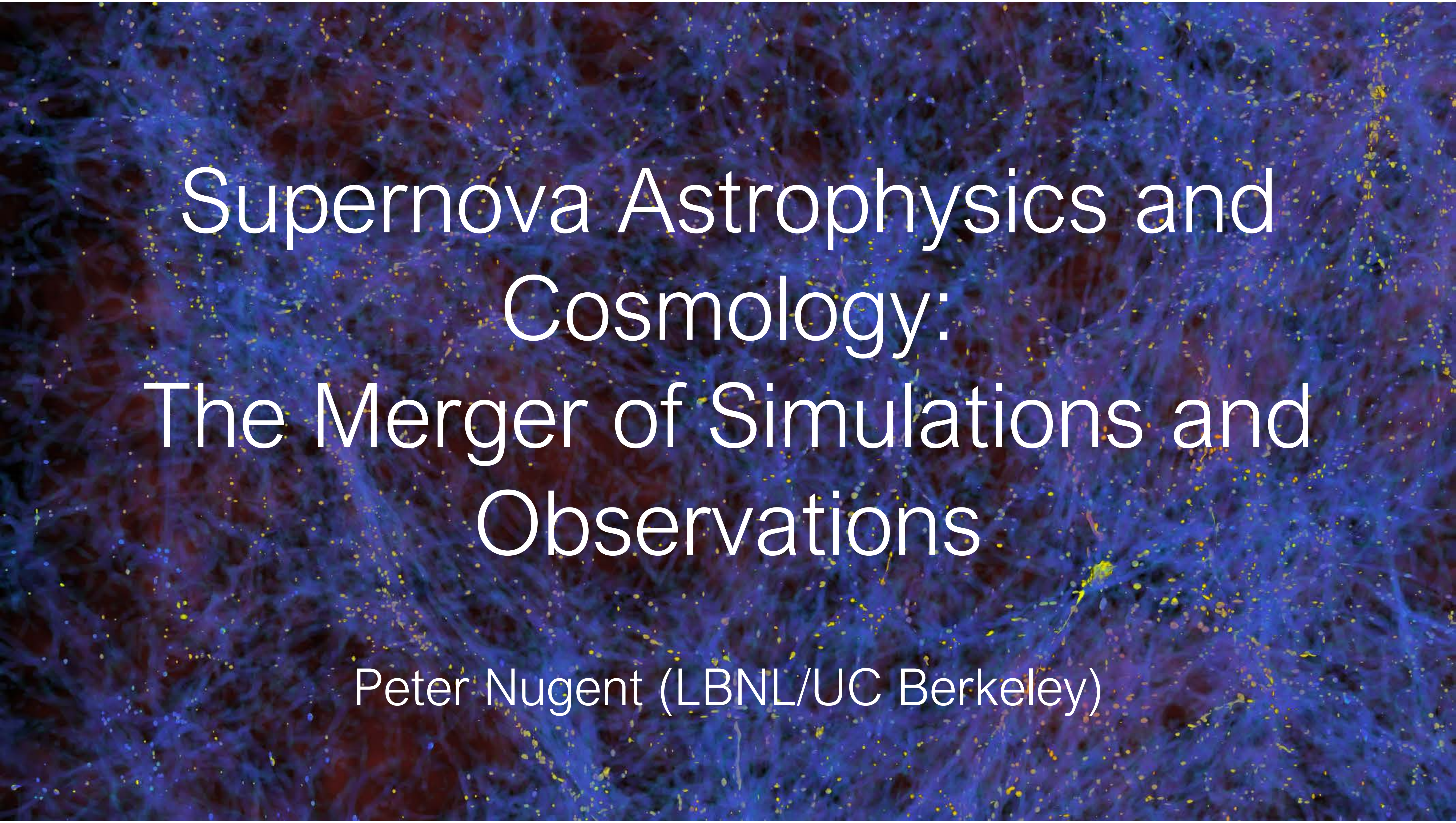
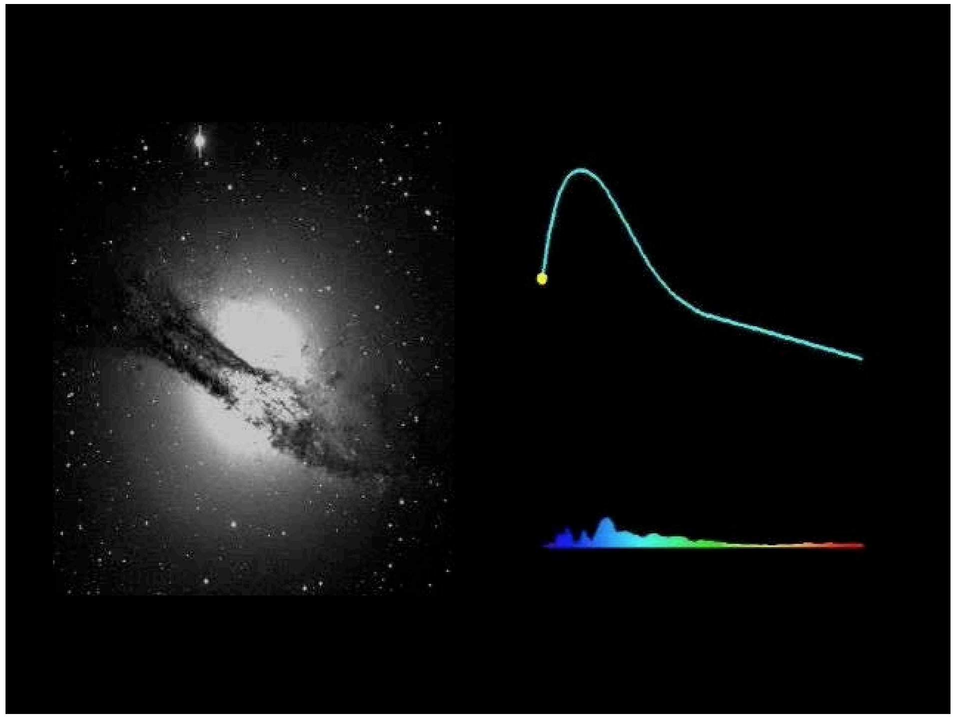


Supernova Astrophysics and Cosmology: The Merger of Simulations and Observations

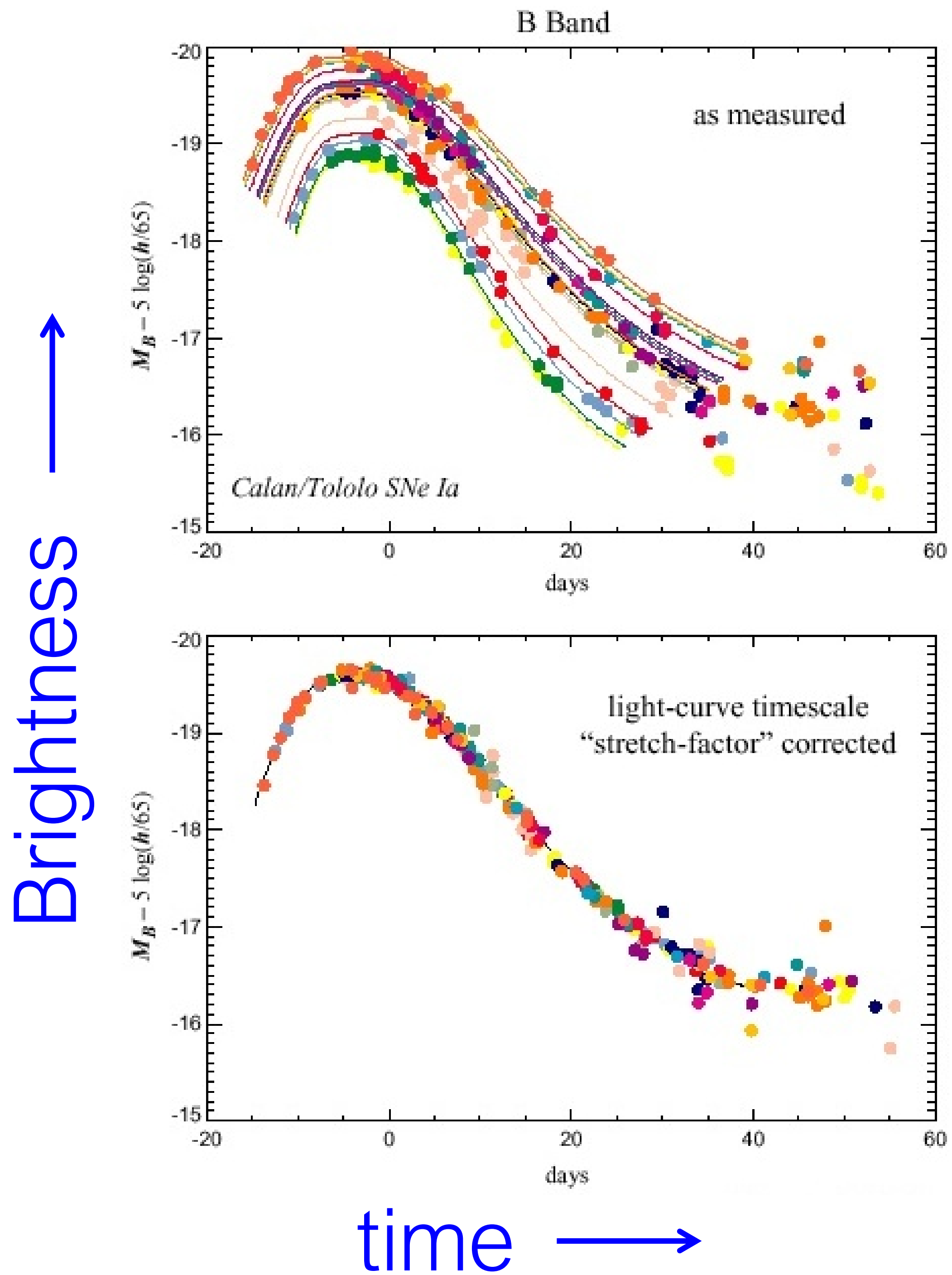
Peter Nugent (LBNL/UC Berkeley)

SN Cosmology



- Bright and powerful explosion of a star.
- Biggest explosions in the Universe.
- Speeds of 10-20% the speed of light.
- Outshine galaxies made of hundreds of billions of stars.
- In ~1 month, emits as much energy as the Sun will over its 10 billion year lifetime.

Standard Candles



In 1993 Mark Phillips discovered the correlation between peak brightness and lightcurve shape.

