Exploring the Hot and Cold Universe

John P. (Jack) Hughes
Rutgers University

Group Members

- Jack Hughes at RU since Sept 1996 (PhD: Columbia)
- Prasiddha Arunachalam grad student
- Peter Doze grad student
- Alumni/ae:
  - Steven Boada (Texas A&M) Data science
  - Amruta Deshpande (Florida, Rutgers) Data science
  - Luke Hovey (East Stroudsburg, Rutgers) Los Alamos National Lab
  - Kris Eriksen (Middlebury, Arizona) LANL
  - Felipe Menanteau (Católica, Cambridge) NCSA, Illinois
  - Neelima Sehgal (Yale, Rutgers) Assoc Prof, StonyBrook
  - Carles Badenes (PhD: Barcelona) Assoc Prof, Pittsburgh
  - Jessica Warren (Vassar, Rutgers)
  - Cara Rakowski (Brown, Rutgers) Patent Office

Job Prospects

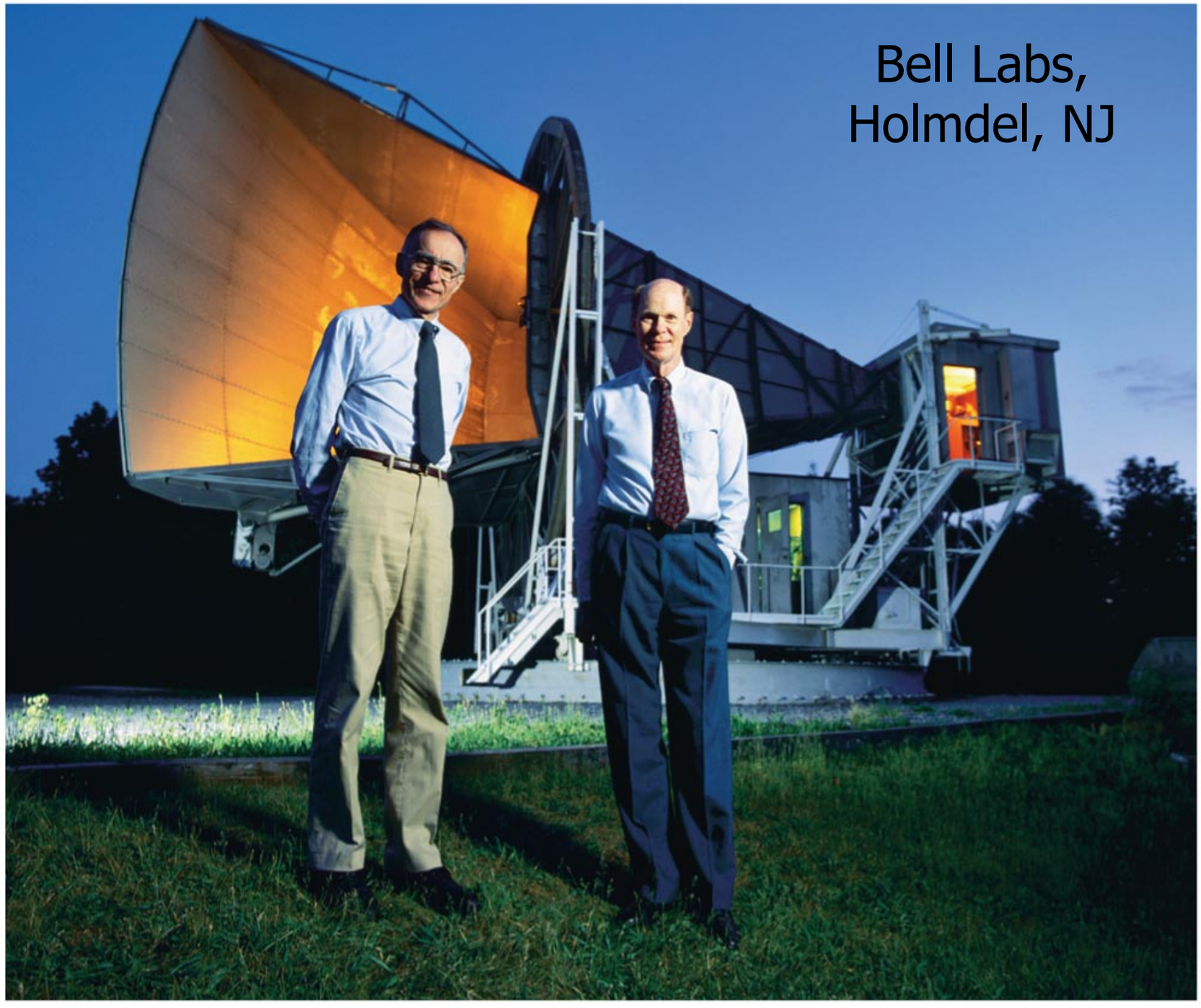
Recent RU astronomy PhD graduates obtained jobs in industry, teaching colleges, NASA centers, government labs, academic post-docs, and research universities
http://www.physics.rutgers.edu/ast/group-ast.html

American Astronomical Society (resource for careers):
http://aas.org

Job Register
https://jobregister.aas.org

Astrophysics Jobs Rumor Mill - Postdoc & Term (>200 PD jobs, ~100 tenure-track faculty jobs this season)
http://www.astrobetter.com/wiki/Rumor+Mill

The Cold Part

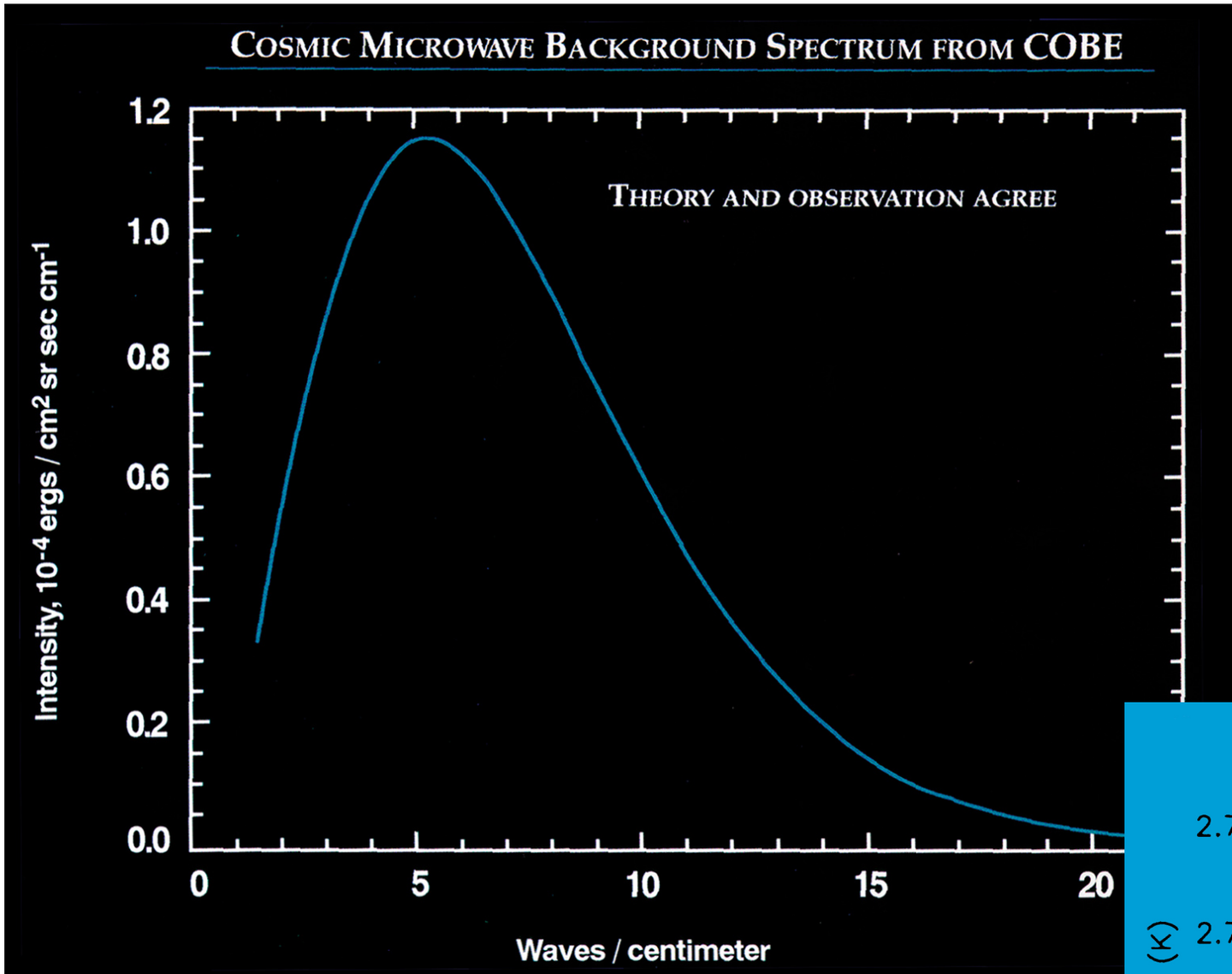


The ***cosmic microwave background***—the radiation left over from the Big Bang—was detected by Penzias and Wilson in 1965 in New Jersey!

1978 Nobel Prize in Physics to Penzias and Wilson

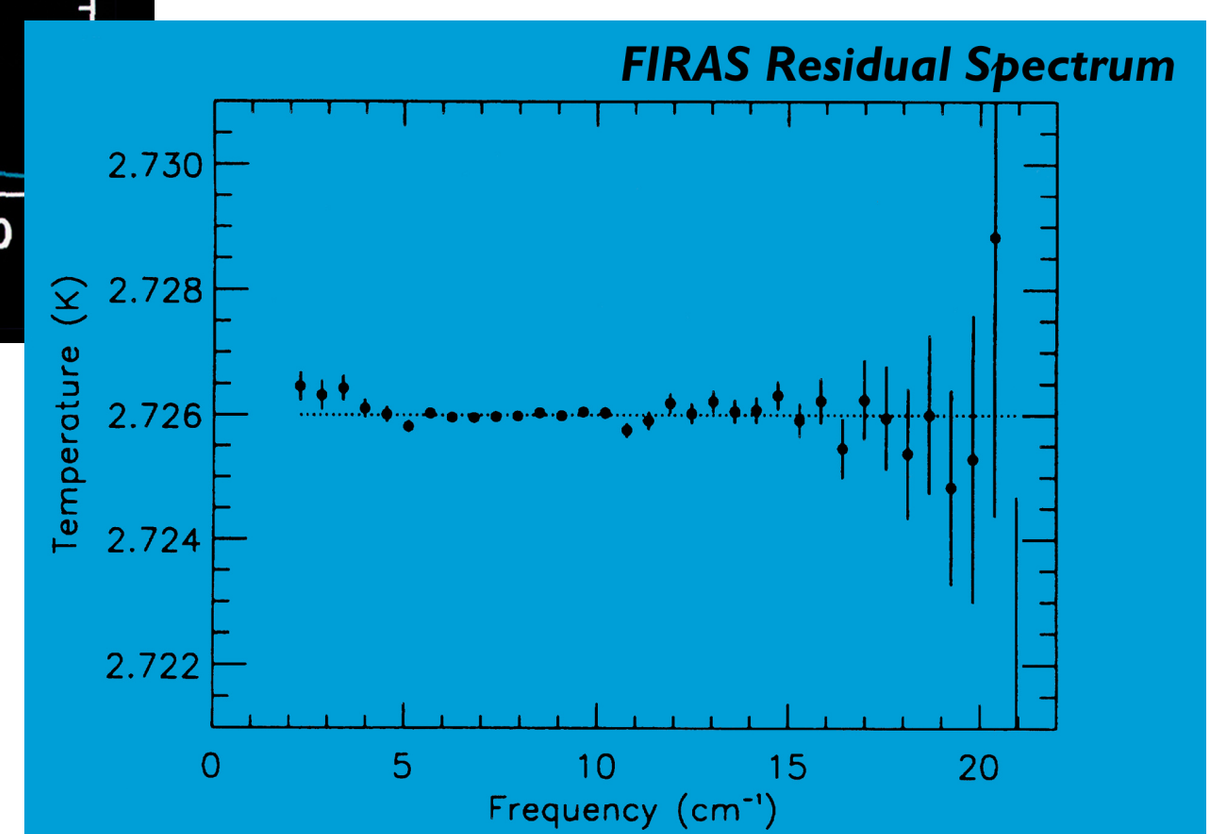
Published as "A Measurement of Excess Antenna Temperature at 4080 Mc/s"

NASA COBE (Launched 1989)

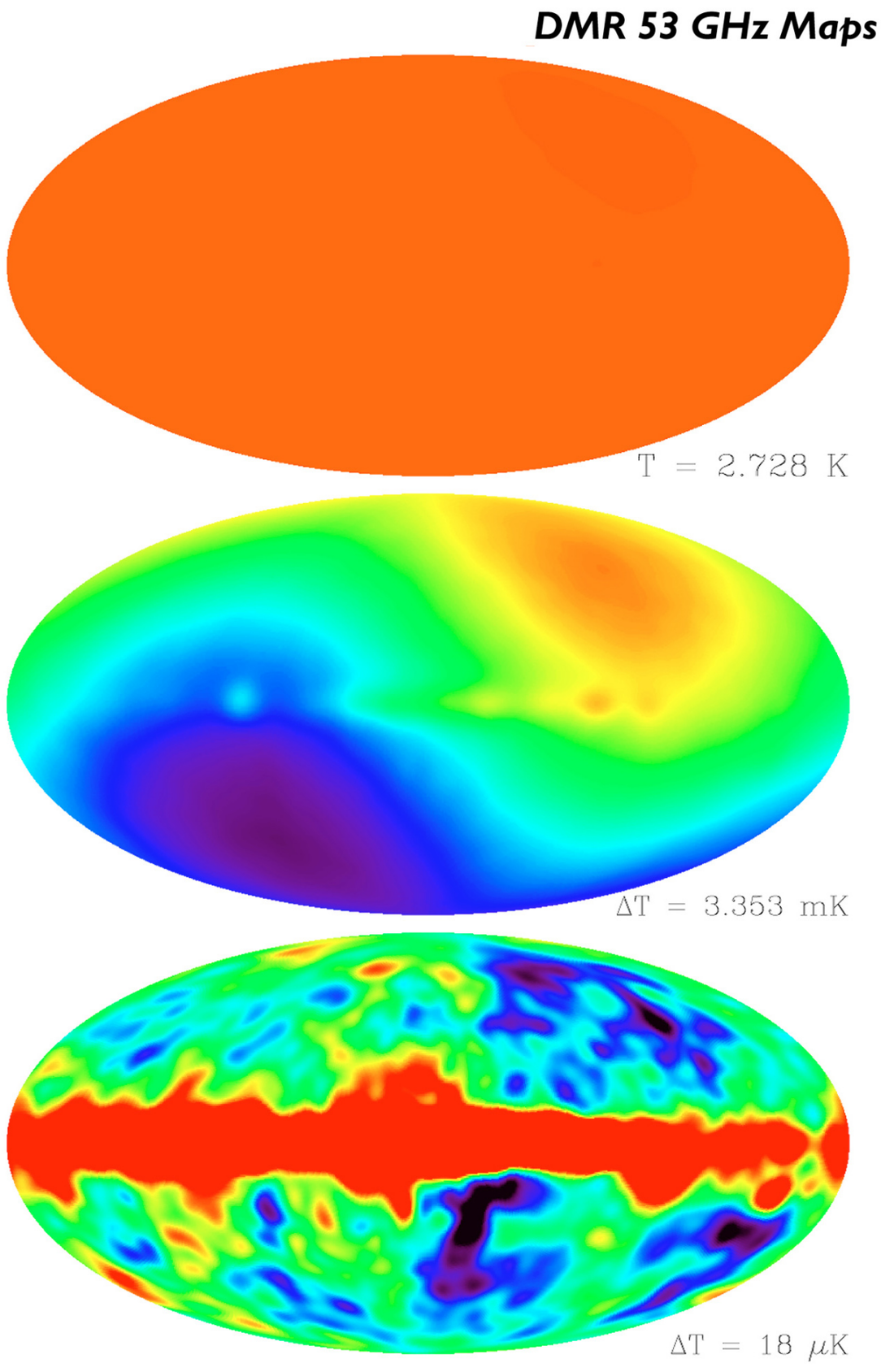


Measured nearly perfect blackbody spectrum with a temperature of 2.725 +/- 0.002 K

Blackbody radiation comes from objects in thermal equilibrium



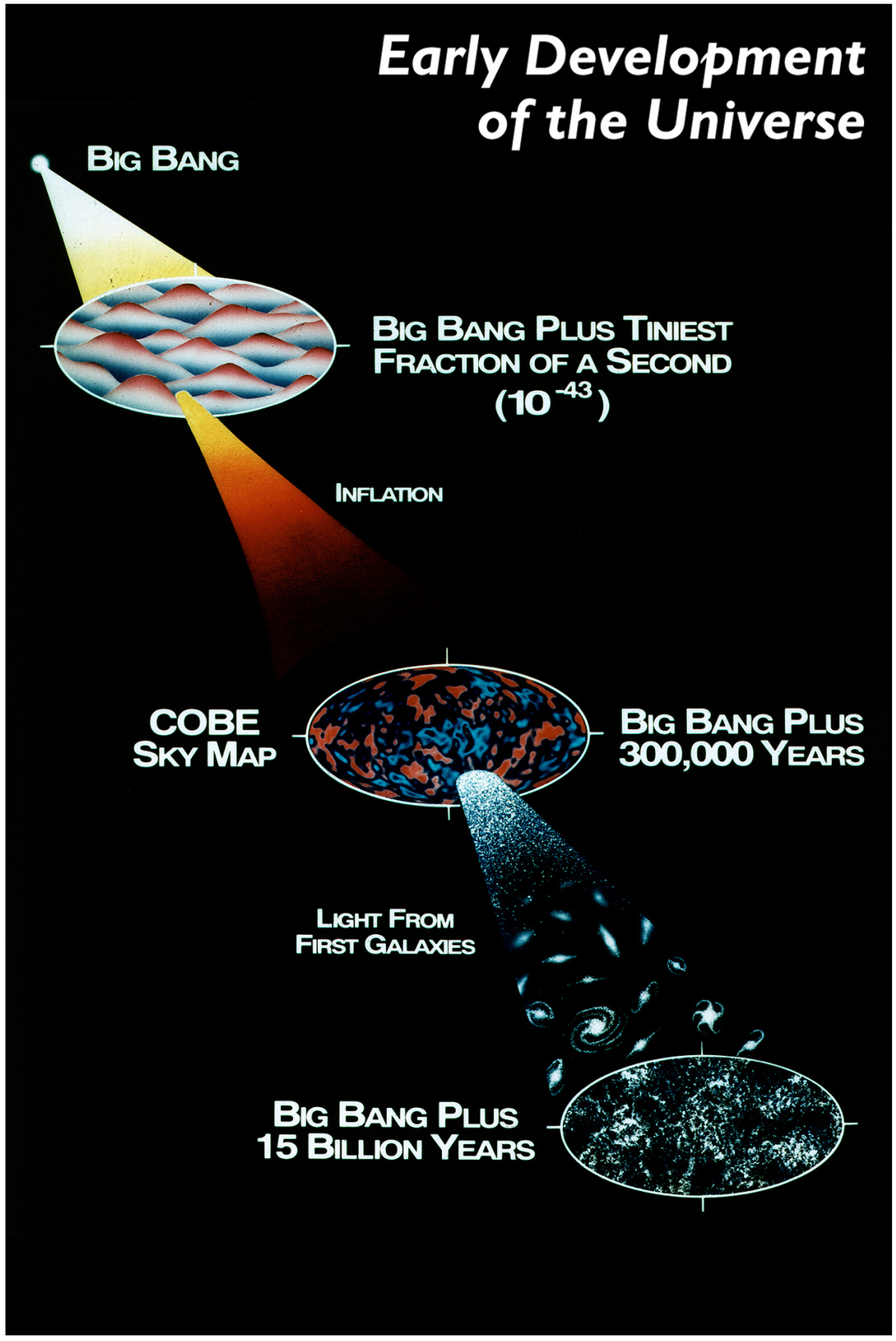
Cosmic Microwave Background (CMB)



NASA/COBE satellite 4-yr all-sky maps

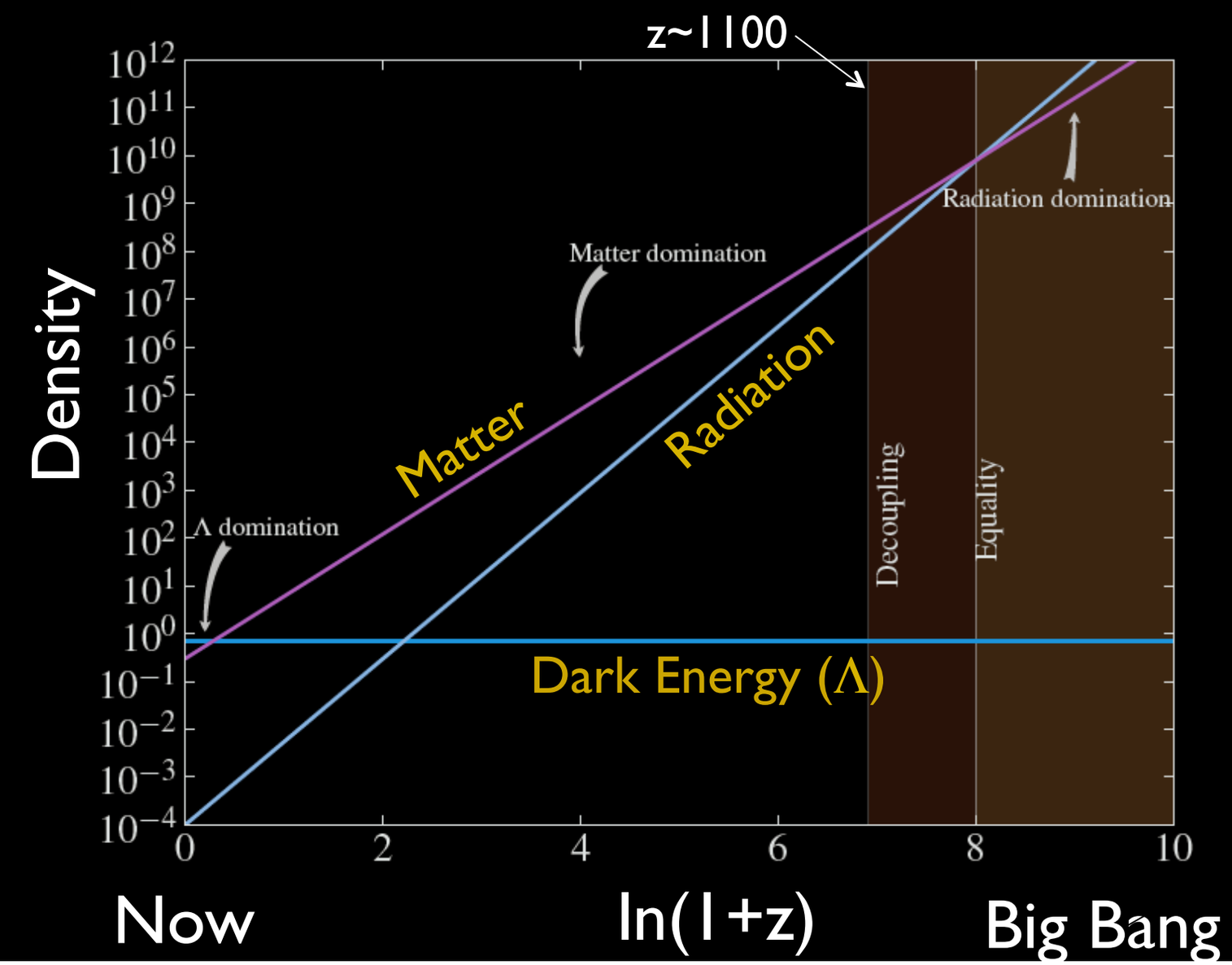
- Top: 0 - 4 K scale <T>~2.7K
- Middle: emphasize dipole from Earth's motion (1 part out 1000)
- Bottom: after subtraction of dipole; cosmic anisotropy at 1 part out of 100,000

2006 Nobel Prize in Physics to Mather and Smoot



- CMB is the relic of a hot early phase of the Universe
- Strong evidence that the Universe went through a hot, dense "Big Bang" phase
- CMB comes to us from a time when the Universe had cooled enough for atoms to form (~380,000 yrs)

Evolution of Universal Density



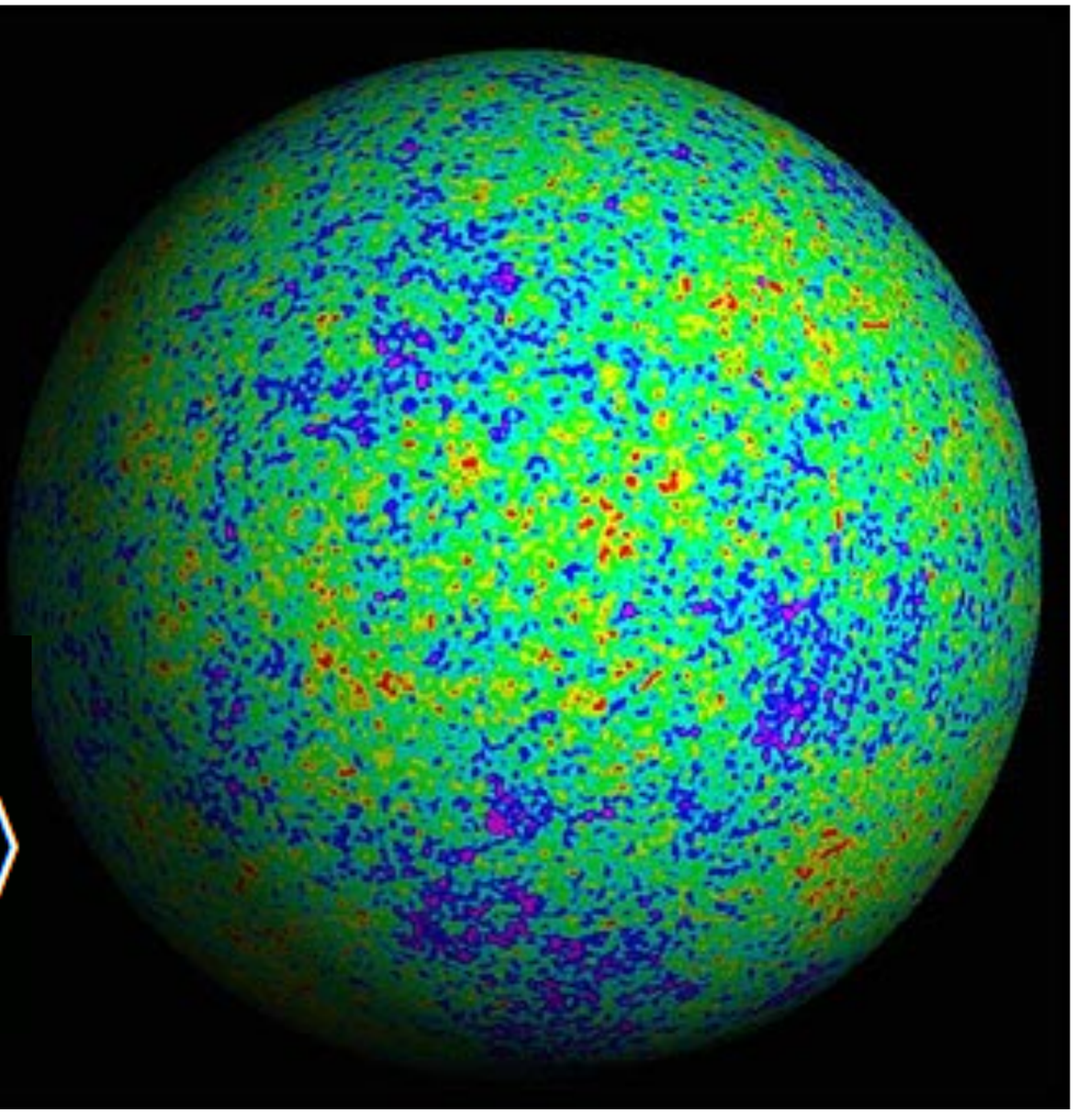
Linear theory ➔ "clean" physics

Basic elements well understood

Analyzing the CMB

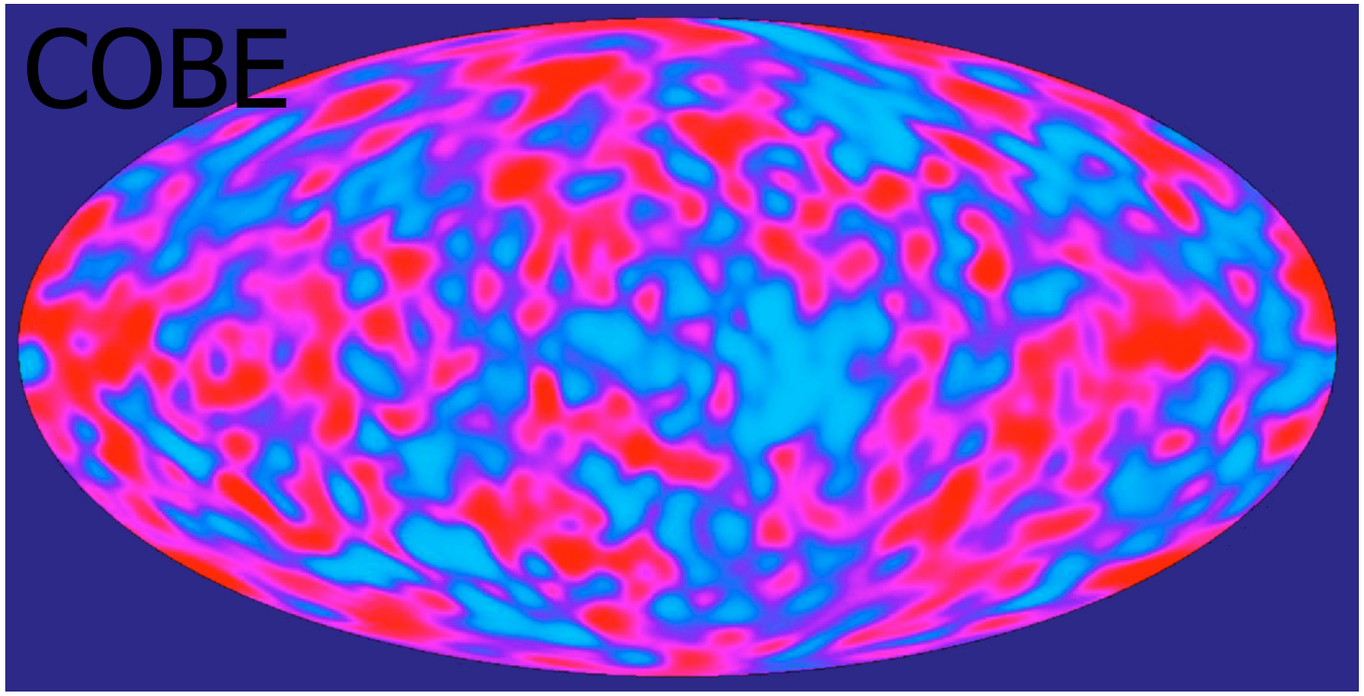
$$T(\hat{\mathbf{n}}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

