Lorentz center

Noncommutative Geometry and Particle Physics

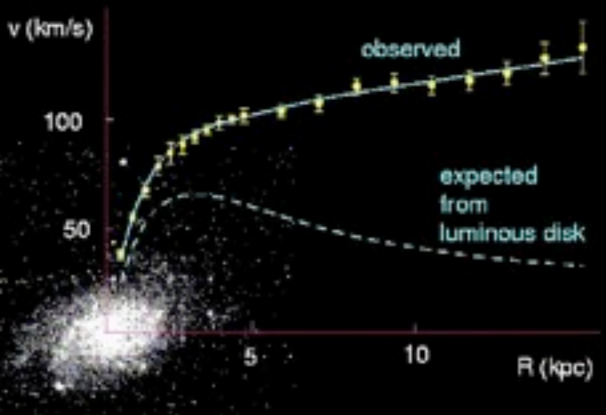
Workshop: 14 – 18 October 2013, Leiden, the Netherlands

Dark Matter Searches

Patrick Decowski
decowski@nikhef.nl

NIKHEF

Much Astronomical Evidence for DM



Rotational Curves

Galaxy Clusters

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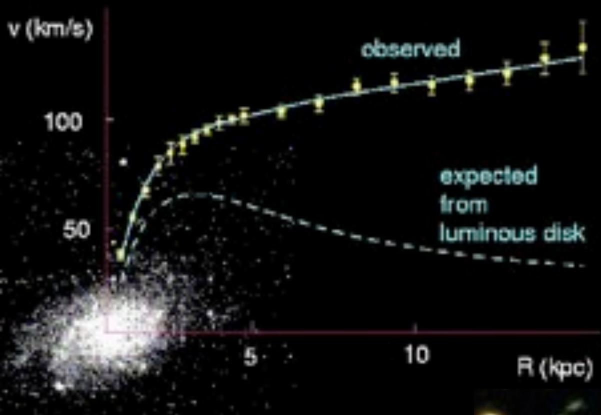

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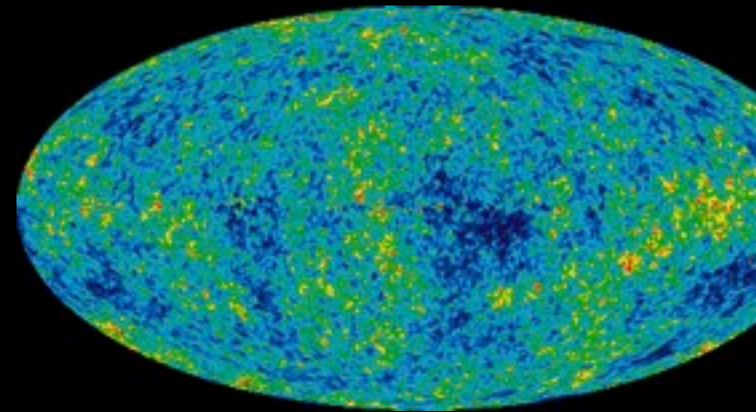
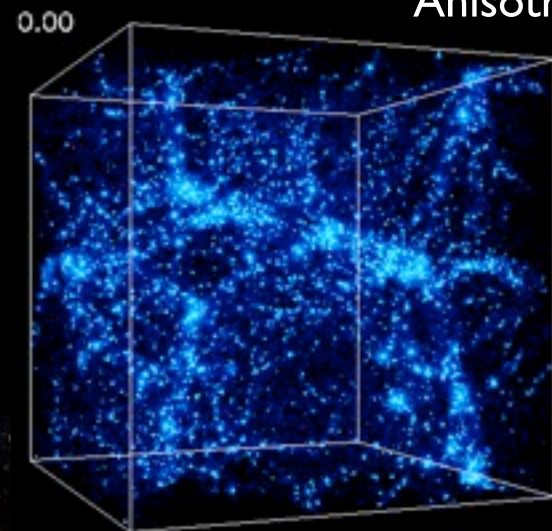


Anisotropy in CMB

Weak Lensing

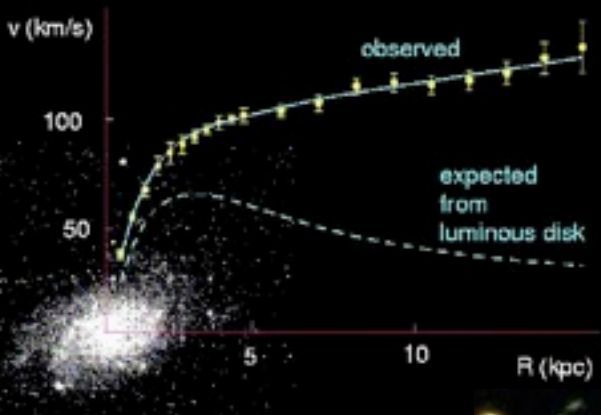


Large Scale Structure

Galaxy Clusters

Much Astronomical Evidence for DM

At **all** scales in the Universe!



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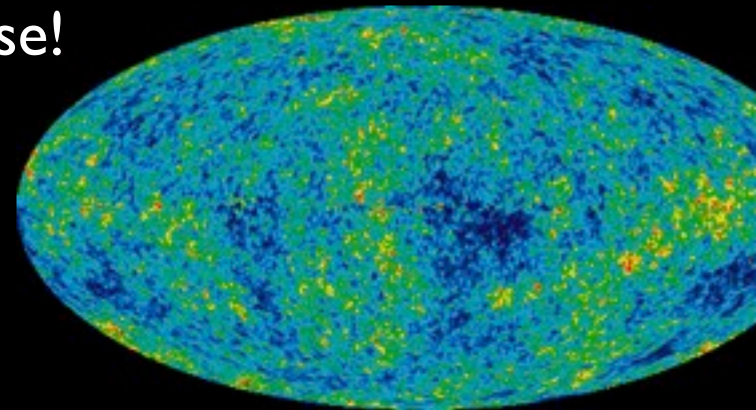

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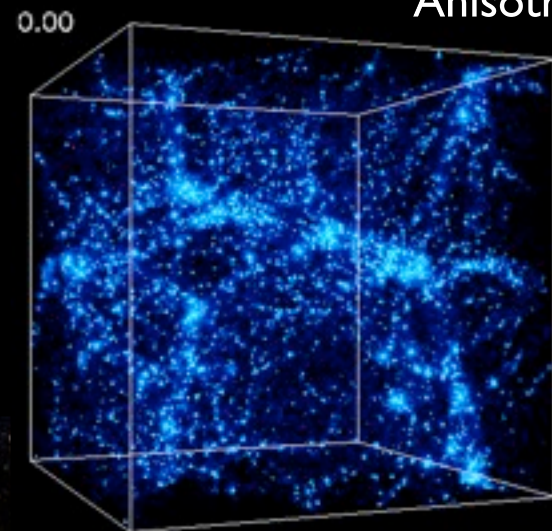
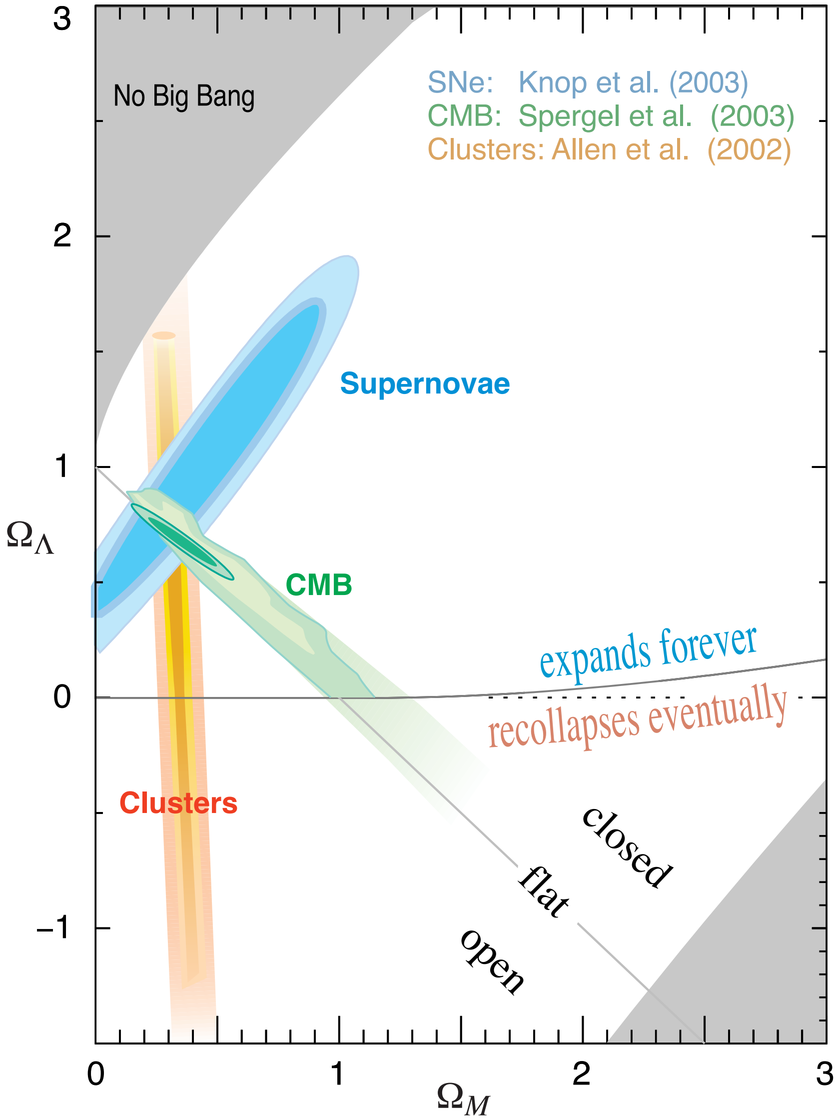
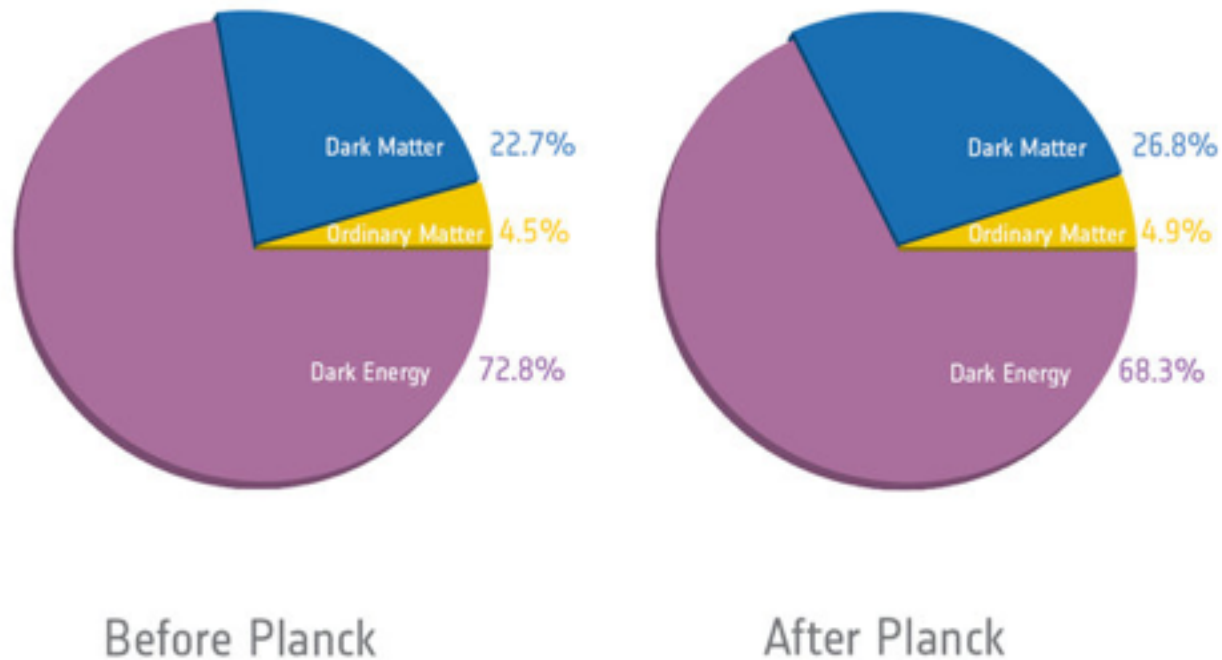


Large Scale Structure

Galaxy Clusters

Dark Matter and Cosmology

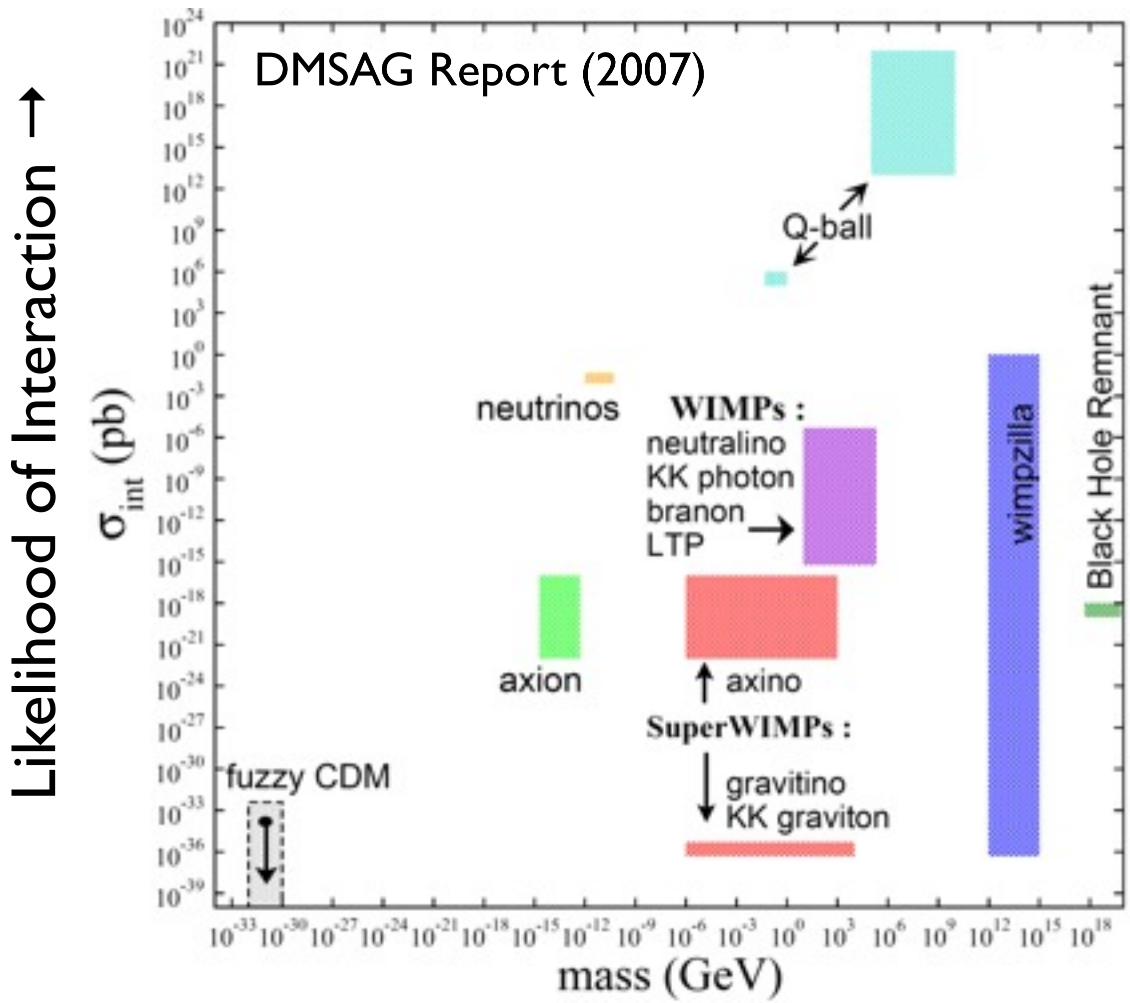




...but what is it made off?

Some DM Candidates

Many candidates, usually some extension of the Standard Model



“10-point test” of DM candidates

Appropriate relic density?
Is it cold?
Is it neutral?
Consistent with BBN?
Leaves stellar evol. unchgnd?
Compat. with self-interactions?
Consist. with direct DM searches?
Consist. with gamma-ray constr.?
Consist. with other astro. constr.?
Can it be probed exp.?

DM candidate	**I.** Ωh^2	**II.** Cold	**III.** Neutral	**IV.** BBN	**V.** Stars	**VI.** Self	**VII.** Direct	**VIII.** γ-rays	**IX.** Astro	**X.** Probed	**Result**
SM Neutrinos	×	×	✓	✓	✓	✓	✓	–	–	✓	×
Sterile Neutrinos	~	~	✓	✓	✓	✓	✓	✓	✓!	✓	~
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	~
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	~	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
B^1 **UED**	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (Little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

M. Taoso, G.Bertone, A.Masiero, JCAP 0803:022,2008

√ =OK | ~ =Still viable | × = NO

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Gravitino	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	~
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Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
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Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

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Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
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First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
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Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

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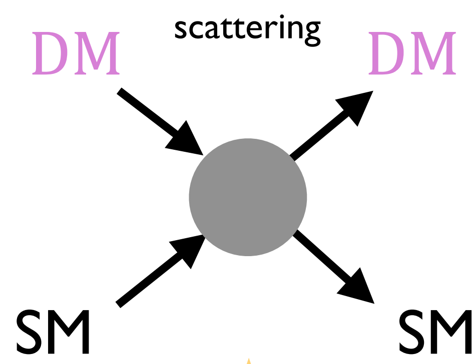
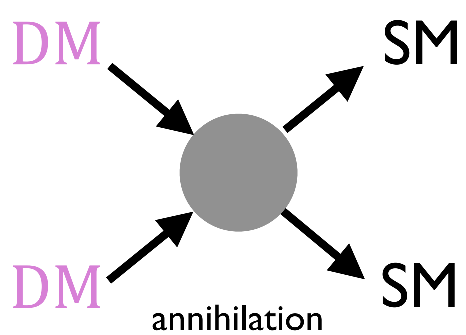
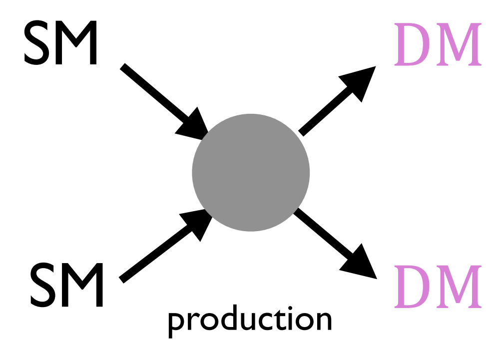
Three ways to find Particle Dark Matter



Three different ways how Dark Matter particles may interact with ordinary Matter





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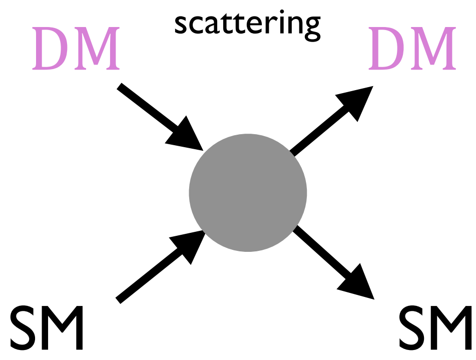
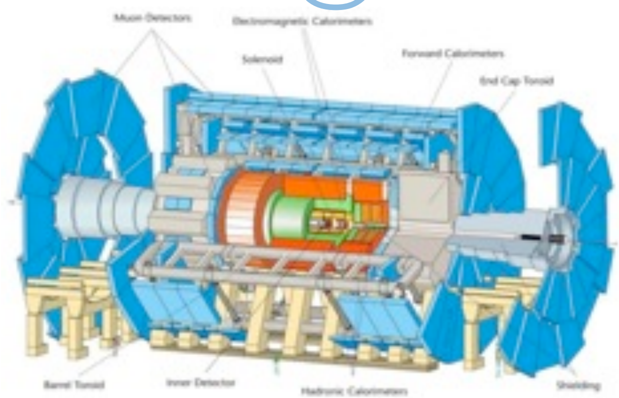
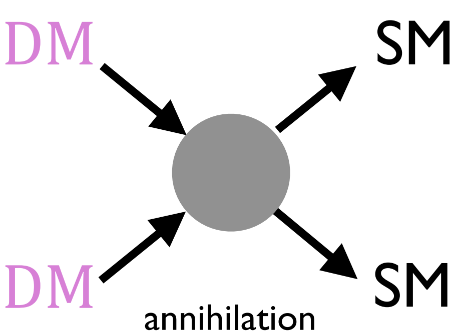


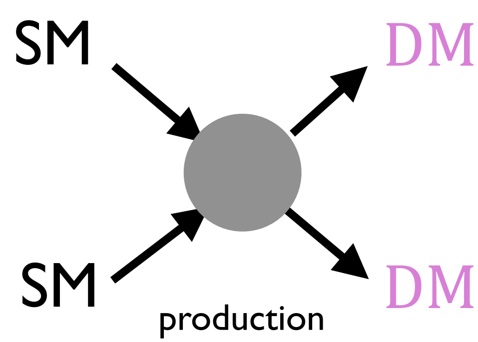
XENON

DM @ LHC

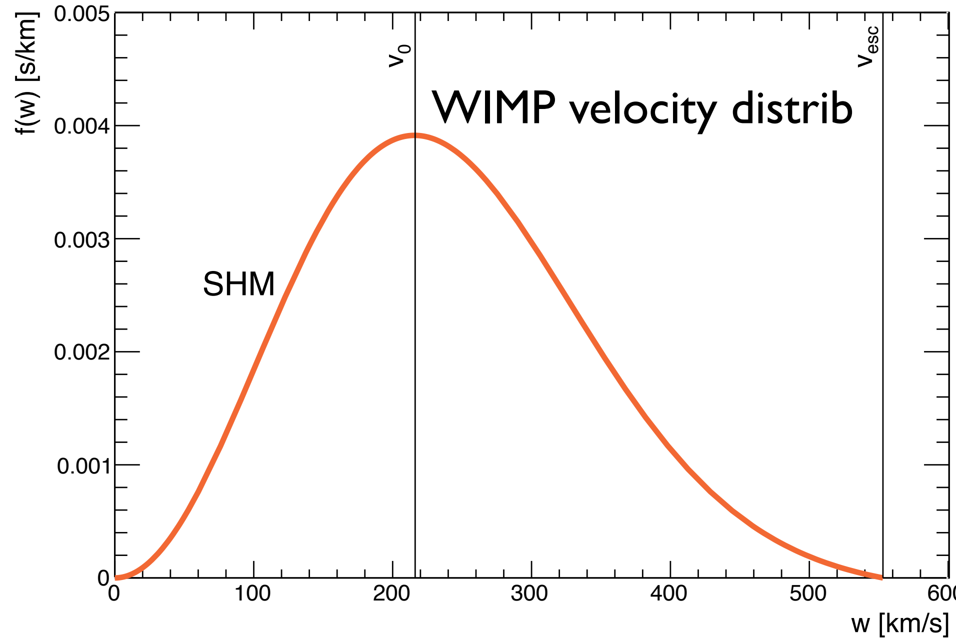




FERMI Satellite

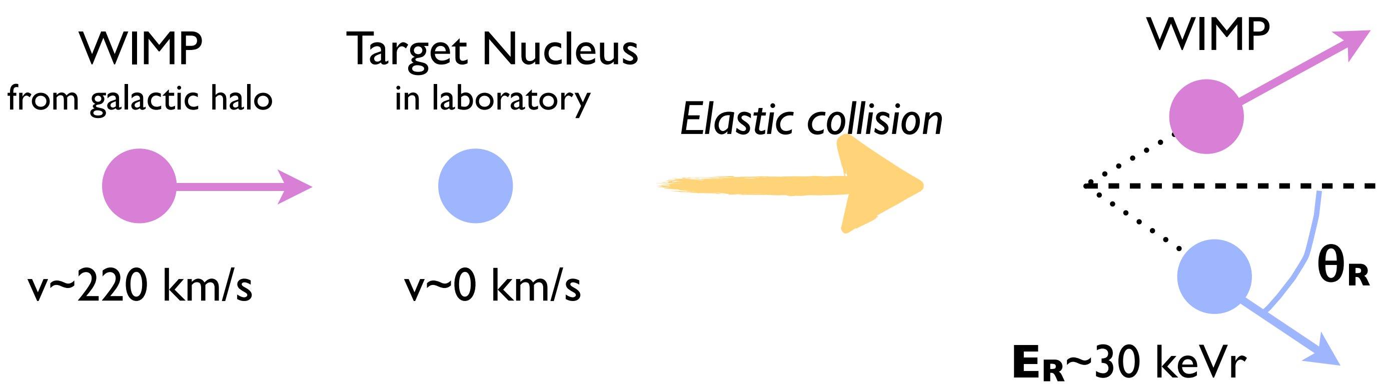


Preliminaries



Assume WIMP is not only gravitationally interacting

M. W. Goodman and E. Witten, Phys. Rev. D 31, 3059 (1985).



$$E_R = \frac{\mu^2 v^2}{m_T}(1 - \cos\theta)$$

$$v_{\min} = \sqrt{\frac{m_T E_{th}}{2\mu^2}}$$

Preliminaries II

We measure:

$$\frac{dR(t)}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \frac{d\sigma}{dE_R} v f(v, v_e(t))$$

with scalar (SI) and axial-vector (SD) couplings:

$$\frac{d\sigma}{dE_R} = \frac{m_T}{2\mu^2 v^2} \left[\sigma_{SI} F_{SI}^2(E_R) + \sigma_{SD} F_{SD}^2(E_R)\right]$$

WIMP-nucleus cross sections:

$$\sigma_{SI} = \frac{4\mu^2}{\pi} \left[Z f_p + (A - Z) f_n\right]^2 \propto A^2$$

Better sensitivity with high A

$$\sigma_{SD} = \frac{32\mu^2}{\pi} G_F^2 \frac{J+1}{J} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2$$

Need nucleus with spin:

^{19}F, ^{23}Na, ^{73}Ge, ^{127}I, ^{129}Xe, ^{131}Xe, ^{133}Cs (but no Ar!)

