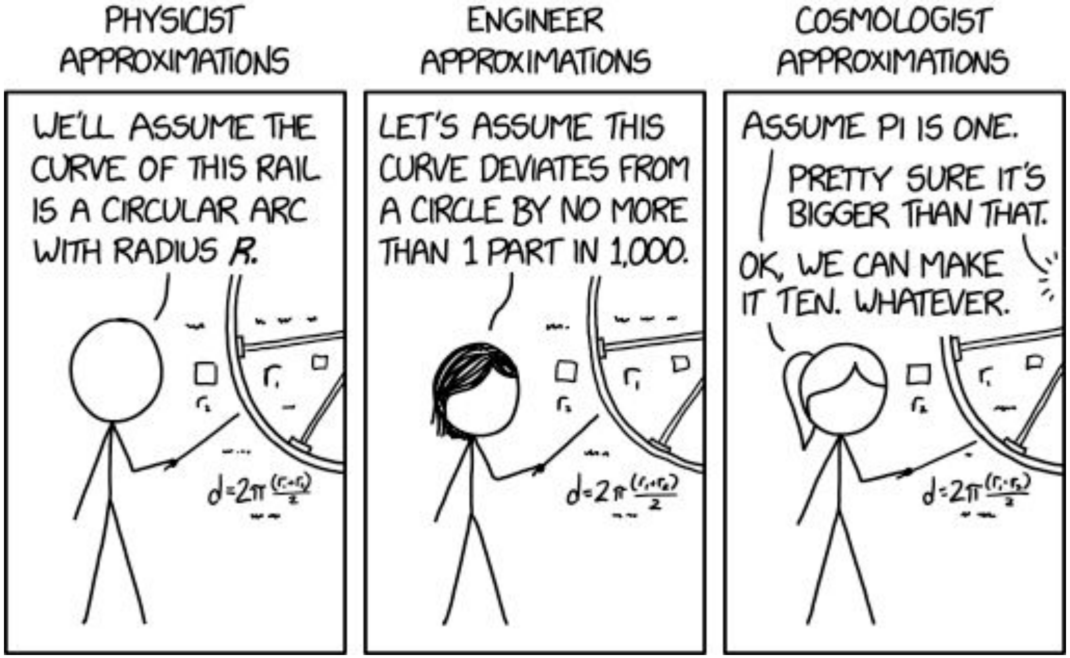
Big Bang, Big Data, Big Iron: 50 Years Of CMB Studies At NERSC

Julian Borrill
Berkeley Lab & UC Berkeley

CAUTION - COSMOLOGISTS AT WORK!

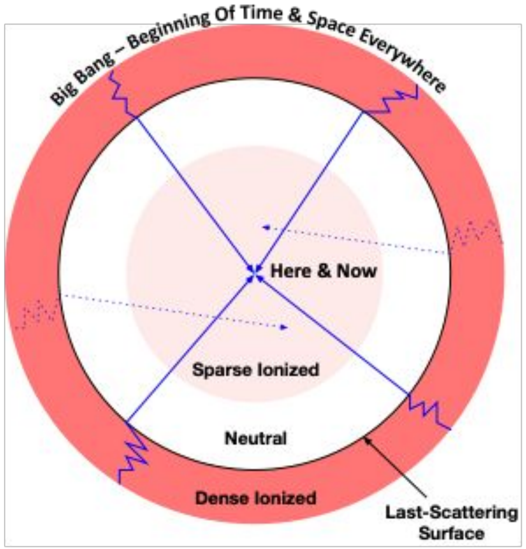
"Cosmologists are often in error, but never in doubt."

Lev Landau



THE COSMIC MICROWAVE BACKGROUND

- After the Big Bang, the hot expanding Universe eventually cools through the ionization temperature of hydrogen: $p^+ + e^- \Rightarrow H$.
- Without free electrons to scatter off, the photons free-stream to us.

