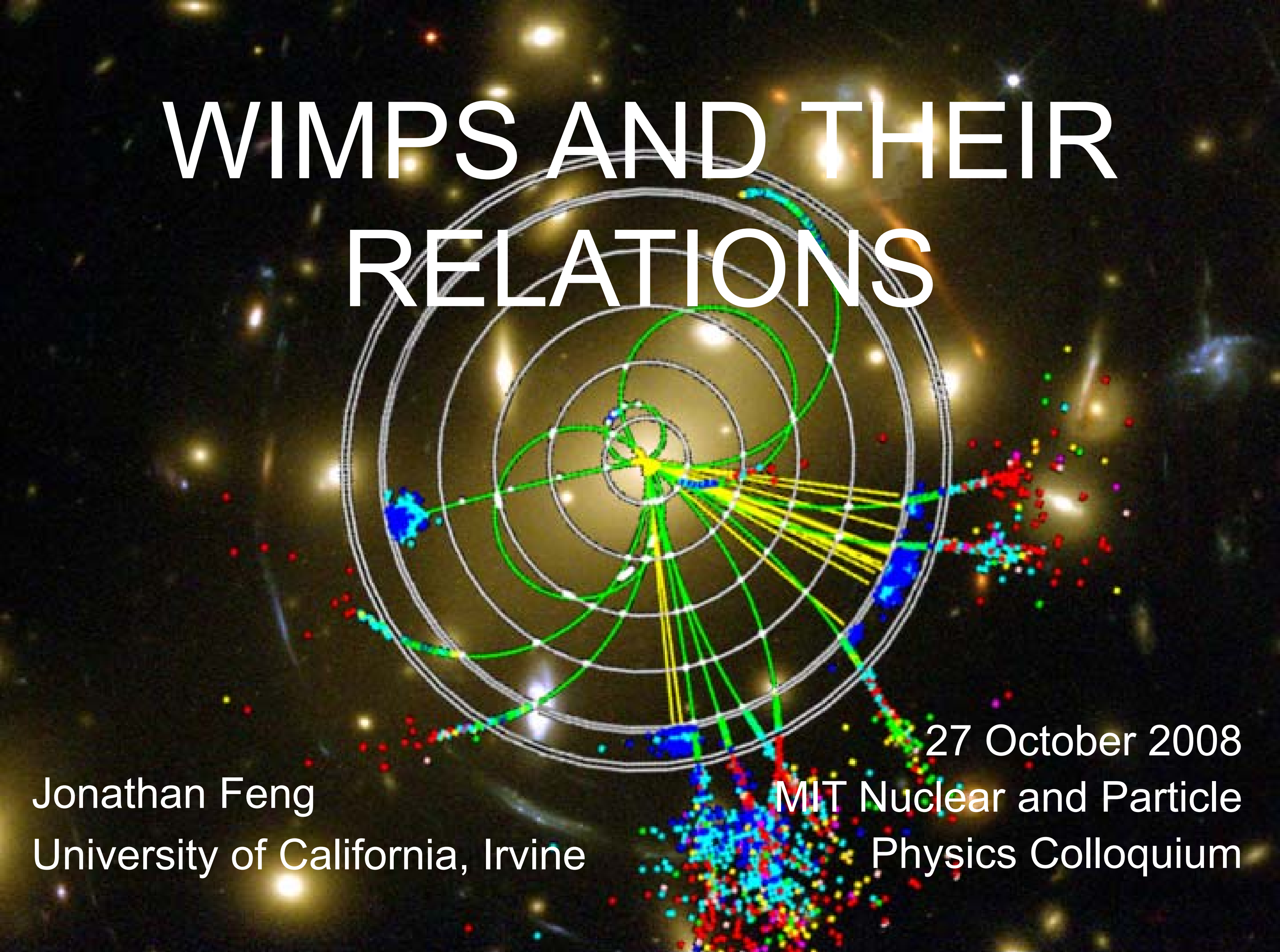
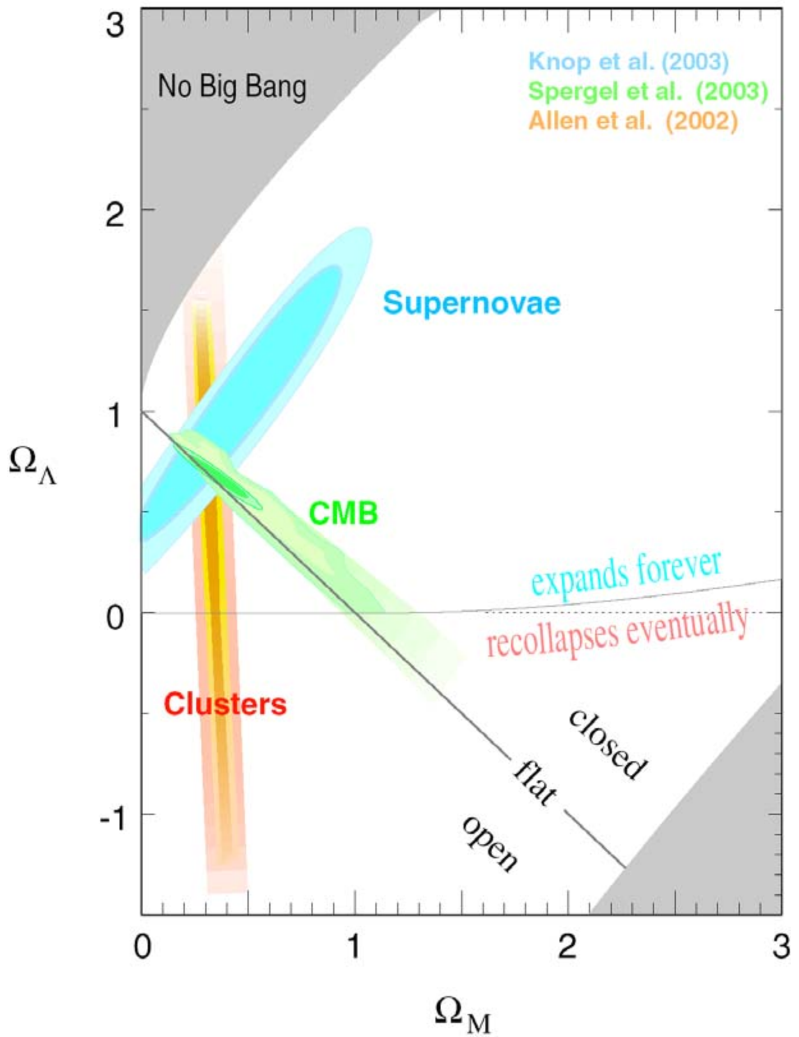
WIMPS AND THEIR RELATIONS



Jonathan Feng
University of California, Irvine

27 October 2008
MIT Nuclear and Particle Physics Colloquium

DARK MATTER



- Unambiguous evidence for new physics
- Intimately connected to central problems
  - electroweak symmetry breaking
  - structure formation
- Remarkable precision
  $\Omega_{DM}h^2 = 0.1099 \pm 0.0062$

WMAP (2008)

