Relic Neutrino Physics with the South Pole Telescope

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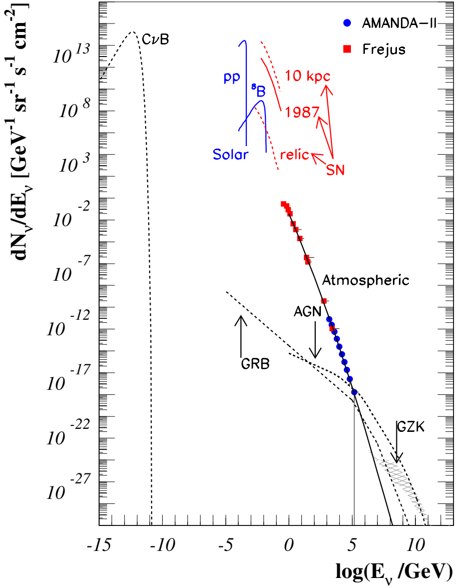
September 8, 2016

Astrophysical Neutrinos



J. Becker, Phys. Rep. 2008

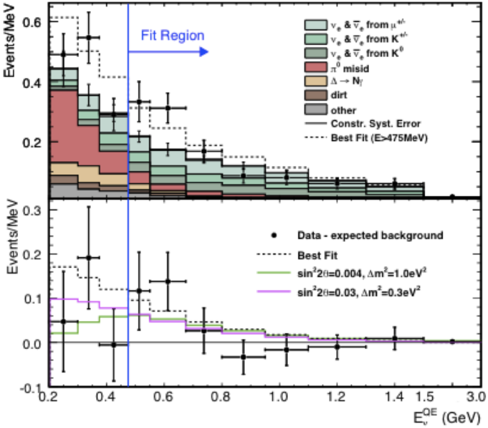
- MeV: Solar Neutrinos, Supernova Neutrinos
  - Detected 1960s
- meV: Cosmic Neutrino Background
  - Detected indirectly 2000s
- TeV+: Astrophysical Neutrinos
  - Detected directly 2013

Big Questions from the CνB

1. How many flavors of neutrinos are there?
2. What is the neutrino mass and hierarchy?

Extra Neutrinos

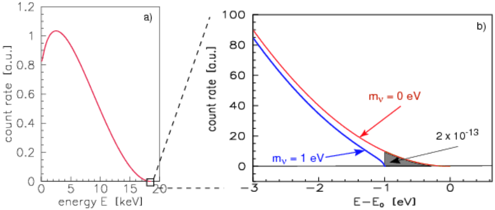
- Evidence from some beam experiments (MiniBooNE, LSND)
- Also normalization issues from reactor experiments
- Compatible with an extra neutrino flavor (or several)
- Neutrino data consistently anomolous, but in parameter space regions that are systematics-limited



MiniBooNE

Neutrino Mass

- In some sense, first BSM physics
- Known to be non-zero from oscillations
- Mass splittings known, but not ordering (hierarchy problem)
- Known to be $\lesssim$ 1 eV from Tritium endpoint
- Both value and mechanism unknown



KATRIN

Laboratory Experiments: Sterile Neutrinos

SNO+

Tremendous experimental effort:

- Reactor experiments
- Lots of experiments in planning stages to put sources inside SNO+, KamLAND, etc.
- Recent IceCube results disfavor some parameter space

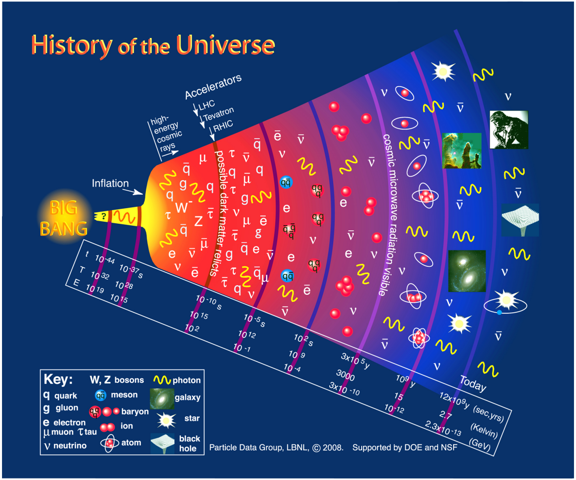
Laboratory Experiments: Neutrino Mass

KATRIN

- Measure tiny delta at end of ^{3}H β spectrum
- KATRIN (soon) and Project 8 (later) current leaders
- Expected sensitivity to $\sim$ 200 meV from KATRIN
- Hard to scale; better sensitivity ($\sim$ 100 meV) from Project 8

Relic Neutrinos

The CνB

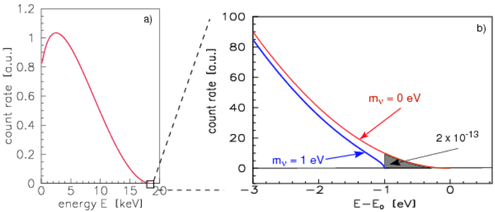


PDG

- Neutrino Pair Production and Annihilation in Equilibrium at Very Early Times
- At t = 1s ($\sim T = 1$ MeV), density drops and neutrinos decouple
- Flying freely since then

Direct Detection

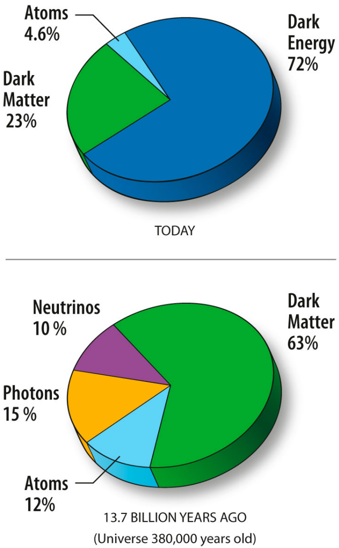
- Tiny energies: no CC interactions, near-zero NC momentum transfer
- In principle can be seen by catalysis of ^3H decay
- Similar problem to, but harder than, mass measurements
- Proposed PTOLEMY experiment to make first detection



