Direct Dark Matter Detection

Status and Outlook 2015

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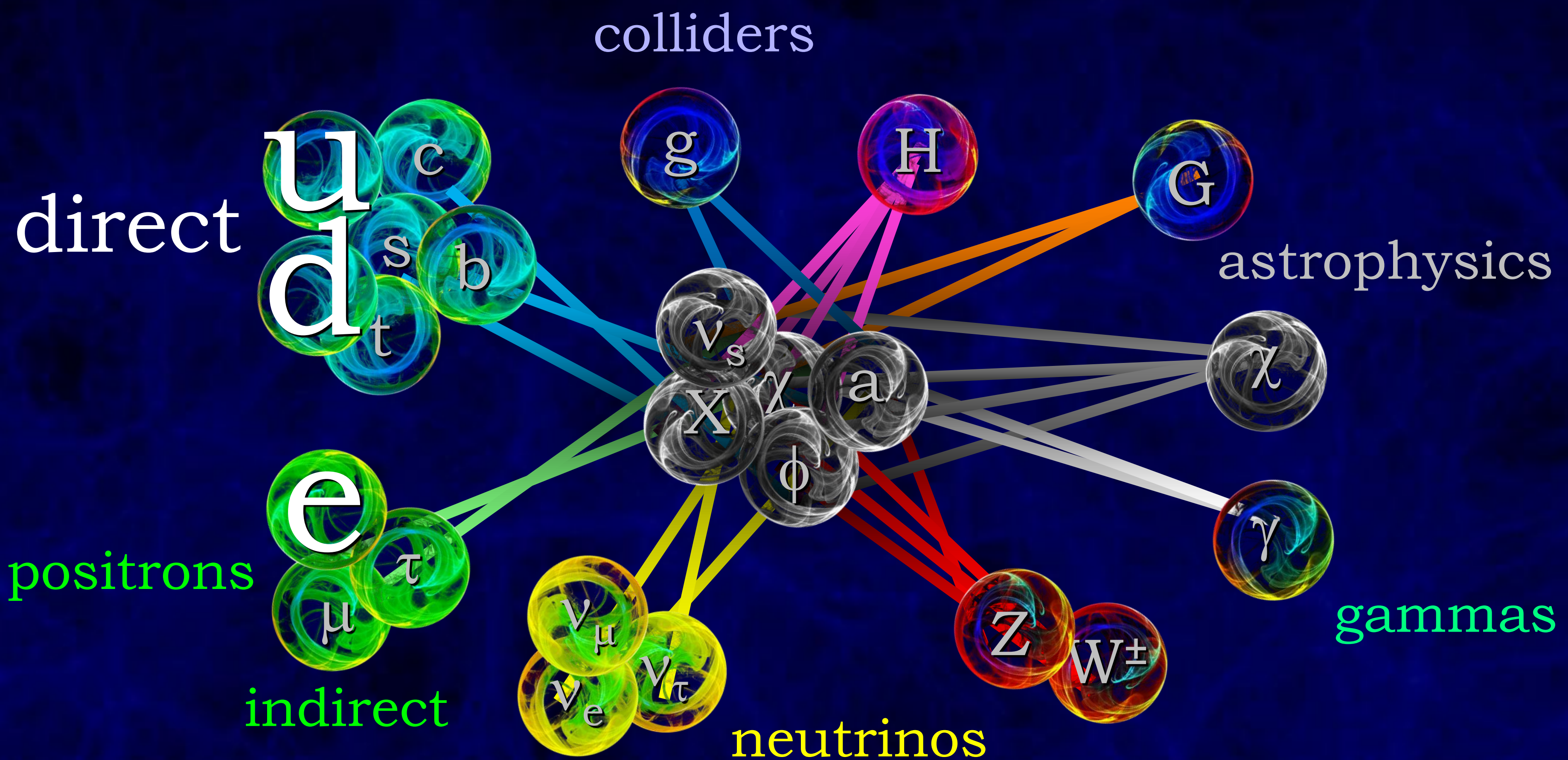
rafael@purdue.edu
Mitchell Workshop, Texas A&M, May 19, 2015

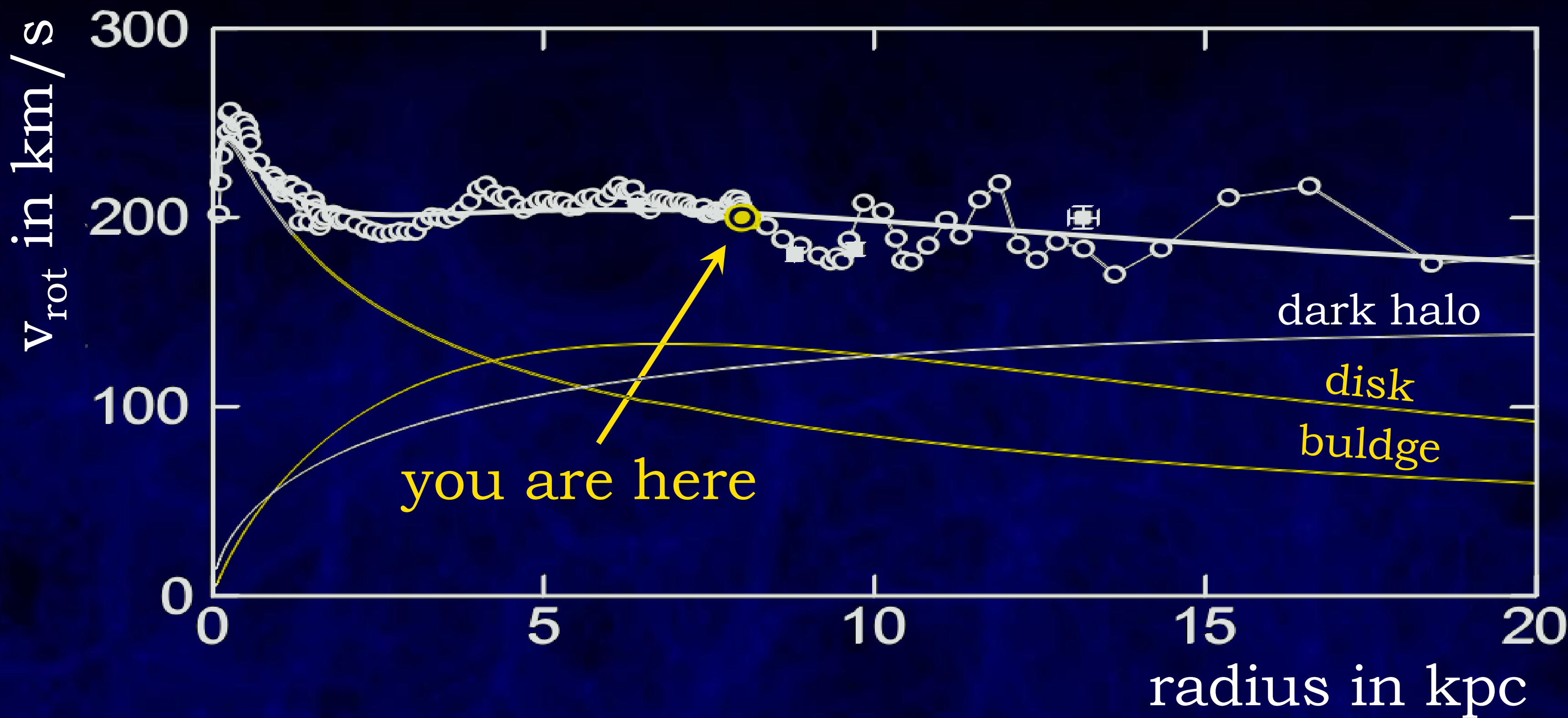
Dark Matter Has Been Discovered

But what are the quanta of Dark Matter?

Study interactions !



The Dark Side is Among Us



Pato,Iocco,Bertone 1504.06325

Milky Way requires Dark Matter to sustain rotation:
Evidence for Dark Matter in your lab

$\varrho_{\rm DM}(r = r_\odot) = (0.42 \pm 0.04)\,{\rm GeV/cm^3} \approx 0.3\,{\rm GeV/cm^3}$

See Fabio's talk Thursday

You're In For A Ride

Axions: · ADMX

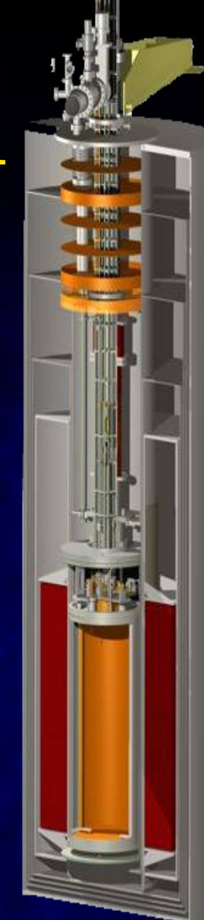
WIMPs: · Overview

Status & Outlook for selected experiments roughly sorted by $m_\chi \uparrow$ or $\sigma \downarrow$

- CRESST-II
- CDMSLite
- SuperCDMS
- PICO
- XMASS
- DEAP-3600
- XENON100
- LUX
- XENON1T

ADMX Resonant Axion Search

- Microwave cavity, up to 8T, down to 100mK



Carosi Aspen2013

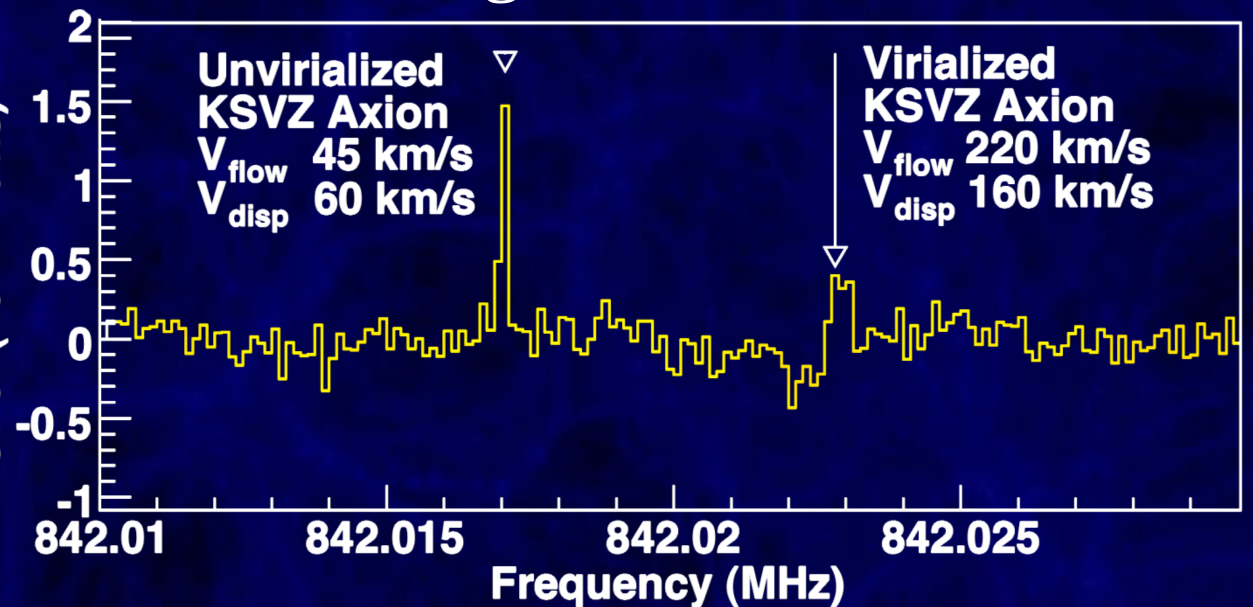
Rosenberg UCLA2014

ADMX Resonant Axion Search

- Microwave cavity, up to 8T, down to 100mK
- Very rich signature

Carosi Aspen2013

simulated signal:

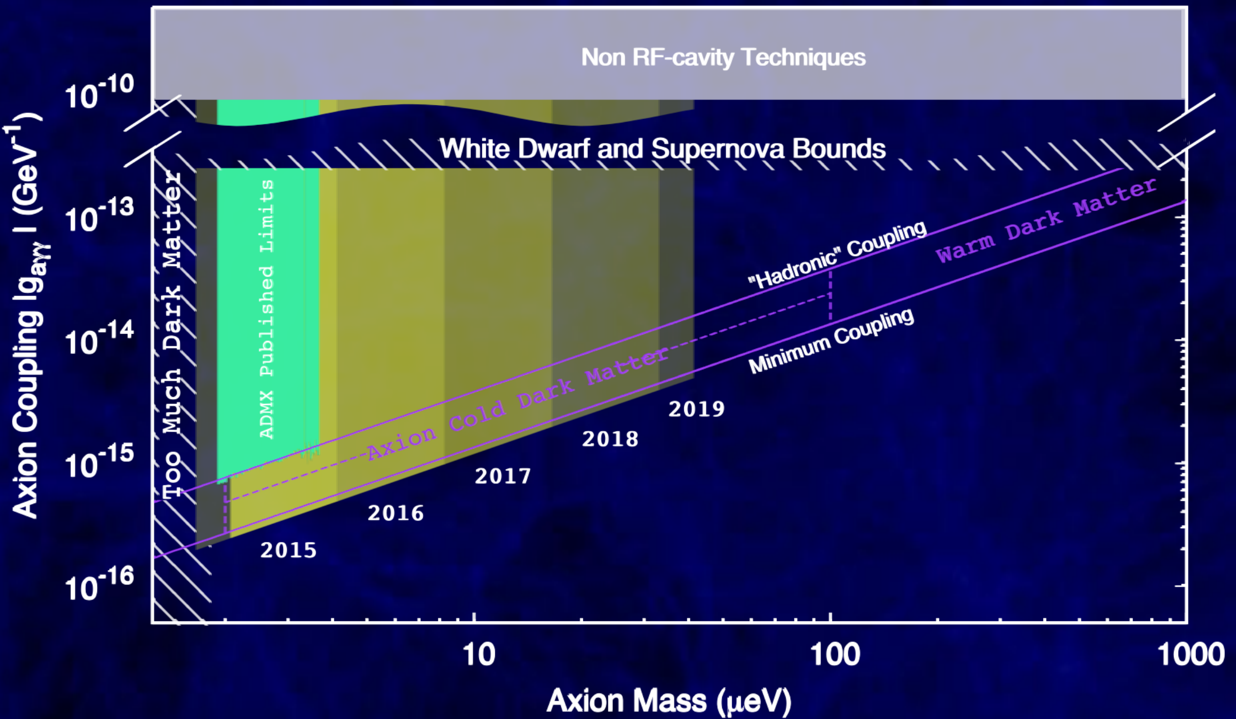


Rosenberg UCLA2014

ADMX Resonant Axion Search

- Microwave cavity, up to 8T, down to 100mK
- Very rich signature
- Initial data this summer, then scan frequencies

Carosi Aspen2013



Rosenberg priv. comm. 2015

You’re In For A Ride

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Back of the Envelope

Rate: ~events per year, per kg or ton of target

$$N = n_{\text{target}} \Phi \, \sigma_{\chi,N} \, A^2 \qquad \text{or } \propto \sigma_{\chi,N} \, J(J+1)$$

Coherent Scattering: Heavy target

$$\frac{\lambda_{\text{deBroglie}}}{2\pi} = \frac{\hbar}{p} = \frac{\hbar c}{mc^2 \, v/c} \sim \frac{197\,\text{MeV fm}}{100\,\text{GeV}\ 10^{-3}} \approx \text{fm} \approx r_{\text{nucleus}}$$

Recoil Energies: Low threshold

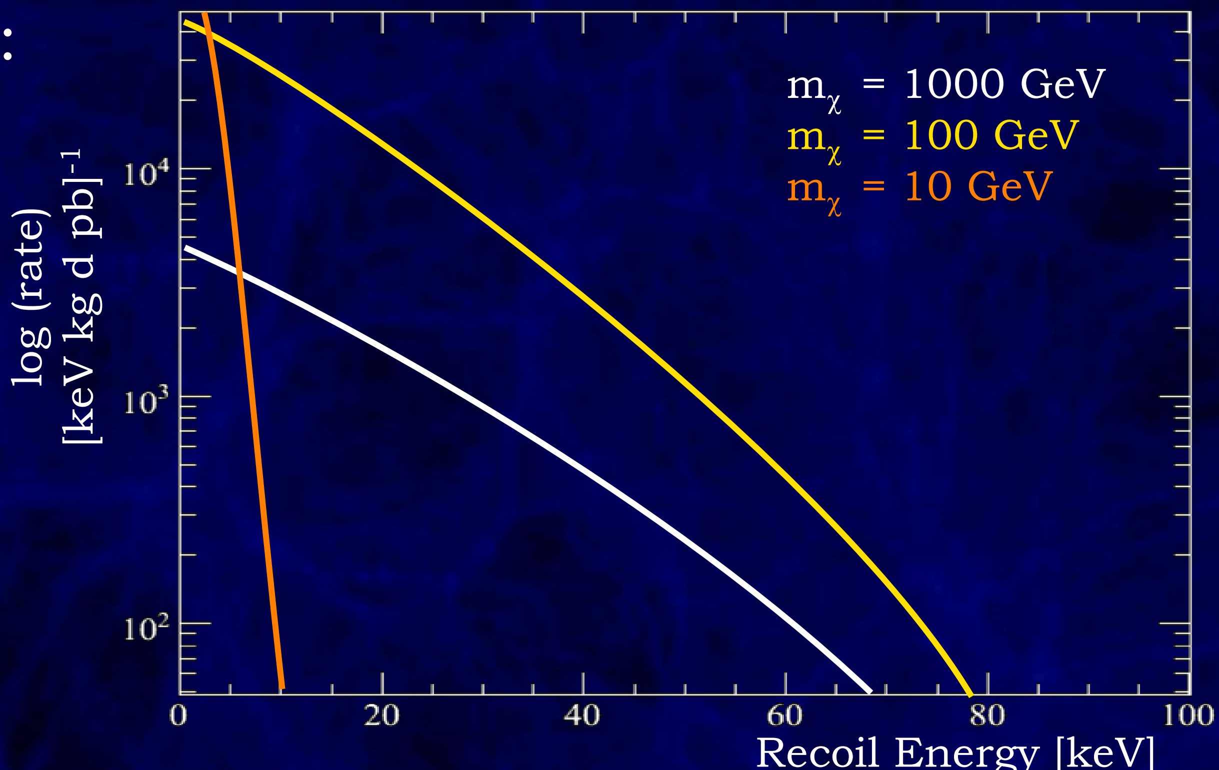
$$E_{\text{r,max}} \sim \frac{p_\chi^2}{2m_{\text{N}}} \sim \frac{\left(100\,\text{GeV/c}^2 \times 10^{-3}\text{c}\right)^2}{2 \times 100\,\text{GeV/c}^2} = 50\,\text{keV}$$

