XENON dark matter constraints: examining the $\mathcal{L}_{\text{eff}}$ dependence

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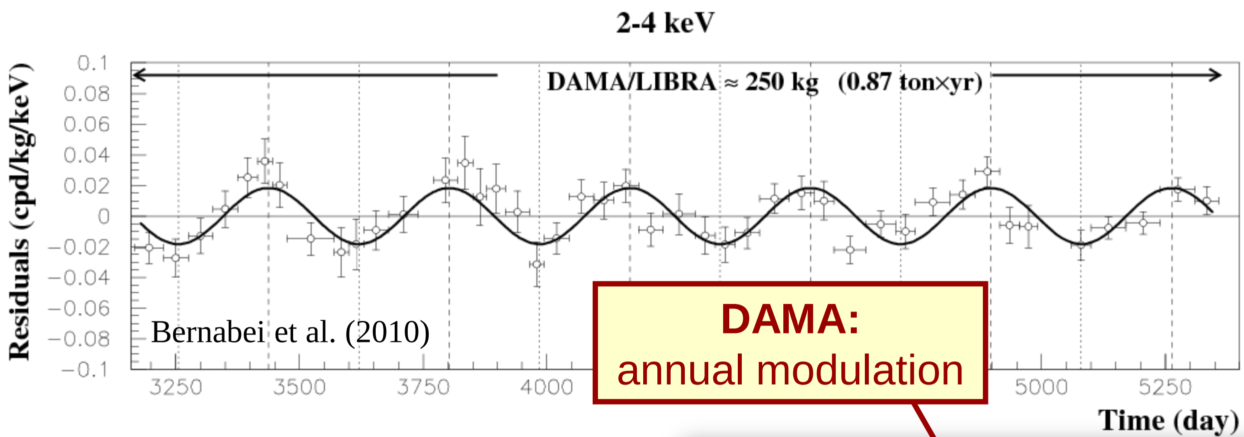
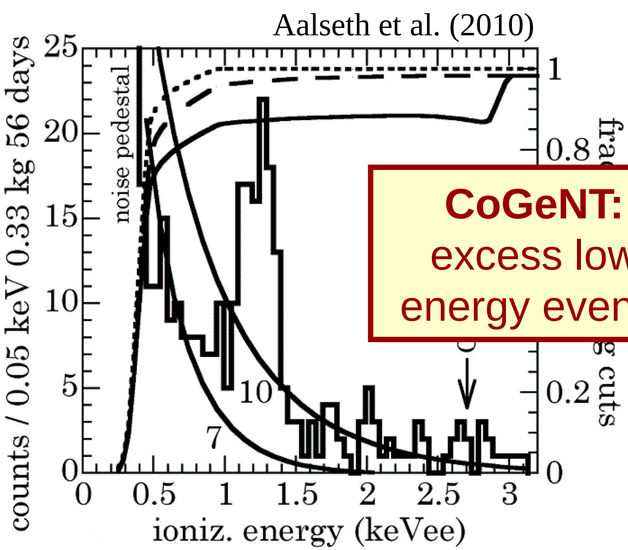
CS, Gelmini, Gondolo & Freese
arXiv:1006.0972 + work in progress

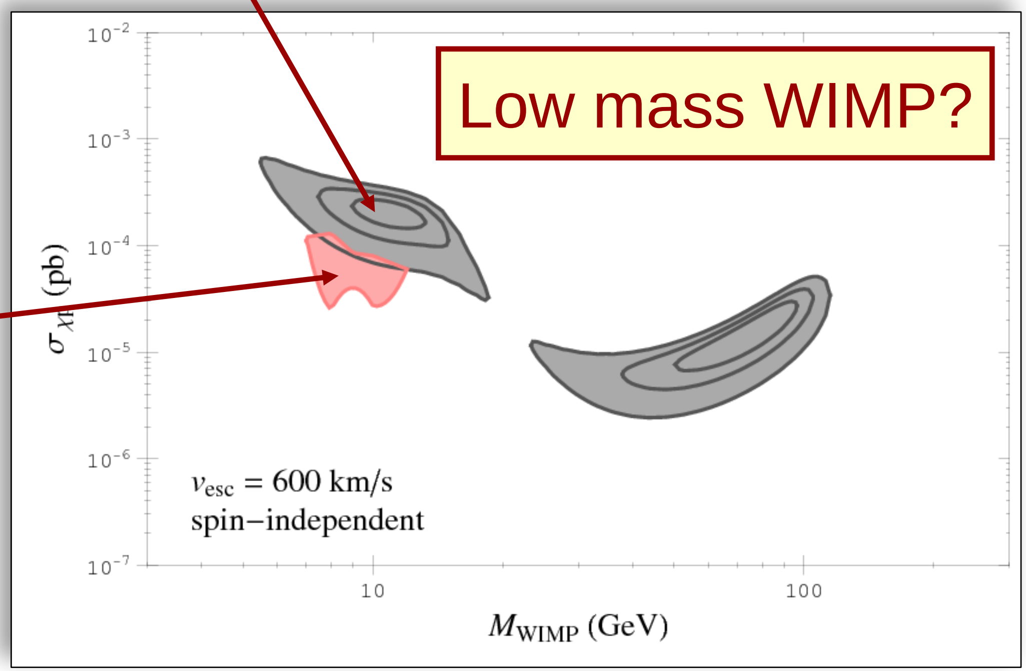
Overview



DAMA: annual modulation



CoGeNT: excess low energy events



Low mass WIMP?

Overview

- What can liquid Xenon (or Argon) detectors tell us about low mass WIMPs?

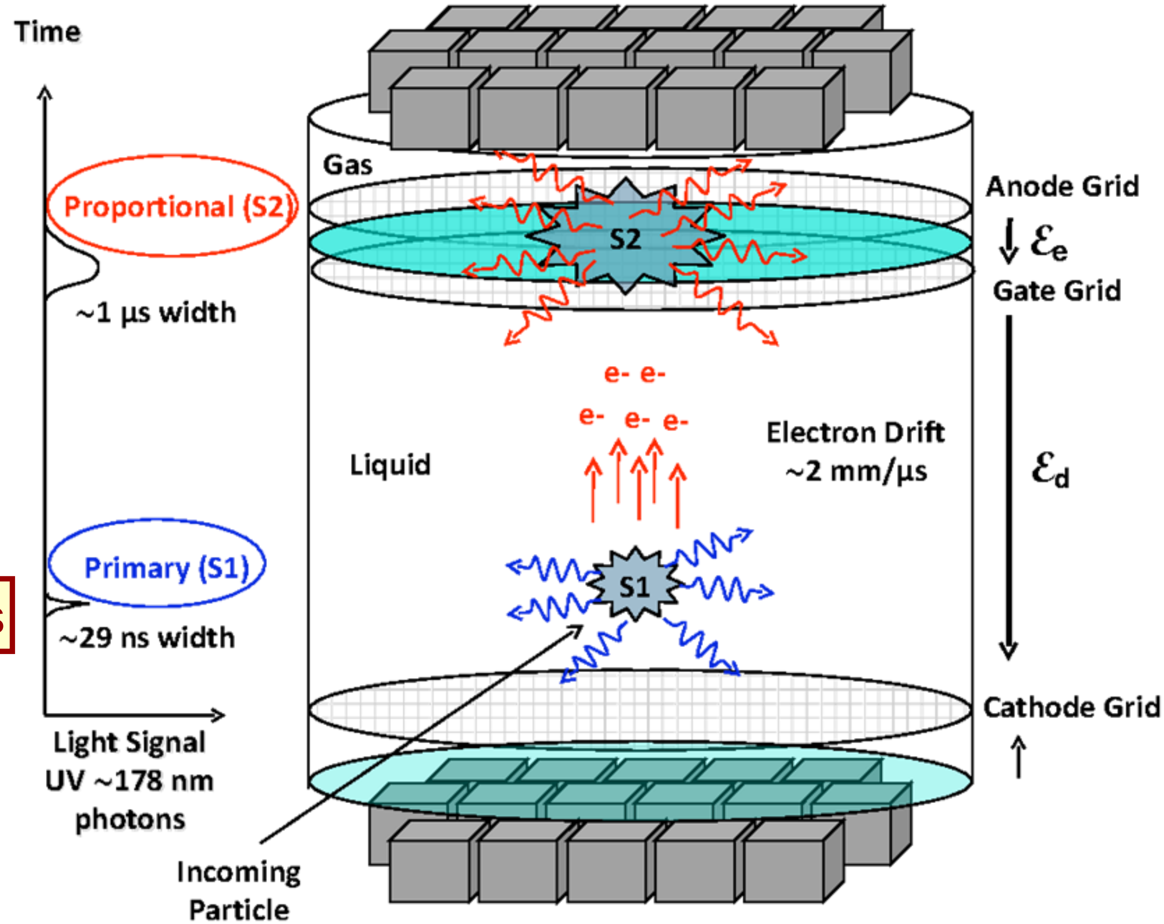
- Two phase detectors
  - Two scintillation signals: S1 & S2 (allows for background rejection)
  - Analysis: must relate S1 & S2 to nuclear recoil energy E_{nr}
    $\Rightarrow$ depends on relative scintillation efficiency factor $\mathcal{L}_{eff}$

- Outline
  - What is $\mathcal{L}_{eff}$?
  - XENON10 and XENON100 constraints

Liquid Xenon/Argon detectors: principles of operation

S2: ionization electrons

S1: prompt photons



Aprile et al. (2010) [XENON10]

