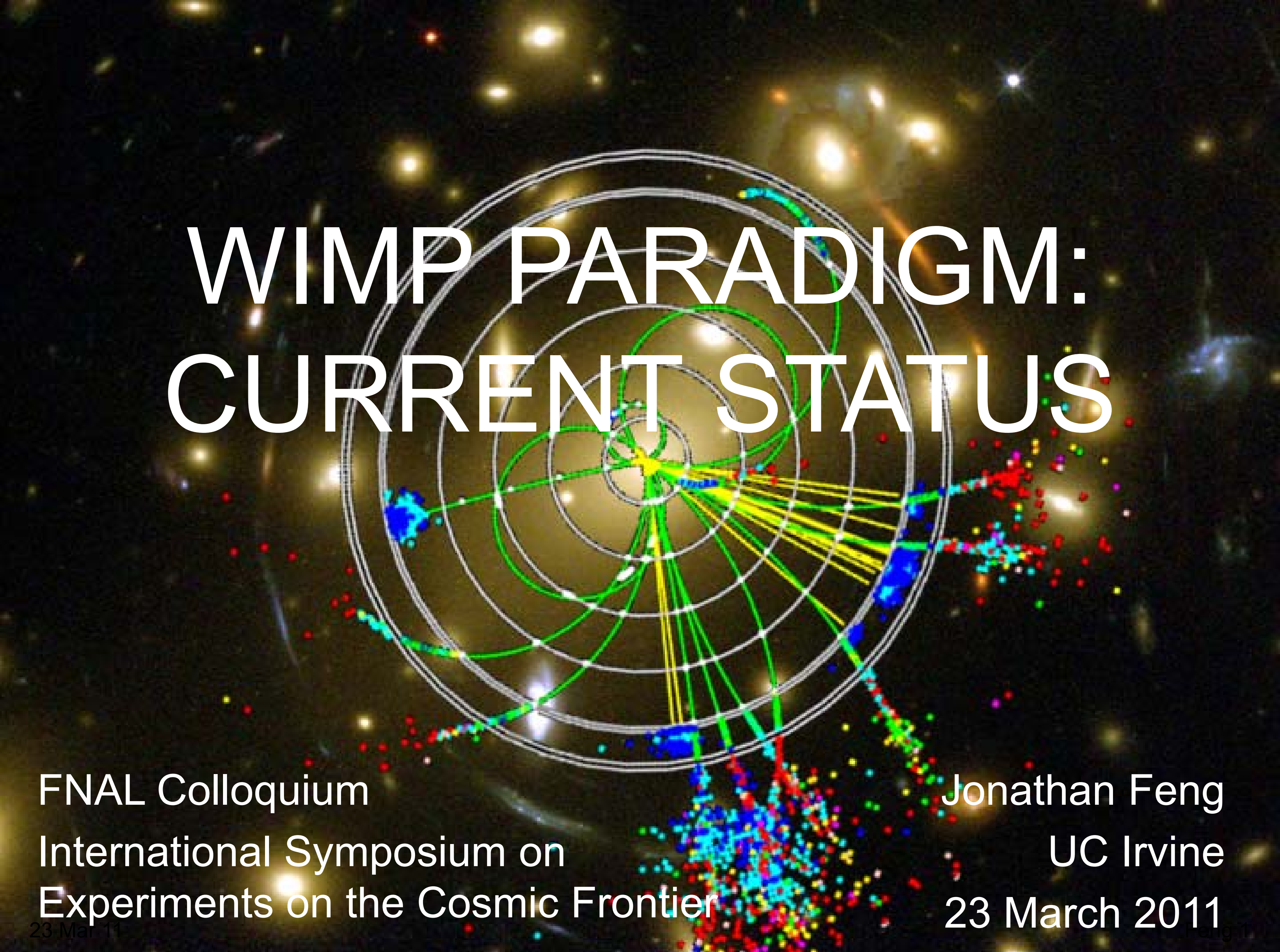


WIMP PARADIGM: CURRENT STATUS

FNAL Colloquium

International Symposium on Experiments on the Cosmic Frontier

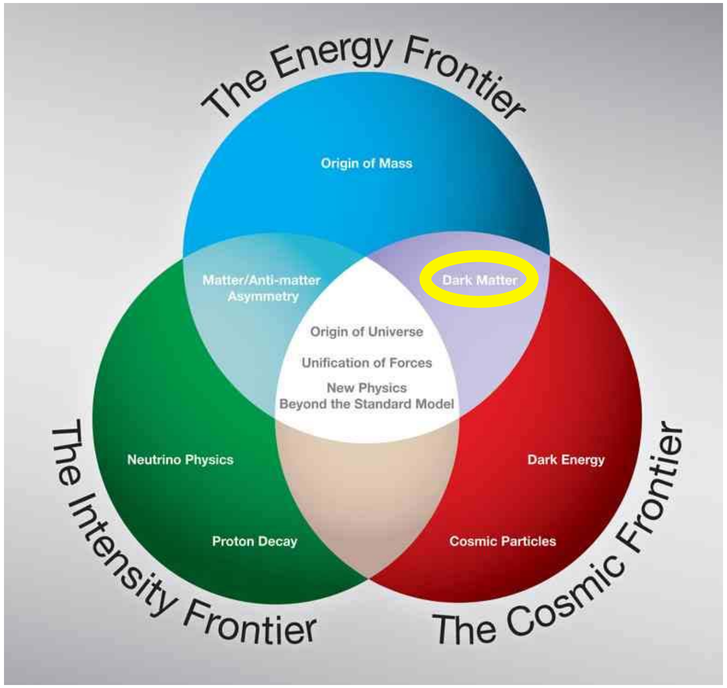
Jonathan Feng

UC Irvine

23 March 2011

THE WIMP PARADIGM

- The WIMP paradigm postulates that particles that help explain the weak scale are the dark matter. It is the glue that joins together much of the high energy and cosmic frontiers.



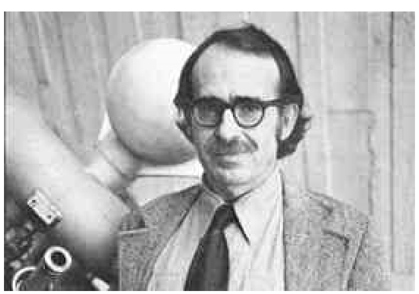
- The Rise of the WIMP Paradigm
- Recent Experimental Progress
- Recent Theoretical Progress

THE COSMIC CONNECTION, c. 1977

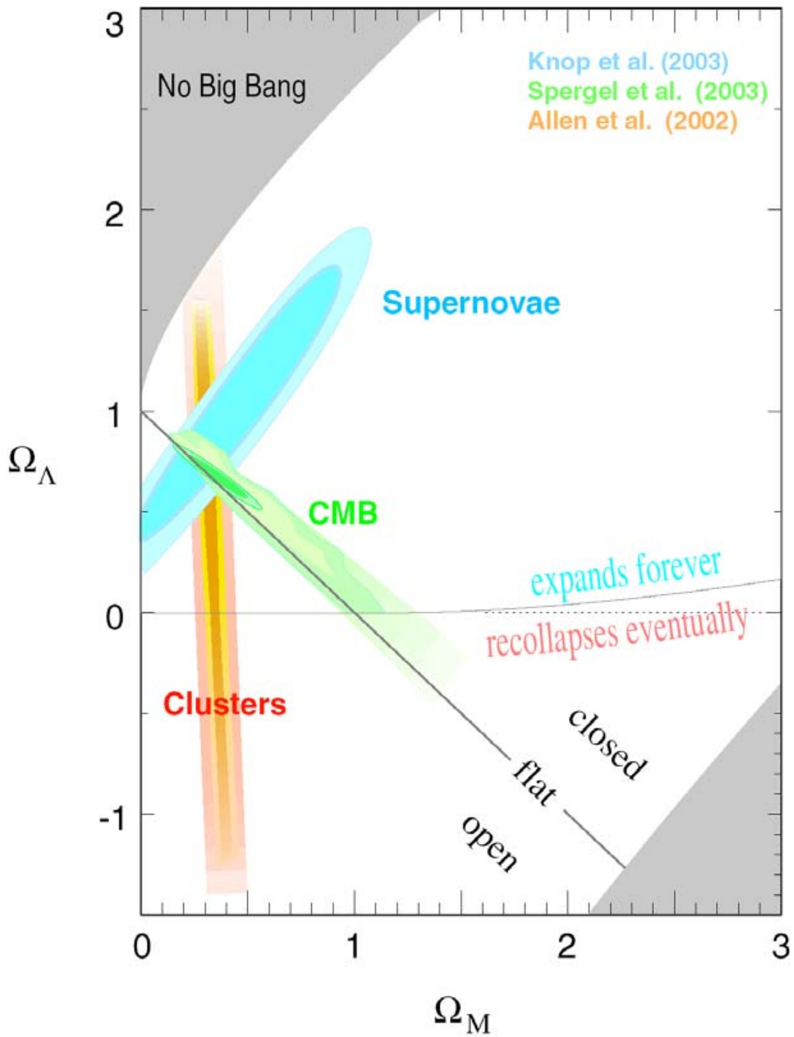
"Over 500 scientists from around the world are expected to attend a conference at Fermilab Oct. 20-22, 1977. For the first time, physicists working in two frontier areas of science – particle physics and cosmology – will unite to explore the relationship of the universe to inner space of the atom." – The Village Crier





THE RISE OF THE WIMP PARADIGM



- We have learned a lot about the Universe in recent years
- There is now overwhelming evidence that normal (atomic) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%

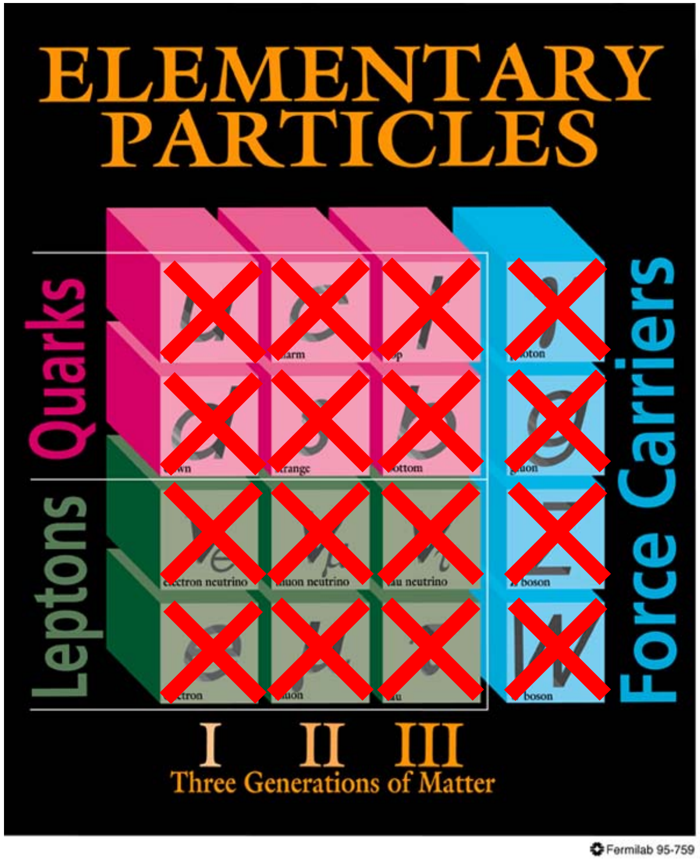
  Dark Energy: 73% ± 4%

  Normal Matter: 4% ± 0.4%

  Neutrinos: 0.2% (Σm_ν/0.1eV)

