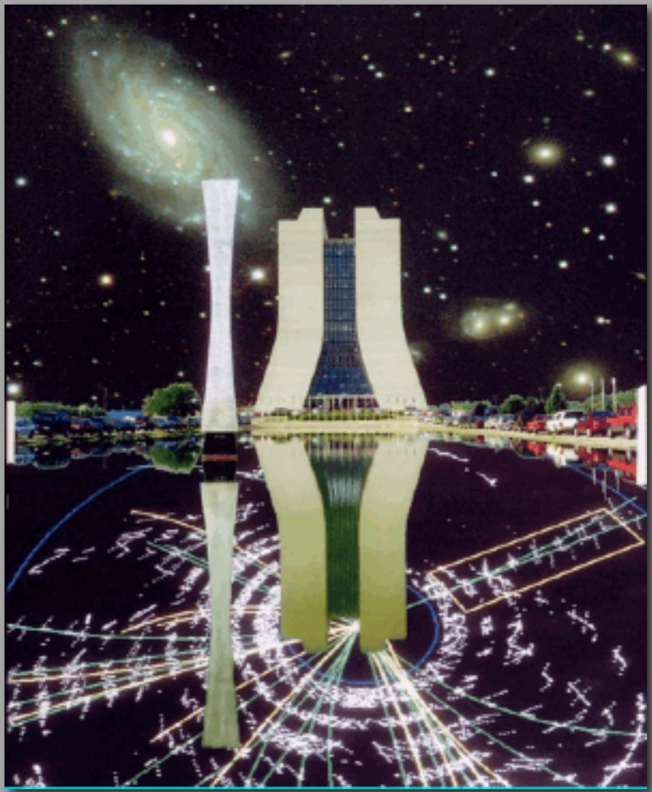
Theoretical Astrophysics At Fermilab

Dan Hooper
Theoretical Astrophysics Group
Center for Particle Astrophysics
Fermilab

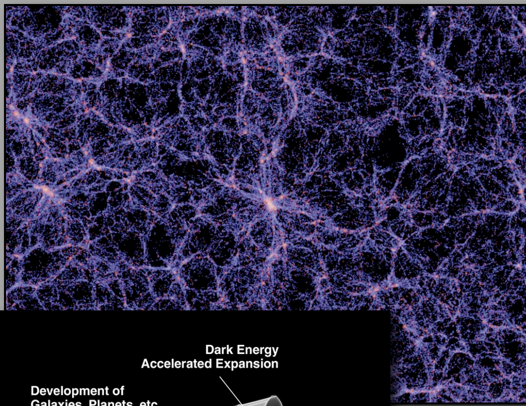
CPA Retreat
April 17, 2009



Some Of The Things We Do…

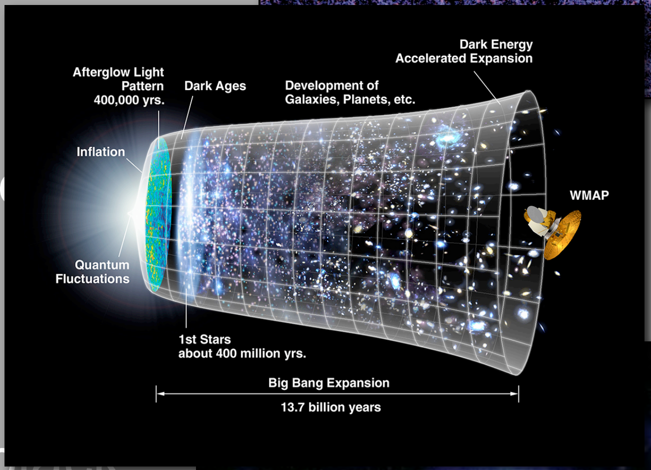
•Theory Connected to Observational Cosmology

cosmic microwave background, structure formation, cosmic history and acceleration



