Solving the LHC Inverse Problem with Dark Matter Observations

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hep-ph/0804.2899

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The “LHC Inverse Problem”

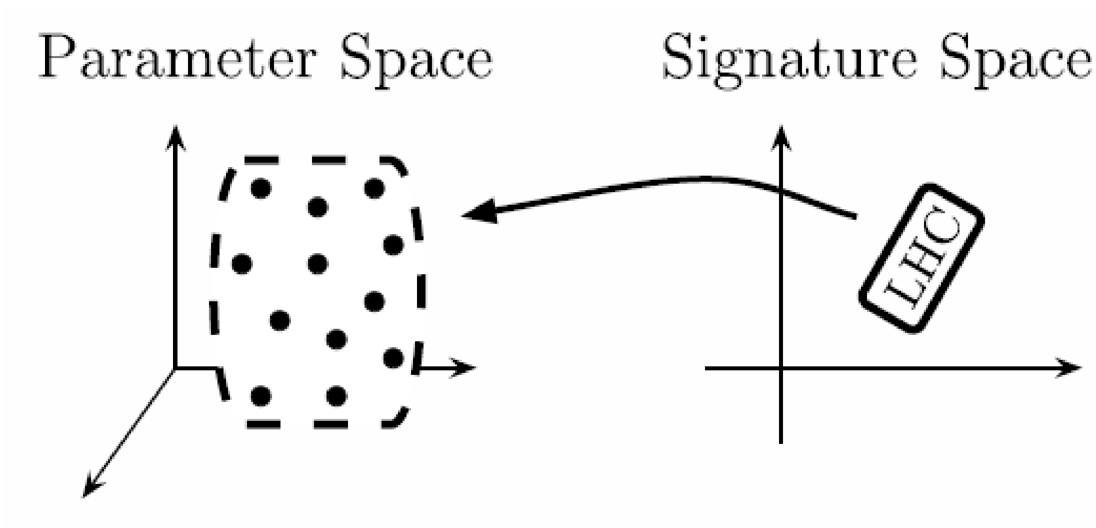
Arkani-Hamed, Kane, Thaler & Wang, “Supersymmetry and the LHC inverse problem,” JHEP **0608**, 070 (2006) [arXiv:hep-ph/0512190].

- Basic premise: multiple SUSY parameter sets are likely to fit the LHC data

$$\left\{ \begin{array}{c} \tan\beta,\ \mu,\ M_1,\ M_2,\ M_3 \\ m_{Q_{1,2}}, m_{U_{1,2}}, m_{D_{1,2}}, m_{L_{1,2}}, m_{E_{1,2}} \\ m_{Q_3}, m_{U_3}, m_{D_3}, m_{L_3}, m_{E_3} \end{array} \right\}$$

- Proven to be true in 10 fb^{-1} of simulated data, using 1808 observables

$\Rightarrow$ A thought experiment: let’s assume LHC data not uniquely invertible



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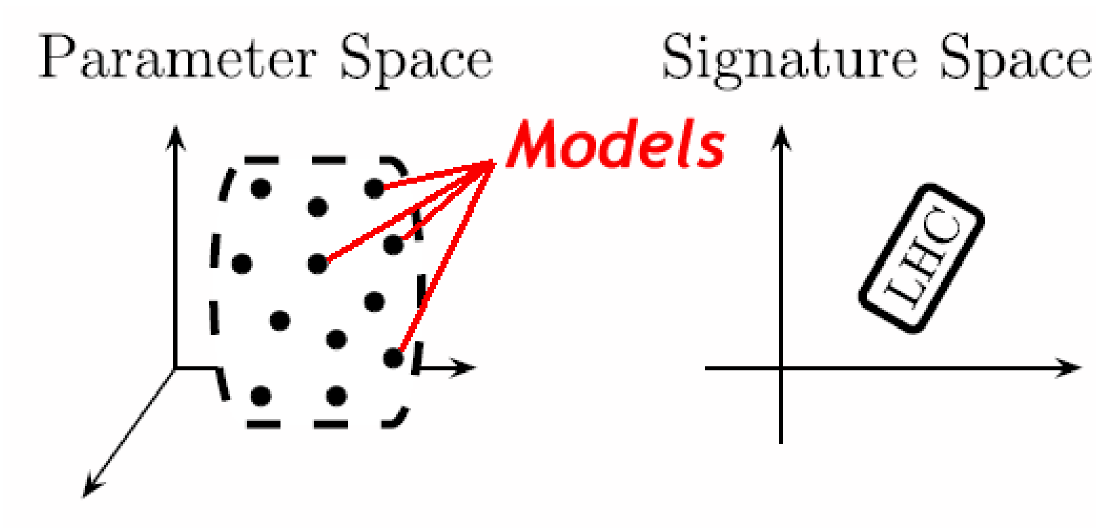

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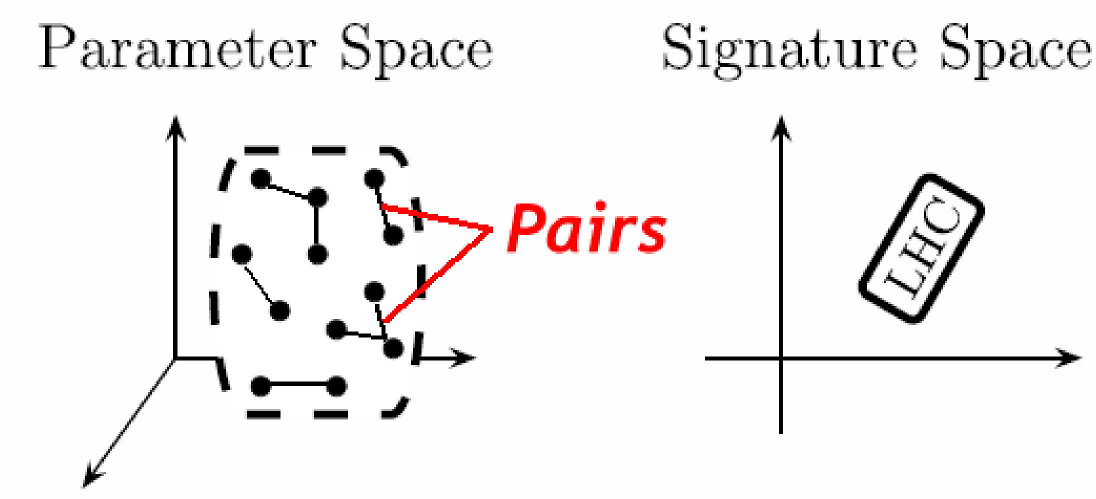

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The Search for Solutions

(1) Make better use of LHC data itself

- Better choice of observables
- Use exclusive measurements/reconstruct decay chains
- Simply wait for more integrated luminosity

$\Rightarrow$ But let's go ahead and take the LHC Inverse Problem at face value

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$\Rightarrow$ But let's go ahead and take the LHC Inverse Problem at face value

(2) Wait for the ILC to rescue us

Berger, Gainer, Hewett, Lillie & Rizzo, arXiv:hep-ph/0711.1374, 0712.2965

- Good News: When charged superpartners accessible, pairs generally separable
- Bad News: Only 57 pairs distinguishable at 5σ at $\sqrt{s} = 500\ \mathrm{GeV}$ ILC (63 at 3σ level)
- Worse News: The earliest we can expect the ILC is 2019...

(3) Use dark matter observables as a discriminant

- Many experiments taking data now or in near future
- WIMP signal rates strongly sensitive to things LHC cannot see (like LSP wavefunction)

Given a WIMP signal can we say definitively that it is consistent with only *one* of our post-LHC models?

$\Rightarrow$ Dark matter arena very different from collider studies!

