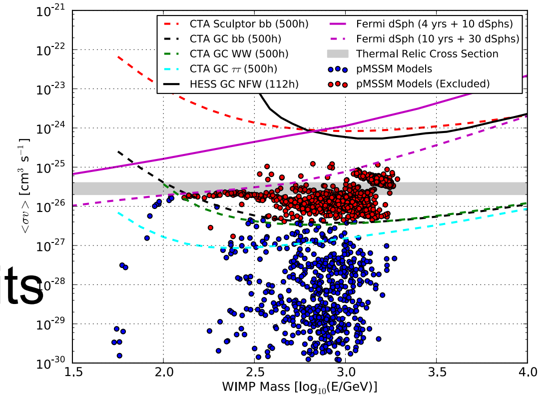
# CF4 Summary

Konstantin Matchev

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Cosmic Frontier Workshop
March 8, 2013

# CF4 activities




- Pre-workshop
  - identify members/contributors
  - identify liaisons with CF1,CF2,HE4, collect limits
  - identify a set of theory models and experts
  - prepare draft of the short Complementarity Document
- At the workshop
  - discussion of the Complementarity Document
    - add: pMSSM example, Conclusions, Venn diagram/science goals
    - subtract: list of individual experiments, references
  - three CF4 sessions with (mostly) theory talks
  - joint sessions with CF1 (two), CF2 (two) and CF3 (one)
- Post-workshop
  - deliver the Complementarity Document (by March 29)
  - begin work on the CF4 Summary Report
    - in final form by July 12

# Complementarity Document: TOC


- Introduction
- Evidence and candidates
- The four pillars of dark matter detection
  - Direct detection
  - Indirect detection
  - Particle colliders
  - Astrophysical probes
- Complementarity
  - Basic features
  - Model-independent examples
  - Post-discovery complementarity
- Conclusions
- Appendix: Dark matter projects

# Appendices: lists of experiments

## DIRECT DETECTION

TABLE I: Current and planned direct detection experiments.

| Status | Experiment | Target | Technique | Location | Major Support | Comments |
|---|---|---|---|---|---|---|
| Current | LUX | 350 kg liquid Xe | Ion., Scint. | SURF | DOE, NSF, European | |
| Planned | LZ | 7 ton liquid Xe | Ion., Scint. | SURF | DOE, NSF, European | |
| Current | Xenon100 | 62 kg liquid Xe | Ion., Scint. | LNGS | DOE, NSF, European | |
| Planned | Xenon1T | 3 ton liquid Xe | Ion., Scint. | LNGS | DOE, NSF, European | |
| Planned | PandaX-1 | 1.2 ton liquid Xe | Ion., Scint. | Jinping | Chinese | |
| Planned | PandaX-2 | 3 ton liquid Xe | Ion., Scint. | Jinping | Chinese | |
| Current | XMASS-I | 800 kg liquid Xe | Scint. | Kamioka | Japanese | |
| Planned | XMASS-1.5 | 5 ton liquid Xe | Scint. | Kamioka | Japanese | |
| Current | DarkSide-50 | 50 kg liquid Ar | Ion., Scint. | LNGS | DOE, NSF, European | |
| Planned | DarkSide-G2 | 5 ton liquid Ar | Ion., Scint. | LNGS | DOE, NSF, European | |
| Current | ArDM | 1 ton liquid Ar | Ion., Scint. | Canfranc | European | |
| Current | MiniCLEAN | 500 kg liquid Ar/Ne | Scint. | SNOLab | DOE | |
| Current | DEAP-3600 | 3.6 ton liquid Ar | Scint. | SNOLab | Canadian | |
| Planned | CLEAN | 40 ton liquid Ar/Ne | Scint. | SNOLab | DOE | |
| Current | COUPP-60 | $CF_3I$ | Bubbles | SNOLab | DOE, NSF | |
| Planned | COUPP-1T | $CF_3I$ | Bubbles | SNOLab | DOE, NSF | |
| Current | PICASSO | | Bubbles | SNOLab | Canadian | |
| Current | SIMPLE | | Bubbles | Canfranc | European | |
| Current | SuperCDMS | 10 kg Ge | Ion., Phonons | Soudan | DOE, NSF | |
| Planned | SuperCDMS | 100 kg Ge | Ion., Phonons | Soudan | DOE, NSF | |
| Current | Edelweiss | 4 kg Ge | Ion., Phonons | Modane | European | |
| Current | CRESST | 10 kg $CaWO_4$ | Scint., Phonons | LNGS | European | |
| Planned | EURECA | Ge, $CaWO_4$ | | | | |
| Current | CoGeNT | Ge | Ion. | Soudan | DOE | |
| Current | TEXONO | Ge | Ion. | | Chinese | |
| Current | DAMA/LIBRA | NaI | | | European | |
| Current | ELEGANT | NaI | | | Japanese | |
| Planned | DM-Ice | NaI | | | | |
| Planned | CINDMS | NaI | | | Chinese | |
| Current | KIMS | CsI | | | | |
| Current | DRIFT | | Ion. | | | |
| Current | DMTPC | $CF_4$ gas | Ion. | WIPP | | |
| Planned | NEXT | Xe gas | Ion., Scint. | Canfranc | | |
| Planned | MIMAC | | Ion. | Modane | | |
| Planned | Superfluid He-4 | | | | | |
| Planned | DNA | DNA | | | | |
| TO BE CONTINUED | | | | | | |