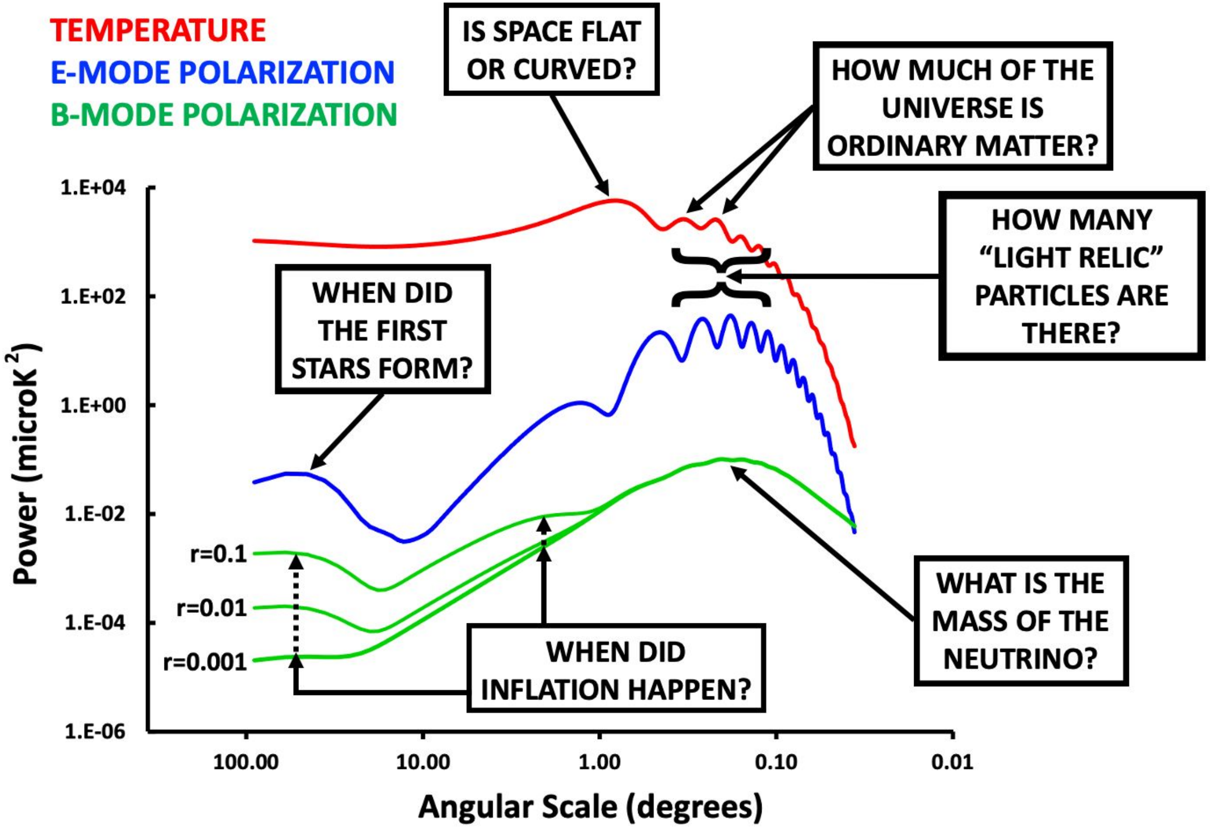


- COSMIC - everywhere in space.
- MICROWAVE - stretched by cosmic expansion to mm-wave radiation today.
- BACKGROUND - primordial photons coming from “behind” all astrophysical sources.

These photons have seen it all! Tiny variations in their temperature and polarization across the sky encode all of fundamental physics and cosmology.

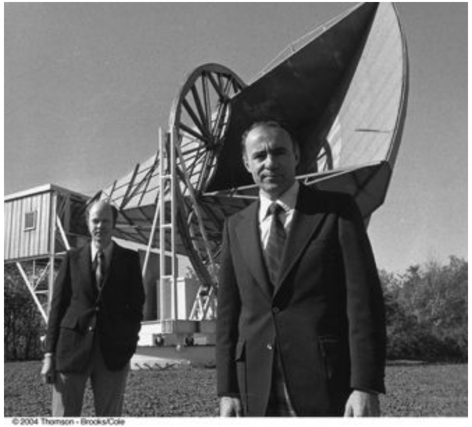
CMB SCIENCE

The power spectra of the CMB measure the strength of these variations ("anisotropies") on different angular scales on the sky.



