DARK MATTER CANDIDATES AND SIGNALS

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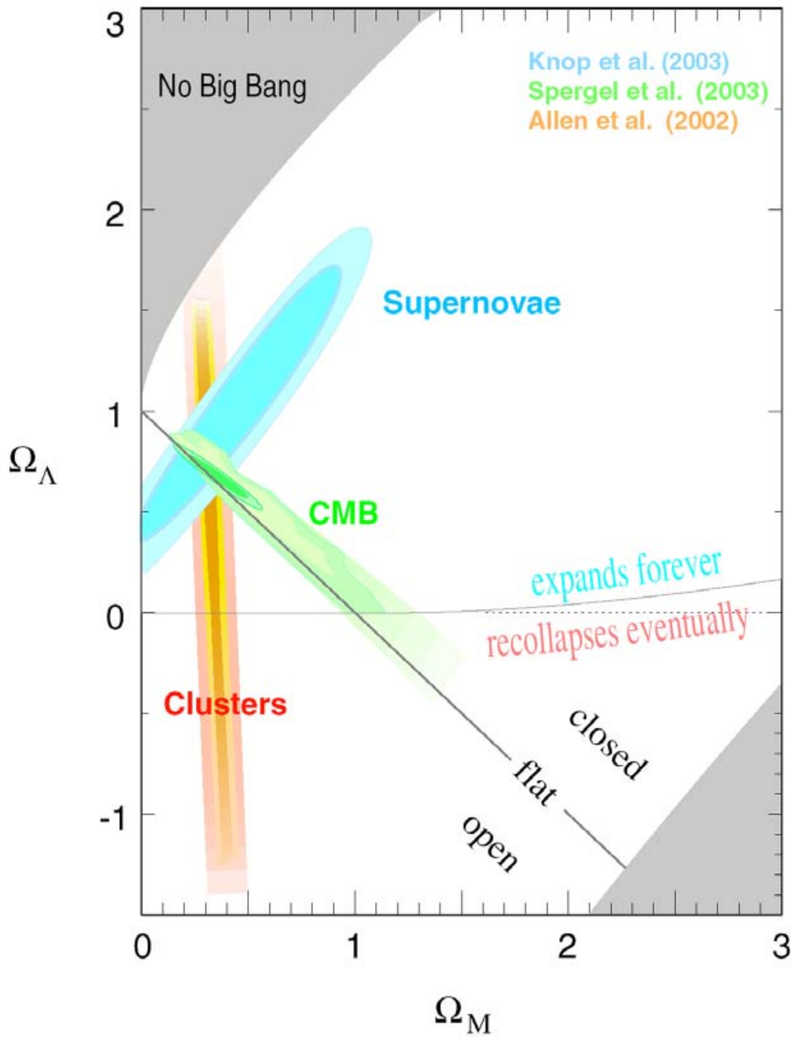
DARK MATTER



- We know how much there is

  $\Omega_{DM}h^2 = 0.1099 \pm 0.0062$

  WMAP (2008)

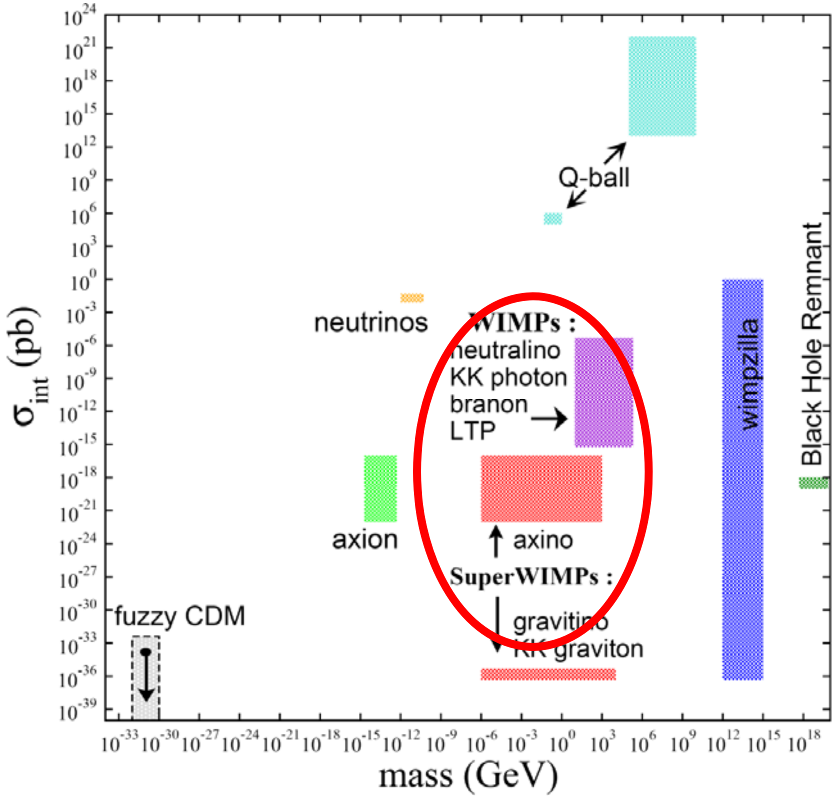
- But what is it?

- Intimately connected to central problems in particle physics and astrophysics
  - new particles and forces
  - structure formation

CANDIDATES

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

- Possible masses and interaction strengths span many, many orders of magnitude



HEPAP/AAAC DMSAG Subpanel (2007)

