Prospects for searches for Dark Matter in the next decade

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Caveats

1. Typo in the program: "decades" -> "decade".

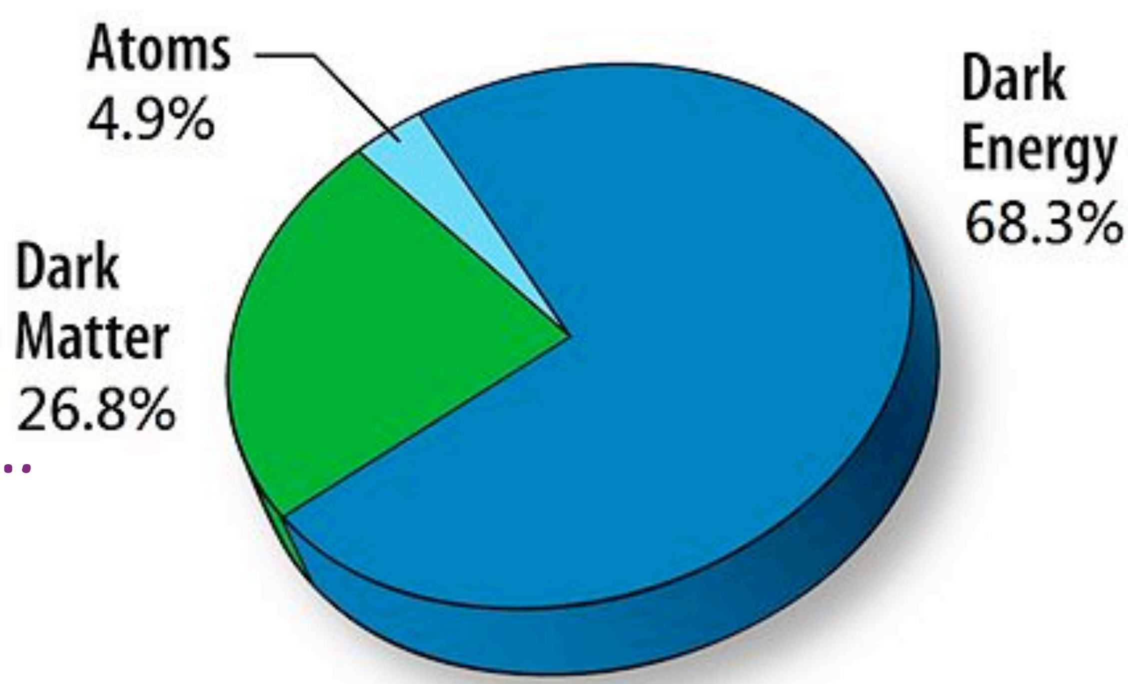
   Also, decade = ~5 yrs +- 3 yrs.

2. I have attempted a sampling of the landscape, not a through review.

[My apologies to experiments that I have failed to include, and also for any plots that are not the "latest" from a given experiment.]

The Dark Matter Problem

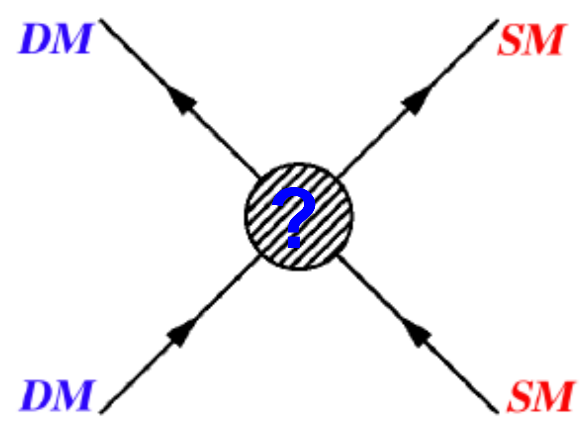
A good problem to have. There is a known effect looking for a particle signature… as opposed to extensions of SM looking for an experimental confirmation of proposed particles.



A real challenge for an experimentalist to study this known energy density.

DM as a fundamental particle

- Our picture of the universe is second quantized (particles and fields) as encapsulated in the Standard Model (SM) of particle physics. Can not easily introduce ether. Hence:
- Postulate 1: DM is a particle.
- Postulate 2: DM and SM particles interact with some force that is very weak but <u>much</u> stronger than gravity.
- Details of this force need to be worked out. However, from cosmological constraints, we can relate mass and number density.
- If DM has a mass of 100 GeV, we expect ~ 3 DM/liter



DM Particle Candidates

Bayonic DM?

-- Gas Clouds? Dim Stars? Black Holes? Not enough.

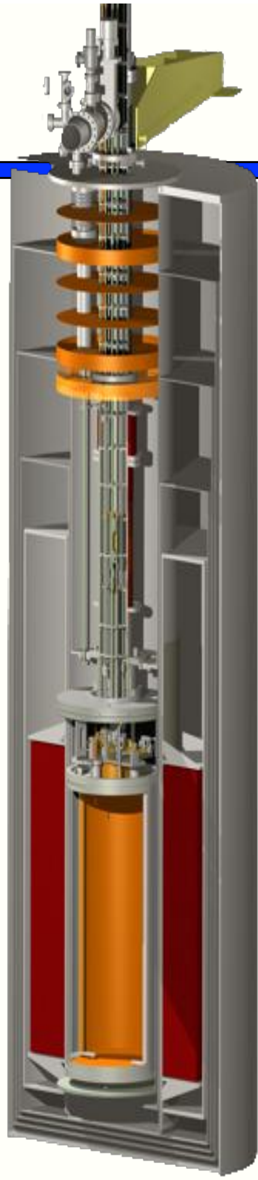
Non-Baryonic Hot DM?

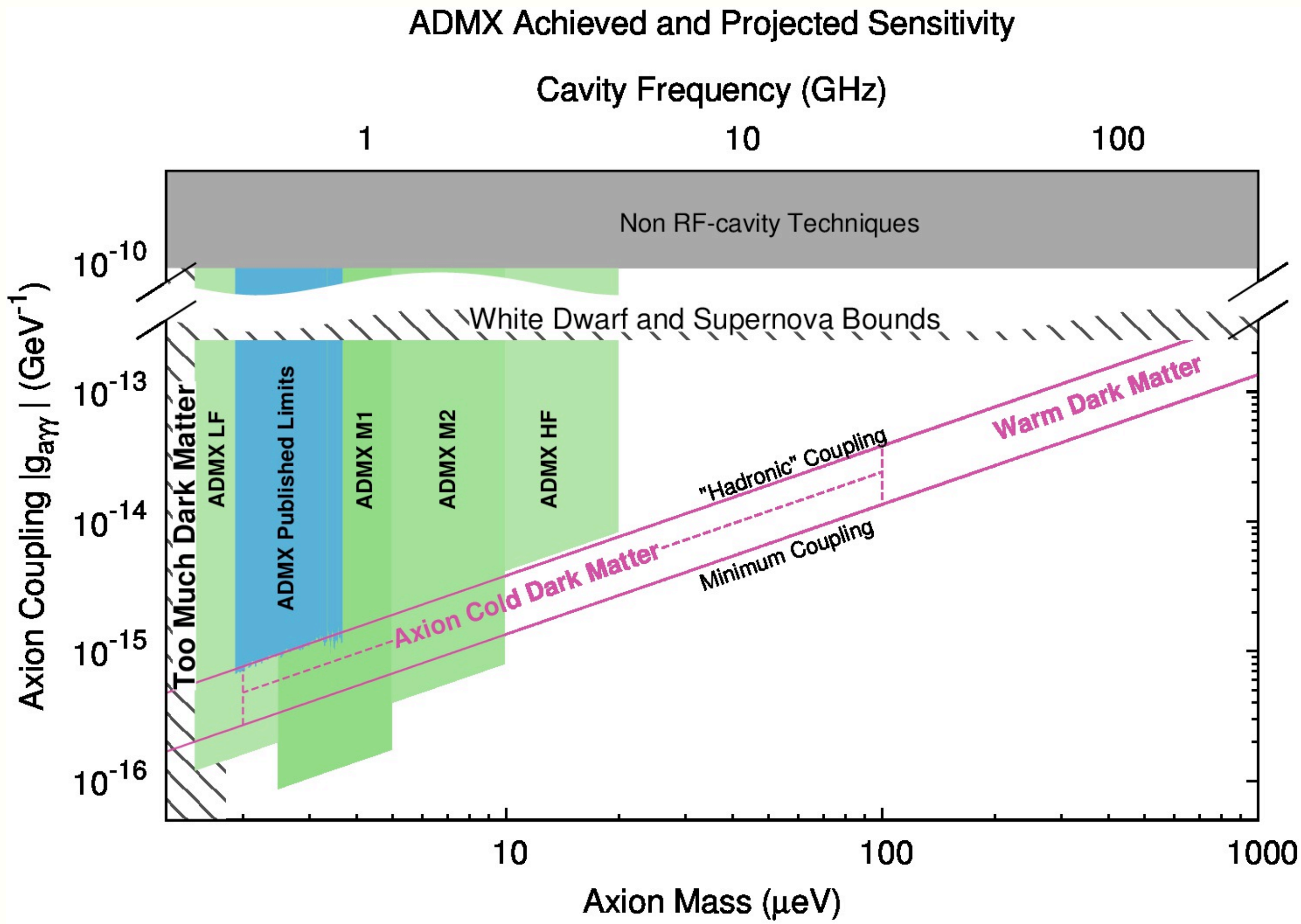
-- Neutrinos? Not enough.

Non-Baryonic Cold DM?

-- Axions? Heavy Sterile Neutrinos? WIMPS?

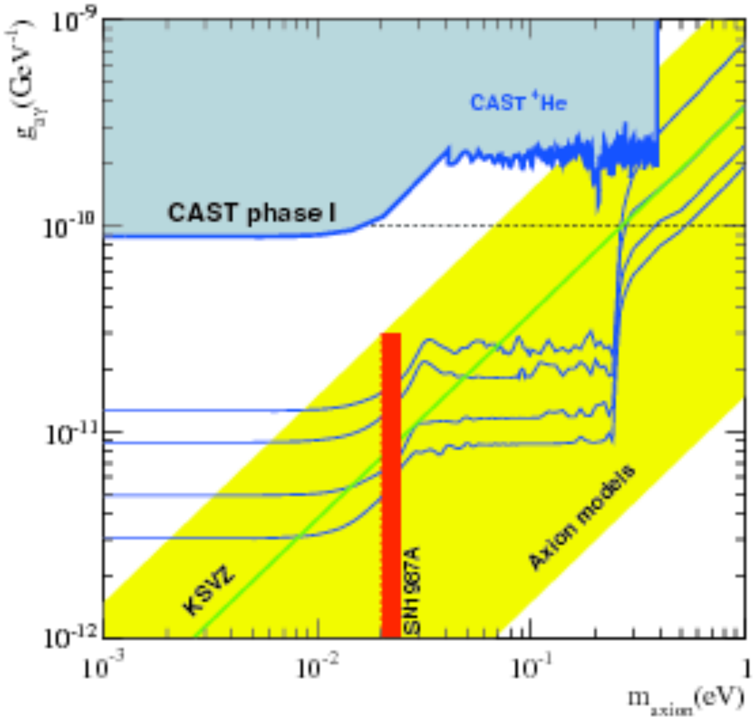
Axions: Microwave cavities

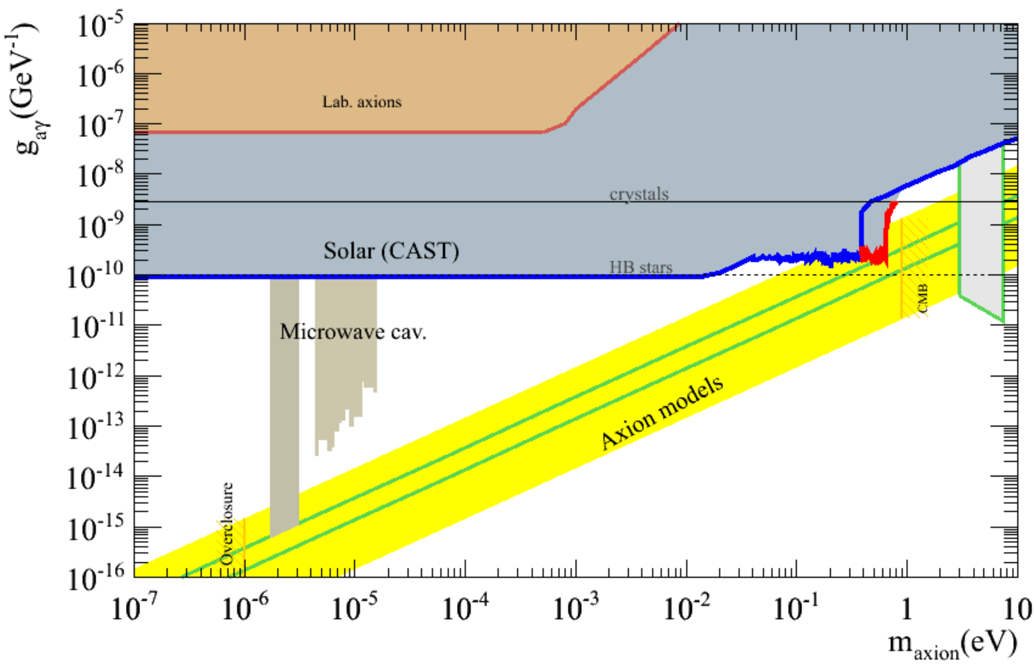




ADMX will be sensitive to cold DM in the 1-20 μeV range. ADMX-II, one of the possible G-2 DM experiments to be operated in the next decade, will cover upto ~100 μeV.

Solar Axions: CAST -> IAXO





Warm DM in the 1 meV – 1 eV range will be covered by IAXO, the next generation axion helioscope.

WIMP Miracle

A happy coincidence implied that new physics at the TeV scale with appropriately weak cross section leads to a dark matter relic (with a new quantum number preventing decay).

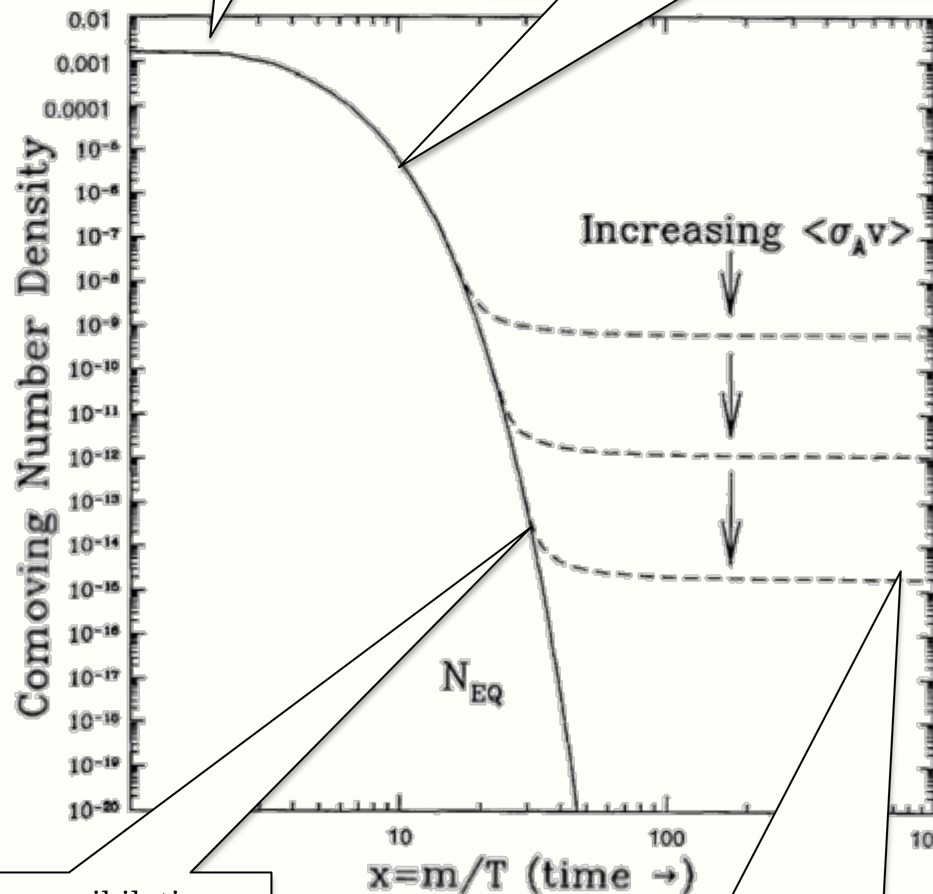
$$\Omega_x h^2 = \frac{3\cdot 10^{-27}\,cm^3/s}{\langle \sigma_A v \rangle} \approx 0.12$$

$$\Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

1. Flat region. Constant density. Equal production and annihilation.
$n_{eq} \sim T^3$

2. Exponential suppression as temperature falls below mass of dark matter particle.

$n_{eq} \sim (m/T)^{3/2}\, e^{-m/T}$



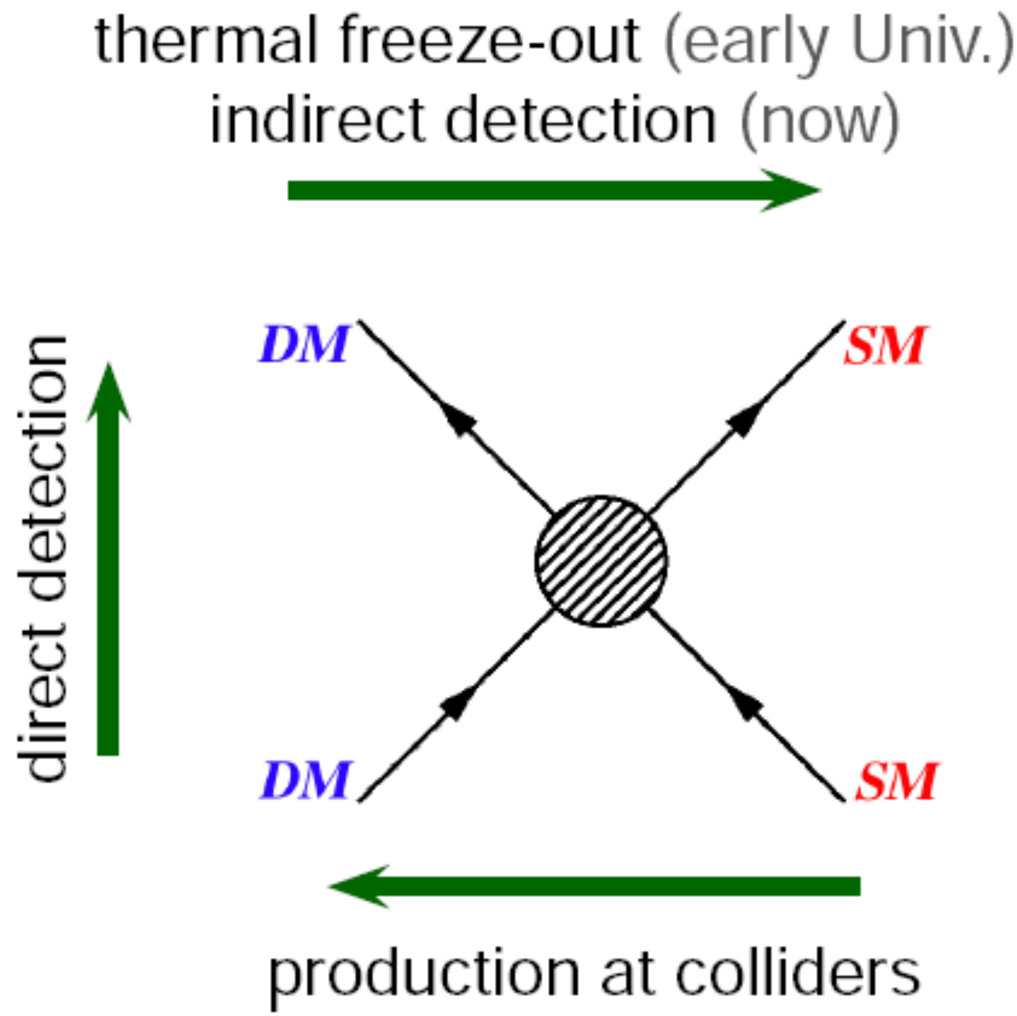
3. Turn over as annihilation rate decreases, becoming smaller than the expansion rate.

4. Relic abundance remains. Larger cross-sections keep annihilations occurring for longer.

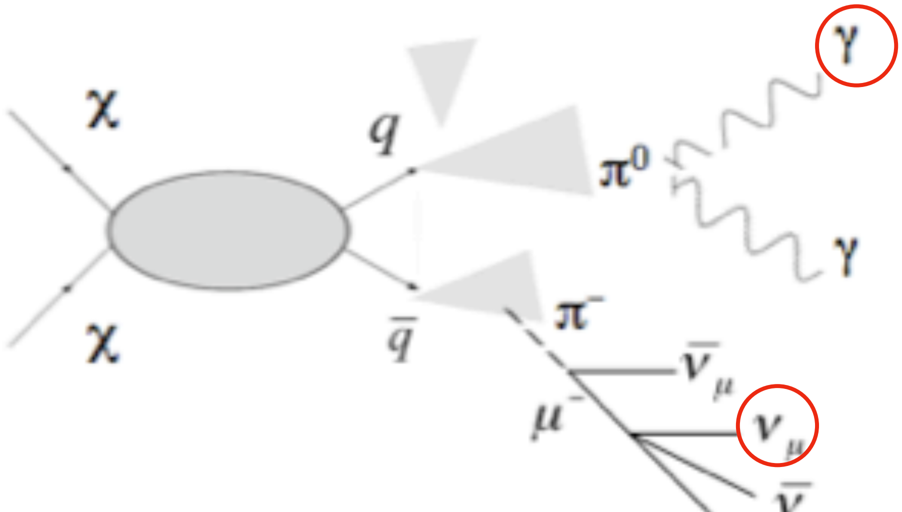
Detection Techniques

- Three major categories of investigations.

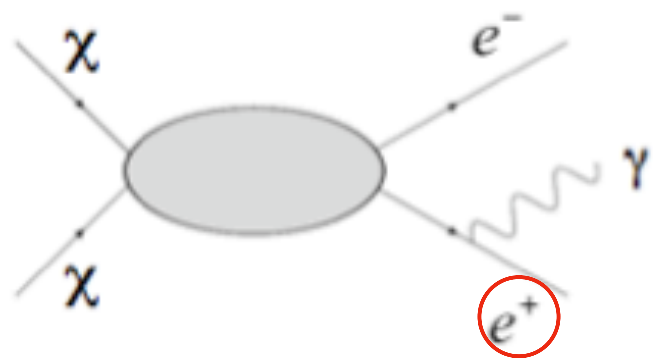
- Important to maintain the theoretical connection between these approaches.