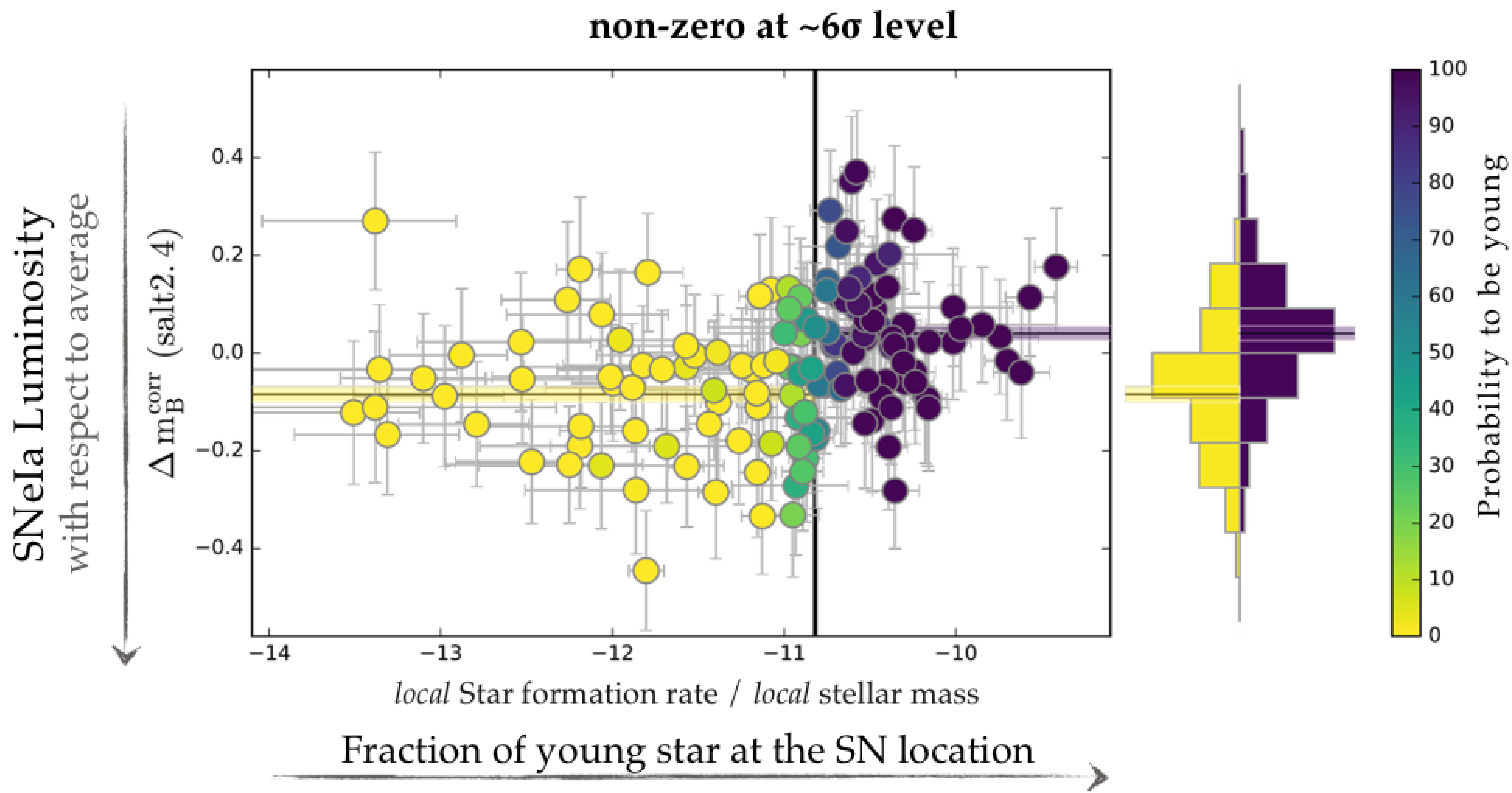
This allowed one to calibrate Type Ia Supernovae to about 8% in distance.

One additional correction used was the observed color to correct for extinction by dust.

Standard Candles-ish?

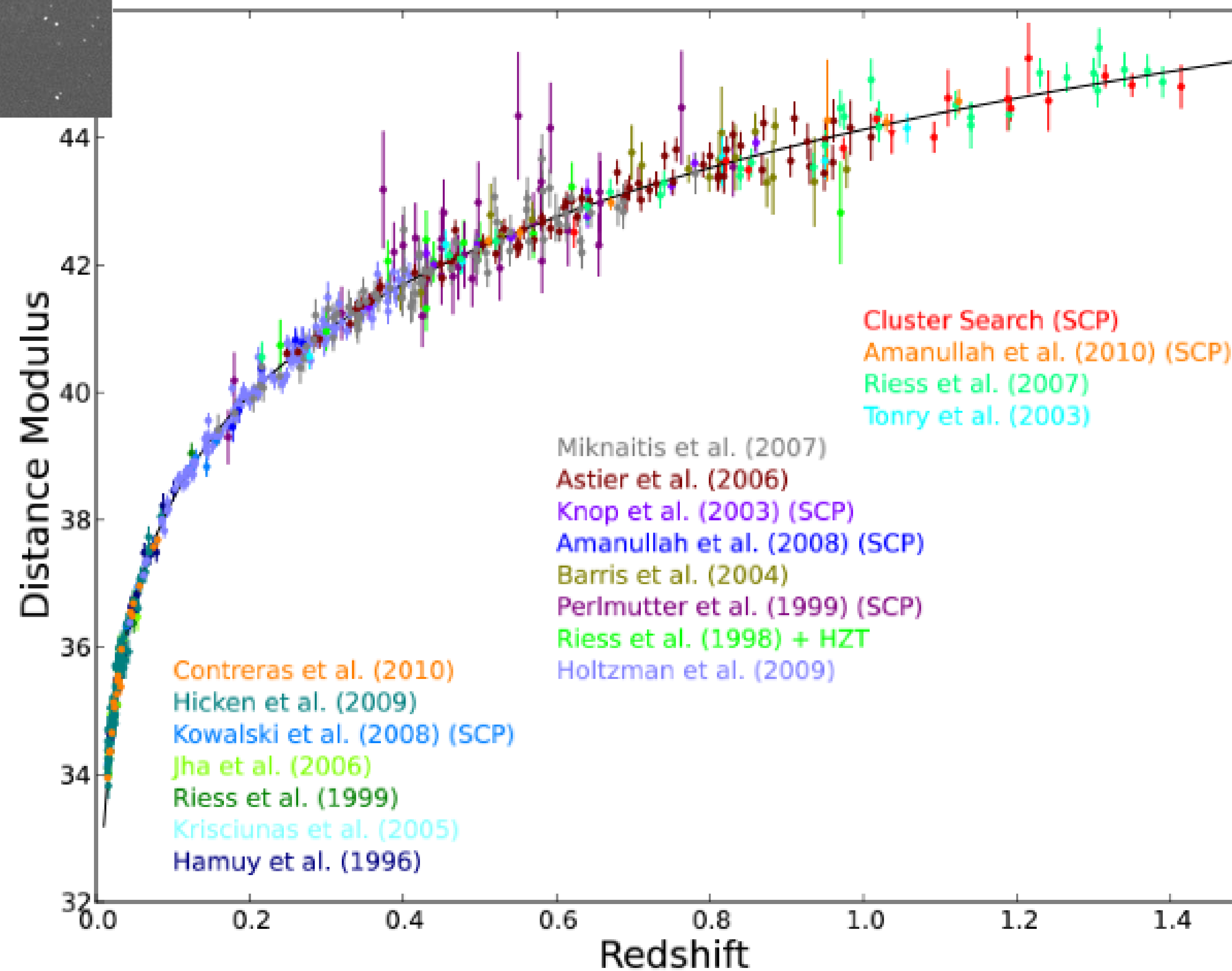
Rigault et al. 2013, 2015

Rigault et al. sub.



Pillars of Cosmology: Supernovae

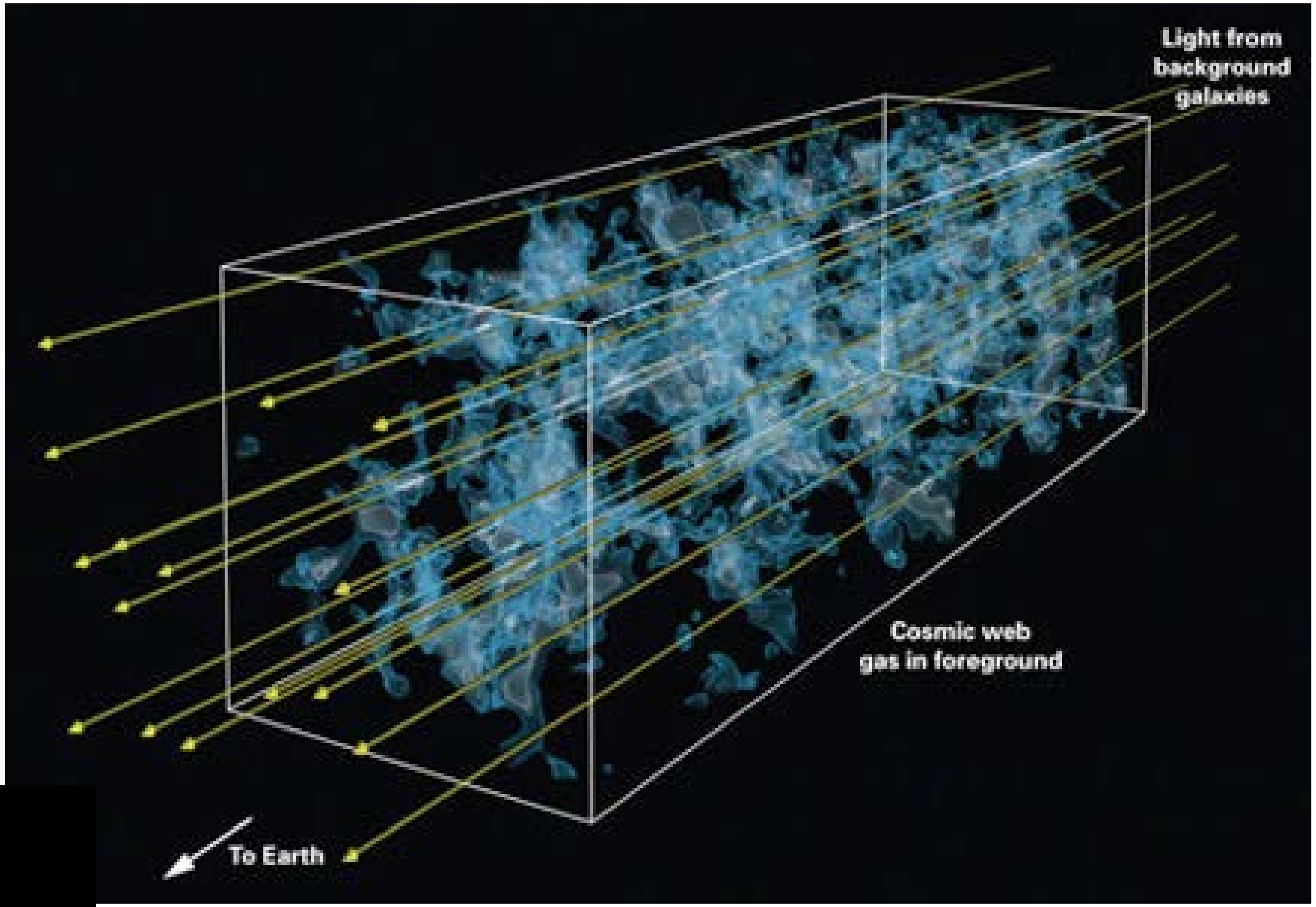
For decades Type Ia supernovae have been used as “standard candles” to measure the relative distances between these events to better than 8%.