## INDIRECT DETECTION

TABLE II: Current and planned indirect detection experiments.

| Status | Experiment | Target | Location | Major Support | Comments |
|---|---|---|---|---|---|
| Current | AMS | $e^+/e^-$, anti-nuclei | ISS | NASA | Magnet Spectrometer, Running |
| | Fermi | Photons, $e^+/e^-$ | Satellite | NASA, DOE | Pair Telescope and Calorimeter, Running |
| | HESS | Photons, $e^-$ | Namibia | German BMBF, Max Planck Society, French Ministry for Research, CNRS-IN2P3, UK PPARC, South Africa | Atmospheric Cherenkov Telescope (ACT), Running |
| | IceCube/ DeepCore | Neutrinos | Antarctica | NSF, DOE, International *Belgium, Germany, Japan, Sweden) | Ice Cherenkov, Running |
| | MAGIC | Photons, $e^+/e^-$ | La Palma | German BMBF and MPG, INFN, WSwiss SNF, Spanish MICINN, CPAN, Bulgarian NSF, Academy of Finland, DFG, Polish MNiSzW | ACT, Running |
| | PAMELA | $e^+/e^-$ | Satellite | | |
| | VERITAS | Photons, $e^+/e^-$ | Arizona, USA | DOE, NSF, SAO | ACT, Running |
| | ANTARES | Neutrinos | Mediterranean | France, Italy, Germany, Netherlands, Spain, Russia, and Morocco | Running |
| Planned | CALET | $e^+/e^-$ | ISS | Japan JAXA, Italy ASI, NASA | Calorimeter |
| | CTA | Photons | ground-based (TBD) | International (MinCyT, CNEA, CONICET, CNRS-INSU, CNRS-IN2P3, Irfu-CEA, ANR, MPI, BMBF, DESY, Helmholtz Association, MIUR, NOVA, NWO, Poland, MICINN, CDTI, CPAN, Swedish Research Council, Royal Swedish Academy of Sciences, SNSF, Durham UK, NSF, DOE | ACT |
| | GAMMA-400 | Photons | Satellite | Russian Space Agency, Russian Academy of Sciences, INFN | Pair Telescope |
| | GAPS | Anti-deuterons | Balloon (LDB) | NASA, JAXA | TOF, X-ray and Pion detection |
| | HAWC | Photons, $e^+/e^-$ | Sierra Negra | NSF/DOE | Water Cherenkov, Air Shower Surface Array |
| | IceCube/ PINGU | Neutrinos | Antarctica | NSF, Germany, Sweden, Belgium | Ice Cherenkov |
| | KM3NeT | Neutrinos | Mediterranean | ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus | Water Cherenkov |
| | ORCA | Neutrinos | Mediterranean | ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus | Water Cherenkov |
| TO BE CONTINUED | | | | | |

