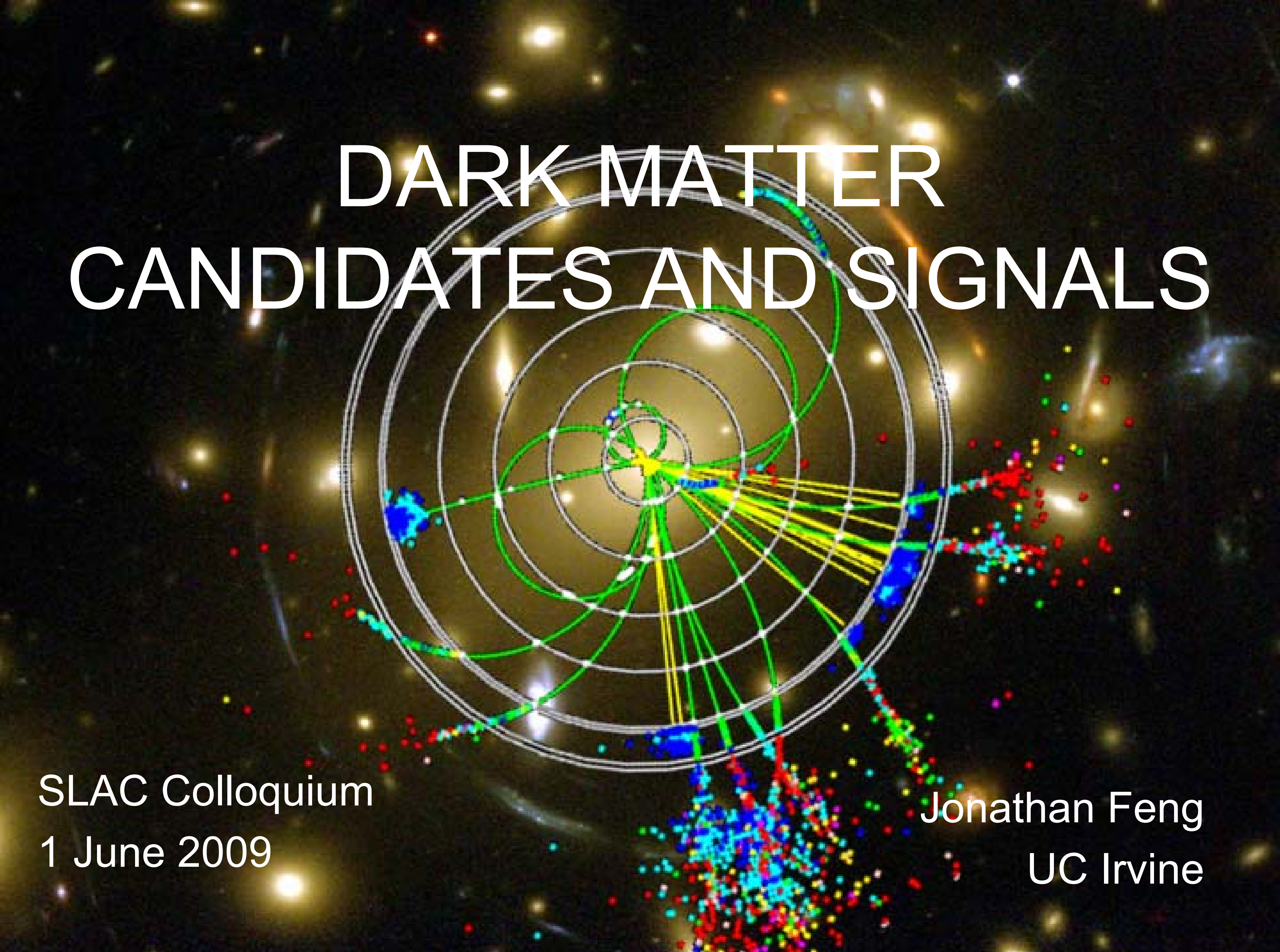
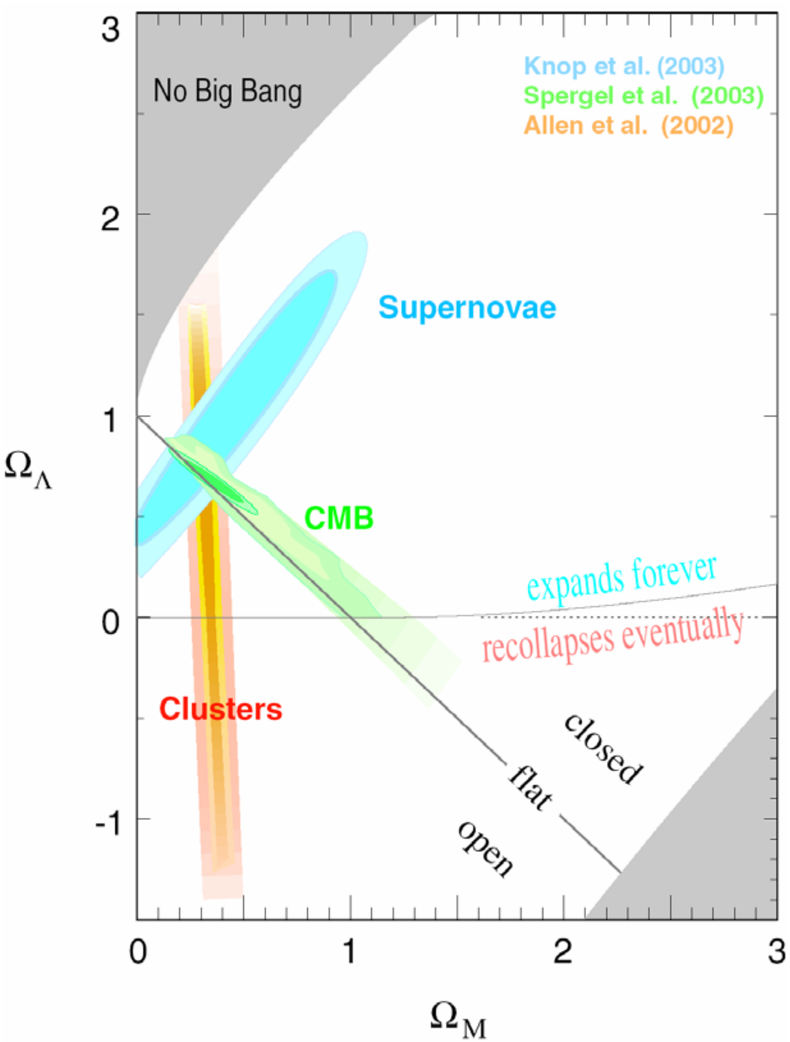
DARK MATTER CANDIDATES AND SIGNALS



SLAC Colloquium
1 June 2009

Jonathan Feng
UC Irvine

EVIDENCE FOR DARK MATTER



- We are living through a golden age in cosmology.

- 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)

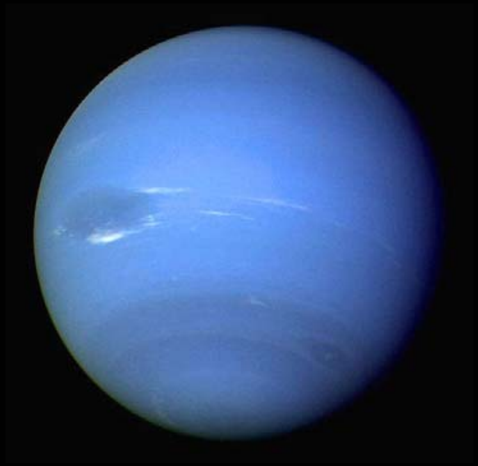
- To date, all evidence is from dark matter's gravitational effects. We would like to detect it in other ways to learn more about it.

A PRECEDENT

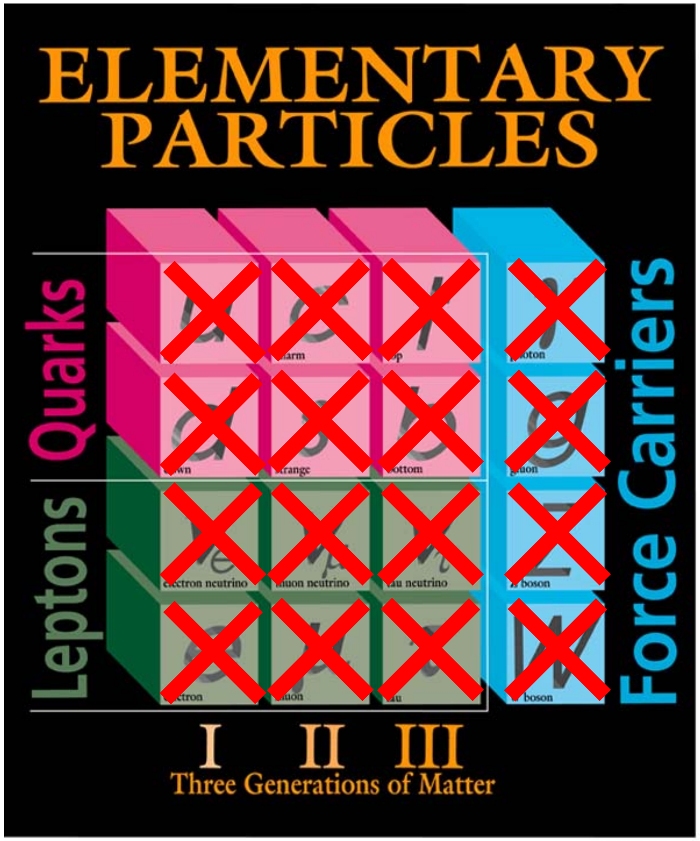
- In 1821 Alexis Bouvard found anomalies in the observed path of Uranus and suggested they could be caused by dark matter

- In 1845-46 Urbain Le Verrier determined the expected properties of the dark matter and how to find it. With this guidance, Johann Gottfried Galle discovered dark matter in 1846.