1. Indirect Detection: Astrophysics



Secondary from π_0 decays



Prompt lepton pair production

$$\Phi_{WIMP}(E,\Psi)=J(\Psi)\times\Phi^{PP}(E)$$

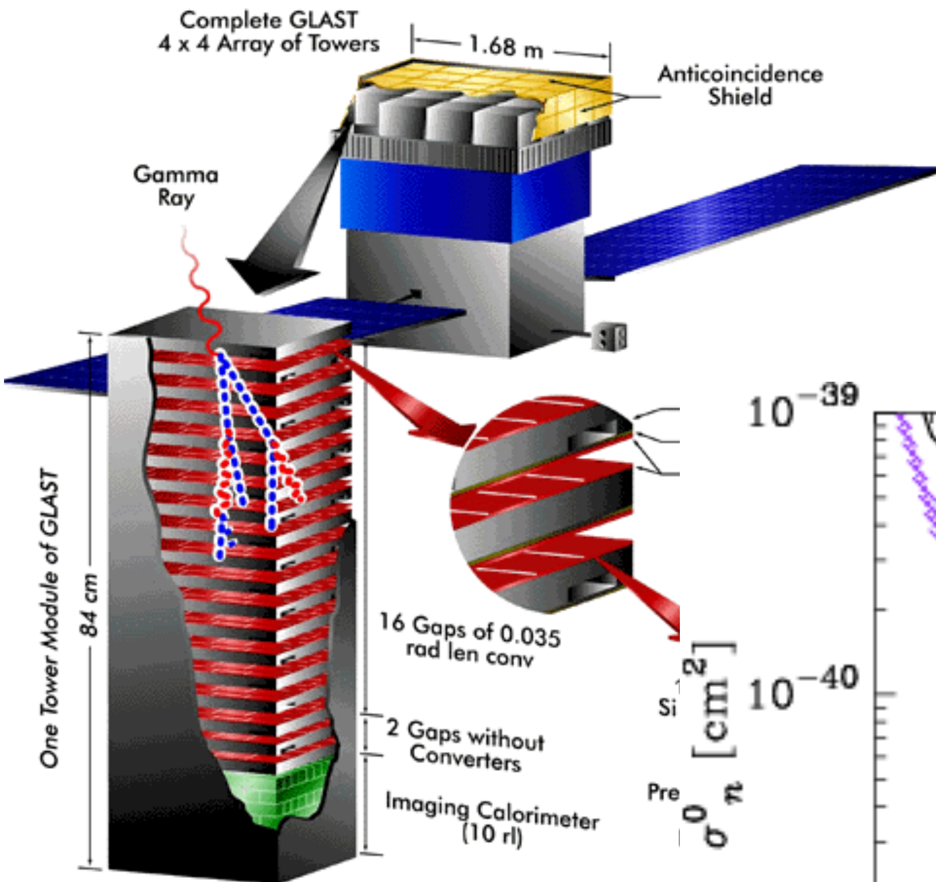
Astrophysical factor

$$J(\Psi)=\int_{l.o.s} dl(\Psi)\,\rho^2(l)$$

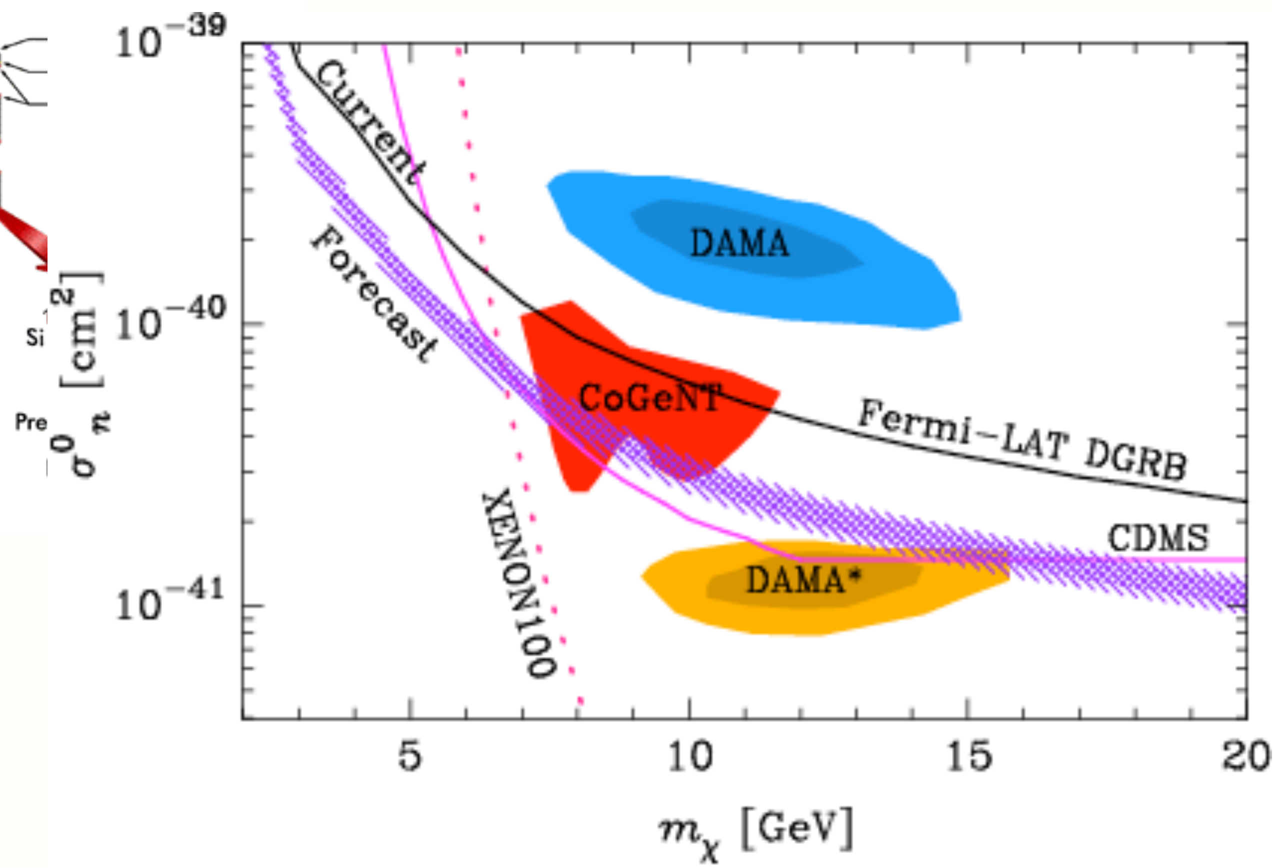
Particle physics factor

$$\Phi^{PP}(E)=\frac{1}{2}\frac{\langle\sigma v\rangle}{m^2_{WIMP}}\sum_f \frac{dN_f}{dE}B_f$$

Space-based: FERMI-LAT



Current and forecast limits from the diffuse gamma-ray background data-set.

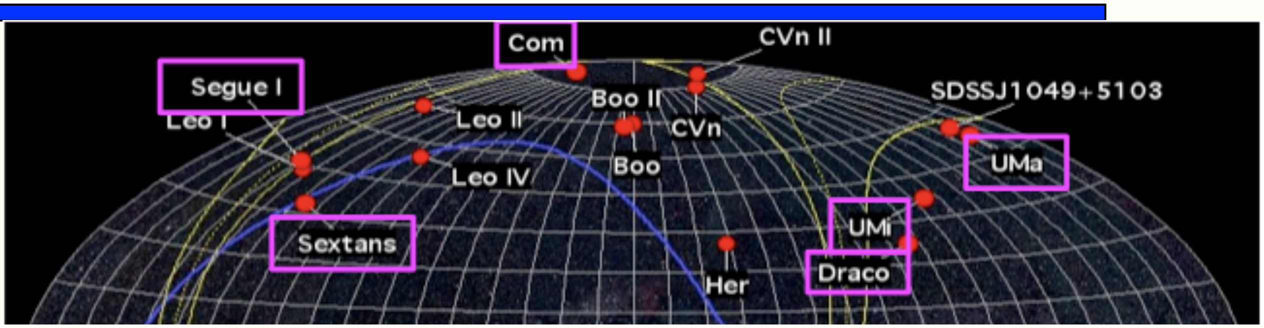


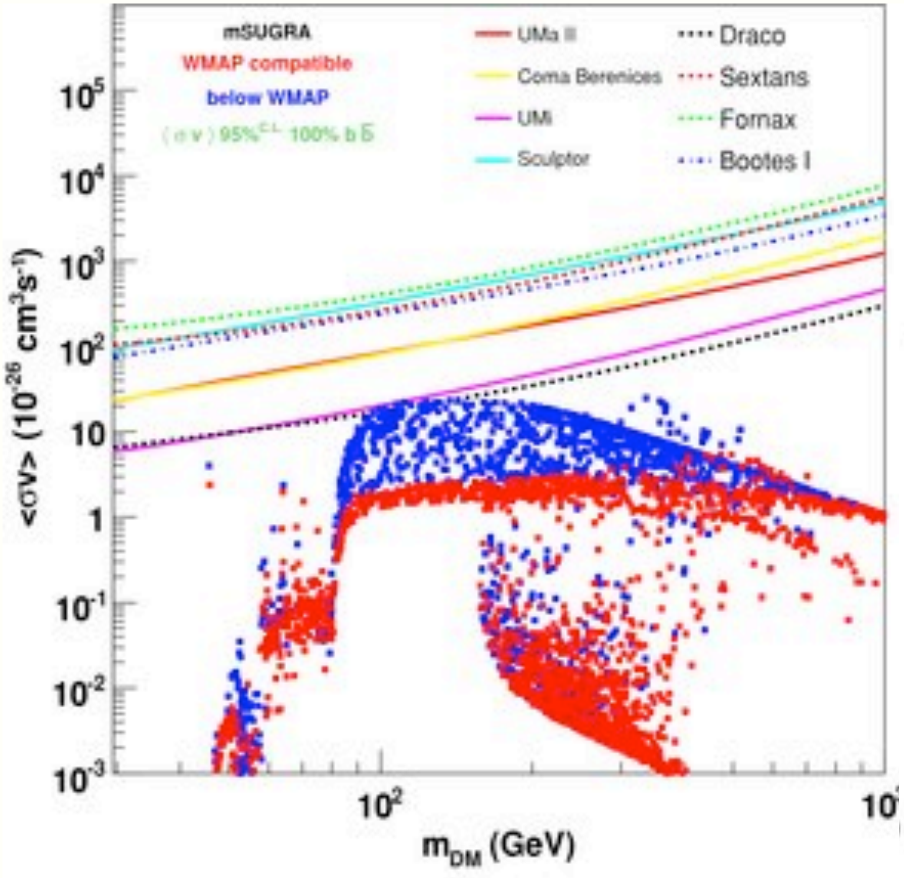
Fermi-LAT: Dwarf Spheroids

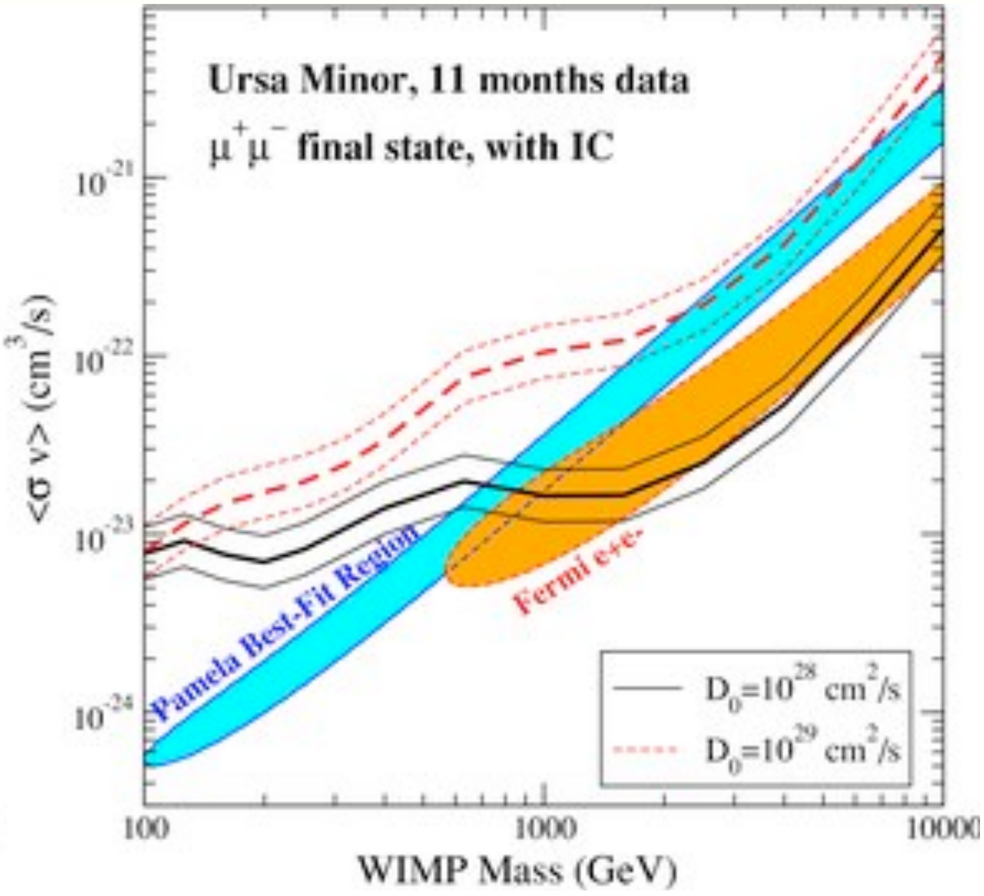
Nearby => High Flux.

M/L ~10-2000.

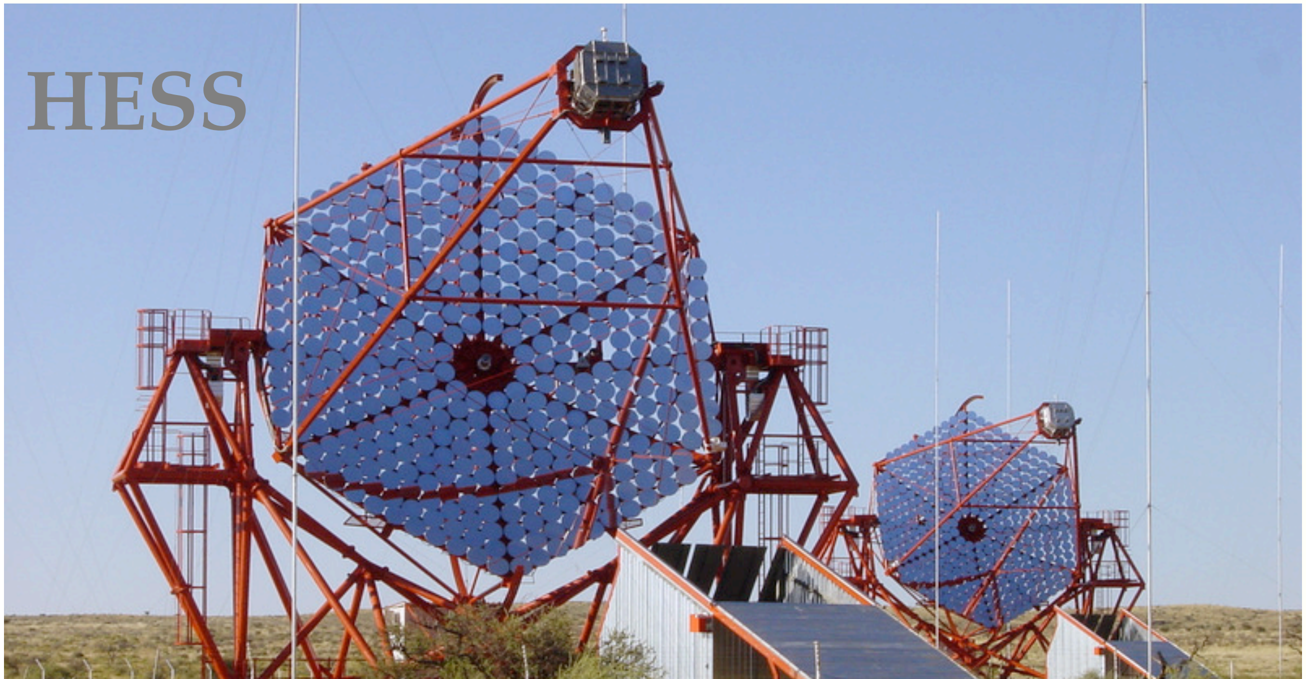
Can be "stacked"

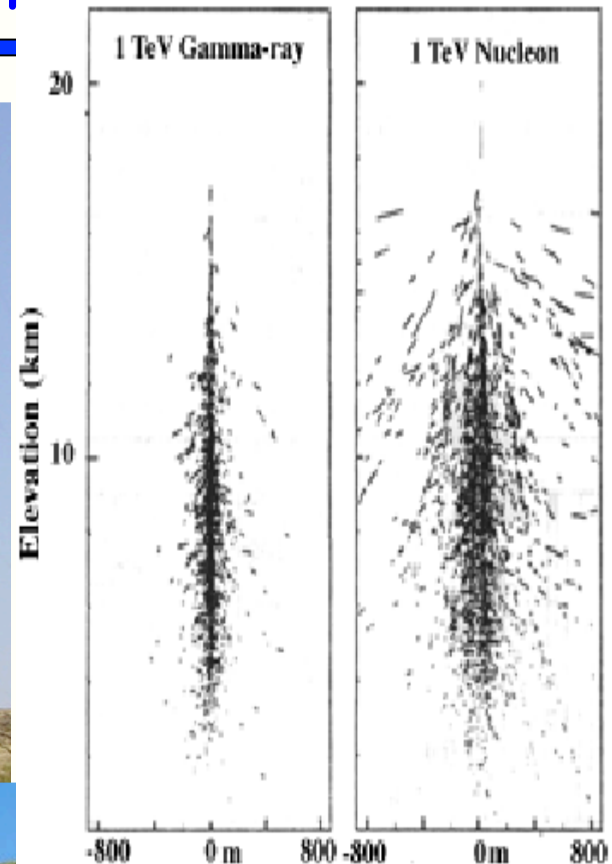


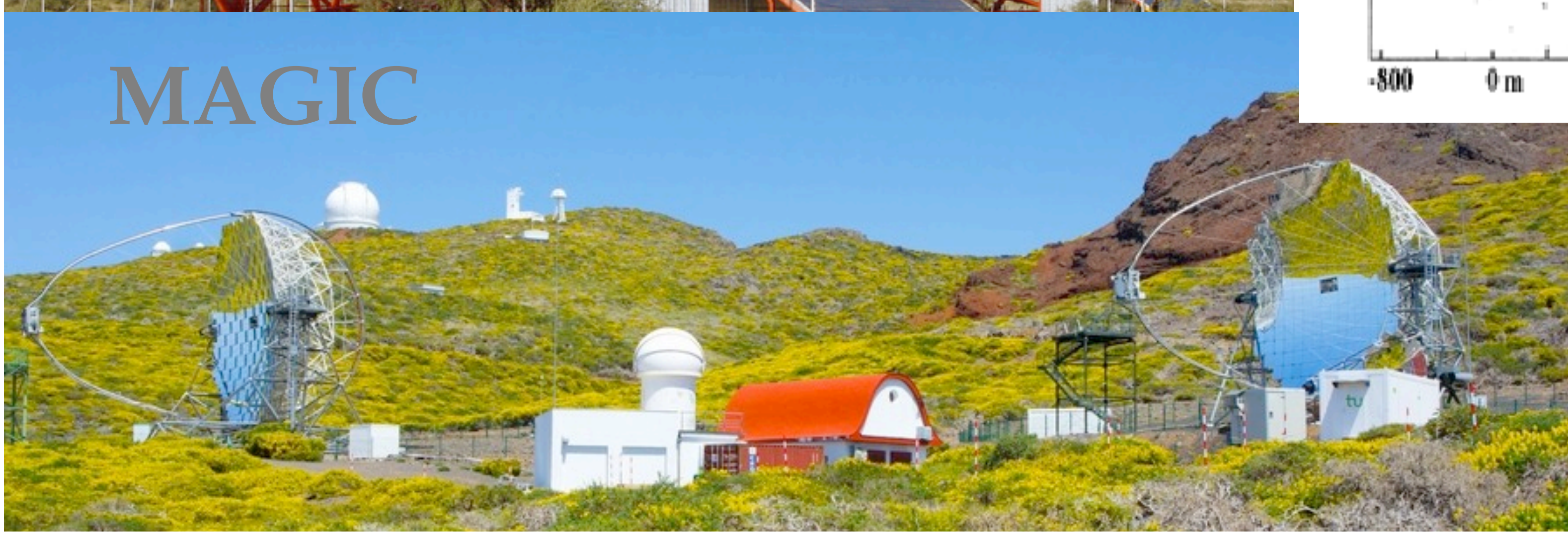




Ground-based: Air Cerenkov Telescopes

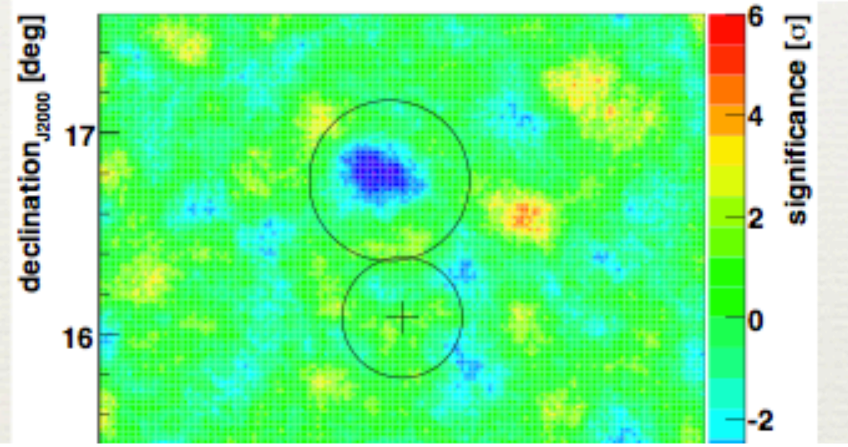


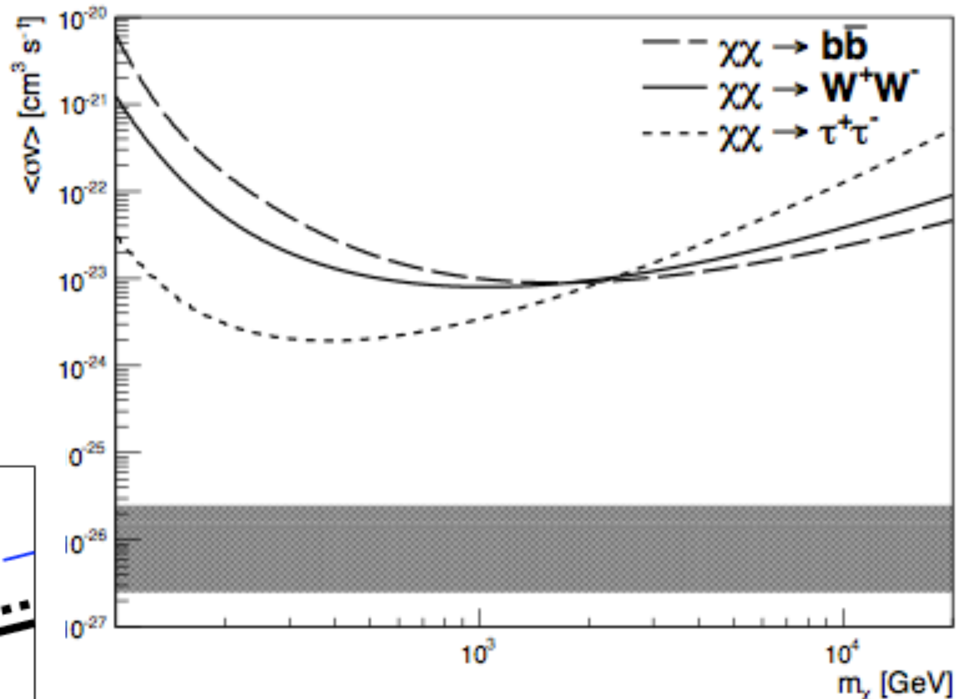


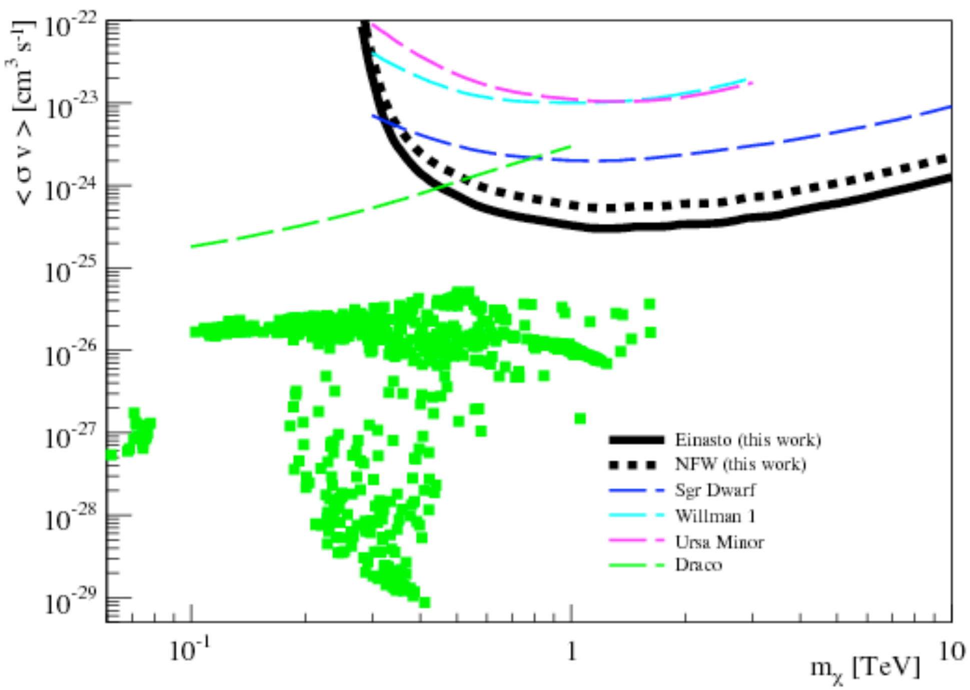


Ground-based Limits

Veritas, arXiv:1202.2144 Segue 1

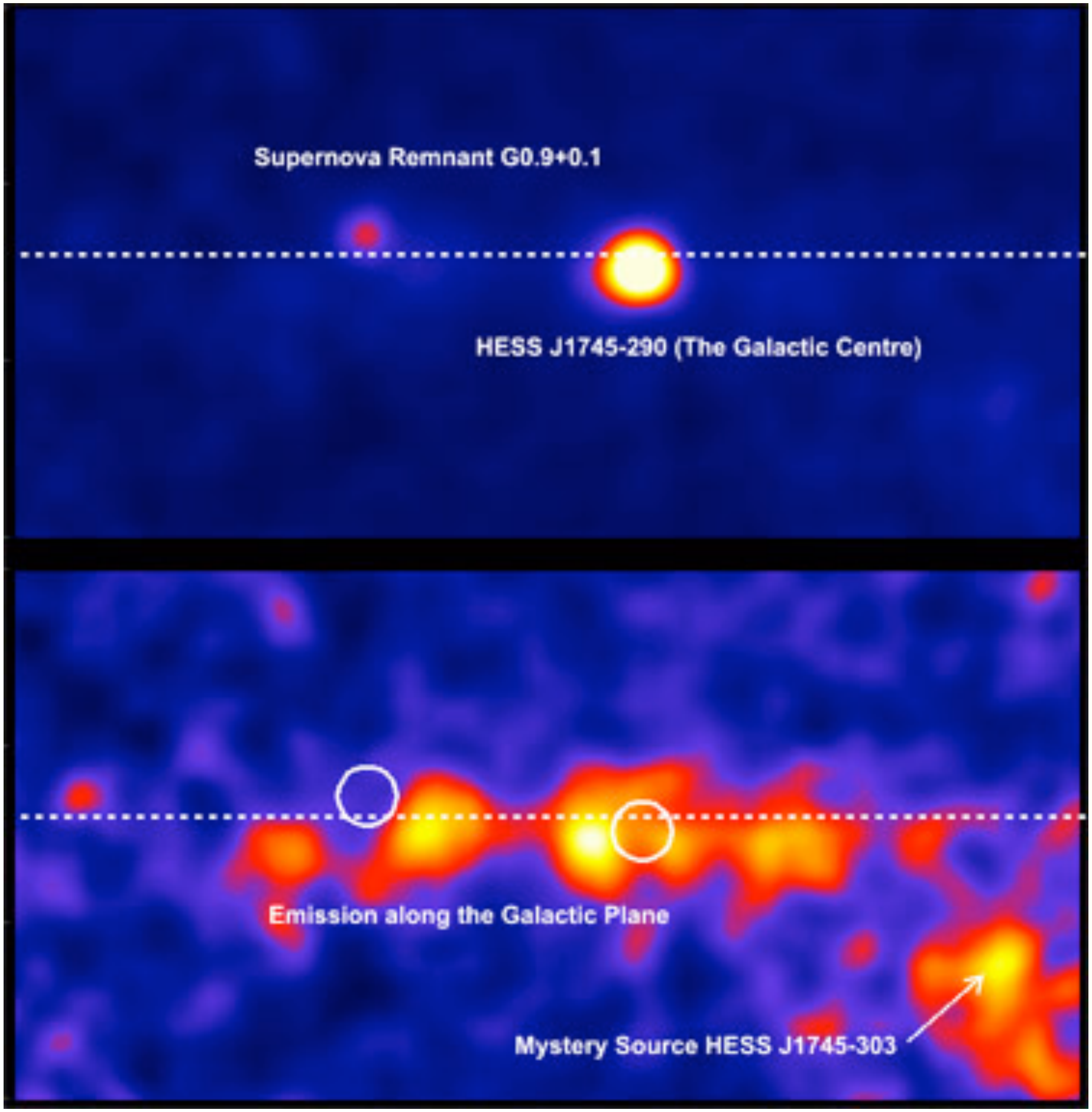






HESS limits from several Dwarfs.

