Effective Models for Dark Matter at the International Linear Collider

Daniel Schmeier

In collaboration with

H. Dreiner, M. Huck, M. Krämer & J. Tattersall

arXiv:1211.2254

arXiv:1308.4409

Helmholtz-Alliance Linear Collider Forum

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universitätbonn bcgs bctp Bethe Center for Theoretical Physics

Contents

Modern Evidence for Dark Matter

Cosmological Principle

- Cosmic Background Radiation is in agreement with a homogenous, isotropic and flat universe
- Einstein's theory of relativity connects curvature with energy density
- If curvature is close to 0, ρ is well known:

Energy Density in the Universe Today

$$\Omega_0 := \rho_0/\rho_c = \frac{8\pi G_N}{3H_0^2}\rho \overset{!}{=} 1$$

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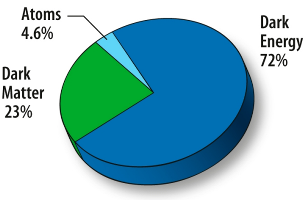


NASA / WMAP Science Team

Energy Density in the Universe Today

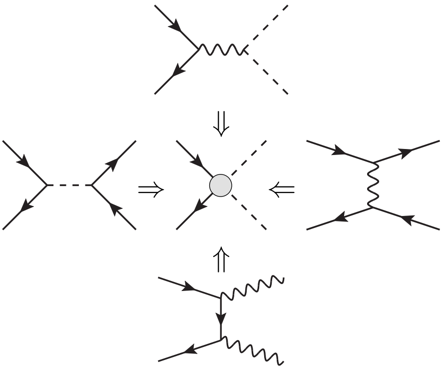
$$\Omega_0 := \rho_0/\rho_c = \frac{8\pi G_N}{3H_0^2}\rho \overset{!}{=} 1$$

- WMAP:
  $\Omega_B \approx 0.05,\ \ \boldsymbol{\Omega_{DM} \approx 0.23},\ \ \Omega_\Lambda \approx 0.72$

Dark Matter

- Conditions: Massive, long lived, weak interaction with SM
- Idea: WIMPs (Weakly Interacting Massive Particles)

Motivation for the Effective Approach



Why Effective WIMP–Theories?

- Small amount of parameters (in our case: WIMP mass and coupling)
- Easy to compare different experimental limits in parameter space

Effective WIMP–Theories

Some Previous Work

- Search for Monojets at Tevatron

Bai, Fox, Harnik arXiv:1005.3797

- LEP Analysis with Monophotons

Fox, Harnik, Kopp, Tsai; arXiv:1103.0240

- LHC Analyses with Monophotons/Monojets

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu; arXiv:1008.1783,
CMS Collaboration; arXiv:1206.5663,
ATLAS Collaboration; ATLAS-CONF-2012-084

- ILC monophotons in nonrelativistic approximation

Birkedal, Matchev, Perelstein; arXiv:hep-ph/0403004
Bartels, Berggren, List; arXiv:1206.6639

Our Work

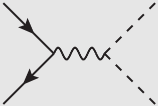
- Extensive list of possible effective, relativistic operators
- ILC monophoton analysis of these, including detector–effects

Effective Approach

Idea

- DM interacts pairwise with SM fermions by a single mediating particle
- For very heavy mediators, we receive one effective coupling G_{eff}

Example: Scalar DM, Vector Mediator ("SV")



$$-\mathcal{L}_{\text{UV}} = g_\psi \bar{\psi}\gamma^\mu \psi Z_\mu + g_\chi Z_\mu \chi^\dagger \overleftrightarrow{\partial}_\mu \chi + \frac{1}{2} M_\Omega^2 Z^\mu Z_\mu$$

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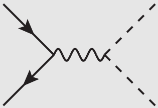

