Experimental Direct Detection of Dark Matter: Present and Future

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Overview

Dark Matter Candidates

Old paradigms and new paradigms for dark matter

Techniques to Search for Dark Matter

Model-independent paradigms

Dark Matter Direct Detection Signatures

Old paradigms and new paradigms for the signatures

Experimental Innovations

Dark Matter Candidates

What do you need?

- Generated in early universe
- Non-relativistic at the time structure formation began
  - To explain connection between CMB power spectrum and LSS today
- Weakly- or non-interacting with normal matter
  - To avoid prior detection
- Cold or warm today
  - To avoid washing out small-scale structure today

The old paradigm

- Favored because natural from particle physics perspective:
  - sterile neutrinos (Kusenko -- this morning), axions, weakly interacting massive particles (WIMPs) esp. SUSY WIMPs
- Reasonably well motivated but unpopular or too esoteric
  - superWIMPs (gravitinos, axinos, etc.), light scalars from string theory, non-perturbative field configurations (Q-balls), ...
- Ad hoc: developed to solve DM problem rather than by other particle physics
  - primordial black holes, superheavy dark matter (WIMPzillas, strangelets, quark nuggets), ...

Axions

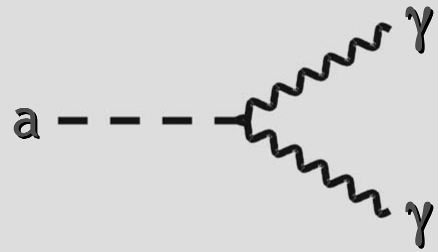
G. Raffelt

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

$m_\pi f_\pi \cong m_a f_a$

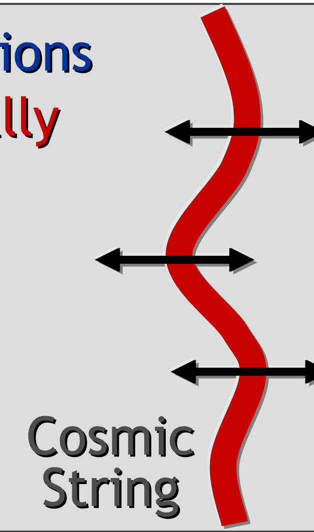


For $f_a \gg f_\pi$ axions are "invisible" and very light

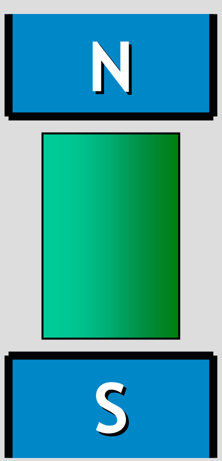
Cosmology

In spite of small mass, axions are born non-relativistically ("non-thermal relics")

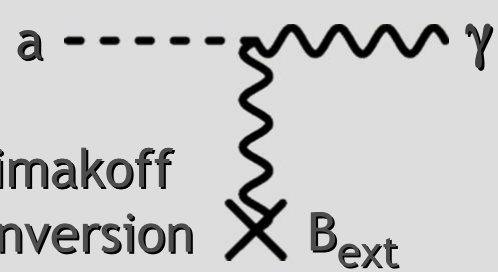
→ Cold dark matter candidate
$m_a \sim$ 1-1000 μeV



Search for Axion Dark Matter



Microwave resonator
(1 GHz = 4 μeV)



Primakoff conversion

BICEP2+ constrains axion mass:

Visinelli and Gondolo (arXiv: 1403.4594):

$$m_a = (71 \pm 2)\,\mu\text{eV}\,(\alpha^{\text{dec}} + 1)^{6/7}$$

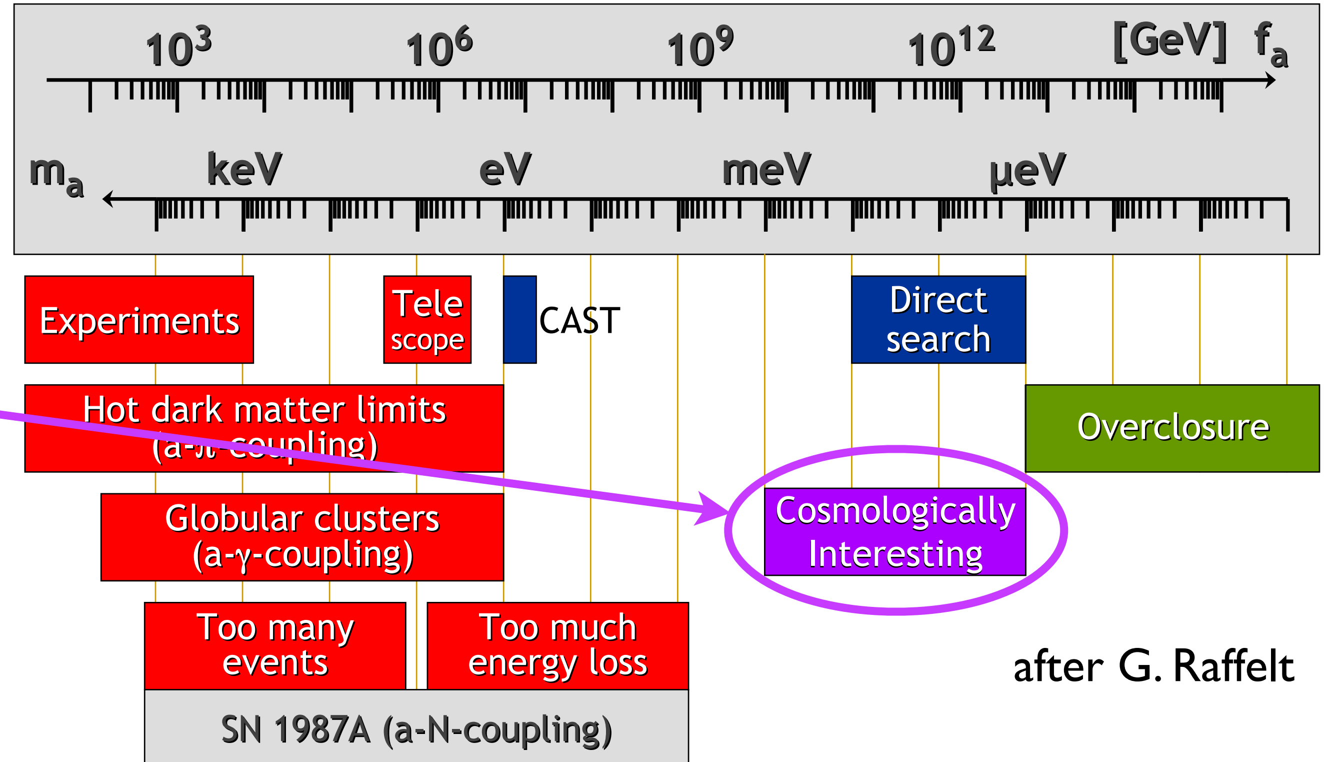
α^{dec} = (mass density due to decays of axionic topological defects)/(mass density due to initial vacuum misalignment)
~ 0.1-200 (?)

Axions: Definitively Testable

Cosmologically interesting: provides appropriate Ω_{DM}, m_a = 1 μeV to 1 meV maybe ~100 μeV

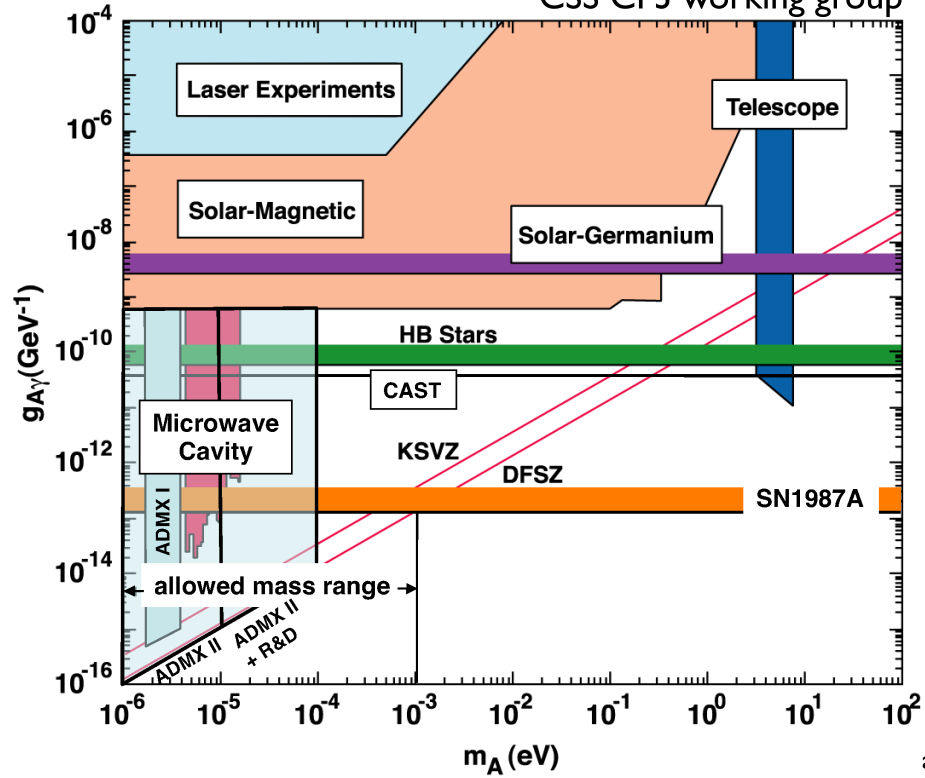
Microwave cavity conversion

- 1 GHz = 4 μeV: use high-Q tunable cavity in high B field; when $f_0 = m_a$, excess power
- Detection: RF amplifier + Fourier transform power spectrum, (excited Rydberg atom photodetection)
- Can cover ~1 μeV to 100 μeV; cavities become too small > 100 μeV
- Good prospects for covering full QCD axion range (KSVZ to DFSZ) up to 100 μeV with near-term dev'ts, perhaps to higher mass



after G. Raffelt

CSS CF3 working group



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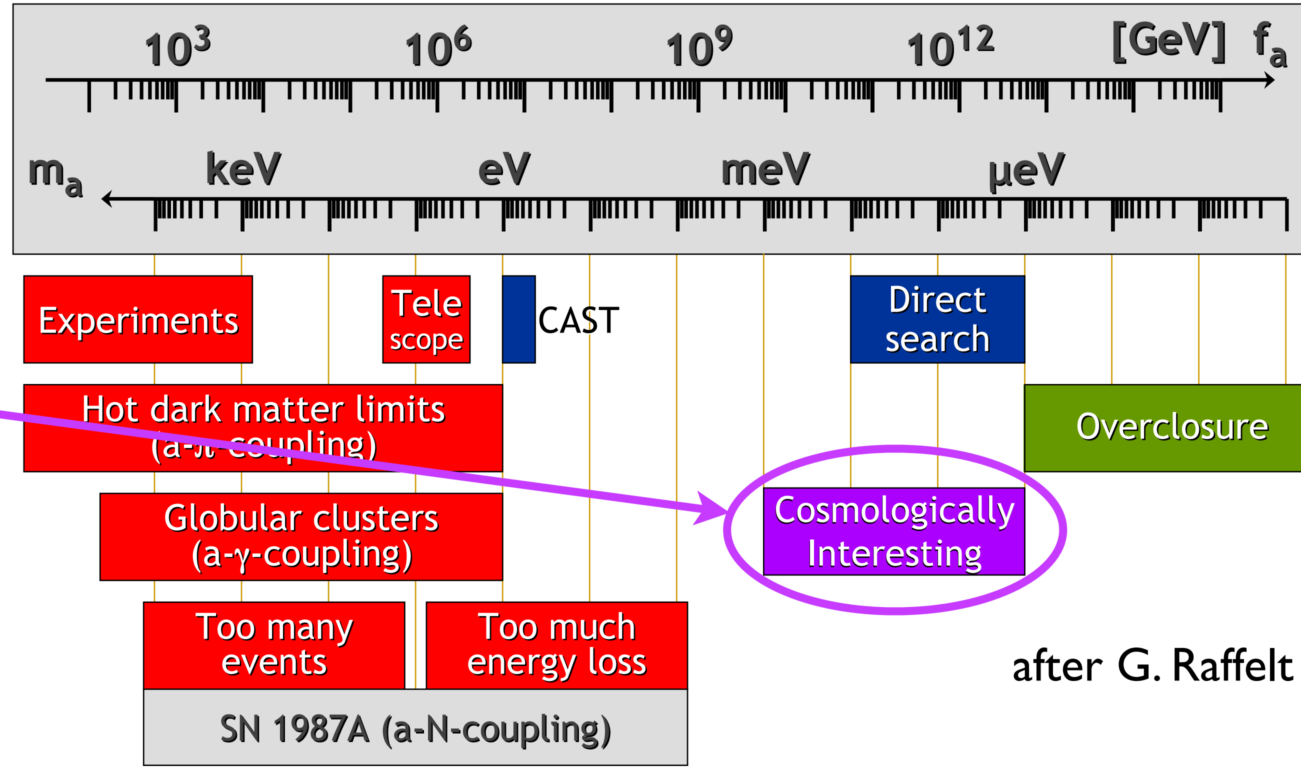

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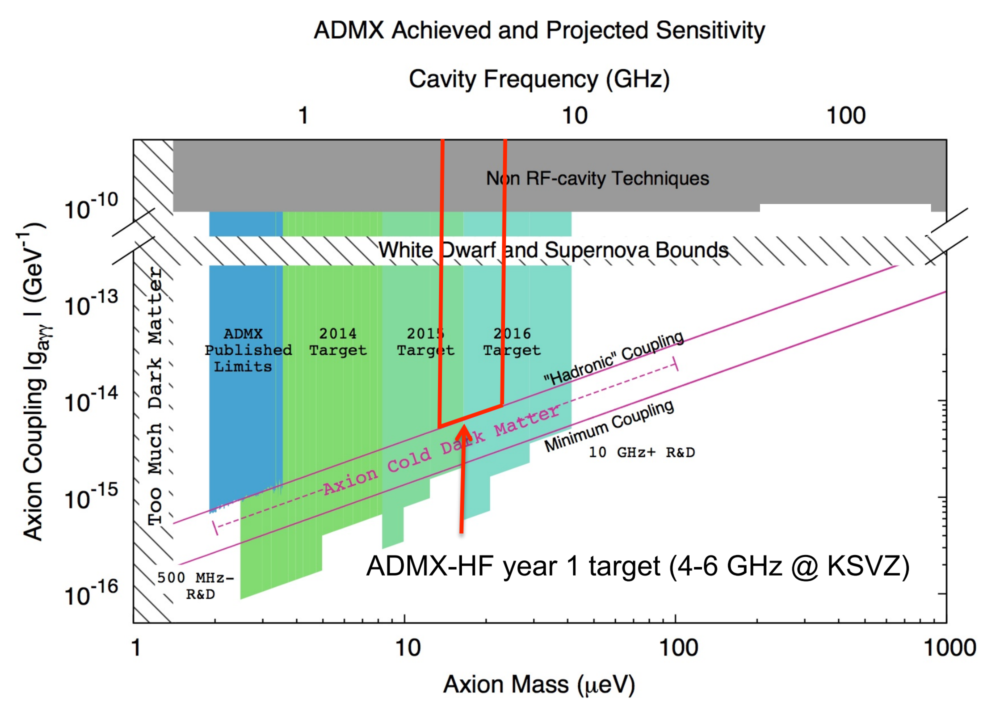


The Classic WIMP Scenario

A WIMP χ is like a massive neutrino: produced when T >> m_χ via pair annihilation/ creation. Reaction maintains thermal equilibrium.

If interaction rates high enough, comoving density drops as $\exp(-m_\chi / T)$ as T drops below m_δ : annihilation continues, production becomes suppressed.

But, weakly interacting → will "freeze out" before total annihilation if

$$H > \Gamma_{ann} \sim \frac{n_\chi}{\langle \sigma_{ann}\, v \rangle}$$

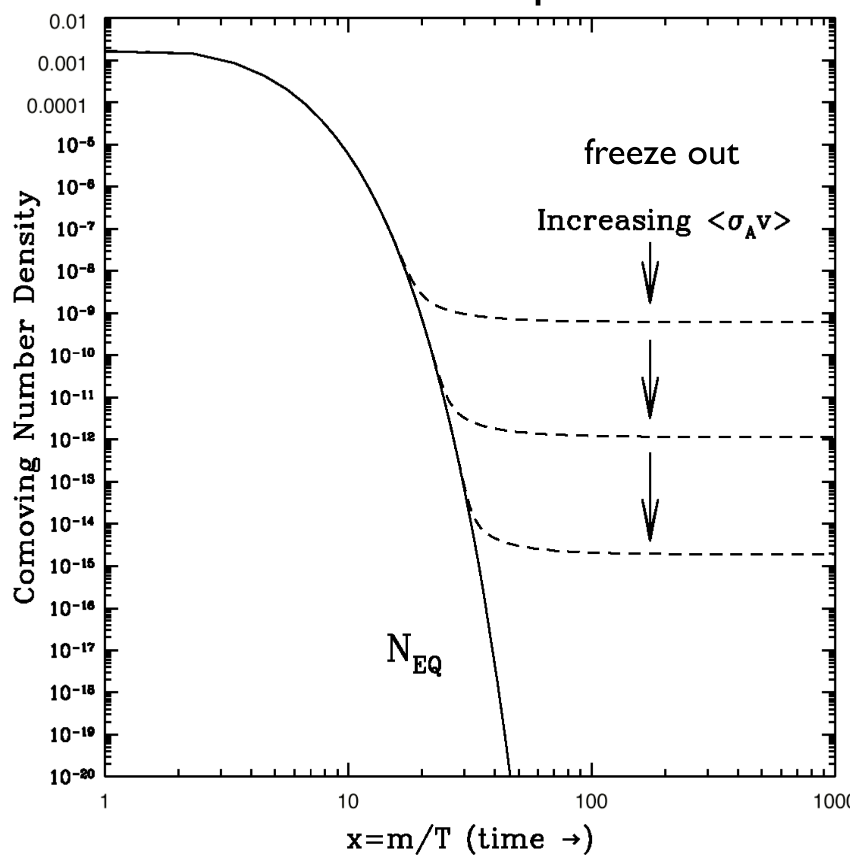
i.e., if annihilation too slow to keep up with Hubble expansion

