DARK MATTER FROM THE EARLY UNIVERSE AND PARTICLE PHYSICS CANDIDATES

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Dark Matter Universe: On the Threshold of Discovery
NAS Sackler Colloquium, Irvine, 18-20 October 2012

THIS IS A SPECIAL TIME

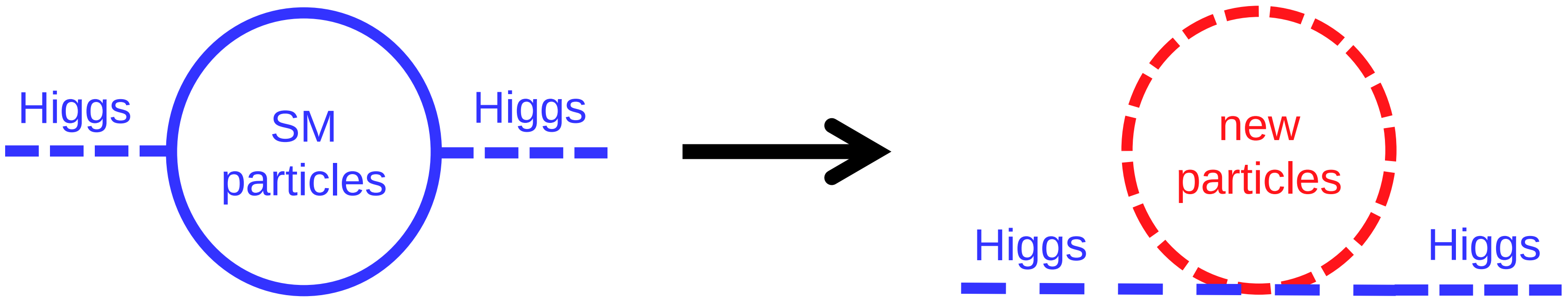
WILL HISTORY REPEAT ITSELF?

- Strong nuclear force
  - 1935: Yukawa postulates a new mass scale ~ 100 MeV
  - 1947: A boson is discovered with this mass, associated with broken (global) symmetry: the charged pion
  - Next 20 years: Many accompanying particles are discovered and studied in particle and astroparticle experiments

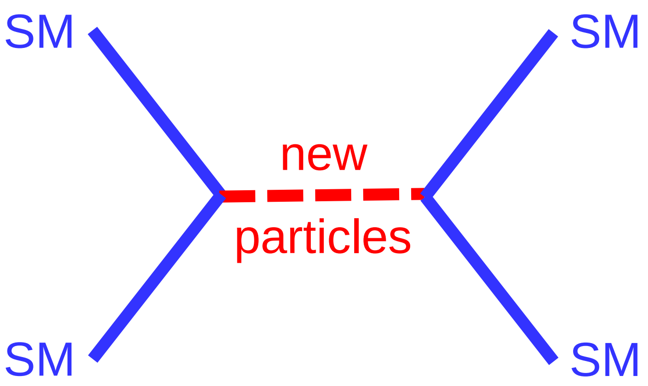
- Weak nuclear force
  - 1930's: Fermi postulates a new mass scale ~ 100 GeV
  - 2012: A boson is discovered with this mass, associated with broken (gauge) symmetry: the Higgs boson
  - Next 20 years: Many accompanying particles, including dark matter, are discovered and studied in particle and astroparticle experiments

REASONS FOR OPTIMISM

- Gauge hierarchy problem → new particles ~ 100 GeV

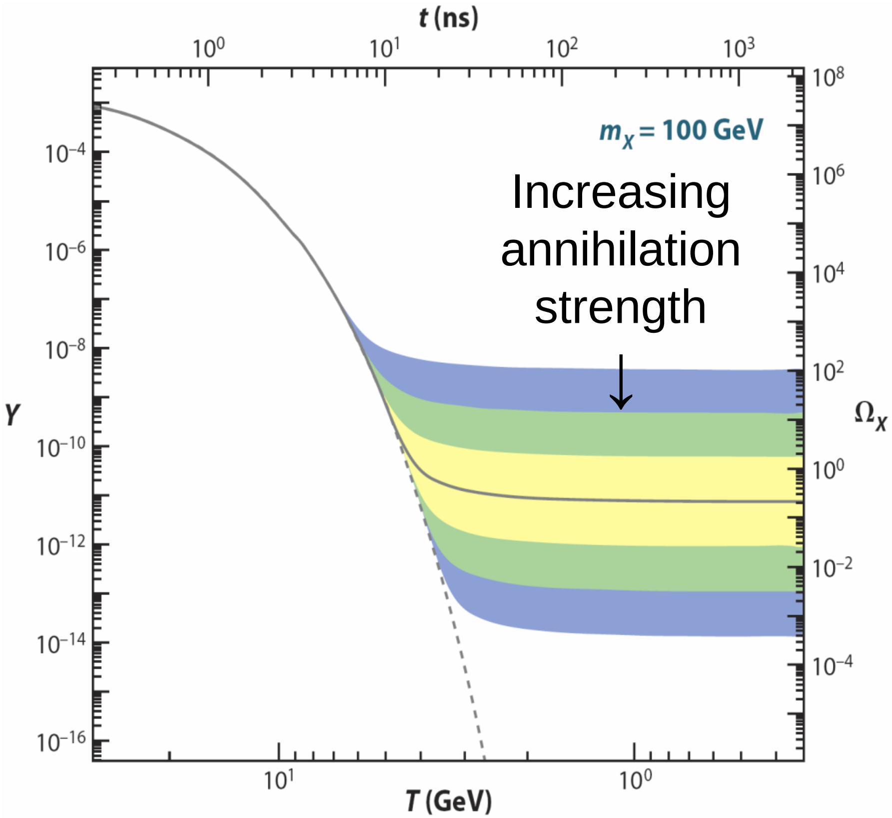


- Electroweak precision measurements → one is stable
  - 100 GeV particles generically violate constraints
  - Simple solution: Impose discrete parity, so all interactions require pairs of new particles
  - consequence: lightest new particle is stable, contributes to dark matter
  - Precision data → qualitatively new conclusions



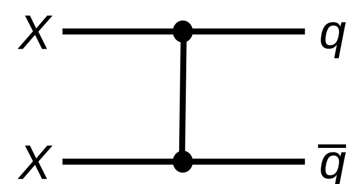
Cheng, Low (2003); Wudka (2003)

THE WIMP MIRACLE



- If you add a new particle to the Universe, the amount of it left over now is related to its annihilation cross section:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



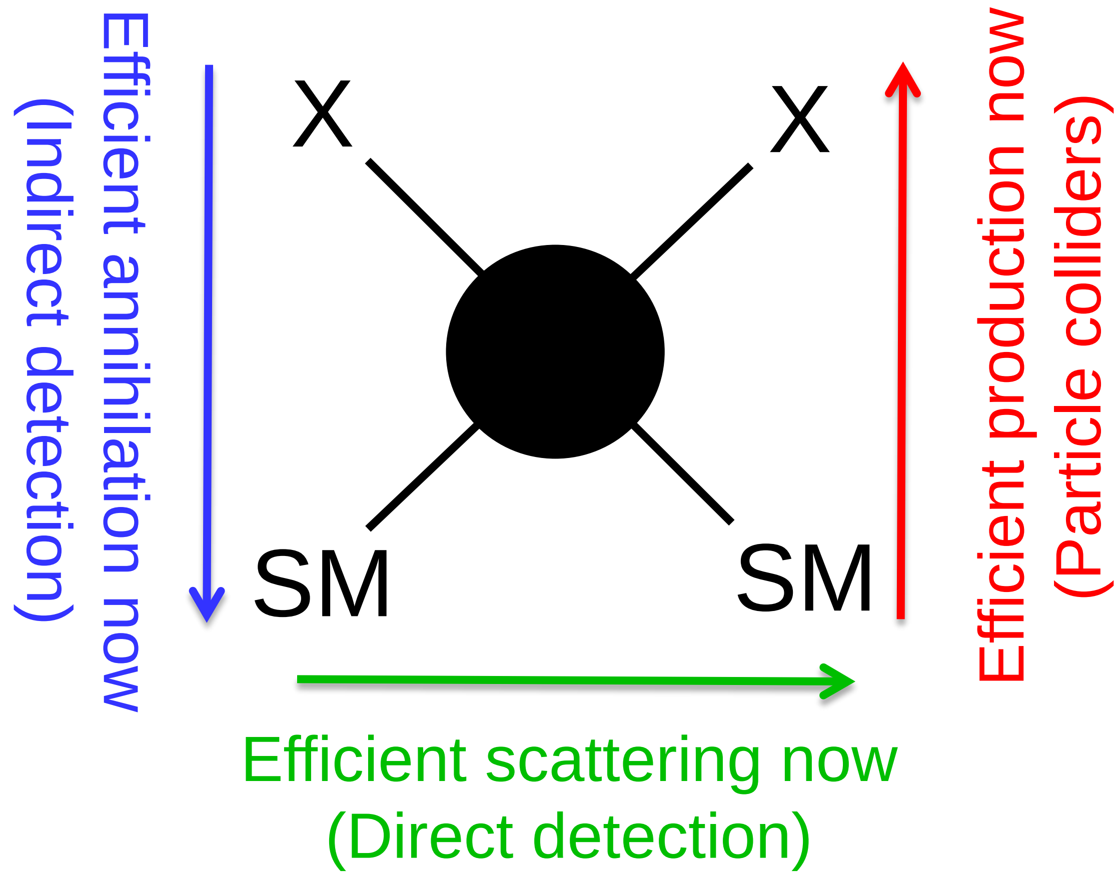
- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

- Remarkable coincidence: both particle physics and cosmology point to the 100 GeV scale for new particles