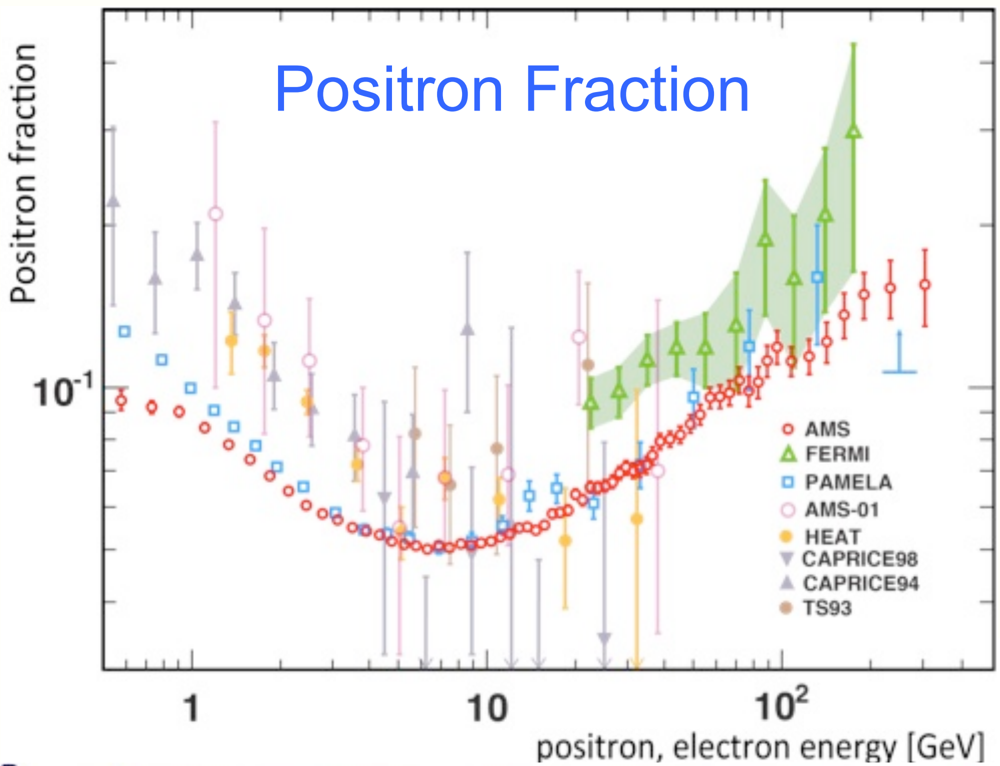
HESS: Galactic Center



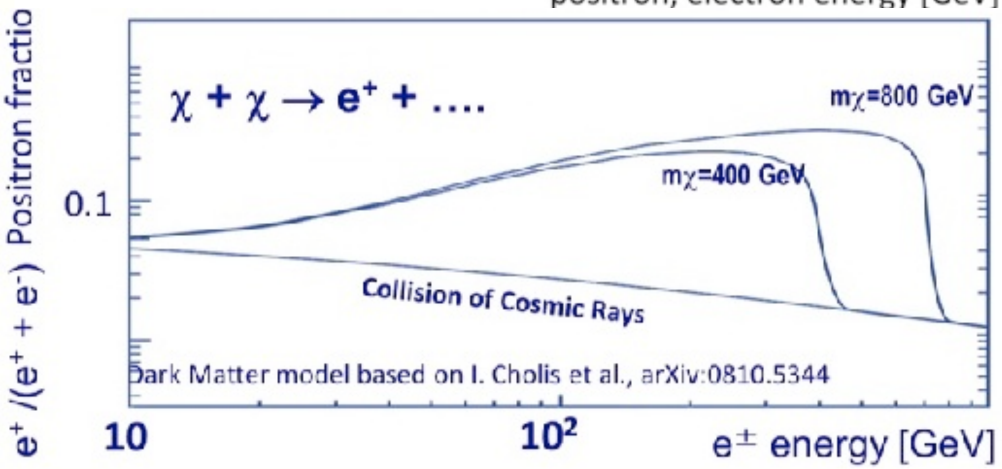
Two bright point sources => bottom plot is after subtraction. The gamma-rays are thought to come from accelerated charge particles impinging on a gas cloud.

Larger telescope (CTA) proposed for operations in the next decade.

AMS-02: Spring 2013 result

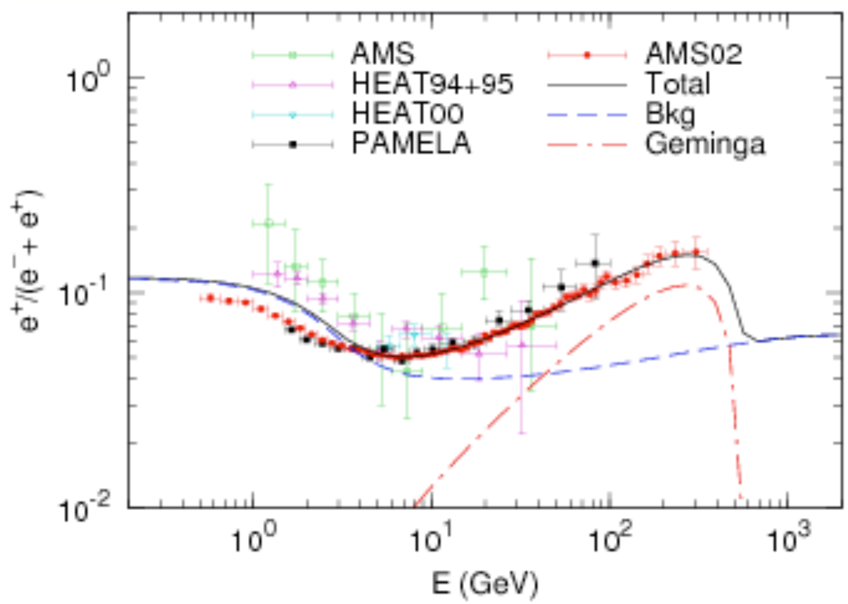


The rise in positron fraction can be attributed to DM annihilation.

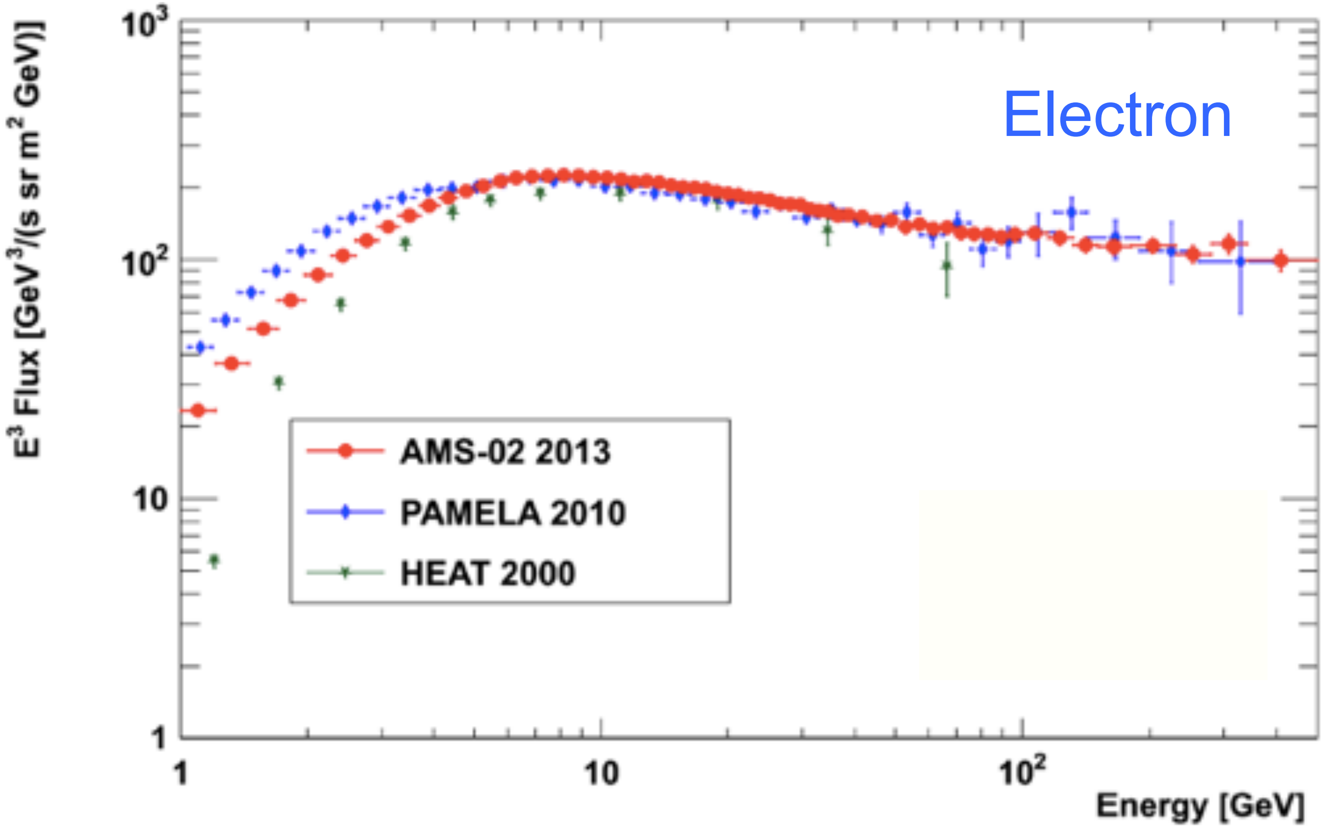


Alternative explanation sums up contributions from pulsars.

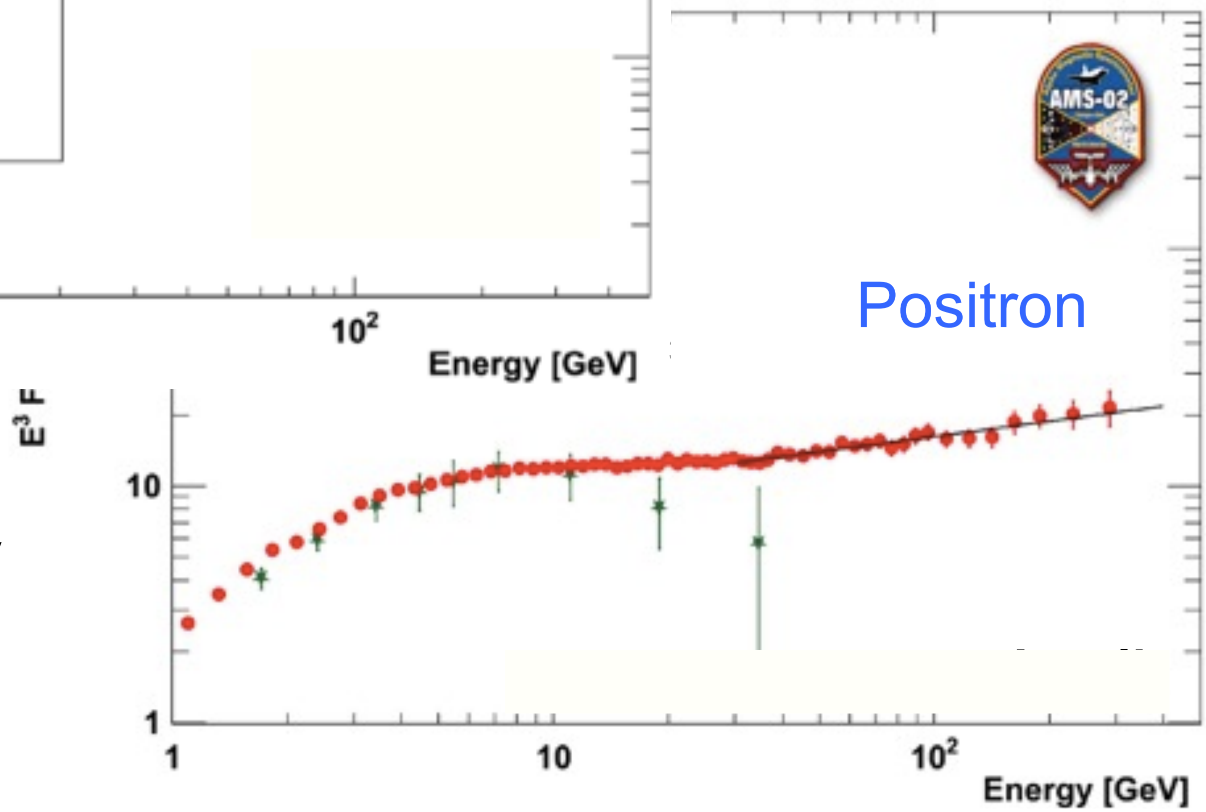
Yin *et al.* Phys.Rev. D88 (2013) 023001



AMS-02: Fall 2013 update

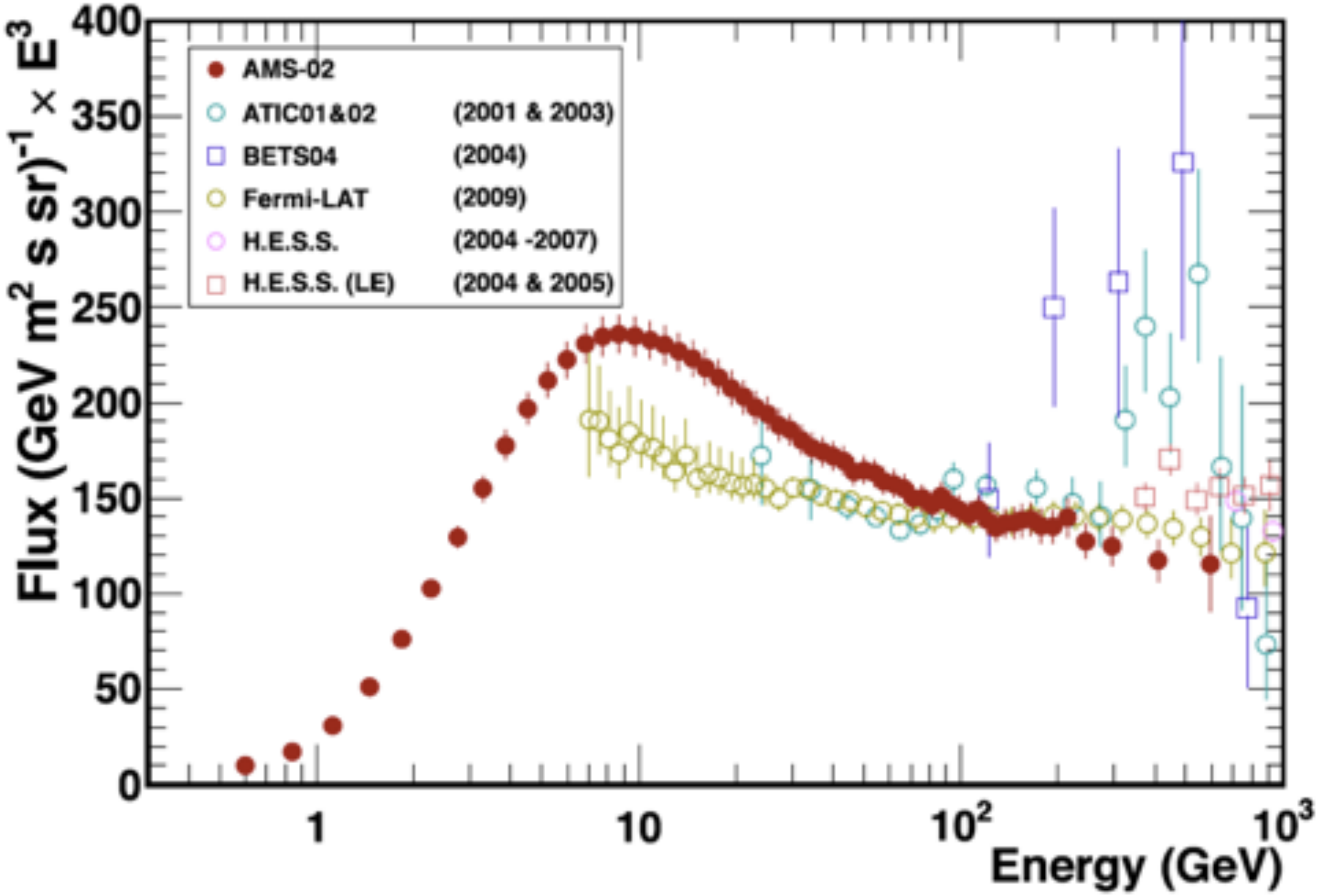


The electron spectrum (xE^3) slowly falls above 10 GeV



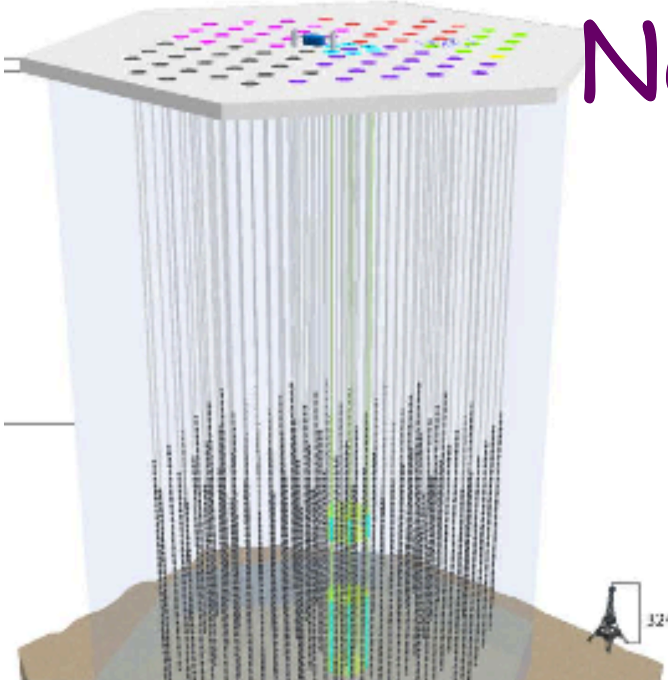
The positron spectrum (xE^3) displays a steady rise above ~30 GeV

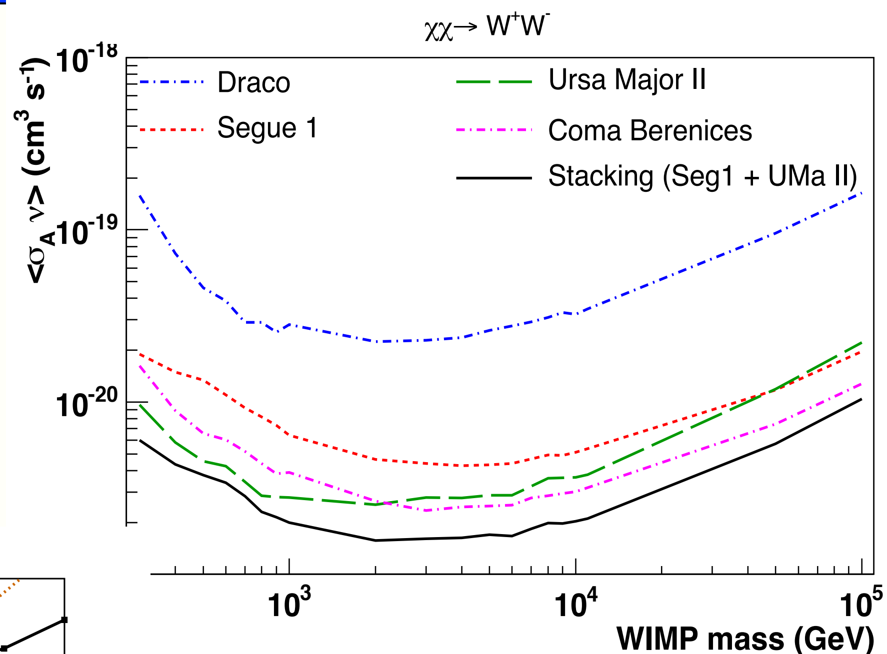
AMS-02: Electron + Positron Flux

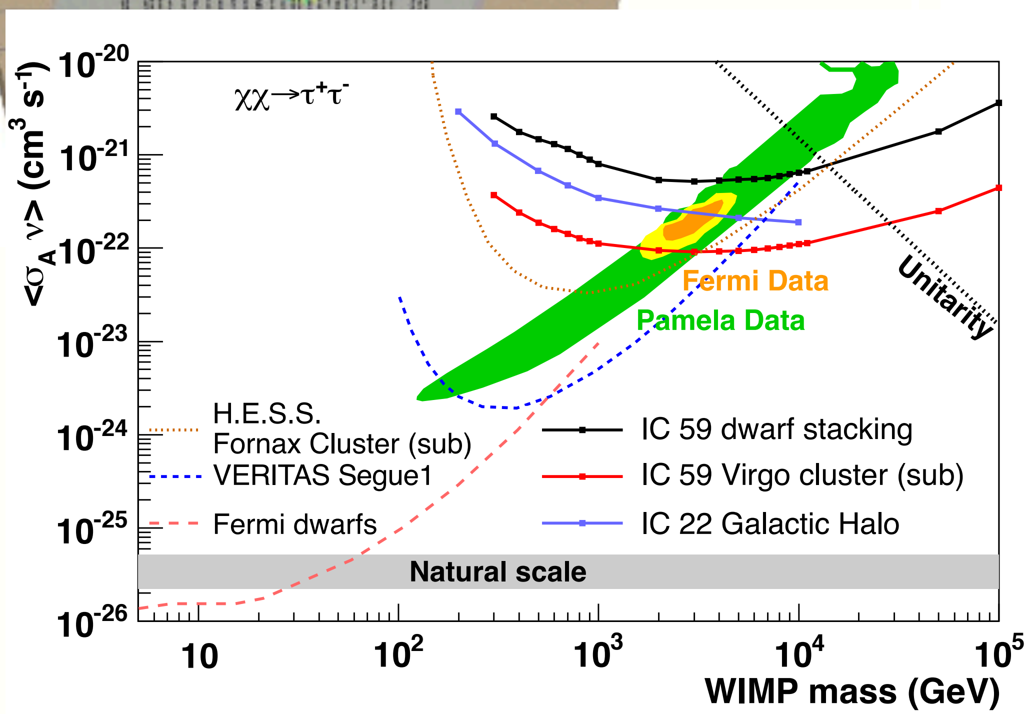


Curves extended to ~700 GeV. No visible structure in the combined flux.