Leaves a relic abundance:

$$\Omega_\chi \left(\frac{H_0}{100\ \mathrm{km/s/Mpc}} \right) \approx \frac{10^{-27}}{\langle \sigma_{ann}\, v \rangle_{fr}}\ \mathrm{cm^3\, s^{-1}}$$

for m_χ = O(100 GeV)
→ if m_χ and σ_{ann} determined by new weak-scale physics, then Ω_χ is O(1)

canonical Kolb and Turner freeze-out plot



LHC Tests of Constrained Minimal Supersymmetry

Assume CMSSM:
  Constrained Minimal Supersymmetric Standard Model

Very narrow blue strips:
  LSP relic density matches DM density

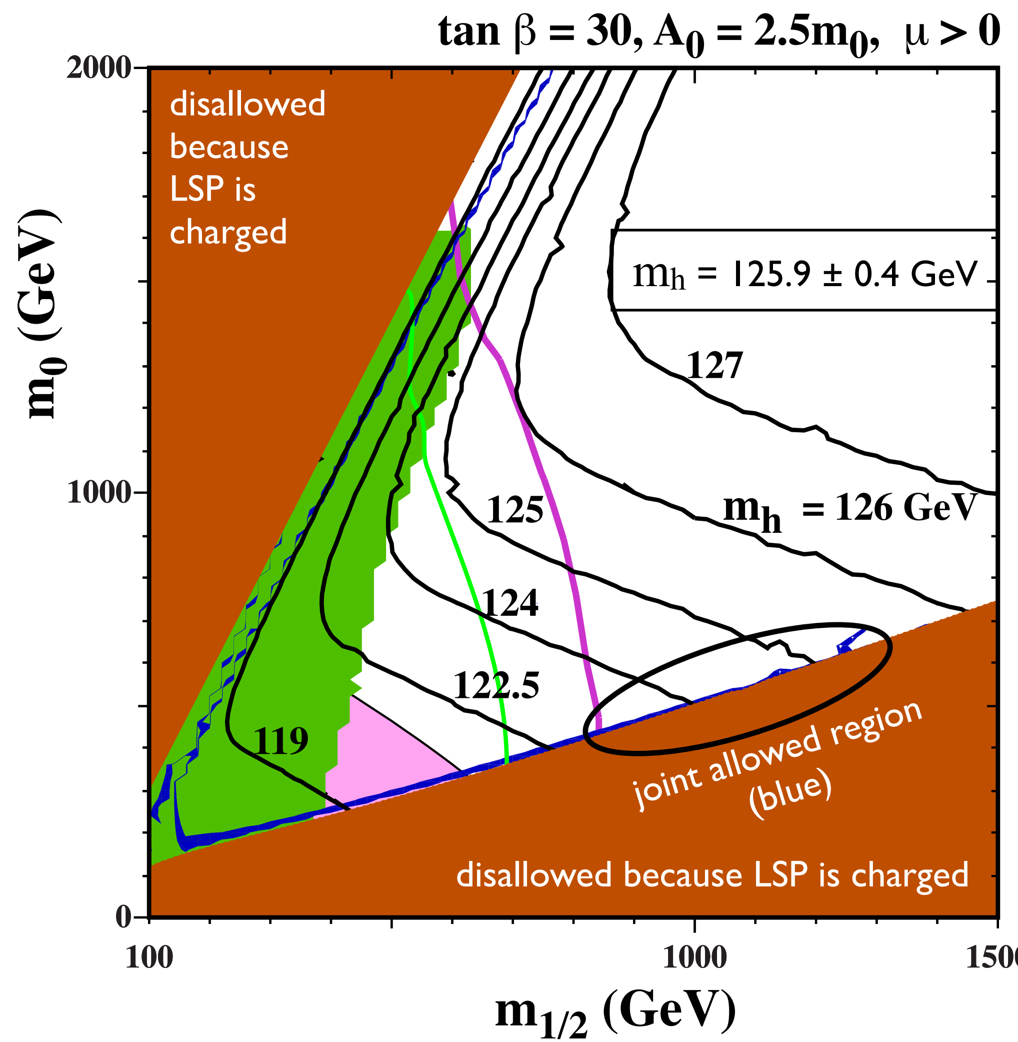
Green: BR($b \rightarrow s\,\gamma$) too large

Pink: $g_\mu - 2$ deviation from SM explained by SUSY

Purple line: lower limit on parameter space due to absence of missing transverse energy events at LHC

Green line: BR($B_s \rightarrow \mu^+\mu^-$) provides lower limit on parameters space

Black lines: Various Higgs mass values

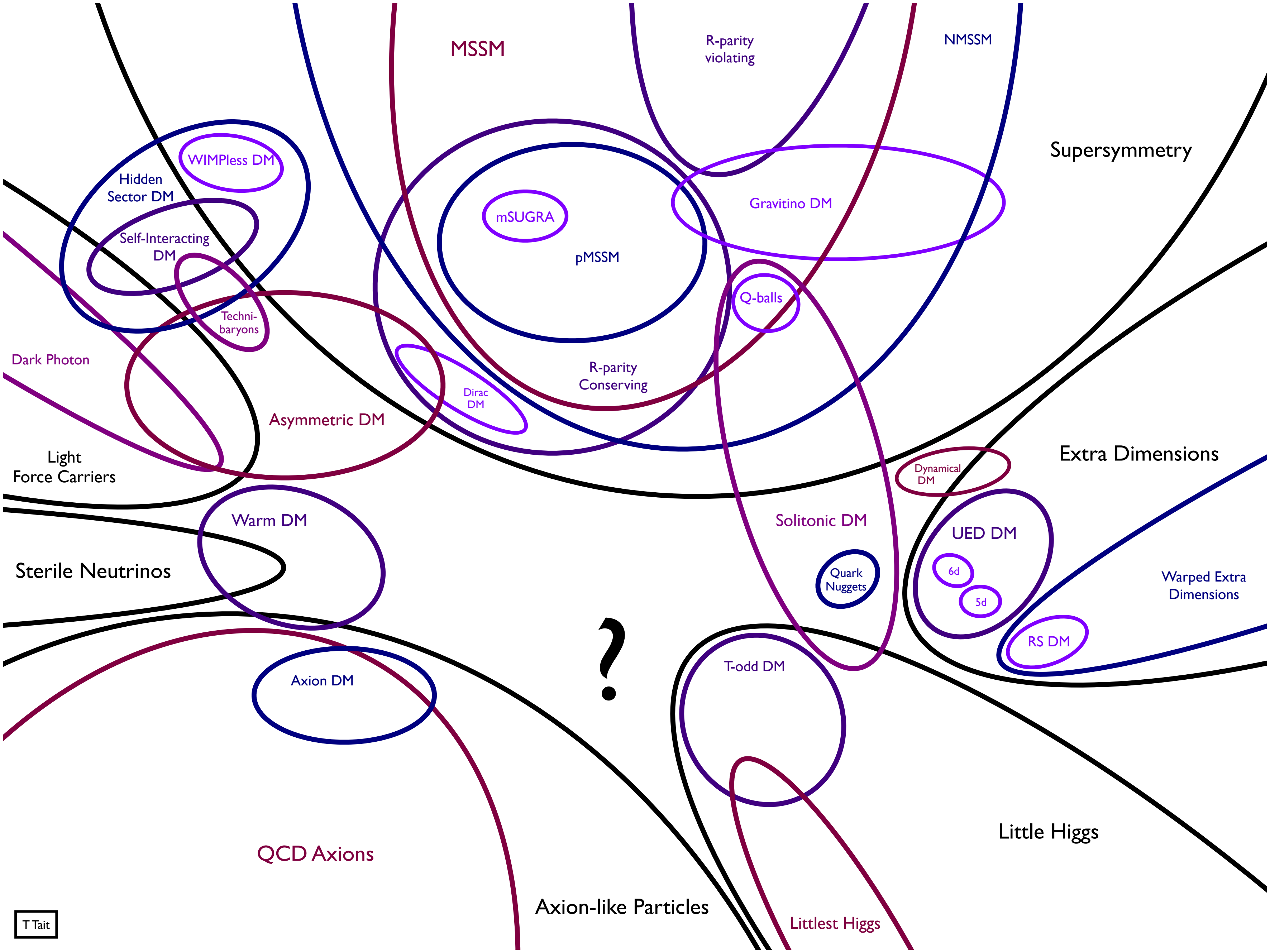


J. Ellis (2013)

Changes in $\tan\beta$ and A_0 affect $m_h \Rightarrow$ reduced compatibility with relic density

Very limited parameter space where LSP relic density can match DM density, complies with excluded regions, and provides acceptable Higgs mass. Cannot explain $g_\mu - 2$. Can release assumptions about SUSY (e.g. non-universal Higgs mass) at cost in elegance.

Shifting Paradigms: Beyond Supersymmetric Dark Matter



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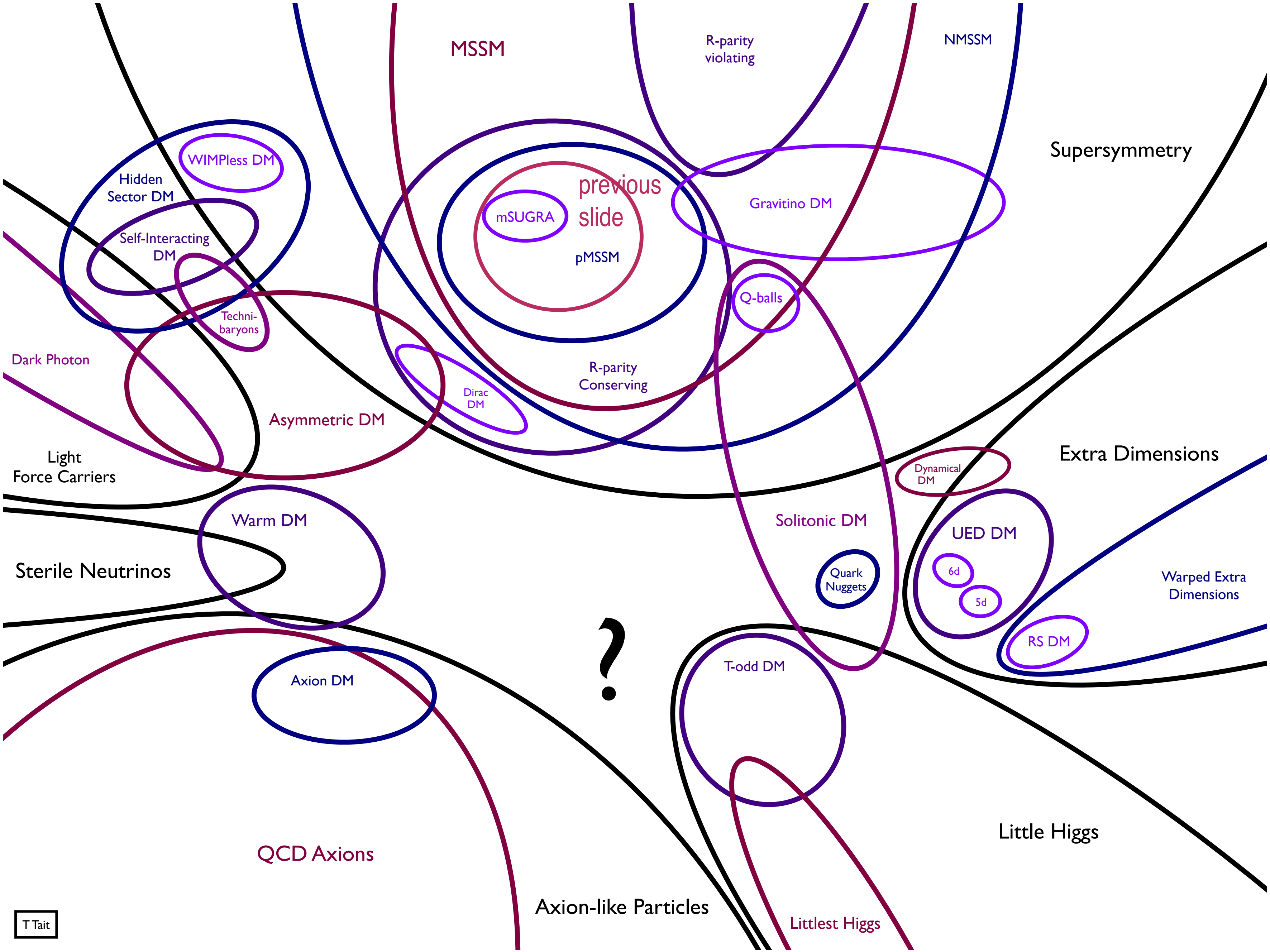
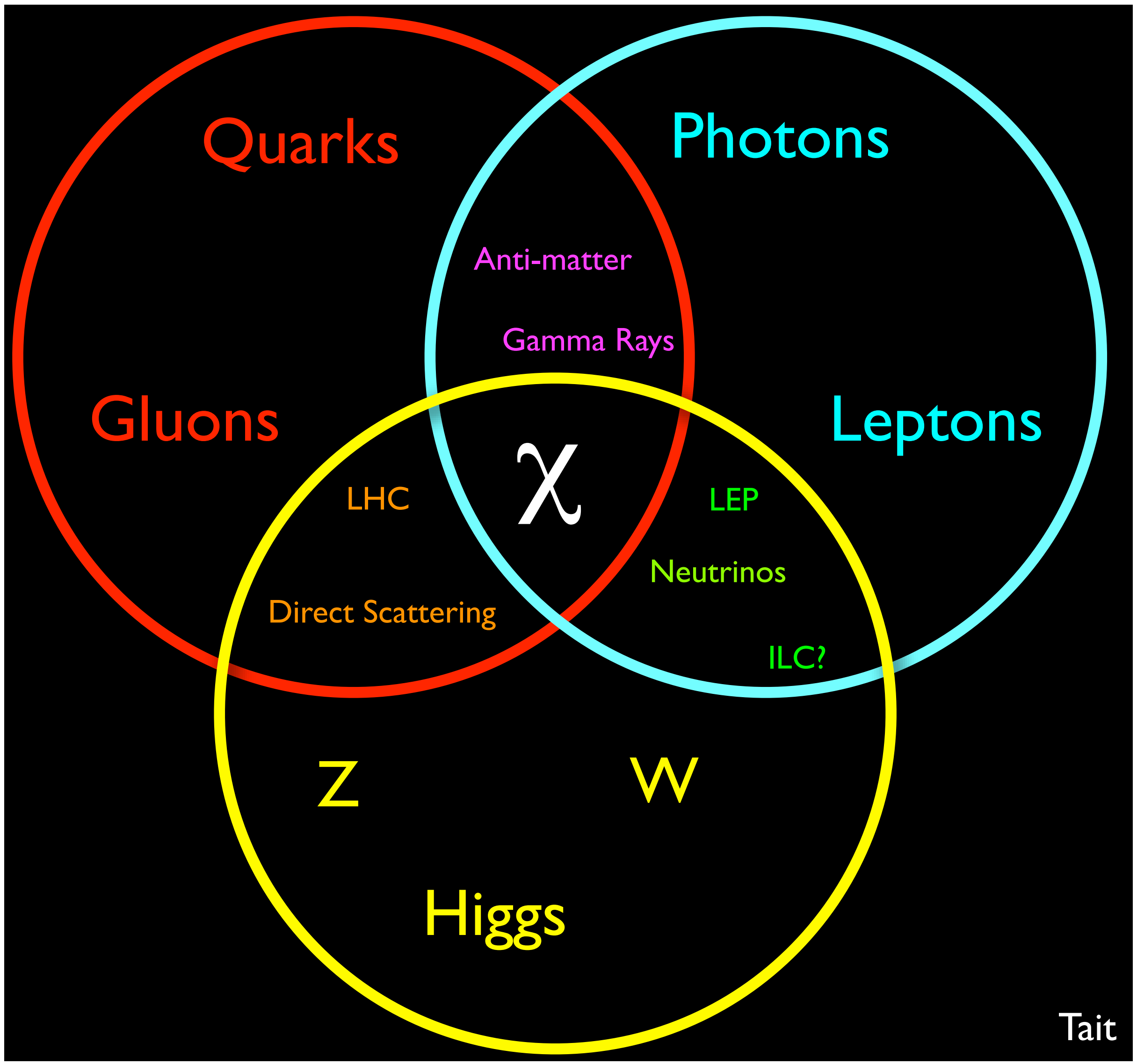


or, perhaps: A Phenomenological Approach to DM

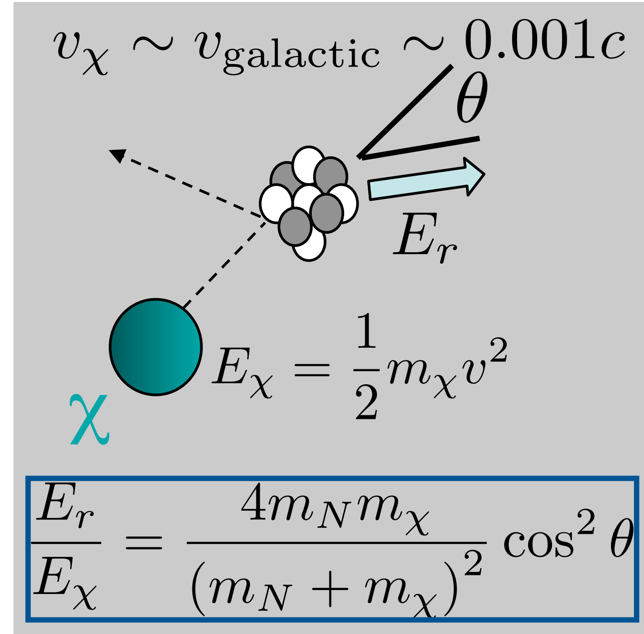
All possible interactions with χ need to be mapped out experimentally using all the tools we have available...

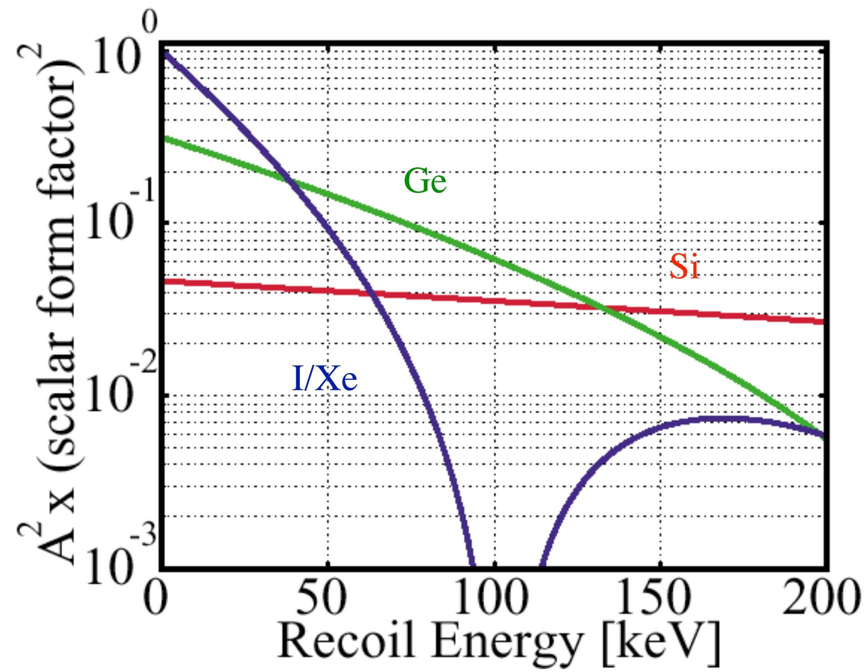


Interaction of Dark Matter with Normal Matter

The old paradigm

- In NR limit, all interactions reduce to spin-independent or spin-dependent couplings of WIMP to quarks
- Coherently sum over quarks in nucleon and nucleons in nucleus to obtain coupling proportional to A^2 or J^2
  - Large A and large J provide best sensitivity
- Billiard ball scattering of WIMP with nucleus: search constrains σ_{SI} and/or combinations of $\sigma_{SD,p}$ and $\sigma_{SD,n}$
- Scattering with nuclei much higher rate than scattering with electrons: *signature of WIMPs is nuclear recoils*
- Form factor describes breakdown of coherence: momentum transfer probes structure of larger nuclear at lower E_R than lighter nuclei