$\mathcal{L}_{eff}$: Relative scintillation efficiency

Bias field correction

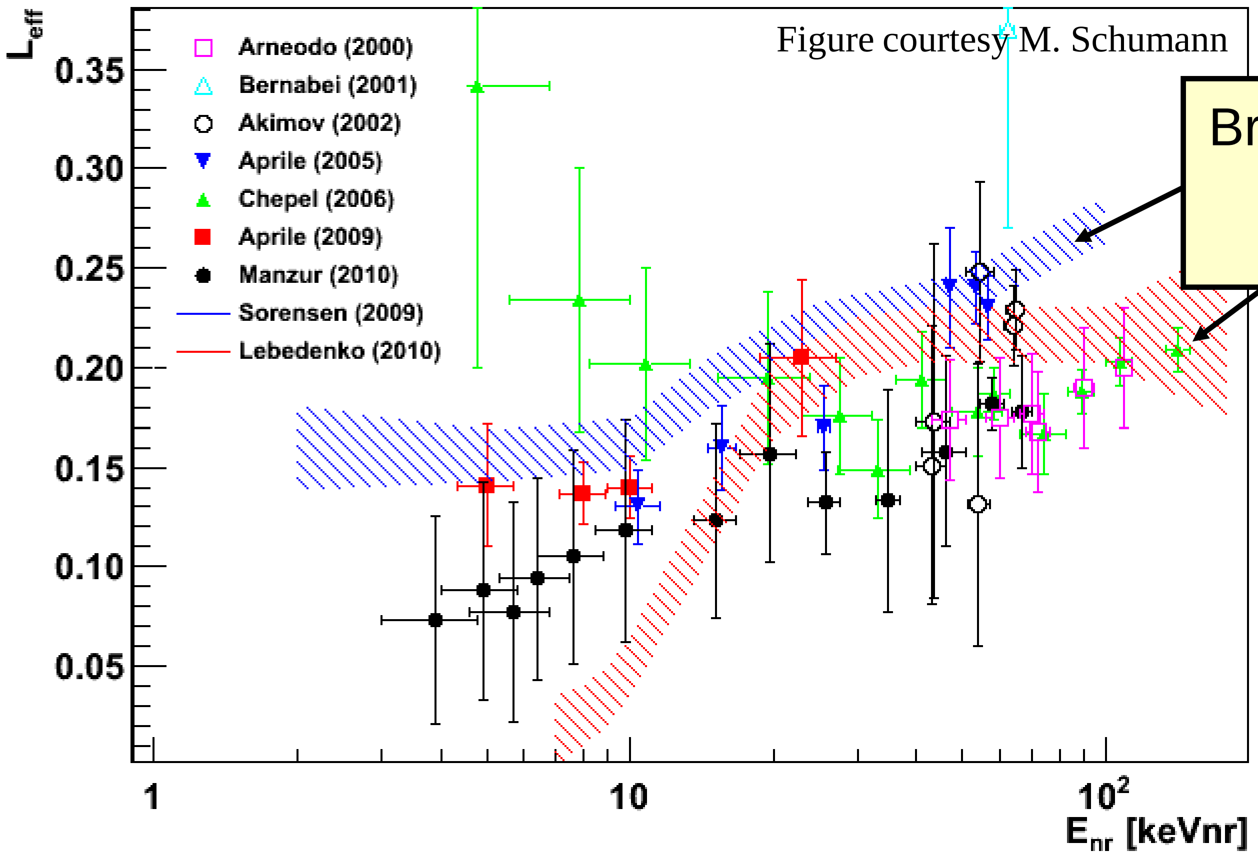
Nuclear recoil energy

$$S1 = \frac{S_{nr}}{S_{ee}} \mathcal{L}_{eff}(E_{nr})\, L_y\, E_{nr}$$

Nuclear recoil scintillation yield

- $\mathcal{L}_{eff}$: nuclear recoil scintillation efficiency relative to fixed reference point
- L_y: light yield for 122 keV γ-rays (electronic recoils); easily measured

$\mathcal{L}_{eff}$ measurements



Broad spectrum:
XENON10
ZEPLIN-III

Fixed energy (neutron beam):
Aprile et al. (2009) Manzur et al. (2010)

$\mathcal{L}_{eff}$ issues

- Which data set(s) to use?

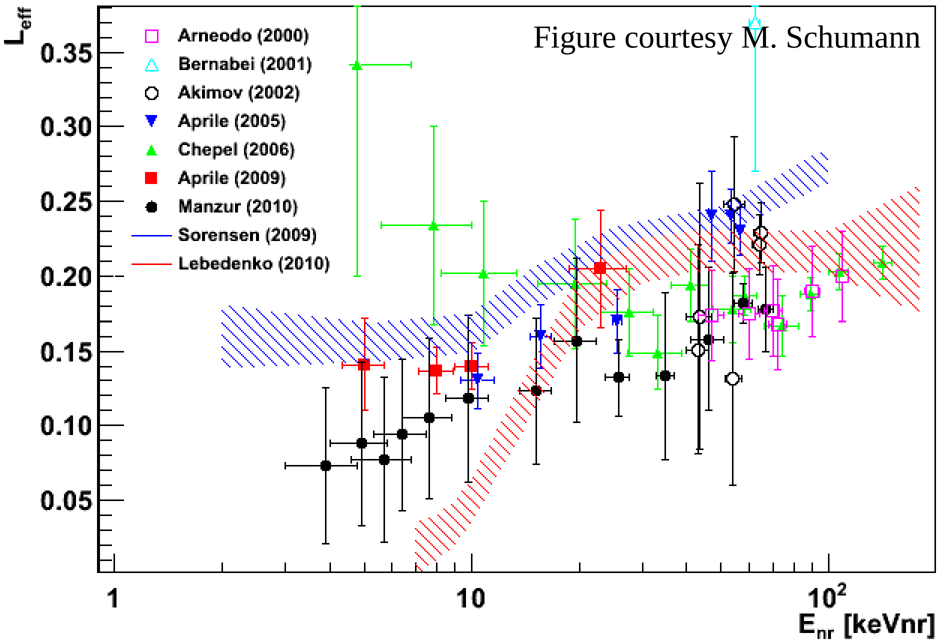
Collar & McKinsey (2010)

Talk by D. McKinsey

  - Lower $\mathcal{L}_{eff}$ gives weaker constraints
  - Conservative case (fixed energy): Manzur et al. (2010)

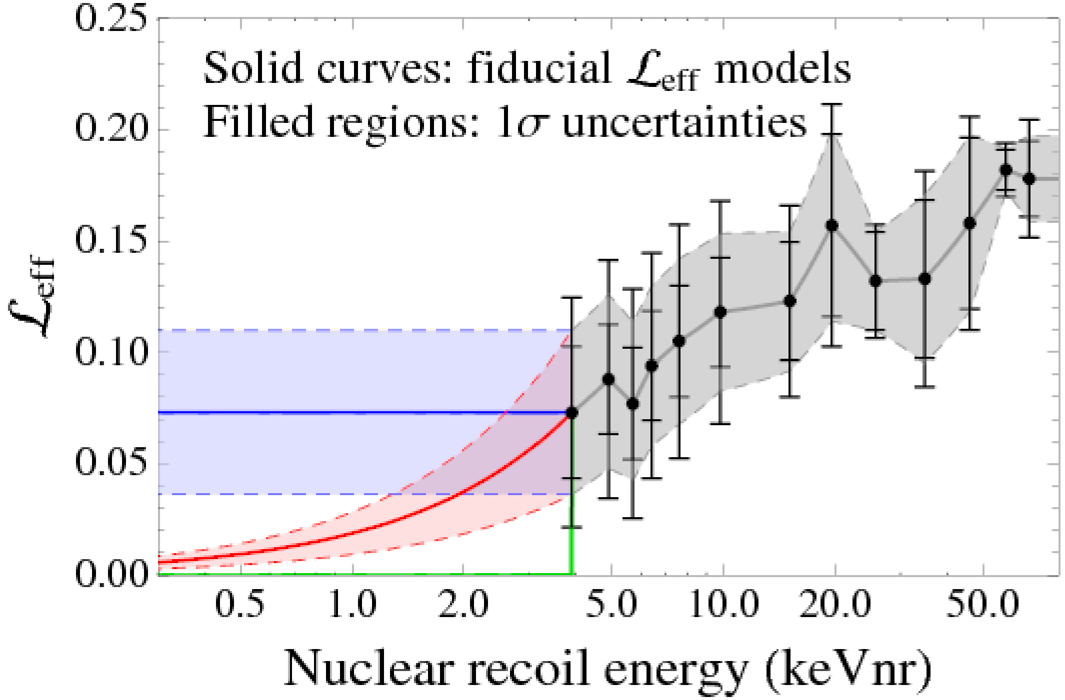
    [Note: conservative, not necessarily "best"]
  - For discussion, see:

    A. Manalaysay, arXiv:1007.3746



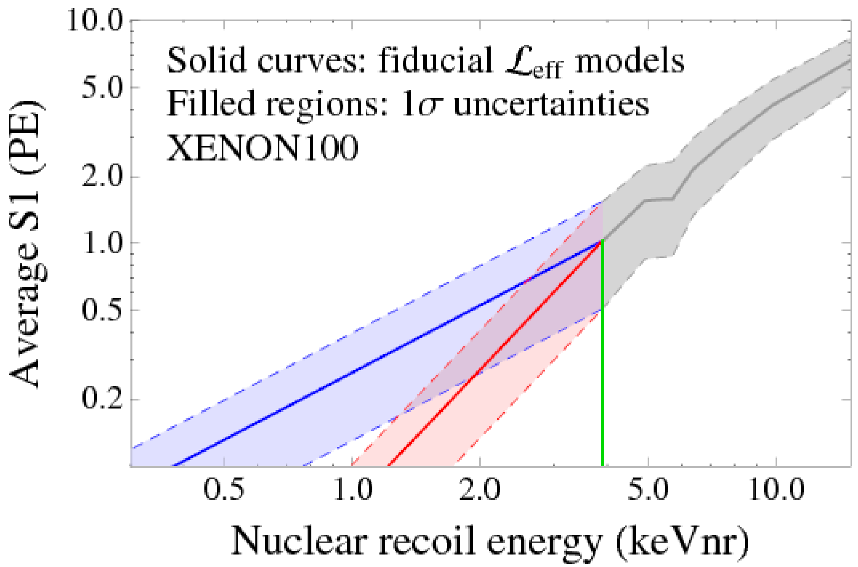
- Low energy behavior?
  - Flat (constant)
  - Falling
  - Zero

