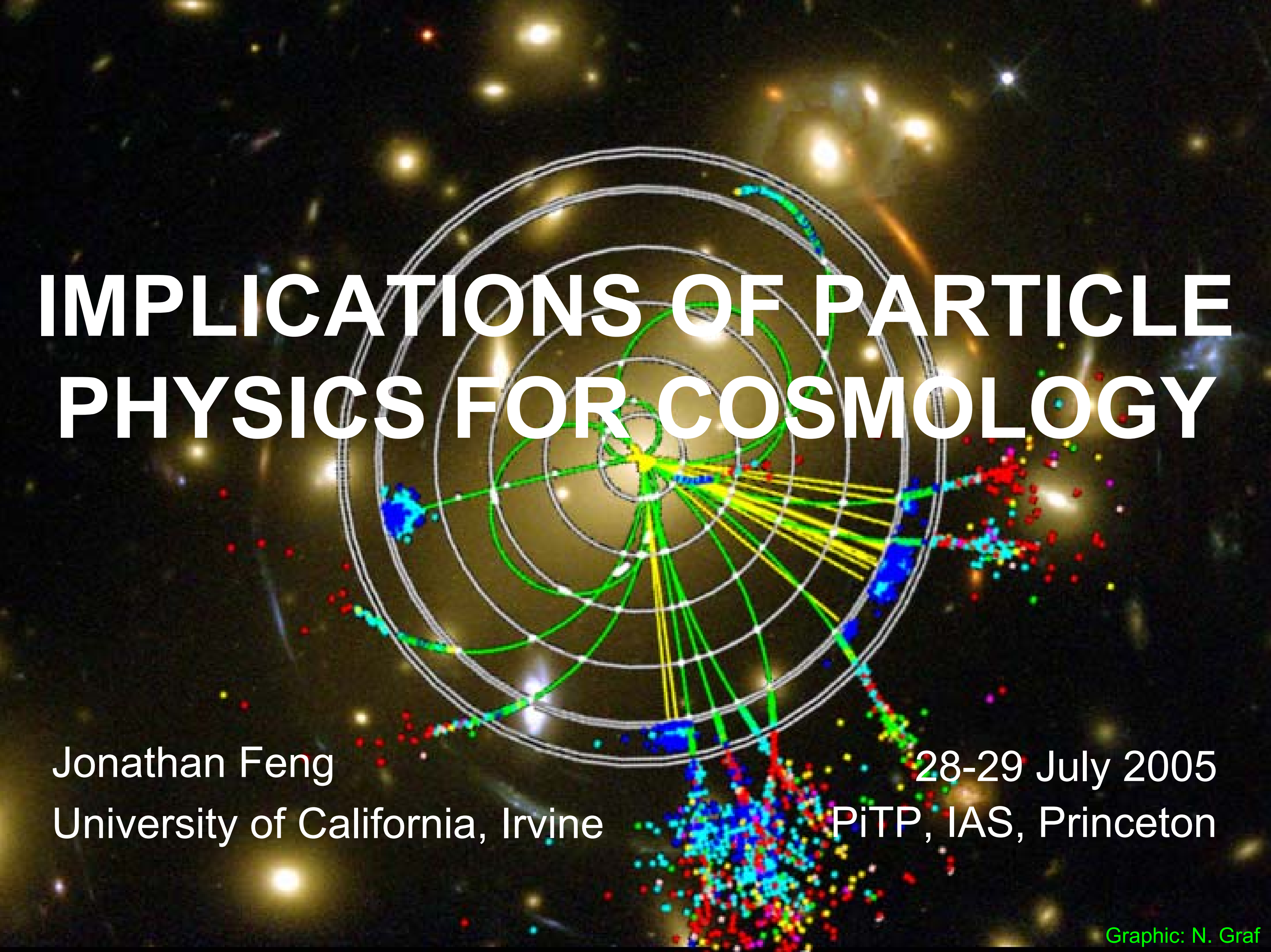


IMPLICATIONS OF PARTICLE PHYSICS FOR COSMOLOGY

Jonathan Feng
University of California, Irvine

28-29 July 2005
PiTP, IAS, Princeton

Graphic: N. Graf

OUTLINE

LECTURE 1

The Universe Observed, WIMP Cosmology

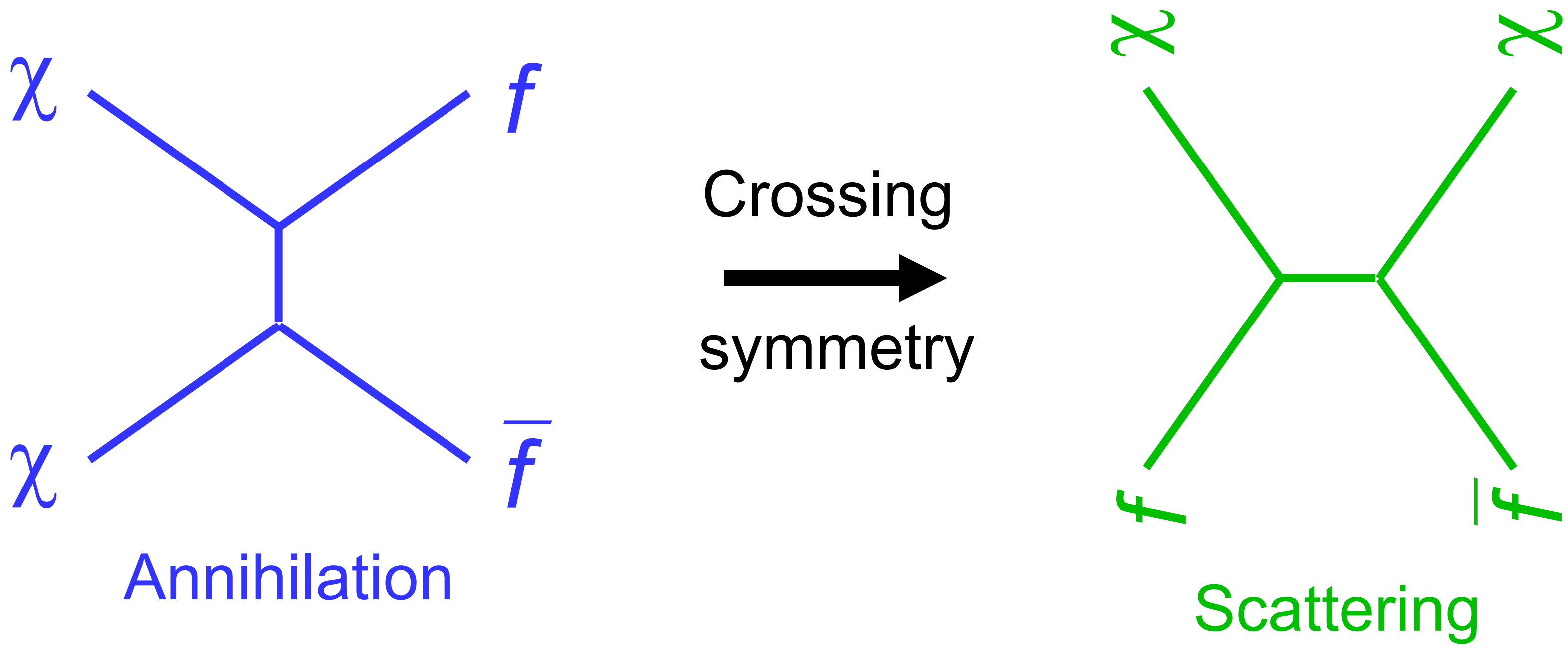
LECTURE 2

WIMP Detection, WIMPs at Colliders

LECTURE 3

Gravitino Cosmology, SuperWIMPs at Colliders

WIMP Detection: No-Lose "Theorem"



Correct relic density → Efficient annihilation then

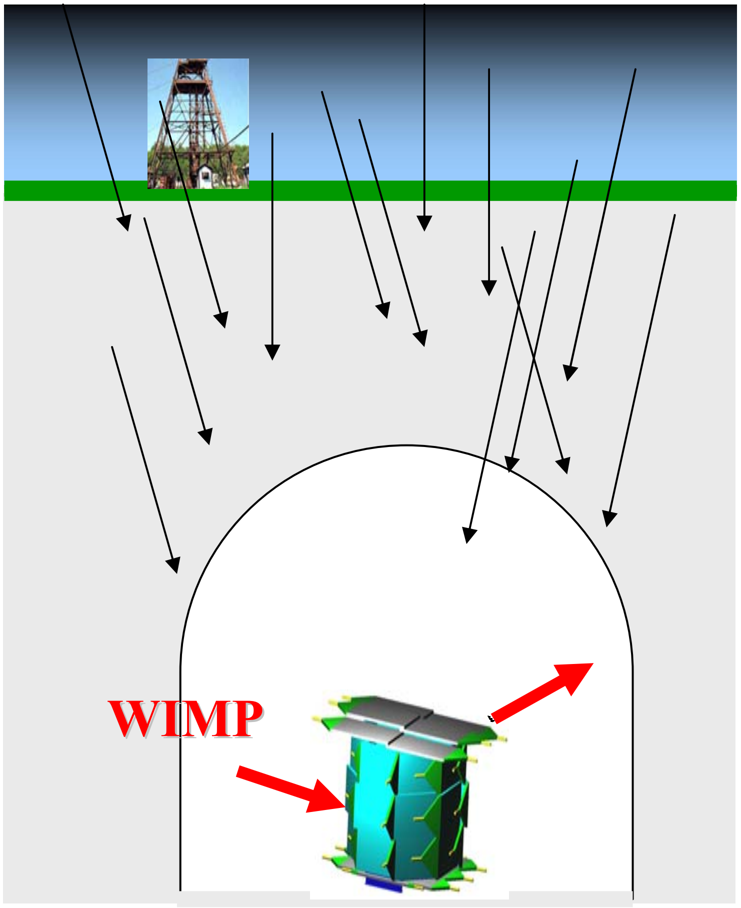
→ Efficient scattering now

→ Efficient annihilation now

Direct Detection

- Most satisfying detection: recoils from dark matter bumping into detectors

- Two strategies:
  - Few event detection (background discrimination)
  - Annual modulation (statistics, systematics)

