Dark Matter Detection in Space

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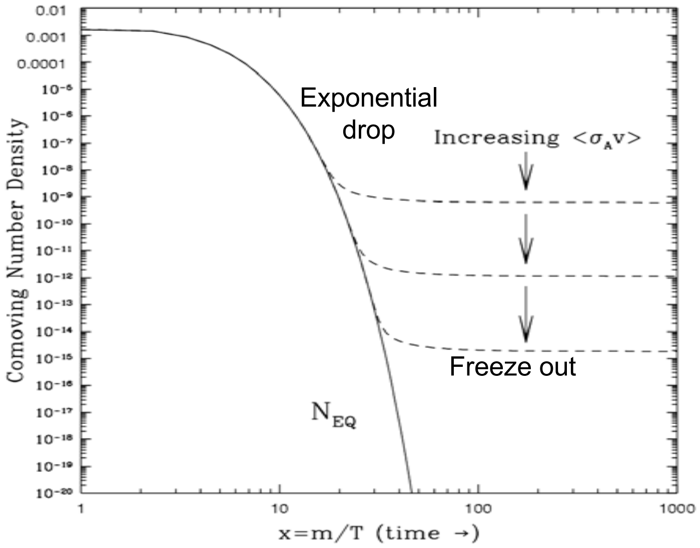
Dark Matter

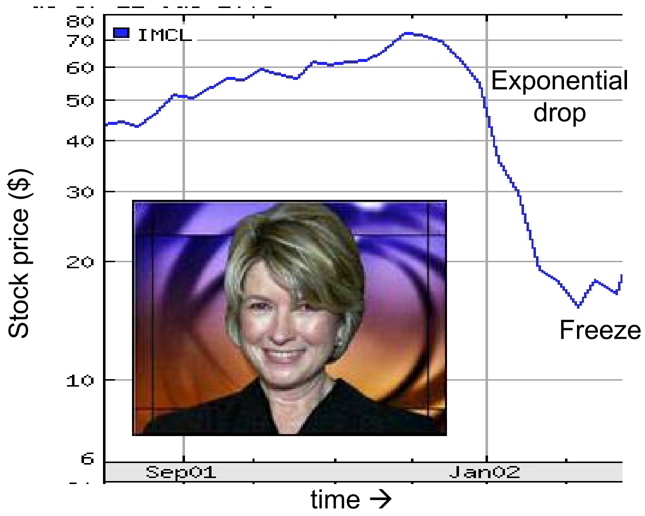
- We live in interesting times:
  - We know there is dark matter, and how much
  - We have no idea what it is

- This talk: Recent developments with a focus on implications for space-based experiments

- The Wild, Wild West of particle physics:
  - Neutralinos, axions, Kaluza-Klein DM, Q balls, wimpzillas, superWIMPs, self-interacting DM, warm and fuzzy DM,…

A Selection Rule: DM and the Weak Scale





- Universe cools, leaves a residue of dark matter with $\Omega_{DM} \sim 0.1 \, (\sigma_{Weak}/\sigma)$ – remarkable!

- 13 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidence? Maybe, but worth investigating!

Neutralino Dark Matter

Goldberg (1983)
Ellis et al. (1983)

- Predicted by supersymmetry, motivated by particle physics considerations
- One of *many* new supersymmetric particles

SUSY Particles

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$

Neutralino Properties

Mass: ~ 100 GeV

Interactions: weak (neutrino-like)

The “typical” WIMP (but note: neutralinos are Majorana fermions – they are their own anti-particle)

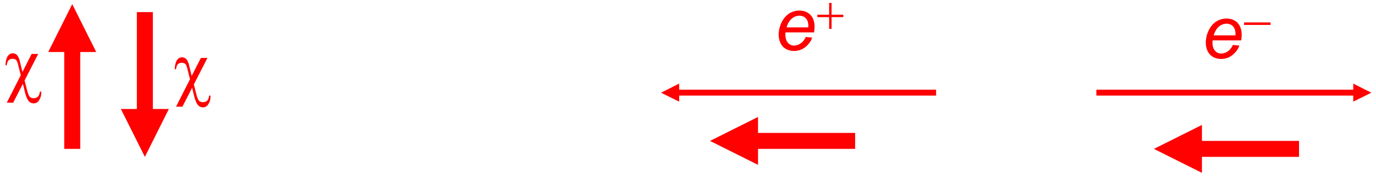
- Direct detection: see Matchev’s talk

- Indirect detection: $\chi\chi$ annihilation
  - in the halo to e^+’s: AMS-02, PAMELA…
  - in the center of the galaxy to γ’s: GLAST, AMS/γ, telescopes,…
  - in the center of the Sun to ν’s: AMANDA, NESTOR, ANTARES,…

Positrons

Turner, Wilczek (1990)
Kamionkowski, Turner (1991)

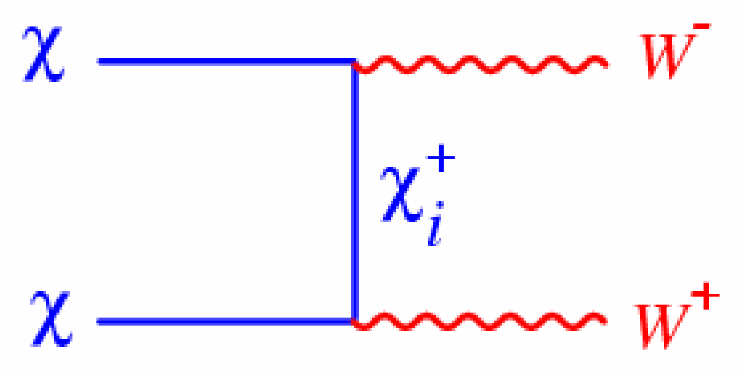
- The signal: hard positrons
- Best hope: $\chi\chi \rightarrow e^+e^-$
- Problem: χ are Majorana-like, so Pauli → $J_{init} = 0$



