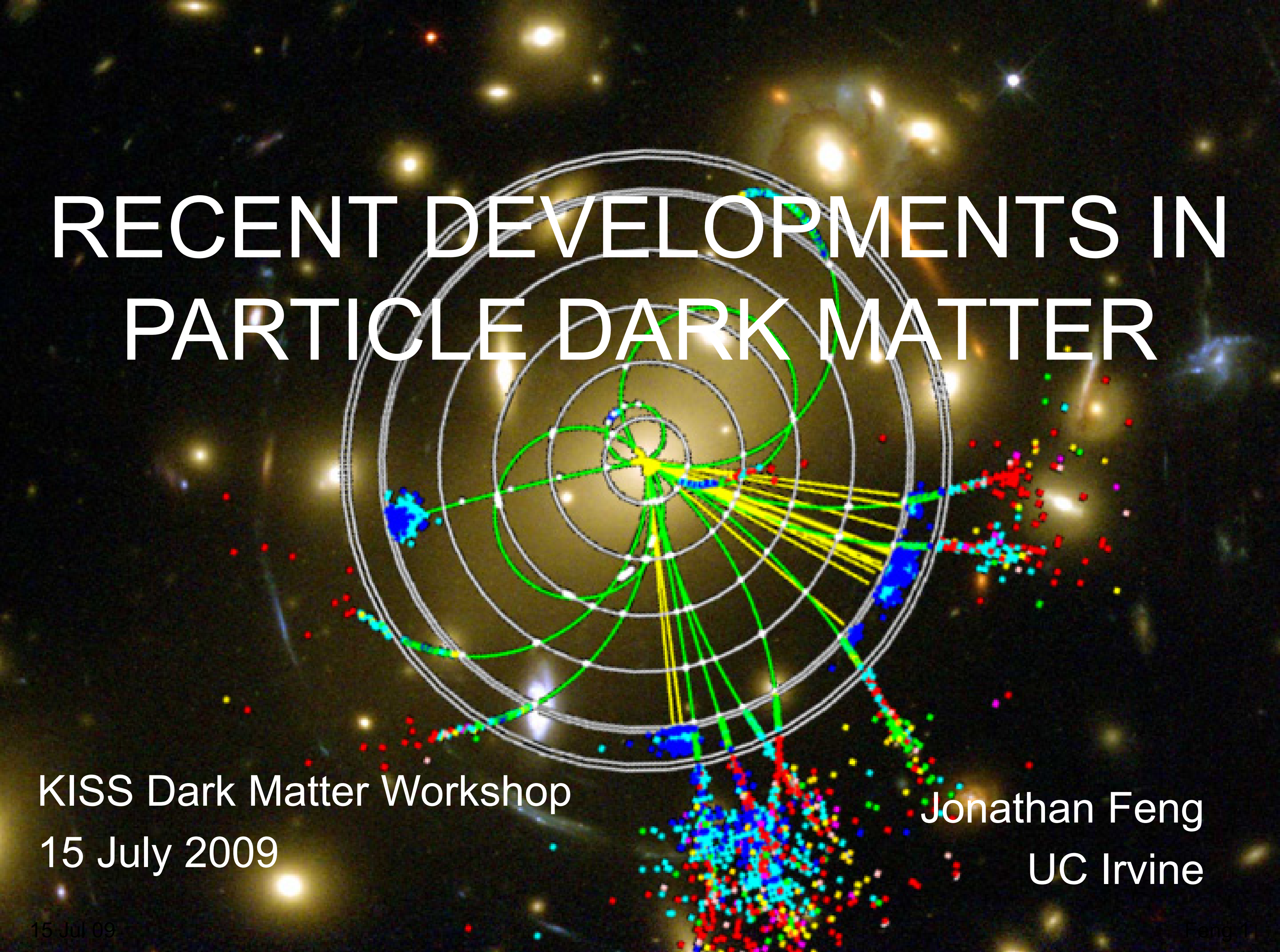
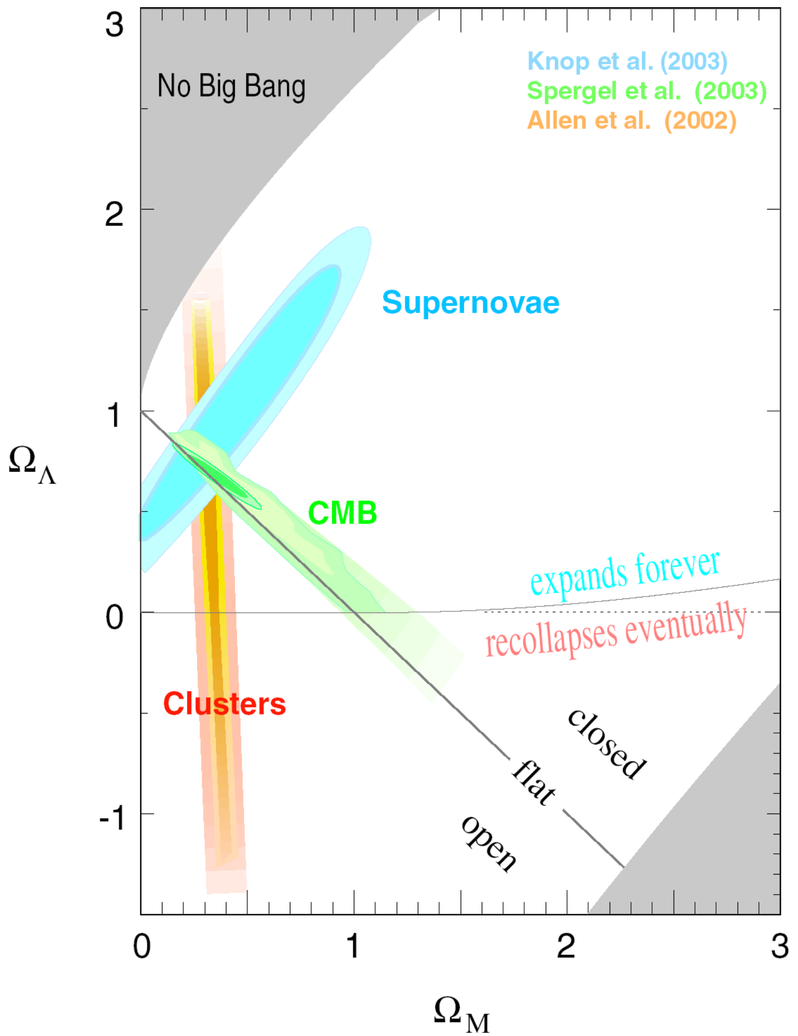


RECENT DEVELOPMENTS IN PARTICLE DARK MATTER

KISS Dark Matter Workshop
15 July 2009

Jonathan Feng
UC Irvine

EVIDENCE FOR DARK MATTER



- There is now overwhelming evidence that normal (standard model) 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)

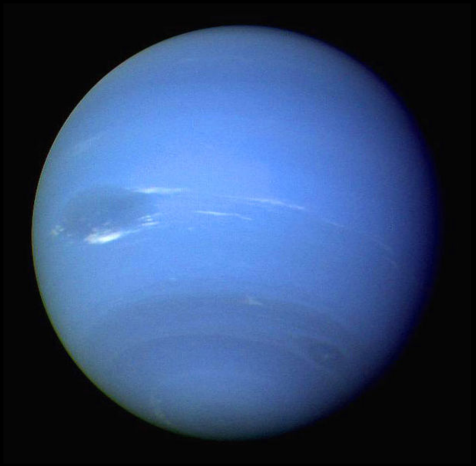
- To date, all evidence is from dark matter's gravitational effects and insensitive to many of its particle properties.

- We would like to detect it in other ways to learn what it is

A PRECEDENT

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

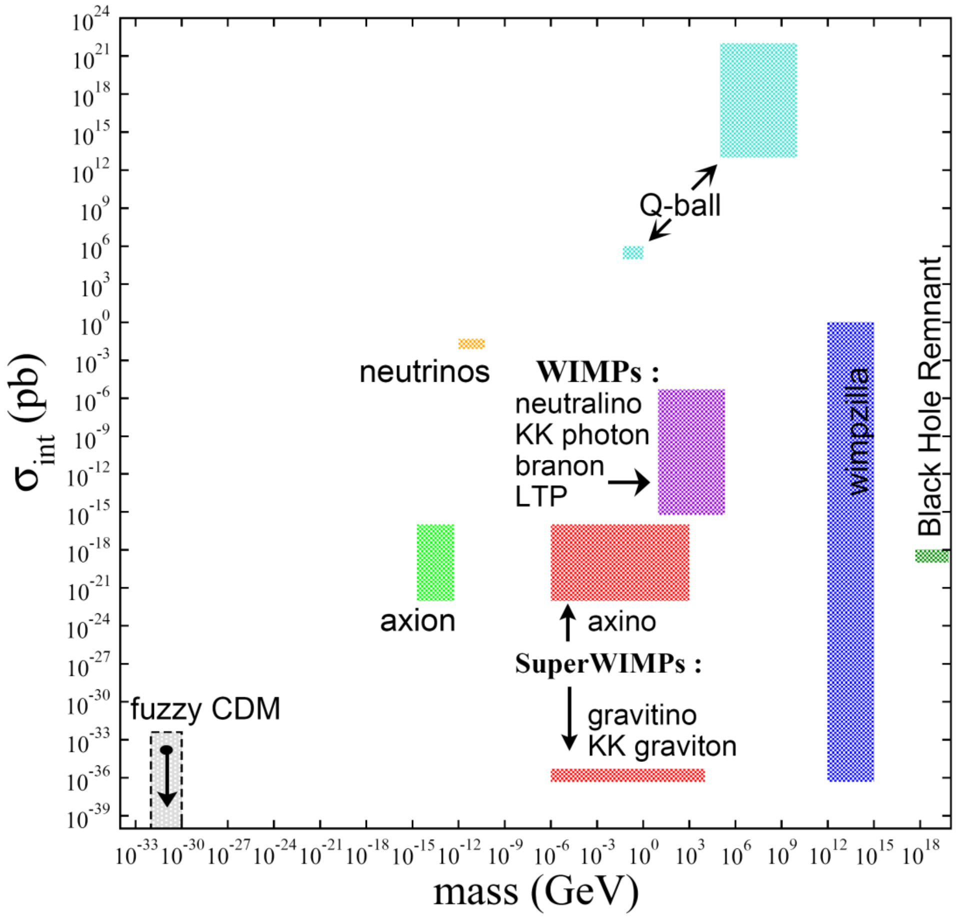
- In 1845-46 Urbain Le Verrier determined the expected properties of the dark matter and how to find it. With this guidance, Johann Gottfried Galle discovered dark matter in 1846.



