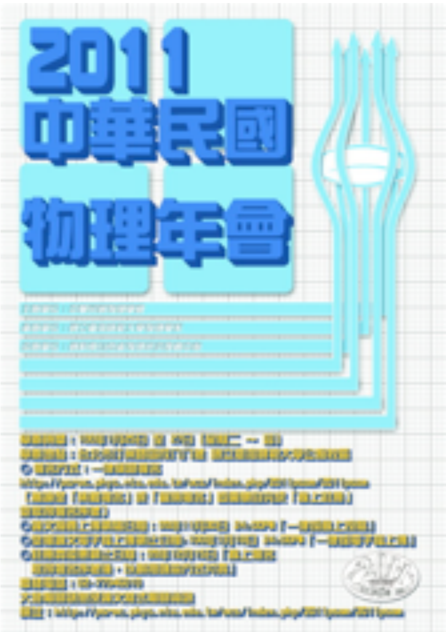


Top Window for Dark Matter

Tzu-Chiang Yuan (阮自強)

Academia Sinica, Taipei, Taiwan

Presented at 2010 物理年會 (Jan 26, 2011, NTNU)

References

- Cheung, Mawatari, Senaha, Tseng and Yuan,
  JHEP 1010:081 (2010), arXiv:1009.0618
- Cheung, Tseng and Yuan,
  JCAP 1101:004 (2011), arXiv:1011.2310
- Cao, Chen, Li and Zhang, arXiv:0912.4511
- Goodman, Ibe, Rajaraman, Shepherd, Tait and Yu, arXiv:1005.1286, arXiv:1008.1783, arXiv:1009.0008
- Fan, Reece and Wang, arXiv:1008.1591

Outline

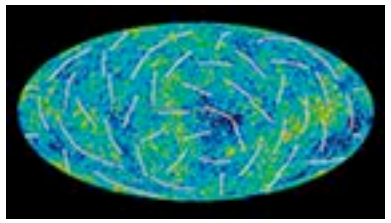
- Introduction
- Effective Interactions
- Relic Density Constraint
- Direct and Indirect Detections Constraints
- Detection at the LHC
- Summary

Introduction

Evidences for Dark Matter

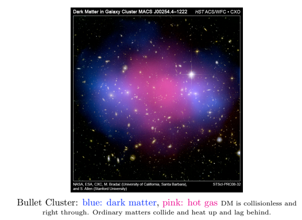
Many hints:

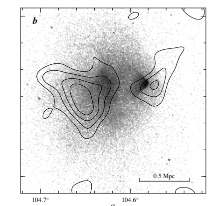
- WMAP



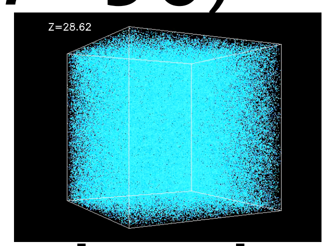
$$\Omega_{\rm CDM}h^2 = 0.1099 \pm 0.0062$$

- Bullet cluster (1E 0657-56)

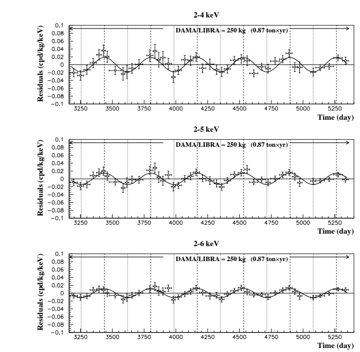




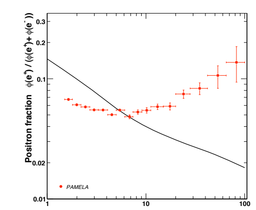
- Large Scale Structure



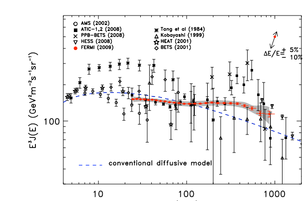
- DAMA: annual modulation in detection rates



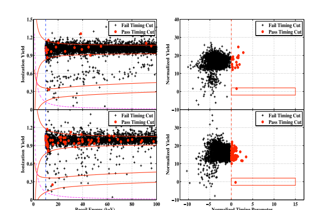
- PAMELA: excessive positron spectrum



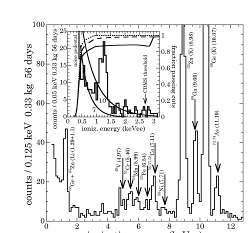
- ATIC, Fermi-LAT: excessive electron flux at 300-800 GeV



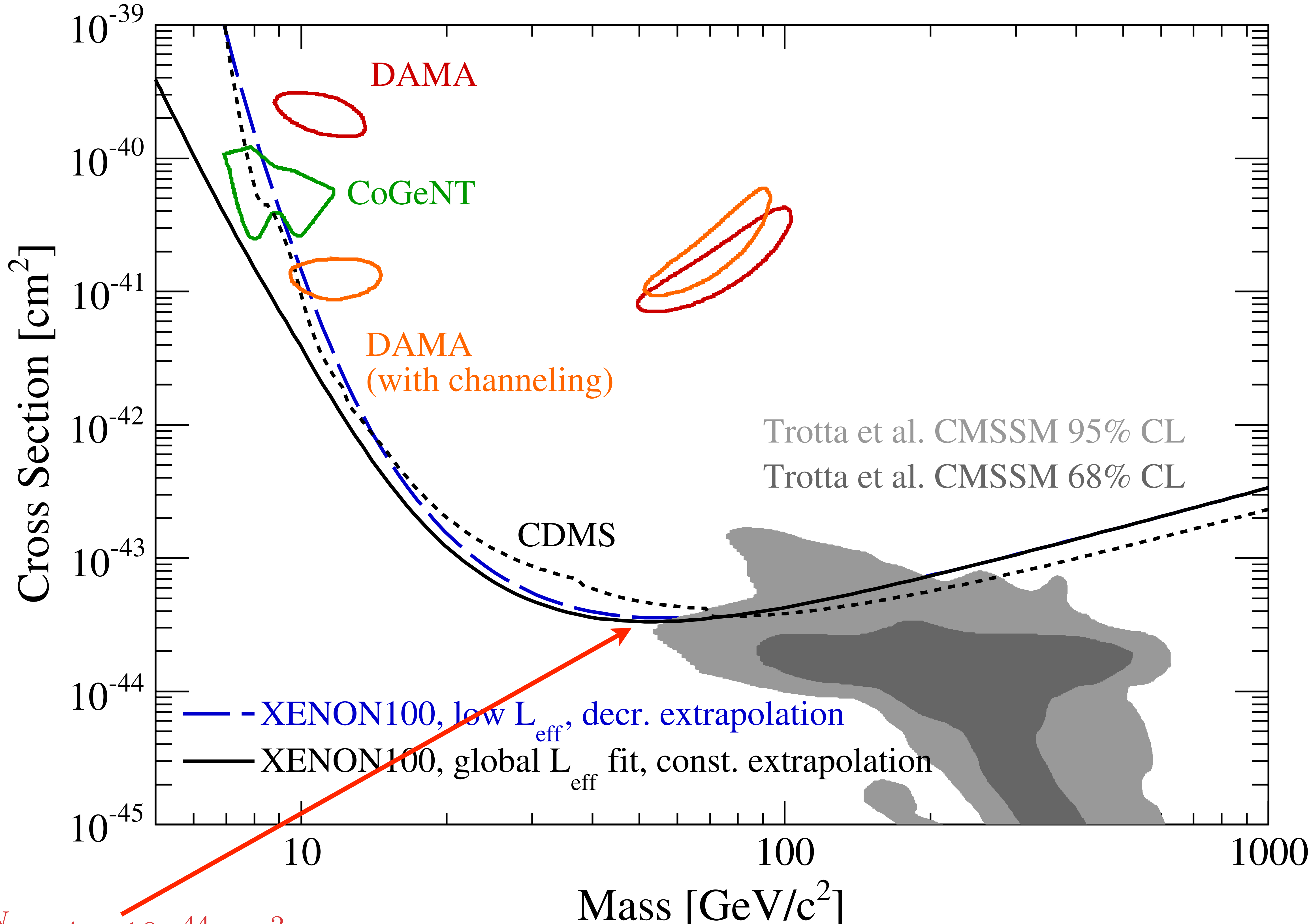
- CDMSII: 2 signal events in blind analysis



