‘Cosmic Frontier’ Theory at Argonne National Laboratory

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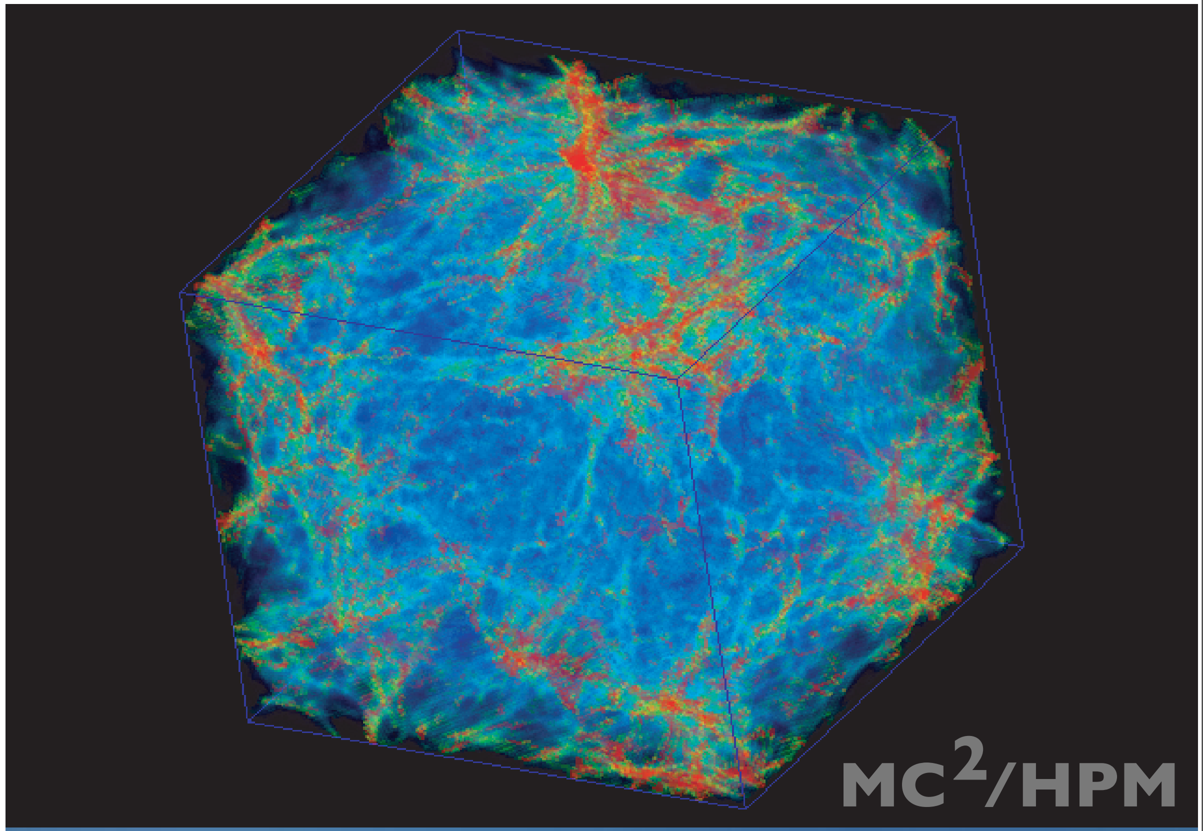
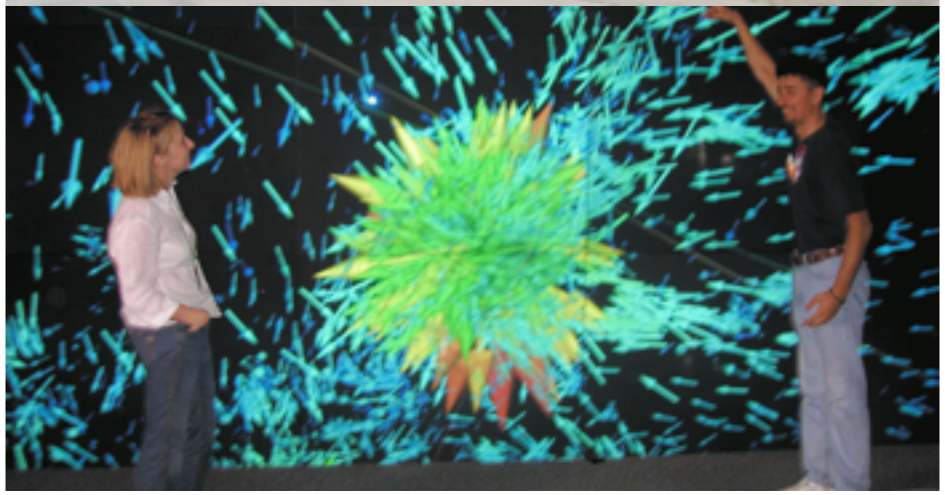
New Effort Overview

- **Primary Target:** Cosmological signatures of physics beyond the Standard Model
- **Structure Formation Probes:** Main focus is to exploit nonlinear regime of structure formation probes
  - **Discovery Science:** Derive signatures of new physics, search for new cosmological probes
  - **Precision Predictions:** Aim to produce the best predictions and error estimates/distributions for structure formation probes (rough analogy with lattice QCD)
  - **Design and Analysis:** Advance ‘science of surveys’; contribute to major dark energy missions: BOSS, DES, LSST, BigBOSS, DESpec --