WIMP HUNTING

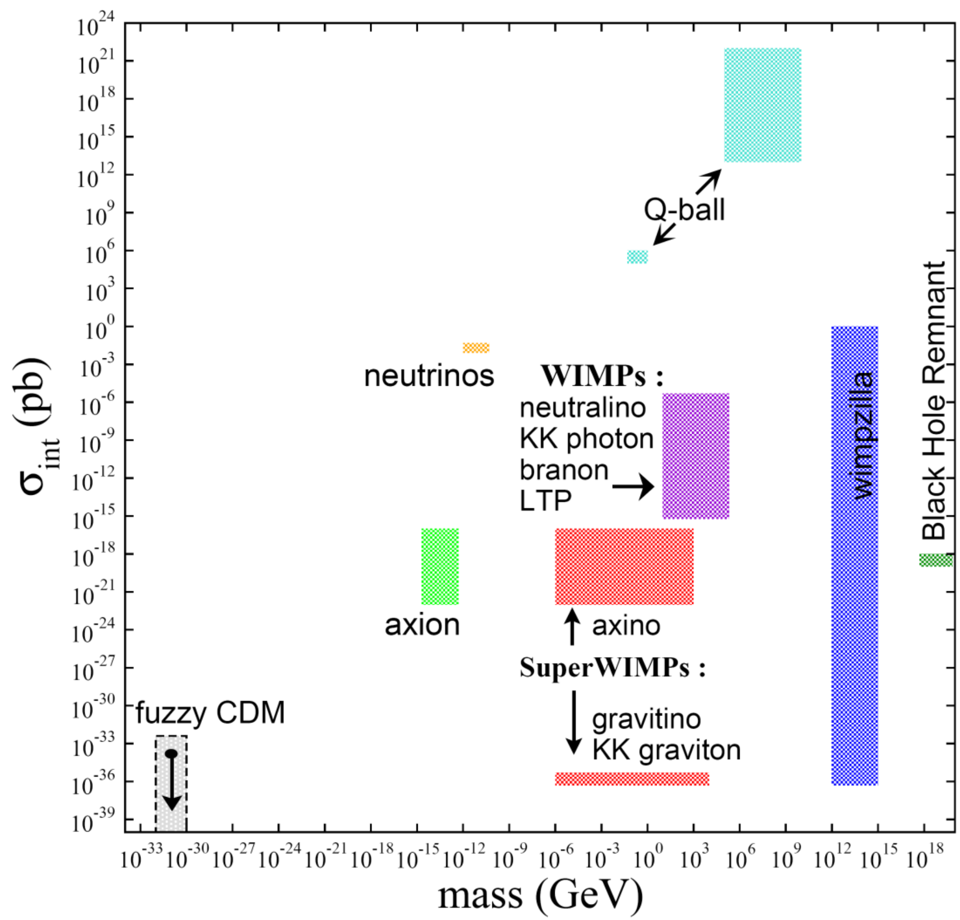
Correct relic density → Efficient annihilation then

- WIMP Miracle
  - Motivates a class of dark matter particles
  - Tells us how to look for them
  - Tells us when to stop



OF COURSE, THIS MAY BE WRONG

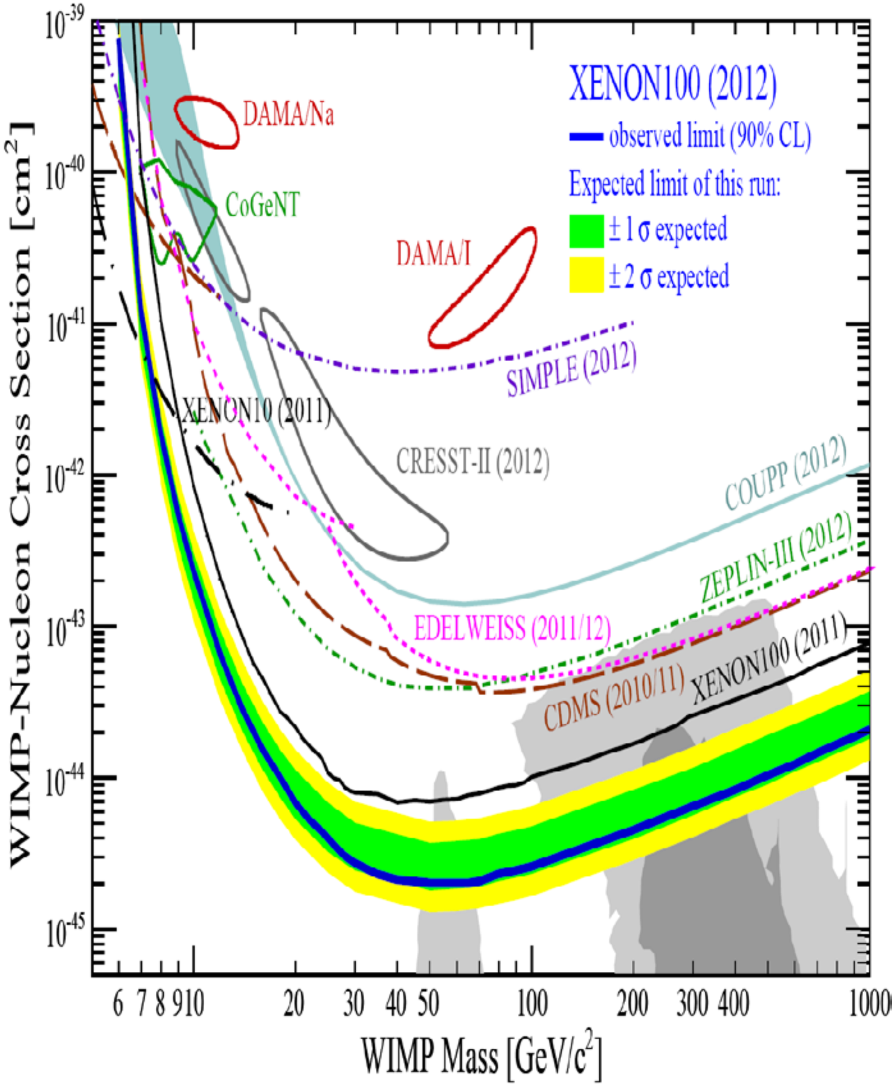
- There are many other candidates
- However, for WIMPs, we are on the threshold of *something*
- Same is true for axions
- Others? See later talks



HEPAP/AAAC DMSAG Subpanel (2007)

WIMP DIRECT DETECTION

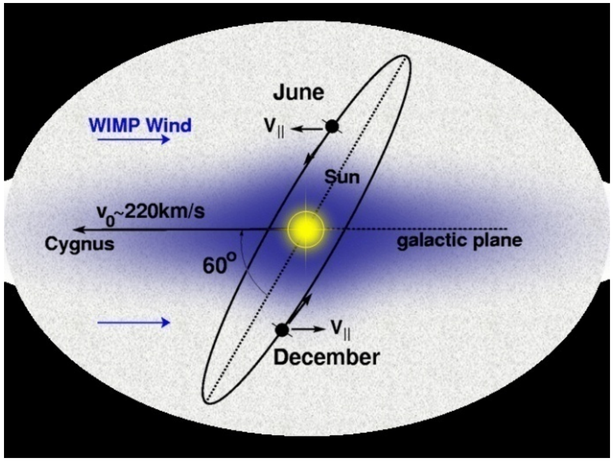
- Spin-independent results typically normalized to DM-nucleon cross sections, assuming DM-proton and DM-neutron couplings are equal
- Rapid progress in recent years
- Two regions of great current interest
  - Low mass frontier
  - Low cross section frontier



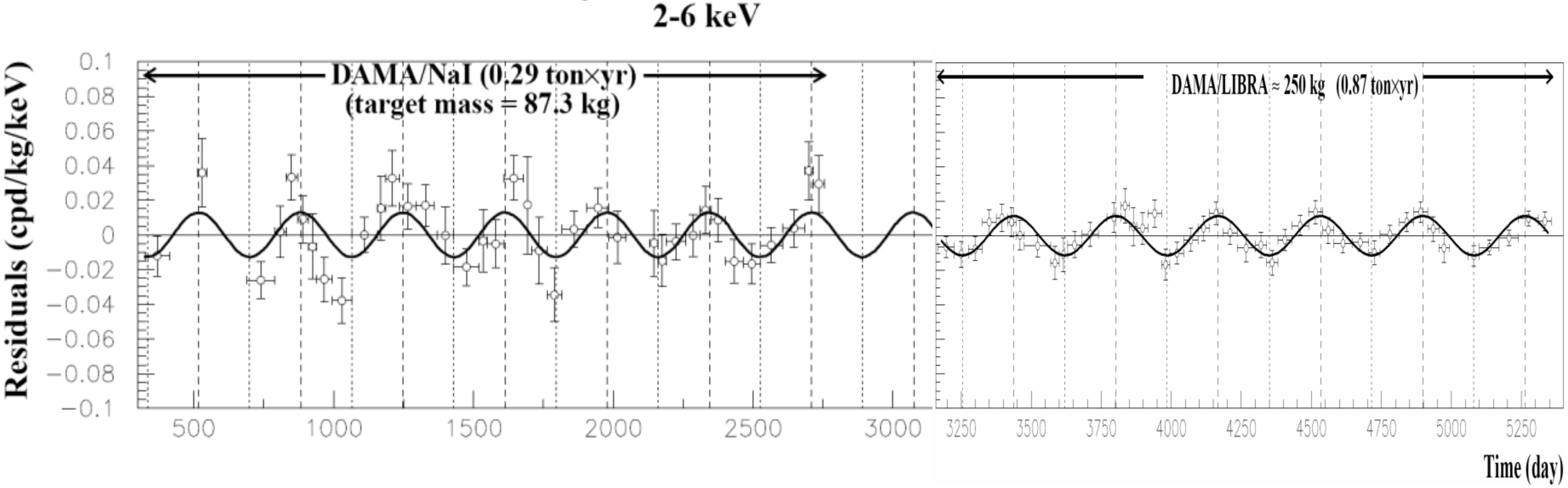
LOW MASS FRONTIER

Some experiments already claim a signal! E.g., collision rate should change as the Earth goes around the Sun → annual modulation

Drukier, Freese, Spergel (1986)



DAMA/LIBRA: 8.9σ signal with T ≈ 1 year, maximum ≈ June 2

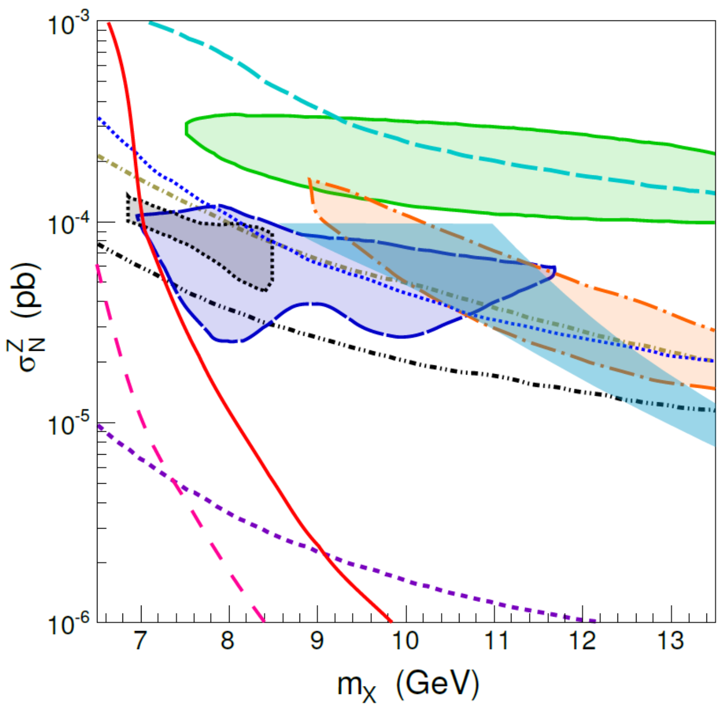


DAMA/LIBRA (2010)