KATRIN

The Cosmological Approach

- CνB, depending on m_ν, is a few % the mass of all normal matter
- Large contributions to the energy of the universe early on
- This gravitationally affects the formation of structure

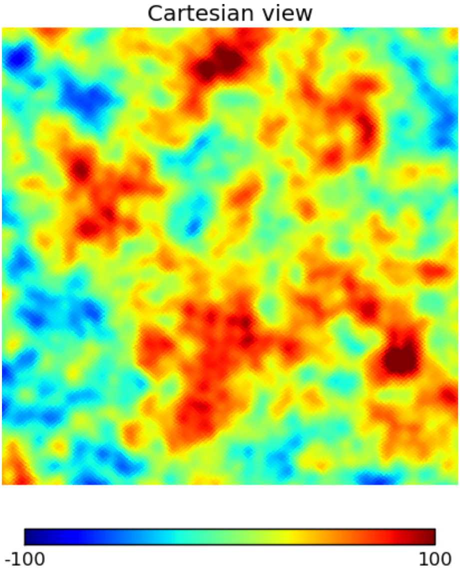


WMAP (NASA)

Big Questions from the CνB

1. How many flavors of neutrinos are there?
2. What is the neutrino mass and hierarchy?

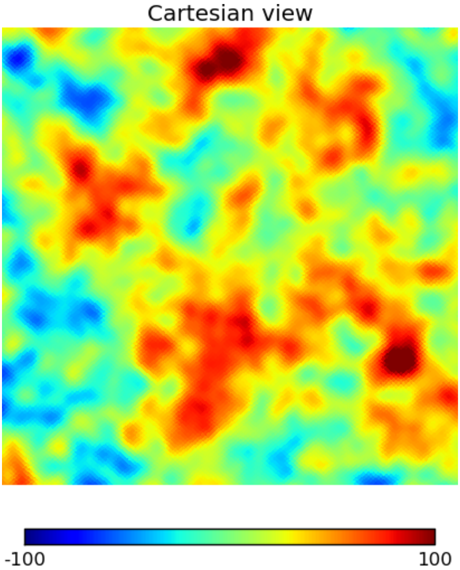
Effect of CνB at Early Times: 2 neutrinos



L. Knox

- Hot Dark Matter
- Smears out structure within free-streaming scale (Hubble radius at early times)
- Energy density $\propto N_{eff}$

Effect of CνB at Early Times: 6 neutrinos



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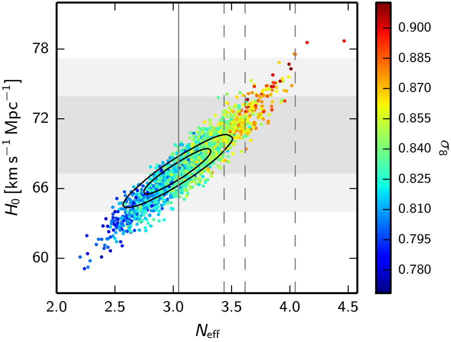
Sterile Neutrinos and CMB: Current Status from Planck



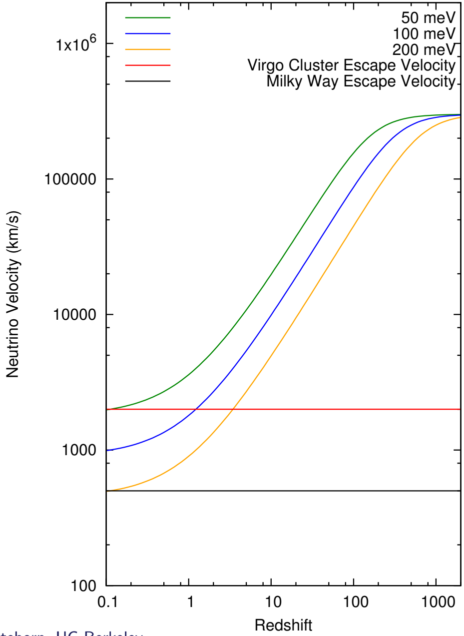
1502.01589

- Planck gives 3.13 ± 0.32 neutrinos
- Strong degeneracy with H_0
- But standard extra neutrino ruled out at 3σ
- Nonstandard scenarios for "neutrinos" still allowed:
  - Very heavy sterile neutrinos
  - Neutrinos with decay modes
  - Axions
  - etc.
- Need new instruments to probe these

Big Questions from the CνB

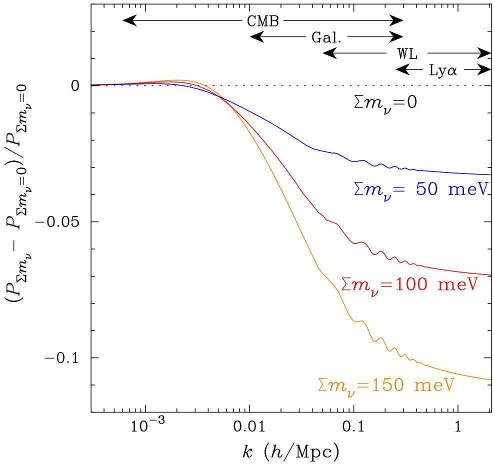
1. How many flavors of neutrinos are there?
2. What is the neutrino mass and hierarchy?

How does cosmology know about neutrino mass?



