The LC and the Cosmos: Connections in Supersymmetry

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Many Big Questions

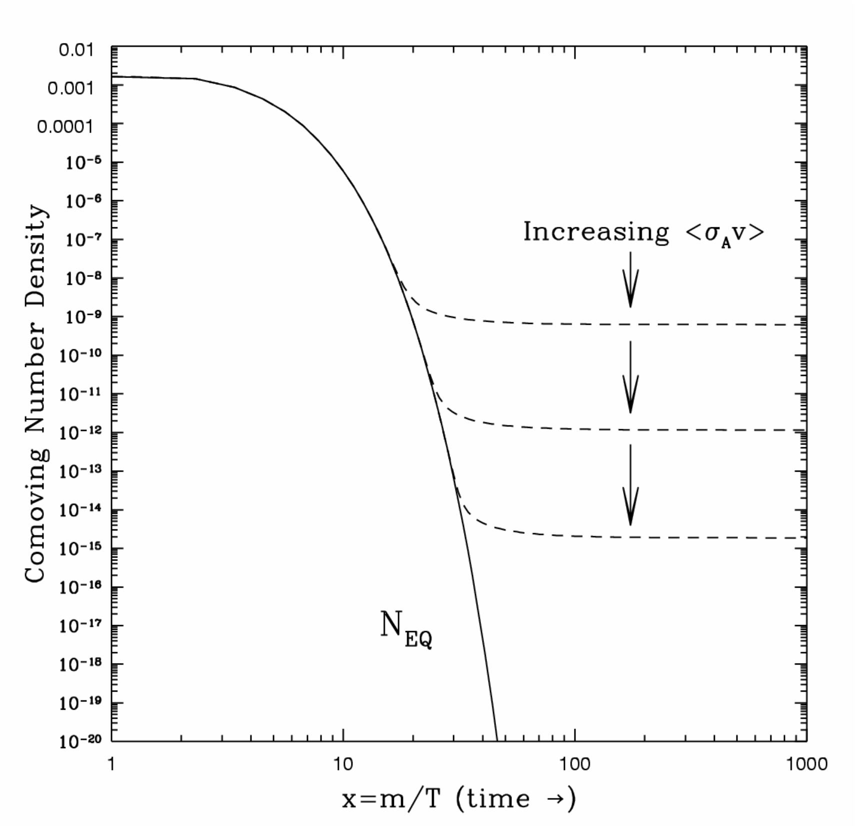
- Baryogenesis
  - Why is there more matter than anti-matter?
- Ultra-high Energy Cosmic Rays
  - What are the highest energy particles detected?
- …
- Dark Matter
  - What is most matter made of?

Dark Matter

- We live in interesting times
  - We know how much dark matter there is (Ω_{DM} = 0.24 +/- 0.05)
  - We have no idea what it is

- Weakly-interacting particles with weak-scale masses naturally provide Ω_{DM}

- This is either a devious coincidence, or dark matter provides a strong, fundamental, and completely independent motivation for new particles at the electroweak scale