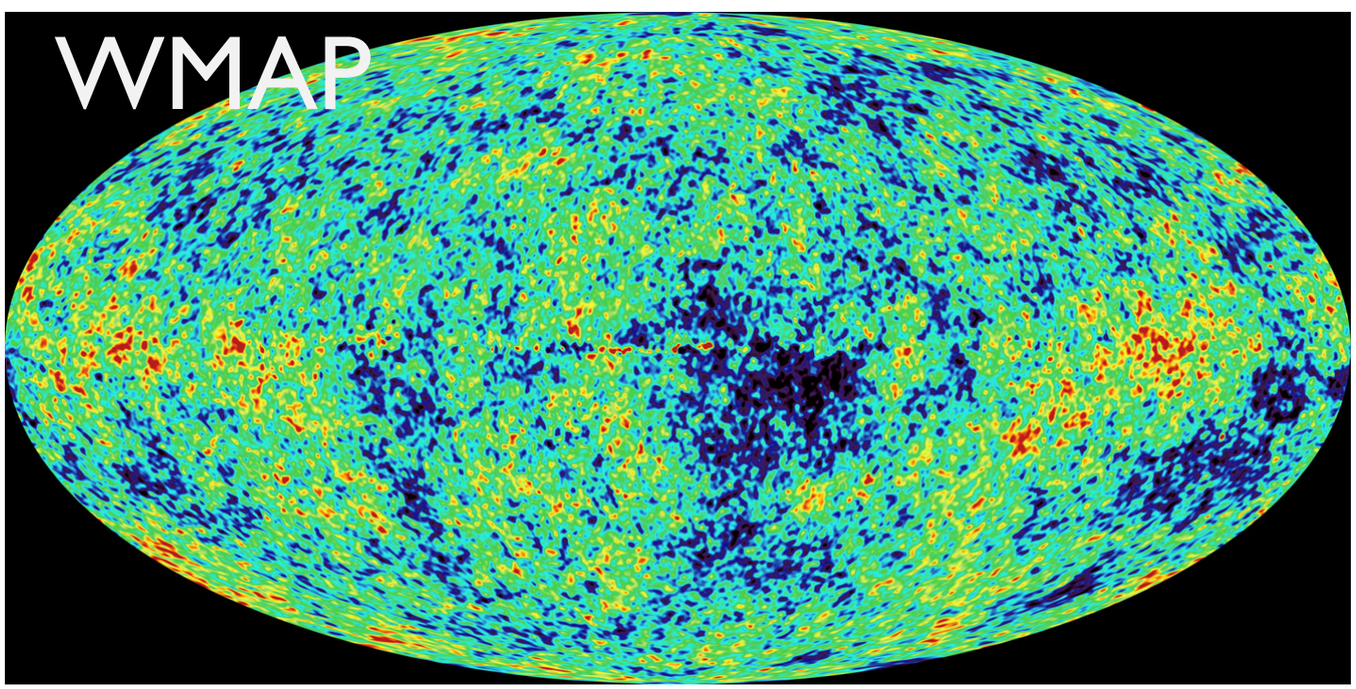
$$C_\ell = \frac{1}{(2\ell+1)} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}|^2 \rangle$$

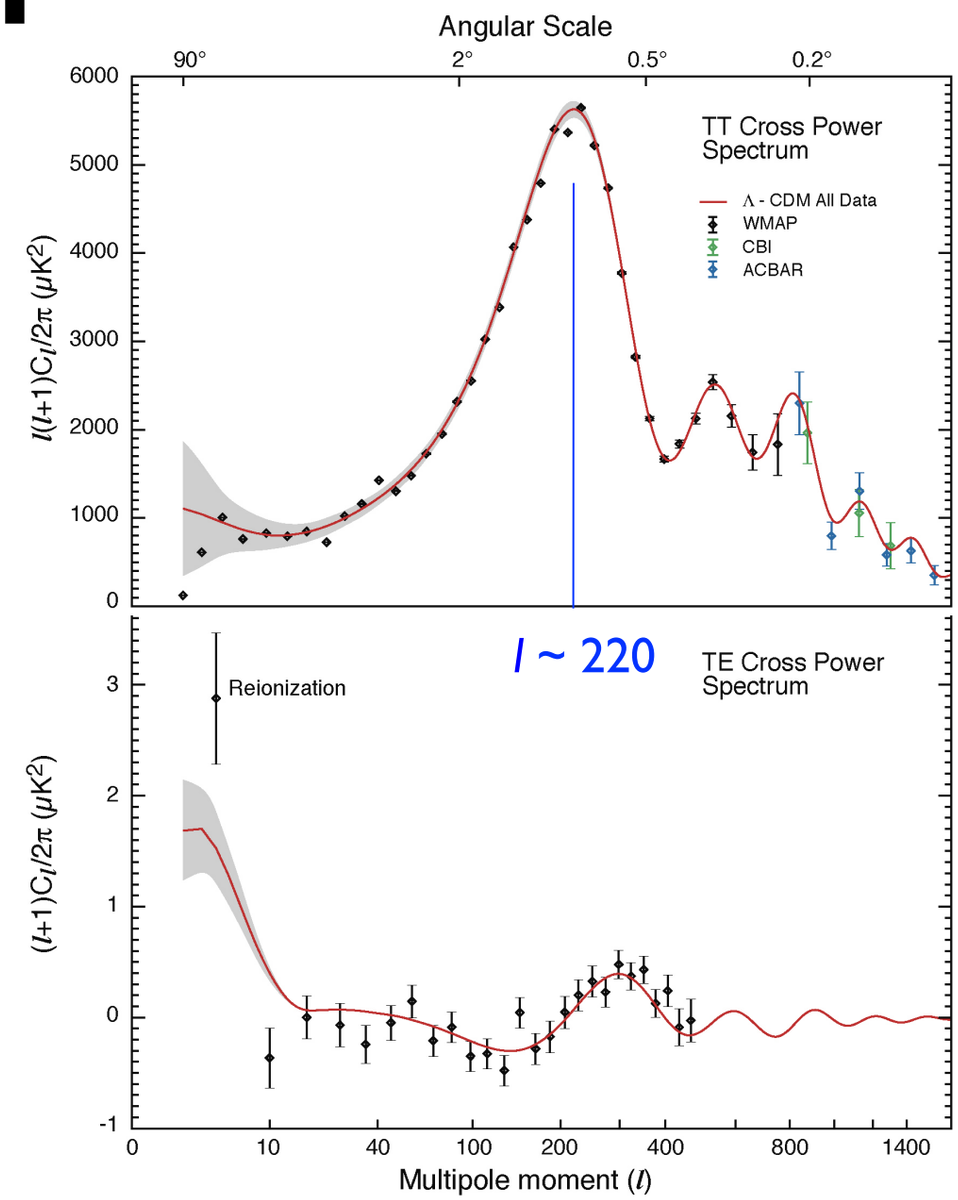


Primordial CMB power spectrum fit by 6 parameter Λ-Cold Dark Matter (ΛCDM) model: baryon density, CDM density, Λ, amplitude and tilt of the matter power spectrum, and optical depth to reionization

Anisotropies

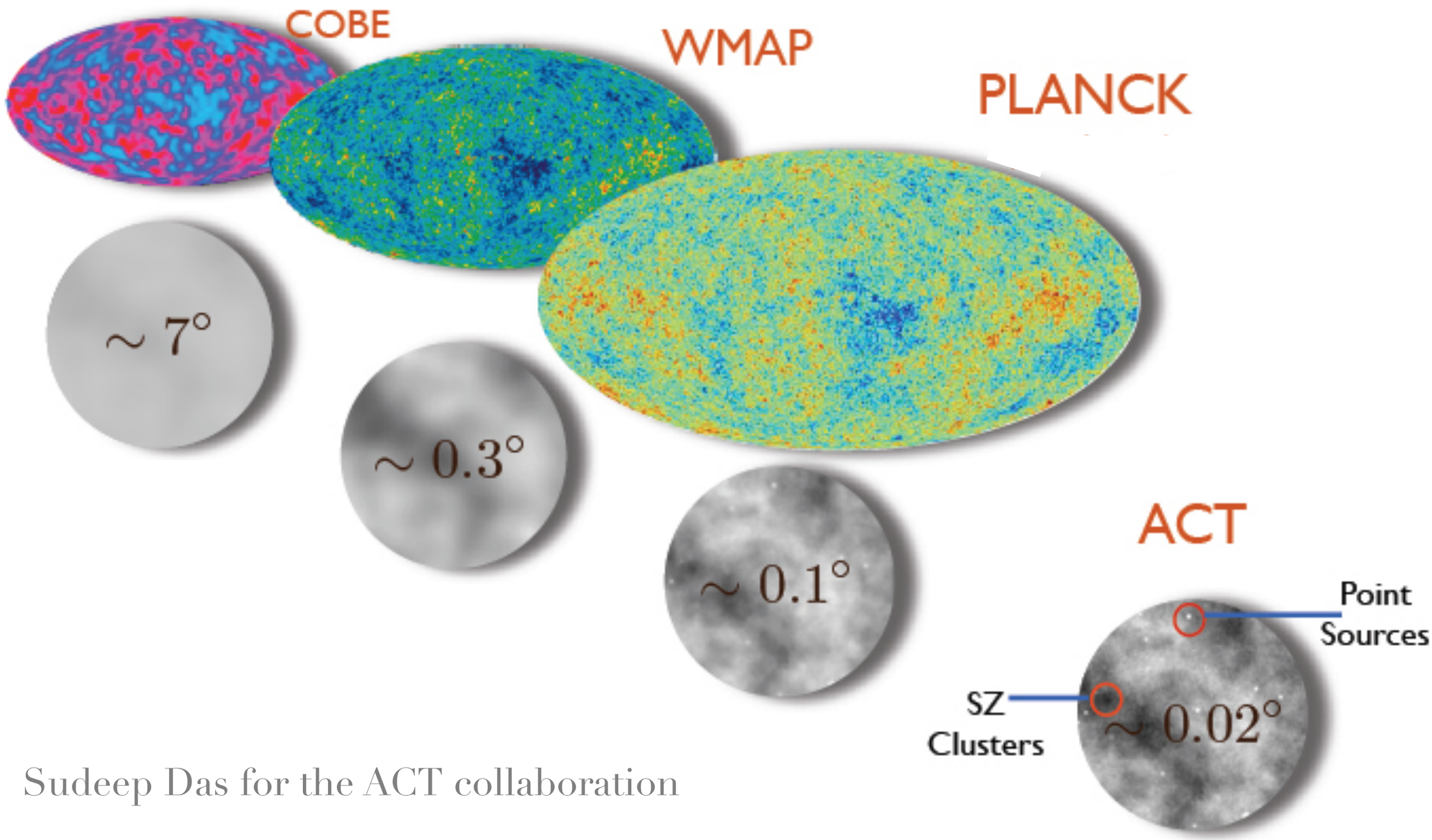






CMB angular power spectrum

The Push for Higher Resolution CMB Maps



Sudeep Das for the ACT collaboration

Atacama Cosmology Telescope

Custom built 6-m telescope and mm-wave camera

Measure arcmin-scale fluctuations in the Cosmic Microwave Background (vs. ~10 arcmin for WMAP and ~5 arcmin for Planck)

Proposed in 2000, funded in 2003

Construction finished in 2007: three full years (2008, 2009, 2010) of survey completed

Upgraded for polarization in 2013

Approved for AdvancedACTPol (2016-…)

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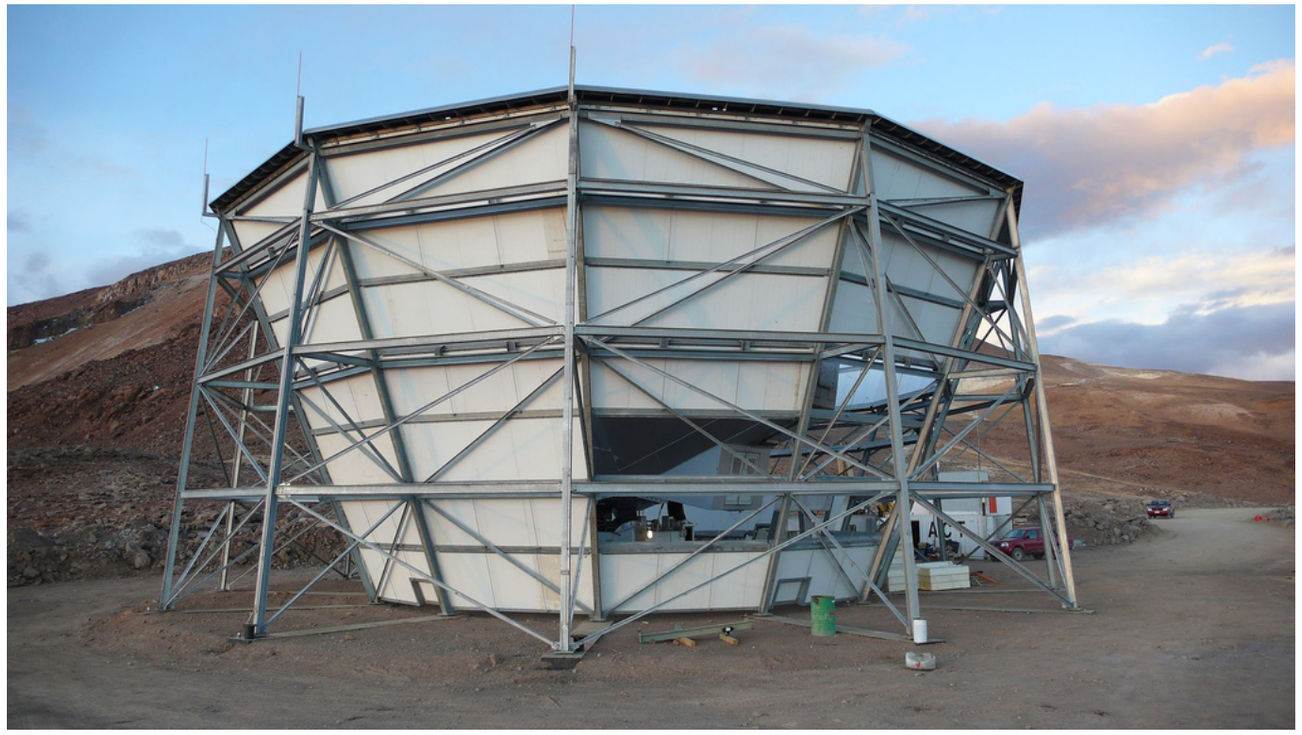

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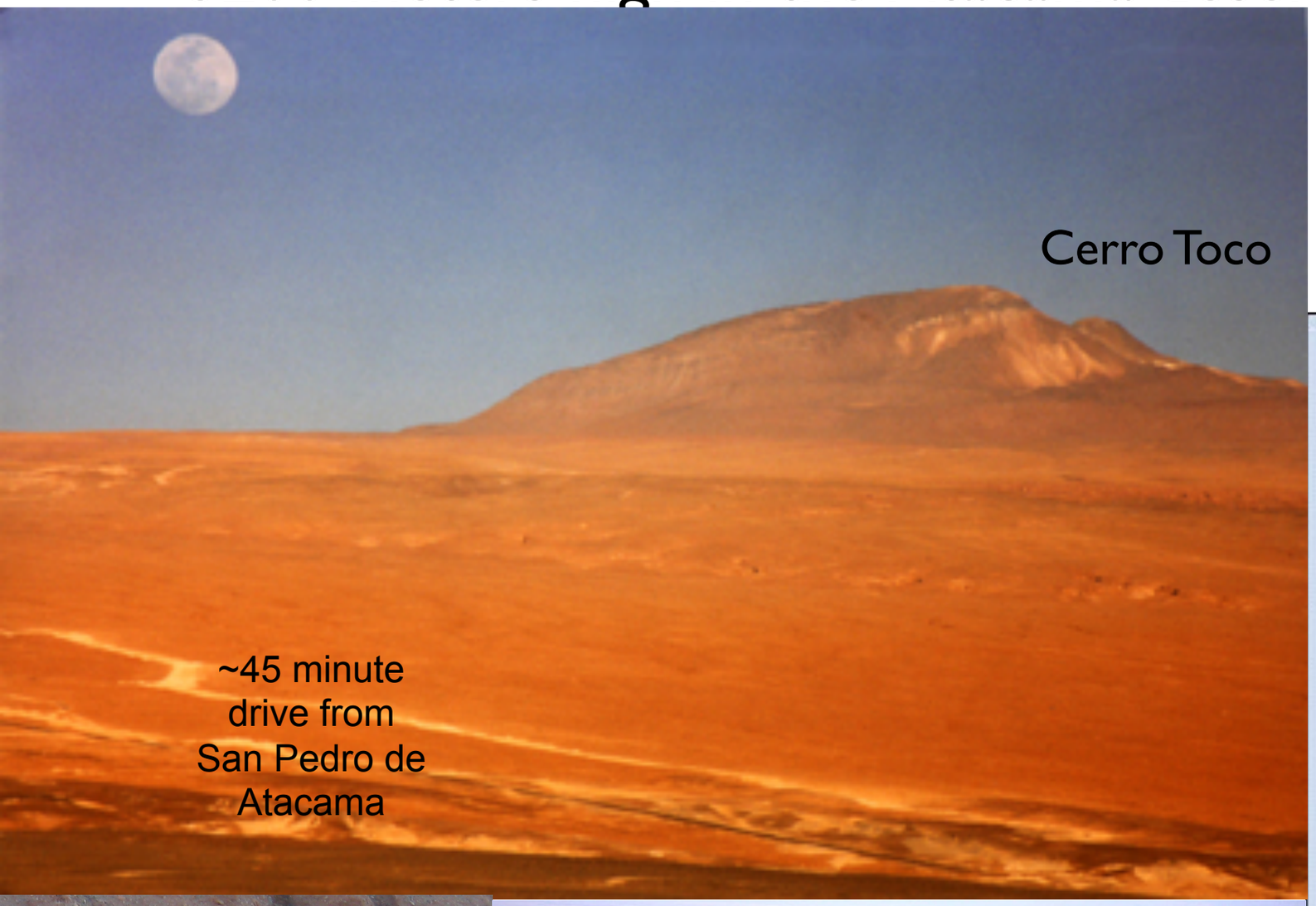
ACT Site

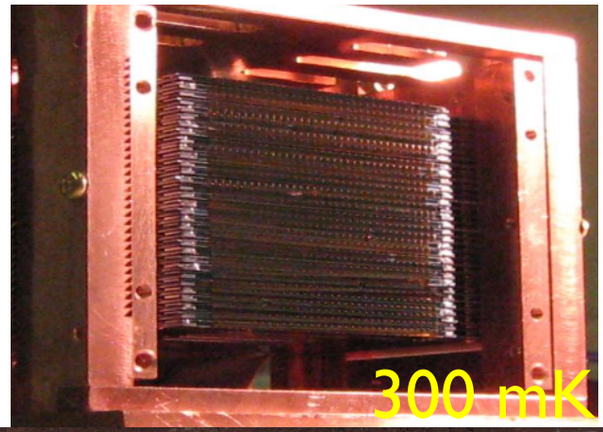
5200 meters high in the Atacama desert of the Chilean Andes

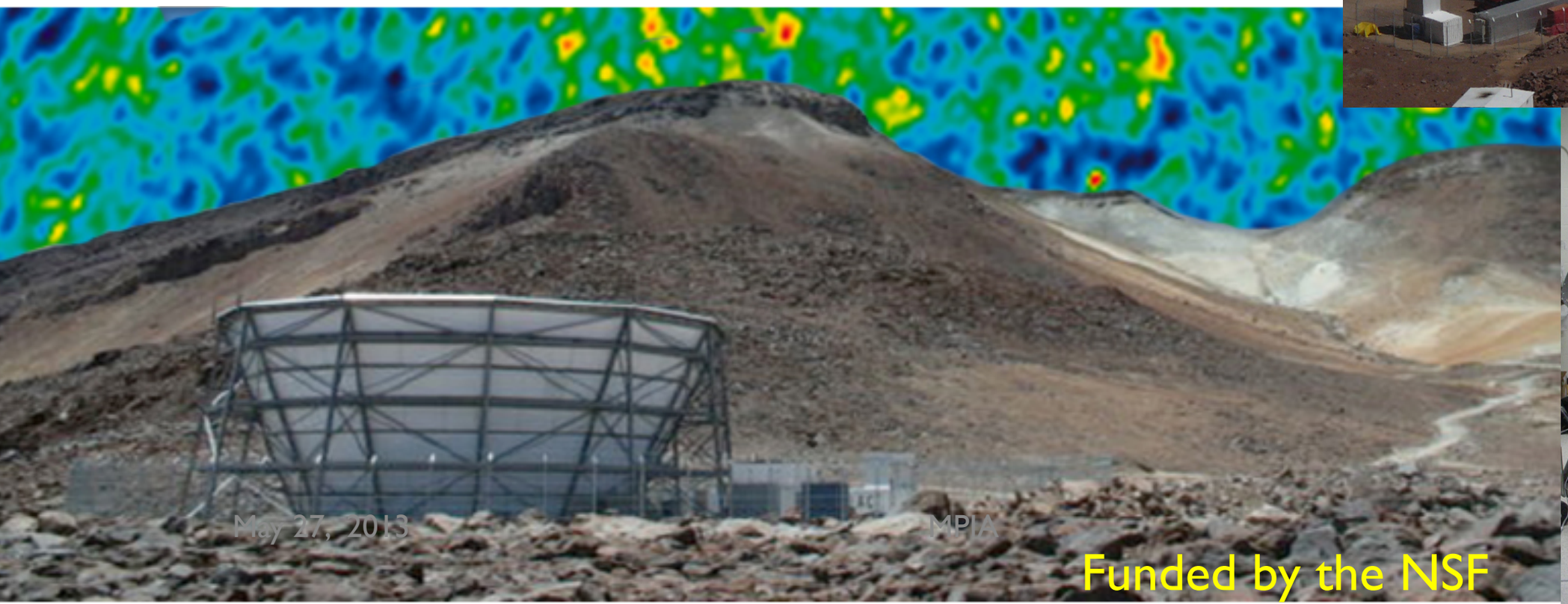


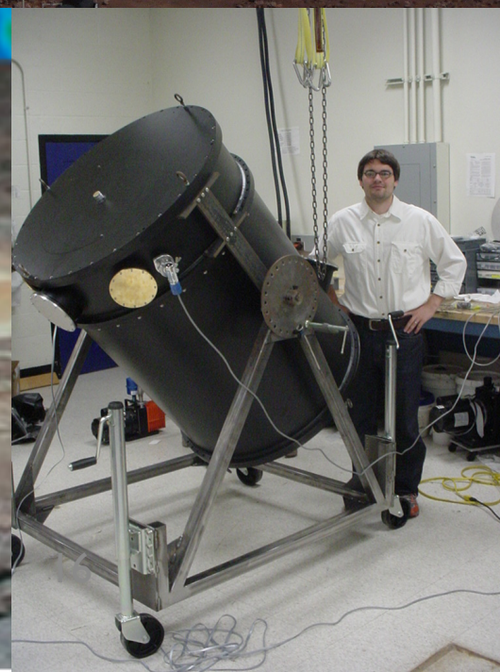
Latitude: 23 deg south
Not far from the ALMA site

The ACT Site, Telescope, and Sensors

- High: One of the highest telescopes on Earth
- Dry: 0.49 mm median Precipitable Water Vapor
- 6-m primary mirror; off-axis Gregorian design
- Three 1000 pixel arrays of Transition Edge Sensors
- Observing frequencies: 148, 218, 277 GHz
- Diffraction limited (~1 arcmin resolution)
- Scans in azimuth 2° per second
- Low ground pick-up (groundscreens)



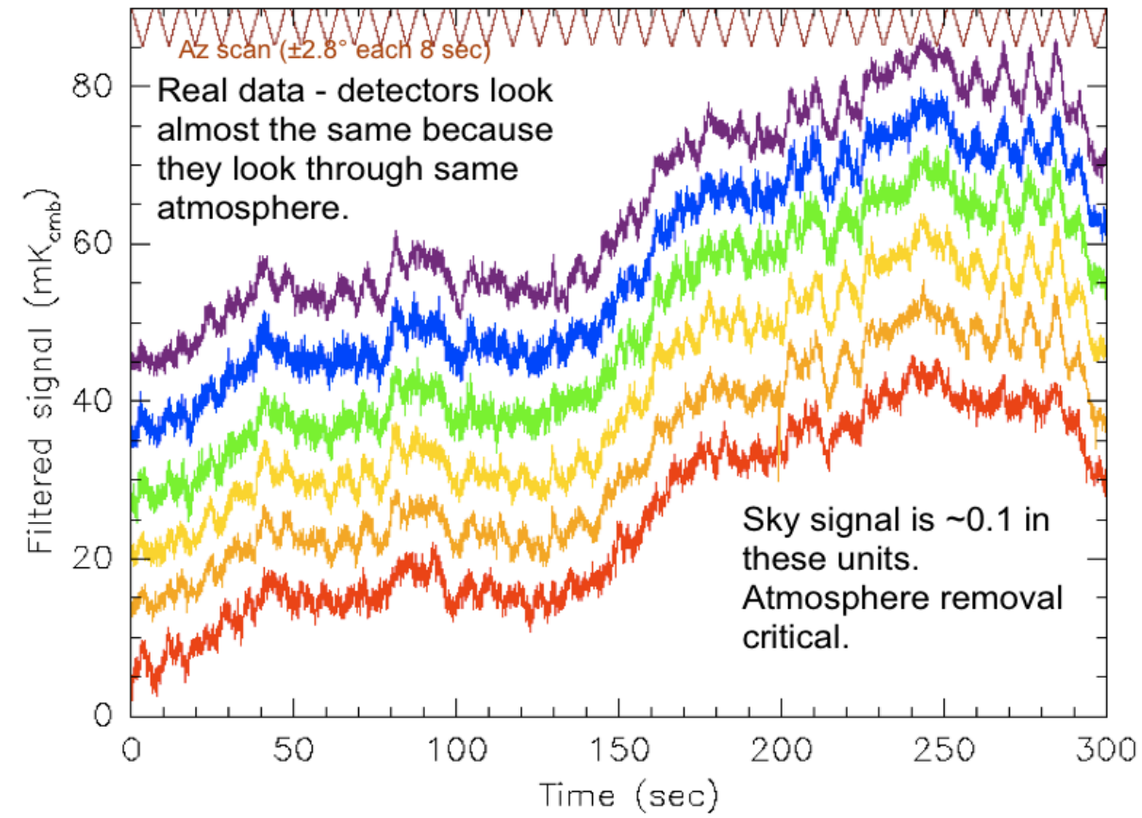




Funded by the NSF

Making Maps

Challenge - data from telescope/ sensors (right) doesn't look like the sky (below). Noise is complicated, includes correlations between detectors from atmosphere, etc.



