Cosmology at Colliders

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Based on work with Konstantin Matchev and Maxim Perelstein.

Cosmology is entering a GOLDEN ERA

- Surprising Breakthroughs $\Omega_\Lambda \neq 0$
- Precision Measurement
- Wonderful, Unexplained Data Λ, Dark Matter

But will the next breakthrough in cosmology come from a particle collider?

Future Experiments (cosmology and Particle Physics)

- WMAP*: $\Omega_\Lambda \sim 0.7$ $\Omega_m \sim 0.3$ $\Omega_b \sim 0.05$
  $\sum_i m_{\nu_i} < 0.63\,eV$ $\Omega_{DM} \sim 0.25$
- LHC: Origin of EWSB, hierarchy problem SUSY? Ex. Dim?
- Zeplin IV and Xenon: Characteristics of Dark Matter
- Planck: Ω_Λ, Ω_m, Ω_b, Ω_{tot} % level or better
- NLC: Precision measurements of LHC discoveries
  Disentangle SUSY vs. Ex. Dim.?

* Recently Ex-Future

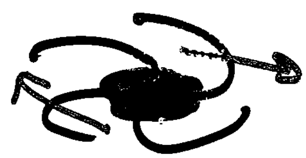
IMPORTANT POINT:

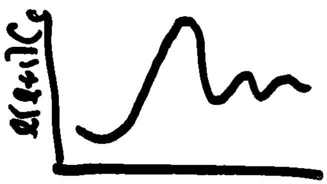
IF WE ASSUME DARK MATTER IS A PARTICLE, THEN **ALL** OF THESE EXPERIMENTS ARE LIKELY MEASURING DARK MATTER!

Dark Matter

From Cosmology

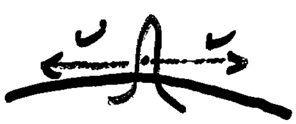
- Galactic Rotation Curves → WMAP

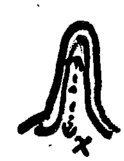




Discovery! $0.094 \leq \Omega_{DM} h^2 \leq 0.129$

- Structure Formation
  Dark Matter is **COLD**
  (non-relativistic) $\sigma v = a + b v^2$



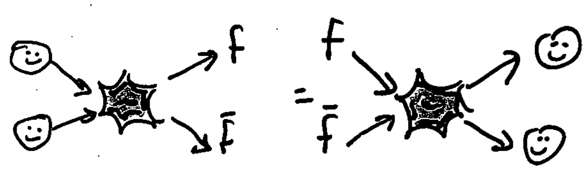


← agrees with data

HOT COLD

From Particle Physics

Disney Version



- Thermal Equilibrium
- Becomes Non-relativistic $T < m_{DM}$ $n \sim (mT)^{3/2} e^{-m/T}$
- Freezes out of thermal eq. $\Gamma_{an} < H$ $n \sim (a(t))^{-3}$

Must be stable and neutral

Dark Matter and Particle Physics II

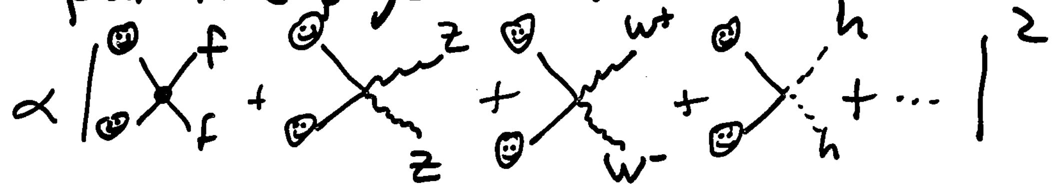
Miramax Version

Boltzmann Equation

$$\frac{dn_{DM}}{dt} + 3H\, n_{DM} = -\langle\sigma_A |v|\rangle\left(n_{DM}^2 - (n_{DM}^{eq})^2\right)$$

$\langle\sigma_A |v|\rangle$:- thermally averaged cross section

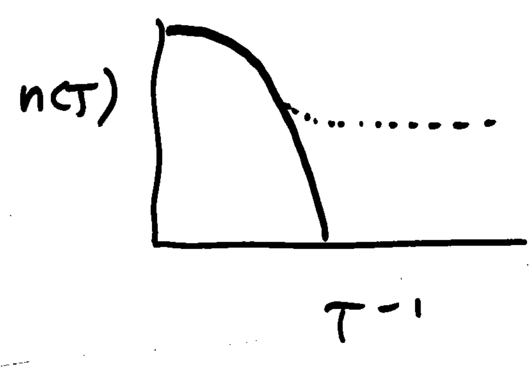
- particle physics input



(CHARACTER BUILDING)

