Direct Detection of Dark Matter: Status and Issues

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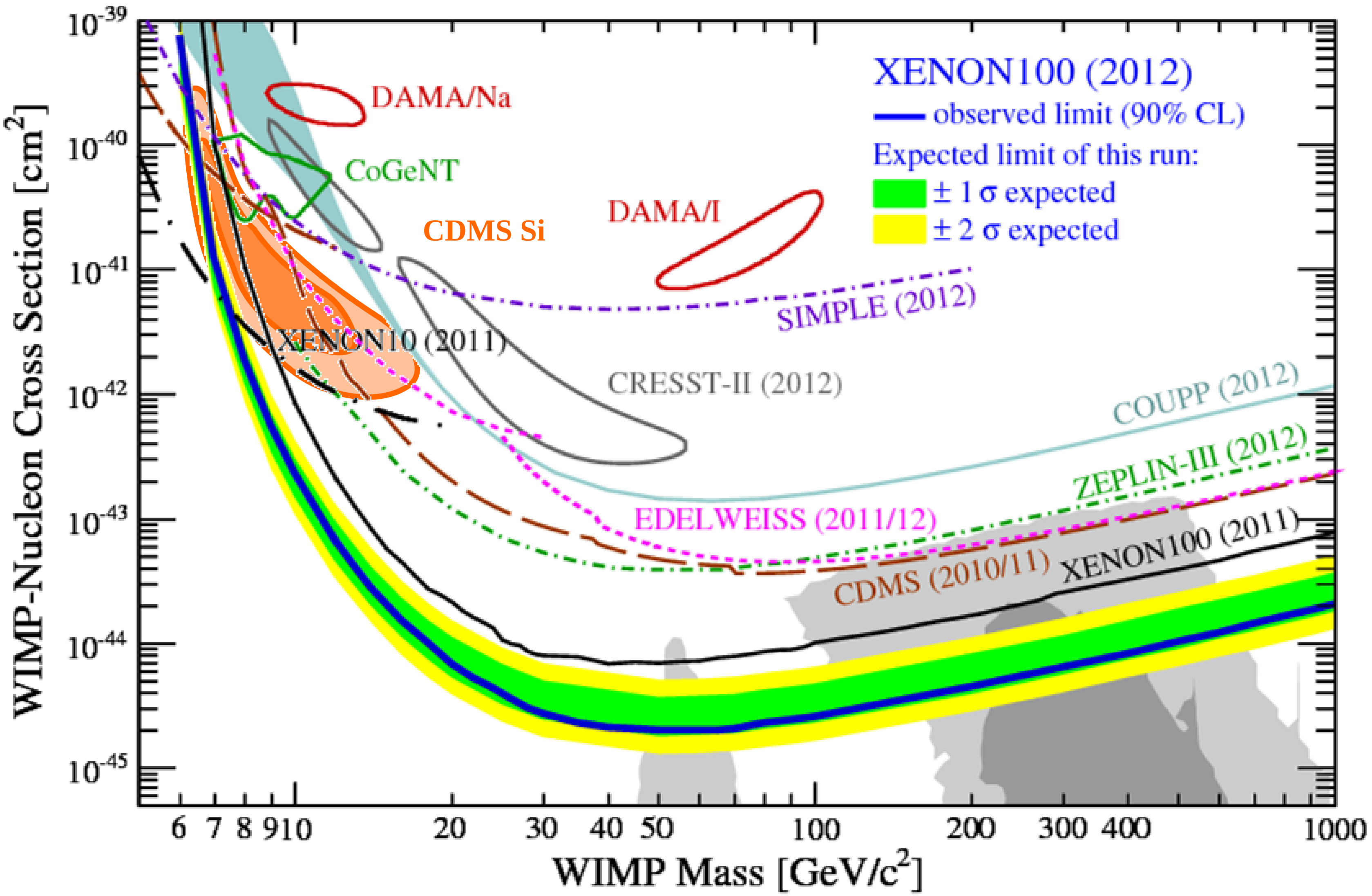
Overview


XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
CDMS Si
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
CDMS (2010/11)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
6 7 8 9 10 20 30 40 50 100 200 300 400 1000

Overview

Are any/all of the experiments seeing dark matter?
Are the results truly incompatible?

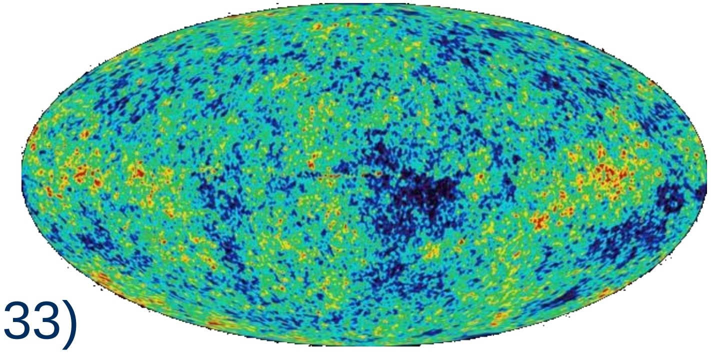
Outline

- Dark matter: what is it and how to detect it? (*WIMPs*)
- Basics of direct detection
- Experiments & results
- Issues
  - Backgrounds
  - Couplings (particle physics)
  - Halo model (astrophysics)
  - Statistical analysis
  - Energy calibration
  - Theory specific

Ask questions at any point !

Why Dark Matter?

- Indirect evidence
  - Velocities of galaxies in clusters (Zwicky 1933)
  - Galaxy rotation curves (Rubin 1960's)
  - Cosmic microwave background
  - Big bang nucleosynthesis
  - Structure formation
  - Gravitational lensing



NASA/WMAP Science Team

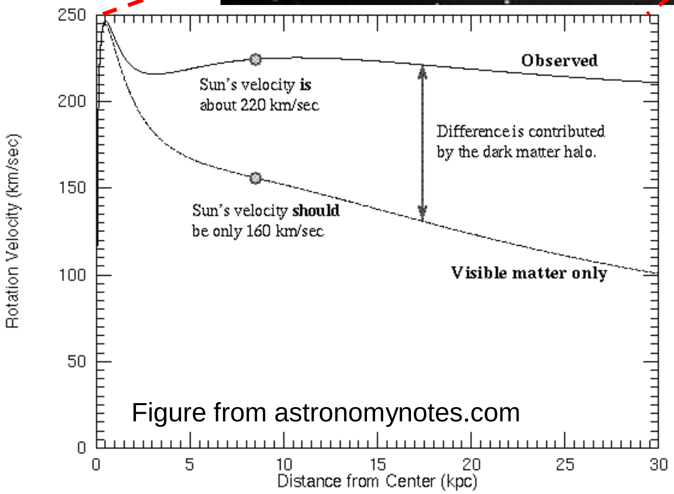


Figure from astronomynotes.com

Colley et al. (HST)

What is Dark Matter?

Is it…

- …astrophysical objects?

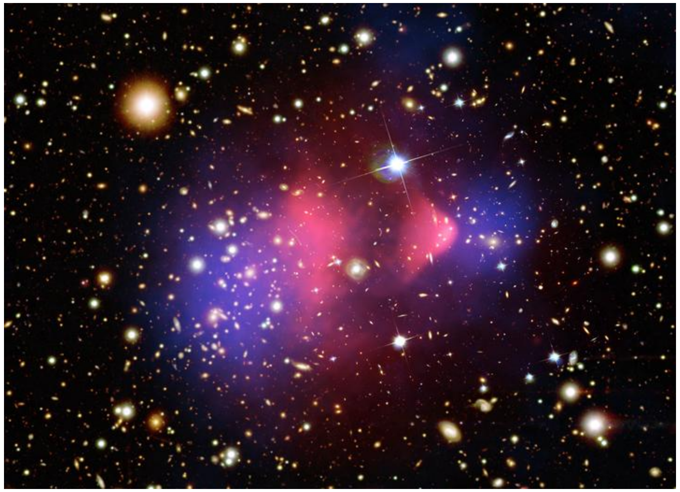
  Massive Astrophysical Compact Halo Objects (MACHOs)

  - Microlensing searches: **not significant contribution to DM**

- …a modification to gravity?

  MOdified Newtonian Dynamics (MOND)

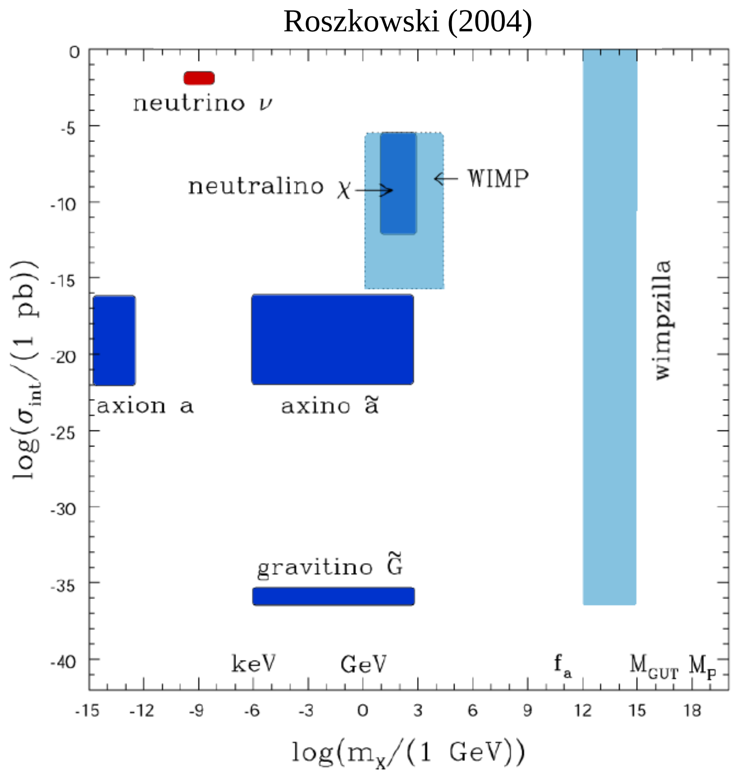
  - Bullet cluster: **MOND disfavored**



NASA/CXC/CfA/M.Markevitch et al.; NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; ESO WFI

What is Dark Matter?

…Particles!

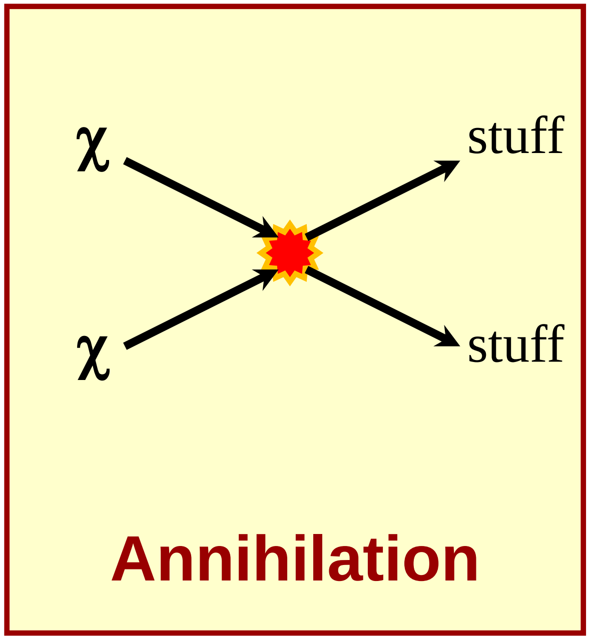


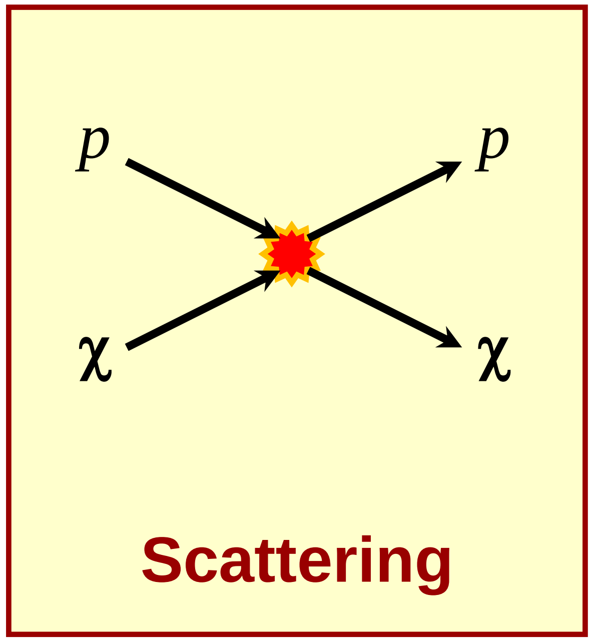
- axions
  - Proposed to solve strong CP problem
- WIMPs

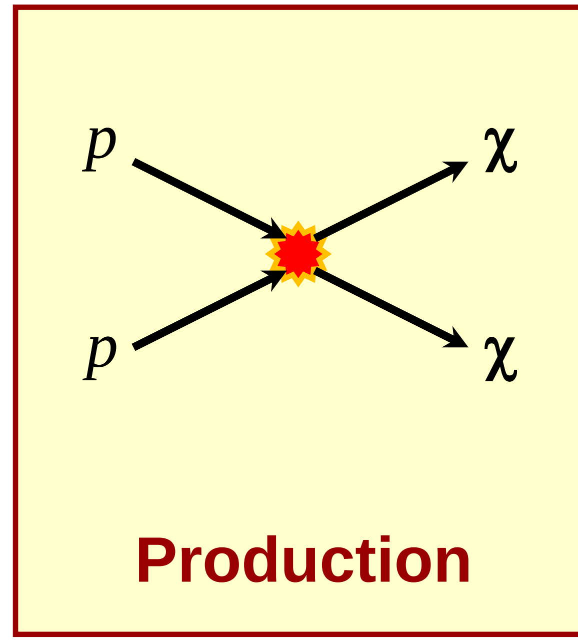
  Weakly Interacting Massive Particles
  - Particle with weak scale mass and weak scale interactions can produce correct relic abundance ("WIMP miracle")
  - Natural candidates arise in supersymmetric theories (neutralino)
  - Other comprehensive frameworks: asymmetric DM, mirror DM, …
  - WIMP-like particles known to exist: neutrinos (too light)
- SIMP, WIMPzilla, gravitino, etc.