Unbiased estimate of all modes from *ell* ~ 100 - 10000

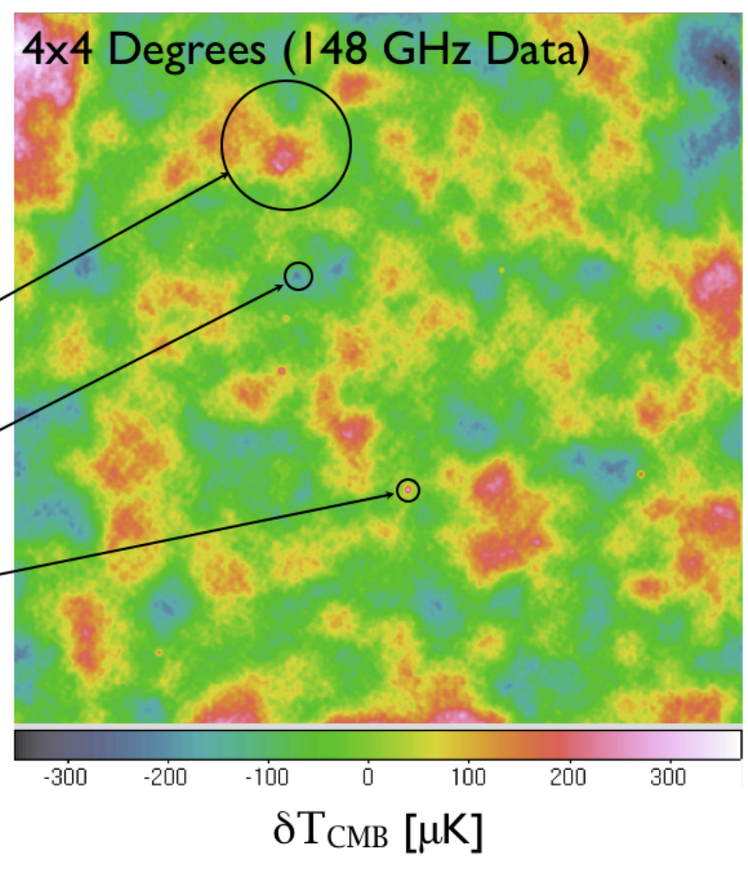
Atmosphere: 2 deg
(Filtered Here)

CMB: 1 deg

Clusters*: (>1.4')-4'

Sources*: 1.4'

* Minimum size set by beam

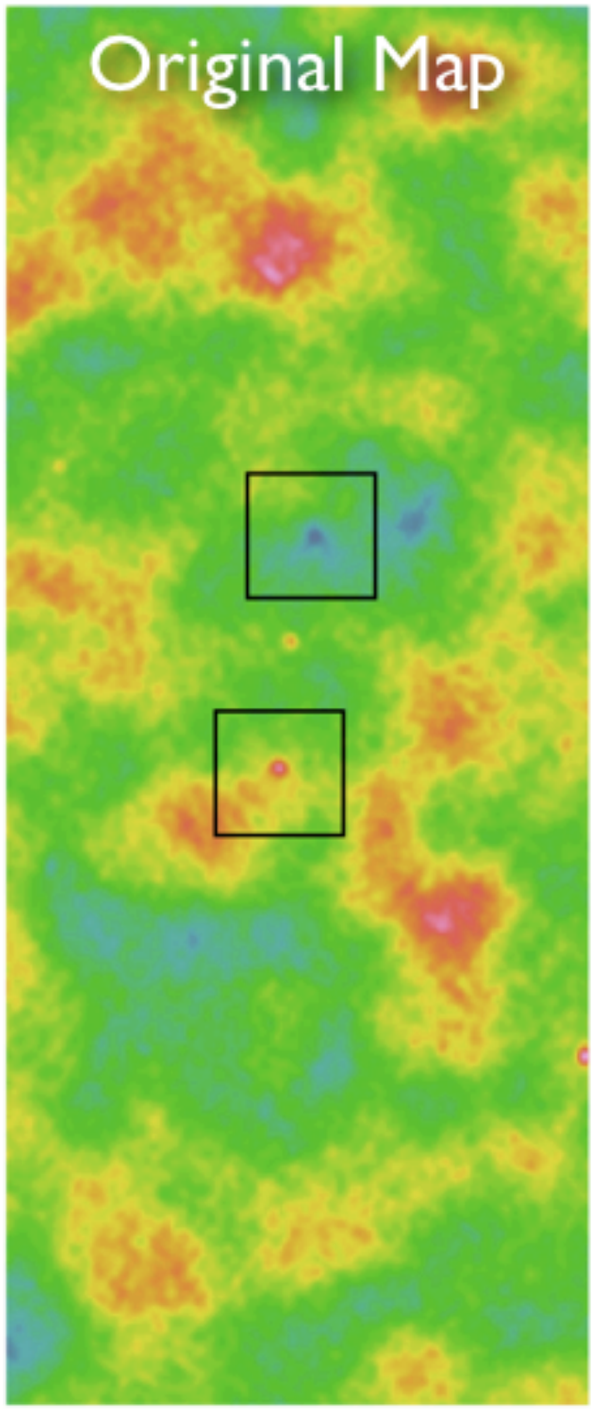


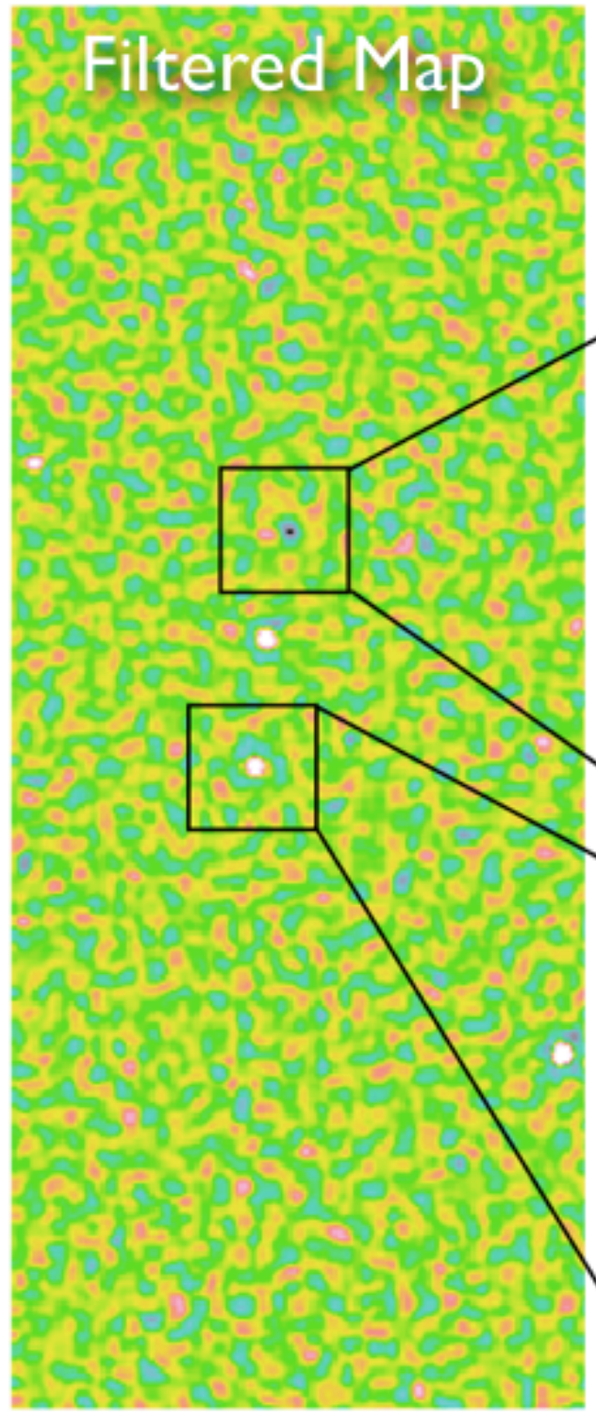
First task is to convert time-ordered-data streams into maps: use multiple "views" of CMB sky on different timescales and with different pixels to construct a maximum likelihood map.

ACT uses custom-built software running on SciNet – large supercomputer at CITA

The goal is an unbiased estimate of all modes from degree to arcmin scales

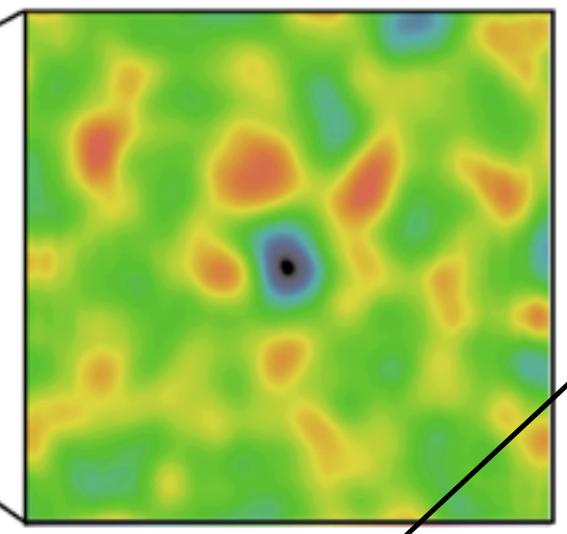
Detecting Sources and Clusters



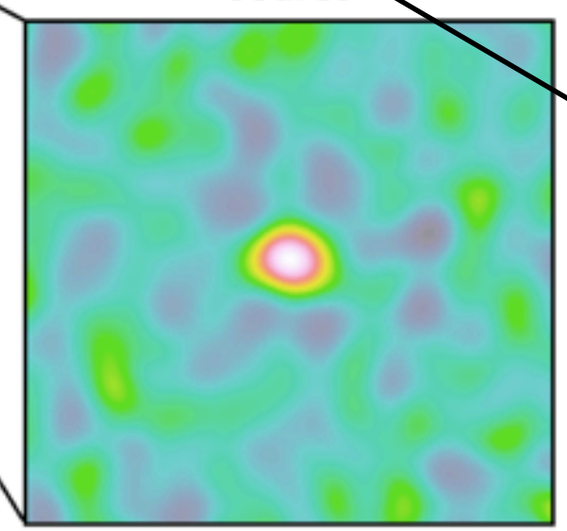


Match Filtering and Extraction

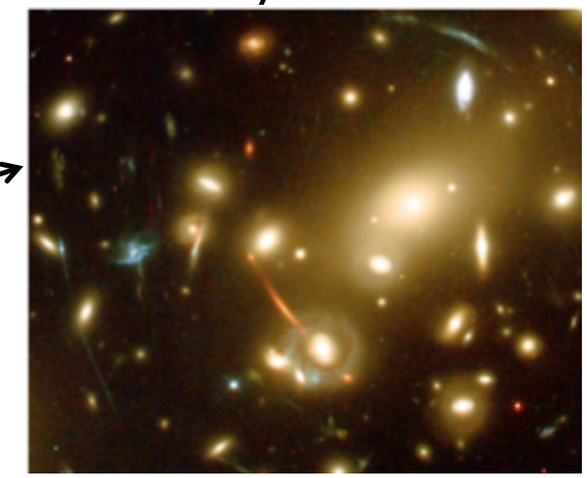
Cluster



Source

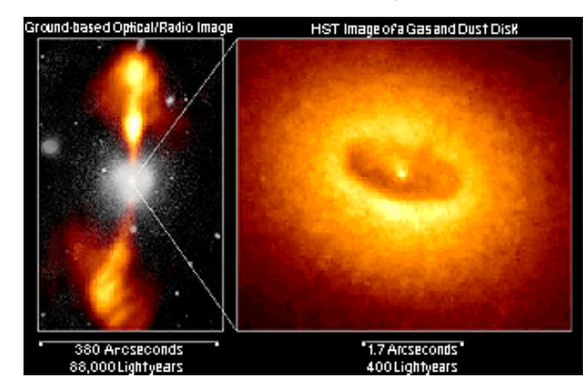


Galaxy Clusters



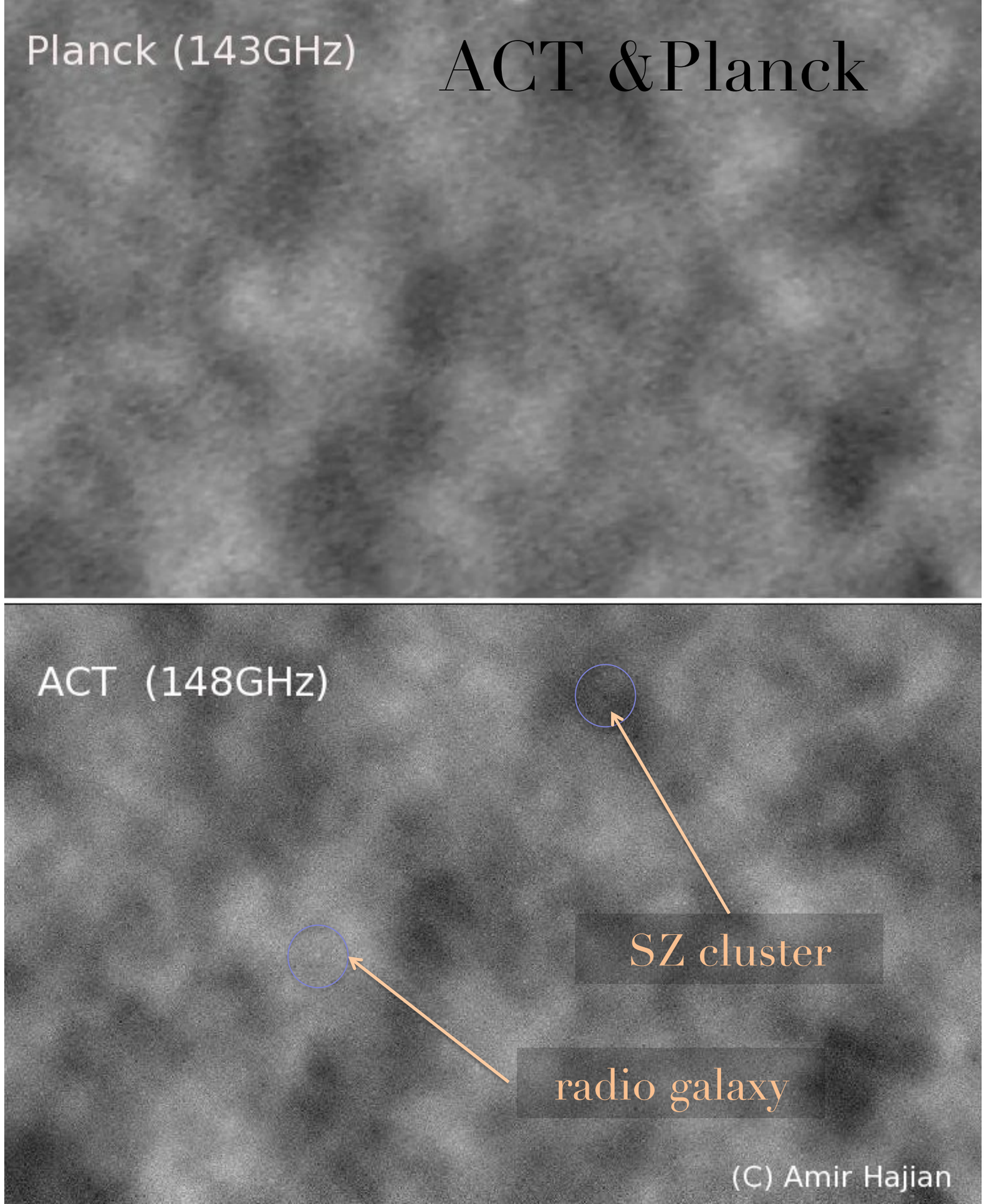
Dusty Starforming Galaxies

Radio Galaxies, AGN



Even with good maps, clusters are buried in the CMB.
At 148 GHz, clusters appear as decrements in the ACT data.

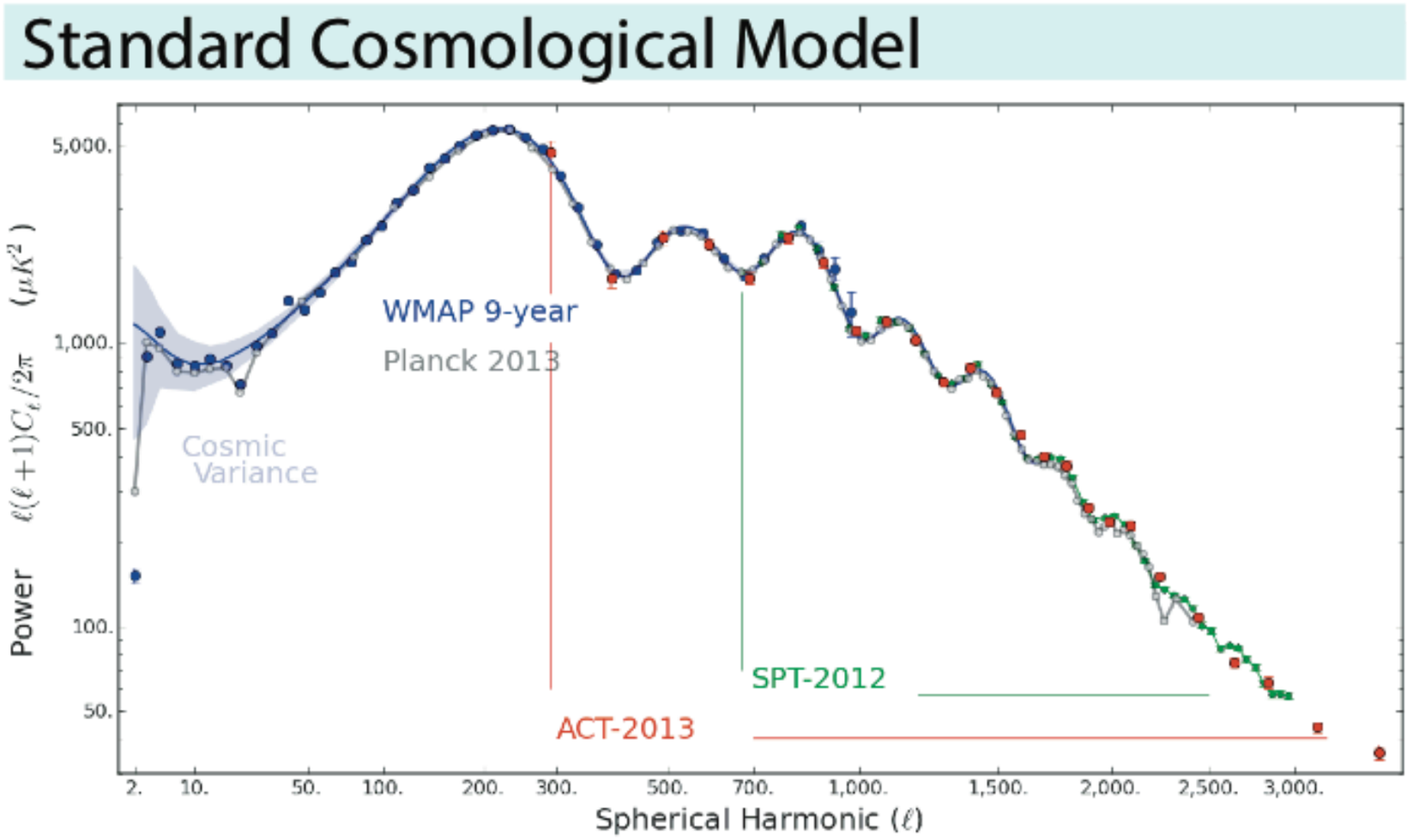
ACT &Planck



These fluctuations are the seeds of all structure in the Universe.

We use them as inputs to large N-body simulations that track the gravitational forces in the expanding Universe.

ACT Discovery Highlights 2011-2013

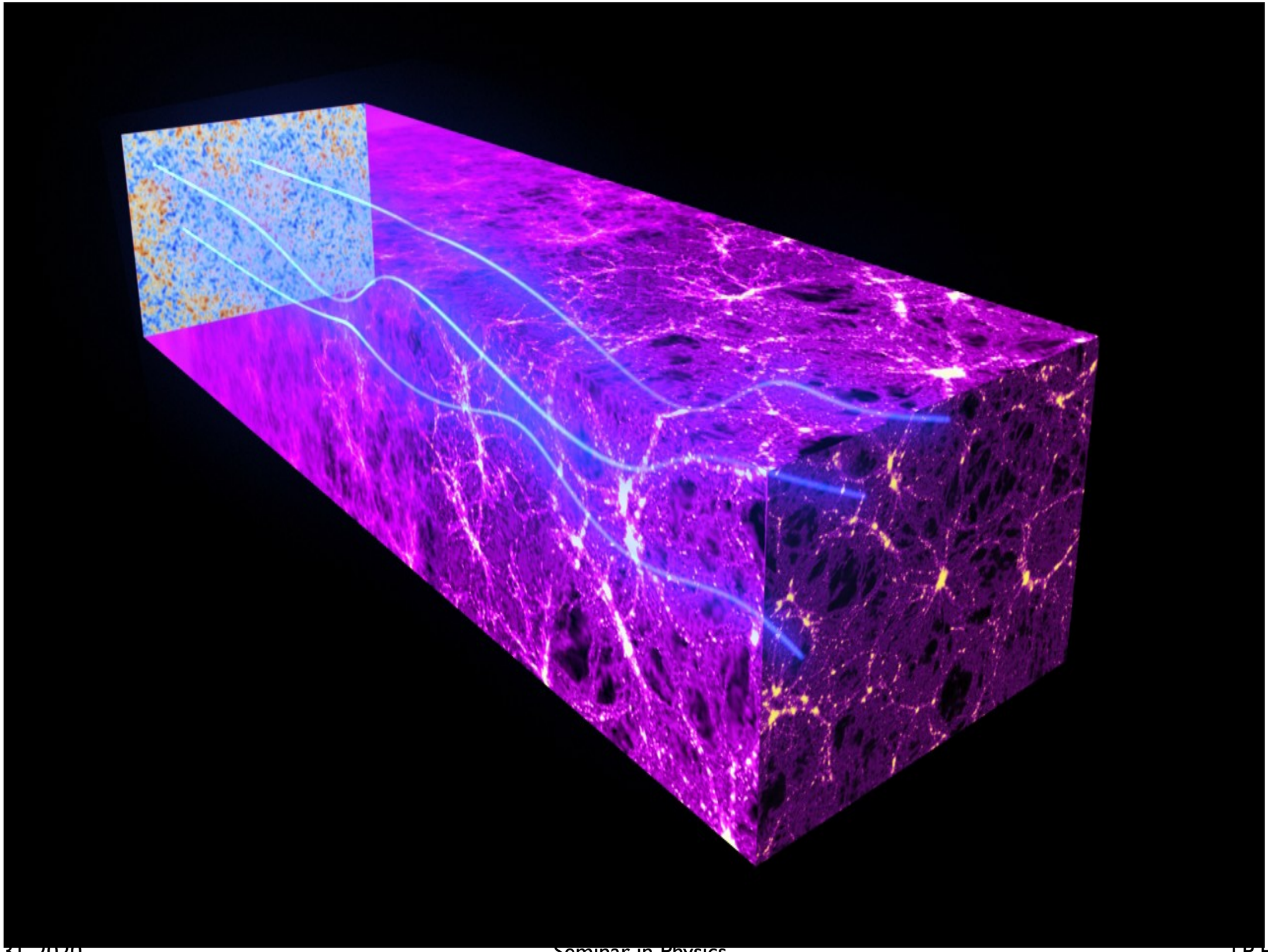


ACT first detected 7 acoustic peaks in the CMB

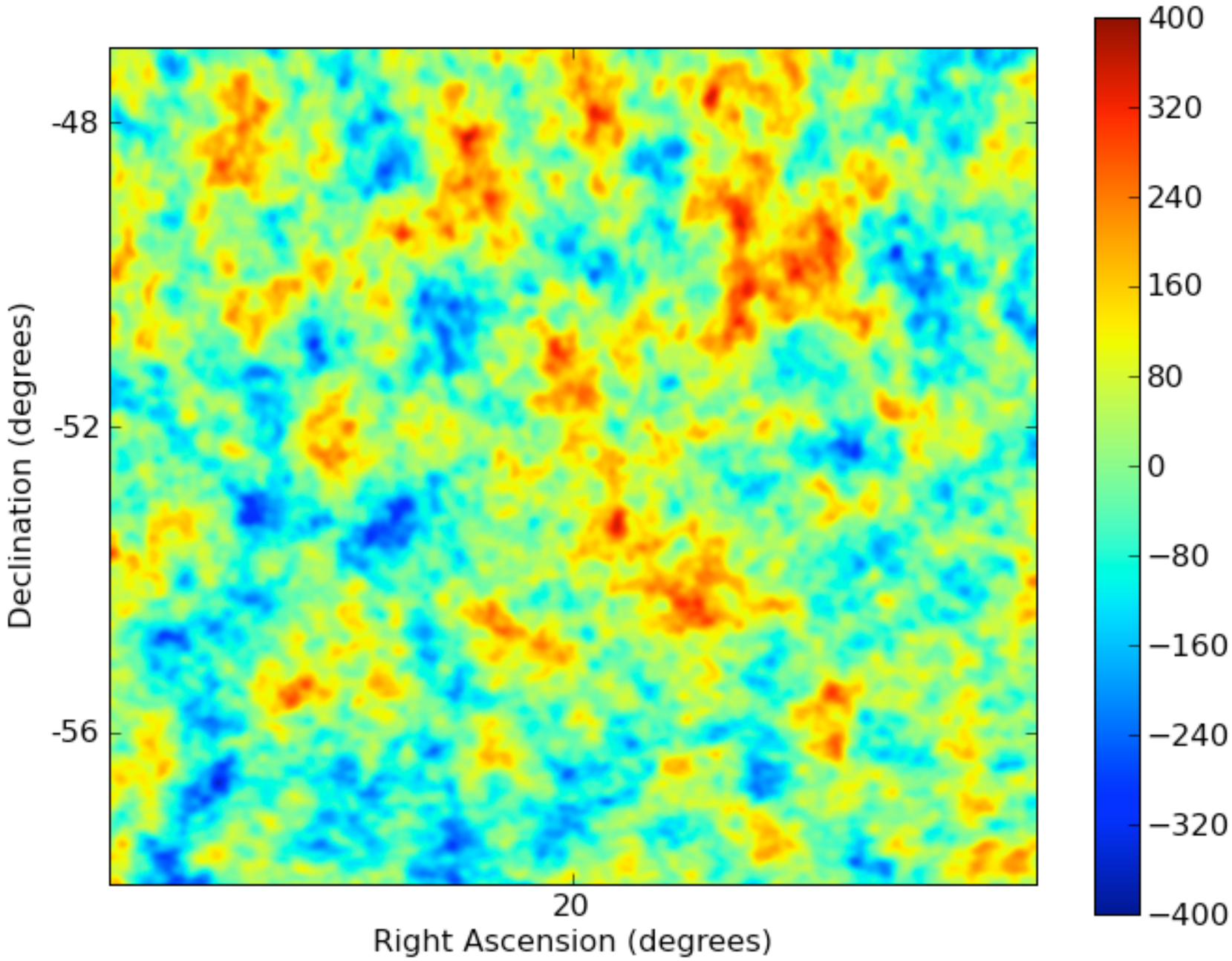
Das et al 2011, ApJ 729, 62
Dunkley et al 2011, ApJ, 739, 52
Sievers et al 2013, JCAP, 10, 60
Das et al 2014, JCAP, 4, 14

ACT, the South Pole Telescope, the WMAP satellite and the *Planck* satellite have provided the cornerstone for the standard ΛCDM cosmological model.

