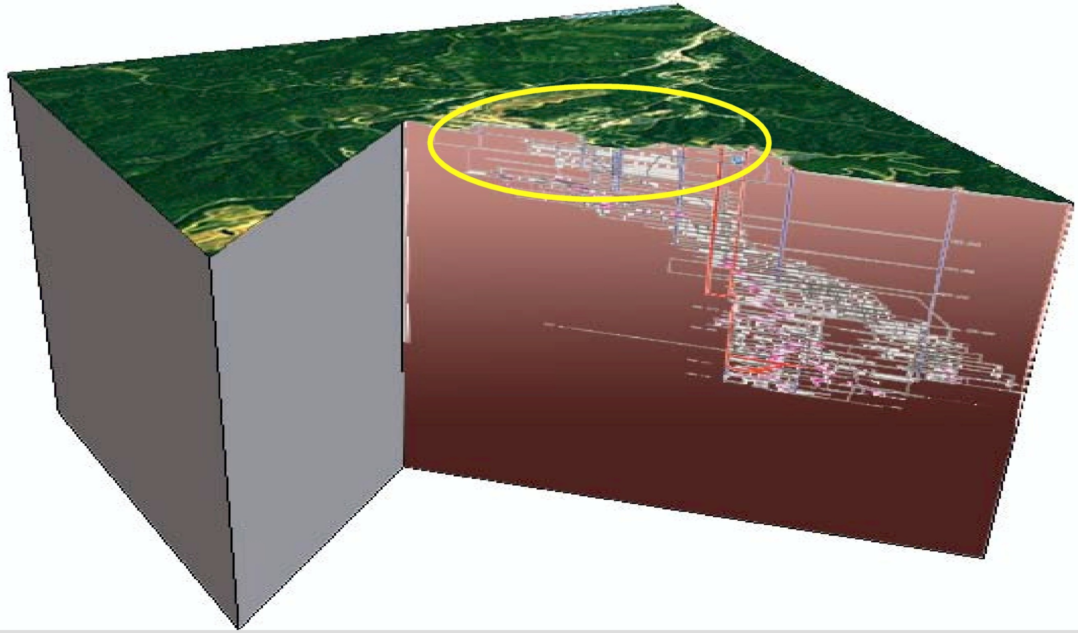
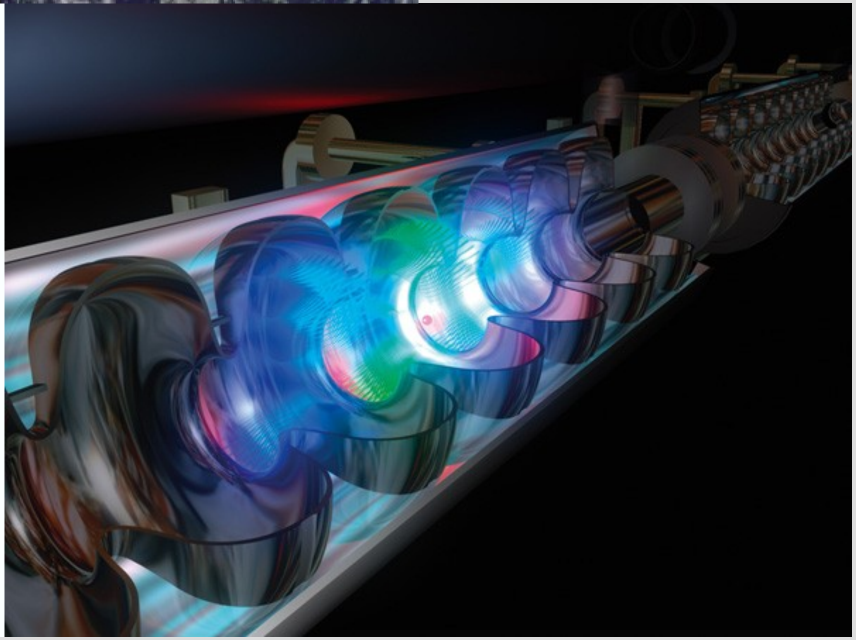
Combining Data on Dark Matter

(How Can We Solve the Dark Matter Problem?)

KIPAC

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 dark matter particles as particles in the galaxy
- 2.) detect dark matter particles in controlled environments at particle accelerators
- 3.) show that these two are the same particle
- To accomplish this we need to combine data from astrophysics and accelerators

Alternative Scenarios

- The WIMP observed at LHC is all / part / none of the dark matter
- The WIMP observed at LHC 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 smooth / clumpy
- The velocity distribution of dark matter is smooth / peaky