This process is highly suppressed

- Next best hope: $\chi\chi \rightarrow W^+W^-$, $ZZ \rightarrow e^+$…

- Problem: conventional wisdom → in simple models, $\chi \approx$ Bino, does not couple to SU(2) gauge bosons



We are left with soft e^+: $\chi\chi \rightarrow \bar{b}b \rightarrow \bar{c}e^+\nu$…

Photons

Urban et al. (1992)
Berezinsky, Gurevich, Zybin (1992)

- $\chi \approx$ Bino also suppresses the photon signal
- Best hope: $\chi\chi \rightarrow \gamma\gamma$ – highly suppressed
- Next best hope: $\chi\chi \rightarrow W^+W^-$, $ZZ \rightarrow \gamma$... – also suppressed

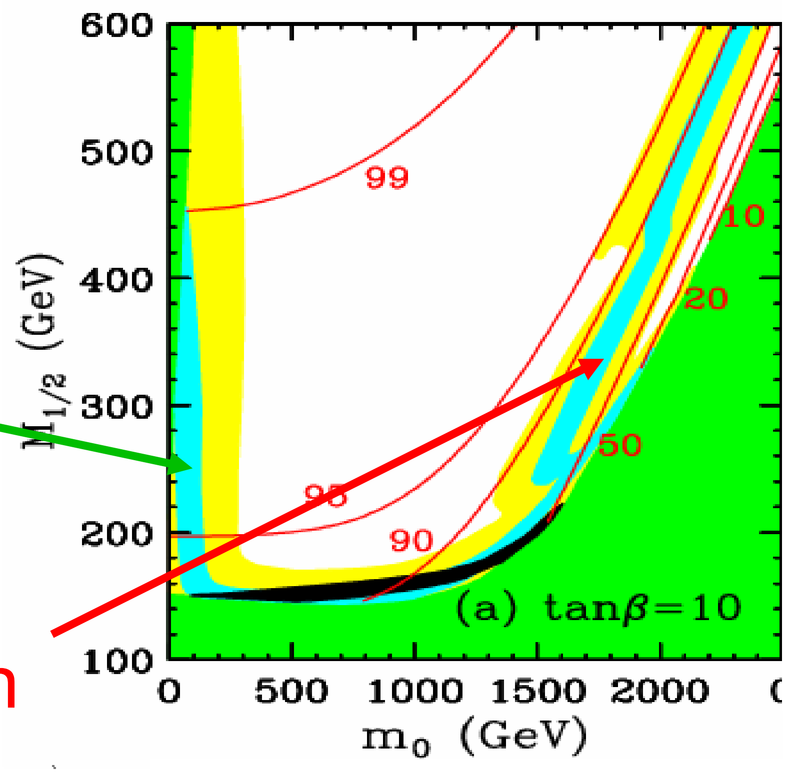
[Both e^+ and γ signals are sensitive to cuspiness, clumpiness in the halo.]

Example: Minimal Supergravity

- A simple model incorporating unification
  - $\chi \approx$ Bino in the $0.1 < \Omega_{DM} < 0.3$ region
- But not always!

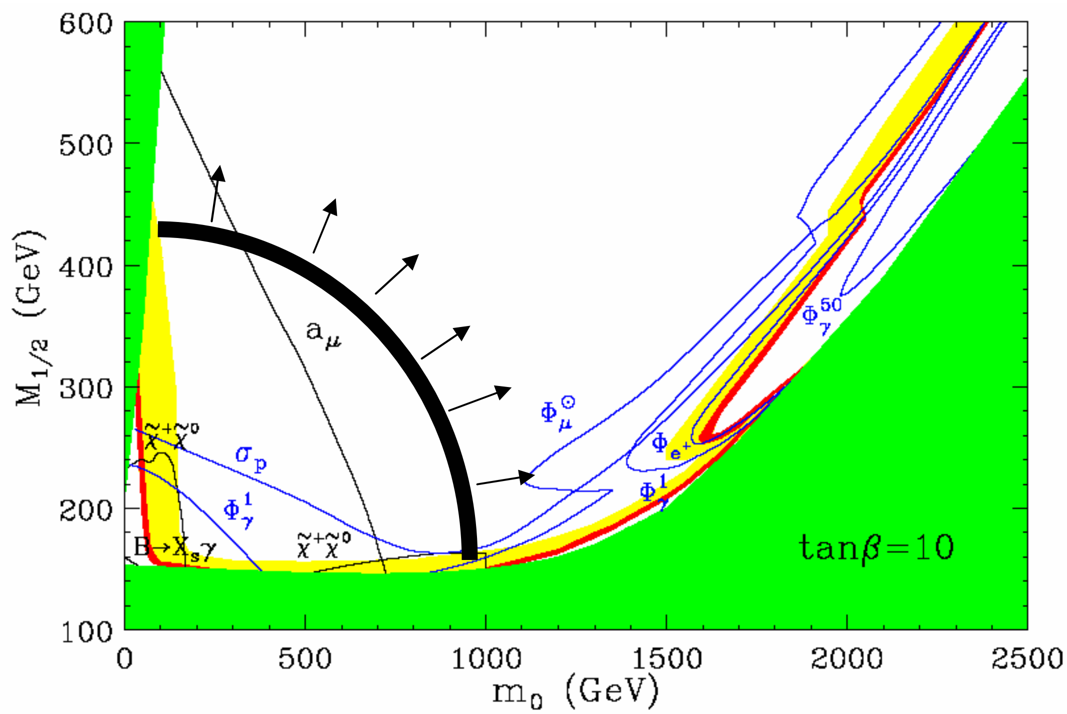
χ = Bino-Higgsino mixture in "focus point region"

