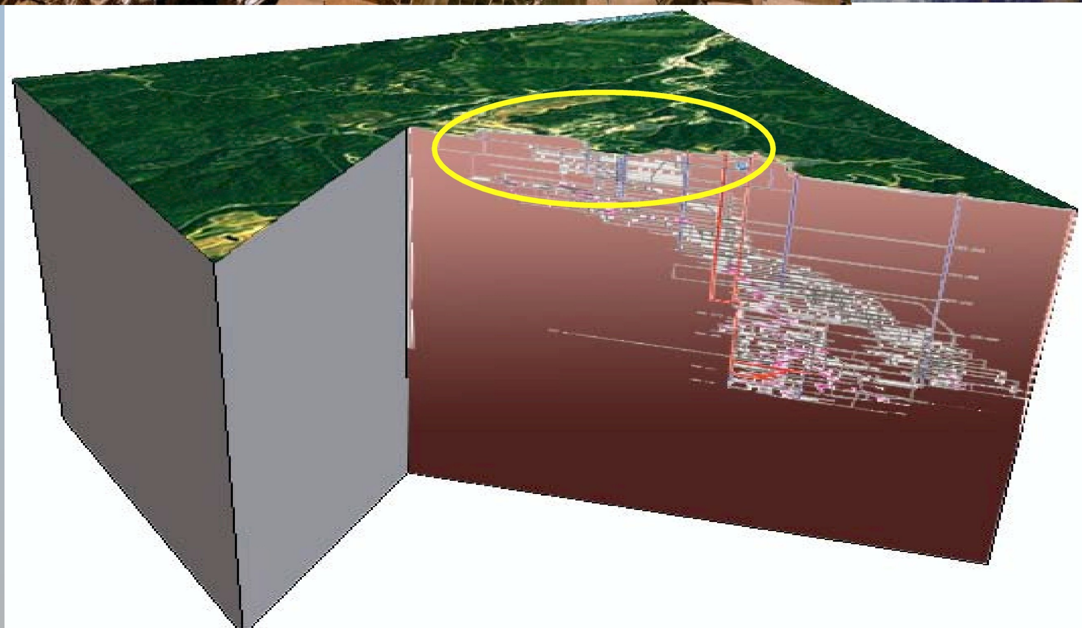
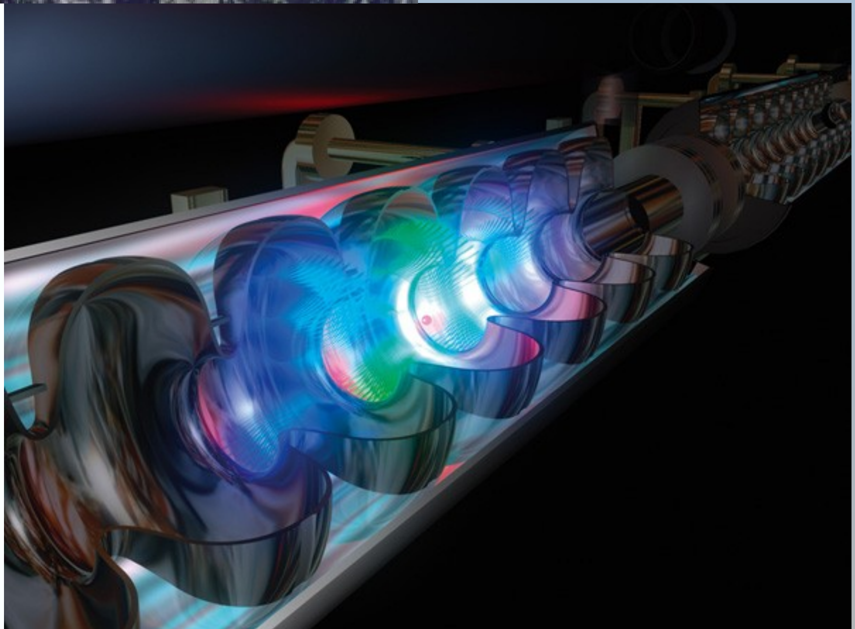
Measuring the Properties of Dark Matter