- DM is non relativistic

$$\sigma v = a + b v^2$$



Cosmology constrains $\langle \sigma_A |v| \rangle$

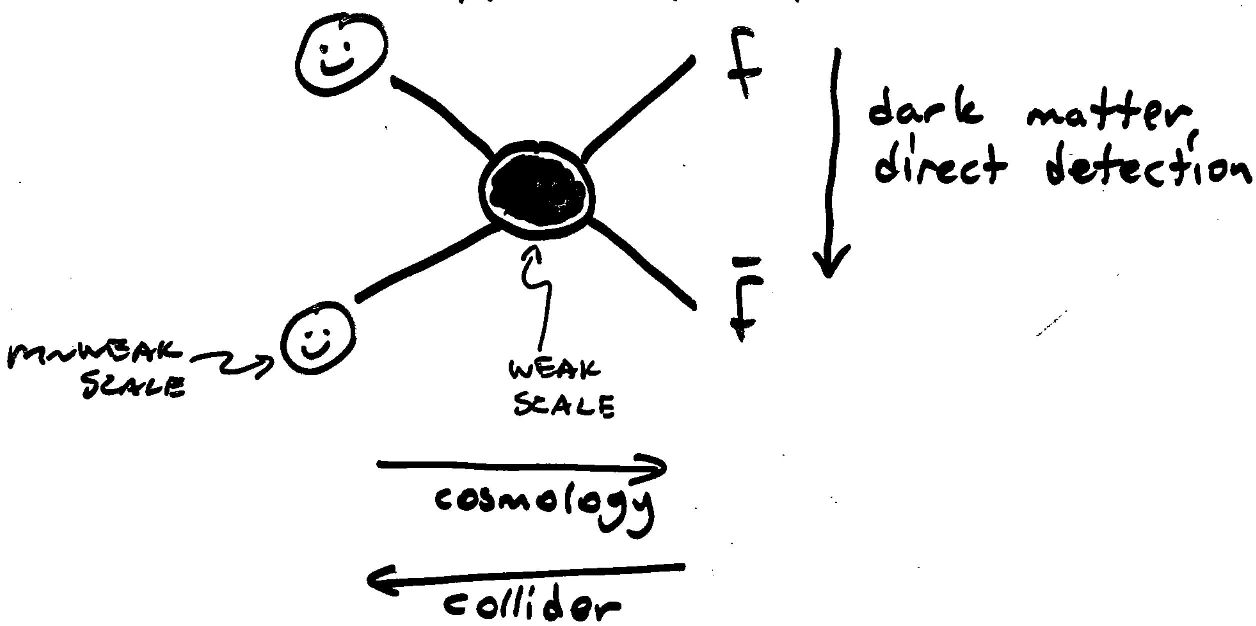
$$\Omega_{DM} h^2 = 40 \sqrt{\frac{\pi}{5}} \frac{h^2}{H_0^2} \frac{s_0}{M_{PL}} \frac{\sqrt{g_*}}{g_{*S}} \frac{1}{J(x_F)}$$

$$\approx \frac{2 \times 10^{-10}\ \mathrm{GeV}^{-2}}{\langle \sigma_A |v| \rangle} \sim 0.1$$

$$\langle \sigma_A |v| \rangle \sim \frac{\alpha_{EW}^2}{M_{EW}^2}$$

RIGHT ON FOR $M_{EW} \sim 100 - 1000\ \mathrm{GeV}$

A WIMP!



Dark Energy: $S = \int d^4x \left(\sqrt{-g}\, \Lambda + \cdots \right)$

$$\Lambda \approx (10^{-3}\ \mathrm{eV})^4 \qquad \text{(SCP, Hi-z)}$$

$$\Lambda \approx \left(\frac{M_{EW}^2}{M_{PL}} \right)^4 \qquad \text{? More Weak Physics?}$$

Motivating Question

Considering the links between particle physics and cosmology (dark matter, ? dark energy ?), can we use cosmological measurements to predict collider signatures/cross sections?

Colliders and Dark Matter
A Model-Independent Approach!

Can we test the "WIMP hypothesis" at a collider?