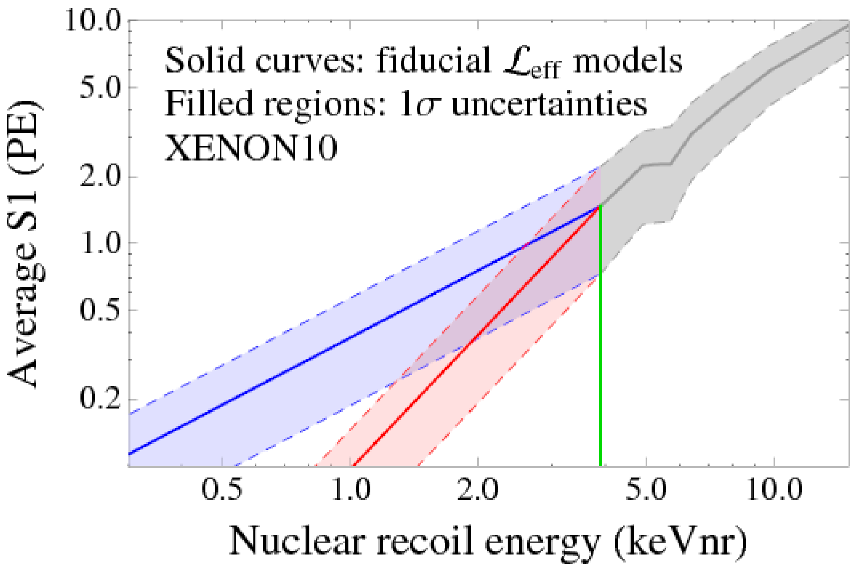
$\mathcal{L}_{eff}$ models



- High energy measurements: Manzur et al. (2010)
- Low energy $\mathcal{L}_{eff}$ extrapolation:
  - Constant
  - Linearly falling
  - Zero

$\mathcal{L}_{eff}$ models





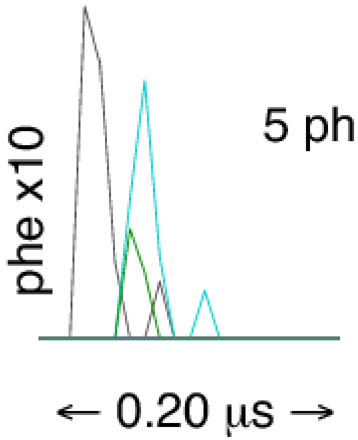
XENON100
S1 threshold: 4 PE

XENON10
S1 threshold: 2 PE

Finite energy resolution

$$\boxed{\langle S1 \rangle} \; \cancel{S1} = \frac{S_{nr}}{S_{ee}} \mathcal{L}_{eff}(E_{nr})\, L_y\, E_{nr}$$

- Measured S1 signal:
  area of peak in electronic readout
  - Due to detector geometry and photocathode efficiency, only a small fraction (~ 10%) of prompt photons produce a photoelectron (PE) in a PMT $\Rightarrow$ Poisson fluctuations
  - Due to digitization, PMT gain, etc., peak area of single PE varies: 1.0 ± 0.6 PE



Aprile et al. (2010) [XENON10]

$\Rightarrow$ S1 fluctuates about average $\langle S1 \rangle$

Finite energy resolution

Reconstructed nuclear recoil energy E′

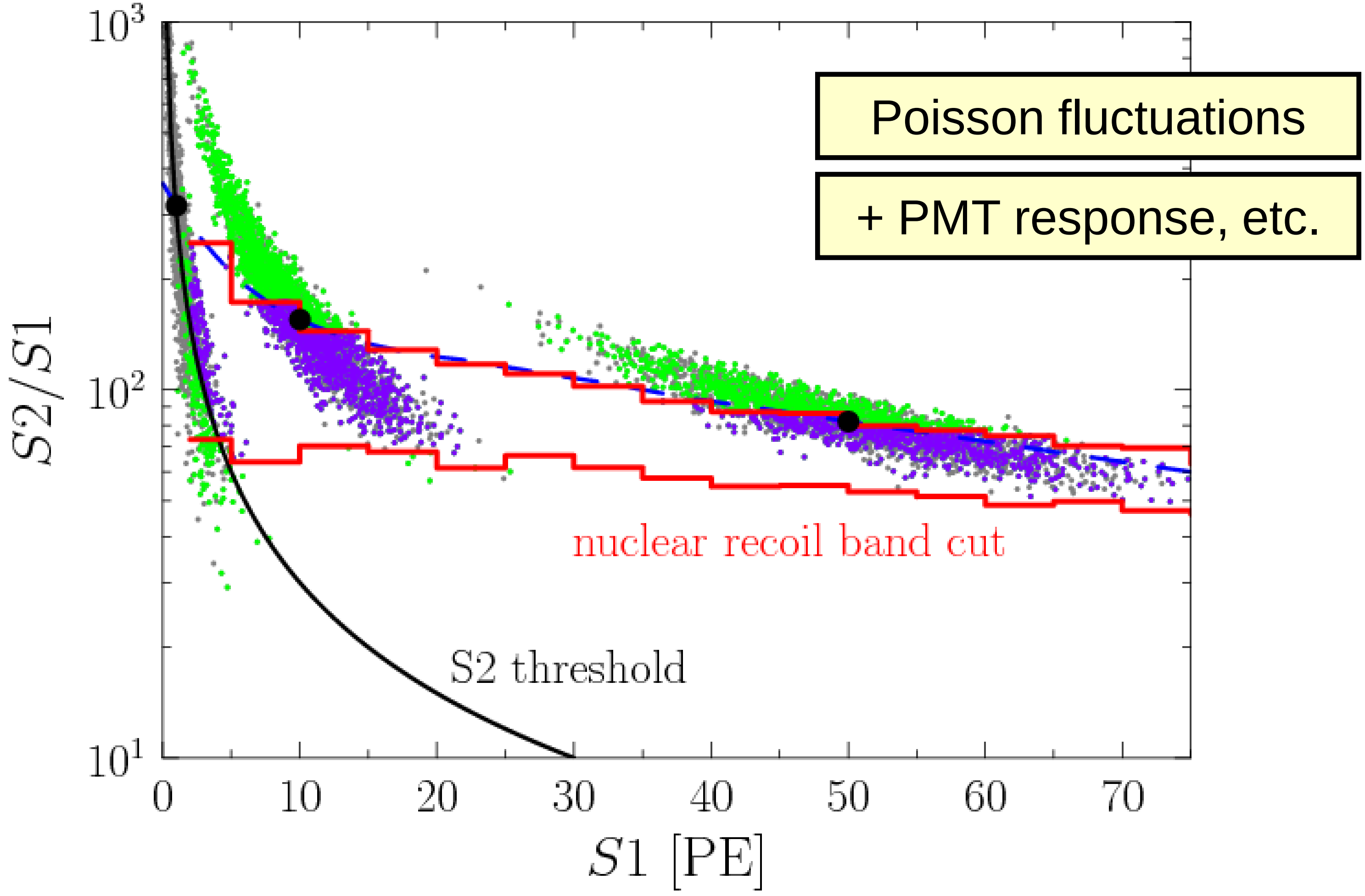
$$E' = \frac{S_{ee}}{S_{nr}} \frac{1}{\mathcal{L}_{eff}(E')\, L_y} S1$$

But $S1 \neq \langle S1 \rangle$, so $E' \neq E_{nr}$

- High energy recoils: good approximation
  $S1 \approx \langle S1 \rangle \quad \Rightarrow \quad E' \approx E_{nr}$
- Low energy recoils: poor approximation

Theory:	$E_{nr} \Leftrightarrow \langle S1 \rangle$
Observations:	$E' \Leftrightarrow S1$

