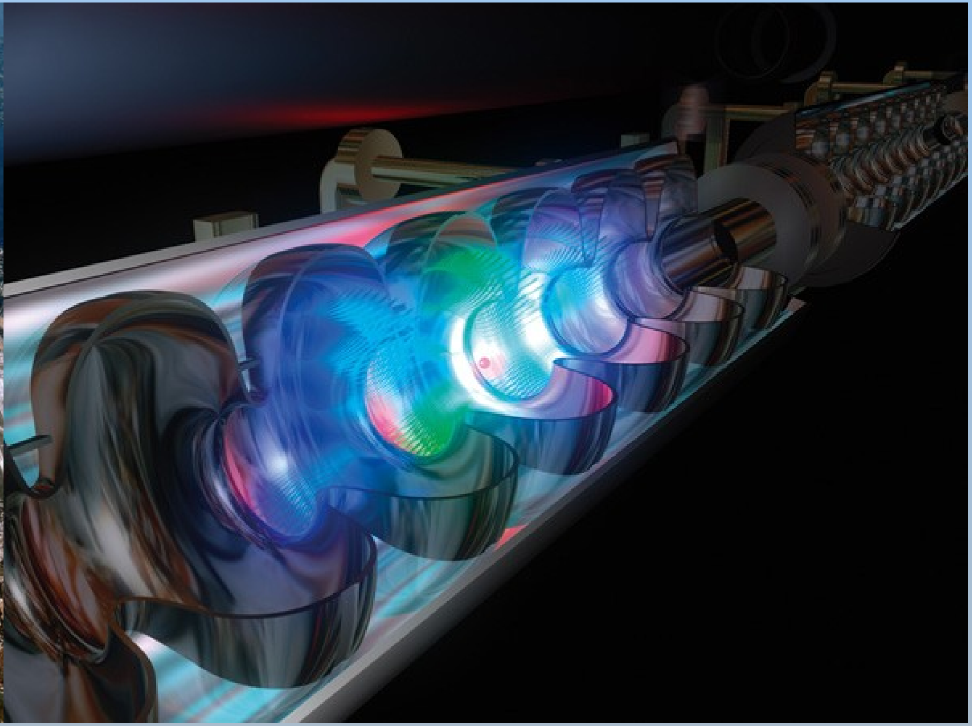
Measuring Dark Matter Properties with High-Energy Colliders



KIPAC

LELAND STANFORD JUNIOR UNIVERSITY
DIE LUFT DER FREIHEIT WEHT
1891

Stanford
Linear
Accelerator
Center

The Dark Matter Problem

- The energy density of the universe is mostly unidentified
  - Baryons: 5%
  - Dark Matter: 20%
  - Dark Energy: 75%
- The dark matter is likely to be “WIMPs”: weakly interacting massive particles in the 100 GeV – TeV range
  - 1 pb annihilation cross section gives correct relic density
- The evidence for this standard cosmological model is overwhelming
  - CMB, big-bang nucleosynthesis, large scale structure, clusters…

To Solve the Dark Matter Problem We Must:

- 1.) detect the constituent particles of our galaxy *as particles*
- 2.) create dark matter particles in the controlled environments of particle accelerators
- 3.) demonstrate that these two are the same
- To accomplish this we need to combine data from astrophysics and accelerators

Alternative Scenarios for WIMPs observed at LHC

- The WIMP is all / part / none of the dark matter
- The WIMP is stable / unstable to a superWIMP
- The underlying physics is SUSY / extra dimensions / TBD
- Cosmology was standard / exotic to temperatures of 100 GeV
- The dark matter halo of the galaxy is clumpy / smooth
- The velocity distribution of dark matter is smooth / has features

- We need the data that will distinguish all of these possibilities.

Direct Detection of Dark Matter

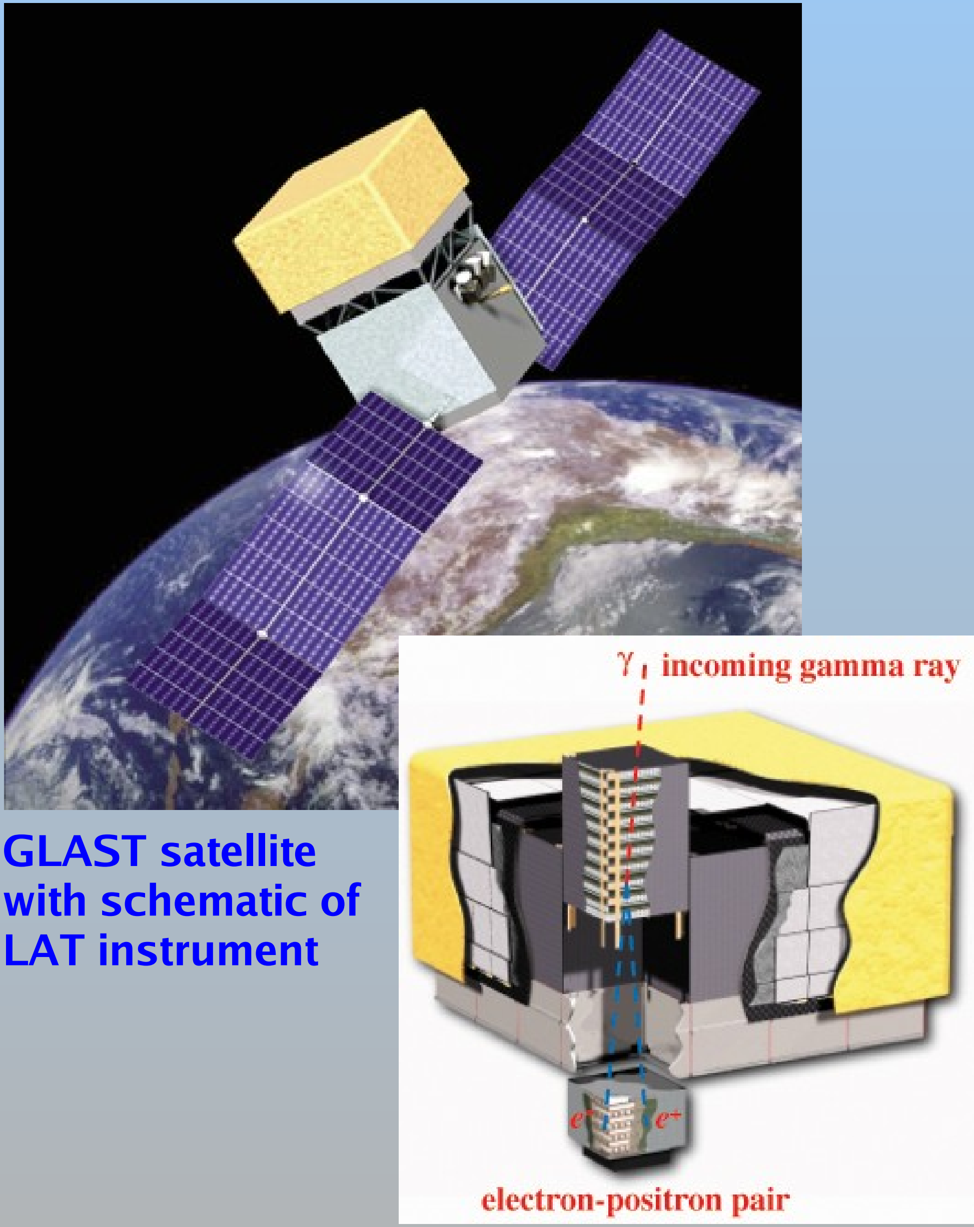
- Nuclear recoils
  - ~50 keV deposited
  - many techniques
    - semiconductors
    - scintillators
    - liquid noble gases
    - bubble chambers
    - TPCs
- Most measure only the recoil energy
- Recoil direction is more difficult, but possible

- See Cosmology Session (Cooley, Shutt)

CDMS fridge + icebox @ Soudan mine

Indirect Detection of Dark Matter

- Indirect detection
  - annihilations in galactic halo
  - energetic particles
    - photons (gamma rays)
    - antiprotons, antideuterons
    - positrons
- Gamma rays, incl. lines!
  - satellites (EGRET, GLAST)
  - ACTs (HESS, VERITAS, MAGIC)
    - follow-up of GLAST sources?
- Antiprotons, positrons
  - PAMELA, AMS, BESS
- Neutrinos
  - AMANDA, IceCube, ANTARES
- See Cosmology Session (Wai)



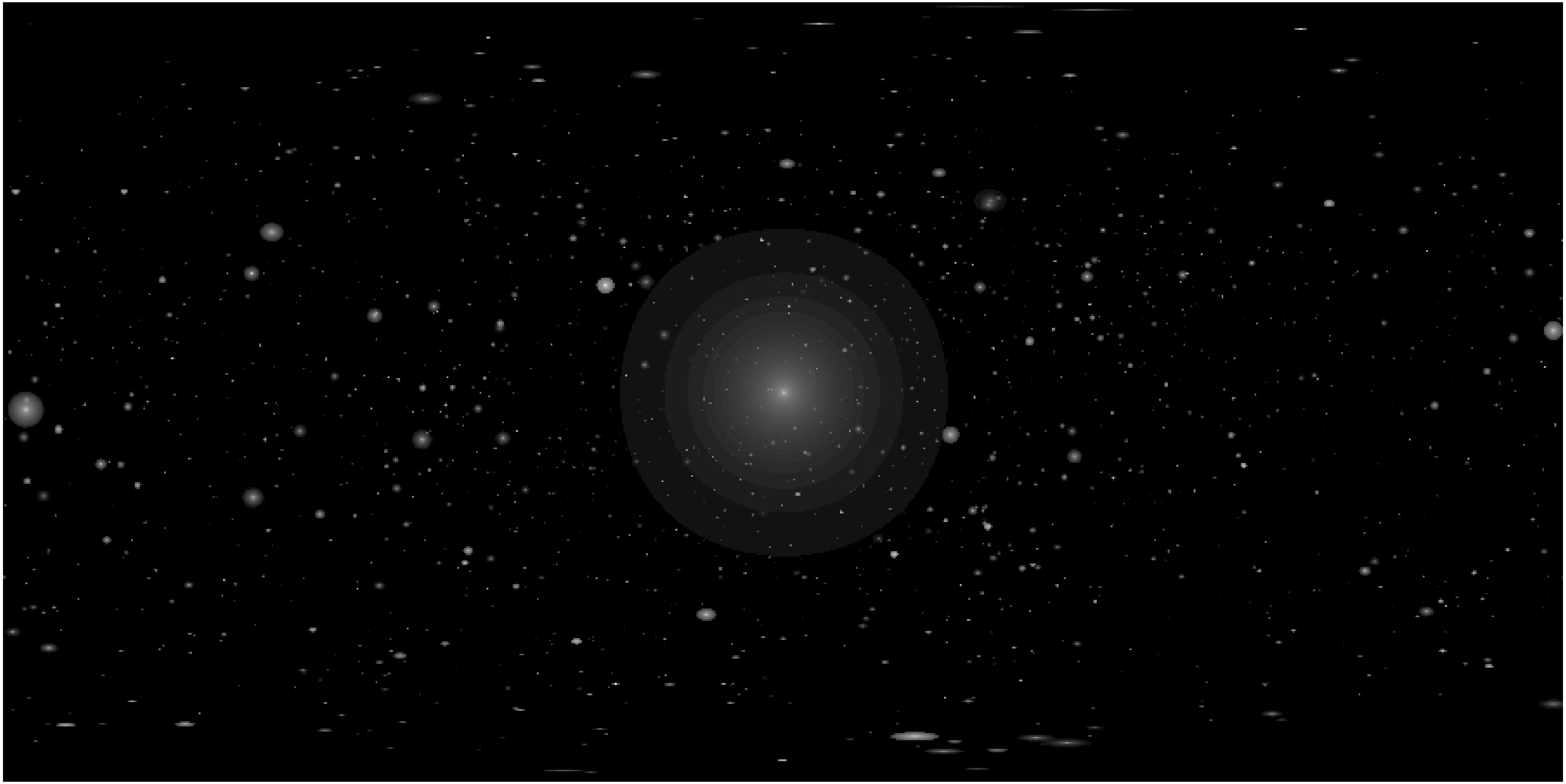
GLAST satellite with schematic of LAT instrument