WIMP hypothesis: (χ)

- stable ($\tau > 10^{10}$ yrs)
- $m_\chi \sim$ EW scale (10 GeV – 1 TeV)
- weak interactions (range $\sim 10^{-16}$ cm)

Gets $\Omega_\chi h^2$ correct ($0.094 \leq \Omega_{DM} h^2 \leq 0.129$)

WMAP determines $\langle \sigma_A |v| \rangle = \sum_i \langle \sigma_i |v| \rangle$

χ - non relativistic at freeze out

$$\sigma_i v = \sum_{J=0}^{\infty} \sigma_i^{(J)} v^{2J}$$

$\uparrow$ $\chi\chi \to X_i \bar{X}_i$

$\sigma_i^{(0)}$ - s-wave

$\sigma_i^{(1)}$ - p-wave

only one dominant

$$\boxed{\sigma_{an} \equiv \sum_i \sigma_i^{(J_0)}}$$

constrained directly by WMAP

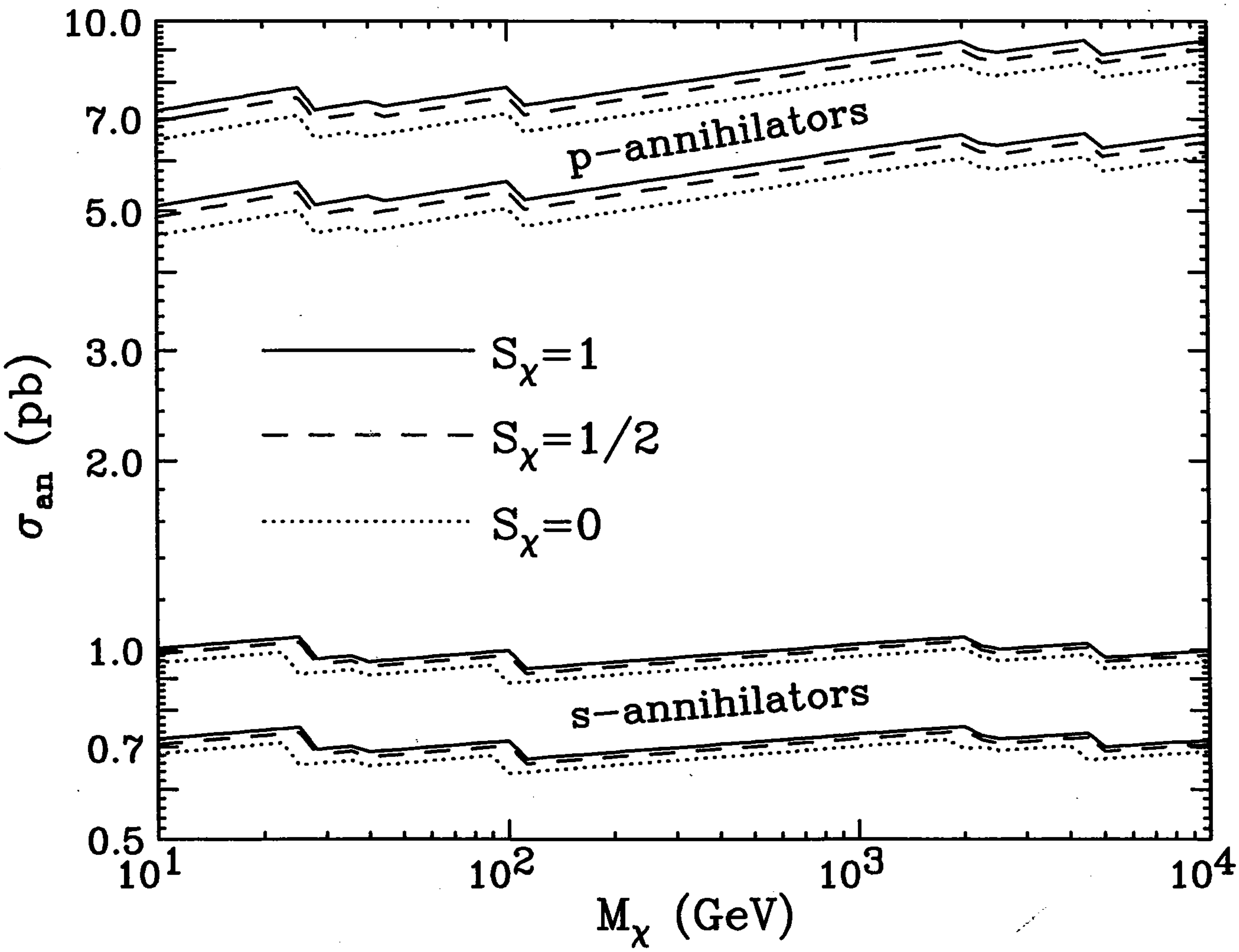


Figure 7: **Necessary cosmological WIMP annihilation cross section.** The necessary value of σ_{an} for a WIMP to provide the WMAP-determined value of the dark matter relic density. Results are given both for s-wave dominated and p-wave dominated annihilation and also for spins of $S_\chi = 0, 1/2, 1$.

- So cosmology gives us model independent information on $\chi\chi \to SM + SM$