How to detect Dark Matter?

Interactions with Standard Model particles







Indirect Detection:
Halo (cosmic-rays), capture in Sun (ν's)

Direct Detection:
Look for scattering events in detector

Accelerators:
LHC

How to detect Dark Matter?

- Direct/indirect:
  - Non-relativistic interactions (~ 100's km/s)
  - Relic dark matter
- Accelerators:
  - Relativistic interactions
  - Cannot distinguish stable particle (DM) from long lived particle

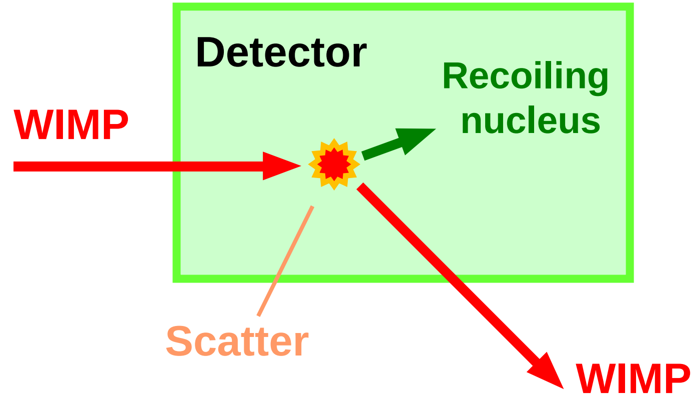
Direct Detection

Direct Detection

Goodman & Witten (1985)

See Freese, Lisanti & CS (2012) for a review

- Elastic scattering of WIMP off detector nuclei



- Recoil spectrum:

$$\frac{dR}{dE}(E,t) = \frac{1}{2m\mu^2}\,\sigma_0 F^2(q)\;\rho_0\,\eta(E,t)$$

$$\eta(E,t) = \int_{v_{\min}(E)}^{\infty} dv\,\frac{1}{v}\,f(v)$$

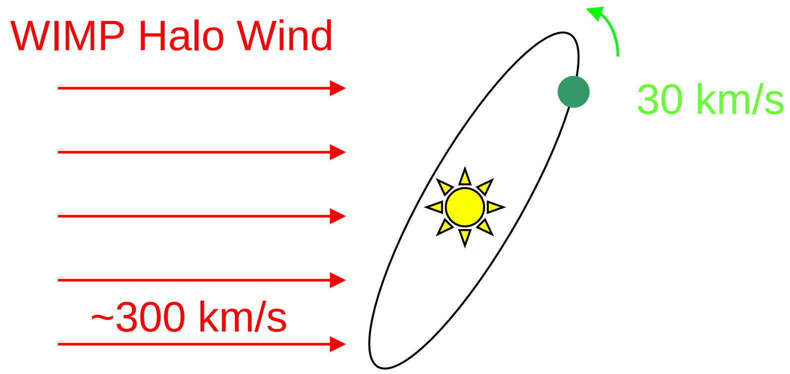
Particle Physics: WIMP-nucleus interaction

Astrophysics: WIMP distribution

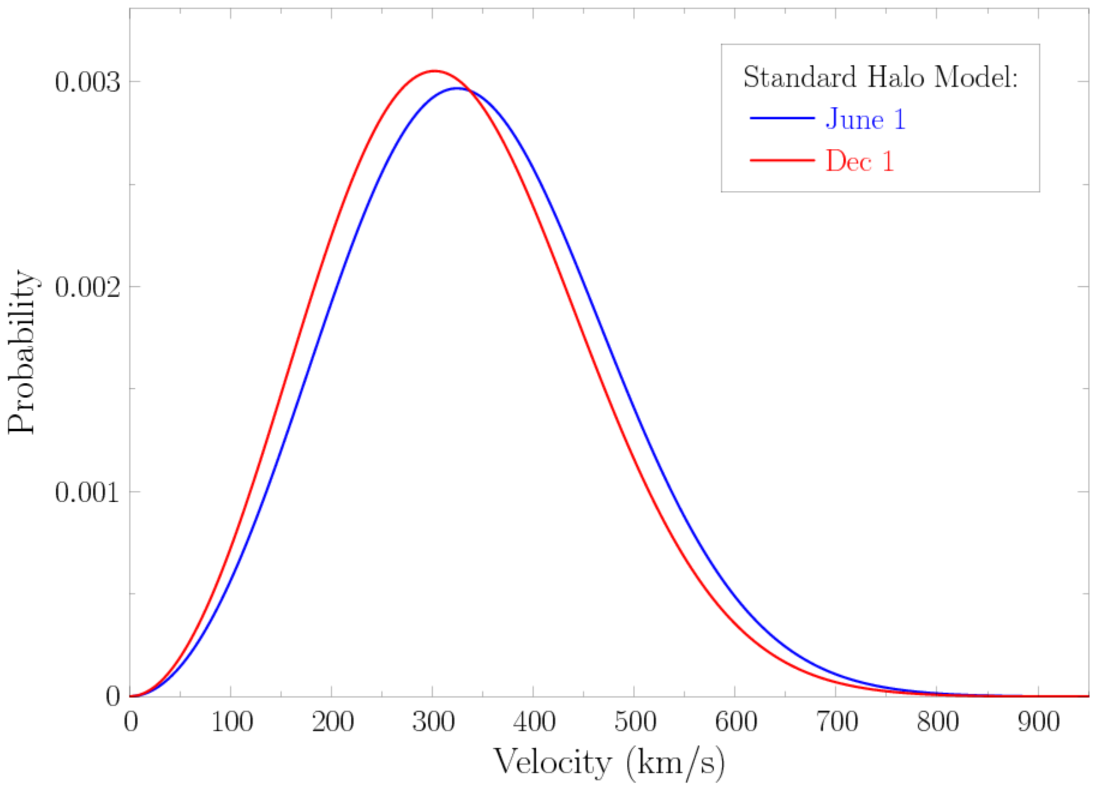
CDMS, EDELWEISS, **CRESST**, COUPP, ZEPLIN, **XENON**, LUX, **CoGeNT**, TEXONO, …

Annual Modulation

Drukier, Freese & Spergel (1986)

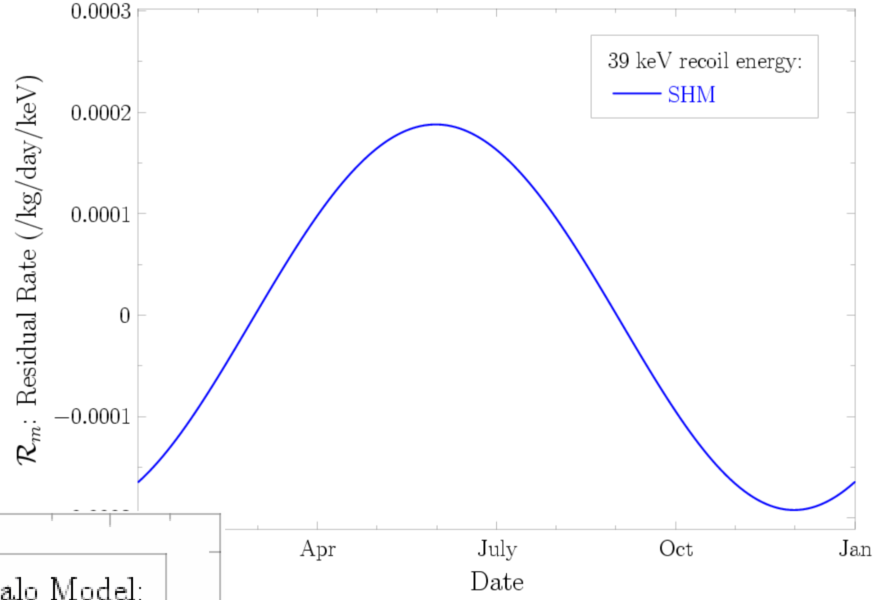


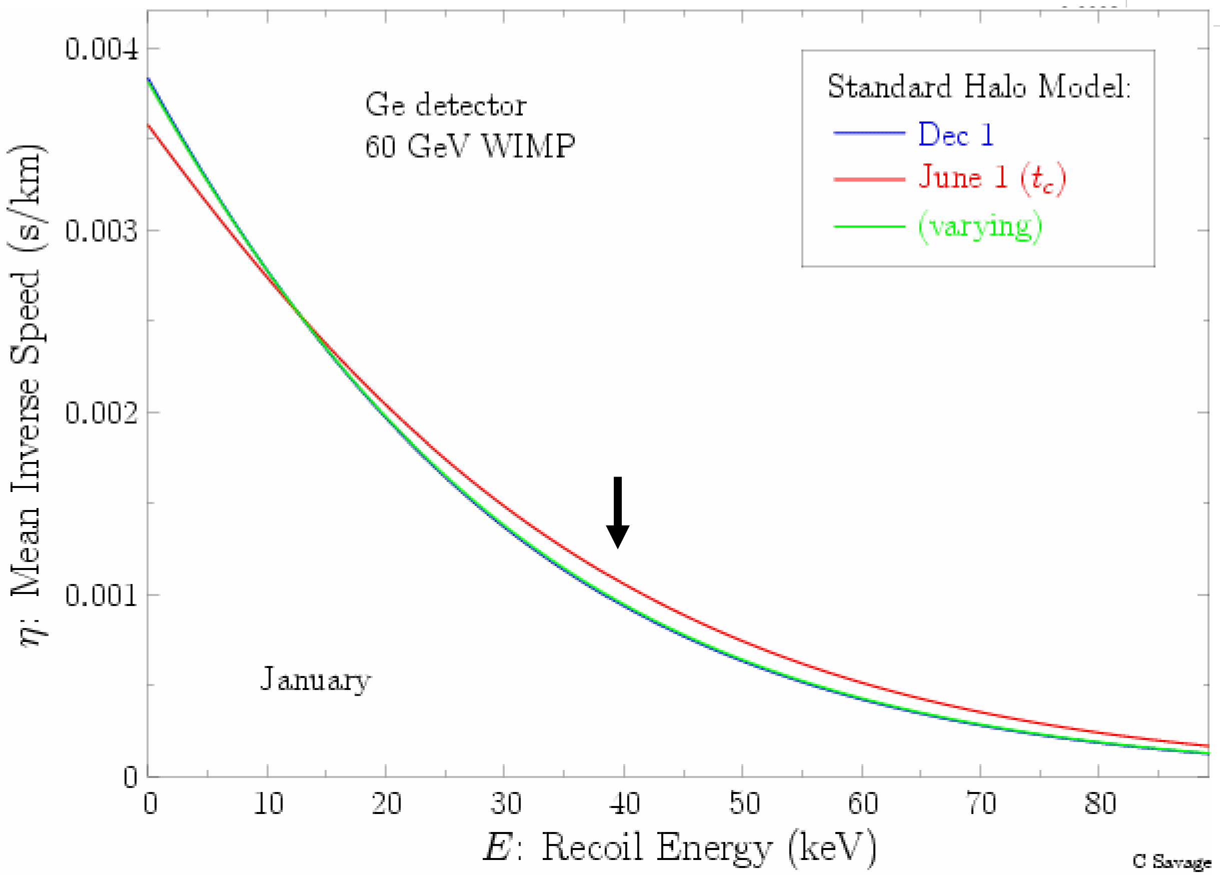
- Dark matter halo non-rotating (to first order)
- Rotating disk (Sun)
  $\Rightarrow$ WIMP wind
- …+ Earth's motion
  - With disk (June)
  - Against disk (December)