- Variety of experiments and detection methodologies
- Backgrounds to WIMP signals less well modeled and understood
- Theoretical assumptions often the biggest source of uncertainty

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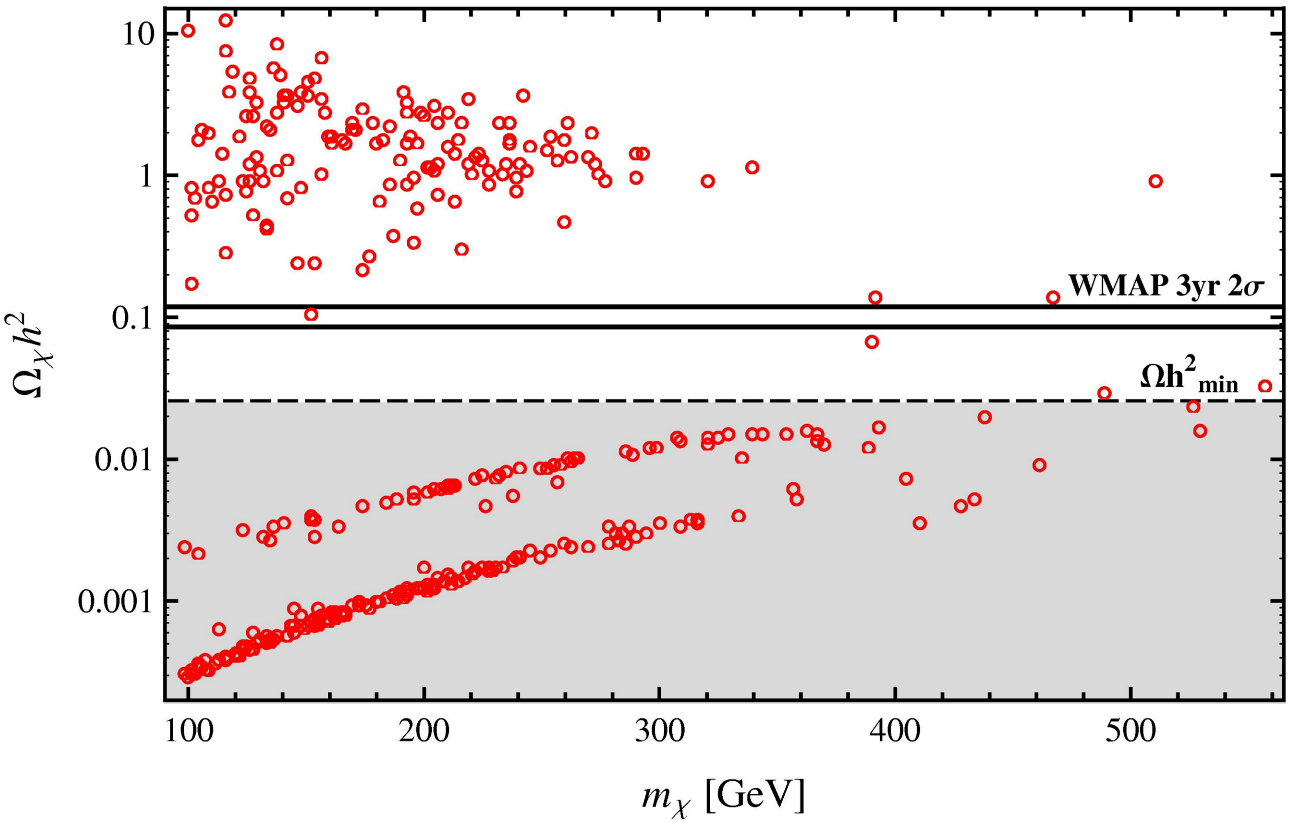
$\Rightarrow$ Biggest uncertainties $\rightarrow$ number density of WIMPs $n_\chi = \rho_\chi / m_\chi$

- We have little idea what this should be...
  but rotation curves give some indication
- Assume a local density normalized by $(\rho_\chi)_0 = 0.3$ GeV/cm^3
- Indirectly related to thermal relic density $\Omega_\chi \mathrm{h}^2$
- Impacts direct detection nuclear recoil rates
- Annihilation rates and branching fraction into interesting final states

$\Rightarrow$ We performed all calculations using `DarkSUSY`

Thermal Relic Density



WMAP 2σ region

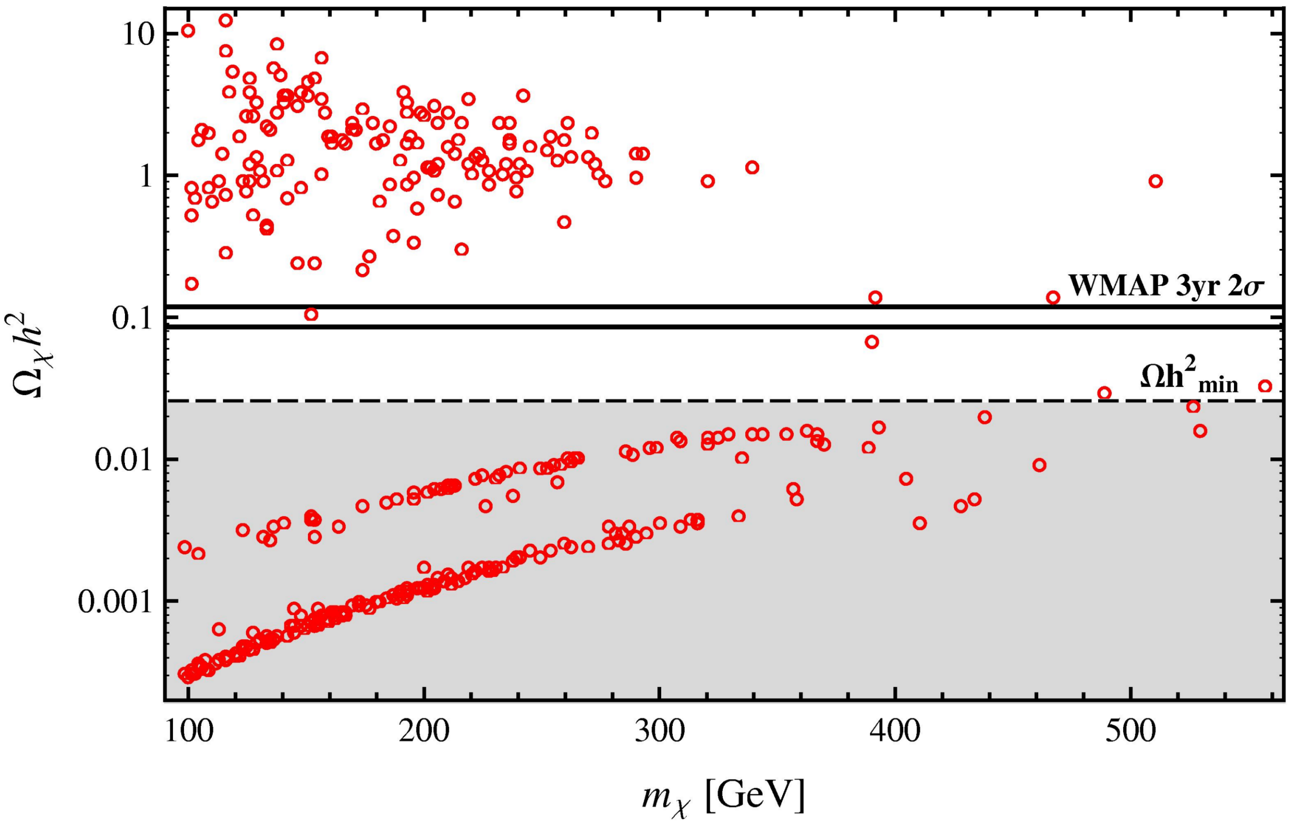
$$0.086 < \Omega_\chi h^2 < 0.119$$

$$\Omega_\chi h^2 \leq 0.025$$
225 models

$$0.025 \leq \Omega_\chi h^2 \leq 0.119$$
8 models

$$\Omega_\chi h^2 > 0.119$$
145 models

Thermal Relic Density



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- Thermal relic density sensitive to small variations in SUSY parameters
- Lots of ways to alter standard predictions for $\Omega_\chi h^2$

Gelmini & Gondolo, **PRD74** (2006) 023510

$\Rightarrow$ Our approach is to consider two possibilities

- **(1)** Assume $(\rho_\chi)_0 = 0.3$ GeV/cm^3 regardless of $\Omega_\chi h^2$ prediction
- **(2)** Rescale $(\rho_\chi)_0$ by a factor $r_\chi = \mathrm{Min}(1,\, \Omega_\chi h^2/0.025)$

Direct Detection Experiments

⇒ What does it mean to distinguish between degenerate models?