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

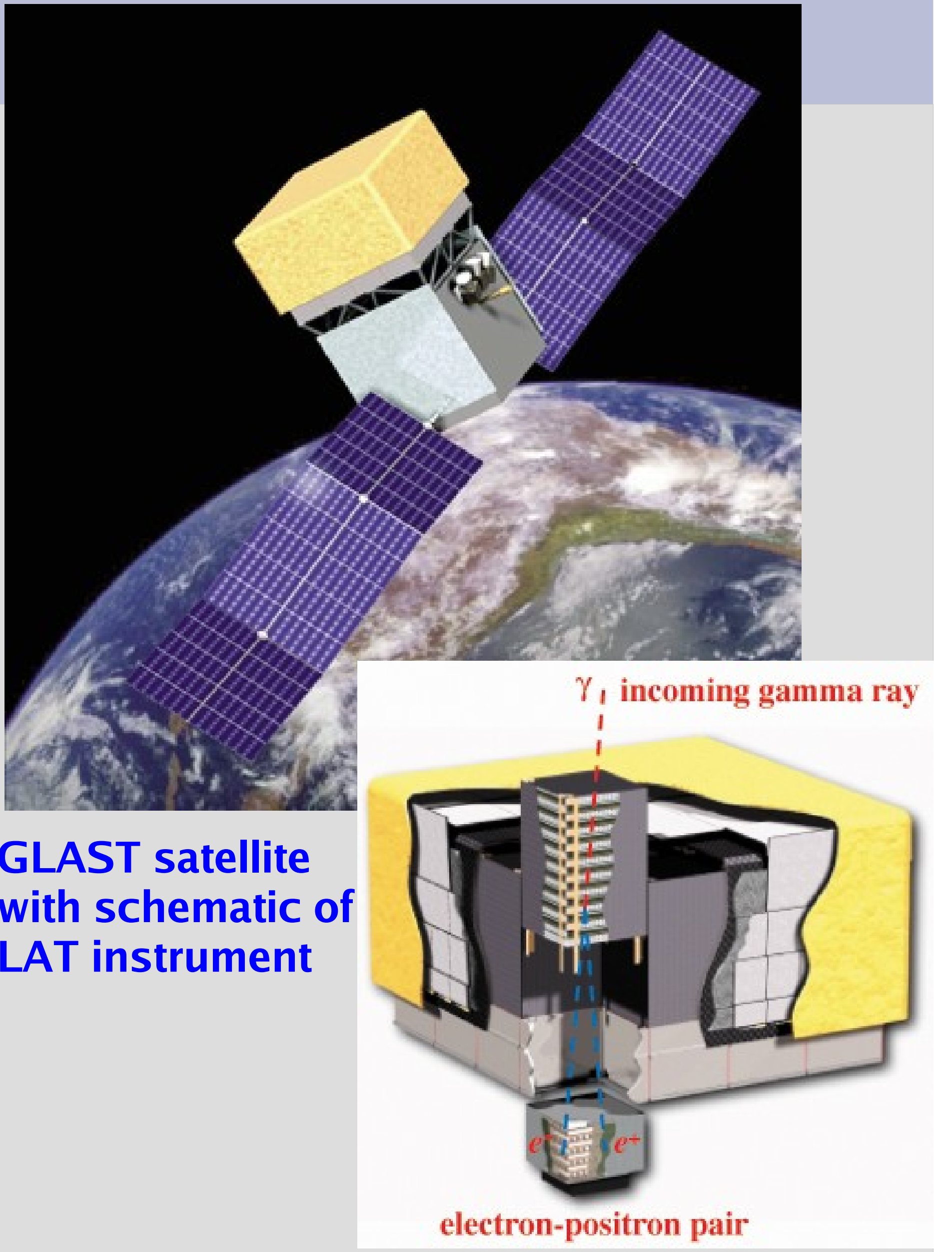
Detecting Dark Matter I

- Direct detection
  - underground (lower CR bkg.)
- Nuclear recoils
  - ~50 keV deposited
  - many detection techniques
    - germanium, silicon (CDMS, EDELWEISS)
    - liquid xenon (ZEPLIN, XENON)
    - sodium iodide (DAMA)
    - calcium tungstate (CRESST)
    - bubble chambers (COUPP)
    - others...

CDMS fridge + icebox @ Soudan mine

Detecting Dark Matter II

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

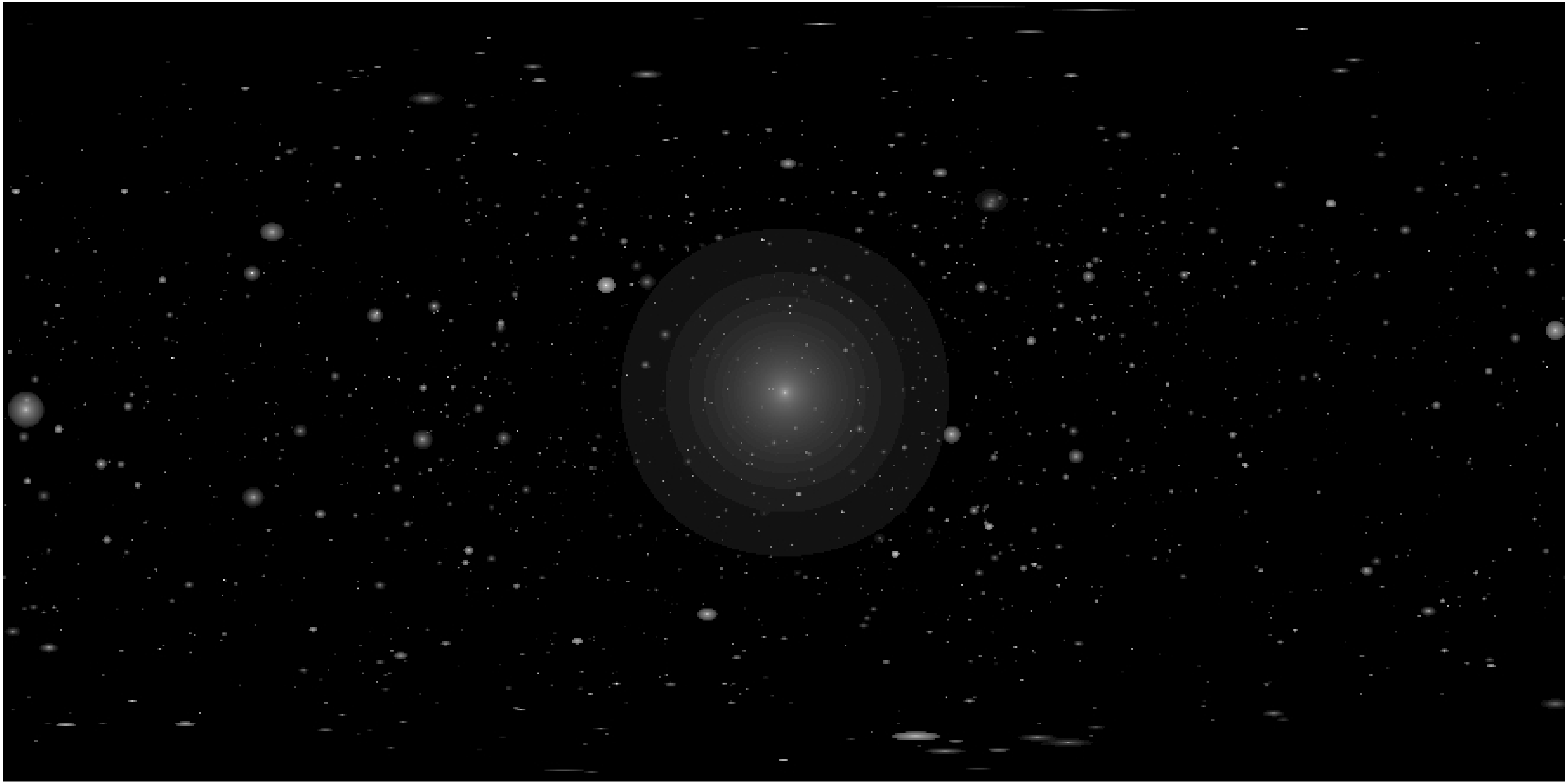


GLAST satellite with schematic of LAT instrument

Dark Matter in the Gamma Ray Sky

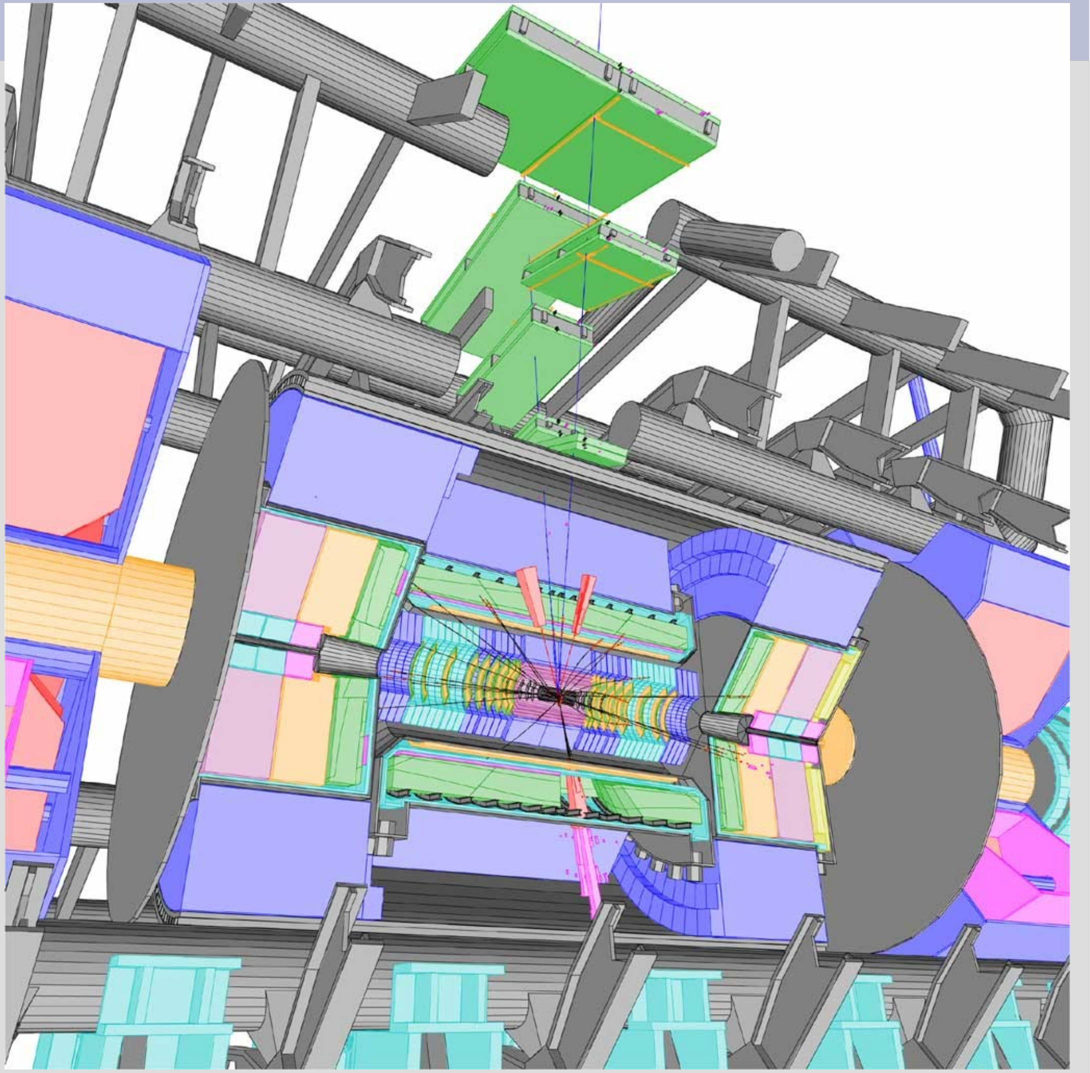
Milky Way Halo simulated by
Taylor & Babul (2005)
All-sky map of gamma ray emission
from dark matter annihilations