Annual Modulation

NAIAD, **DAMA**, **CoGeNT**, DM-Ice, …



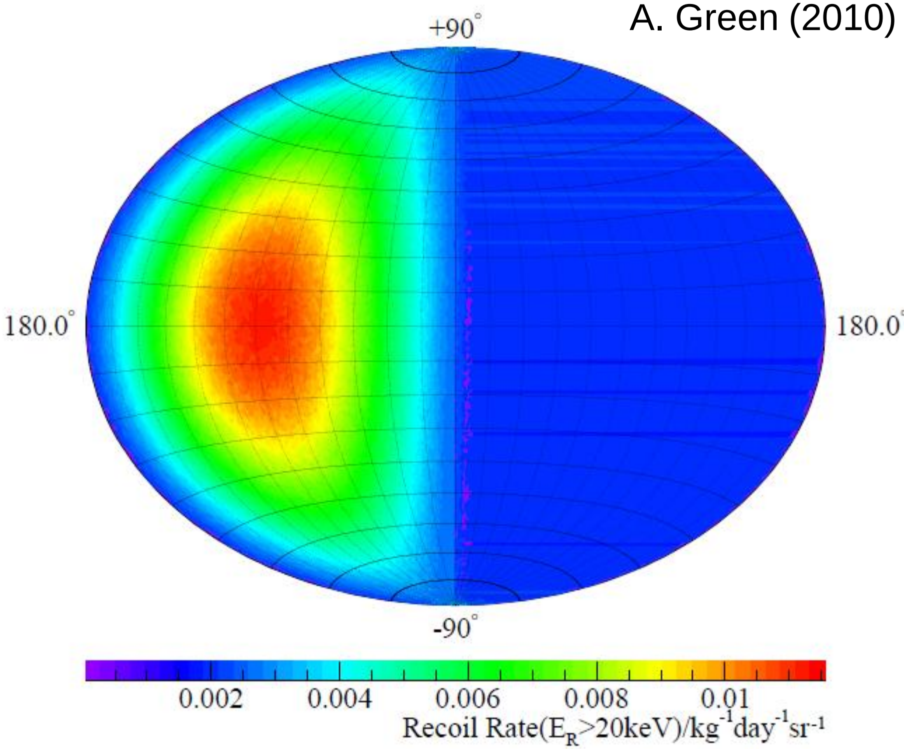


Directional Detection

- Determine direction of recoiling nucleus
- Greater sensitivity to halo models

DRIFT, …

A. Green (2010)



Direct Detection

Non-relativistic velocities O(100 km/s):

$\Rightarrow$ O(10 keV) recoil energies

- Depend on nuclear & WIMP masses (kinematics)
- Requires very sensitive detectors

- Typical signatures of recoiling nucleus
  - Ionization
  - Scintillation
  - Phonons (heat)

- Backgrounds
  - Electron recoils: gammas, betas
  - Nuclear recoils: neutrons

Reduce backgrounds:
material selection,
deep underground

Direct Detection

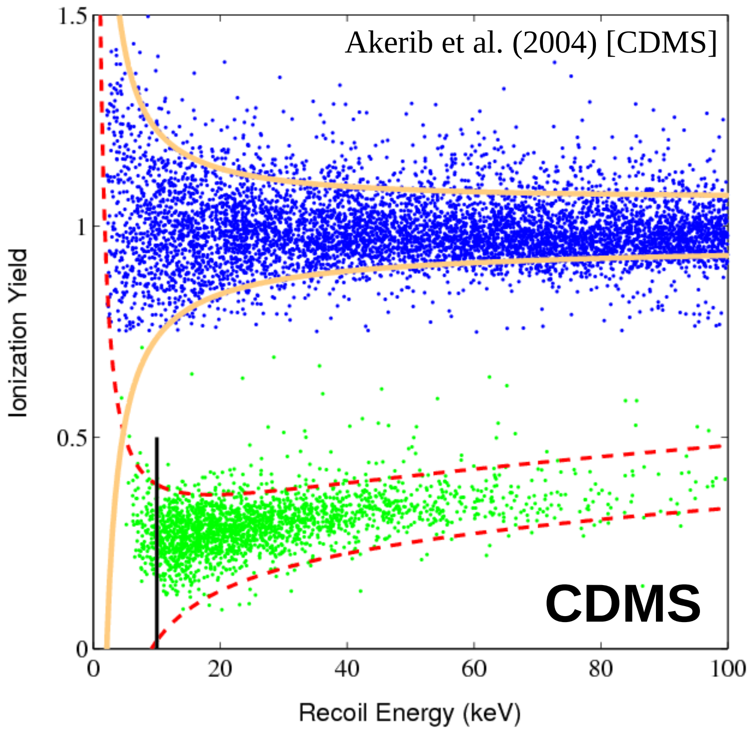
- Basic recoil rate
  - Background contamination
  - Background discrimination using multiple signals: detection with only few events
- Annual modulation
  - Most backgrounds do not modulate
  - Requires large number of events
- Directional
  - Difficult to reach same target masses
  - Better characterization of WIMP velocity distribution

Like hadron collider: first to see signal, but messy

Like lepton collider: use for precision measurements

Background Discrimination

- Good discrimination
  - CDMS: phonons & ionization
  - CRESST: phonons & scintillation
  - XENON: ionization & scintillation
- Poor discrimination
  - CoGeNT: ionization only
  - DAMA: scintillation only
- Also:
  - Signal risetimes
  - Multiple scatters (incl. neutrons)
  - …



(phonons)

γ source (electron recoils)

n source (nuclear recoils)

Experiments and Results

Standard assumptions

Spin-independent, elastic scattering

- Cross-section $\sigma \propto A^2\sigma_p$
- WIMP mass

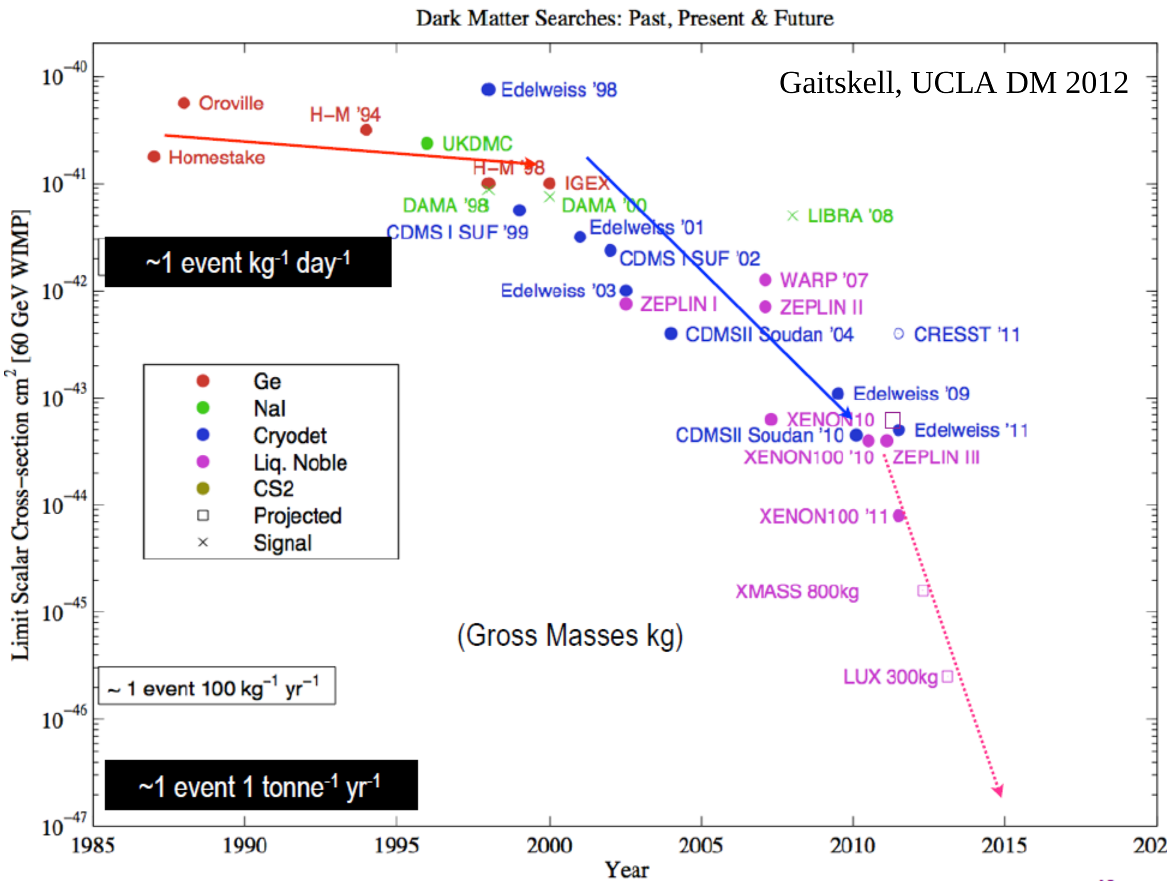
Standard Halo Model

- Isothermal sphere (Maxwell-Boltzmann)
- Non-rotating

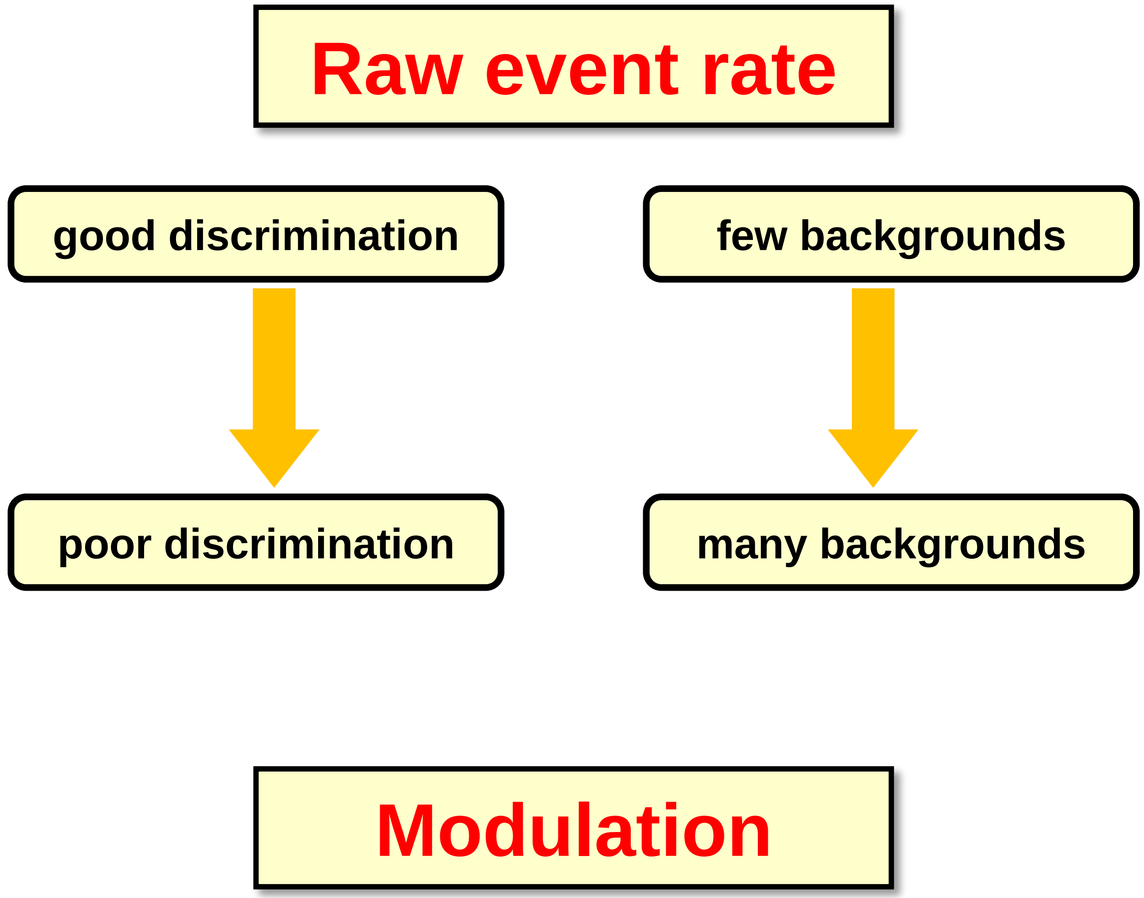
D. Dixon, cosmographica.com

Experiments

- Aim: higher target mass, lower backgrounds, lower threshold
- Every detector is test bed for future detector
  - e.g. XENON1 → XENON10 → XENON100 → *XENON1T*