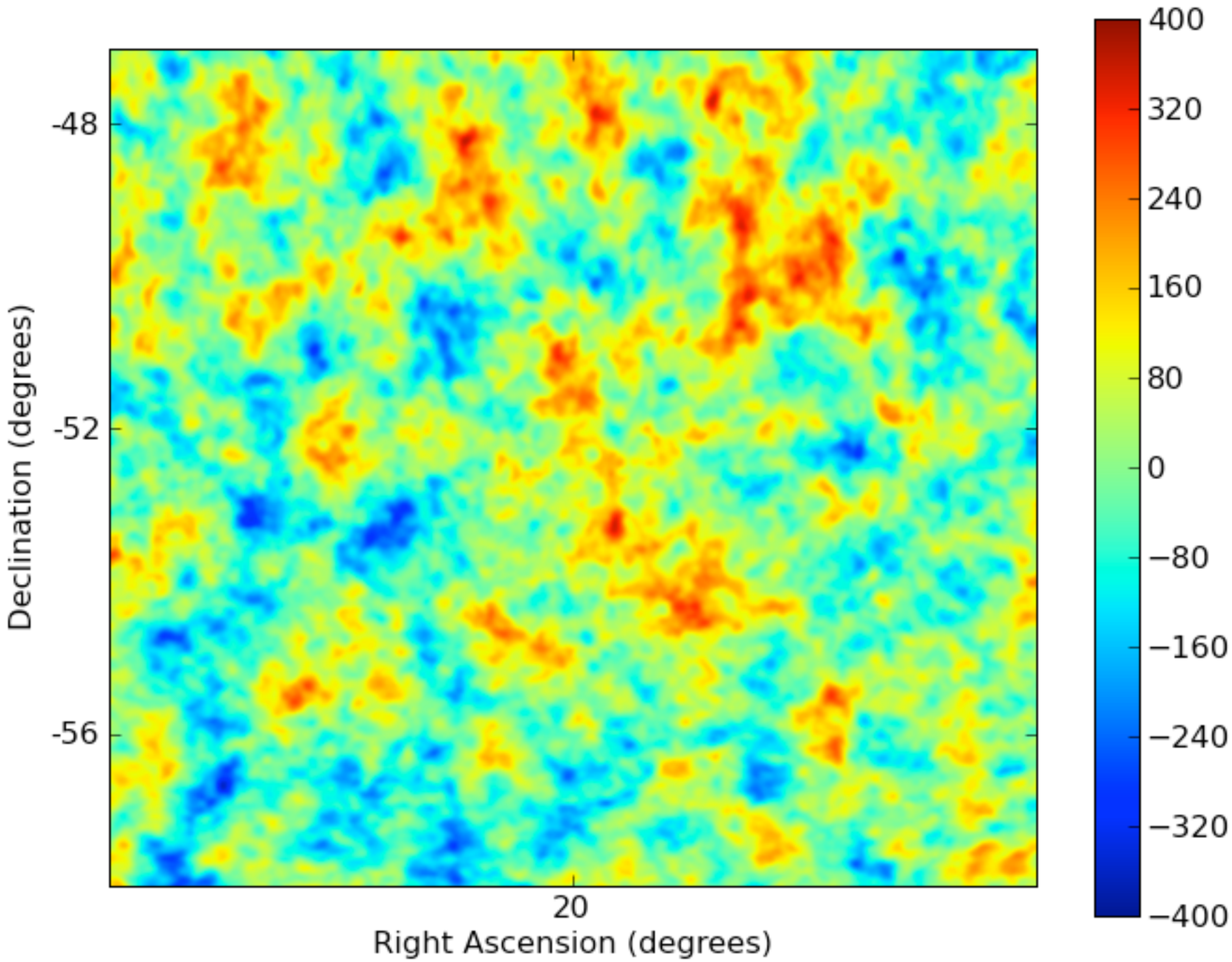
The CMB illuminates the Universe!



Unlensed CMB



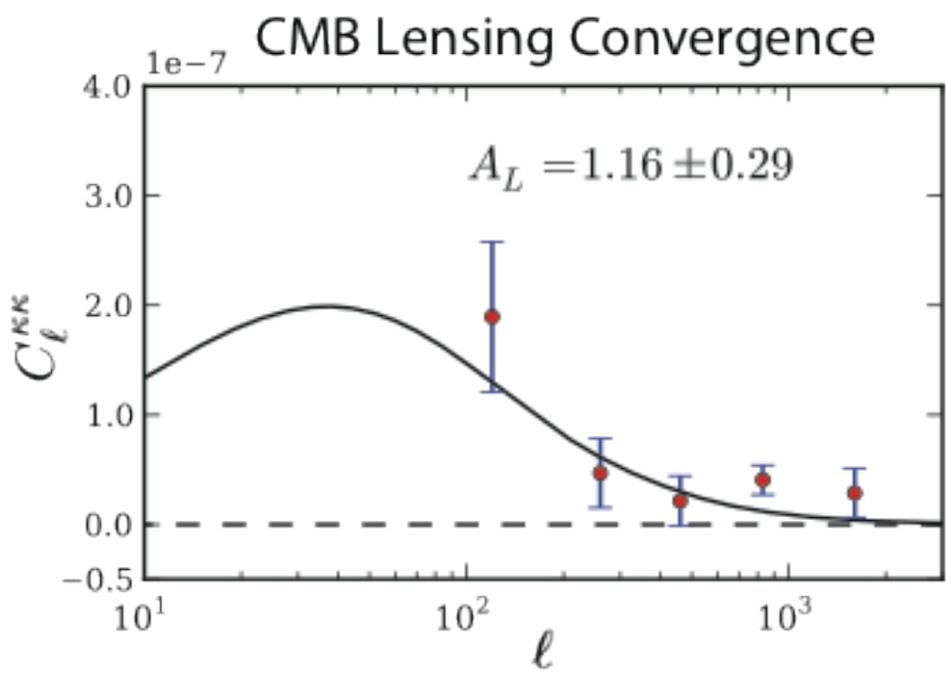
Lensed CMB



Rule of 2-3

ACT Discovery Highlights 2011-2013

Gravitational Lensing



First measurement of the gravitational lensing convergence of the CMB

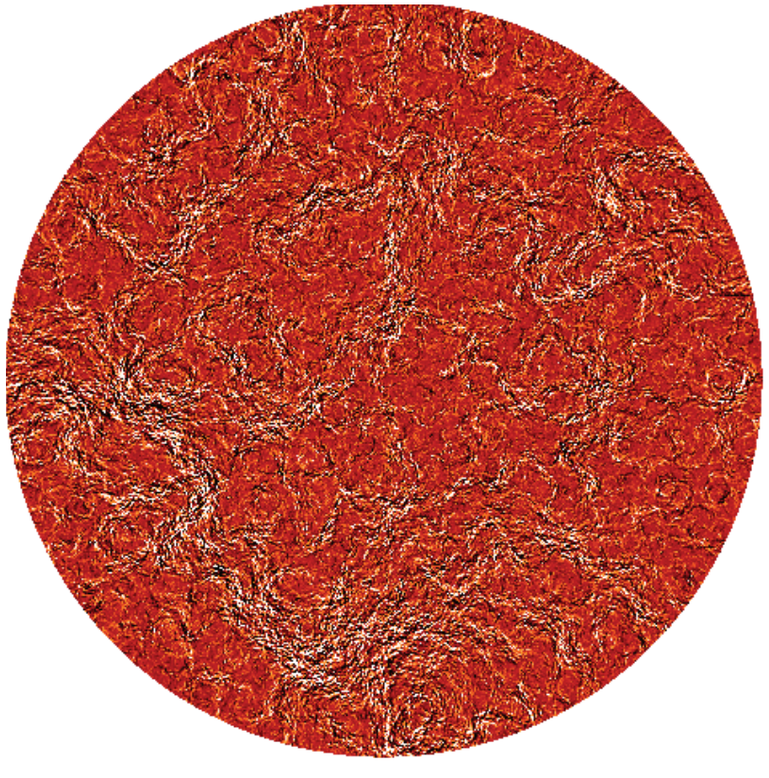
Das et al 2011, PRL 107(2):021301

Combined with ACT's power spectrum first detected dark energy using only CMB data.

Sherwin et al 2011, PRL 107(2):021302

Selected by *Physics Today* as one of only seven Discovery Highlights of 2011.

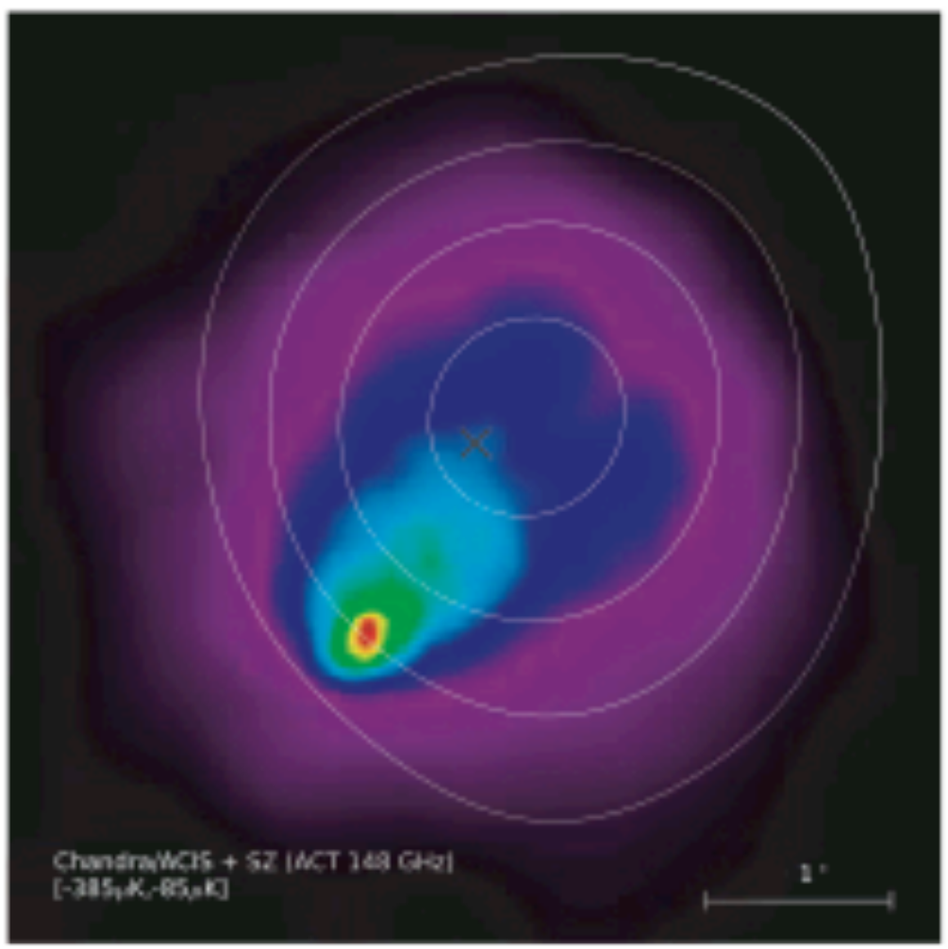
Lensed minus unlensed CMB



ACT Discovery Highlights 2011-2013

Sunyaev-Zel'dovich Effect

El Gordo: SZ + Xray

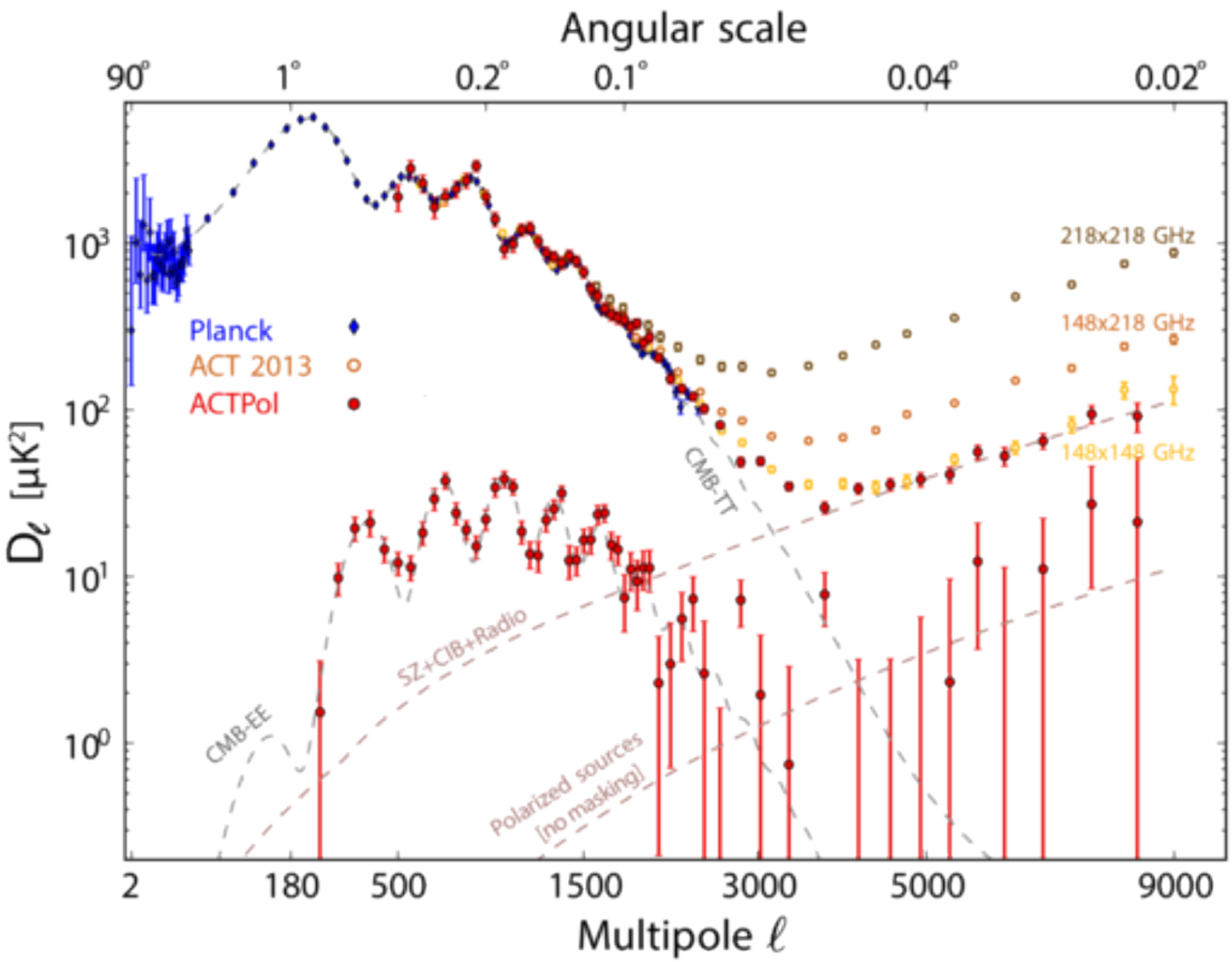


The discovery of ACT-CL J0102-4915, a high redshift, merging galaxy cluster, the most extreme known, nicknamed "El Gordo" because of its high mass (more than 2×10^{15} $M_{\odot}$).

Menanteau et al 2010, ApJ 723, 1523
Menanteau, JPH, et al 2012, ApJ, 748, 7

Highlighted in Discover Magazine 2012 Year in Science issue; also on NPR "All Things Considered"

ACTPol



Power spectrum of the temperature of the CMB (TT) and the E-mode polarization signal (EE) from 3 months of observations in 2014 with ACTPol.

Naess et al 2014, JCAP, 1410, 007

The Hot Part

Growth of Structure

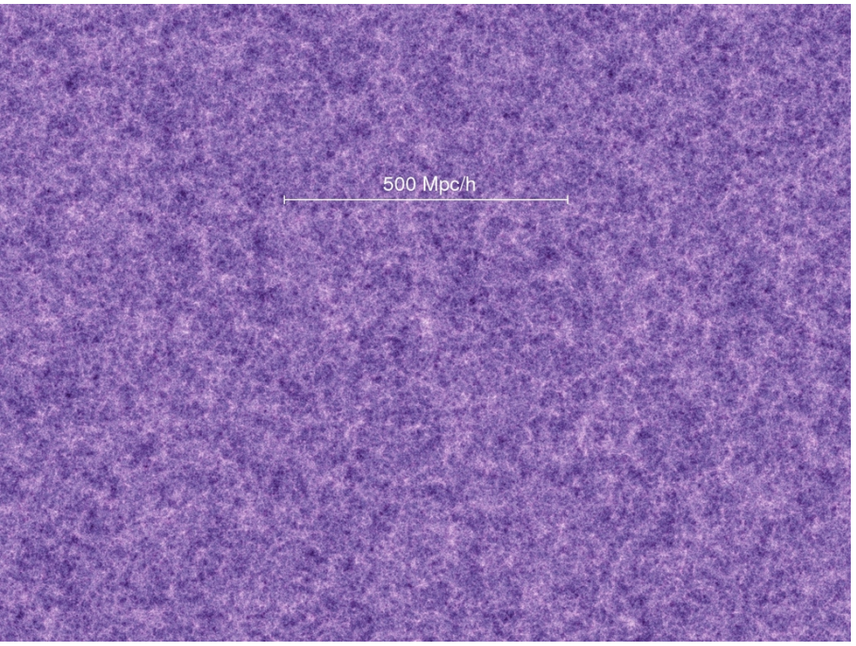
- CMB anisotropies are fluctuations in the mass density of the Universe when it was 380,000 yrs old

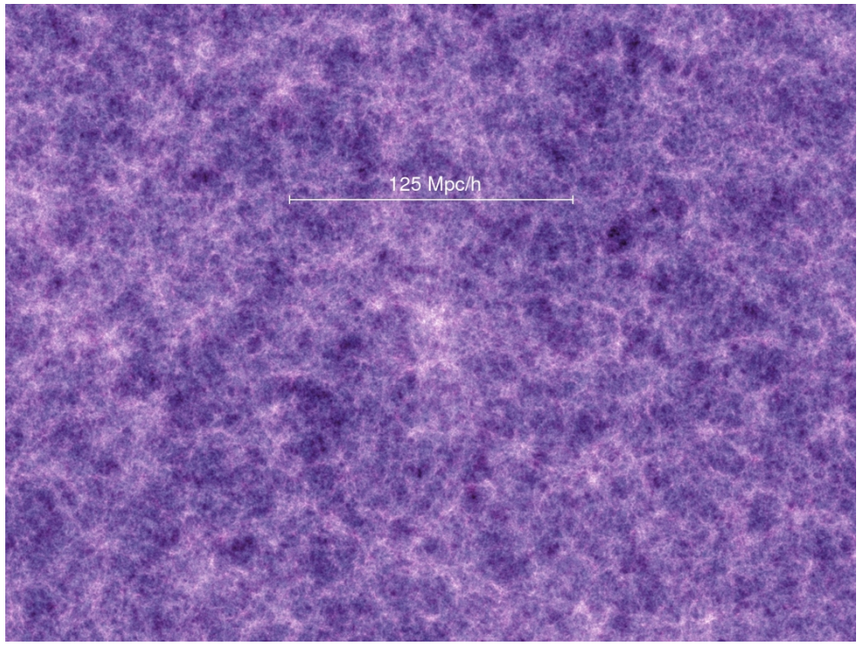
- The fluctuations evolve under gravity (Einstein's General Theory of Relativity) and expansion to form the observed distribution of mass (traced by galaxies)

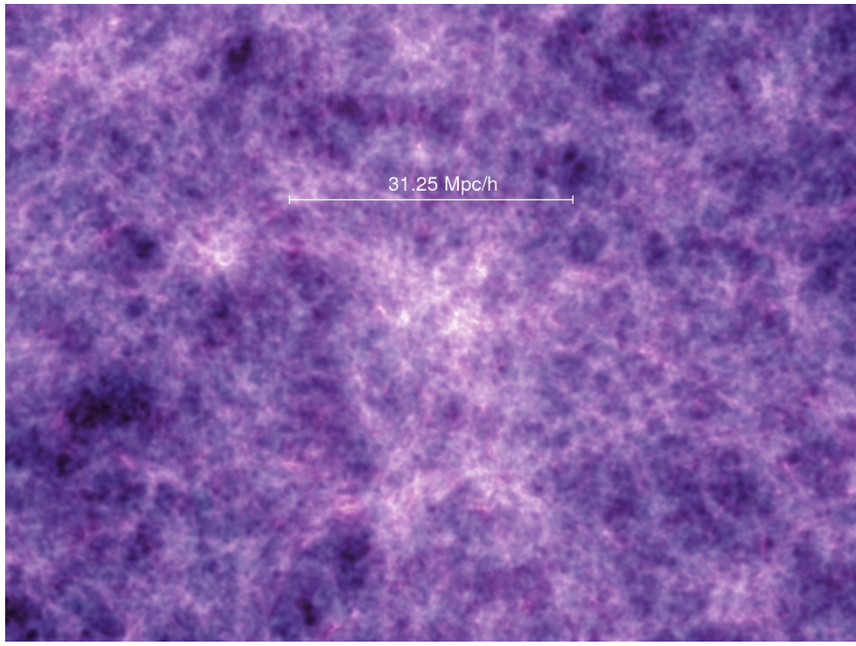
- In other words, the CMB anisotropies are the seeds of all structure in the Universe – from people and planets to stars and galaxies!

