COSMOLOGY AT COLLIDERS

Jonathan Feng
University of California, Irvine

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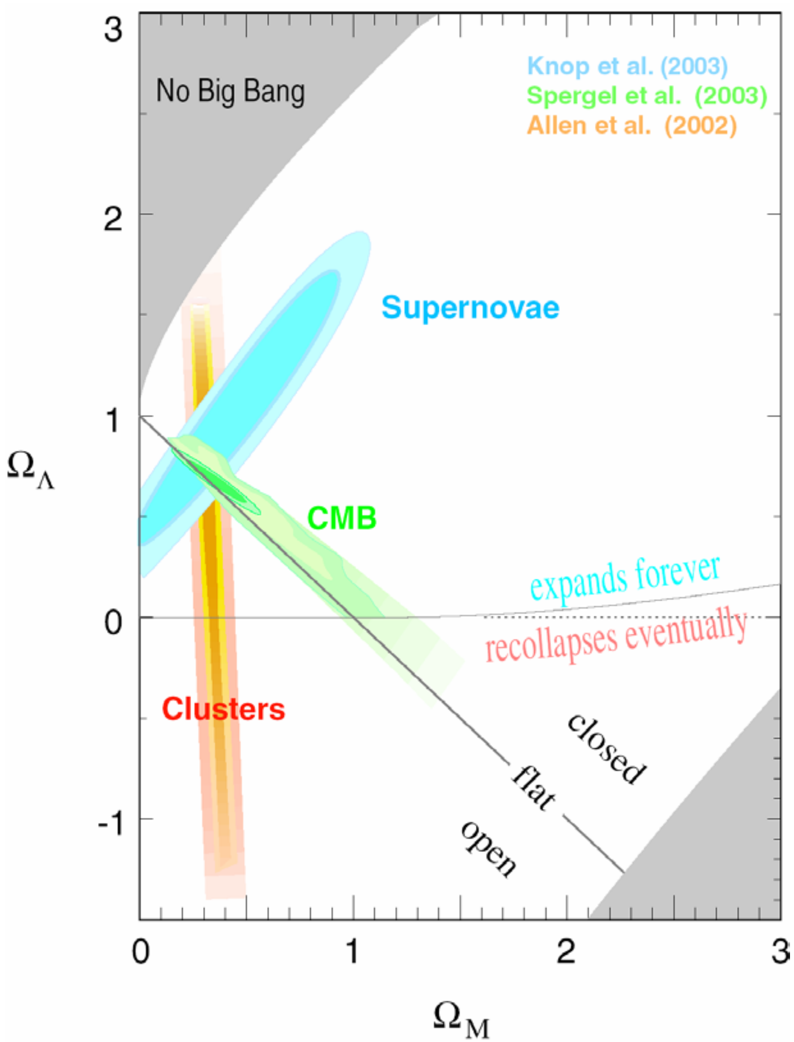
SoCal Strings Seminar

Graphic: N. Graf

COSMOLOGY NOW

We are living through a revolution in our understanding of the Universe on the largest scales

For the first time in history, we have a complete <u>picture</u> of the Universe



- Remarkable agreement

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  [Baryons: 4% ± 0.4%
  Neutrinos: ~0.5%]

- Remarkable precision (~10%)

- Remarkable results

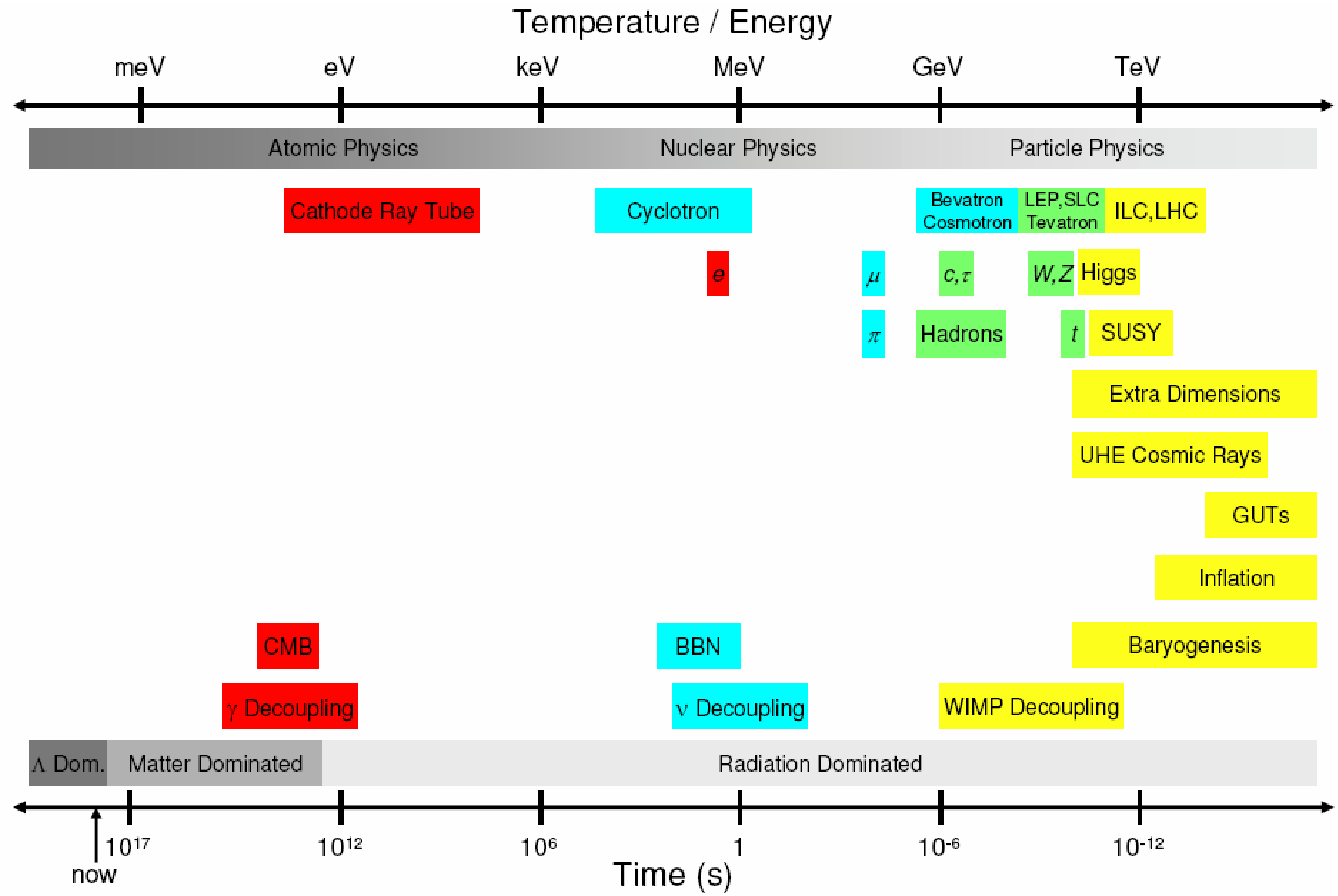
OUTSTANDING QUESTIONS

- Dark Matter: What is it? How is it distributed?
- Dark Energy: What is it? Why not $\Omega_\Lambda \sim 10^{120}$? Why not $\Omega_\Lambda = 0$? Does it evolve?
- Baryons: Why not $\Omega_B \approx 0$?
- UHE Cosmic Rays: What are they? Where do they come from?

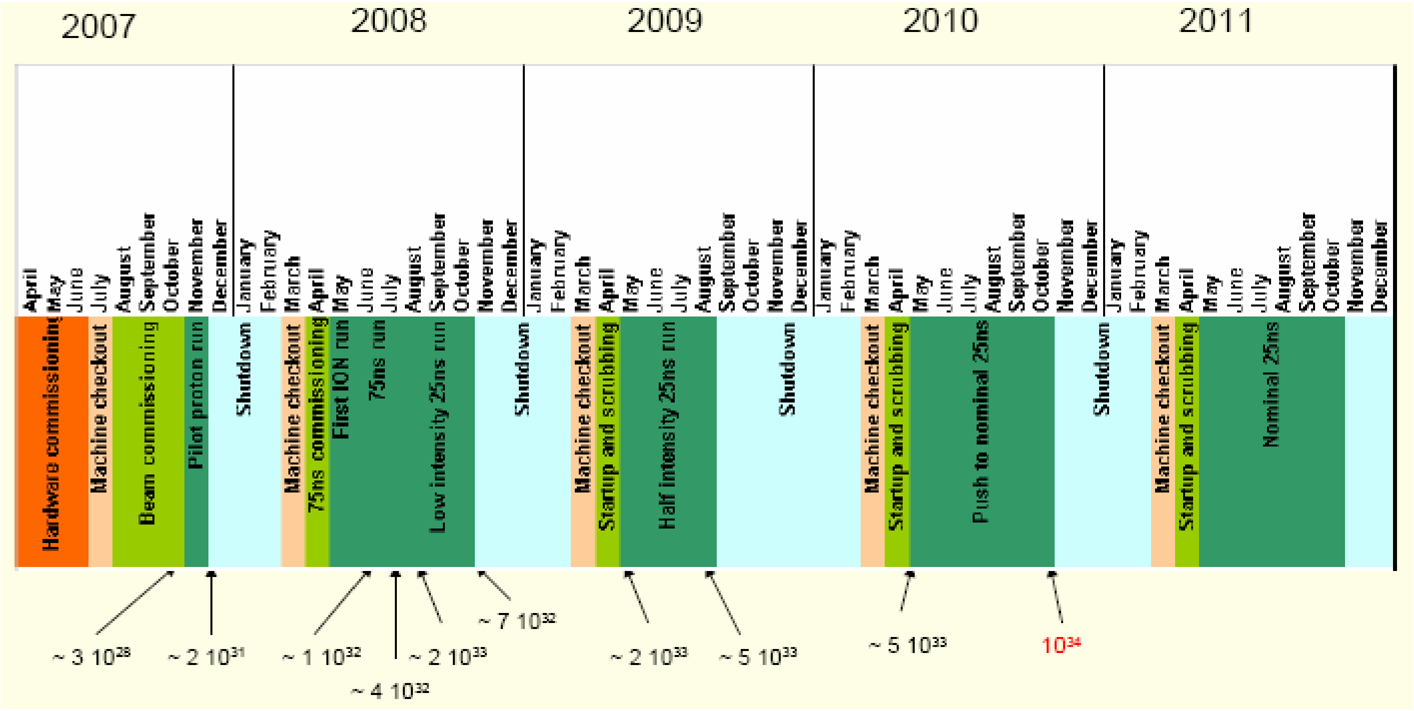
…

What tools do we need to address these?

