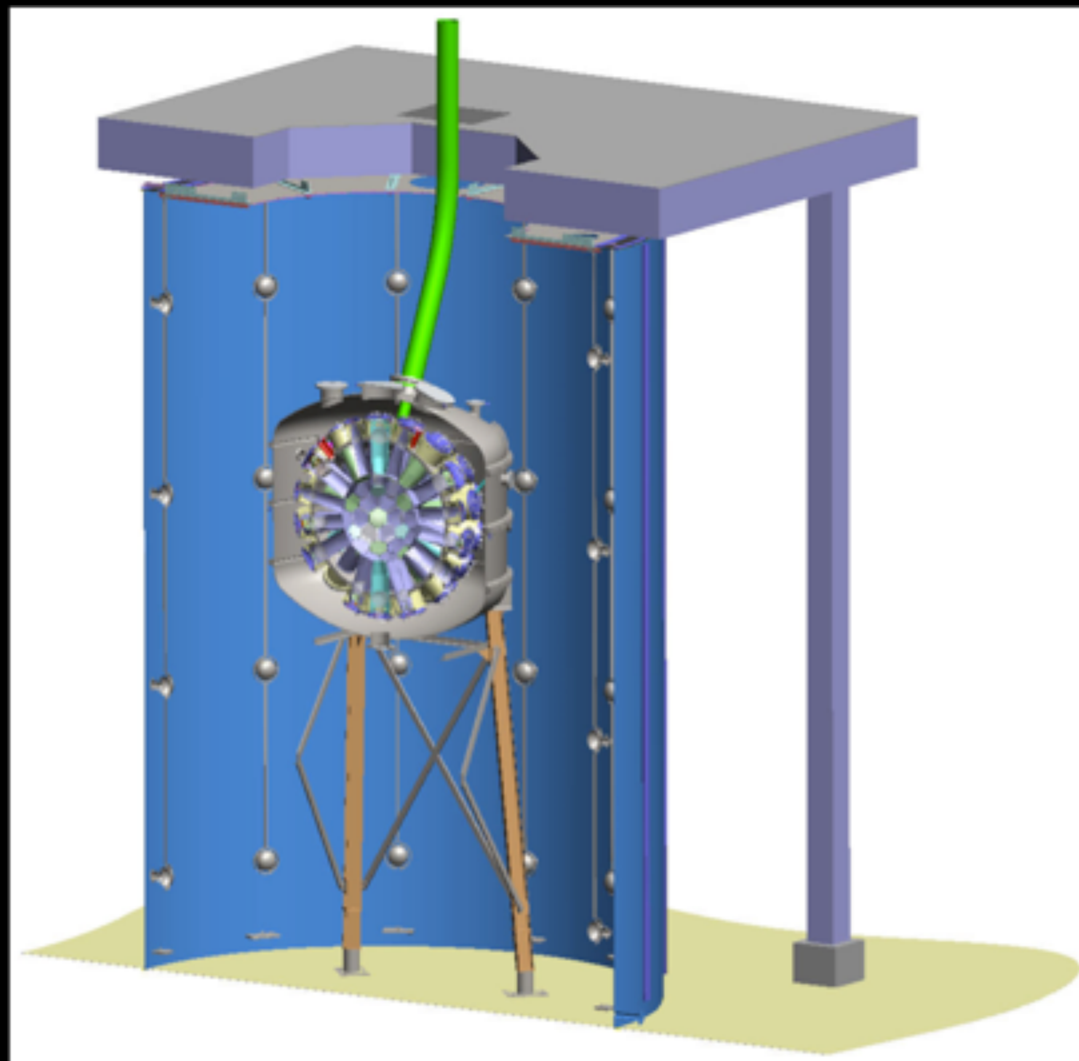
MiniCLEAN

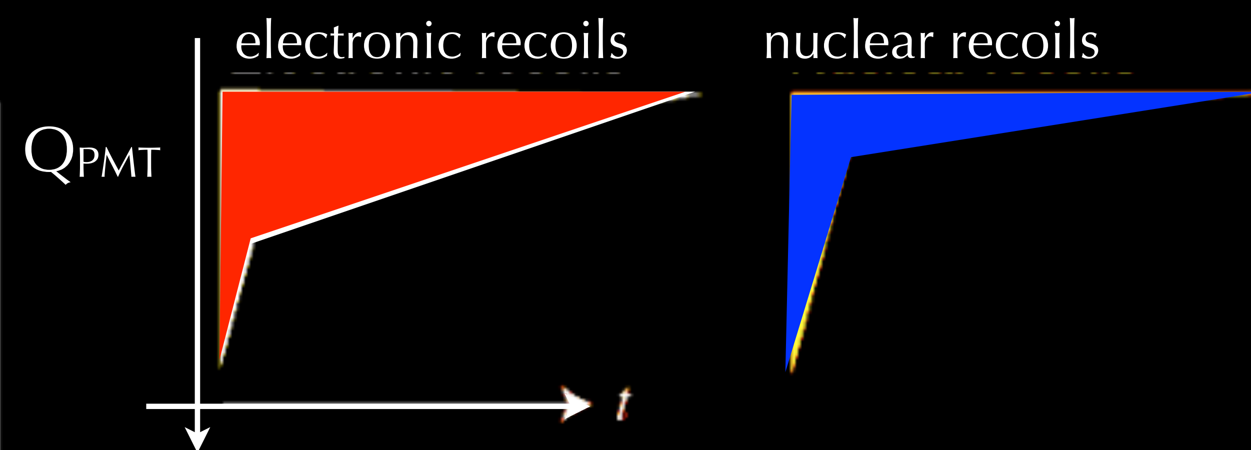
70°K cryostat

water shield outside

150 kg Argon (Fiducial)

92 8″ PMTs

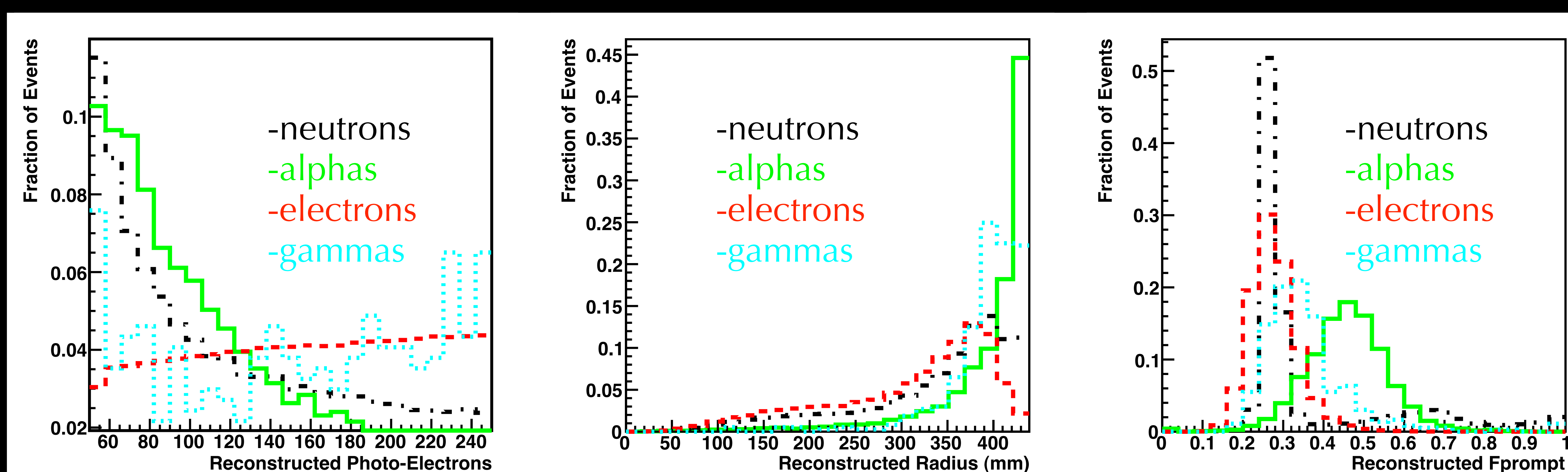




- pulse shape discrimination against 39Ar e- backgrounds at 1:10^8 level *Lippincott, Phys.Rev.C78:035801 (2008)*
- no E fields, ~no pile-up
- maximize light collection, demonstrated 6 pe/keV *Lippincott, et al., arXiv:0911.5453*
- if there is a signal, verify A^2 dependence by swapping targets (Argon/Neon)

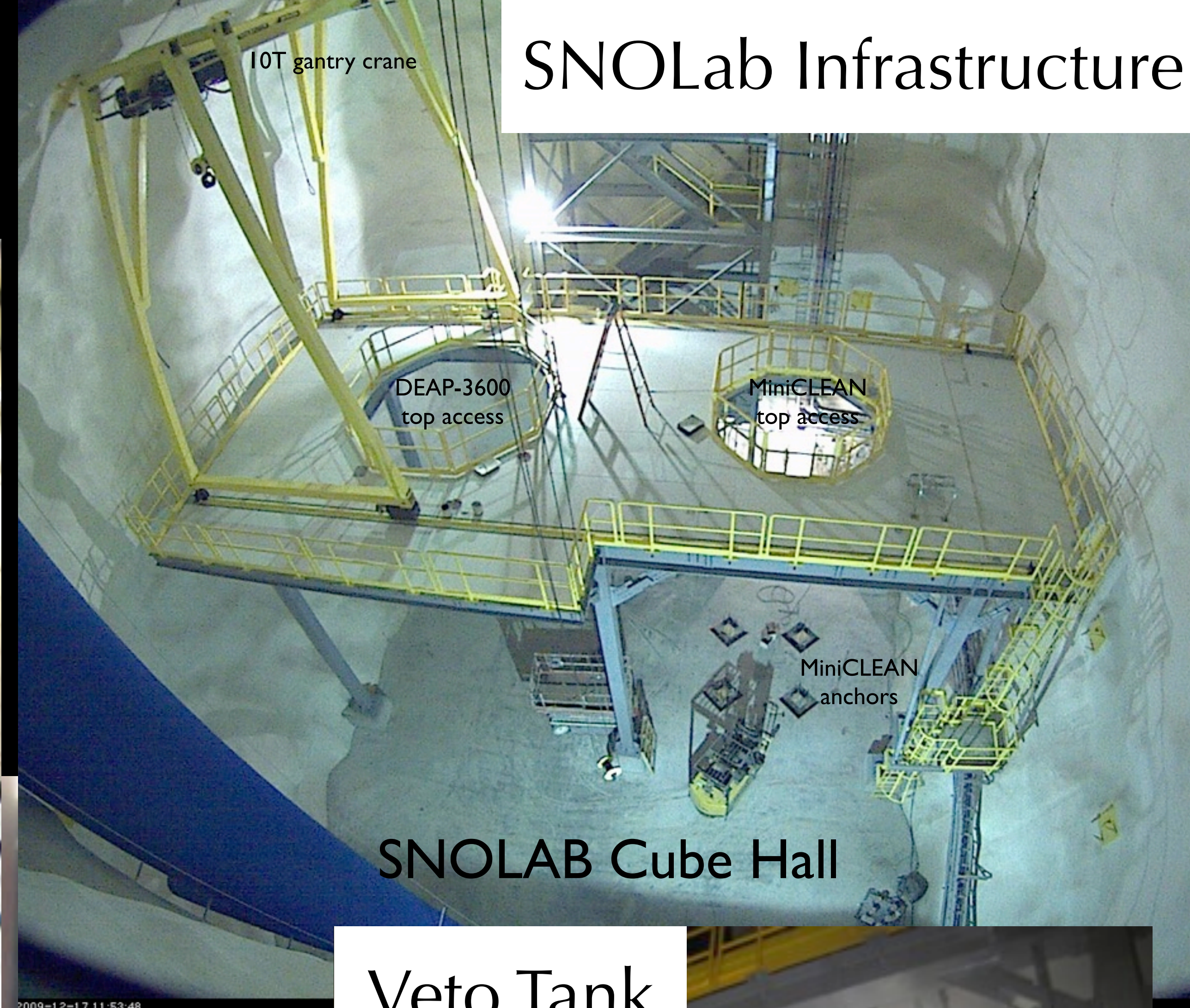
background simulation:

energy, radius, fraction of prompt photons



Construction Progress


Outer Vessel



SNOLab Infrastructure


Inner Vessel

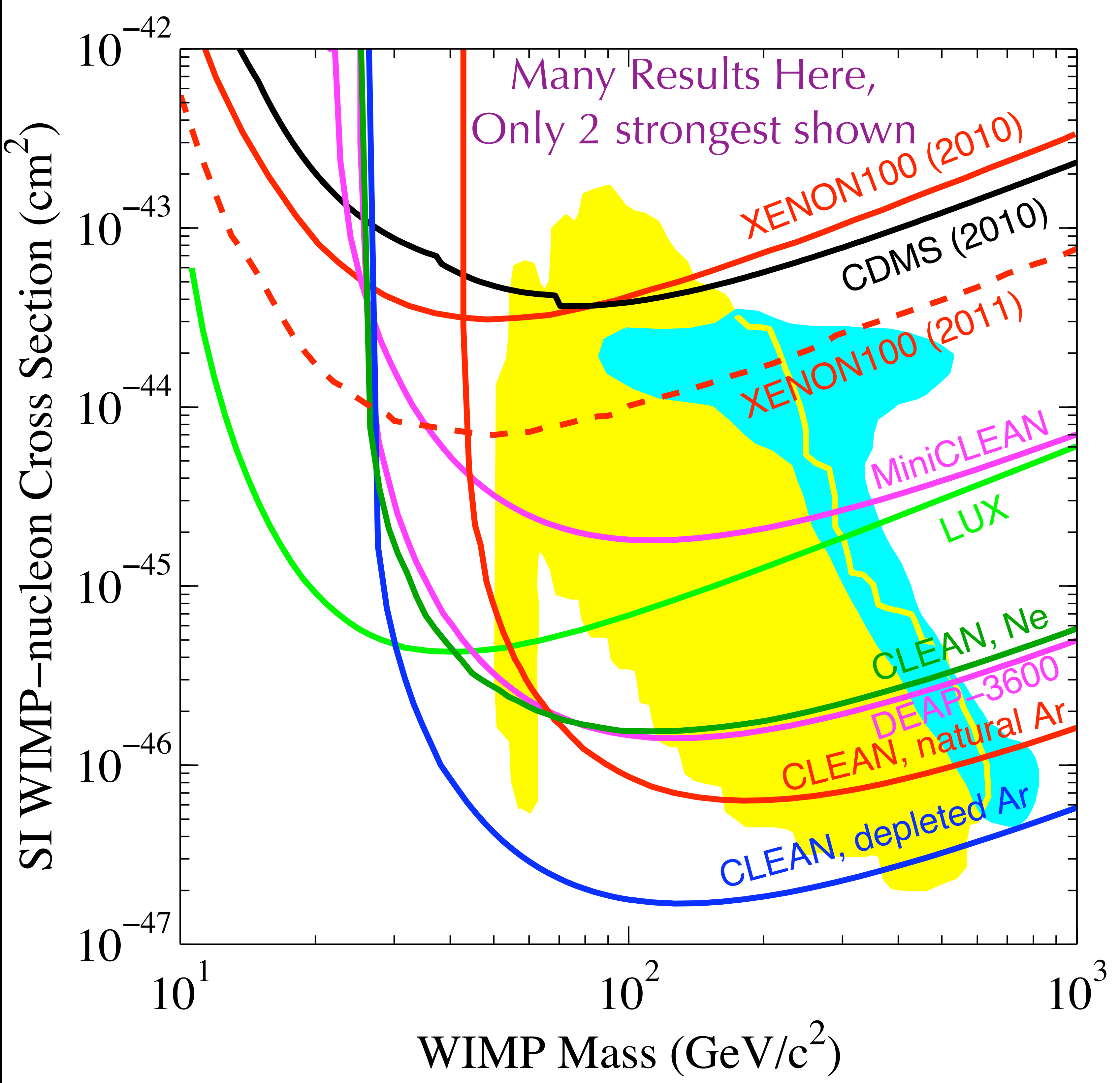

Veto Tank

Spin-Independent Cross Section Limits

1. Null Results

2. Near-Future Searches

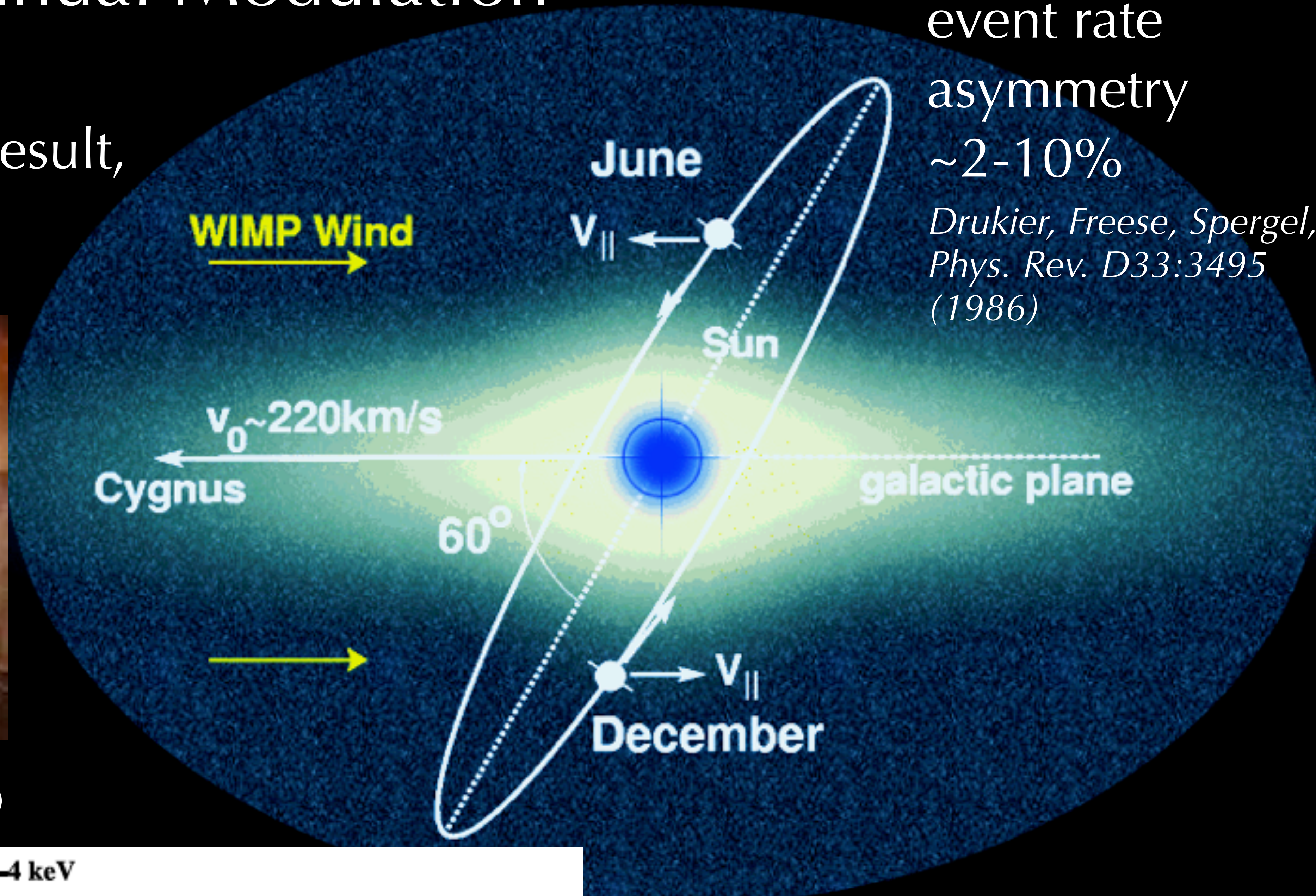
3. Signals?



DAMA/LIBRA: Annual Modulation

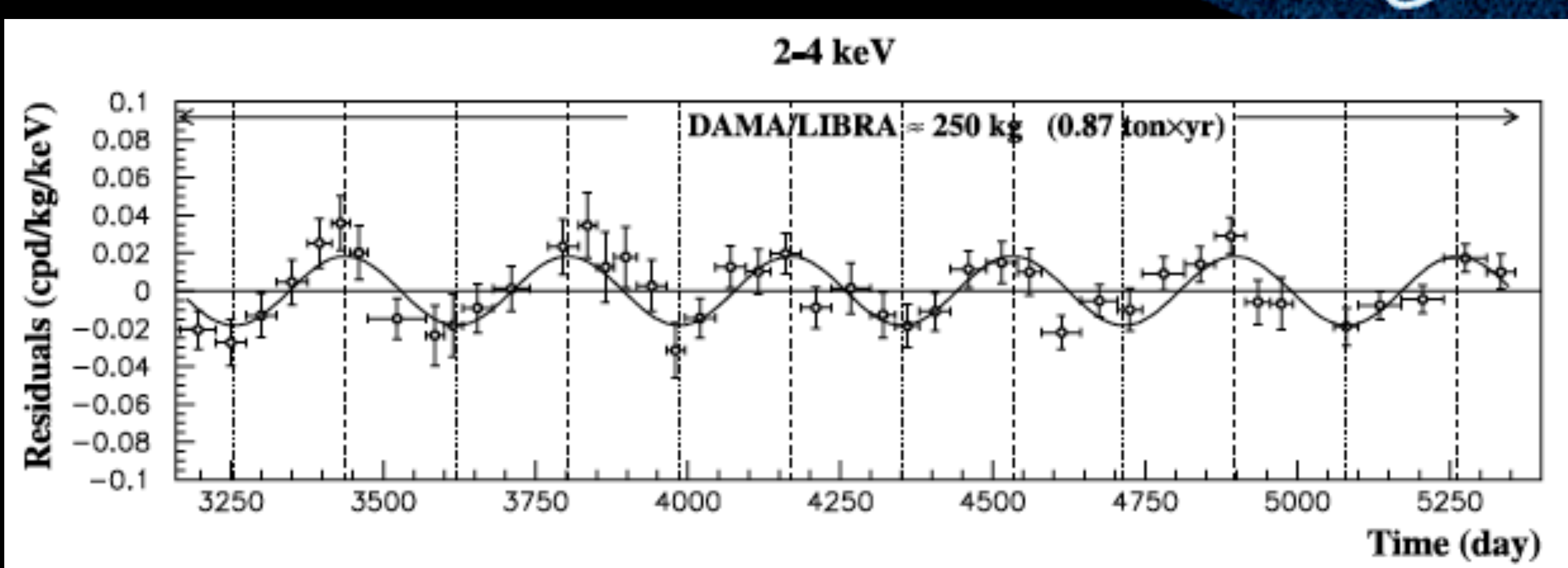
DAMA/Libra positive result, $>8\sigma$, *not seen by others*

Eur. Phys. J. C56:333-355 (2008)



June-December event rate asymmetry ~2-10%

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

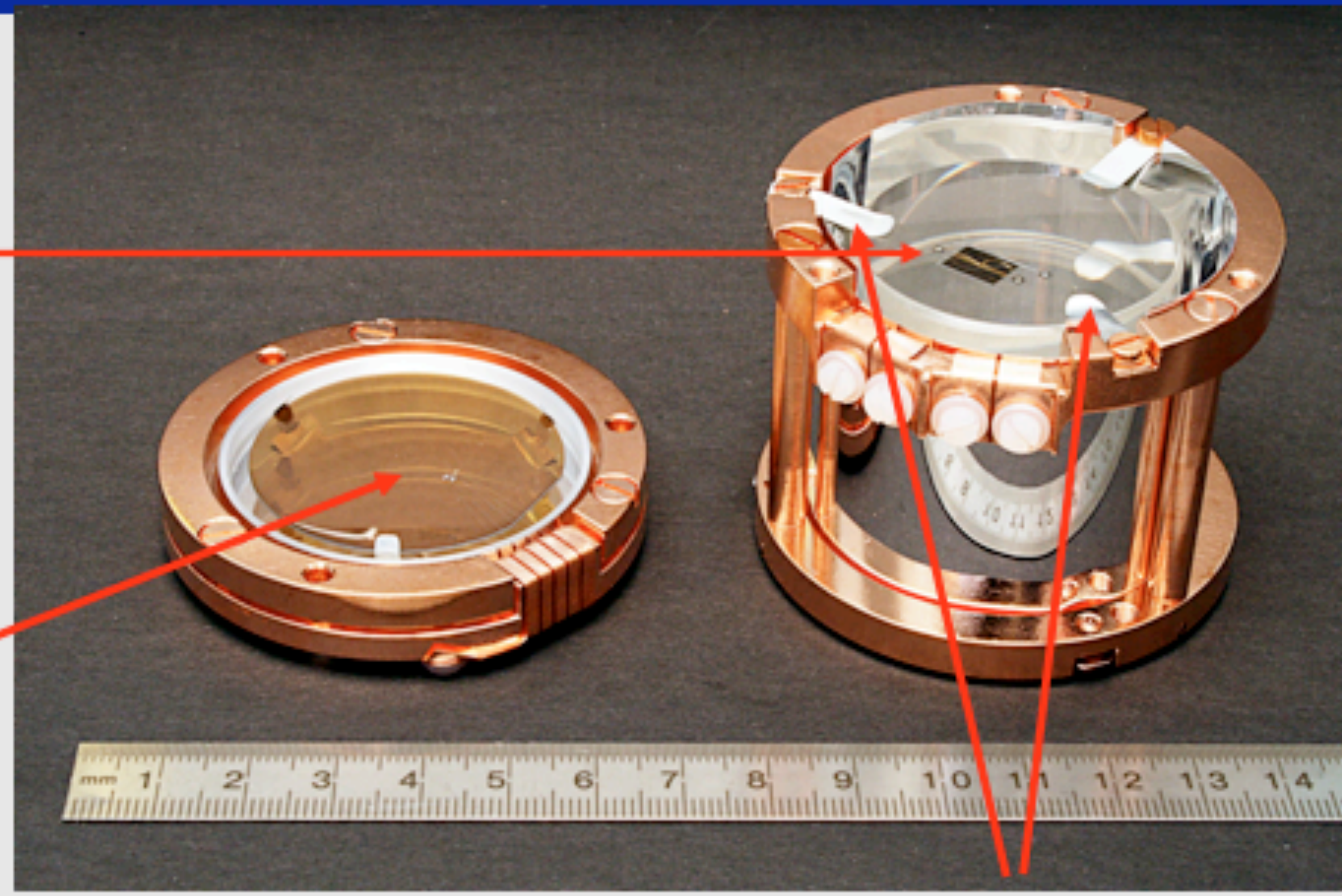


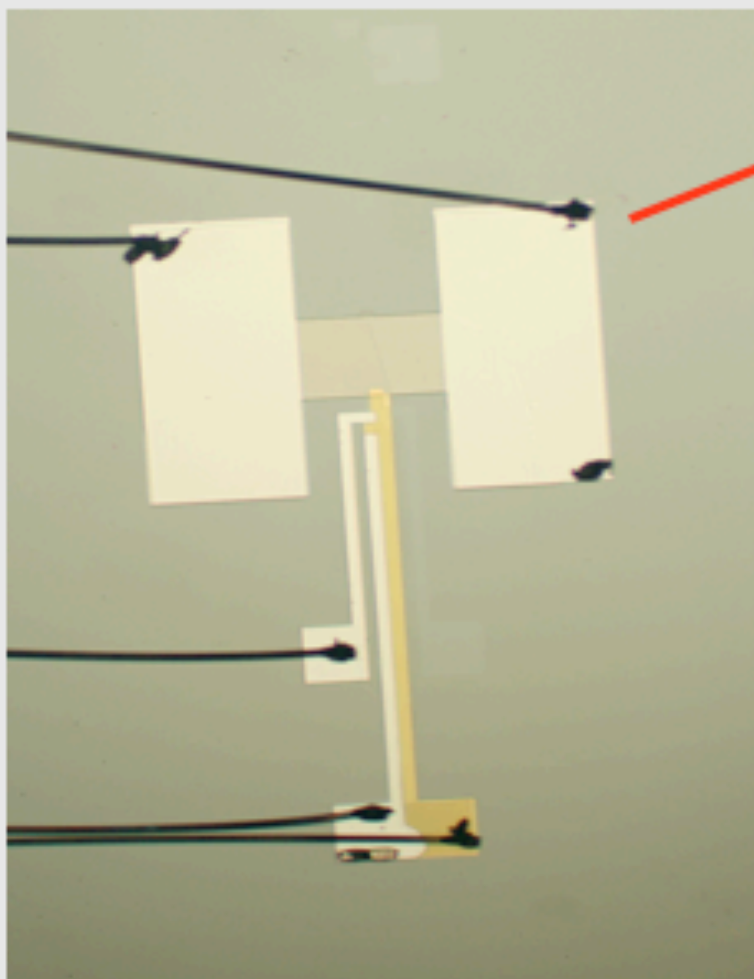
Modulation signal of 0.0116 ± 0.0013 cpd/kg/keV in 2-6 keVee, with 1.17 ton × yr, 13 anual cycles

CRESST-II

300 g CRESST-II Detector Module

The phonon detector:
300 g cylindrical $CaWO_4$ crystal. Evaporated tungsten thermometer with attached heater.