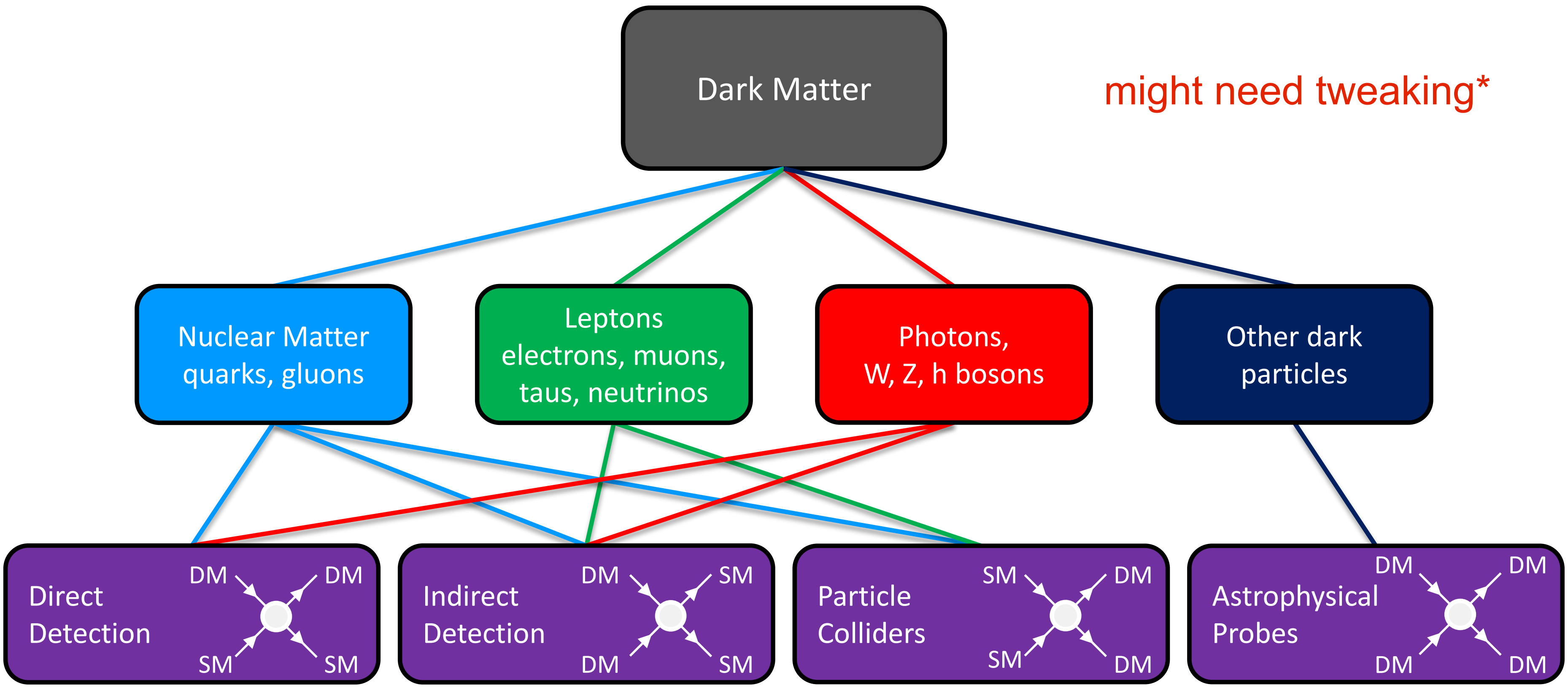
## COLLIDERS

TABLE III: Current and proposed particle colliders.

| Status | Collider | Type | $E_{COM}$, Luminosity | Major Support | Comments |
|---|---|---|---|---|---|
| Current | LHC | pp | 8 TeV, 20 $fb^{-1}$ | DOE, NSF | |
| Upcoming | LHC | pp | 14 TeV, 300 $fb^{-1}$ | DOE, NSF | |
| Proposed | HL LHC | pp | 14 TeV, 3000 $fb^{-1}$ | | |
| Proposed | VLHC | pp | 33-100 TeV | | |
| Proposed | Higgs Factory | $e^+e^-$ | 250 GeV | | |
| Proposed | ILC, CLIC | $e^+e^-$ | 0.5-3 TeV | | |
| Proposed | Muon Collider | $\mu^+\mu^-$ | 6 TeV | | |
| TO BE CONTINUED | | | | | |

# DM interactions vs. DM probes

- For the purposes of this report, DM candidates are categorized according to their basic interactions

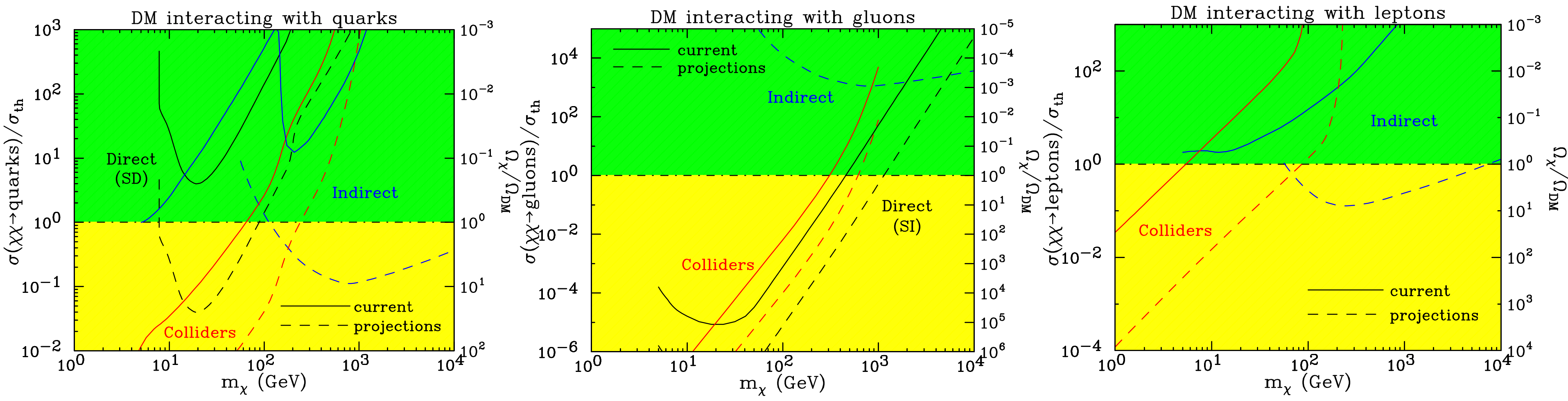


# Model-independent examples

- In the short Complementarity Document:
  - Be agnostic about the underlying theory model
- Parameterize our ignorance about
  - the origin of SUSY breaking
    - pMSSM talks (Ismail, Cotta, Cahill-Rowley, Drlica-Wagner)
  - the type of DM-SM interactions and their mediators
    - effective operators (Shepherd)
- The longer CF4 summary document will also consider specific theory models:
  - CMSSM (Sanford)
  - NUSUGRA (Baer)
  - UED (Kong)
  - NMSSM (McCaskey, Shaughnessy)

# I. Effective operator approach

- Effective theory of SM+DM.



