Determining the WIMP mass using the complementarity between direct detection, indirect detection and the ILC

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Based on N.Bernal, A.G., Y.Mambrini, C.Muñoz,
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(arXiv:0804.1976 [hep-ph])

Outline

Dark matter detection is a quite challenging task...

- Parameter spaces for thermal candidates are seriously starting to be explored now: CDMS-II, Xenon, Fermi, PAMELA...
- The situation can be even worse for non-thermal candidates (gravitinos, right-handed neutrinos etc)
- "Positive detection" reports generate much controversy: HESS, EGRET, DAMA, PAMELA...
- An example: Models can explain e^+ data from PAMELA but fail elsewhere.

$\Longrightarrow$ Need to combine as much information as possible.

A slightly different question:

- Suppose we see an excess.
- Suppose this excess can be nicely explained through DM annihilations/scatterings/pair-production etc...

How well shall we be able to constrain the DM properties?

$\looparrowright$ We shall be focusing on WIMPs.

Direct Detection: The event rate

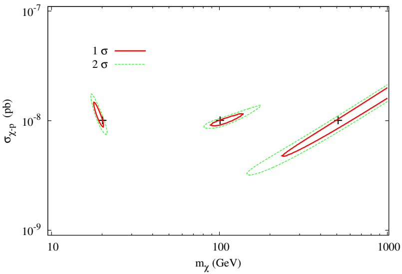
$$\frac{dN}{dE_r} = \frac{\sigma_{\chi-N} \cdot \rho_0}{2\, M_r^2\, m_\chi} F(E_r)^2 \int_{v_{\min}(E_r)}^{v_{esc}} \frac{f(v)}{v}\, dv$$

Where:

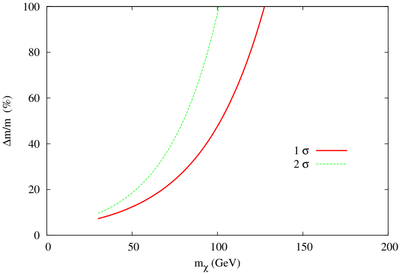
- N: Number of scatterings $(\mathrm{s}^{-1}\mathrm{kg}^{-1})$
- E_r: Nuclear recoil energy (∼few keV)
- m_χ: WIMP mass
- $M_r = \frac{m_\chi\, m_N}{m_\chi + m_N}$: WIMP - Nucleus Reduced Mass
- $\sigma_{\chi-N}$: WIMP-Nucleus cross-section (Spin-independent coupling)
- ρ_0: Local WIMP density $(0.3\ \mathrm{GeV\ cm}^{-3})$
- $f(v)$: WIMP local velocity distribution (Maxwell-Boltzmann)
- F: Nuclear form factor (Woods-Saxon)

Direct Detection in a XENON-like experiment

Mass and cross-section discrimination



Mass Resolution



In fact:

$$m_\chi \ll m_N \Rightarrow \frac{dN}{dE_r} \simeq e^{-E_r/m_\chi^2}$$

$$m_\chi \gg m_N \Rightarrow \frac{dN}{dE_r} \simeq e^{-E_r}$$

$\Rightarrow$ **Better discrimination capacity for small masses**

3 years of XENON100.
Ignoring backgrounds/theoretical uncertainties.

Indirect Detection: The γ-ray flux

$$\Phi_\gamma(E_\gamma) = 0.94 \cdot 10^{-13}\text{cm}^{-2}\text{sec}^{-1}\text{GeV}^{-1}\text{sr}^{-1} \sum_i Br_i \frac{dN_\gamma^i}{dE_\gamma}$$
$$\times \left(\frac{\langle\sigma v\rangle}{10^{-29}\text{cm}^3\text{sec}^{-1}}\right)\left(\frac{100\text{GeV}}{m_\chi}\right)^2 \bar{J}(\Delta\Omega)\Delta\Omega$$

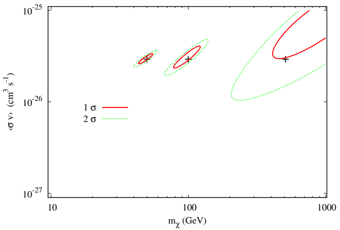
Where:

- Br_i: Branching Ratio of annihilation into i-th SM particle
- dN_γ^i/dE_γ: Functions describing SM particles' decays into γ-rays (PYTHIA + fit)
- $\langle\sigma v\rangle$: Total WIMP self-annihilation cross-section ($\approx 3 \cdot 10^{-26}\text{cm}^3\text{sec}^{-1}$)
- $\bar{J}$: Astrophysical factor: Depends on DM distribution.