DAMA signal now supplemented by CoGeNT, CRESST

CURRENT STATUS

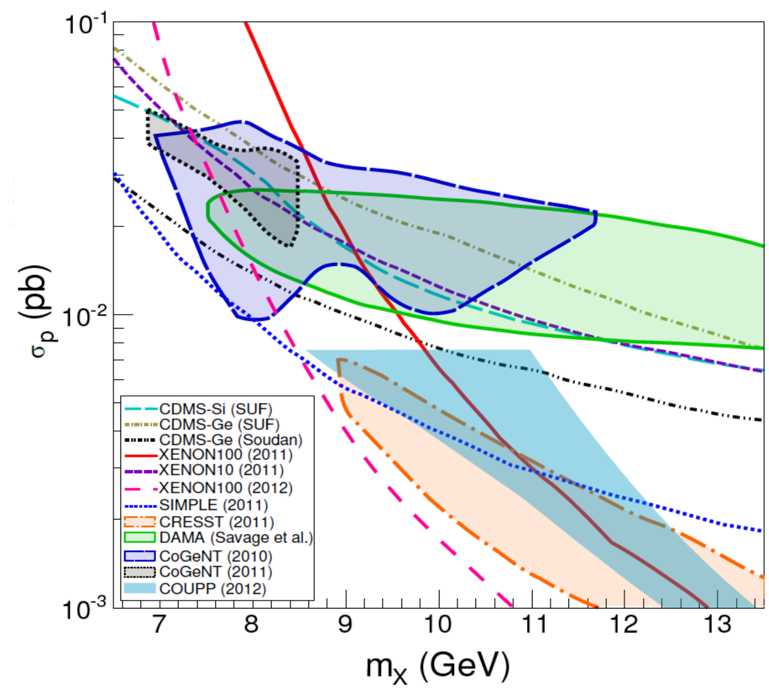
- Puzzles
  - Low mass and high σ
  - DAMA ≠ CoGeNT
  - Excluded by XENON, CDMS
- Many proposed solutions



- E.g.: Isospin Violating DM

Giuliani (2005); Chang, Liu, Pierce, Weiner, Yavin (2010)
Feng, Kumar, Marfatia, Sanford (2011); …

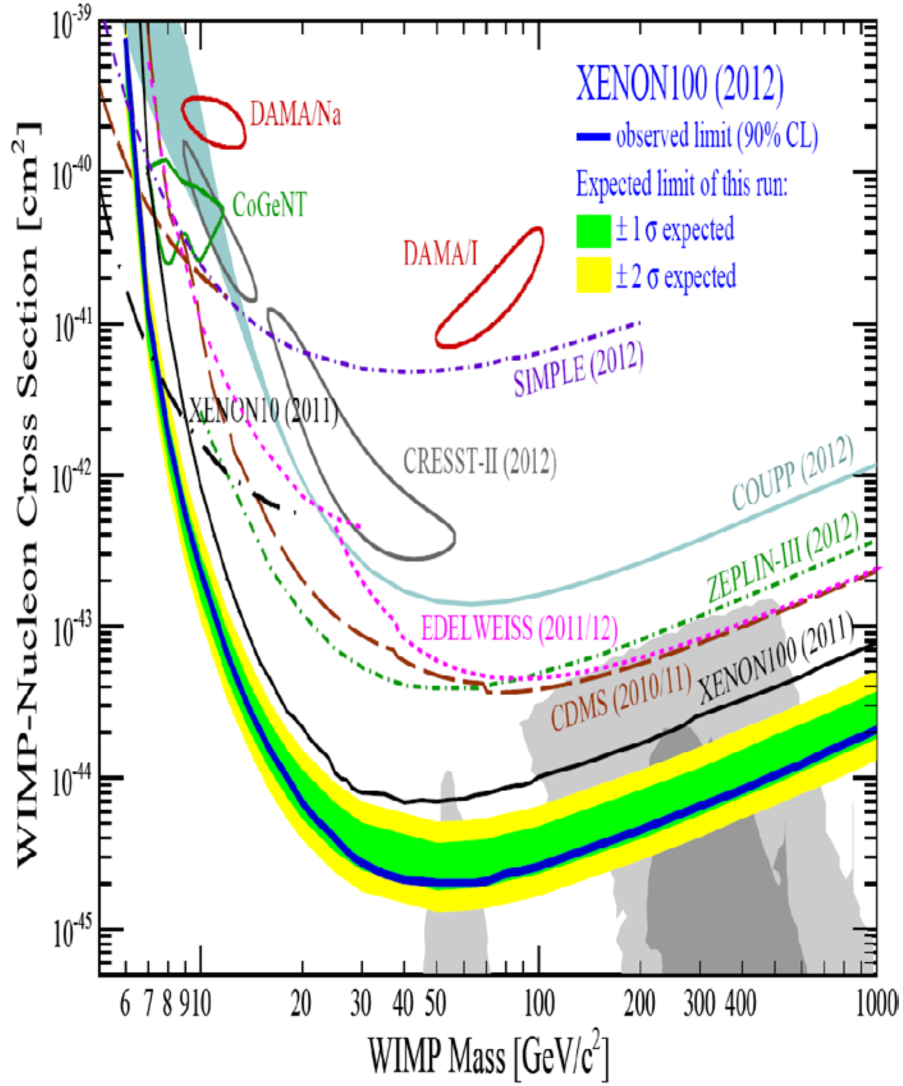
  - $\sigma_A \sim [\, f_p Z + f_n (A-Z)\,]^2$; relax $f_n = f_p$
  - Feb 11: Can reconcile all data with f_n=-0.7 f_p
  - Oct 12: New data clouds this interpretation (and all others)



LOW CROSS SECTION FRONTIER

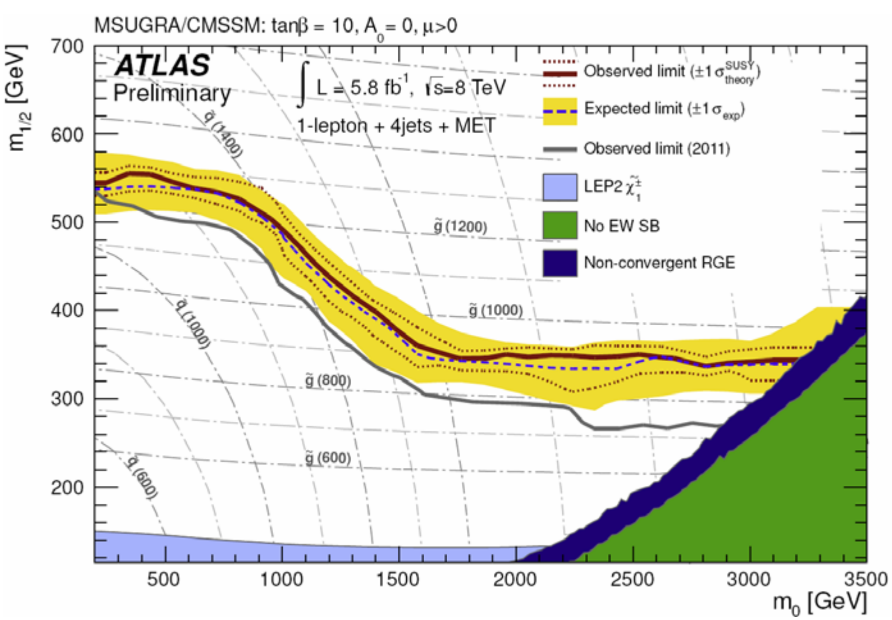
- Excitement comes from rapid experimental progress, and confrontation with theory, especially supersymmetic predictions

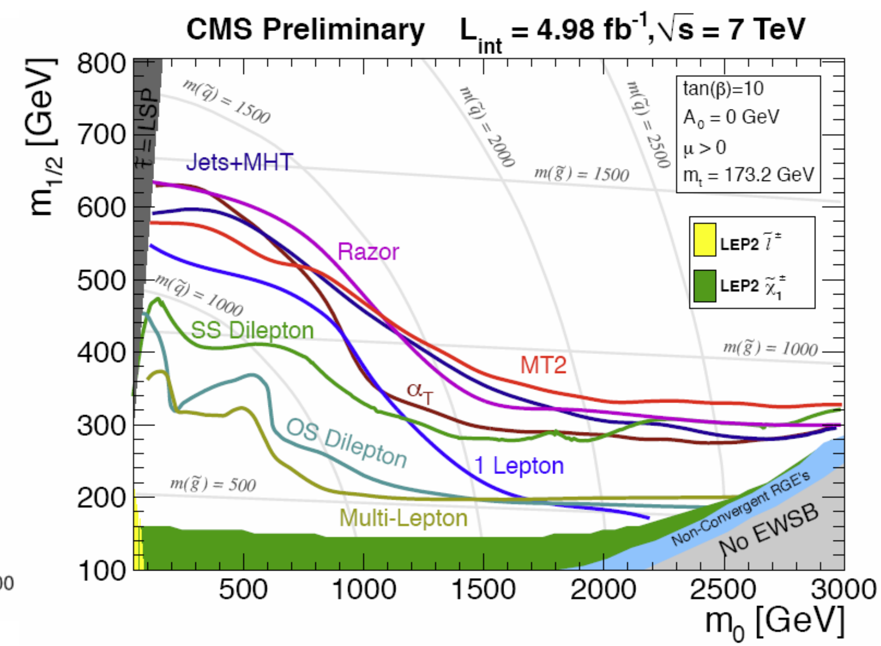
- Consider minimal supergravity / CMSSM



STATUS OF MSUGRA / CMSSM

- One often hears now that mSUGRA / CMSSM is excluded by the LHC
- The focus point region of parameter space remains viable, contains an excellent dark matter candidate: the thermal relic neutralino