Clamps not scintillating

The light detector:
Ø=40 mm silicon on sapphire wafer.
Tungsten thermometer with attached aluminum phonon collectors and thermal link.
Part of thermal link used as heater

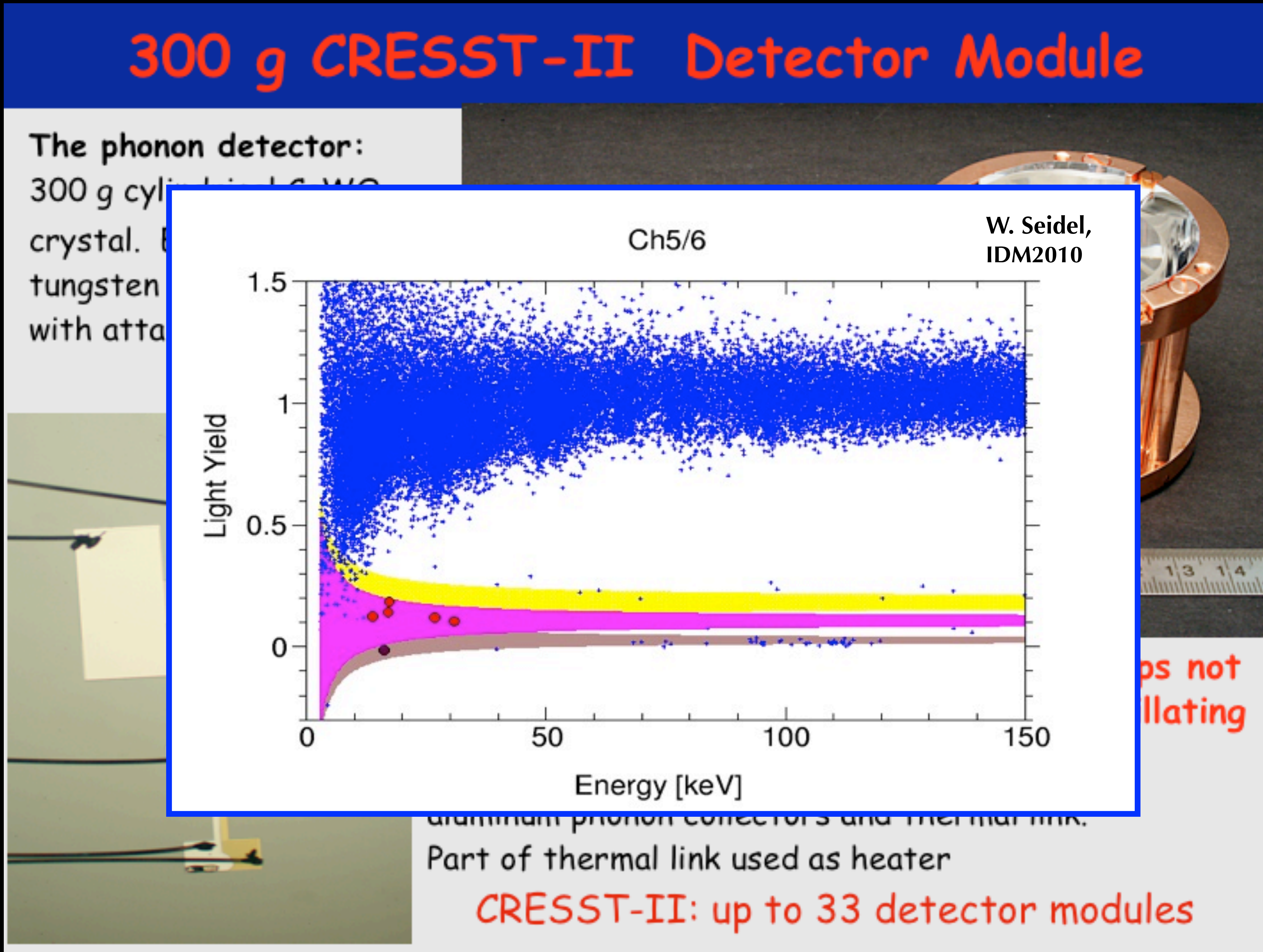
CRESST-II: up to 33 detector modules

(W. Seidel, IDM2010)

CRESST-II

expected 9 events, observed 32

(W. Seidel, IDM2010)

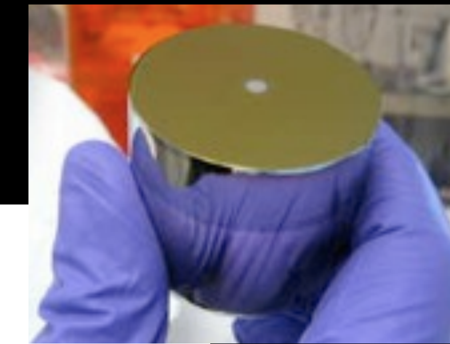


update expected soon...

CoGeNT

(J. Collar)

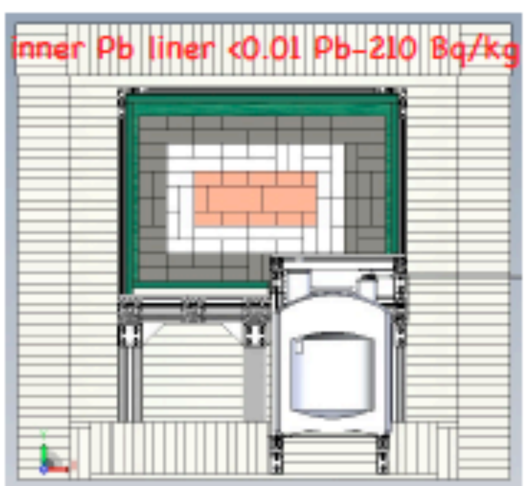
arXiv:1002.4703



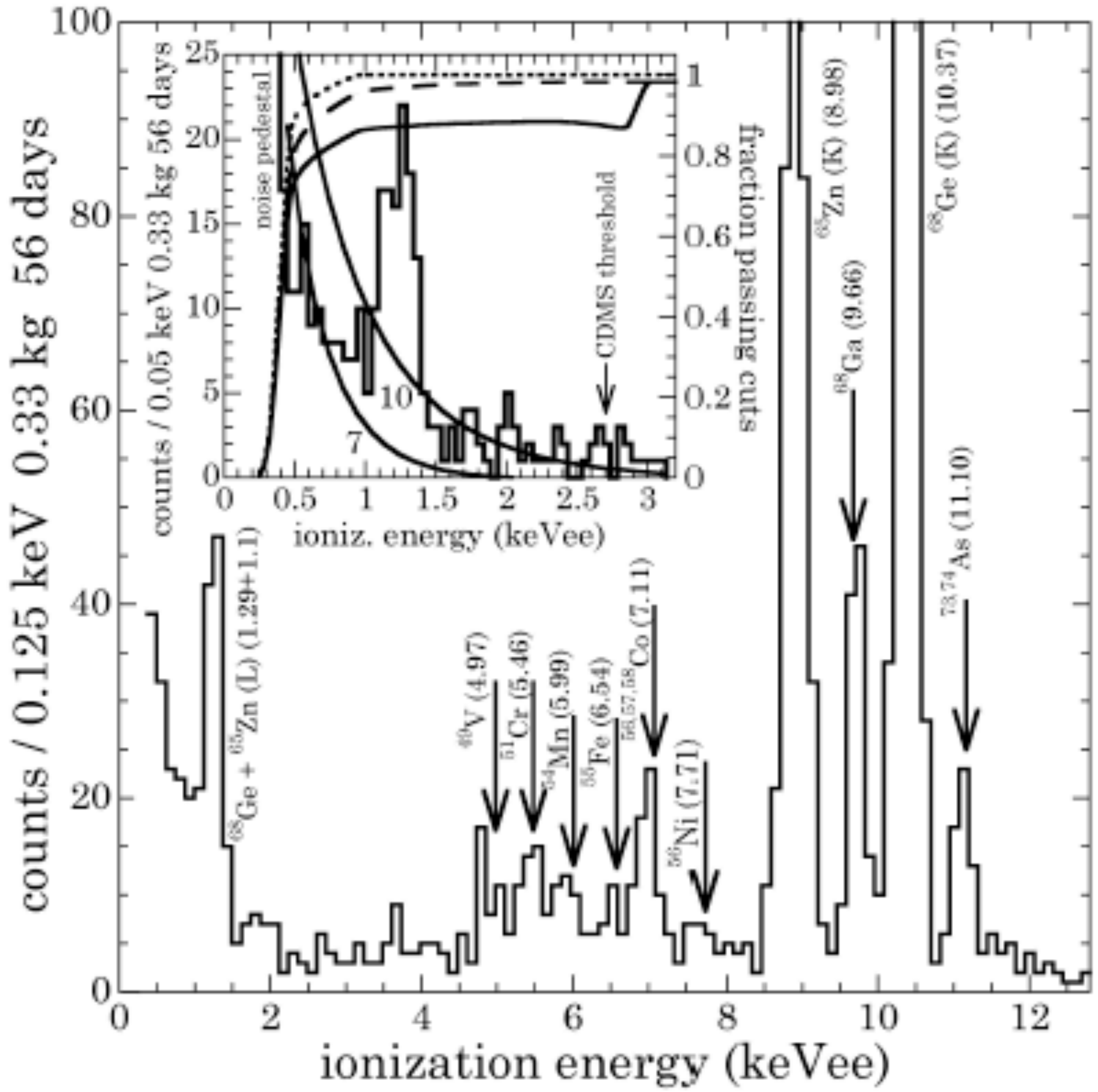
Making an excellent detector even better:
PPCs can reject surface events using rise time cuts

Based on a phenomenon ~40 years old (embarrasing!)

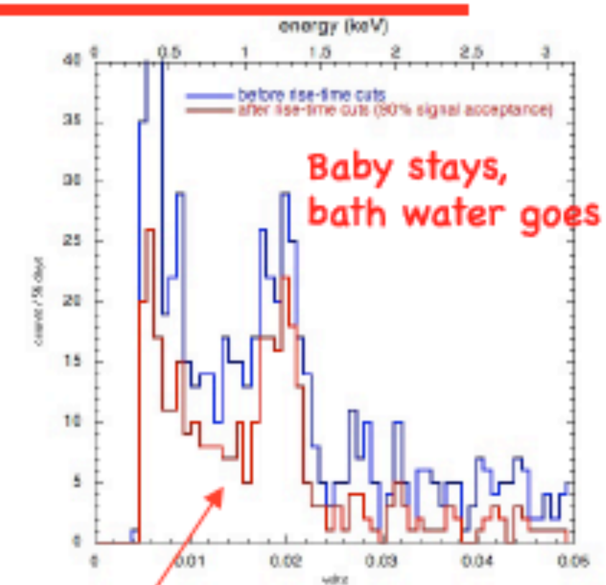
COGENT running
~20 m away from CDMS
(just to keep them honest... ;-)



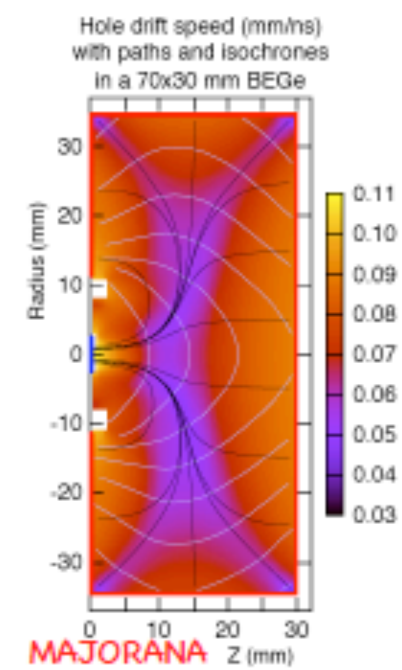
NOT nearly "best effort" yet.
MAJORANA Demonstrator
background goal is ~x1000 lower



Cuts remove 2-3 times the background above threshold at low-E. Not a massive cut, but enough to start to reveal all expected cosmogenics already at this level of exposure.



Bulk signal acceptance monitored down to 1 keVee via L/K EC peak ratios.
We need more info on surface background rejection, but it does not look bad at all.



Charge Collection time modelled (small 100 ns correction)

MAJORANA BEGe

CoGeNT 2

(J. Collar)

The "take-home" message transparency

- For m_χ ~7-11 GeV, a WIMP fits the data nicely (90% confidence interval on best-fit WIMP coupling incompatible with zero, good χ^2/dof).

- Red "island" tells you ~where to look (if you believe in WIMPs). Additional knowledge (e.g., more calibrations for fiducial volume and SA/BR) could wiggle it around some (so do the other regions shown, depending on who plots them).

- Not a big deal on its own, it simply means that our irreducible bulk-like bckg is ~exponential (the background model without a WIMP component fares just as well).