Recoil Spectrum

Recoil spectrum: Simple falling exponential

$$\frac{\mathrm{d}N}{\mathrm{d}E_r} \propto \Phi \propto \langle v \rangle \propto \int_{v_\chi}^{\infty} \frac{f_{\mathrm{MB}}(v)}{v}\,\mathrm{d}v \propto \mathrm{e}^{-v_\chi^2} \propto \mathrm{e}^{-E_r}$$

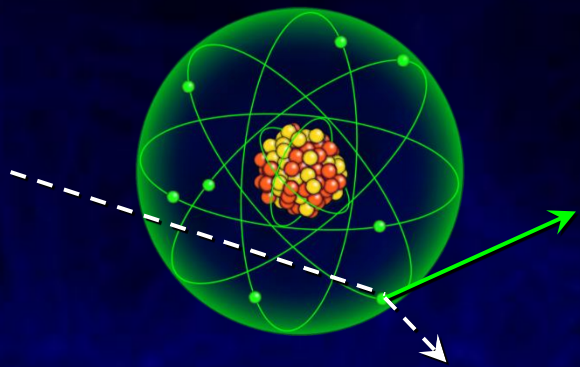
e.g. xenon (generic):



Pitfall !
Acceptance turns this into bump after all

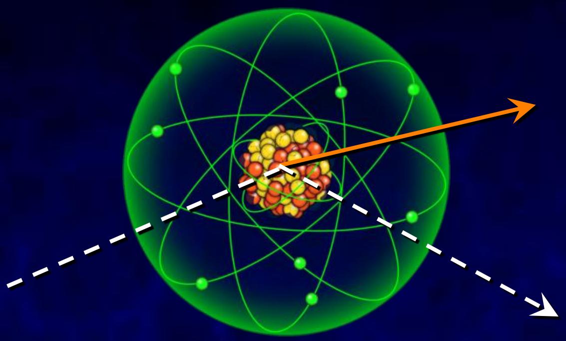
Discrimination: Need Information

e^-/γ: electronic recoil



Background

α/n/WIMPs: nuclear recoil



Signal

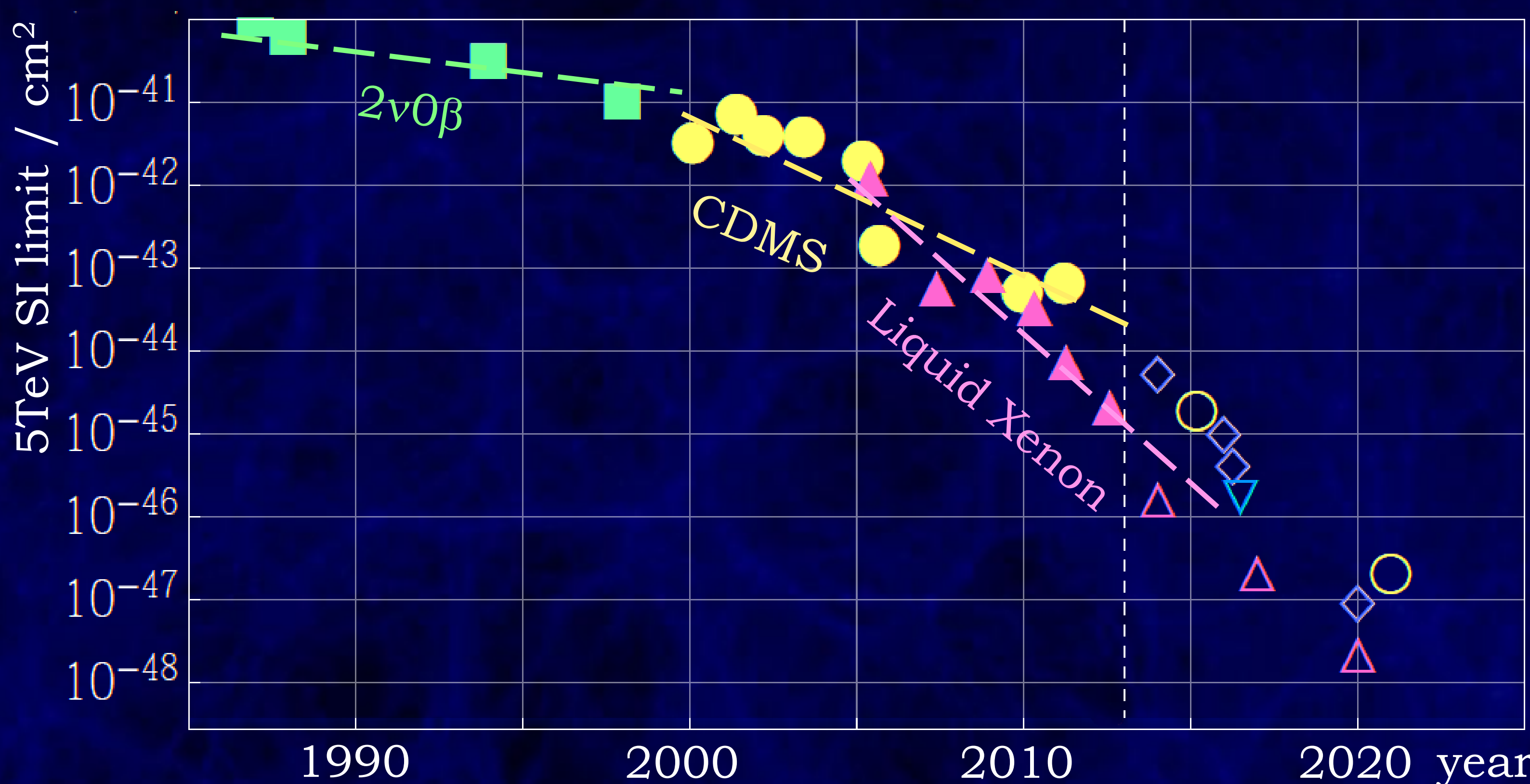
Discriminate by measuring two parameters

- Energy
- Ionization yield
- Scintillation yield
- Pulse decay time
- Acoustic signal

Most dangerous:
Detector artefacts!
→ Extract as much information as possible

Outstanding Performance

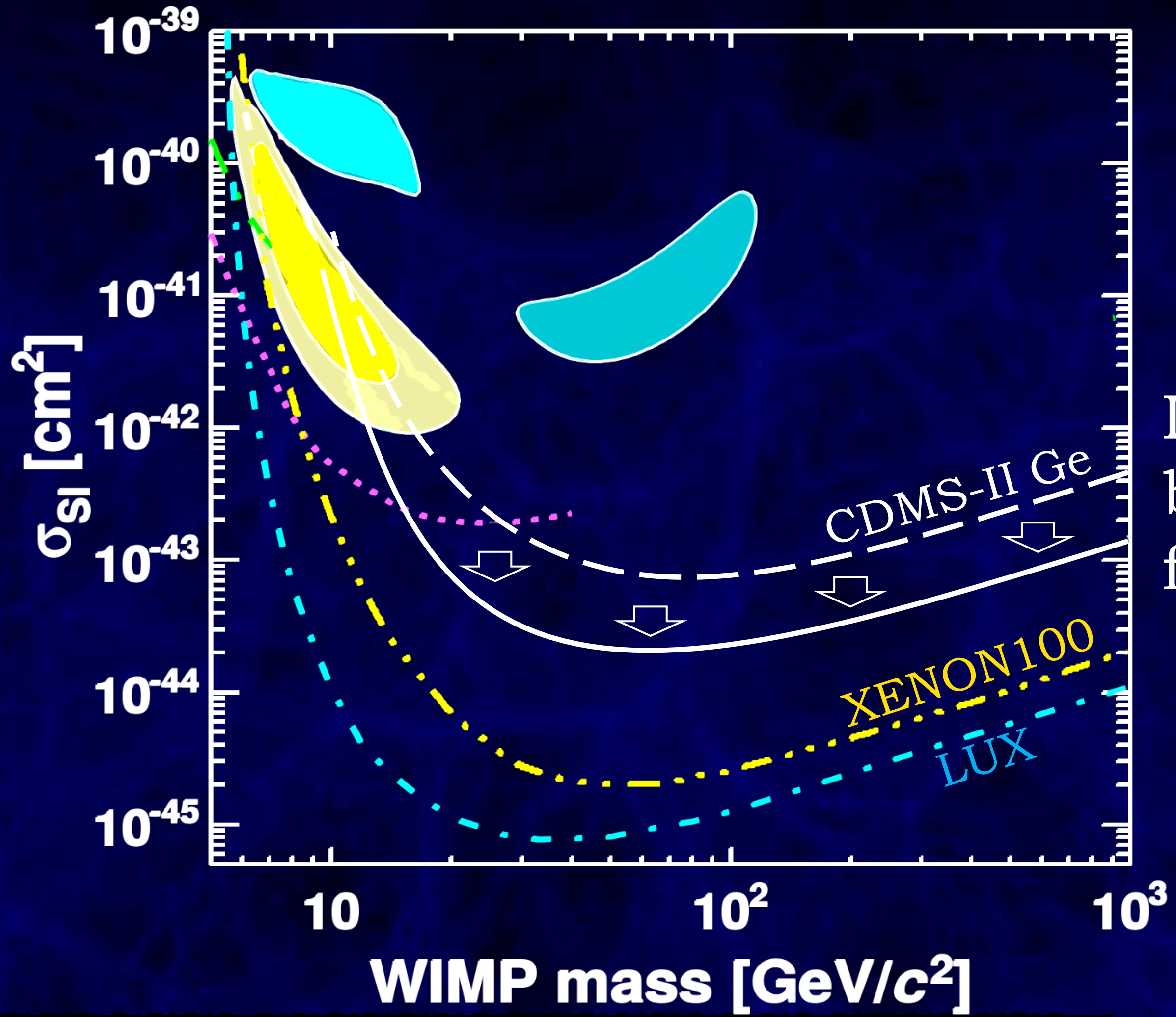
- Very good control of systematic uncertainties (%-level)
- Elaborate analyses (e.g. machine learning)
- Sensitivity doubles every year (exceeding Moore's law)



SWONMASS 1310.8327

Advanced Analyses

e.g. CDMS-II re-analysis of existing data (“5D χ^2”)

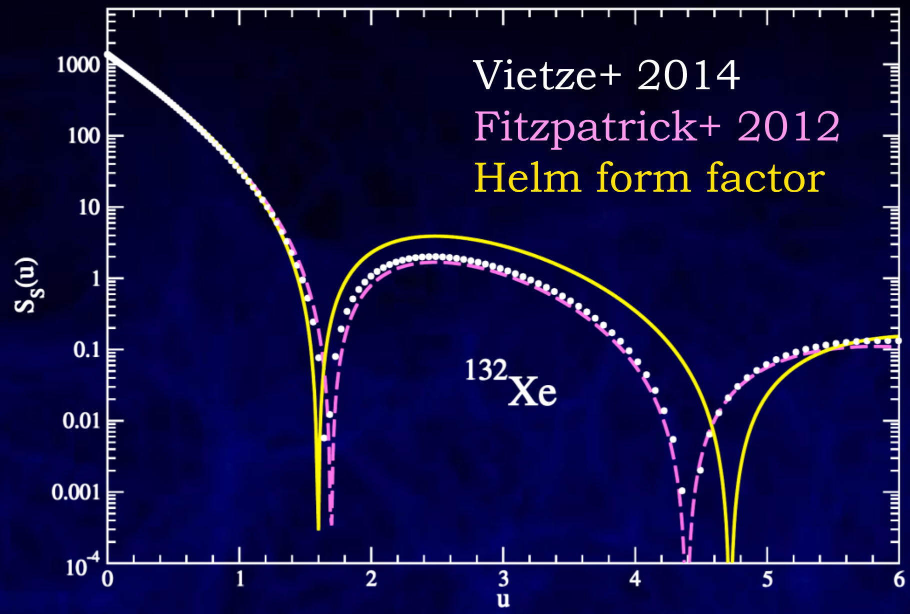


Improvement by more than factor 2

SuperCDMS 1504.05871

In parallel: Theory developments

- Nuclear Physics known at %-level too:



Vietze+ 1412.6091

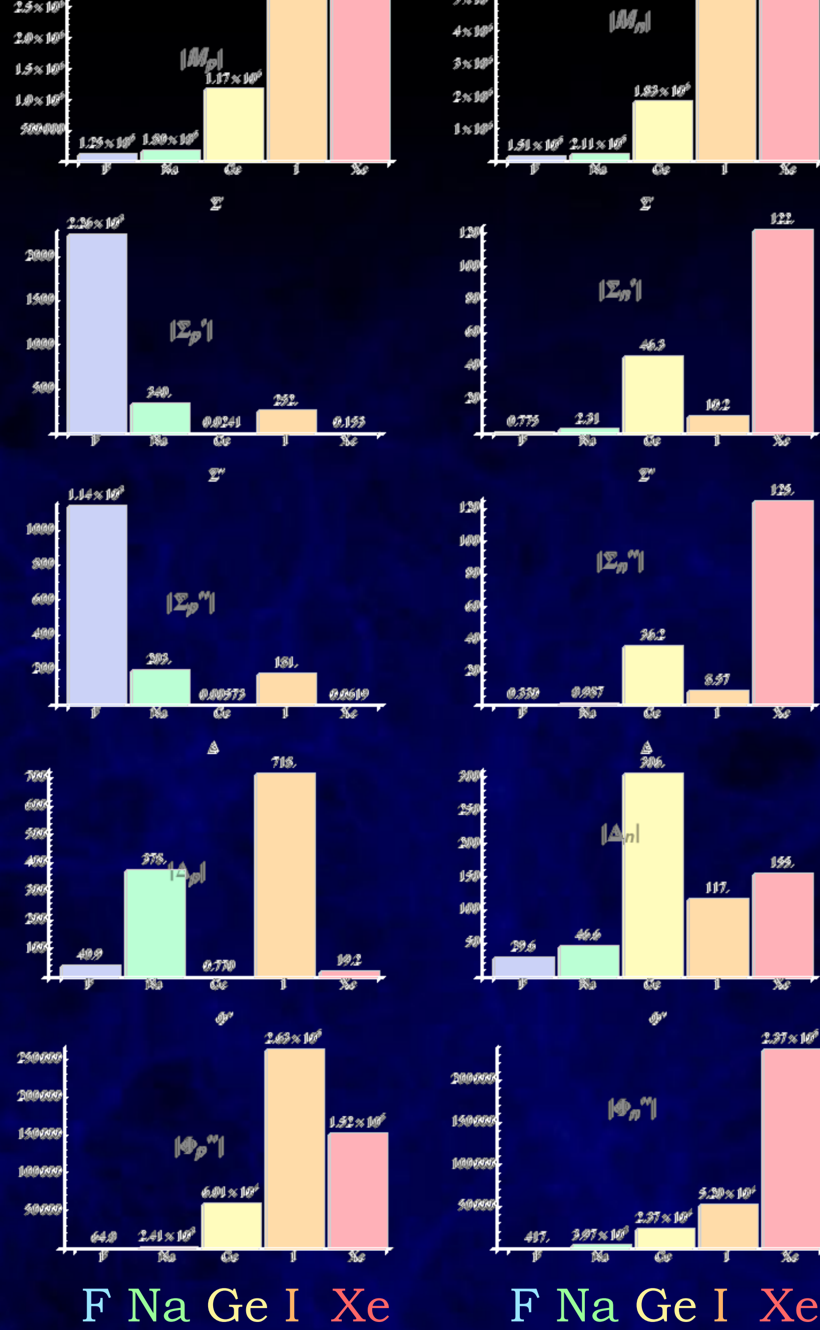
- Transition from spin-dependent/independent to effective field theory approach

Fan, Reece & Wang 1008.1591, Fitzpatrick+ 1203.3542, 1211.2818
Anand, Fitzpatrick & Haxton 1405.6690, Catena 1406.0524
see also the code packages 1308.6288 and 1307.5955
SuperCDMS 1503.03379

Effective Theory

- Vastly different sensitivities of various targets: Variety indispensable
- Some require dedicated analyses
- Use relativistic or non-relativistic operators?
- Present results for each operator individually?