PARTICLE PHYSICS AT THE ENERGY FRONTIER



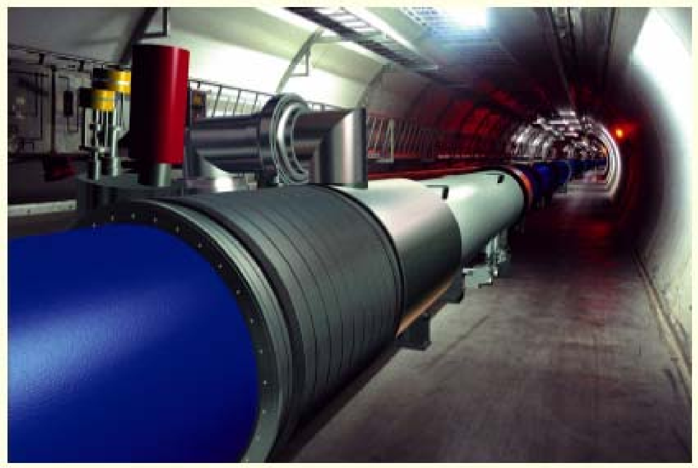
LHC Schedule

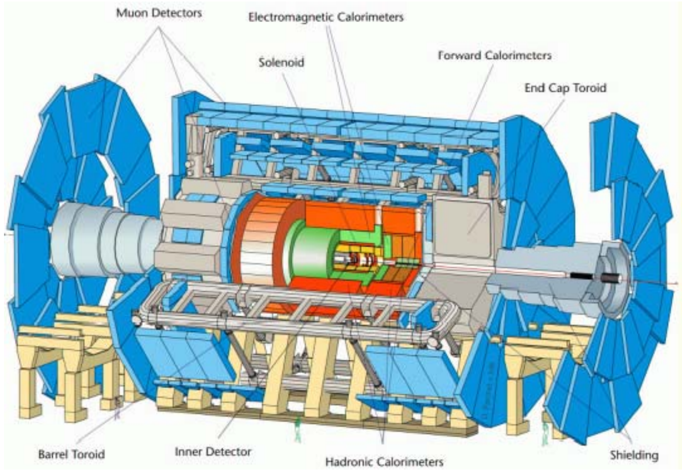


LHC

ATLAS

Drawings





Reality!

DARK MATTER

- Requirements: cold, non-baryonic, gravitationally interacting
- Candidates: primodial black holes, axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,…
- Masses and interaction strengths span many, many orders of magnitude

THERMAL RELICS

(1) Initially, DM is in thermal equilibrium:

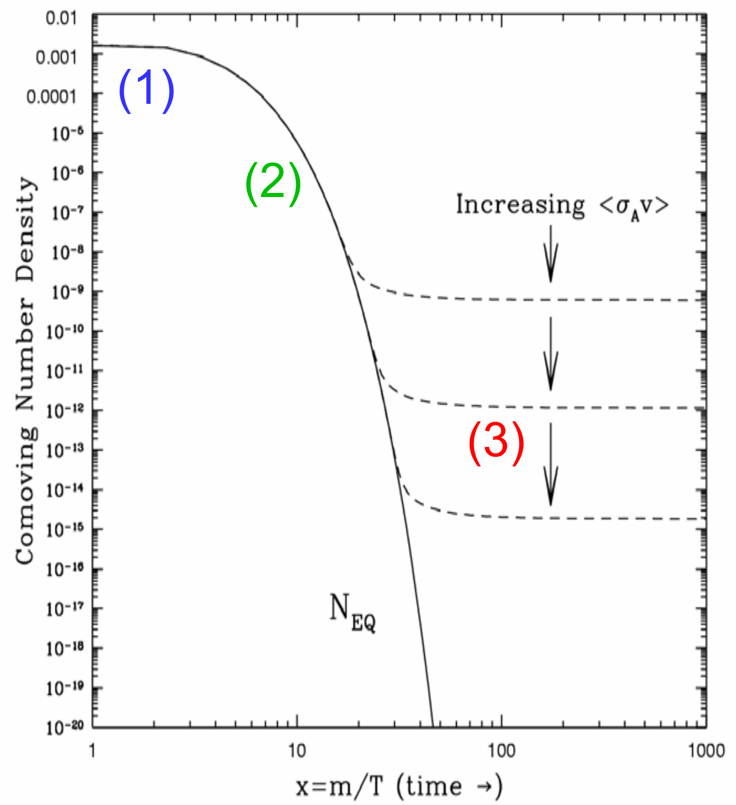
$$\chi\chi \leftrightarrow \bar{f} f$$

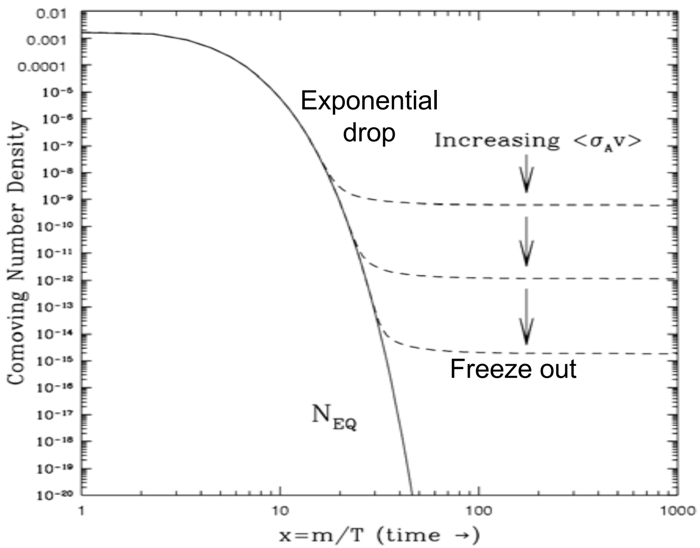
(2) Universe cools:

$$N = N_{EQ} \sim e^{-m/T}$$

(3) χs "freeze out":

$$N \sim \text{const}$$

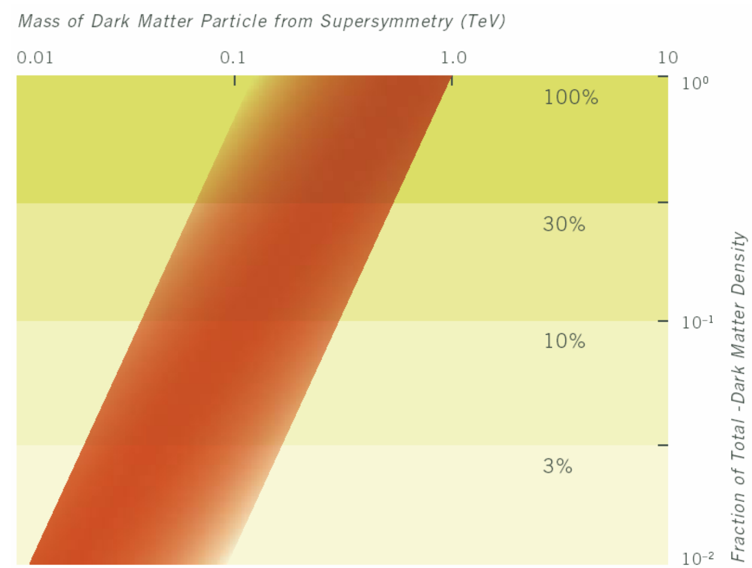




- Impose a natural relation: $\sigma_A \sim \alpha^2/m^2$

- Final $N \sim 1/\sigma_A$.

What's the constant of proportionality?



HEPAP Subpanel (2005)

Remarkable "coincidence": even without the hierarchy problem, cosmology tells us we should explore the weak scale

STABILITY

- This assumes the new weak-scale particle is stable
- Problems (p decay, extra particles, large EW corrections)

$\updownarrow$

Discrete symmetry

$\updownarrow$

Stability

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

QUANTITATIVE ANALYSIS OF DM

Battaglia, Feng, Graf, Peskin, Trodden et al. (2005)

The Approach:

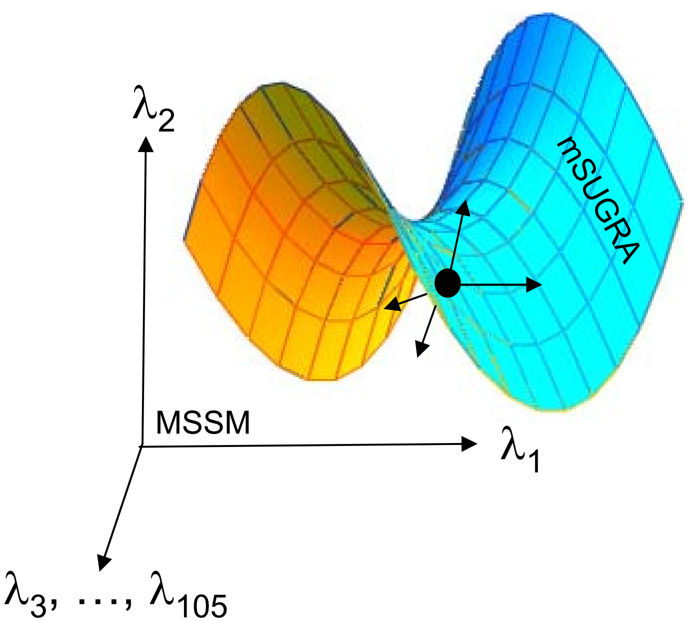
- Choose a concrete *example*: neutralinos

Goldberg (1983)

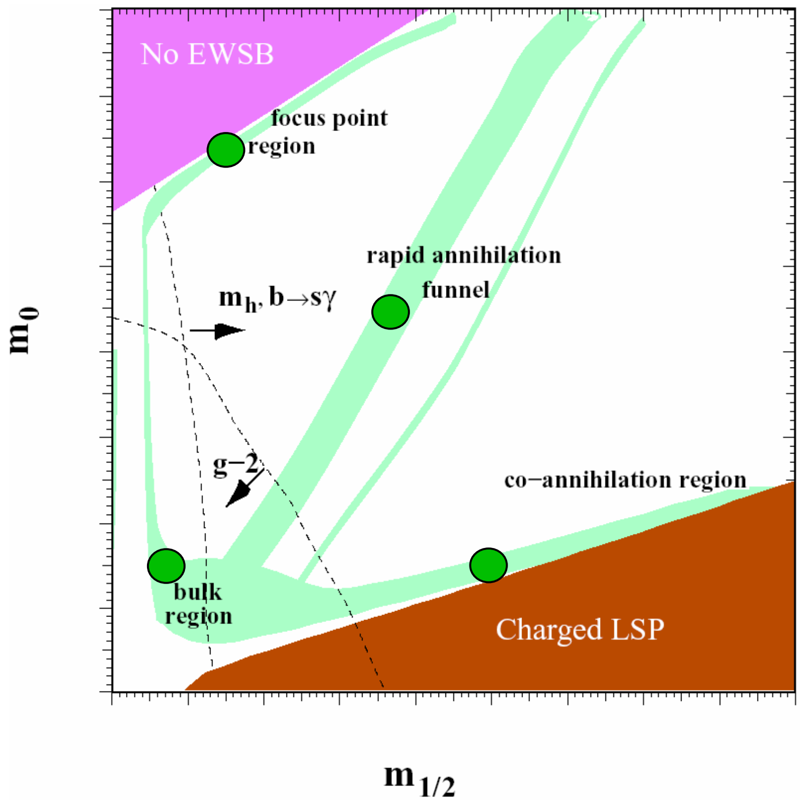
- Choose a simple model framework that encompasses many qualitatively different behaviors: mSUGRA

- Relax model-dependent assumptions and determine parameters

- Identify cosmological, astroparticle implications



Neutralino DM in mSUGRA



Cosmology excludes much of parameter space (Ω_χ too big)