- Here's how they evolve

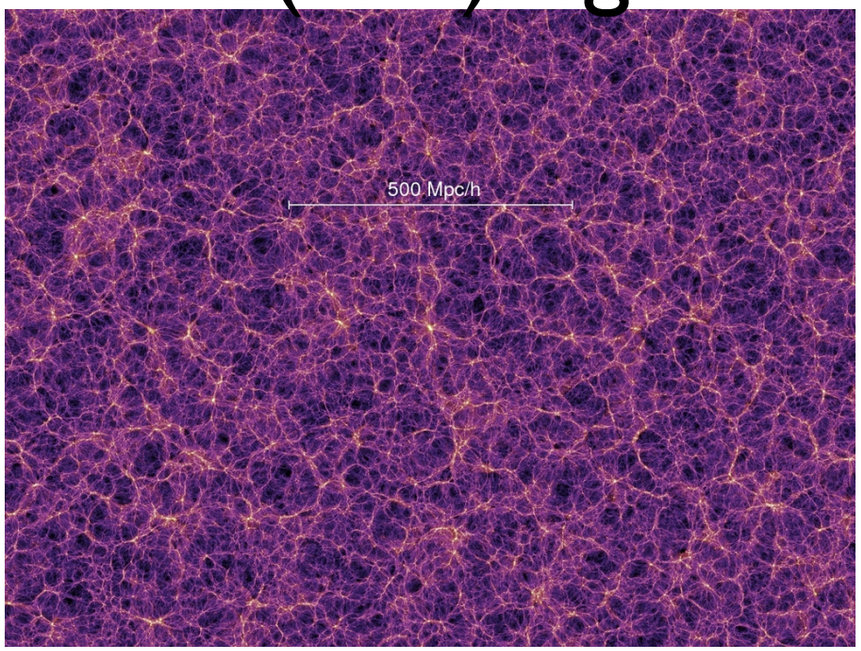
Early (z=18.3) Age=0.21 Gyr

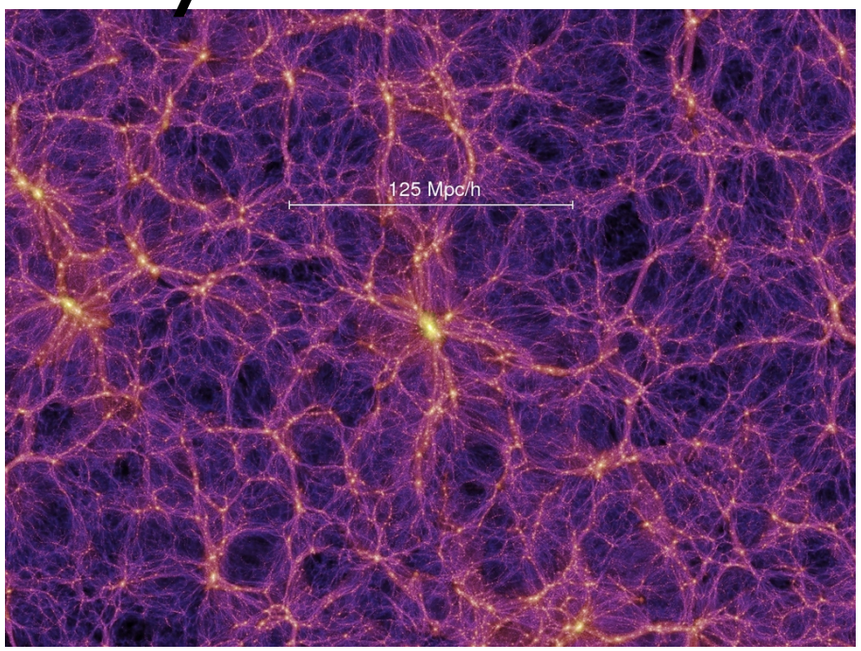


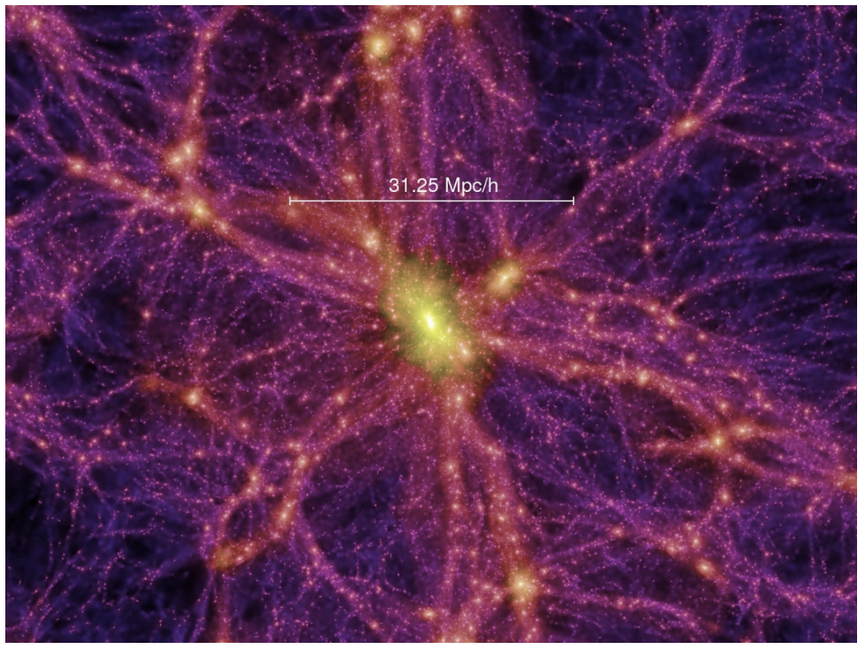




Now (z=0) Age=13.6 Gyr





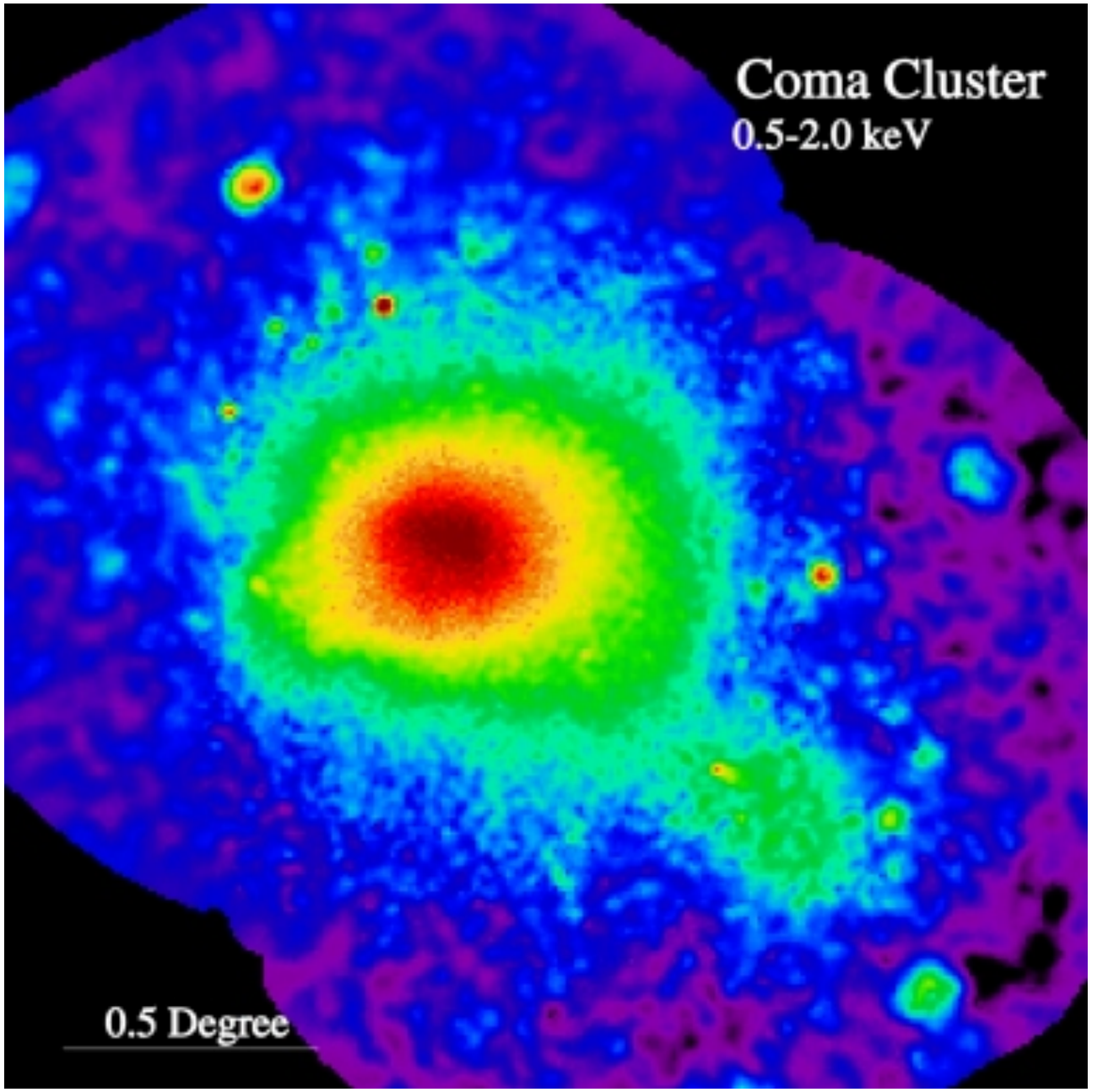


Clusters of Galaxies

Largest organized systems in the Universe

- 10's to 1000's of galaxies covering 25 Mpc^3 (10^{75} cm^3)
  - Typical galaxy velocity ~ 100 – 1000 km s^{-1}
  - Velocity distribution determines cluster's gravitational mass
- Intracluster medium filled with hot (10^6-10^8 K), low density (<10^{-3} atoms/cm^3) gas
  - Mass of gas is 5-10 times the entire stellar mass in galaxies
  - Gas not primordial, must have been processed through stars.
  - Amount of gas and its temperature determines cluster's gravitational mass
- Total mass up to 10^{15} $M_\odot$ (10^{48} gm)
  - Only ~10% of the mass is baryonic (i.e., normal matter) – the nature of the rest (the so-called "dark matter") is unknown – DM is known to exist only because of its gravitational effects.

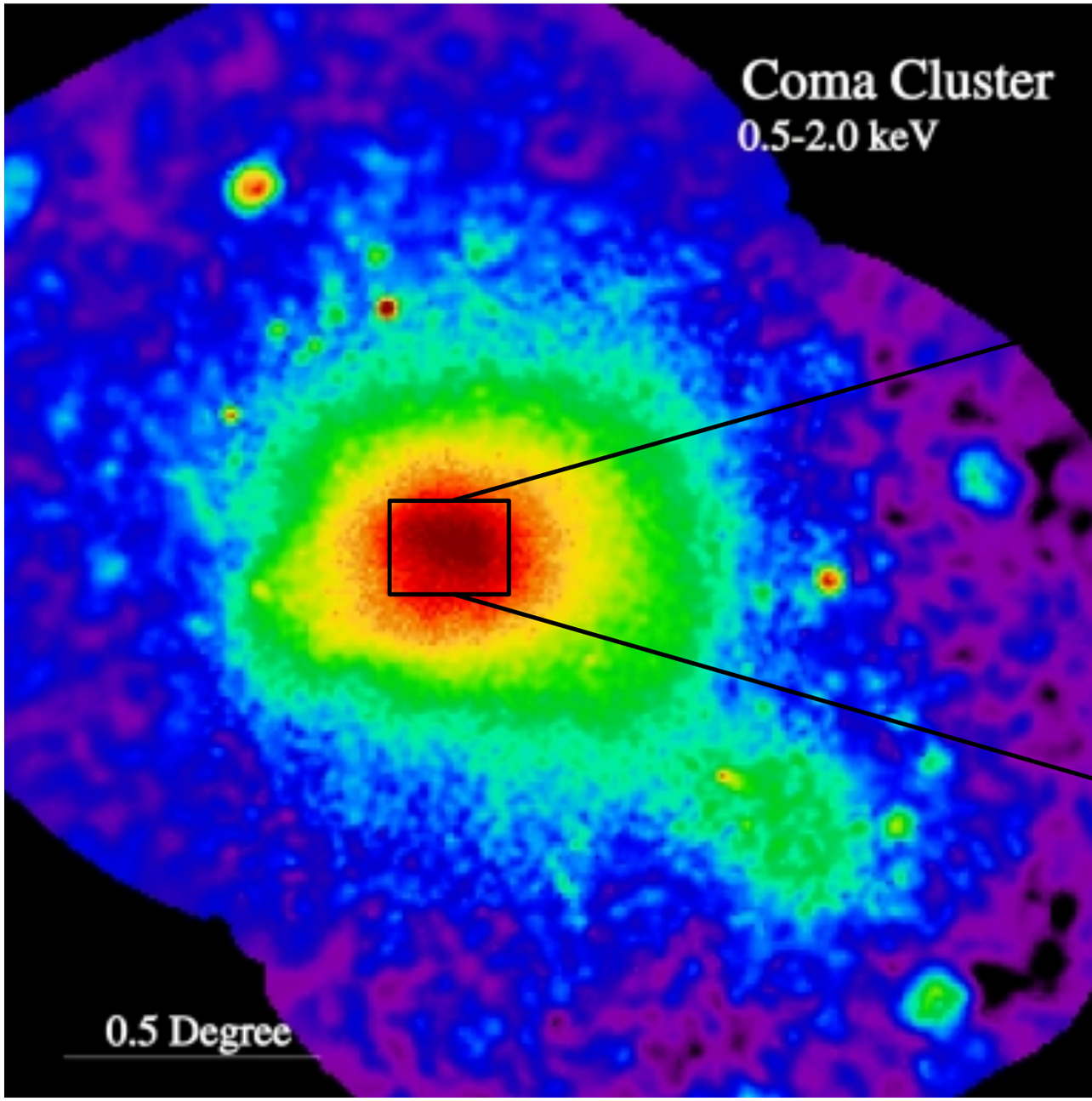
Clusters of Galaxies (example)



X-ray (*ROSAT*)

Optical
(Central region)

Clusters of Galaxies (example)



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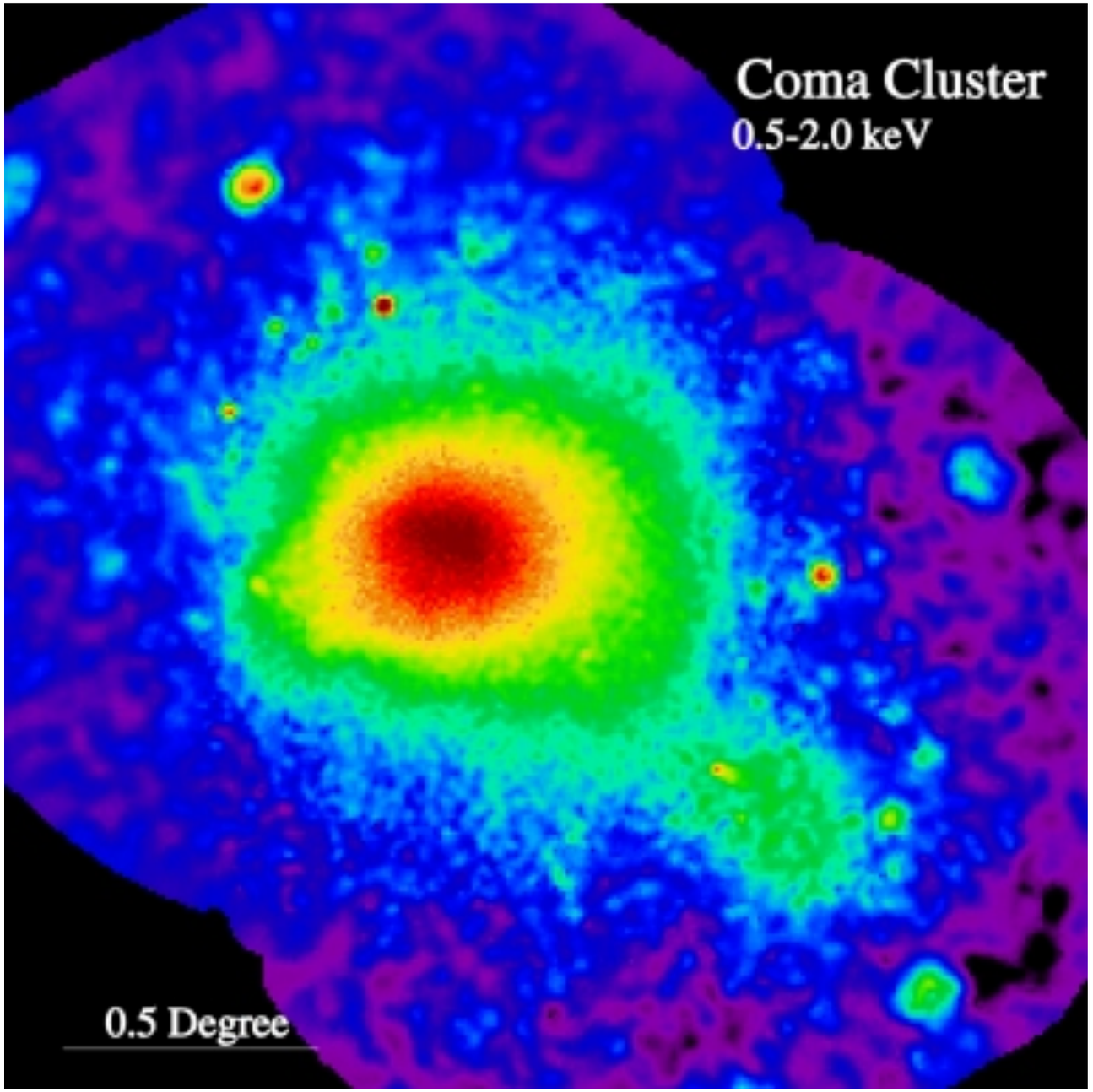

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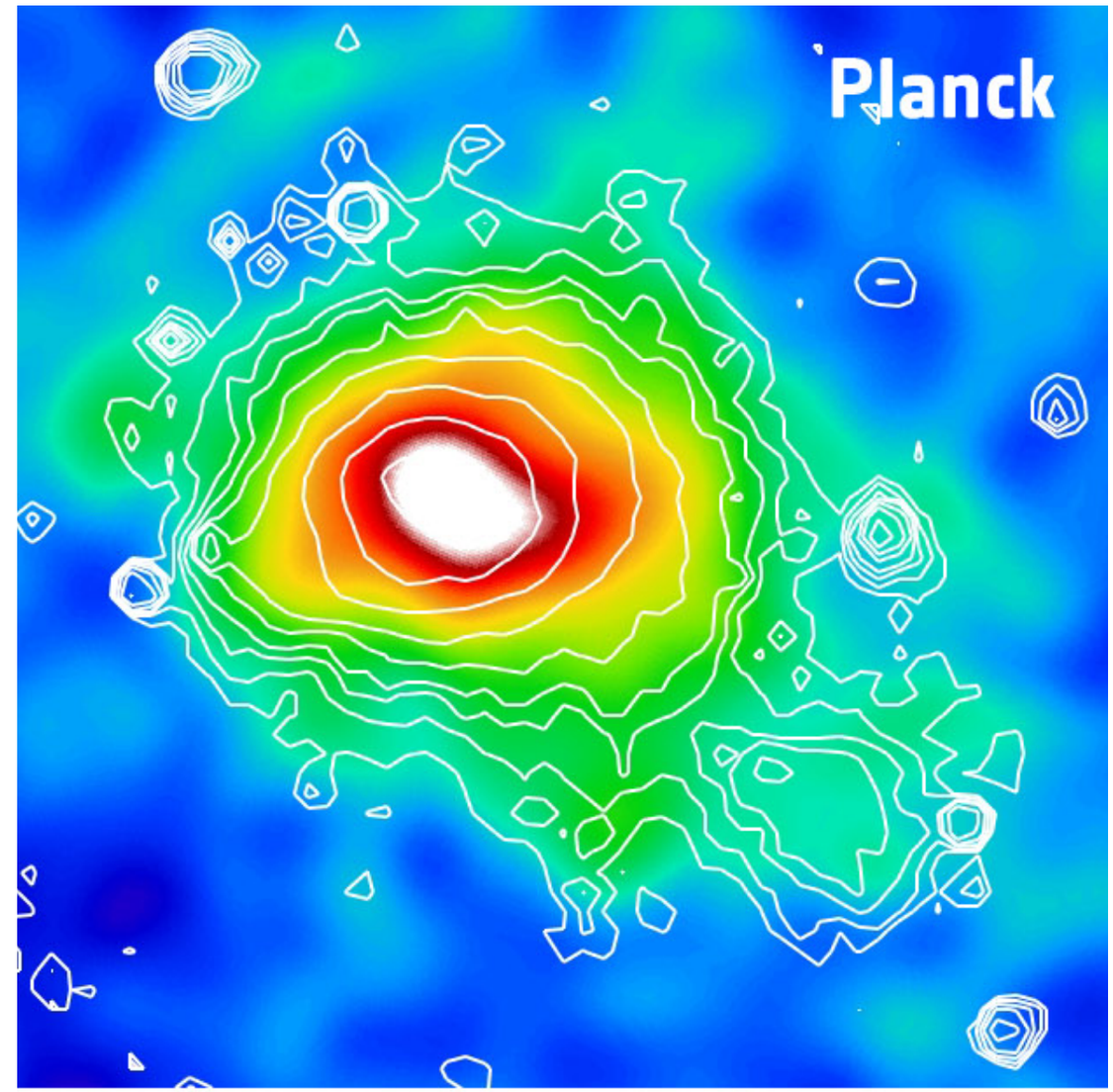


SZ (*Planck*)

Physics of the Sunyaev-Zel'dovich Effect (SZE)

Inverse Compton scatter

- Net energy change of photon in a Compton collision:

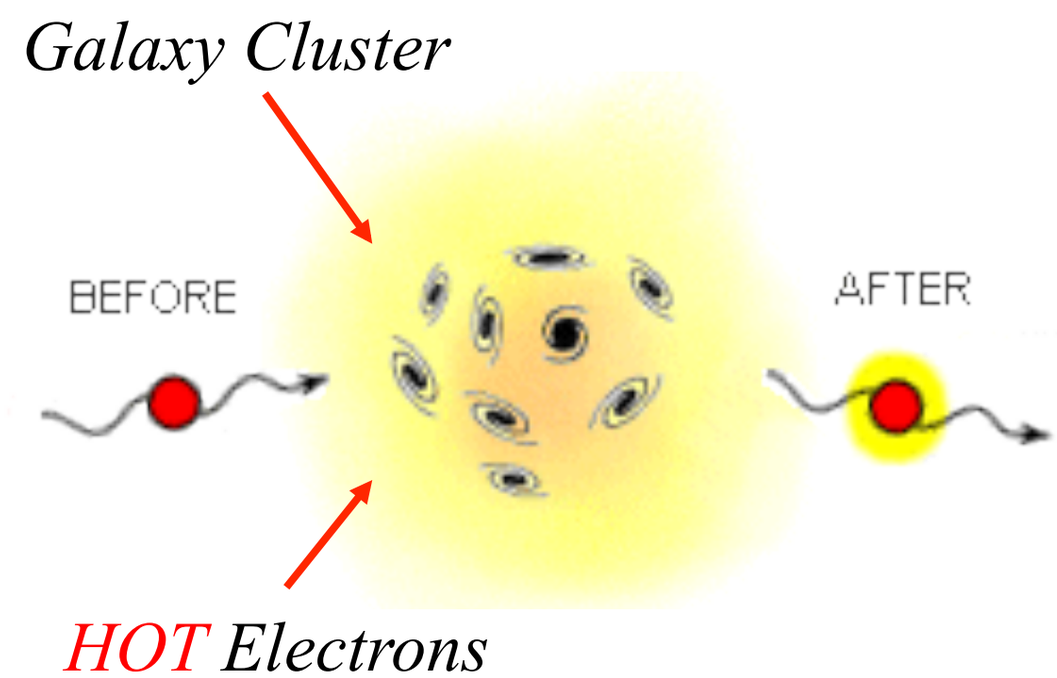
$$\frac{\Delta\epsilon}{\epsilon} = -\frac{h\nu_0}{m_e c^2} + \frac{4kT}{m_e c^2}$$

- Optical depth for Thomson scattering

$$\tau_e = n_e \sigma_T l$$

- Comptonization parameter

$$y = \int \frac{kT_e}{m_e c^2} n_e \sigma_T dl$$



Electrons in a cluster are hot ~10^7 K
CMB photons are cold ~2.7 K
So photons tend to get boosted in energy
This distorts the CMB blackbody spectrum

Physics of the (thermal) SZE

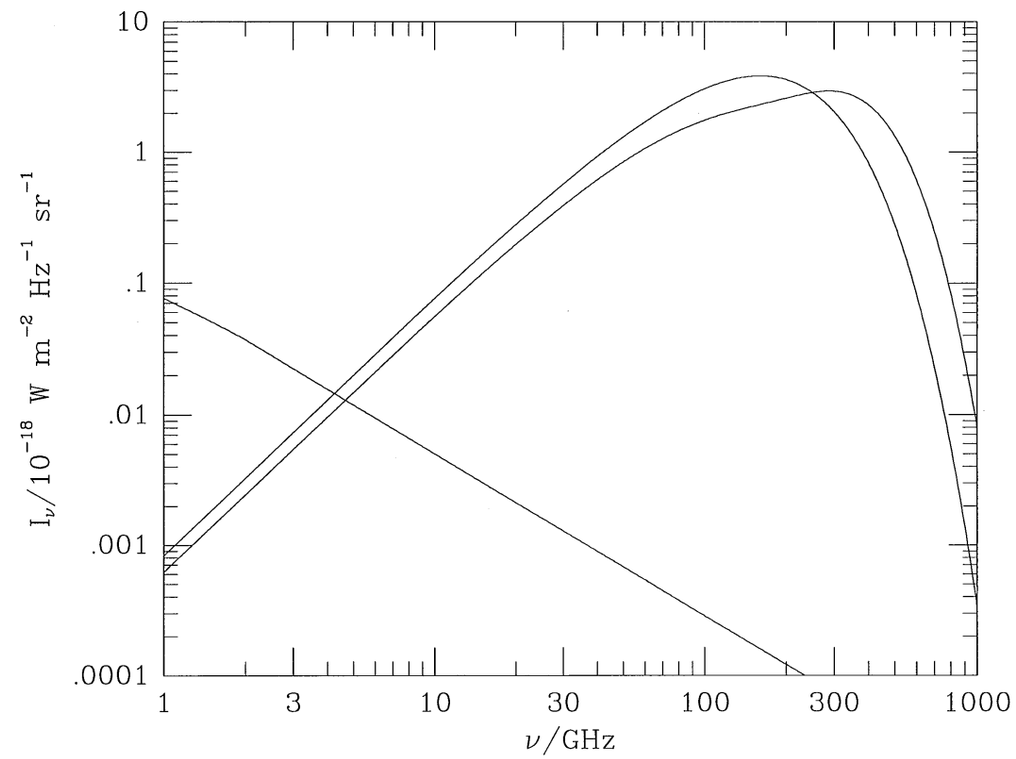
- Kompaneets (1956) eqn.
  - Describes how photon field evolves in energy and "time"

$$\frac{\partial n}{\partial y} = \frac{1}{x_e^2}\frac{\partial}{\partial x_e} x_e^4 \left(\frac{\partial n}{\partial x_e} + n + n^2 \right)$$

  - where $x_e \equiv h\nu / kT_e$.
  - We can drop the *n* and n^2 terms and then set $x_e = x \equiv h\nu / kT_{\rm CMB}$. Solution for the spectral change due to scattering is:

$$\frac{\Delta u_\nu}{u_\nu} = y \frac{x \exp x}{\exp x - 1} \left(x \frac{\exp x + 1}{\exp x - 1} - 4 \right)$$

- In this approximation, locations of the minimum, maximum, and null are independent of T_e



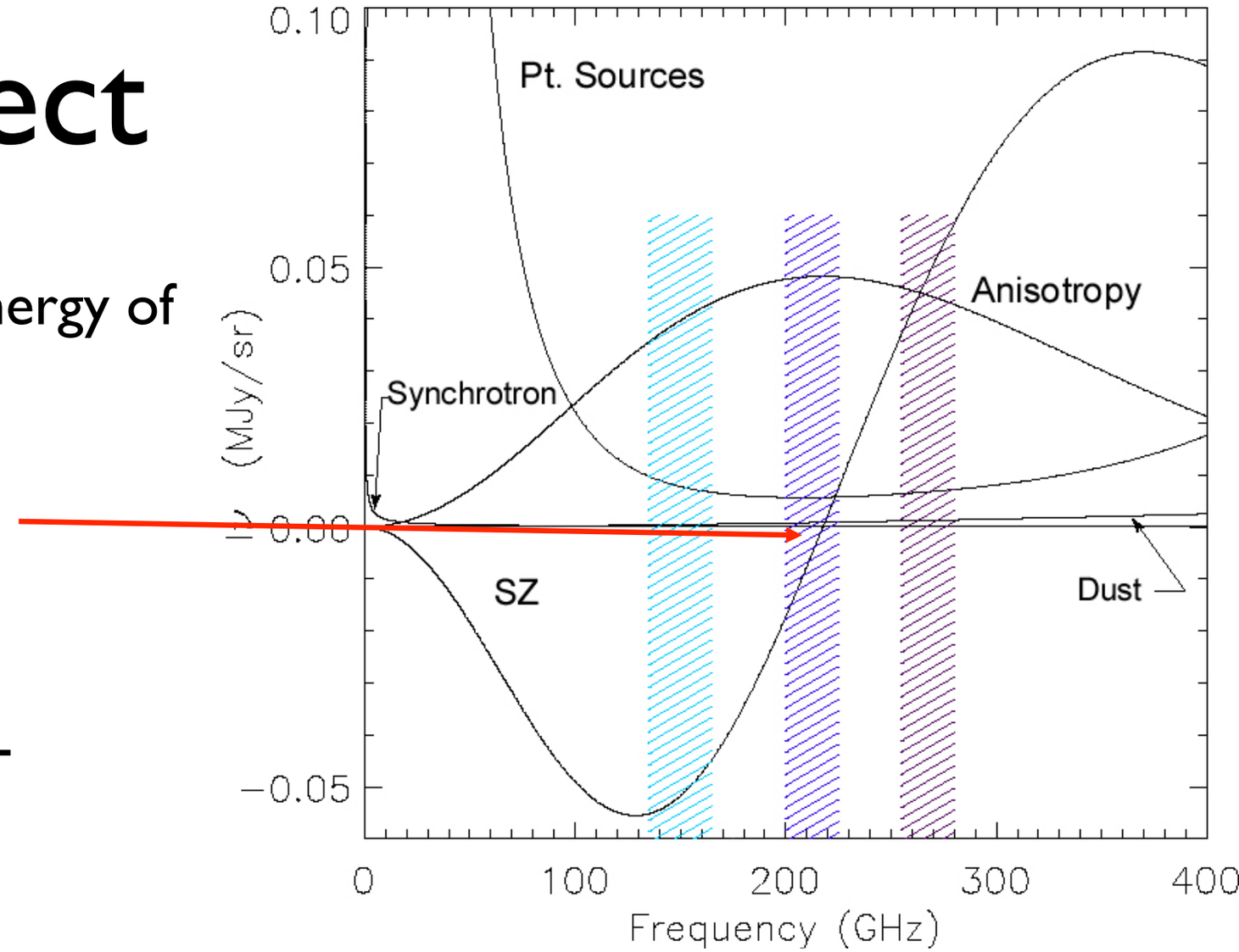
Rayleigh-Jeans limit

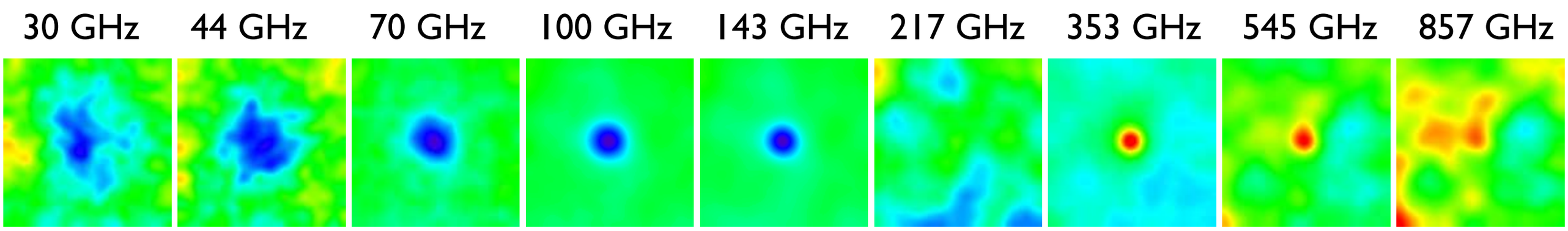
$$\frac{\Delta I_\nu}{I_\nu} \approx -2y \qquad y = \int \frac{kT_e}{m_e c^2} n_e \sigma_T dl$$

SZE is quite small; typically only 10^{-3} of the CMB itself

Thermal SZ effect

- Inverse Compton Scattering
  - Hot cluster electrons boost energy of CMB photons
- Spectral Signature
  - SZ null at ~220 GHz
- Redshift independent
  - "clean" cluster selection
- tSZ Effect proportional to $n_e T$
  - probes cluster pressure