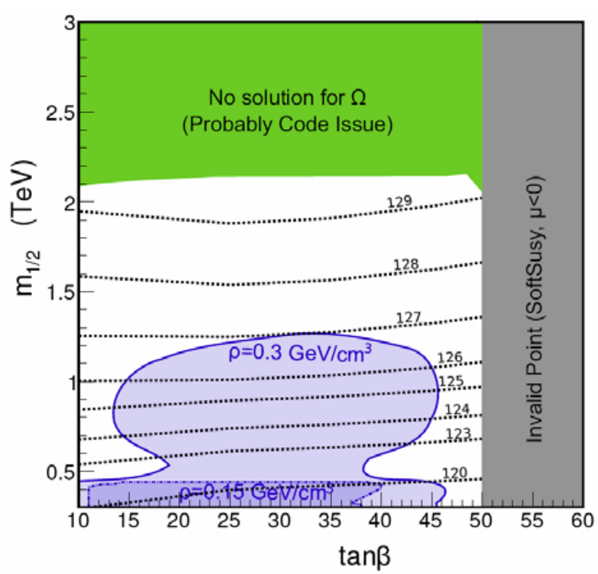


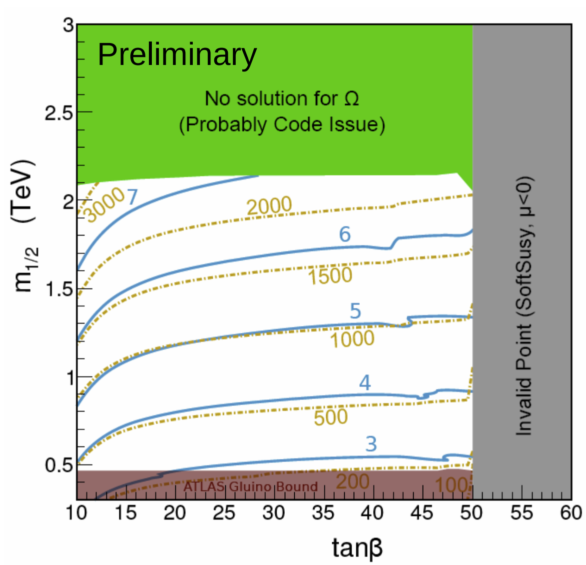


STATUS OF MSUGRA / CMSSM

- Statements that "the CSSM is excluded" presumably stem from considerations of the Higgs mass and fine-tuning
- But in work in progress, we find m_h(3-loop) – m_h(2-loop) ~3 GeV in focus point SUSY, fine-tunings ~ O(500) and 4 TeV squarks are allowed

Harlander, Kant, Milaila, Steinhauser (2008); Kant, Harlander, Mihaila, Steinhauser (2010)



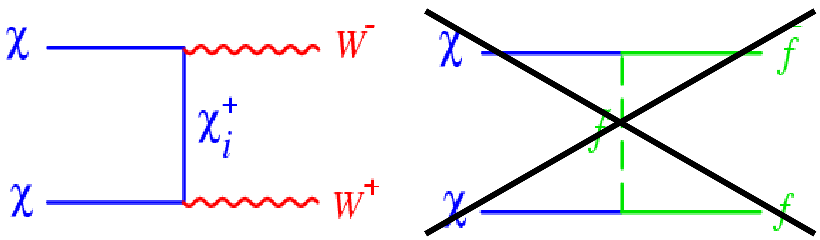


Draper, Feng, Kant, Sanford (in progress)

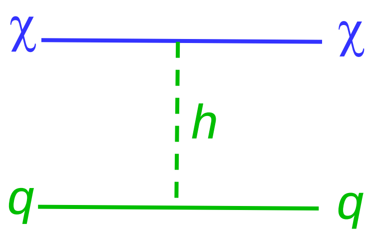
- MSUGRA /CMSSM in the focus point region is more useful than ever as an effective theory for viable SUSY models

LOW CROSS SECTION FRONTIER

- The LHC is simplifying SUSY DM. If no co-annihilation, resonances, $M_2 > M_1$, Ω fixes the DM's coupling to Ws

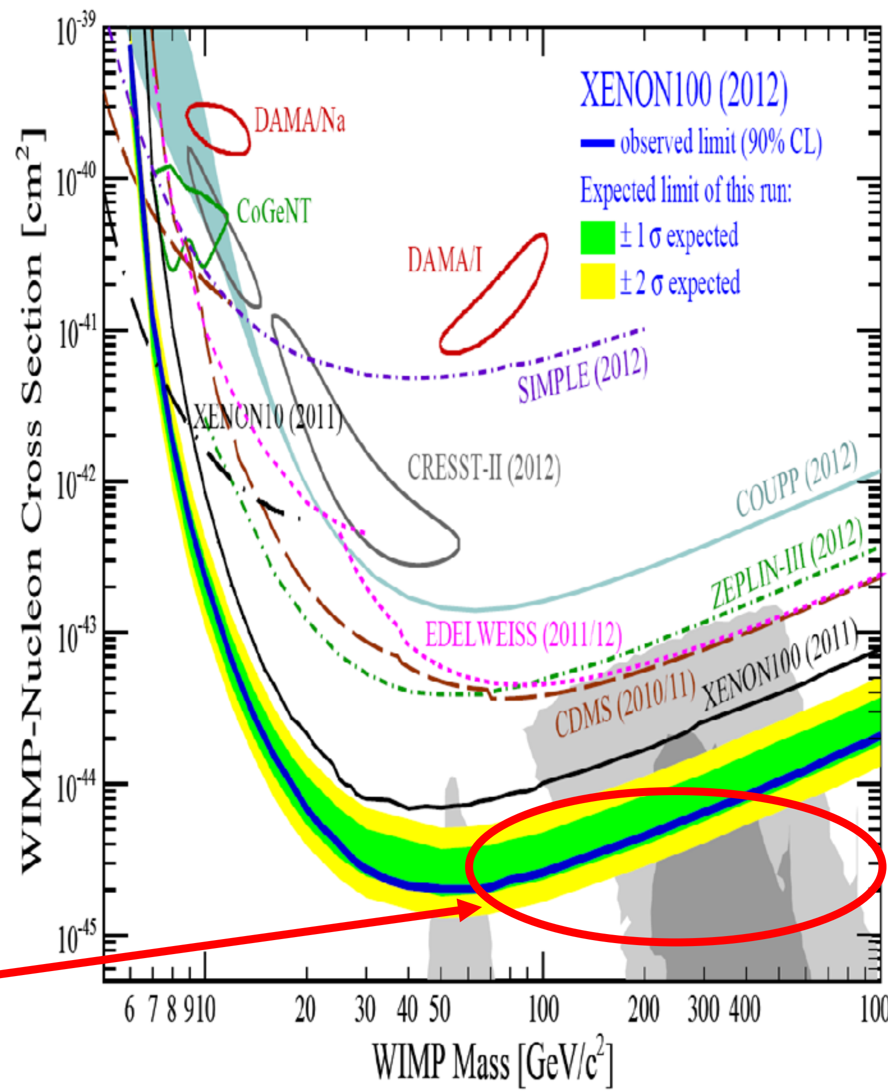


- But this also fixes the DM's coupling to the Higgs boson

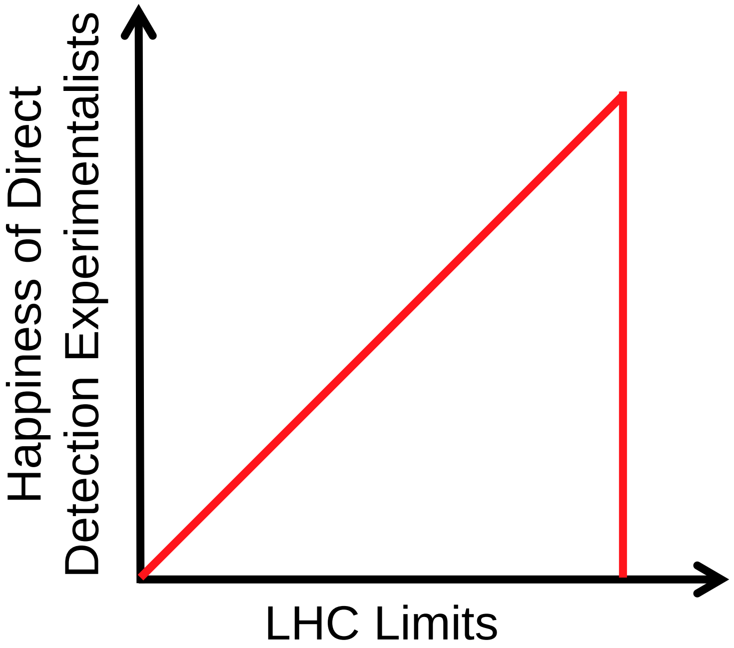


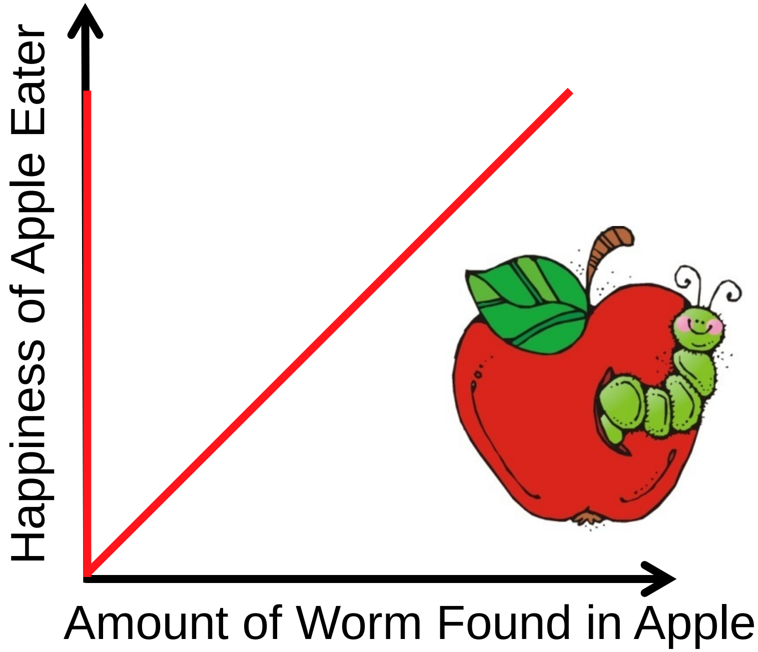
predictions collapse to a small region with σ ~ 1-10 zb

- Improvement by factors of a few will discover/exclude neutralino DM in minimal SUSY!