dark matter substructure exhibits:
1. characteristic γ-ray spectrum
2. spatially extended emission



Detecting Dark Matter III

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

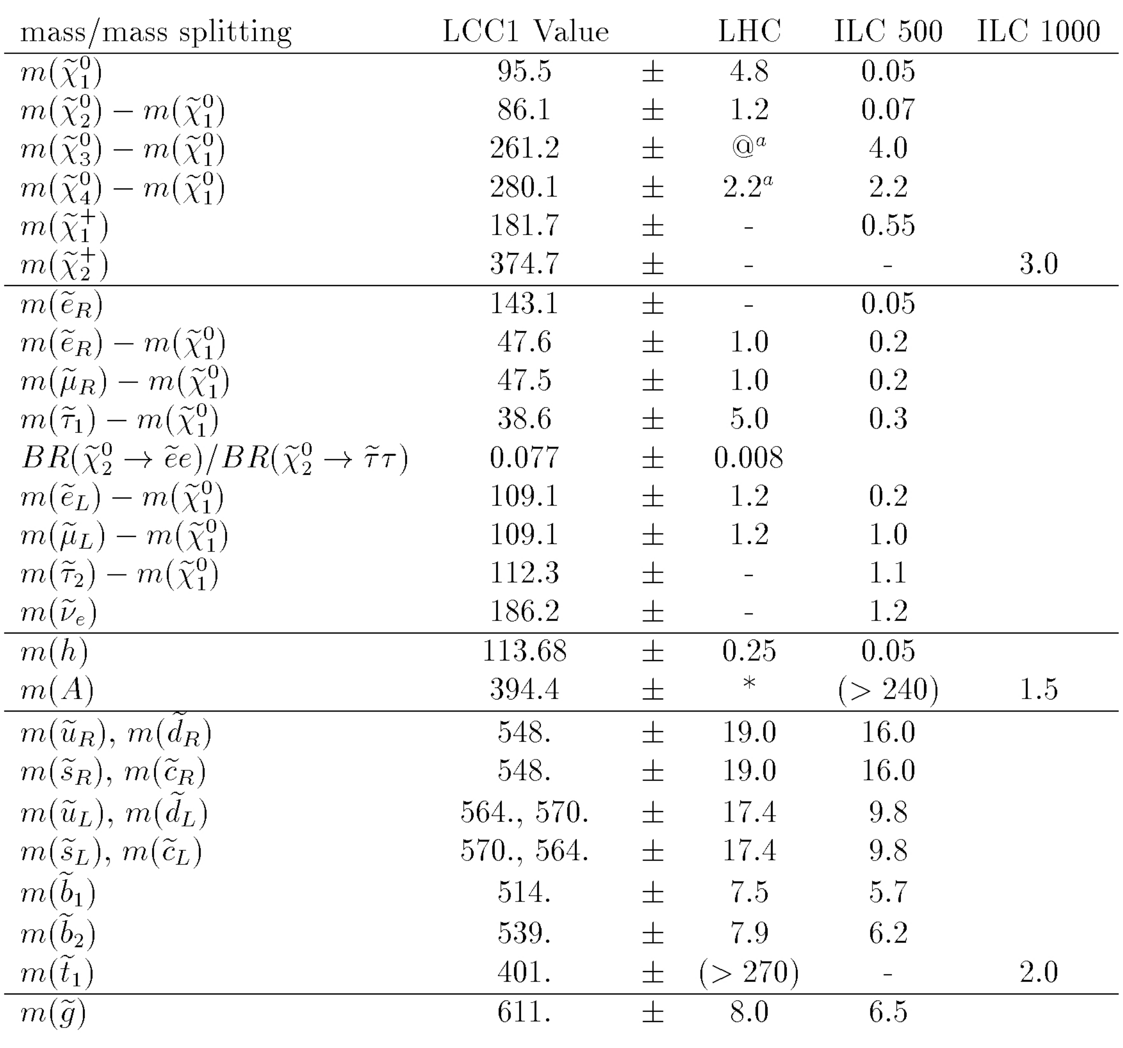


Simulation of event in ATLAS @ LHC

Dark Matter Microphysics: Examples from Supersymmetry

- Work done with M. Battaglia, M. Peskin and T. Wizansky
  - hep-ph/0602187 (120 pages)
- Assume SUSY – study 4 “benchmark” points
  - LCC1-4, chosen by ALCPG: dark matter and ILC-500
- Identify expected collider measurements
  - masses, polarized production cross-sections, FB asymmetries
- Generate 1e6 SUSY models consistent with measurements
  - 24 parameters – most general MSSM conserving flavor and CP
- Study the range of properties relevant to dark matter
- Three cases:
  - Large Hadron Collider
  - International Linear Collider – 500 GeV CM energy
  - ILC – TeV CM energy

