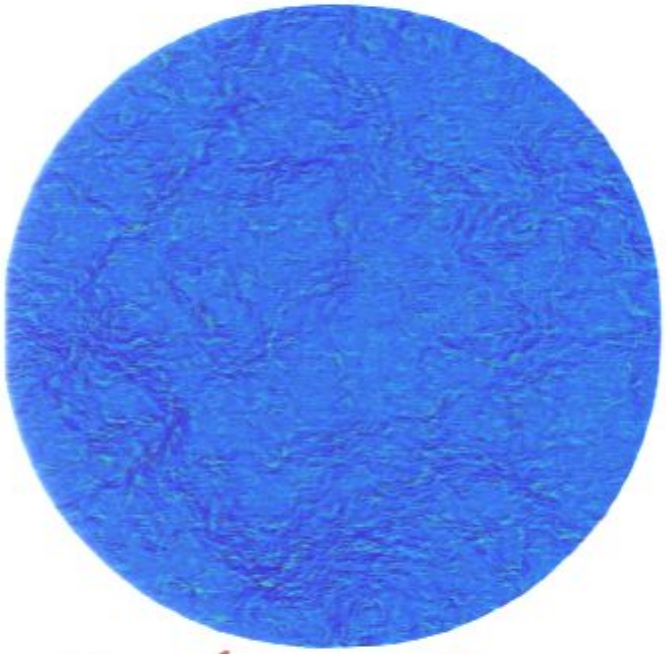
Title: A New View of the Cosmic Microwave Background with ACT

Date: Feb 15, 2011 10:30 AM

URL: http://pirsa.org/11020140

Abstract: Over the coming decade, tiny fluctuations in temperature and polarization of the Cosmic Microwave Background (CMB) will be mapped with unprecedented resolution. The Planck Surveyor, the Atacama Cosmology Telescope (ACT), and the South Pole Telescope (SPT) are already making great advances. In a few years, high resolution polarization experiments, such as PolarBear, ACTPol, and SPTPol will be in full swing. While these new arc-minute resolution observations will continue to help constrain the physics of the early universe, they will also be unique in a new way - they will allow us to measure the gravitational lensing of the CMB, i.e., the deflection of CMB photons by intervening large scale structure. CMB lensing will probe the growth of structure over cosmic time, helping constrain the total mass of neutrinos and the behavior of dark energy. In the first part of the talk, I will review the recent progress made with ACT, a powerful tool with new capabilities. In the second part, I will discuss the scientific potential of the CMB lensing signal, and its various applications in cross-correlation with other datasets. Finally, I will discuss the upcoming polarized counterpart of ACT --- the ACTPol project, which will have sixteen times better mapping speed than ACT, and will be a premier CMB lensing experiment. I will describe our plans to extract different flavors of science from the ACTPol data, including the cross-correlations with optical lensing and galaxy surveys, such as SDSS, BOSS, DES and LSST.