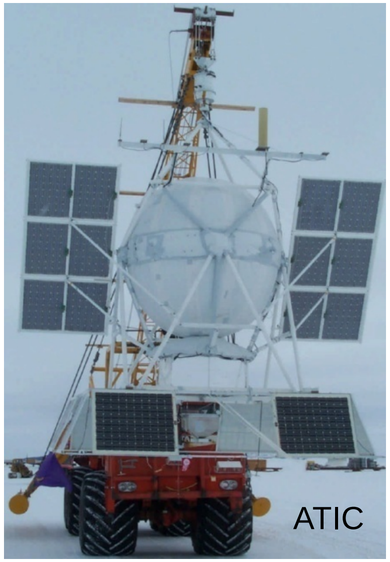
NEUTRALINO DM IN MINIMAL SUSY



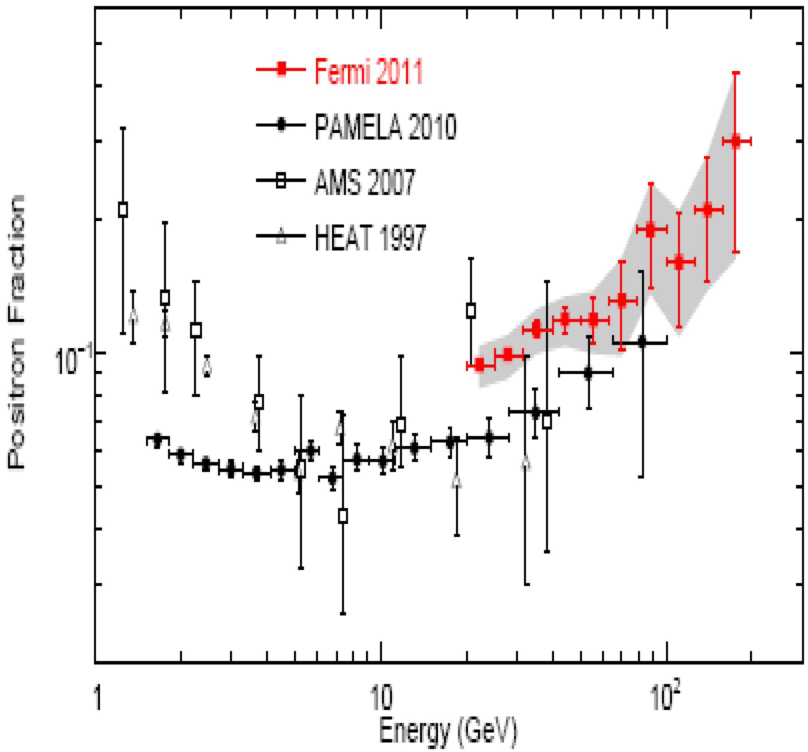


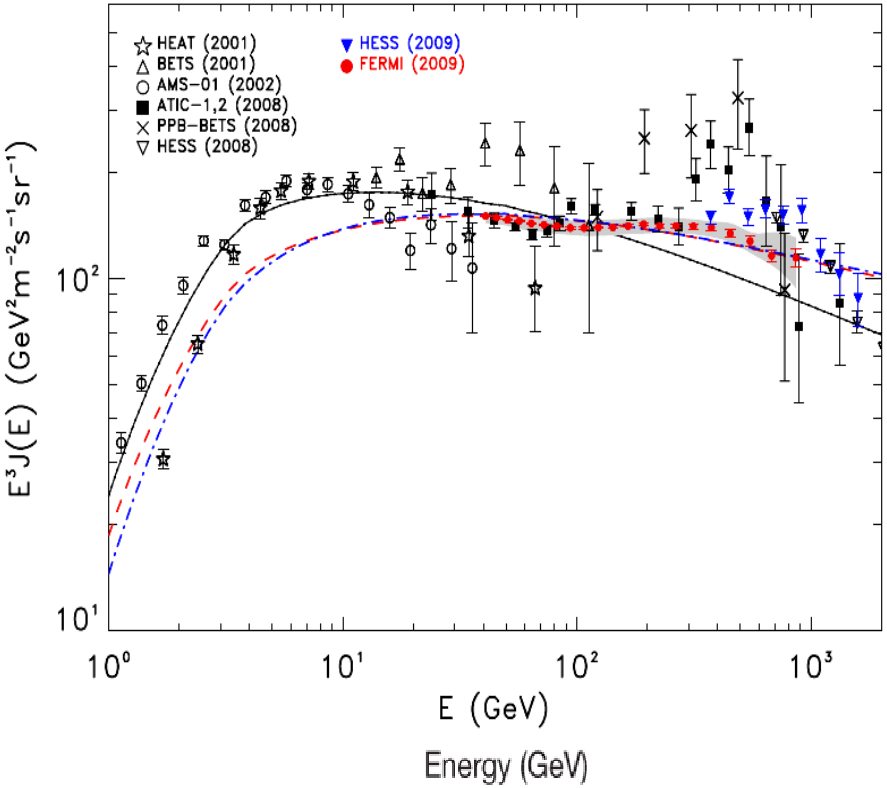
INDIRECT DETECTION: POSITRONS

Dark Matter annihilates in the galactic halo (a place) to positrons (some particles), which are detected by PAMELA/ATIC/Fermi… (an experiment).



POSITRON SIGNALS

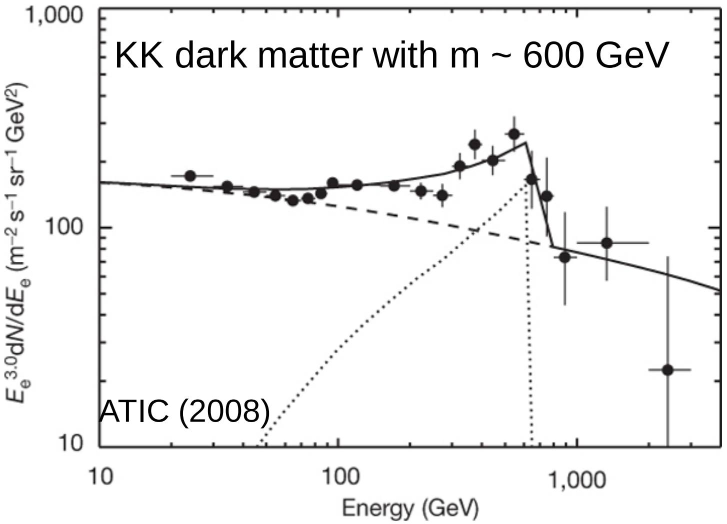


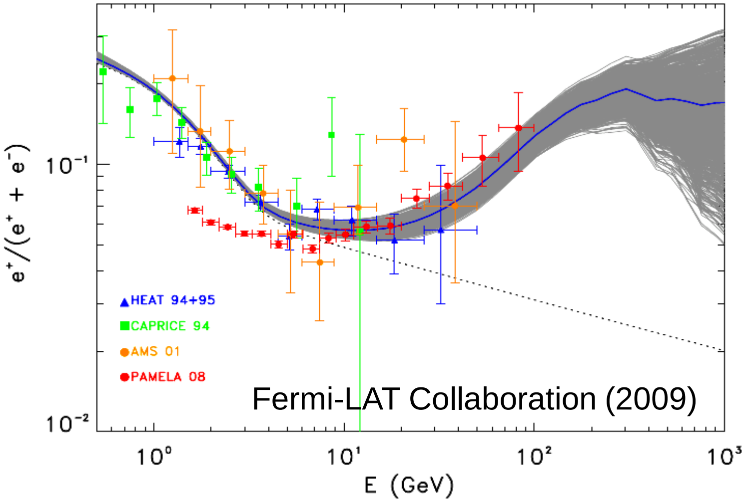


Solid lines are the astrophysical bkgd from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

- The shape of the energy spectrum is consistent with WIMPs; e.g., Kaluza-Klein dark matter
- Unfortunately, the flux is a factor of 100-1000 too big for a thermal relic; requires
  - Enhancement from particle physics
  - Alternative production mechanism
- At this point, pulsars are a more likely explanation



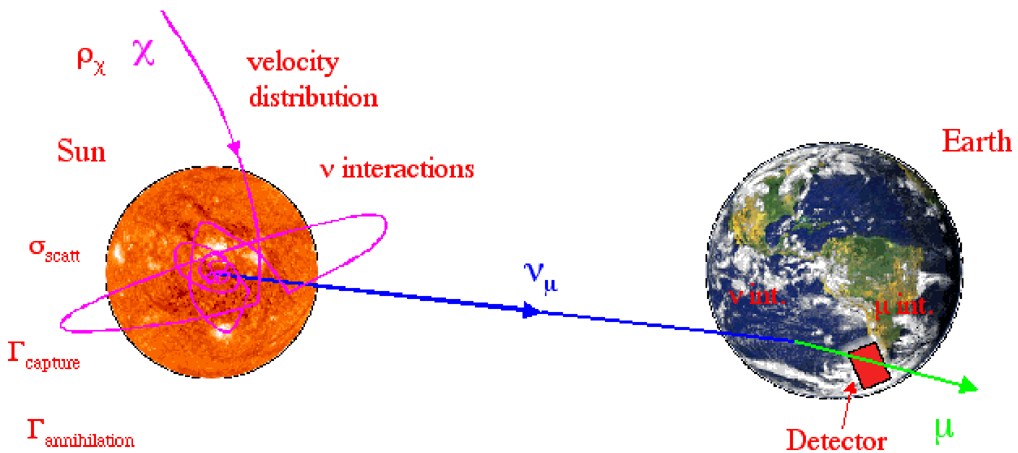


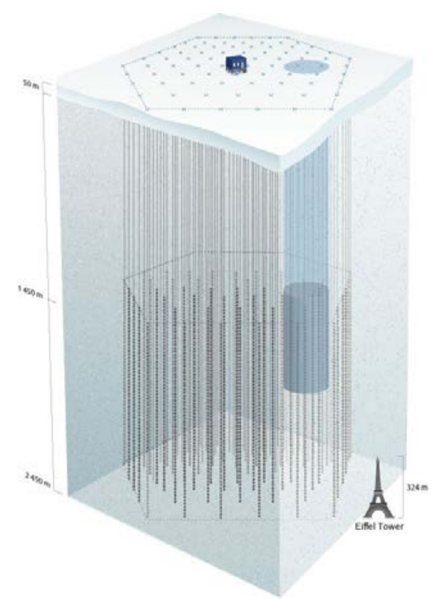
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008); Profumo (2008)
Fermi-LAT Collaboration (2009)