- CoGeNT: cosmogenic peaks in favor of DM ~ 5 - 10 GeV



XENON Cross Sections Limits



$\sigma_{SI}^{\chi N} \sim 4 \times 10^{-44}\ \mathrm{cm}^2$

PRL 105, 131302 (2010)

Motivations

- *Weakly-interacting massive particle* (WIMP) is the most motivated DM candidate. The relation between the relic density and the thermal annihilation rate around the time of freeze-out is

$$\Omega_\chi h^2 \simeq \frac{0.1\ \mathrm{pb}}{\langle \sigma v \rangle} \ ,$$

  Given the measured $\Omega_{\rm CDM} h^2 = 0.11$ the annihilation rate is about 1 pb or $10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$.

- This is exactly one would expect from an electroweak interaction. The WIMP may be closely related to electroweak symmetry breaking (EWSB).

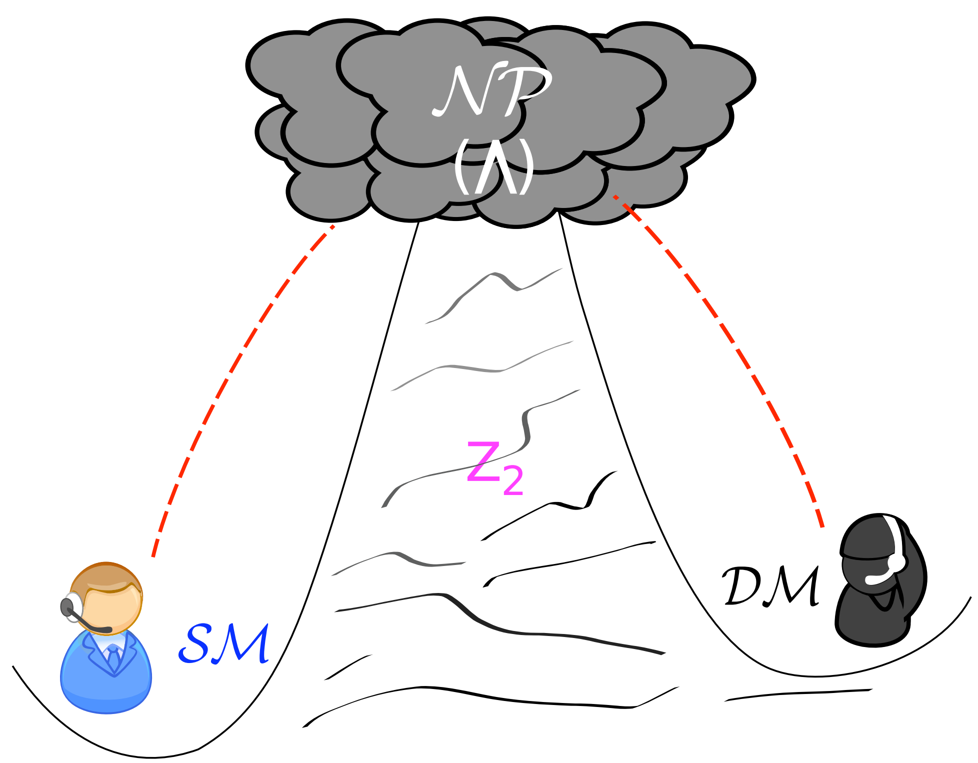
- The top quark with a mass $172 - 175$ GeV is almost exactly at the VEV of the SM Higgs doublet ($v/\sqrt{2} = 174$ GeV). The top quark is perhaps the best window to probe the EWSB.

- The logic is that both the WIMP and top quark are closely related to the EWSB, we argue that the top quark may be the only window to probe the DM. This is our scenario.

Prototype Models

- One simple model consists of the SM plus a hidden sector which contains a pair of Dirac/Majorana fermions and a new gauge boson couples only to the SM top quark.
- SM and a hidden sector which contains the dark matter and a scalar boson as a portal to the SM Higgs. This scalar couples to the top most sizable and to WW, ZZ can be suppressed in certain 2HDM.
- Dark matter couples to Z' which acts as a portal to SM. The couplings to light d.o.f. are suppressed but is strongest to top. [Jackson et al., JCAP 1004:004 (2010), 0912.0004]

Effective Interactions



[Cao, Chen, Li, Zhang, 0912.4511]

Effective Couplings between DM and Top

- We use 4-fermion interaction to parameterize the interaction, assuming that Λ is the scale of quanta exchanged

$$\mathcal{L} = \frac{g_\chi^2}{\Lambda^2} \left(\overline{\chi}\Gamma\chi\right) \left(\bar{t}\Gamma t\right) ,$$

where

$\Gamma = \gamma^\mu$	for a vector gauge boson
$\Gamma = \gamma^\mu \gamma^5$	for an axial-vector gauge boson
$\Gamma = 1\,(\gamma^5)$	for scalar (pseudoscalar) boson interaction
$\Gamma = \sigma^{\mu\nu}(\gamma^5)$	tensor (axial-tensor) interaction

- For Majorana fermion the γ^μ and $\sigma^{\mu\nu}$ interactions are ZERO.
- Take the dark matter particle to be Dirac for simplicity.
- With these interactions we can calculate the relic density, scattering cross section with nucleons, annhilation rates into antimatter and gamma rays, and production at colliders.