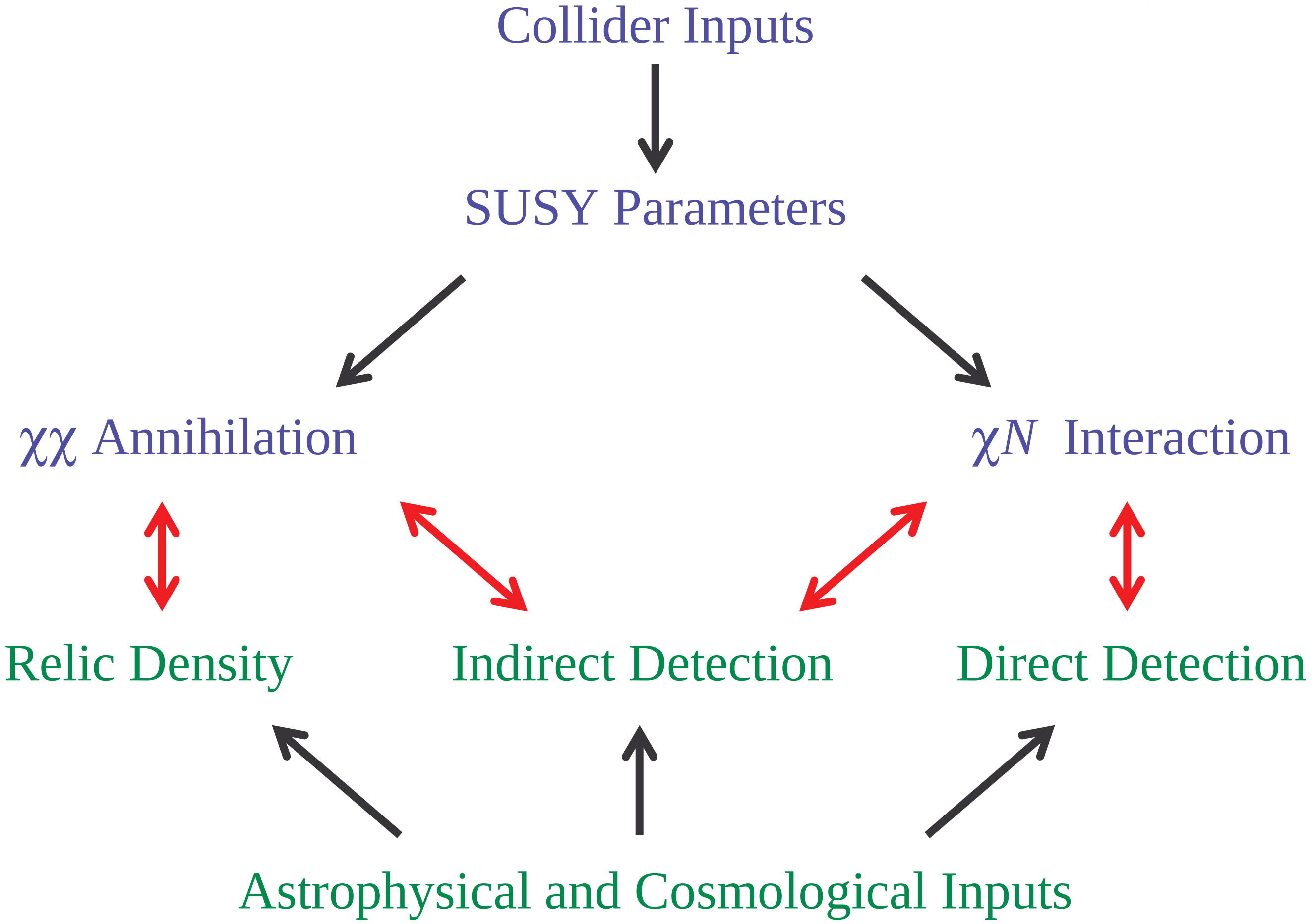


Limitations of Separate Approaches

- Dark matter experiments cannot discover SUSY
  - can only provide rough 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

Synergy

Feng, Nojiri (2002)



Collider Inputs

SUSY Parameters

$\chi\chi$ Annihilation

χN Interaction

Relic Density

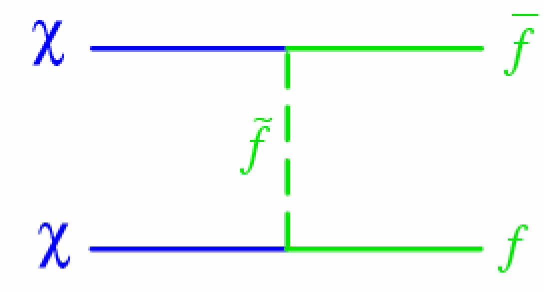
Indirect Detection

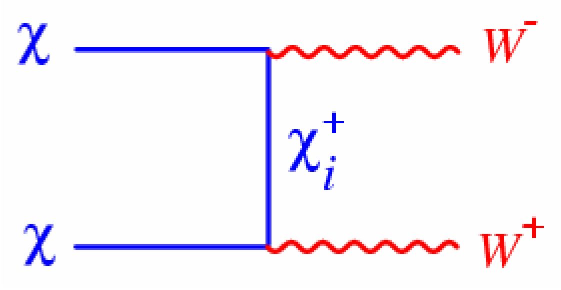
Direct Detection

Astrophysical and Cosmological Inputs

Relic Density

- Neutralino freeze out: sensitive to most SUSY parameters





- Co-annihilations ➔ Extreme sensitivity to degeneracies

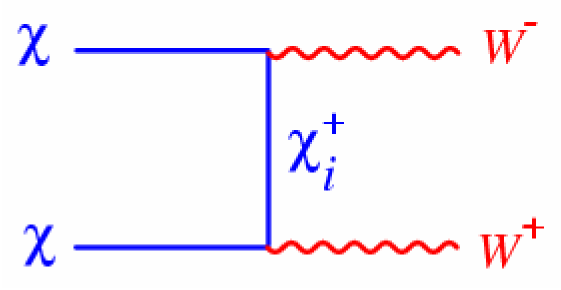
- E.g., $\chi - \tau$ co-annihilation requires mass measurements much better than

$$\Delta m \sim T \sim m/25$$

- Requires full capabilities of LC (see Dutta's talk)