INDIRECT DETECTION: NEUTRINOS

Dark Matter annihilates in __the center of the Sun__ to
a place

__neutrinos__ , which are detected by ______IceCube______ .
some particles an experiment



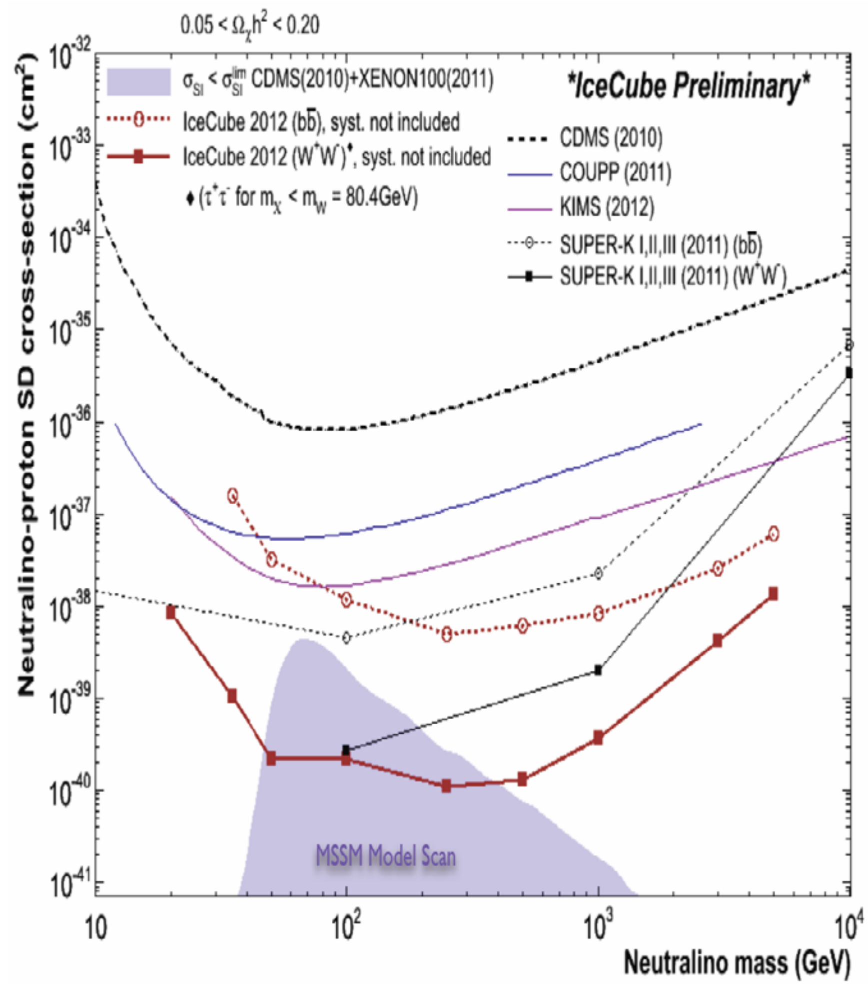


NEUTRINO SIGNALS

- If the Sun is in equilibrium, scattering (direct detection) and annihilation (indirect detection) are related

$$\frac{dN}{dt} = C - C_A N^2$$

- Indirect detection surpasses direct detection for spin-dependent scattering, is beginning to probe viable theoretical models (spin-independent interesting also)



INDIRECT DETECTION: GAMMA RAYS

Dark Matter annihilates in <u> GC, dwarf galaxies </u> to
a place

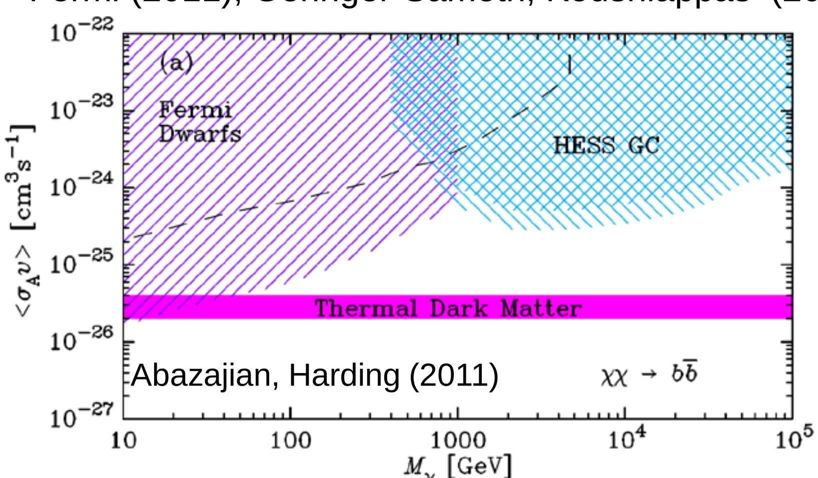
<u> photons </u> , which are detected by <u> Fermi, HESS, VERITAS, … </u>
some particles an experiment

GAMMA RAY SIGNALS

- Continuum: *X X* → *f f* → γ
- For some annihilation channels, bounds exclude light thermal relics

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

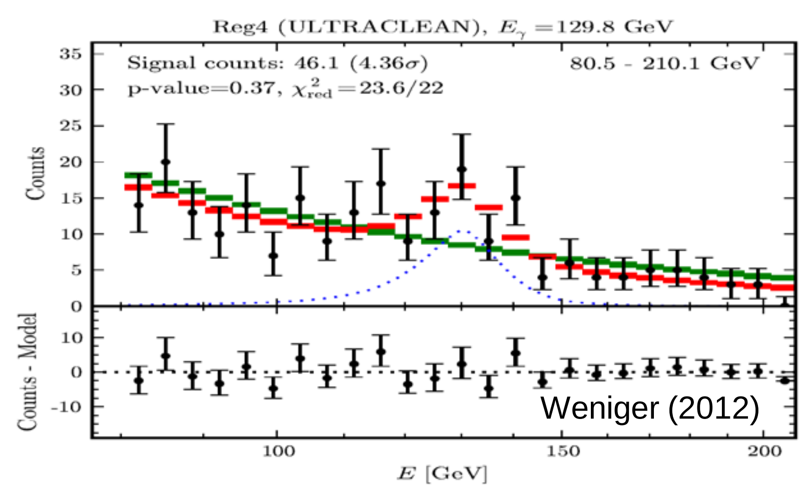
Fermi (2011); Geringer-Sameth, Koushiappas (2011)



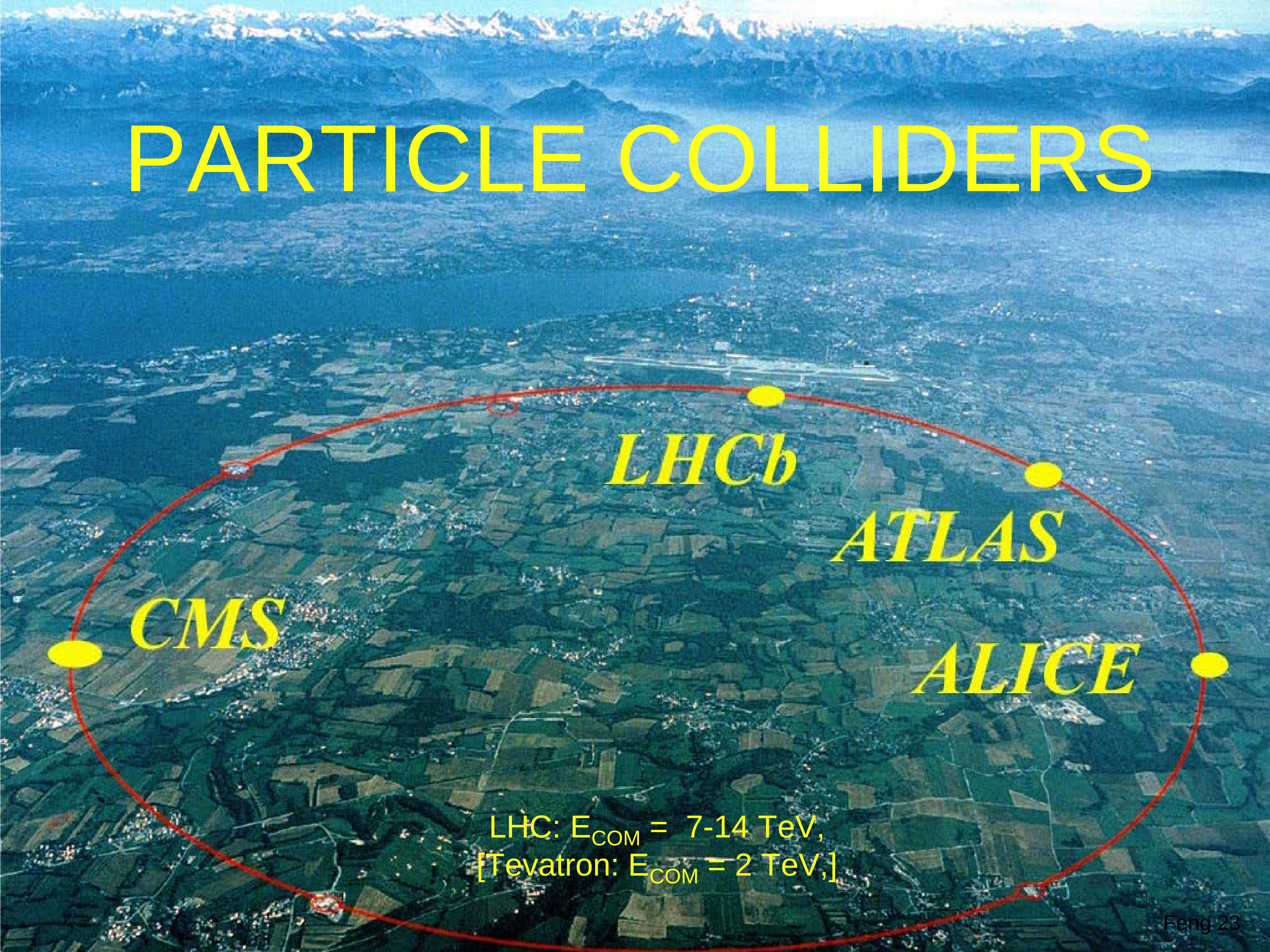
- Lines: *X X* → γγ, γ*Z* (loop-level)
- Great current interest: 3-5σ signal at E_γ =130 GeV, ⟨σv⟩ = 1·10^{-27} cm^3/s

Weniger (2012); Tempel, Hektor, Raidal (2012); Rajaraman, Tait, Whiteson (2012); Su, Finkbeiner (2012); …

Future: HESS2, HAWC, CTA, GAMMA-400, CALET, …



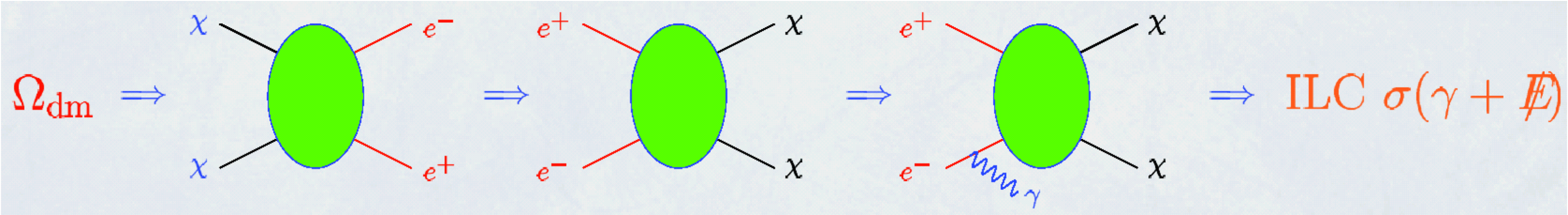
PARTICLE COLLIDERS



DIRECT PRODUCTION AT COLLIDERS

- Thermal relic WIMPs annihilate to SM particles, and so should be produced directly at colliders

