Direct detection: overview and issues for SUSY scans

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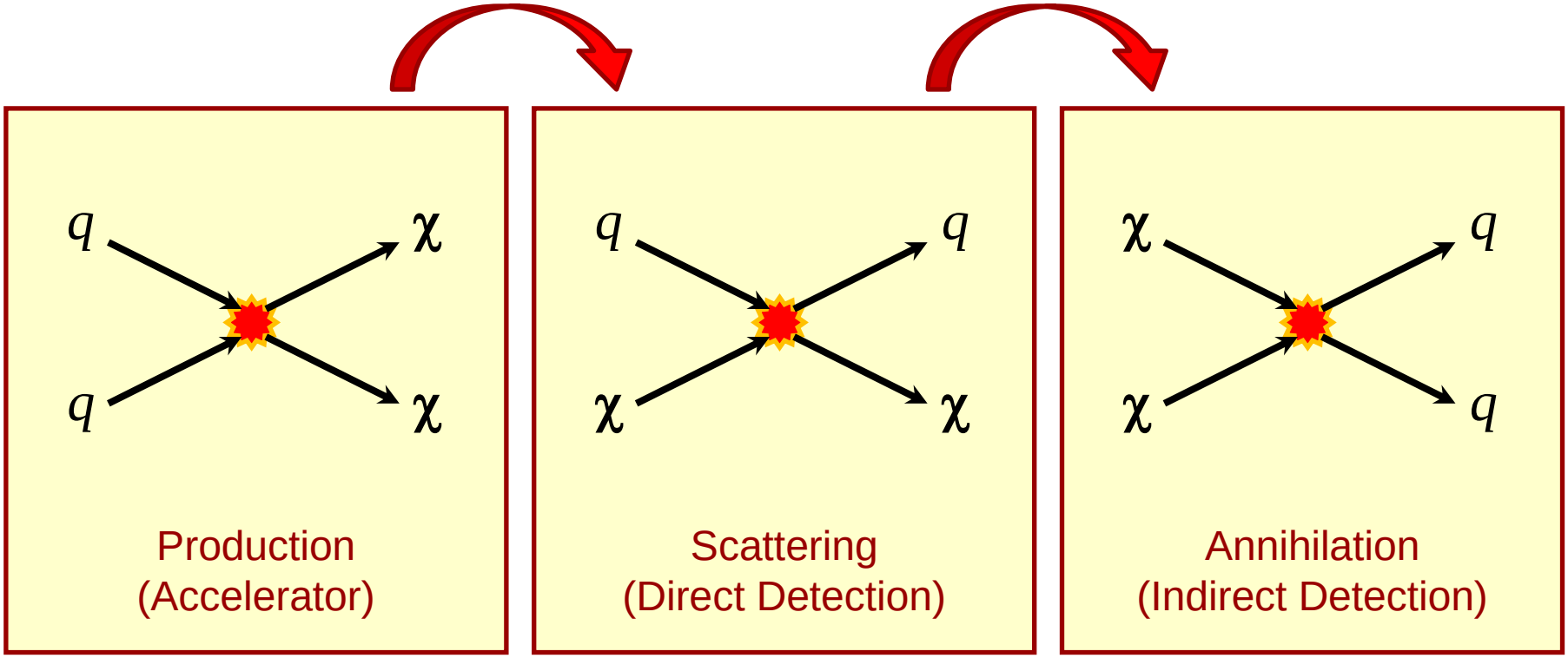
WIMP dark matter



Outline

- Direct detection: principles and techniques
- Experiments: current & future
- Issues
  - Energy resolution/detector behavior
  - Backgrounds
  - Halo models
  - Hadronic uncertainties
- Reconstruction examples

Principles and Techniques

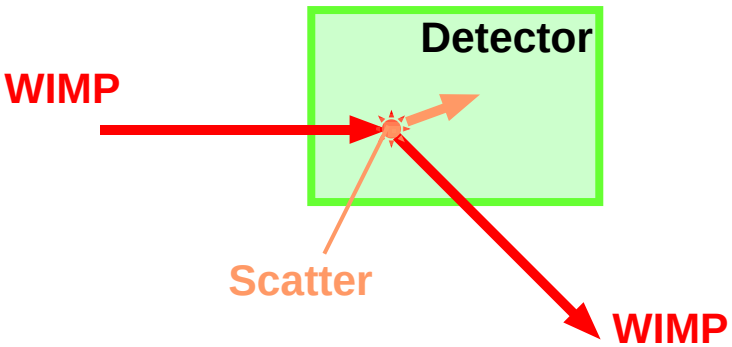
Direct Detection

Goodman & Witten (1985)

- Elastic scattering of WIMP off detector nuclei

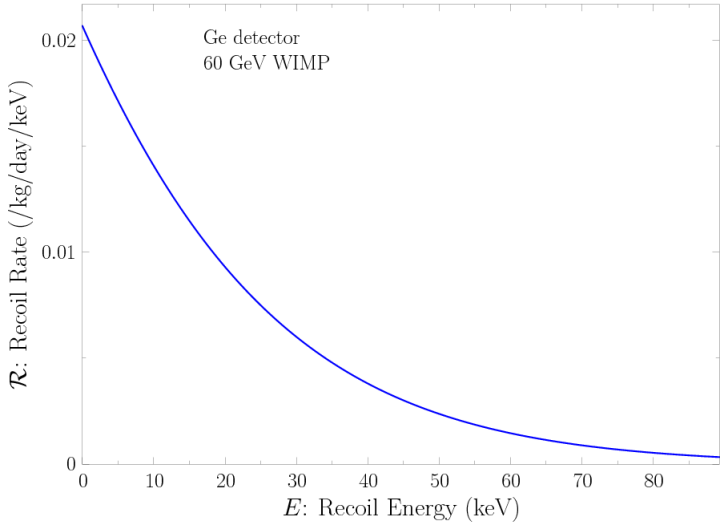
$$\frac{dR}{dE}(E,t) = \frac{1}{2m\mu^2}\,\sigma_0 F^2(q)\,\rho_0\,\eta(E,t)$$

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



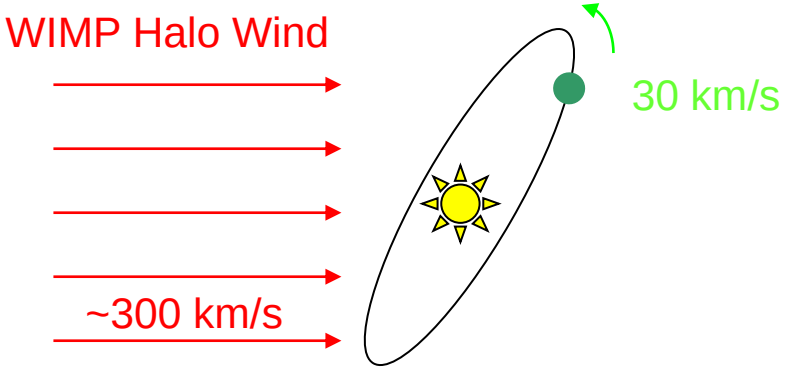
- Efficiencies, quenching, energy resolution, multiple elements

CDMS, EDELWEISS, CRESST, ZEPLIN, XENON, LUX, COUPP, CoGeNT, TEXONO, etc.

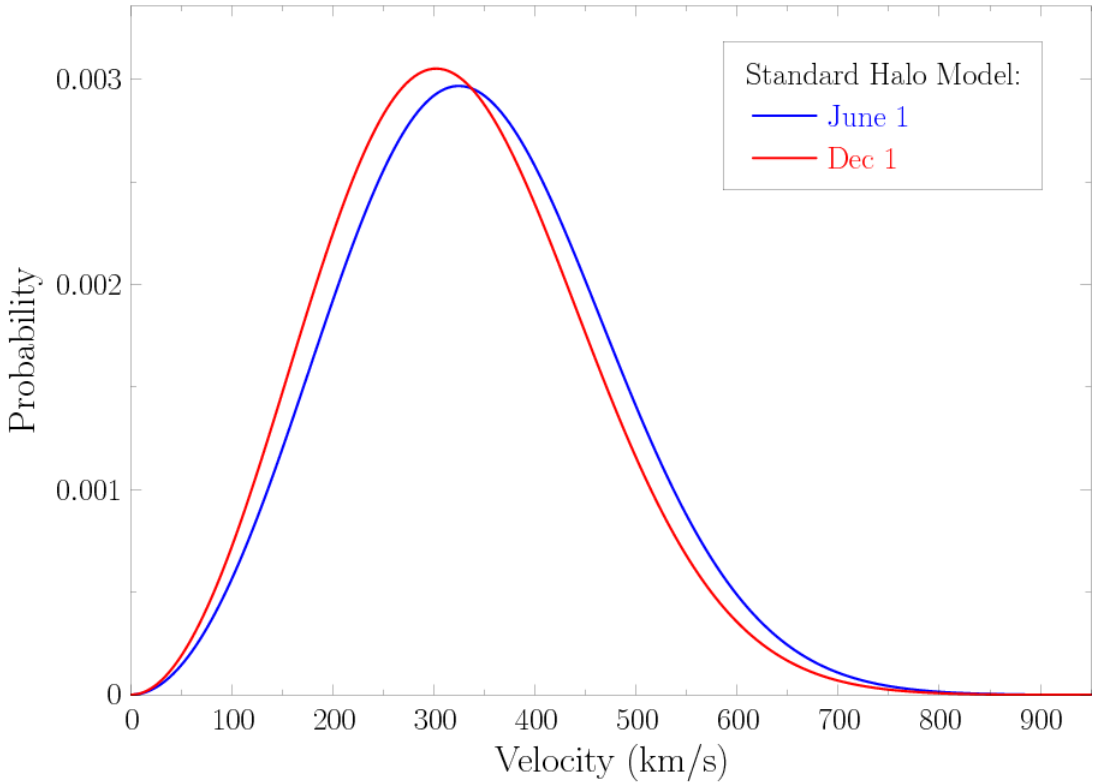


Annual Modulation

Drukier, Freese & Spergel (1986)