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Need input from Astrophysics

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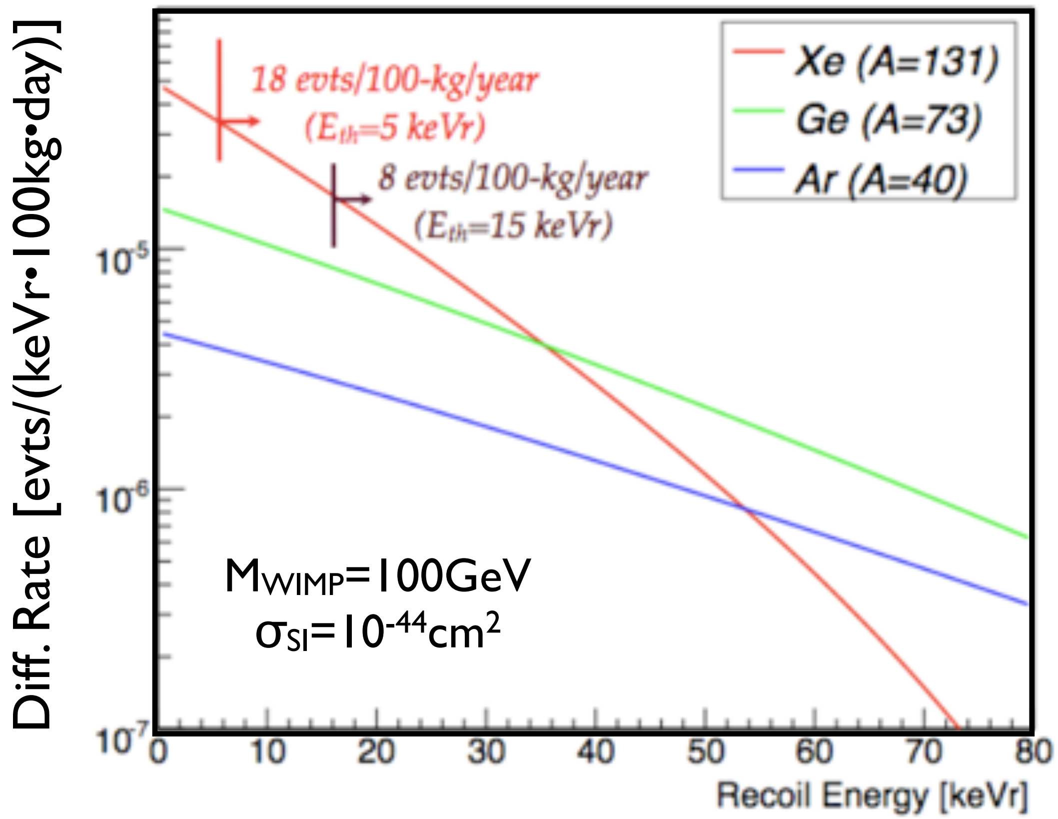
Expected Energy Spectrum

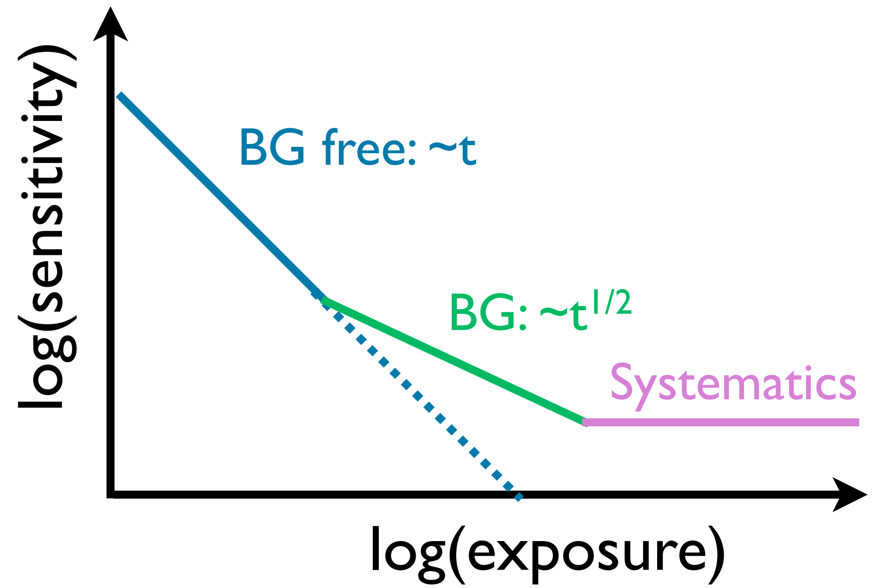
WIMP Scatt. Rates per 100kg per day
for different targets (Xe, Ge, Ar)



- Elastic collisions with nuclei
  - WIMP velocity ~10^{-3}c
- Energy of recoiling nucleus is tiny : <50 keV
- Rates are uncertain, since they depend on model
- Spectrum is featureless (no peaks)

Minimizing Backgrounds

- Critical aspect of any rare event search - minimize backgrounds!
- Purity of materials
  - Copper, germanium, xenon among the cleanest with no natural occurring long-lived isotopes
  - Ancient lead, if free of ^{210}Pb
- Shielding
  - External U/Th/K backgrounds
- Krypton and Radon mitigation
- Material handling and assaying
  - Surface preparation, cosmic activation
- Underground siting and active veto
  - Avoid muon-induced neutrons
- Detector-based discrimination



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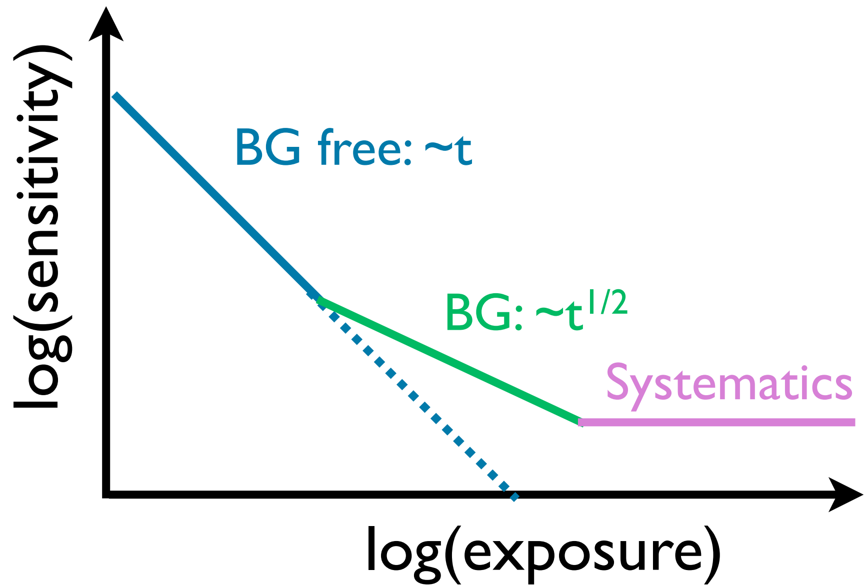
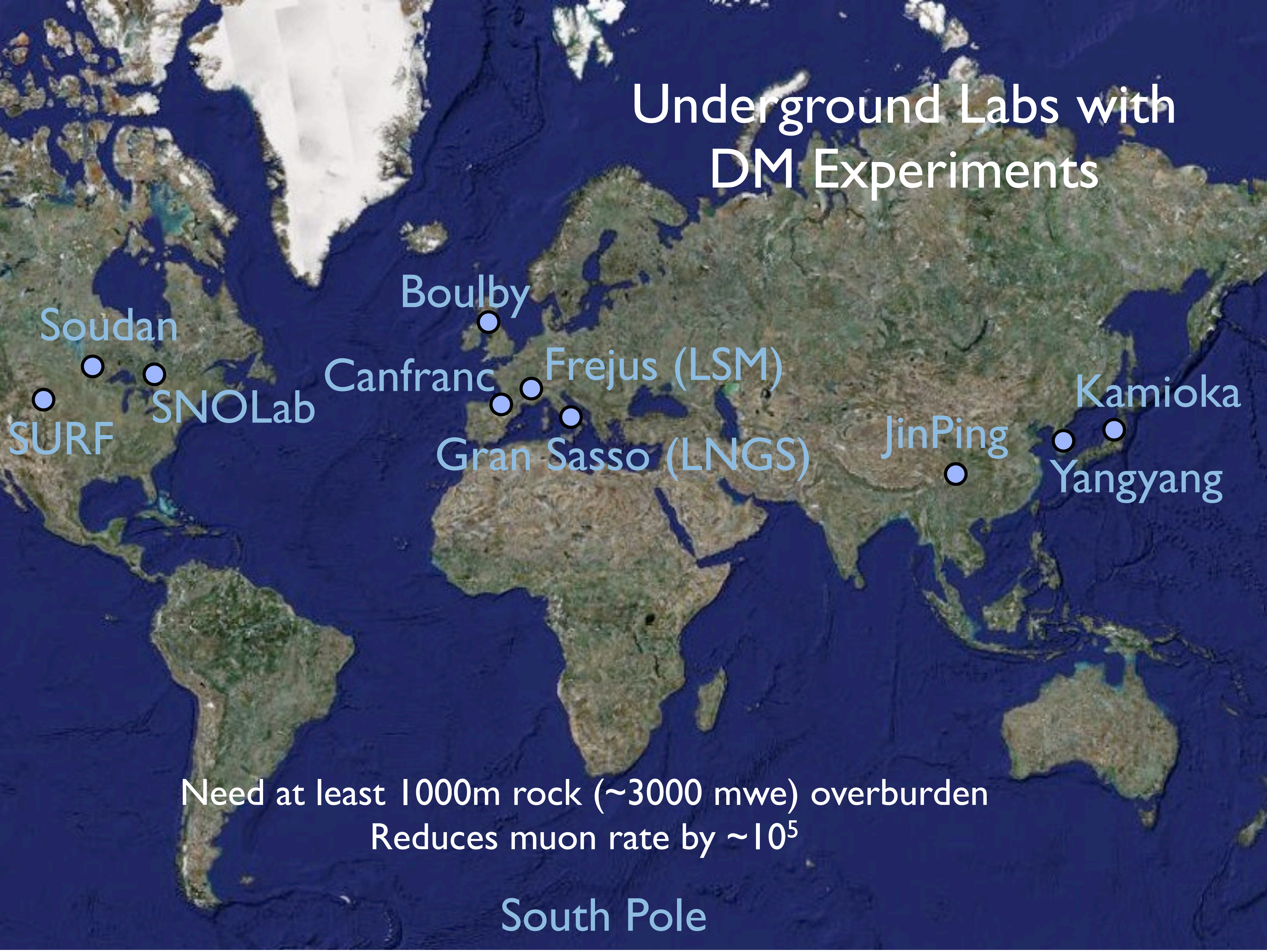
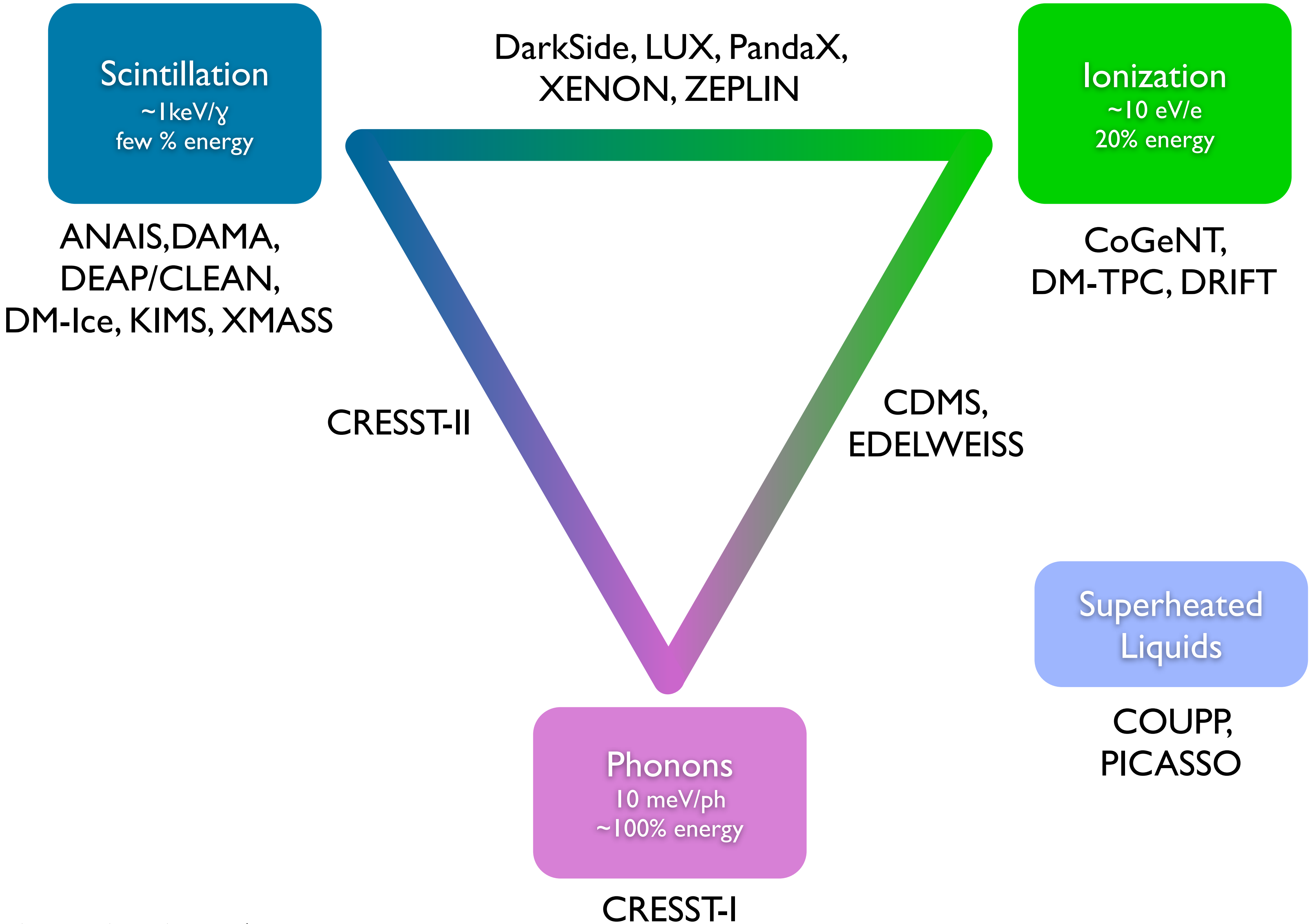


Current state-of-the-art: <1 ev/(kg·yr)
Moving to: 1 ev/(ton·yr)


Underground Labs with
DM Experiments
Boulby
Soudan
SNOLab
SURF
Canfranc
Frejus (LSM)
Gran Sasso (LNGS)
JinPing
Kamioka
Yangyang
Need at least 1000m rock (~3000 mwe) overburden
Reduces muon rate by ~10^5
South Pole

Detection Techniques



Particle-dependent Response

CDMS, CRESST, DarkSide, LUX, XENON etc.

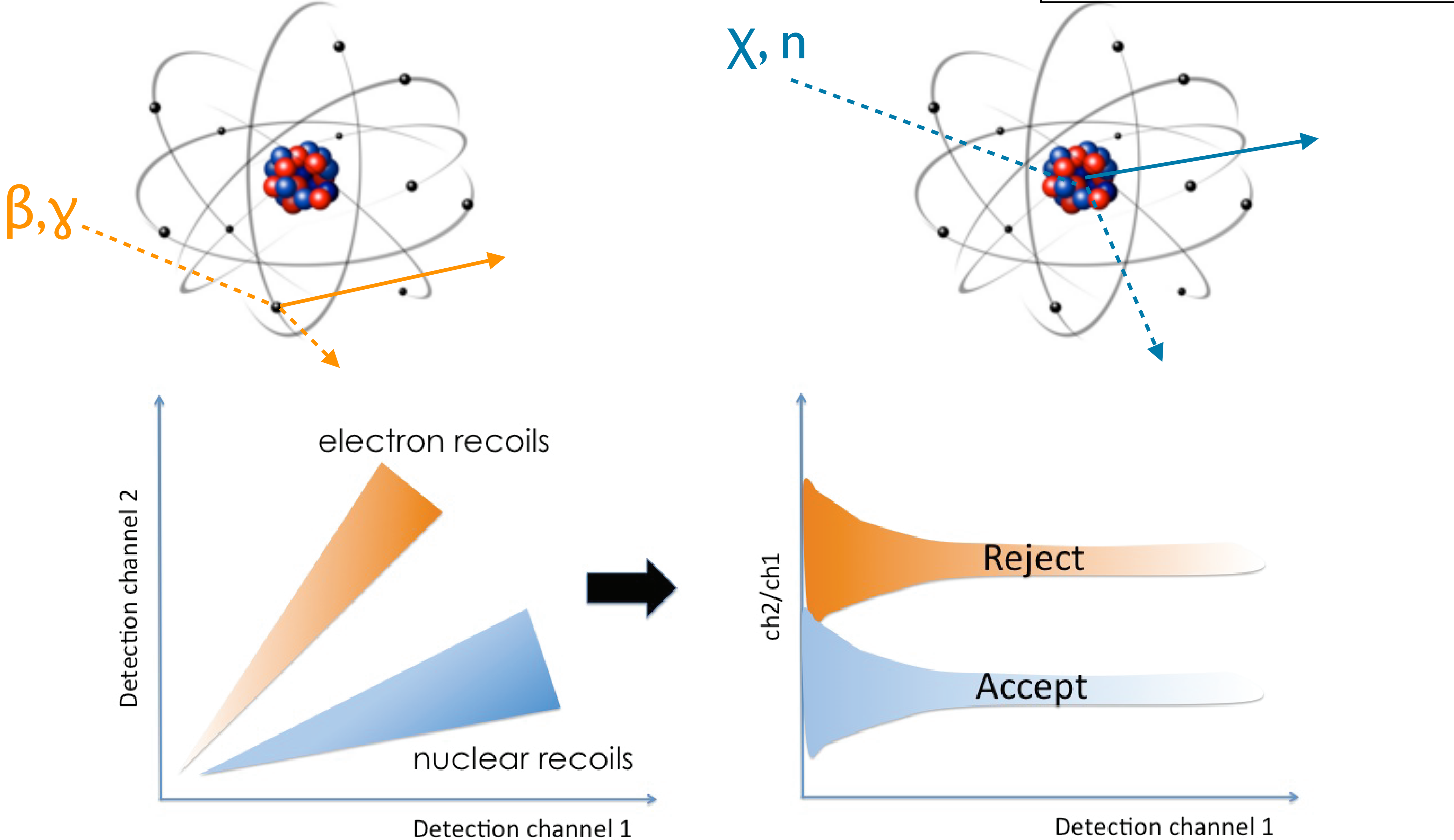


Image E.Pantic

Current Dark Matter Search Status

- Claims
  - **DAMA**: Annual modulations - long-time claim
    - Community is sceptical: something is modulating, but not DM
  - **CRESST-II**: More events than expected from background
  - **CDMS-Si**: 3 events when 0.7 BG events were expected
  - **CoGeNT**: Low energy spectrum has unexpected feature; annual modulation
- Exclusions
  - **XENON100**: excludes virtually all the above signals, some of them by large margins
  - **CDMS-Ge / CDMSlite**: excludes most of the above signals
  - **Others** (e.g. COUPP, EDELWEISS, ZEPLIN-III, SIMPLE): exclude most above signals