New Views of The CMB from ACT

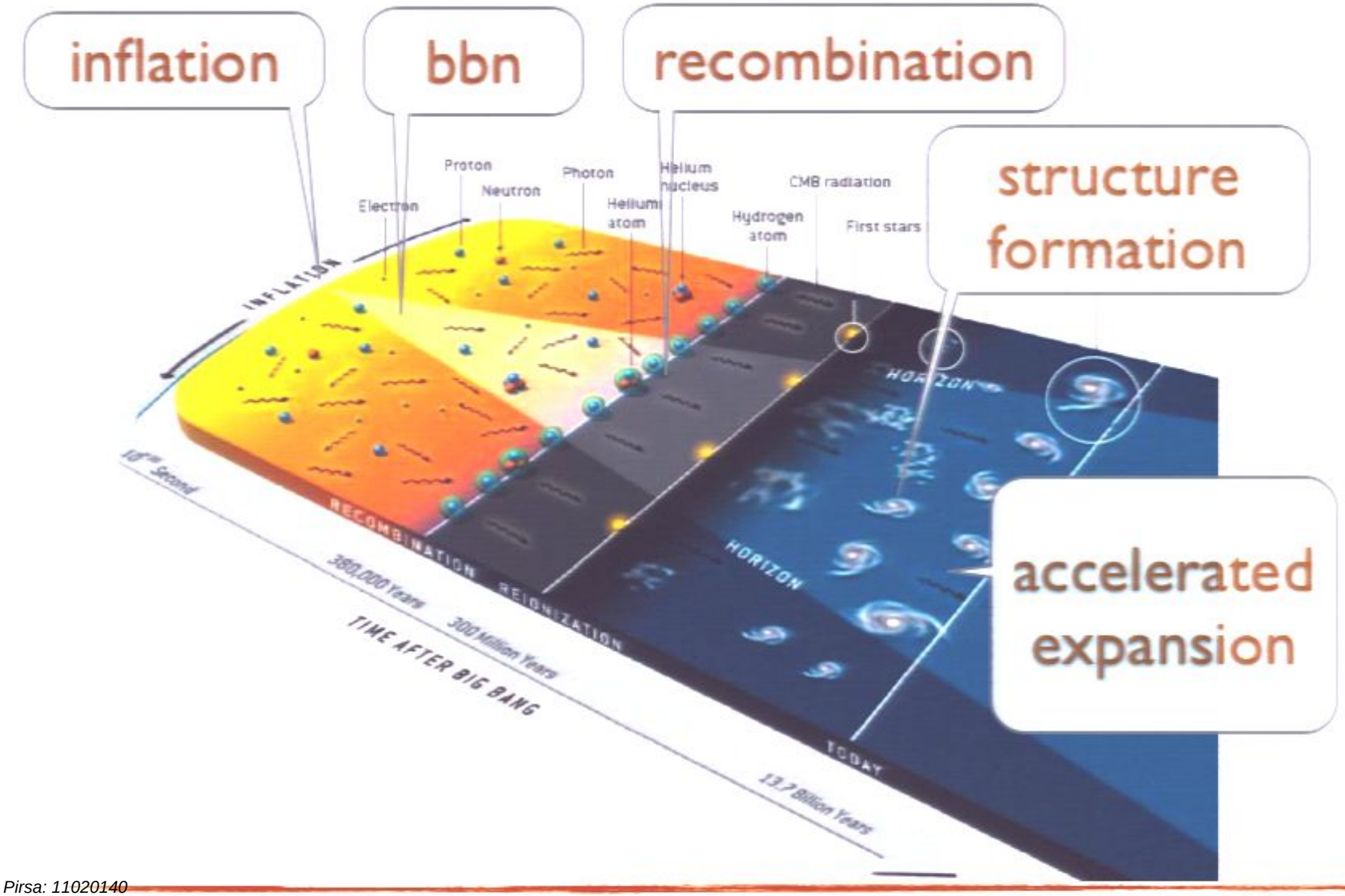


Sudeep Das

Berkeley Center for Cosmological Physics

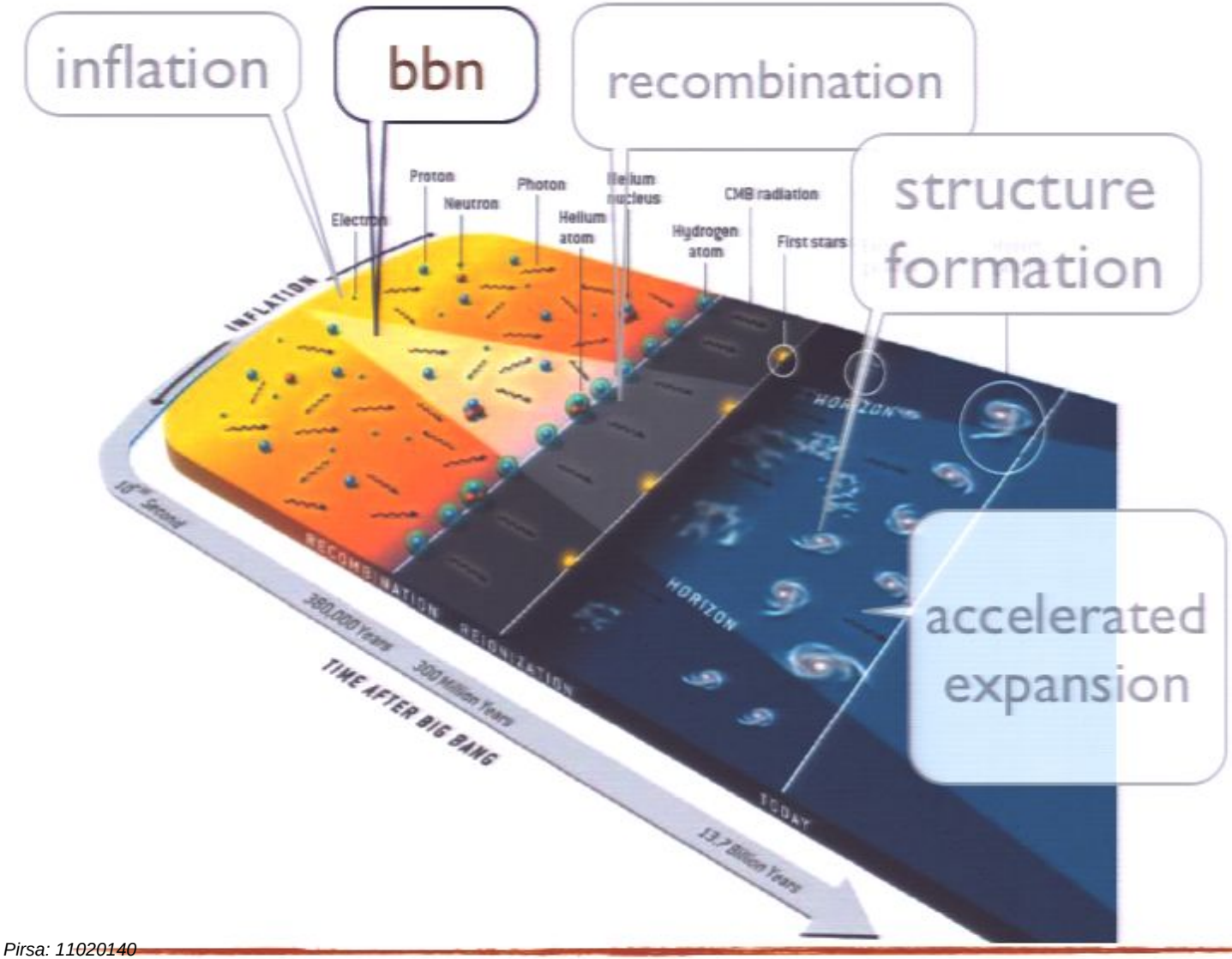
PLANCK DAY FEB 15, 2011