- As neutrinos cool, transition from hot dark matter to cold dark matter: smearing turns off slowly
- Free streaming scale slowly shrinks
- Time dependence to structure growth
- Given known energy of neutrinos, time of this transition depends on m_ν

Matter Power Spectrum



arXiv:1309.5383

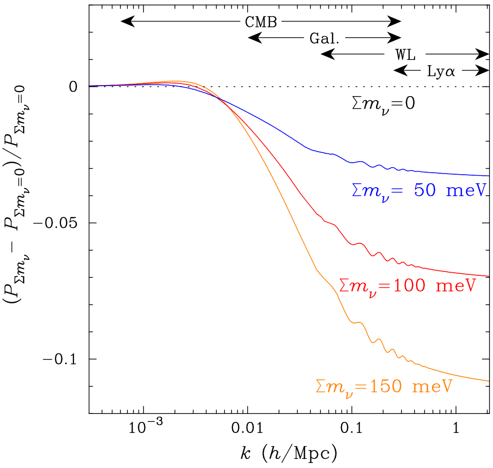
- 5-10% effect on matter power spectrum
- CMB in good position both to measure the deficit (lensing) and normalize it (primordial fluctuations)

Measuring the expansion history of the universe through the CMB

To see this robustly, need to measure clumpiness of structure at various redshifts:

- CMB at $z = 1100$
- Gravitational Lensing at $z \approx 2$
  - Integrated gravitational potential along line of sight
  - Accessible through CMB temperature map
  - More precisely through CMB polarization
- Clusters of Galaxies at $0 < z < 3$
  - Big fluctuations in the density distribution: counting gives clustering
  - Measurable redshifts
  - Systematically tricky
  - Backlit by the CMB, cause systematic spectral shift

What Do We Need For This?

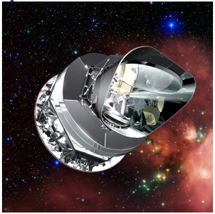


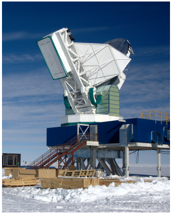
arXiv:1309.5383

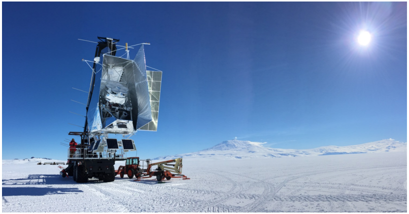
- Large and small scales → good angular resolution
- Polarization for precision lensing and small scales
- Several frequency bands to see clusers
- Low atmospheric contamination
- Significant fraction of the sky to get statistics
- Cosmological parameters of interest: H_0, σ_8, τ

CMB Experiment Landscape: Space, Ground, and Balloons

- Space
  - WMAP (2001-2010)
  - Planck (2009-2013)
- Ground
  - Atacama Cosmology Telescope
  - POLARBEAR/Simons Array
  - South Pole Telescope
  - BICEP
  - Keck Array
- Balloons
  - EBEX
  - SPIDER

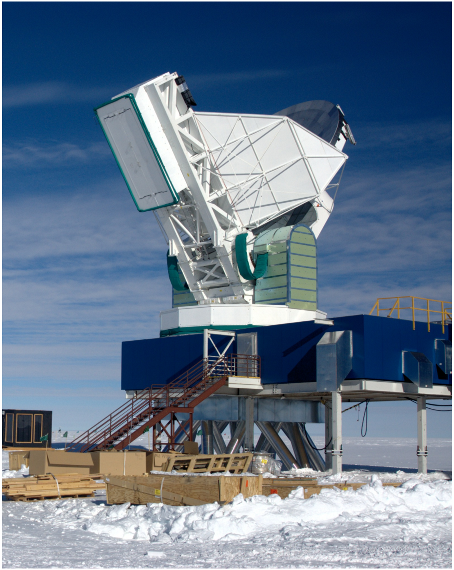






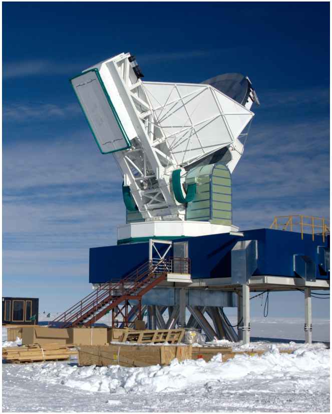
The South Pole Telescope

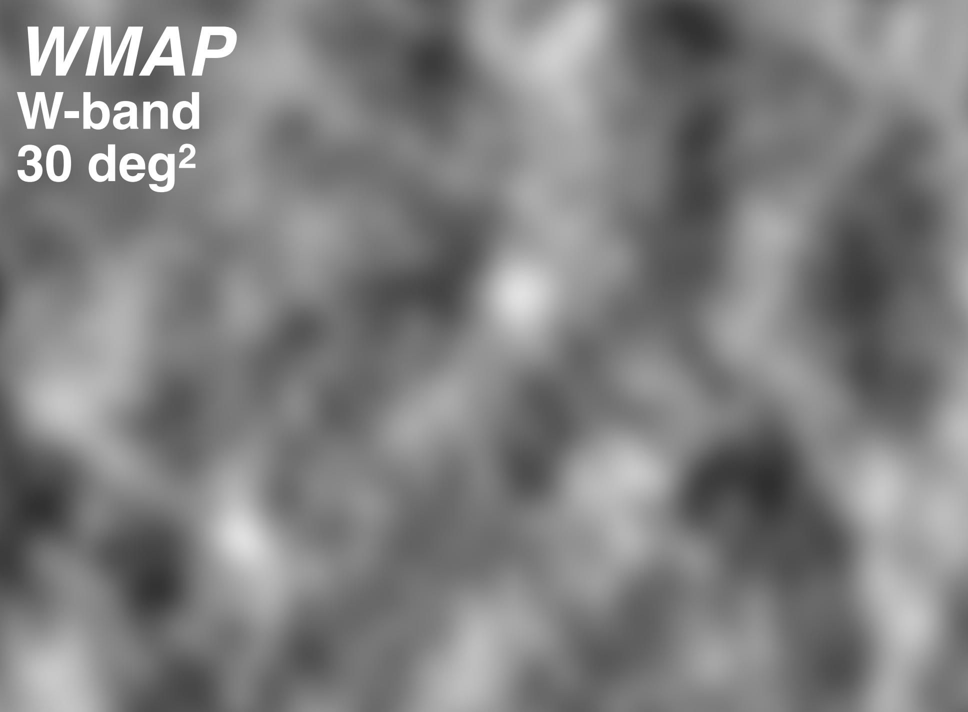
- South pole location gives excellent transmission in 100 GHz band where CMB brightest
- 10 meter primary mirror
- Arcminute angular resolution: well matched to observe clusters
- Current receiver is SPTpol: 360 95 GHz detectors and 1176 150 GHz
- NSF and DOE Support

