The Plan

LECTURE 1

SUSY Essentials

Neutralino Cosmology
- Relic Density
- Detection

LECTURE 2

Gravitino Cosmology
- Relic Density
- Detection

Particle/Cosmo Synergy

Gravitino Cosmology

- In Lecture 1, the gravitino made a brief appearance in the SUSY spectrum, then we ignored it. Why?
- Gravitinos have a bad reputation, causing all sorts of trouble.
- But interesting implications for CMB, BBN, inflation, reheating,…

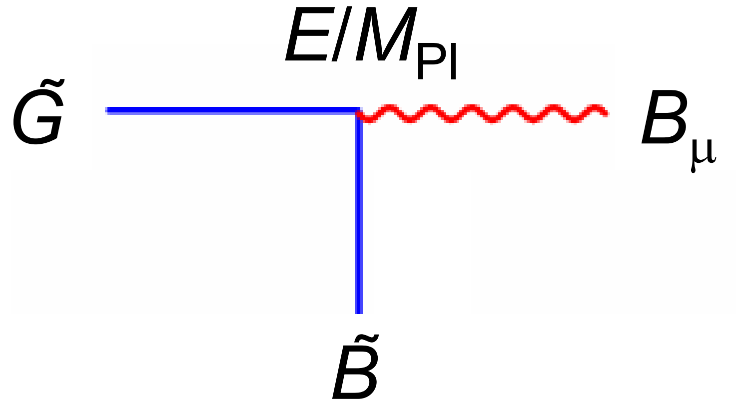
Gravitino Properties

- $\tilde{G}$ mass: expect ~ 100 GeV – 1 TeV

[high-scale SUSY breaking]

- $\tilde{G}$ interactions: $$-\frac{i}{8M_{\rm Pl}}\bar{\tilde{G}}_\mu \left[\gamma^\nu, \gamma^\rho\right] \gamma^\mu \tilde{B} F_{\nu\rho}$$

Couplings grow with energy:



Gravitino Relic Density

- If the universe cools from $T \sim M_{\rm Pl}$, expect $n_{\tilde{G}} \sim n_{\rm eq}$.
- Gravitinos decouple while relativistic, keep the same thermal density.

- Stable:

$$\Omega_{\tilde{G}} < 1 \Rightarrow m_{\tilde{G}} < 1 \text{ keV}$$

(cf. neutrinos)

Pagels, Primack (1982)

- Unstable:

$$\tau_{\tilde{G}} \sim \frac{M_{\rm Pl}^2}{m_{\tilde{G}}^3} \sim 1 \text{ yr} \left[\frac{100 \text{ GeV}}{m_{\tilde{G}}}\right]^3$$

BBN → $m_{\tilde{G}}$ > 10-100 TeV

Weinberg (1982)

Both inconsistent with natural mass range. But gravitinos may be DM if stable and bound saturated (introduce new scale).

Gravitinos from Reheating

- More modern view: gravitino density is diluted by inflation.

- But gravitinos regenerated in reheating. What happens?

$$\sigma_{\rm SM} n \sim T \gg H \sim \frac{T^2}{M_{\rm Pl}} \gg \sigma_{\tilde{G}} n \sim \frac{T^3}{M_{\rm Pl}^2}$$

SM interaction rate >> expansion rate >> $\tilde{G}$ interaction rate

- Thermal bath of SM particles: occasionally they interact to produce a gravitino: $f\, f \to f\, \tilde{G}$

Gravitinos from Reheating

- The Boltzmann equation:

$$\frac{dn}{dt} = \underbrace{-3Hn}_{\text{Dilution from expansion}} - \langle \sigma v \rangle \left[\underbrace{\cancelto{0}{n^2}}_{f\tilde{G} \to f\bar{f}} - \underbrace{n_{\rm eq}^2}_{f\bar{f} \to f\tilde{G}} \right]$$

- Change variables:

$$t \to T \qquad n \to Y \equiv \frac{n}{s}$$

- New Boltzmann equation:

$$\frac{dY}{dT} = -\frac{\langle \sigma_{\tilde{G}} v \rangle}{HTs} n^2 \sim \langle \sigma_{\tilde{G}} v \rangle \frac{T^3 T^3}{T^2 T T^3}$$