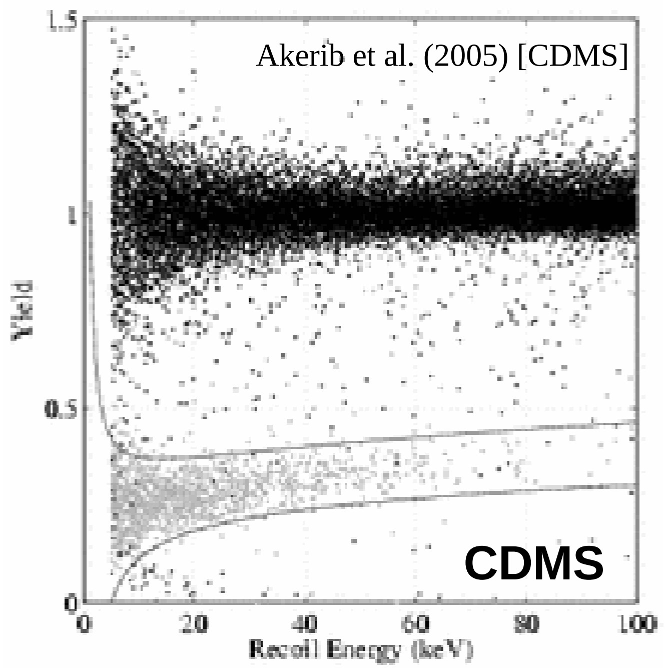
Experiments



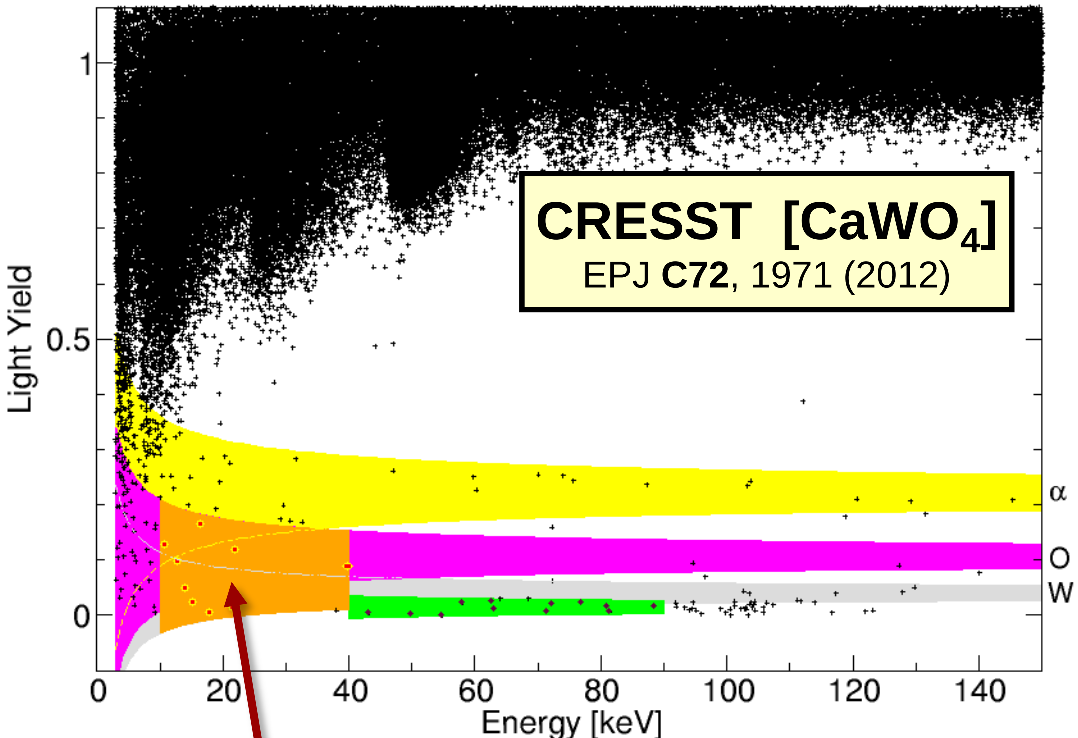
Low-background analyses

Standard analysis for multi-signal experiments

- Choose cuts to have ~ 1 background event (on average)
- Discrimination worse at low energies: analysis threshold well above trigger threshold
- Best limits for moderate/high WIMP masses
- No sensitivity to light WIMPs