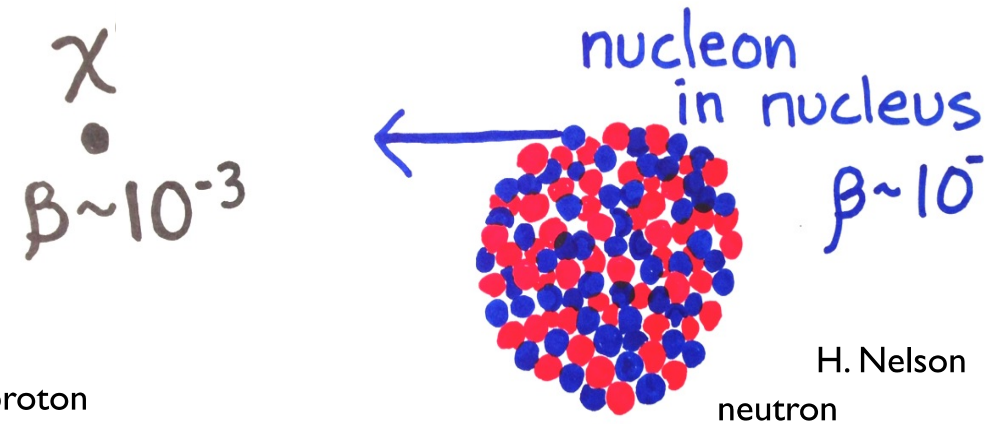


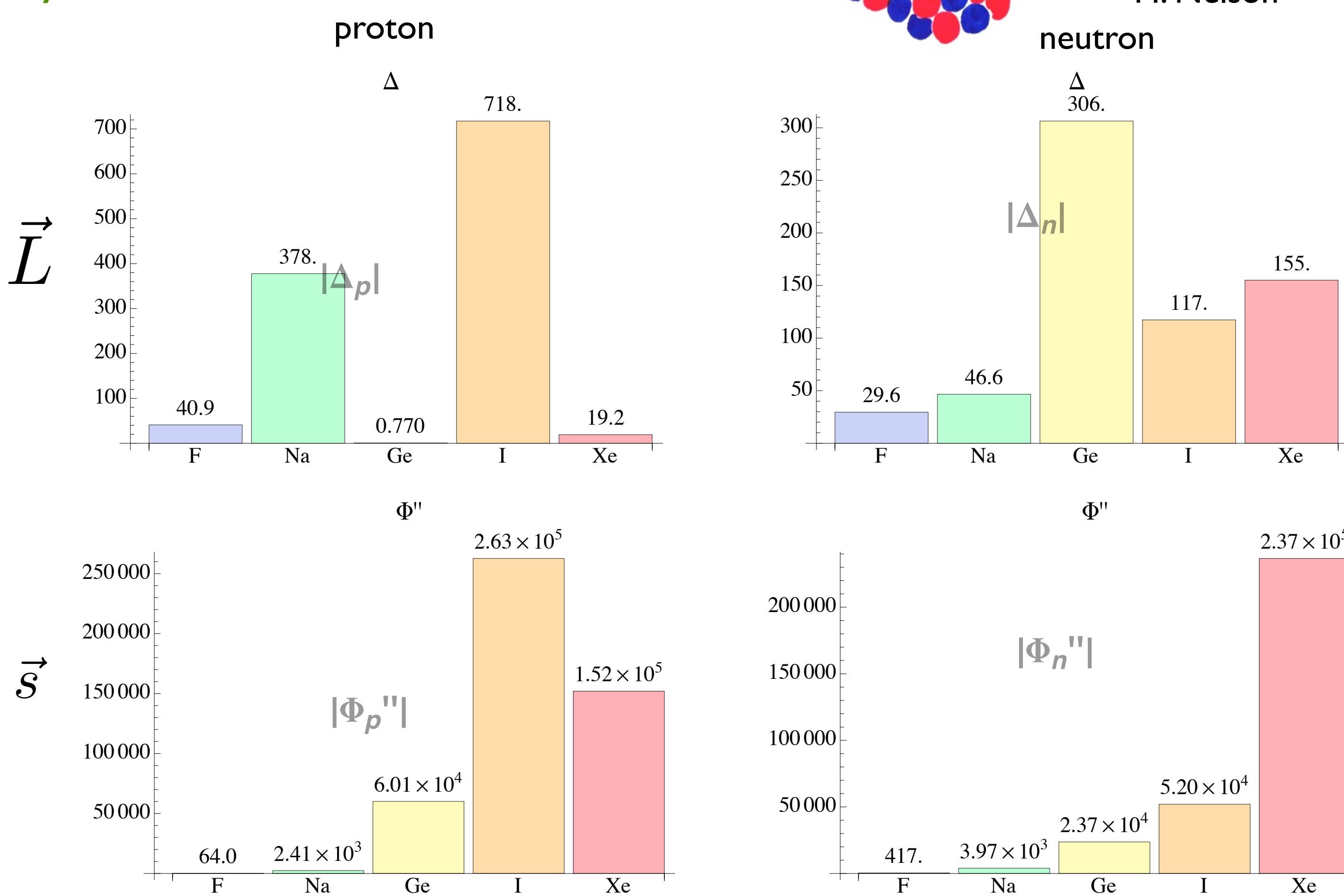


Interaction of Dark Matter with Normal Matter

The new paradigm

- NR limit not ok for nucleons!
- Fitzpatrick, Haxton, Katz, Lubbers, Xu 2013:
  - Generic effective theory
  - Need to consider much larger set of couplings to nucleons (8)
  - Orbital angular momentum of nucleons can be important
  - Changes nature of coherence
  - Surprising patterns
- Why not violate isospin?

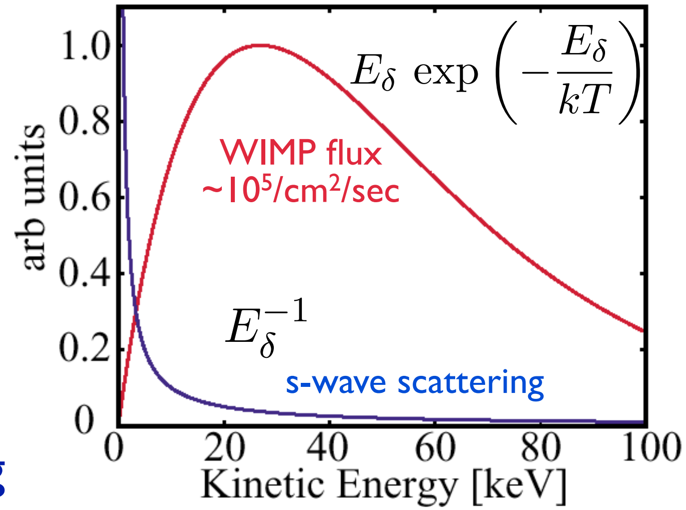


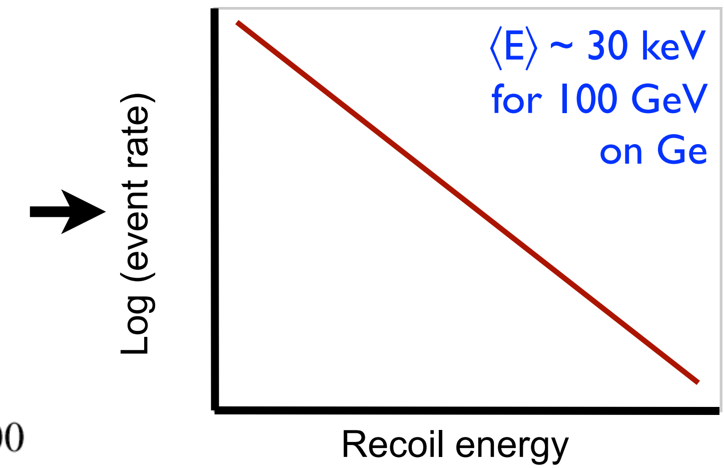


The Dark Matter "Beam" and Recoil Energy Spectrum

The old paradigm

- Maxwell-Boltzmann halo
- v_c = 220 km/s
- σ_v = 270 km/s
- v_{esc} = 544 km/s
- flux × s-wave scattering → exponential recoil energy spectrum





The new paradigm (c.f. first half of afternoon)

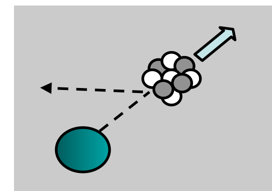
- Deviations from Maxwell-Boltzmann (Green 2011):
  - excess particles at low speeds
  - lower, flatter peak
  - circular velocity does match most likely speed: v_c/v_0 ~ 0.85
- Imperfect relaxation
  - Clumpiness, spikes in phase space due to tidal streams
- Dark disk?

Signal Characteristics

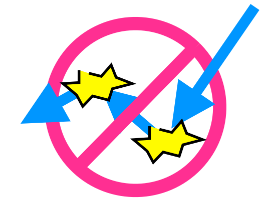
Event-by-event characteristics:

- Nuclear recoils ~ keV to tens of keV
- Single-scatter

EVENT-BY-EVENT



Nuclear recoils

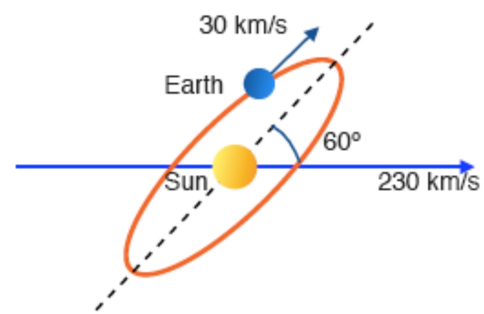


No multiplicity

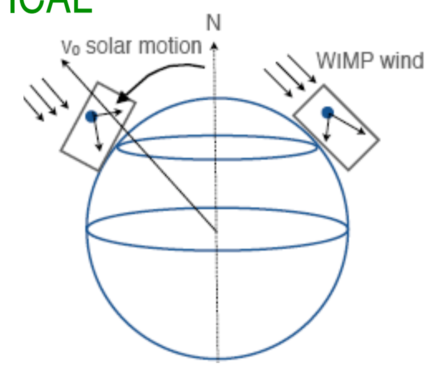
Statistical properties: modulation by WIMP beam kinematics

- Annual modulation:
  - few % addition/subtraction from Sun's velocity
- Diurnal modulation:
  - O(unity) variation in recoil direction with time of day

STATISTICAL



Annual flux modulation



Diurnal direction modulation

Backgrounds

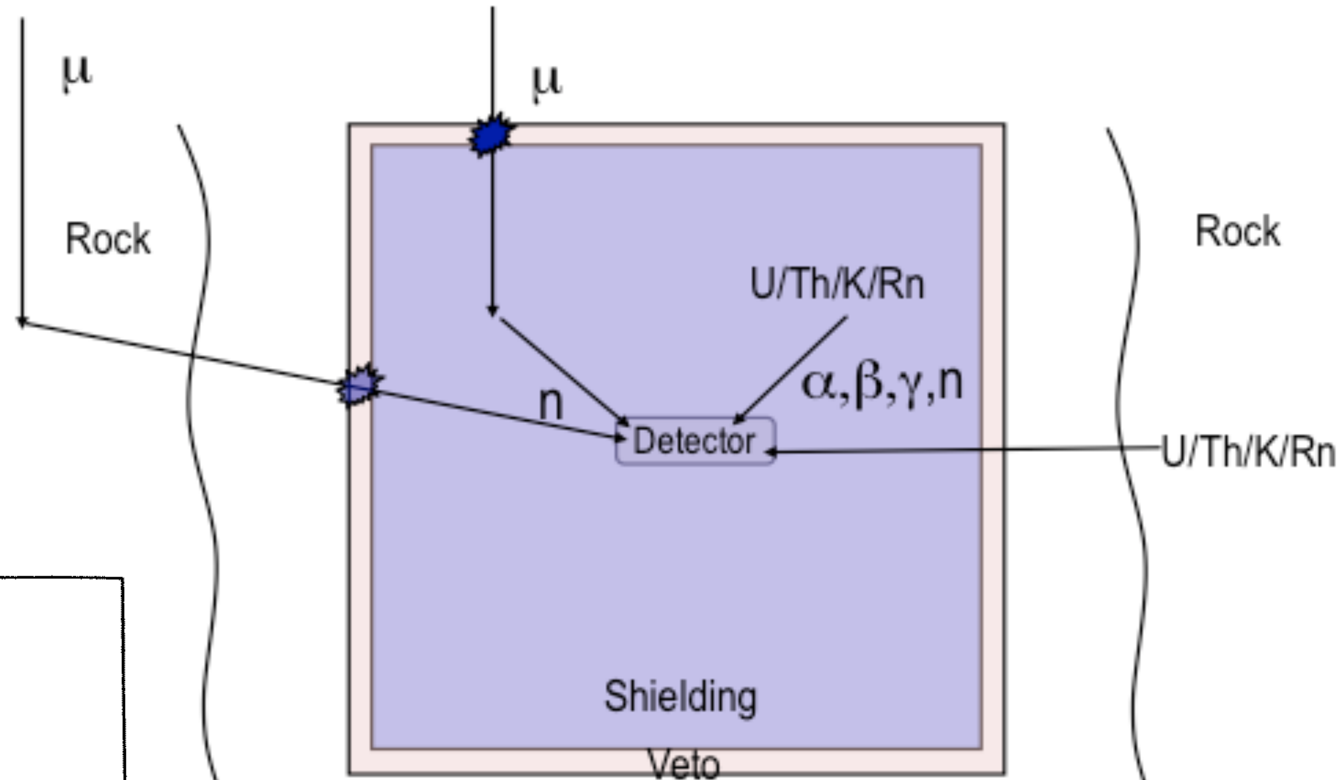
Particle types:

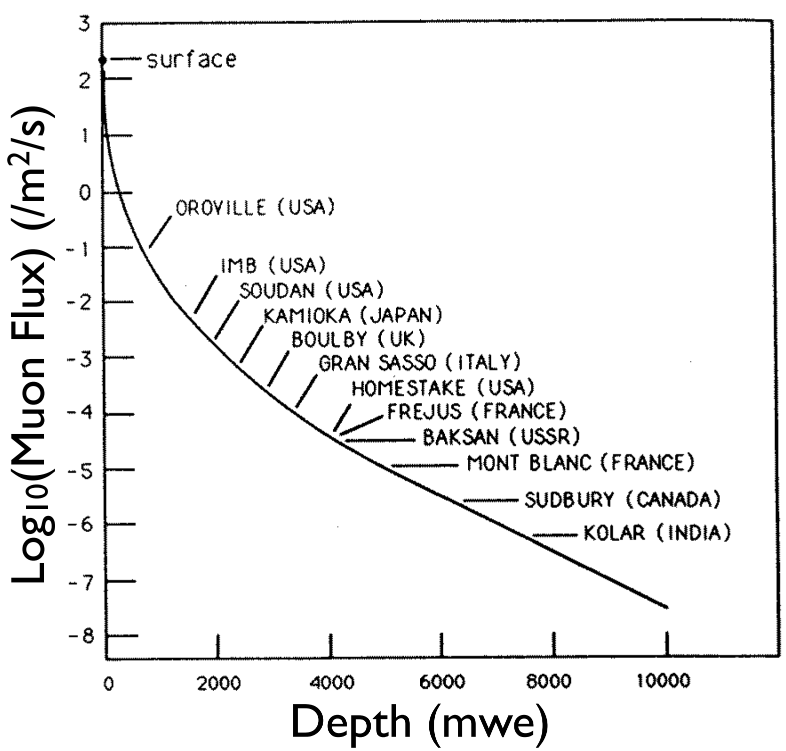
α, β, γ, n

Source:

radiogenic

cosmogenic





Parent location:

in the target

on the surface

on nearby surfaces

in surrounding materials

Backgrounds

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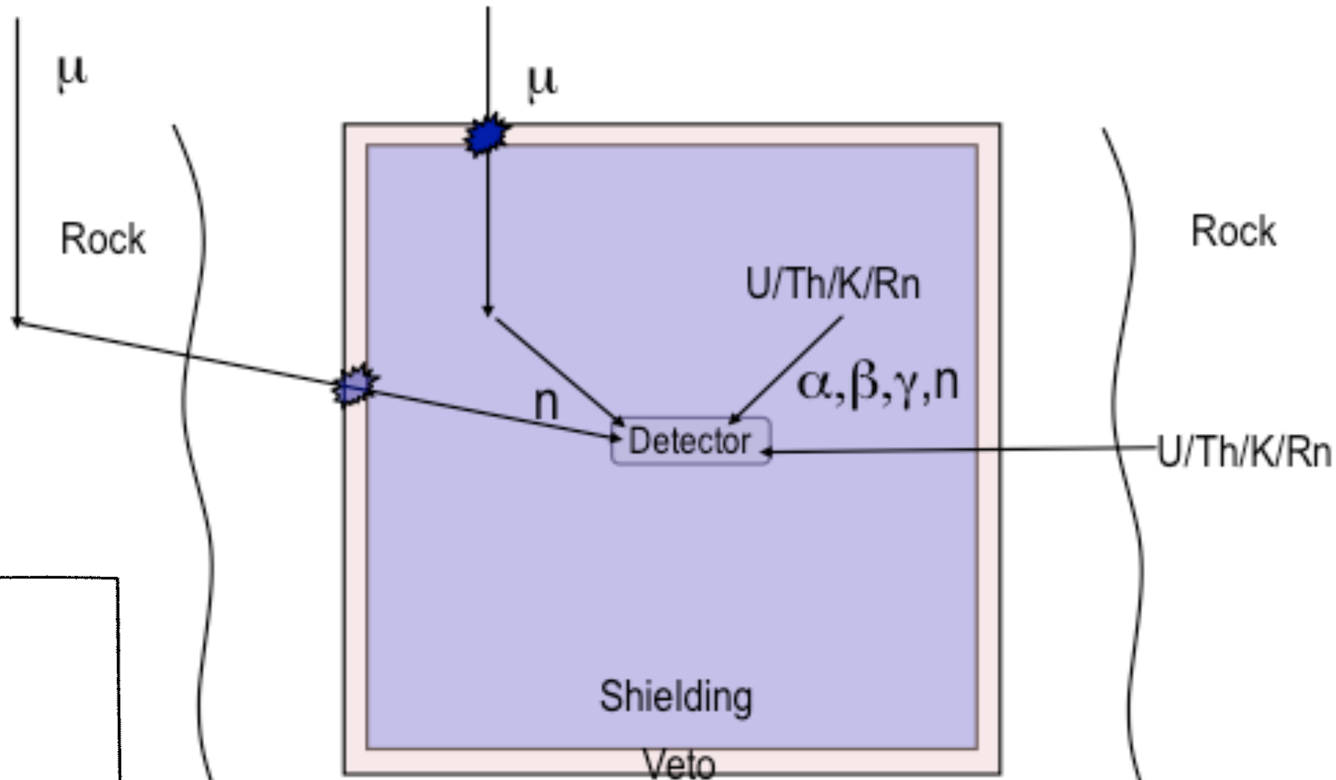

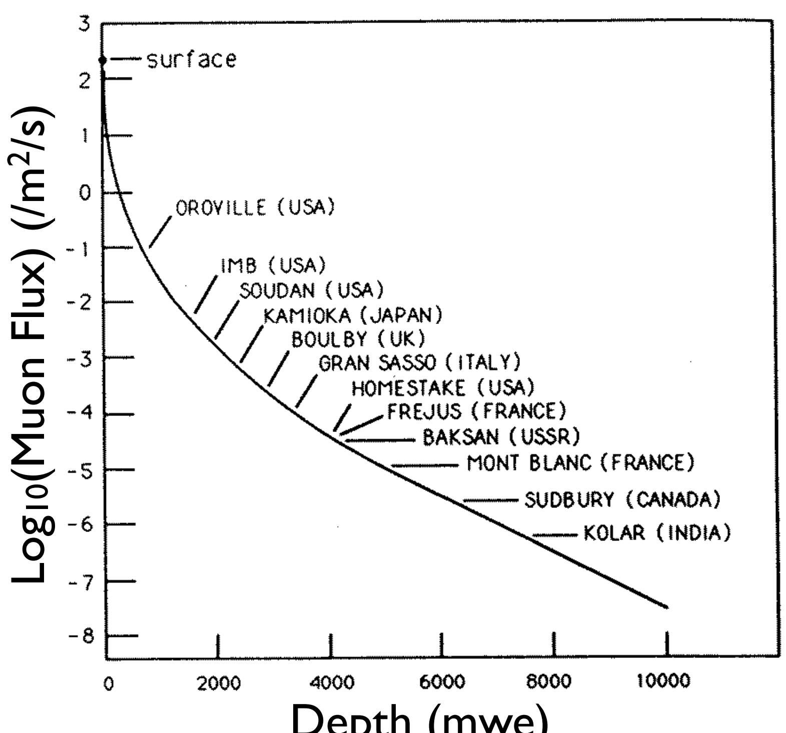

Parent location:

in the target

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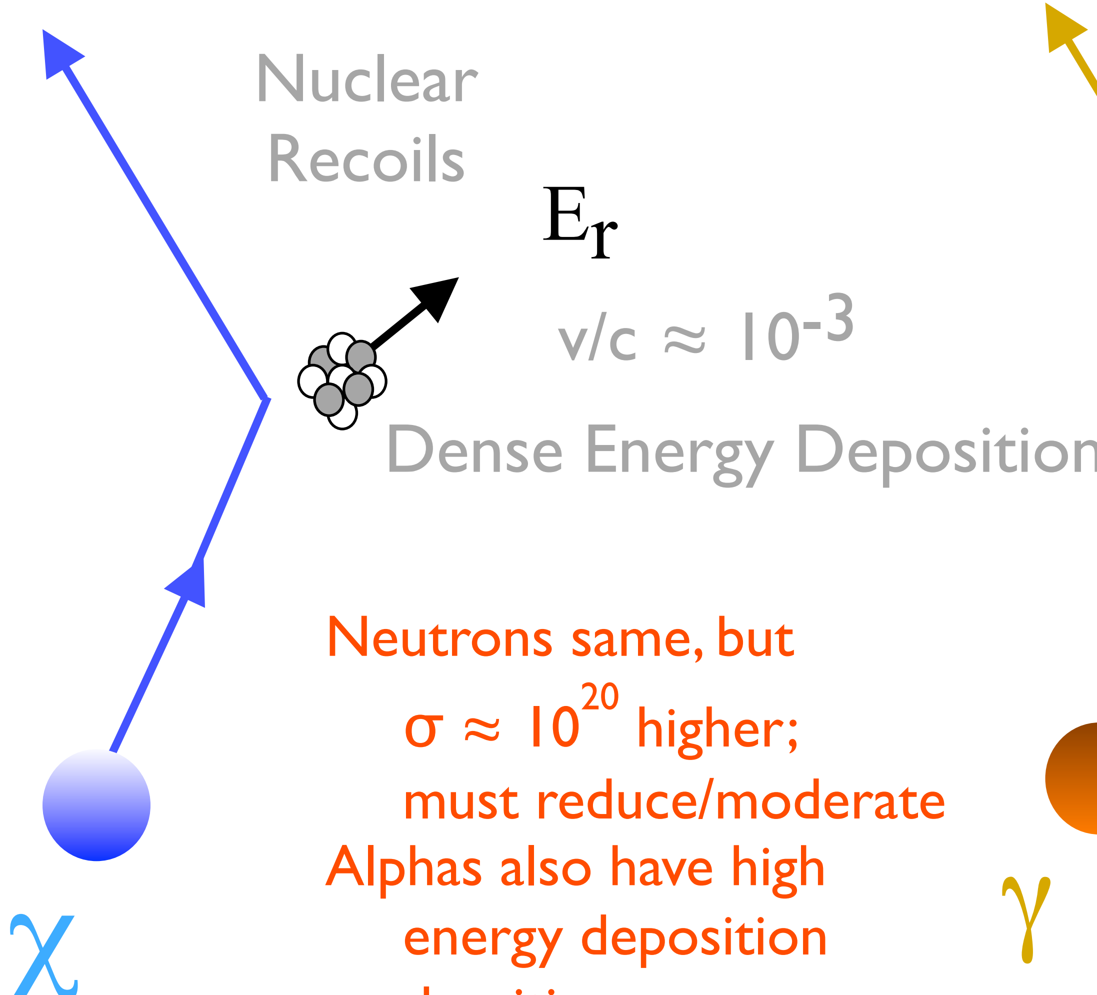
in surrounding materials

<u>+ eventually, the ultimate background:</u>
coherent nuclear scattering of solar, atmospheric, and diffuse supernova bgnd neutrinos. Irreducible!