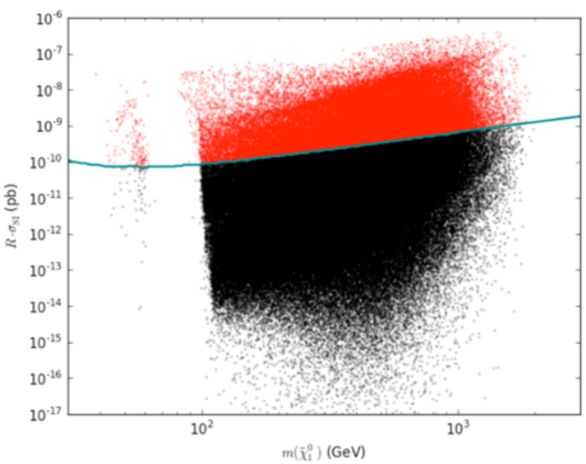

$$\frac{1}{M_q^2}\ \bar{\chi}\gamma^\mu\gamma_5\chi\sum_q\bar{q}\gamma_\mu\gamma_5 q+\frac{\alpha_S}{M_g^3}\ \bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu}+\frac{1}{M_\ell^2}\ \bar{\chi}\gamma^\mu\chi\sum_\ell\bar{\ell}\gamma_\mu\ell$$

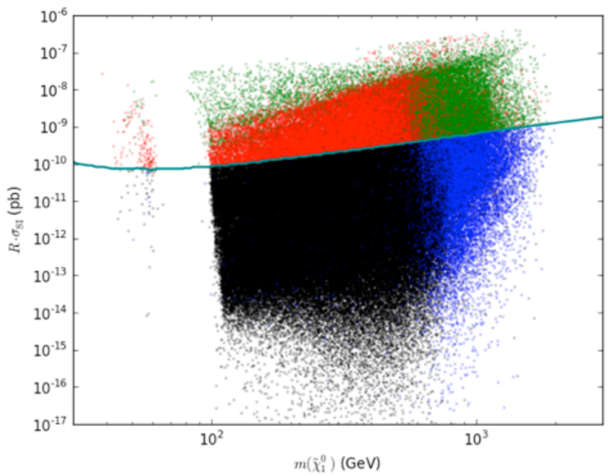
D8 D11 D5

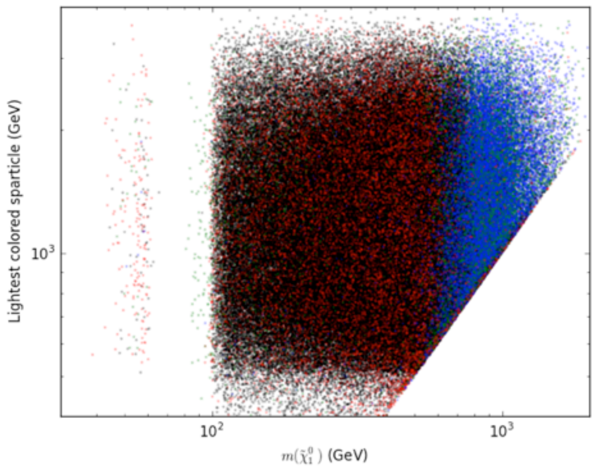
# II. The pMSSM approach
## (SUSY without prejudice)

talks by: M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, A. Ismail, T. Rizzo, M. Wood

- Sequentially apply projected constraints from
  - direct detection (red versus black)
  - indirect detection (red->green; black->blue)
  - LHC



# Where are the benchmark points?

- Still under discussion in the High Energy Frontier
- Not all HEF models are suitable for DM studies
- We have begun collecting good DM benchmark models at the workshop
  - will be linked to the CF4 twiki
  - synchronization exercises?

pMSSM Benchmarks for Snowmass 2013 - Chromium

www.slac.stanford.edu/~aismail/snowmass/index.html

# pMSSM Benchmarks for Snowmass 2013

This page contains benchmark pMSSM points and slopes for the Snowmass 2013 study. Comments and questions should be directed to aismail AT stanford DOT edu.

A brief introduction to these benchmarks

We present several benchmark points in the phenomenological Minimal Supersymmetric Standard Model (pMSSM). We select these models as experimentally well-motivated examples of the MSSM which predict the observed Higgs mass and dark matter relic density while evading the current LHC searches. In some cases, we use a benchmark to generate a slope in parameter space by scaling the mass parameters in a manner which keeps the Higgs mass and relic density approximately constant.