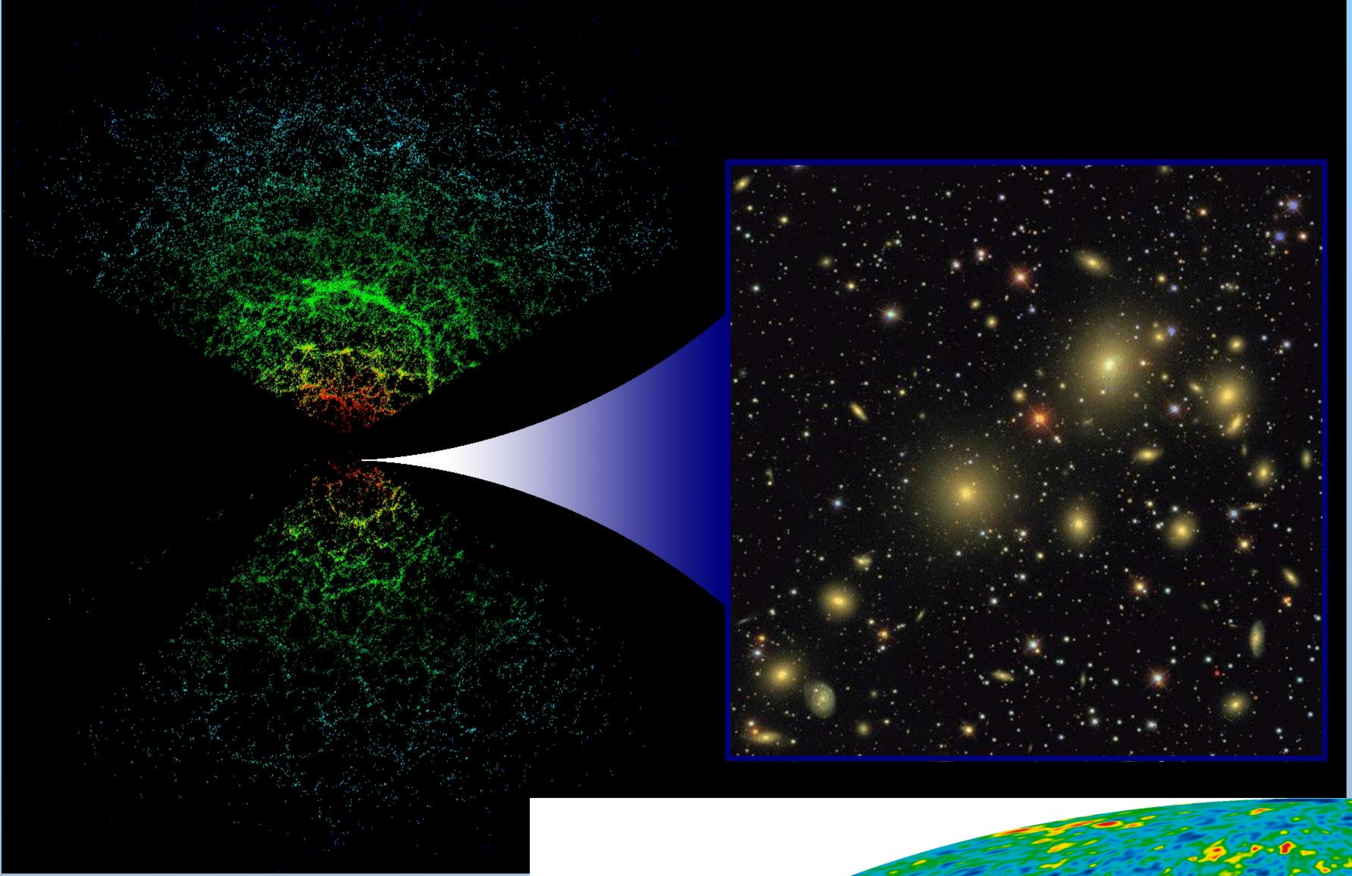




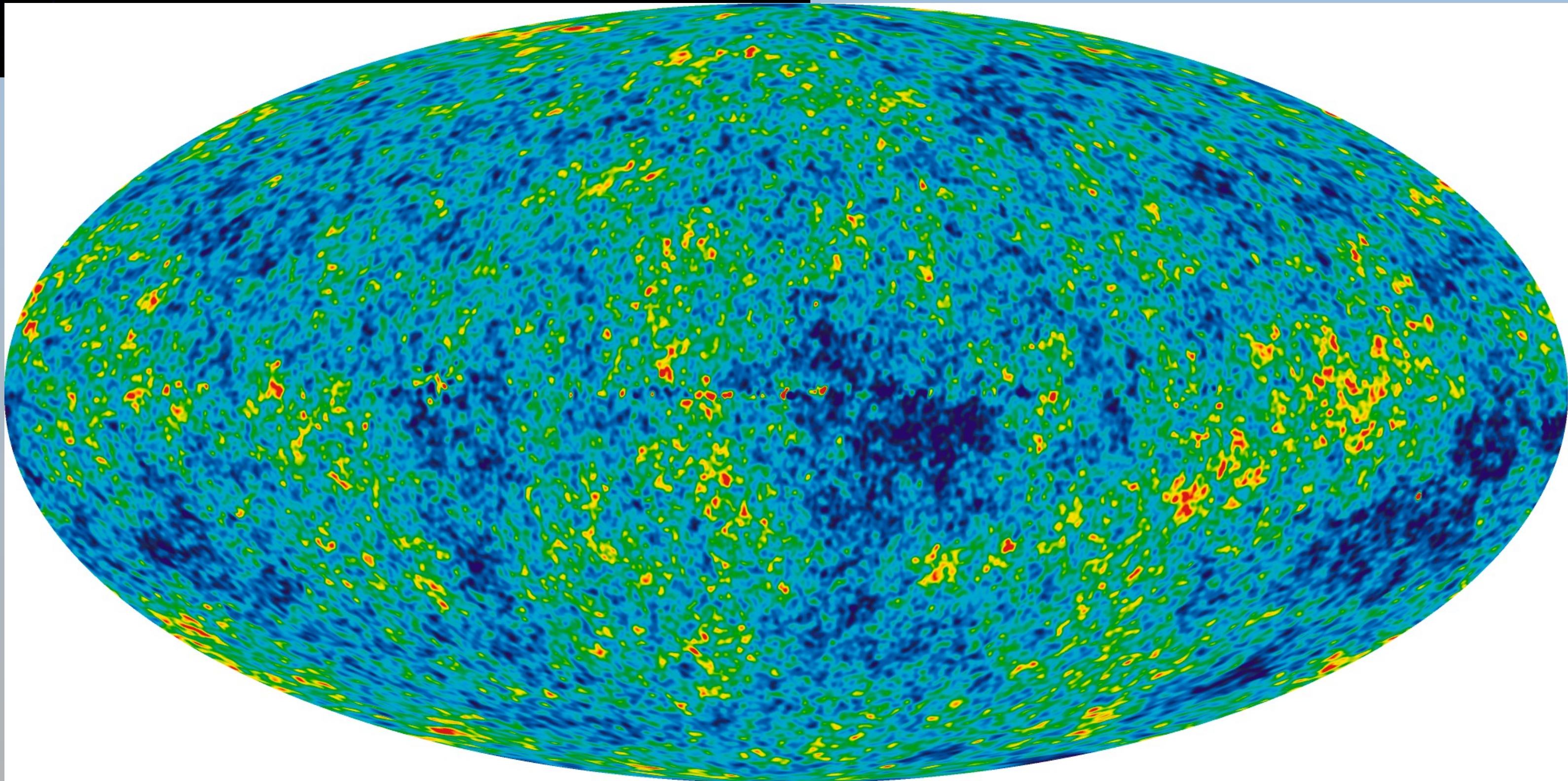
The Dark Matter Problem

- 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…

Dark Matter At Large Scales



SDSS



WMAP

To Solve the Dark Matter Problem We Must Do Three Things

- 1.) Demonstrate that the dark matter in the galaxy is made of particles
- 2.) Create dark matter candidates in the controlled environments of accelerators
- 3.) Demonstrate that these two are the same
- To accomplish this we need to combine data from astrophysics and accelerators
  - Any one of these three would be a discovery of fundamental importance!

Alternative Scenarios for WIMPs (which might be observed at the 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.