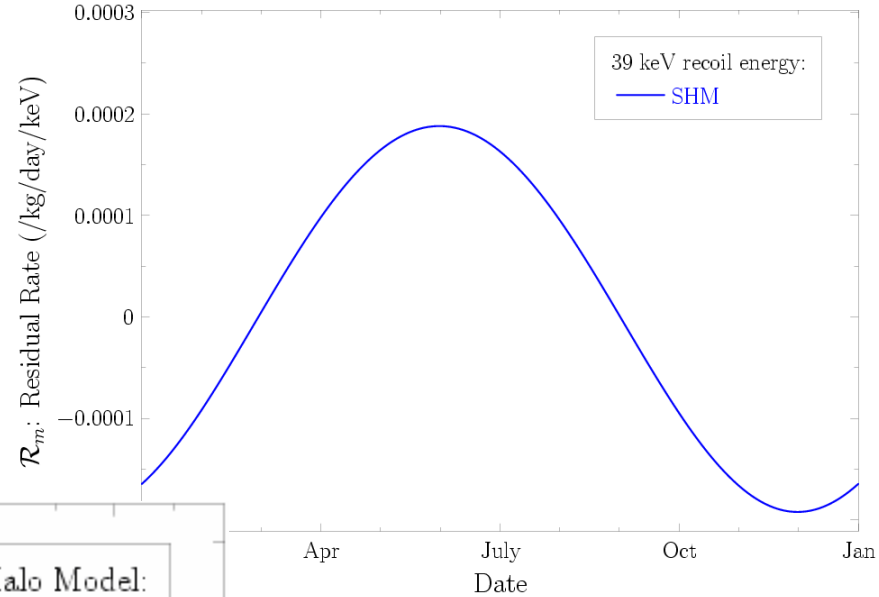


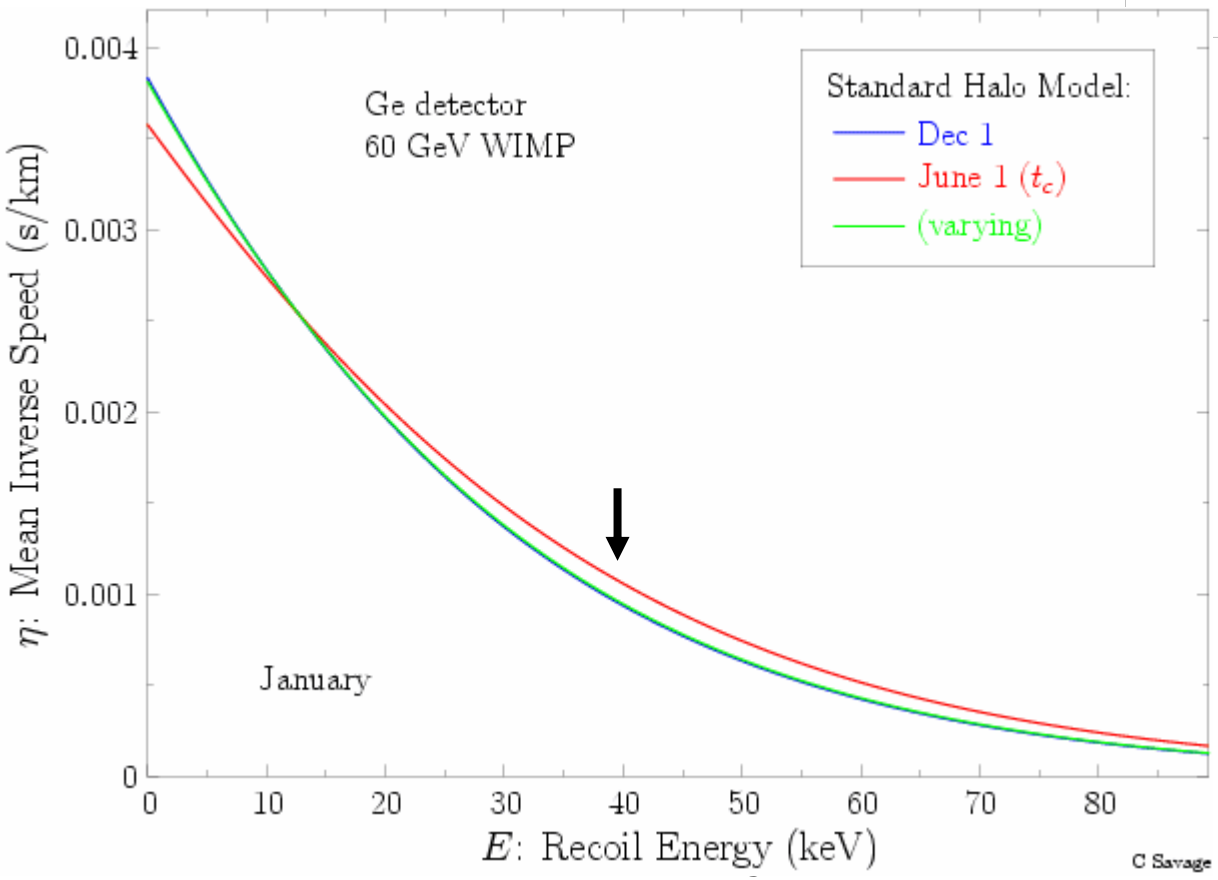
- Earth's motion
  - With disk (June)
    Against disk (December)



Annual Modulation

- e.g. DAMA/NaI, DAMA/LIBRA





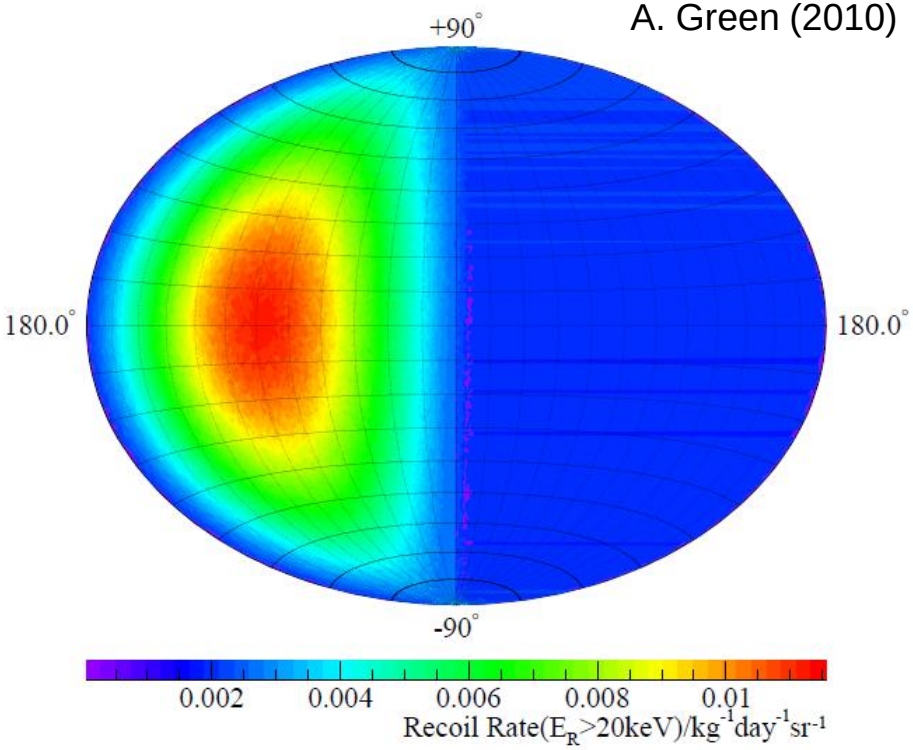
Directional detection

- Determine direction of recoiling nucleus

- Greater sensitivity to halo models

e.g. DRIFT

A. Green (2010)



Scattering Cross-Sections

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

f_p, f_n ⇔ $\sigma_{SI,p}$, $\sigma_{SI,n}$

$$\sigma_{SD} = \frac{32\mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

a_p, a_n ⇔ $\sigma_{SD,p}$, $\sigma_{SD,n}$

Spin-independent

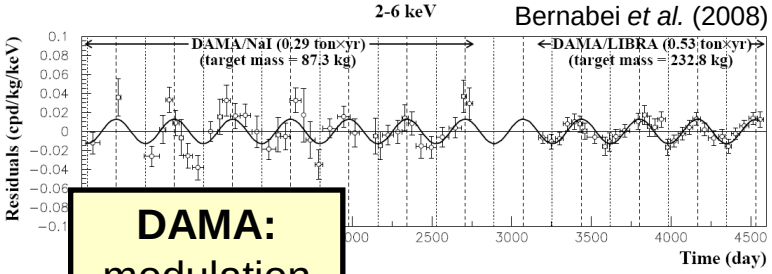
- Scales as A^2:
  Heavy elements have high sensitivity to SI interactions
- Common case: $f_p \approx f_n$
  ⇒ only one independent parameter ($\sigma_{SI,p}$)

Spin-dependent

- Scales with spin of nucleus: No increase with mass
- Sensitivity to two couplings depends on whether spin is carried by proton or neutron group
- Many isotopes have no spin

Experiments

Current experiments



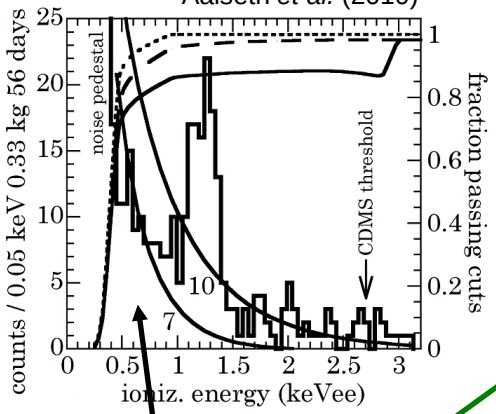
DAMA: modulation

CDMSII (final): 2 events
(expected background ~ 0.9 + 0.6)