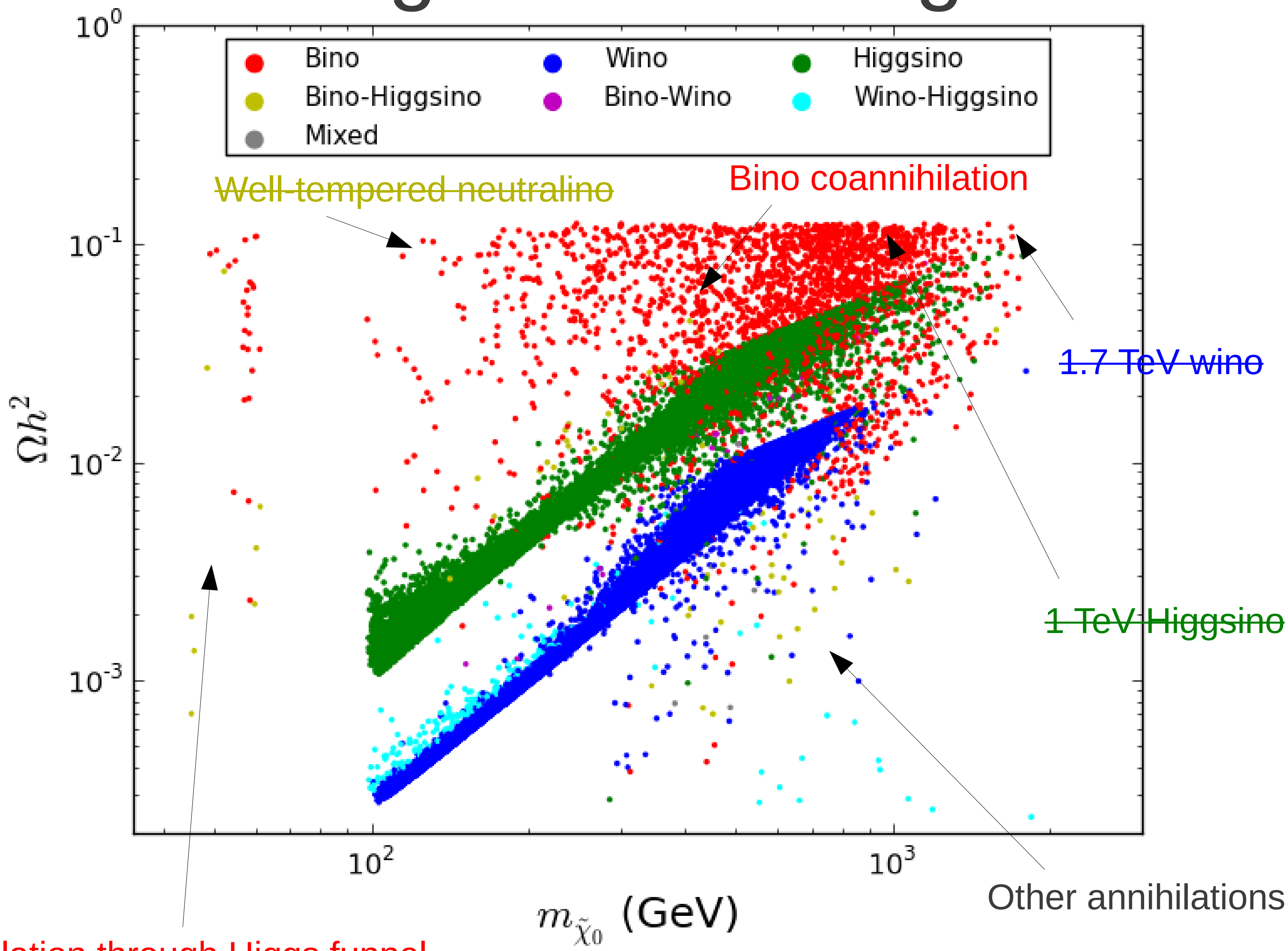
After the January meeting of the BSM working group, we have introduced modified versions of many of our benchmarks, now with degenerate 1st/2nd generation squark and/or slepton masses. The original benchmarks are still available.

## Bino-stop coannihilation

SLHA file
Spectrum
Dark matter info
Slopes to come!
Modified SLHA file and spectrum after January BSM group meeting

talk by A. Ismail “Complementarity in the pMSSM”

# Most surviving LSPs are eigenstates




Bino annihilation through Higgs funnel

# Focus Point Benchmark Points ($\mu$ < 0)

- Set $m_0$ = 9 TeV to produce correct Higgs mass
- Choose $A$ to produce $\Omega_\chi = \Omega_{\rm DM}$
- All points have $m_h$ in range 125-126 GeV

| $M_{1/2}$ (TeV) | $A$ (TeV) | $m_\chi$ (GeV) | $m_{\tilde{g}}$ (TeV) | $\sigma_p^{\rm SI}$ (zb) $f_s = 0.05$ | $\sigma_p^{\rm SD}$ (ab) | Solar $\mu$ Flux (km$^{-2}$ yr$^{-1}$) | $\mathcal{B}(\gamma\gamma)$ ($\times 10^{-4}$) |
|---|---|---|---|---|---|---|---|
| 0.7 | -4.81 | 302.5 | 1.79 | 5.34 | 89.8 | 30.4 | 0.338 |
| 0.8 | -4.57 | 345.6 | 2.01 | 6.45 | 80.9 | 35.0 | 0.569 |
| 0.9 | -4.34 | 388.9 | 2.23 | 7.43 | 71.8 | 34.5 | 0.858 |
| 1.2 | -3.65 | 519.6 | 2.87 | 9.39 | 49.5 | 26.4 | 2.058 |
| 1.4 | -3.18 | 606.7 | 3.29 | 10.2 | 39.0 | 19.2 | 3.176 |
| 1.6 | -2.69 | 692.9 | 3.71 | 10.6 | 30.8 | 13.6 | 4.604 |
| 1.8 | -2.16 | 777.4 | 4.11 | 10.3 | 23.6 | 9.37 | 6.387 |
| 2.0 | -1.57 | 858.4 | 4.52 | 8.99 | 16.9 | 5.97 | 8.624 |
| 2.5 | 4.38 | 1010 | 5.50 | 2.93 | 39.1 | 1.47 | 16.82 |
| 3.0 | 1.24 | 1047 | 6.50 | 7.33 | 90.8 | 0.42 | 24.67 |