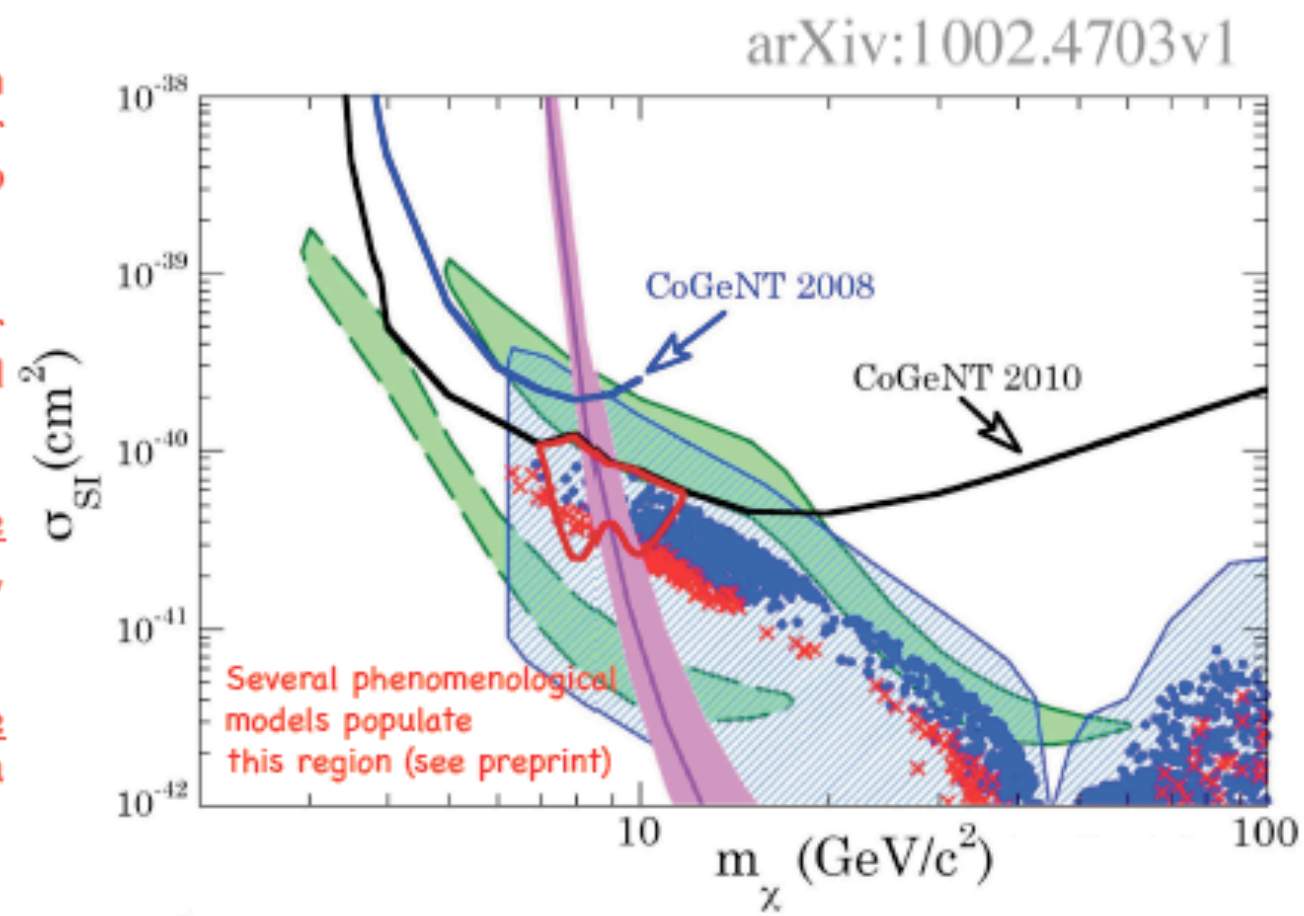
- We presently cannot find an obvious known source. But we can fancy some unexplored possibilities. It is not neutrons, and there is no evidence yet of detector contamination.

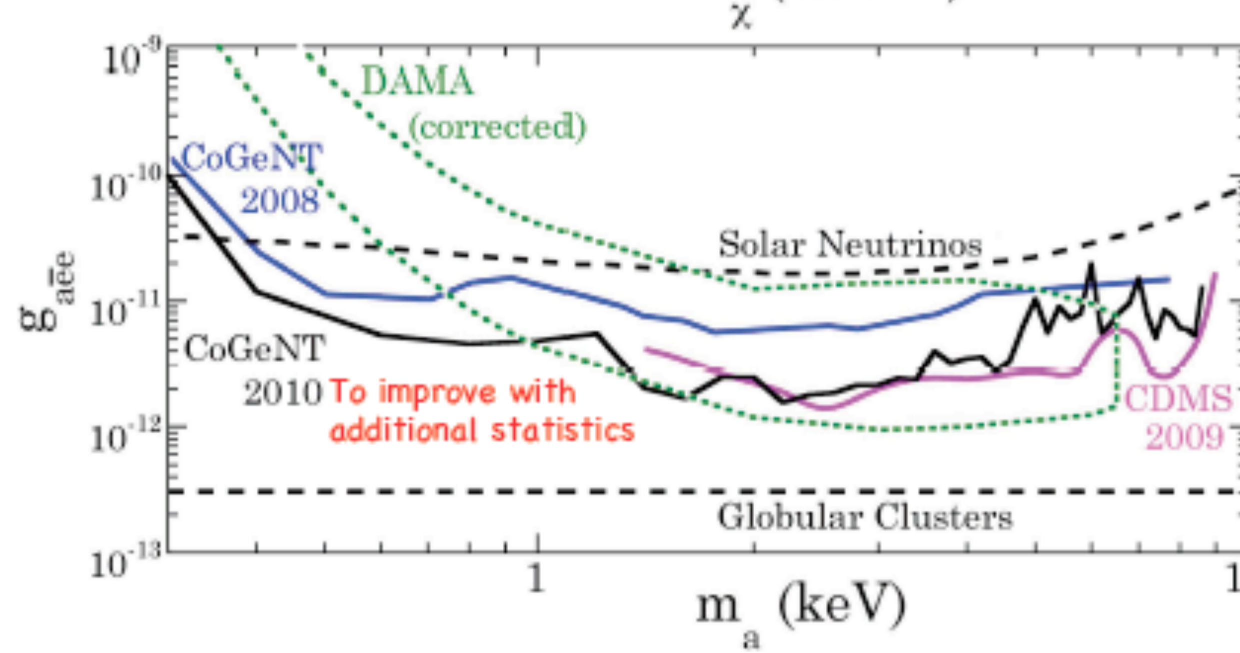
- The low-E excess is composed of asymptomatic bulk-like events (very different from electronic noise), coming in at a constant rate (76 days into data taking).

- The possible subject of interest is where we "got stuck" in phase space (a number of curious coincidences there), for a spectrum where most (if not all) surface events are removed (<- major contributors to low-energy spectrum). Caveat Emptor: without DAMA, would we have models there?

- We will attempt to strip the low-E data from known sources of background after a longer exposure, but all of them seem modest (see preprint). Planned additional calibrations will provide improved information on signal acceptance, background rejection and fiducial volume.

- Others will tell if this is cosmologically reasonable or not. BONUS: it seems readily falsifiable by other experiments.





CoGeNT@APS2011 (May 2, 2011) *(J. Collar)*

Soudan mine fire:
detector warmed up, opened the box to check the data (442 days x 440 gm)

result: **2.8 sigma annual modulation!** (~3 events/day) "paper next week"

consistent in phase with DAMA/LIBRA

May be first independent confirmation of DAMA signal!
BUT, inconsistent with Xenon, CDMS
(debate: arXiv:1103.3481v1)

plan: install 4-tower (O(2kg)) detector set in Soudan in 2012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Second experiment hints at seasonal dark matter signal

02:09 03 May 2011 by Valerie Jamieson, Anaheim
For similar stories, visit the Cosmology Topic Guide

PRINT

Things just got a little less lonely for researchers who have been insisting for years not only that their experiment has found dark matter, but also that the dark matter signal varies with the seasons. Now a second experiment, called CoGeNT, is reporting similar findings, though both results are in conflict with two other teams' observations.

Outline

1. Dark Matter Direct Detection Overview

2. Review of Spin-Independent Results

3. Review of Spin-Dependent Results

Spin-Independent Cross Section Limits

PICASSO:

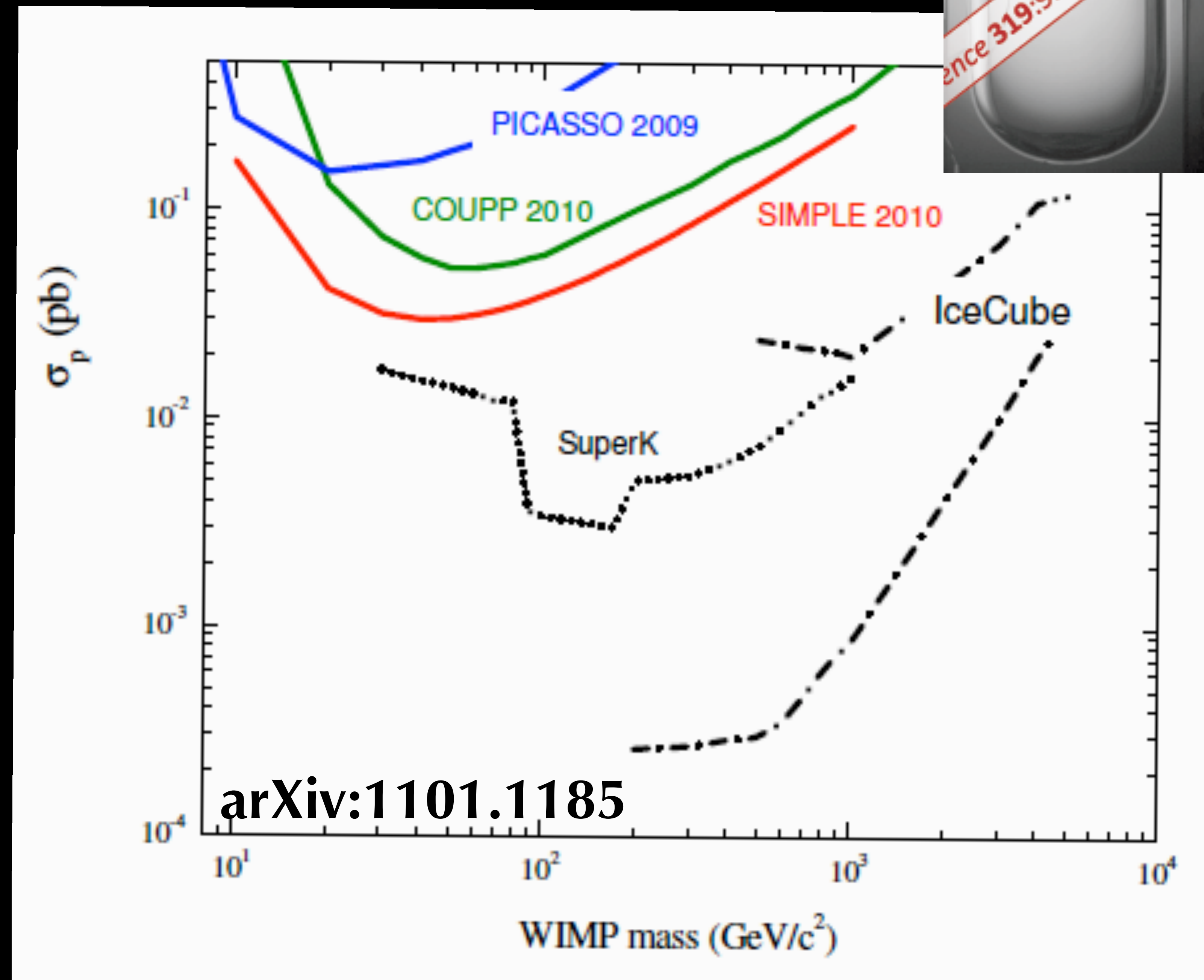
superheated bubble detector,
optical + acoustic readout,
taking ~16x exposure in SNOLab

COUPP:

“, CF_3I bubble chamber,
4 kg detector (3 events, “exp.” 0)
background is internal neutrons,
re-instrumented, taking data
exposure at SNOLab

SIMPLE:

acoustic readout of superheated
droplet detectors in GESA,
14 kg-days (0.2 kg C_2ClF_5),
14 events observed, FC limit
with background subtraction