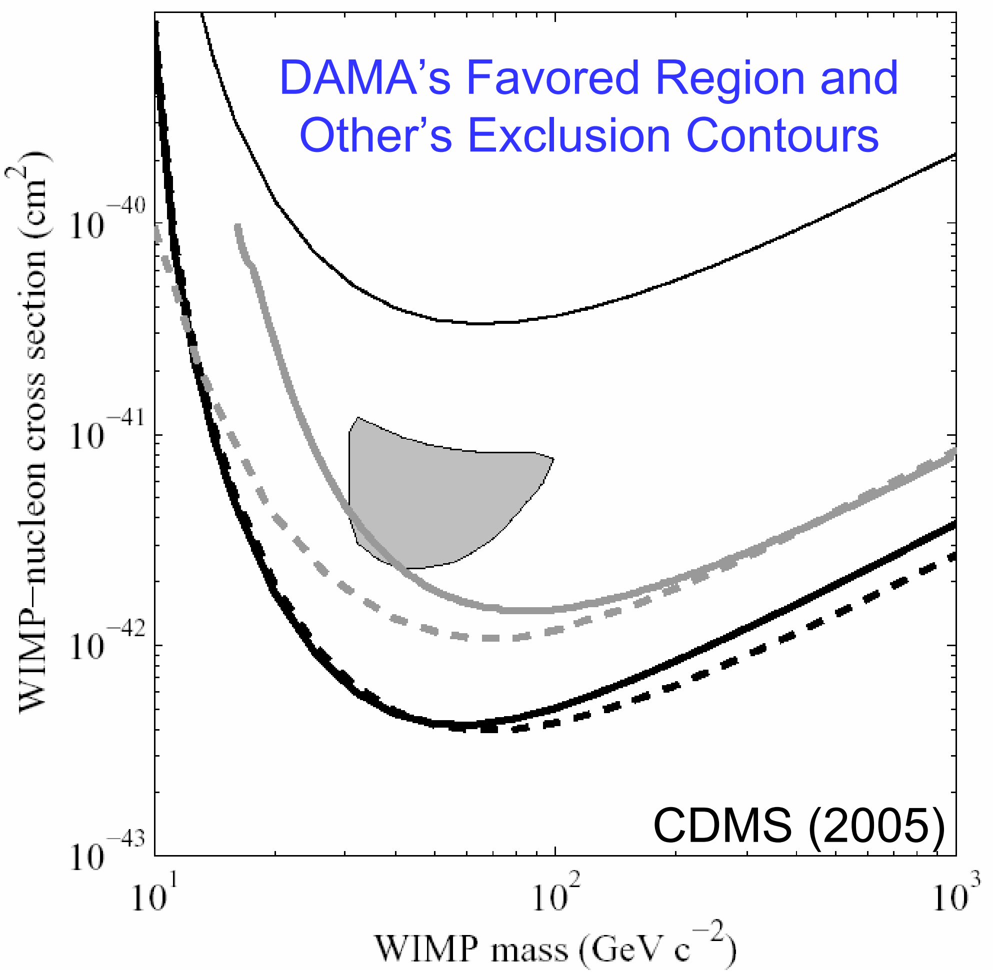


Direct Detection: Current

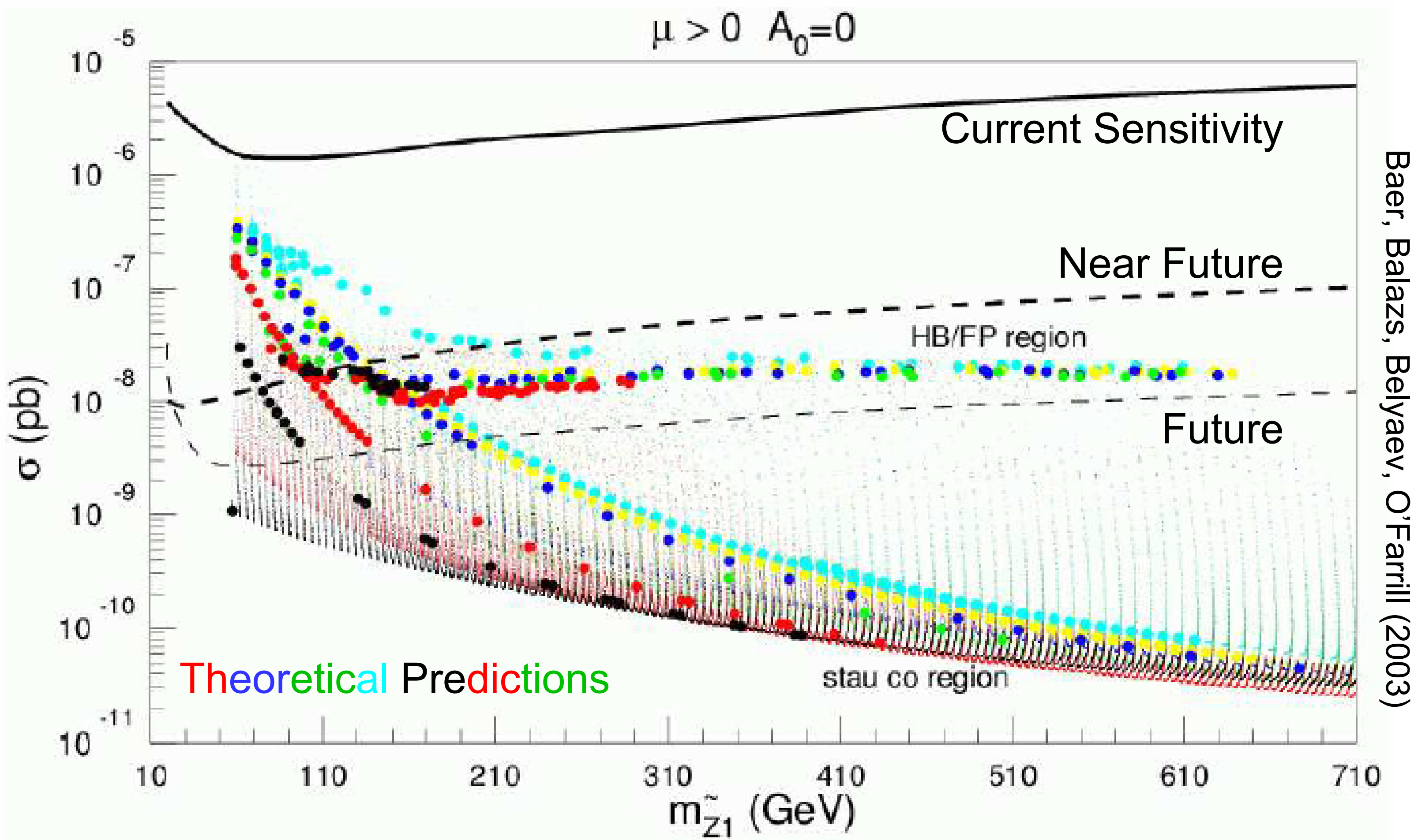
- Spin-independent scattering most promising for SUSY

Goodman, Witten (1984)

- Theorists: χq scattering
- Expts: χ nucleus scattering
- Meet in middle: χp scattering



Direct Detection: Future



Indirect Detection

Dark Matter Madlibs!

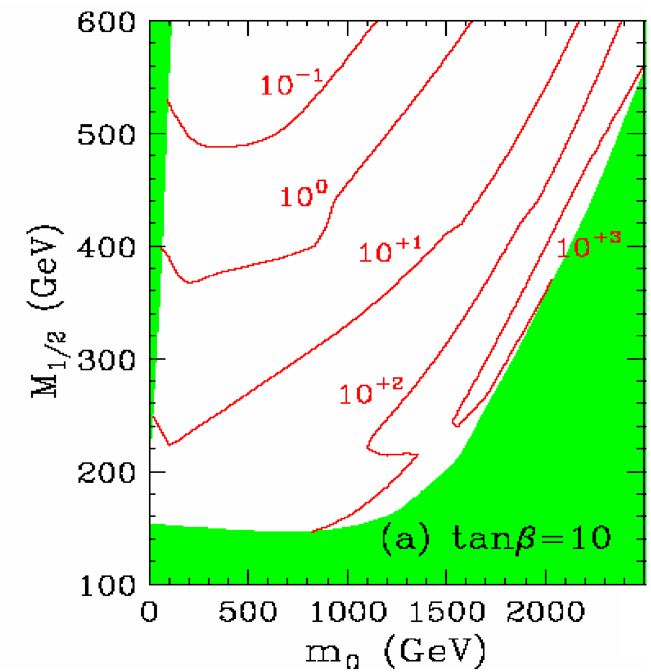
Dark matter annihilates in ____________________ to
a place

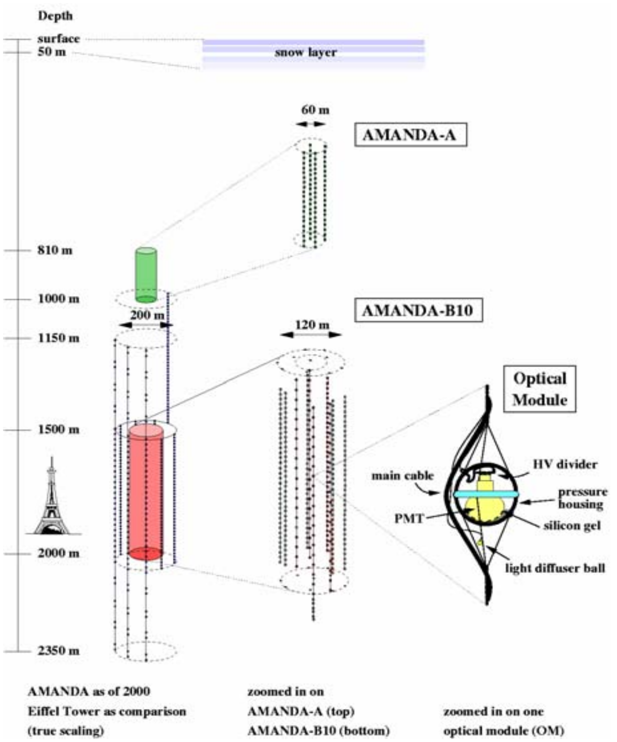
____________ , which are detected by ________________ .
particles an experiment