Nuclear Recoil Discrimination

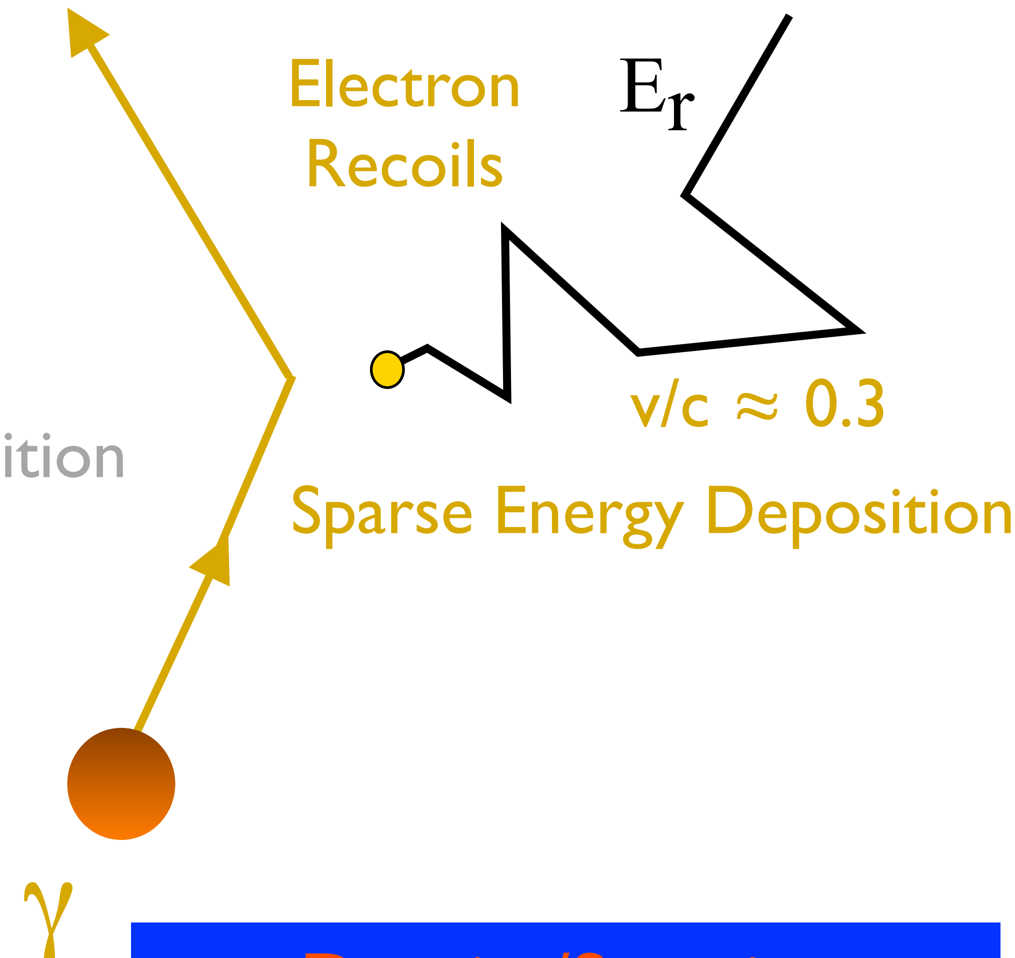
Signal



Neutrons same, but
$\sigma \approx 10^{20}$ higher;
must reduce/moderate

Alphas also have high
energy deposition
densities

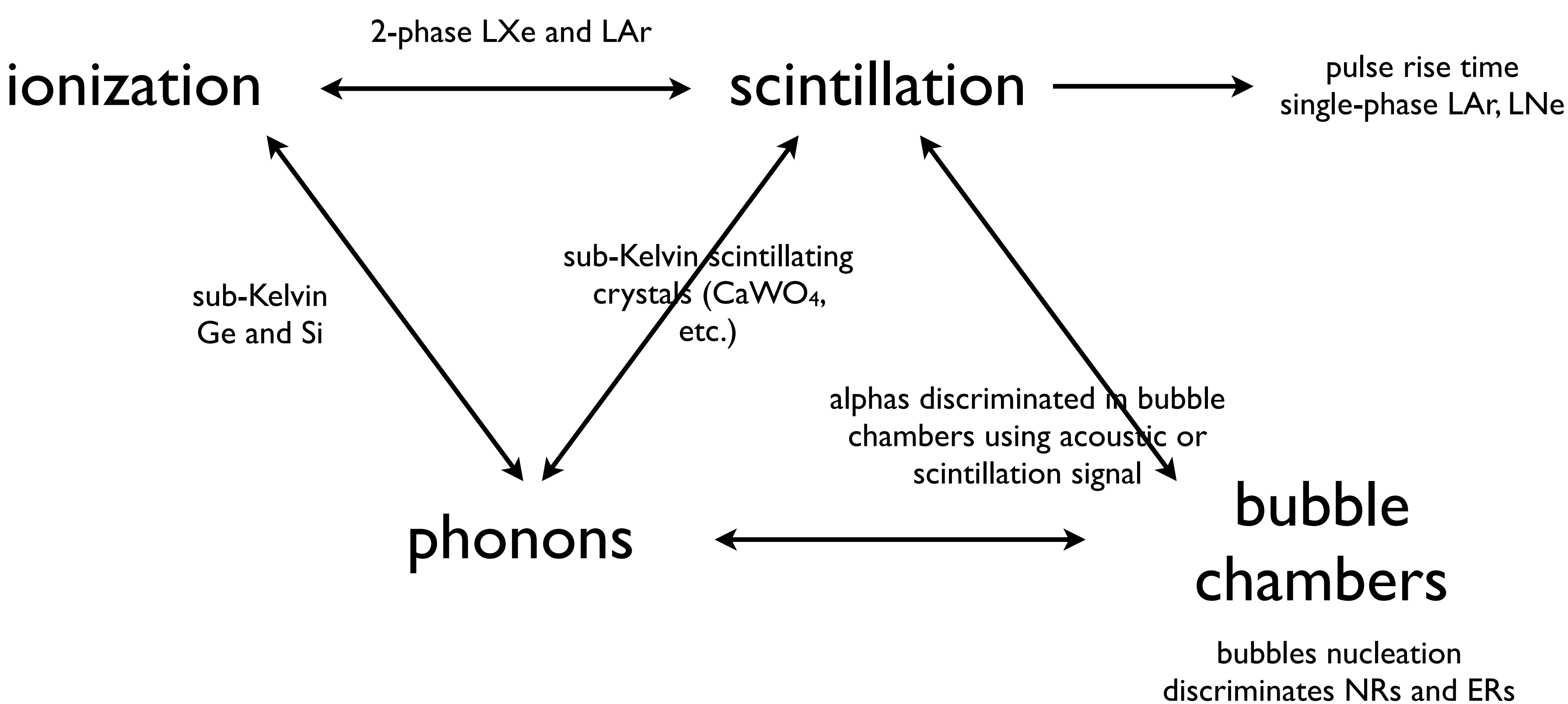
Background



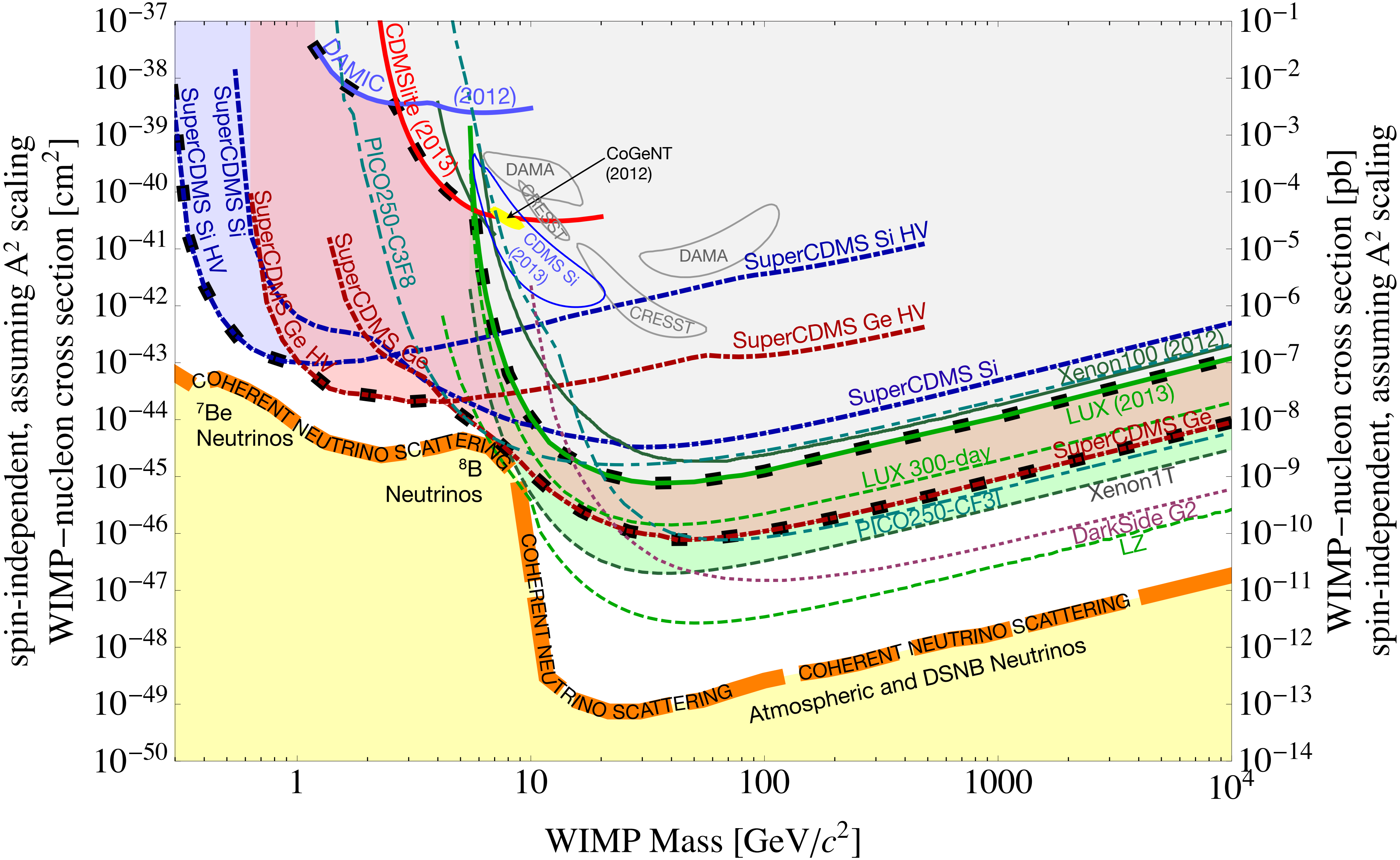
Density/Sparsity:
Basis of Discrimination

Discrimination Techniques

Need sensitivity to energy deposition characteristics (density, energy) to discriminate nuclear recoils (NRs), electron recoils (ERs), and alphas



Where We Are, Where We Are Going



Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

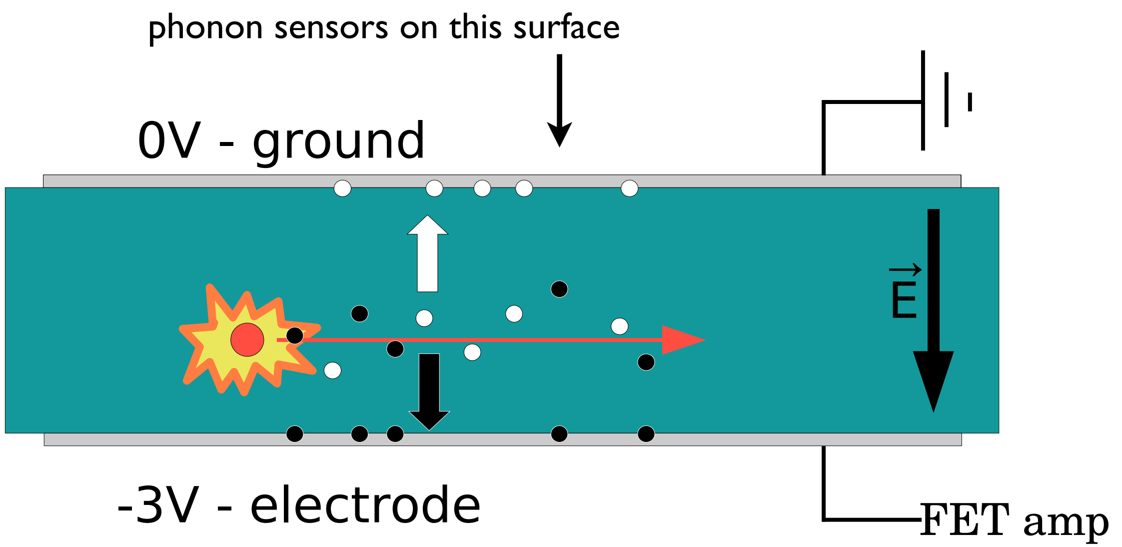
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

- sophisticated electrode structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor promises phonon asymmetry discrimination
- measure ionization only using phonons with high field: new sensitivity to low mass



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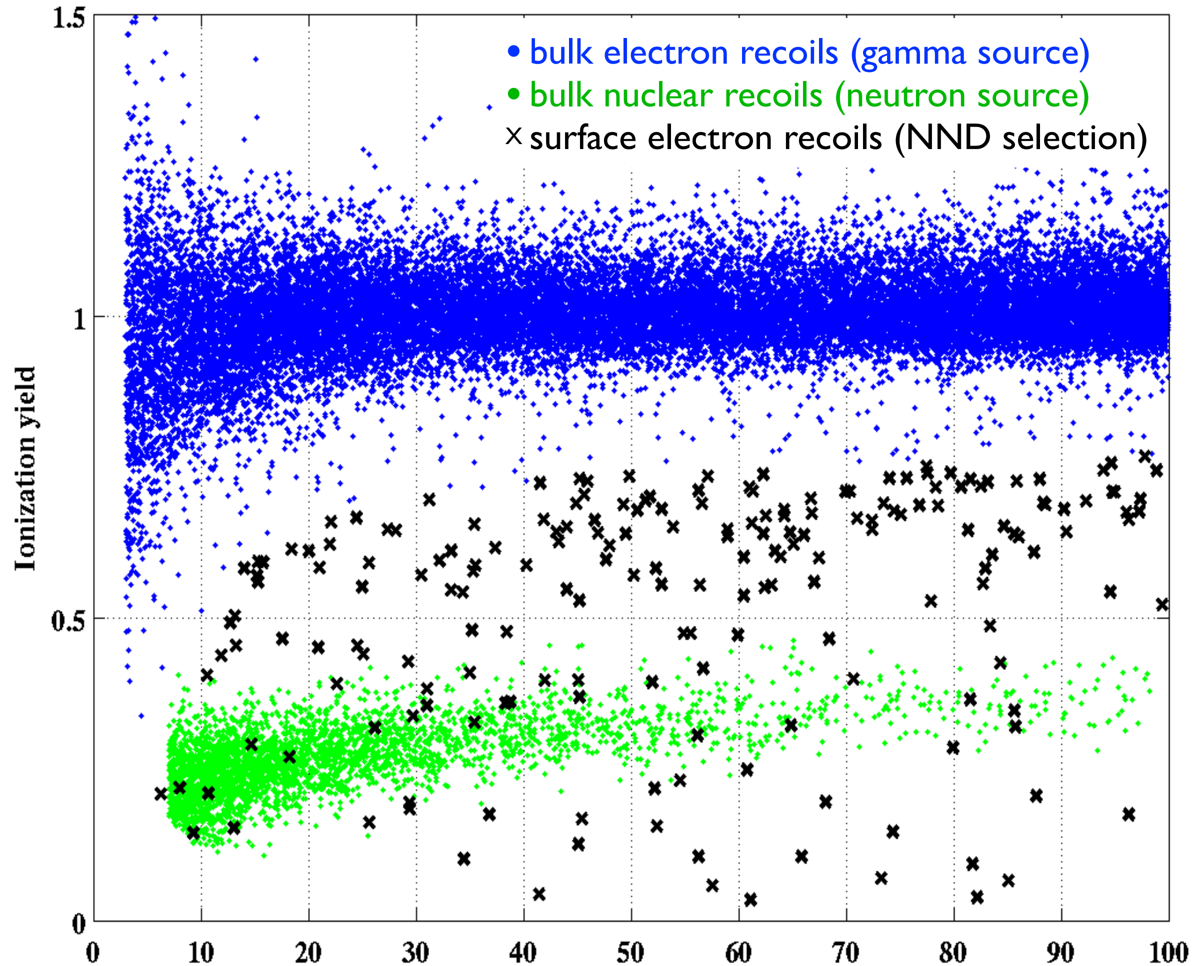