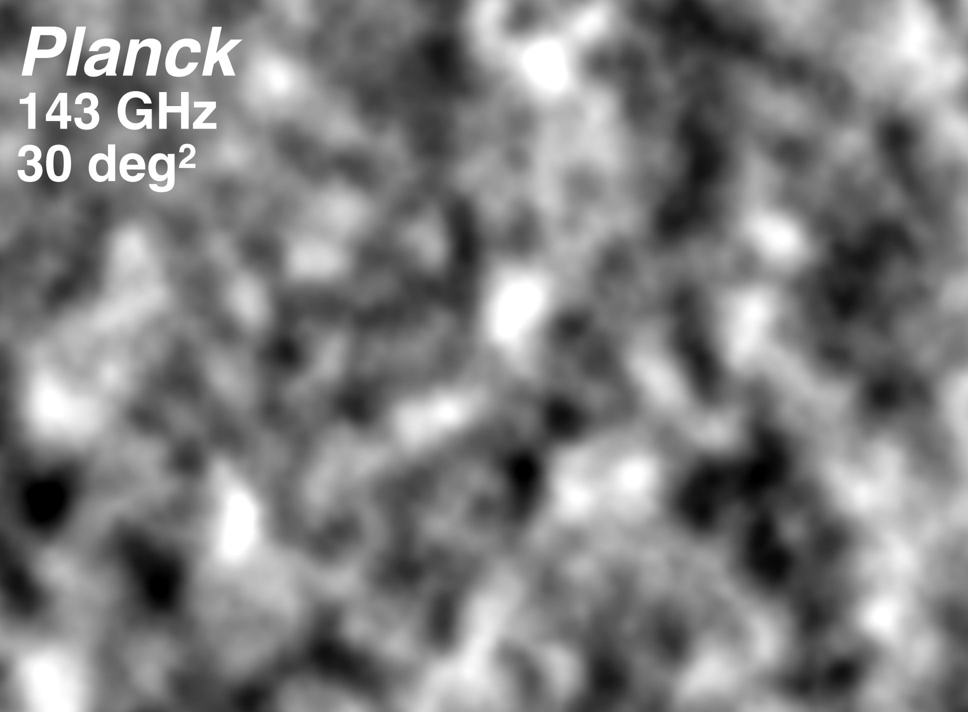


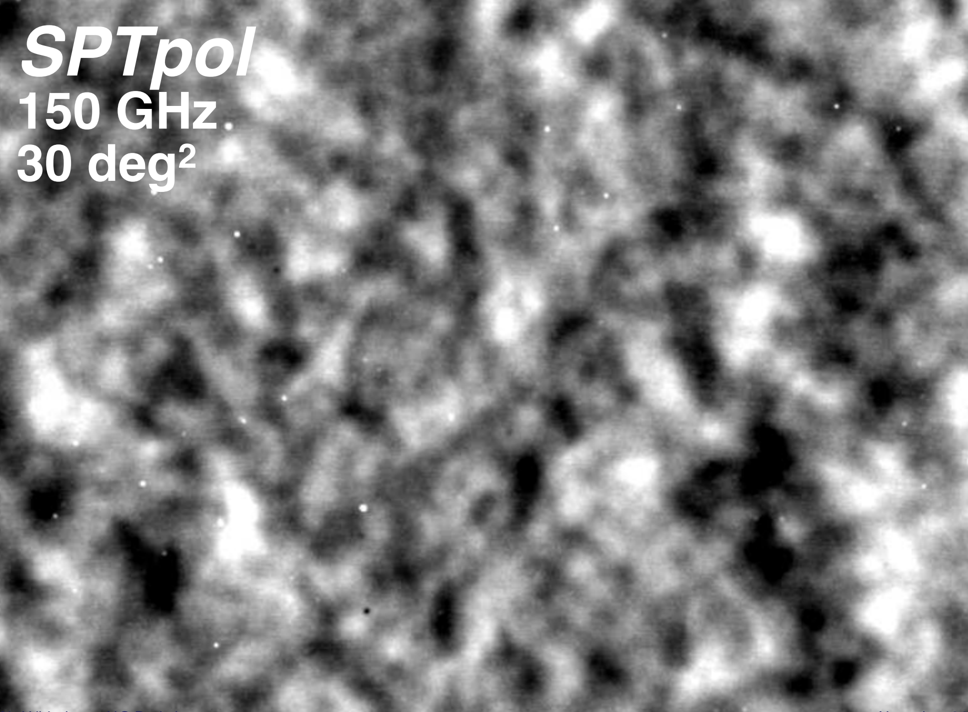
Science Reach of SPT

- CMB temperature fluctuations to arcminute scales
- Measurement of E and B polarization modes
- Gravitational lensing measurements
- Galaxy clusters through Sunyaev-Zel'dovich effect
- Neutrino mass and number of species
- Inflation
- High-z star-forming galaxies
- Orphan Gamma-Ray Bursts (NW+ 2016)
- ...