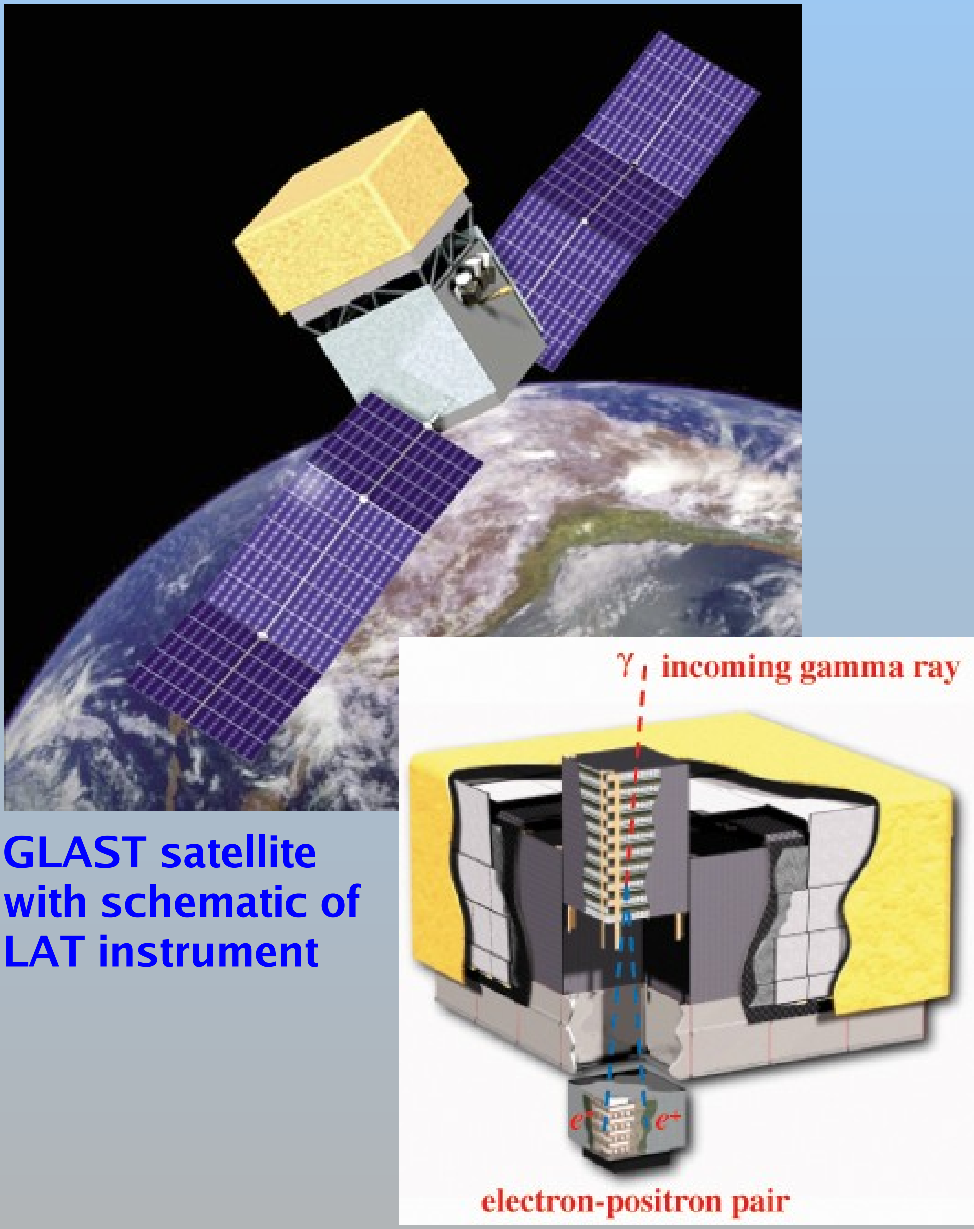
Direct Detection of Dark Matter

- 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

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

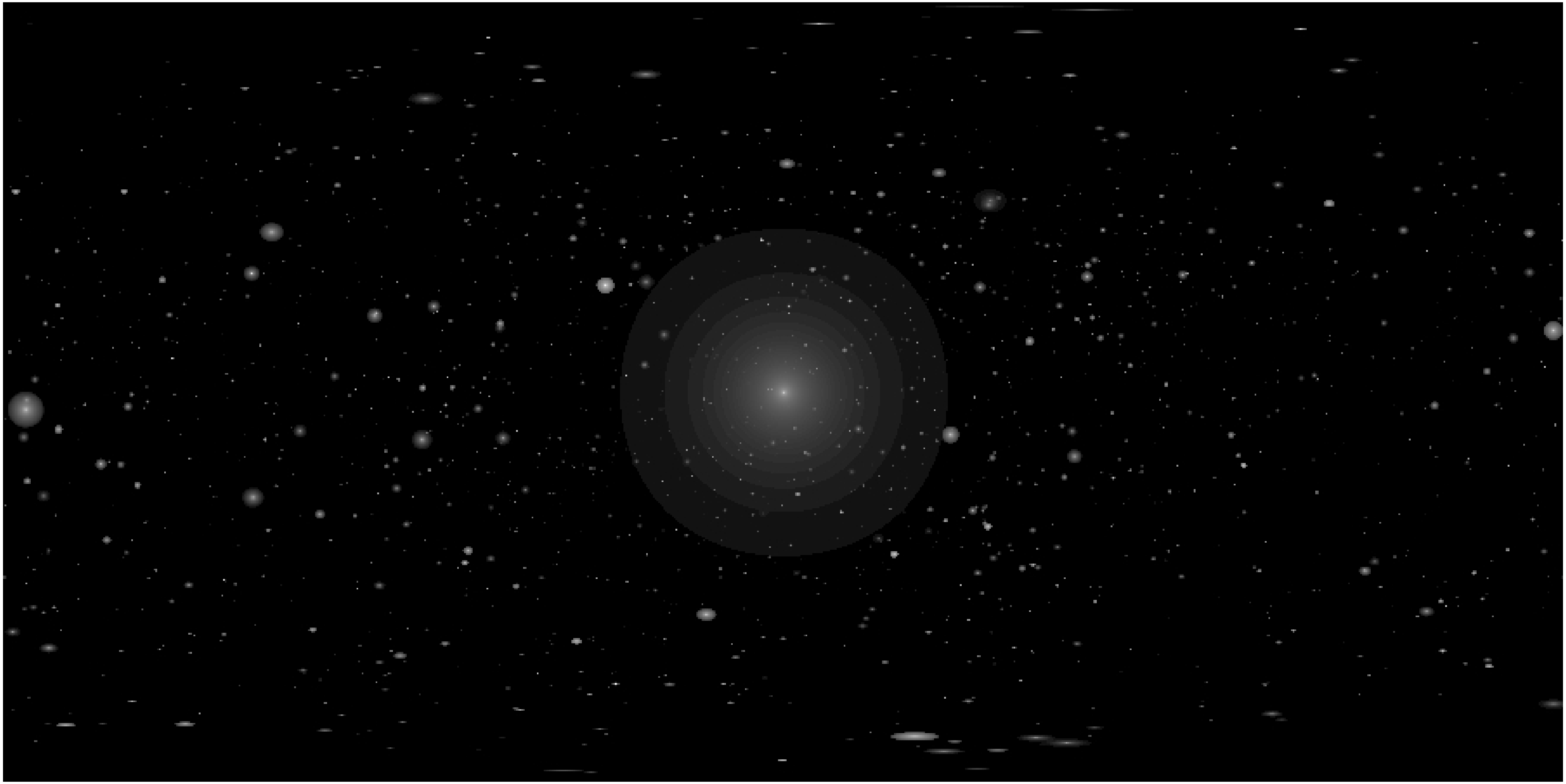


GLAST satellite with schematic of LAT instrument

Dark Matter in the Gamma Ray Sky

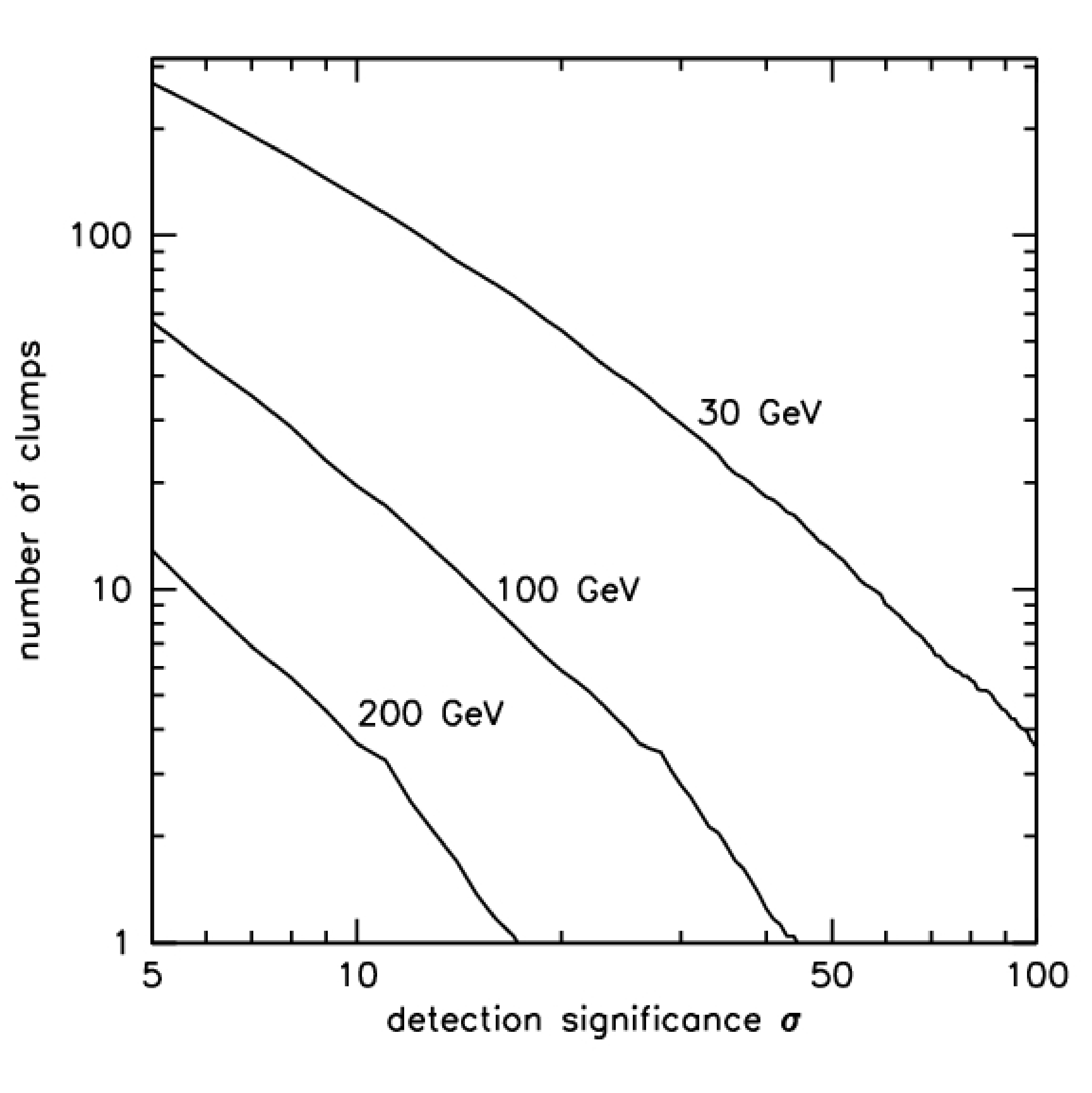
Milky Way Halo simulated by
Taylor & Babul (2005)
All-sky map of gamma ray emission
from dark matter annihilations

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



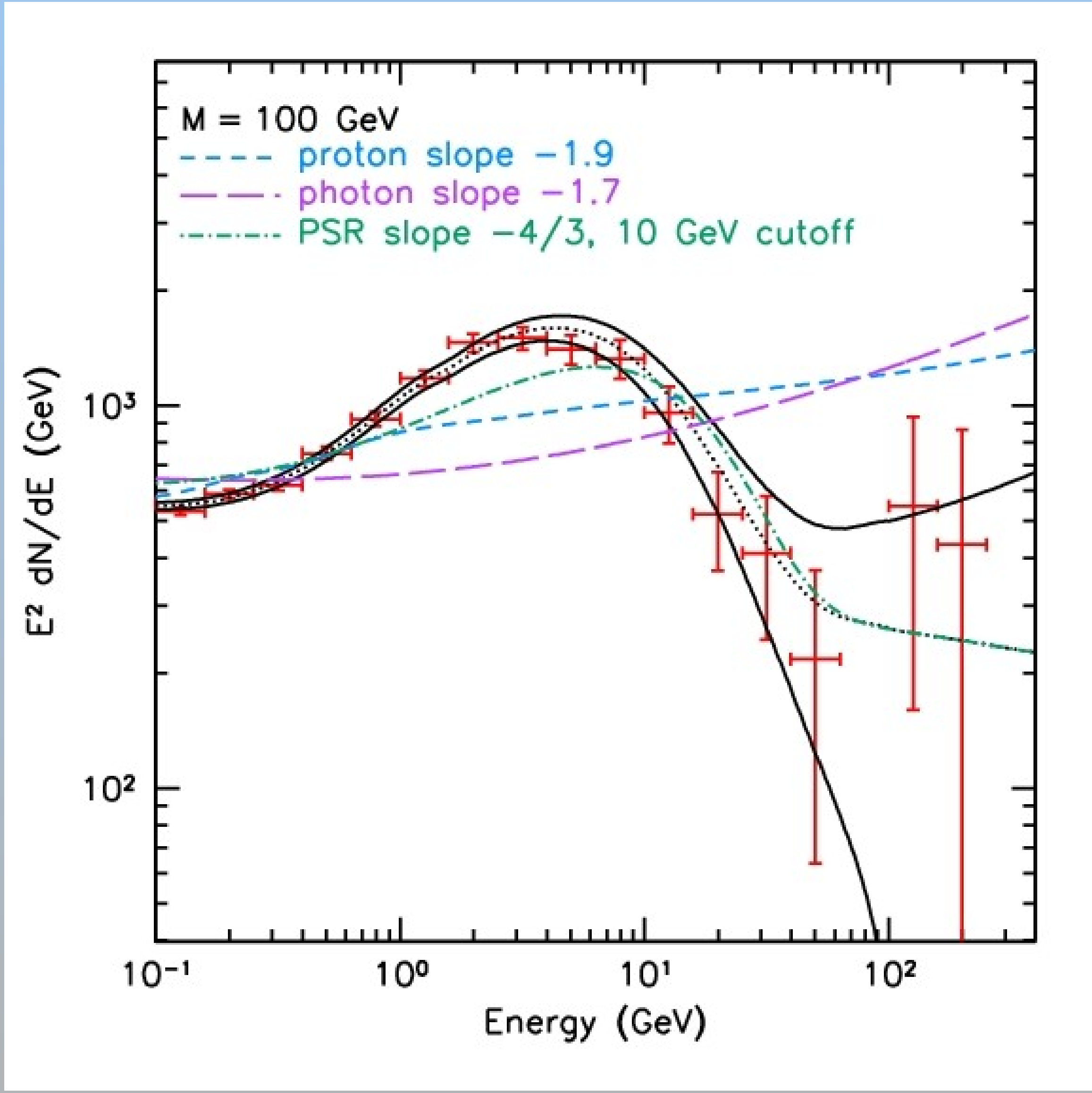
Substructure In the Galactic Halo

- Spectrum of halo sub-structure like M^-2
- Density profiles are 1/r, giving "surface brightness" proportional to 1/r