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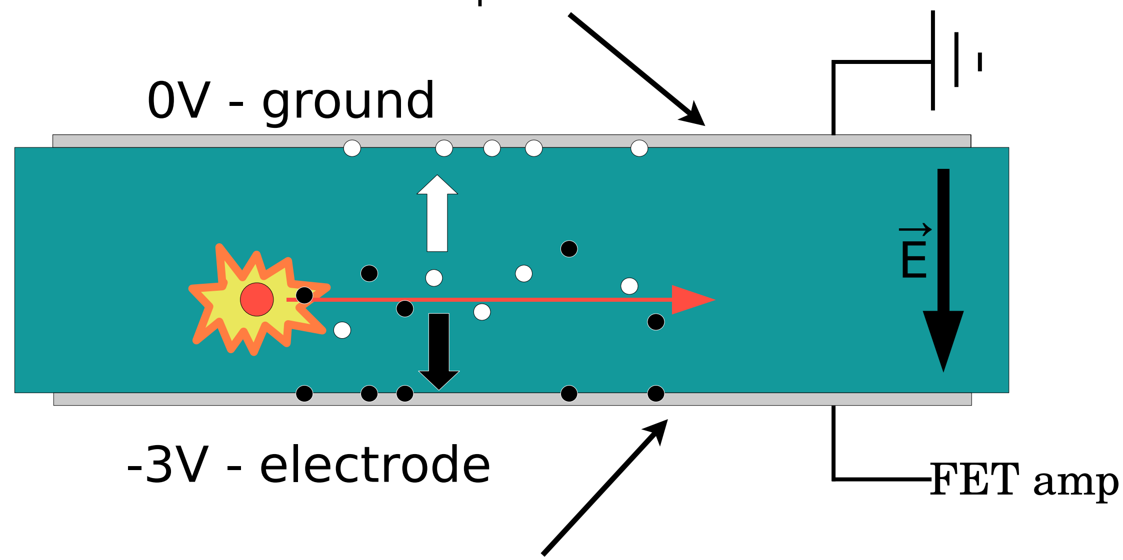

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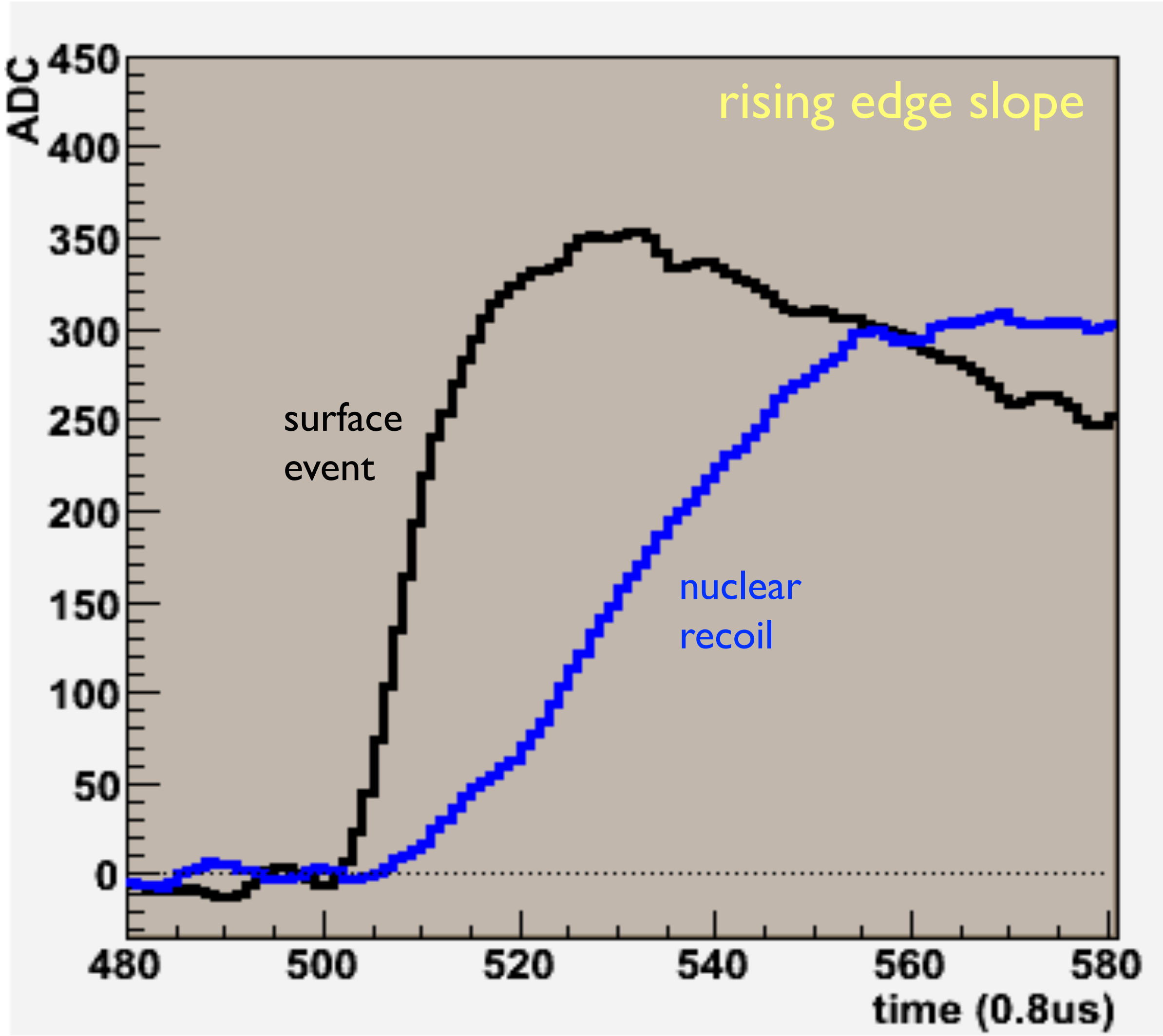

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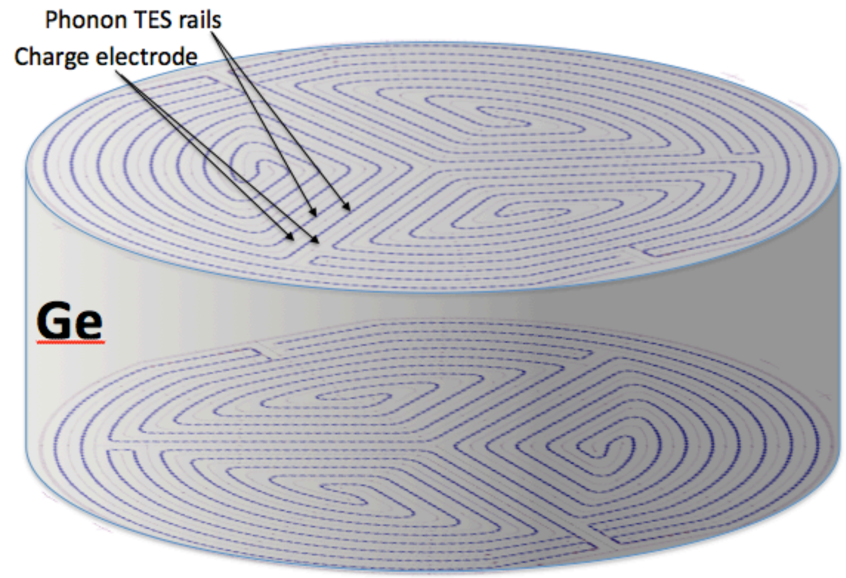

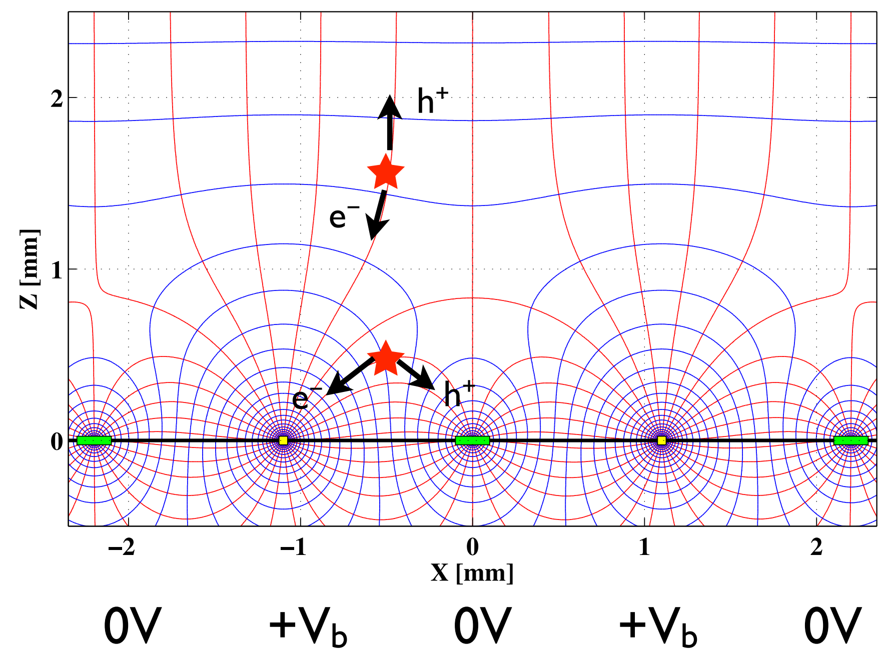

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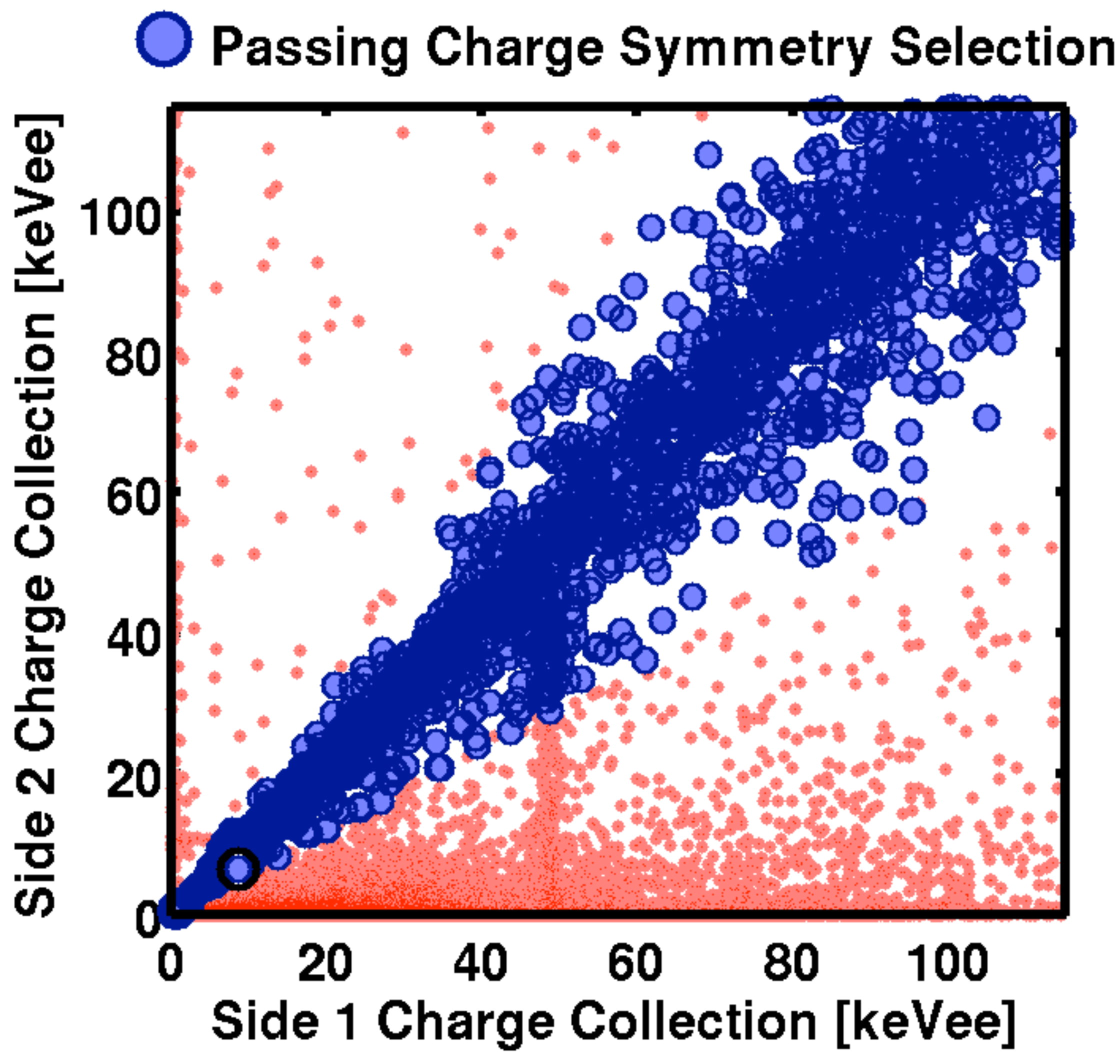

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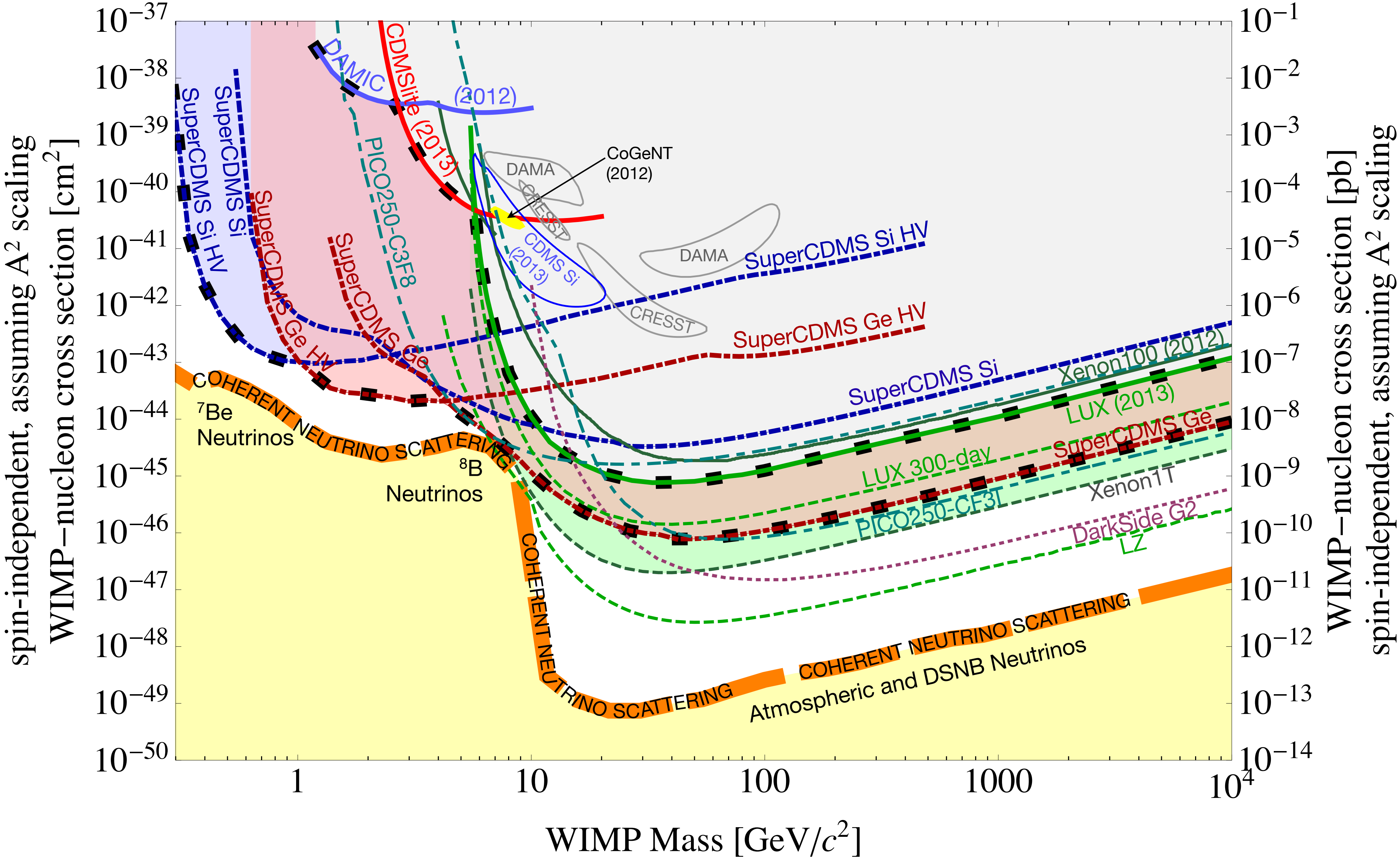

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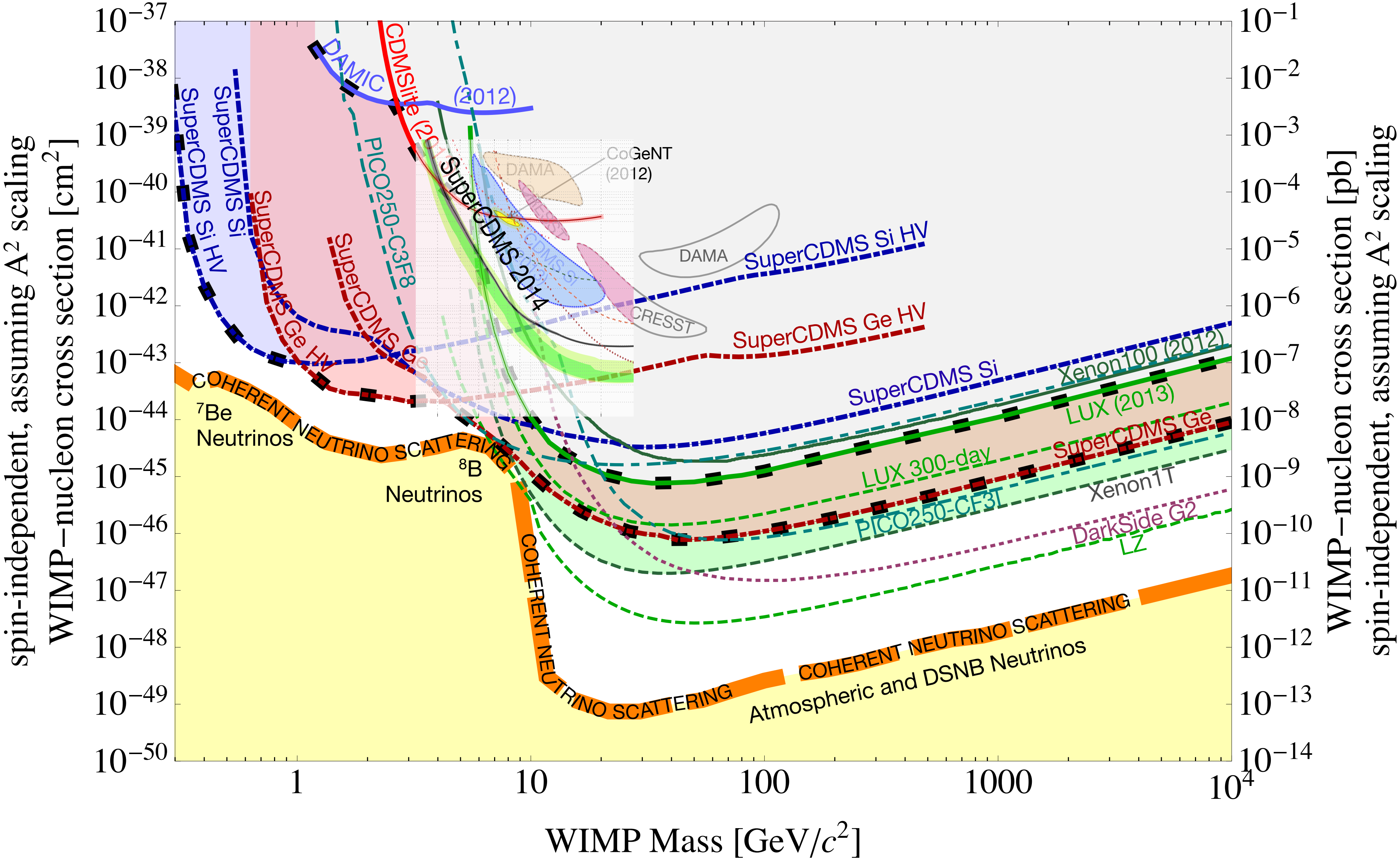