- 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 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 PLAN

- WIMP Dark Matter
  – Direct Detection
  – Indirect Detection
  – Colliders

discussions on Friday and next week

- Beyond WIMP Dark Matter
  – Astrophysical Signals

WIMP DARK MATTER

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

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

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

THE WIMP MIRACLE

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

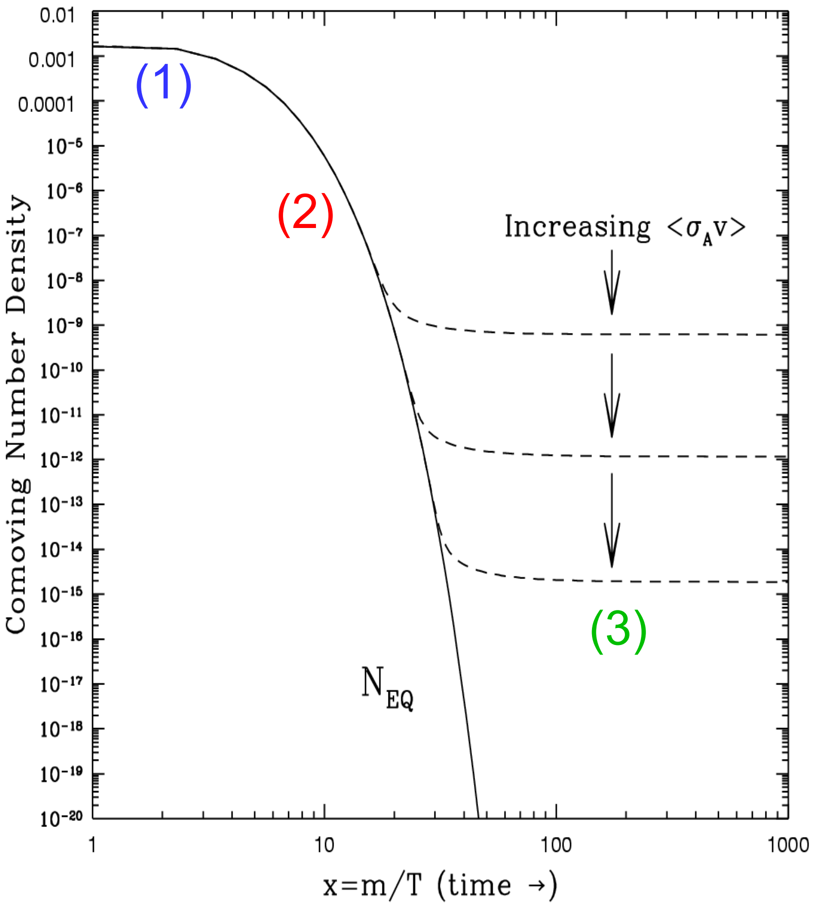
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \;\substack{\rightarrow \\ \not\leftarrow}\; \bar{f} f$$

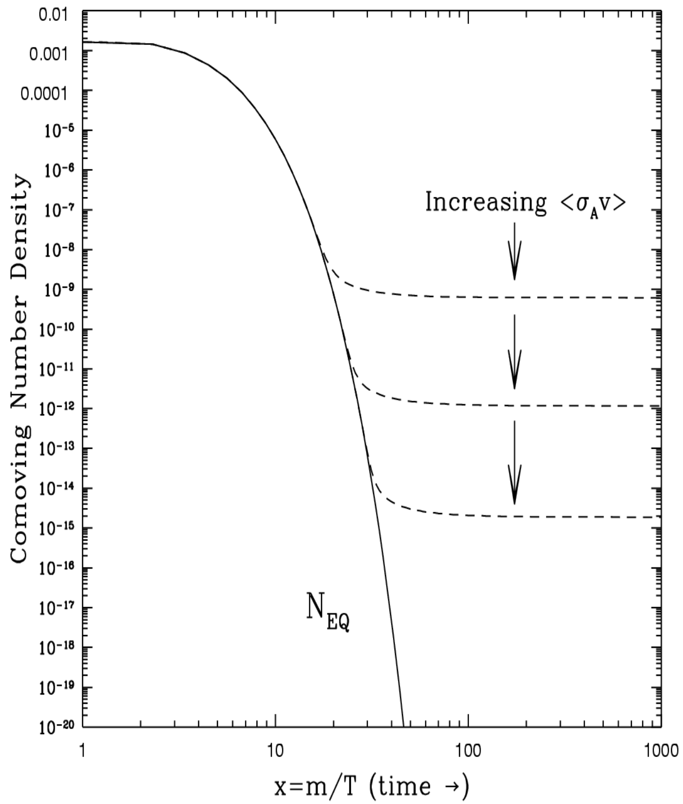
(3) χs "freeze out":

$$\chi\chi \;\substack{\not\rightarrow \\ \not\leftarrow}\; \bar{f} f$$



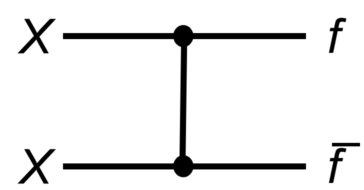
Zeldovich et al. (1960s)

THE WIMP MIRACLE



- The resulting relic density is

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



- For a WIMP, $m_X \sim 100$ GeV and $g_X \sim 0.6$ → $\Omega_X \sim 0.1$

- 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

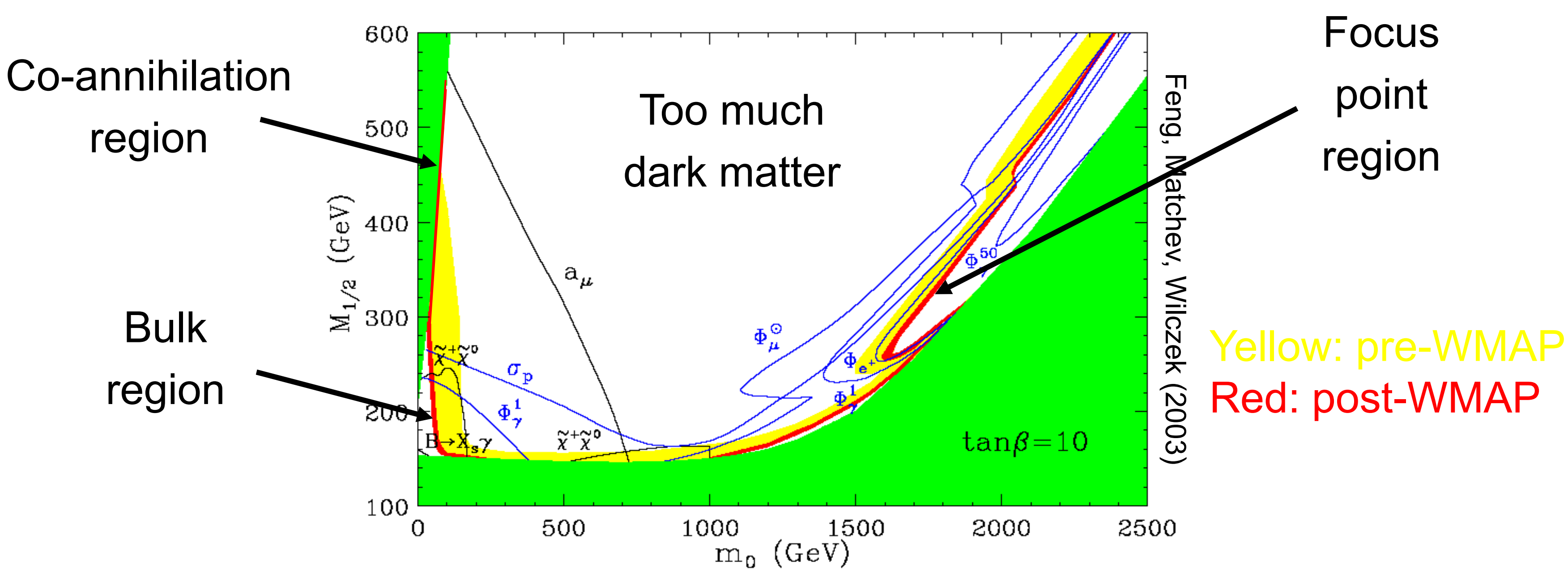
Goldberg (1983); Ellis et al. (1983)

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, mass ~ 100 GeV. All the right properties for WIMP dark matter!

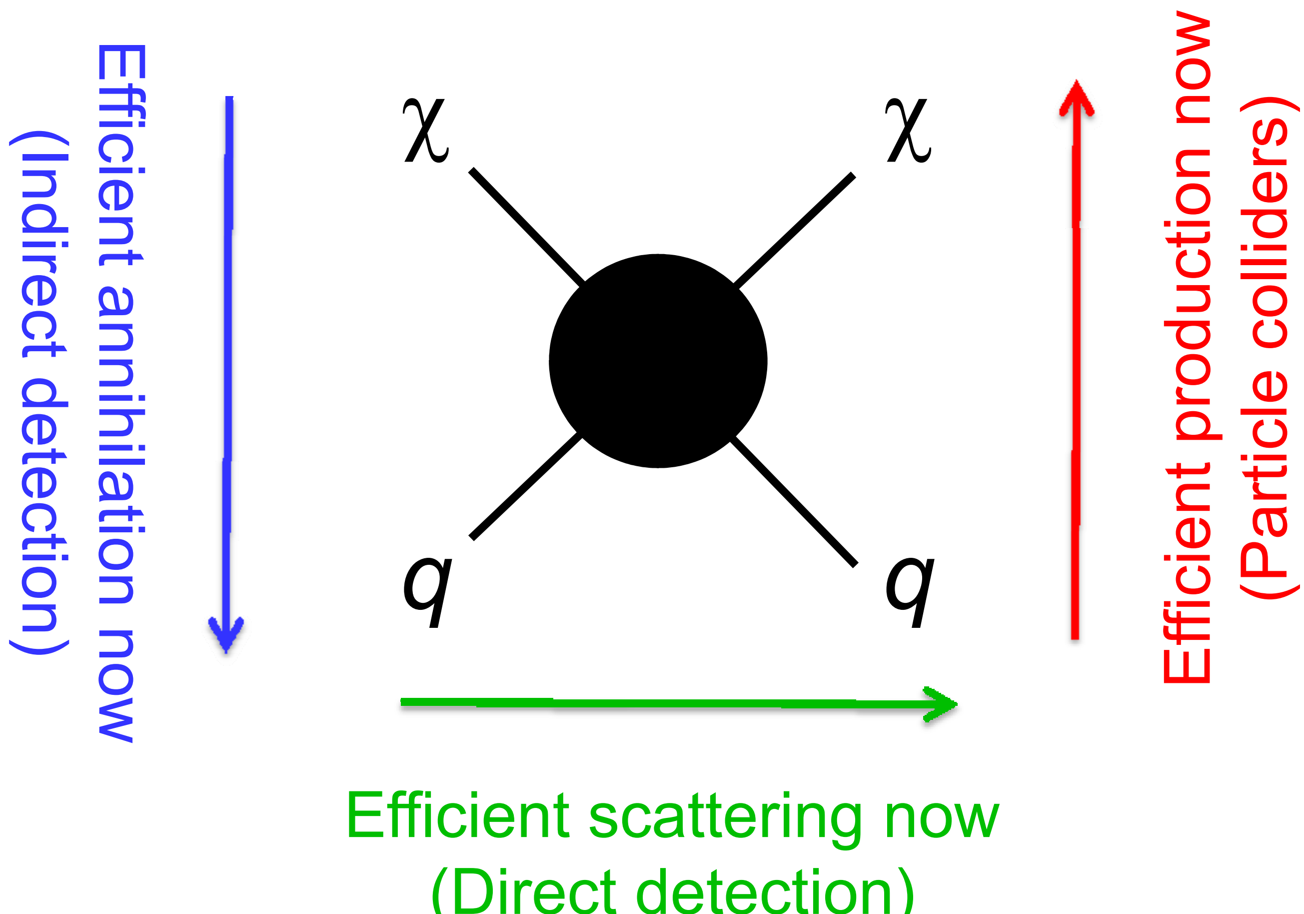
Ω_{DM} = 23% ± 4% stringently constrains models