  - With a size of 1 degree, resolved by GLAST!
- Detectable objects can be low-mass (10^6 M_sun), tidally stripped (100 pc) and nearby (few kpc)



Gamma Ray Spectrum from Dark Matter Annihilations

- Hadronization produces pions, decaying into high energy photons
- Spectrum is difficult to mimic astrophysically
  - Gamma-ray pulsars are the most troublesome
  - 25% mass measurement at 100 GeV possible
- Bright GLAST sources separable from pulsars, molecular clouds, blazars, SN remnants…
  - Gamma ray spectrum AND spatial extent



Particle Physics with GLAST

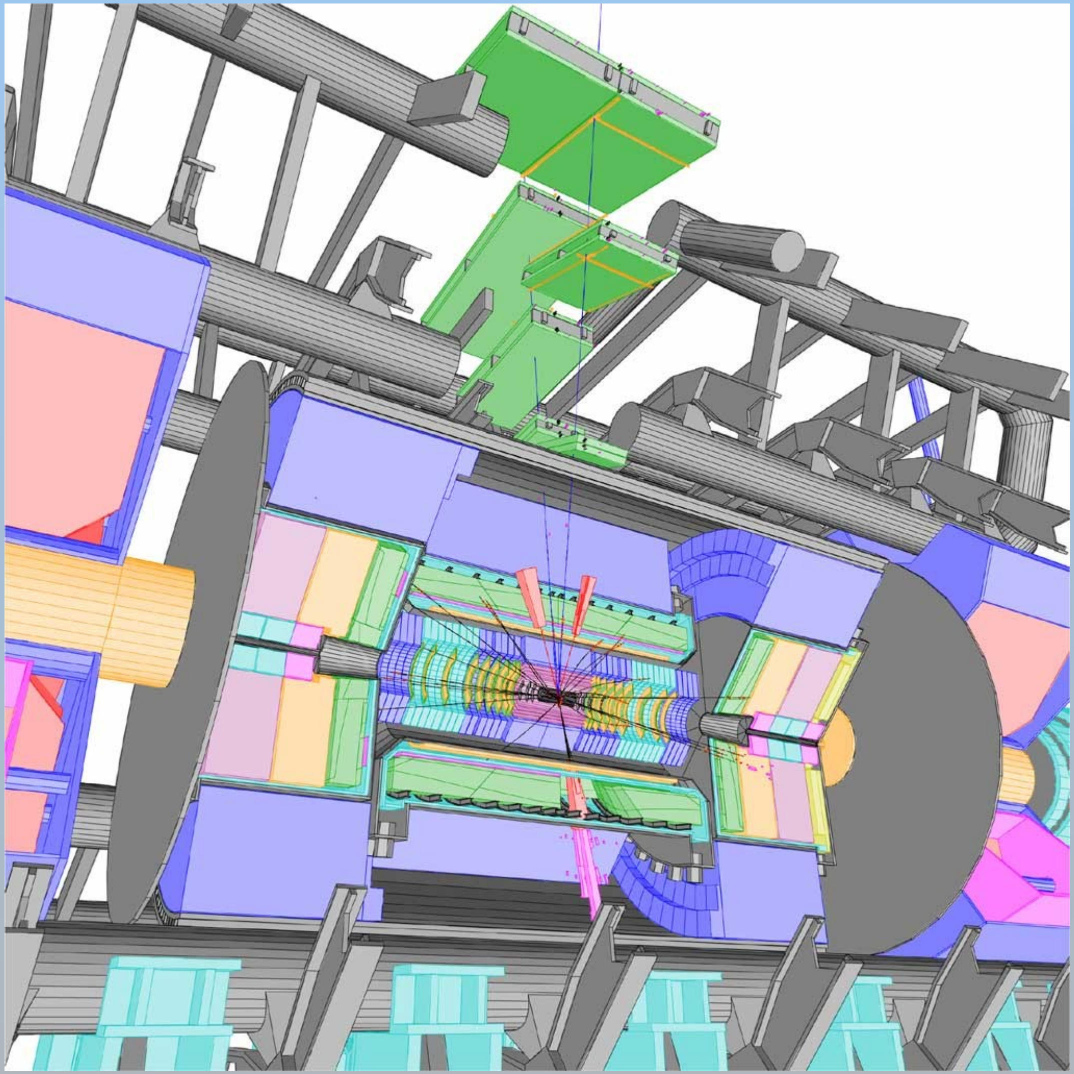
- Astrophysical uncertainties dominate: we would in fact like to measure the dark matter density using collider inputs