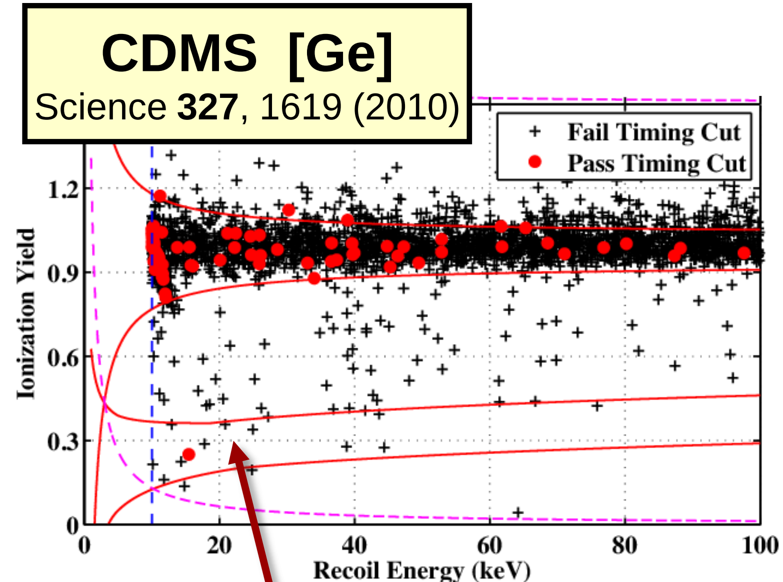


CDMS, CRESST & XENON

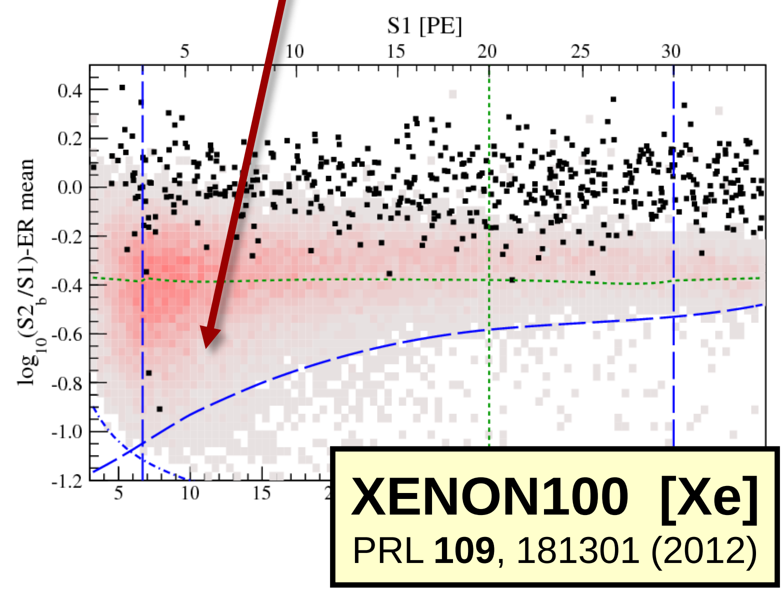


Too many events in nuclear recoil band

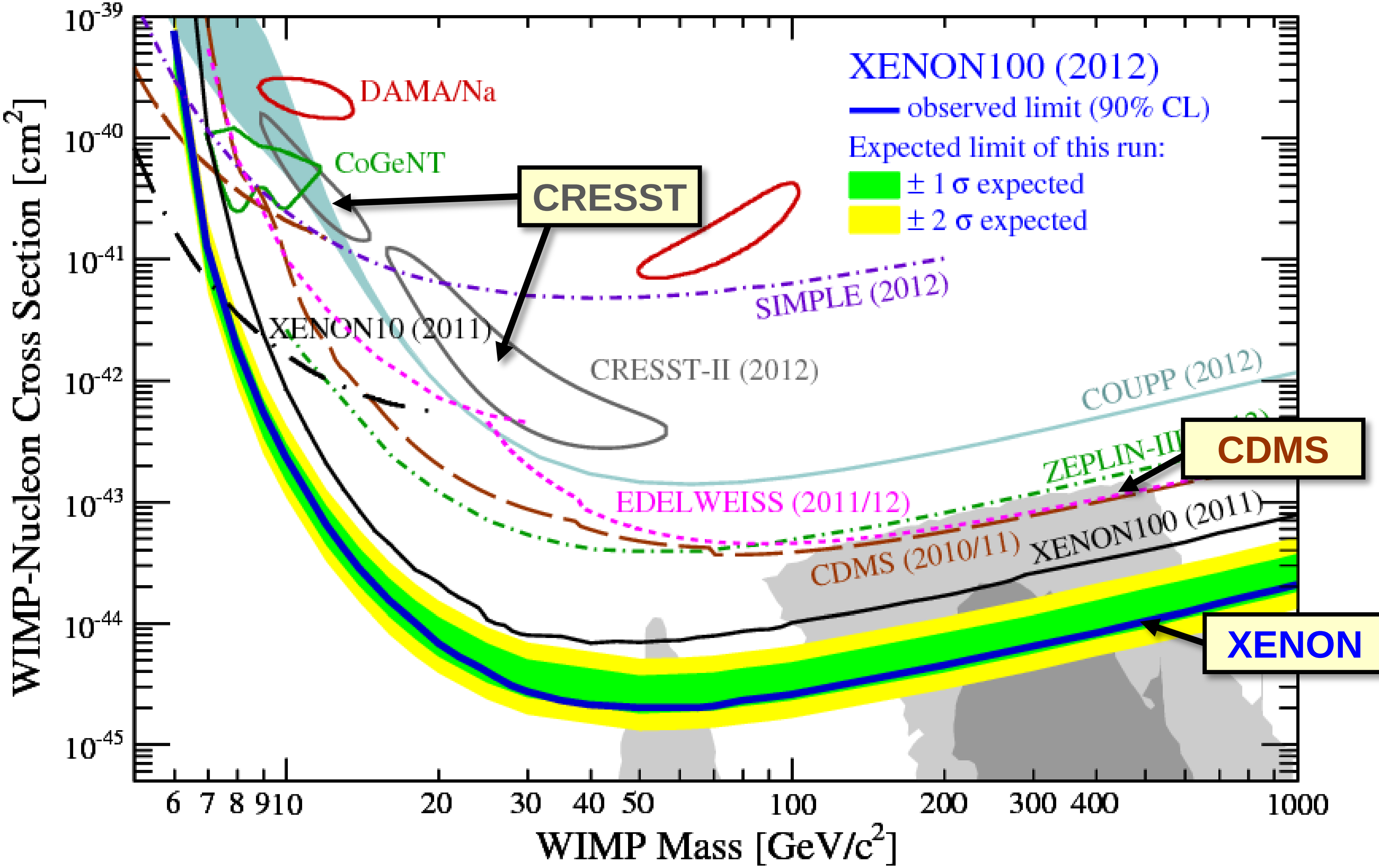
background-only rejected at 4.7σ



No significant excess

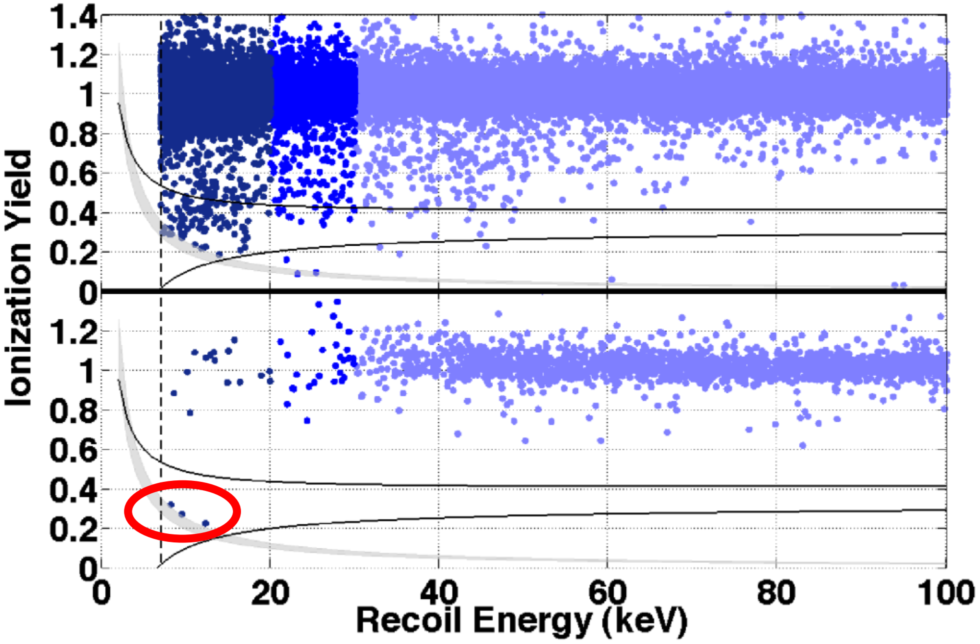


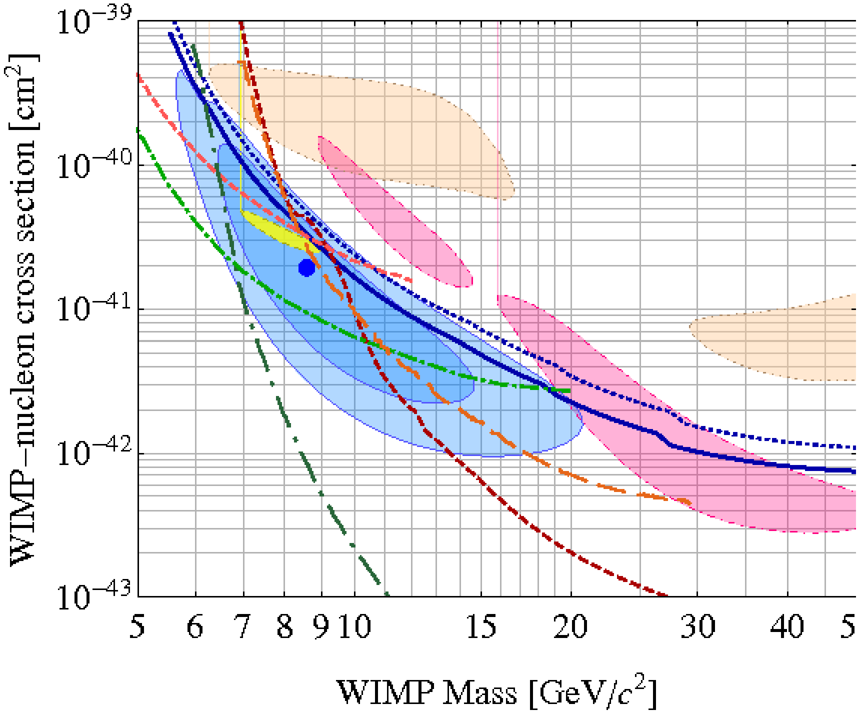
CDMS, CRESST & XENON



CDMS Silicon

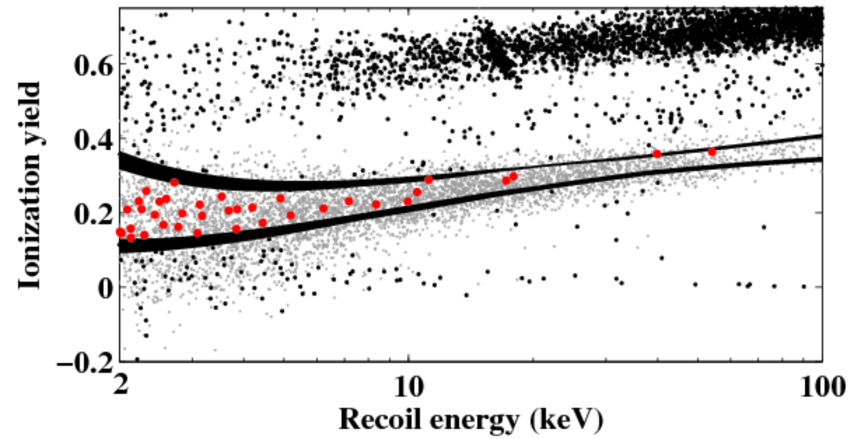
CDMS [Si]
arxiv:1304.4279





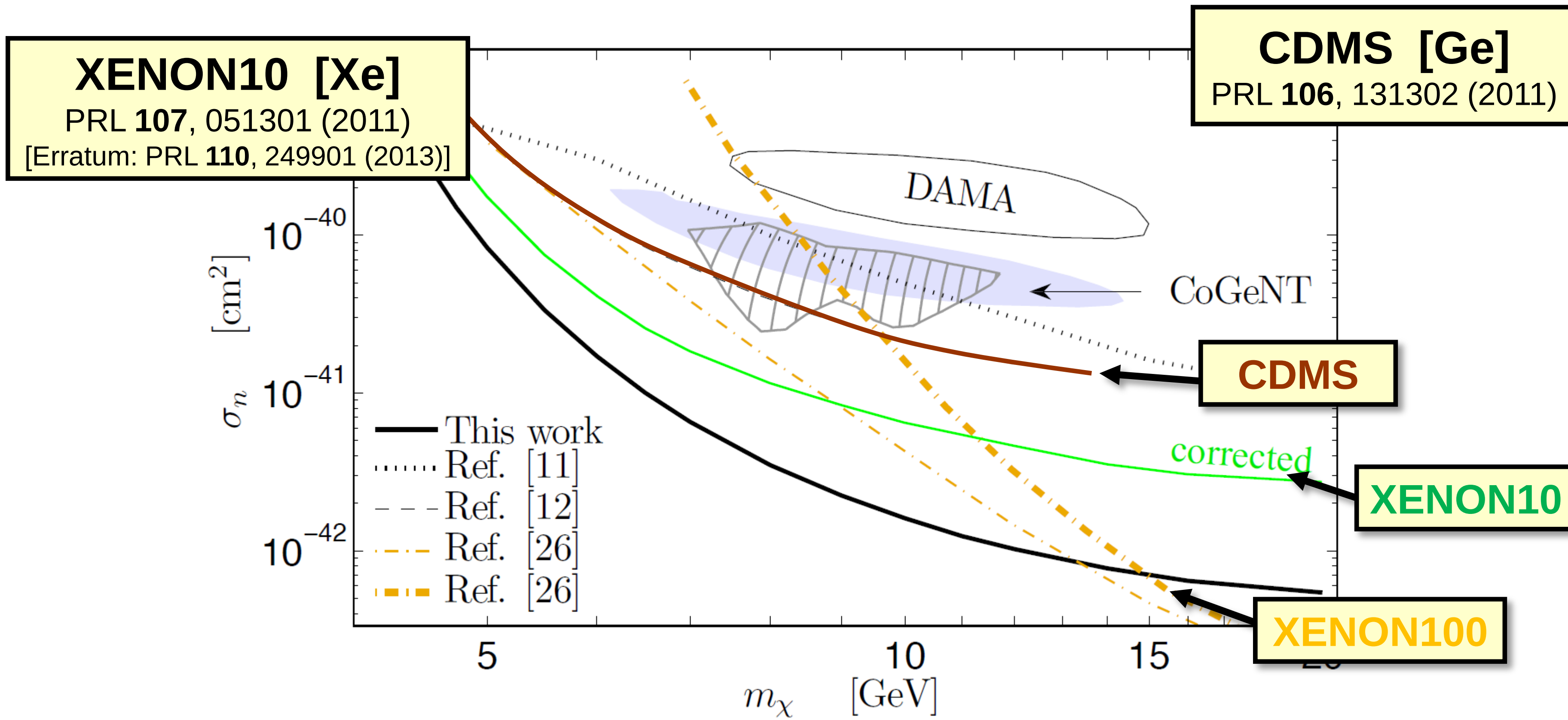
background-only rejected at 99.8%

Low-threshold analyses



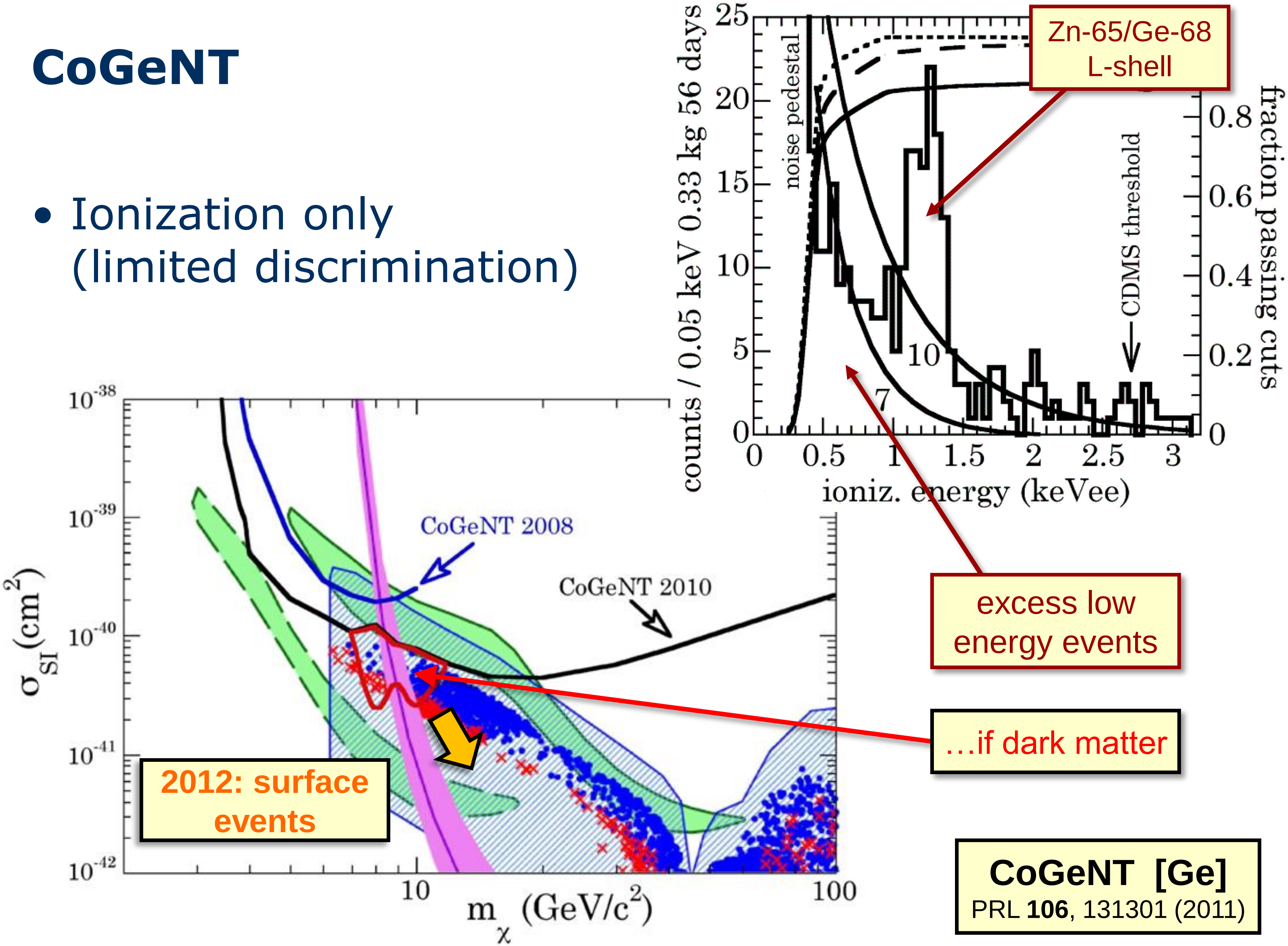
Trade discrimination for lower threshold