Cosmology focuses attention on particular regions (Ω_χ just right)

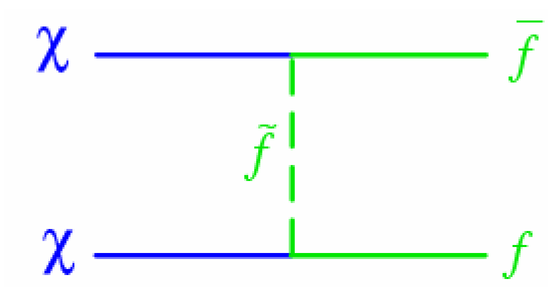
Choose representative points for detailed study

Baer et al., ISAJET   Gondolo et al., DARKSUSY   Belanger et al., MICROMEGA

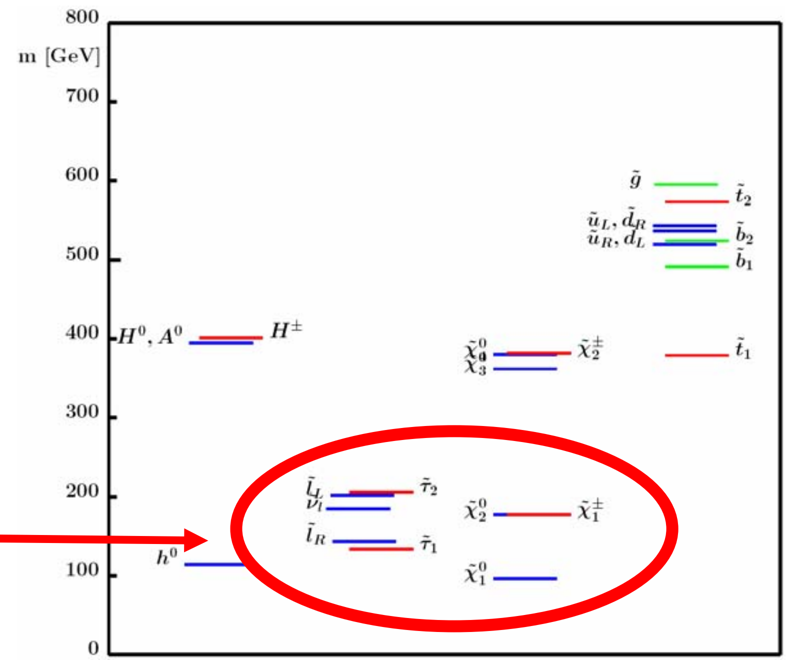
BULK REGION LCC1 (SPS1a)

$m_0, M_{1/2}, A_0, \tan\beta = 100, 250, -100, 10$ [$\mu>0$, $m_{3/2}>m_{LSP}$]

- Correct relic density obtained if χ annihilate efficiently through light sfermions:



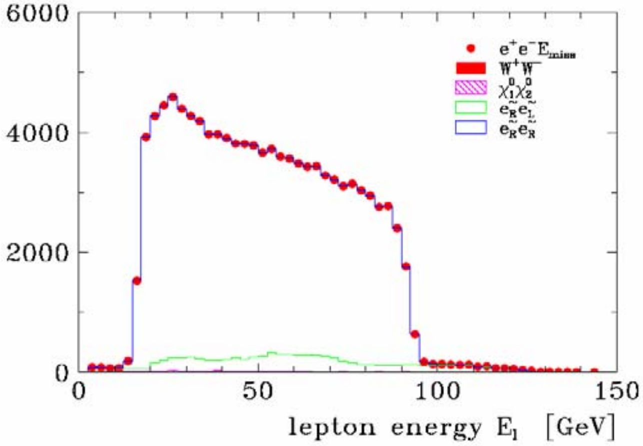
- Motivates SUSY with light $\chi, \tilde{l}$

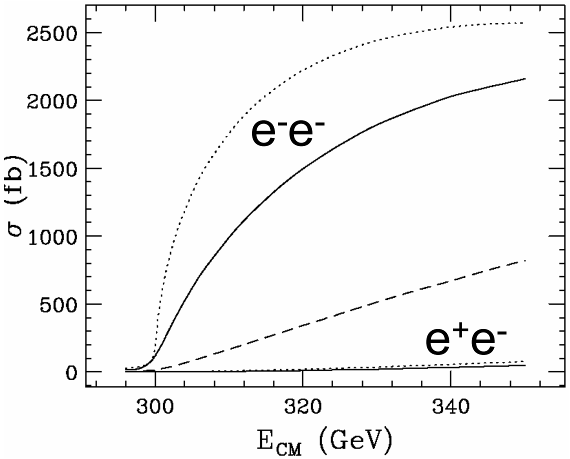


Allanach et al. (2002)

PRECISION MASSES

- Kinematic endpoints, threshold scans:
  - variable beam energy
  - e^- beam polarization
  - e^-e^- option





Feng, Peskin (2001)
Freitas, Manteuffel, Zerwas (2003)

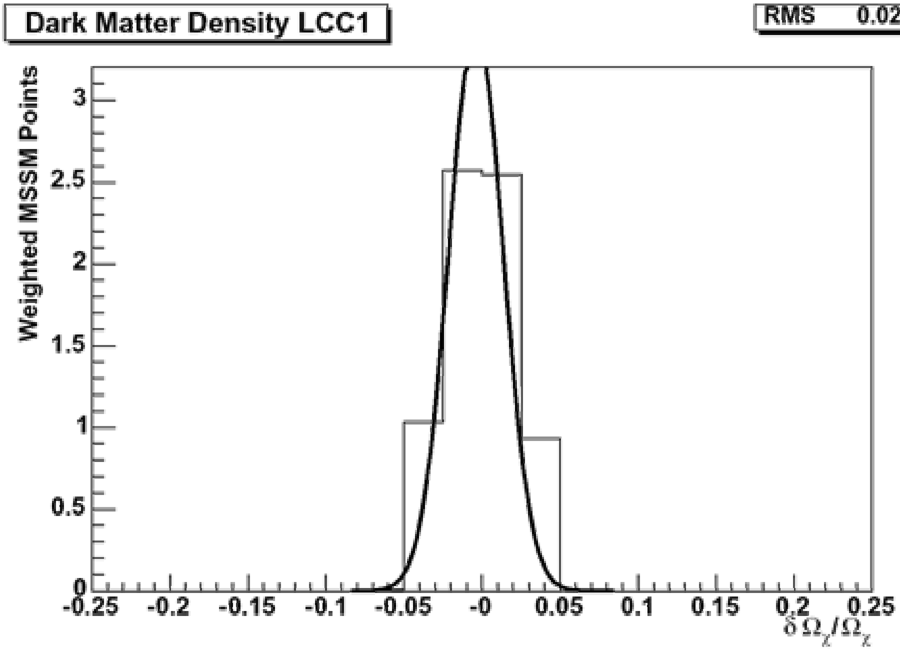
	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm, W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0\tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	3 – 5	spectra $\tilde{\chi}_3^0 \to Z\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, > 1000 fb^{-1}
$\tilde{\chi}_4^0$	377.8	3 – 5	spectra $\tilde{\chi}_4^0 \to W\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0\tilde{\chi}_4^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, > 1000 fb^{-1}
$\tilde{e}_R$	143.0	0.05	e^-e^- threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	e^-e^- threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [36]
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	206.1	1.1	estimate threshold scan, 60 fb^{-1} [36]
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{\min}()$, 1TeV, 1000 fb^{-1}

Weiglein, Martyn et al. (2004)

- Must also verify insensitivity to all other parameters

BULK RESULTS

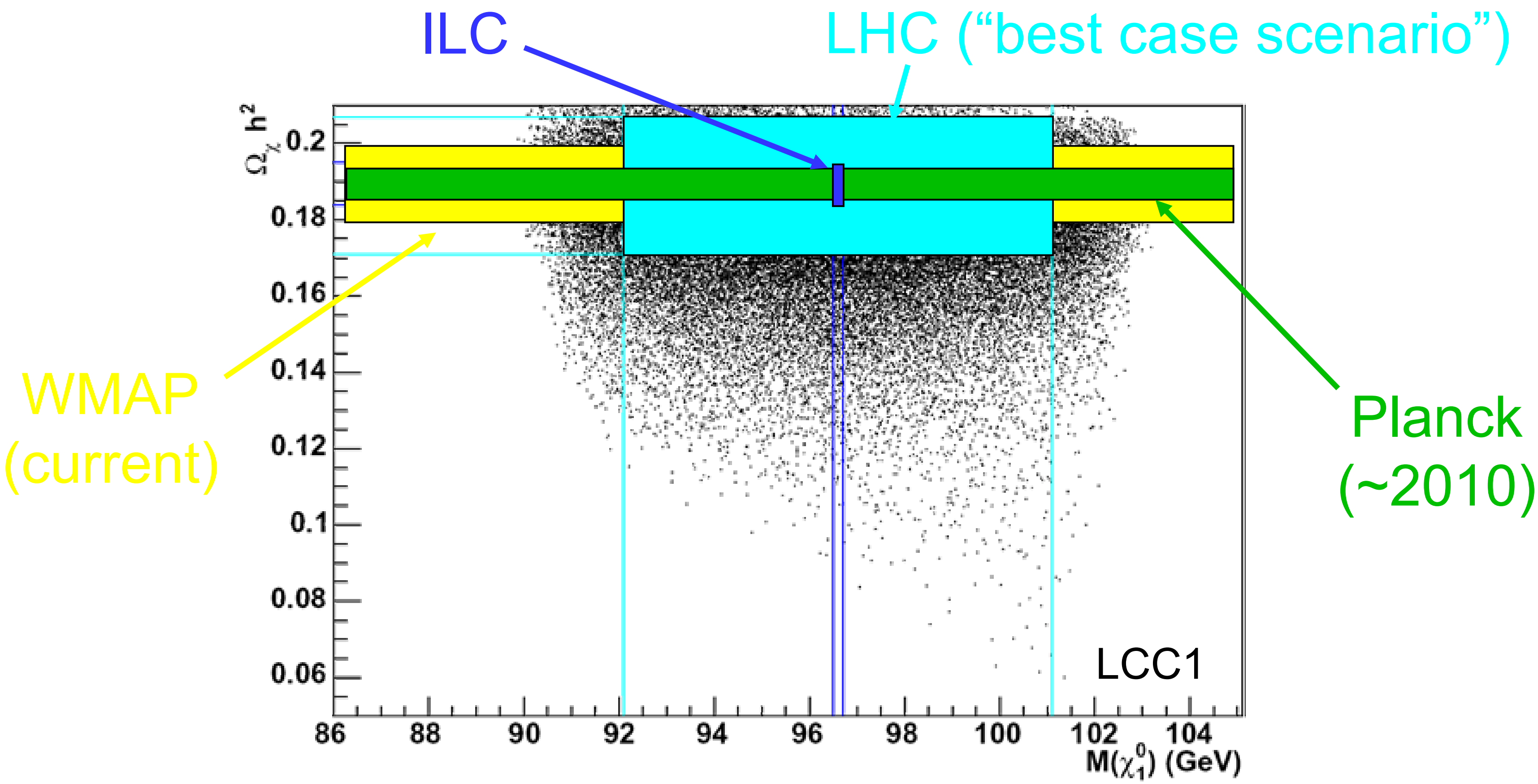
- Scan over ~20 most relevant parameters
- Weight each point by Gaussian distribution for each observable
- ~50K scan points