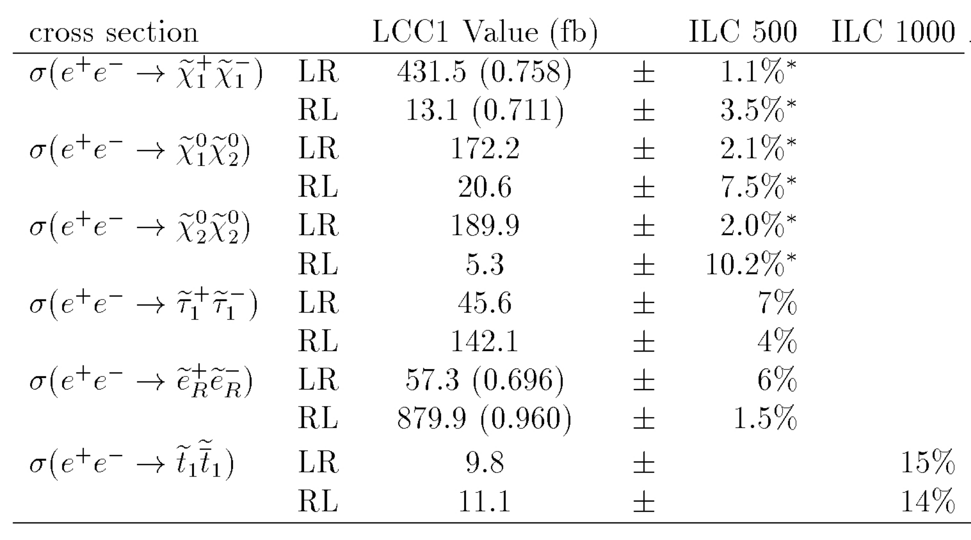
Collider measurements: LCC1



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

cross sections



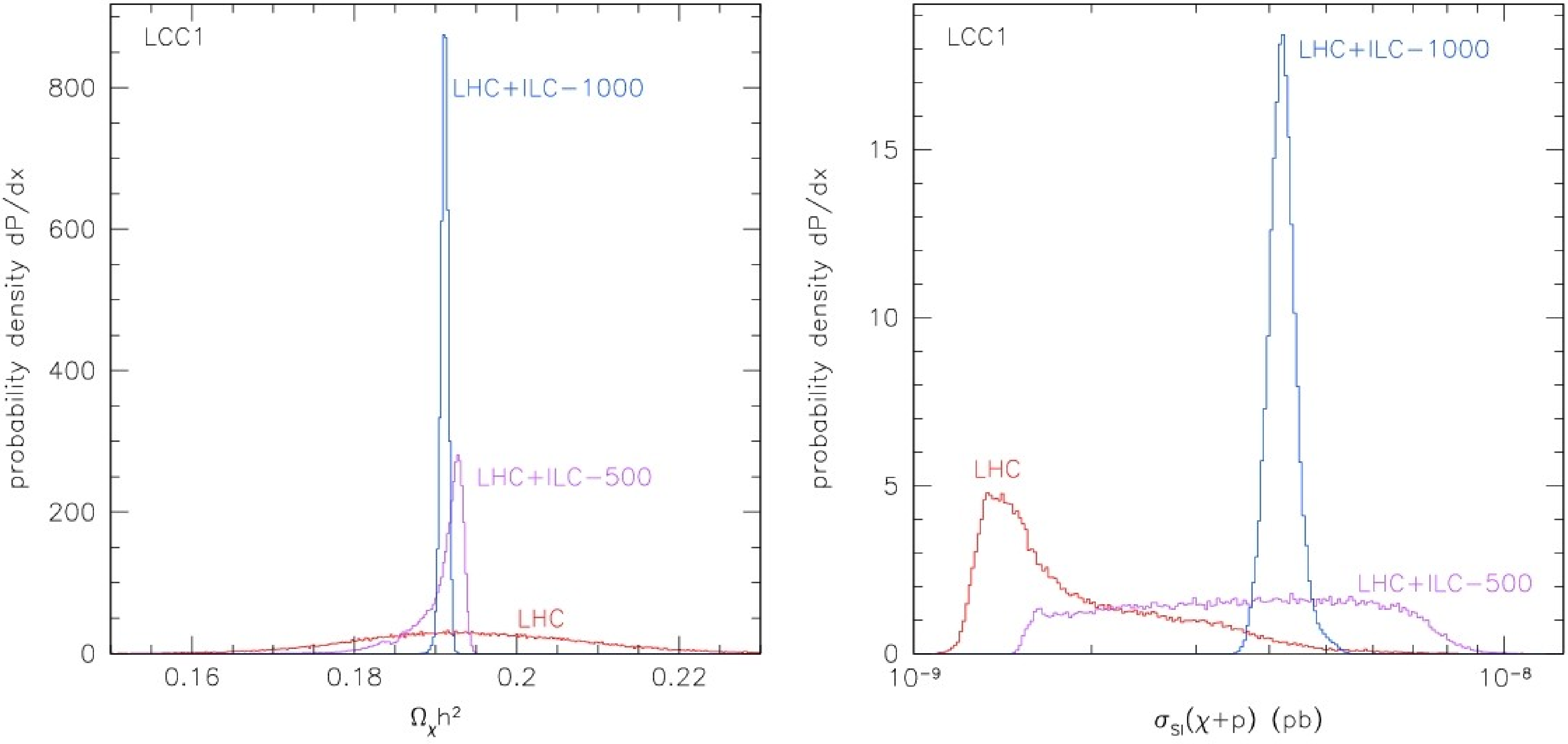
cross section		LCC1 Value (fb)		ILC 500	ILC 1000
$\sigma(e^+e^- \to \tilde\chi_1^+\tilde\chi_1^-)$	LR	431.5 (0.758)	±	$1.1\%^*$	
	RL	13.1 (0.711)	±	$3.5\%^*$	
$\sigma(e^+e^- \to \tilde\chi_1^0\tilde\chi_2^0)$	LR	172.2	±	$2.1\%^*$	
	RL	20.6	±	$7.5\%^*$	
$\sigma(e^+e^- \to \tilde\chi_2^0\tilde\chi_2^0)$	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%	
$\sigma(e^+e^- \to \tilde t_1\bar{\tilde t}_1)$	LR	9.8	±		15%
	RL	11.1	±		14%

(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

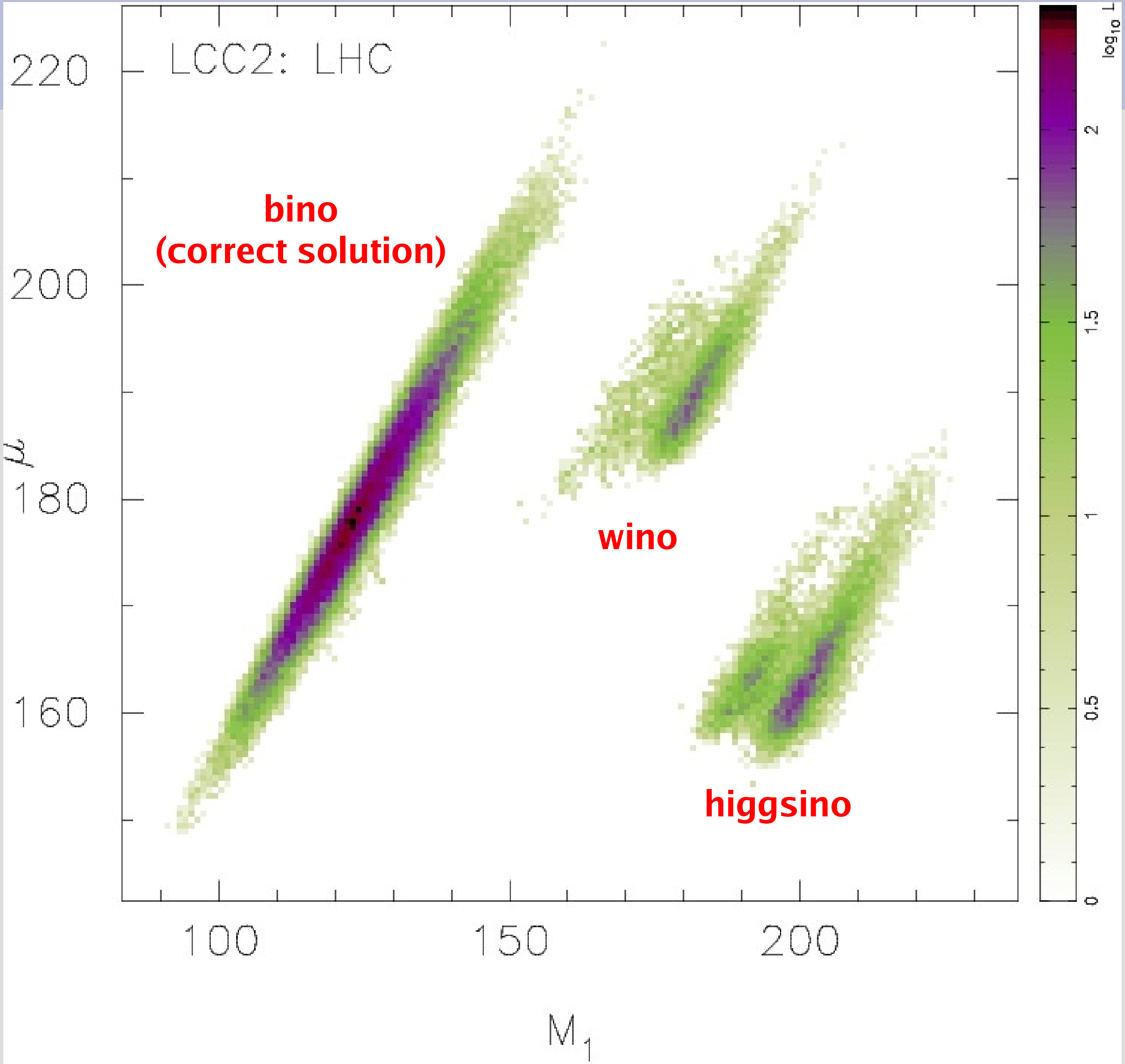
LCC1: Prediction of Relic Density and Detection Cross Section