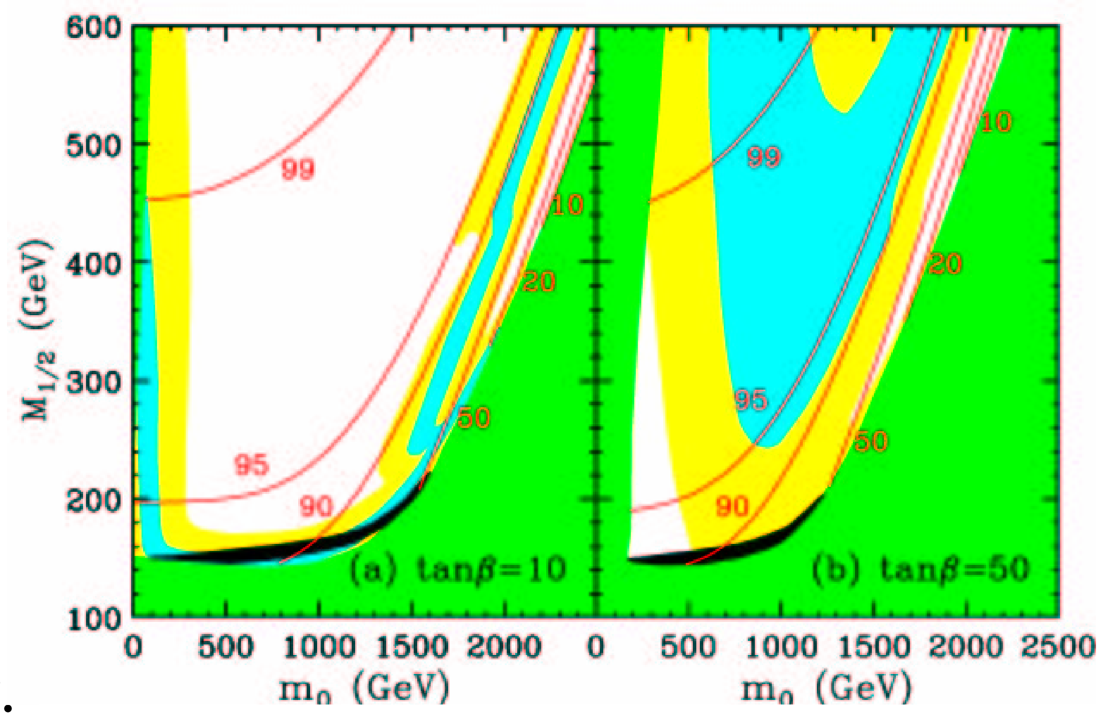
Relic Density

- Extreme sensitivity to neutralino mixing:



vanishes for pure Bino, even 10% gaugino-ness changes Ω_{DM} drastically.