Neutrinos: Ice Cube

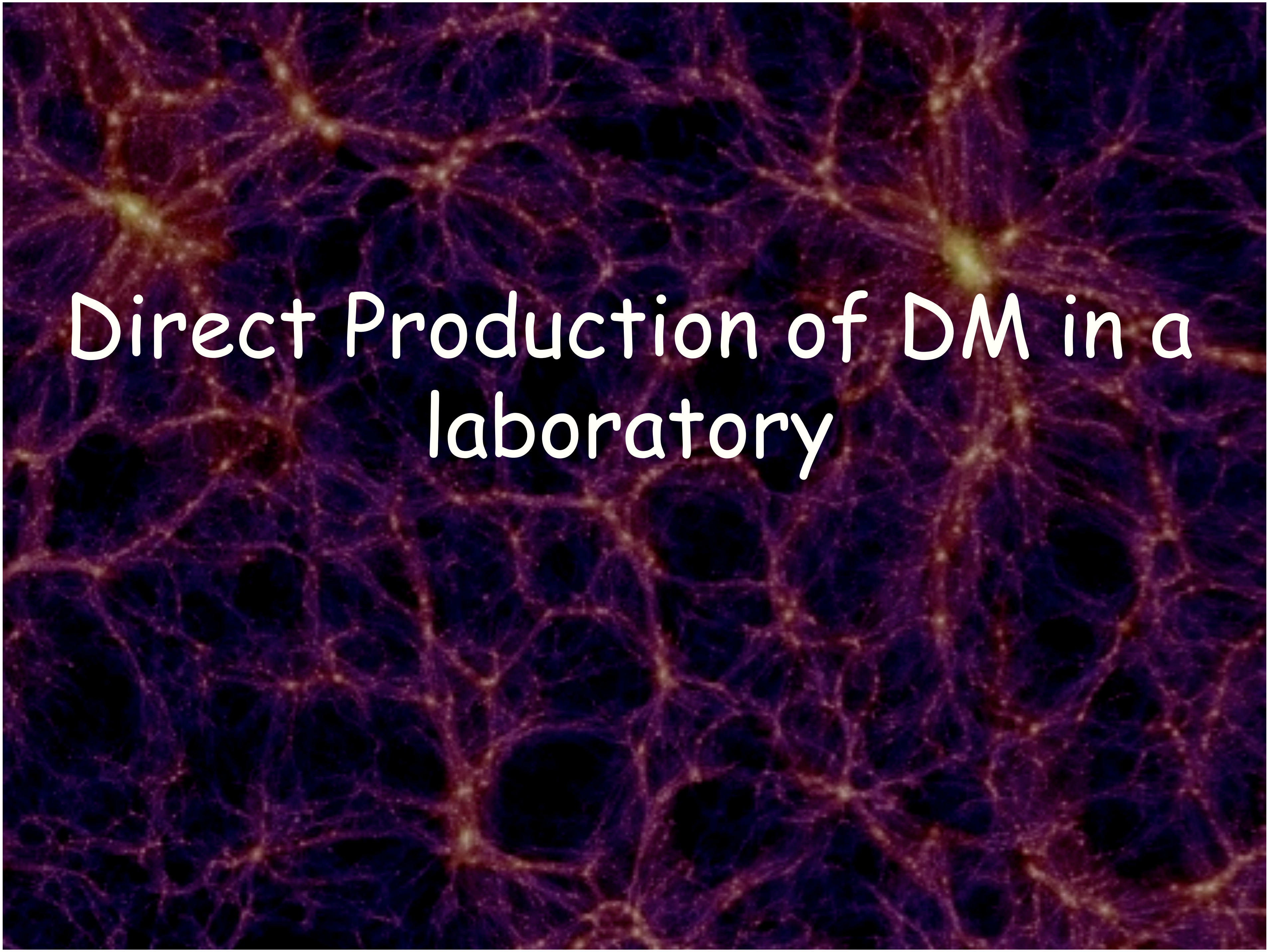






More sensitivity from Virgo cluster than stacking of Dwarfs.

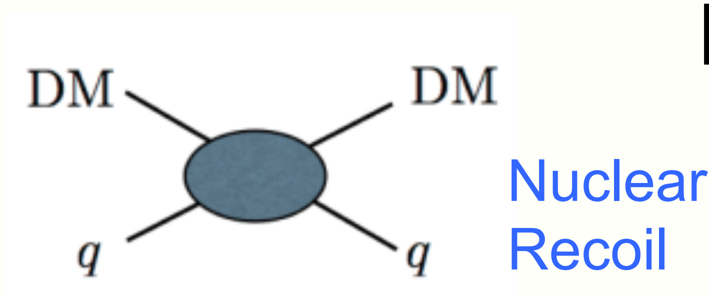
A lot more running left in this program!

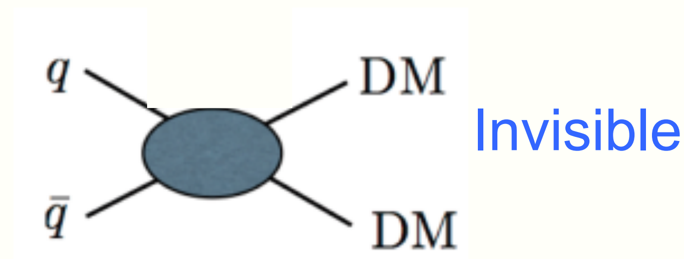

Direct Production of DM in a
laboratory

2. Dark Matter Production: LHC

Elastic Scattering (t-channel)

Pair Production (s-channel)

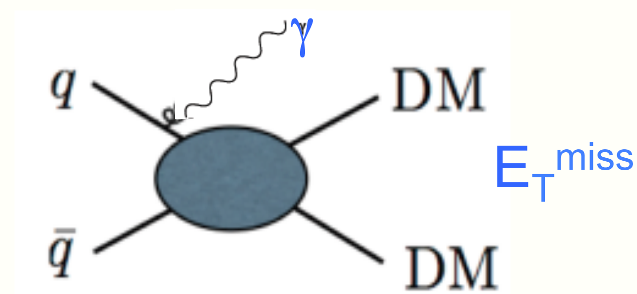




Direct Searches

Collider Searches

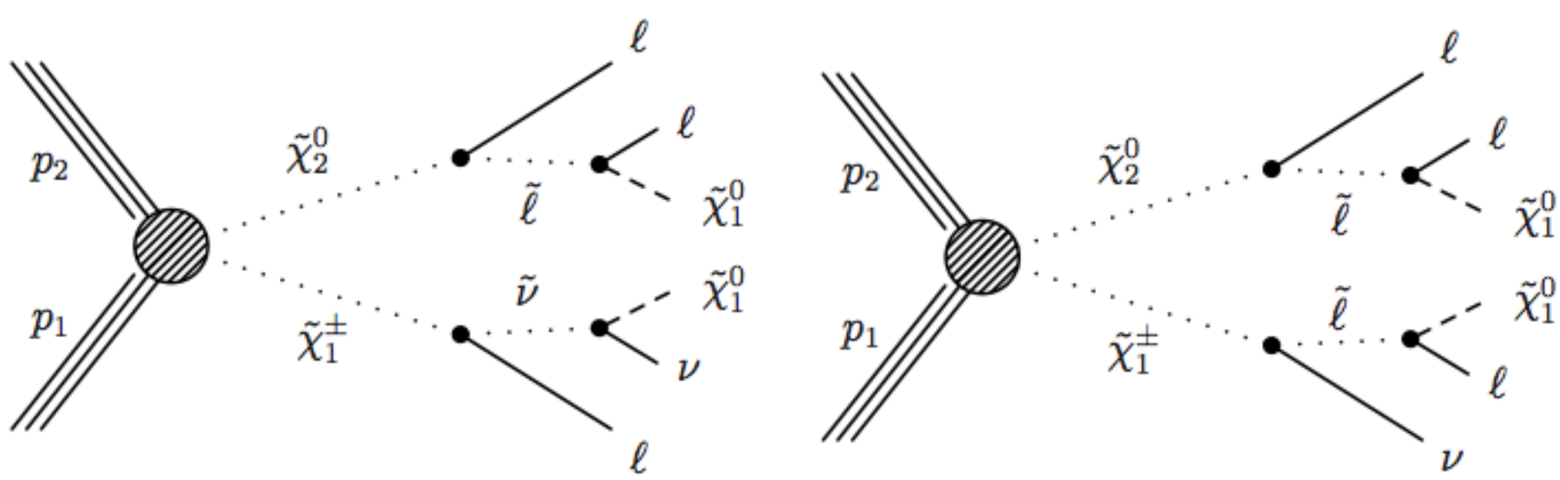
Radiation of a boson (photon, gluon, W, Z) in the initial state makes the process visible.
SM vertex well understood. Search for such "mono-boson" states.



SUSY Production @ LHC

SUSY based search for DM involves investigating neutralino production as the fundamental technique. Two types of processes: 1) Cascade decays into LSP from heavier SUSY states and 2) direct gaugino production.

Example of direct production: the tri-lepton final state.



No detailed presentation of SUSY searches in this talk.
See Sunil Somalwar's talk.

Model Independent Phenomenology-I

Fox, Harnik, Knopp and Tsai Phys. Rev. D 85, 056011 (2012)

Cast this process as a contact interaction with effective operators. The two important operators used by CMS are:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Vector Operator

$$O_A = \frac{(\bar{\chi}\gamma_\mu\gamma^5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Axial-Vector Operator

The operators provide cross sections that depend on the scale Λ and m_{DM}, the mass of the DM particle. The vector operator leads to spin-independent (SI) and the axial-vector operator to the spin-dependent (SD) cross section:

$$\sigma_{SI} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

(SI)

$$\sigma_{SD} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

(SD)

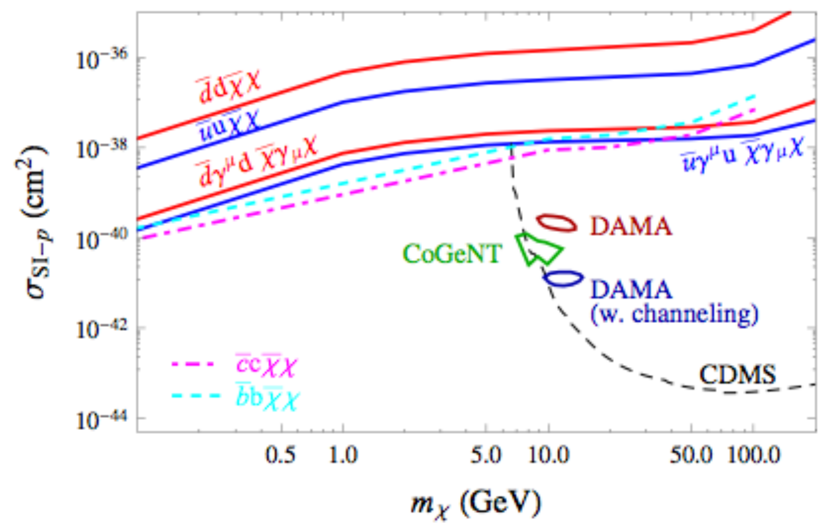
Where μ is the reduced mass

$$\mu = \left(\frac{m_{DM}\, m_p}{m_{DM} + m_p}\right)$$

LHC Phenomenology-I (contd.)

Bai, Fox and Harnik, JHEP12(2010)048

Scalar operators predict a much larger cross section than vector -> use the vector operator phenomenology for spin-independent limits.



Axial-scalar operator is only relevant for low mediator mass case.

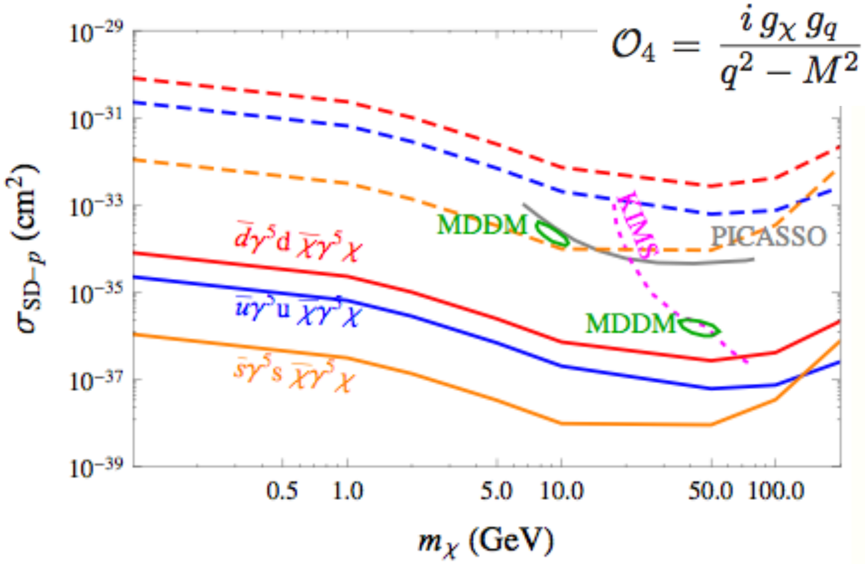
$$\mathcal{O}_1 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}q)(\bar{\chi}\chi)$$

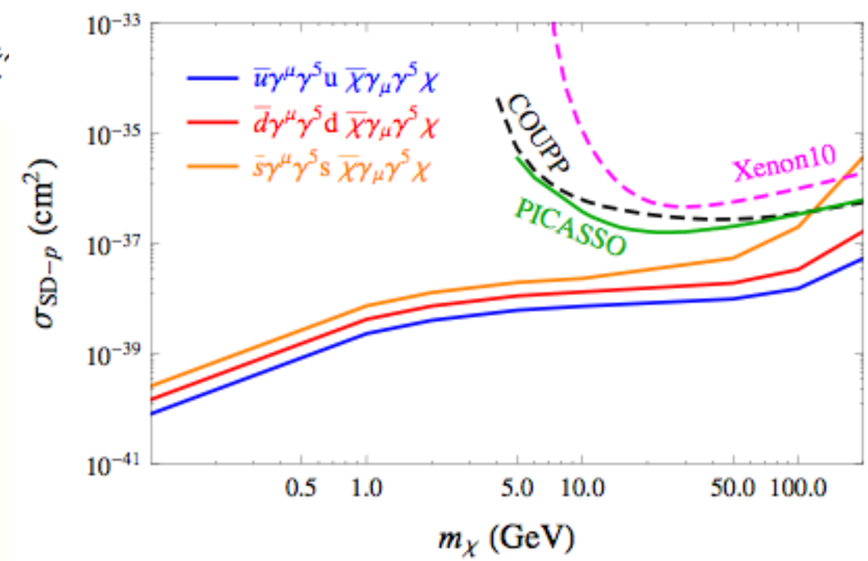
$$\mathcal{O}_2 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}\gamma_\mu q)(\bar{\chi}$$

$$\mathcal{O}_3 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}\gamma_\mu\gamma_5 q)(\bar{\chi}\gamma^\mu\gamma_5\chi)$$

$$\mathcal{O}_4 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}\gamma_5 q)(\bar{\chi}$$

Axial vector operator for spin-dependent case.





LHC Phenomenology-II

Goodman, Ibe, Rajaraman, Shepherd, Tait and and Yu, Phys. Rev. D 82, 116010 (2010)

Considers a comprehensive set of effective operators. DM is assumed to be a Dirac particle. The ATLAS analysis makes use of 5 of these operators:

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Not used in CMS analyses (D9, D11)

LHC Phenomenology-II (contd.)

Rather than set limits on WIMP-nucleon cross section, the ATLAS Monojet approach is to examine the M_*-M_{DM} plane, where M_* is the suppression scale:

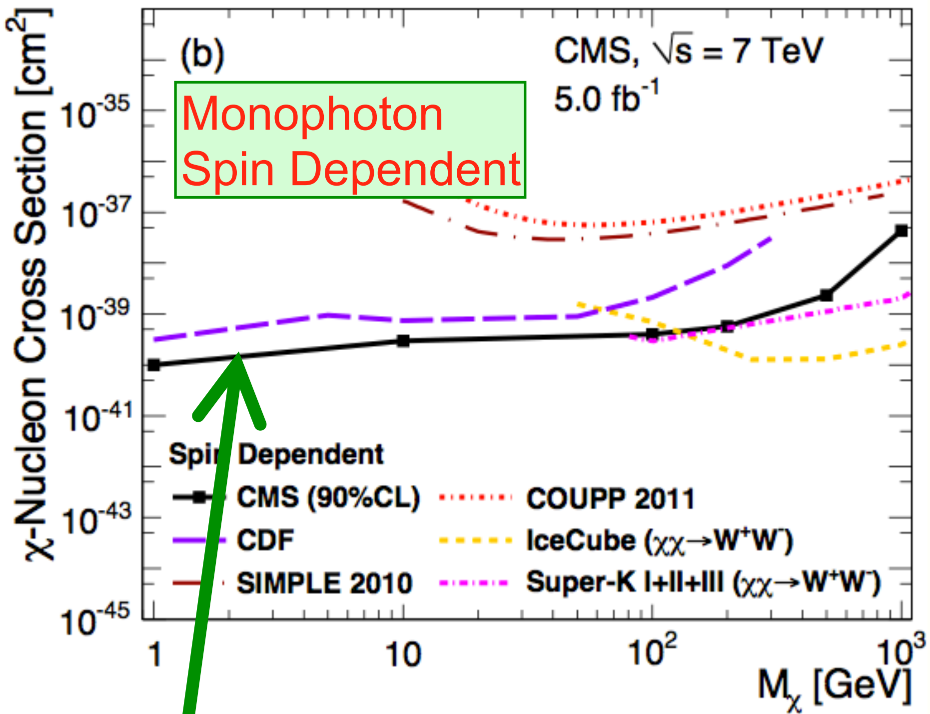
$M_* = M_m/(g_{DM} * g_{qq})^{1/2}$, where the g's are the couplings of the mediator to DM and to quarks. M_m is mediator mass.

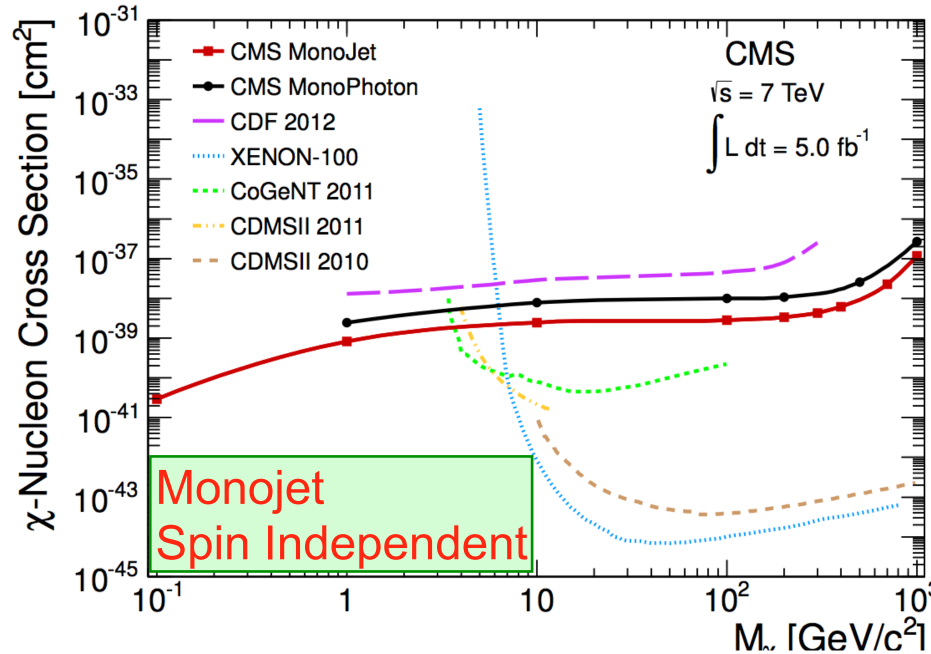
Observed upper limits on the cross section are converted into lower bound on M_*.

In ATLAS analyses, exclusion regions are established for a variety of the operators in this plane.

Recent work from these authors includes the case of Majorana DM particles. J. Goodman, *et. al*, Phys. Lett. B 695, 185 (2011)

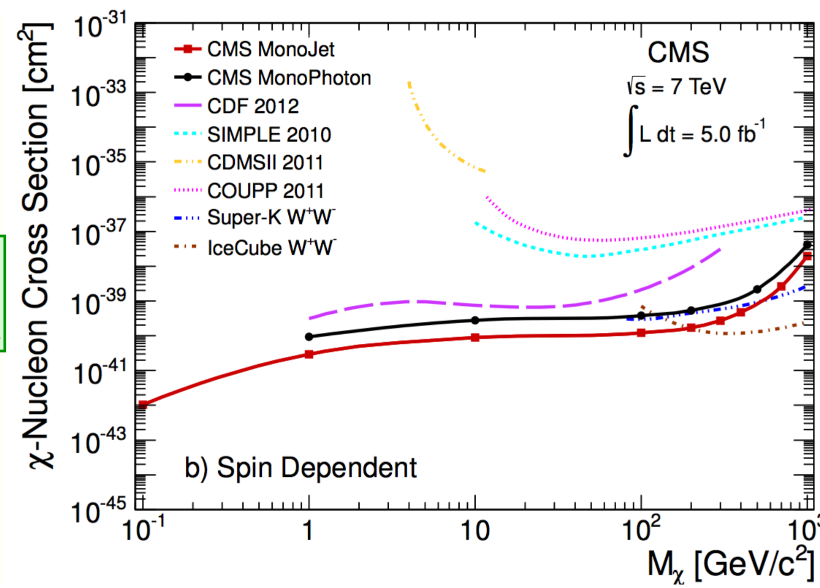
CMS Limits



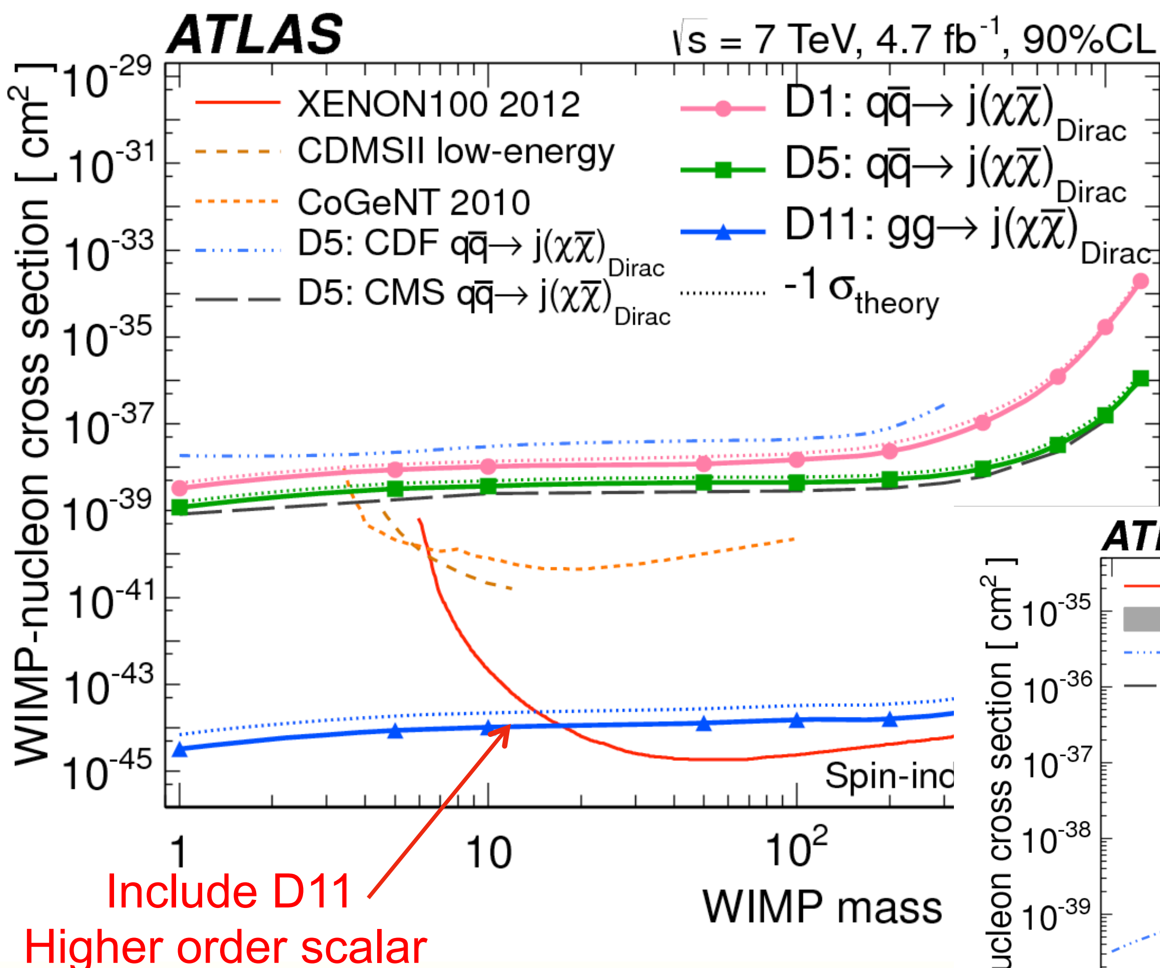


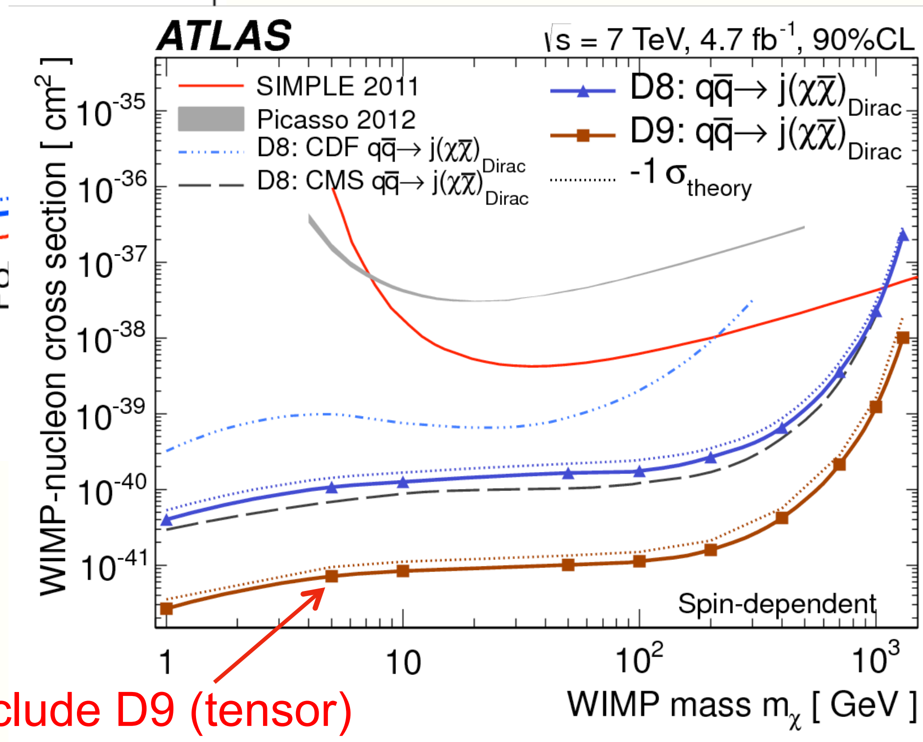
There is no mass threshold. The analysis has been restricted to be > 1 GeV.