Effective Operators between DM and Light Stuff

[Tait et al; Cao et al; Keung et al; See Tseng's talk]

Operator	Coefficient
Dirac DM, Vector Boson Exchange	
$O_1 = (\bar{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu q)$	$\frac{C}{\Lambda^2}$
$O_2 = (\bar{\chi}\gamma^\mu\gamma^5\chi)\,(\bar{q}\gamma_\mu q)$	$\frac{C}{\Lambda^2}$
$O_3 = (\bar{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$
$O_4 = (\bar{\chi}\gamma^\mu\gamma^5\chi)\,(\bar{q}\gamma_\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$
$O_5 = (\bar{\chi}\sigma^{\mu\nu}\chi)\,(\bar{q}\sigma_{\mu\nu} q)$	$\frac{C}{\Lambda^2}$
$O_6 = (\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi)\,(\bar{q}\sigma_{\mu\nu} q)$	$\frac{C}{\Lambda^2}$
Dirac DM, Scalar Boson Exchange	
$O_7 = (\bar{\chi}\chi)\,(\bar{q}q)$	$\frac{Cm_q}{\Lambda^3}$
$O_8 = (\bar{\chi}\gamma^5\chi)\,(\bar{q}q)$	$\frac{iCm_q}{\Lambda^3}$
$O_9 = (\bar{\chi}\chi)\,(\bar{q}\gamma^5 q)$	$\frac{iCm_q}{\Lambda^3}$
$O_{10} = (\bar{\chi}\gamma^5\chi)\,(\bar{q}\gamma^5 q)$	$\frac{Cm_q}{\Lambda^3}$
Dirac DM, Gluonic	
$O_{11} = (\bar{\chi}\chi)\,G_{\mu\nu}G^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^3}$
$O_{12} = (\bar{\chi}\gamma^5\chi)\,G_{\mu\nu}G^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^3}$
$O_{13} = (\bar{\chi}\chi)\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^3}$
$O_{14} = (\bar{\chi}\gamma^5\chi)\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^3}$
Complex Scalar DM, Vector Boson Exchange	
$O_{15} = (\chi^\dagger\overleftrightarrow{\partial_\mu}\chi)\,(\bar{q}\gamma^\mu q)$	$\frac{C}{\Lambda^2}$
$O_{16} = (\chi^\dagger\overleftrightarrow{\partial_\mu}\chi)\,(\bar{q}\gamma^\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$
Complex Scalar DM, Scalar Vector Boson Exchange	
$O_{17} = (\chi^\dagger\chi)\,(\bar{q}q)$	$\frac{Cm_q}{\Lambda^2}$
$O_{18} = (\chi^\dagger\chi)\,(\bar{q}\gamma^5 q)$	$\frac{iCm_q}{\Lambda^2}$
Complex Scalar DM, Gluonic	
$O_{19} = (\chi^\dagger\chi)\,G_{\mu\nu}G^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^2}$
$O_{20} = (\chi^\dagger\chi)\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^2}$

Relic Density Constraint

Calculation of Annihilation Rates

- Take the first case $\Gamma = \gamma^\mu$. The cross section for $\chi\bar{\chi} \to t\bar{t}$ is

$$\frac{d\sigma}{dz} = \frac{g_\chi^4}{\Lambda^4} \frac{N_C}{16\pi s} \frac{\beta_t}{\beta_\chi} \left[u_m^2 + t_m^2 + 2s(m_\chi^2 + m_t^2)\right]$$

where $t_m = t - m_\chi^2 - m_t^2 = -s(1 - \beta_t \beta_\chi z)/2$, $\beta_{t,\chi} = (1 - 4m_{t,\chi}^2/s)^{1/2}$.

- Integrate over $z = \cos\theta$ and obtain $\sigma v \simeq \sigma(2\beta_\chi)$.

- The σv is constrained by

$$\Omega_\chi h^2 \simeq \frac{0.1 \text{ pb}}{\langle \sigma v \rangle} = 0.1099 \pm 0.0062$$

$$\Rightarrow \langle \sigma v \rangle \simeq 0.91 \text{ pb} .$$

- The calculation is repeated for other $\Gamma = \sigma^{\mu\nu}(\gamma^5),\ \gamma^\mu\gamma^5,\ \gamma^5, 1$:

$$\frac{d\sigma}{dz} = \frac{g_\chi^4}{\Lambda^4}\frac{N_C}{4\pi s}\frac{\beta_t}{\beta_\chi}\left[2\left(t_m^2+u_m^2\right)+2s(m_t^2+m_\chi^2)+8m_t^2m_\chi^2-s^2\right]$$

$$\frac{d\sigma}{dz} = \frac{g_\chi^4}{\Lambda^4}\frac{N_C}{16\pi s}\frac{\beta_t}{\beta_\chi}\left[t_m^2+u_m^2-2s(m_t^2+m_\chi^2)+16m_t^2m_\chi^2\right]$$

