VUB, Oct 18, 2013

The Search for Dark Matter Particles

Patrick Decowski
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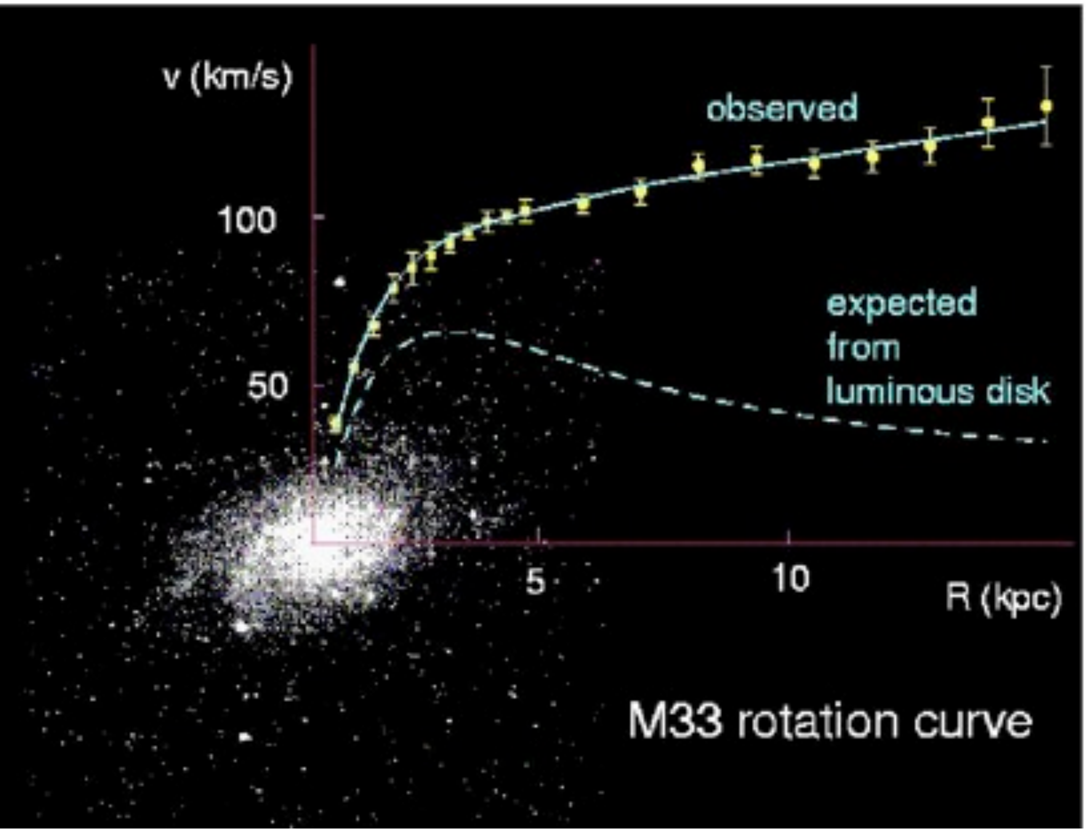
NIKHEF

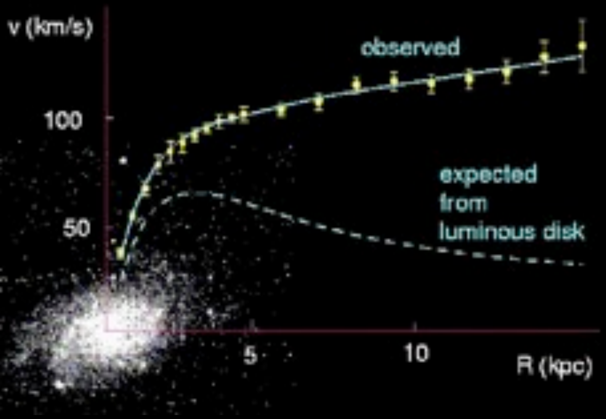
Rotation Curves



- Zwicky in 1933: luminous matter insufficient to describe gravitational binding in clusters of galaxies
- Vera Rubin in early ’70: Rotational curves of spiral galaxies do not follow Newtonian expectation based on mass in luminous disk

Need non-luminous “Dark Matter”

Much Astronomical Evidence for DM



Rotational Curves

Galaxy Clusters

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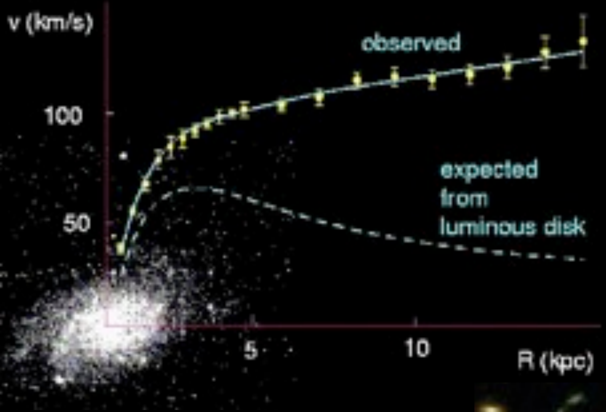

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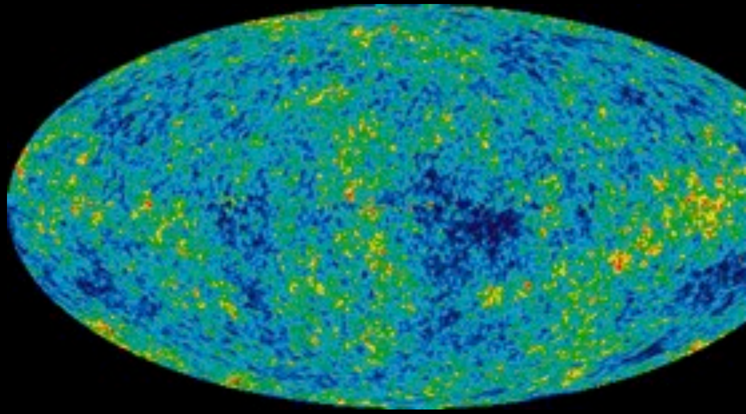
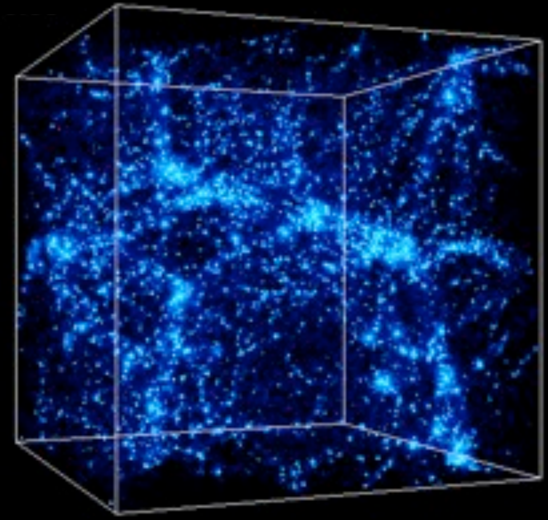


Anisotropy in CMB

Weak Lensing

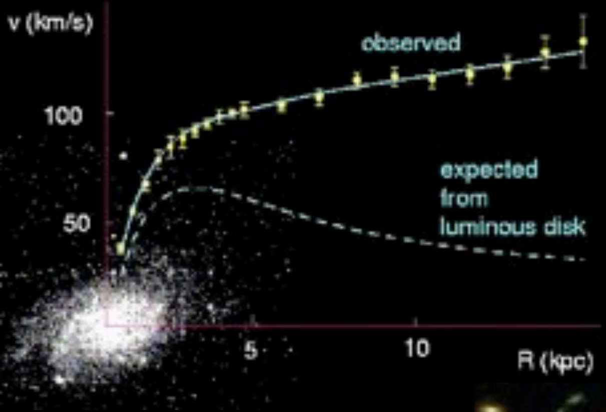


Large Scale Structure

Galaxy Clusters

Much Astronomical Evidence for DM

At **all** scales in the Universe!



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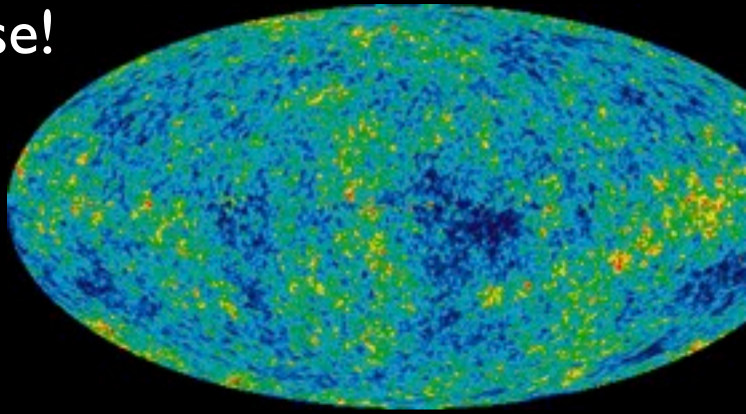

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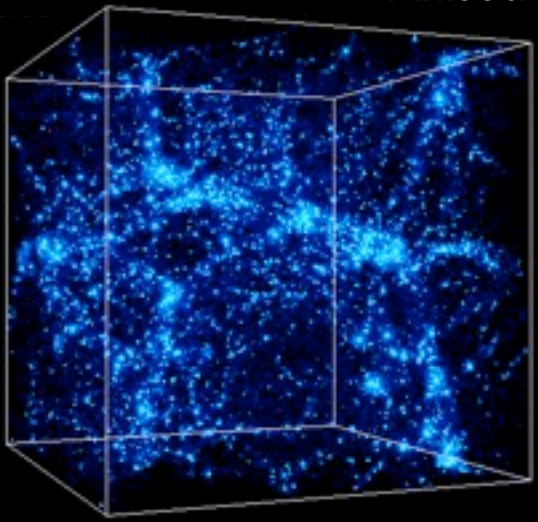
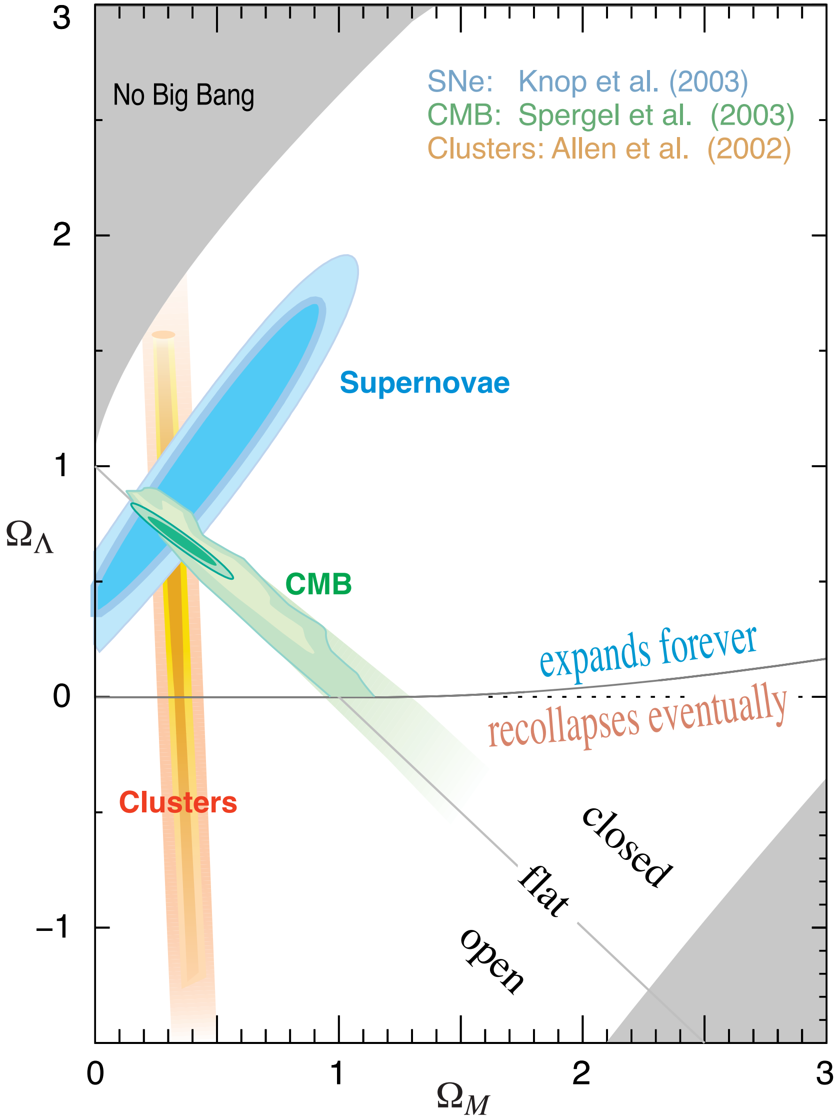
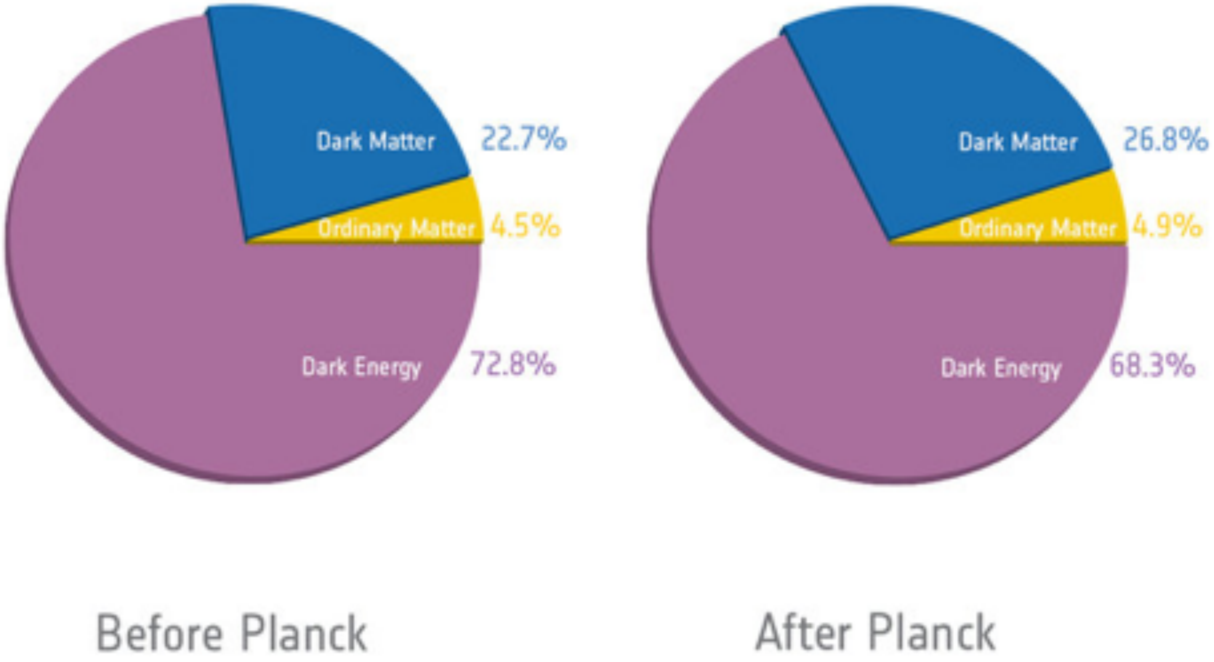


Large Scale Structure

Galaxy Clusters

Dark Matter and Cosmology





...but what is it made off?

Properties of Dark Matter

- Known properties of DM:
  - Gravitationally interacting
  - No EM interactions
  - “Cold” i.e. non-relativistic
  - Non-baryonic
  - Long lived

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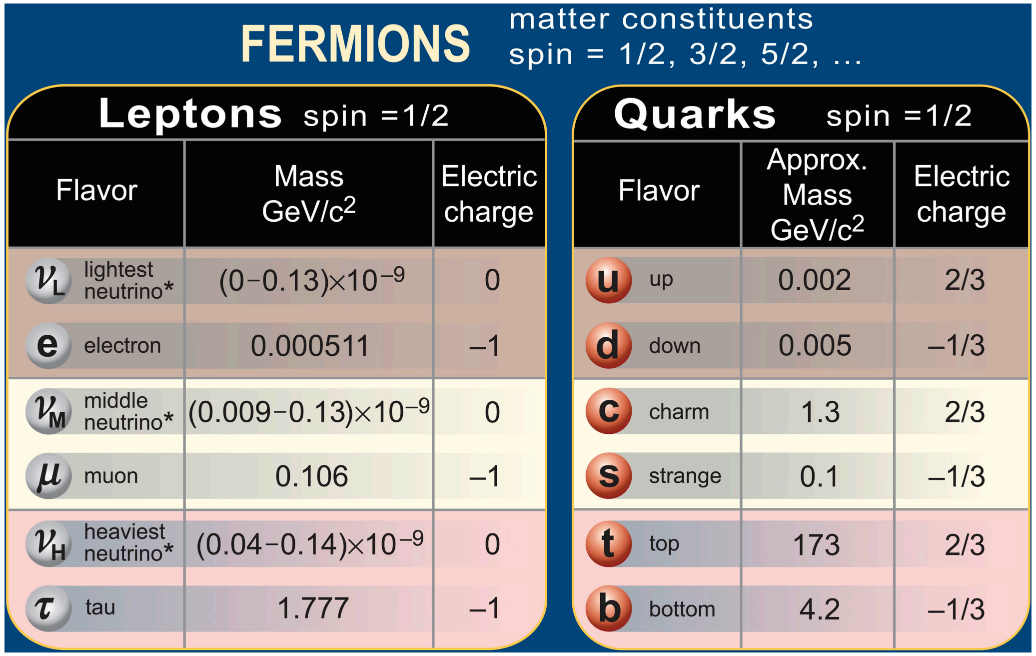

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

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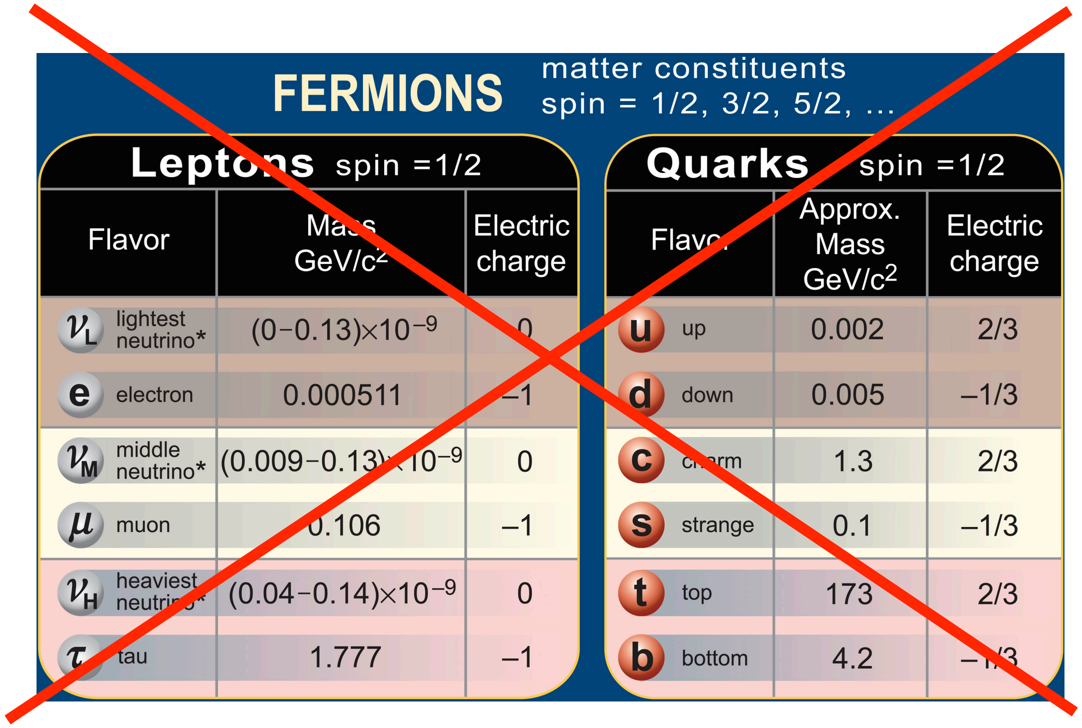

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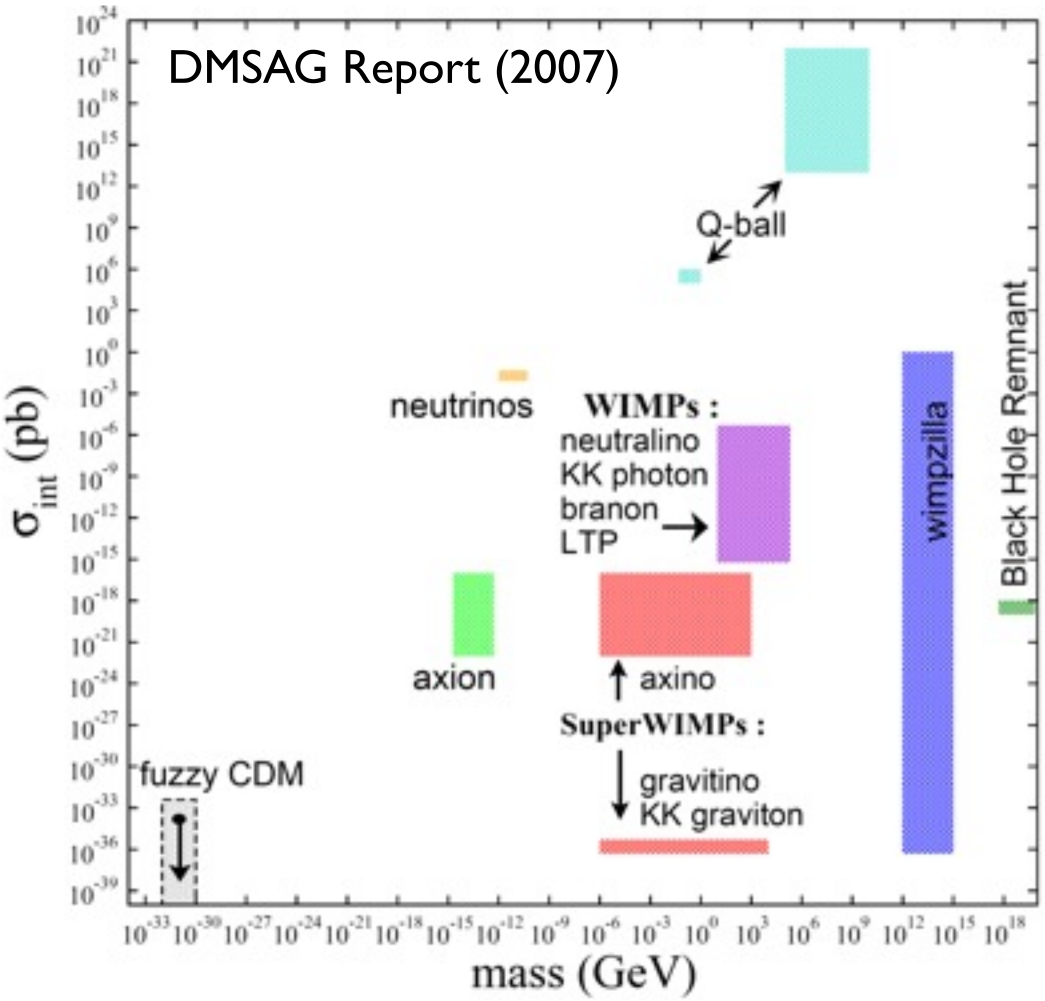
Has to be some new, unknown, particle

Some DM Candidates

Many candidates, usually some extension of the Standard Model



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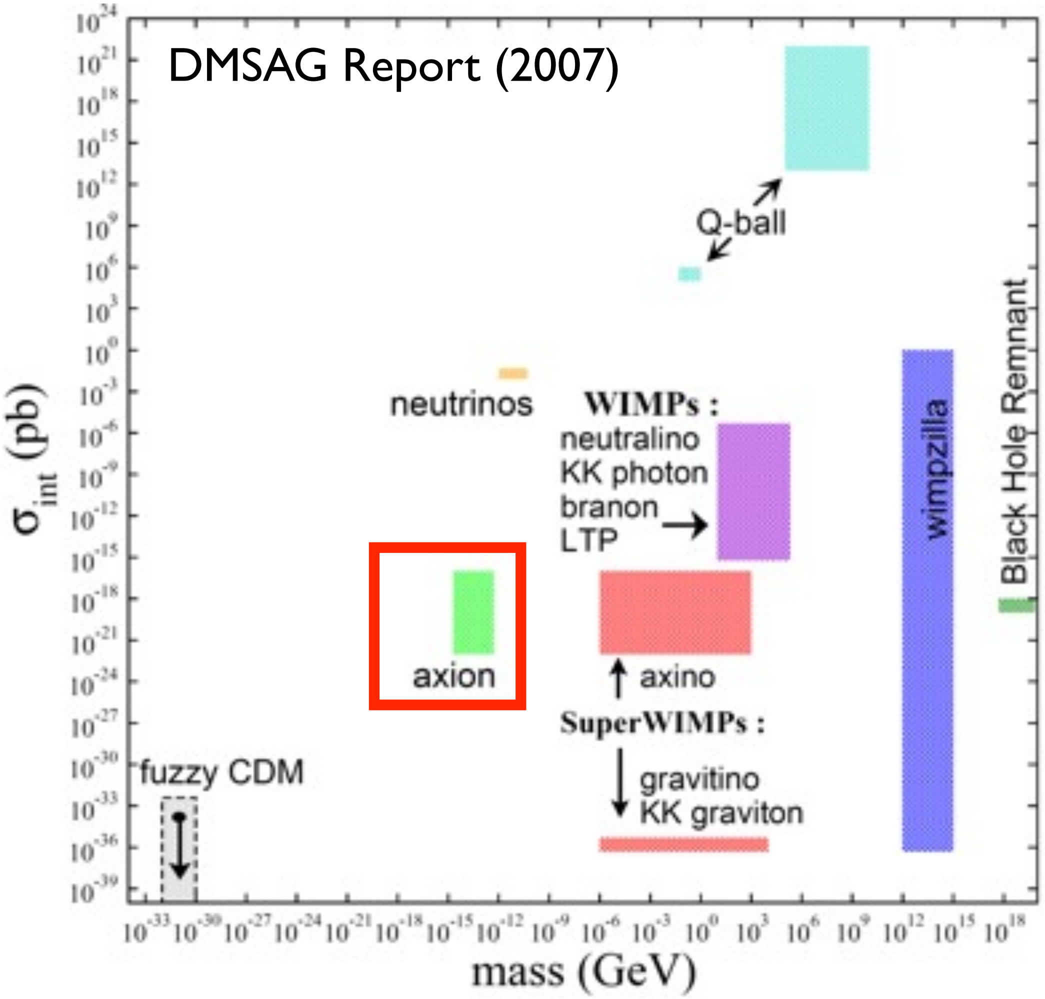
DMSAG Report (2007)

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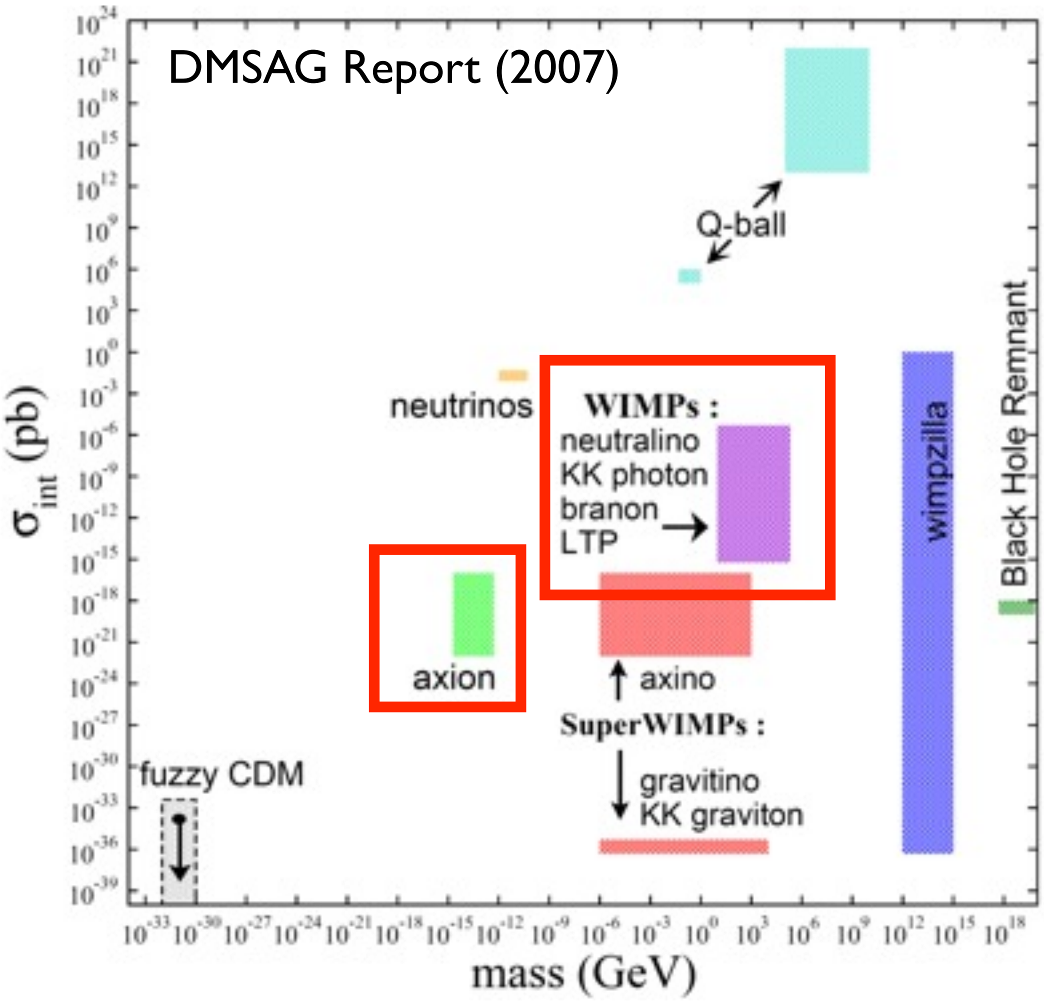
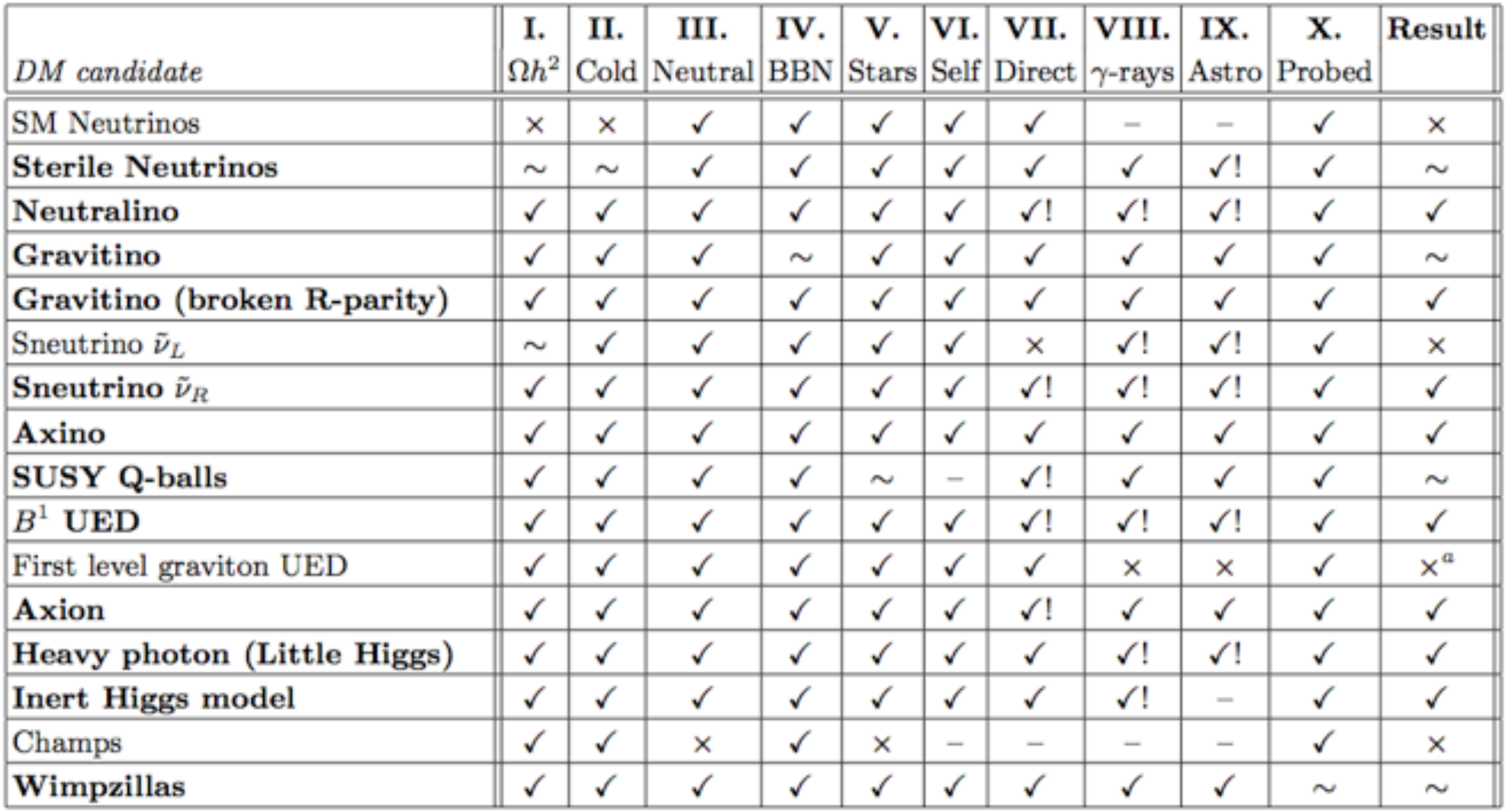