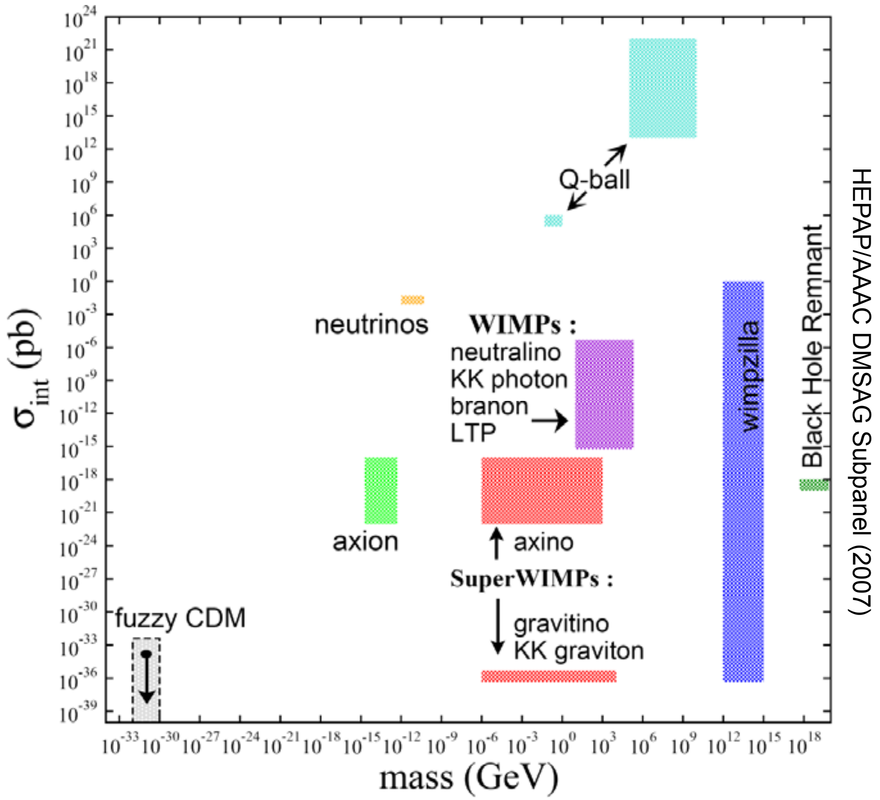
OPEN QUESTIONS

- What particle forms dark matter?
- What is its mass?
- What is its spin?
- What are its other quantum numbers and interactions?
- Is dark matter composed of one particle species or many?
- How was it produced?
- When was it produced?
- Why does Ω_{DM} have the observed value?
- What was its role in structure formation?
- How is dark matter distributed now?
- Is it absolutely stable?

CANDIDATES

- Observational constraints
  – Not baryonic (≠ weakly-interacting)
  – Not hot (≠ cold)
  – Not short-lived (≠ stable)

- Masses and interaction strengths span many, many orders of magnitude



- Focus on WIMPs, superWIMPs, WIMPless dark matter

THE "WIMP MIRACLE"

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

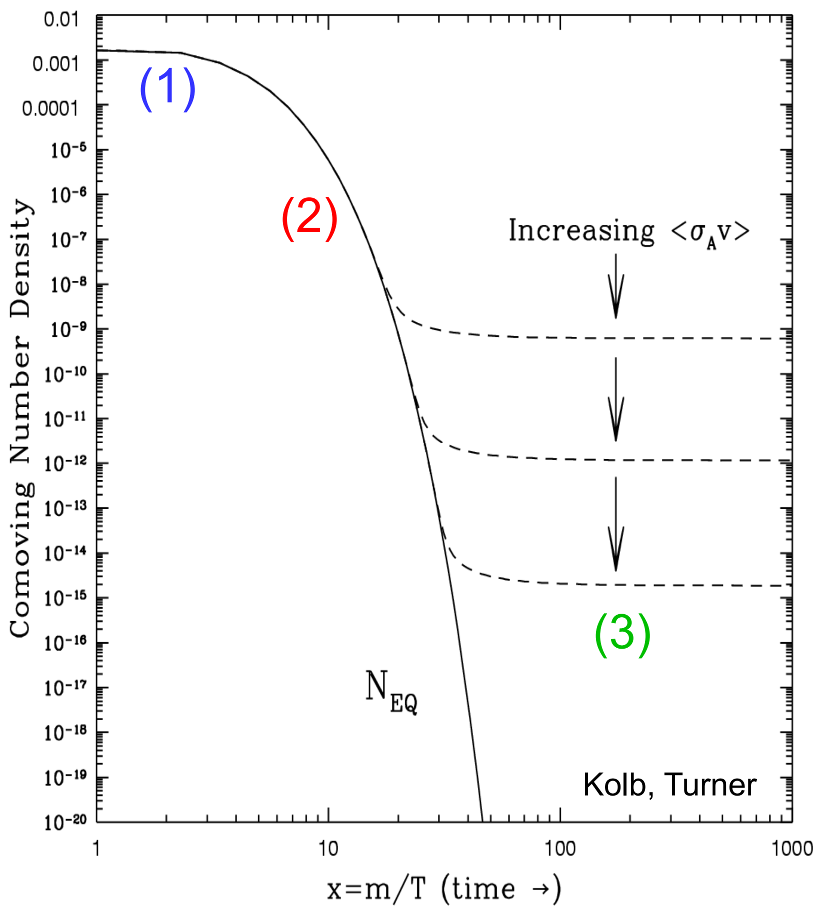
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \begin{smallmatrix}\rightarrow \\ \not\leftarrow\end{smallmatrix} \bar{f} f$$

(3) χs "freeze out":

$$\chi\chi \begin{smallmatrix}\not\rightarrow \\ \not\leftarrow\end{smallmatrix} \bar{f} f$$



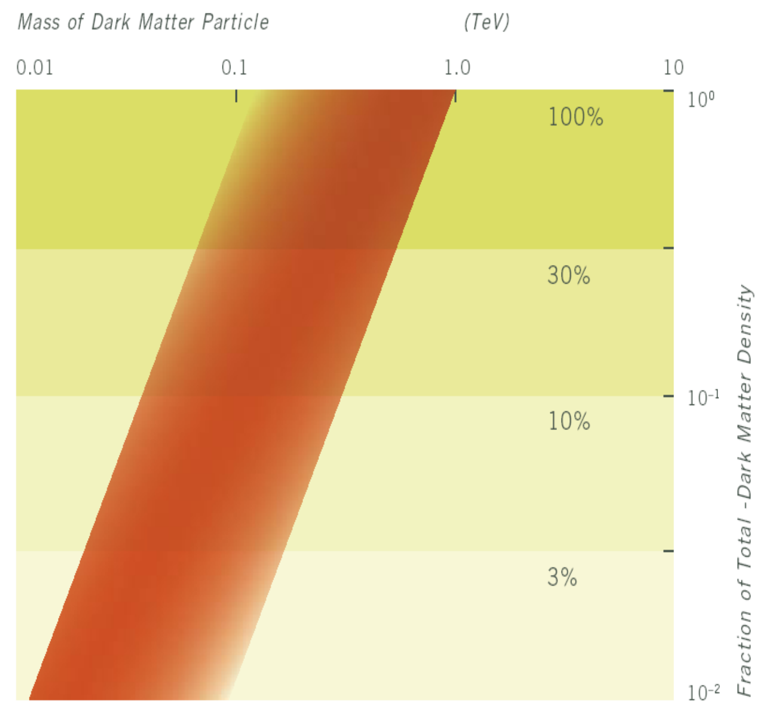
- The amount of dark matter left over is inversely proportional to the annihilation cross section:

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

- What is the constant of proportionality?