- Focus on candidates with mass around m_{weak} ~ 100 GeV

PARTICLE PHYSICS

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

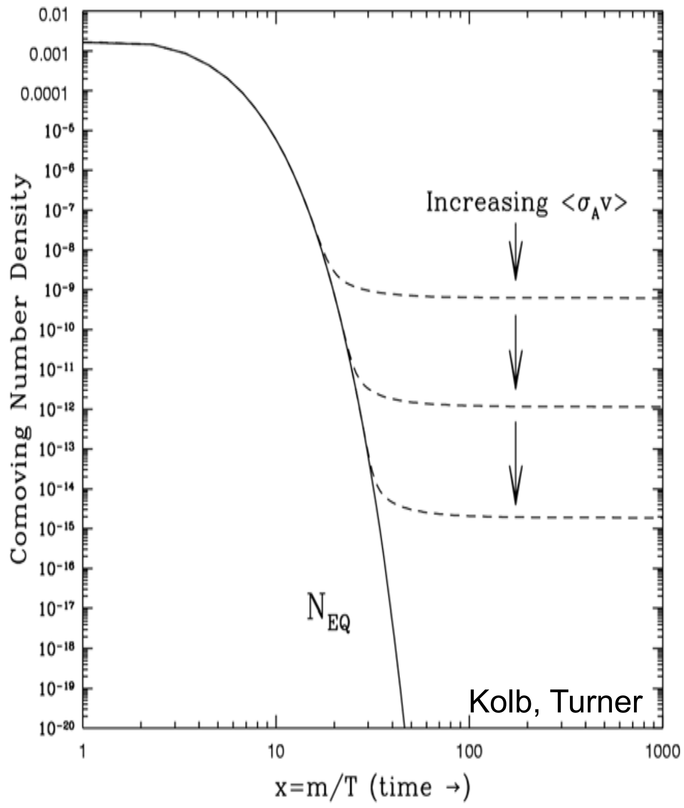
$$n \rightarrow p\, e^- \bar{\nu}$$

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



- Assume a new (heavy) particle X is initially in thermal equilibrium

- Its relic density is

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

- $m_X \sim 100$ 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 $\tilde{X}$

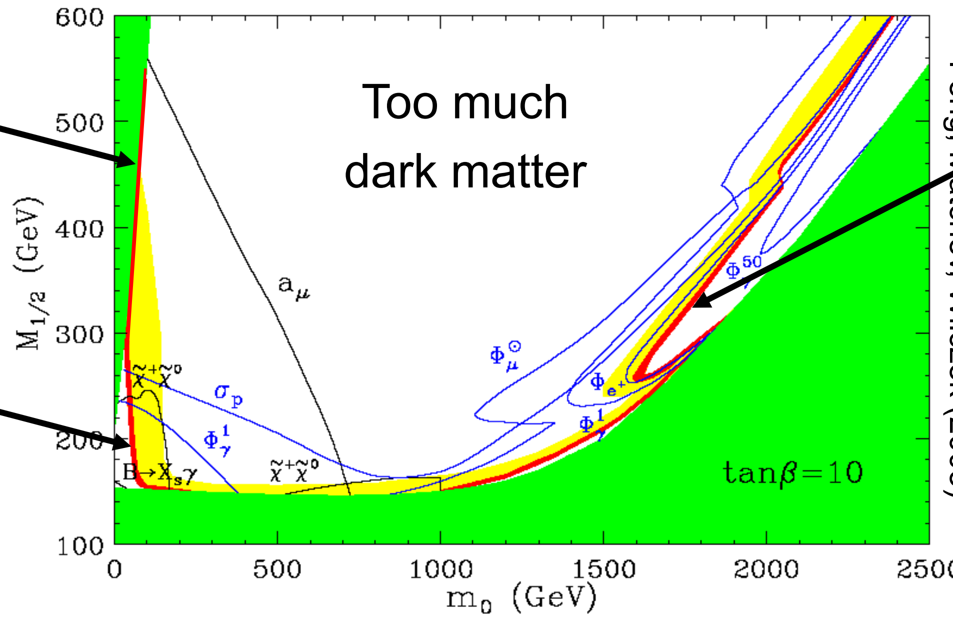
Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

χ is usually the 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: before 2003
Red: after 2003

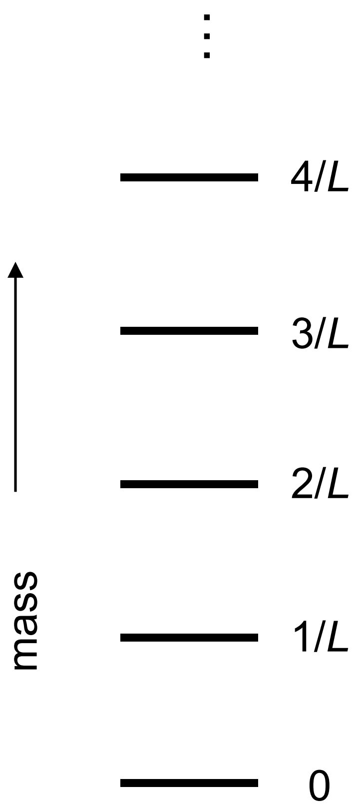
Cosmology excludes many possibilities, favors certain regions

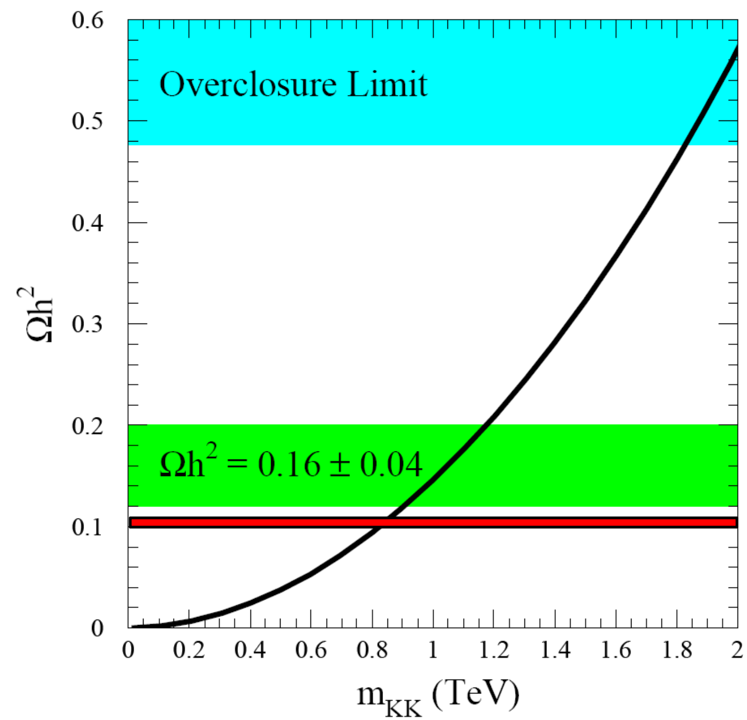
WIMPS FROM EXTRA DIMENSIONS

Extra dimensional theories predict Kaluza-Klein dark matter.

