The Future Is Dark
A personal outlook on dark matter

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CAP 2014, Sudbury, ON

Art credit: Jan Graf von der Pahlen

Whatever could dark matter be?

Mass>0, electrically neutral, *at best* weakly interacting, and not baryons

Pre-LHC, it was really common to throw around SUSY buzzwords like neutralino when discussing DM. I myself predicted in 2003 that LHC would be the first to discover dark matter particles. LHC data to date dashes cold water on these dreams (but verdict still out: wait for 14TeV data!)

Even “WIMP” as a generic term is too unimaginative. Increasing attention is being paid to alternatives:

- axions
- massive sterile neutrinos
- hidden sector particles: dark photons from hidden U(1) symmetries

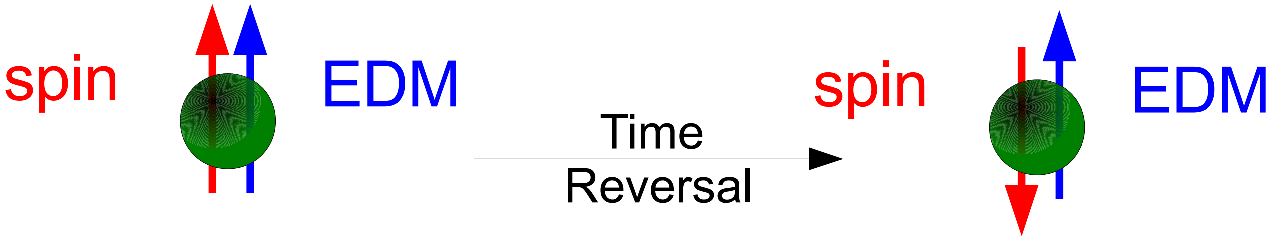
Assuming it's a WIMP, how does it interact?

Old paradigm: elastic scattering of spin 0 particle, mediated by Z boson (so M_{WIMP} > 45 GeV), with equal couplings to all up and down, with $\sigma \propto A^2$ at weak scale.

Unproven assertions:

- Spin 0: need to consider spin-dependent alternatives
- Elastic scattering: why not scatter to excited states, reducing deposited energy?
- Mediated by Z: why not Z'? Weakly mixed dark photons? Another new particle? Mass could easily be <45 GeV.
- Isospin symmetric: unproven, and can introduce nuclear target dependencies
- Cross section at weak scale: desirable to get Ω_{DM} ~ 0.25, but not guaranteed
- Just one dominant species: what if DM mass budget is spread across 20 particles, some of which don't couple at all? Abundance could be lower than you thought!

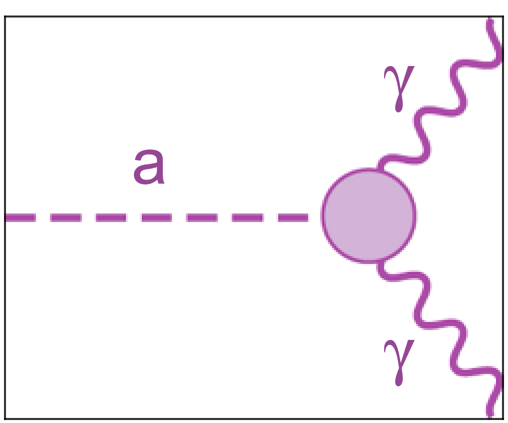
Axions & the SM parameter no one talks about



CP violation by strong force would produce neutron EDM ... which isn't seen.

$\theta_{CP} < 10^{-9}$ ... tiny! Why so fine-tuned?

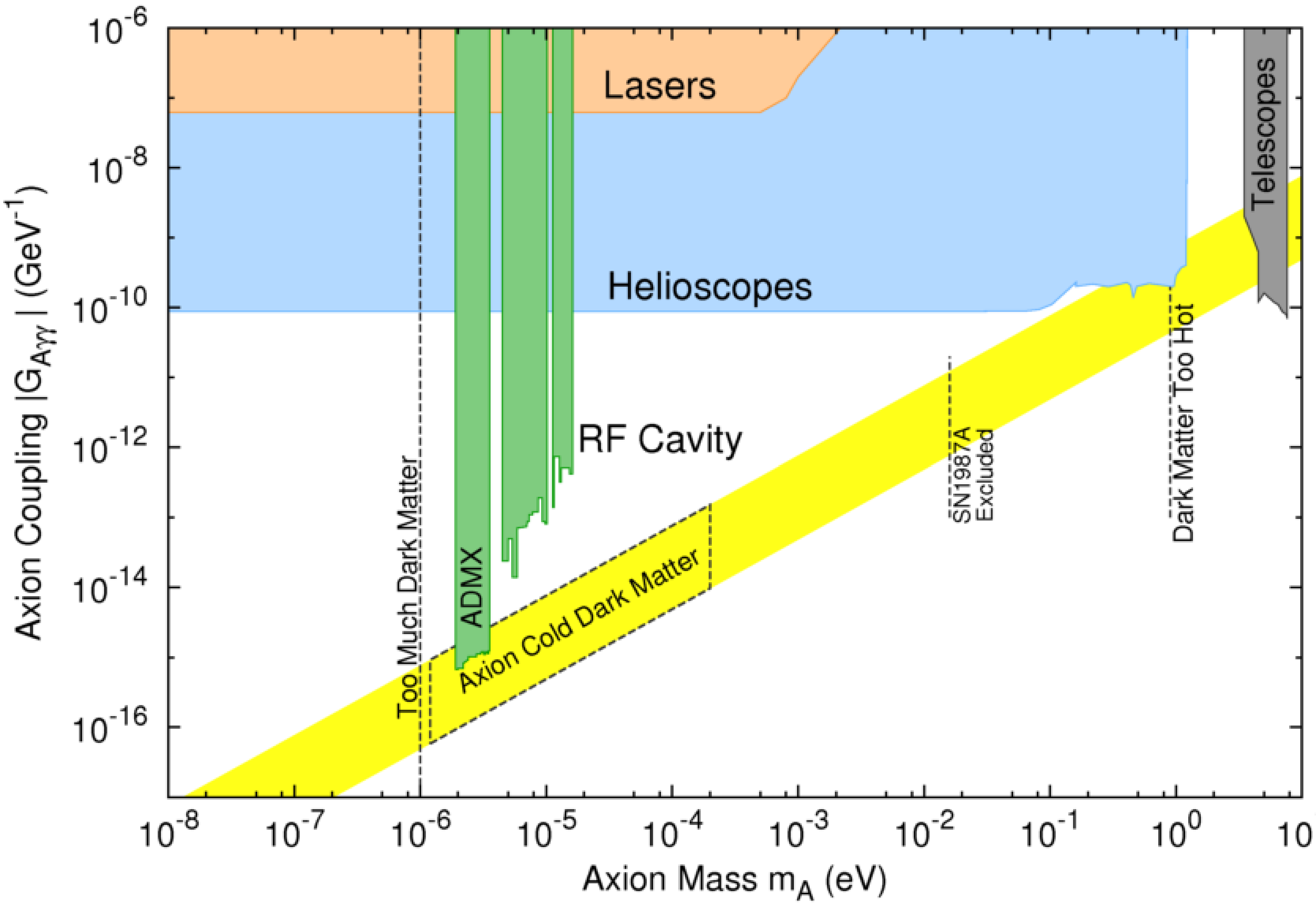
Peccei-Quinn model: a new spontaneously broken symmetry cancels any strong CP violation, and produces a new pseudoscalar Goldstone boson, called the axion



The theory predicts both the mass, and the coupling constant, as a function of the energy scale of symmetry breaking.