“10-point test” of DM candidates

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 | ! = To be/being explored

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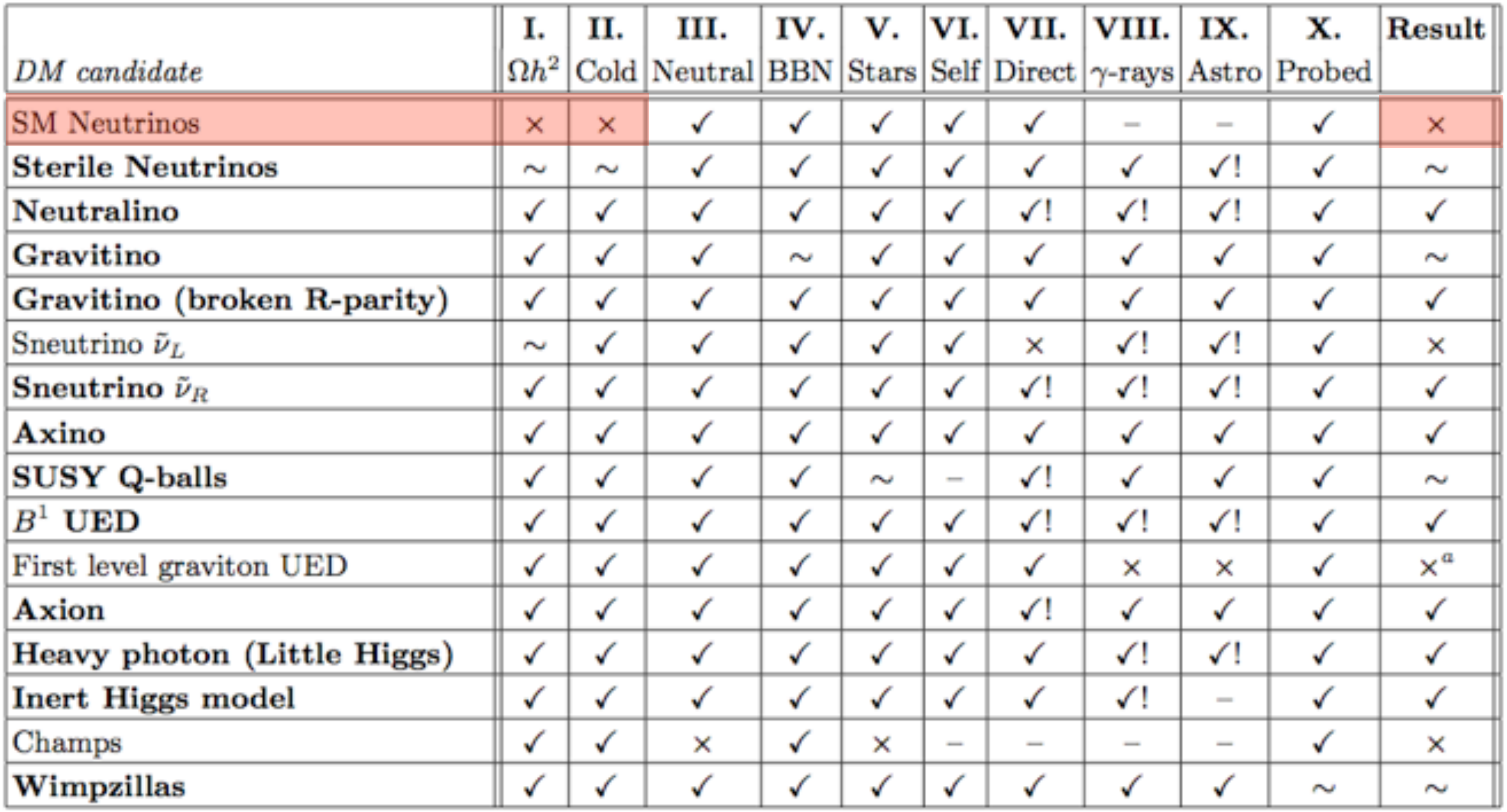

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Sterile Neutrinos	~	~	✓	✓	✓	✓	✓	✓	✓!	✓	~
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	~
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	~	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
B^1 UED	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (Little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

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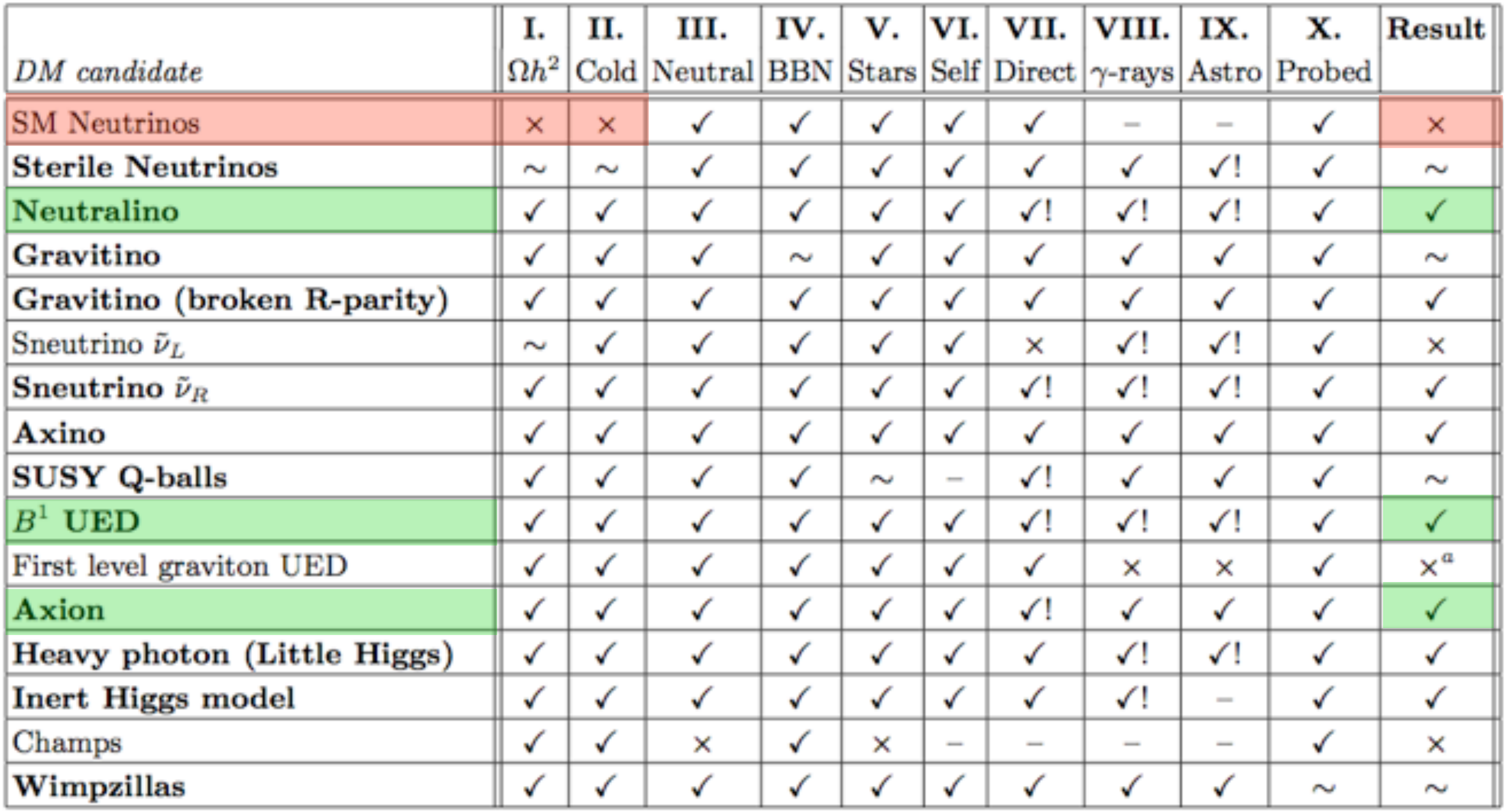

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Sneutrino $\tilde{\nu}_L$	~	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
B^1 UED	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
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Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

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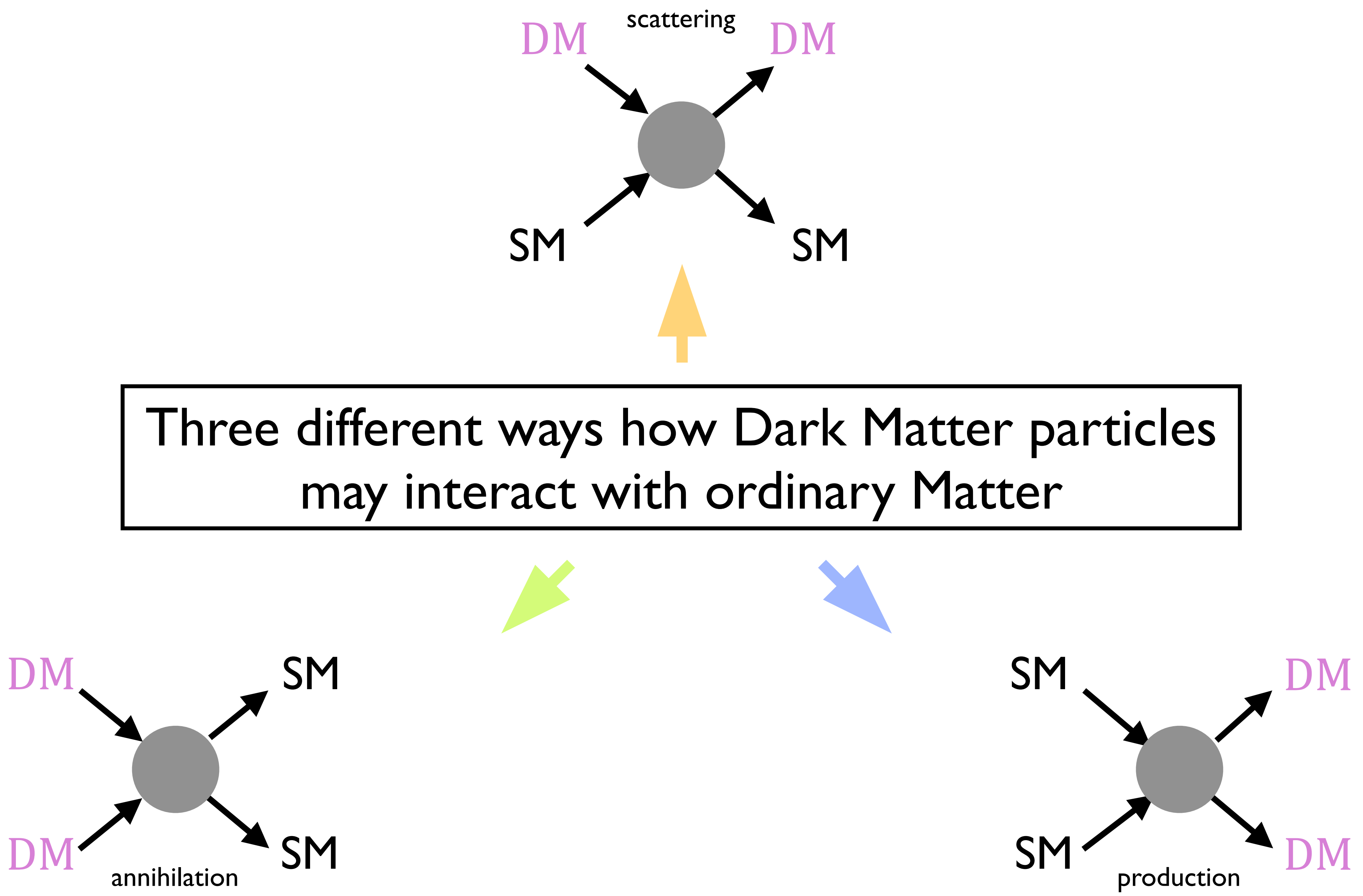
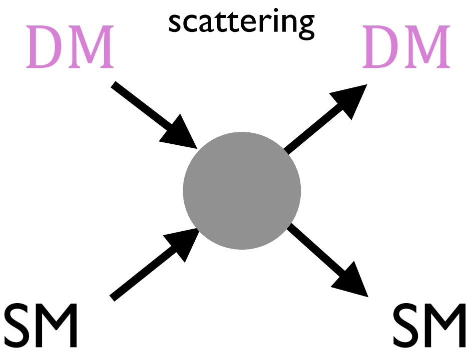
Three ways to find Particle Dark Matter



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

Patrick Decowski

Three ways to find Particle Dark Matter

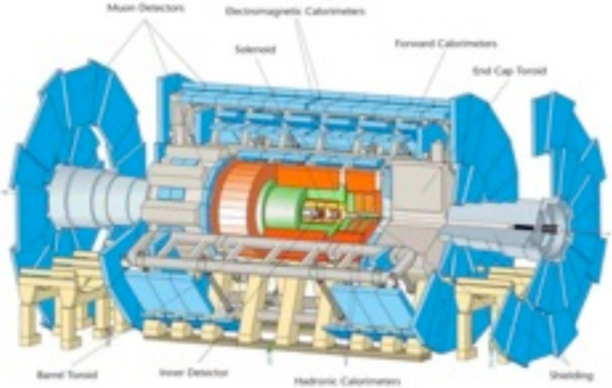


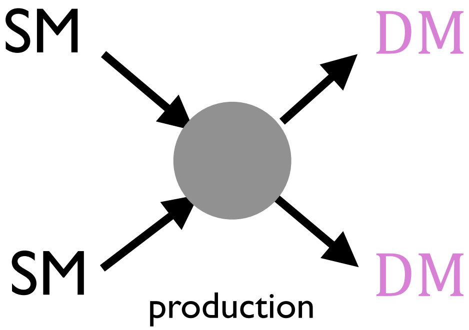
DM scattering DM

SM SM

XENON

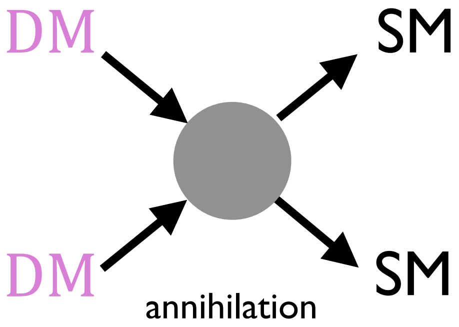
DM @ LHC





SM DM

SM production DM



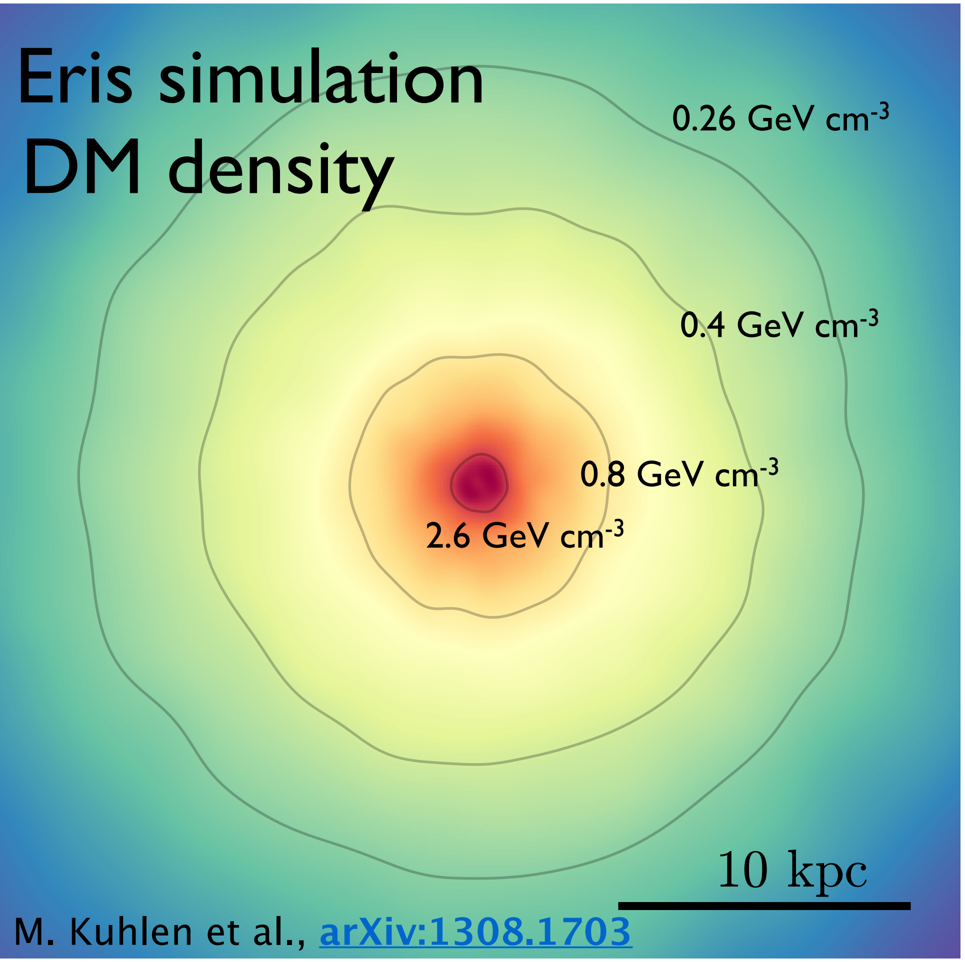
DM SM

DM annihilation SM

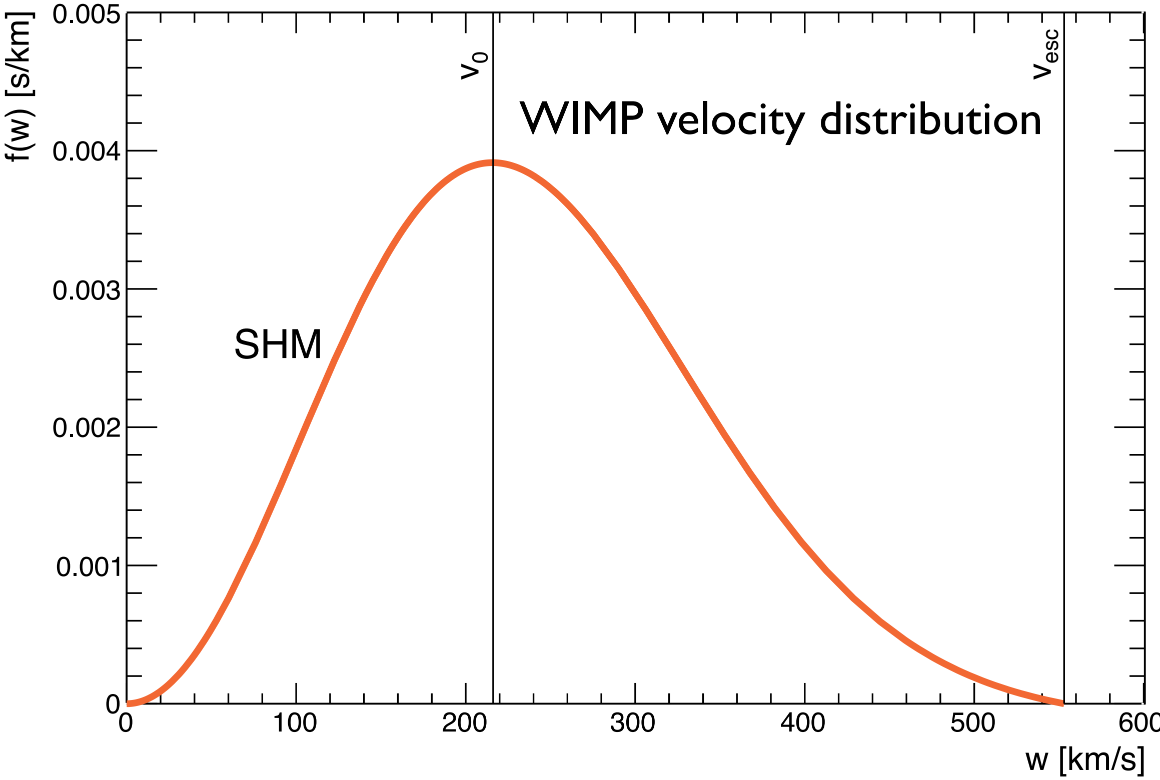
FERMI Satellite

Dark Matter density and velocity distribution

From astrophysics: observation & simulation



M. Kuhlen et al., arXiv:1308.1703



Local DM density: ρ_{DM} = 0.3 GeV cm^{-3}

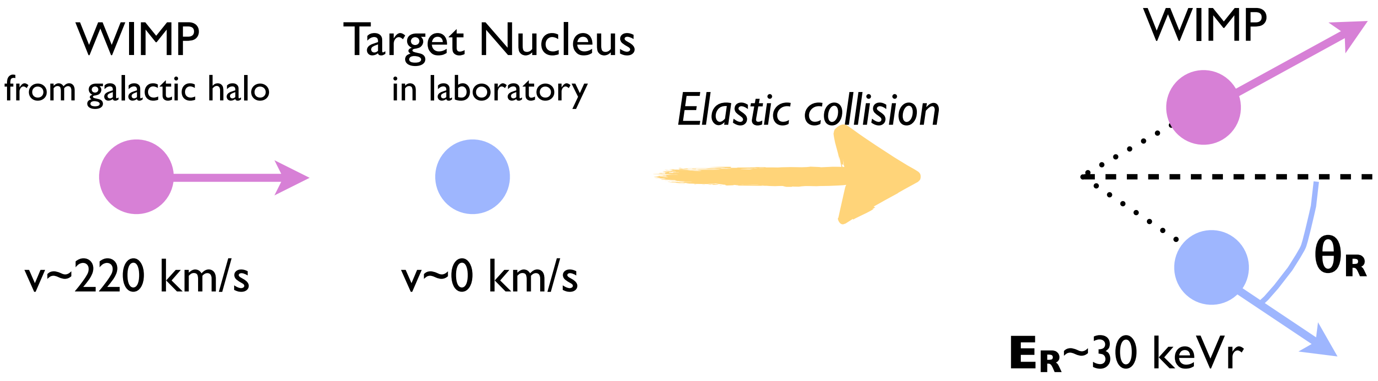
→ Flux of 10^5 cm^{-2} s^{-1} for a 100 GeV WIMP

Preliminaries

Sun velocity vector pointing roughly to Cygnus

Assume WIMP is not only gravitationally interacting

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



WIMP
from galactic halo

v~220 km/s

Target Nucleus
in laboratory

v~0 km/s

Elastic collision

WIMP

θ_R

E$_R$~30 keVr

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

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

Preliminaries II

We measure:

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

Effective interaction Lagrangian (low E limit, v~10^{-3}c):

$$\mathcal{L}_{\rm eff} = f_q \bar{\chi}\chi\bar{q}q + d_q \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q + \ldots$$

Scalar Axial

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

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

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Need input from Astrophysics

Effective interaction Lagrangian (low E limit, v~10^{-3}c):

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WIMP-Nucleus Cross Section

Spin-independent cross section:

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

Better sensitivity
with high A

Spin-dependent cross section:

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

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

Only axial vector describing state of nucleus as q → 0

WIMP-Nucleus Cross Section

Spin-independent cross section:

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

Better sensitivity
with high A

Spin-dependent cross section:

Nuclear model:
$\langle S_{p,n} \rangle = \langle N | S_{p,n} | N \rangle$

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

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WIMP couplings to protons & neutrons

WIMP-Nucleus Cross Section

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

Better sensitivity
with high A

Spin-dependent cross section:

Need nucleus with spin:

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

Nuclear model:
$\langle S_{p,n}\rangle = \langle N|S_{p,n}|N\rangle$

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

Only axial vector
describing state
of nucleus as q → 0

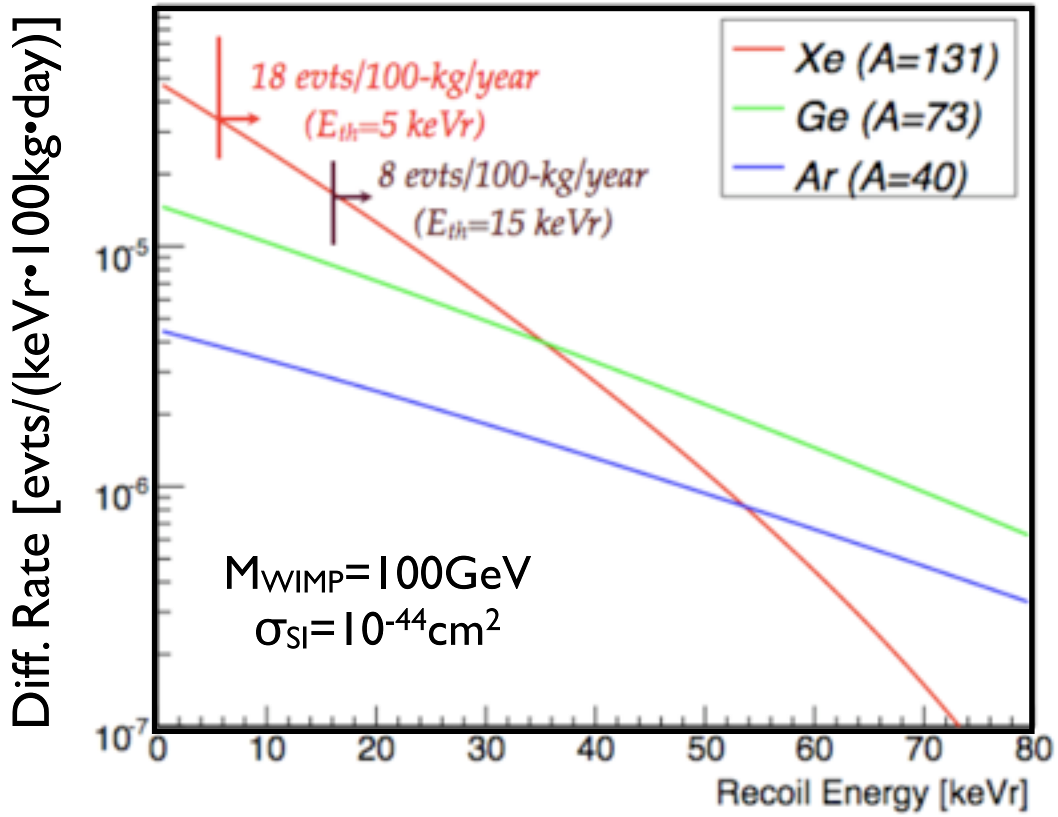
WIMP couplings to protons & neutrons

WIMP-nucleus scattering

- Need to consider 3 energy scales for WIMP-nucleus elastic scattering
  - Electroweak scale: determines composition and mass of WIMP
    - E.g. the SUSY part of the problem → sweeps through SUSY parameter space
  - QCD scale: determines quark distributions inside the nucleons (both spin&density)
    - This has been measured to high precision
  - Nuclear physics: at the modest scattering energies, interaction is with the entire nucleus:
    - Not measurable and need to rely on calculations → e.g. nuclear shell model

Expected Energy Spectrum

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

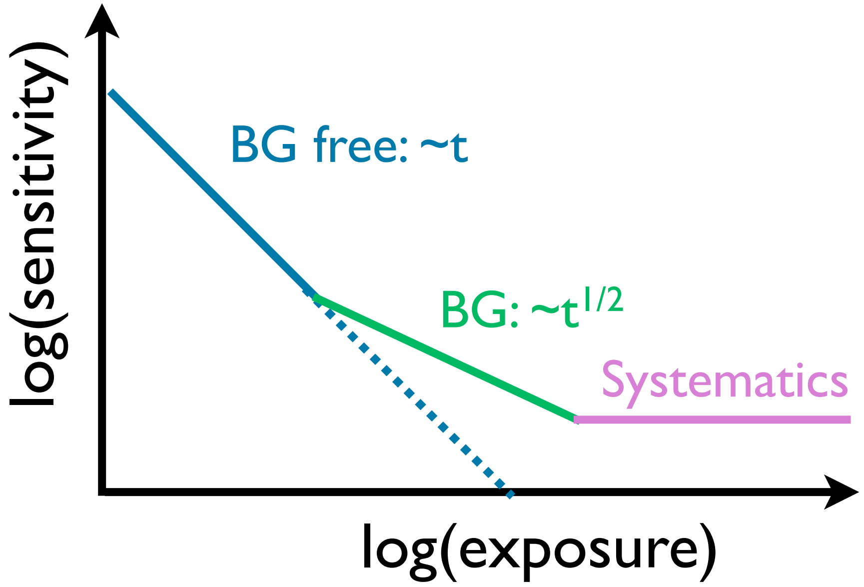


M_{WIMP}=100GeV
$\sigma_{SI}=10^{-44}\text{cm}^2$

- 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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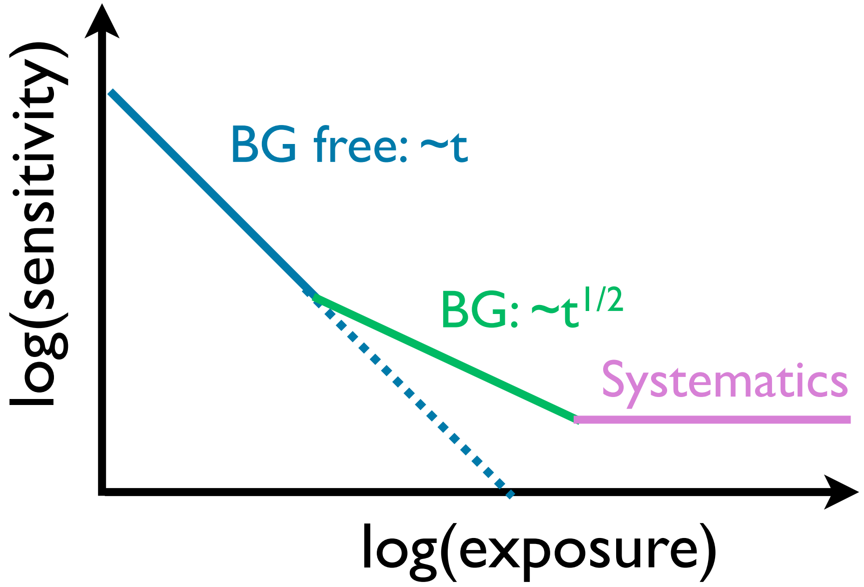
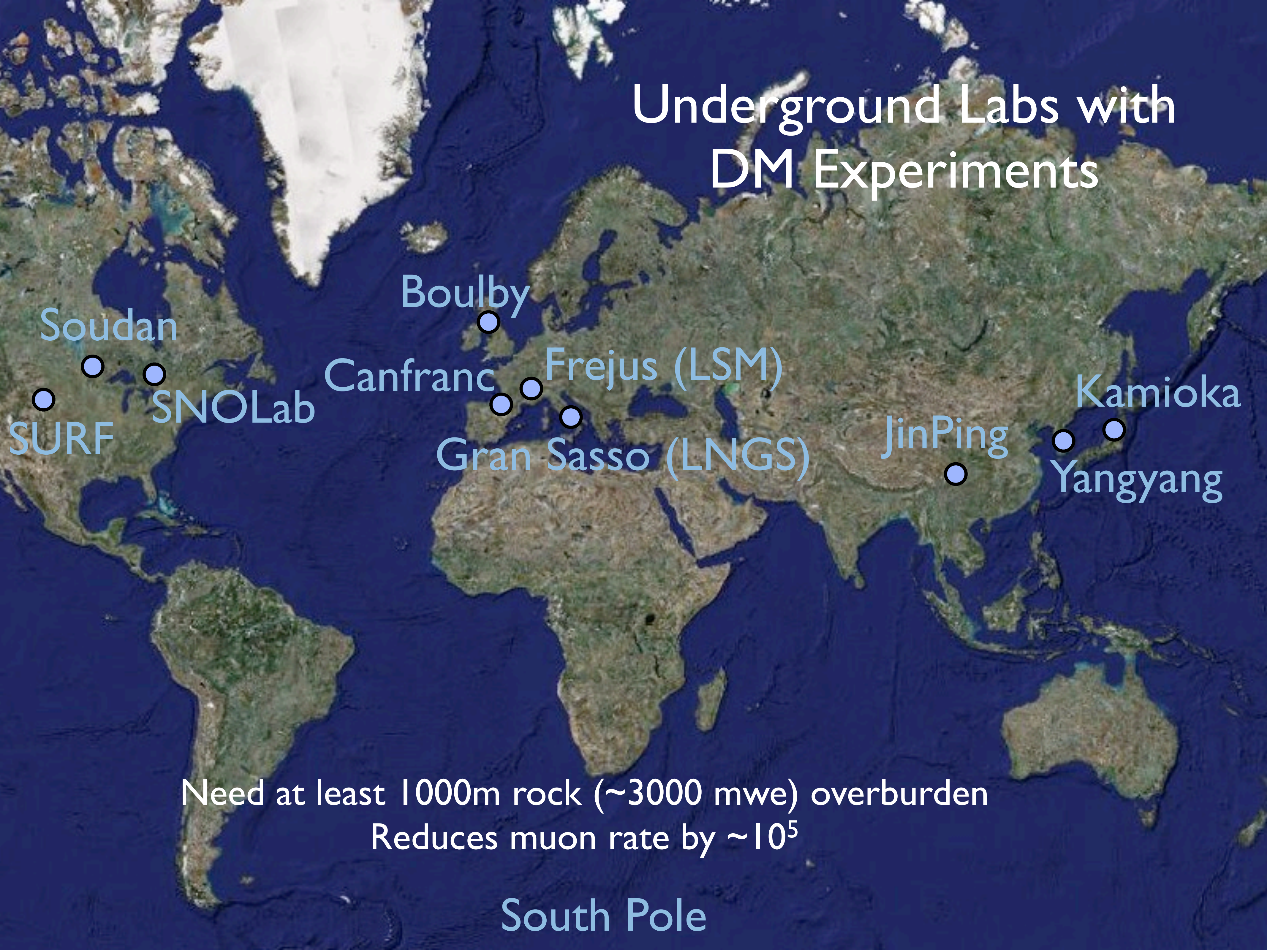