- Sensitivity to light WIMPs
- Weaken limits elsewhere



CoGeNT

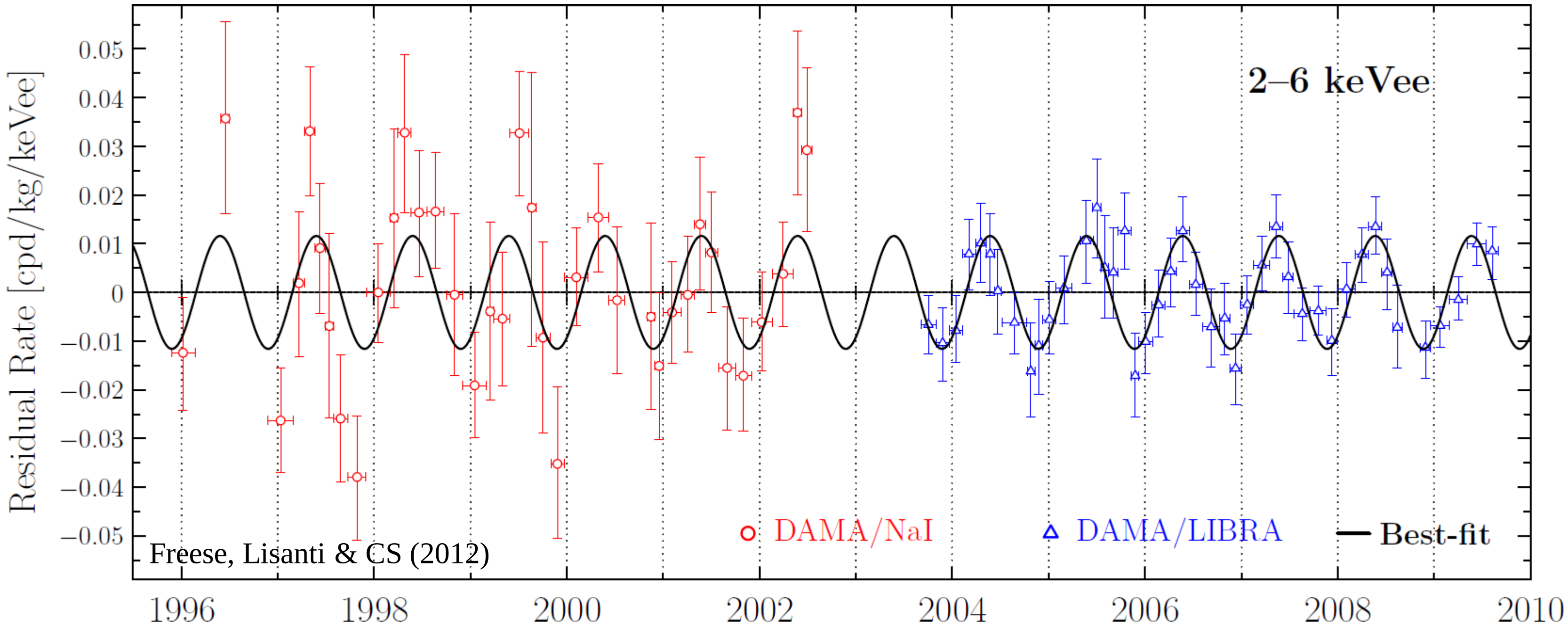
- Ionization only (limited discrimination)



CoGeNT [Ge]
PRL **106**, 131301 (2011)

Modulation: DAMA

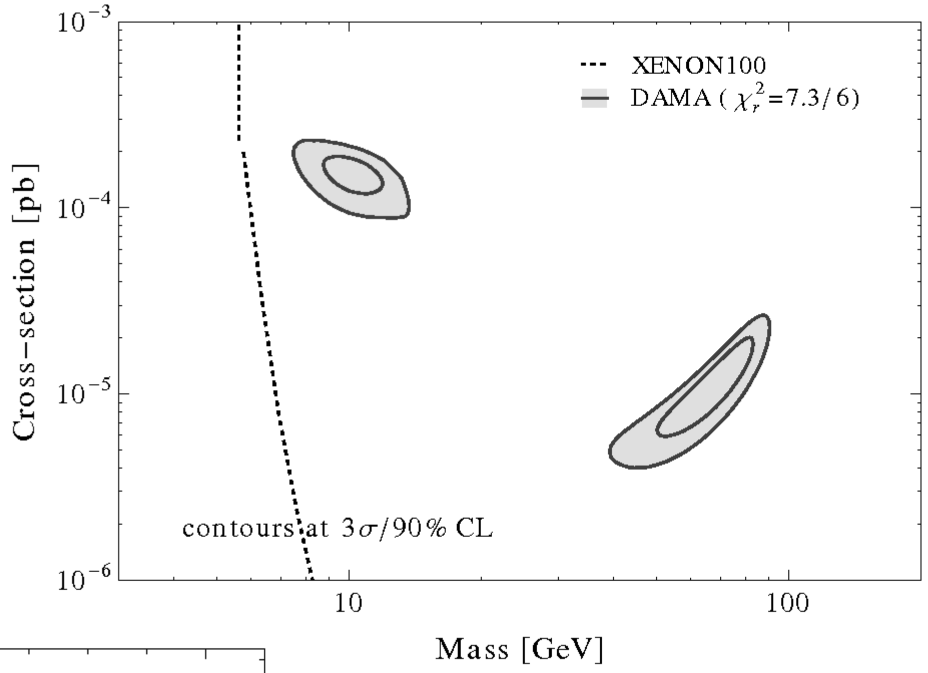
- Modulation search using NaI crystals (scintillation only)
  - DAMA/NaI: 1996-2002 — R. Bernabei *et al.*, Riv. Nuovo Cim. **26N1**, 1 (2003)
  - DAMA/LIBRA: 2003-2009 — R. Bernabei *et al.*, Eur. Phys. J. **C67**, 039 (2010)

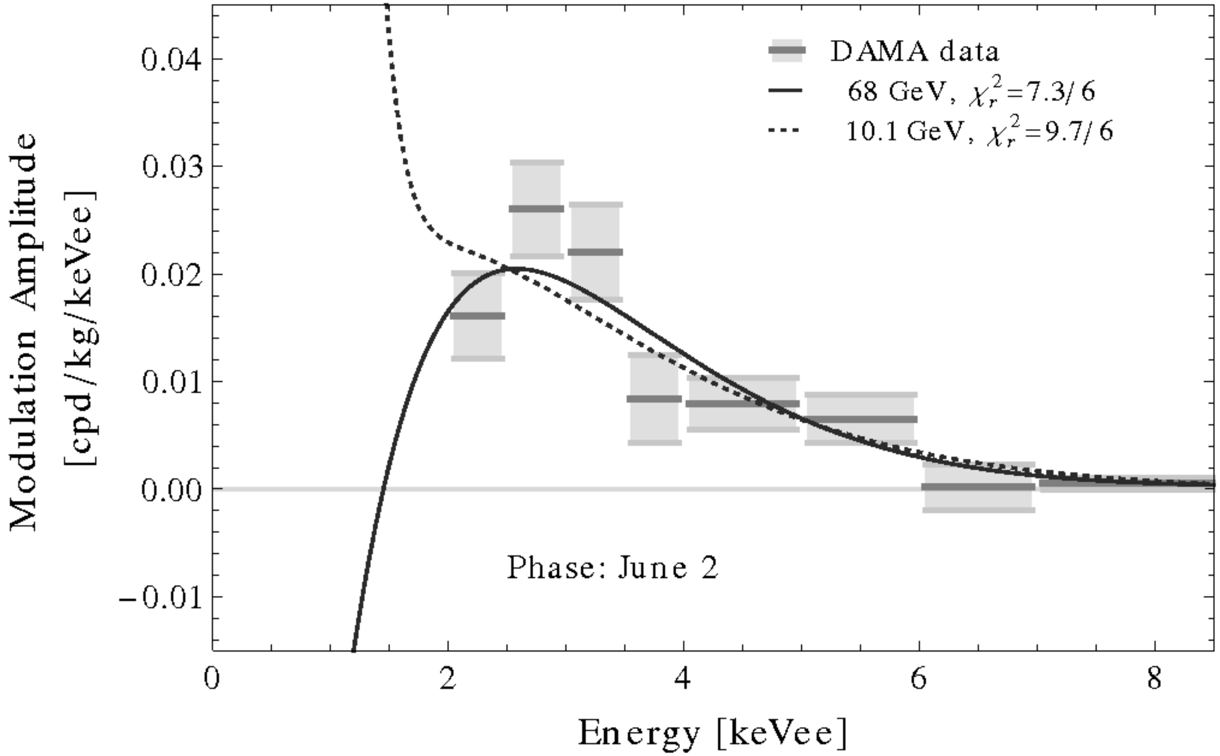


8.9σ annual modulation

Modulation: DAMA

Kelso, Sandick & CS (2013)

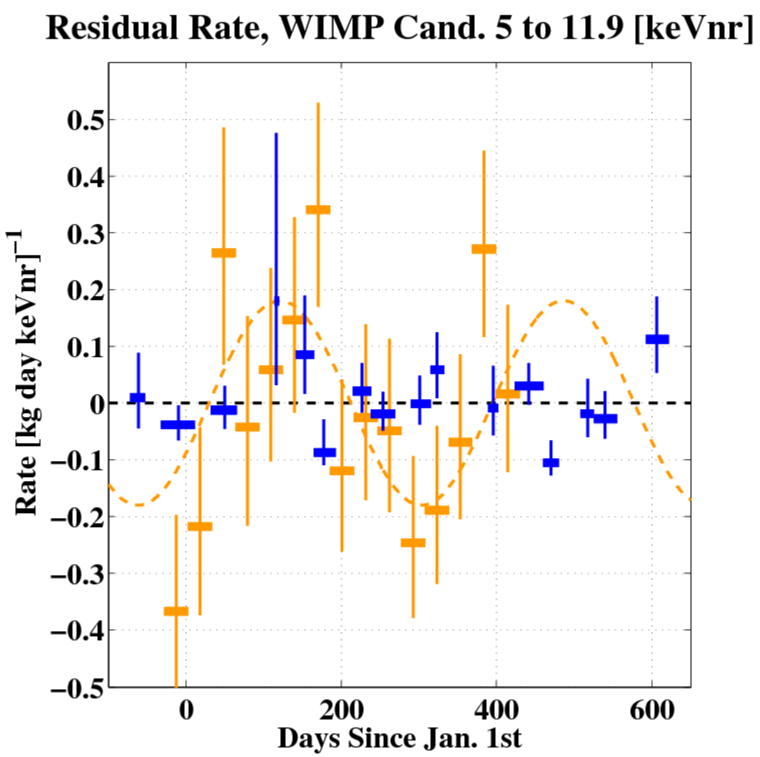




Modulation: CDMS & CoGeNT

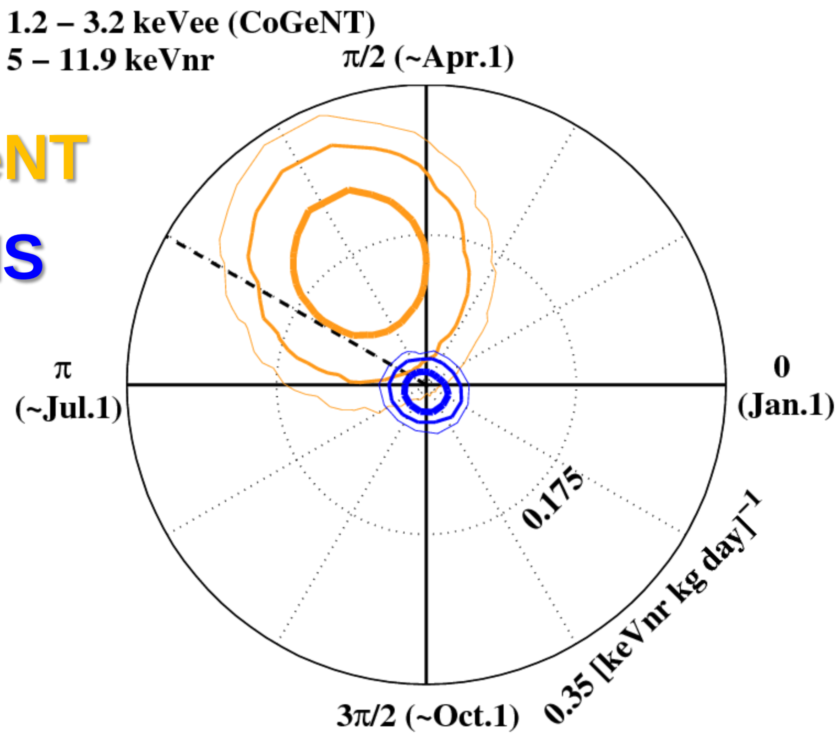
CoGeNT [Ge]
PRL **107**, 141301 (2011)