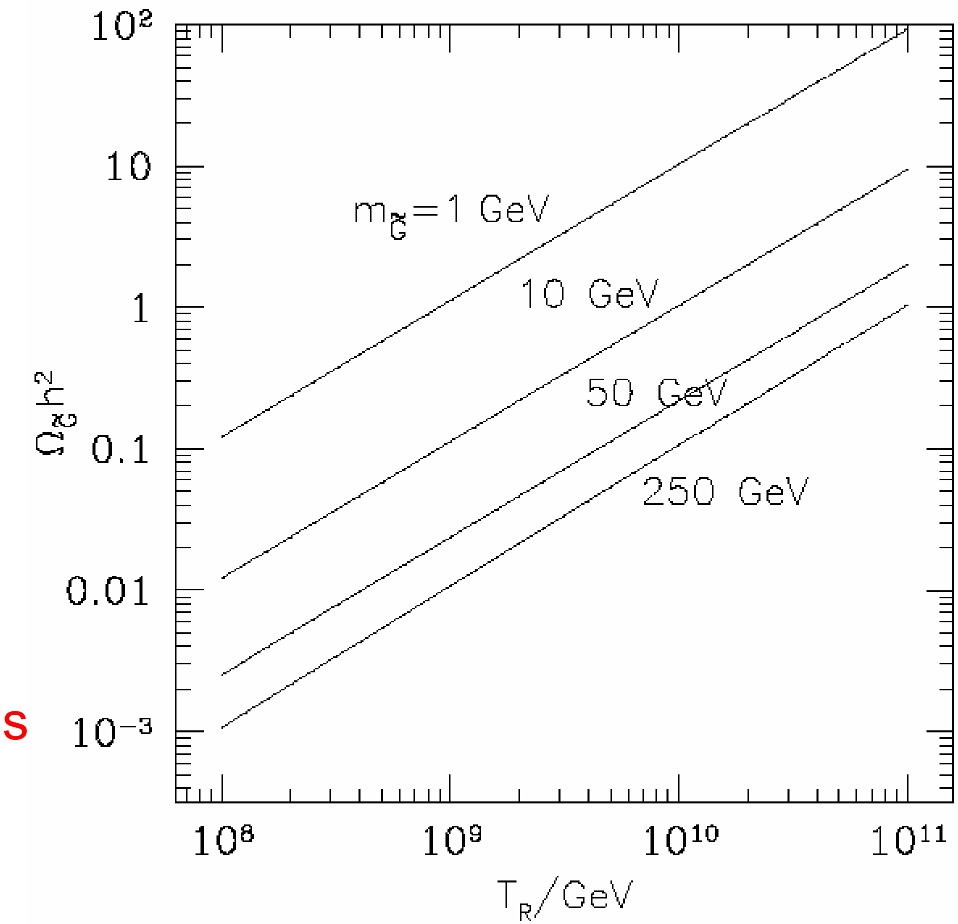
- Really simple: *Y* ~ reheat temperature

Bounds on T_{RH}

- $<\sigma v>$ for important production processes:

	process i	$\lvert\mathcal{M}_i\rvert^2 / \frac{g^2}{M^2}\left(1 + \frac{m_{\tilde{g}}^2}{3m_{\tilde{G}}^2}\right)$
A	$g^a + g^b \to \tilde{g}^c + \tilde{G}$	$4(s + 2t + 2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde{g}^b \to g^c + \tilde{G}$	$-4(t + 2s + 2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde{q}_i + g^a \to q_j + \tilde{G}$	$2s\lvert T^a_{ji}\rvert^2$
D	$g^a + q_i \to \tilde{q}_j + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
E	$\bar{\tilde{q}}_i + q_j \to g^a + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
F	$\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{G}$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde{g}^a \to q_j + \tilde{G}$	$-4(s + \frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
H	$\tilde{q}_i + \tilde{g}^a \to \tilde{q}_j + \tilde{G}$	$-2(t + 2s + 2\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
I	$q_i + \bar{q}_j \to \tilde{g}^a + \tilde{G}$	$-4(t + \frac{t^2}{s})\lvert T^a_{ji}\rvert^2$
J	$\tilde{q}_i + \bar{\tilde{q}}_j \to \tilde{g}^a + \tilde{G}$	$2(s + 2t + 2\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$

- $T_{\mathrm{RH}} < 10^8 - 10^{10}$ GeV; constrains inflation, leptogenesis
- $\tilde{G}$ DM if bound saturated (introduce new scale).

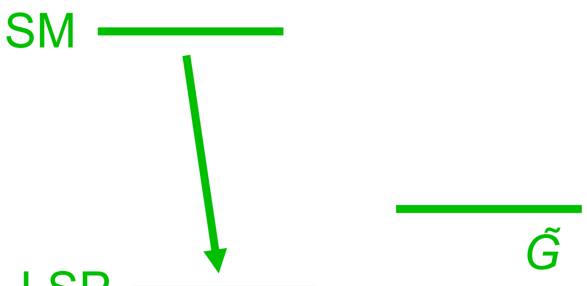


Bolz, Brandenburg, Buchmuller (2001)

Gravitinos from Late Decay

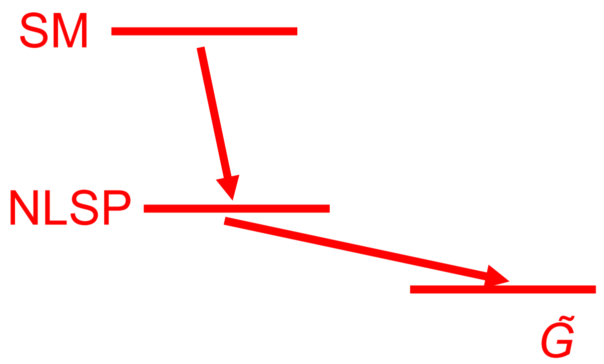
- What if gravitinos are diluted by inflation, and the universe reheats to low temperature?