Battaglia (2005)

- (Preliminary) result: $\Delta\Omega_\chi/\Omega_\chi$ = 2.2% ($\Delta\Omega_\chi h^2$ = 0.0026)

RELIC DENSITY DETERMINATIONS



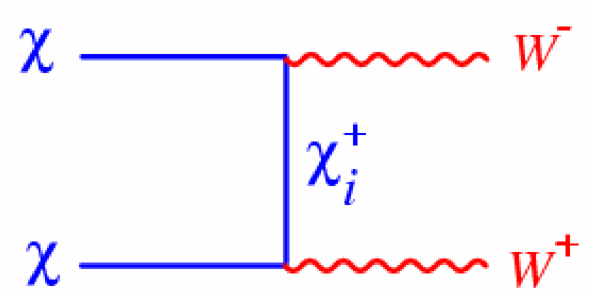
Parts per mille agreement for Ω_χ → discovery of dark matter

FOCUS POINT REGION LCC2

m_0, $M_{1/2}$, A_0, $\tan\beta$ = 3280, 300, 0, 10 [$\mu>0$, $m_{3/2}>m_{LSP}$]

- Correct relic density obtained if χ is mixed, has significant Higgsino component to enhance

Feng, Matchev, Wilczek (2000)



$$\mathcal{M}_N = \begin{pmatrix} M_1 \cos^2_W + M_2 \sin^2_W & (M_2 - M_1)\sin_W \cos_W & 0 & 0 \\ (M_2 - M_1)\sin_W \cos_W & M_1 \sin^2_W + M_2 \cos^2_W & m_Z & 0 \\ 0 & m_Z & \mu \sin 2\beta & -\mu \cos 2\beta \\ 0 & 0 & -\mu \cos 2\beta & -\mu \sin 2\beta \end{pmatrix}$$

Gauginos

Higgsinos

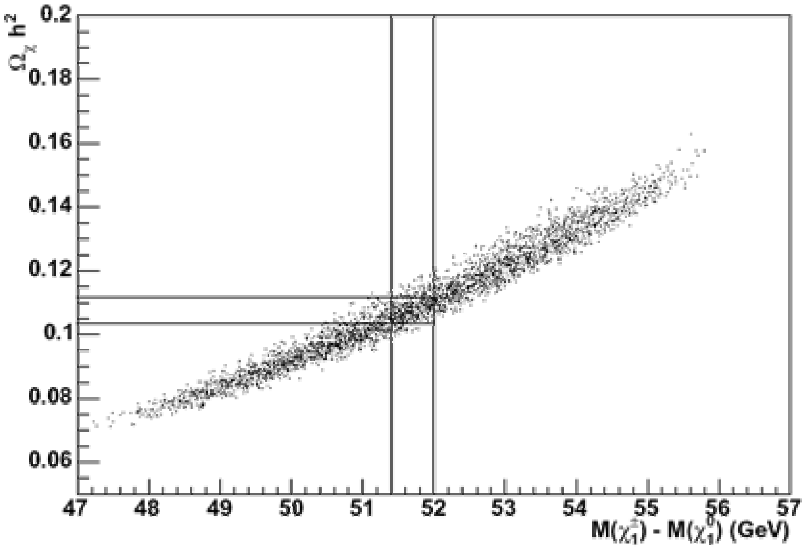
$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

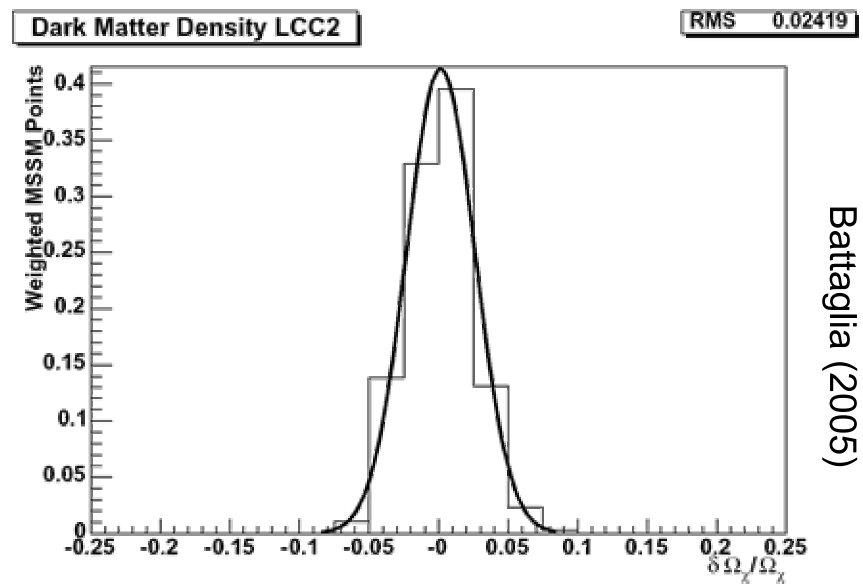
- Motivates SUSY with
  light neutralinos, charginos

FOCUS POINT RESULTS

- Ω_χ sensitive to Higgsino mixing, chargino-neutralino degeneracy

Alexander, Birkedal, Ecklund, Matchev et al. (2005)

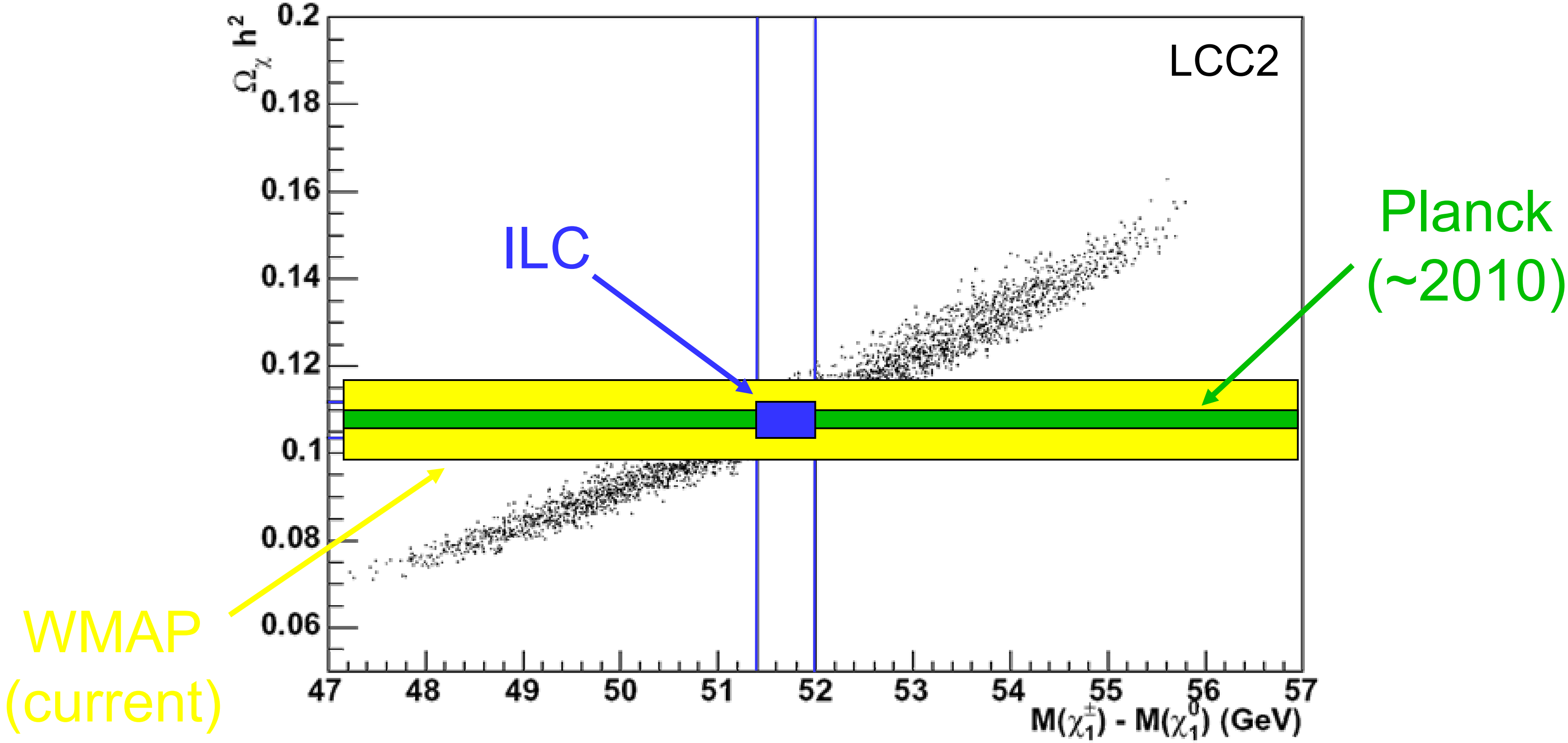




Battaglia (2005)