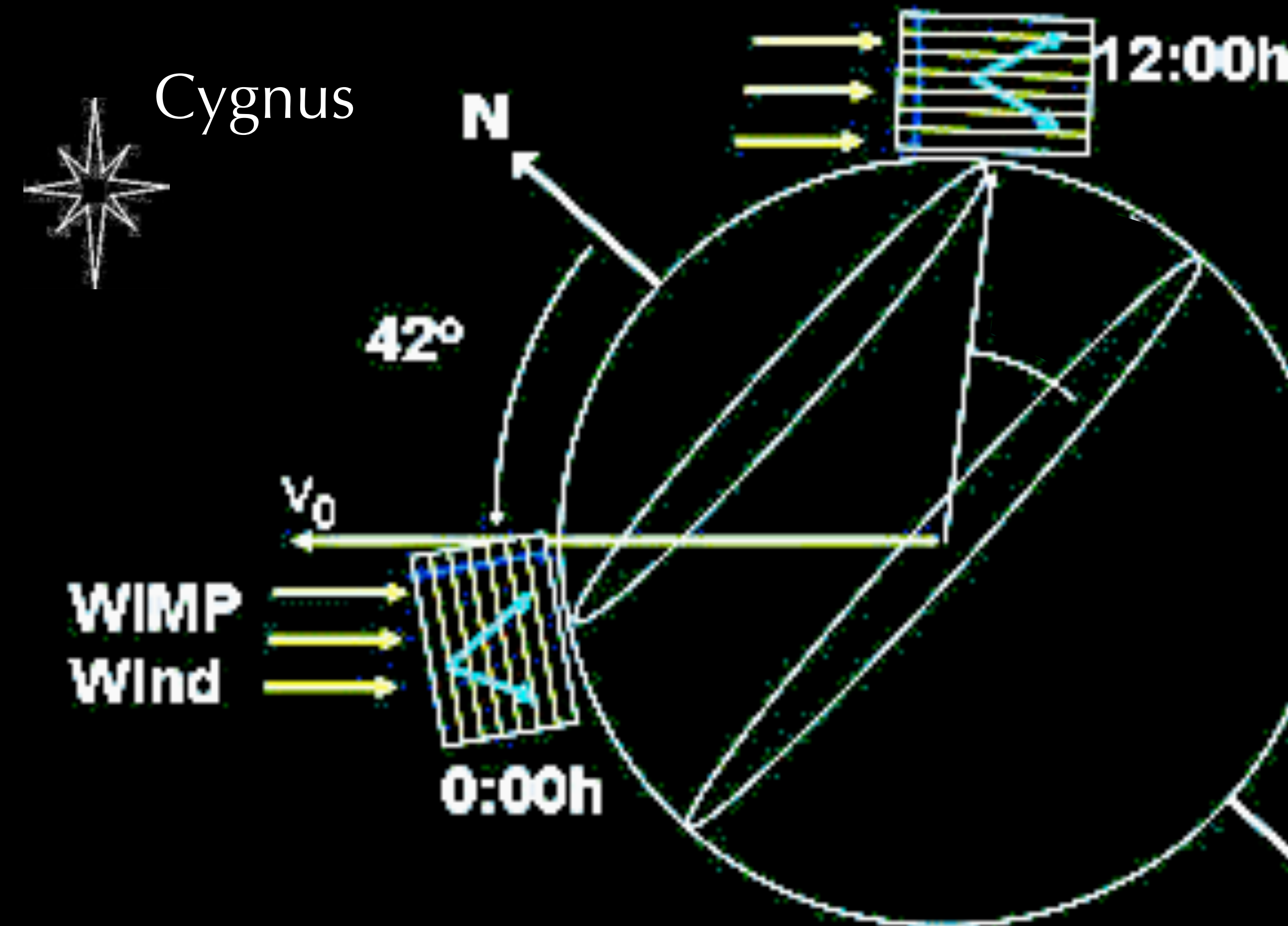


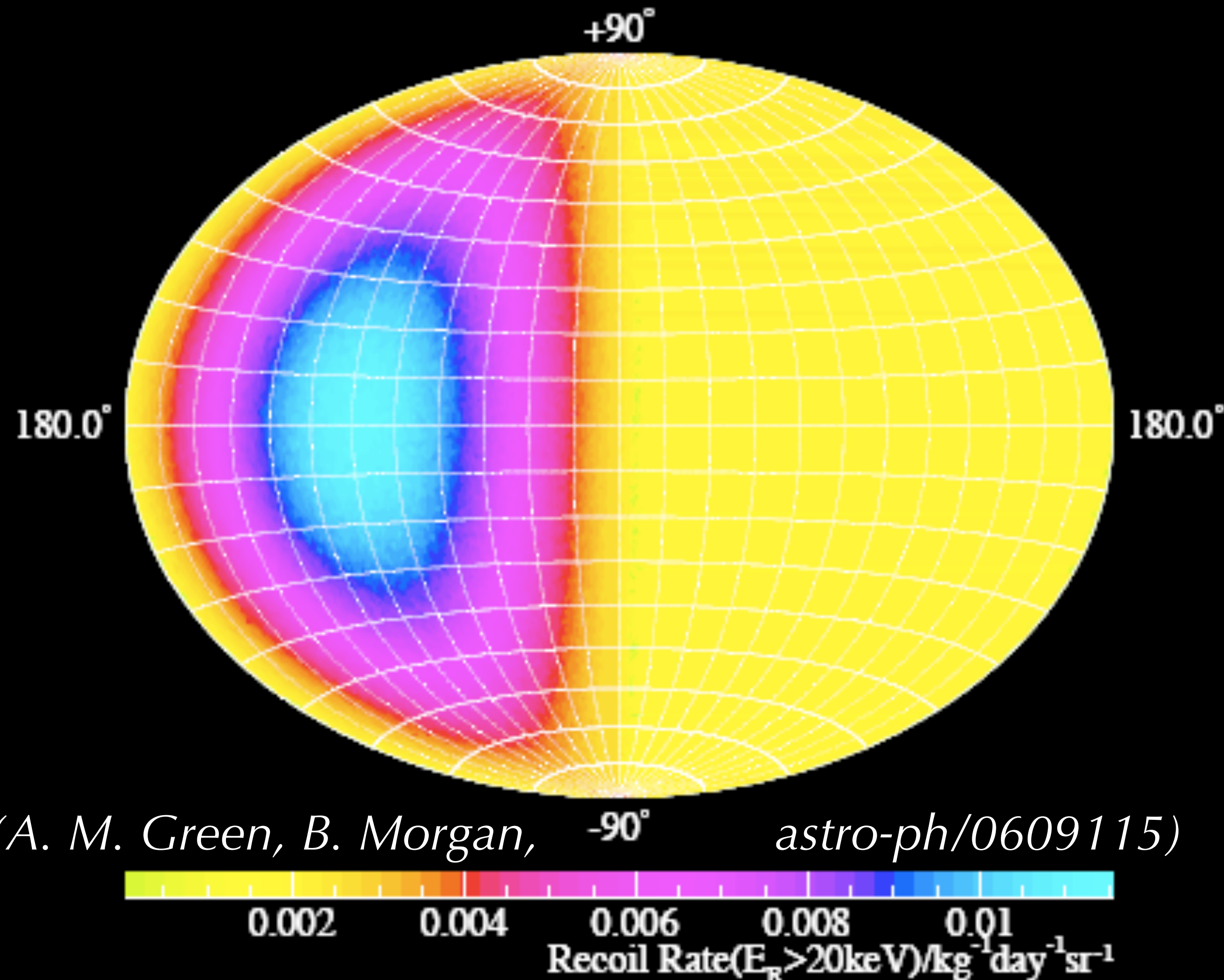
interesting development: directional detectors are starting to catch up...

Direction Modulation

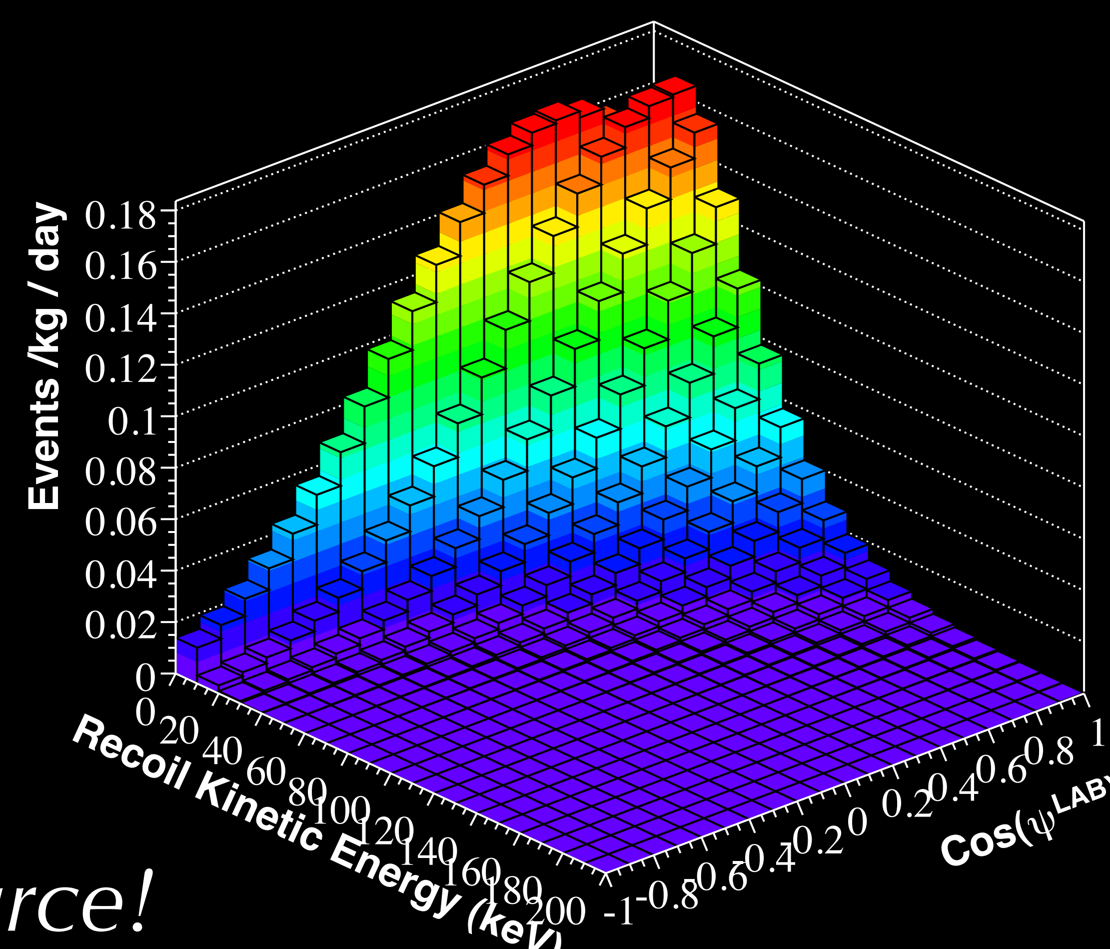
test astrophysical origin of candidate signal with sidereal asymmetry ~ 20-100% in forward-backward event rate.

Spergel, Phys. Rev. D37:1358 (1988)





(A. M. Green, B. Morgan, astro-ph/0609115)



search for a dark matter source!

Directionality Around the World

DRIFT: in Boulby (UK), wire readout, CS_2 CF_4 gas, negative ion drift, competitive kg-day exposure

S. Burgos et al., Astropart. Phys. 28, 409 (2007)

NEWAGE: in Kamioka, μ−pattern gas detector readout, CF_4 gas, *first* directional dark matter limit!

K. Miuchi, et al., Phys.Lett.B654:58-64 (2007)

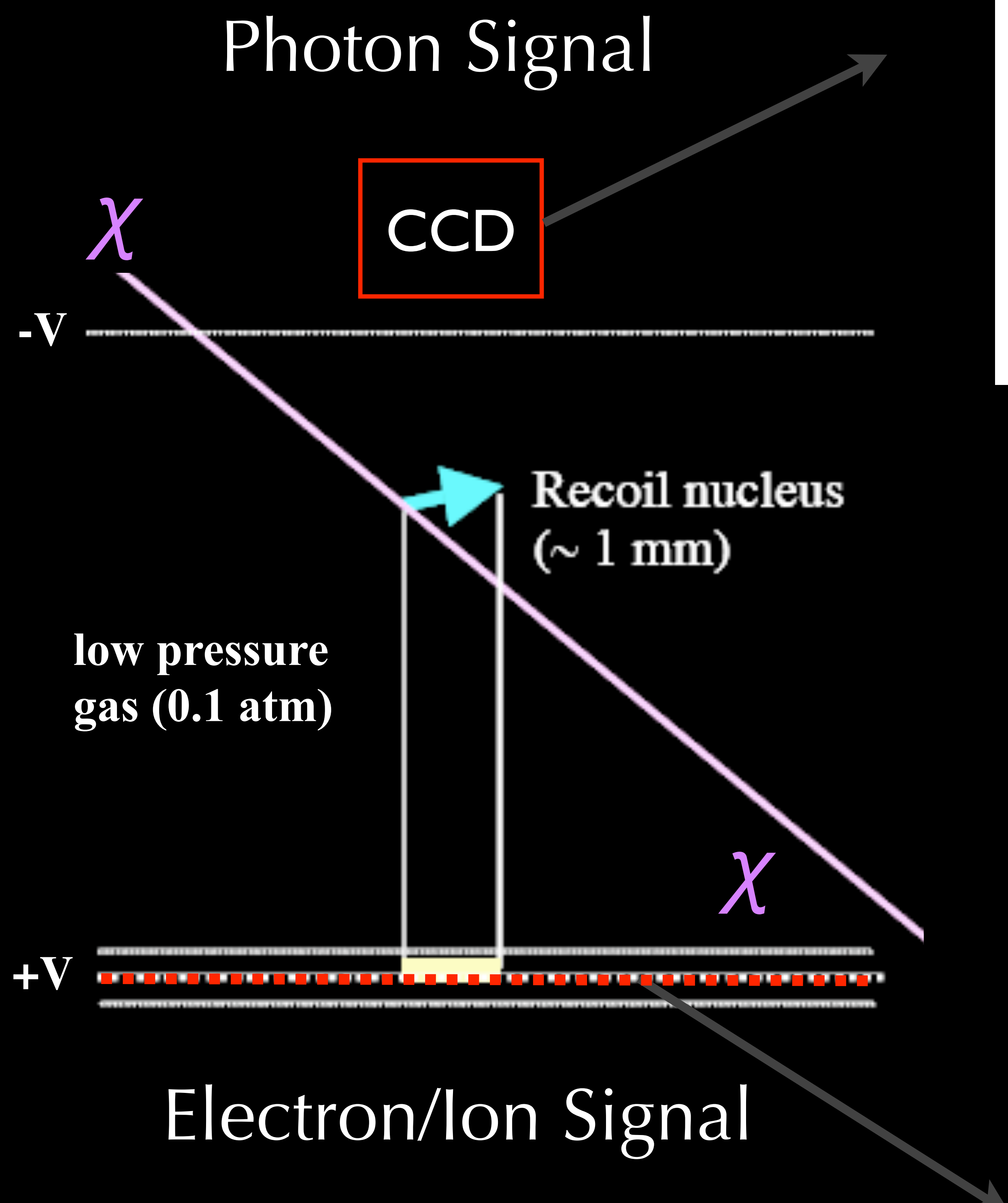
MiMAC-He3: (ILL) above-ground R&D, He_3 gas, MicroTPC readout, A-dependence