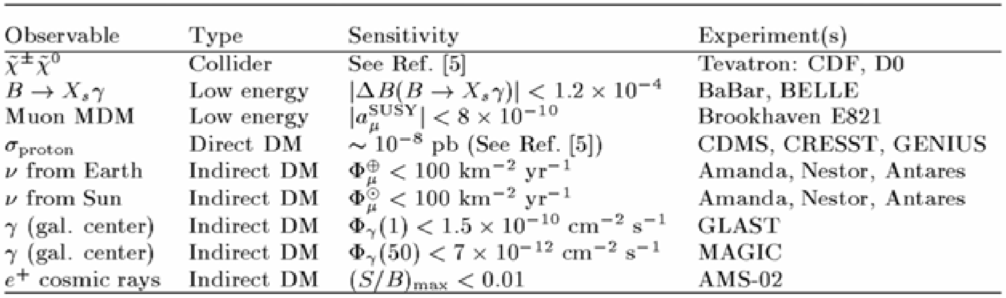
Relic density regions and Bino-ness (%)



Feng, Matchev, Wilczek (2000)

SUSY WIMP Detection





Observable	Type	Sensitivity	Experiment(s)
$\tilde{\chi}^\pm\tilde{\chi}^0$	Collider	See Ref. [5]	Tevatron: CDF, D0
$B \to X_s\gamma$	Low energy	$\lvert\Delta B(B \to X_s\gamma)\rvert < 1.2 \times 10^{-4}$	BaBar, BELLE
Muon MDM	Low energy	$\lvert a_\mu^{\rm SUSY}\rvert < 8 \times 10^{-10}$	Brookhaven E821
$\sigma_{\rm proton}$	Direct DM	$\sim 10^{-8}$ pb (See Ref. [5])	CDMS, CRESST, GENIUS
ν from Earth	Indirect DM	$\Phi_\mu^\oplus < 100\ {\rm km}^{-2}\ {\rm yr}^{-1}$	Amanda, Nestor, Antares
ν from Sun	Indirect DM	$\Phi_\mu^\odot < 100\ {\rm km}^{-2}\ {\rm yr}^{-1}$	Amanda, Nestor, Antares
γ (gal. center)	Indirect DM	$\Phi_\gamma(1) < 1.5 \times 10^{-10}\ {\rm cm}^{-2}\ {\rm s}^{-1}$	GLAST
γ (gal. center)	Indirect DM	$\Phi_\gamma(50) < 7 \times 10^{-12}\ {\rm cm}^{-2}\ {\rm s}^{-1}$	MAGIC
e^+ cosmic rays	Indirect DM	$(S/B)_{\rm max} < 0.01$	AMS-02

Synergy:

Particle probes

Dark matter detection

Recent data:

- $m_h > 115$ GeV
- $B(b \to s\gamma)$ ~ SM
- $(g-2)_\mu$ ~ SM (maybe)
- Ω_{DM} low (red region)

Conclusion: indirect detection favored

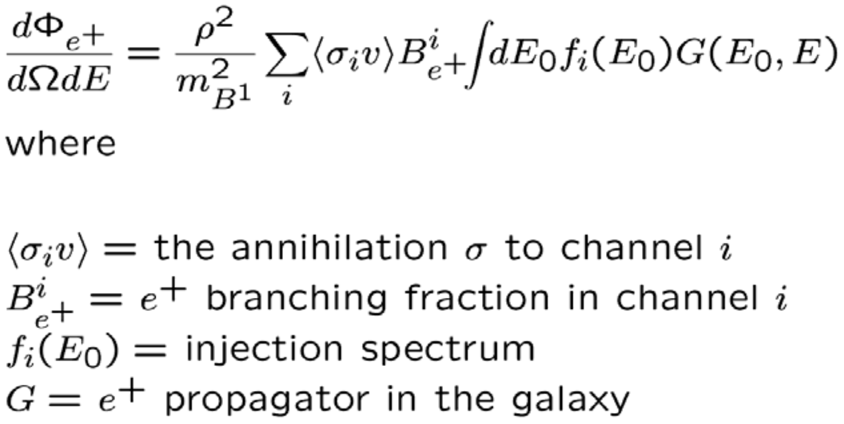
(valid beyond mSUGRA)

Extra Dimensional Dark Matter

- Extra dimensions generically predict Kaluza-Klein particles with mass *n*/*R*. What are they good for?
- If $R \sim \text{TeV}^{-1}$, the lightest KK particle may be a WIMP
- Consider B^1, the first partner of the hypercharge gauge boson

Positrons

- Recall in SUSY:
  $\chi\chi \rightarrow e^+e^-$ suppressed by angular momentum



$$\frac{d\Phi_{e+}}{d\Omega dE} = \frac{\rho^2}{m_{B^1}^2}\sum_i \langle\sigma_i v\rangle B^i_{e+}\int dE_0 f_i(E_0) G(E_0,E)$$

where

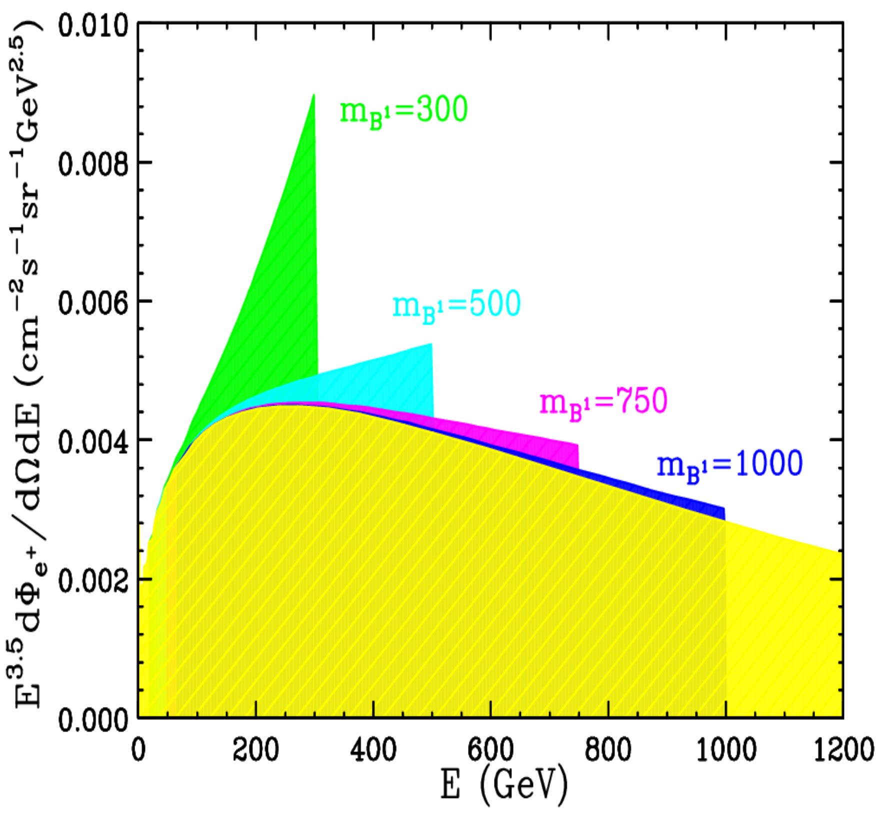
$\langle\sigma_i v\rangle$ = the annihilation σ to channel i
B^i_{e+} = e^+ branching fraction in channel i
$f_i(E_0)$ = injection spectrum
G = e^+ propagator in the galaxy