Dark Matter in the Gamma Ray Sky

Milky Way Halo simulated by
Taylor & Babul (2005)
All-sky map of gamma ray emission
from dark matter annihilations

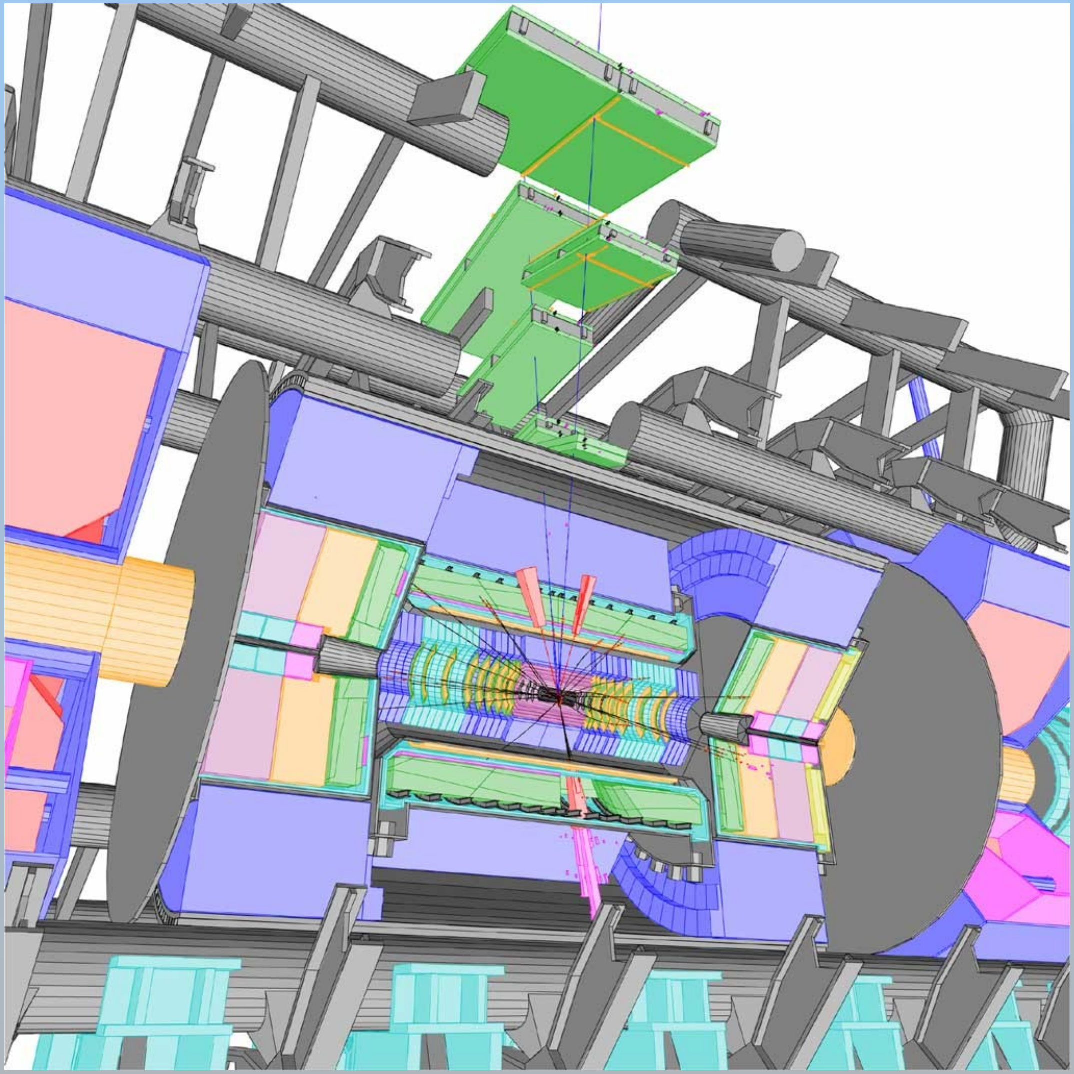
dark matter substructure exhibits:

1. characteristic γ-ray spectrum
2. spatially extended emission



Laboratory Creation of Dark Matter

- LHC
  - find particles up to 2+ TeV in missing energy events
- Linear collider
  - mass reach not as high
  - precision measurements
- Make a connection to astrophysical searches



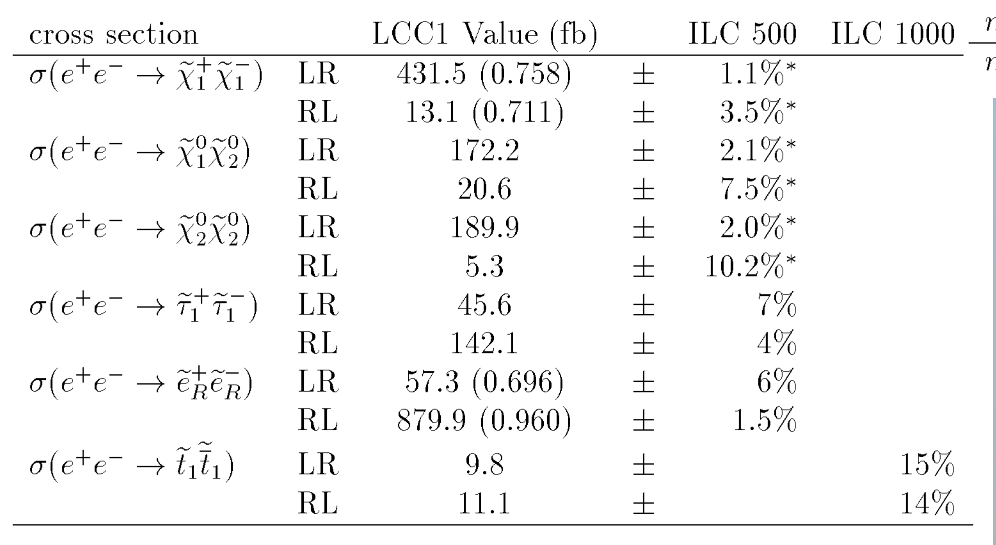
Simulation of event in ATLAS @ LHC

Dark Matter Microphysics

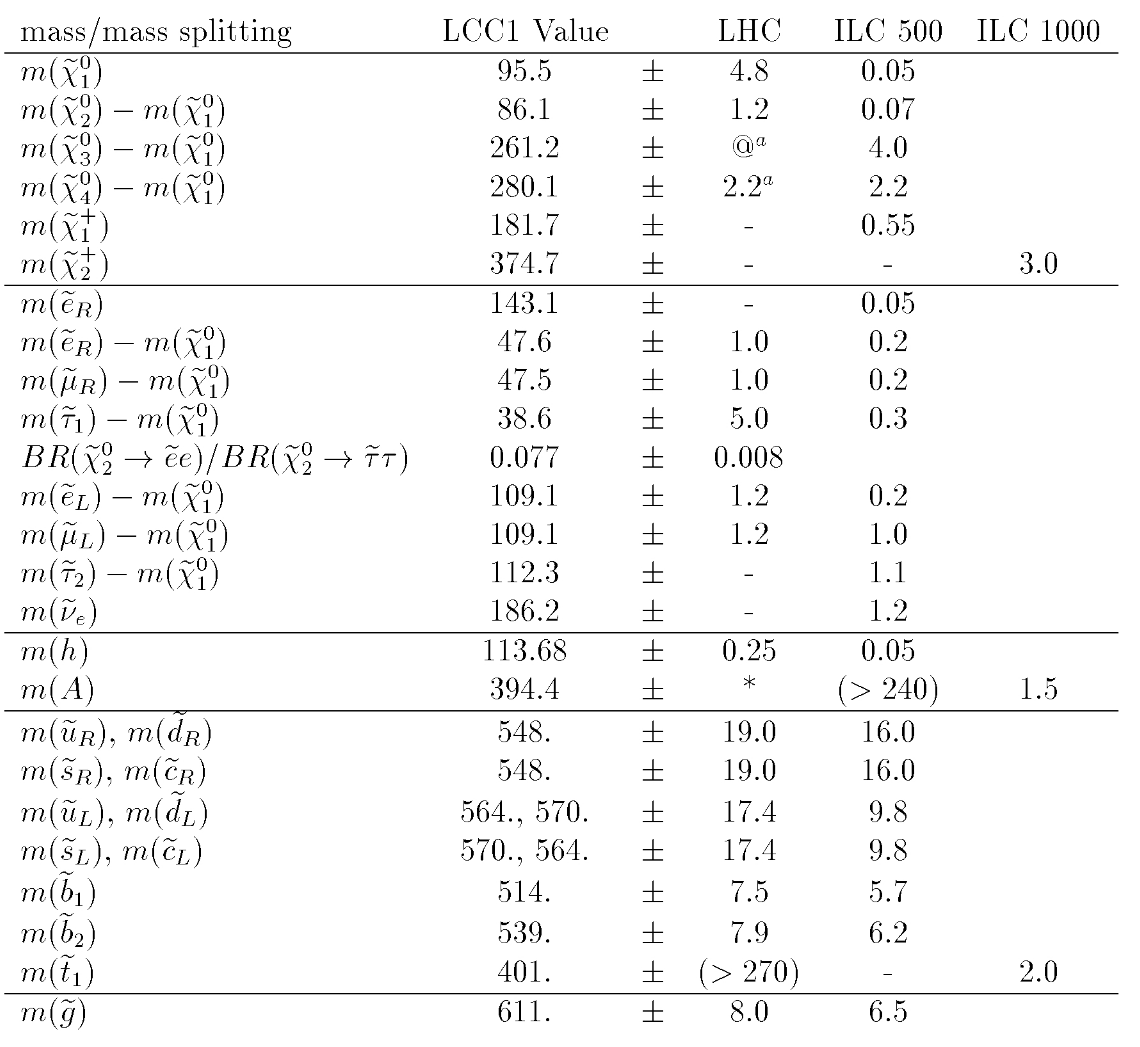
- Much of the discussion is generic to WIMPs, but we take examples from SUSY models
  - EAB, M. Battaglia, M. Peskin and T. Wizansky hep-ph/0602187
- Study 4 "benchmark" SUSY points
  - LCC1-4, chosen by ALCPG: dark matter and ILC-500
- Identify expected collider measurements
  - masses, polarized production cross-sections, FB asymmetries
- Generate ~ millions of models consistent with measurements
  - 24 parameters – most general MSSM conserving flavor and CP
- Study the predictions of properties relevant to dark matter, given the collider measurements at each benchmark point
  - LHC, ILC-500, ILC-1000