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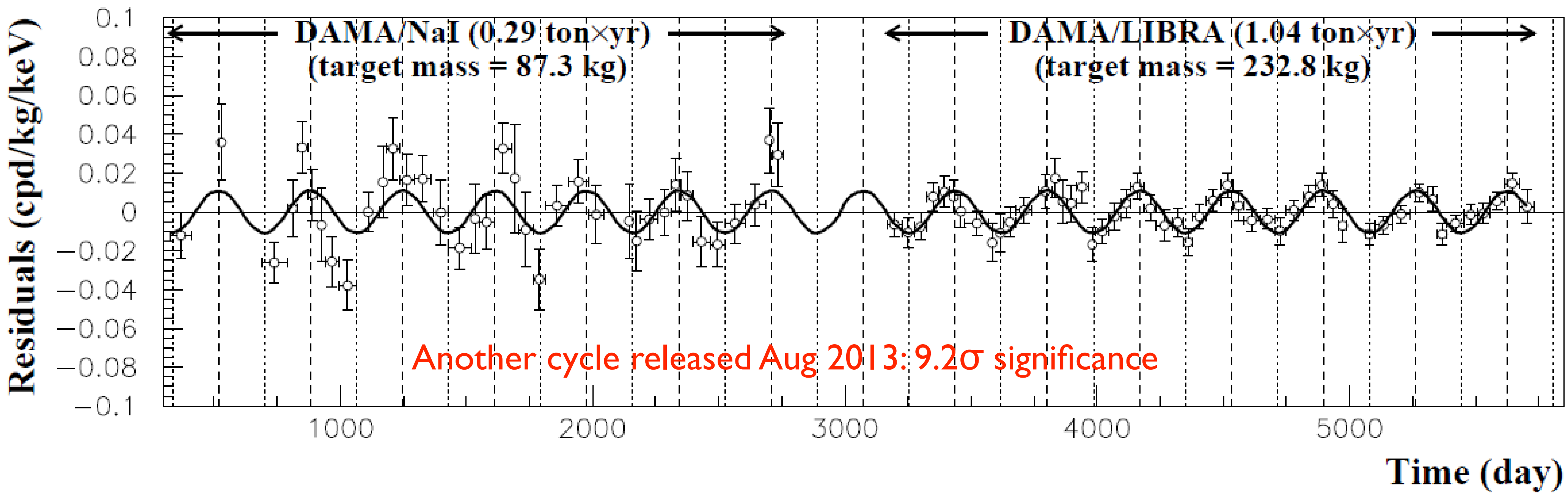
Modulation present in 2-6 keV, absent above 6 keV



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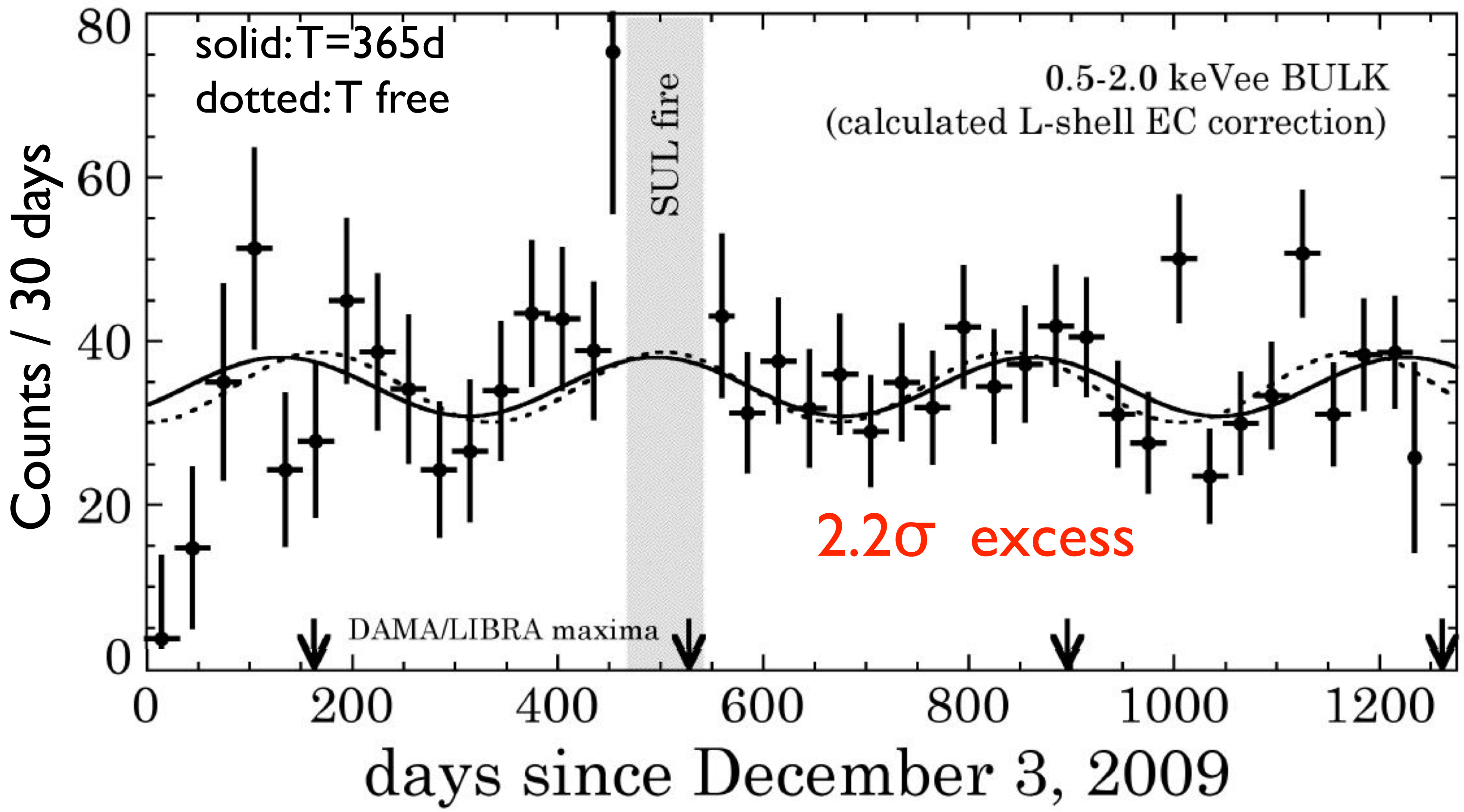
    - **XENON100**: excludes virtually all the above signals, some of them by large margins
    - **CDMS-Ge / CDMSlite**: excludes most of the above signals
    - **Others** (e.g. COUPP, EDELWEISS, ZEPLIN-III, SIMPLE): exclude most above signals

Current Dark Matter Search Status

- Claims

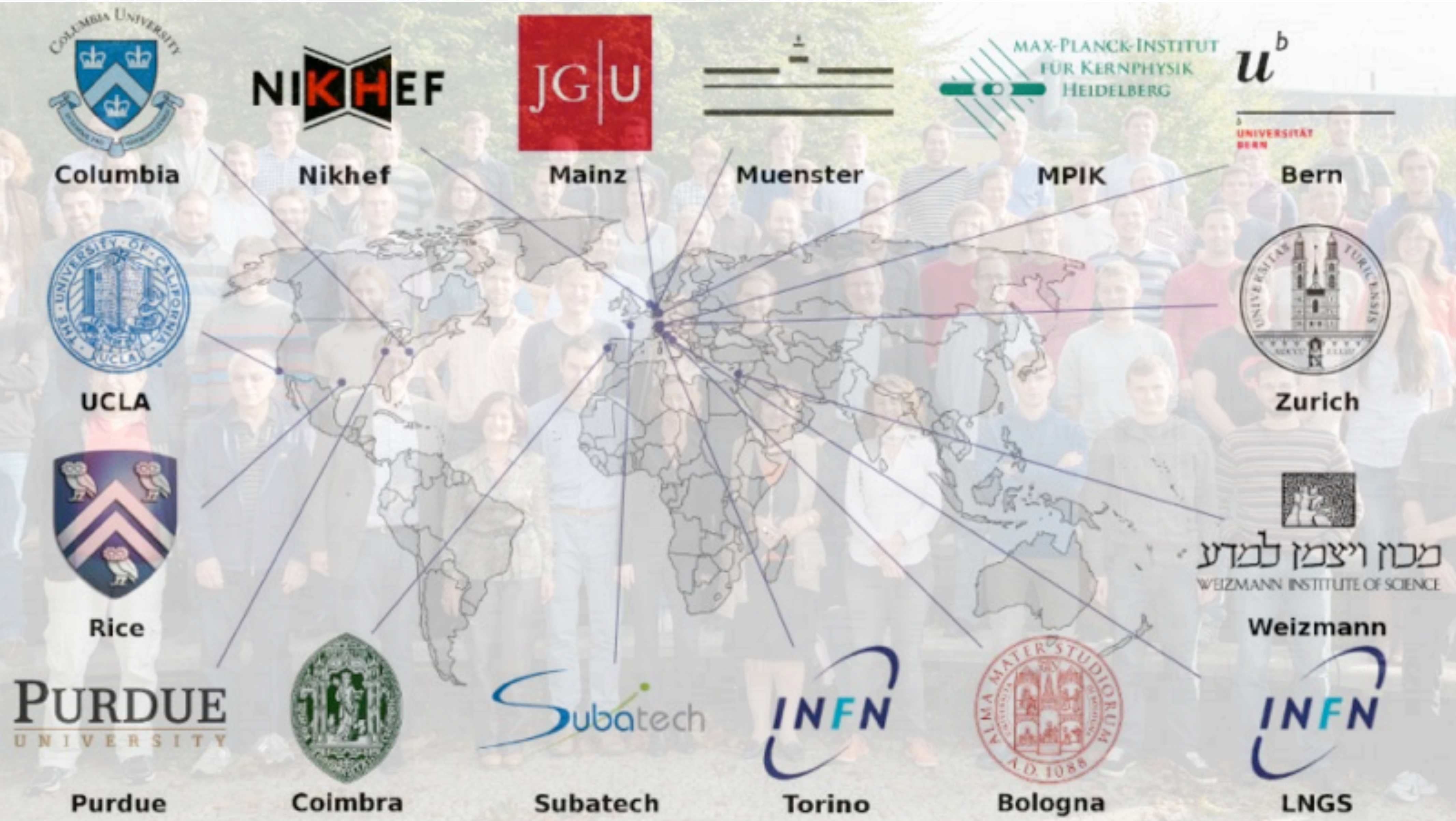
CoGeNT results presented at TAUP2013: ~2.5x more data



Current Dark Matter Search Status

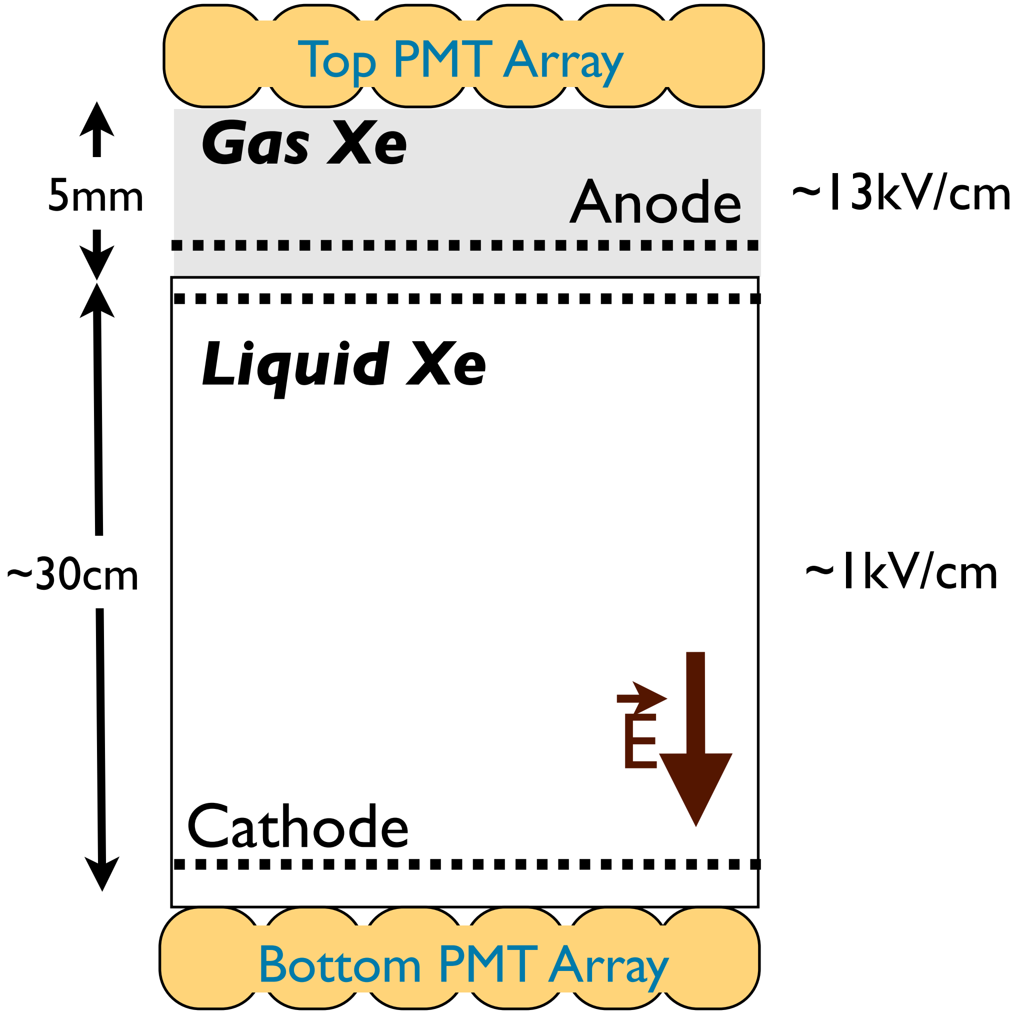
- Claims
  - **DAMA**: Annual modulations - long-time claim
    - Community is sceptical: something is modulating, but not DM
  - **CRESST-II**: More events than expected from background
  - **CDMS-Si**: 3 events when 0.7 BG events were expected
  - **CoGeNT**: Low energy spectrum has unexpected feature; annual modulation
- Exclusions
  - **XENON100**: excludes virtually all the above signals, some of them by large margins
  - **CDMS-Ge / CDMSlite**: excludes most of the above signals
  - **Others** (e.g. COUPP, EDELWEISS, ZEPLIN-III, SIMPLE): exclude most above signals

XENON Collaboration

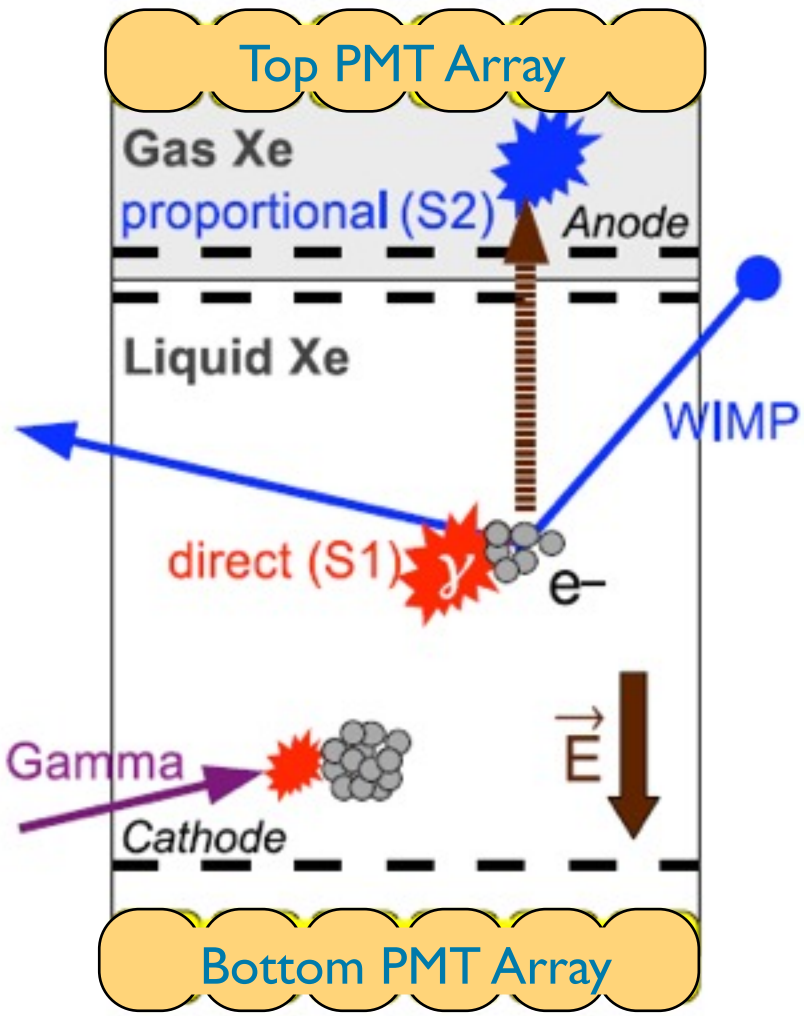


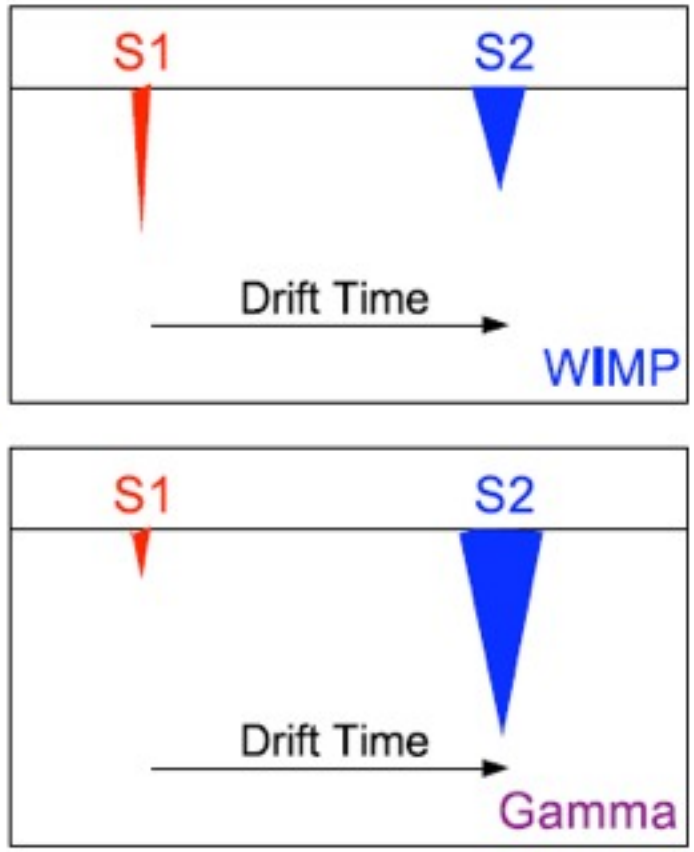
XENON10, XENON100, XENON1T, XENONnT

Dual-Phase Xe TPC



Detection Properties





Signal:
Nuclear recoil

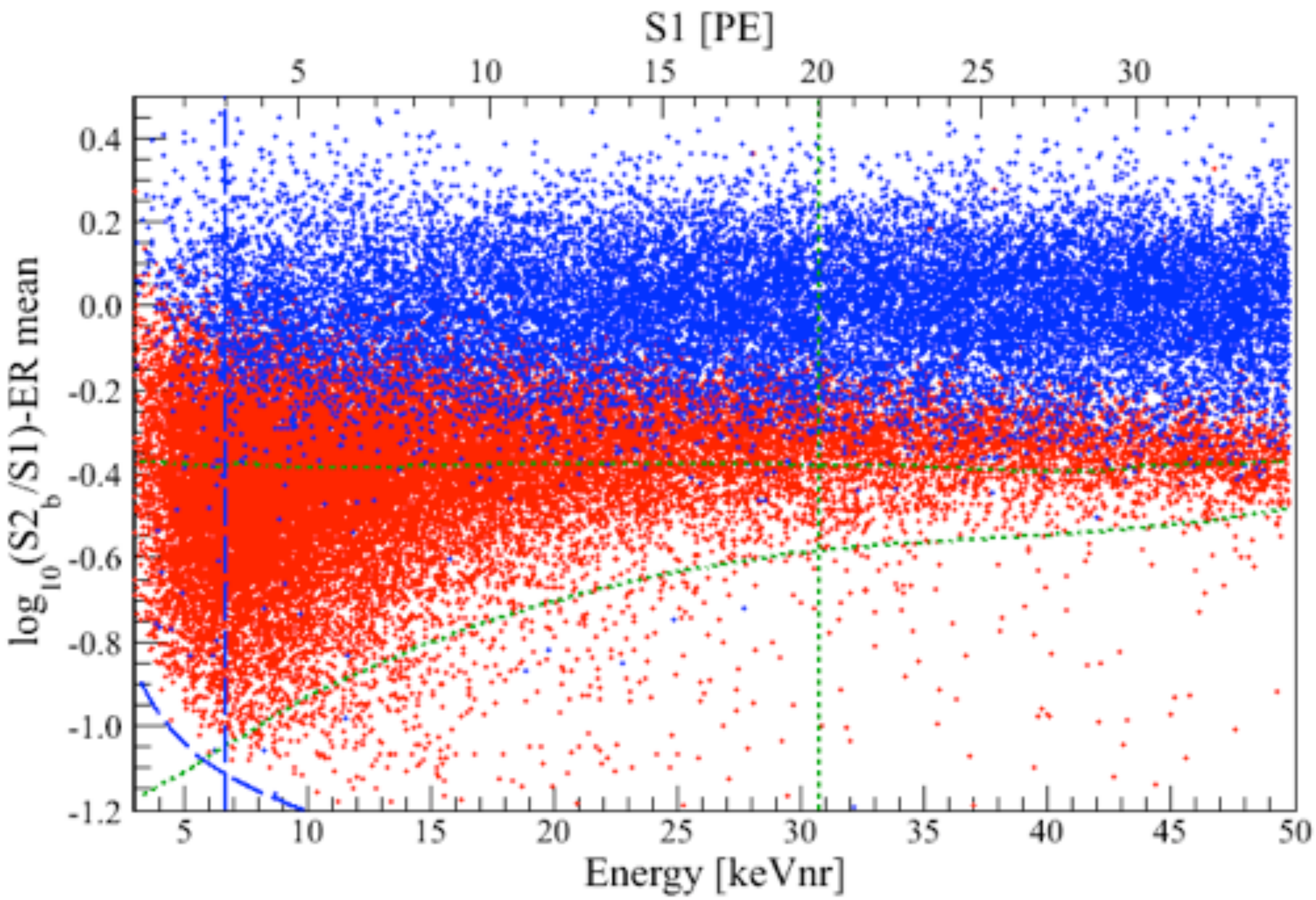
Background:
Electron recoil

$(S2/S1)_{WIMP} \ll (S2/S1)_{Gamma}$

Discriminating Nuclear from Electron Recoils

Using dedicated radioactive source runs

ER vs NR discr. Parameter



BG-like

^{60}Co & ^{232}Th:

γ-source

Signal-like

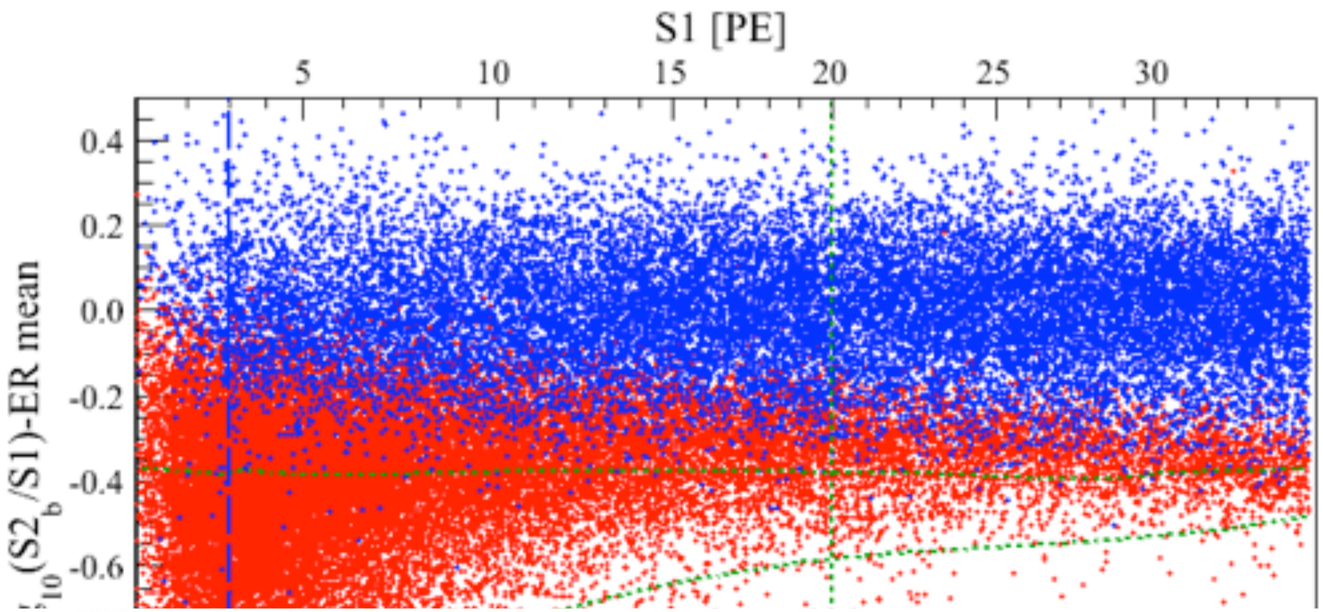
AmBe:

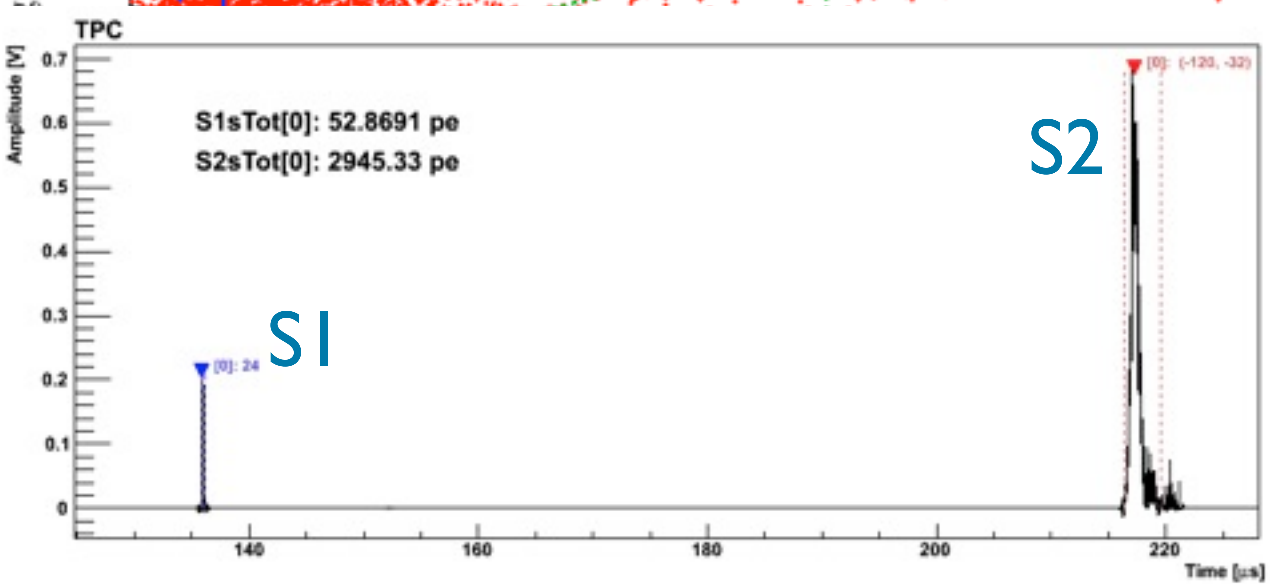
neutron source

Discriminating Nuclear from Electron Recoils

Using dedicated radioactive source runs

ER vs NR discr. Parameter





BG-like

^{60}Co & ^{232}Th:

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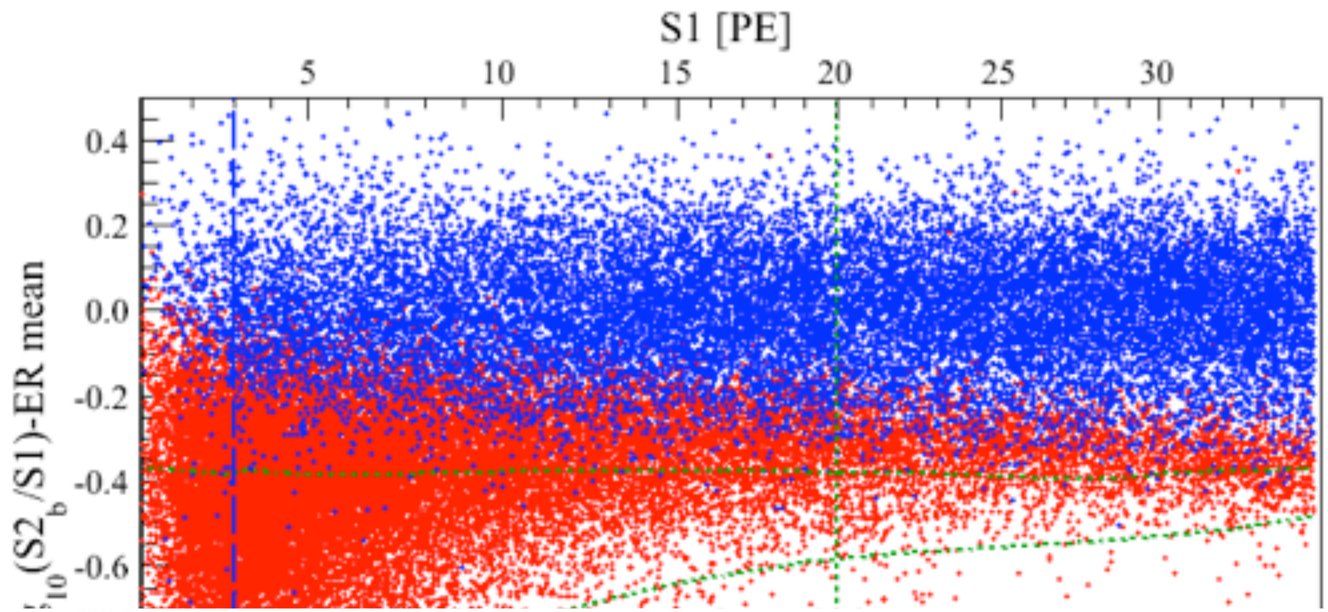
Discriminating Nuclear from Electron Recoils

Using dedicated radioactive source runs

ER vs NR discr. Parameter

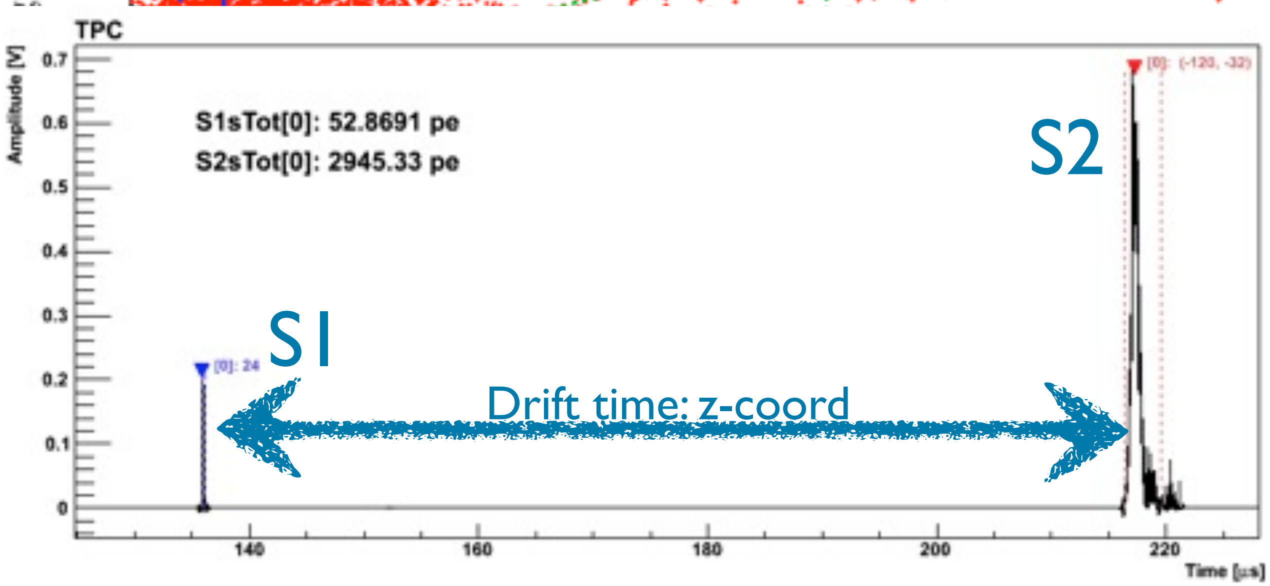


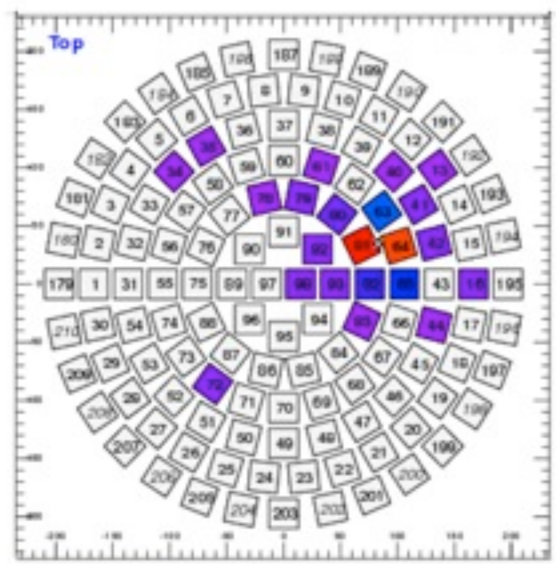
BG-like

^{60}Co & ^{232}Th:

γ-source

Signal-like

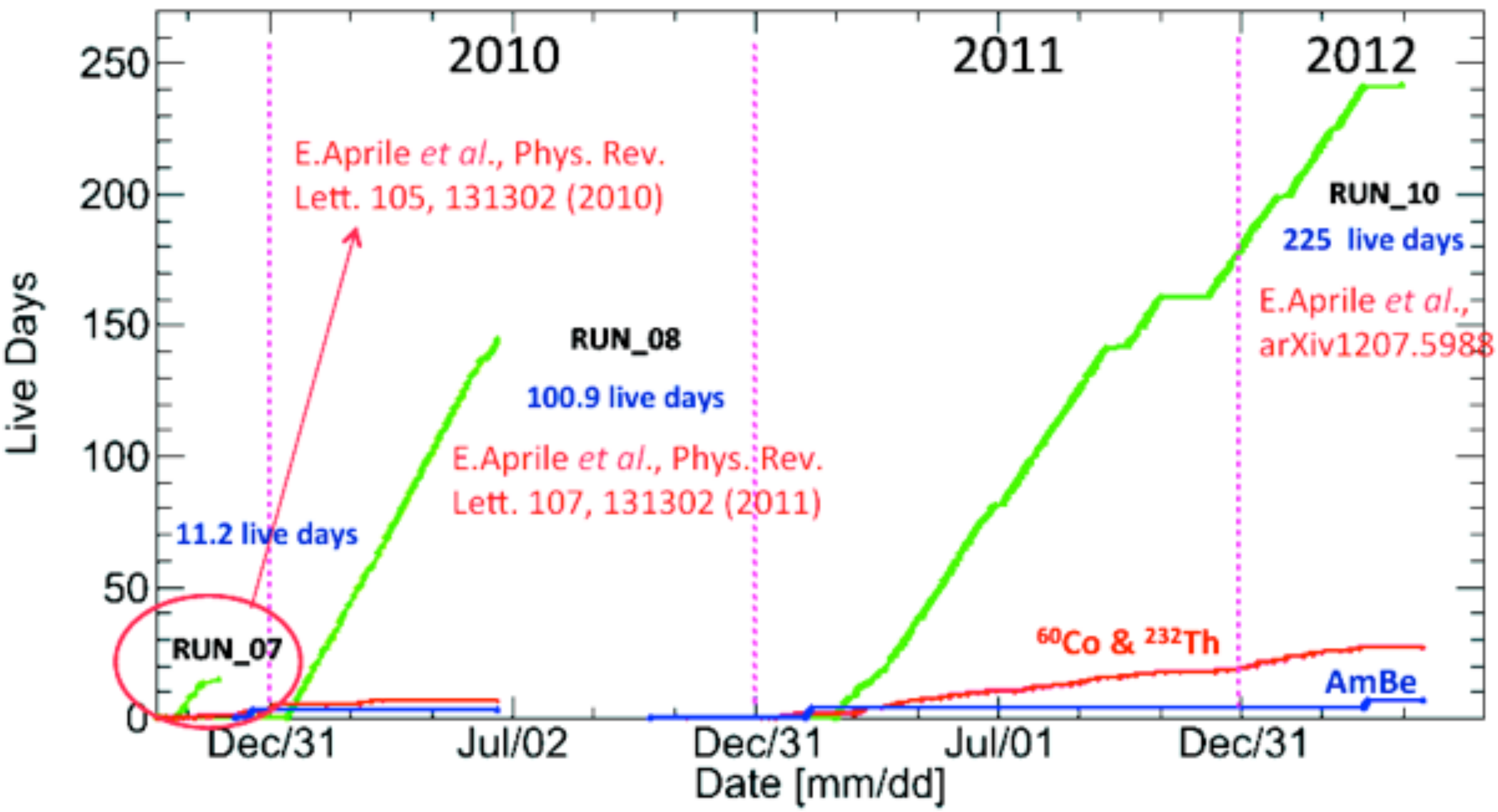




x-y coord

Our Luminosity plot

Regular calibrations are critical

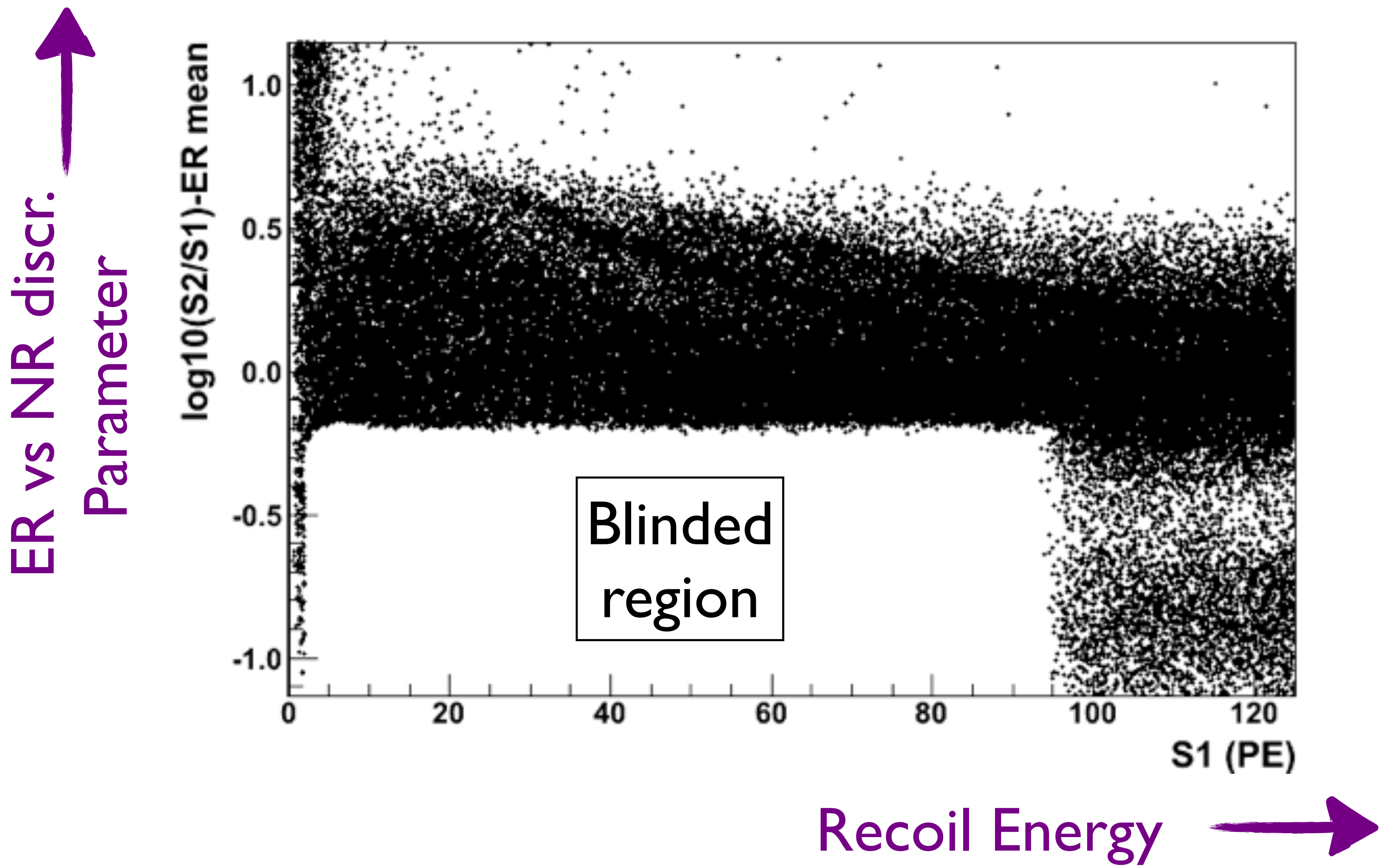


3rd data release from XENON100 - 225 livedays

Patrick Decowski

Analysis Steps

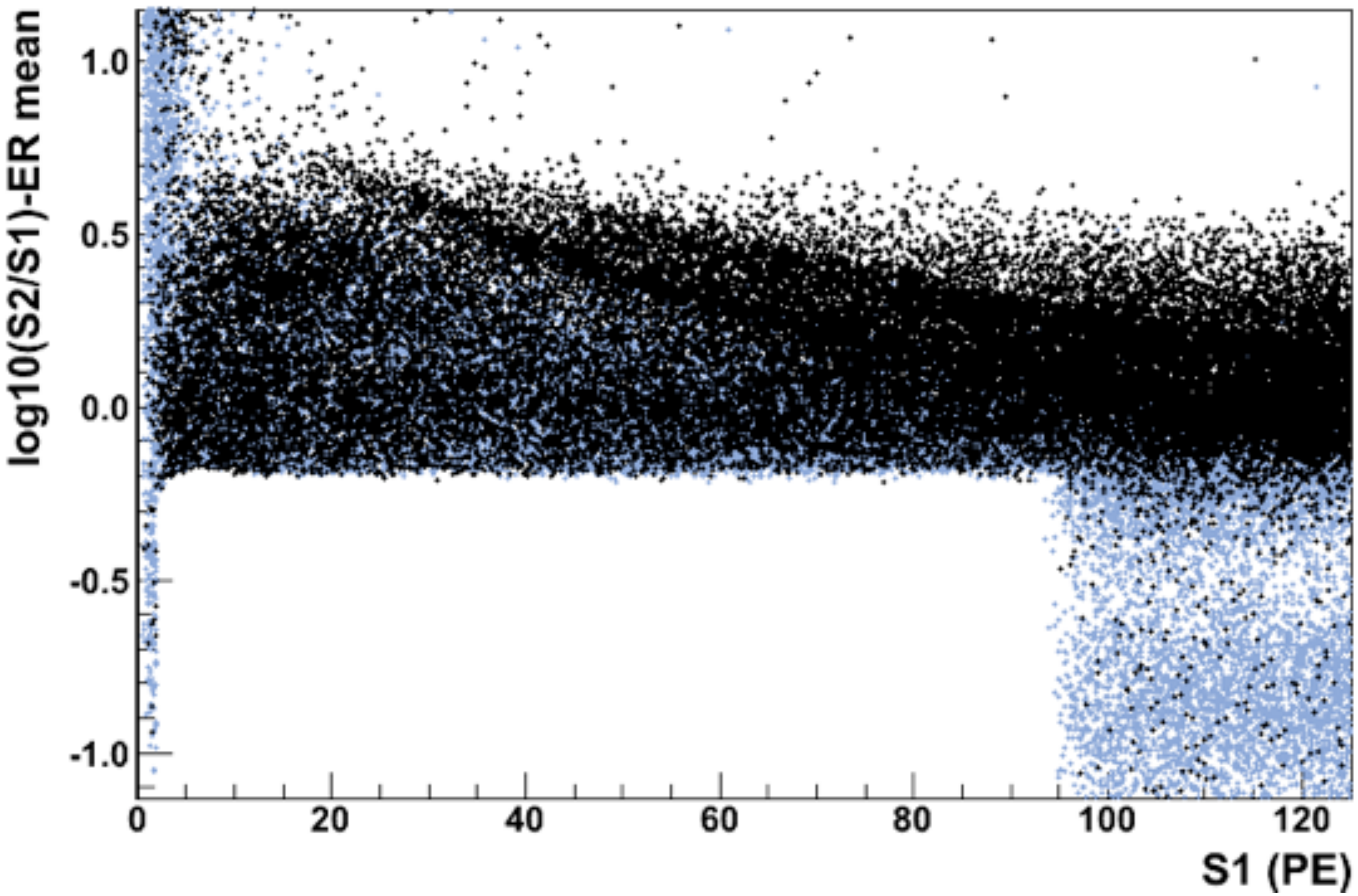
All events in 48kg Fiducial Region



Patrick Decowski

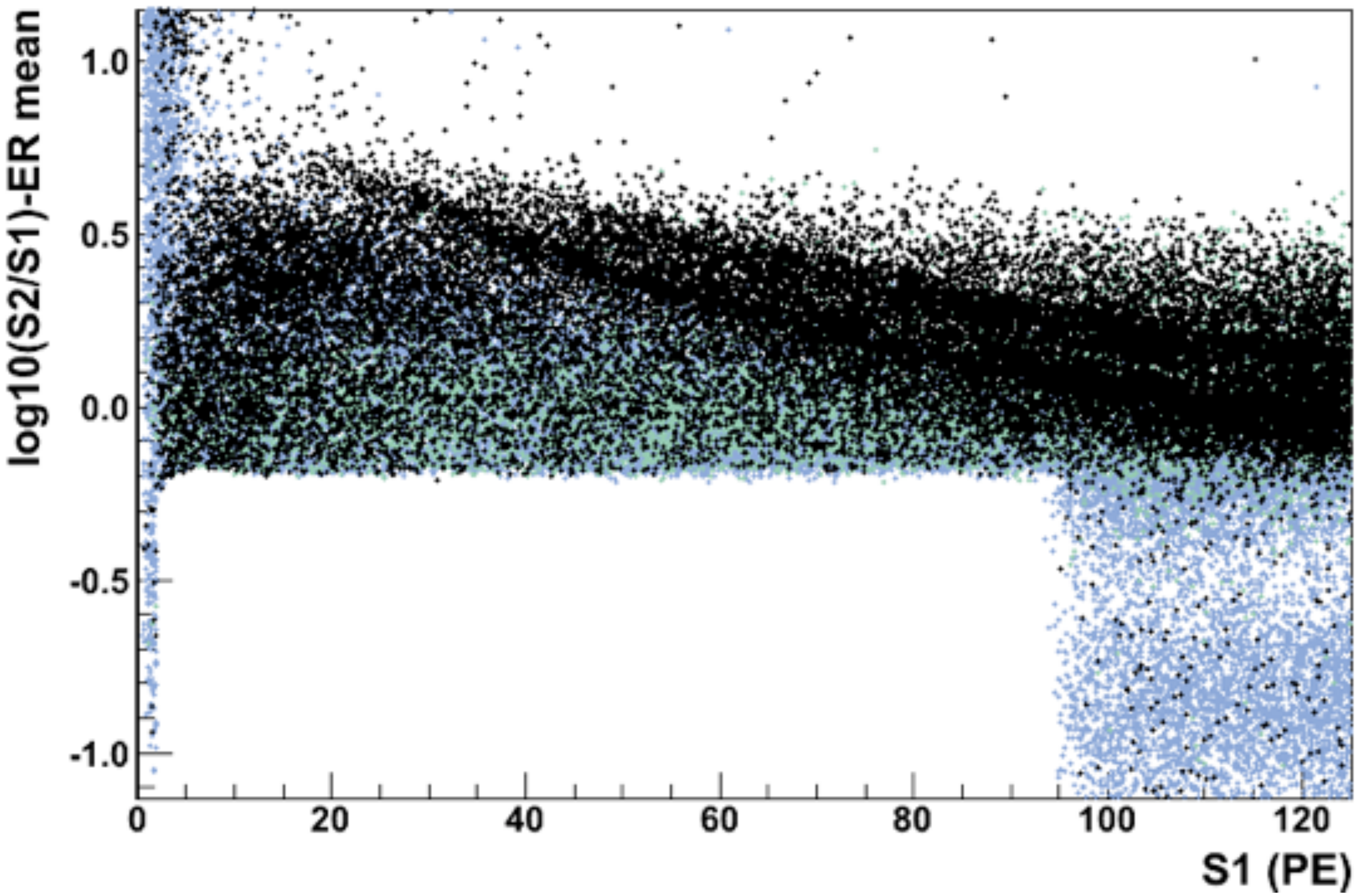
Analysis Steps

Apply basic noise cuts



Analysis Steps

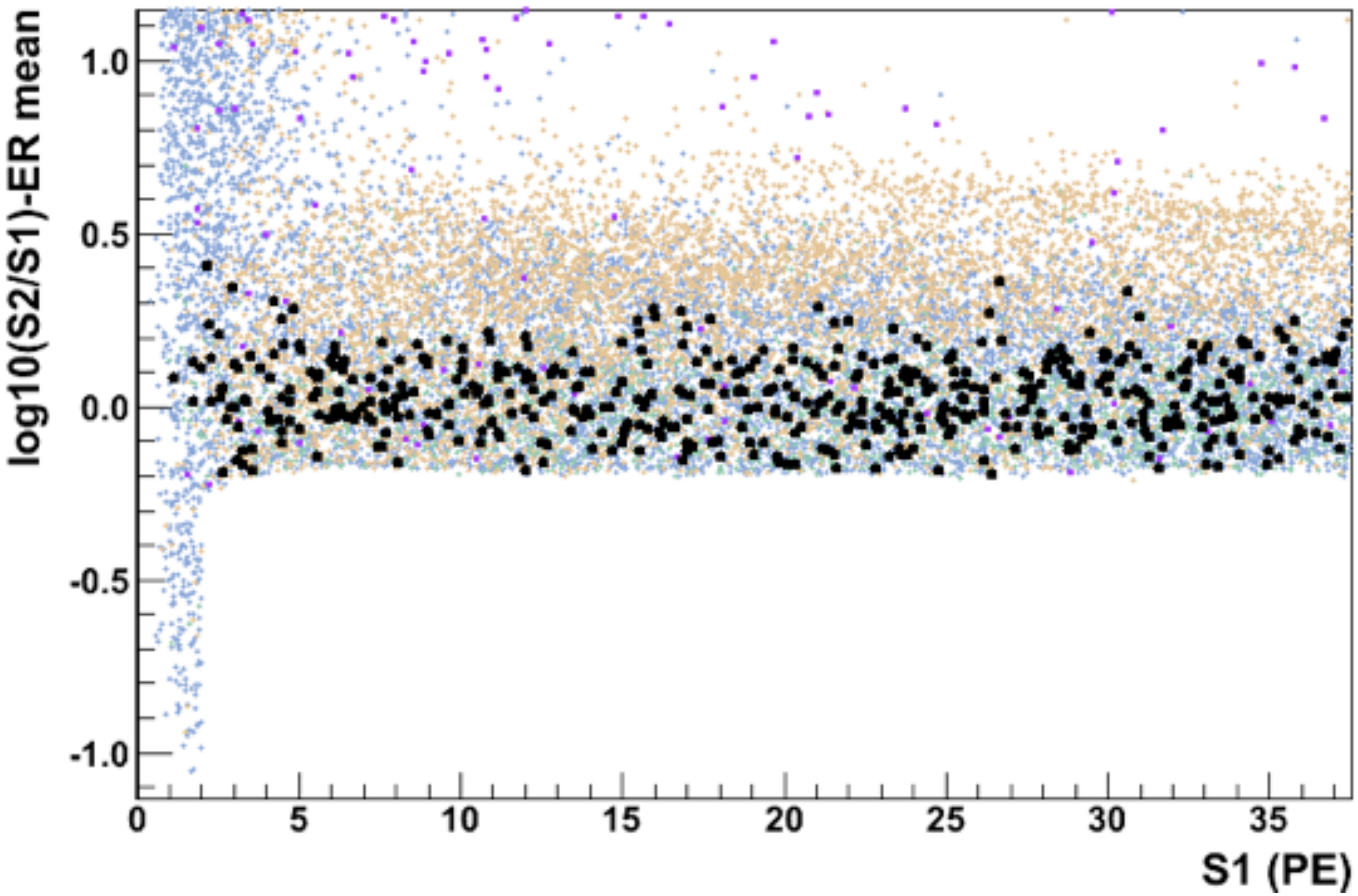
Single Scatter Cut: WIMPs don't multiple-scatter



Patrick Decowski

Analysis Steps

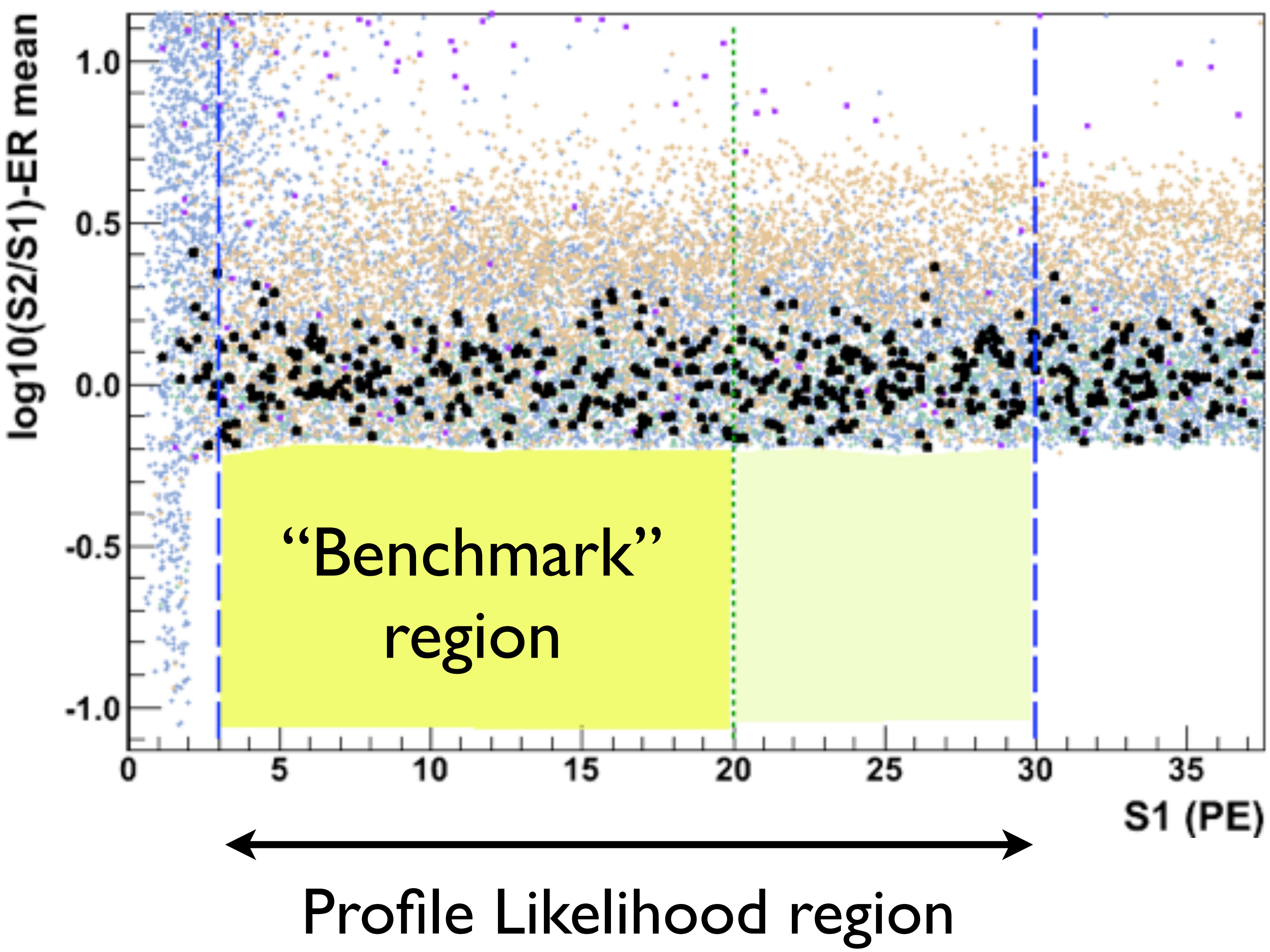
Set lower E threshold & restrict E range
(+ various consistency cuts)



Analysis Steps

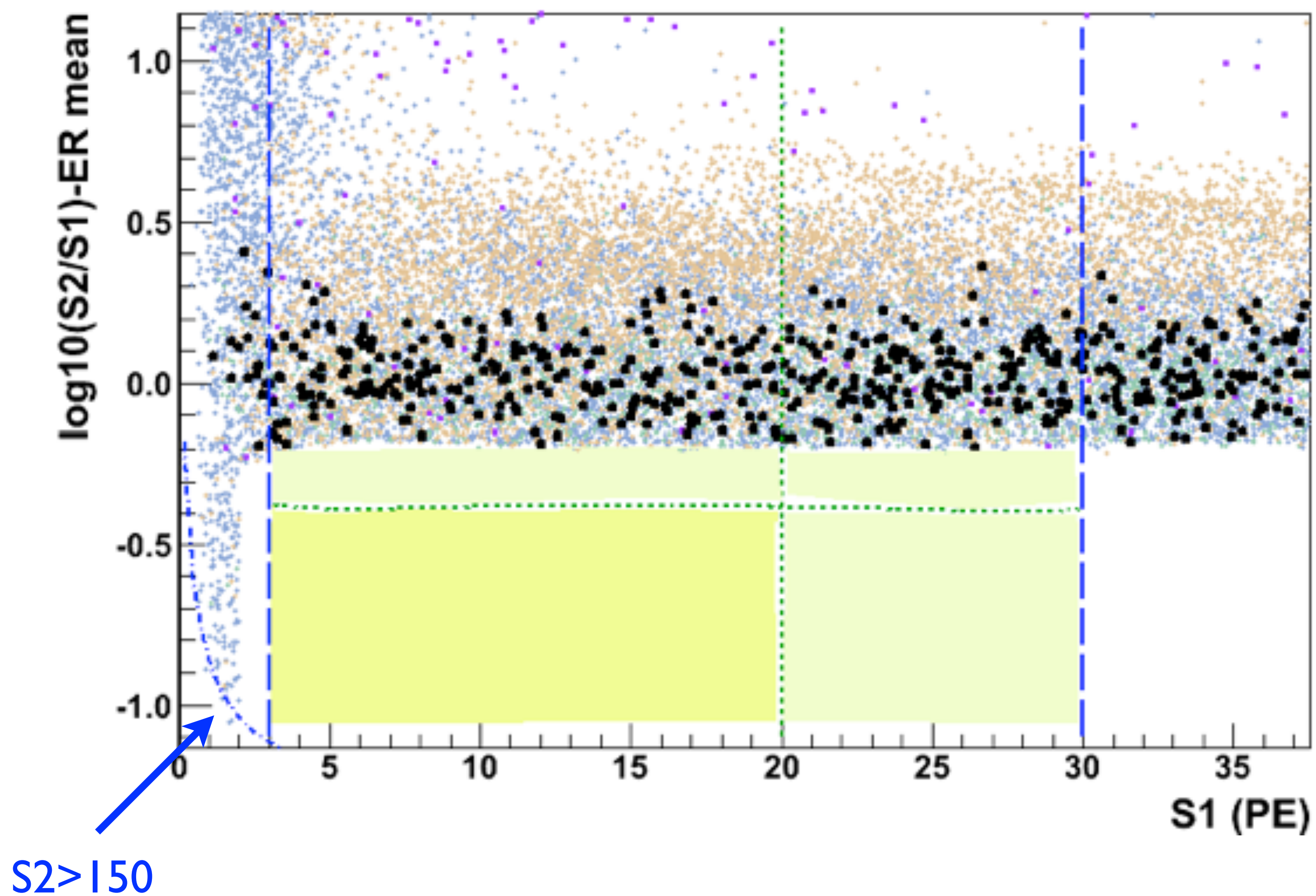
Two analyses:

1. Old-style cut-based analysis as a "Benchmark"
2. Profile Likelihood analysis in wider E range



Analysis Steps

For benchmark region: require 99.75% ER discrimination



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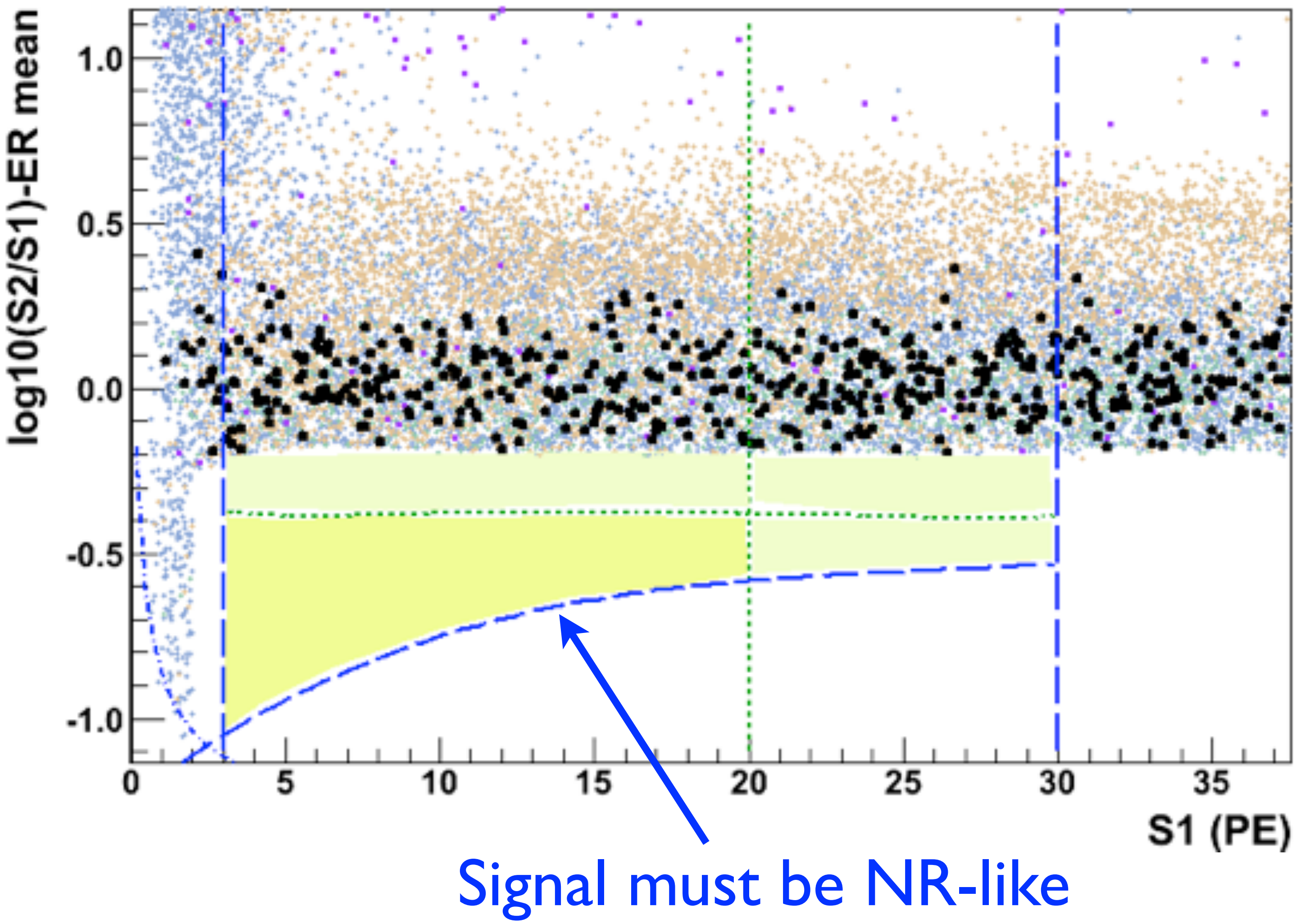
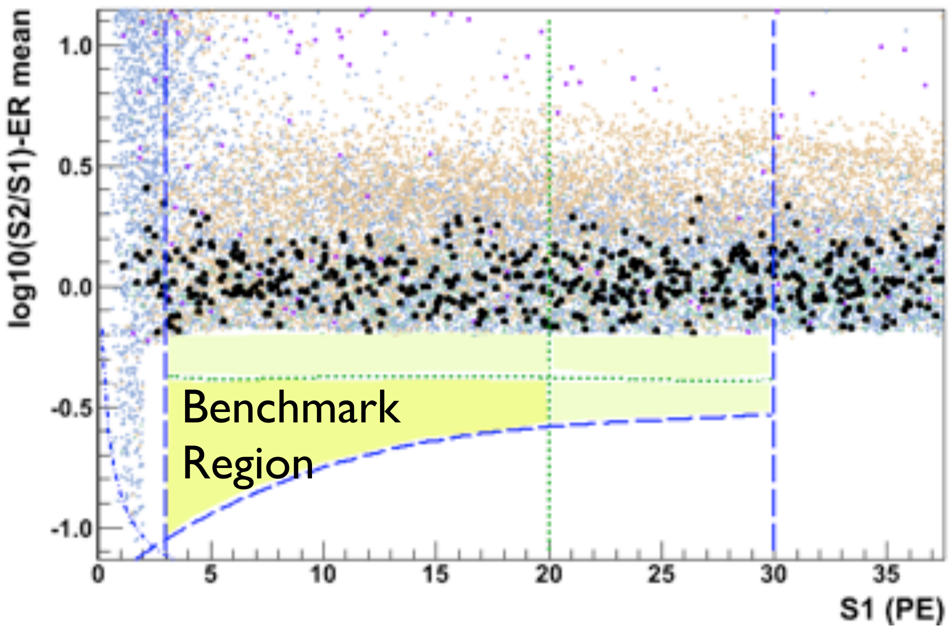
Analysis Steps

Restrict from below to ensure signal is NR-like



Expected Background & Efficiencies

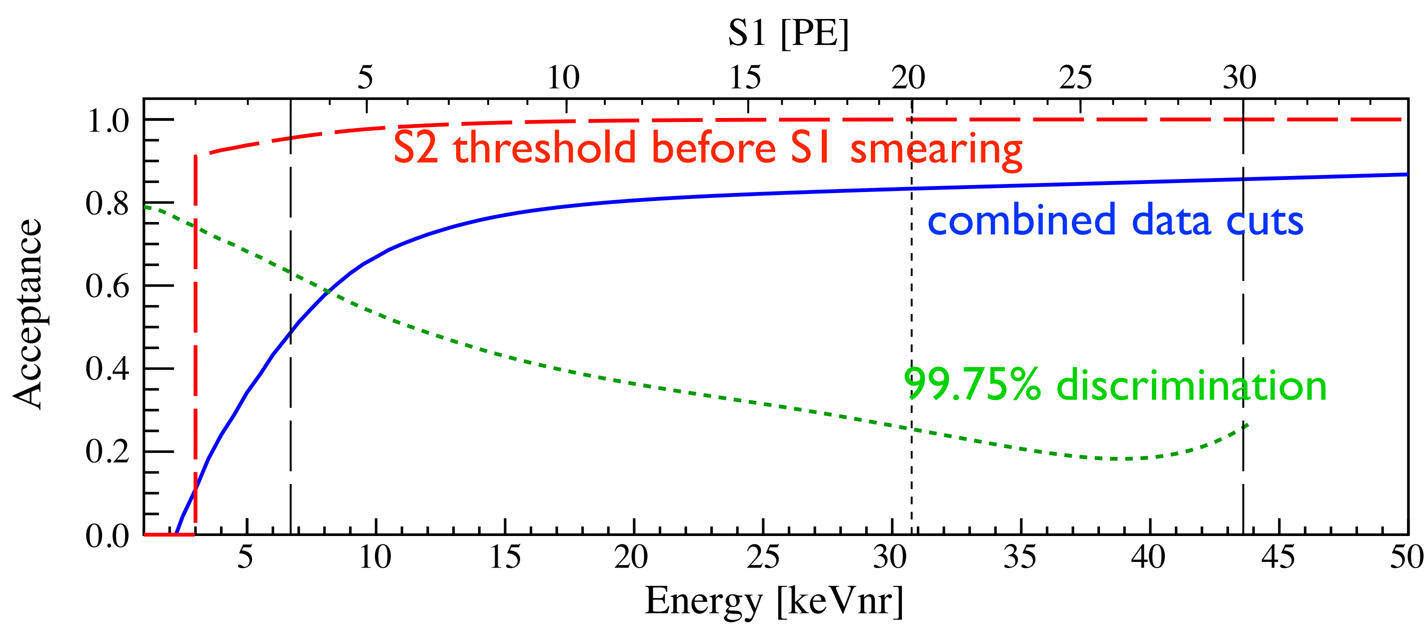


Profile likelihood uses detailed BG model

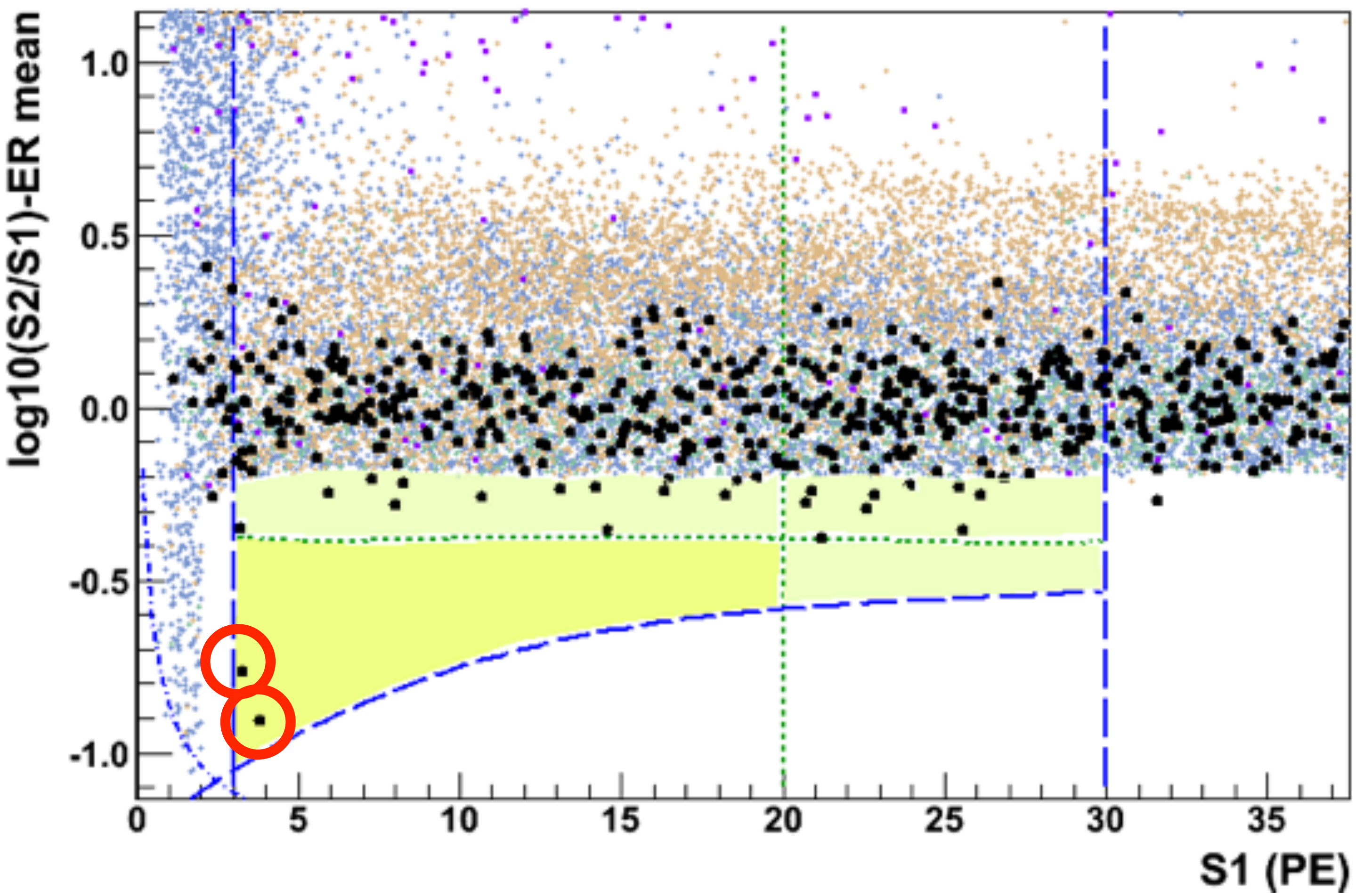
In Benchmark Region:

ER leakage	0.79 ± 0.16 ev
Neutrons (est. from MC)	$0.17^{+0.12}_{-0.07}$ ev
Total	1.0 ± 0.2 ev

Efficiencies:

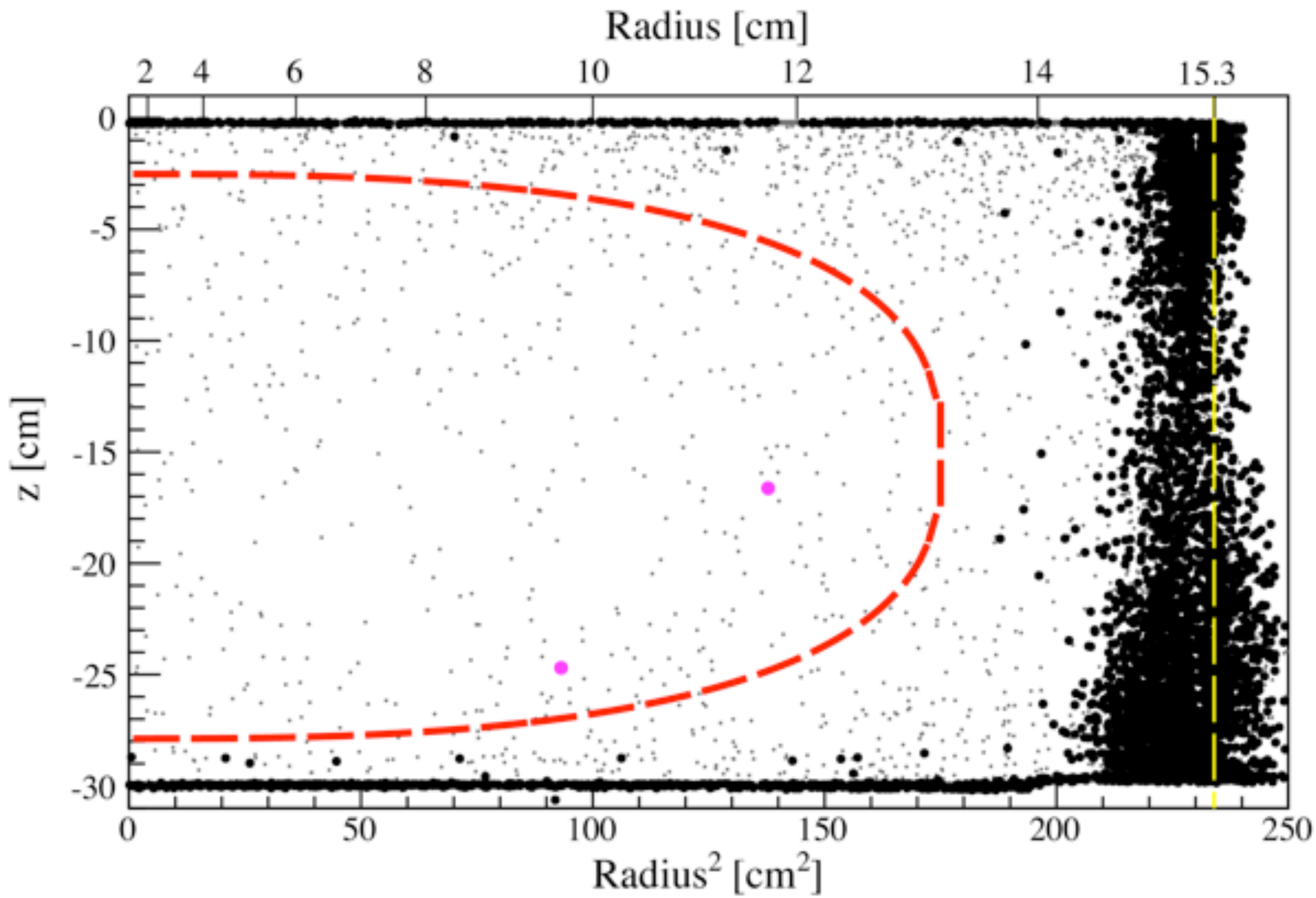


After Unblinding



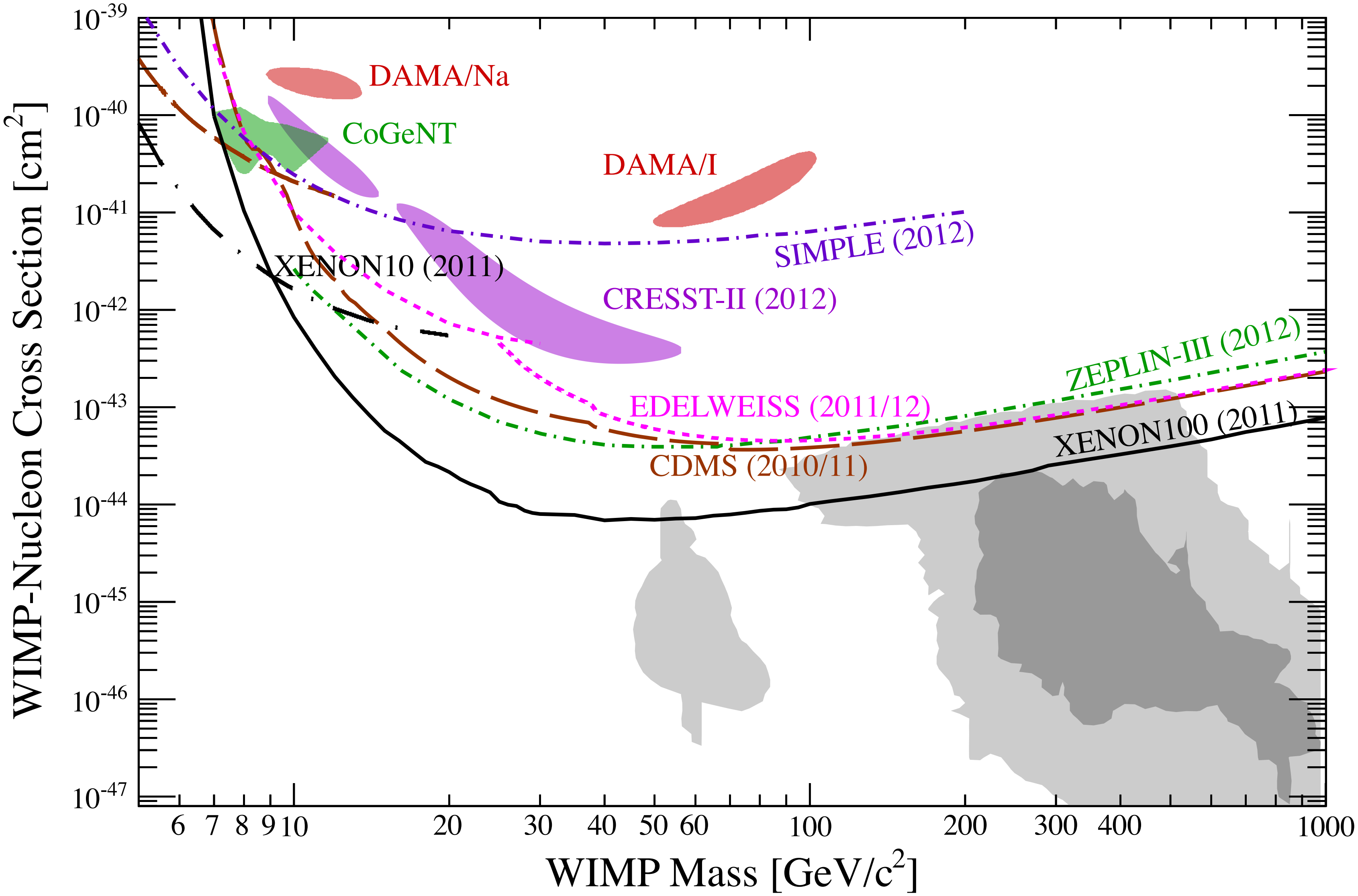
2 events in “Benchmark” region

After Unblinding



2 events in “Benchmark” region

Limits From XENON100



Adapted from
Aprile et al. [XENON100]
PRL 109, 181301 (2012).

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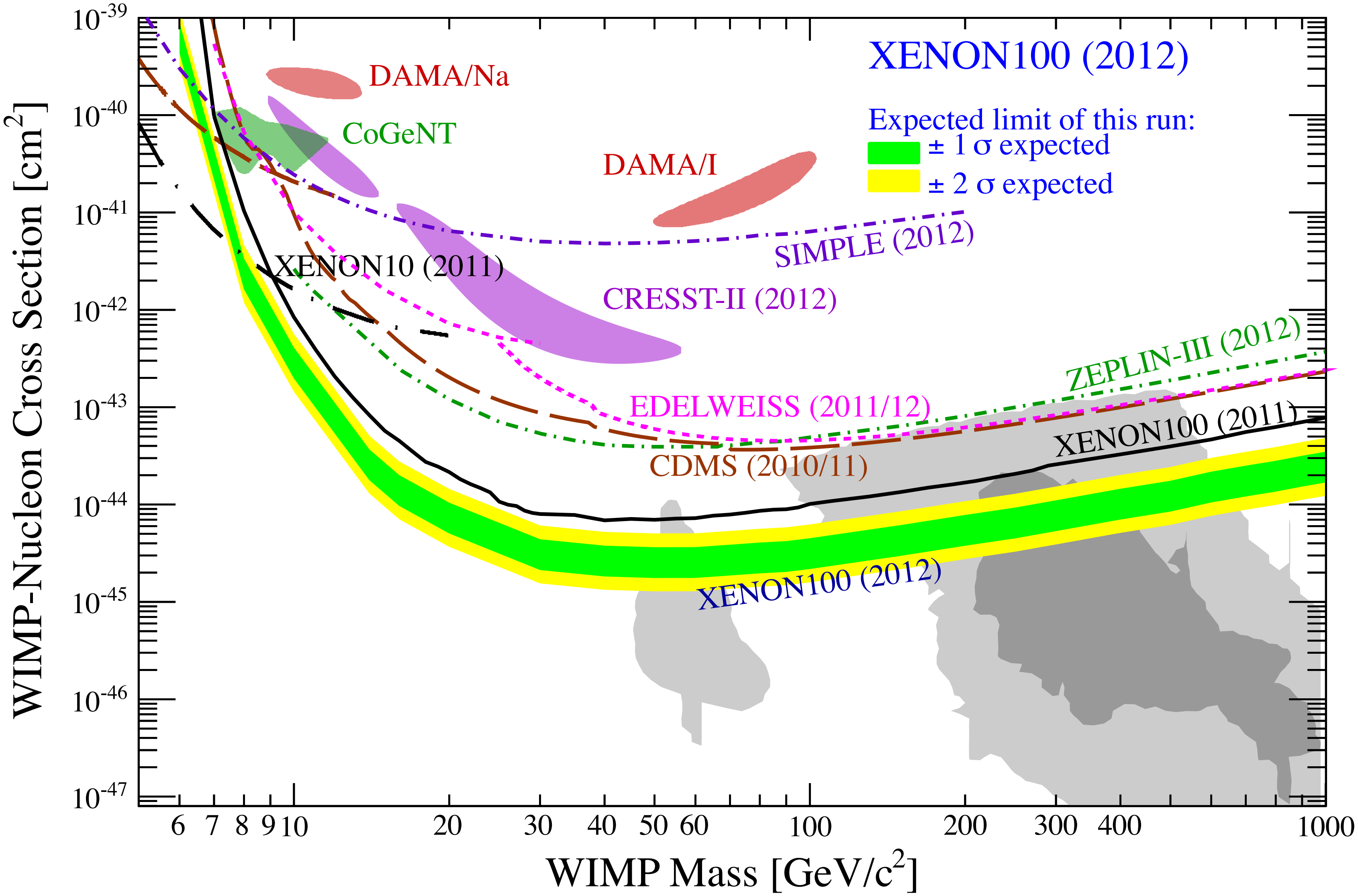
Limits From XENON100



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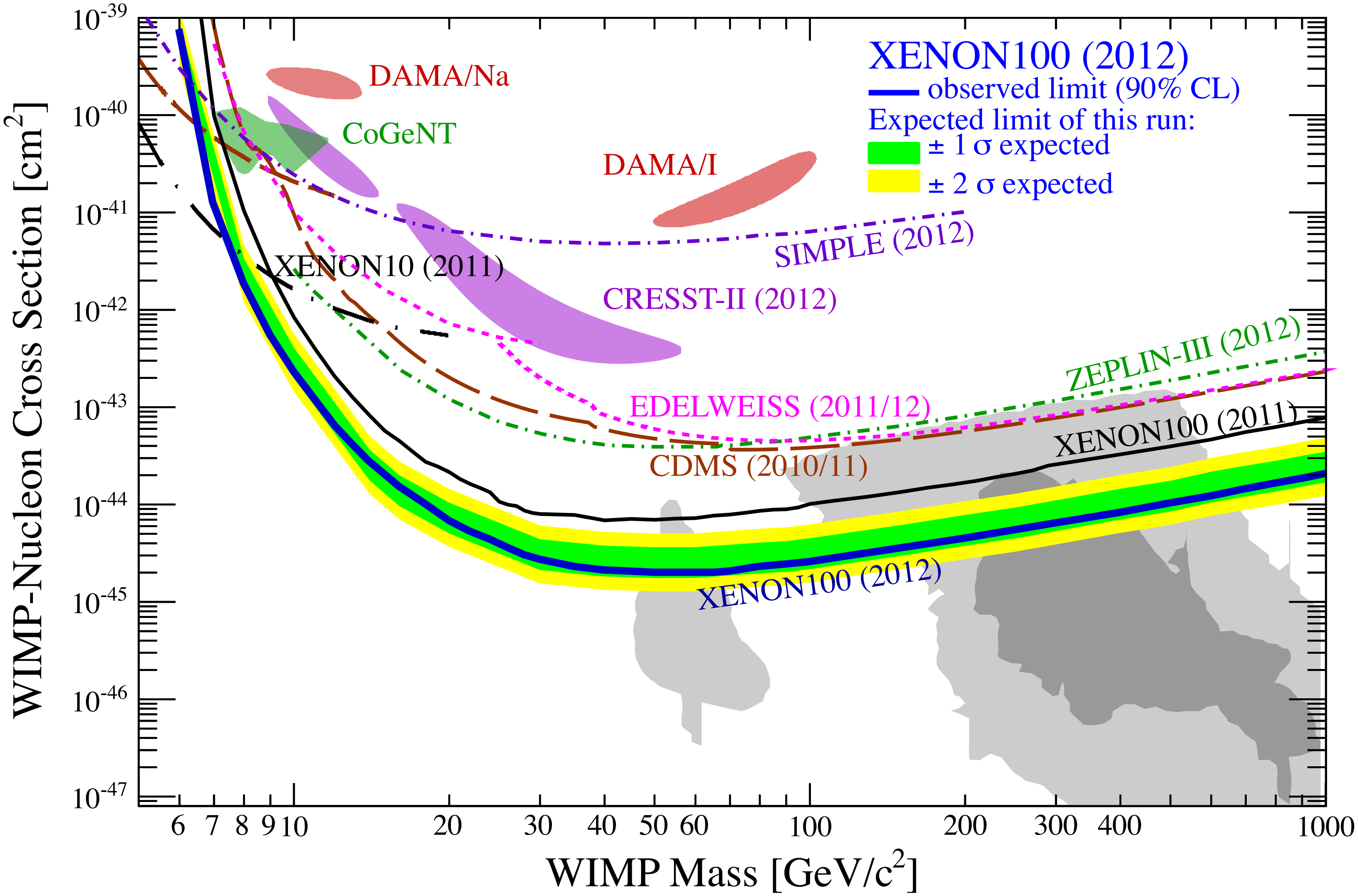
Limits From XENON100



Adapted from
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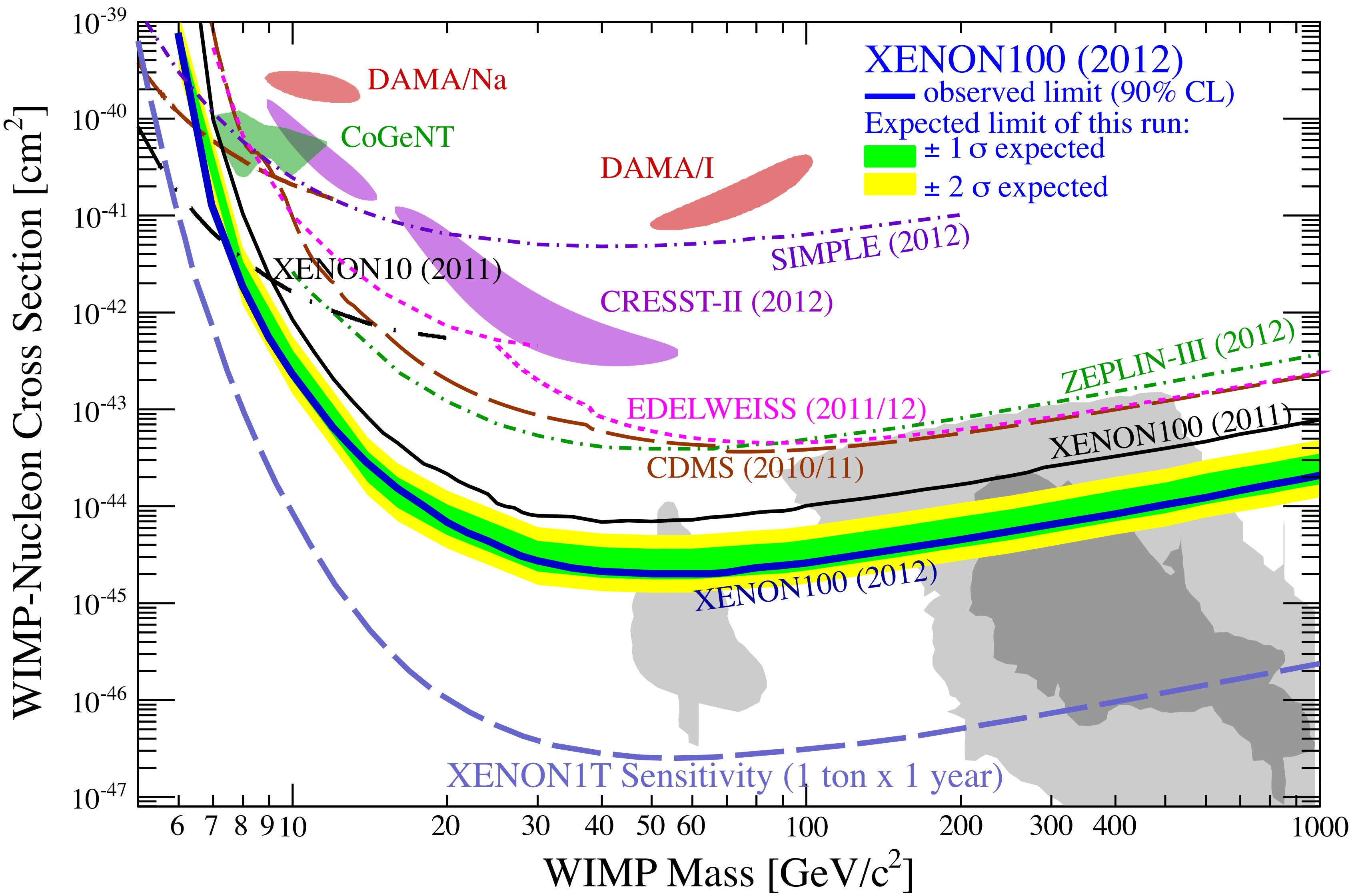
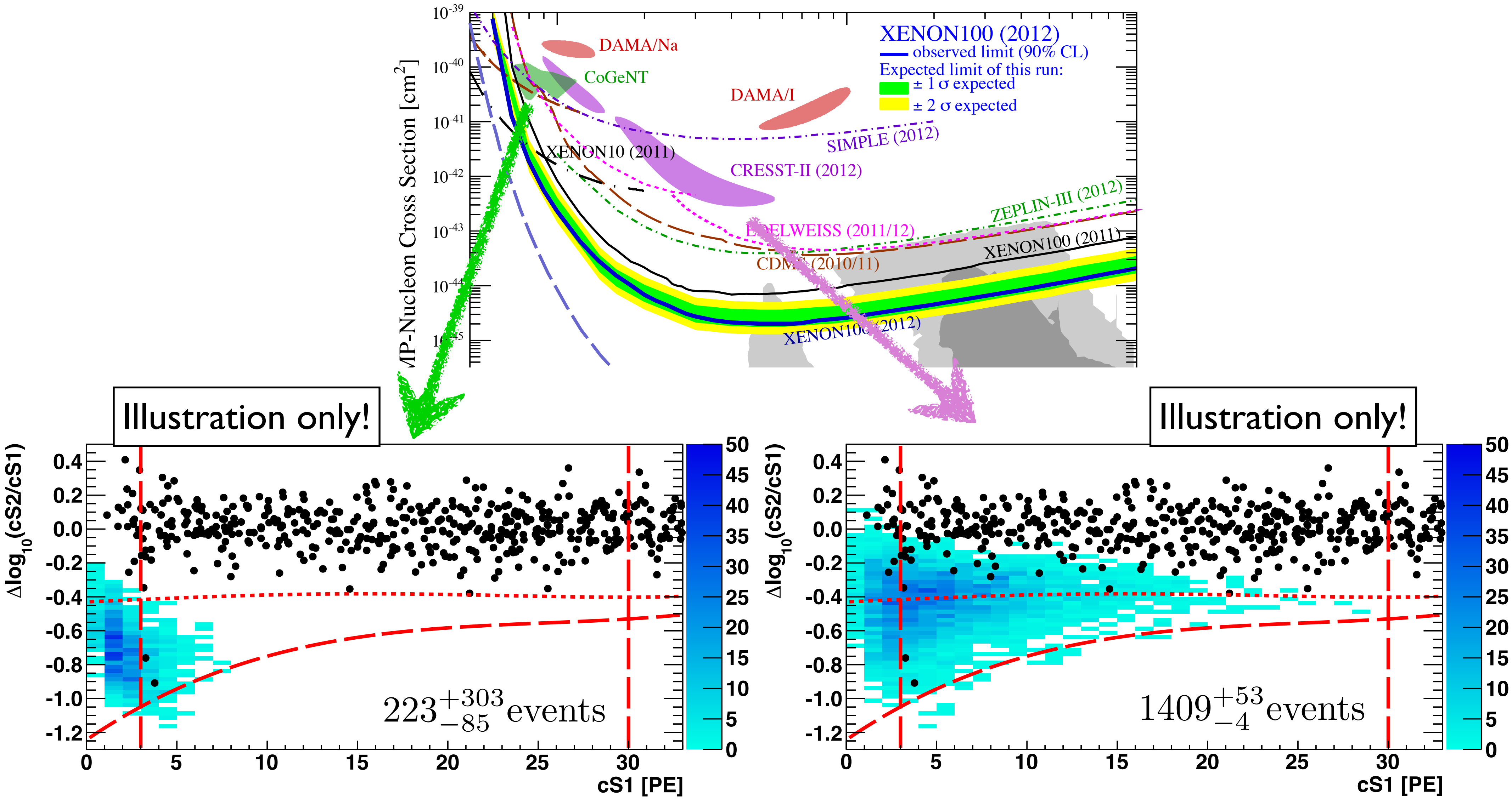
Limits From XENON100



Adapted from
Aprile et al. [XENON100]
PRL 109, 181301 (2012).