Cosmology excludes many possibilities, favors certain regions

WIMP DETECTION

Correct relic density → Efficient annihilation then



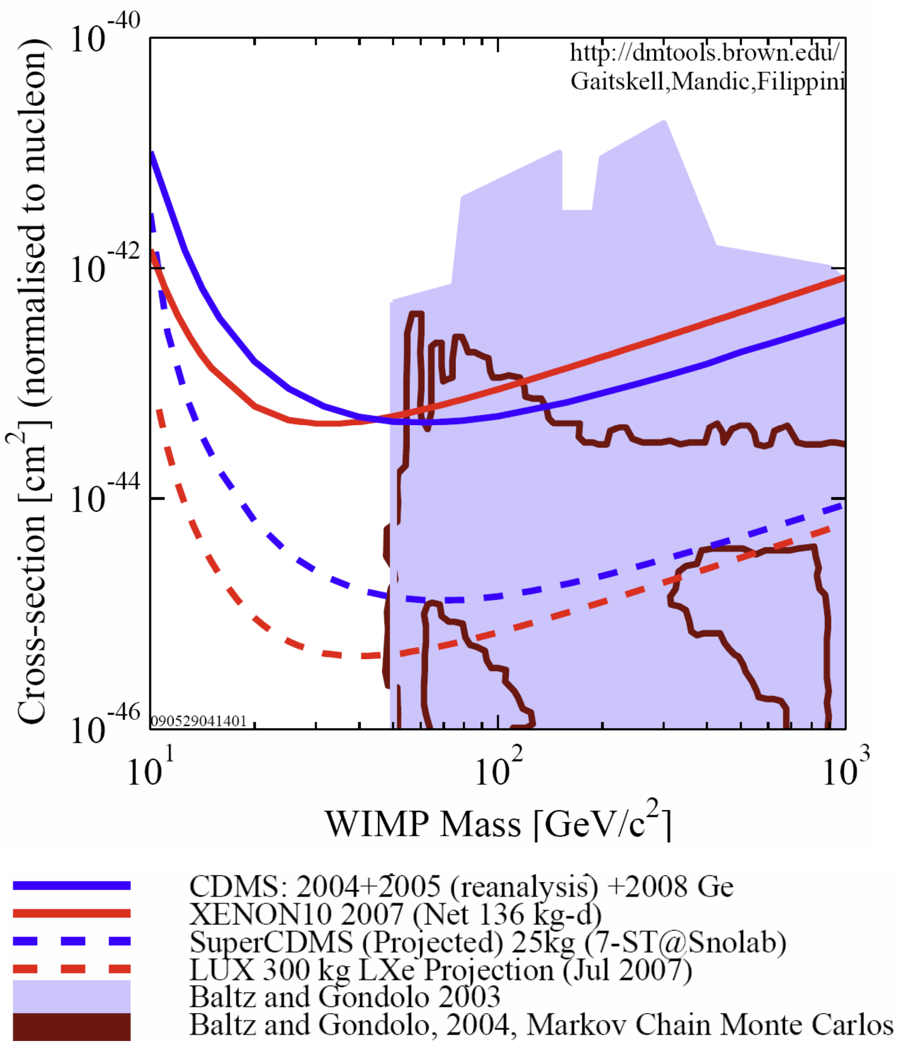
DIRECT DETECTION

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

- Detected by recoils off ultra-sensitive underground detectors

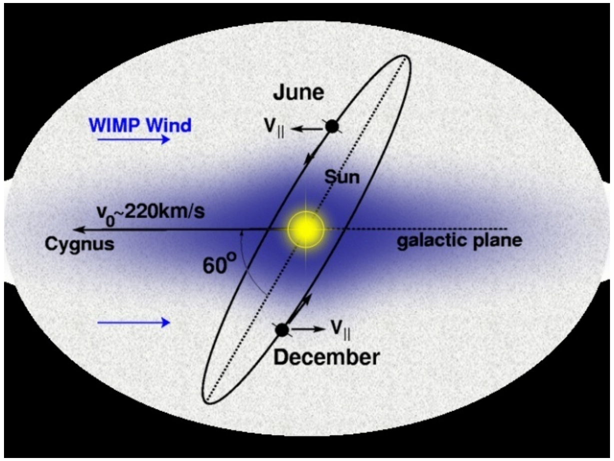
- Area of rapid progress (CDMS, XENON, LUX, …)

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



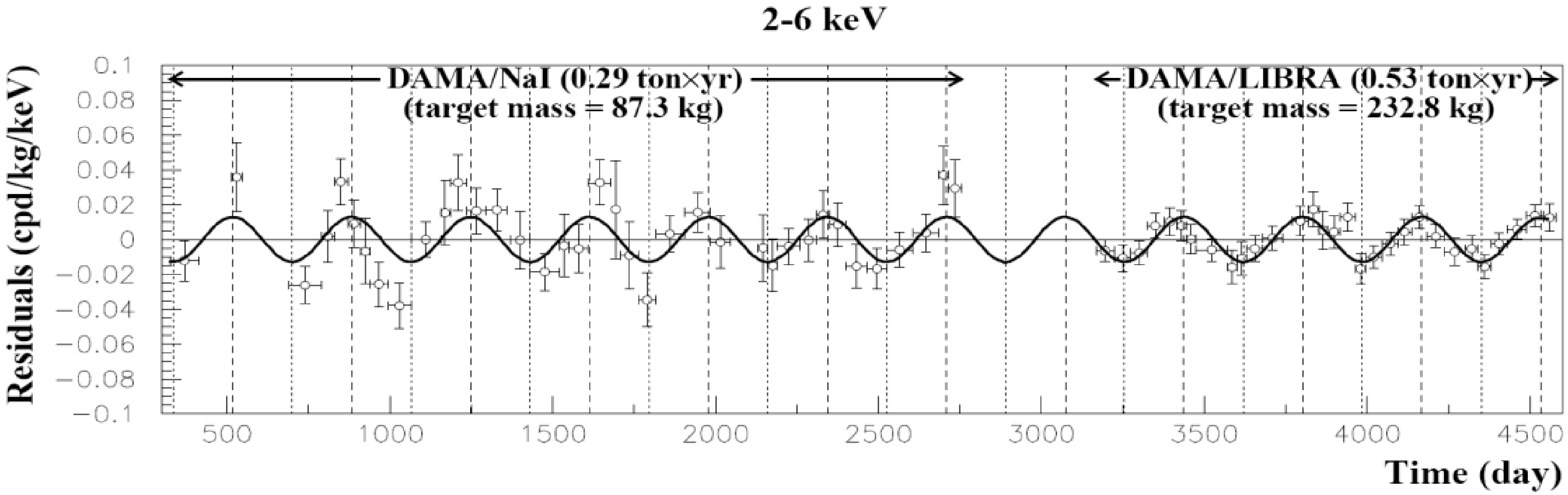
DIRECT DETECTION: DAMA

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

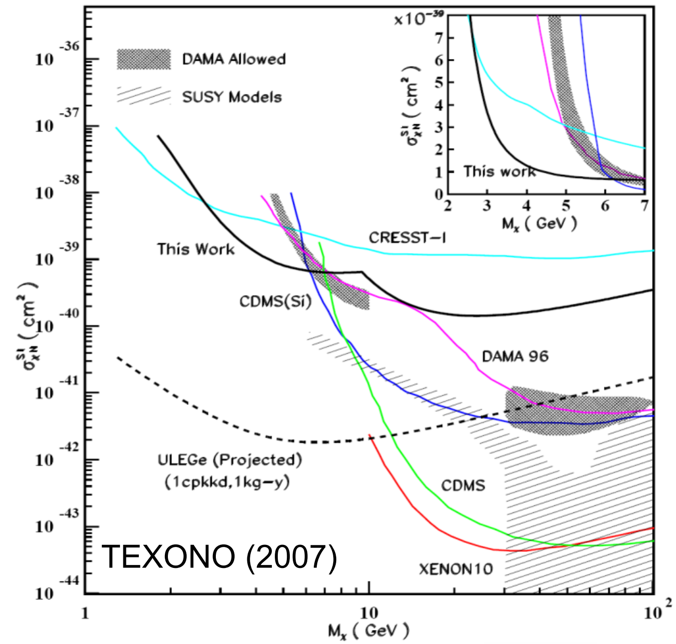
- DAMA's result is puzzling, in part because the favored region was considered excluded by others

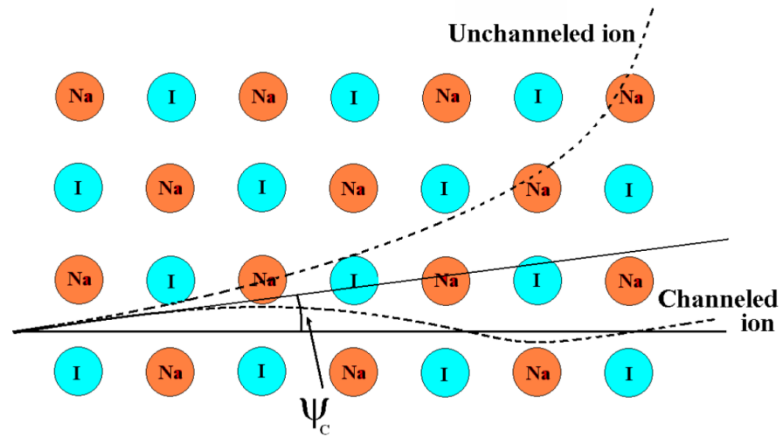
- This may be ameliorated by
  - Astrophysics
  - Channeling: in crystalline detectors, efficiency for nuclear recoil energy → electron energy depends on direction