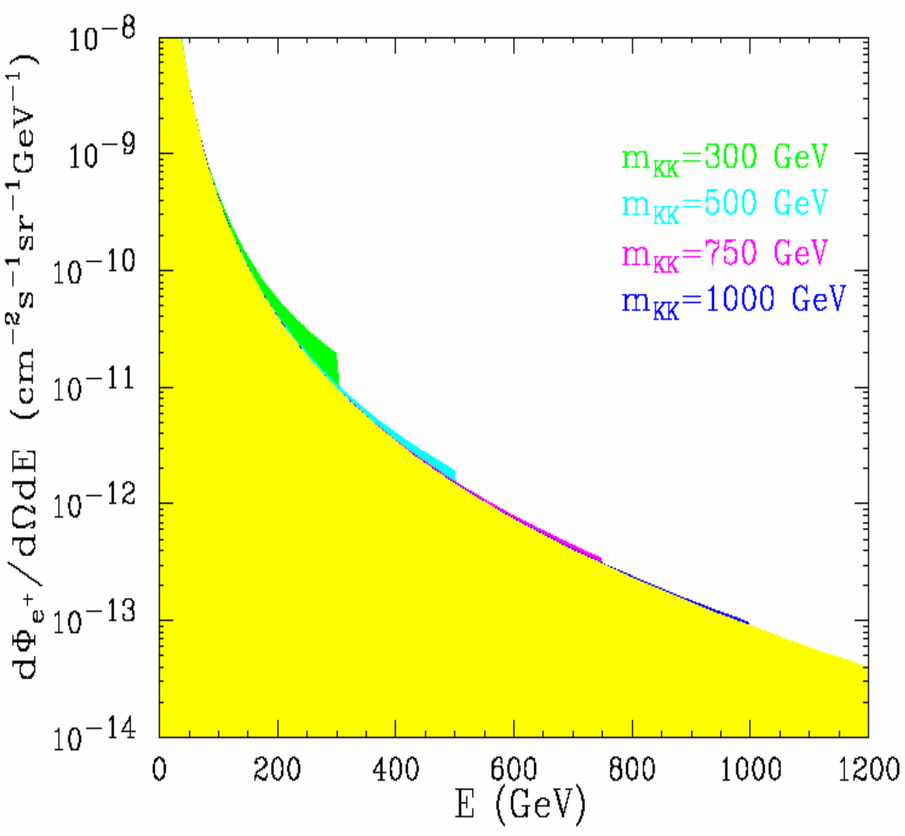
Moskalenko, Strong (1999)

- But B^1 has spin 1
- $B^1B^1 \rightarrow e^+e^-$ is large, ~20% of all annihilations
- Here $f_i(E_0) \sim \delta(E_0 - m_{B^1})$. Is the peak is erased by propagation?

Positrons from KK Dark Matter

Cheng, Feng, Matchev (2002)





Precision data → dark matter discovery *and* mass measurement

SuperWIMP Dark Matter

- Both SUSY and extra dimensions predict partner particles for all known particles. What about the gravitino $\tilde{G}$ or the 1st graviton excitation G^1?

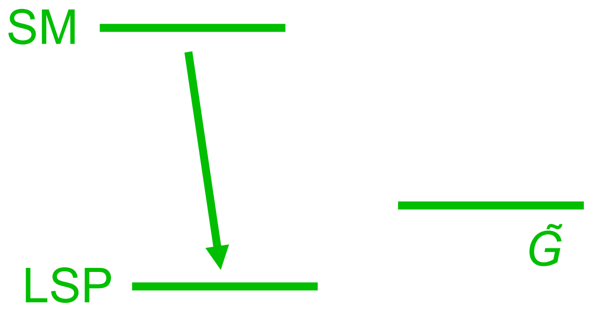
- $\tilde{G}$ and G^1 interact only gravitationally, but that's sufficient for dark matter

- Consider $\tilde{G}$; the G^1 case is identical up to $O(1)$ factors

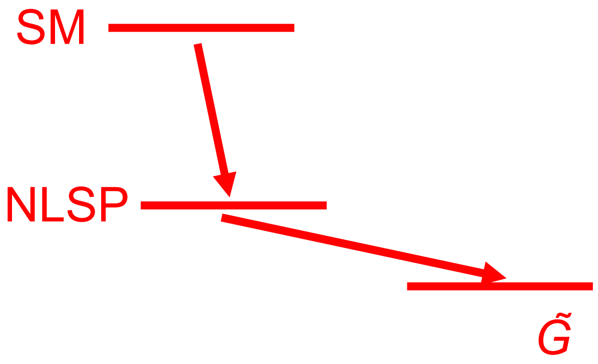
Gravitinos from Late Decay

- Assume gravitinos are diluted by inflation, and the universe reheats to low temperature.