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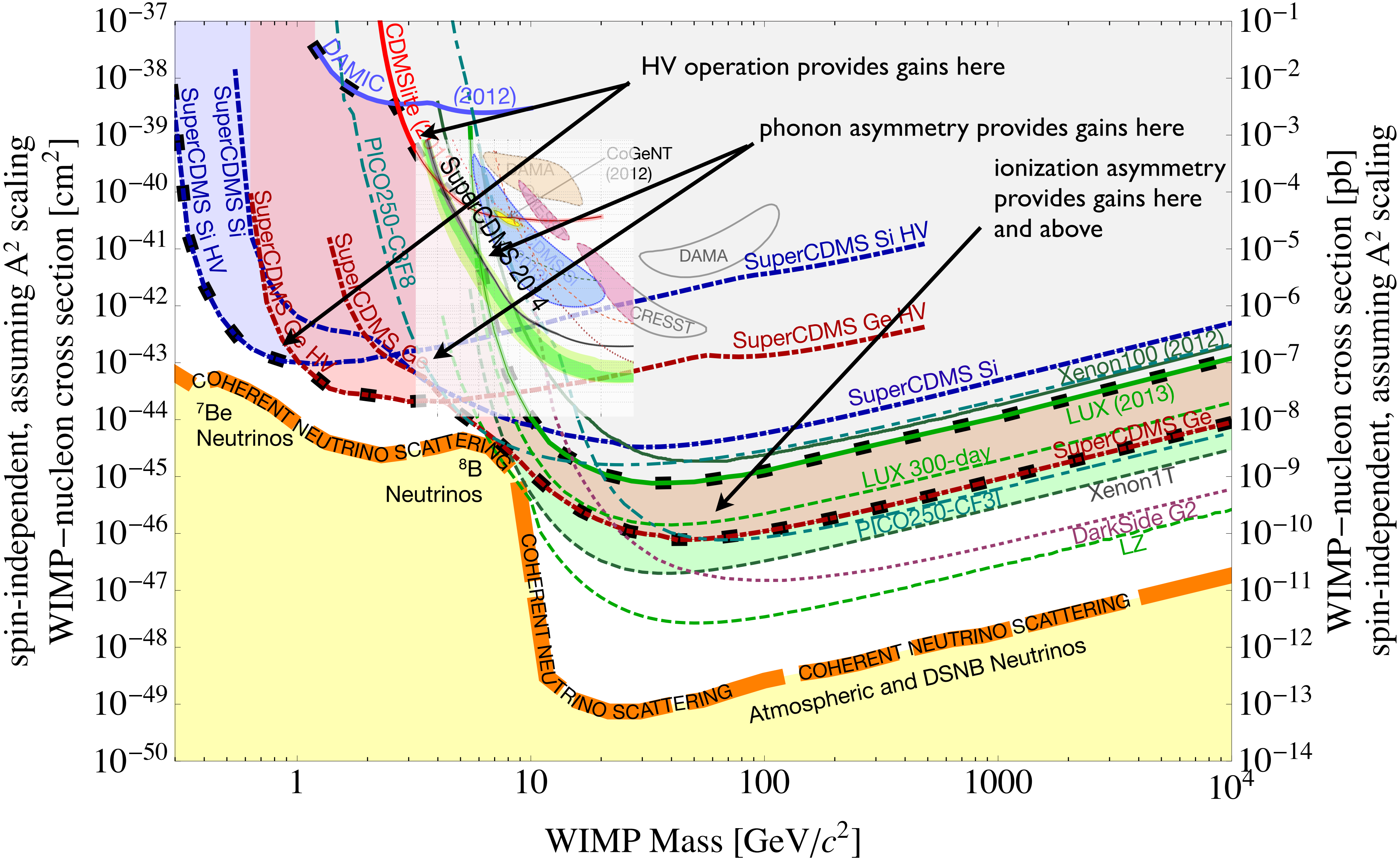
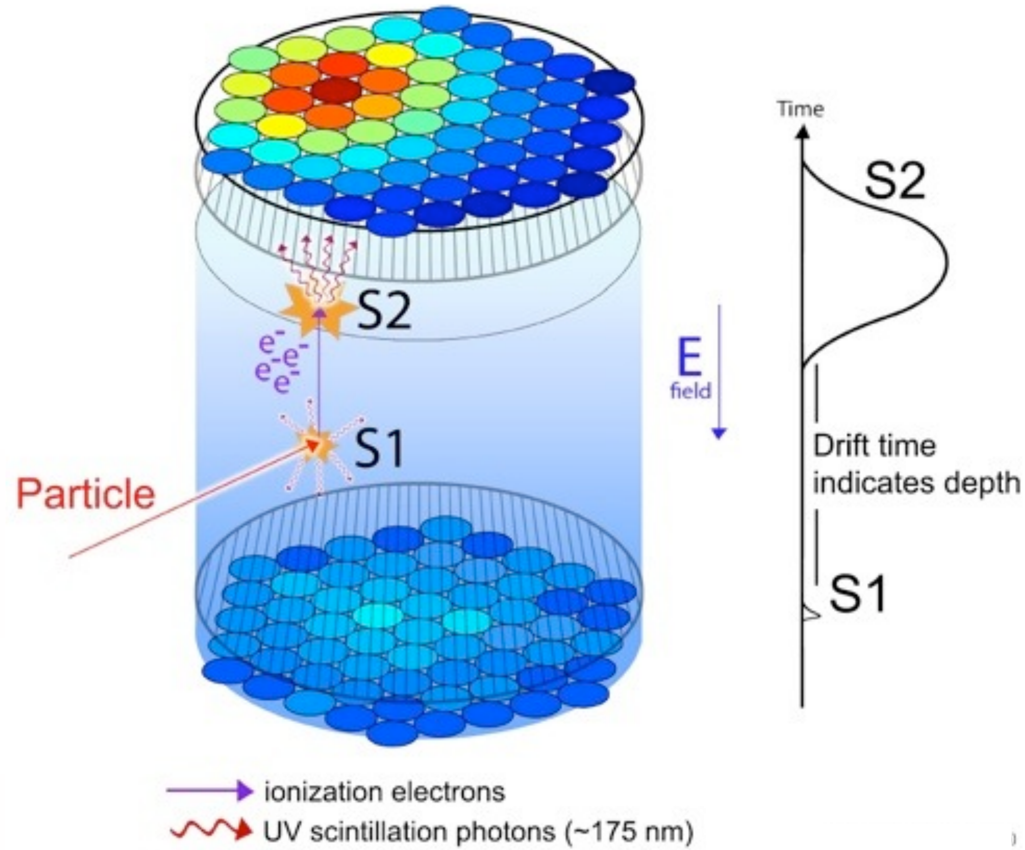


Innovation in Techniques: 2-Phase Liquid Nobles

2-Phase Liquid Nobles

- Multiple realizations ~ 2000
  - scintillation/ionization (S1/S2) discriminates NRs from ERs in LXe, LAr
  - scintillation (S1) rise time discriminates NRs from ERs in LAr (and LNe)
  - LXe has no worrisome isotopes and is highly purifiable
    - primarily Kr, Rn, and e-attaching impurities to be worried about
- Around 2005
  - Self-shielding could make up for limited ER rejection (99%-99.9%) of LXe
  - Light collection key to LXe low-mass sensitivity
  - Underground Ar could provide LAr low in ^{39}Ar beta decay



Very successful program thanks to these innovations:

- LXe: XENON100, LUX have best limits at high mass; XENON1T to commission this year
- LAr: DArkSide 50 recently completed atmospheric Ar commissioning run
- Multi-ton experiments proposed
- Single-phase (S1 only) LAr close to starting to take data (MiniCLEAN, DEAP-3600)

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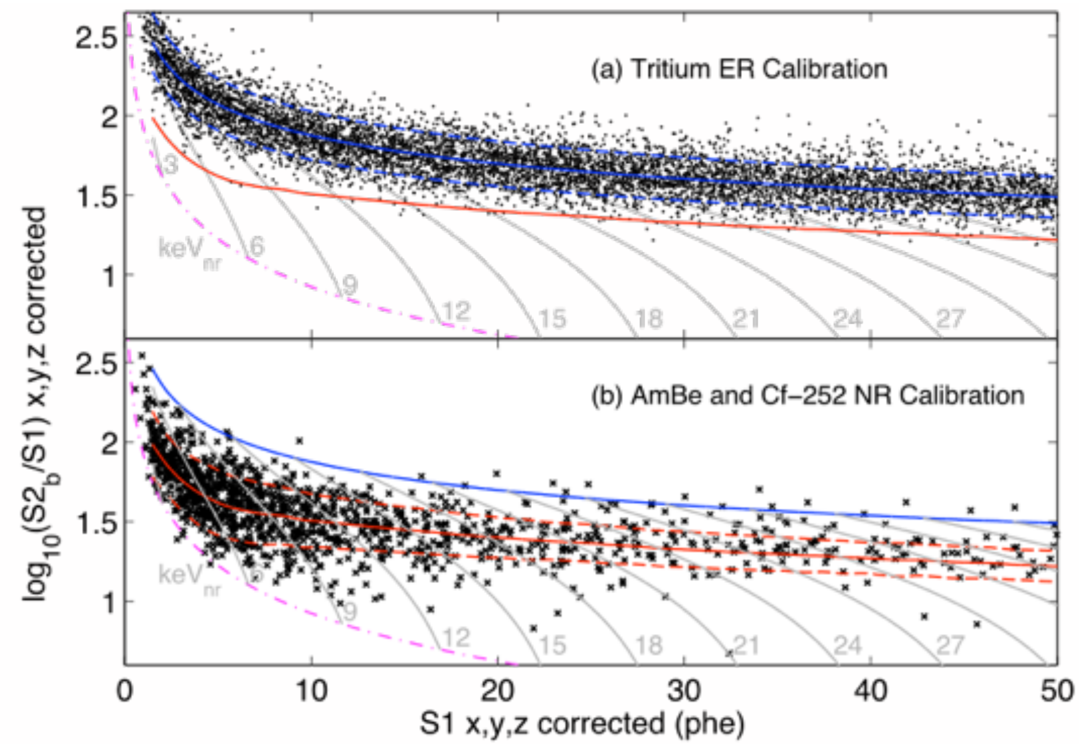

Very successful program thanks to these innovations:

- LXe: XENON100, LUX have best limits at high mass; XENON1T to commission this year
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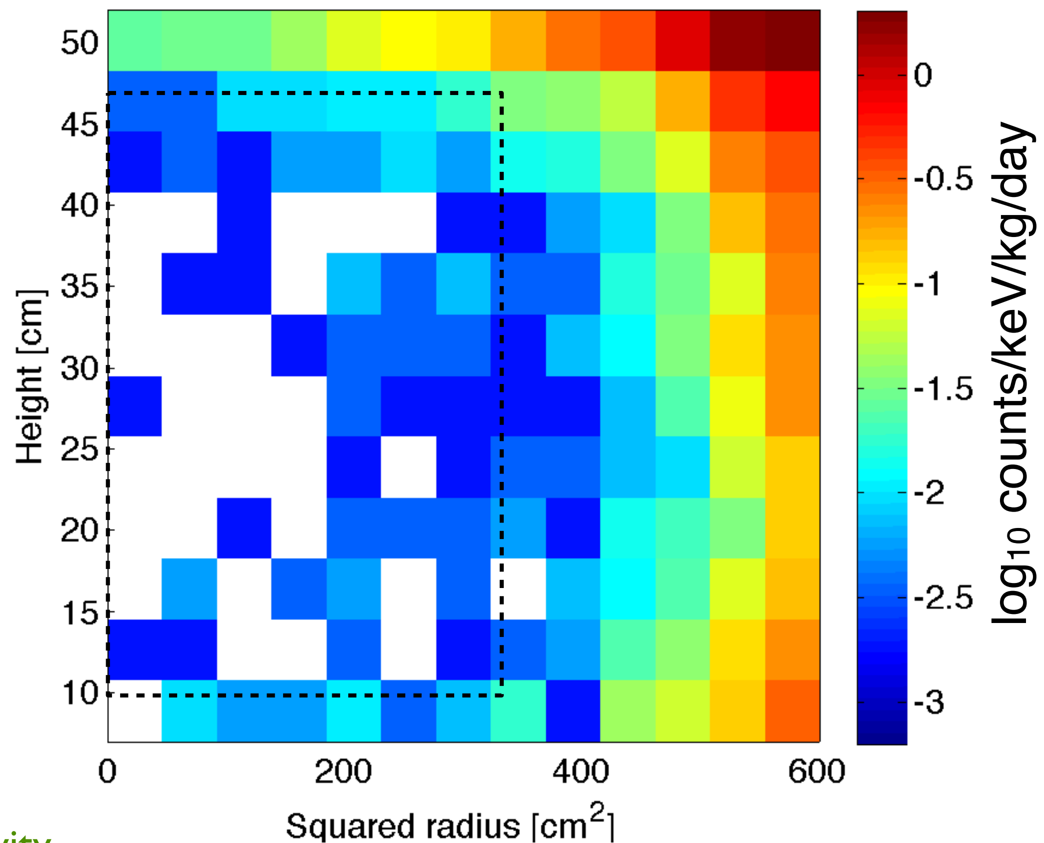
Innovation in Techniques: 2-Phase Liquid Nobles



2-Phase Liquid Nobles

- Multiple realizations ~ 2000
  - scintillation/ionization (S1/S2) discriminates NRs from ERs in LXe, LAr
  - scintillation (S1) rise time discriminates NRs from ERs in LAr (and LNe)
  - LXe has no worrisome isotopes and is highly purifiable
    - primarily Kr, Rn, and e-attaching impurities to be worried about
- Around 2005
  - Self-shielding could make up for limited ER rejection (99%-99.9%) of LXe
  - Light collection key to LXe low-mass sensitivity
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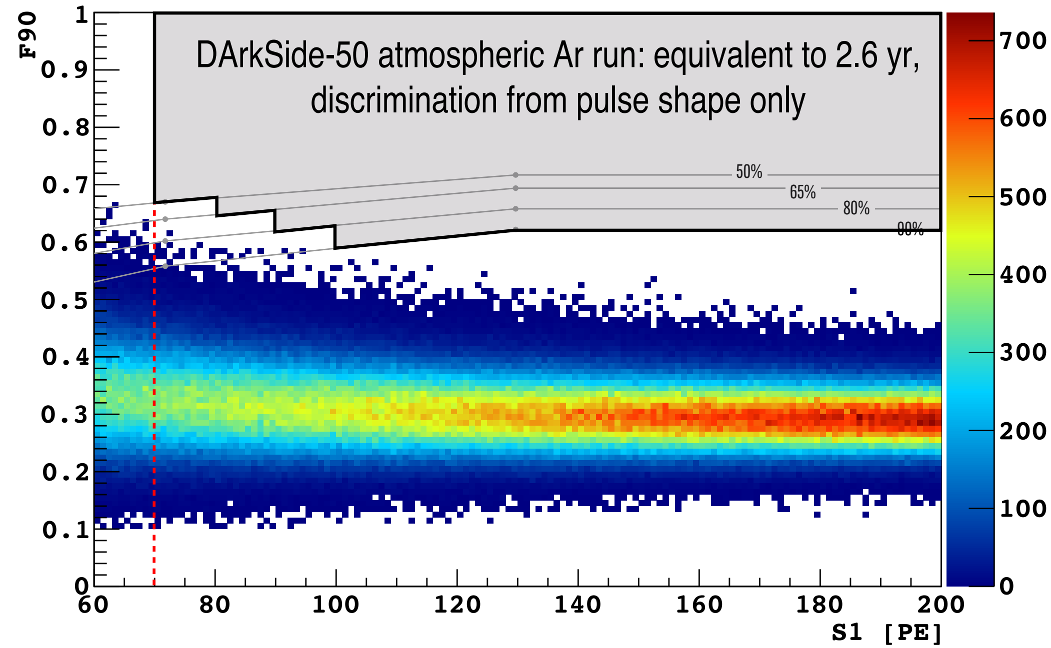

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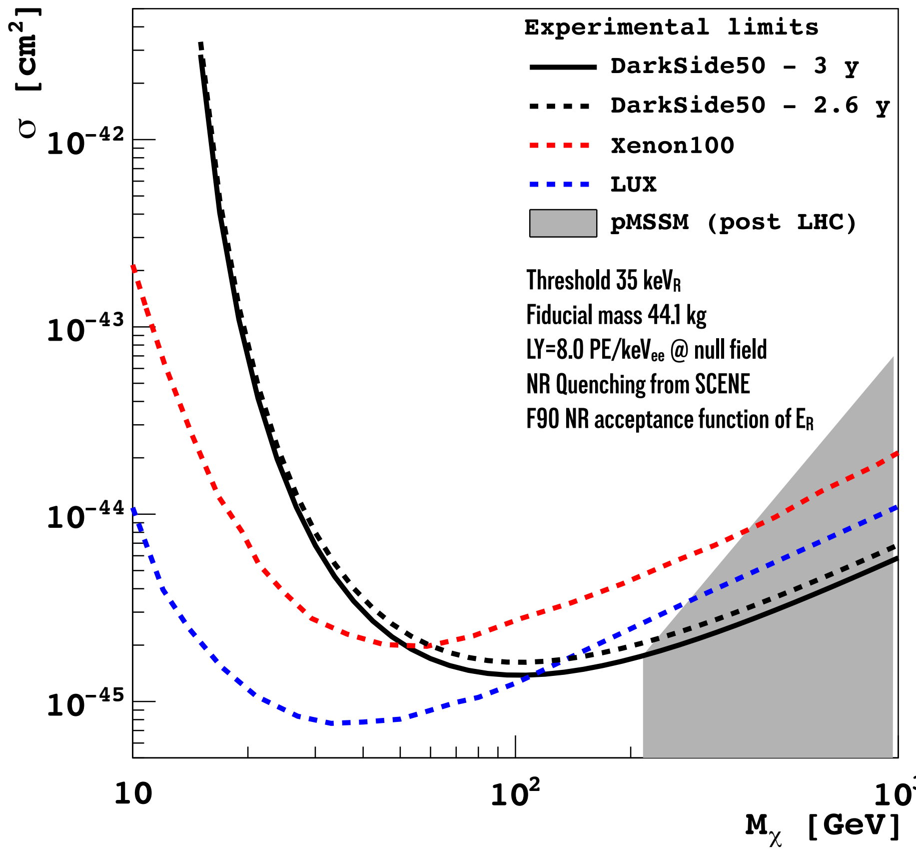