What would supposed signal look like?



CoGeNT/CDMS-Si-like WIMP

CRESST-like WIMP

m_χ = 8 GeV, σ = 3x10^{-41} cm^2

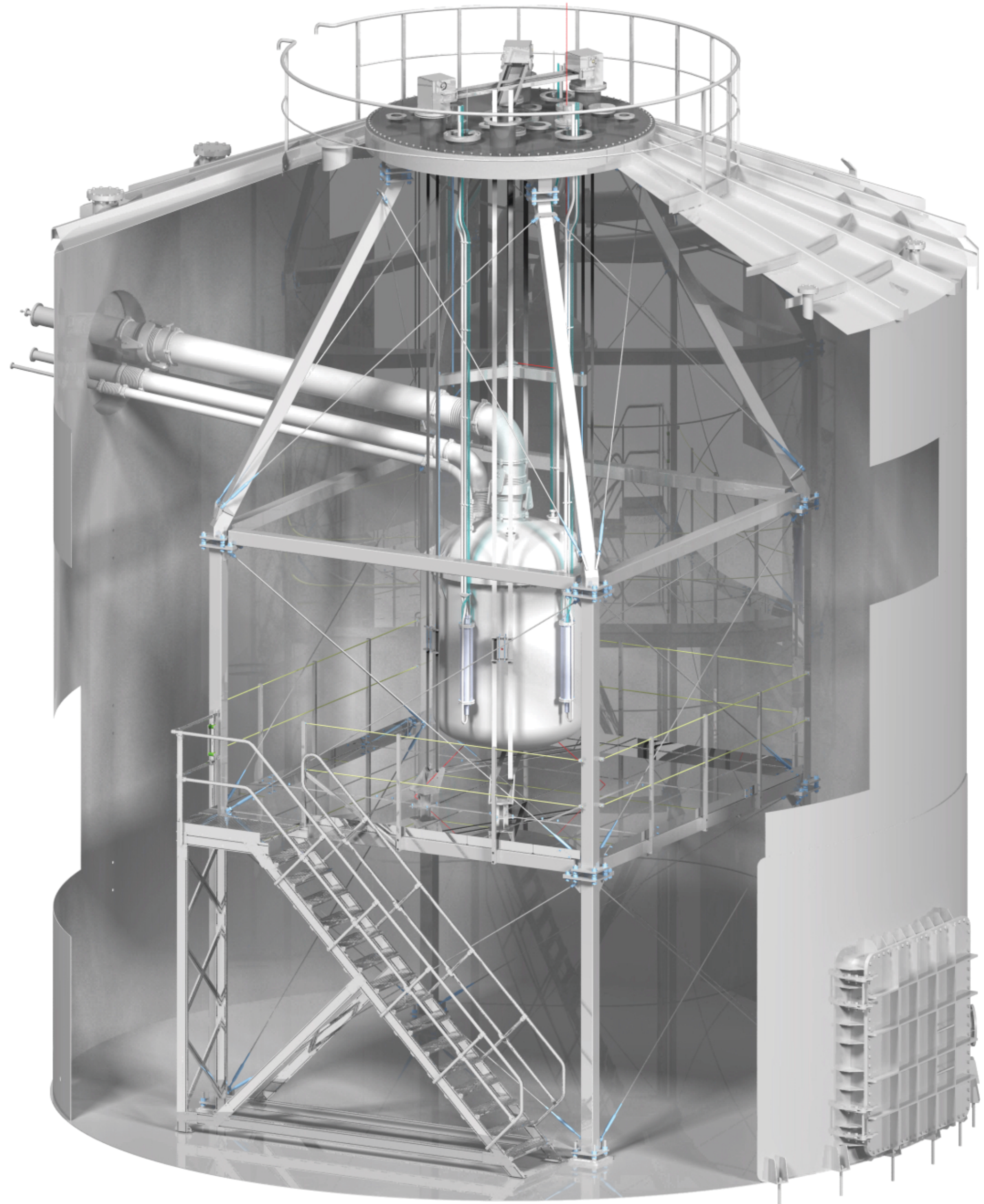
m_χ = 25 GeV ,σ = 1.6x10^{-42} cm^2

Patrick Decowski

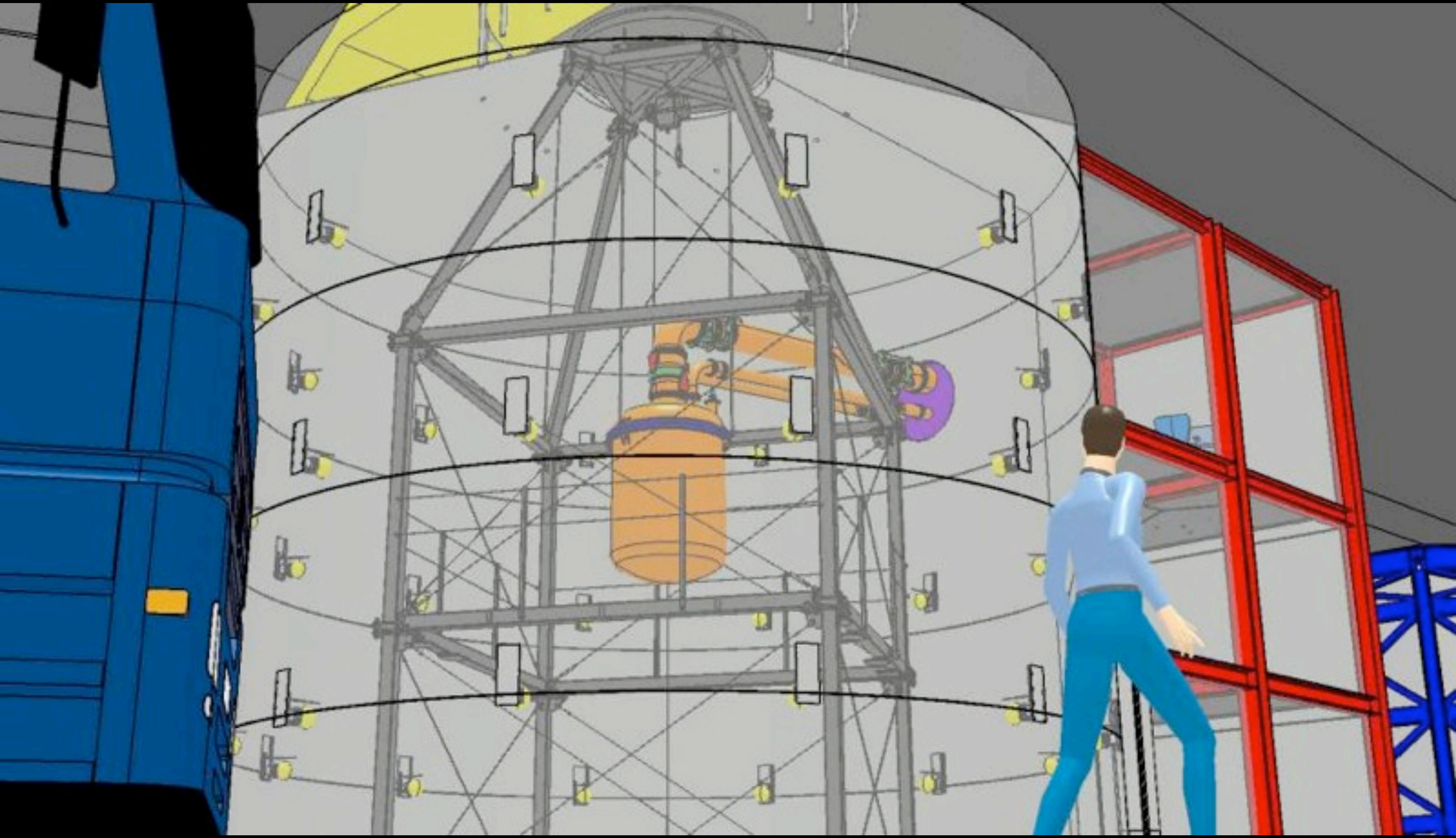
XENON100 Coll, Phys.Rev. D88 (2013) 012006

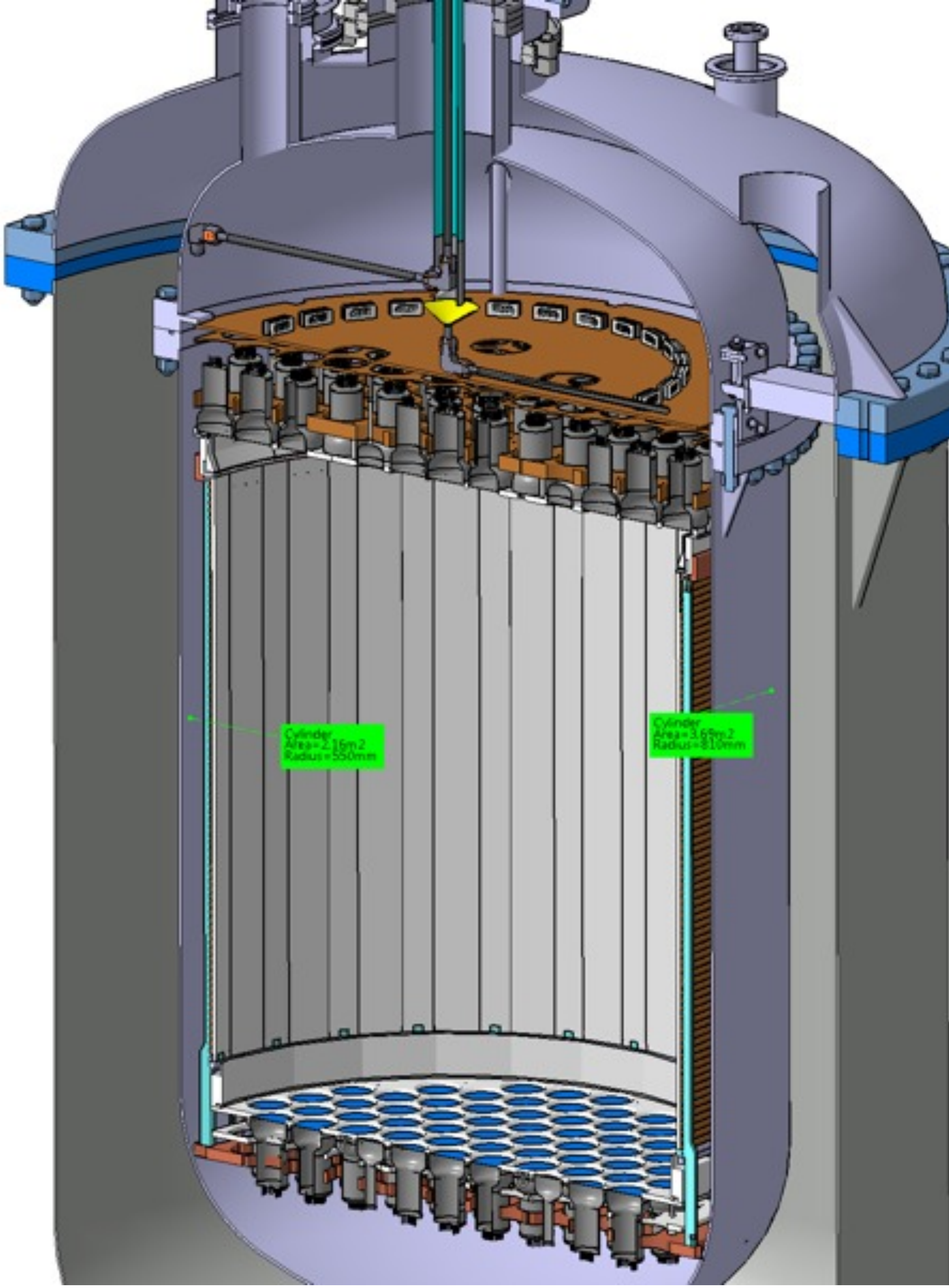
XENON1T

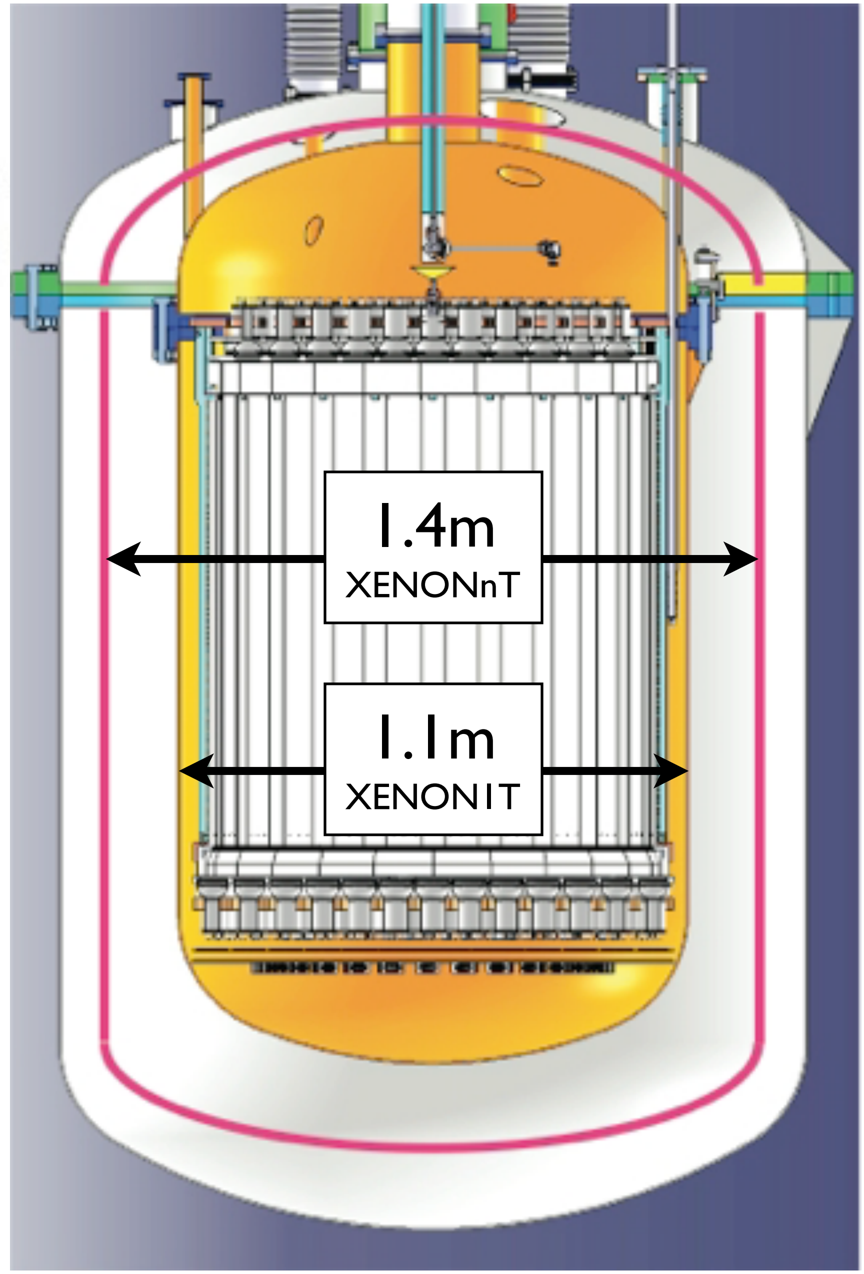
- 100x more sensitive than XENON100
- Around 3 tons of Xe, cleaner materials
- Upgrade option to large detector
- Start of science in 2015
- Building has started!