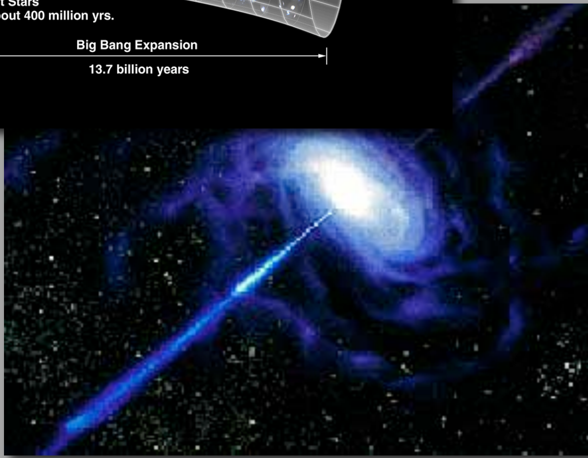
•High Energy Astrophysics

gamma rays, cosmic rays, particl matter, early universe cosmology

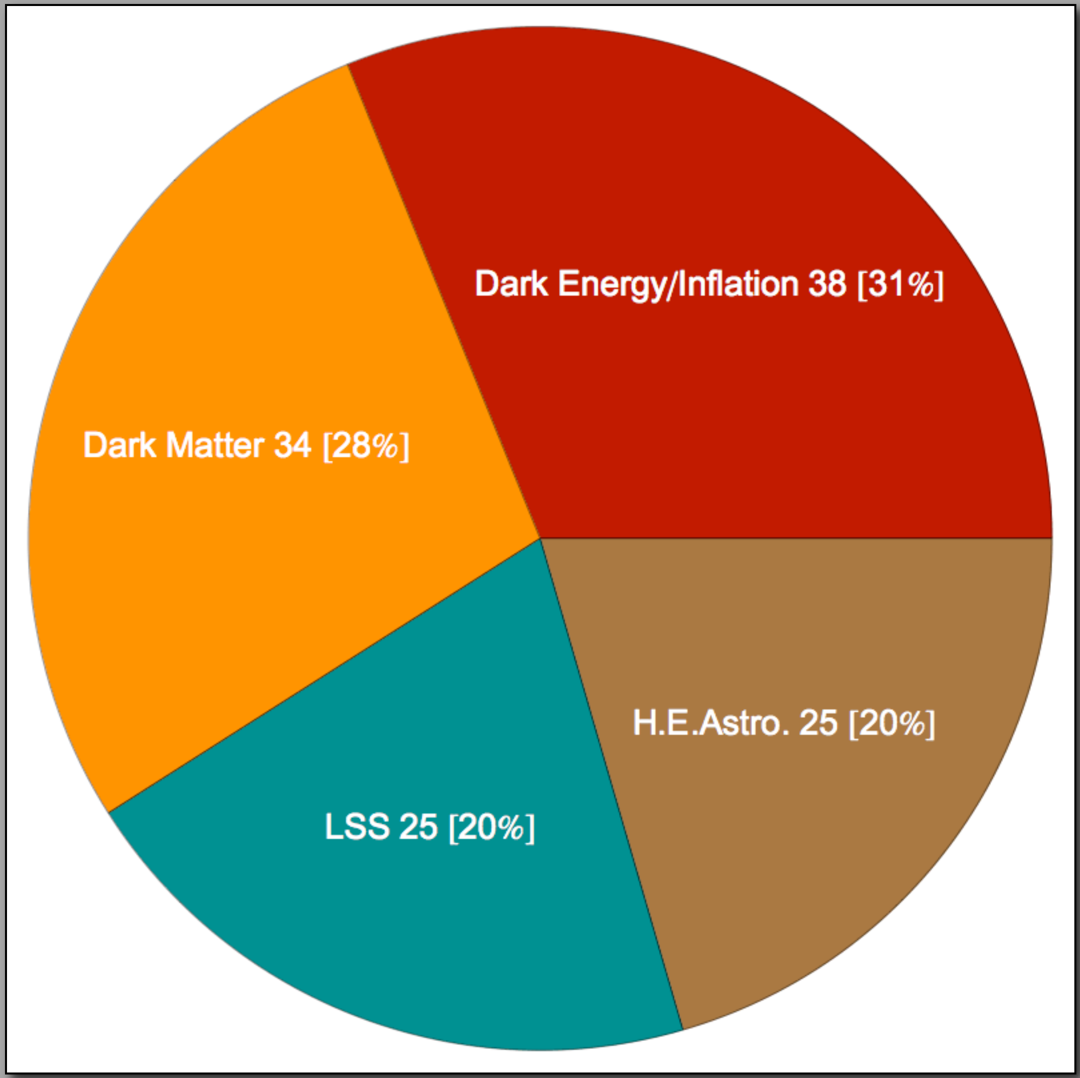


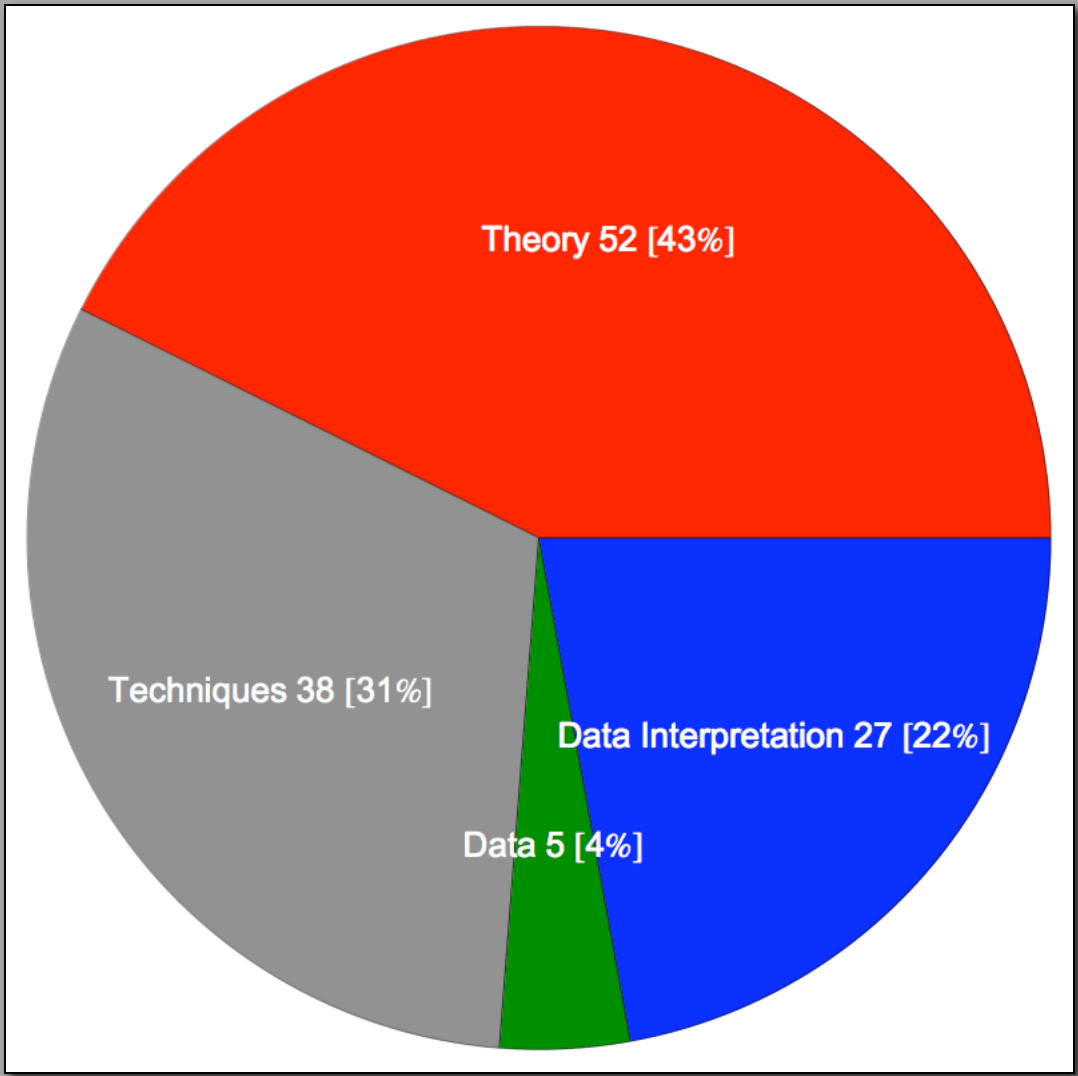
•Numerical Cosmology

galaxy formation, supermassive b holes, reionization



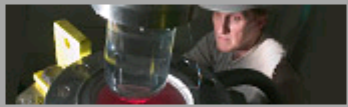
Attempting to connect cosmological and astrophysical observations to fundamental physics!


Dark Energy/Inflation 38 [31%]
Dark Matter 34 [28%]
H.E.Astro. 25 [20%]
LSS 25 [20%]


Theory 52 [43%]
Techniques 38 [31%]
Data Interpretation 27 [22%]
Data 5 [4%]

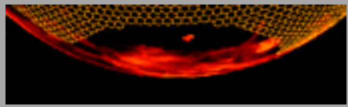
Experimental Astrophysics @ FNAL

Chicagoland Observatory for Underground Particle Physics (COUPP)



Cryogenic Dark Matter Search (CDMS)

Dark Energy Survey (DES)



GammeV

Pierre Auger Observatory

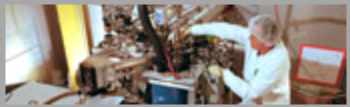
Sloan Digital Sky Survey (SDSS)

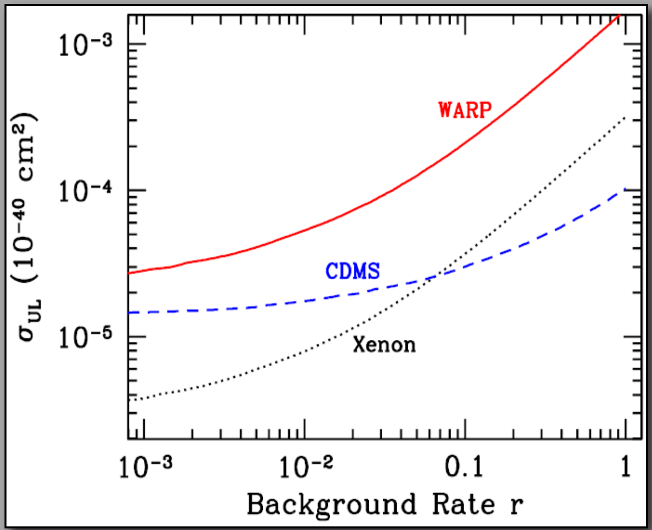
SuperNova Acceleration Probe (SNAP)

Direct Detection of Dark Matter

Chicagoland Observatory for Underground Particle Physics (COUPP)

Cryogenic Dark Matter Search (CDMS)





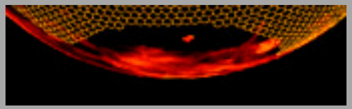
-Direct Detection Figure of Merit
(Bauer, Dodelson, Sadoulet, 2008)

-Connection between direct detection and those of Higgs Tevatron
(Hooper, Carena, Skands, Vallinotto, 2006)

-Dozens of other papers on the topic of particle dark matter

Observational Cosmology

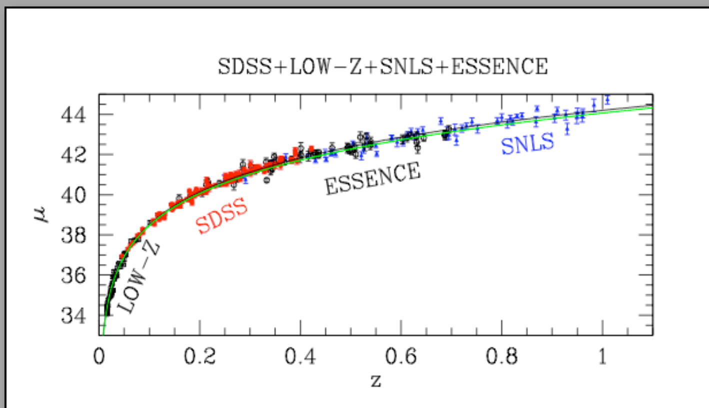
Dark Energy Survey (DES)



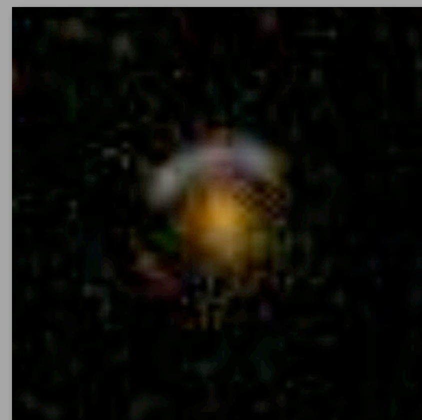
Sloan Digital Sky Survey (SDSS)

SuperNova Acceleration Probe (SNAP)

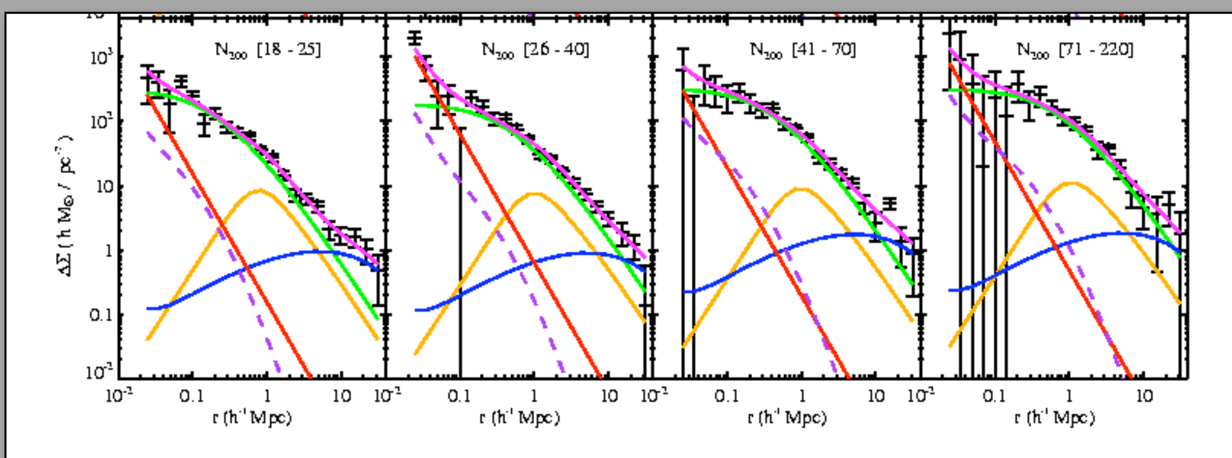
Science With the Sloan Digital Sky Survey