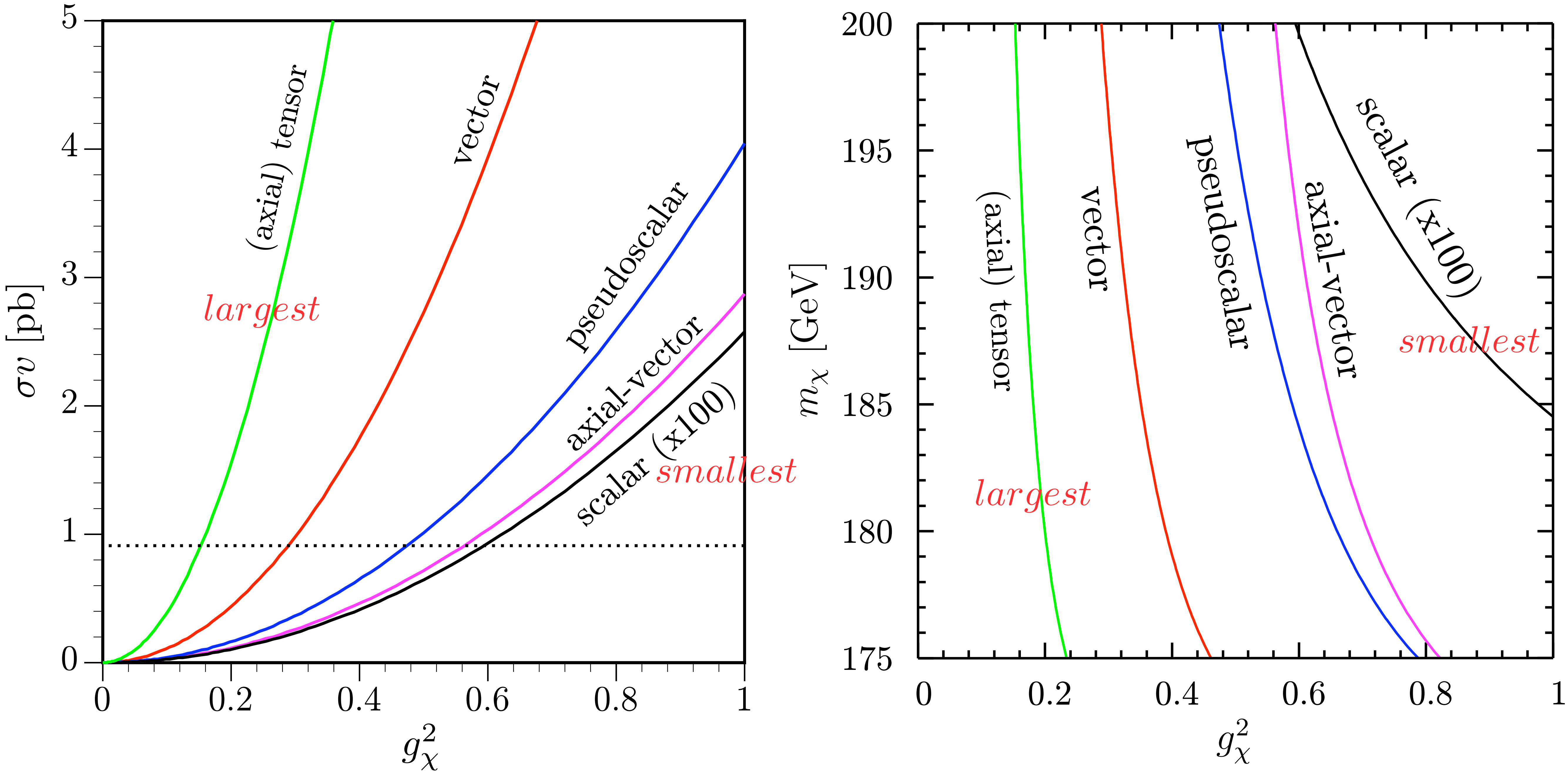
$$\frac{d\sigma}{dz} = \frac{g_\chi^4}{\Lambda^4}\frac{N_C}{32\pi}s\frac{\beta_t}{\beta_\chi}$$

$$\frac{d\sigma}{dz} = \frac{g_\chi^4}{\Lambda^4}\frac{N_C}{32\pi}s\beta_\chi\beta_t^3$$

- The WMAP relic density (if all DM from the thermal source) requires (for $m_\chi = 200$ GeV)

$$\boxed{g_\chi^2 \simeq 0.2 - 0.6}$$

- For larger g_χ^2 the thermal relic density falls below the data. But there could be other nonthermal sources.



$m_\chi = 200$ GeV

Contours of $\sigma v = 0.91$ pb

$g_\chi^2 \approx 0.2 - 0.6$

$v \approx 0.3$ around freeze out

Direct and Indirect Detections Constraints

Kinematics of Direct Detection

- Relative velocity of DM particle $\sim 270\ \mathrm{km\,s^{-1}} \simeq 10^{-3}c$, with a gaussian tail.
- Average kinetic energy of the DM particle $\sim \frac{1}{2}mv^2 \simeq 0.5m$ keV (m in GeV); of order 50 keV for a 100 GeV DM particle.
- Energy transfer to nucleus is therefore the total or part of the k.e., ie., recoil spectrum $\langle E \rangle \sim 50$ keV.

Direct Detection Rate

[Bertone, Hooper, Silk, 0404175]

- SI cross section can arise from scalar-type and vector-type interactions. Suppose the interactions are

$$\mathcal{L} = \sum_{q=u,d,s,c,b,t} \{\alpha_q^S \, \overline{\chi}\chi \, \bar{q}q + \alpha_q^V \, \overline{\chi}\gamma^\mu\chi \, \bar{q}\gamma_\mu q\} \ ,$$

- The SI cross section between the DM and *each nucleon* is

$$\sigma_{\chi N}^{\mathrm{SI}} = \frac{\mu_{\chi N}^2}{\pi} \left(\left| G_s^N \right|^2 + \frac{|b_N|^2}{256} \right) \ ,$$

where

$$G_s^N = \sum_{q=u,d,s,c,b,t} \langle N|\bar{q}q|N\rangle \, \alpha_q^S \ ,$$

and $\langle N|\bar{q}q|N\rangle = f_{Tq}^N (m_N/m_q)$.

- The expression for b_N of a whole nucleus (A, Z) is $b_N \equiv \alpha_u^V (A+Z) + \alpha_d^V (2A - Z)$. We take the average between proton and neutron and assume their numbers are the same. Thus

obtain for a single nucleon

$$b_N = \frac{3}{2} \left(\alpha_u^V + \alpha_d^V \right)$$

- In our case, only α_t^S contributes. Thus

$$G_s^N = \langle N|\bar{t}t|N\rangle \left(\frac{g_\chi^2}{\Lambda^2}\right) = \frac{m_N}{m_t} f_{Tt}^N \left(\frac{g_\chi^2}{\Lambda^2}\right)$$

$$\rightarrow \frac{m_N}{m_t}\left(\frac{2}{27} f_{Tg}^N\right)\left(\frac{g_\chi^2}{\Lambda^2}\right)$$

