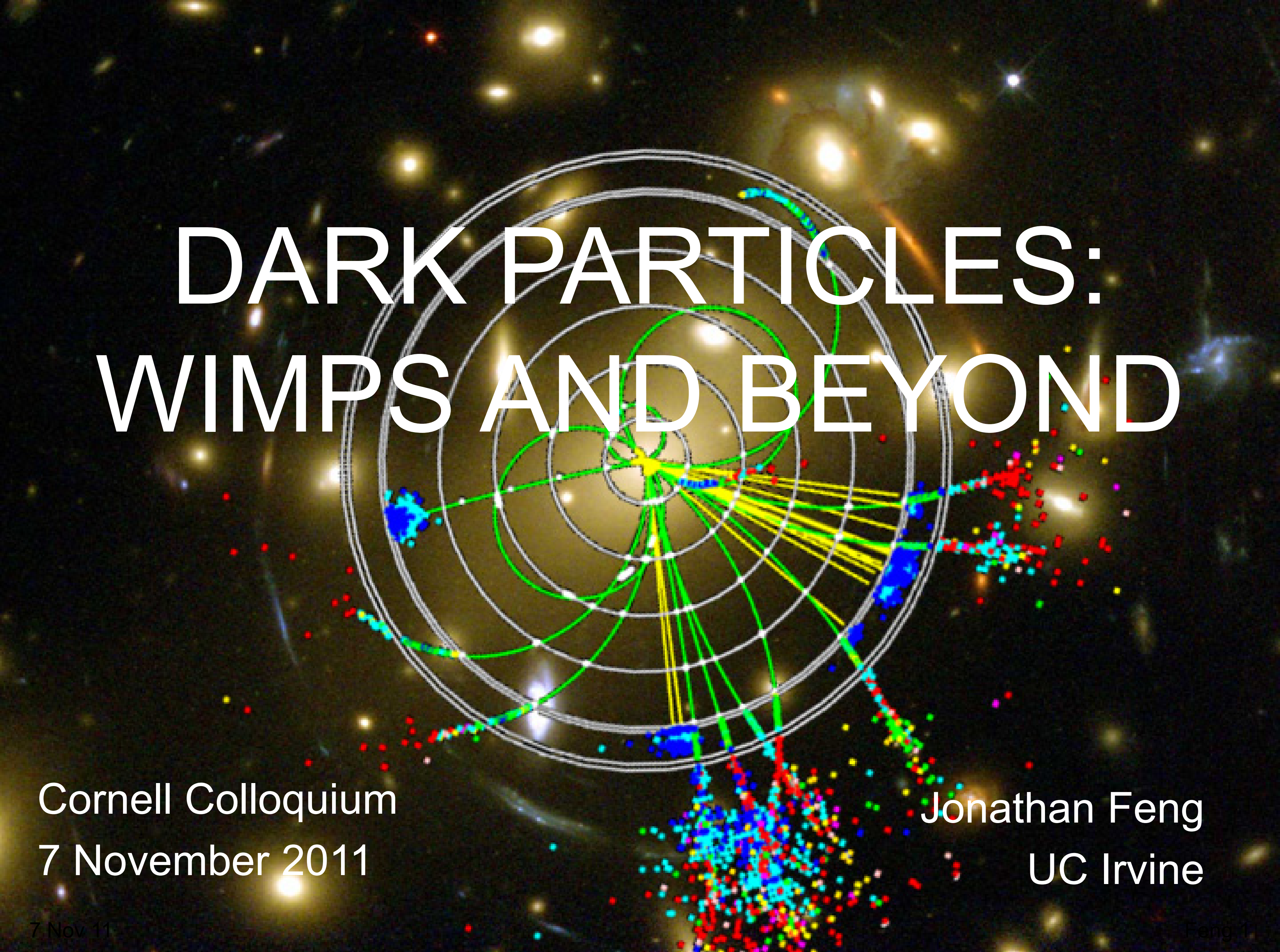
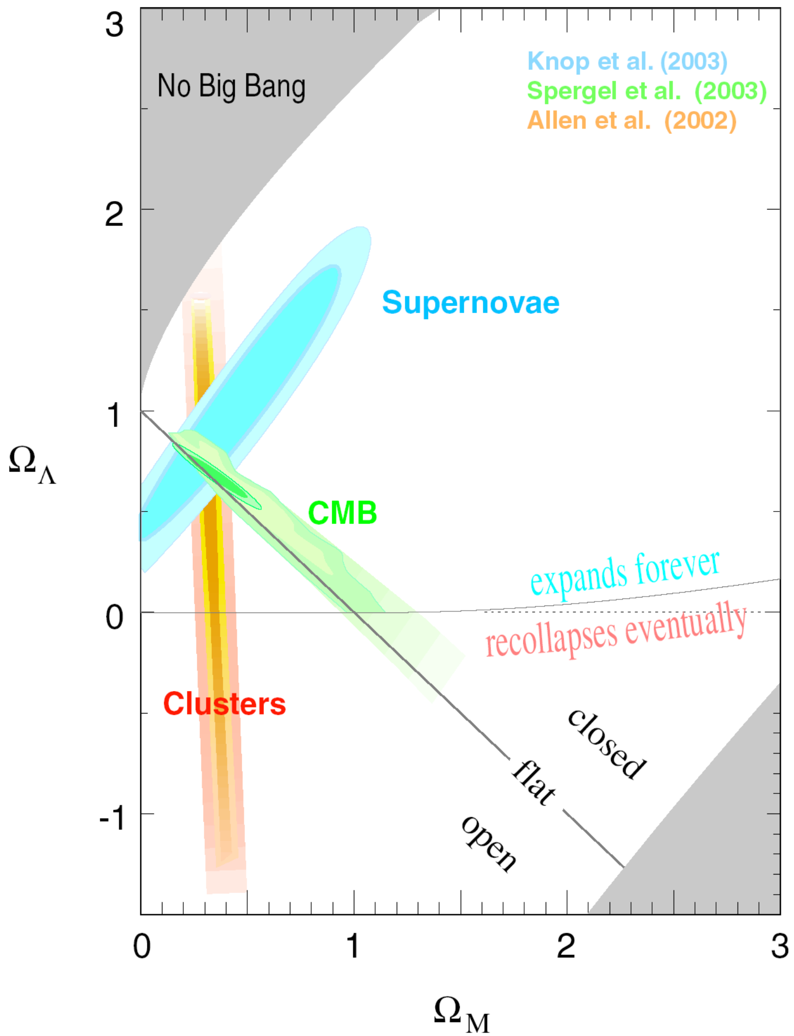


DARK PARTICLES: WIMPS AND BEYOND

Cornell Colloquium
7 November 2011

Jonathan Feng
UC Irvine

EVIDENCE FOR DARK MATTER



- 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%

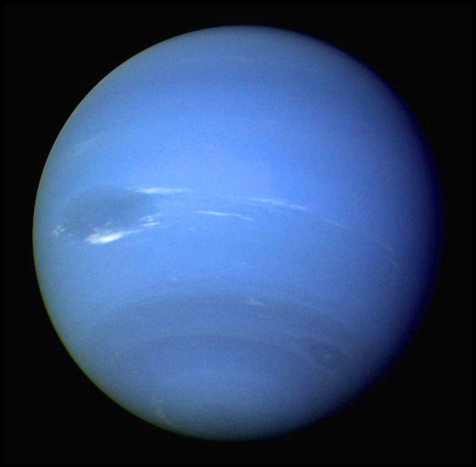
  Neutrinos: 0.2% (Σm_ν/0.1eV)

- To date, all evidence is from dark matter's gravitational effects; to identify it, we need to see it in other ways

A PRECEDENT

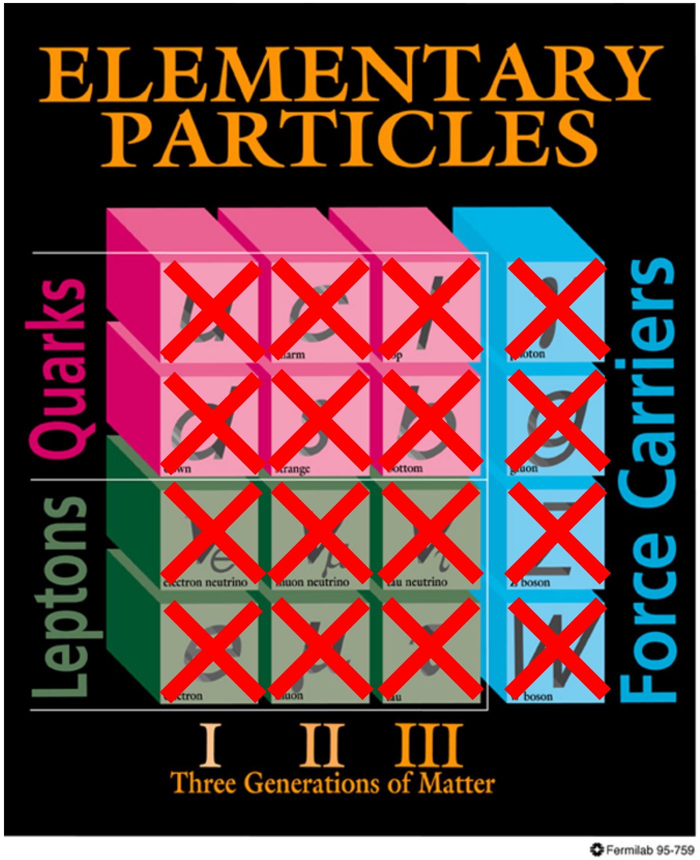
- In 1821 Alexis Bouvard found anomalies in the observed path of Uranus and suggested they could be caused by dark matter

- 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



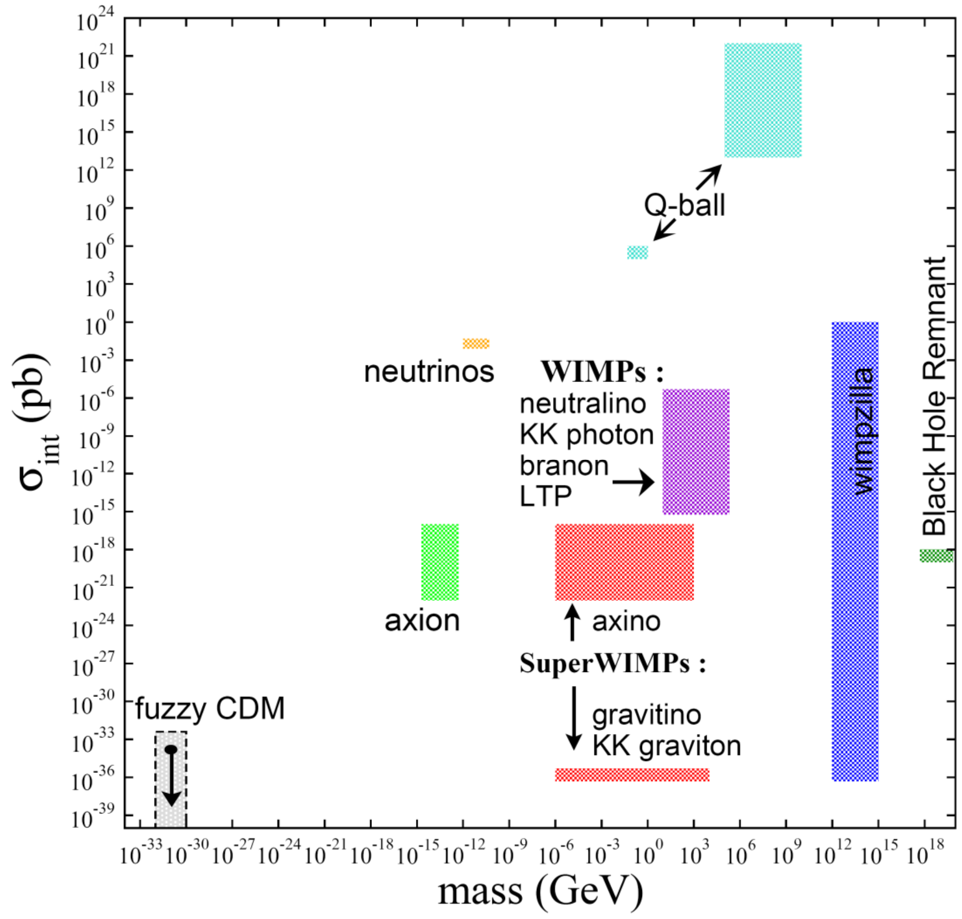
Known DM properties

- 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 similarly motivated



HEPAP/AAAC DMSAG Subpanel (2007)