WMAP
W-band
30 deg^2


Planck
143 GHz
30 deg²


SPTpol
150 GHz
30 deg²

SPT Receivers

SPT-SZ (2007-2011)

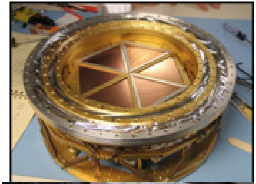
- 95, 150, 220 GHz
- First SZ cluster discovery
- 960 channels
- First arcminute CMB

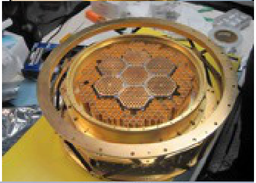
SPTpol (2012-2016)

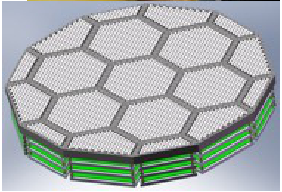
- 95, 150 GHz
- Polarization
- First B-modes
- 1500 channels

SPT-3G (2017-2021)

- 95, 150, 220 GHz
- Polarization
- 16000 channels
- Deploying in 3 months

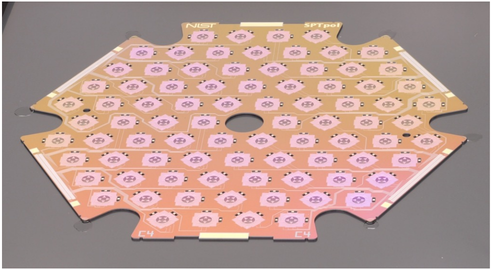






TES Detectors

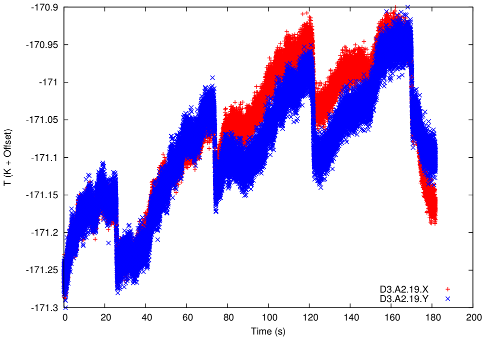
- Superconducting material at T_c
- Small $\Delta T \rightarrow$ large ΔR
- Coupled to mm-band antennas



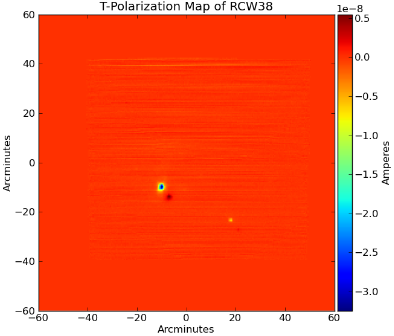
- Need to minimize wiring to ultra-cold focal plane
- Wire pair for each detector untenable
- Frequency-division multiplexing can be done with only passive cold components
- Achieving 68 detectors per wire pair for SPT3G in the 1-5 MHz band

Timestream Data Analysis

- Main task from the ground is seeing through the atmosphere
- No event-by-event selection
  - Average the atmosphere down with time
  - Depends on precision calibration and characterization
- Interesting shifts correspond to pA and pV stability in detector bias point

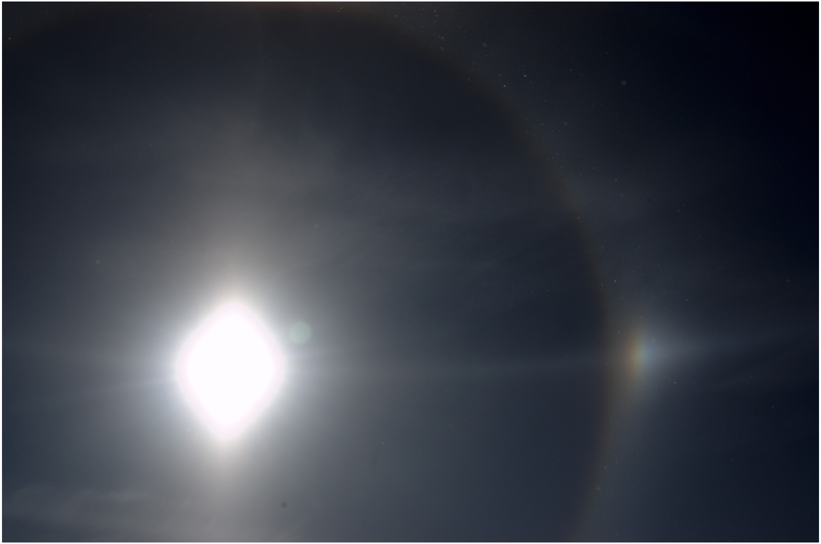


Instrument Characterization and Calibration

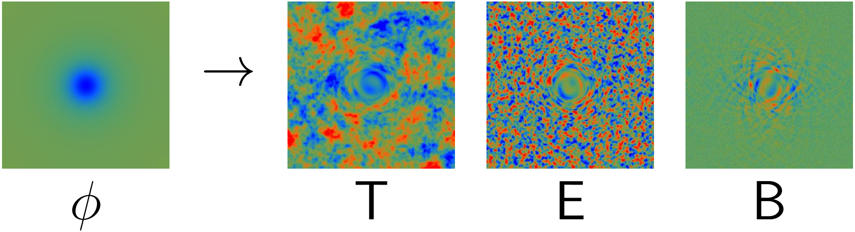


- Need to characterize instrument response to sub-% level: averaging down atmosphere depends on stability!
- Need to characterize in detail:
  - Angular response of detectors
  - Polarization and temp response
  - Crosstalk
  - RF and magnetic field pickup
  - Astrophysical foregrounds