- Le Verrier wanted to call it “Le Verrier,” but it is now known as Neptune, the farthest known planet (1846-1930, 1979-99, 2006-present)



DARK MATTER



Fermilab 95-759

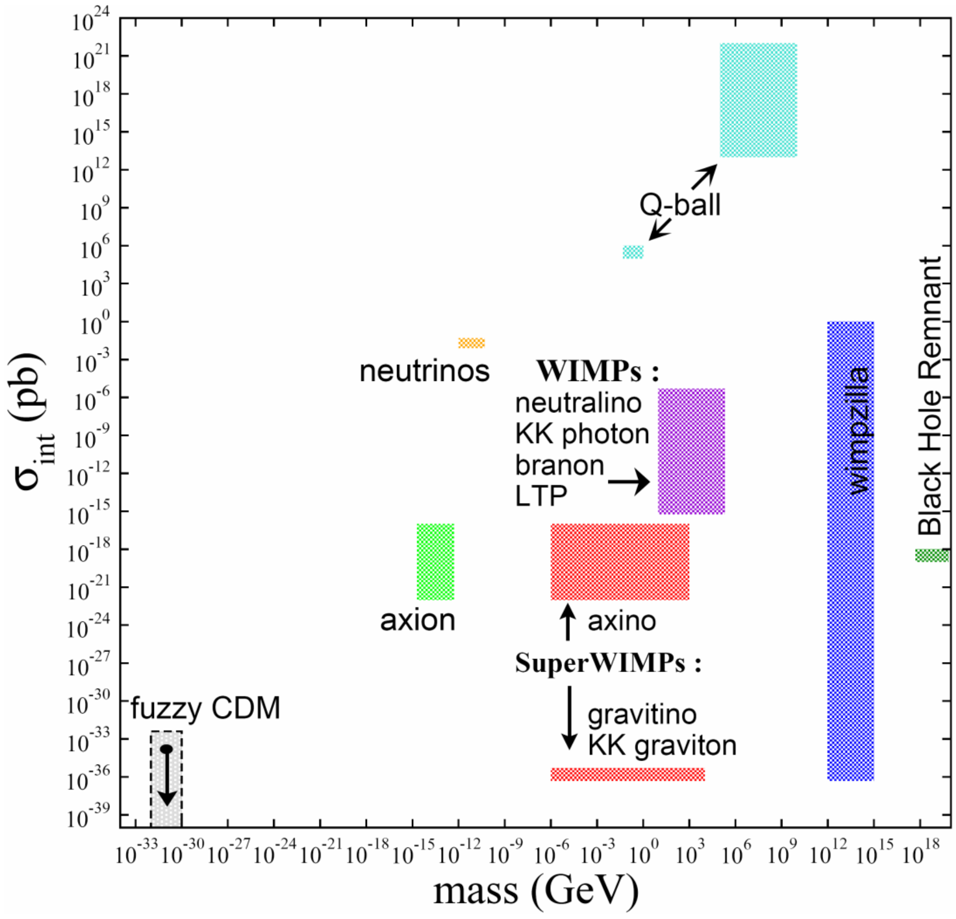
Known DM properties

- 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 not all candidates are equally motivated



HEPAP/AAAC DMSAG Subpanel (2007)

THE WEAK MASS SCALE

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

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

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

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

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

THE WIMP MIRACLE

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

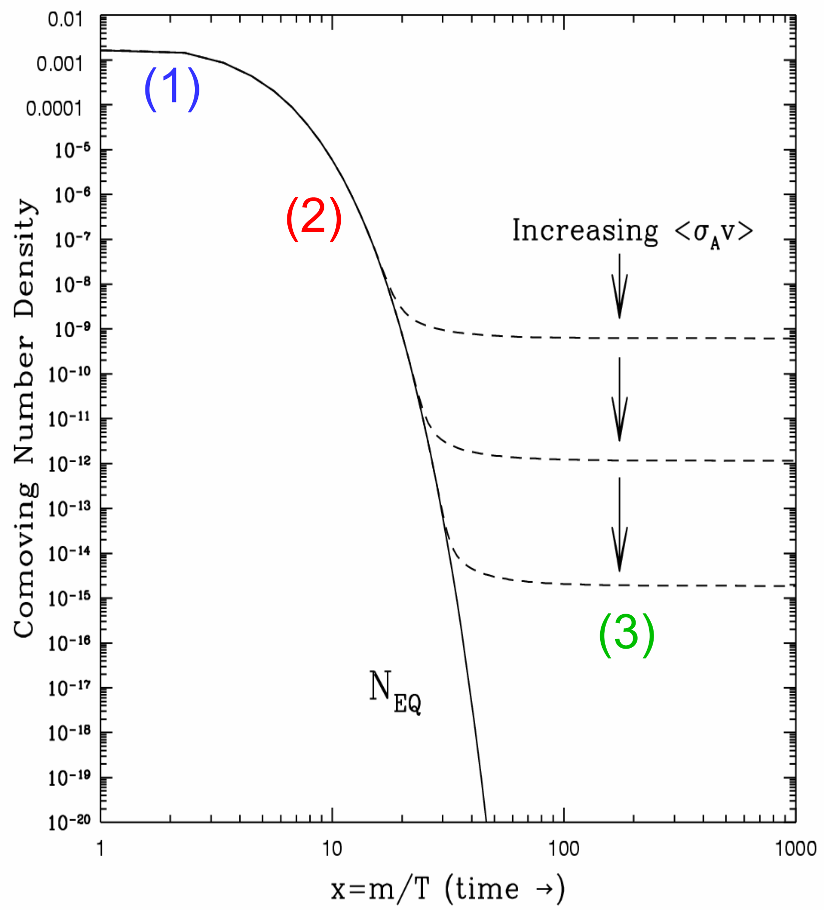
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \rightleftarrows\!\!\!\!\!/ \ \bar{f} f$$

(3) χs "freeze out":

$$\chi\chi \not\rightleftarrows \bar{f} f$$



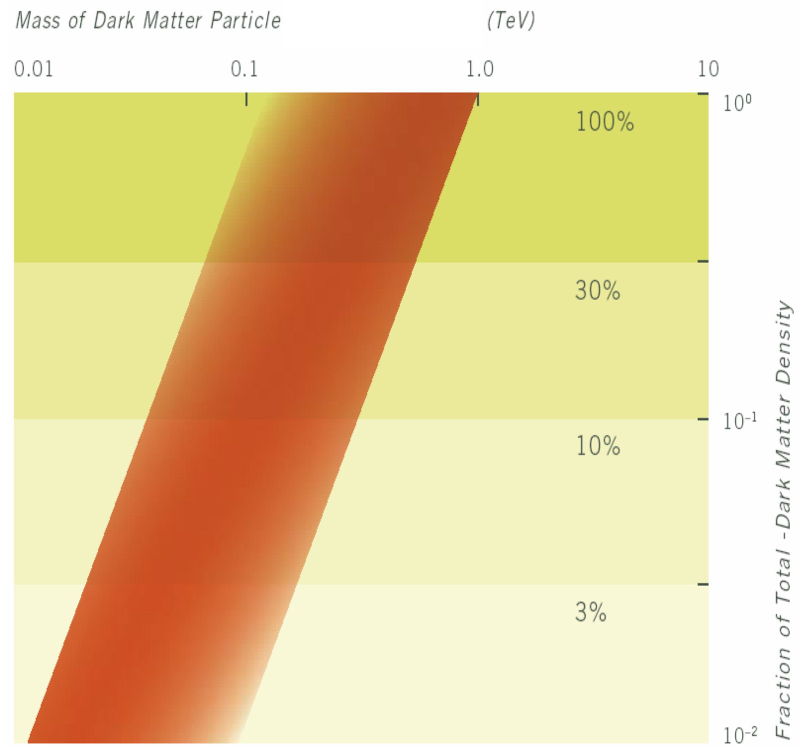
Zeldovich et al. (1960s)

- The amount of dark matter left over is inversely proportional to the annihilation cross section:

$$\Omega_{DM} \sim \langle\sigma_A v\rangle^{-1}$$

- What is the constant of proportionality? Impose natural relations:

$$\sigma_A = k g^4/m^2, \quad g \sim 1 \quad \rightarrow \Omega_{DM} \sim m^2$$



HEPAP LHC/ILC Subpanel (2006)

[band width from k = 0.5 – 2, S and P wave]

Remarkable "coincidence": $\Omega_{DM} \sim 0.1$ for m ~ 100 GeV – 1 TeV; particle physics independently predicts particles with the right density to be dark matter

WIMPS FROM SUPERSYMMETRY

The classic WIMP: neutralinos predicted by supersymmetry

Goldberg (1983); Ellis et al. (1983)

Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces,… For every known particle X, predicts a partner particle $\tilde{X}$

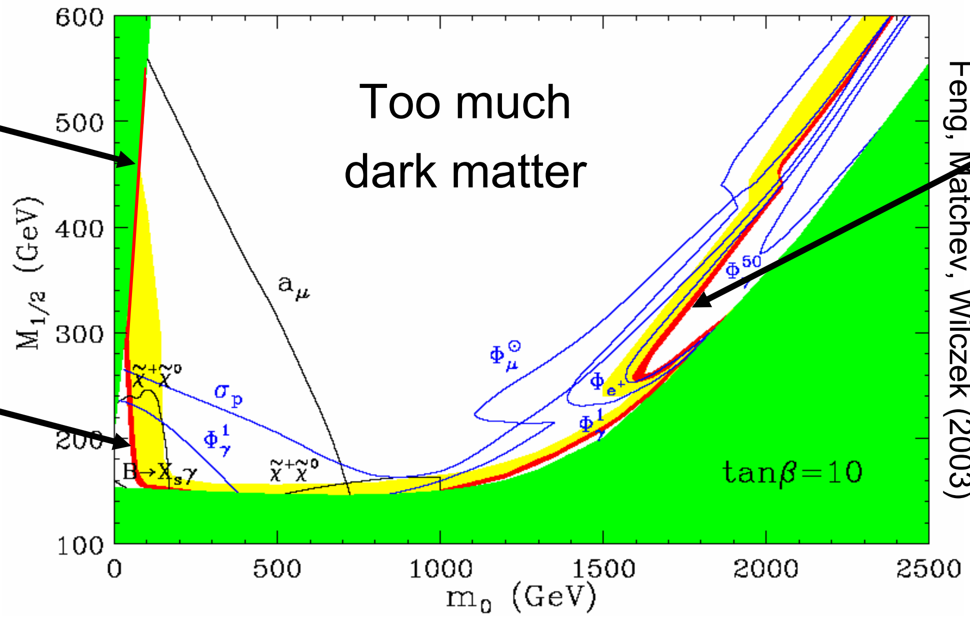
Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}u, \tilde{H}d)$

Particle physics alone → χ is lightest supersymmetric particle, stable, mass ~ 100 GeV. All the right properties for WIMP dark matter!