Cosmology: An Argonne View

- **Cosmology is Multi-Disciplinary:** Modern cosmology needs physics, astronomy, computer science, engineering, statistics, --
- **Cosmology is Diverse:** Many avenues for people to contribute in different ways
- **Precision Cosmology as Big Science:** Small and large team efforts: ‘HEP style science’
- **Leadership Computing:** Cosmology is one field that can and must exploit next-generation supercomputing (‘science at scale’)
- **Large Data Sets:** Simulations and observations are driving a new approach to data-centric science (potentially good connection with HEP data efforts)
- **National/International Collaborations:** National Labs as collaboration/science hubs



New Faces at Argonne

HEP staff:

Salman Habib [ANL LDRD]
Katrin Heitmann [ANL LDRD]

HEP post-docs:

Suman Bhattacharya [NSF/NASA/UChicago]
Sanghamitra Deb [ANL LDRD]
Juliana Kwan [ANL LDRD]
Adrian Pope [ANL Named Fellow]
Amol Upadhye [ANL Director's Fellow]

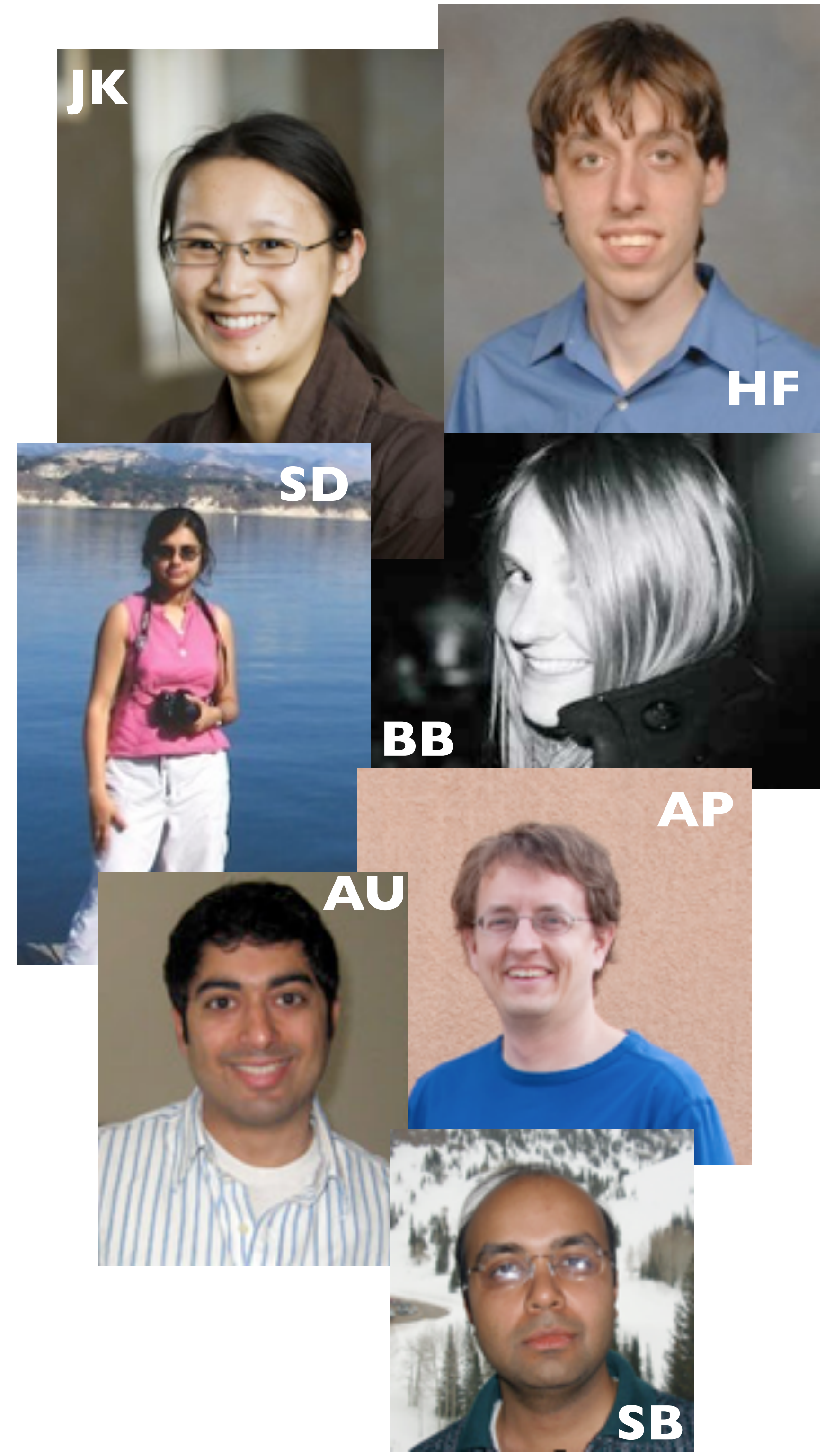
ALCF post-doc:

Hal Finkel [Mira ESP]

ALCF student:

Brittney Bullis [Mira ESP]

Work very closely with local/area theorists, observers, experimentalists, and computer scientists --