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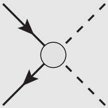
$$\overset{s \ll M_\Omega^2}{\Longrightarrow} -\mathcal{L}_{\text{eff}} = \frac{g_\chi g_\psi}{M_\Omega^2} \chi^\dagger \overleftrightarrow{\partial_\mu} \chi \bar{\psi}\gamma^\mu \psi$$



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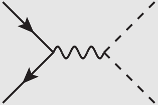

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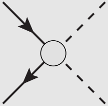
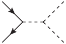
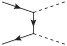
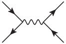
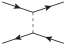
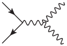
$$\overset{s \ll M_\Omega^2}{\Longrightarrow} -\mathcal{L}_{\text{eff}} = G_{\text{eff}} \chi^\dagger \overleftrightarrow{\partial_\mu} \chi \bar{\psi}\gamma^\mu\psi$$



Further Examples (+ many more)

Model	Diagram	$-\mathcal{L}_{\text{eff}}$
SS Scalar		$G_{\text{eff}}\chi^\dagger\chi\bar\psi\psi$
SF Pseudosc.		$G_{\text{eff}}\left[-\bar\psi\psi\chi^\dagger\chi + \frac{1}{M_\Omega}\chi^\dagger\bar\psi\gamma^\mu\partial_\mu\left(\psi\chi\right)\right]$
FV Chiral		$G_{\text{eff}}\bar\psi\gamma^\mu P_L\psi\ \bar\chi\gamma_\mu P_L\chi$
FtV Vector		$G_{\text{eff}}\bar\psi\gamma^\mu\chi\bar\chi\gamma_\mu\psi$
VV Axialv.		$iG_{\text{eff}}\bar\psi\gamma^\mu\gamma^5\psi\left[\chi^\nu\partial\chi^\dagger_{\mu\nu} - \chi^{\dagger,\nu}\partial\chi_{\mu\nu} + \partial^\nu\left(\chi^\dagger_\nu\chi_\mu - \chi^\dagger_\mu\chi_\nu\right)\right]$

We distinguish between models with ...

- different spins (0, 1/2, 1) for DM and mediator
- (pseudo)scalar, (axial)vector or chiral couplings in s– or t–channel
- complex or real DM

Further Examples (+ many more)

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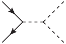
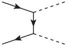
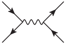
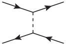
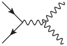
SS Scalar		$G_{\text{eff}}\chi^\dagger\chi\bar\psi\psi$
SF Pseudosc.		$G_{\text{eff}}\left[-\bar\psi\psi\chi^\dagger\chi + \frac{1}{M_\Omega}\chi^\dagger\bar\psi\gamma^\mu\partial_\mu\left(\psi\chi\right)\right]$
FV Chiral		$G_{\text{eff}}\bar\psi\gamma^\mu P_L\psi\ \bar\chi\gamma_\mu P_L\chi$
FtV Vector		$G_{\text{eff}}\bar\psi\gamma^\mu\chi\bar\chi\gamma_\mu\psi$
VV Axialv.		$iG_{\text{eff}}\bar\psi\gamma^\mu\gamma^5\psi\left[\chi^\nu\partial\chi^\dagger_{\mu\nu} - \chi^{\dagger,\nu}\partial\chi_{\mu\nu} + \partial^\nu\left(\chi^\dagger_\nu\chi_\mu - \chi^\dagger_\mu\chi_\nu\right)\right]$

We distinguish between models with ...