Constraints: LCC1 (SPS1a)

cross sections



cross section		LCC1 Value (fb)		ILC 500	ILC 1000
$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	LR	431.5 (0.758)	±	1.1%*	
	RL	13.1 (0.711)	±	3.5%*	
$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	LR	172.2	±	2.1%*	
	RL	20.6	±	7.5%*	
$\sigma(e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0)$	LR	189.9	±	2.0%*	
	RL	5.3	±	10.2%*	
$\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-)$	LR	45.6	±	7%	
	RL	142.1	±	4%	
$\sigma(e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-)$	LR	57.3 (0.696)	±	6%	
	RL	879.9 (0.960)	±	1.5%	
$\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1)$	LR	9.8	±		15%
	RL	11.1	±		14%



mass/mass splitting	LCC1 Value		LHC	ILC 500	ILC 1000
$m(\tilde{\chi}_1^0)$	95.5	±	4.8	0.05	
$m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$	86.1	±	1.2	0.07	
$m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)$	261.2	±	@^{a}	4.0	
$m(\tilde{\chi}_4^0) - m(\tilde{\chi}_1^0)$	280.1	±	2.2^a	2.2	
$m(\tilde{\chi}_1^+)$	181.7	±	-	0.55	
$m(\tilde{\chi}_2^+)$	374.7	±	-	-	3.0
$m(\tilde{e}_R)$	143.1	±	-	0.05	
$m(\tilde{e}_R) - m(\tilde{\chi}_1^0)$	47.6	±	1.0	0.2	
$m(\tilde{\mu}_R) - m(\tilde{\chi}_1^0)$	47.5	±	1.0	0.2	
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	38.6	±	5.0	0.3	
$BR(\tilde{\chi}_2^0 \to \tilde{e}e)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}\tau)$	0.077	±	0.008		
$m(\tilde{e}_L) - m(\tilde{\chi}_1^0)$	109.1	±	1.2	0.2	
$m(\tilde{\mu}_L) - m(\tilde{\chi}_1^0)$	109.1	±	1.2	1.0	
$m(\tilde{\tau}_2) - m(\tilde{\chi}_1^0)$	112.3	±	-	1.1	
$m(\tilde{\nu}_e)$	186.2	±	-	1.2	
$m(h)$	113.68	±	0.25	0.05	
$m(A)$	394.4	±	*	(> 240)	1.5
$m(\tilde{u}_R), m(\tilde{d}_R)$	548.	±	19.0	16.0	
$m(\tilde{s}_R), m(\tilde{c}_R)$	548.	±	19.0	16.0	
$m(\tilde{u}_L), m(\tilde{d}_L)$	564., 570.	±	17.4	9.8	
$m(\tilde{s}_L), m(\tilde{c}_L)$	570., 564.	±	17.4	9.8	
$m(\tilde{b}_1)$	514.	±	7.5	5.7	
$m(\tilde{b}_2)$	539.	±	7.9	6.2	
$m(\tilde{t}_1)$	401.	±	(> 270)	-	2.0
$m(\tilde{g})$	611.	±	8.0	6.5	

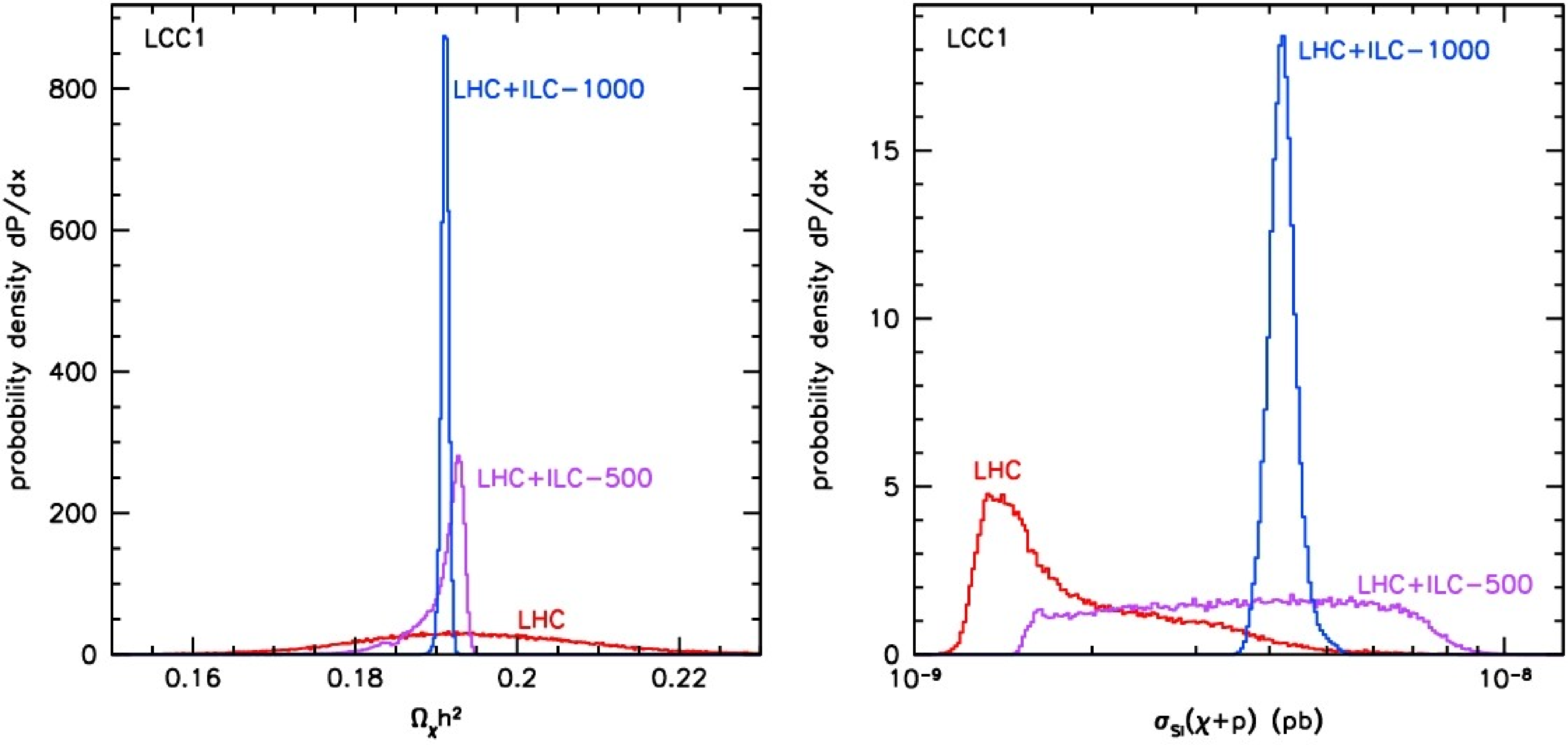
masses

(Weiglein et al., Phys. Rep., 2006)

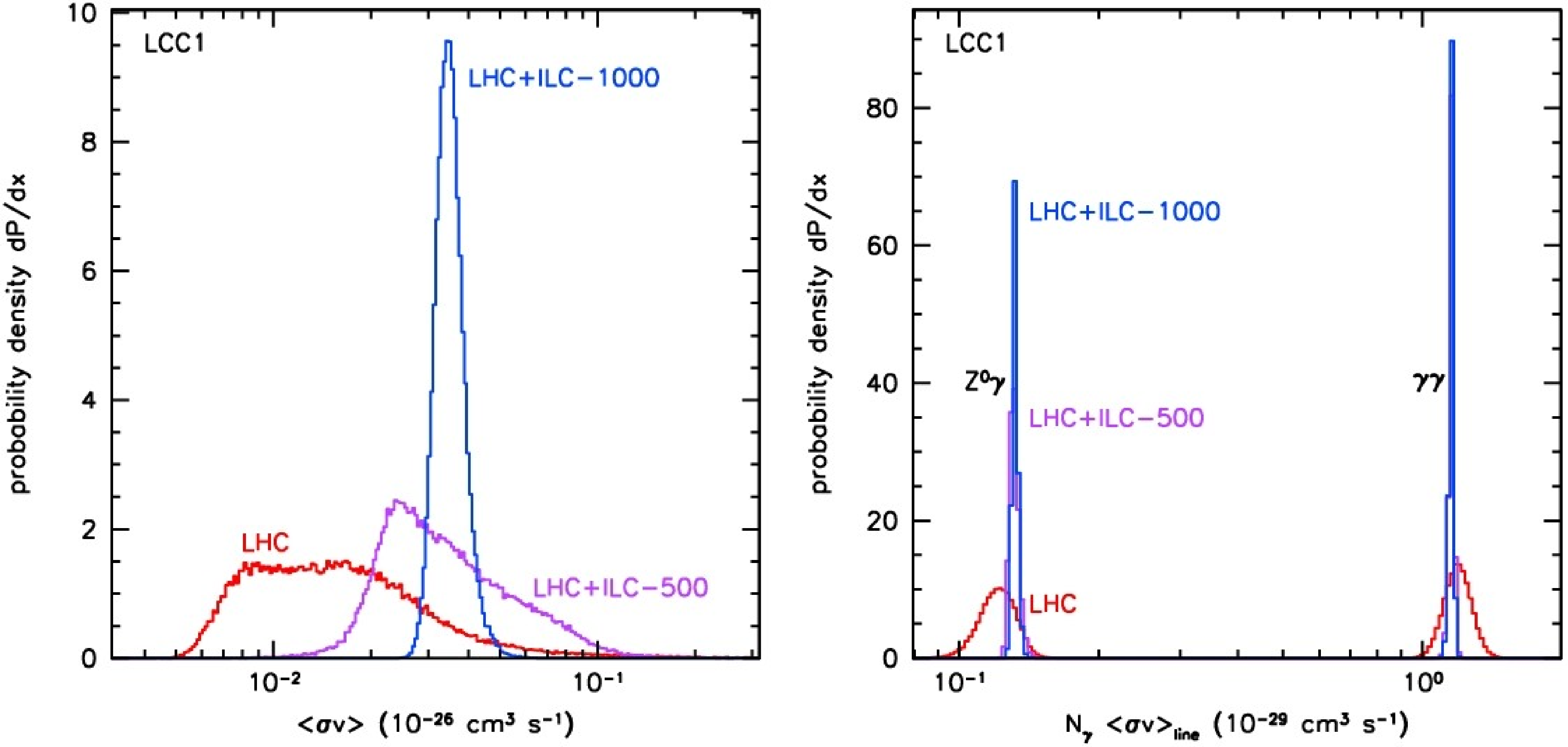
Results: LCC1

- "Bulk" region: most superpartners are light
    - LHC discovers 3 neutralinos, gluino, all squarks except stops, all sleptons except heavy stau, light Higgs boson
    - ILC 500 discovers heavy stau, light chargino, electron sneutrino, production cross sections
    - ILC TeV discovers heavy chargino, light stop, heavy Higgs
- In this case alone, the ILC-TeV can infer relic density with comparable precision to future CMB measurements (Planck satellite, 0.5% accuracy)
- Direct detection dominated by heavy Higgs – need this measurement (ILC TeV) or constraint from e.g. SuperCDMS
- Annihilation cross section is small – dominated by b bbar with large helicity suppression

