

# GOLDSTONE FERMION DARK MATTER

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# The WIMP Miracle

Contains factors of  $M_{\text{Pl}}, s_0, \dots$

$$\Omega_{\text{DM}} h^2 \approx 0.1 \left( \frac{x_f}{20} \right) \left( \frac{g_*}{80} \right)^{-\frac{1}{2}} \left( \frac{\langle \sigma v \rangle_0}{3 \times 10^{-26} \text{ cm}^3/\text{s}} \right)$$

$$\sim \left\langle \frac{\alpha^2 v}{(100 \text{ GeV})^2} \right\rangle$$

Within orders of magnitude!

# $\Omega h^2$ vs direct detection

Tension between annihilation cross section and direct detection bounds

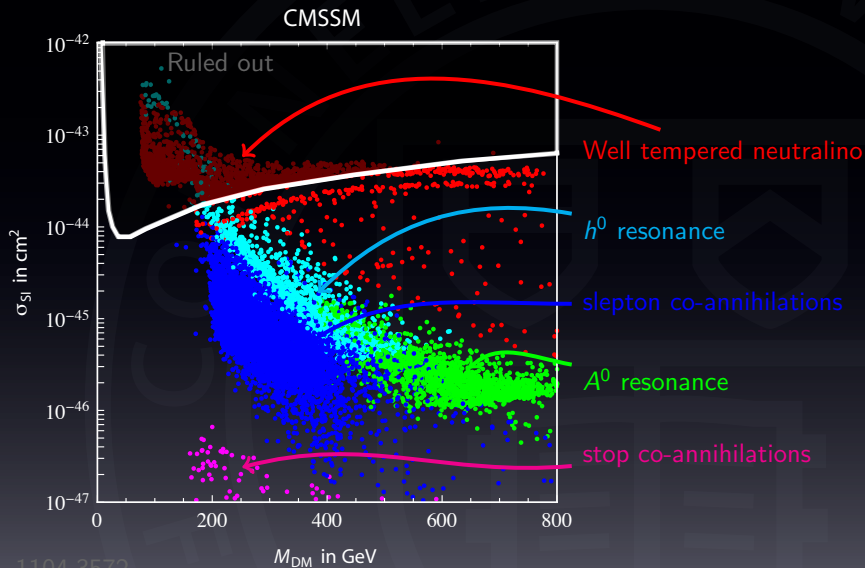
$$\sigma_{\text{ann.}} \sim 0.1 \text{ pb}$$

$$\sigma_{\text{SI}} \sim 7.0 \times 10^{-9} \text{ pb}$$

50 GeV WIMP

Typical strategy: pick parameters such that  $\sigma_{\text{SI}}$  is **suppressed**, then use tricks to **enhance**  $\sigma_{\text{ann.}}$ .

# $\Omega h^2$ vs direct detection



1104.3572

# Motivation I: a natural WIMP

Typical MSSM WIMP:  $\sigma_{SI}$  **too large**

Want to naturally suppress direct detection while maintaining 'miracle' of successful abundance.

If LSP is part of a **Goldstone multiplet**,  $(s + ia, \chi)$ , additional suppression from derivative coupling.

- Like a weak scale axino, but unrelated to CP
- Like singlino DM, but global symmetry broken in SUSY limit

# Motivation I: a natural WIMP

**Annihilation:**  $p$ -wave decay to Goldstones

$$\frac{1}{f} \bar{\chi} \gamma^\mu \gamma^5 \chi \partial_\mu a \quad \Rightarrow \quad \langle \sigma v \rangle \approx \left( \frac{m_\chi}{f^2} \right)^2 \left( \frac{T_f}{m_\chi} \right) \approx 1 \text{ pb}$$

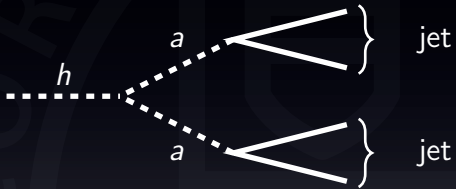
**Direct detection:** CP-even Goldstone mixing with Higgs

$$\frac{m_\chi v}{f^2} \sim 0.01 \quad \Rightarrow \quad \sigma_{\text{SI}} = \left( \frac{m_\chi v}{f^2} \right)^2 \sigma_{\text{SI}}^{\text{MSSM}} \approx \mathcal{O}(10^{-45} \text{ cm}^2)$$

# Motivation II: Buried Higgs

**Idea:** Light Higgs buried in QCD background

Global symmetry at  $f \sim 500$  GeV with coupling  $\frac{1}{f^2} h^2 (\partial a)^2$



0906.3026, 1012.1316, 1012.1347

Can we **bury** the Higgs through  $a$  decays,  
but **dig up** dark matter in  $\chi$ ?