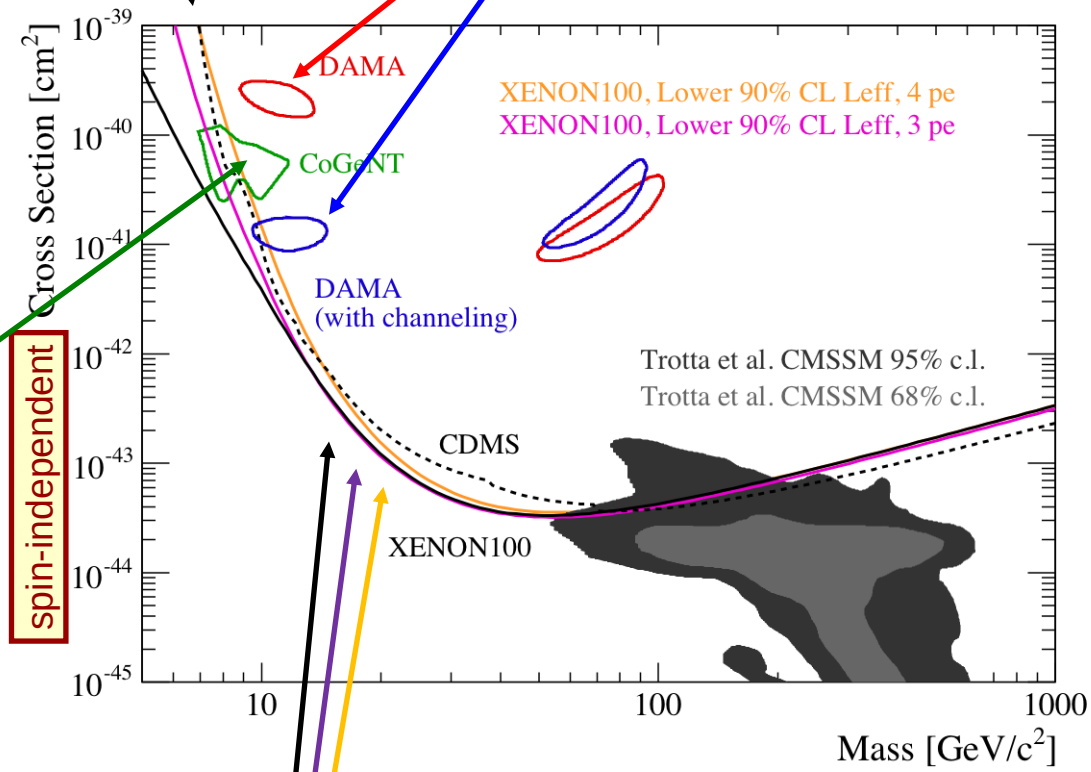
(dashed)

Bozorgnia, Gelmini & Gondolo (2010): channeling no longer viable?

Aalseth *et al.* (2010)



CoGeNT: excess low energy events?



spin-independent

Aprile *et al.* (2010)

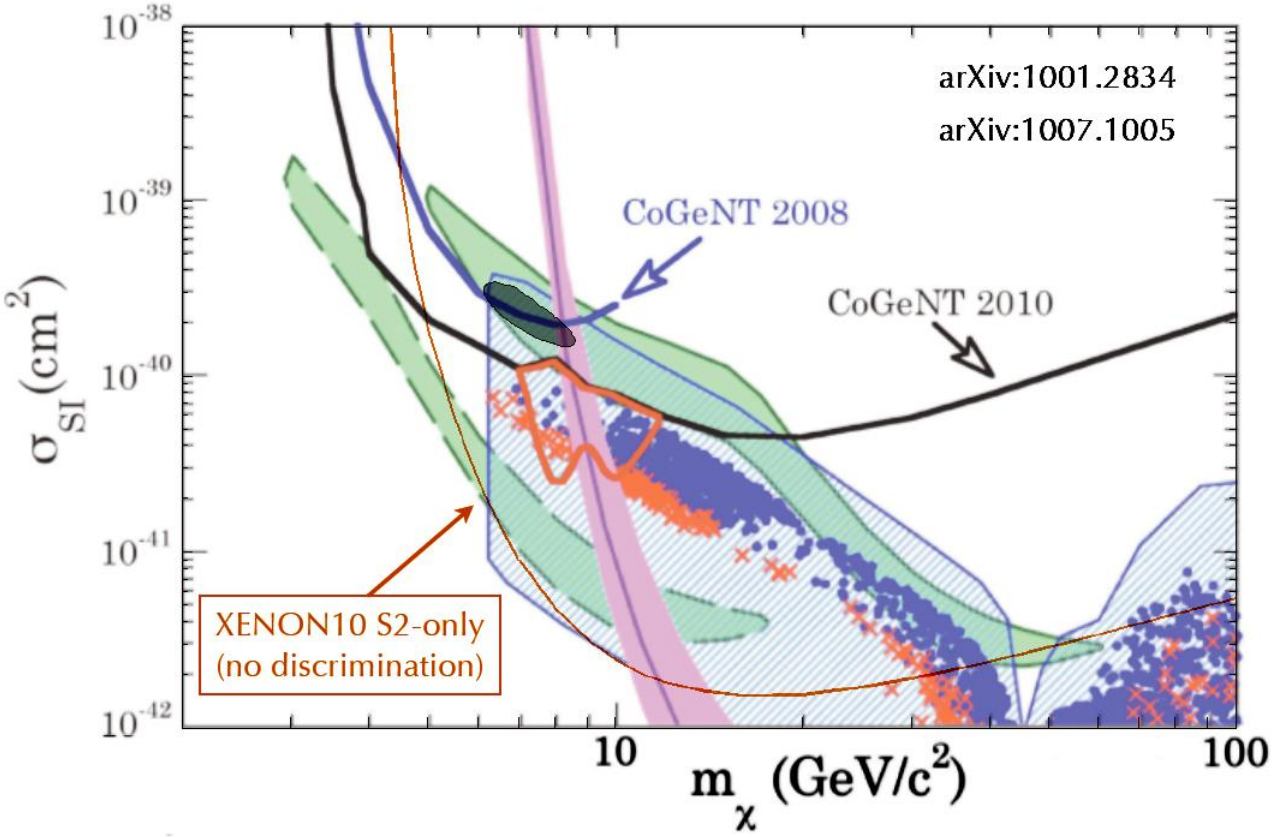
XENON100 (first results): 0 events
(thresholds, calibration assumptions)

Not shown:
many, many others...

XENON10: alternate analysis

P. Sorensen, IDM 2010

- XENON10: 15 kg-days exposure



- Max Gap 90% C.L. upper limit between 1.6 keVr and 3.8 keVr
- 12.5 live days
- 1.2 kg target
- conservative -1σ Q_y energy calibration
- no account of resolution (this would improve limits)

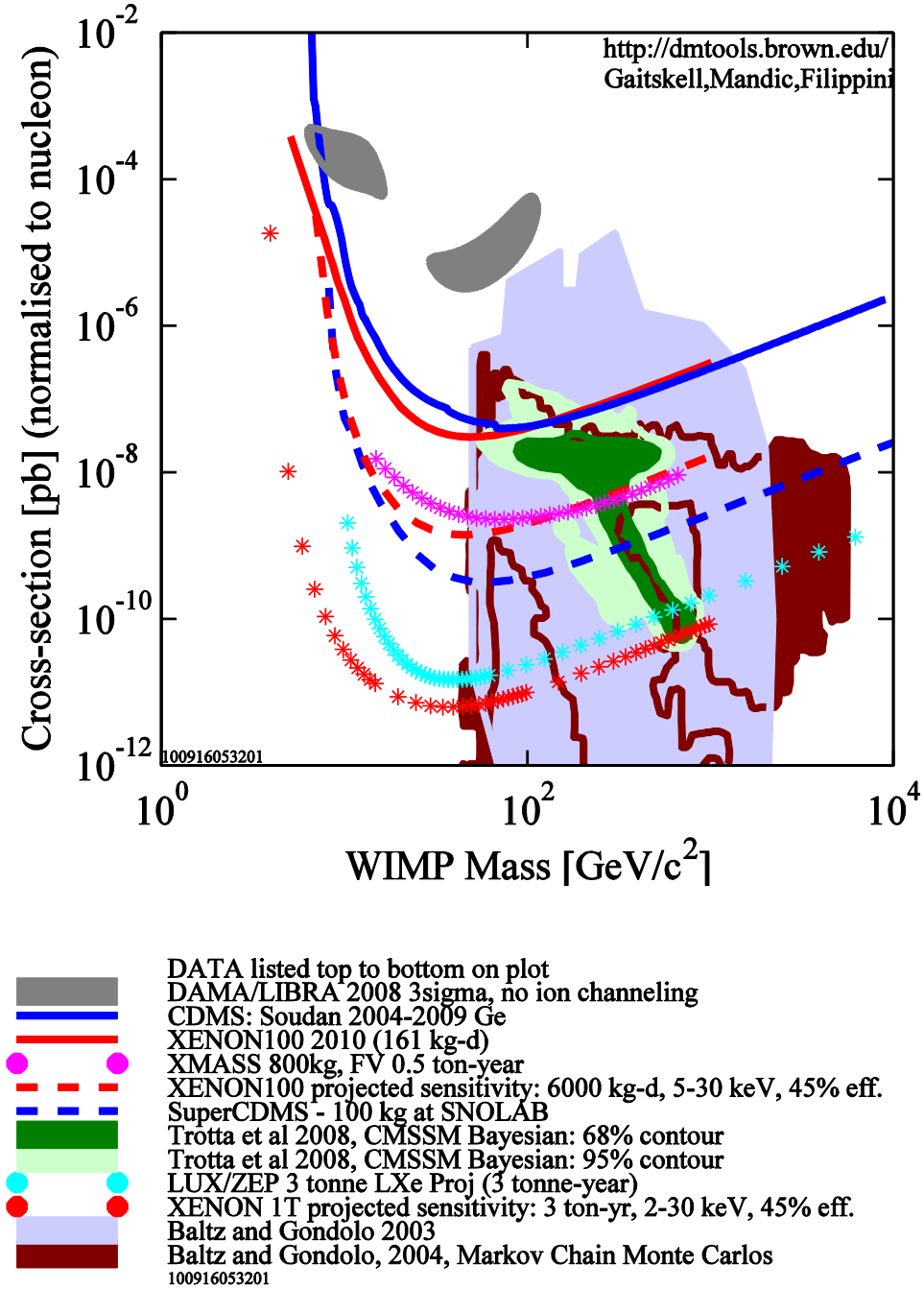
Future experiments

Next generation:

- XENON100,
  SuperCDMS,
  XMASS,
  + others
- XENON100 constraint is for next data set (full exposure ×10?)

