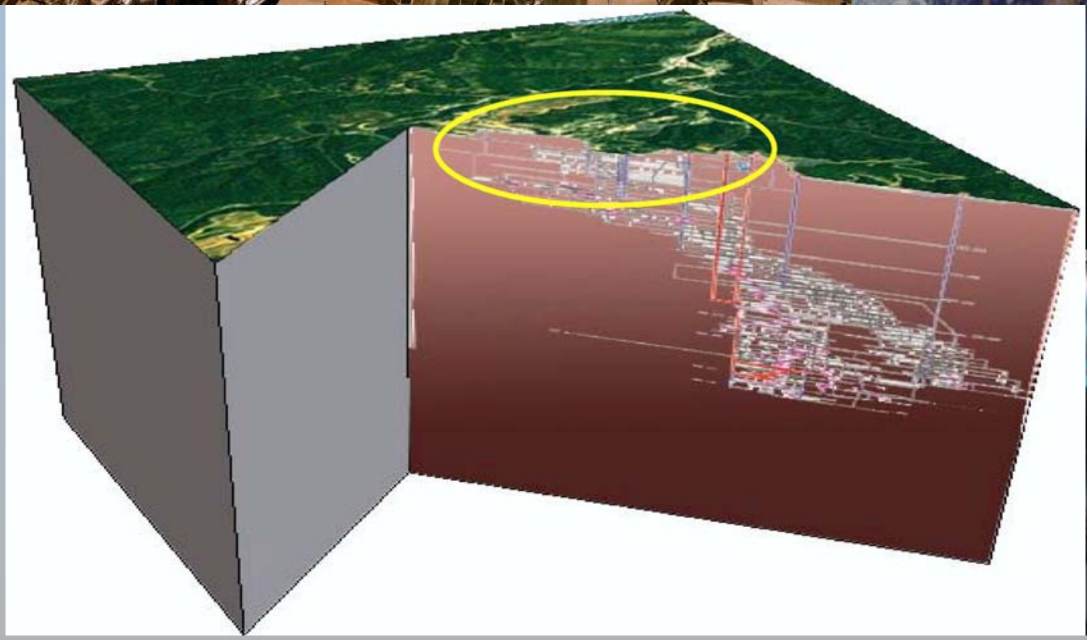
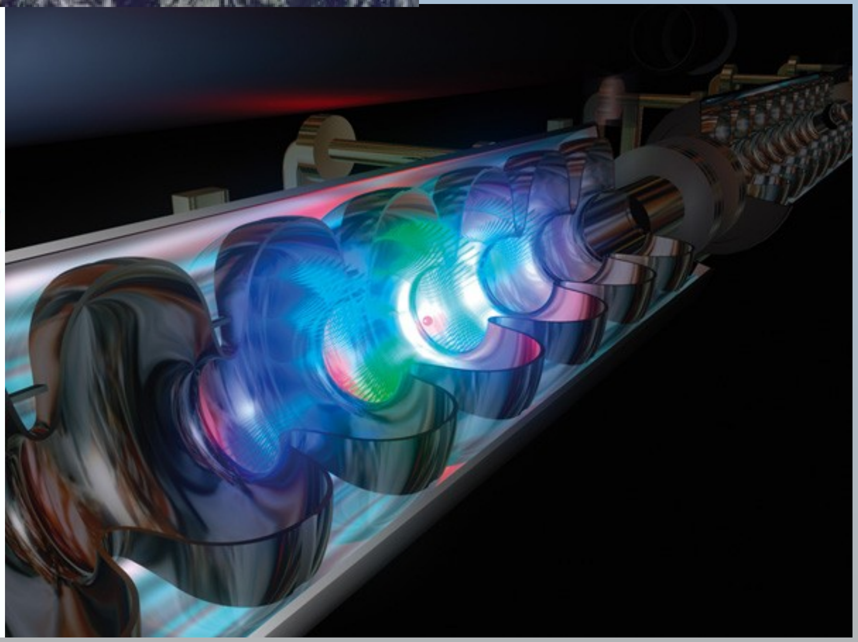
Dark Matter and the International Linear Collider

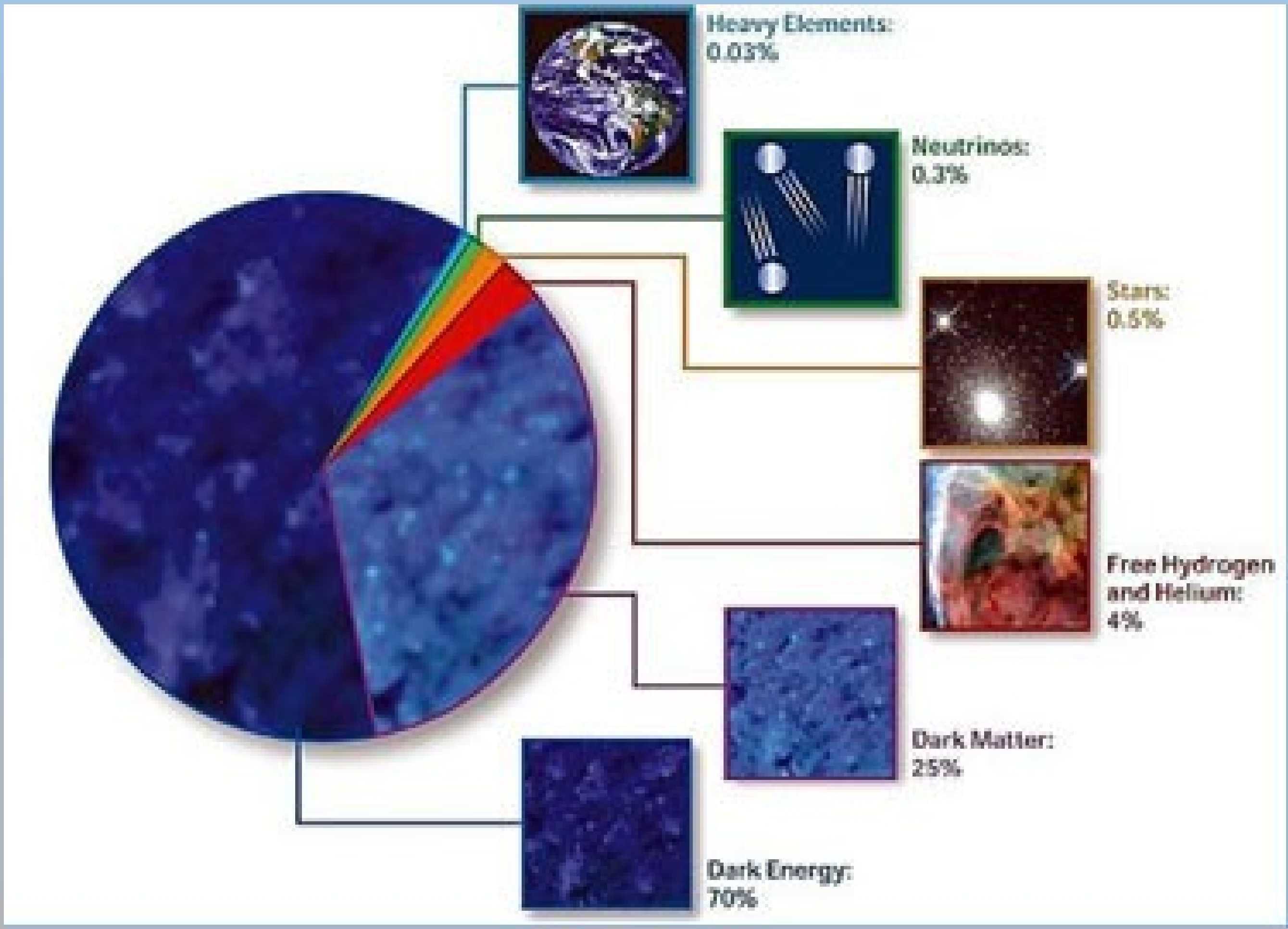




Edward A. Baltz (KIPAC, SLAC)

Mass-Energy Budget of the Universe

- **The energy density of the universe is for the most part unidentified**
  - Baryons: ~4%
  - Dark Matter: ~25%
  - Dark Energy: ~70%
- **What is all of this?**
- **These densities are the best measurements of physics beyond the Standard Model**
  - What exactly is being measured?



Hypothesis: The Dark Matter Consists of Weakly Interacting Massive Particles

- WIMPs with masses 100 GeV – 1 TeV and typical couplings have annihilation cross sections of order 1 pb
  - this is exactly what is required to give the measured relic abundance with a thermal freeze-out in the hot big bang model
- The weak scale is thus naively related to dark matter
  - a compelling coincidence!
- How can we test this hypothesis?

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
- We need astrophysical observations and accelerator experiments

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.