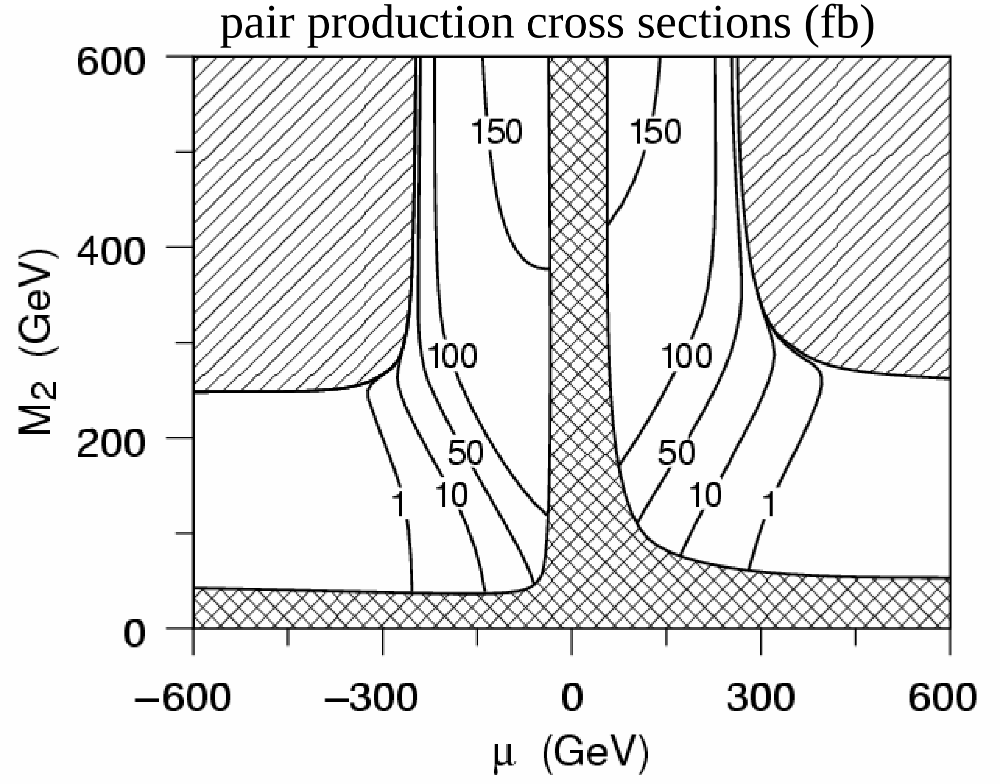
Relic density regions and gaugino-ness contours



Feng, Matchev, Wilczek (2000)

- Many handles at colliders
  - LC: Polarized measurements of chargino pair production
  - LHC/LC: Mass measurements of all charginos and neutralinos

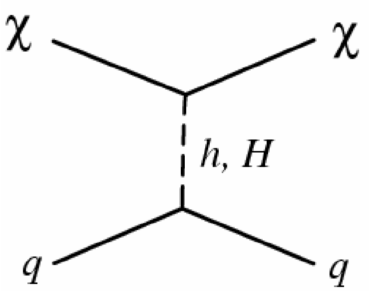
LC500 Right-polarized chargino pair production cross sections (fb)

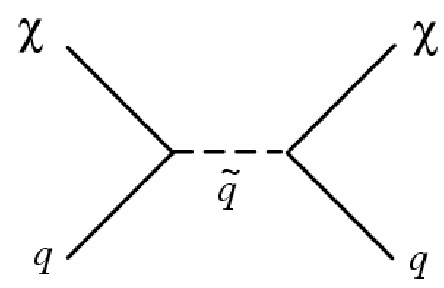


Feng, Murayama, Peskin, Tata (1995)

Dark Matter Detection

- Direct detection depends on χN scattering





- Indirect detection depends on $\chi\chi$ annihilation

$\chi\chi \rightarrow \gamma$ in galactic center
$\chi\chi \rightarrow e+$ in halo
$\chi\chi \rightarrow$ anti-protons