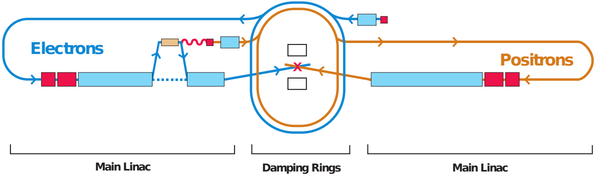
- different spins (0, 1/2, 1) for DM and mediator
- (pseudo)scalar, (axial)vector or chiral couplings in s– or t–channel
- complex or real DM

- universal or Yukawa–like coupling
- coupling to all SM fermions or to leptons only

Exclusion limits at the ILC

General

- ILC = International Linear Collider
- Accelerates polarised electrons/positrons to $\sqrt{s} = 500\text{GeV}/1\text{TeV}$
- Pair production can be analysed through $e^+e^- \to \chi\chi\gamma$



ILC Reference Design Report

Advantages of the ILC

- Up to 5 times more energy compared to LEP
- No QCD uncertainties involved (as for the LHC)
- Polarisation improves the S/B ratio

Analysis

Detector effects based on ILD simulation study by C. Bartels, J. List und M. Berggren: arXiv:1206.6639v1 [hep-ex]

Background Processes

- $\nu\bar{\nu}\gamma(\gamma)$: Mainly left–chiral due to W–exchange
- $e^+e^-\gamma$: No polarisation dependence. Small efficiency (two undetected leptons) but high cross section (purely QED)

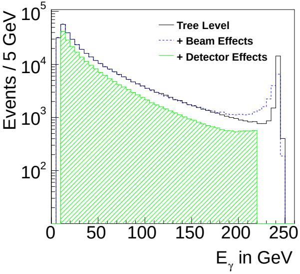
Simulation of Signal and $\nu\bar{\nu}\gamma(\gamma)$

- CalcHEP with ISR + Beamstrahlung for $M_\chi \in [1\text{GeV}, 490\text{GeV}]$
- ΔE and ϵ based on ILC Letter of Intent and 1206.6639

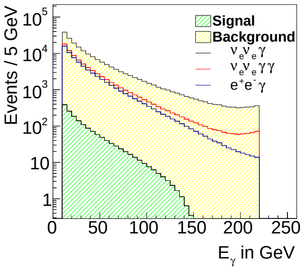
$e^+e^-\gamma$–background

- Detector Effects crucial $\rightarrow$ Results from 1206.6639

Distributions for $\mathcal{L} = 50\text{fb}^{-1}$, $P^{\pm} = 0$



Simulated neutrino background with beam– and detector effects



Photon energy distribution for signal(FS, $M_\chi = 150\text{GeV}$) and background after selection

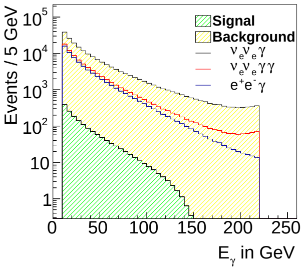
Events normalised to 50 fb^{-1} ($\times$1000)

P^-/P^+	$\nu\nu\gamma$	$\nu\nu\gamma\gamma$	e^+e^-
$0/0$	113	11	61
$+0.8/-0.3$	25	3	61
$-0.8/+0.3$	255	26	61

Distributions for $\mathcal{L} = 50\text{fb}^{-1}$, $P^{\pm} = 0$

What does this tell us?

- Polarization can remove neutrinos but not Bhabha.
- Bhabha extremely hard to simulate, photon distribution not reliably known
  $\rightarrow$ Our analysis is based on event counts, not on event shape!



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Analysis — 4

Model Test

G_{eff} is allowed if the corresponding signal number S is smaller than the expected background uncertainty ΔB

Systematic Uncertainties

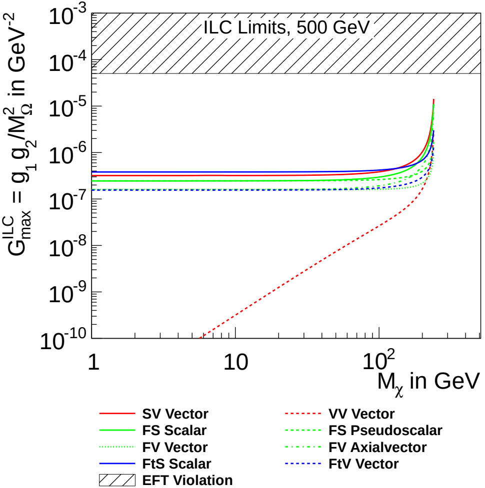
- Efficiency for signal depends on the a priori unknown model: $\Delta\epsilon = 2\%$
- Experimental fluctuation in polarisation: $\Delta P/P = 0.025$ (0.01)
- Other sources (luminosity, ...) negligible

