Direct Detection of Dark Matter: Status and Issues

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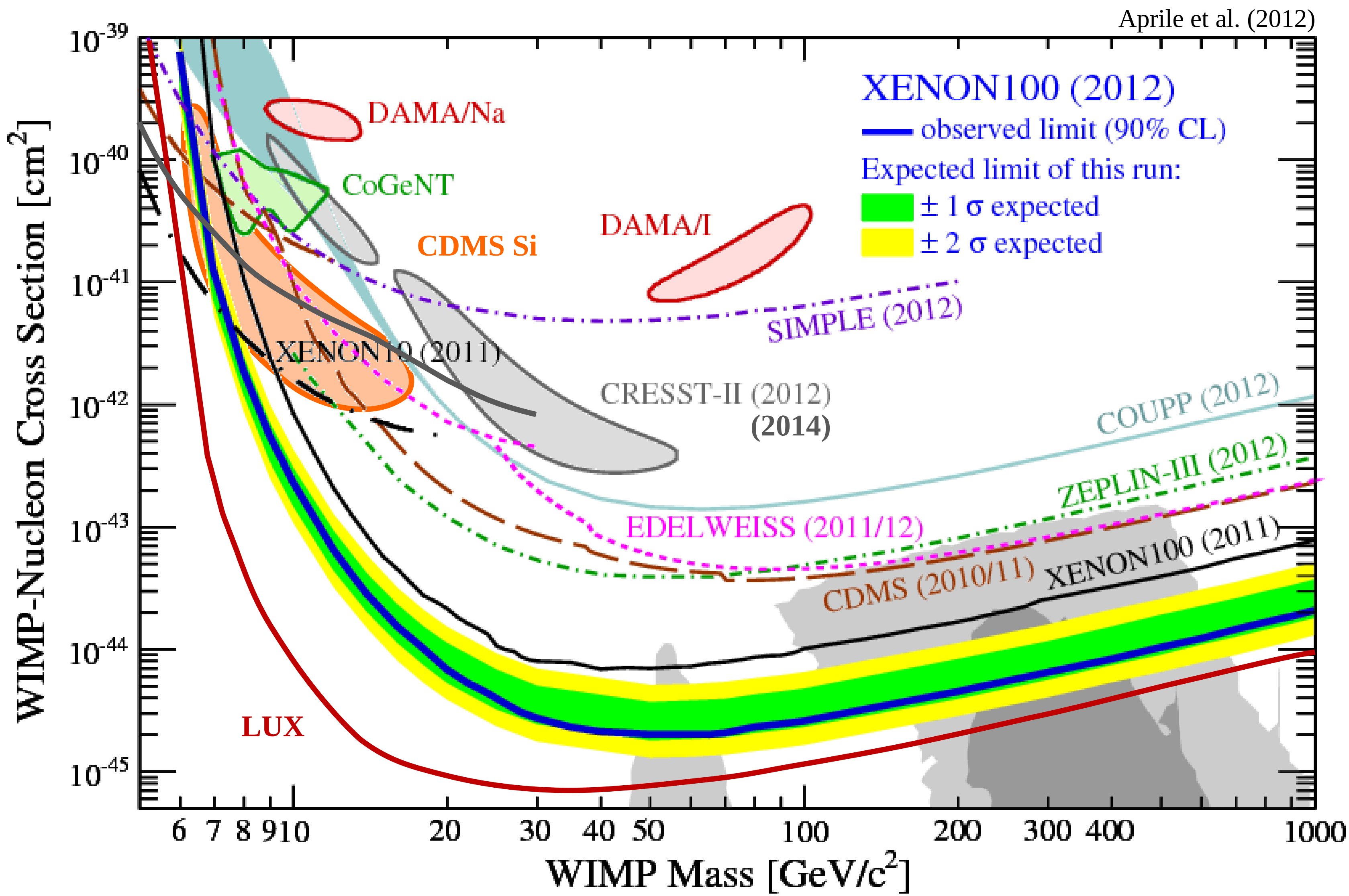
Overview



Aprile et al. (2012)
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)
(2014)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
XENON100 (2011)
CDMS (2010/11)
LUX
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]

Overview

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

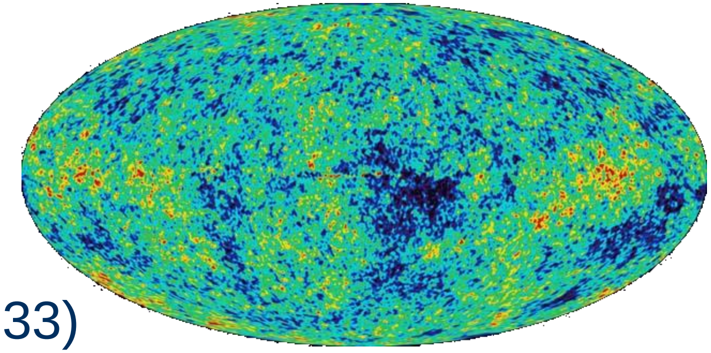
Outline

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

Ask questions at any point !

Dark Matter Overview

Why Dark Matter?



NASA/WMAP Science Team

- 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

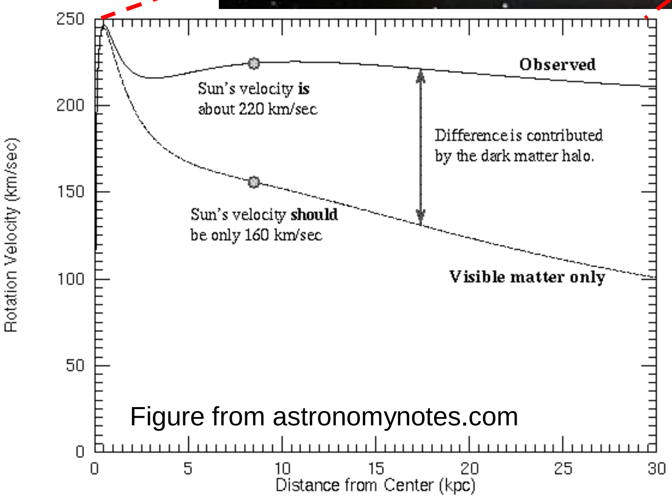


Figure from astronomynotes.com

Colley et al. (HST)

What is Dark Matter?

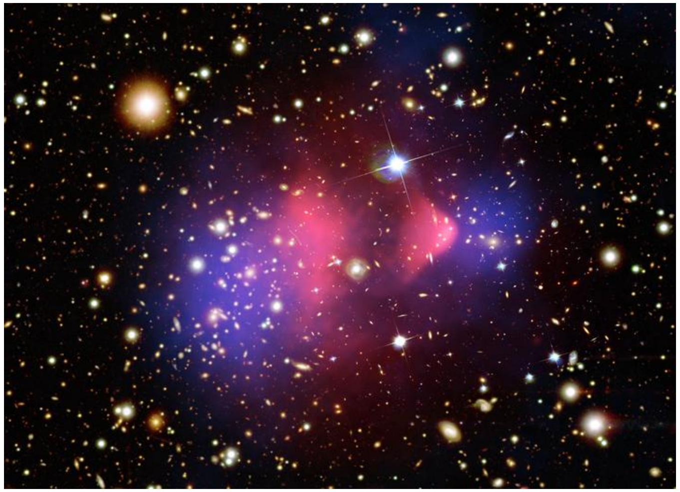
Is it...

- ...astrophysical objects?

  Massive Astrophysical Compact Halo Objects (MACHOs)
  - Microlensing searches: **not significant contribution to DM**

- ...a modification to gravity?

  MOdified Newtonian Dynamics (MOND), Tensor-Vector-Scalar gravity (TeVeS)
  - Bullet cluster: **disfavored**
  - …also: poor fit to CMB & LSS



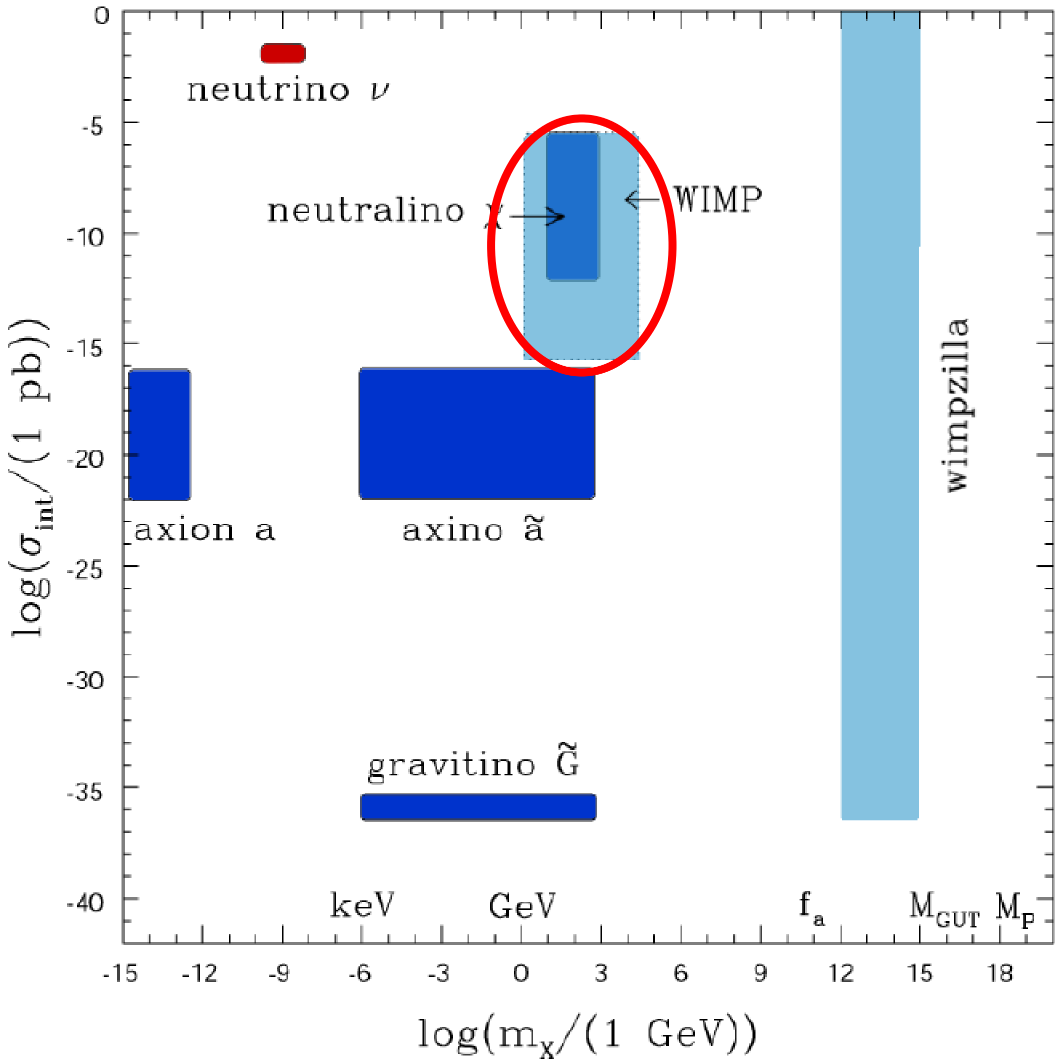
NASA/CXC/CfA/M.Markevitch et al.; NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; ESO WFI

What is Dark Matter?

...Particles!

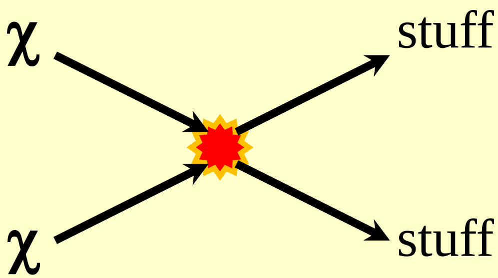
- Axions
- WIMPs
- Gravitino
- Sterile neutrinos
- WIMPzilla
- …

Roszkowski (2004)

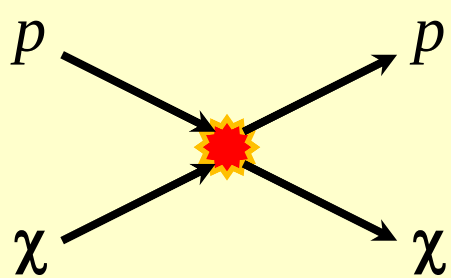


How to detect Dark Matter?

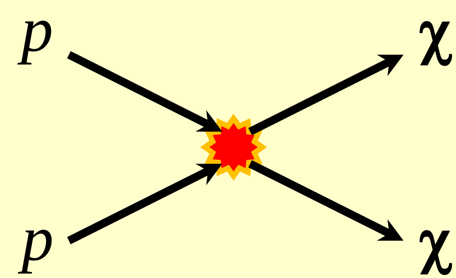
Interactions with Standard Model particles



Annihilation



Scattering



Production

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

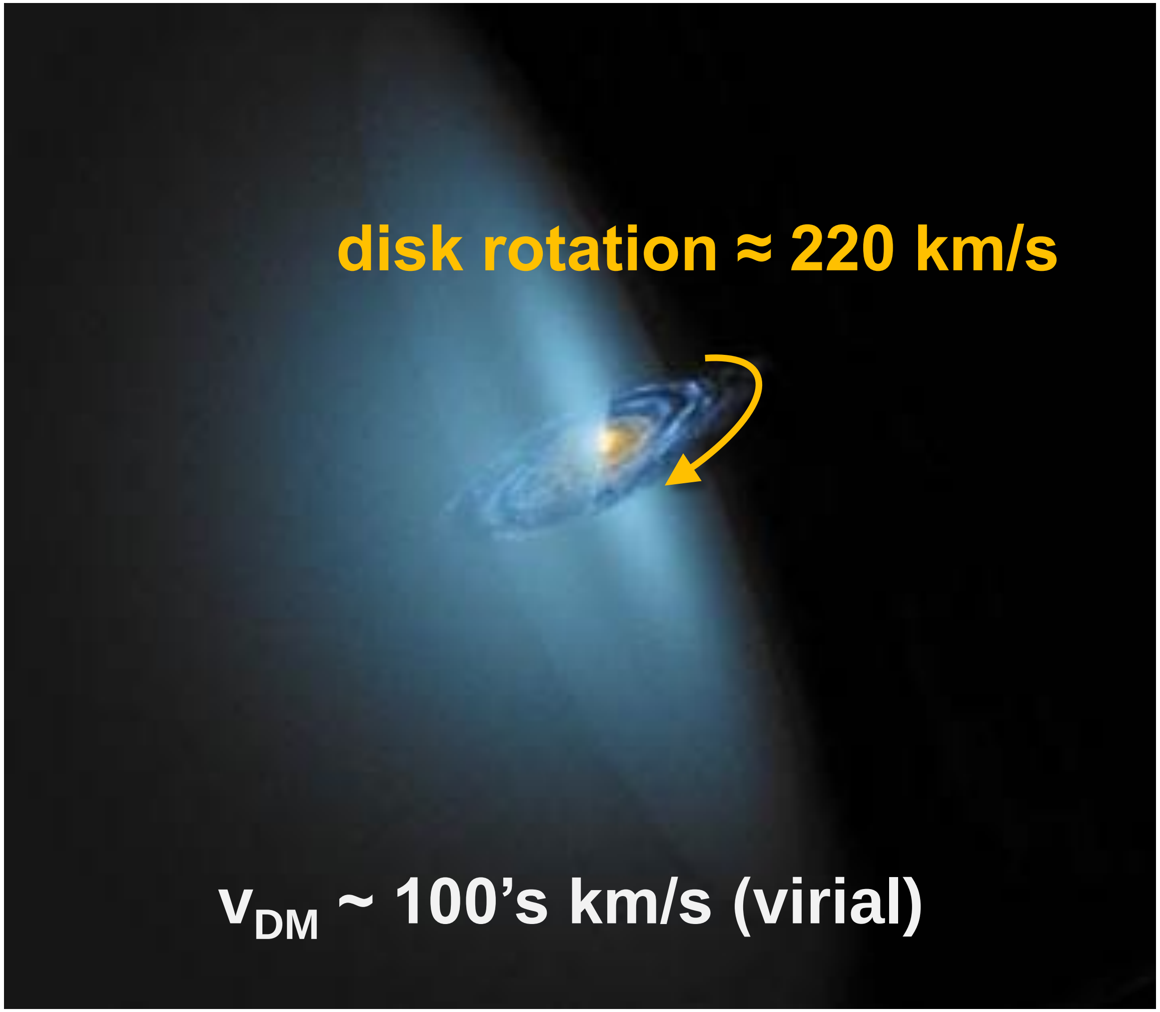
Direct Detection:
Look for scattering events in detector

Accelerators:
LHC

Direct Detection

Dark Matter Halo

D. Dixon, cosmographica.com

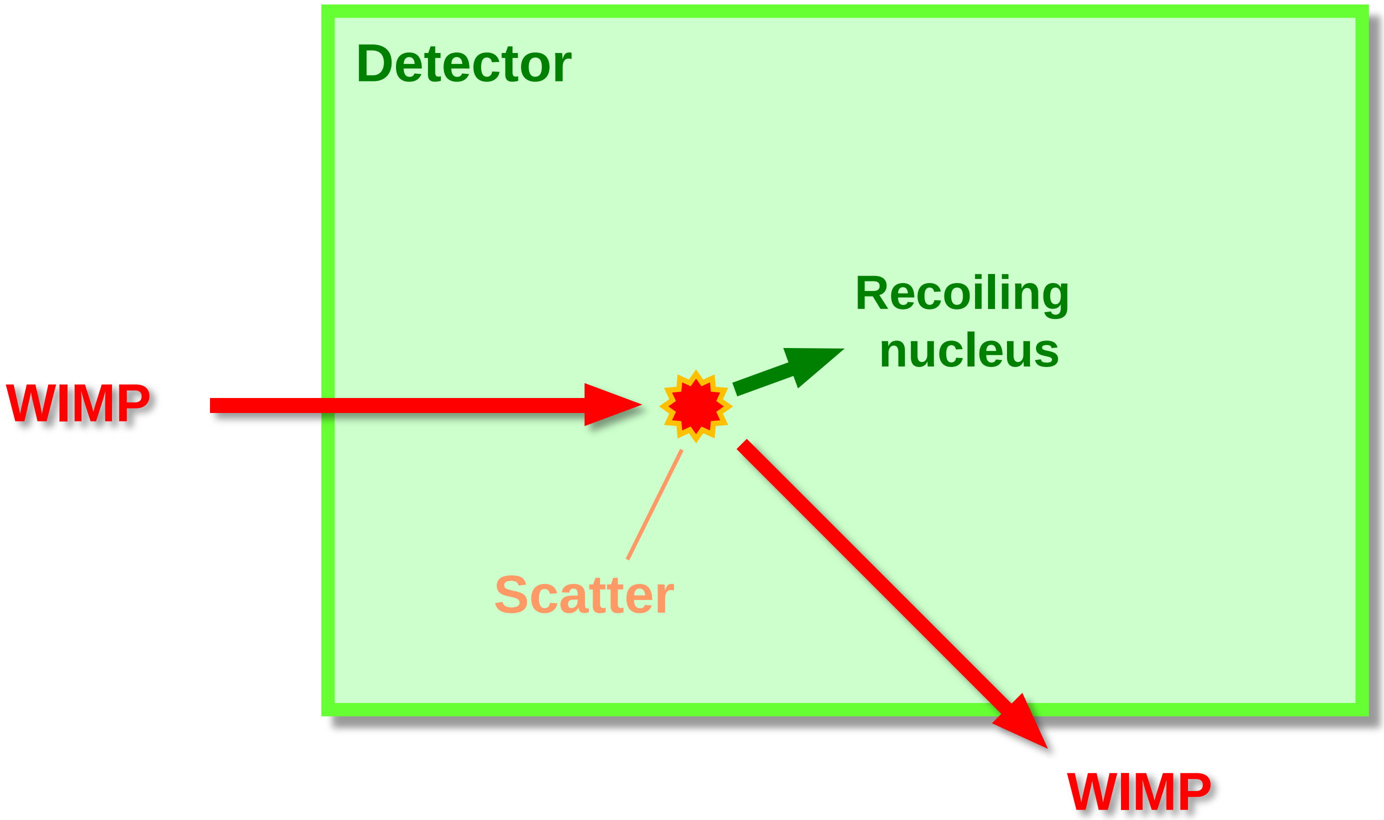


Direct Detection

Goodman & Witten (1985)