- or both

$\chi\chi \rightarrow \nu$ in centers of the Earth and Sun

Indirect Detection Experiments

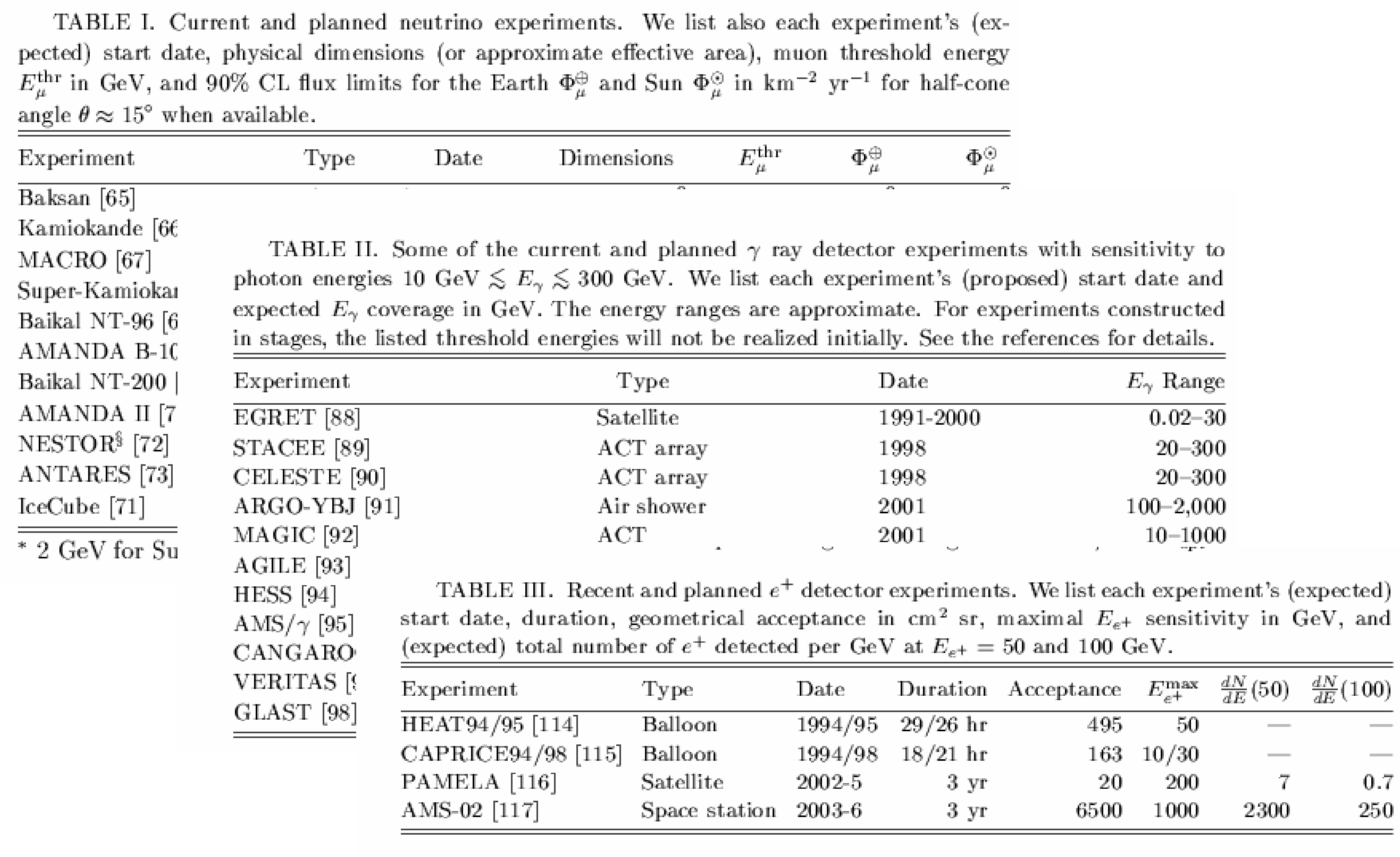


TABLE I. Current and planned neutrino experiments. We list also each experiment's (expected) start date, physical dimensions (or approximate effective area), muon threshold energy E_μ^{thr} in GeV, and 90% CL flux limits for the Earth $\Phi_\mu^{\oplus}$ and Sun $\Phi_\mu^{\odot}$ in km^{-2} yr^{-1} for half-cone angle $\theta \approx 15°$ when available.

Experiment	Type	Date	Dimensions	E_μ^{thr}	$\Phi_\mu^{\oplus}$	$\Phi_\mu^{\odot}$
Baksan [65]						
Kamiokande [6						
MACRO [67]						
Super-Kamioka						
Baikal NT-96 [6						
AMANDA B-1						
Baikal NT-200						
AMANDA II [7						
NESTOR§ [72]						
ANTARES [73]						
IceCube [71]						