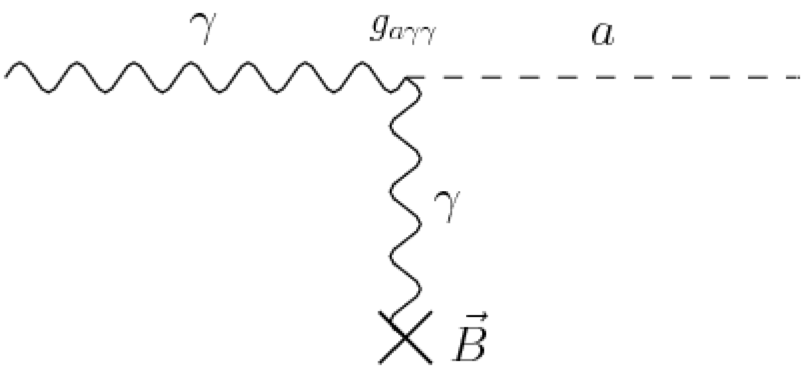
Axions couple to two photons! They are very light (<eV), and *could* constitute all of the DM! (Or they might not exist ...)

A well-defined search window



Plot lifted from Gray Rybka's TAUP2013 talk

Detecting axion conversion in a magnetic field using a resonant cavity



Primakoff Effect

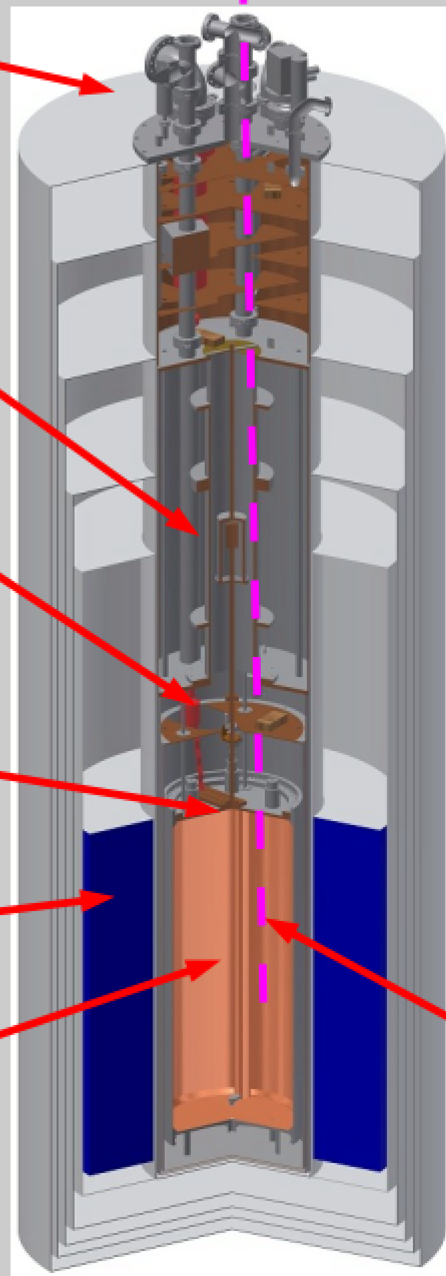
Virtual photon in magnetic field converts to real photon by interacting with axion. The energy of the photon is determined by the axion mass---radio emission at a specific frequency

Amplify the extremely weak signal using a resonant microwave cavity with very high Q value. Keep noise as low as possible---close to quantum limit if you can!

Scan over frequency looking for resonant peak. Noise determines how long you need to integrate at each frequency, and hence how quickly you can scan.

ADMX Design

Dump liquid helium in here



SQUID Amplifier package

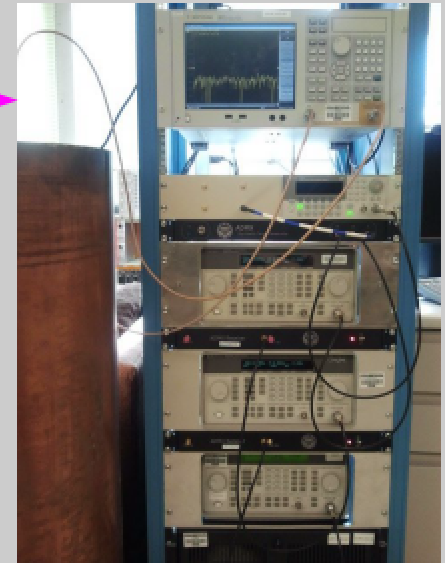
Refrigeration

Antennas

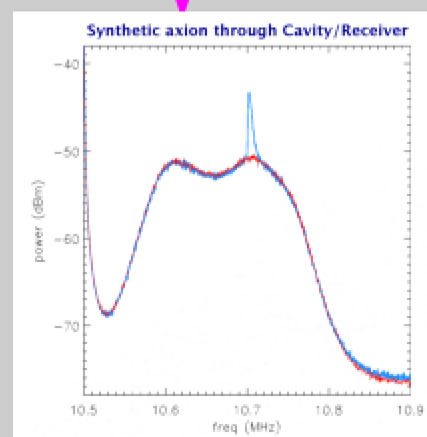
8 Telsa Magnet

Microwave cavity (axions go in here)