Dark Matter annihilates in __the center of the Sun__ to
a place

__neutrinos__ , which are detected by __AMANDA, IceCube__ .
some particles an experiment

$\nu \rightarrow \mu\ (\mathrm{km}^{-2}\ \mathrm{yr}^{-1})$

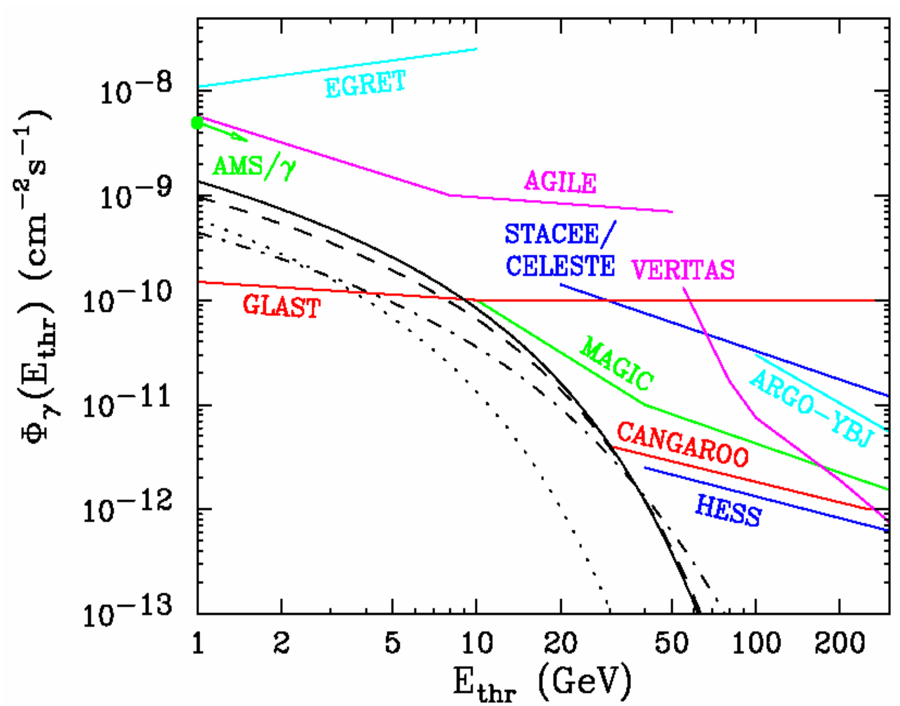




AMANDA in the Antarctic Ice

Dark Matter annihilates in __the galactic center__ to
a place

__photons__ , which are detected by __HESS, GLAST, …__ .
some particles an experiment

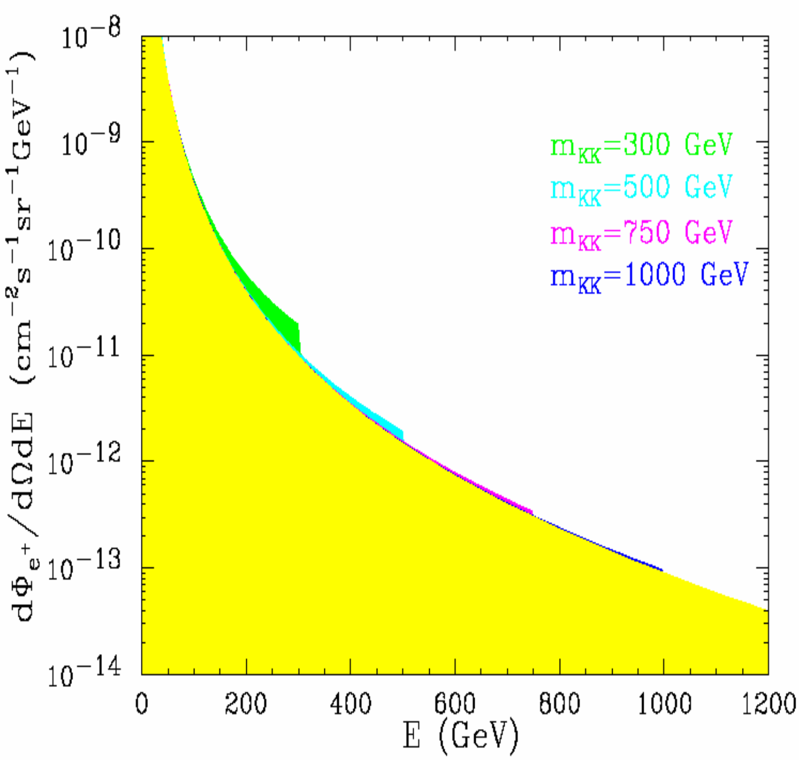


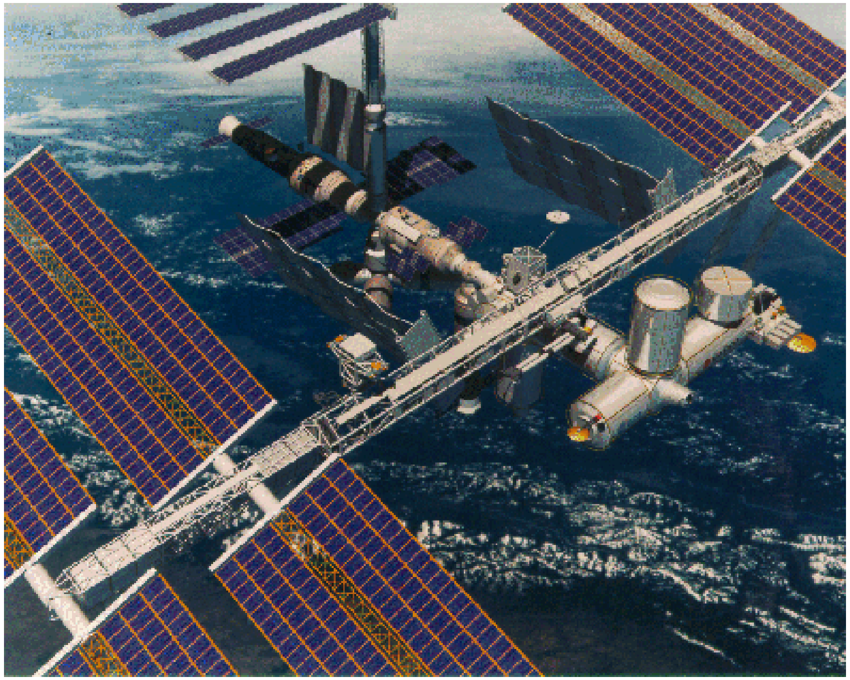
Typically $\chi\chi \not\to \gamma\gamma$,

so $\chi\chi \to f\bar{f} \to \gamma$

Dark Matter annihilates in ______the halo______ to
a place

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

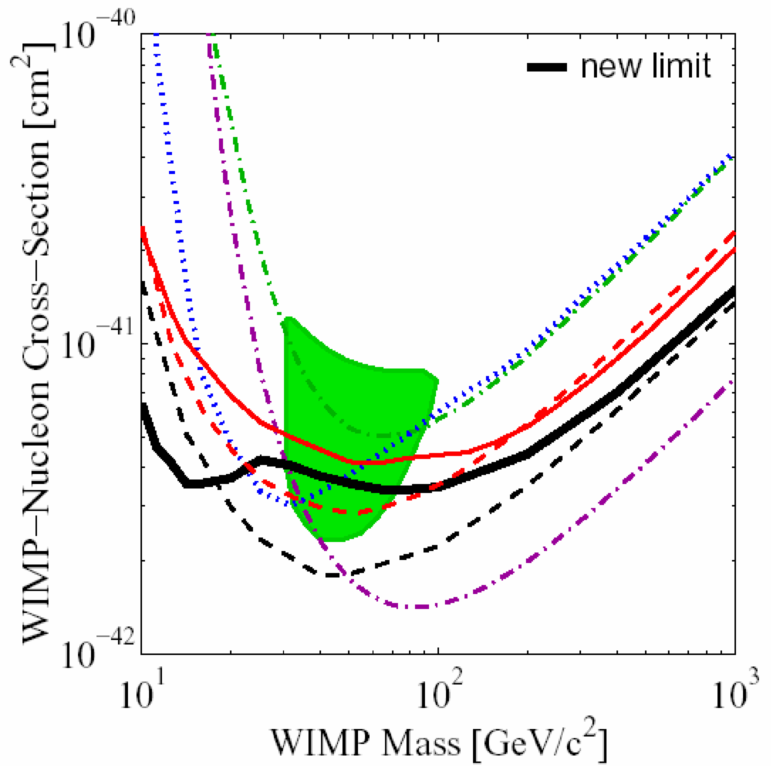


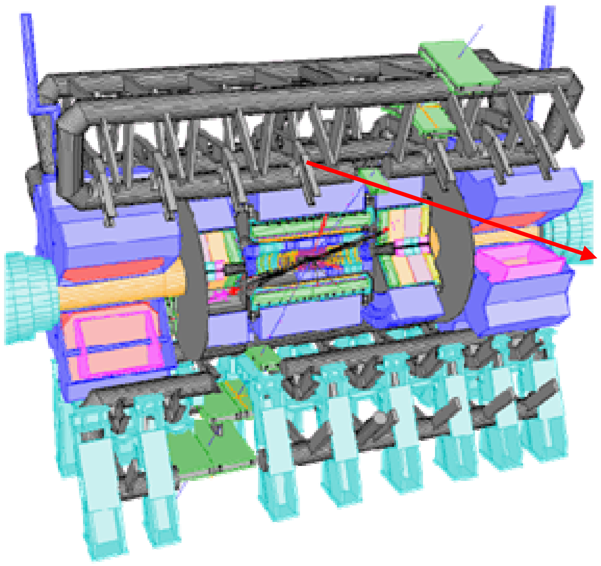


WIMPS AT COLLIDERS

What can colliders add to our understanding?