# The Goldstone Supermultiplet

sGoldstone

Goldstone boson

Goldstone fermion

$$A = \frac{1}{\sqrt{2}} (s + i a) + \sqrt{2}\theta \chi + \theta^2 F$$

Carries the low-energy degrees of freedom of the UV fields,

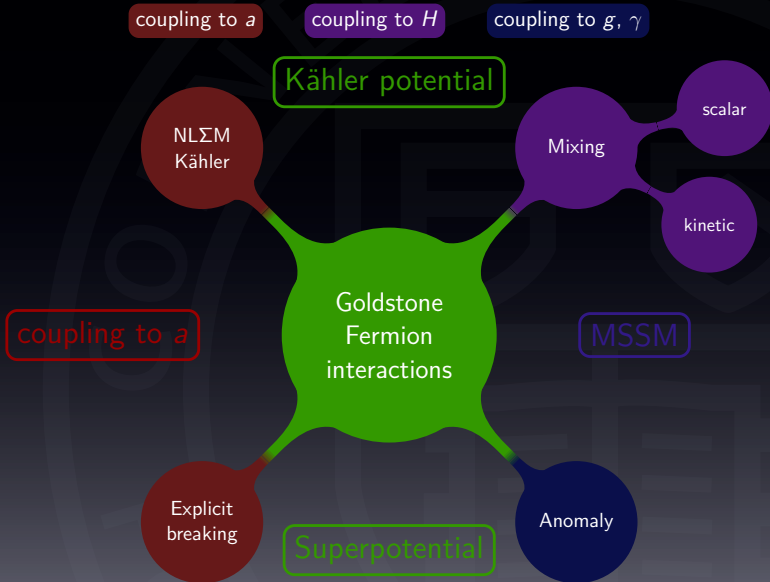
$$\Phi_i = f_i e^{q_i A/f}$$

$$f^2 = \sum_i q_i^2 f_i^2$$

$SUSY \Rightarrow$  explicit  $s$  mass,  $m_\chi \approx q_i \langle F_i \rangle / f$ ,  $a$  massless



# Interactions: Overview



# Interactions: $NL\Sigma M$ Kähler potential

Non-linear realization of the global  $U(1)$

$\Rightarrow$  Kähler interactions of the Goldstone multiplet:

$$\frac{\partial^2 K}{\partial A \partial A^\dagger} = 1 + b_1 \frac{q}{f} (A + A^\dagger) + \dots \quad b_1 = \frac{1}{qf^2} \sum_i q_i^3 f_i^2$$

Note  $K = K(s)$ , manifest shift-invariance.

$$\mathcal{L} = \left( 1 + b_1 \frac{\sqrt{2}}{f} s + \dots \right) \left( \frac{1}{2} (\partial s)^2 + \frac{1}{2} (\partial a)^2 + \frac{i}{2} \bar{\chi} \gamma^\mu \partial_\mu \chi \right) + \frac{1}{2\sqrt{2}} \left( b_1 \frac{1}{f} + b_2 \frac{\sqrt{2}}{f^2} s + \dots \right) (\bar{\chi} \gamma^\mu \gamma^5 \chi) \partial_\mu a + \dots$$

Phys. Lett. B 87 (1979) 203

$b_1$  controls the annihilation cross section.

# Interactions: scalar mixing

MSSM fields are uncharged under the global U(1), but may mix with the Goldstone multiplet through higher-order terms in  $K$ :

$$K = \frac{1}{f} (A + A^\dagger) (c_1 H_u H_d + \dots) + \frac{1}{2f^2} (A + A^\dagger)^2 (c_2 H_u H_d + \dots)$$

The new scalar interactions take the form

$$\mathcal{L} \supset \left[ \frac{1}{2} (\partial a)^2 + \frac{1}{2} \bar{\chi} \not{\partial} \chi \right] \left( 1 + c_h \frac{v}{f} h + \dots \right)$$

$c_h$  depends on  $c_i$  and the Higgs mixing angles.

$c_h$  controls direct detection

# Interactions: kinetic mixing

The higher order terms in  $K$  also induce kinetic  $\tilde{H}-\chi$  mixing.

$$\mathcal{L} \supset i\epsilon_u \bar{\chi} \gamma^\mu \partial_\mu \tilde{H}_u^0 + i\epsilon_d \bar{\chi} \gamma^\mu \partial_\mu \tilde{H}_d^0 + \text{h.c.}$$

where  $\epsilon \sim v/f$ . For large  $\mu$ ,  $\chi$  has a small  $\tilde{H}$  of order  $v m_\chi / f \mu$ .