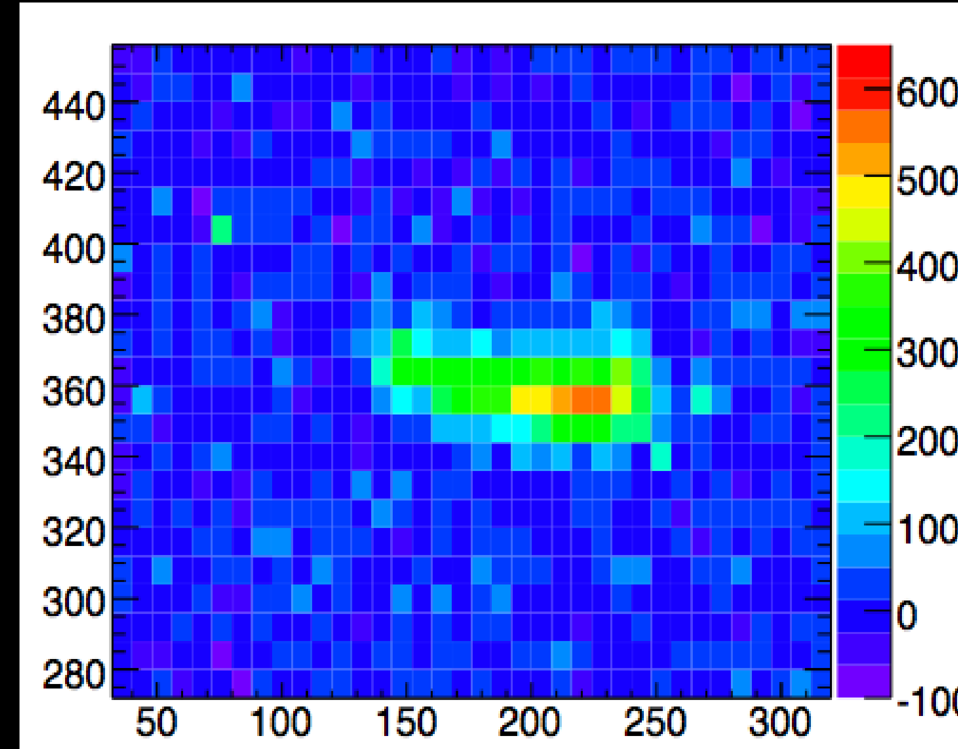
D. Santos, et al., J. Phys. Conf. Ser. 65, 021012 (2007)

DMTPC: (Boston) in WIPP (US), CF_4 gas, CCD readout, vector direction tag

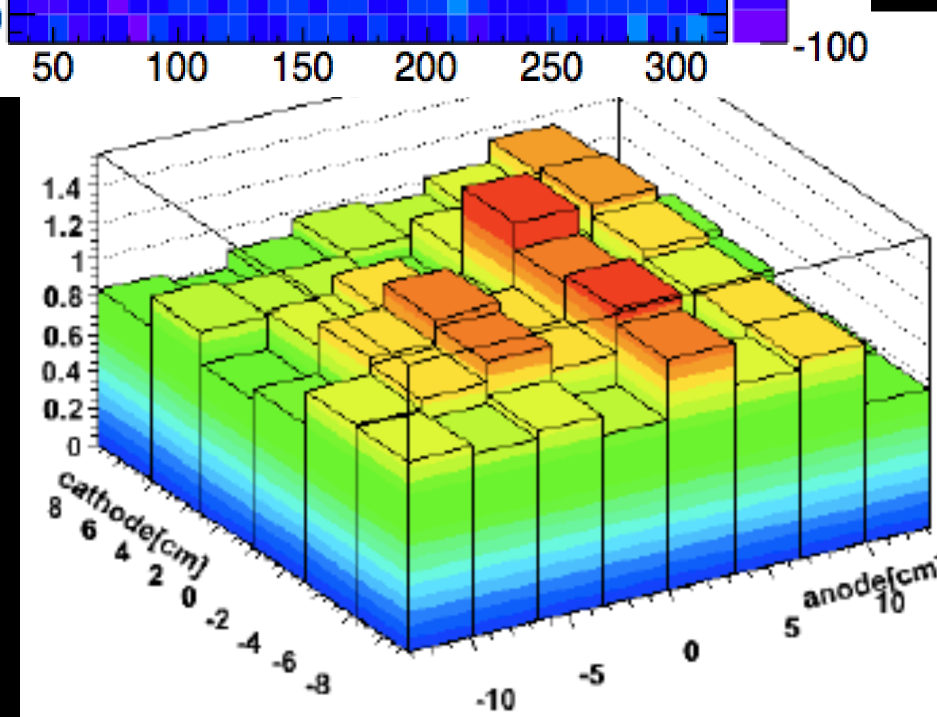
D. Dujmic, et al., NIM A 584:337 (2008)

Detection

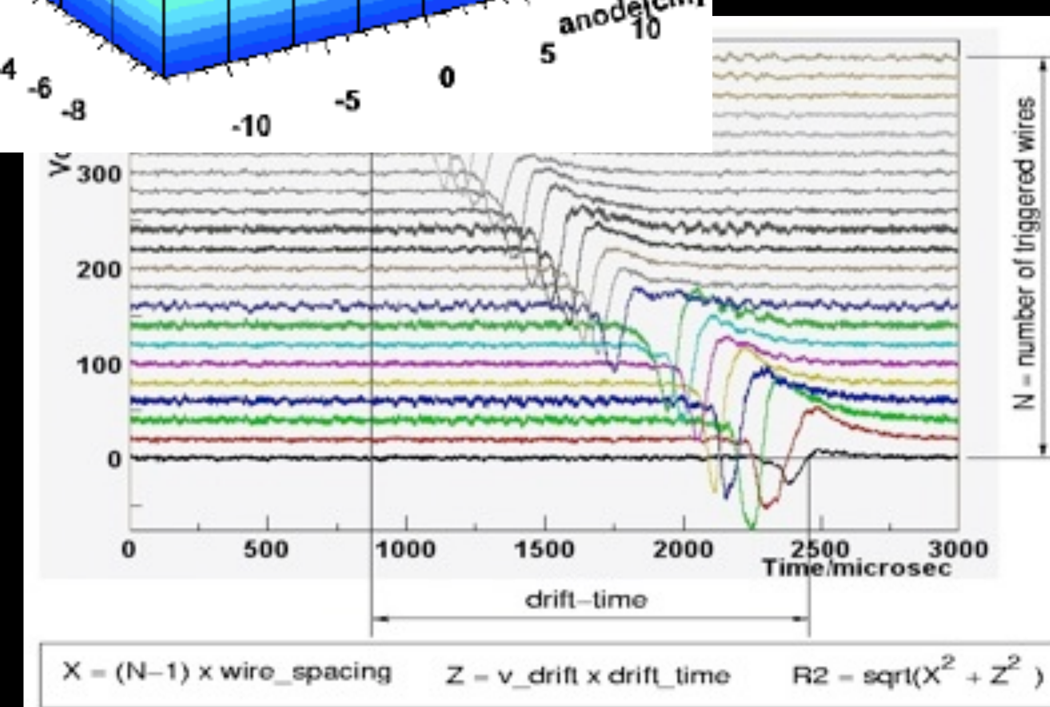




(DMTPC)



(NEWAGE)



(DRIFT)

Spin Dependent *Directional* Dark Matter Detection

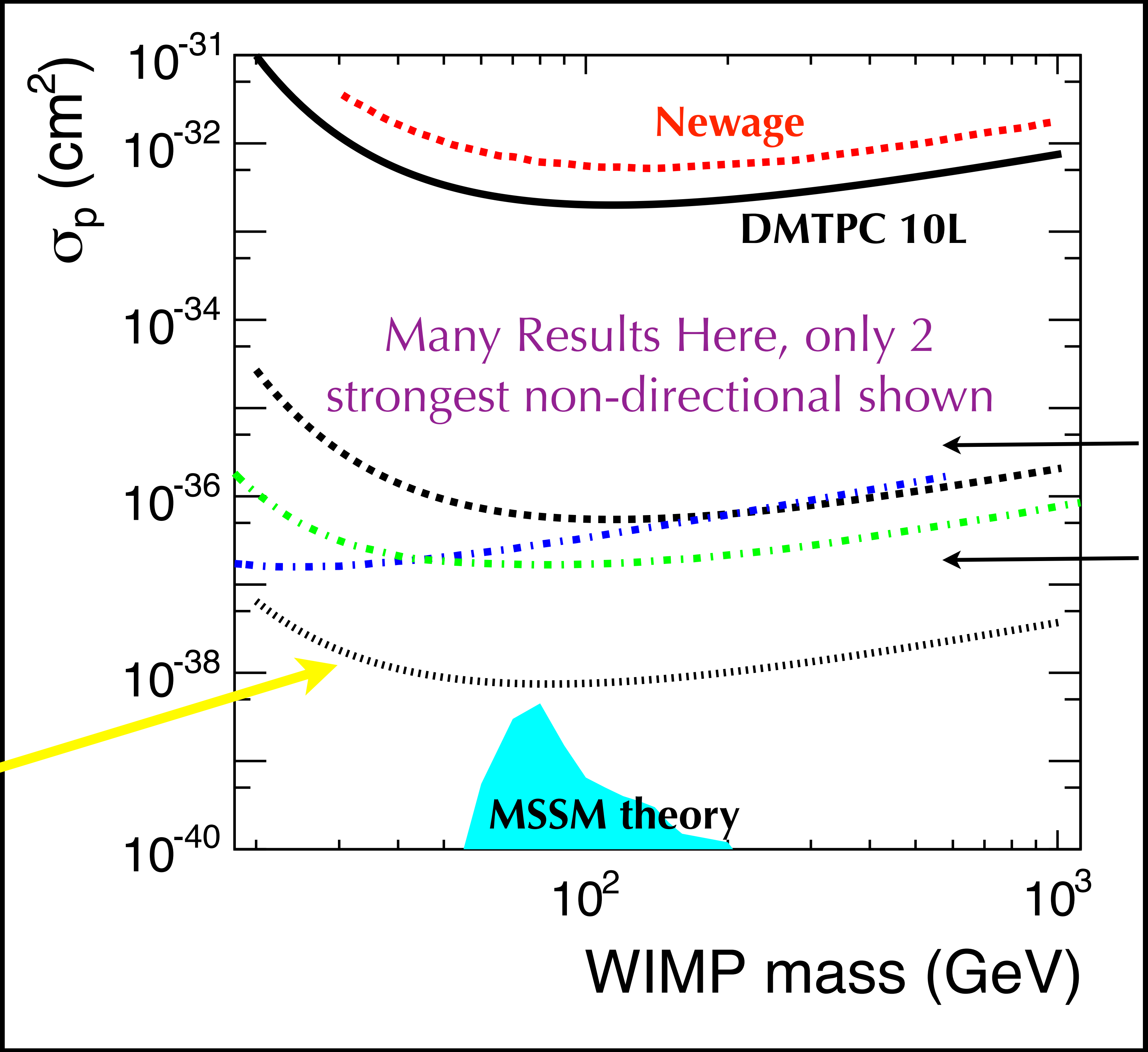
NEWAGE limit (Kamioka)

K. Miuchi et al., Phys.Lett.B686:11-17 (2010)

DMTPC limit (surface)

S. Ahlen et al., arXiv:1006.2928

$1m^3$ at WIPP projected sensitivity



directional results

DRIFT, IDM2010

1D results COUPP, IDM2010

Next steps for DMTPC: low-background detector, DMTPCino at WIPP ($1m^3$)

Conclusions

The nature of dark matter is a hot topic today, the "low-background frontier" may be on the verge of a discovery.

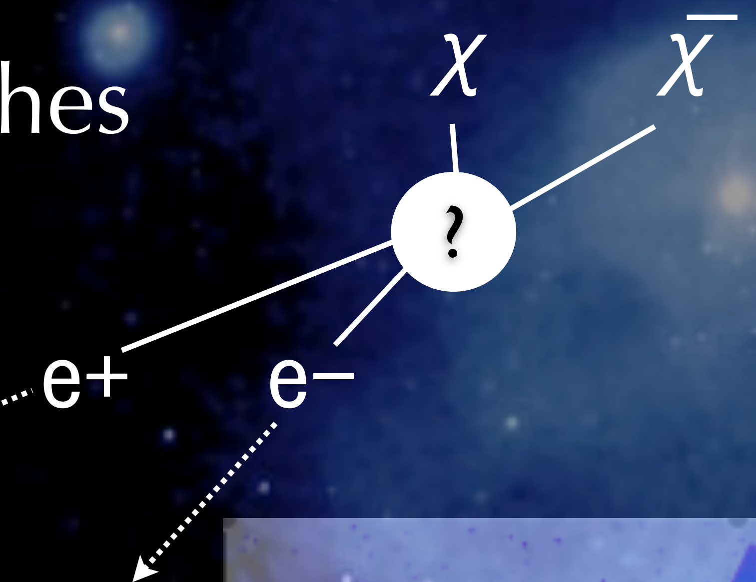
Hot off the presses: first independent confirmation of DAMA/LIBRA? Appears inconsistent with Xenon100 and CDMS, how reliable is energy scale at 2 keVee? Now time to focus on systematic uncertainties.