* 2 GeV for Su

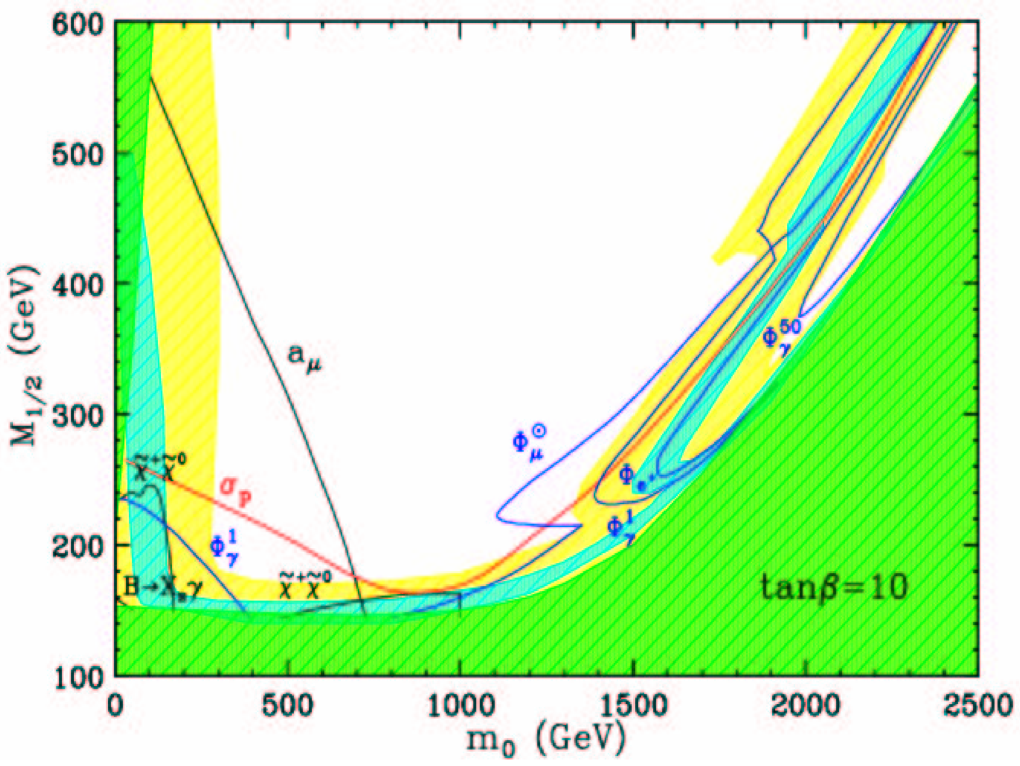
TABLE II. Some of the current and planned γ ray detector experiments with sensitivity to photon energies 10 GeV $\lesssim E_\gamma \lesssim$ 300 GeV. We list each experiment's (proposed) start date and expected E_γ coverage in GeV. The energy ranges are approximate. For experiments constructed in stages, the listed threshold energies will not be realized initially. See the references for details.

Experiment	Type	Date	E_γ Range
EGRET [88]	Satellite	1991-2000	0.02–30
STACEE [89]	ACT array	1998	20–300
CELESTE [90]	ACT array	1998	20–300
ARGO-YBJ [91]	Air shower	2001	100–2,000
MAGIC [92]	ACT	2001	10–1000
AGILE [93]			
HESS [94]			
AMS/γ [95]			
CANGARO			
VERITAS [			
GLAST [98]			

TABLE III. Recent and planned e^+ detector experiments. We list each experiment's (expected) start date, duration, geometrical acceptance in cm^2 sr, maximal E_{e^+} sensitivity in GeV, and (expected) total number of e^+ detected per GeV at $E_{e^+} = 50$ and 100 GeV.

Experiment	Type	Date	Duration	Acceptance	$E_{e^+}^{\max}$	$\frac{dN}{dE}(50)$	$\frac{dN}{dE}(100)$
HEAT94/95 [114]	Balloon	1994/95	29/26 hr	495	50	—	—
CAPRICE94/98 [115]	Balloon	1994/98	18/21 hr	163	10/30	—	—
PAMELA [116]	Satellite	2002-5	3 yr	20	200	7	0.7
AMS-02 [117]	Space station	2003-6	3 yr	6500	1000	2300	250

Dark Matter 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	$\lvert a_\mu^{\mathrm{SUSY}}\rvert < 8 \times 10^{-10}$	Brookhaven E821
σ_{proton}	Direct DM	$\sim 10^{-8}$ pb (See Ref. [5])	CDMS, CRESST, GENIUS
ν from Earth	Indirect DM	$\Phi_\mu^\oplus < 100\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$	Amanda, Nestor, Antares
ν from Sun	Indirect DM	$\Phi_\mu^\odot < 100\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$	Amanda, Nestor, Antares
γ (gal. center)	Indirect DM	$\Phi_\gamma(1) < 1.5 \times 10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	GLAST
γ (gal. center)	Indirect DM	$\Phi_\gamma(50) < 7 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	MAGIC
e^+ cosmic rays	Indirect DM	$(S/B)_{\max} < 0.01$	AMS-02