Step 1: Detailed Balance

$$\frac{\sigma(\chi\chi \to e^+e^-)}{\sigma(e^+e^- \to \chi\chi)} = 2\,\frac{v_e^2}{v_\chi^2}\,\frac{(2S_e+1)^2}{(2S_\chi+1)^2} = \frac{8}{v_\chi^2 (2S_\chi+1)^2}\,!$$

NR χs $\longleftrightarrow$ close to 2χ production threshold

$$\sigma(\chi\chi \to e^+e^-) \simeq \sigma_e^{(J_0)}\, v_\chi^{2J_0-1}$$

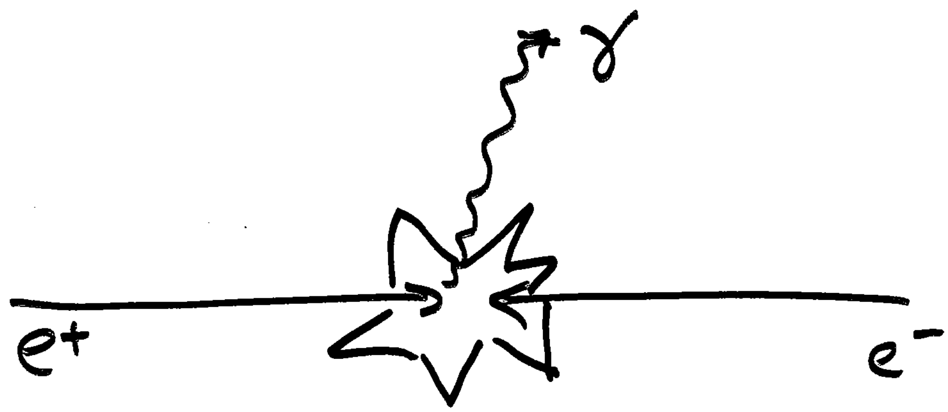
One unknown parameter: "annihilation fraction"

$$\kappa_e = \frac{\sigma_e^{(J_0)}}{\sigma_{an}} \qquad \left(\begin{array}{l}\text{typically} \\ \kappa_e \sim 20\%\end{array}\right)$$

Prediction for WIMP pair production:

$$\sigma(e^+e^- \to 2\chi) = \frac{1}{16}\kappa_e\,\sigma_{an}(2S_\chi+1)^2\,2^{2J_0}\left(1-\frac{4m_\chi^2}{s}\right)^{\frac{1}{2}+J_0}$$

But this is



Hard to see...

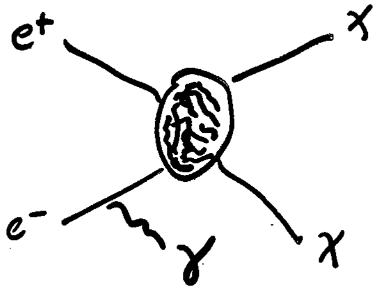
Wait!

We know how to look for

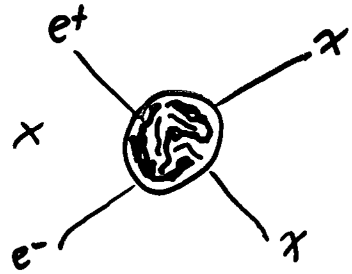
$$e^+e^- \to \gamma + \not{E}$$

Step 2 Soft Factorization

If E_γ is small



$= S(p_\gamma) \times$



↑ calculable, universal, Standard Model "soft factor"