THE WEAK MASS SCALE

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

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

- $G_F \approx 1.1 \cdot 10^{-5}\ \text{GeV}^{-2} \rightarrow$ 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:

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

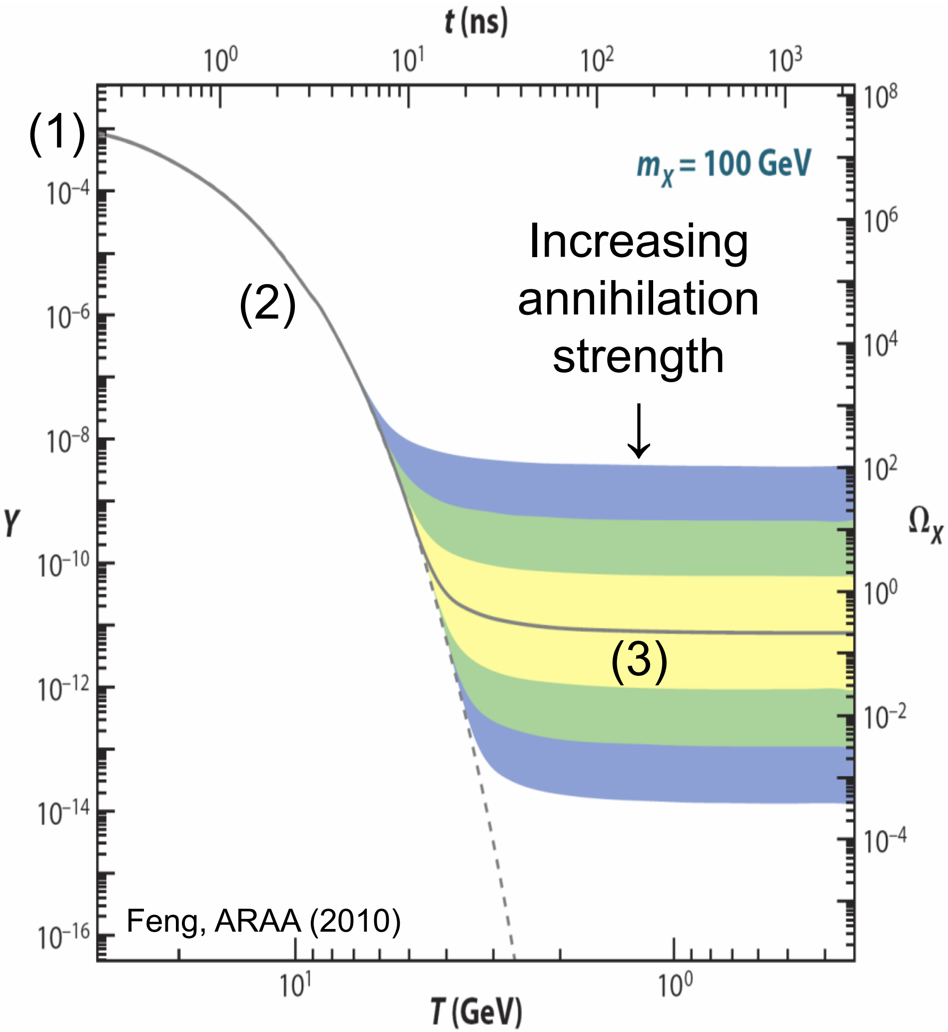
(2) Universe cools:

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

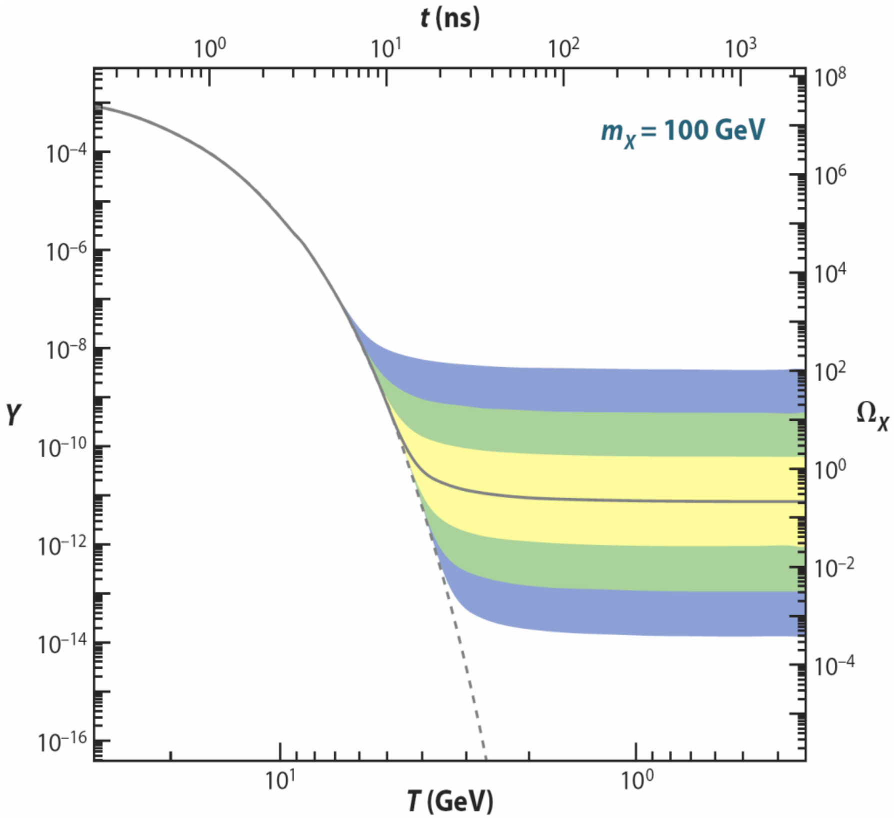
(3) Universe expands:

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

Zeldovich et al. (1960s)

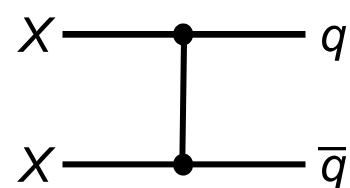


THE WIMP MIRACLE



- 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

WIMPS FROM SUPERSYMMETRY

The classic WIMP: neutralinos predicted by supersymmetry

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

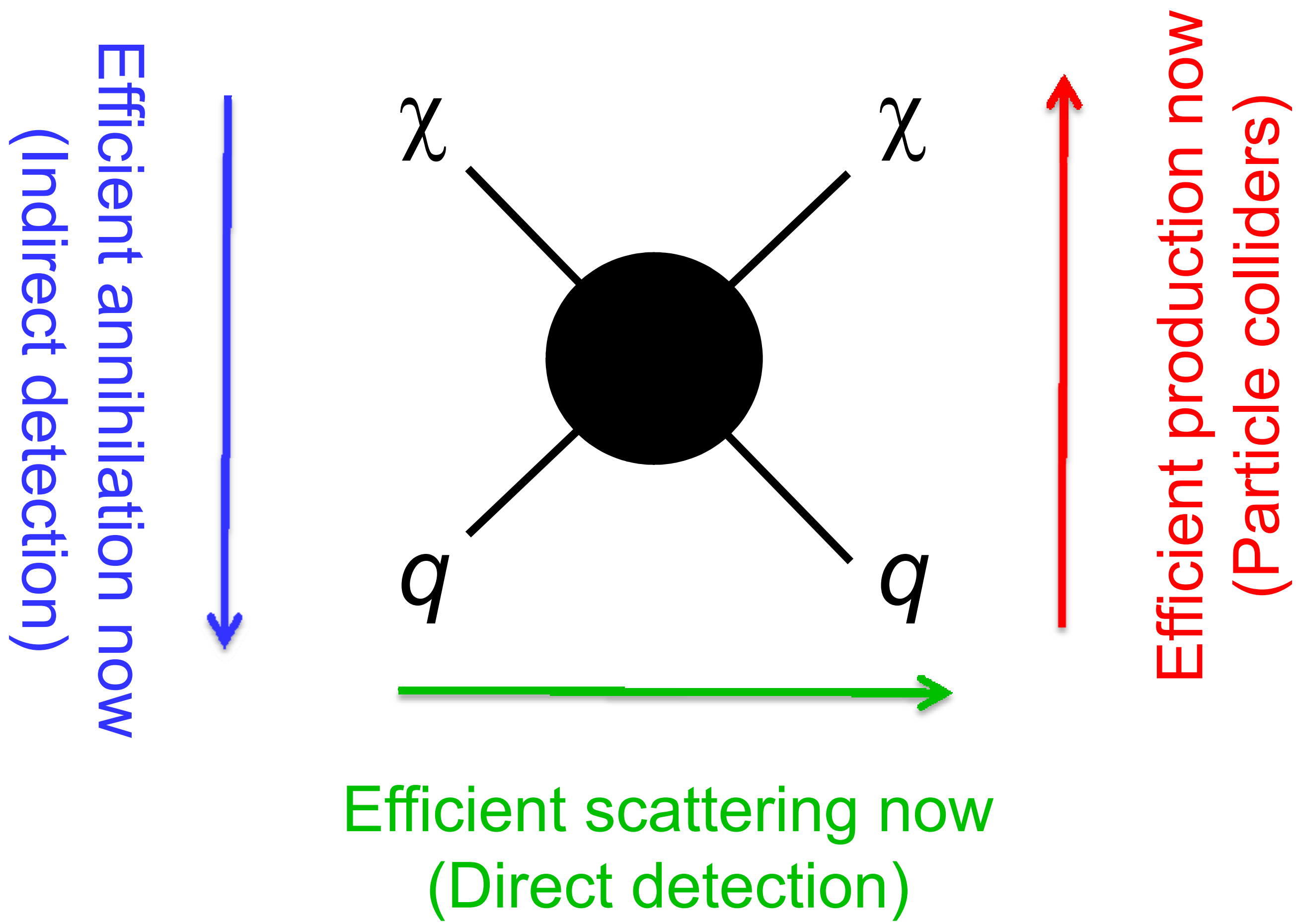
Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces,… For every known particle X, predicts a partner particle $\tilde{X}$