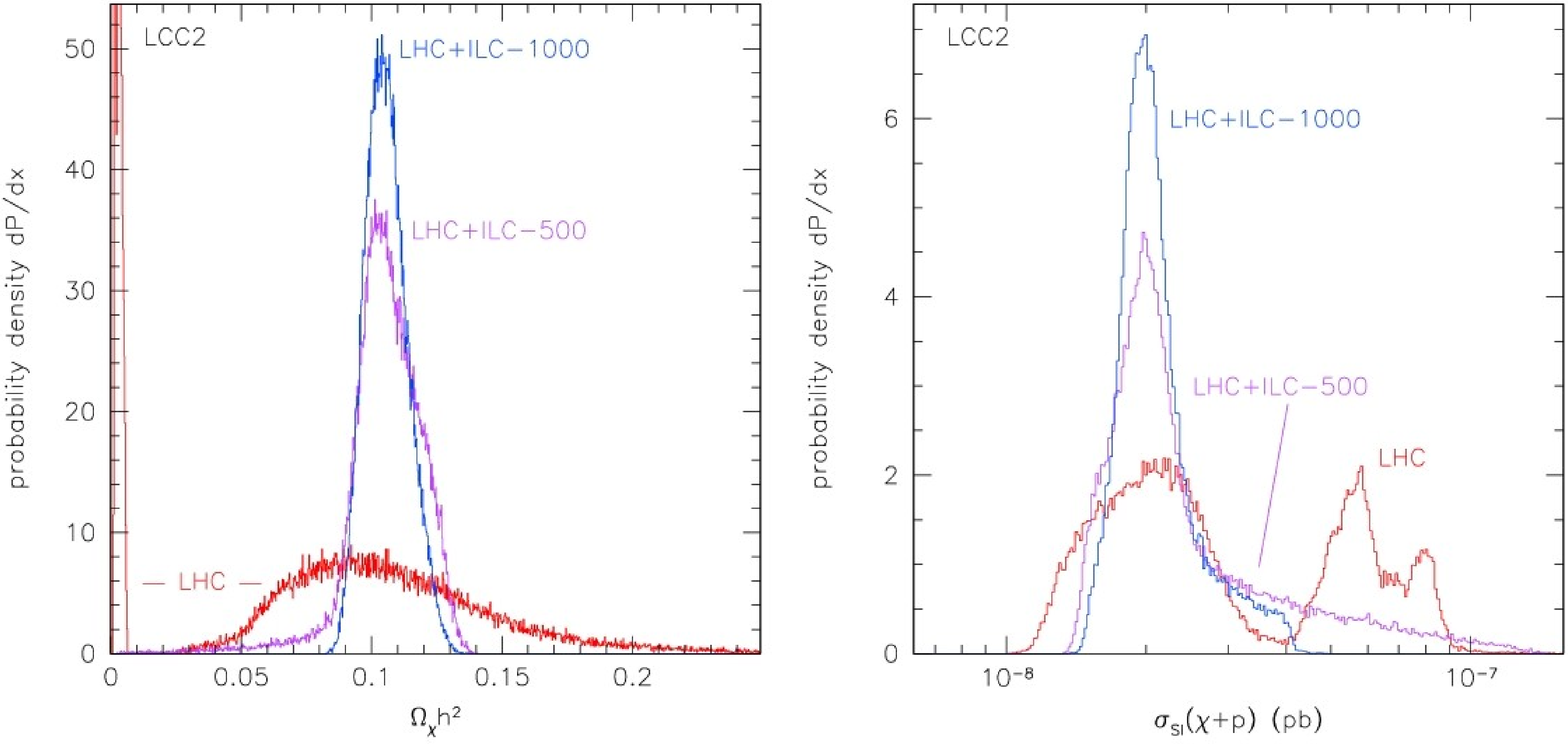
Results: LCC2

- “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
- Direct detection is dominated by light Higgs
- Annihilation cross section is large – dominated by W pairs
  - promising for gamma ray experiments