Monojet
Spin Dependent



ATLAS Limits: Monojets @ 7TeV

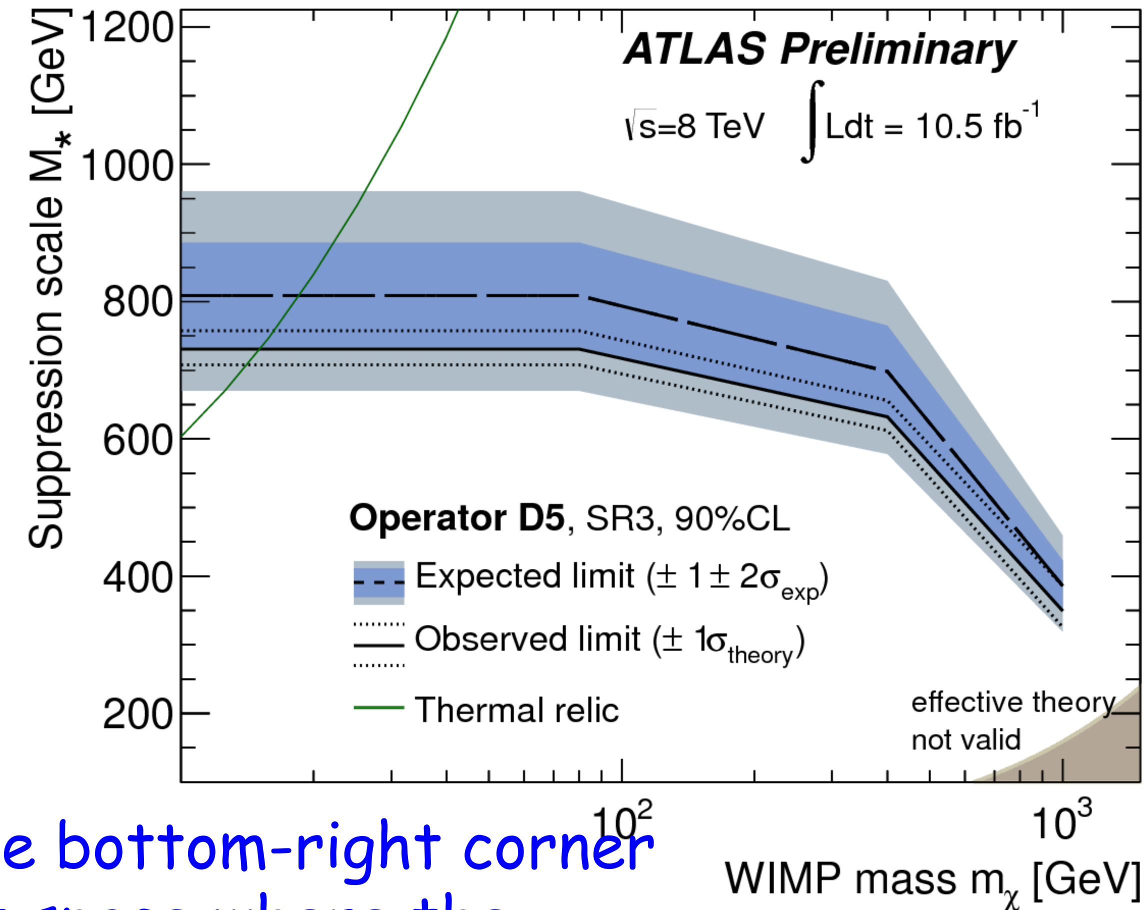




ATLAS Limits: Monojets w/Vector Operator

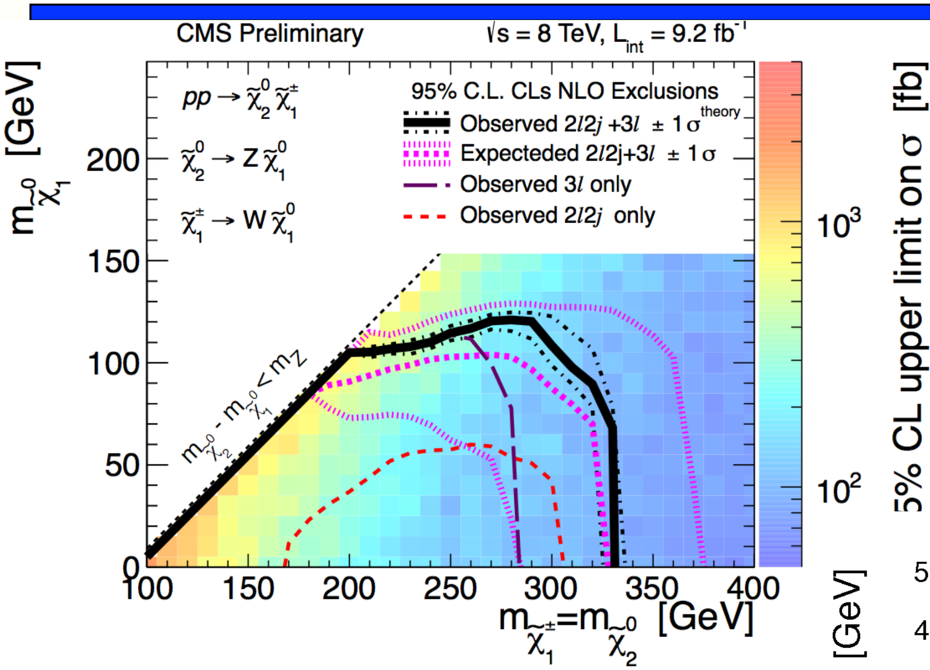
Results are presented in the form of an expected and observed limit for the case of each assumed operator.

Thermal relic line is derived by setting the effective coupling, such that the correct relic abundance is preserved.



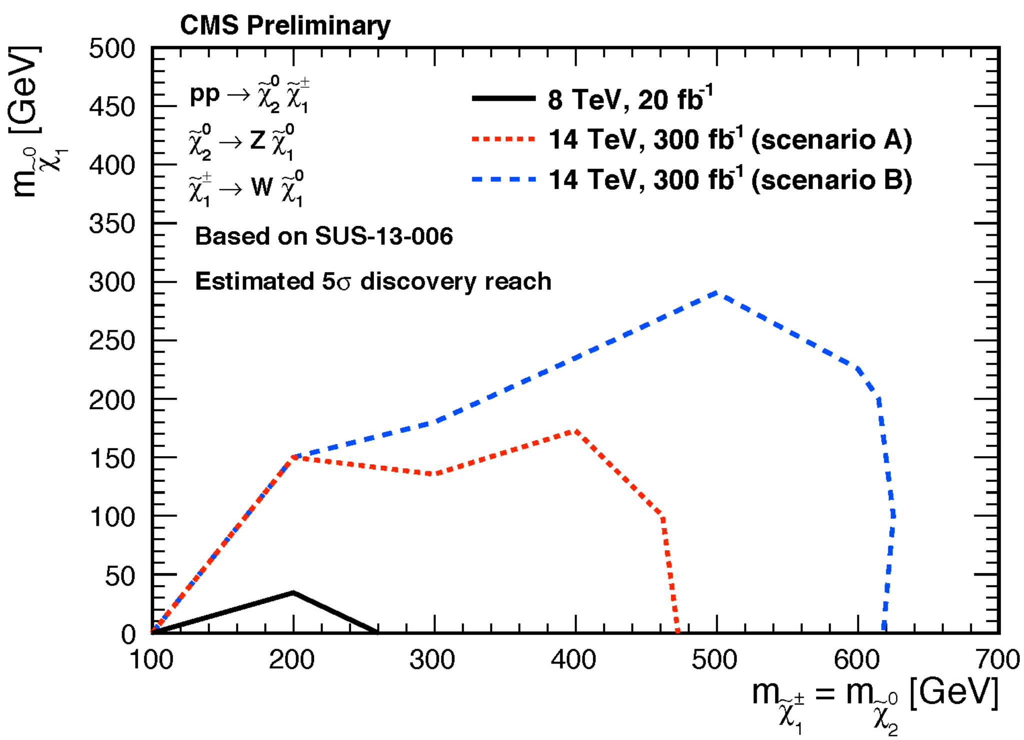
The shaded regions in the bottom-right corner correspond to parameter space where the effective theory is not valid.

CMS: SUSY



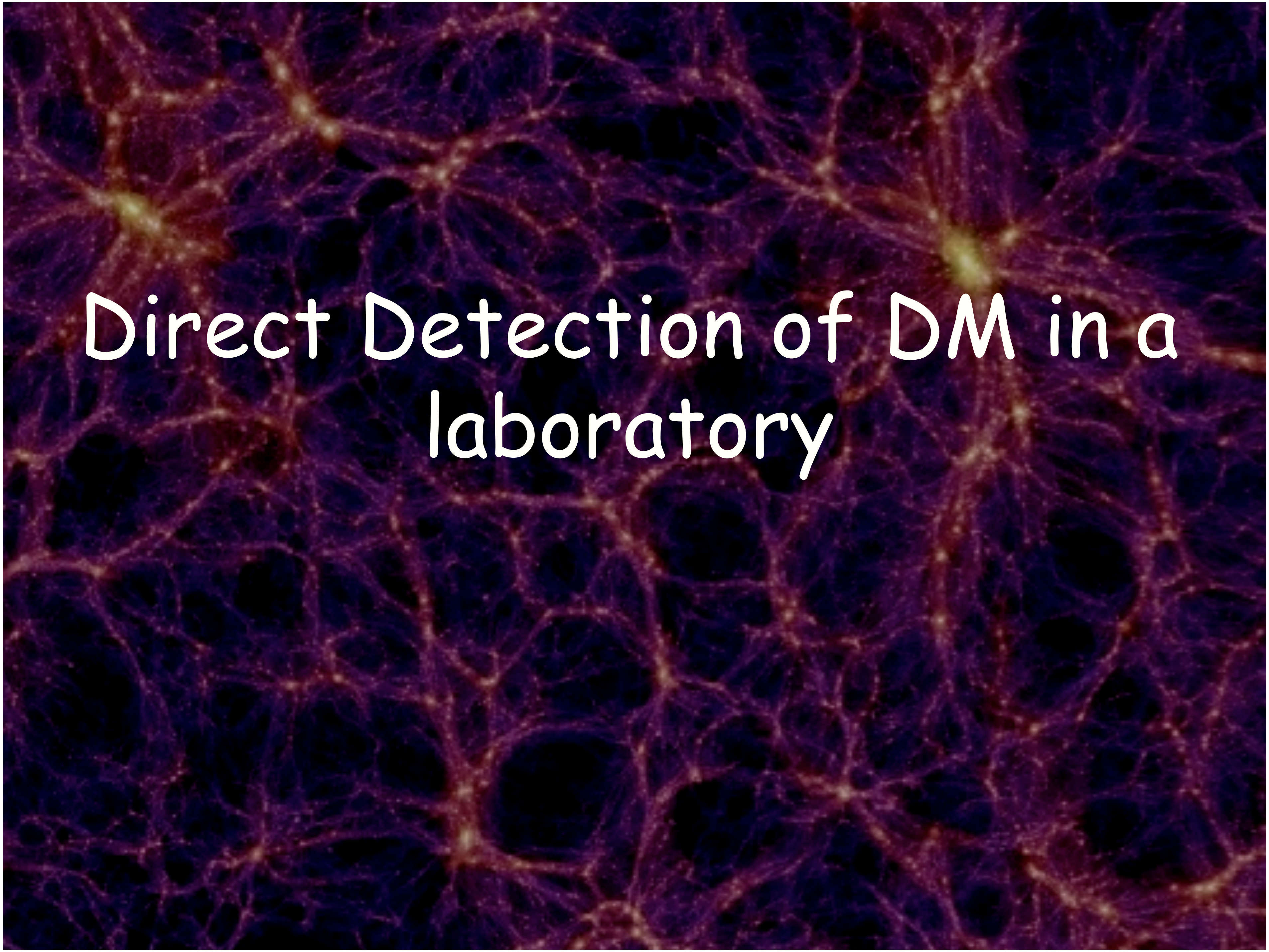
Current limits on neutralino

Projections for 14 TeV



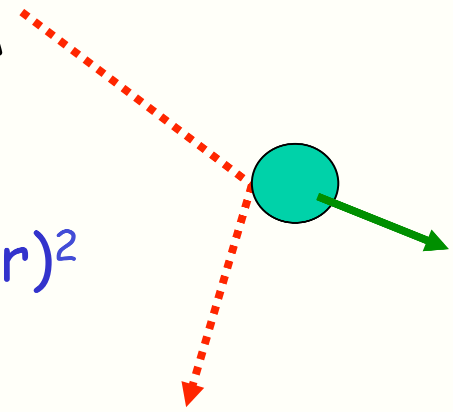
See Sunil Somalwar's talk

Direct Detection of DM in a laboratory



3. Direct Detection

Basic goal: search for nuclear recoil from DM elastic scattering.

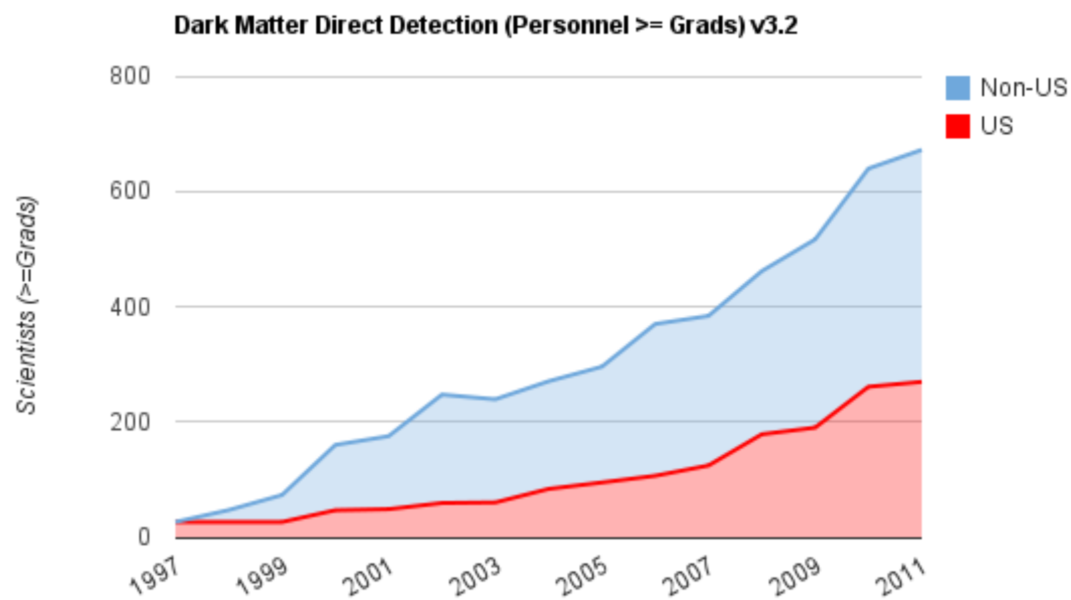


Simple dynamics. Cross section α (form factor)^2

Spin-independent: Nucleon form factor gives rise to A^2 enhancement due to coherence.

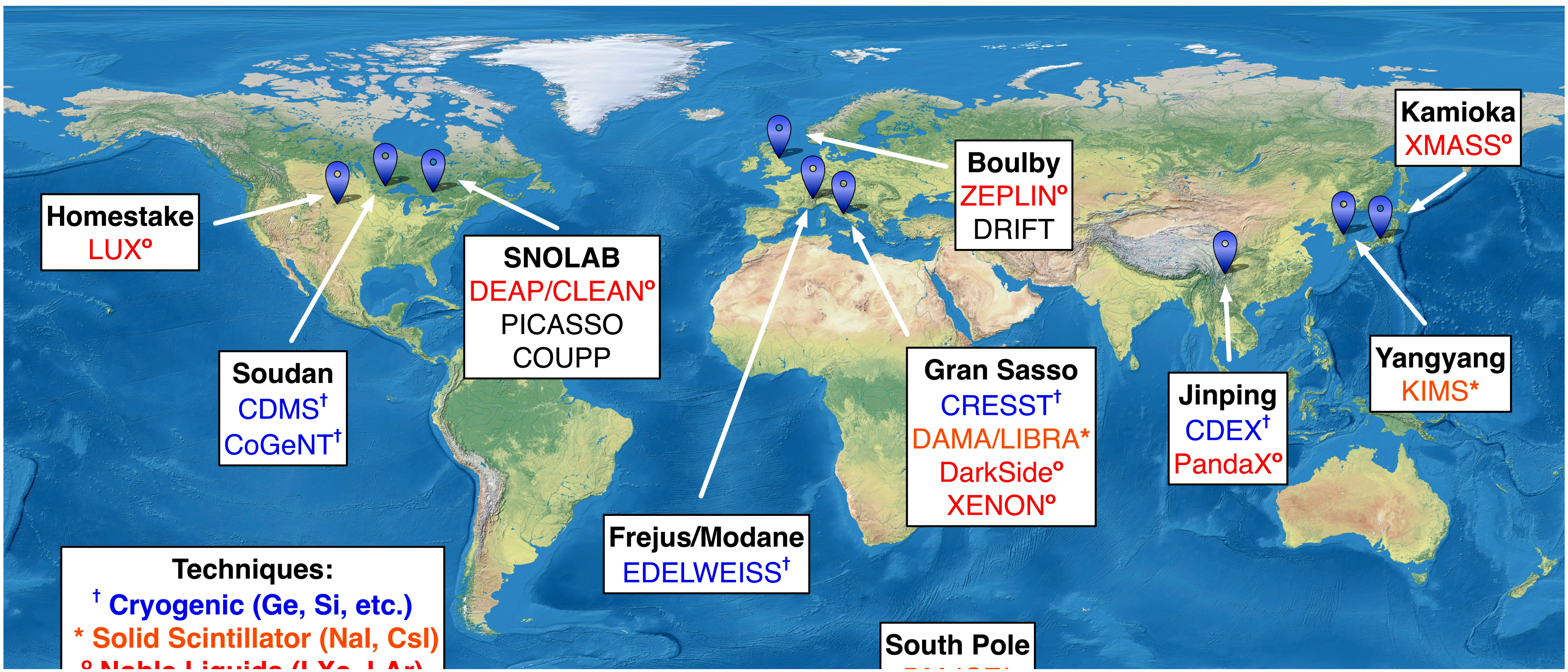
The dependence on q^2 is also contained in the form-factors.

Spin-dependent: Form factor depends on nuclear spin. No coherence enhancement.



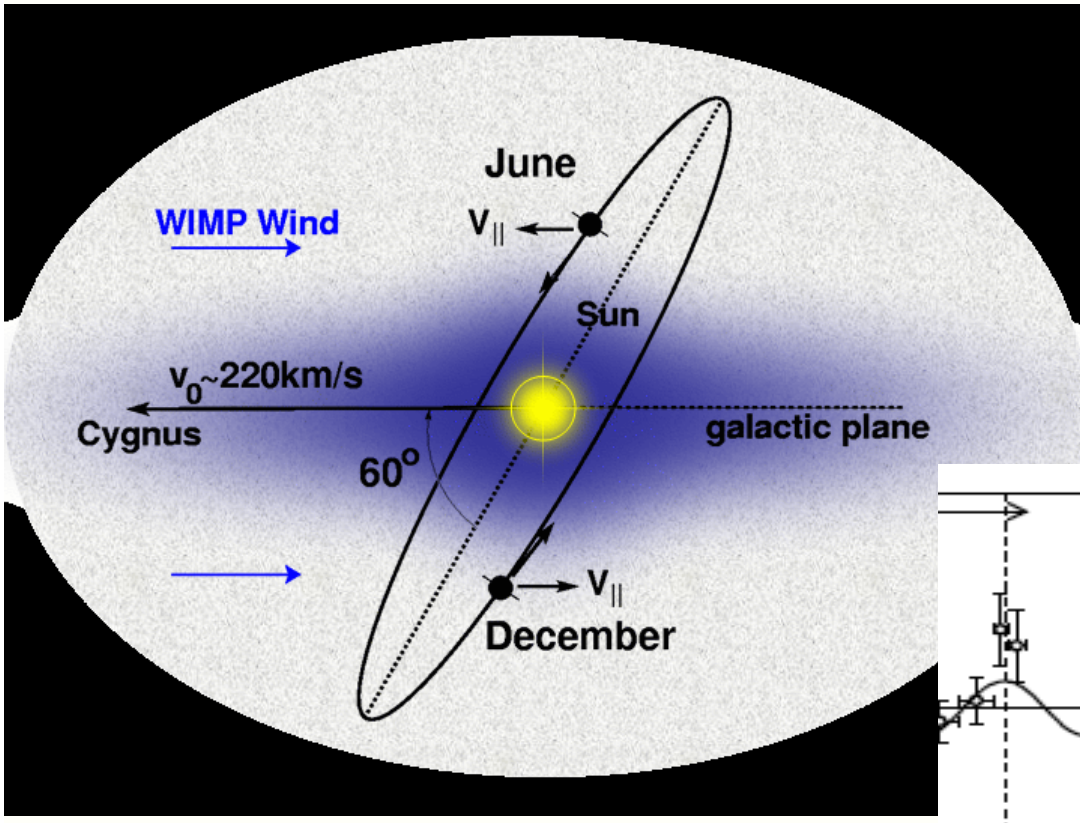
A rapidly growing community.

New experiments coming online around the world.