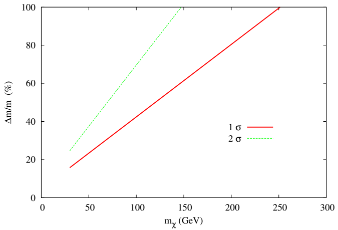
	a (kpc)	α	β	γ	$\bar{J}(4 \cdot 10^{-3}\text{sr})$
NFW	20	1	3	1	$5.859 \cdot 10^2$
NFW_c	20	0.8	2.7	1.45	$3.254 \cdot 10^4$
Moore et al.	28	1.5	3	1.5	$2.574 \cdot 10^4$
Moore_c	28	0.8	2.7	1.65	$3.075 \cdot 10^5$

Indirect Detection with FERMI

Mass and cross-section discrimination for a NFW halo profile



Mass Resolution

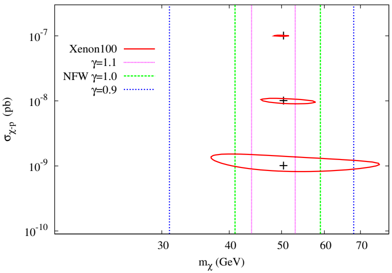


- Again, better resolution for smaller masses (due to strong differences in the spectrum form in the $[1, 300]$ GeV region!).
- Strong dependence on the halo profile.
- Background: ~~EGRET PS~~ + HESS PS + HESS diffuse.

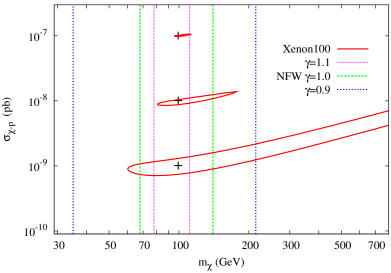
6-year mission, GC in field of view half of the time.
Interesting theoretical/experimental uncertainties!

Direct vs Indirect Detection

Example for $m_\chi = 50$GeV



Example for $m_\chi = 100$GeV

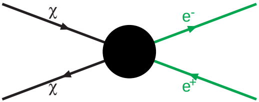


- Complementarity more obvious for not too optimistic astrophysical considerations and $\sigma_{\chi-p}$ cross-sections.
- In any case, results can be improved with a more elaborate statistical treatment.

ILC: The Method

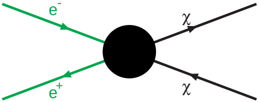
The General Idea: Birkedal, Matchev, Perelstein, arXiv:hep-ph/0403004

WIMP Pair - Annihilation (Galaxy - WMAP)



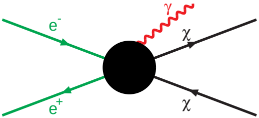
⇓ (Detailed Balancing)

WIMP Pair - Production (Colliders - Invisible)



⇓ (Collinear Approximation)

Radiative WIMP Production (Colliders - Visible!)



ILC: Radiative WIMP Production Rate

$$\frac{d\sigma(e^+e^- \to 2\chi + \gamma)}{dx d\cos\theta} \approx \frac{\alpha\kappa_e\sigma_{an}}{16\pi}\frac{1+(1-x)^2}{x}\frac{1}{\sin^2\theta}2^{2J_0} \times (2S_\chi + 1)^2\left(1 - \frac{4{m_\chi}^2}{(1-x)s}\right)^{1/2+J_0}$$

Where:

- $x = 2E_\gamma/\sqrt{s}$
- θ: Photon emission angle
- σ_{an}: Total annihilation cross-section (WMAP) ($\backsim$ 7pb, under assupmptions.)
- J_0: Dominant (s- or t-) annihilation channel
- S_χ: WIMP's spin
- $\kappa_e = \sigma_e^{(J_0)}/\sigma_{an}$: Annihilation fraction into e^+e^- pairs.

ILC: Subtleties

Approach valid for soft/collinear photons → **Undetectable!**

• Nevertheless, it gives satisfactory results outside the soft/collinear region for **nonrelativistic** WIMPs.

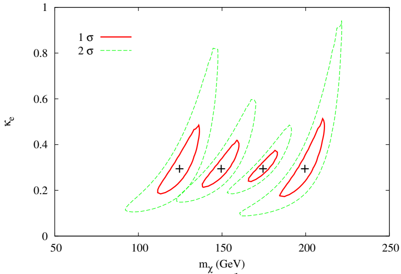
To ensure the WIMPs' non-relativistic nature we impose the following kinematical cuts:

$$\frac{\sqrt{s}}{2}\left(1-\frac{8m_\chi^2}{s}\right) \leq E_\gamma \leq \frac{\sqrt{s}}{2}\left(1-\frac{4m_\chi^2}{s}\right).$$

• Main background process: Radiative neutrino production (CalcHEP 2.5).