Ω_{DM} = 23% ± 4% stringently constrains models

Co-annihilation region

Bulk region



Feng, Matchev, Wilczek (2003)

Focus point region

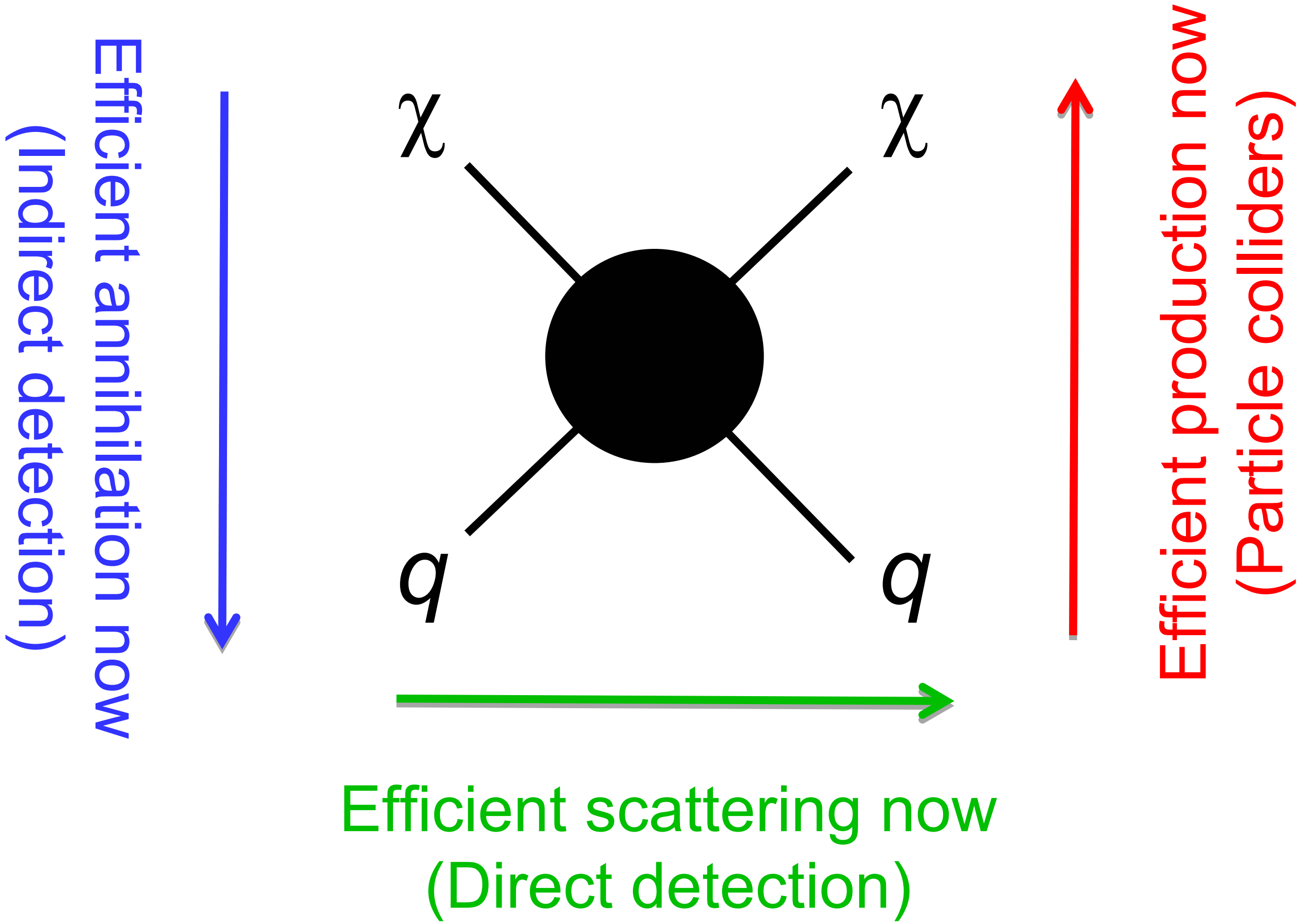
Yellow: pre-WMAP

Red: post-WMAP

Cosmology excludes many possibilities, favors certain regions

WIMP DETECTION

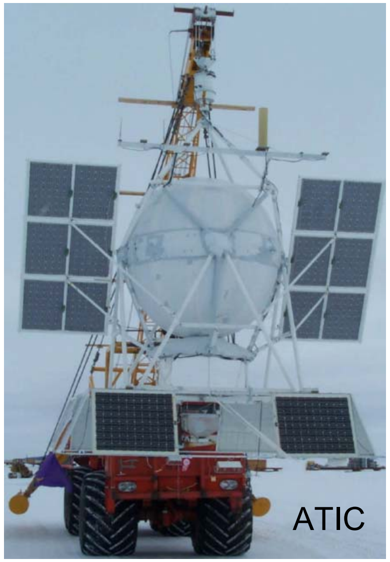
Correct relic density → Efficient annihilation then



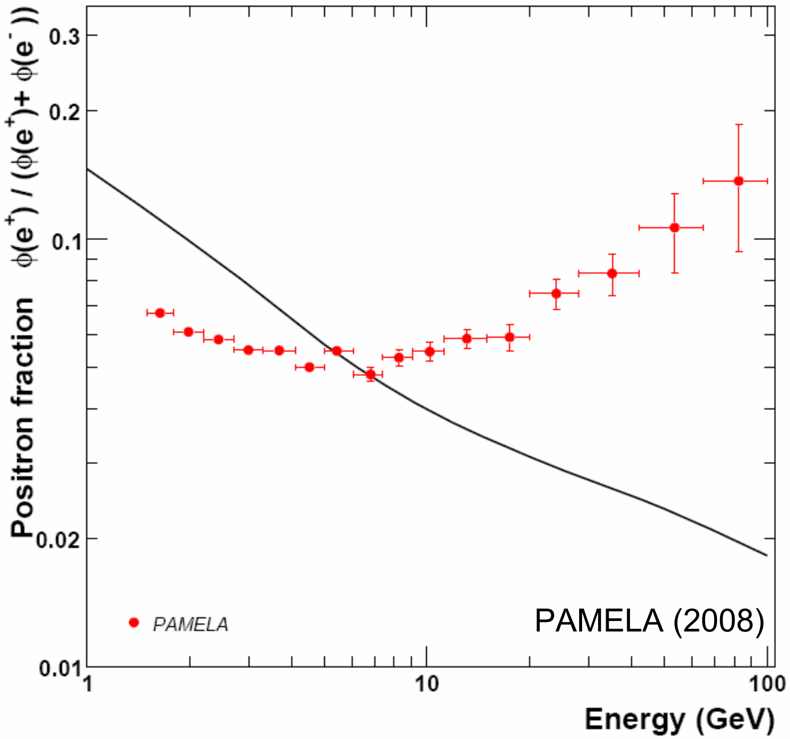
INDIRECT DETECTION

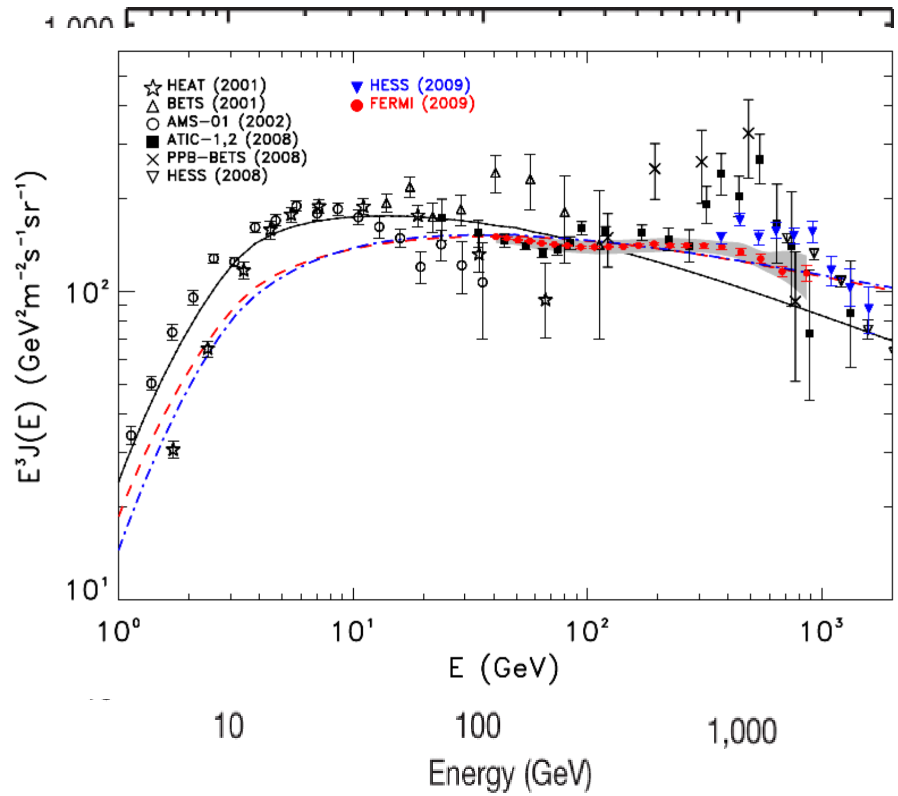
Dark Matter annihilates in ___the halo___ to
a place