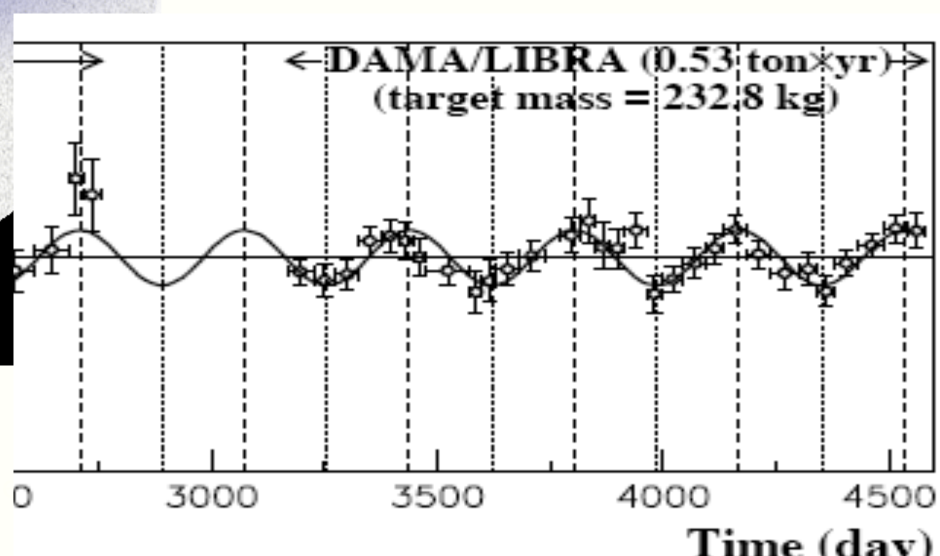


Annual WIMP Modulations

A WIMP detection signal should vary over the course of the year as Earth revolves around the Sun, which is traversing the galaxy.

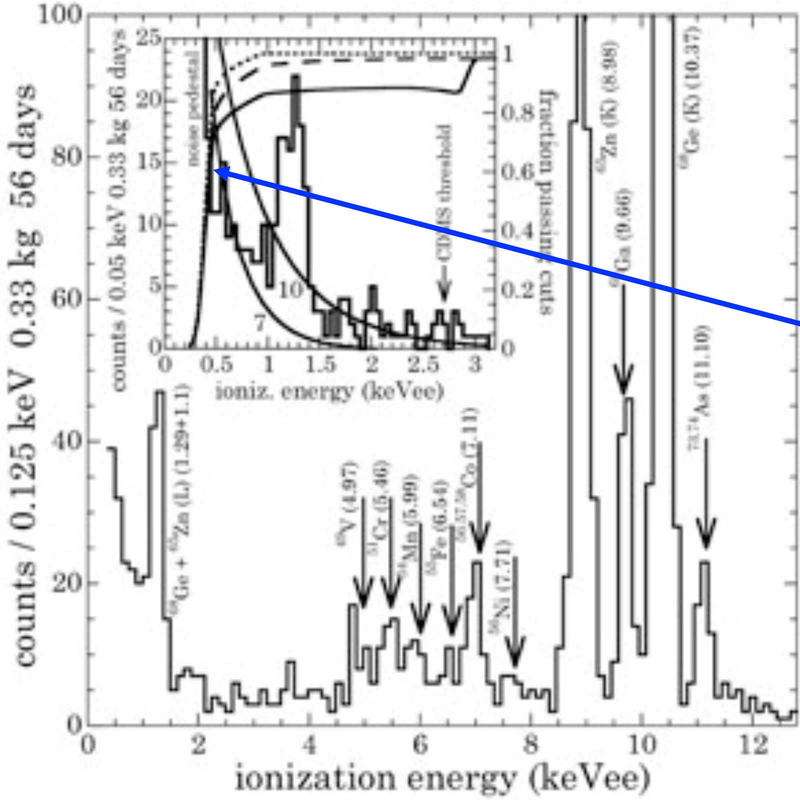


DAMA experiment claims a signal.



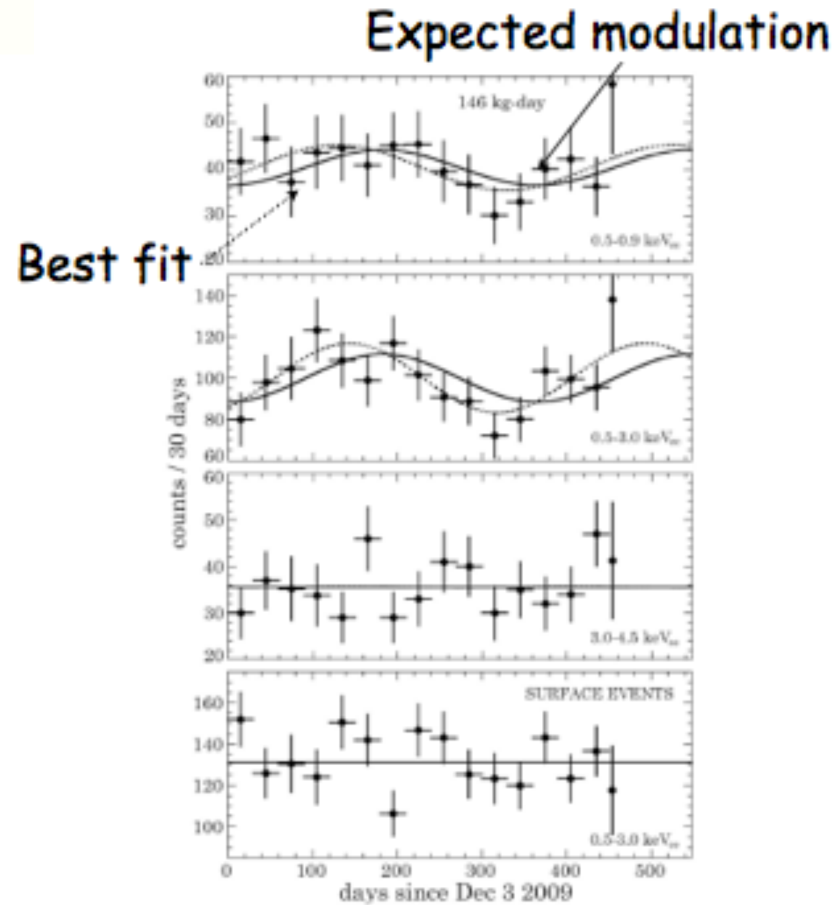
Cross-checks planned, at Gran Sasso and South Pole (DM-Ice?)

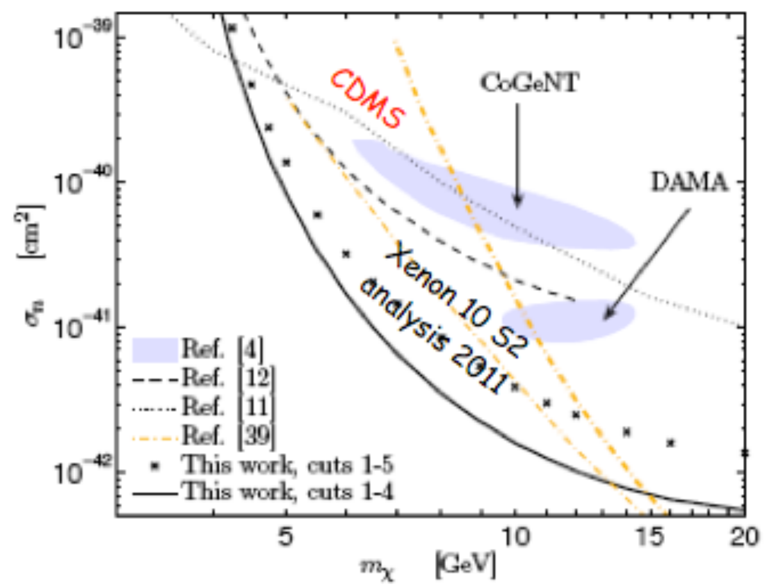
CoGeNT



CoGeNT is a Ge detector in Soudan Lab. It sees an excess in the region~1 KeVee.

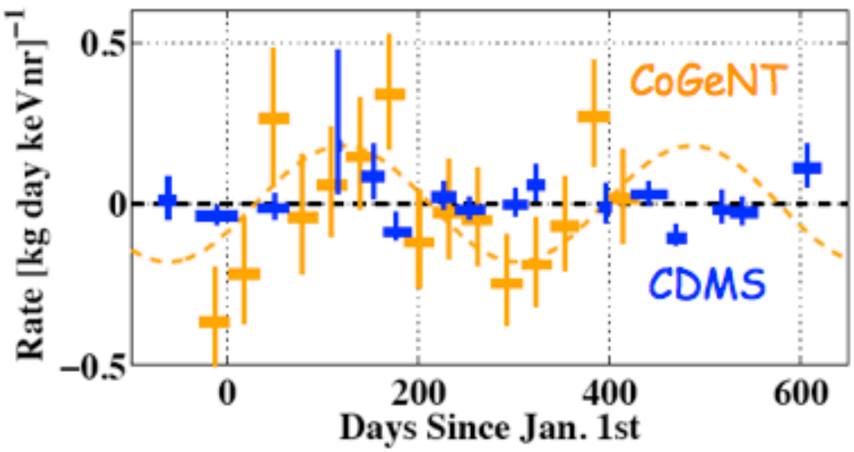
Aalseth et al. ArXiv: 11060650

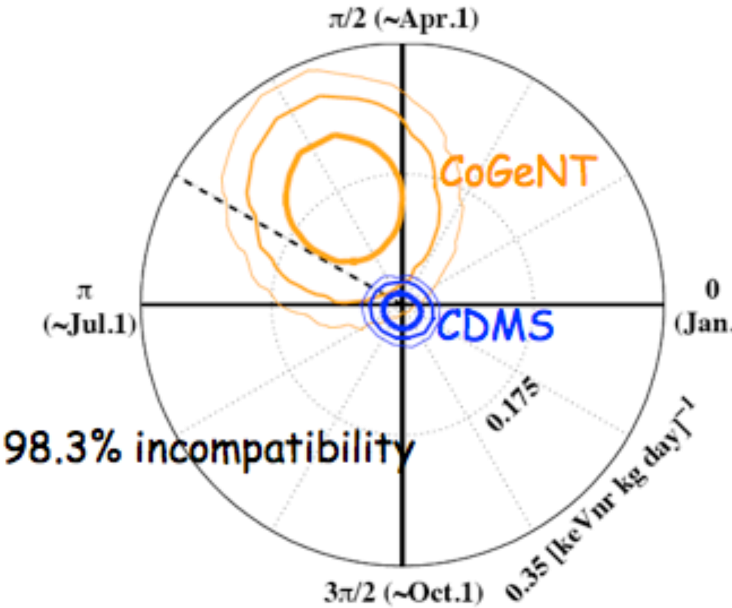




March 2012 … CDMS refutes the modulation claim

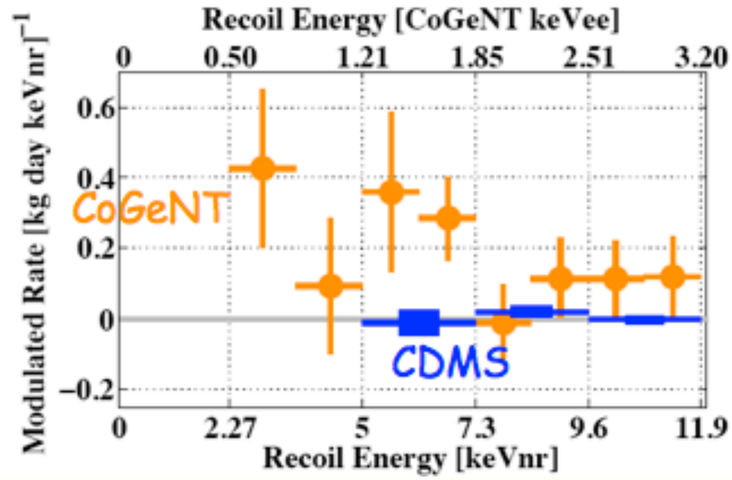
5 keV-11.9 keV nuclear recoil:
arXiv:1203.1309



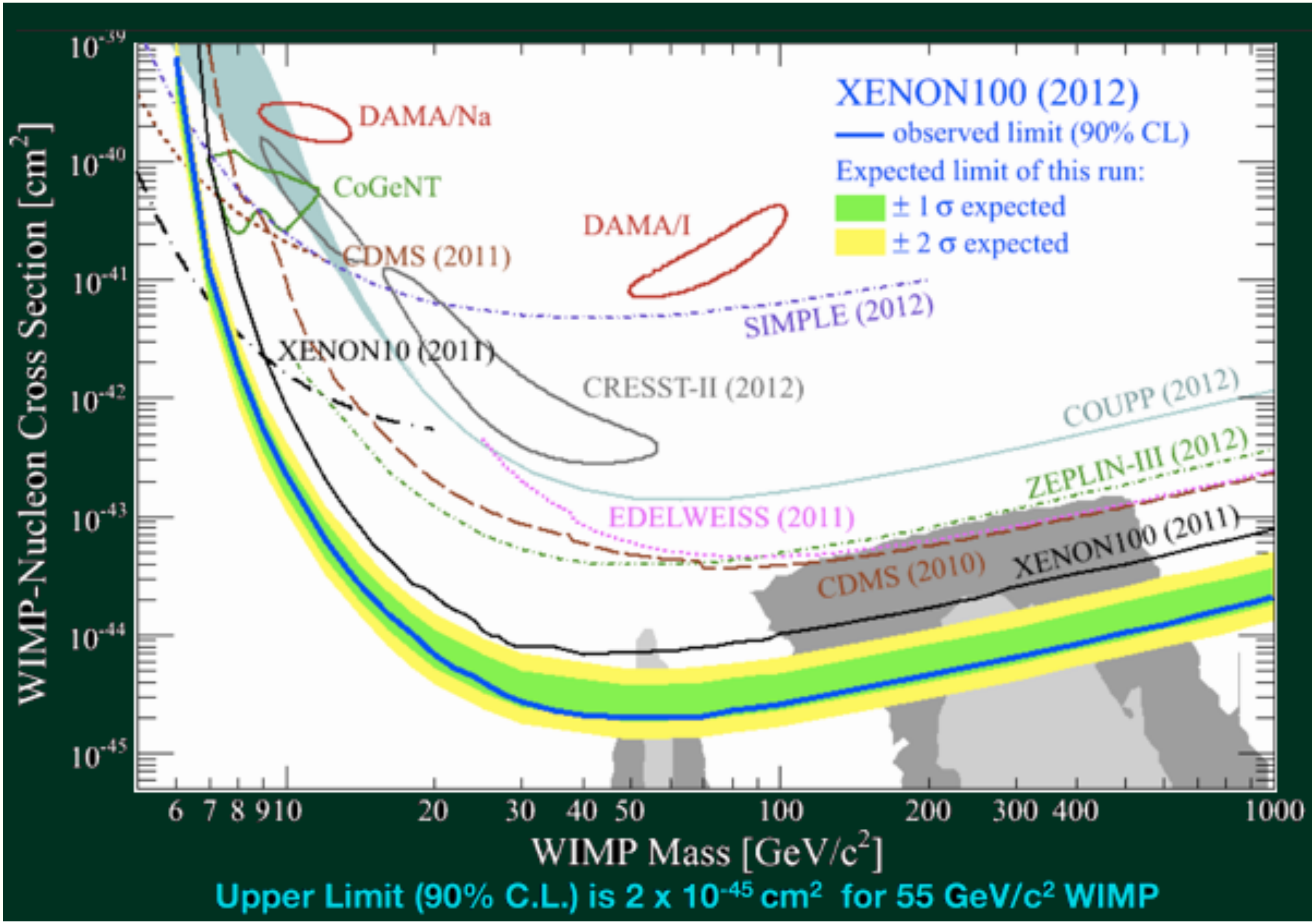


We are of course looking at lower energy

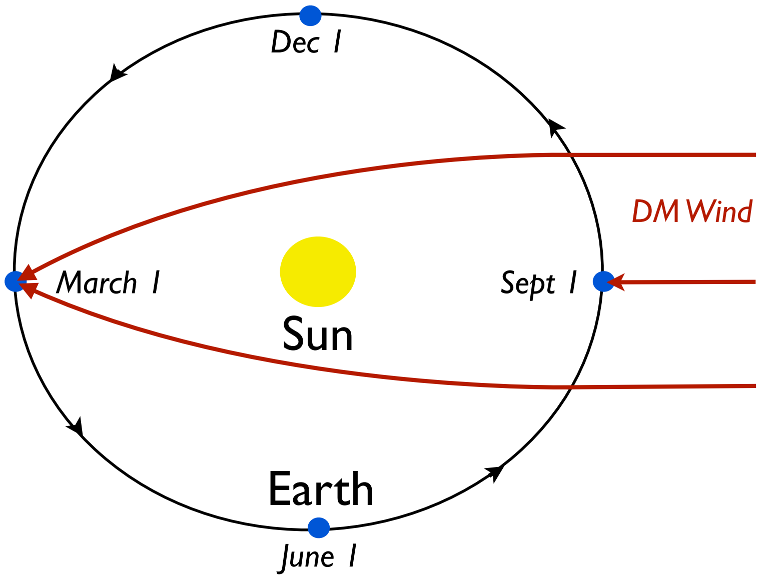
Hope to have a solid result at lower energy soon!

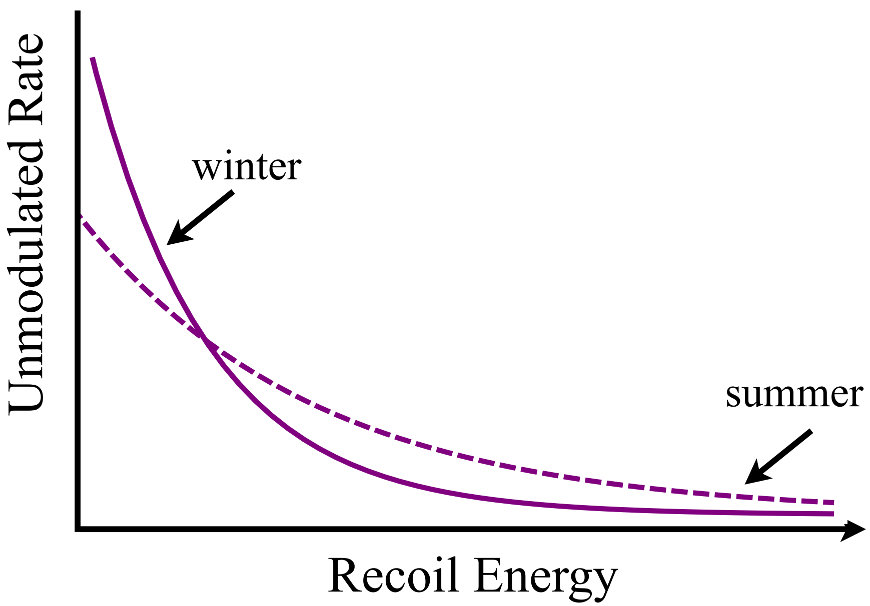


Xenon 100 Limit from July 2012



A new twist to the modulation claim





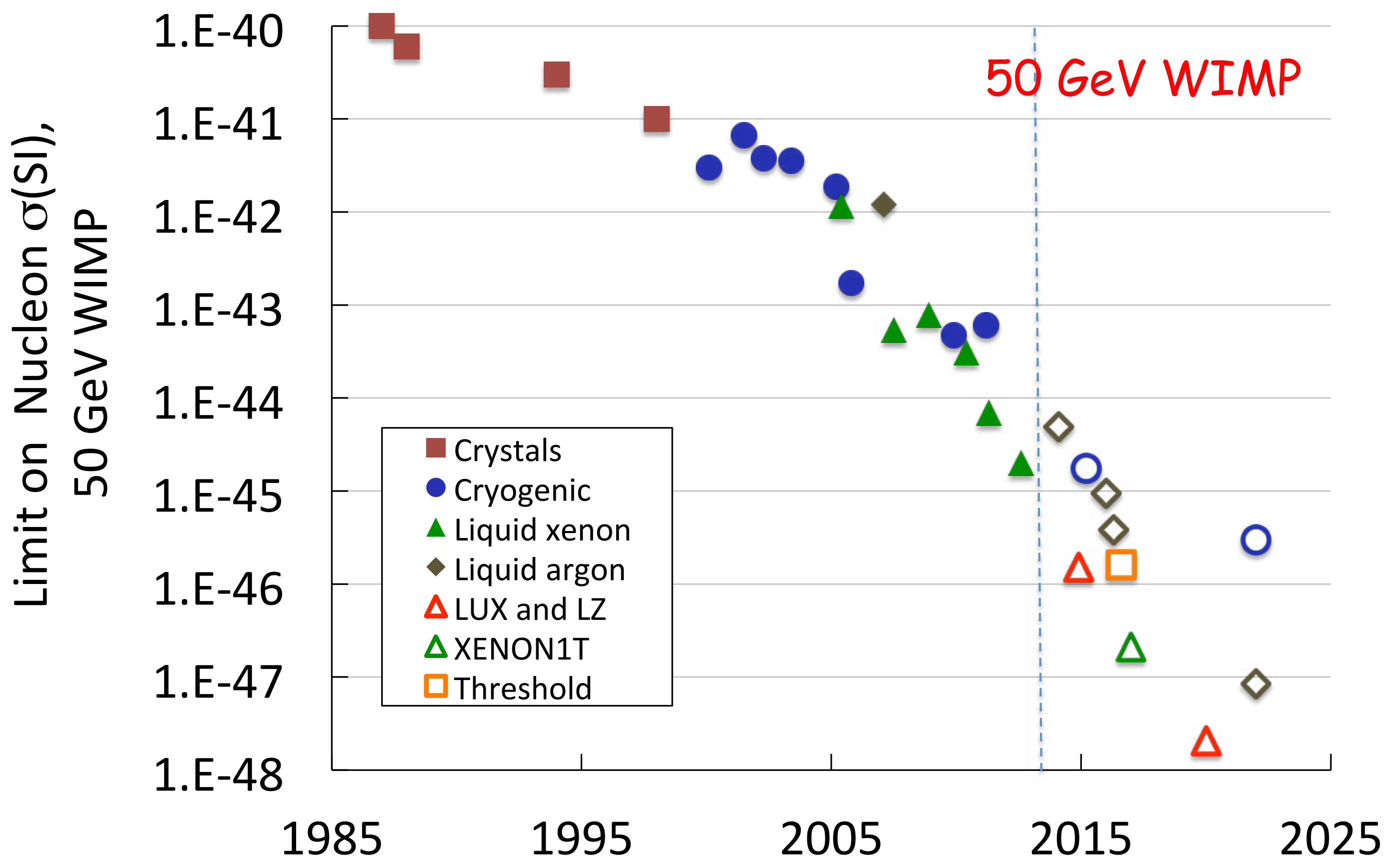
Lee *et. al*, arXiv:1308.1953v1

Gravitational focusing by the sun enhances the DM flux around March.

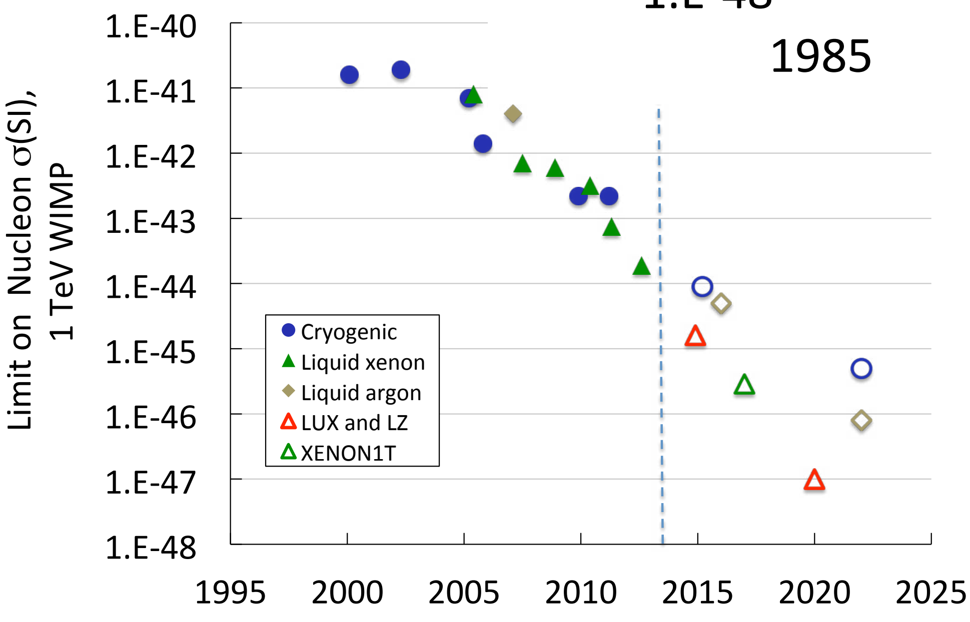
The change in velocity distribution also distorts the modulation size and phase.

Need to include this effect in the various analyses.