LCC1: Prediction of Relic Density and Direct Detection Cross Section



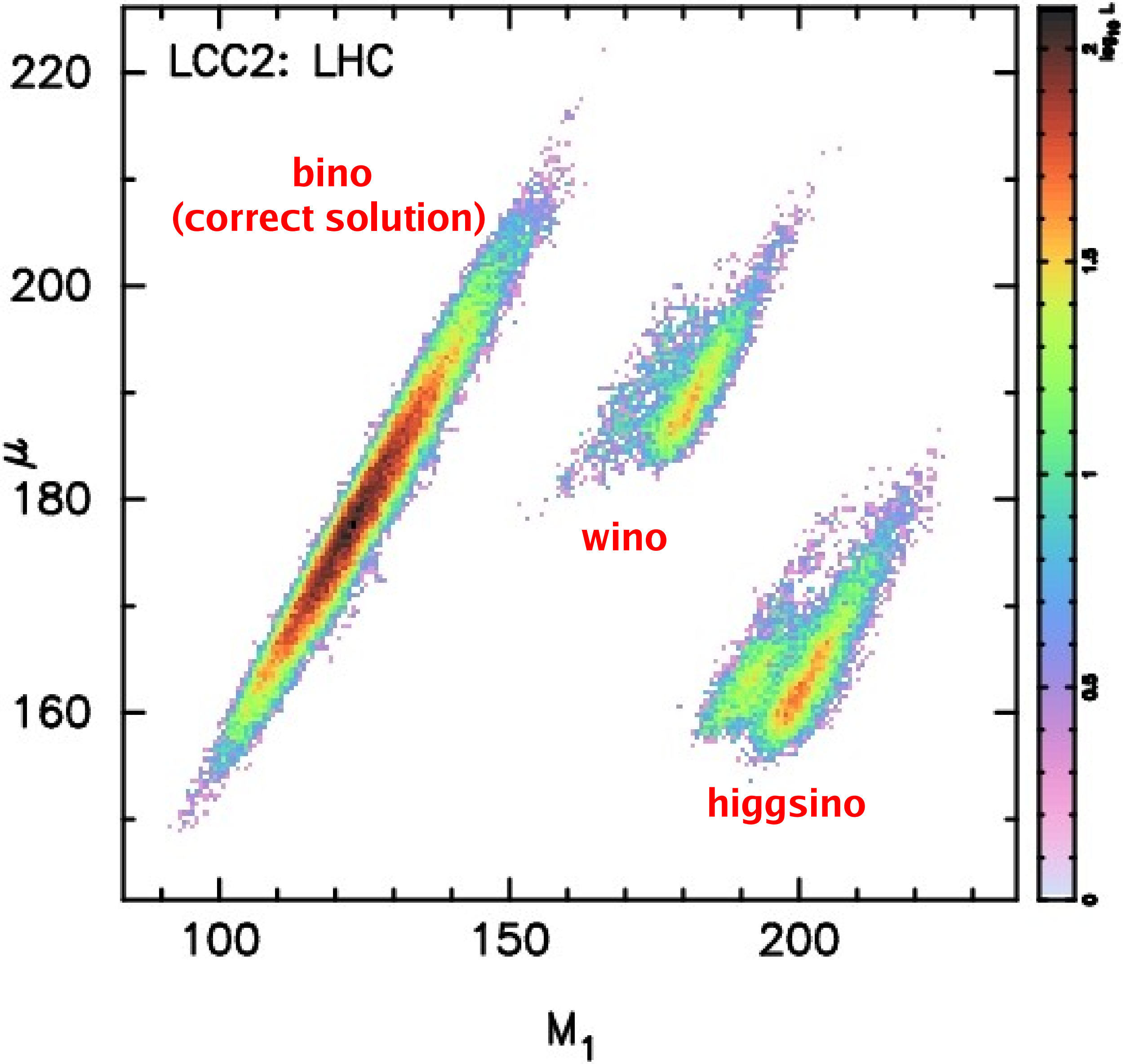
LCC1: Prediction of Annihilation Cross Sections



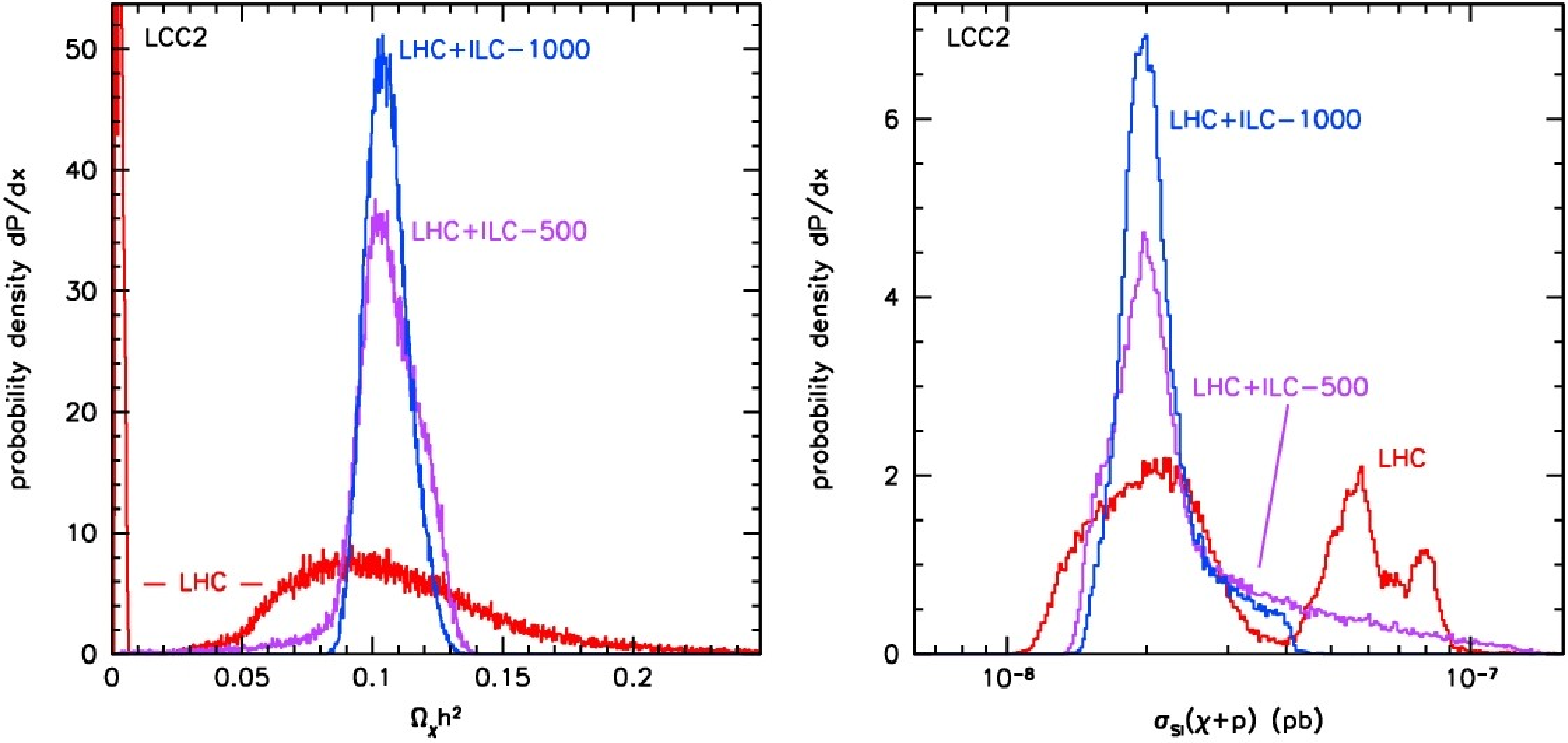
Results: LCC2

- "Focus point" region: gauginos, higgsinos are light, sfermions are all inaccessible to any collider
  - LHC discovers 3 neutralinos, gluino, light higgs
  - ILC 500 discovers light chargino
  - ILC TeV discovers heavy chargino, 4th neutralino
- Relic density estimate has 10% accuracy with ILC TeV
  - CMB measurement is doing collider physics!
- Direct detection is dominated by light Higgs
- Annihilation cross section is large – dominated by W pairs
  - promising for gamma ray experiments

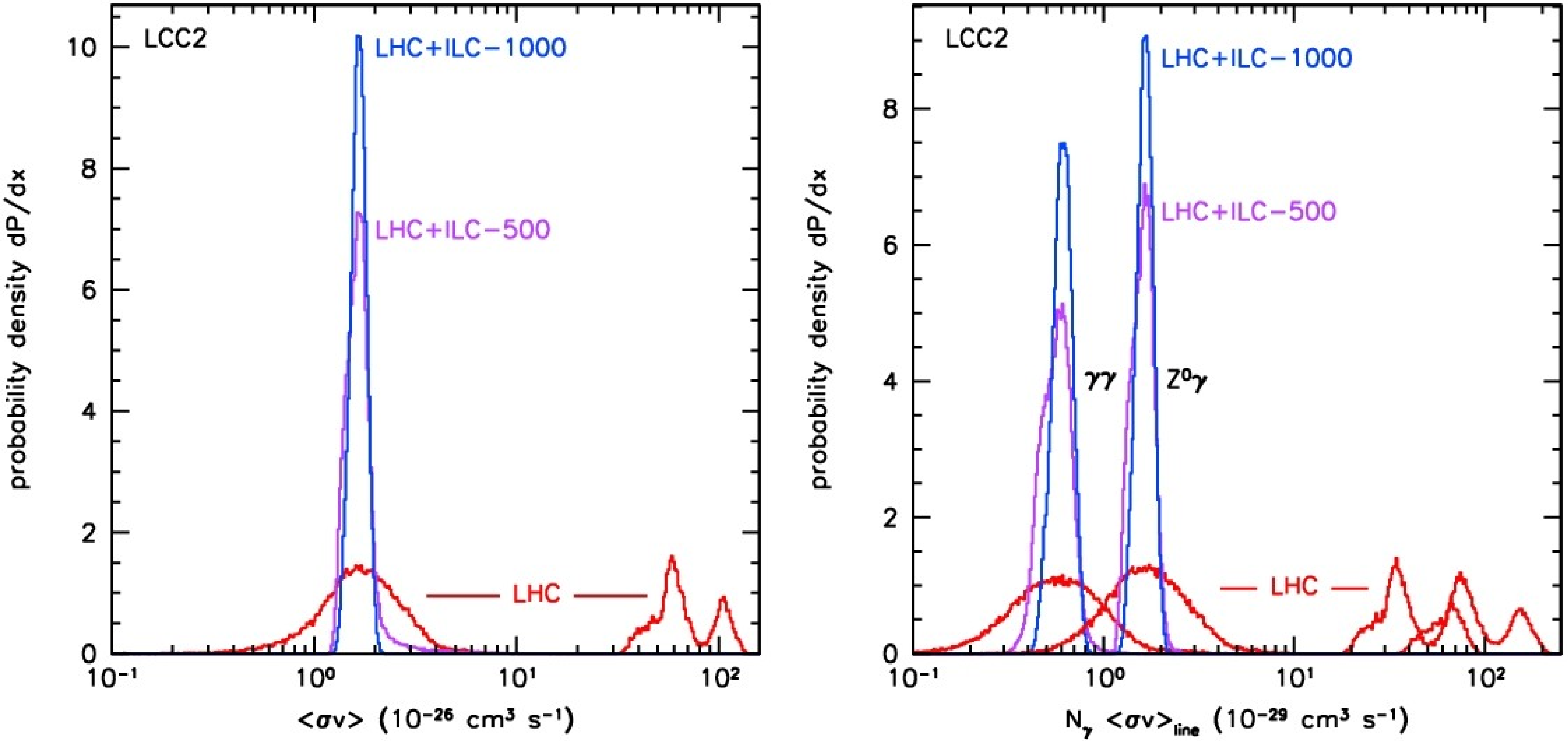
LCC2: Probability Islands for Neutralinos @ LHC