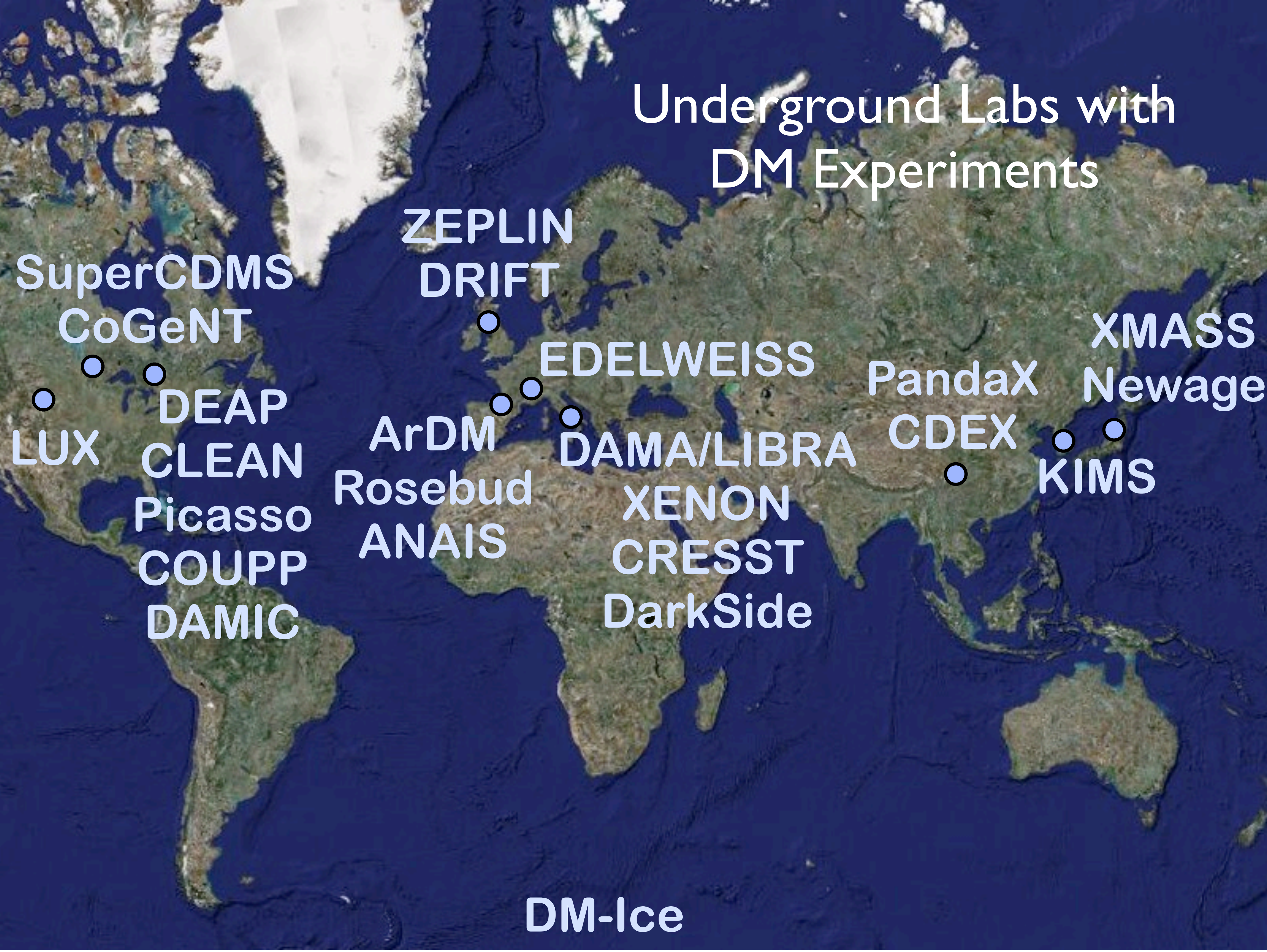
Current state-of-the-art: <1 ev/(kg·yr)
Moving to: 1 ev/(ton·yr)

Underground Labs with DM Experiments

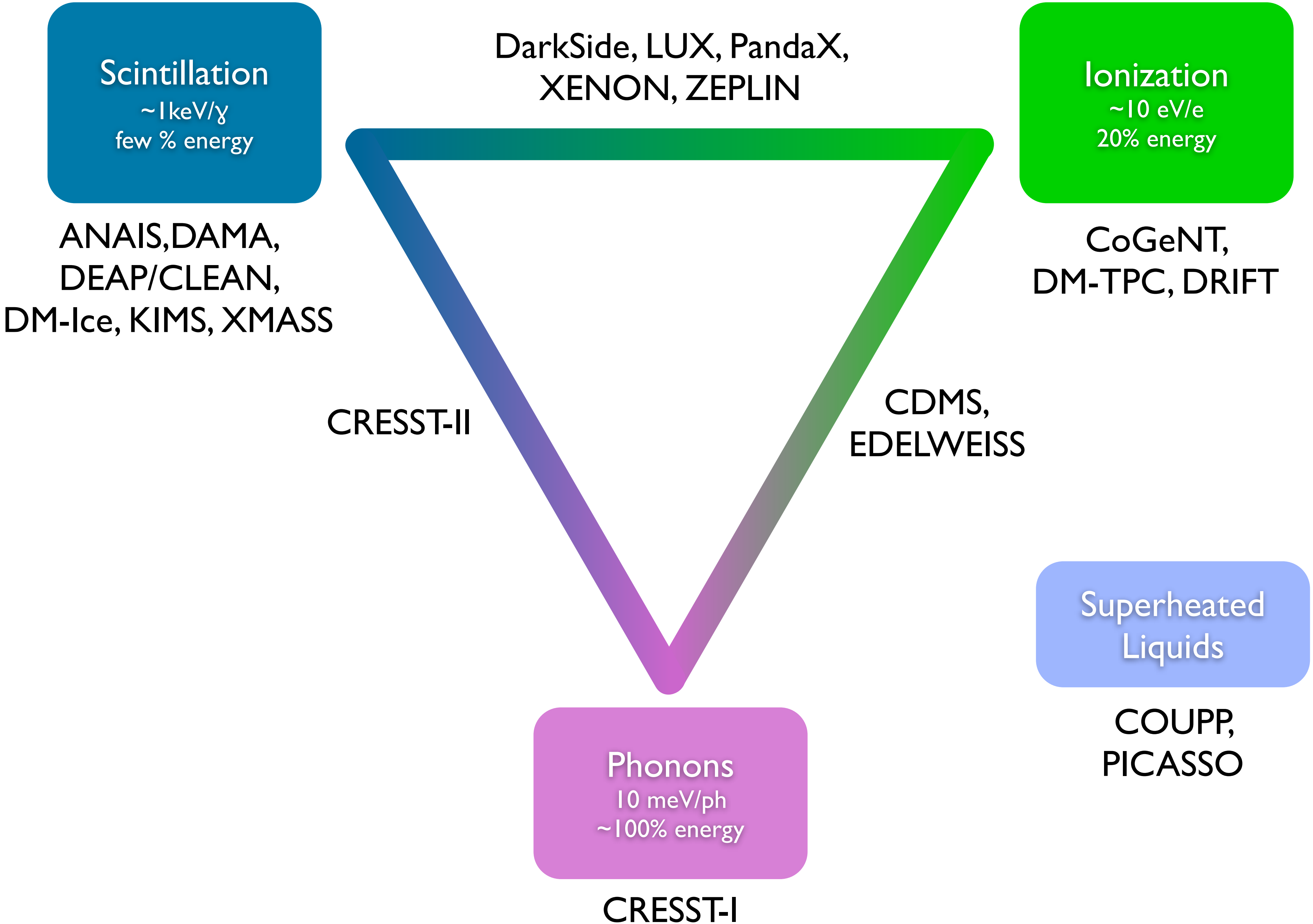


Need at least 1000m rock (~3000 mwe) overburden
Reduces muon rate by ~10^5

Underground Labs with DM Experiments



Detection Techniques



Scintillation
~1keV/ɣ
few % energy

ANAIS,DAMA,
DEAP/CLEAN,
DM-Ice, KIMS, XMASS

DarkSide, LUX, PandaX,
XENON, ZEPLIN

Ionization
~10 eV/e
20% energy

CoGeNT,
DM-TPC, DRIFT

CRESST-II

CDMS,
EDELWEISS

Superheated Liquids

COUPP,
PICASSO

Phonons
10 meV/ph
~100% energy

CRESST-I

Particle-dependent Response

CDMS, CRESST, DarkSide,
LUX, XENON etc.

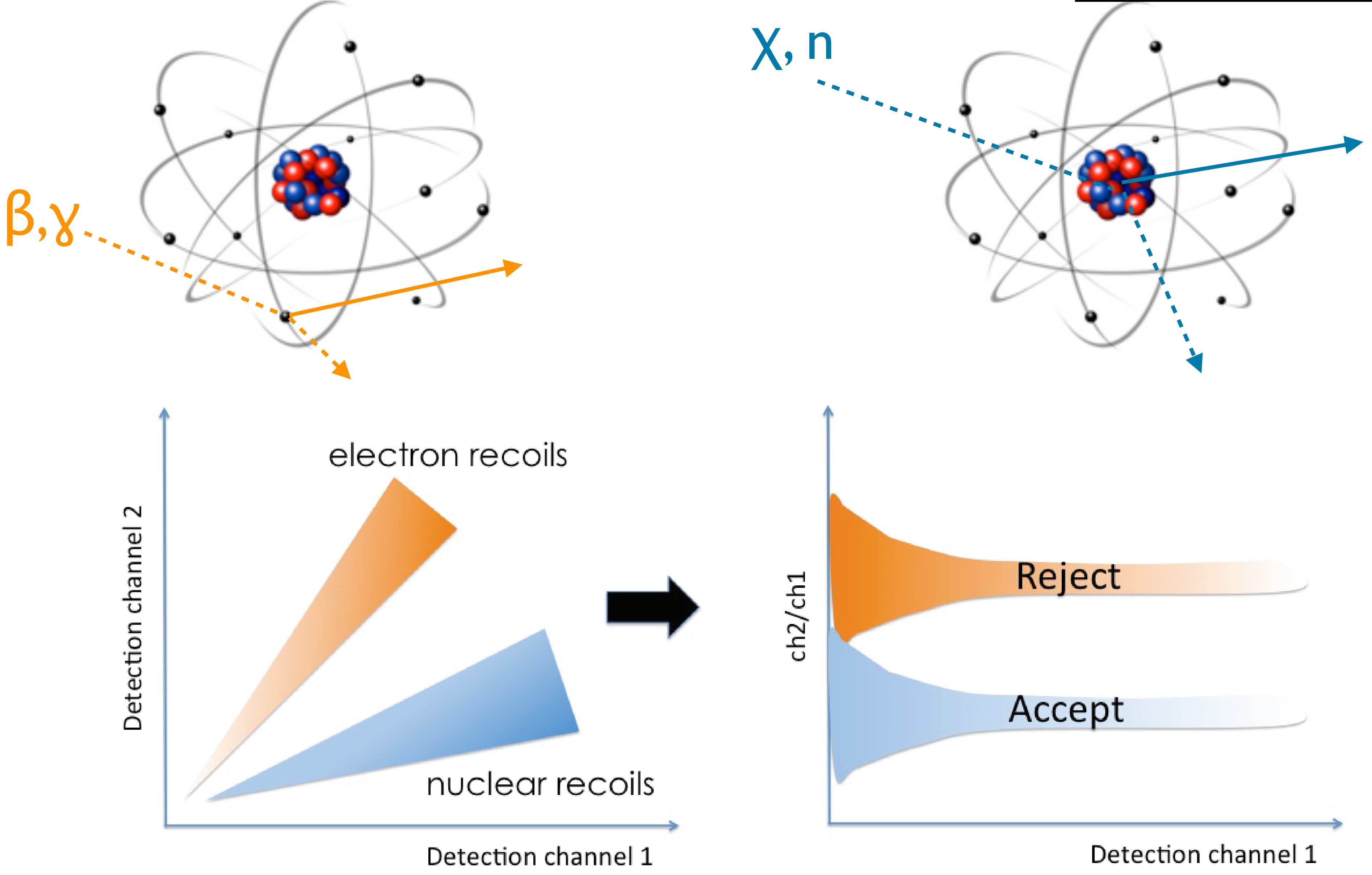


Image E.Pantic

Patr

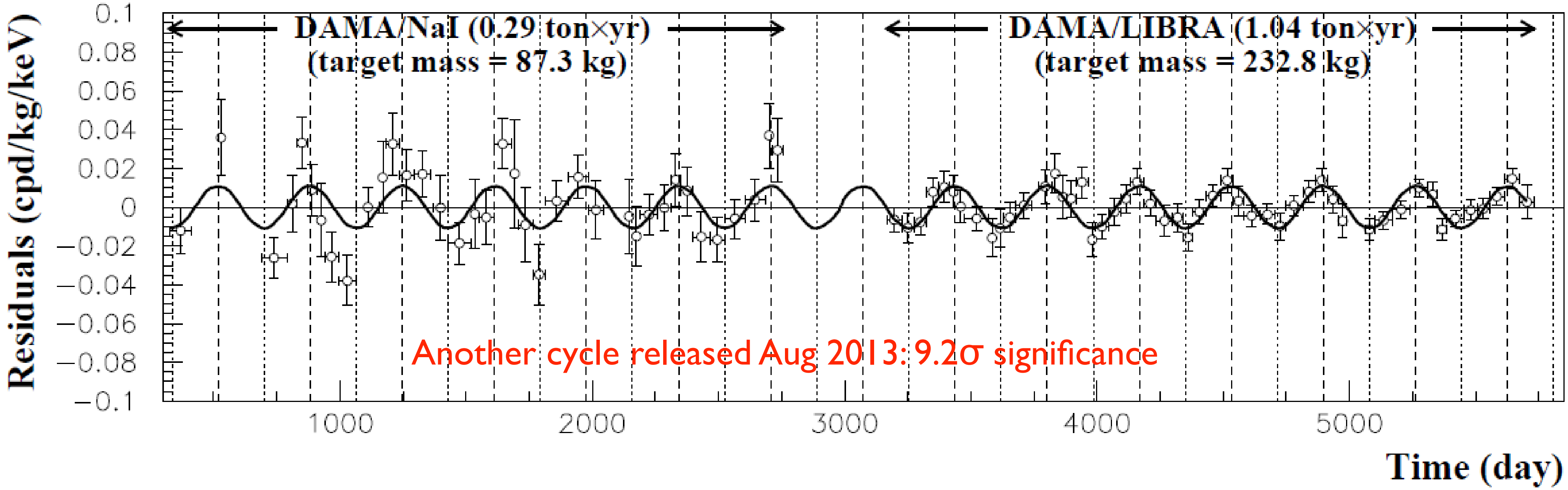
Current Dark Matter Search Status

- Claims
  - **DAMA**: Annual modulations - long-time claim
    - Community is sceptical: something is modulating, but probably 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

Current Dark Matter Search Status

- Claims
  - **DAMA**: Annual modulations - long-time claim

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



Another cycle released Aug 2013: 9.2σ significance

  - **Others** (e.g. COUPP, EDELWEISS, ZEPLIN-III, SIMPLE): exclude most above signals

Current Dark Matter Search Status

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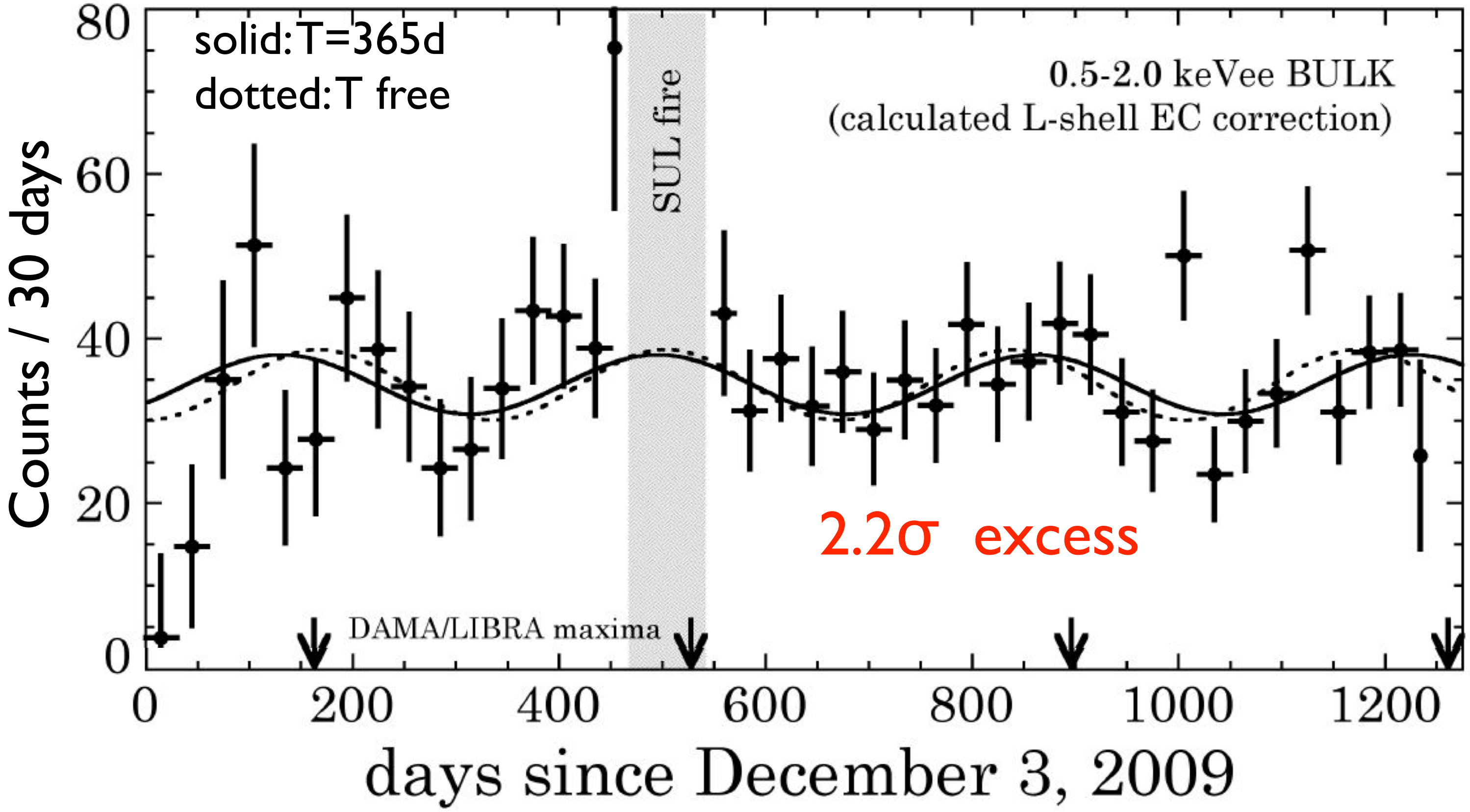
Current Dark Matter Search Status

- <u>Claims</u>

CoGeNT results presented at TAUP2013: ~2.5x more data


solid: T=365d
dotted: T free

2.2σ excess

Current Dark Matter Search Status

- Claims
  - **DAMA**: Annual modulations - long-time claim
    - Community is sceptical: something is modulating, but probably not DM
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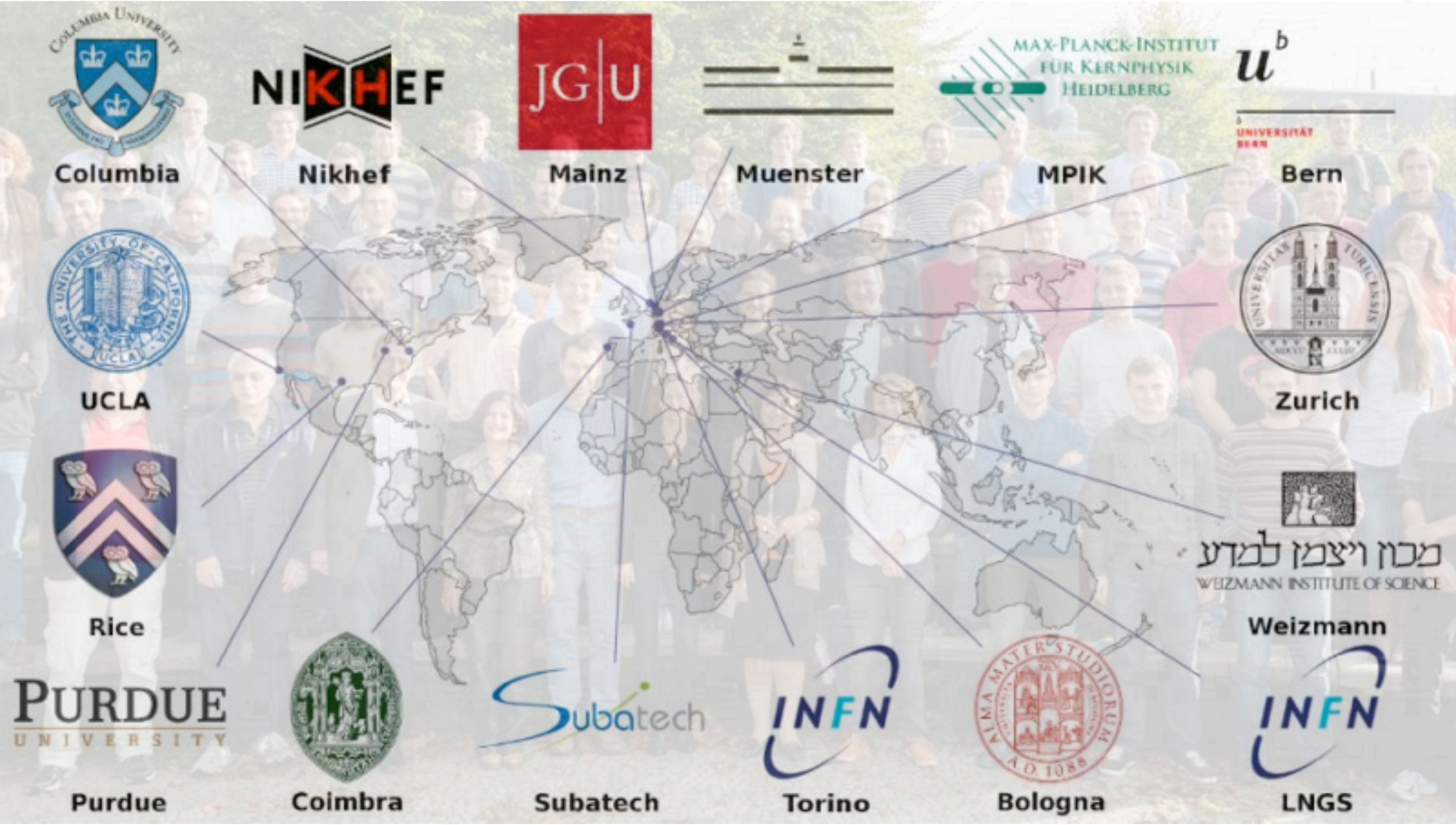
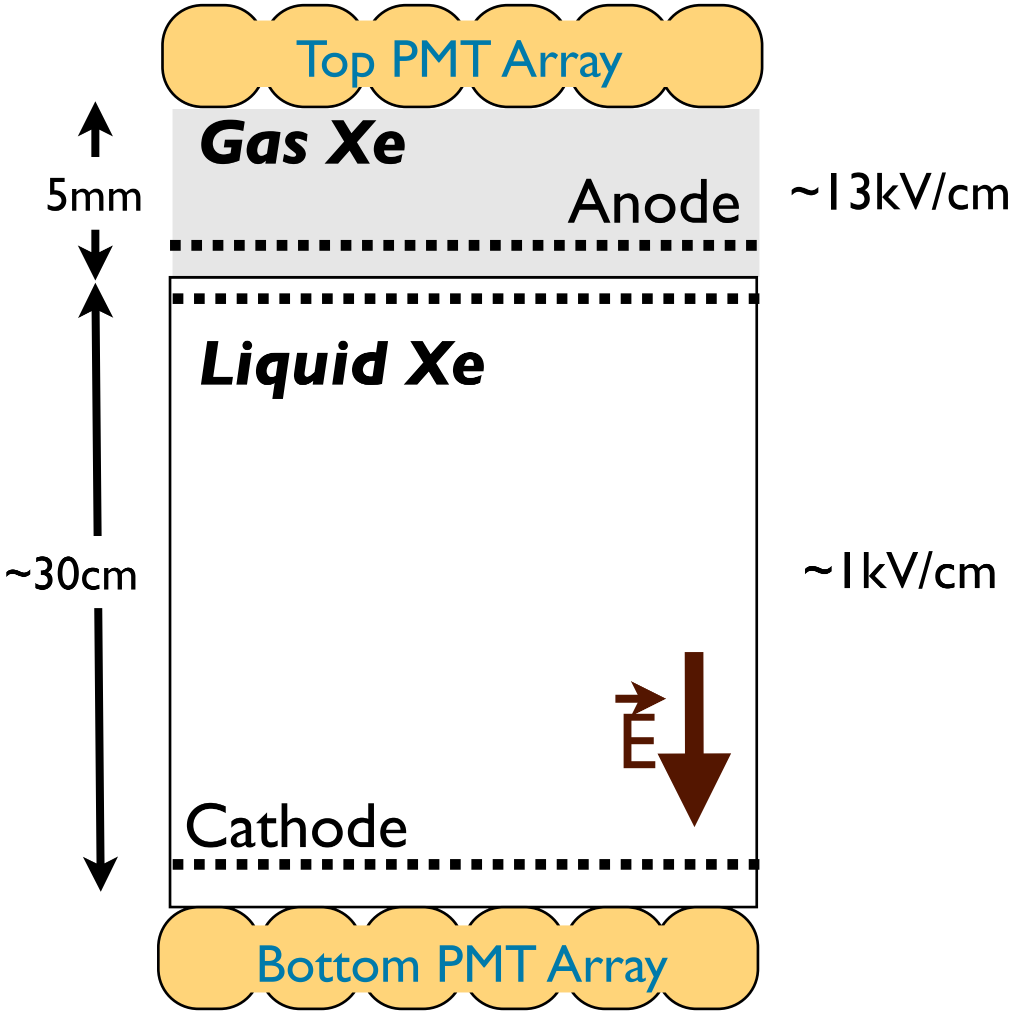
XENON Collaboration