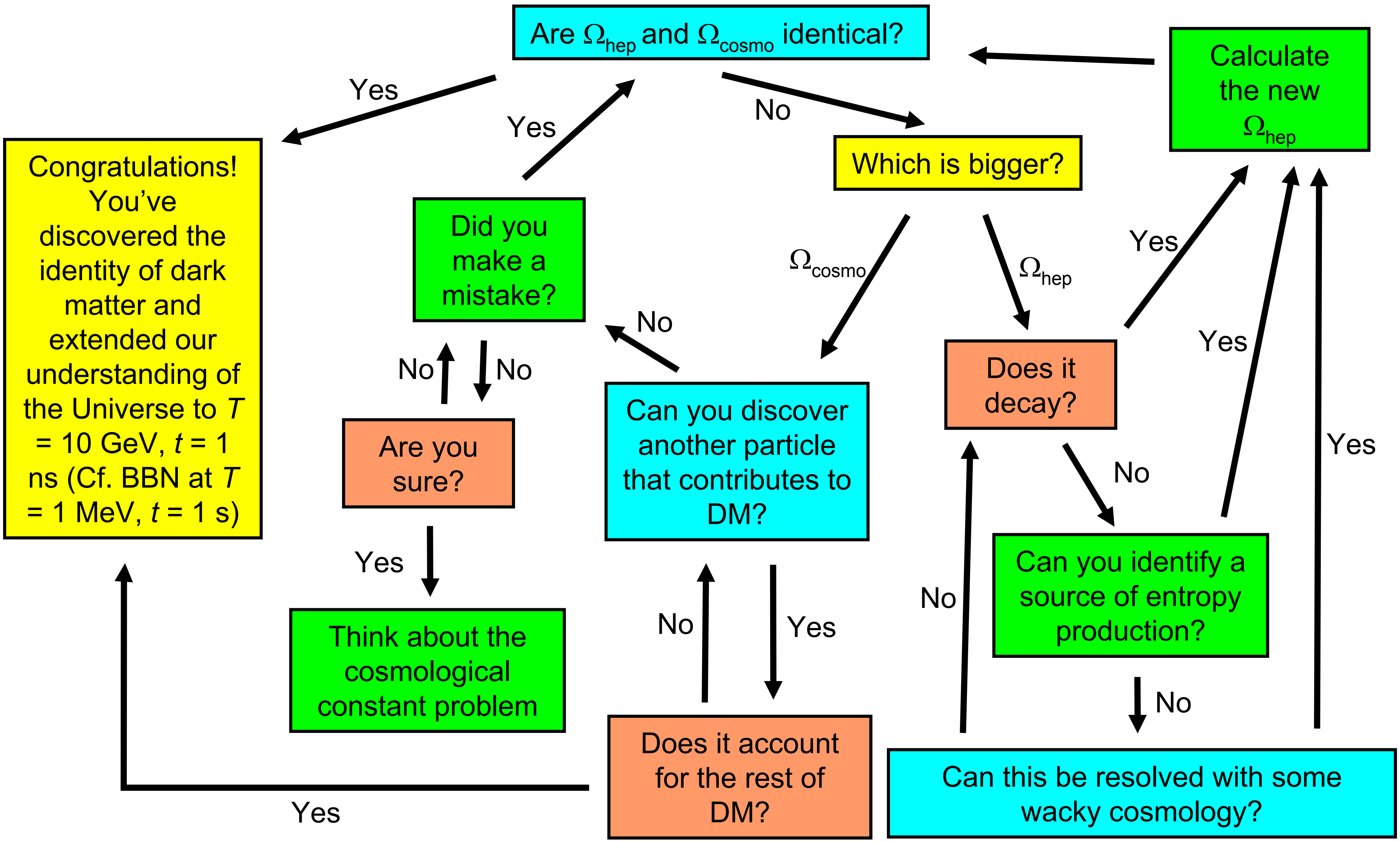
(Preliminary) result: $\Delta\Omega_\chi/\Omega_\chi$ = 2.4% ($\Delta\Omega_\chi h^2$ = 0.0029)