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



RECENT DATA



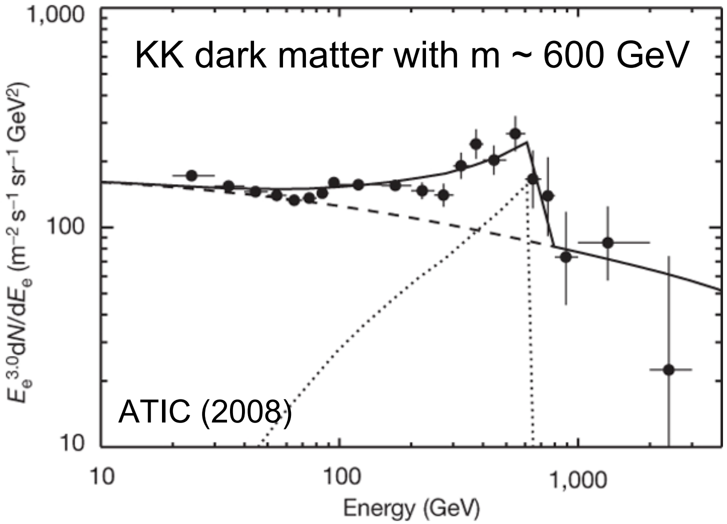


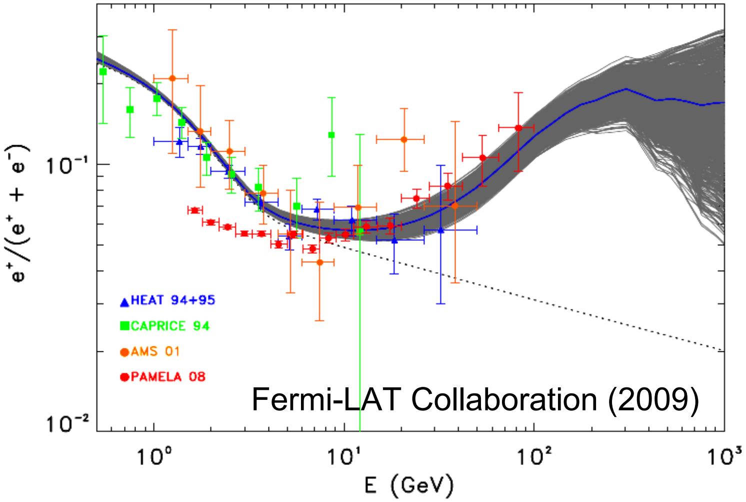
Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

- Energy spectrum shape consistent with some 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
- No excess seen in anti-protons
- Pulsars can explain PAMELA

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





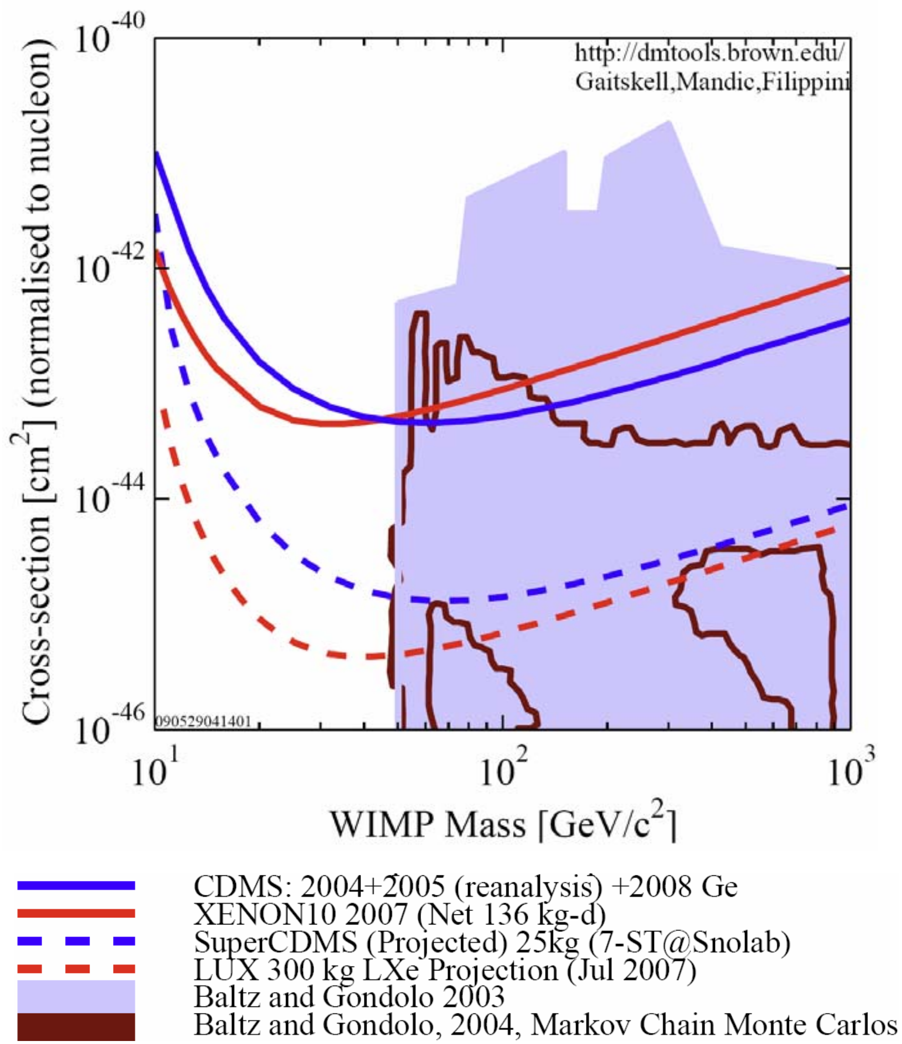
DIRECT DETECTION

- WIMP properties:
  $v \sim 10^{-3}$ c
  Kinetic energy ~ 100 keV
  Local density ~ 1 / liter

- Detected by recoils off ultra-sensitive underground detectors

- Area of rapid progress (CDMS, XENON, …)

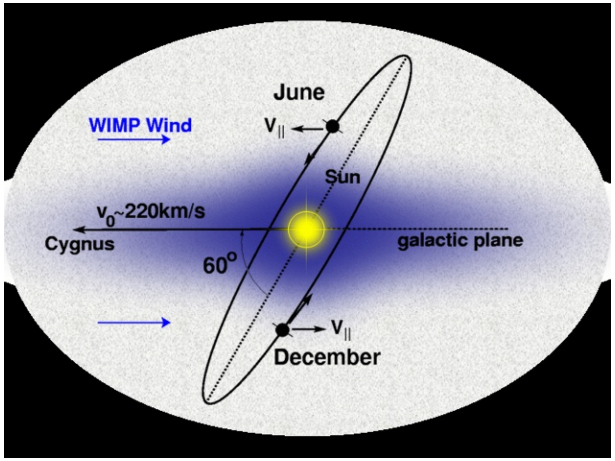
- Theory predictions vary, but many models → 10^{-44} cm^2



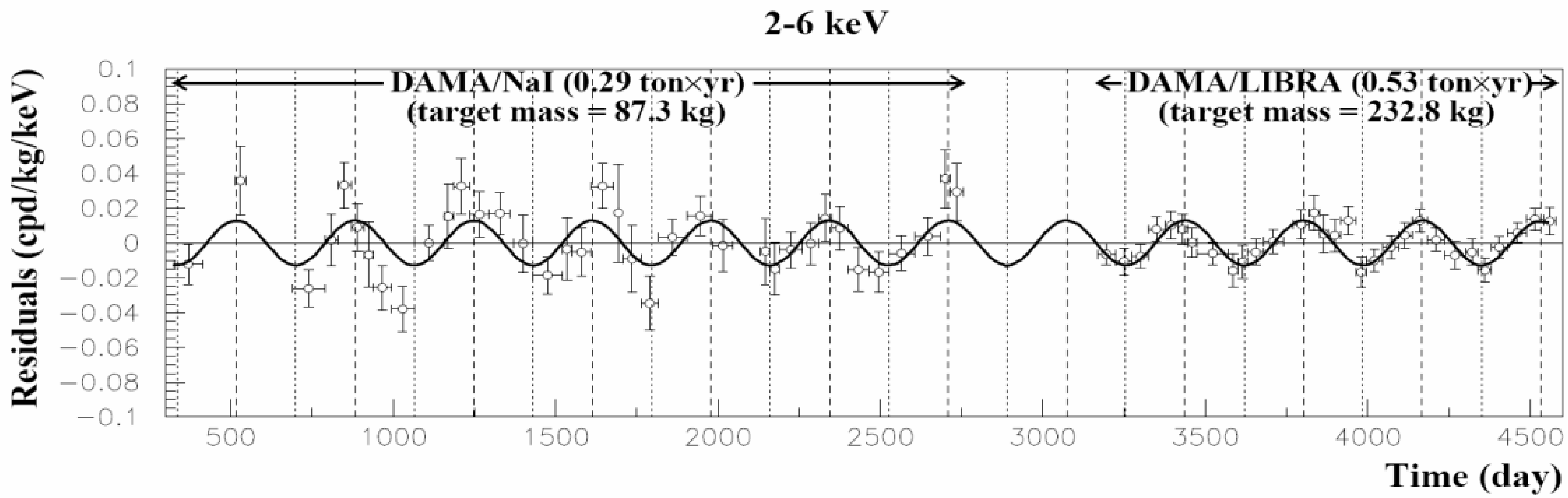
DIRECT DETECTION: DAMA

Annual modulation: Collision rate should change as Earth's velocity adds constructively/destructively with the Sun's.