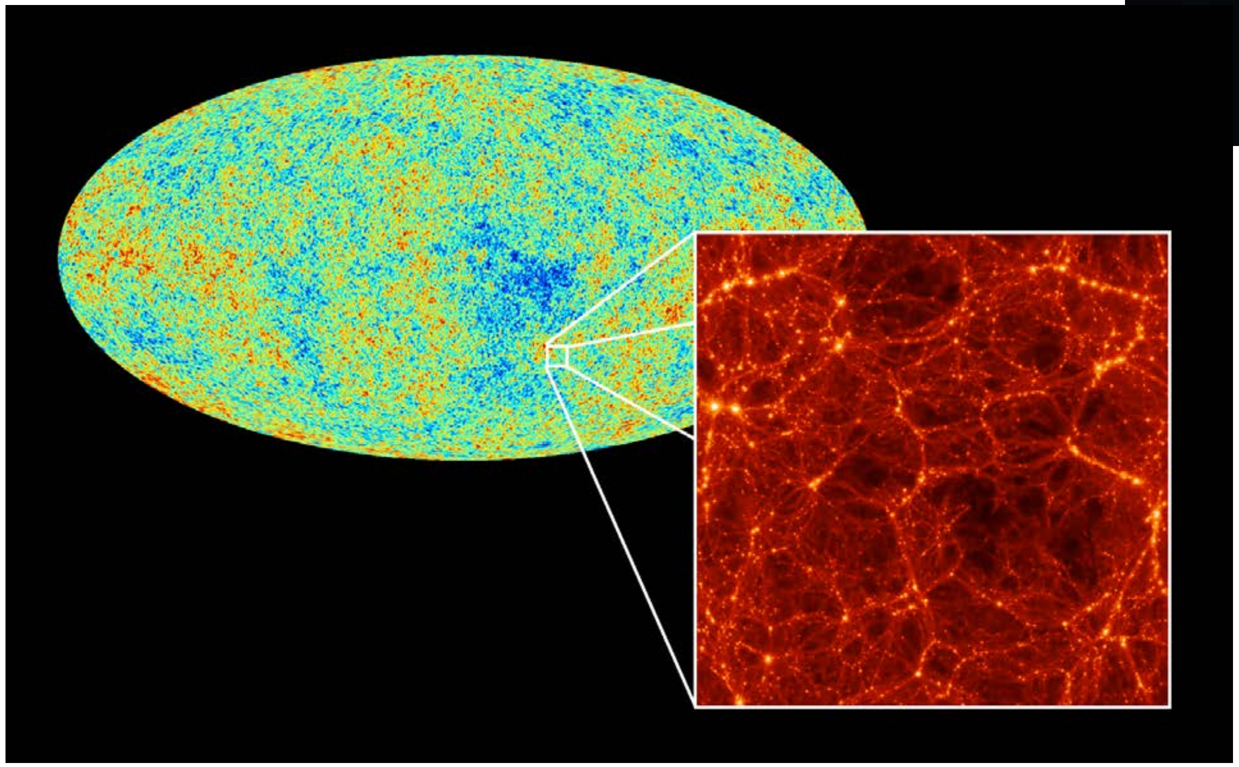


Experiments: SNfactory, PTF, DES, ZTF, LSST, WFIRST

Pillars of Cosmology: BAO

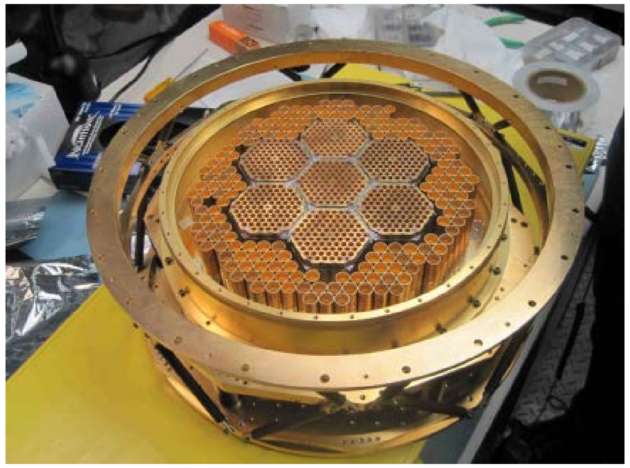
As Type Ia supernovae provide a standard candle for determining cosmic distances, patterns in the distribution of distant galaxies provide a "standard ruler”. The acoustic pressure waves of the over and under densities in the universe were frozen into place during the epoch of recombination when protons and electrons came together to form neutral hydrogen.

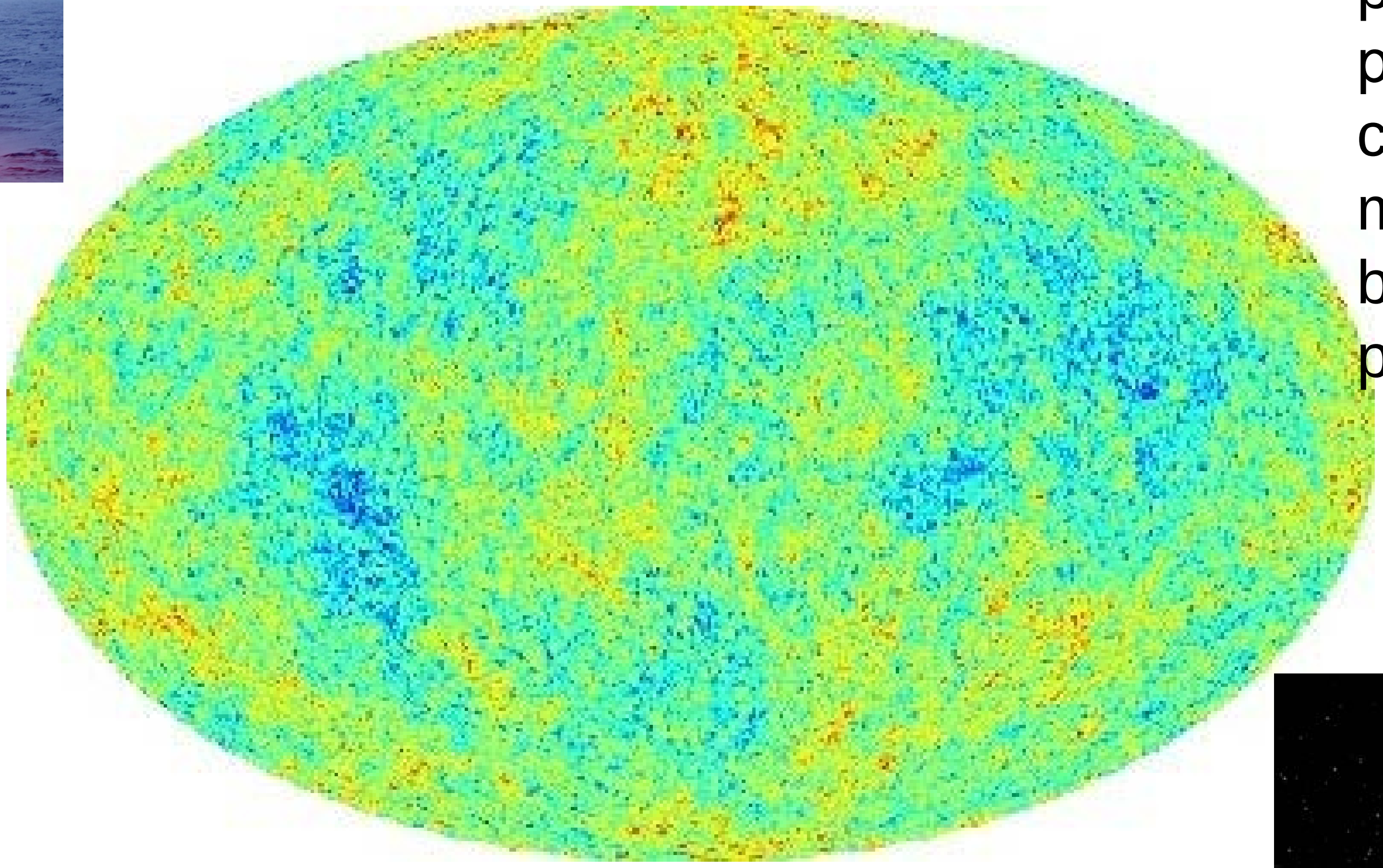




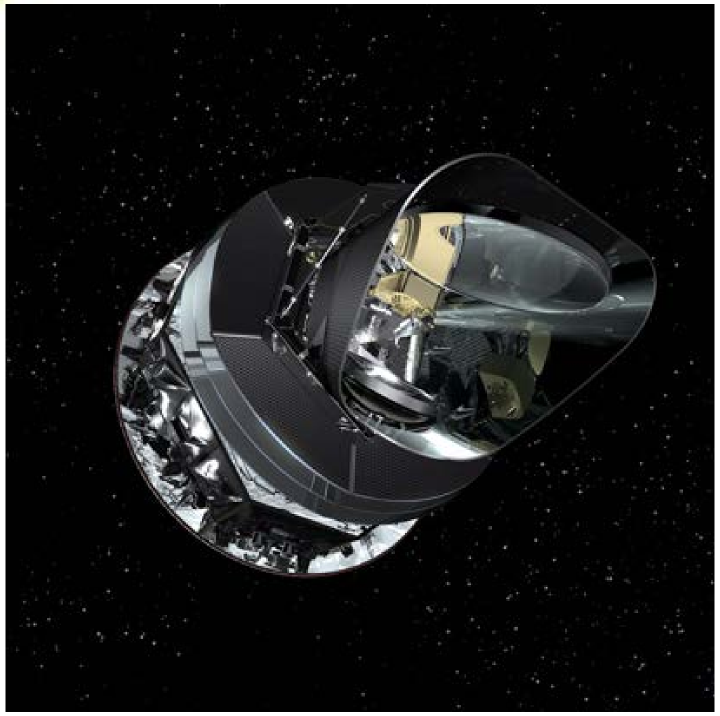
Experiments: DES, DESI, LSST, Euclid

Pillars of Cosmology: CMB





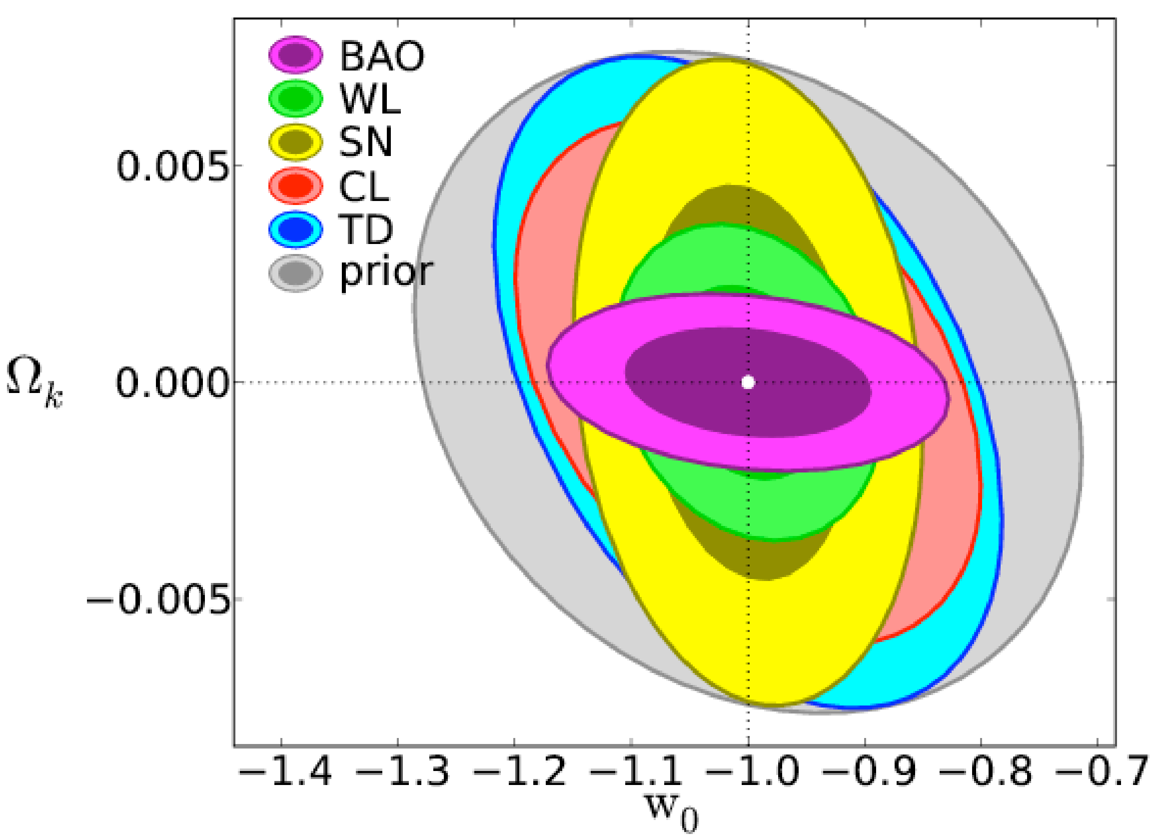
Exquisitely sensitive probe of basic physics shortly after the big-bang which provides a precise 6-parameter ΛCDM cosmology measurement. Used by all cosmology probes.