- Cosmology can't discover SUSY
- Particle colliders can't discover DM

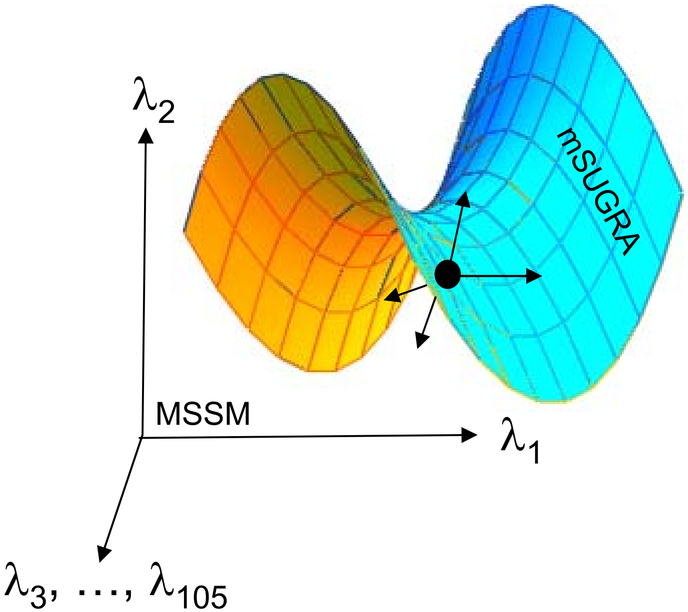




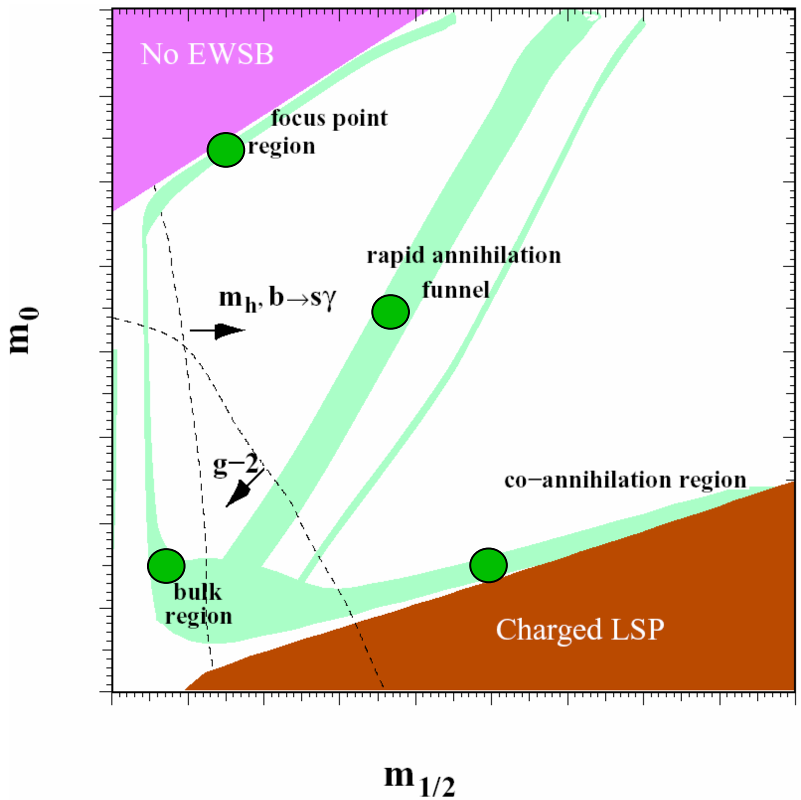
Lifetime > 10^{-7} s → 10^{17} s ?

WIMPS AT COLLIDERS

- Choose a concrete *example*: neutralinos
- Choose a simple model framework that encompasses many qualitatively different behaviors: mSUGRA
- Relax model-dependent assumptions and determine parameters
- Identify cosmological, astrophysical implications



Neutralino DM in mSUGRA



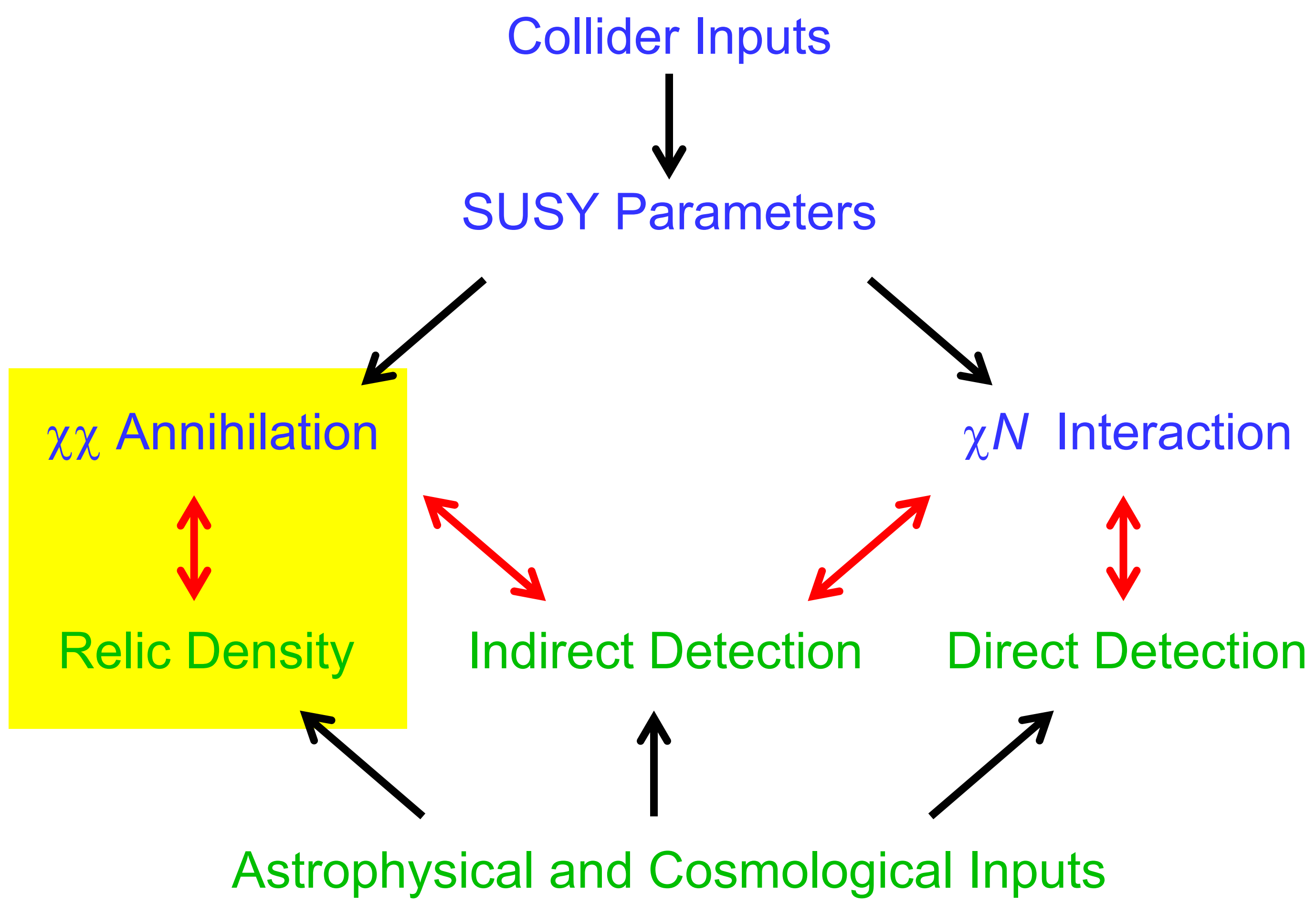
Cosmology excludes much of parameter space (Ω_χ too big)

Cosmology focuses attention on particular regions (Ω_χ just right)

Choose 4 representative points for detailed study

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

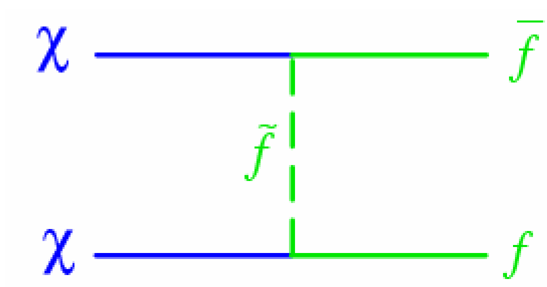
SYNERGY IN DM STUDIES



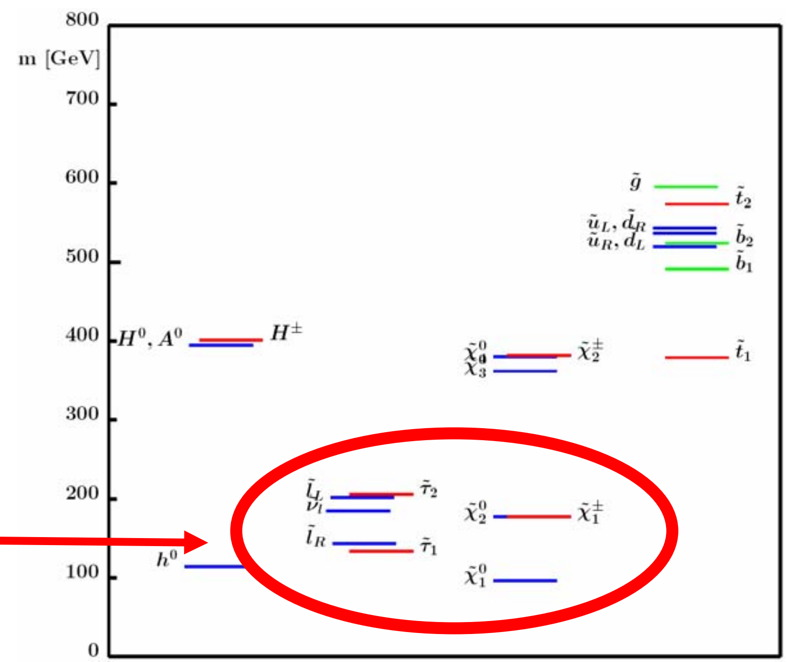
BULK REGION LCC1 (SPS1a)