Drukier, Freese, Spergel (1986)



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



DAMA (2008)

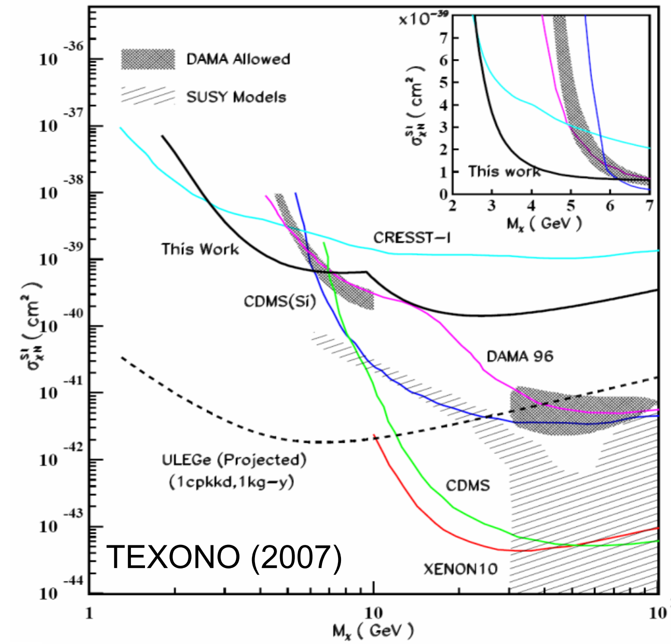
CHANNELING

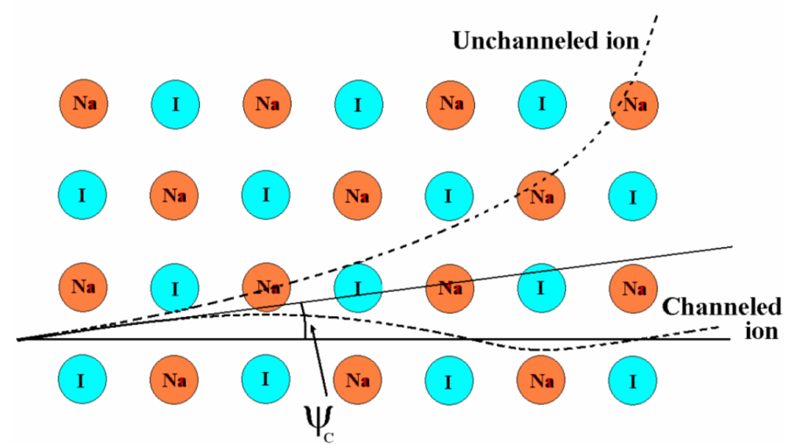
- DAMA's result is puzzling, in part because the favored region was considered excluded by others

- This may be ameliorated by
  - Astrophysics
  - Channeling: in crystalline detectors, efficiency for nuclear recoil energy → electron energy depends on direction

Gondolo, Gelmini (2005)

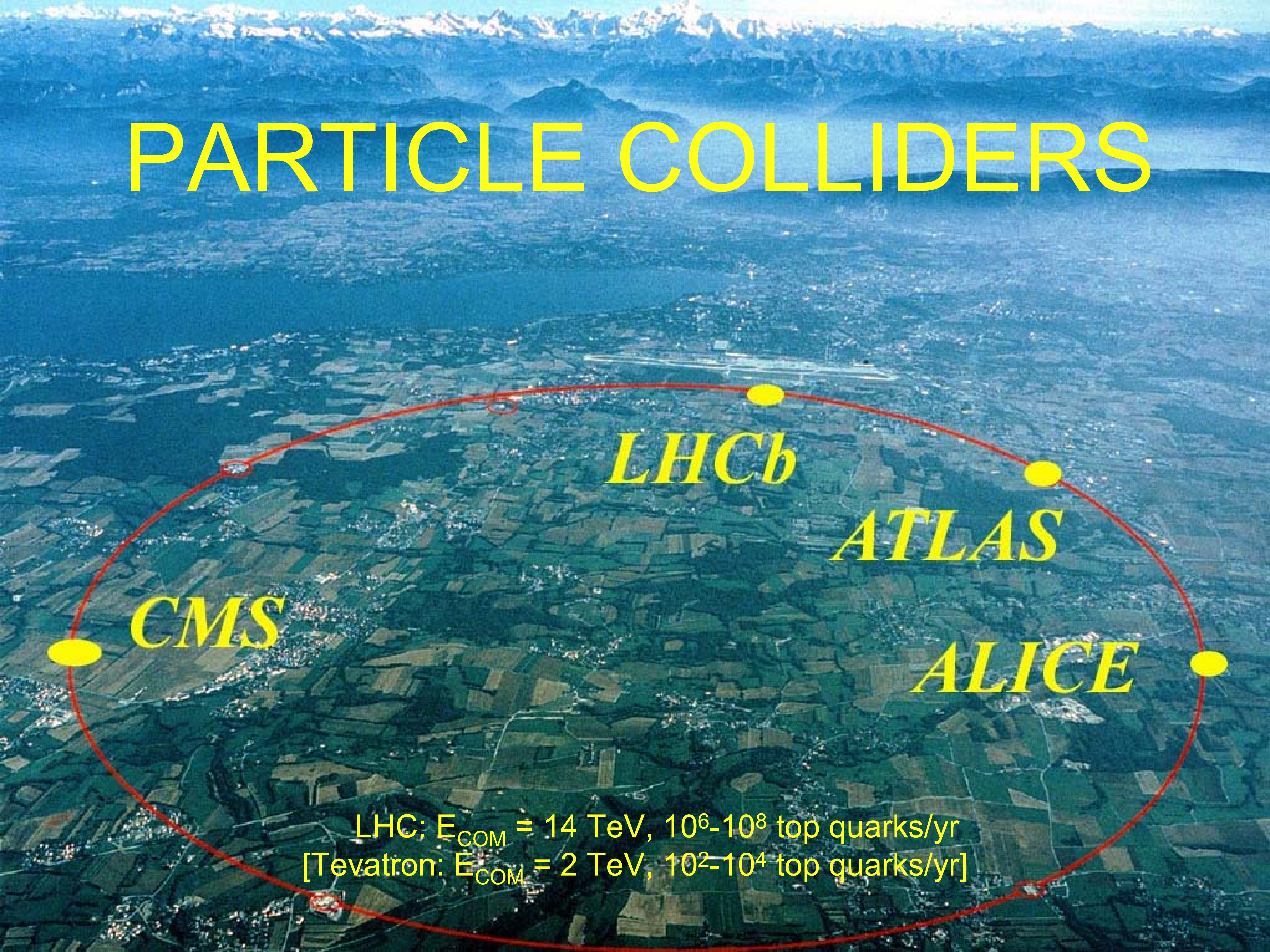
Drobyshevski (2007), DAMA (2007)





- Channeling reduces threshold, shifts allowed region to
  - Rather low WIMP masses (~GeV)
  - Very high σ_{SI} (~10^{-39} cm^2)

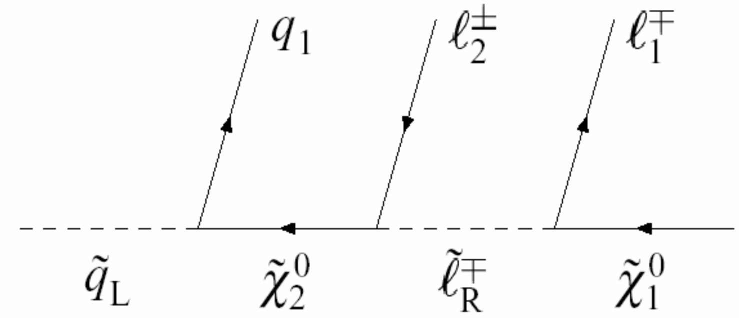
PARTICLE COLLIDERS

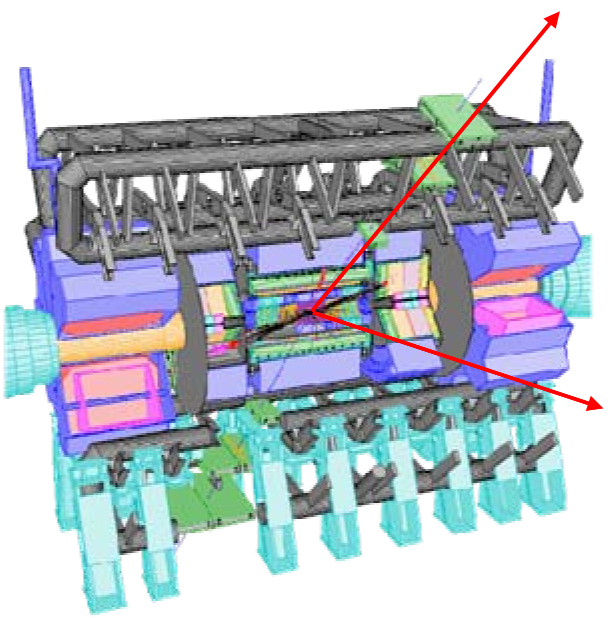


LHC: E_{COM} = 14 TeV, 10^6-10^8 top quarks/yr
[Tevatron: E_{COM} = 2 TeV, 10^2-10^4 top quarks/yr]

WHAT THEN?

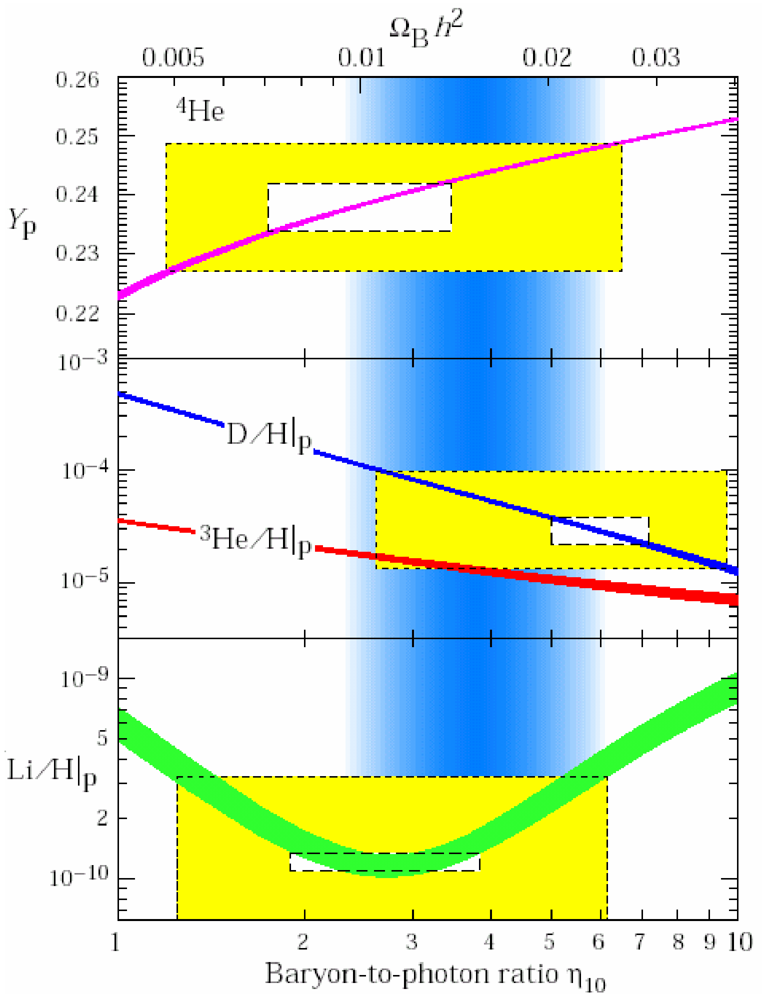
- What LHC actually sees:
  - E.g., $\tilde{q}\tilde{q}$ pair production
  - Each $\tilde{q} \rightarrow$ neutralino χ
  - 2 χ's escape detector
  - missing momentum





- This is not the discovery of dark matter
  - Lifetime > 10^{-7} s $\rightarrow$ 10^{17} s?