RELIC DENSITY DETERMINATIONS

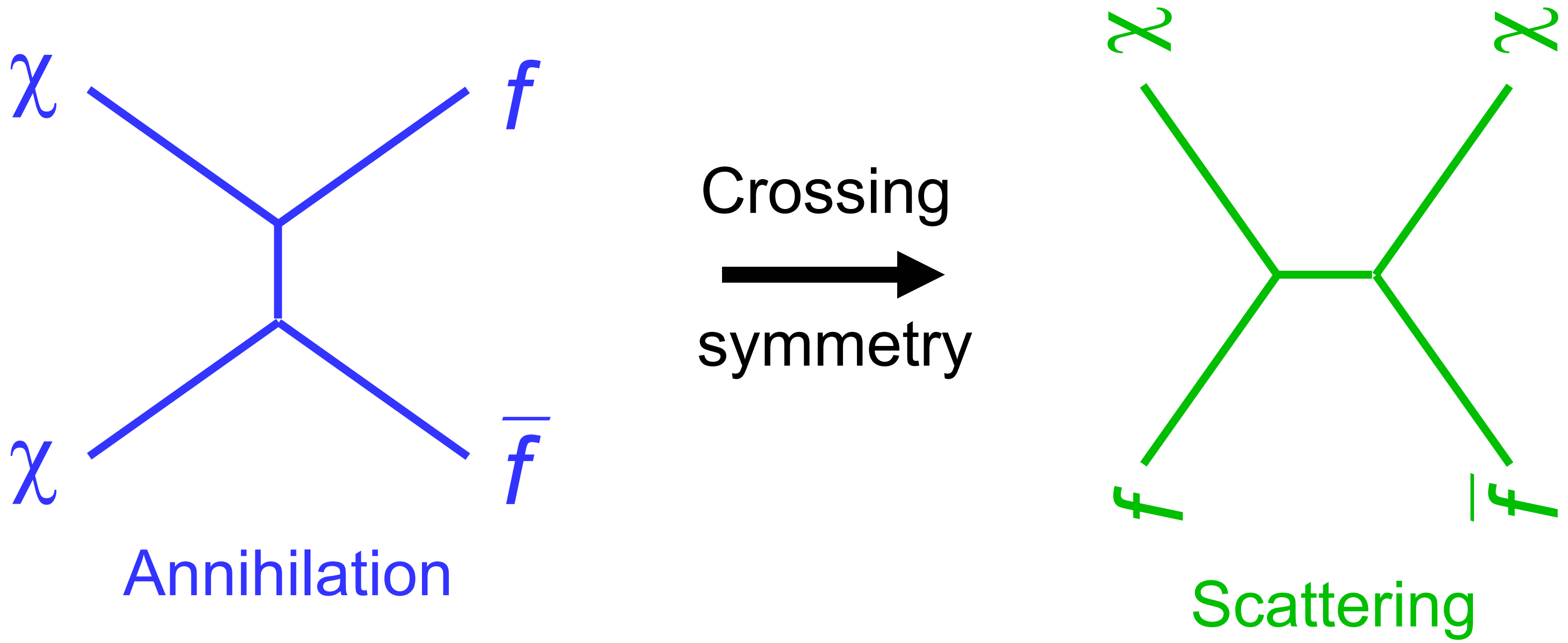


Parts per mille agreement for Ω_χ → discovery of dark matter

IDENTIFYING DARK MATTER



IMPLICATIONS FOR ASTROPARTICLE PHYSICS

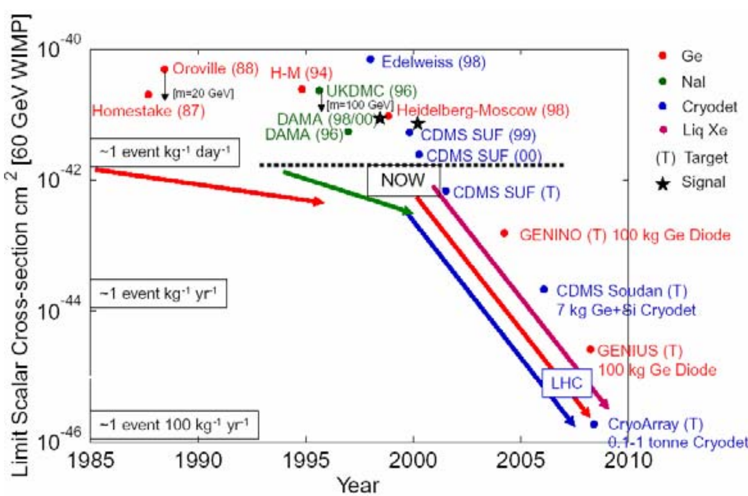


Correct relic density → Efficient annihilation then

→ Efficient scattering now

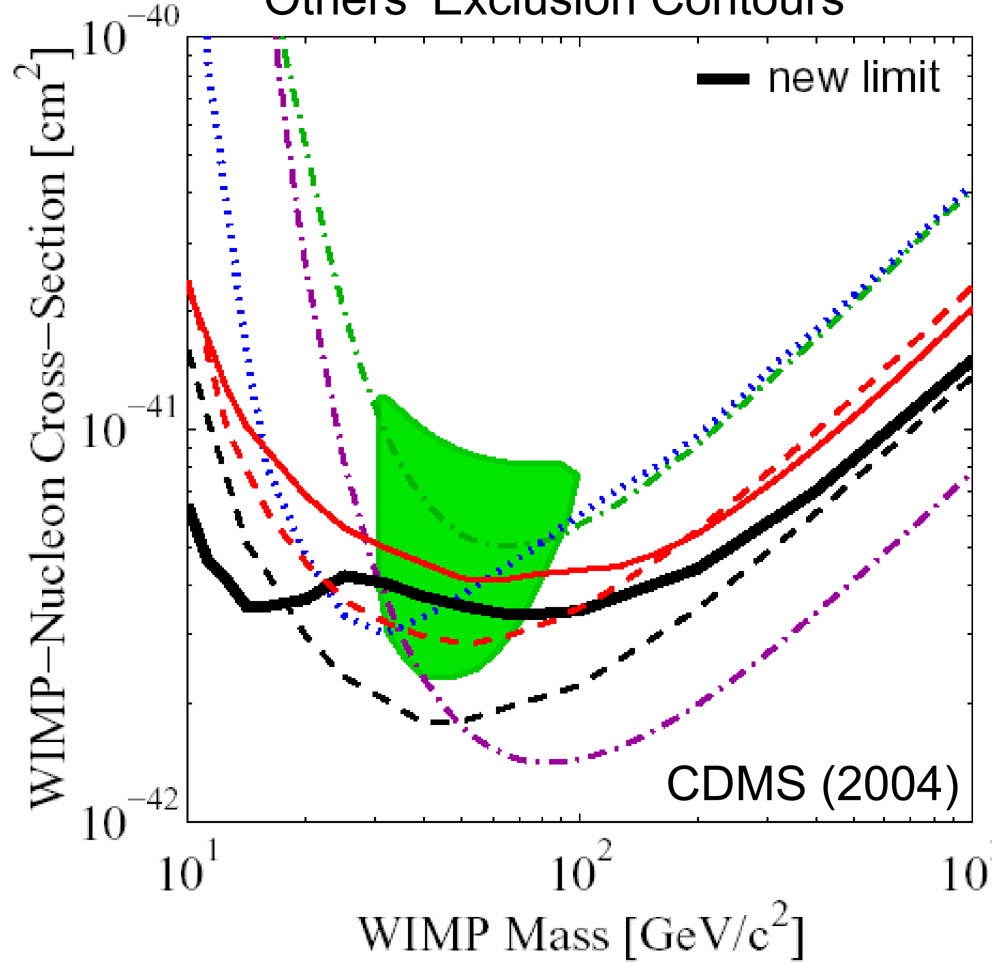
→ Efficient annihilation now

Direct Detection



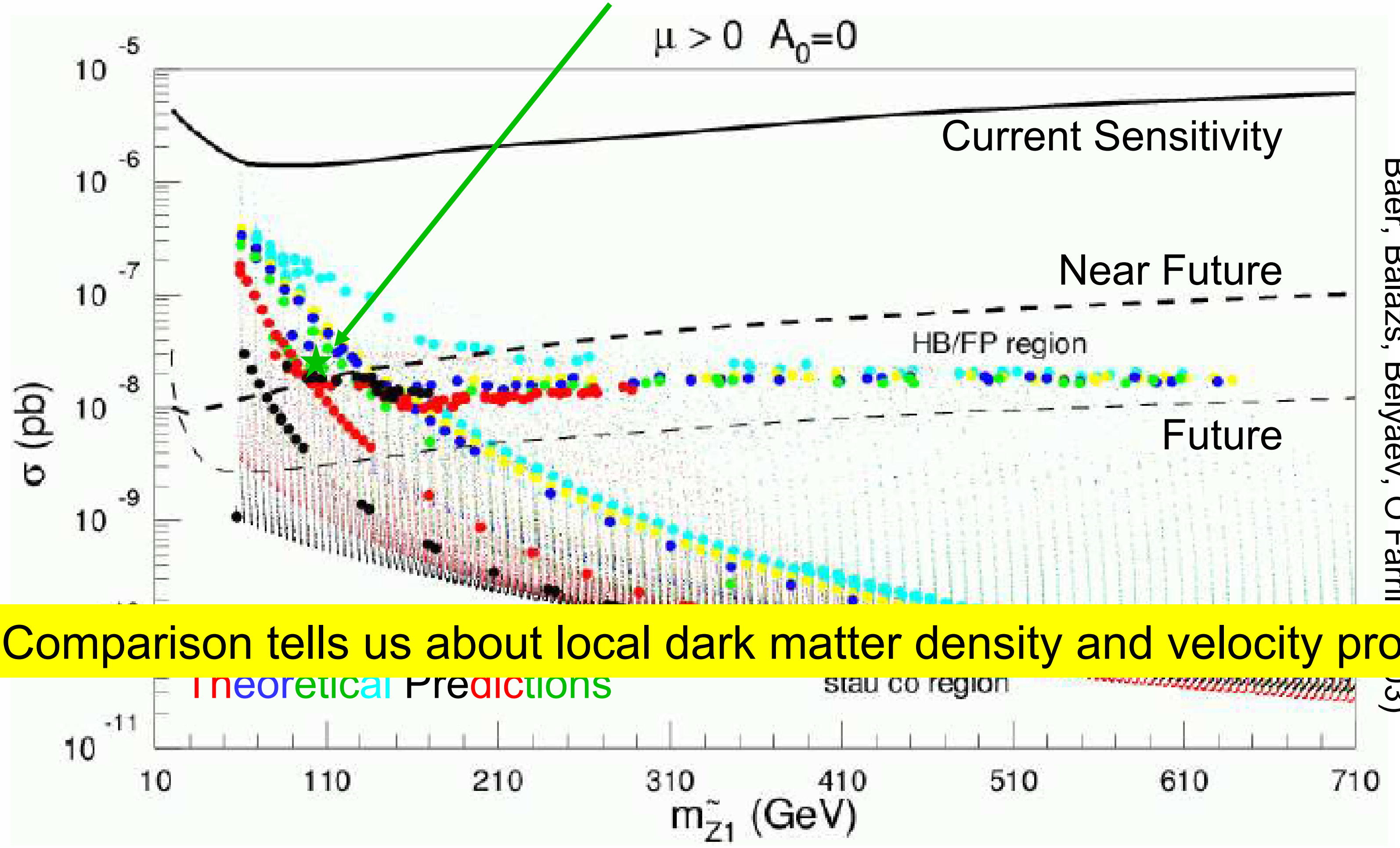
Gaitskell (2001)

DAMA Signal and
Others' Exclusion Contours



ILC IMPLICATIONS

LCC2 → m < 1 GeV, Δσ/σ < 10%

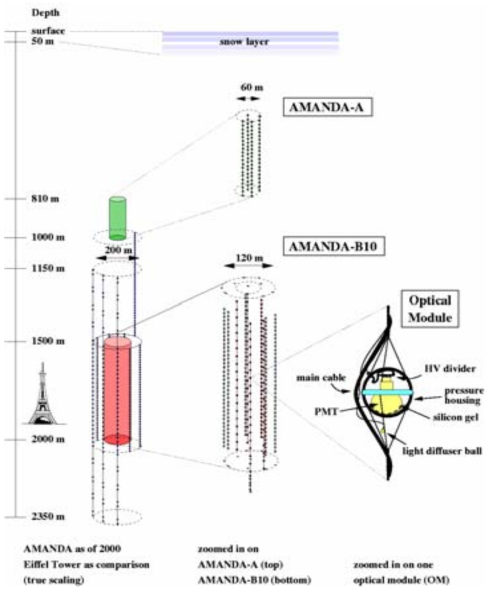


Comparison tells us about local dark matter density and velocity profiles

INDIRECT DETECTION

Dark Matter may annihilate in the center of the Sun to neutrinos, which are detected by AMANDA, IceCube.

- Comparison with colliders constrains dark matter density in the Sun, capture rates



AMANDA in the Antarctic Ice

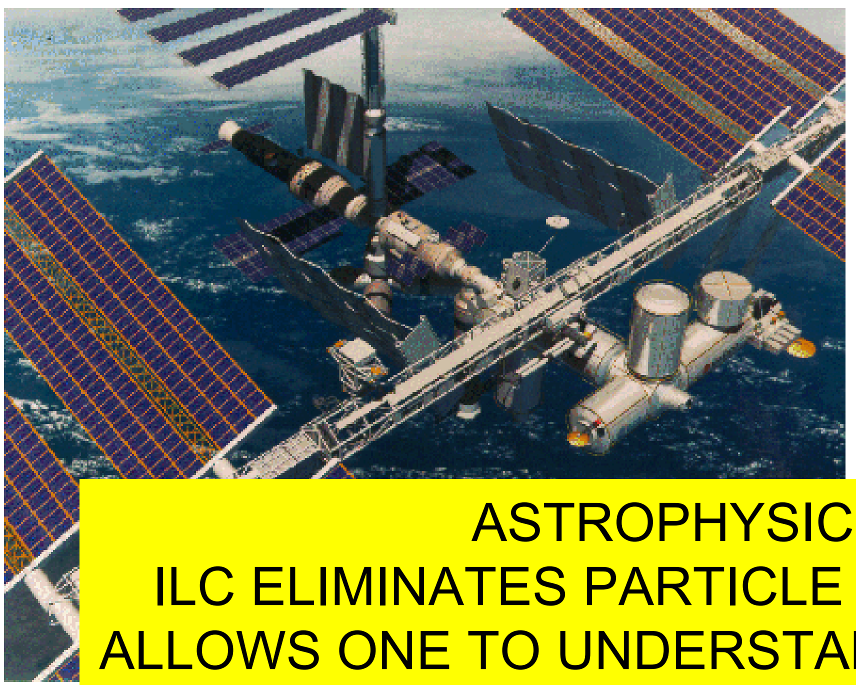
Dark Matter annihilates in __the galactic center__ to
a place

__photons__ , which are detected by _GLAST, HESS, ..._ .
some particles an experiment

Comparison with colliders constrains DM density at the center of the galaxy

Dark Matter annihilates in ______the halo______ to
a place

__positrons__ , which are detected by _AMS on the ISS__ .
some particles — an experiment



- Comparison with colliders constrains dark matter density profiles in the halo

ASTROPHYSICS VIEWPOINT:
ILC ELIMINATES PARTICLE PHYSICS UNCERTAINTIES,
ALLOWS ONE TO UNDERSTAND STRUCTURE FORMATION

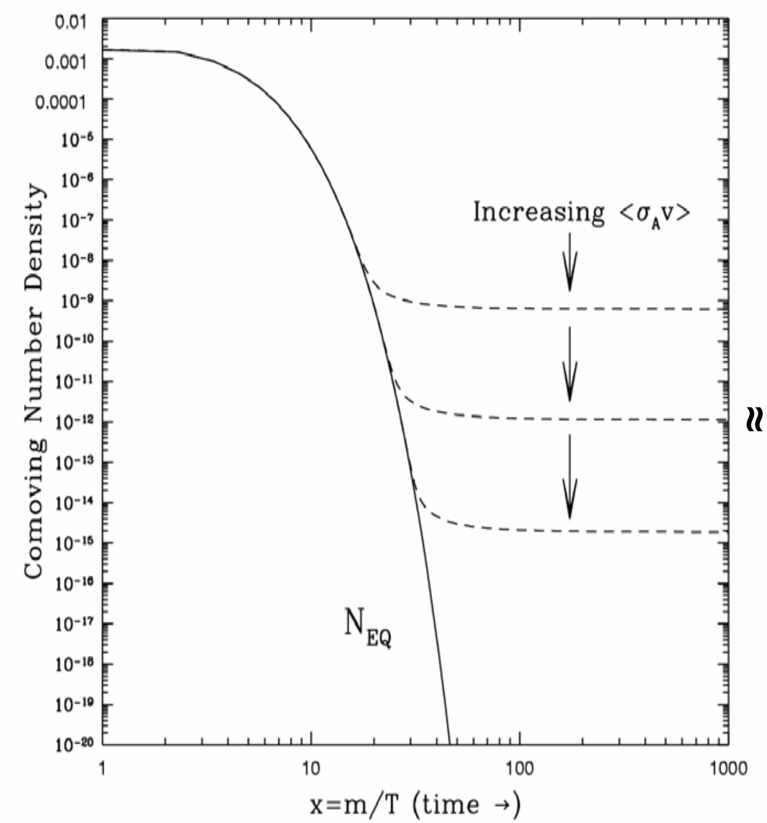
ALTERNATIVE DARK MATTER

- All of these signals rely on DM having electroweak interactions. Is this required?
- No – the only required DM interactions are gravitational (much weaker than electroweak).
- But the relic density argument strongly prefers weak interactions.

Is there an exception to this rule?

SUPERWIMPS

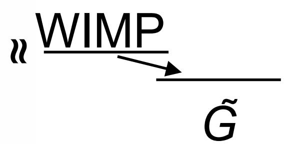
Feng, Rajaraman, Takayama (2003)



- Consider SUSY again:

  Gravitons → gravitinos $\tilde{G}$

- What if the $\tilde{G}$ is the lightest superpartner?



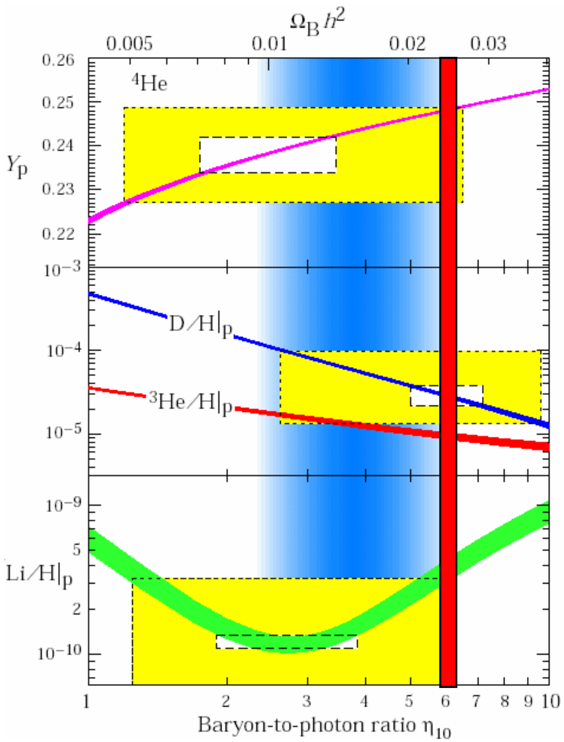
M_{Pl}^2/M_W^3 ~ month

- A month passes…then all WIMPs decay to gravitinos – a completely natural scenario with long decay times

Gravitinos naturally inherit the right density, but they interact only gravitationally – they are “superWIMPs”

Big Bang Nucleosynthesis

Late decays may modify light element abundances



Fields, Sarkar, PDG (2002)

After WMAP

- $\eta_D = \eta_{CMB}$
- Independent ^{7}Li measurements are all low by factor of 3:

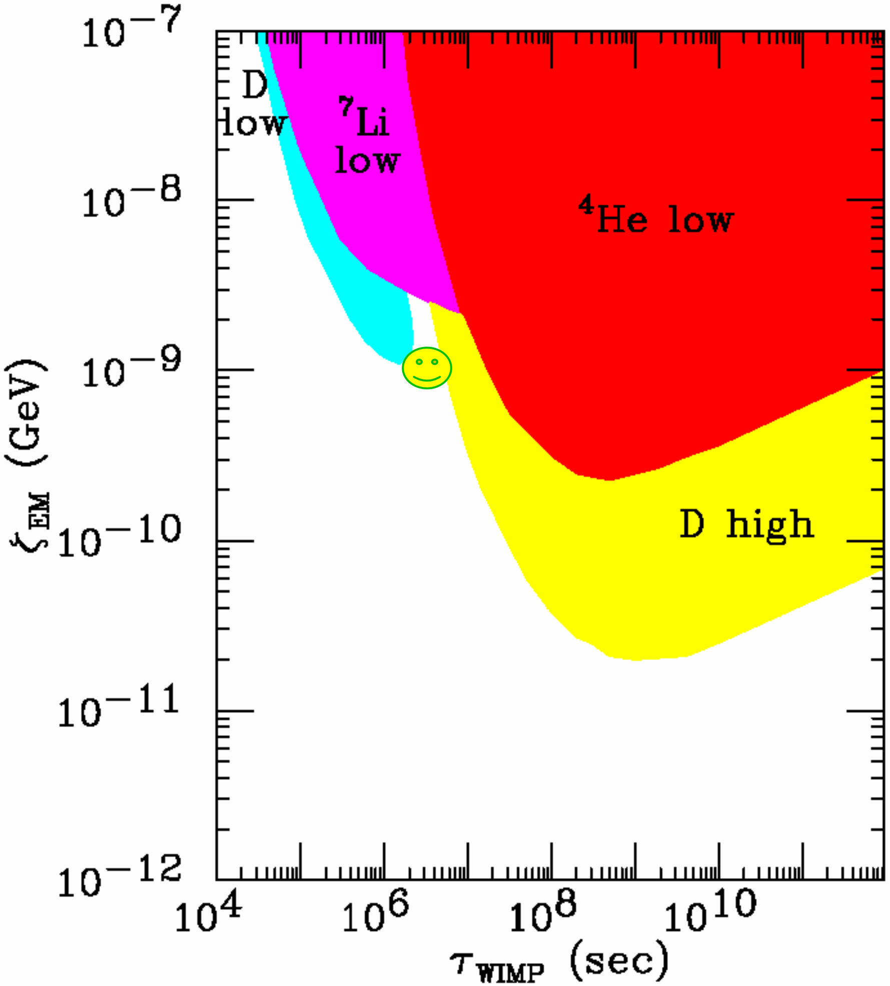
$$^7\mathrm{Li/H} = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\%\ \mathrm{CL})\ [27]$$
$$^7\mathrm{Li/H} = 1.72^{+0.28}_{-0.22} \times 10^{-10} \quad (1\sigma + \mathrm{sys})\ [28]$$
$$^7\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (\mathrm{stat} + \mathrm{sys},\ 95\%\ \mathrm{CL})\ [29]$$

- ^{7}Li is now a serious problem

Jedamzik (2004)

BBN EM Constraints

- NLSP = WIMP → Energy release is dominantly EM (even mesons decay first)
- EM energy quickly thermalized, so BBN constrains (τ , ζ_{EM})
- BBN constraints weak for early decays: hard γ , e^- thermalized in hot universe
- Best fit reduces ^{7}Li: ☺



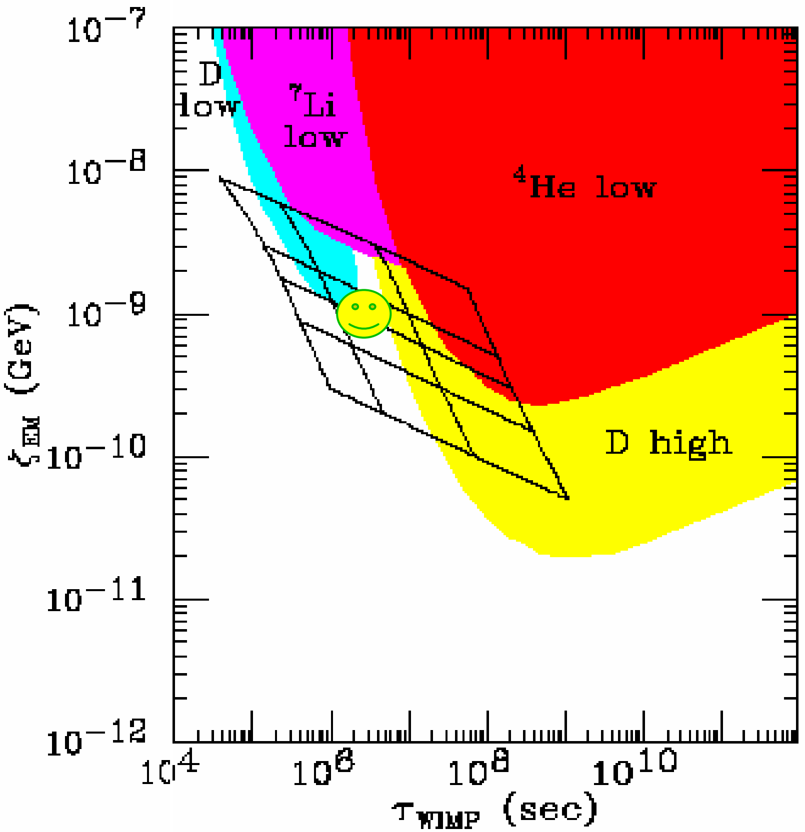
Cyburt, Ellis, Fields, Olive (2002)

BBN EM Predictions

- Consider $\tilde{\tau} \rightarrow \tilde{G}\,\tau$
- Grid: Predictions for

  $m_{\tilde{G}}$ = 100 GeV – 3 TeV (top to bottom)

  Δm = 600 GeV – 100 GeV (left to right)
- Some parameter space excluded, but much survives
- SuperWIMP DM naturally explains ^{7}Li !



Feng, Rajaraman, Takayama (2003)

SuperWIMP Warm Dark Matter

- Problems for cold dark matter: cuspy halos, dense cores predicted but not observed.

- Some proposed solutions:

  - Self-interacting cold dark matter

    Spergel, Steinhardt (1999)
    Kusenko, Steinhardt (2001)

  - 3 extra nm-sized dimensions

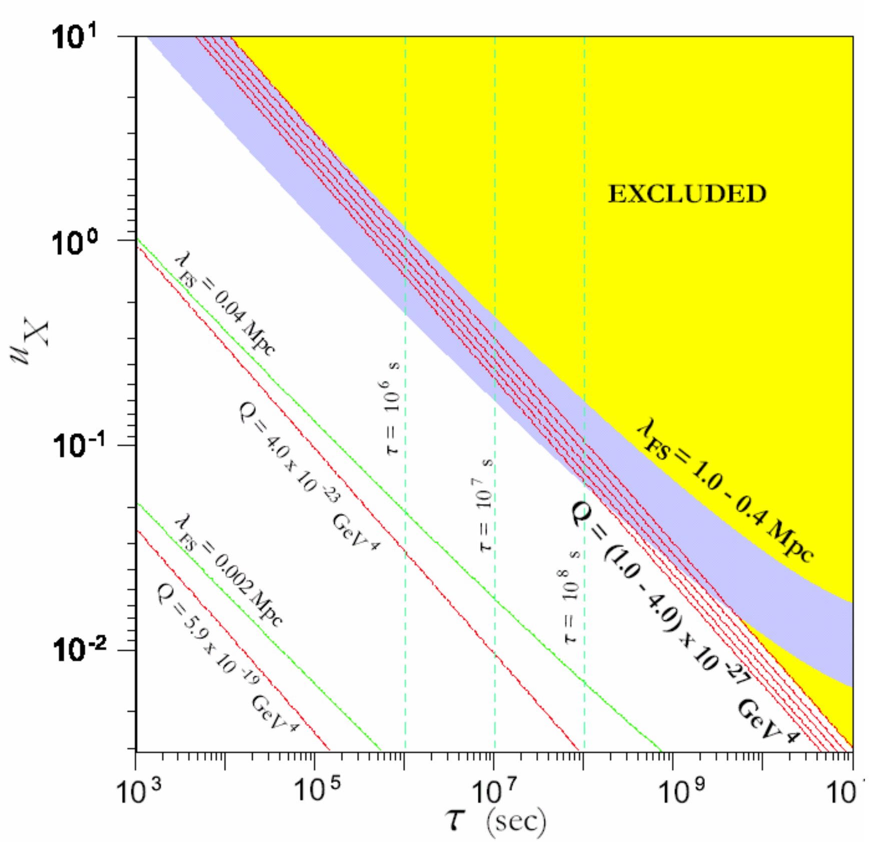
    Qin, Pen, Silk (2005)

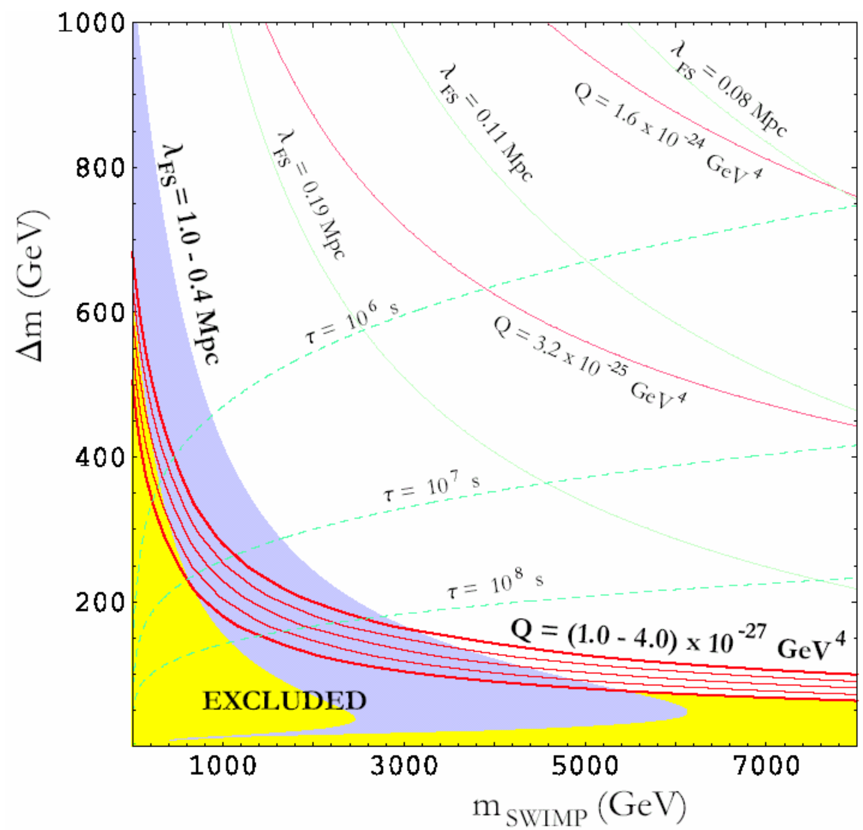
- SuperWIMPs are created at late times with significant velocity – they are warm!