Farther down the road:

- XENON1T,
  LUX/ZEPLIN 1T,
  CDMS 1T (not shown),
  + others



Issues

Likelihood

Goal for SUSY scans

- Number of events: little sensitivity to m_χ

$$L(N \mid \mu) = P_\lambda(N \mid \mu) \qquad \text{(Poisson)}$$

COUPP

- Event energies: energy spectrum depends on m_χ

$$L(N, E_{k=1..N} \mid \mu, \ldots) \propto P_\lambda(N \mid \mu) \prod_{k=1..N} f(E_k)$$

CDMS
XENON

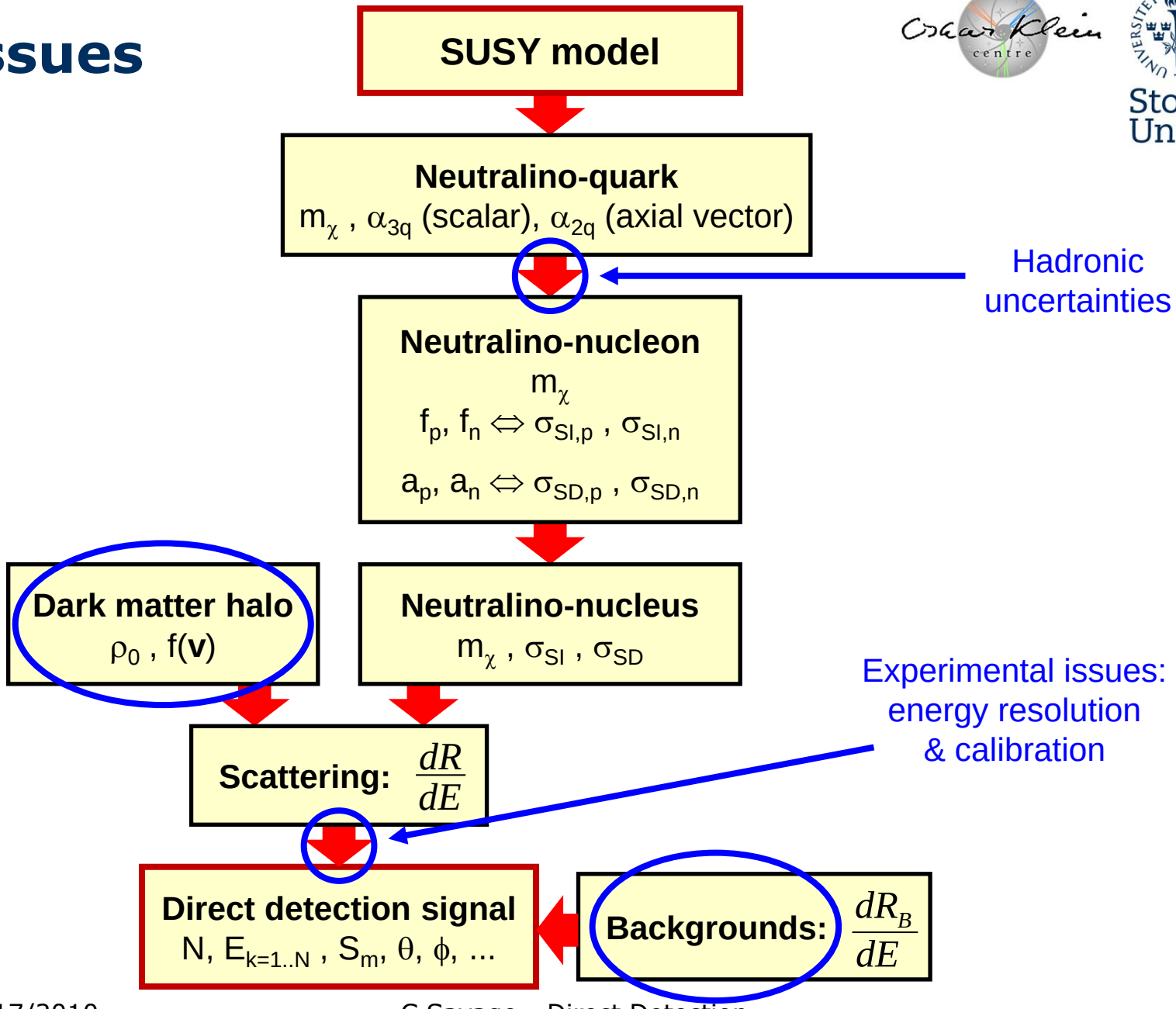
- Modulation amplitudes: binned spectrum (chi-squared)

$$-2 \ln L(S_{m,k=1..N} \mid S_{th,k=1..N}) = \sum_{k=1..N} \frac{\left(S_{m,k} - S_{th,k}\right)^2}{\sigma_k^2}$$

DAMA

What is μ? What is f? Do we *really* know E_k?

Issues


SUSY model
Neutralino-quark
m_χ , α_{3q} (scalar), α_{2q} (axial vector)
Hadronic uncertainties
Neutralino-nucleon
m_χ
f_p, $f_n \Leftrightarrow \sigma_{SI,p}$, $\sigma_{SI,n}$
a_p, $a_n \Leftrightarrow \sigma_{SD,p}$, $\sigma_{SD,n}$
Dark matter halo
ρ_0 , f(**v**)
Neutralino-nucleus
m_χ , σ_{SI} , σ_{SD}
Experimental issues: energy resolution & calibration
Scattering: $\frac{dR}{dE}$
Direct detection signal
N, $E_{k=1..N}$, S_m, θ, ϕ, ...
Backgrounds: $\frac{dR_B}{dE}$

Experimental issues

Detector physics, data cuts:
not all recoil events observed/tagged (efficiencies)

Recoil energy E not directly measured:
inferred from some observable(s) X

- X = scintillation, ionization, phonons/heat

Theory: $\frac{dR}{dE}$

?

Experiment: $\frac{d\tilde{R}}{dX}$

Energy calibration: use observable X to estimate E

- Very low energy events make direct calibration difficult
- Use high energy calibration events, extrapolate to lower energies
- Can be non-linear
- Reconstruction not possible on event-by-event basis?

e.g. quenching in NaI: E_{ee}

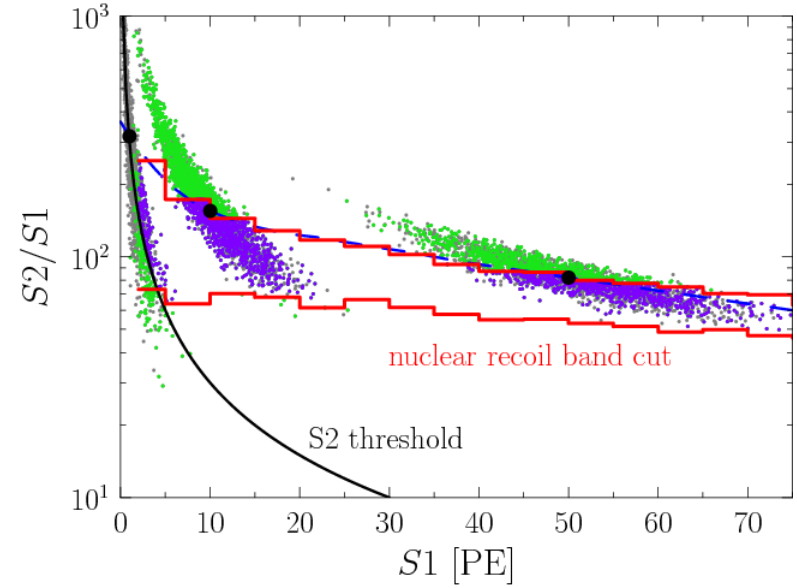
Energy resolution: random fluctuations in X for given E

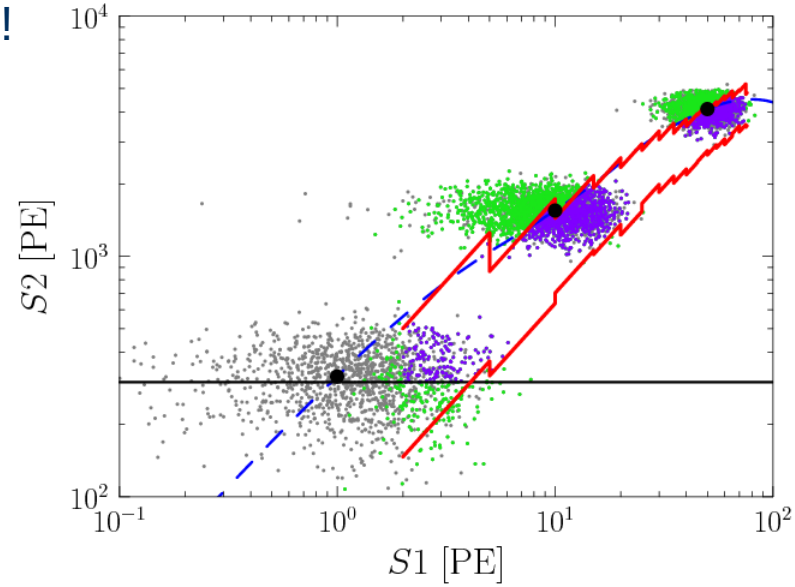
- Atomic processes, low counting statistics, electronics, detector response,…
- Reconstructed energy E' not same as actual energy E

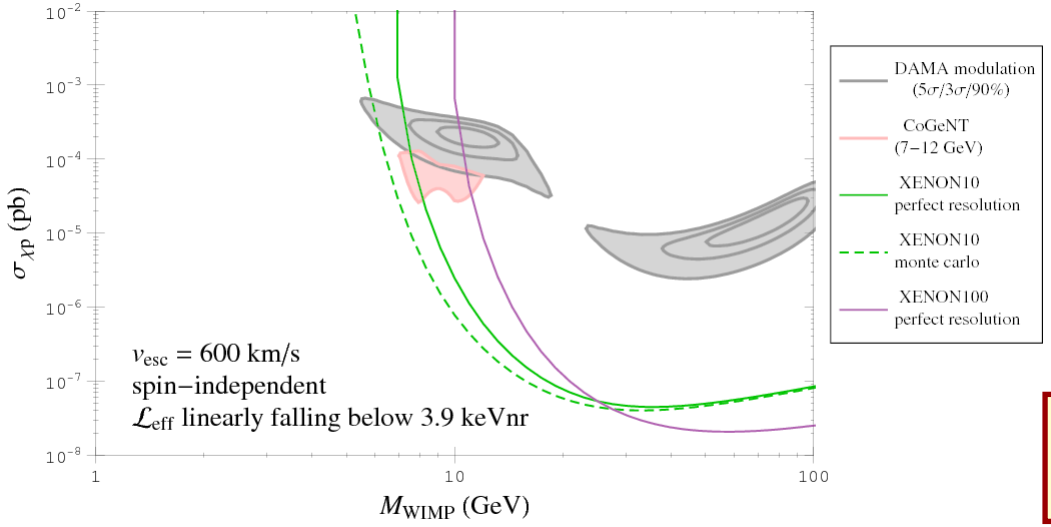
Warning: thresholds/events given as X or E', not E