with J. Feng, K. Matchev, J. Gainer

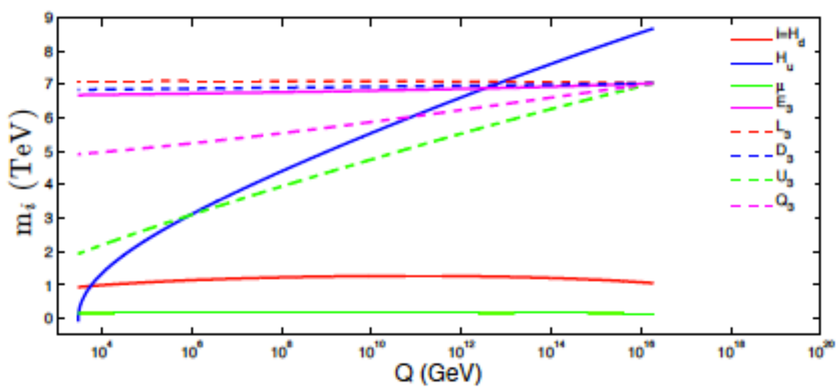
Constrained by COUPP60 1 yr expected sensitivity

# Next: how can $-m_{H_u}^2(m_{weak}) \sim m_Z^2/2$ ?

## Large top Yukawa radiatively drives $m_{H_u}^2$ to small negative values

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

$$X_t = m_{Q_3}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 + A_t^2$$




Large logs are a feature, not a hindrance; they are large because m(t)=173.2 GeV.

Why is m(t) so large?
I don’t know, but I am glad it is.

In mSUGRA, this only happens in HB/FP region where stops also are heavy;
in NUHM models, this can occur even if lighter stops

$$m_{H_u}^2(m_{GUT}) \sim (1-2)m_0^2$$

talk by H. Baer "Perspectives on SUSY in the post-LHC era"

# SUSY spectra from radiatively-driven natural SUSY (RNS)

## scan NUHM2 space:

- light higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_{1,2}$ with mass $\sim 100-300$ GeV,
- gluinos with mass $m_{\tilde{g}} \sim 1-4$ TeV,
- heavier top squarks than generic NS models: $m_{\tilde{t}_1} \sim 1-2$ TeV and $m_{\tilde{t}_2} \sim 2-5$ TeV,
- first/second generation squarks and sleptons with mass $m_{\tilde{q},\tilde{\ell}} \sim 1-8$ TeV. The $m_{\tilde{\ell}}$ range can be pushed up to 20-30 TeV if non-universality of generations with $m_0(1,2) > m_0(3)$ is allowed.

| parameter | RNS1 | RNS2 | NS2 |
|---|---|---|---|
| $m_0(1,2)$ | 10000 | 7025.0 | 19542.2 |
| $m_0(3)$ | 5000 | 7025.0 | 2430.6 |
| $m_{1/2}$ | 700 | 568.3 | 1549.3 |
| $A_0$ | -7300 | -11426.6 | 873.2 |
| $\tan\beta$ | 10 | 8.55 | 22.1 |
| $\mu$ | 150 | 150 | 150 |
| $m_A$ | 1000 | 1000 | 1652.7 |
| $m_{\tilde{g}}$ | 1859.0 | 1562.8 | 3696.8 |
| $m_{\tilde{u}_L}$ | 10050.9 | 7020.9 | 19736.2 |
| $m_{\tilde{u}_R}$ | 10141.6 | 7256.2 | 19762.6 |
| $m_{\tilde{e}_R}$ | 9909.9 | 6755.4 | 19537.2 |
| $m_{\tilde{t}_1}$ | 1415.9 | 1843.4 | 572.0 |
| $m_{\tilde{t}_2}$ | 3424.8 | 4921.4 | 715.4 |
| $m_{\tilde{b}_1}$ | 3450.1 | 4962.6 | 497.3 |
| $m_{\tilde{b}_2}$ | 4823.6 | 6914.9 | 1723.8 |
| $m_{\tilde{\tau}_1}$ | 4737.5 | 6679.4 | 2084.7 |
| $m_{\tilde{\tau}_2}$ | 5020.7 | 7116.9 | 2189.1 |
| $m_{\tilde{\nu}_\tau}$ | 5000.1 | 7128.3 | 2061.8 |
| $m_{\widetilde{W}_2}$ | 621.3 | 513.9 | 1341.2 |
| $m_{\widetilde{W}_1}$ | 154.2 | 152.7 | 156.1 |
| $m_{\widetilde{Z}_4}$ | 631.2 | 525.2 | 1340.4 |
| $m_{\widetilde{Z}_3}$ | 323.3 | 268.8 | 698.8 |
| $m_{\widetilde{Z}_2}$ | 158.5 | 159.2 | 156.2 |
| $m_{\widetilde{Z}_1}$ | 140.0 | 135.4 | 149.2 |
| $m_h$ | 123.7 | 125.0 | 121.1 |
| $\Omega^{std}_{\widetilde{Z}_1} h^2$ | 0.009 | 0.01 | 0.006 |
| $BF(b \to s\gamma) \times 10^4$ | 3.3 | 3.3 | 3.6 |
| $BF(B_s \to \mu^+\mu^-) \times 10^9$ | 3.8 | 3.8 | 4.0 |
| $\sigma^{SI}(\widetilde{Z}_1 p)$ (pb) | $1.1 \times 10^{-8}$ | $1.7 \times 10^{-8}$ | $1.8 \times 10^{-9}$ |
| $\Delta$ | 9.7 | 11.5 | 23.7 |