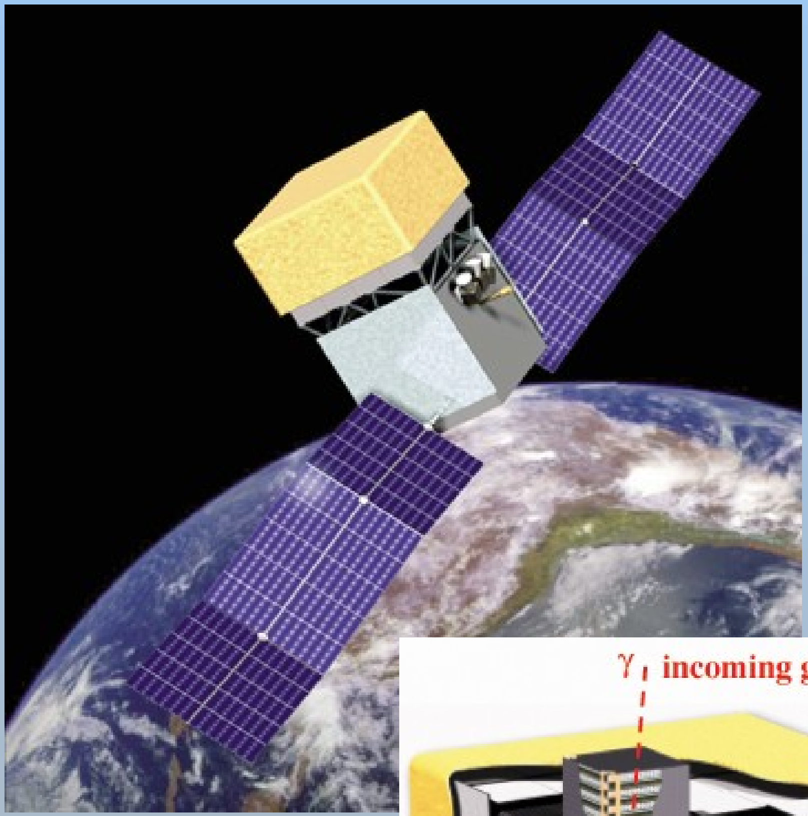
Direct Detection of Dark Matter

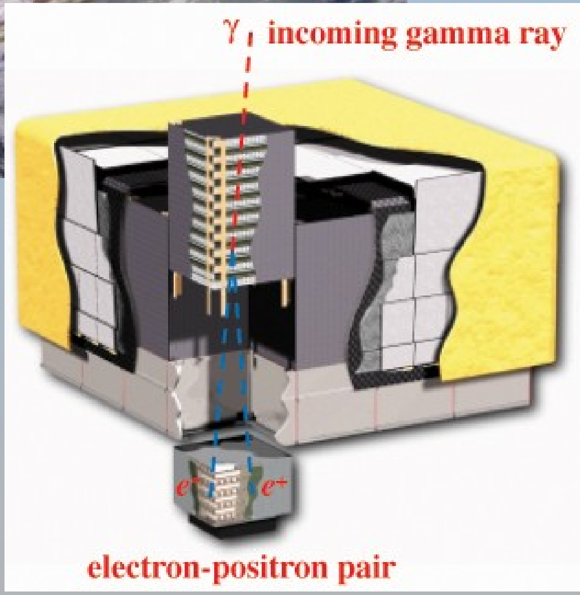
- Nuclear recoils
  - ~50 keV deposited
  - many techniques
    - semiconductors
    - scintillators
    - liquid noble gases
    - bubble chambers
    - TPCs
- Most measure only the recoil energy
- Recoil direction is more difficult, but possible

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



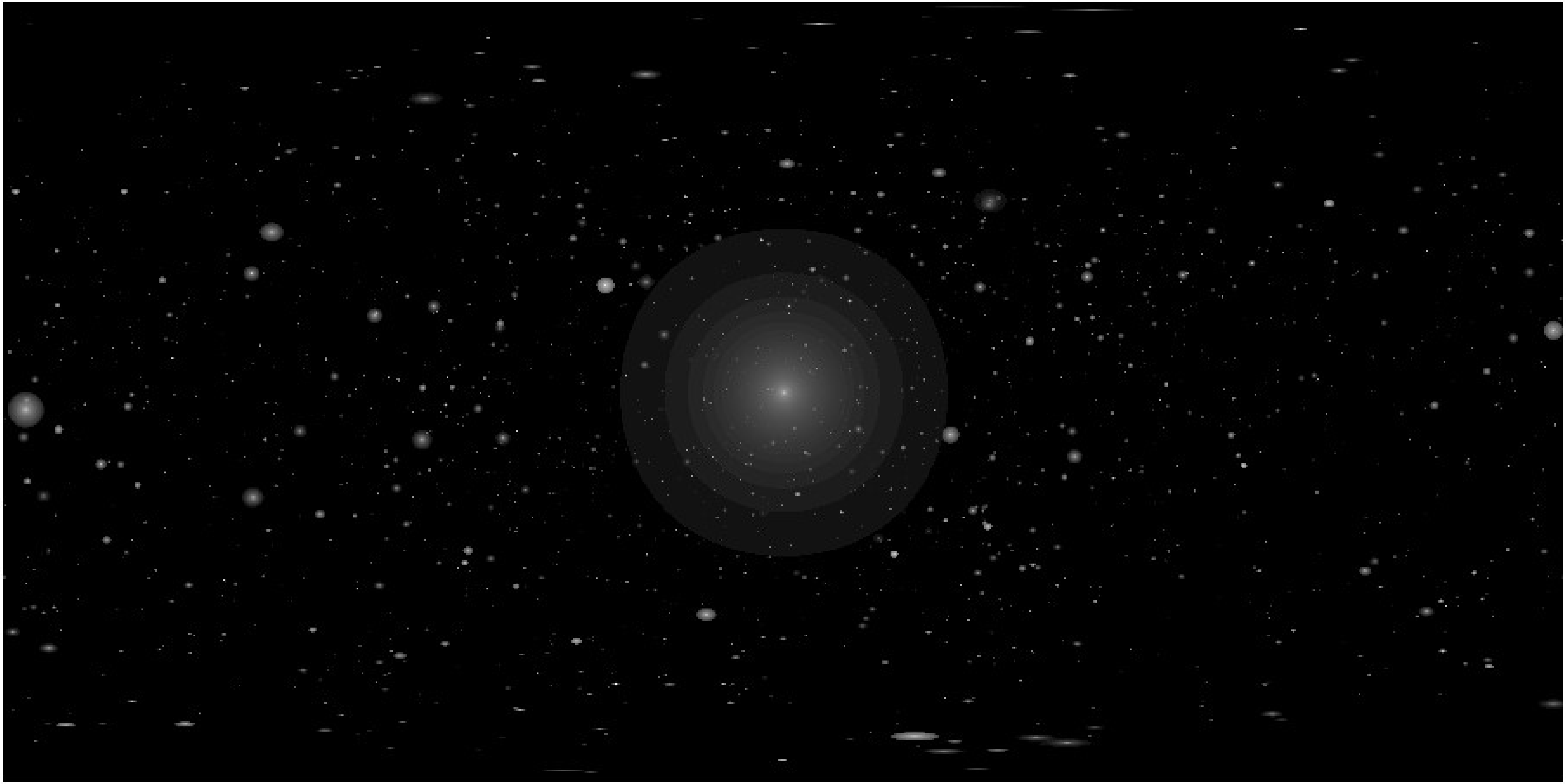


GLAST satellite with schematic of LAT instrument

Dark Matter in the Gamma Ray Sky

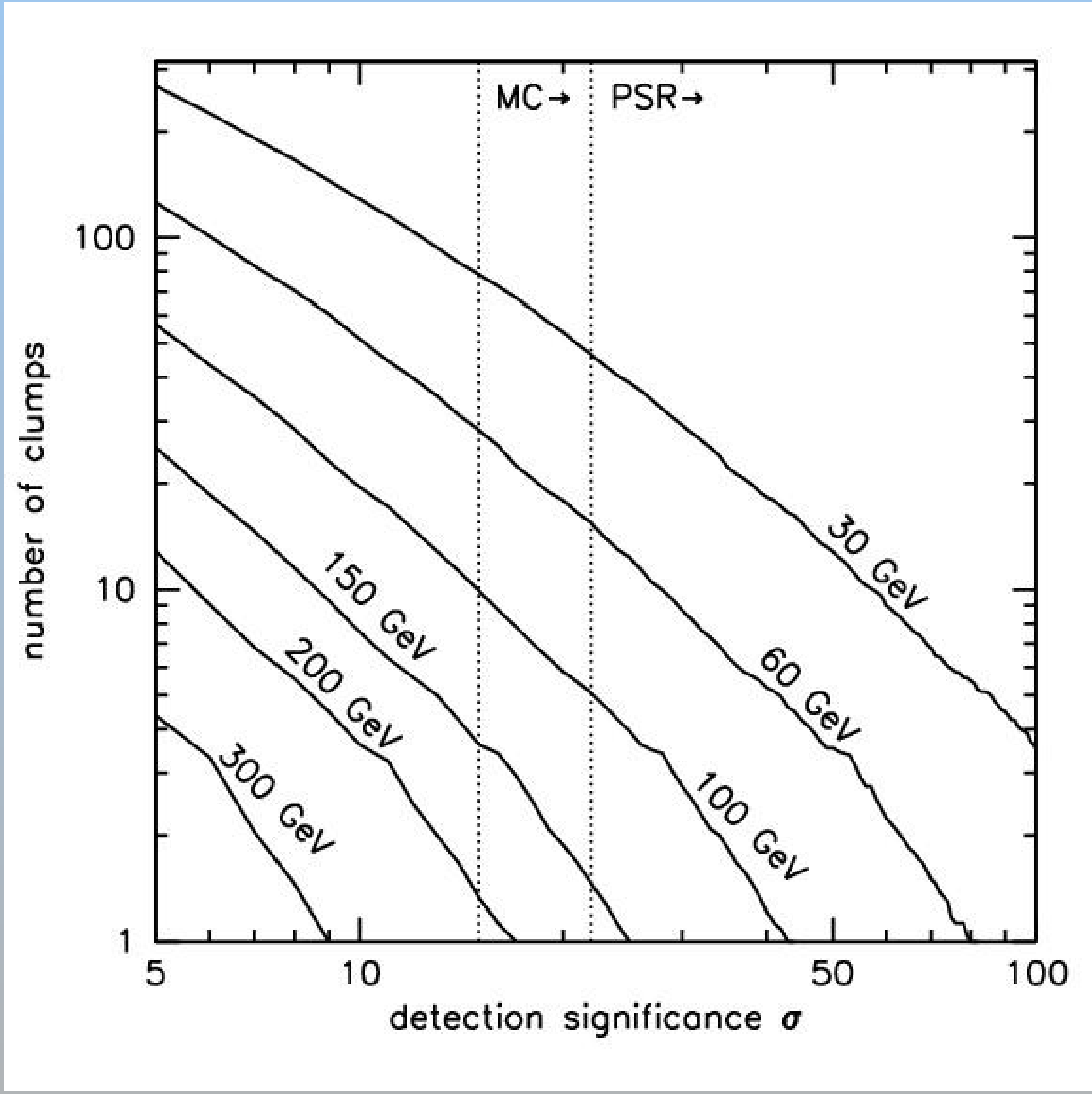
Milky Way Halo simulated by
Taylor & Babul (2005)
All-sky map of gamma ray emission
from dark matter annihilations