- $\tilde{G}$ not LSP



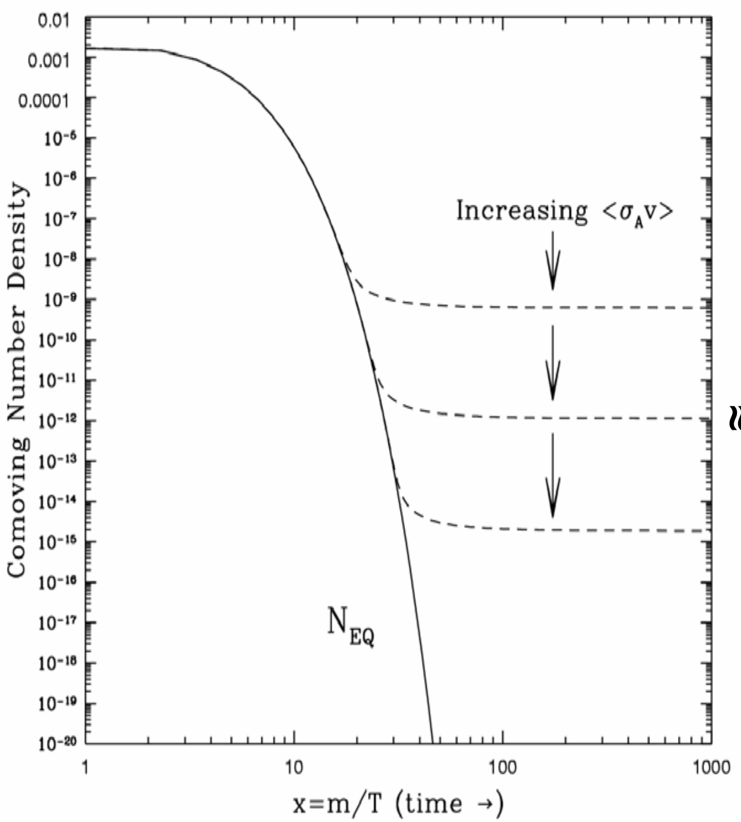
- No impact – implicit assumption of Lecture 1

- $\tilde{G}$ LSP



- More trouble/opportunities

Gravitinos from Late Decay



- Early universe behaves as usual, WIMP freezes out with desired thermal relic density
- A year passes…then

WIMP → $\tilde{G}$

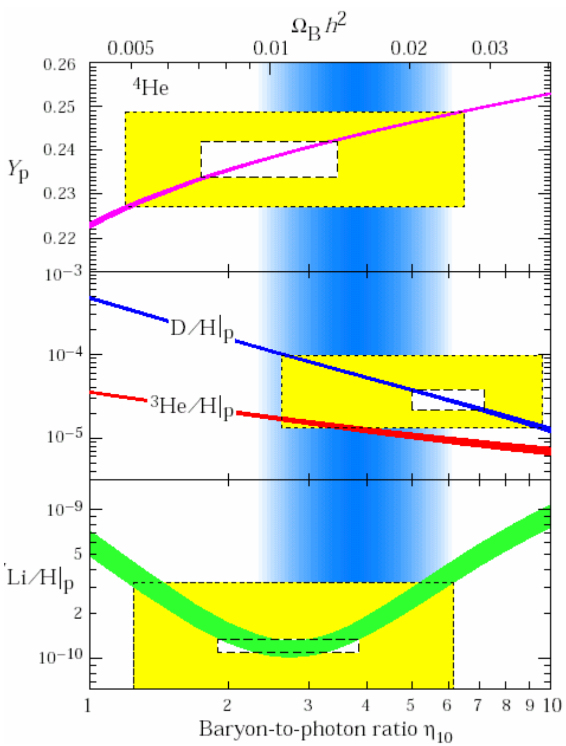
all WIMPs decay to gravitinos

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

Gravitino cold dark matter again, but now no new scales

Gravitino Cosmology: Detection

- Gravitinos undetectable now. But late decays occur before CMB but after BBN. This can be tested.

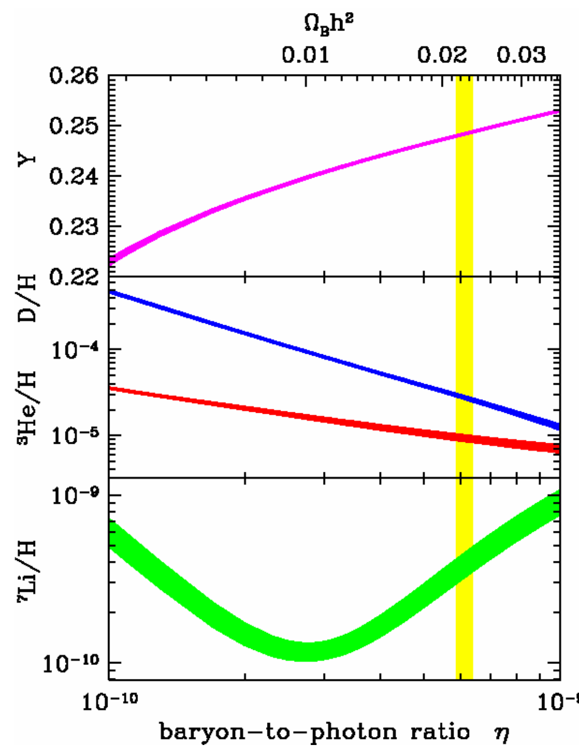


Baryometry

WMAP

$\eta_D = \eta_{CMB}$

[^{7}Li low]