- To date, all evidence is from dark matter's gravitational effects

DARK MATTER



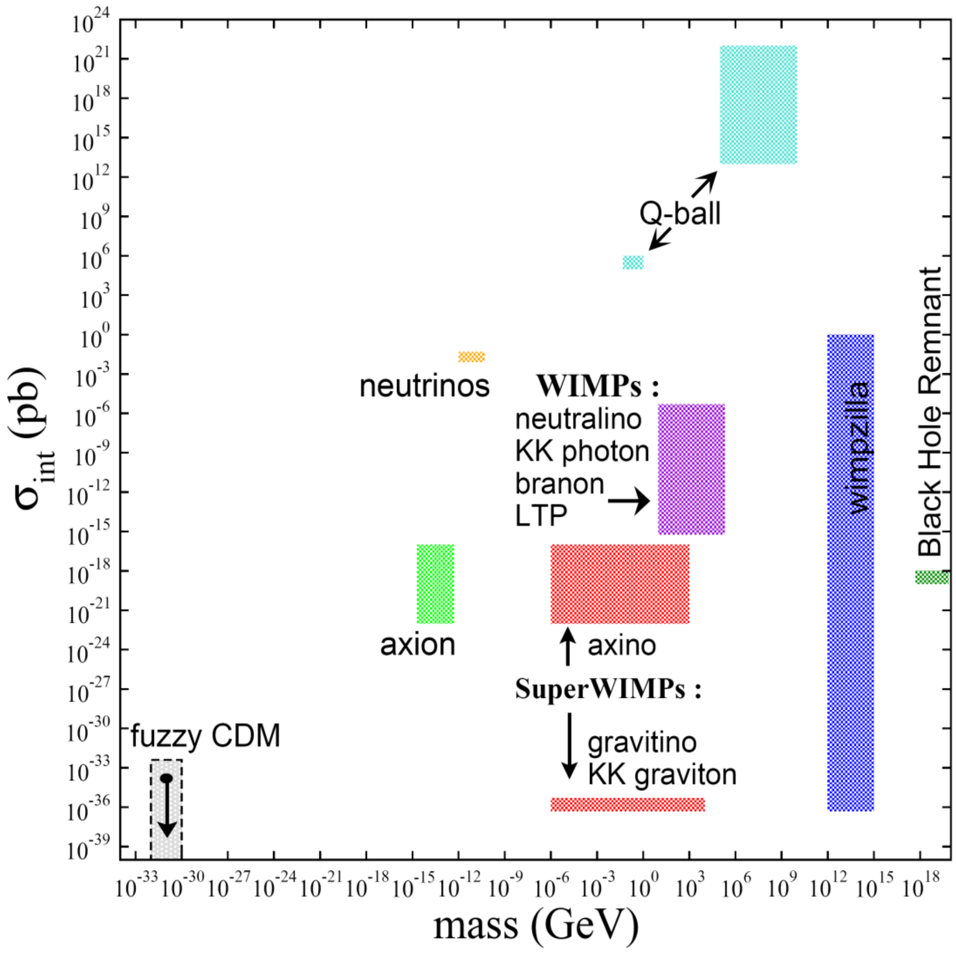
Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new particles

DARK MATTER CANDIDATES

- The observational constraints are no match for the creativity of theorists
- Masses and interaction strengths span many, many orders of magnitude, but masses near the weak scale m_{weak} ~ 100 GeV are especially motivated



HEPAP/AAAC DMSAG Subpanel (2007)

THE WEAK MASS SCALE

- Fermi's constant G_F introduced in 1930s to describe beta decay

$$n \rightarrow p\, e^- \bar{\nu}$$

- $G_F \approx 1.1 \cdot 10^{-5}$ GeV^{-2} → a new mass scale in nature

$$m_{weak} \sim 100 \text{ GeV}$$

- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

FREEZE OUT

(1) Assume a new heavy particle *X* is initially in thermal equilibrium:

$$XX \leftrightarrow \bar{q}q$$

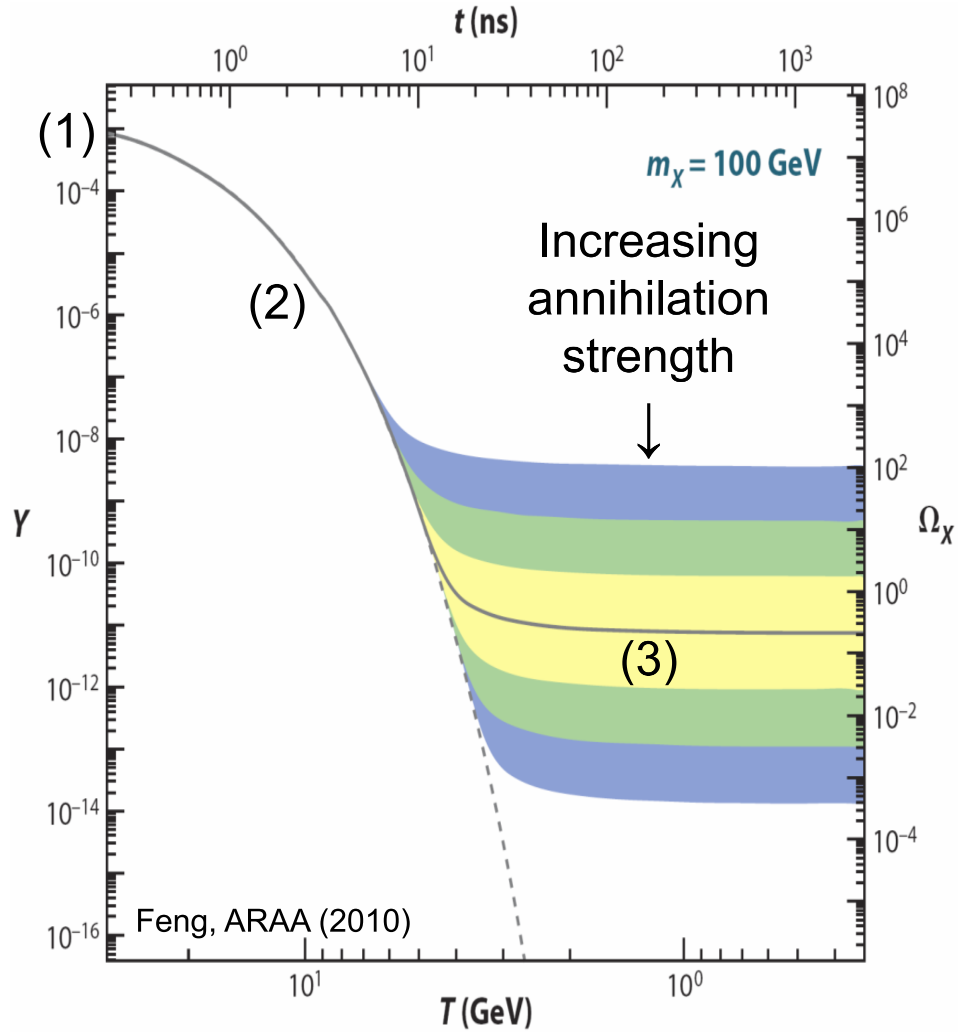
(2) Universe cools:

$$XX \underset{\not\leftarrow}{\rightarrow} \bar{q}q$$

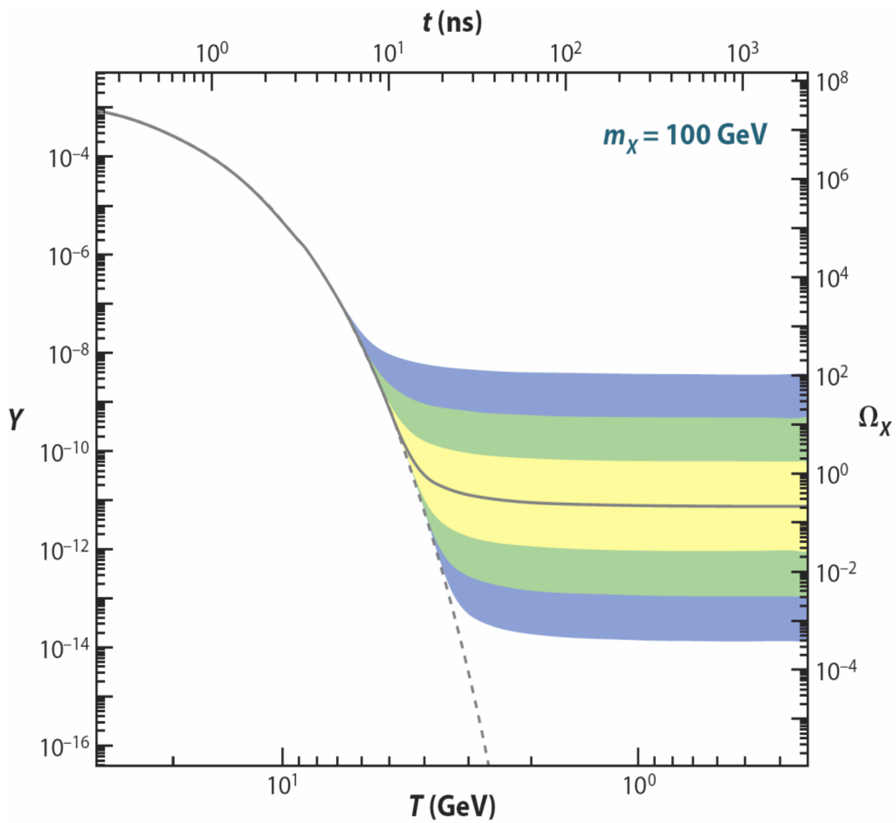
(3) Universe expands:

$$XX \underset{\not\leftarrow}{\not\rightarrow} \bar{q}q$$

Zeldovich et al. (1960s)

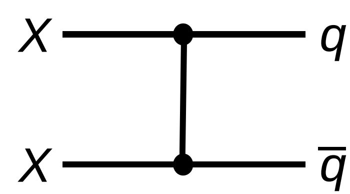


THE WIMP MIRACLE



- The relation between Ω_X and annihilation strength is wonderfully simple:

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

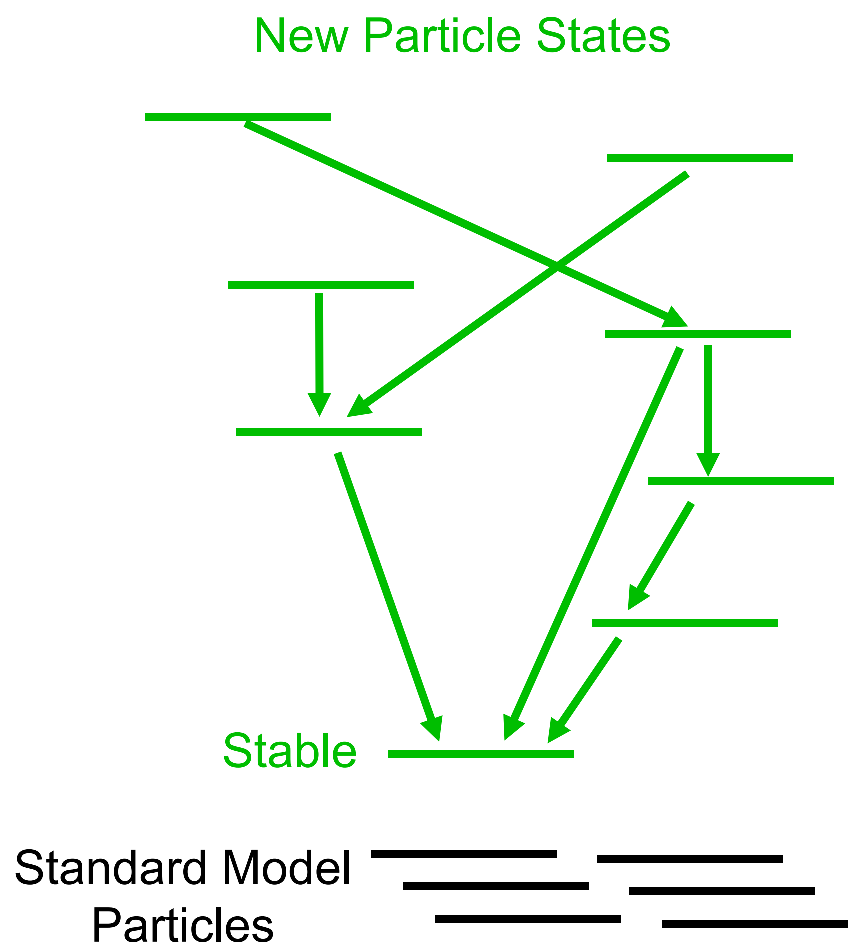


- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

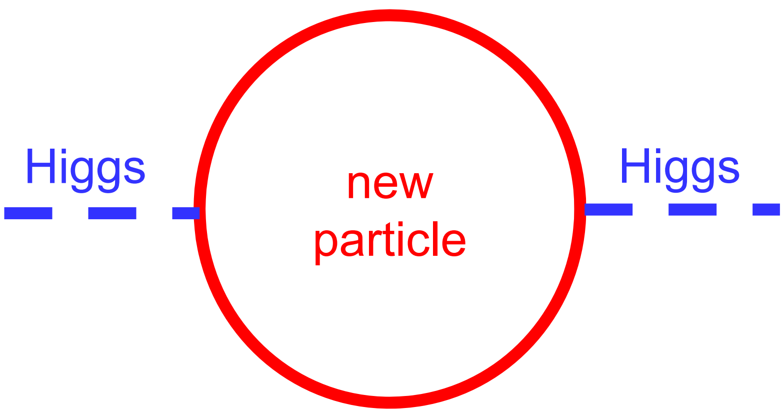
STABILITY

- This all assumes the WIMP is stable
- How natural is this?