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

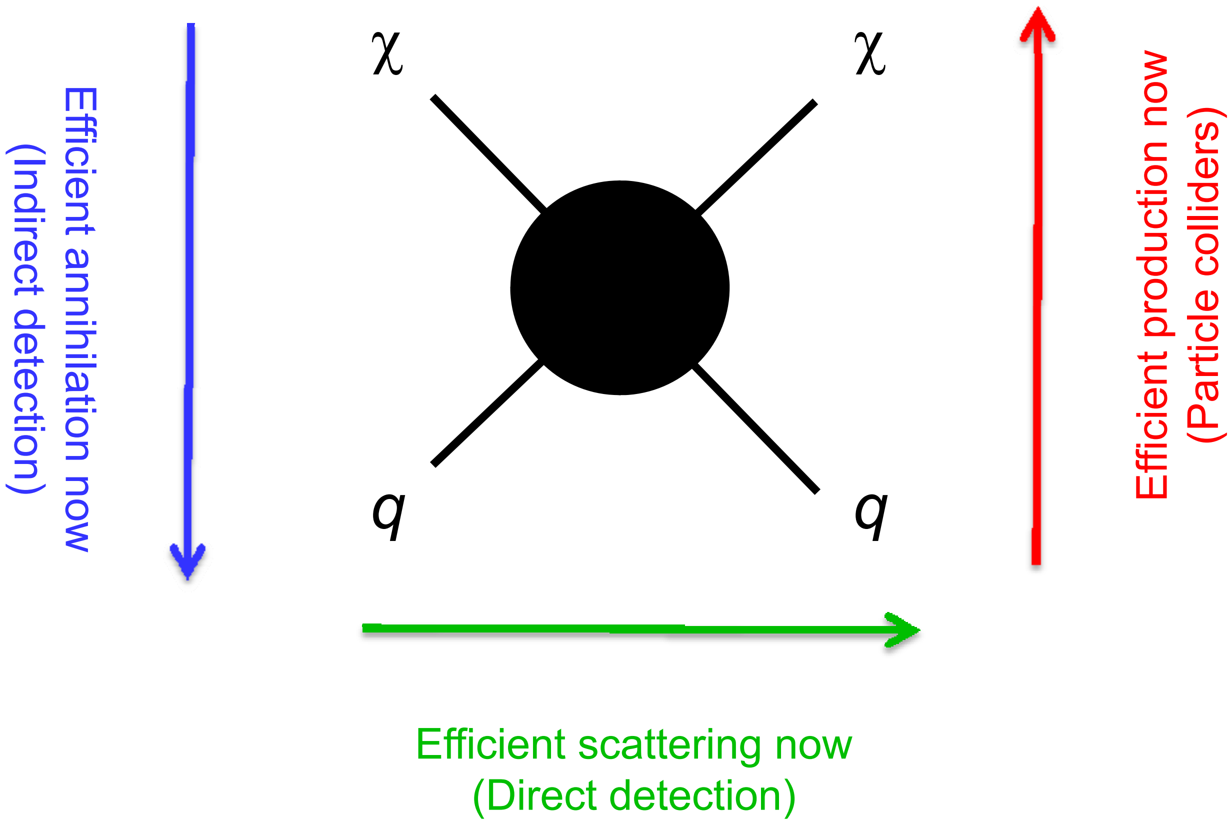
- A particle moving in an extra dimension of size *L* appears to us as a tower of particle states
- The lightest can be dark matter





WIMP DETECTION

Correct relic density → Efficient annihilation then

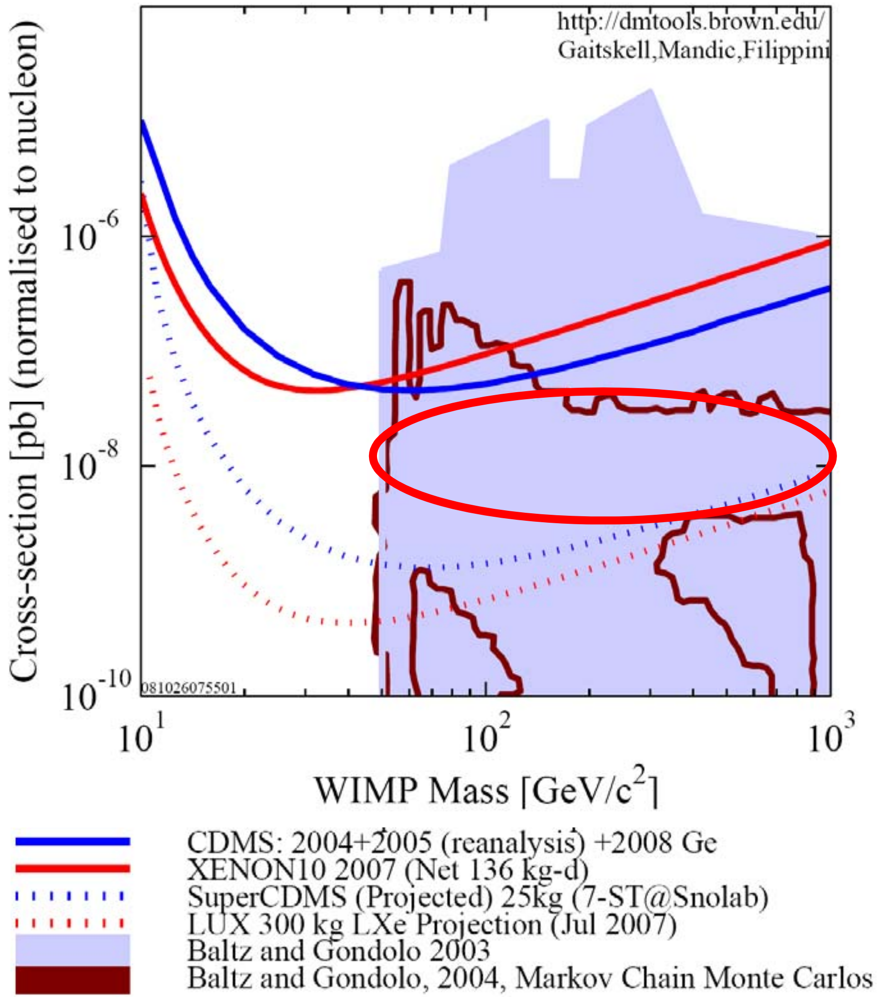


DIRECT DETECTION

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

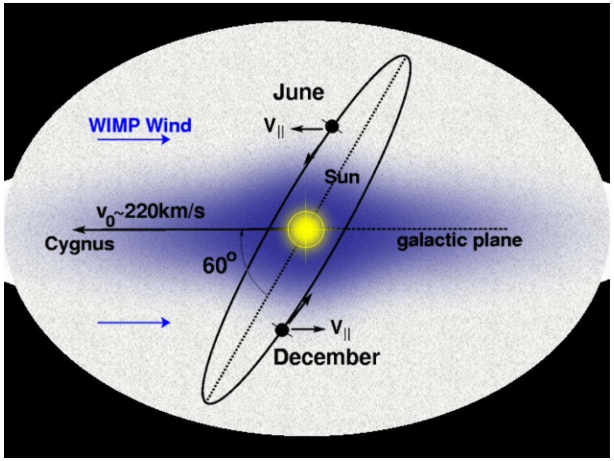
- Detected by nuclear recoil in underground detectors. Two approaches:

  1. Background-free detection
     - CDMS, XENON, …
     - Exclude regions of the (m,σ) plane
     - Already interesting, will probe the heart of SUSY parameter space in the next few years



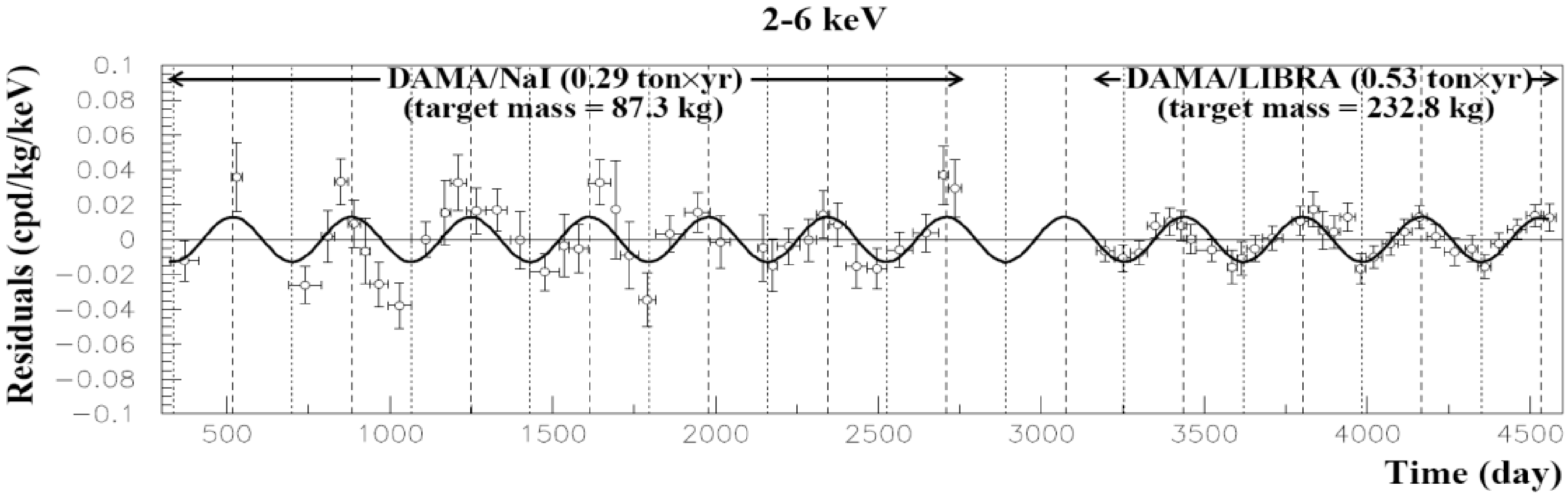
2. Annual modulation

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



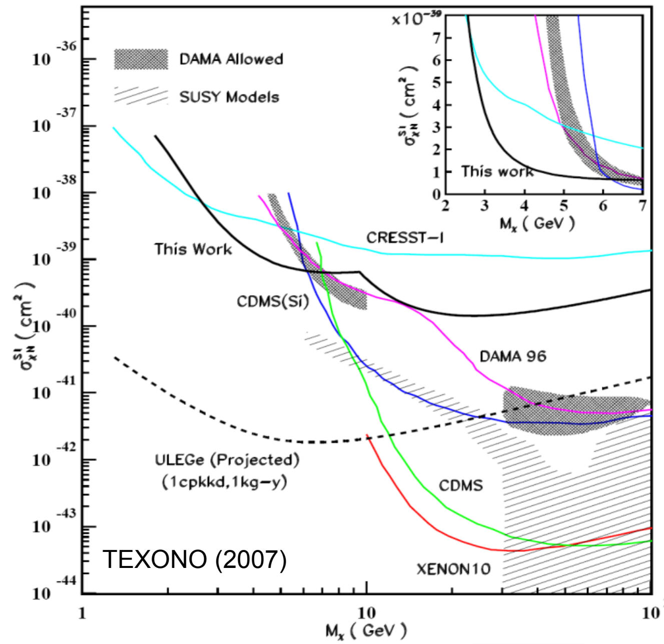
DAMA (2008)

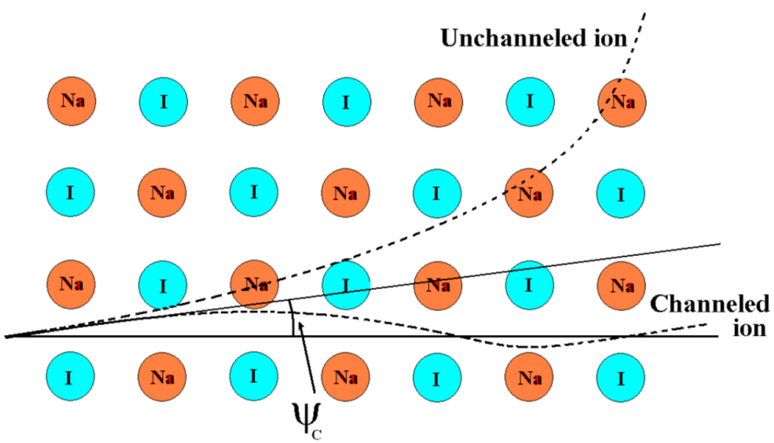
CHANNELING

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

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

- Channeling reduces threshold, shifts allowed region to lower masses. Consistency possible, but requires uncomfortably low WIMP masses (~ GeV)





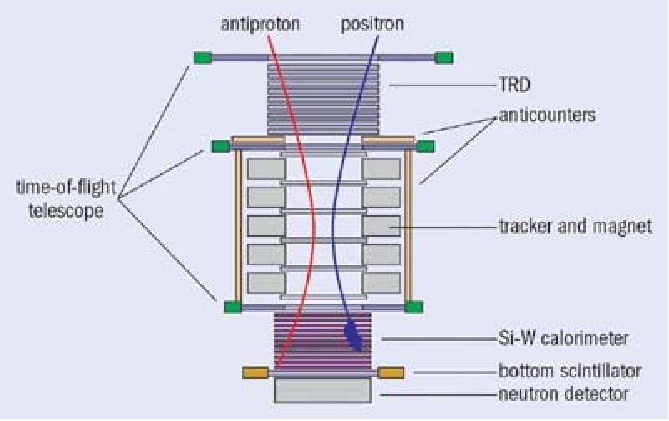
Gondolo, Gelmini (2005)
Drobyshevski (2007), DAMA (2007)