Mixing with other MSSM fields is suppressed. Assuming MFV,

$$K = \frac{1}{f} (A + A^\dagger) \left( \frac{Y_u}{M_u} \bar{Q} H_u U + \dots \right)$$

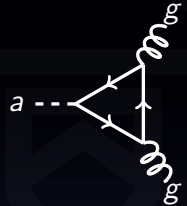
where the scales  $M_{u,d,\ell}$  are unrelated to  $f$  or  $v$  and can be large and dependent on the UV completion

# Interactions: anomaly

Fermions  $\Psi$  charged under global U(1) and Standard Model

$$\mathcal{L}_{\text{an}} \supset \frac{c_{\text{an}}}{f\sqrt{2}} \left( a G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + 2\bar{\chi} G_{\mu\nu}^a \sigma^{\mu\nu} \gamma^5 \lambda^a \right)$$

$$c_{\text{an}} = \frac{\alpha}{8\pi} \sqrt{2} \sum_i^{N_\Psi} \left( \frac{y_i f}{m_{\Psi_i}} \right) = \frac{\alpha}{8\pi} q_\Psi N_\Psi$$



Assumed: degenerate  $m_\Psi$  and  $y = m_\Psi q_\Psi / f\sqrt{2}$

Also  $\gamma\gamma$

Integrating out  $\lambda^a$  generates  $\chi$  couplings to gluons

$$\mathcal{L} \supset - \left( \frac{c_{\text{an}}^2}{2M_\lambda f^2} \right) \bar{\chi} \chi G G - i \left( \frac{c_{\text{an}}^2}{2M_\lambda f^2} \right) \bar{\chi} \gamma^5 \chi G \tilde{G}$$

These contribute to collider and astro operators.

# Interactions: explicit breaking

Include explicit  $U(1)$  spurion  $R_\alpha = \lambda_\alpha f$  with  $\lambda_\alpha \ll 1$

$$W_{U(1)} = f^2 \sum_\alpha R_{-\alpha} e^{aA/f}$$

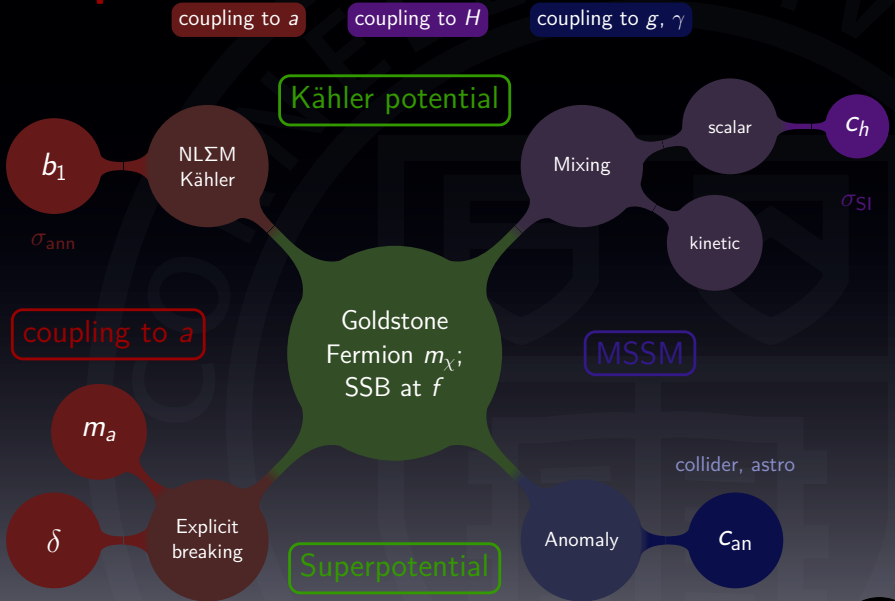
Preserve SUSY  $\Rightarrow$  at least two spurions with opposite charge.

This generates  $m_a = m_\chi = m_s$  and couplings

$$\mathcal{L} \supset - \underbrace{\frac{m_a}{2\sqrt{2}f}(\alpha + \beta)}_\delta i a \bar{\chi} \gamma^5 \chi + \underbrace{\frac{m_a}{8f^2}(\alpha^2 + \alpha\beta + \beta^2)}_\rho a^2 \bar{\chi} \chi$$

By integration by parts this is equivalent to a shift in the  $b_1$  coefficient from the Kähler potential

# Main parameters



# Parameter space scan

**Abundance:**  $\langle \sigma v \rangle \approx \frac{b_1^4}{8\pi} \frac{T_f}{m_\chi} \frac{m_\chi^2}{f^4} \approx 1 \text{ pb}$