See Pyungwon's talk for pitfalls



Fitzpatrick+ 1203.3542

Overview

Axions: · ADMX

WIMPs: · Status of the field

Status & Outlook for selected experiments

roughly sorted by $m_\chi\uparrow$ or $\sigma\downarrow$

- CRESST-II
- CDMSLite
- SuperCDMS

cryogenic

- PICO

bubbles

- XMASS
- DEAP-3600

single phase

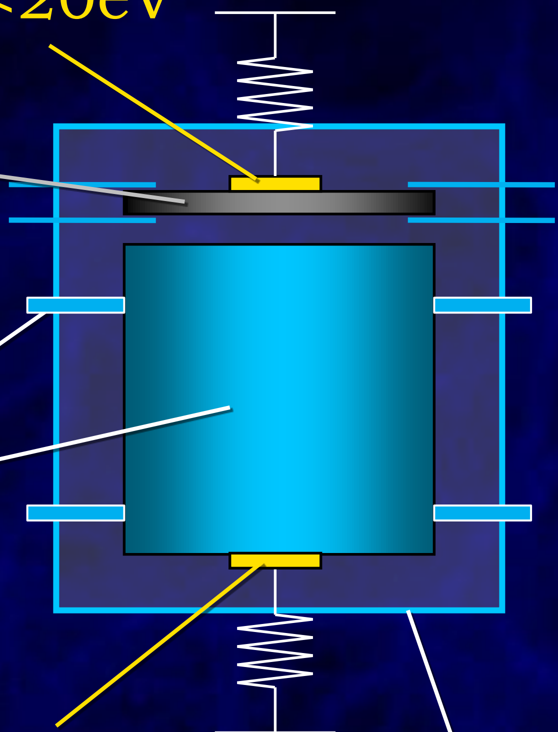
- XENON100
- LUX
- XENON1T

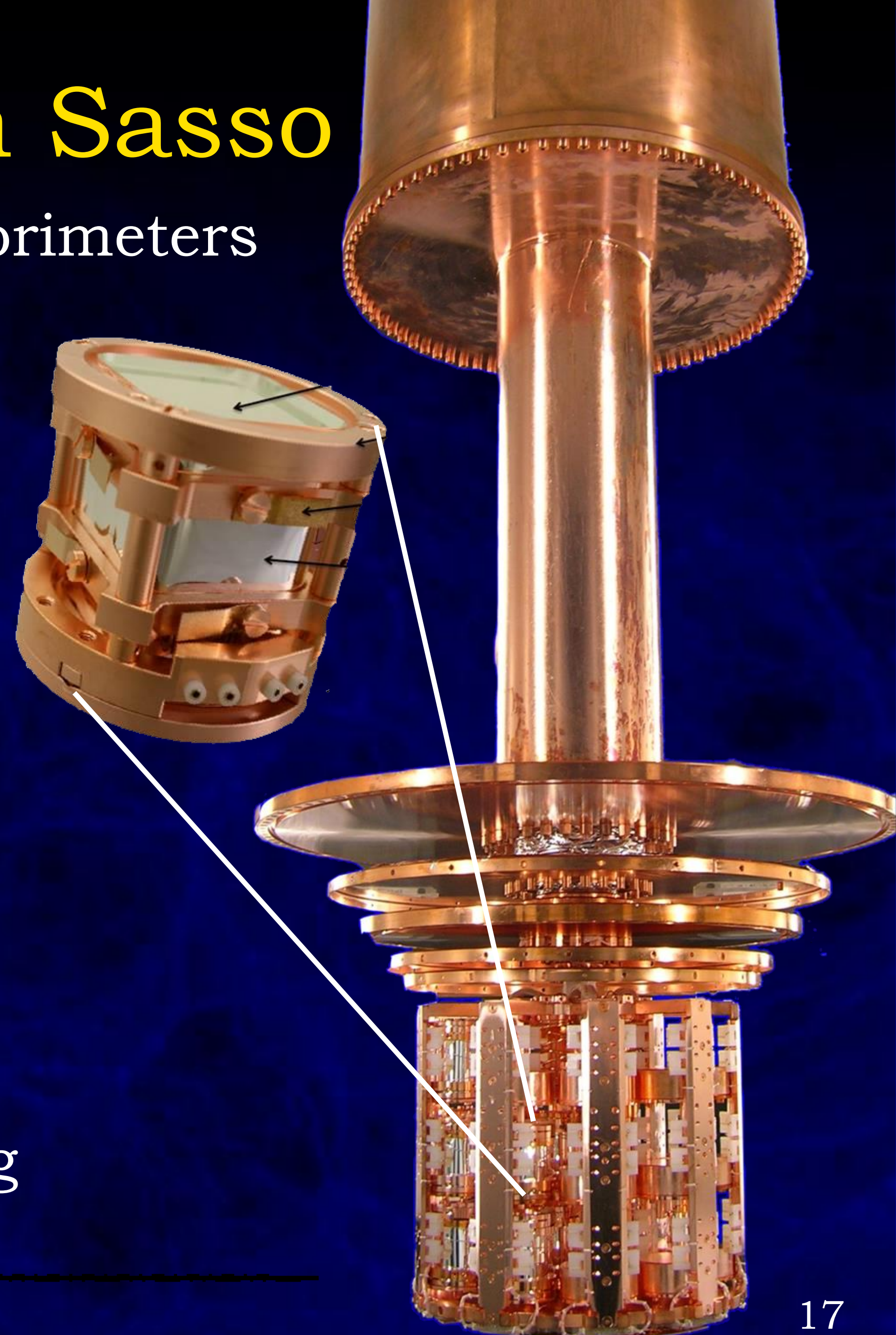
LXe TPCs

CRESST-II @Gran Sasso

Scintillating 300g $CaWO_4$ calorimeters

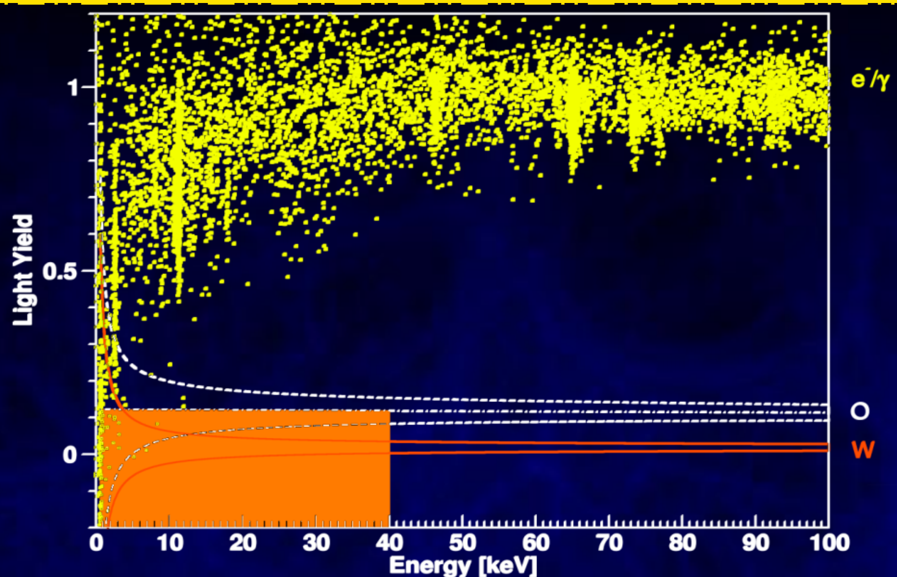
thermometer threshold <20eV

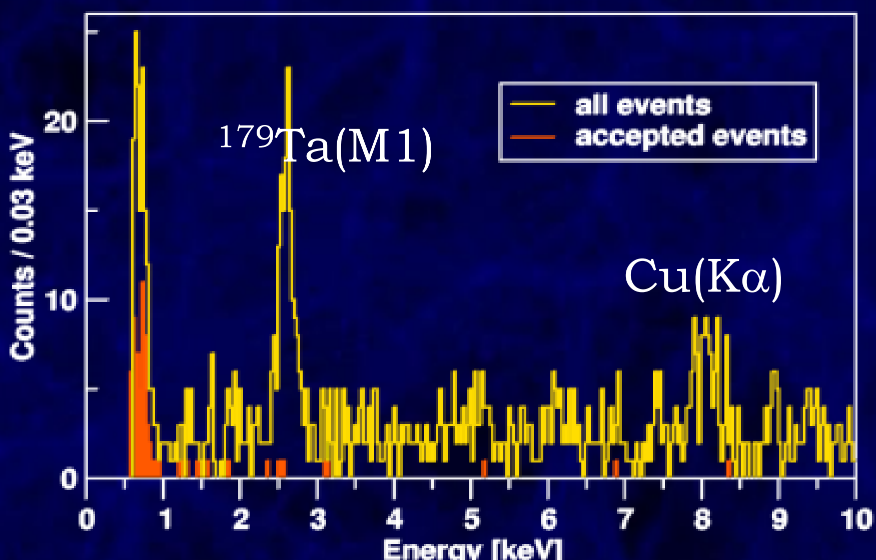




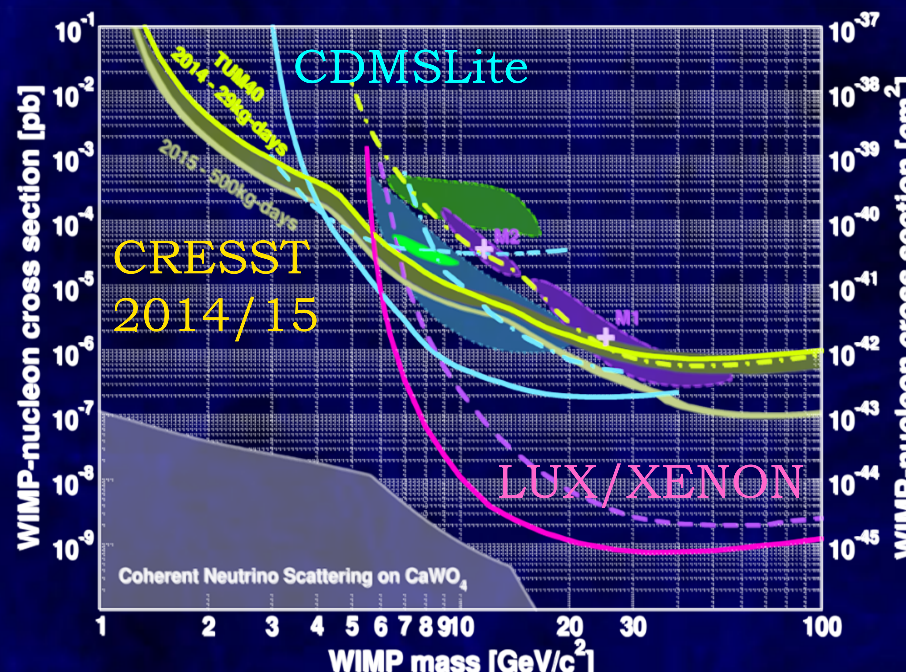
CRESST-II: Multi-Target Built-In

CRESST 1407.3146





- 29 kg days
- Ca, O for light WIMPs, W for heavy WIMPs
- Threshold ~600eV
- Expect better limit, ~300eV threshold 2015

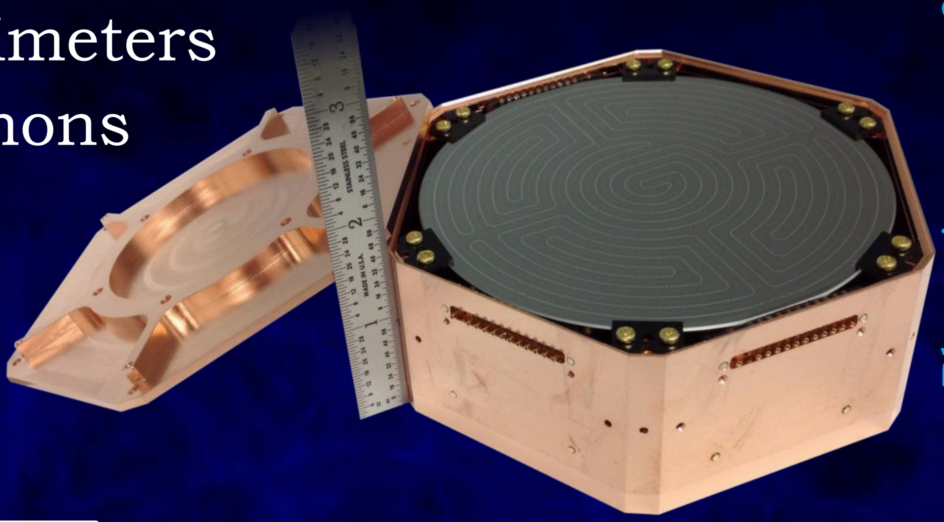


F. Petricca priv.comm. 2015

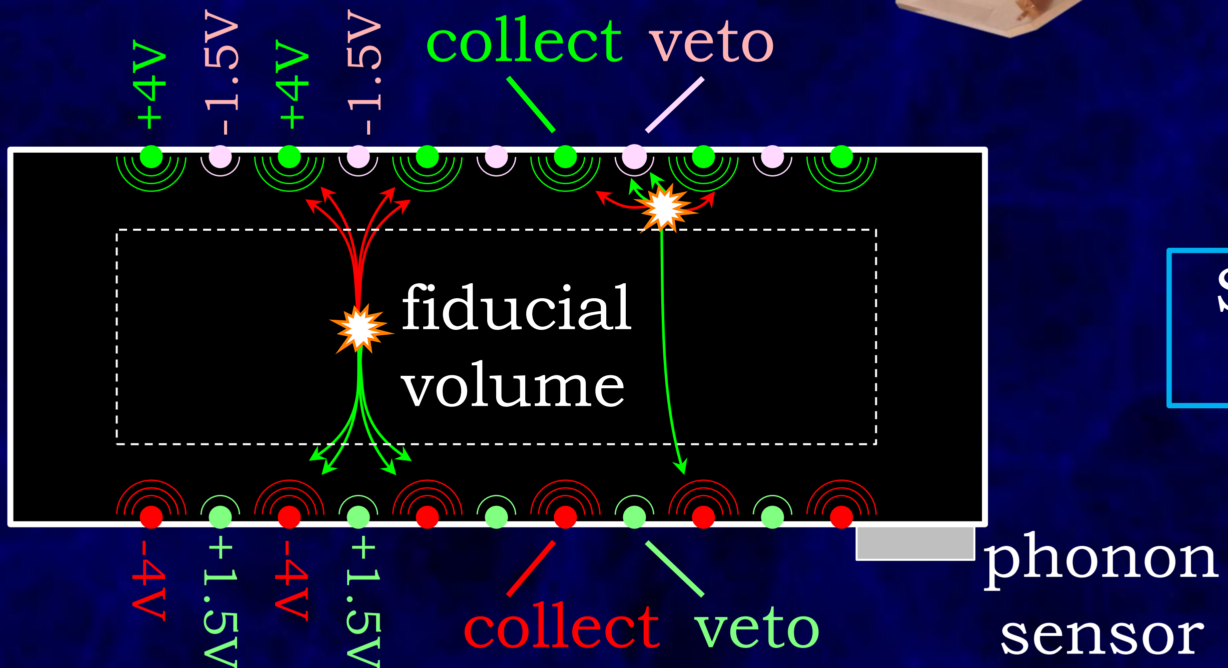
SuperCDMS

2015 still at Soudan
Then move to SNOLAB

Segmented detector, up to 1.4kg Ge each & 60kg total
Germanium or Silicon calorimeters
Cooled to mK to collect phonons
Interleaved electrodes
for ionization



Blas priv. comm. 2015

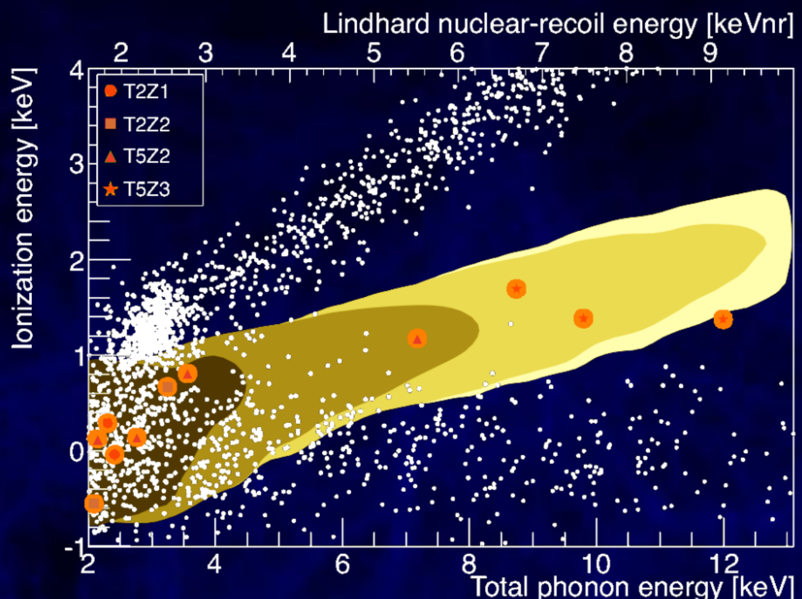


See Peter's talk Thursday

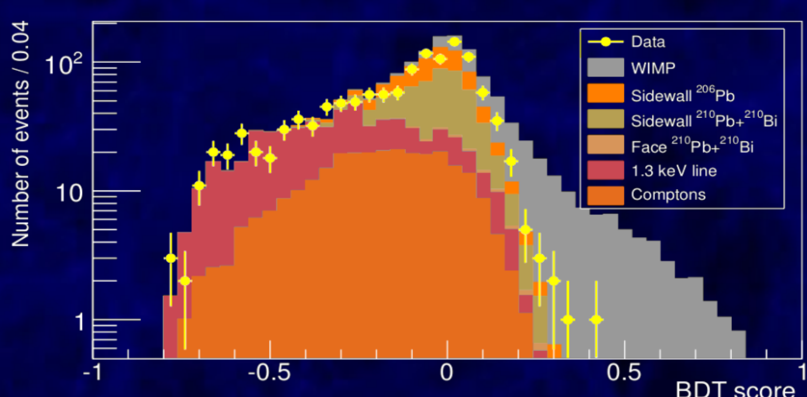
cdms.berkeley.edu

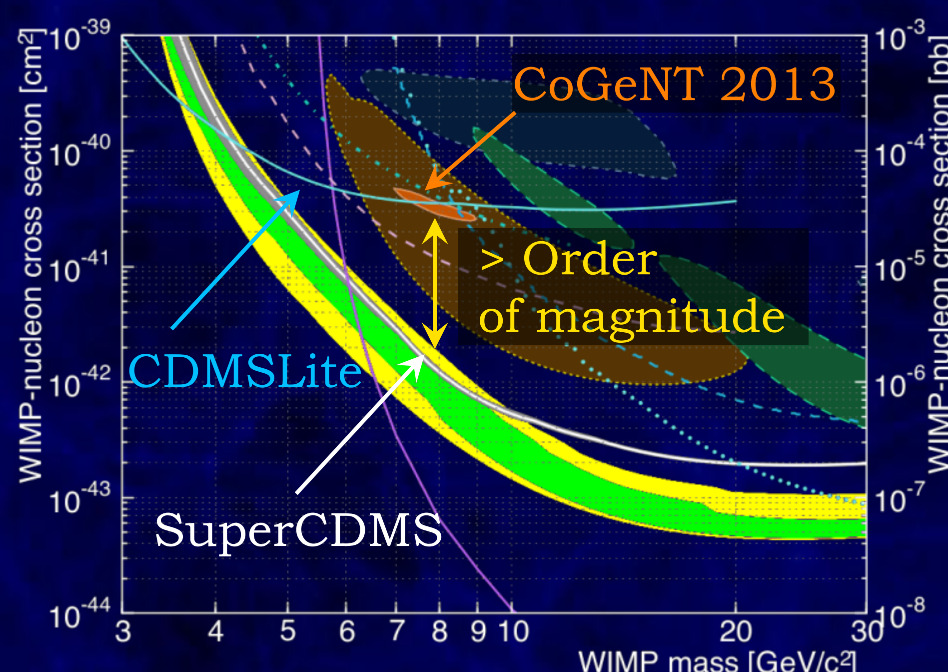
SuperCDMS first analysis

577 kg days optimized for ~GeV WIMPs:



Expect $6.2^{+1.1}_{-0.8}$ events
Observe 11 (8+3)
Excludes CoGeNT
(and CDMS-Si) excess



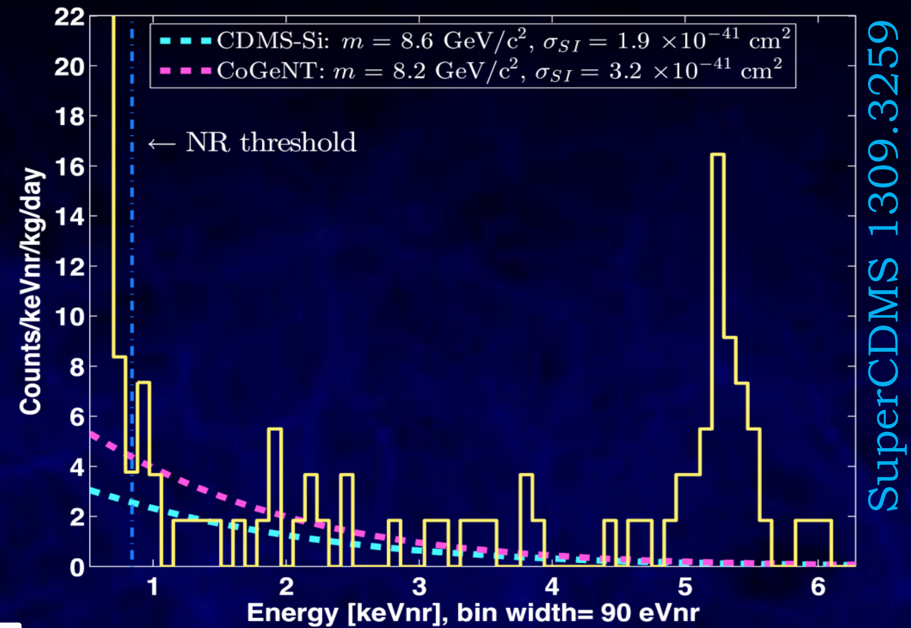


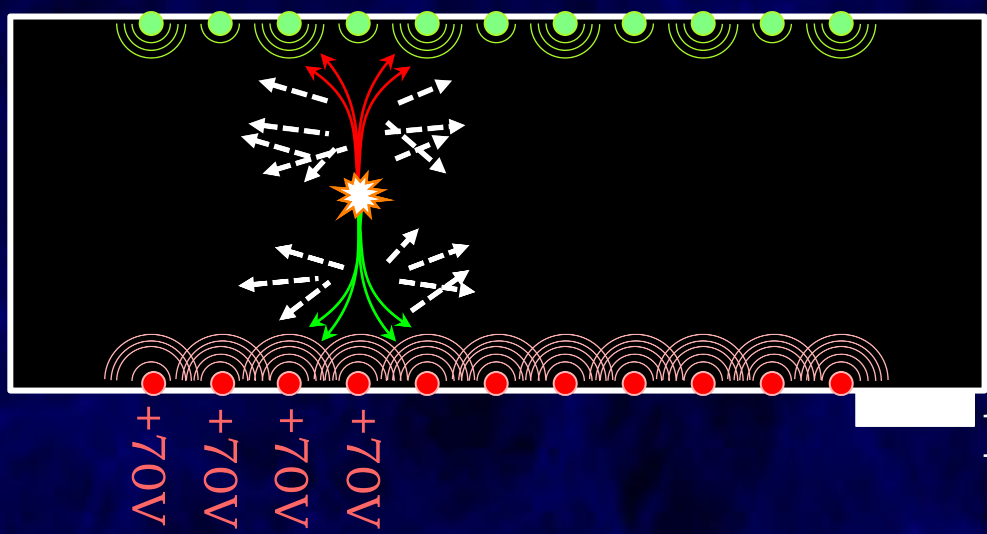
SuperCDMS 1402.7137

CDMSLite: Charge Amplification

Neganov-Luke amplification gives extra phonons

reduce energy threshold to ~800eV$_{nr}$
Expect more data this year





PICO @SNOLAB (=COUPP/PICASSO)

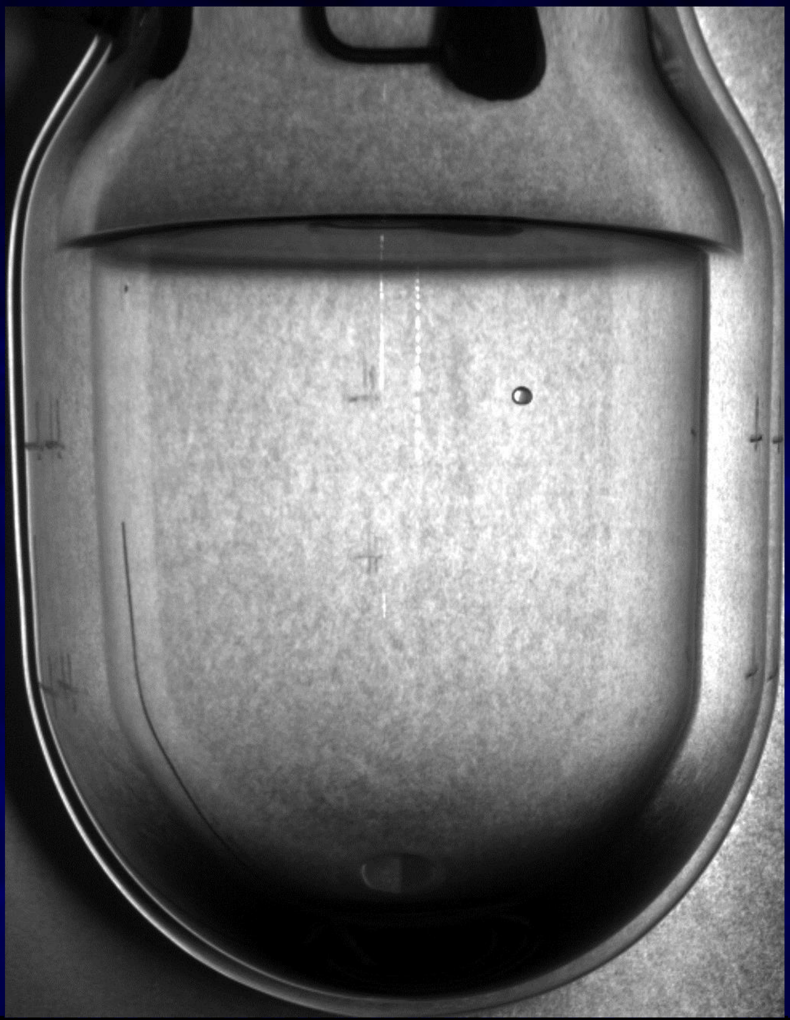
- Bubble chambers
- CF_3I or C_3F_8 targets: spin-dependent / light WIMPs
- Nucleate if $\int_R \mathrm{d}E/\mathrm{d}x$ sufficient

  detector blind ($<10^{-10}$) to electronic recoils
- Only integral energy spectrum; measure with different thresholds

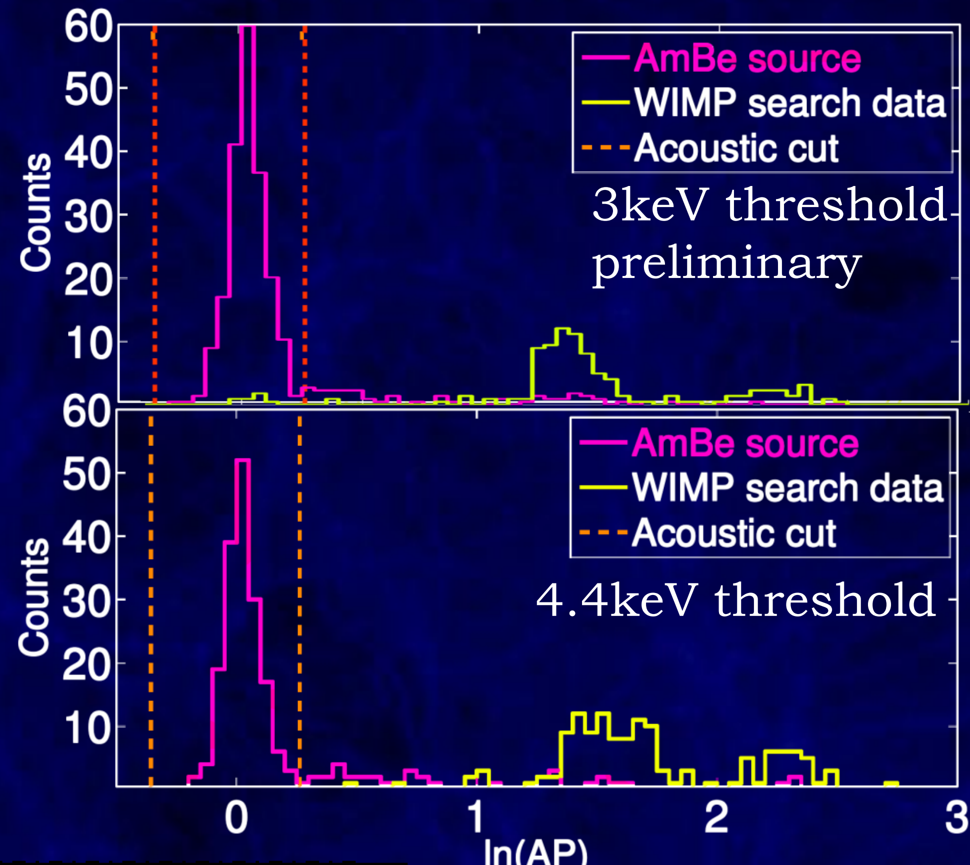
H. Lippincott TAUP2013

PICO Results 2015

Photograph:



Acoustic signal: Alphas pop louder than nuclear recoils, discriminate >98%



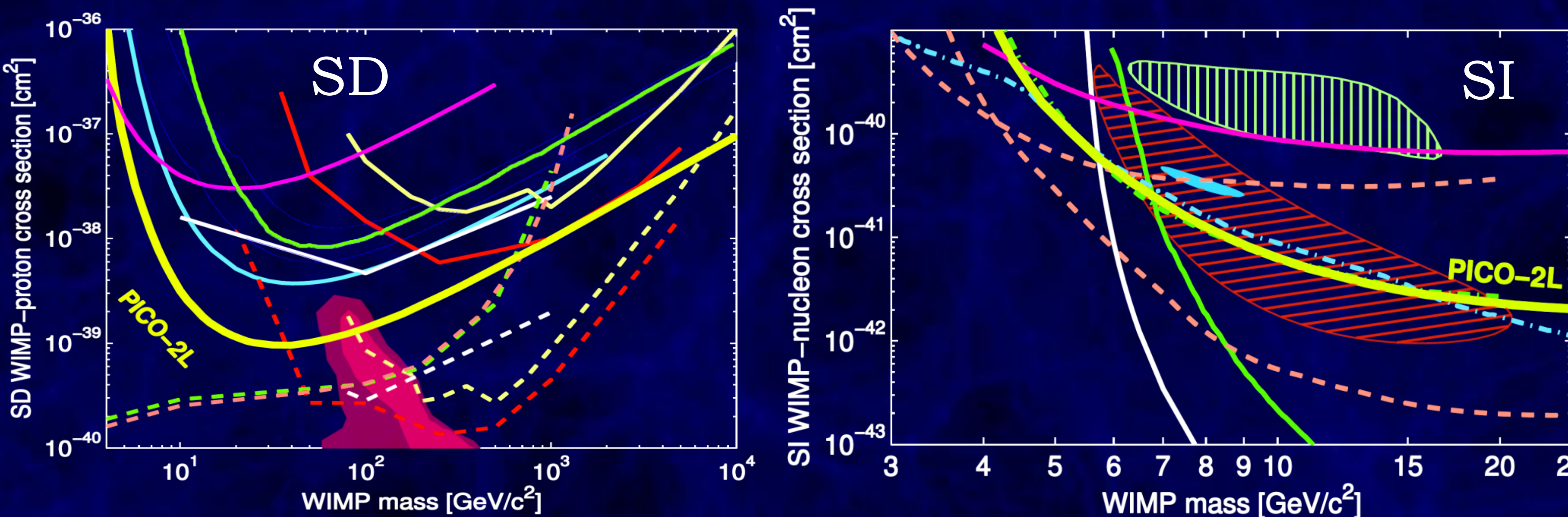
O. Harris LLWI2015

O.Harris LLWI2015 PICO 1503.00008

PICO recent limit and outlook

- Limits from 2.9kg C_3F_8 chamber
- 211 kg days total at 4 thresholds (3-8keV)
- 12 events observed (1 expected), correlated with expansion cycles (corrosion particles?)
- Leading spin-dependent (proton only) limits

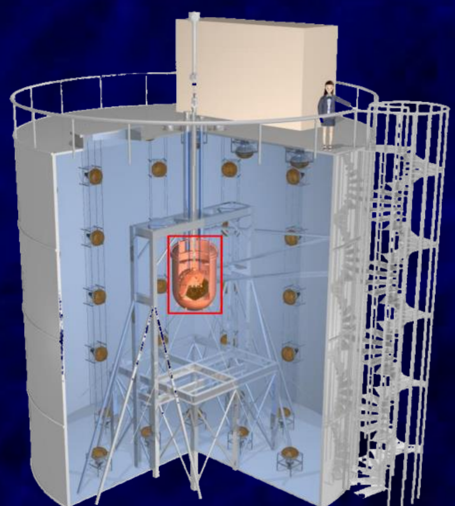
PICO 1503.00008



Soon: >3000 kg days from 25kg CF_3I chamber (PICO 60)

XMASS @ Kamioka

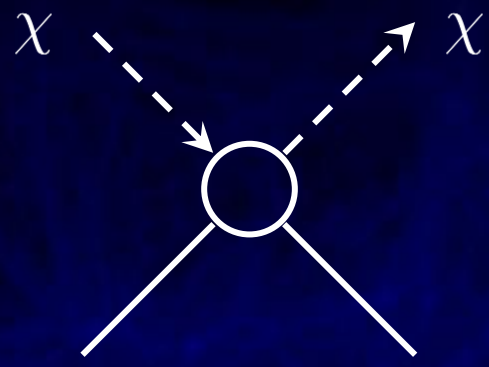
- Single-phase liquid xenon
- 642 2.5” hex PMTs
- 830kg total, 100kg fiducial
- Position from PMT hit pattern; self-shielding
- Patched after initial run, data taking since Nov 2013, rate ~1 evt/keV/ton/day