- Impose a natural relation:

$\sigma_A = k\alpha^2/m^2$, so $\Omega_{DM} \sim m^2$



HEPAP LHC/ILC Subpanel (2006)

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

Remarkable “coincidence”: $\Omega_{DM} \sim 0.1$ for $m \sim 0.1 – 1$ TeV

Cosmology alone tells us we should explore the weak scale

STABILITY

- This all assumes the new particle is stable. Why should it be?
- LEP's Cosmological Legacy

Problems

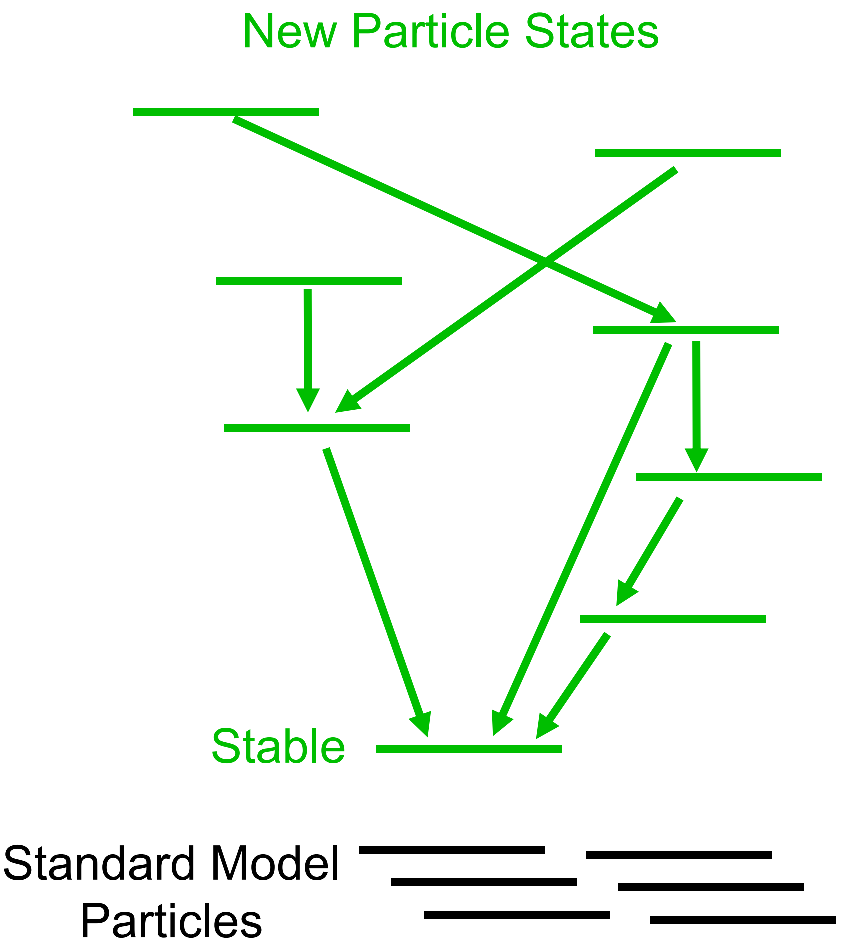
↕

Discrete symmetry

↕

Stability

- In many theories, dark matter is easier to explain than no dark matter



WIMPS

Recent proliferation of examples:

- Supersymmetry: R-parity → Neutralinos

  Goldberg (1983); Ellis et al. (1984)

- Universal Extra Dimensions: KK-parity → Kaluza-Klein DM

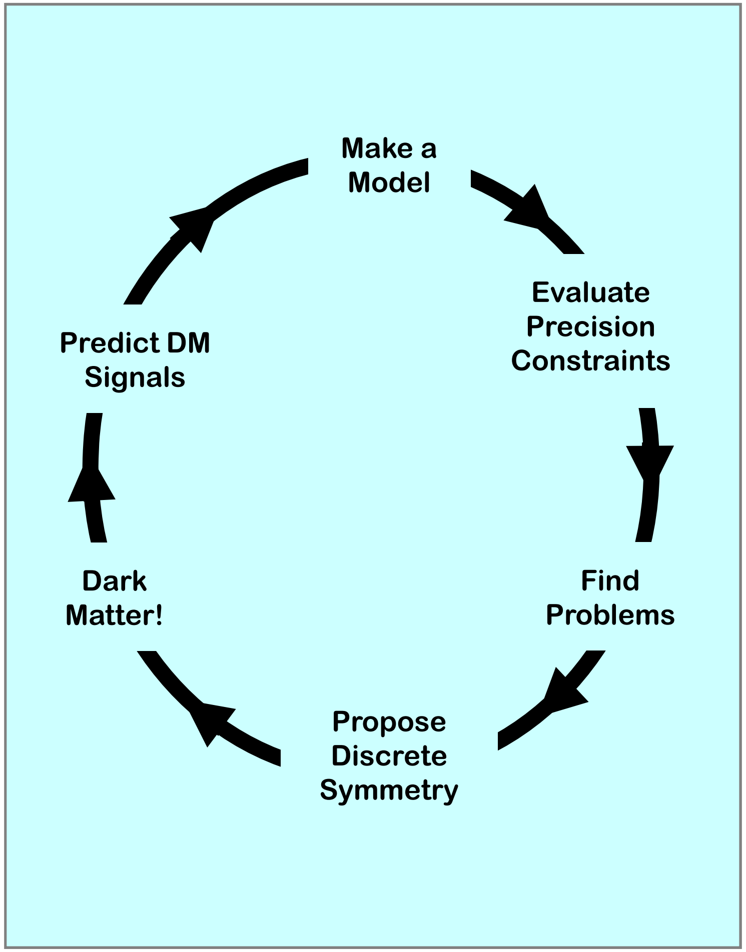
  Servant, Tait (2002); Cheng, Feng, Matchev (2002)

- Branes: Brane-parity → Branon DM

  Cembranos, Dobado, Maroto (2003)

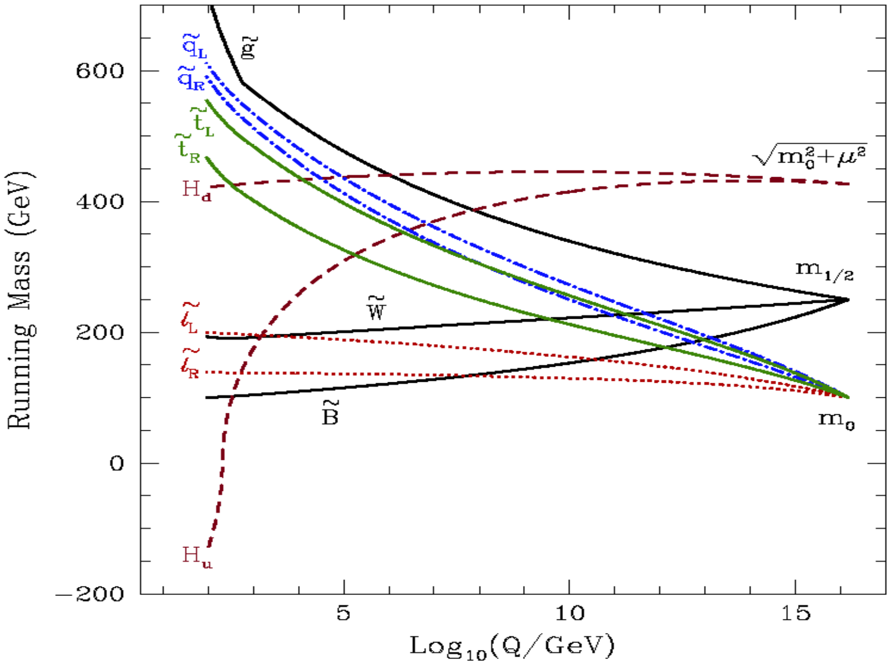
- Little Higgs: T-parity → T-odd DM

  Cheng, Low (2003)



NEUTRALINOS

- The neutralino is the classic WIMP
  - $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$
  - ~ 50 GeV – 1 TeV
  - weakly-interacting
  - naturally the lightest standard model superpartner in many models