$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:



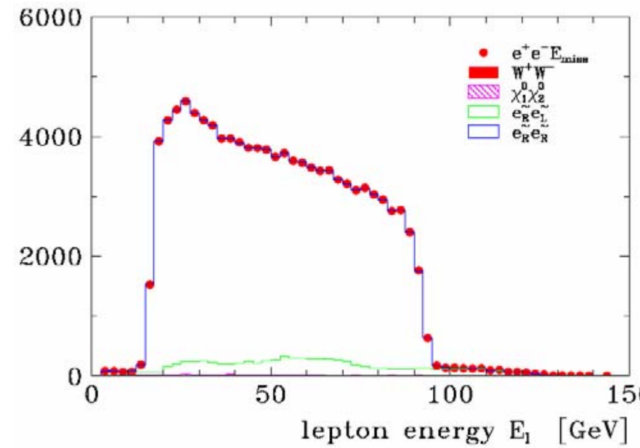
- Motivates SUSY with light $\chi, \tilde{l}$

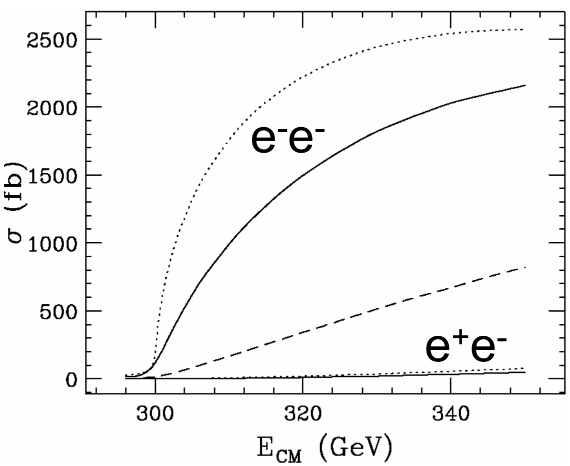


Allanach et al. (2002)

PRECISION MASSES

- LHC: See below
- ILC: Exploit all properties: kinematic endpoints, threshold scans
  - variable beam energy
  - e^- beam polarization
  - e^-e^- option





Feng, Peskin (2001)

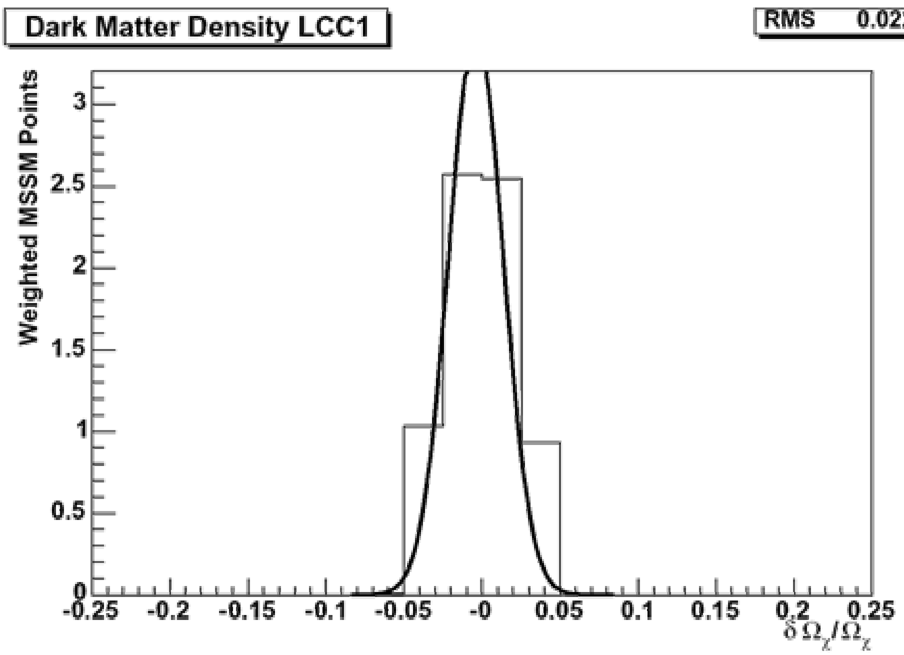
	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm, W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	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

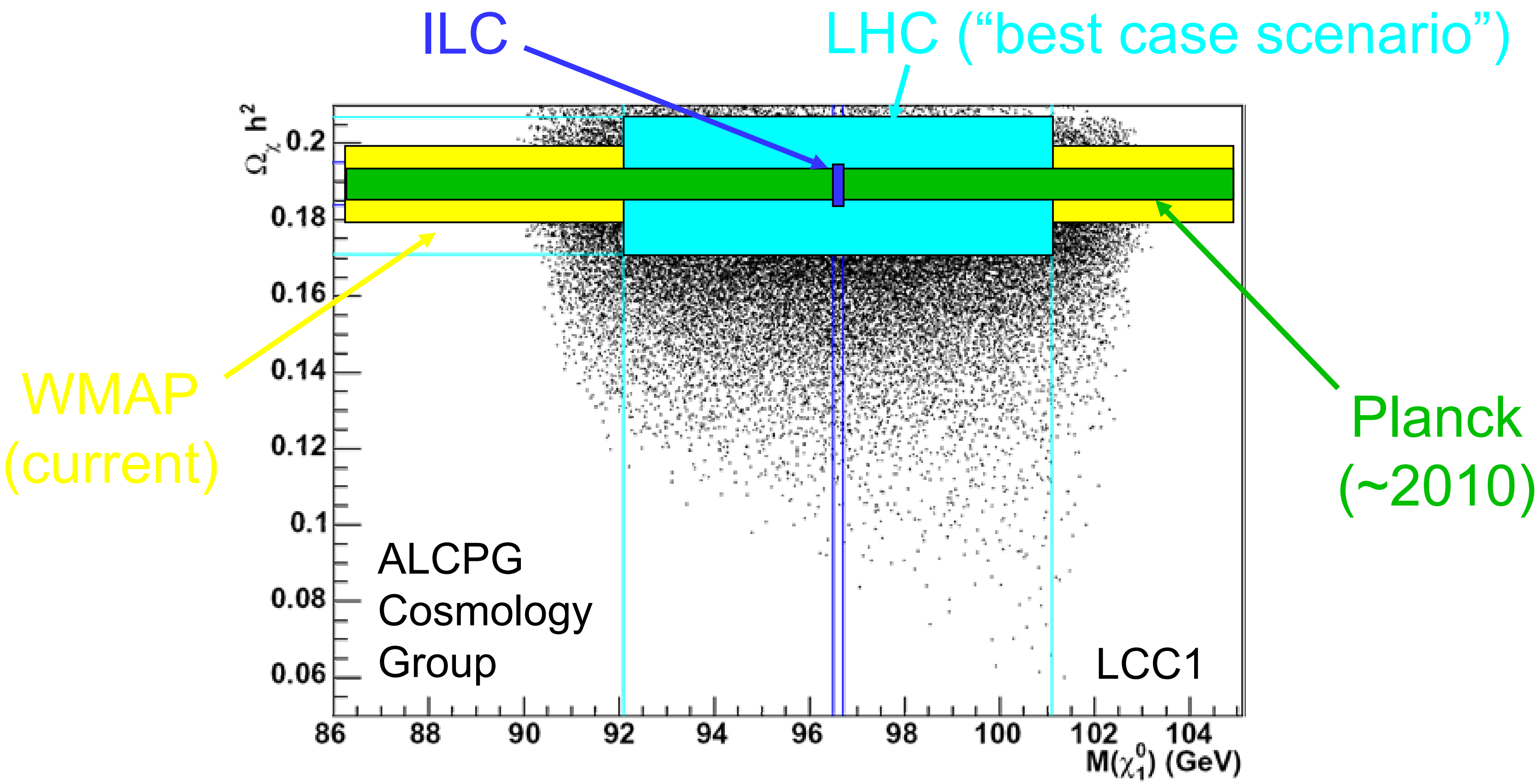
- Scan over ~20 most relevant parameters
- Weight each point by Gaussian distribution for each observable
- ~50K scan points



Battaglia (2005)