CMB DETECTIONS

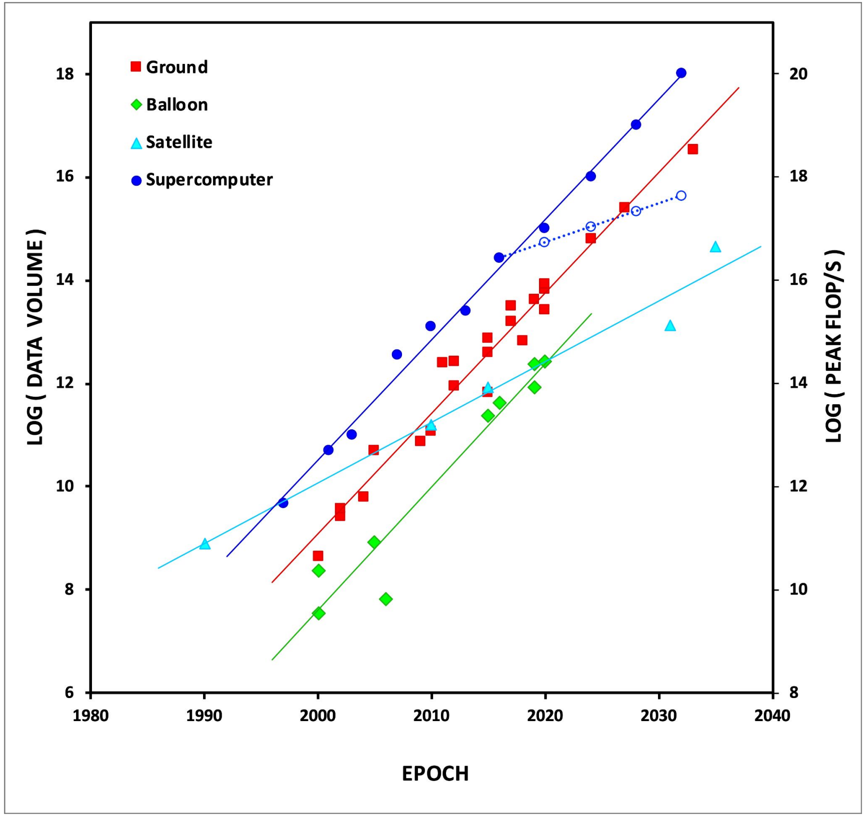
- 1964: Penzias & Wilson accidentally discover the CMB, confirming the Big Bang theory and winning them the 1978 Nobel Prize in Physics.



- 1992: The COBE satellite first detects anisotropies in the CMB, winning George Smoot a share of the 2006 Nobel Prize in Physics.

CMB & SUPERCOMPUTING

- The CMB signals we want to detect are milli- to micro-Kelvin variations about a 3K mean value.
- We need huge datasets to achieve the necessary signal-to-noise.
- The exponential growth of CMB data volumes over 50 years keeps us on the bleeding edge of supercomputing.
  - Suborbital experiments have the same exponent as Moore's Law!