- Values of s_i^A and s_i^B need to be large enough that both are detectable above the relevant background for the experiment in question
- Values of s_i^A and s_i^B need to be sufficiently separated to give a statistically significant difference when measured with respect to the appropriate mutual error σ_i^{AB}

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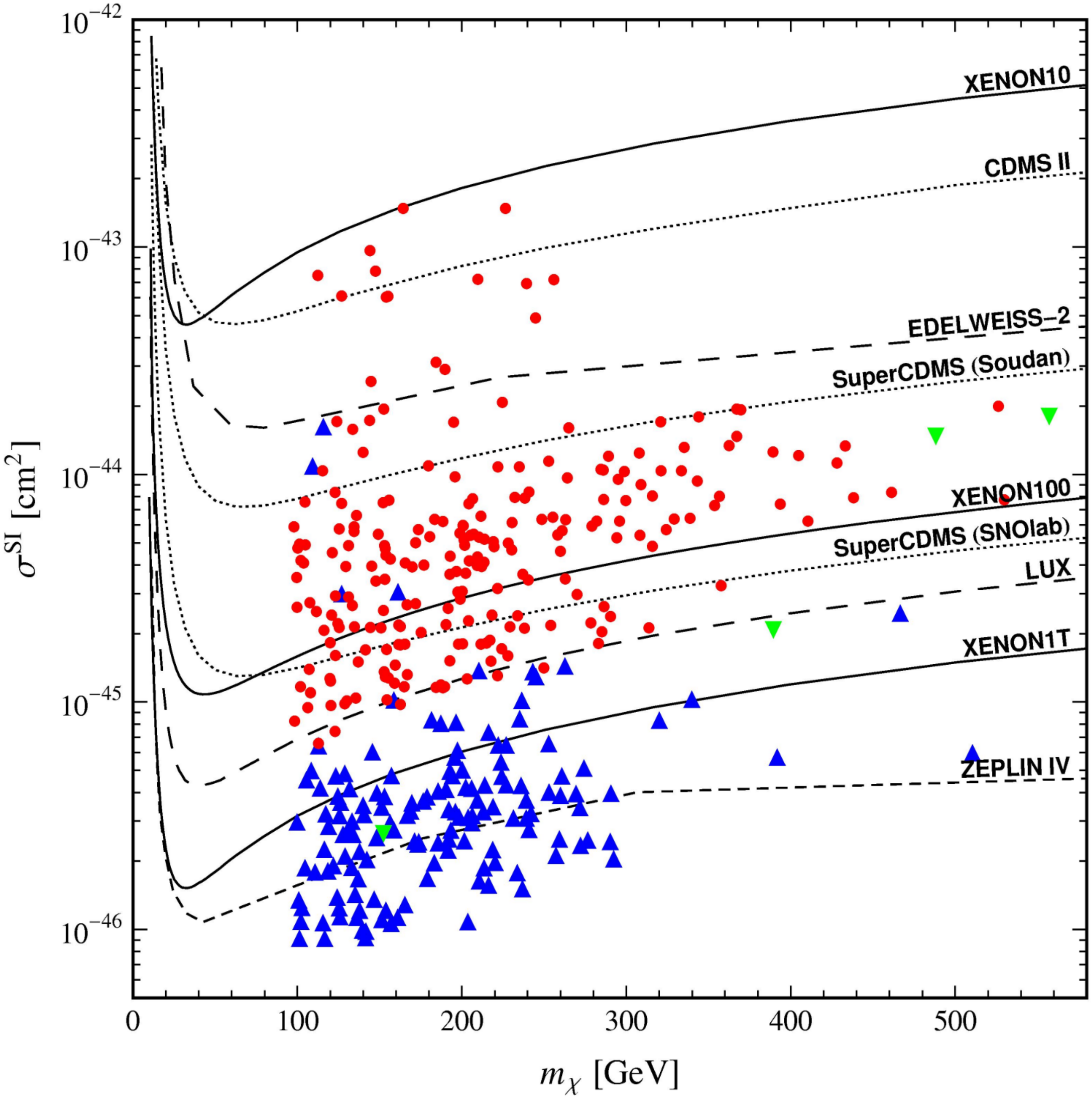
⇒ Direct detection experiments look for scattering of WIMPS from heavy nuclei

- The actual observable (s_i) is the number of recoil events observed over some time interval
- The rate for such events is approximated by

$$R \sim \sum_i \Phi_\chi \frac{\sigma_{\chi i}^{\mathrm{SI}}}{M_i} = \sum_i \frac{\langle v_\chi \rangle \rho_\chi \sigma_{\chi i}^{\mathrm{SI}}}{m_\chi M_i},$$

with M_i being the mass of i-th nucleus and $\langle v_\chi \rangle \simeq 270 \mathrm{km/s}$

Direct Detection: HEP Theory Style



Red circles
$\Omega_\chi h^2 < 0.025$

Green triangles
$0.025 \leq \Omega_\chi h^2 \leq 0.1189$

Blue triangles
$\Omega_\chi h^2 > 0.1189$

Name	Target
CDMS II	3.75 kg Ge
XENON10	5.4 kg Xe
ZEPLIN II	7.2 kg Xe
SuCDMS (Soudan)	7.5 kg Ge
SuCDMS (SNOlab)	27 kg Ge
SuCDMS (DUSEL)	1140 kg Ge
EDELWEISS-2	9 kg Ge
XENON100	170 kg Xe
XENON1T	1000 kg Xe
LUX	350 kg Xe
ZEPLIN III	8 kg Xe
ZEPLIN IV	1000 kg Xe