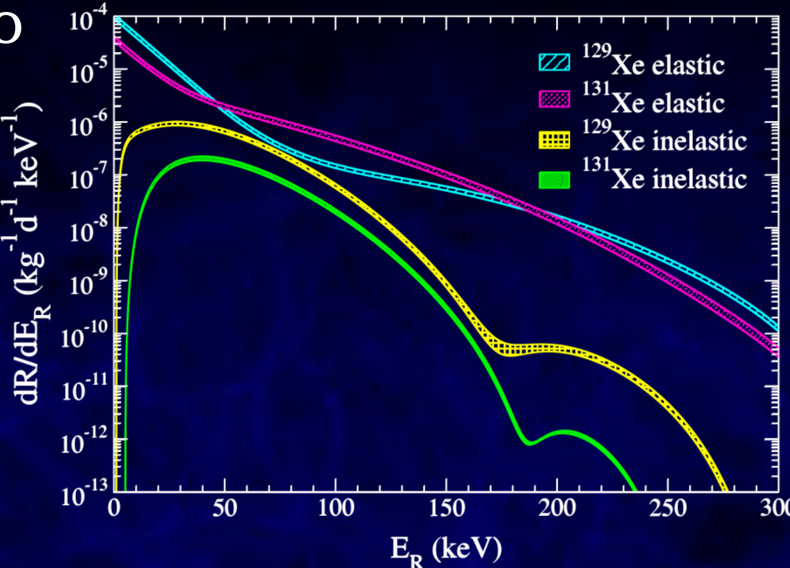
Moriyama, IDM2010

Inelastic Scattering

cross-check limits, measure halo

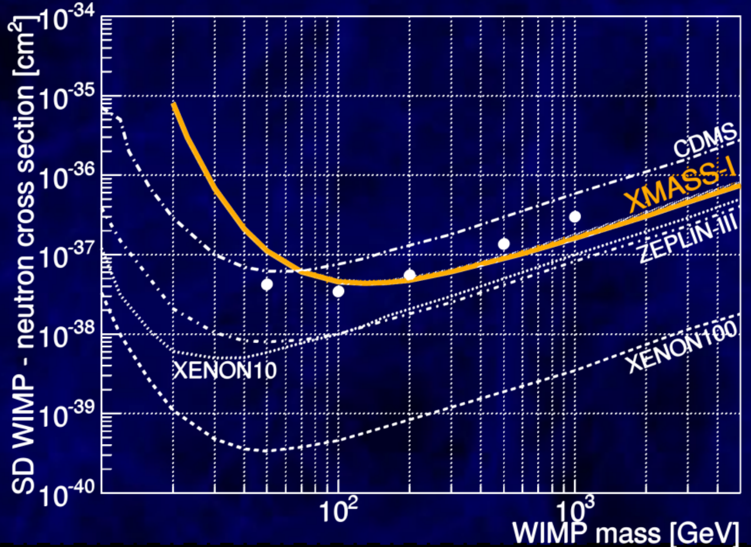


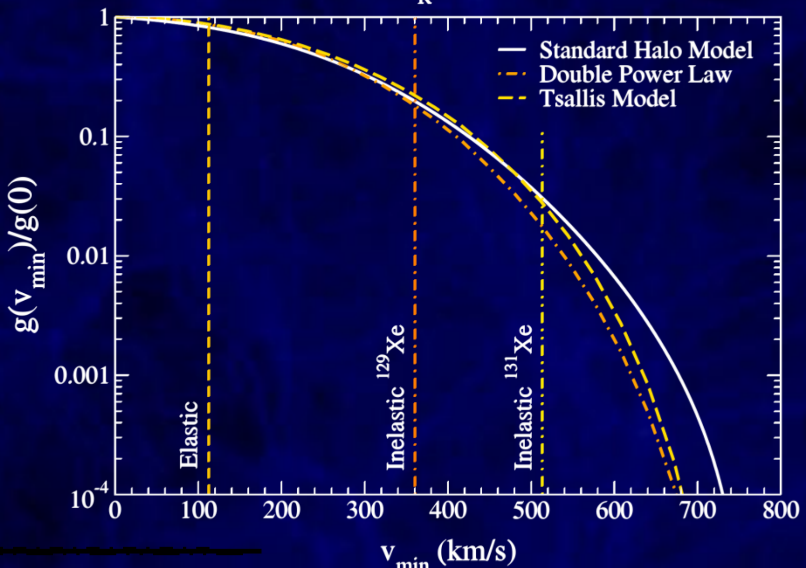
$^{129}Xe \qquad {}^{129}Xe^{*} \longrightarrow {}^{129}Xe + \gamma_{40keV}$



Baudis+ 1309.0825

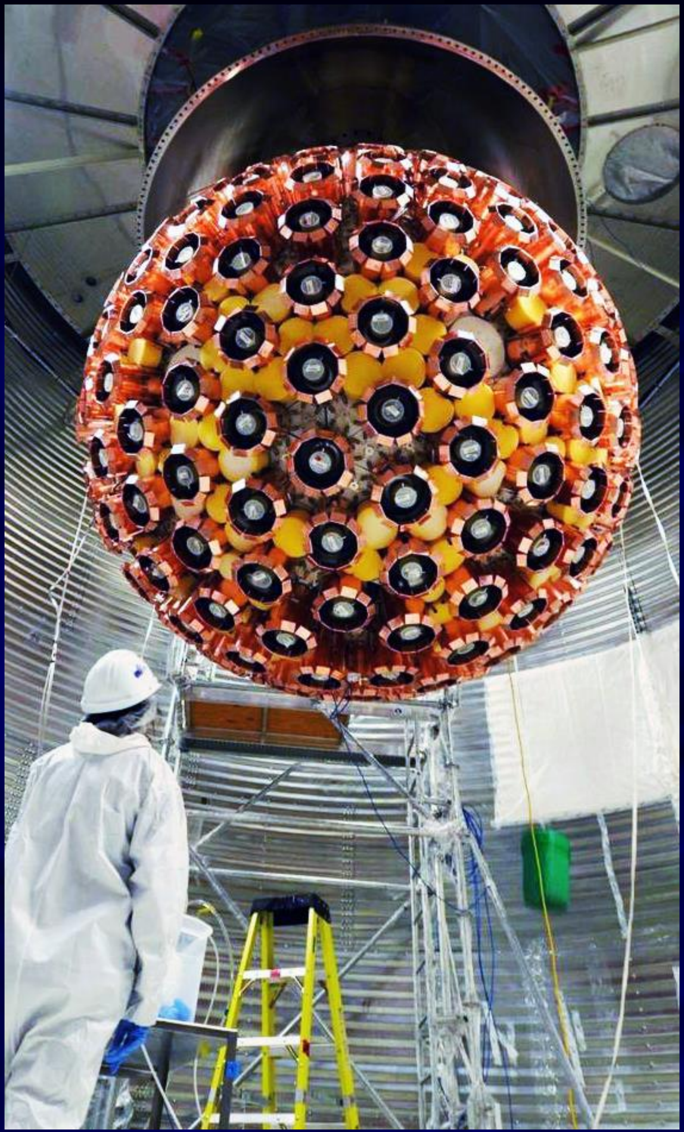
XMASS 1401.4737





DEAP-3600 @ SNOLAB

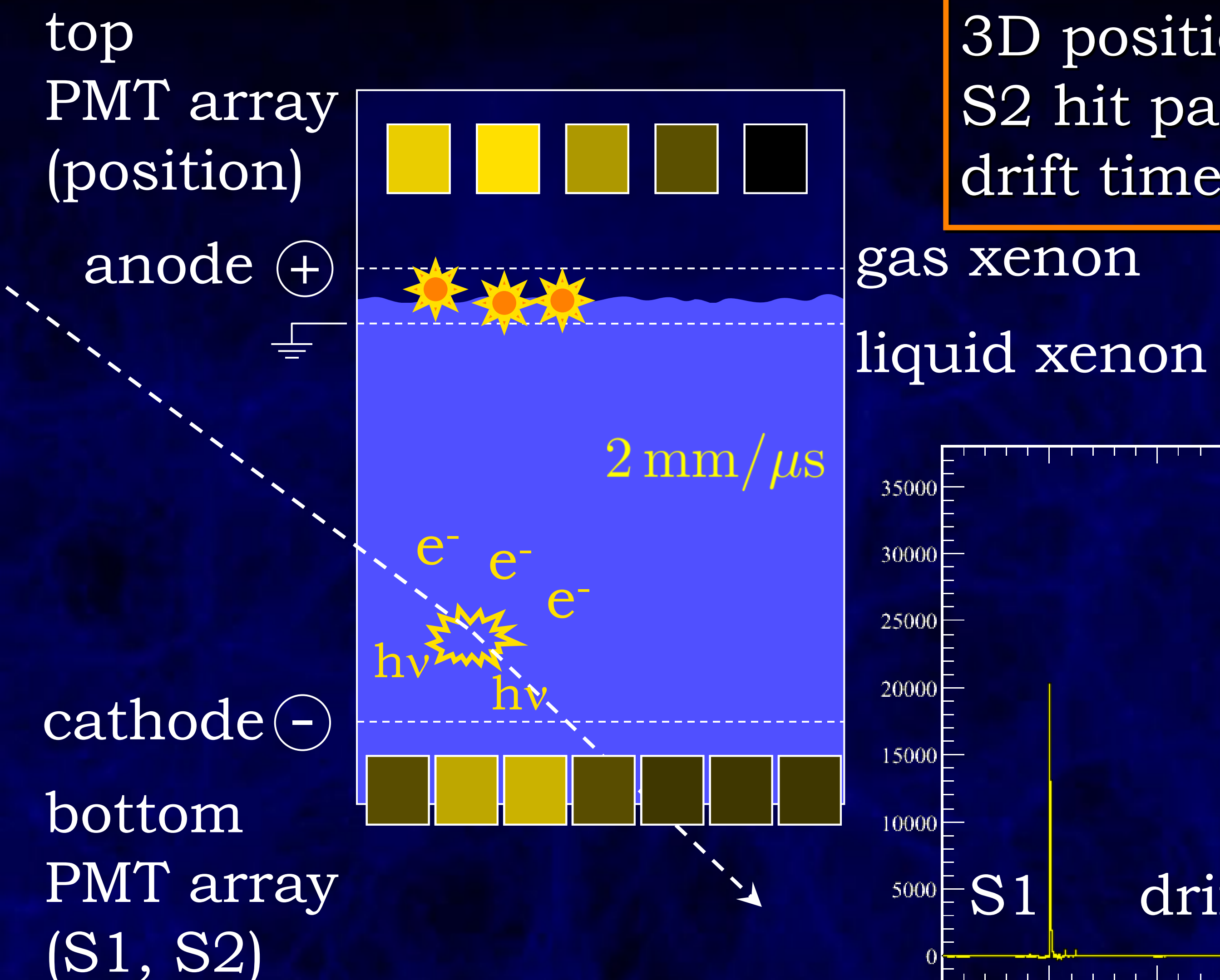
- Single phase liquid argon
- Acrylic vessel
- 3.6t argon total, 1t fiducial
- 255 8” PMTs
- Pulse shape discrimination
- 10^{-46}cm^2 sensitivity after 3 years
- LAr data this summer

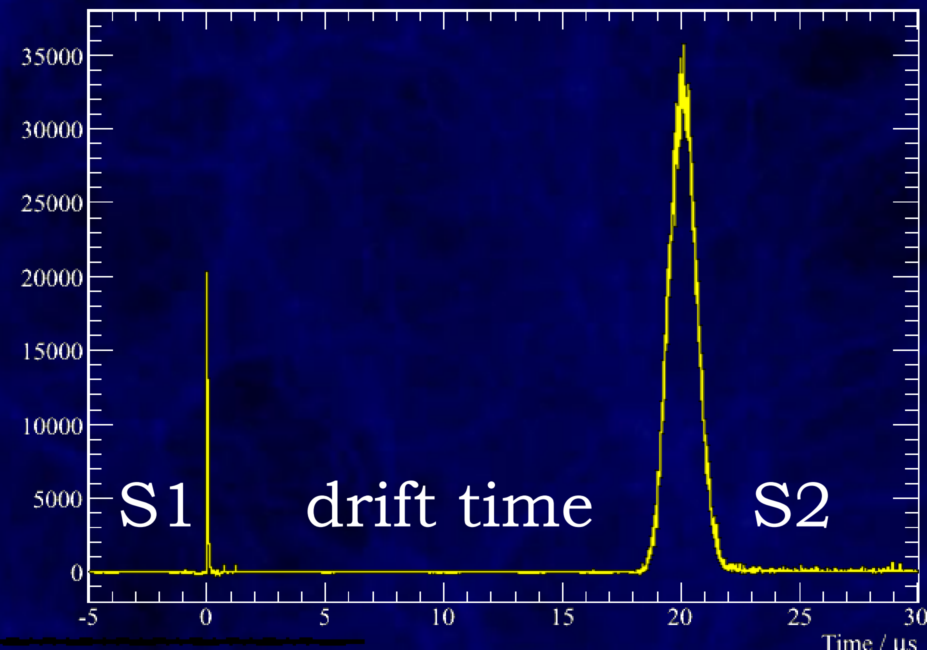


Twitter @SNOLABscience

Xenon Time Projection Chambers

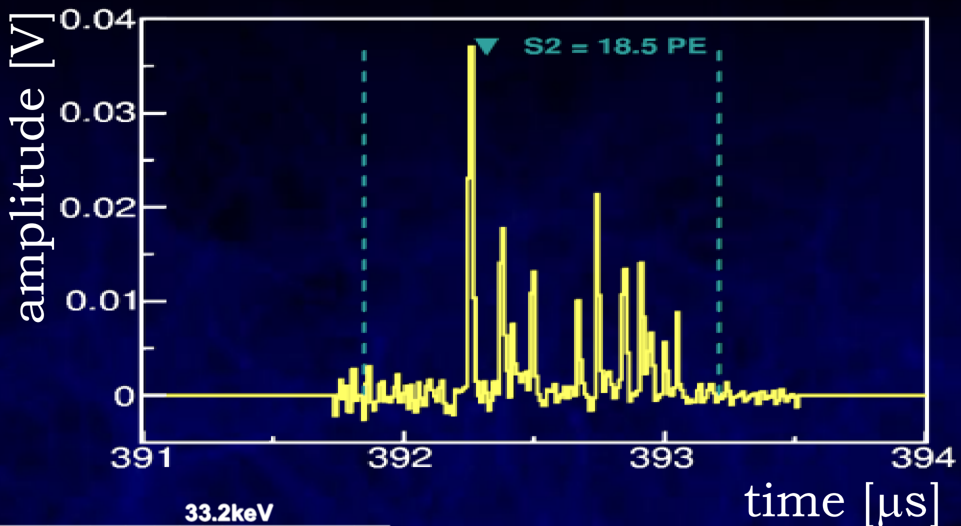
3D position information
S2 hit pattern: $\delta r < 3\,\mathrm{mm}$
drift time: $\delta z < 300\,\mu\mathrm{m}$



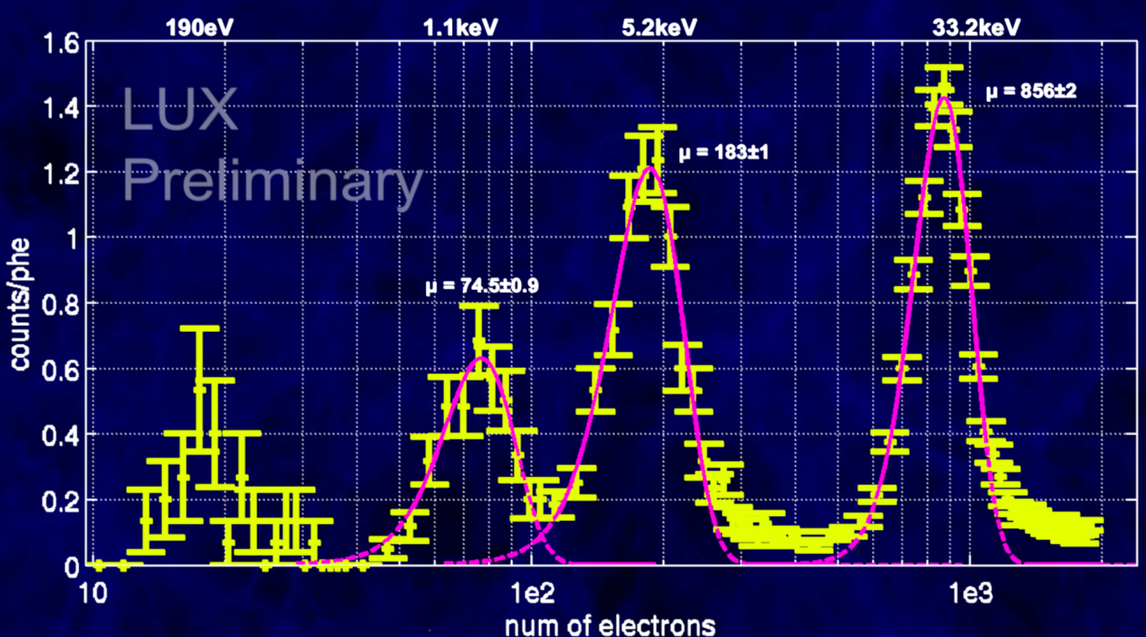


Extreme Low-Energy Sensitivity

Detect even individual electrons liberated in an interaction:



XENON100 1311.1088



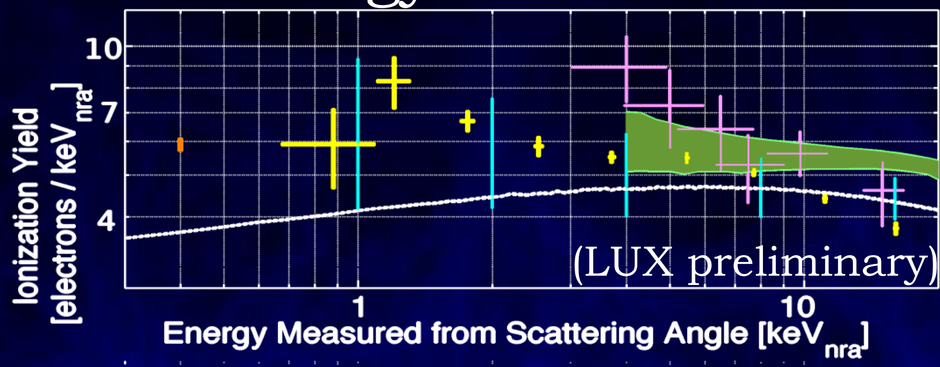
LUX D.Huang APS2015

^{127}Xe EC (from cosmic activation) calibration as low as 190eV

LUX @Soudan

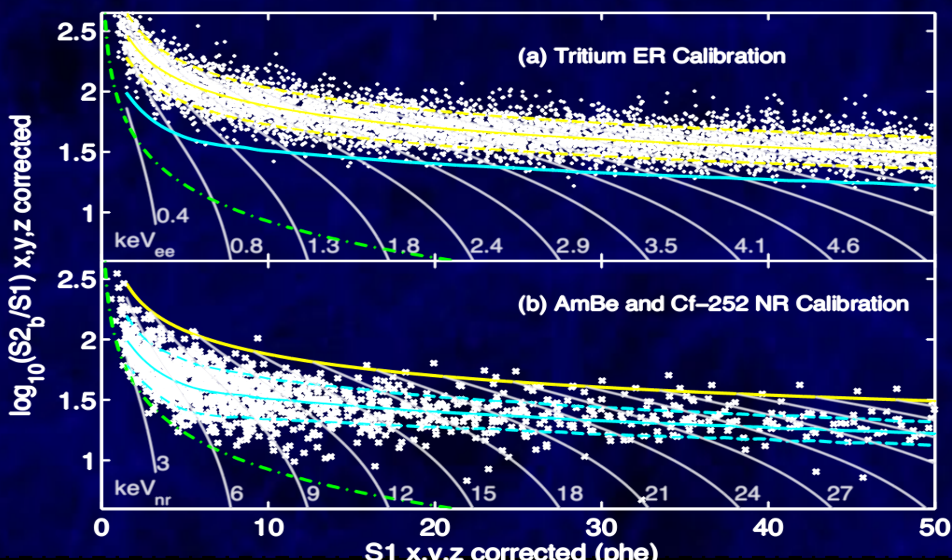
in situ energy calibration

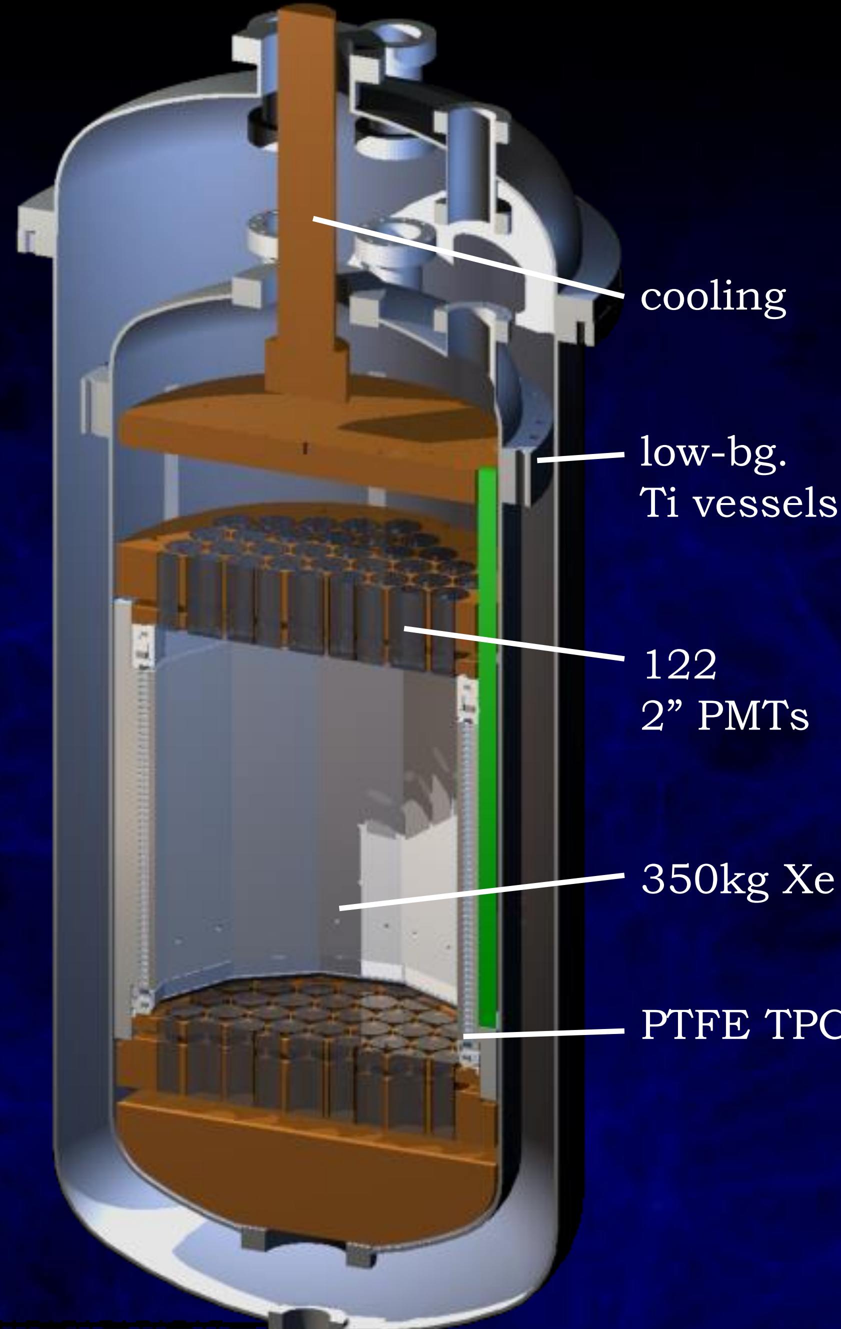
Verbus UCLA2014



tritium background calibration

LUX 1310.8214

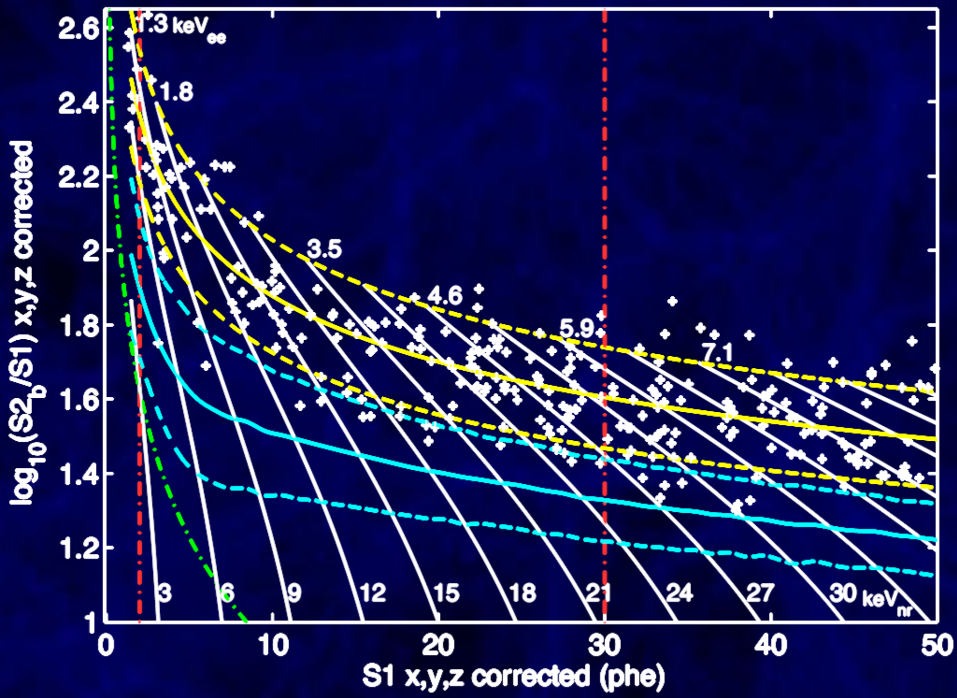




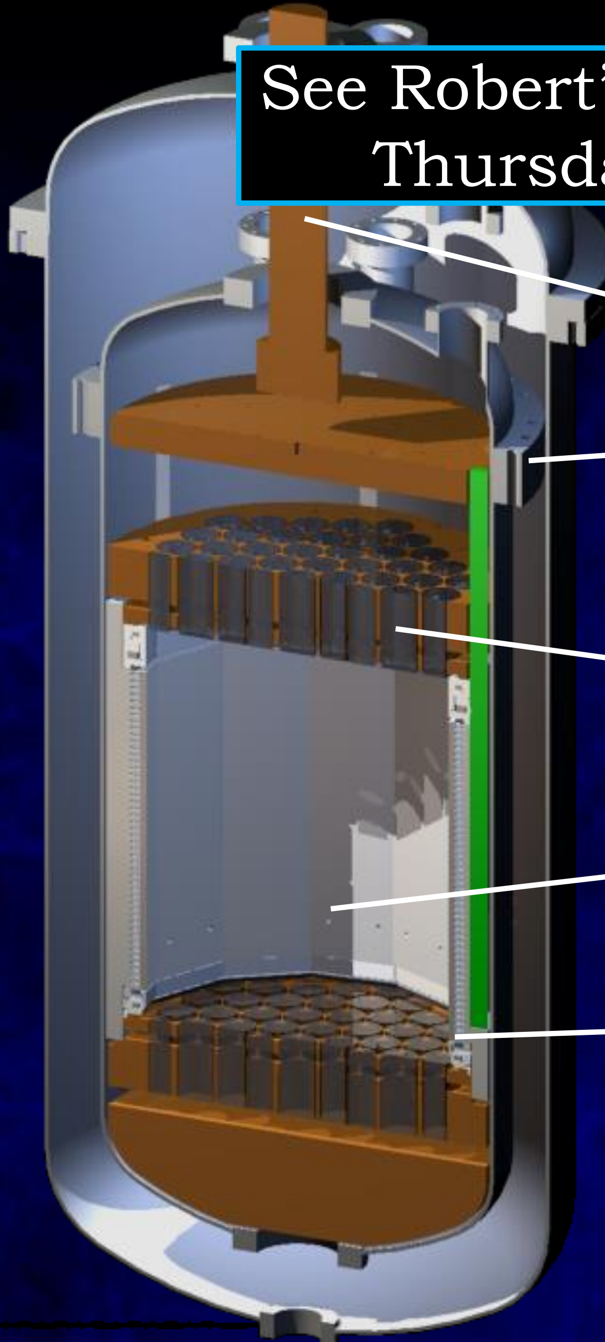
LUX: Xenon TPC

first results:
85 live days, 118 kg
non-blind analysis
strongest limit to-date

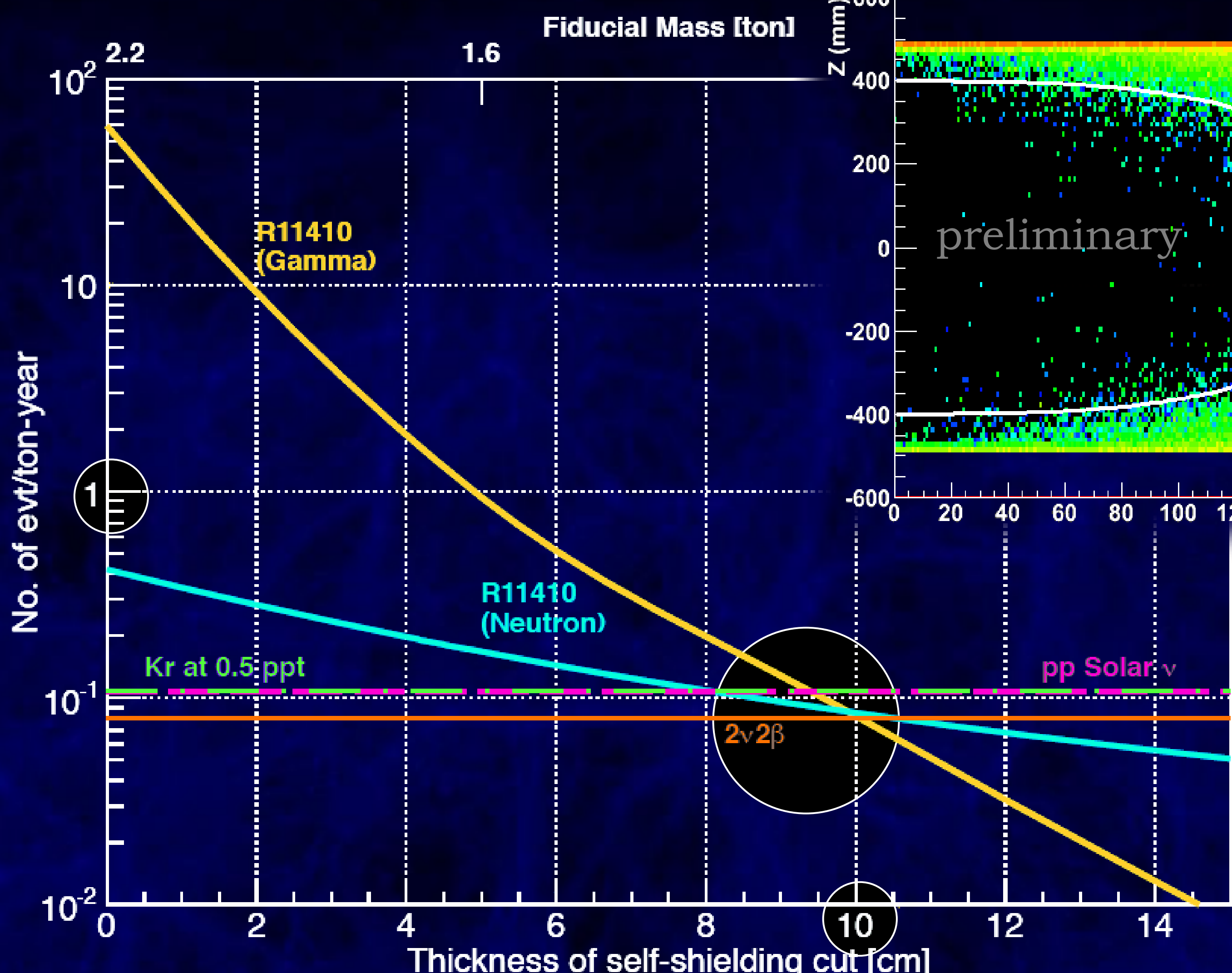
LUX 1310.8214

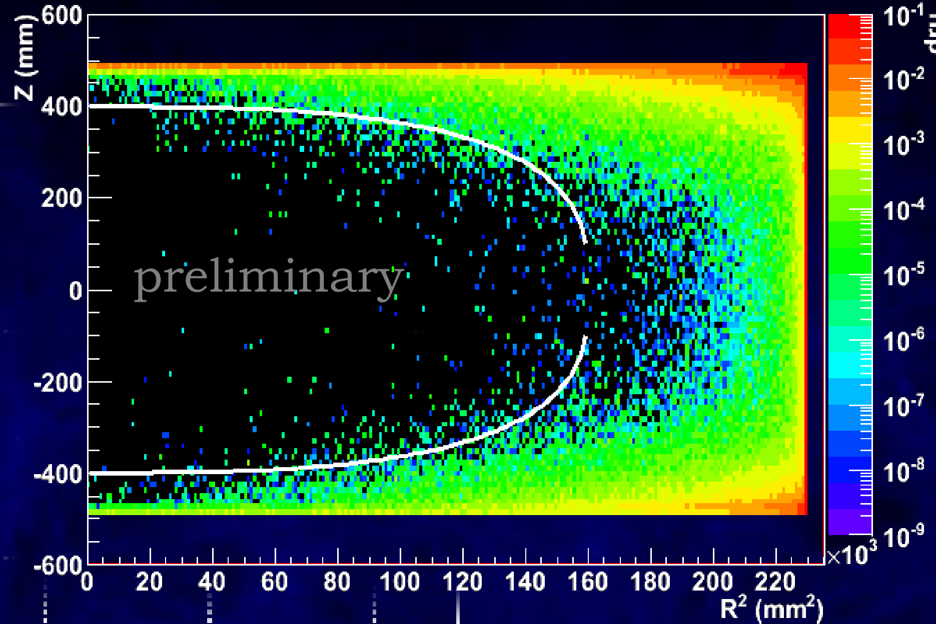


See Robert's talk Thursday



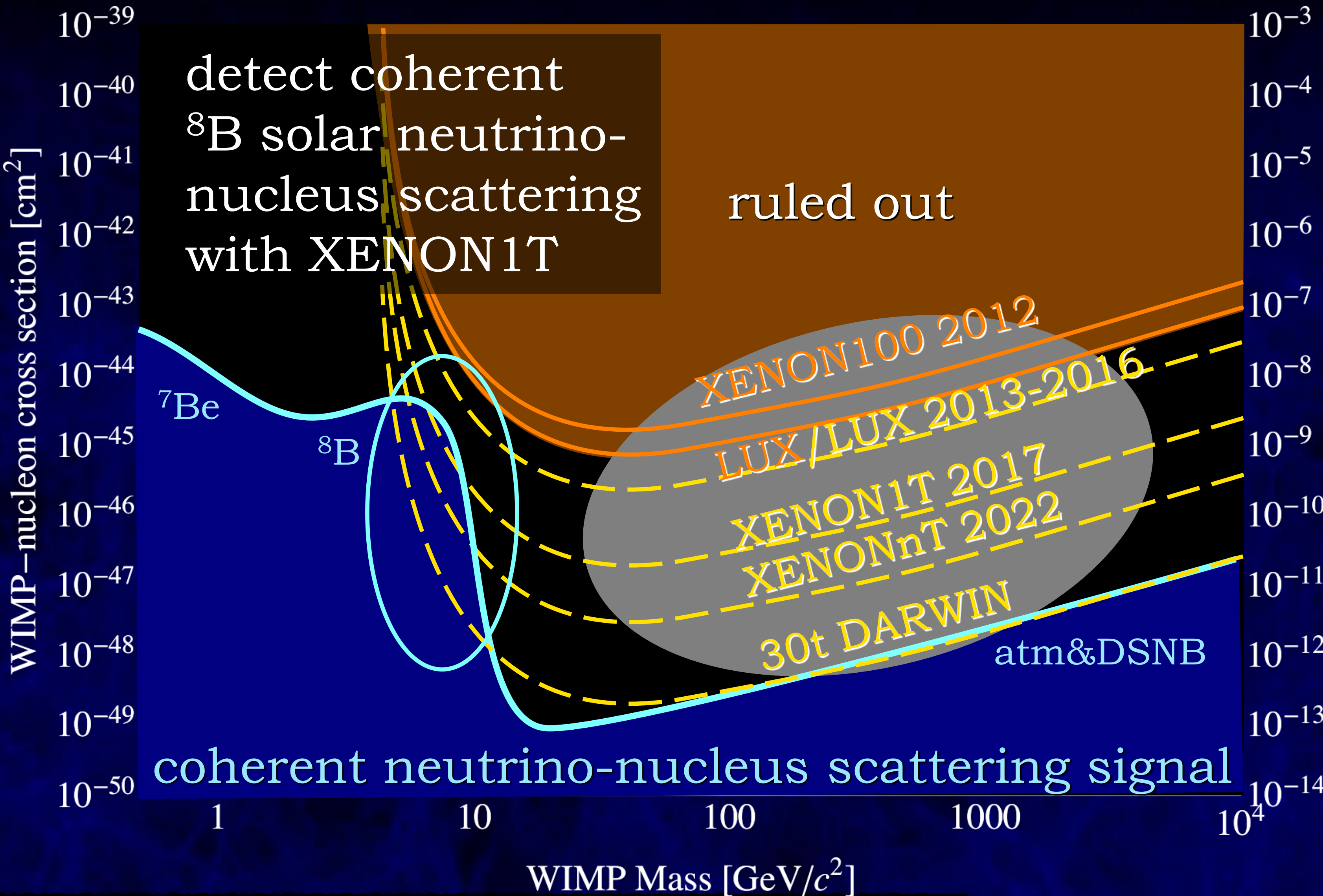
XENON1T Background Optimization





total BG:
<0.2 ER/t/a
<0.3 NR/t/a

Probing Coherent Neutrino Scattering



Billard, Strigari, Figueroa 1307.5458

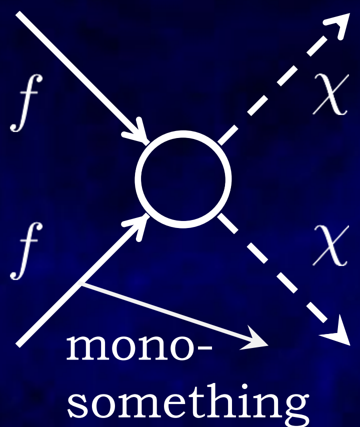
Expect XENON1T Data this Fall

Summary

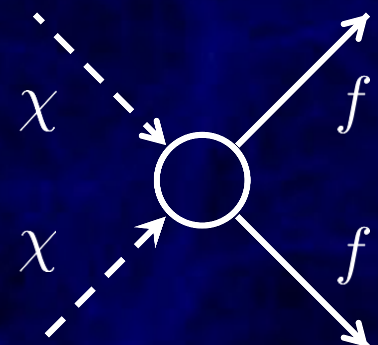
- Direct Dark Matter detection a mature field; Systematics under control, advanced detectors & elaborate analyses.