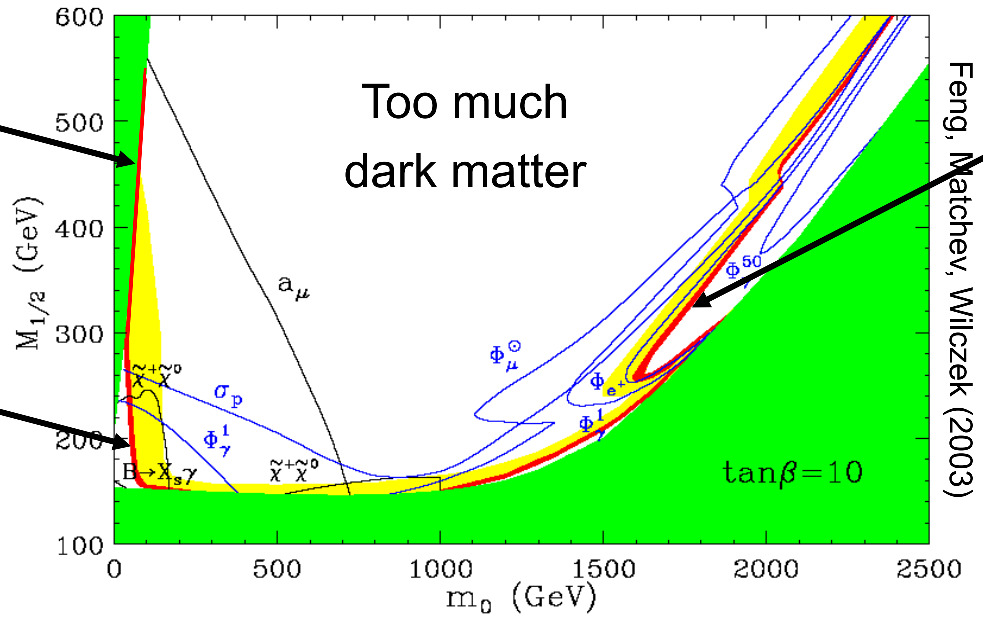
- Particle physics alone → neutralinos have all the right properties to be WIMP dark matter