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

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

WIMP DETECTION

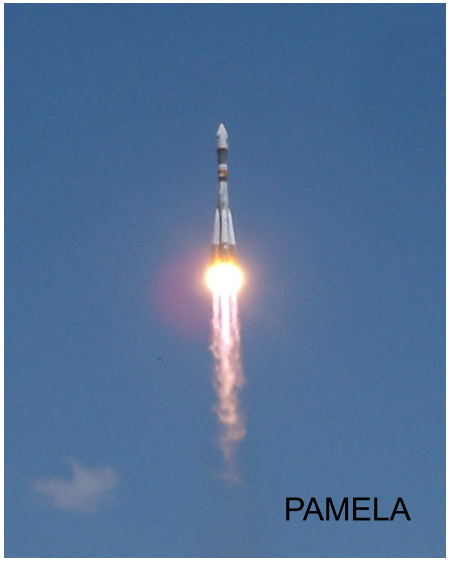
Correct relic density → Efficient annihilation then

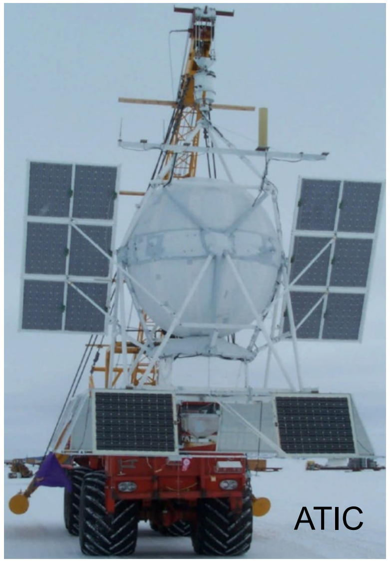


INDIRECT DETECTION

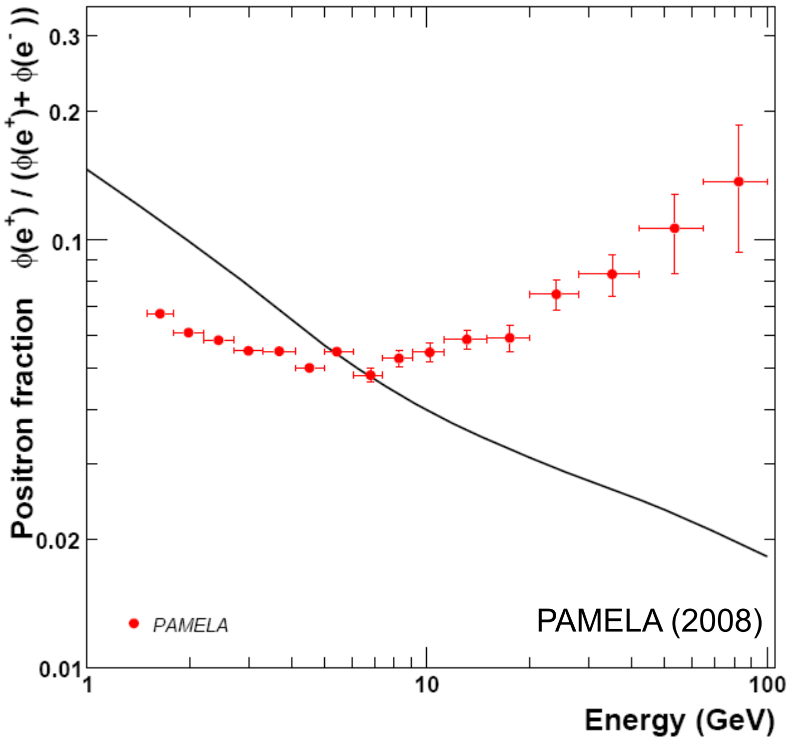
Dark Matter annihilates in ___the halo___ to
a place

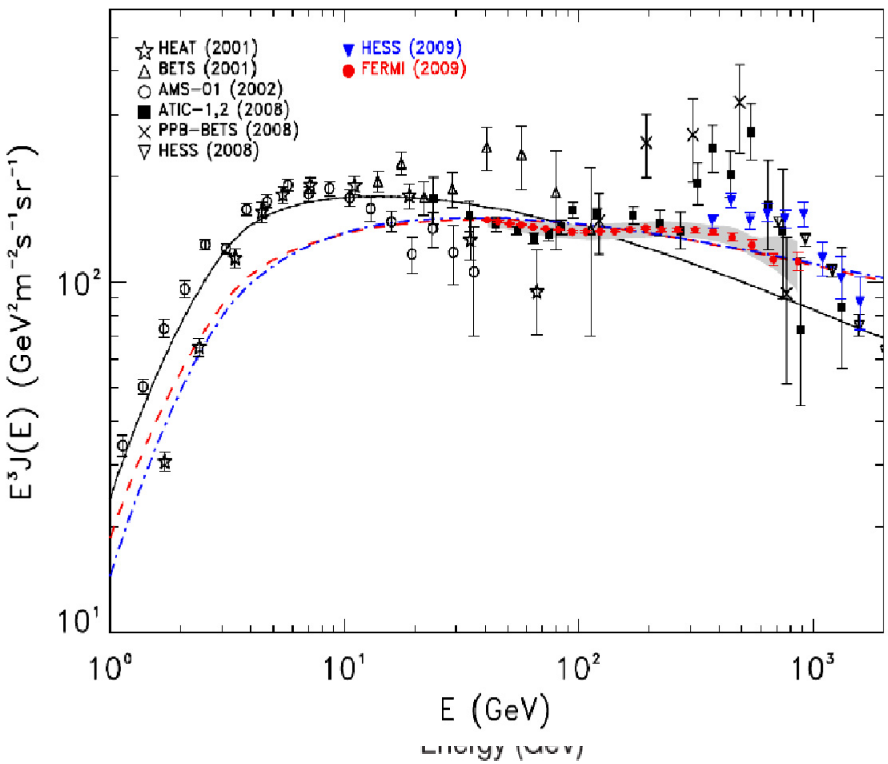
___positrons___, which are detected by ___PAMELA/ATIC/Fermi…___.
some particles — an experiment





CURRENT STATUS





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

ARE THESE DARK MATTER?

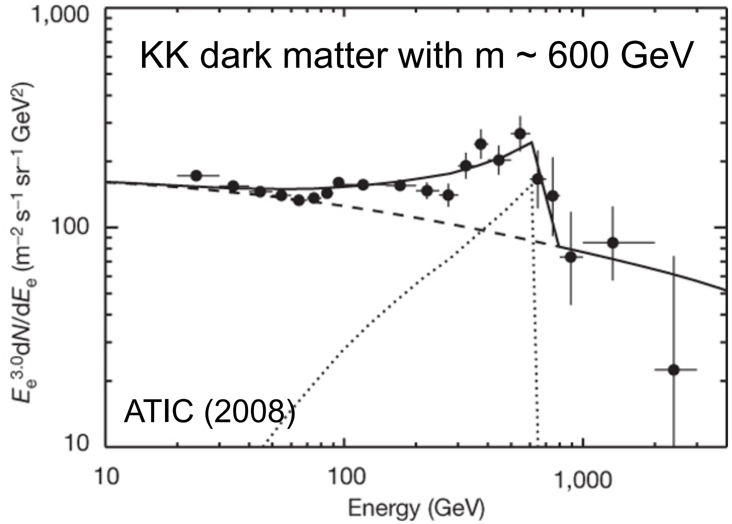
- Energy spectrum shape consistent with WIMP dark matter candidates

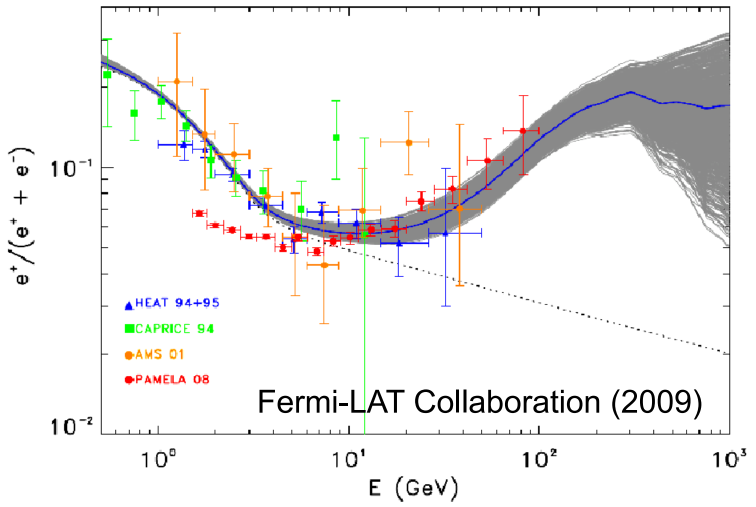
- Flux is a factor of 100-1000 too big for a thermal relic; requires
  - Enhancement from astrophysics (very unlikely)
  - Enhancement from particle physics
  - Alternative production mechanism

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

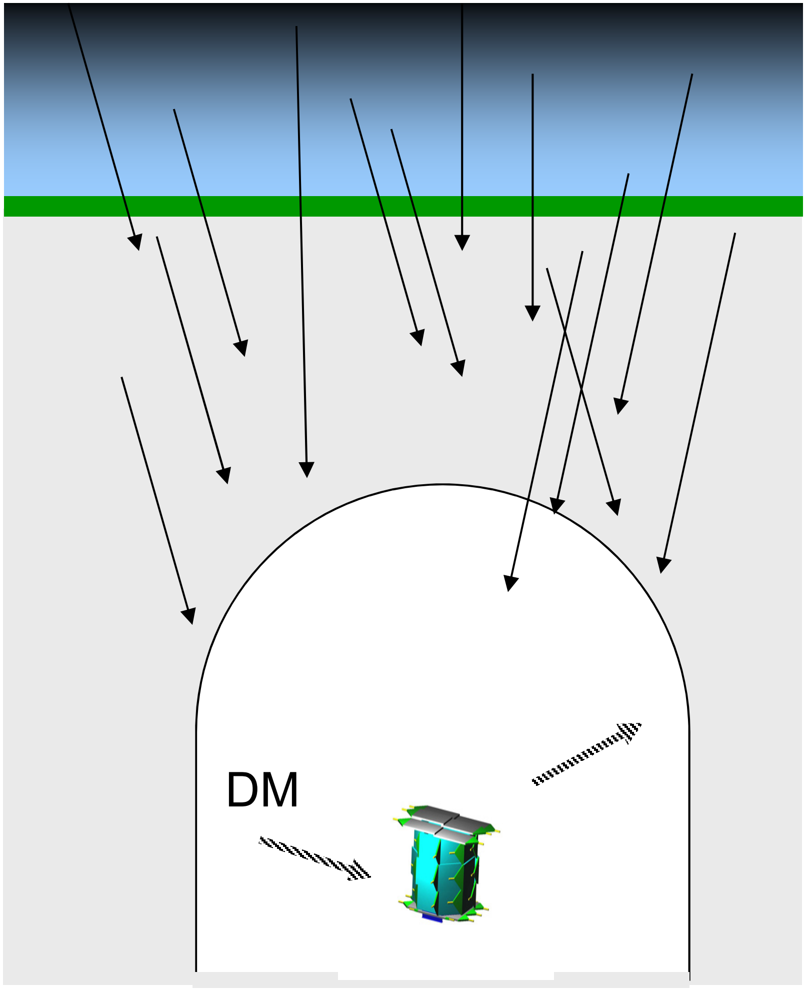
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008); Profumo (2008)
Fermi-LAT Collaboration (2009)