Fields, Sarkar, PDG (2002)

Cyburt, Fields, Olive (2003)

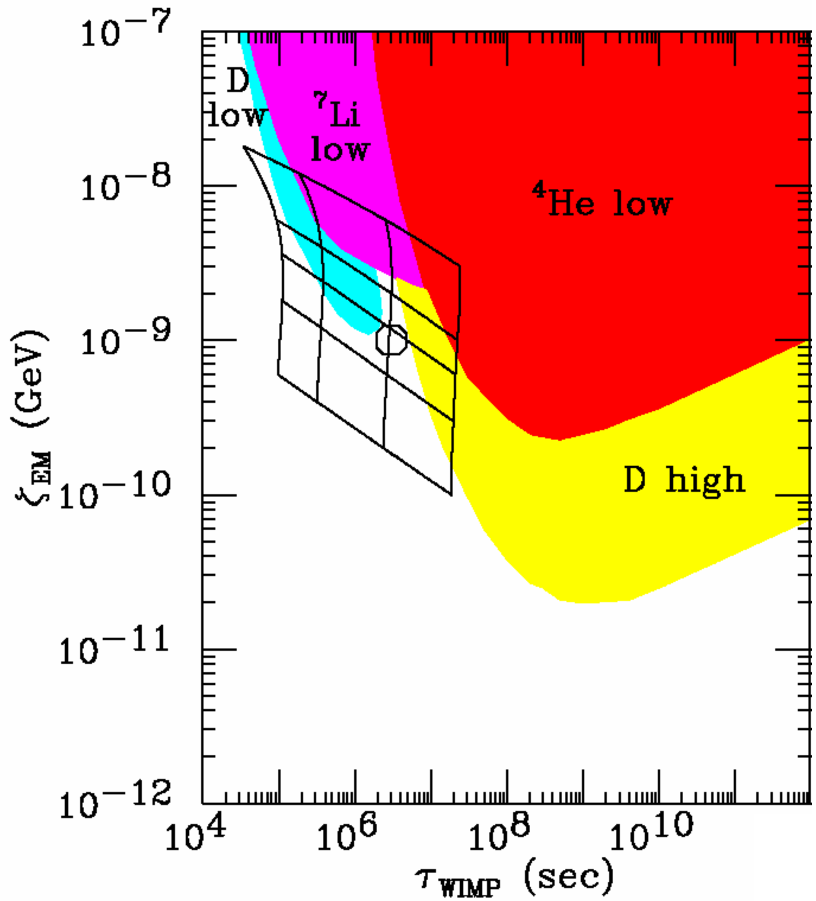
Gravitino Signals: BBN

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

- m_{WIMP} and $m_{\tilde{G}}$ and determine
  Decay time: τ_X
  Energy release: $\zeta_{EM} = \Delta m\, n_{\tilde{G}} / n_\gamma$
  $(\Omega_{\tilde{G}} = \Omega_{DM})$

BBN excludes shaded regions

Cyburt, Ellis, Fields, Olive (2002)



Feng, Rajaraman, Takayama (2003)

$\tilde{G}$ DM predicts grid region, distortions in precision BBN (including low ^{7}Li).

Gravitino Signals: CMB

- Late decays may also distort the CMB spectrum.