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

RELIC DENSITY DETERMINATIONS

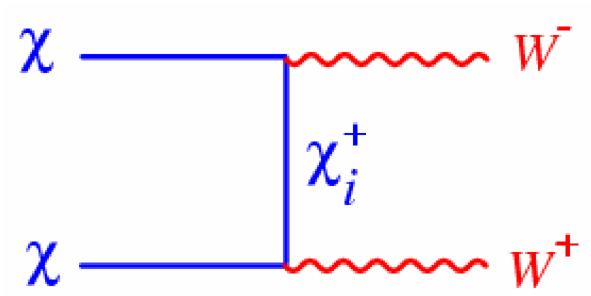


Parts per mille agreement for Ω_χ → discovery of dark matter

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



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

Gauginos

Higgsinos

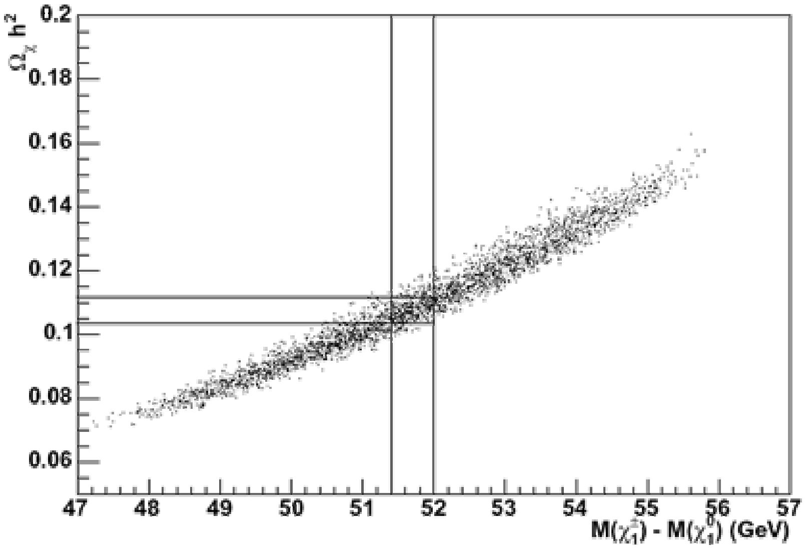
$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

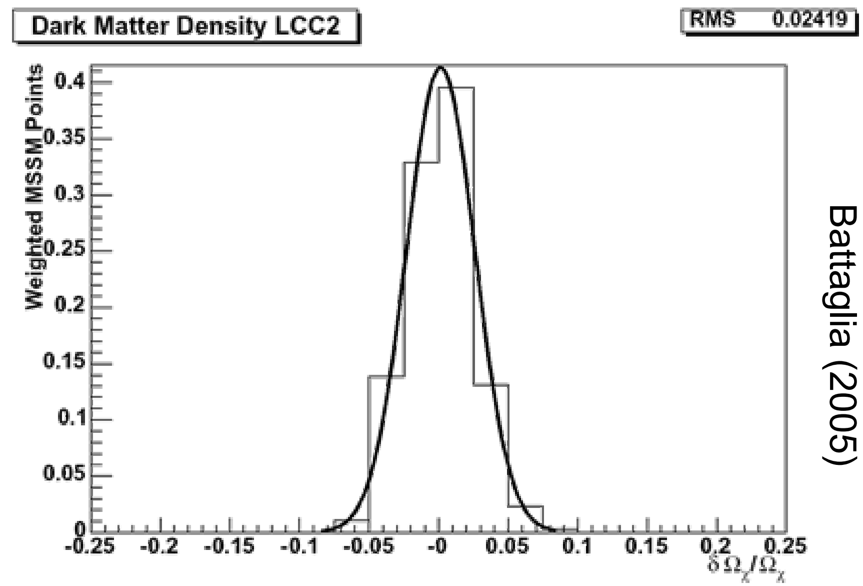
- Motivates SUSY with light neutralinos, charginos

FOCUS POINT RESULTS

- Ω_χ sensitive to Higgsino mixing, chargino-neutralino degeneracy

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

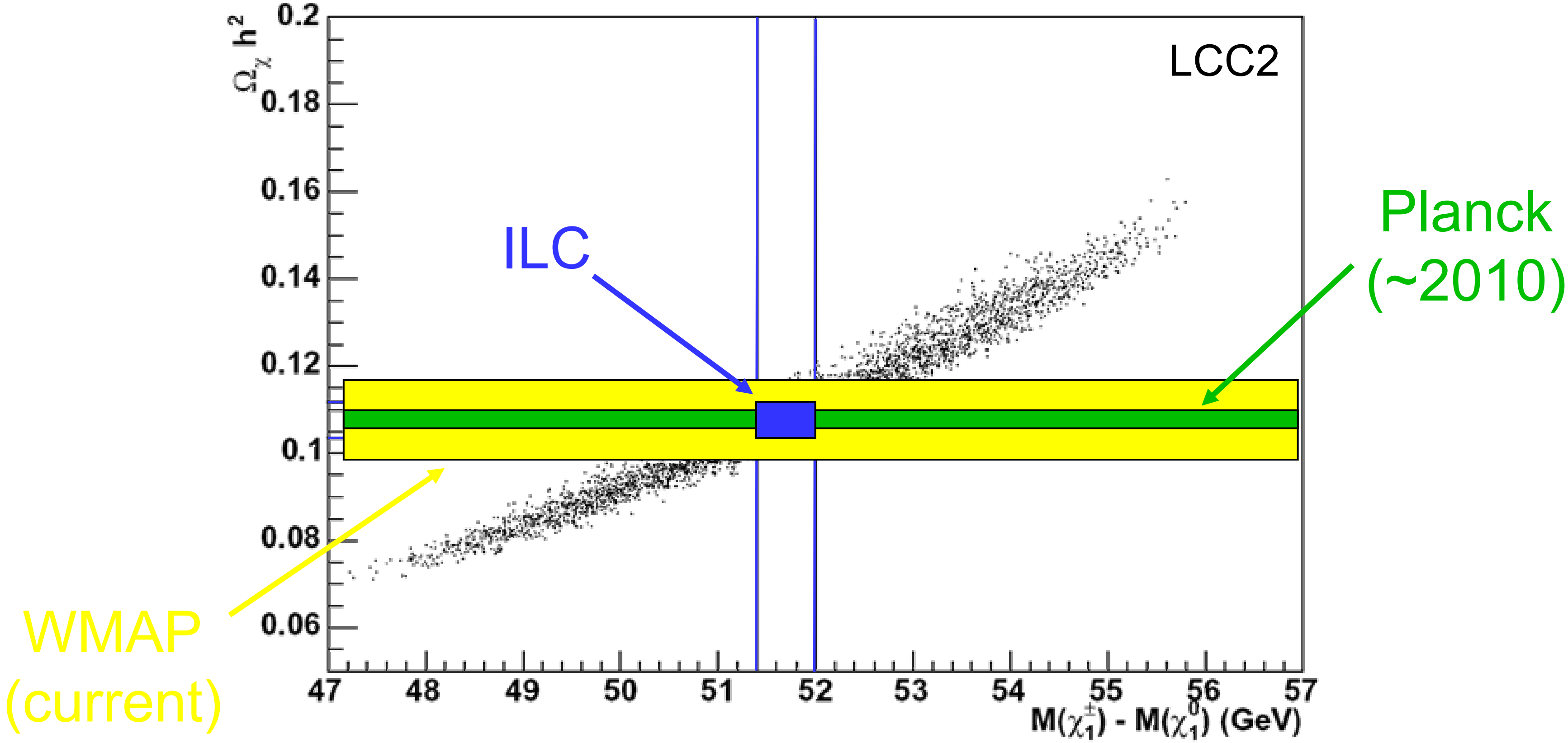




Battaglia (2005)

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

RELIC DENSITY DETERMINATIONS



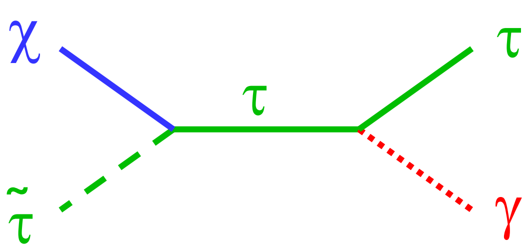
Parts per mille agreement for Ω_χ → discovery of dark matter

CO-ANNIHILATION REGION LCC3

$m_0, M_{1/2}, A_0, \tan\beta$ = 210, 360, 0, 40 [$\mu>0$, $m_{3/2}>m_{LSP}$]

- If other superpartners are nearly degenerate with the χ LSP, they can help it annihilate

Griest, Seckel (1986)



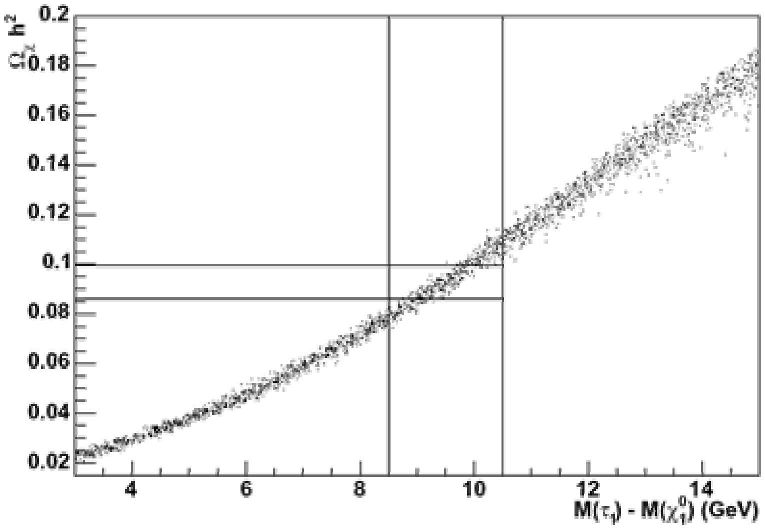
- Requires similar $e^{-m/T}$ for χ and $\tilde{\tau}$, so (roughly)