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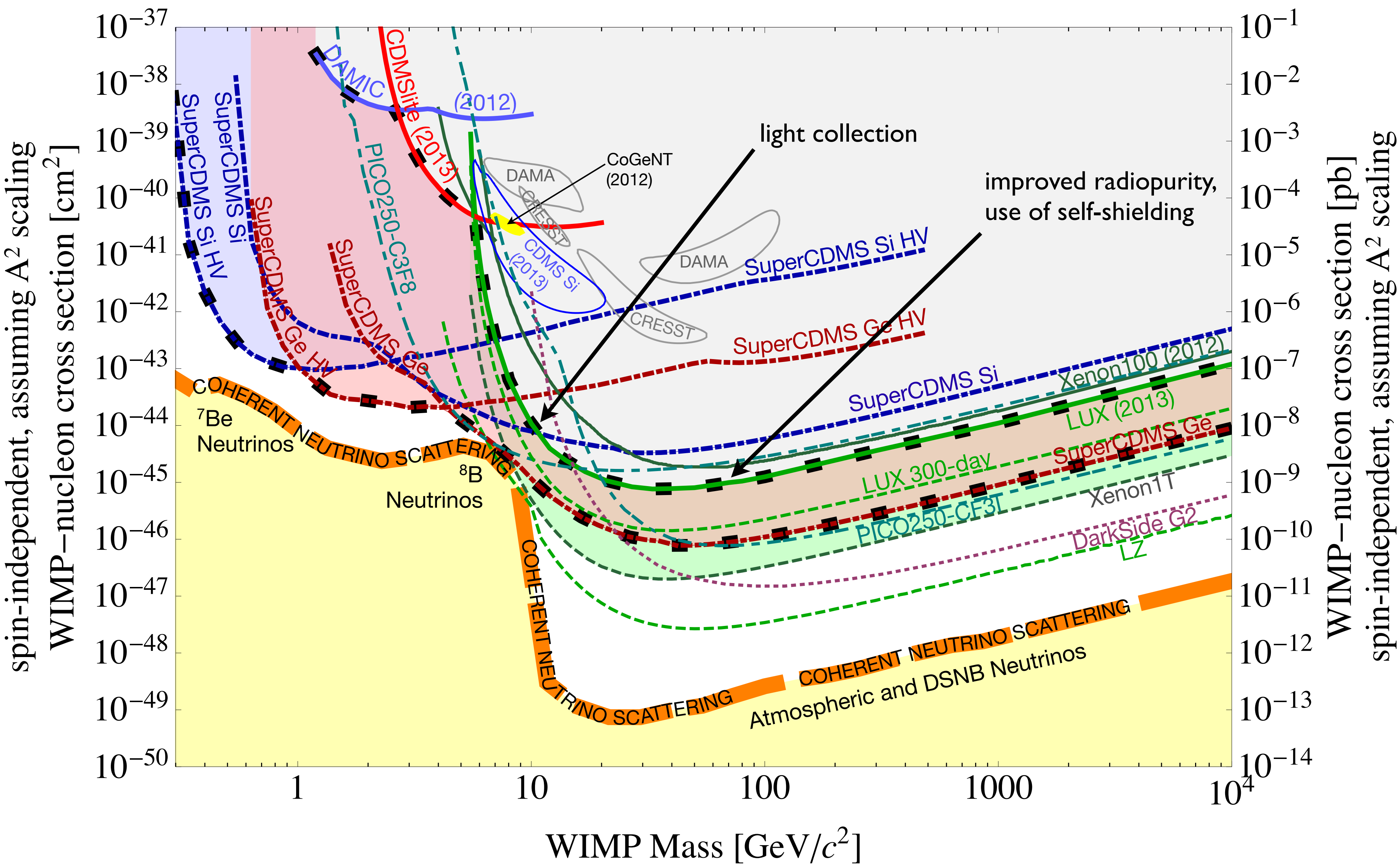
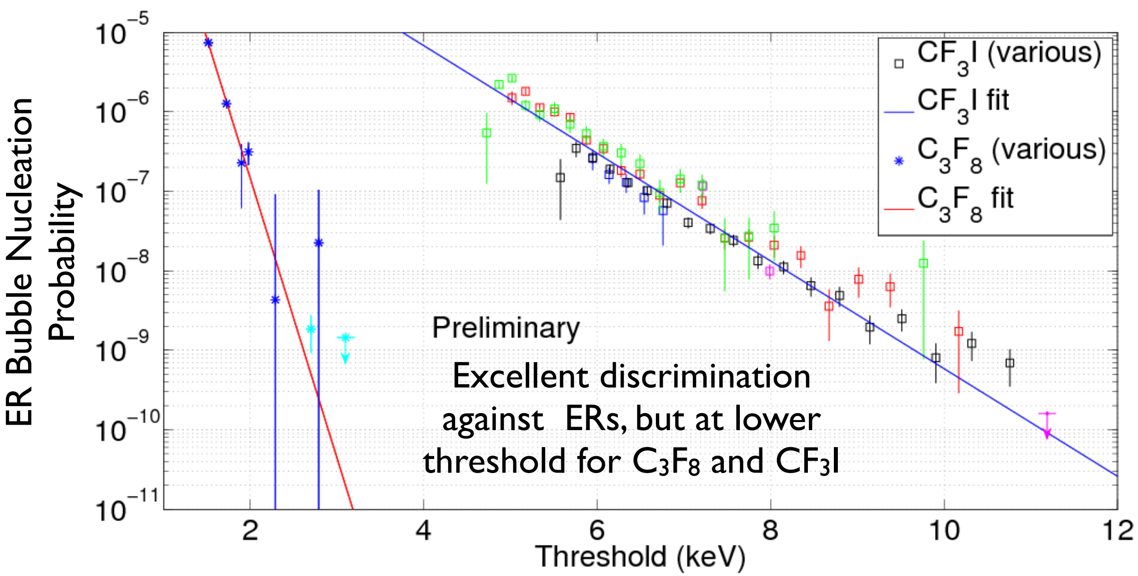


Innovation in Techniques: Bubble Chambers

Bubble Chambers

Classic Seitz bubble theory gave incredible discrimination against ERs



But: alphas from Rn contamination

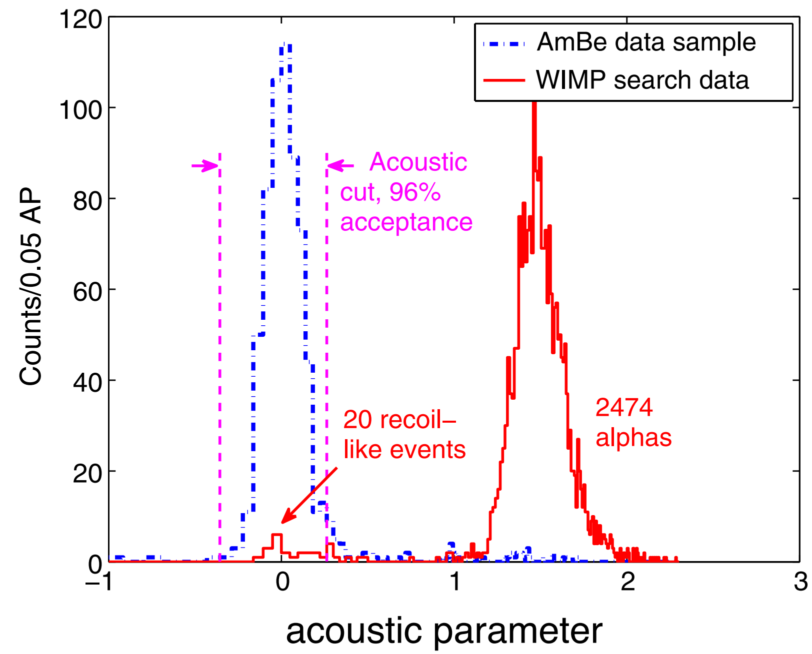
→ acoustic measurements discriminate alphas

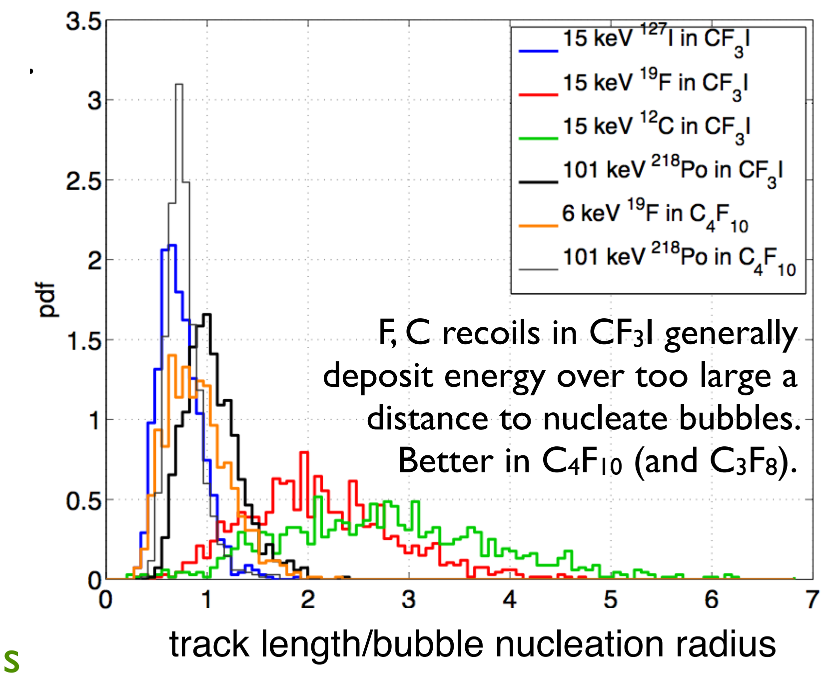
Higher threshold, poorer F (and C) recoil efficiency than desired in CF_3I

→ develop C_3F_8

No energy information

Develop bubble chambers with scintillating materials





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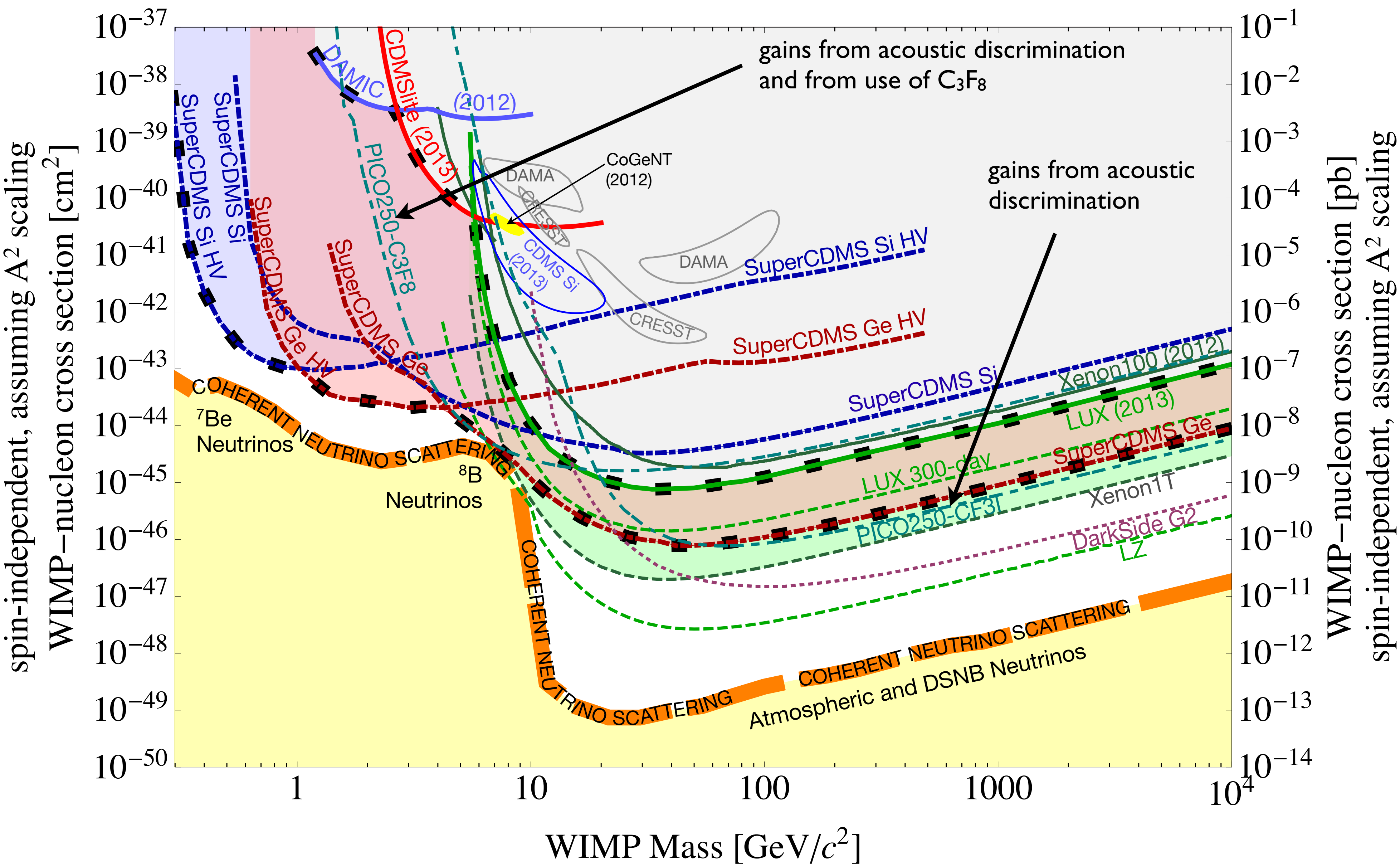
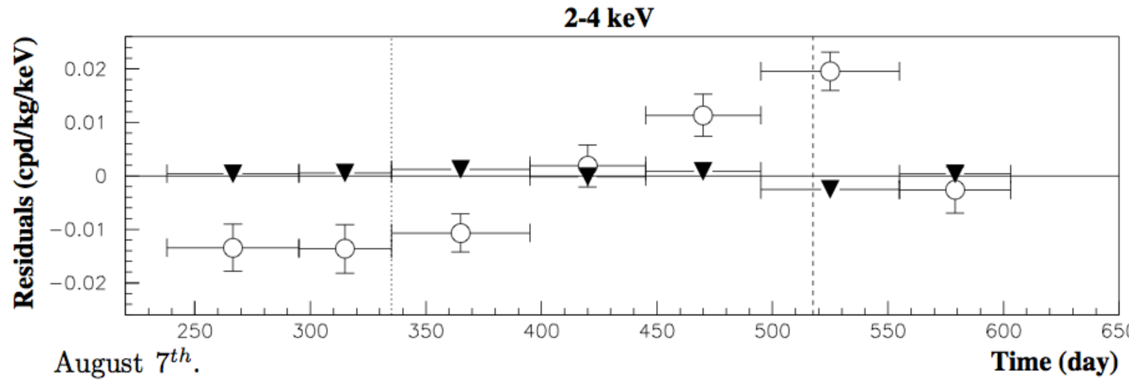


Innovation in Techniques: Addressing DAMA

DAMA annual modulation a sore point for community

- Huge statistical significance
- No other existing expt uses Na and I



New efforts to test underway!

- DM-ICE: NaI with different systematics
  - southern hemisphere, situated inside IceCube
  - also a movable copy: run in N and S
  - operation in ice demo'd, ice v. clean
  - working on reducing contaminations
- SABRE: NaI with reduced backgrounds
  - Better source powder for NaI
  - Lower radioactivity photomultipliers
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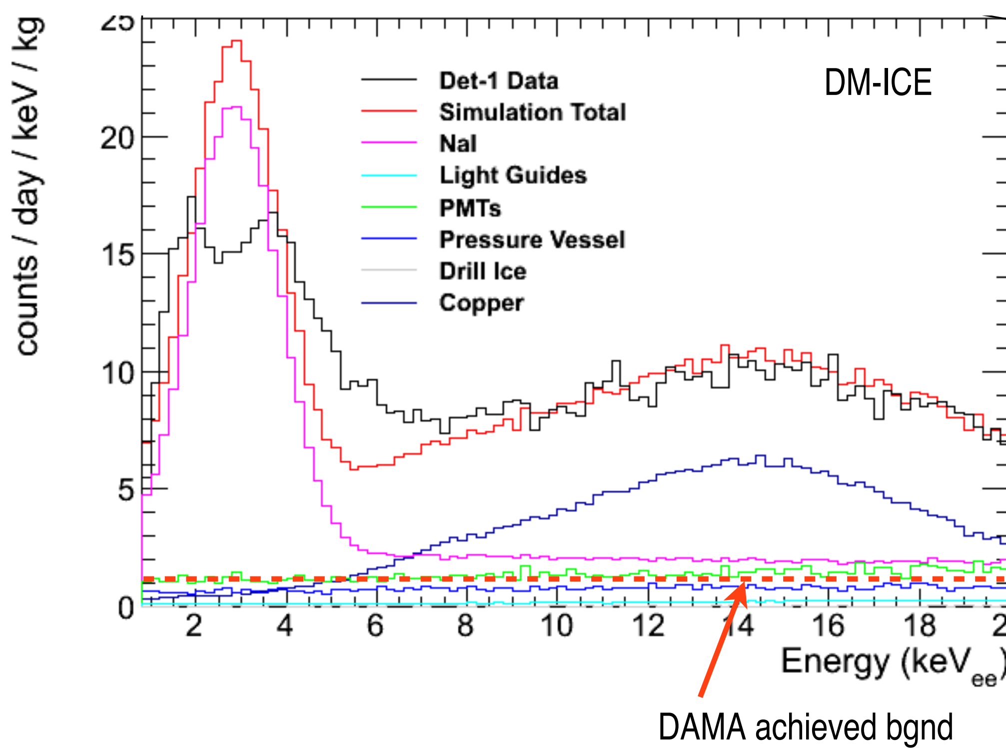

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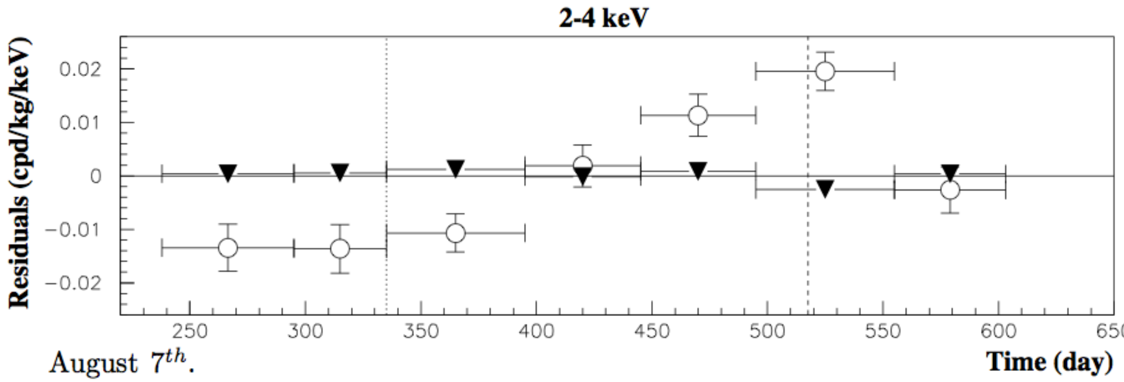

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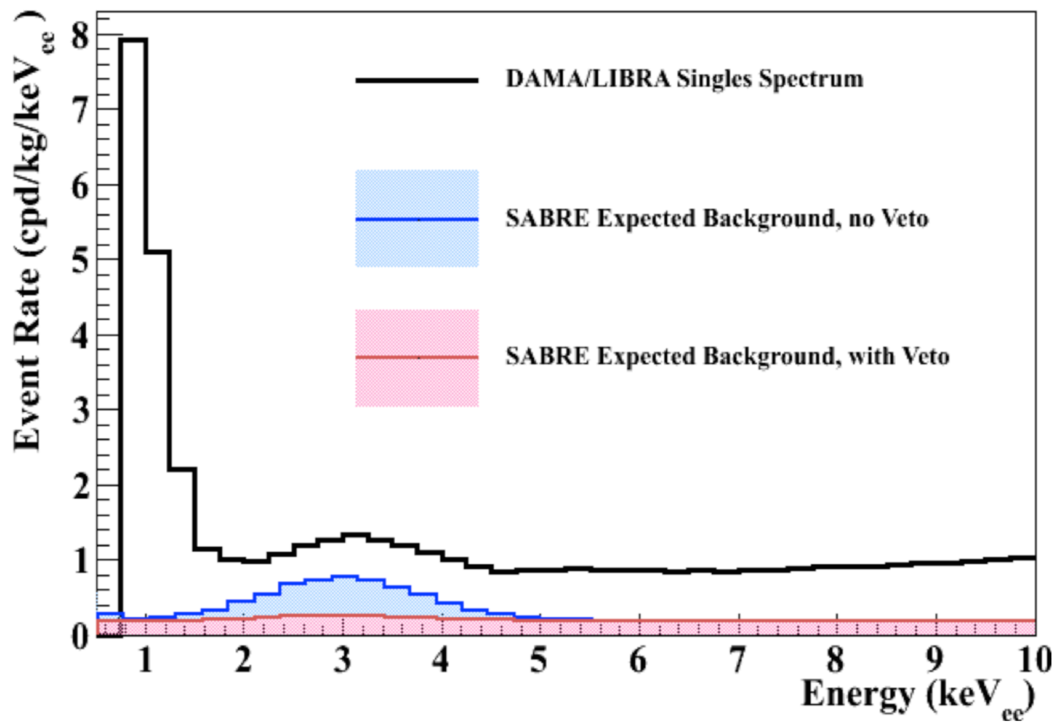

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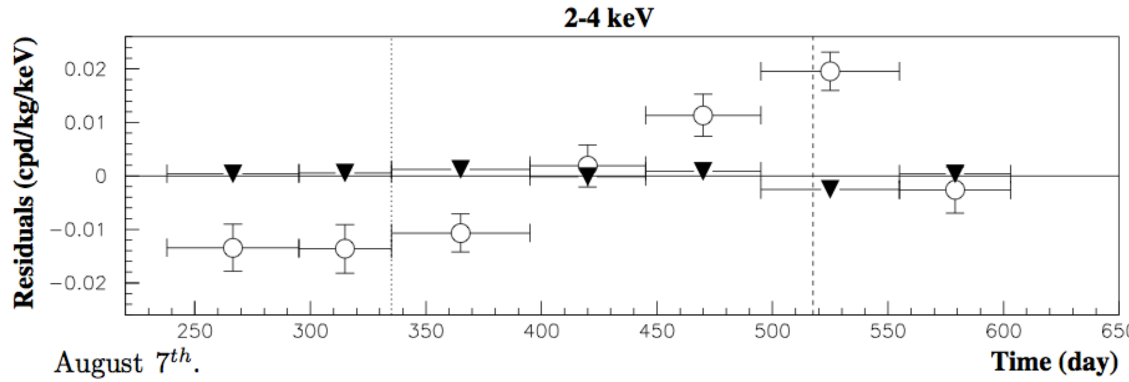

