Determining the WIMP mass using the complementarity between direct and indirect searches and the ILC

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PLANCK 08

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in collaboration with A. GOUDELIS, Y. MAMBRINI & C. MUÑOZ

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Direct detection

Direct detection experiments are designed to detect **dark matter particles** by their **elastic collision with target nuclei**, placed in a detector on the Earth.

Recoil rates

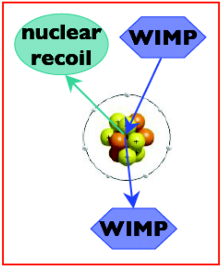
$$\frac{dN}{dE_r} = \frac{\sigma_{\chi-p} \cdot \rho_0}{2\, M_r^2\, m_\chi} F(E_r)^2 \int_{v_{\min}(E_r)}^{v_{esc}} \frac{f(v)}{v}\, dv$$

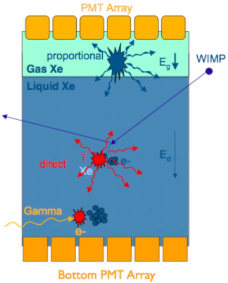
Reduced mass $M_r = \dfrac{m_\chi\, m_N}{m_\chi + m_N}$

N: number of scatterings $(\mathrm{s}^{-1}\mathrm{kg}^{-1})$
E_r: nuclear recoil energy ~few keV
m_χ: WIMP mass
$\sigma_{\chi-p}$: WIMP-proton cross-section
(Assuming spin-independent coupling)
ρ_0: local WIMP density 0.3 GeV cm^{-3}
$f(v)$: WIMP local vel. distribution M.B.
F: nuclear form factor Woods-Saxon

7 energy bins $[4.5, 26.9]$ keV

XENON 100 **kg**





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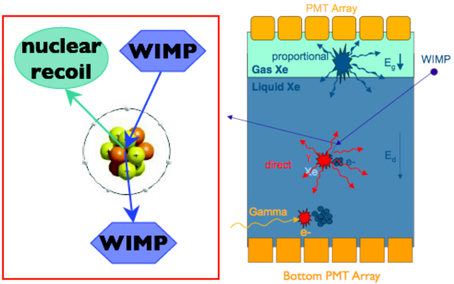
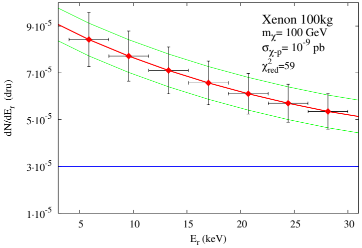


Discrimination method: χ^2

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{N_i^{tot} - N_i^{bkg}}{\sigma_i} \right)^2$$

Gaussian error: $\sigma = \sqrt{\dfrac{N_i^{tot}}{M \cdot T}}$

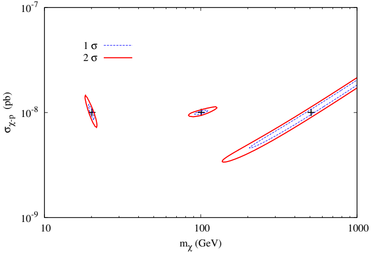
Xenon100 typical signal after 3 years



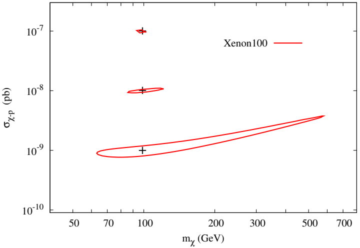
Direct detection

Direct detection experiments can determine the mass of the WIMP
by measuring the distribution of the recoil energy.

→ **Xenon** M=100kg T=3 years



Wimp mass and cross section discrimination



✓ $m_\chi \ll m_N$: $\frac{dN}{dE_r} \propto e^{\frac{-E_r}{m_\chi^2}}$

✗ $m_\chi \gg m_N$: $\frac{dN}{dE_r} \propto e^{-E_r}$

☎ $m_\chi \lesssim$ 10 GeV → detector energy threshold

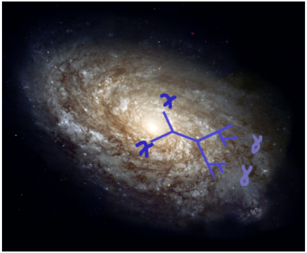
☎ $m_\chi \gtrsim$ 500 GeV → only a lower limit

★ Independent of the microscopic theory.