Finite energy resolution

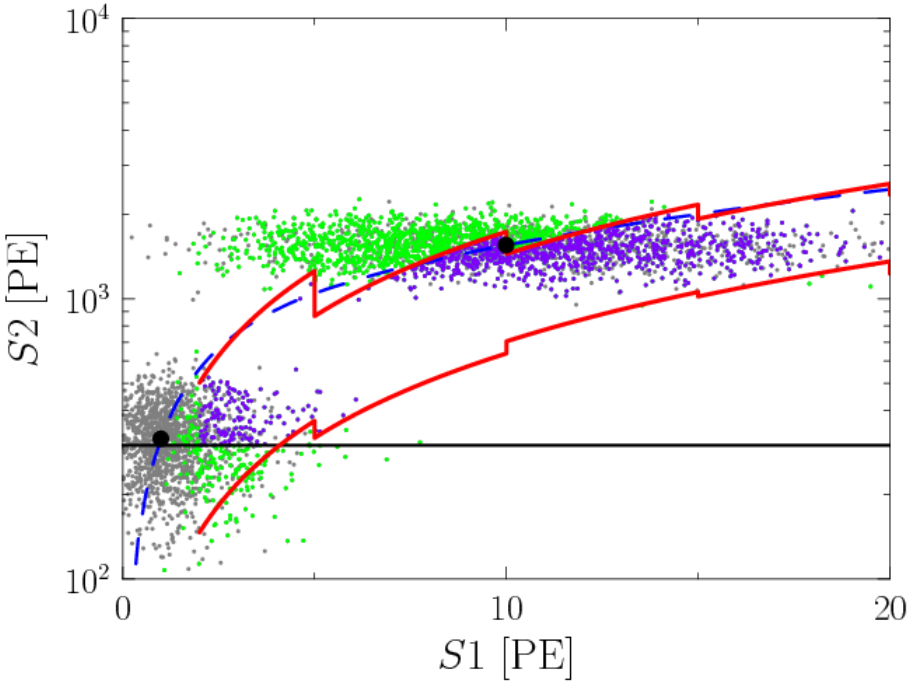


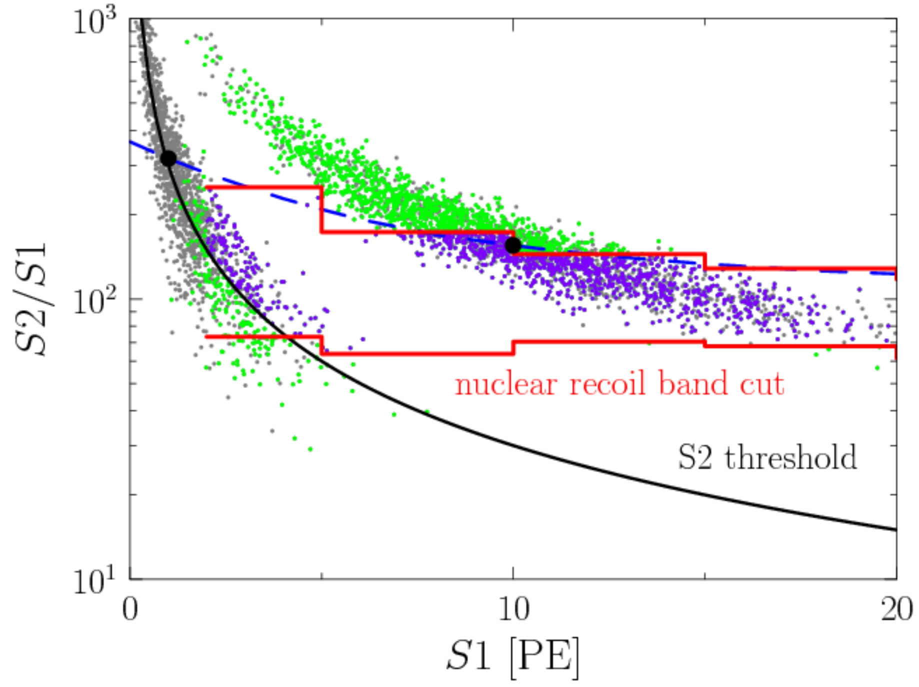
Finite energy resolution

S1 and S2 fluctuations

Poisson fluctuations

+ PMT response, etc.



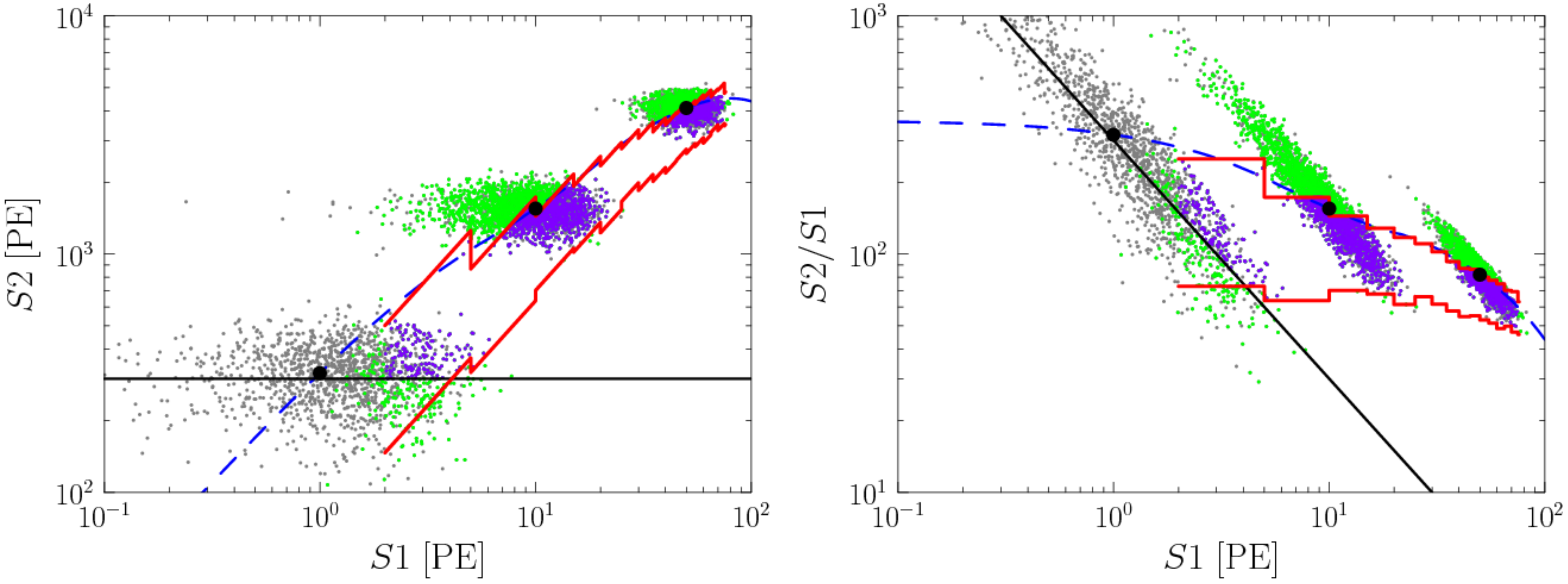


Finite energy resolution

S1 and S2 fluctuations: relative size increases at low recoil energies

Poisson fluctuations

+ PMT response, etc.



Efficiencies: monte carlo

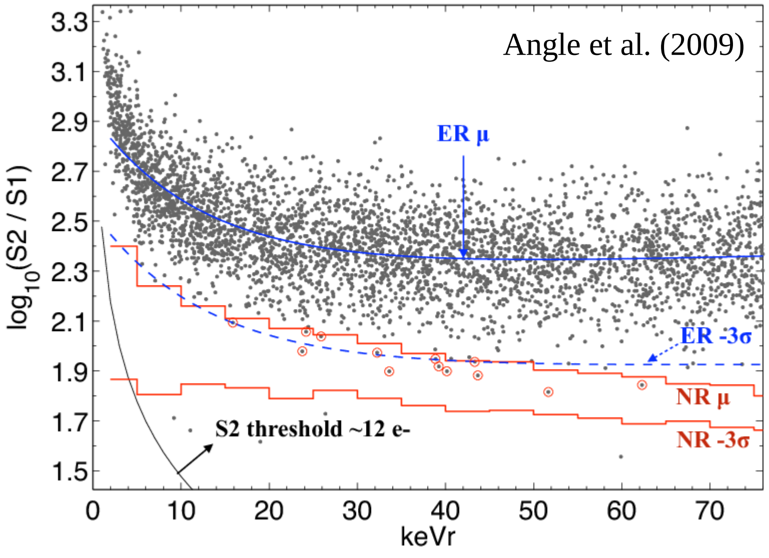
See also P. Sorensen, arXiv:1007.3549

Stockholm University

- For each ⟨S1⟩, generate S1 & S2 signals for a large number of random events
  - Poisson fluctuations in ionization electrons, photoelectrons
  - Fluctuations in PMT peak areas (digitization, gain, etc.)

- Efficiency: fraction that pass all cuts
  - S1 > 2 PE
  - S2 > 300 PE
  - S2/S1: nuclear recoil band cut
  - η_{S1}: peak finding efficiency factor
  - ε_p: PMT hit pattern
  - ε_f: S1 pulse shape

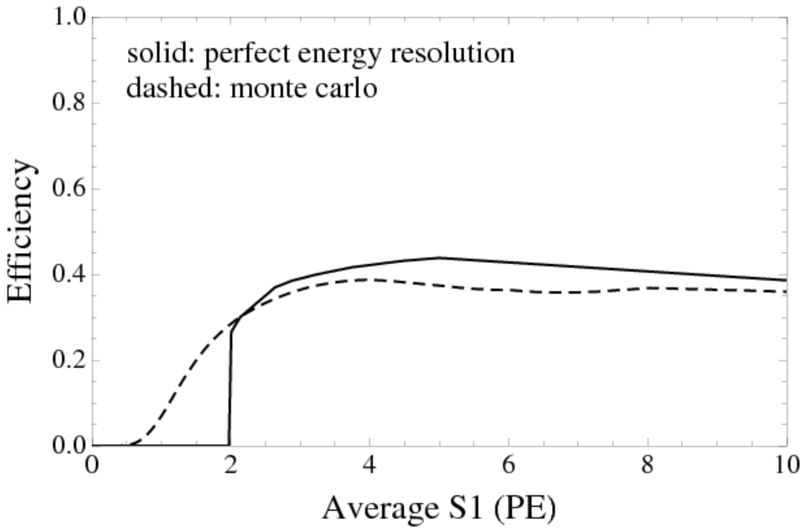
XENON10: PRD 80, 115005 (2009)

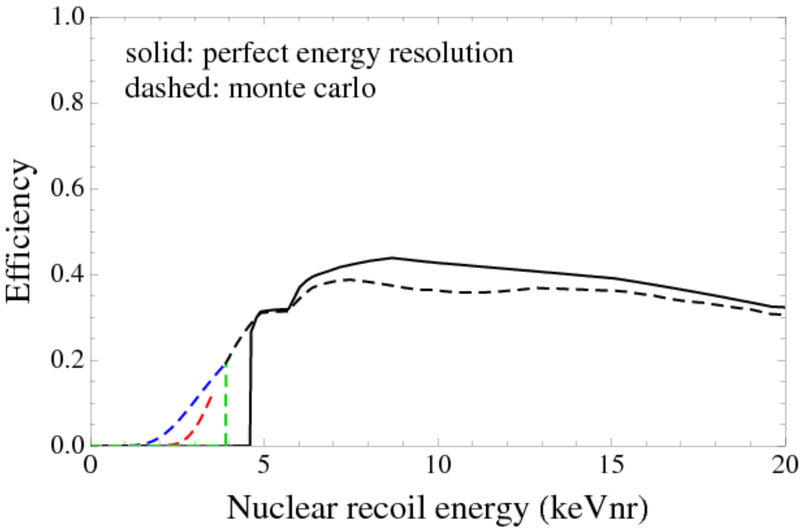


XENON100: no monte carlo
apply ⟨S1⟩ ≥ 1 PE cutoff (conservative)