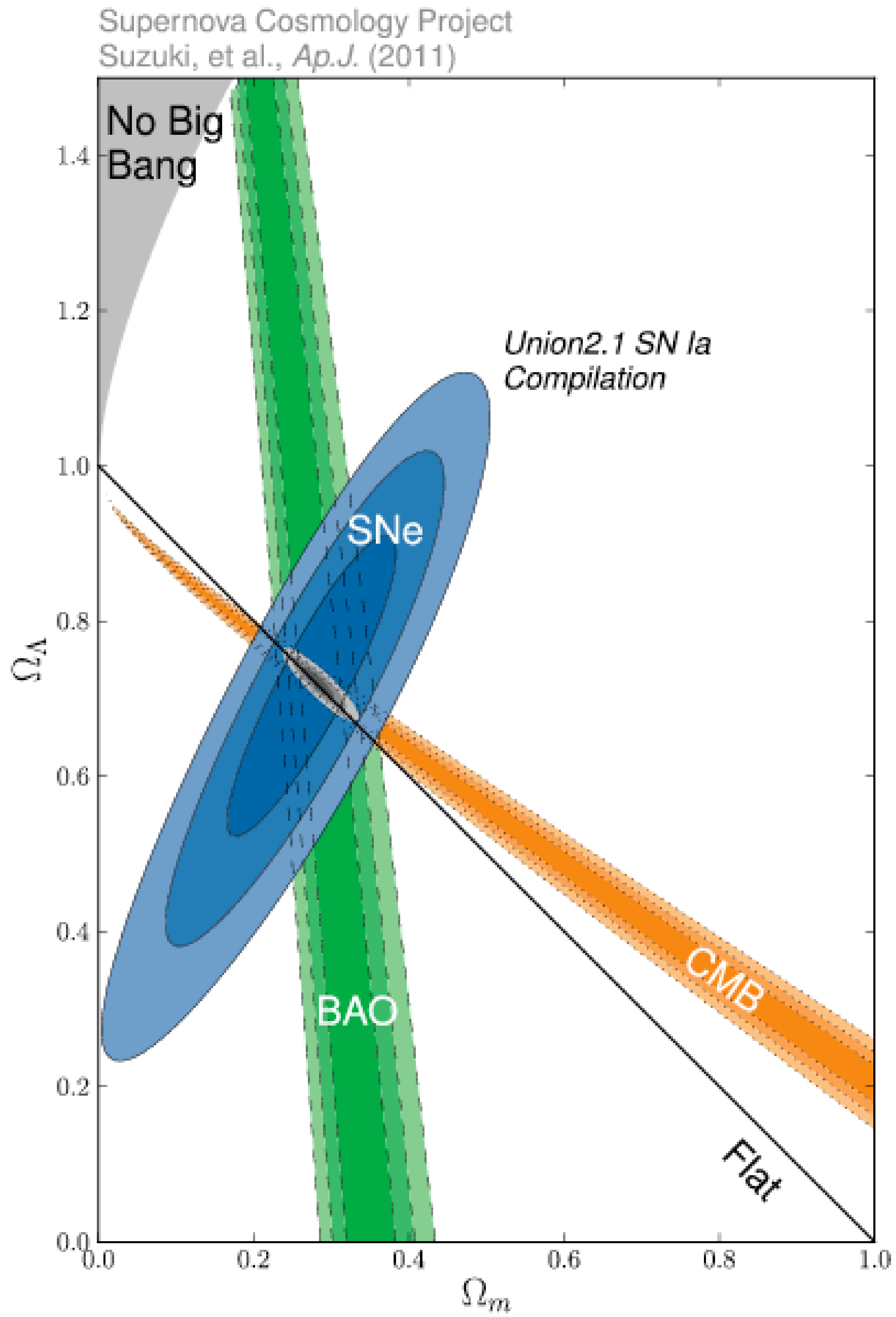


Experiments: Planck, SPT, ACT, PolarBear, CMB-S4

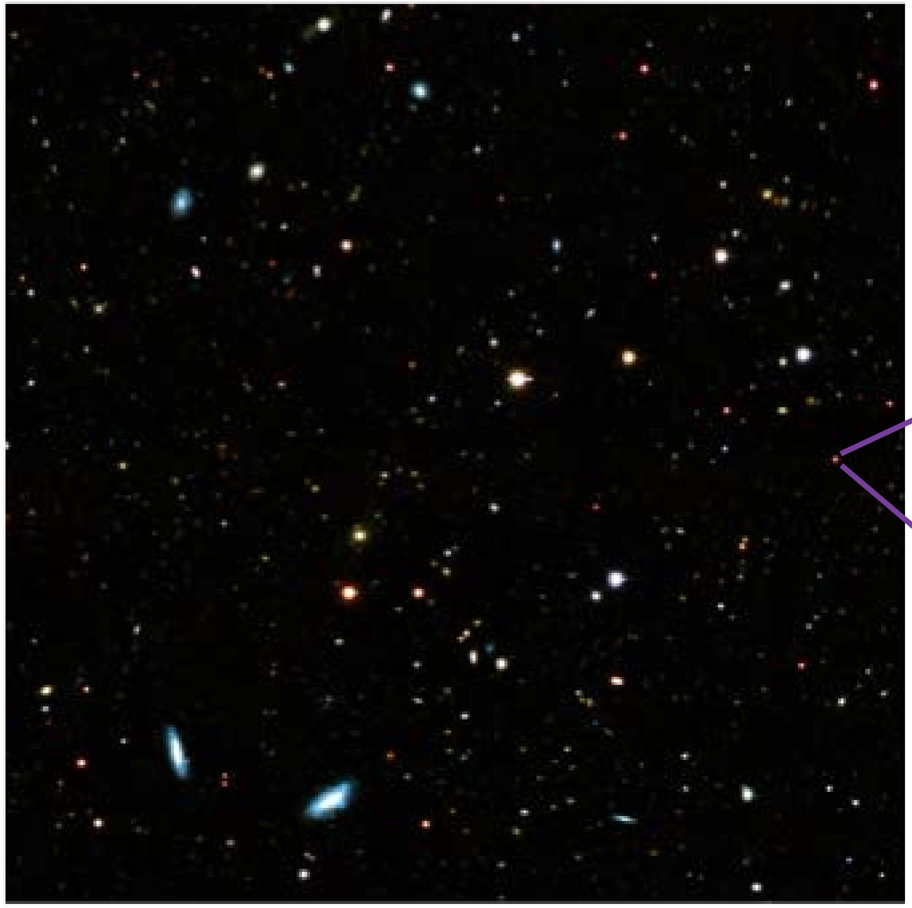
Cosmic Complementarity

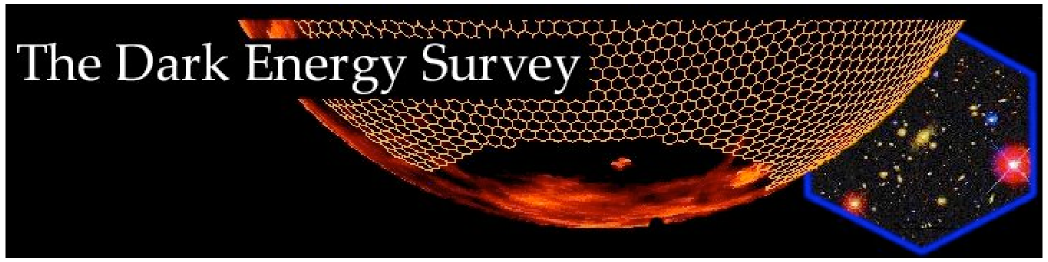
These optical and infrared observational surveys, combined with observations of the geometry of the universe from the Cosmic Microwave Background experiments, compliment each other and allow us to perform precision cosmology measurements. This is highly important since most of these experiments are now dominated by systematics.



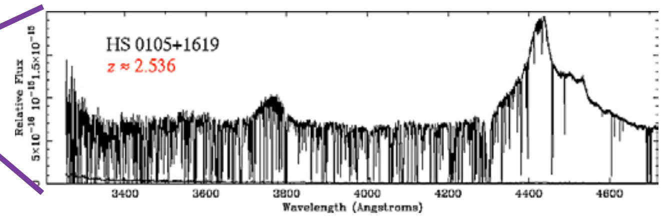


Observational Cosmology Data Sets

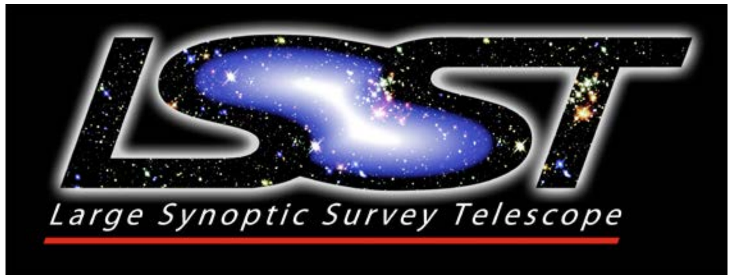




1-2 PB



2-3 PB

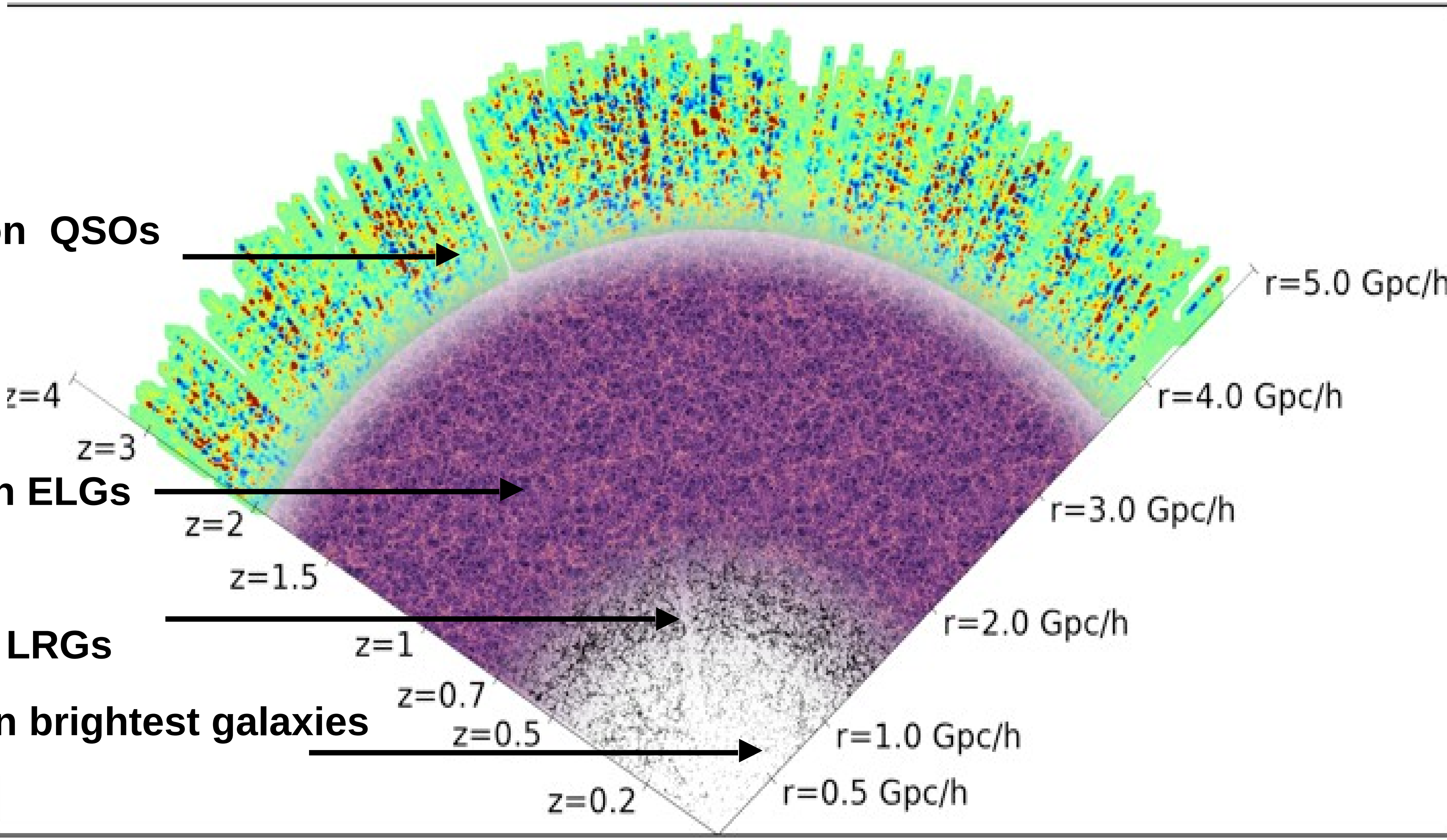


~500 PB

- **Imaging surveys of the sky**
  - Digital images cover a fraction of a square degree (41,000 square degrees on the sky)
  - Typically 2,000 * 4,000 pixels with most detections occupying only 9 pixels
  - 20,000 detections with a signal-to-noise ratio > 5 per image
  - Done in several filter passbands to provide not only shape and brightness, but "color" information on each detection (used to determine its approximate type and distance)
- **Spectroscopic surveys of the sky**
  - For each object, precisely measure the flux as a function of wavelength
  - Use the imaging surveys to provide targets for spectroscopy

DESI: Dark Energy Spectroscopic Instrument

Five target classes spanning redshifts z=0 ➔ 3.5.
~35 million redshifts over 14,000 sq. degrees (baseline survey).