talk by K. Kong “Dark Matter Complementarity: UED review”

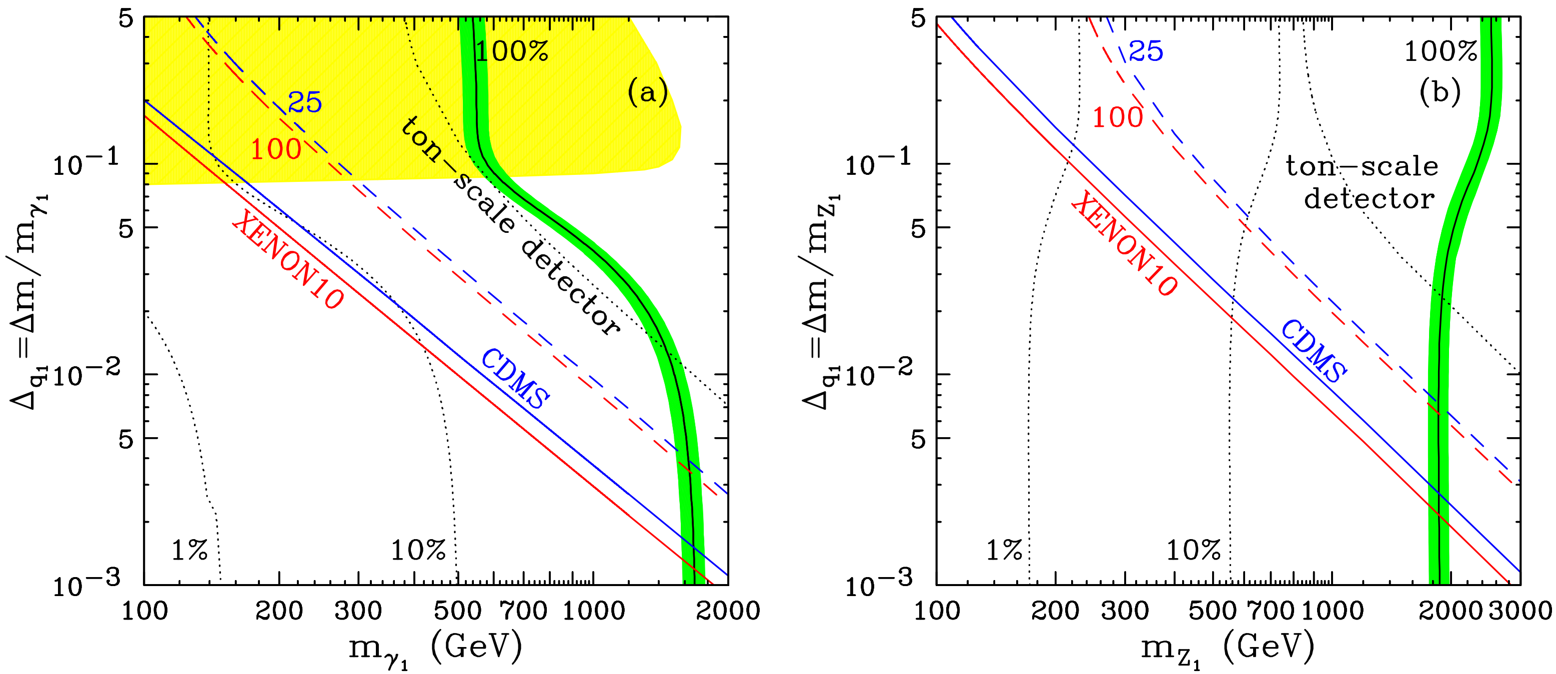
# HF4: UED Benchmarks

- We propose the following:
  - Consider 5D UED only
    - 6D model needs to address an issue with DM (too low KK scale)
  - Minimal UED
    - two parameters: R and Lambda (cutoff)
    - cutoff dependence is only logarithmic
    - mass spectrum from radiative correction (no boundary terms)
    - compressed mass spectrum
  - Non-minimal UED with brane terms for strong sector
    - two additional parameters: rG and rQ (for universal brane terms)
  - Signatures (standard SUSY search + resonances)
    - level 1: jets + n-leptons + met, n=0,1,2,3,4
    - level 2: dijet, dilepton and lepton-neutrino final states

talk by K. Kong "Dark Matter Complementarity: UED review"

# KK Dark Matter: complementarity

- Treat the LKP mass and mass splitting as free parameters.
- Gives a better chance for the LHC, and direct detection.