Change frequency/ mass sensitivity with tuning rods

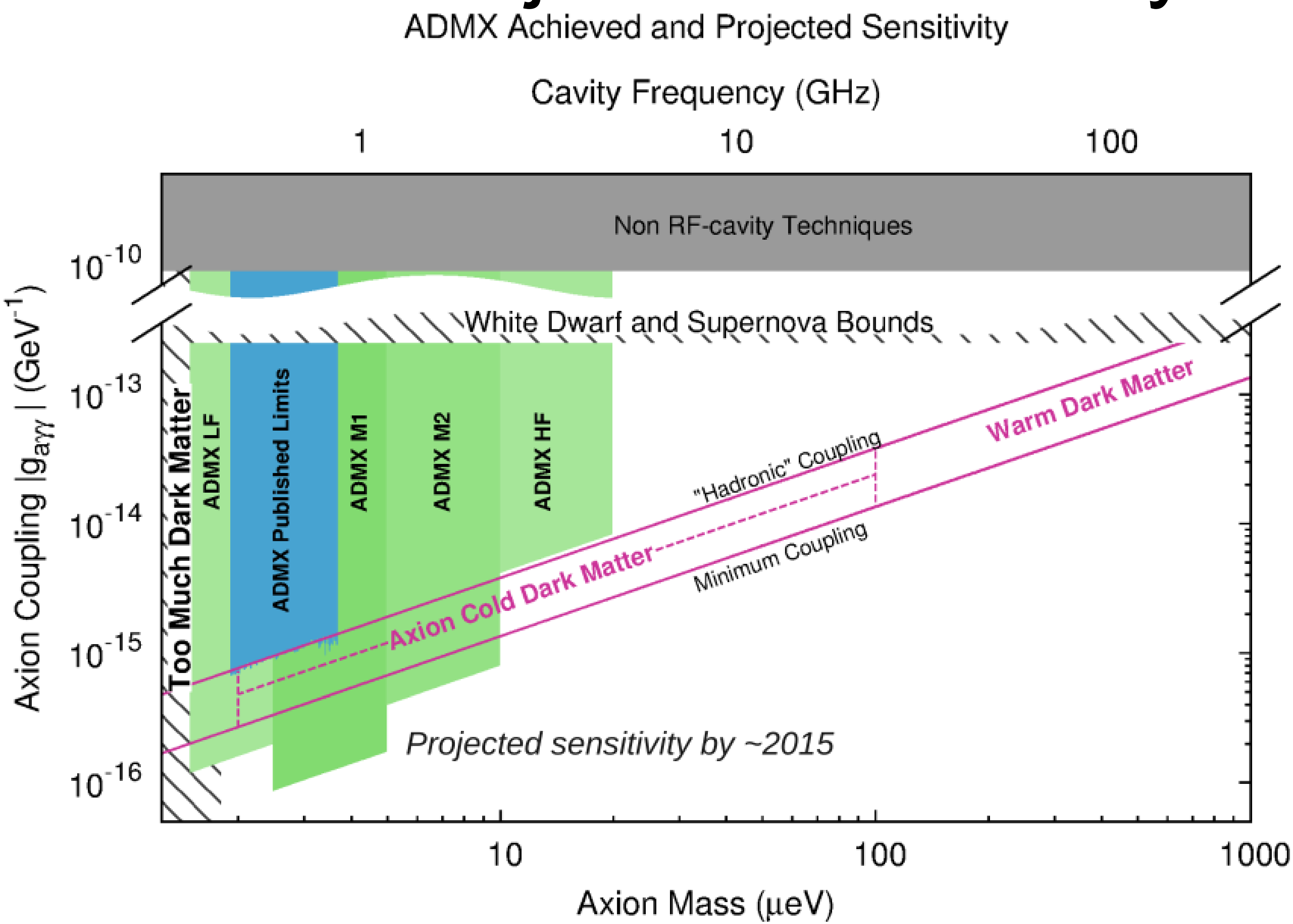


Amplify, mix signal from ~1 GHz to ~10.7 MHz, then digitize



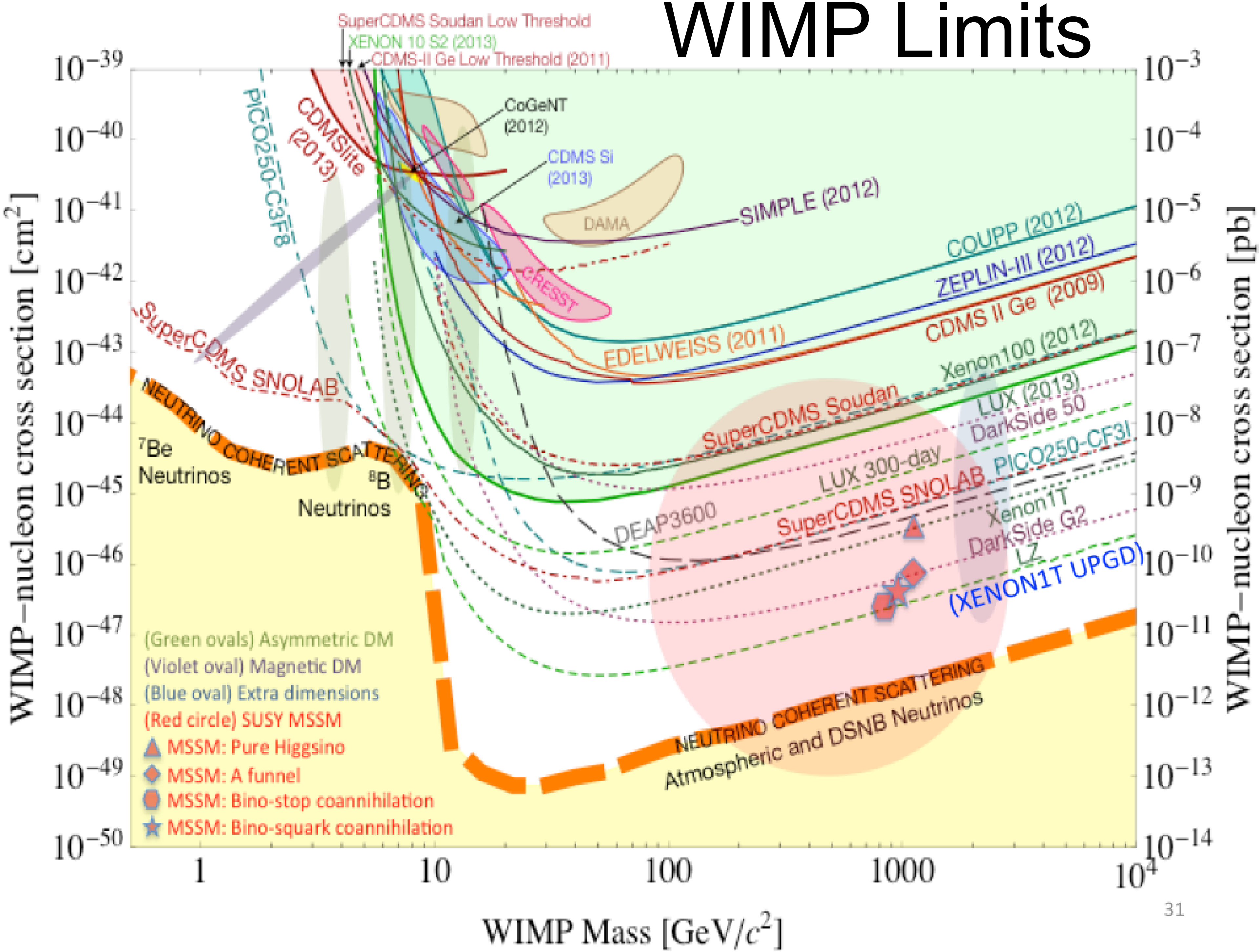
Look for excess power in power spectrum

ADMX Projected Sensitivity

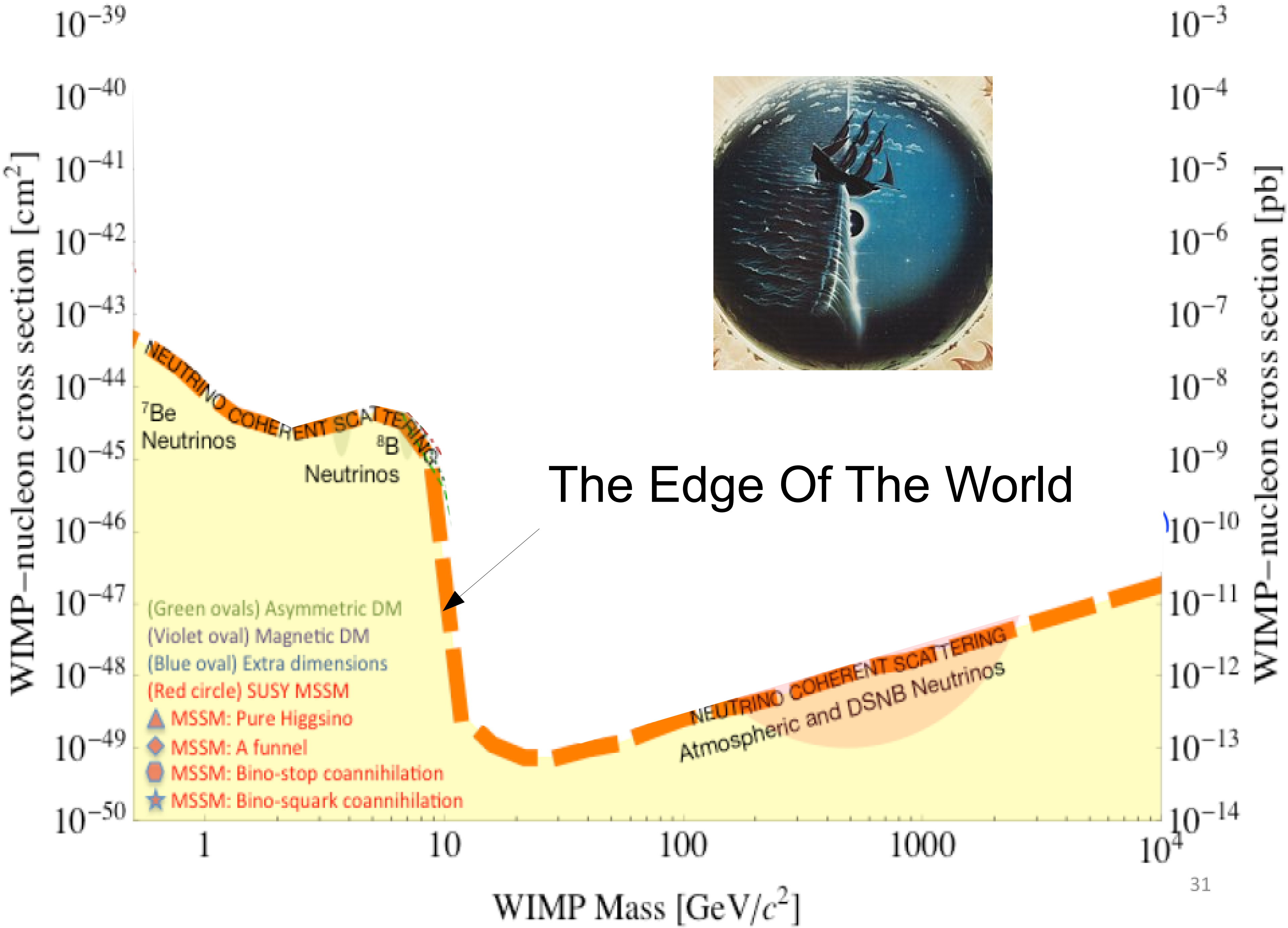


My Prediction: This experiment will be funded by the ongoing US DM competition.