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



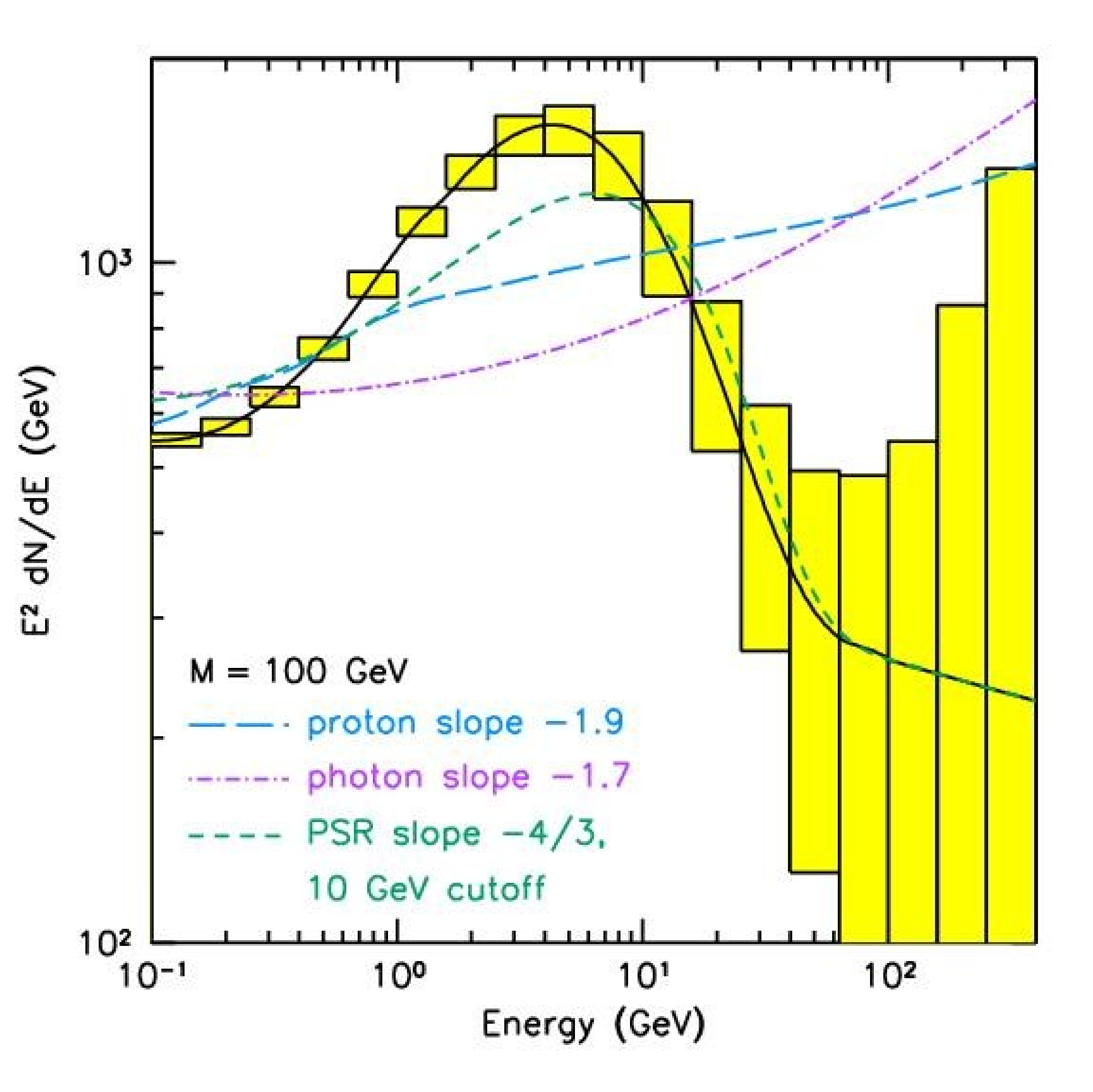
Substructure In the Galactic Halo

- 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)



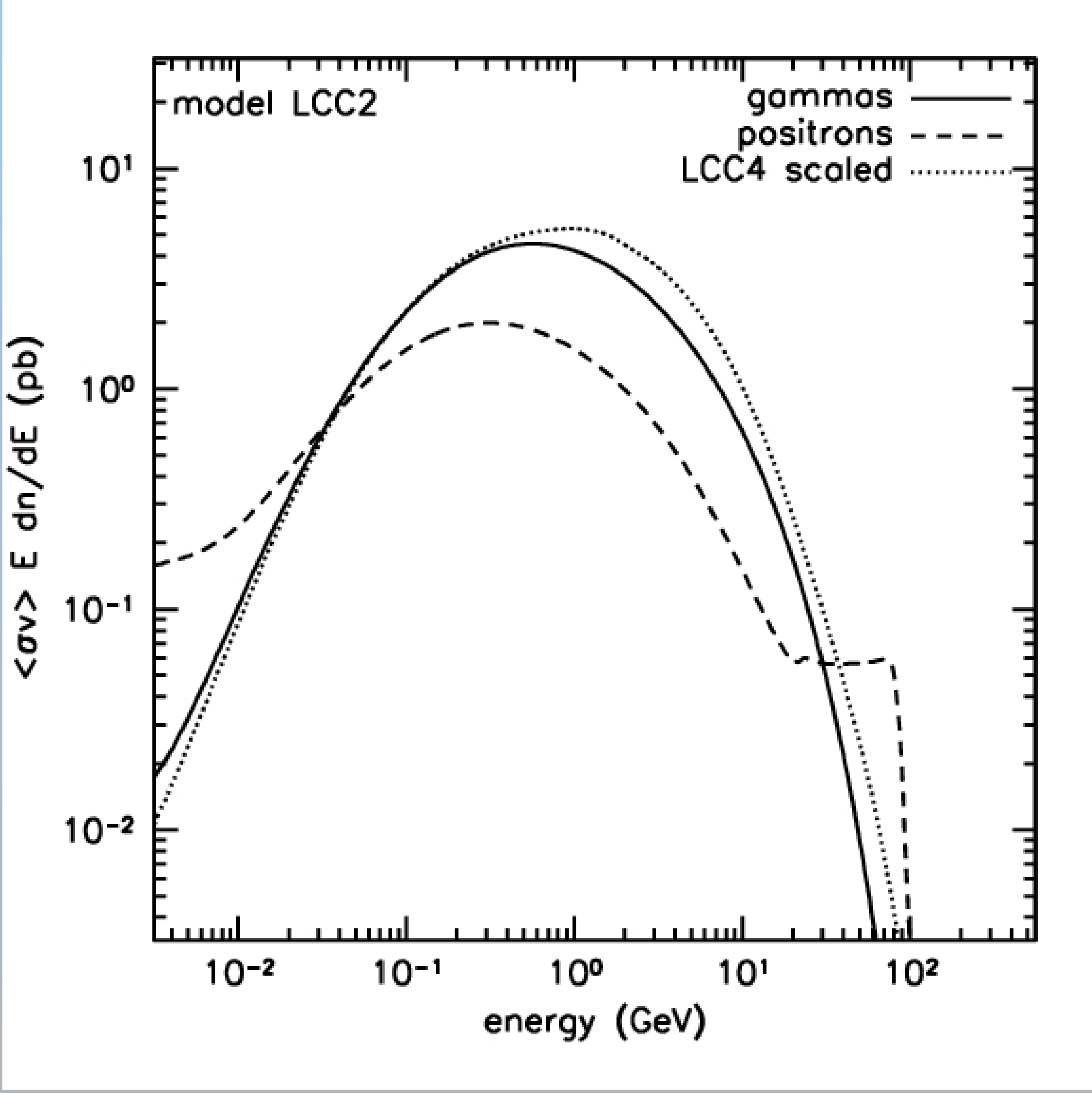
Gamma Ray Spectrum from Dark Matter Annihilations