Analysed Parameter Settings

integrated luminosity:	50 fb^{-1}, 500 fb^{-1}
center of mass energy:	500 GeV, 1000 GeV
inaccuracy in polarisation:	$\Delta P/P = 0.025$ and 0.01
lepton polarisation:	$P^- = \pm 0.8, \quad P^+ = \pm(0.3, 0.6)$

ILC Results

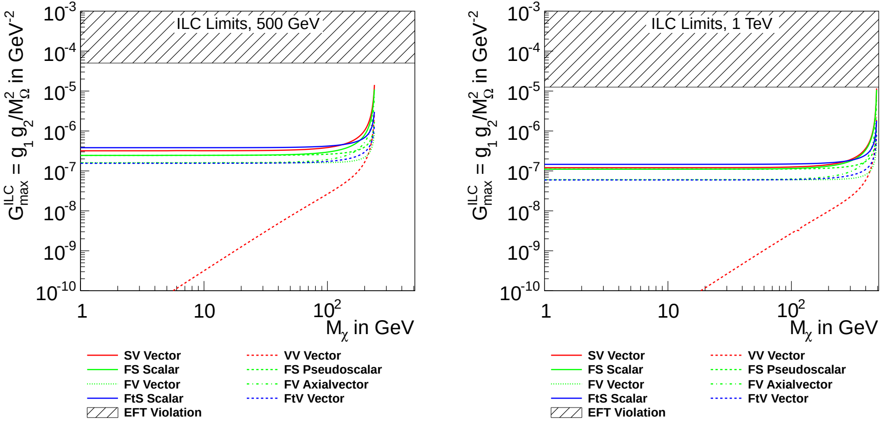
- We show results for $\mathcal{L} = 500\text{fb}^{-1}$, $\sqrt{s} = 500\text{GeV}$, $\Delta P/P = 0.01$
- Polarisation with largest $S/\Delta B$ ($P^+ = \pm 0.3$ can be better than 0.6)



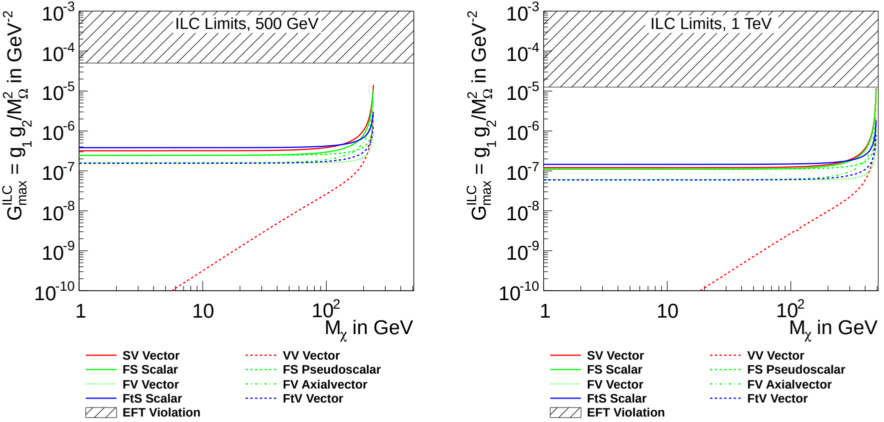
Remarks

- Exclusion limits are given to 90% CL
- $G = 10^{-7}\text{GeV}^{-2}$ corresponds to about $\sigma = 0.3$ fb
- Models with vector WIMPs have theoretical problems ($\sigma \propto s/M_\chi^4$)

ILC Results


ILC Limits, 500 GeV
ILC Limits, 1 TeV
$G^{ILC}_{max} = g_1 g_2 / M^2_\Omega$ in GeV^{-2}
M_χ in GeV
SV Vector
FS Scalar
FV Vector
FtS Scalar
EFT Violation
VV Vector
FS Pseudoscalar
FV Axialvector
FtV Vector

ILC Results



How can these numbers compete with other experiments?