LCC2: Prediction of Relic Density and Direct Detection Cross Section



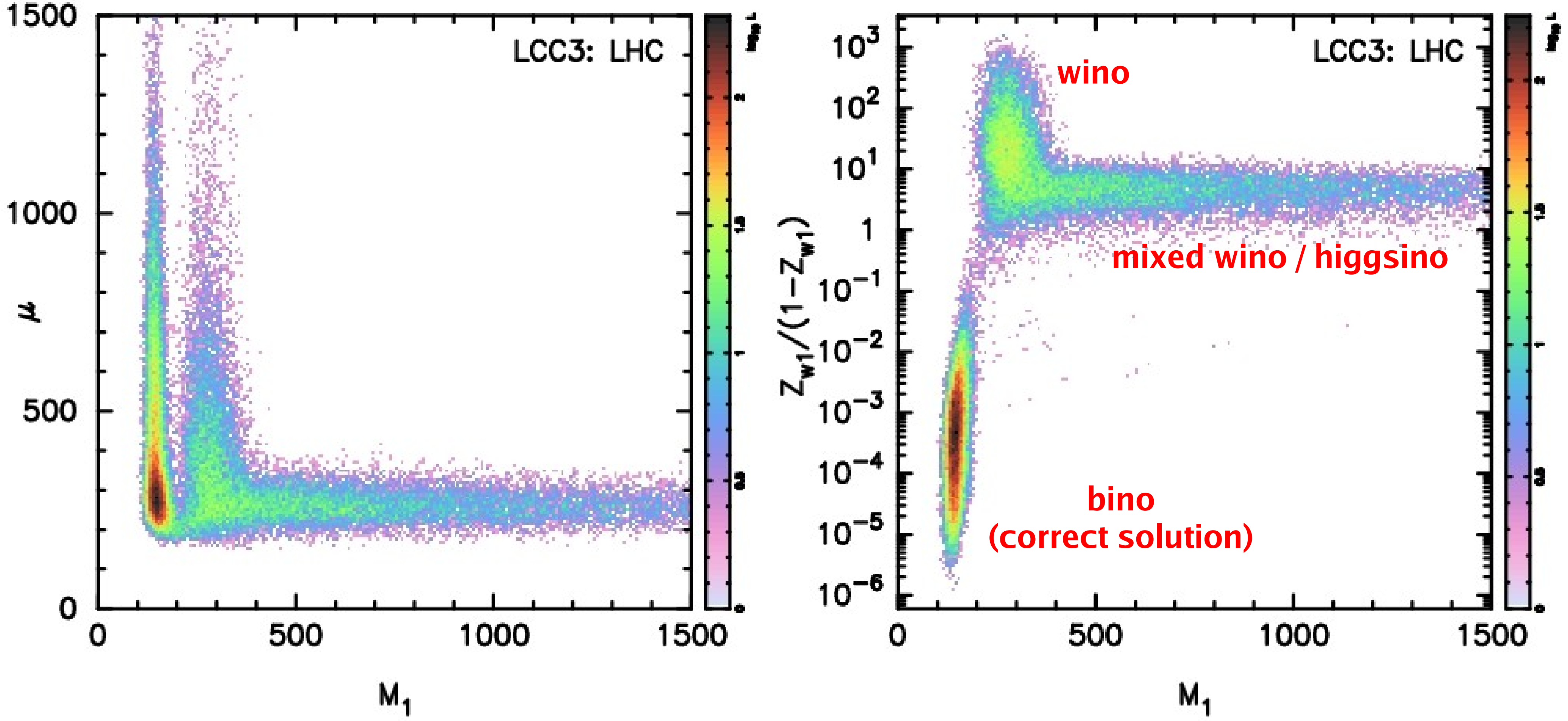
LCC2: Prediction of Annihilation Cross Sections



Results: LCC3

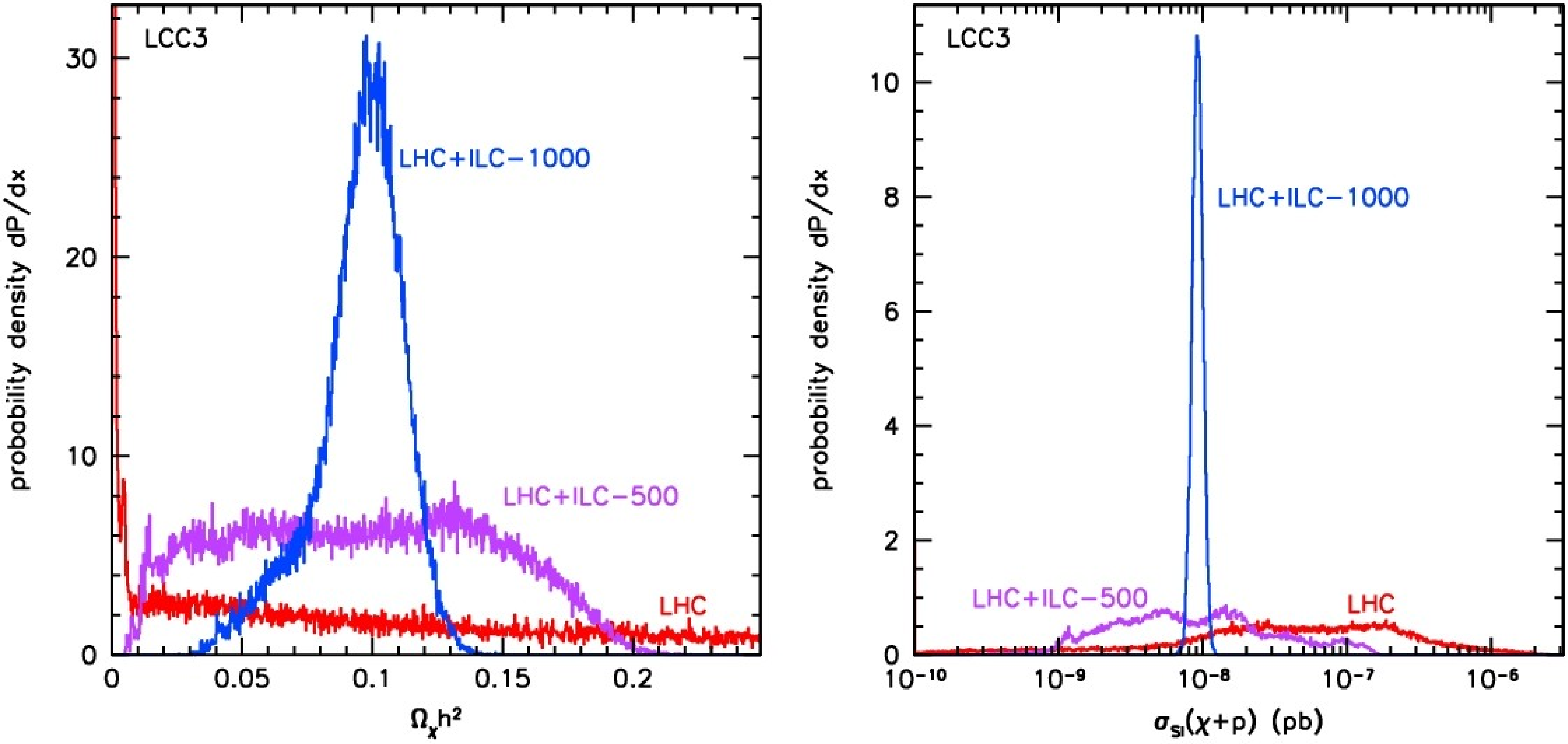
- “Coannihilation” region: light stau very close to neutralino
    - LHC discovers 2 neutralinos, gluino, e_R, mu_R, squarks except stops, light higgs, heavy higgs
    - ILC 500 discovers light stau
    - ILC TeV discovers light chargino, all charged sleptons, decay width of heavy Higgs
- Relic density estimate has ~20% accuracy with ILC TeV
- Direct detection is dominated by heavy Higgs
- Annihilation cross section is moderate – dominated by b bar