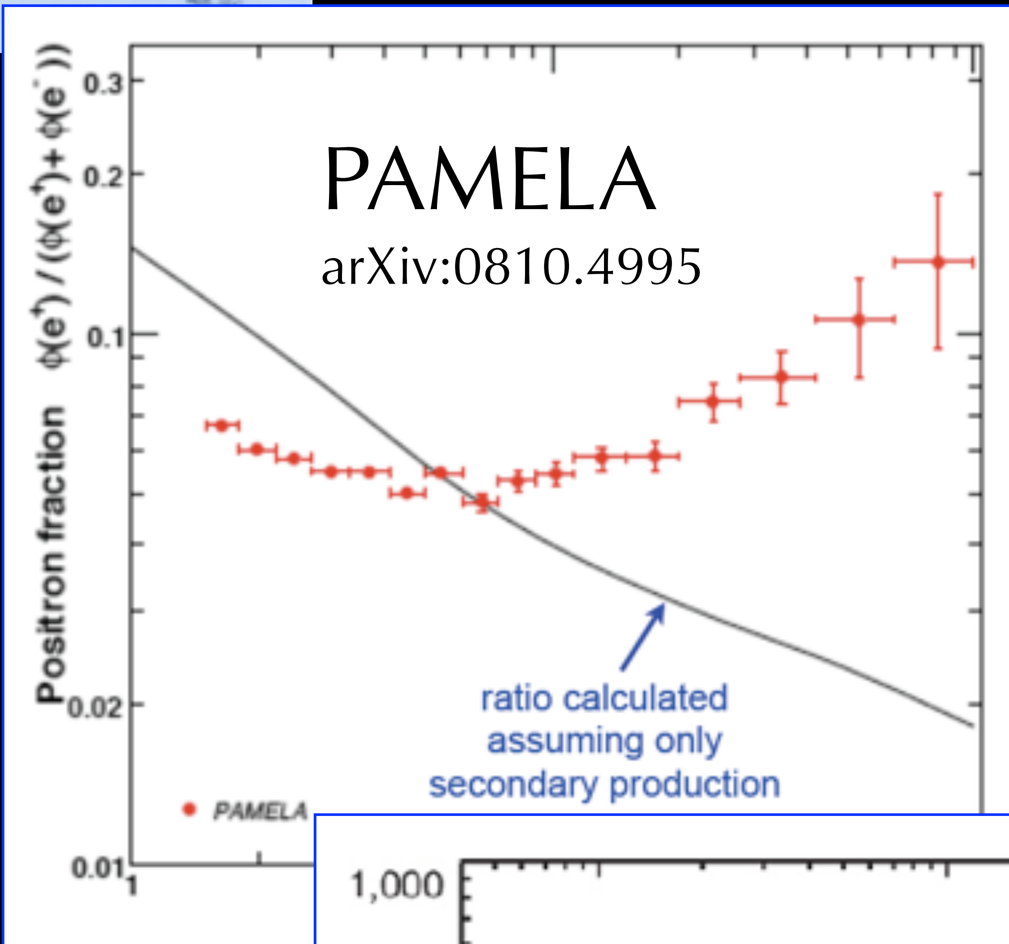
The liquid argon program will be the first to reach 1 tonne! Scalability and new approaches to backgrounds are key. May need directional detectors soon to test astrophysical origin of candidate signals.

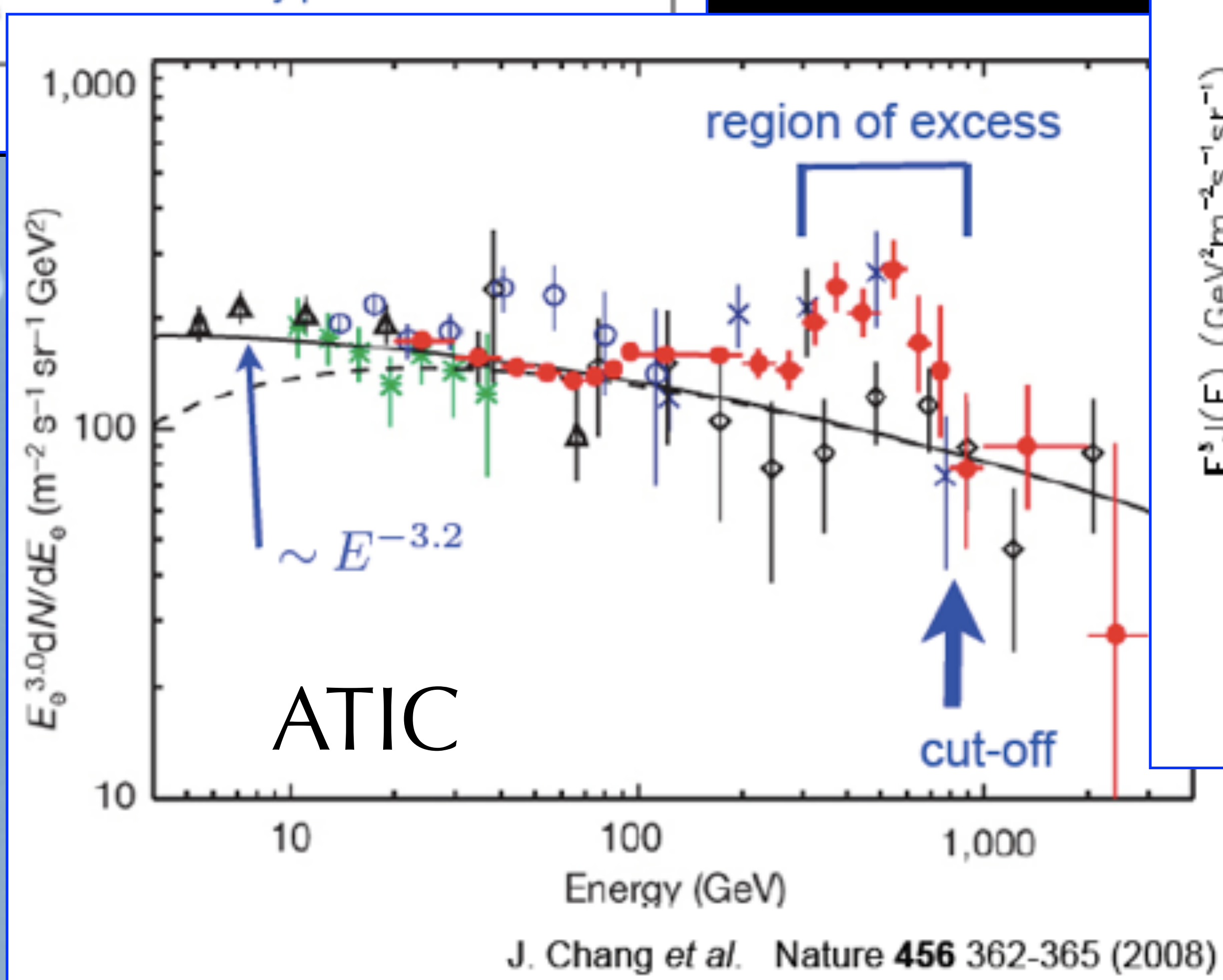
Stay tuned...

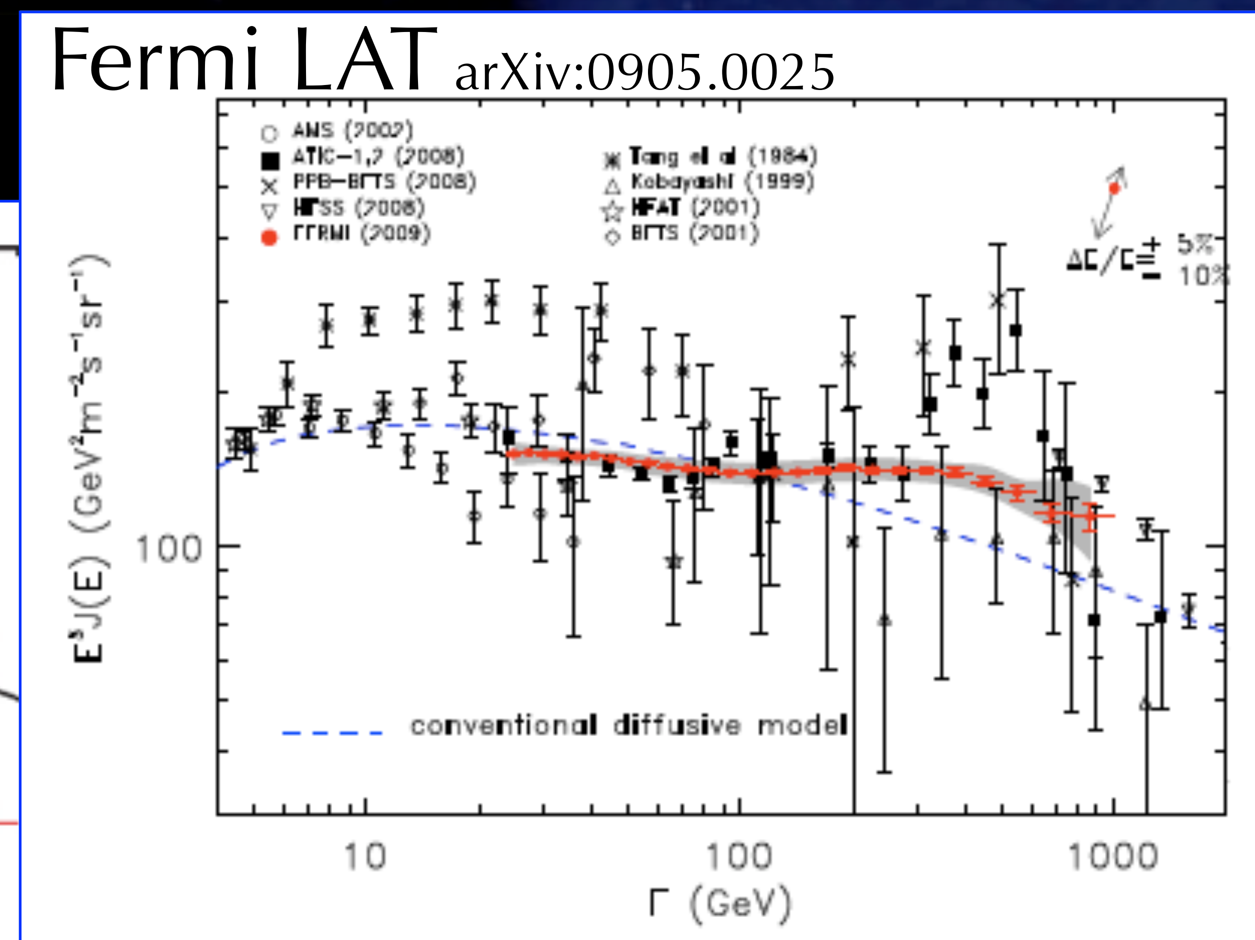
Extra Slides

Indirect Dark Matter Searches









dark matter? local astrophysics?

February 16, 2011

CDMS

Search at low energy threshold **arXiv:1011.2482v1**

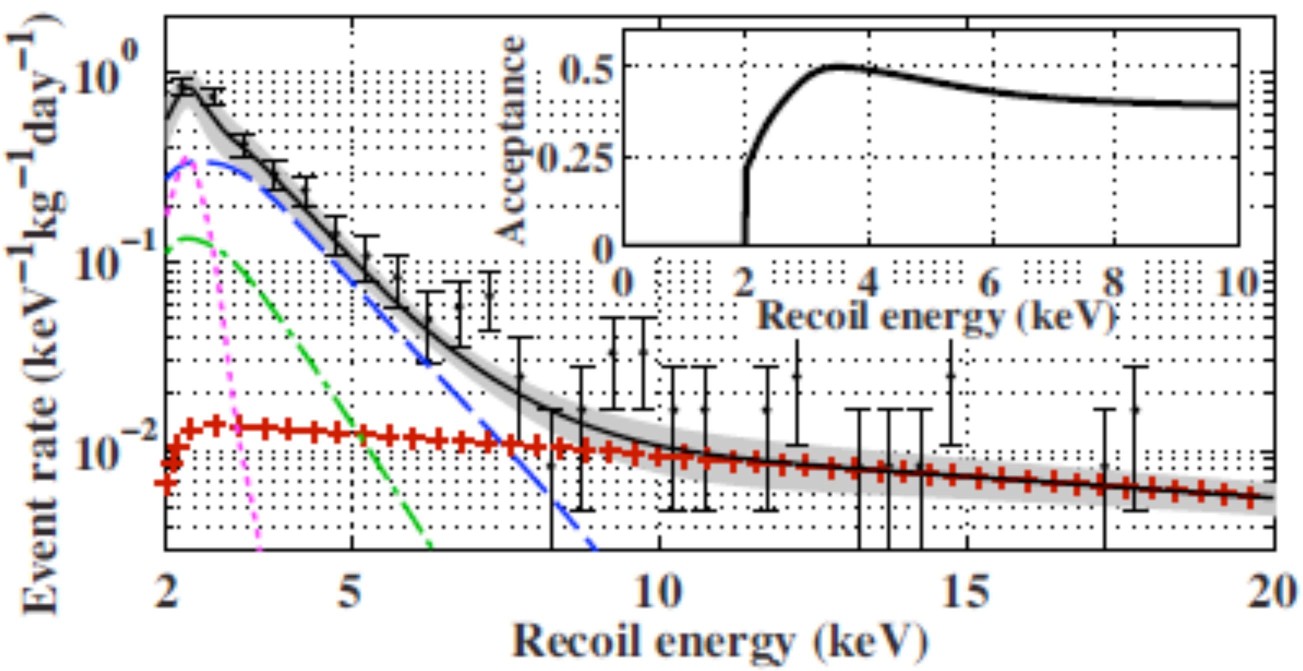


FIG. 1. (color online). Comparison of the energy spectra for the candidate events and background estimates, co-added over the 8 detectors used in this analysis. The observed event rate (error bars) agrees well with the electron-recoil background estimate (solid), which is a sum of the contributions from zero-charge events (dashed), surface events (+), bulk events (dash-dotted), and the 1.3 keV line (dotted). The gray band denotes the 1σ statistical errors on the background estimate. The selection efficiencies have been applied to the background estimates for direct comparison with the observed rate, which does not include a correction for the nuclear-recoil acceptance. The inset shows the measured nuclear-recoil acceptance efficiency, averaged over all detectors.