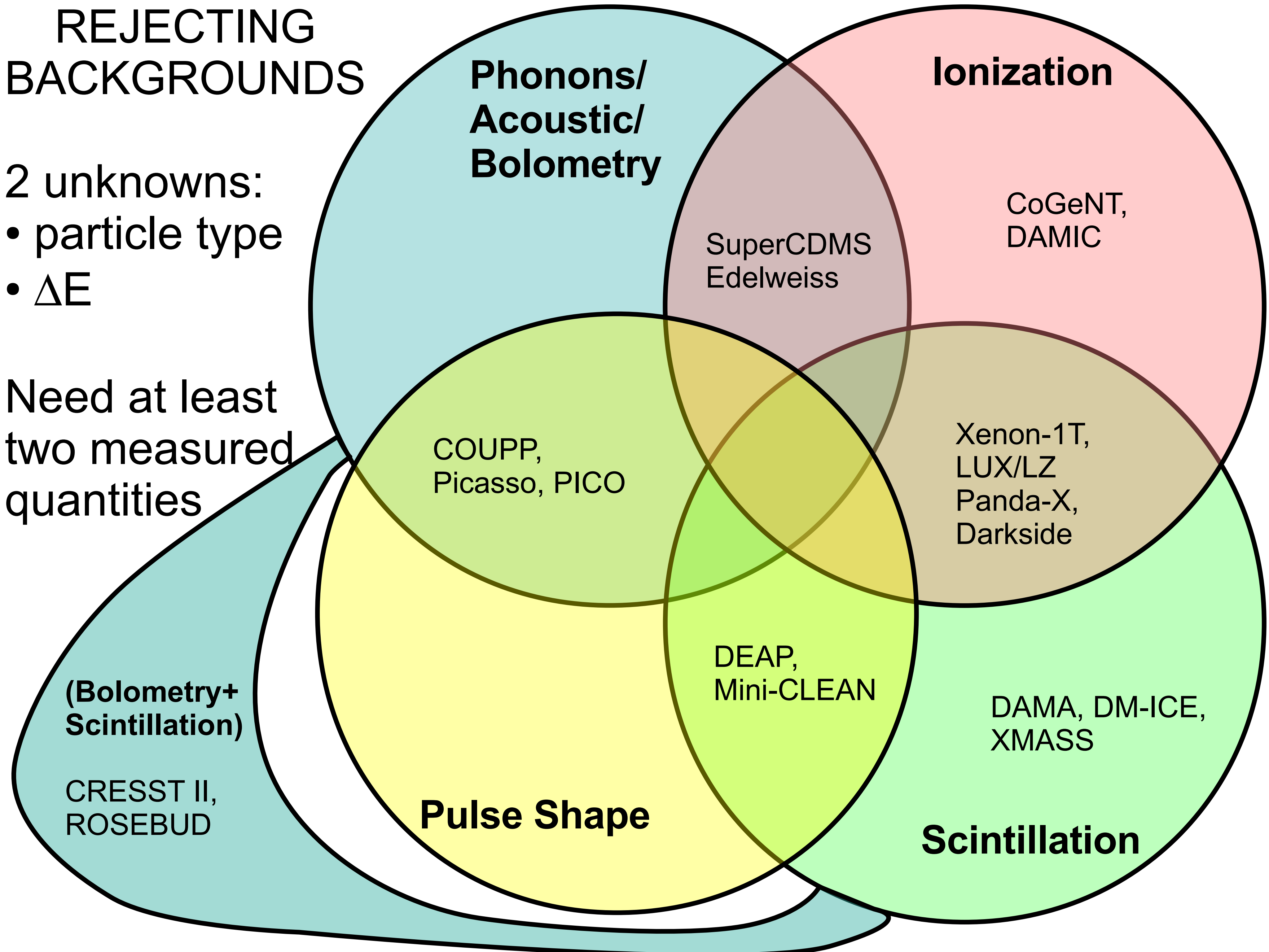
WIMP Limits



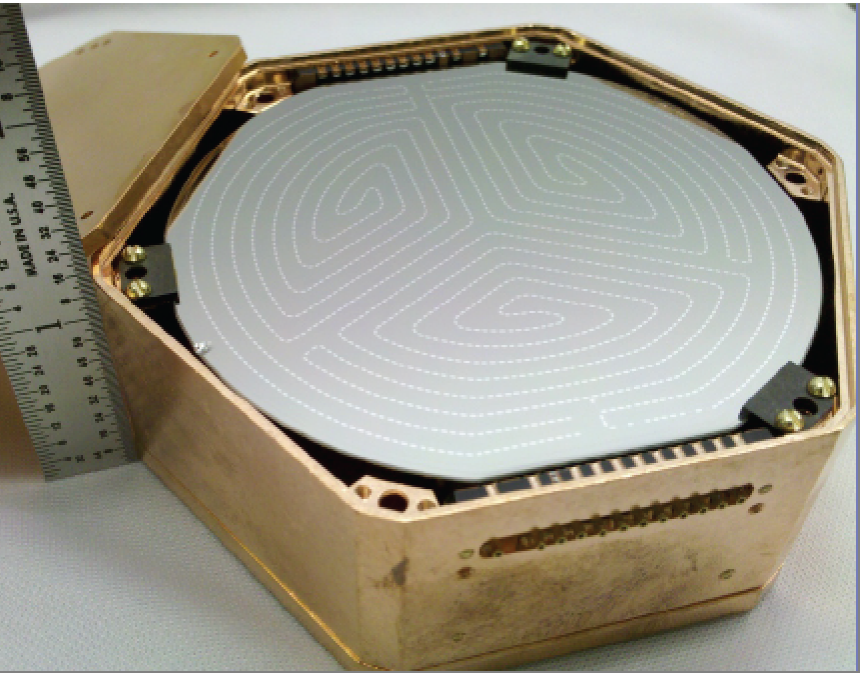
Dashed lines are projected sensitivities: guilty until proven innocent



The Edge Of The World
WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation


REJECTING BACKGROUNDS
2 unknowns:
• particle type
• ΔE
Need at least two measured quantities
Phonons/ Acoustic/ Bolometry
Ionization
CoGeNT, DAMIC
SuperCDMS Edelweiss
COUPP, Picasso, PICO
Xenon-1T, LUX/LZ Panda-X, Darkside
DEAP, Mini-CLEAN
DAMA, DM-ICE, XMASS
(Bolometry+ Scintillation)
CRESST II, ROSEBUD
Pulse Shape
Scintillation