- $\tilde{G}$ not LSP



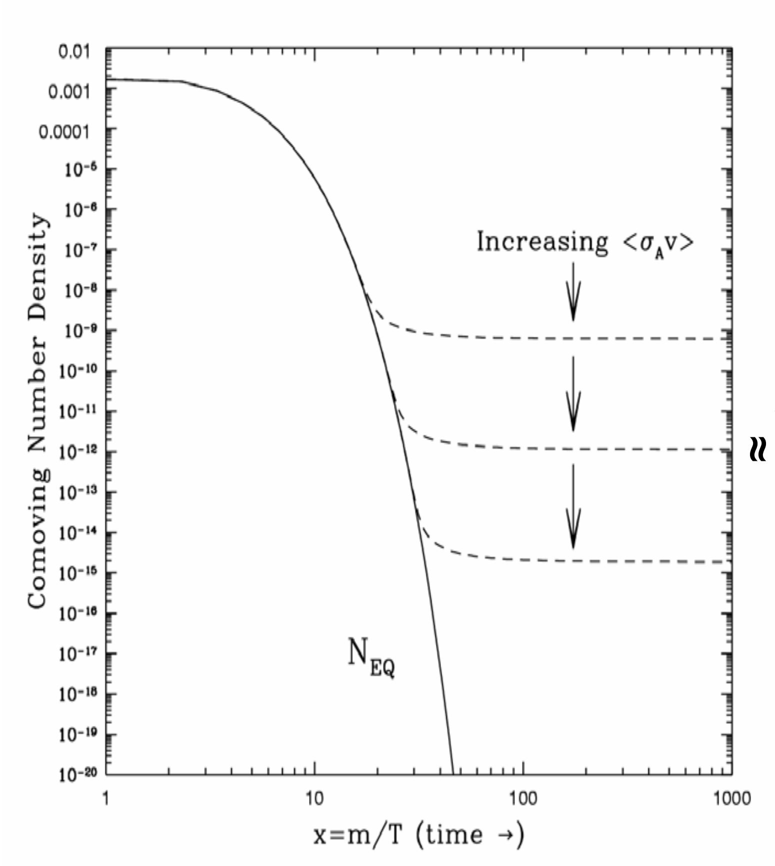
- $\tilde{G}$ LSP



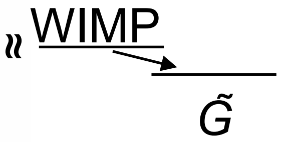
- No impact – implicit *assumption* of most of literature

- Qualitatively new cosmology

Gravitinos from Late Decay



- Early universe behaves as usual, WIMP freezes out with desired thermal relic density



M_{Pl}^2/M_W^3 ~ year

- A year passes…then all WIMPs decay to gravitinos

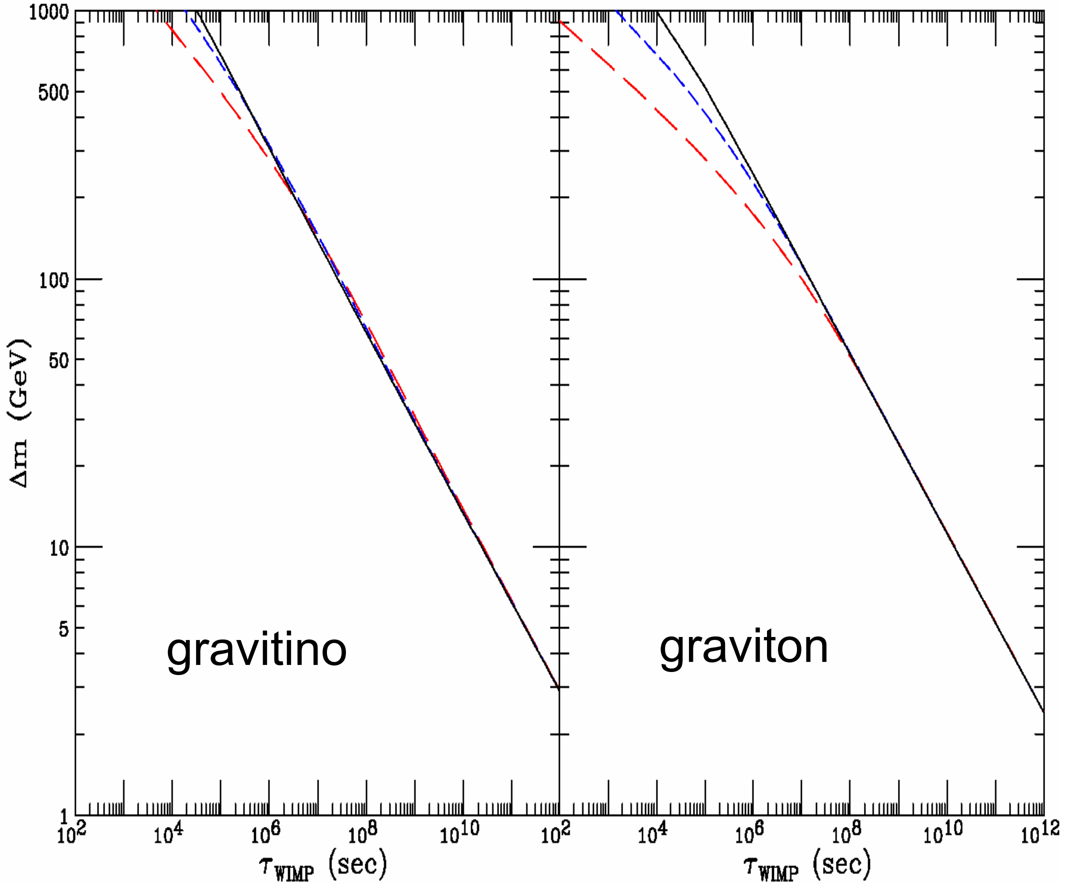
Gravitinos naturally inherit WIMP density,
but are superweakly-interacting – “superWIMPs”