- Astrophysical and particle searches are complementary

- SUSY at LC500 requires some dark matter signal before ~2007 (in mSUGRA)

- Relic Density →
  - scalars light or
  - Higgsinos light (neutralinos mixed)

  Rich physics at LC

Feng, Matchev, Wilczek (2000)

Cosmo/Astro Inputs/Outputs

- Thermal relic density need not be the actual relic density – late decays, etc.
  - The mismatch tells us about the history of the universe between 10 GeV > T > 1 MeV or 10^{-8} s < t < 1 s

- The detection rate need not be the actual detection rate
  - the mismatch tells us about halo profiles, dark matter velocity distributions

- LHC/LC not only required to identify SUSY, but also sheds light on “astrophysical” problems

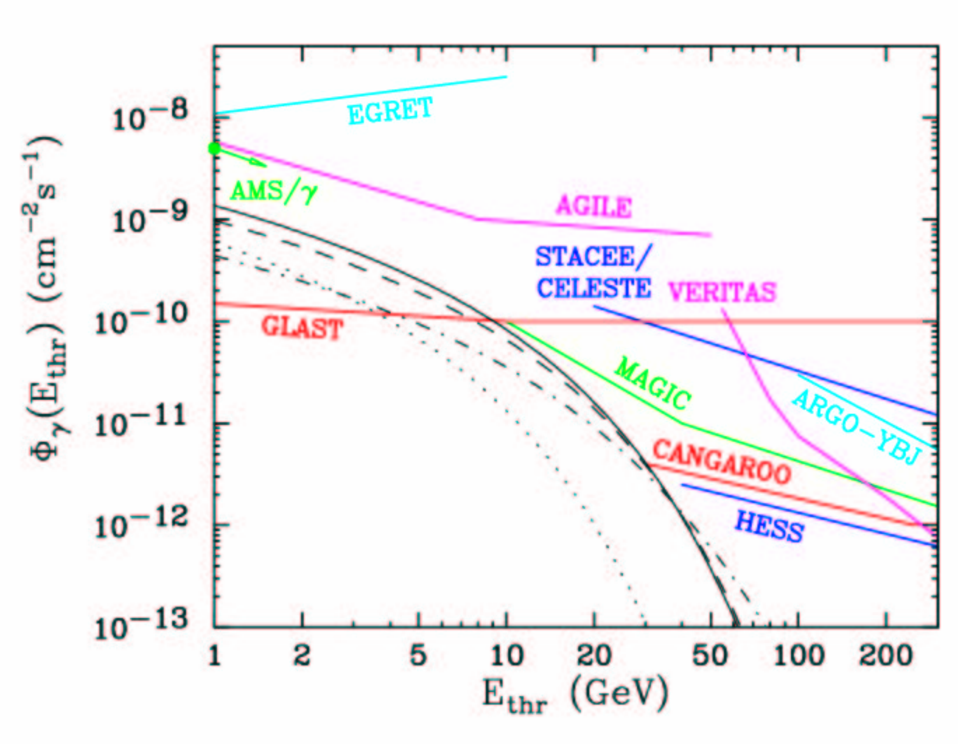
Example: Halo profile at the galactic center

- Halo profiles are extremely poorly known (cuspy, clumpy, …)

- An indirect dark matter signal is photons from the galactic center:

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

Buckley et al. (1999)



Feng, Matchev, Wilczek (2000)

superWIMPs

- WIMP motivations are strong, and suggest optimism for detection:
  weaker interactions → too much relic density

- But one can break this relation:

  E.g., gravitino LSP, sneutrino NLSP
  - Sneutrino freezes out to WIMP density, then decays to roughly degenerate gravitino
  - gravitino is a superWIMP, interacts only gravitationally

Feng, Rajaraman, Takayama (2003)

Implications

- Dark matter escapes all dark matter experiments

- Astrophysical superWIMP detection depends on character of NLSP

  ν superWIMP
    - CMB signature

  γ superWIMP
    - diffuse γ signature
    - BBN signature

  e superWIMPs, *q* superWIMPs, …

- Colliders see meta-stable massive charged particles, etc. provide invaluable information

Conclusions

- Dark matter and EWSB are independent motivations for new physics; both point to the weak scale
- Both colliders and dark matter experiments are required to get anywhere
- High sensitivity to SUSY parameters – LC inputs are likely to be extremely valuable