2.4 million QSOs

17 million ELGs

6 million LRGs

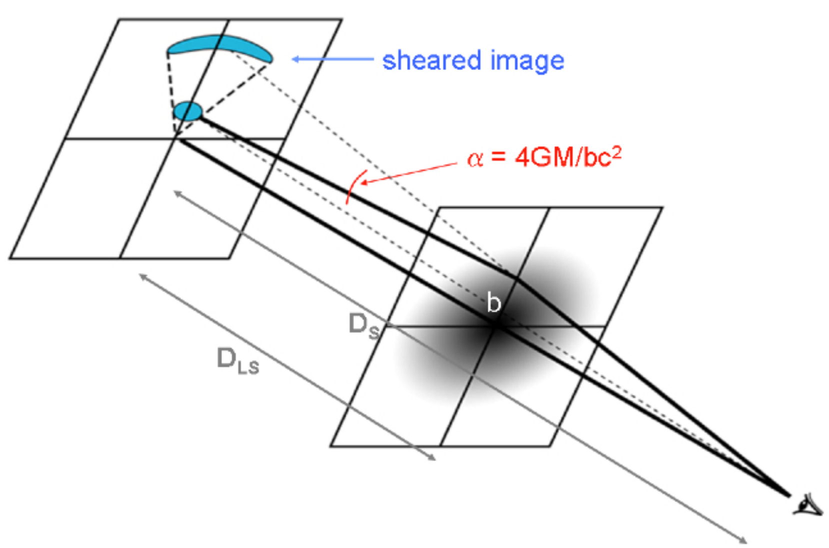
10 million brightest galaxies

LSST: Large Synoptic Survey Telescope

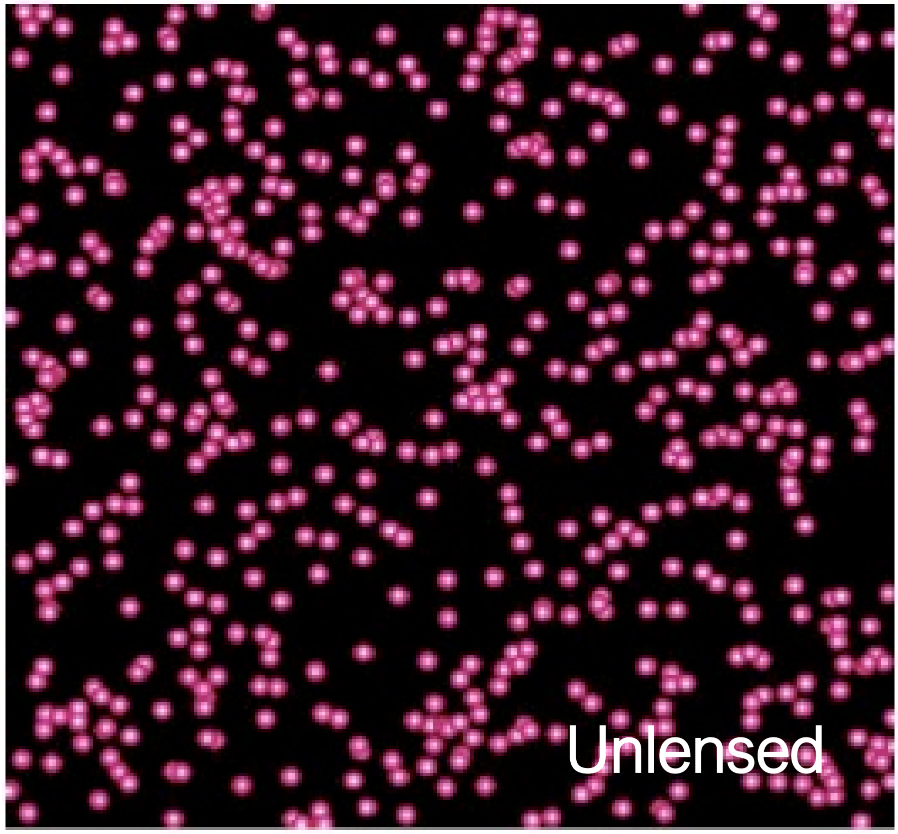
Gravitational lensing

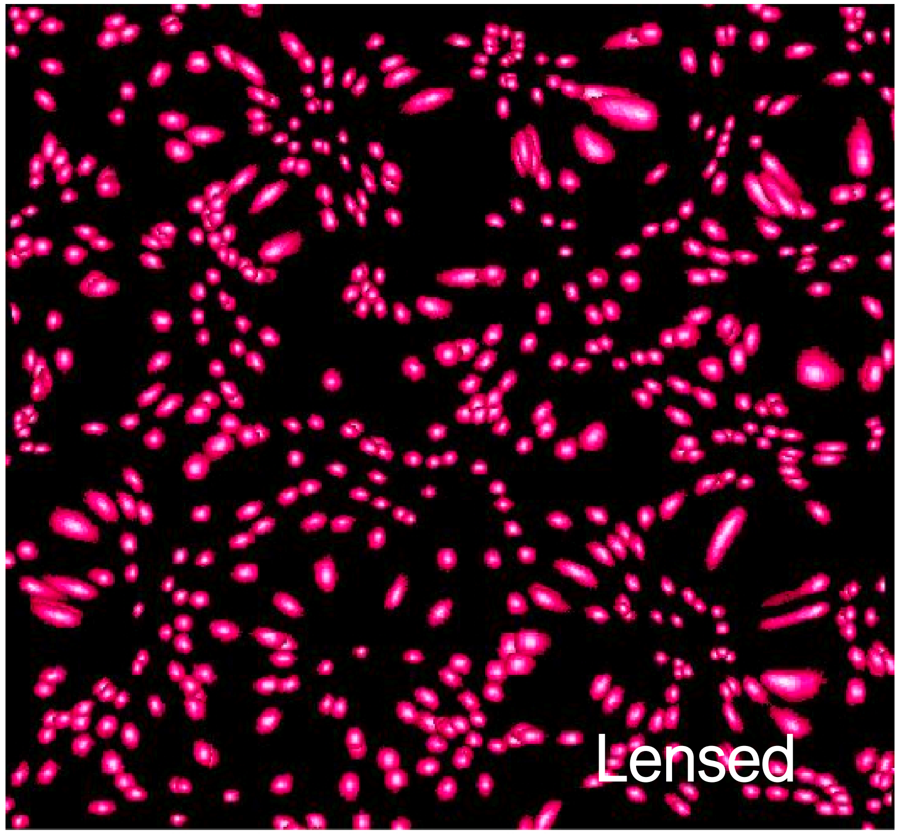
Lensing deflection of light:

$$\hat{\alpha} = \frac{4G}{c^2}\frac{M(<\xi)}{\xi}$$

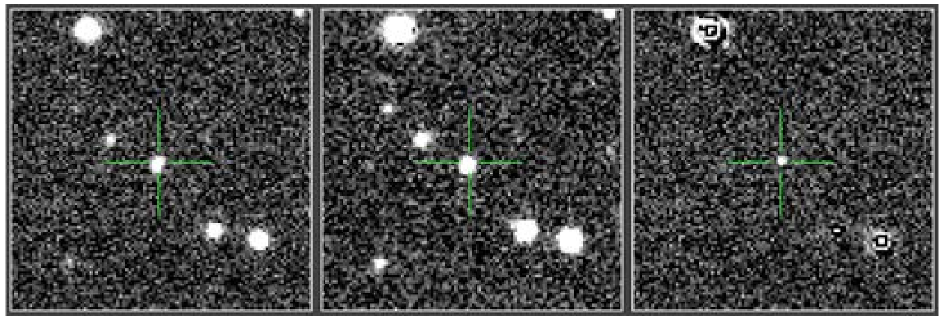


Sensitive to all the matter between the galaxy and the observer.