SuperWIMP Detection

- SuperWIMPs evade all conventional dark matter searches
- The only possible signal: WIMP → superWIMP decays in the early universe
- Decay time is sensitive to

  $\Delta m = m_{\mathrm{WIMP}} - m_{\mathrm{sWIMP}}$

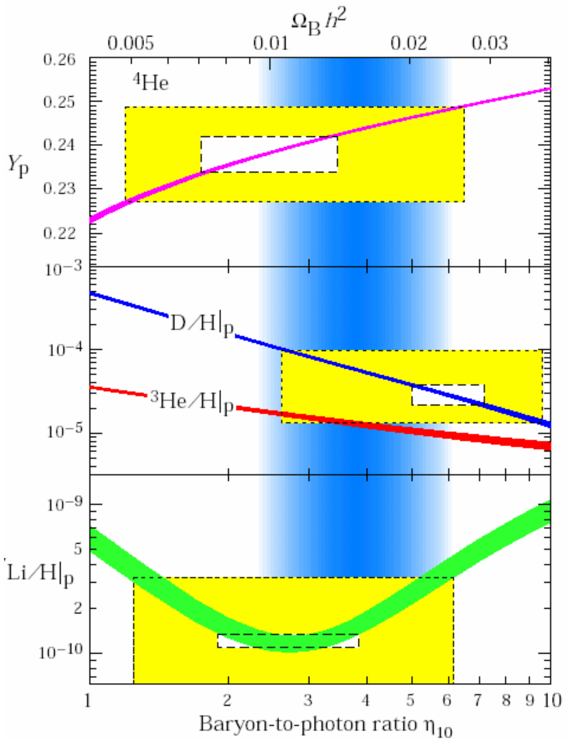
m_{sWIMP} = 0.1, 0.3, 1 TeV (from below)



Feng, Rajaraman, Takayama (2003)

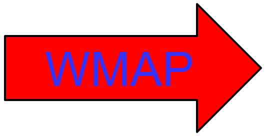
Gravitino Cosmology: Detection

- For $\Delta m \sim O(100\text{ GeV})$, WIMP → superWIMP decays occur before CMB and after BBN. This can be tested.



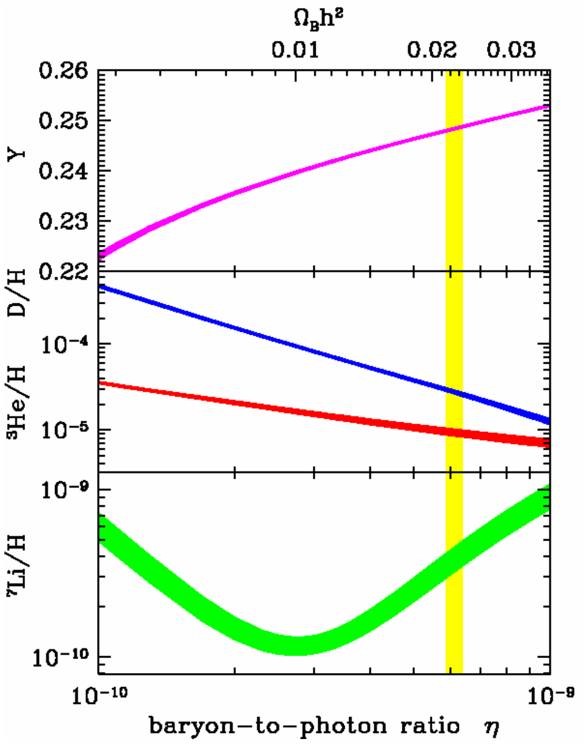
Fields, Sarkar, PDG (2002)

Baryometry



$\eta_D = \eta_{CMB}$

[^{7}Li low]



Cyburt, Fields, Olive (2003)

$\tilde{G}$ Signals: BBN

- Signals are determined by WIMP: e.g., $\tilde{B} \rightarrow \tilde{G}\,\gamma$,…

- m_{WIMP} , $m_{\tilde{G}}$ determine

  Decay time: τ_X

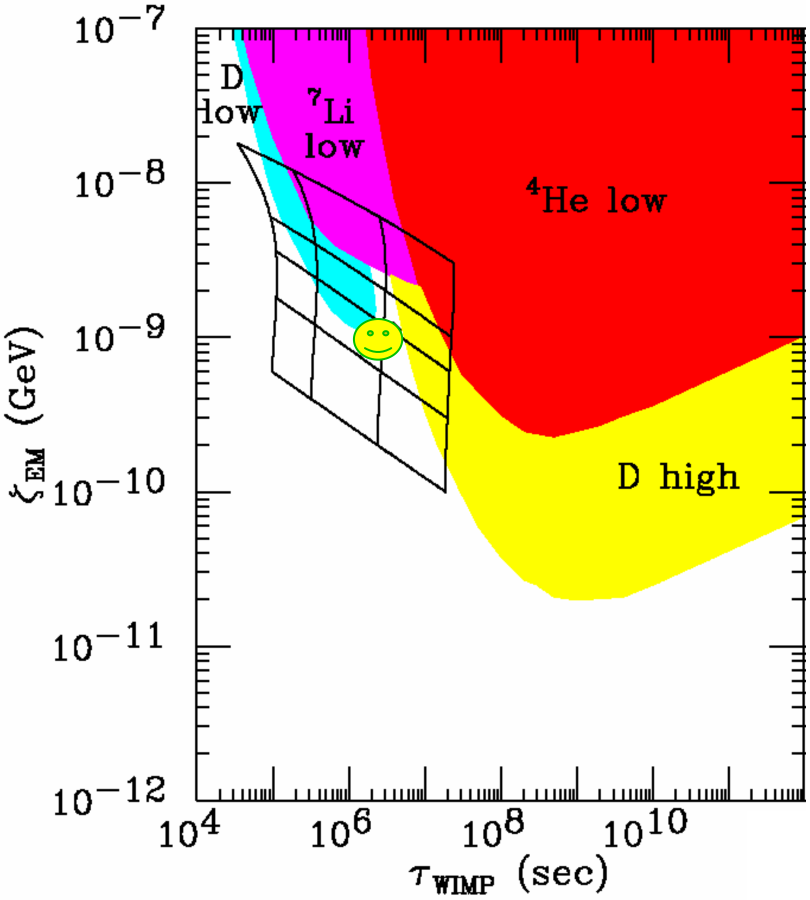
  Energy release: $\zeta_{EM} = \Delta m\, n_{\tilde{G}} / n_\gamma$