- The spin independent cross section is

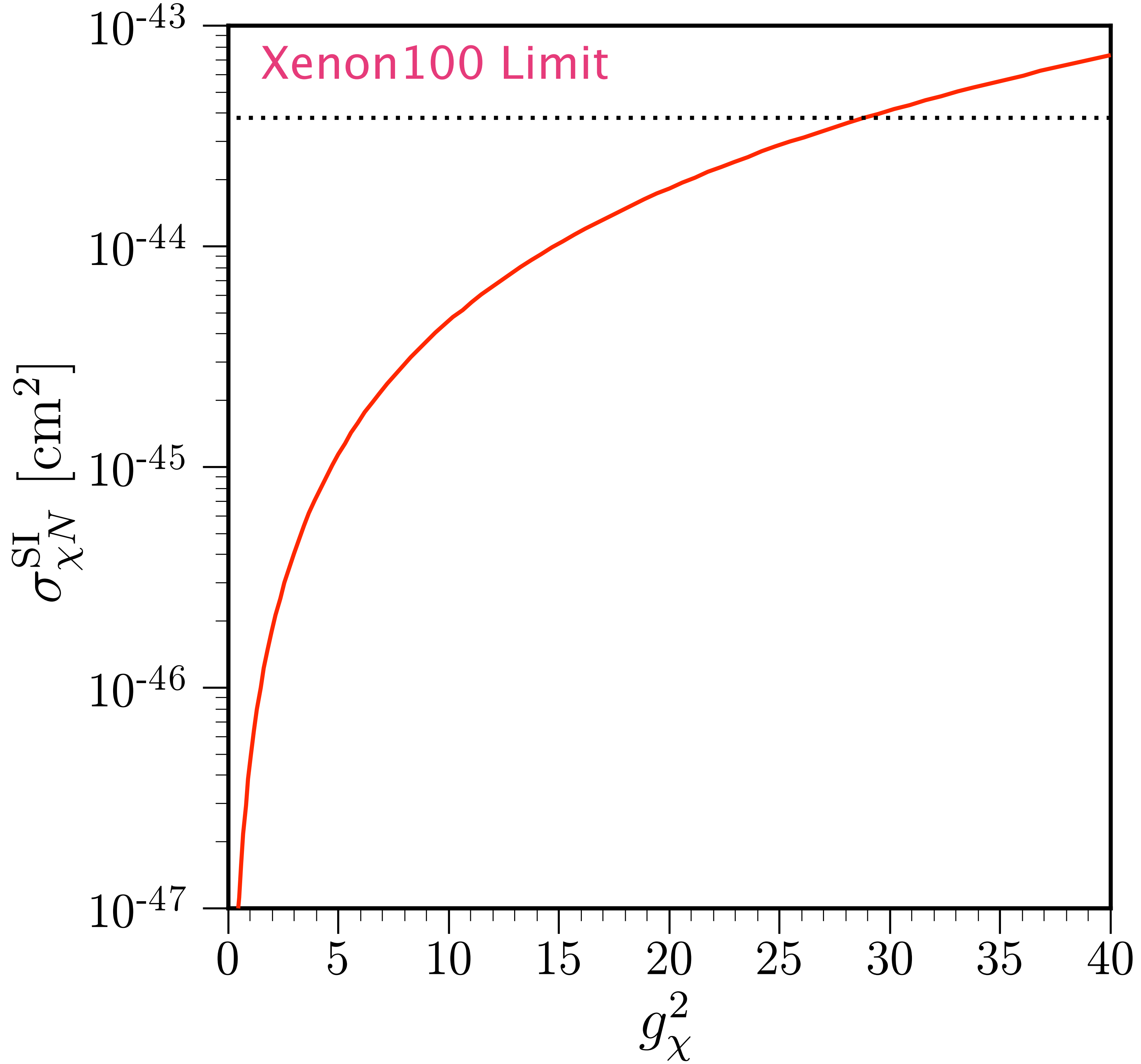
$$\sigma_{\chi N}^{SI} \approx \frac{\mu_{\chi N}^2}{\pi}\left(\frac{g_\chi^2}{\Lambda^2}\right)^2 \left(\frac{m_N}{m_t}\right)^2 \left(\frac{2}{27} f_{Tg}^N\right)^2$$

$$f_{Tt}^N \rightarrow \frac{2}{27} f_{Tg}^N$$

$$f_{Tg}^p = 1 - f_{Tu}^p - f_{Td}^p - f_{Ts}^p \approx 0.84$$

$$f_{Tg}^n = 1 - f_{Tu}^n - f_{Td}^n - f_{Ts}^n \approx 0.83$$

Spin Independent Cross Section



$\sigma_{\chi N}^{SI} < 4.10^{-44}$ cm^2 allows g_χ^2 as large as 30 for $\Lambda = 1$ TeV.

Indirect Detection

Indirect detection of DM can provide better constraints if background can be understood better.

- Gamma rays (line or continuum)
  - Fermi-LAT, ...
- Positron, antiproton, etc
  - PAMELA, AMS02, ...
- Neutrinos
  - ICECUBE, ANTARES, ...

Positron and Antiproton Fluxes

- The Milky Way Halo may contain clumps of dark matter, from where the annihilation of dark matter particles may give rise to large enough signals.
- The positron flux observed at the Earth is given by

$$\Phi_{e^+}(E) = \frac{v_{e^+}}{4\pi} f_{e^+}(E) \; ,$$

The function $f_{e^+}(E)$ satisfies the diffusion equation of

$$\frac{\partial f}{\partial t} - K(E)\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) = Q \; ,$$

where the diffusion coefficient is $K(E) = K_0 (E/\mathrm{GeV})^\delta$ and the energy loss coefficient is $b(E) = E^2/(\mathrm{GeV} \times \tau_E)$ with $\tau_E = 10^{16}$ sec.

- The source term Q due to the annihilation is

$$Q_{\mathrm{ann}} = \eta \left(\frac{\rho_{\mathrm{CDM}}}{M_{\mathrm{CDM}}}\right)^2 \sum \langle \sigma v \rangle_{e^+} \frac{dN_{e^+}}{dE_{e^+}} \; ,$$

where $\eta = 1/2(1/4)$ for identical (nonidentical) DM particle in the initial state.

- The summation includes all possible channels that give rise to e^+ in the final state, e.g., $\chi\bar{\chi} \to W^+W^- \to e^+\nu_e + X$, $\chi\bar{\chi} \to e^+e^-$, $\chi\bar{\chi} \to \tau^+\tau^- \to e^+ + X$.

- The treatment for $\bar{p}$ flux is similar, but with different diffusion coefficients and source terms:

$$Q_{\rm ann} = \eta \left(\frac{\rho_{\rm dm}}{M_{\rm dm}}\right)^2 \sum \langle \sigma v \rangle_{\bar{p}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

- Possible channels for $\bar{p}$ include: $\chi\bar{\chi} \to q\bar{q} \to \bar{p} + X$, $\chi\bar{\chi} \to W^+W^- \to q\bar{q}'q\bar{q}' \to \bar{p} + X$, etc.

- GALPROP is a publicly available code for calculating the propagation of the positron and electron fluxes, and proton and antiproton fluxes.