RELIC DENSITY

$\Omega_{DM}h^2$ stringently constrains models

Co-annihilation region

Bulk region



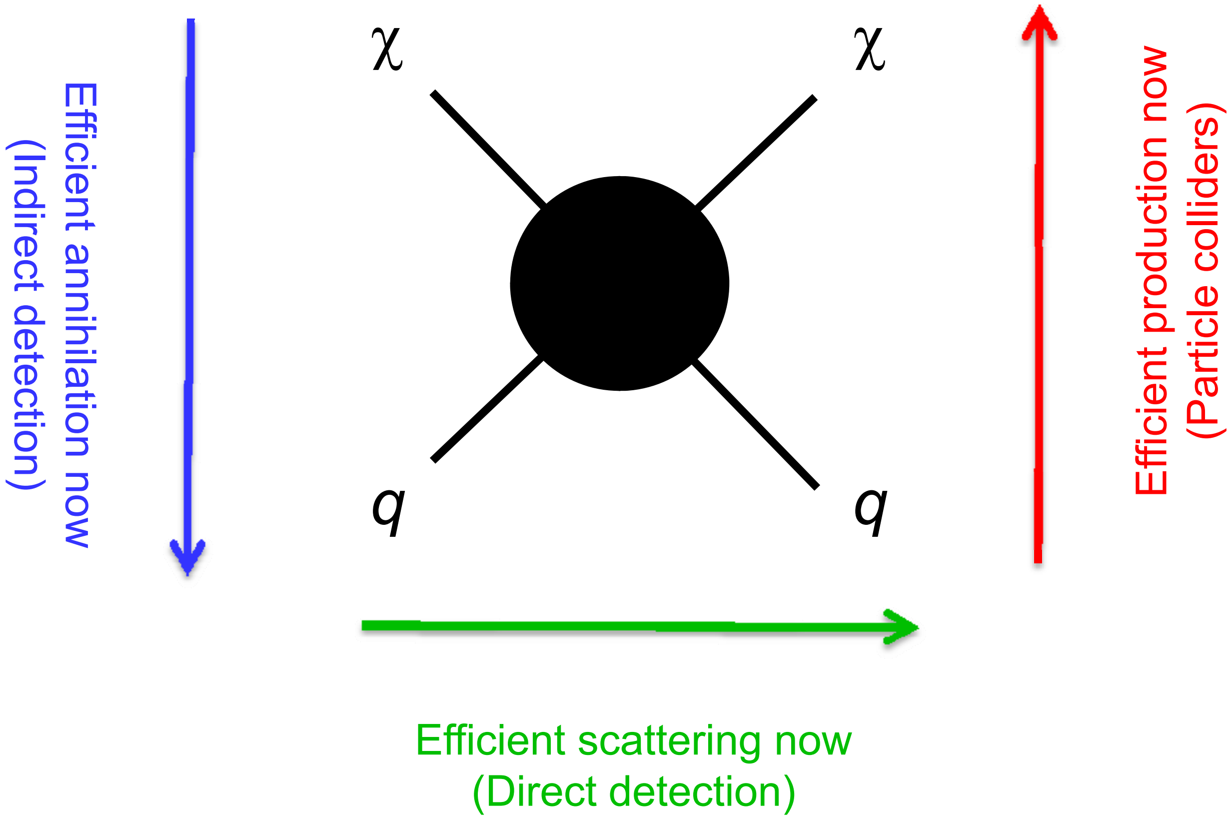
Focus point region

Yellow: pre-WMAP
Red: post-WMAP

Cosmology excludes many possibilities, favors certain regions

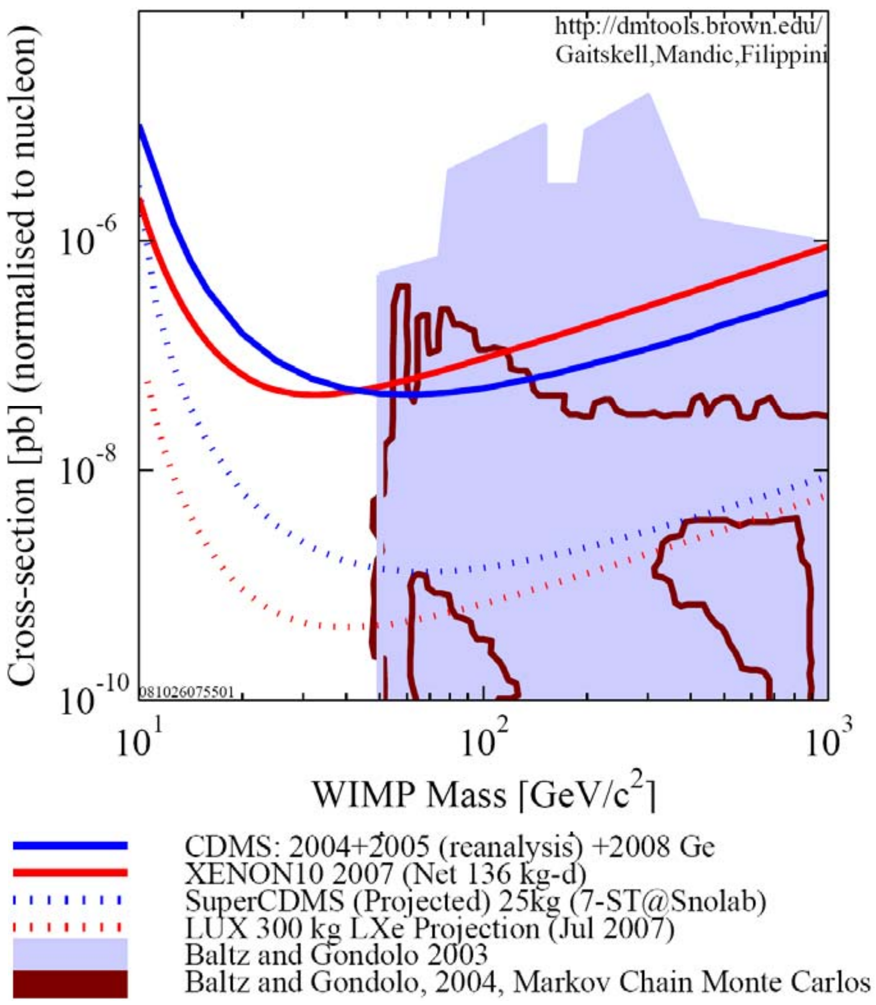
WIMP DETECTION

Correct relic density → Efficient annihilation then



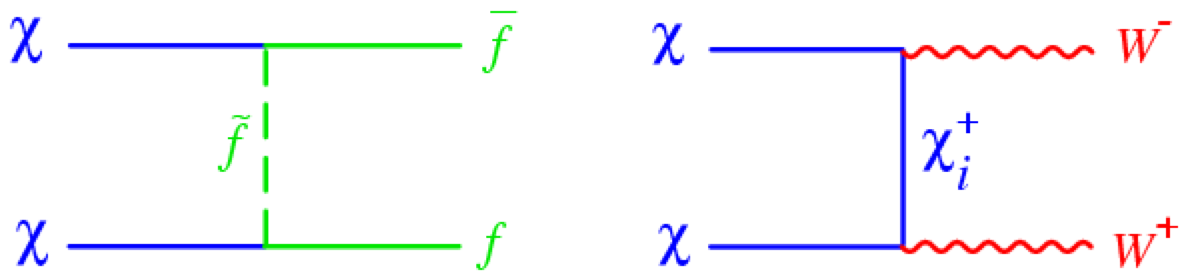
DIRECT DETECTION

- WIMP properties:
  $v \sim 10^{-3}$ c
  Kinetic energy ~ 100 keV
  Local density ~ 1 / liter
- Detected by nuclear recoil in underground detectors. Two approaches:
  - Background-free detection
  - Annual modulation
- Spin-independent scattering
  - Theories: χq
  - Experiments: χ-nucleus
  - Meet in the middle: χp



THEORETICAL PREDICTIONS

- Model-dependent, but in SUSY we can say something. There are two classes of annihilation processes:



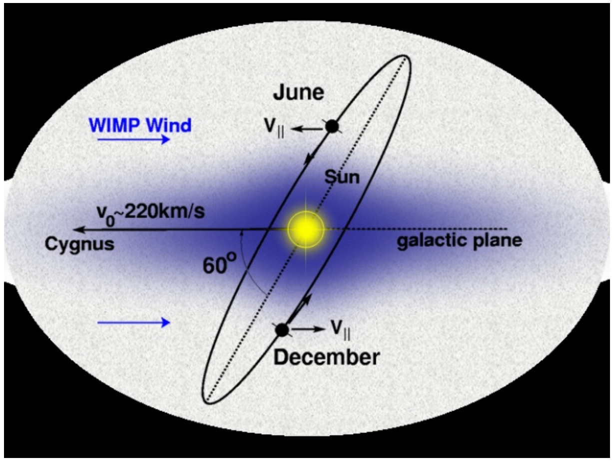
- Neutralino DM → gravity-mediation
  SUSY flavor and CP problems → heavy sleptons and squarks
  Relic density → mixed Bino-Higgsino neutralinos with $\sigma \sim 10^{-8}$ pb

- Many SUSY models (mSUGRA, general focus point SUSY, gaugino-mediated, more minimal SUSY, 2-1 models, split SUSY) will be tested in the next few years

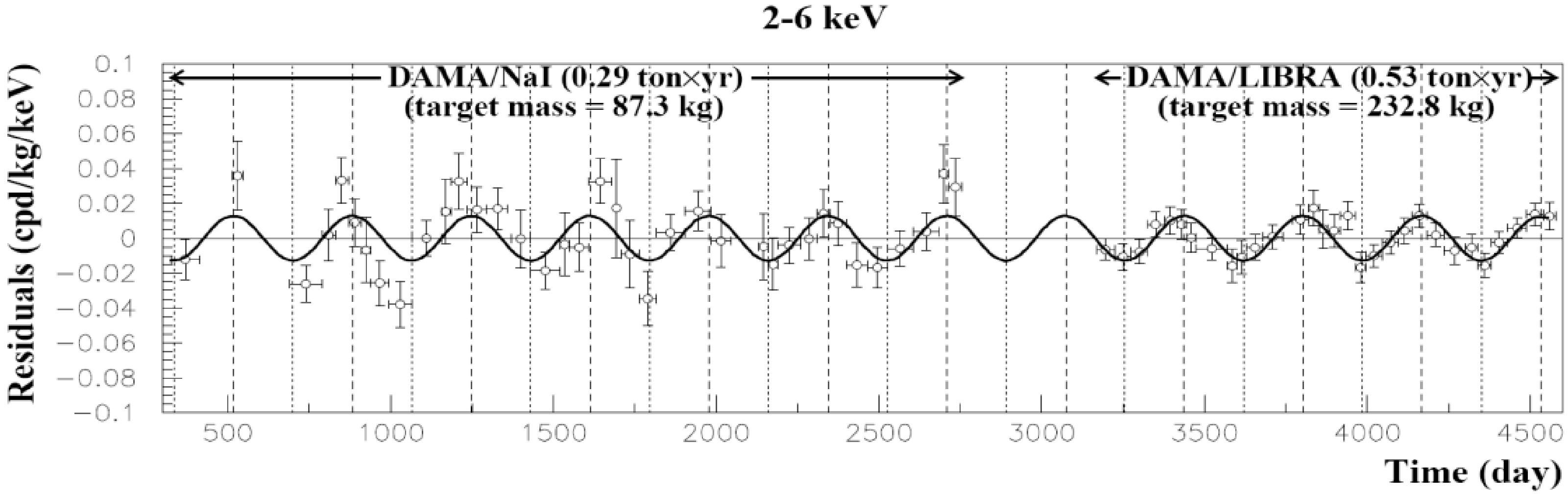
DIRECT DETECTION: DAMA

- Annual modulation expected

Drukier, Freese, Spergel (1986)



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



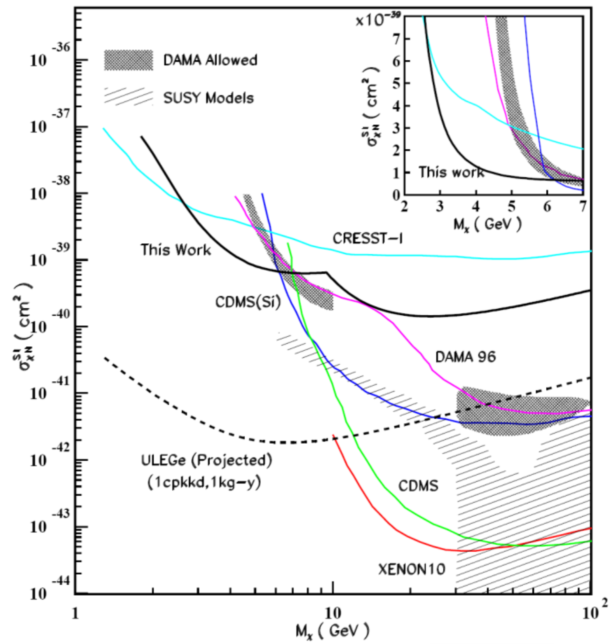
DAMA Collaboration (2008)

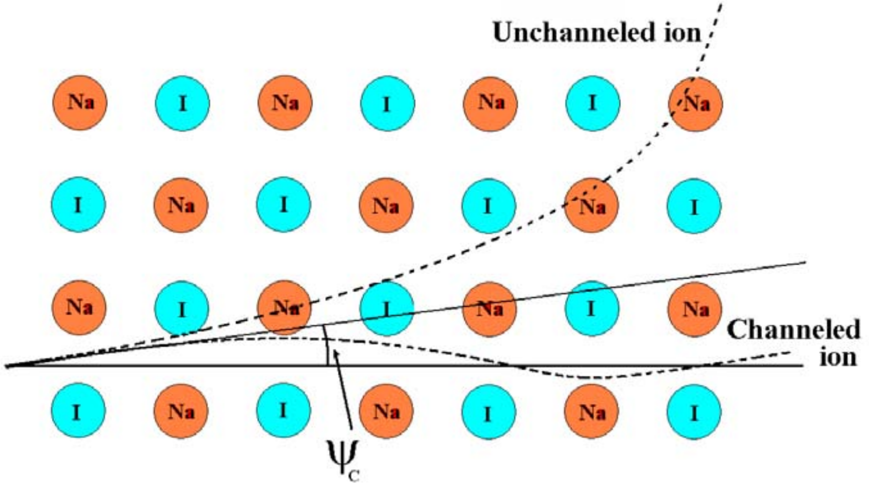
CHANNELING

- DAMA's results have been puzzling, in part because the allowed region is excluded by experiments

- This may be ameliorated by astrophysics and channeling: in crystalline detectors, efficiency for nuclei recoil energy → electron energy depends on direction

- Channeling reduces threshold, shifts allowed region to lower masses. Consistency restored?