☎ Better discrimination capacity for
small masses
big WIMP-proton cross-sections

Indirect detection

We study the ability of **gamma-ray** experiments to identify **DM annihilation** radiation from the Galactic Center region by using spectral information.



The spectrum depends on the nature of χ

$\chi\bar{\chi} \to b\bar{b}, \underline{WW}, ZZ, \tau\bar{\tau}, HZ \cdots \to \gamma + \dots$

Gamma-ray flux

$$\Phi_\gamma(E_\gamma, \psi) = \sum_i \frac{dN_\gamma^i}{dE_\gamma} \langle \sigma_i v \rangle \frac{1}{8\pi {m_\chi}^2} \int_{los} \rho(r)^2 dl$$

$\frac{dN}{dE}$: spectrum of secondary particles
E_γ: gamma energy
$\langle \sigma v \rangle$: thermally averaged annihilation cross-section
$\langle \sigma v \rangle \sim 3 \cdot 10^{-26}\ \mathrm{cm^3 s^{-1}}$
$\rho(r)$: dark matter halo profile

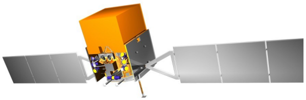
$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma [1 + (r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$

$$\rho(r) \propto r^{-\gamma} \quad \text{at the galactic center} \quad r \ll R$$

	R (kpc)	α	β	γ
NFW	20.0	1.0	3.0	1.0
Moore	28.0	1.5	3.0	1.5
Iso	3.5	2.0	2.0	0

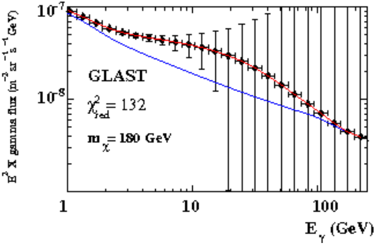
Indirect detection

Once gamma rays are identified as having been produced in DM annihilations, such observations could then be used to measure the characteristics of the DM particle, including its m_χ and $\langle\sigma v\rangle$. Such determinations are an important step towards identifying the particle nature of DM.



Glast Gamma-ray telescope (June '08)

→ **GLAST** typical signal after 3 years



Conservative background:
interpolation between HESS and EGRET

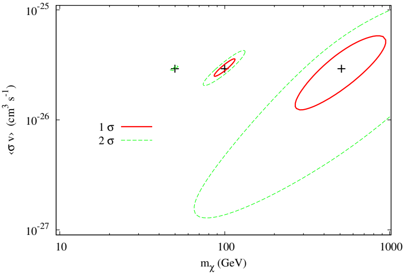
25 energy bins distributed $[1, 300]$ GeV
$2^\circ \times 2^\circ$ field view $\rightarrow \Delta\Omega = 4 \cdot 10^{-3}$ sr
Acceptance $A = 10^4$ cm^{2}sr
We examine the inner (~ 7 kpc) Milky Way

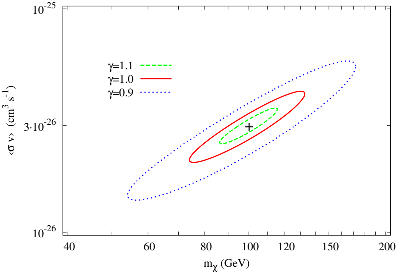
$$\chi^2 = \sum_{i=1}^{n} \left(\frac{\Phi_i^{tot} - \Phi_i^{bkg}}{\sigma_i} \right)^2 ; \quad \sigma_i = \sqrt{\frac{\Phi^{tot}}{A \cdot T}}$$

★ Independent of the microscopic theory
☎ Strong dependence on the halo profile
☎ Coannihilation not taken into account
☎ No clumpiness included

Indirect detection

Gamma-ray experiments can determine the mass of the WIMP by measuring the spectrum from the galactic center





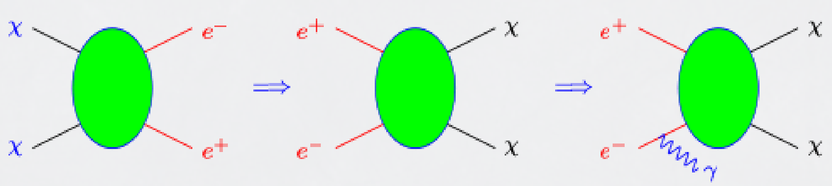
25 energy bins distributed $[1, 300]$ GeV
$2^\circ \times 2^\circ$ field view $\rightarrow \Delta\Omega = 4 \cdot 10^{-3}$ sr
Acceptance $A = 10^4$ cm^{2}sr