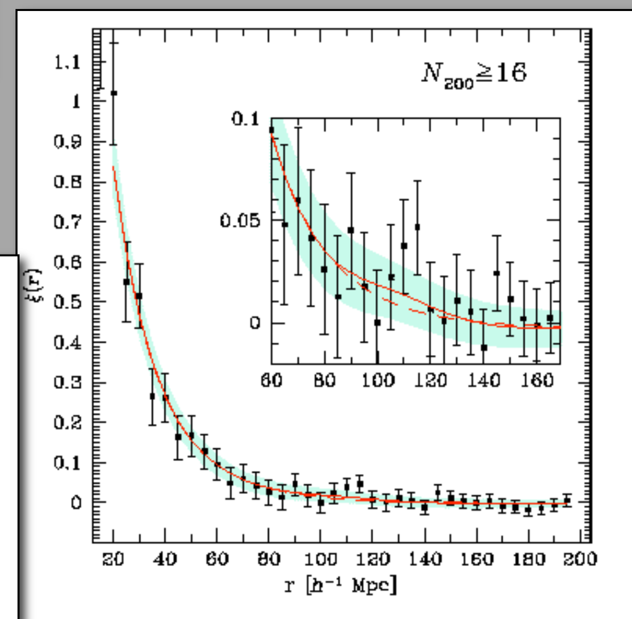
500 SN *Frieman et al. 2008*



8 O'clock Arc *Allam et al. 2006-8*

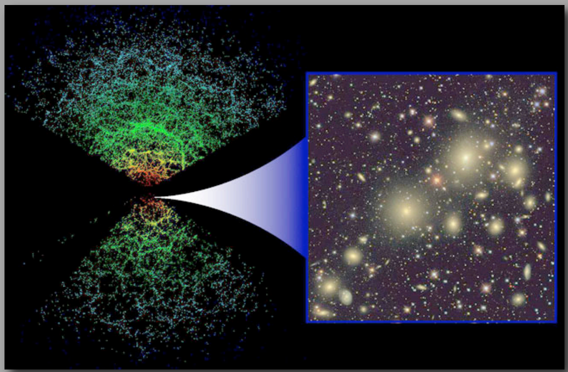


Weak Lensing by Clusters *Johnston et al 2007*

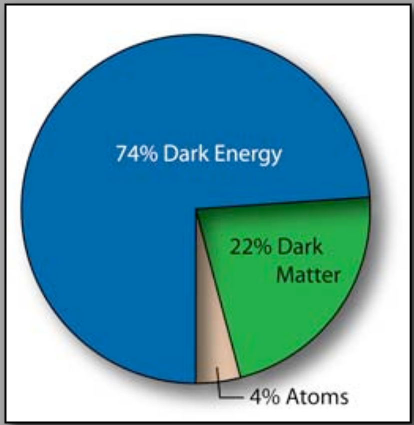


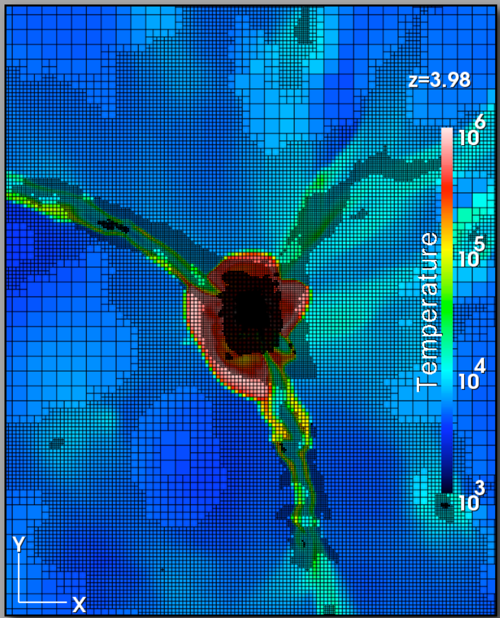
Cluster Correlation Function
Estrada, Sefusatti, Frieman 2008

Simulations are Essential if we are to Extract Science from Surveys



- Dark Matter
- Dark Energy
- Neutrino Mass
- Inflation

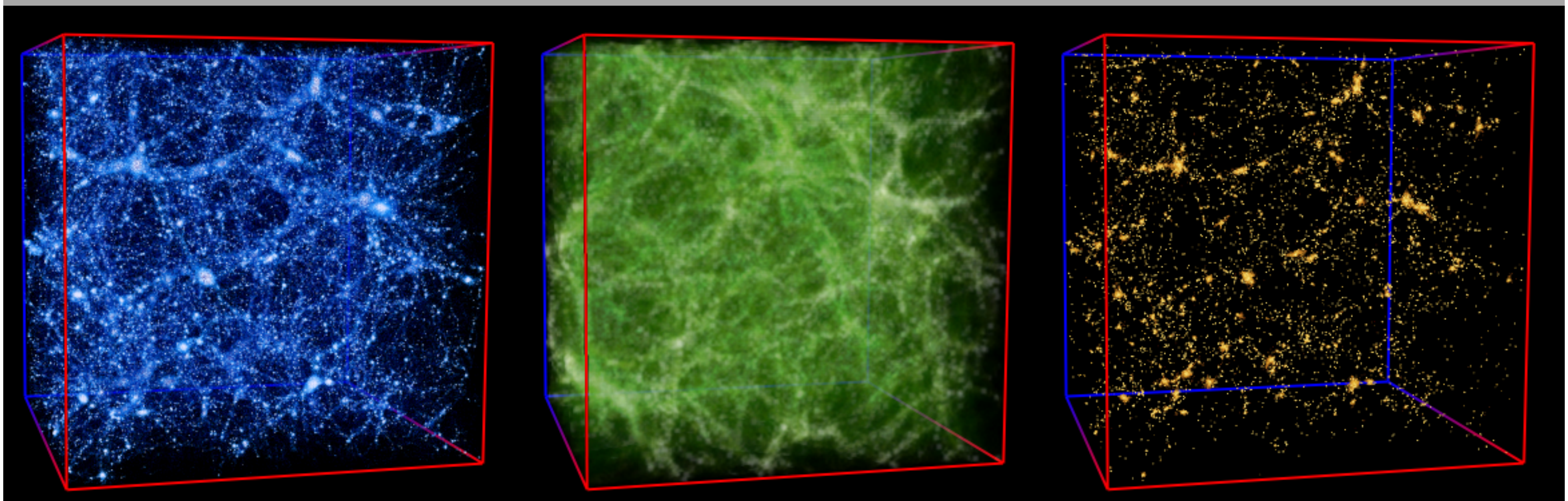




- Gravitational Instability is nonlinear
- Baryons governed by hydrodynamics
- Radiation Field affects and is affected by structure
- Stars form, Supernovae explode, …

Baryons Matter!

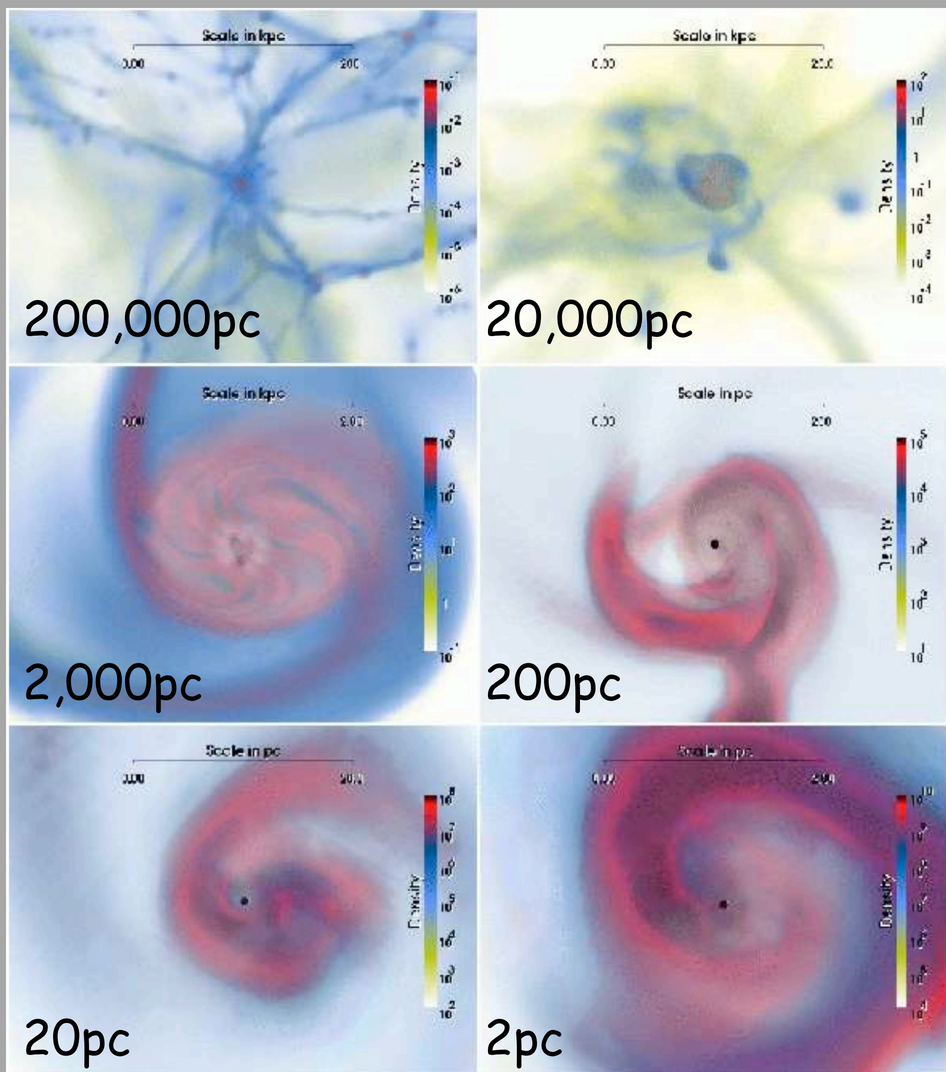
w/ state of the art Adaptive Mesh Refinement



Dark matter Gas Galaxies

Modeling baryonic effects on large scales is important for unbiased calibration of weak lensing signal from future Dark Energy experiments.

LSS Highlights: Galaxy/BH Formation

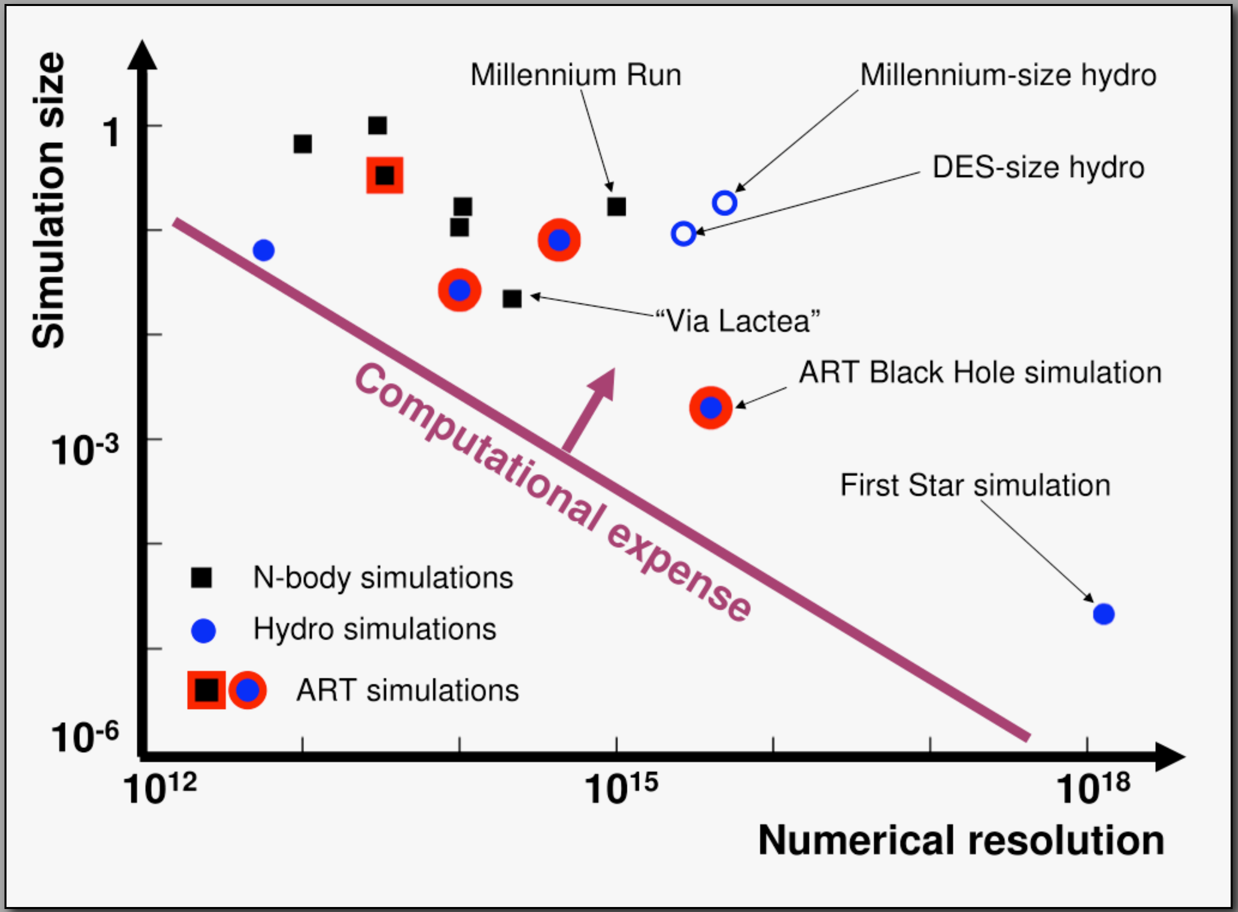


Mpc to mpc
Adaptive Refinement Tree

Understanding galaxy and black hole formation is a primary goal of modern astrophysics, and is also important for calibrating Dark Energy experiments.