SuperCDMS-SNOLAB

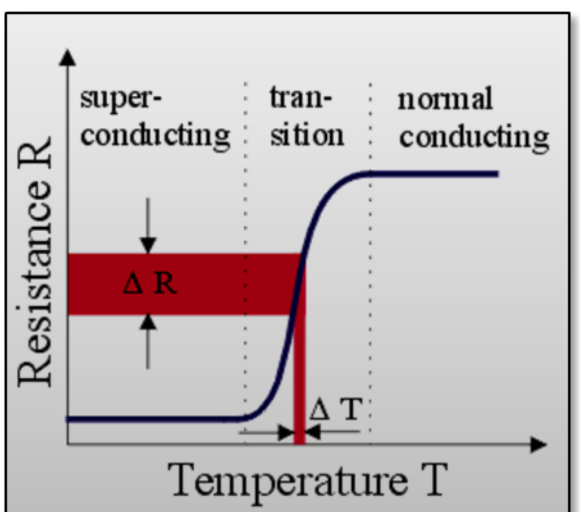


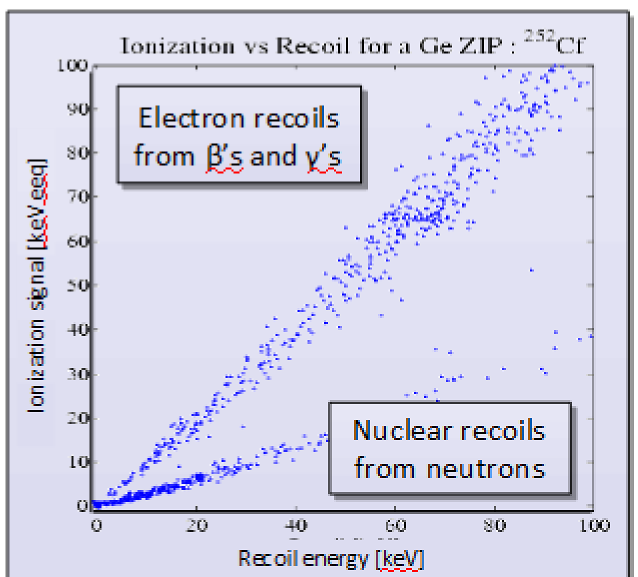
Technique: ionization yield vs. phonon energy

Payload: 92kg Ge, 11kg Si, 7kg of lower threshold Ge/Si

Proposed site: SNOLAB

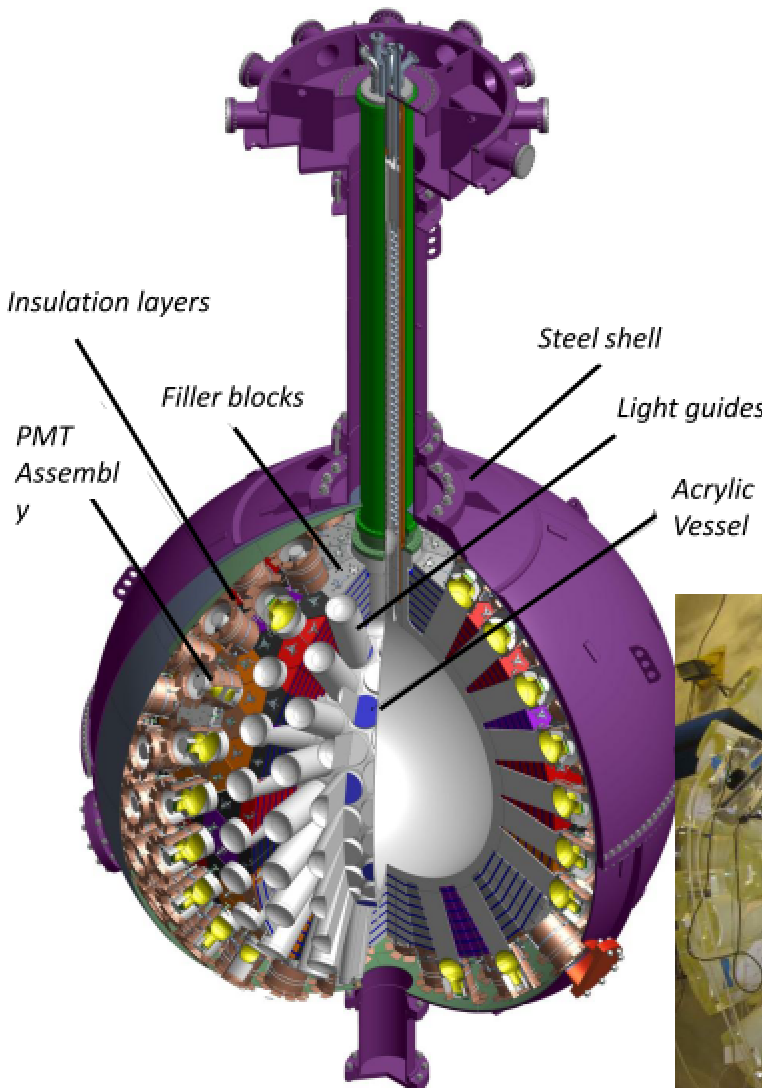
Distinctive features:
- reach to <1 GeV
- multiple targets
- scaling is $$





Funding status:
Funded in Canada (CFI), awaiting US decision

DEAP-3600

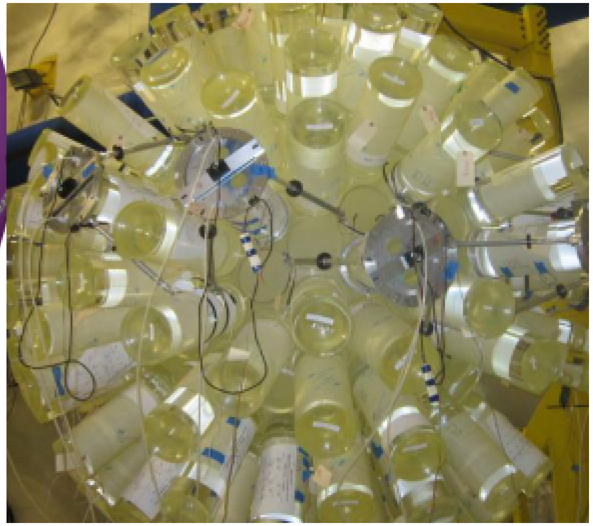


Technique: scintillation yield vs. risetime

Payload: 3600 kg liquid Ar (1000kg fiducial volume)

Site: SNOLAB

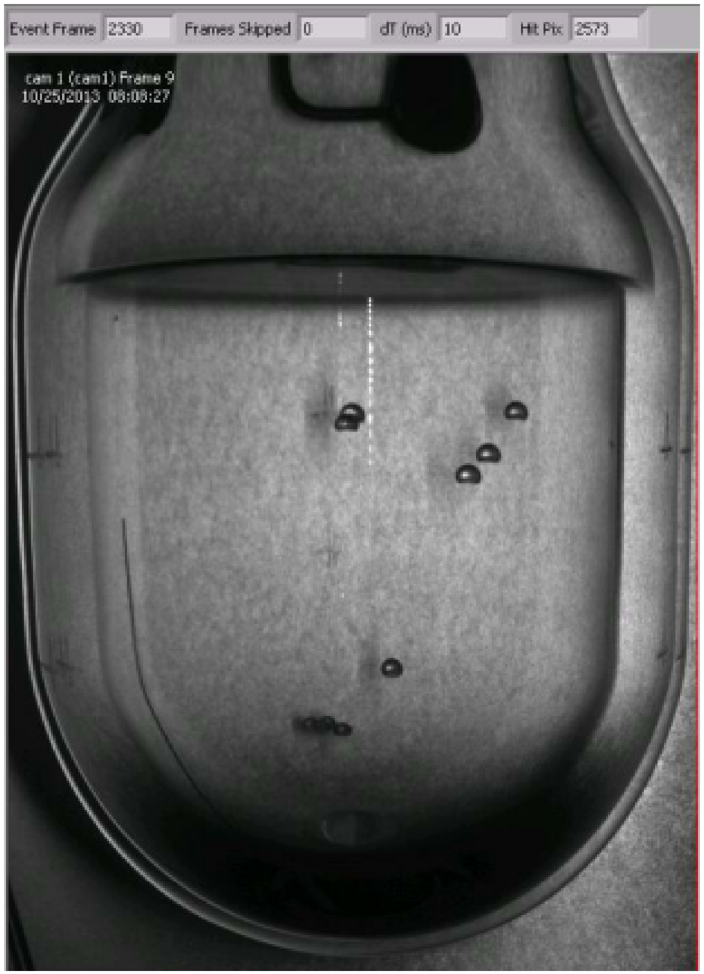
Distinctive features:



- significant ^{39}Ar bkgd, requires 10^{10} rejection or depleted Ar
- unique rejection from risetime
- filling this year!