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

- Non-relativistic: elastic scattering of WIMP off detector nuclei → O(10 keV) recoil

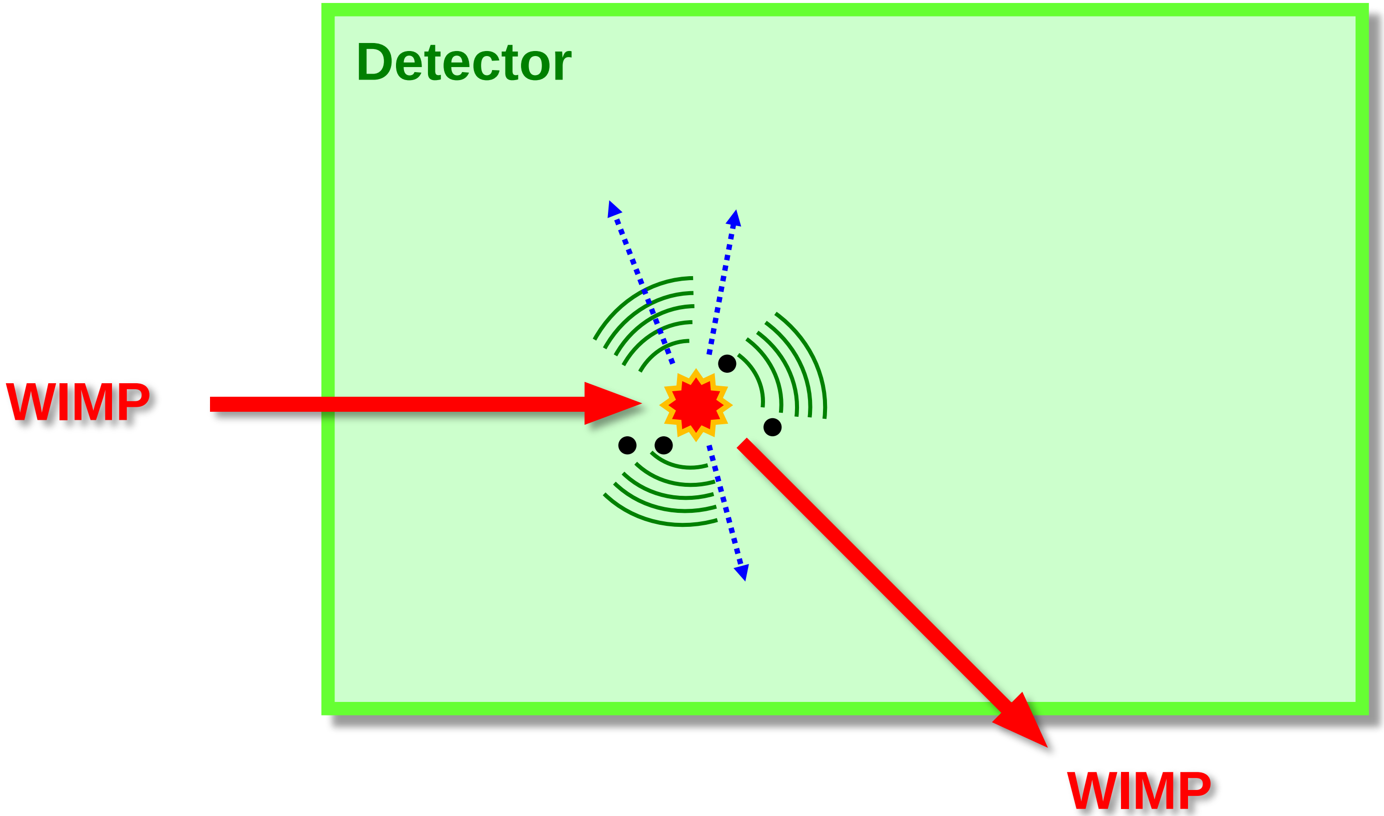


Direct Detection

Goodman & Witten (1985)

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

- Observables:
  phonons/heat, **scintillation**, **ionization**

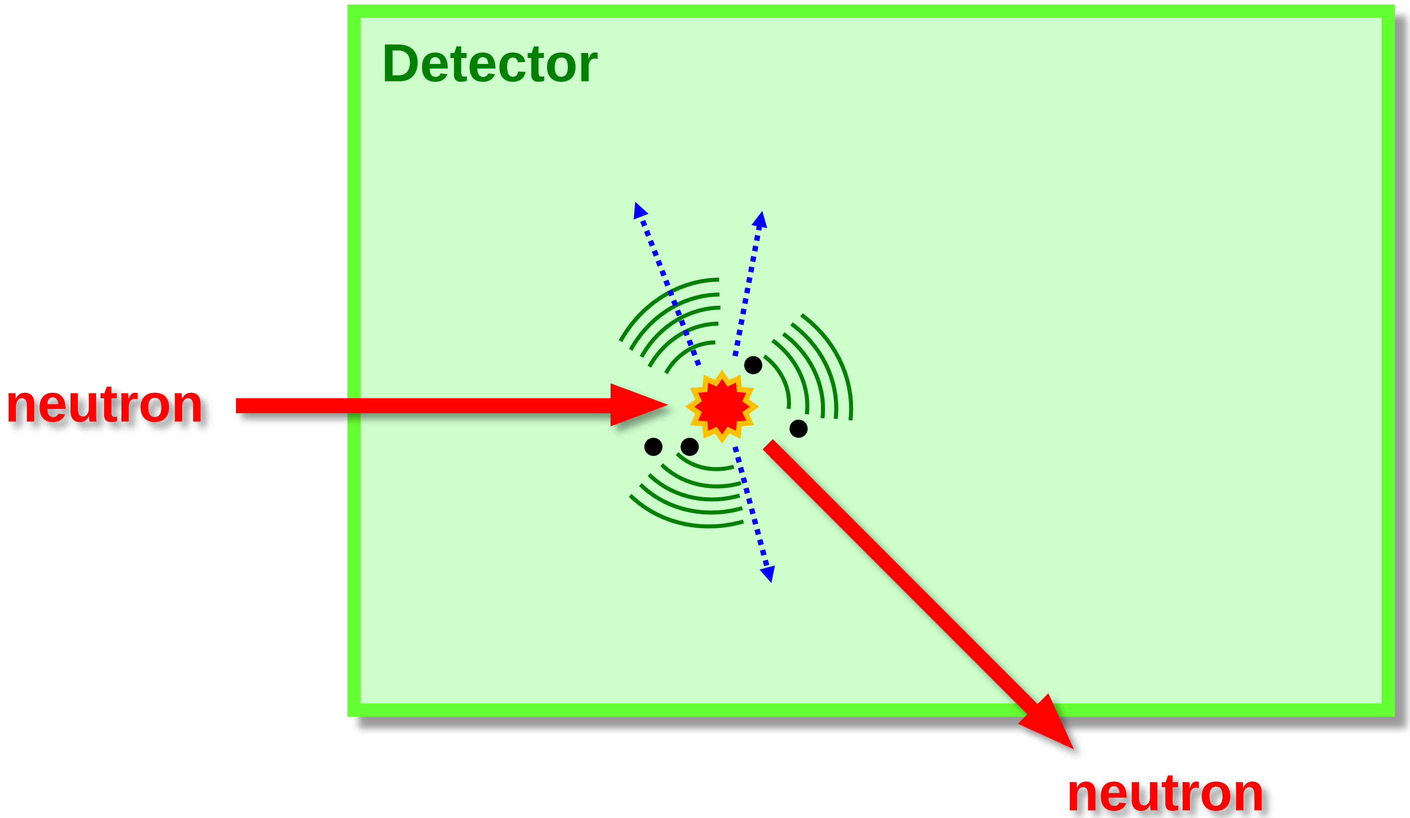


Direct Detection

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

Goodman & Witten (1985)

- Backgrounds:
  neutrons (nuclear recoils)



Direct Detection

Goodman & Witten (1985)

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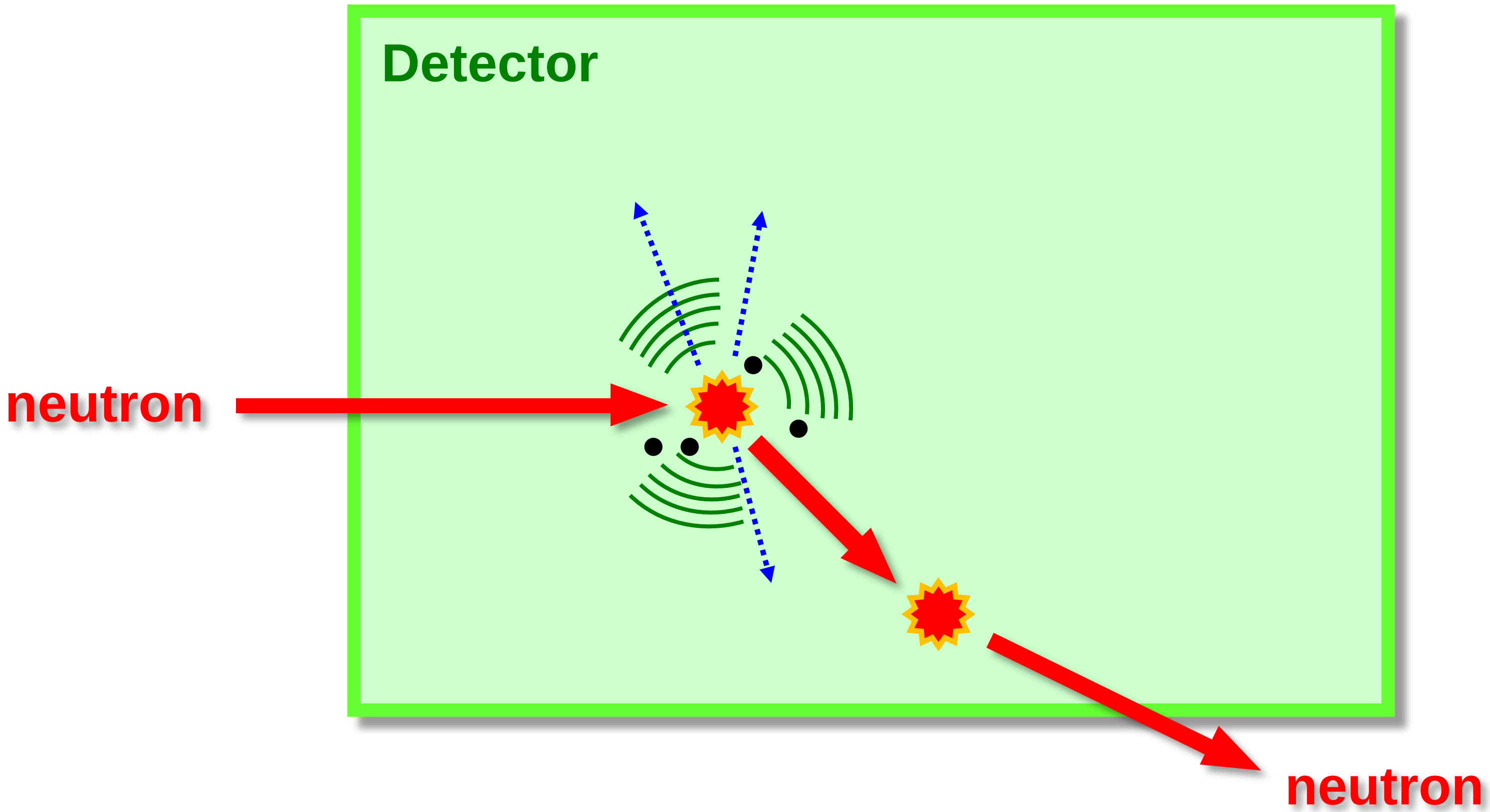
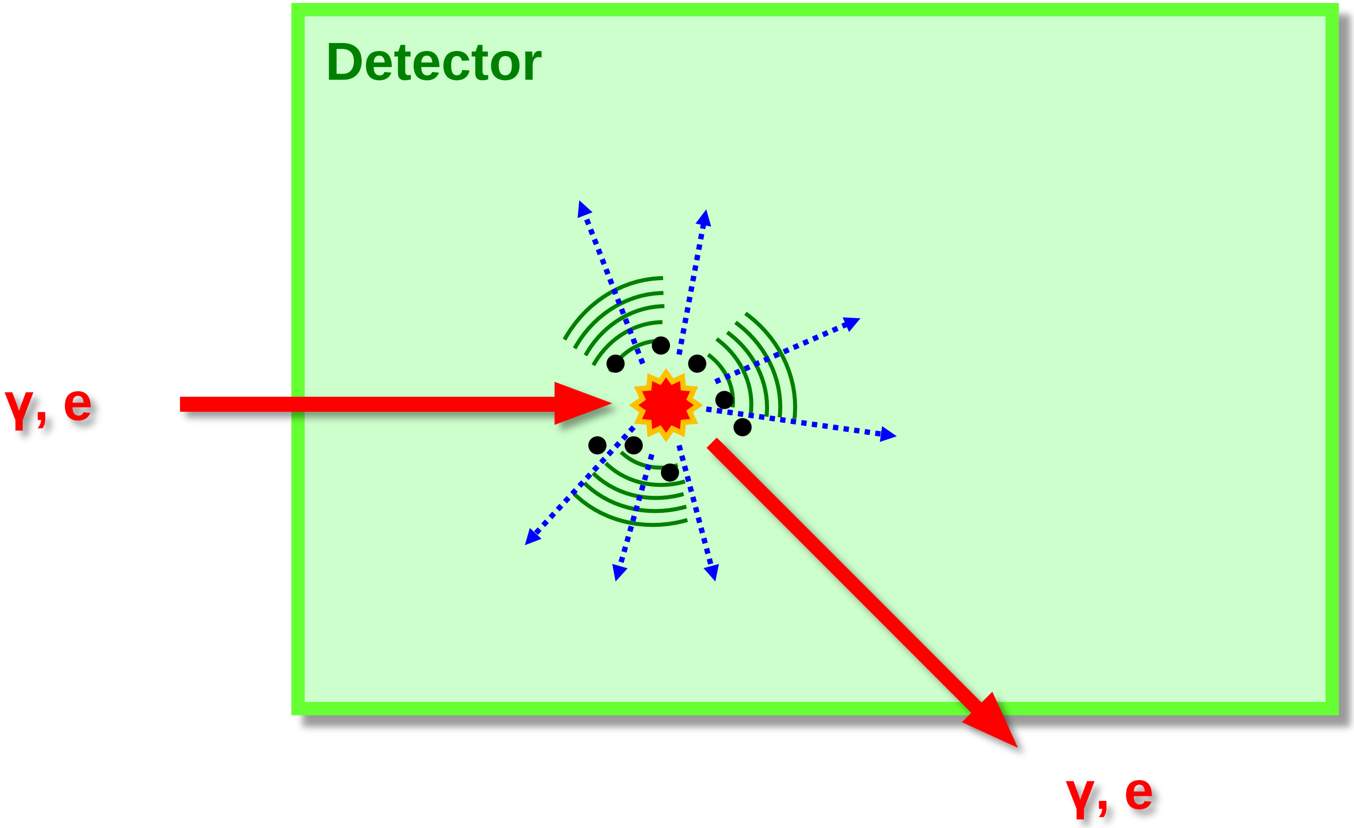


Direct Detection

Goodman & Witten (1985)

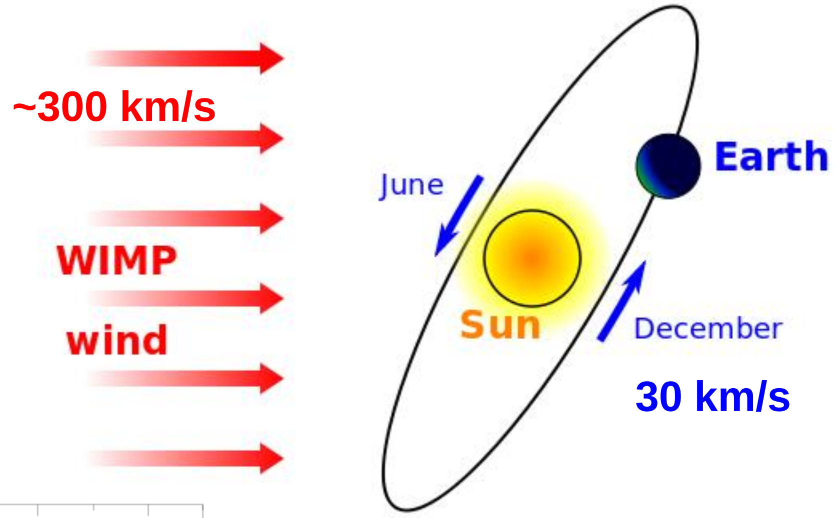
See Freese, Lisanti & CS (2012)
for a review