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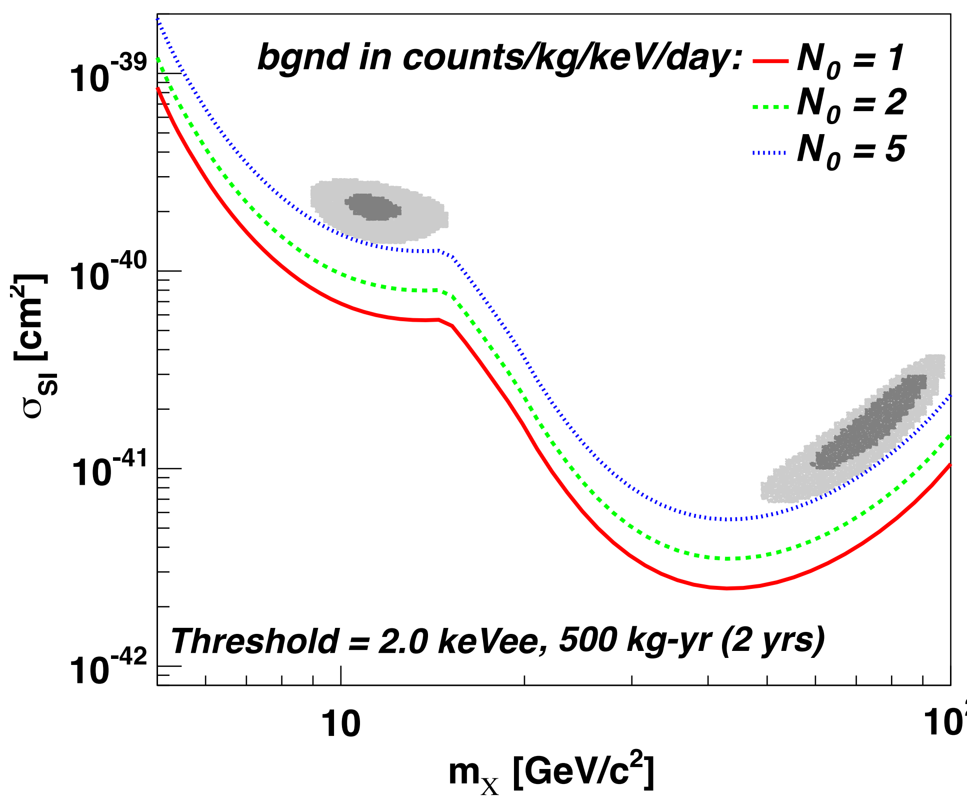
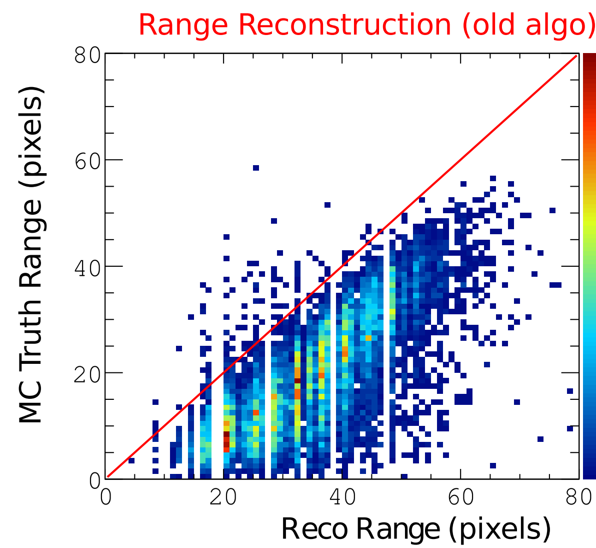


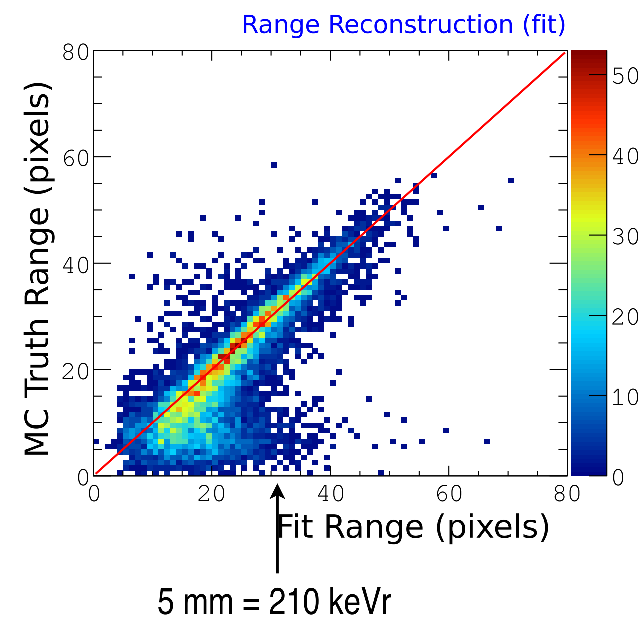
Innovation in Techniques: Directional Detection

Demonstrators continue to make good progress

DMTPC:

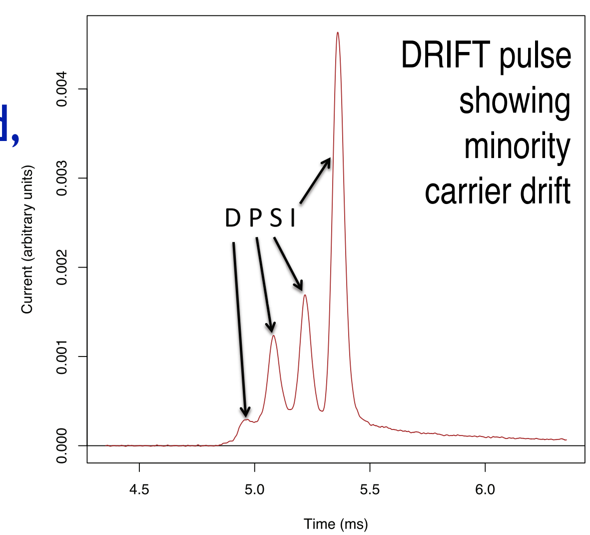
- Improved range reconstruction provides better head-tail sensitivity, critical for directional signal
- Scaling up to 1 m^3, running 1L prototype at WIPP

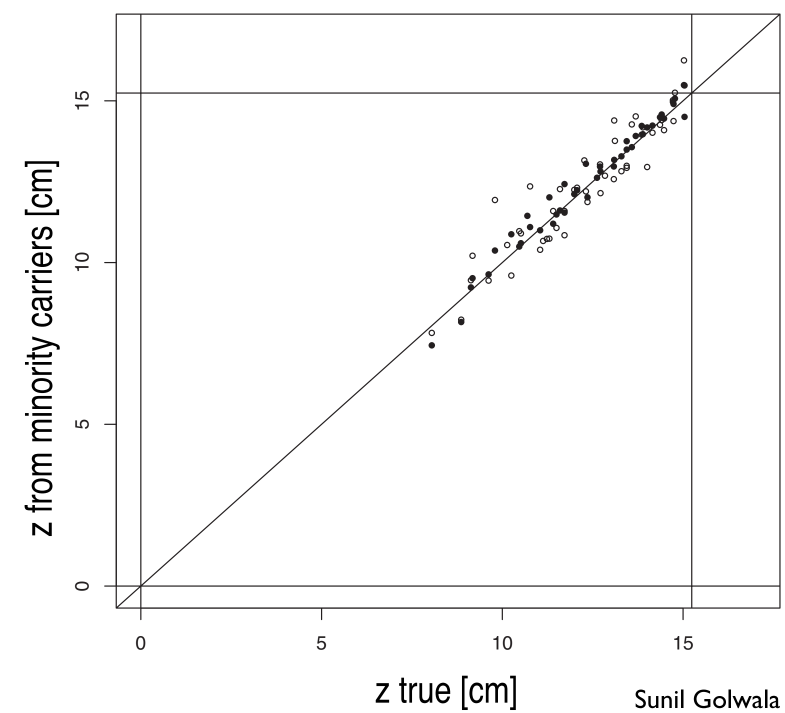




DRIFT

- "Minority carriers" have different speed, provides t_0 and rejection of surface backgrounds
- Deploying DRIFT IIe toward DRIFT III





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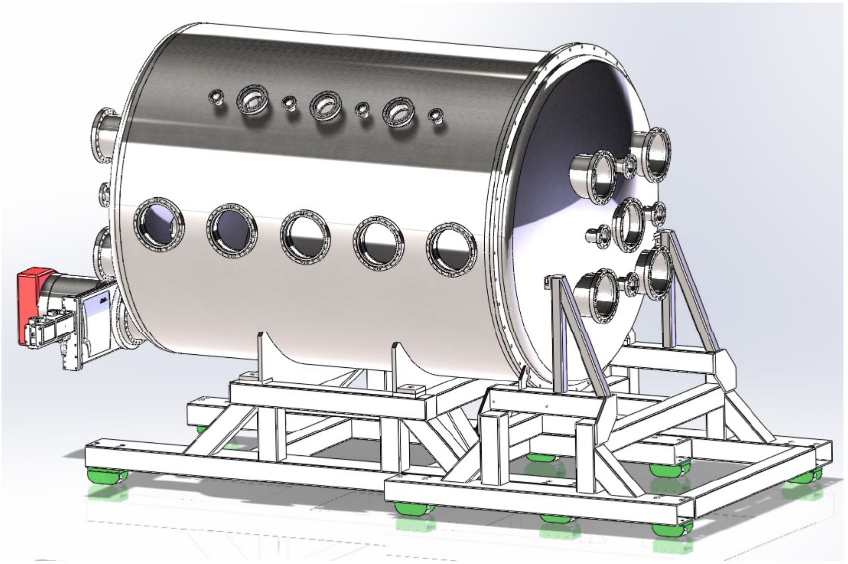

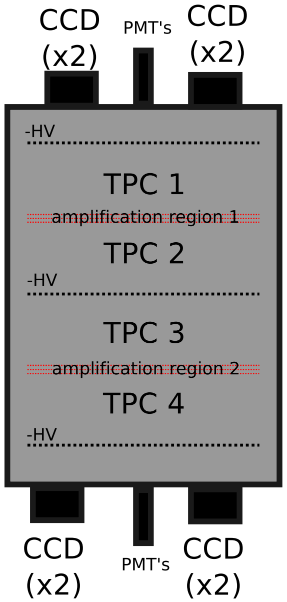

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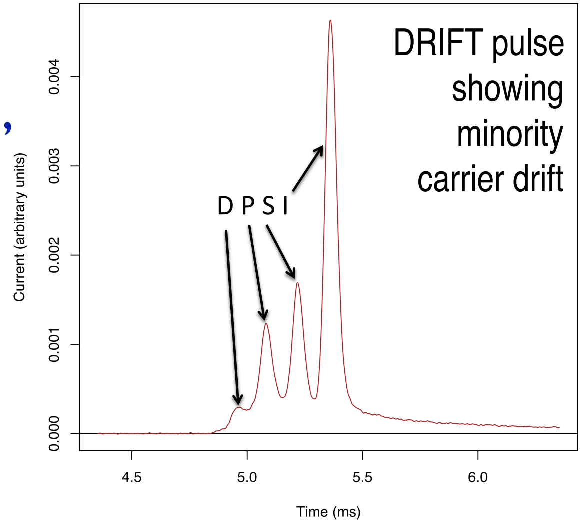

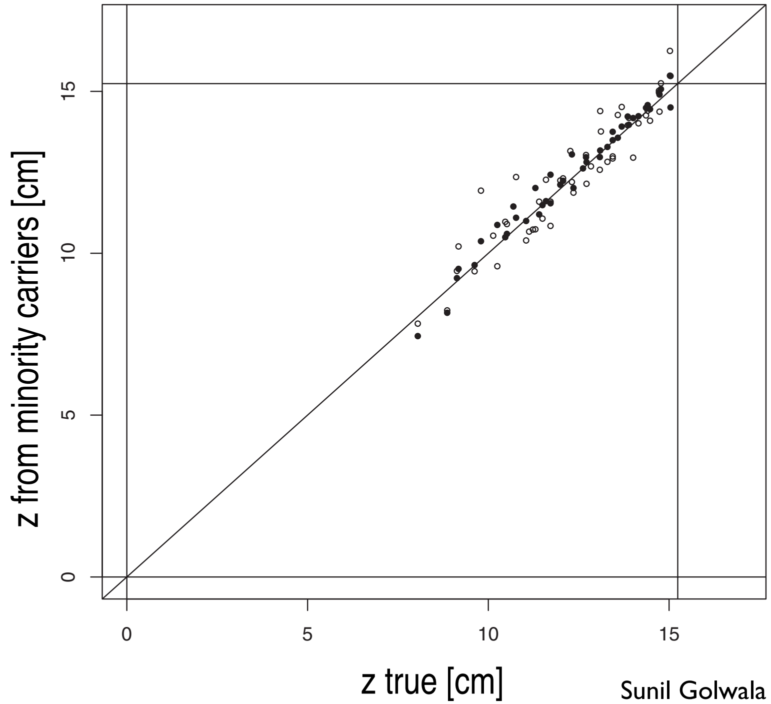

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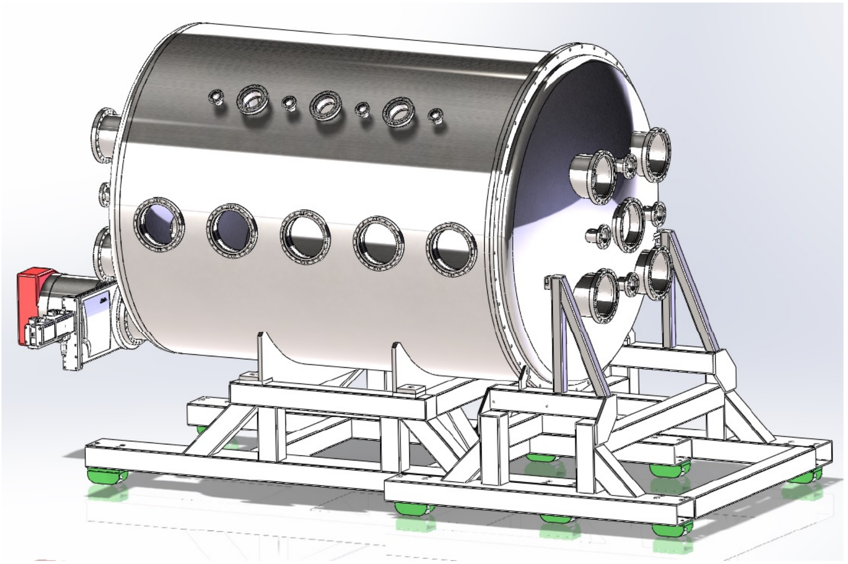

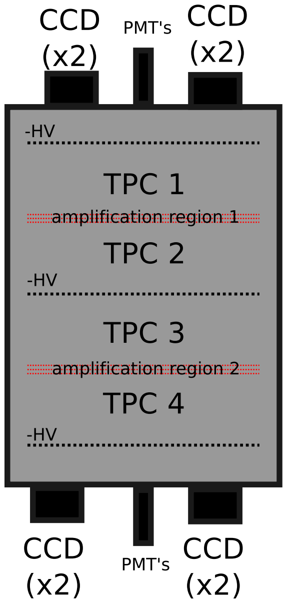

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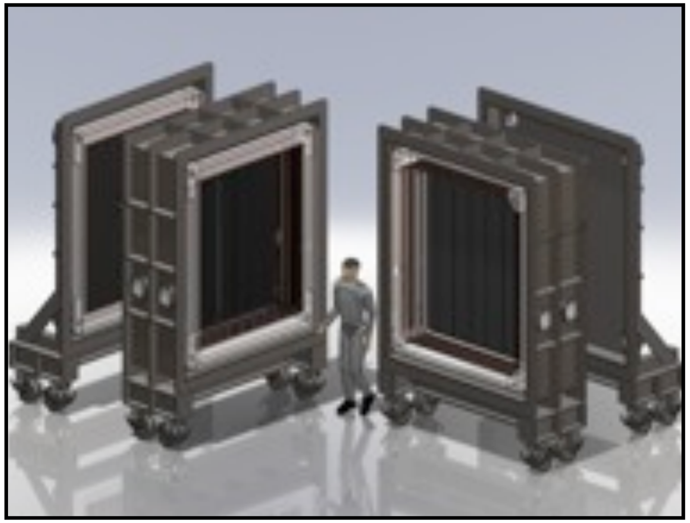
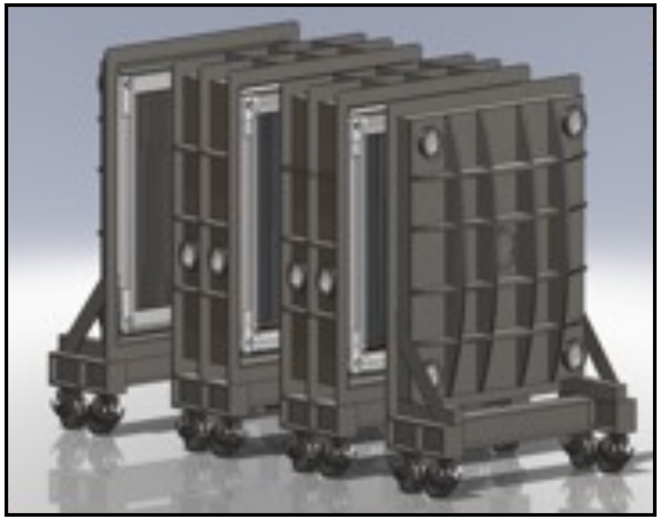




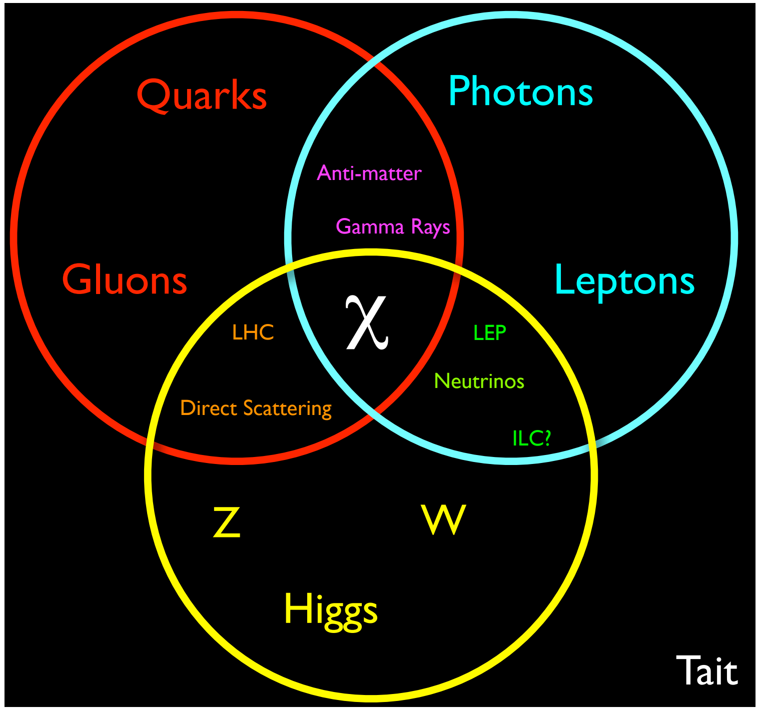
A View to the Future

We would like to see:

- Accelerator production via multiple consistent channels
- Indirect detection in multiple channels with consistent parameters
- Direct detection in multiple targets
- Eventually, direct detection with recoiling particle directionality

These will tell us:

- The couplings of dark matter to a variety of normal matter particles
- The local density and velocity structure of the dark matter halo
- The dark matter abundance globally in the halo of our galaxy and in nearby galaxies
- Is what we detect enough?



A lot of work to do, and will require broad interactions (between people as well as particles)