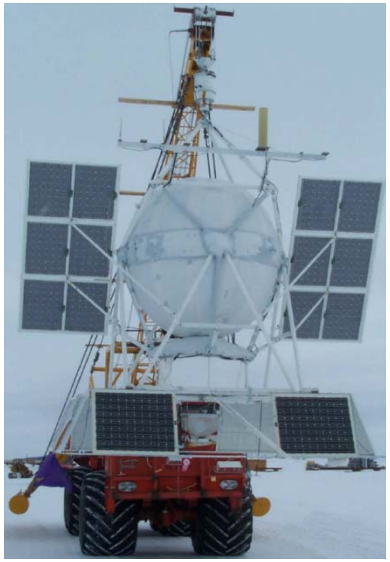
INDIRECT DETECTION

Dark Matter annihilates in ___the halo___ to
a place

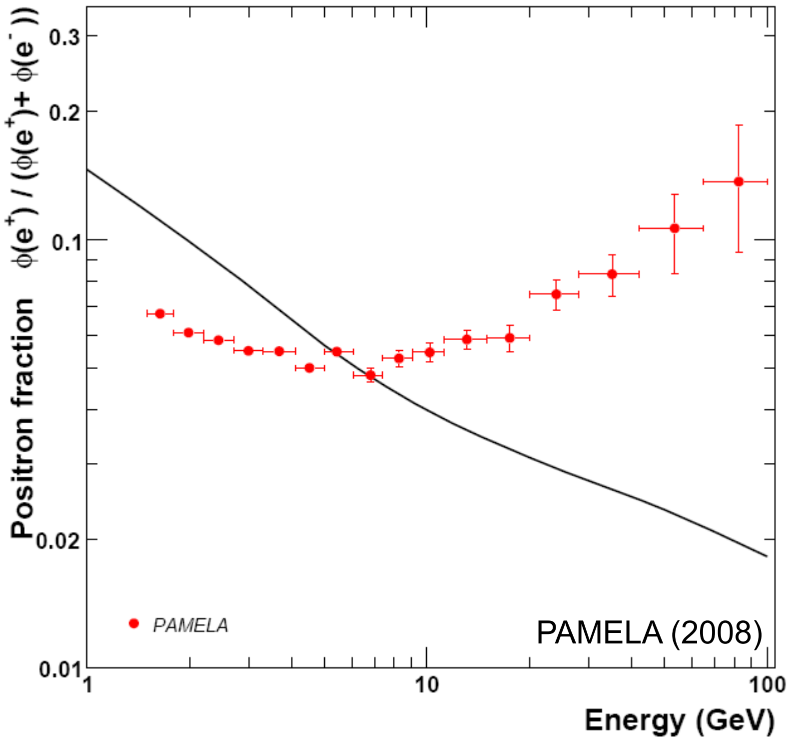
___positrons___ , which are detected by ___PAMELA/ATIC/…___.
some particles an experiment