Finite energy resolution

- Example: XENON10
  - Naïve calibration: E = (2 keV)×S1
    - Observables S1 and S2 for multiple events at 2, 20 & 100 keV
    - Analysis threshold: E' > 4 keV (S1 > 2) …some E = 2 keV events pass threshold!
- Larger issue for light WIMPs
- Can account for statistically



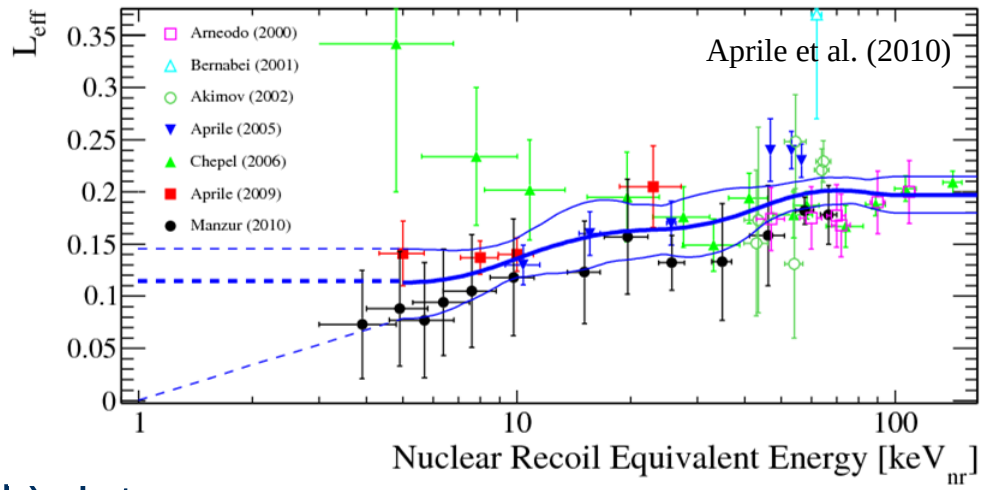




CS, Gelmini, Gondolo & Freese (2010)
+ work in progress

Energy calibration

- Example: XENON10
  - S1 ~ $\mathcal{L}_{eff}(E)$ E
  - Three different low energy extrapolations of Manzur (black) data

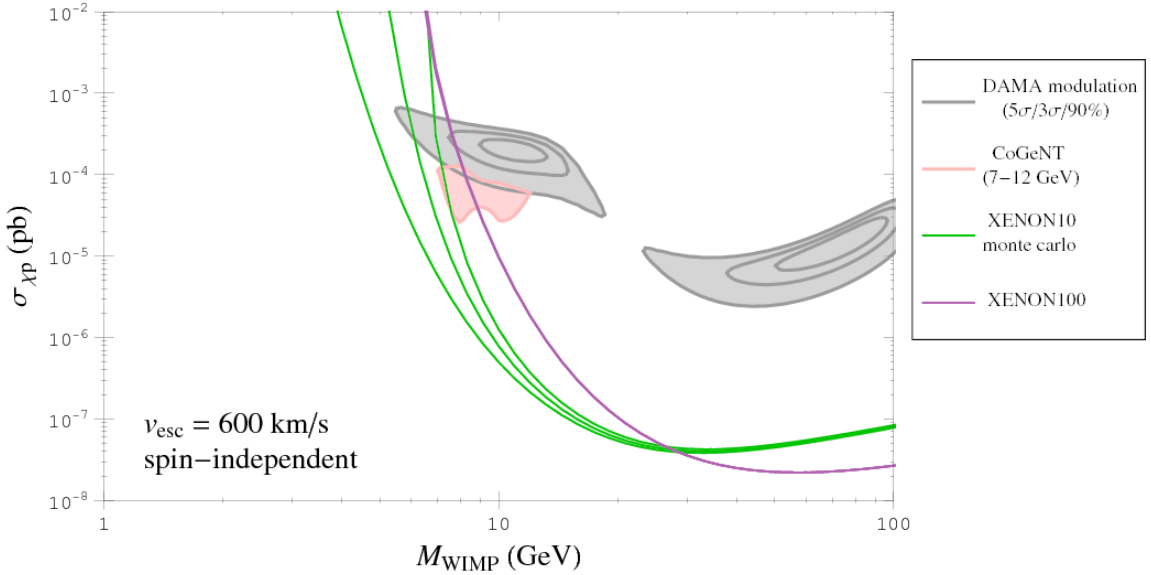


CS, Gelmini, Gondolo & Freese (2010)
+ work in progress

- May or may not be important for heavy WIMPs

  e.g. quenching factors

- Systematic errors



Backgrounds

- Looking for low energy recoil events in a detector.
  Also produced by:
  - Electron recoils: electrons, γ's
  - Nuclear recoils: neutrons

$\Rightarrow$ backgrounds

- Many sources of backgrounds:
  cosmic rays, Argon, radioactive contaminants, …

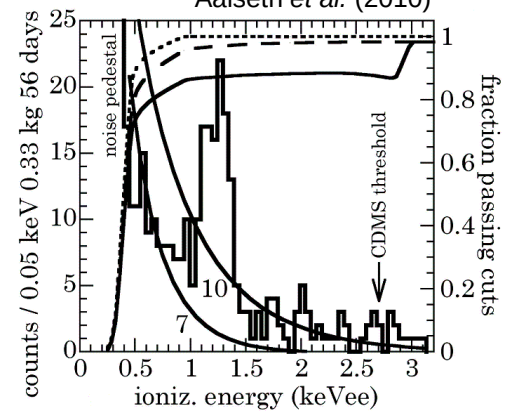
- Most of experimental work involves reducing/characterizing backgrounds:
  shielding, discrimination, limiting radioactive contamination, …

- Determining the backgrounds is difficult!

Backgrounds

- Backgrounds are often poorly known or simply not characterized at all
- Even when backgrounds are estimated, there may be concerns about reliability of estimates

Aalseth *et al.* (2010)



CoGeNT

- Typical analyses assume arbitrary unknown background:
  Yellin's Maximum Gap/Optimum Interval method
  - Defines a p-value used for excluding parameters at some C.L.
  - No likelihood defined!

- SUSY scans: need likelihood, which depends on background
  (need both background rate *and spectrum*)

$$\mu = \mu_S + \mu_B \qquad f(X) = w\, f_S(X) + (1-w)\, f_B(X)$$

Local Halo: Density

- No direct measurement of $\rho_0 \Rightarrow$ Estimates only
  - Galactic rotation: ~ 0.3 GeV/cm^3 [canonical]

- Smooth halo
  - Spherical: 0.2 – 0.4 — Binney & Tremaine (1987), Jungman, Kamionkowski & Griest (1996), Weber & de Boer (2009)
    - 0.39 ± 0.03 — Catena & Ullio (2009)
    - $0.43 \pm 0.11 \pm 0.10$ — Salucci et al. (2010)
  - Elliptical: 0.2 – 0.7 GeV/cm^3 — Gates, Gyuk & Turner (1995), Kamionkowski & Kinkhabwala (1998)
  - DM density near disk 1-41% higher than shell average — Pato et al. (2010)

- Substructure: clumps, tidal streams, dark disk?

- Hierarchical formation:
  Small as 0.04 GeV/cm^3 possible, but likely $\geq$ 0.2 GeV/cm^3 — Kamionkowski & Koushiappas (2008)

Local Halo: Velocity Distribution

- Canonical halo model:

  isotropic, isothermal sphere

  (shift by disk rotation speed v_{rot})

$$f(\mathbf{v}) \sim e^{-\mathbf{v}^2/v_0^2}\ \theta\left[v_{esc} - |\mathbf{v}|\right]$$

  - Canonical: $v_0 = v_{rot} = 220$ km/s , $v_{esc} = 650$ km/s
  - Reid (2008): $v_{rot} = 254 \pm 16$ km/s

    Bovy, Hogg & Rix (2009) [236 ± 11 km/s]

    McMillan & Binney (2009) [wide range]
  - NFW: $v_0 \neq v_{rot}$
  - Smith et al. (2007): $v_{esc} = 544$ km/s (498 – 608 km/s at 90% CL)

    Caveat: assumes $v_{rot} = 220$ km/s

- Non-Maxwellian, anisotropic?

- Structure: dark disk, cold flows

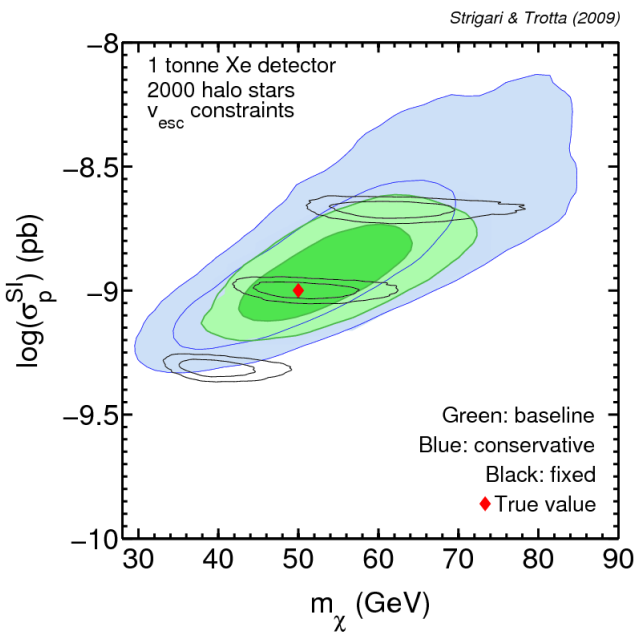
Halo models + direct detection: see various works by Anne M. Green

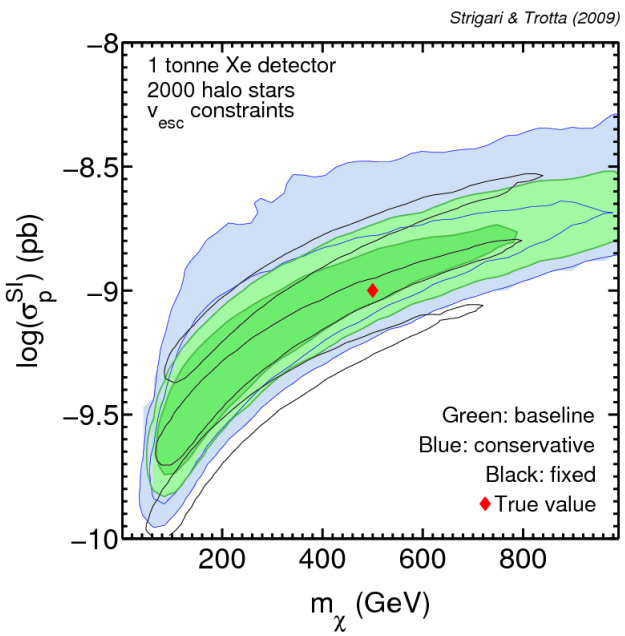
Local Halo: m_χ-σ reconstruction

Strigari & Trotta, JCAP **11**, 019 (2009)

- Reconstructing mass and cross-section with/without including halo uncertainties

  (what if assumed local density is off by ×2?)