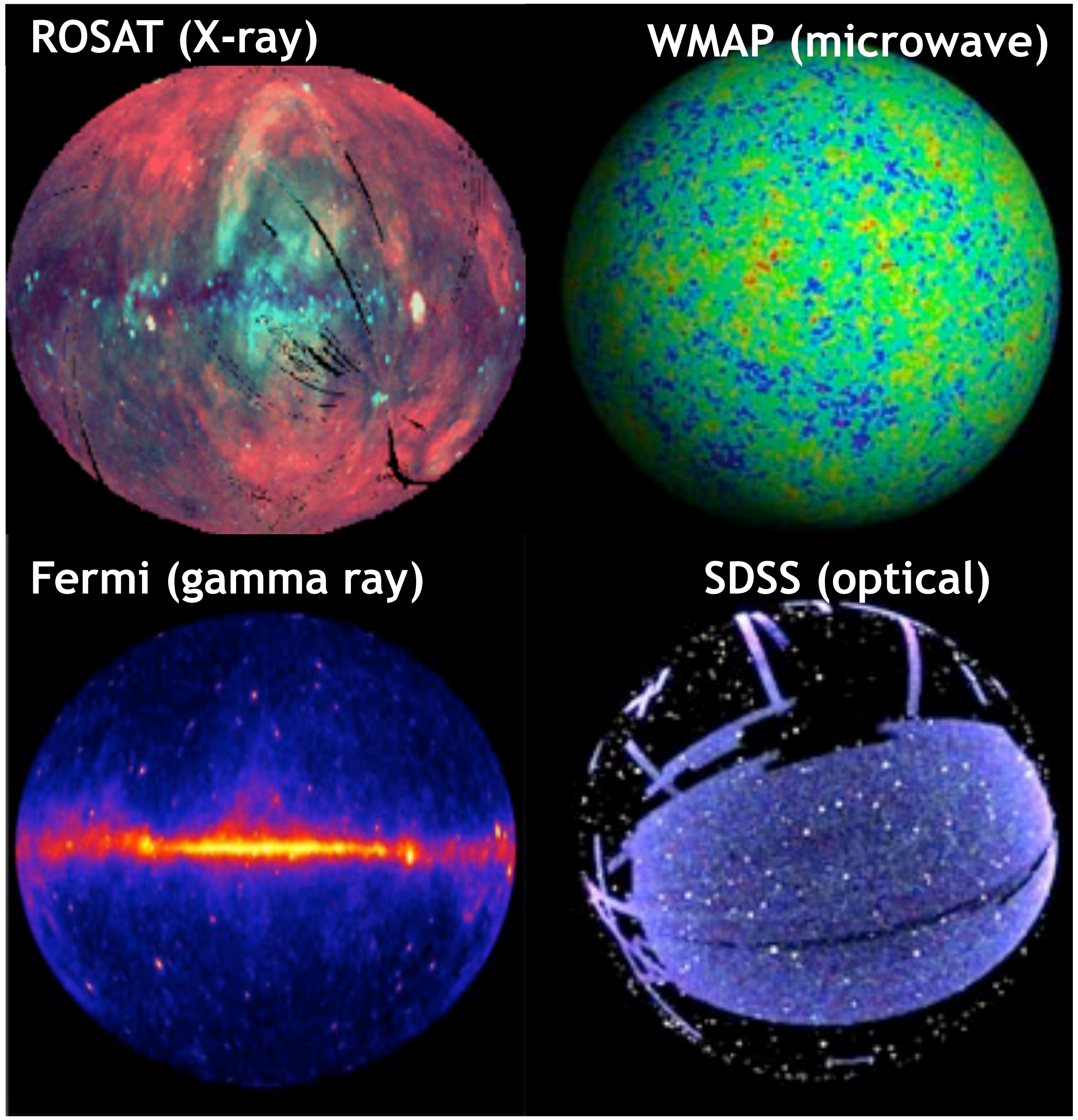


Collaborations and Projects

Kev Abazajian, Jim Ahrens, Ujjaini Alam, Debbie Bard, Sergei Bashinsky, Andrew Benson, Gary Bernstein, Joe Bernstein, Derek Bingham, Rahul Biswas, Anna Cabre, Jordan Carlson, Joanne Cohn, Andrew Connolly, David Daniel, Nehal Desai, Scott Dodelson, Tim Eifler, Gus Evrard, Patricia Fasel, Hume Feldman, Wu Feng, Josh Frieman, David Higdon, Tracy Holsclaw, Chung-Hsing Hsu, Bhuvnesh Jain, Steve Kahn, Lloyd Knox, Savvas Koushiappas, Steve Kuhlmann, Earl Lawrence, Herbie Lee, Adam Lidz, Zarija Lukic, Chris Miller, Charles Nakhleh, Mike Norman, Alex Pang, Uliana Popov, Darren Reed, Paul Ricker, Robert Ryne, Bruno Sanso, Paul Sathre, Michael Schneider, Sergei Shandarin, Alex Szalay, Tony Tyson, Licia Verde, Alexei Vikhlinin, Christian Wagner, Mike Warren, Martin White, Brian Williams, Tim Williams, Jon Woodring, ---

Cosmological Probes of Physics Beyond the Standard Model

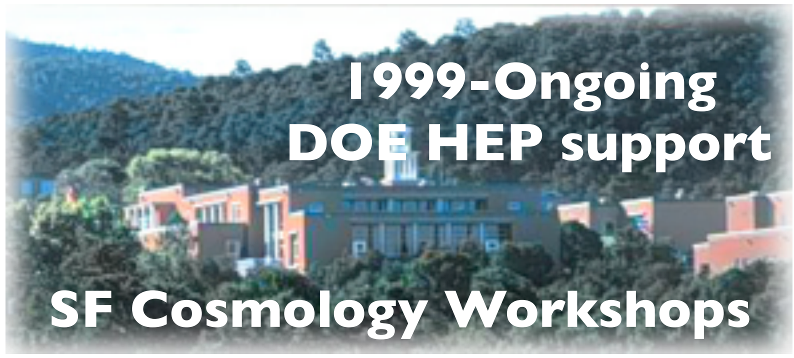
- **Dark Energy:** Properties of DE equation of state, modifications of GR, other models?
  Sky surveys, terrestrial experiments
- **Dark Matter:** Direct/Indirect searches, clustering properties, constraints on model parameters
  Sky surveys, targeted observations, terrestrial experiments
- **Inflation:** Probing primordial fluctuations, CMB polarization, non-Gaussianity
  Sky surveys
- **Neutrino Sector:** CMB, linear and nonlinear matter clustering
  Sky surveys, terrestrial experiments