CDMS [Ge]
arxiv:1203.1309



CoGeNT

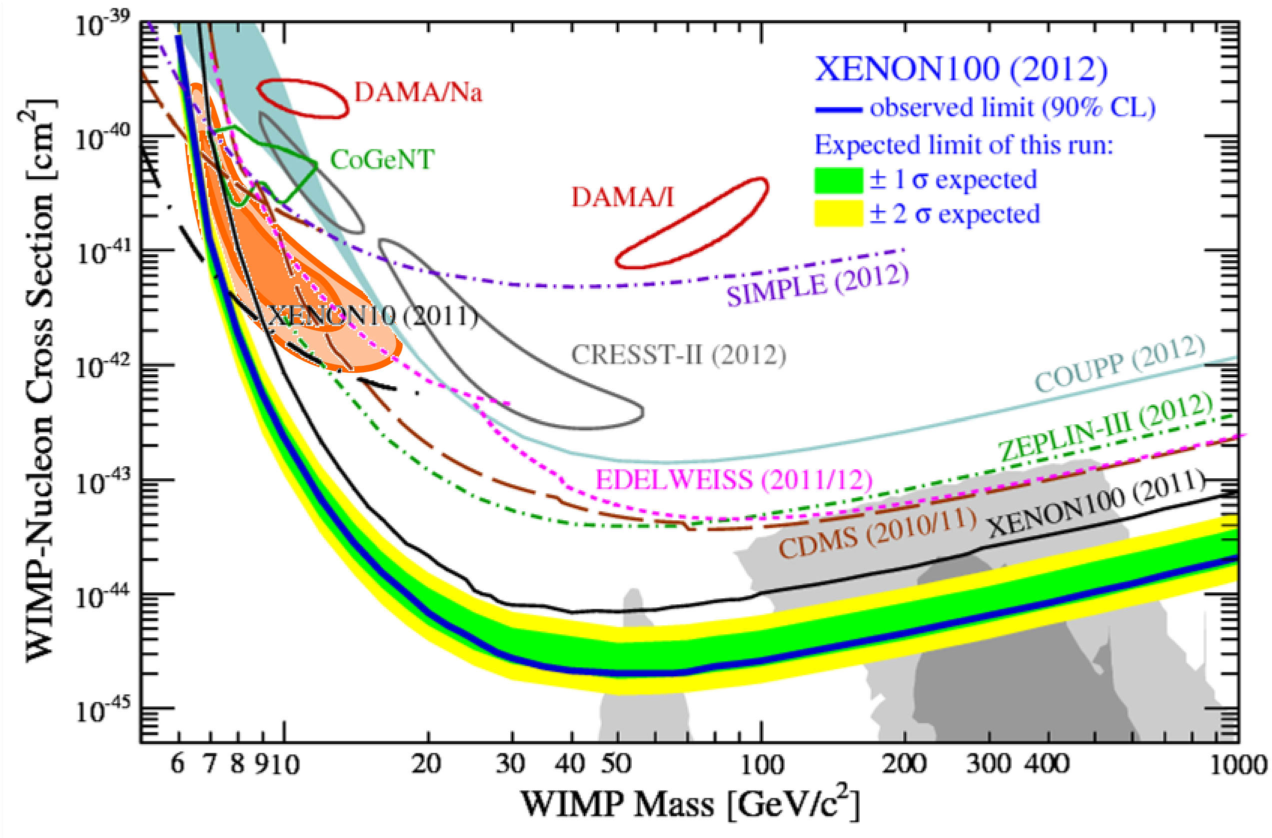
CDMS



CoGeNT: 2.8σ modulation

Experimental Status

- CDMS (Si), CoGeNT, CRESST & DAMA signals inconsistent with each other …and preferred SUSY region
- If any of the signals are from dark matter, CDMS (Ge) and/or XENON should have had more events



Issues

Issues

What issues can affect interpretation of direct detection results?

- Particle physics (interactions)
- Astrophysical uncertainties (halo)
- Unknown backgrounds
- Statistical analysis
- Detector energy calibrations
- Theory specific issues

Issue:
particle physics

Particle Physics Issues

- Assumption: single cross-section $\sigma \propto A^2\sigma_p$
- Non-relativistic limit:
  both spin-independent (SI) and spin-dependent (SD) cross-sections possible
- Other possibilities:
  - Mirror dark matter (Rutherford scattering)
    See e.g. R. Foot, Phys. Lett. B703, 7 (2011)
  - Isospin-violating dark matter
  - Inelastic scattering
  - Couplings to electrons instead of nuclei
  - …

Particle Physics Issues

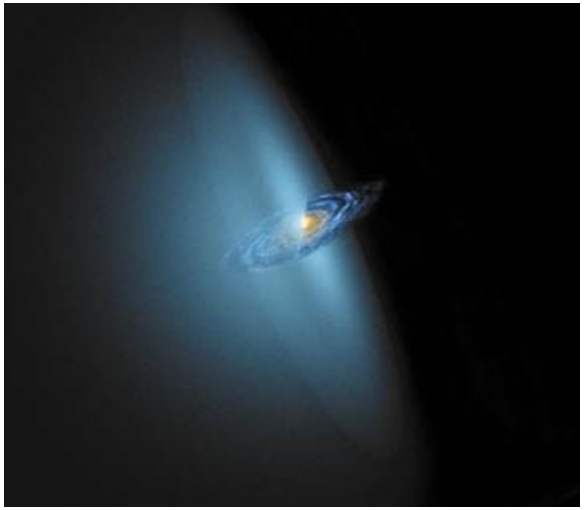
- Spin-dependent (no)
- Isospin-violating (probably not, fine-tuned)
- Inelastic scattering (now excluded*)
- Electron coupling
- …

Range from well motivated to ad-hoc particle construction. How to connect to larger theory (e.g. supersymmetry)?

Are we throwing away reasons we expect to have WIMPs?

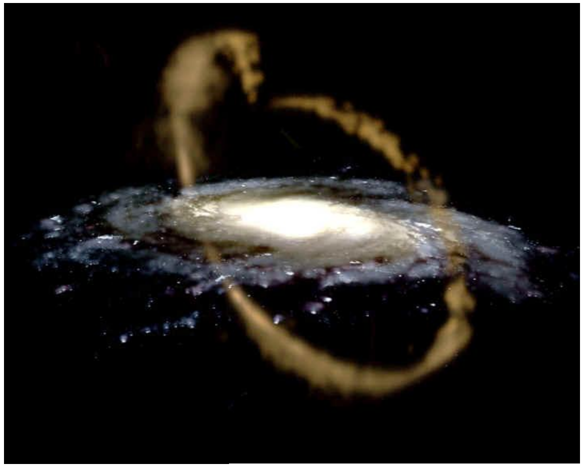
Issue: astrophysics

Halo Models



D. Dixon, cosmographica.com

- Fiducial case: isothermal sphere
  - Maxwell-Boltzmann distribution (with cutoff)
- Actual case
  - Smooth (virialized) halo
  - Structure: tidal streams, dark disk, …
- Relevant quantities
  - Local DM density
  - Local velocity distribution
    - SHM-like? If so, what parameters?
    - If not, what? ⇒ N-body



D. Martinez-Delgado & G. Perez

Astrophysics Issues

See e.g.:
Pato, Strigari, Trotta & Bertone (2012)

- Local halo dominated by smooth background
  - N-body: Maxwell-Boltzmann close enough?
  - Does not alter experimental compatibility
- Structure
  - Can have significant impact in certain cases, even when small
  - Predicted by some simulations, but severely limited by others
  - Difficult to make general conclusions regarding compatibility, but…
- Halo model independent analyses

  Fox, Liu & Weiner (2011); Frandsen et al. (2012); Gondolo & Gelmini (2012)
  - Use conservative bounds on halo kinematics behavior
  - Severely constrain astrophysical explanation of experimental results

Issue:
unknown backgrounds

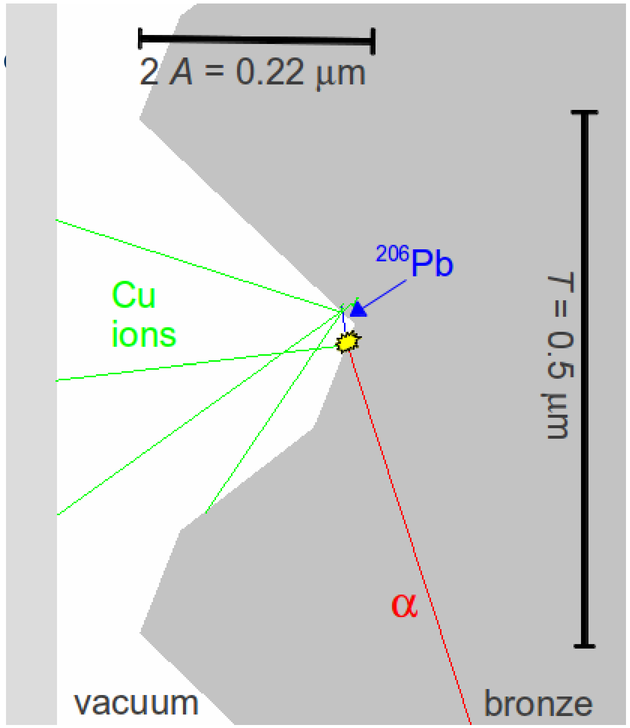
Unknown Backgrounds

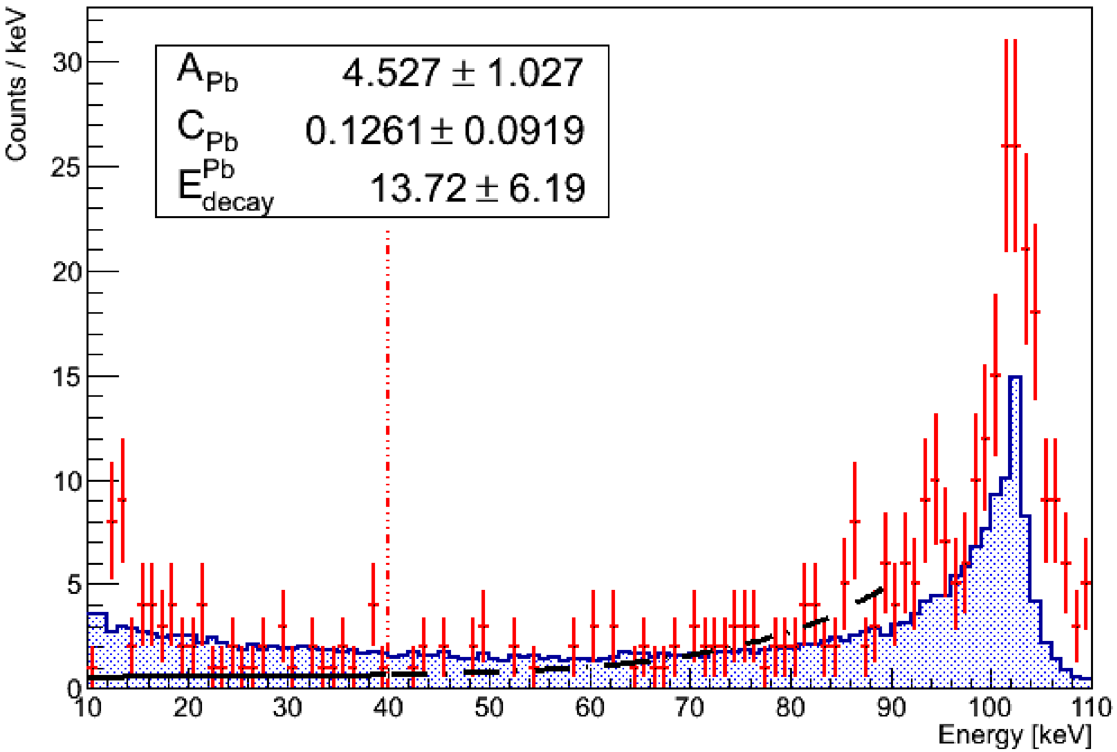
- Low energy, low rate detectors
  - Backgrounds often not well characterized/understood
  - Novel detectors sometimes present new and unexpected sources of background events
- Potential source of “signal” in CDMS (Si), CoGeNT, CRESST, and DAMA
- Example backgrounds
  - Muon-induced events in DAMA
  - Lead recoils in CRESST
  - Surface/zero-charge events in CDMS, CoGeNT

Lead Recoils in CRESST

Kuzniak, Boulay & Pollmann, Astrop. Phys. **36**, 77 (2012)

- Background: $^{210}Po \rightarrow {}^{206}Pb + \alpha$ (at surface)
- Monte carlo simulations: flat vs. rough surface
  $\Rightarrow$ underestimating background events!