Sensitivity curves taken from: `http://dmtools.berkeley.edu/limitplots/`

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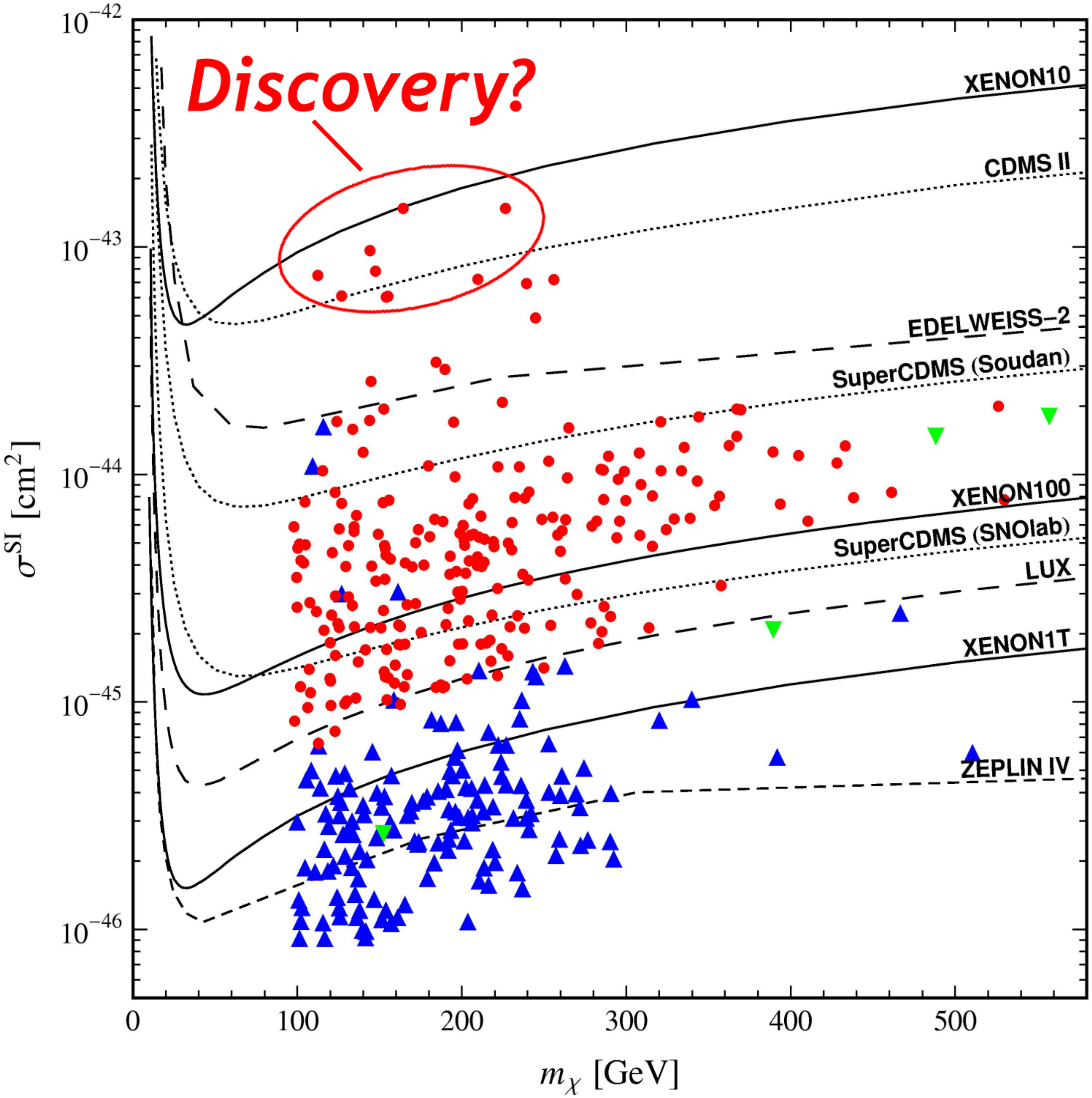

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Direct Detection: How to Do Better

$\Rightarrow$ Direct detection experiments measure recoil rates, not cross-sections

- The latter is *inferred* from an assumed ρ_χ
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$\Rightarrow$ Is that enough for a discovery? Depends on backgrounds!

- Primary backgrounds: nuclear recoils/ionization charge induced by radioactive decays/cosmic rays
- Expectation:
  $\sim \mathcal{O}(1)$ events/experiment/year in germanium;
  $\sim \mathcal{O}(10)$ events/experiment/year in liquid xenon

$\Rightarrow$ Calculation of integrated event rate depends on experimental configuration

$$R = \int_{E_{\min}}^{E_{\max}} \frac{dR}{dE}\, dE \qquad \begin{array}{ll} R_1 \ (\mathrm{Xenon}) & : 5\,\mathrm{keV} \leq E_{\mathrm{recoil}} \leq 25\,\mathrm{keV} \\ R_2 \ (\mathrm{Germanium}) & : 10\,\mathrm{keV} \leq E_{\mathrm{recoil}} \leq 100\,\mathrm{keV} \end{array}$$

Direct Detection: Less Naive

1. Counts N_A and N_B (N_i = rate$_i$ $\times$ exposure) must *both* exceed $N_{\rm min}$ events
2. The two quantities N_A and N_B must differ by at least $5\,\sigma^{AB}$
3. Allow for experimental error/background beyond purely statistical via parameter f: $\sigma^{AB} = \sqrt{(1+f)(N_A + N_B)}$

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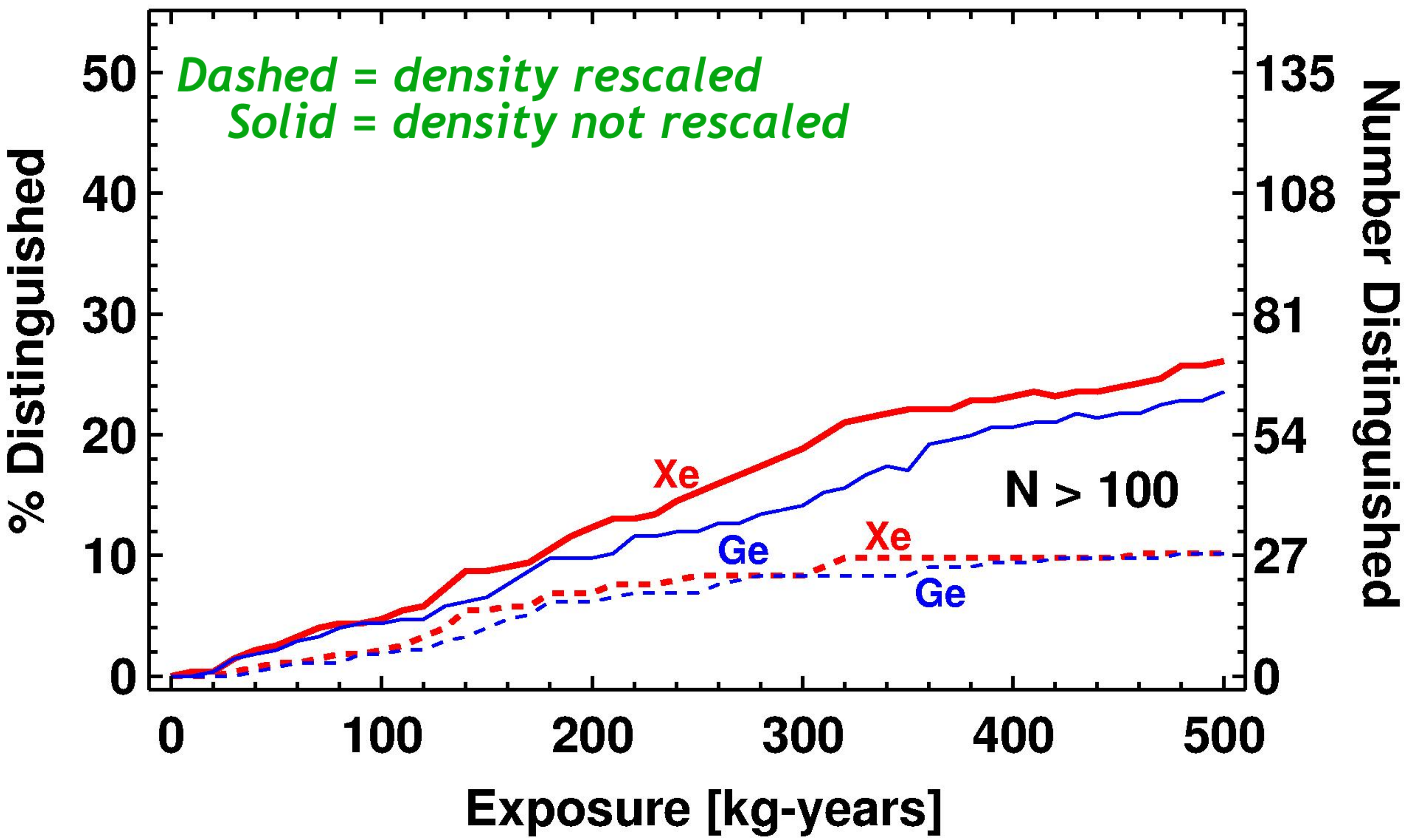