Explosion of information from sky maps: Precision Cosmology

Getting Ready for the 'Great Surveys'

- **Community Effort Needed**
  - Lab-University teams/partnerships
  - Public release(s) of results and tools
- **New Generation of Simulations Necessary**
- **Active Interaction of Simulations with Data**
- **ANL Collaboration Examples:**
  - 'Chicagoland'/National Computational Cosmology Plan (ANL+Chicago+Fermilab/HEP Labs and associated universities)
  - LSST/DES catalogs (Caltech, Berkeley/LBNL, SLAC/Stanford, Swinburne, Washington, ---)
  - Weak Lensing (Berkeley/LBNL, Chicago, Fermilab, Ohio State, Penn, SLAC/Stanford, ---)
  - LSST 'end-to-end' modeling (Davis, LLNL, Purdue, Washington, ---)
  - DISC and large datasets (Hopkins, IPAC, NCSA, ---)



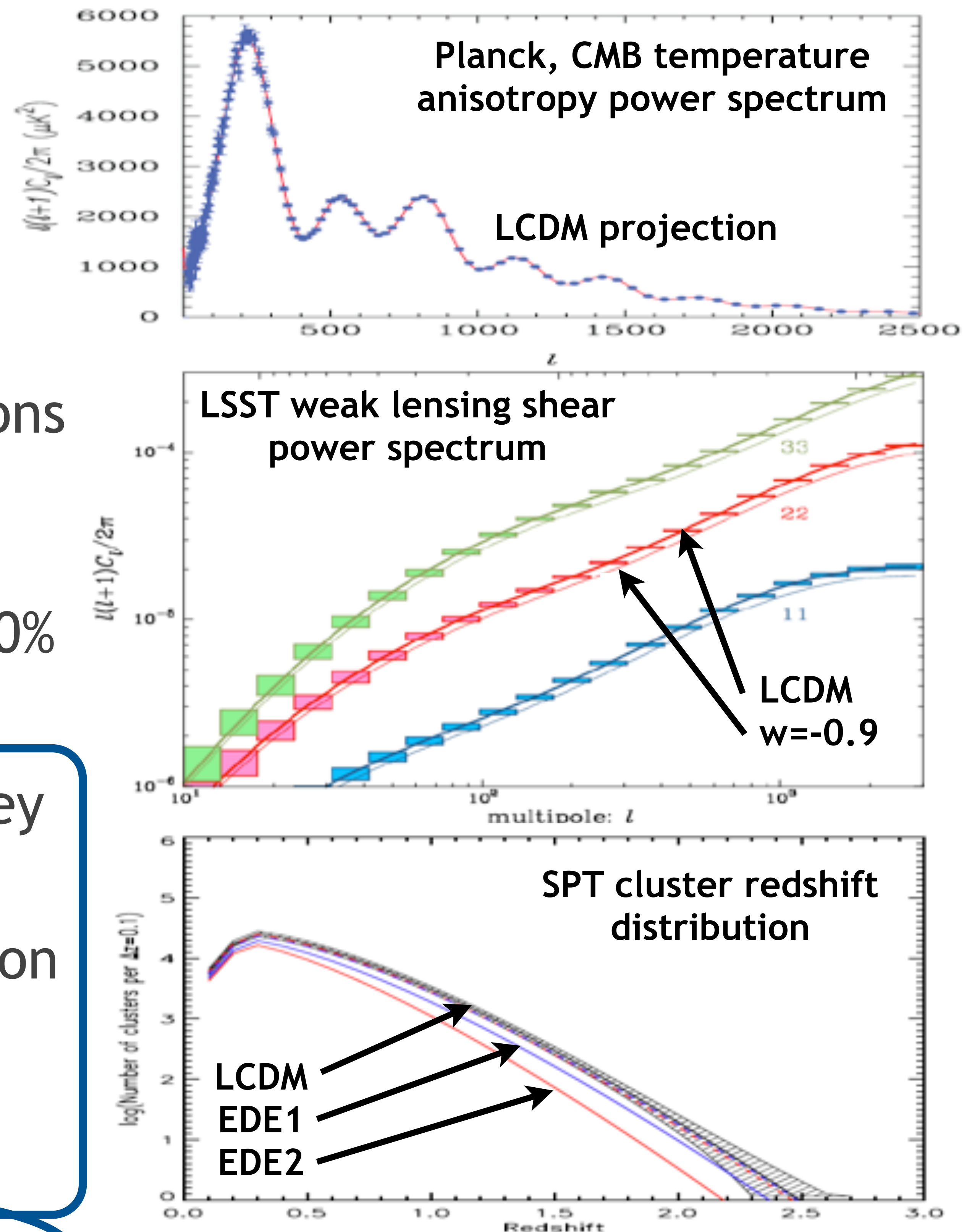
ICiS Institute for Computing in Science
August 2011
Large Datasets in Astrophysics & Cosmology
Workshops & Programs

Argonne National Laboratory
Computation Institute
The University of Chicago
Fermilab
'Chicagoland' Computing

Precision Cosmology: "Inverting" the 3-D Sky

- **Cosmic Inverse Problem:** From sky maps to scientific inference
- **Cosmological Probes:** Measure geometry and presence/growth of structure (linear and nonlinear)
- **Examples:** Baryon acoustic oscillations (BAO), cluster counts, CMB, weak lensing, galaxy clustering, --
- **Standard Model:** Verified at the 5-10% level across multiple observations
- **Future Targets:** Aim to control survey measurements to the ~1% level
- **The Challenge:** Theory and simulation must satisfy stringent criteria for inverse problems and precision cosmology not to be theory-limited!