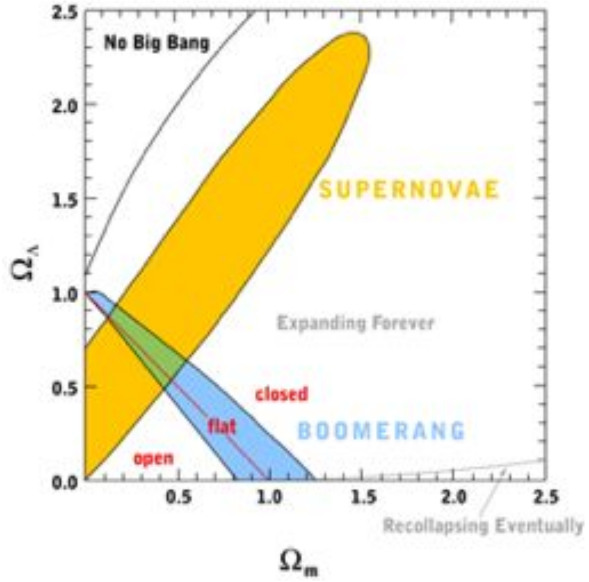


2000: BOOMERANG

- 1998/99 circumpolar balloon flight.
- Data analysis performed on the Cray T3E using my Microwave Anisotropy Computational Analysis Package (MADCAP).
  - Spawned MADbench benchmarking & procurement code.
- The analysis showed that the Universe was flat.

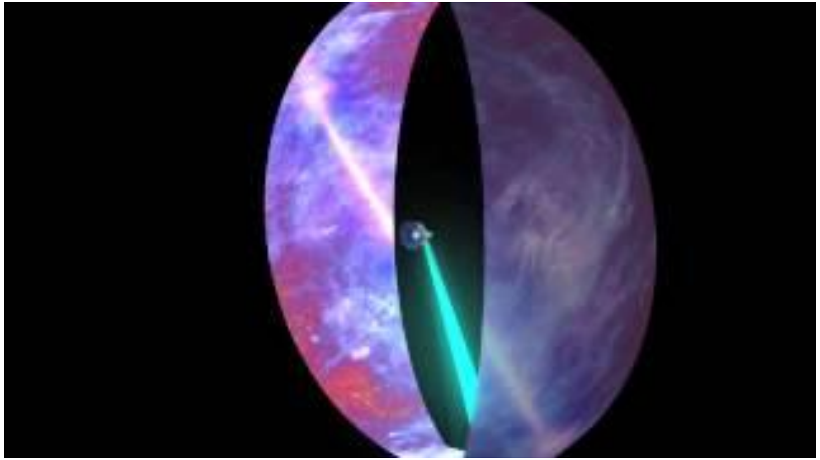
THE CONCORDANCE COSMOLOGY

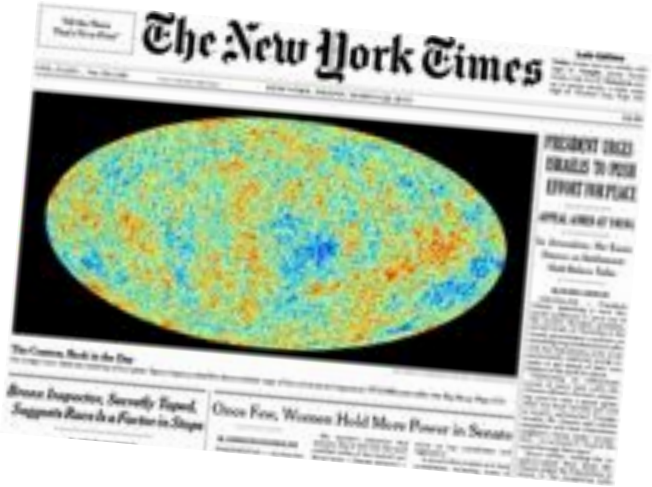
- CMB measures cosmic geometry
  - Expected result: flat
- Supernovae measure cosmic dynamics
  - Unexpected result: accelerating
- Together they overturned the then-standard model of cosmology!
- New concordance cosmology
  - 70% “dark energy”
  - 25% “dark matter”
  - 5% regular (baryonic) matter
- We have measured our ignorance!