- Hadronization produces pions, decaying into high energy photons
- Bright GLAST sources distinguishable from astrophysical objects
  - Gamma-ray pulsars are the most troublesome
  - 25% mass measurement at 100 GeV possible
  - Gamma ray spectrum AND spatial extent

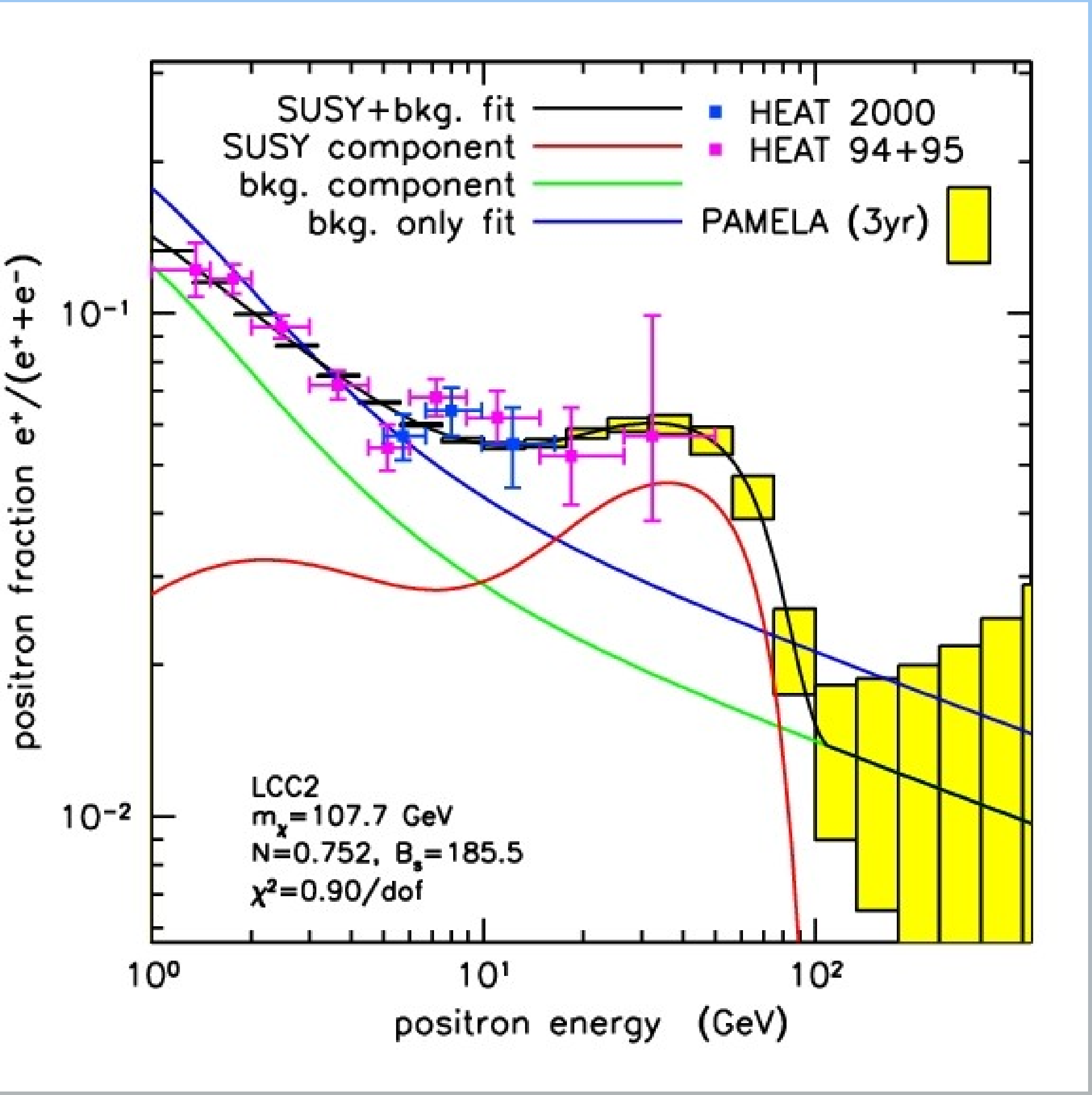


Positrons From Annihilations

- Spectral features can survive galactic effects (diffusion, synchrotron, IC)
  - shelf from W, Z decay
  - lines possible in KK models
- Peak in positron spectrum is difficult to arrange by astrophysical means
- HEAT reports an excess of positrons around 10 GeV
  - annihilation component?
- PAMELA satellite
  - launched last June
  - large improvement in sensitivity to ~10 GeV positrons, antiprotons



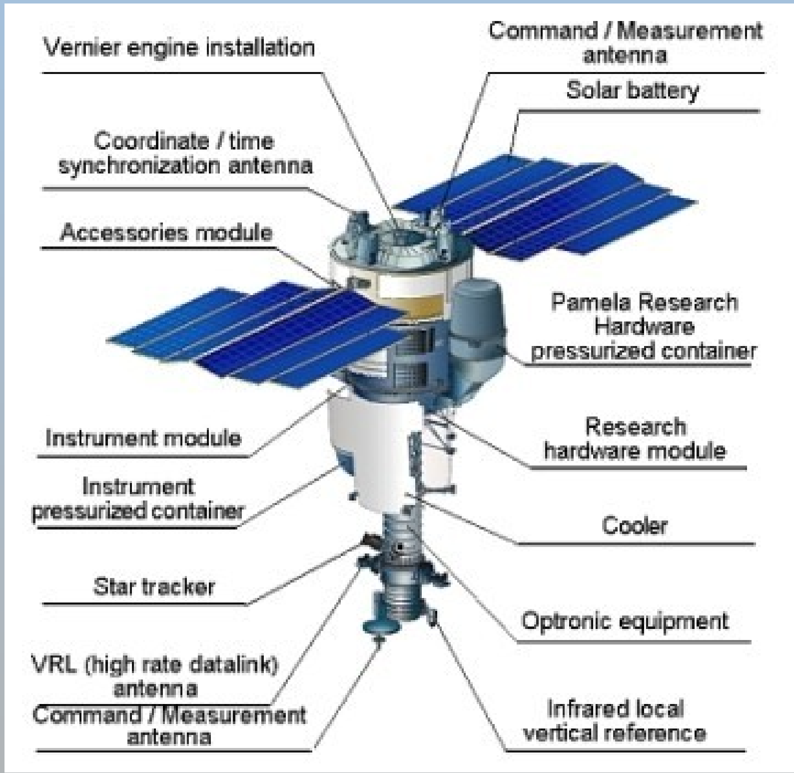
Current and Near-Future Cosmic Ray Positron Data



The HEAT positron excess requires SUSY signal enhancement of ~ 100x (Baltz, Edsjo 99, BEFG 02)