- CDMS and LXe TPC experiments extract ample information; allow discovery claim from a single detector.
- Require confirmation though: We are in thin air. Span orders of magnitude in parameter space with only little experimental redundancy.
- Sensitivity is at level of best-motivated models; Covers most of expected parameter space within a couple years.

Thermal Relics Scatter

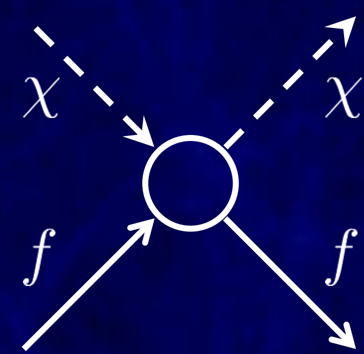
Production:
collider searches



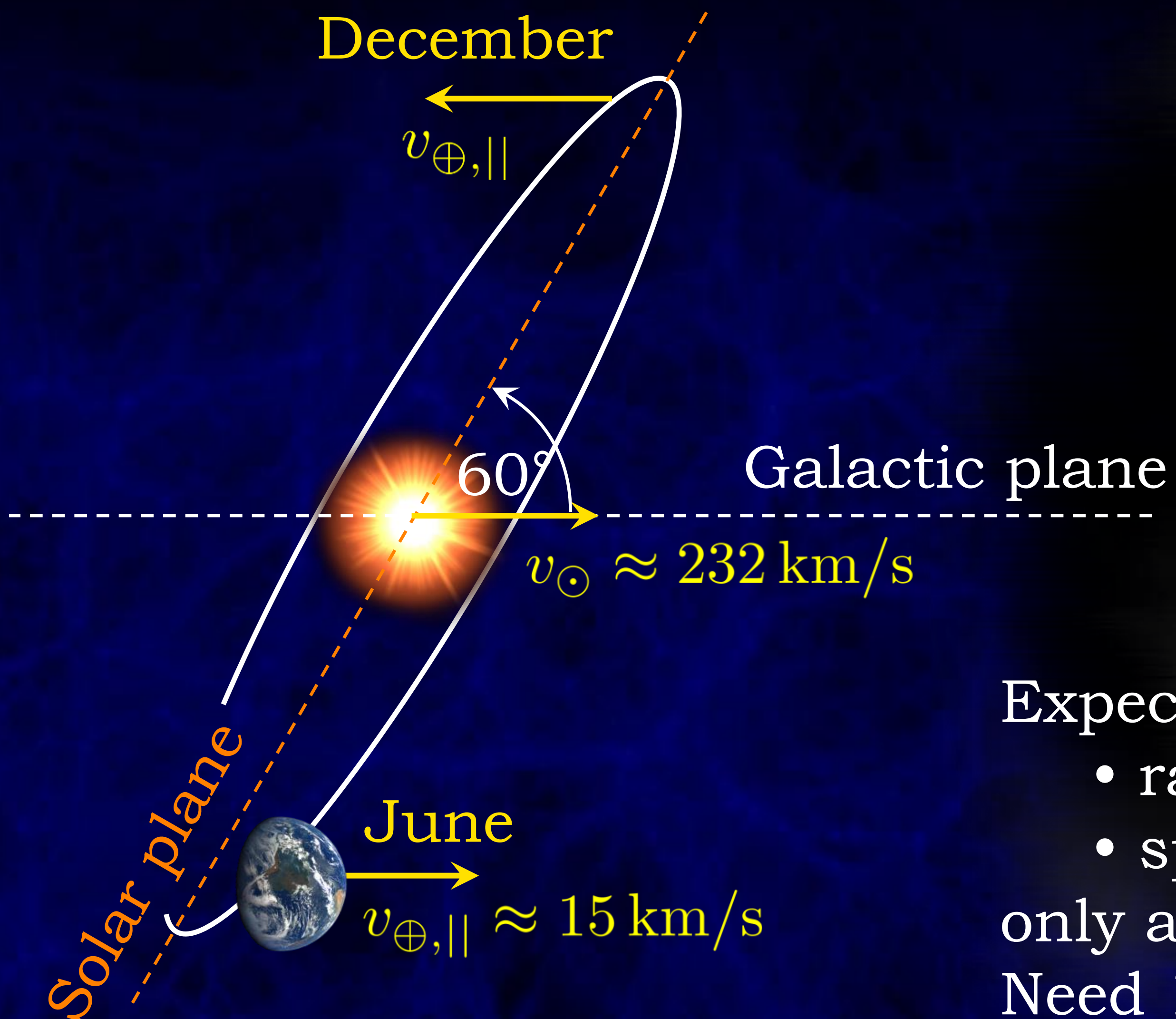
Annihilation:
indirect searches



Scattering:
direct detection



Simple Non-Relativistic Scattering



Expect modulation of
- rate
- spectral shape

only at percent level:
Need 100s of events

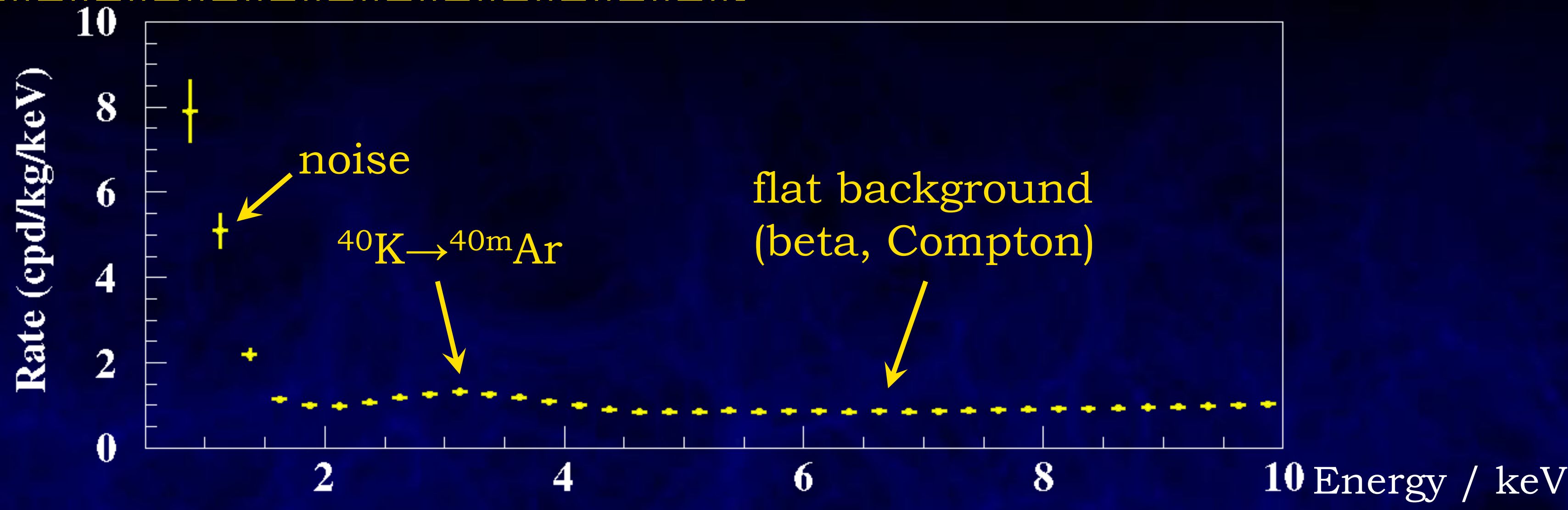
DAMA/LIBRA

230kg ultra-pure NaI(Tl) scintillators
by far largest and longest exposure but no discrimination

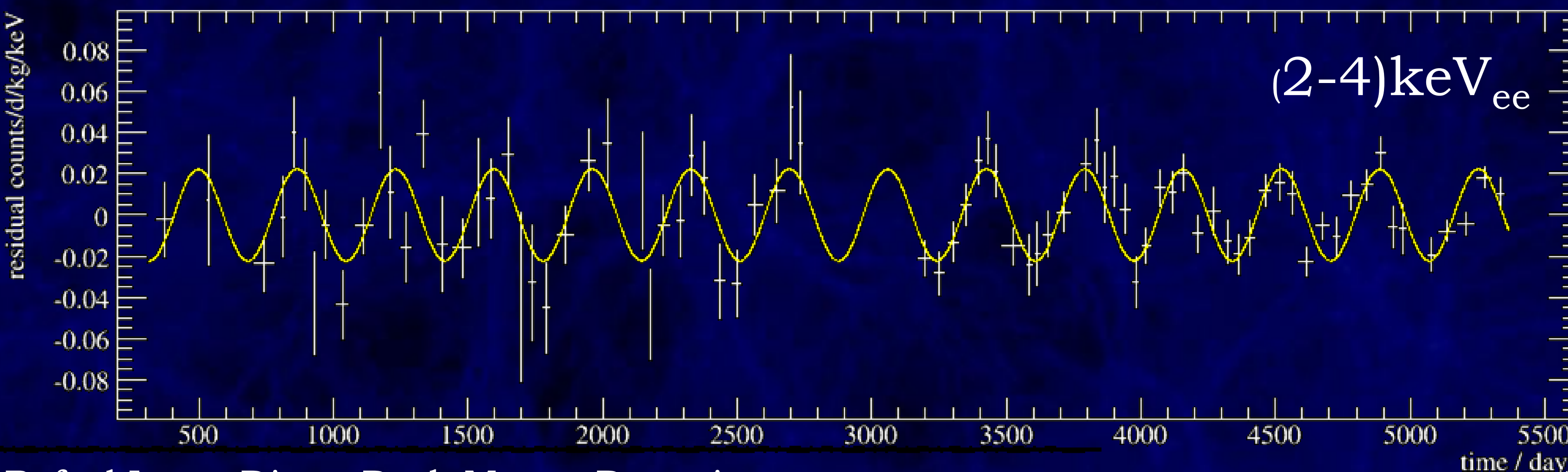


DAMA/LIBRA Data

arXiv:0804.2741
arXiv:1210.7548



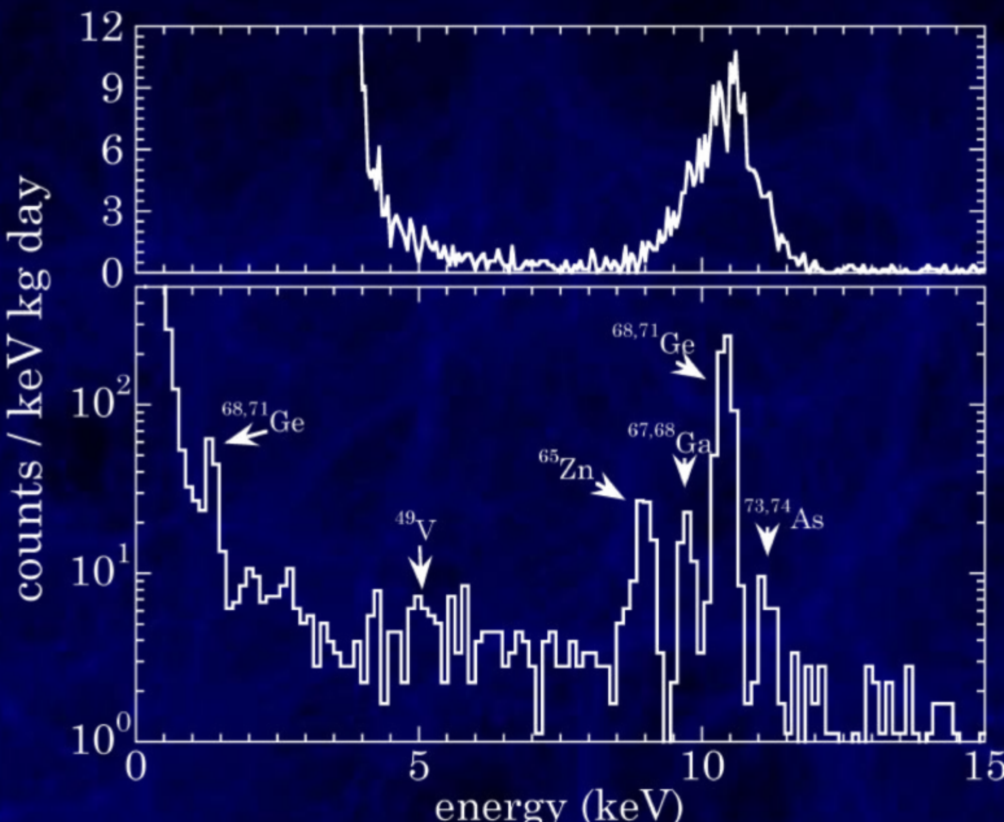
fully explained by background, no room for dark matter, but