- Pair production is invisible, so consider photon radiation



Birkedal, Matchev, Perelstein (2004)

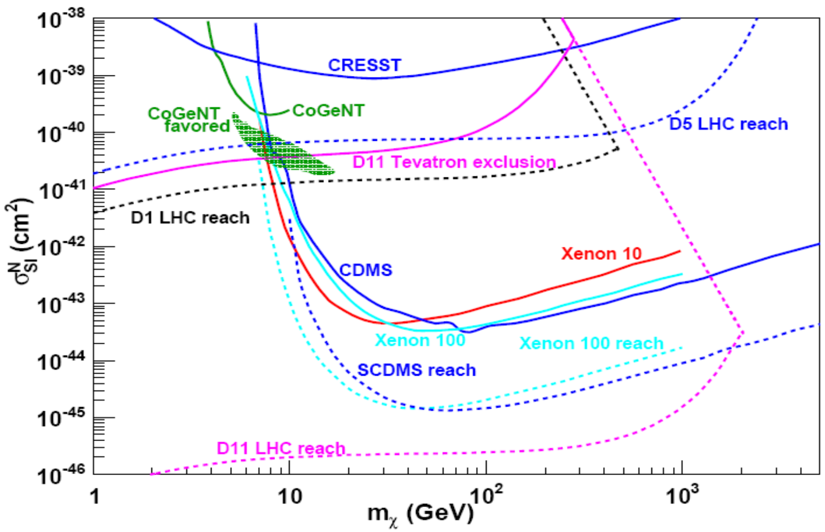
- Also mono-jets, mono-photons at Tevatron and LHC

Feng, Su, Takayama (2005); Beltran, Hooper, Kolb, Krusberg, Tait (2010)

Konar, Kong, Matchev, Perelstein (2009)

WIMP EFFECTIVE THEORY

- This idea has recently been extended and studied systematically
- Assume WIMPs are light, integrate out all other particles, yielding a list of effective operators (motivated by DAMA, CoGeNT, CRESST, for example)



Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)

Bai, Fox, Harnik (2010); …

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

BEYOND WIMPS

- Does the WIMP paradigm imply WIMPs?

- The WIMP miracle seemingly implies that dark matter is
  - Weakly-interacting
  - Cold
  - Collisionless

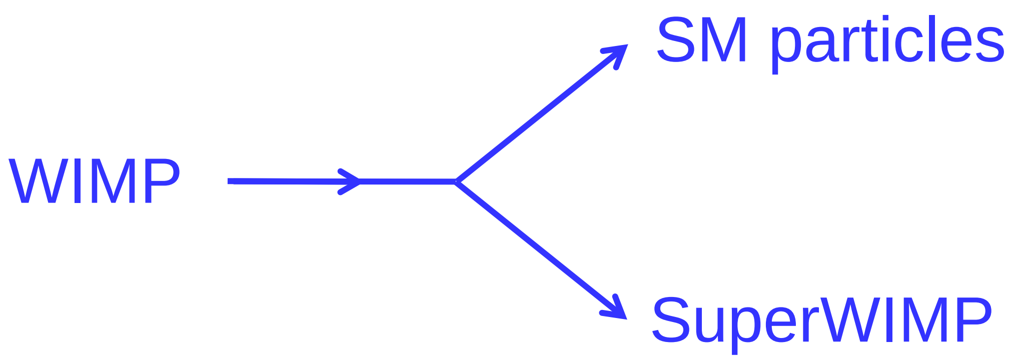
  Are all WIMP miracle-motivated candidates like this?

- No! Recently, many new classes of candidates have been proposed. Some preserve the motivations of the WIMP paradigm, but have qualitatively different properties relevant even for astrophysicists!

SUPERWIMPS

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmuller, Hamaguchi, Ratz, Yanagida (2004); …

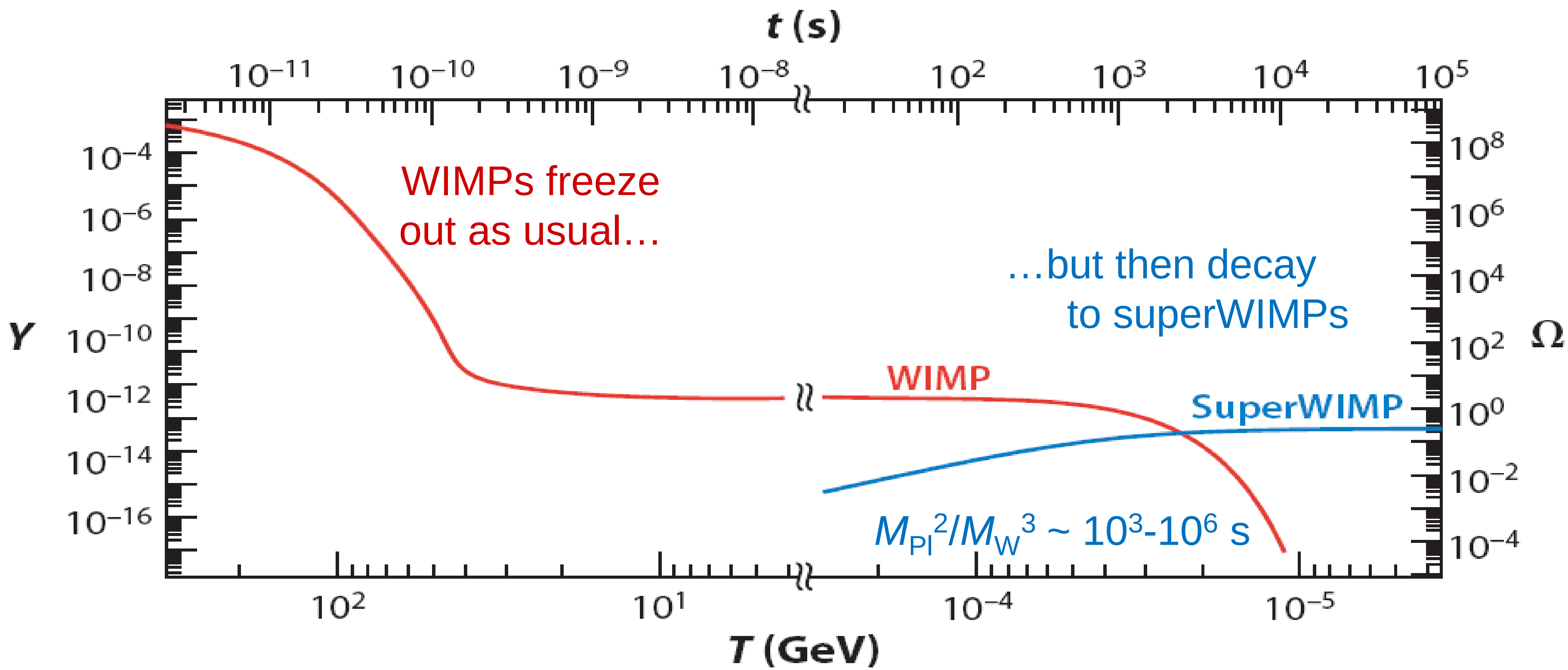
- Suppose the WIMP can decay into a superweakly-interacting particle (superWIMP):



- This is not completely contrived: it happens about ½ the time in simple SUSY, where the gravitino plays the role of the superWIMP:

WIMP (mass + charge) → superWIMP (mass) + SM particles (charge)

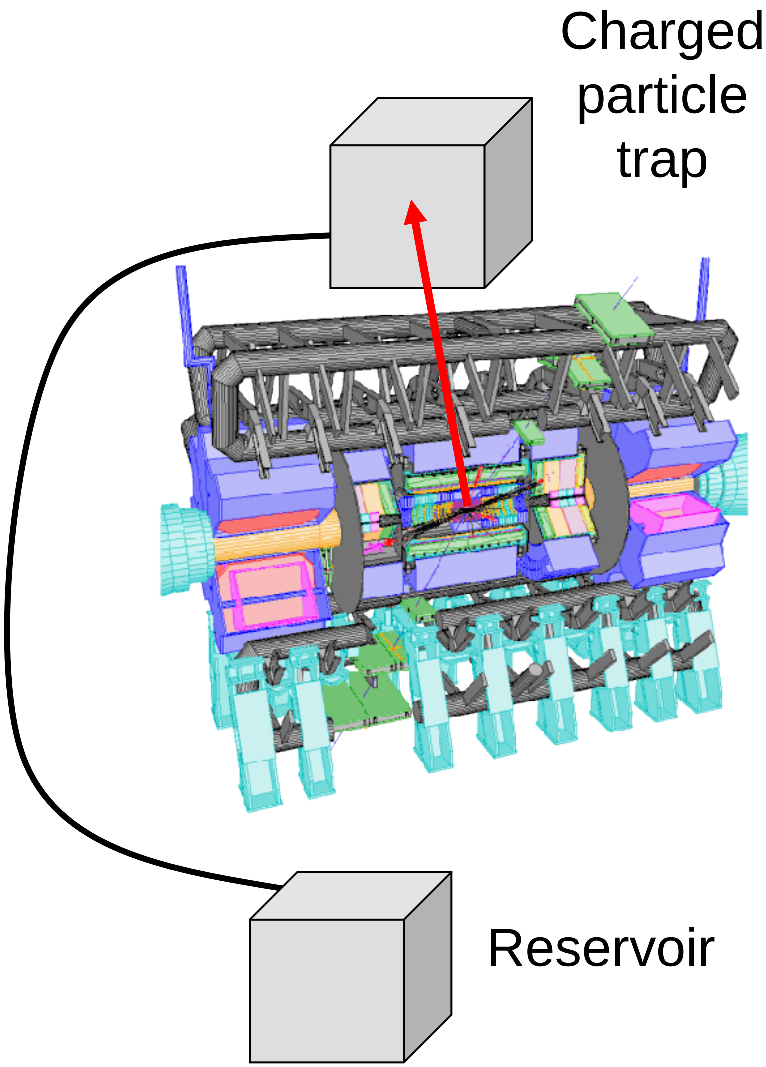
FREEZE OUT WITH SUPERWIMPS



SuperWIMPs naturally inherit the right density; share all motivations of WIMPs, but are much more weakly interacting: no direct, indirect signals