Polarization: E and B



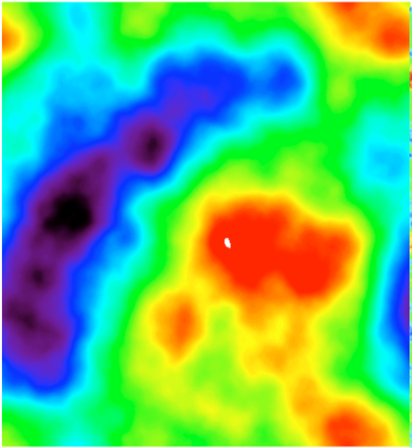
Map Analysis: Extreme Example



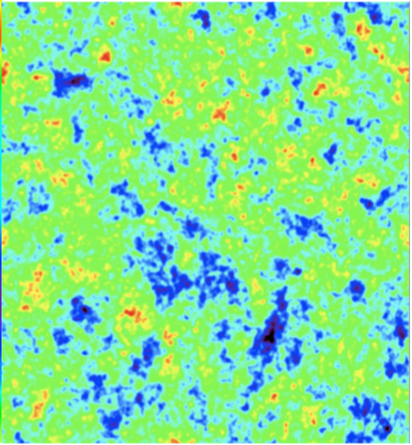
- Looking for coherent distortion of structure that correlates fluctuations at large scales and small ones
- Hazards from astrophysical sources, instrumental convolutions (beam effects), and filtering operations
- B modes (right) cleaner, but smaller, since no native B-modes in general

Fig. from Hu and Okamoto 2001

Realistic T Lensing Example



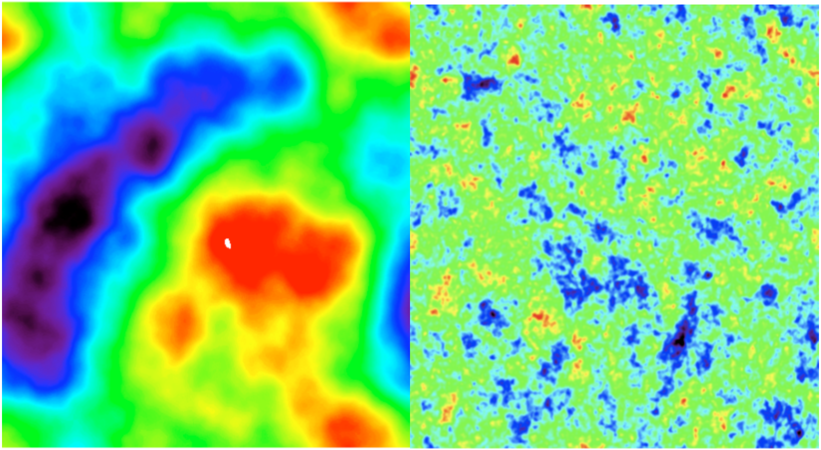
ϕ



Unlensed

Points shifted by $\nabla\phi$ (2.5' RMS, coherent on degree scales)

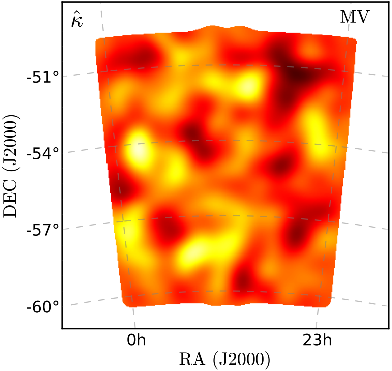
Realistic T Lensing Example

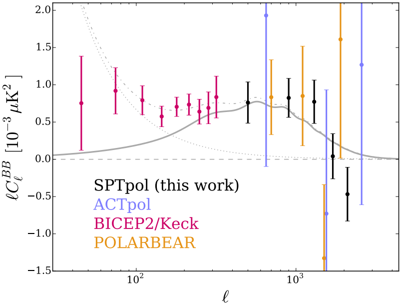


ϕ Lensed

Points shifted by $\nabla\phi$ (2.5' RMS, coherent on degree scales)

Lensing Results





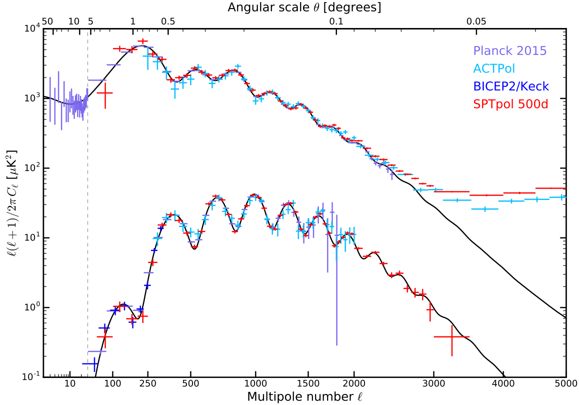
Story+ 2015 (1412.4760)

Keisler+ 2015 (1503.02315)

- First, and best, measurements of lensing B-modes (7.7σ)
- Proof of concept for next-gen detectors: polarization reaching below T, which will improve on Planck limits (230 meV)
- Next round of results (500 deg^2, 7 μK-arcmin) coming in next few months

SPTpol 500d EE Results

PRELIMINARY



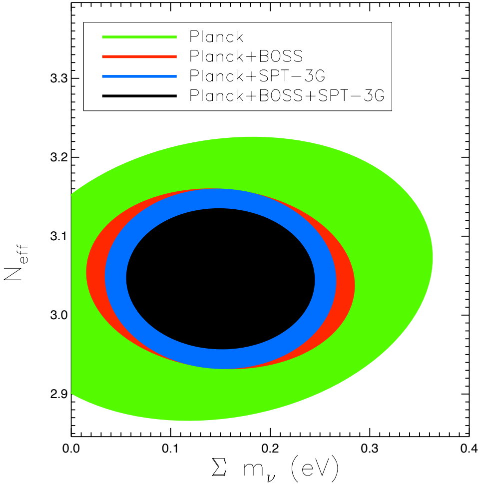
- Probing EE damping tail to unprecedented accuracy
- $N_{eff} = 3.10 \pm 0.28$

SPT-3G

- 16000 detectors
- 2500 deg^2 survey
- Polarization in 3 bands (95, 150, 220 GHz)
- 20x improvement in mapping speed
- Target $3\mu K$-arcmin
- Deployment this winter