Now combining:

$$\frac{d\sigma}{dE_\gamma \, d\cos\theta}(e^+e^- \to 2\chi + \gamma) =$$

$$\frac{\alpha}{8\pi} \frac{1}{E_\gamma} \frac{1}{\sin^2\theta} \kappa_e \, \sigma_{an} (2S_\chi + 1)^2 \, 2^{2J_0} \left(1 - \frac{4m_\chi^2}{s}\right)^{\frac{1}{2}+J}$$

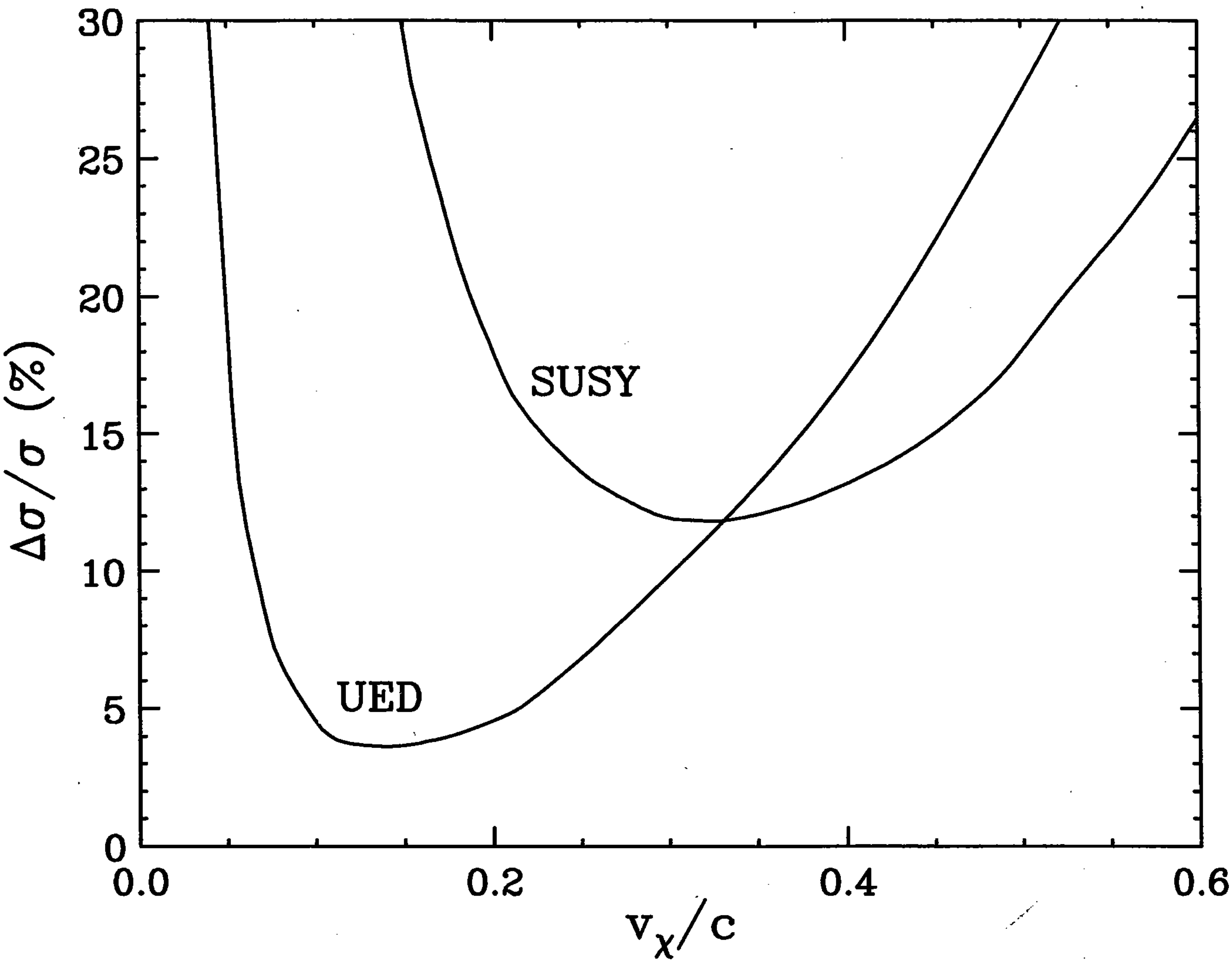


Figure 8: Accuracy of $e^+e^- \rightarrow \chi\chi\gamma$ prediction. The error incurred in utilizing soft factorization and velocity expansion in the determination of detectable WIMP signal. Examples are given for universal extra dimensions (UED), which has a spin-1 WIMP, and supersymmetry (SUSY), which has a spin-1/2 WIMP.