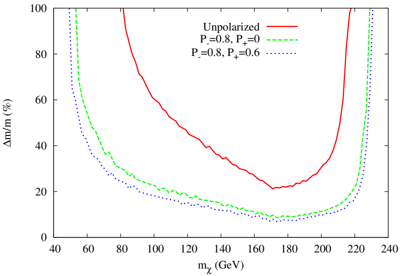
ILC: Mass Discrimination

WIMP mass - annihilation fraction discrimination capacity



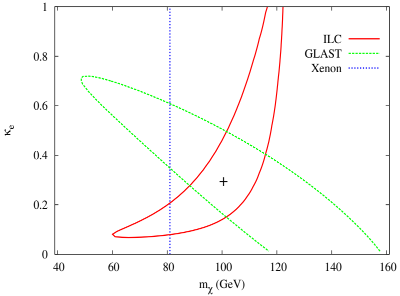
(500GeV Unpolarized beams, 500fb^{-1} integrated luminosity)

Relative error in WIMP's mass discrimination



- Discrimination capacity peaks significantly for $m_\chi = 175\text{GeV}$ (optimal combination of uncut spectrum - phase space).
- Significant improvement in mass resolution for polarized beams.

DM Experiments/ILC complementarity



An example at 95% CL:

- $m_\chi = 100$GeV
- 3 years of exposure,
- $\sigma_{\chi-p} = 10^{-8}$ pb
- NFW profile and a
- 500 GeV unpolarized linear collider with an integrated luminosity of 500fb^{-1}

m_χ	XENON	GLAST	ILC
50 GeV	$-5/+7$ GeV	± 12 GeV	–
100 GeV	$-19/+75$ GeV	$-50/+60$ GeV	$-40/+20$ GeV
175 GeV	$-65/$ GeV	-125 GeV	$-20/+15$ GeV
500 GeV	–	–	–

Summarizing...

- We presented a simple way to exploit simultaneously different kinds of experiments to extract **model-independent** information on WIMP Dark Matter.
- For quite reasonable (i.e. not too optimistic) considerations on the WIMP-nucleus scattering cross-section and the DM halo profile we saw that different kinds of experiments can act highly complementary:
  $\longrightarrow$ The precision is comparable.
  $\longrightarrow$ Possibility to cover different regions in the parameter space.

Further questions:

- What about other channels? ($\bar{p}$'s, antideuterons, synchrotron etc...)
- More elaborate techniques are starting to develop for colliders: M_{T_2} approach, EFT techniques.
- Even if we determine the mass of an invisible particle in a collider, another issue is its cosmological relevance!

A few more details...

Discrimination Method

Analysis based on extended likelihood function:

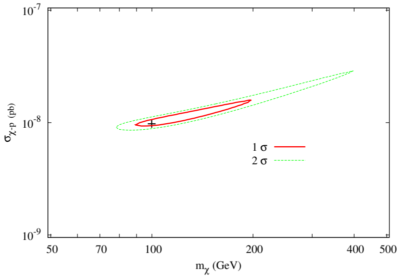
$$L = \frac{(N_{th}^{scan})^{N_{Exp}}}{N_{Exp}!} \exp\left(-N_{th}^{scan}\right) \prod_{i=1}^{N_{Exp}} f(E; m_\chi, \sigma_{\chi-p})$$

- Calculate the theoretical number of events, N_{th}, for the input mass and cross-section.
- Draw an "experimental" nb of events, N_{Exp}, from a Poisson distribution.
- Scan the (m_χ, $\sigma_{\chi-N}$) parameter space and find the experiment's estimation, taking into account the theoretical nb of events of every point in the PS, N_{th}^{scan}.
- Generate a large number of experiments, repeat the procedure, pick the one that averages all experiments' results.
- From this experiment, plot (m_χ, $\sigma_{\chi-N}$) non-discrimination regions.

$\Longrightarrow$ This method allows to account for random deviations from the expected number of events.

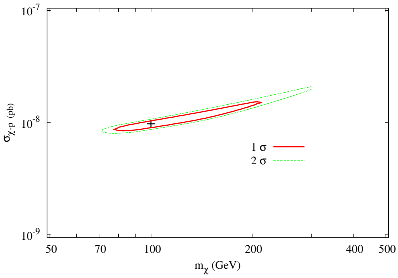
Direct Detection: Uncertainties

Background considerations



Inclusion of an exponential background mimicking the signal.