  $(\Omega_{\tilde{G}} = \Omega_{DM})$

- Large energy release destroys successes of BBN

  Cyburt, Ellis, Fields, Olive (2002)

- But $\tilde{G}$ DM is allowed and low ^{7}Li may even be superWIMP signal



Feng, Rajaraman, Takayama (2003)

$\tilde{G}$ Signals: CMB

- Late decays may also distort the CMB spectrum

- For 10^5 s < τ < 10^7 s, get "μ distortions":

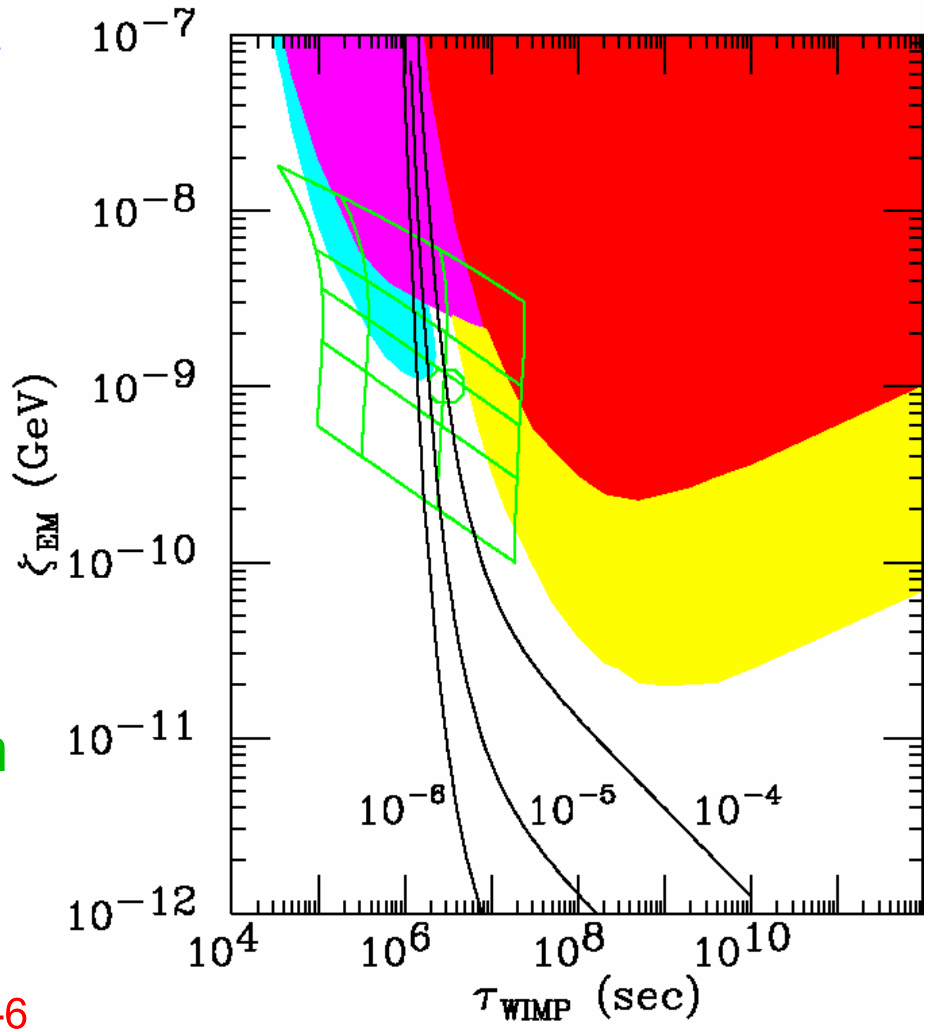
$$\frac{1}{e^{E/(kT)-\mu}-1}$$

$\mu=0$: Planckian spectrum

$\mu\neq0$: Bose-Einstein spectrum

- Current bound: $|\mu| < 9 \times 10^{-5}$

Future (DIMES): $|\mu| \sim 2 \times 10^{-6}$



$\tilde{G}$ Signals: Diffuse Photon Flux

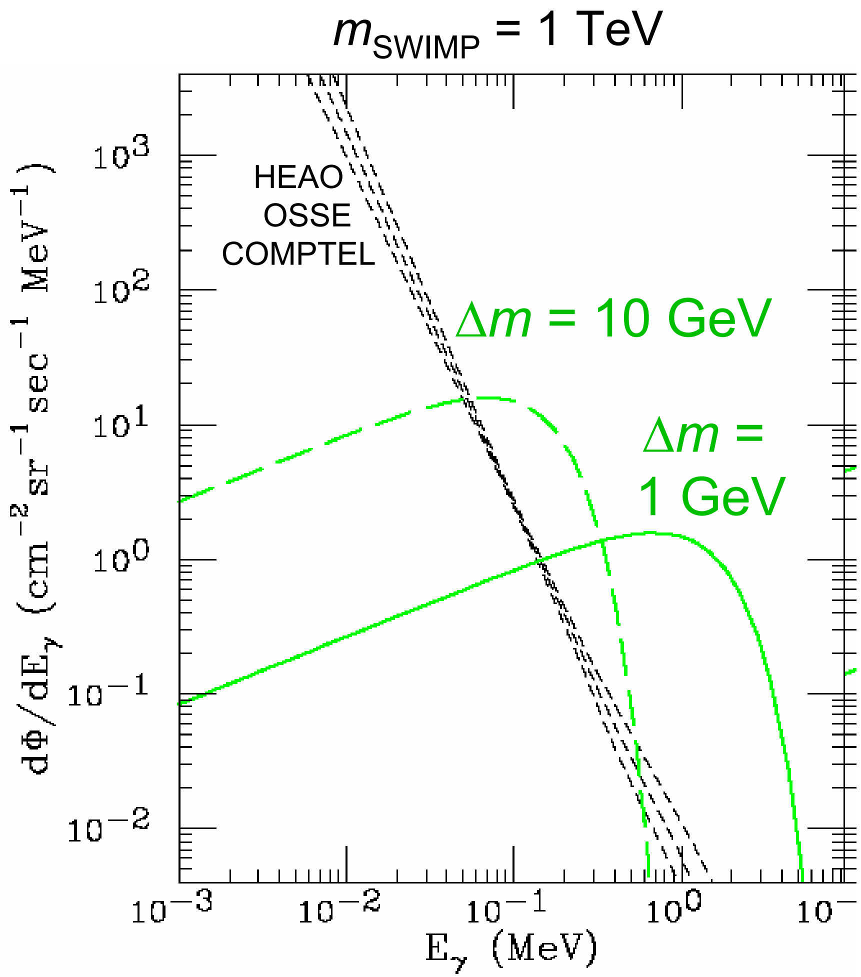
- For small Δm, decays may be very late