2015: PLANCK

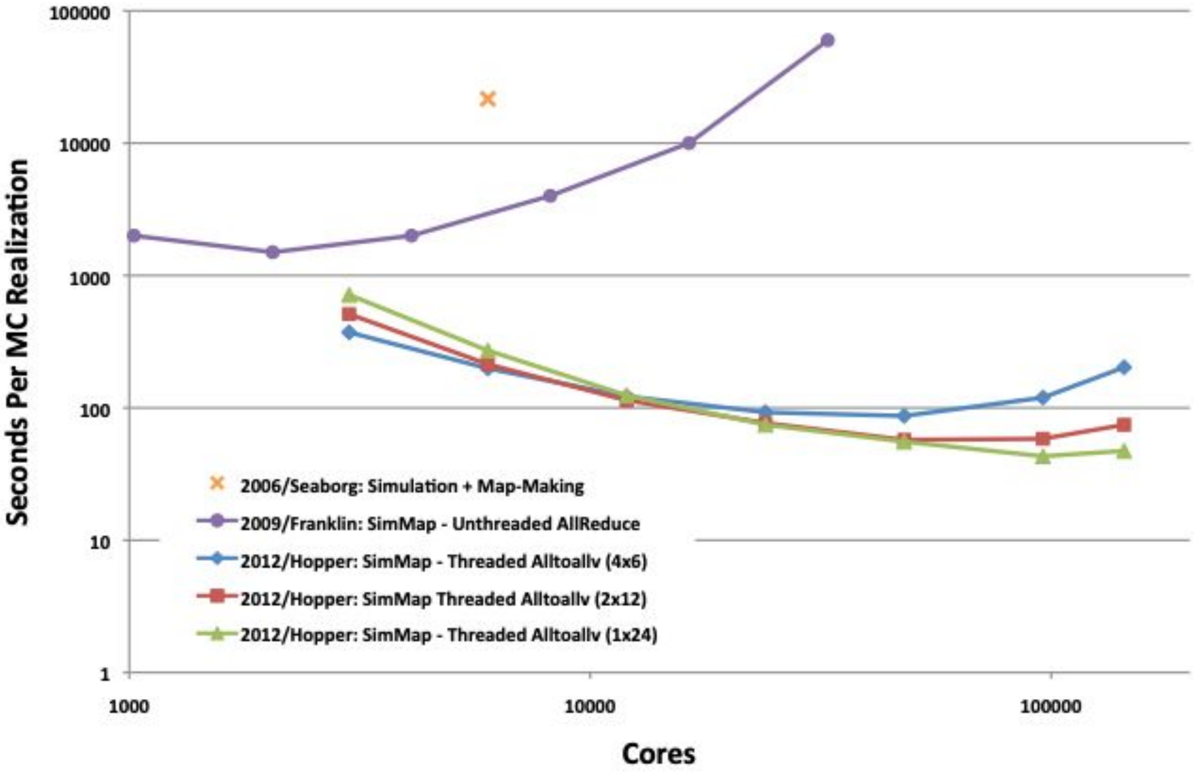
- ESA/NASA satellite mission.
- 1000 times the data volume of BOOMERanG - can no longer afford MADCAP's dense linear algebra ScaLAPACK-based exact solution.
- Approximate methods require Monte Carlo uncertainty quantification.
- C3 CMB team developed the Time-Ordered Astrophysics Scalable Tools (TOAST) package.