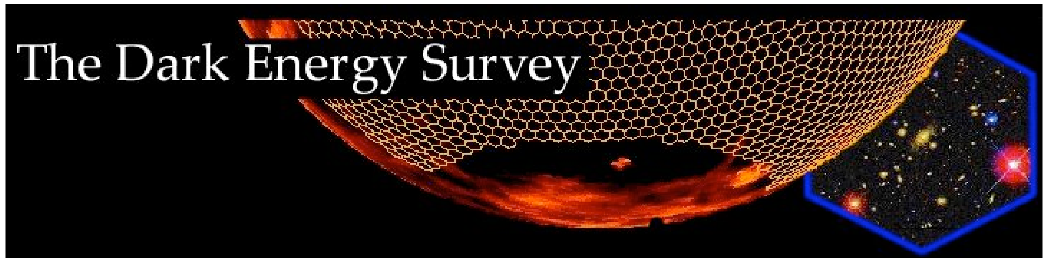




Observational Data Pipelines



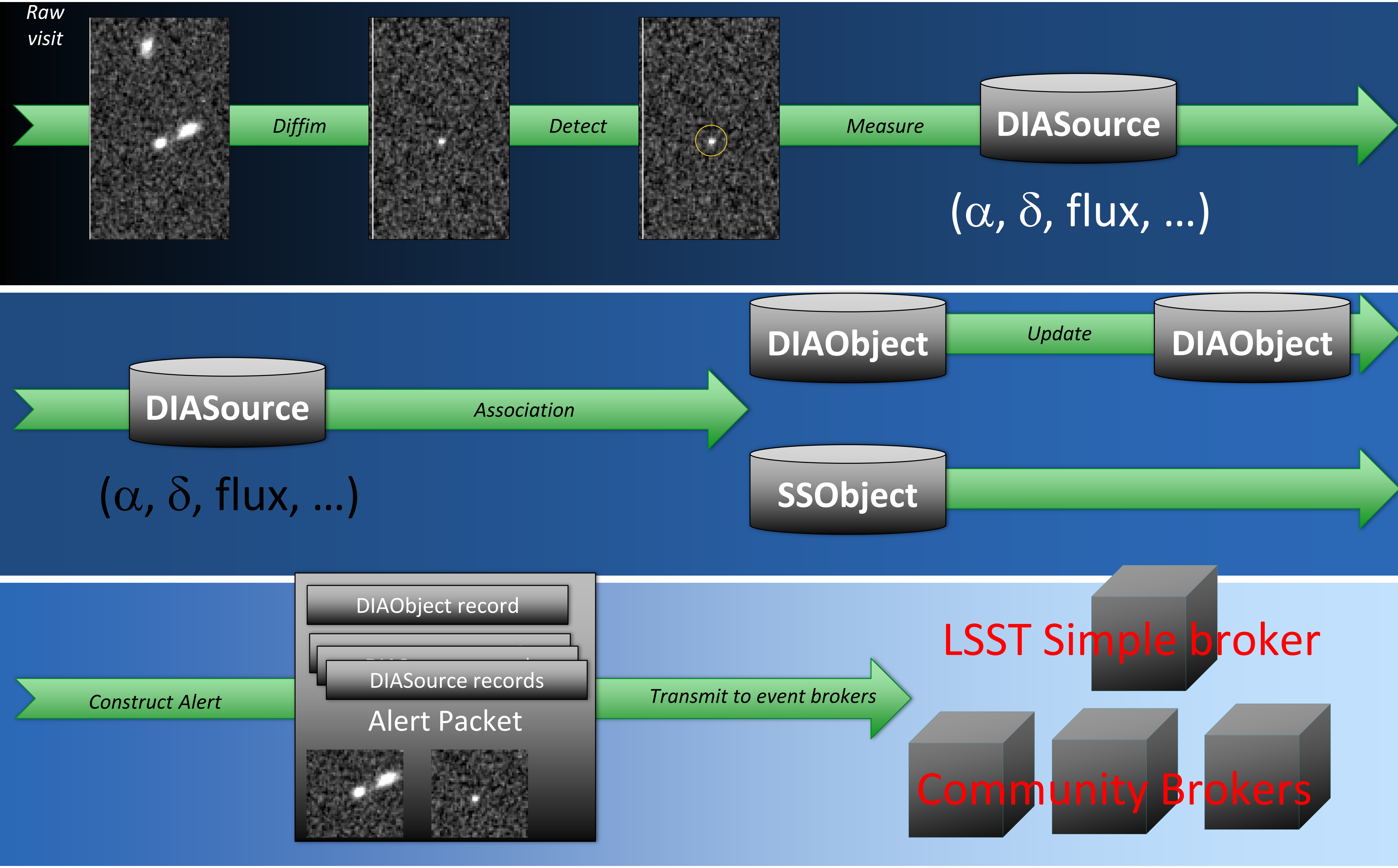
SN Subtraction



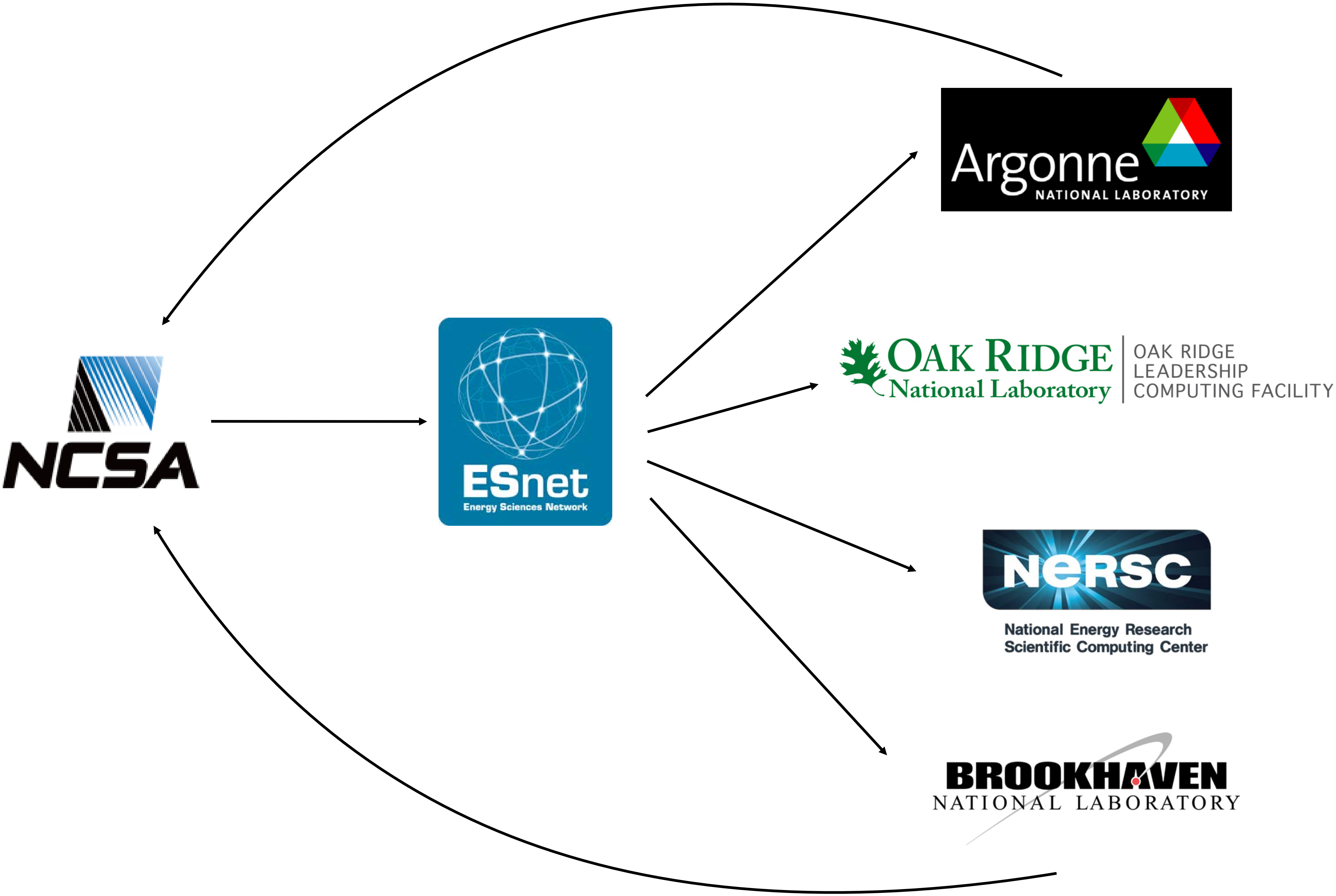
Lensing Analysis

- **Imaging Pipeline**
  - Runs in real-time (to provide immediate quality assessment) as well as annually and at the end of the survey.
  - Handles image de-trending: removal of electronic biases, pixel-to-pixel response, removal of artifacts, object identification, etc.
  - Aligns images wrt each other and with an overall sky solution
  - Determines the depth of each image (were there clouds, and how much?)
  - Measures the location, shape of the object (stars, galaxies, etc.), and their brightnesses
  - Often employs several codes, patched together with perl, python, bash, etc. with calls to databases in between.
  - Can have different ones within the same survey depending on the science