THE TIMELINE OF THE UNIVERSE HAS FIVE MAJOR MILESTONES



Sudeep Das, PI, CITA Day, Feb 15, 2011

Big Bang Nucleosynthesis (BBN) sets the abundance of light elements

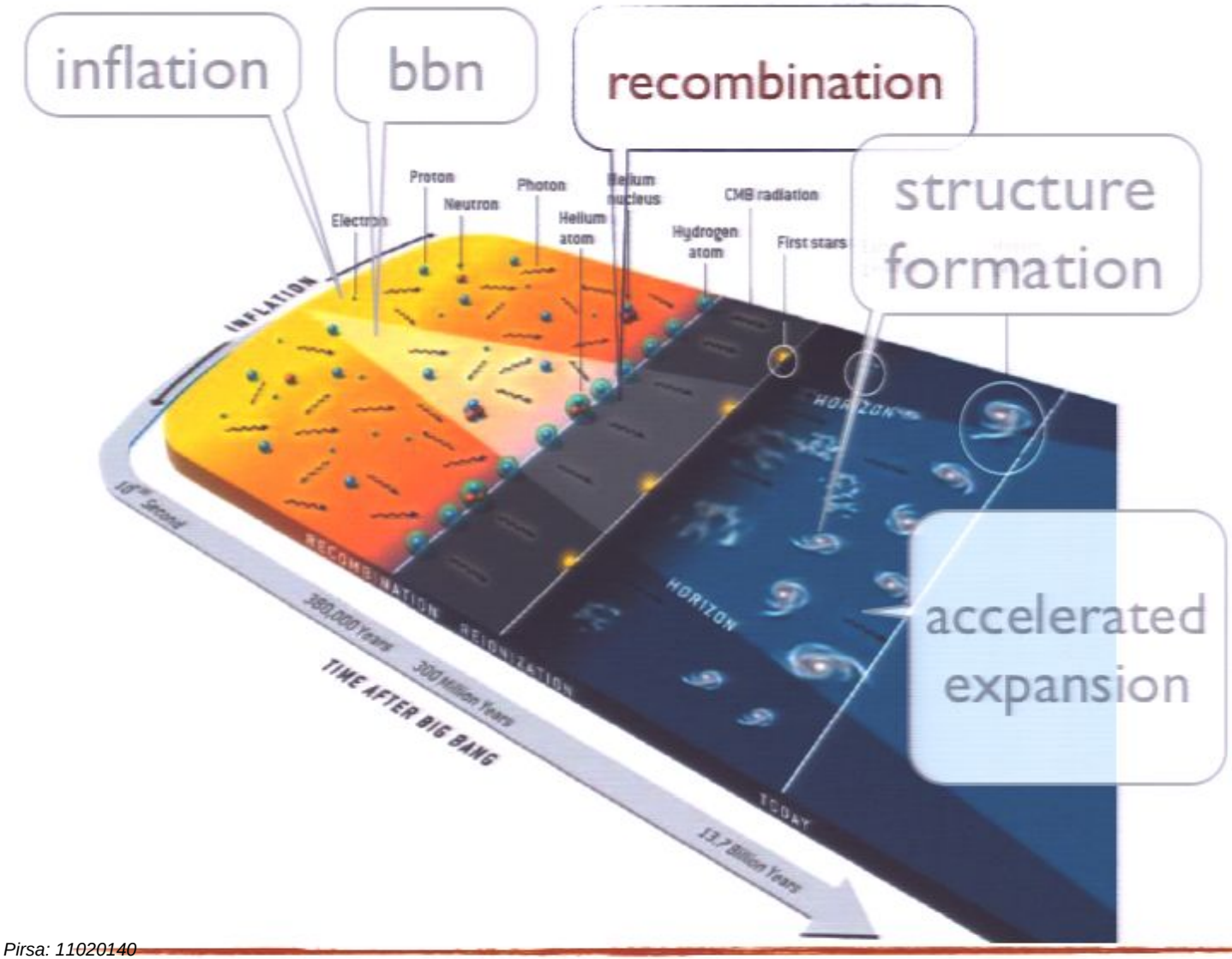


3-20 mins since BB

D, ^{3}He, ^{4}He, ^{7}Li, ... nuclei are formed.

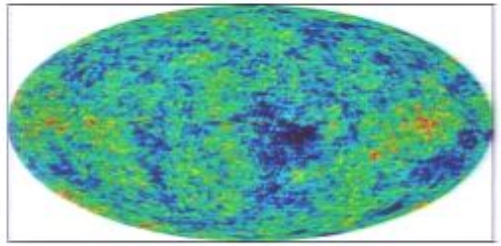
The Standard Model with 3 neutrino species (SBBN) seems to predict the abundance of these elements in overall good agreement with observations.