DIRECT DETECTION

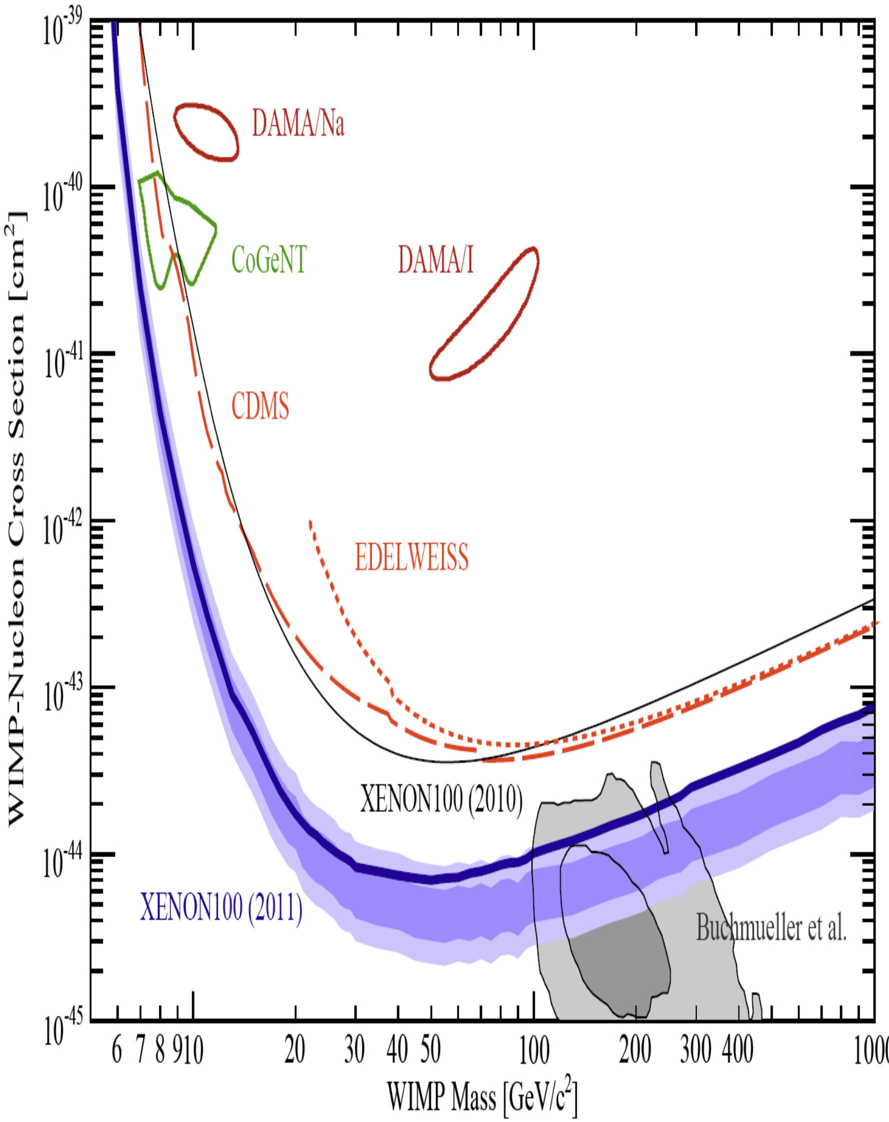
- WIMP properties
  - m ~ 100 GeV
  - local density ~ 1 per liter
  - velocity ~ 10^{-3} c
  - ~ 1 interaction per kg per year
- Can look for normal matter recoiling from WIMP collisions in ultra-sensitive detectors placed deep underground
- An area of rapid progress on two fronts



WEAK INTERACTION FRONTIER

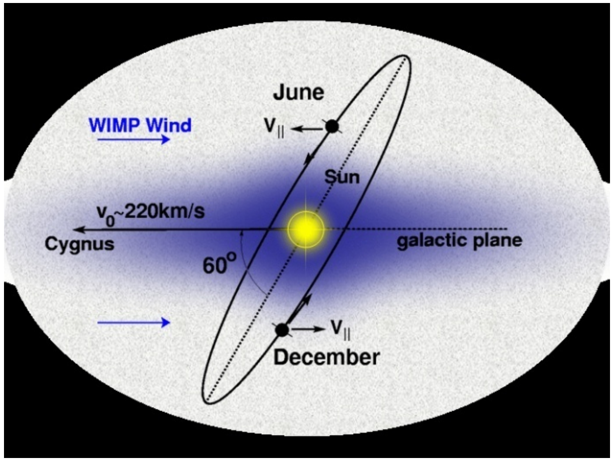
- Results typically normalized to X-proton cross sections

- For masses ~ 100 GeV, many models → 10^{-44} cm^2 (see LHC below)



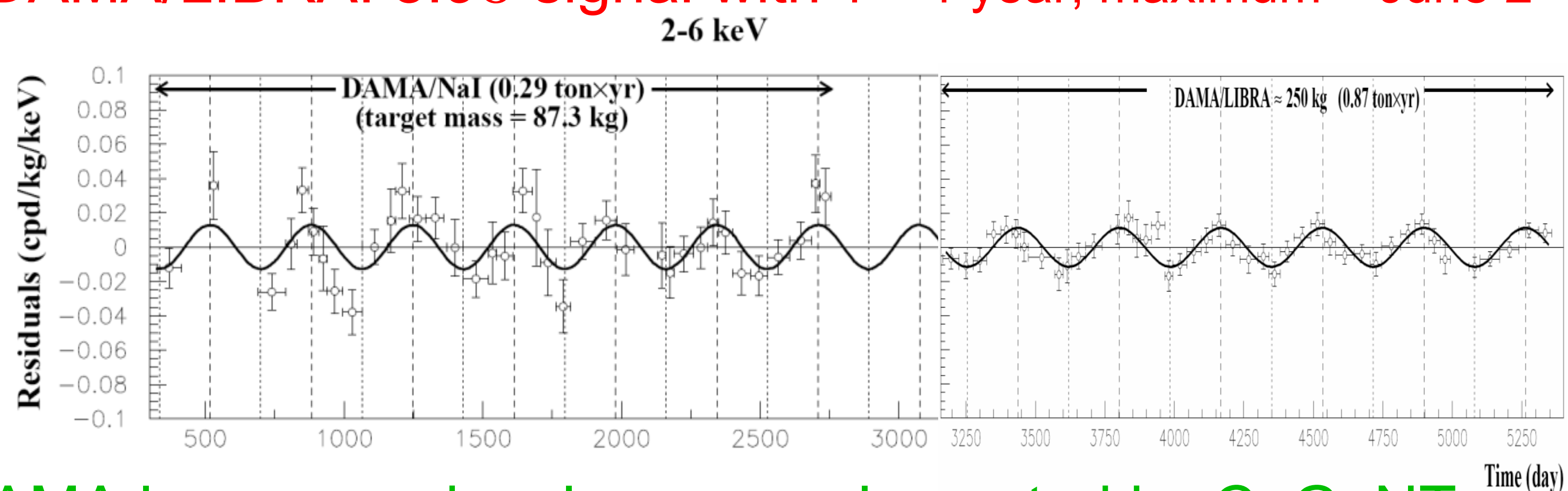
LOW MASS FRONTIER

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



Drukier, Freese, Spergel (1986)

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

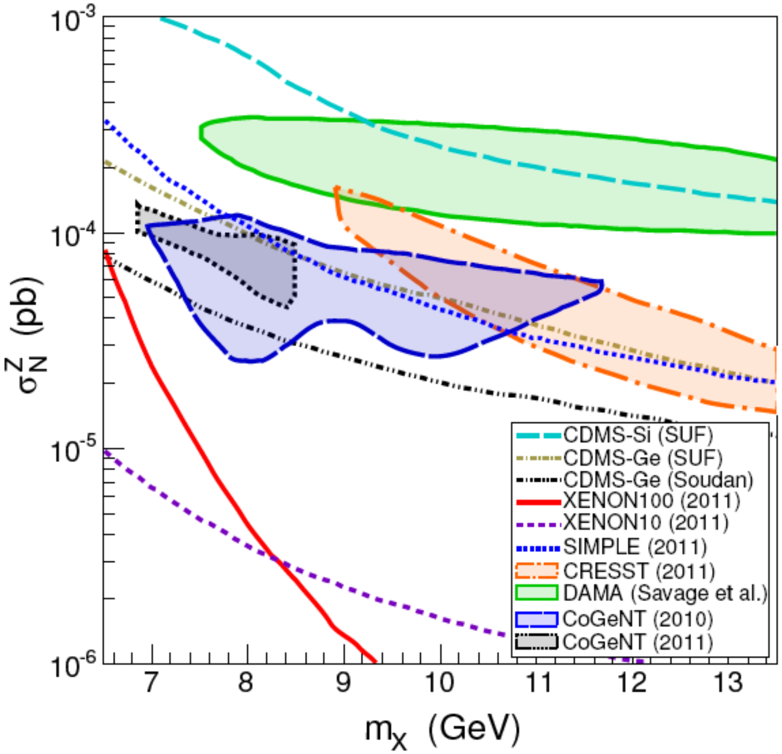


DAMA/LIBRA (2010)