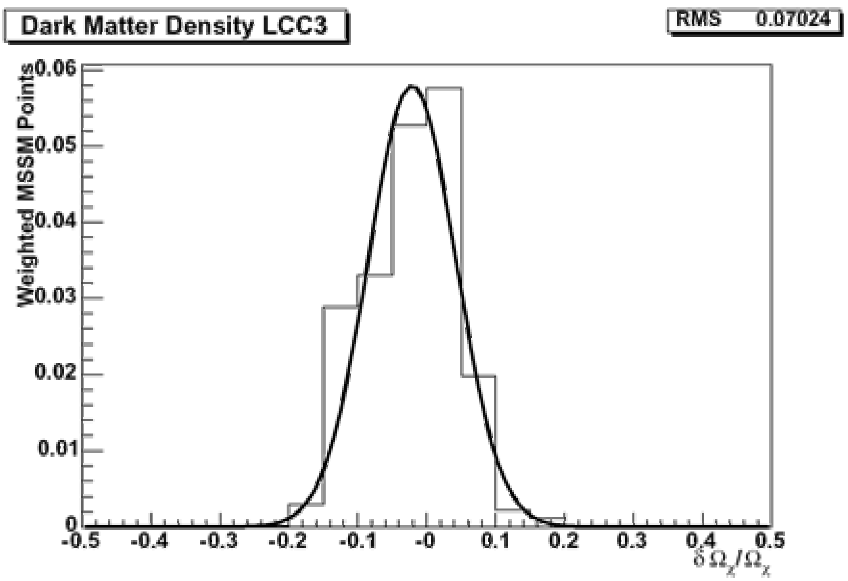
$$\Delta m < T \sim m_\chi/25$$

- Motivates SUSY with $\tilde{\tau} \rightarrow \tau\chi$ with Δm ~ few GeV

CO-ANNIHILATION RESULTS

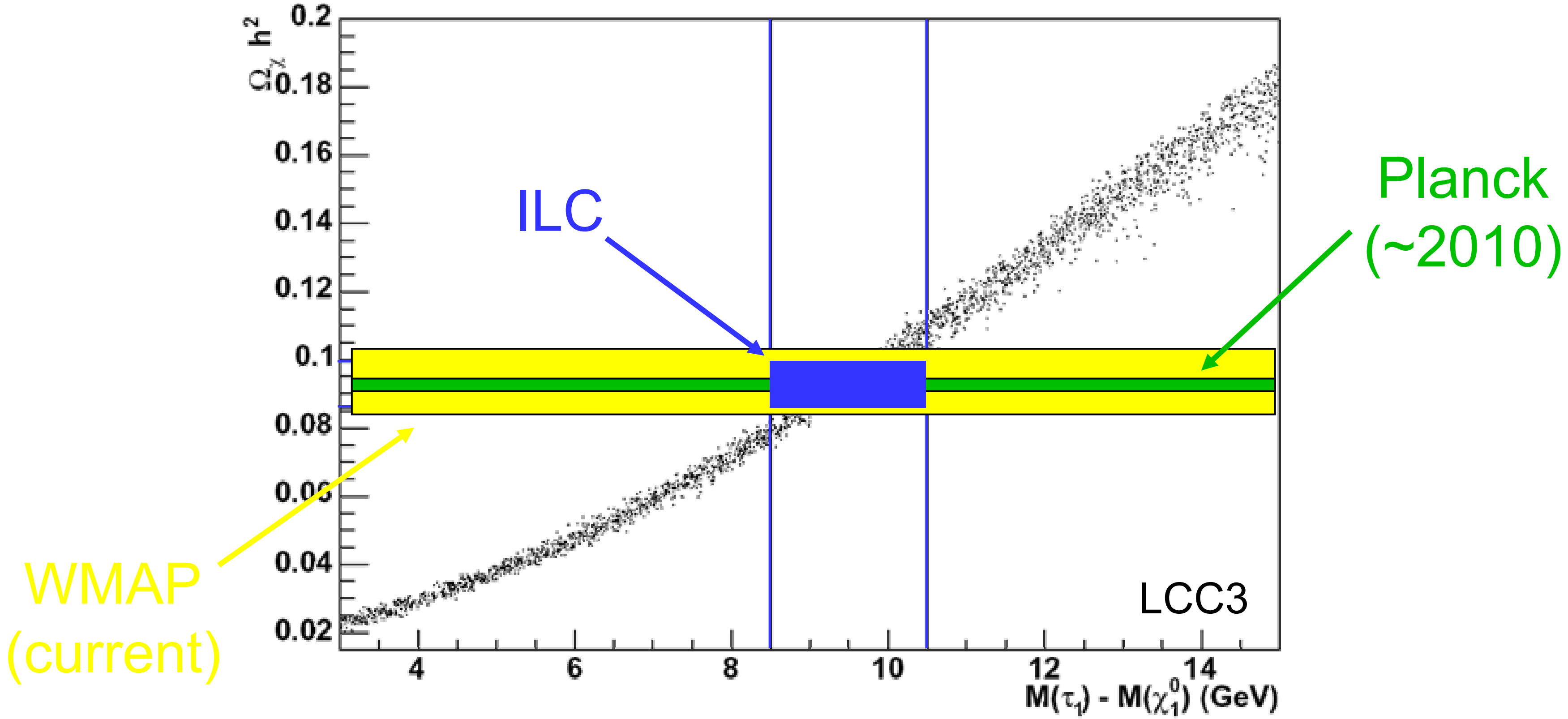
Dutta, Kamon; Nauenberg et al.; Battaglia (2005)





(Preliminary) result: $\Delta\Omega_\chi/\Omega_\chi$ = 7.0% ($\Delta\Omega_\chi h^2$ = 0.0084)

RELIC DENSITY DETERMINATIONS



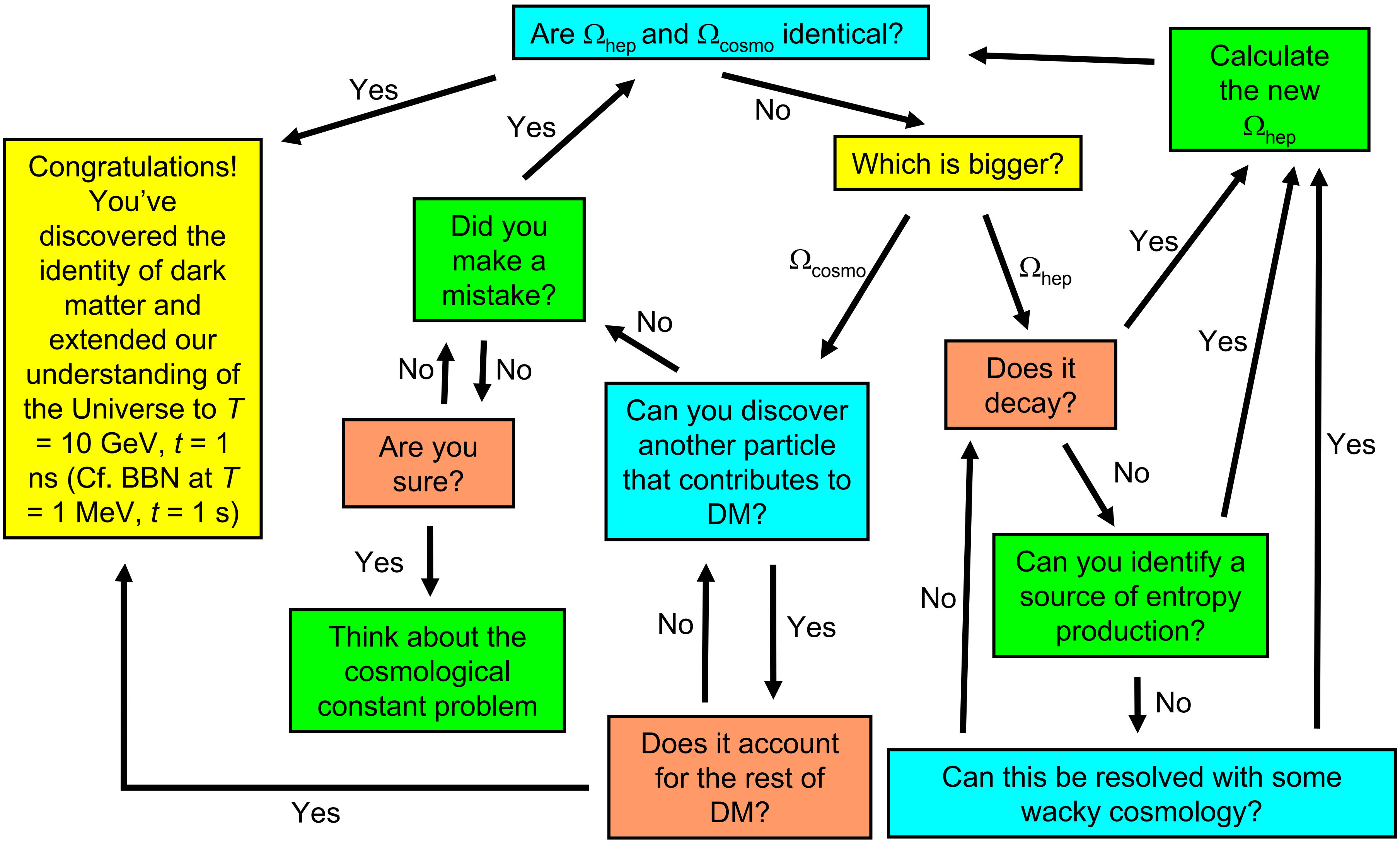
% level agreement for Ω_χ → discovery of dark matter

- The bottom line: LHC and International Linear Collider can discover WIMPs and determine their properties at the % level.