A compact history of WIMP Searches



1 TeV WIMP



LZ is poised to possibly provide an end-point to this saga … hopefully by discovering WIMPs or, by ruling out most of the theoretical and experimentally accessible landscape.

Plots compiled by Mike Witherell, UCSB

Why Xenon?

Nobel element => Inert. Can be purified via gettering techniques.

No long-lived radio-isotopes. Metastable istopes useful in calibration.

High density (~3g/cm^3)
=> Powerful self-shielding.

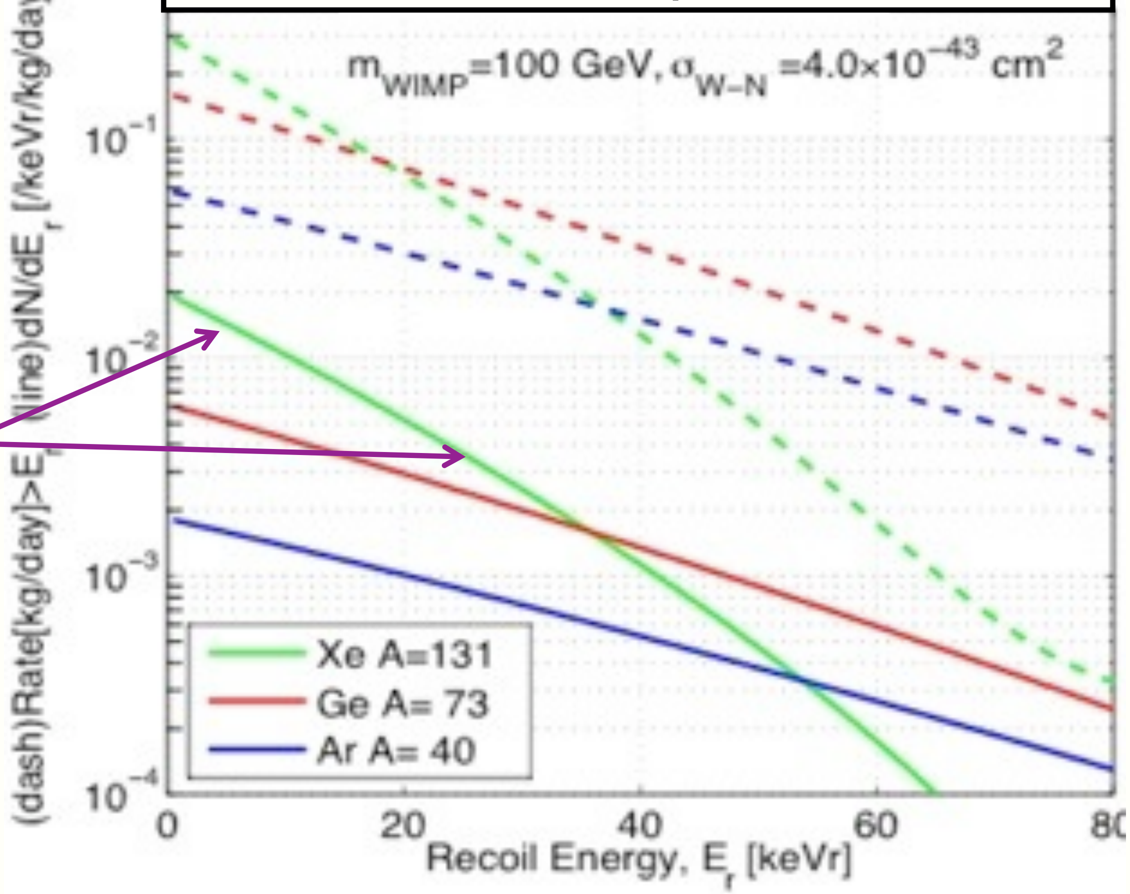
High A (131) => Large elastic σ

Higher Sensitivity in the range 5 keV < E < 25 keV.

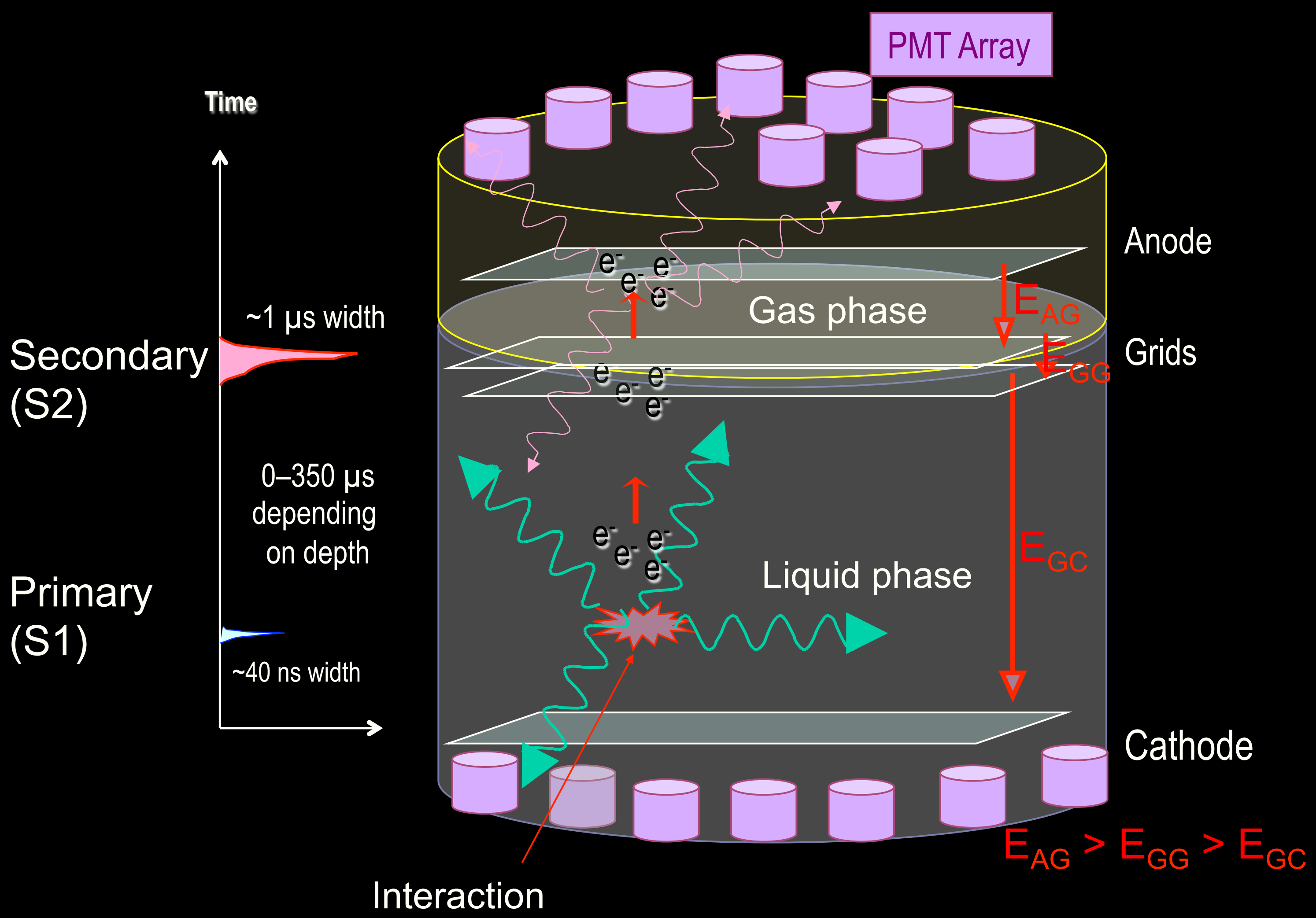
Long electron drift lengths (few m) => scalable

Efficient scintillator

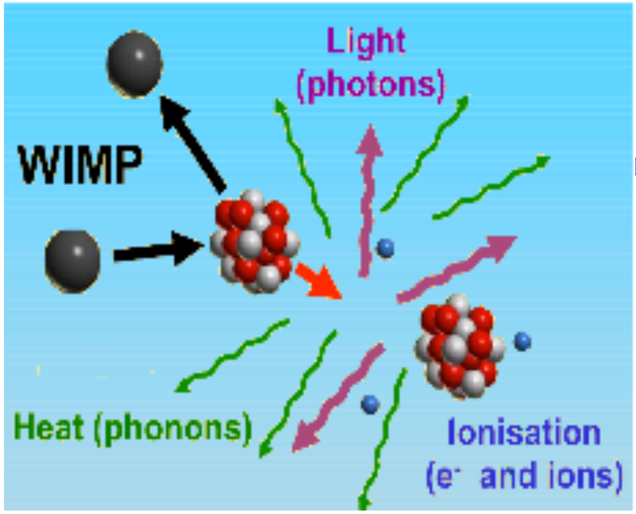
Recoil Spectra

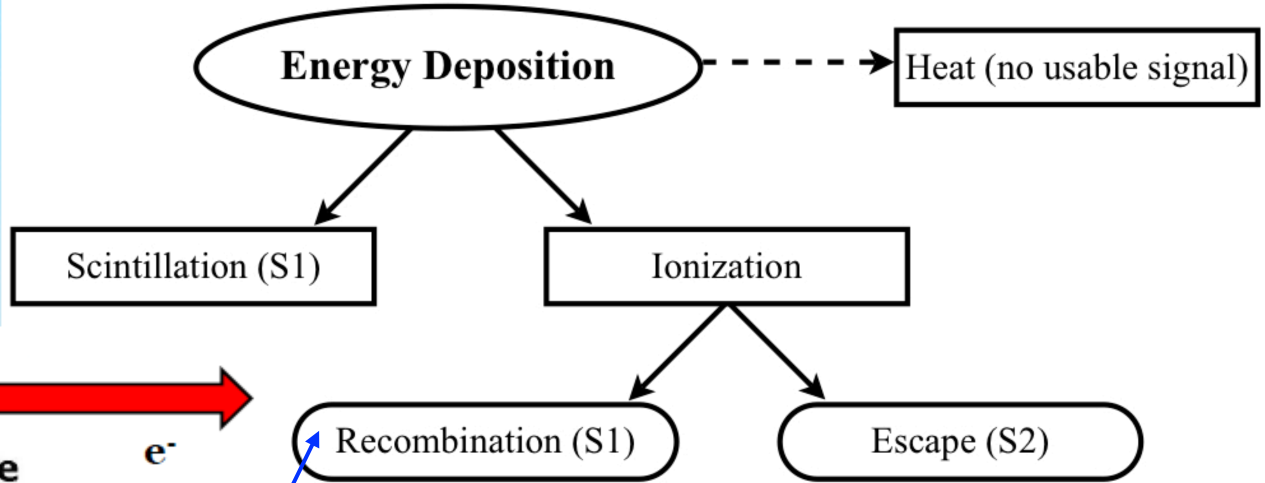


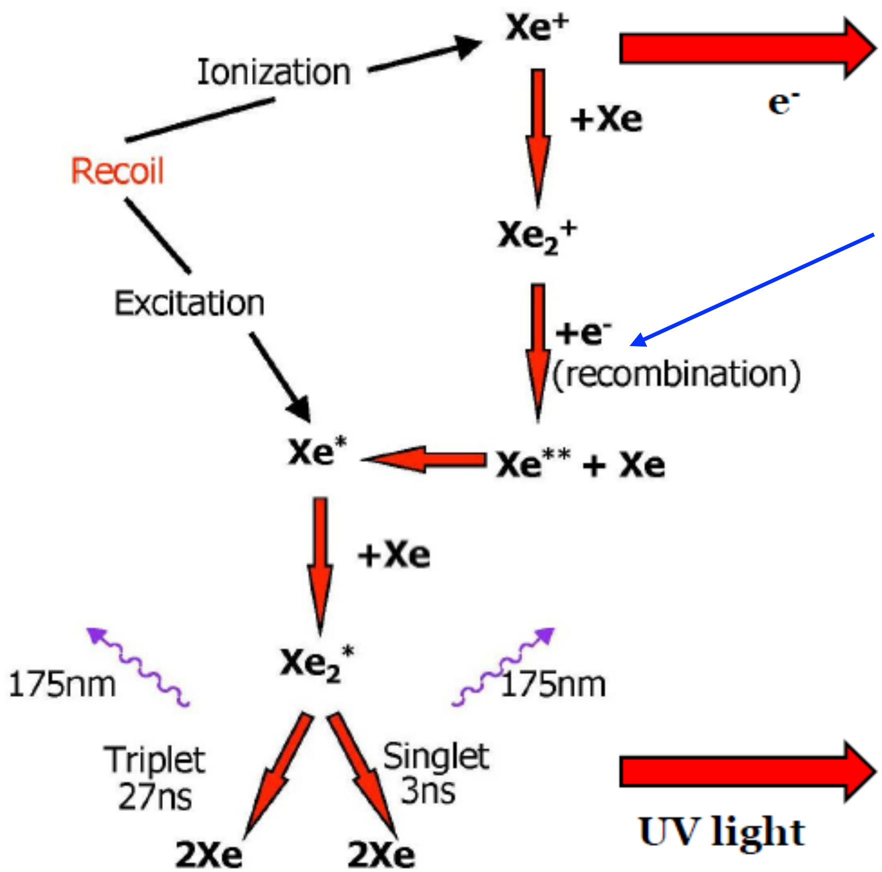
Two-phase XE TPC: Two Signal Technique



Scintillation process in LXe







Difference in in recombination efficiency is exploited to discriminate between electron and nuclear recoils.

Xenon is transparent to its own scintillation light !

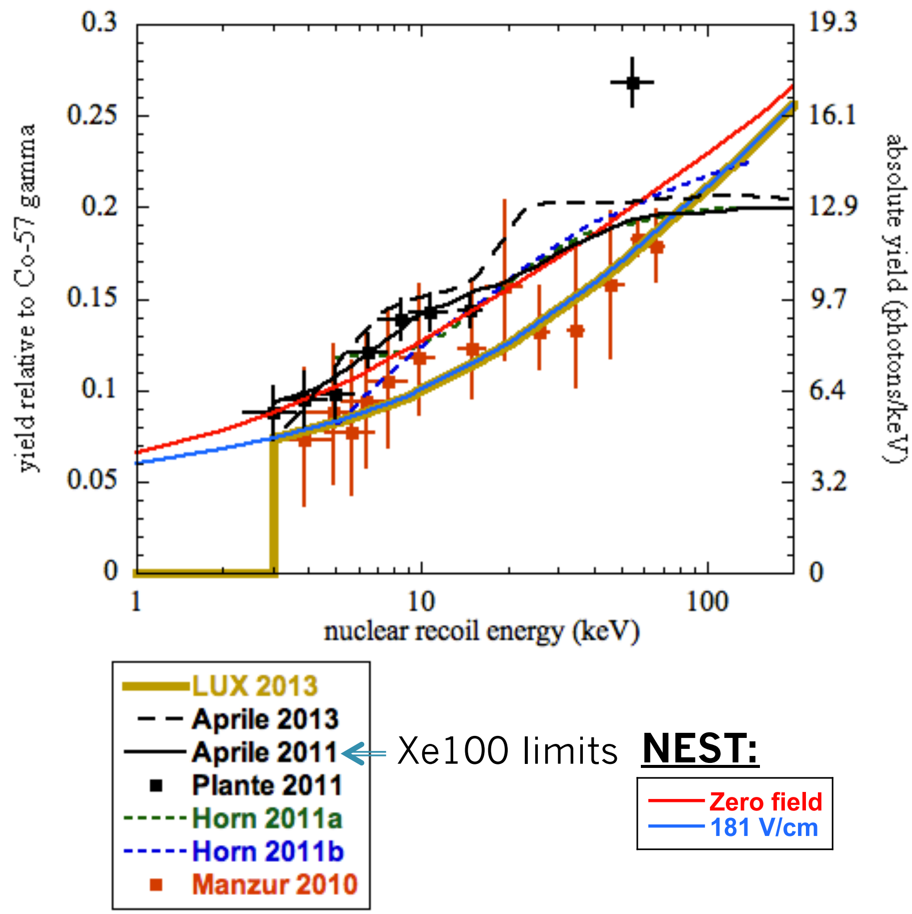
Figure of merit derived from plots of:

Log (charge escaping recombination/ total primary light produced)

NR Scintillation Yield

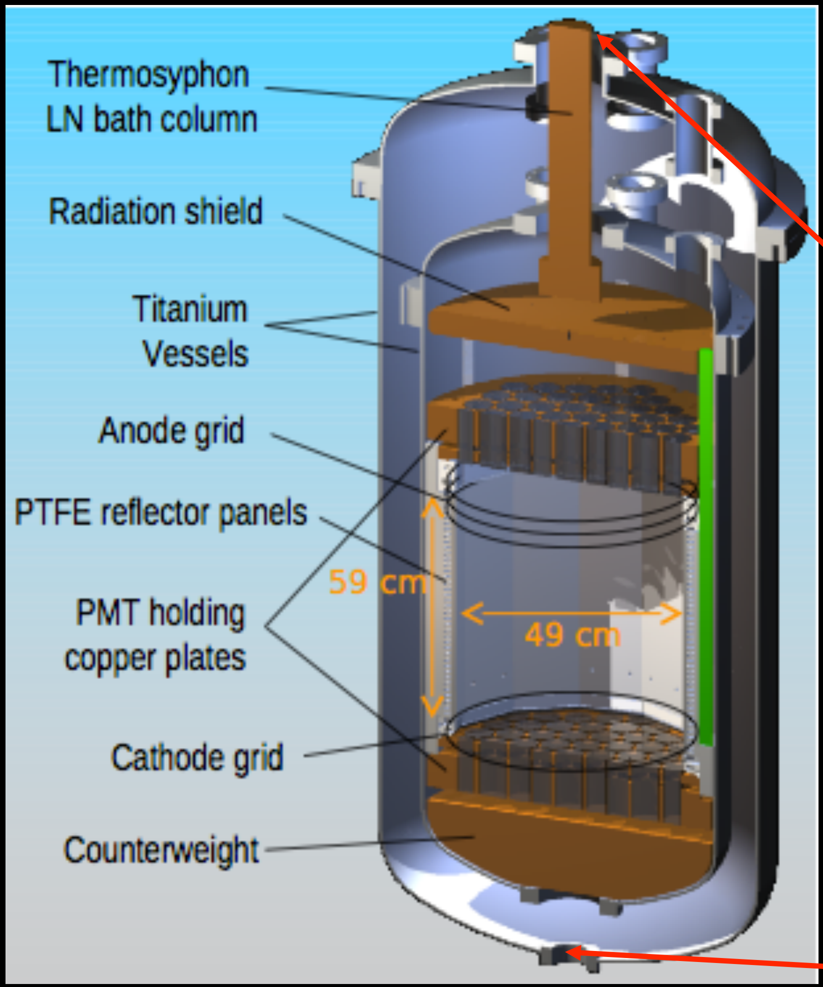
Understanding the quenching at low energies in nuclear recoil is the key establishing the threshold.

Modeled using NEST and G4 optical model for light collection

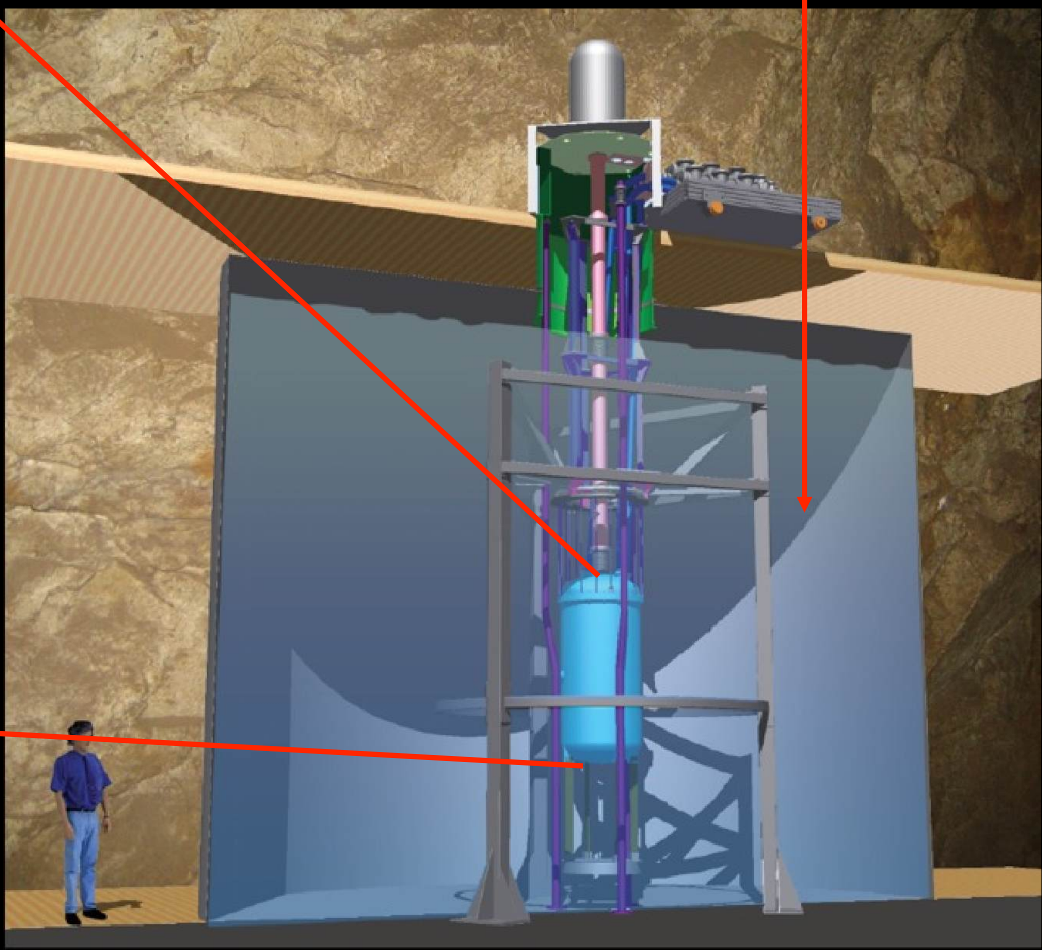


Data taken at non-zero field is translated by those reporting the results, assuming reduction of 0.95 (Aprile 2013, 730 V/cm) or 0.9 (Horn 2011, ~4000 V/cm, from ZEPLIN-III). LUX is 181 V/cm. All other data points actually taken at zero field.

The LUX detector

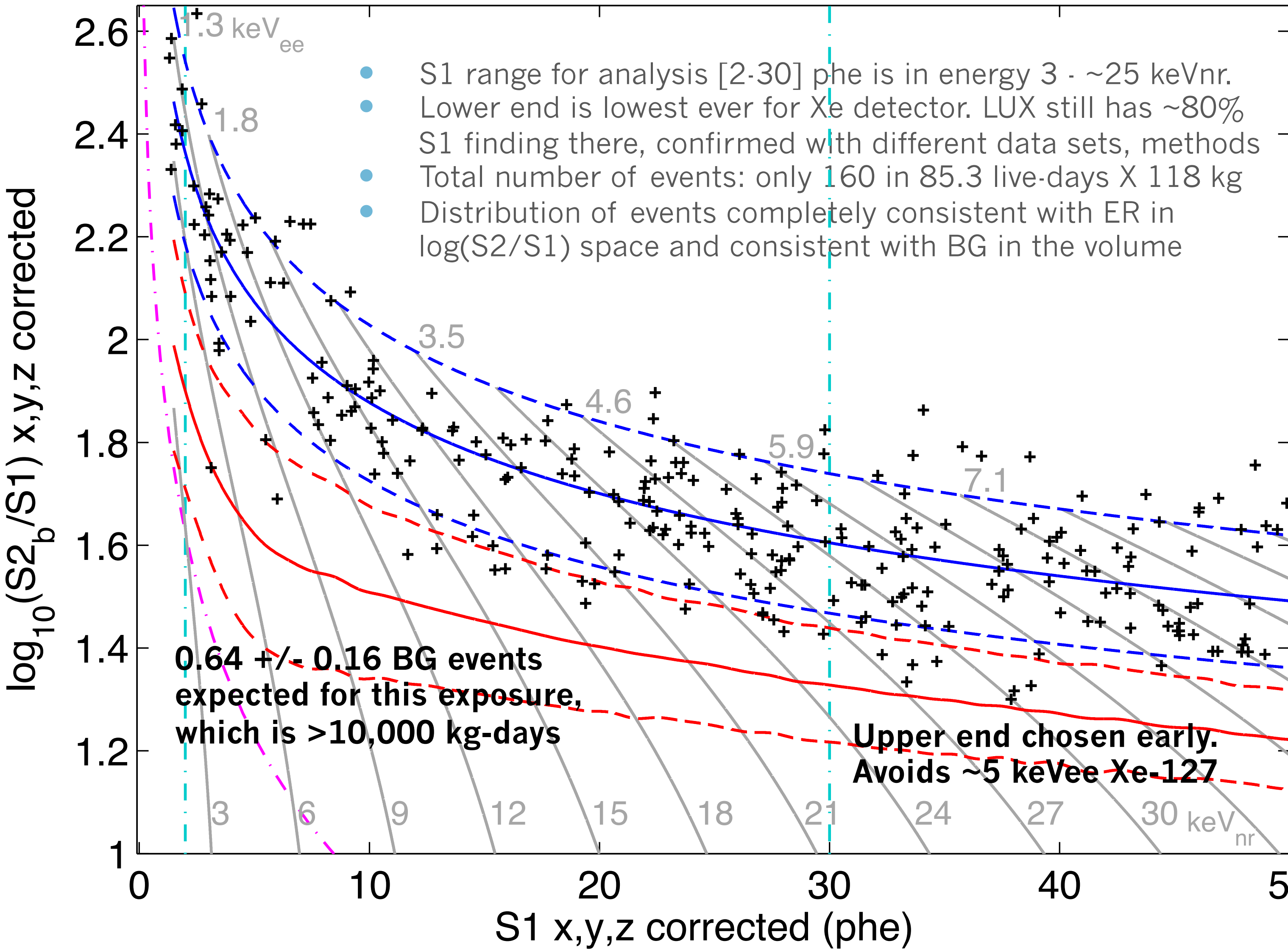


~ 7m diameter Water Cerenkov Shield.