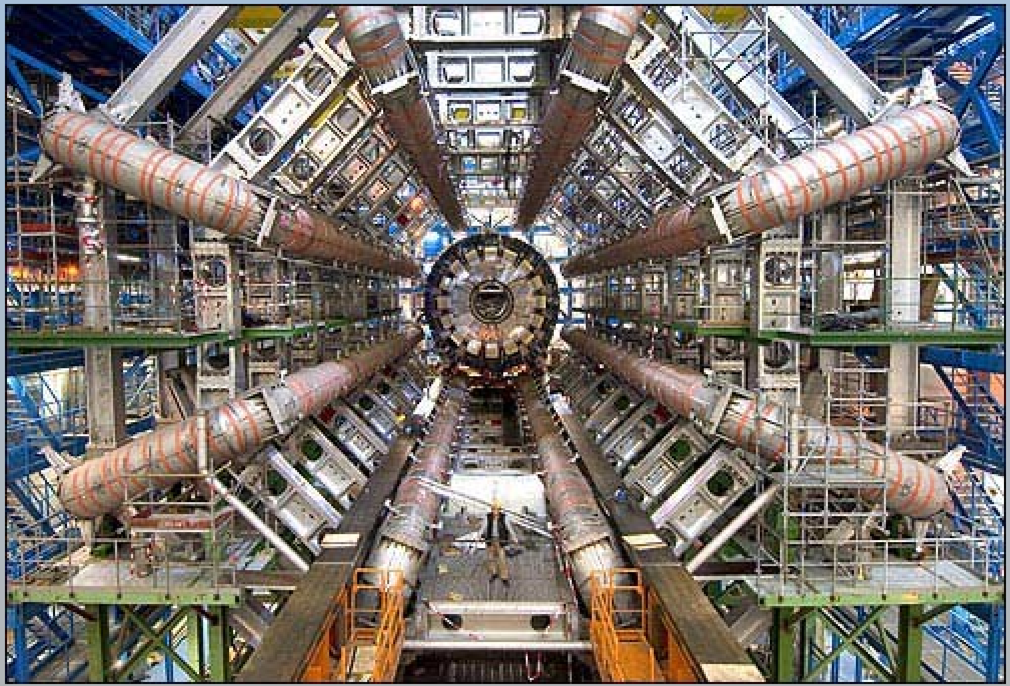
PAMELA will sort this out

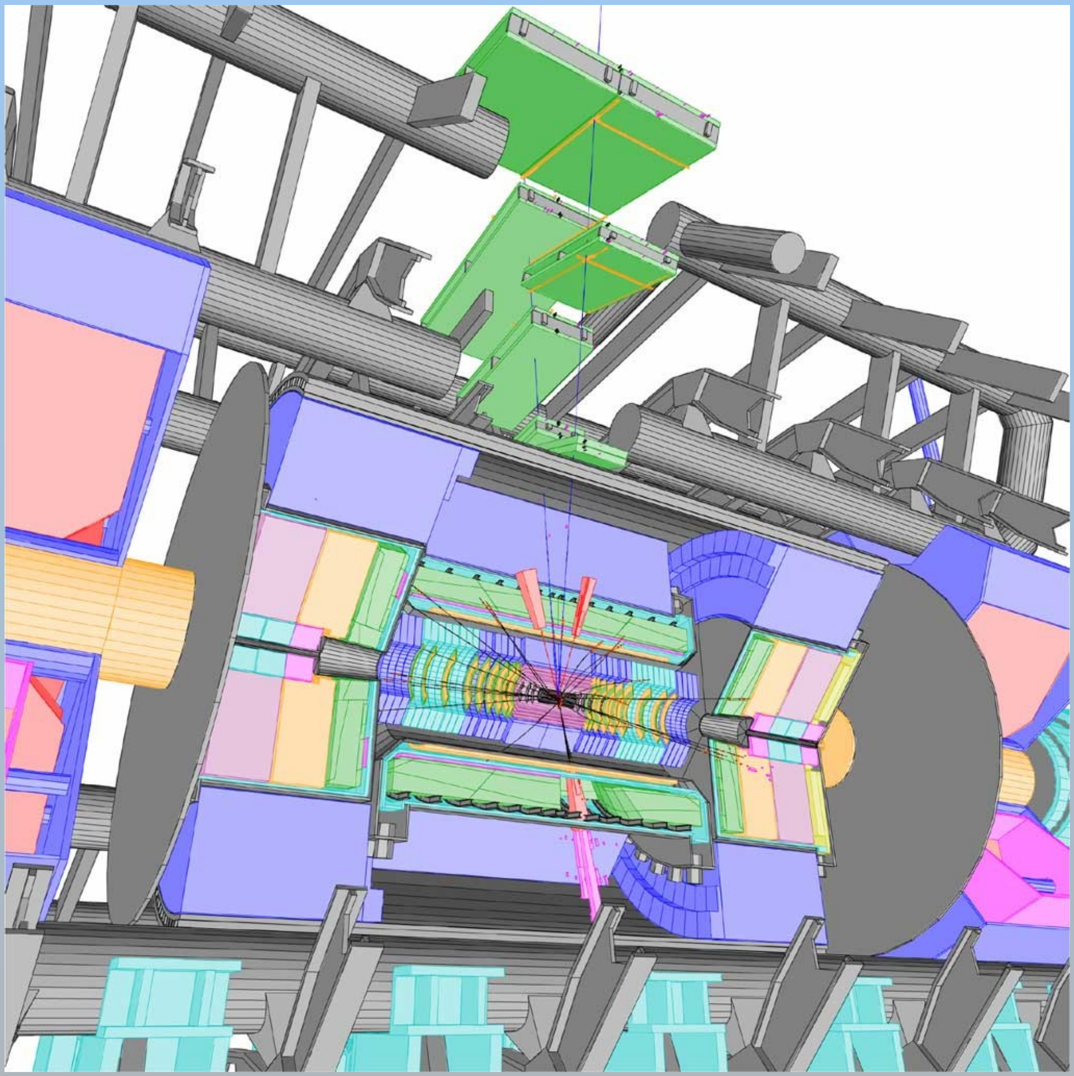
Smaller signals will be accessible



Laboratory Creation of Dark Matter

- **Large Hadron Collider**
  - **find particles up to 2+ TeV in jets+missing energy events**
  - **late 2007!**
- **International Linear Collider**
  - **mass reach not as high**
  - **precision measurements**