- Not much information in spectral shape – universal over hadronic channels including W's, Z's
  - One exception: annihilation to taus gives very hard spectrum, but this is difficult to arrange in SUSY

- There may be information in branching ratios – astrophysical densities cancel
  - line / continuum ratio is the line branching fraction, a function only of the parameters in the Lagrangian
  - line ratio 2 gamma vs. Z gamma is similar

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
- For each of 4 points, identify measurements possible at colliders
  - masses, polarized production cross-sections, FB asymmetries
- For each of 4 points, generate several million SUSY models consistent with simulated 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
- Calculated with ISAJET 7.69 and DarkSUSY 4.1

Constraints: LCC1 (SPS1a)

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

masses

cross sections

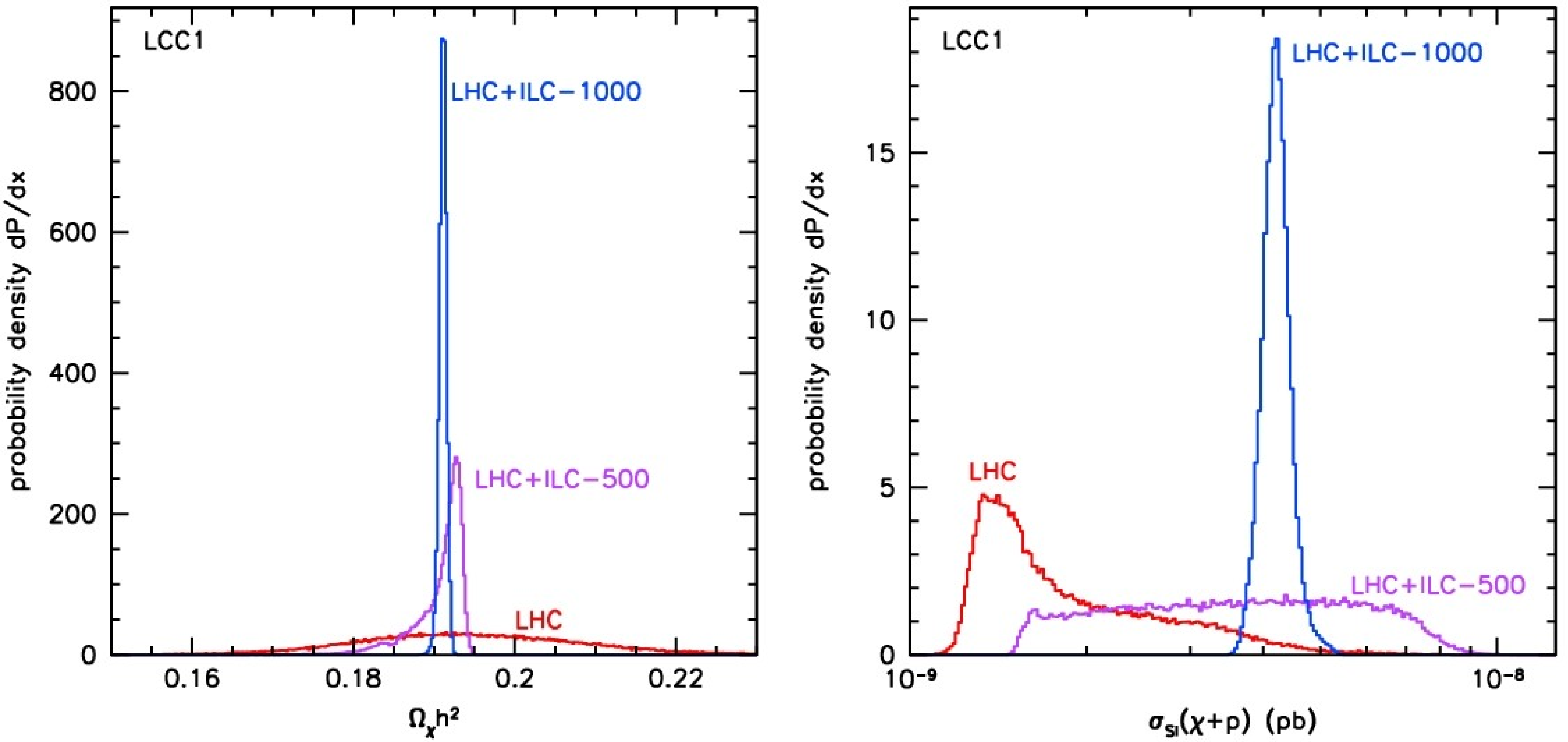
cross section		LCC1 Value (fb)		ILC 500	ILC 1000
$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	LR	431.5 (0.758)	$\pm$	1.1%*	
	RL	13.1 (0.711)	$\pm$	3.5%*	
$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	LR	172.2	$\pm$	2.1%*	
	RL	20.6	$\pm$	7.5%*	
$\sigma(e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0)$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

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

Results: LCC1

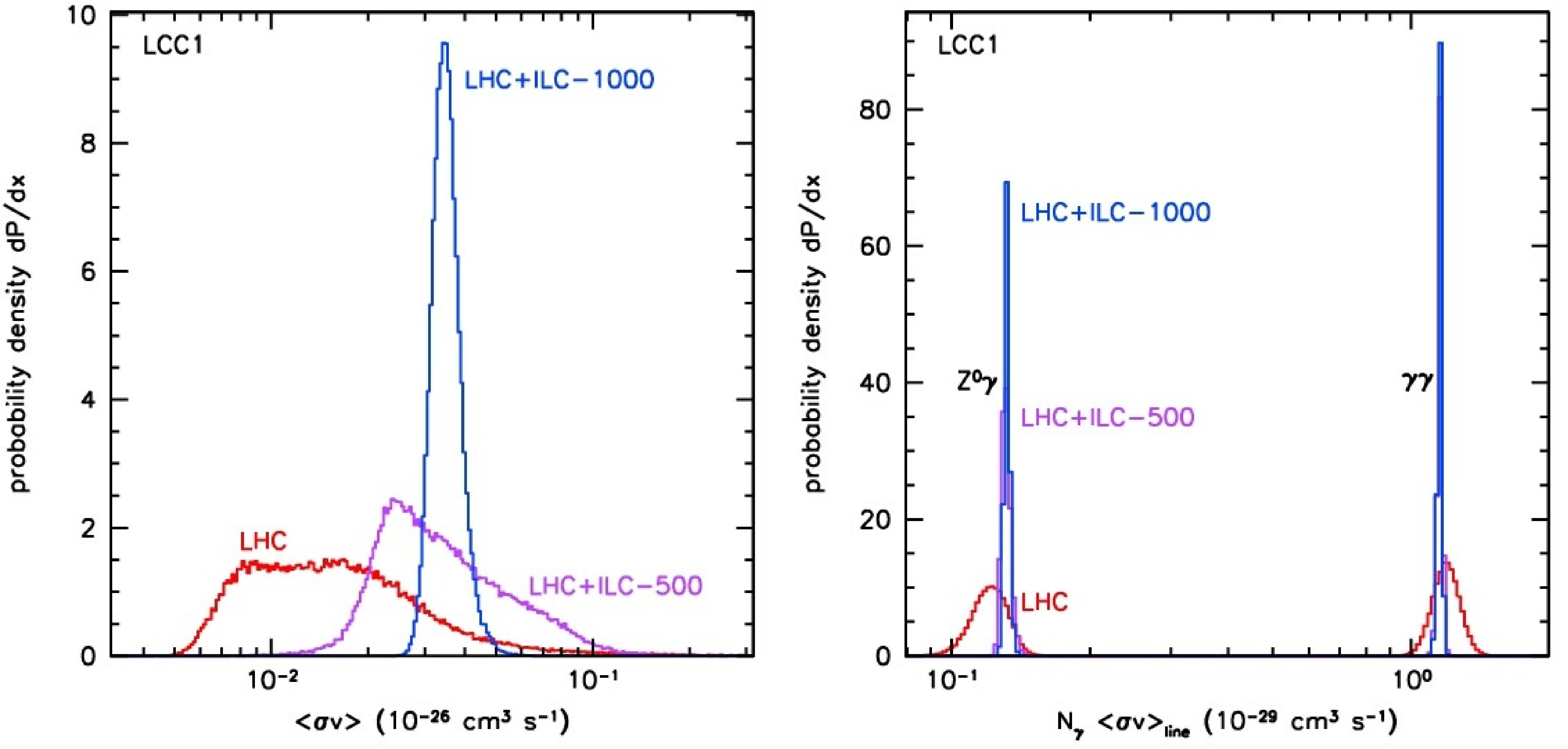
- "Bulk" region: most superpartners are light
  - LHC discovers a large number of the superpartners
  - ILC discovers (in two stages: 500 GeV and 1 TeV) most of the remaining ones, and measures cross sections
- In this case alone, the ILC-TeV can infer relic density with comparable precision to future 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



probability distribution functions for dark matter quantities given possible accelerator measurements and assuming a supersymmetric model