DAMA low mass signal now supplemented by CoGeNT

CURRENT STATUS

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

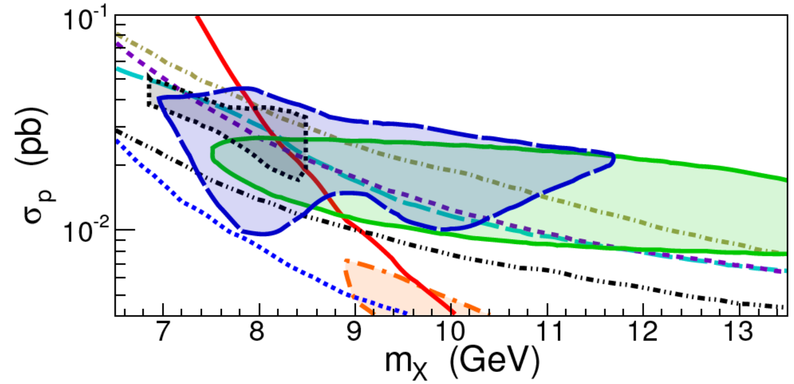


- Many proposed solutions

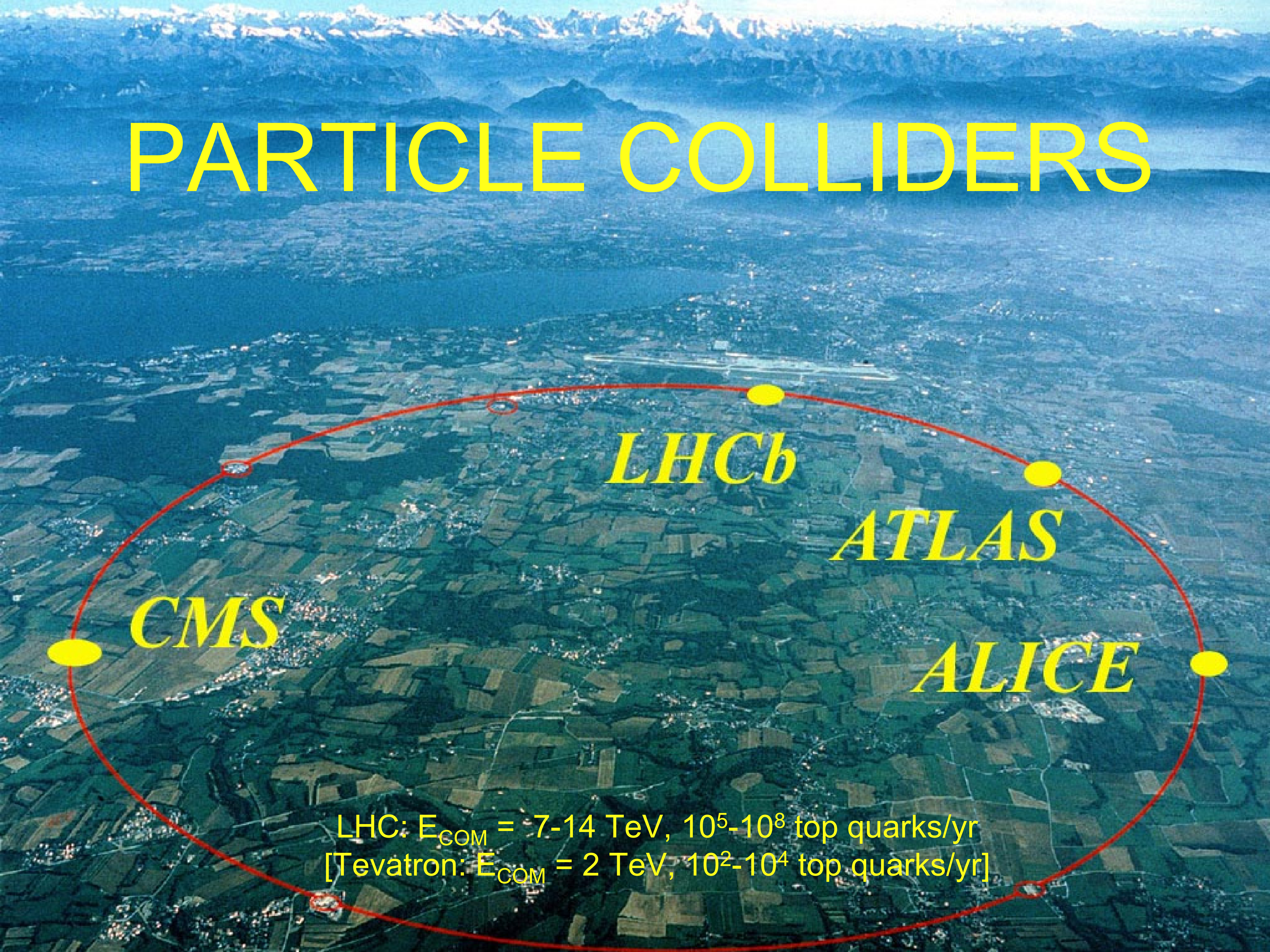
E.g.: Isospin Violating DM

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

- Typical plot assumes equal DM couplings to p and n
- Feb 2011: Can reconcile all the data with $f_n = -0.7 f_p$
- Nov 2011: New data clouds this interpretation (and all others)



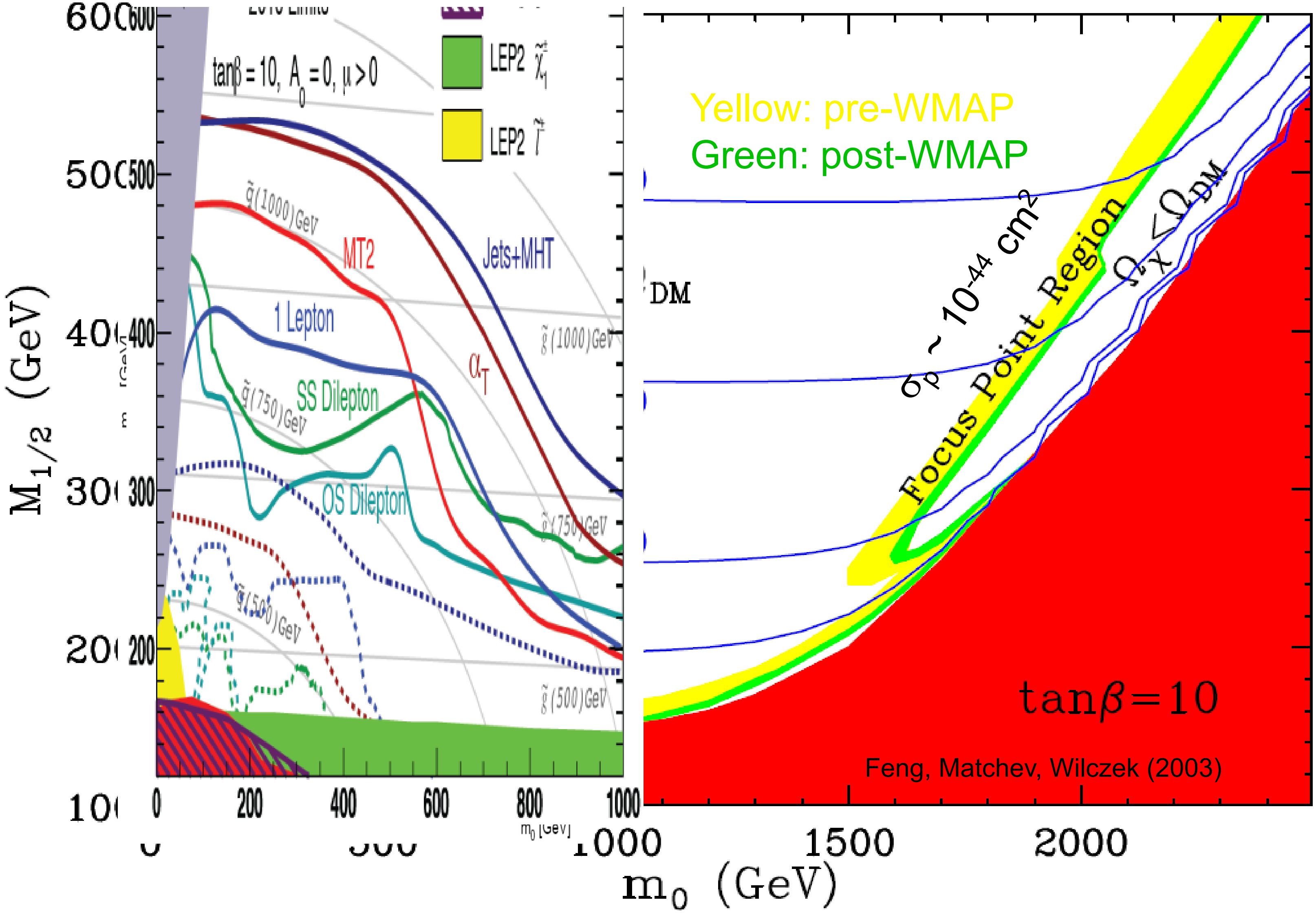
PARTICLE COLLIDERS



LHC: E_{COM} = 7-14 TeV, 10^5-10^8 top quarks/yr

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

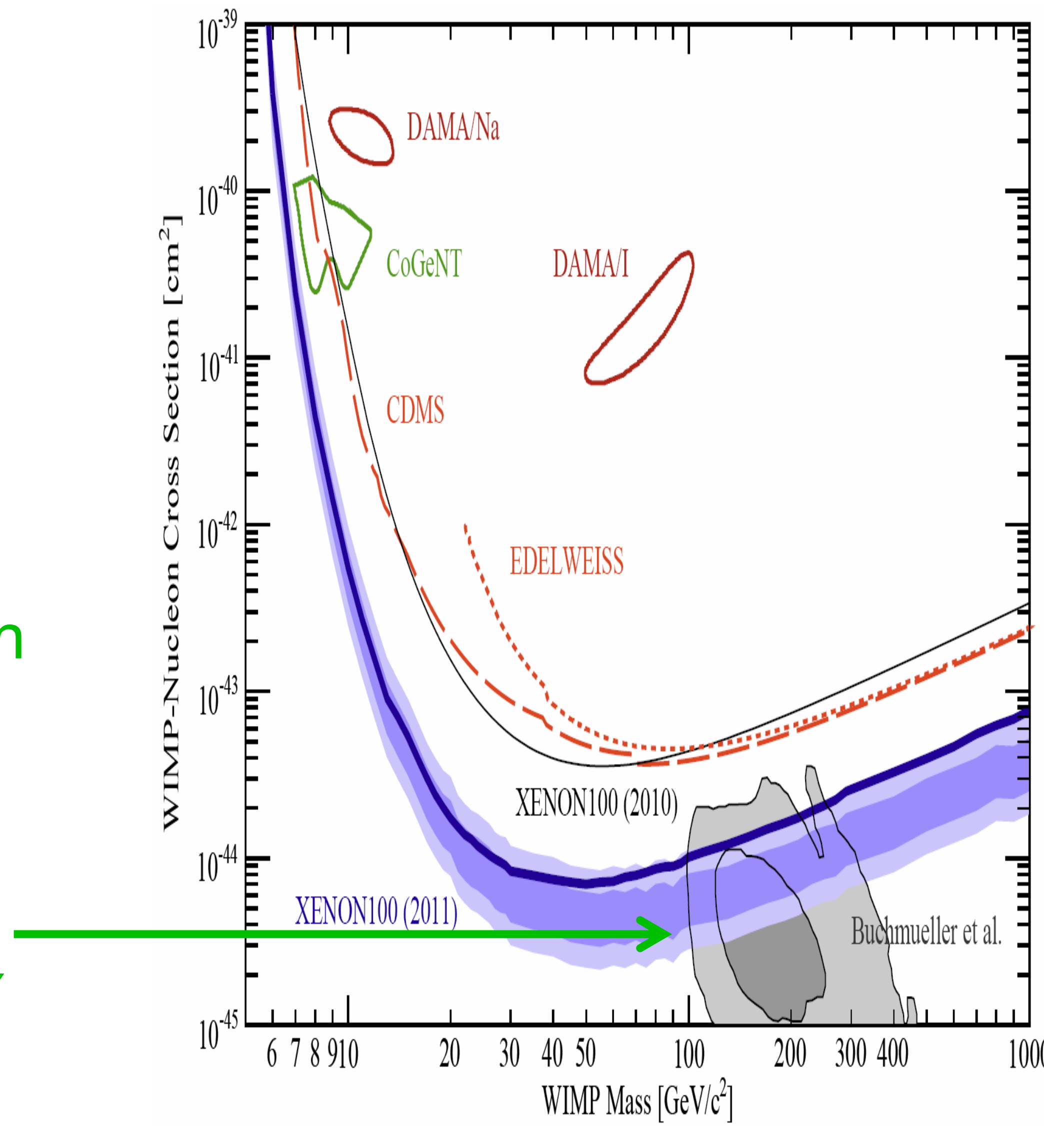
LHC MAY PRODUCE DARK MATTER



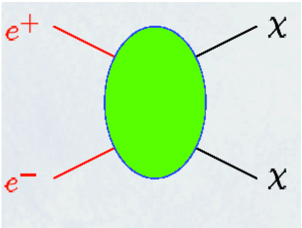
CURRENT STATUS

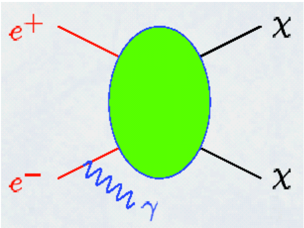
- Pessimist
  - No sign of new physics so far
  - Some models now excluded

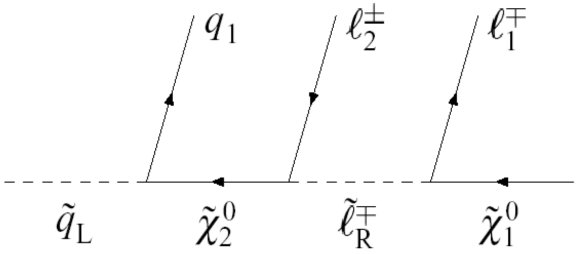
- Optimist
  - Many models remain
  - LHC constraints sharpen some dark matter predictions dramatically; e.g., neutralinos in SUSY



WHAT IF THE LHC SEES A SIGNAL?