THE EXAMPLE OF BBN

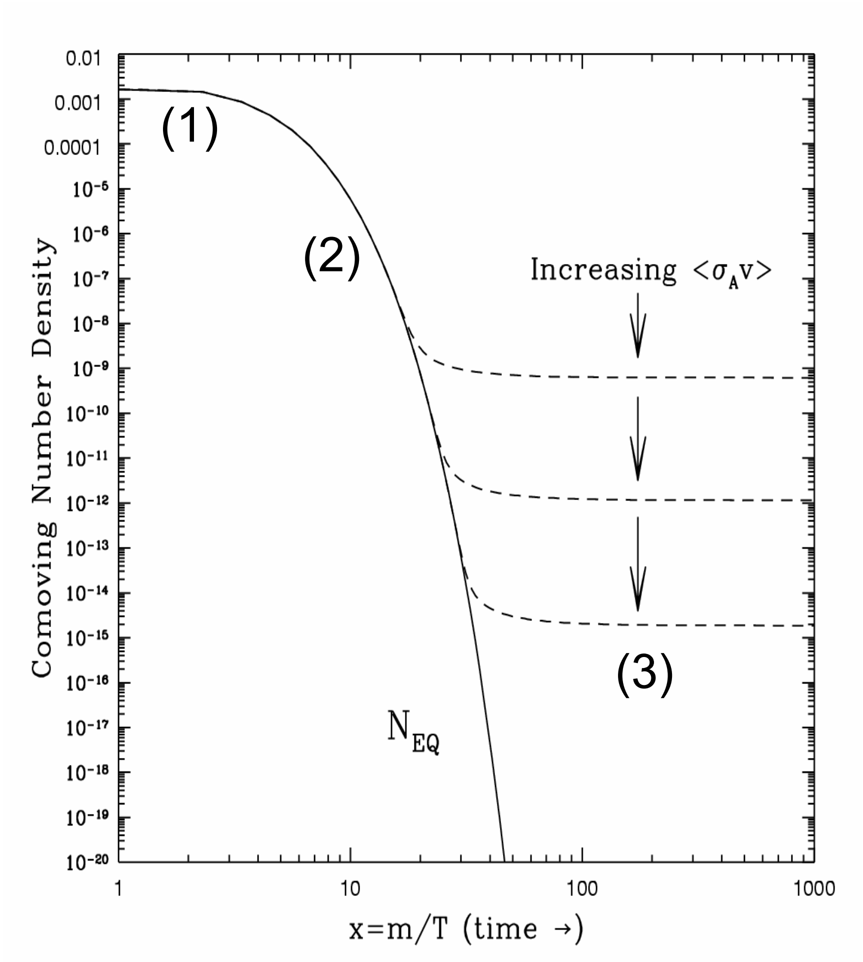


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

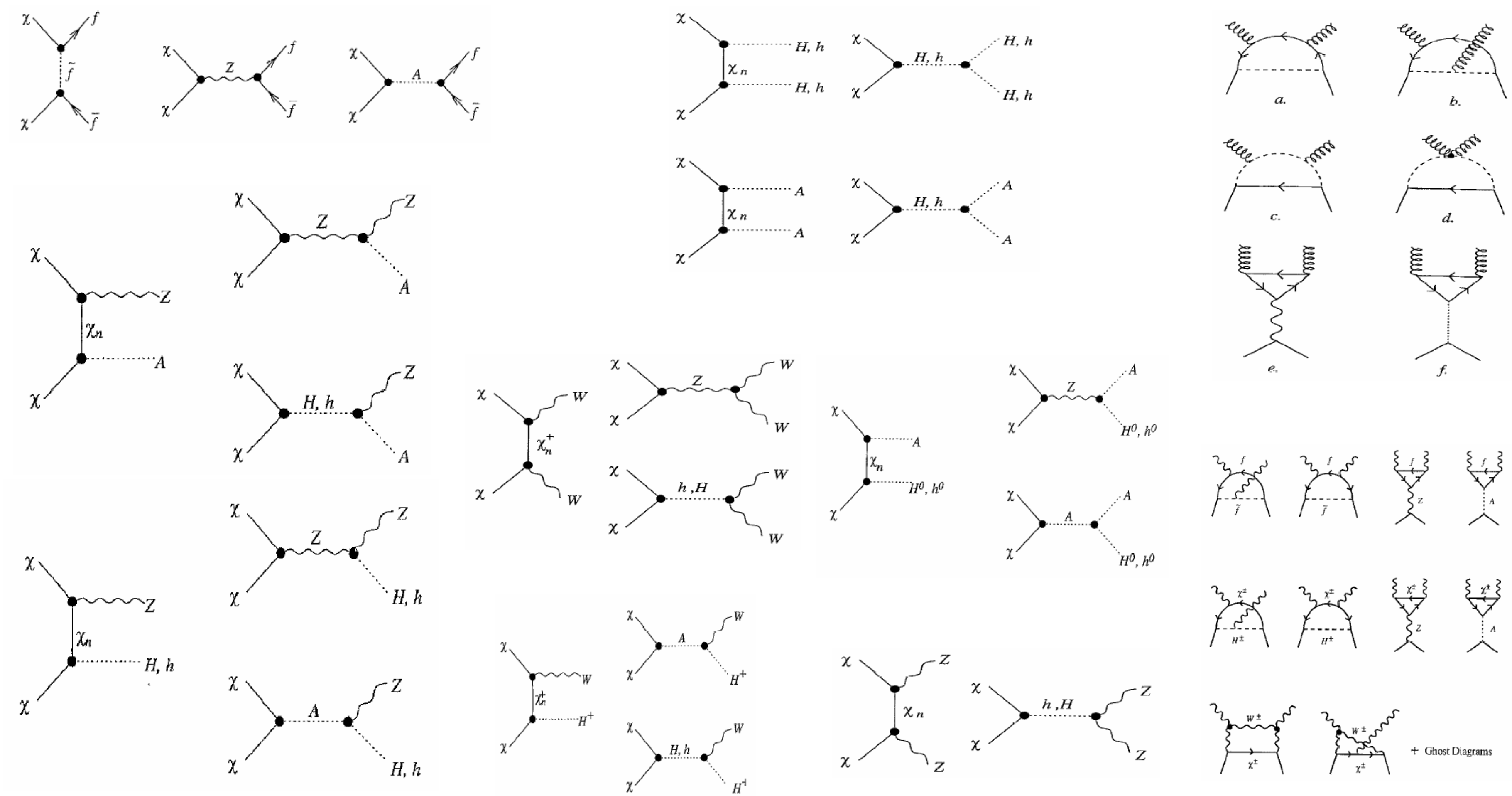
  t ~ 1 sec

DARK MATTER ANALOGUE



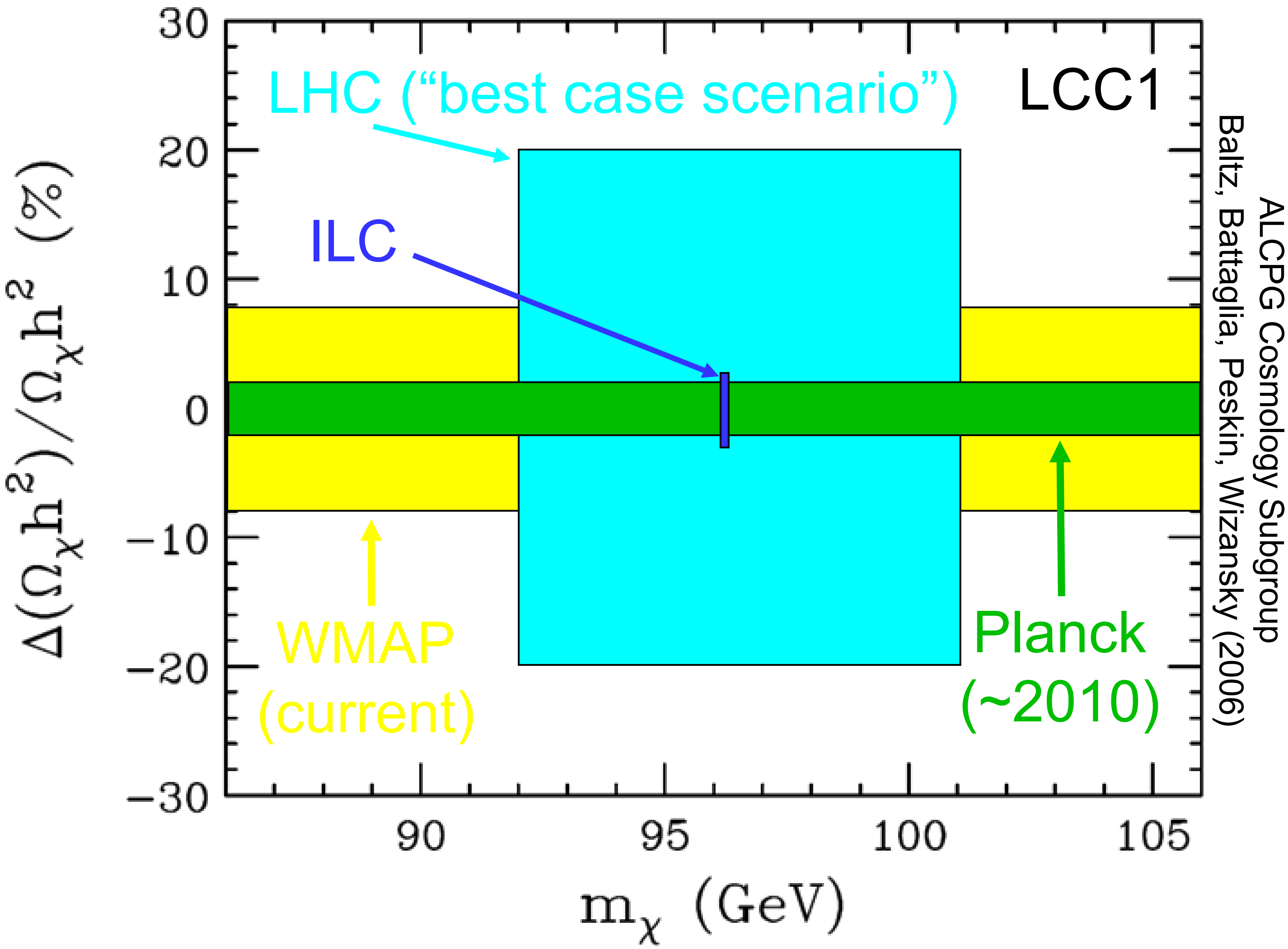
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