data from arXiv:0804.2741 and arXiv:1002.1028

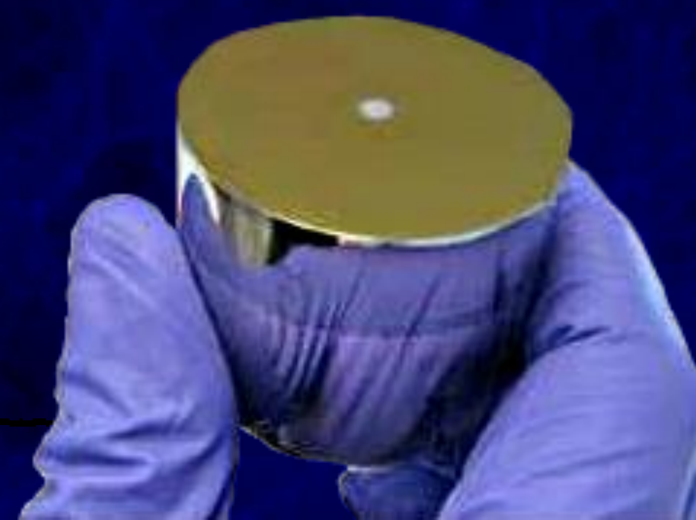
CoGeNT

440g P-type point-contact Ge detector
now >3 years of continuous data taking



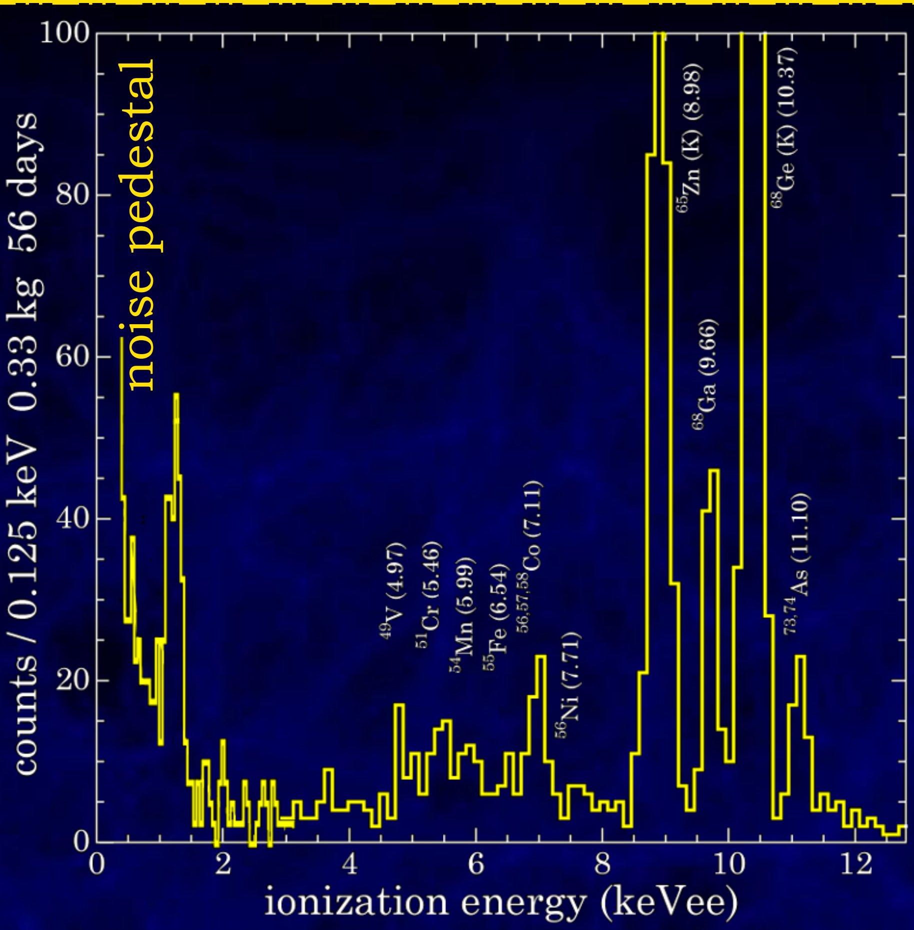
conventional
coaxial HPGe

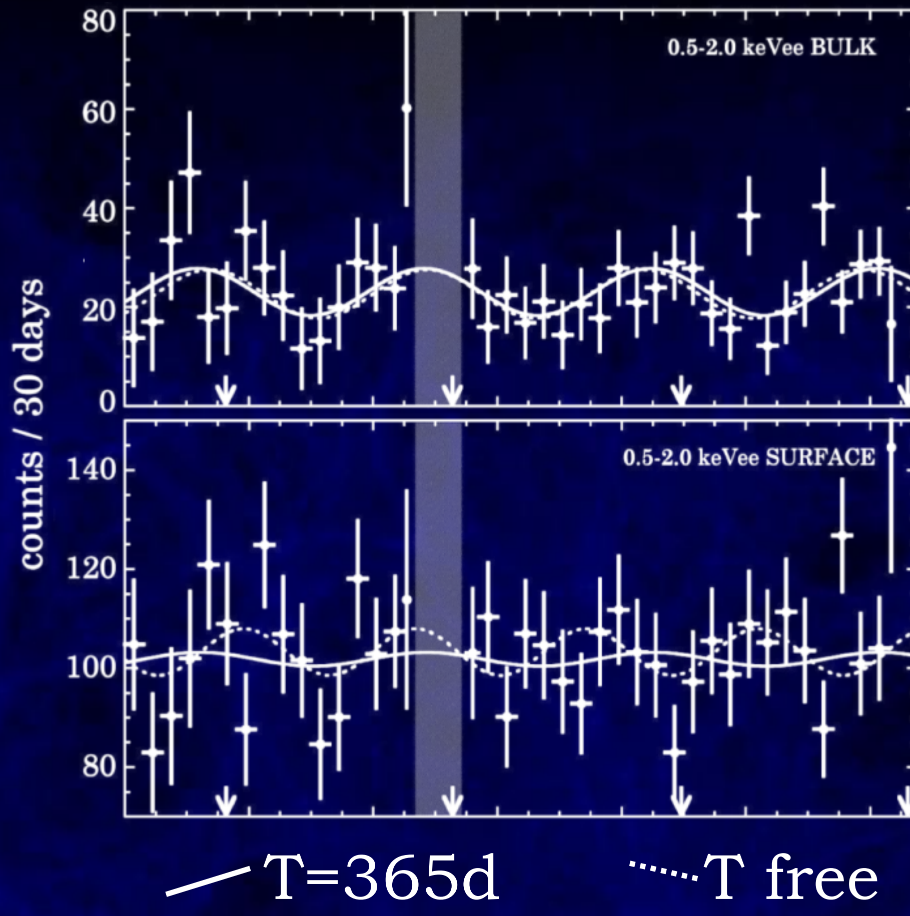
P-type point-
contact HPGe
threshold 400eV



Collar, UC Davis and other talks, 2010

CoGeNT Data





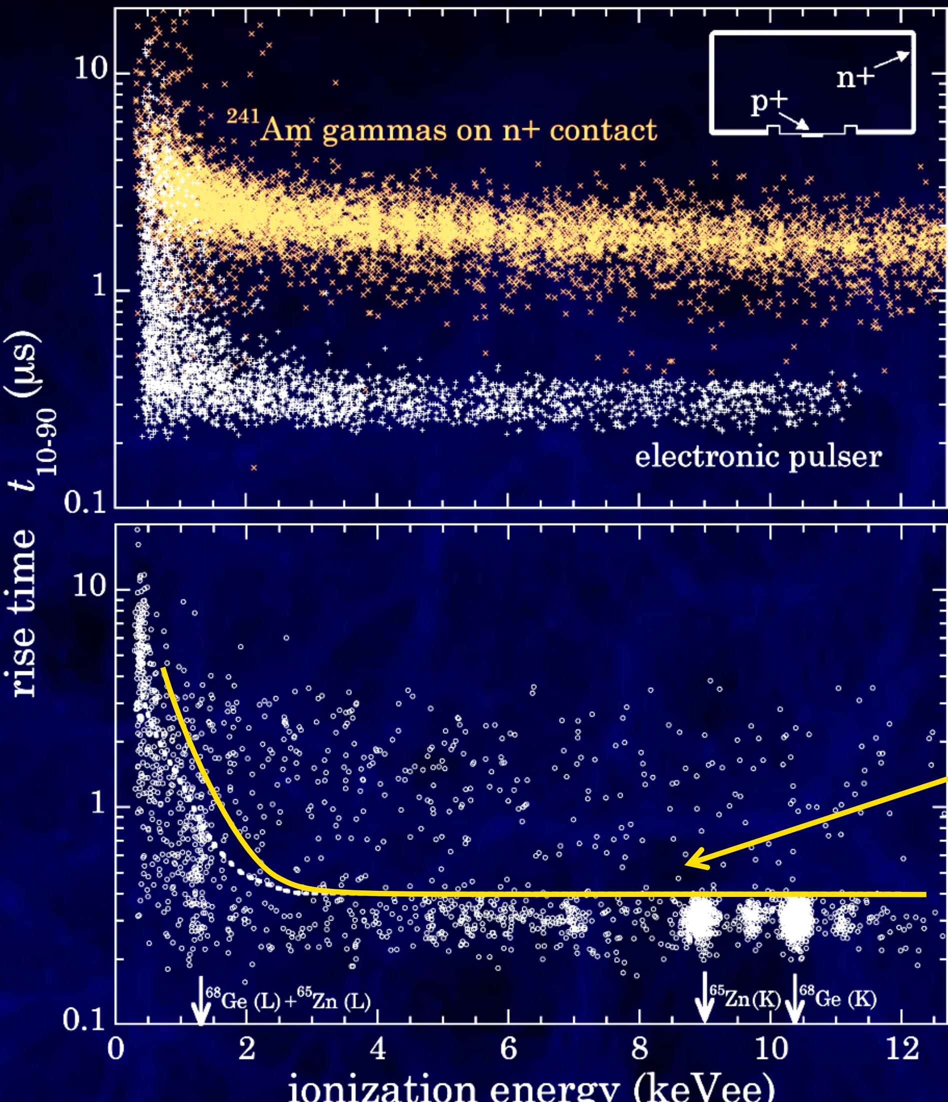
J. Collar, TAUP2013

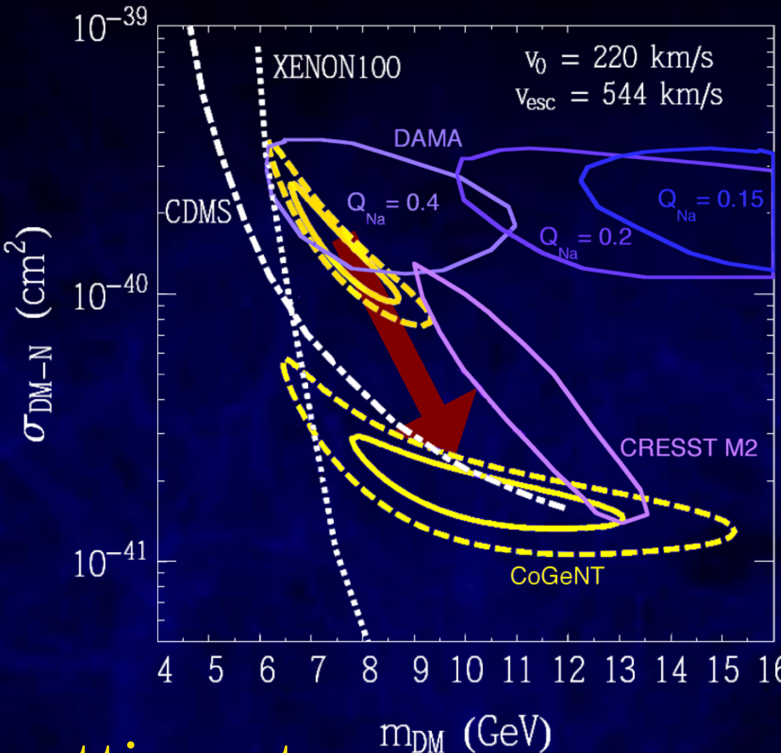
arXiv:1002.4703

exponential rise at low energy

~2σ modulation after 3.4 years; high amplitude

CoGeNT With Background





cutting at
constant acceptance

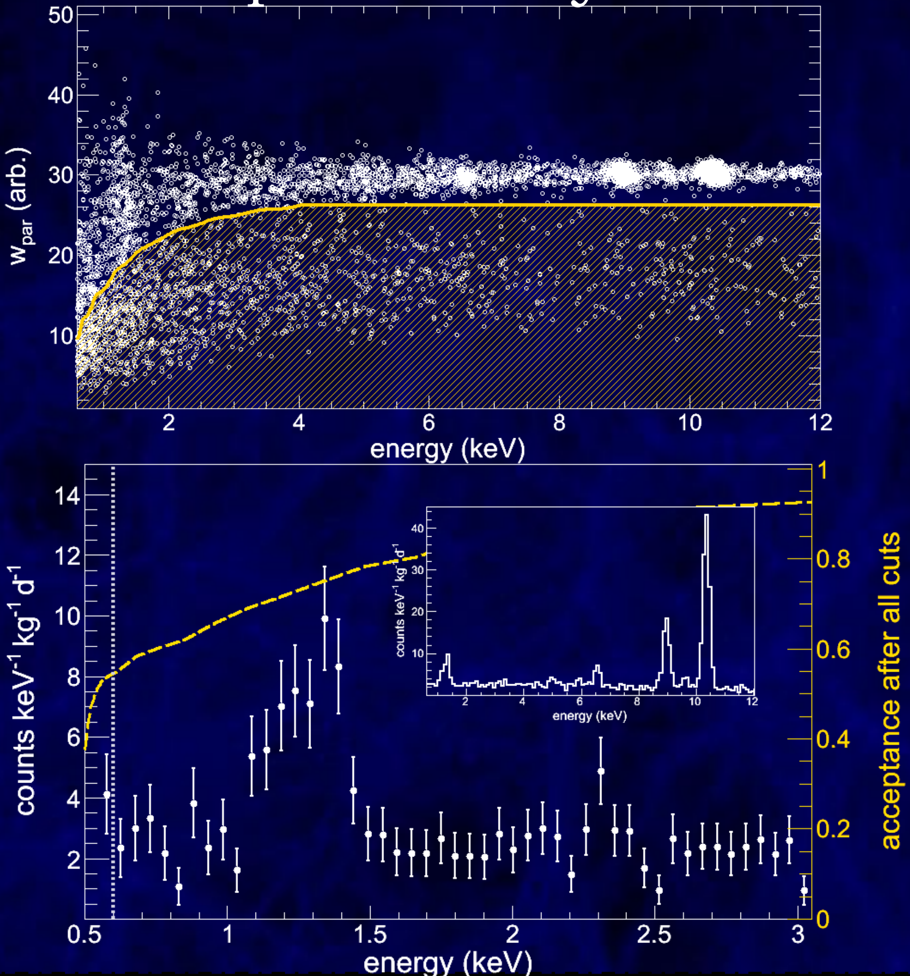
lower limit shifts down
by >10σ !
Still different from zero?

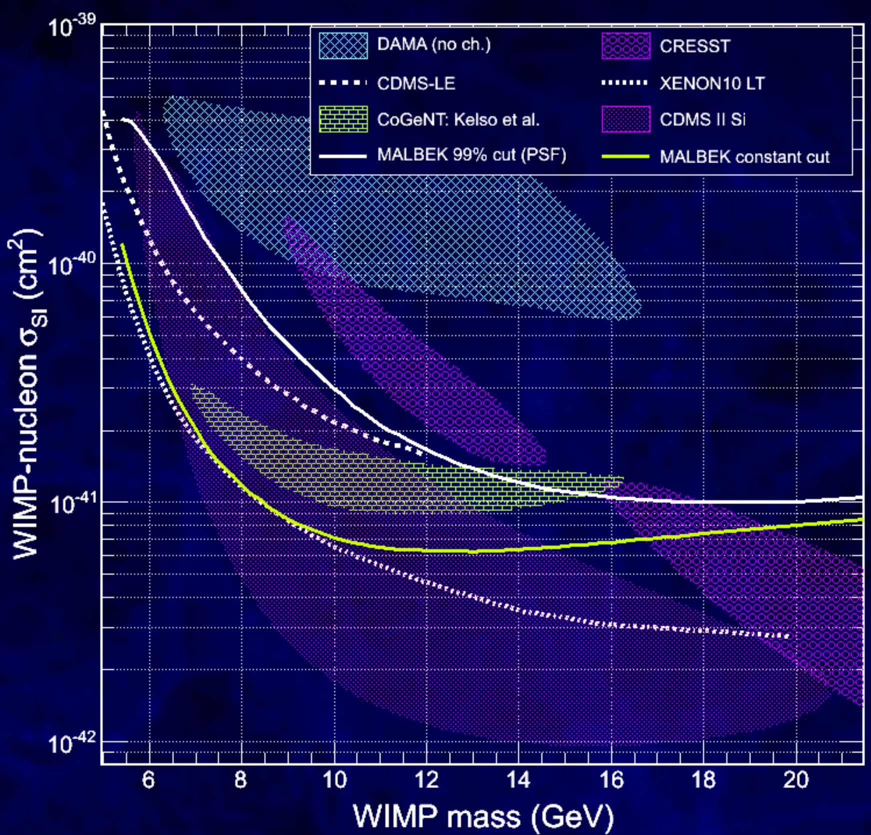
J. Collar, Marina del Rey 2012

arxiv:1002.4703

MALBEK (MAJORANA)

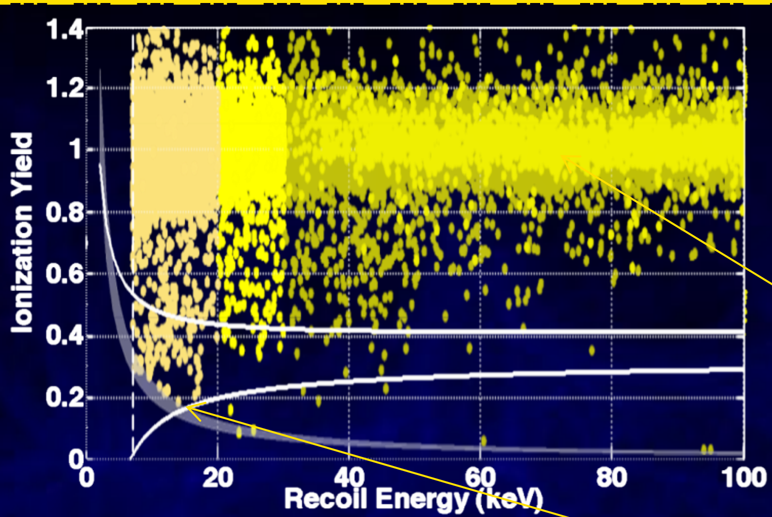
- p-type point contact Ge detectors (like CoGeNT)
- here: preliminary results





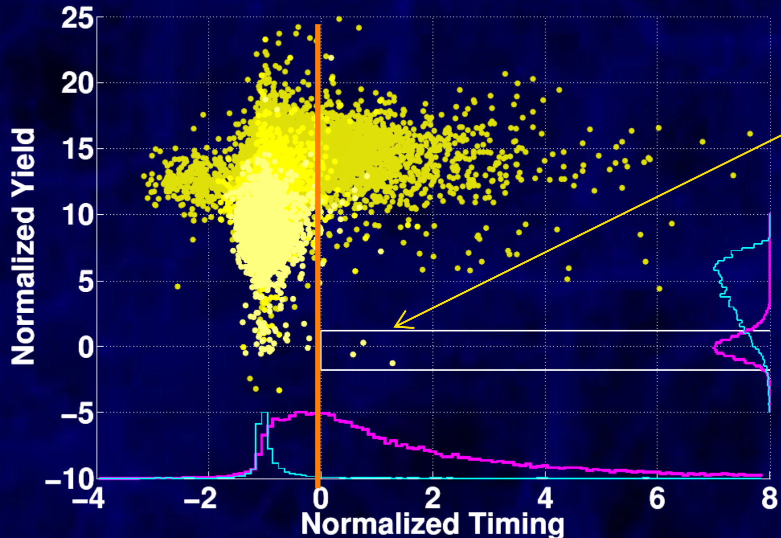
G. Giovanetti, TAUP 2013

CDMS-II Silicon Results 2013



140 kg days shown here
also another data set
with 56 kg days & 0 events

background



signal

3 events observed

expected $0.4^{+0.2}_{-0.1}(\mathrm{stat})^{+0.4}_{-0.2}(\mathrm{sys})$

statistically significant?

origin of signal?

arXiv:1304.4279