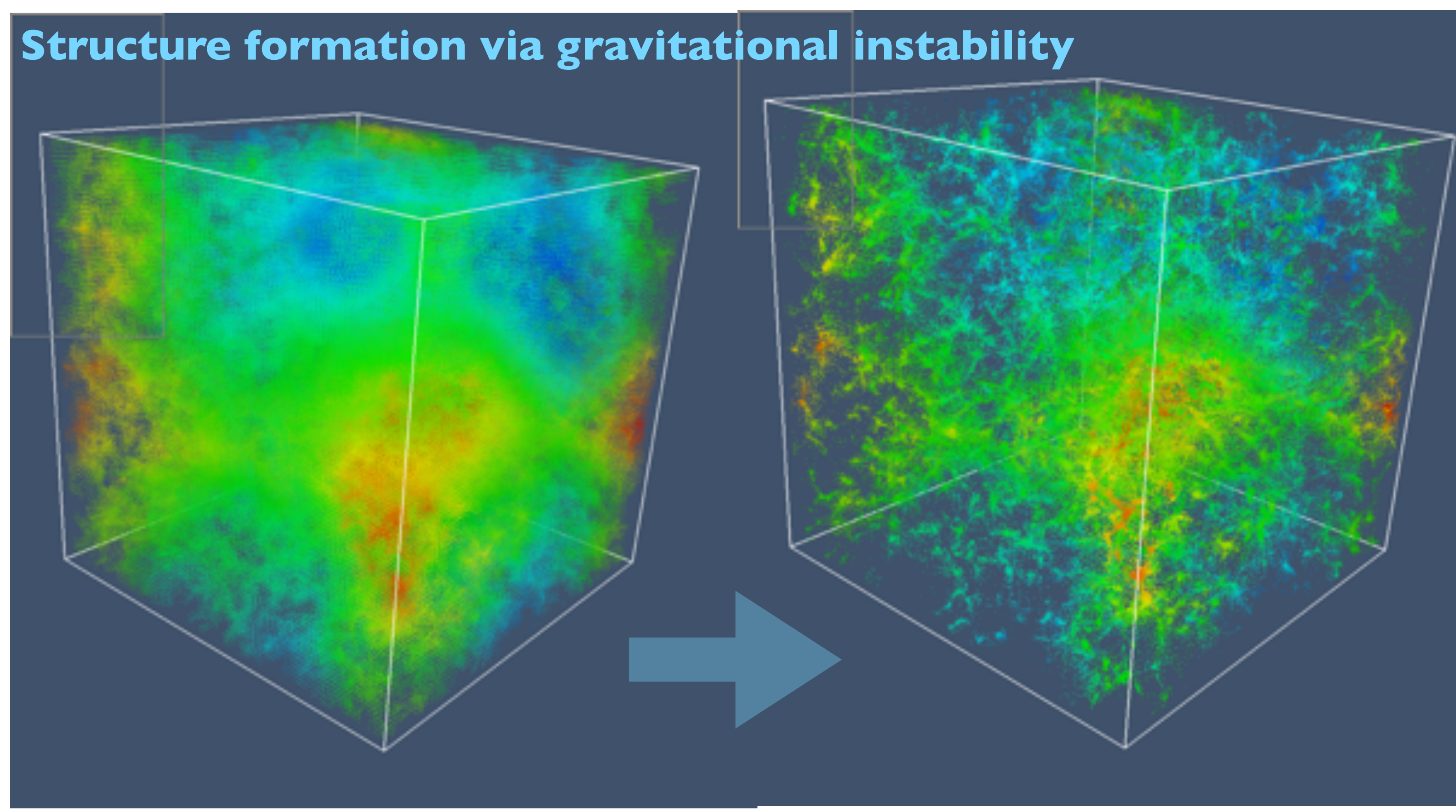
See Katrin's talk --



Forward Problem: Simulating the Universe

- **Gravity dominates at large scales:** Solve the Vlasov-Poisson equation (VPE)
- **Nonlinearity:** 6-D VPE cannot be solved as a PDE, must use N-body methods
- **Errors:** How well can they be controlled?
- **Astrophysics:** At small scales need to add gas physics, feedback, ‘sub-grid’ physics
- **Phenomenology:** Calibrate theory and simulations against observations (‘self-calibration’)

$$
\begin{aligned}
\frac{\partial f_i}{\partial t} + \dot{\mathbf{x}}\frac{\partial f_i}{\partial \mathbf{x}} - \nabla\phi\frac{\partial f_i}{\partial \mathbf{p}} &= 0, \qquad \mathbf{p} = a^2\dot{\mathbf{x}},\\
\nabla^2\phi &= 4\pi G a^2(\rho(\mathbf{x},t) - \langle\rho_{\rm dm}(t)\rangle) = 4\pi G a^2\Omega_{\rm dm}\delta_{\rm dm}\rho_{\rm cr},\\
\delta_{\rm dm}(\mathbf{x},t) &= (\rho_{\rm dm} - \langle\rho_{\rm dm}\rangle)/\langle\rho_{\rm dm}\rangle,\\
\rho_{\rm dm}(\mathbf{x},t) &= a^{-3}\sum_i m_i \int d^3\mathbf{p}\, f_i(\mathbf{x},\dot{\mathbf{x}},t).
\end{aligned}
$$