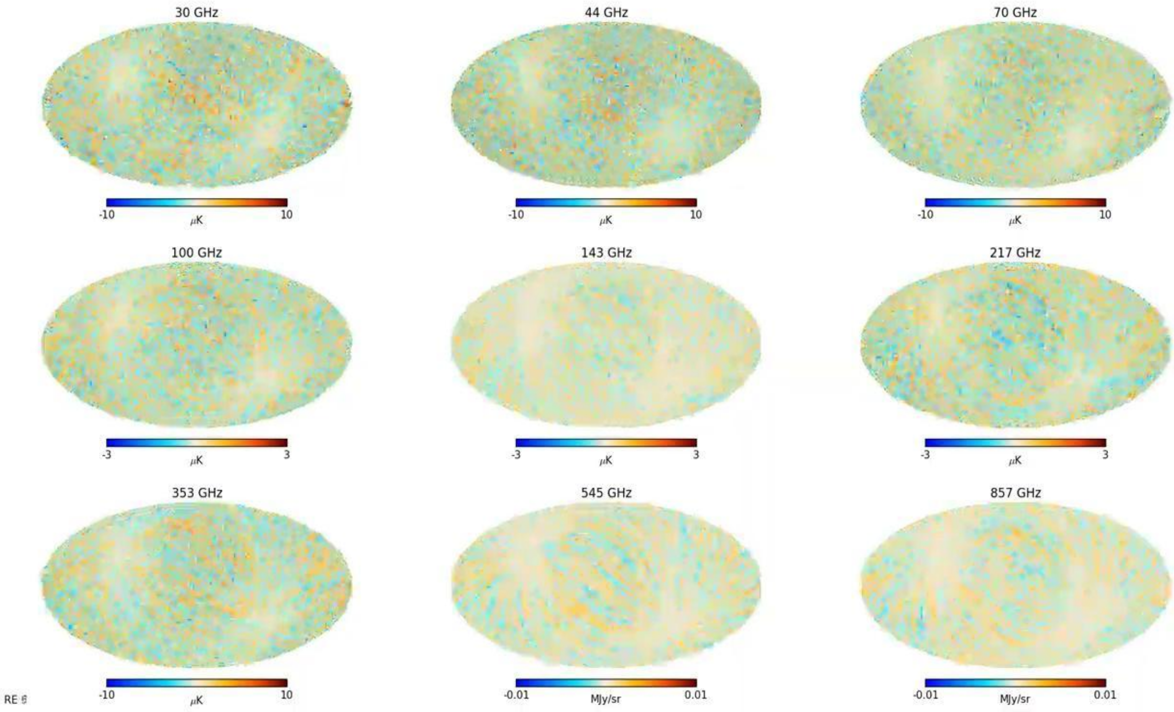
TOAST/NERSC EVOLUTION

- Implementation and deployment evolve with NERSC flagship system.
- 1000x speedup by the time the code is needed for real data analysis.



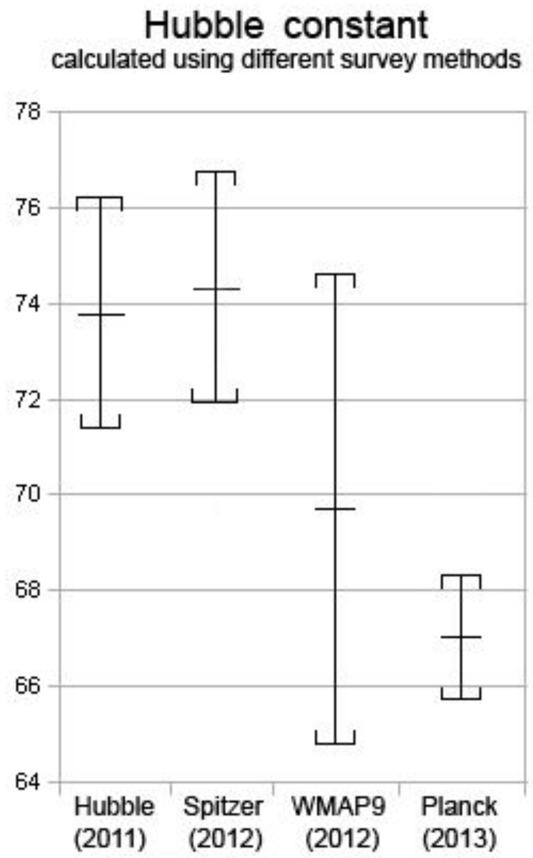
PLANCK NOISE MONTE CARLO

- 10,000 realizations reduced to 1,000,000 maps enabling 1% level uncertainty.
- Orders of magnitude bigger than any other CMB MC set.
- Critical to precision cosmology.