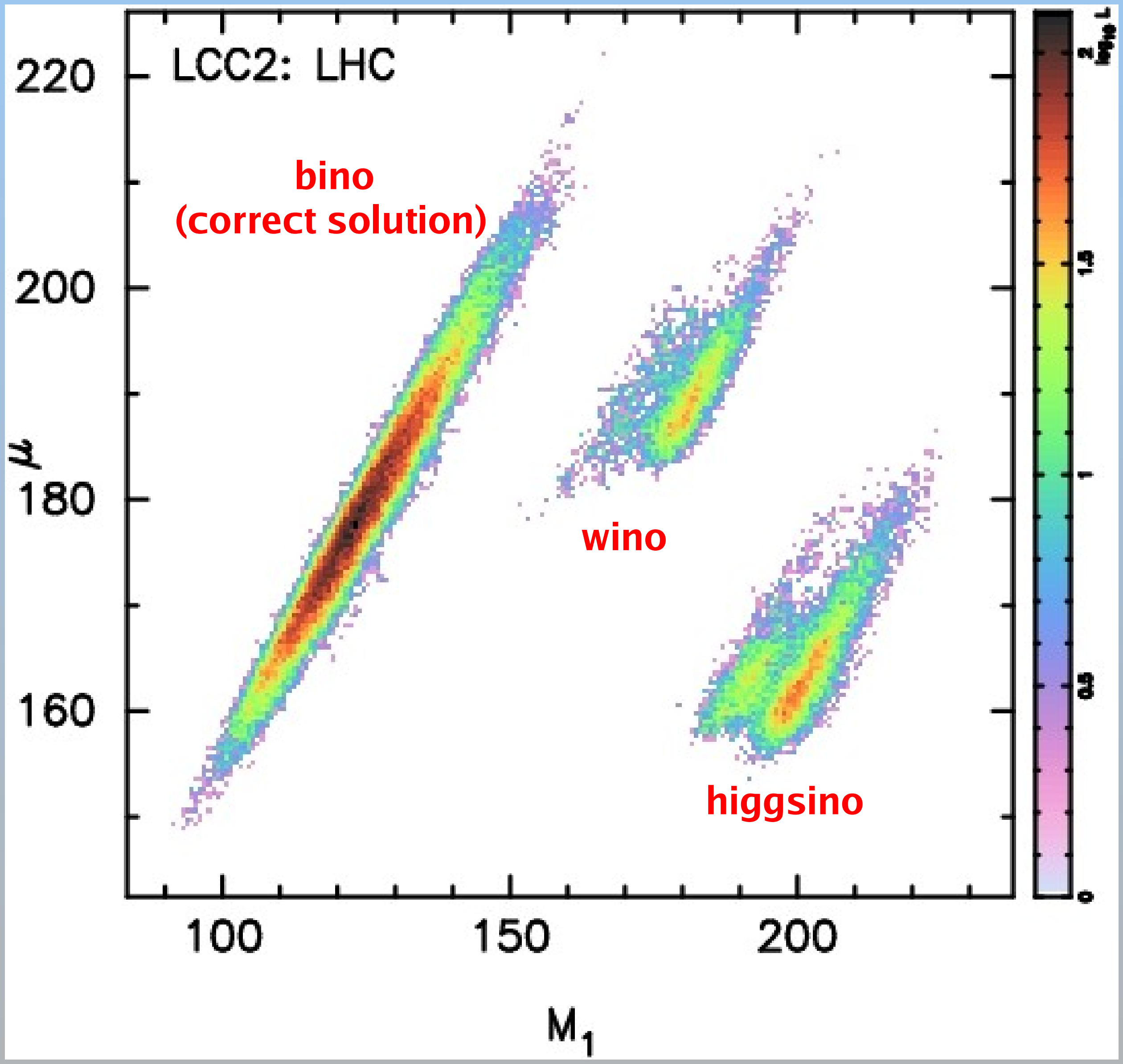
LCC1: Prediction of Annihilation Cross Sections



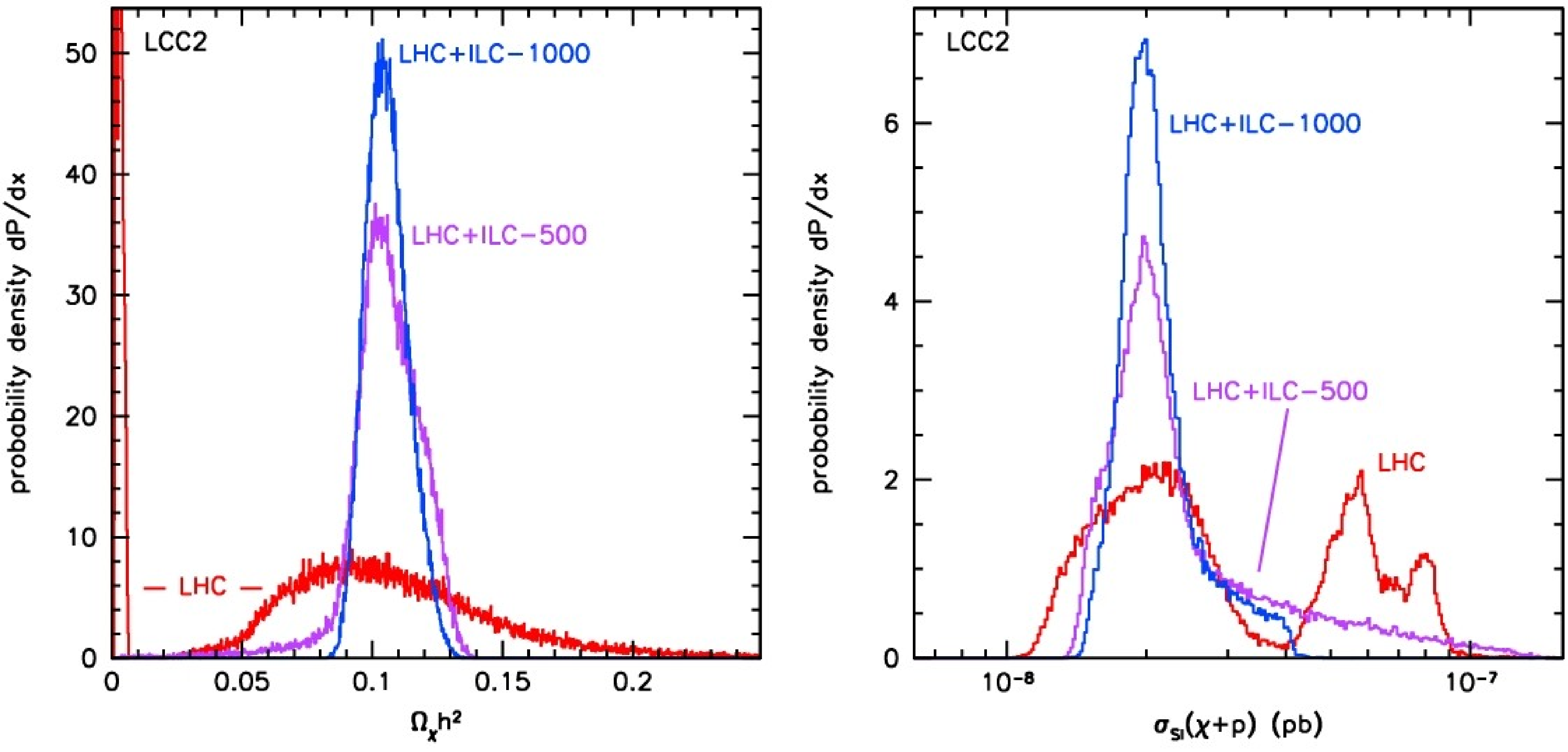
Results: LCC2

- "Focus point" region: gauginos, higgsinos are light, sfermions are all inaccessible to any collider
  - LHC discovers most gauginos + Higgsinos, one Higgs boson
  - ILC discovers the remaining gauginos / Higgsinos, measures various cross sections
- 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

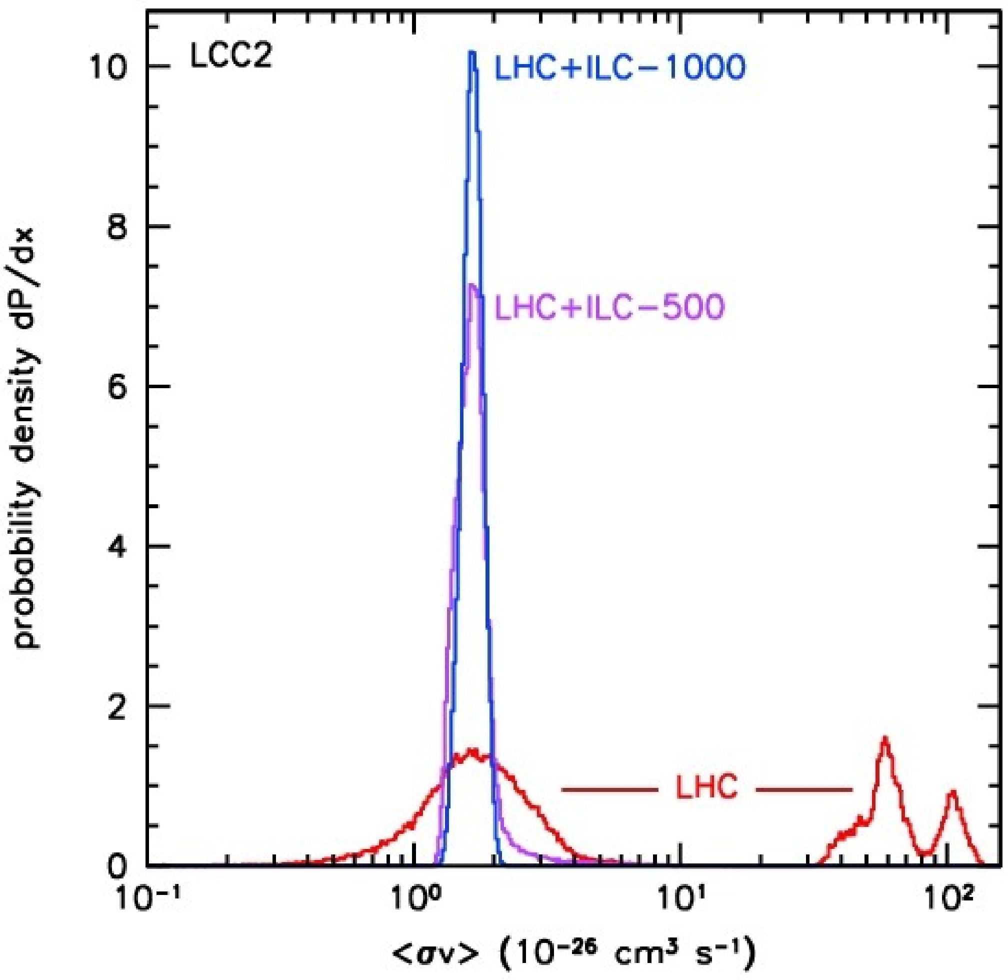
LCC2: Probability Islands for Neutralinos @ LHC