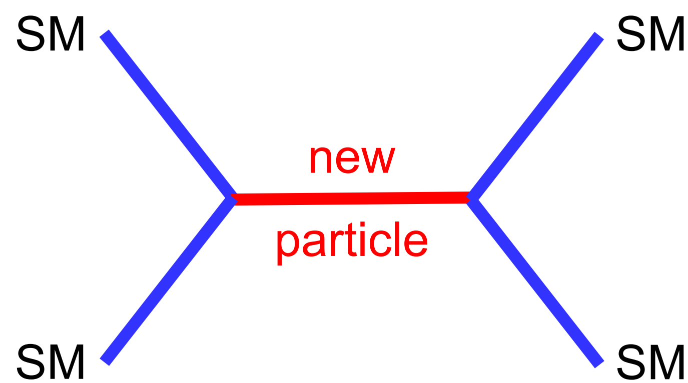


LEP'S COSMOLOGICAL LEGACY

Gauge Hierarchy requires



Precision EW excludes



- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable:

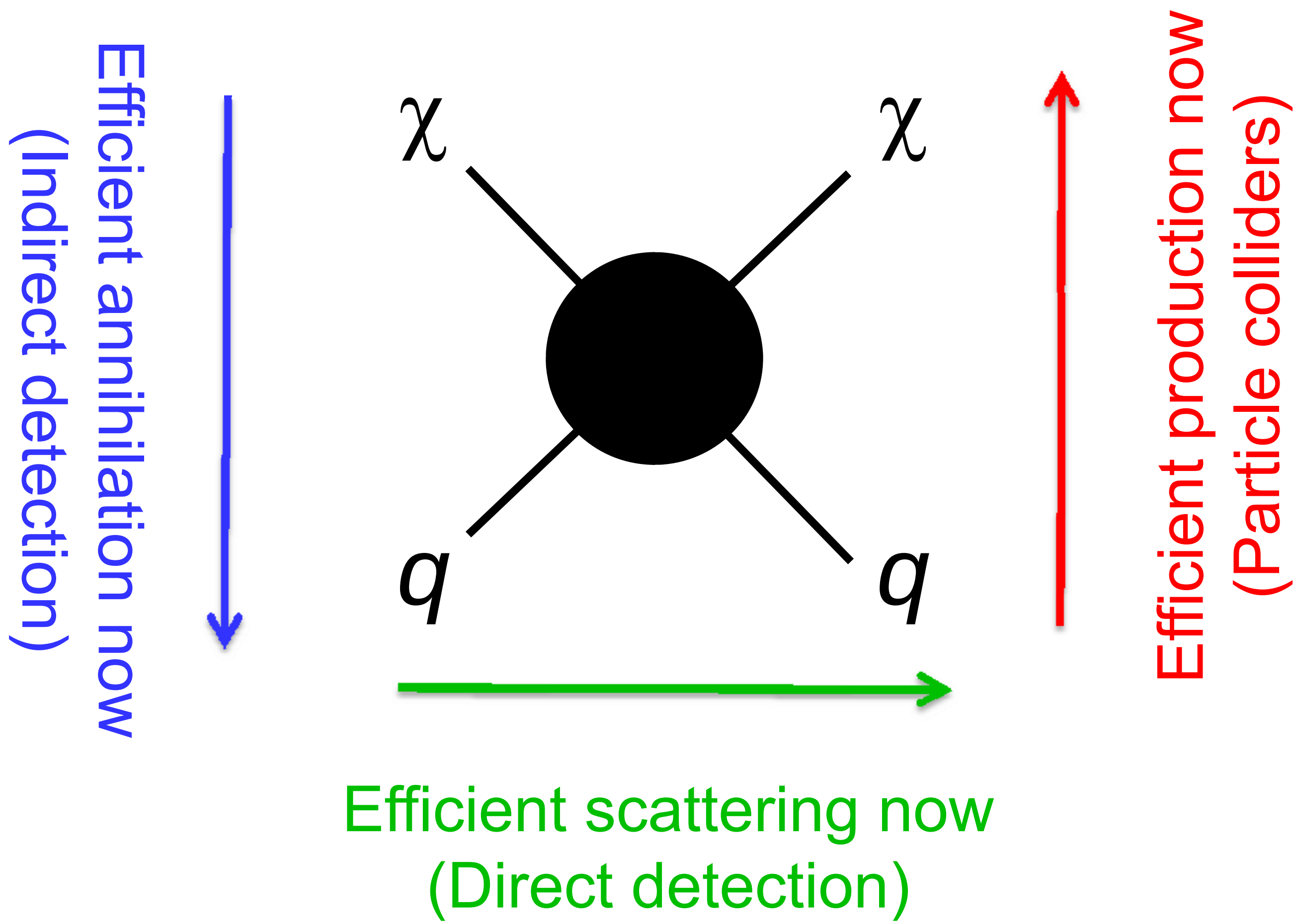
  LEP constraints ↔ Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)

- The result: dark matter is easier to explain than no dark matter, and the WIMP paradigm is more natural than ever before, leading to a proliferation of candidates

EXPERIMENTAL PROBES

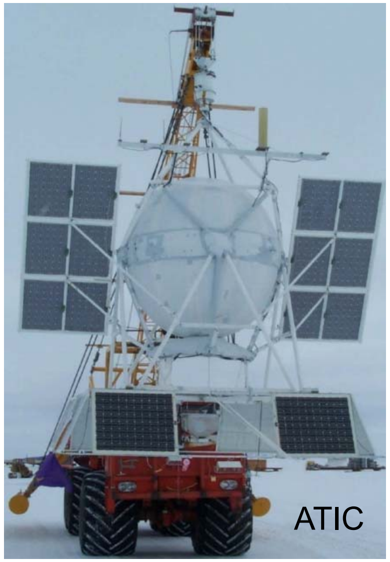
Correct relic density → Efficient annihilation then



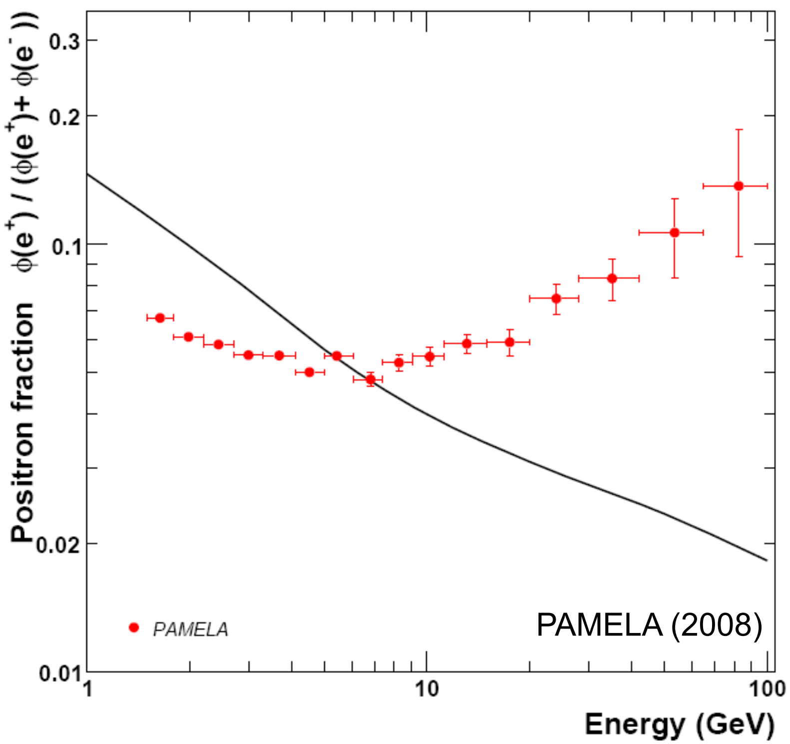
INDIRECT DETECTION

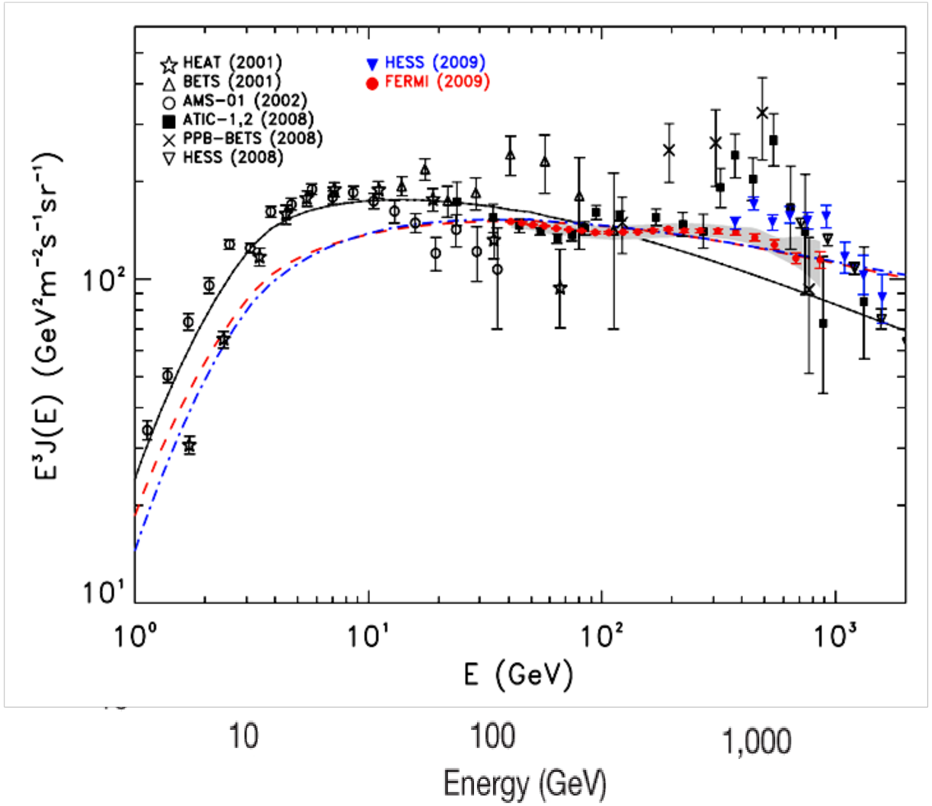
Dark Matter annihilates in ___the halo___ to
a place

___positrons___ , which are detected by ___PAMELA/ATIC/Fermi…___.
some particles an experiment



CURRENT STATUS





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

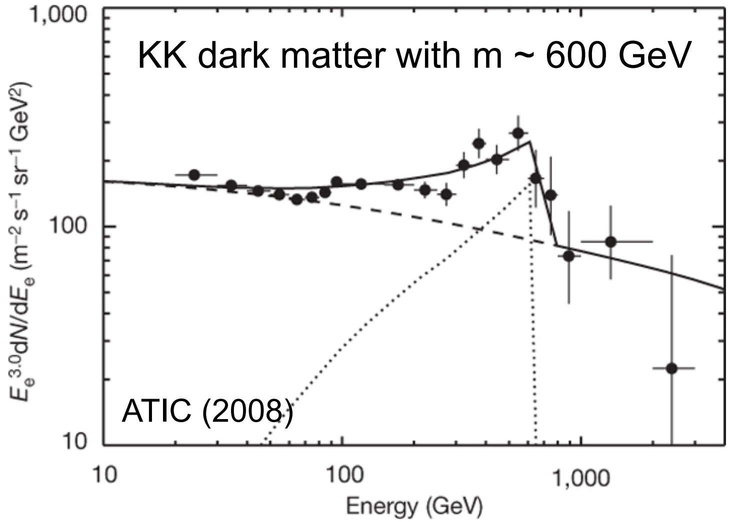
ARE THESE DARK MATTER?