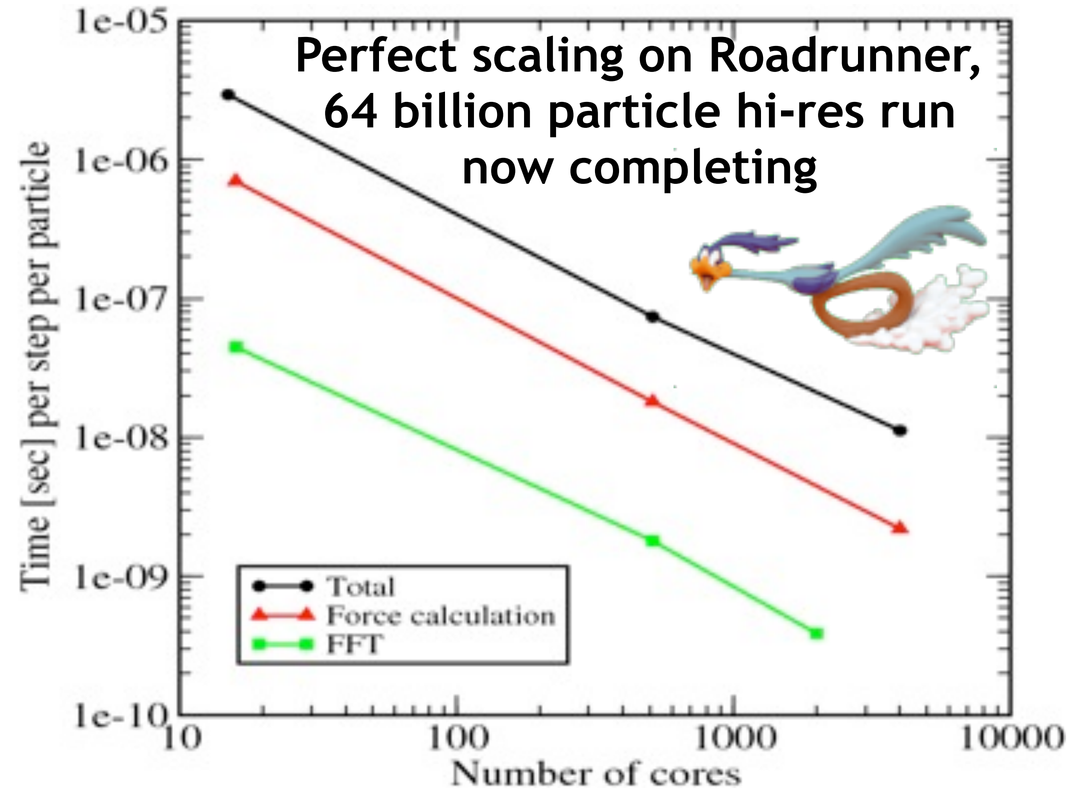


Computing the Universe: Simulating Surveys

- **Simulation Volume:** Large survey sizes impose simulation volumes ~ (3 Gpc)^3, with memory requirements ~**100** TB
- **Number of Particles:** Mass resolutions depend on ultimate object to be resolved, ~**10^8 --10^{10}** solar masses, N~**10^{11}--10^{12}**
- **Force Resolution:** ~kpc, yields a (global) spatial dynamic range of **10^6**
- **Hydrodynamics/Sub-Grid Models:** Phenomenological treatment of gas physics and feedback greatly adds to computational cost
- **Throughput:** Large numbers of simulations required (**100's --1000's**), development of analysis suites, and emulators; peta-exascale computing exploits
- **Data-Intensive-SuperComputing:** End-to-End simulations and observations must be brought together in a DISC environment (theory-observation feedback)

Hardware-Accelerated Cosmology Code (HACC) Framework

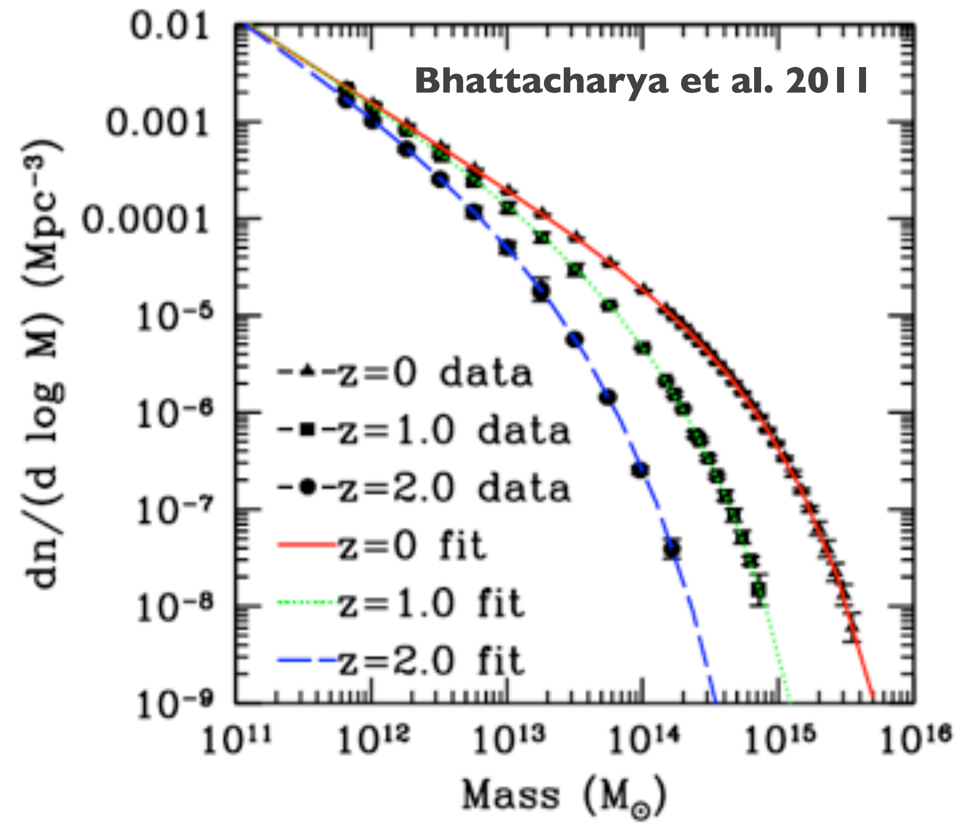
- **Architecture Challenge:** HPC is rapidly evolving (clusters/BG/CPU+GPU/MIC --)
- **Code for the Future:** Melds optimized performance, low memory footprint, embedded analysis, and scalability
- **Implementation:** Long/short-range force matching with spectral force-shaping (long-range=PM, short-range=PP, tree)
- **Key Features:** Hybrid particle/grid design, particle overloading, spectral operators, mixed-precision, node-level 'plug-ins', ~50% of peak Flops
- **Cross-Platform:** Designed for all current and future supercomputing platforms
- **Embedded Analysis:** High performance with low I/O and storage requirement