Levine *et al.* 2008

The Cosmological Computing Initiative



To perform dark matter/hyrodynamical simulations appropriate to calibrate DES, we will be developing appropriate computer resources

The Cosmological Computing Initiative

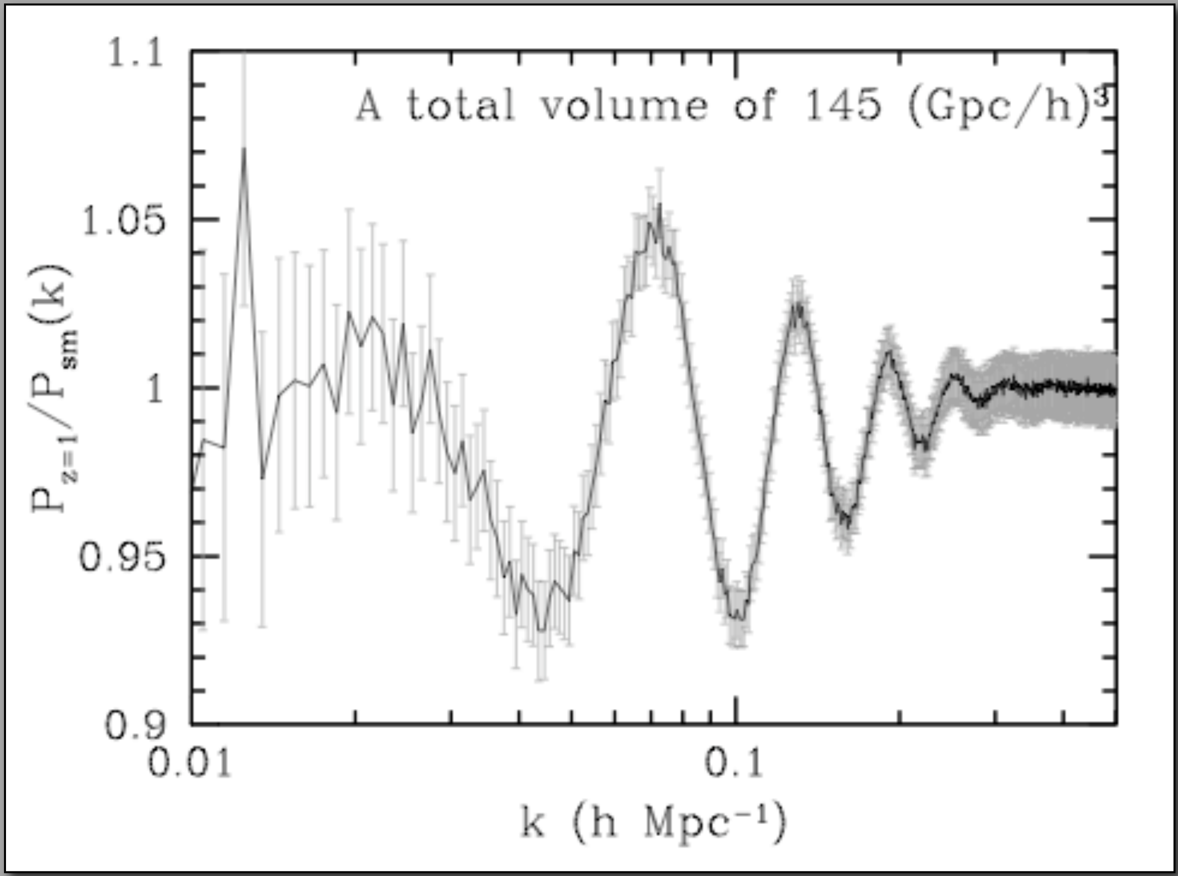
Science	Single DES-size hydro Multiple Millennium N-body Millennium-size hydro Multiple DES-size hydro
Hardware	300 processors 1,000 processors 10,000 processors 500 processors 3,000 processors
Software	ART (core only) Enzo 4D parallel ART ART (full)
Funding	KICP, FNAL, FRA NSF (postdocs) Argonne LDRD SciDAC (software) DOE Office of Science (hardware)
Collaboration	FNAL, UC SLAC UCLA, NMSU, UIUC, Argonne LANL Washington, Princeton, LBL Harvard, Michigan, …
	2007 2008 2009 2010 2011 2012

The Need for Medium Scale Computing

- Cosmological surveys often require many medium-sized simulations
- Medium scale local clusters are ideally matched to the problems at hand
- Medium scale clusters allow further development to scale to the largest machines available
- Medium scale machines needed for analysis

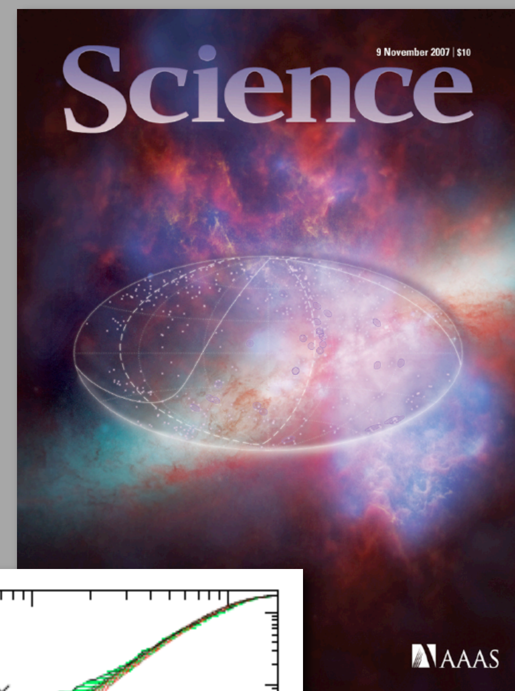
Future R&D: 21 cm

Theorists working with Accelerator Physicists (with RF expertise) on 21cm R&D. Might be a cheap way of probing dark energy at $0.5<z<2$.



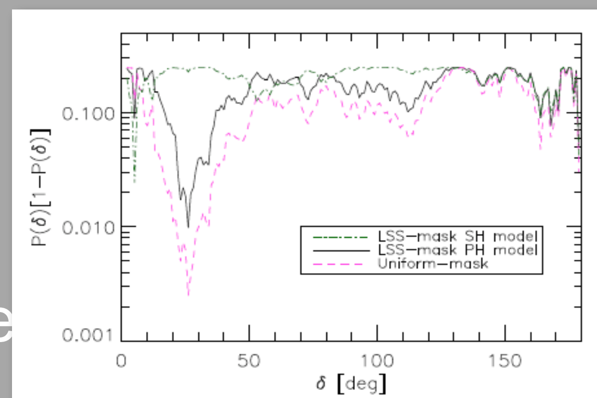
Ultra High Energy Cosmic Ray Physics

Pierre Auger Observatory

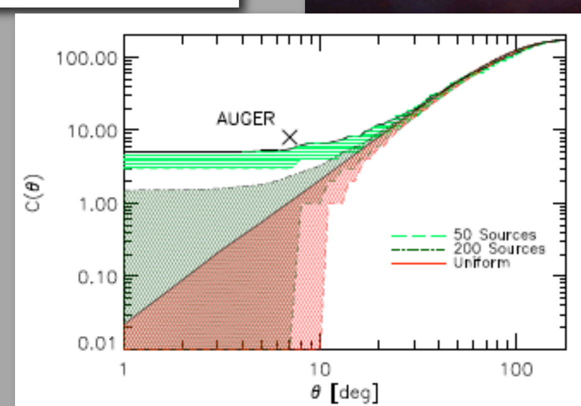


•Auger has observed a correlation between UHECR arrival directions and AGN

•Looking for clustering in UHECRs is another first step toward identifying sources



•The highest energy events in pre-Auger data match particularly well with the structure of the nearby universe ($z < 0.02$)



(Cuoco, Miele, Serpico, 2007; Cuoco, Hannestad,Haugbolle, Kachelreis, Serpico, 2007)

Ultra High Energy Cosmic Ray Physics

Pierre Auger Observatory 

Observations from the Pierre Auger Observatory have taught us a great deal about the highest energy cosmic rays; yet many questions remain unanswered:

-What are the sources of the ultra-high energy cosmic rays?