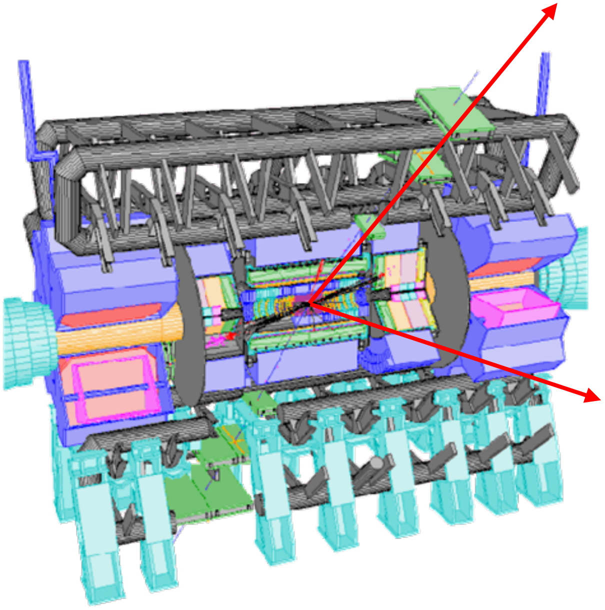




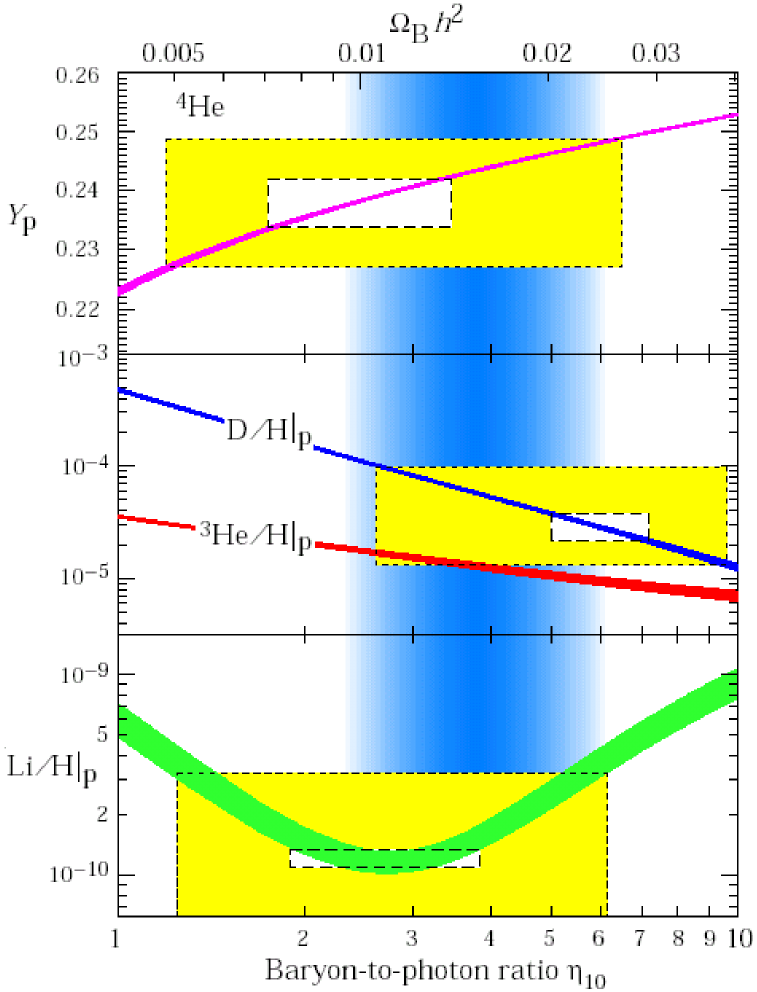


Birkedal, Matchev, Perelstein (2004)

- What LHC actually sees:
  - E.g., monophoton, or $\tilde{q}\tilde{q}$ pair production followed by $\tilde{q} \rightarrow \chi$
  - 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