LCC3: Unknown Composition of Neutralinos @ LHC

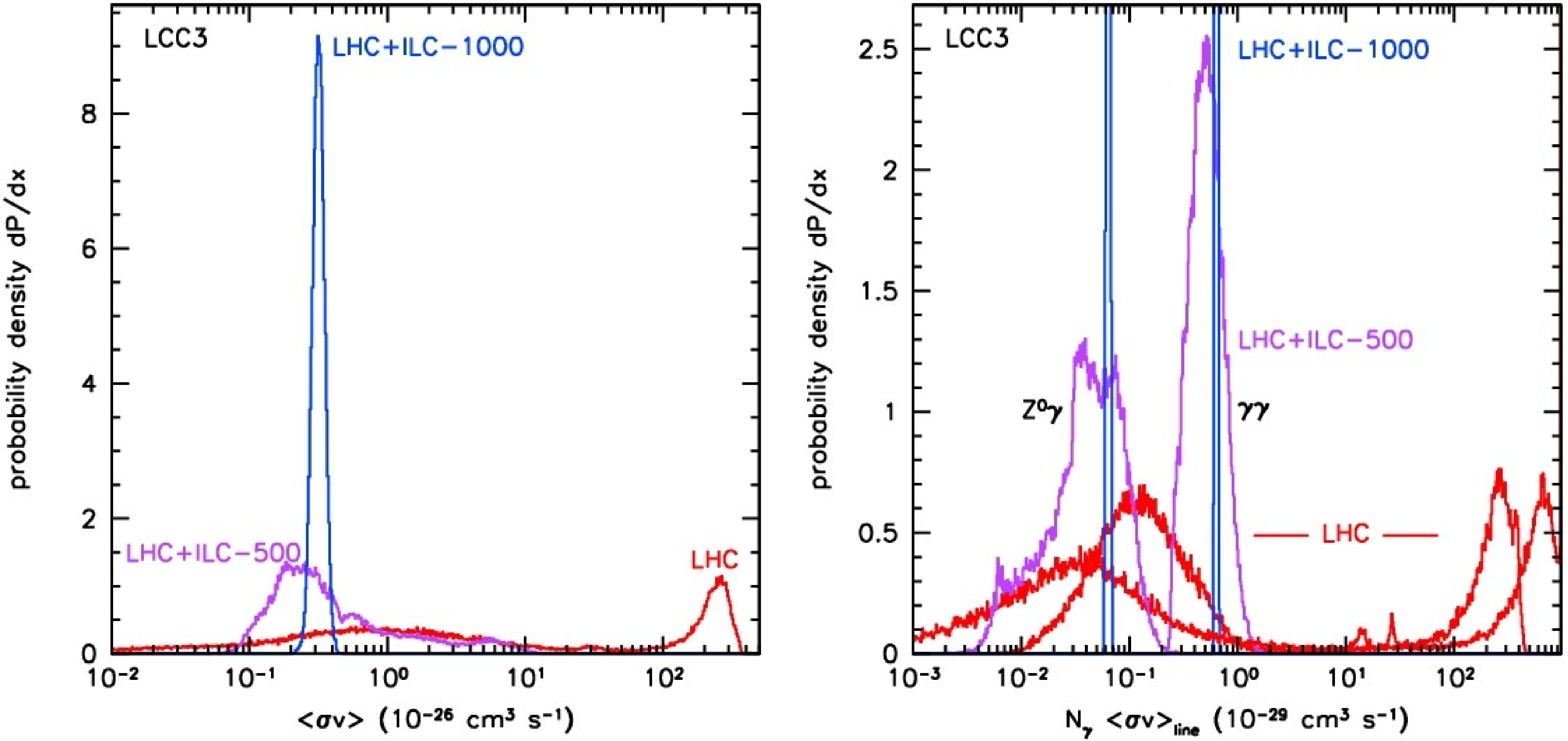


“F” structure: N1 is bino or wino, N2 can be bino, wino, higgsino

LCC3: Prediction of Relic Density and Direct Detection Cross Section



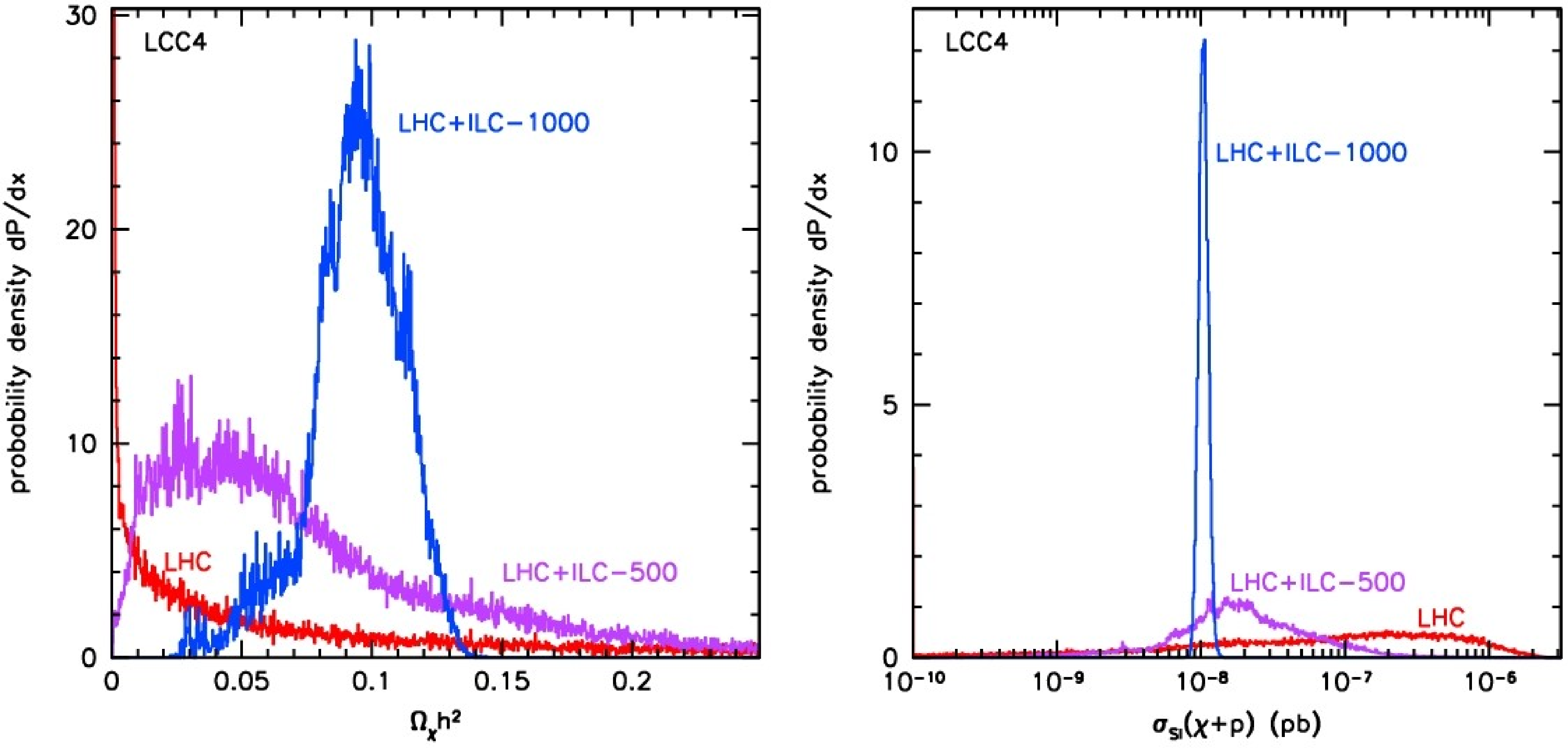
LCC3: Prediction of Annihilation Cross Sections



Results: LCC4

- “Resonance” region: annihilation through CP-odd Higgs
  - LHC discovers 2 neutralinos, gluino, squarks except stops, light higgs, heavy higgs
  - ILC 500 discovers light stau
  - ILC TeV discovers light chargino, all light sleptons, decay width of heavy Higgs
- Relic density estimate has ~20% accuracy with ILC TeV
- Similar in character to LCC3, except in relic density

LCC4: Prediction of Relic Density and Direct Detection Cross Section



The Situation in 2012 for LCC2

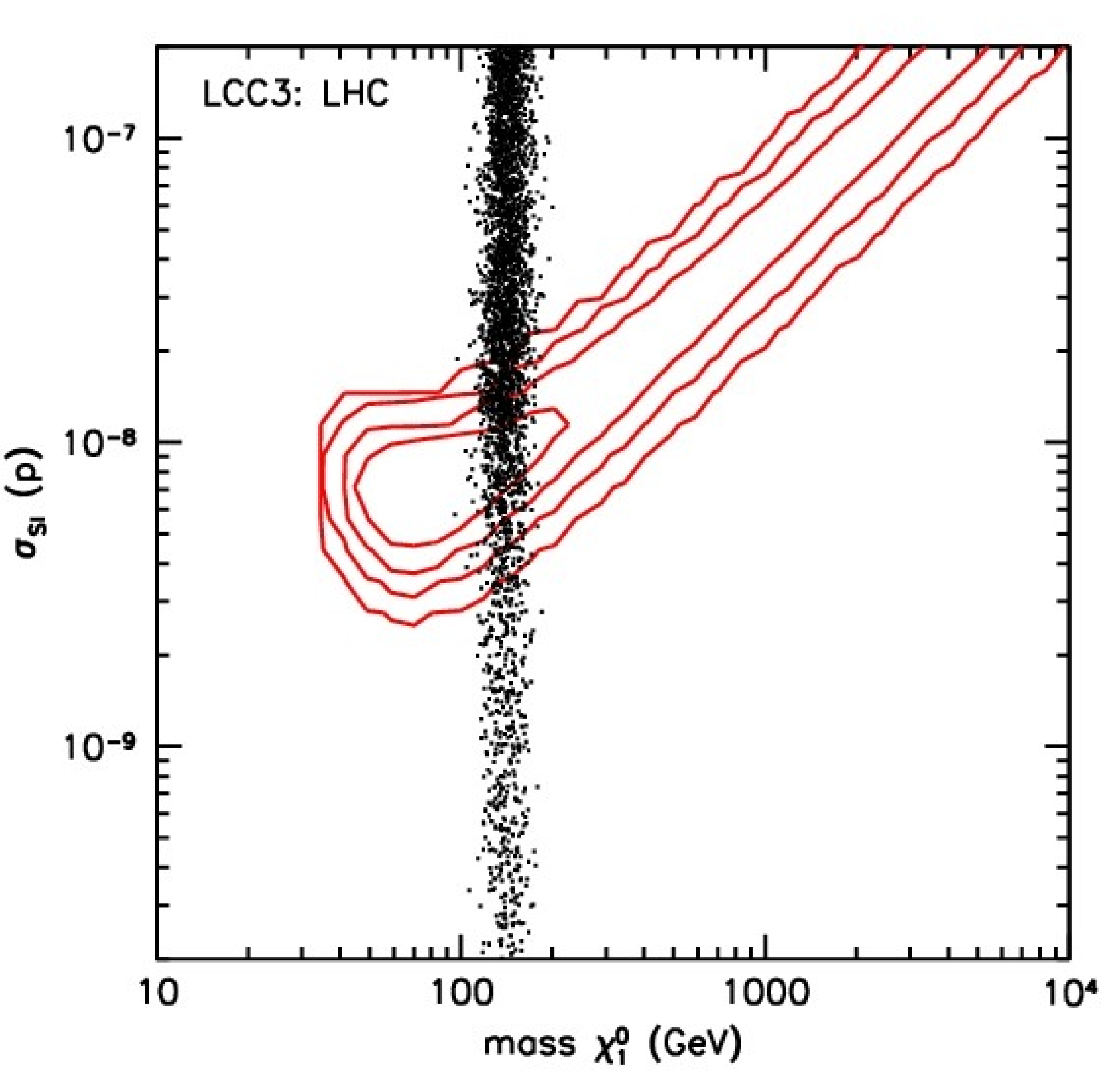
- LHC has seen missing energy events, and measured masses for new particles including a dark matter candidate
  - What is the underlying theory? Spins are difficult to measure.
  - The standard cosmology chooses the SUSY bino solution
- GLAST has obtained a 4+ year sky survey, and has observed anomalous gamma ray sources
  - Mass is in the same range
  - Evidence for dark matter clustering?
- Direct detection experiments have detected ~70 events, measured mass to 30%
  - Mass is consistent with LHC
  - Measure the local dark matter density, assuming the SUSY solution