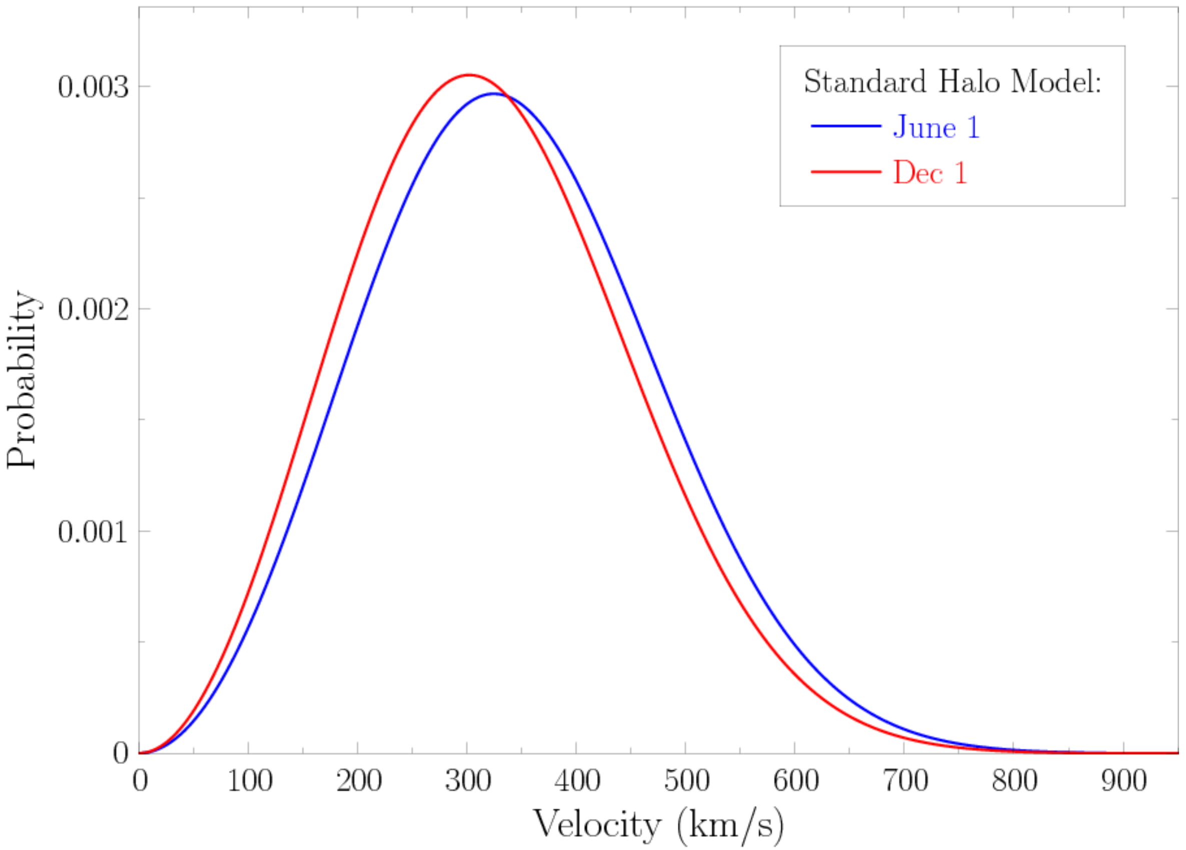
- Backgrounds:
  x-rays, gamma-rays, betas (electron recoils)



Annual Modulation

Drukier, Freese & Spergel (1986)





Recoil Spectrum

- Recoil rate:

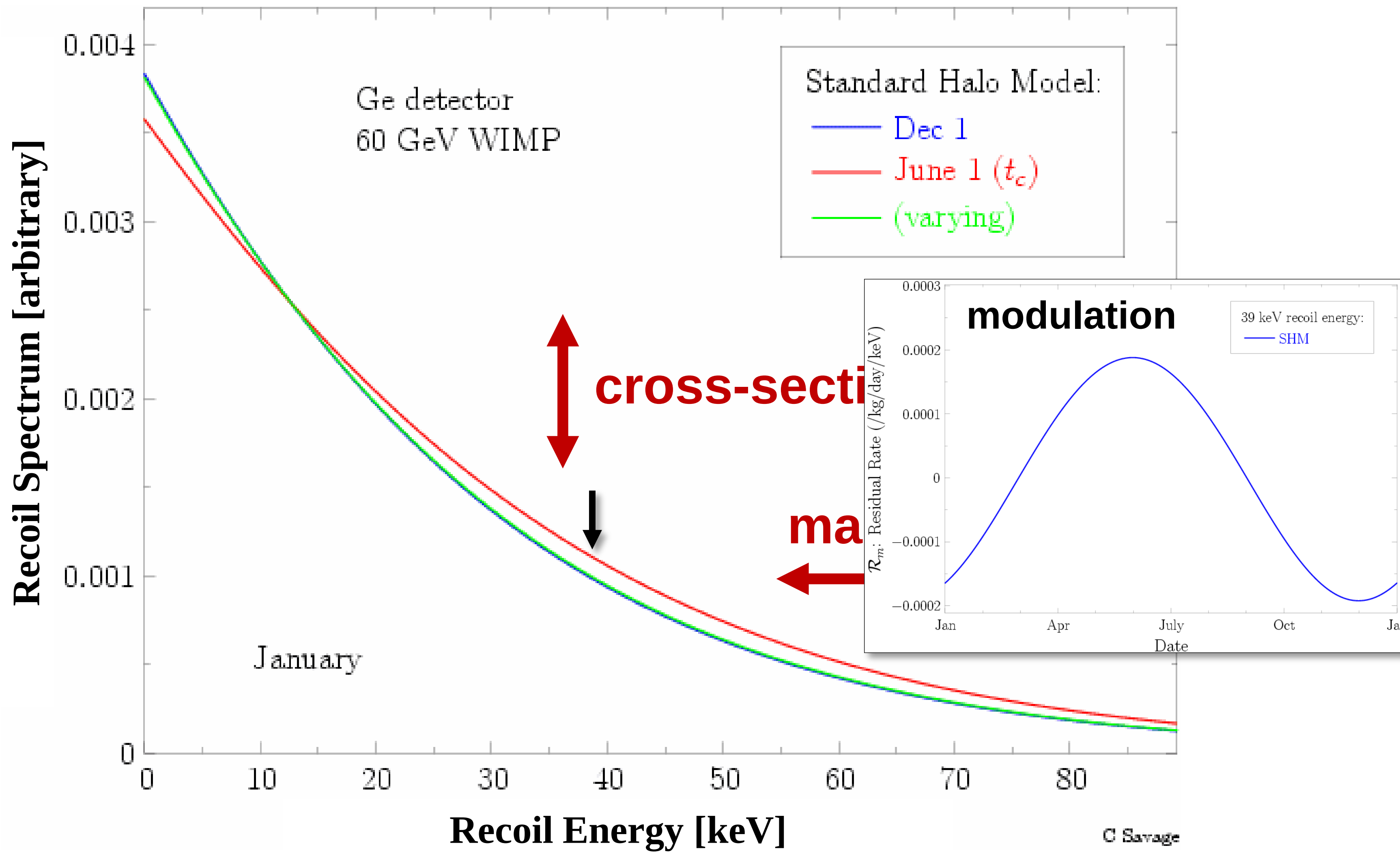
$$R \sim n_\chi \langle \sigma v \rangle$$

$$\eta(E,t) \equiv \int_{v > v_{\min}(E)} d^3v \, \frac{1}{v} \, f(\mathbf{v},t)$$

- Recoil spectrum (isotropic scattering):

$$\frac{dR}{dE}(E,t) = \underbrace{\frac{1}{2m\mu^2} \sigma_0 F^2(q)}_{\substack{\textbf{Particle Physics:} \\ \text{WIMP-nucleus interaction}}} \; \underbrace{\rho_0 \, \eta(E,t)}_{\substack{\textbf{Astrophysics:} \\ \text{WIMP distribution}}}$$

Recoil Spectrum



Direct Detection (summary)

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)

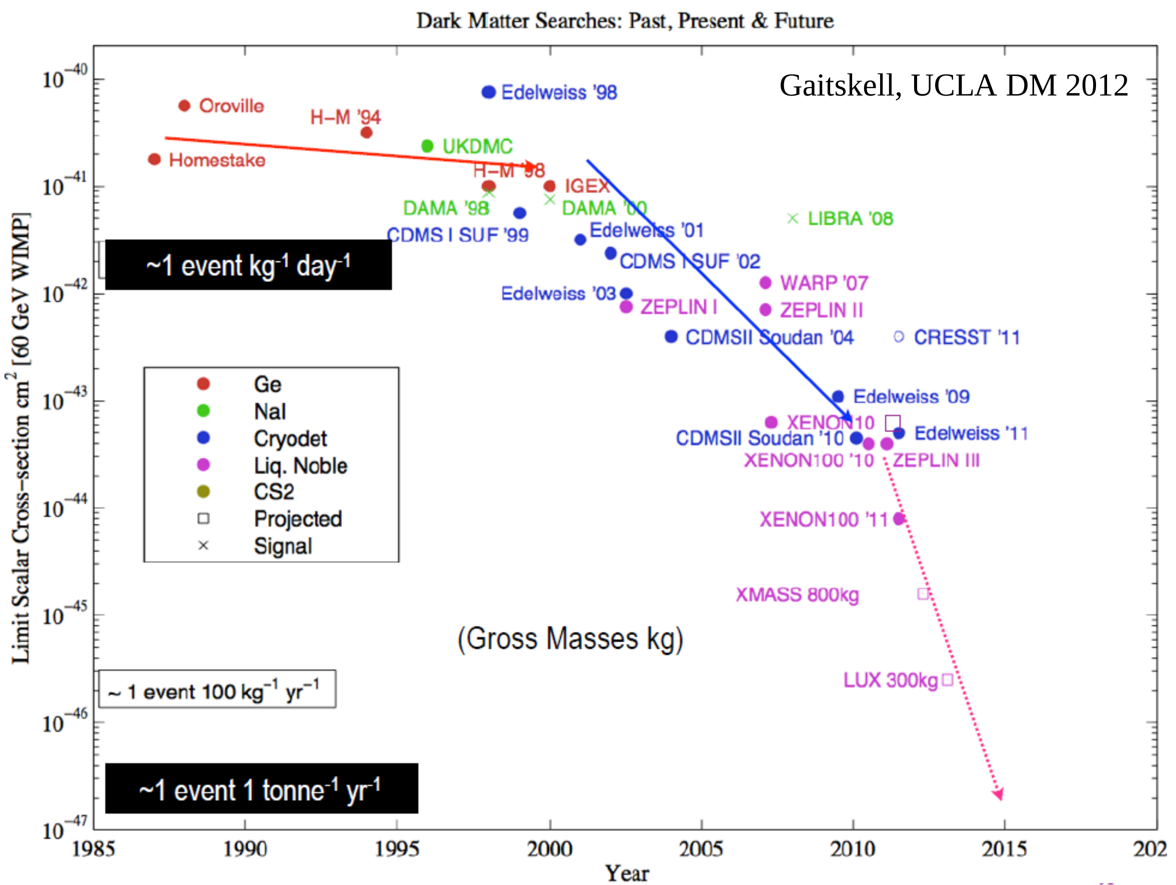
- Backgrounds
  - Electron recoils: gammas, betas
  - Nuclear recoils: neutrons

Reduce backgrounds: material selection, deep underground

Experiments and Results

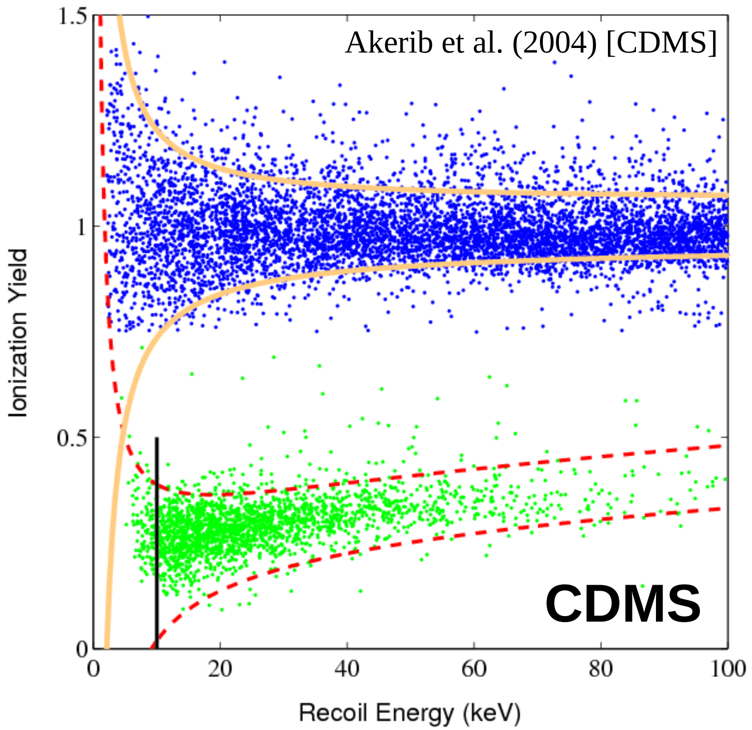
Experiments

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



Background Discrimination

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



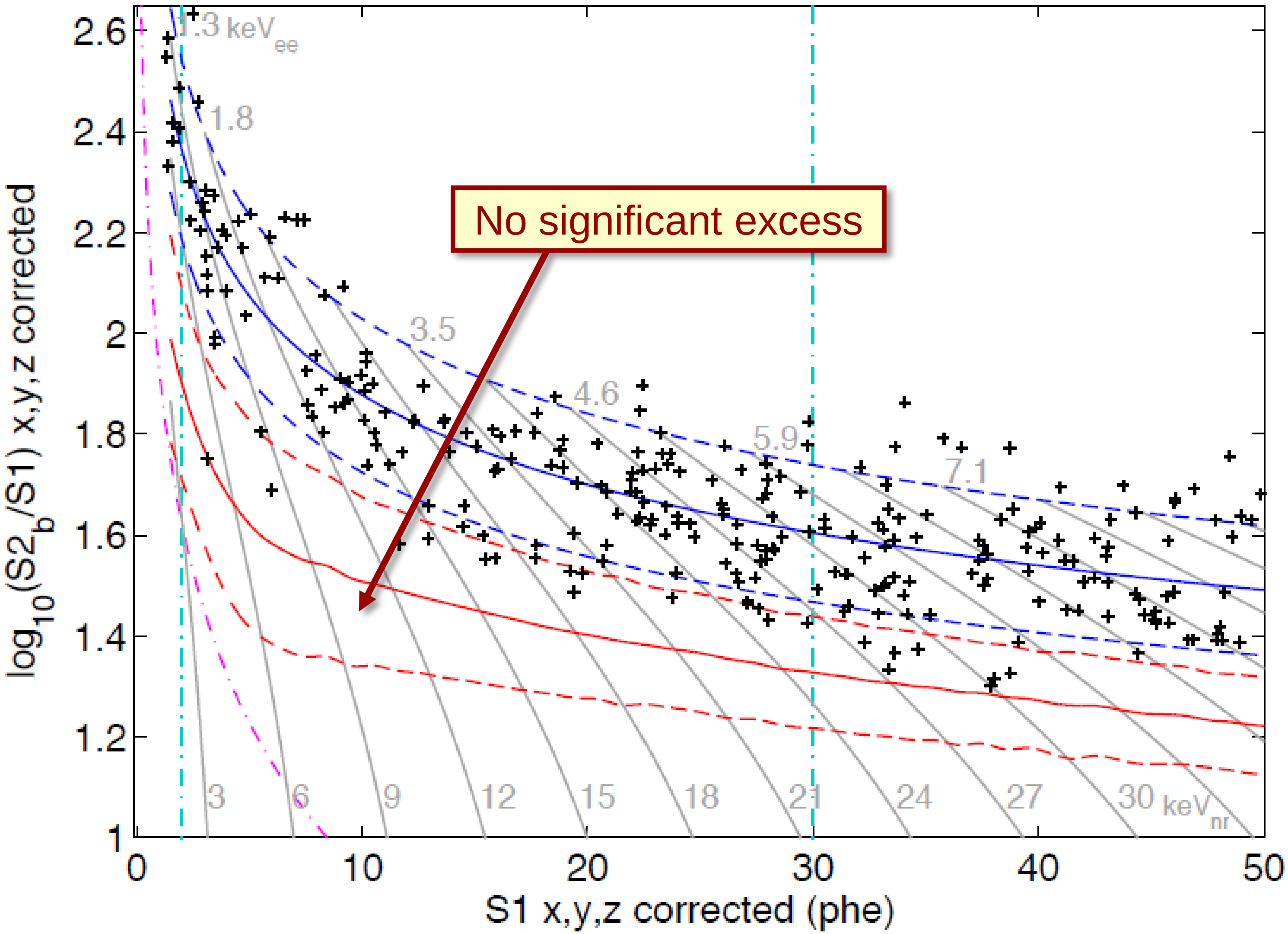
(phonons)

γ source (electron recoils)

n source (nuclear recoils)