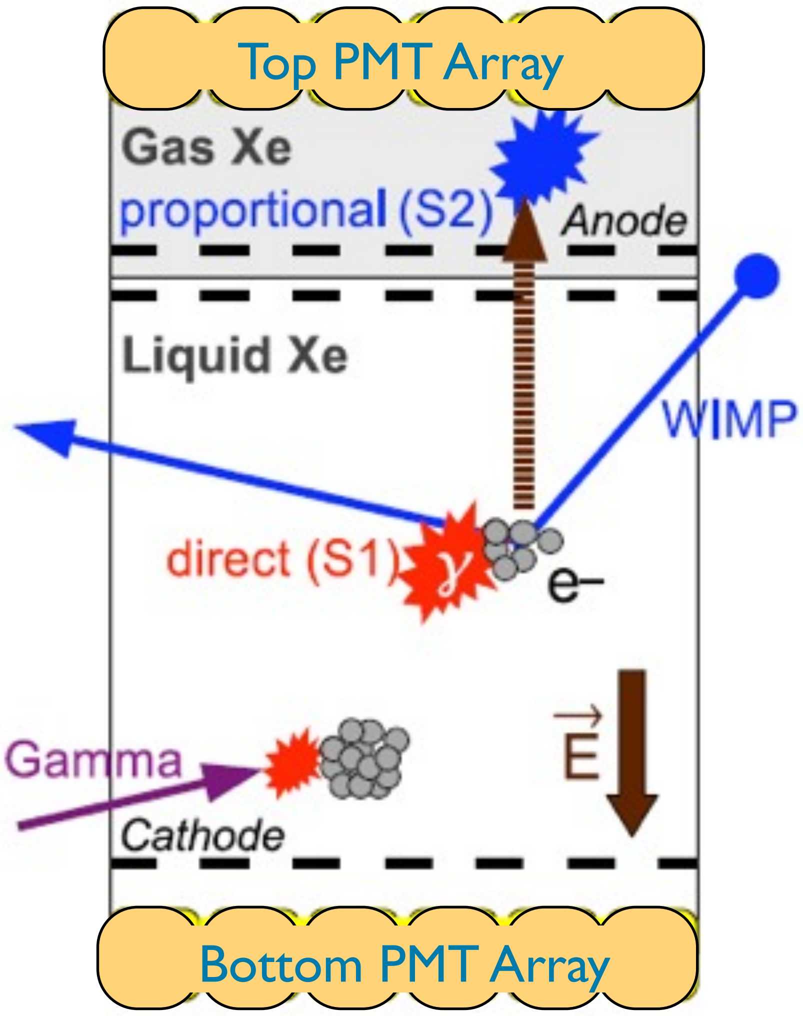


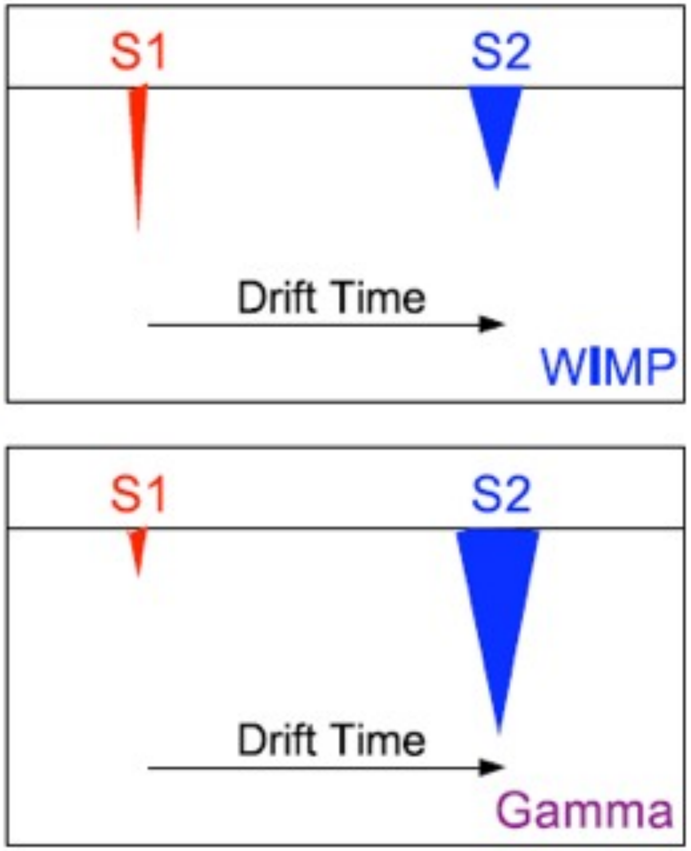
XENON10, XENON100, XENON1T, XENONnT

Dual-Phase Xe TPC



Detection Properties



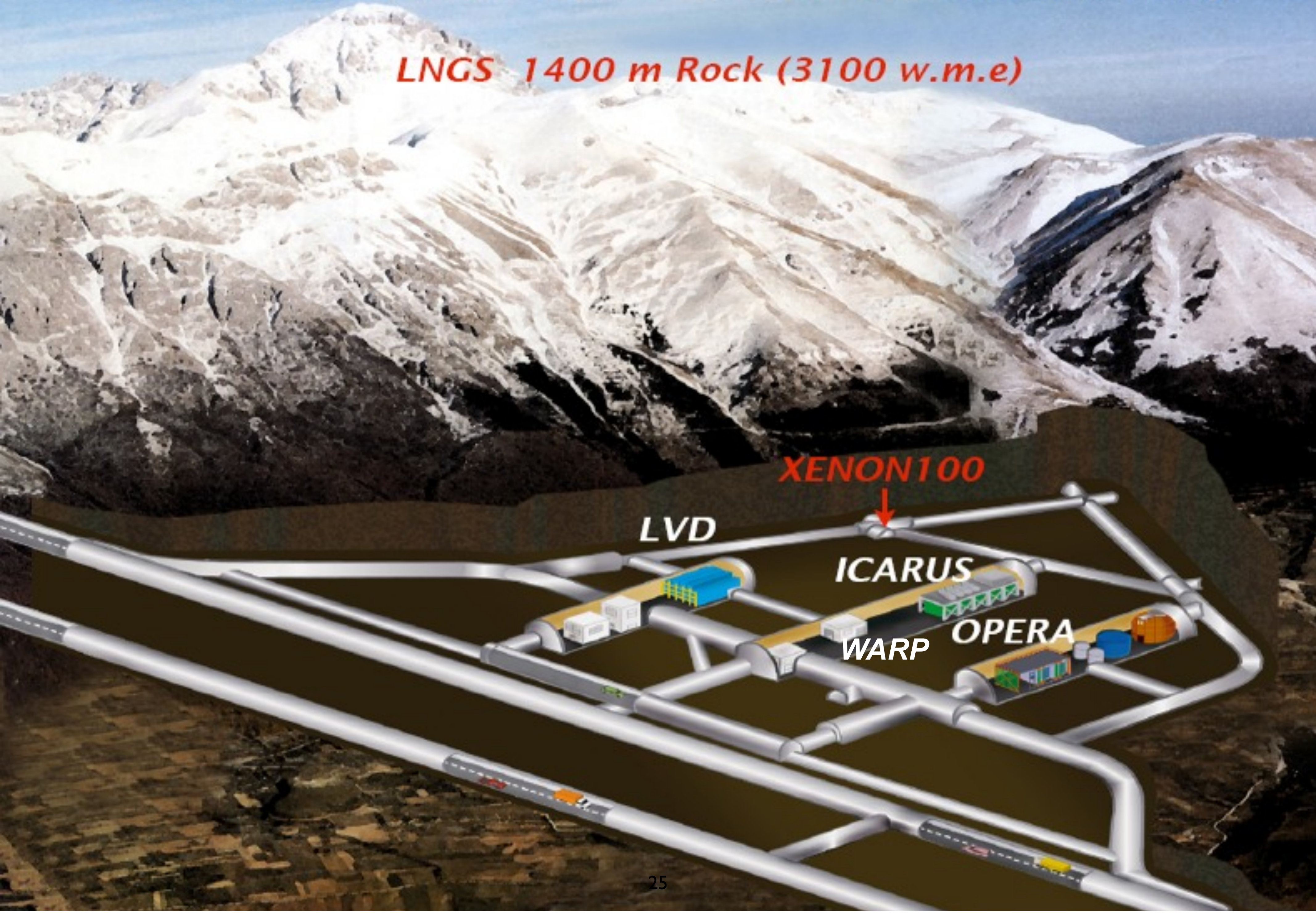


Signal:
Nuclear recoil

Background:
Electron recoil

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

Laboratori Nazionali del Gran Sasso, Italy



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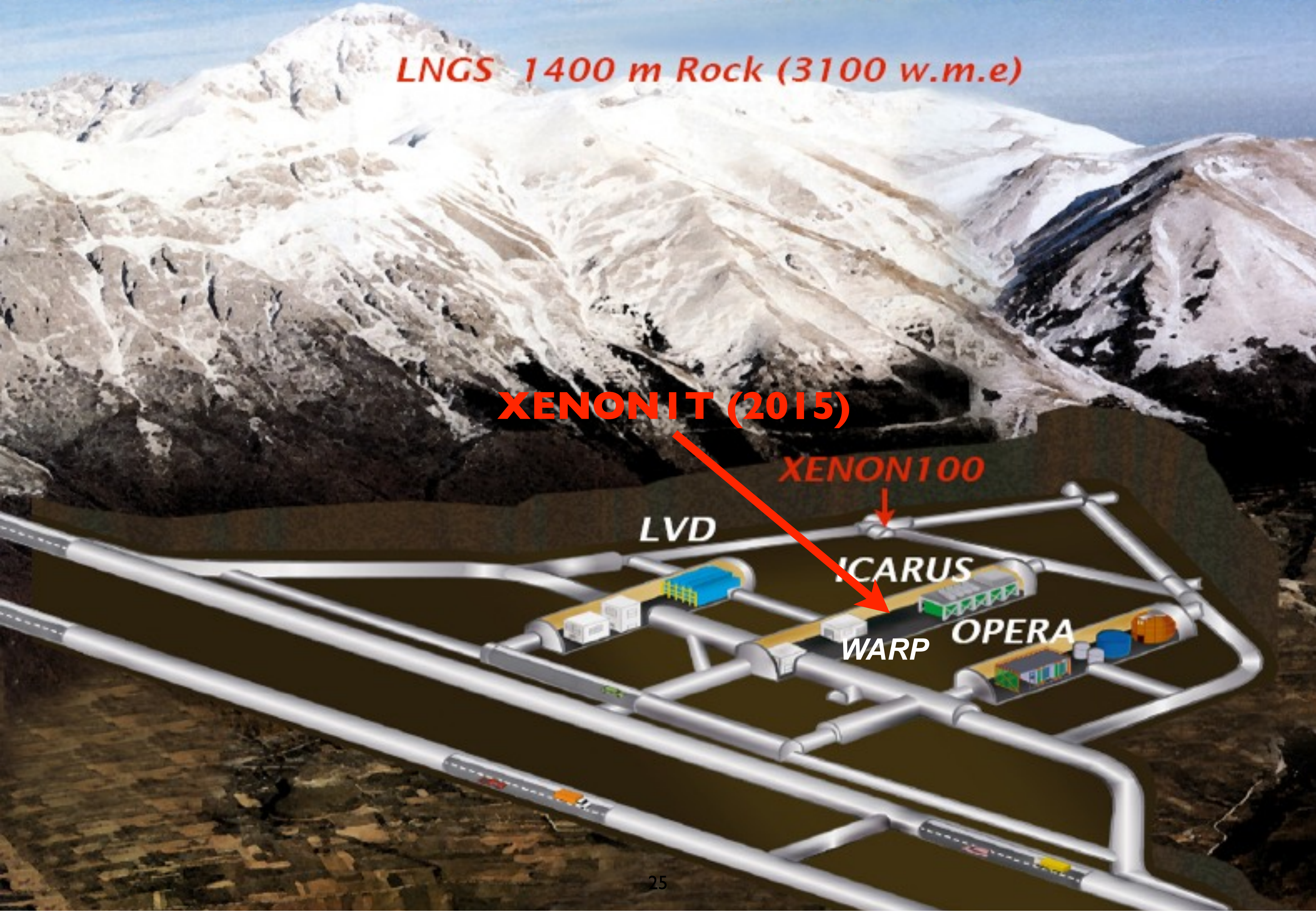
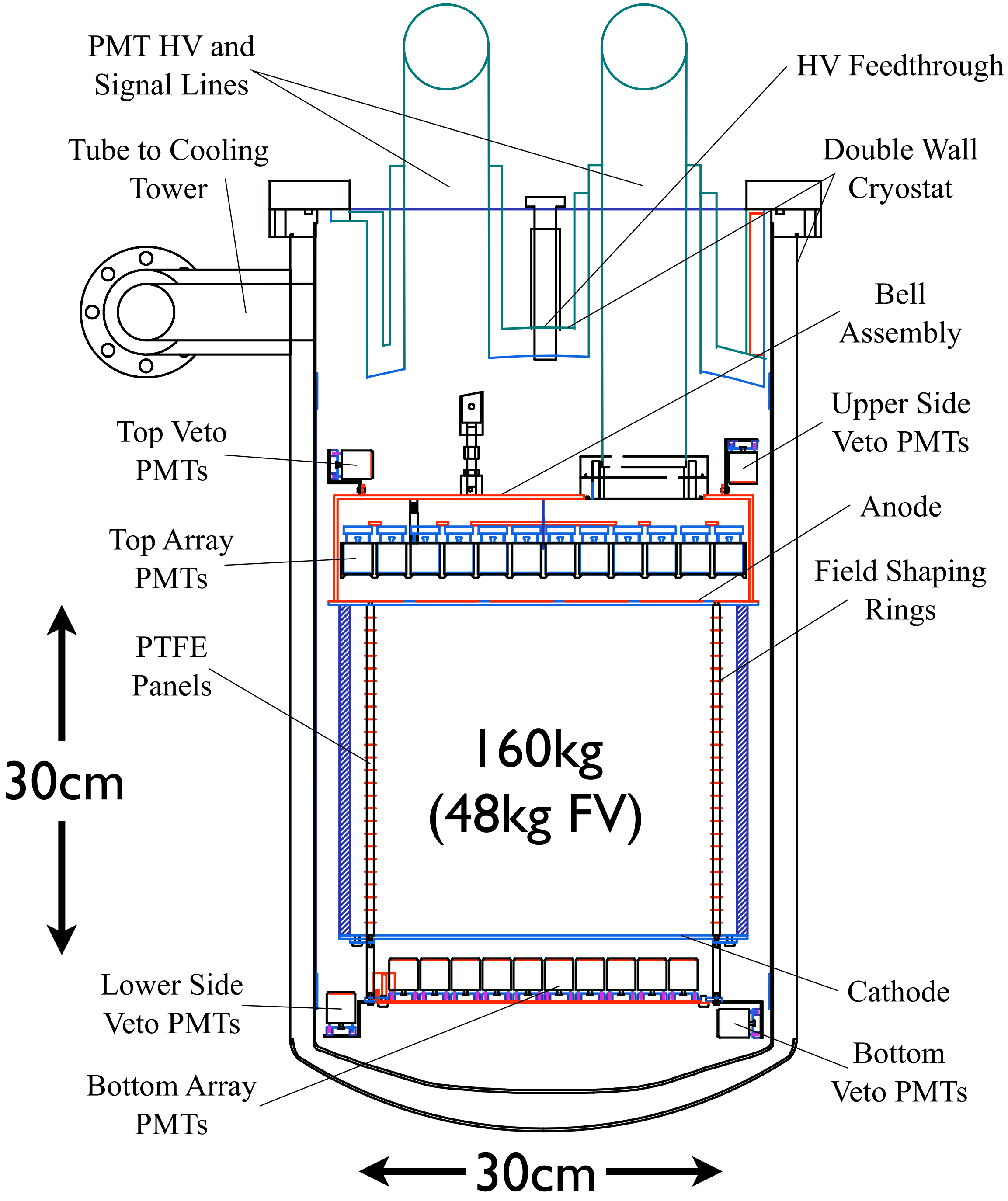
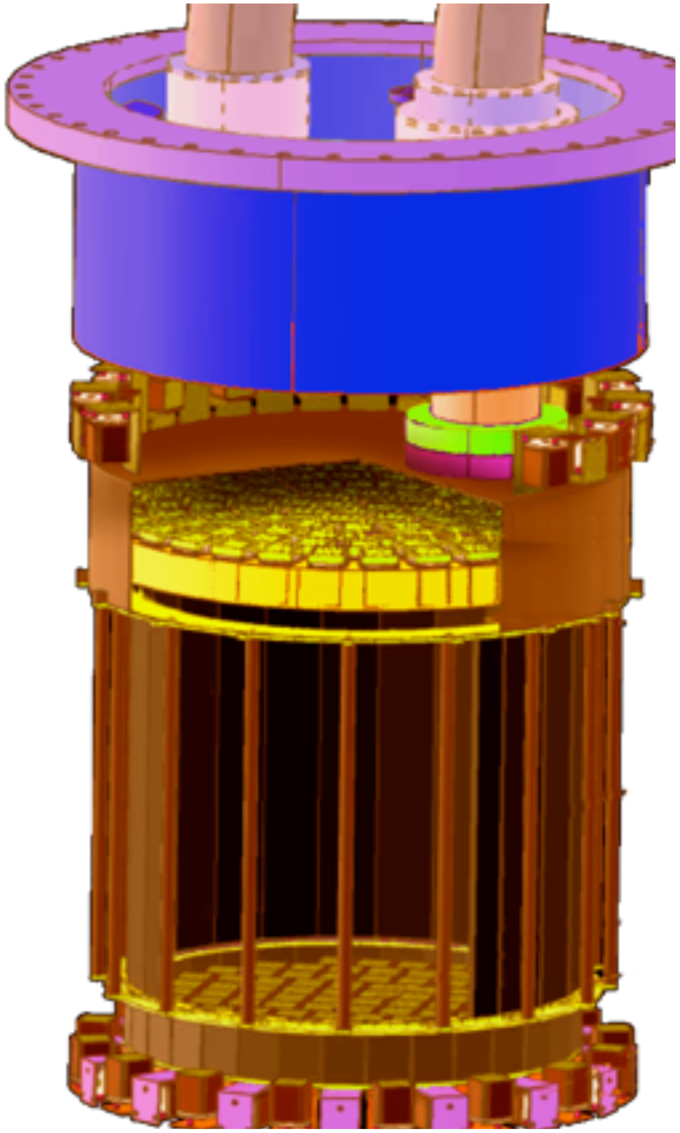


XENON100



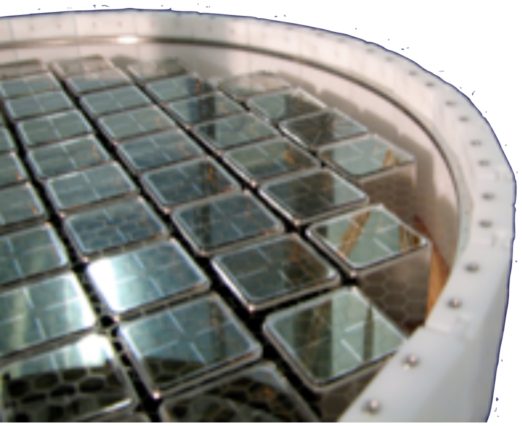


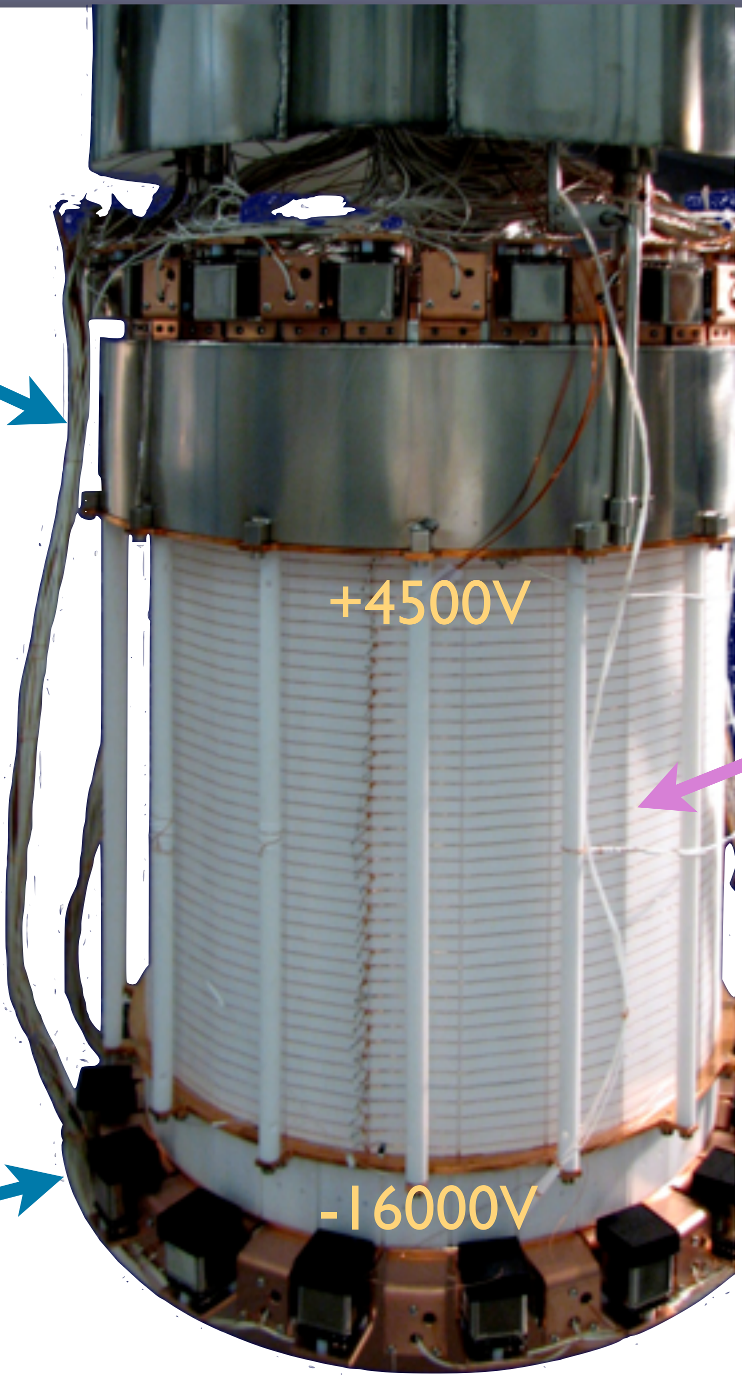
XENON100 started physics run in early 2010

XENON100

Top array: 98 PMTs

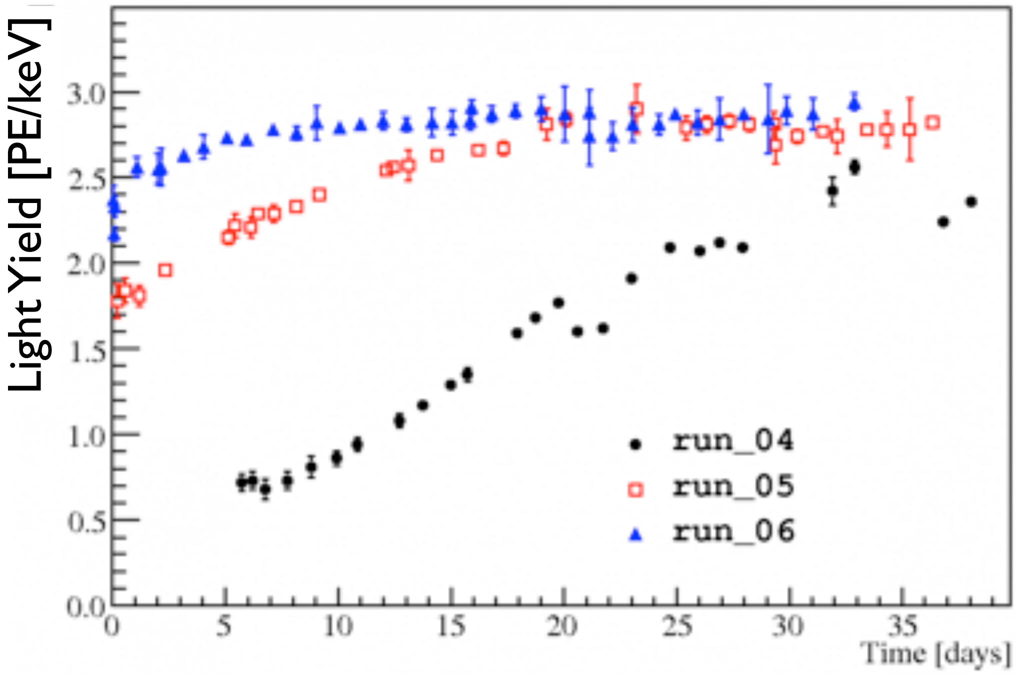
Bottom array: 80 PMTs





PTFE TPC,
Field shaping rings

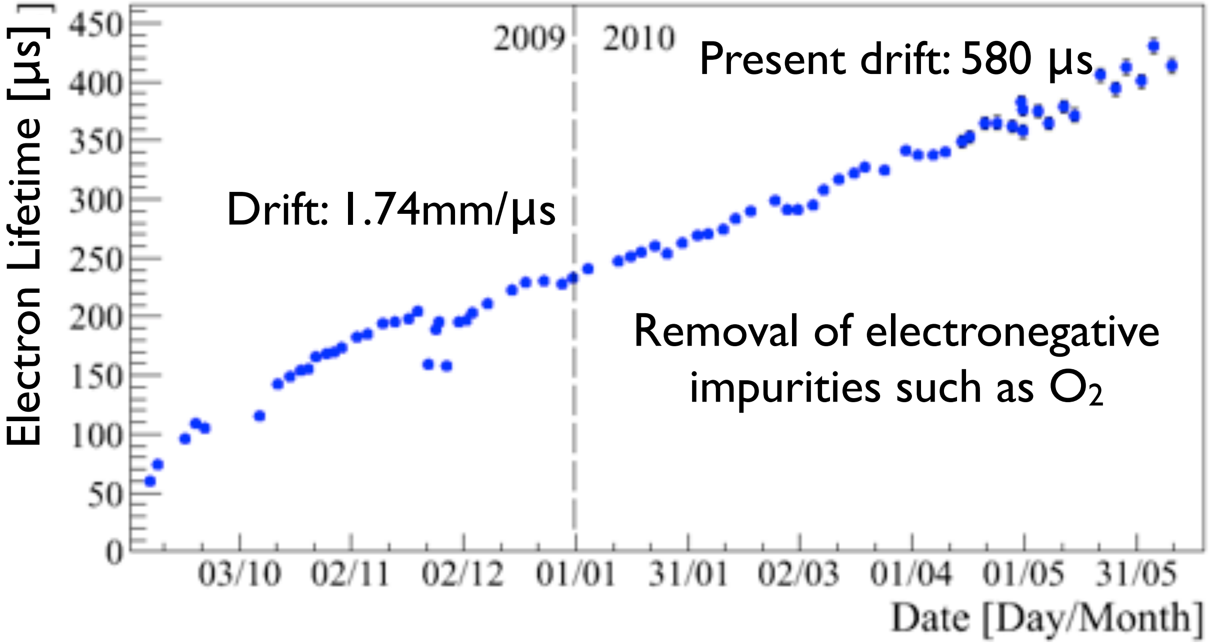
Impurities



Non-radioactive impurities have an impact on:

- Light Yield
- Electron Lifetime

→ Purify continuously

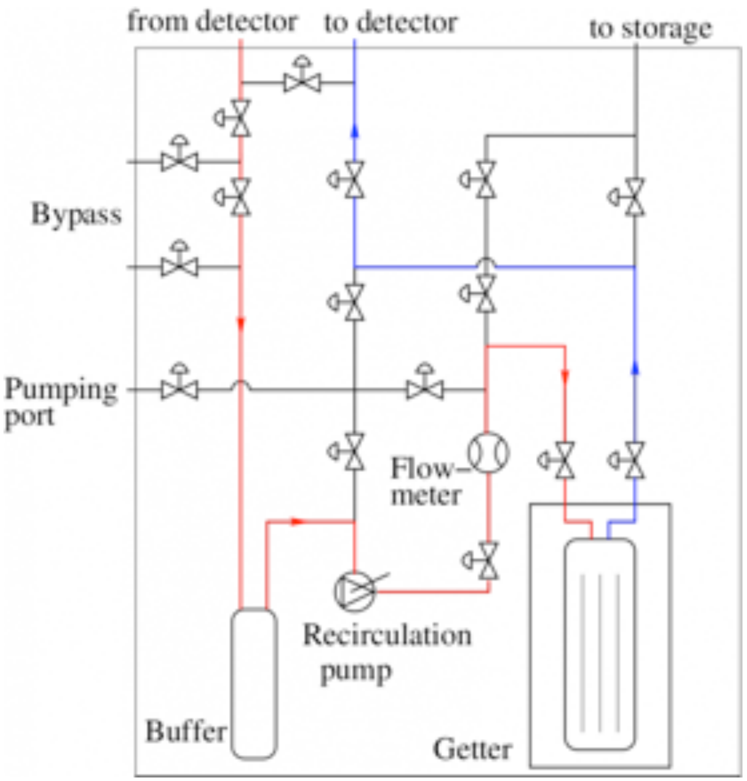


Present drift: 580 µs

Drift: 1.74mm/µs

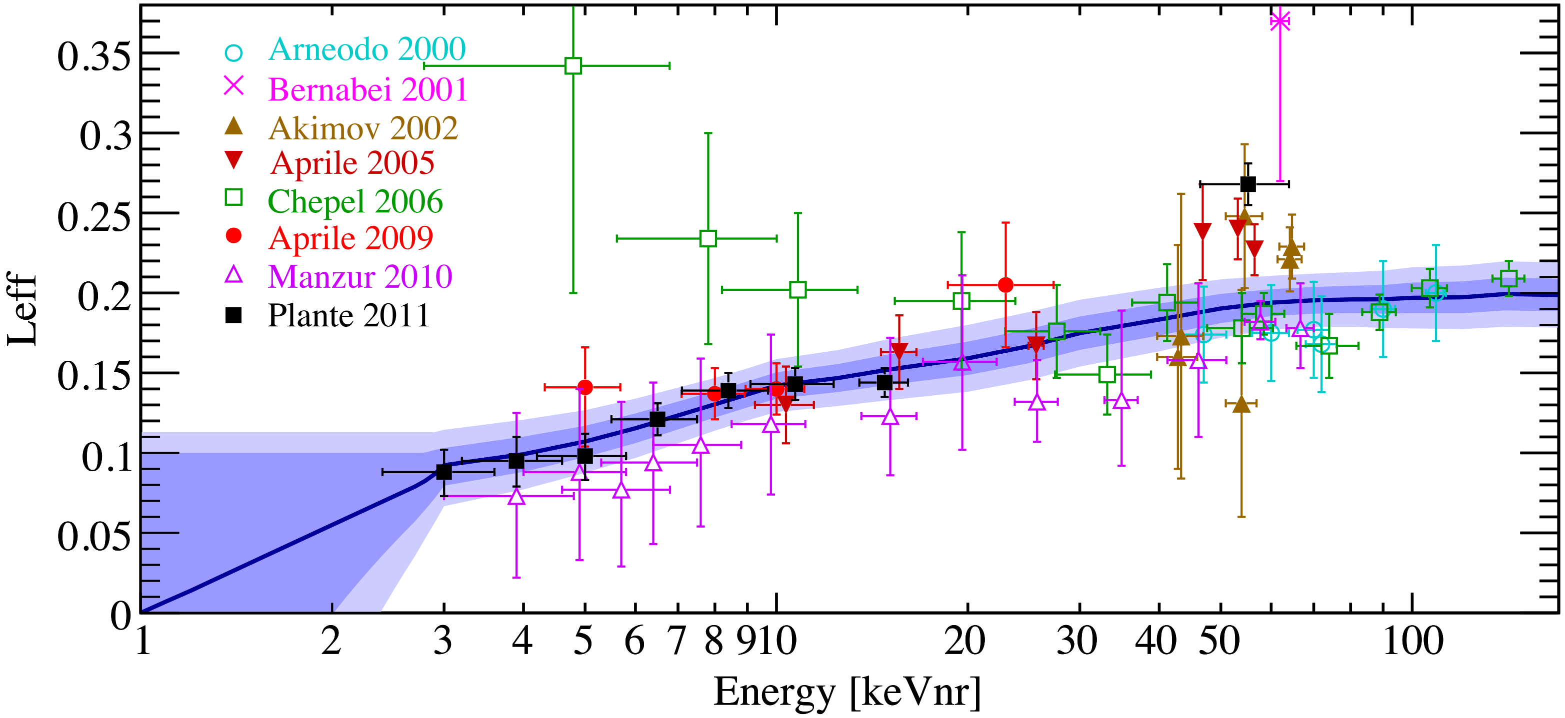
Removal of electronegative impurities such as O_2

Gas purification system



Energy determination

E_{nr} = fcn(S1) → measured in dedicated setups



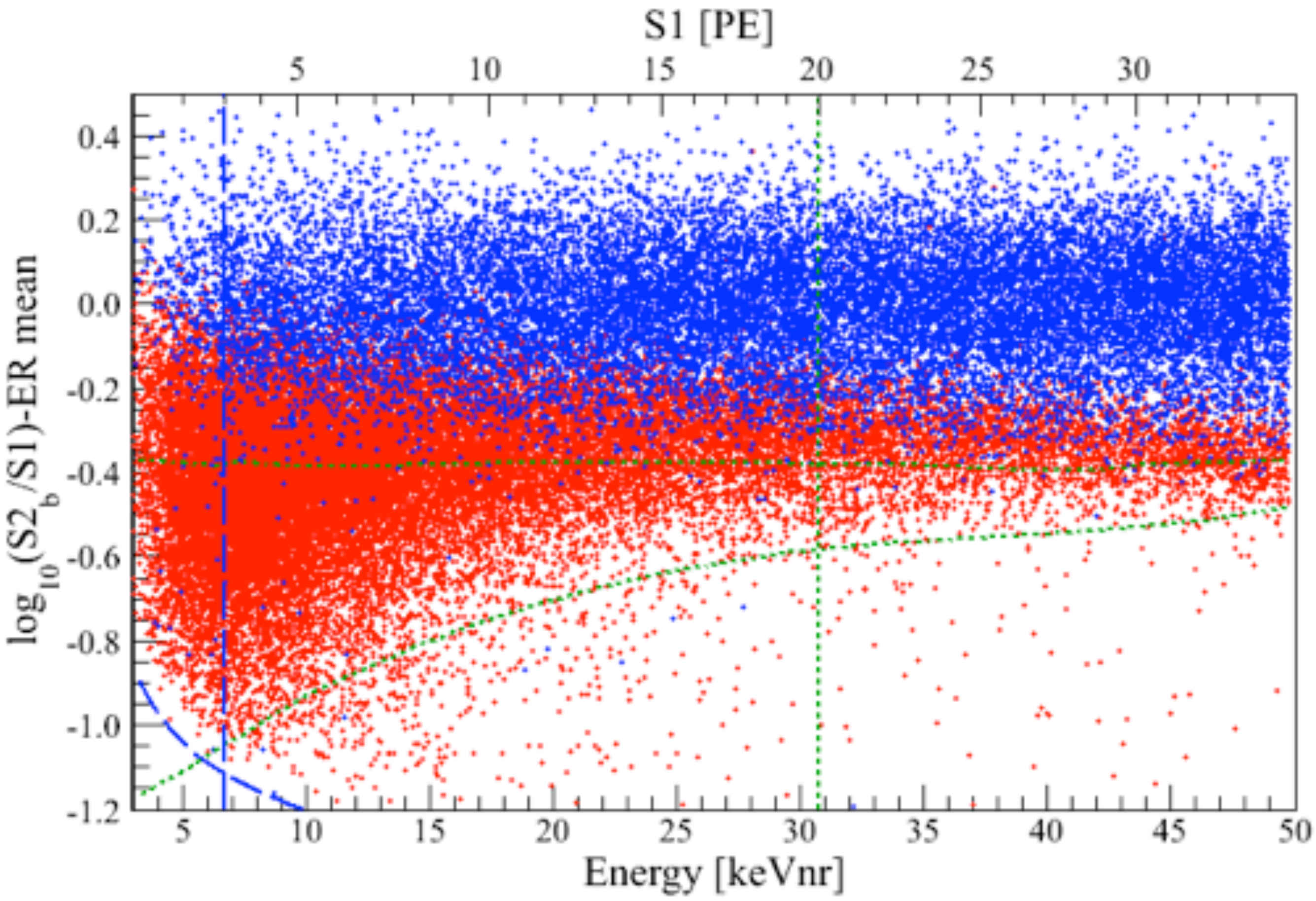
$$E_{nr} = \frac{S_1}{L_y \cdot \mathcal{L}_{eff}} \cdot \frac{S_e}{S_n}$$

Patrick Decowski - Nikhef

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

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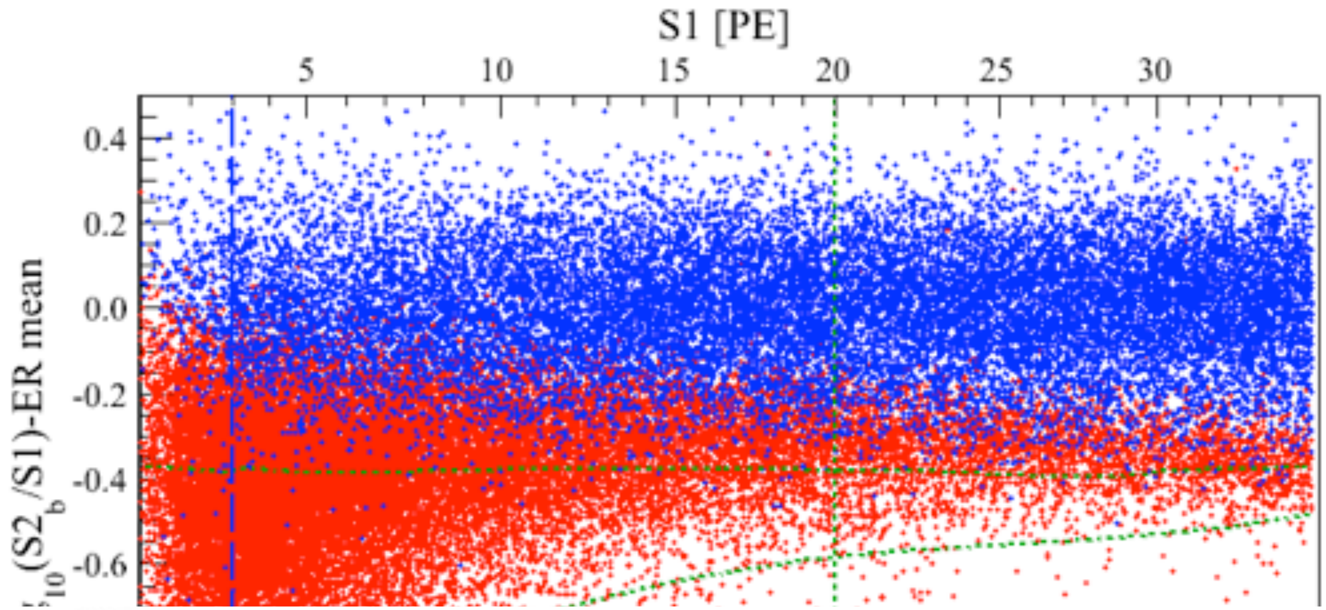