Gondolo, Gelmini (2005)
Drobyshevski (2007), DAMA (2007)

TAKING STOCK

- WIMPs are astrophysically identical
  - Weakly-interacting
  - Cold
  - Stable

- Is this true of all DM candidates?

- No. But is this true of all DM candidates motivated by particle physics and the “WIMP miracle”?

- No! SuperWIMPs: identical motivations, but qualitatively different implications

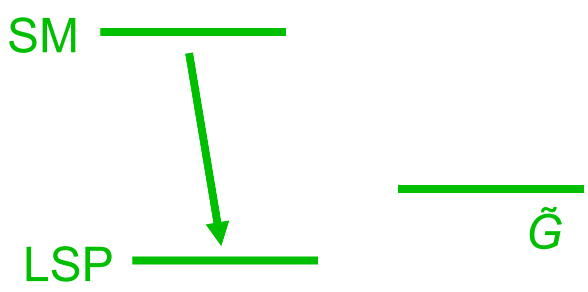
SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

Supersymmetry: Graviton → Gravitino $\tilde{G}$

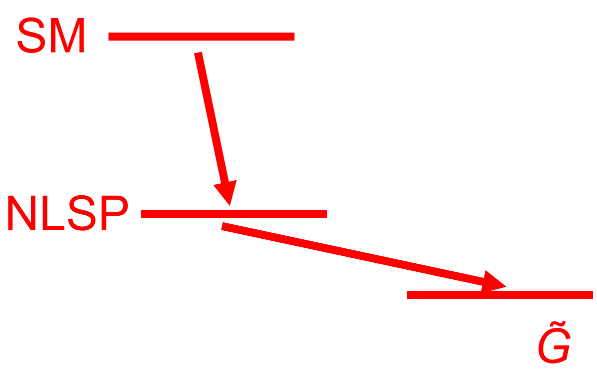
Mass ~ 100 GeV; Interactions: only gravitational (superweak)

- $\tilde{G}$ not LSP



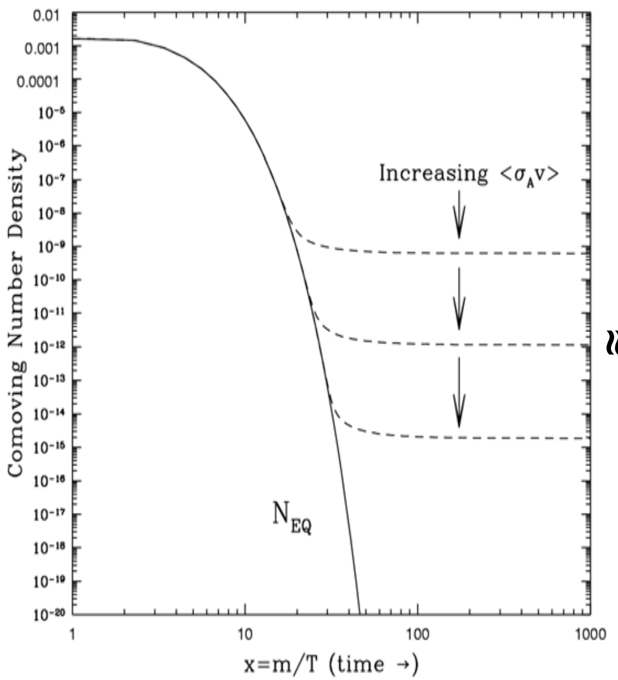
- Assumption of most of literature

- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

SUPERWIMP RELICS



- Suppose the gravitino $\tilde{G}$ is the LSP

- WIMPs freeze out as usual

WIMP → $\tilde{G}$

- But then all WIMPs decay to gravitinos after

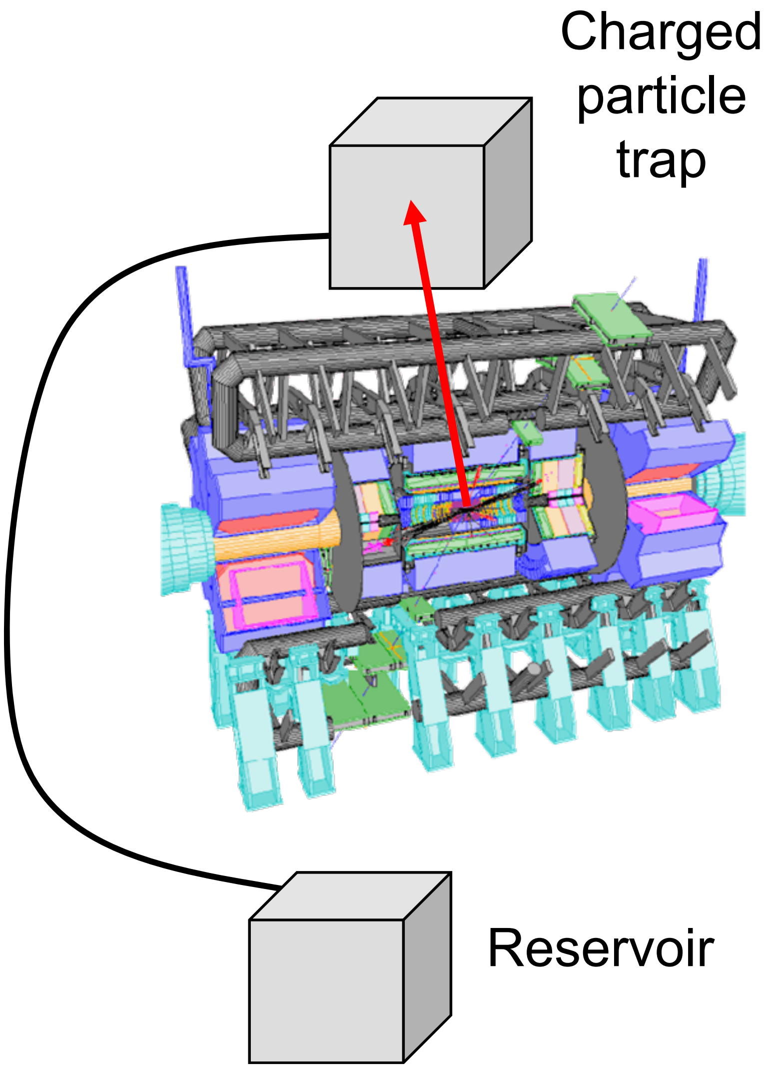
M_{Pl}^2/M_W^3 ~ seconds to months

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs (also KK gravitons,, 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); …

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)

IMPLICATIONS FROM CHARGED PARTICLE DECAYS

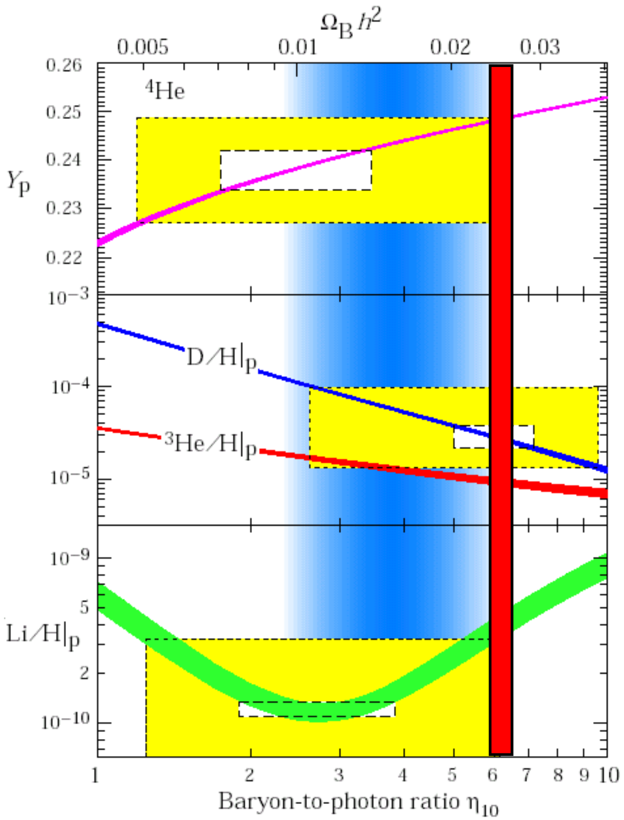
$$\tau(\tilde{l} \to l\tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^5} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^{-4}$$