Example: LEP 2 Search for WIMPS

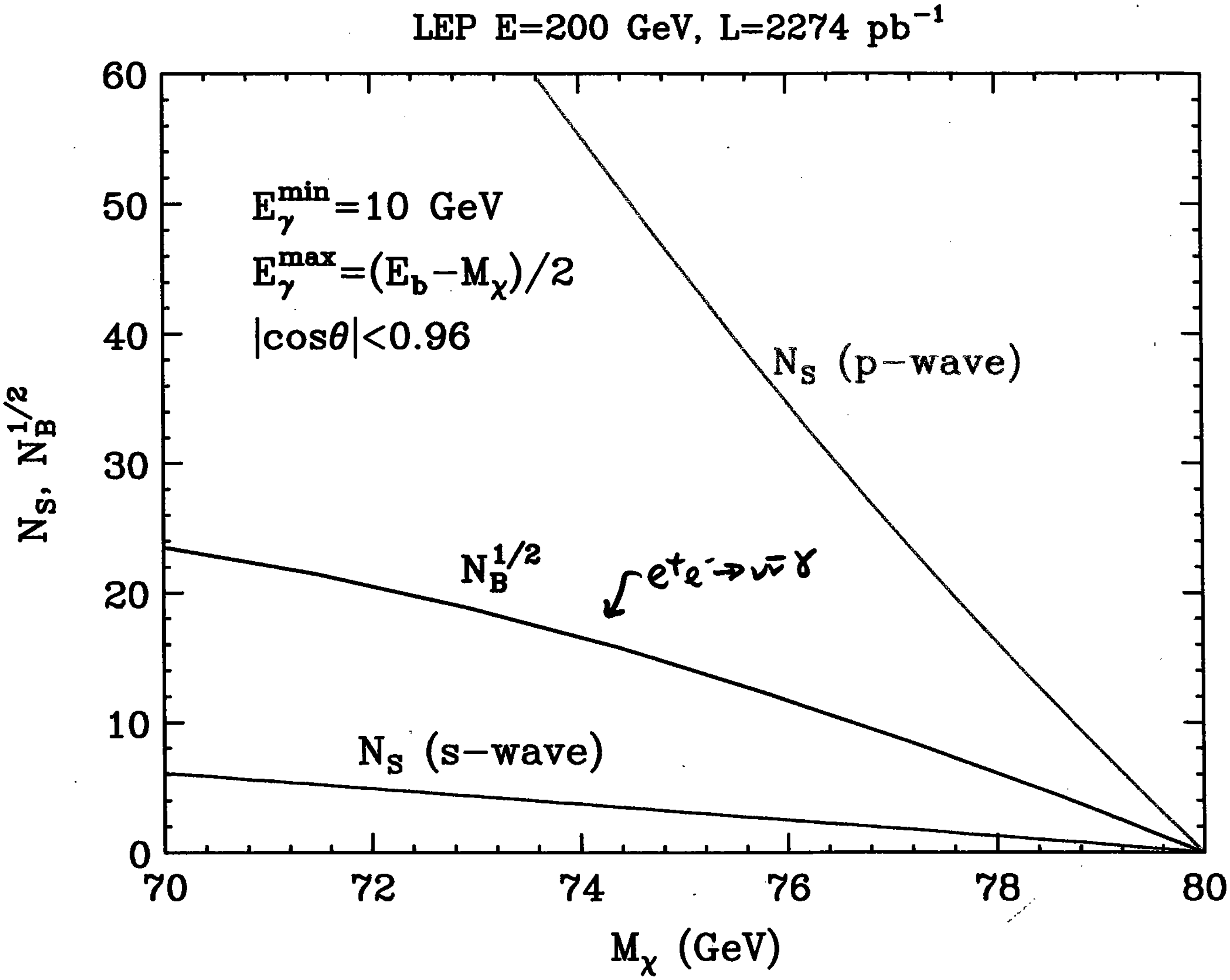


Figure 9: Expected Signal at LEP. The expected number of events at LEP for s-wave, p-wave and background.