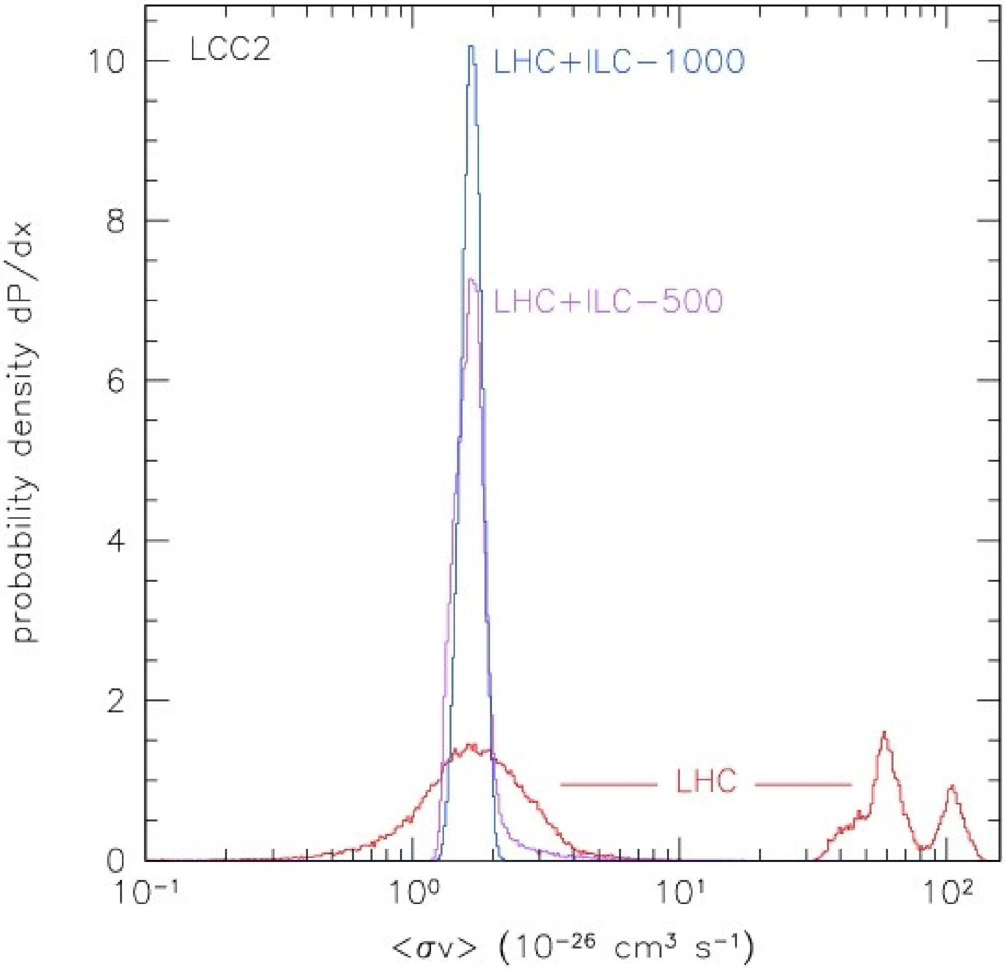
LCC2: Probability Islands @ LHC

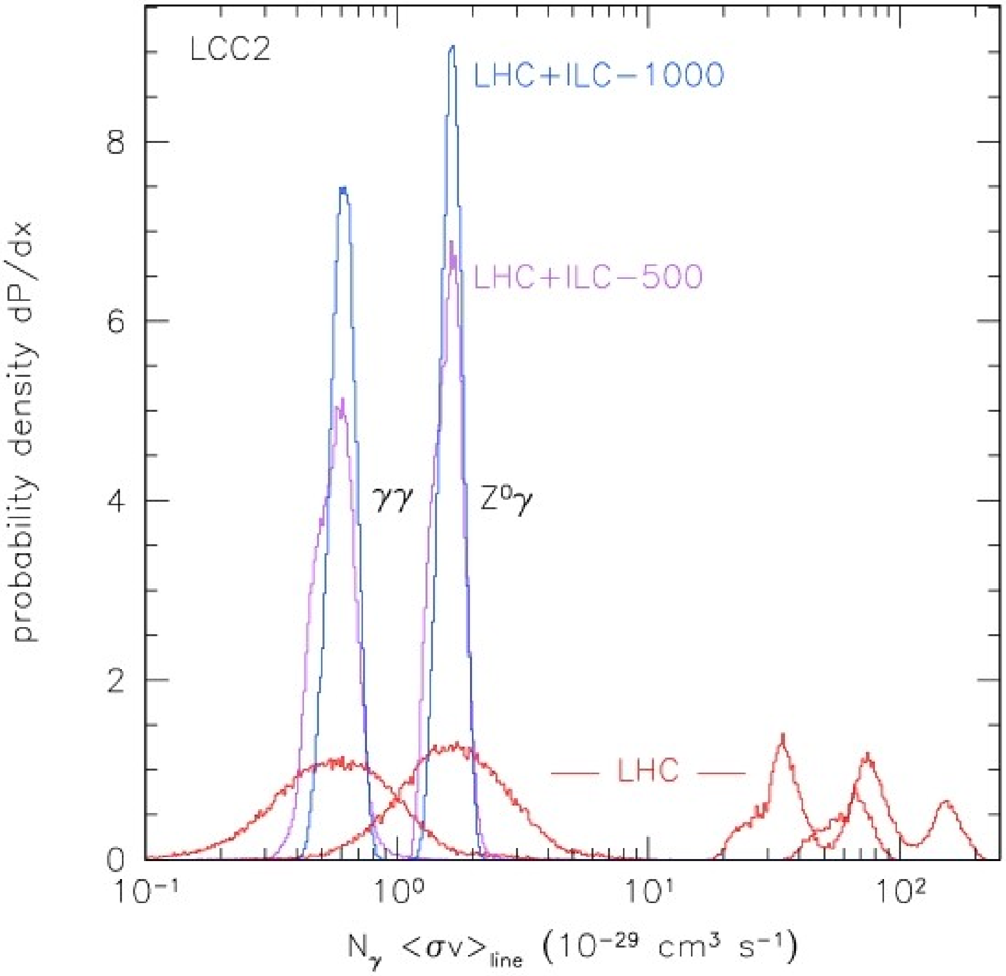


LCC2: Prediction of Relic Density and Detection Cross Section



LCC2: Gamma Rays





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

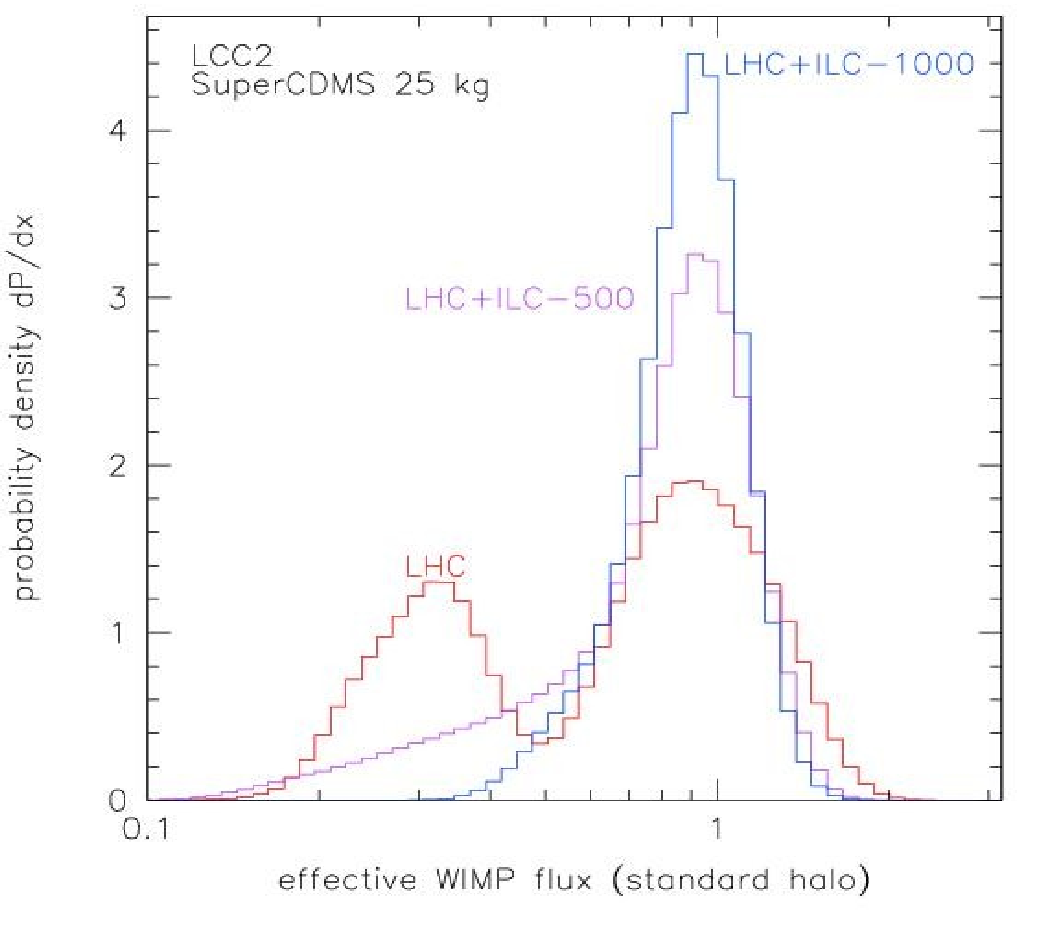
Combination of Collider and Astrophysical Data