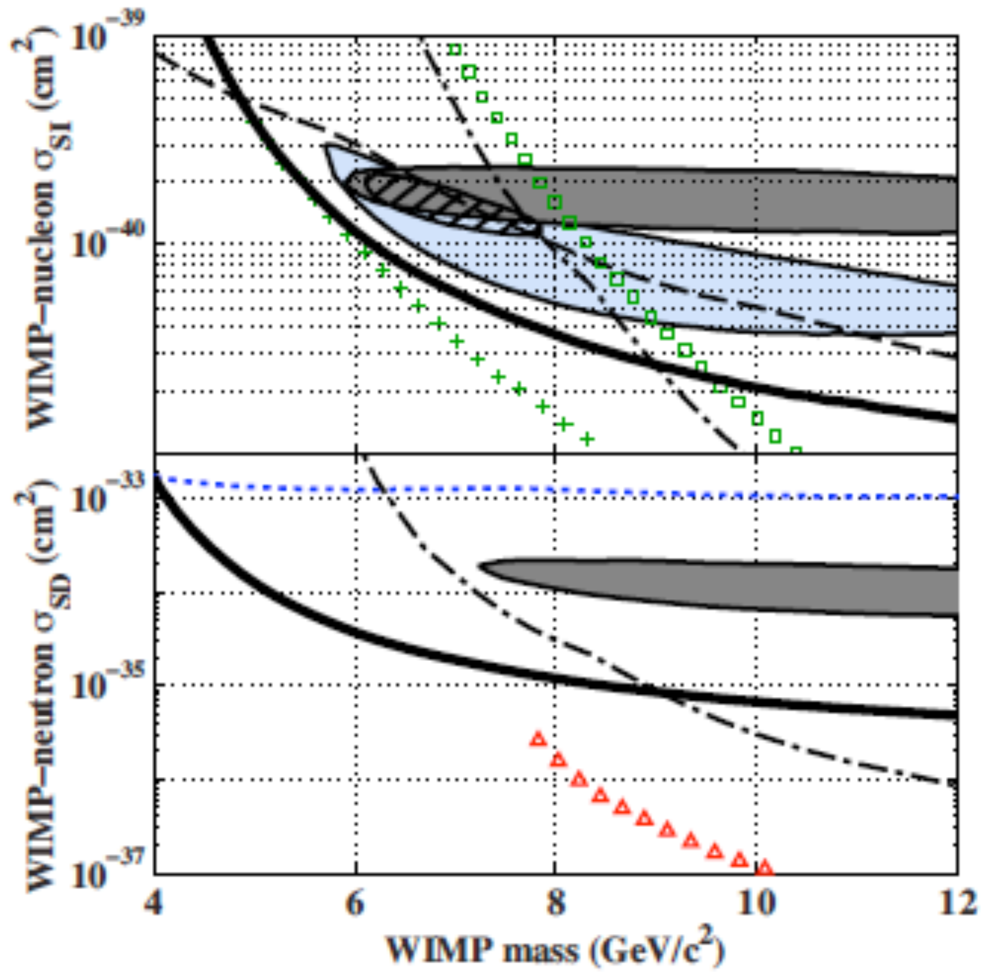
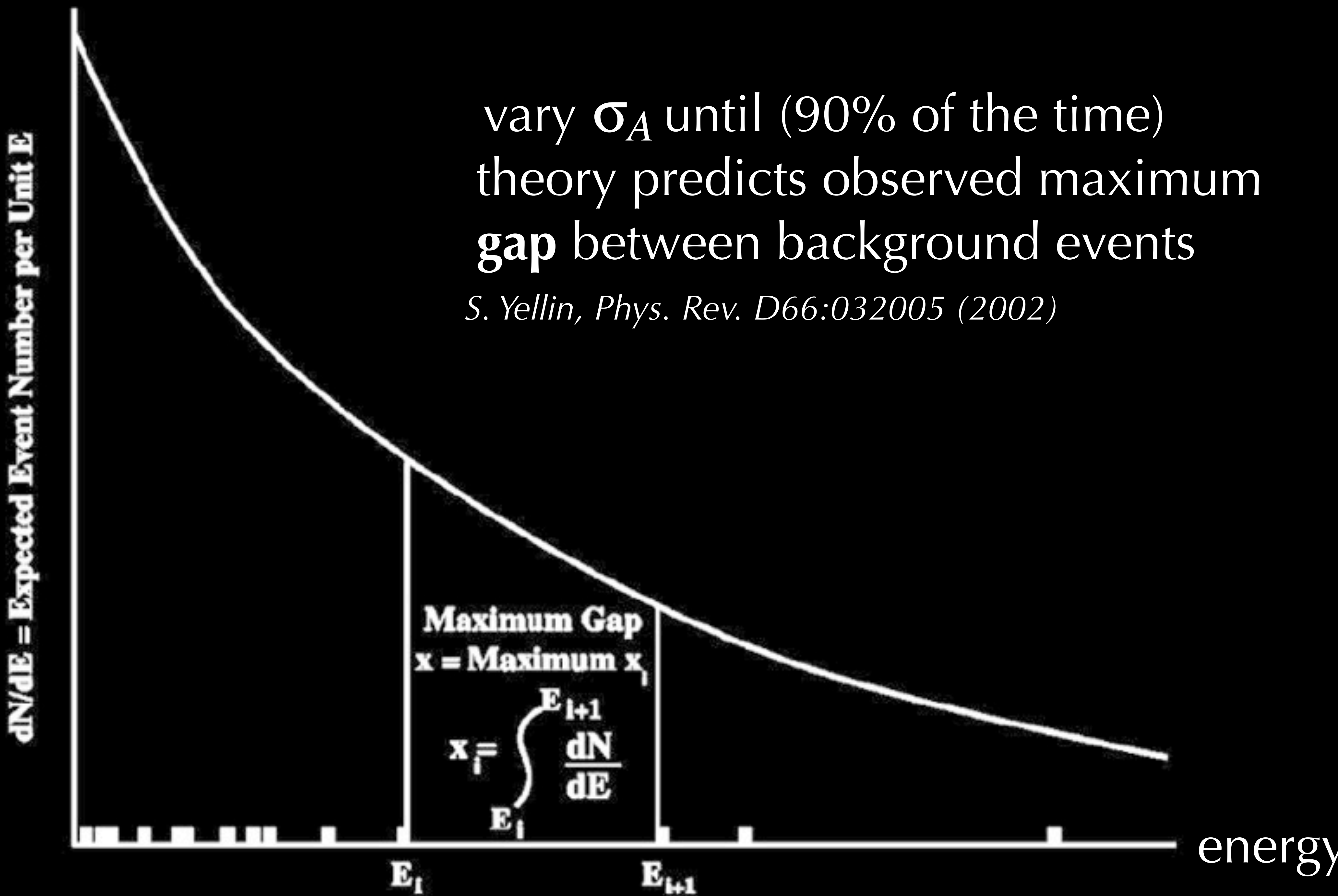


FIG. 3. (color online). Top: comparison of the spin-independent (SI) exclusion limits from these data (solid) to previous results in the same mass range (all at 90% C.L.). Limits from a low-threshold analysis of the CDMS shallow-site data [16] (dashed), CDMS II Ge results with a 10 keV threshold [13] (dash-dotted), recalculated for lower WIMP masses, and XENON100 with constant (+) or decreasing (□) scintillation-efficiency extrapolations at low energy [17] are also shown. The filled regions indicate possible signal regions from DAMA/LIBRA [6, 8] (dark), CoGeNT (light) [7, 8], and a combined fit to the DAMA/LIBRA and CoGeNT data [8] (hatched). Bottom: comparison of the WIMP-neutron spin-dependent (SD) exclusion limits from these data (solid), CDMS II Ge results with a 10 keV threshold (dash-dotted), XENON10 [18] (△), and CRESST [19] (dotted). The filled region denotes the 99.7% C.L. DAMA/LIBRA allowed region for neutron-only scattering [20]. An escape velocity of 544 km/s was used for the CDMS and XENON100 exclusion limits, whereas the other results assume an escape velocity from 600–650 km/s.

Setting a Limit in the Presence of Background

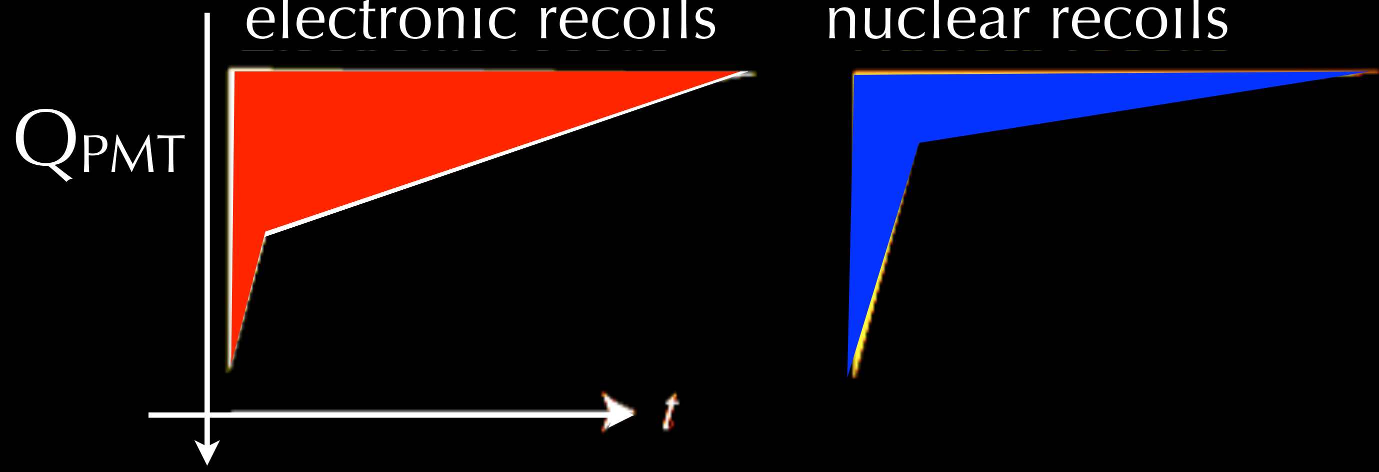
vary σ_A until (90% of the time) theory predicts observed maximum **gap** between background events

S. Yellin, Phys. Rev. D66:032005 (2002)



Yellin gap method: a way to make a “zero-background” measurement over a restricted range of an experiment’s acceptance (zero signal too)

Scalability: Single Phase



Liquid argon dark matter target, scintillates ~30,000 photons/MeV!

Lippincott, Phys.Rev.C78:035801 (2008)

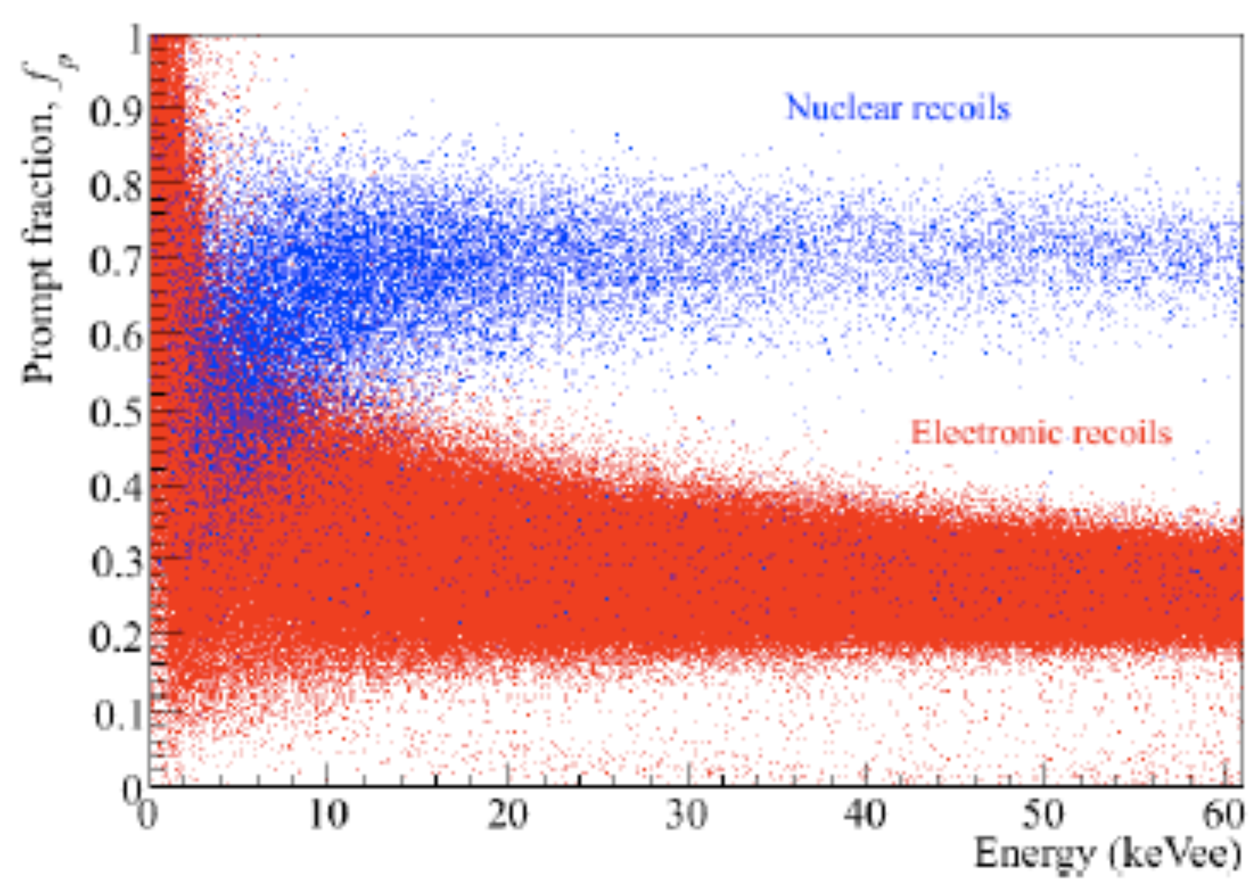


FIG. 7: A scatter plot of f_p vs. energy for tagged electronic and nuclear recoils, where $\xi = 90$ ns.

Dark Matter Signal: measure recoil energy deposited as scintillation photons vs. time

Background Strategy: identify, reject electronic backgrounds via pulse shape vs. time difference
Boulay and Hime, Astropart. Phys. 25, 179 (2006)

Directional Detection Future

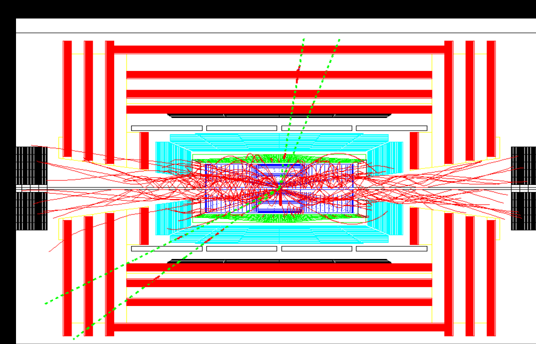
Eventually: large detector, 10^{-46} cm^2 sensitivity, sited at DUSEL?

MiniBooNE: $6 \times 6 \times 6$ m^3

DMTPC Observatory $16 \times 16 \times 16$ m^3

1 ton of CF_4 @50Torr

CMS: $15 \times 15 \times 22$ m^3



SNO: $21 \times 21 \times 34$ m^3

SuperK: $40 \times 40 \times 40$ m^3

detector size for 10^{-44} cm^2 SI sensitivity