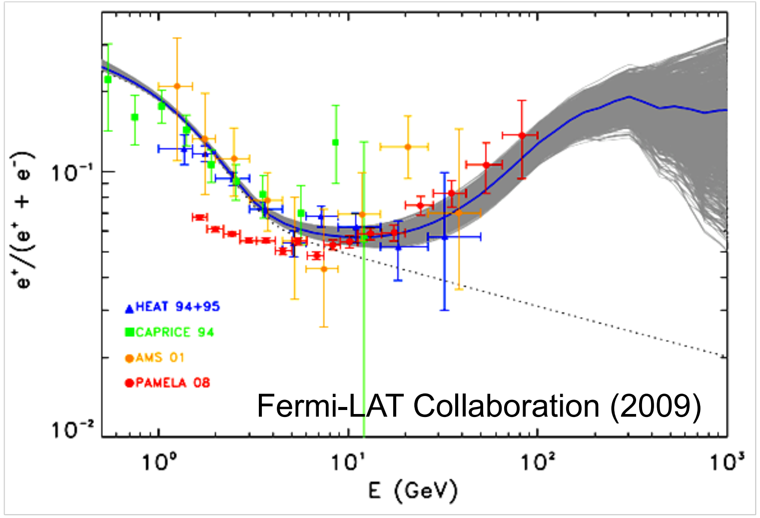
- Energy spectrum shape consistent with WIMP dark matter candidates
- Flux is a factor of 100-1000 too big for a thermal relic; requires
  - Enhancement from astrophysics (very unlikely)
  - Enhancement from particle physics
  - Alternative production mechanism

Cirelli, Kadastik, Raidal, Strumia (2008)
Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)
Feldman, Liu, Nath (2008); Ibe, Murayama, Yanagida (2008)
Guo, Wu (2009); Arvanitaki et al. (2008)

- Pulsars can explain PAMELA

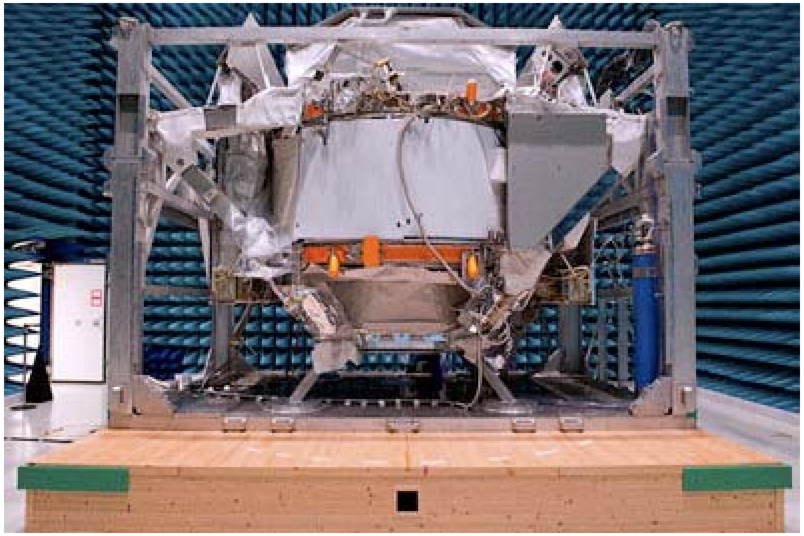
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008); Profumo (2008)
Fermi-LAT Collaboration (2009)

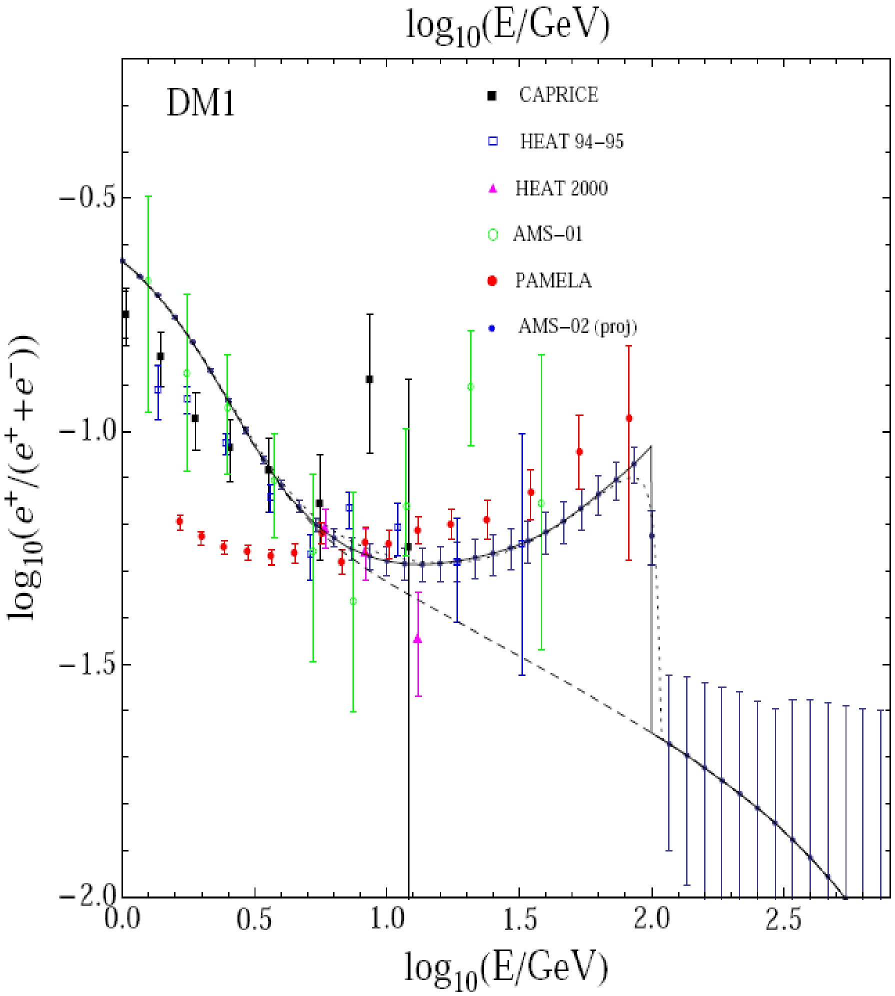




ALPHA MAGNETIC SPECTROMETER

- A landmark experiment
- Scheduled for launch in April to the International Space Station
- Can AMS-02 disentangle dark matter from pulsars?

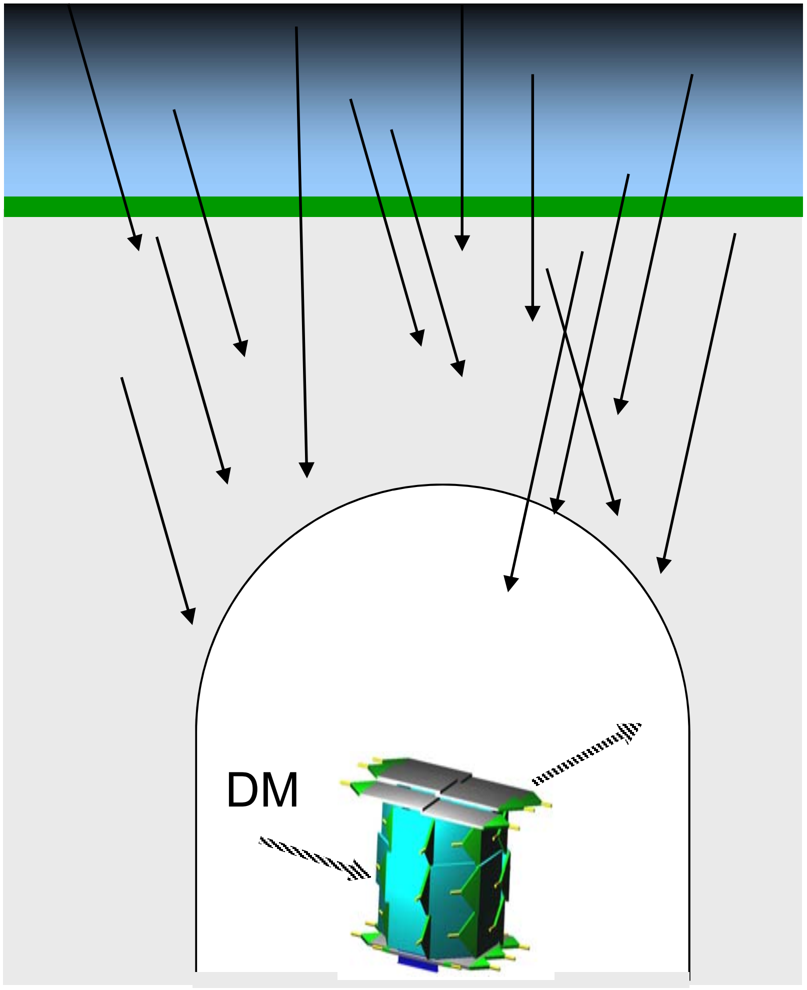




Pato, Lattanzi, Bertone (2010)

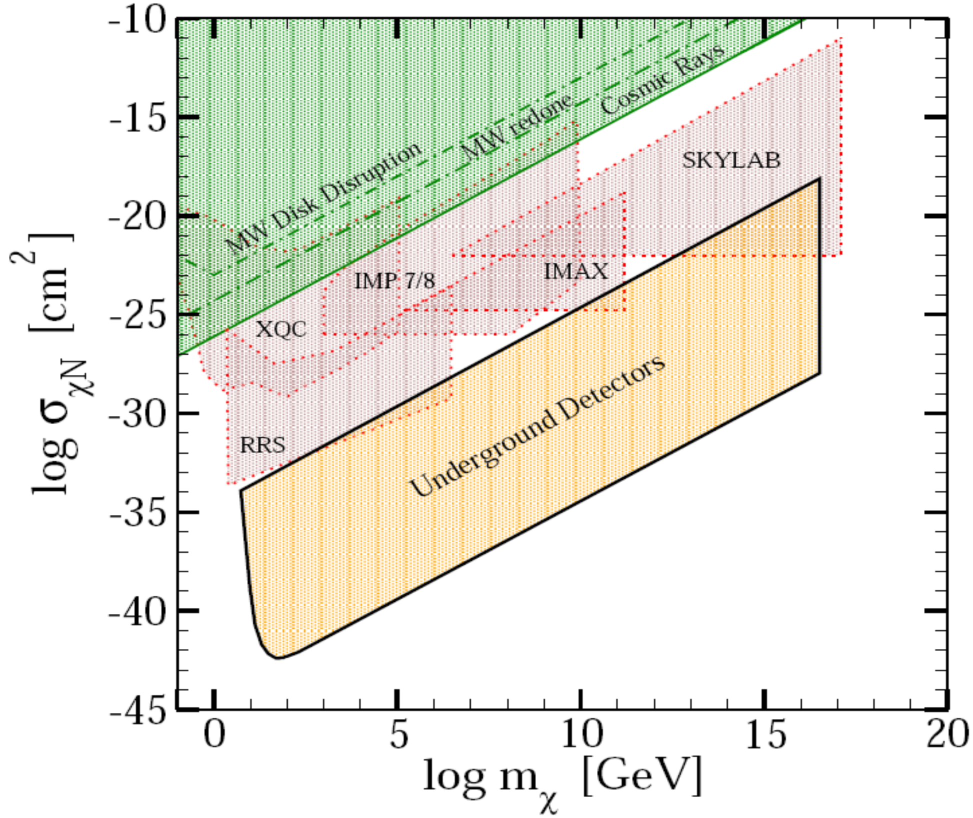
DIRECT DETECTION

- Can look for normal matter recoiling from DM collisions
- WIMP properties
  - m ~ 100 GeV
  - velocity ~ 10^{-3} c
  - Recoil energy ~ 1-100 keV
- Typically focus on ultra-sensitive detectors placed deep underground
- But first, what range of interaction strengths are possible to investigate?



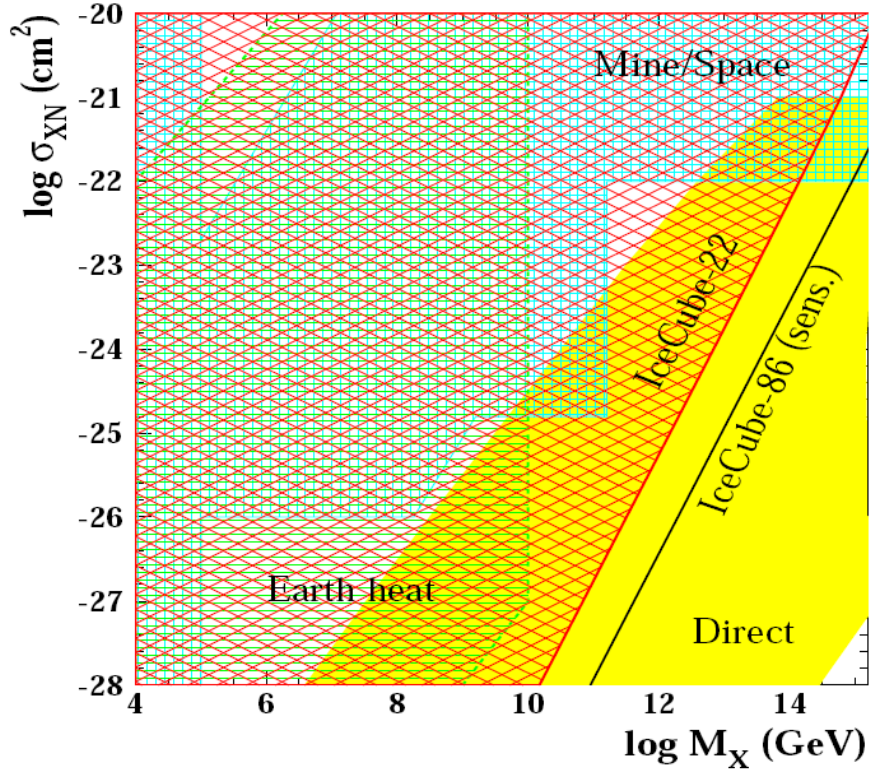
STRONGLY-INTERACTING MASSIVE PARTICLES

- The big picture



Mack, Beacom, Bertone (2007)