Efficiencies: monte carlo

Fractions of events passing all cuts
in XENON10 ($2 \leq S1 \leq 75$ PE)

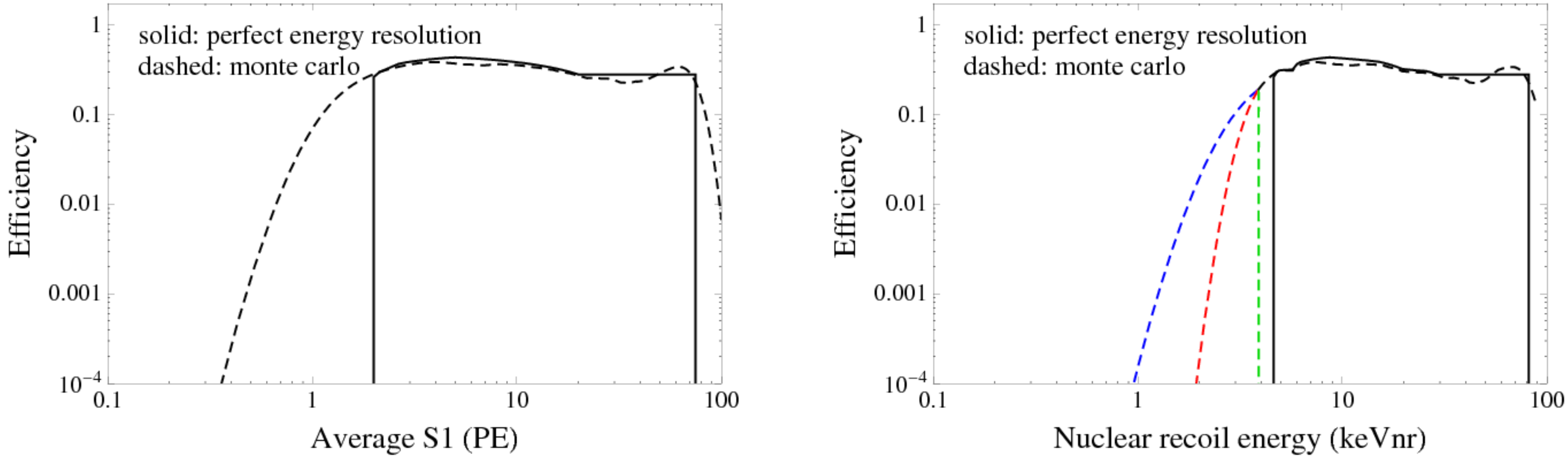




constant/falling/zero $\mathcal{L}_{eff}$

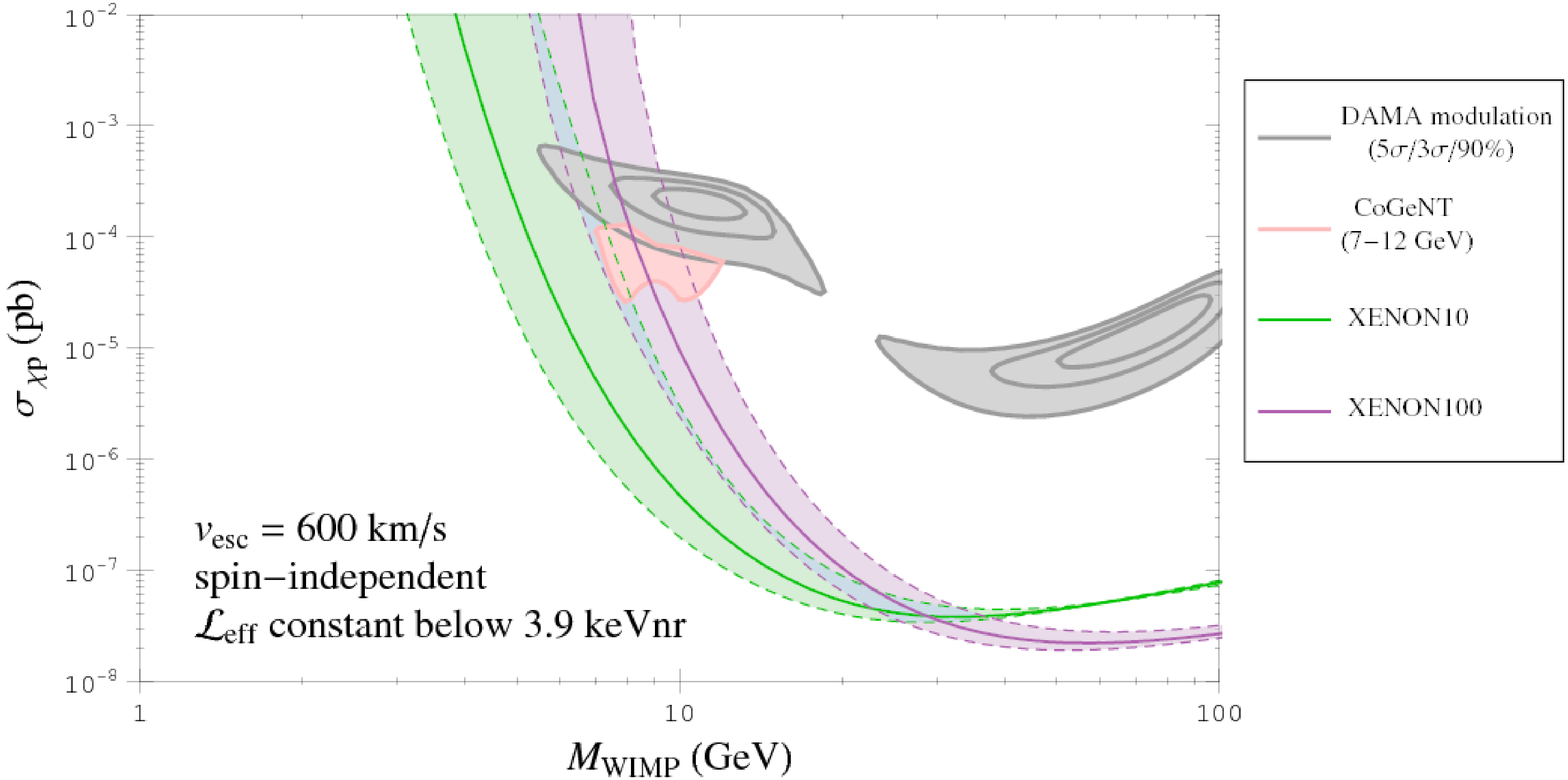
Efficiencies: monte carlo

Fractions of events passing all cuts
in XENON10 ($2 \leq S1 \leq 75$ PE)



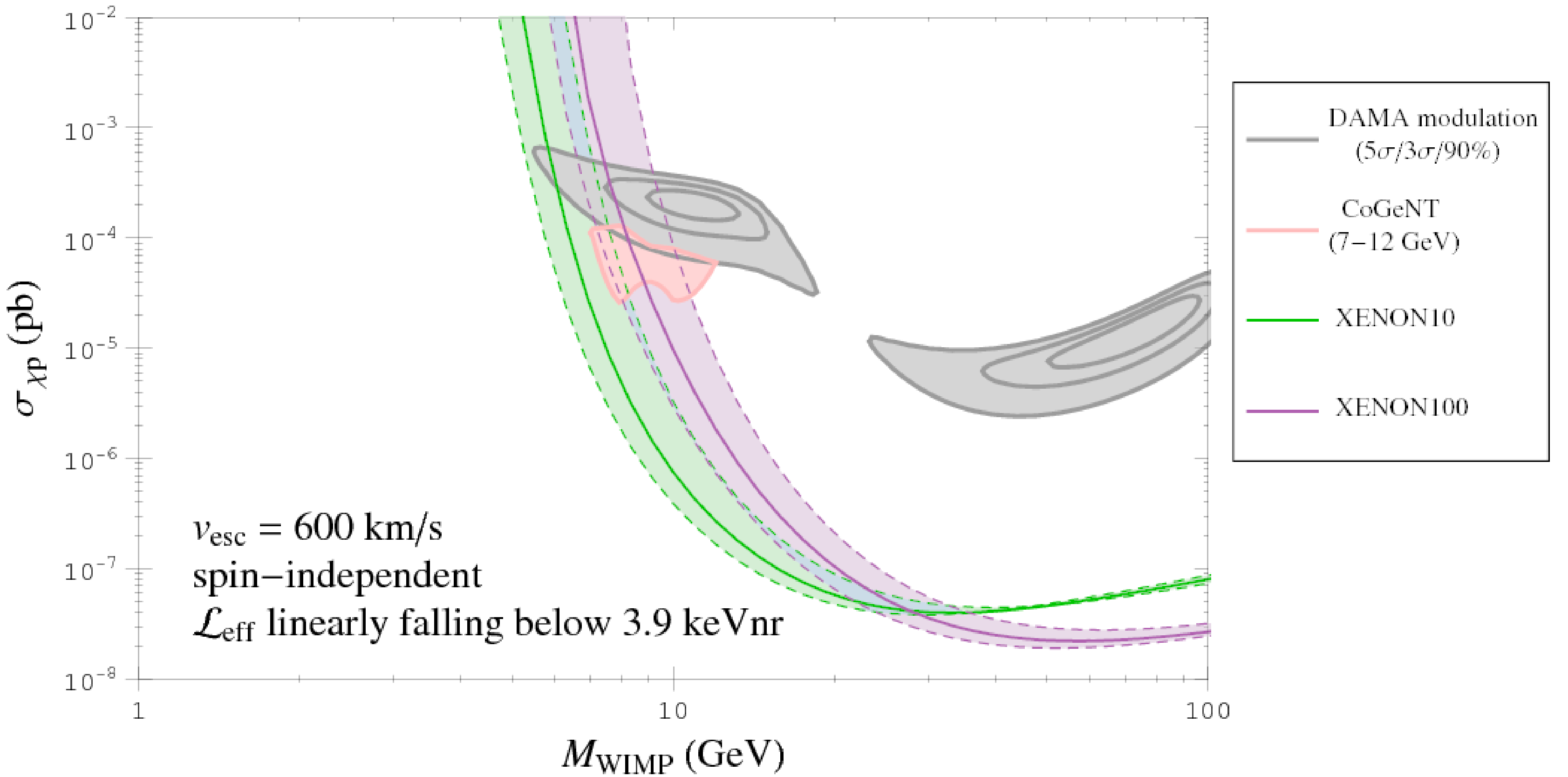
constant/falling/zero $\mathcal{L}_{eff}$