$p$ -wave:  $b_1 \gtrsim 1$ , all other parameters take natural values

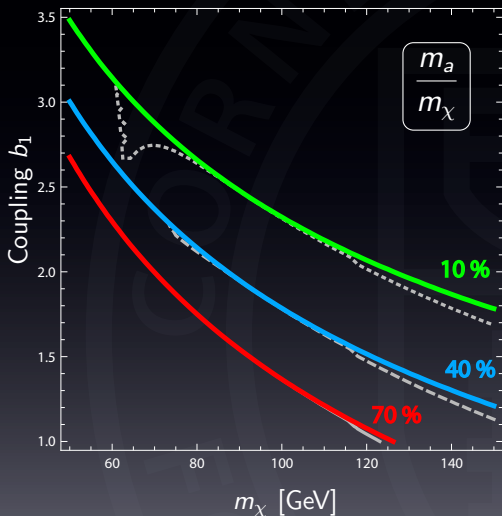
Parameter	Description	Scan Range
$f$	Global symmetry breaking scale	500 GeV – 1.2 TeV
$m_\chi$	Goldstone fermion mass (SUSY)	50 – 150 GeV
$m_a$	Goldstone boson mass	8 GeV – $f/10$
$b_1$	$\chi\chi a$ coupling	[0, 2]
$c_{an}$	Anomaly coefficient	0.06
$c_h$	Higgs coupling	[-1, 1]
$\delta$	Explicit breaking $ia\bar{\chi}\gamma^5\chi$ coupling	3/2

$$\mathcal{L} \supset \left[ \frac{1}{2}(\partial a)^2 + \frac{1}{2}\bar{\chi}\not{\partial}\chi \right] c_h \frac{v}{f} h + \frac{b_1}{2\sqrt{2}f} (\bar{\chi}\gamma^\mu\gamma^5\chi) \partial_\mu a + \frac{c_{an}}{f\sqrt{2}} a G\tilde{G} + i\delta a\bar{\chi}\gamma^5\chi$$



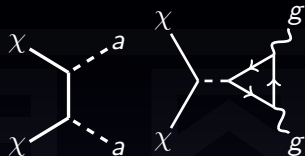
# Contours of fixed $\Omega$

$$\Omega h^2 = 0.11$$



## Dominant contribution

Kähler, anomaly,  $U(1)$



## Subleading

Mixing with Higgs



## Negligible

$\chi\chi \rightarrow s \rightarrow aa$ ,  $\chi\chi \xrightarrow{t,u} hh$

# Direct Detection

Higgs exchange typically dominates by a factor of  $\mathcal{O}(10^3)$ .

$$\sigma_{\text{SI}}^{\text{H}} \approx 3 \cdot 10^{-45} \text{ cm}^2 c_h^2 \left( \frac{115 \text{ GeV}}{m_h} \cdot \frac{700 \text{ GeV}}{f} \right)^4 \left( \frac{m_\chi}{100 \text{ GeV}} \cdot \frac{\mu_\chi}{\text{GeV}} \cdot \frac{\lambda_N}{0.5} \right)^2$$

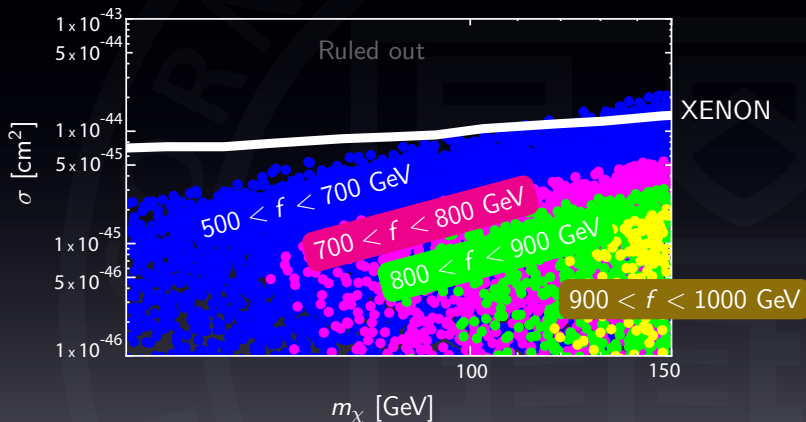
Compare this to the MSSM Higgs with  $\mathcal{L} = \frac{1}{2}cg\bar{\chi}\chi h$ :

$$\sigma_{\text{SI}}^{\text{MSSM}} \sim \frac{c^2 g^2 \lambda_N^2 \mu^2 m_N^2}{2\pi m_h^2 v^2} \approx c^2 \times 10^{-42} \text{ cm}^2$$