- SIMP window is now essentially closed



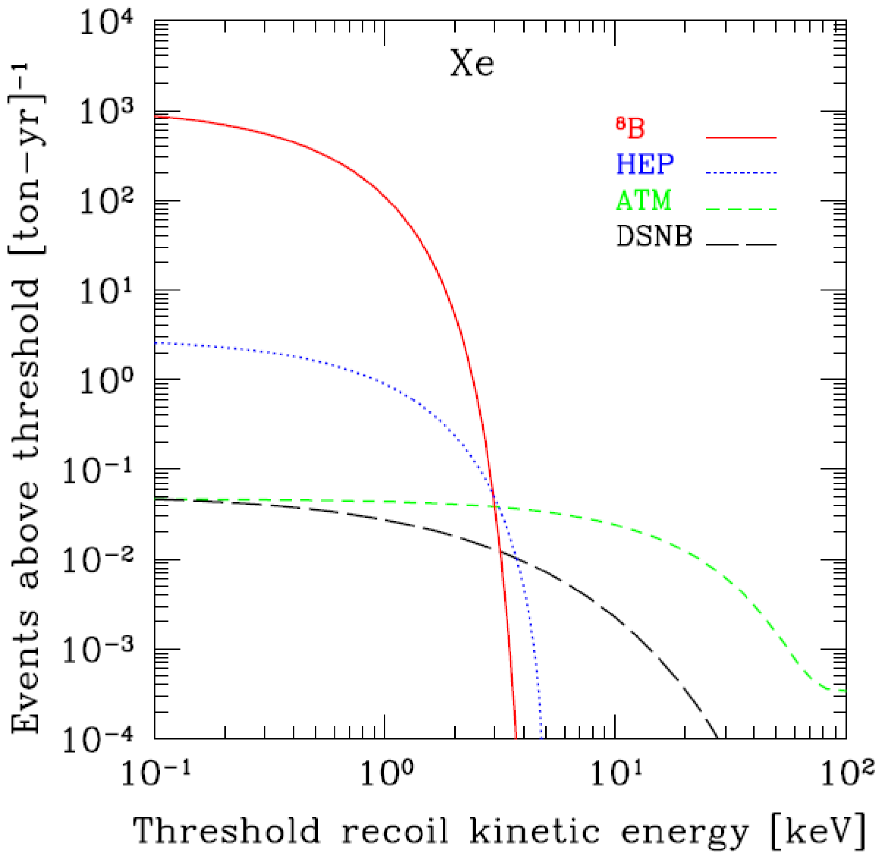
Albuquerque, de los Heros (2010)

LOWER LIMIT ON DIRECT DETECTION

- Solar, atmospheric, and diffuse supernova background neutrinos provide an "irreducible background"

- The limits of background-free, non-directional direct detection searches (and also the metric prefix system!) will be reached by ~10 ton experiments probing

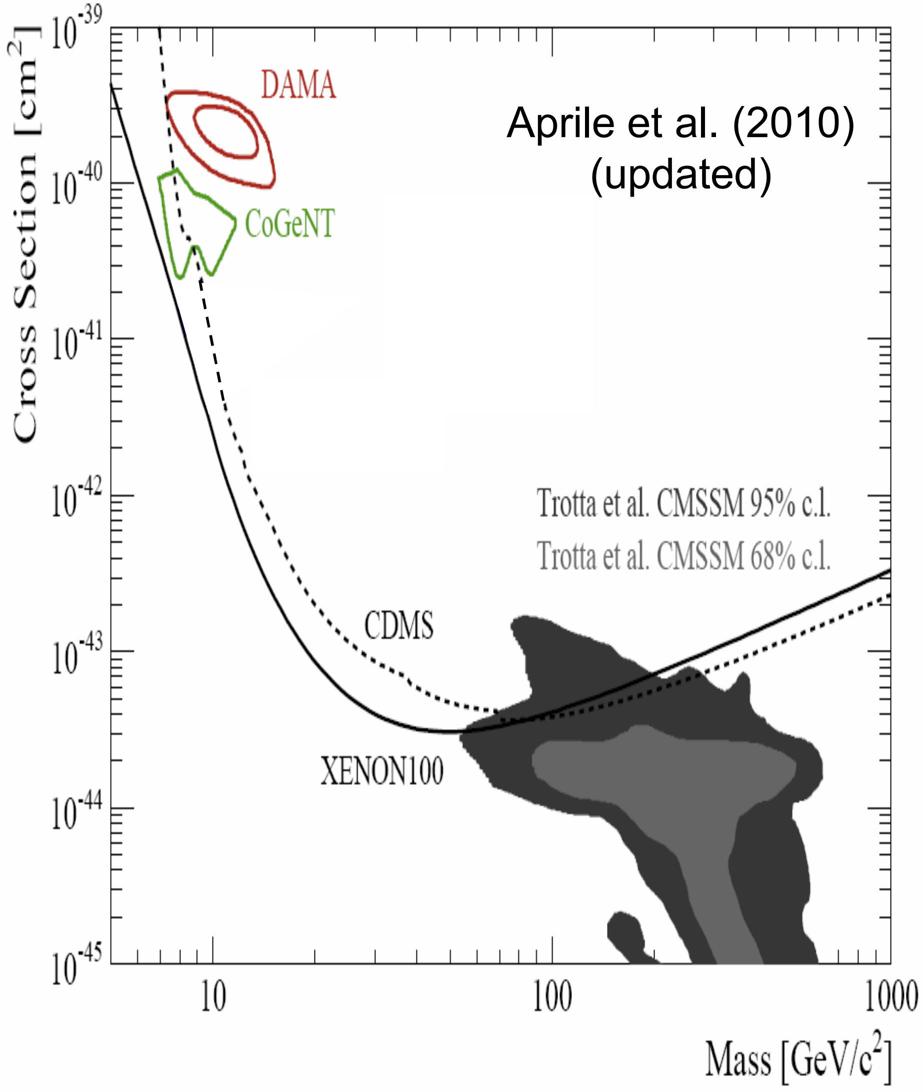
  $\sigma \sim 1$ yb (10^{-12} pb, 10^{-48} cm^2)



Strigari (2009); Gutlein et al. (2010)

LOW CROSS SECTION FRONTIER

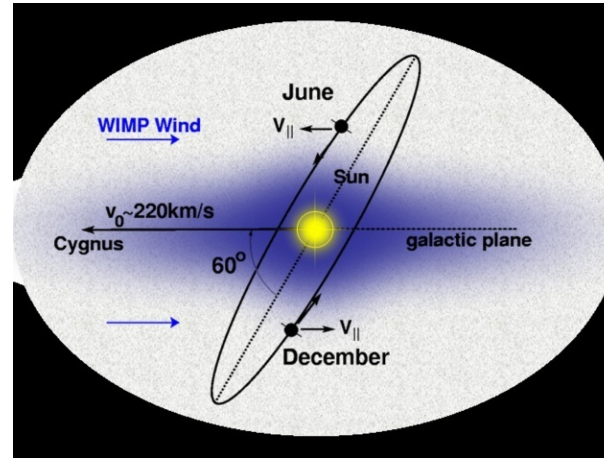
- Focus here on spin-independent results, which are typically normalized to X-proton cross sections
- Weak interaction frontier: For masses ~ 100 GeV, many models → 10^{-44} cm^2 (see LHC below)



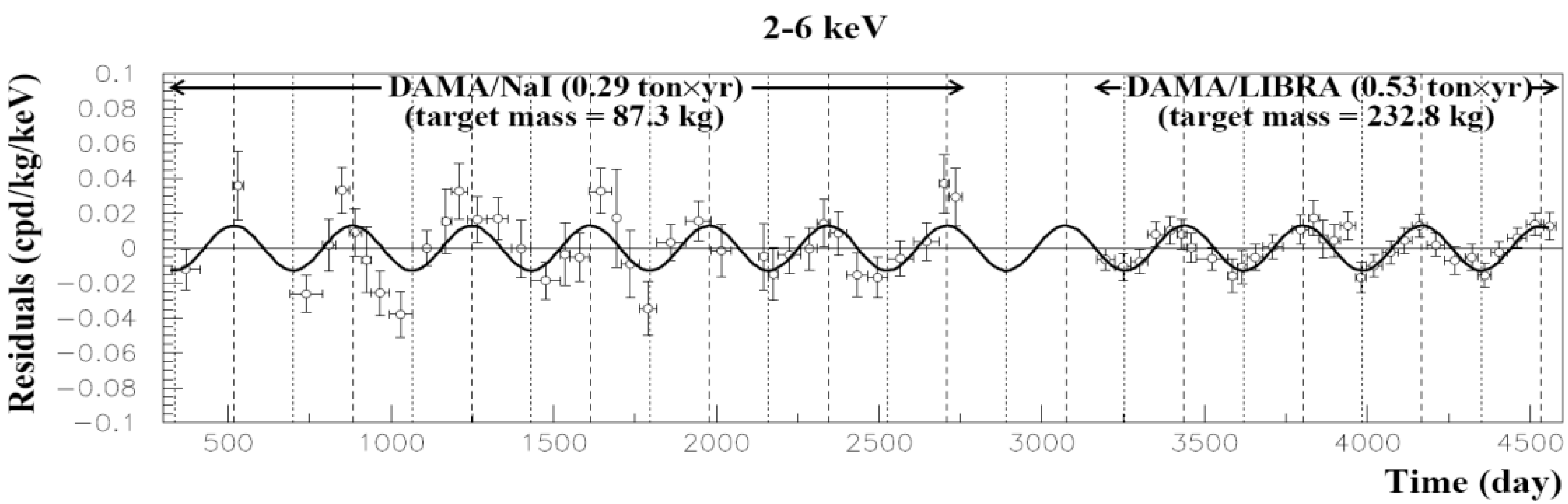
LOW MASS FRONTIER

Collision rate should change as Earth's velocity adds constructively/destructively with the Sun's → annual modulation

Drukier, Freese, Spergel (1986)



DAMA: 8σ signal with T ~ 1 year, max ~ June 2



DAMA (2008)

DAMA low mass signal now supplemented by CoGeNT

ARE THESE DATA CONSISTENT?

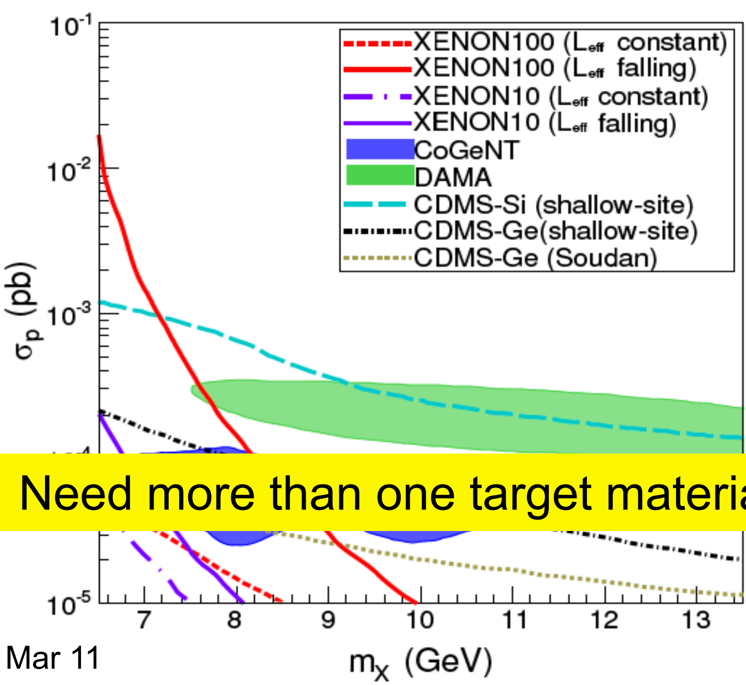
- Puzzles
  - Low mass and high σ
  - DAMA ≠ CoGeNT
  - Excluded by XENON, CDMS