- Measurement of τ , $m_{\tilde{l}}$ and E_l → $m_{\tilde{G}}$ and *GN*
  - Probes gravity in a particle physics experiment!
  - Measurement of G_N on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines *F* : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

Hamaguchi et al. (2004); Takayama et al. (2004)

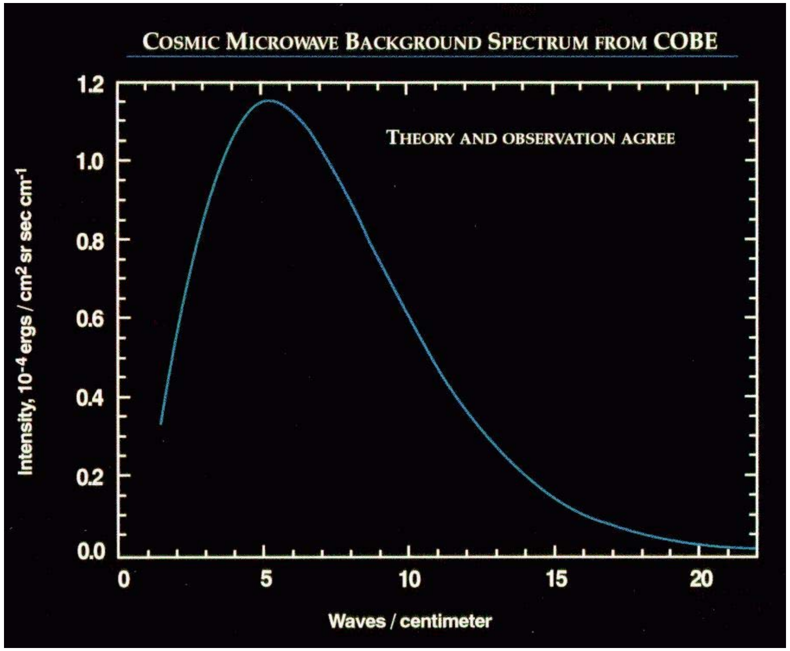
SUPERWIMP COSMOLOGY

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



Fields, Sarkar, PDG (2002)

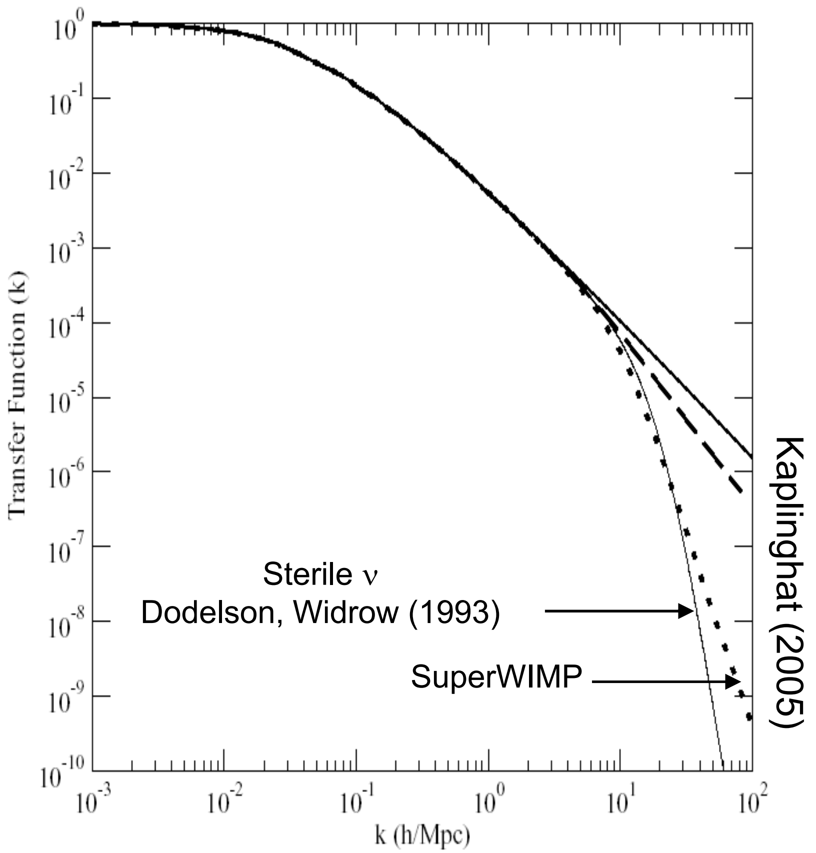
Late decays can modify CMB
black body spectrum
(μ distortions)



Fixsen *et al.* (1996)

SMALL SCALE STRUCTURE

- 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

- 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*

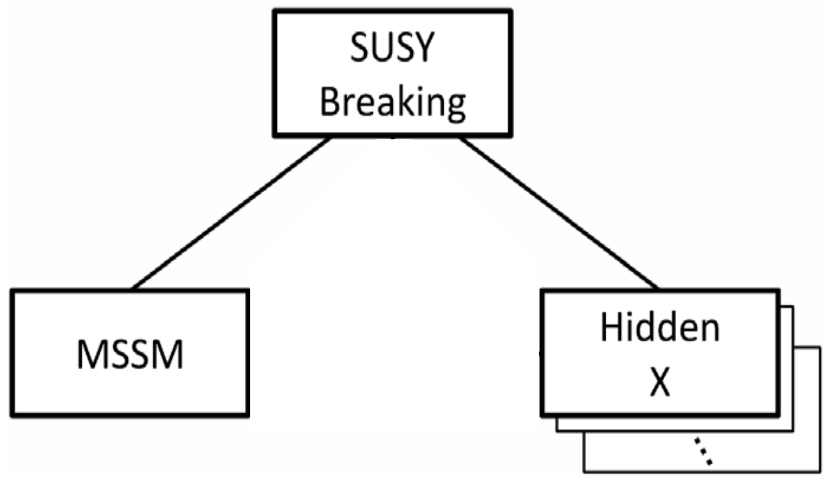
Lee, Yang (1956); Gross, Harvey, Martinec, Rohm (1985)

- What one seemingly loses
  - The WIMP miracle
  - Non-gravitational signals

HIDDEN SECTORS

- Can we recover the WIMP miracle, but with hidden DM?
- Consider gauge-mediated SUSY breaking with one or more hidden sectors
- Each hidden sector has its own gauge groups and couplings

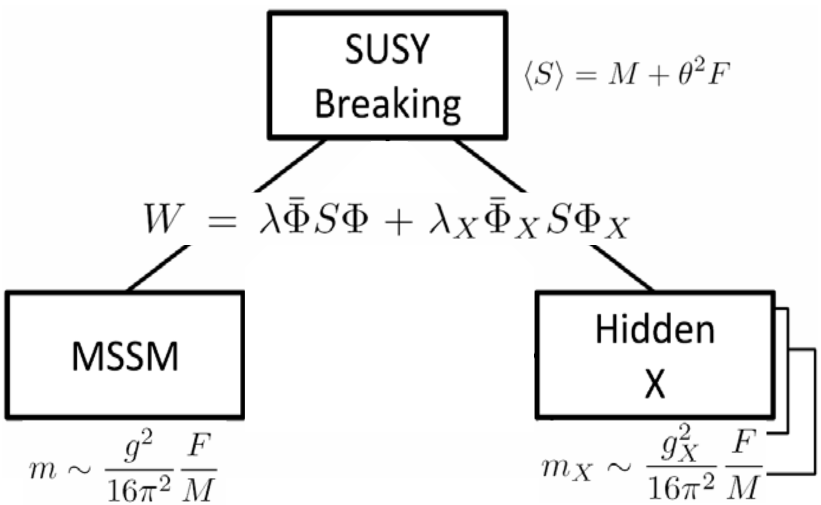
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