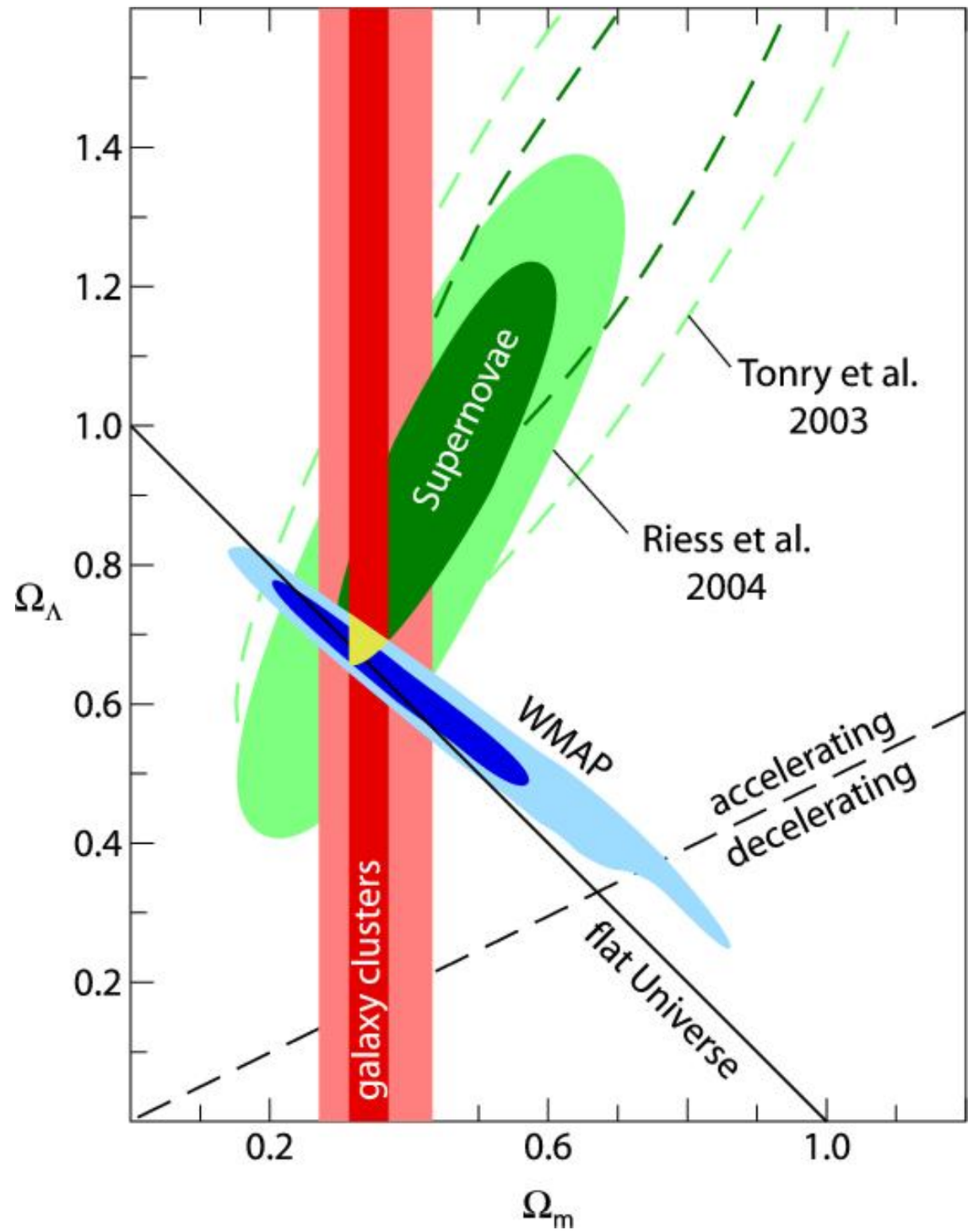


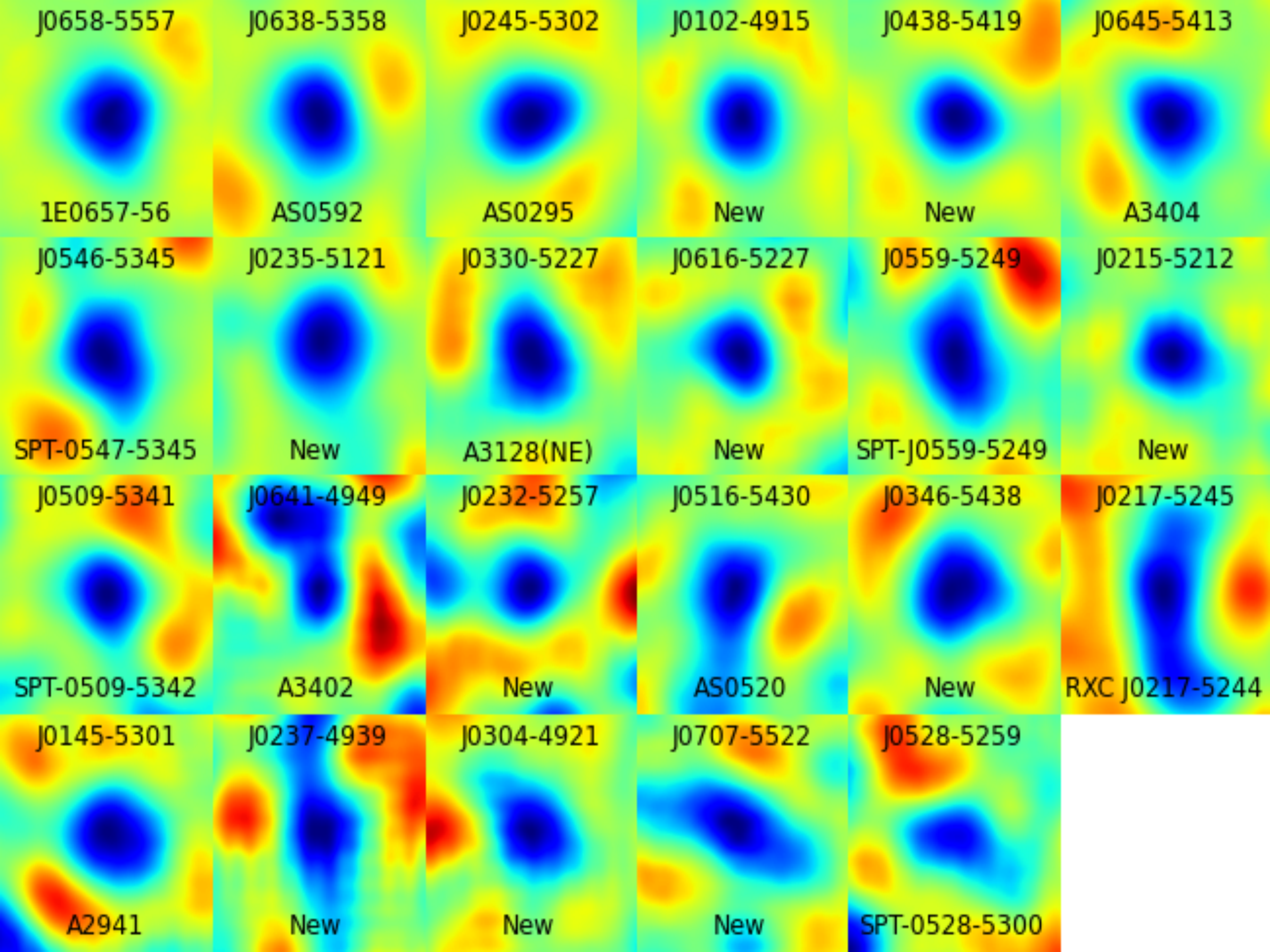


Planck stacked images of confirmed clusters in 9 frequency bands showing decrements, null, and increments

Why An SZ Survey for Clusters?

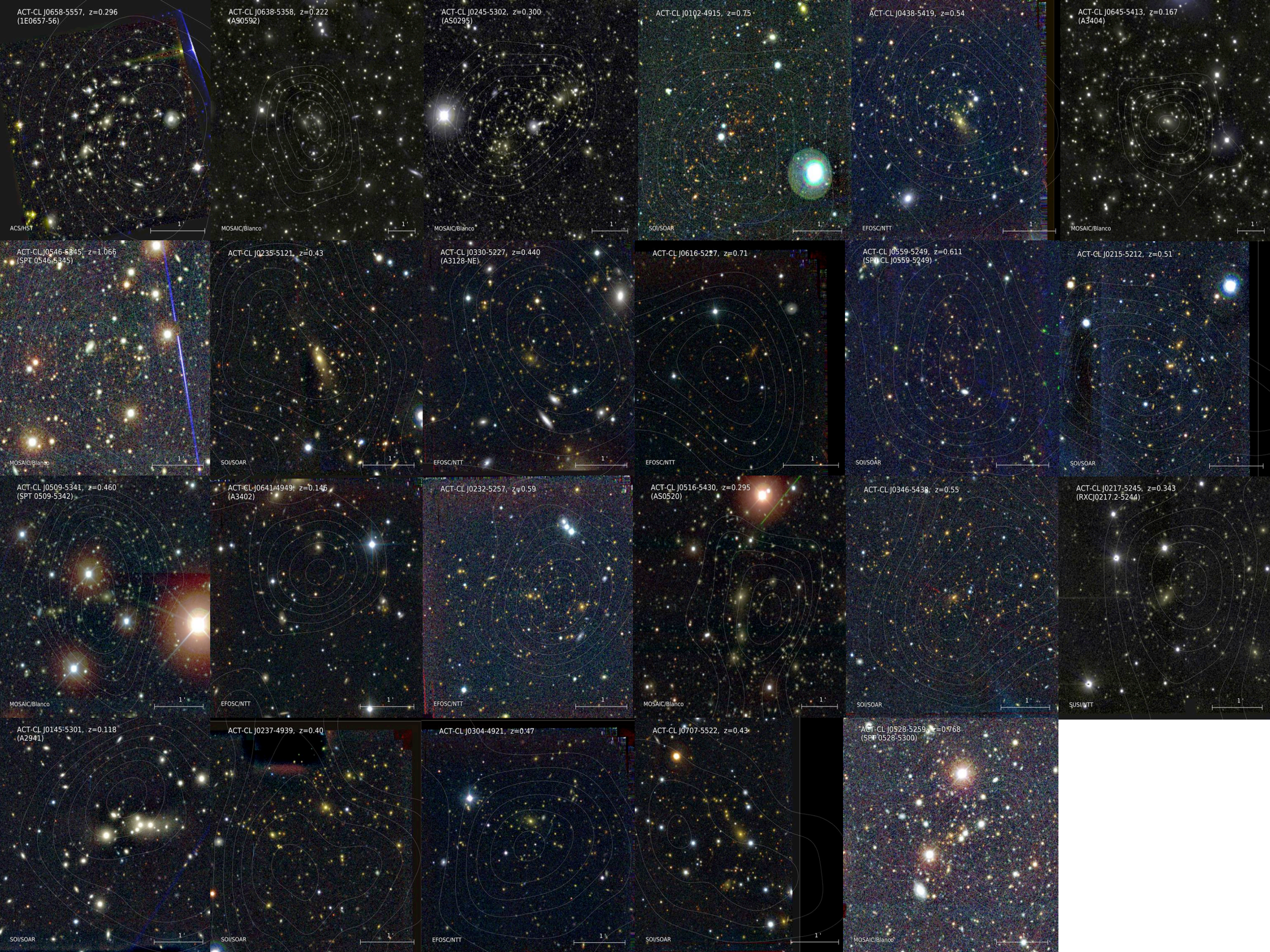
- Clusters are exponentially sensitive to the growth of structure in the Universe
- Can set constraints on the cosmological model
- SZE is redshift independent
- SZE integrated Y parameter is tightly correlated to cluster mass with low scatter
- SZE has strong sensitivity to cluster mass
- kSZE measures velocity field – can also probe growth of structure



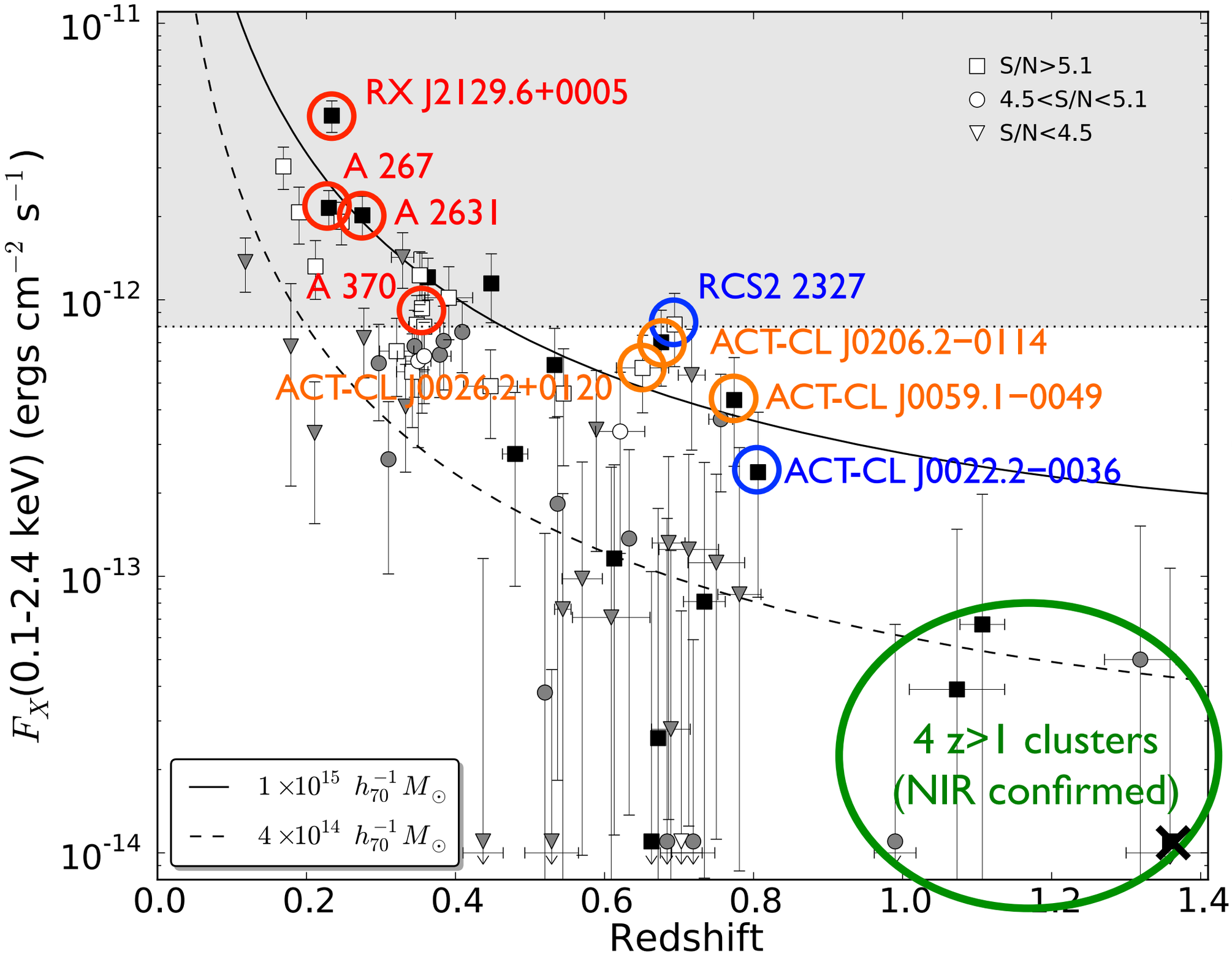

J0658-5557
1E0657-56
J0638-5358
AS0592
J0245-5302
AS0295
J0102-4915
New
J0438-5419
New
J0645-5413
A3404
J0546-5345
SPT-0547-5345
J0235-5121
New
J0330-5227
A3128(NE)
J0616-5227
New
J0559-5249
SPT-J0559-5249
J0215-5212
New
J0509-5341
SPT-0509-5342
J0641-4949
A3402
J0232-5257
New
J0516-5430
AS0520
J0346-5438
New
J0217-5245
RXC J0217-5244
J0145-5301
A2941
J0237-4939
New
J0304-4921
New
J0707-5522
New
J0528-5259
SPT-0528-5300


Jack's run @ Blanco: Aug 2009


Felipe @ SOAR: Dec 2009


ACT-CL J0658-5557, z=0.296
(1E0657-56)
ACS/HST
1'
ACT-CL J0638-5358, z=0.222
(AS0592)
MOSAIC/Blanco
1'
ACT-CL J0245-5302, z=0.300
(AS0295)
MOSAIC/Blanco
1'
ACT-CL J0102-4915, z=0.75
SOI/SOAR
1'
ACT-CL J0438-5419, z=0.54
EFOSC/NTT
1'
ACT-CL J0645-5413, z=0.167
(A3404)
MOSAIC/Blanco
1'
ACT-CL J0546-5345, z=1.066
(SPT 0546-5345)
MOSAIC/Blanco
1'
ACT-CL J0235-5121, z=0.43
SOI/SOAR
1'
ACT-CL J0330-5227, z=0.440
(A3128-NE)
EFOSC/NTT
1'
ACT-CL J0616-5227, z=0.71
EFOSC/NTT
1'
ACT-CL J0559-5249, z=0.611
(SPT-CL J0559-5249)
SOI/SOAR
1'
ACT-CL J0215-5212, z=0.51
SOI/SOAR
1'
ACT-CL J0509-5341, z=0.460
(SPT 0509-5342)
MOSAIC/Blanco
1'
ACT-CL J0641-4949, z=0.146
(A3402)
EFOSC/NTT
1'
ACT-CL J0232-5257, z=0.59
EFOSC/NTT
1'
ACT-CL J0516-5430, z=0.295
(AS0520)
MOSAIC/Blanco
1'
ACT-CL J0346-5438, z=0.55
SOI/SOAR
1'
ACT-CL J0217-5245, z=0.343
(RXCJ0217.2-5244)
SUSI/NTT
1'
ACT-CL J0145-5301, z=0.118
(A2941)
SOI/SOAR
1'
ACT-CL J0237-4939, z=0.40
SOI/SOAR
1'
ACT-CL J0304-4921, z=0.47
EFOSC/NTT
1'
ACT-CL J0707-5522, z=0.43
SOI/SOAR
1'
ACT-CL J0528-5259, z=0.768
(SPT 0528-5300)
MOSAIC/Blanco
1'

X-rays from ACT Clusters



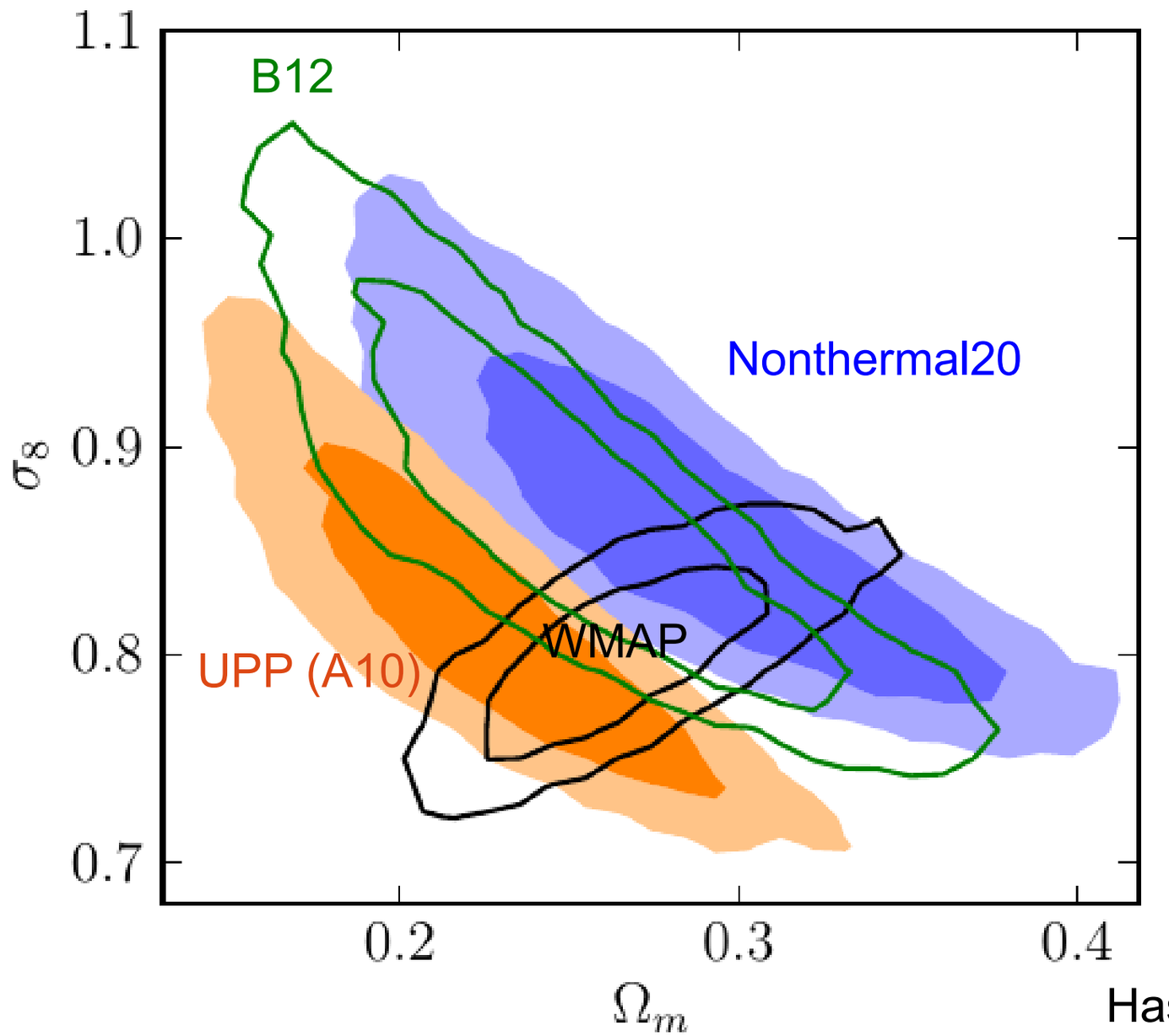
68 SZE clusters (49 in S82; 19 beyond) with ACT S/N>4.0

X-ray fluxes from ROSAT All Sky Survey in 0.1-2.4 keV band

Curves show estimated fluxes for 10^{15} $M_\odot$ and 4×10^{14} $M_\odot$ clusters

Cosmological Constraints

- ACT equatorial clusters (15 at z > 0.2) + BBN + H0 (i.e., no CMB)
- Fixed scaling relations, different models (from Bode et al. 2012, Trac et al. 2011)



Hasselfield et al. (2013)

Cosmological Constraints

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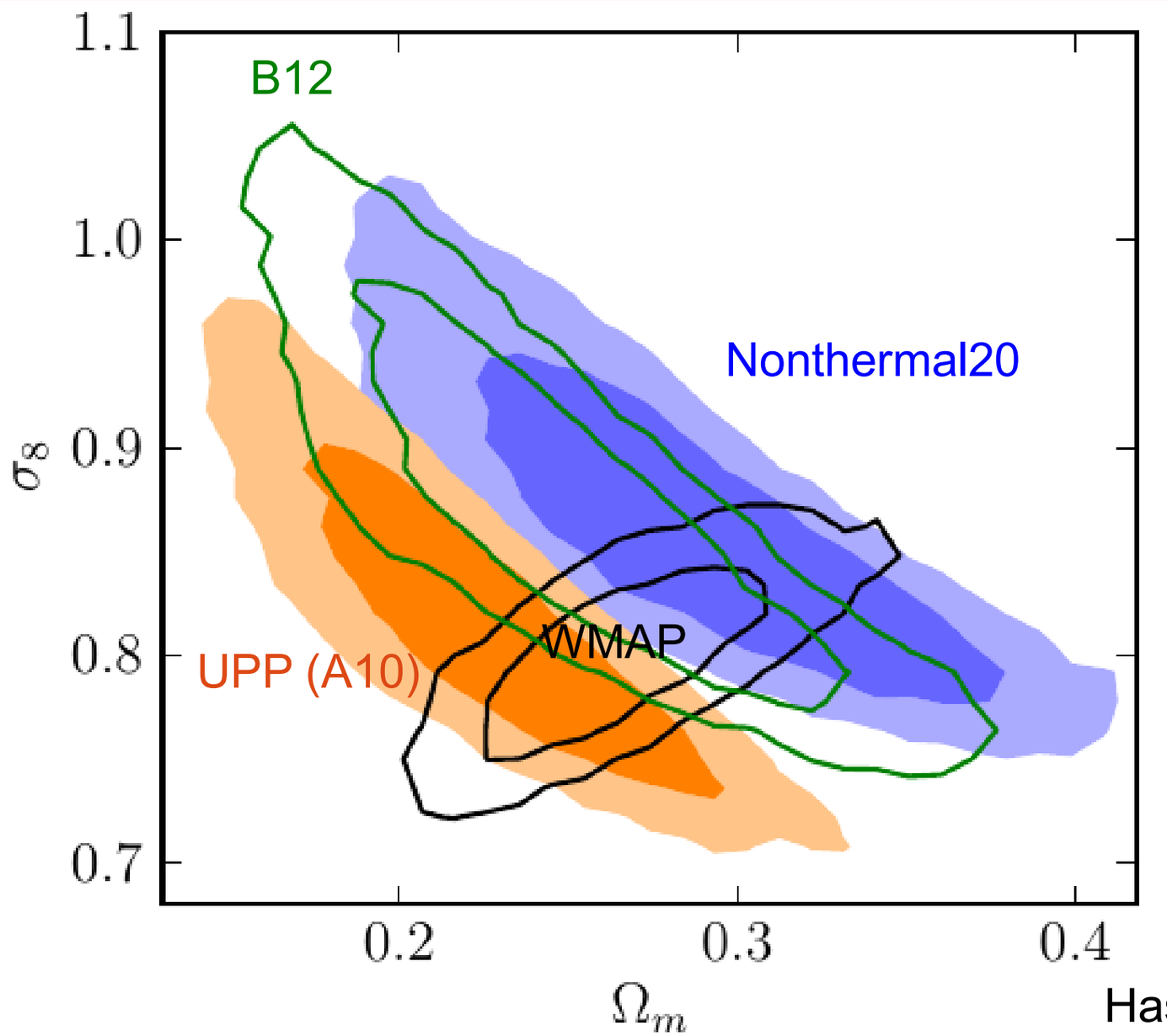


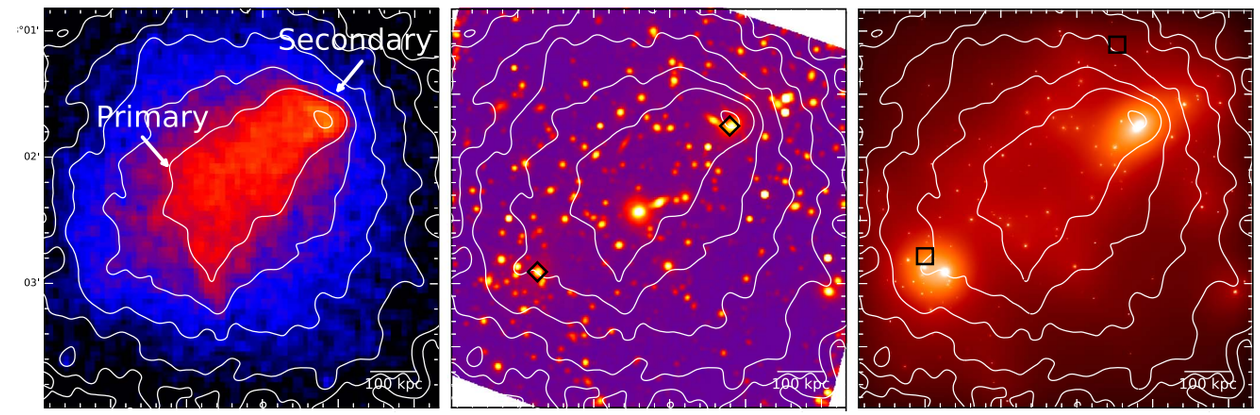
Interest area of research focus on ACT: to obtain weak lensing mass calibration

Hasselfield et al. (2013)