Funding status: Funded

PICO-250L



Technique: bubbles in super-heated fluid, w/ acoustic analysis

Payload: 250L of CF_3I or C_3F_8

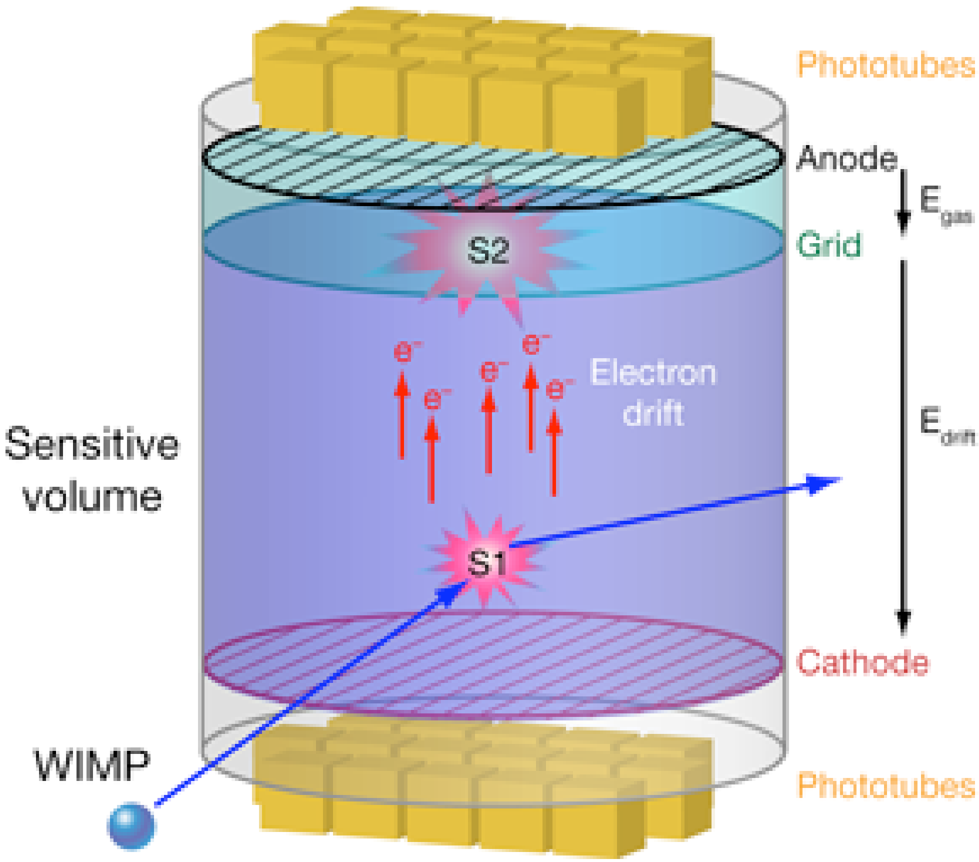
Site: SNOLAB

Distinctive features:

- mostly insensitive to electron recoils ... but α's are a concern
- integral rate above threshold
- spin dependent sensitivity!
- merger of Picasso & COUPP

Funding status: Awaiting US G2 funding decision, and ongoing CFI

Liquid Noble Gas Time Projection Chambers



Measure scintillation light & ionization charge---ratio discriminates between nuclear vs. electron recoils.

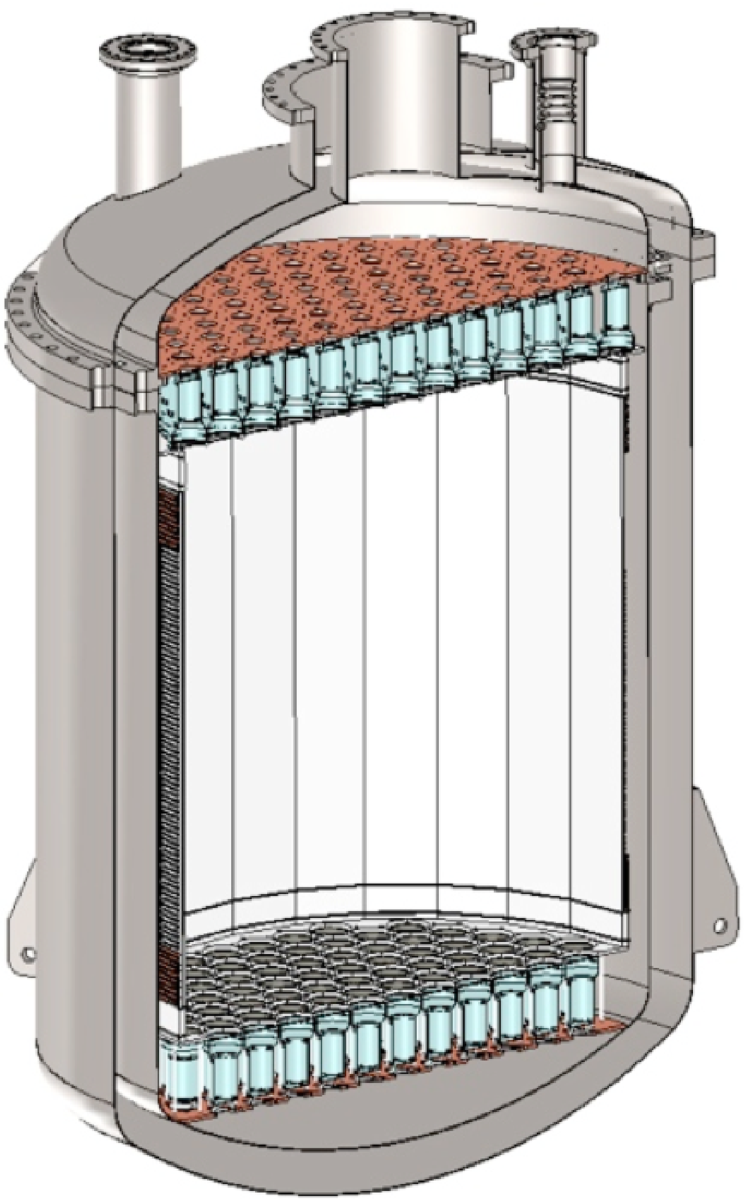
Part of cost scales like surface area!

Xe: high A, good self-shielding, lower intrinsic background rejection than other targets. ^{85}Kr and Rn backgrounds critical.

Ar: lower A, ^{39}Ar background, but better intrinsic rejection

Currently this technology leads in sensitivity, but will unanticipated backgrounds surface as size is scaled up?