**Natural suppression:**  $(m_\chi v/f^2)^2$  due to Goldstone nature

# Parameter space scan

## Direct Detection



# Indirect detection & Colliders

$\bar{p}$  spectrum: below PAMELA

- (Einsasto DM Halo profile) 1104.3572

$\gamma$ -ray line search:  $\mathcal{O}(10)$  smaller than bound

- $\chi\chi \rightarrow a \rightarrow \gamma\gamma$

Diffuse  $\gamma$ -ray spectrum:  $\mathcal{O}(10)$  smaller than bound

- $\chi\chi \rightarrow a \rightarrow gg \rightarrow \pi's$

Photo-production from annihilation:  $\sigma$  3x lower than bound

- Low mass DM  $m_\chi \lesssim 60$  GeV, constrains  $bb$  decays

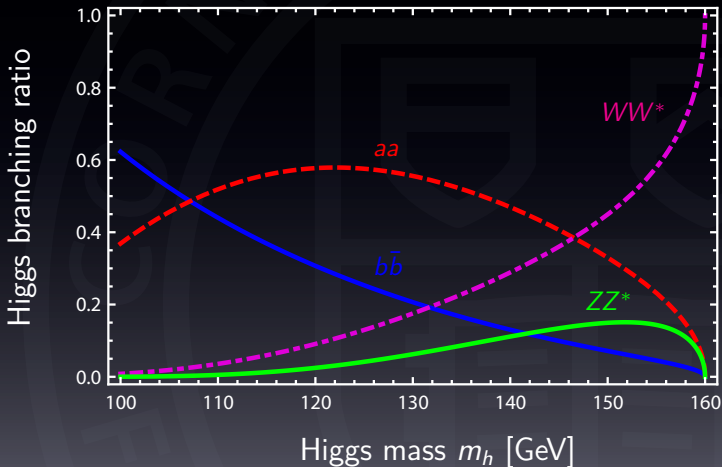
ISR monojets at colliders: dim-7 operators too small

$$\mathcal{L} \supset -\frac{C_{an}^2}{2M_\lambda f^2} \bar{\chi}\chi GG - \frac{iC_{an}^2}{2M_\lambda f^2} \bar{\chi}\gamma^5\chi G\tilde{G}$$

# Non-standard Higgs decays

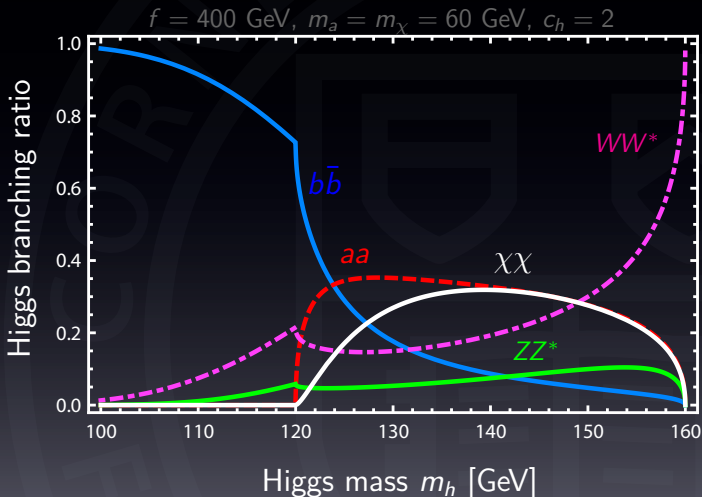
Hard to completely bury the Higgs. LEP:  $\text{Br}(\text{SM}) \gtrsim 20\% \Rightarrow m_h \gtrsim 110 \text{ GeV}$

$f = 500 \text{ GeV}$ ,  $m_a = 45 \text{ GeV}$ ,  $m_\chi = 100 \text{ GeV}$ ,  $c_h = 2$



# Non-standard Higgs decays

Partially buried & invisible: Suppressed SM channels, MET,  $\Gamma_{\text{tot}} < 1$



# Conclusions

Executive summary: Goldstone Fermion dark matter

- SSB: global  $U(1) \Rightarrow$  Goldstone boson  $a$  and fermion  $\chi$
- $\chi$  is LSP and DM,  $a$  gives 'buried' Higgs channel

Simple extension of MSSM with natural WIMP dark matter

- Kähler  $\chi\chi a$  interaction controls abundance
- Higgs mixing, anomaly controls direct detection
- Novel collider signature: partially buried/invisible Higgs

Further directions:

- $p$ -wave Sommerfeld enhancement (can push  $m_a, m_\chi$  to 10 GeV)
- Non-abelian generalization

# Extra Slides



# Examples of Linear Models

Simplest example:

$$W = yS \left( \bar{N}N - \mu^2 \right) + \underbrace{N\bar{\phi}\phi}_{\text{anomaly}} + \underbrace{SH_uH_d}_{\text{mixing}} + \underbrace{W_{\text{explicit}}}_{\text{explicit } U(1)}$$

Example with  $|b_1| \geq 1$ :

$$W = \lambda XYZ - \mu^2 Z + \frac{\tilde{\lambda}}{2} Y^2 N - \tilde{\mu} \bar{N}N$$

$q_Z = 0$ ,  $q_N = -q_{\bar{N}} = -2q_Y = 2q_X$ . Goldstone multiplet:

$$A = \sum_i \frac{q_i f_i \psi_i}{f} = \frac{q_Y}{f} \left( Y f_Y - X f_X + 2\bar{N} F_{\bar{N}} \right)$$

$$b_1 = \frac{-f_X^2 + f_Y^2 + 8f_N^2}{f_X^2 + f_Y^2 + 4f_N^2}$$

# Tamvakis-Wyler Theorem

Phys. Lett B 112 (1982) 451; Phys. Rev. D 33 (1986) 1762

Global symmetry:  $W[\Phi_i] = W[e^{i\alpha q_i} \Phi_i]$  so that

$$0 = \frac{\partial W[e^{i\alpha q_i} \Phi_i]}{\partial \alpha} = \sum_j W_j q_j \Phi_j,$$