LUX

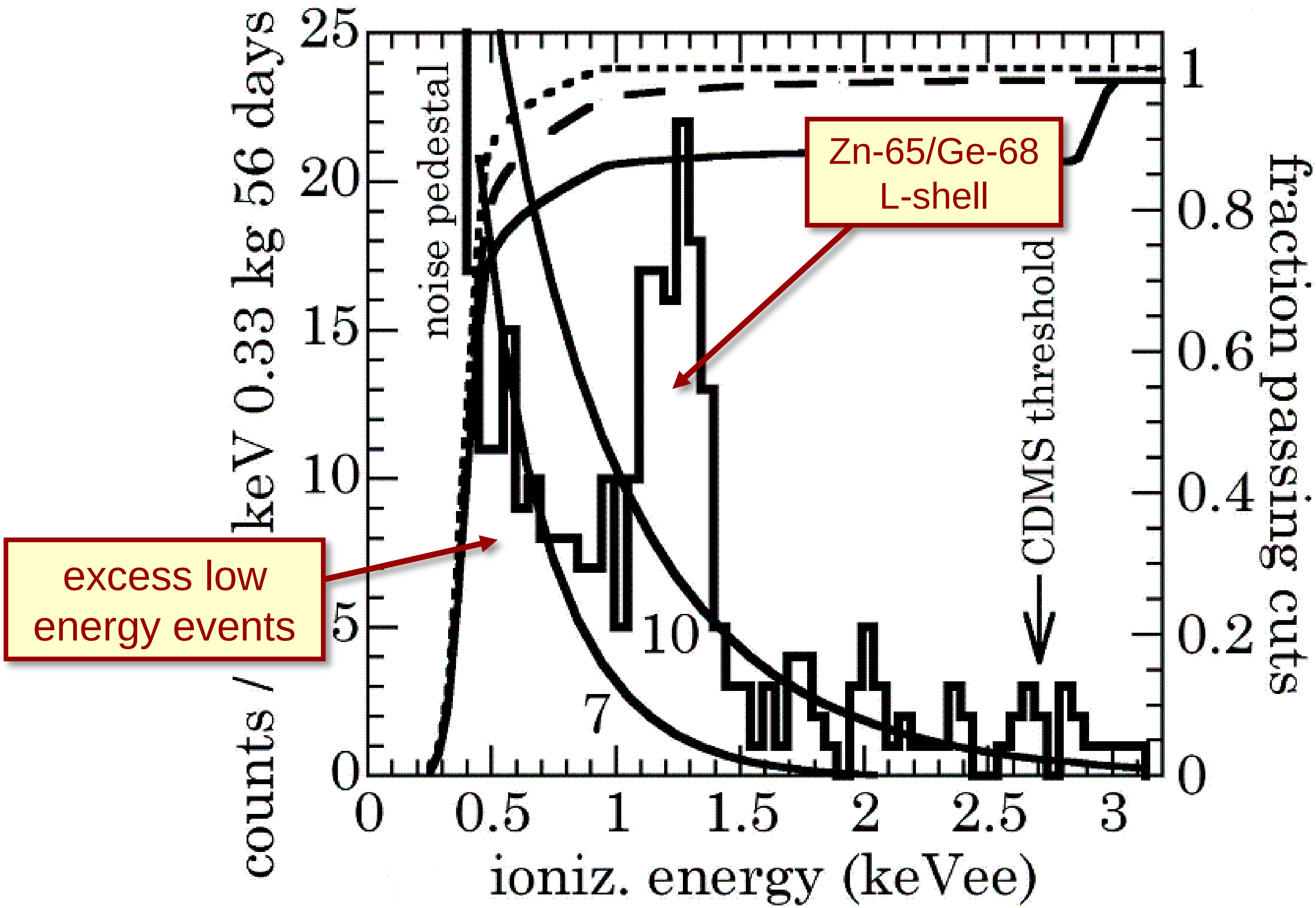
LUX [Xe]
arxiv:1310.8214



CoGeNT

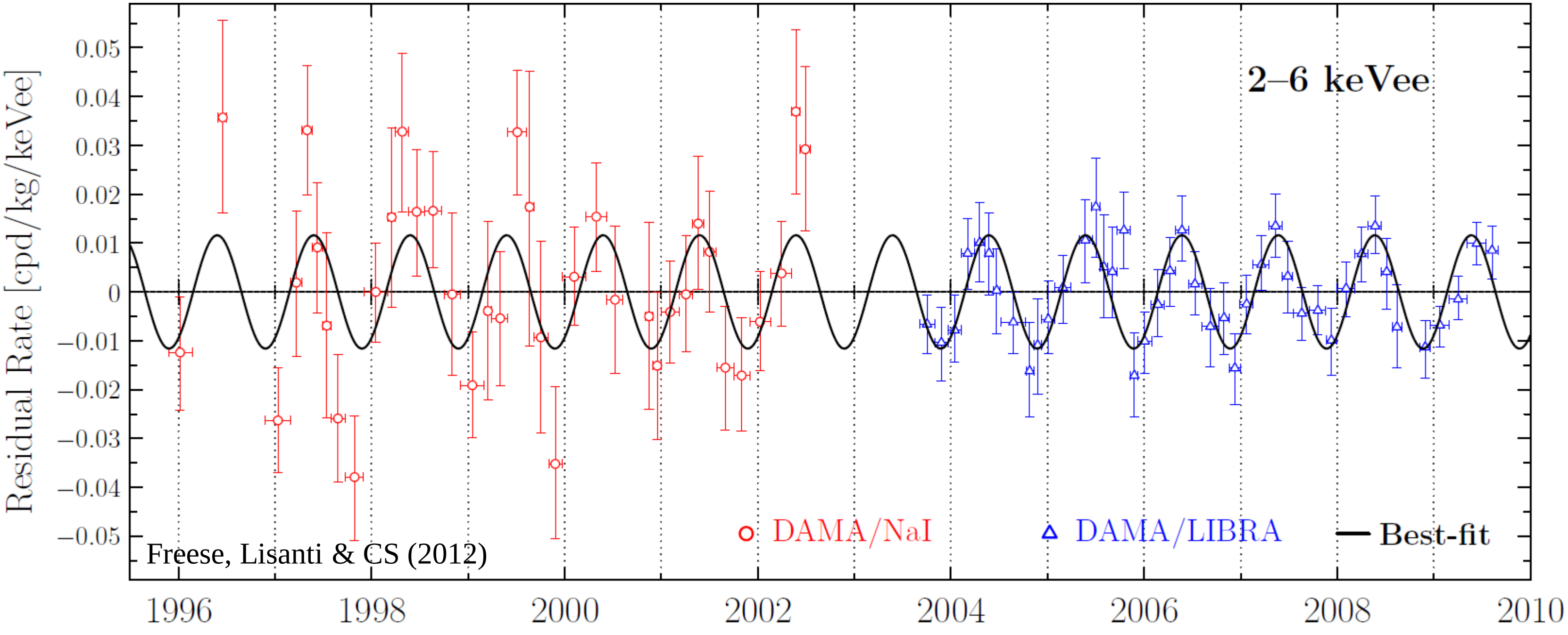
CoGeNT [Ge]
PRL **106**, 131301 (2011)

- Ionization only (limited discrimination)



DAMA results

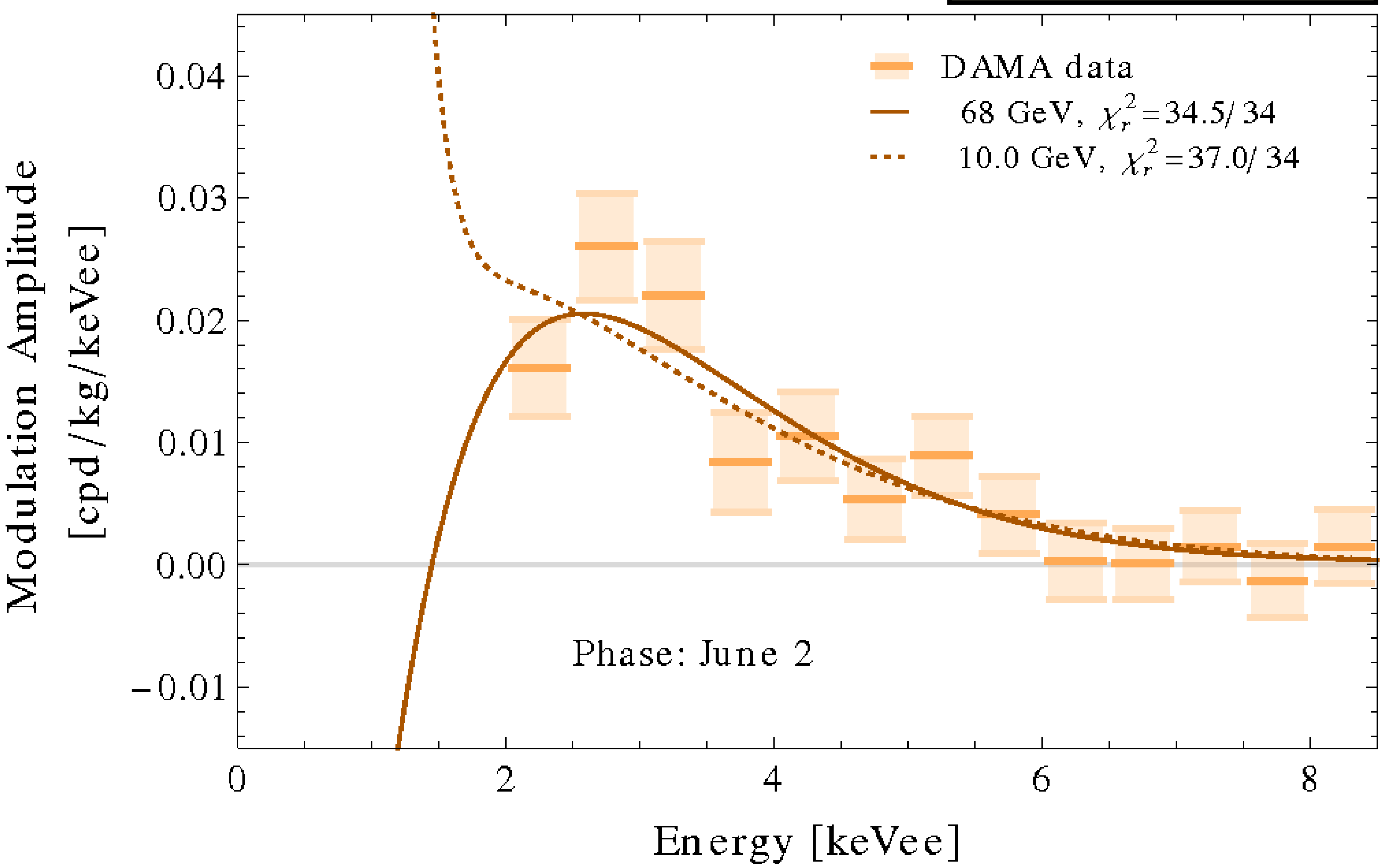
- Modulation search using NaI crystals (scintillation only)
  - DAMA/NaI: 1996-2002 R. Bernabei *et al.*, Riv. Nuovo Cim. **26N1**, 1 (2003)
  - DAMA/LIBRA: 2003-2009 R. Bernabei *et al.*, Eur. Phys. J. **C67**, 039 (2010)



8.9σ annual modulation

DAMA results/fits

Kelso, Sandick & CS (2013)



Other experiments

- Possible signals
  - CDMS silicon: see 3 events, modeled bkgds < 1 event
  - CoGeNT modulation (< 3σ)
  - CRESST: see ~ 70 events, expected ~ 40 bkgd events (2012)
- Null results
  - CDMS germanium, XENON100 (low-background)
  - CDMS (modulation)
  - SuperCDMS, XENON10 (low-threshold)
  - COUPP, CRESST (2014), DEAP/CLEAN, DM-Ice, DRIFT, EDELWEISS, PICASSO, SIMPLE, TEXONO, XMASS, ZEPLIN,…
- Future
  - XENON1T, DARWIN,…

Experimental analysis: standard assumptions

Spin-independent, elastic scattering

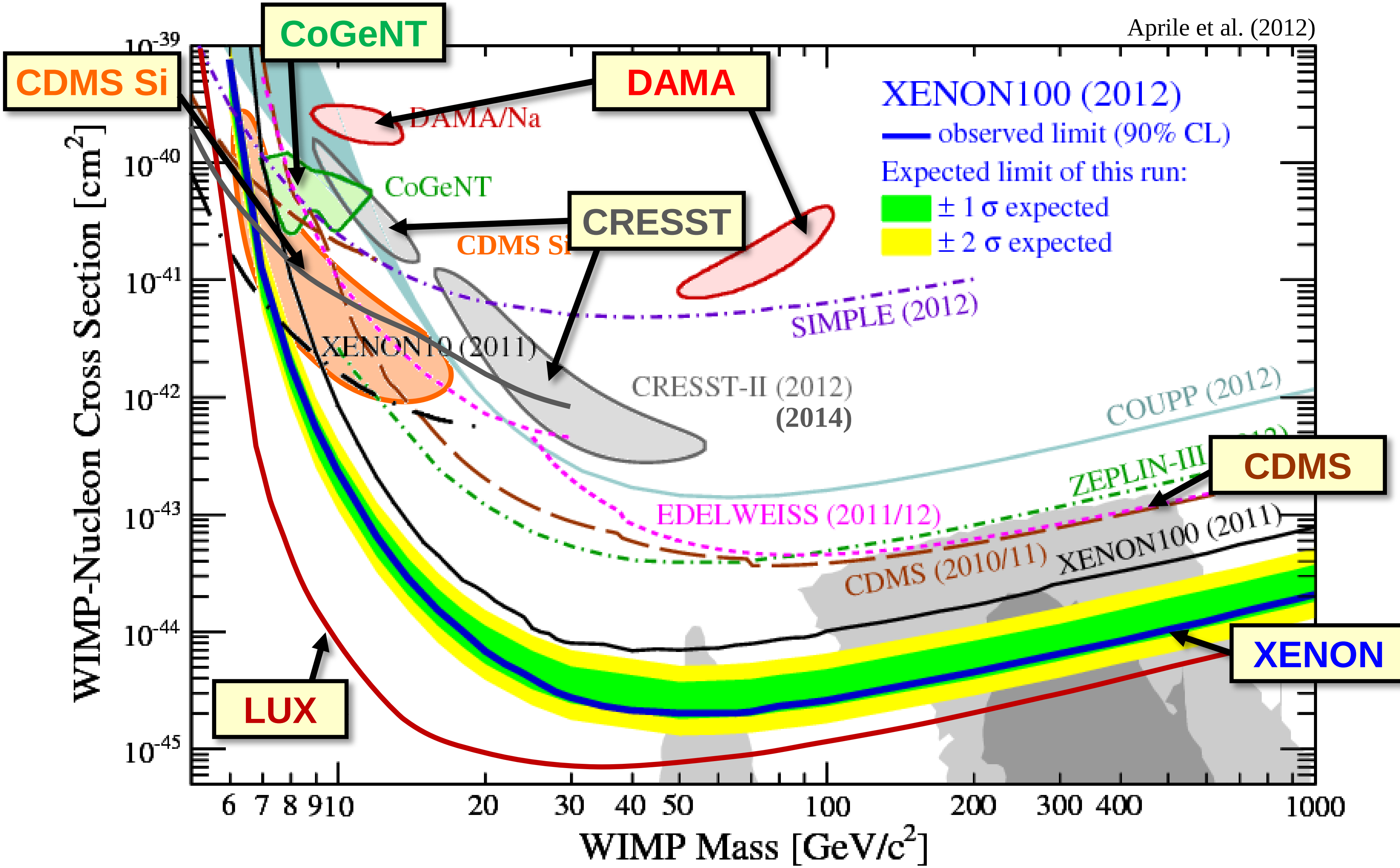
- WIMP mass
- Cross-section $\sigma \propto A^2\sigma_p$

Standard Halo Model

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

D. Dixon, cosmographica.com

Experimental results



Issues

Issues

What issues can affect interpretation of direct detection results?

- Particle physics (interactions)
- Astrophysical uncertainties (halo)
- Poorly understood/unknown backgrounds
- Statistical analysis
- Detector energy calibrations

Particle Physics Issues

Assumption: single SI cross-section

Other possibilities:

- Spin-dependent couplings — no (SIMPLE, PICASSO)
- Isospin-violating dark matter — probably not, fine tuned
- Inelastic scattering — now excluded*
- Couplings to electrons instead of nuclei — technical difficulties
- Asymmetric DM, Mirror DM, composite DM,…

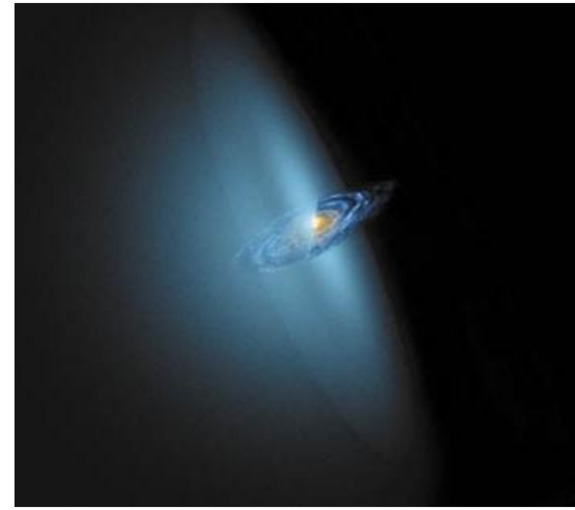
  See e.g. Petraki & Volkas, IJMPA 28, 1330028 (2013); Foot, Phys. Lett. B703, 7 (2011); Khlopov, Mod. Phys. Lett. A26, 2823 (2011)
- …

Ad hoc, fine-tuning, marginal compatibility,…

Astrophysical Issues

- Assumed isothermal sphere.
  How reasonable is this?