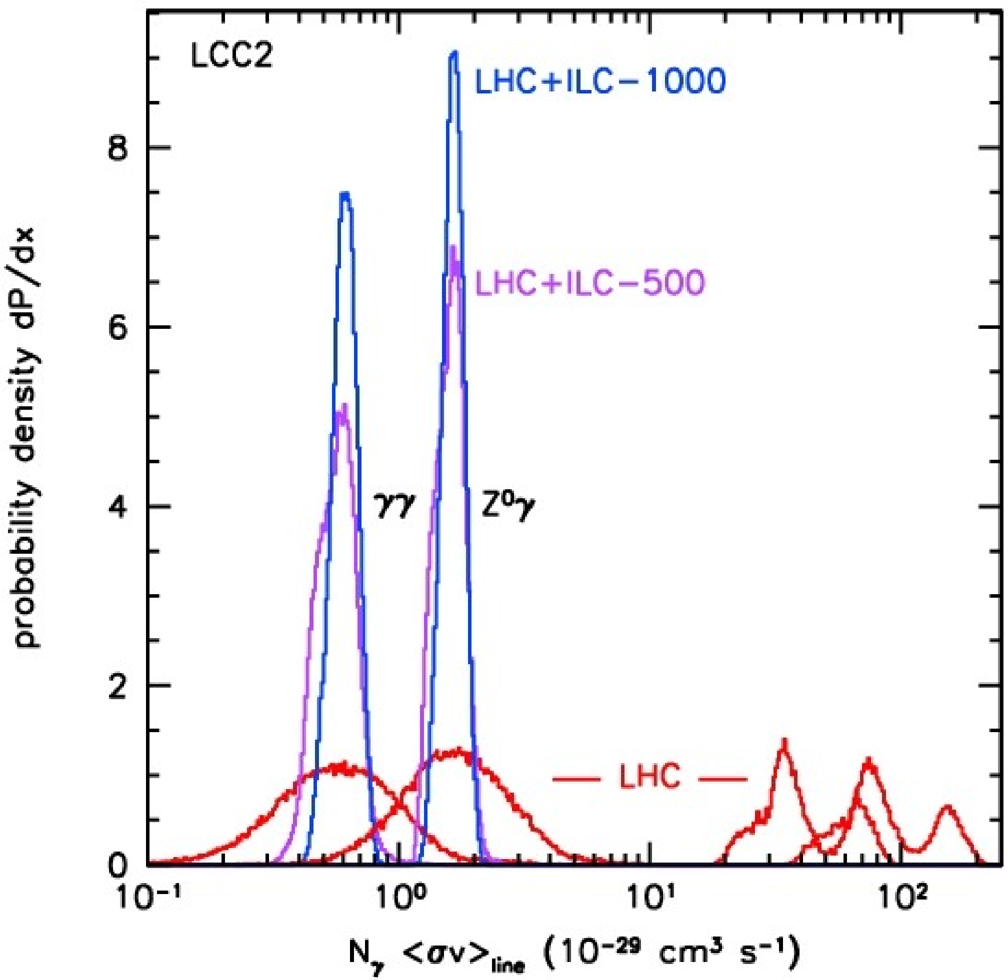


LCC2: Prediction of Relic Density and Direct Detection Cross Section



LCC2: Prediction of Annihilation Cross Sections

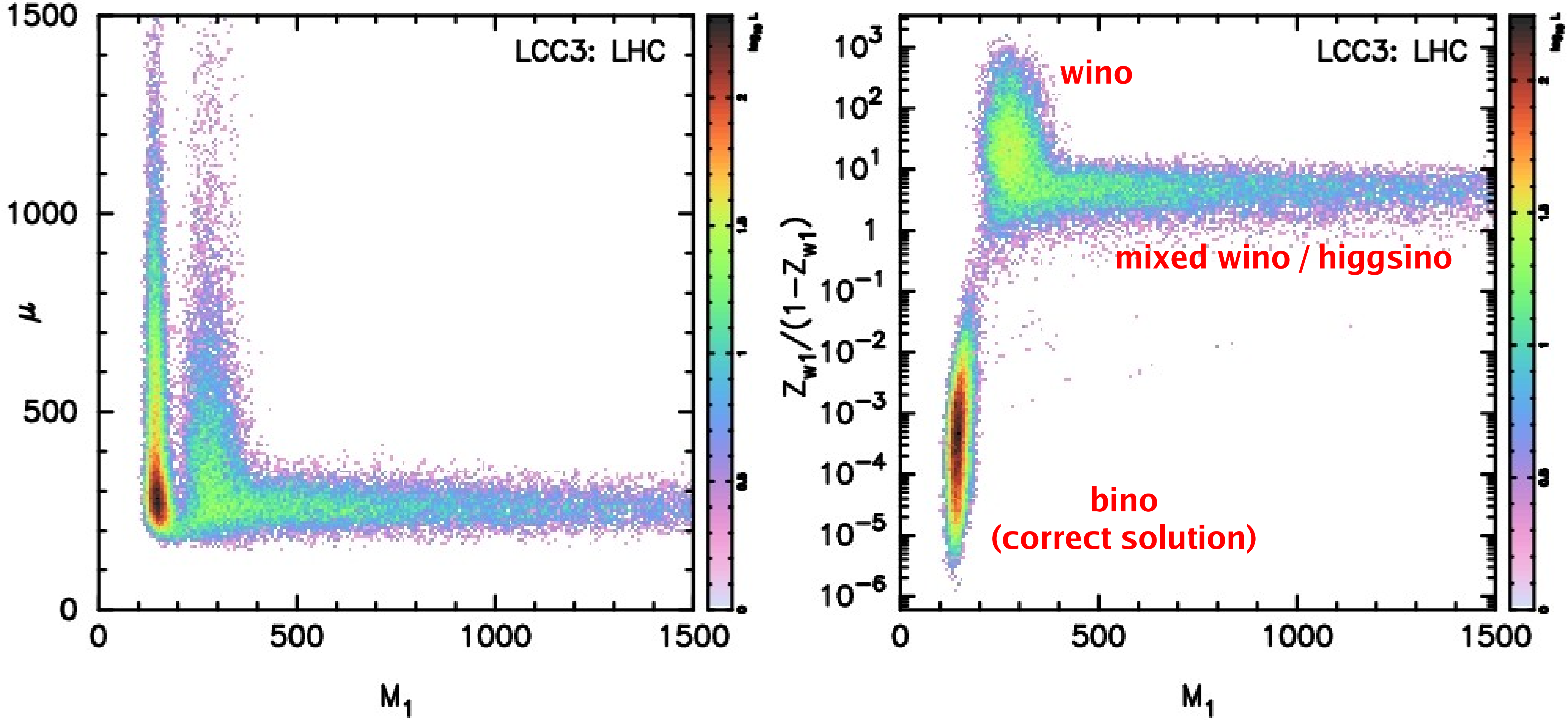




Results: LCC3

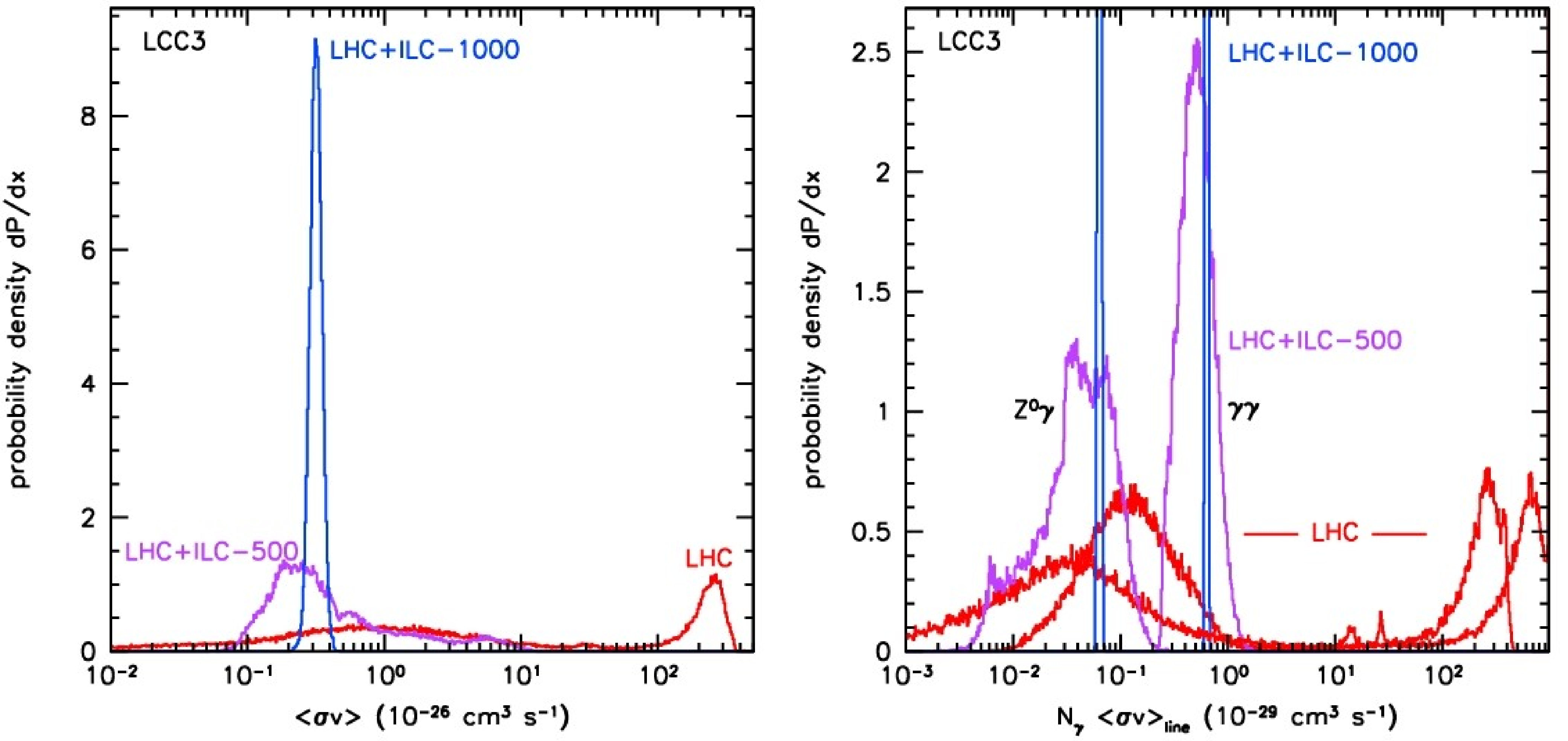
- "Coannihilation" region: light stau very close to neutralino
  - LHC discovers some gauginos and light sfermions, multiple Higgs bosons, stau may be possible
  - ILC discovers chargino, light stau, remaining charged sleptons
- Relic density estimate has ~20% accuracy with ILC TeV
- Direct detection 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 Annihilation Cross Sections



The Situation in 2012 for LCC2

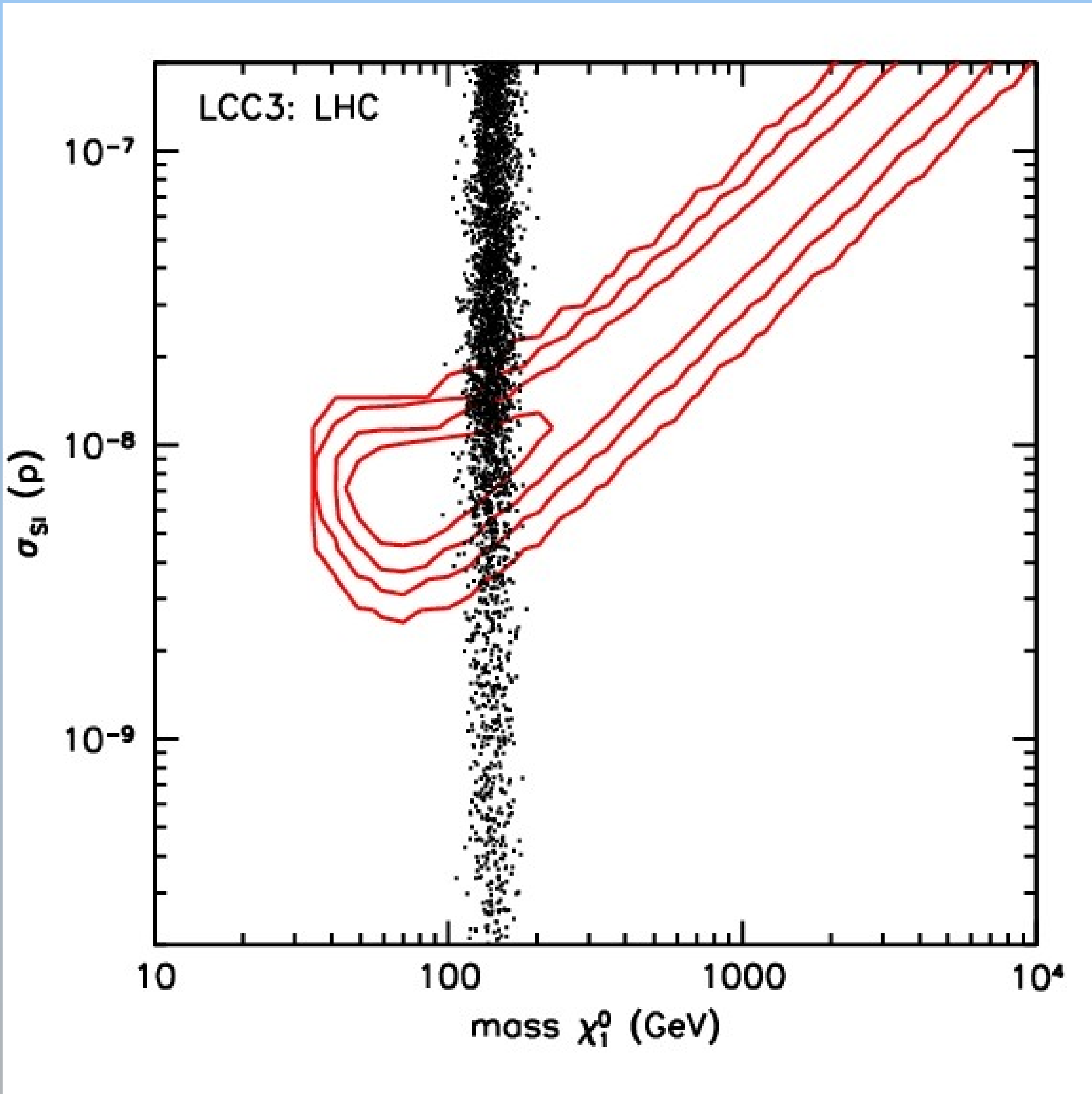
- LHC has seen missing energy events, and measured masses for new particles including a dark matter candidate
  - What is the underlying theory? Spins are difficult to measure.
  - The standard cosmology chooses the SUSY bino solution
- GLAST has obtained a 4+ year sky survey, and has observed anomalous 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

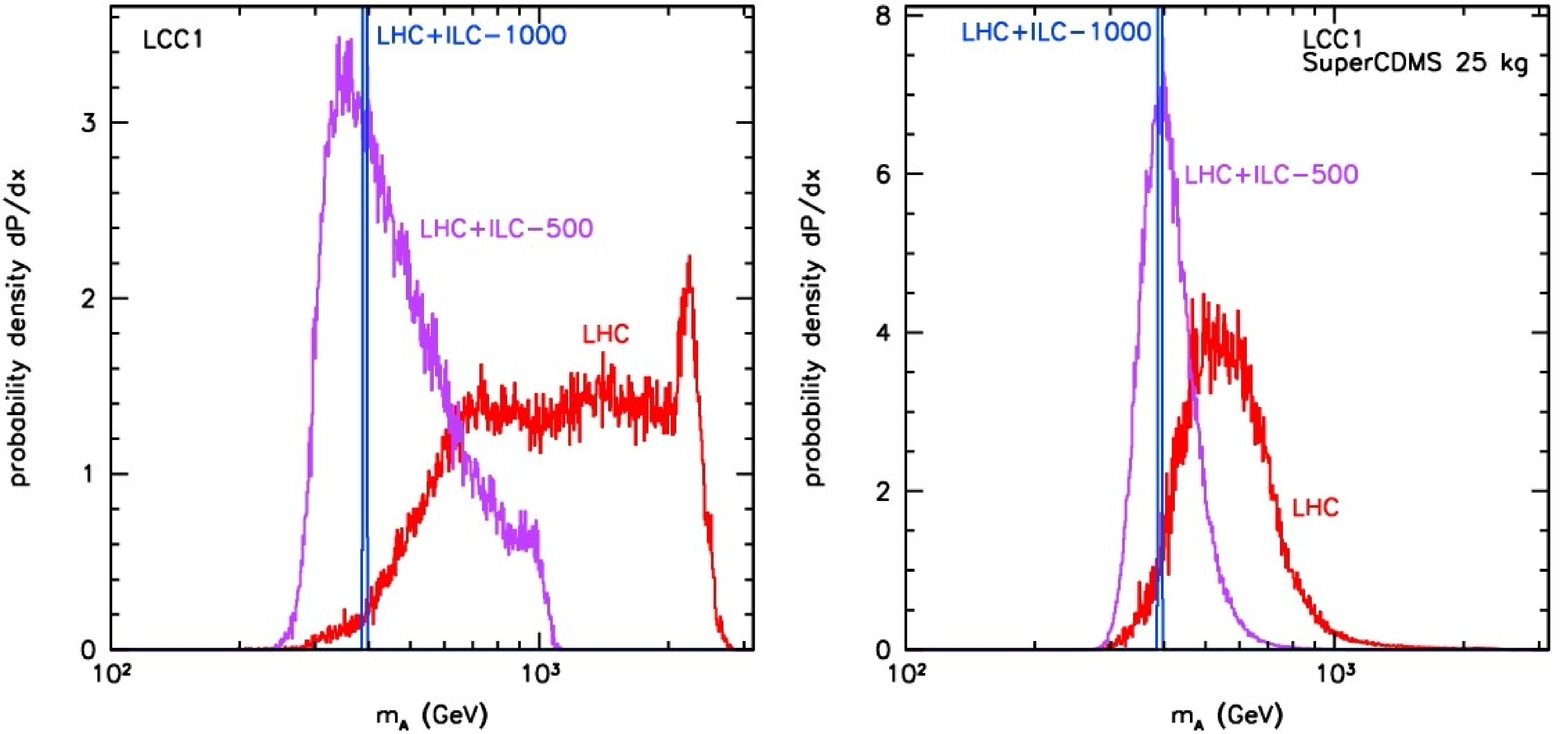
LHC measures the mass, but not the elastic scattering cross section