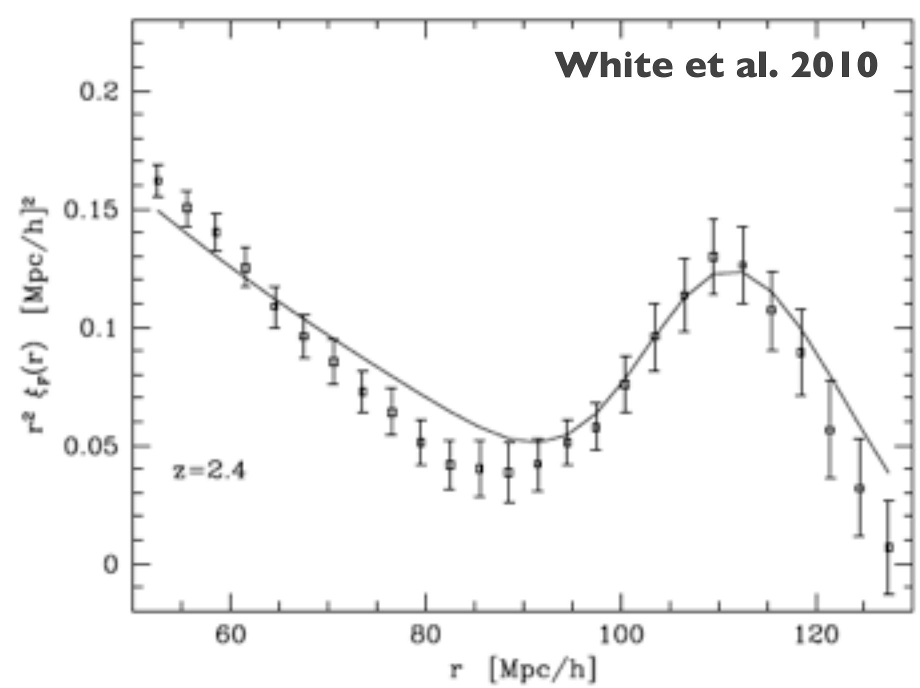


Habib et al. 2009, Pope et al. 2010

Science Goals

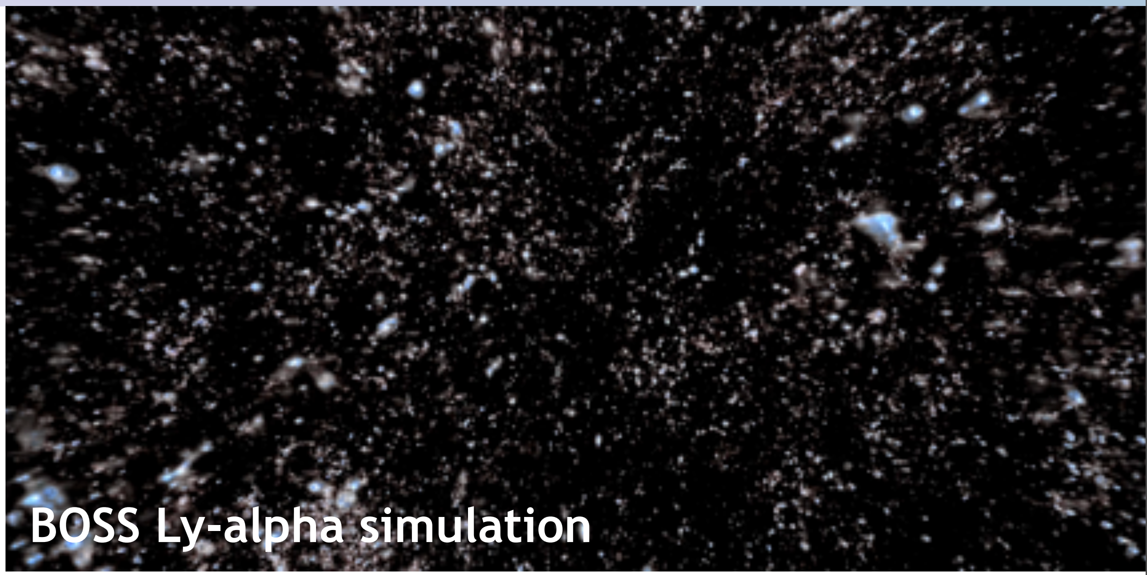
- **Halo Statistics:** Mass function, concentration-mass relation, bias, merger statistics, n-point functions, -- (SB, AP, SH, KH)
- **Galaxy Surveys:** Redshift space distortions, velocity fields, baryon acoustic oscillations (BAO), clustering, Lyman-α forest, 21cm surveys, -- (SD, JK, AP, SH, KH)
- **Weak and Strong Lensing:** Cosmic shear, cluster lensing, lensing peaks, CMB, -- (SD, AP, SH, KH)
- **Cluster Cosmology:** Sunyaev-Zel'dovich observations, mass-observable relations, cluster formation, fossil groups, -- (SB, SH, KH)
- **Inflation:** Gravitational waves, precision predictions of fluctuations, non-Gaussianity, -- (SB, HF, SH, KH)
- **Terrestrial Probes:** Modified gravity, dark matter, -- (AU, SH)
- **Neutrinos:** Mass, sterile neutrinos, -- (SH, KH)