N-body w/ baryons: reasonable



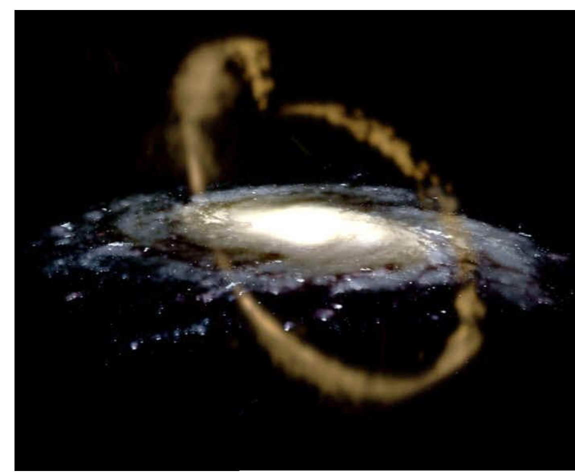
D. Dixon, cosmographica.com

- Structure? (e.g. tidal streams)

Halo-independent analyses:
compatibility not possible
Fox, Liu & Weiner (2011); Frandsen et al. (2012);
Gondolo & Gelmini (2012)

- Local density: uncertain by $\times 2$

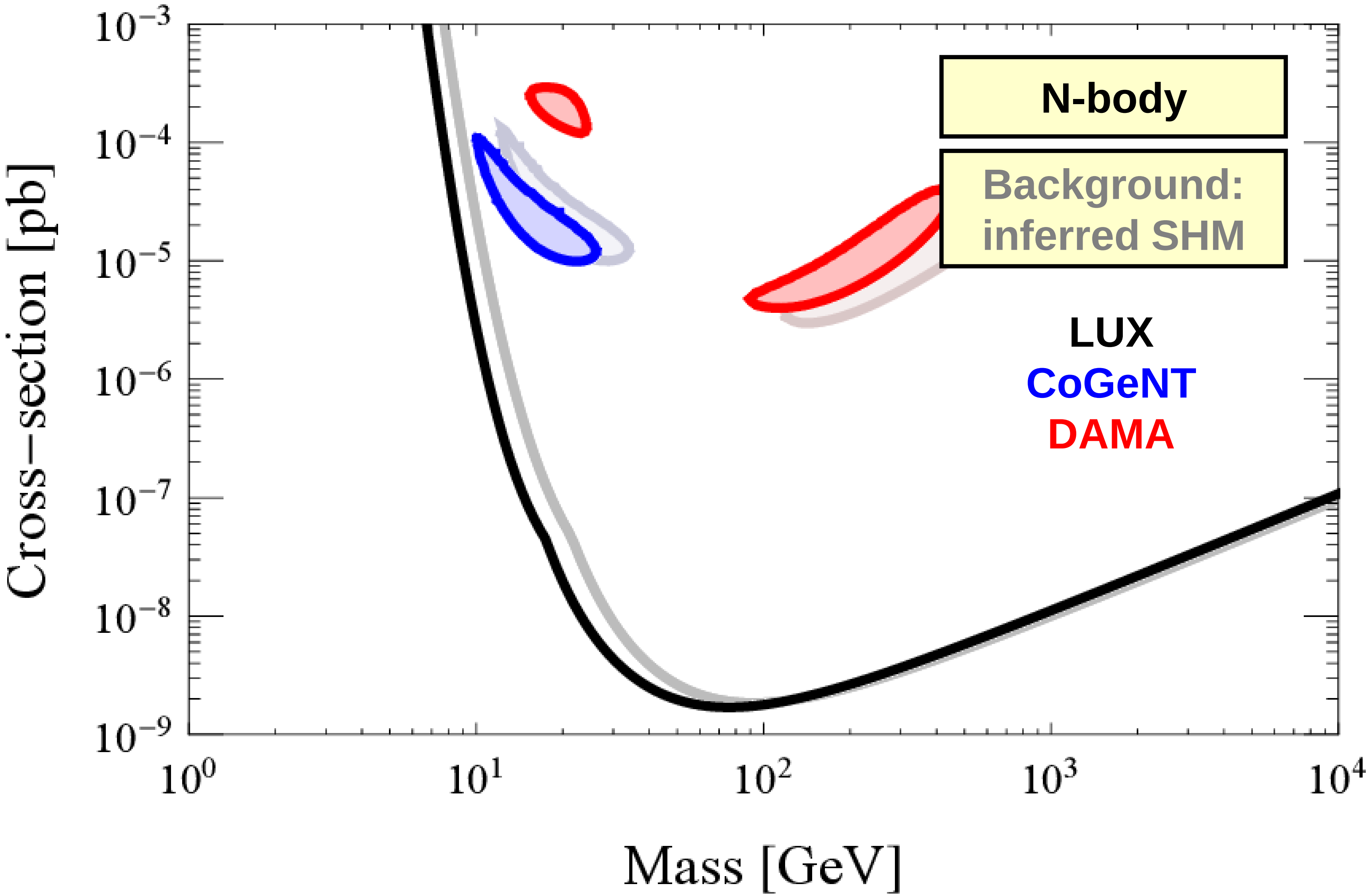
Does not affect compatibility
(…but issue for theorists)



D. Martinez-Delgado & G. Perez

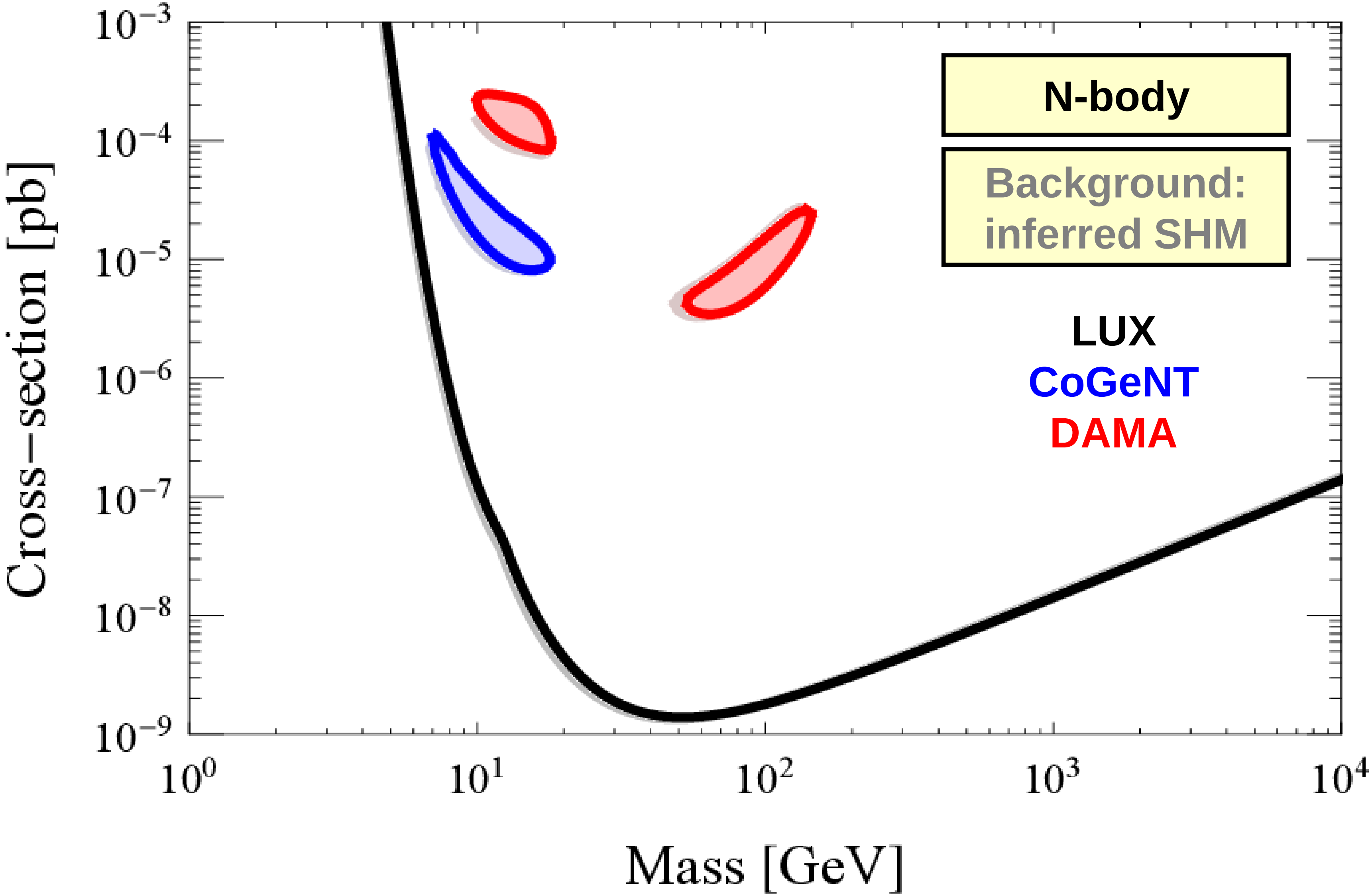
N-body simulation (DM-only)

CS, Kelso, Valluri, Freese & Stinson (in progress)



N-body simulation (DM+baryons)

CS, Kelso, Valluri, Freese & Stinson (in progress)



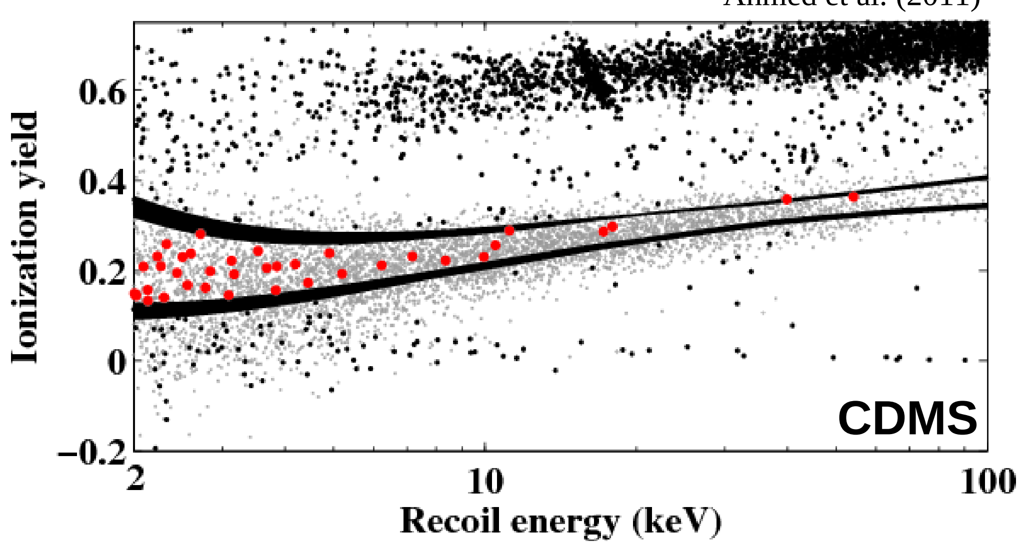
Backgrounds

Be cautious near thresholds…

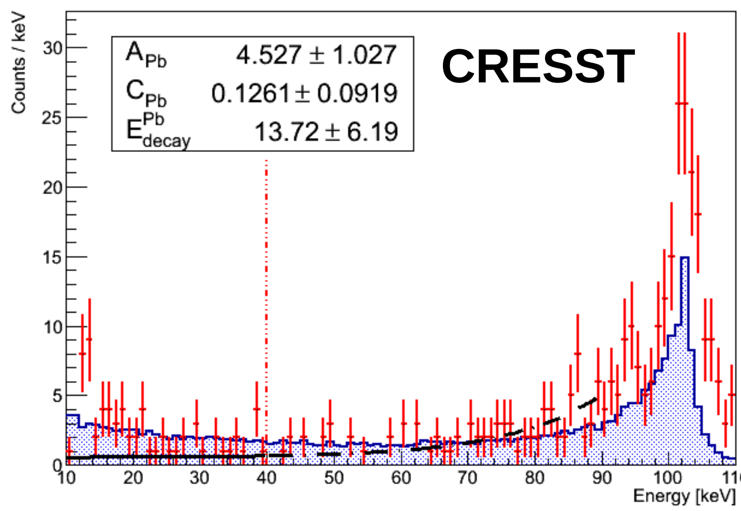
- Low energy, low rate detectors
  - Backgrounds often not well characterized/understood
  - Novel detectors sometimes present new and unexpected sources of background events

- Potential source of “signal”

Ahmed et al. (2011)



Kuzniak et al. (2012)



Also: CoGeNT surface events [Davis et al. (2014)]

Statistical Analysis Issues

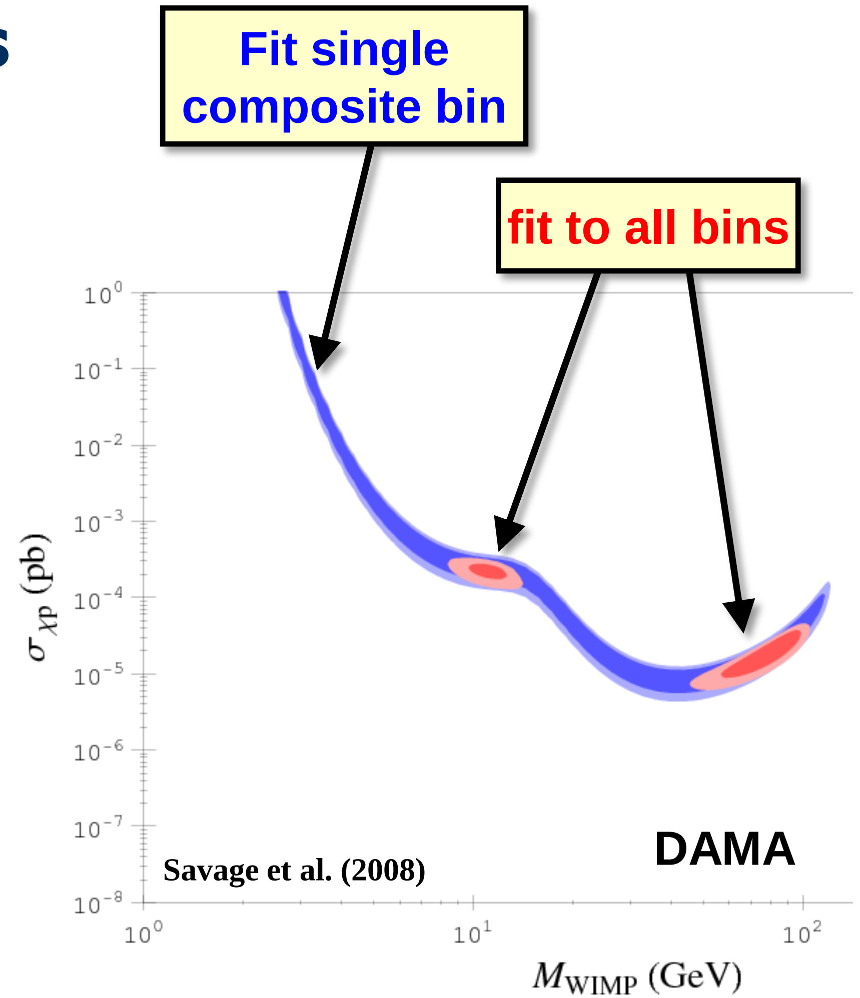
- Ease of analysis
  vs. statistical power

- Flawed/misleading analysis

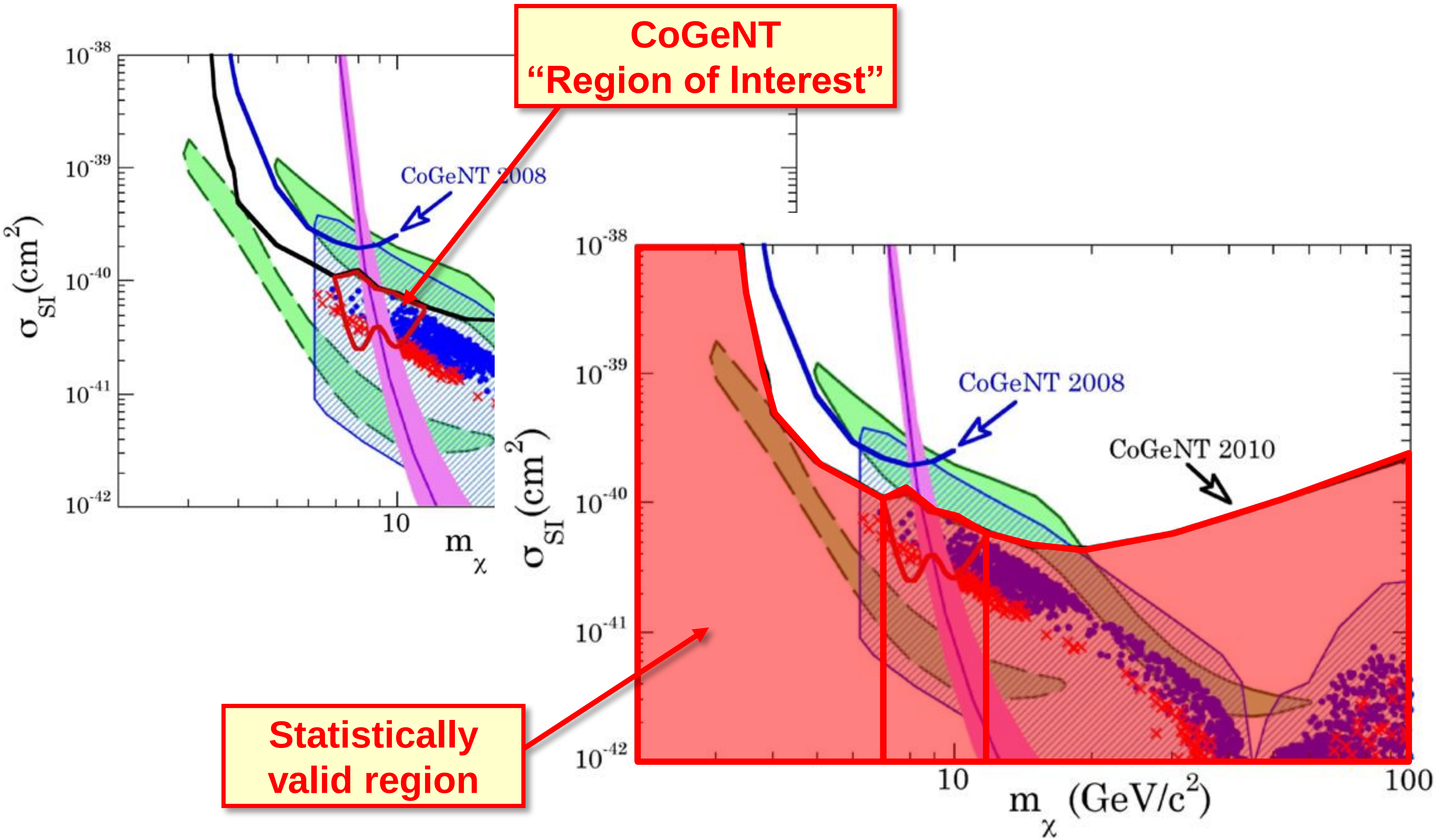
- Missing/incomplete statistics

  Example: Collar & Fields (2012)
  - Likelihood reanalysis of CDMS data
    ⇒ 5σ preference for DM signal
  - Missing: goodness-of-fit check
    ⇒ DM signal excluded at 3σ
    (bad background model?)