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

Bottom Line: we can measure masses of Higgs bosons without direct observation



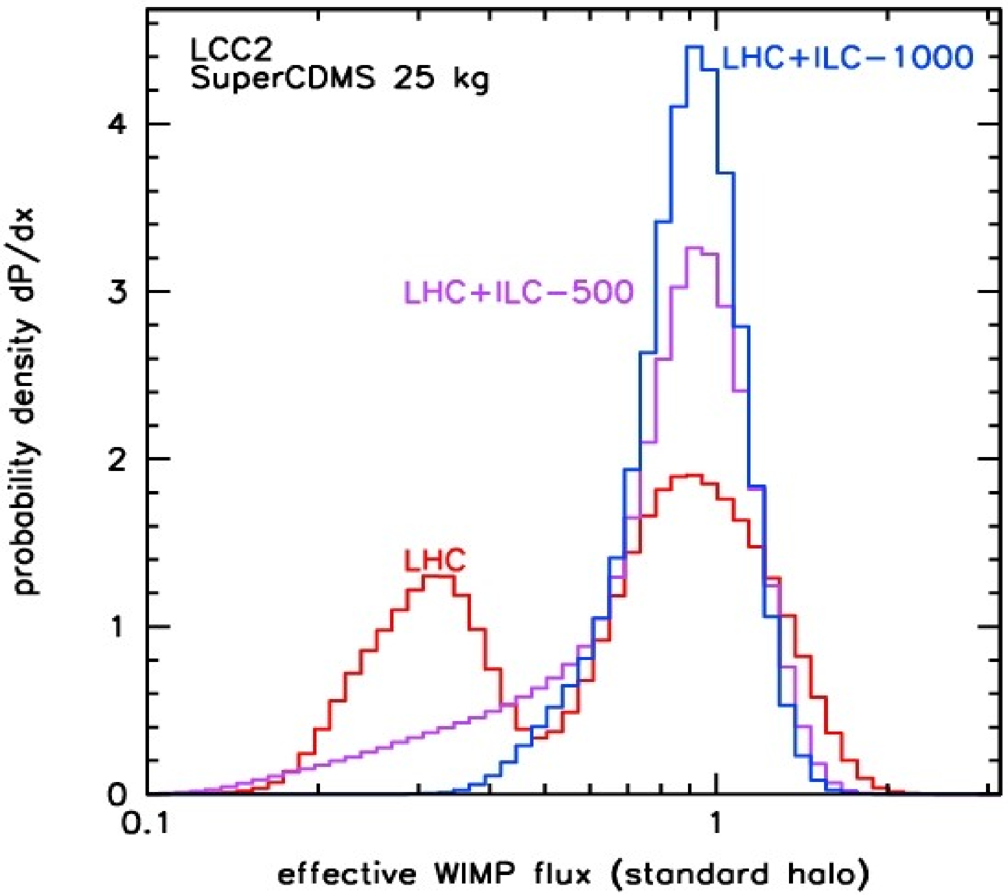
Astrophysical Prediction for Particle Physics

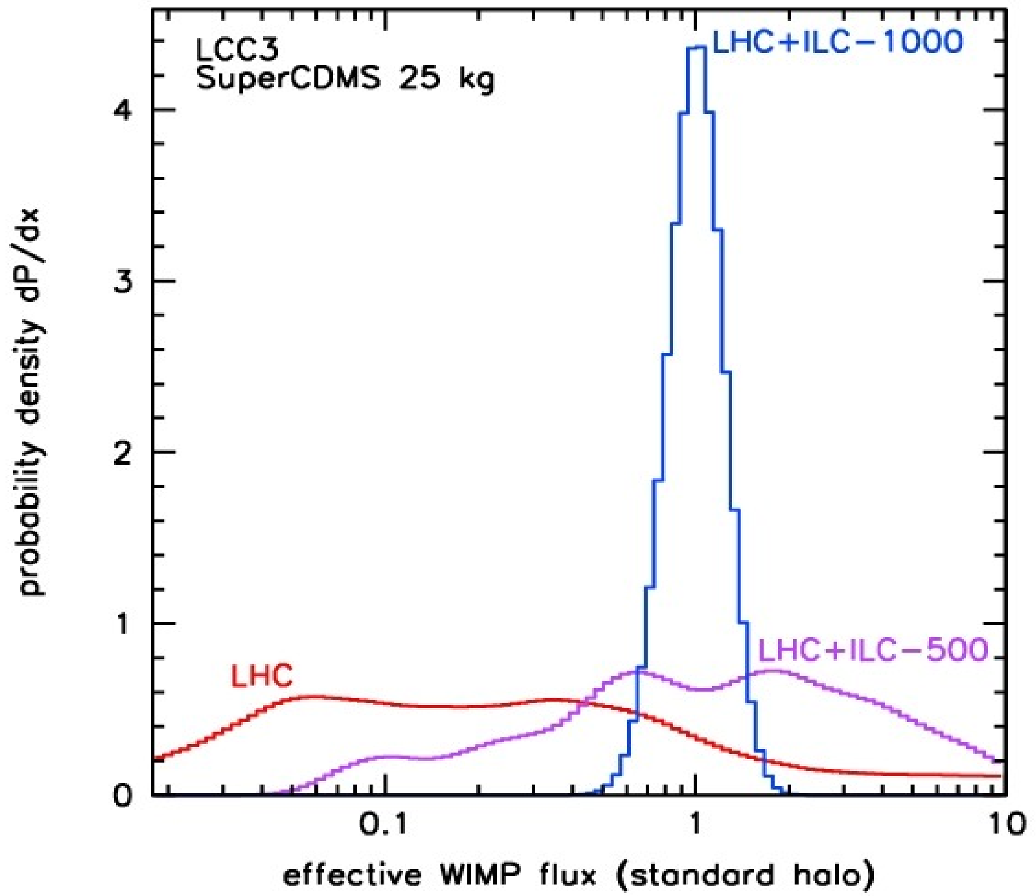


H, A can only be directly discovered at the ILC-1000
direct detection (with ~4 inverse zb) provides strong evidence before this

Local Flux of Neutralinos

LCC2 | **LCC3**

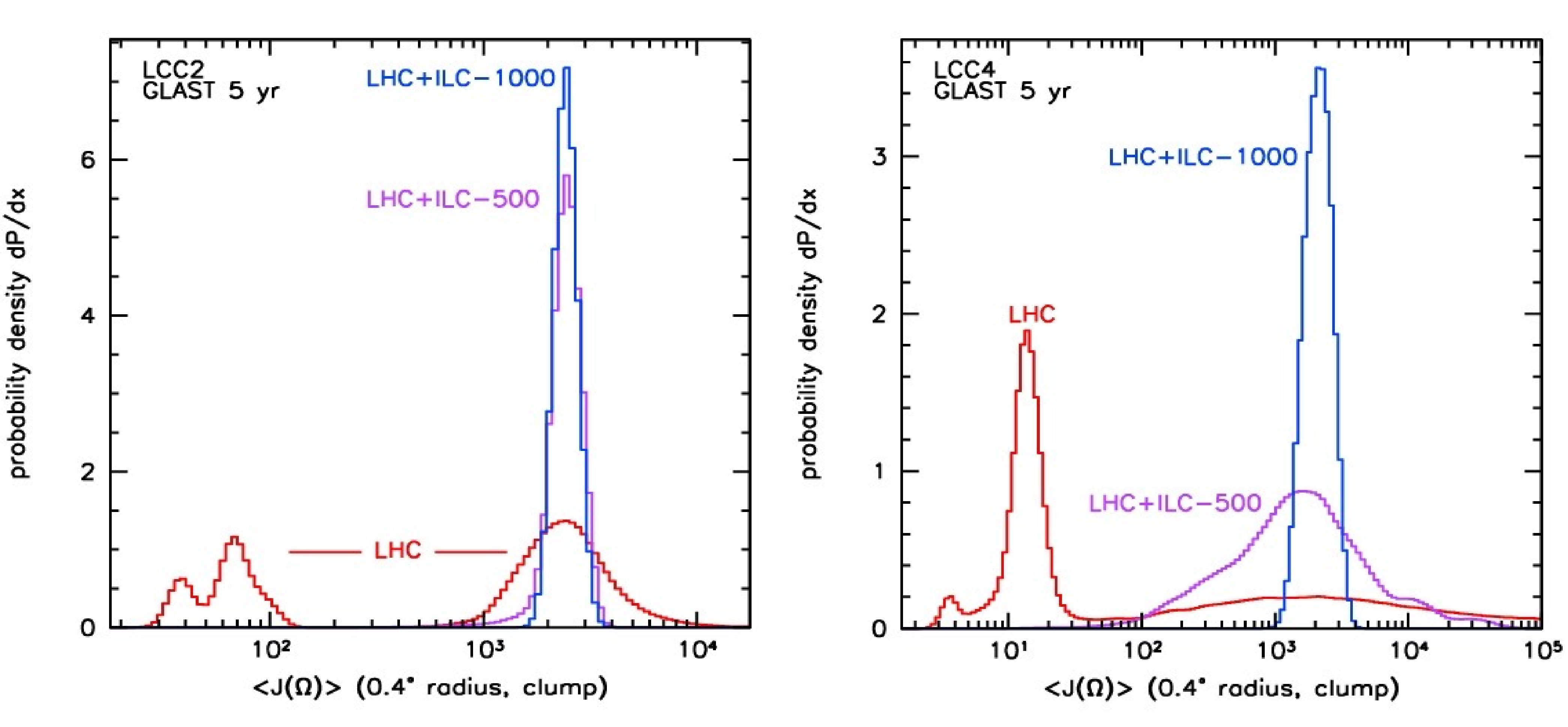




input data: collider + number of counts in direct detection experiment determine WIMP flux with no astrophysical / cosmological assumptions

Dark Matter Annihilation Rate

LCC2 **LCC4**



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

input data: collider + number of counts in GLAST for one clump
determine J with no astrophysical / cosmological assumptions

Summary

- Solving the dark matter problem requires detecting dark matter in the galaxy, studying its properties in the laboratory, and being able to make the connection between the two
- Experimental approaches are complementary: accelerators, direct detection, indirect detection
  - We need LHC *and* ILC *and* CDMS *and* GLAST
- We can learn about fundamental physics in astrophysical settings, and learn about our galaxy at high-energy colliders