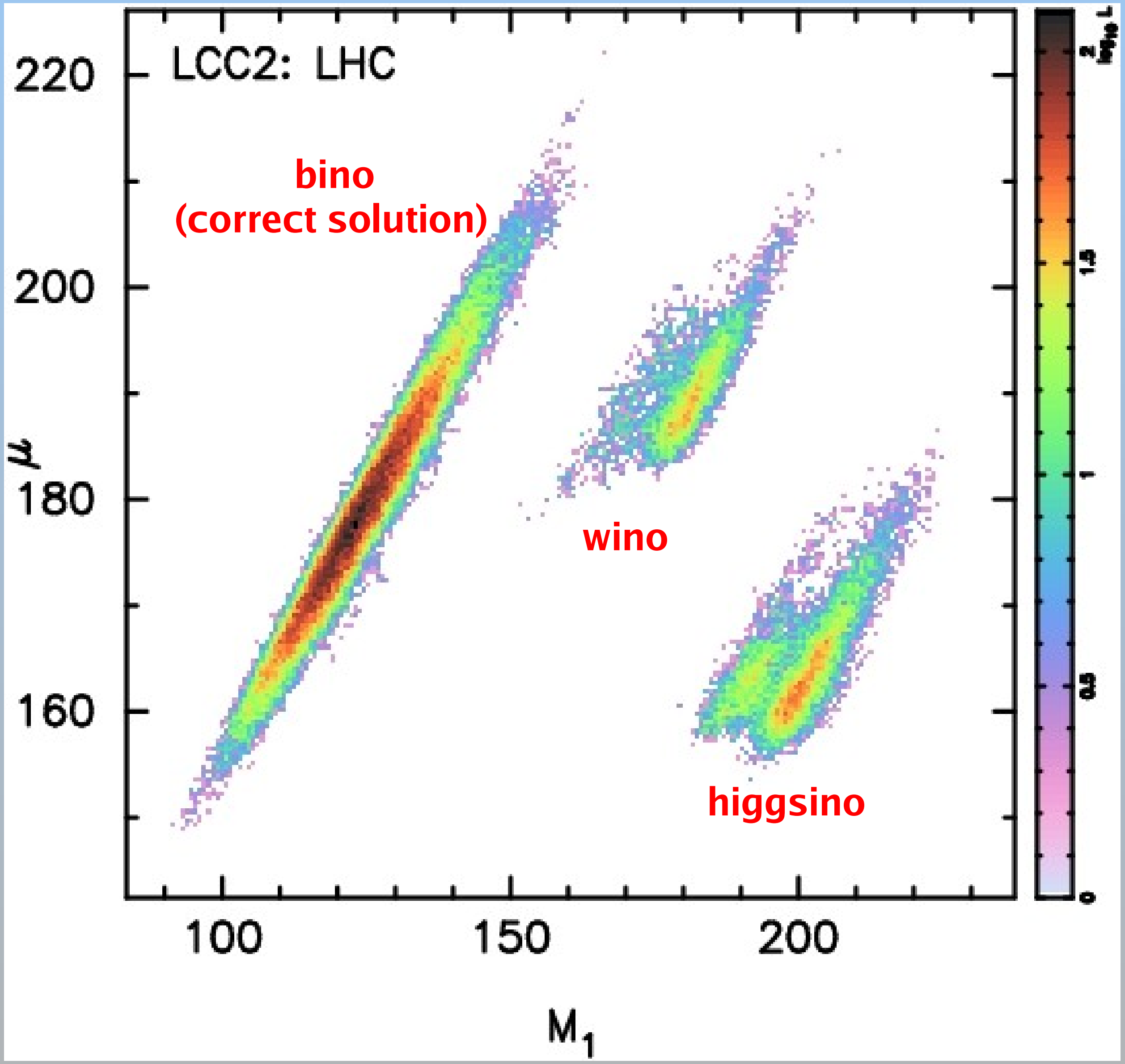


Simulation of event in ATLAS @ LHC

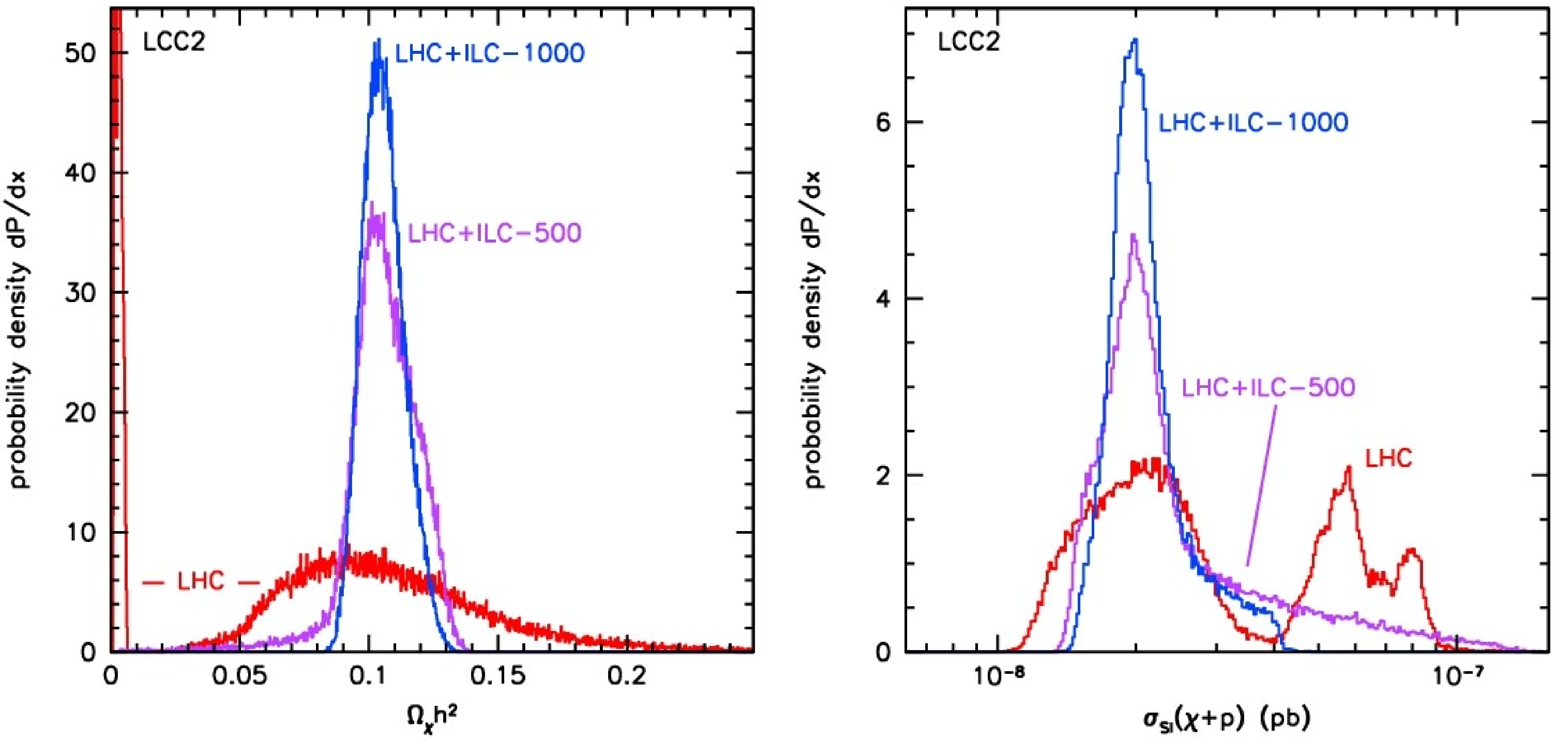
Choose a SUSY model (LCC2) and Explore Consequences

- "Focus point" region: gauginos, higgsinos are light, sfermions are all inaccessible to any collider
  - LHC discovers most gauginos + Higgsinos, one Higgs boson
    - Dark matter candidate mass measured at 10% level
  - ILC discovers the remaining gauginos + Higgsinos, measures various cross sections
- Relic density prediction has 10% accuracy with ILC TeV
  - CMB measurement (Planck, 0.5%) is doing collider physics!
- Direct detection is dominated by exchange of light Higgs
  - The usually dominant heavy Higgs is so heavy that it's irrelevant
  - Hint of a signal possible with current CDMS setup
- Annihilation cross section is large – dominated by W pairs
  - Promising for gamma ray experiments

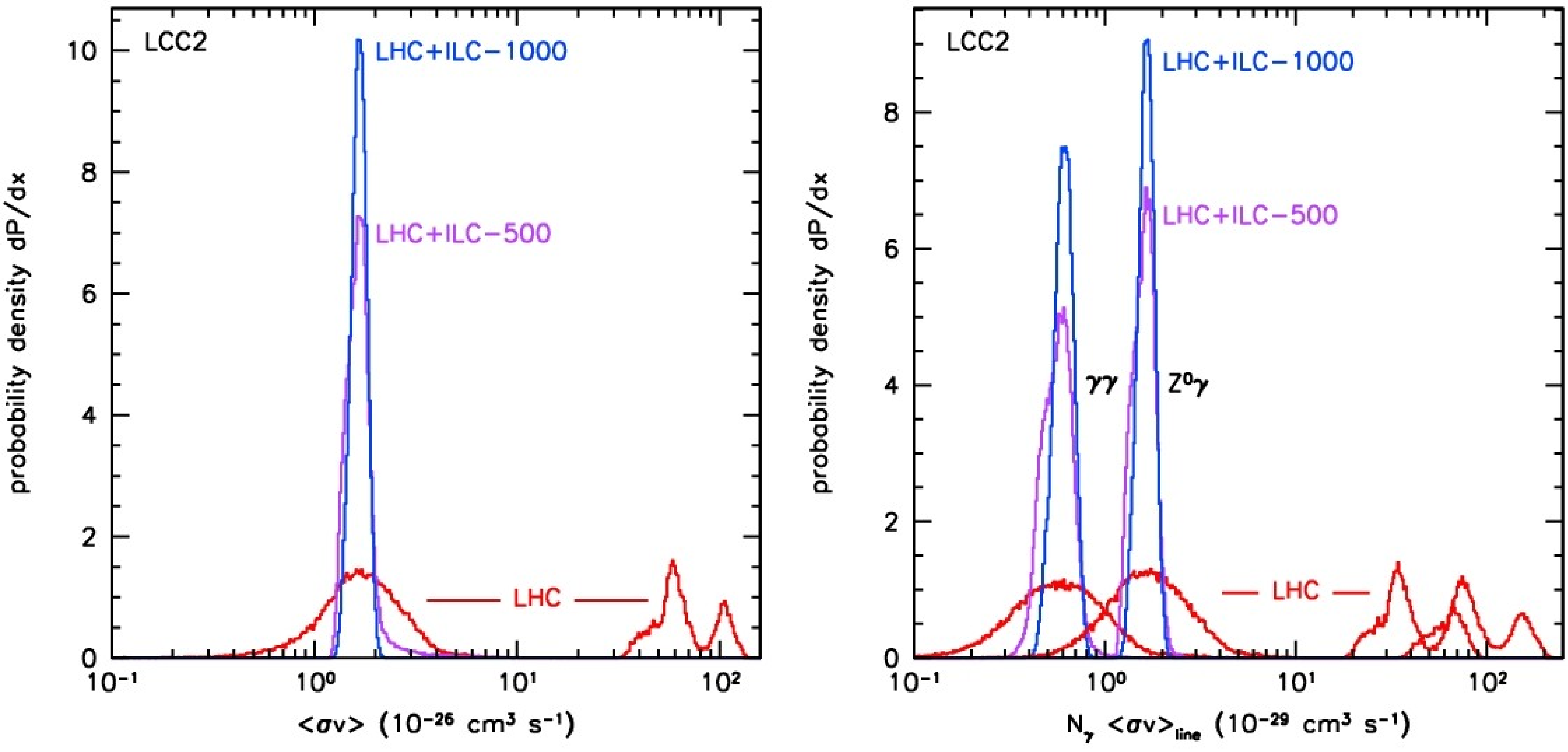
LCC2: Probability Islands for Neutralinos @ LHC



LCC2: Prediction of Relic Density and Direct Detection Cross Section



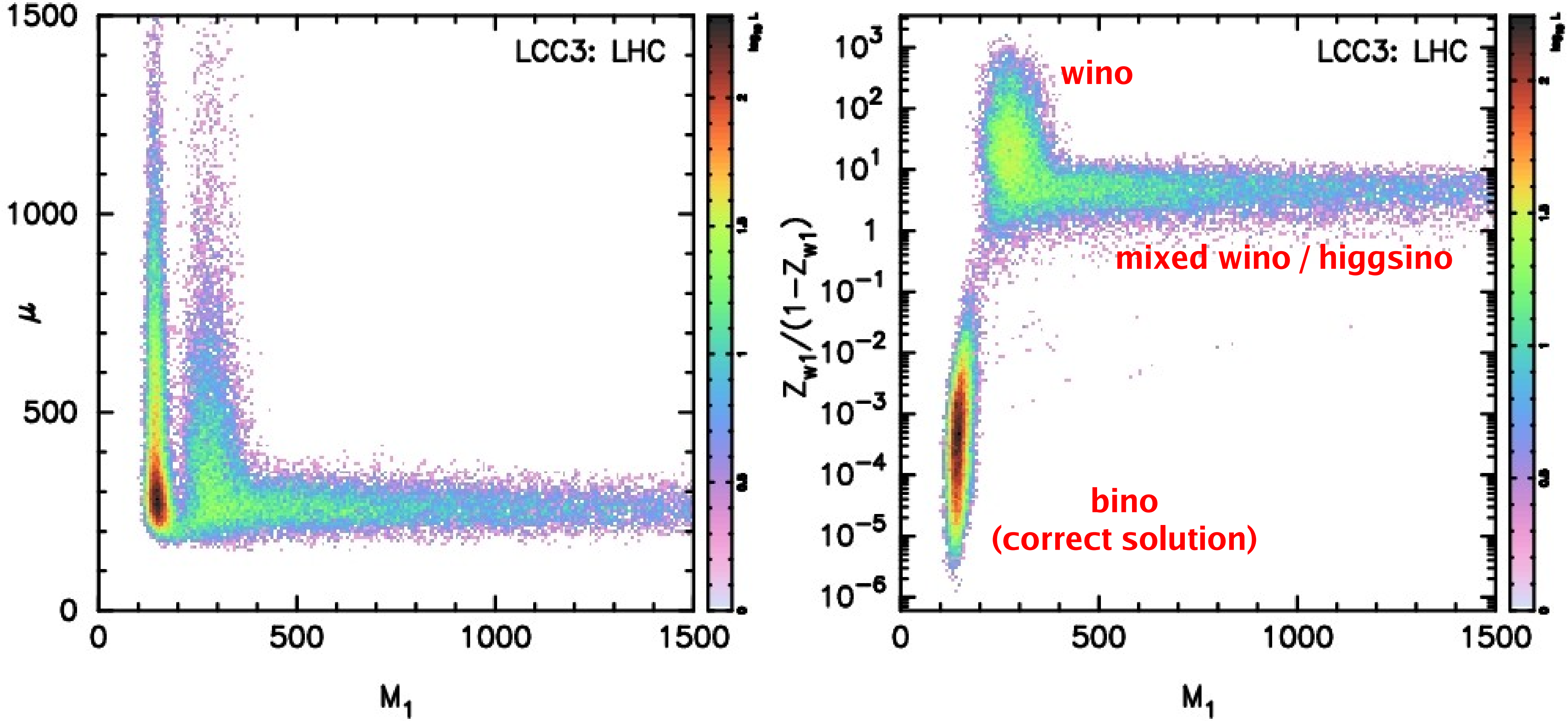
LCC2: Prediction of Annihilation Cross Sections