Taking a derivative  $\partial/\partial\Phi_i$  gives:

$$0 = \frac{\partial}{\partial \Phi_i} \left( \sum_j W_j q_j \Phi_j \right) \Big|_{\langle \Phi \rangle} = \sum_j W_{ij} q_j f_j + W_i q_i$$

# SUSY NL $\Sigma$ M

Phys. Lett. B 87 (1979) 203

Expand Kähler potential, drop total derivatives, integrate out  $F$ :

$$\begin{aligned}\mathcal{L} = & K'' \left( \frac{i}{2} \partial\chi\sigma\bar{\chi} + |\partial\phi|^2 \right) \\ & + \frac{K'''}{4} i\chi\sigma\bar{\chi}\partial(\phi - \phi^*) \\ & + \frac{1}{4} \left( K'''' - \frac{(K''')^2}{K''} \right) \chi^2\bar{\chi}^2\end{aligned}$$

These terms can be understood in terms of geometric properties of the vacuum manifold, see e.g. [hep-th/0101055](https://arxiv.org/abs/hep-th/0101055).

# SUSY Breaking and $\chi$ mass

We assume that soft SUSY terms that also explicitly break the global U(1) are negligible. Neglect  $D$ -term mixing with  $\lambda^a$ , then fermion mass matrix is  $W_{ij}$ . Tamvakis-Wyler:

$$\sum_j W_{ij} q_j f_j = -q_i W_i = -q_i F_i$$

so that  $\chi = \sum_i q_i f_i \psi_i / f$  mass depends on how U(1)-charged  $F$ -terms in the presence of soft SUSY terms.

If  $W$  has an unbroken  $R$  symmetry, then  $R[\chi] = -1$  which prohibits a Majorana mass. However, while soft scalar masses preserve  $R$ ,  $A$ -terms are holomorphic and generally break  $R$  symmetries to contribute to  $m_\chi$ .

# SUSY Breaking and $\chi$ mass

The  $A$ -term contribution to  $m_\chi$  is equivalent to  $F$ -term mixing between U(1) charged fields and the SUSY spurion,  $X$ . This was recently emphasized in 1104.0692 as an irreducible  $\mathcal{O}(m_{3/2})$  contribution to the Goldstone fermion

For concreteness, consider gravity mediation with  $m_{\text{soft}} \sim F/M_{\text{Pl}}$ .

$$K = \sum_i Z(X, X^\dagger) \phi_i^\dagger \phi_i$$

Analytically continue into superspace [hep-ph/9706540](https://arxiv.org/abs/hep-ph/9706540)

$$\phi \rightarrow \phi' \equiv Z^{1/2} \left( 1 + \frac{\partial \ln Z}{\partial X} F \theta^2 \right) \phi$$

Canonical normalization generates  $A$ -terms:

$$\Delta \mathcal{L}_{\text{soft}} = \left. \frac{\partial W}{\partial \Phi} \right|_{\Phi=\phi} Z^{-1/2} \left( - \frac{\partial \ln Z}{\partial \ln X} \frac{F}{M} \right)$$

# SUSY Breaking and $\chi$ mass

$$\Delta\mathcal{L}_{\text{soft}} = \left. \frac{\partial W}{\partial \Phi} \right|_{\Phi=\phi} Z^{-1/2} \left( -\frac{\partial \ln Z}{\partial \ln X} \frac{F}{M} \right)$$

Completely incorporates  $F$ -term mixing of the form  $FF_i^\dagger \Phi_i$ . The  $\chi$  mass is determined by the induced  $F_i$  obtained by minimizing

$$V = \left| \frac{\partial W}{\partial \phi_i} \right|^2 + A_i \frac{\partial W}{\partial \phi_i} \phi_i + \text{h.c.} + m_i^2 |\phi_i|^2$$

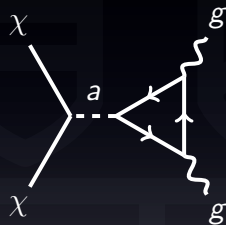
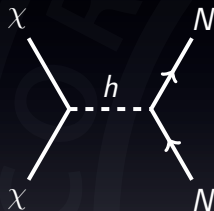
Assuming  $A_i, m_i < f_i$ , generic size is  $|F_i| \approx A_i f_i$  so that  $m_\chi \sim A_i q_i$ . Often the  $A$ -terms are suppressed relative to other soft terms, so it's reasonable to expect  $\chi$  to be the LSP.