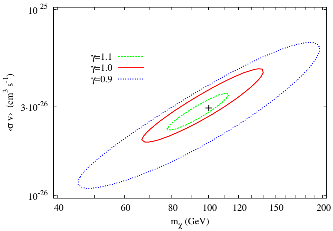
Velocity distribution



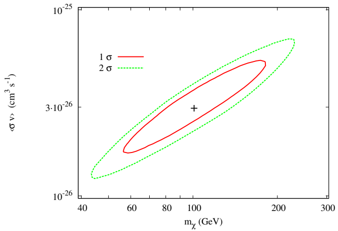
$$f(v_\chi)\, d^3 v_\chi = \frac{1}{(v_\chi^0)^3 \pi^{3/2}}\, e^{-(v_\chi / v_\chi^0)^2}\, d^3 v_\chi$$

Indirect Detection: Uncertainties

Fun with γ!



Impact of final states



- Recent *N*-body simulations seem to disfavour highly cusped profiles.
- What about baryons?
- And the backgrounds?

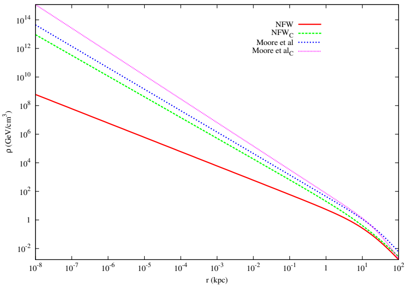
- We include a 30%τ final state.
- Subtle for γ's: Role of other leptonic channels (signal mostly renormalized). Should look into other wavelengths.

Halo Profiles

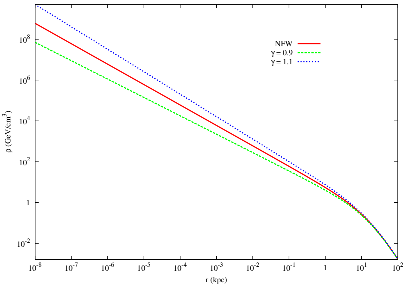
The most usual parametrization:

$$\rho(r) = \frac{\rho_0[1+(R_0/a)^\alpha]^{(\beta-\gamma)/\alpha}}{(r/R_0)^\gamma[1+(r/a)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Some well motivated profiles



Fun with γ!!!

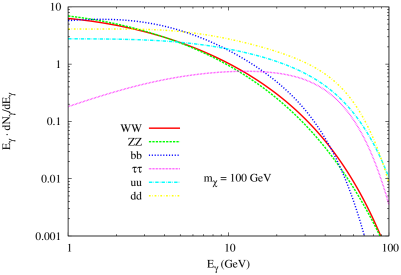


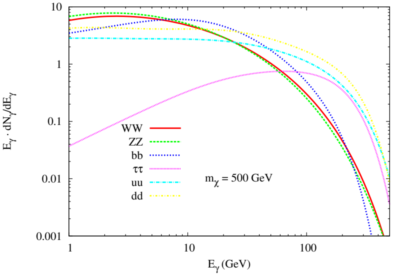
Spectral Functions

PYTHIA result fit performed through functions of the form:

$$\frac{dN^i_\gamma}{dx} = \exp[F_i(\ln(x))]$$

with $x = E_\gamma/m_\chi$ and F being 7th order polynomial functions.





- The τ spectrum has a characteristic hard form, other leptons have zero contribution.

Some Points on the ILC Treatment

- The detailed balancing equation:

$$\frac{\sigma(\chi + \chi \rightarrow X_i + \bar{X}_i)}{\sigma(X_i + \bar{X}_i \rightarrow \chi + \chi)} = 2\frac{v_X^2(2S_X + 1)^2}{v_\chi^2(2S_\chi + 1)^2}$$

We can expand the total thermally averaged CS:

$$\sigma_i v = \sum_{J=0}^{\infty} \sigma_i^{(J)} v^{2J} \overset{v \ll c}{\Longrightarrow} \sigma_{an} = \sum_i \sigma_i^{(J_0)}$$

For soft/collinear photons:

$$\frac{d\sigma(e^+e^- \rightarrow 2\chi + \gamma)}{dx d\cos\theta} \approx \mathcal{F}(x, \cos\theta)\tilde{\sigma}(e^+e^- \rightarrow 2\chi)$$