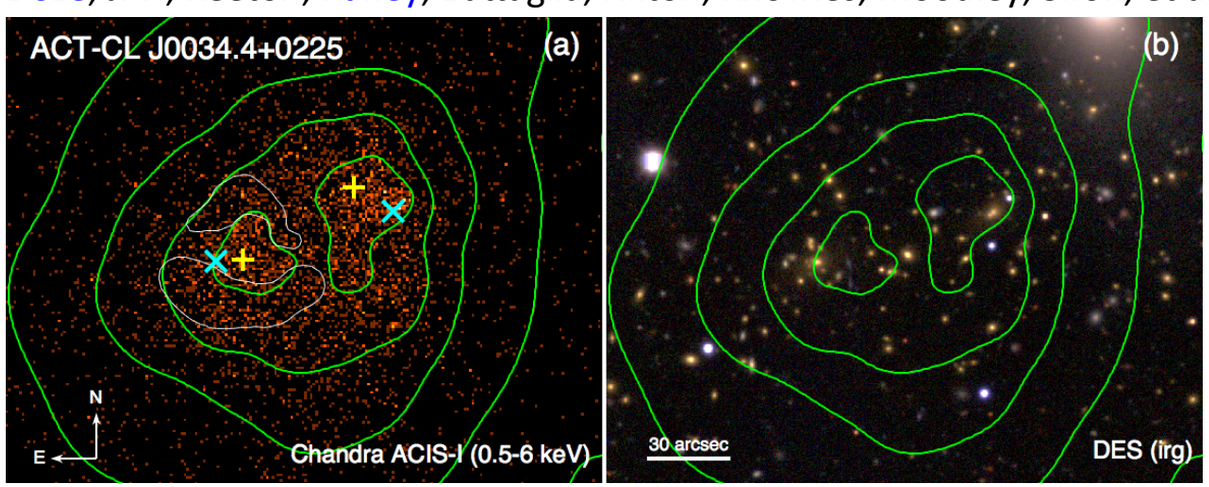
Merging/Interacting Clusters

Another area of research

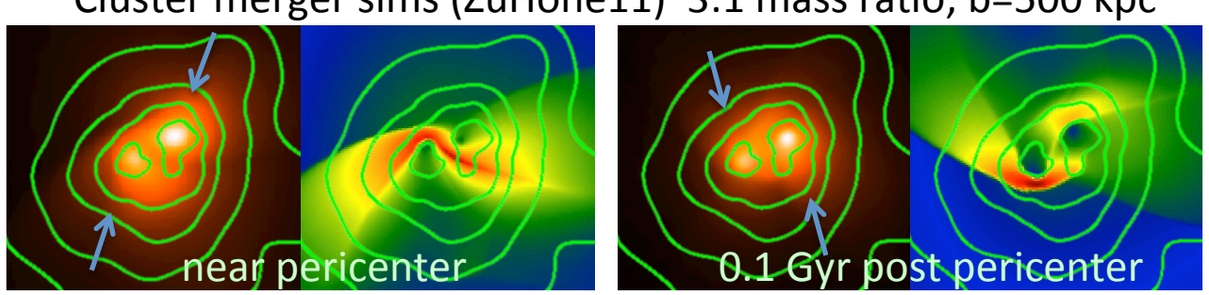
ACT-CL J0245−5302 AS0295

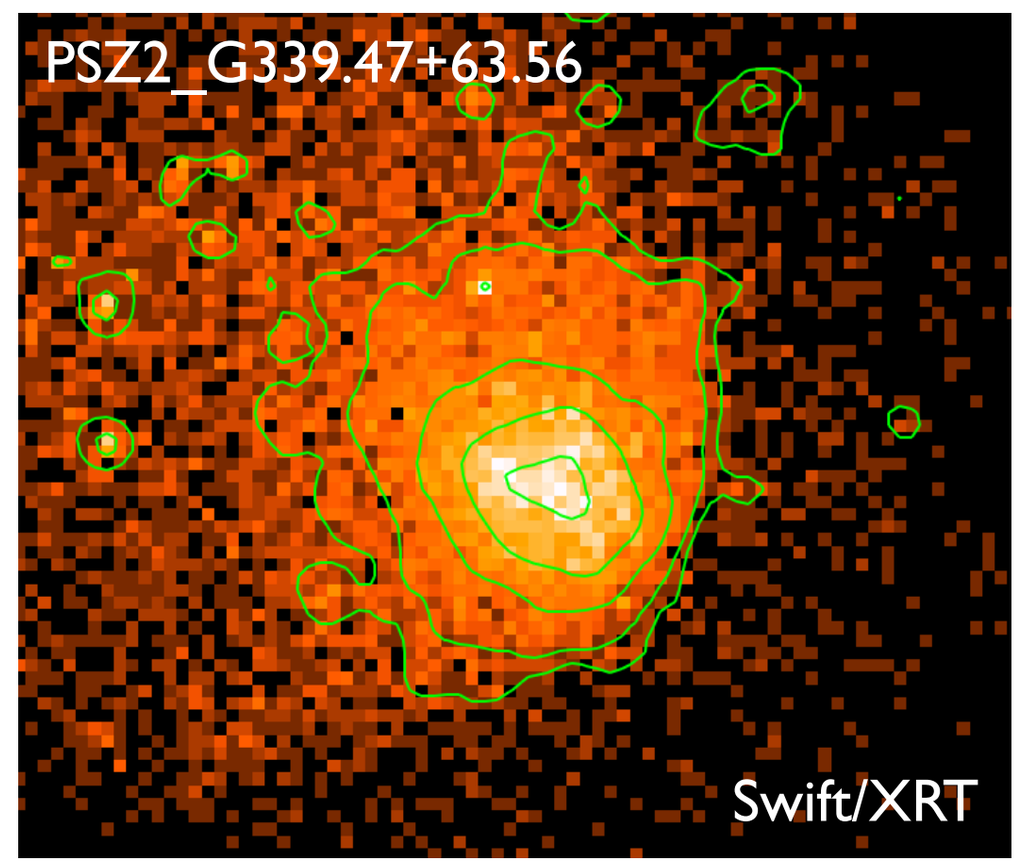


Doze, JPH, Keeton, Raney, Battaglia, Hilton, Knowles, Moodley, Sifon, et al

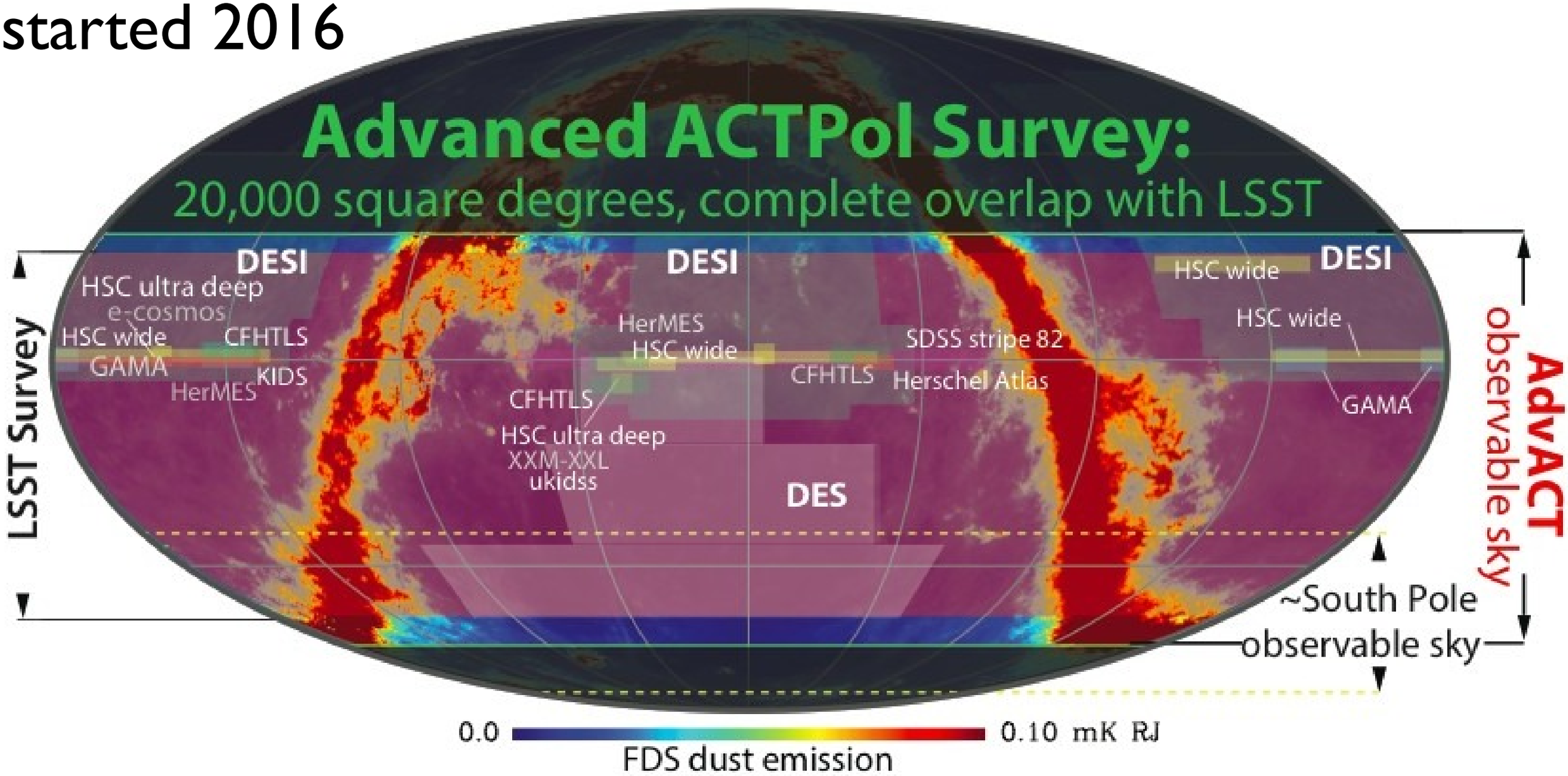


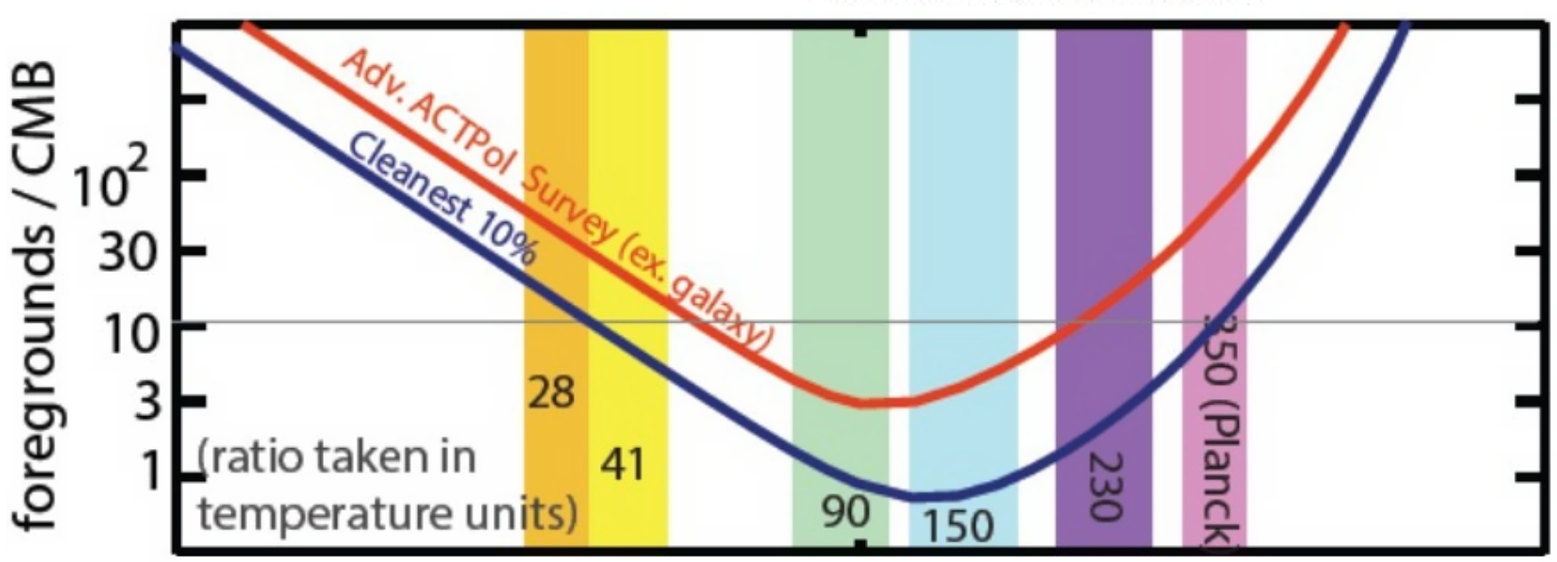
Cluster merger sims (ZuHone11) 3:1 mass ratio; b=500 kpc

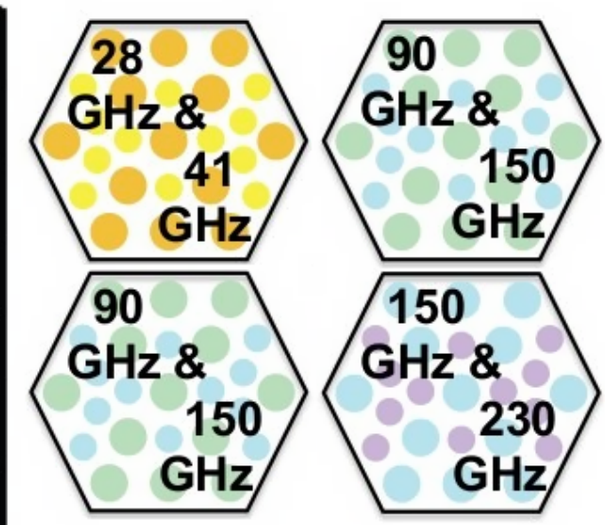




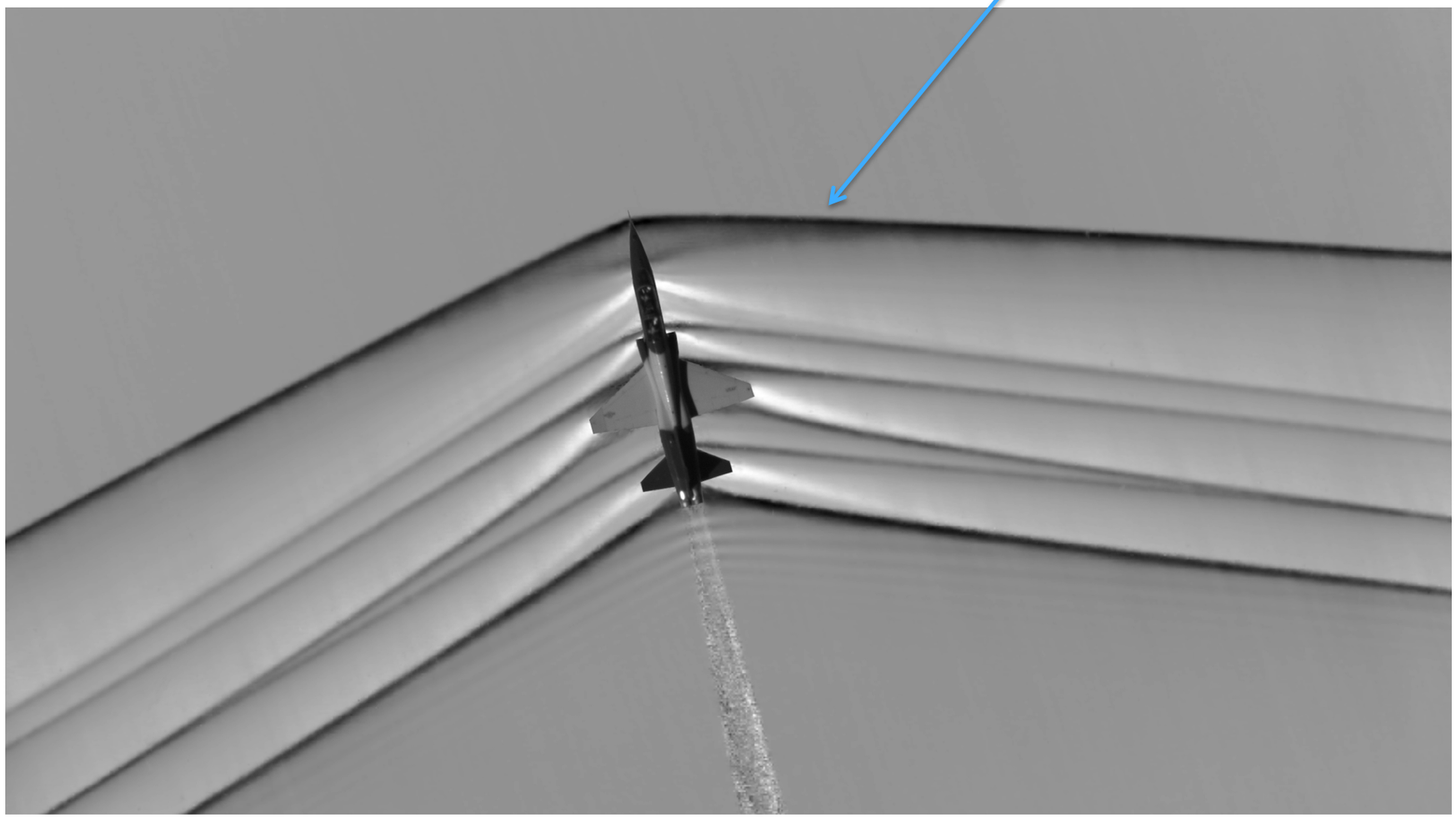
started 2016







High Speed Shock Waves



Supersonic jet flying at Mach 1.09, Schlieren imaging

When a wave moves faster than the sound speed it becomes a shock wave.

This produces a nearly discontinuous change in the pressure, temperature, and density of the medium.

High Speed Shock Waves

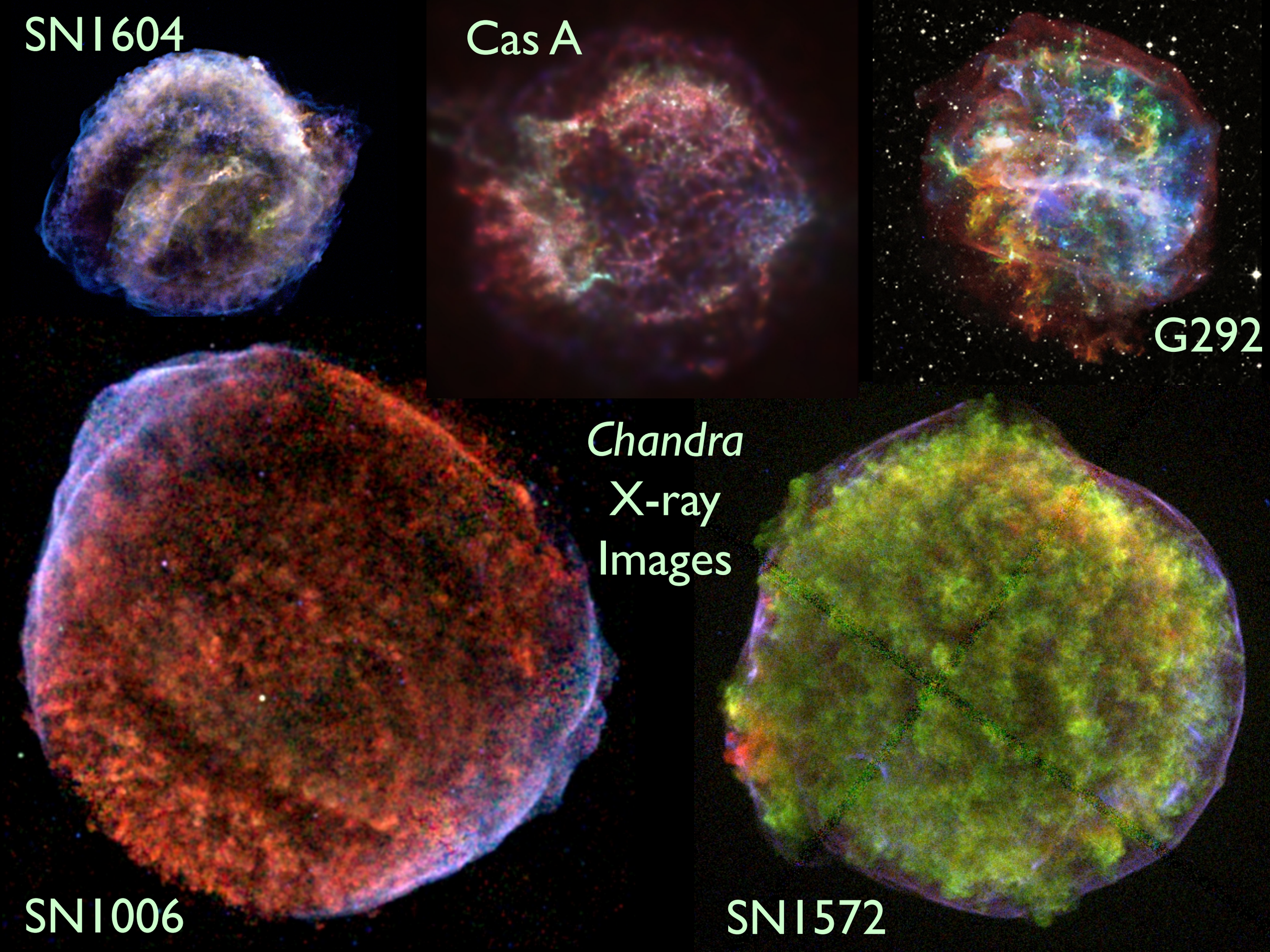
Terrestrial shock waves are fairly rare
Typically result from supersonic motion and explosions

High Speed Shock Waves

Terrestrial shock waves are fairly rare
Typically result from supersonic motion and explosions

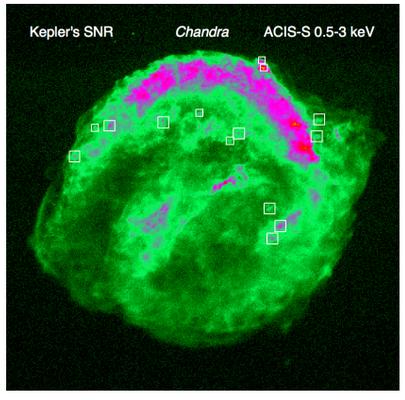
Bullet at Mach 2.5 plus muzzle blast, Schlieren imaging

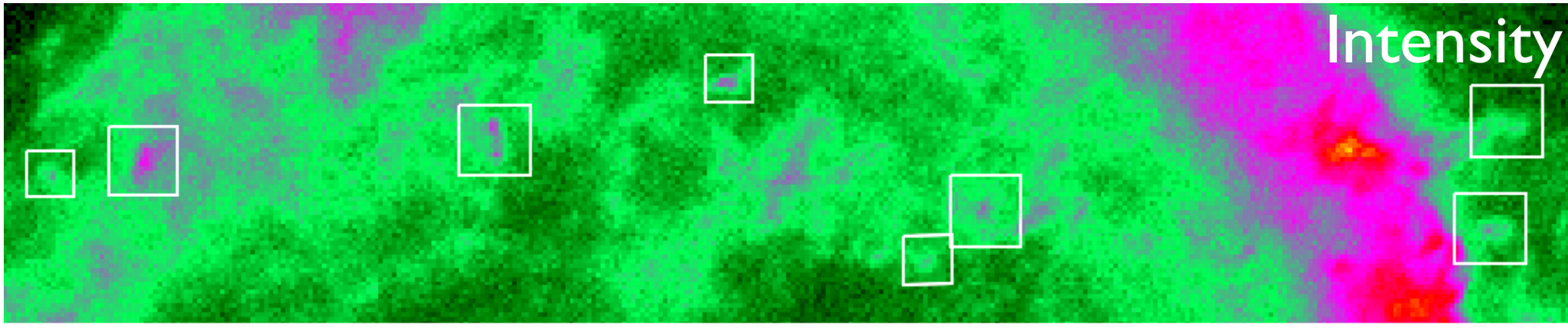
https://www.youtube.com/embed/BUREX8aFbMs


SN1604
Cas A
G292
Chandra
X-ray
Images
SN1006
SN1572

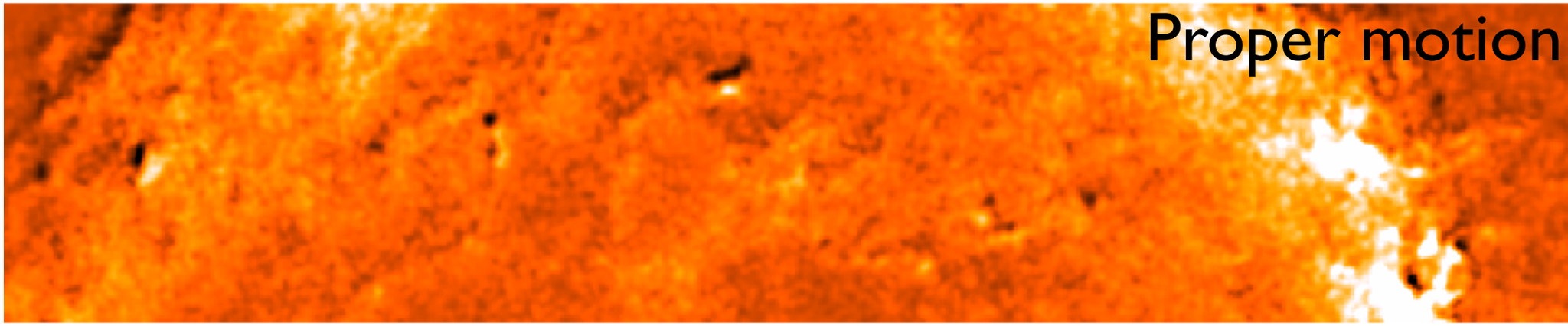
Knots in Kepler's SNR

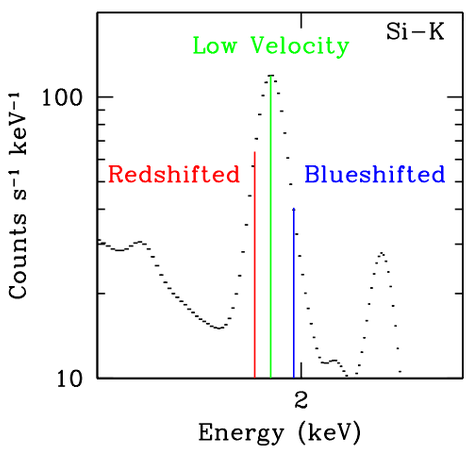
- Identify compact knots in intensity or redshift using *Chandra*
  Knot types: 9 ejecta (N, NE, SW); 3 CSM; 2 knots matched to optical (Sankrit+16)
- Determine proper motion and radial velocity