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)

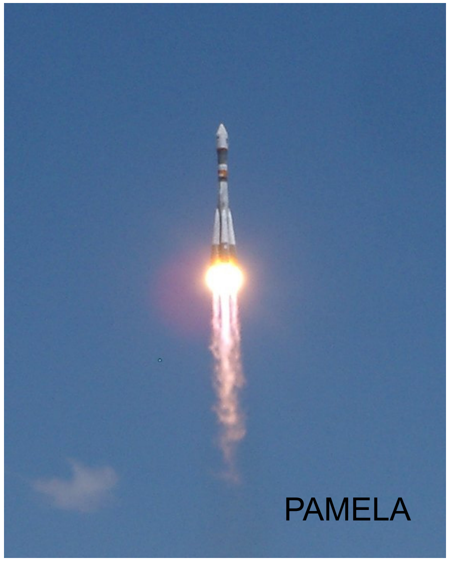


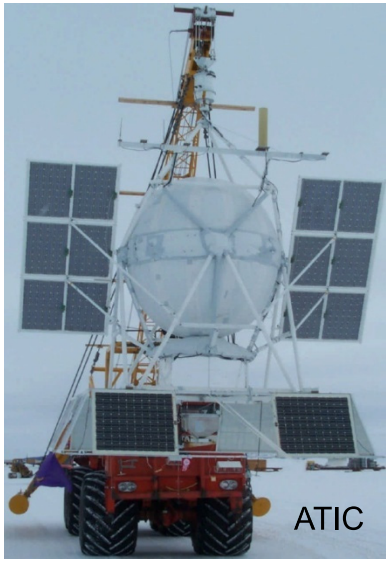


INDIRECT DETECTION

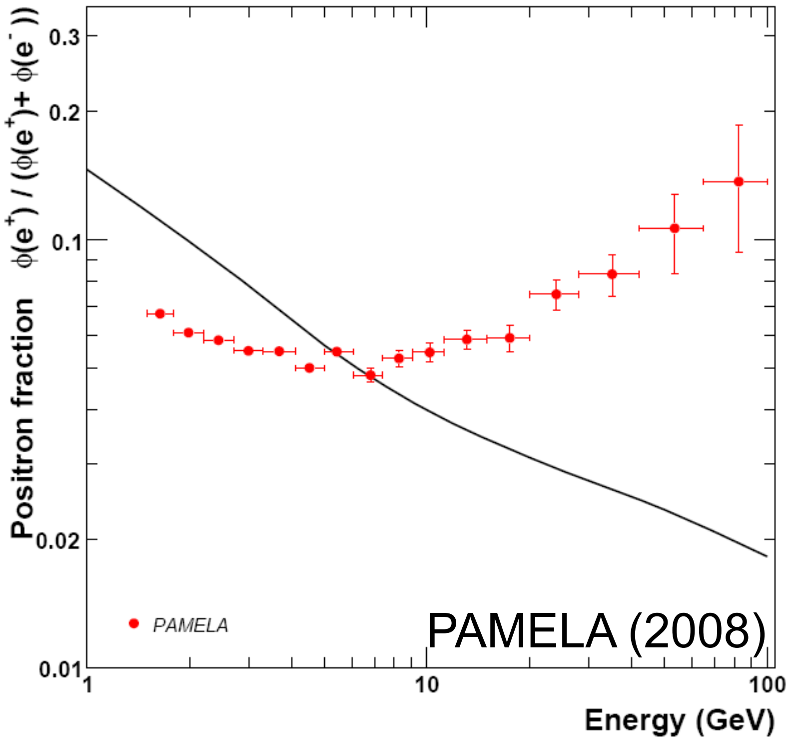
Dark Matter annihilates in ___the halo___ to
a place

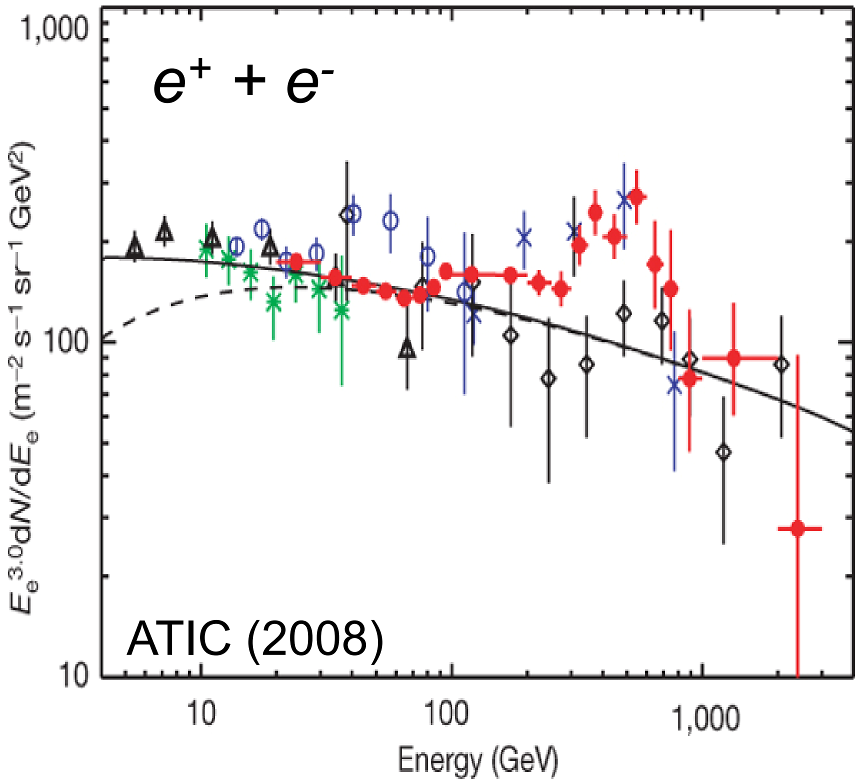
___positrons___ , which are detected by ___PAMELA/ATIC/Fermi…___.
some particles / an experiment





PAMELA AND ATIC 2008



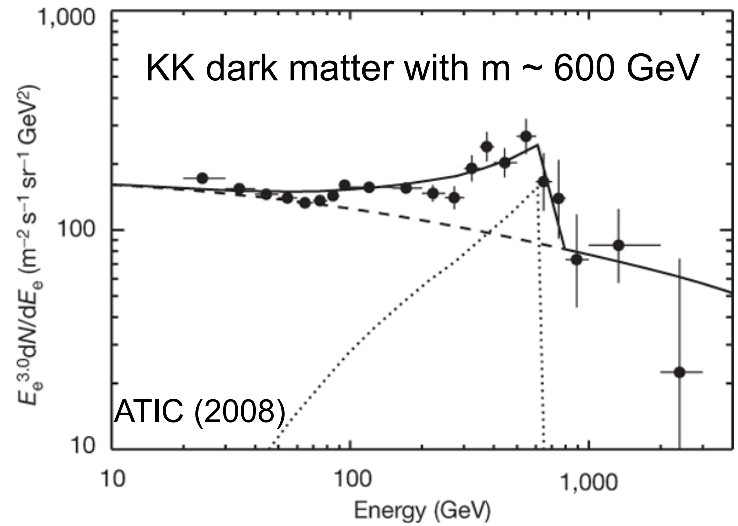


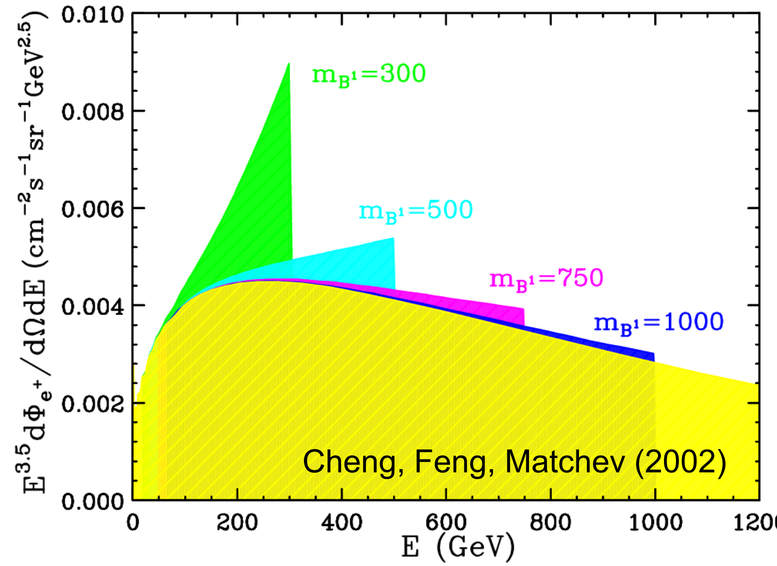
Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

- Must fit spectrum, not violate other constraints (photons, anti-protons, …)
- Neutralinos in supersymmetry
  - $\chi\chi \rightarrow e^+e^-$ suppressed by angular momentum conservation
  - $\chi\chi \rightarrow WW \rightarrow e+$ gives softer spectrum, also accompanied by large anti-proton flux
- Kaluza-Klein dark matter from extra dims

  Appelquist, Cheng, Dobrescu (2001)
  - $B^1B^1 \rightarrow e^+e^-$ unsuppressed, hard spectrum
  - B^1 couples to hypercharge, $B(e^+e^-) = 20\%$
  - B^1 mass ~ 600-1000 GeV to get right Ω
- BUT: flux is a factor of 100-1000 too big for a thermal relic; requires enhancement
  - astrophysics (very unlikely)
  - particle physics