Contributions from soft scalar masses are on the order of  $m_i^2/f_i$  which can easily be suppressed.

# Direct Detection

Relevant couplings from EWSB and anomaly:

$$\mathcal{L} \supset \frac{c_h^V}{2f} \bar{\chi} \not{\partial} \chi h - \frac{c_{an}^2}{2M_\lambda f^2} \bar{\chi} \chi GG - \frac{i c_{an}^2}{2M_\lambda f^2} \bar{\chi} \gamma^5 \chi G \tilde{G}$$



Effective coupling to nucleons:  $\mathcal{L} = G_{\text{nuc}} \bar{N} N \bar{\chi} \chi$ ,

$$G_{\text{nuc}} = c_h \frac{\lambda_N}{2\sqrt{2}} \left( \frac{m_\chi m_N}{m_h^2 f^2} \right) + \frac{4\pi c_{an}^2}{9\alpha_s} \frac{m_N}{M_\lambda f} \left( 1 - \sum_{i=u,d,s} f_i^{(N)} \right)$$

# Direct detection: nucleon matrix elements

Nucleon matrix elements can be parameterized via

Phys. Rev. D38 2869, Phys. Lett. B219 347, 0801.3656, 0907.417

$$m_i \langle N | \bar{q}_i q_i | N \rangle = f_i^{(N)} m_N$$

The heavy quark contribution via gluons can be calculated by the conformal anomaly, Phys. Lett. B78 433

$$f_j^{(N)} m_N = \frac{2}{27} \left( 1 = \sum_{q=u,d,s} f_q^{(N)} \right) \quad j = c, b, t$$

Relevant quantity in Higgs exchange:  $c_q$ , diagonalized Yukawa

$$\lambda_N = \sum_{q=u,d,s} c_q f_q^{(N)} + \frac{2}{27} \left( 1 = \sum_{q=u,d,s} f_q^{(N)} \right) \sum_{q'=c,b,t} c_{q'}$$



# Direct Detection

Some details:

$$G_{\chi N} = c_h \frac{\lambda_N}{2\sqrt{2}} \left( \frac{m_\chi m_N}{m_h^2 f^2} \right) + \frac{4\pi c_{an}^2}{9\alpha_s} \frac{m_N}{M_\lambda f} \left( 1 - \sum_{i=u,d,s} f_i^{(N)} \right)$$

For reduced mass  $\mu_\chi = (m_\chi^{-1} + m_N^{-1})^{-1}$ ,

$$\sigma_{\text{SI}}^{\text{Higgs}} = \frac{4\mu_\chi^2}{A^2\pi} [G_{\chi p} Z + G_{\chi n} (A - Z)]$$

$$\sigma_{\text{SI}}^{\text{H}} \approx 3 \cdot 10^{-45} \text{ cm}^2 c_h^2 \left( \frac{115 \text{ GeV}}{m_h} \right)^4 \left( \frac{700 \text{ GeV}}{f} \right)^4 \left( \frac{m_\chi}{100 \text{ GeV}} \right)^2 \left( \frac{\mu_\chi}{1 \text{ GeV}} \right)^2 \left( \frac{\lambda_N}{0.5} \right)^2$$

$$\sigma_{\text{SI}}^{\text{glue}} \approx 2 \cdot 10^{-48} \text{ cm}^2 \left( \frac{700 \text{ GeV}}{M_\lambda} \right)^2 \left( \frac{700 \text{ GeV}}{f} \right)^4 \left( \frac{N_\psi}{5} \right)^4 \left( \frac{q_\psi}{2} \right)^4 \left( \frac{\mu}{1 \text{ GeV}} \right)^2$$

using  $c_{an} = \alpha_s q_\psi N_\psi / 8\pi$

# Why are the $\chi\chi \rightarrow aa$ annihilations $p$ -wave?

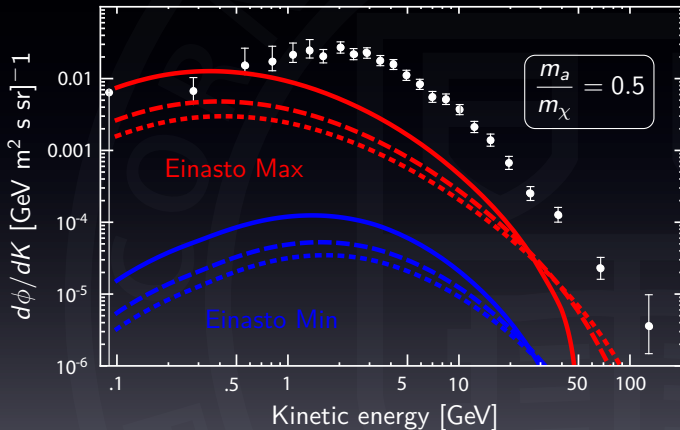
If the initial state is a particle-antiparticle pair with zero total angular momentum and the final state is CP even, then the process must vanish when  $\nu = 0$ .