Positron Fraction In Our Scenario

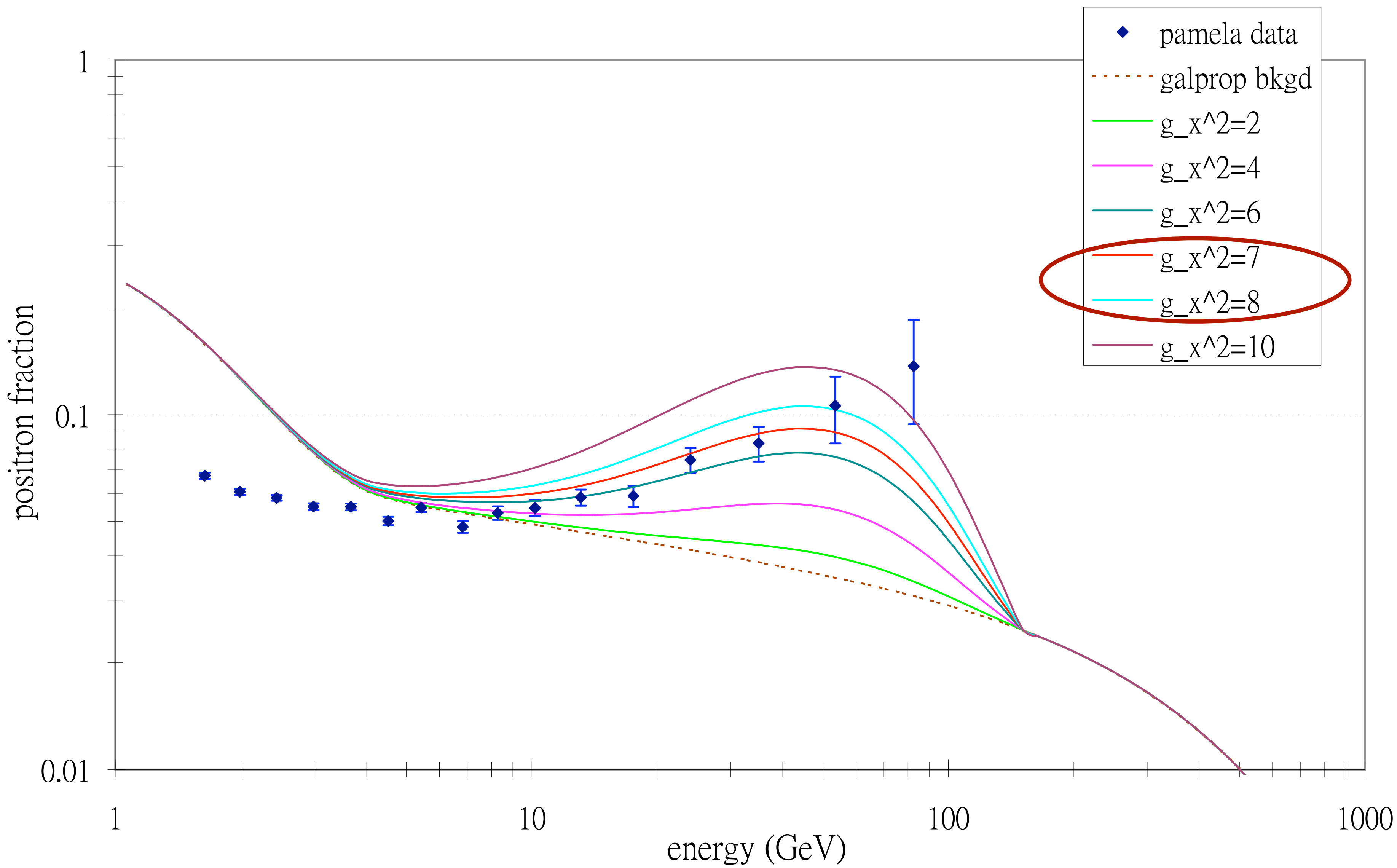
- The most energetic positron comes from

$$\chi\bar{\chi} \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (be^+\nu_e) + X$$

- Calculate the source term

$$Q_{\rm ann} = \frac{1}{4}\left(\frac{\rho_{\rm CDM}}{M_{\rm CDM}}\right)^2 \langle\sigma v\rangle_{\chi\bar{\chi}\to t\bar{t}}\,\frac{dN_{e^+}}{dE_{e^+}}\,,$$

and feed it into GALPROP.



Antiproton Fraction In Our Scenario

[See also Tseng's talk]

- The most important $\bar{p}$ source is

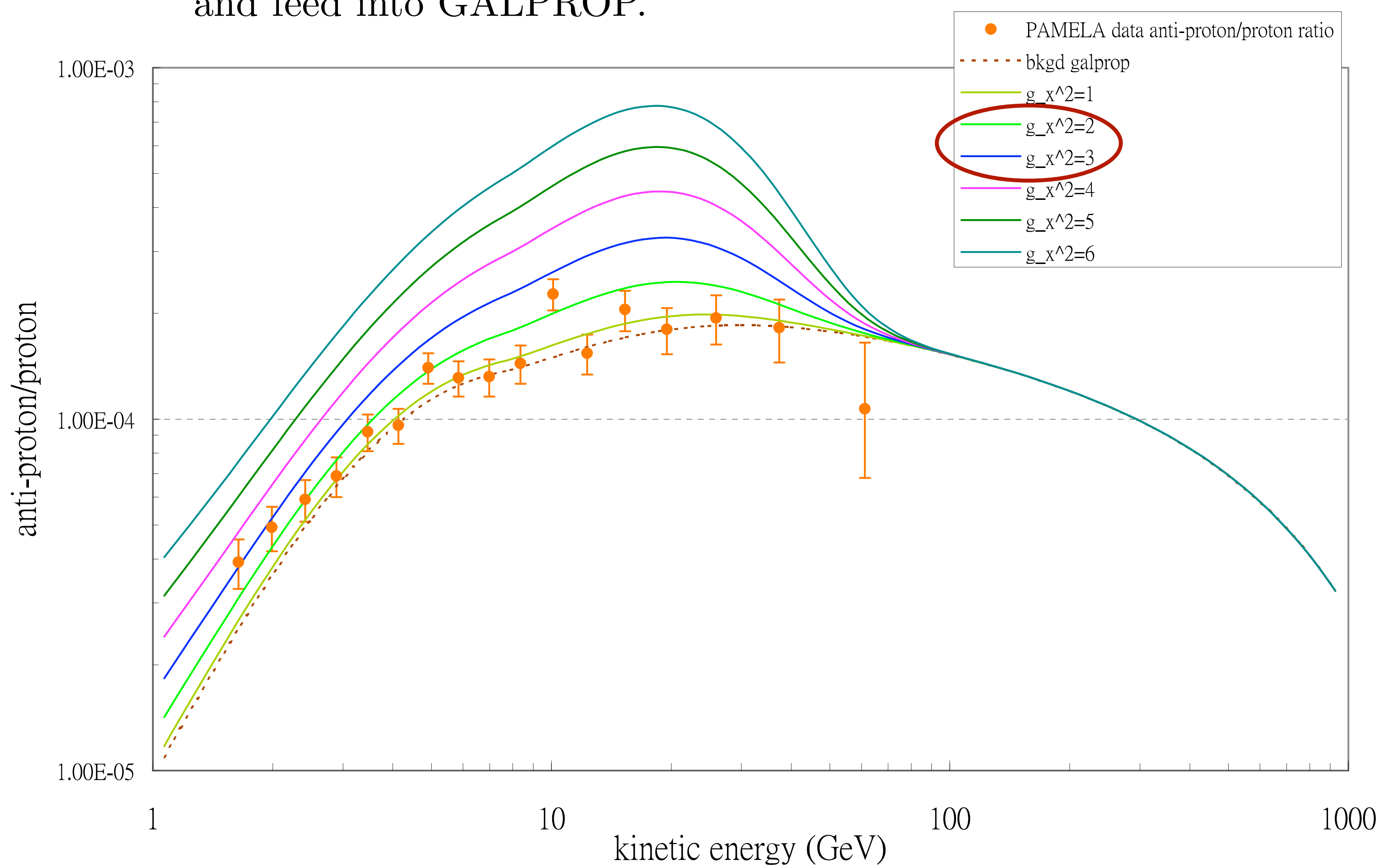
$$\chi\bar{\chi} \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (bq\bar{q}')(\bar{b}q\bar{q}') \to \bar{p} + X$$

in which all the $b\,\bar{b}, q, \bar{q}'$ have probabilities fragmenting into $\bar{p}$.