★ Independent of the microscopic theory
☎ Better resolution for smaller masses
(strong differences on the spectrum form in the [1, 300]GeV region)
✗ Strong dependence on the halo profile
✗ coannihilation not taken into account

Colliders: ILC

Can cosmology teach us about true DM signals at colliders?
Birkedal, Matchev, Perelstein, arXiv:hep-ph/0403004

➜ Cosmology provides a precise, model-independent measurement of $\sigma(\chi+\chi\to$SM+SM)



WMAP $\Omega_{DM}h^2$ unobservable ✗ observable! ✔

Detailed balancing **Collinear approximation**

Assumptions:

☎ Generic mass spectrum (no resonances, no coannihilations)

☎ At the time of χ decoupling, the only important reactions are $\chi+\chi\leftrightarrow X_i+X_j$

☎ Non-relativistic WIMPs, can be expanded as: $\sigma_i v=\sigma_i^{(0)}+\sigma_i^{(1)}v^2+\ldots$

☎ Dominated by either s-wave or p-wave

Colliders: ILC

Cross section $e^+e^- \to \chi+\chi+\gamma$**:**

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

$x \equiv 2 \cdot E_\gamma/s$
θ: Photon emission angle
$\sigma_{\rm an}$: Total annihilation cross-section $\sim$ 7 pb
J_0: Dominant (s- or t-) annihilation channel
S_χ: WIMP's spin
$\kappa_e = \sigma_e^{(J_0)}/\sigma_{\rm an}$: Annihilation fraction into e^+e^- pairs

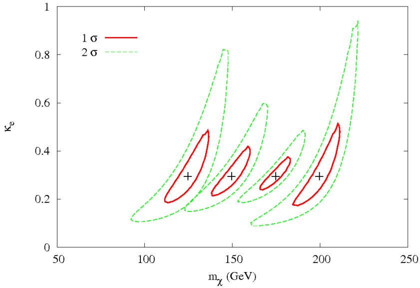
☎ Non-relativistic WIMPs → kinematical cuts: $\frac{\sqrt{s}}{2}\left(1-\frac{8\,{m_\chi}^2}{s}\right) \leq E_\gamma \leq \frac{\sqrt{s}}{2}\left(1-\frac{4\,{m_\chi}^2}{s}\right)$

☎ Main background: $e^+e^- \to \nu\nu\gamma$

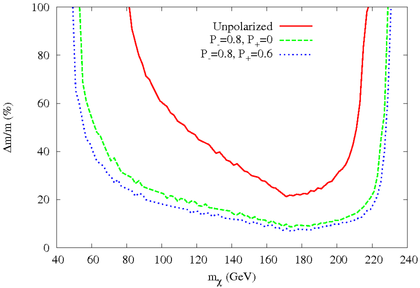
★ Independent of the microscopic theory.

Colliders: ILC

WIMP mass vs. annihilation fraction capacity



Relative error in WIMP's mass discrimination

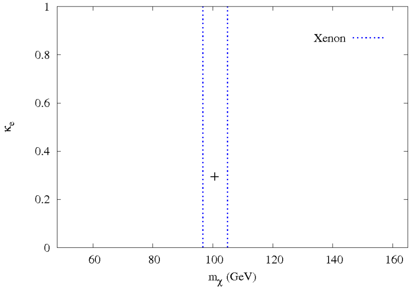


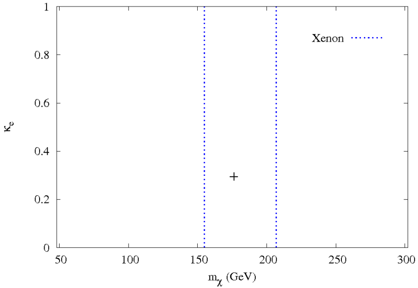
ILC: $\sqrt{s} = 500$ GeV unpolarized beams, 500 pb^{-1} integrated luminosity

- Significant improvement in mass resolution for polarized beams
- Discrimination capacity peaks significantly for $m_\chi = 175$ GeV
  (uncut spectrum → bigger phase space)