75 GeV p-annihilator: discovered/ruled out at $\boxed{3\sigma}$
(assuming $\kappa_e = 1$)

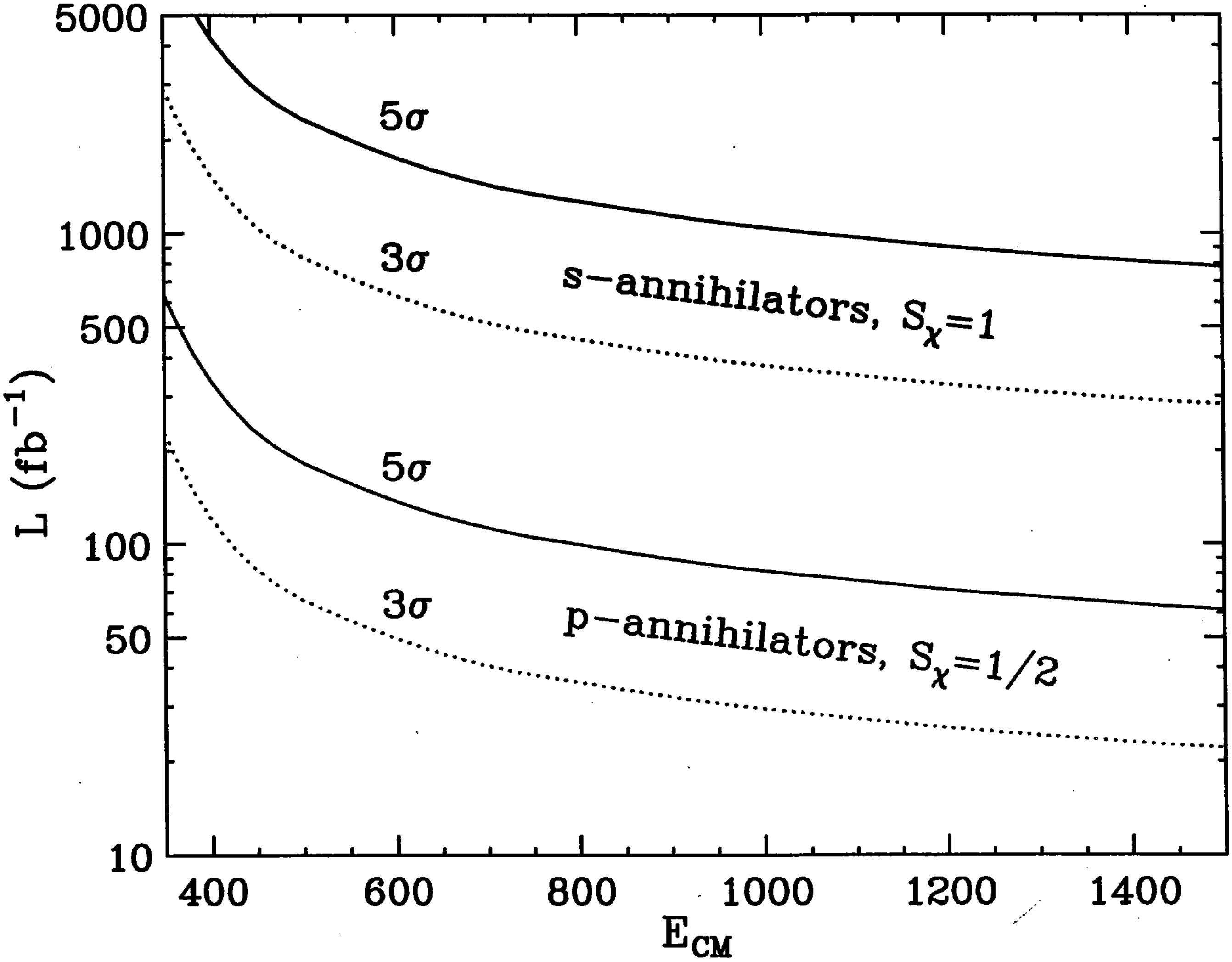


Figure 11: **Necessary luminosity for discovery of** $e^+e^- \to \chi\chi\gamma$.

Comments on our model-independent approach

- Analysis for hadron colliders - in progress
- Results true in SUSY (mSUGRA or not) (everybody)

  UED (Servant + Tait; Cheng, Feng + Matchev)

  Little Higgs (A.B. + J. Wacker; Cheng + Low; Katz + Nelson)

  ...

  <u>Any</u> WIMP

- The rates discussed here are <u>guaranteed</u> by the WIMP hypothesis, regardless of the model!

- Our analysis establishes a direct connection between cosmology and collider experiments!