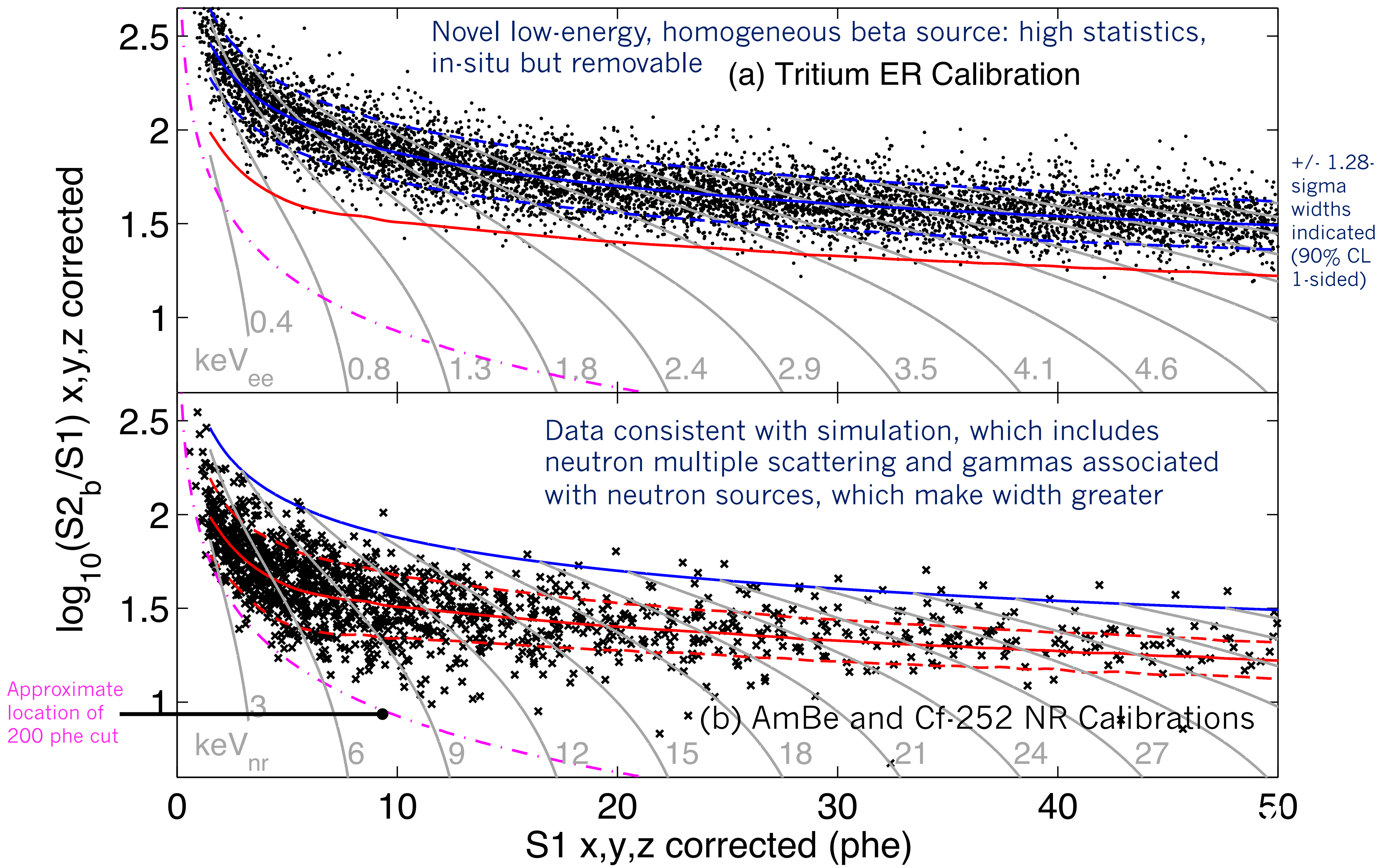


- 350 kg of Lxe
- 122 photomultiplier tubes (top plus bottom)

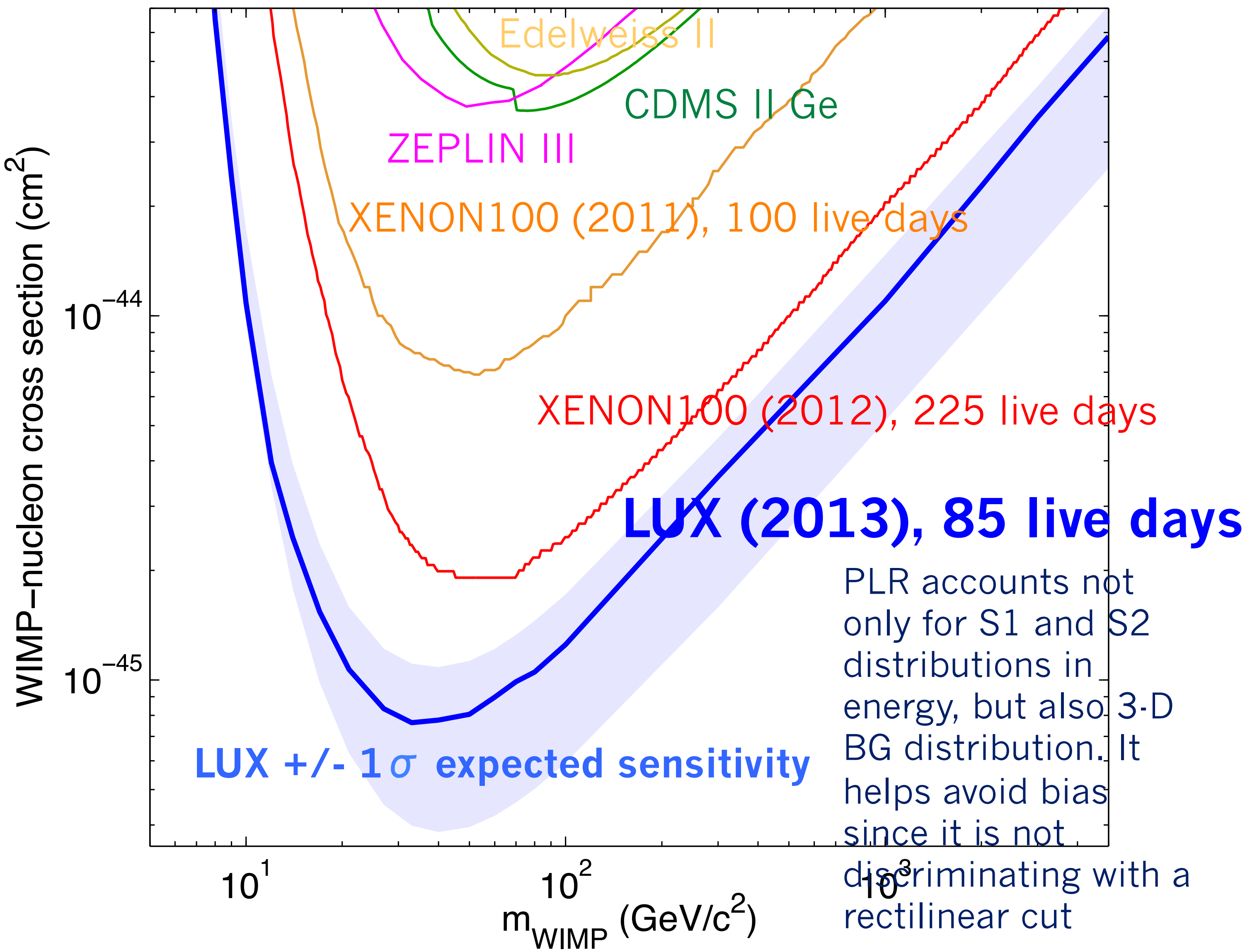
LUX: WIMP Search Result



ER and NR Band Calibrations

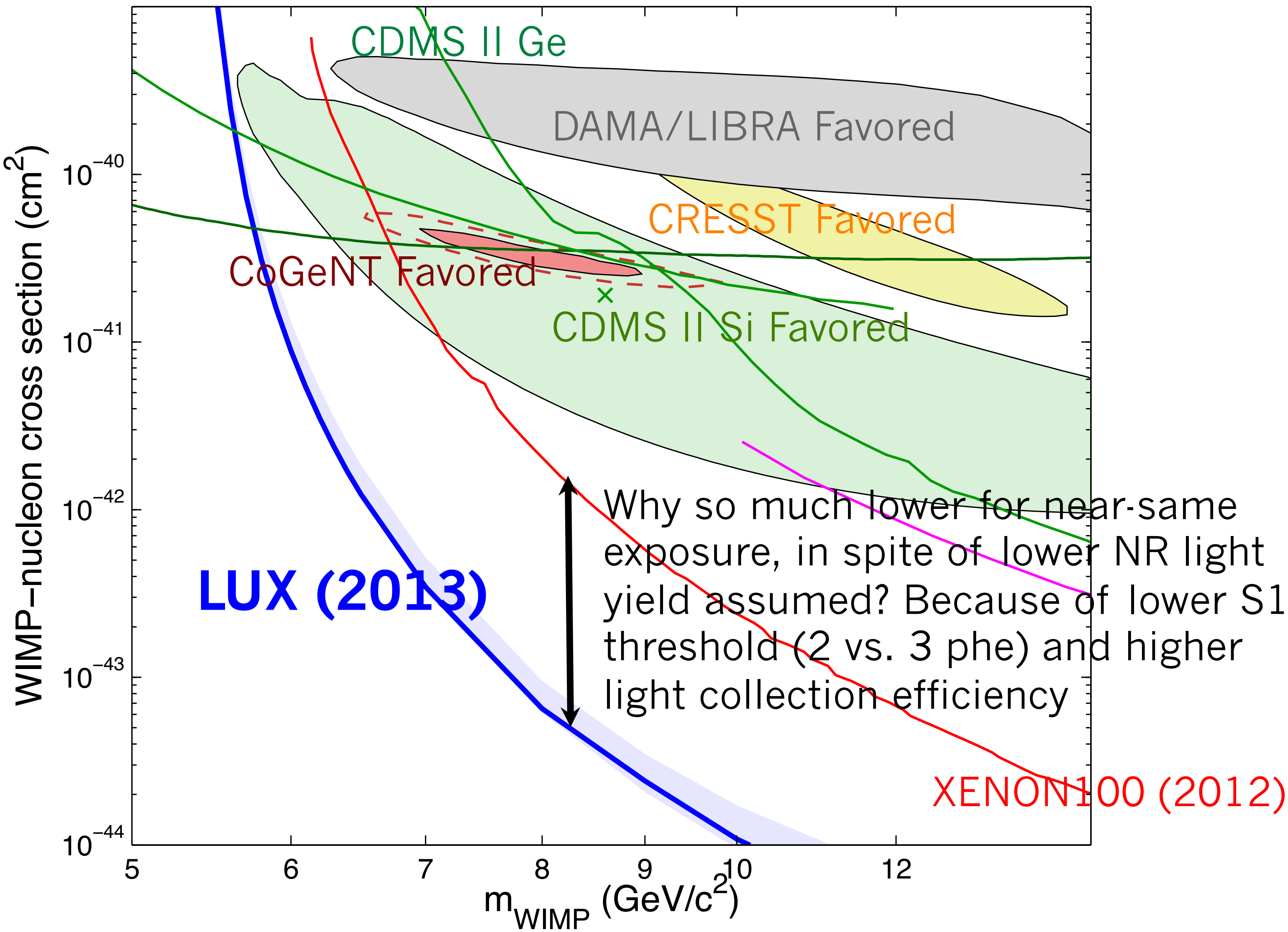


LUX Limit

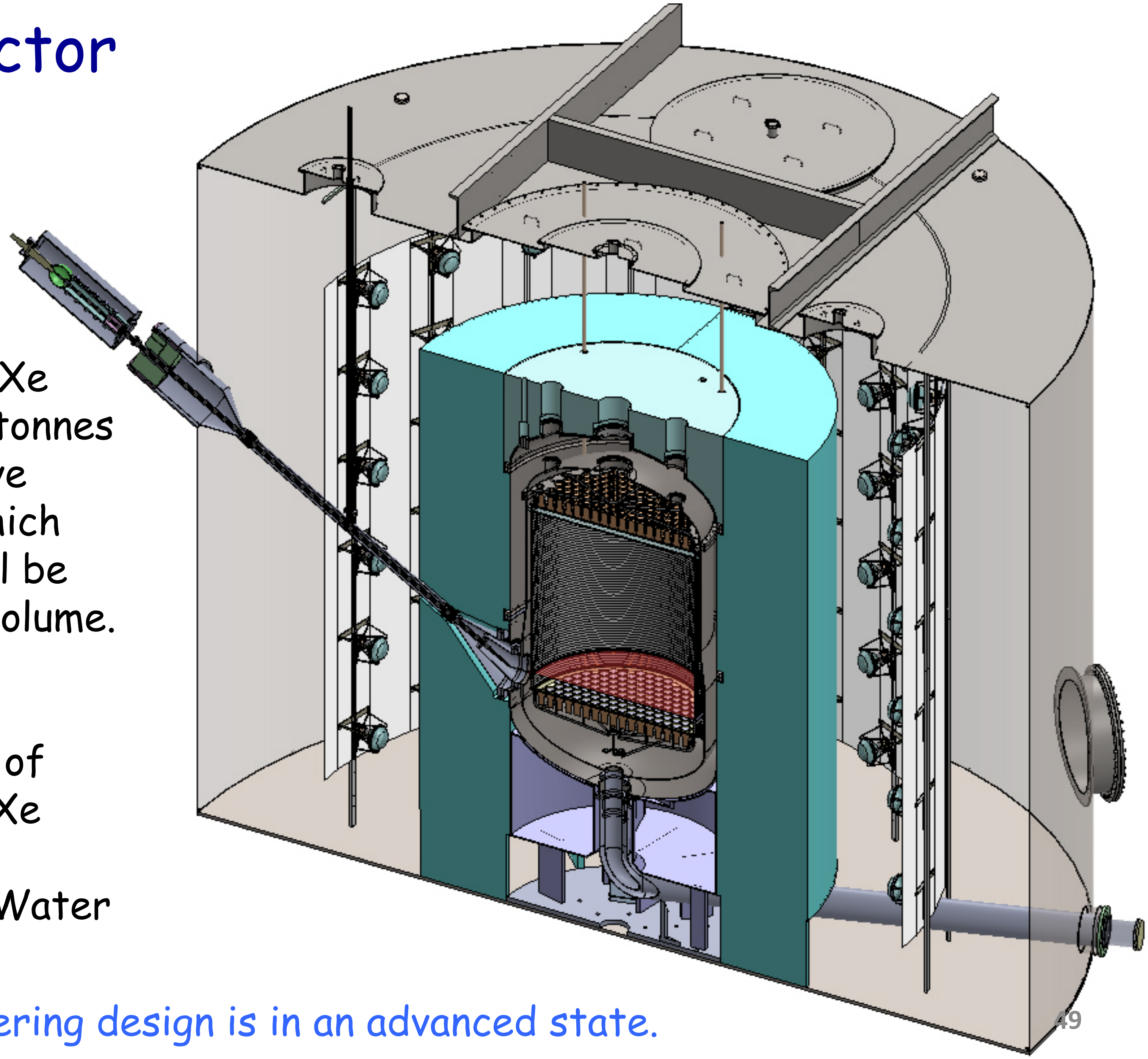


PLR accounts not only for S1 and S2 distributions in energy, but also 3-D BG distribution. It helps avoid bias since it is not discriminating with a rectilinear cut

Low-Mass WIMP Region



LZ Detector

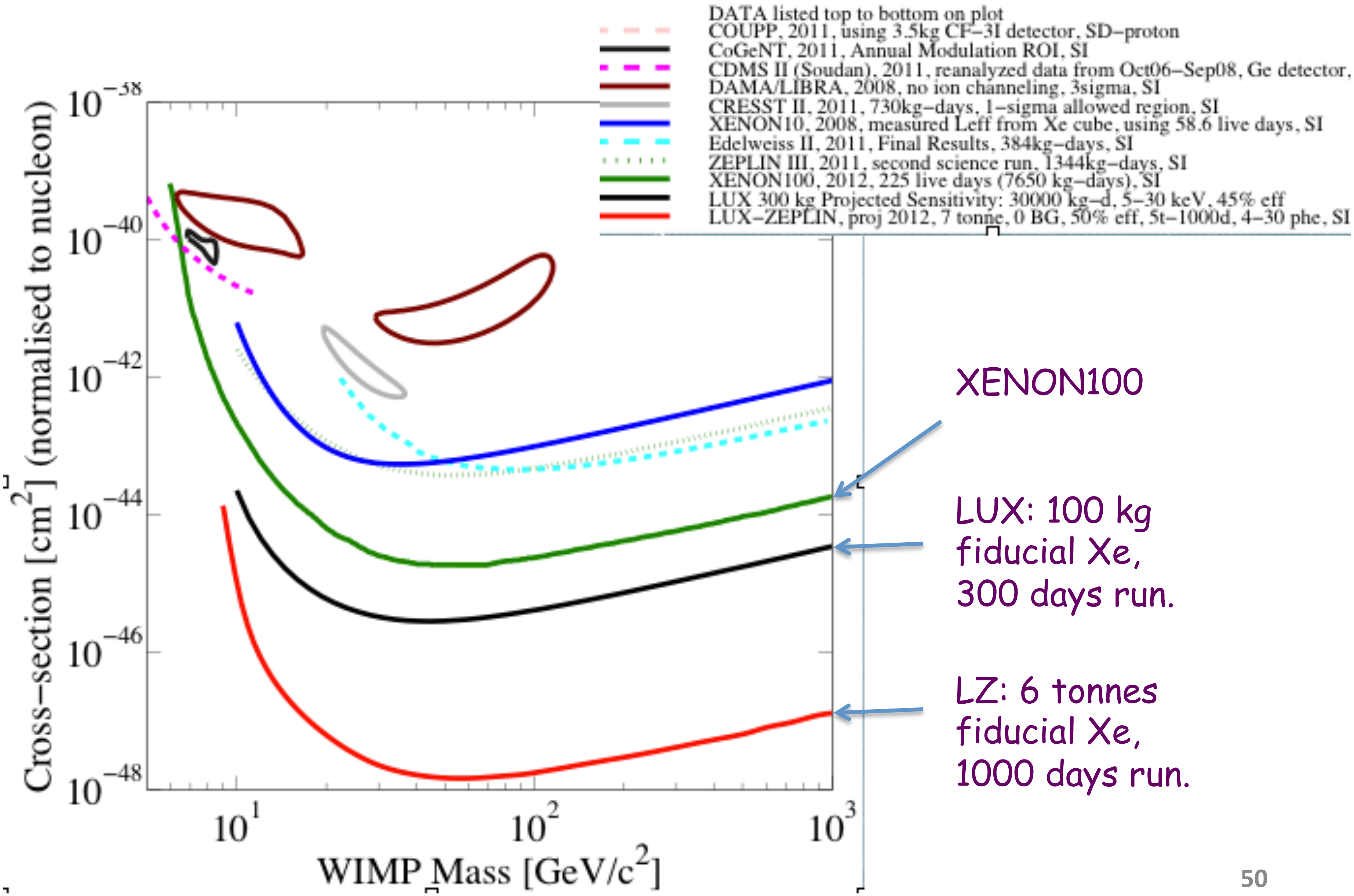


A two-phase Xe TPC with ~7 tonnes of Xe in active volume, of which ~6 tonnes will be the fiducial volume.

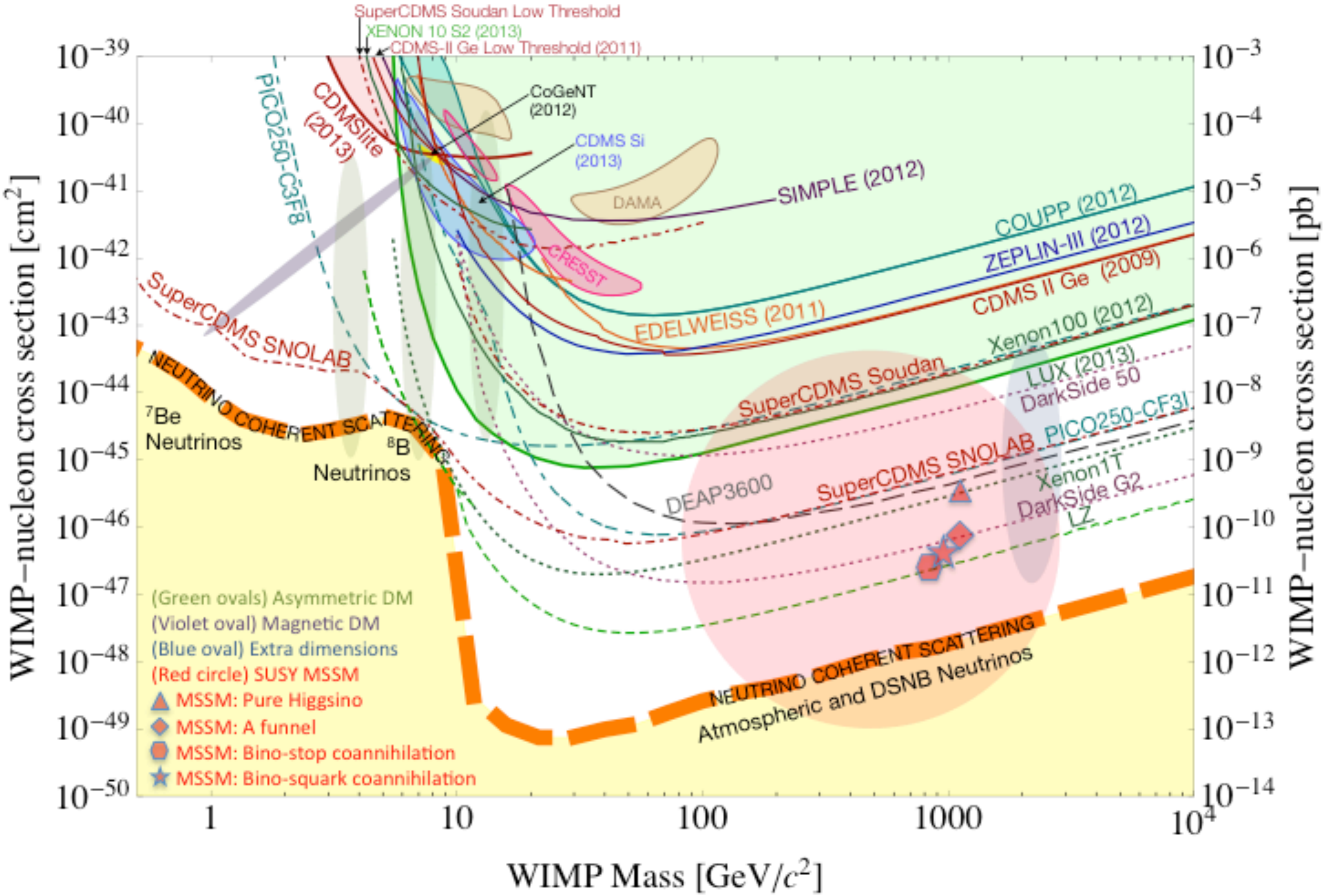
Three layers of shield/veto: Xe "skin", Liquid Scintillator, Water tank.

Engineering design is in an advanced state.

LZ Reach for WIMP Search



Snowmass Projections



Summary

- Dark Matter remains one of the leading problems in physics today. It appeals to the public's imagination and attracts scientifically creative minds to work on it.
- The problem is being attacked in numerous ways.
- LHC will contribute in unique ways, in both model independent and SUSY-based searches.
- LZ holds the promise to be the ultimate G2 direct WIMP search experiment.