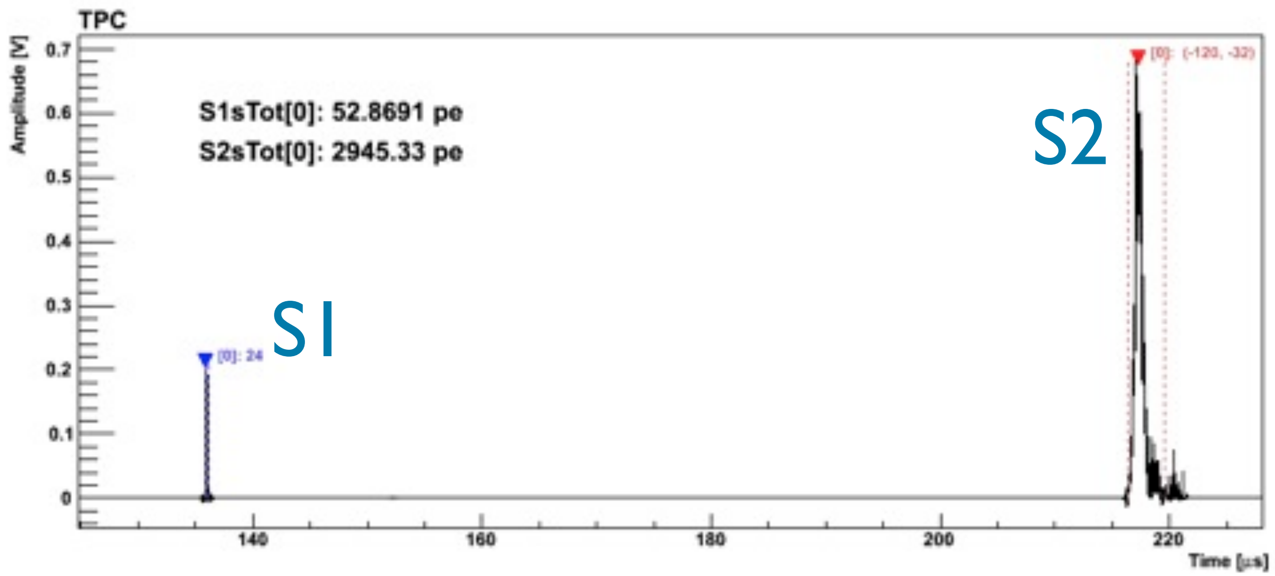

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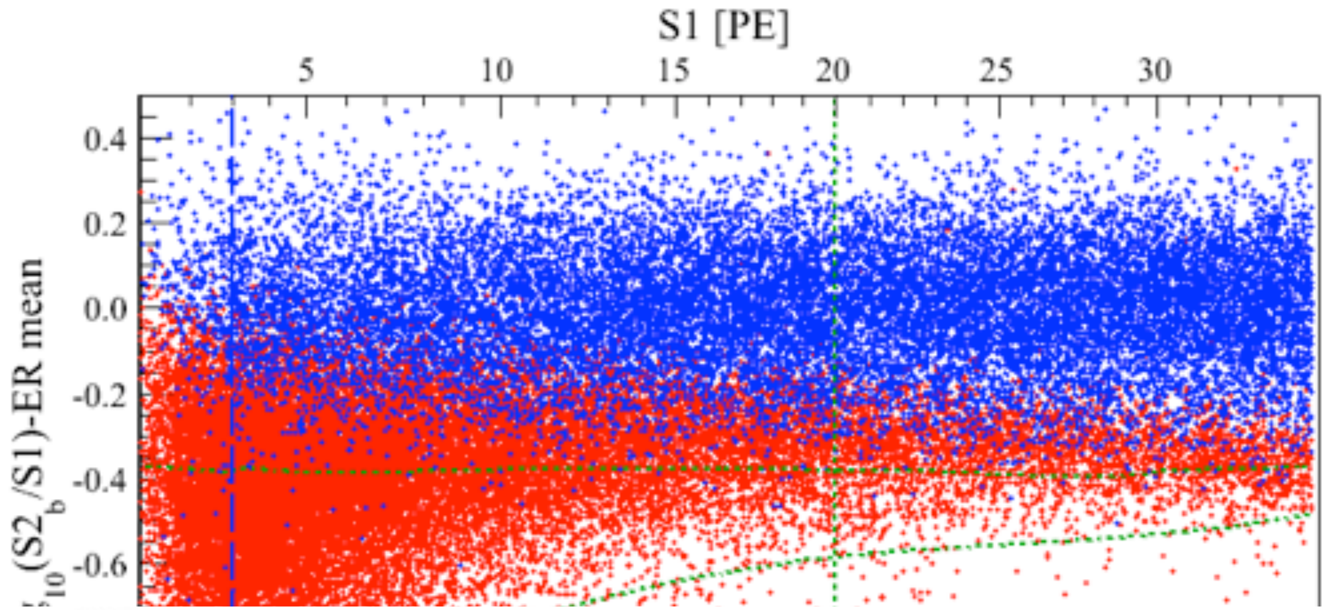

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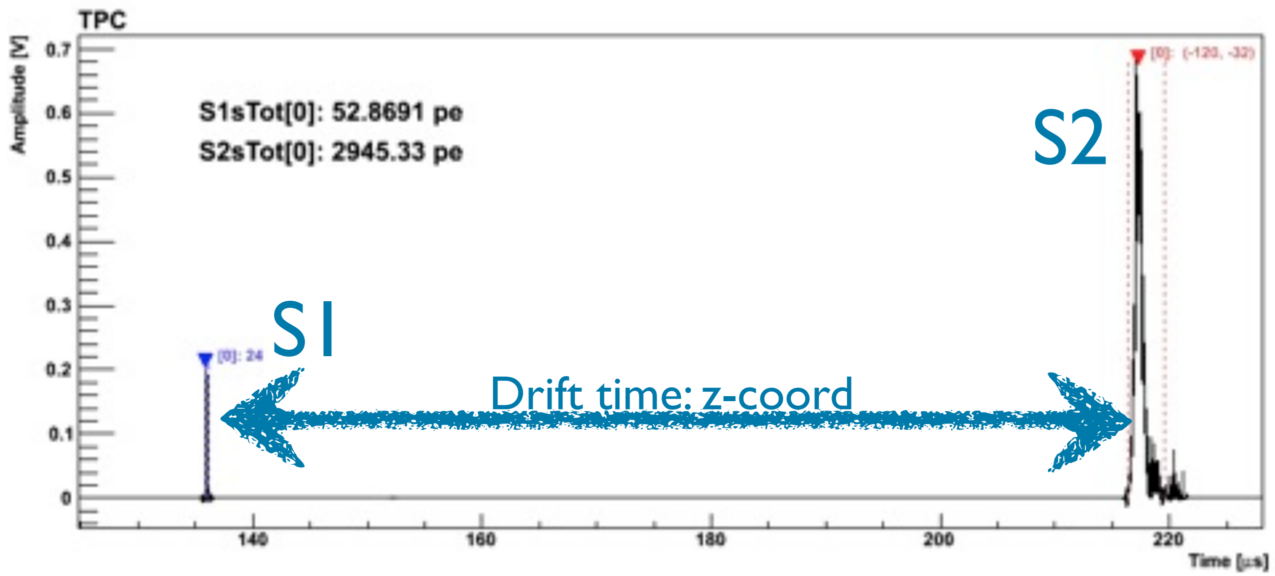
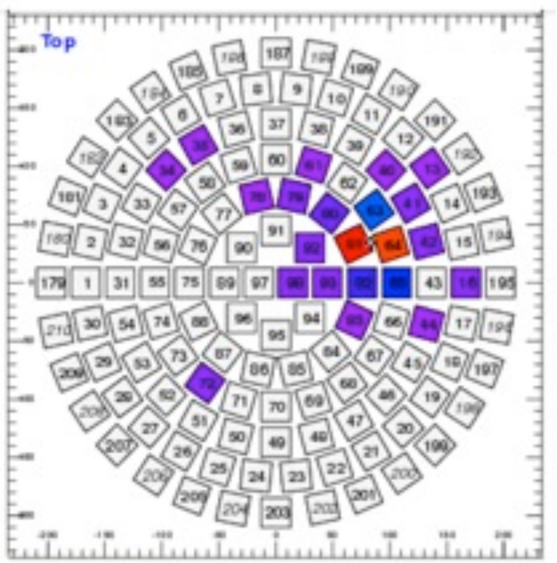
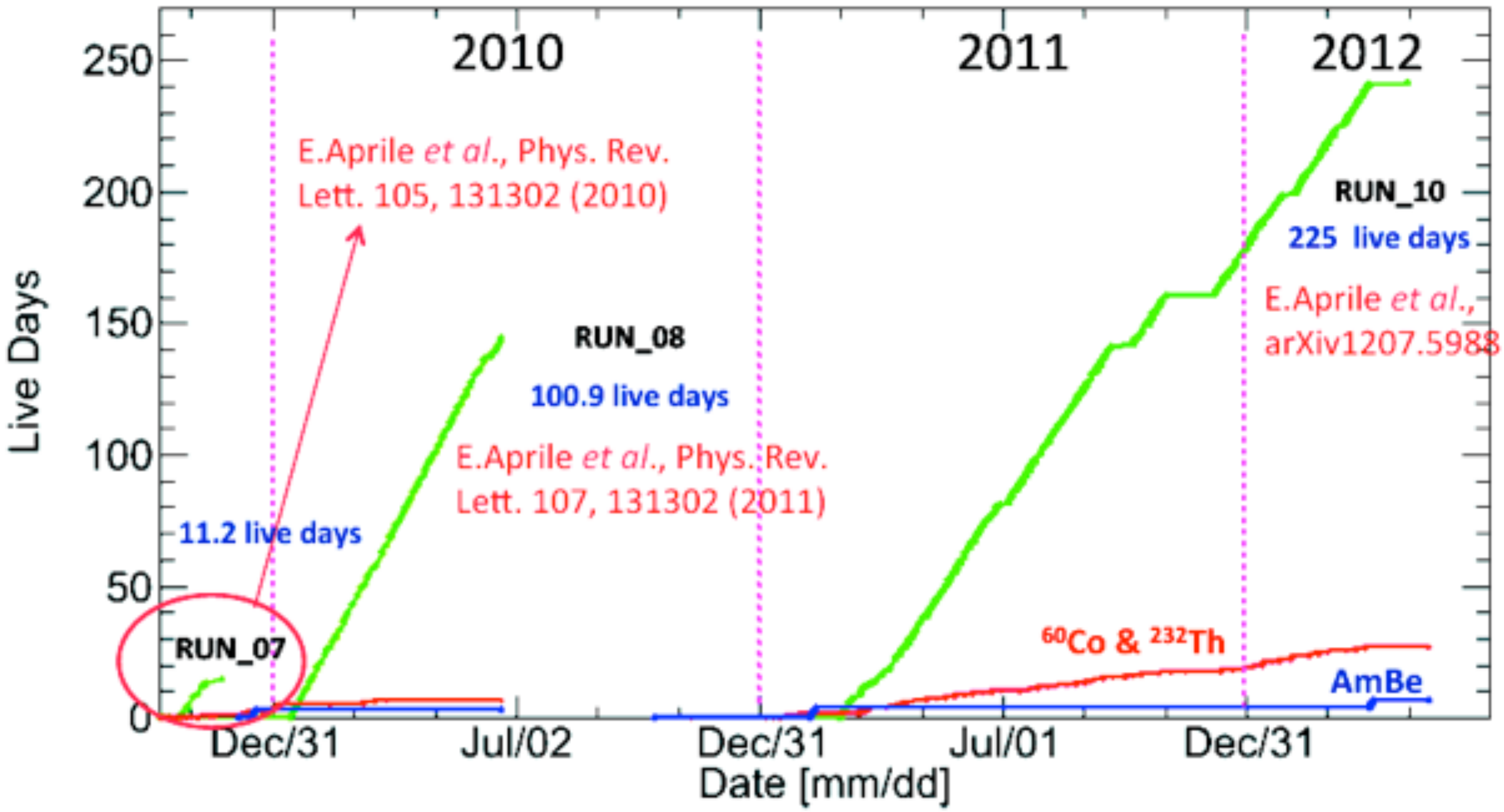




x-y coord

Our Luminosity plot

Regular calibrations are critical



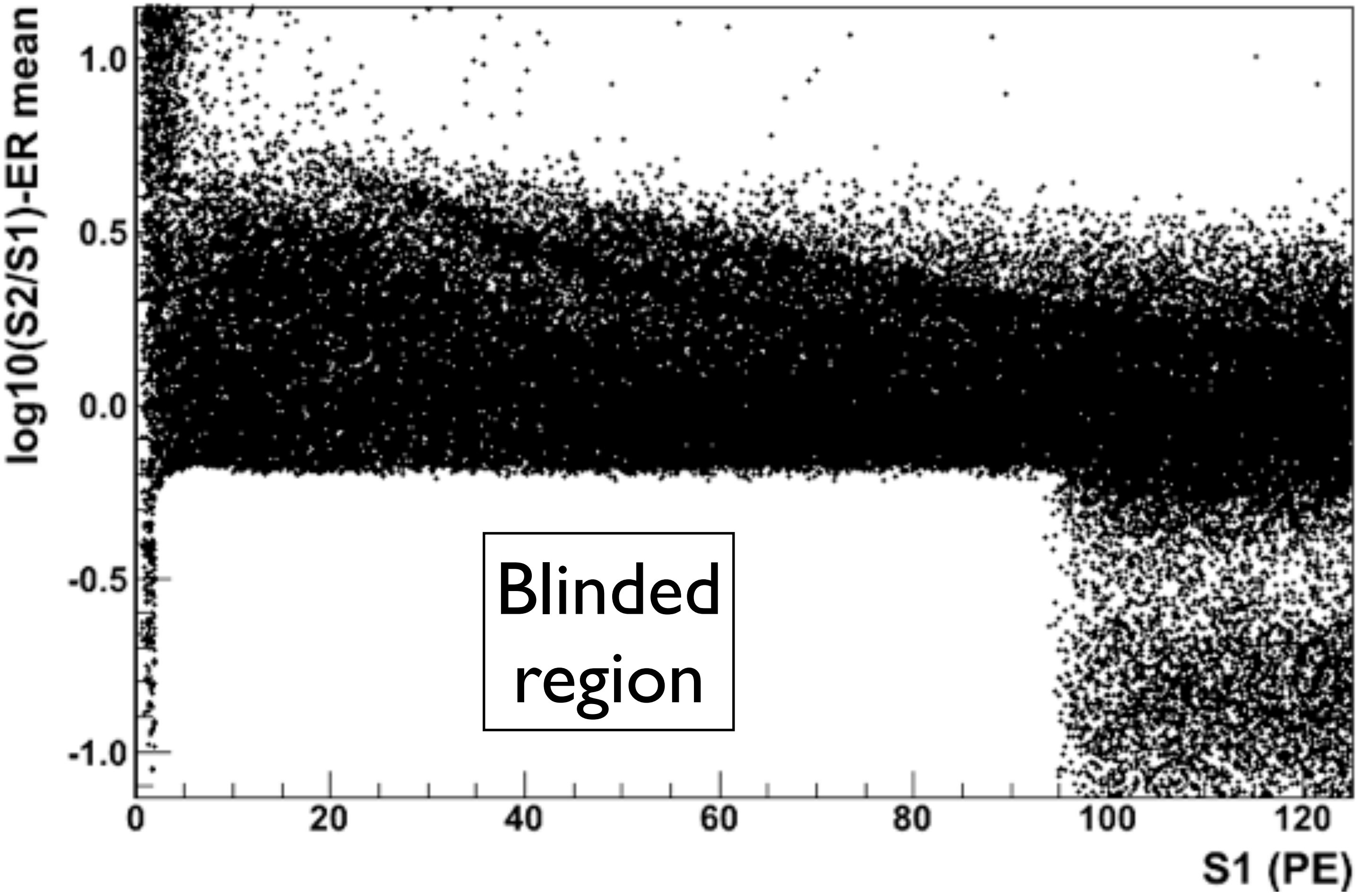
3rd data release from XENON100 - 225 livedays

Patrick Decowski

Analysis Steps

All events in 48kg Fiducial Region

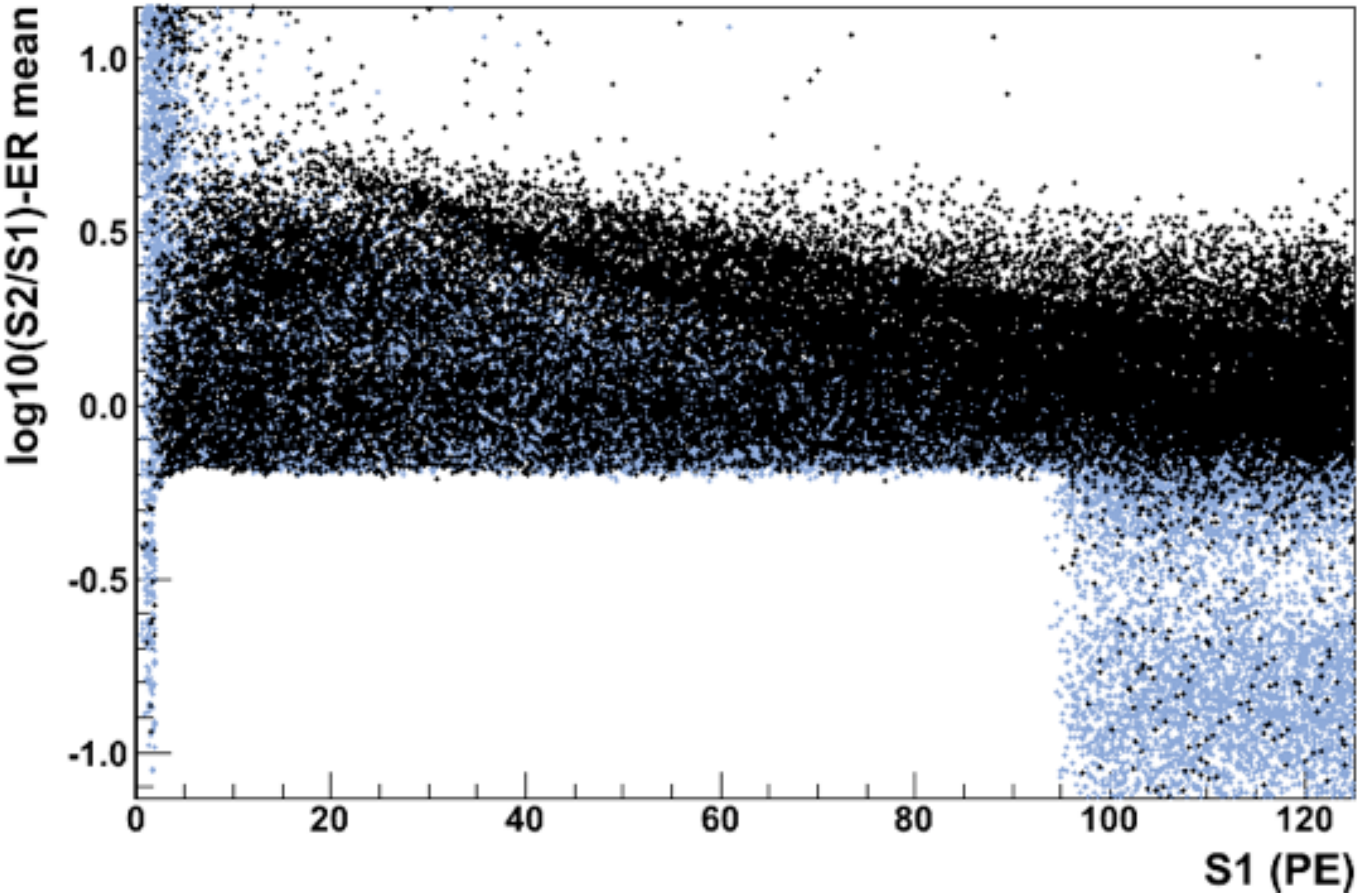
ER vs NR discr. Parameter



Recoil Energy

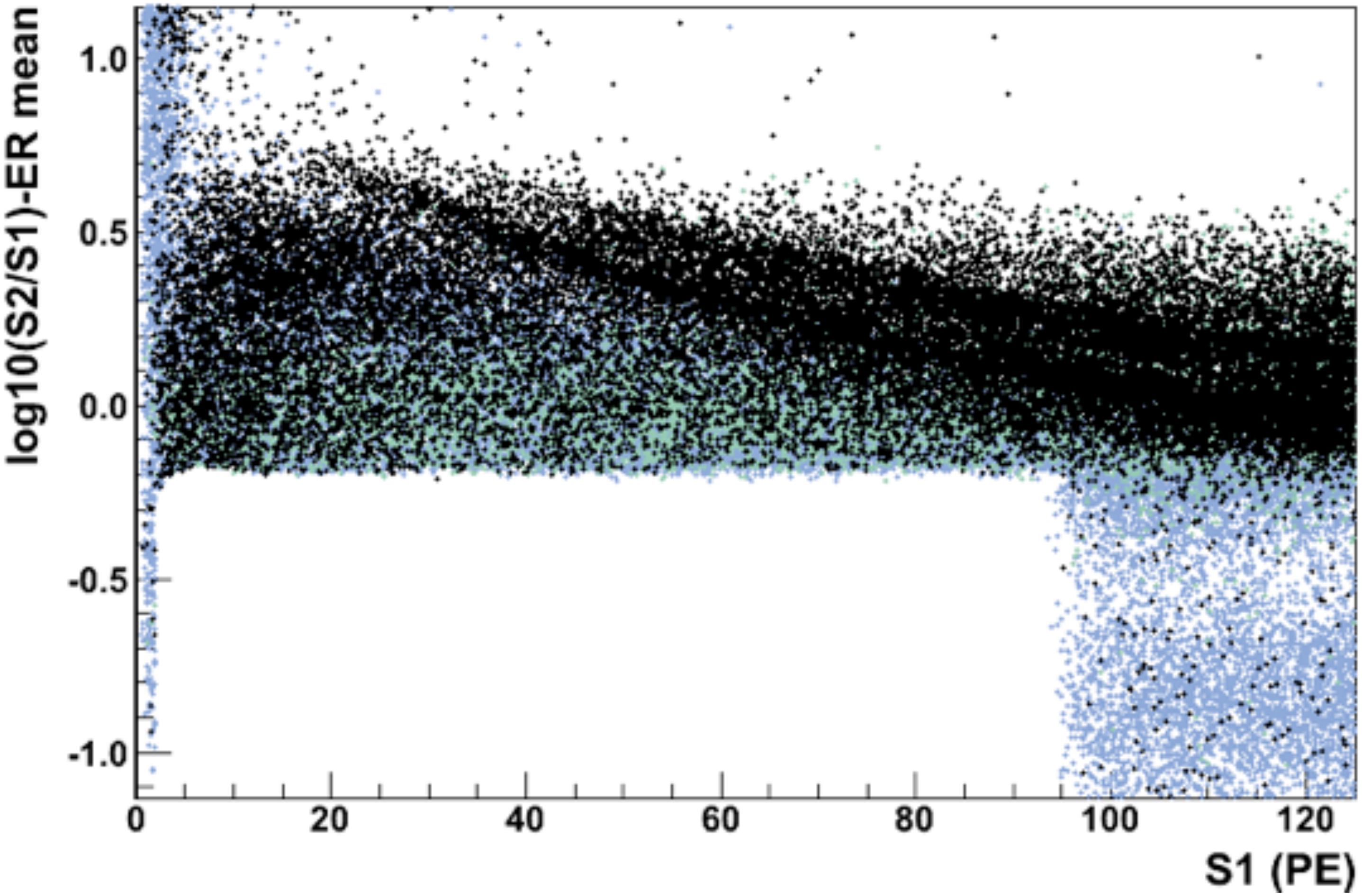
Analysis Steps

Apply basic noise cuts



Analysis Steps

Single Scatter Cut: WIMPs don’t multiple-scatter



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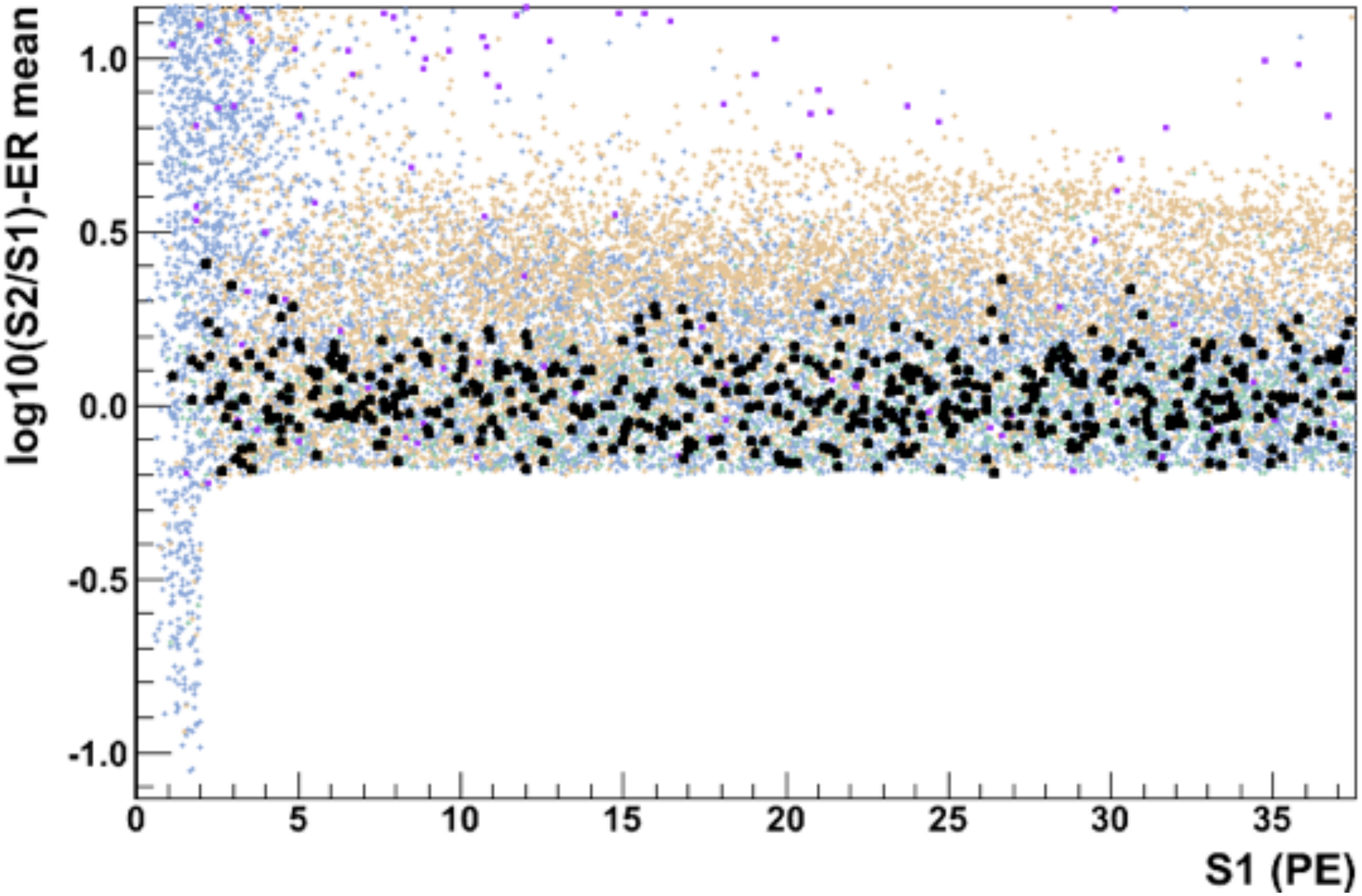
Analysis Steps

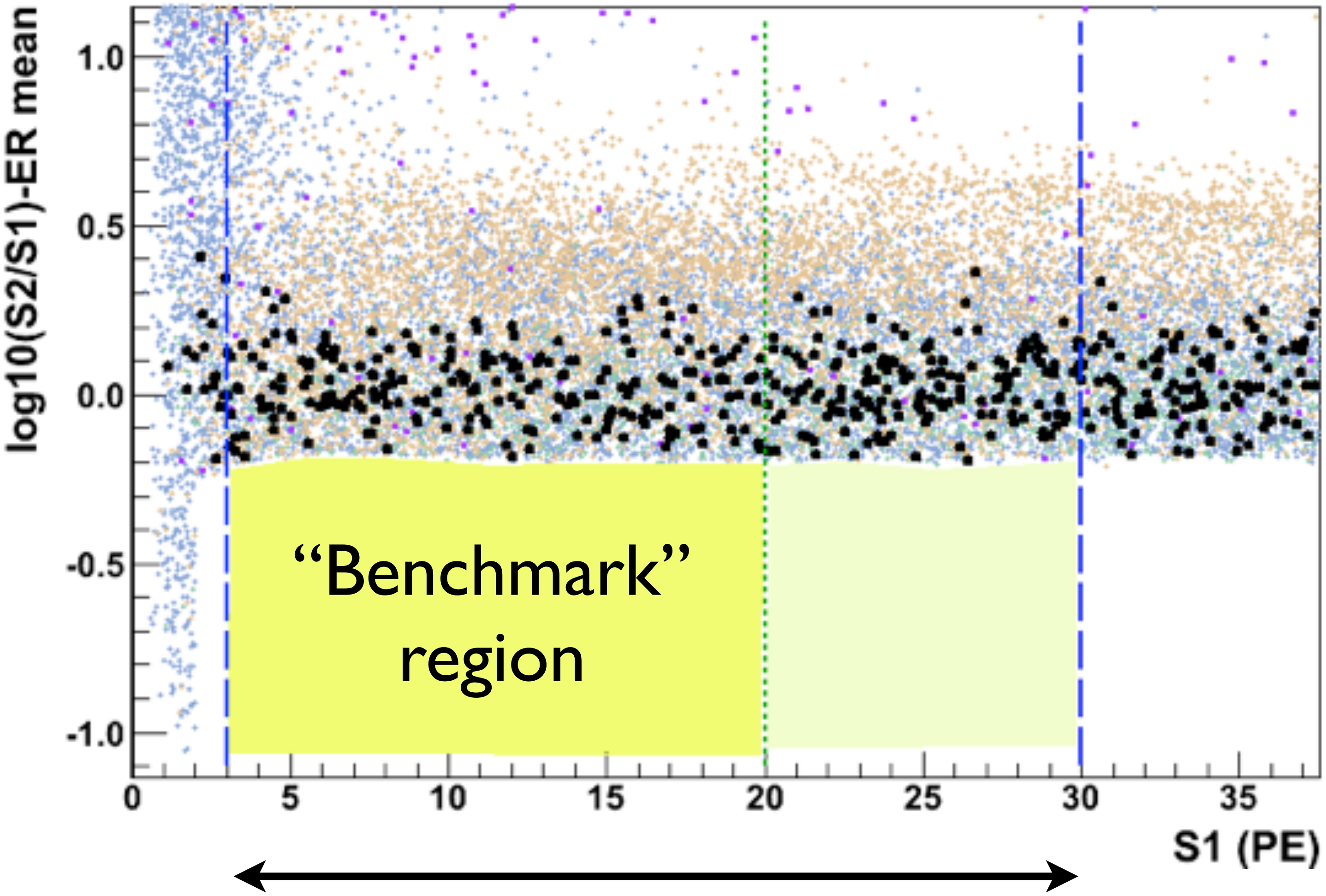
Set lower E threshold & restrict E range
(+ various consistency cuts)



Analysis Steps

Two analyses:

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



Profile Likelihood region

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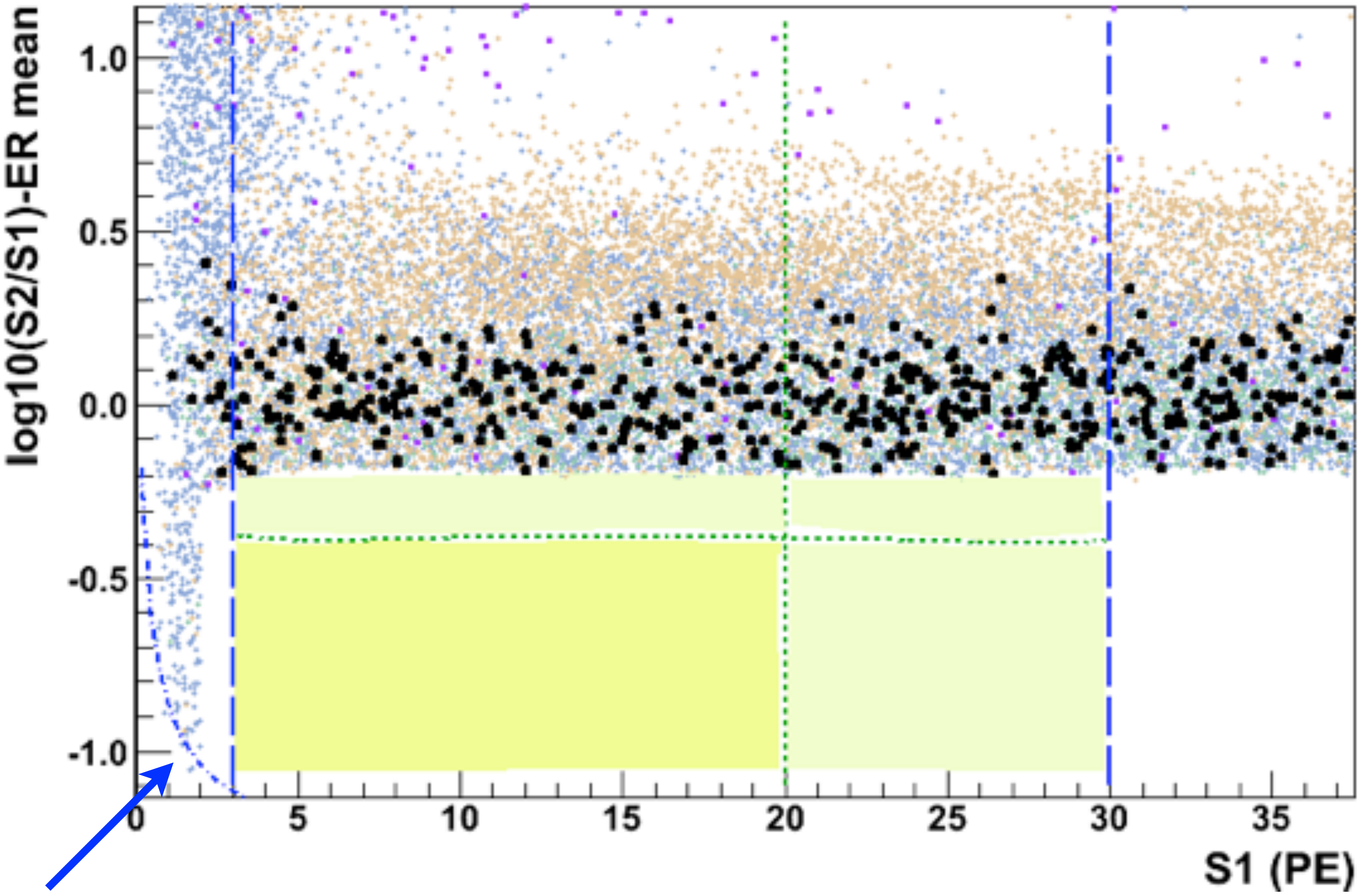
Analysis Steps