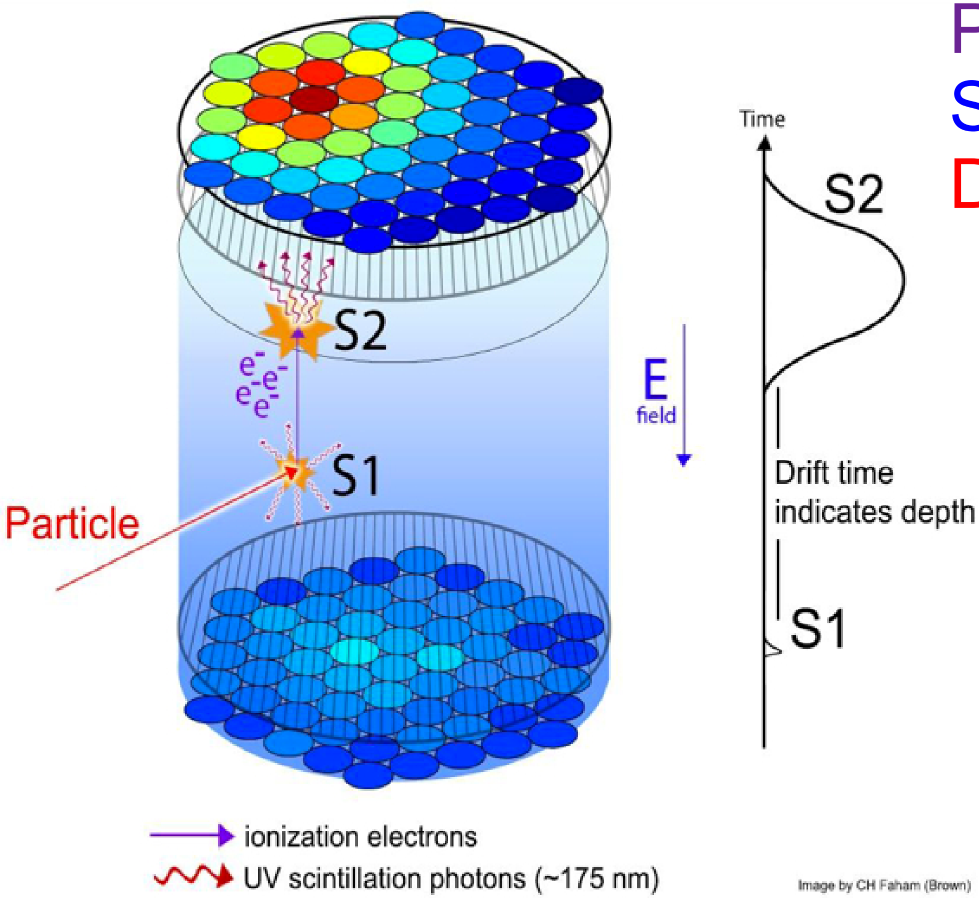
XENON-1T



Technique: 2-phase Xe TPC
Payload: 1tonne (fiducial) liquid Xe
Site: Gran Sasso
Distinctive features:
- Thick water Cherenkov muon veto
- Requires 100x reduction in bkgd beyond XENON-100kg.
- best projected sensitivity of any experiment currently under construction ... but will it reach it?

Funding status: Funded, under construction, data-taking in 2015.

LUX/LZ



Technique: 2-phase Xe TPC

Payload: 7tonne (fiducial) liquid Xe

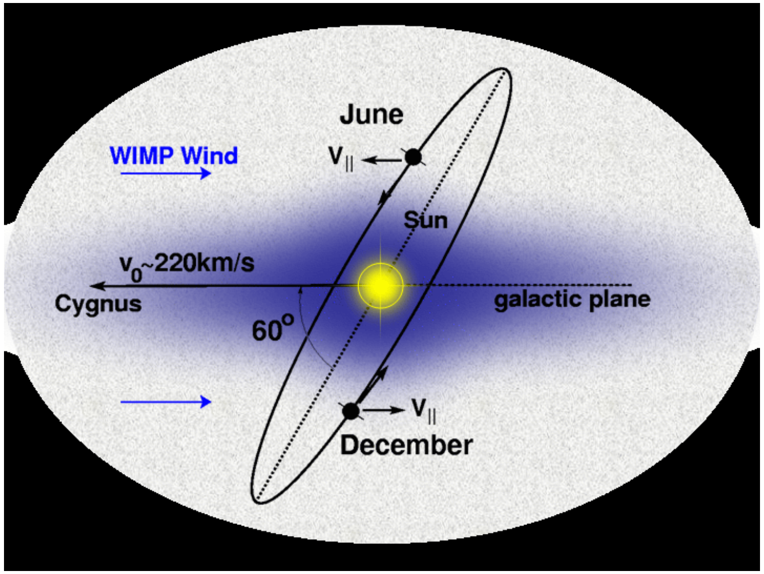
Site: Homestake

Distinctive features:

- Merger of LUX and ZEPLIN
- LUX currently has best limits
- If this looks a lot like XENON-1T, it's because it is!
- XENON-nT proposes to upgrade XENON-1T to achieve same reach
- *On paper*, best sensitivity at high mass by large factor

Funding status: Competing in ongoing US G2 dark matter competition---most expensive proposal on offer

Directional signals: the DRIFT experiment

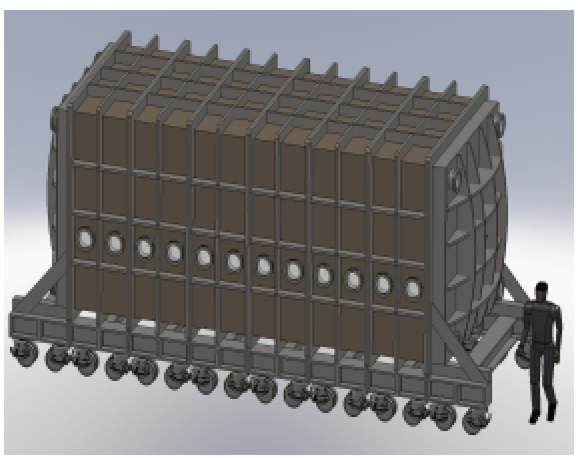


Novel background rejection technique: look at direction of nuclear recoil relative to Earth's motion through the WIMP wind

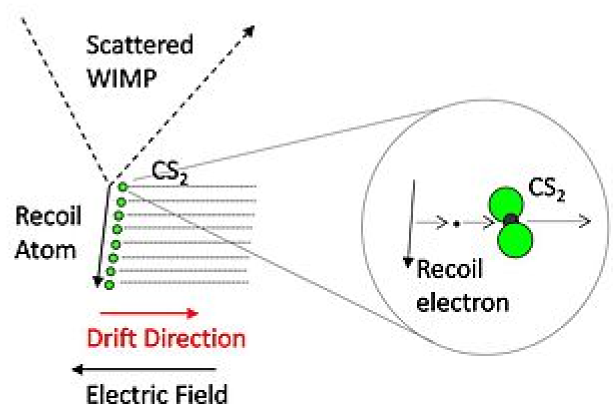
Payload: low pressure CS_2:CF_4 gas

Distinctive features:

- directional sensitivity (duh!)
- very low density, small target mass
- spin-dependent sensitivity
- proposed 10m^3 volume detector (DRIFT-III)