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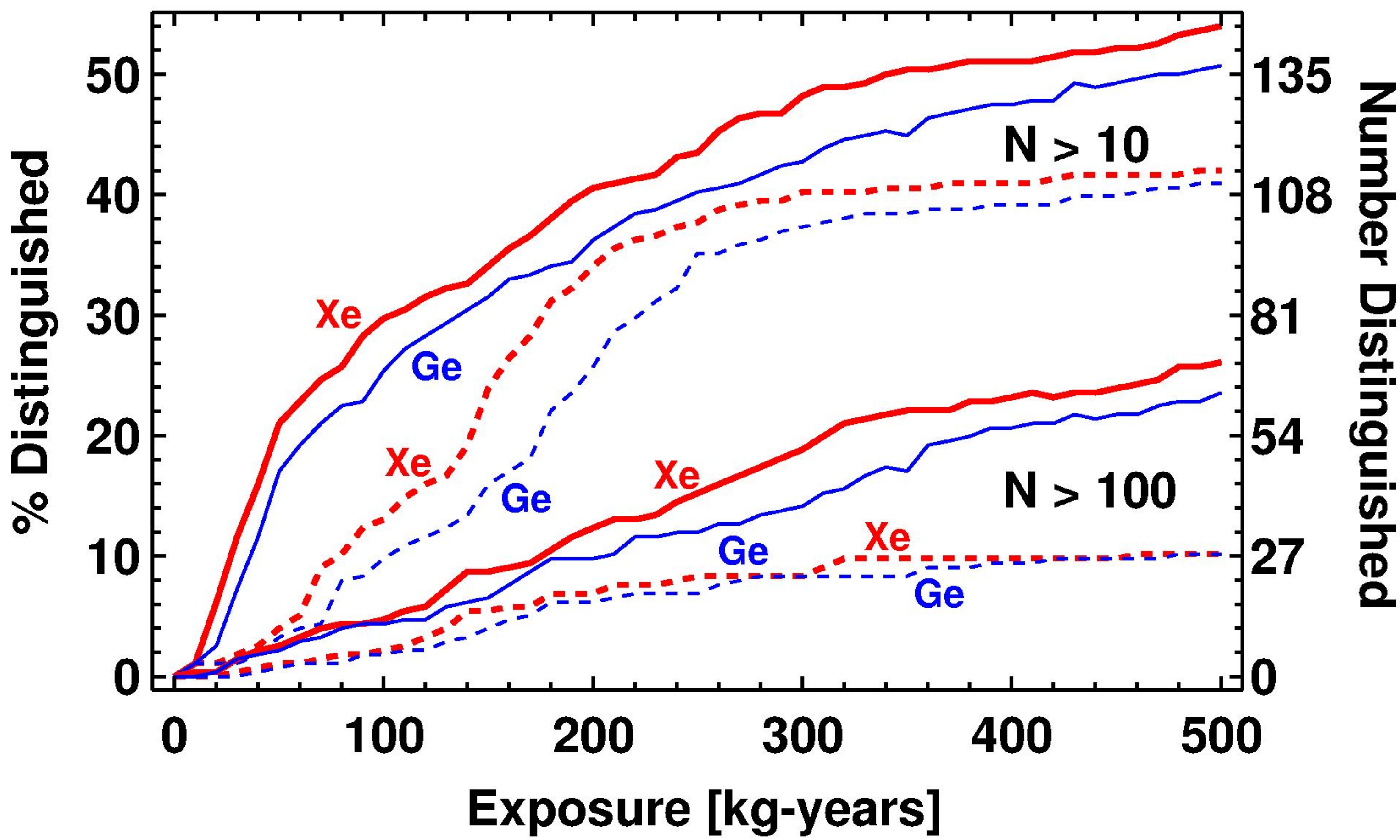
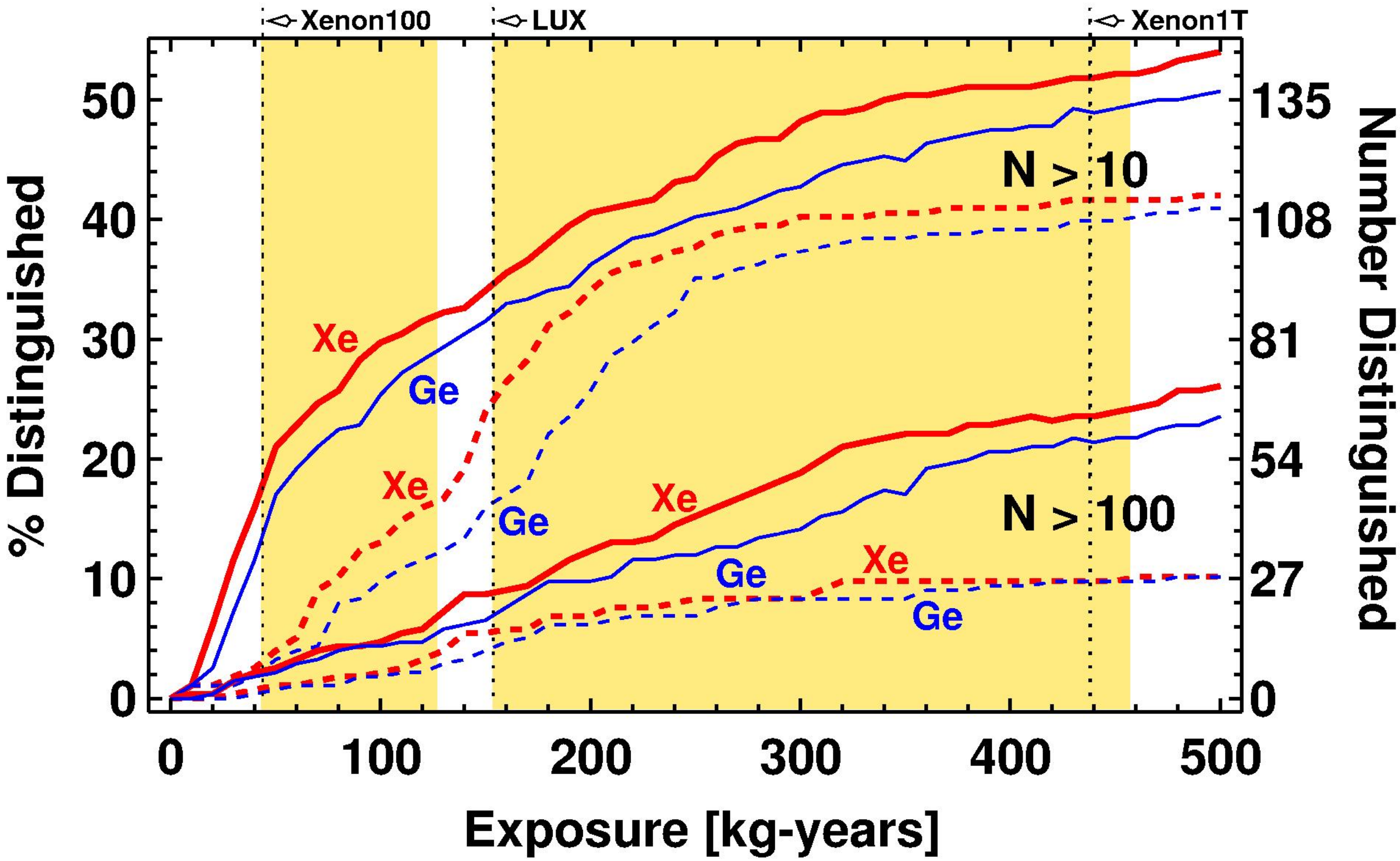
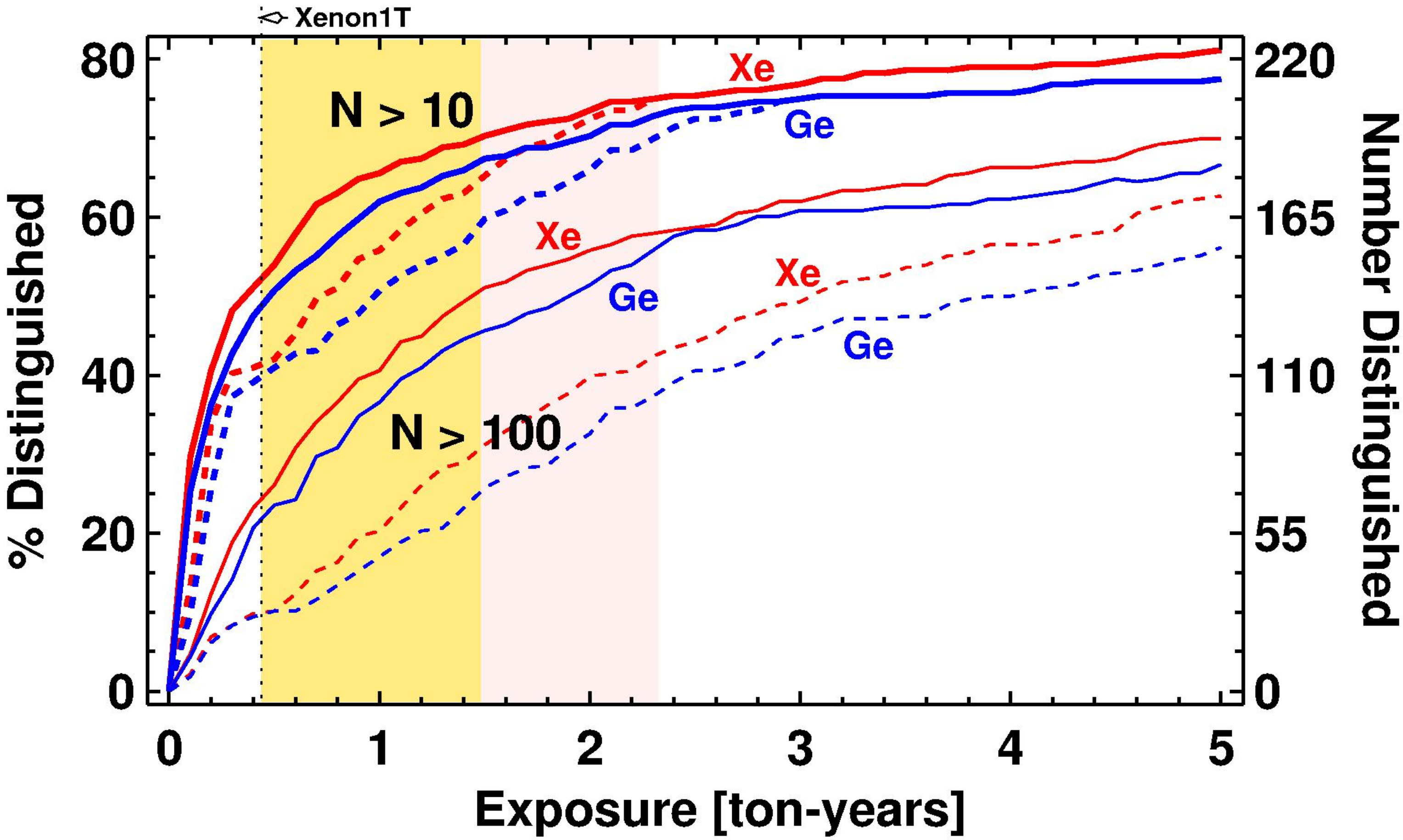