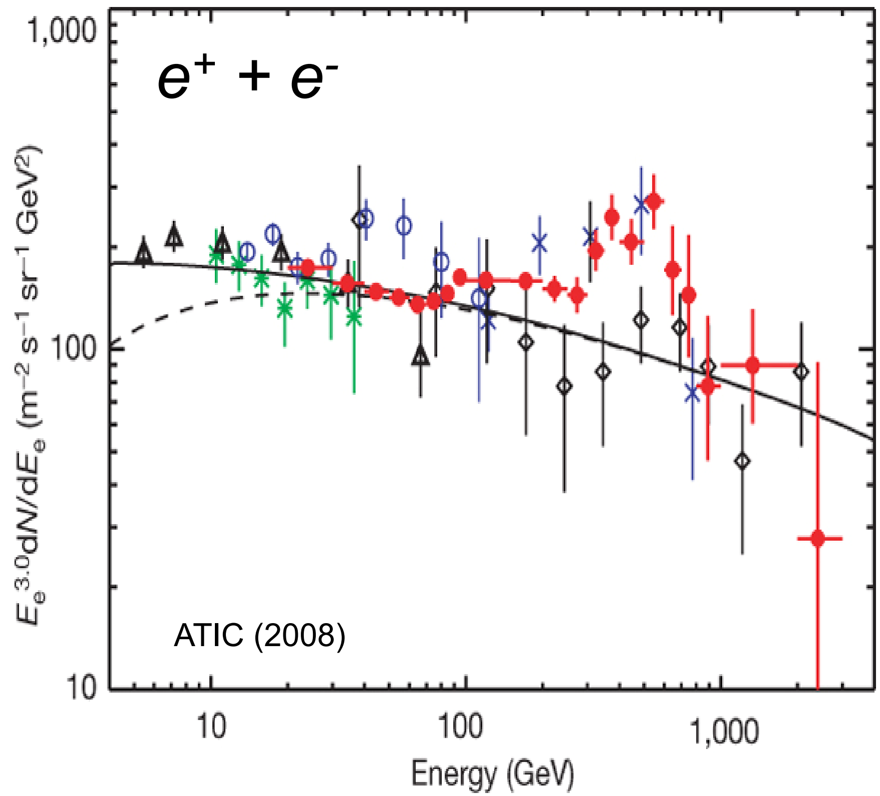

June 2006





PAMELA AND ATIC RESULTS

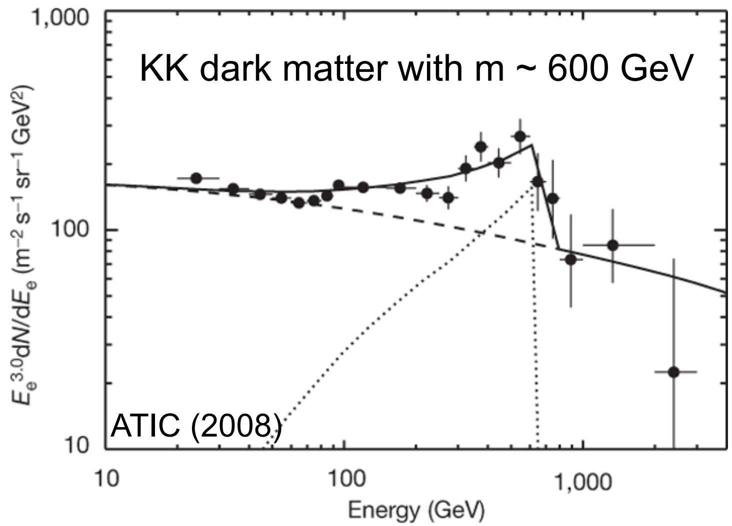




Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

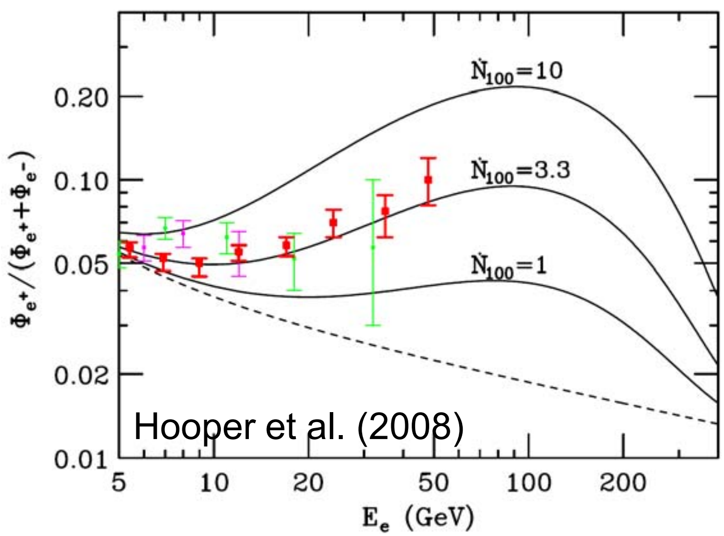
- Shape consistent with *some* dark matter candidates, but flux ~ 100 too big; requires enhancement from astrophysics or particle physics



- Pulsars can explain the excess

Hooper, Blasi, Serpico (2008)

Yuksel, Kistler, Stanev (2008)



- Critical tests from other experiments: Fermi, AMS…

HIDDEN DARK MATTER

- The anomalies (DAMA, PAMELA, ATIC, …) are not easily explained by canonical WIMPs

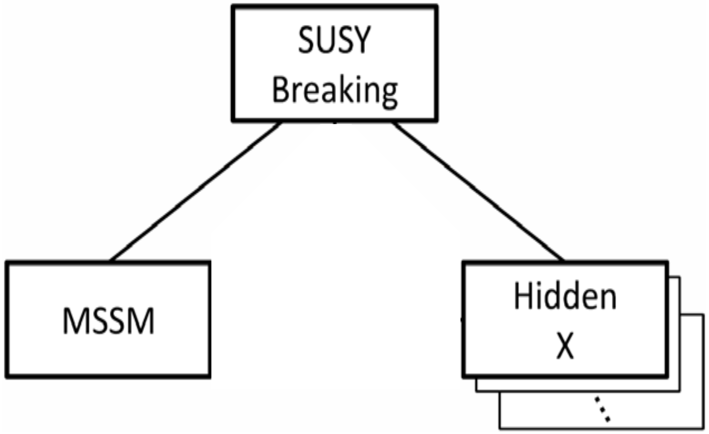
- Start over: What do we really know about dark matter?
  - All solid evidence is gravitational
  - Also solid evidence *against* strong and EM interactions

- A reasonable 1st guess: dark matter has no SM gauge interactions, i.e., it is *hidden*

- What one seemingly loses: the WIMP miracle and non-gravitaitonal signals

WIMP MIRACLE REVISITED

- Hidden sectors appear generically in SUSY. Each has its own
  - mass scales m_X
  - gauge couplings g_X



- But in some well-motivated models,

m_X/g_X^2 ~ constant

across all sectors, and so Ω_X is also constant

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

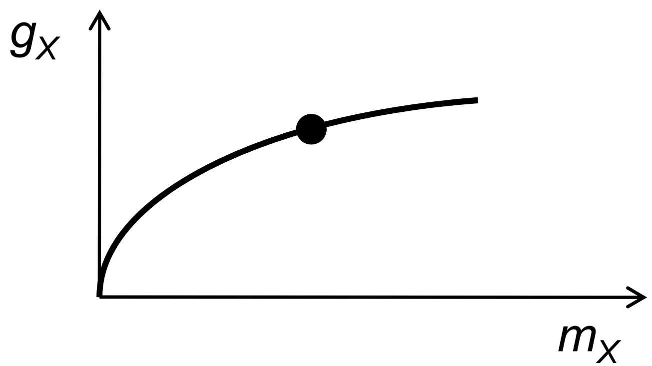
WIMPLESS DARK MATTER

Feng, Kumar (2008)

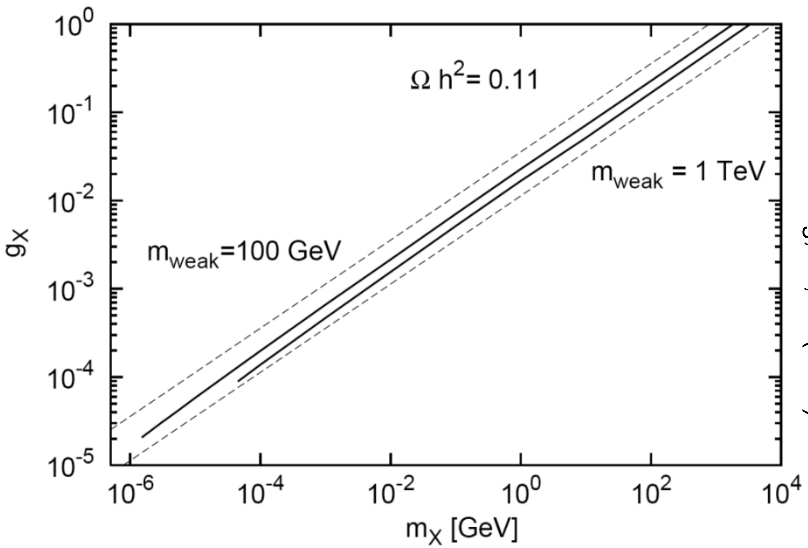
- The thermal relic density constrains only one combination of g_X and m_X

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

- These models map out the remaining degree of freedom



- This framework decouples the WIMP miracle from WIMPs, motivates candidates with a range of masses/couplings