Contributions to Neutralino WIMP Annihilation



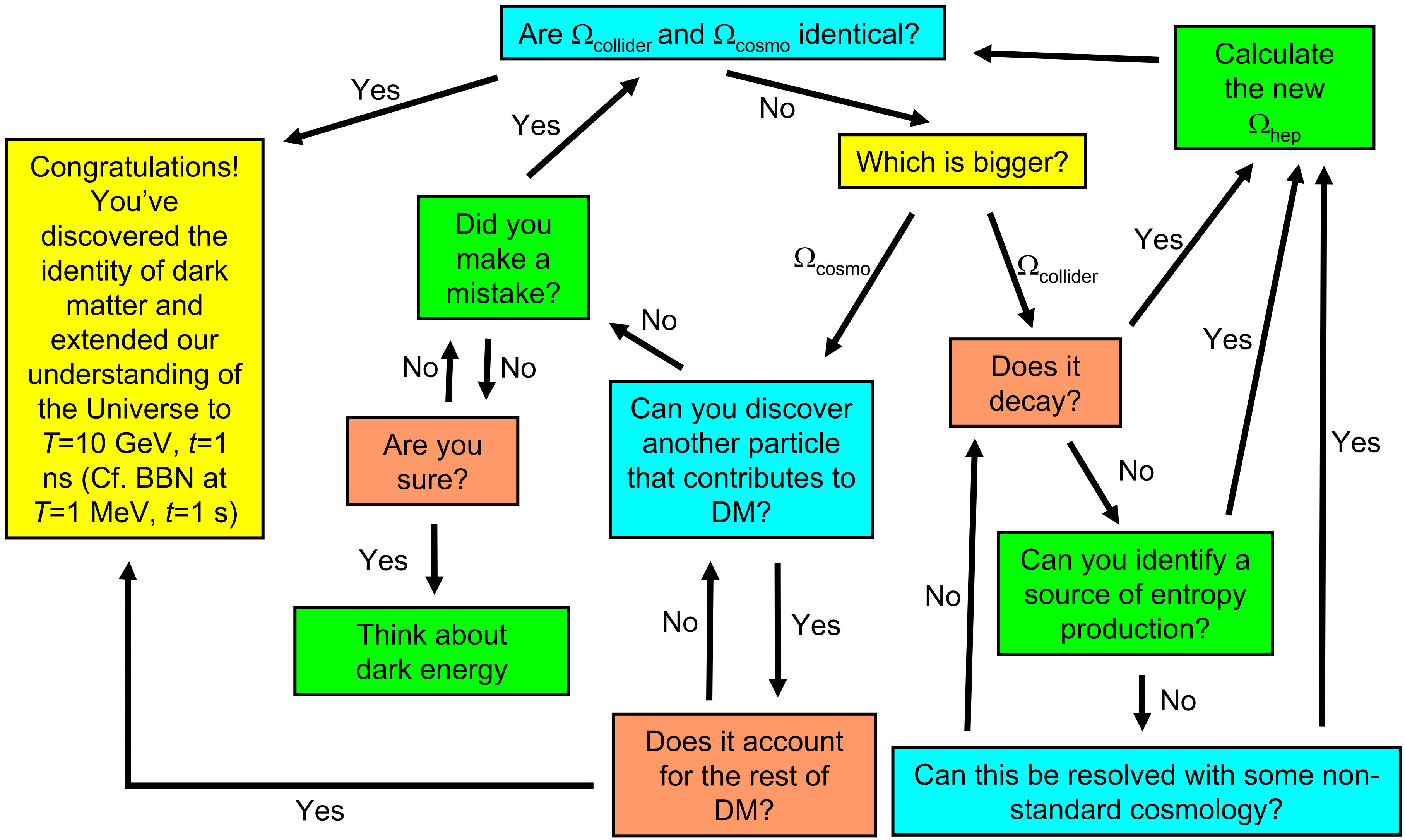
Jungman, Kamionkowski, Griest (1995)

RELIC DENSITY DETERMINATIONS



% level comparison of predicted $\Omega_{collider}$ with observed Ω_{cosmo}

IDENTIFYING DARK MATTER



BEYOND WIMPS

- Dark matter has been detected only through gravity

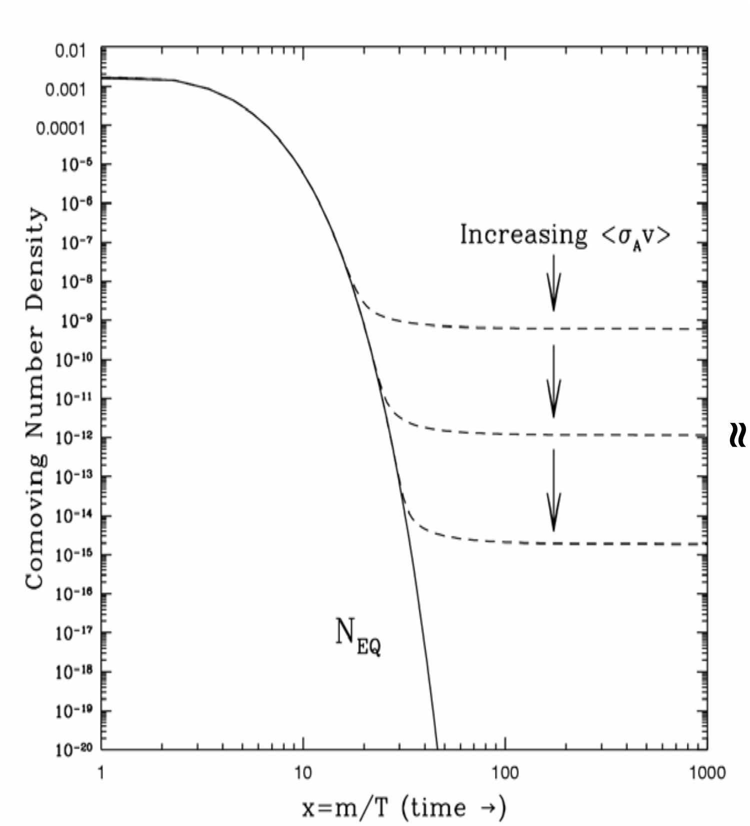
- But the WIMP miracle is our prime reason to expect progress, and it seemingly implies that dark matter is
  - Weakly-interacting
  - Cold
  - Collisionless

  Are all WIMP miracle-motivated candidates astrophysically equivalent?

- No! Recently, have seem many new classes of candidates. Some preserve the motivations of WIMPs, but have qualitatively different implications

SUPERWIMPS

Feng, Rajaraman, Takayama (2003)



- Suppose there is a superweakly-interacting particle (superWIMP) lighter than the WIMP

- WIMPs freeze out as usual

≈ WIMP → $\tilde{G}$

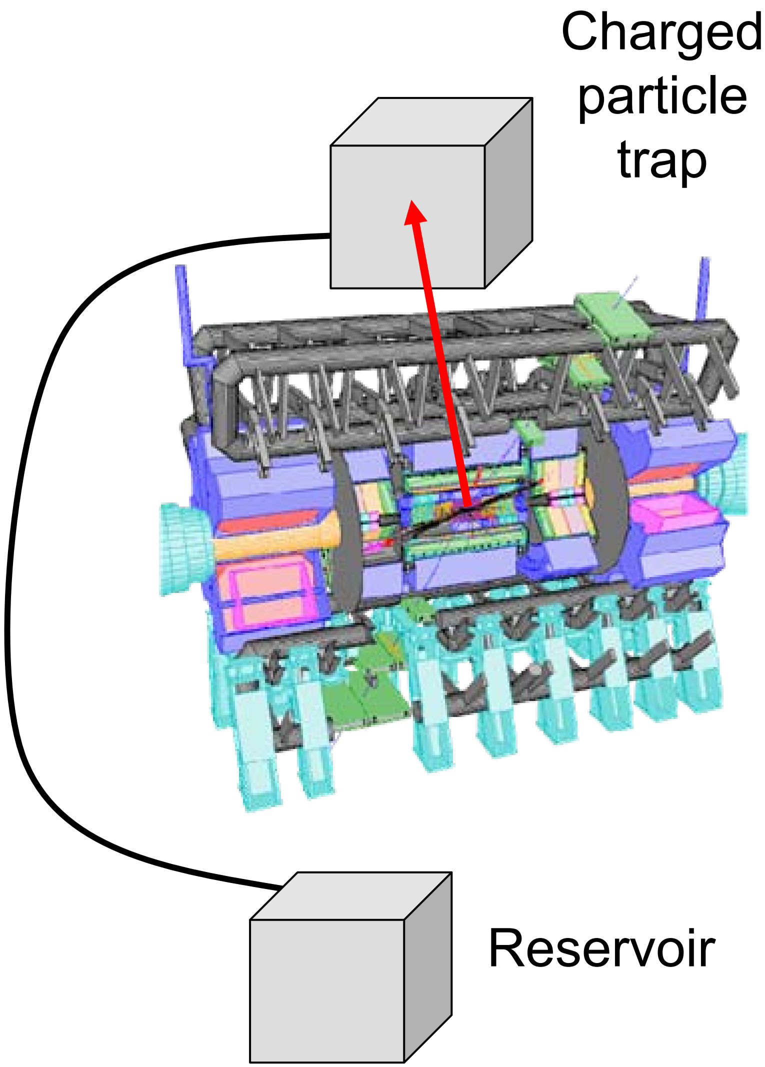
- But then all WIMPs decay to superWIMPs! In the canonical example of gravitinos, lifetime is