Actual

0, **3**, **7** astrophysical parameters in fit

density assumed to be ×**0.5**, **1**, **2** of actual

Scattering Couplings

$$\frac{f_N}{m_N} = \sum_{u,d,s} f_{Tq}^N \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_{TG}^N \sum_{c,b,t} \frac{\alpha_{3q}}{m_q}$$

$$a_N = \sum_{u,d,s} \frac{\alpha_{2q}}{\sqrt{2}} \Delta_q^N$$

$$f_{Tq}^N \equiv m_q \langle N | \bar{q} q | N \rangle$$

$$f_{TG}^N = 1 - \sum_{u,d,s} f_{Tq}^N$$

SUSY

Hadronic/Standard Model

Spin-independent

$\langle N|qq|N\rangle$: hadronic matrix elements

$\Leftrightarrow \Sigma, \sigma_0$

Spin-dependent

Δ_q: polarized parton densities (quark spin contribution)

Couplings to Nucleons

Ellis, Olive & CS (2008)

Stockholm University

Spin-independent

$\langle N|qq|N\rangle$: hadronic matrix elements

$$\sigma_0 \equiv \tfrac{1}{2}(m_u + m_d)\langle N|(\bar{u}u + \bar{d}d - 2\bar{s}s)|N\rangle$$

- 36 ± 7 MeV
  Borasoy & Meissner (1997)

$$\Sigma \equiv \tfrac{1}{2}(m_u + m_d)\langle N|(\bar{u}u + \bar{d}d)|N\rangle$$

π-nucleon sigma term Σ (from πN scattering)

See: Bottino et al. (2002), Ellis et al. (2005)

- 36 MeV — Naïve model ($\langle N|ss|N\rangle = 0$)
- 45 ± 8 MeV — Gasser, Leutwyler & Sainio (1991), Knecht (1999)
- 64 ± 8 MeV — Cheng-Dashen Point
  Pavan, Arndt, Strakovsky & Workman (2002)
- Lattice calculation
  63 ± 21 MeV — Andre Walker-Loud (private correspondence)
  47 ± 9 MeV — Young & Thomas (2009)

Spin-dependent

Δ_q: polarized parton densities

Strange quark Δ_s:

- -0.09 ± 0.03
  Alekseev et al. (2007) [COMPASS]

Individual Uncertainties

CMSSM benchmark model C from Ellis, Olive & CS (2008)

		$\sigma_{SI,p}$ (pb)	$\sigma_{SD,p}$ (pb)	$\sigma_{SI,n} / \sigma_{SI,p}$	$\sigma_{SD,n} / \sigma_{SD,p}$
Fiducial values:		2.85×10^{-9}	2.19×10^{-6}	1.029	1.28
m_u / m_d	0.553 ± 0.043	±3.5%	~ 0.	±0.08%	~ 0.
m_s / m_d	18.9 ± 0.9	±5.2%	~ 0.	±0.07%	~ 0.
σ_0	36 ± 7 MeV	+34% -27%	-	+1.2% -0.7%	-
Σ	64 ± 8 MeV	+45% -32%	-	+0.7% -0.4%	-
a_3	1.2695 ± 0.0029	-	±0.5%	-	±0.06%
a_8	0.585 ± 0.025	-	±2.2%	-	±4.2%
Δ_s	-0.09 ± 0.03	-	+14% -12%	-	+30% -21%

Combined Uncertainties (Confidence Intervals)

CMSSM benchmark models from Ellis, Olive & CS (2008)

$\Sigma = 64 \pm 8$ MeV only

Model:	C	L	M
$\sigma_{SI,p}$ (pb)	2.9×10^{-9}	2.4×10^{-8}	1.3×10^{-10}
68.3% C.L.	$(1.7 – 4.9) \times 10^{-9}$	$(1.2 – 4.0) \times 10^{-8}$	$(0.8 – 2.0) \times 10^{-10}$
95.4% C.L.	$(0.8 – 6.5) \times 10^{-9}$	$(0.5 – 6.0) \times 10^{-8}$	$(0.4 – 2.8) \times 10^{-10}$
$\sigma_{SD,p}$ (pb)	2.2×10^{-6}	1.8×10^{-6}	2.4×10^{-8}
68.3% C.L.	$(1.9 – 2.5) \times 10^{-6}$	$(1.6 – 2.0) \times 10^{-6}$	$(2.2 – 2.6) \times 10^{-8}$
95.4% C.L.	$(1.6 – 2.8) \times 10^{-6}$	$(1.4 – 2.3) \times 10^{-6}$	$(2.0 – 2.9) \times 10^{-8}$
$\sigma_{SI,n} / \sigma_{SI,p}$	1.029	1.042	1.026
68.3% C.L.	1.020 – 1.042	1.028 – 1.065	1.018 – 1.037
95.4% C.L.	1.015 – 1.066	1.020 – 1.114	1.013 – 1.056
$\sigma_{SD,n} / \sigma_{SD,p}$	1.28	1.15	1.02
68.3% C.L.	1.00 – 1.65	0.93 – 1.44	0.85 – 1.22
95.4% C.L.	0.78 – 2.14	0.75 – 1.80	0.71 – 1.46
$\sigma_{SD,p} / \sigma_{SI,p}$	770	77	187
68.3% C.L.	480 – 1350	46 – 151	121 – 319
95.4% C.L.	320 – 2730	30 – 373	83 – 616

Reconstruction examples

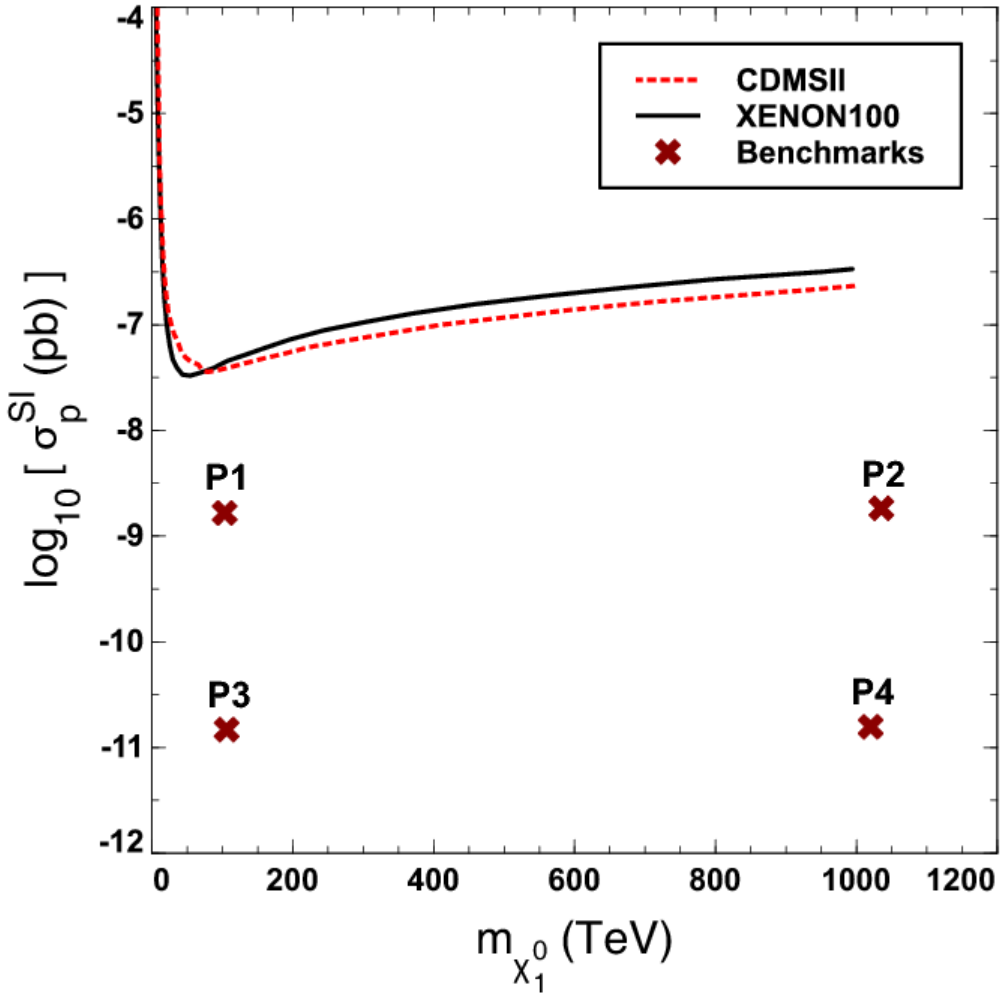
CMSSM and direct detection

Y. Akrami, J. Conrad, J. Edsjö, CS, P. Scott (*work in progress*)

- CMSSM scans with future DD results only
  - DarkSUSY + SuperBayeS (MultiNest)
- Future experiments
  - XENON1T: number of events and spectrum (Xe, neutron odd)
  - CDMS1T: number of events and spectrum (Ge, neutron odd)
  - COUPP1T: number of events only (CF3I, proton odd)