A Different Model: LCC3

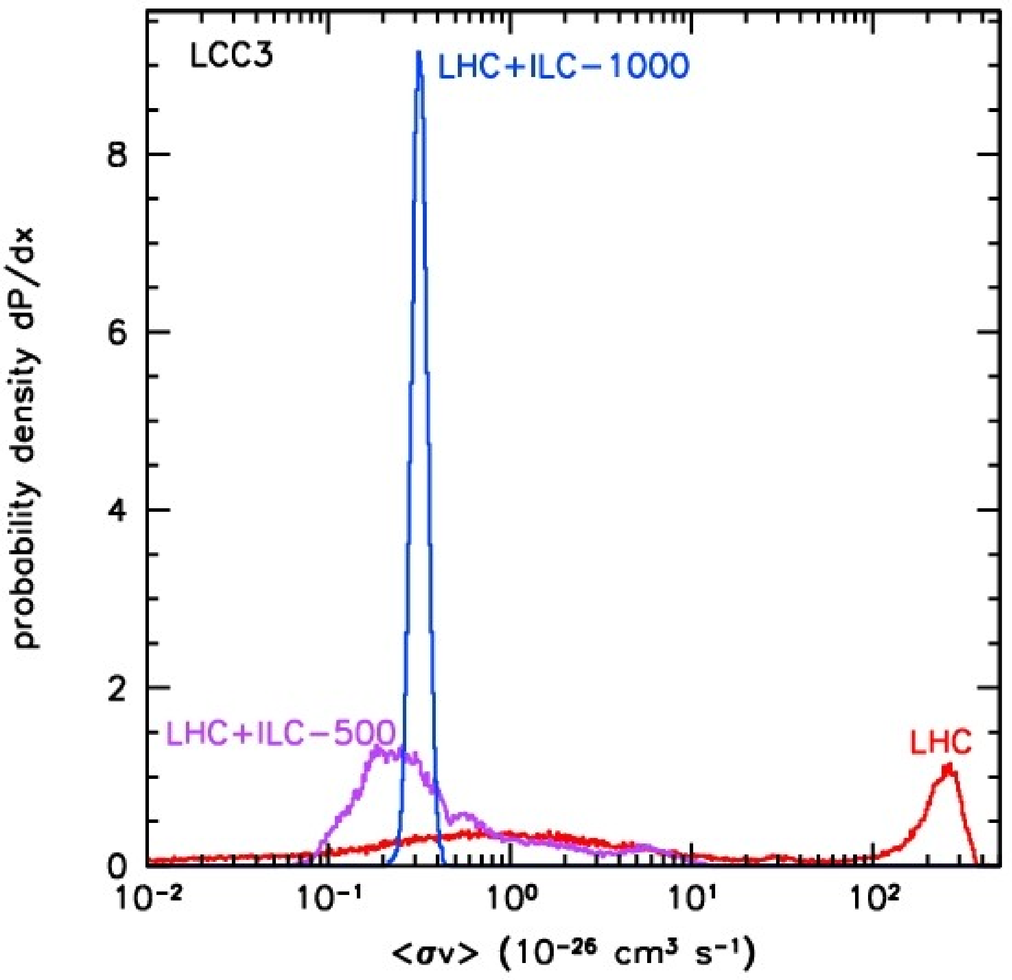
- “Coannihilation” region: light stau very close to neutralino
  - LHC discovers some gauginos and light sfermions, multiple Higgs bosons, stau may be possible
  - ILC discovers chargino, light stau, remaining charged sleptons
- Relic density estimate has ~20% accuracy with ILC TeV
- Direct detection is dominated by heavy Higgs
- Annihilation cross section is moderate – dominated by b bar

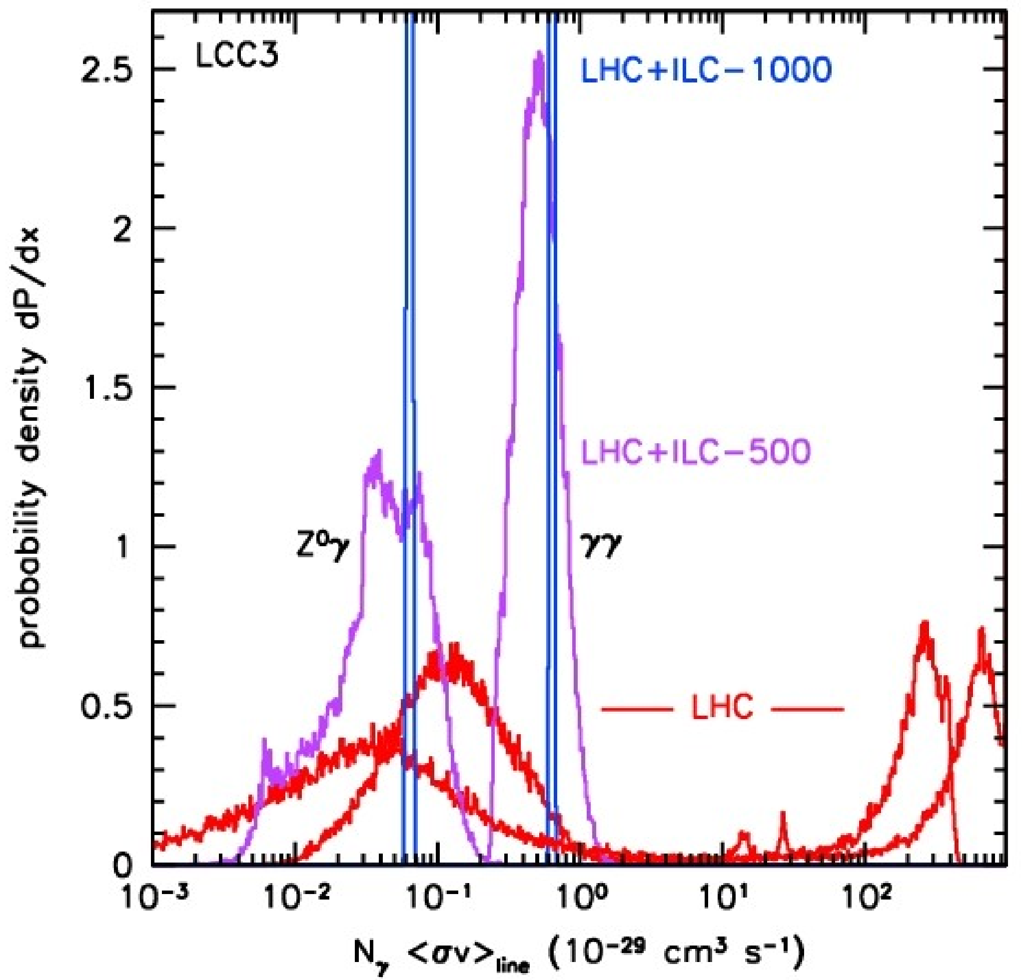
LCC3: Unknown Composition of Neutralinos @ LHC