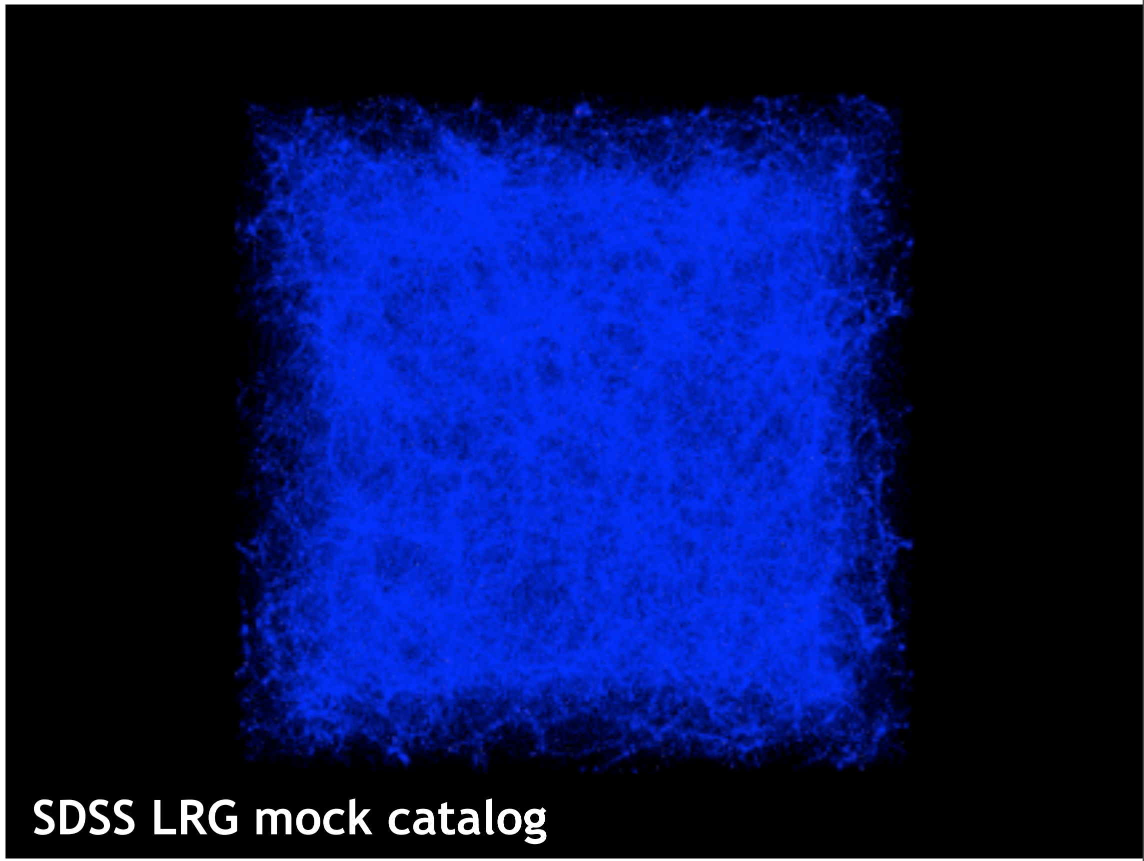


Summary and Near-Term Outlook

- **HACC:** Up and running on GPU and Cell accelerated hardware
- **Cosmic Calibration:** Emulators enable solutions to inverse problems in the nonlinear regime
- **ESP on Mira:** 150M CPU hours, tree implementation almost completed, full-time post-doc and student
- **Hydrodynamics:** HACC optimal for particle-in-cell approach, algorithm development initiated, aim to complete by Mira arrival
- **HACC and Large Datasets:** Simulations and mocks need to be where the data is -- ANL provides state of the art resources via ALCF, Habib co-chair of now-forming Integrated System Simulation Working Group for LSST



Roadrunner view (halos) of the Universe at z=2 from a 64 billion particle run



Mock catalog for SDSS luminous red galaxies (orange) and satellite galaxies (green), in coll. with M. White

Ultimate Vision for a National Lab Effort

- **Clean up 'Discovery Space':** Robust theory with subtle signals
- **Precision Cosmic Calibration at Scale:** 'All Sky' solution of the cosmic inverse problems in the nonlinear regime
- **Cosmology Simulations at the Exascale:** Next-generation computing and beyond as essential theoretical and analysis tools

10^{18} INTERNATIONAL EXASCALE SOFTWARE PROJECT

SciDAC Scientific Discovery through Advanced Computing

- **Large Data:** Simulation & observational datastreams: Archiving, serving, quality assurance, (joint) analyses
- **Simulation/Data/Analysis:** Cross-platform, multi-source, analysis and interrogation frameworks