$$M_{Pl}^2/M_W^3 \sim \text{seconds to months}$$

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

CHARGED PARTICLE TRAPPING

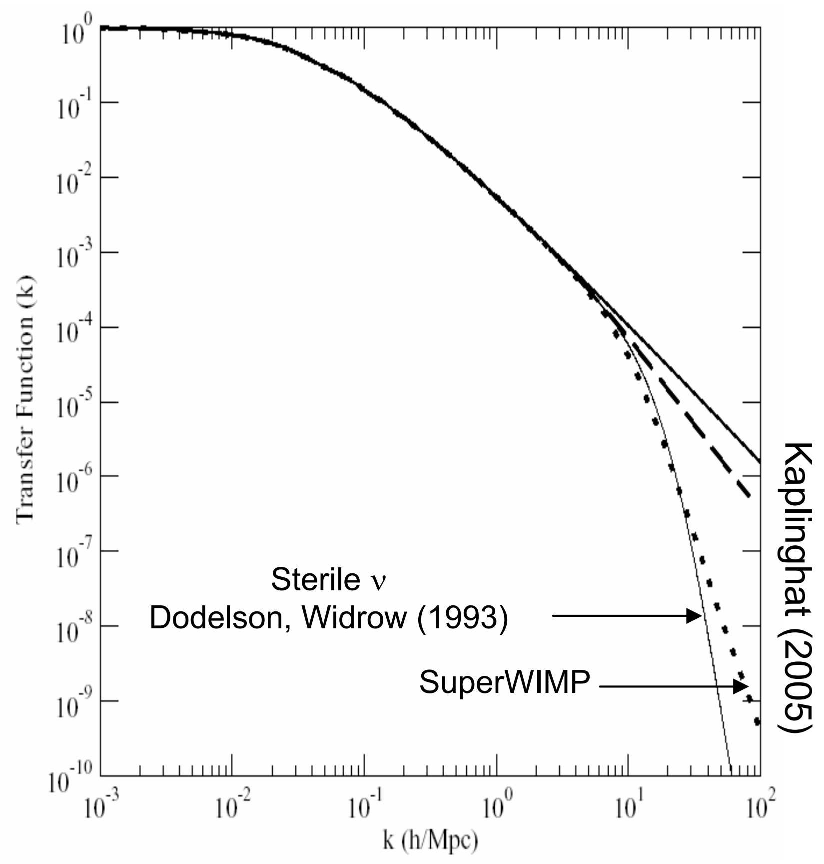
- SuperWIMPs are produced by decays of metastable particles, which can be charged
- Charged metastable particles will be obvious at colliders, can be trapped and moved to a quiet environment to study their decays
- Can catch 1000 per year in a 1m thick water tank



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

WARM SUPERWIMPS

- SuperWIMPs are produced in late decays 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)

WIMPLESS DARK MATTER

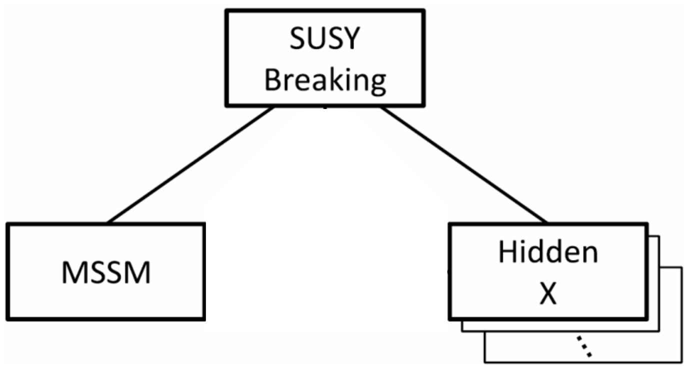
- In some well-known supersymmetric models, hidden sectors contain particles with $m_X \sim g_X^2$

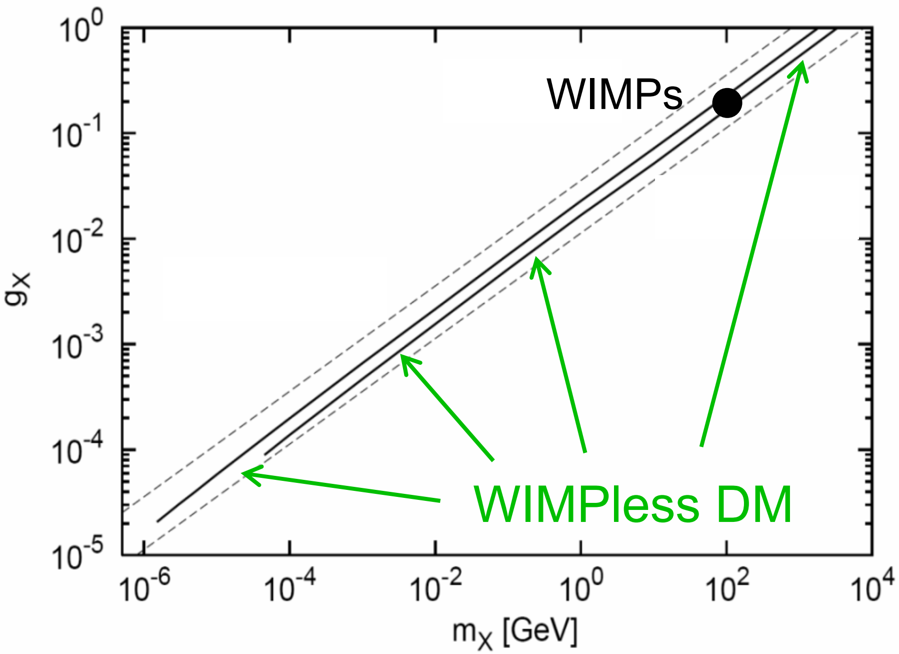
- This leaves the relic density invariant

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

- "WIMPless Miracle": dark matter candidates have a range of masses/couplings, but always the right relic density

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

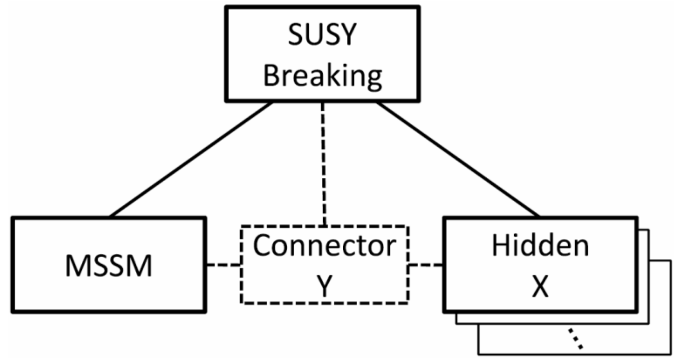




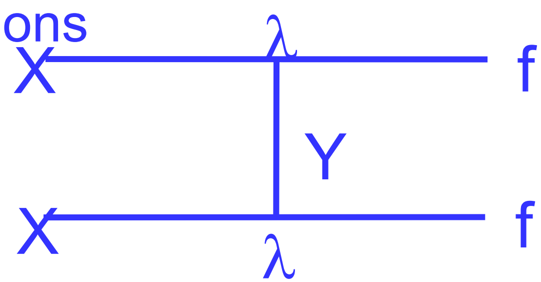
HIDDEN DM SIGNALS

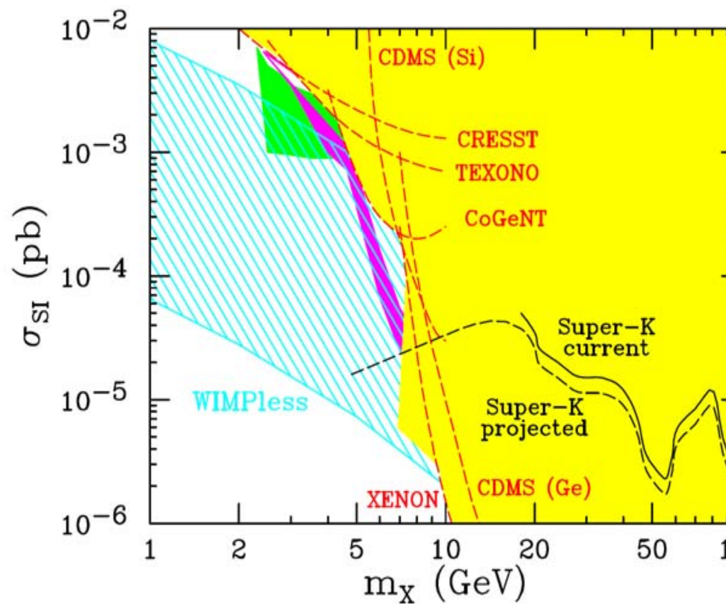
- Hidden DM may have only gravitational effects, but still interesting: e.g., it may have hidden charge, Rutherford scattering → self-interacting DM

Feng, Kaplinghat, Tu, Yu (2009)



- Alternatively, hidden DM may interact with normal matter through non-gauge interactions





Feng, Kumar, Learned, Strigari (2008)

- Many new, related ideas

Pospelov, Ritz (2007); Hooper, Zurek (2008)
Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)
Ackerman, Buckley, Carroll, Kamionkowski (2008)

CONCLUSIONS

- Particle Dark Matter
  - Central topic at the interface of cosmology and particles
  - Both cosmology and particle physics → weak scale ~ 100 GeV
- Candidates
  - WIMPs: Many well-motivated candidates
  - SuperWIMPs, WIMPless dark matter: Similar motivations, but qualitatively new possibilities (warm, collisional, only gravitationally interacting)
  - Many others
- LHC collisions begin in 2009-10, direct and indirect detection, astrophysical probes are improving rapidly – this field will be transformed soon