"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

Mapping the Dark Matter in the Galaxy

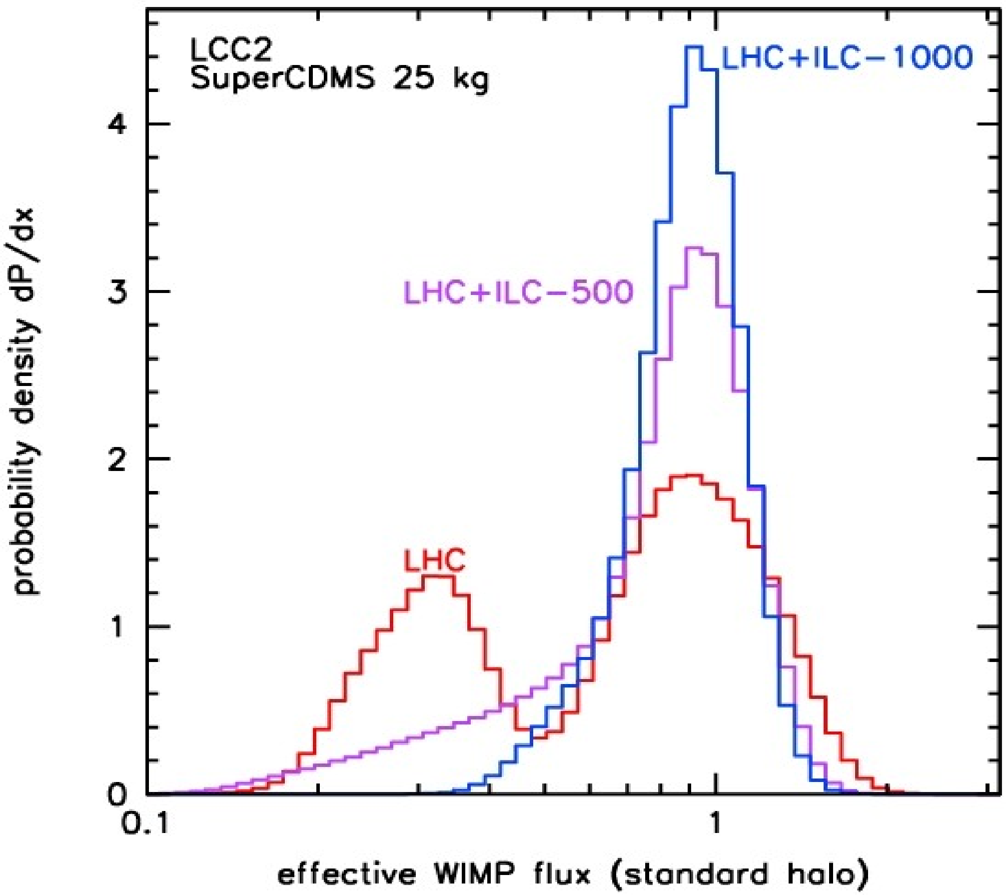
- Local flux of dark matter particles can be determined from the direct detection rate IF collider data can predict the elastic scattering cross section

- Dark matter density squared along a line of sight can be determined from gamma ray flux IF collider data can predict the annihilation cross section

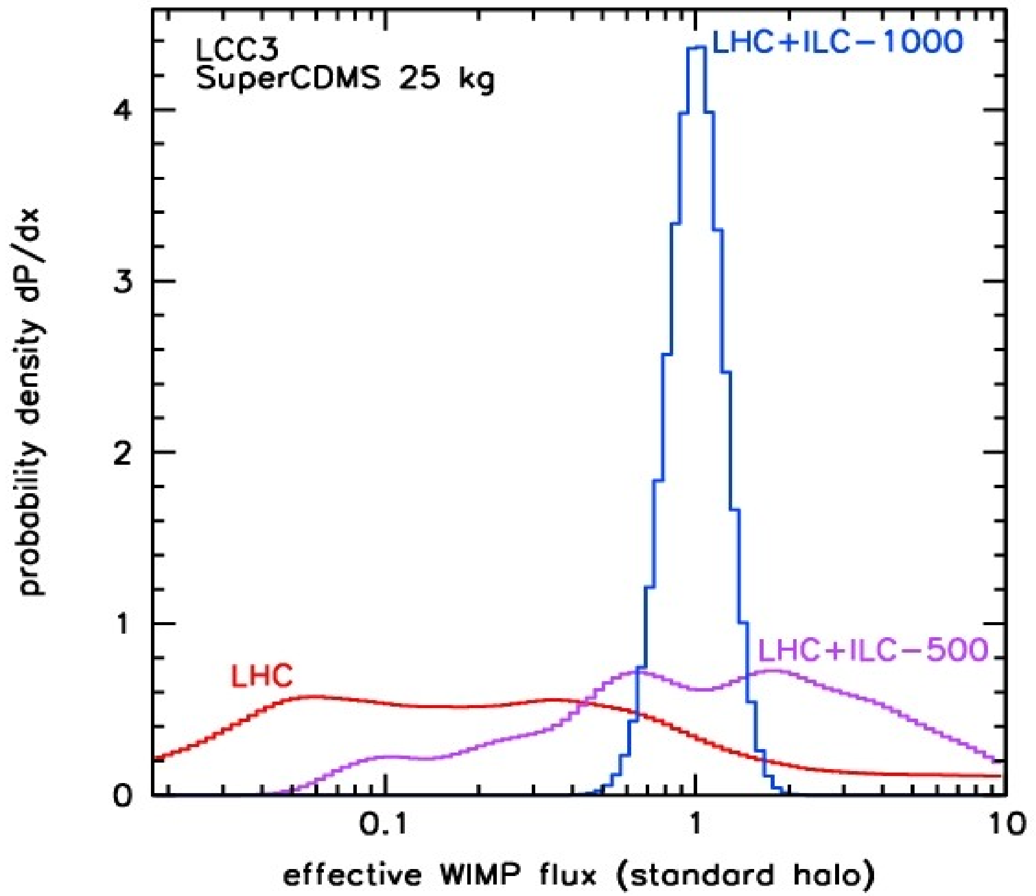
- These can be done without any astrophysical assumptions

Local Flux of Neutralinos

LCC2



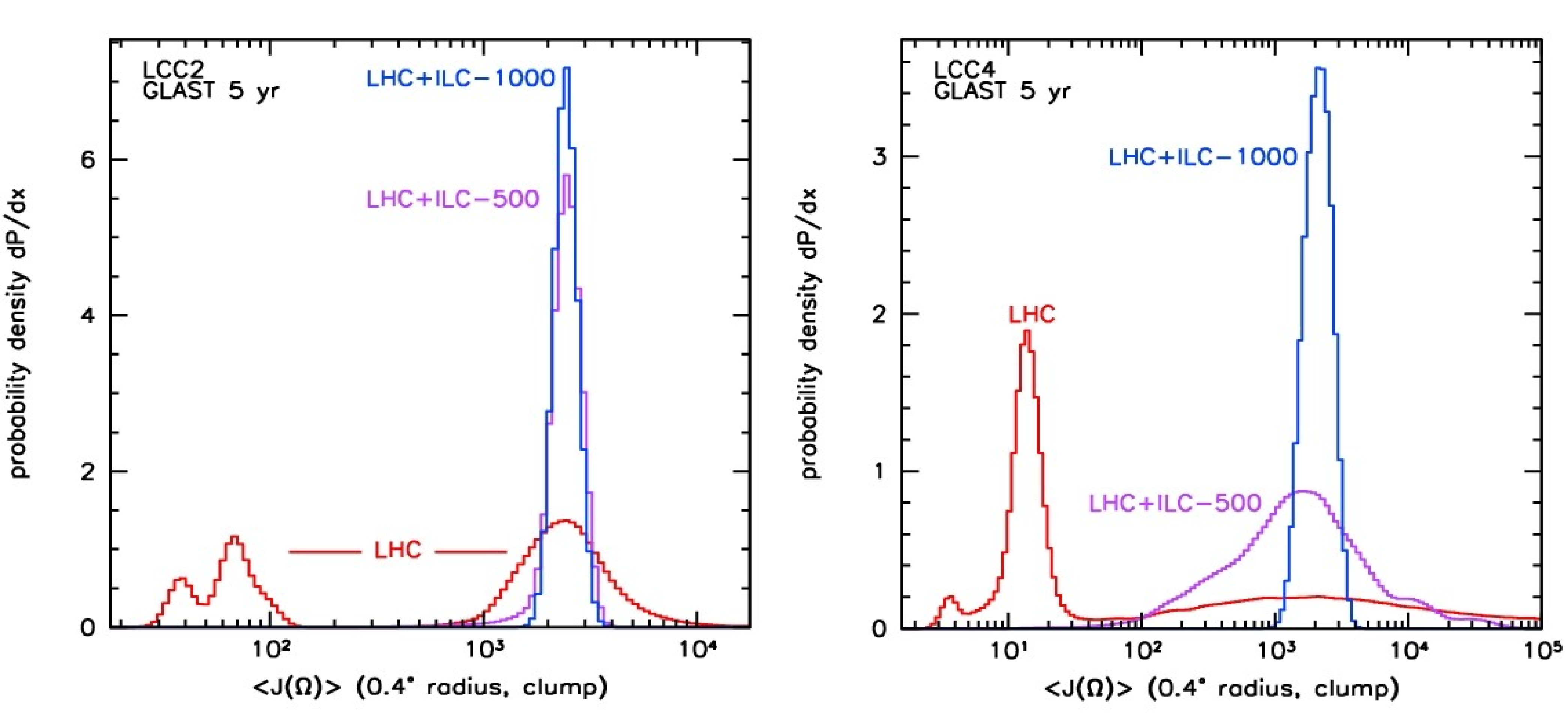
LCC3



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

Why Do We Need the ILC to Understand Dark Matter?

- Dark matter physics depends on small parameters
  - wino / higgsino mixing angle of bino-like neutralino appears in direct detection cross section and branching ratio to W's
- Heavy Higgs mass scale
  - resonant annihilation region (the "funnel") can be important
  - direct detection cross section
- Accurate sparticle masses and mass splittings
  - overall mass scale, and splittings with e.g. stau, chargino
- Tan Beta appears everywhere

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
  - Taken together, a consistent picture may emerge

- We can learn about fundamental physics in astrophysical settings, and learn about our galaxy at high-energy colliders