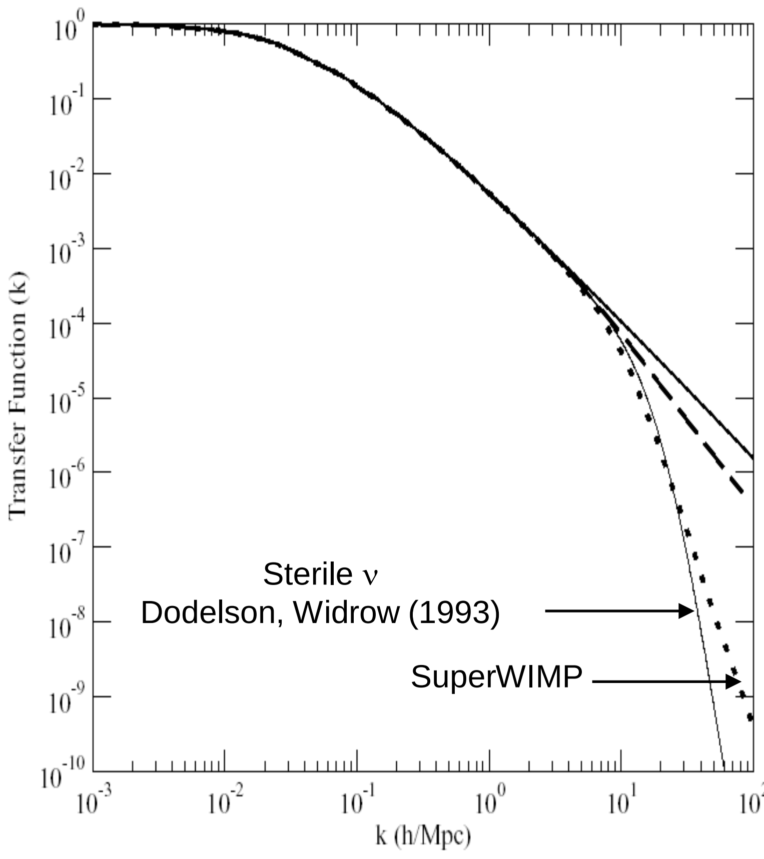
CHARGED PARTICLE TRAPPING

- SuperWIMPs are produced by decays of metastable particles, which can be charged
- Collider implications: signal is not missing E_T, but charged metastable particles, CHAMP searches are important for dark matter
- Can be trapped and moved to a quiet environment to study their decays



WARM SUPERWIMPS

- SuperWIMPs are produced at “late” times with large velocity (0.1c – c)
- Suppresses small scale structure, as determined by λ_{FS}
- Warm DM with cold DM pedigree



Kaplinghat (2005)

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)

WIMPLESS DARK MATTER

Feng, Kumar (2008); Feng, Tu, Yu (2009); McKeen (2009); Feng, Kaplinghat, Yu (2010); Das, Sigurdson (2010); Barger, Kumar, Marfatia, Sessolo (2010); Feng, Shadmi (2011); Feng, Rentala, Surujon (2011); …

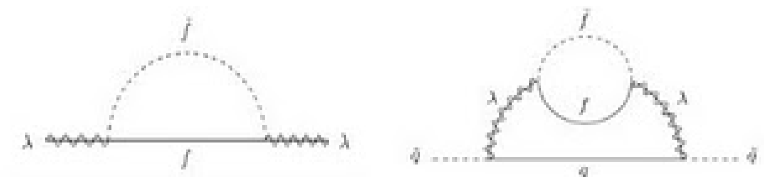
- Dark matter could be hidden, with no SM couplings; this is viable, since all solid evidence for DM is gravitational

- We could even give it the right coupling and mass to freeze out with the correct relic density

- However, it suffers from several drawbacks
  - Missing particle physics motivations of more popular DM candidates
  - Too much model-building freedom, lack of predictivity
  - Nothing miraculous about it

WIMPLESS DARK MATTER

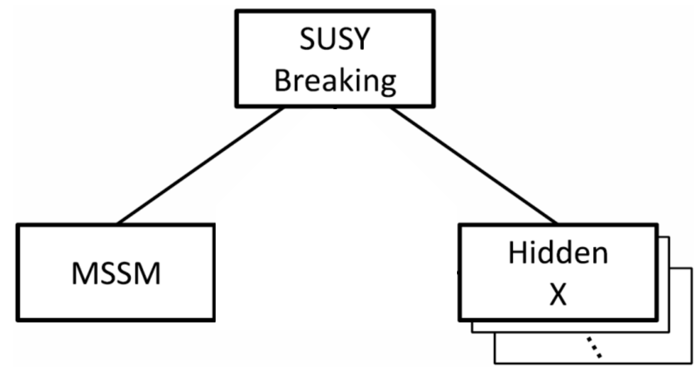
- Consider SUSY with a hidden sector. In models that suppress flavor violation (GMSB, AMSB…), $m_X \sim g_X^2$

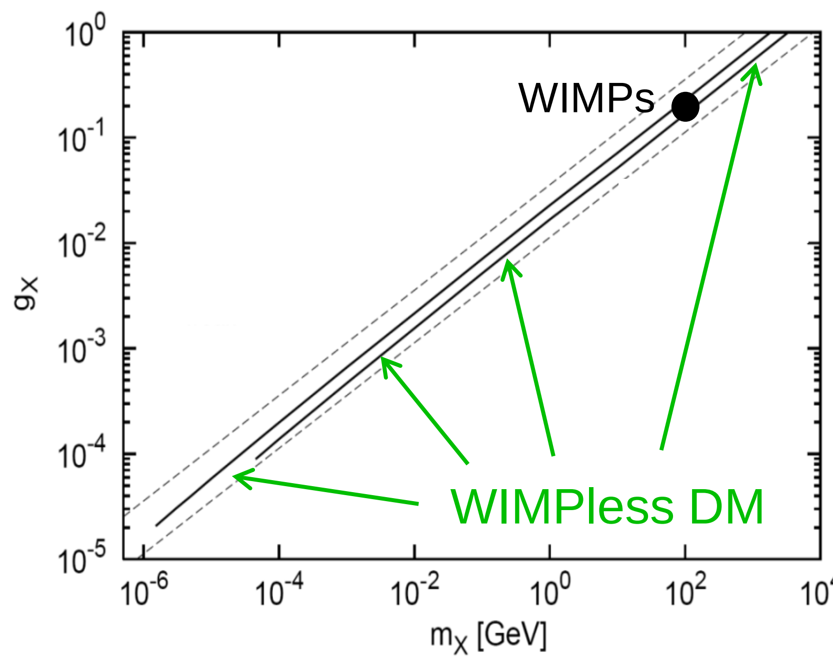


- This leaves the relic density invariant

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- Restores WIMP virtues
  - Strong particle motivations
  - Increased structure, predictivity
  - WIMPless miracle: hidden sectors of these theories automatically have DM with the right Ω
  - Is this what the new physics flavor problem has been trying to tell us?



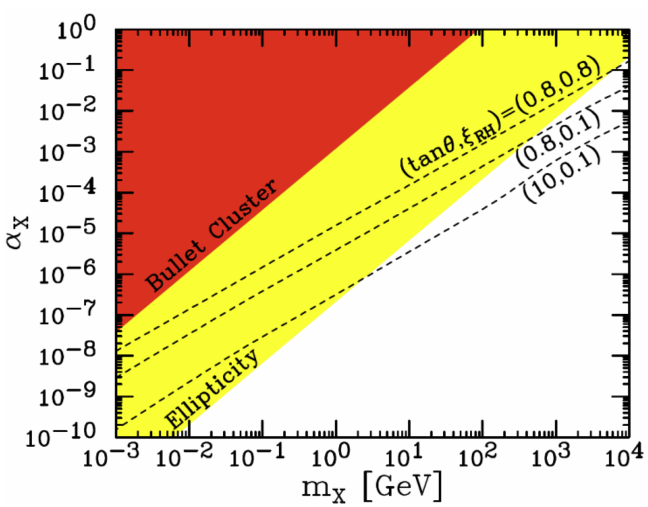


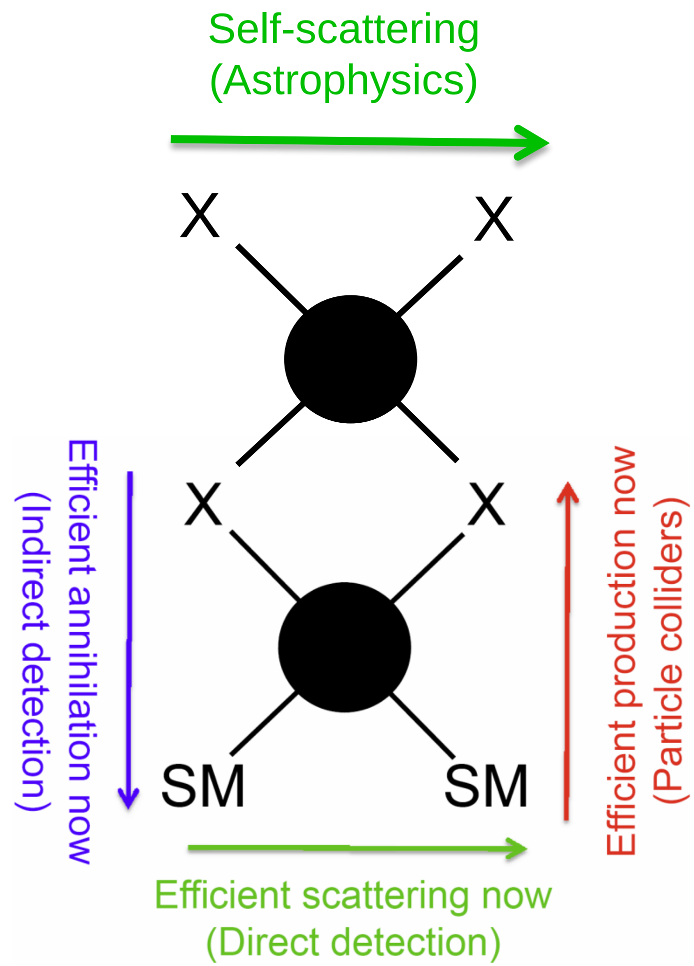
WIMPLESS DM SIGNALS

- Hidden DM may have only gravitational effects, but still interesting: e.g., it may interact through "dark photons" with several interesting effects
  - DM stabilized by charge conservation
  - Hidden photon contributes to N_{eff}
  - Self-interactions through Rutherford scattering

Ackerman, Buckley, Carroll, Kamionkowski (2008)

Feng, Kaplinghat, Tu, Yu (2009)





CONCLUSIONS

- The Higgs boson discovery signals a new era
- Both particle physics and cosmology point to the 100 GeV scale as a natural place for dark matter to appear
- WIMPs: LHC is running, direct detection, and indirect detection are improving rapidly – this field is being transformed now
- The WIMP miracle does not necessarily imply vanilla dark matter: SuperWIMPs, WIMPless DM may be warm, self-interacting,…astrophysical probes very interesting