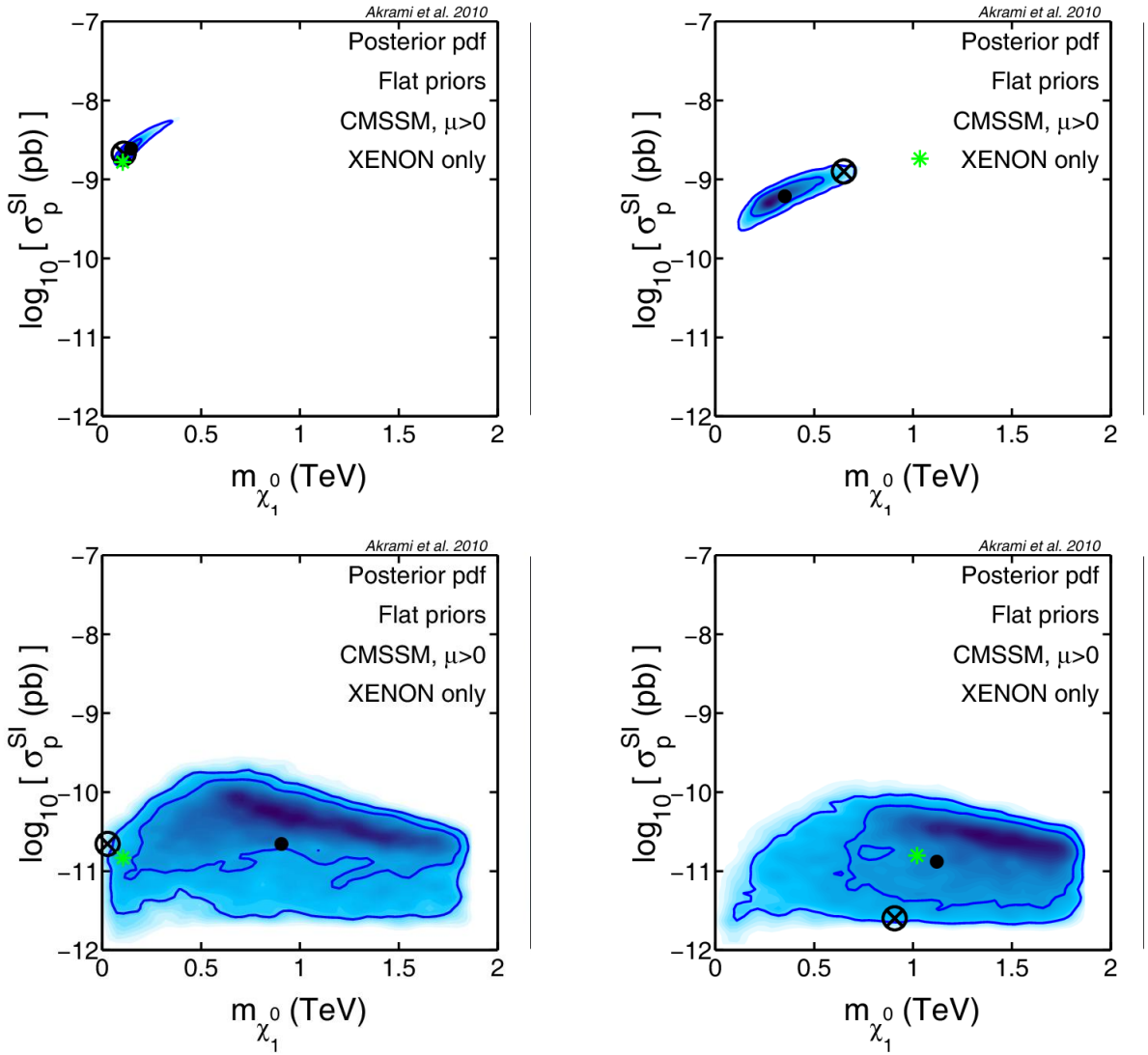
  - Includes typical energy resolutions, thresholds, efficiencies, etc.
  - Includes backgrounds at target levels (~ 2 events), known spectrum
  - Does not yet include hadronic and halo uncertainties (*in progress*)