- Calculate the source term for $\bar{p}$:

$$Q_{\rm ann} = \frac{1}{4}\left(\frac{\rho_{\rm CDM}}{M_{\rm CDM}}\right)^2 \langle\sigma v\rangle_{\chi\bar{\chi}\to t\bar{t}}\,\frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

and feed into GALPROP.



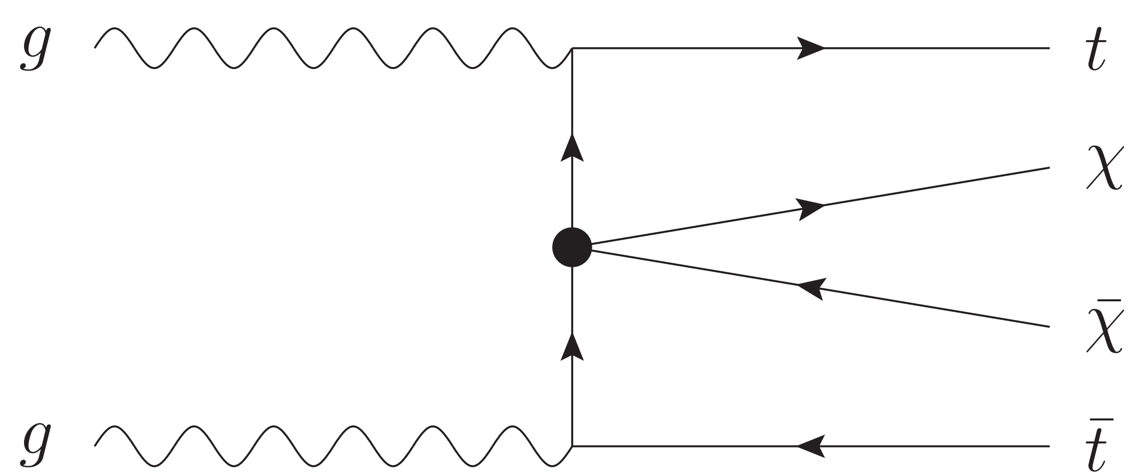
Detection at the LHC

Production of $t\bar{t}\chi\bar{\chi}$ at the LHC

- The dominant $t\bar{t}$ production at the LHC is

$$q\bar{q} \to t\bar{t} \,, \qquad\qquad gg \to t\bar{t}$$

we can attach the 4-fermion vertex to anyone of the t legs.



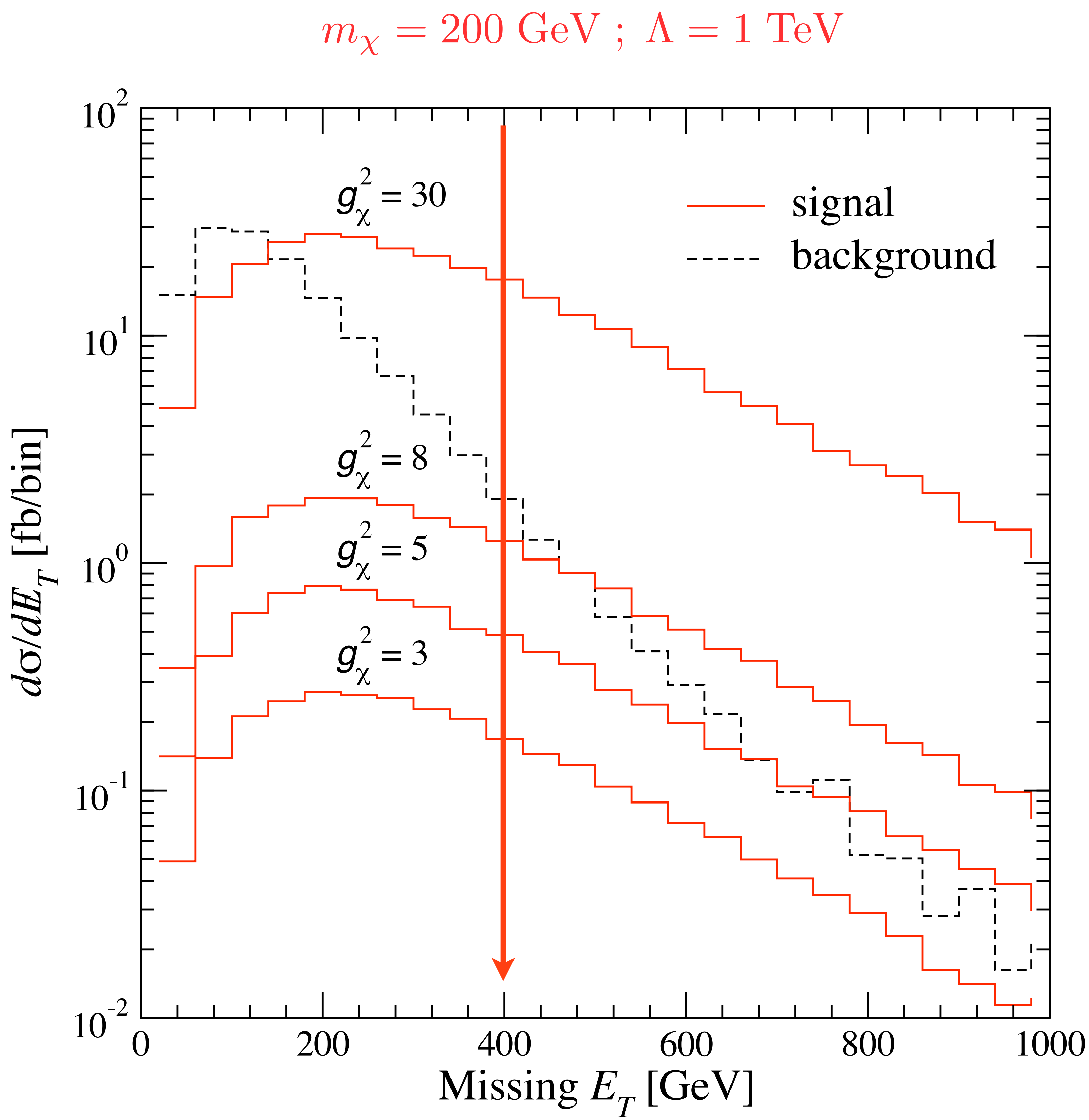
- Irreducible background comes from

$$pp \to t\bar{t} + Z \to t\bar{t}\nu\bar{\nu}$$

- We use MADGRAPH to calculate the signal and background.