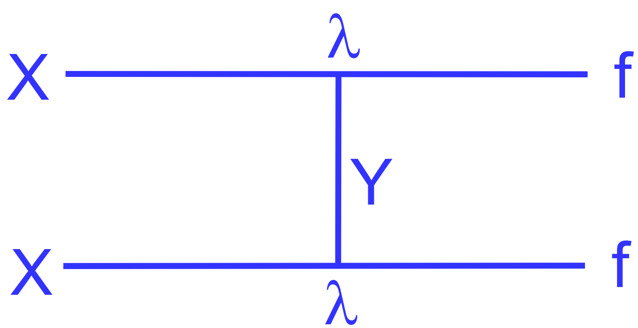


Feng, Tu, Yu (2008)

WIMPLESS SIGNALS

- WIMPless DM may have only gravitational effects

- But WIMPless matter may also interact with normal matter through non-gauge interactions

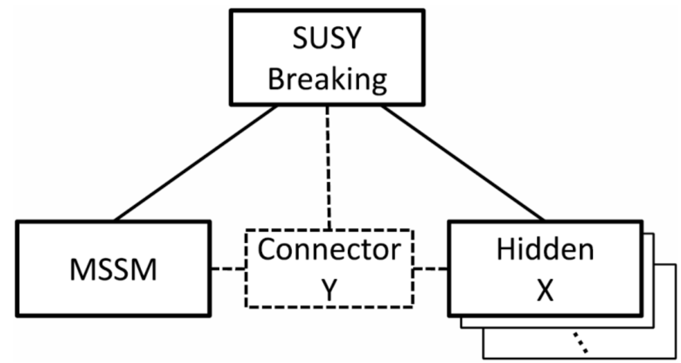


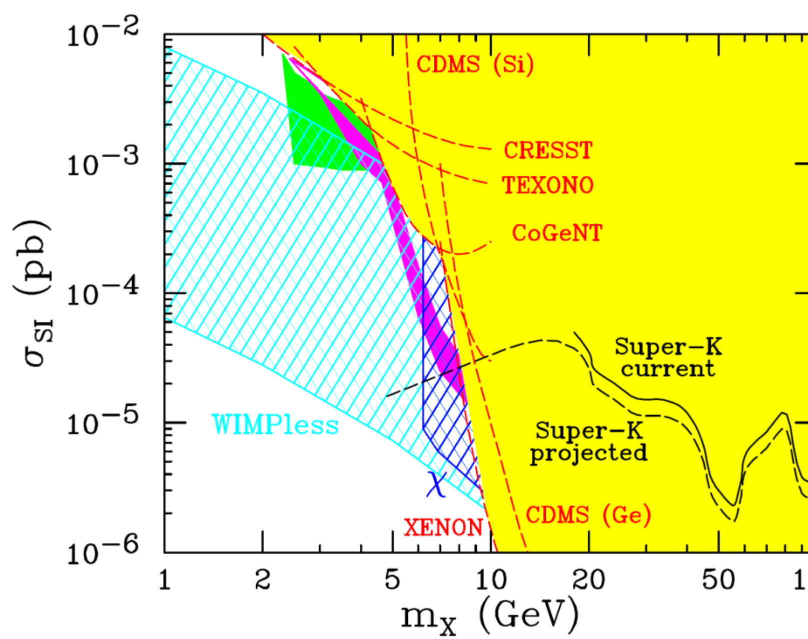
- Many new, related ideas

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

Pospelov, Ritz (2008)

…





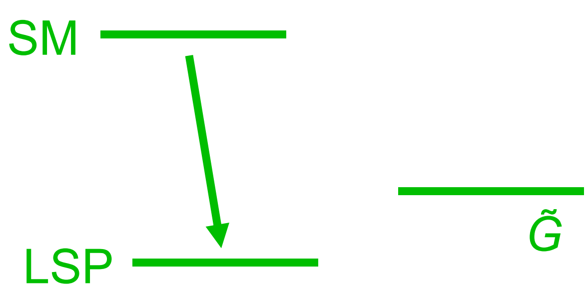
Feng, Kumar, Learned, Strigari (2008)

SUPERWIMPS

Many new particle theories include superweakly-interacting particles. E.g., Supersymmetry: Graviton → Gravitino $\tilde{G}$

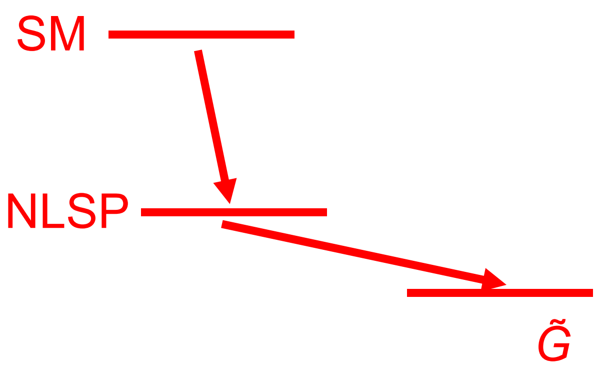
Mass ~ 100 GeV; only gravitational interactions