Under CP a particle/antiparticle pair picks up a phase  $(-)^{L+1}$ . When  $\nu = 0$  momenta are invariant and thus the initial state gets an overall minus sign. Since final state is CP even, the amplitude must vanish in this limit. For Dirac particles  $P$  is sufficient, but for Majorana particles  $CP$  is the well-defined operation.

This is why  $\chi\chi \rightarrow G\tilde{G}$  is  $s$ -wave while  $\chi\chi \rightarrow aa$  is  $p$ -wave.

# Indirect detection: $\bar{p}$ flux vs. PAMELA

$$f = 700 \text{ GeV}, Q_\Psi = 2, \delta = \frac{3}{2}, N_\Psi = 5$$



Dotted:  $m_\chi = 150 \text{ GeV}, b_1 = 1$   
Dashed:  $m_\chi = 100 \text{ GeV}, b_1 = 1.5$   
Solid:  $m_\chi = 50 \text{ GeV}, b_1 = 3$

Using Einasto DM Halo profile in 1012.4535, 1009.0224

# Indirect detection: Fermi-LAT

**$\gamma$ -ray line search:** 30 – 200 GeV

- Upper bound  $\langle\sigma v\rangle_{\gamma\gamma} < 2.5 \times 10^{-27} \text{ cm}^3/\text{s}$
- $\chi\chi \rightarrow a \rightarrow \gamma\gamma$  via anomaly
- For SU(5) fundamentals,  $\langle\sigma v\rangle_{\gamma\gamma} \sim 2 \times 10^{-3} \langle\sigma v\rangle_{gg}$
- $\mathcal{O}(10)$  smaller than bound even for extreme parameters

**Diffuse  $\gamma$ -ray spectrum:** 20 – 100 GeV

- Bounds  $\chi\chi$  to charged particles,  $\pi^0$ s
- $\chi\chi \rightarrow a \rightarrow gg$  via anomaly
- $\mathcal{O}(10)$  smaller than bound

**Photo-production from DM annihilation:** spheroidal galaxies

- Low mass DM  $m_\chi \lesssim 60 \text{ GeV}$ , constrains  $bb$  decays
- GF: annihilation  $\sigma$  always at least a factor of 3 lower

<http://fermi.gsfc.nasa.gov/science/symposium/2011/program>

# Collider production

Collider production through gluons. **ISR monojet** signature is sensitive to  $\sigma_{SI}^N \sim 10^{-46} \text{ cm}^2$  at the LHC with  $100 \text{ fb}^{-1}$ .

The dim-7 anomaly operators are too small:

$$\mathcal{L} \supset -\frac{C_{an}^2}{2M_\chi f^2} \bar{\chi} \chi G G - \frac{i C_{an}^2}{2M_\chi f^2} \bar{\chi} \gamma^5 \chi G \tilde{G}$$

$gg \rightarrow a^* \rightarrow \chi\chi$  may be within  $5\sigma$  reach with  $100 \text{ fb}^{-1}$

1005.1286, 1005.3797, 1008.1783, 1103.0240, 1108.1196

**Cascade decays:**  $\text{LOSP} \rightarrow \chi$  through

- $\bar{\chi} G \lambda$  anomaly
- $\chi - \tilde{H}$  kinetic mixing

Decays typically prompt,  $a$  reconstruction is difficult for light masses.

Heavy fermions  $\Psi$  in anomaly may appear as “fourth generation” quarks

# Nuclear matrix element and matching

The nucleon matrix element at vanishing momentum transfer:

$$M_N = \langle \Theta_{\mu}^{\mu} \rangle = \langle N | \sum_{i=u,d,s} m_i \bar{q}_i q_i + \frac{\beta(\alpha)}{4\alpha} G_{\alpha\beta}^a G_{\alpha\beta}^a | N \rangle$$

from: Shifman, Vainshtein, Zakharov. Phys. Lett 78B (1978)

$\beta = -9\alpha^2/2\pi + \dots$  contains only the light quark contribution,  $M_N$  is the nucleon mass. The  $GG$  matches onto the nucleon operator  $\bar{N}N$ .

$$M_N f_{i=u,d,s}^{(N)} = \langle N | m_i \bar{q}_i q_i | N \rangle \quad f_g^{(N)} = 1 - \sum_{i=u,d,s} f_i^{(N)}$$

# Nuclear matrix element and matching

$$\frac{\beta(\alpha)}{4\alpha} G_{\alpha\beta}^a G_{\alpha\beta}^a \longrightarrow M_N \left( 1 - \sum_{i=u,d,s} f_i^{(N)} \right) \bar{N} N$$

Where  $f_{u,d}^{(N)} \ll f_s^{(N)} \approx 0.25$ . For a detailed discussion, see 0801.3656 and 0803.2360.

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