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

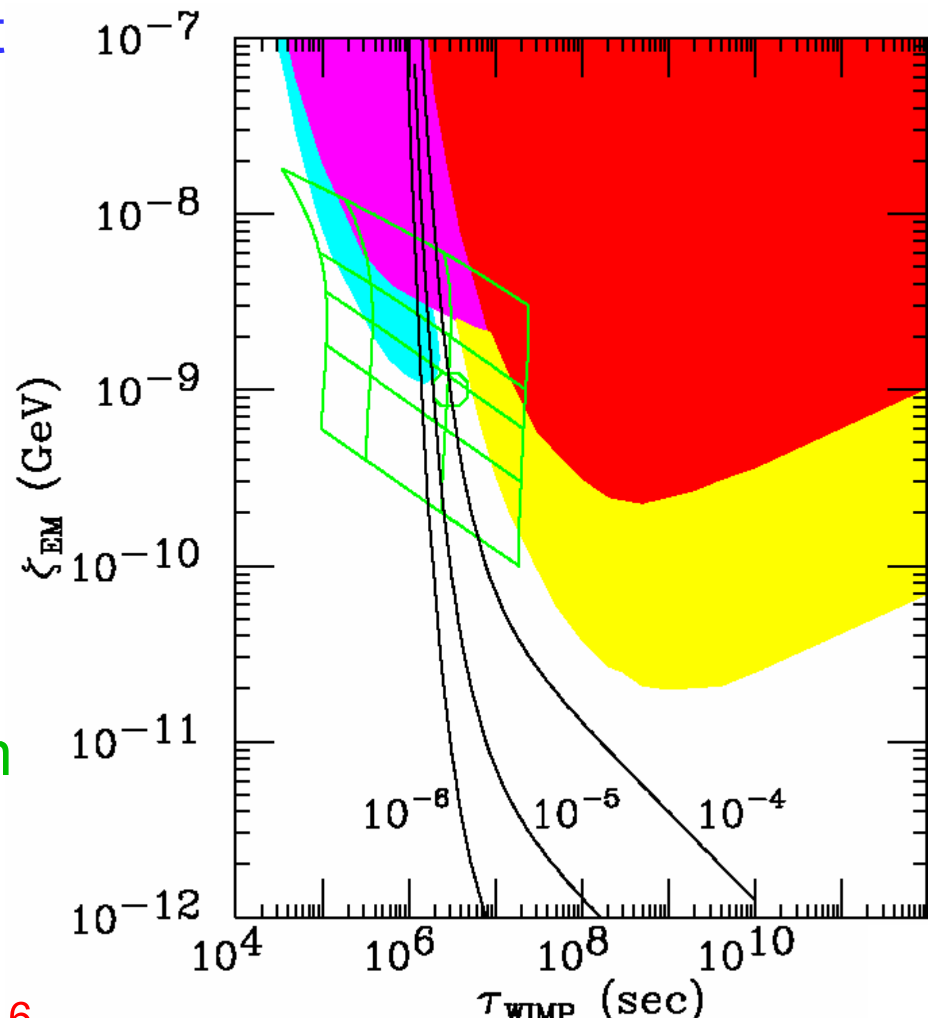
$$\frac{1}{e^{E/(kT)-\mu} - 1}$$

  μ=0: Planckian spectrum

  $\mu \neq$0: Bose-Einstein spectrum

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

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



Gravitino Cosmology: Summary

- Gravitinos: many production mechanisms, may be dark matter.
- Interact only gravitationally, so escape all conventional dark matter searches, but…
- Detection possible in BBN, CMB, diffuse photon background, metastable heavy charged particles at colliders, …

Particle/Cosmo Synergy

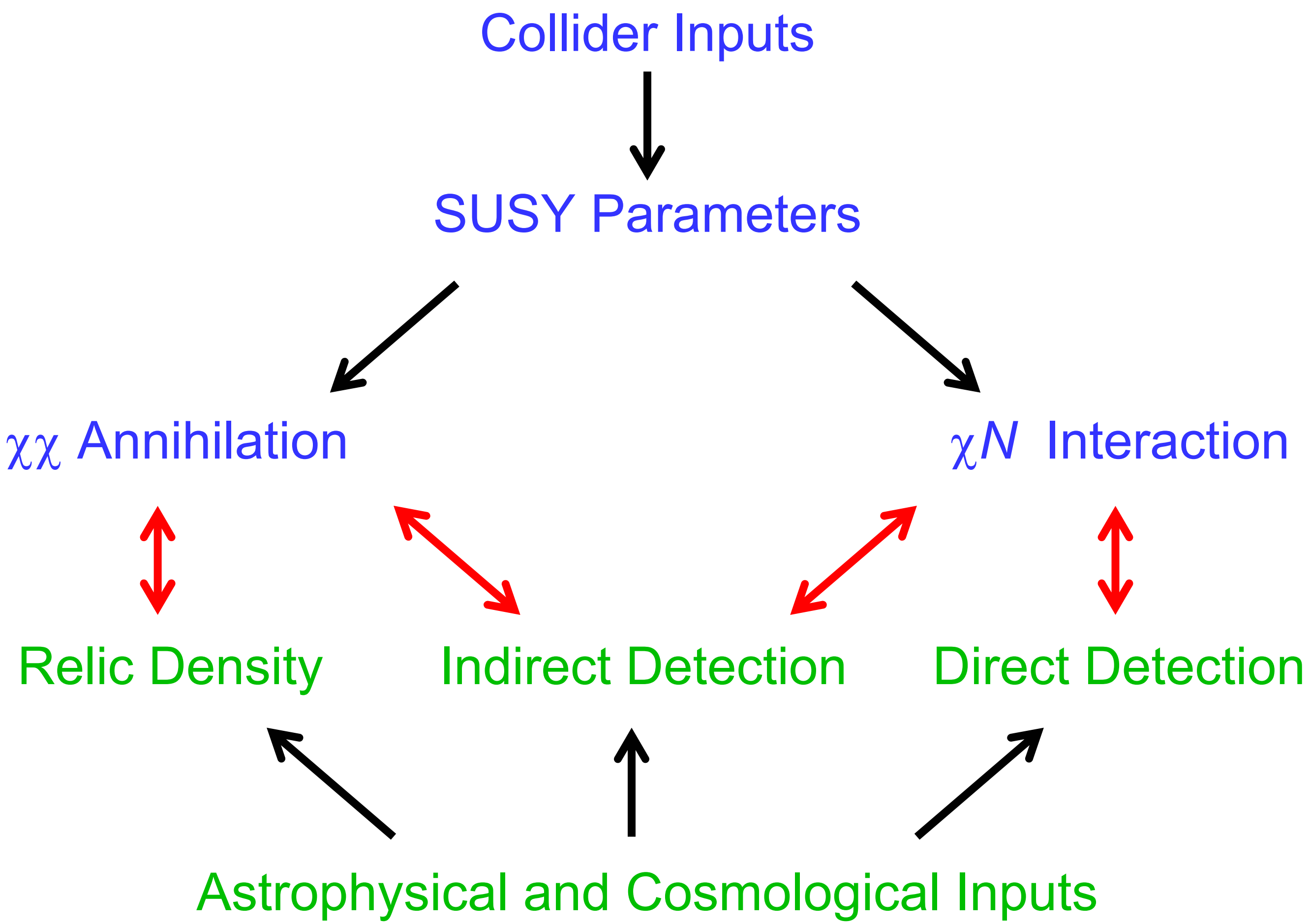
- We've seen many SUSY implications for cosmology (and we've omitted many SUSY scenarios, other well-studied possibilities, ideas not yet conceived,…)
- What prospects are there for sorting this out?
- Consider neutralino dark matter (not so optimistic about prospects for baryogenesis, dark energy,…)