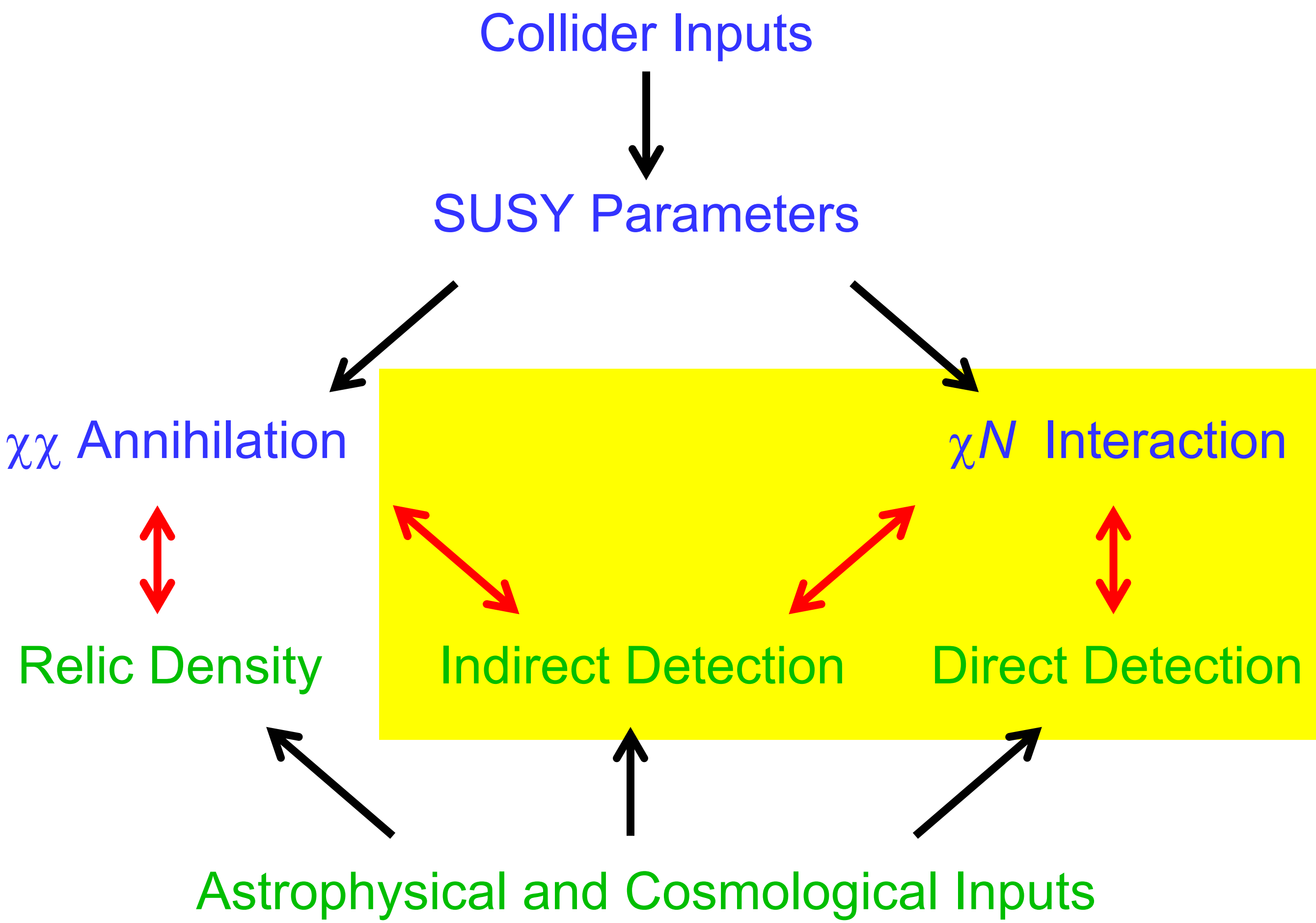
- These allow precise predictions of relic densities from high energy physics, which we can compare to cosmological data.

- What do we learn?

IDENTIFYING DARK MATTER

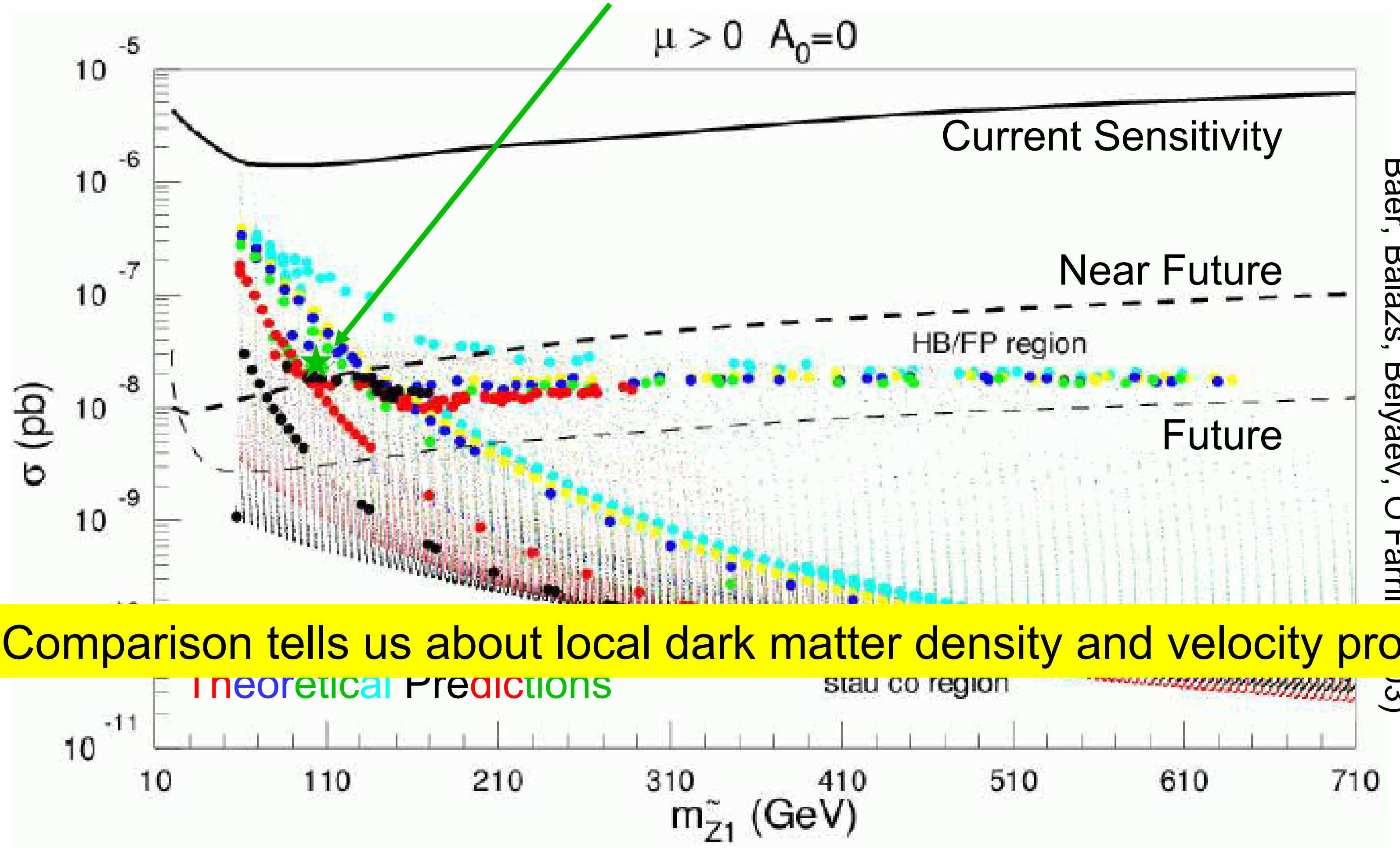


SYNERGY IN DM STUDIES



ILC IMPLICATIONS

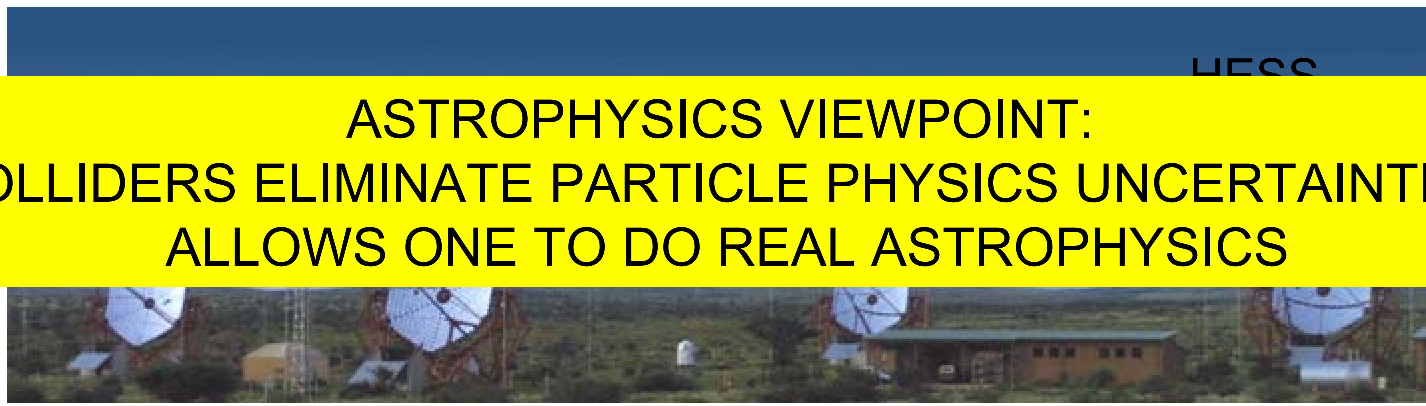
ILC → $\Delta m < 1$ GeV, $\Delta\sigma/\sigma < 10\%$



Comparison tells us about local dark matter density and velocity profiles

Dark Matter annihilates in __the galactic center__ to
a place

__photons__ , which are detected by __GLAST, HESS, …__ .
some particles — an experiment



ASTROPHYSICS VIEWPOINT:
COLLIDERS ELIMINATE PARTICLE PHYSICS UNCERTAINTIES,
ALLOWS ONE TO DO REAL ASTROPHYSICS

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

Halo profiles are poorly understood, controversial near the galactic center

LECTURE 2 SUMMARY

- If a WIMP is part of dark matter, the LHC and the ILC together can measure its properties precisely
- Comparison of predicted and observed relic density can lead to discovery (finally!) of the identity of dark matter, or require the existence of another component
- Comparison of predicted and observed detection rates will tell us about the distribution of dark matter in the galaxy, structure formation