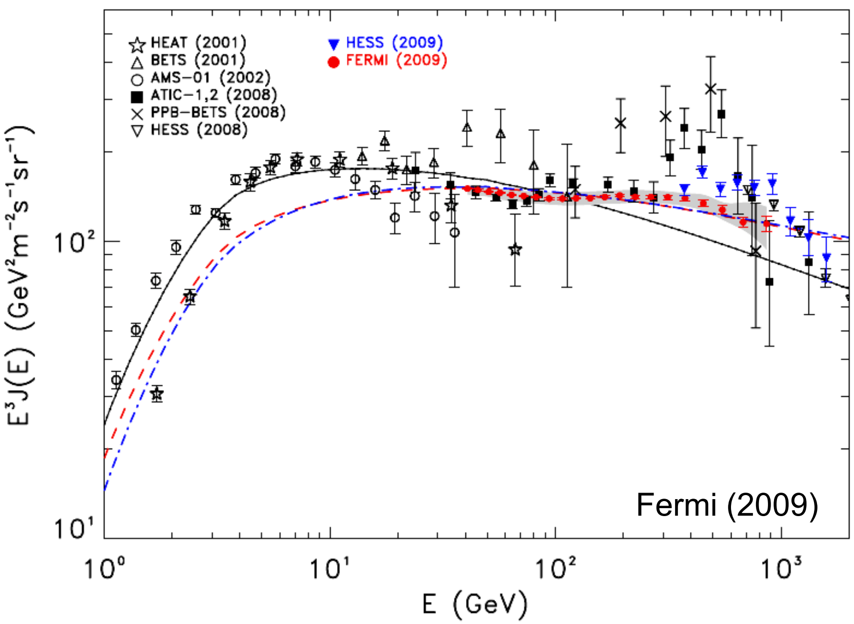


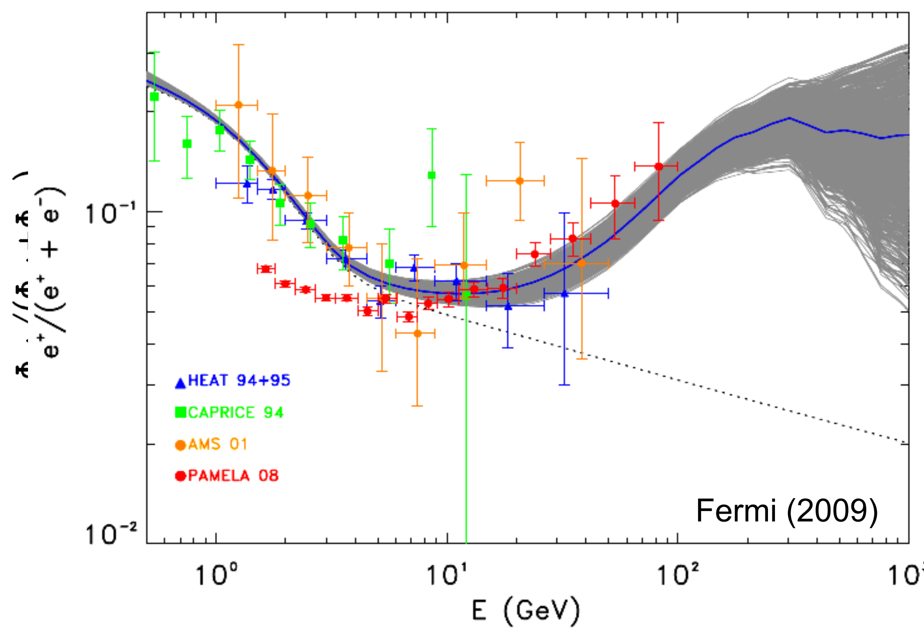
FERMI AND HESS 2009

- Fermi and HESS do not confirm ATIC: no feature, consistent with background with modified spectral index

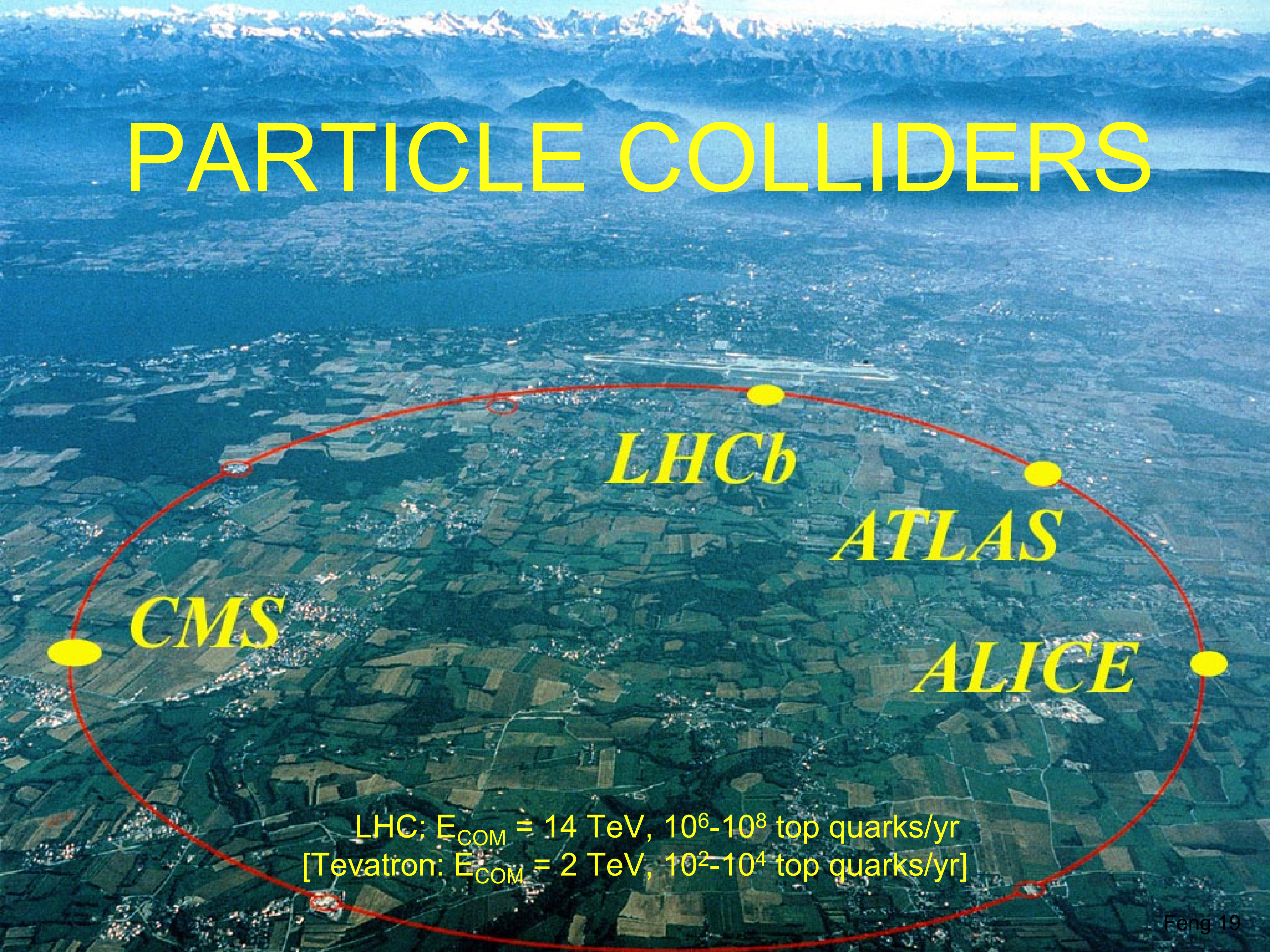
- Pulsars can explain PAMELA

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





PARTICLE COLLIDERS

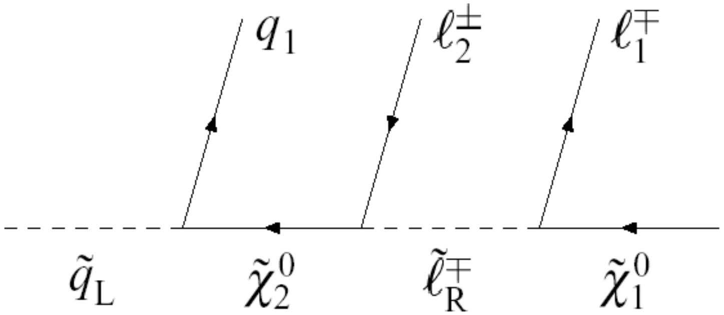


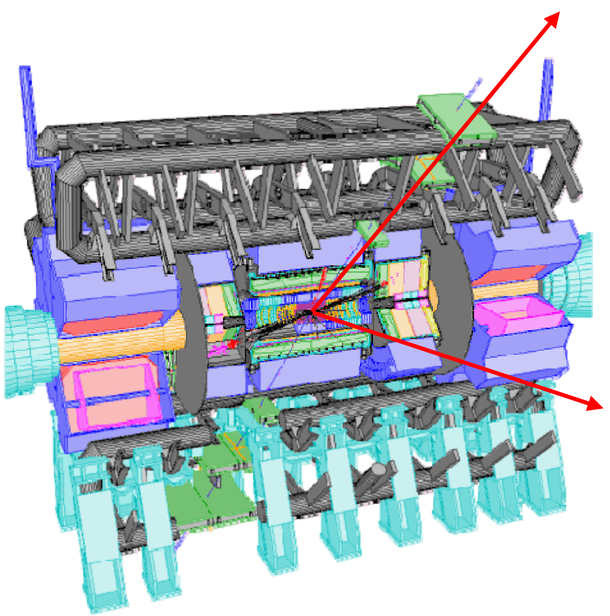
LHC: E_{COM} = 14 TeV, 10^6-10^8 top quarks/yr

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

WHAT THEN?

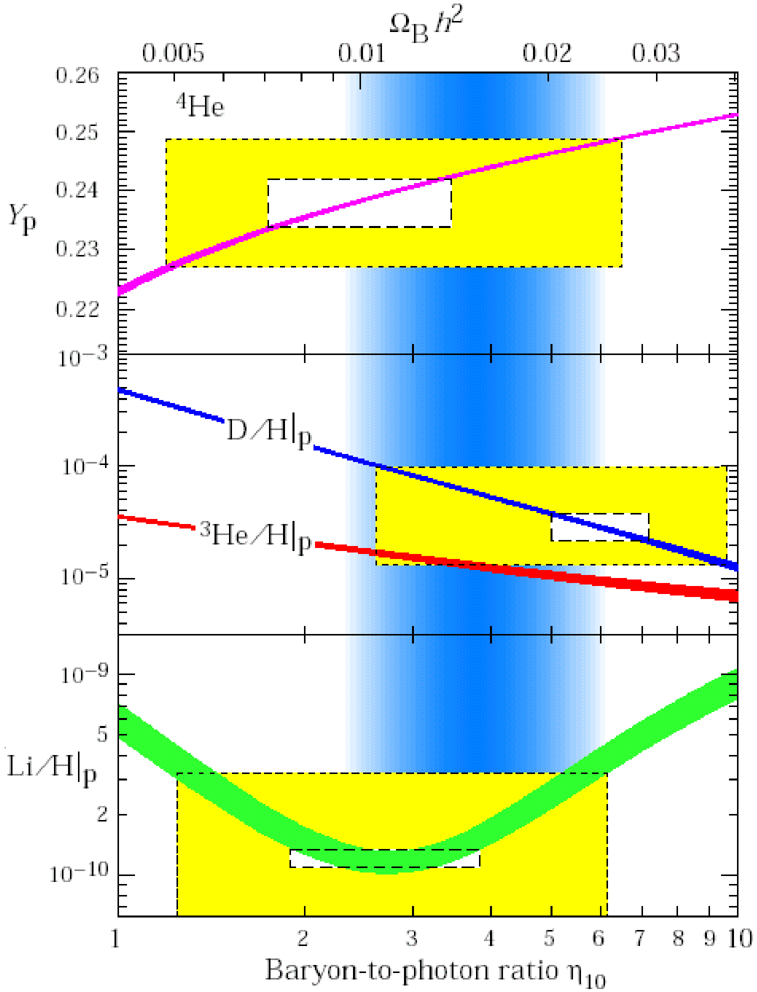
- What LHC actually sees:
  - E.g., $\tilde{q}\tilde{q}$ pair production
  - Each $\tilde{q}$ → neutralino χ
  - 2 χ's escape detector
  - missing momentum