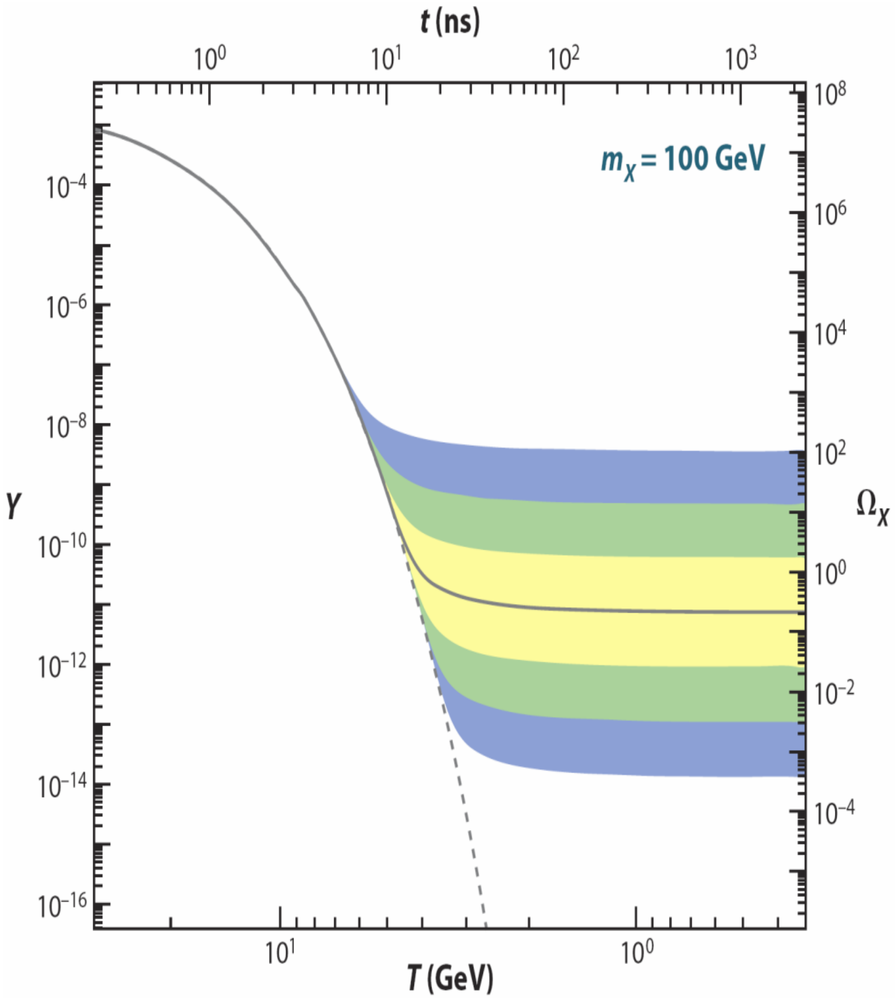


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

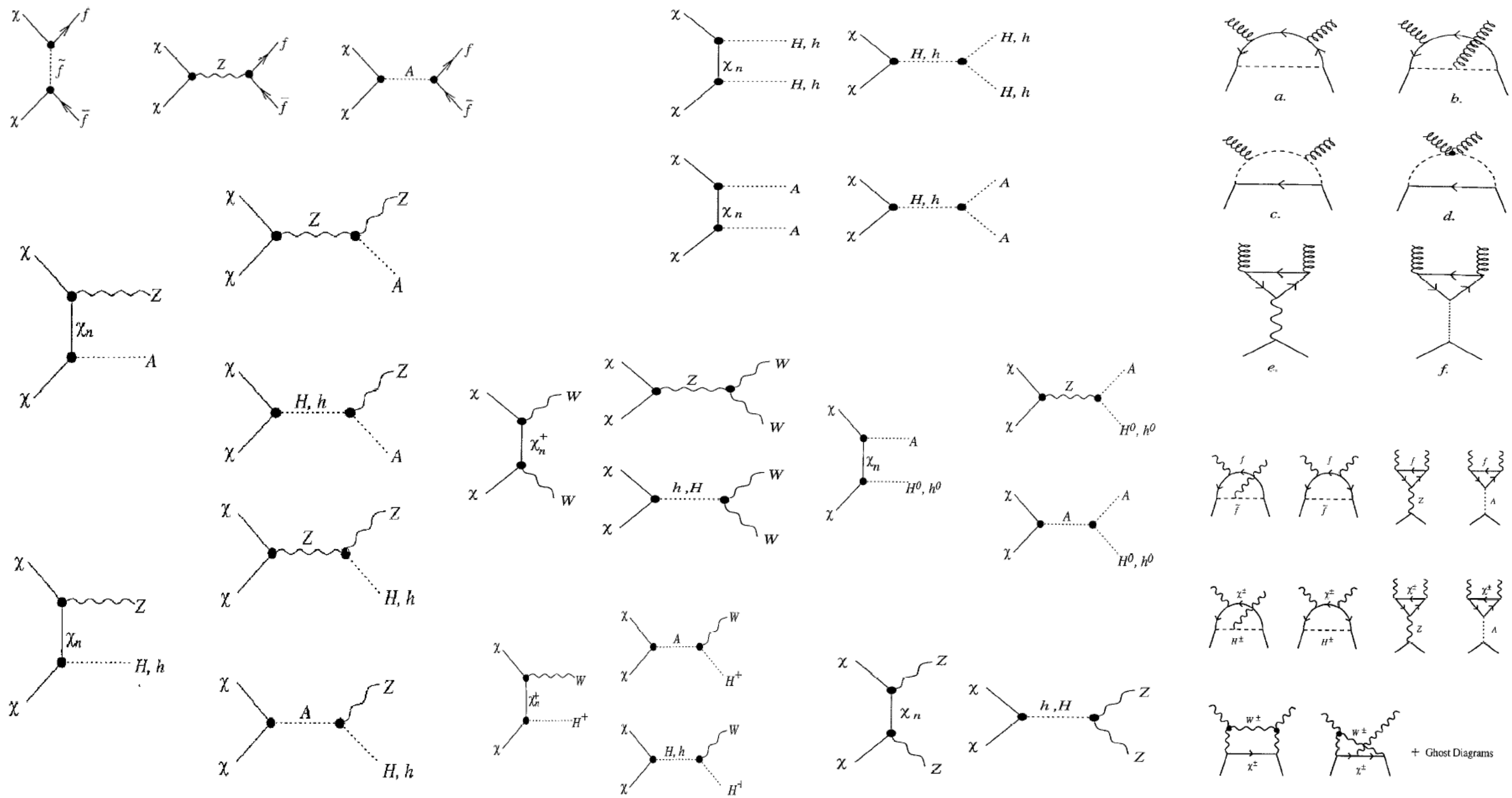
  t ~ 1 sec

DARK MATTER ANALOGUE



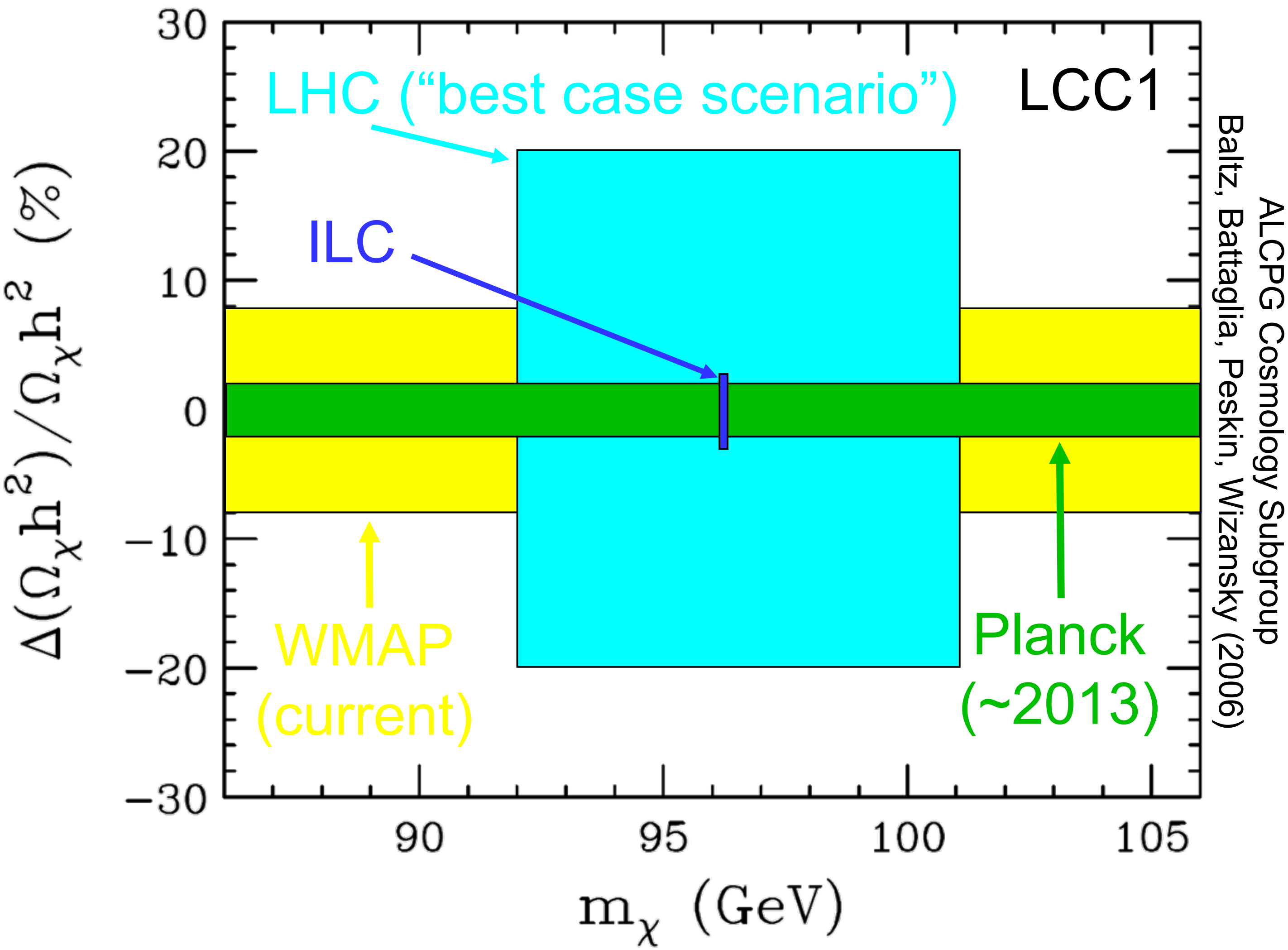
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

WIMP ANNIHILATION PROCESSES



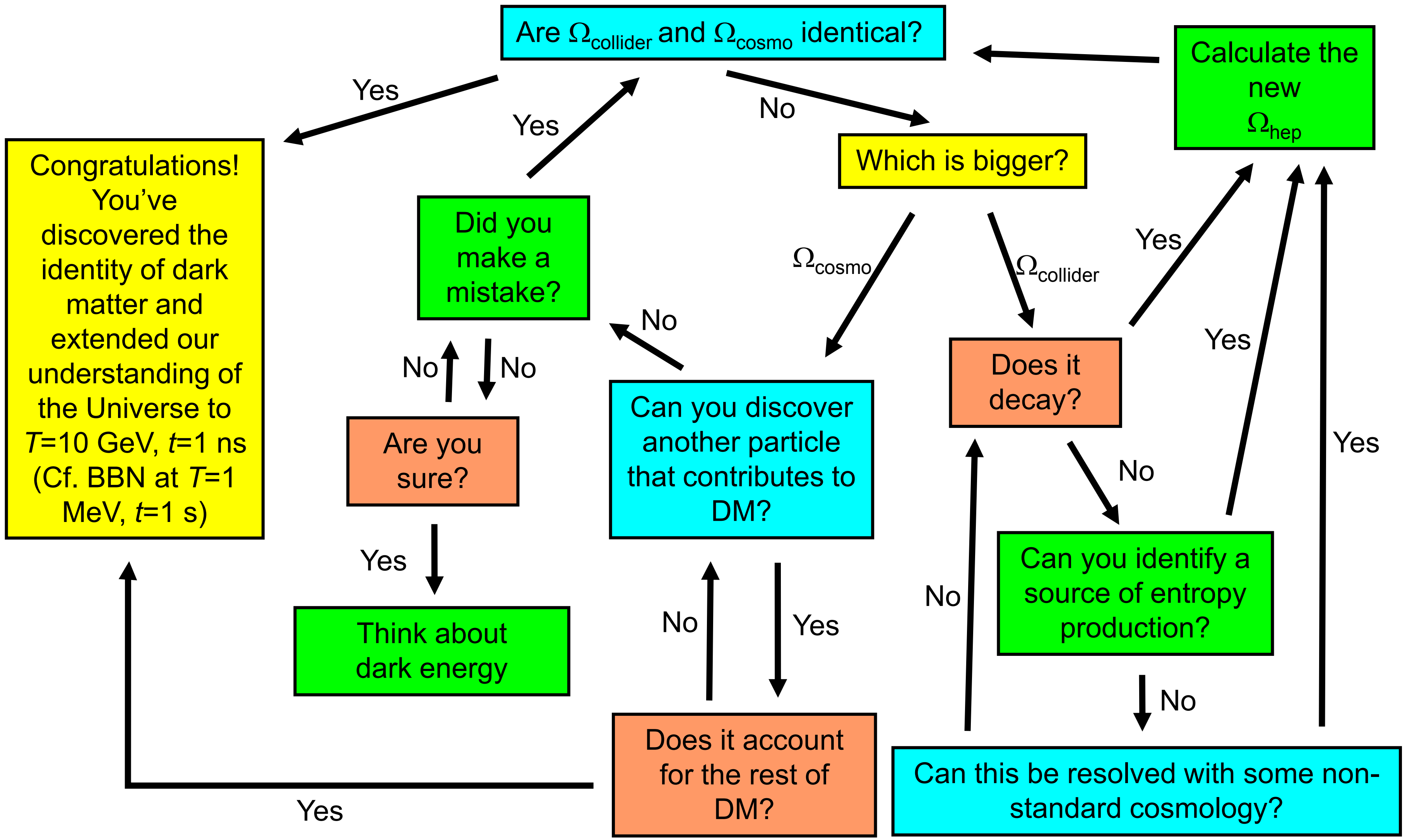
Jungman, Kamionkowski, Griest (1995)

RELIC DENSITY DETERMINATIONS



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

IDENTIFYING DARK MATTER



BEYOND WIMPS

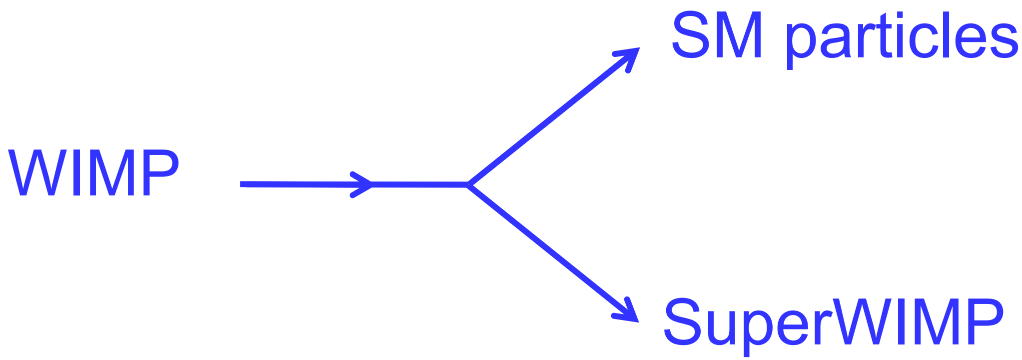
- Dark matter has been detected only through gravity
- But the WIMP miracle is a prime reason for optimism, and it seemingly implies that dark matter is
  - Weakly-interacting
  - Cold
  - Collisionless

  Are all WIMP miracle-motivated candidates like this?
- 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)

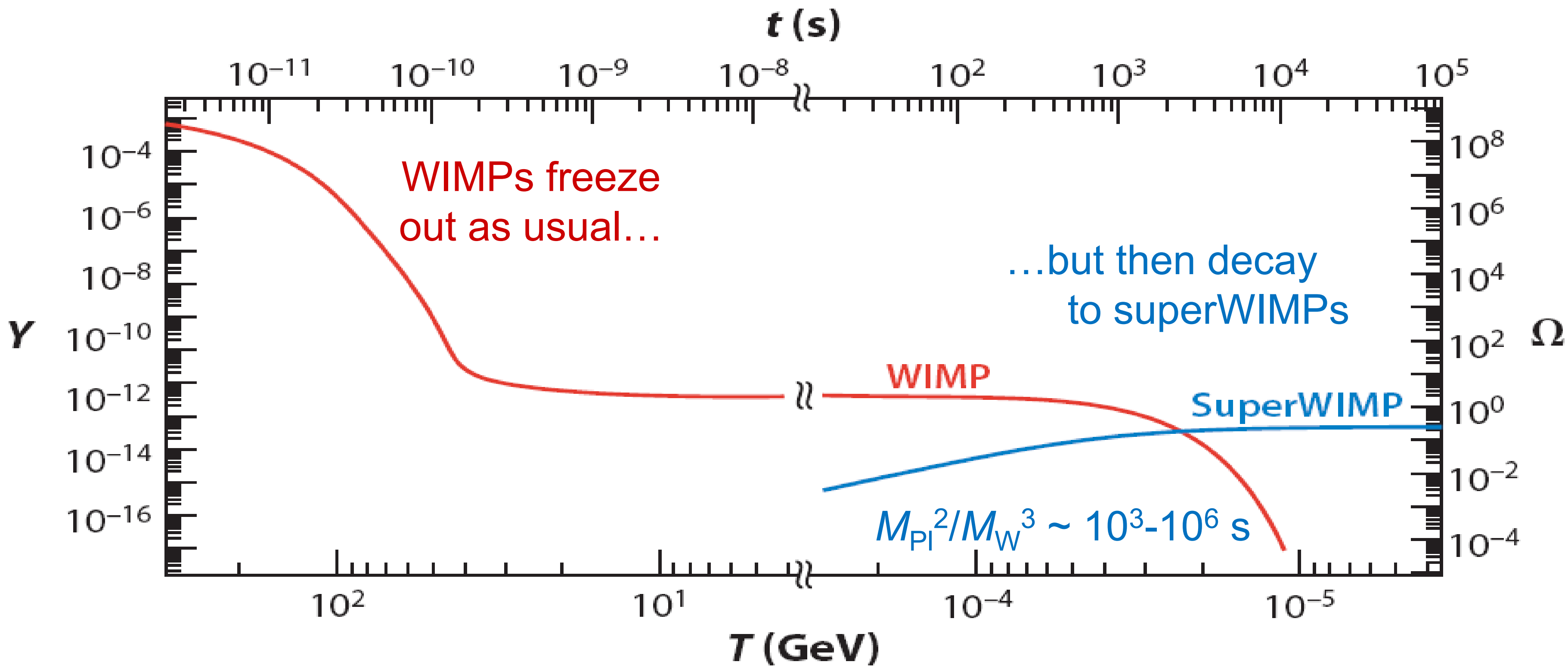
- Suppose the WIMP can decay into a superweakly-interacting particle (superWIMP):