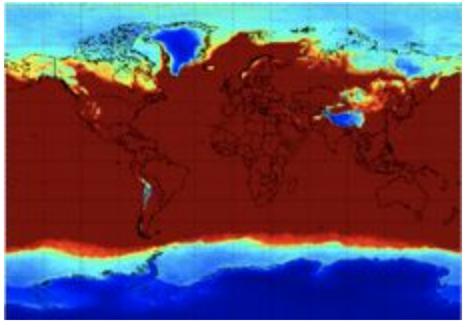
HUBBLE TENSION

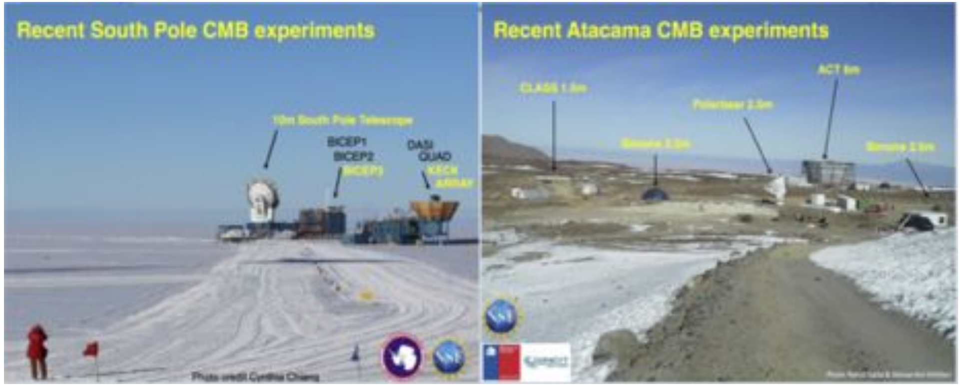
- Until relatively recently, the Hubble Constant was either 50 or 100 km/s/Mpc depending on which camp you were in (hence the xkcd joke)
- Precision cosmology resolved this to 70±10.
- Ultra-precision cosmology from Planck has split us into two camps again, but now driven by different types of data
  - 74±2 from “standard candles”
  - 67±1 from the CMB



2030s: CMB-S4

- The ultimate ground-based CMB experiment.
- Bringing together the existing groups working at the South Pole and in the high Atacama Desert in Chile.
- 1000x the data volume of Planck.
- LBNL chosen as lead lab in significant part because of the history of CMB data analysis at NERSC.

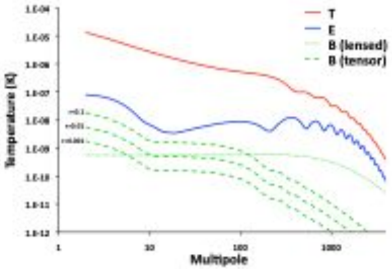




CMB-S4 DATA CHALLENGES

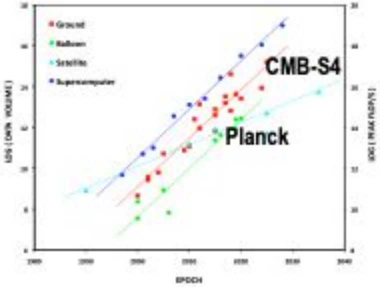
PRECISION - ALGORITHMS

- 1000x higher systematics
  - Atmosphere, ground pickup, polarization modulation, etc
- 100x lower systematic threshold



PERFORMANCE - IMPLEMENTATION

- 1000x large data volume



- 100x fewer watts per FLOP
  - End of Moore’s Law & era of power-constrained computing

Requires a 10,000,000,000x improvement in our computational efficiency!

CONCLUSIONS

- The Cosmic Microwave Background radiation provides a unique probe of the entire history of the Universe.
- Our quest to detect fainter and fainter signals requires
  - bigger and bigger data volumes, and
  - tighter and tighter control of systematics.
- Exponential data growth and increasingly complex analyses compel us to stay on the leading edge of high performance computing.
- Our analysis methods, algorithms and implementations necessarily evolve with both the data volumes and HPC architectures.
- Our collaboration with NERSC has been spectacularly successful in addressing these challenges to date - long may it continue!