- ILC verifies that the underlying model is SUSY
- ILC chooses the correct SUSY solution
- ILC-500 and ILC-TeV determine the SUSY parameters with increasing precision

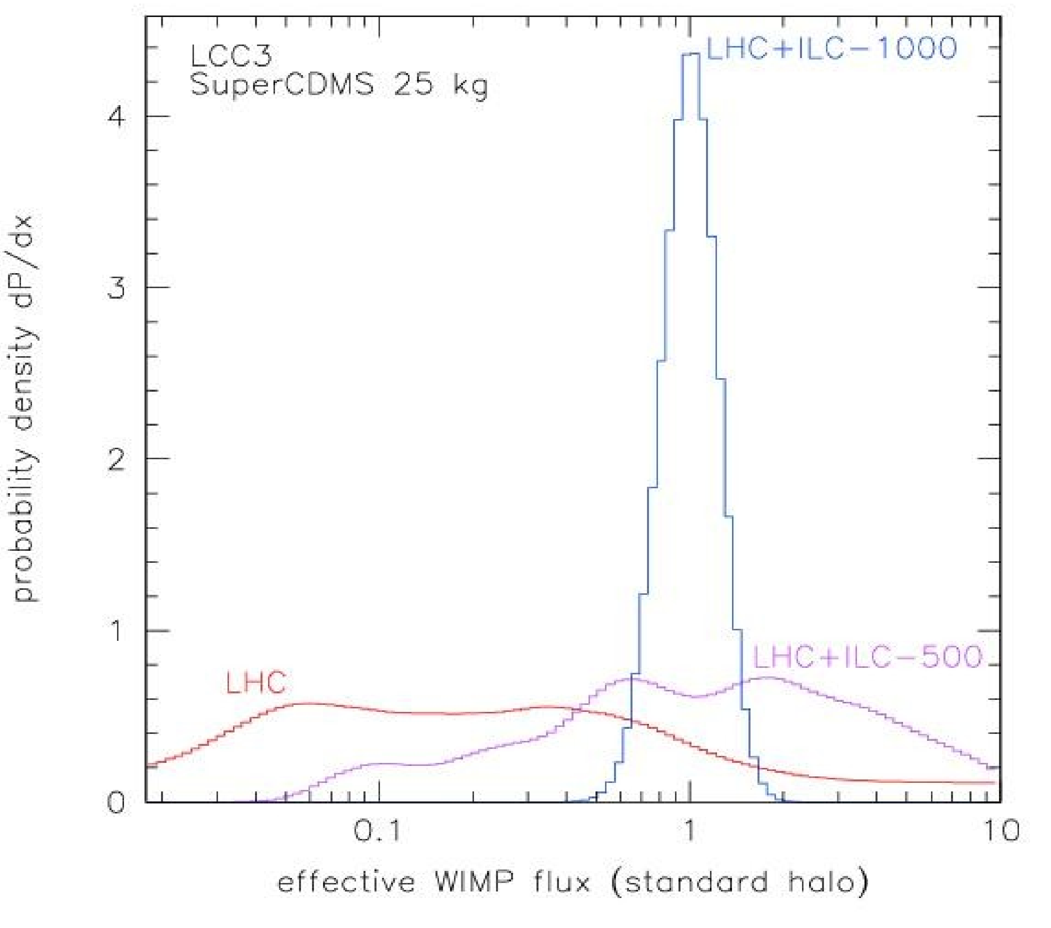
- Explore the implications for astrophysics