Comparing Experimental Sensitivities

Xenon / Lux

- Wait until a Wimp bumps into an atom, whose recoil is measured
- $\rightarrow$ No excess translates into a limit on $\sigma^{\mathsf{max}}(\chi p \rightarrow \chi p)$

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Ilc

- From $G_{\text{eff}}^{\text{max}}$ one can calculate $\sigma^{\text{max}}(\chi p \rightarrow \chi p)$ (easy task with effective operators)

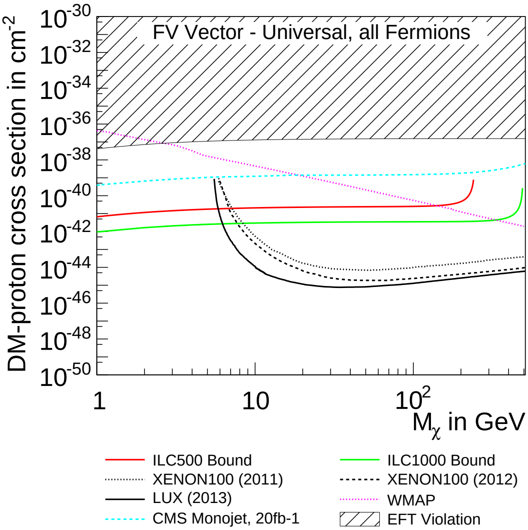
Lhc

- Search for events with single jets at CMS puts limits on $G_{\text{eff}}^{\text{max}}$ in similar manner

Wmap

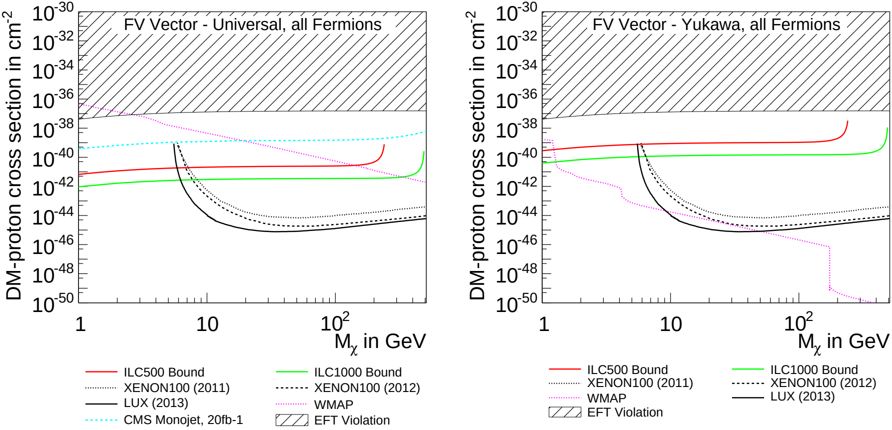
- Show $\sigma^{\text{min}}(\chi p \rightarrow \chi p)$ that corresponds to minimum coupling which gives not too much dark matter today