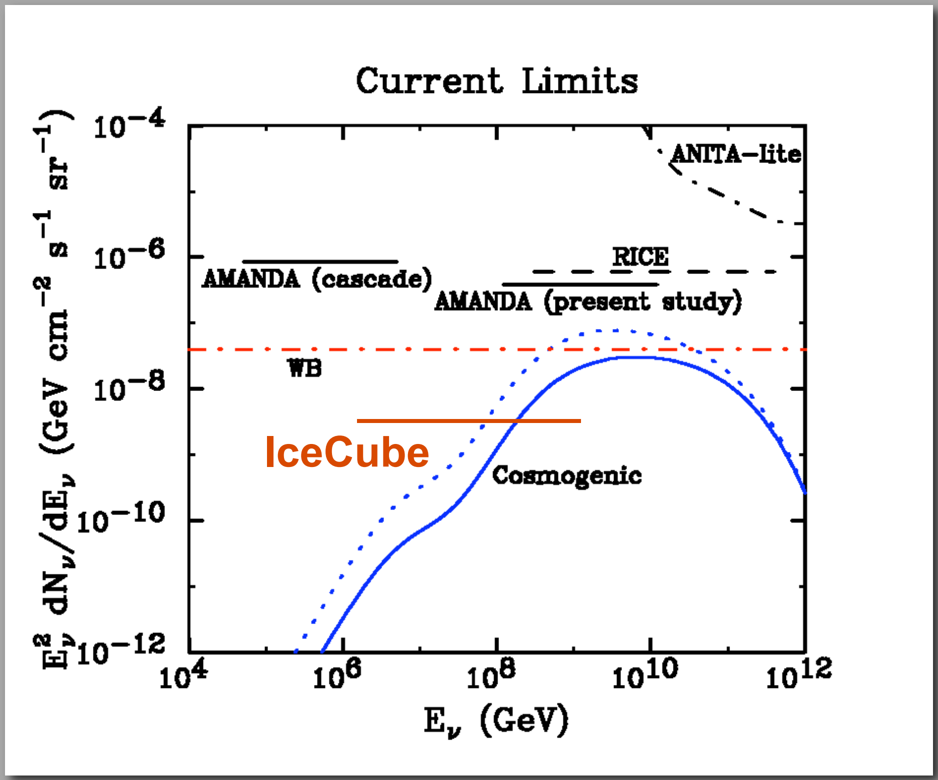
-What is the composition of these particles? (protons, iron, something more exotic?)

To answer these questions, a combination of cosmic ray, neutrino and gamma ray observations will likely be needed

Ultra-High Energy Particle-Astro Physics

The UHECR Connection To High Energy Neutrino Astronomy

Neutrinos produced in UHECR propagation (cosmogenic neutrinos) has long been thought of as a guaranteed source of observable UHE neutrinos

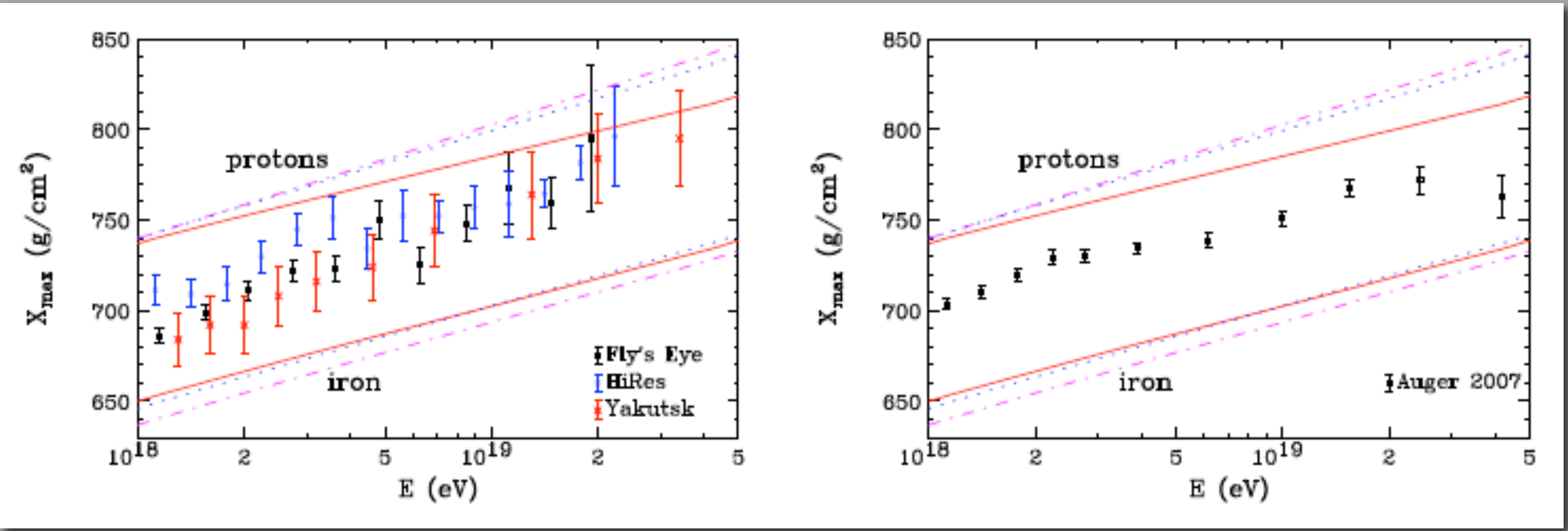


(F. Halzen, D. Hooper, PRL 2006)

Ultra-High Energy Particle-Astro Physics

The UHECR Connection To High Energy Neutrino Astronomy

The UHECR spectrum, however, appears likely to consist in part of nuclei and not only protons, unlike has often been assumed

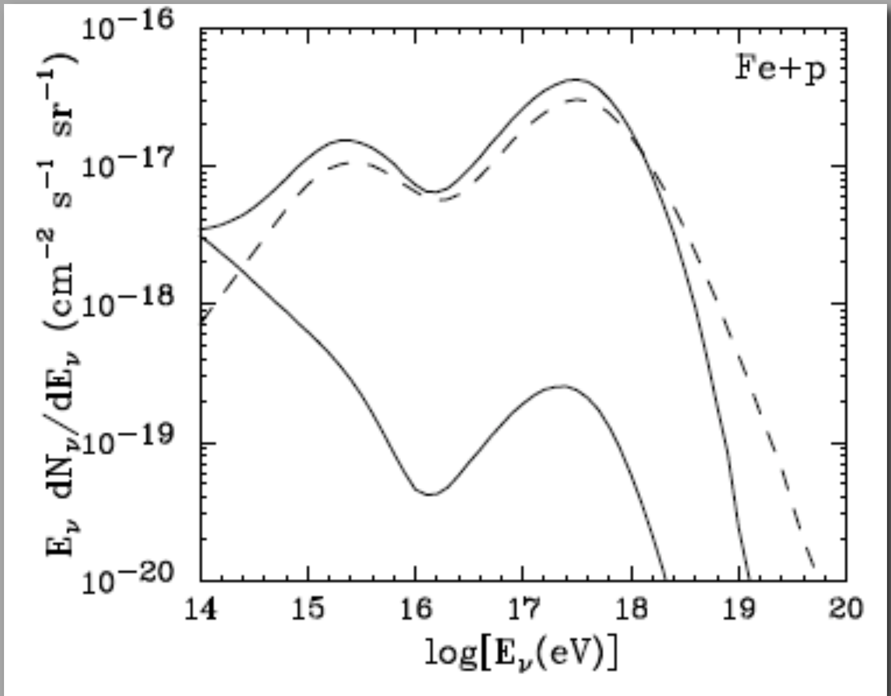


A nuclei dominated UHECR spectrum can lead to the suppression of the cosmogenic neutrino flux

Ultra-High Energy Particle-Astro Physics

The UHECR Connection To High Energy Neutrino Astronomy

- Considering departures from an all-proton spectrum, the current Auger data is consistent with models which predict a wide range of neutrinos fluxes (~1 event per year to ~1 per century)
- More Auger data will allow us to make more accurate predictions
- A profound connection exists between UHE neutrino and cosmic ray physics



(Anchrodoqui, Goldberg, Hooper, Sarkar and Taylor, arXiv:0709.0734)