XENON constraints: including energy resolution



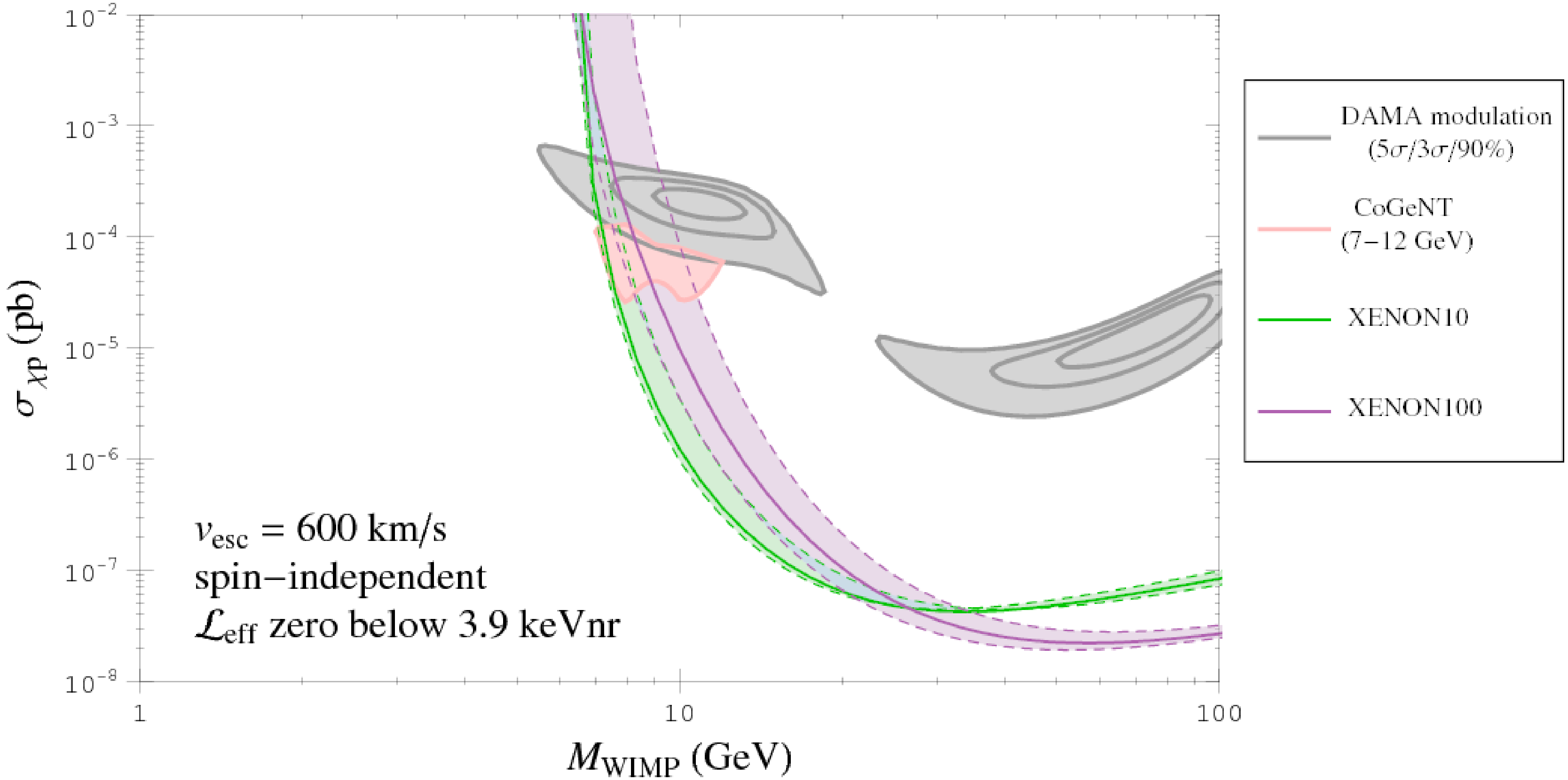
$\mathcal{L}_{eff}$ constant below 3.9 keVnr

XENON constraints: including energy resolution



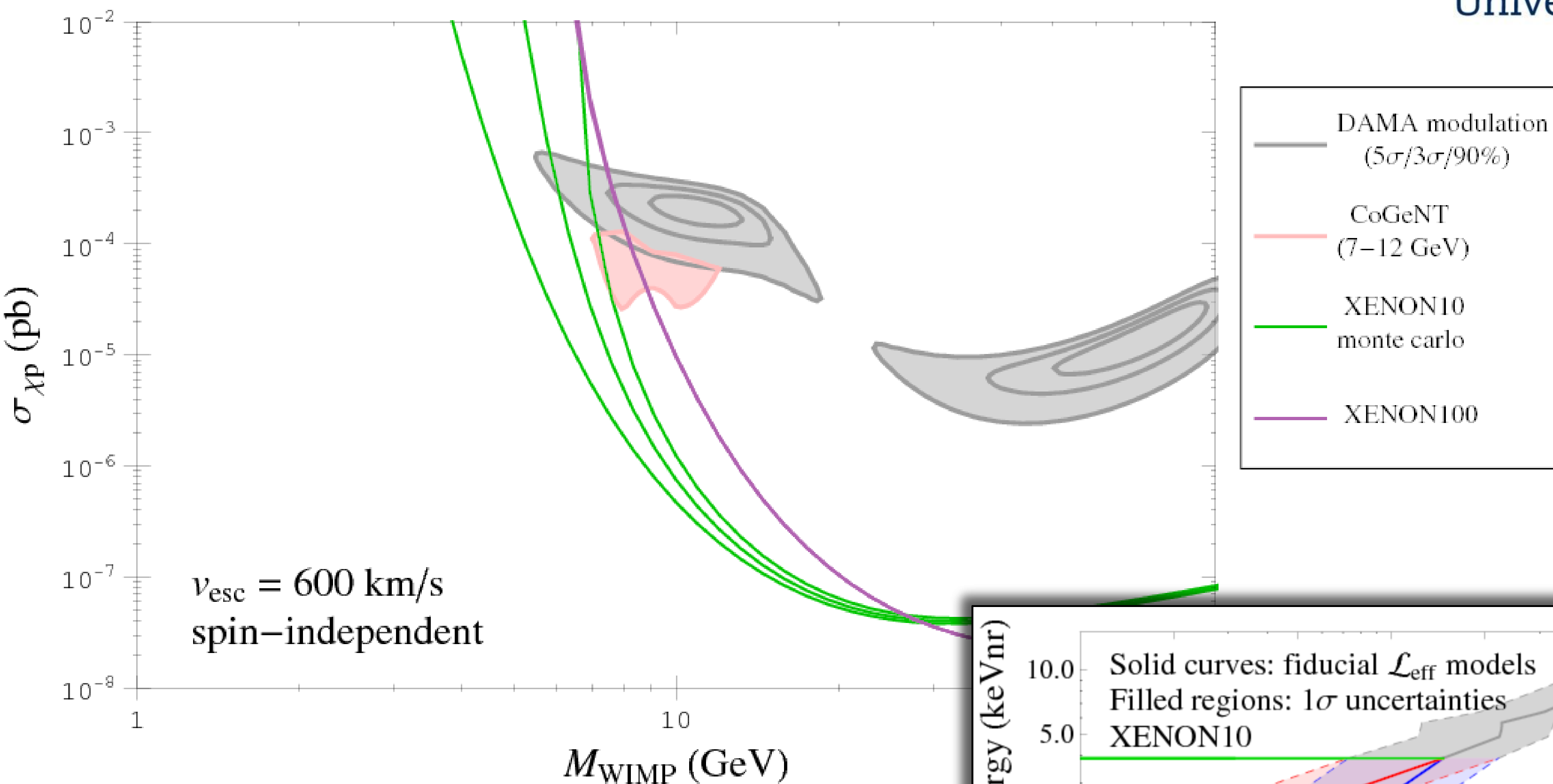
$\mathcal{L}_{\rm eff}$ linearly falling below 3.9 keVnr

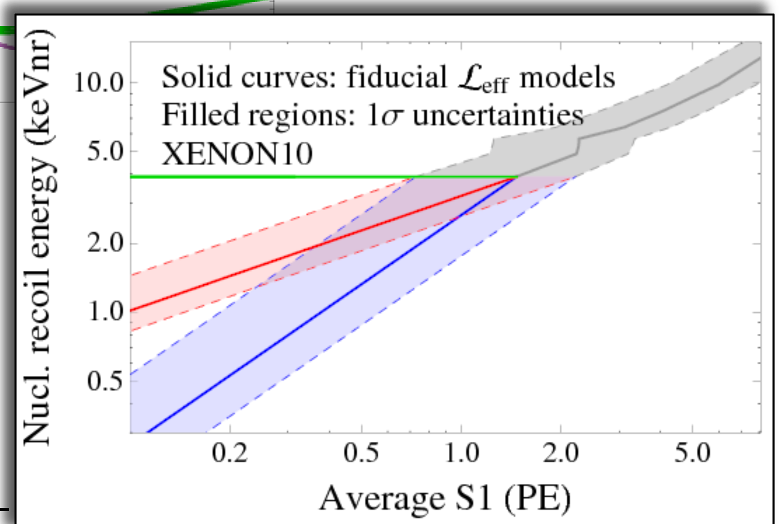
XENON constraints: including energy resolution