Results — Spin Independent



- ILC good for low GeV WIMPs

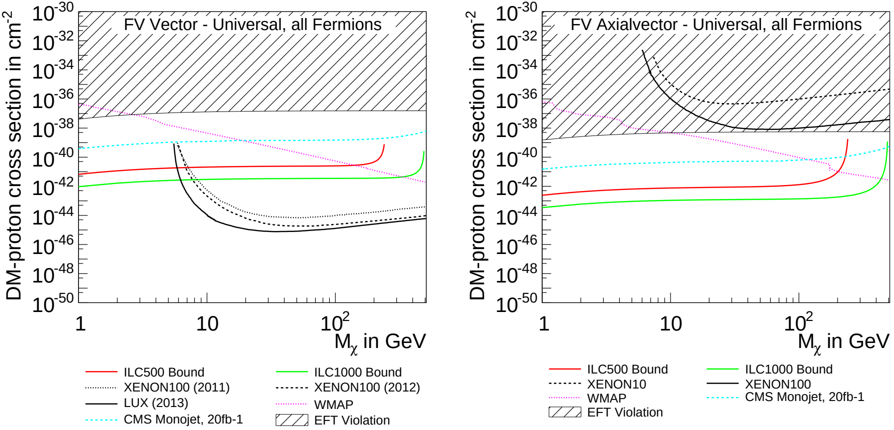
Results — Universal vs. Yukawa



Remarks

- ILC bounds become weaker since $m_{\text{electron}} < m_{\text{quark}}$
- Better agreement with WIMP relic density

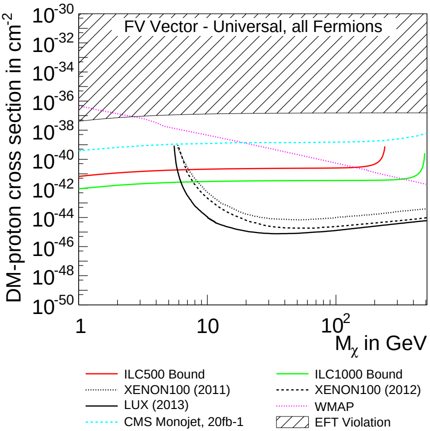
Results — Spin Independent/Dependent

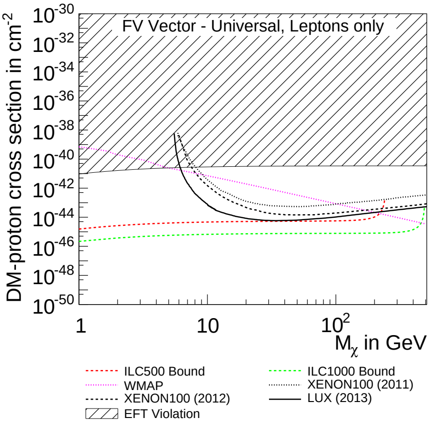


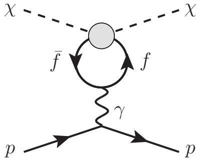
Remarks

- If interaction depends on spin, one scatters with one nucleon only
- SD: ILC gives strongest limits over whole accesible M_χ range

Results — Fermions vs. Leptons only







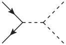
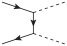
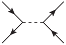
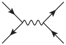
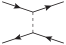
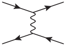
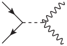
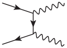
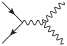
Remarks

- WIMP couplings are loop suppressed
- ILC limits are strongly enhanced

Summary

- Effective models describe SM–interactions with only two parameters: M_χ and G_eff
- Colliders and direct detection experiments give upper limit on $G_\text{eff}(M_\chi)$
- ILC can look for pair produced WIMPs in monophoton events
- Polarisation can help reducing the background.
- LHC limits can be improved by orders of magnitude
- Stronger limits than direct detection experiments can generally be expected for $M_\chi < 8\text{GeV}$
- For SD interactions or hadrophobic models, ILC is strong also for $M_\chi > 8\text{GeV}$