Limitations of Separate Approaches

- Dark matter experiments cannot discover SUSY
  - can only provide reasonable constraints on mass, interaction strengths

- Colliders cannot discover dark matter
  - can only verify $\tau > 10^{-7}$ s, 24 orders of magnitude short of the age of the universe

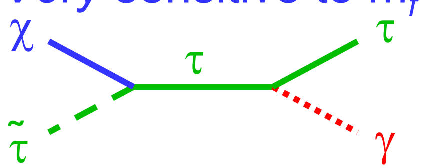
Particle/Cosmo Interface



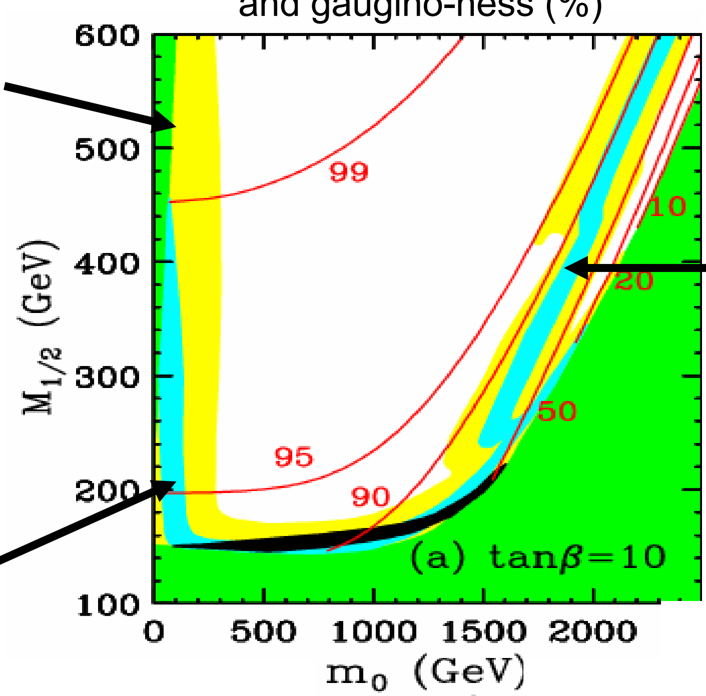
Relic Density

- Cosmology: $\Omega_{DM} = 0.23 \pm 0.04$. What can HEP tell us?

Co-annih. region
$\chi \approx$ pure Bino
Very sensitive to $m_{\tilde{f}}$

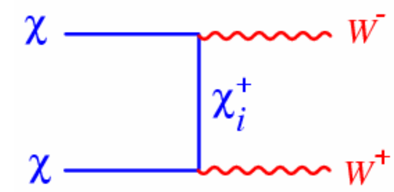


Relic density regions
and gaugino-ness (%)

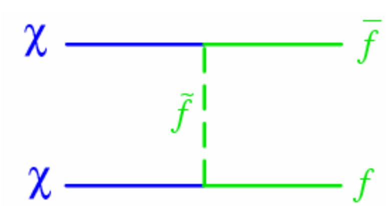


Feng, Matchev, Wilczek (2000)