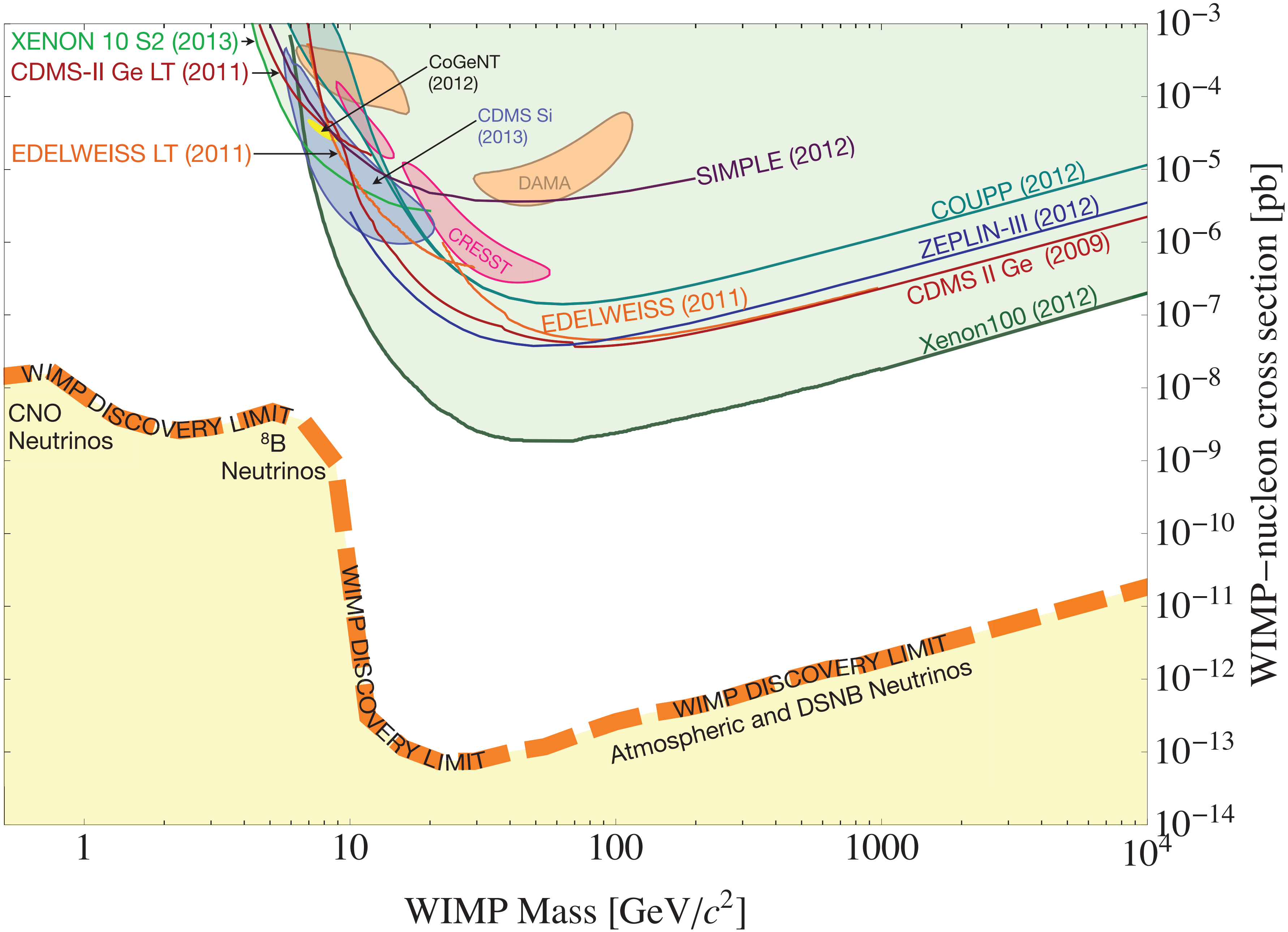

ICARUS



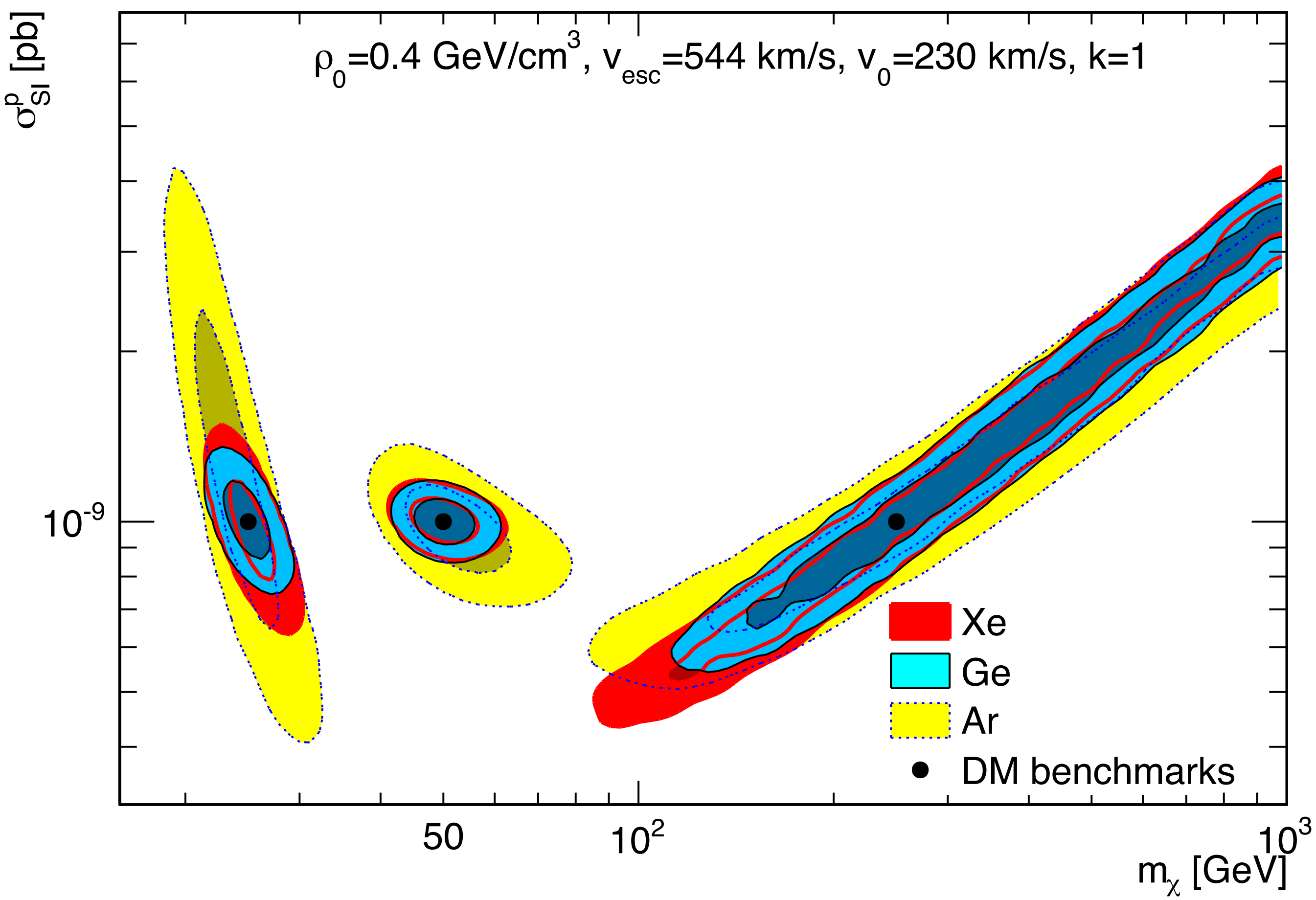

Cylinder
Area=2.16m2
Radius=550mm
Cylinder
Area=3.69m2
Radius=810mm


1.4m
XENONnT
1.1m
XENON1T

Neutrinos are the ultimate background

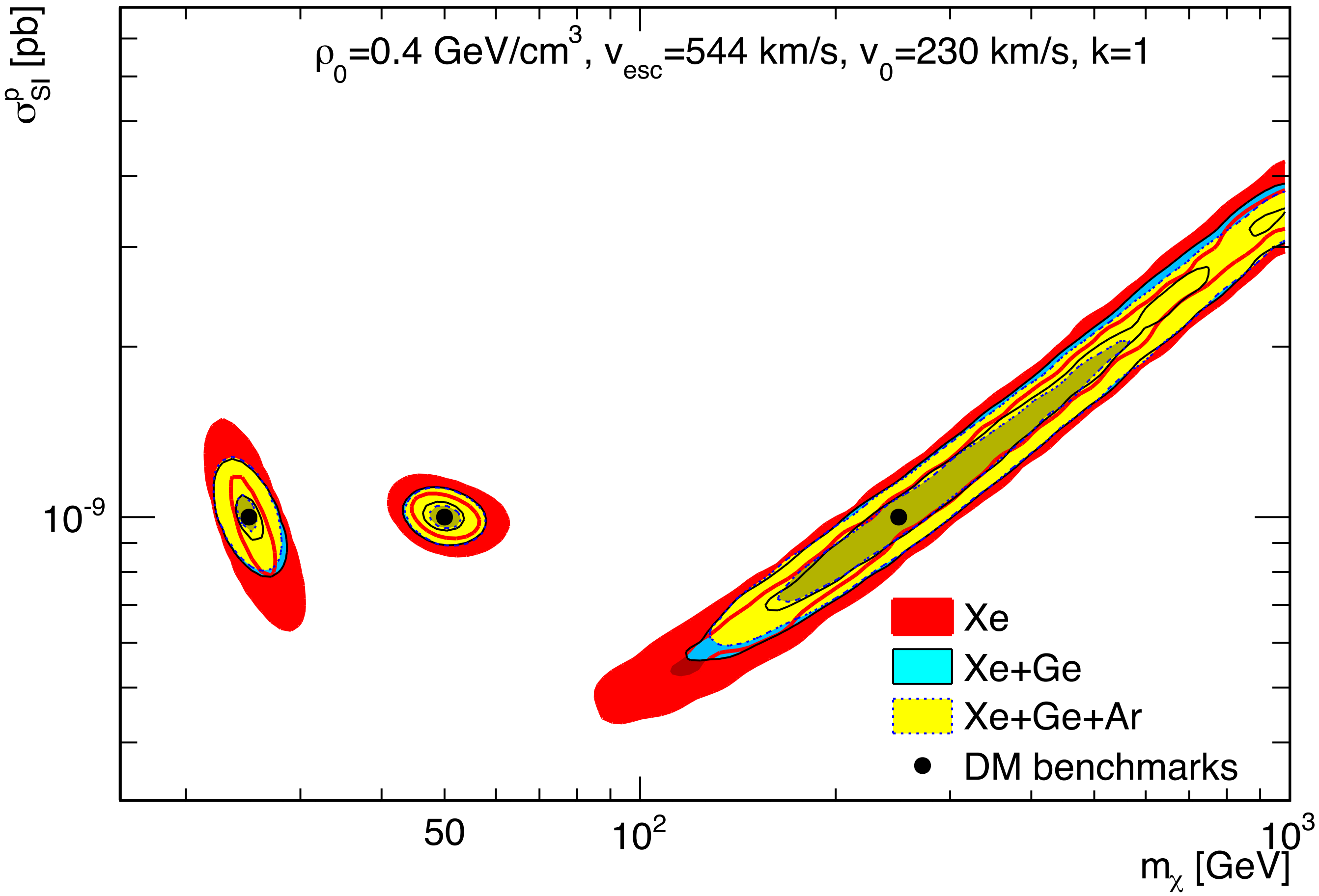


Astrophysical Uncertainties



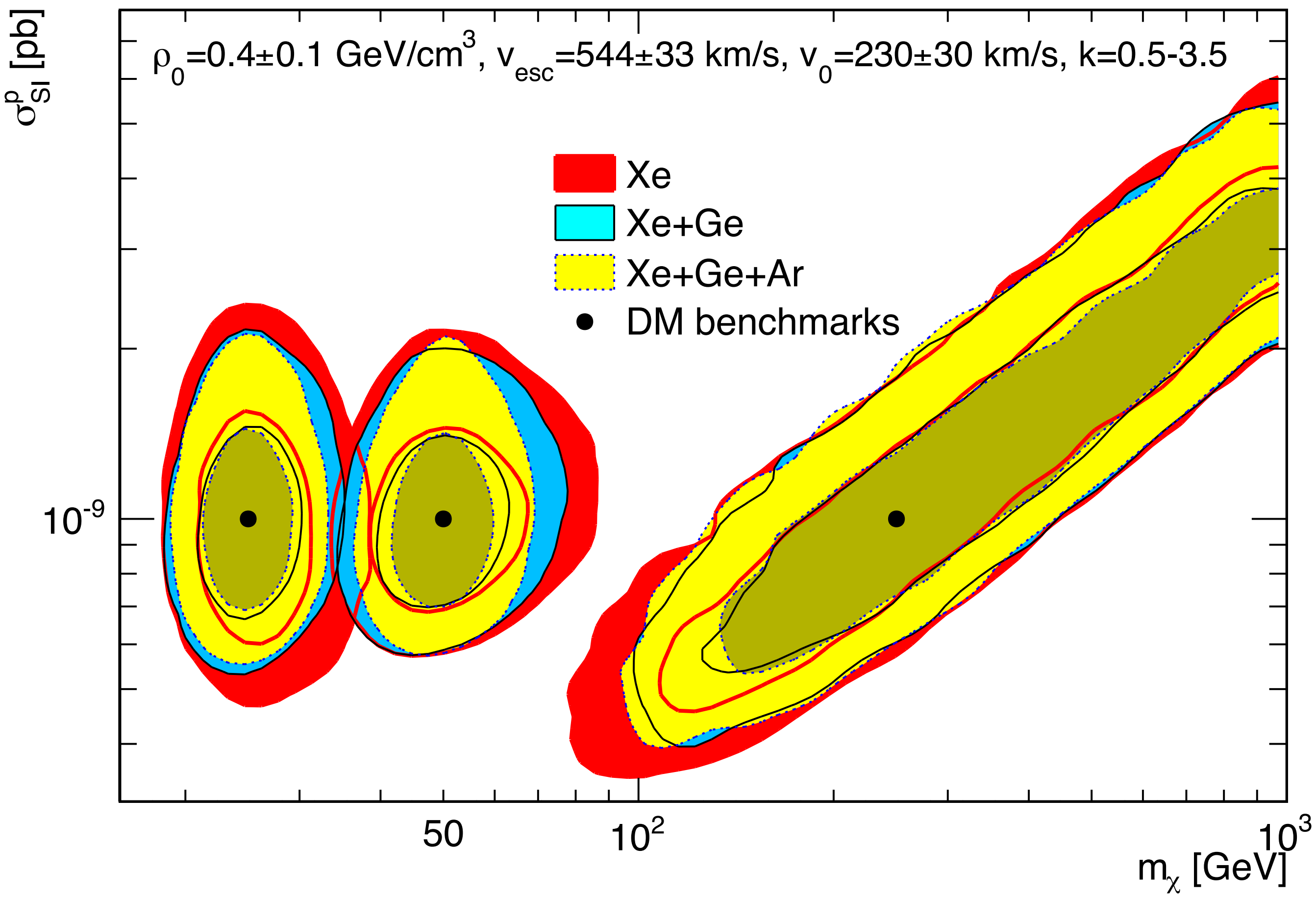
Pato *et al.*, Phys.Rev.D83:083505,2011

Astrophysical Uncertainties



Pato *et al.*, Phys.Rev.D83:083505,2011

Astrophysical Uncertainties



Pato *et al.*, Phys.Rev.D83:083505,2011

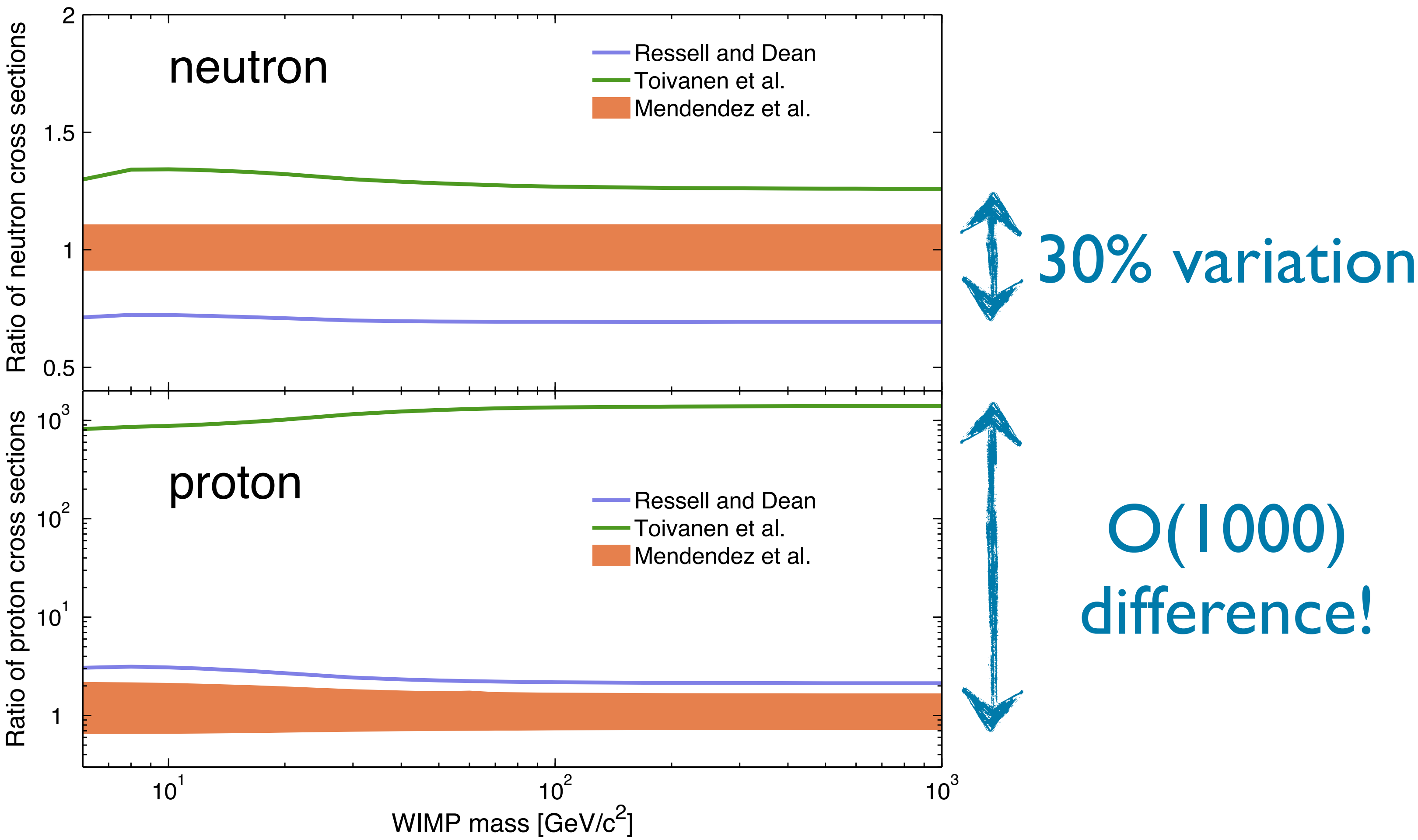
Nuclear Models: Interpreting SD limits

Rate on nucleus→ Nuclear Model → WIMP-nucleon spin-dependent limits

Xe specific case… (others?)

$$\sigma_{p,n}(q) = \frac{3}{4}\frac{\mu_{p,n}^2}{\mu_A^2}\frac{2J+1}{\pi}\frac{\sigma_{SD}(q)}{S_A(q)}$$

Nuclear structure uncertainties



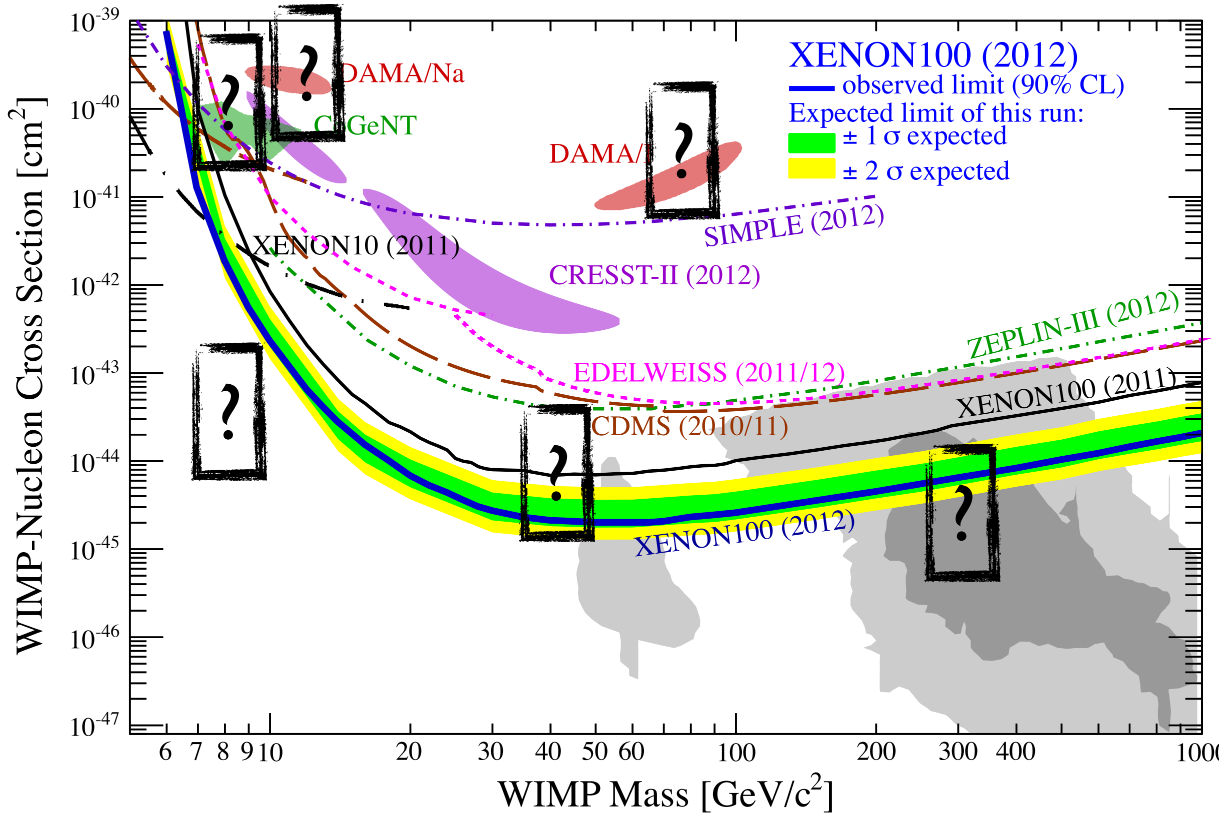
XENON100 Coll, Phys.Rev.Lett. 111 (2013) 021301

Affects **interpretation** of WIMP-proton SD limits.

Measurements to help constrain nuclear models?

What will near future bring?

- This year:
  - LUX running
  - XMASS back running
  - DarkSide-50 running
  - COUPP-60 running
- SuperCDMS running (2012)
- CoGeNT about to release
- DAMA running high QE PMTs since Dec 2010…
- Start of XENON1T in early 2015
- …



We are in an exciting period!

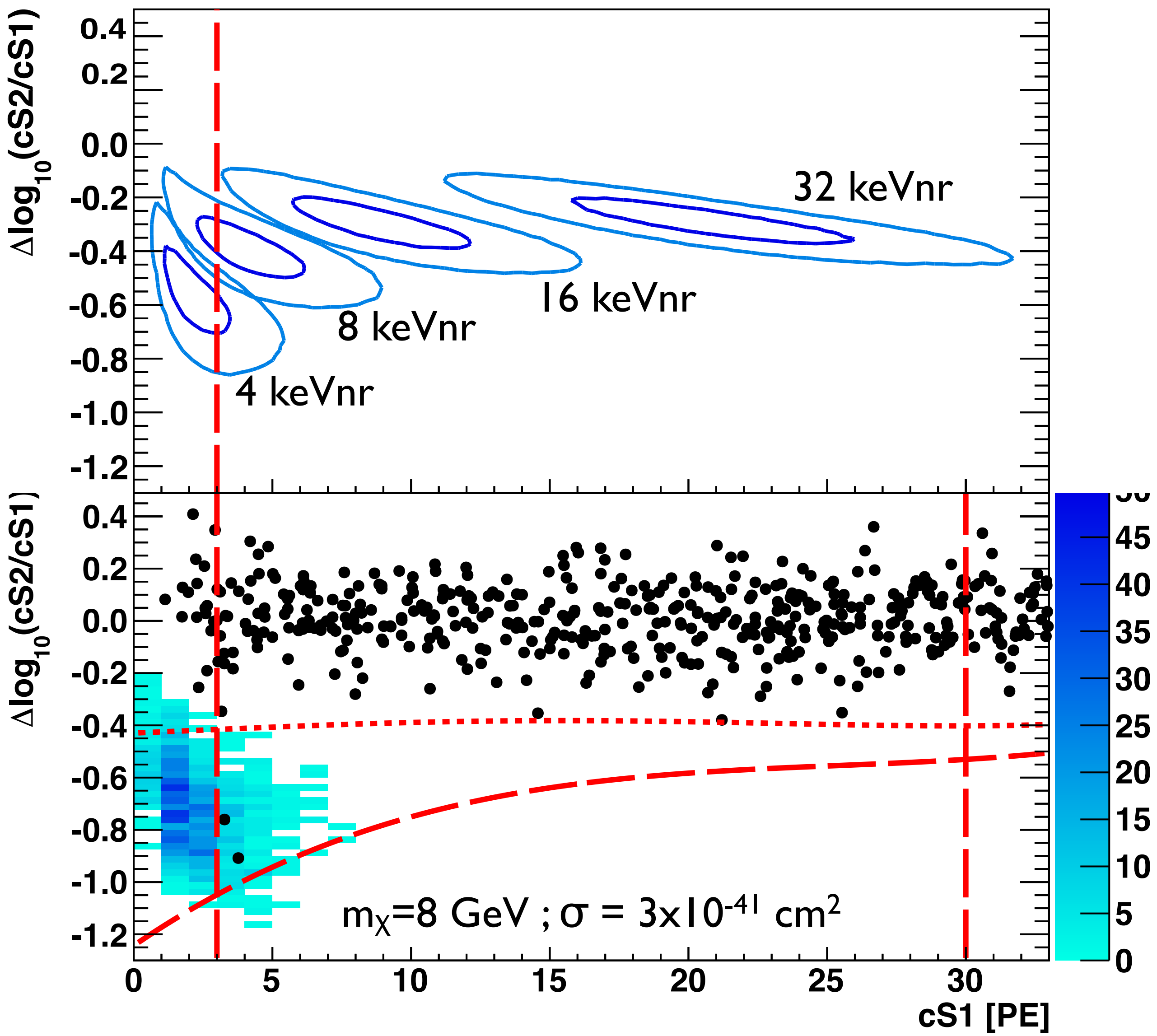
How many sigma?

Search	Degree of surprise	Impact	LEE	Systematics	Number of σ
Higgs search	Medium	Very high	Mass	Medium	5
Single top	No	Low	No	No	3
SUSY	Yes	Very high	Very large	Yes	7
B_s oscillations	Medium/low	Medium	Δm	No	4
Neutrino oscillations	Medium	High	$sin^2(2\theta), \Delta m^2$	No	4
$B_s \rightarrow \mu\mu$	No	Low/Medium	No	Medium	3
Pentaquark	Yes	High/very high	M, decay mode	Medium	7
$(g-2)_\mu$ anomaly	Yes	High	No	Yes	4
H spin $\neq$ 0	Yes	High	No	Medium	5
4^{th} generation q, l, ν	Yes	High	M, mode	No	6
v_ν > c	Enormous	Enormous	No	Yes	>8
Dark matter (direct)	Medium	High	Medium	Yes	5
Dark energy	Yes	Very high	Strength	Yes	5
Grav waves	No	High	Enormous	Yes	7

Table 1: Summary of some searches for new phenomena, with suggested numerical values for the number of σ that might be appropriate for claiming a discovery.

Lyons, arXiv:1310.1284

Nuclear Recoil Response



Patrick Decowski