- (Overly-)conservative analyses



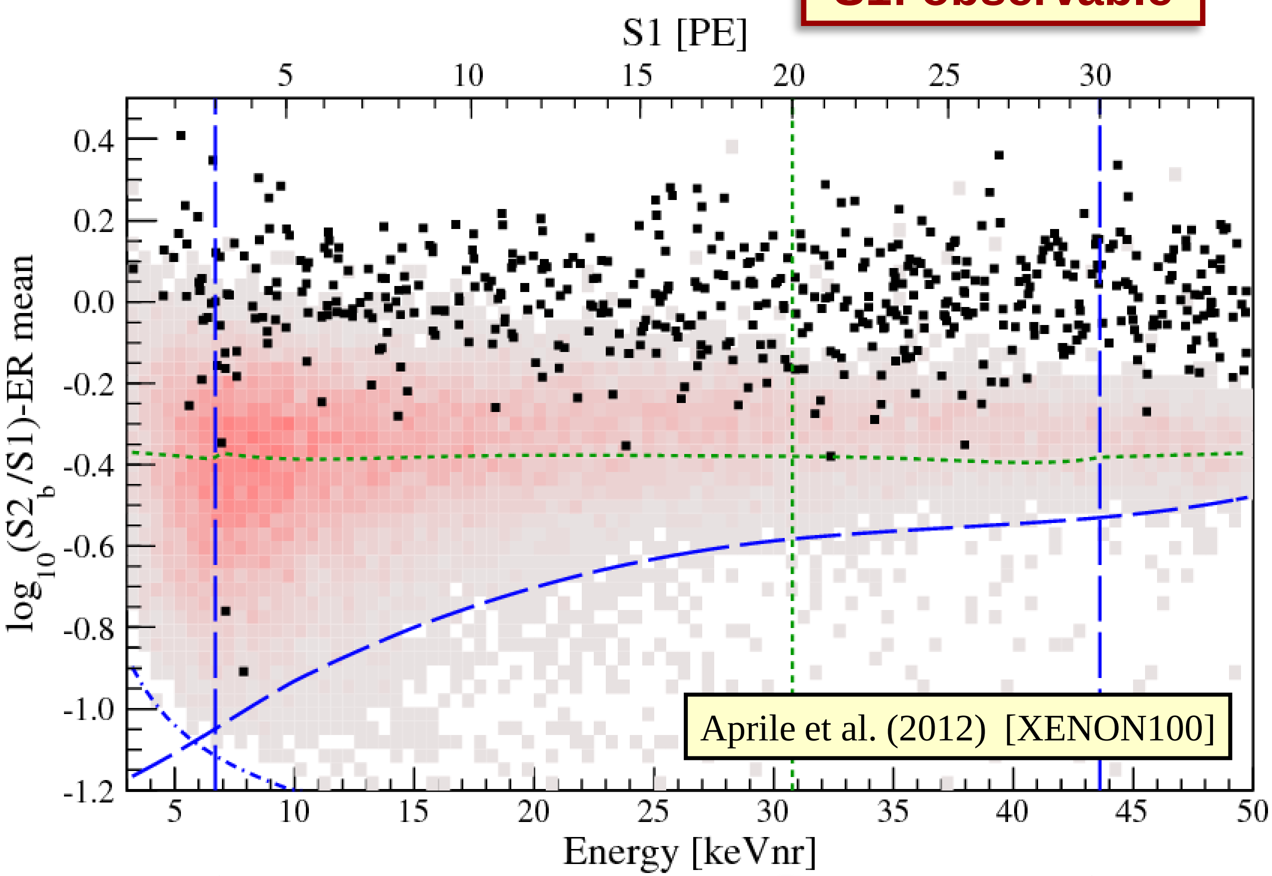
Statistical Analysis Issues: CoGeNT (2010)



How to get it back (2011+): drop exponential background contribution

Energy Calibration/Resolution

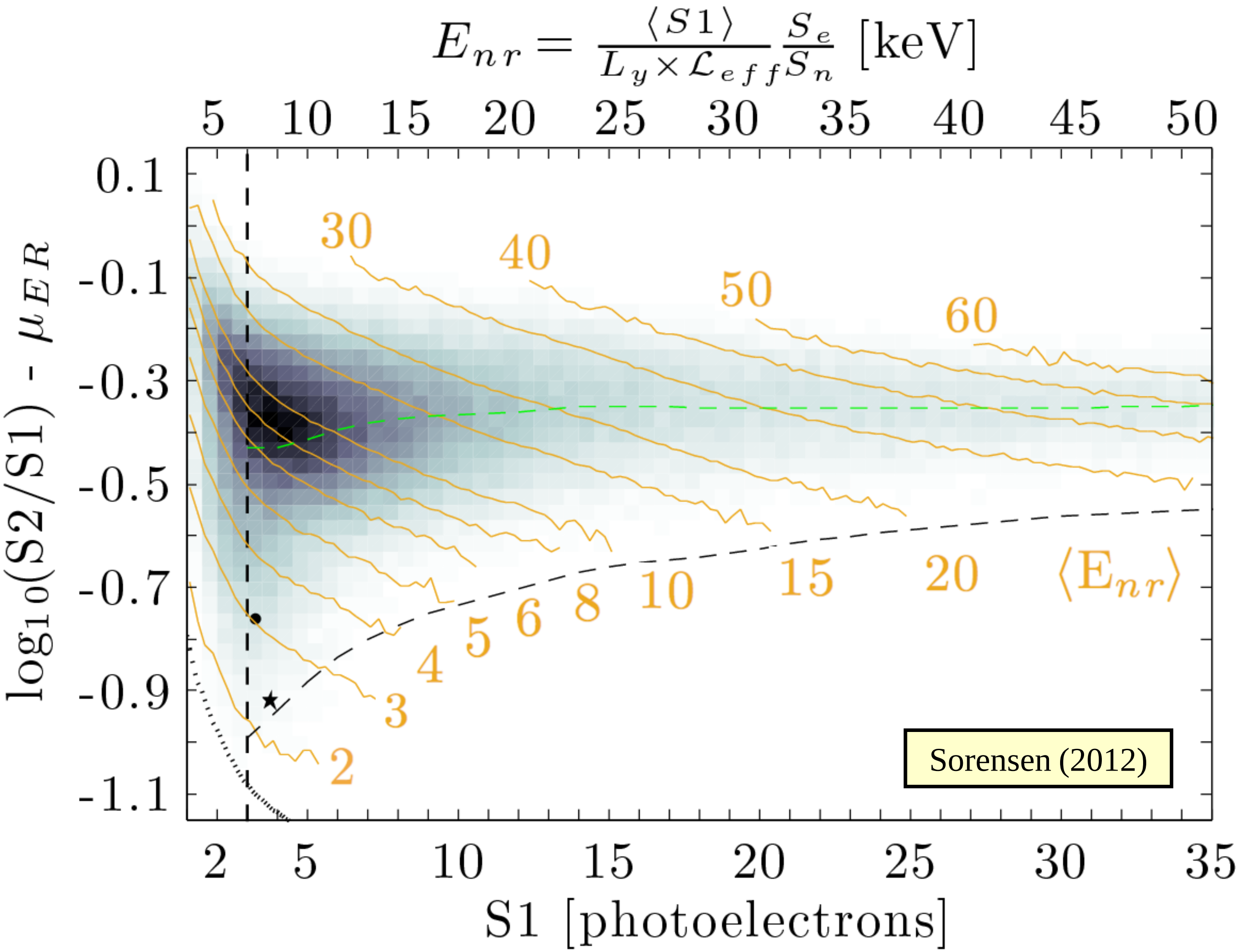
S1: observable



“6.6 – 43.3 keV”

Bad energy estimator

Energy Calibration/Resolution

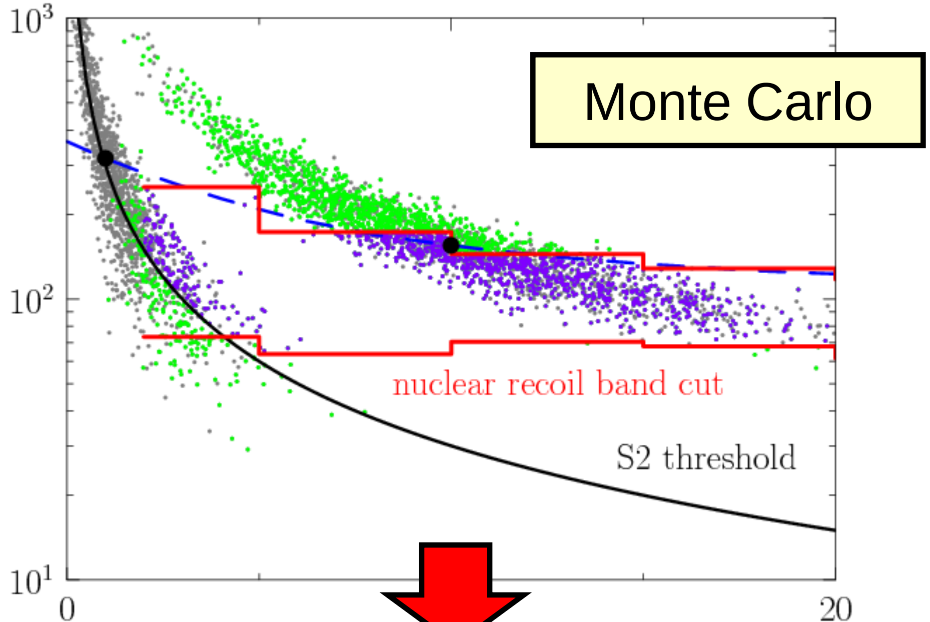


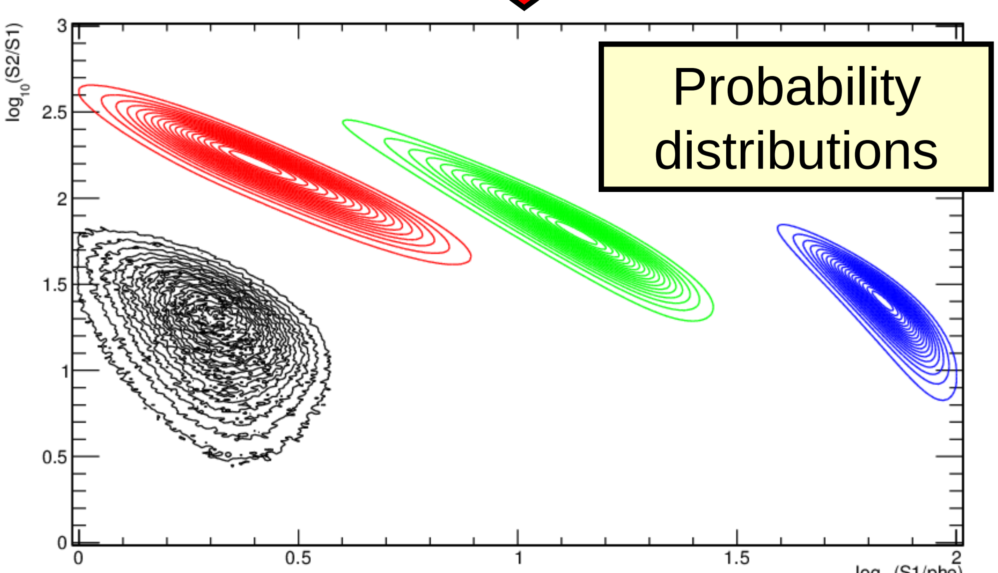
Energy Calibration/Resolution

CS & Pato (in progress)

Full 2D event likelihood analysis

- Monte Carlo (detector physics)
- Tuning (calibration data)



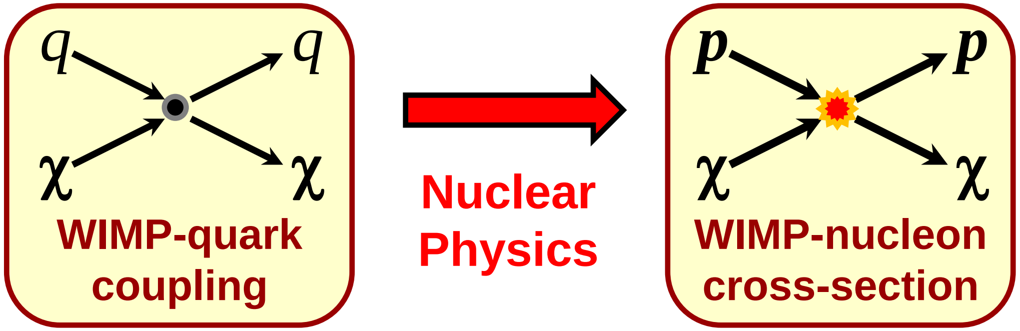


MicrOMEGAs?

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
  - Up to $\times$3-5 uncertainty in cross-section for given WIMP-quark coupling (lattice QCD vs. experimental extrapolations)



See e.g.: Ellis, Olive & CS (2008)

- Heavier masses preferred?

Summary and Remarks

Summary and Remarks

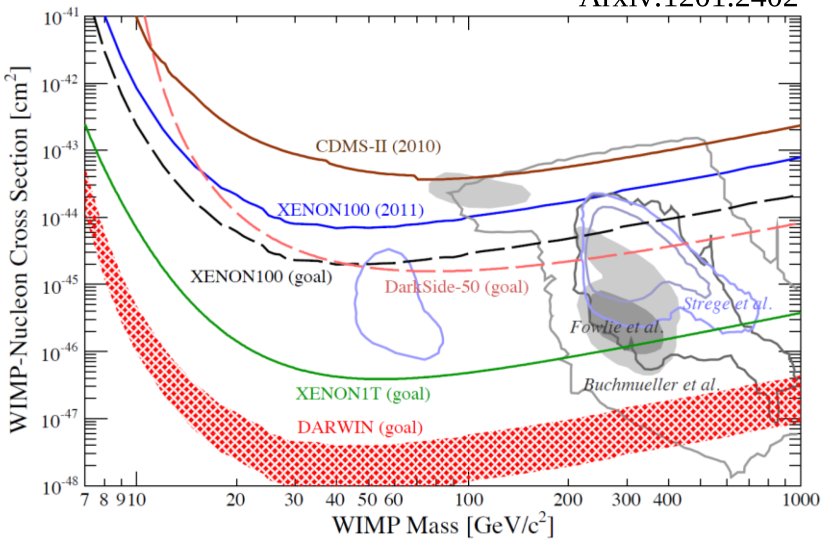
- Four (possibly) positive signals for dark matter, numerous negative results
- Difficult to reconcile some experimental results (let alone all of them)
- Possibilities
  - Particle physics: maybe, but at what cost?
  - Astrophysics: no
  - Unknown backgrounds: significant possibility
    - Modified/unconsidered backgrounds for CDMS, CoGeNT, CRESST
  - Energy calibration: making things *worse*
- Answers in upcoming results...

Future

Low mass region

- **CDMSlite**: very low energy, ionization-only [this year]
- **DM-Ice**, **SABRE**: southern hemisphere [???]
(also ANAIS, KIMS)

Arxiv:1201.2402



SUSY “preferred” regions

- **LUX**: ×3 improvement in sensitivity [next year]
- **XENON1T**: ×30 [2015]
- **DARWIN**: ×1000 [2018+]
- …

…and beyond: solar neutrino background

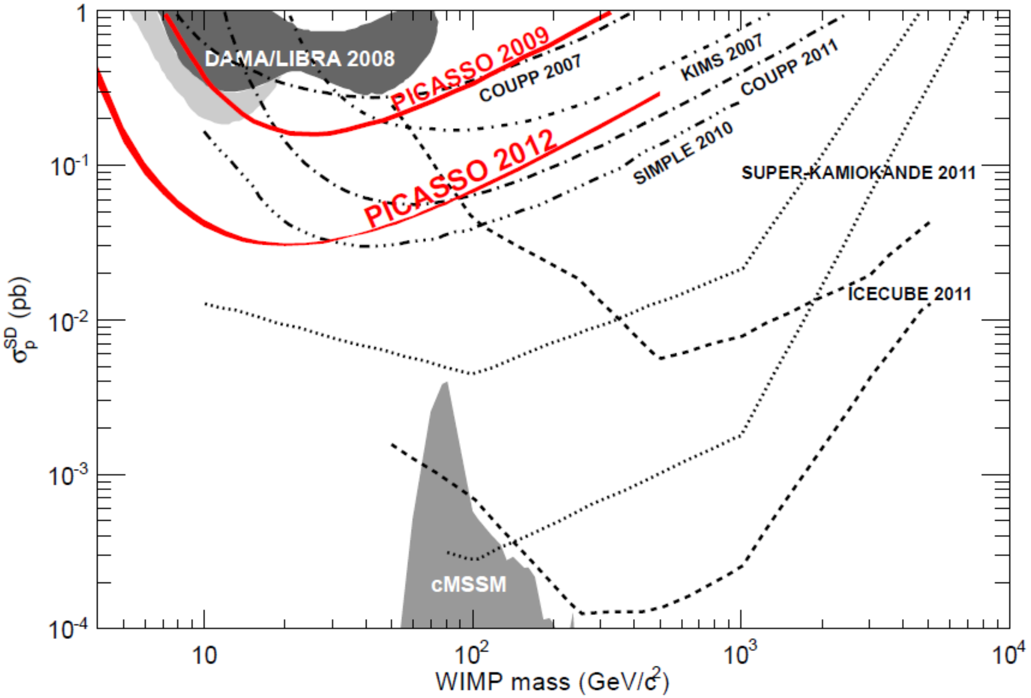
Backup Slides

Issue:
particle physics

Spin-dependent

- Coupling to spin rather than mass
- DAMA proton-odd, most others proton-even
  $\Rightarrow$ proton-only SD coupling explains DAMA + null results
- 2012: PICASSO closes DAMA SD window

Archambault et al., PLB **711**, 153 (2012)



Isospin-violating

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

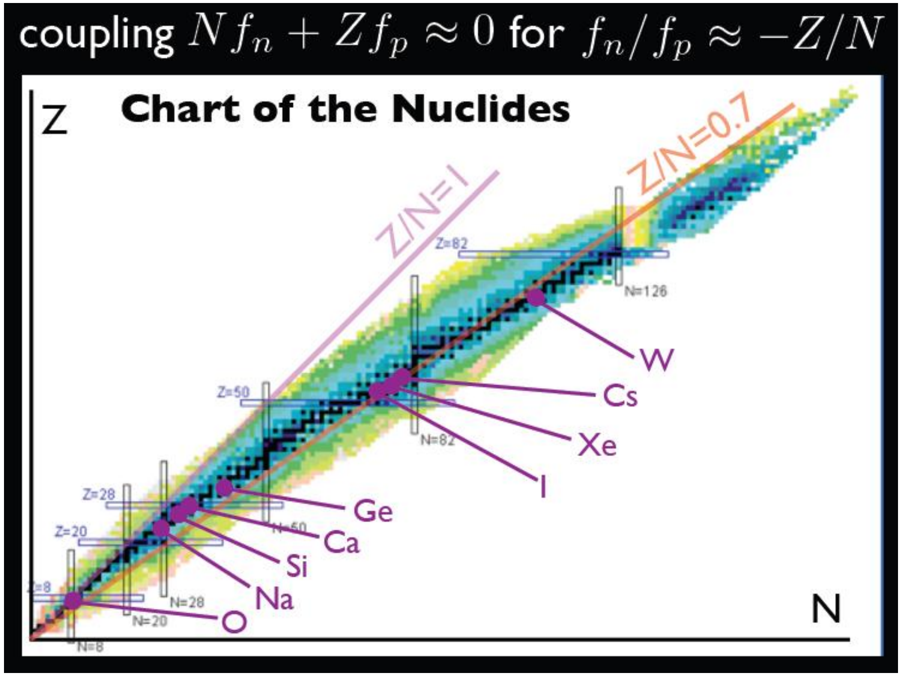
Leading order only:
next order terms affect canceling
[Cirigliano, Graesser & Ovanesyan (2012)]

- SI coupling to proton significantly different than neutron
  - neutralino (scalar): $f_p \approx f_n$
  - heavy neutrino: $f_p \approx -(1-4\sin^2\theta_W)\,f_n$

- For $f_p \approx -0.7\,f_n$, can exactly cancel SI cross-section for a heavy isotope