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

THE EXAMPLE OF BBN

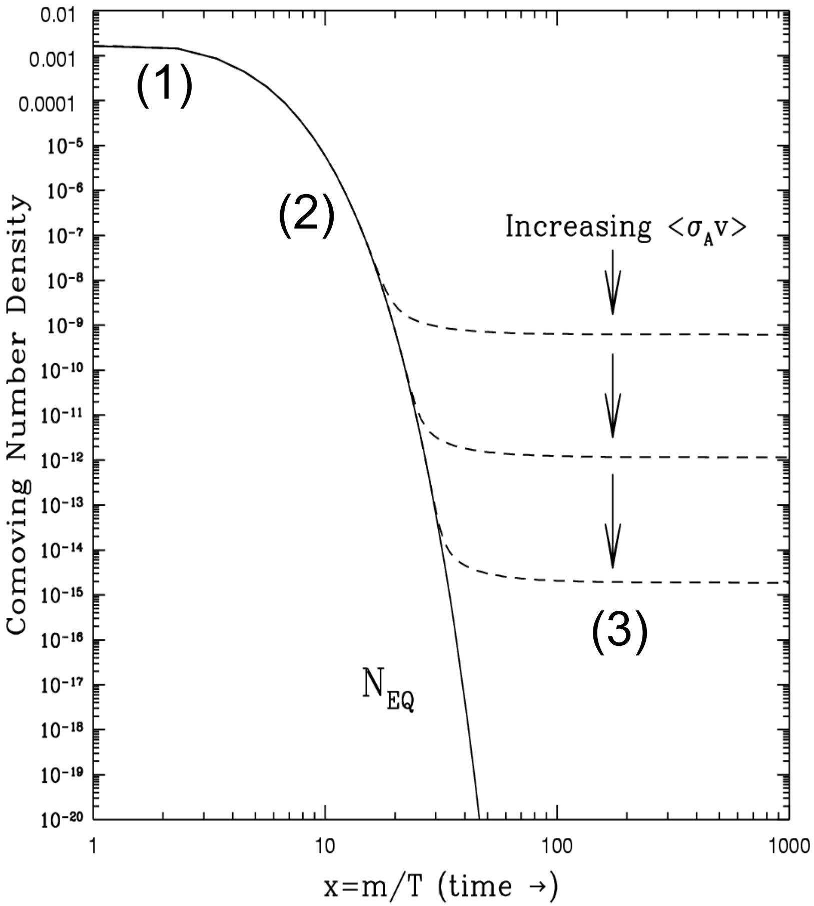


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

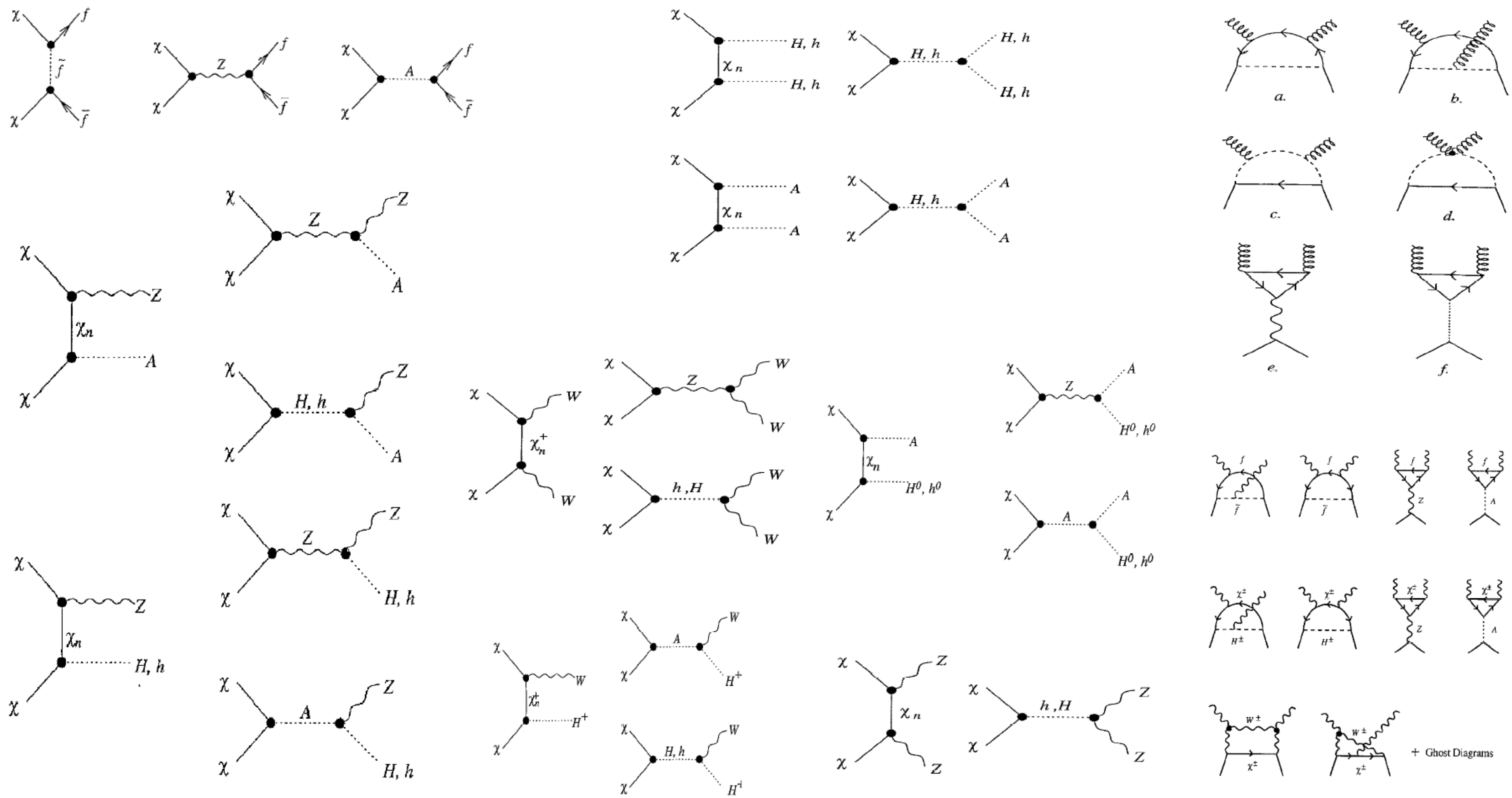
  t ~ 1 sec

DARK MATTER ANALOGUE



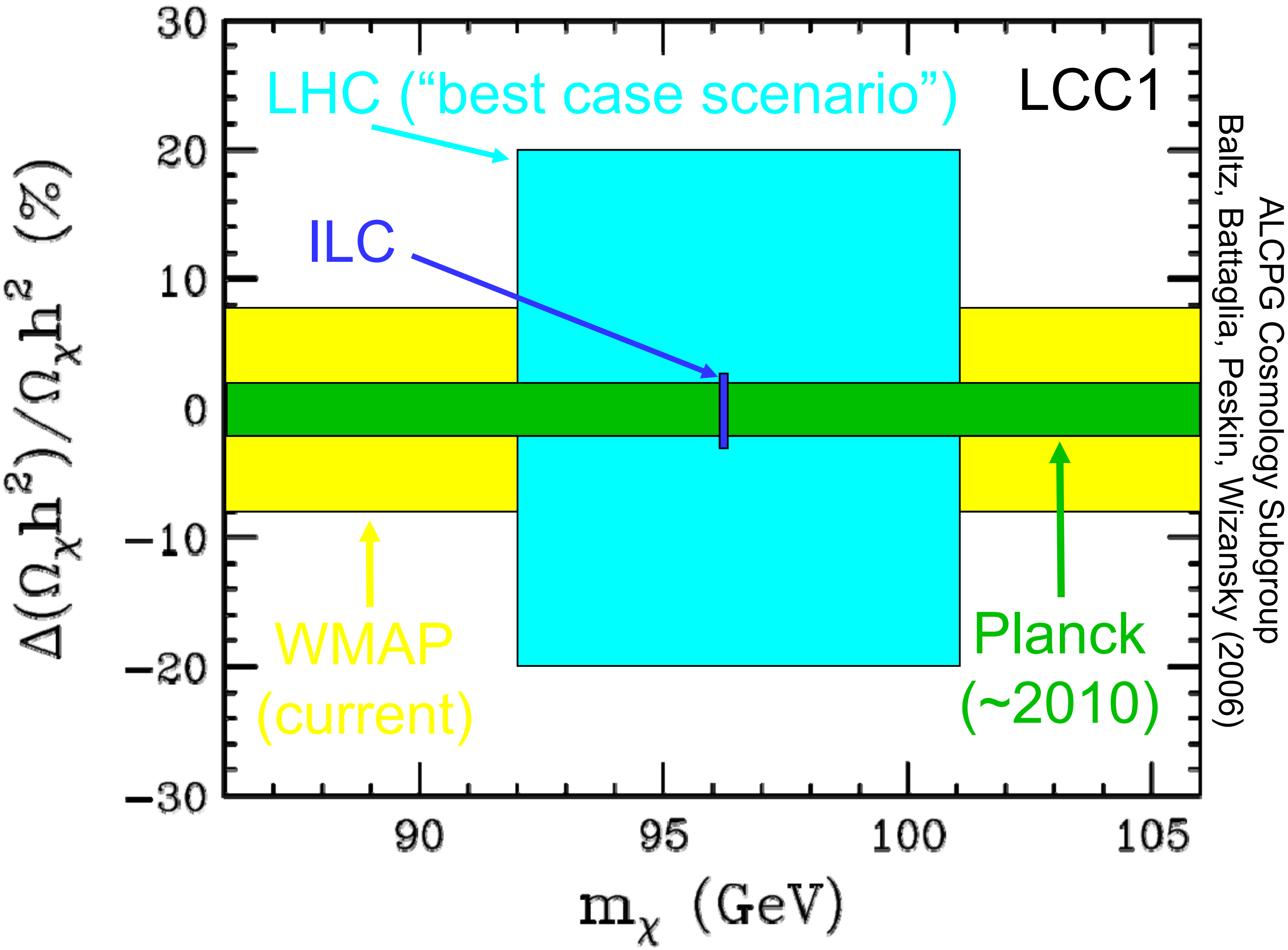
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