THE WIMPLESS MIRACLE

Feng, Kumar (2008)

- Particle Physics



Superpartner masses, interaction strengths depend on gauge couplings

- Cosmology

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}$$

Ω depends only on the SUSY breaking sector:

$$\Omega_X \sim \Omega_{WIMP} \sim \Omega_{DM}$$

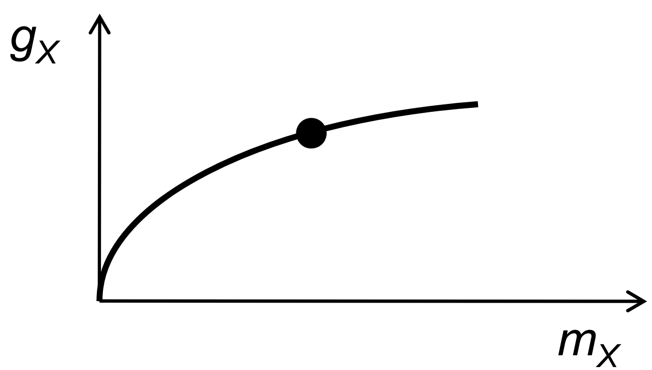
Any hidden particle with mass ~ m_X will have the right thermal relic density (for *any* m_X)

WIMPLESS DARK MATTER

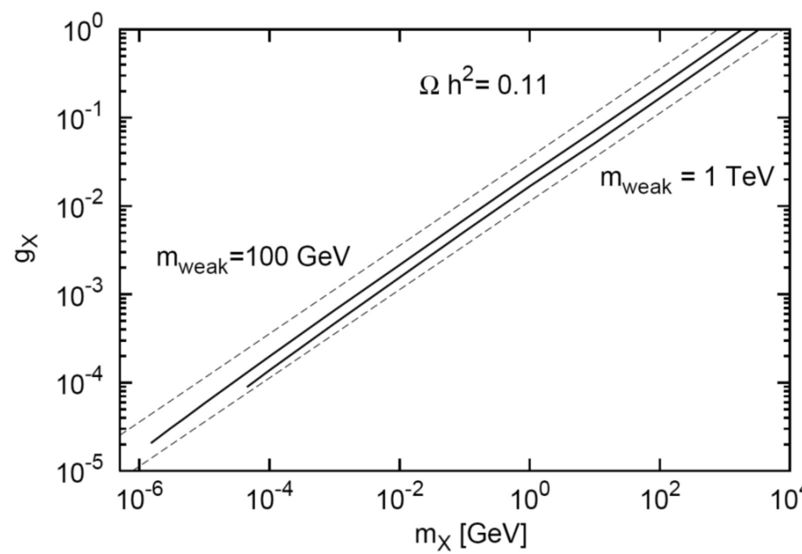
- The thermal relic density constrains only one combination of g_X and m_X

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

- These models map out the remaining degree of freedom



- This framework decouples the WIMP miracle from WIMPs, gives a new class of candidates with WIMP pedigree, but with a range of masses/couplings



Feng, Tu, Yu (2008)

STABILITY

- This requires that an m_X particle be stable. Can one be?

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

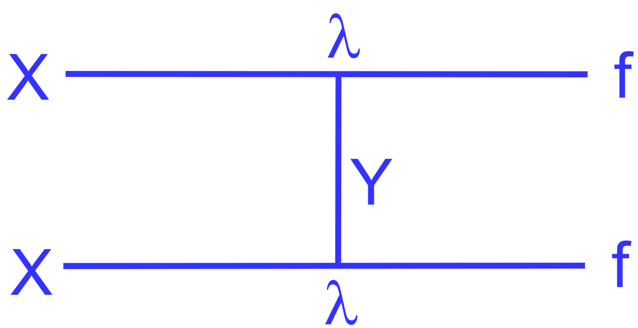
Flavor-free MSSM O(1) Yukawas	
m_X	sparticles, W, Z, q, l, $\tilde{\tau}$ (or τ)
0	g, γ, ν, $\tilde{G}$

- If the hidden sector is a flavor-free MSSM, a natural NLSP candidate, the stau (or tau), would be stabilized by charge conservation.

WIMPLESS DETECTION

- WIMPless DM may have only gravitational effects

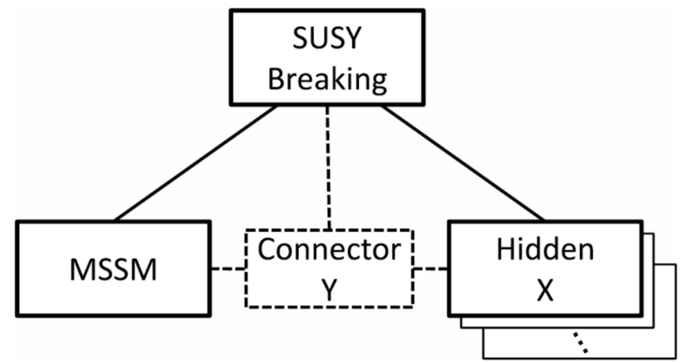
- But connectors with both MSSM and hidden charges may mediate interactions with the SM

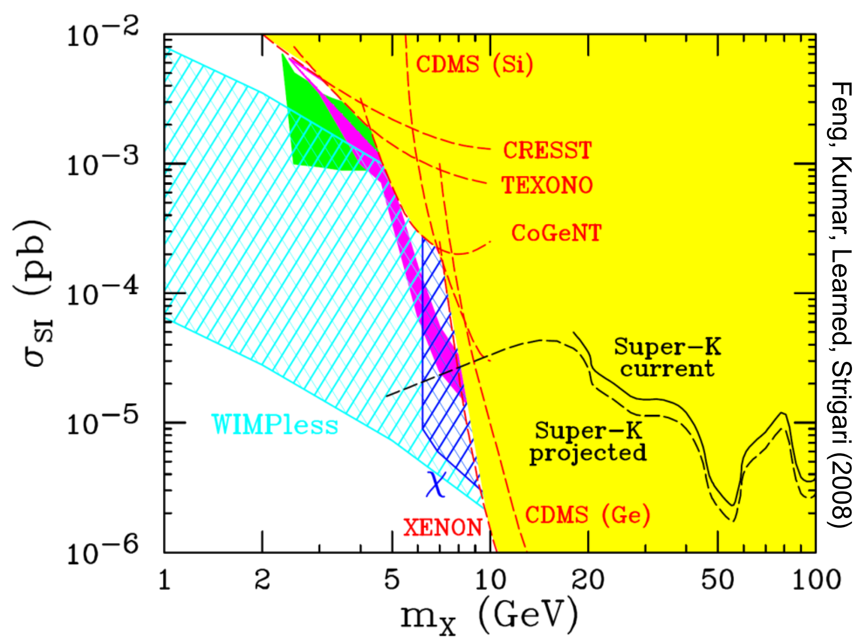


- Related ideas

Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)

Pospelov, Ritz (2008)





CONCLUSIONS

- WIMPs and related ideas have never been more motivated
  - WIMP miracle
  - Cosmological legacy of LEP → stable new particle
- The WIMP miracle motivates three classes of candidates
  - WIMP dark matter
  - superWIMP dark matter
  - WIMPless dark matter
- If anything discussed here is realized in nature, life will be very interesting in the coming years