Focus point region
$\chi \approx$ Bino-Higgsino
Sensitive to χ composition

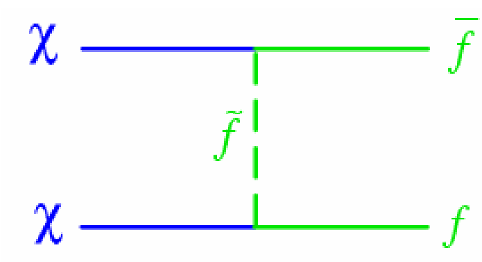


Bulk region
$\chi \approx$ pure Bino
Sensitive to $m_{\tilde{f}}$



Relic Density: LHC

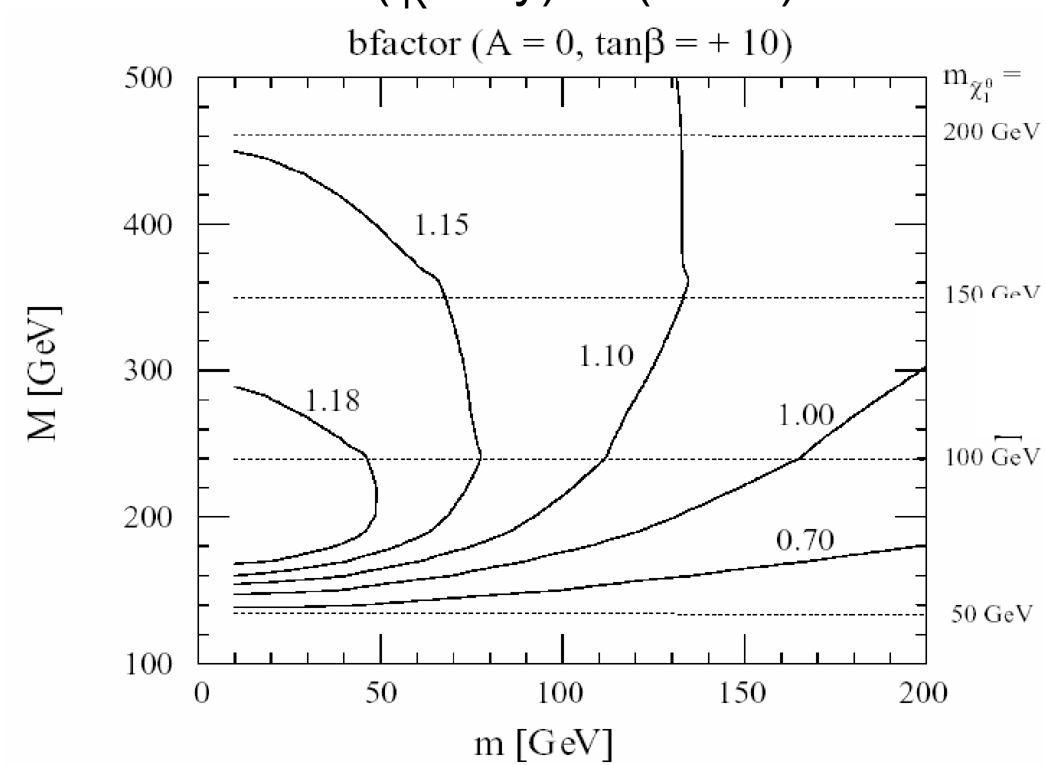
- Assume $\chi \approx$ pure Bino, $\tilde{l}_R$ flavor degenerate



- $\langle\sigma v\rangle$ determined primarily by χ and $\tilde{e}_R$ masses ($\tilde{e}_R$ light and has large hypercharge)

- Can find Ω_χ to ~ 20%. Then try to confirm assumptions.

$\sigma(\tilde{l}_R$ only) / σ(exact)



Drees, Kim, Nojiri, Toya, Hasuko, Kobayashi (2000)

Relic Density: LC

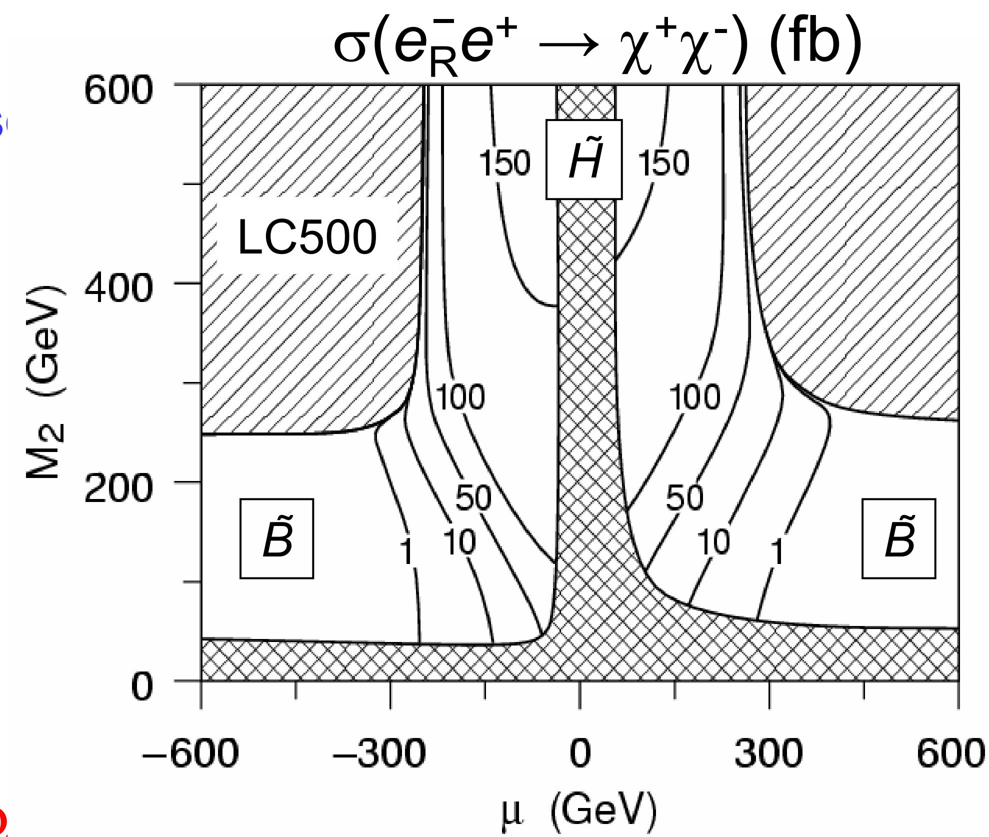
Ω_χ *typically* implies light SUSY:

- Either light sleptons, or
- Mixed gaugino-Higgsino LSP, s light neutralinos and charginos

If sleptons accessible, typically measure masses to ~1%.

Gaugino-ness measured through spectrum or polarized cross sections.

Potential for highly model-independent measurement of Ω_χ to ~ few % at LHC/LC.



Feng, Murayama, Peskin, Tata (1995)

Consistency

- Particle Physics + standard cosmology → predictions for

  Ω_χ

  Direct detection rates

  Indirect detection rates

- If observations and experiments corroborate each other, we understand the universe back to 10^{-8} sec (T ~ 10 GeV) !

  [Cf. Big Bang nucleosynthesis at 1 sec (T ~ 1 MeV)]

Discrepancies

- Thermal relic density need not be the actual relic density (e.g., late decays)
  - The mismatch tells us about the history of the universe between 10^{-8} s < t < 1 s

- Detection rates need not be the actual detection rates
  - the mismatch tells us about halo profiles, dark matter velocity distributions,…

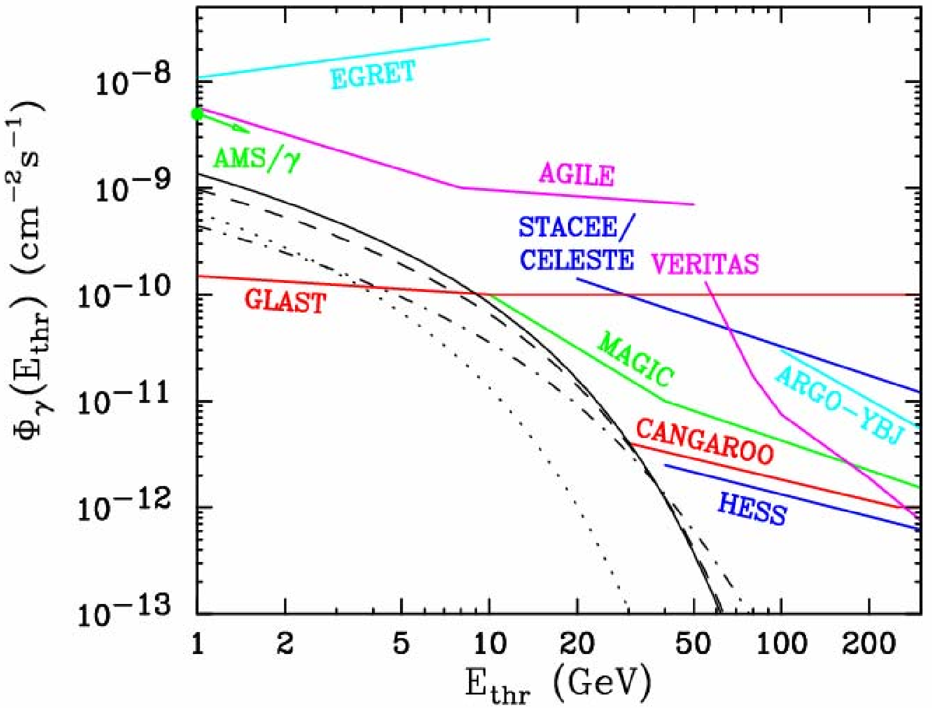
- LHC/LC not only may identify DM as SUSY, but also may shed light on "astrophysical" problems

Example: Galactic Halo Profile

- Halo profiles are not well-known (cuspy, clumpy, …)
- An indirect dark matter signal is photons from the galactic center:

$$\underbrace{\frac{d\Phi_\gamma}{d\Omega dE}}_{\text{Astrophysics}} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Halo Profile}}$$

Buckley et al. (1999)



Feng, Matchev, Wilczek (2000)

- Flux + LHC/LC → halo profile

Summary

- Particle physics and cosmology both point to new physics at the weak scale
- Neutralino and gravitino cosmology provide rich arenas for exploring the wealth of possibilities
- The golden age of particle physics / astroparticle / cosmology is yet to come!