- Photons produced at later times have smaller initial

  $$E_\gamma \sim \Delta m$$

  but also redshift less; in the end, they are harder

- SuperWIMPs may produce excesses in keV-MeV photon spectrum (INTEGRAL)



m_{SWIMP} = 1 TeV

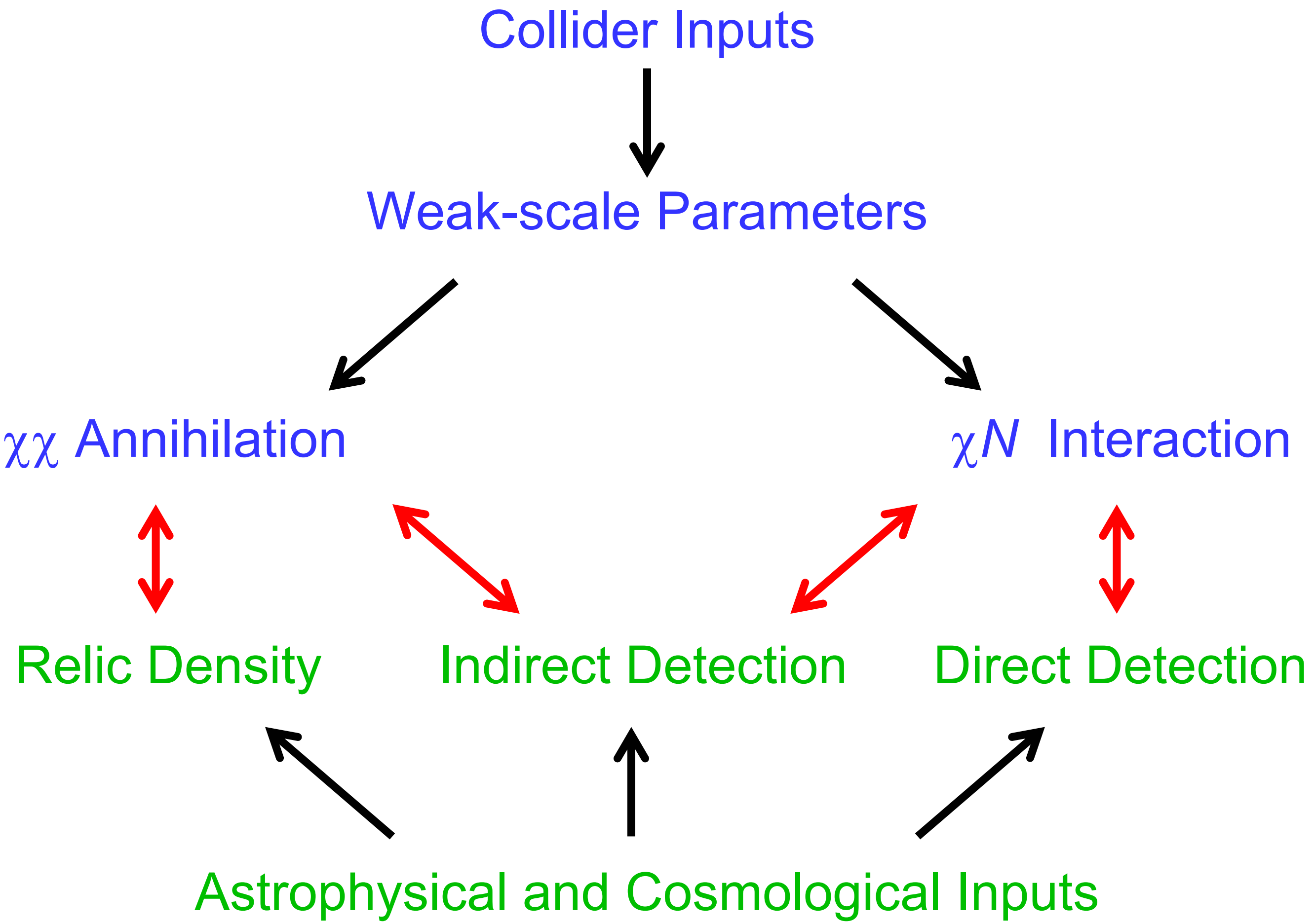
Feng, Rajaraman, Takayama (2003)

Summary and Outlook

- New dark matter possibilities (all satisfying the selection rule):
  - Bino-Higgsino dark matter
  - Kaluza-Klein dark matter
  - superWIMP dark matter

- New theoretical possibilities → new signals for dark matter in space

What’s in our Future?



Collider Inputs

Weak-scale Parameters

$\chi\chi$ Annihilation

χN Interaction

Relic Density

Indirect Detection

Direct Detection

Astrophysical and Cosmological Inputs