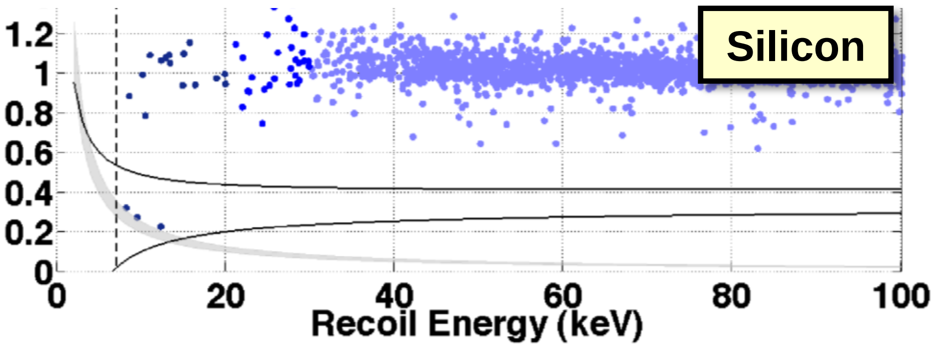




CDMS: Trigger Threshold

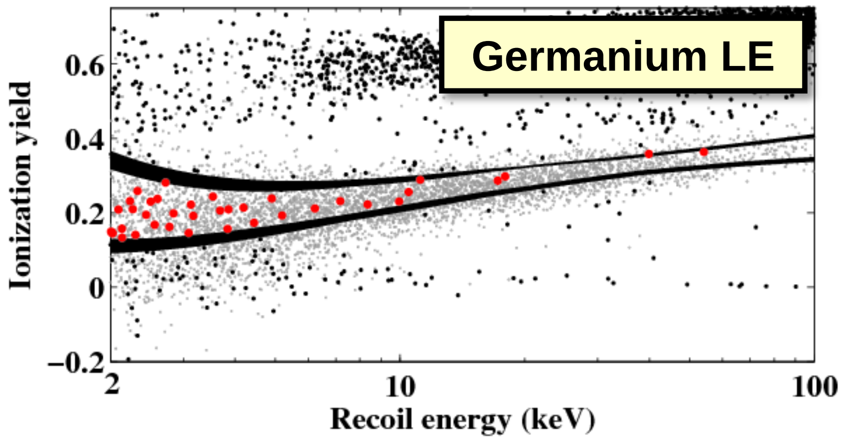
- Are there potential populations of events below trigger threshold?

Agnese et al. (2013)



- Answer: YES
  - Zero-charge events
  - …

Ahmed et al. (2011)



XENON: also has known population of events below S1 trigger

Unknown Backgrounds

- Significant fraction of CoGeNT “signal” now attributed to surface events
  - Still claim excess events
  - Still have modulation

- Very reasonable CRESST background explanation

- Many potential modulation backgrounds in DAMA have been excluded
  - Not easy to match all DAMA data

- …but new backgrounds often uncovered.
  What are we missing?

- Be cautious near thresholds!

Issue:
statistical analysis

Statistical analysis issues

- Weak statistics
- Flawed/misleading statistics
- Missing/incomplete statistics
- (Overly-)conservative statistics

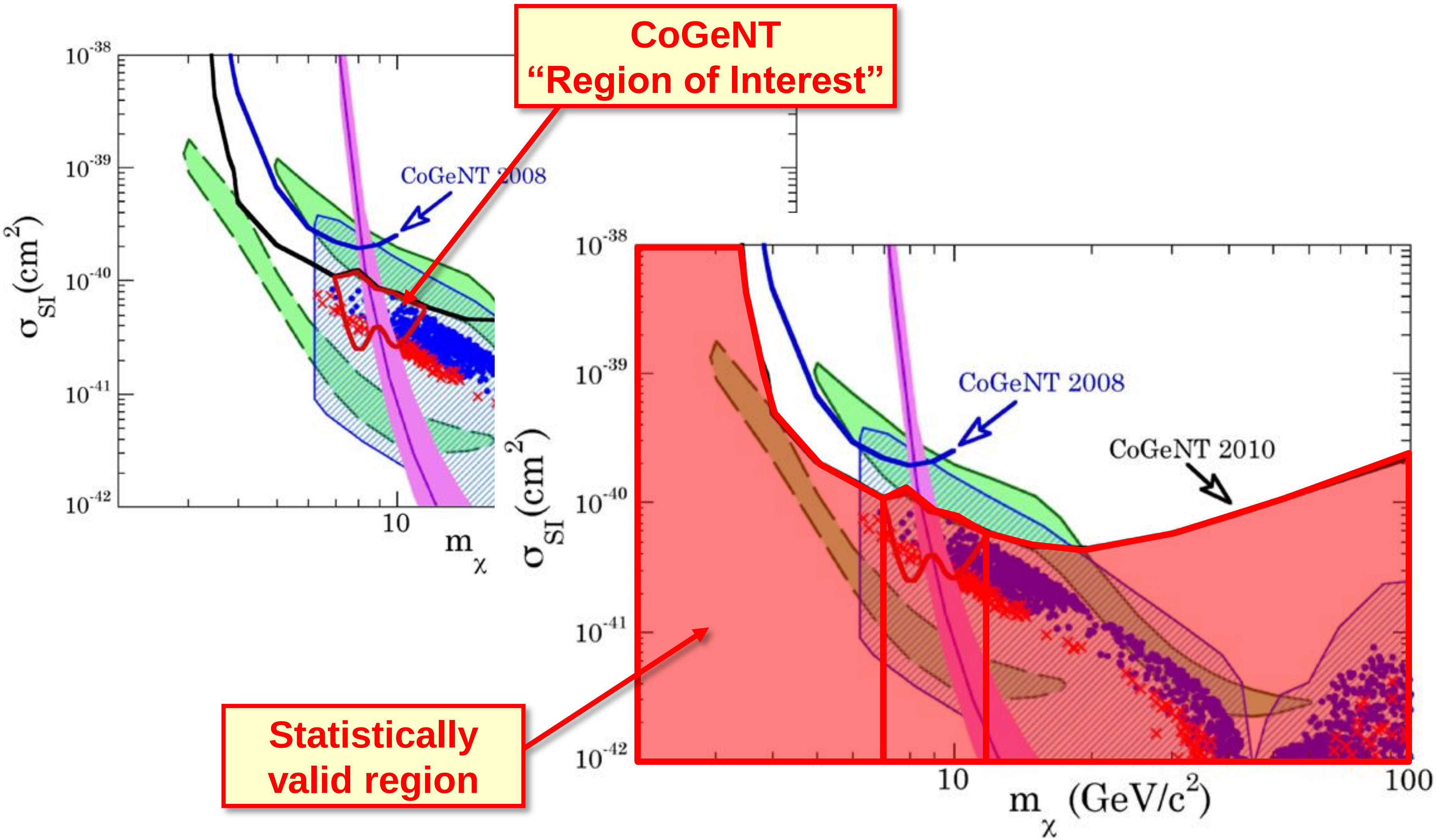
- Examples:
  - Threshold and counts-only analyses (weak statistics)
  - DAMA binning (weak statistics)
  - CoGeNT 2010 analysis (flawed/misleading statistics)
  - Collar & Fields (2012) reanalysis of CDMS low-energy data (missing/incomplete statistics)
  - XENON100 energy calibration (conservative) [later]

CoGeNT (2010)

Statistical issues:

- Cut away regions that were “uninteresting” (misleading)
- Improperly calculated regions (flawed)
  - Less than 0.5σ result (much less 90%)
  - Black box numerical routine?
- Misunderstand degrees of freedom

CoGeNT (2010)


CoGeNT
"Region of Interest"
Statistically
valid region
CoGeNT 2008
CoGeNT 2010
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
σ_{SI} (cm^2)
10
100
m_χ (GeV/c^2)

Issue:
energy calibrations

Energy Calibration

- How to reconstruct recoil energy from observed signal (e.g. scintillation)?
  - Some calibrations based upon poorly measured quantities
- Proper calibration important for sensitivity to light WIMPs since most signal is near threshold
- Examples:
  - Quenching factor **Q** in NaI (DAMA)
  - Scintillation efficiency factor **Leff** (XENON)
  - Energy resolution (XENON)

XENON Leff & energy resolution

- Can Leff uncertainties be used to reconcile experimental results?
- Assumptions are already very conservative (and *known* to be overly conservative)
  - Constraints almost certainly cannot be made weaker
  - Constraints are *very probably* significantly better at low masses
- Conservative Leff + no upward Poisson fluctuations: overkill
- Be skeptical of claims of compatibility using events over 6.7-30.5 keV

Theory specific issues

Theory specific issues

Some issues arise in relating DD results to fundamental theories (e.g. SUSY)

- Examples
  - Local dark matter density (irrelevant for compatibility)
  - Hadronic matrix elements (beyond effective nucleon-WIMP coupling framework)

Theory specific issues

Local dark matter density

- Irrelevant for compatibility
- $\Rightarrow \times 2$ uncertainty in cross-section constraints

- Hadronic matrix elements
  - Beyond effective nucleon-WIMP coupling framework
  - Irrelevant for compatibility
  - $\Rightarrow \times$3-5 uncertainty in cross-section for given WIMP-quark coupling

Summary and Remarks

- Four (possibly) positive signals for dark matter, numerous negative results

- Difficult to reconcile some experimental results (let alone all of them)

- Possibilities
  - Particle physics: maybe, but at what cost?
  - Astrophysics: unlikely
  - Unknown backgrounds: significant possibility
    - Modified/unconsidered backgrounds for CRESST, CDMS
  - Energy calibration: making things *worse*

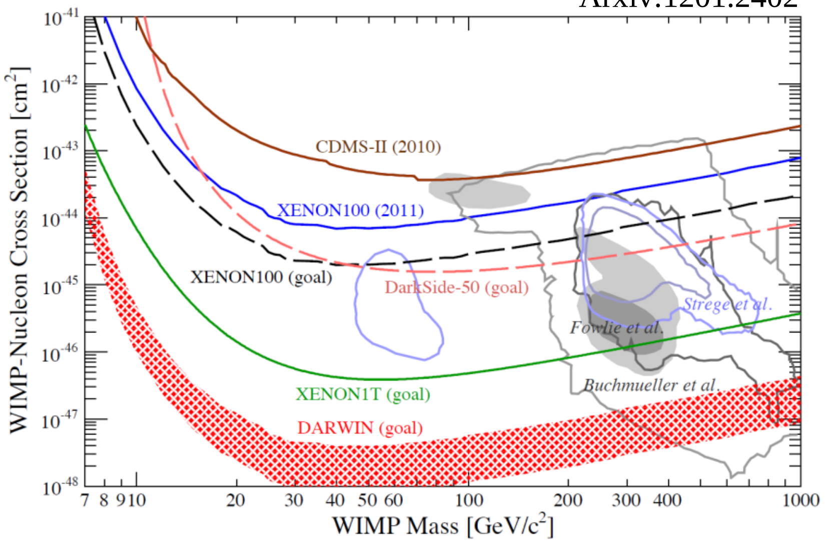
Summary and Remarks

- **DAMA**: most difficult to reconcile, but impervious to postulated backgrounds (so far)
- **CoGeNT**: how to reconcile with CDMS low-energy results? (same material & energy range)
- **CRESST**: explained by surface roughness?
- **CDMS Silicon**: need to lower trigger threshold
- Answers in upcoming results…

Future

- Low mass region
  - **LUX**: XENON-like, better light collection [this year]
  - **SuperCDMS**: low-energy analysis with cleaner detectors [this year]
  - **CDMSlite**: very low energy, ionization-only [this year]
  - **DM-Ice**: southern hemisphere [???]
    (also ANAIS, KIMS)

Arxiv:1201.2402



- SUSY "preferred" regions
  - **LUX**: ×10 improvement in sensitivity [this year]
  - **XENON1T**: ×100 [2015]
  - **DARWIN**: ×1000 [2018]
  - …

- …and beyond: solar neutrino background