Full List of Models

DM	Med.	Diagram	$-\mathcal{L}_{\text{eff}}$
S	S		$\frac{g_\chi}{M_\Omega^2}\chi^\dagger\chi\bar{\psi}(g_s+ig_a\gamma^5)\psi$
S	F		$\frac{1}{M_\Omega^2}\left[M_\Omega(g_s^2-g_a^2)\bar{\psi}\psi\chi^\dagger\chi+\chi^\dagger\bar{\psi}\left(g_s^2+g_a^2-2g_sg_a\gamma^5\right)\gamma^\mu\partial_\mu\left(\psi\chi\right)\right]$
S	V		$\frac{g_\chi}{M_\Omega^2}\bar{\psi}\gamma^\mu\left(g_LP_L+g_RP_R\right)\psi\left(\phi^\dagger\partial_\mu\phi-\phi\partial_\mu\phi^\dagger\right)$
F	S		$\frac{1}{M_\Omega^2}\bar{\chi}\left(g_s+ig_a\gamma^5\right)\chi\bar{\psi}\left(g_s+ig_a\gamma^5\right)\psi$
F	V		$\frac{1}{M_\Omega^2}\bar{\psi}\gamma^\mu\left(g_LP_L+g_RP_R\right)\psi\;\bar{\chi}\gamma_\mu\left(g_LP_L+g_RP_R\right)\chi$
F	tS		$\frac{1}{M_\Omega^2}\bar{\psi}\left(g_s-g_a\gamma^5\right)\chi\bar{\chi}\left(g_s+g_a\gamma^5\right)\psi$
F	tV		$\frac{1}{M_\Omega^2}\bar{\psi}\gamma^\mu\left(g_LP_L+g_RP_R\right)\chi\bar{\chi}\gamma_\mu\left(g_LP_L+g_RP_R\right)\psi$
V	S		$-\frac{g_\chi}{M_\Omega^2}\chi^\mu\chi_\mu\bar{\psi}\left(g_s+ig_a\gamma^5\right)\psi$
V	F		$\frac{1}{M_\Omega^2}\left[M_\Omega g_Lg_R\bar{\psi}\gamma^\nu\gamma^\rho\psi\;\chi_\nu^\dagger\chi_\rho+i\chi_\nu^\dagger\bar{\psi}\gamma^\nu\gamma^\mu\gamma^\rho\left(g_L^2P_L+g_R^2P_R\right)\partial_\mu\left(\psi\chi_\rho\right)\right]$
V	V		$\frac{ig_\chi}{M_\Omega^2}\bar{\psi}\gamma^\mu\left(g_LP_L+g_RP_R\right)\psi\left[\chi^\nu\partial\chi_{\mu\nu}^\dagger-\chi^{\dagger,\nu}\partial\chi_{\mu\nu}+\partial^\nu\left(\chi_\nu^\dagger\chi_\mu-\chi_\mu^\dagger\chi_\nu\right)\right]$

Quantitative Prediction of Ω_0^{DM}

Definitions

$$x_F \equiv M_\chi / T_F , \qquad \sigma_{ann} \approx a(G_{eff})/v + b(G_{eff}) + \mathcal{O}(v)$$

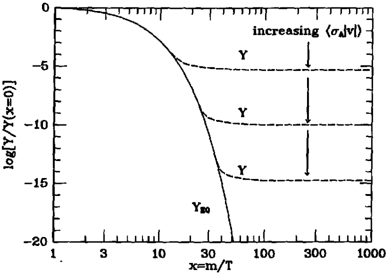
$$g_* \approx \sum \text{rel. bosonic d.o.f.} + \frac{7}{8} \sum \text{rel. fermionic d.o.f.}$$

Freeze–Out Temperature

$$x_F \approx \ln \left[0.0478 \, \frac{m_{Pl} M_\chi (a + 6b/x_f)}{\sqrt{x_f}\sqrt{g_*}} \right]$$

Relic Density

$$\Omega_0 \approx \frac{2e9 \text{GeV}^{-1} \cdot x_f}{m_{Pl}\sqrt{g*}(a + 3b/x_f)}$$



Kolb, Turner

Measurement of $\Omega_{DM} \approx 0.23$ gives lower bound on G_{eff}