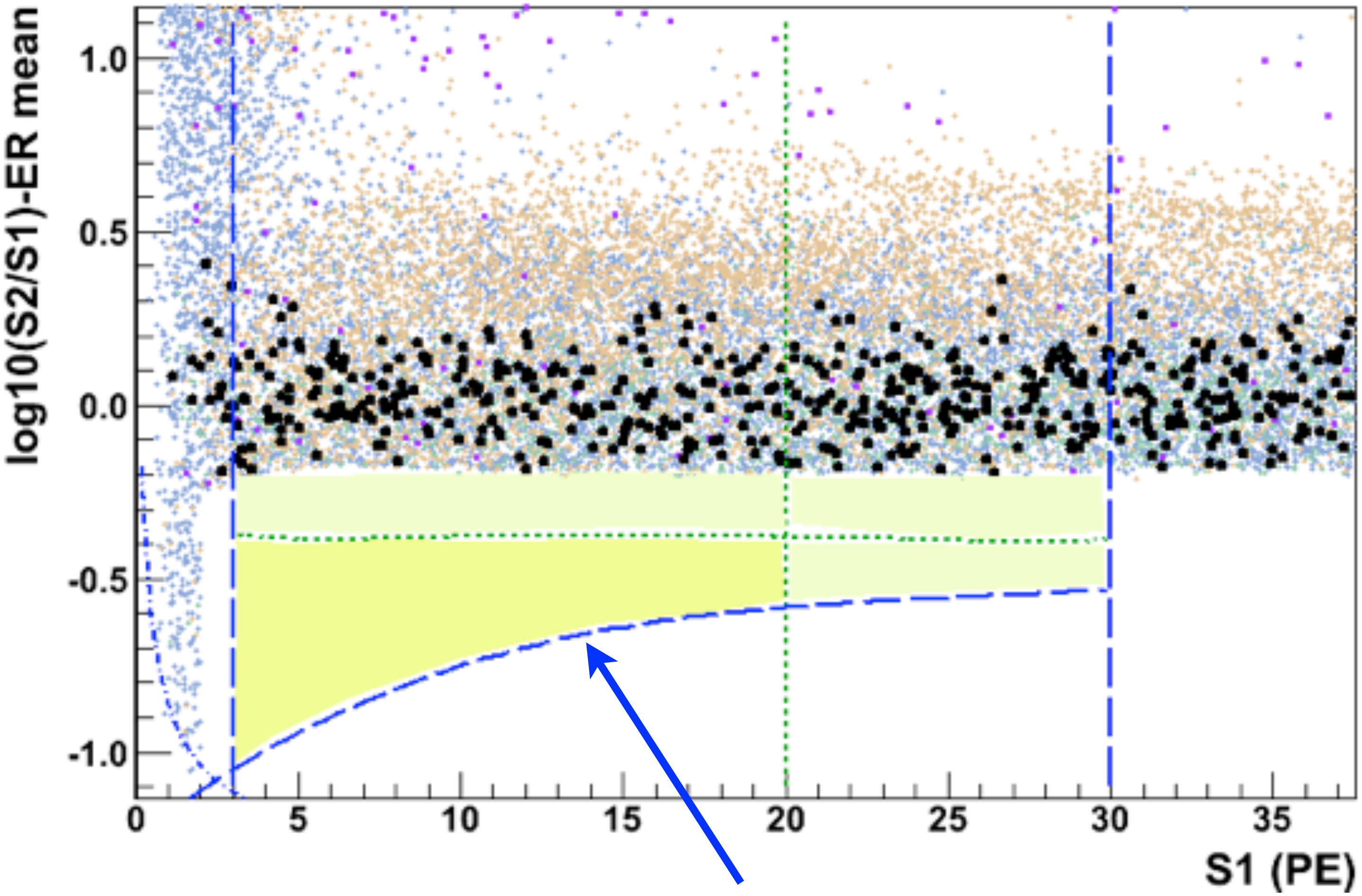
For benchmark region: require 99.75% ER discrimination



S2>150

Analysis Steps

Restrict from below to ensure signal is NR-like



Signal must be NR-like

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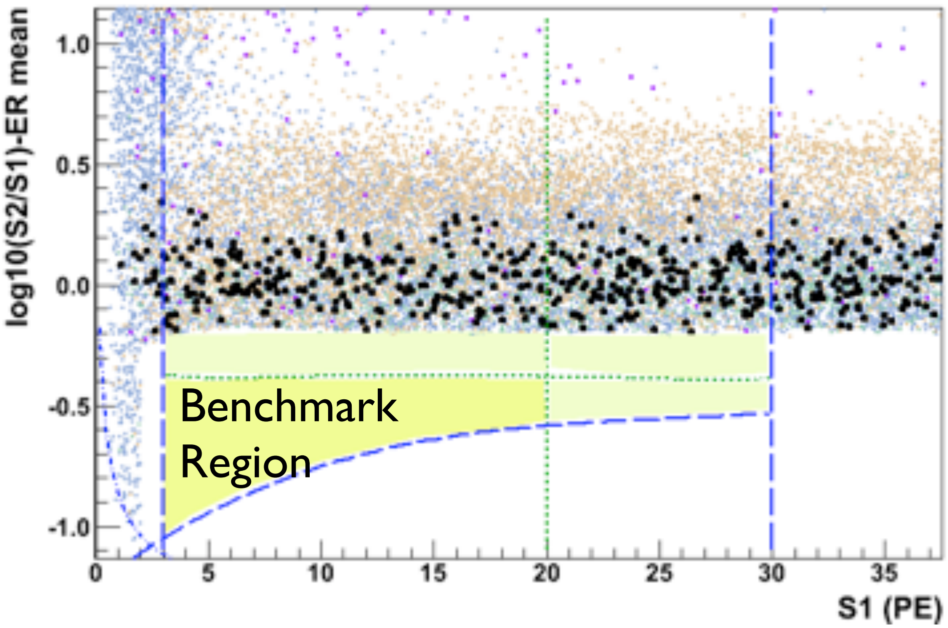
Expected Background & Efficiencies

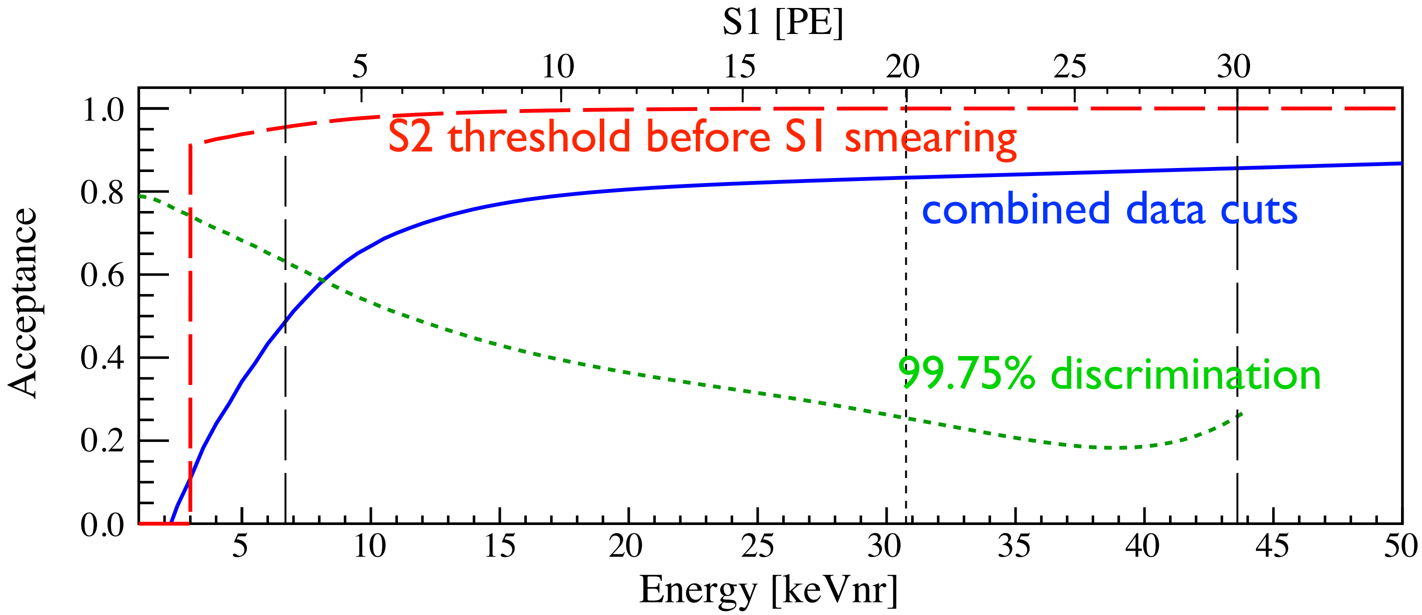


Profile likelihood uses detailed BG model

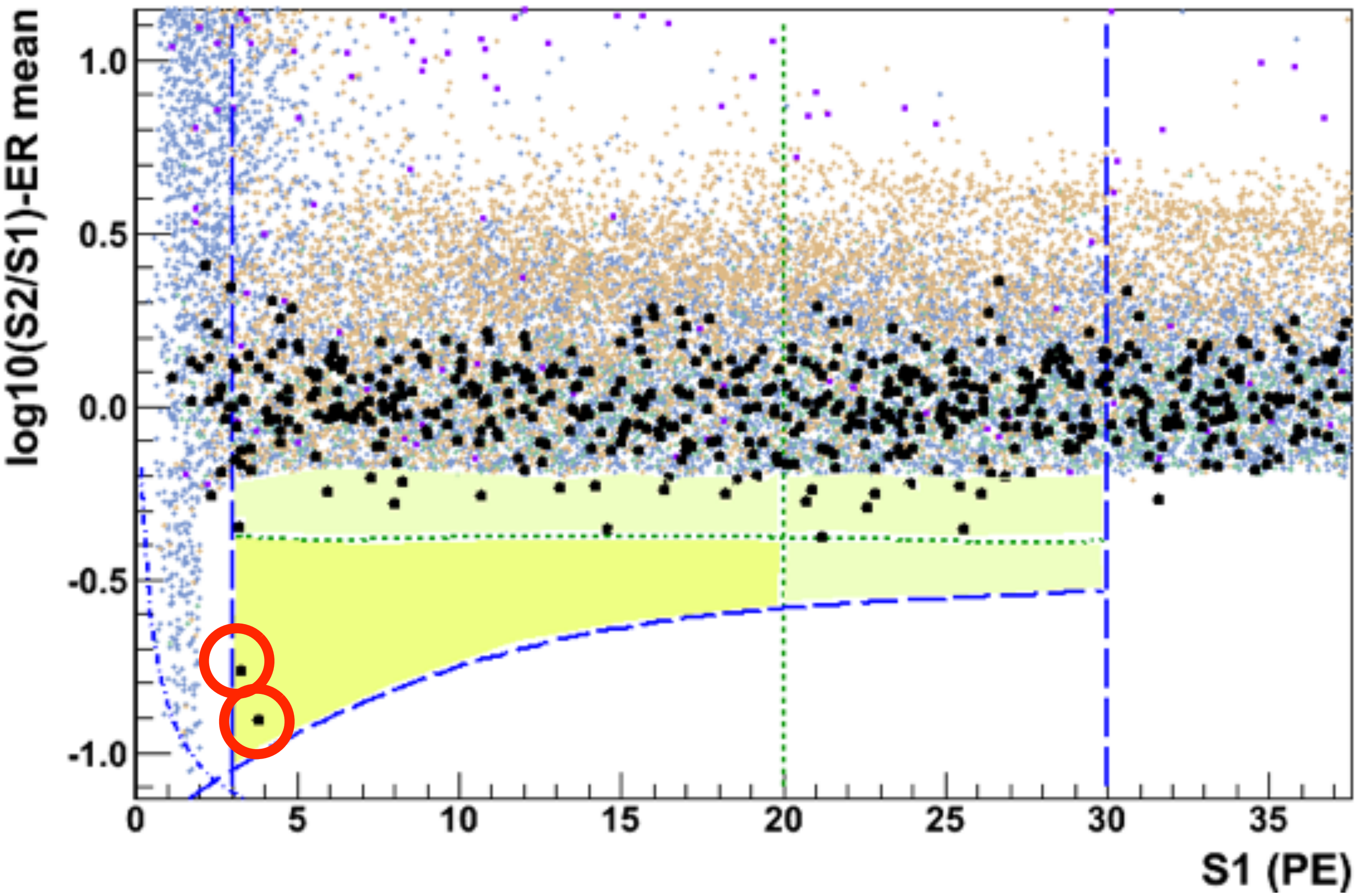
In Benchmark Region:

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

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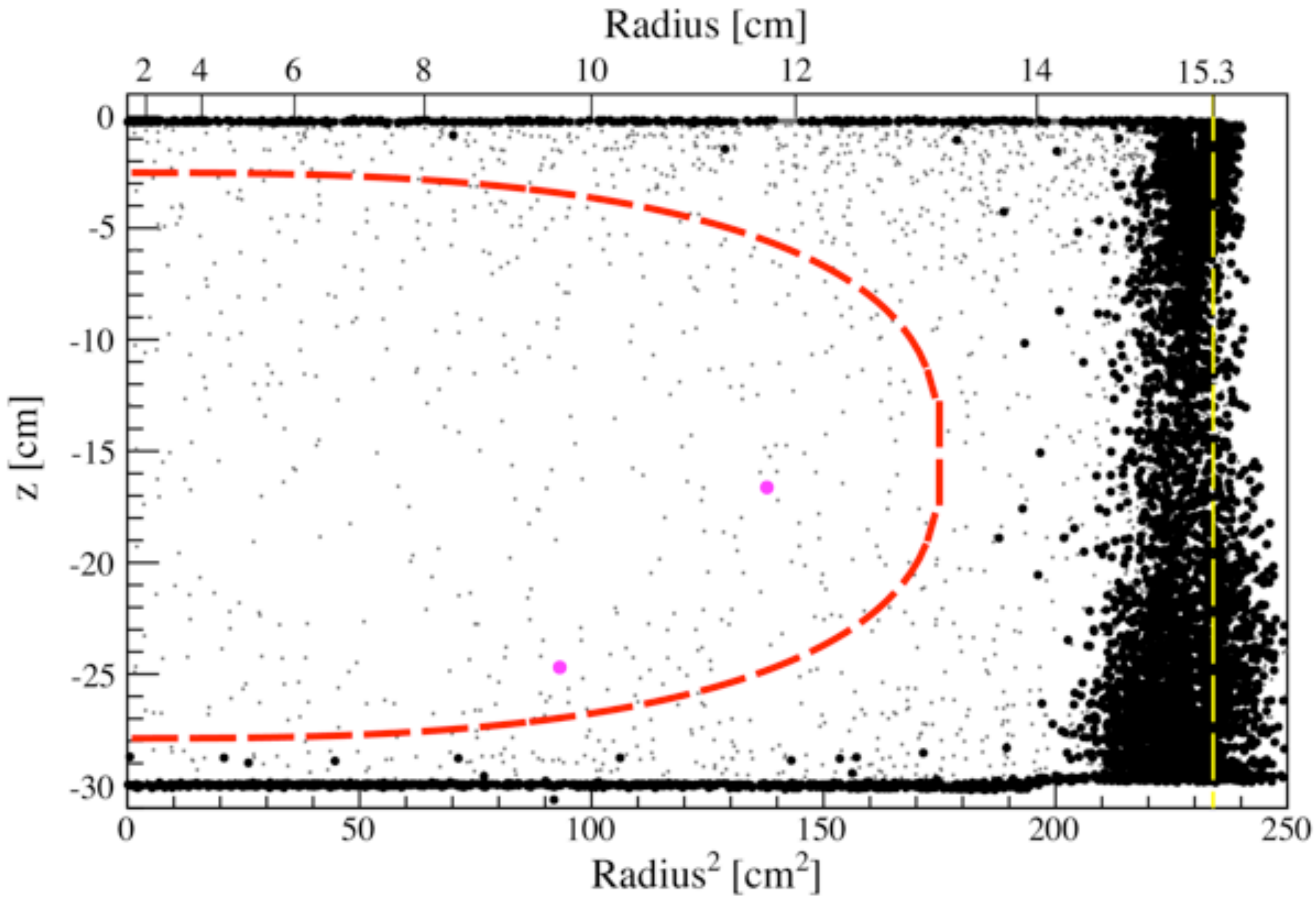
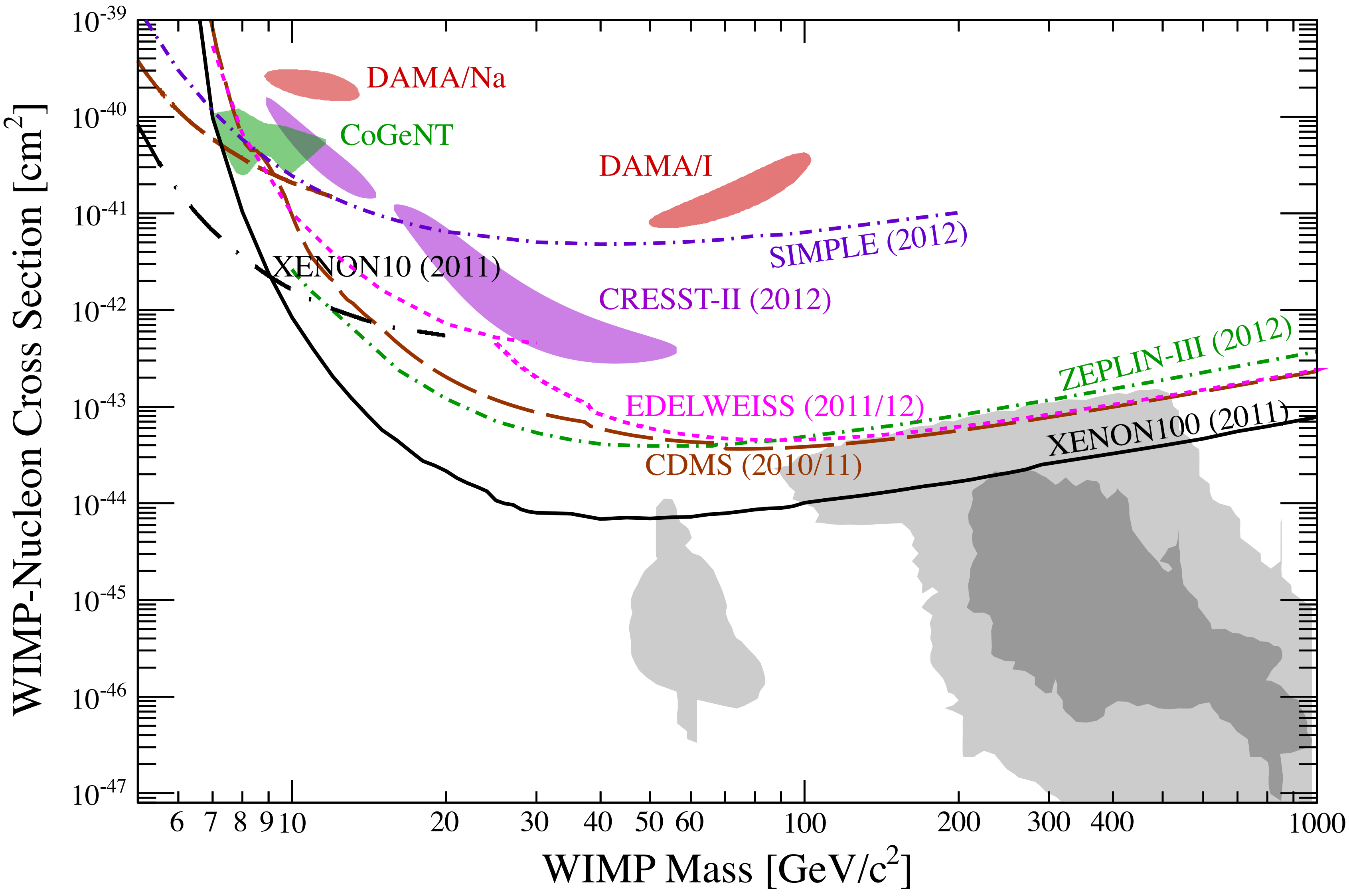
After Unblinding



2 events in “Benchmark” region

Limits From XENON100



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

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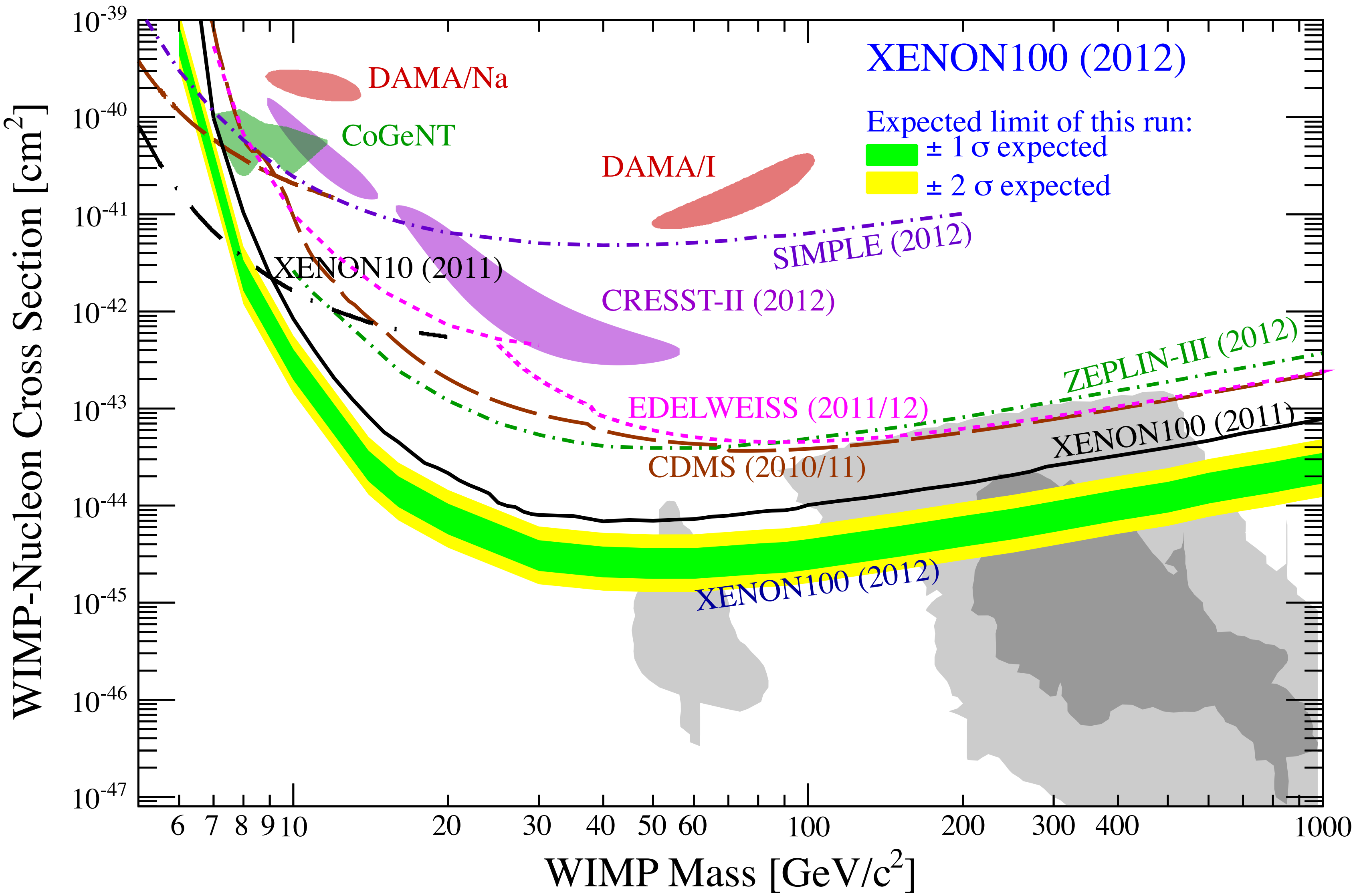
Limits From XENON100



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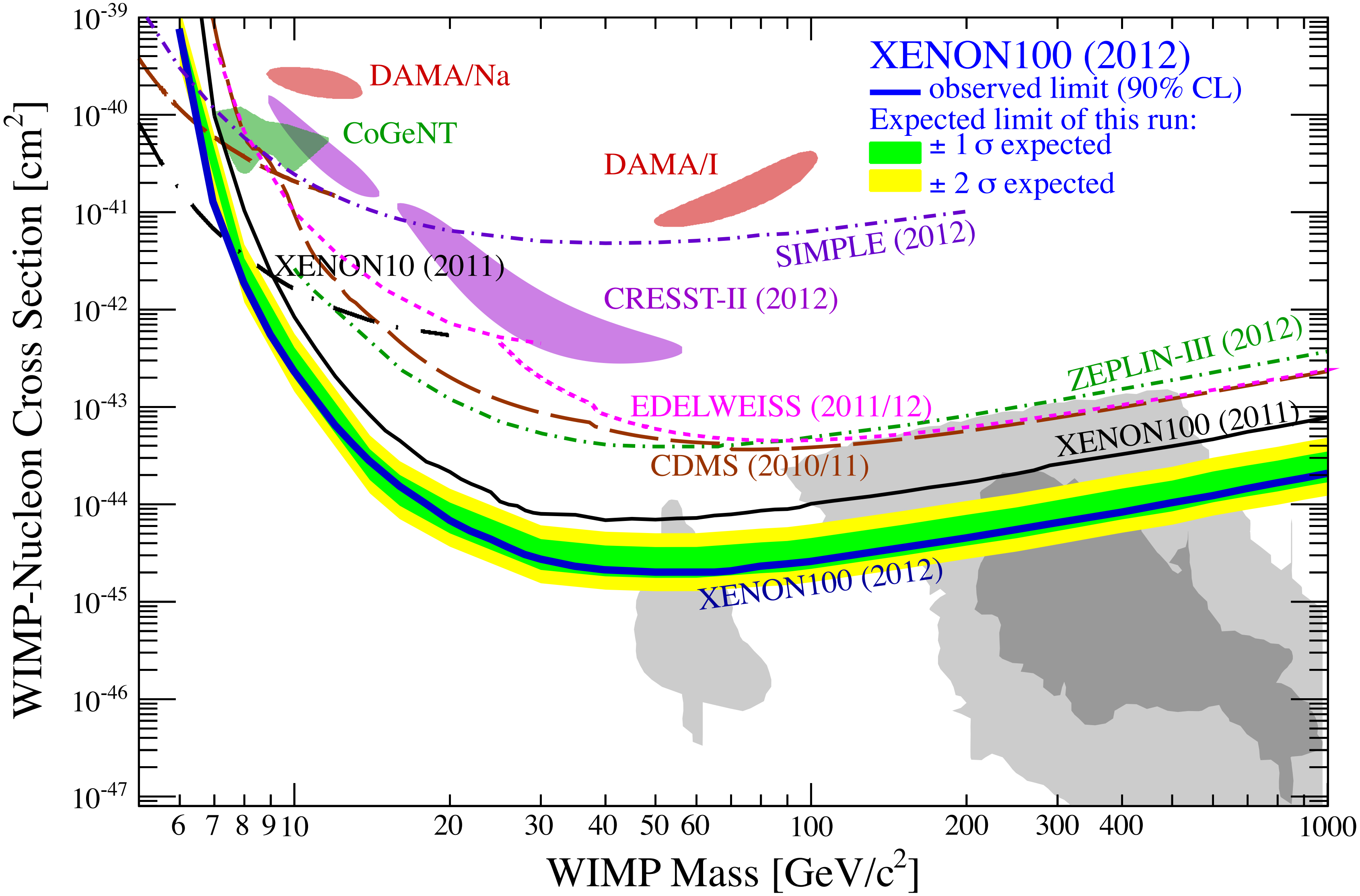

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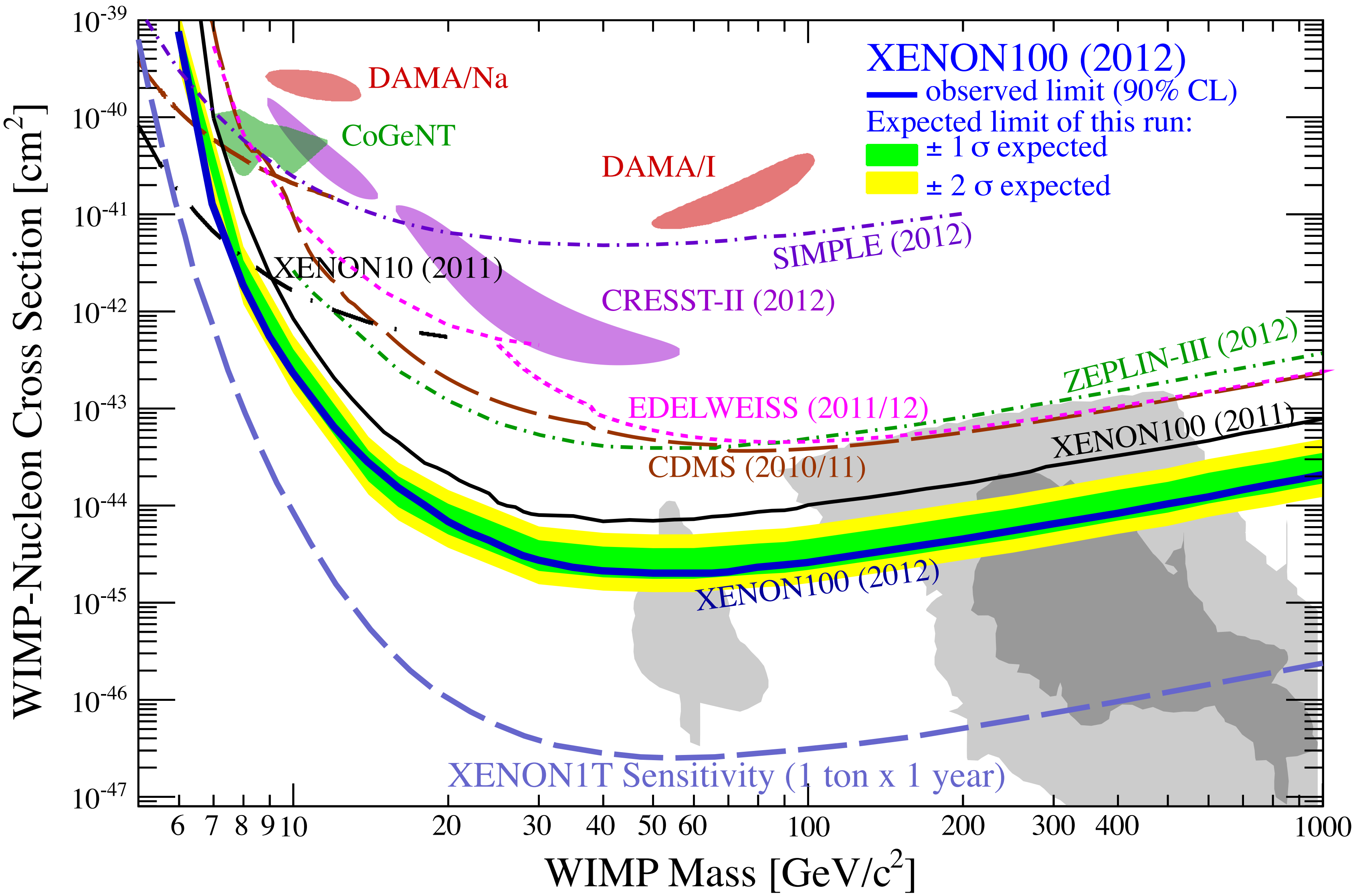

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Aprile et al. [XENON100]
PRL 109, 181301 (2012).

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What would supposed signal look like?

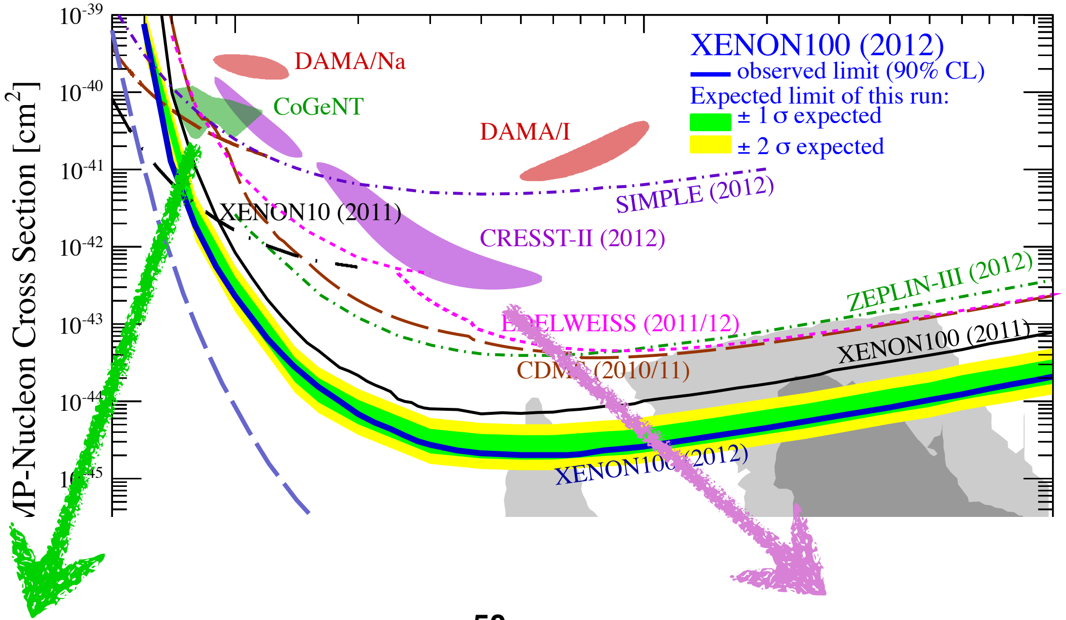


Illustration only!