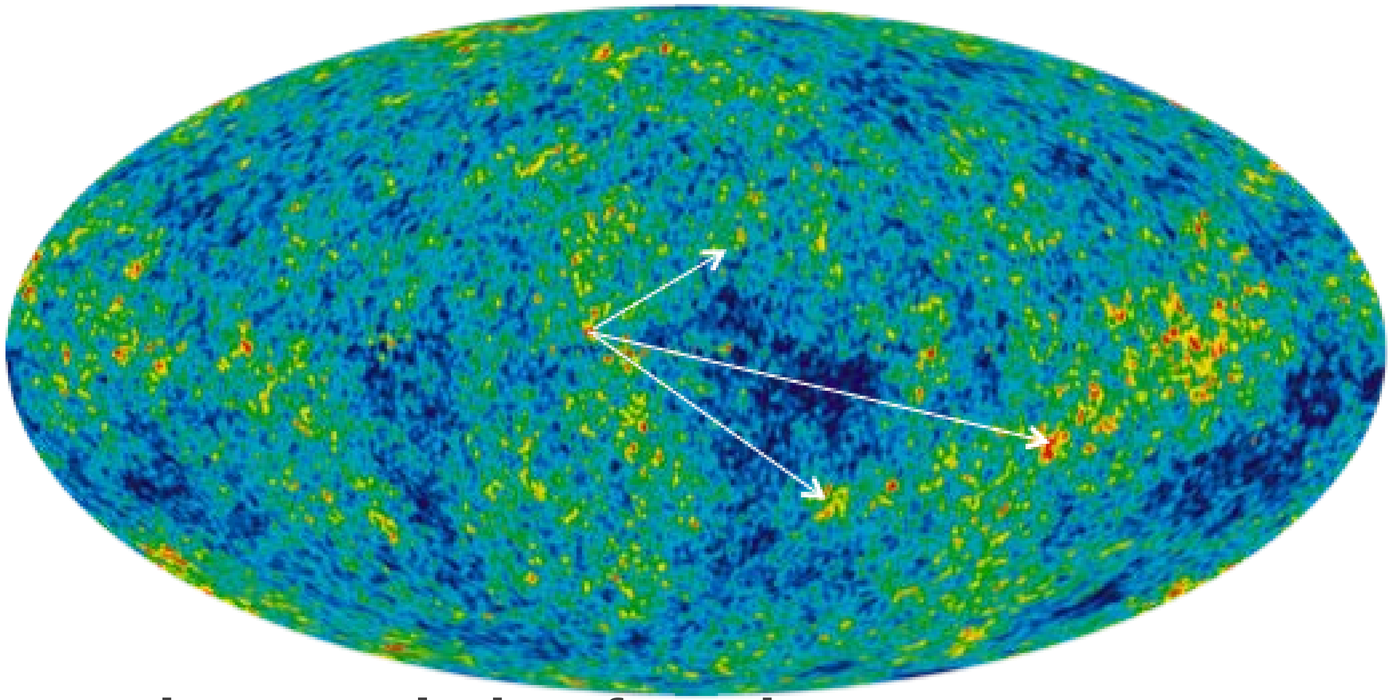
LSST: Streaming Data

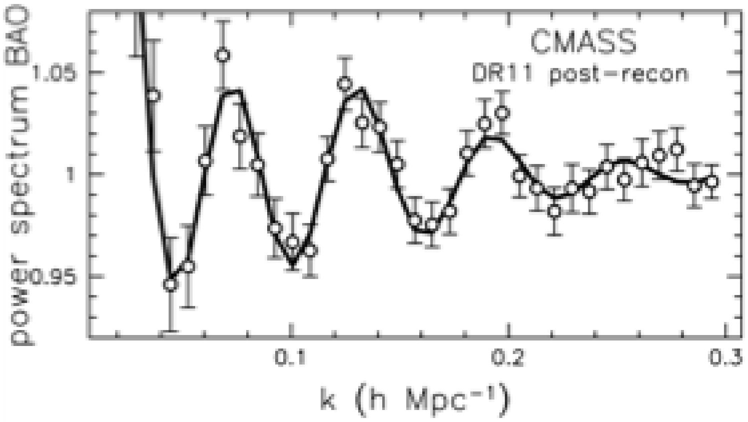


NERSC Shifters/Docker + HPC + ESnet

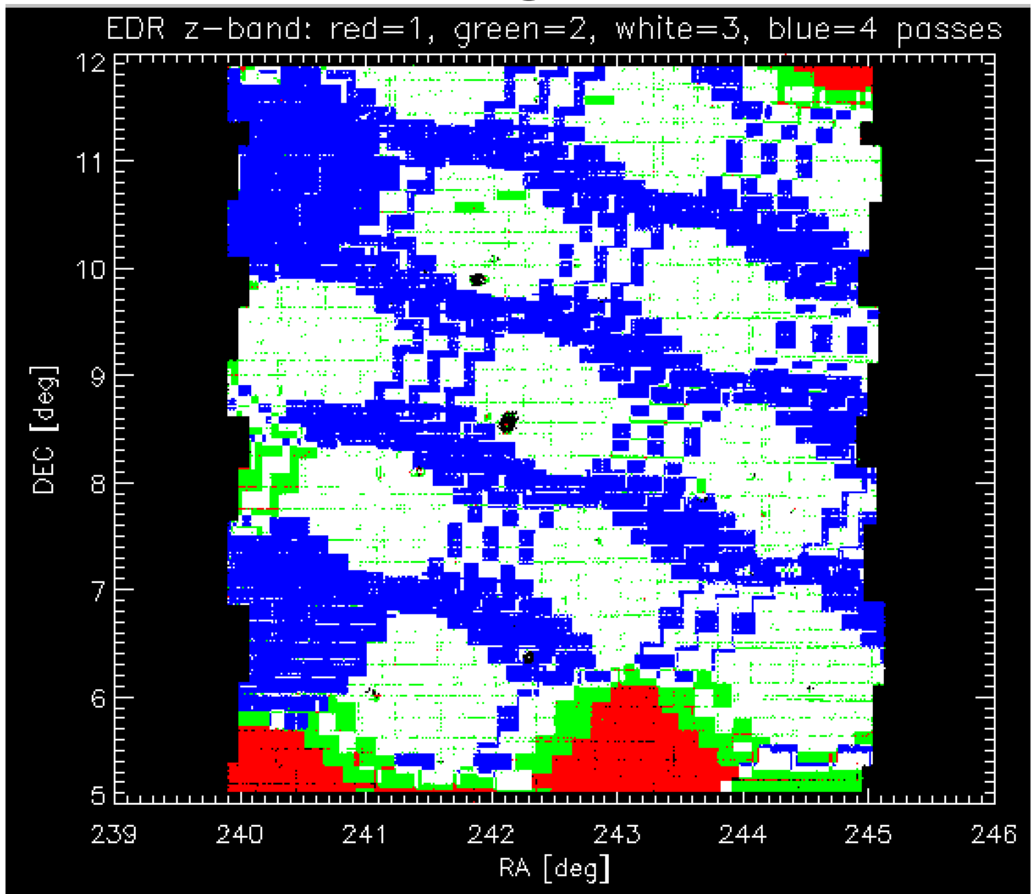


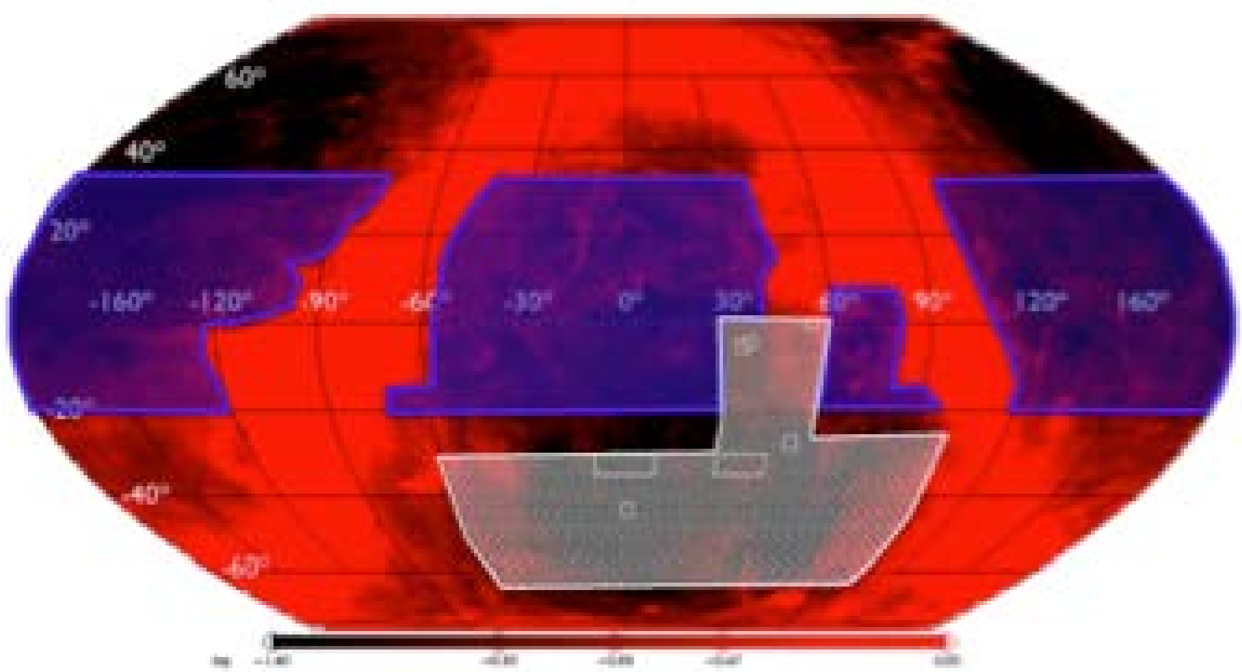
DECam Processing at NERSC for DESI



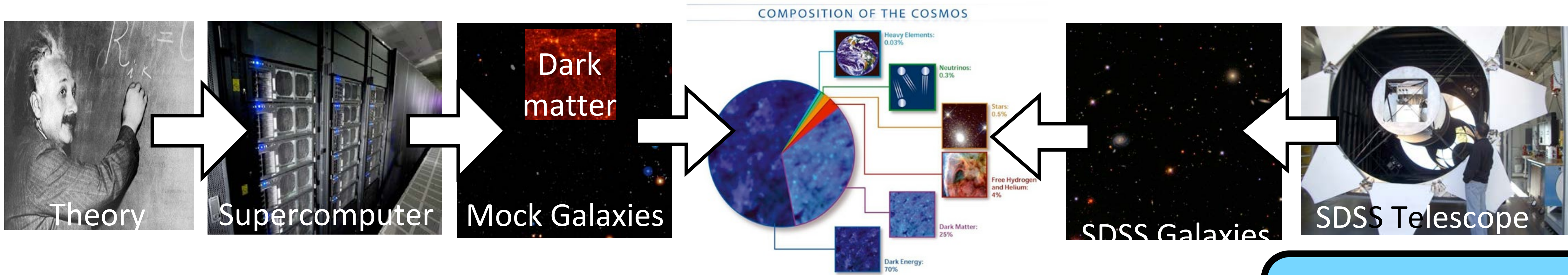


Two point correlation functions are a way to measure cosmology: what is the power spectrum of distances between every galaxy and every other galaxy as a function of time (redshift)? It requires a deep understanding of the systematics involved in how one selects the galaxies and how well (complete) they did it across the sky…

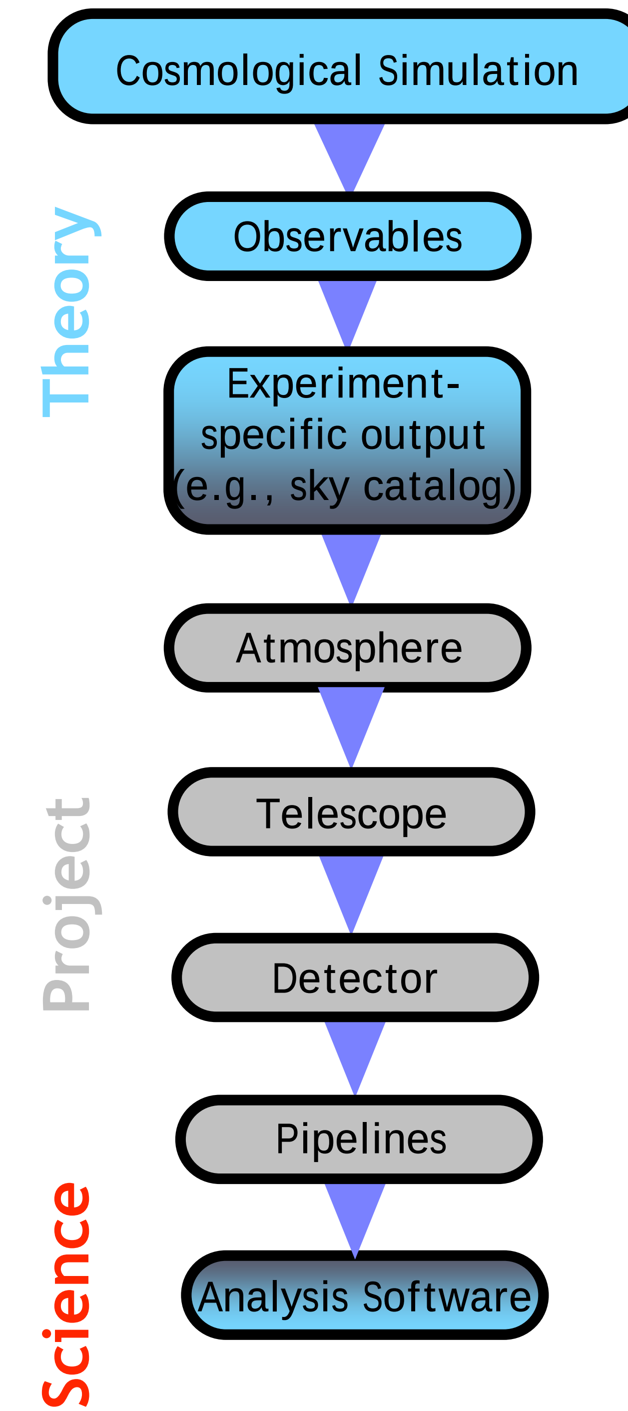




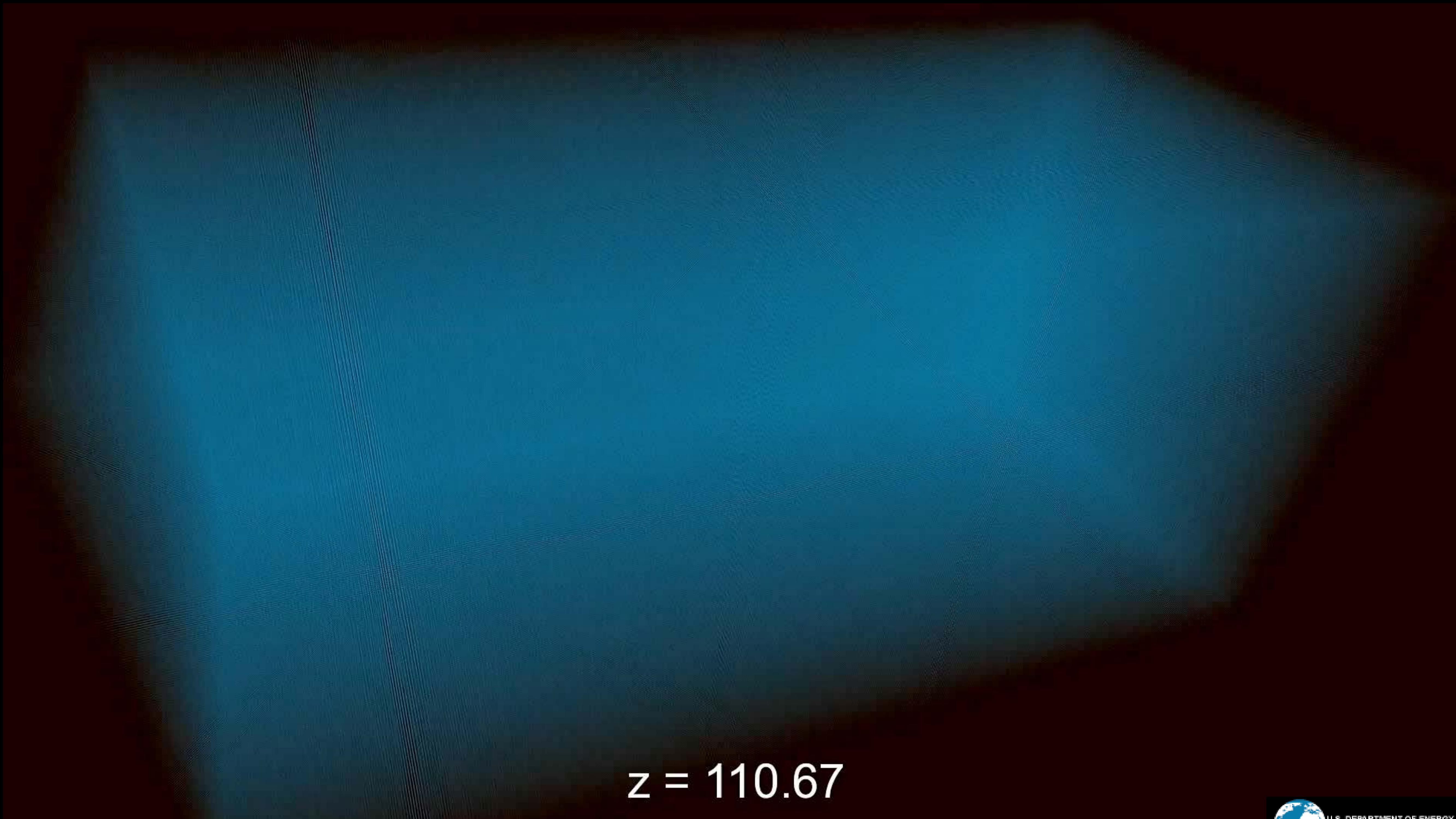
Computational Cosmology: Role of Simulations



- **Three Roles of Cosmological Simulations**
  - Basic theory of cosmological probes
  - Production of high-fidelity ‘mock skies’ for end-to-end tests of the observation/analysis chain
  - Essential component of analysis toolkits: Control systematics
- **Extreme Simulation and Analysis Challenges**
  - Large dynamic range simulations; control of subgrid modeling and feedback mechanisms
  - Design and implementation of complex analyses on large datasets; new fast (approximate) algorithms
  - Solution of large statistical inverse problems of scientific inference (many parameters, ~10-100) at the ~1% level



The high resolution Q Continuum Simulation, finished July 13 on ~90% of Titan under INCITE, evolving more than half a trillion particles. Shown is the output from one node (~33 million particles), 1/16384 of the full simulation