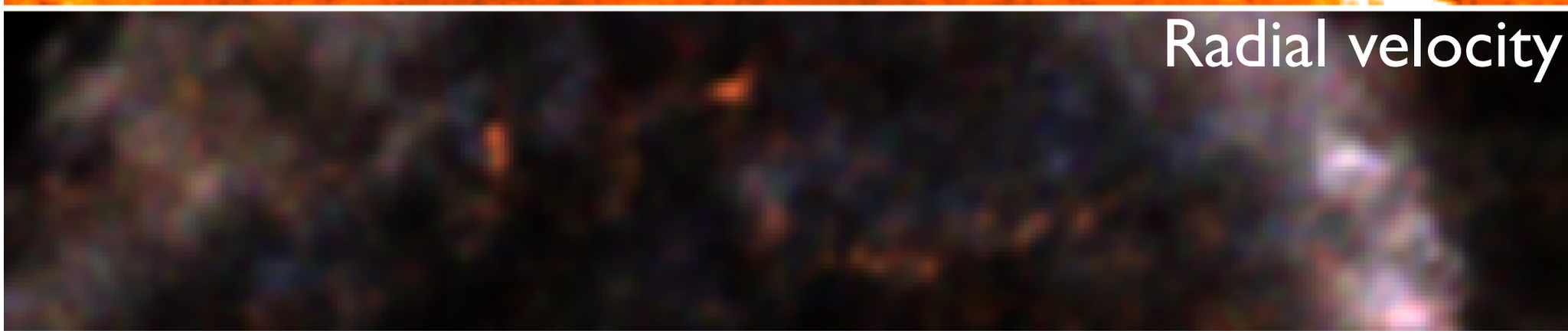




Epoch 2000 minus epoch 2014



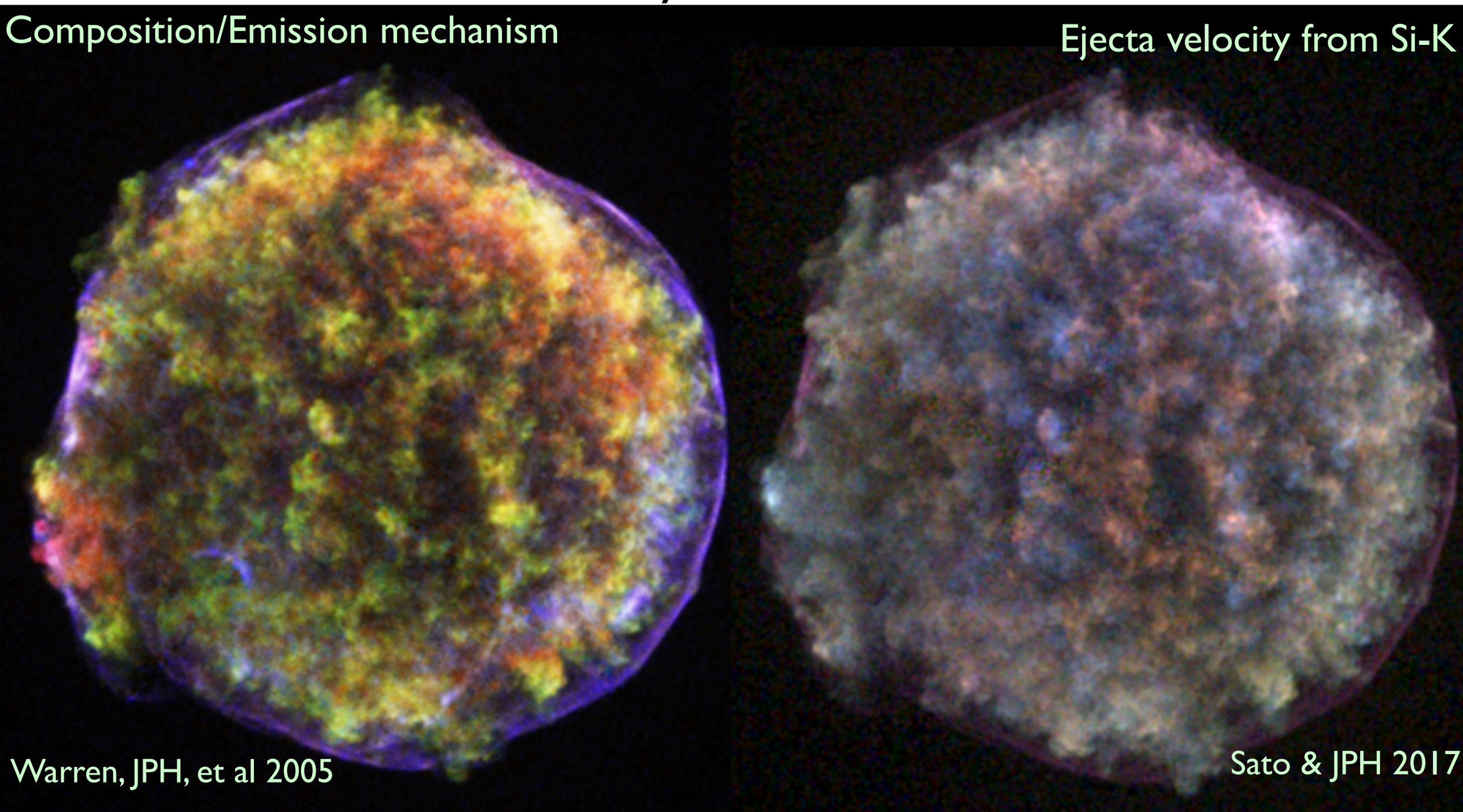




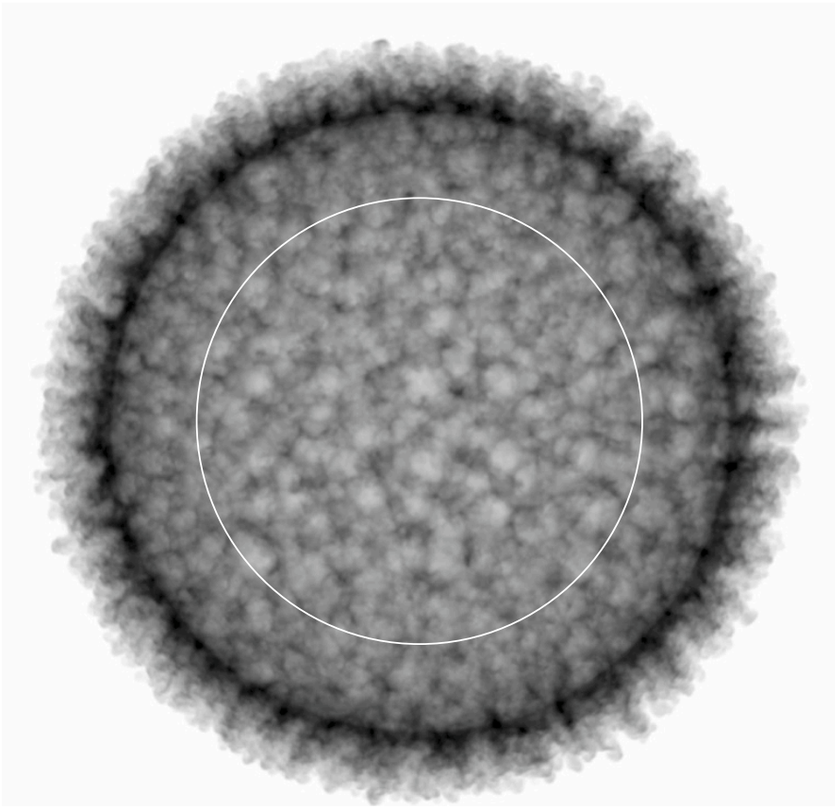
4 epochs: 2000, 2004, 2006, 2014 (49 ks, 46 ks, 741 ks, 139 ks)

Knots in Tycho's SNR

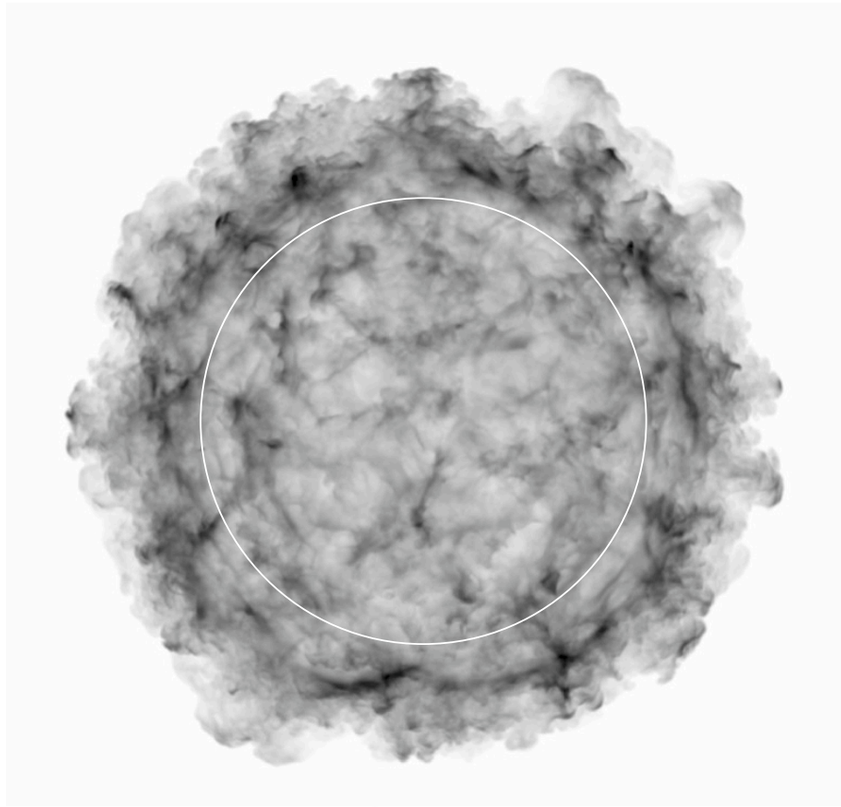
- Knots not so compact in Tycho – more like blobs – but also visible in intensity or redshift using *Chandra*
- Determine radial velocity



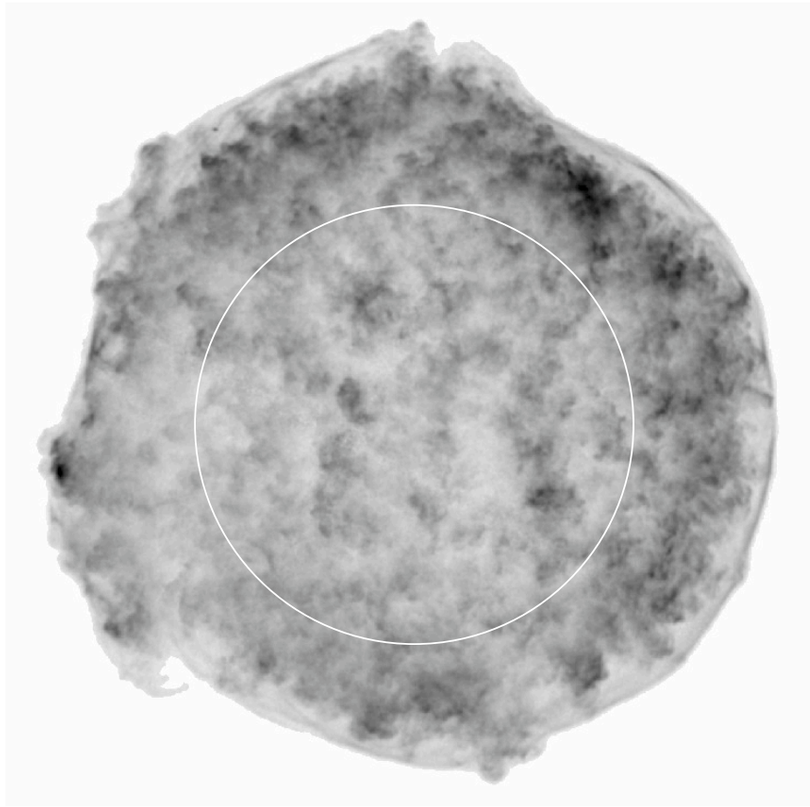
How to Quantify Differences in Morphology?



Smooth

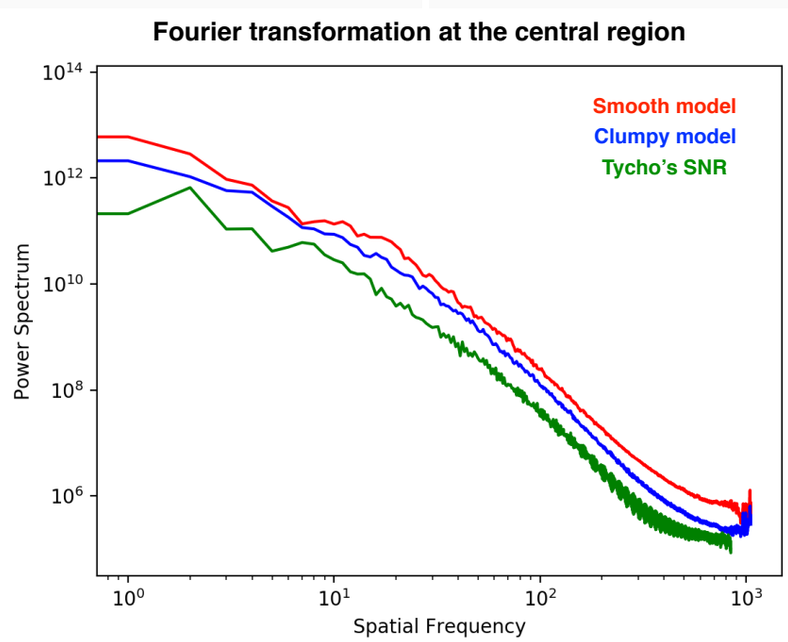


Clumpy

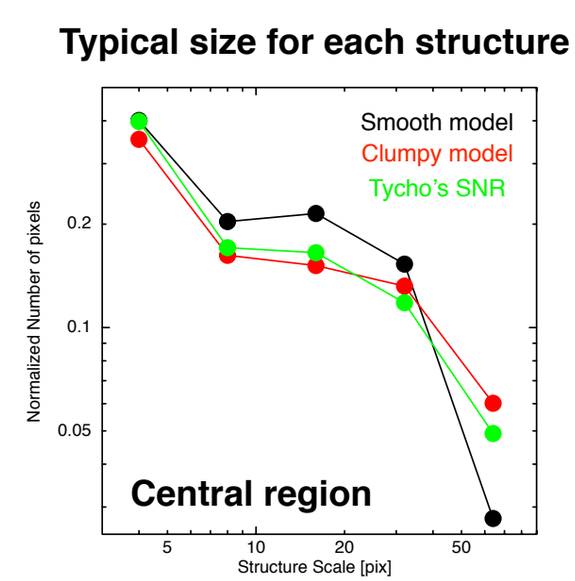


Tycho's SNR

Phase-averaged Fourier power-spectrum

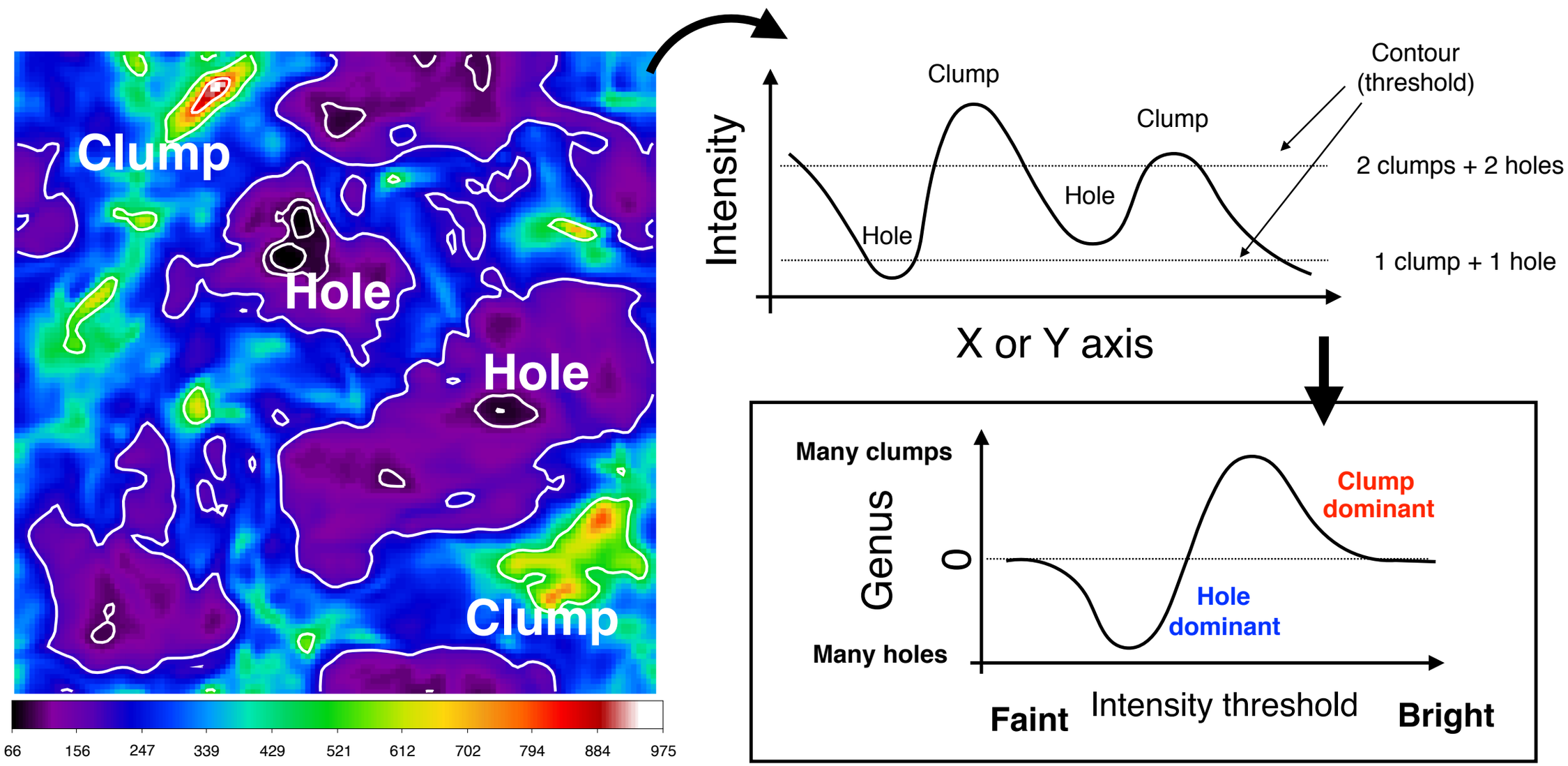


Wavelet-transform size analysis



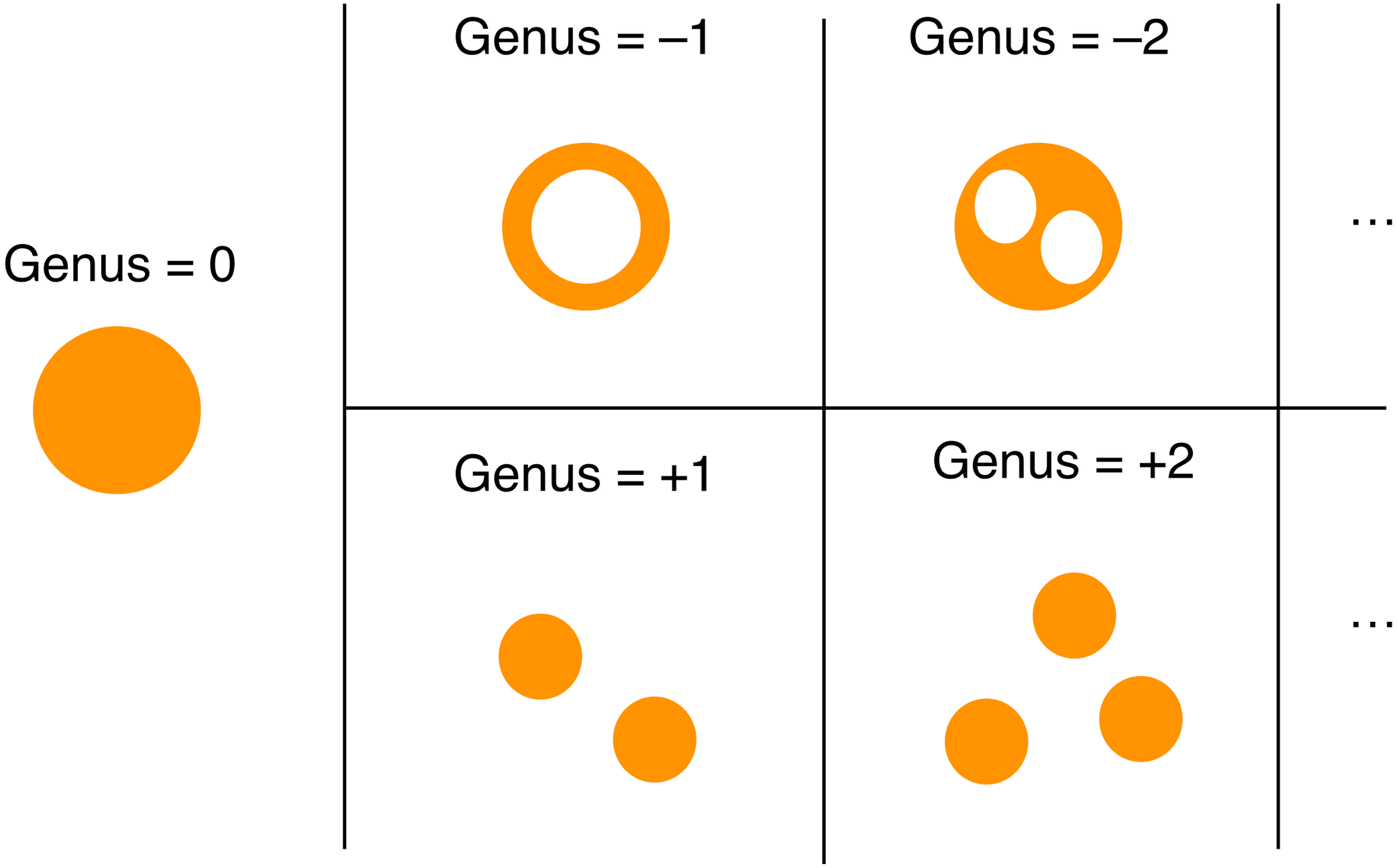
What is the Genus Statistic?

- A method to analyze topology (in 2D & 3D)
- One calculates the homology count (# of holes and clumps) as a function of contour (intensity) level



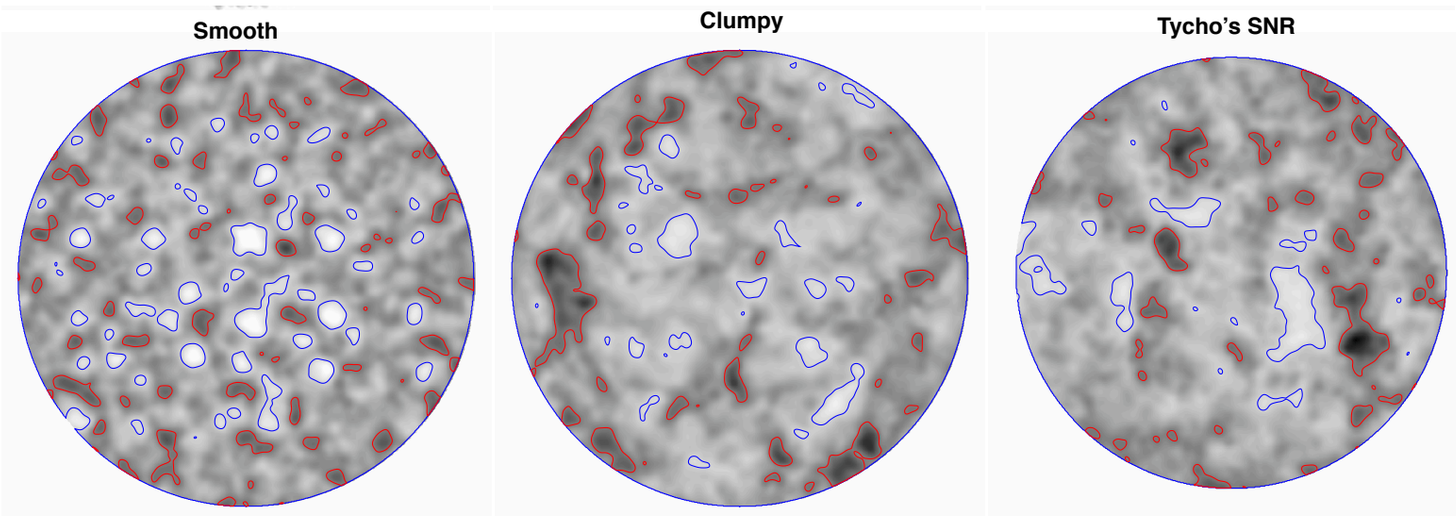
Usually in terms of RMS from mean

What is the Genus Statistic?



$$G \equiv (\text{number of isolated high-density regions}) - (\text{number of isolated low-density regions})$$

Comparison with Hydro Models



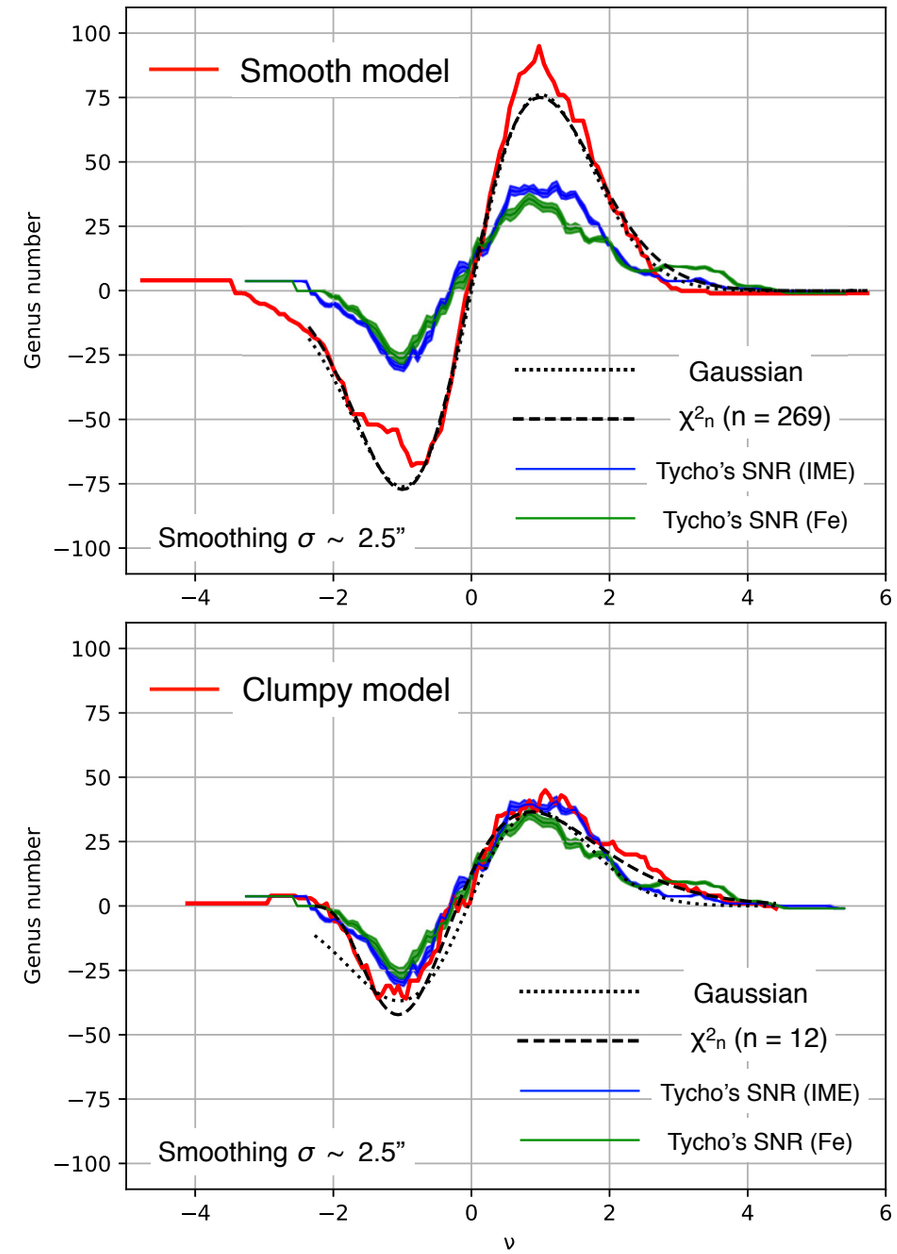


Figure 10. Comparison of the genus curves for the smooth model (top) and the clumpy model (bottom) with the smoothing $\sigma = 6$ pixels ($= 2\farcs4$). The dot and broken lines show the analytic models for the Gaussian and χ^2 distribution, respectively. The blue lines show the genus curves for Tycho's SNR with the smoothing $\sigma = 5$ pixels ($= 2\farcs46$).

Smooth model (which includes only RTI during SNR evolution) is a much poorer fit than the clumpy model (with *ad hoc* structure for ejecta introduced soon after the explosion)

Observational Resources

Southern African Large Telescope: RU has 10% share of observing time

Advanced ACTPol: Large area sky survey of CMB for multiple science goals. RU closely involved in Galaxy Cluster. Significant upgrade to Simons Observatory in process

Swift, Chandra, XMM-Newton, NuSTAR: Operating X-ray satellites for cluster confirmation and detailed follow-up study