Complementarity

Direct detection
Ability to reconstruct the WIMP mass:



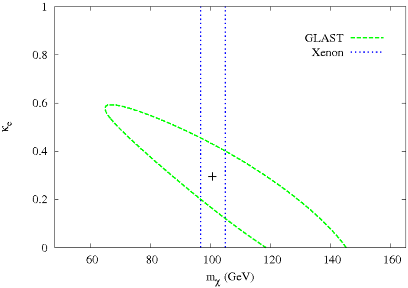


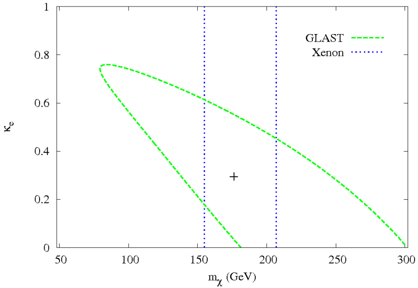
m_χ	XENON
50	± 1
100	± 6
175	$-25/+35$
500	$-250/**$

[$\sigma_{\chi-p} = 10^{-7}$ pb
3 years taking data]

Complementarity

Indirect & **Direct** detection
Ability to reconstruct the WIMP mass:



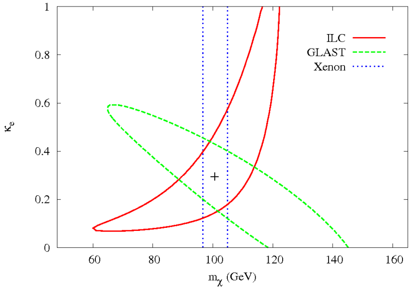


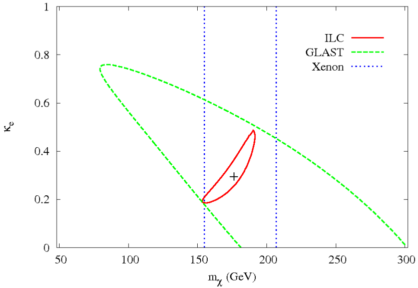
m_χ	XENON	GLAST
50	$\pm$ 1	$\pm$ 8
100	$\pm$ 6	$-25/+32$
175	$-25/+35$	$-70/+100$
500	$-250/**$	$-350/**$

[$\langle\sigma v\rangle = 3 \cdot 10^{26}$ cm^{3}s^{-1}
NFW DM halo profile
3 years taking data]

Complementarity

Indirect & **Direct** detection ✚ **ILC**
Ability to reconstruct the WIMP mass:



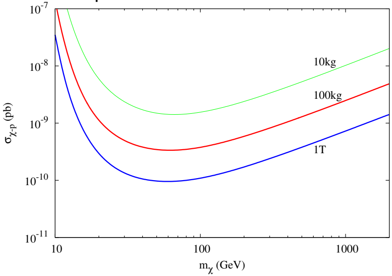


m_χ	XENON	GLAST	ILC
50	± 1	± 8	**
100	± 6	$-25/+32$	$-40/+20$
175	$-25/+35$	$-70/+100$	$-20/+15$
500	$-250/**$	$-350/**$	**

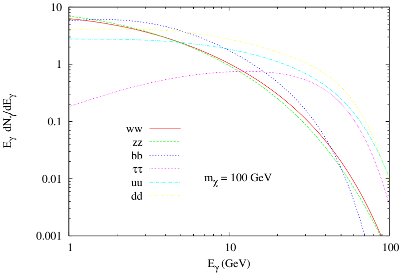
☎ The precision is comparable
☎ Possibility to cover different regions in the parameter space
★ Model independent analysis

Bonus track

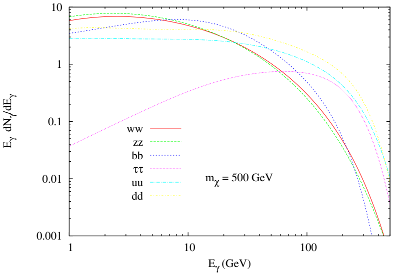
Xenon M=100kg T=3 years
spin ind. exclusion limits:



Bonus track



E_γ dN_γ/dE_γ
E_γ (GeV)
ww
zz
bb
ττ
uu
dd
m_χ = 100 GeV



E_γ dN_γ/dE_γ
E_γ (GeV)
ww
zz
bb
ττ
uu
dd
m_χ = 500 GeV