Direct Detection Experiments: Near Future



⇒ NOTE: We assume 200 days of data-taking per calendar year using 80% of nominal target mass

Direct Detection Experiments: Far Future



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Summary of Direct Detection Capability

	Conservative	Moderate	Optimistic
Direct detection, xenon	**48**		
Direct detection, germanium	**4**		

- Conservative
  - Density rescaled
  - $N \geq 100$ recoil events
  - Error $f = 0.2$
  - 100 kg-years Ge, 1 ton-year Xe
-
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  - ⋆ 100 kg-years Ge, 1 ton-year Xe
- Moderate
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  - ⋆ Error $f = 0$
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- Moderate
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- Optimistic
  - ⋆ Density *not* rescaled
  - ⋆ $N \geq 10$ recoil events
  - ⋆ Error $f = 0$
  - ⋆ 1 ton-year Ge, 5 ton-years Xe

Indirect Detection

⇒ Indirect detection experiments look for products of LSP annihilation

- Many possible signals: neutrinos, gamma rays, anti-matter
- Gamma rays special: travel directly from source, relatively easy to detect
- Can therefore focus search in direction of expected high density areas – like galactic center

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⇒ Halo profiles especially important in this situation

- Annihilation rates scale like the *square* of the density
- We observe the entire line-of-sight to the galactic center – therefore need to know the halo *profile* $\rho_\chi(r)$
- Many possible profiles suggested in literature; each can be summarized by one parameter $\overline{J}(\Delta\Omega)$

$$\overline{J}(\Delta\Omega) \equiv \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega'\, J(\psi')\,; \quad J(\psi) = \frac{1}{8.5\,\mathrm{kpc}}\int_{\mathrm{l.\,o.\,s.}} ds(\psi)\left(\frac{\rho_\chi(r)}{0.3\ \mathrm{GeV}\,/\mathrm{cm}^3}\right)^2$$

Indirect Detection Experiments: Experiments

⇒ Two types of signal: continuous spectrum and mono-energetic lines

$$\frac{d\Phi_\gamma}{dE_\gamma} = 0.94 \times 10^{-13} \sum_i \frac{dN_\gamma^i}{dE_\gamma} \left(\frac{\langle \sigma_i v \rangle}{10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}} \right) \left(\frac{100\ \mathrm{GeV}}{m_\chi} \right)^2 \overline{J}(\Delta\Omega)\Delta\Omega$$

- Typical sensitivities require $\Phi_{\min} \sim 10^{-10}$ photons/cm^2/sec

⇒ We therefore consider the NFW profile model

Navarro, Frenk & White, APJ **462** (1996) 563; **490** (1997) 493

- Plain vanilla version gives $\overline{J}(10^{-5}\,\mathrm{sr}) = 1.3 \times 10^4$
- With effects of adiabatic compression $\overline{J}(10^{-5}\,\mathrm{sr}) = 1.0 \times 10^6$

⇒ Two classes of experiments: satellite telescopes and earth-based atmospheric Cherenkov Telescopes (ACTs)

	$E_{\min}$	$E_{\max}$	σ_E/E	A_{eff}	$\Delta\Omega$
GLAST	50 MeV	300 GeV	10%	1×10^4 cm^2	1×10^{-5} sr
ACT	100 GeV	10 TeV	15%	3×10^8 cm^2	1×10^{-5} sr

- Continuous spectrum cuts off quickly at $E_\gamma \simeq m_\chi$
- For our models $98\ \mathrm{GeV} \leq m_\chi \leq 557\ \mathrm{GeV}$ with 85% having $m_\chi \leq 300\ \mathrm{GeV}$
- Thus we choose to only consider GLAST for the continuous spectrum

Indirect Detection Experiments: Backgrounds

⇒ No way to distinguish photons from WIMP annihilation and those from generic astrophysical sources

$$\frac{d\Phi_\gamma^{\rm bkg}}{dE_\gamma} = 9 \times 10^{-11} \times \left(\frac{E_\gamma}{1\ \rm GeV}\right)^{-2.7} \ \rm photons/cm^2/s/GeV$$

⇒ New wrinkle: both ACTs and satellites (EGRET) observe an excess of gamma ray photons from the galactic center!