CMSSM and direct detection: benchmarks



CMSSM and direct detection: XENON1T

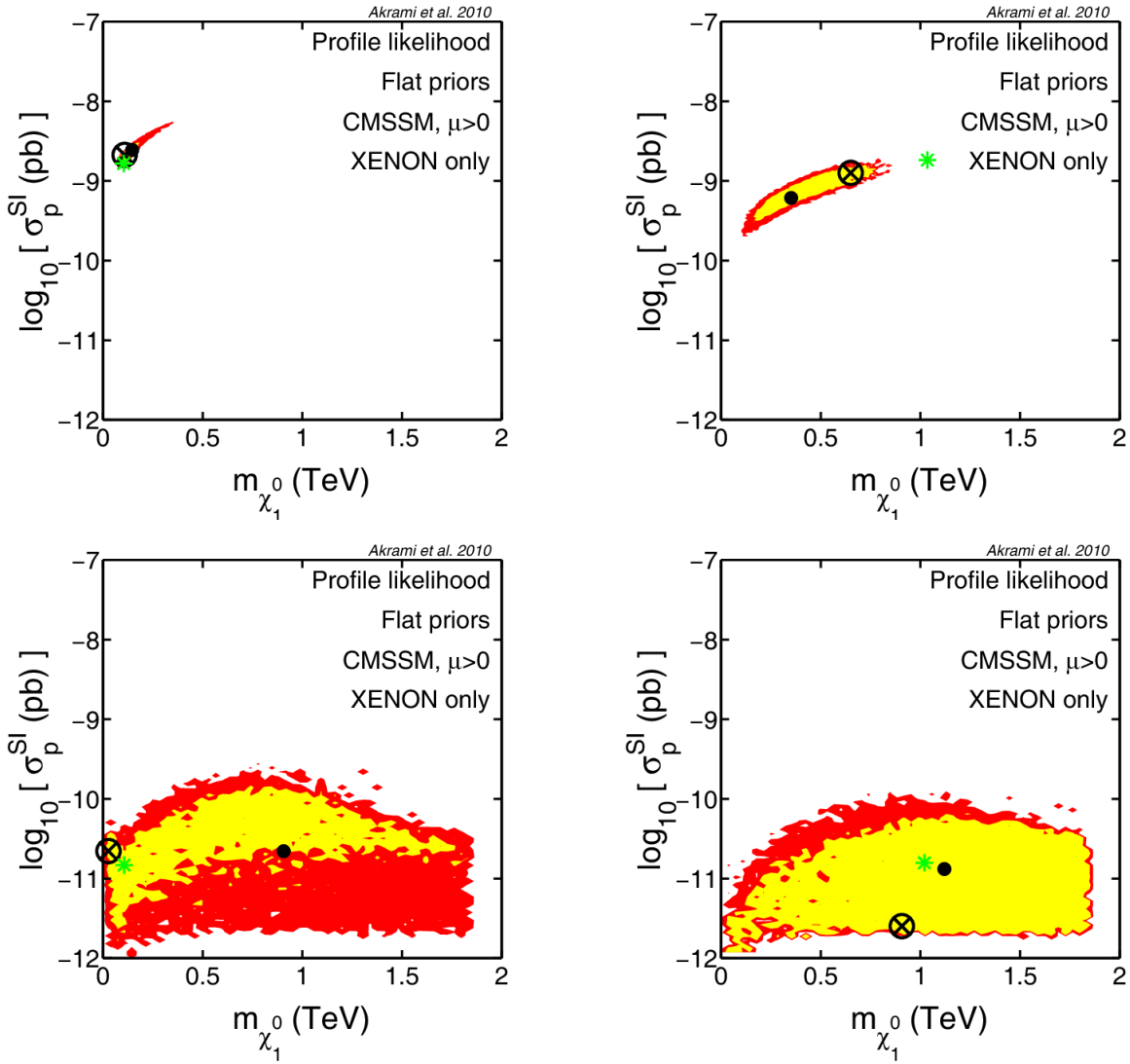
Preliminary



Posterior PDF

CMSSM and direct detection: XENON1T

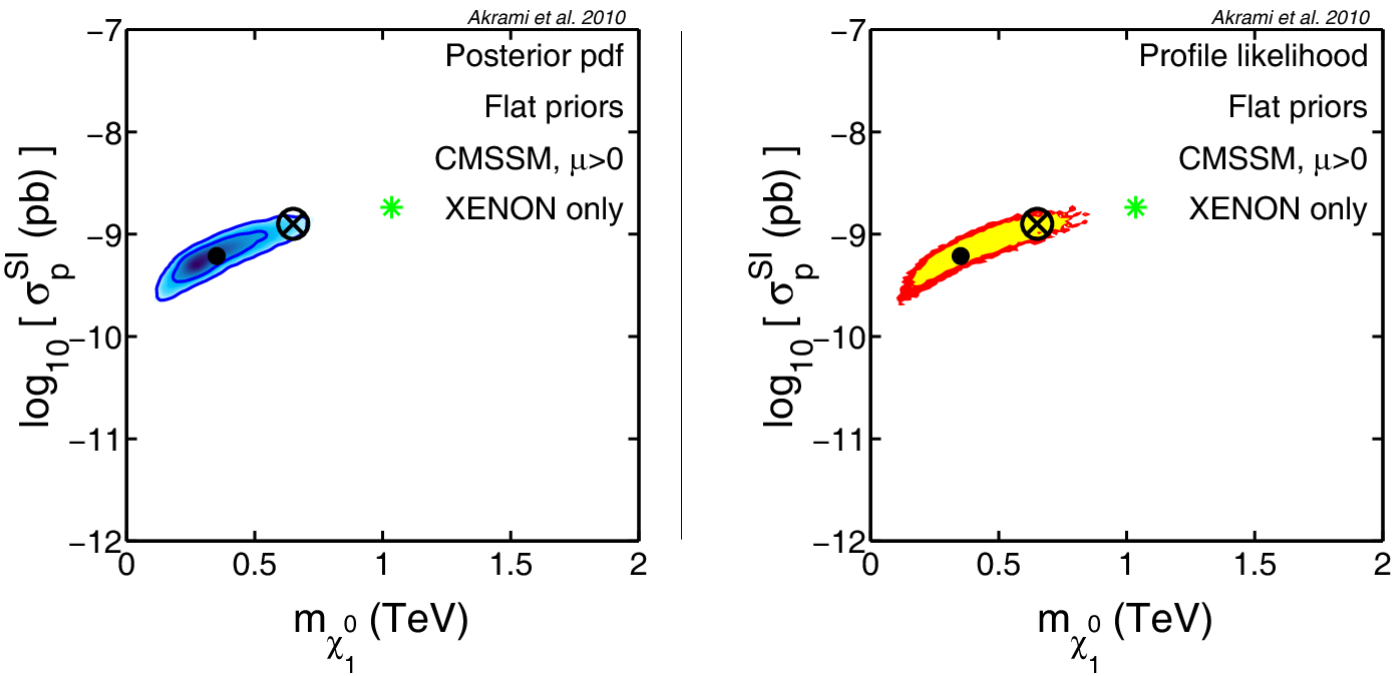
Preliminary



Profile Likelihood

CMSSM and direct detection: XENON1T

Preliminary

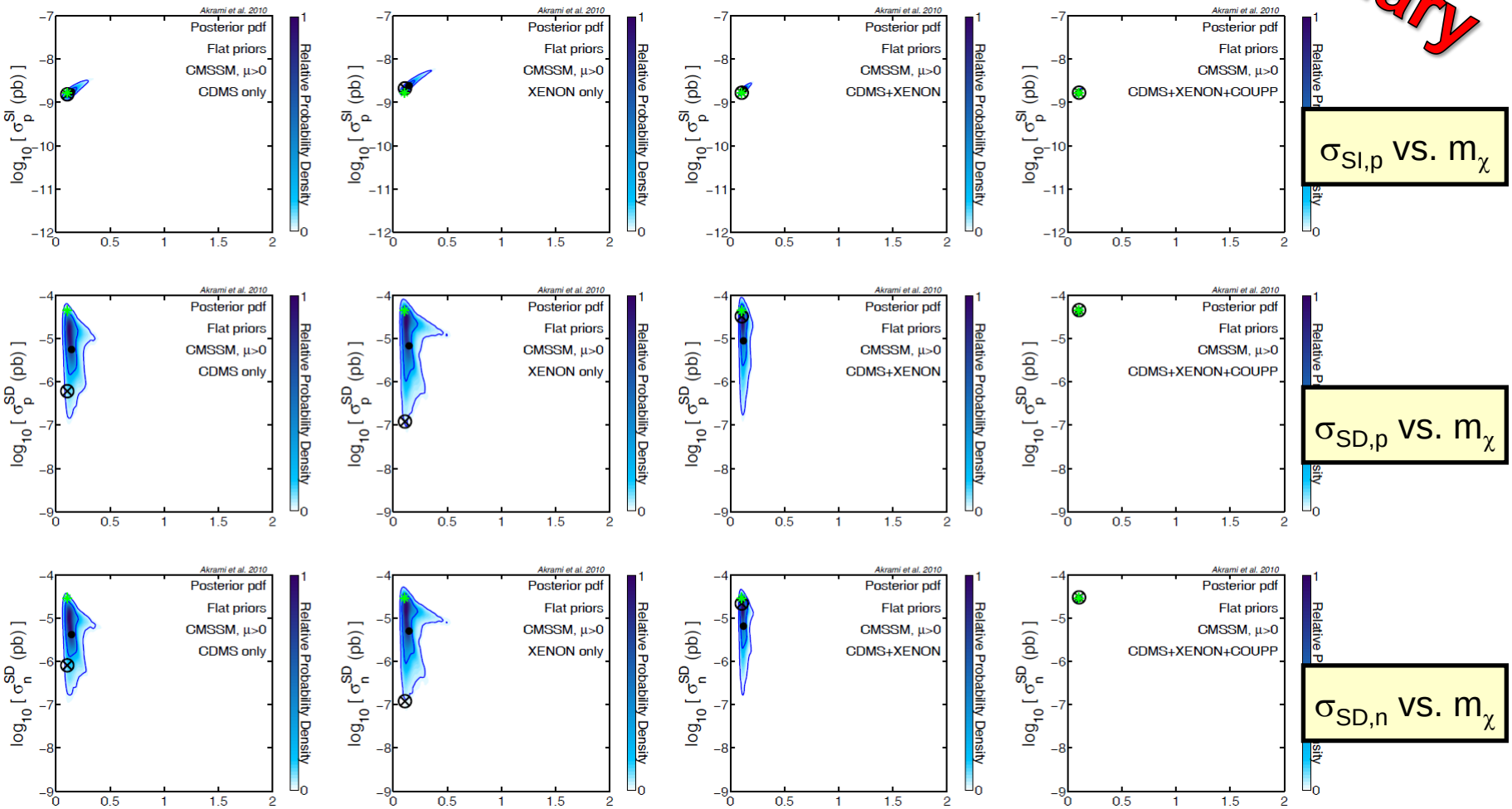


Heavy WIMPs: identical spectrum

$\Rightarrow$ degeneracy along fixed $(\rho_0 / m\chi)\ \sigma_{SI,p}$

CMSSM and direct detection: Complementarity

Preliminary



CDMS1T | XENON1T | XENON1T +CDMS1T | +COUPP1T

CMSSM and direct detection: Complementarity

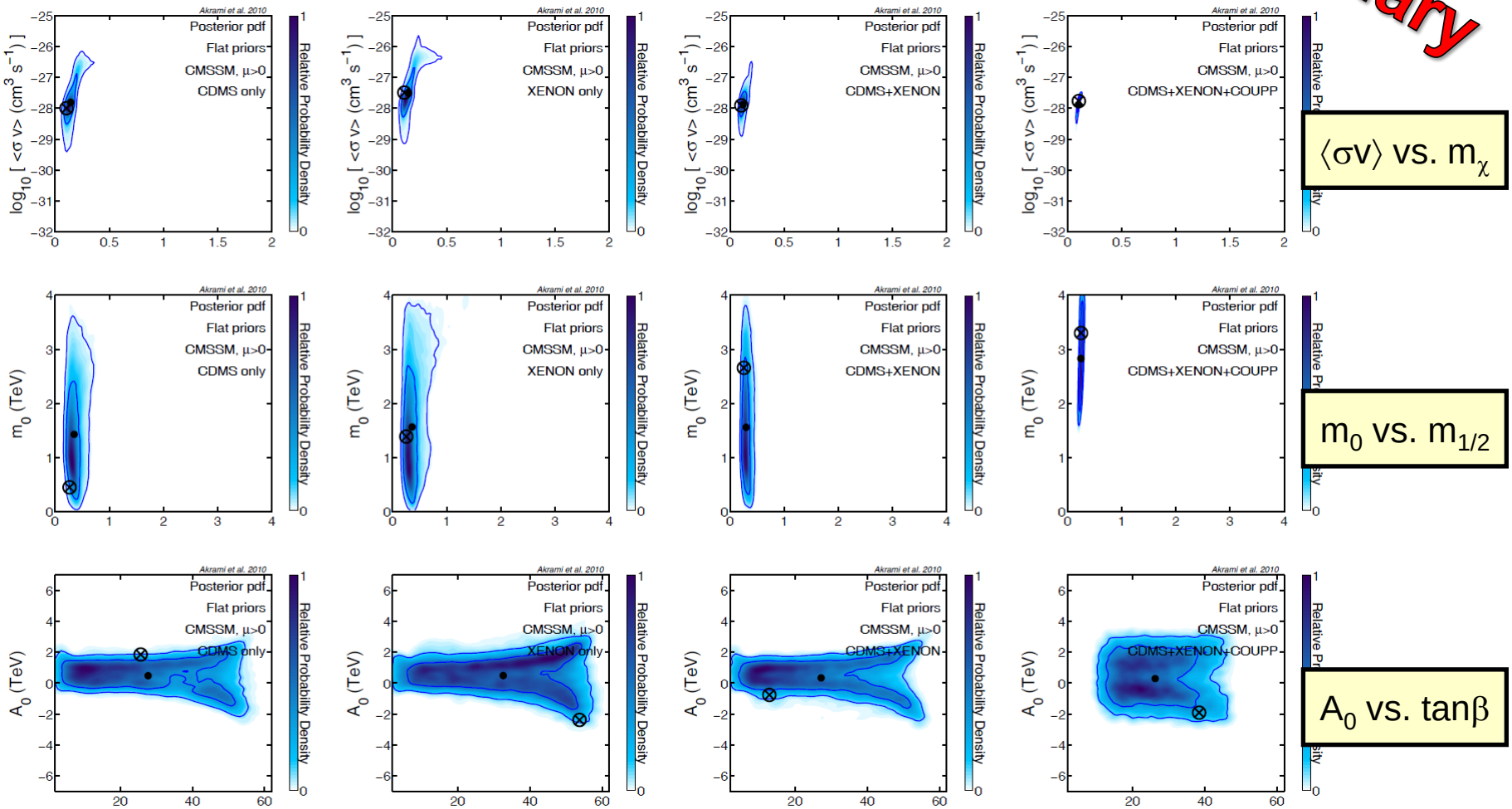
Expected events:

	SI	SD
▪ XENON1T	219.5	23.5
▪ CDMS1T	142.4	4.8
▪ COUPP1T	298.7	448.1

- XENON1T/CDMS1T spectrum: WIMP mass
- XENON1T/CDMS1T number of events: SI cross-section
  poor constraint on SD cross-sections
- COUPP1T breaks SD degeneracy

CMSSM and direct detection: Complementarity

Preliminary



CDMS1T

XENON1T

XENON1T +CDMS1T

+COUPP1T

Conclusions/final thoughts

Direct detection beginning to push into interesting SUSY regions

- Useful addition to collider, indirect detection results for constraining SUSY models

- However, there are various issues to be addressed and limitations to be aware of
  - **Detector behavior:** simple treatment may be OK in some cases (for now)
  - **Backgrounds:** need to push experiments for estimates (if available), otherwise Bayesian treatment?
  - **Halo model:** directional detection might help
  - **Hadronic uncertainties:** irrelevant for experimentalists, but an issue for SUSY scanning

SUSY model

Neutralino-quark
m_χ , α_{3q} (scalar), α_{2q} (axial vector)

Neutralino-nucleon
m_χ
$f_p, f_n \Leftrightarrow \sigma_{SI,p}$, $\sigma_{SI,n}$
$a_p, a_n \Leftrightarrow \sigma_{SD,p}$, $\sigma_{SD,n}$

Dark matter halo
ρ_0 , f(**v**)

Neutralino-nucleus
m_χ , σ_{SI} , σ_{SD}

Scattering: $\frac{dR}{dE}$

Direct detection signal
N, $E_{k=1..N}$, S_m, θ, ϕ, ...

Backgrounds: $\frac{dR_B}{dE}$

Theorists:
DarkSUSY
MicrOMEGAs

Experiments & phenomenologists:
20+ private codes
no public codes

Want to connect everything together: can this be done?

Do we need more involvement from the experiments?