Local Flux of Neutralinos

LCC2



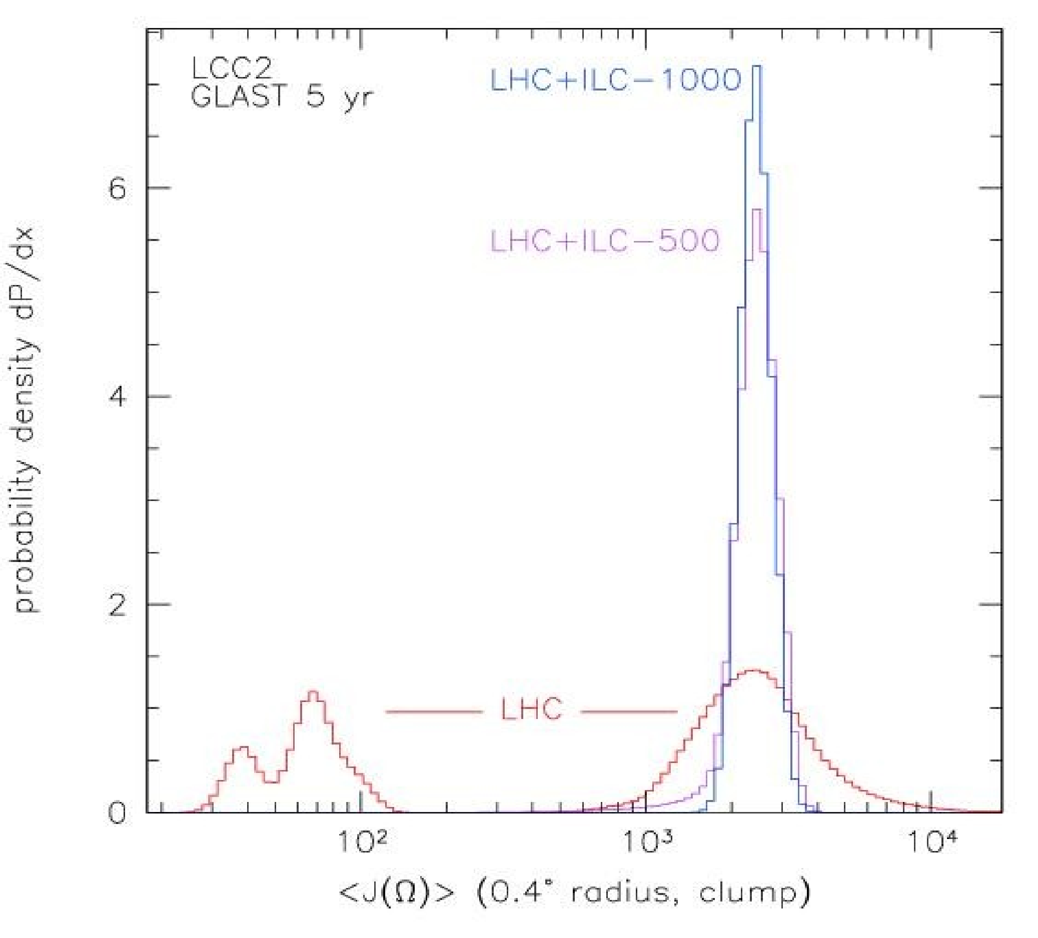
LCC3



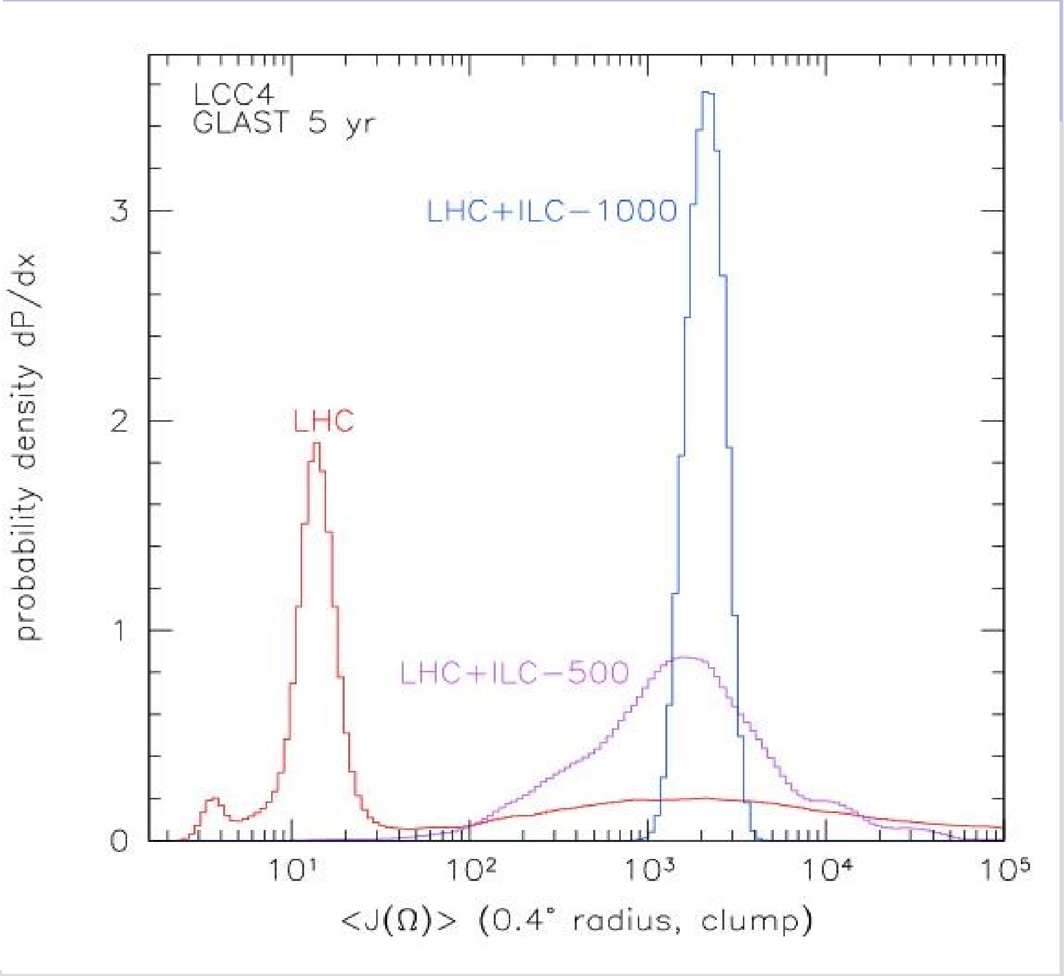
determine WIMP flux with no astrophysical / cosmological assumptions

Dark Matter Clustering

LCC2



LCC4

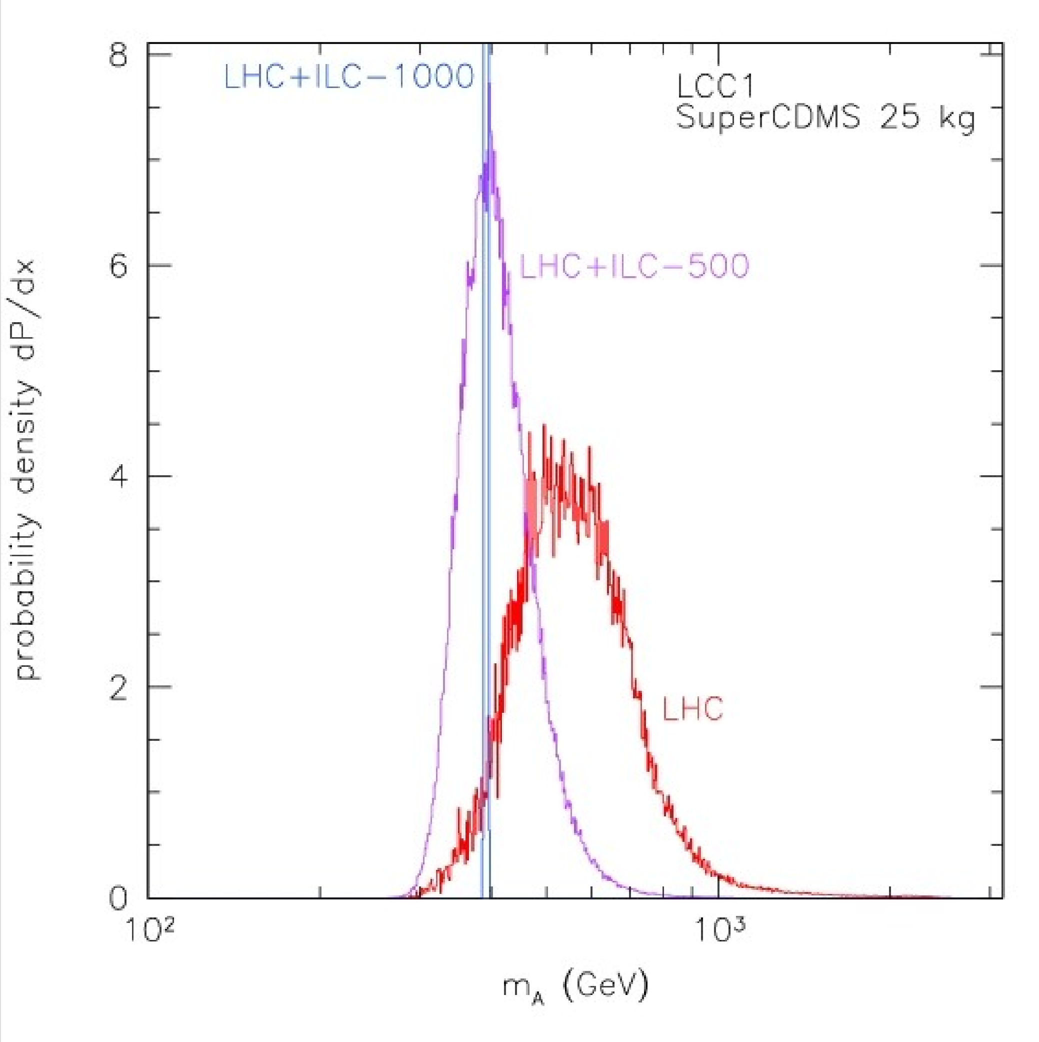


$$J \propto \int dr\ \rho^2, \qquad N_\gamma \propto J \langle \sigma v \rangle / m^2$$

determine J with no astrophysical / cosmological assumptions

Astrophysical Prediction for Particle Physics

H, A can only be directly discovered at the ILC-1000, direct detection provides strong evidence before this



Broader Perspective on Astrophysical Experiments

- Direct detection cross sections vary widely, local halo density uncertain at the factor of 2 level

- Annihilation cross sections are near maximal for “half” of SUSY models, predictions for density squared vary over many orders of magnitude

- For “standard” astrophysical assumptions, there are SUSY models exhibiting all possibilities, ca. 2012:
  - WIMPs visible only to GLAST
  - WIMPs visible only to direct detection
  - WIMPs visible to both
  - WIMPs visible to neither

Summary

- Solving the dark matter problem requires both detecting dark matter in the galaxy and studying its properties in the laboratory

- All approaches are needed:
  - direct detection
  - indirect detection
  - accelerators

- We can both learn fundamental physics astrophysically, and learn astrophysics from colliders