Projected SPT3G Constraints

- Expected $\sigma_{\sum m_\nu}$: 61 meV (stat.+sys.), 18 meV (stat.)
- $> 4\sigma$ detection at KATRIN sensitivity
- If zero best-fit, begins to disfavor inverted hierarchy
- Sensitivity approaching even minimum from normal hierarchy (58 meV)



arXiv:1407.2973

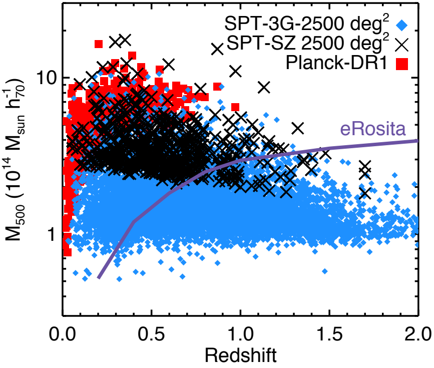
Physics from Systematics

Error budget is systematics dominated, but those errors are (often) interesting physics!

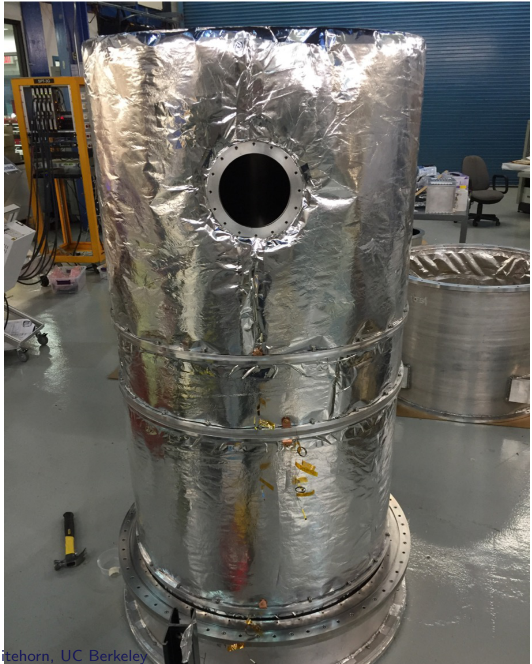
- Sterile neutrinos show up in N_{eff}, but effect depends on behavior
- "Neutrinos" here just means light stable particles
- Comparison of results with terrestrial mass/sterile neutrino experiments probes parameter space unreachable on Earth

SPT3G Clusters

- Clusters have the ability to track structure formation with redshift
- Mass is the critical parameter, but hard to calibrate
- SPT3G lensing will reach few % mass calibration
- $\sim$ 10000 expected clusters
- Proof-of-concept work in SPTpol (similar map noise in 100 deg^2 field)

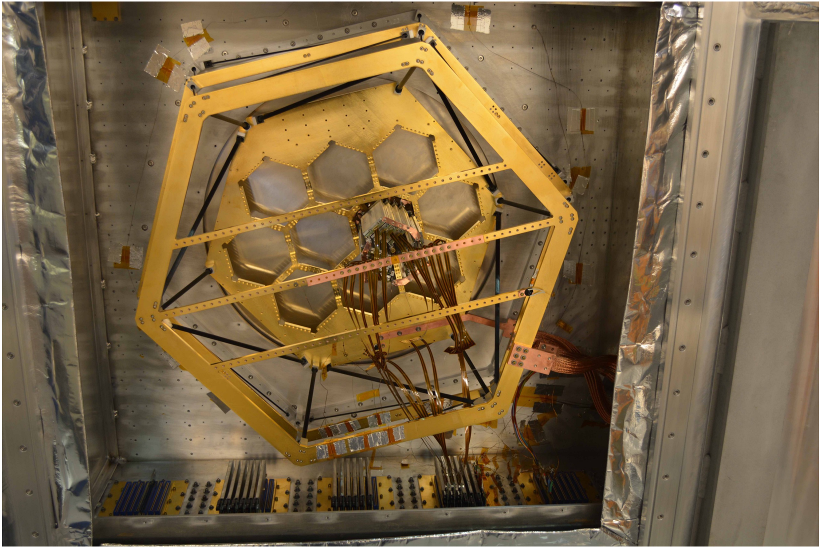


SPT3G Status



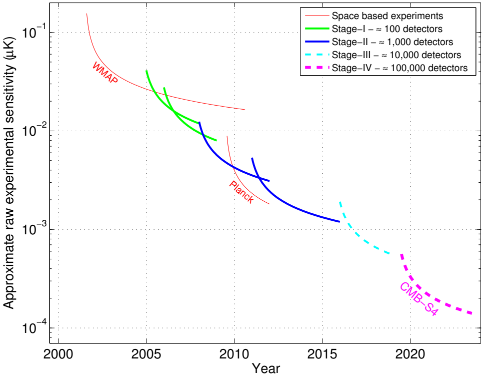
- ✔ AuTi detector fab on track
- ✔ Readout electronics working
- ✔ Cryostat assembled
- ✔ Optics complete
- Ironing out nits in the readout system
- Tooling up software for data acquisition and analysis
- On track for deployment starting in 10 weeks, first light Jan. 1