- $\tilde{G}$ not LSP



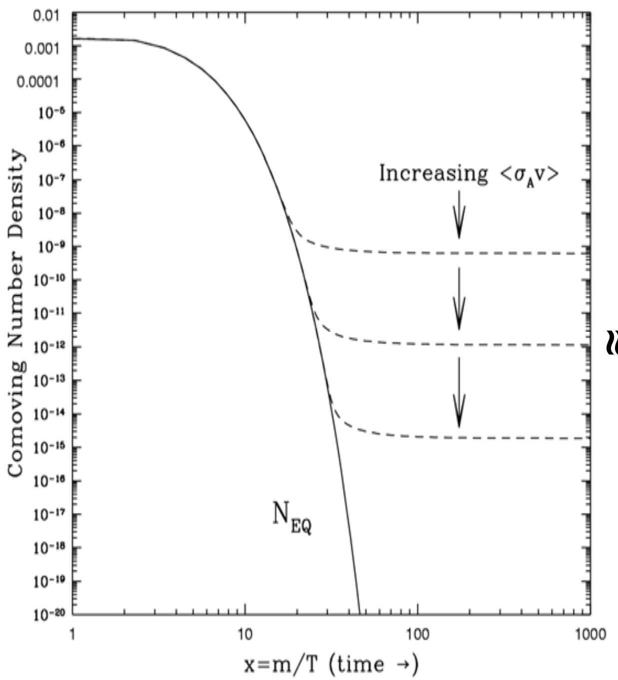
- Assumption of most of literature

- $\tilde{G}$ 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

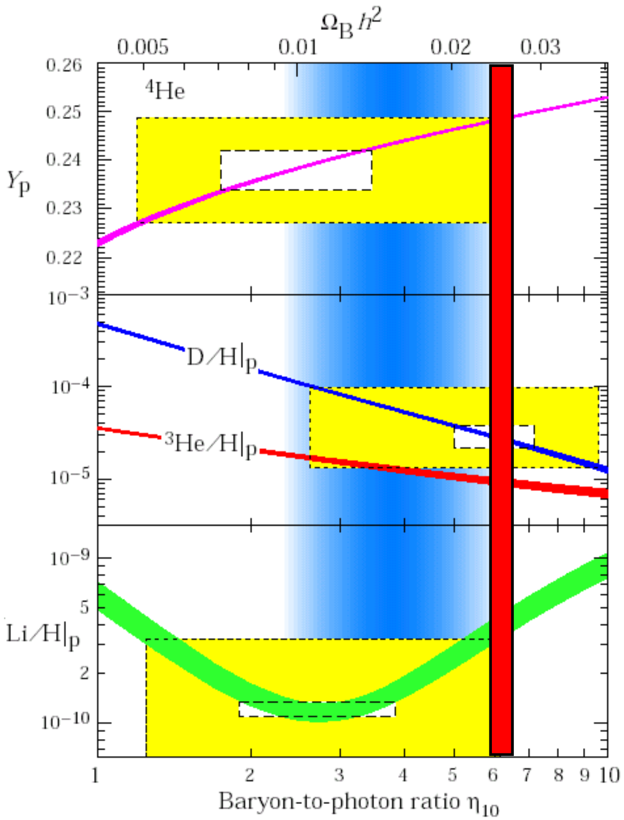
  M_{Pl}^2/M_W^3 ~ seconds to months

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); …

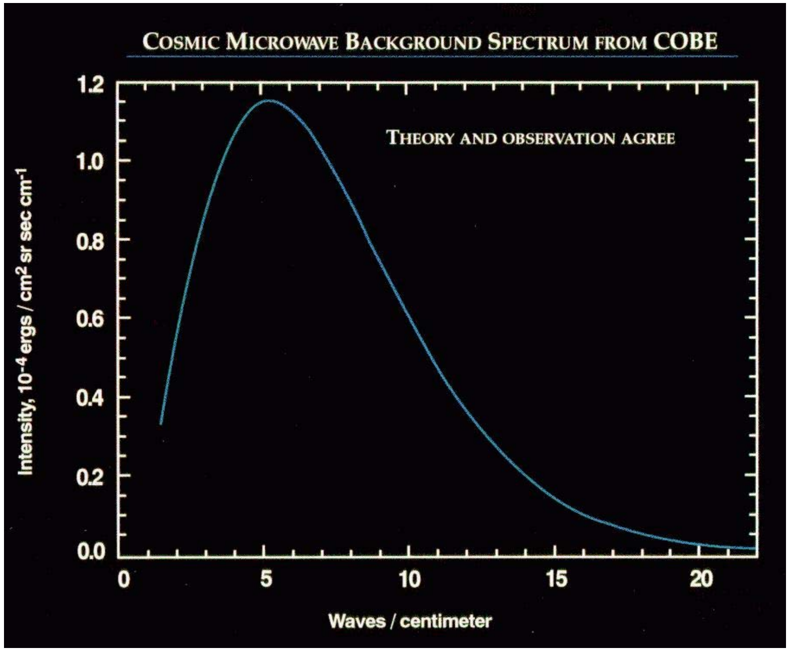
SUPERWIMP COSMOLOGY

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



Fields, Sarkar, PDG (2002)

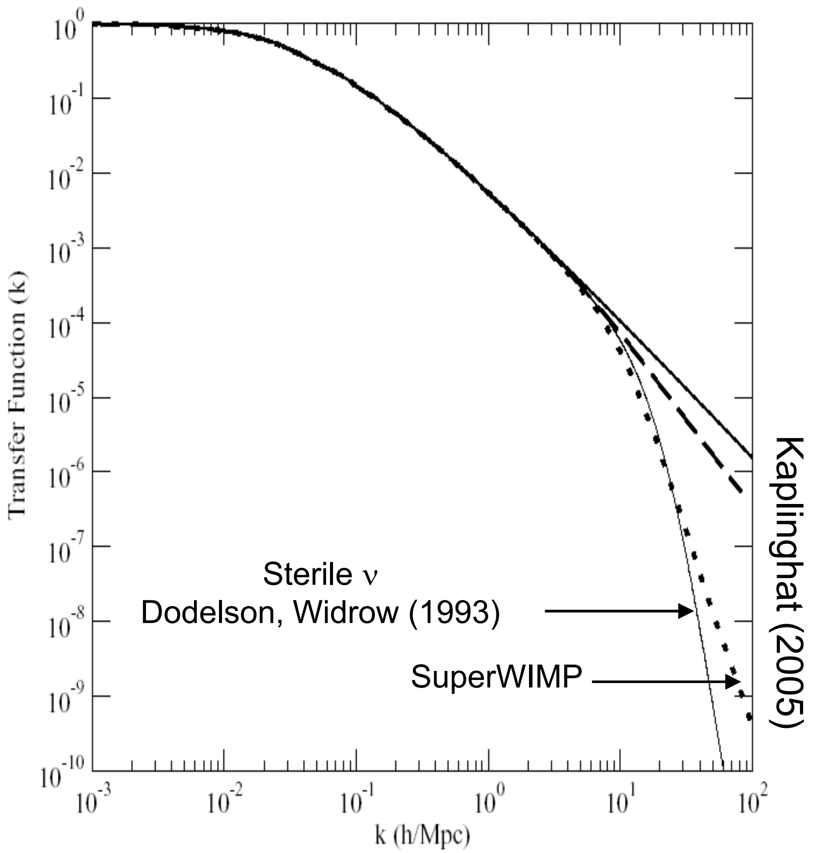
Late decays can modify CMB
black body spectrum
(μ distortions)



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)

CONCLUSIONS

- Recent anomalies (DAMA, PAMELA, ATIC, …)
- Rapid experimental progress
  - Direct detection
  - Indirect detection
  - Colliders (LHC)
- Proliferation of new classes of candidates
  - WIMP dark matter
  - WIMPless dark matter
  - superWIMP dark matter
- If anything discussed here is realized in nature, life will be very interesting in the coming years