Contributions to Neutralino WIMP Annihilation



Jungman, Kamionkowski, Griest (1995)

RELIC DENSITY DETERMINATIONS



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

BEYOND WIMPS

- The WIMP miracle 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

SUPERWIMP DARK MATTER

Feng, Rajaraman, Takayama (2003)

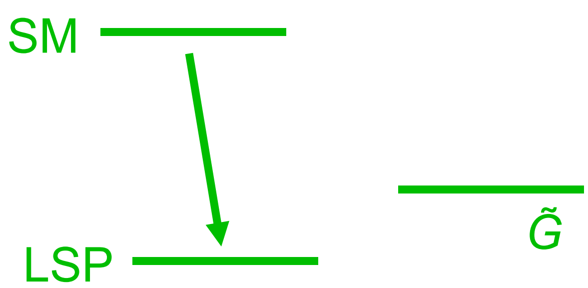
A new class of candidates. An example: Supersymmetry:

Graviton → Gravitino $\tilde{G}$

Pagels, Primack (1982)

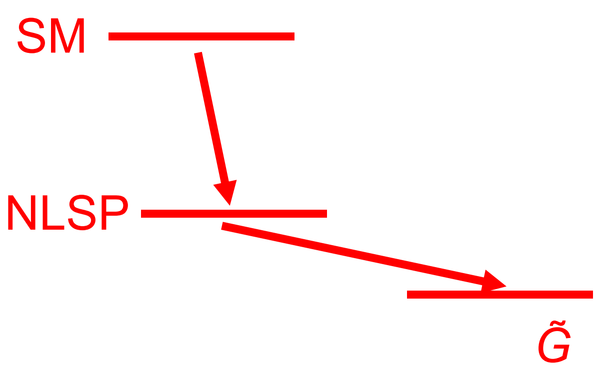
Mass ~ 100 GeV; Interactions: only gravitational (superweak)

- $\tilde{G}$ not LSP



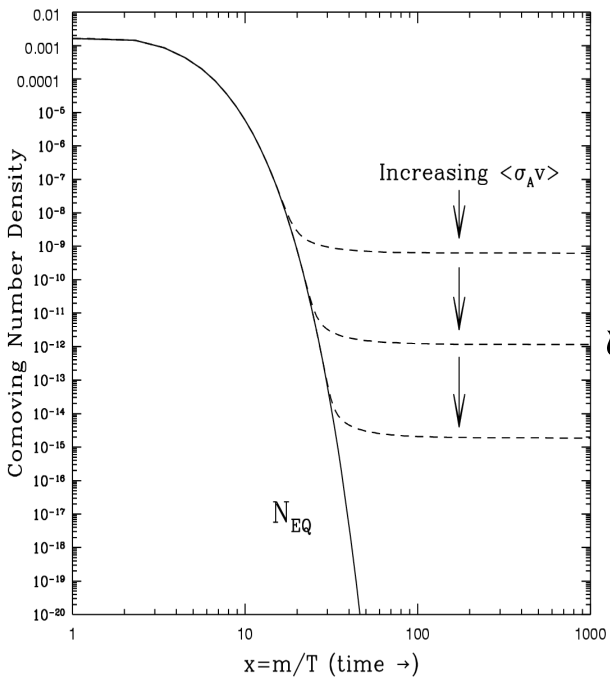
- Assumption of most of literature

- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

SUPERWIMP RELICS



- Suppose gravitinos $\tilde{G}$ are the LSP

- WIMPs freeze out as usual

WIMP ≈ → $\tilde{G}$ (+ γ, e, …)

- But then all WIMPs decay to gravitinos after

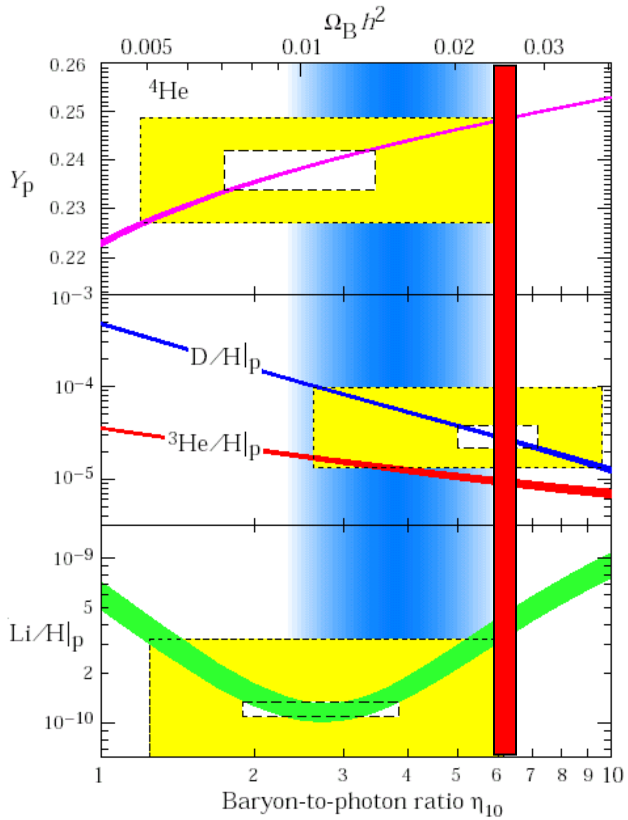
M_{Pl}^2/M_W^3 ~ seconds to months

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs (also KK gravitons, quintessinos, axinos, etc.)

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); Roszkowski, Ruiz de Austri, Choi (2004); Brandeburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); …

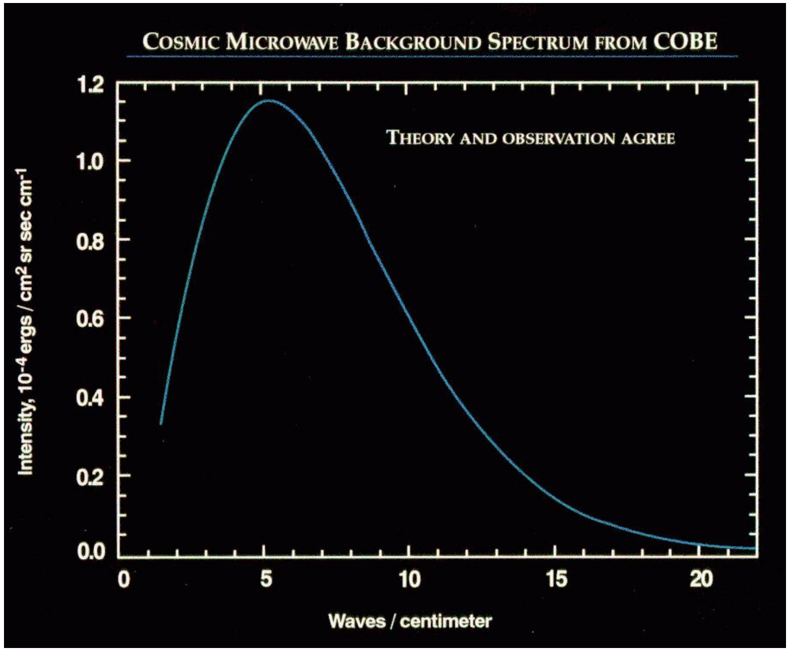
SUPERWIMP COSMOLOGY

Late decays can modify BBN
(Resolve ^{6,7}Li problems?)



Fields, Sarkar, PDG (2002)

Late decays can modify CMB
black body spectrum
(μ distortions)

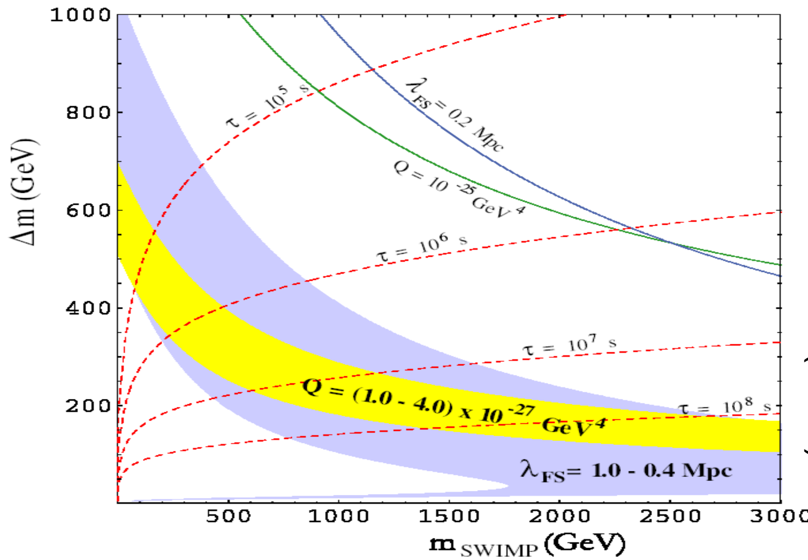


Fixsen *et al.* (1996)

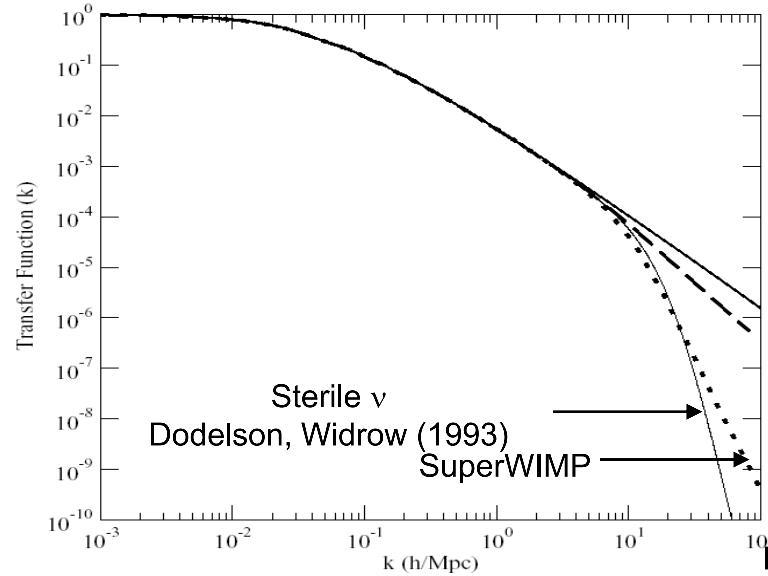
WARM SUPERWIMPS

- 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)