SPT3G Status



CMB-S4

- Successor experiment in planning stages
- Part of Snowmass process
- Consortium of current facilities with ~ 100000 channels
- Aiming for 4σ detection of neutrino mass even at minimum value



arXiv:13909.5383

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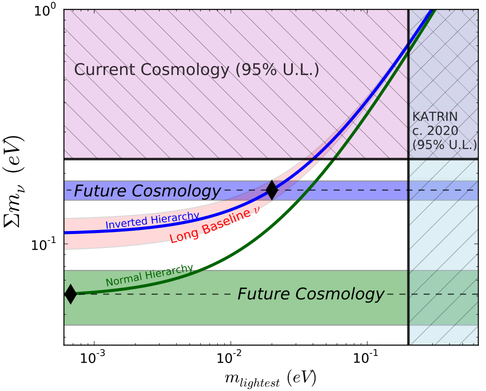
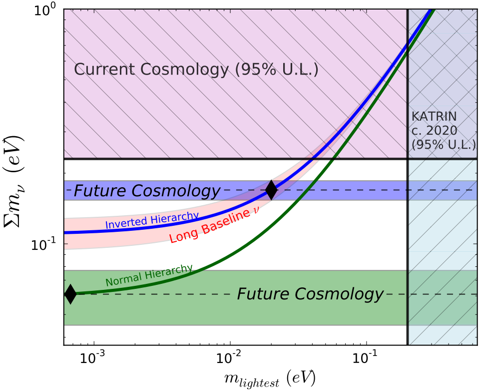


arXiv:13909.5383

Lab and Cosmology Complementarity

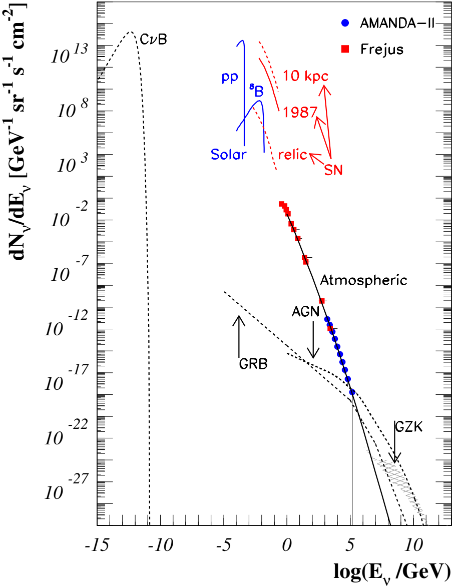
Most interesting science comes from combination with lab measurements. Can probe:

- Neutrinos with decay modes
- Axions
- Properties of arbitrary extra light species
- Mass hierarchy



arXiv:13909.5383

Conclusions

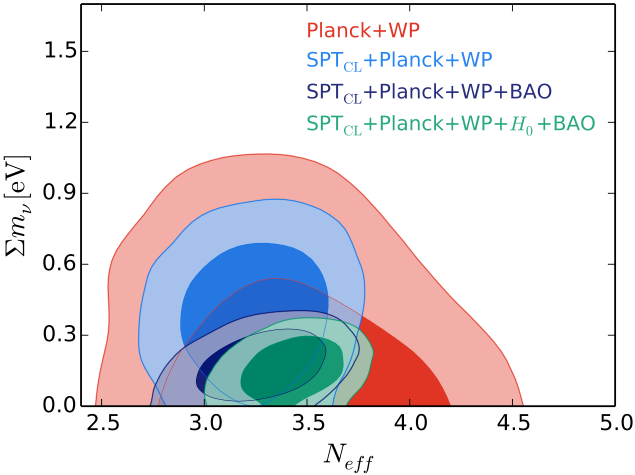


J. Becker, Phys. Rep. 2008

- MeV astrophysical neutrinos have revealed a huge amount of physics over the last 45 years
- First detections at meV and at PeV in the last few years
- Tremendously exciting time as we begin to characterize them

End

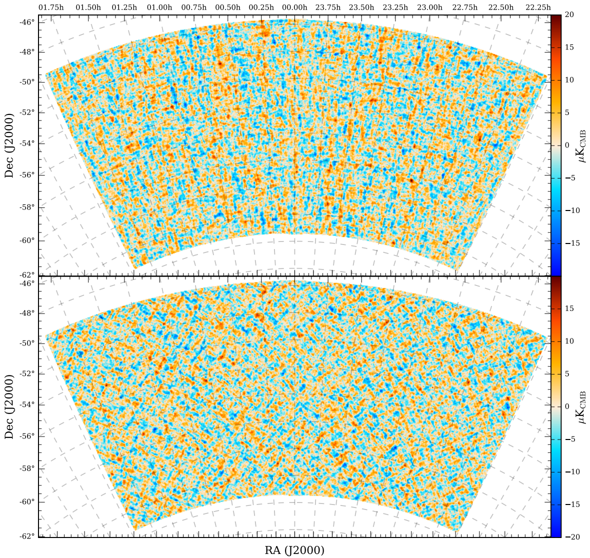
SPT Cluster Results



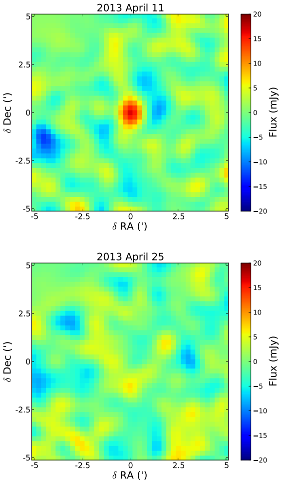
arXiv:1603.06522

- Clusters provide a powerful late-time tracer
- $\sum m_\nu = 0.16 \pm .08$ eV
- Limited by mass calibration

500d EE Results PRELIMINARY

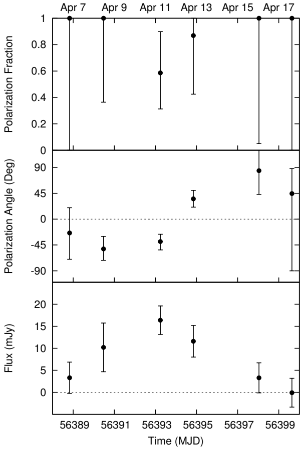


SPTpol transient



- Analysis to look for orphan GRB afterglows, which peak in mm band
- One candidate object found on the sky for one week at 150 GHz
- Qualitatively similar to GRB afterglow, but extremely bright
- No sources known at this location

SPTpol transient



- Nearly 100% linearly polarized
- Independent 3.6σ evidence for a real source
- 90° polarization angle rotation consistent with off-axis jet break