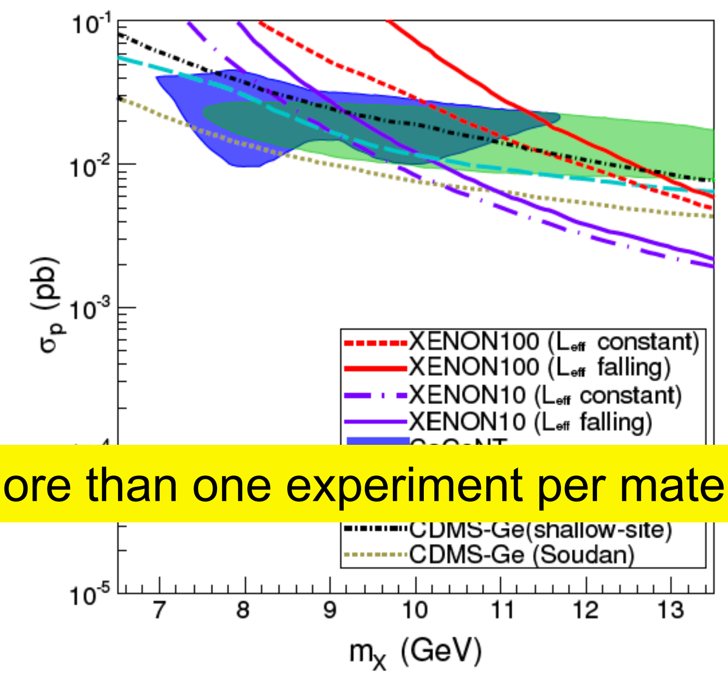
- Many proposed explanations

Hooper, Collar, Hall, McKinsey (2010); Fitzgerald, Zurek (2010); Fox, Liu, Weiner (2010)

- Isospin-Violating Dark Matter
  - Scattering is coherent:
    $\sigma_A \sim [\ f_p Z + f_n\ (A-Z)\ ]^2$
  - Typical plot assumes $f_n = f_p$
  - Can reconcile DAMA, CoGeNT, XENON with $f_n = -0.7\ f_p$

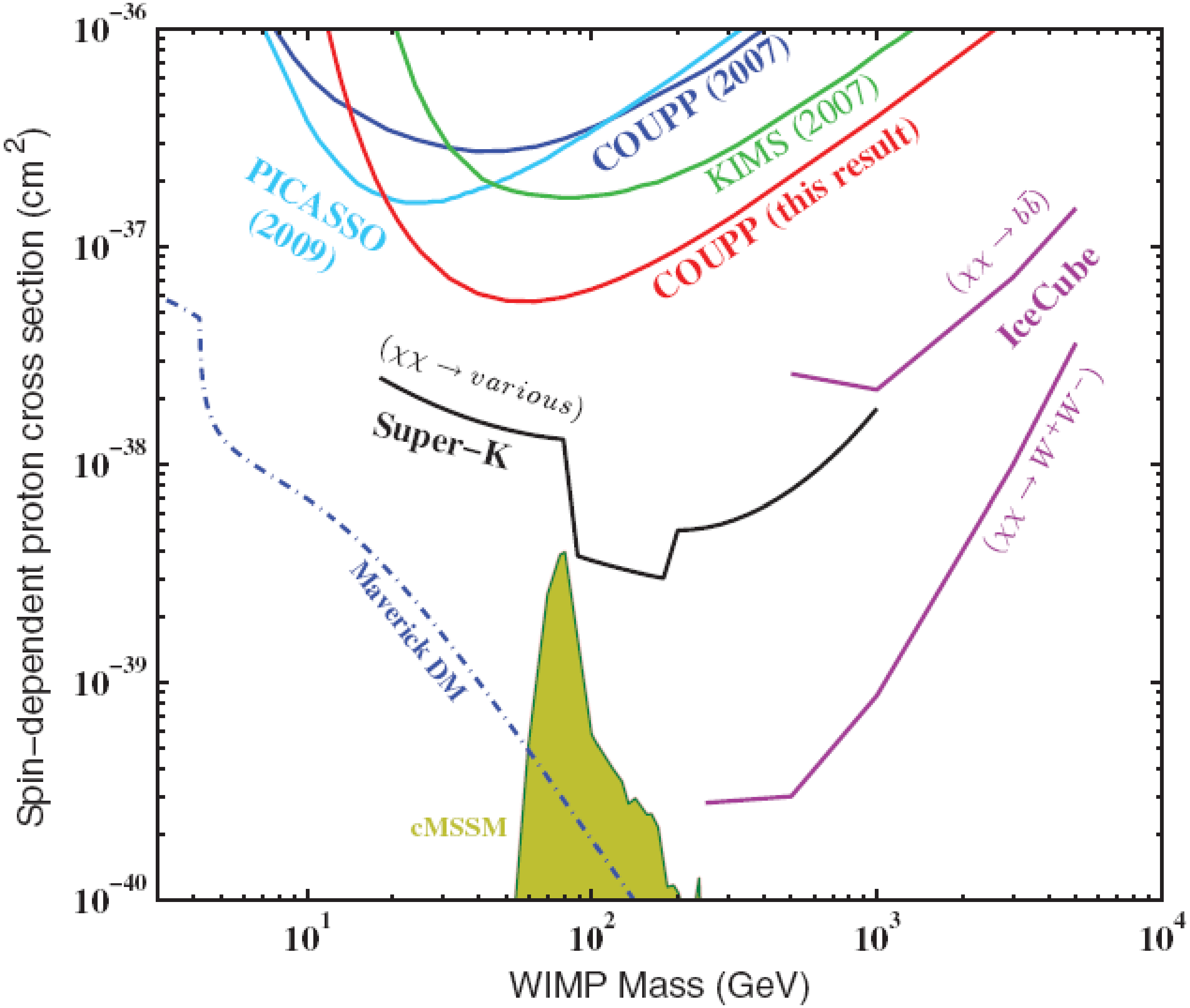
Giuliani (2005); Chang, Liu, Pierce, Weiner, Yavin (2010)
Feng, Kumar, Marfatia, Sanford (2011)



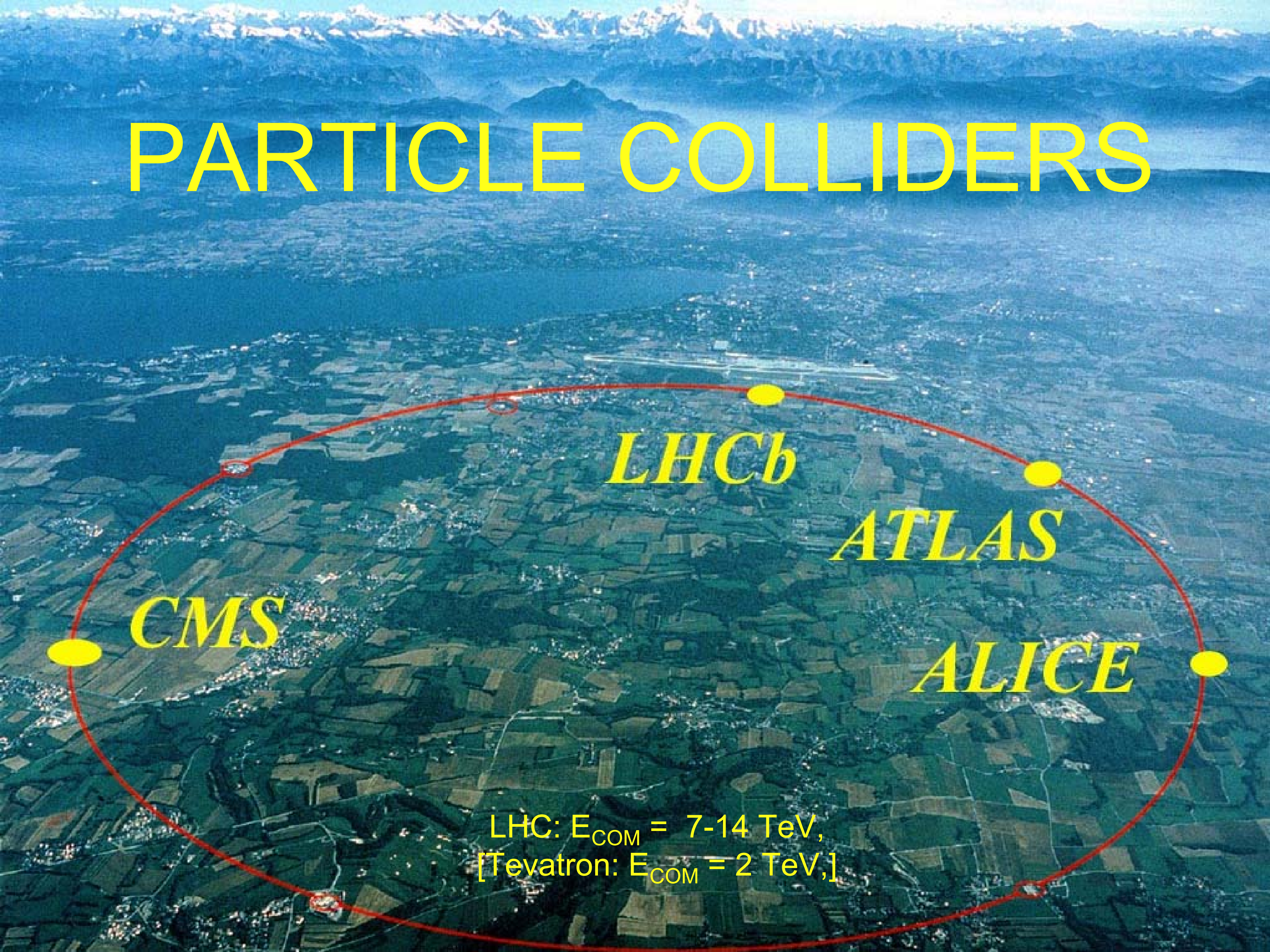


Need more than one target material and more than one experiment per material

SPIN-DEPENDENT SCATTERING

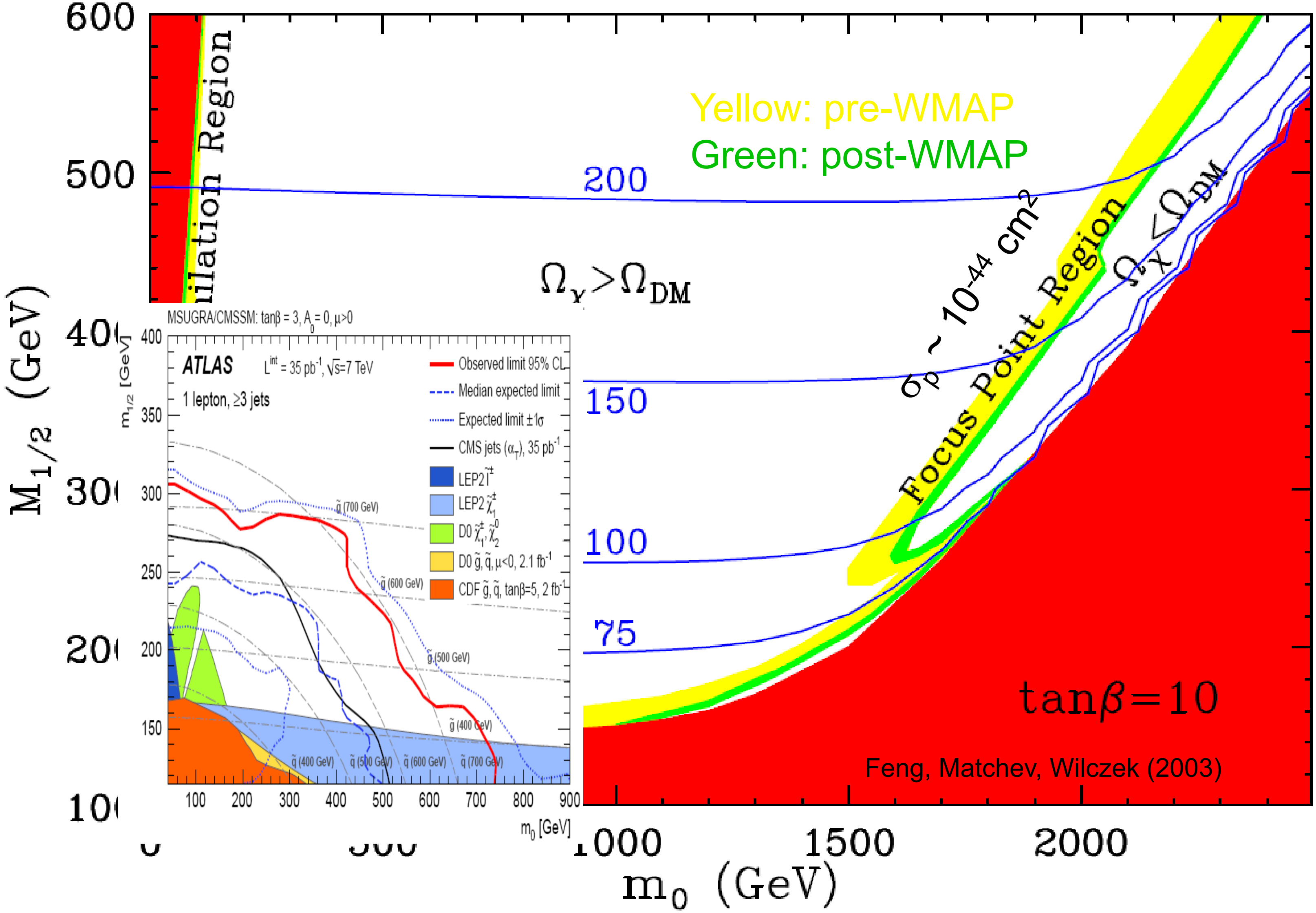


PARTICLE COLLIDERS



LHC: E_{COM} = 7-14 TeV,
[Tevatron: E_{COM} = 2 TeV,]