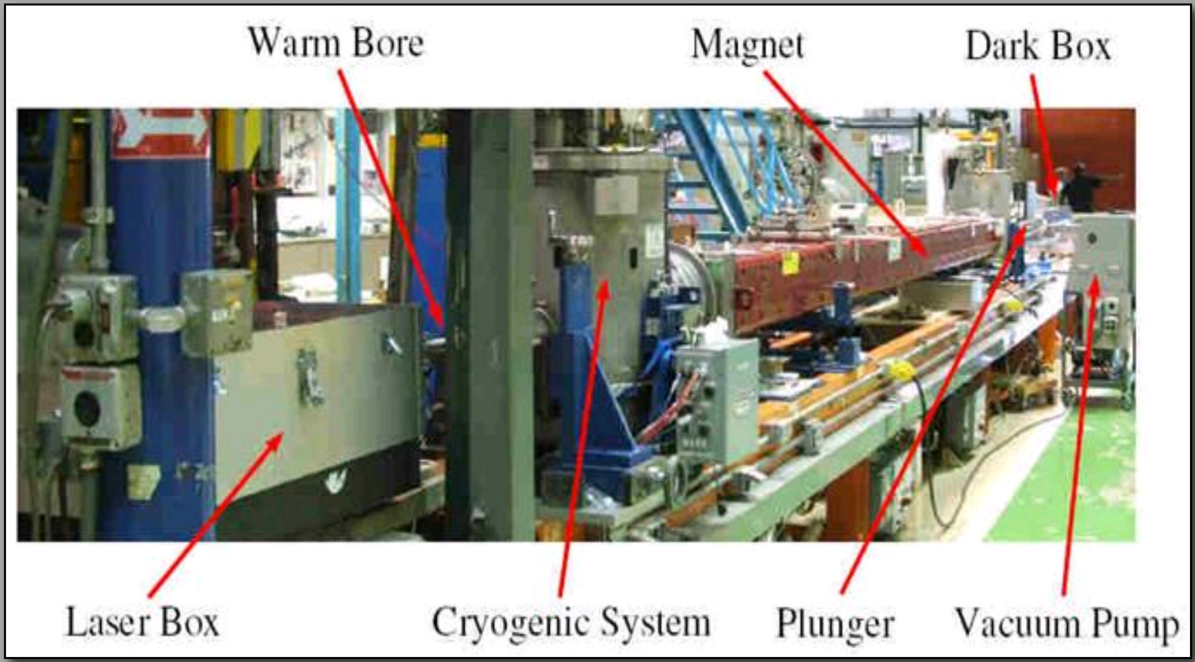
Exotic Particle Searches

GammeV_

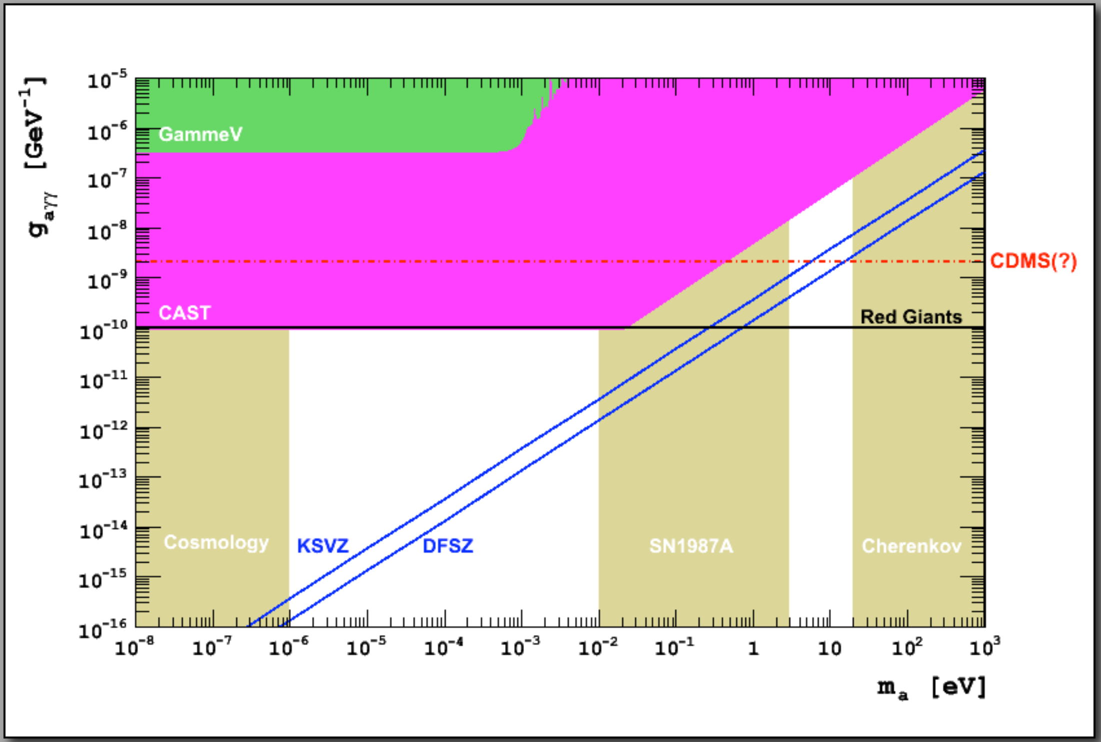
GammeV

“I've been a kind of "consultant", rather than playing a structured role in the collaboration. For months, I've had weekly (at some times daily) discussions with JongHee, Aaron, Jason, Fritz, etc. mostly clarifying to the collaboration members some aspects of the physics of axions (I do remember long discussions on the Quantum Mechanics of Lasers and the role of Axion states...). I' ve also helped in identifying the relevant literature and in updating them on similar efforts worldwide. (I think that I first clarified them the importance of "being quick" in the GammeV game)”

Pasquale Serpico



Axions in CDMS/Solid Xenon



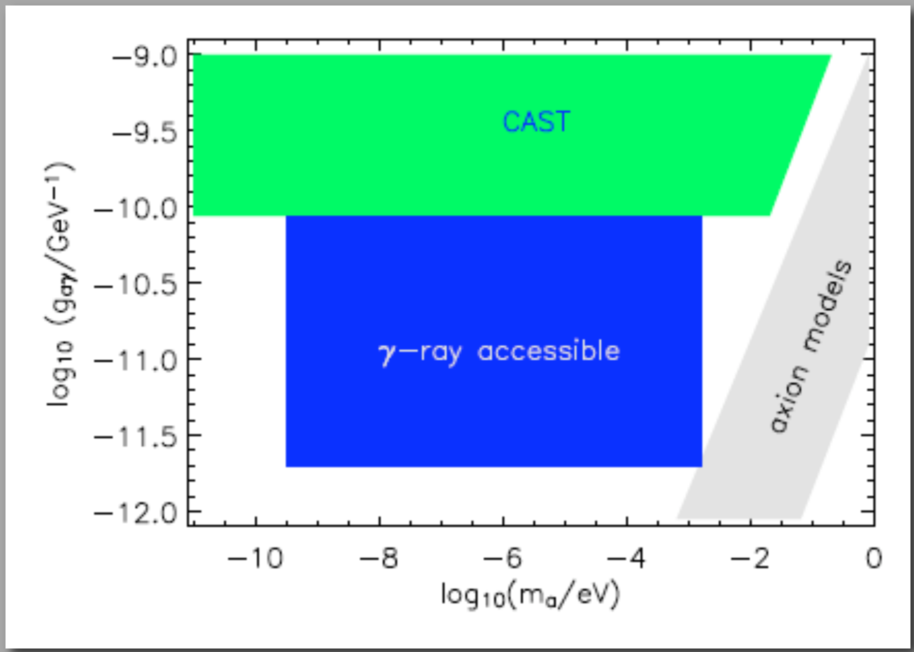
Gamma Ray Astronomy and Axion-Like Particles

•In the presence of magnetic fields, photons and axions can mix via the term:

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

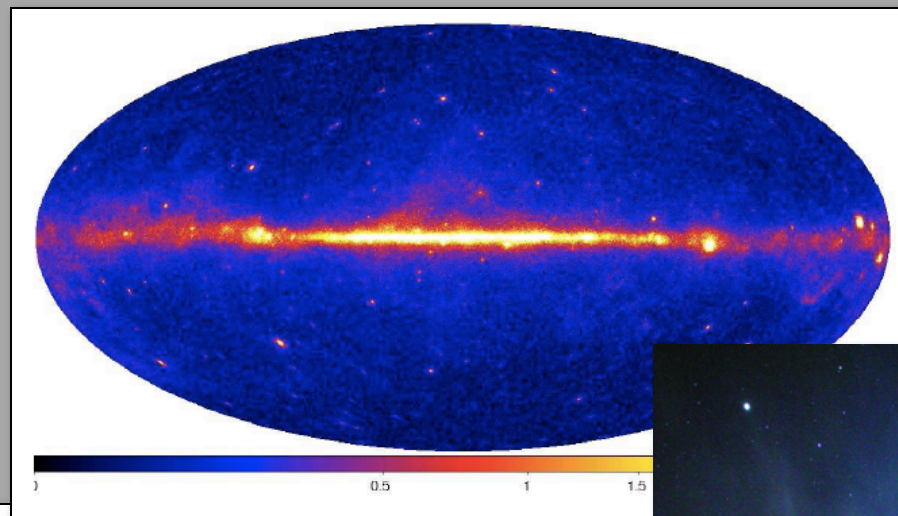
•May occur only at high energy, providing a natural opportunity gamma ray astronomy

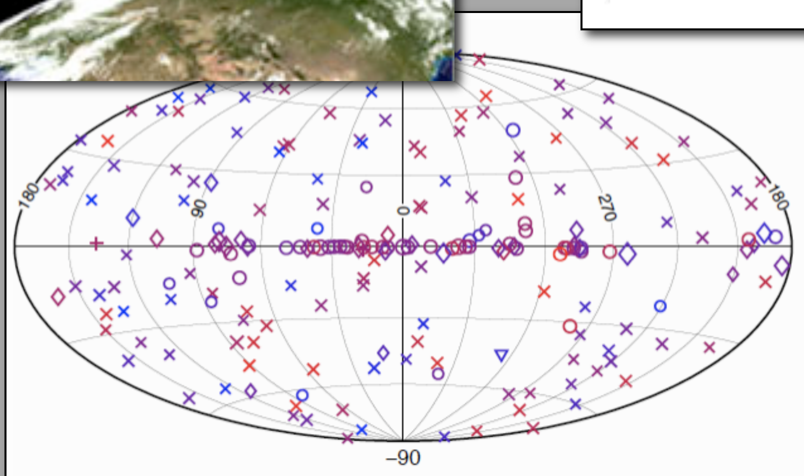
•Potential way to test/detect beyond the reach of other axion probes

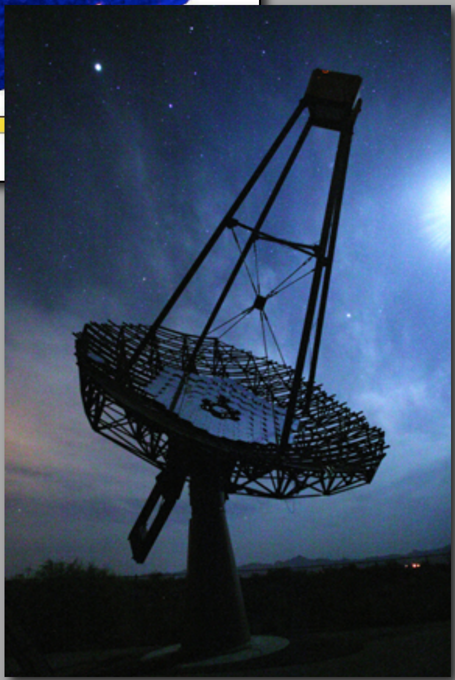


(D. Hooper, P. Serpico, arXiv:0706.3203; Mirizzi, Raffelt, P. Serpico, PRD, arXiv:0704.3044; Simet, D. Hooper, P. Serpico, PRD, arXiv:0712:2825)