Cembranos et al. (2005)



Kaplinghat (2005)

HIDDEN DARK MATTER

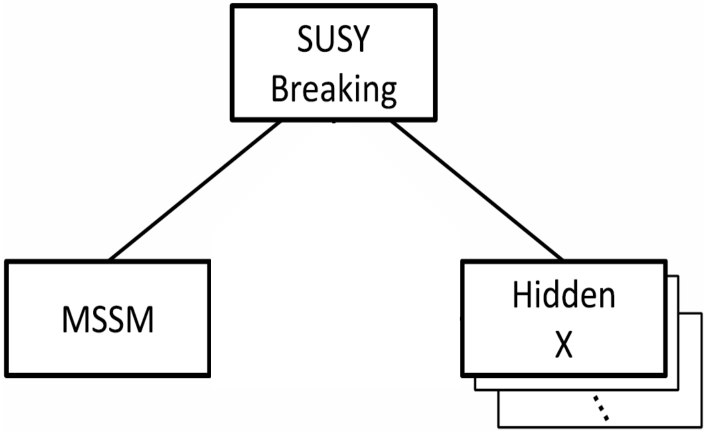
- Start over: What do we really know about dark matter?
  - All solid evidence is gravitational
  - Also solid evidence *against* strong and EM interactions
- A reasonable 1st guess: dark matter has no SM gauge interactions, i.e., it is *hidden*

Kobsarev, Okun, Pomeranchuk (1966); many others

- What one seemingly loses
  - Connections to central problems of particle physics
  - The WIMP miracle
  - Signals

CONNECTIONS TO CENTRAL PROBLEMS IN PARTICLE PHYSICS

- We want hidden sectors



- Consider SUSY
  - Connected to the gauge hierarchy problem
  - Hidden sectors are already required to break SUSY

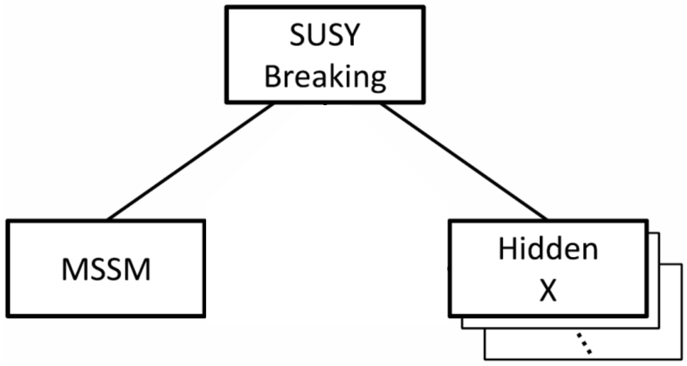
- Hidden sectors each have their own
  - particle content
  - mass scale m_X
  - Interactions, gauge couplings g_X

- What can we say about hidden sectors in SUSY?

- Generically, nothing. But in the attractive SUSY models (that solve the flavor problem: gauge-mediated models, anomaly-mediated models) the superpartner masses are determined by gauge couplings

$$m_X \sim g_X^2$$

- This leaves the relic density invariant!



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

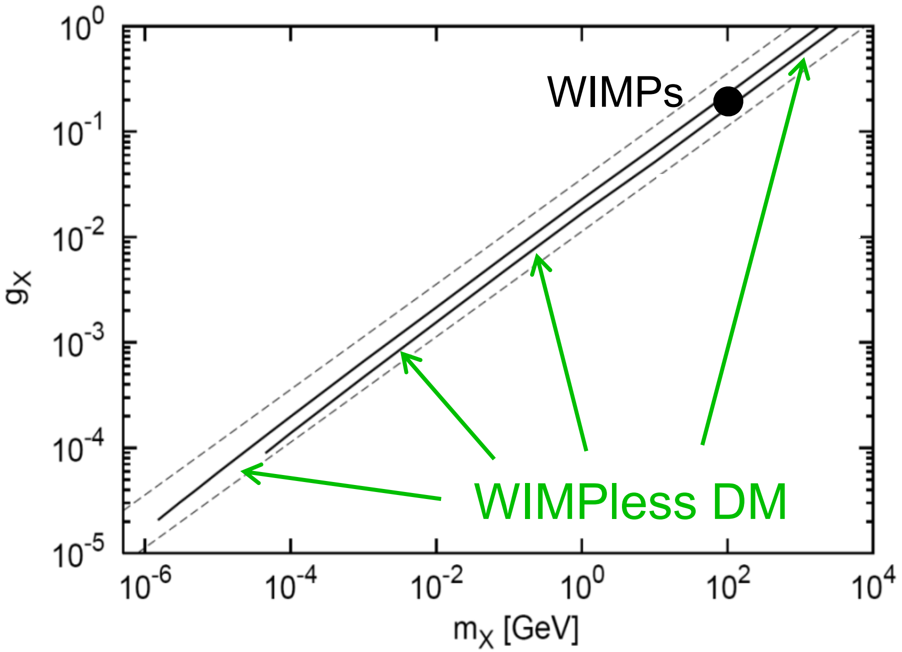
THE WIMPLESS MIRACLE

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

- The thermal relic density constrains only one combination of g_X and m_X

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

- These models map out the remaining degree of freedom; candidates have a range of masses and couplings, but always the right relic density



- Naturally accommodates multi-component DM, all with relevant Ω

HIDDEN CHARGED DM

How is hidden dark matter stabilized?

If the hidden sector is standard model-like, the most natural possibility is that the DM particle has hidden charge, and so is stabilized by charge conservation (cf. the electron)

MSSM	
m_W	sparticles, W, Z, t
~GeV	q, l
0	p, e, γ, ν, $\tilde{G}$

Hidden, flavor-free MSSM	
m_X	sparticles, W, Z, q, l, $\tilde{\tau}$ (or τ)
0	g, γ, ν, $\tilde{G}$

HIDDEN CHARGED DM

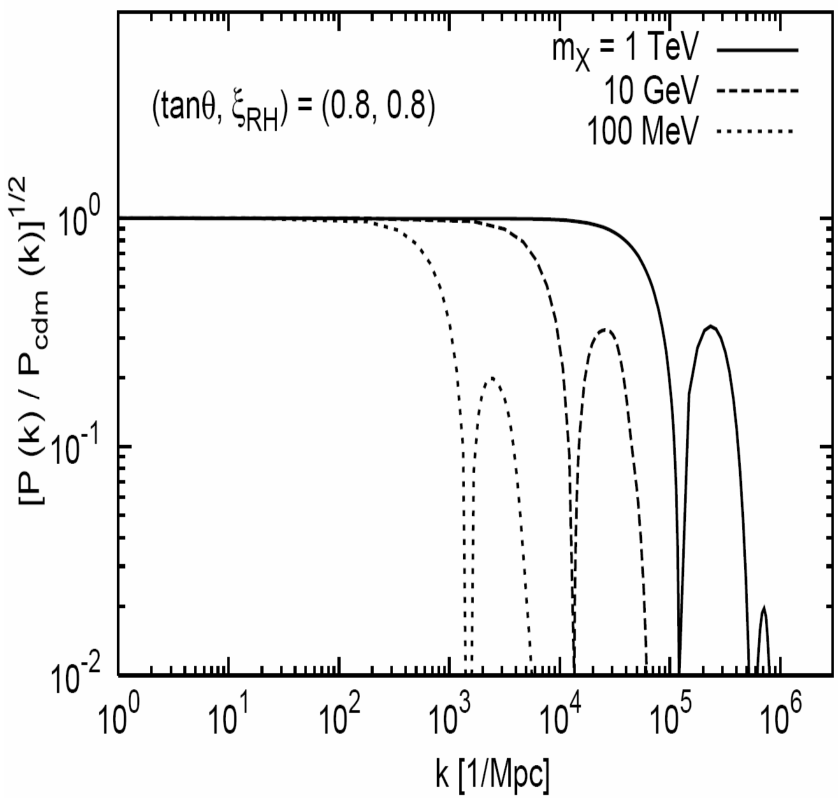
Feng, Kaplinghat, Tu, Yu (2009)

- This scenario shares all WIMP motivations, but now there are strong DM-DM interactions, with many novel astrophysical implications

- E.g., Compton scattering

  $$X\,\gamma^h \rightarrow X\,\gamma^h$$

  delays kinetic decoupling → small scale structure



DM SELF-INTERACTIONS

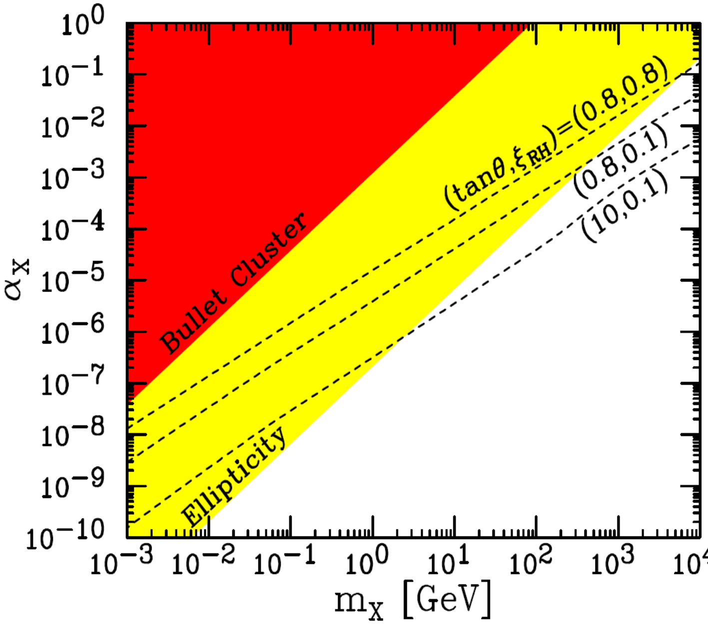
- Also have DM self-interactions through Rutherford scattering
  - Highly velocity-dependent
  - constrained by existence of non-spherical halos, bullet cluster

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_X^2}{4 m_X^2 v^4 \sin^4(\theta/2)}$$

- If dark sector has only EM, hard to get correct thermal relic density

Ackerman, Buckley, Carroll, Kamionkowski (2008)

- With dark SM, weak interactions can give the right Ω, lots of freedom



Feng, Kaplinghat, Tu, Yu (2009)

CONCLUSIONS

- This is an area of rapid progress in both theory and experiment
- Theory: proliferation of new candidates, some as motivated as WIMPs, with widely varying implications for particle physics *and astrophysics (warm, self-interacting, …)*
- Experiment: direct detection, indirect detection, LHC, astrophysical probes