- EGRET data only covers low energy range...

$$\frac{d\Phi_\gamma^{\rm EG}}{dE_\gamma} = 2.2 \times 10^{-7} \times \exp\left(-\frac{E_\gamma}{30\ \rm GeV}\right) \times \left(\frac{E_\gamma}{1\ \rm GeV}\right)^{-2.2} \ \rm photons/cm^2/s/GeV$$

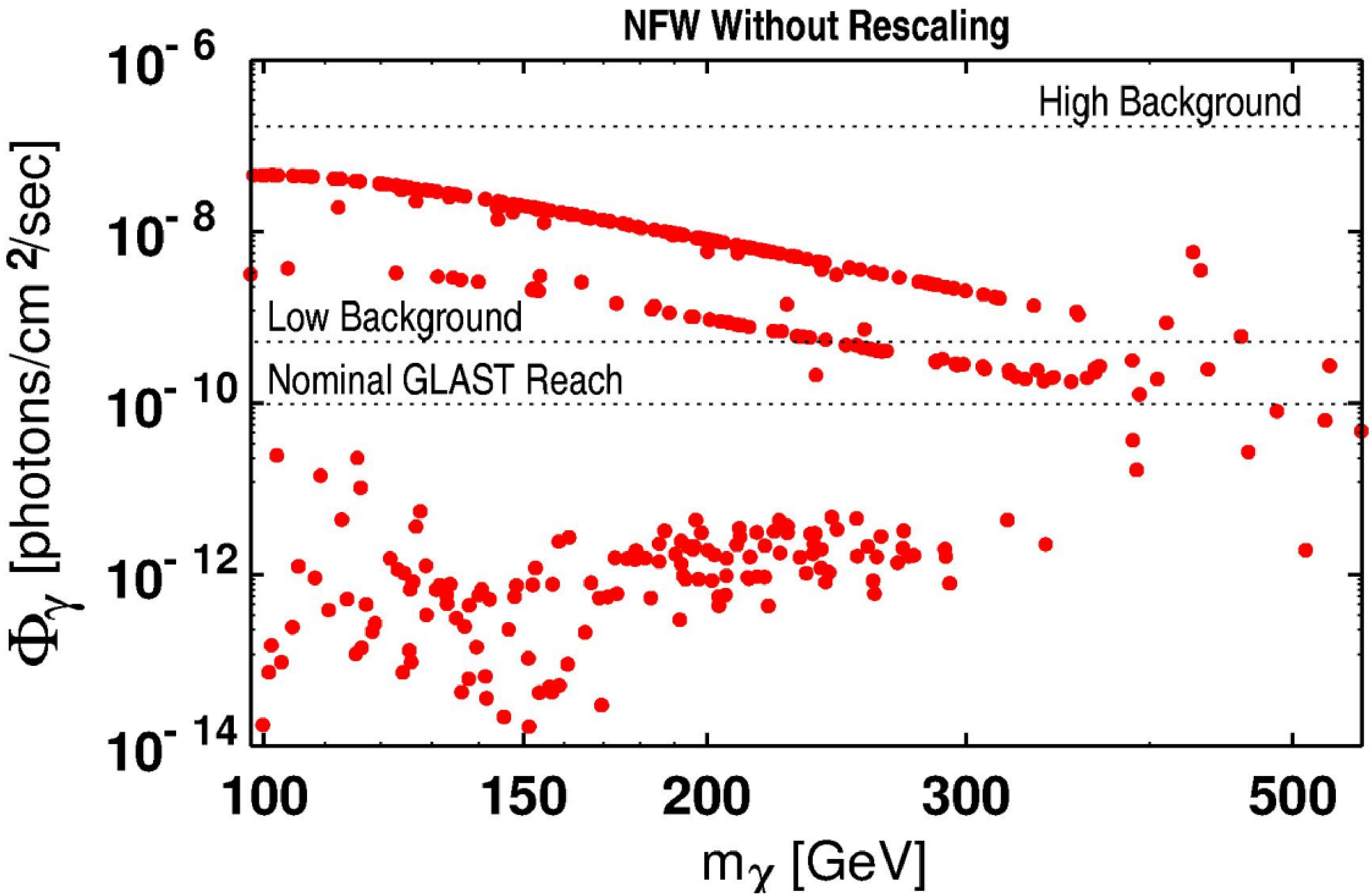
- ACT data covers much higher energy range....

⇒ Our treatment: consider both the “low” background and the EGRET normalized “high” background

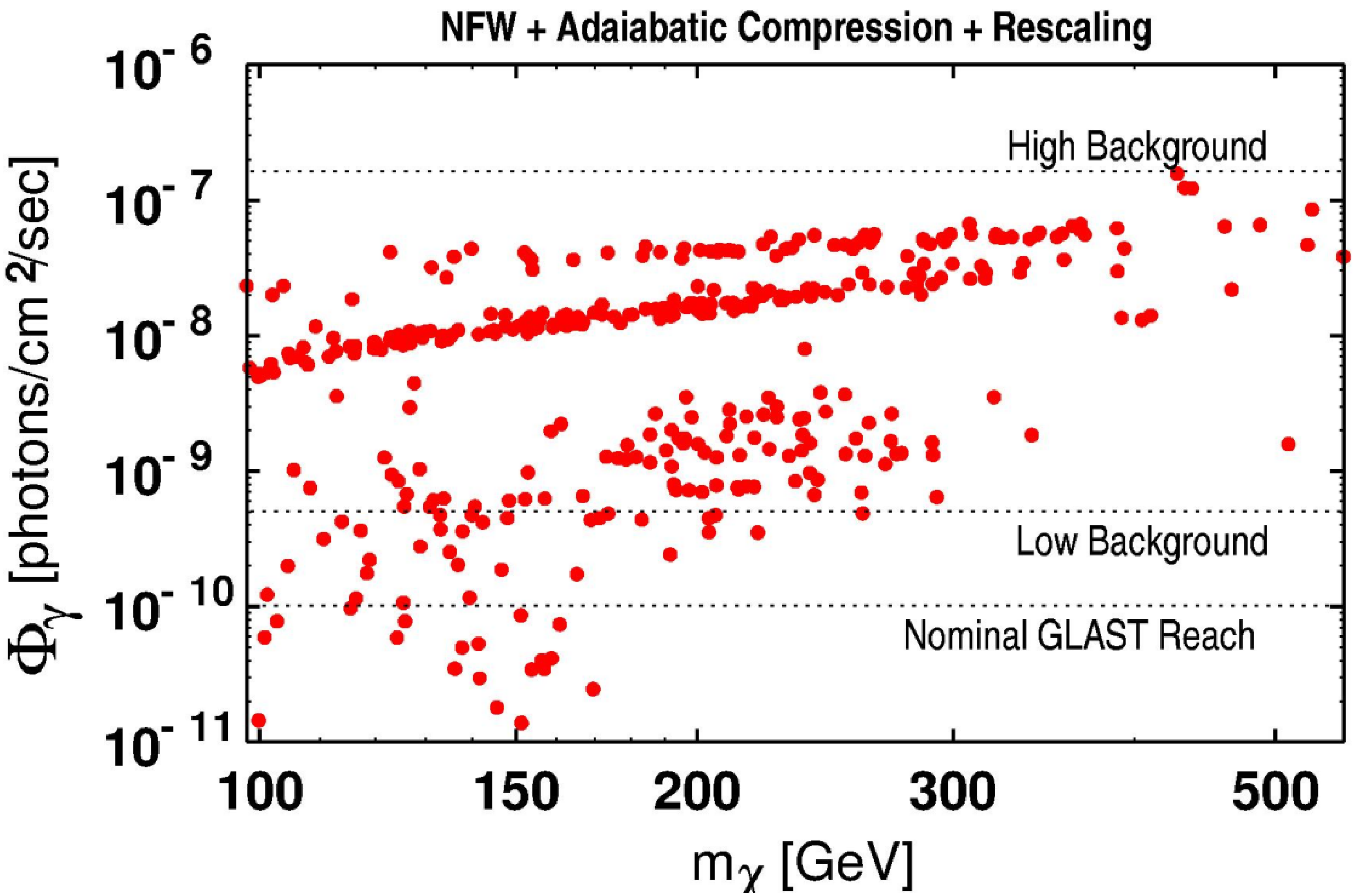
- Conservative: EGRET data likely consistent with point sources
- Might be possible to remove with angular information