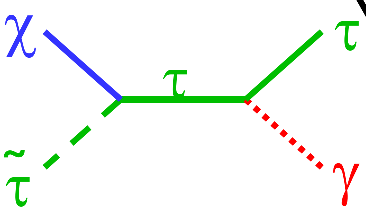
CURRENT BOUNDS FOR SUSY



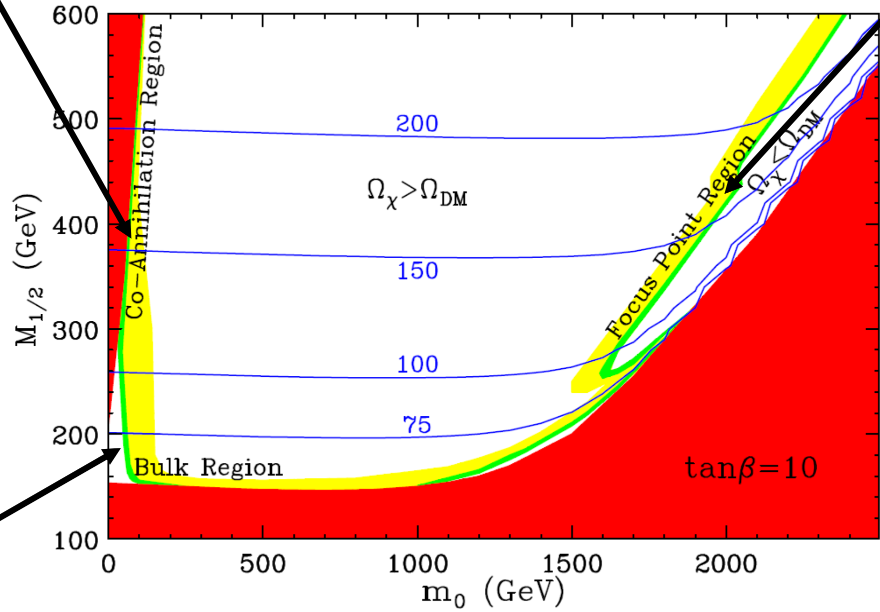
HOW MODEL-INDEPENDENT IS THIS?

Neutralinos need an efficient annihilation channel

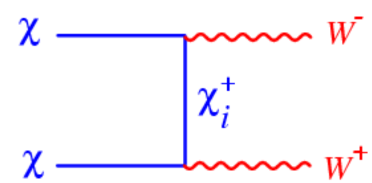
Co-annihilation region



Degenerate χ and stau

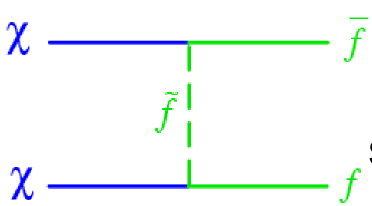


Focus point region



Mixed Higgsino-Bino Neutralinos

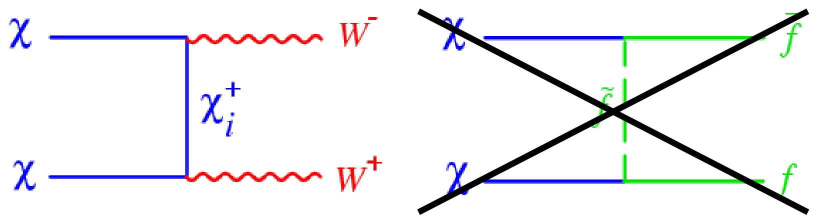
Bulk region



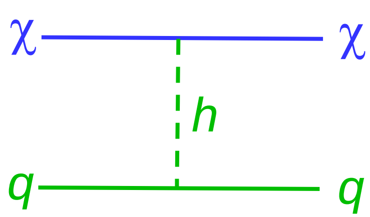
Light sfermions

THE SIGNIFICANCE OF 10^{-44} CM^2

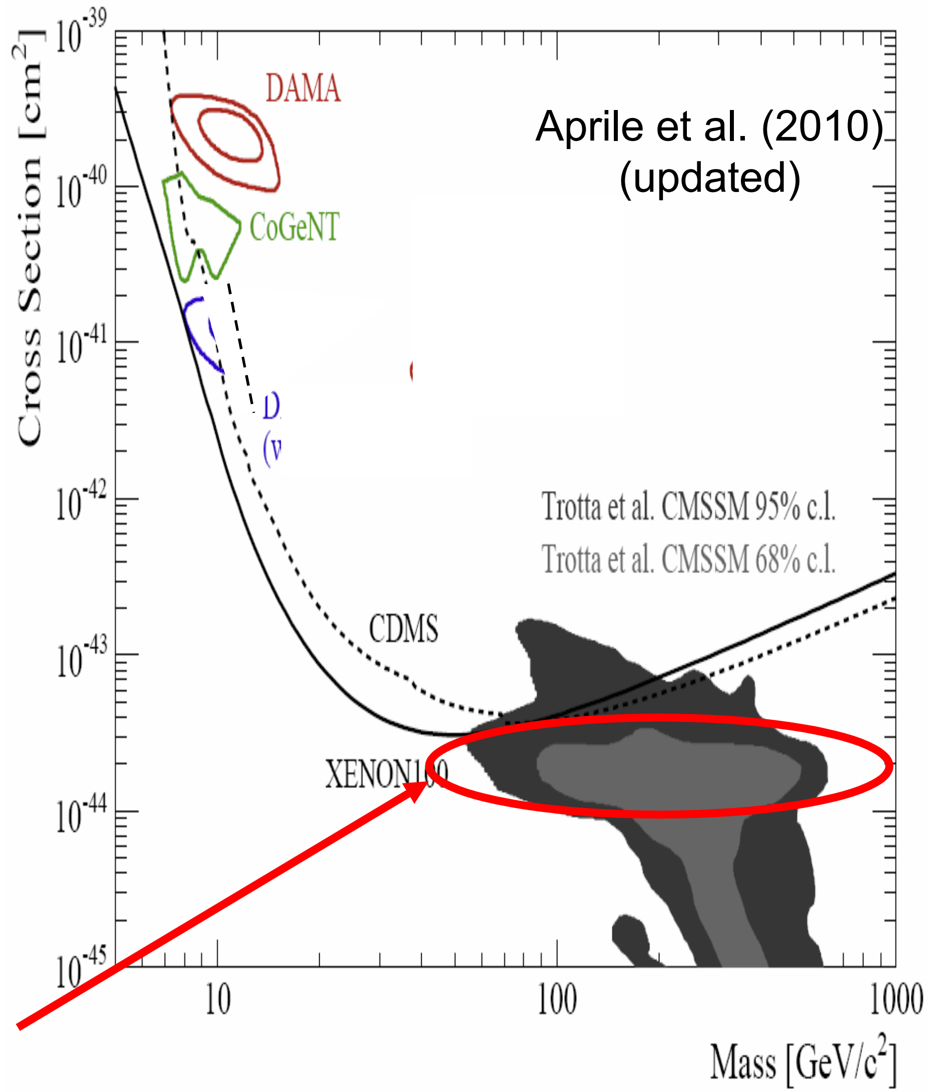
- The LHC is eliminating one process. If $M_2 > M_1$, no co-annihilation, resonances, this fixes the neutralino's coupling to Ws



- But this also fixes the DM scattering through Higgs



- Predictions collapse to a band



STATUS OF NEUTRALINO DM

few 10^{-44} cm^2

few 10^{-45} cm^2

No signal

Signal

BEYOND WIMPS

- Does the WIMP paradigm imply WIMPs?

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

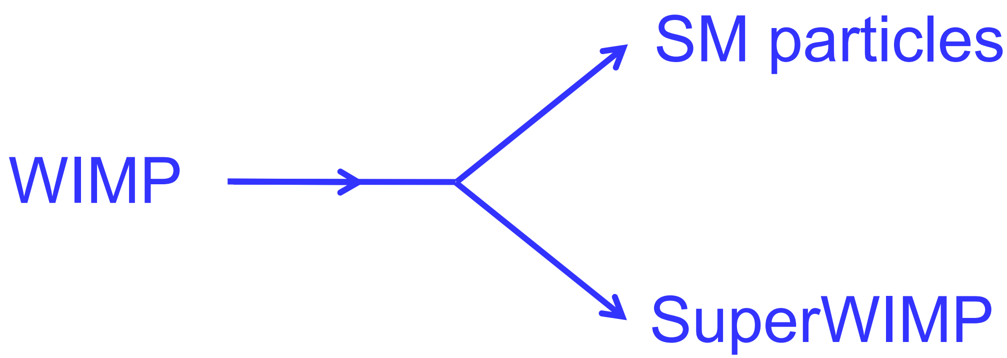
  Are all WIMP miracle-motivated candidates like this?

- No! Recently, have seen many new classes of candidates. Some preserve the motivations of the WIMP paradigm, but have qualitatively different properties

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); …

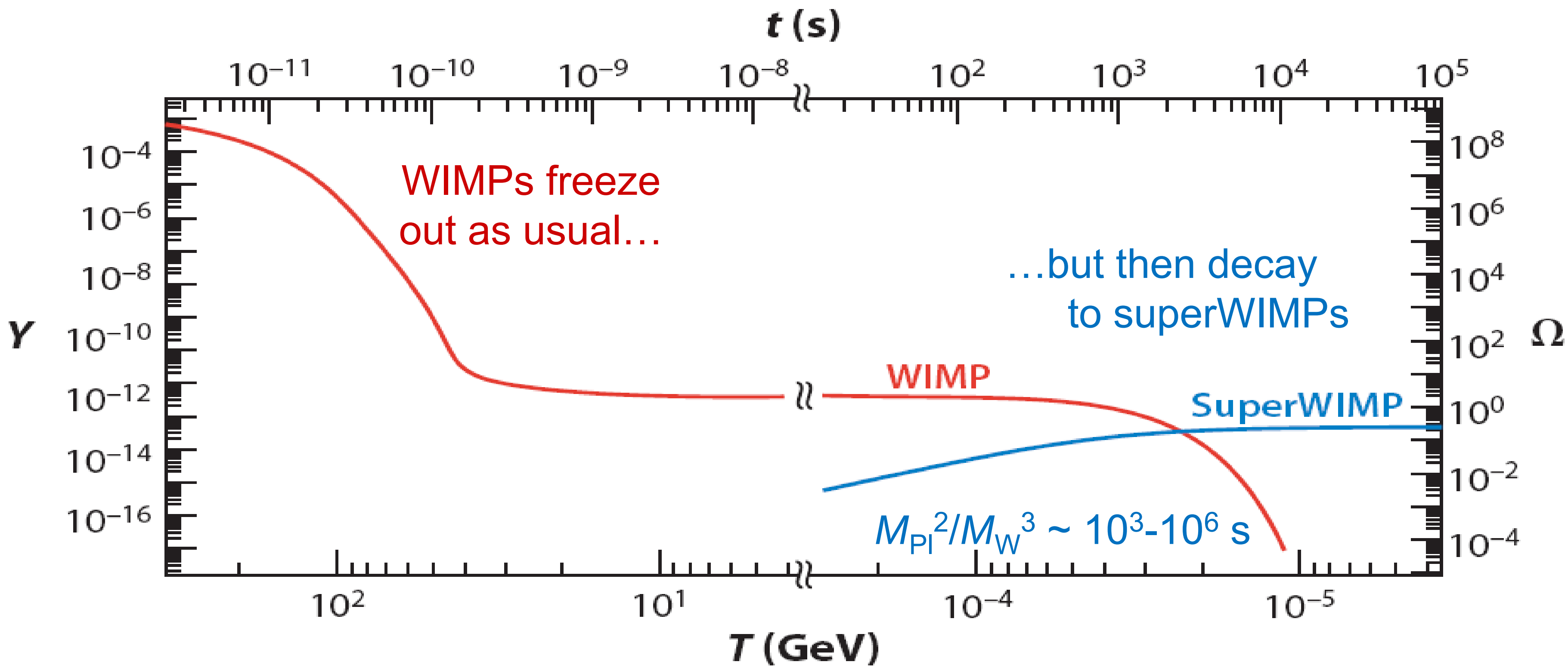
- Suppose the WIMP can decay into a superweakly-interacting particle (superWIMP):