- Cannot cancel all CDMS and XENON isotopes at same time

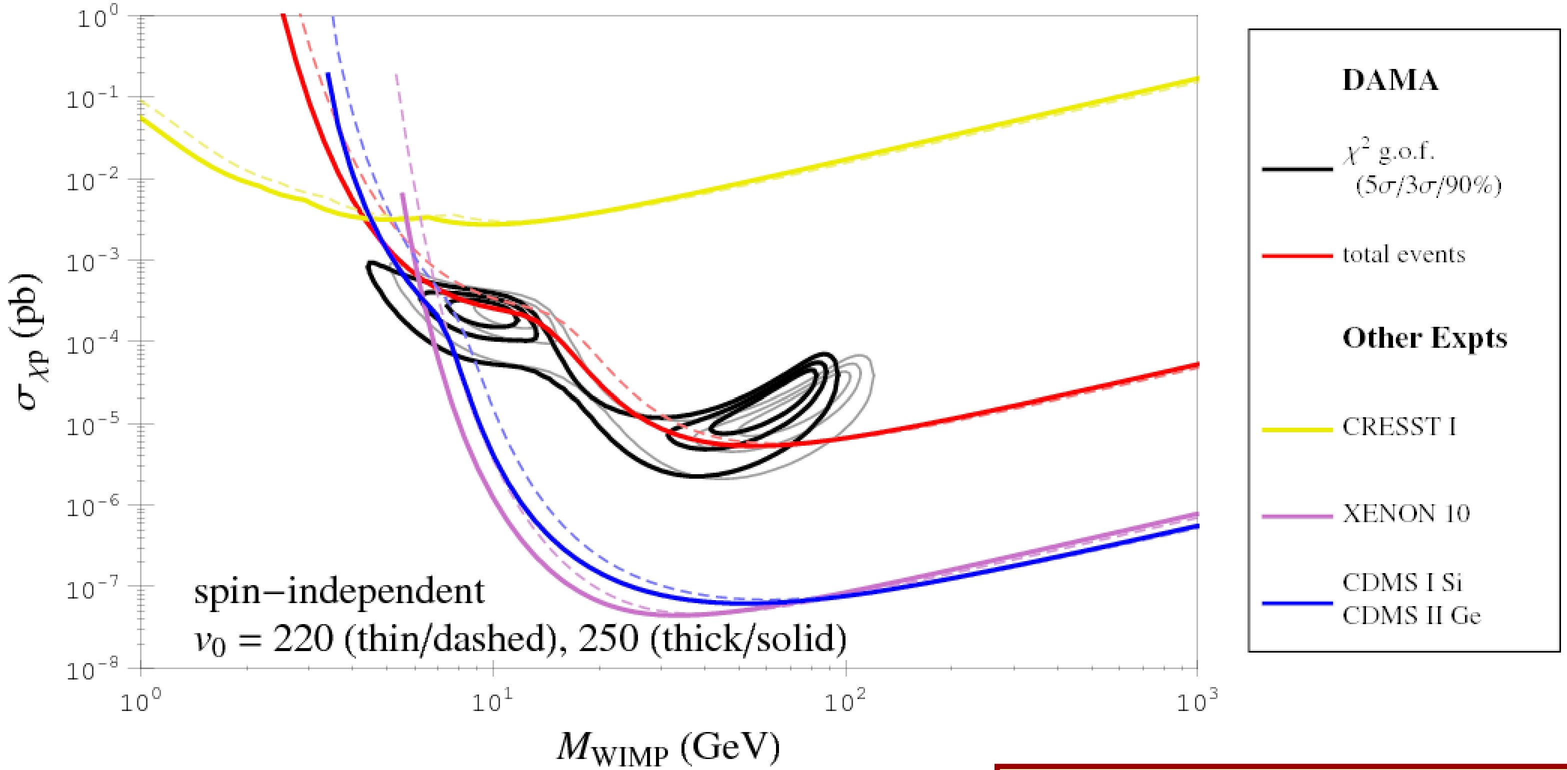
- Fine-tuning!



Issue: astrophysics

Smooth background halo: SHM

- SHM: uncertainty in parameters (v_{rot}, v_0, v_{esc})
- Affect compatibility? **not significantly**

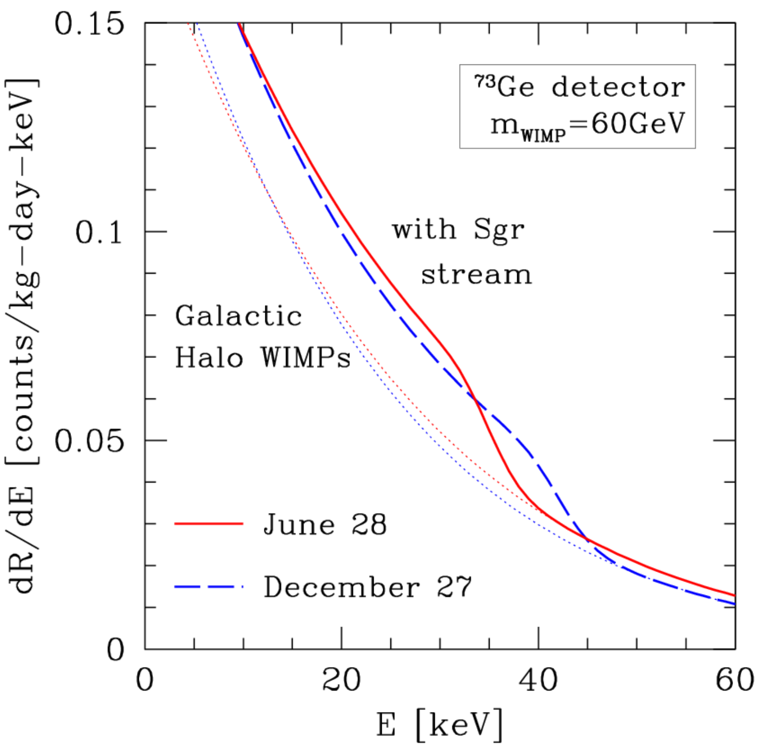


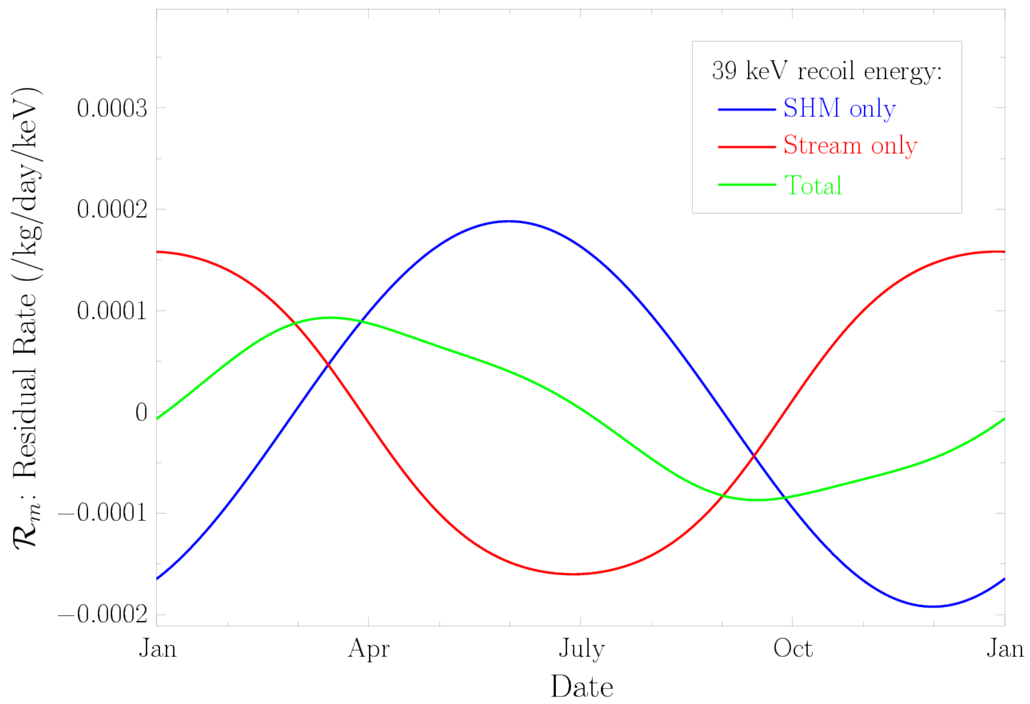
CS, Freese, Gondolo & Spolyar (2009)

See also (e.g.): Hooper & Kelso (2011)

Substructure: Sagittarius Stream

- Sgr dwarf tidal tail passes near solar neighborhood



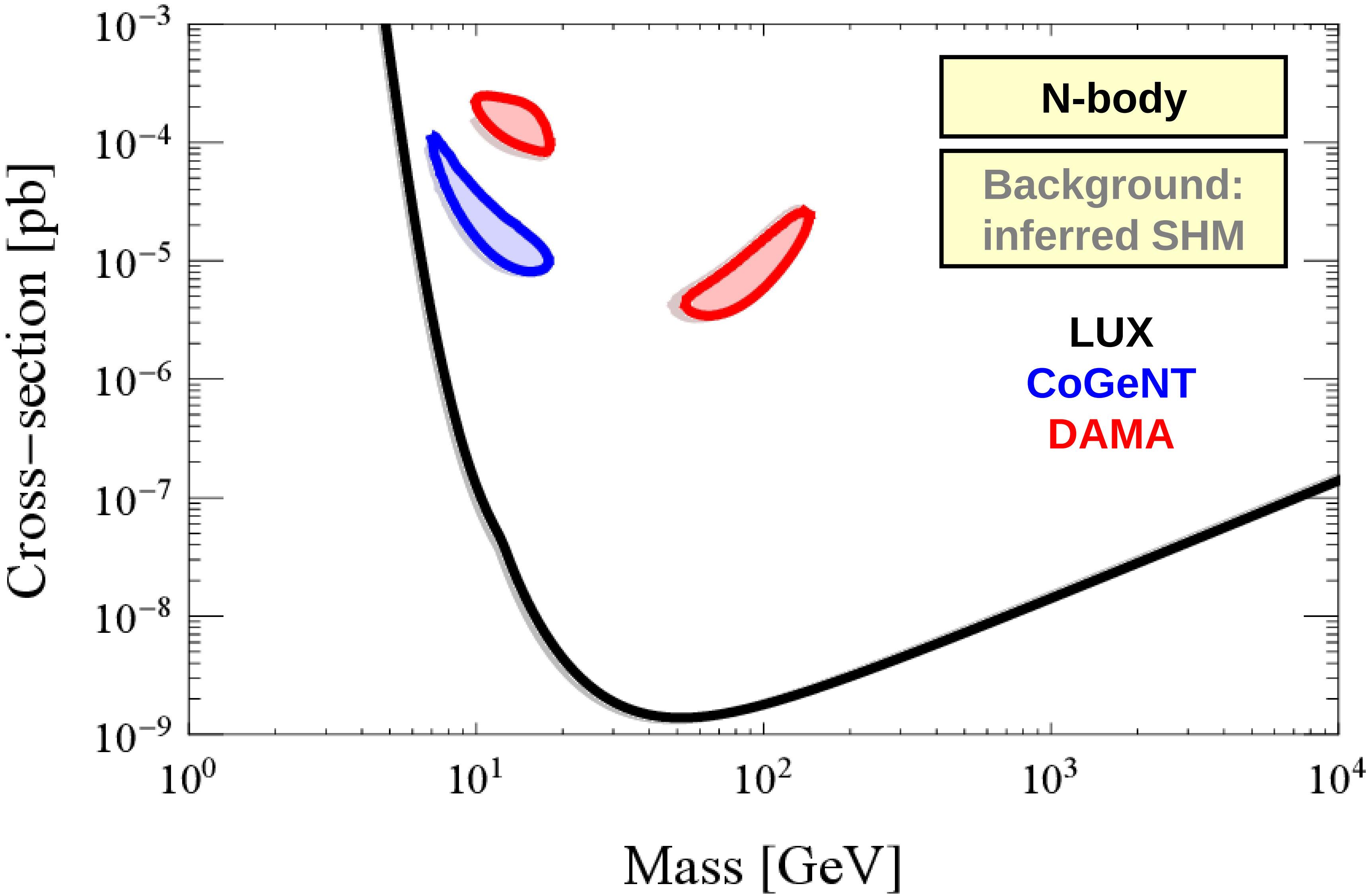


Freese, Gondolo & Newberg (2003)

CS, Freese & Gondolo (2006)

N-body simulation (DM+baryons)

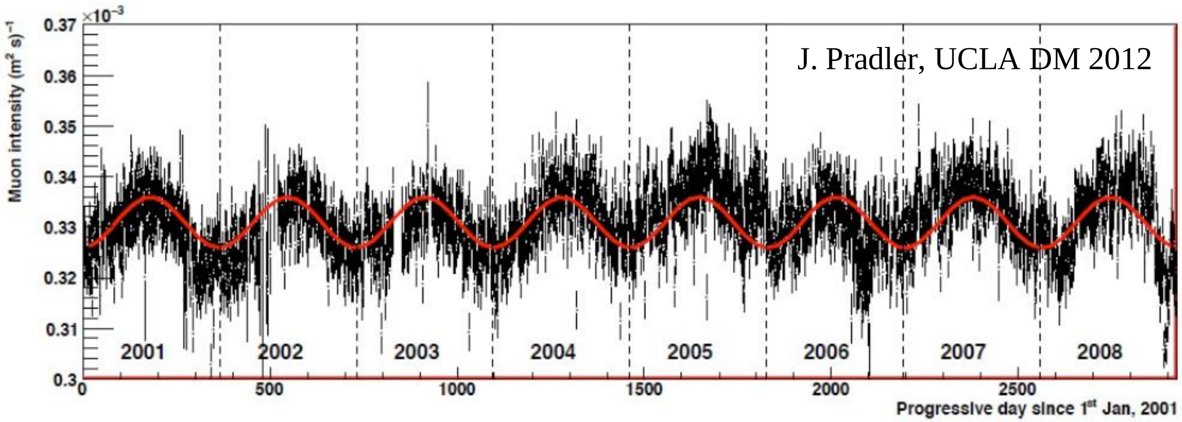
CS, Kelso, Valluri, Freese & Stinson (in progress)



Issue: backgrounds

Muons in DAMA

- Cosmic-ray muon flux known to modulate
  - Depends on height of atmosphere, which changes with seasons
- Muon vetoing: muons cannot be direct cause. Indirect cause?
  - Showers
  - Delayed phosphorescence [Nygren (2011)]



[Selvi, 2009]

Muons in DAMA

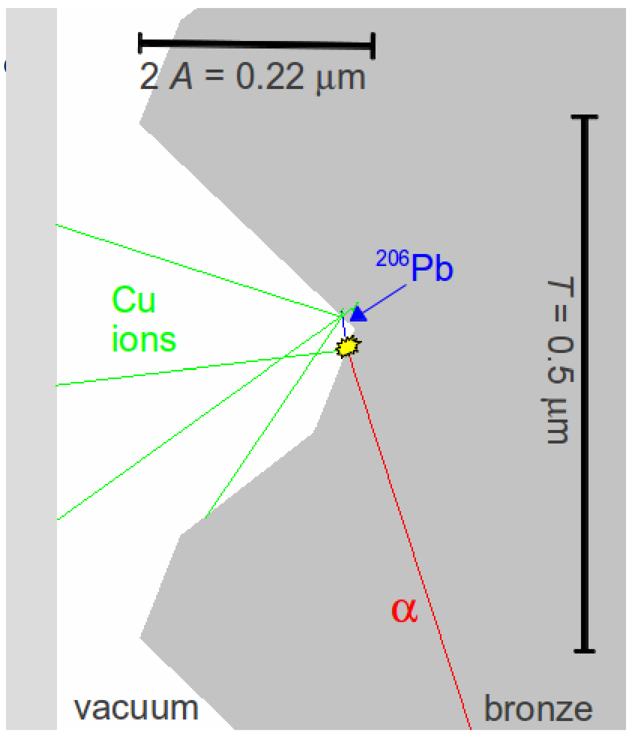
Any muon-induced events (direct or indirect) strongly disfavored

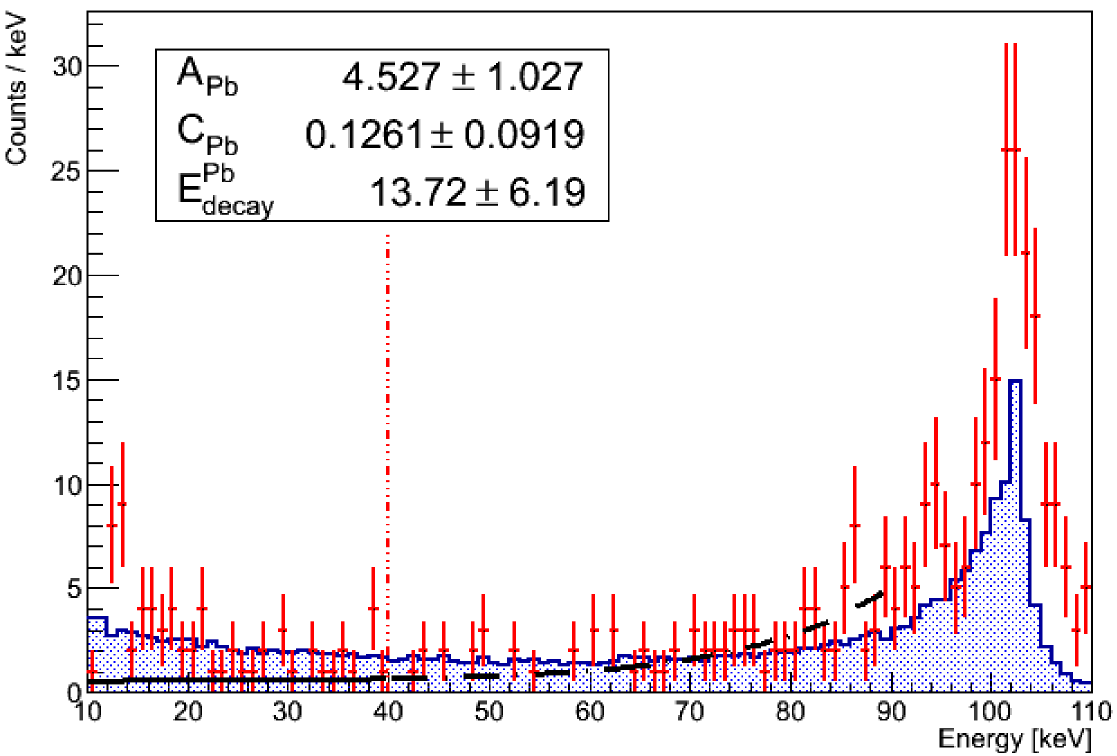
- Phase of muon flux *lags* DAMA modulation
- DAMA has consistent phase, muon flux does not (and is not expected to)
- Statistical arguments: Poisson fluctuations should be *much* larger than observed fluctuations in DAMA