An Exciting New Era For Gamma Ray Astronomy







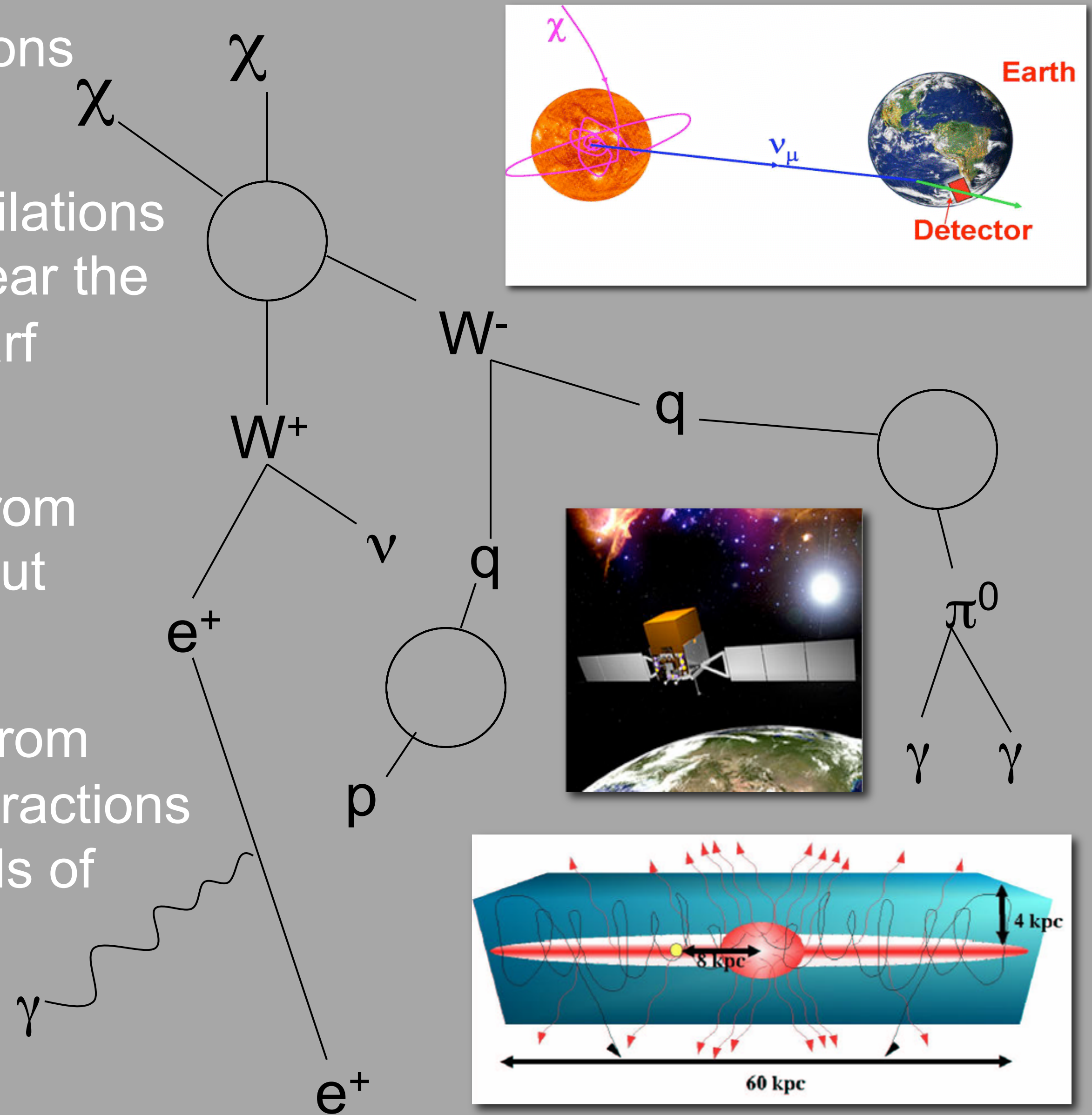
Indirect Detection of Dark Matter

Neutrinos from annihilations in the core of the Sun

Gamma Rays from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.

Positrons/Antiprotons from annihilations throughout the galactic halo

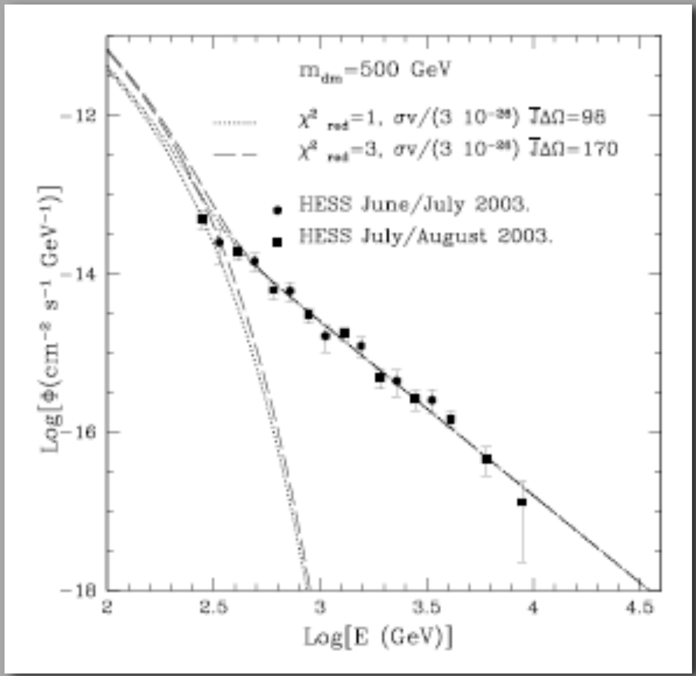
Synchrotron Radiation from electron/positrons interactions with the magnetic fields of the inner galaxy



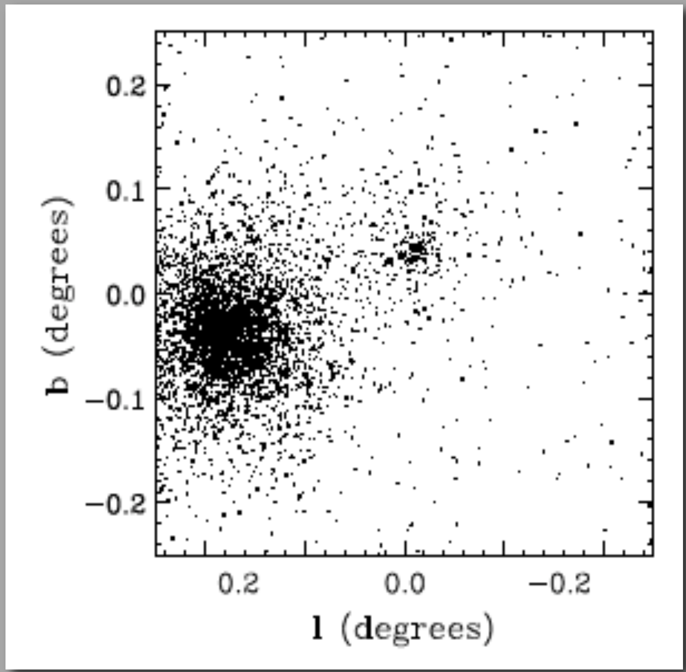
Dark Matter in the Galactic Center Region

•Astrophysical backgrounds near the Galactic Center require non-trivial methods to separate from dark matter annihilation products

•We have explored ways to exploit the full body of angular and spectral information to be collected by FERMI to identify or constrain the gamma-ray signal from dark matter



Zaharajias and Hooper, 2006



Dodelson, Hooper and Serpico, 2007

…And Beyond the Galactic Center

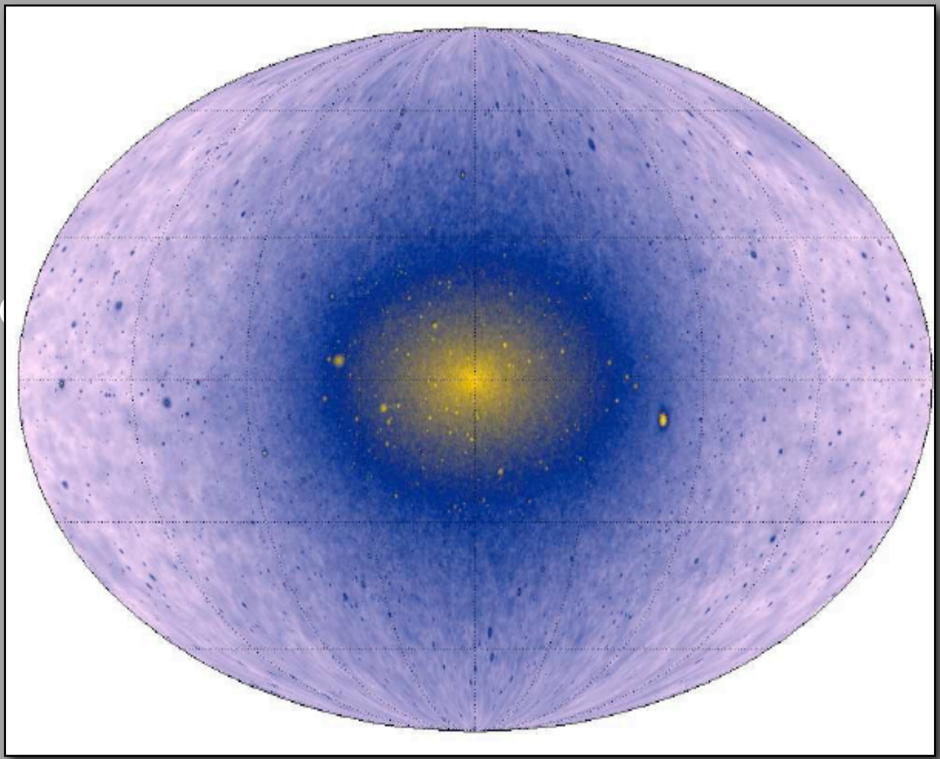
•Spectral and angular information will be important for identifying any dark matter annihilation radiation in the extragalactic diffuse background and galactic halo emission - Important to fully exploit all information contained in FERMI data

•Angular signatures include:

-Anisotropy due to the motion of the system (the cosmological *and* galactic Compton-Getting eff

-Effects of nearby dark matter structures

-Angular distribution due to offset position of the Sun



(Hooper and Serpico, JCAP, astro-ph/0702328; Dodelson, Belikov, Hooper and Serpico, arXiv: 0903.2829)

Dark Matter Searches With the Next Generation of Ground Based Gamma Ray Telescopes

- Following the successes of HESS, VERITAS and MAGIC, the gamma ray astronomy community has begun to look ahead
- High sensitivity, low threshold, large field-of-view telescope arrays
- We are currently evaluating different telescope array designs with regard to their sensitivity to
  dark matter annihilation
- Designs optimal for
  astrophysical sources a
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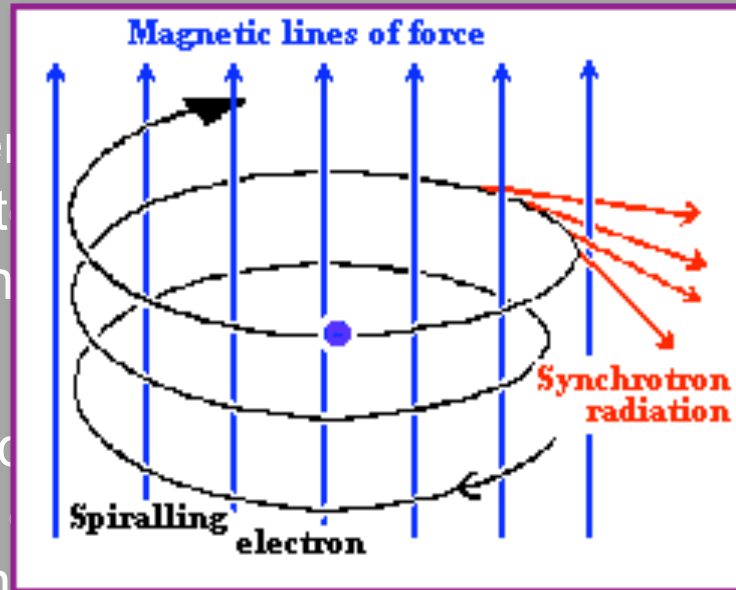
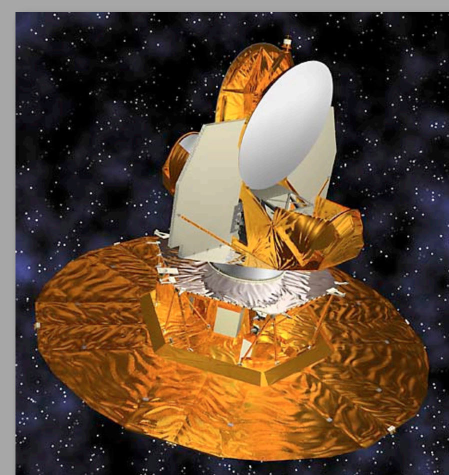
Indirect Detection With Synchrotron and Inverse Compton Radiation