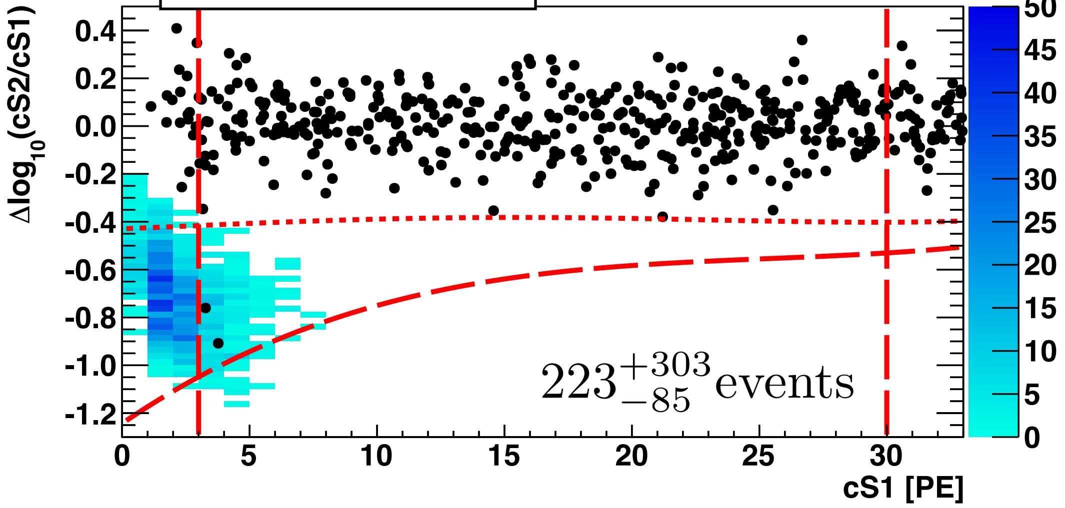
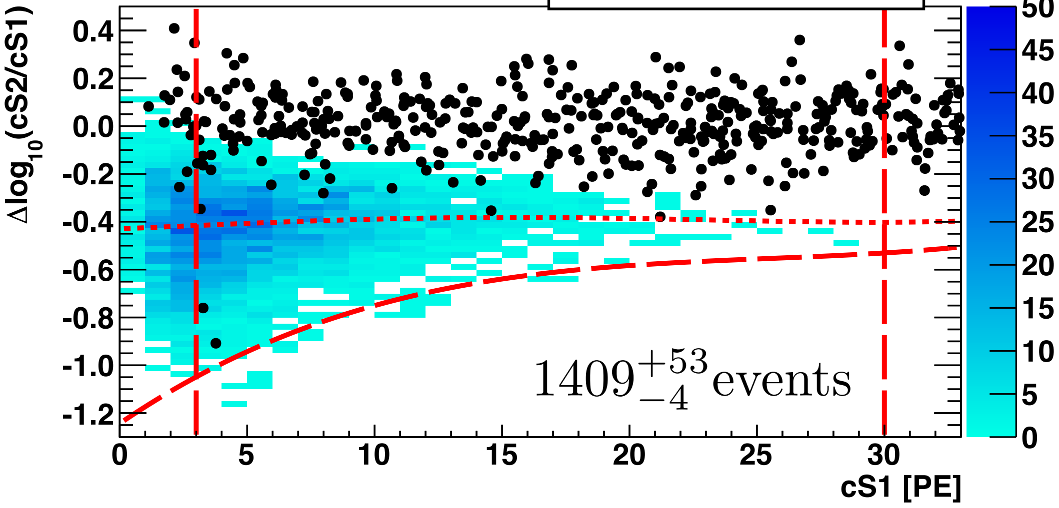


Illustration only!



CoGeNT/CDMS-Si-like WIMP

CRESST-like WIMP

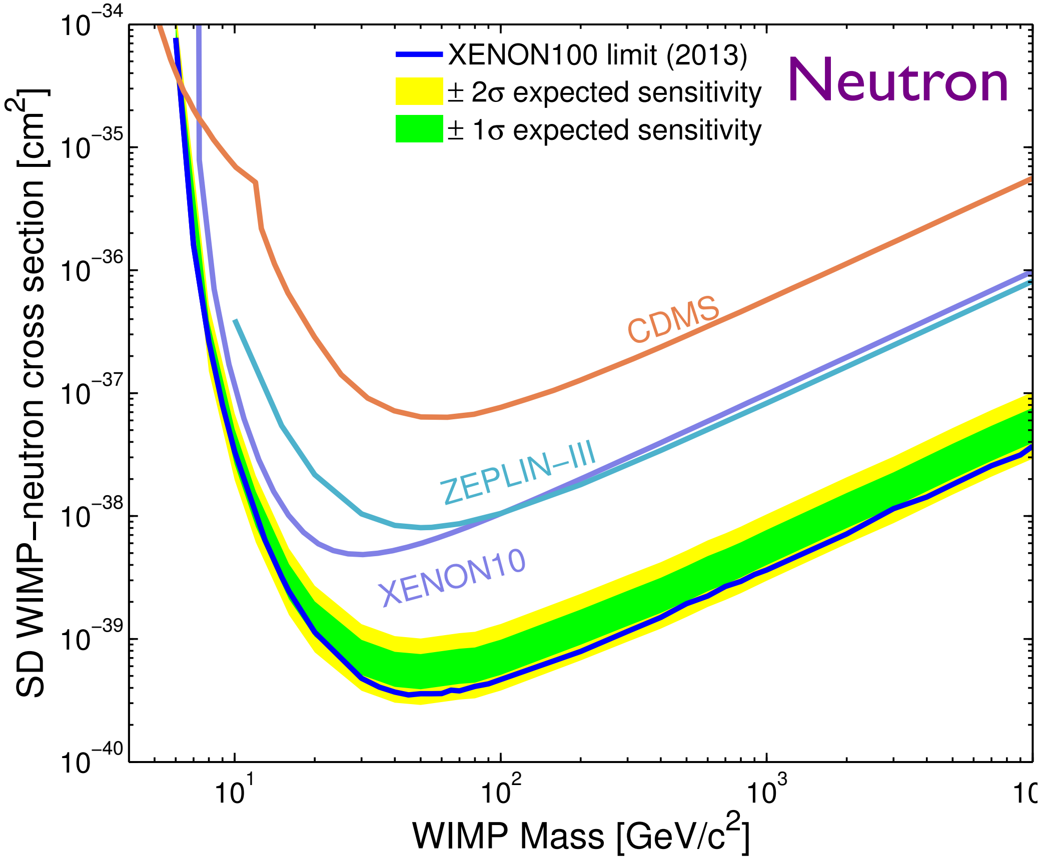
$m_\chi = 8$ GeV, $\sigma = 3\times10^{-41}$ cm^2

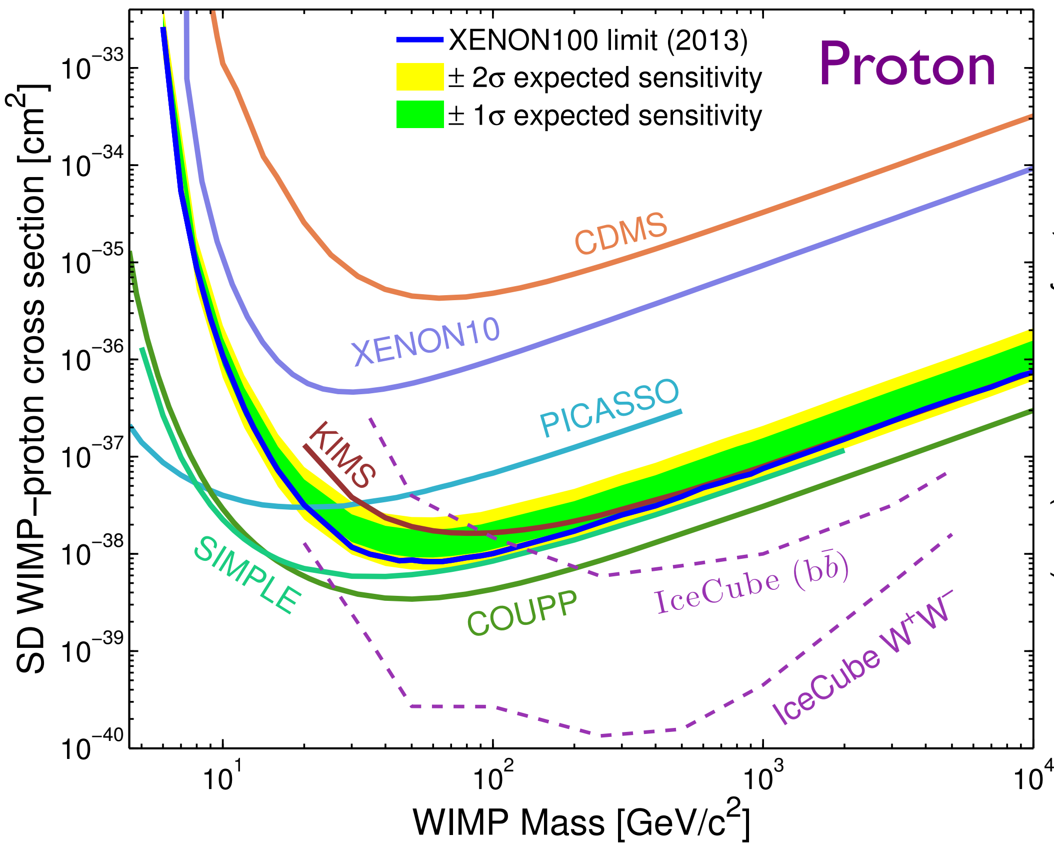
$m_\chi = 25$ GeV, $\sigma = 1.6\times10^{-42}$ cm^2

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

Spin-dependent Limits

Reinterpret rate limits as spin-dependent WIMP-nucleon limits





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

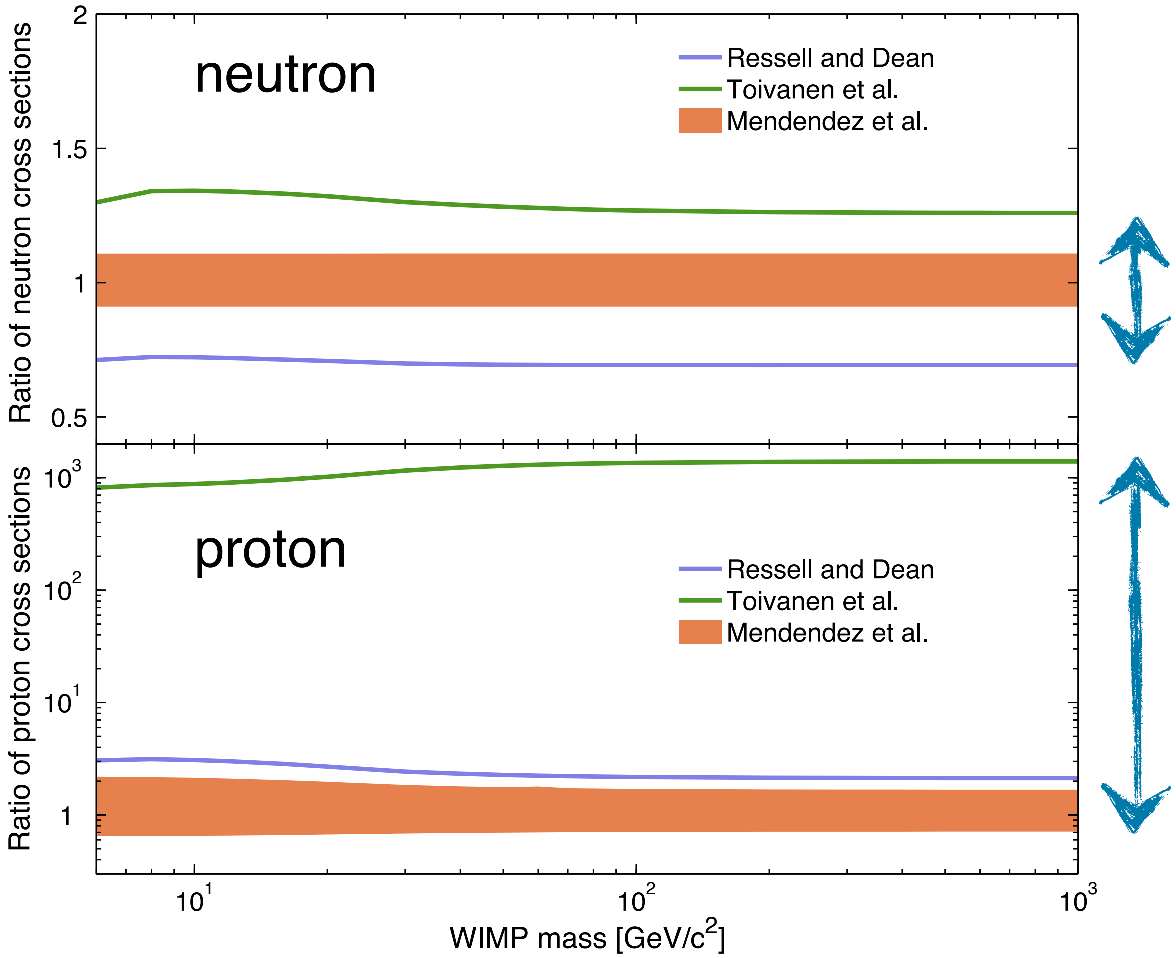
Nuclear Models: Interpreting SD limits

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



30% variation

O(1000) difference!

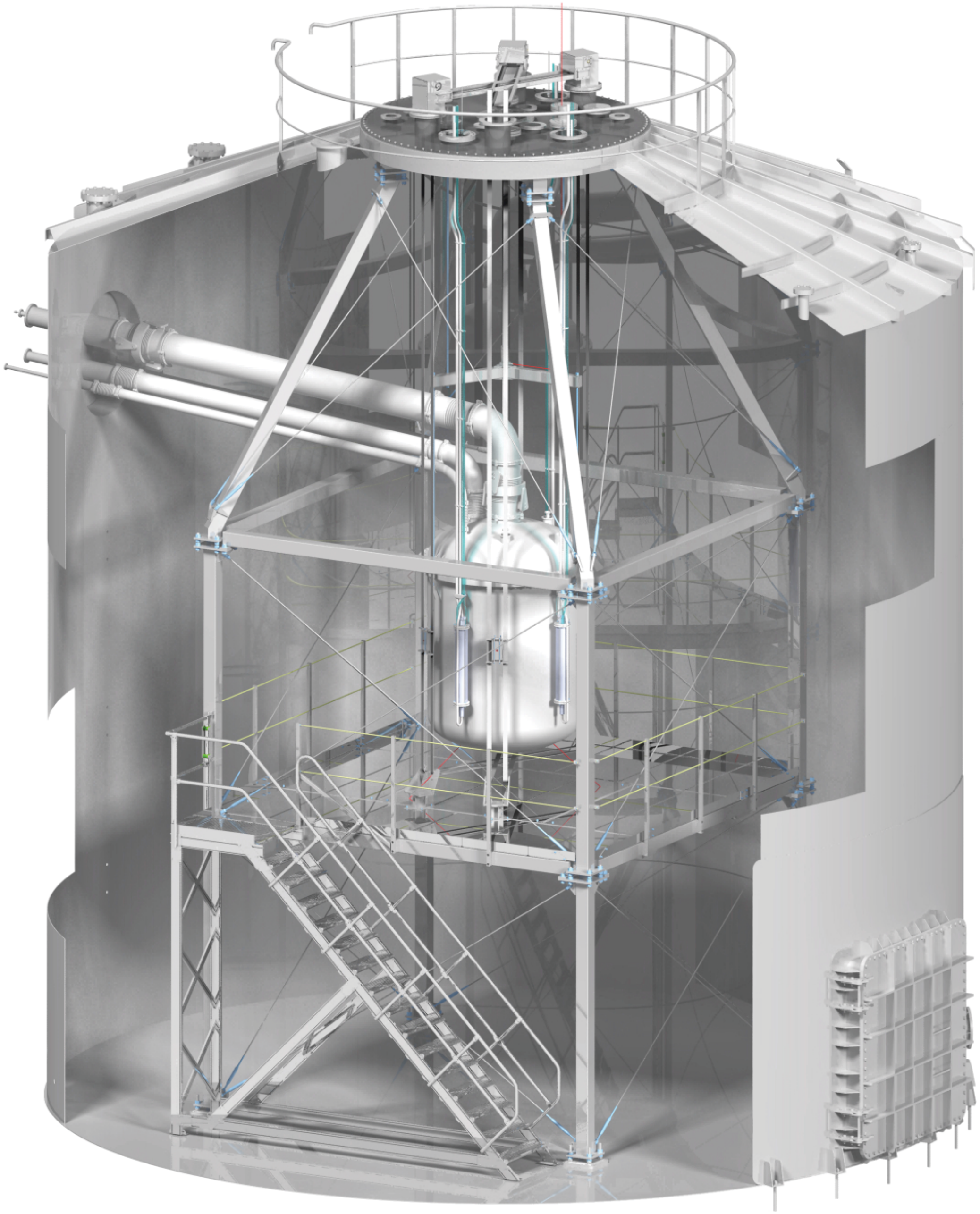
XENON100 Coll, Phys.Rev.Lett. 111 (2013) 021301

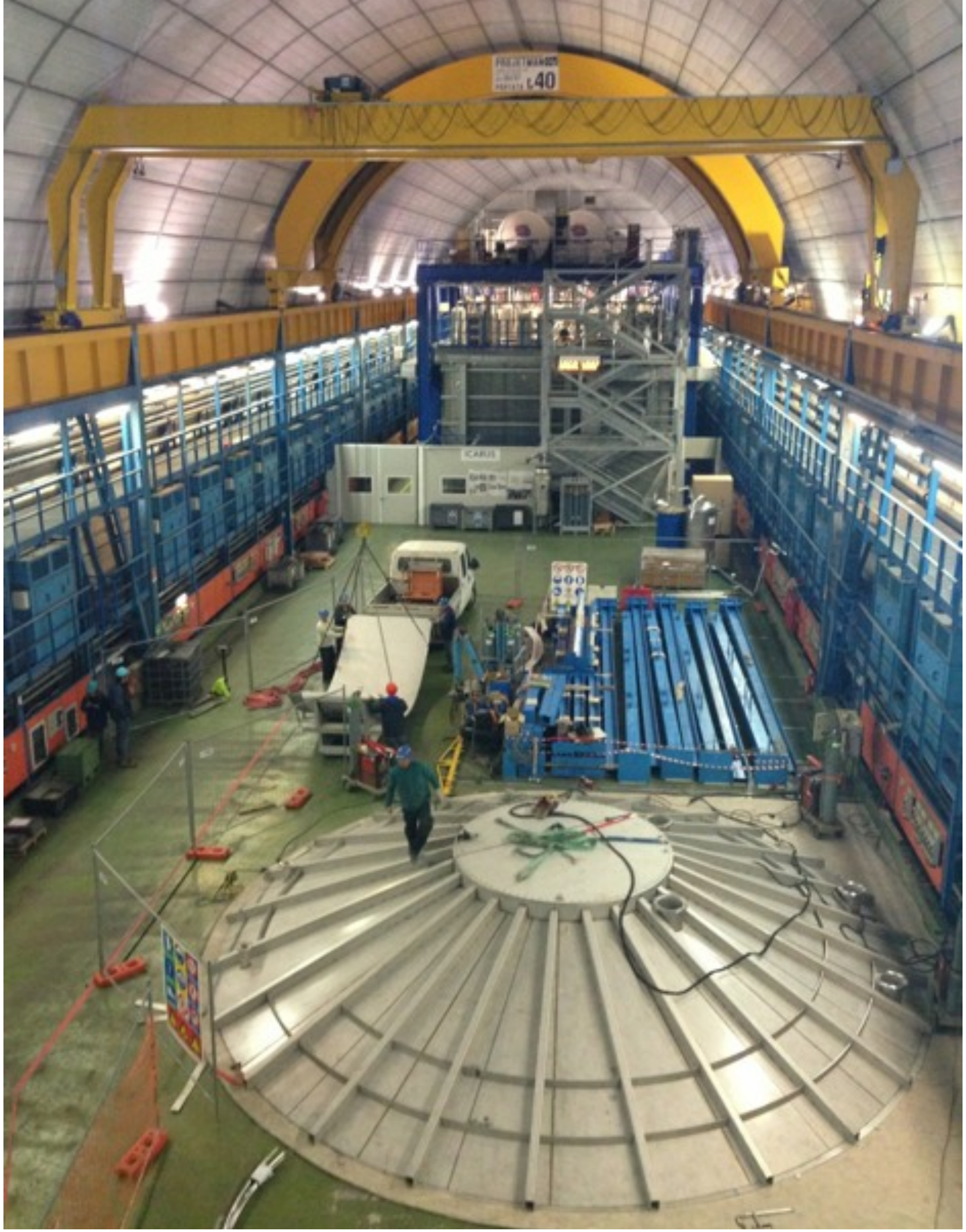
Affects **interpretation** of WIMP-proton SD limits.

Measurements to help constrain nuclear models?

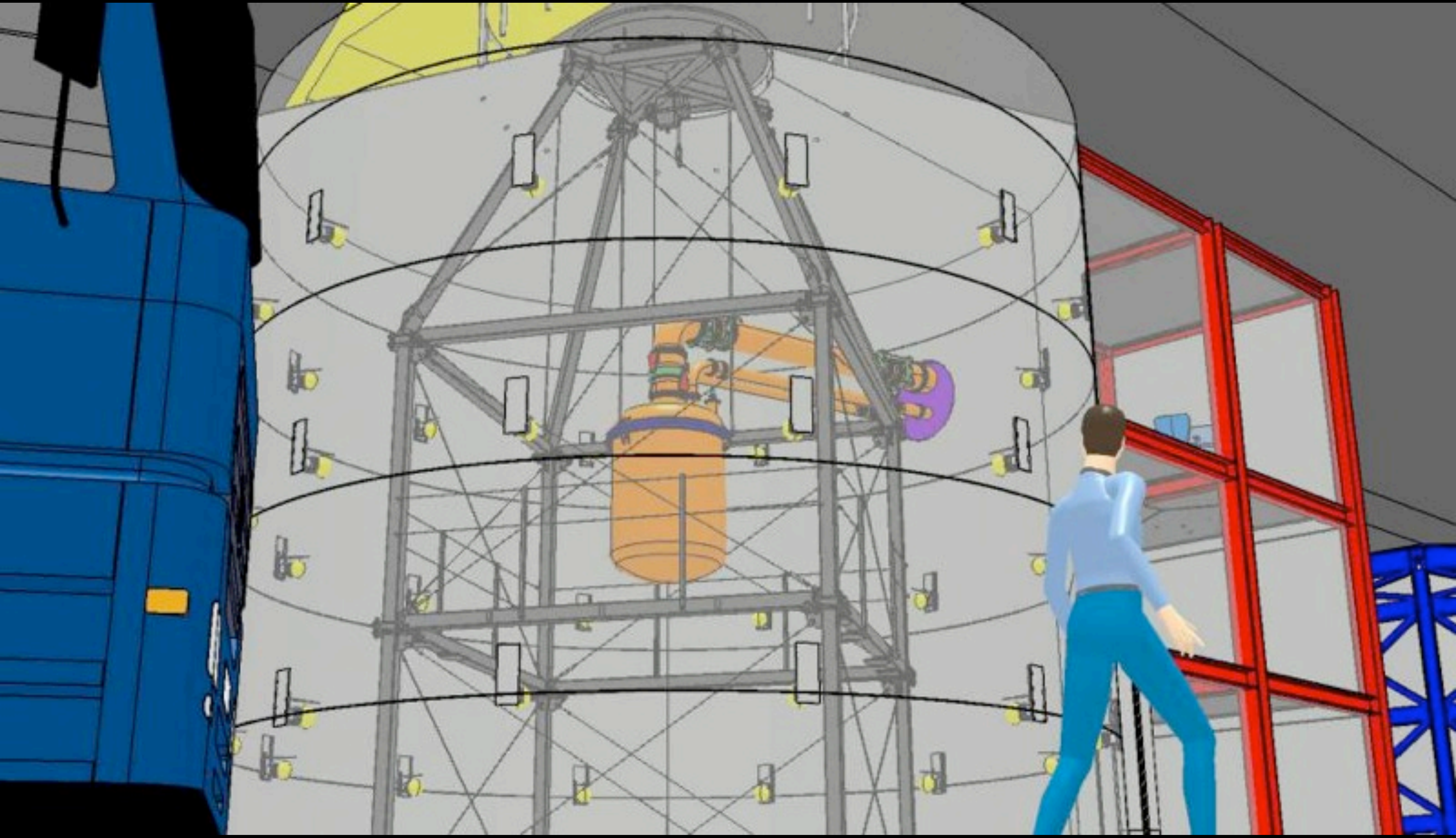
XENON1T

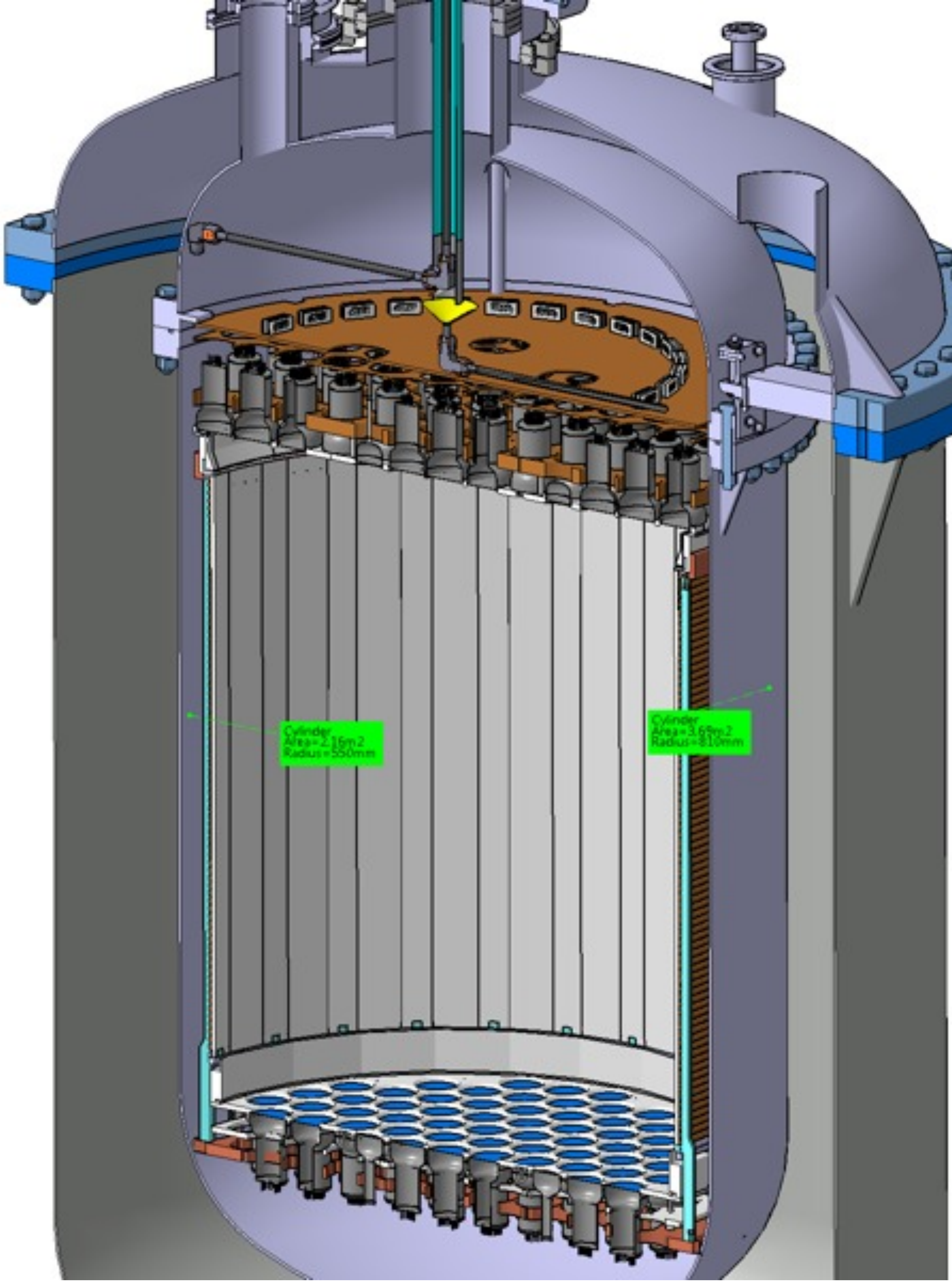
- 100x more sensitive than XENON100
- Around 3 tons of Xe, cleaner materials
- Upgrade option to large detector
- Start of science in 2015
- Building has started!