Lead Recoils in CRESST

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

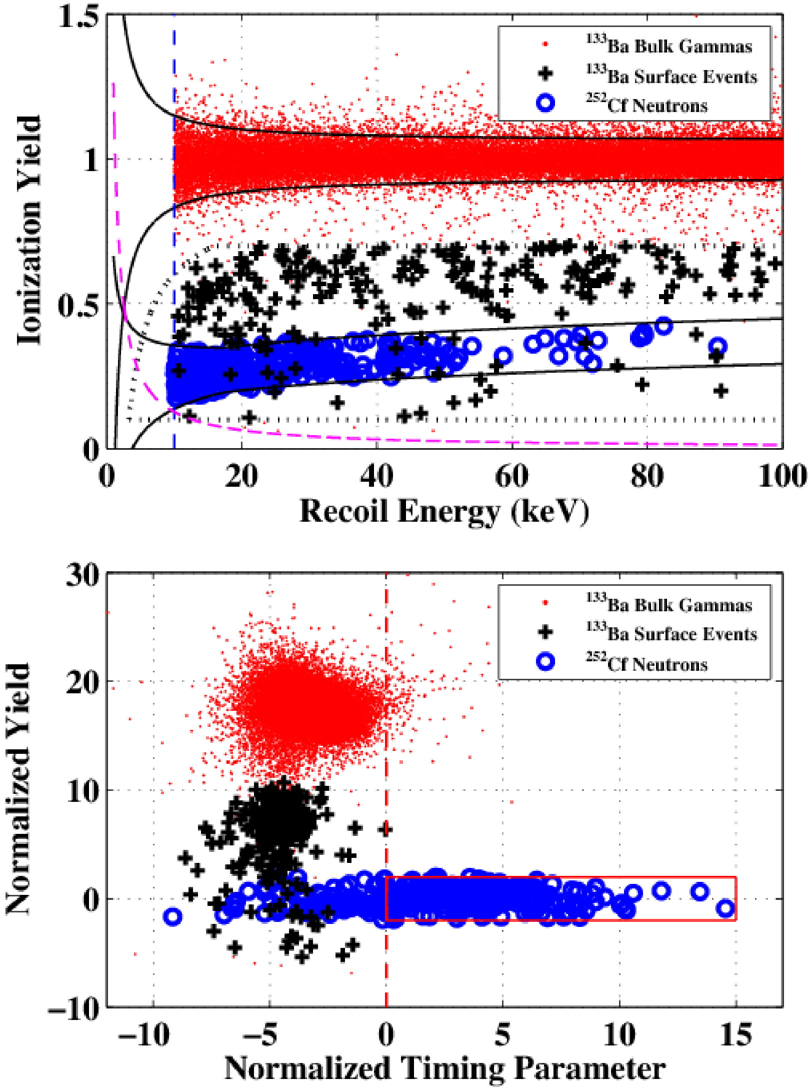
- Background: $^{210}Po \rightarrow {}^{206}Pb + \alpha$ (at surface)
- Monte carlo simulations: flat vs. rough surface
  $\Rightarrow$ underestimating background events!





Surface Events

- Radiation can impact the surface of the detector
- Signals from events on surface may differ from bulk
  - Example: incomplete charge collection near surface in CDMS makes betas look like nuclear recoils (a low ionization/phonon ratio).



Ahmed *et al.*, Science **327**, 1619 (2010)

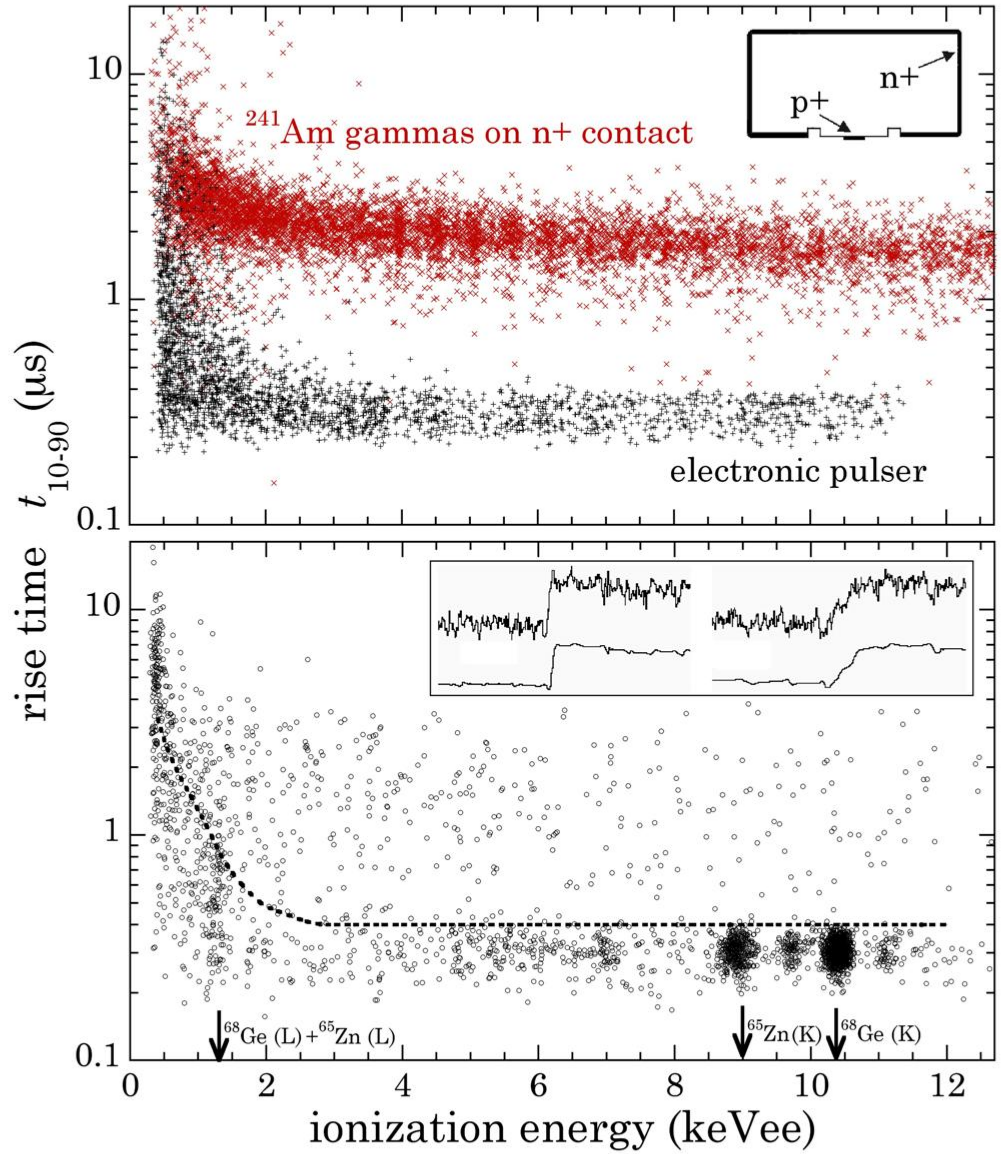
Surface Events (CoGeNT)

Aalseth et al. (2010)

Calibration:

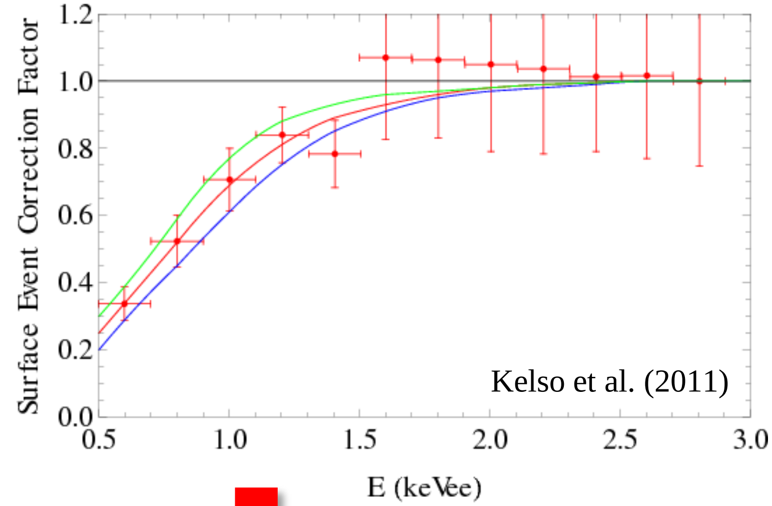
Data:

Increasing contamination at low energies

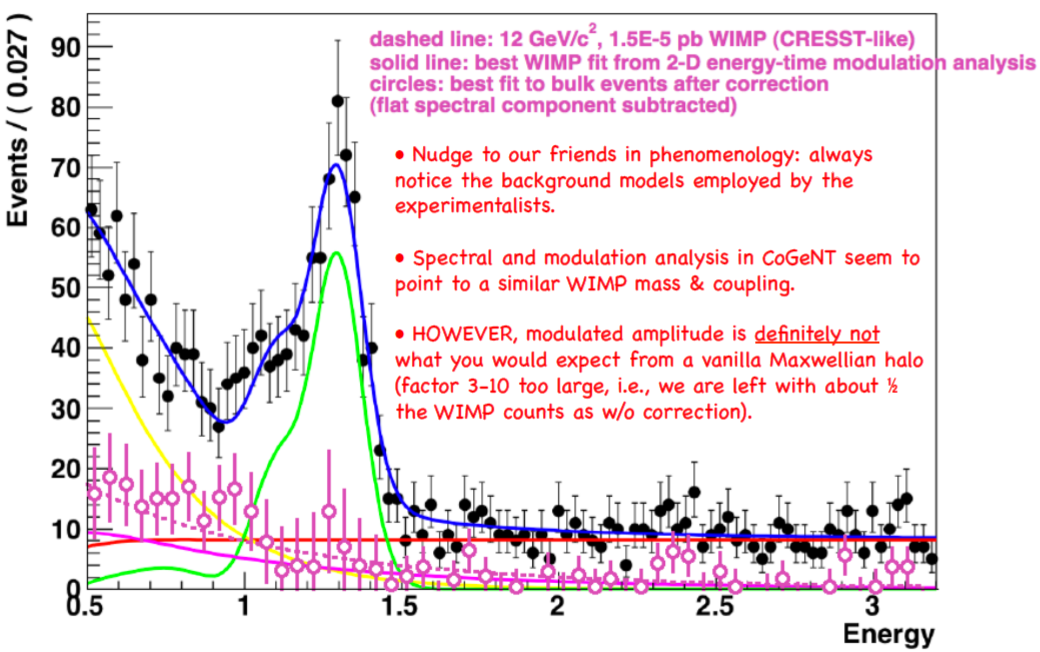


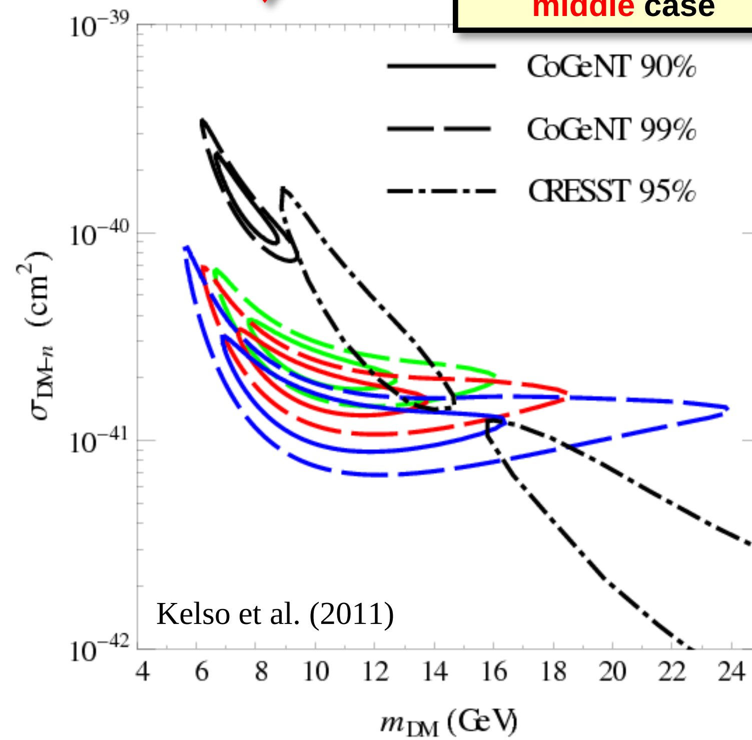
Surface Events (CoGeNT)

- J Collar @ TAUP 2011: significant number of surface events



Aalseth et al. (2012): middle case

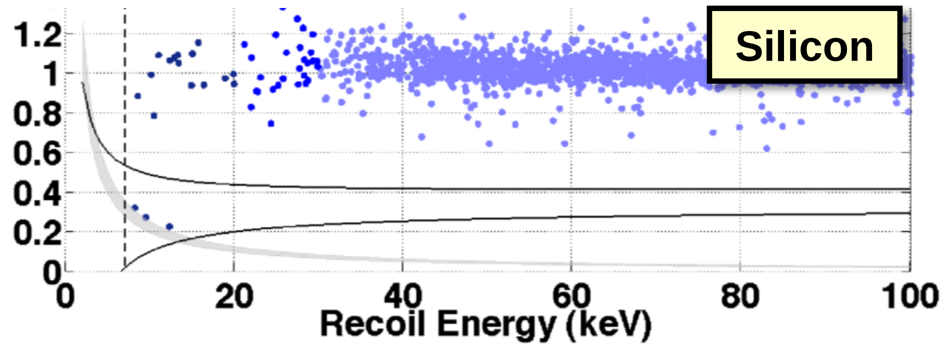




CDMS: Trigger Threshold

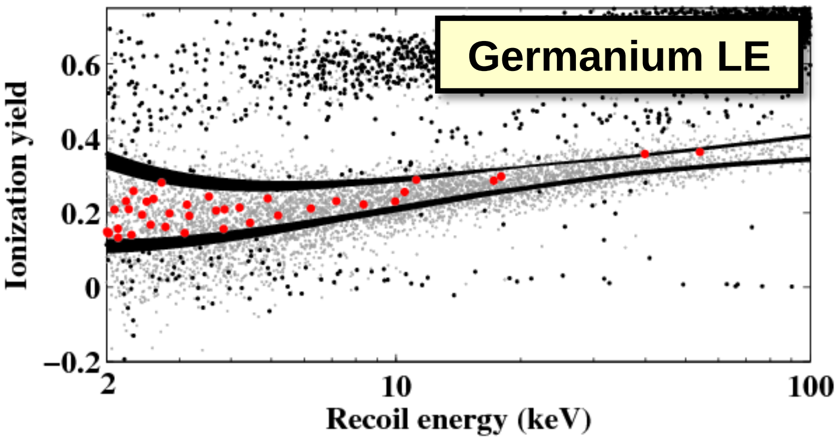
- Are there potential populations of events below trigger threshold?

Agnese et al. (2013)



- Answer: YES
  - Zero-charge events
  - …

Ahmed et al. (2011)



XENON: also has known population of events below S1 trigger

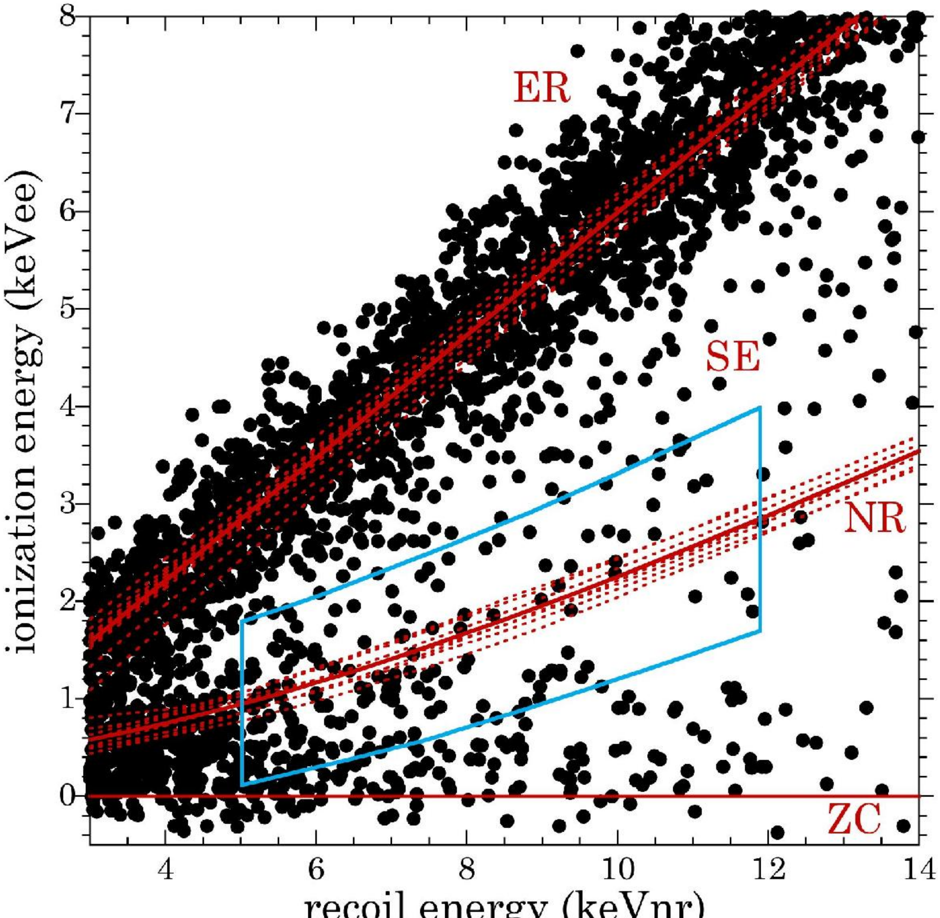
Issue:
statistical analysis

CDMS low-energy reanalysis

A Maximum Likelihood Analysis of Low-Energy CDMS Data, Collar & Fields, arxiv:1204.3559.

- Recoil energy & charge for each event
- Model backgrounds:
  - Electron recoils
  - Surface events
  - Zero charge (edge events)
- +nuclear recoils (signal)

$\Rightarrow$ **Likelihood analysis**



Claim: 5.7σ excess

CDMS low-energy reanalysis

- Missing: goodness-of-fit check
- Likelihood analysis for each of 8 detectors: results incompatible (goodness-of-fit is poor)
- Conclusion:

  If the backgrounds are correctly modeled

  …the background only case is rejected at > 5σ

  …*but the excess is inconsistent with WIMPs at > 3σ*
- Why?
  - Modeling of distribution tails does not match data
  - Incorrectly modeled distribution virtually guaranteed to find “signal” (whether or not it is really there)