Using Direct Detection to Measure Particle Properties

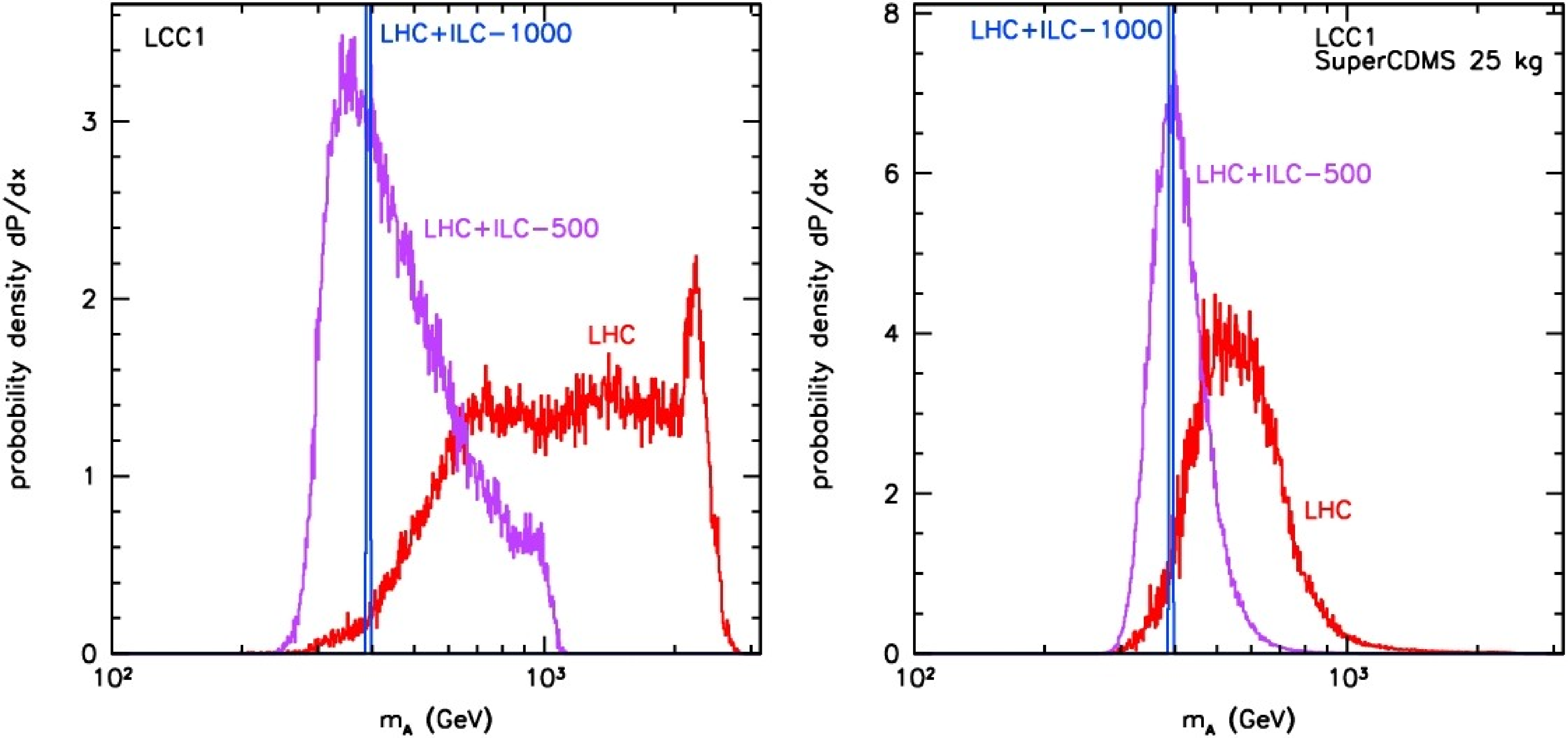
LHC measures the mass, but not the elastic scattering cross section

Direct detection provides this accurately, if given the mass (and assuming the standard galactic halo)

Warning: strangeness content of nucleon needed at higher accuracy (lattice?)



Astrophysical Prediction for Particle Physics



H, A can only be directly discovered at the ILC-1000
direct detection (with ~4 inverse zb) provides strong evidence before this

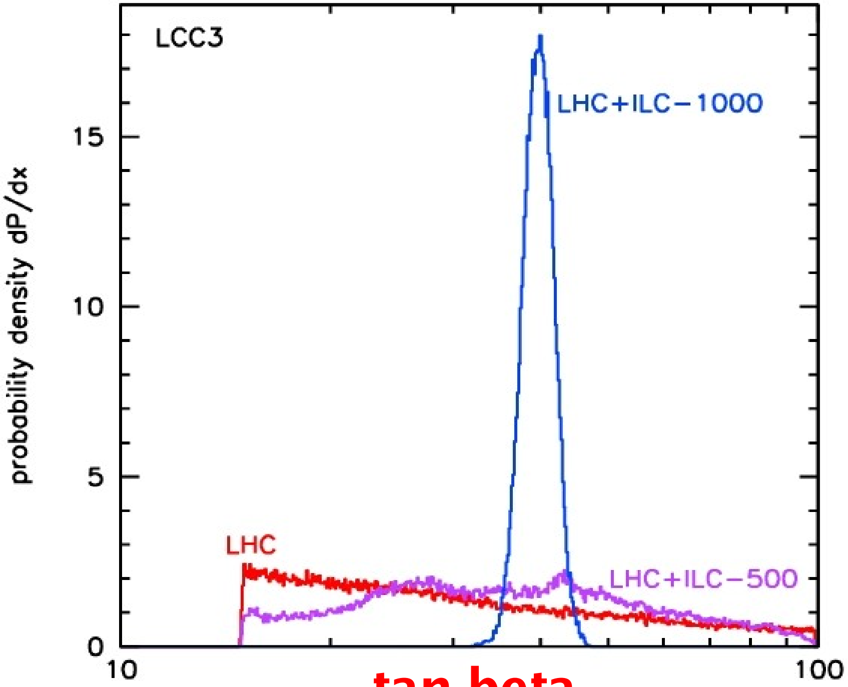
LCC3:

LHC

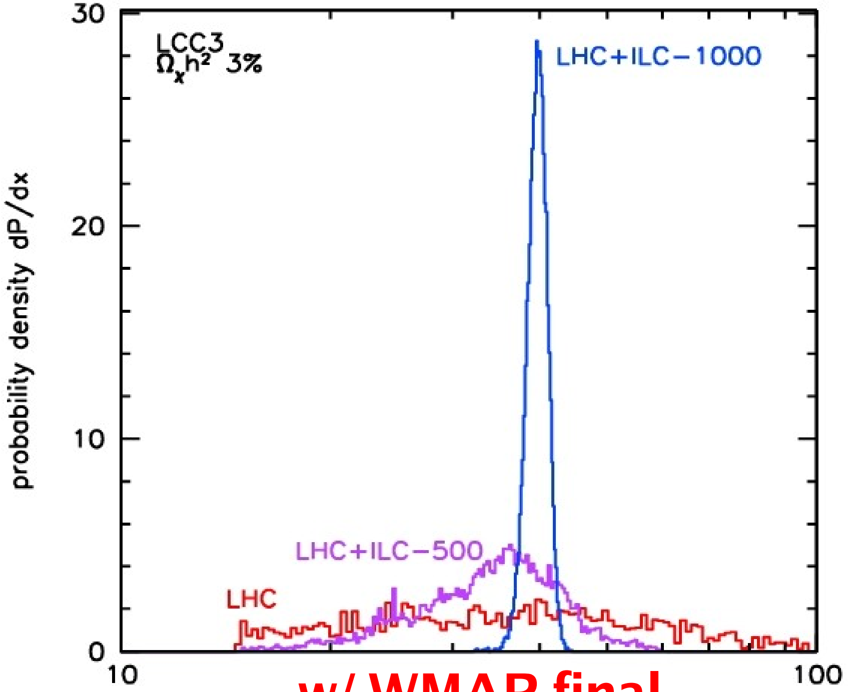
ILC

CMB

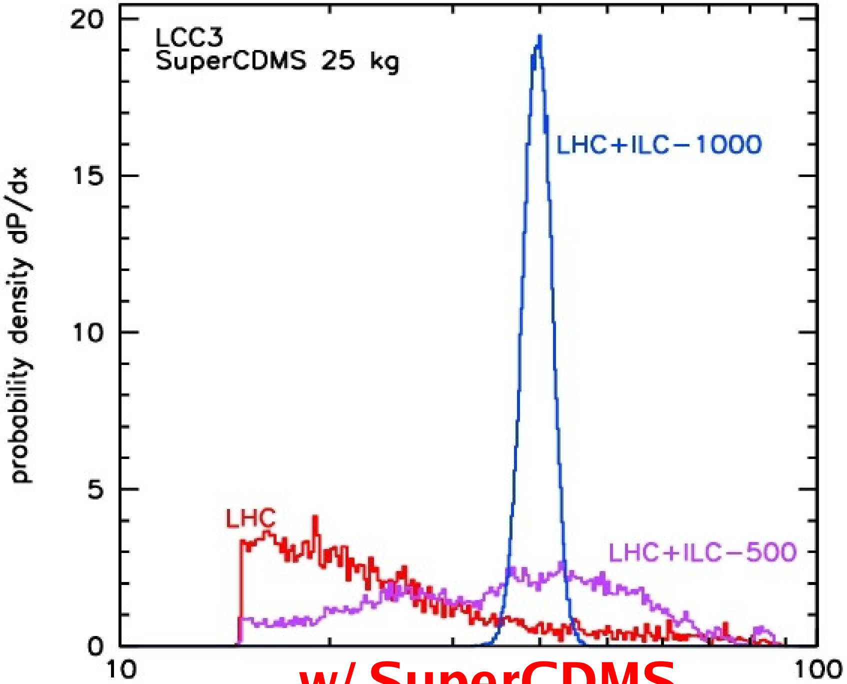
Direct Detection



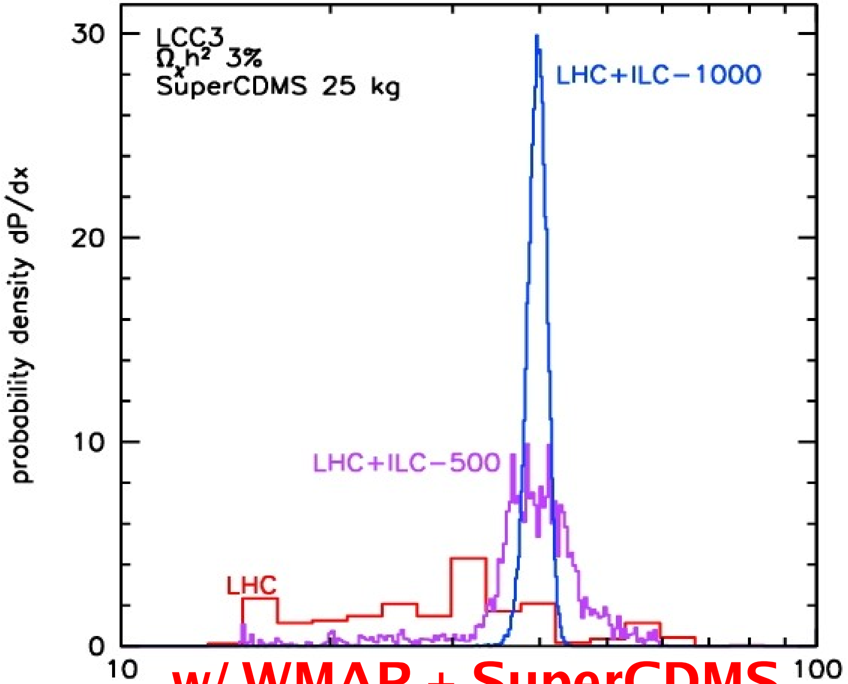
tan beta



w/ WMAP final



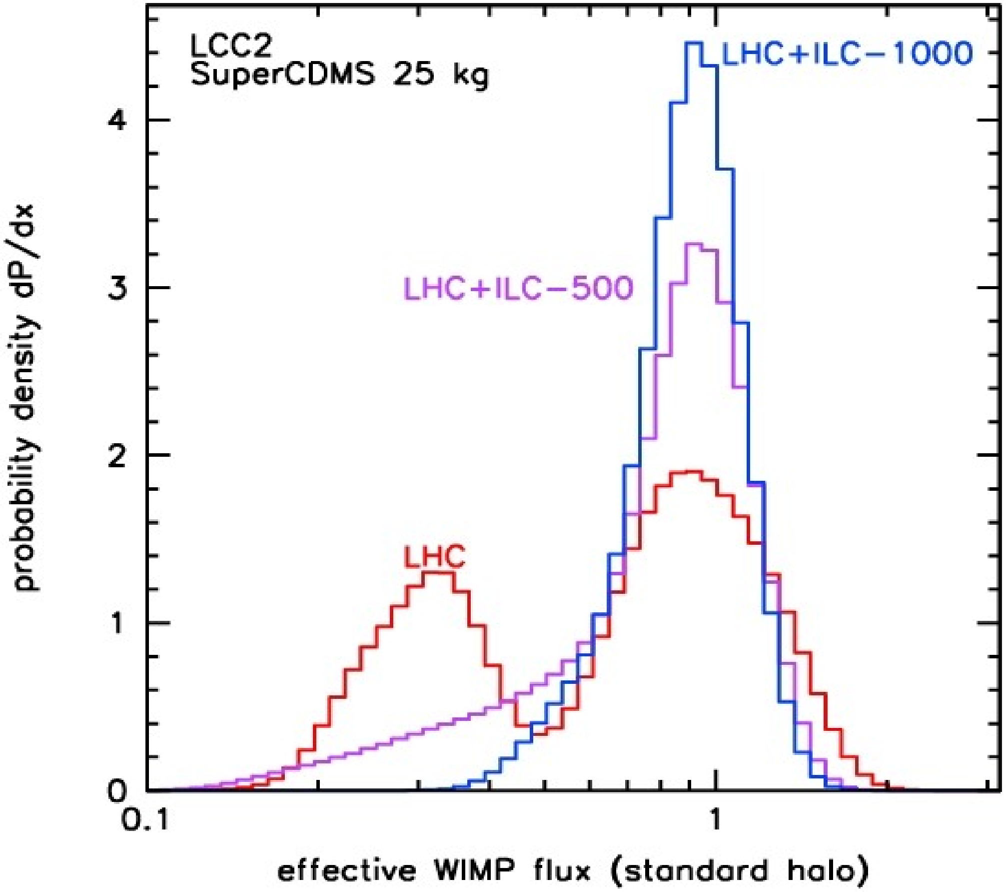
w/ SuperCDMS



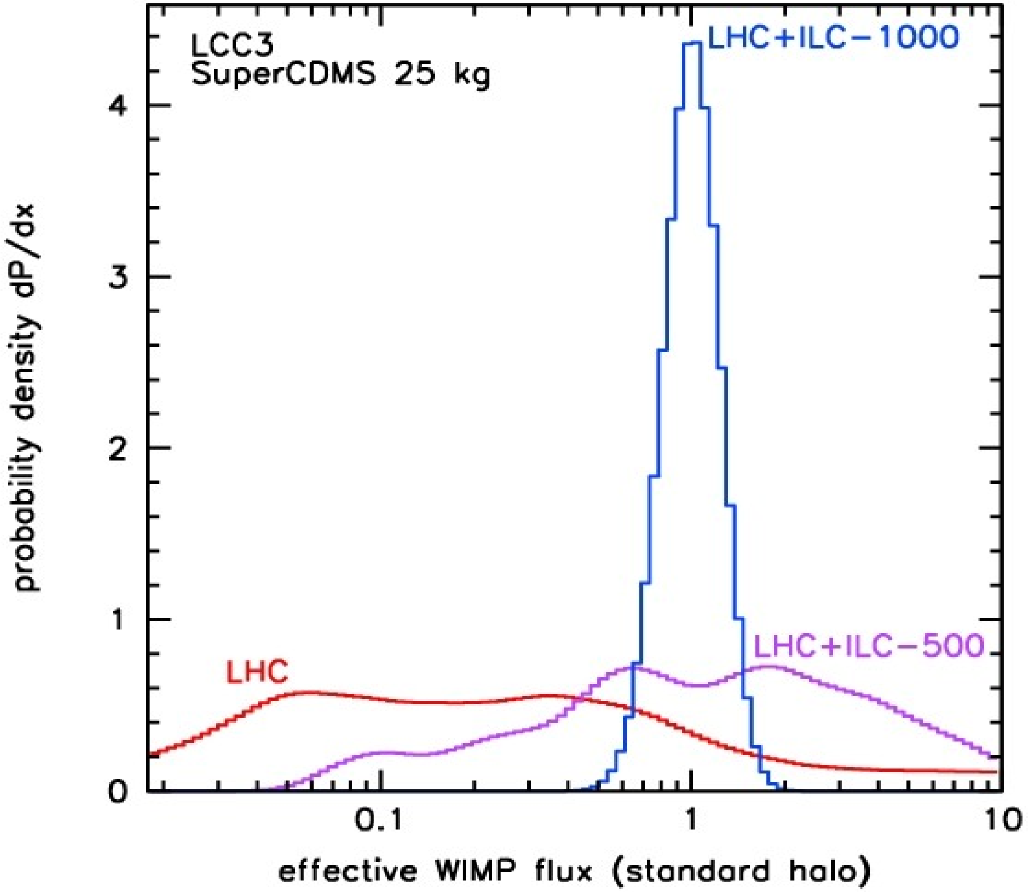
w/ WMAP + SuperCDMS

Local Flux of Neutralinos

LCC2



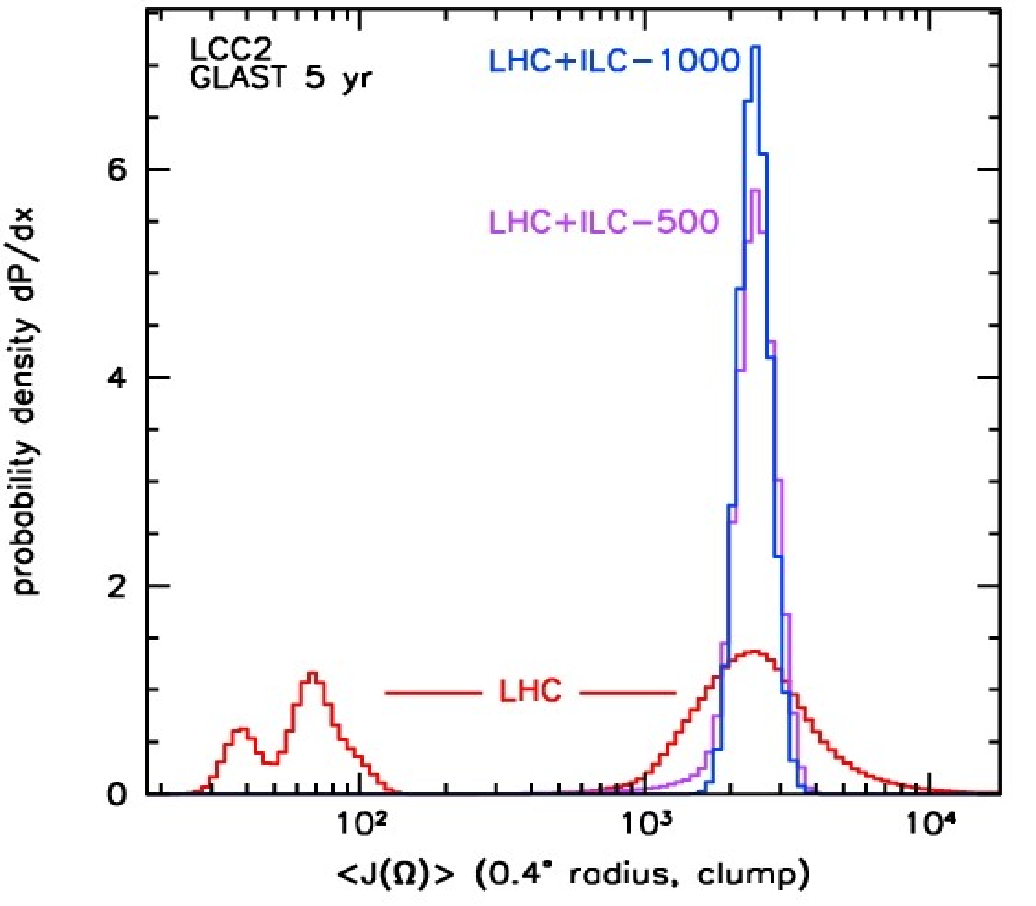
LCC3



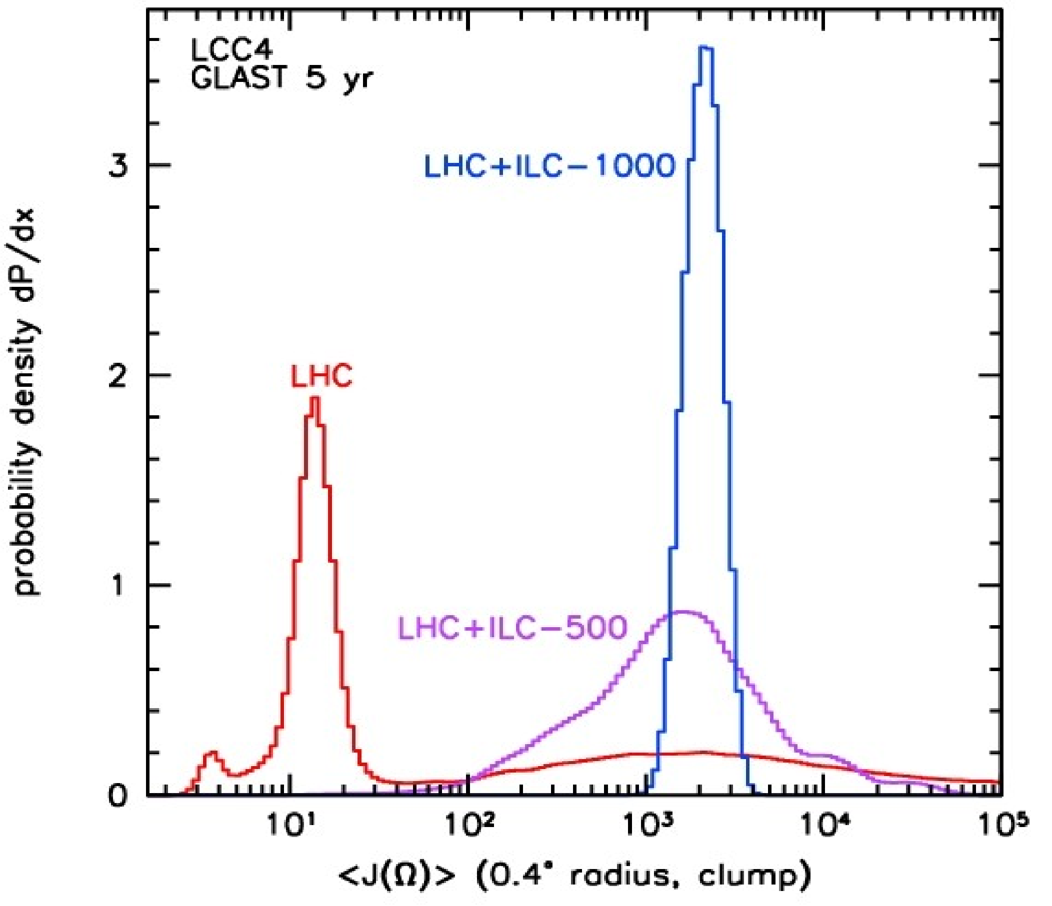
determine WIMP flux with no astrophysical / cosmological assumptions

Dark Matter Annihilation Rate

LCC2



LCC4



$$J \propto \int dr\ \rho^2, \qquad N_\gamma \propto J \langle \sigma v \rangle / m^2$$

determine J with no astrophysical / cosmological assumptions

Summary

- Solving the dark matter problem requires both detecting dark matter in the galaxy and studying its properties in the laboratory
- Experimental approaches are complementary: accelerators, direct detection, indirect detection
- We can learn about fundamental physics in astrophysical settings, and learn about our galaxy at high-energy colliders
- The International Linear Collider is an absolutely crucial part of the experimental effort toward understanding dark matter