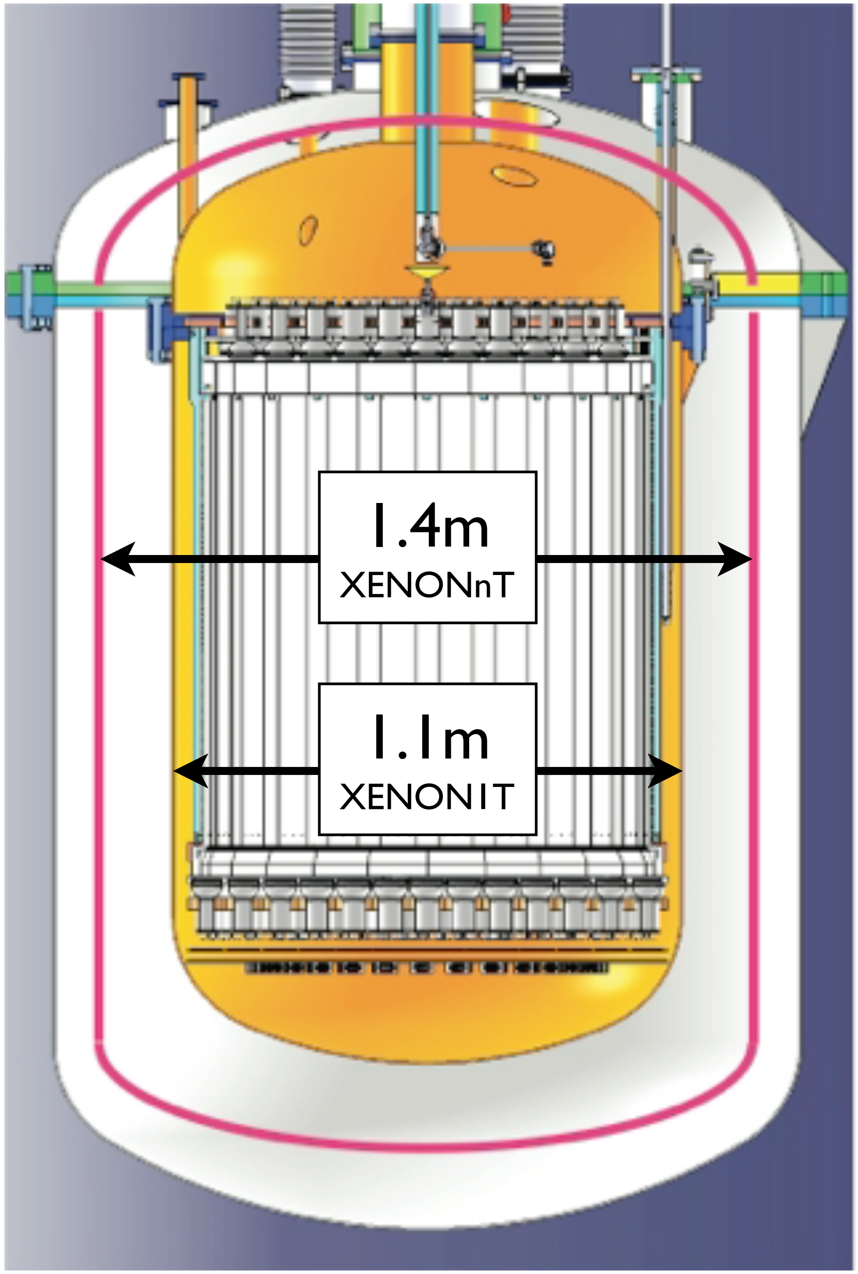



ICARUS

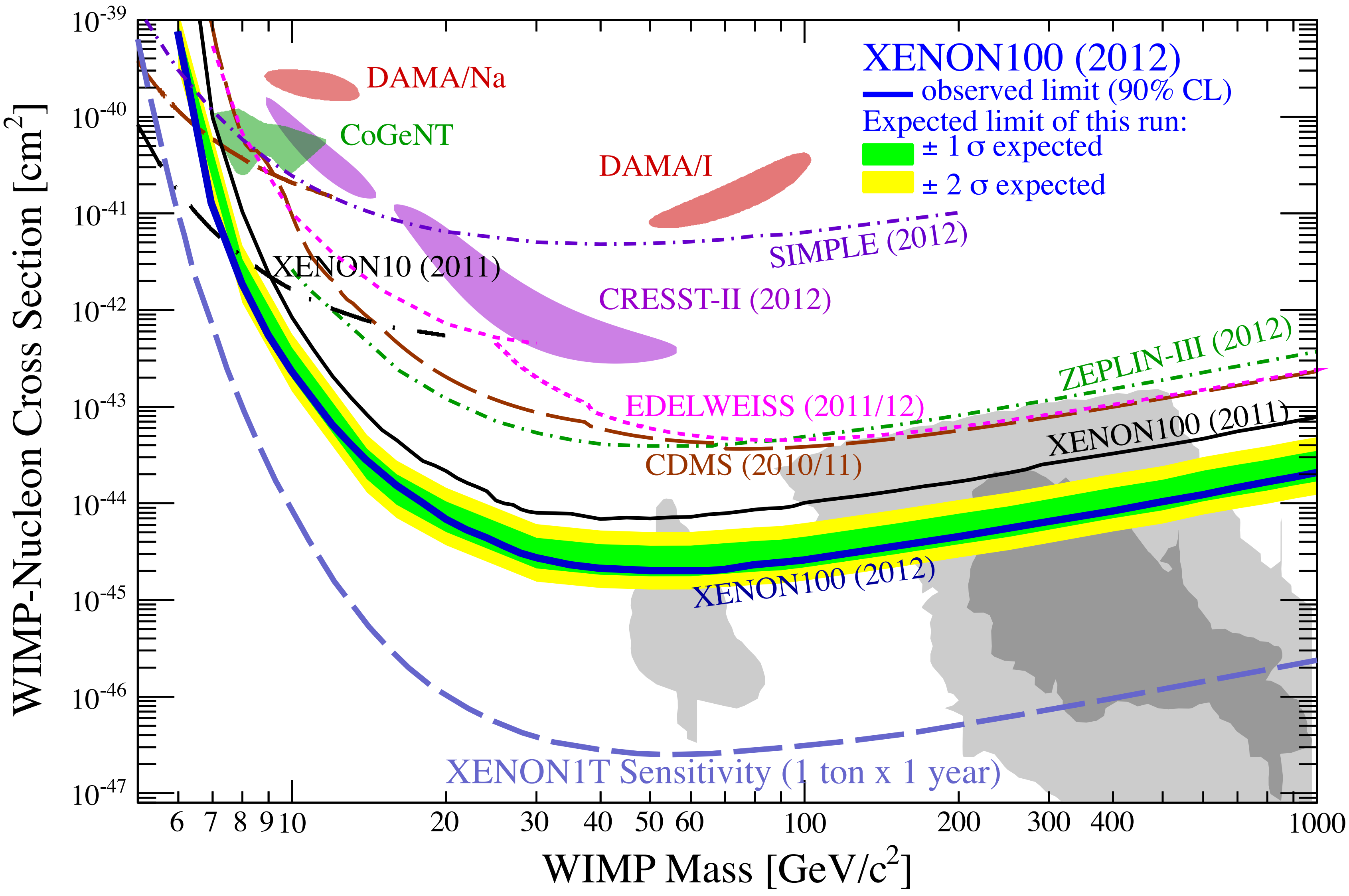
ICARUS




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


1.4m
XENONnT
1.1m
XENON1T

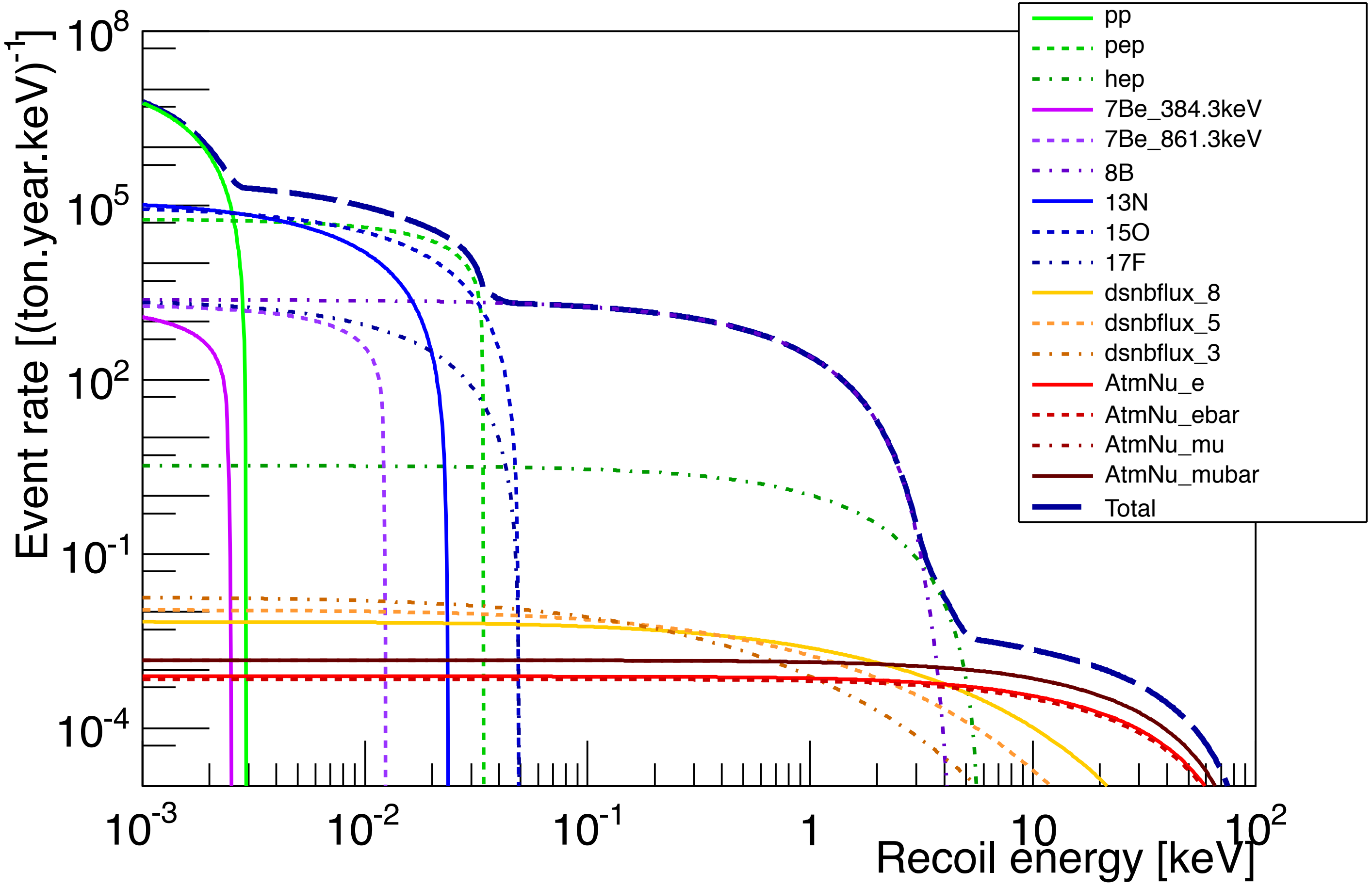
XENON1T Sensitivity



Patrick Decowski - Nikhef/UvA

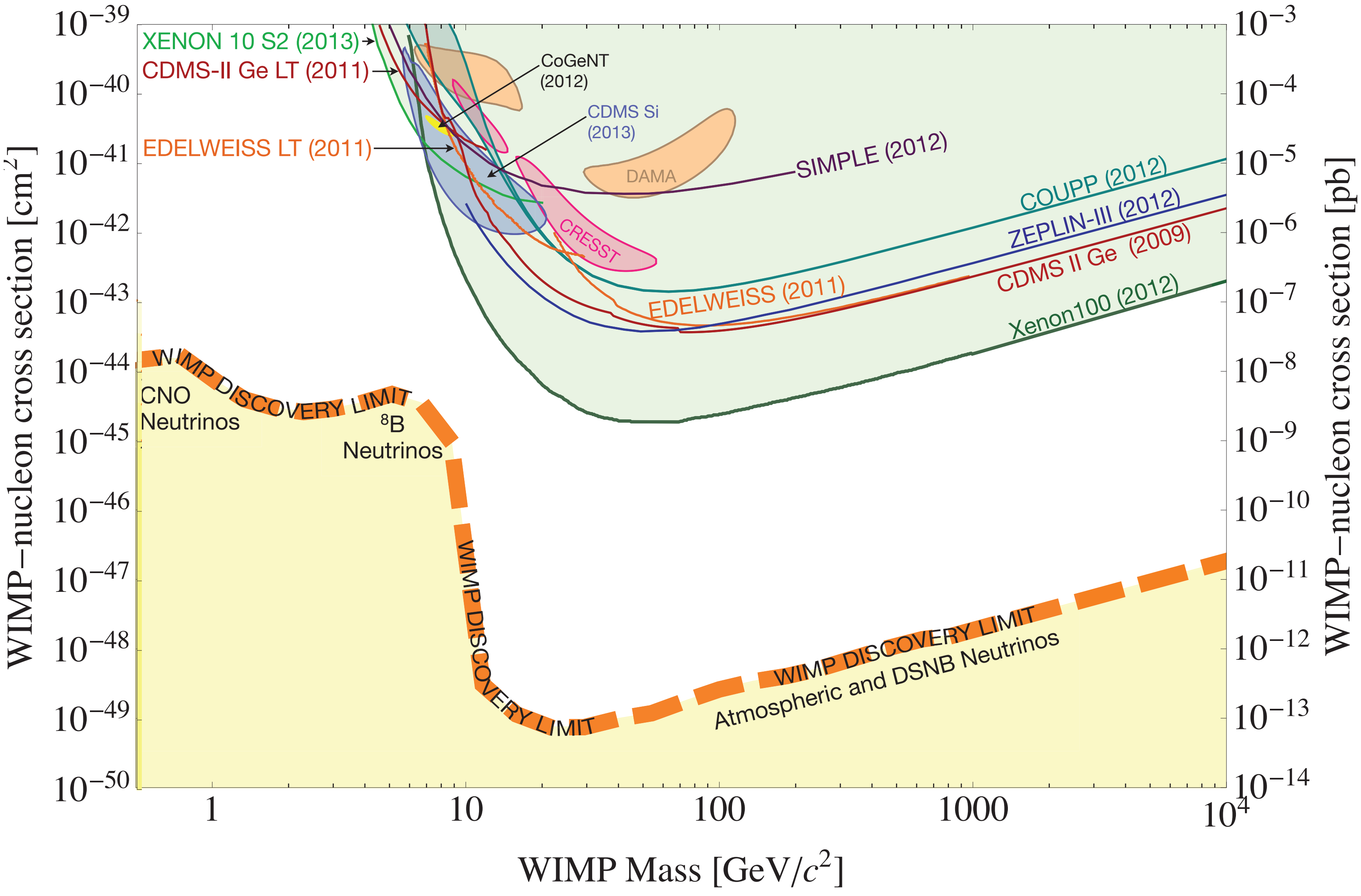
Neutrinos are the ultimate background

Neutrino-induced nuclear recoils: Coherent Neutrino Scattering



J. Billard, E. Figueroa-Feliciano & L. Strigari, arXiv:1307.5458

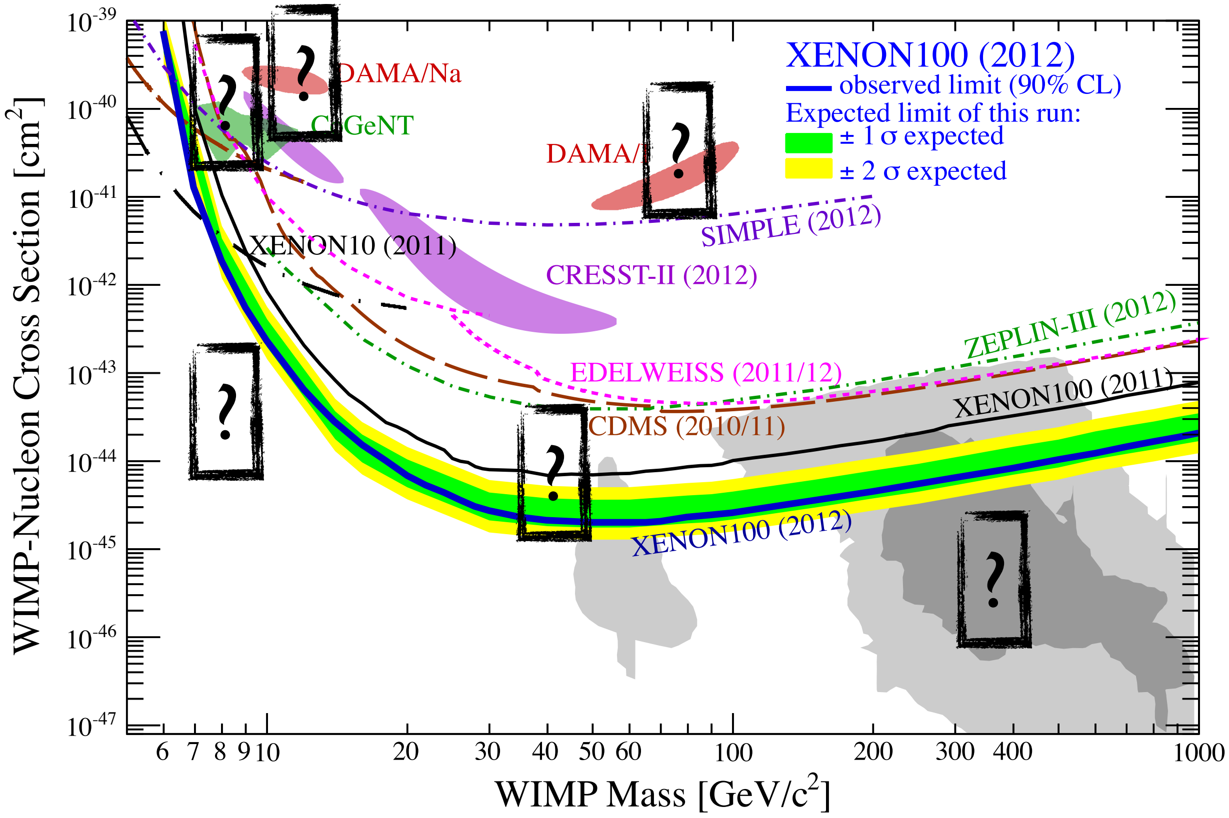
Neutrinos are the ultimate background



J. Billard, E. Figueroa-Feliciano & L. Strigari, arXiv:1307.5458

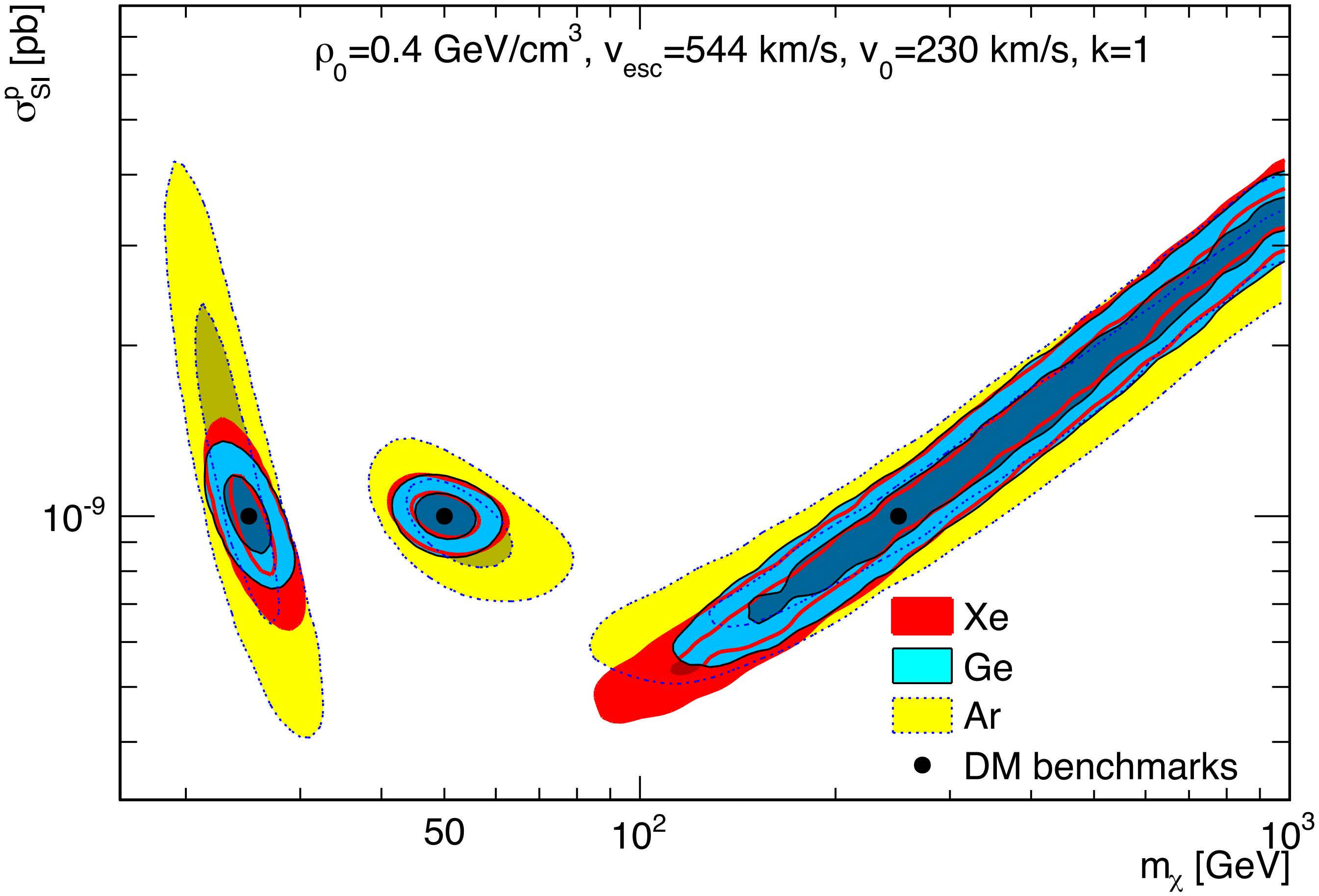
What will near future bring?

- This year:
  - LUX running: Oct 30
  - 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!

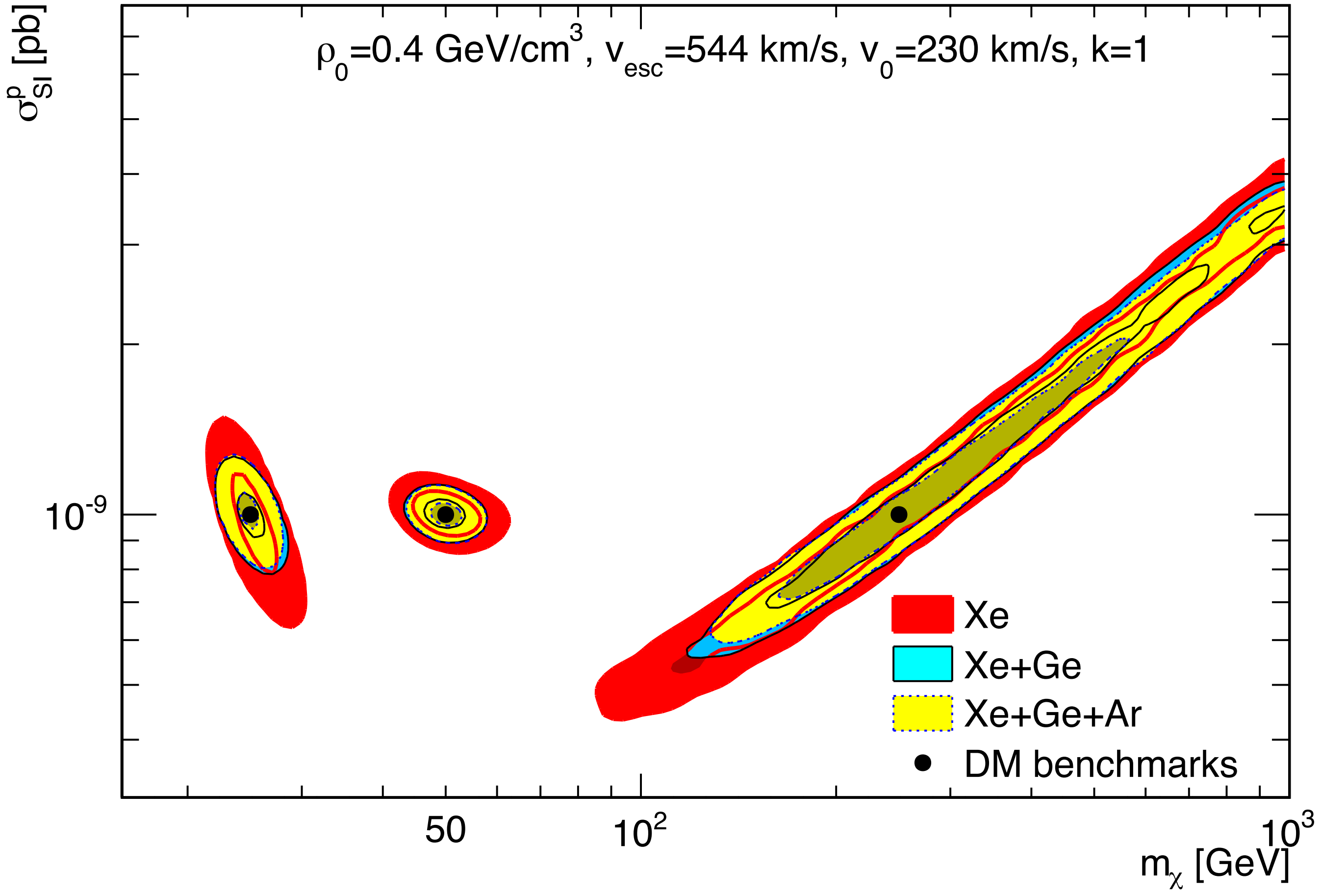
Astrophysical Uncertainties



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

Patrick Decowski - Nikhef/UvA

Astrophysical Uncertainties



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

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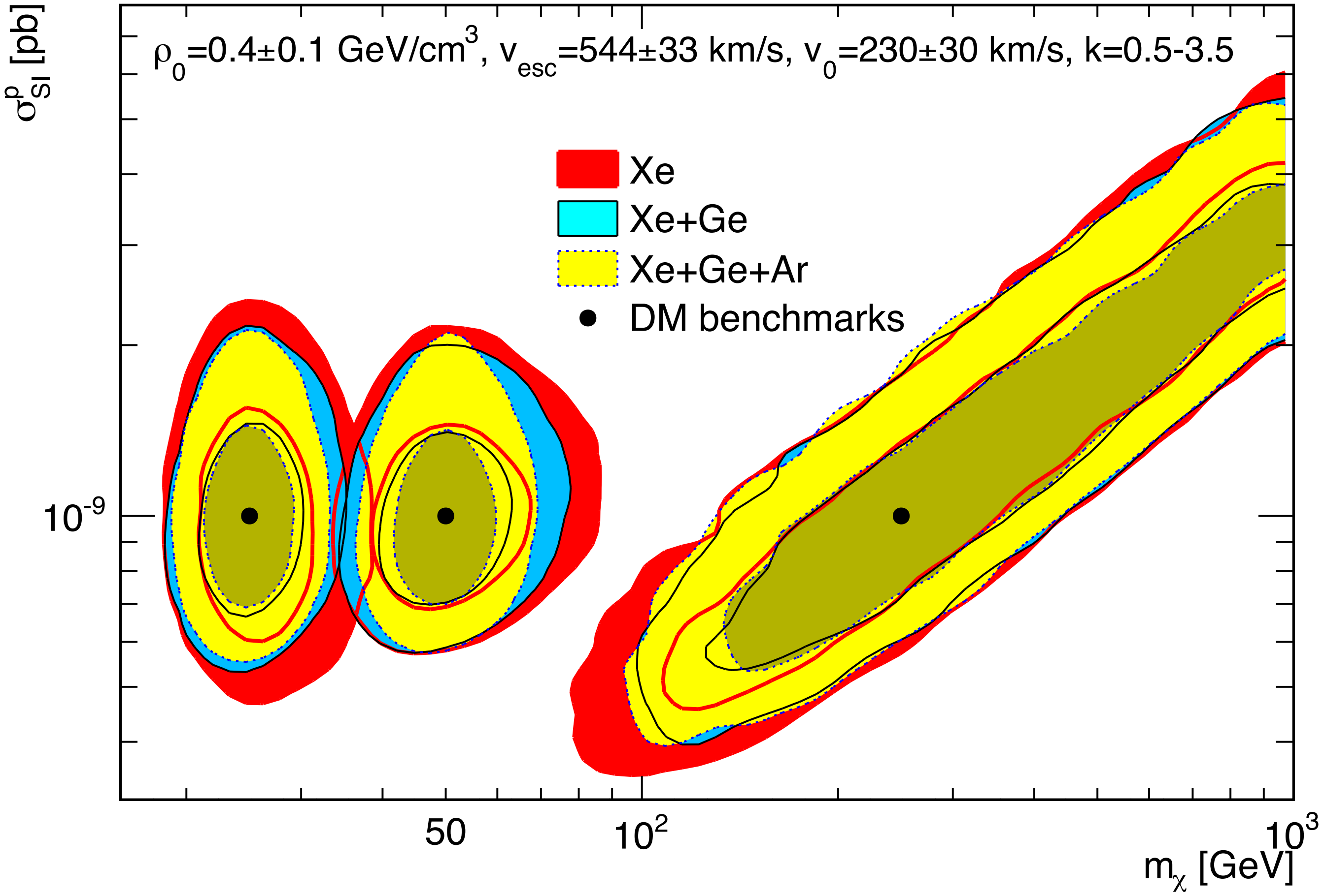
Astrophysical Uncertainties



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

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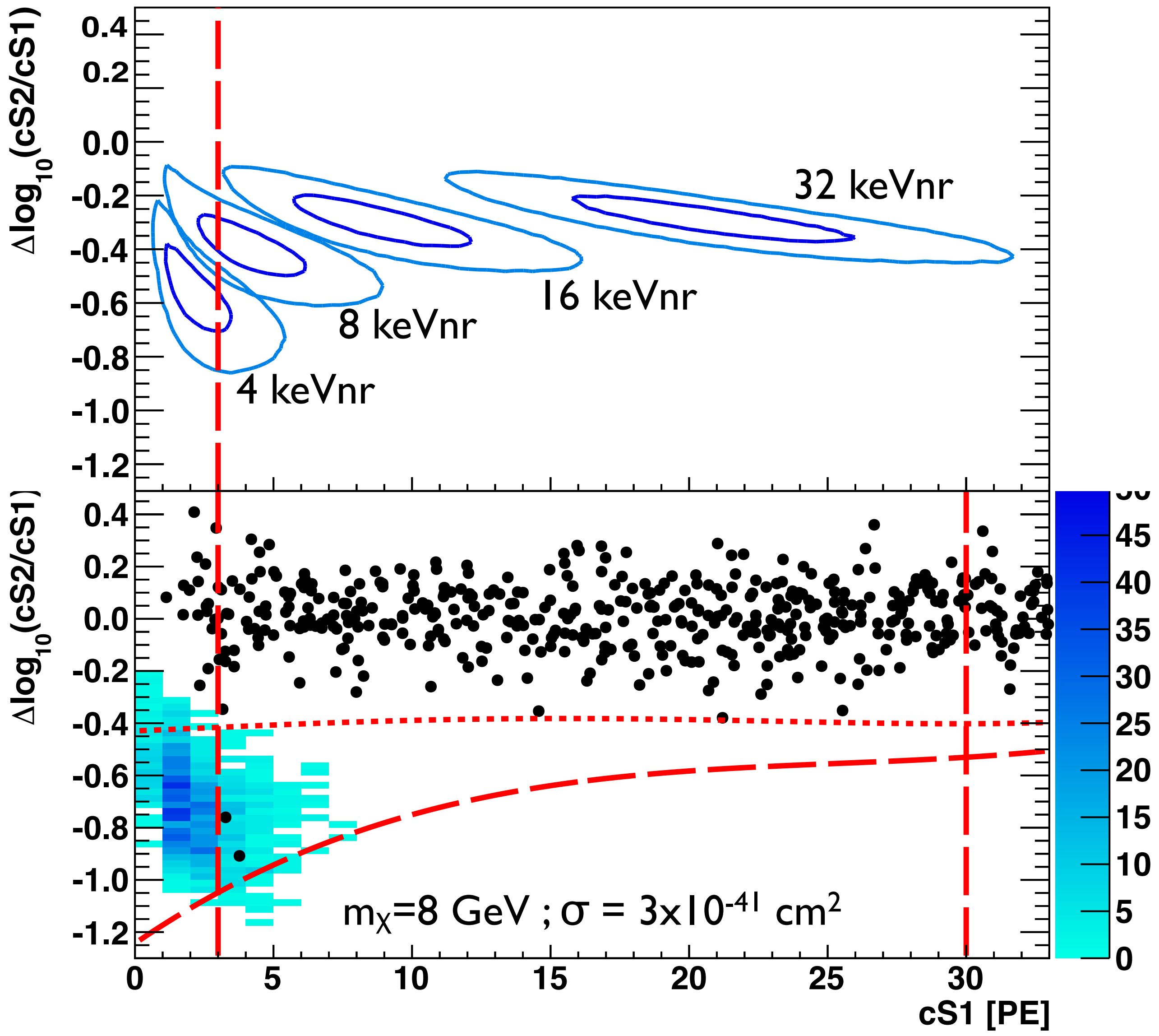
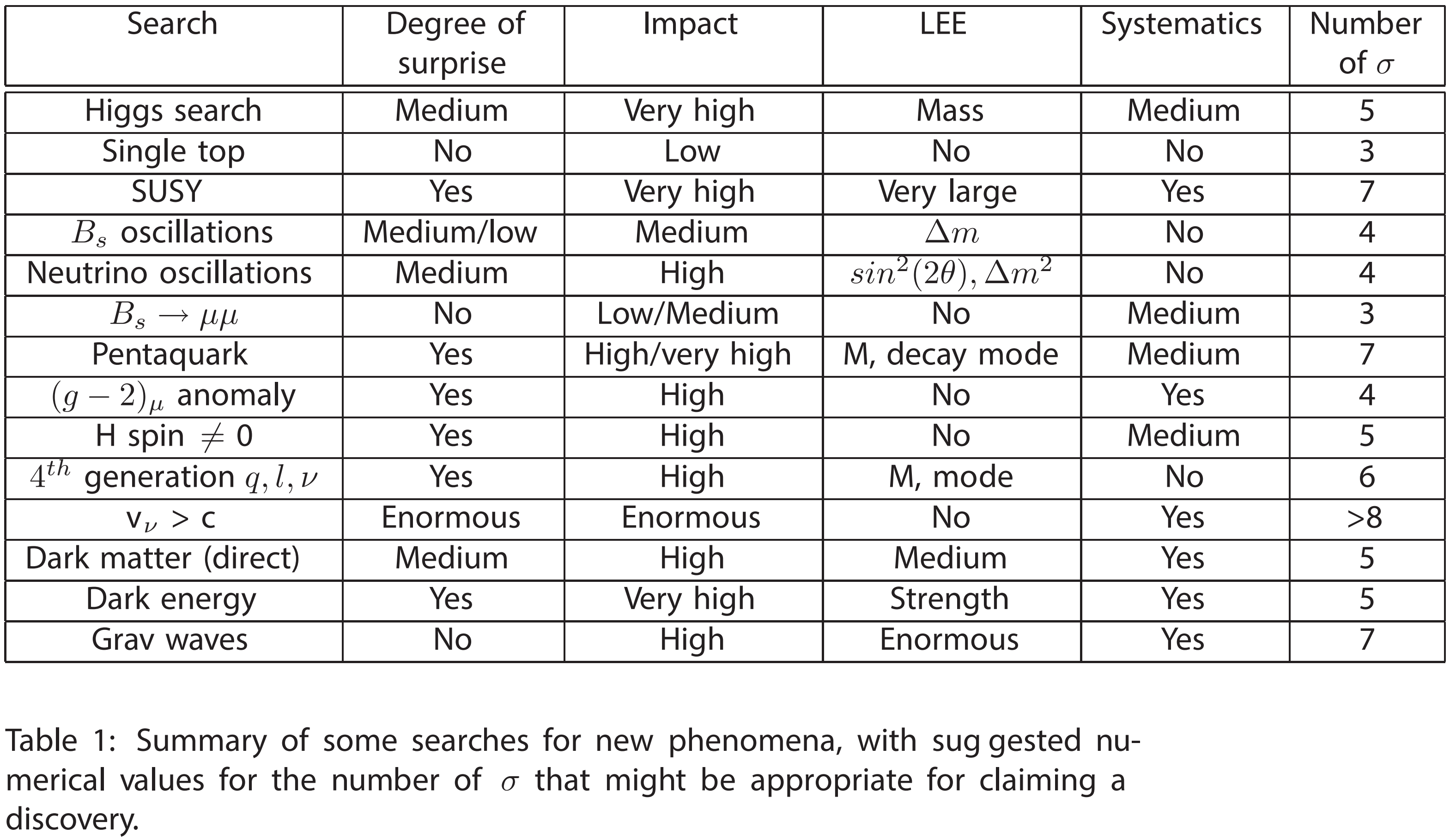
Nuclear Recoil Response



Patrick Decowski

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$_\nu$ > 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