  Kaplinghat (2005)
  Cembranos, Feng, Rajaraman, Takayama (2005)

SuperWIMP Warm Dark Matter

Late decays around 10^6 s naturally solve small scale structure problems -- in standard SUSY !





Cembranos, Feng, Rajaraman, Takayama (2005)

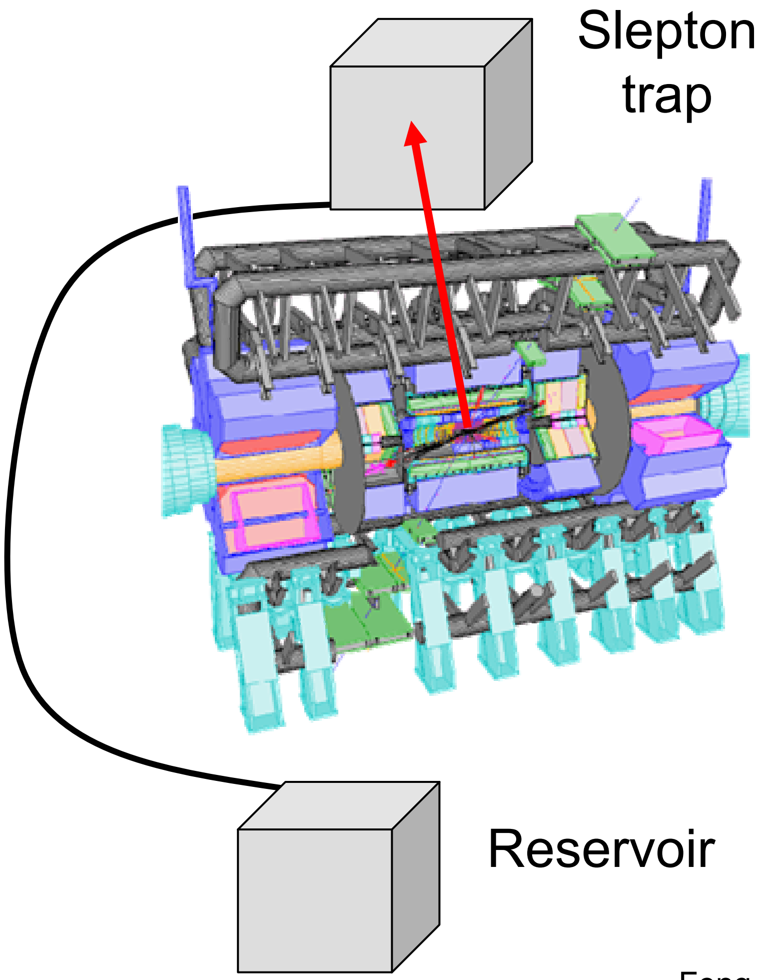
WORST CASE SCENARIO?

Looks bad – dark matter couplings suppressed by 10^{-16}

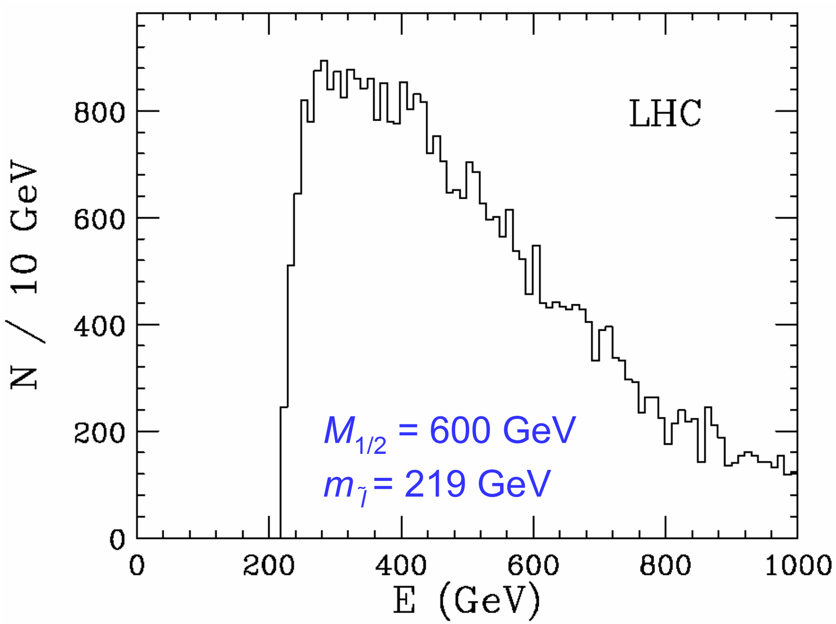
But, cosmology → decaying WIMPs are sleptons: heavy, charged, live ~ a month – can be trapped, then moved to a quiet environment to observe decays.

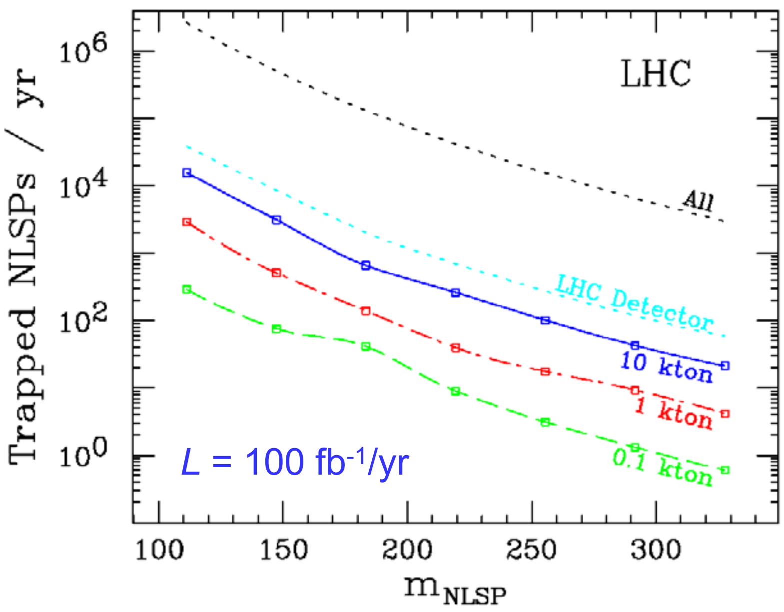
How many can be trapped?

Hamaguchi, Kuno, Nakaya, Nojiri (2004)
Feng, Smith (2004)



Large Hadron Collider



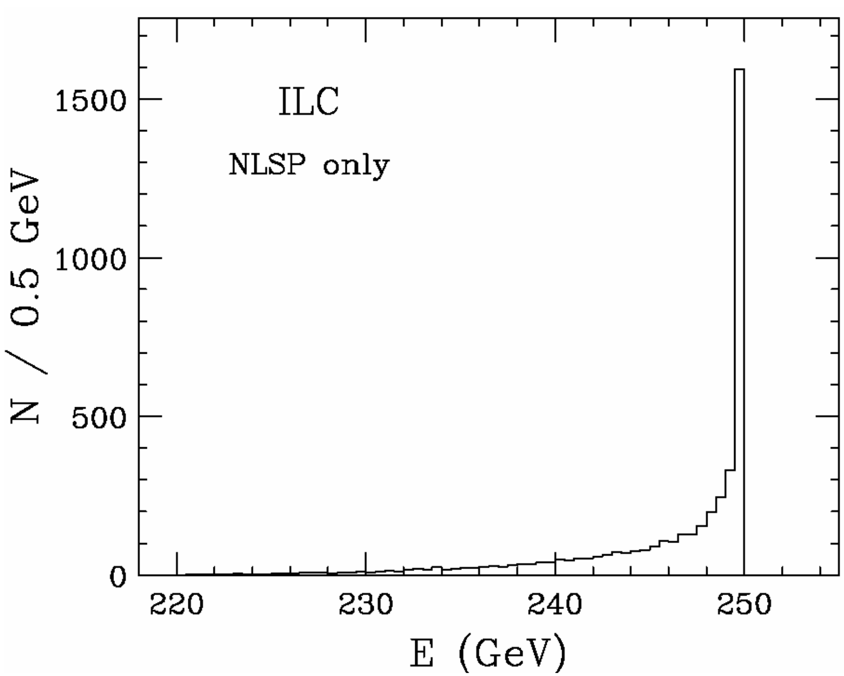


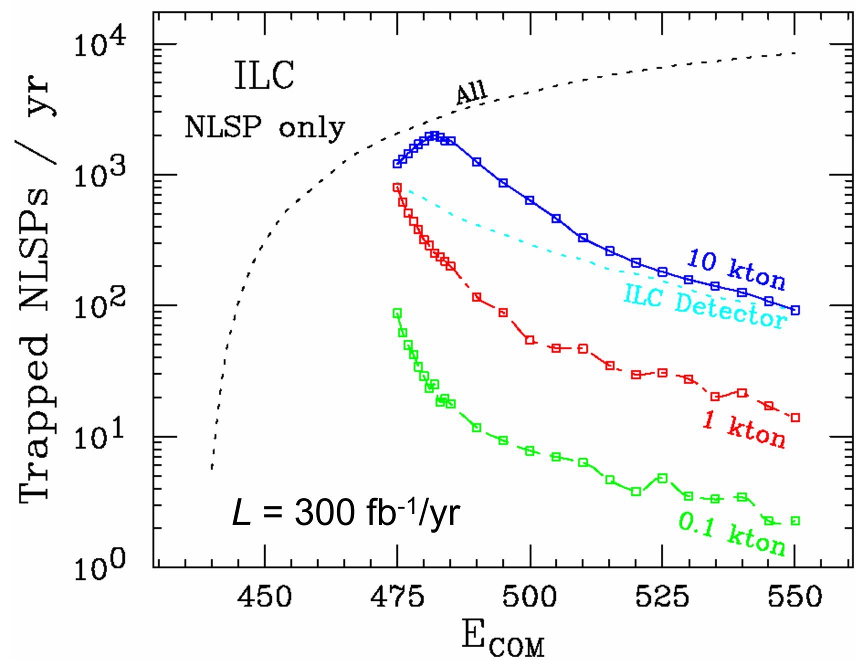
If squarks, gluinos light, many sleptons, but most are fast:

O(1)% are caught in 10 kton trap

International Linear Collider

$m_{\tilde{\tau}_R}$ 219.3 GeV } NLSP only





Can tune beam energy to produce slow sleptons:

75% are caught in 10 kton trap

IMPLICATIONS FROM SLEPTON DECAYS

$$\Gamma(\tilde{\ell} \to \ell \tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{\ell}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^2}\right]^4$$

- Measurement of Γ *and* $E_l \rightarrow m_{\tilde{G}}$ *and* M_*
  - Probes gravity in a particle physics experiment!
  - Measurement of G_{Newton} on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - BBN, CMB in the lab

  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines F : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

CONCLUSIONS

- Cosmology now provides sharp problems that require particle physics answers.
- Dark matter at colliders is highly motiviated; two classes: WIMPs and superWIMPs
- If DM is either of these, we will identify DM with the LHC and ILC.