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

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

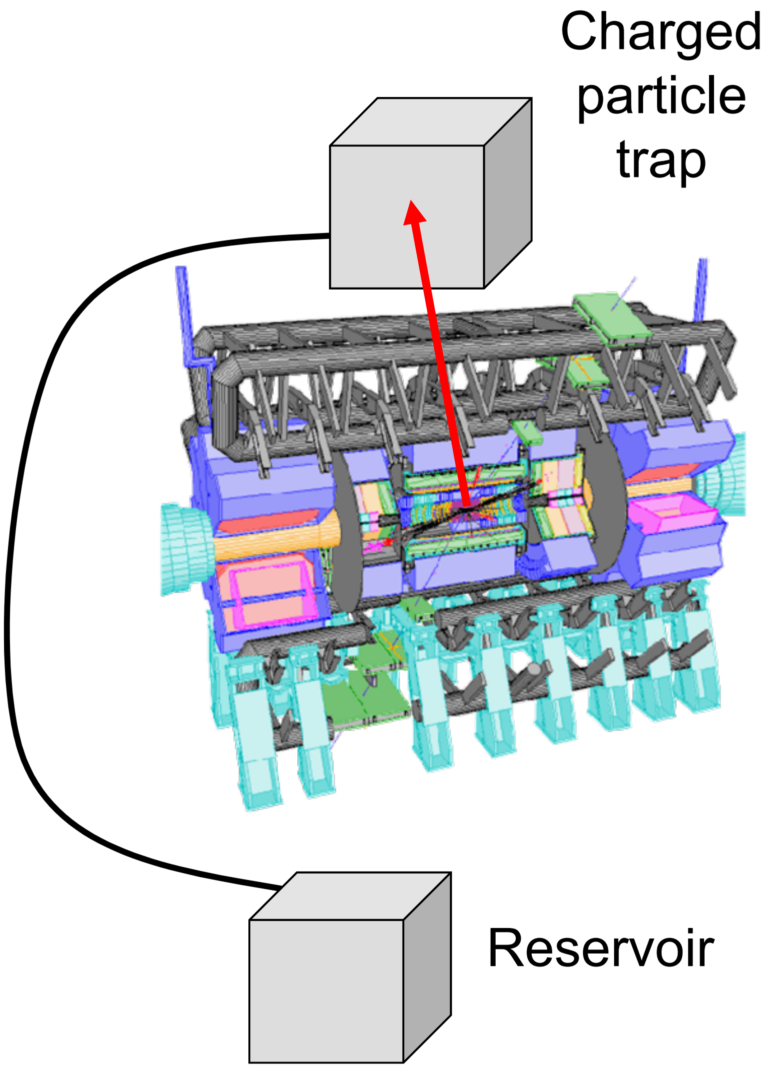
FREEZE OUT WITH SUPERWIMPS



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

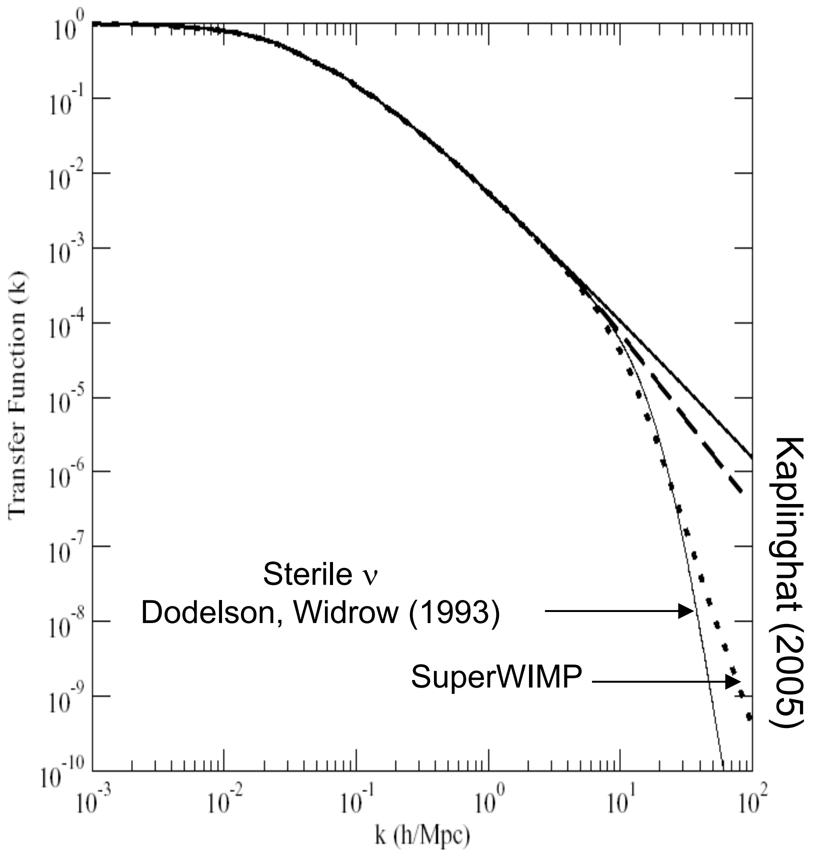


Feng, Smith (2004)
Hamaguchi, Kuno, Nakawa, Nojiri (2004)
De Roeck et al. (2005)

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)



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)

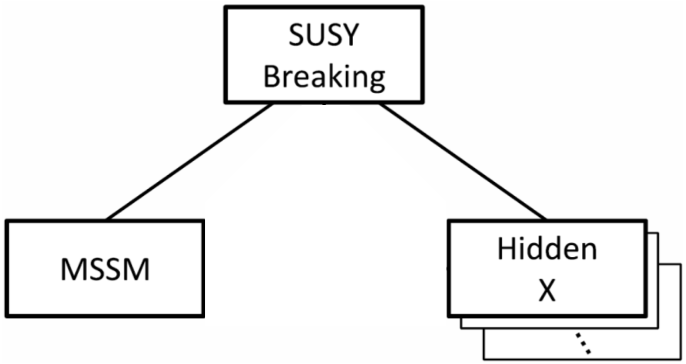
THE WIMPLESS MIRACLE

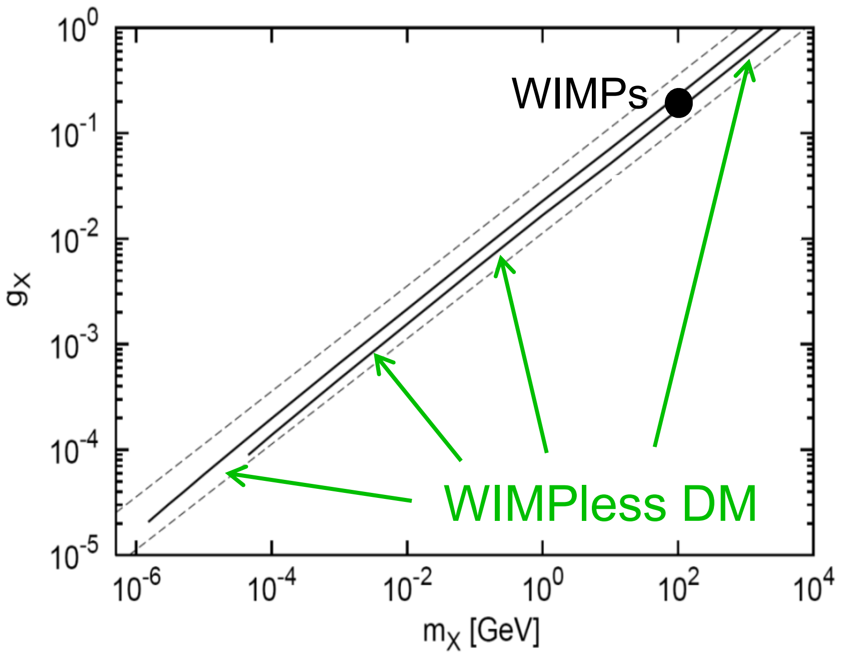
Feng, Kumar (2008)

- 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

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

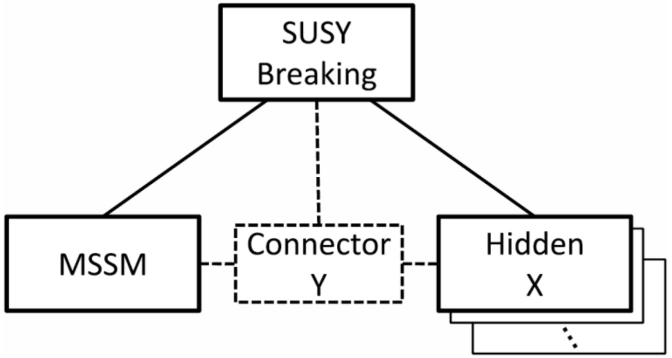
- "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω (but they aren't WIMPs)





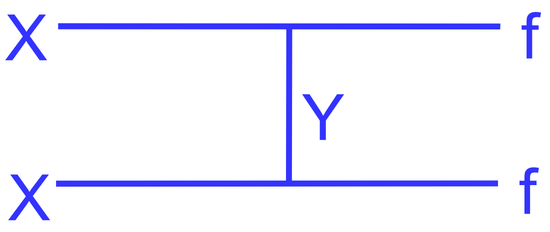
WIMPLESS DM SIGNALS

- Hidden DM may have only gravitational effects, but still interesting
  - It may self-interact through "dark photons," Coulomb interactions
  - Light degrees of freedom can change the expansion history of the Universe



Ackerman, Buckley, Carroll, Kamionkowski (2008)
Feng, Kaplinghat, Tu, Yu (2009)
Feng, Shadmi (2011)
Feng, Rentala, Surujon (2011)

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



CONCLUSIONS

- Particle Dark Matter
  - Central topic at the interface of cosmology and particle physics
  - 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 (only gravitational interactions, warm, self-interacting, new light degrees of freedom)
  - Many others
- LHC, direct and indirect detection, astrophysical probes are improving rapidly – this field is being transformed now