Dodelson, Hooper & Serpico, PRD **77** (2008) 063512

Nominal Reach – NFW w/o Rescaling



Nominal Reach – NFW + a.c. w/ Rescaling



Our Requirements

1. Use `DarkSUSY` to compute $d\Phi/dE_\gamma$ over range $1\ \mathrm{GeV} \leq E_\gamma \leq 200\ \mathrm{GeV}$

2. Differential rate integrated over six energy bins

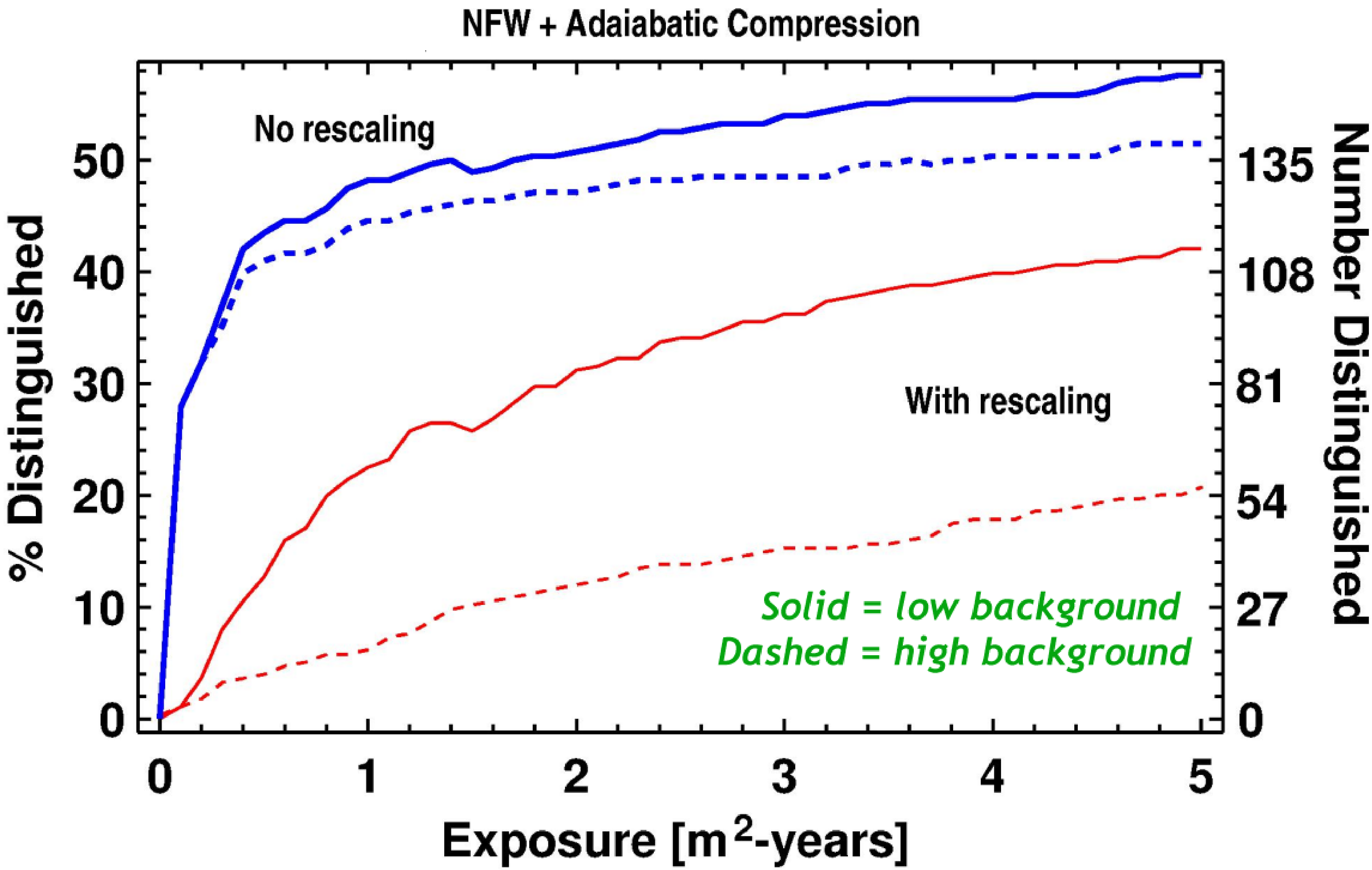
$$\begin{array}{cc} 1-10\,\mathrm{GeV} & 60-100\,\mathrm{GeV} \\ 10-30\,\mathrm{GeV} & 100-150\,\mathrm{GeV} \\ 30-60\,\mathrm{GeV} & 150-200\,\mathrm{GeV} \end{array}$$

3. Require $N_\gamma > 100$ for *both* models in the model pair, where N_γ is photon count over the full energy range $1\ \mathrm{GeV} \leq E_\gamma \leq 200\ \mathrm{GeV}$

4. Require excess over background in *multiple, adjacent* energy bins: $N_i > 2\sqrt{N_i^{\mathrm{bkg}}}$ for three of the six energy bins

5. To be distinguishable, we also require $|N_i^A - N_i^B| > 5\sqrt{N_i^A + N_i^B + 2N_i^{\mathrm{bkg}}}$ holds for at least three adjacent bins, simultaneously.

Separating Models at GLAST



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	Conservative	Moderate	Optimistic
Gamma rays, continuum	**56**	**115**	**158**

⇒ All estimates assume NFW profile model with adiabatic compression and imagine 5 m^2-years of exposure for GLAST towards the galactic center

Conservative Density is rescaled and “high” background rate used

Moderate Density is rescaled and “low” background rate used

Optimistic Density is *not* rescaled and “low” background rate used

Summary of Distinguishability

	Conservative	Moderate	Optimistic
All Pairs			
Direct detection, xenon	48	112	224
Direct detection, germanium	4	14	147
Gamma rays, continuum	56	115	158
Gamma rays, monochromatic	23	34	36
All Pairs, All Signals	**101**	**186**	**245**
Physical Pairs Only	34	55	77
ILC Inseparable Only	32	62	81

- Total number of degenerate pairs = 276

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$\Rightarrow$ *And all before the ILC is even a year old!*