- 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)

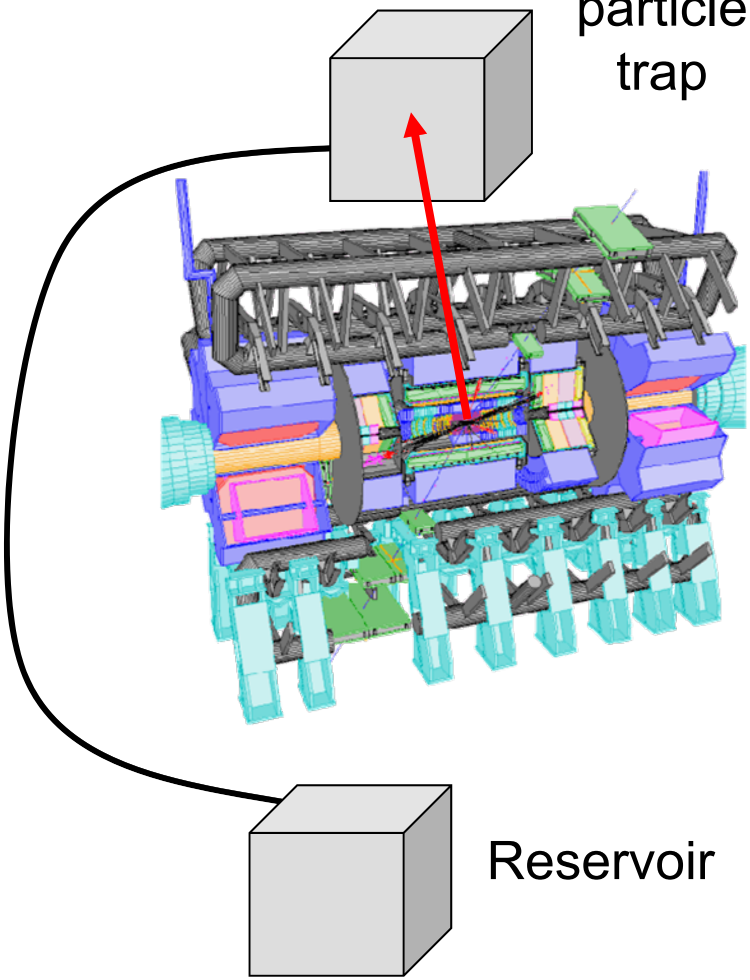
FREEZE OUT WITH SUPERWIMPS



SuperWIMPs naturally inherit the right density; share all the motivations of WIMPs, but are much more weakly interacting

CHARGED PARTICLE TRAPPING

- SuperWIMPs are produced by decays of metastable particles, which can be charged
- Charged metastable particles will be obvious at colliders, can be trapped and moved to a quiet environment to study their decays
- Can catch 1000 per year in a 1m thick water tank

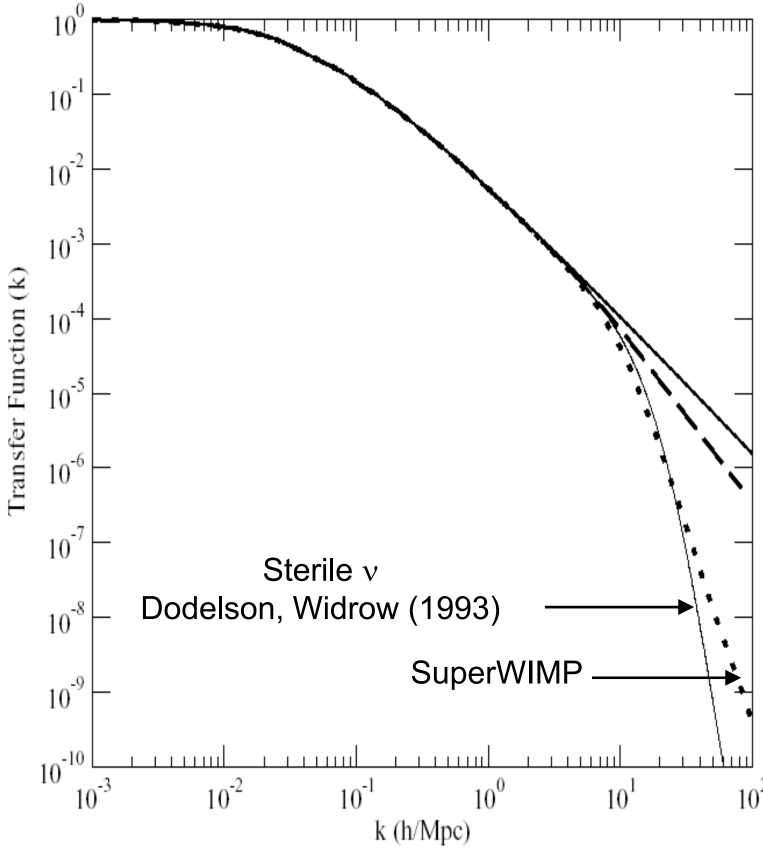


Feng, Smith (2004)
Hamaguchi, Kuno, Nakawa, Nojiri (2004)
De Roeck et al. (2005)

WARM SUPERWIMPS

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

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)



Kaplinghat (2005)

HIDDEN DARK MATTER

- Hidden sectors are composed of particles without SM interactions (EM, weak, strong)

- Dark matter may be in such a sector
  - Interesting self-interactions, astrophysics
  - Less obvious connections to particle physics
  - No WIMP miracle

Spergel, Steinhardt (1999); Foot (2001)

THE WIMPLESS MIRACLE

Feng, Kumar (2008); Feng, Tu, Yu (2009)

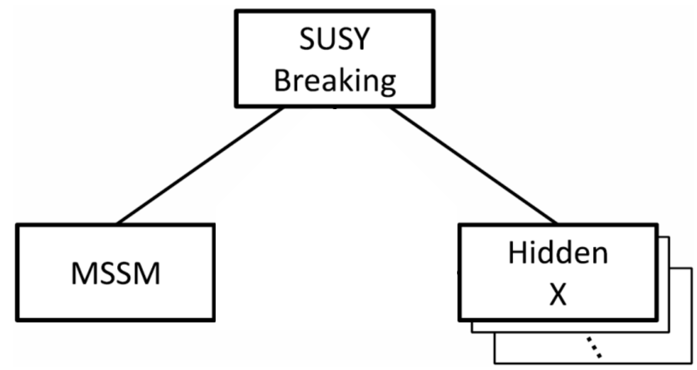
- In SUSY, however, there may be additional structure. E.g., in GMSB, AMSB, the masses satisfy $m_X \sim g_X^2$

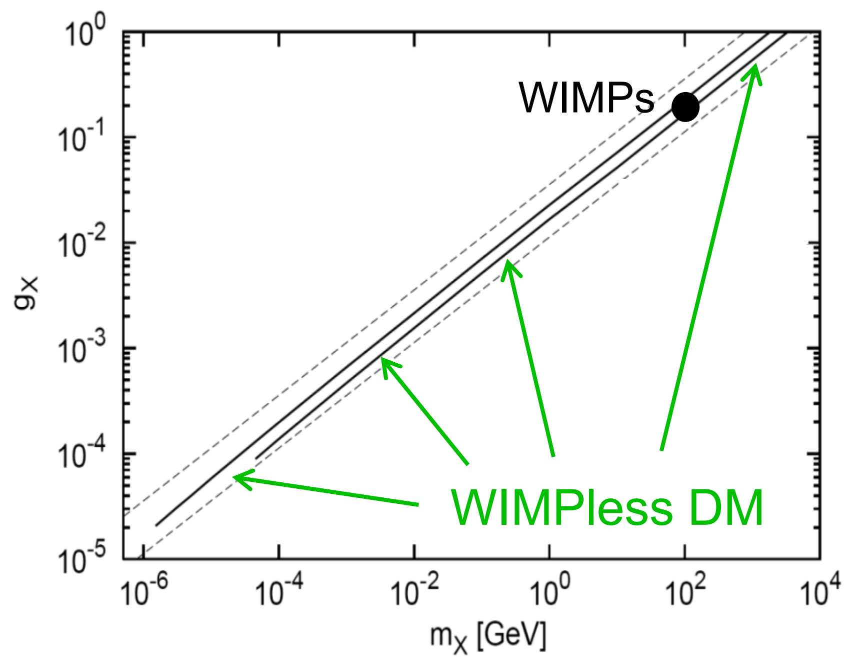
- This leaves the relic density invariant

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

- "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω (but they aren't WIMPs)

- Is this what the new physics flavor problem is telling us?!



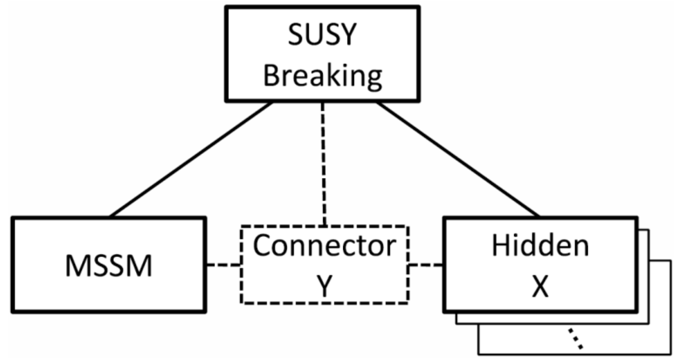


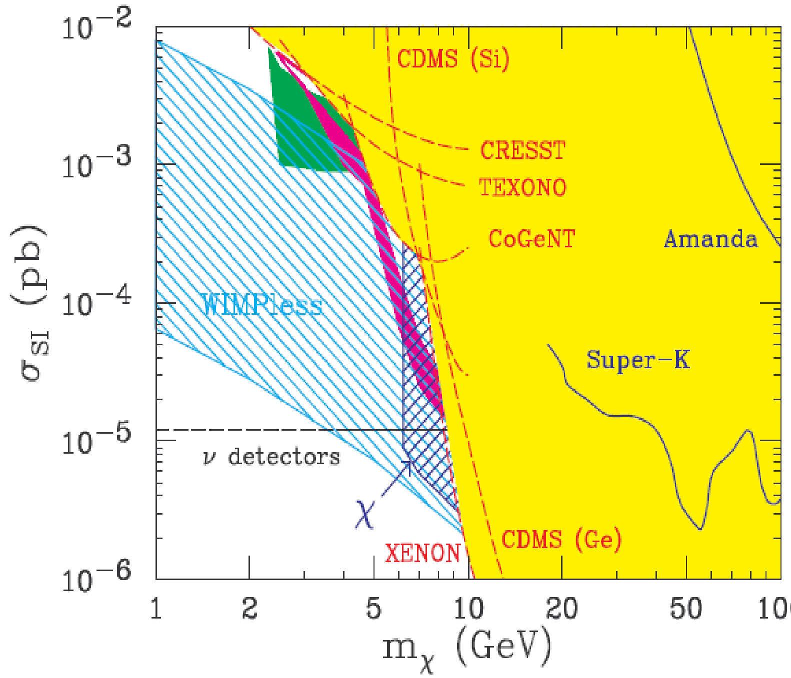
WIMPLESS DM SIGNALS

- Hidden DM may have only gravitational effects, but still interesting: e.g., it may interact through “dark photons”, self-interact through Rutherford scattering

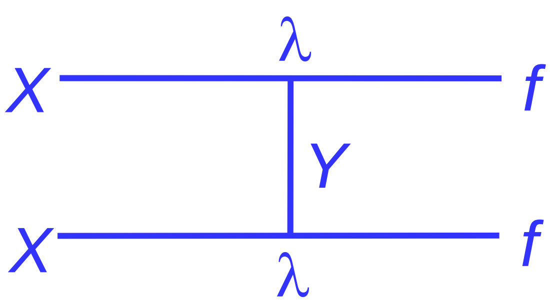
Ackerman, Buckley, Carroll, Kamionkowski (2008)
Feng, Kaplinghat, Tu, Yu (2009)

- Alternatively, hidden DM may interact with normal matter through connector particles, can explain DAMA and CoGeNT signals





Kumar, Learned, Smith (2009)



CONCLUSIONS

- Particle Dark Matter
  - Central topic at the interface of cosmology and particles
  - Both cosmology and particle physics → weak scale ~ 100 GeV
- WIMP Paradigm
  - WIMPs: Many well-motivated candidates
  - SuperWIMPs, WIMPless dark matter: Similar motivations, but qualitatively new possibilities (warm, collisional, only gravitationally interacting)
  - Many others
- LHC is running, direct and indirect detection, astrophysical probes are improving rapidly – this field will be transformed soon