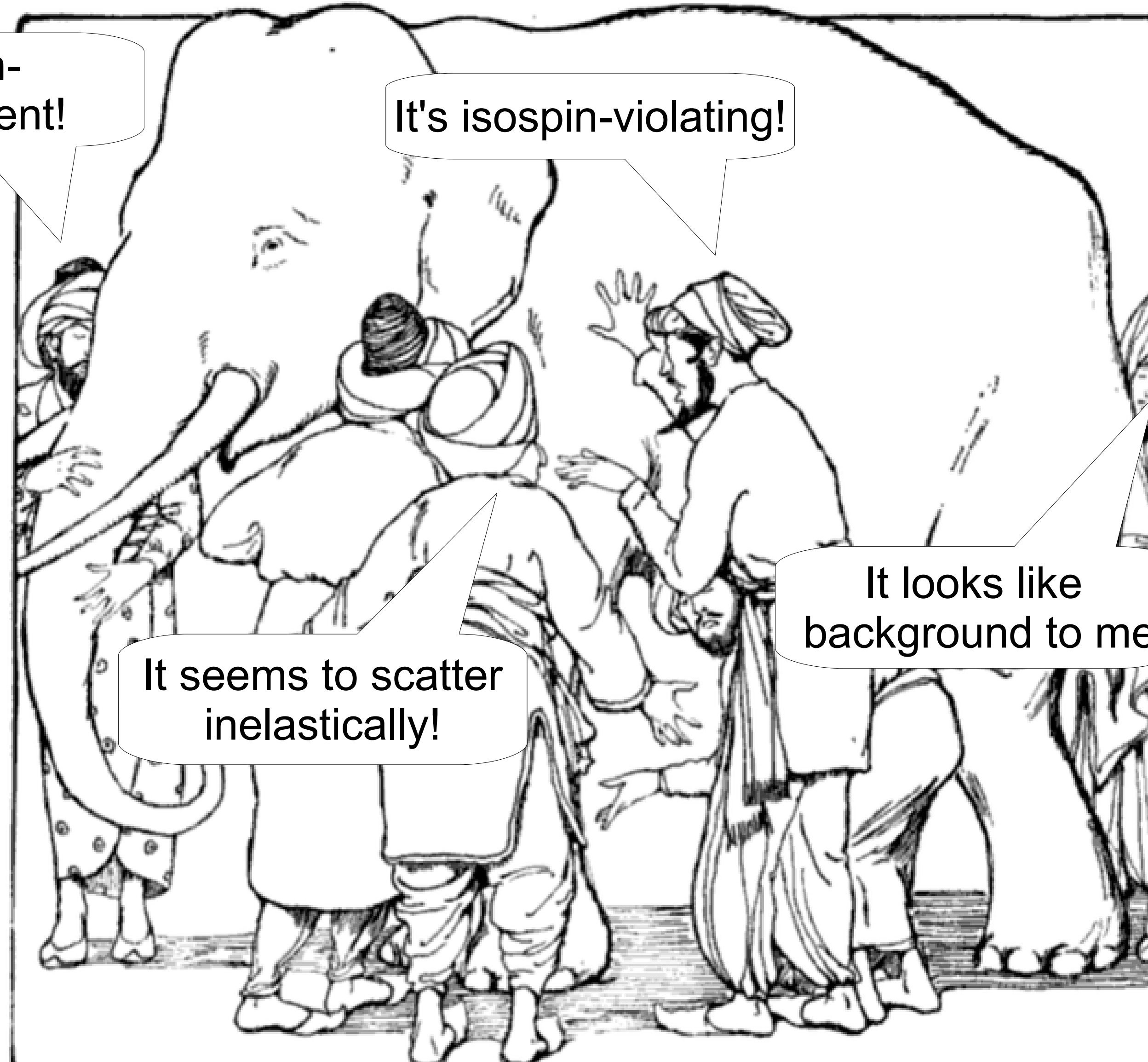


DRIFT-III proposal



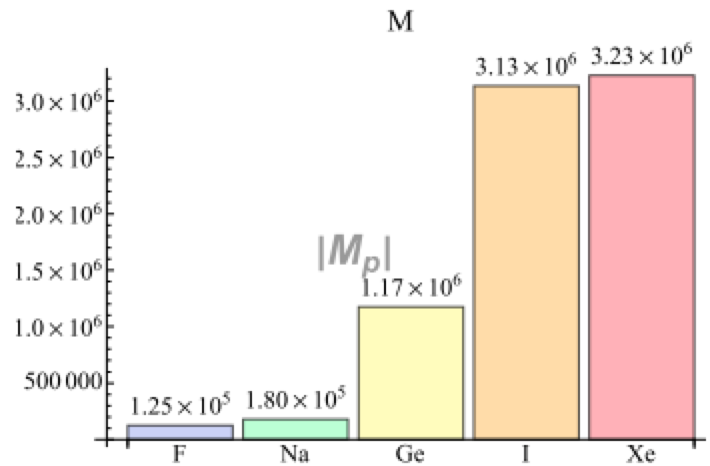
My personal bias: the target mass is too small to be competitive. Maybe this is a followup experiment for a future detection with another detector.

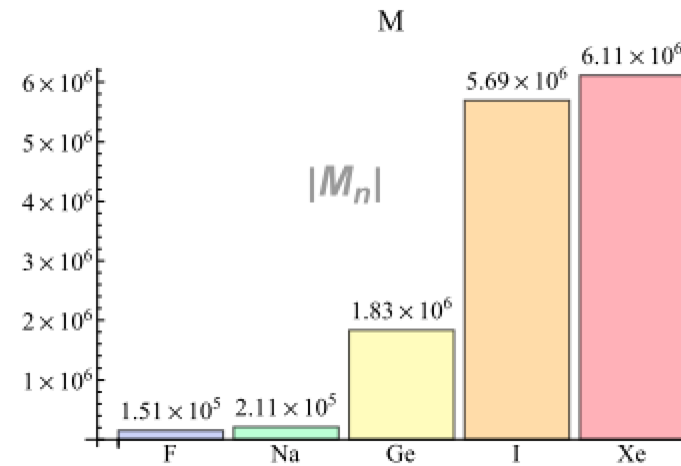
Multiple targets are critical



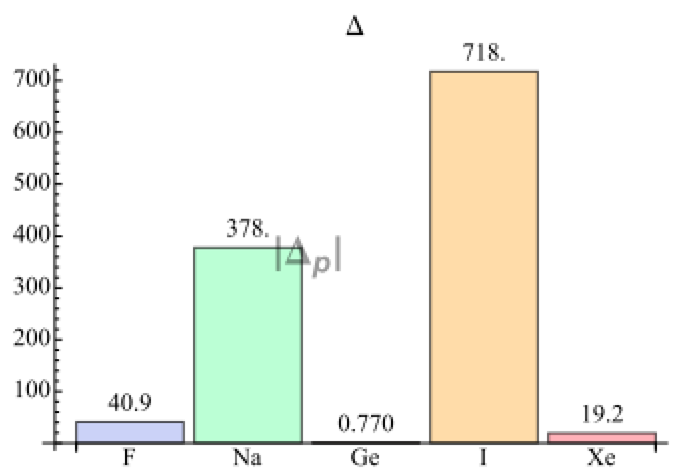
Fitzpatrick et al have written down an effective field theory for dark matter interactions and parametrized allowed operators, including 6 nuclear form factors. They emphasize that dark matter itself could be composite (just like ordinary matter) and have non-trivial form factors (eg. multipole moments of “dark charges”). Different nuclei have very different sensitivities to these terms:

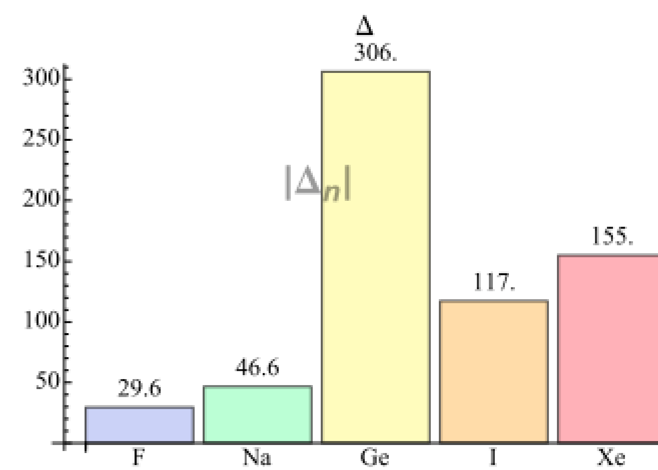
“Charge-like” form factors





“Transverse Magnetic” form factors





http://arxiv.org/abs/1203.3542

The limiting factor in DM sensitivity

The limiting factor in DM sensitivity

Much of community waiting (and waiting) for US "G2 competition" results. Between $32-46M available between DOE & NSF. Submitted proposals total $113M, so seemingly hard decisions to make. Enough money to pay for one expensive proposal (eg. LZ or SuperCDMS) and maybe one much smaller project.

However, the recent US Particle Physics Project Prioritization Panel (P5) says the US should do better:

Recommendation 19: *proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.*

An optimistic, but plausible future?

My best guess, subject to availability of funding in US ...

- ADMX will be funded, no matter what
- LZ funded on a slower timescale (stretching over more years), to accommodate costs and give a chance for design to learn from first results from XENON-1T. It then becomes a Generation 2½ experiment. (Very hard to imagine that a US-based experiment won't be funded!)
- SuperCDMS funded, to give low mass reach and two different target nuclei. Possibility of European groups contributing more payload.
- PICO-250L funded to cover spin-dependent couplings

Conclusions

- Increasing attention being paid to non-SUSY-like DM (axions, sterile neutrinos, dark photons, etc).
- "Generation 2" WIMP searches will cover more than half of the allowed parameter space above the neutrino background
- Probably no more than a couple of ~$100M experiments in "Generation 3" will push down into the neutrino background. If nothing is found by then, we need to look elsewhere for DM.
- Understanding any signal (and showing it's signal and not background) requires multiple targets and techniques. The community must not put all of its eggs in one basket!