Q Continuum: Extradimensional plane of existence

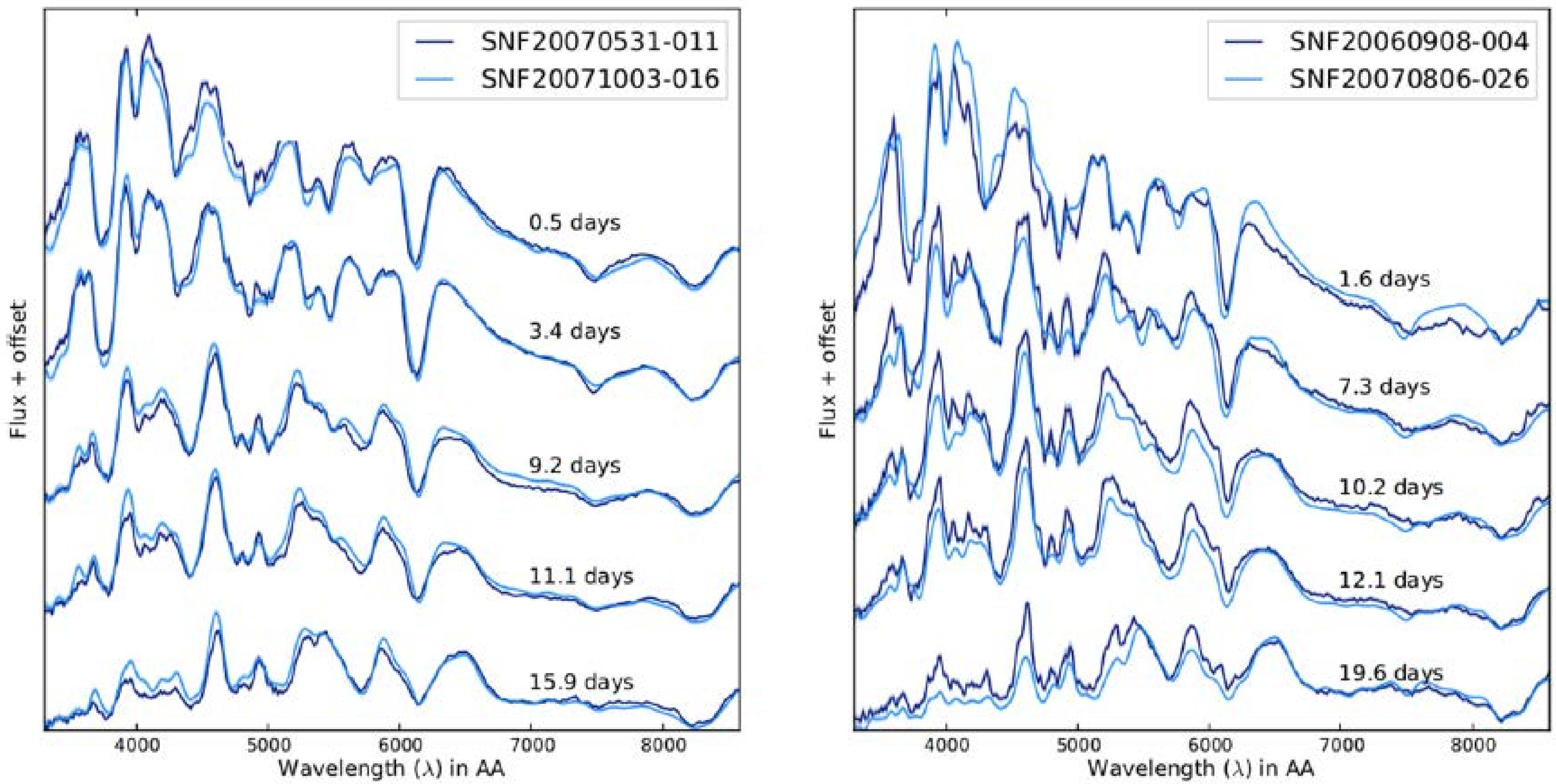
Visualization: Silvio Rizzi, Joe Insley et. al., Argonne

Need for SN Simulations?

- Sadly, for all the Type Ia Supernovae we have found, we still don’t know what they are…
- This exposes us to potential systematics, especially if there are multiple ways to make one explode and these mechanisms evolve with the age of the universe.
- So how do we compare apples to apples and oranges to oranges?

Best Observations

Fakhouri et al. (2015)



Twins: Find the apples and oranges - but this is too expensive!

Sub-Chandrasekhar models

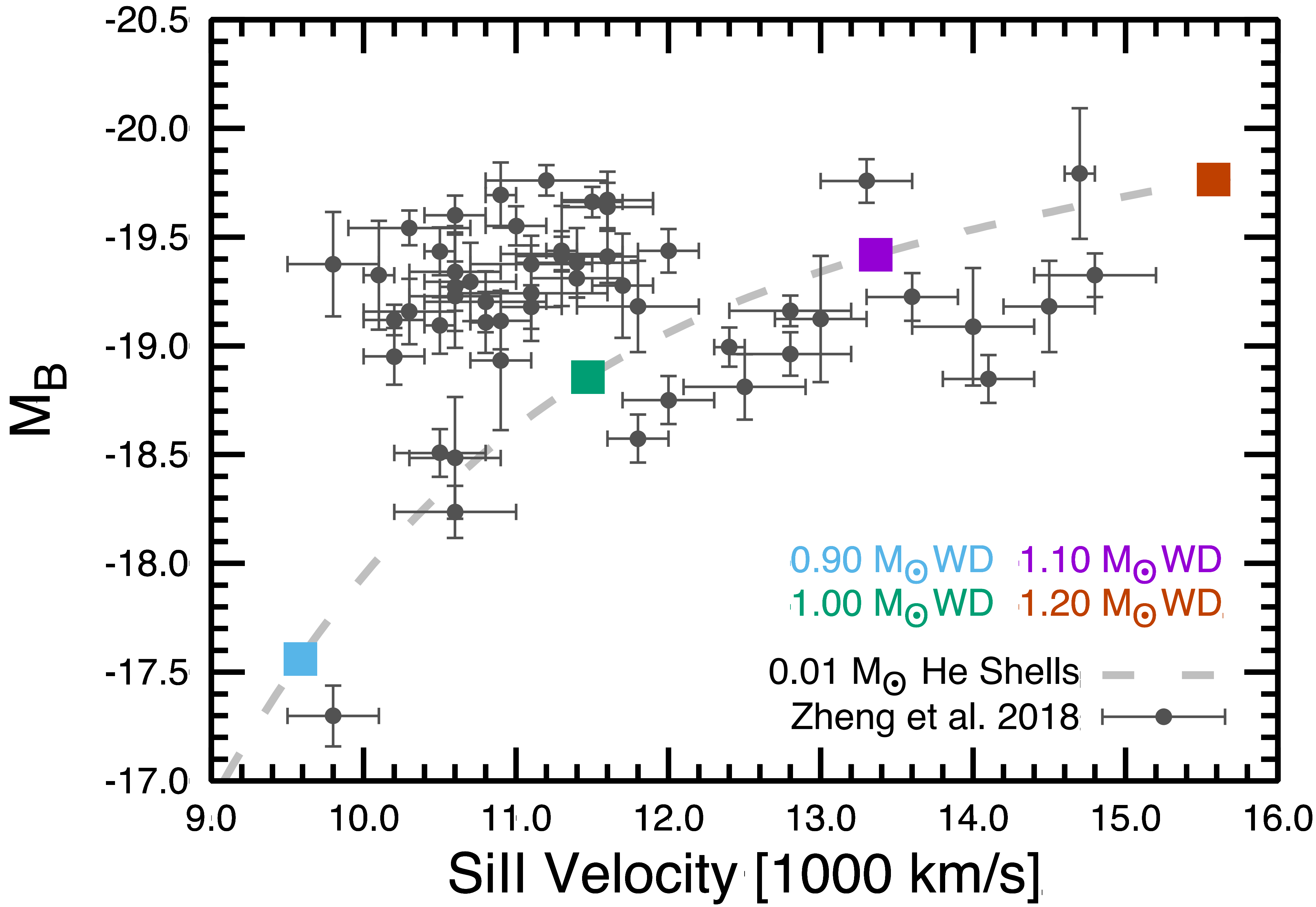
Density

Temp

IME

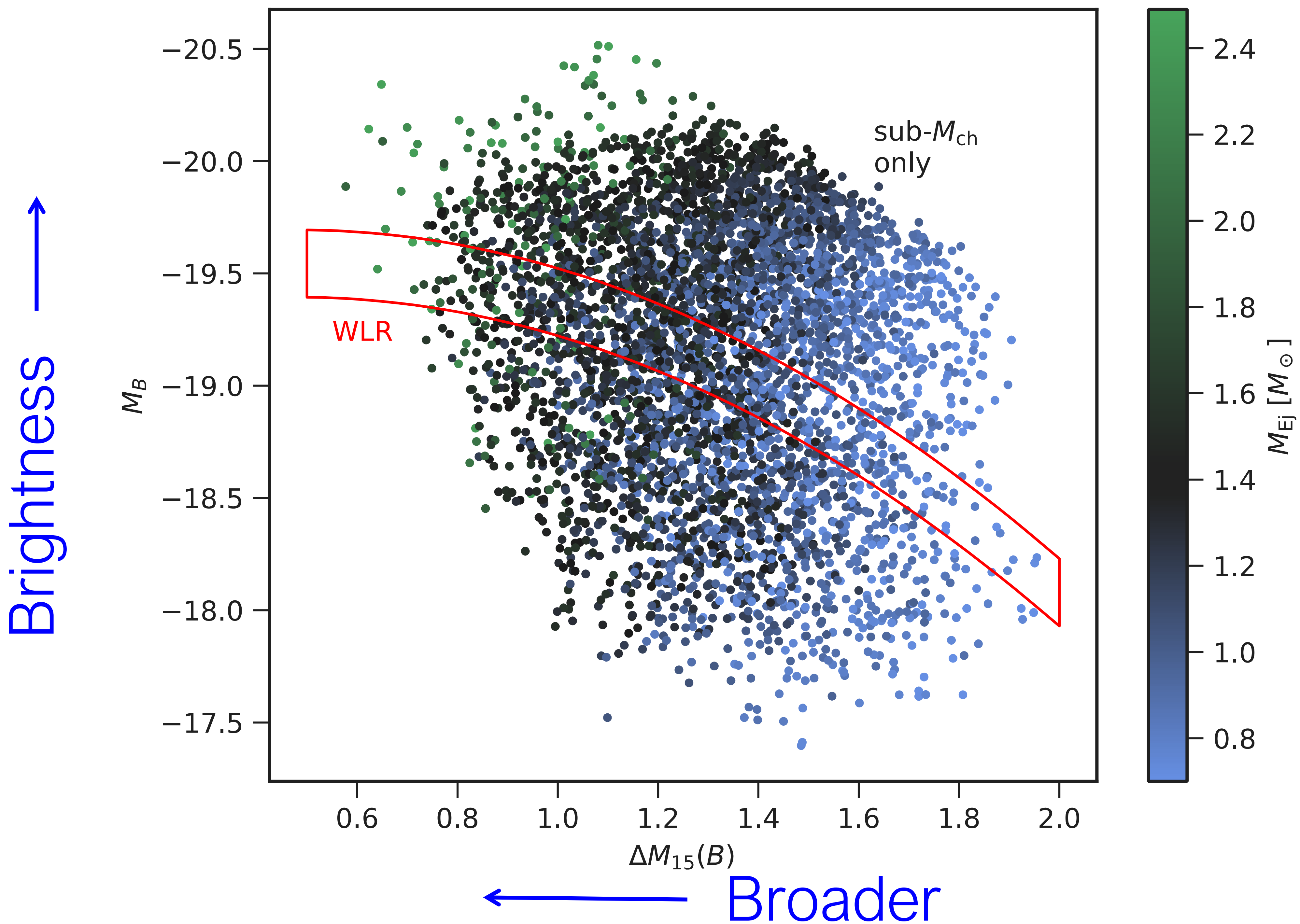
Do these Exist in Nature?

Polin, Nugent & Kasen (2019)



Going beyond Nature w/ Simulations

Goldstein & Kasen (2018)



Conclusions

We've been able to show that complex data processing pipelines in astrophysics can be ported in a reasonably simple way to a variety of HPC systems (through Shifters/Docker) and that complex, parallel, simulation analysis workflows are just starting to be run by non-HPC experts through a web-based science portals… There are still several challenges:

- **Seamless and trivial data movement from one HPC filesystem to another, to tape, to burst buffer, etc.**
- **Optimization of Shifters and ability to run on, almost, any HPC systems**
- **Ability to handle PB's of observational data and orders of magnitude more simulation data**
- **Merging of data-processing and analysis of observational data with simulation generated data. This is critical for the next set of precision cosmology measurements where the goal is to completely understand the systematics in the survey and achieve sub-percent measurements of the cosmological parameters.**