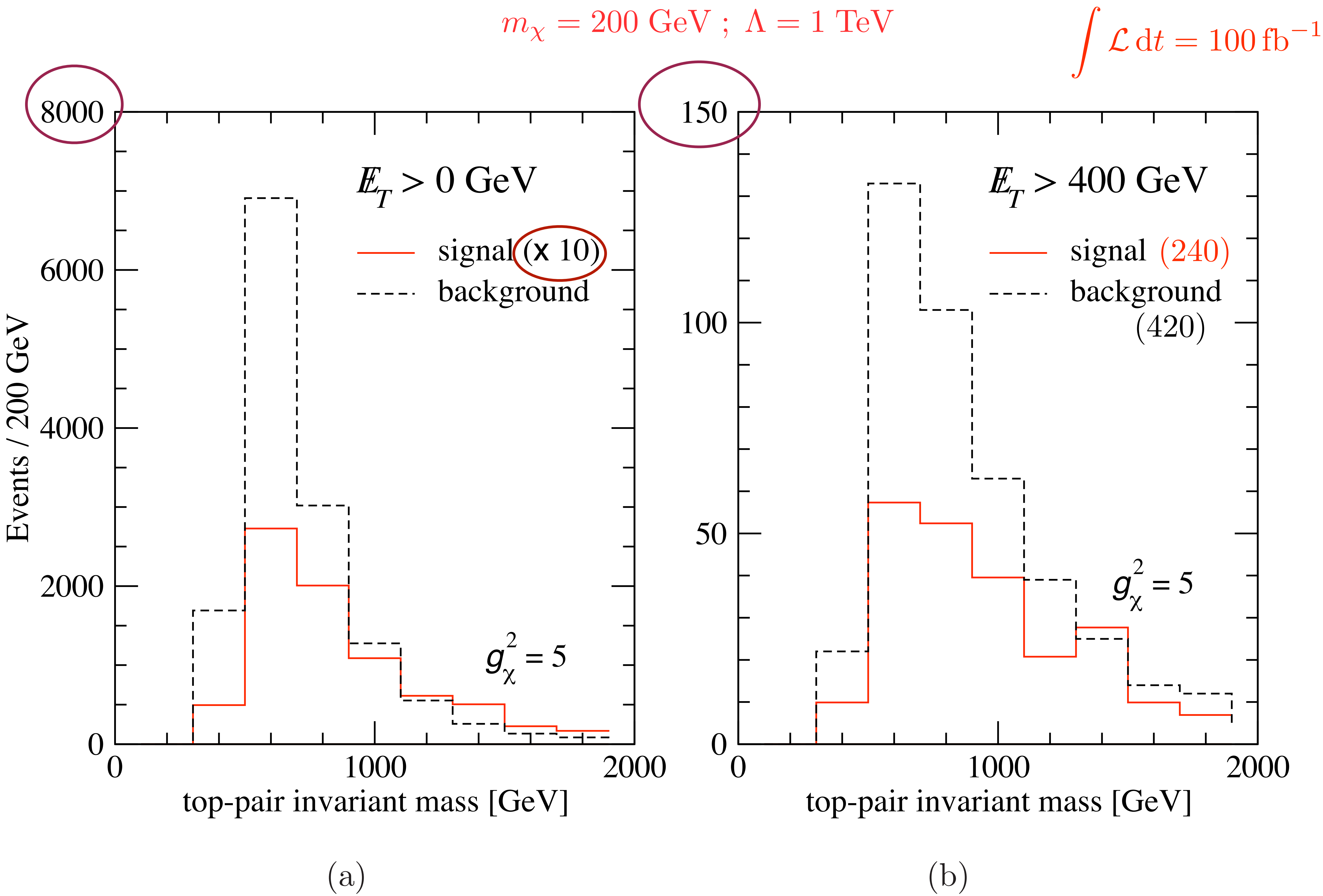
- We expect a large $\not{p}_T$ in the signal

Missing Transverse Energy Distribution



A $\not{p}_T > 400$ GeV cut can suppress the background.

Event Numbers versus Invariant Mass



Cross Sections (fb)

$m_\chi = 200$ GeV ; $\Lambda = 1$ TeV

TABLE I. Cross sections in fb for the signal $pp \to t\bar{t} + \chi\bar{\chi}$ and the background $pp \to t\bar{t}Z \to t\bar{t} + \nu\bar{\nu}$ at the LHC. We used $g_\chi^2 = 5$ for illustration. The signal cross section scales as g_χ^4. The significance $S/\sqrt{B}$ is calculated with an integrated luminosity of 100 (30) fb^{-1}.

$\not{E}_T >$	$pp \to t\bar{t} + \chi\bar{\chi}$	$p \to t\bar{t}Z \to t\bar{t}\nu\bar{\nu}$	S/B	$S/\sqrt{B}$ (100 (30) fb^{-1})
0 GeV	8.2	140.3	0.06	6.9 (3.8)
300 GeV	3.6	10.7	0.34	11.0 (6.0)
400 GeV	2.4	4.2	0.57	11.8 (6.4)
500 GeV	1.5	1.9	0.78	10.6 (5.9)

Cross Sections

$m_\chi = 200$ GeV ; $\Lambda = 1$ TeV

TABLE II. Cross sections in fb for the signal $pp \to t\bar{t} + \chi\bar{\chi}$ for vector, axial-vector, pseudoscalar, and scalar interactions at the LHC. We have imposed the $\not{E}_T > 400$ GeV cut. The S/B and $S/\sqrt{B}$ are shown. The background is from Table I. The significance $S/\sqrt{B}$ is calculated with an integrated luminosity of 100 (30) fb^{-1}.

	Signal cross section (fb)	S/B	$S/\sqrt{B}$
Vector	2.4	0.57	11.8 (6.4)
Axial-vector	1.9	0.45	9.3 (5.1)
Pseudoscalar	0.82	0.20	4.0 (2.2)
Scalar	0.55 Not severely suppressed here!	0.13	2.7 (1.5)

(1) Note that the relic density from the scalar interaction might be too large and over-close the universe!
(2) Tensor not available yet in MADGRAPH!

Summary

- Effective interactions between DM and top quark are studied

- Relic density requires $g_\chi^2 \sim 0.2 - 0.6$. Larger g_χ^2 requires non-thermal sources

- Direct detection gives only loose constraint like $g_\chi^2 \leq 30$

- Indirect antiproton flux from PAMELA gives the most stringent constraints $g_\chi^2 \leq 4 - 6$

- LHC signals: $t\bar{t}$ plus large missing energy are interesting; $p_T|_{\rm cut} > 400$ GeV can reduce background significantly

- With $g_\chi^2 = 5$, $S/\sqrt{B} \sim 6$ can be achieved with 30 fb^{-1} of data
  ($m_\chi = 200$ GeV ; $\Lambda = 1$ TeV)

Happy Year of the Rabbit!

Thank You!