$\mathcal{L}_{\rm eff}$ zero below 3.9 keVnr

XENON constraints: including energy resolution

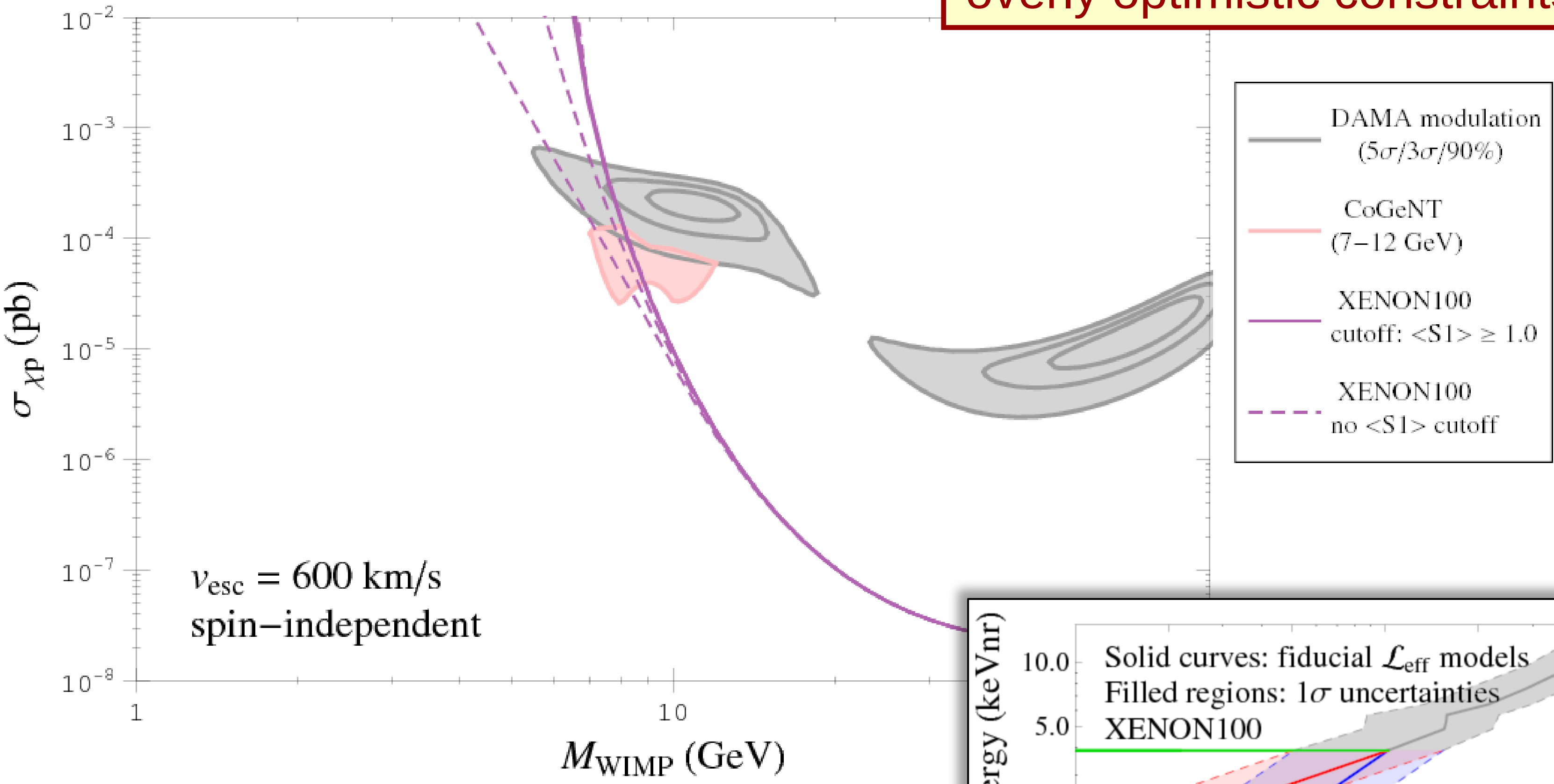


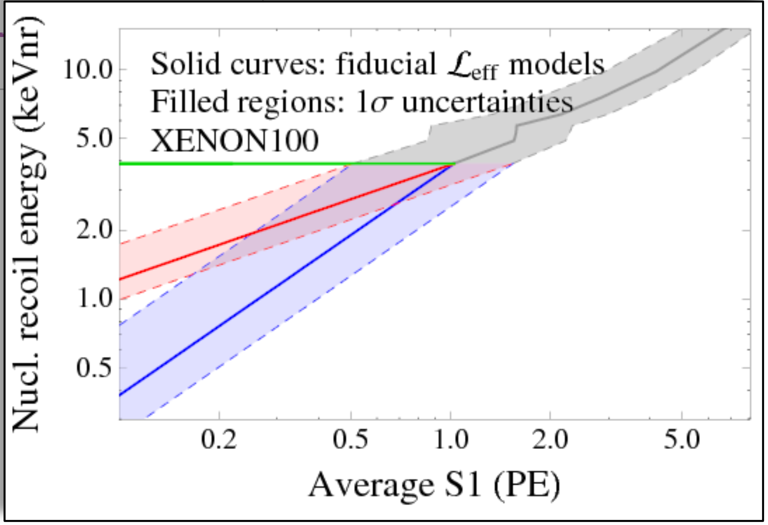


Left to right: constant, falling, zero $\mathcal{L}_{\mathrm{eff}}$ below 3.9 keVnr

XENON100 constraints: relaxing the ⟨S1⟩ cutoff

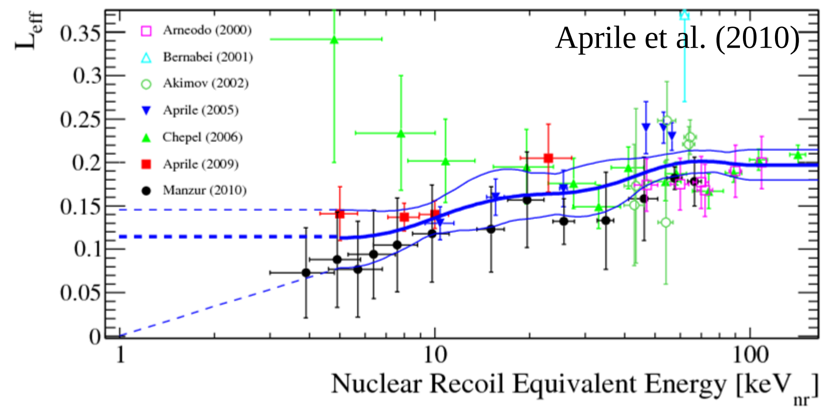
Ignores NR band issues: overly optimistic constraints



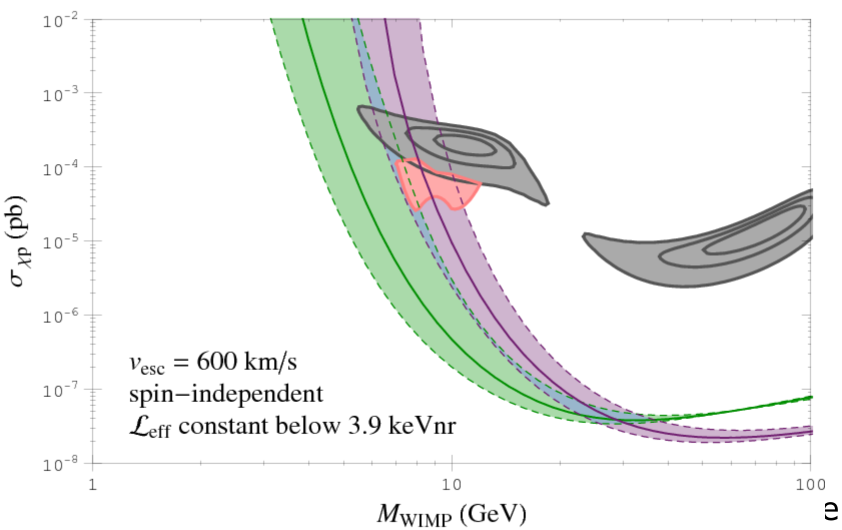


Left to right: constant, falling, zero $\mathcal{L}_{\rm eff}$ below 3.9 keVnr

$\mathcal{L}_{eff}$ measurements: fixed energy comparison



- Aprile et al. (2009) measurements
  - Left half of Manzur 1σ band is right half of Aprile 1σ band (approx.)
- XENON100 analysis: weighted average of fixed energy measurements **Talk by M. Schumann**
  - Central curve: similar to Manzur 1σ upper bound, constant $\mathcal{L}_{eff}$
  - Lower curve: similar to Manzur central values, linearly falling $\mathcal{L}_{eff}$



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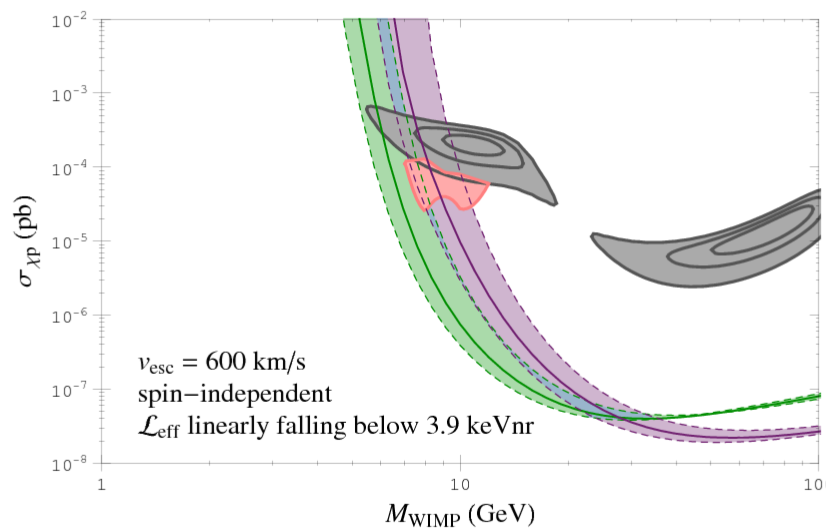


Summary

Dependence on $\mathcal{L}_{eff}$:

- Low energy $\mathcal{L}_{eff}$ extrapolation not significant for XENON100 when using Manzur data, choice of data sets more important
- Both $\mathcal{L}_{eff}$ data set and extrapolation important for XENON10

Comparing experiments:

- XENON10 highly incompatible with DAMA regions
- XENON10 strongly constrains CoGeNT region

Possibilities for compatibility:

- Quenching factors
- Halo models
- Spin-dependent
- Inelastic scattering
- Etc.