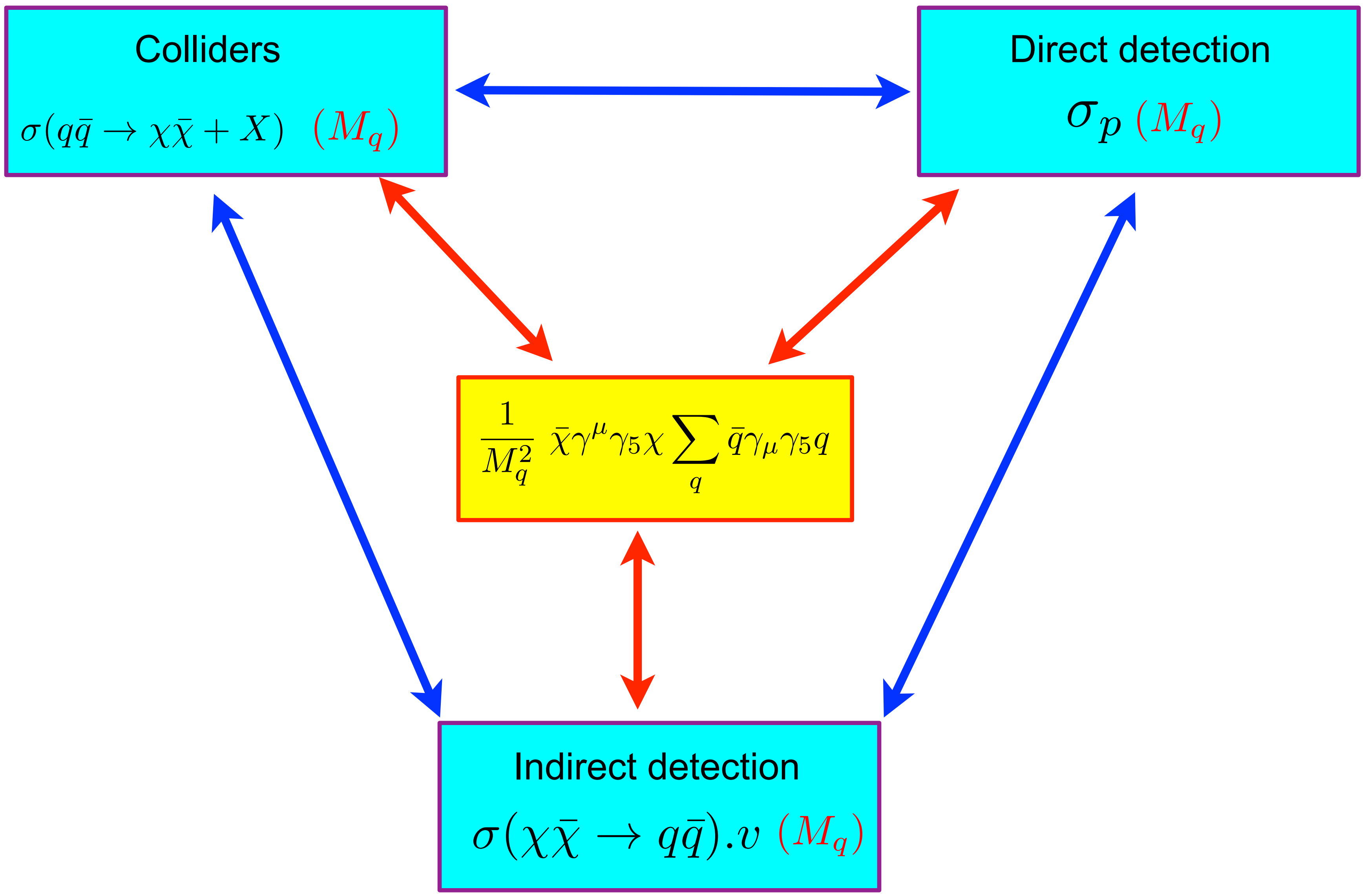

- Yellow: 4 leptons plus MET at 14 TeV LHC with 100 fb-1
- Green: relic abundance

Arrenberg, Baudis, Kong, Matchev, Yoo 2008

# Looking ahead

- Finish the complementarity document by March 29
  - only a few loose ends left
- Begin work on the CF4 summary report
  - use the short Complementarity Document as a starting point
  - identify additional topics
    - theory model examples discussed here at the workshop
      - contributors are identified
      - solicit (white paper style) contributions
    - discuss astrophysical probes
      - (talks by A. Peter, M. Boylan-Colchin, W. Dawson)
- Attend upcoming Snowmass related workshops
  - All-hands EF meetings at BNL, U. Washington
  - SnowDark workshop in Snowbird
  - Theory workshop at KITP
  - All-frontier Snowmass meeting in Minnesota

# BACKUPS


Colliders
$\sigma(q\bar{q} \to \chi\bar{\chi} + X)$ $(M_q)$
Direct detection
$\sigma_p$ $(M_q)$
$\frac{1}{M_q^2} \bar{\chi}\gamma^\mu\gamma_5\chi \sum_q \bar{q}\gamma_\mu\gamma_5 q$
Indirect detection
$\sigma(\chi\bar{\chi} \to q\bar{q}).v$ $(M_q)$