- Electrons/positrons produced in dark matter annihilations inverse Compton scatter with starlight/CMB and emit synchrotron phot as they propagate through the Galactic Magn Field

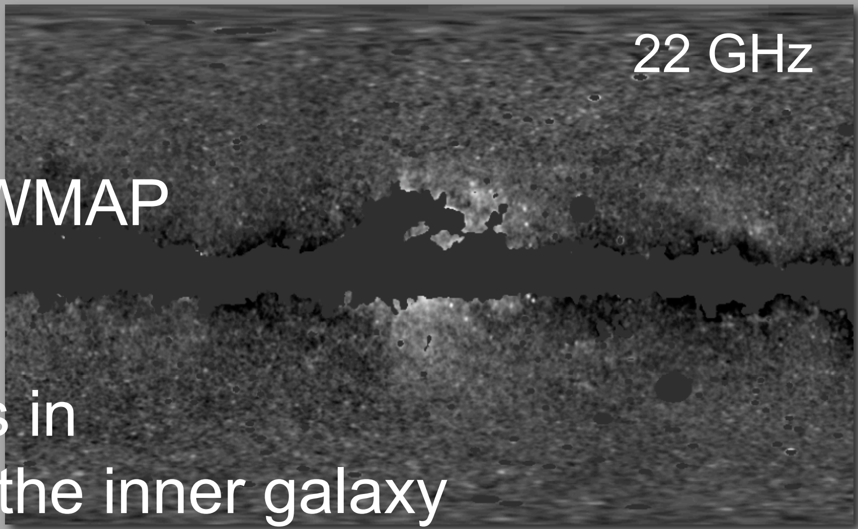
- These annihilation products have been stud far less than prompt gamma rays, antimatter neutrinos (several hundred papers on gamma ray searches; only ~10-20 on synchrotron/inverse Compton)

- For electroweak-scale dark matter, the resulting synchrotron radiation falls within the frequency range of CMB experiments, such as WMAP



(Hooper, PRD, arXiv:0801.4378; Hooper, Dobler, Finkbeiner, PRD, arXiv:0705.3655)

Dark Matter in the WMAP Sky



- Excess of hard synchrotron is seen in the inner galaxy by WMAP

- Indicates a new population of energetic electrons/positrons in the inner galaxy

- Consistent with a cusped halo profile and a 100-1000 GeV WIMP, with an annihilation cross section of $\sim 3\times10^{-26}$ cm^3/s

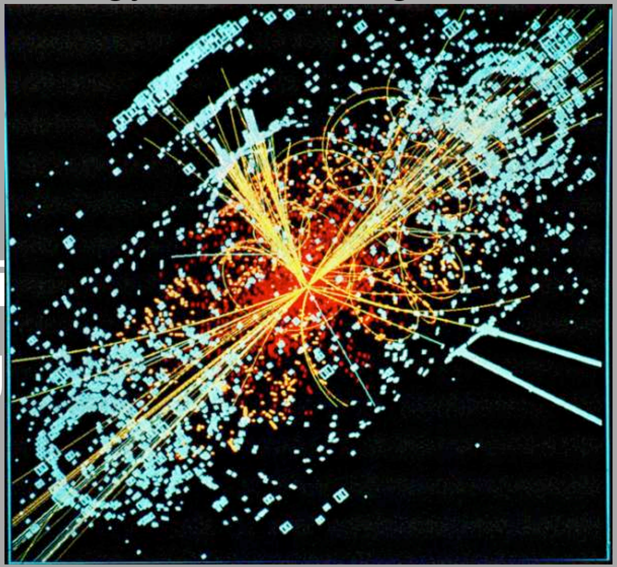
Exciting new area to explore! Fermilab is playing a leading role!

Hooper, G. Dobler and D. Finkbeiner, PRD, arXiv:0705.3655

Future Directions: The LHC Era

In the recent past, our group has been involved with a number of studies connecting astrophysics to collider experiments:

- D. Hooper, T. Plehn, A. Vallinotto, Neutralino Dark Matter and Trilepton Searches in the MSSM (PRD, arXiv:0801.2539)
- D. Hooper, S. Profumo, Dark Matter and Collider Phenomenology of Universal Extra Dimensions (Phys. Rept., hep-ph/0701197)
- M. Carena, D. Hooper, A. Vallinotto, The Interplay Between Collider Searches for Supersymmetric Higgs Bosons and Direct Dark Matter Experiments (PRD, hep-ph/0611065)
- M. Carena, D. Hooper, P. Skands, Implications of Direct Dark Matter Searches for MSSM Higgs Searches at the Tevatron (PRL, hep-ph/0603180)
- D. Hooper, T. Plehn, Dark Matter and Collider Phenomenology with Two Light Supersymmetric Higgs Bosons (PRD, hep-ph/0506061)



As the LHC era begins, we are excited to play a major role in exploring the cosmological/astrophysical implicati of its finding

Future Directions: The Dark Matter Discovery Era

In the next few years, we expect:

- New results from the indirect dark matter searches of FERMI, PAMELA, IceCube, Planck, and others
- Direct dark matter searches to become sensitivity to WIMP-nucleon scattering cross sections at the 10^{-9} pb (10^{-45} cm^2) level
- The first results from the LHC

$\Rightarrow$ ***Incredible discovery potential!***

Future Directions: The Dark Matter Discovery Era

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•The first results from the LHC

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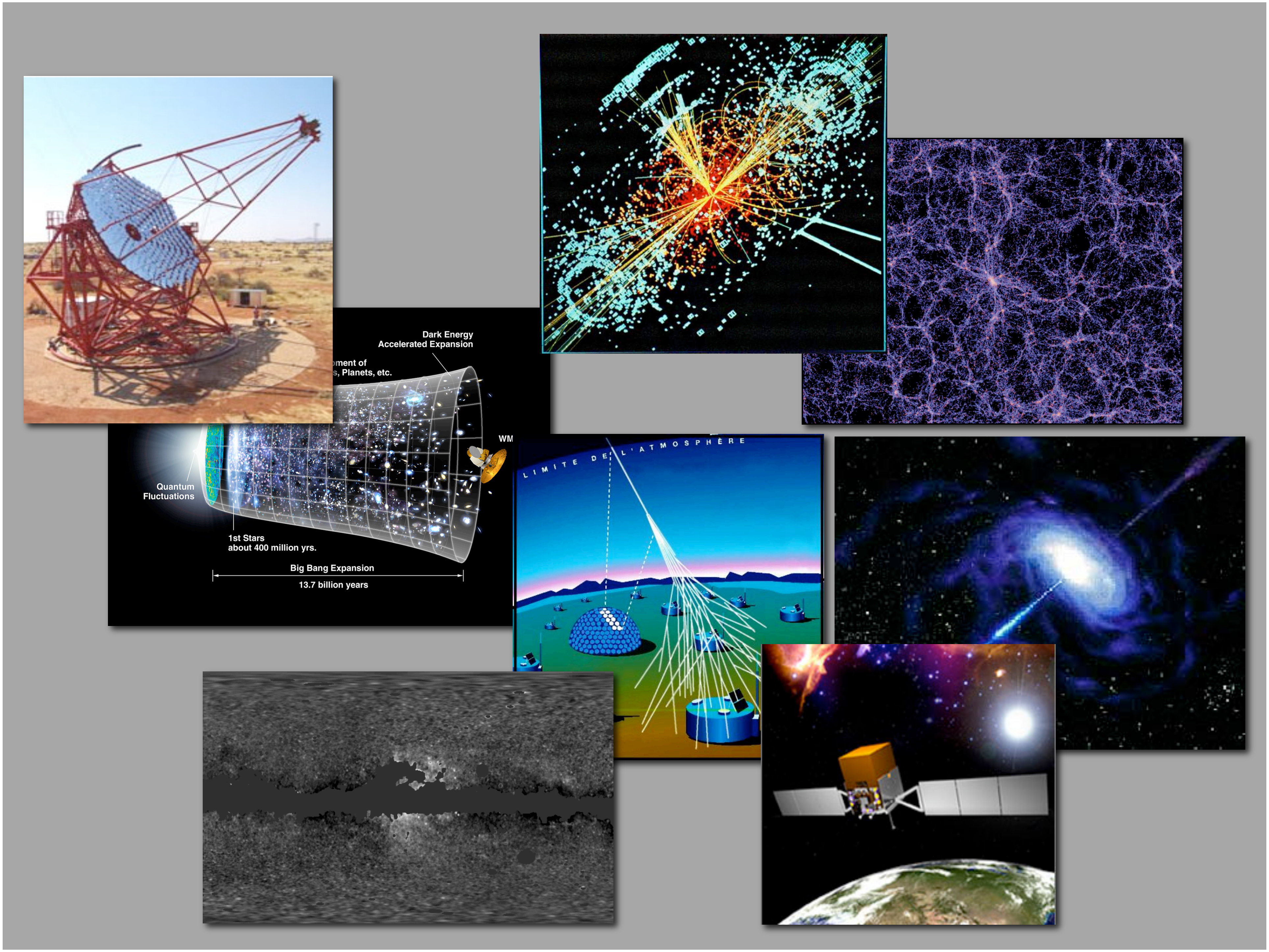
If dark matter consists of particles with electroweak scale masses and couplings, then it is very likely to be conclusively detected through one or more techniques in the near future

Much as in the case of the detection of CMB anisotropies, the first detection(s) of particle dark matter will generate many important new questions to answer and problems to solve


Dark Energy
Accelerated Expansion
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
LIMITE DE L'ATMOSPHÈRE