Hooper, Collar, Hall & McKinsey (2010)

XENON and low mass WIMPS: prospects

Sensitivity to low mass WIMPs possible

- Low thresholds necessary (more background?)
- Credibility of low mass limits at issue until $\mathcal{L}_{eff}$ becomes better characterized at low recoil energies
- Conservative limits still possible, but want better

  $\Rightarrow$ *New $\mathcal{L}_{eff}$ measurements in progress*

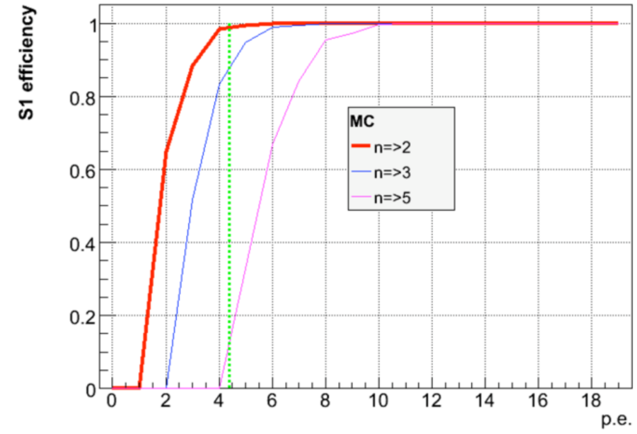
Better analysis for low masses: S2 only?

- No discrimination: more background
- Lower threshold: more signal
  DAMA & CoGeNT regions predict $10^3 - 10^4$+ low energy events in XENON detectors
- Strong constraints even with background

Talk by P. Sorensen

Backup Slides

Aprile et al. (2010) [XENON10]



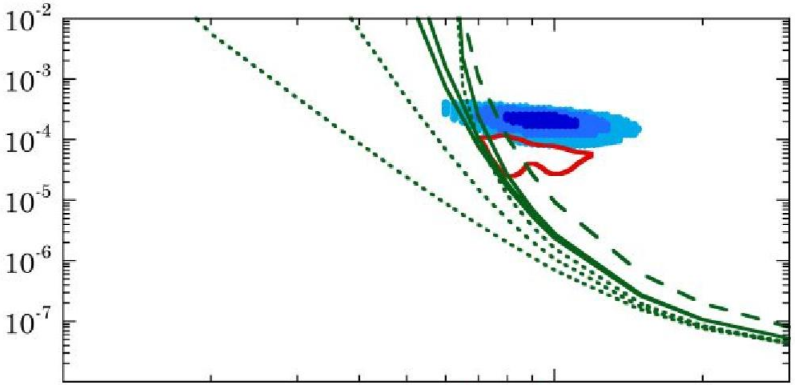
Effect of η_{S1}

- Peak finding efficiency factor: probability of tagging at least two PMT hits

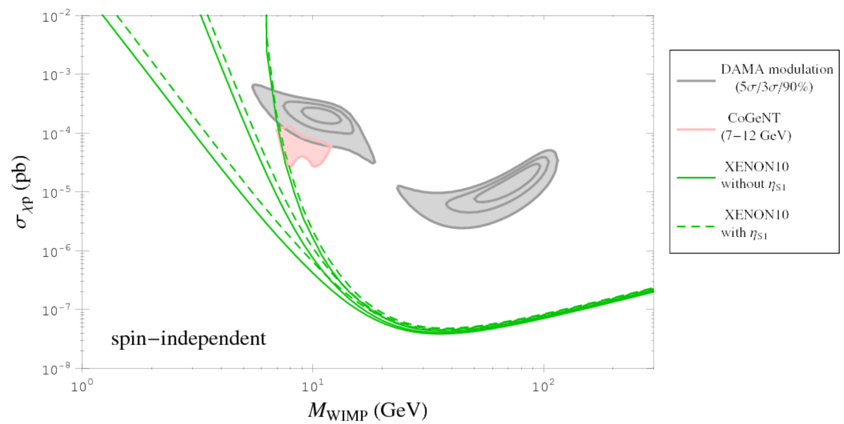
Example:

- Recoil energy that gives an average S1 of $\langle S1 \rangle$ = 0.5 PE
- Efficiency of those events that produce S1 = 2 PE (Poisson fluctuations):

$\eta_{S1}(0.5)$ [incorrect] $\eta_{S1}(2.0)$ [correct]

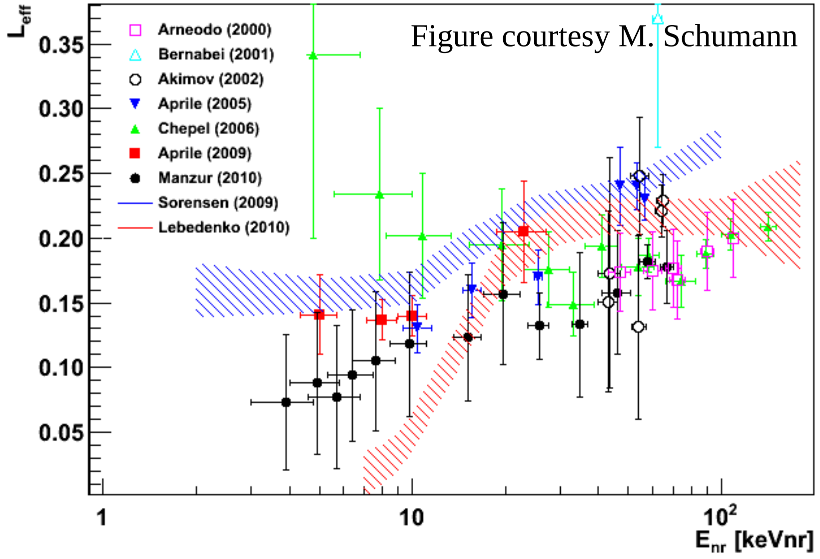


J. Collar, arXiv:1006.2031



Does not account for NR band cut (larger effect)

$\mathcal{L}_{eff}$ measurements: consistent with zero?



ZEPLIN-III broad spectrum fit:

$\mathcal{L}_{eff}$ falls to zero at E_{nr} ~ 8 keVnr?

- Not 1σ or 90% CL band
- Does not include systematic uncertainties
- Manzur and Aprile data highly incompatible with $\mathcal{L}_{eff} \approx 0$

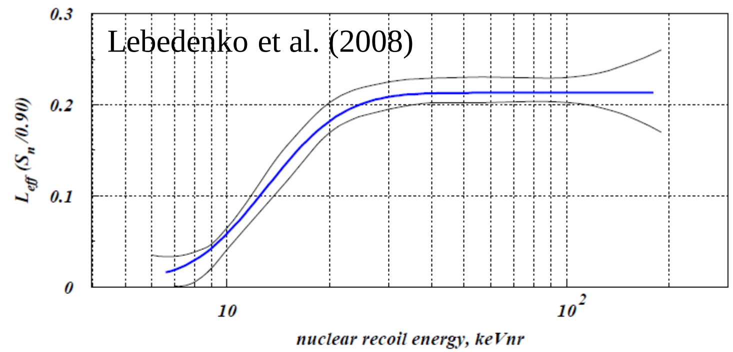
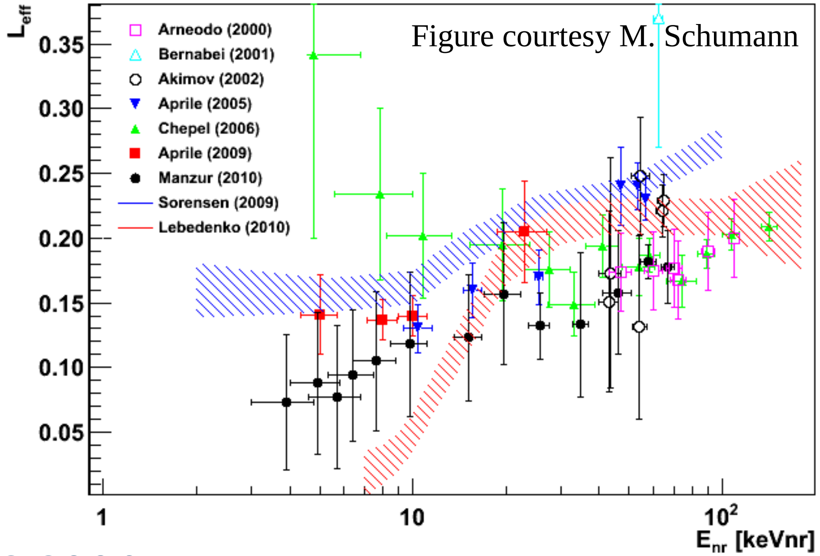


FIG. 15: The derived energy-dependent behaviour of $L_{eff} \cdot S_n$. The thick curve shows the best fit to the data, but other curves producing very similar goodness-of-fit indicators are obtained within the envelope shown. The constraints become very weak outside the energy range shown.

See Manalaysay, arXiv:1007.3746 for discussion of potential issues

$\mathcal{L}_{eff}$ measurements: consistent with zero?



Manzur data

- Naïve estimate: within ~ 2σ of zero?
- χ^2 of fit grows rapidly $\mathcal{L}_{eff}$ as decreases
- Significant amount of scintillation events seen not easily attributable to any background