AT RECOMBINATION, THE CMB IS FORMED

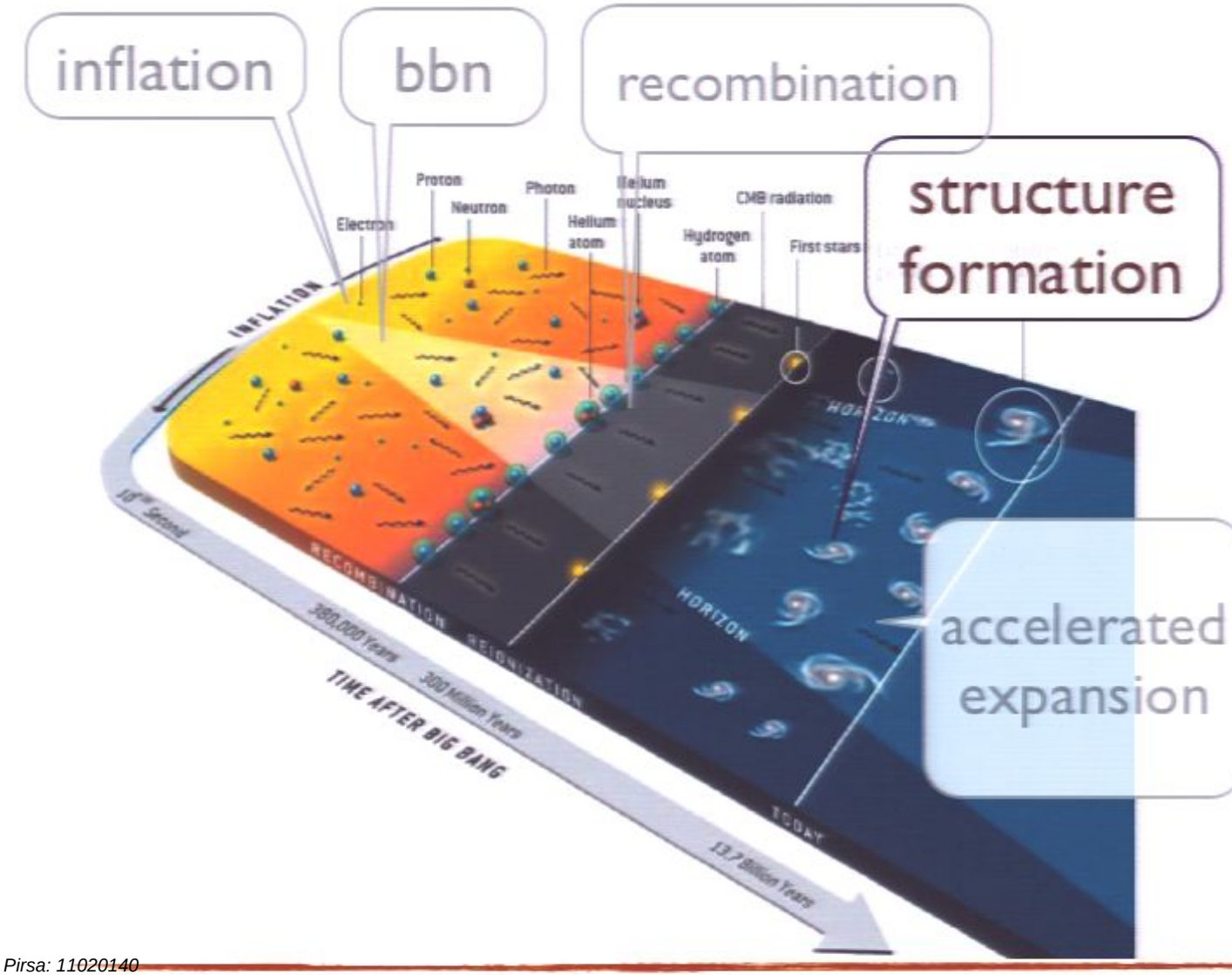


~ 380,000 years since BB

Universe has cooled enough to allow neutral H to form. Free electrons get depleted, and photons start streaming freely.

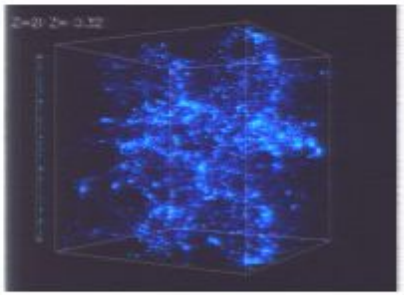


THE COSMIC WEB STARTS TAKING SHAPE



~ 500 million years since BB to present (13.7 billion years)

The initial seed fluctuations in matter starts growing into nonlinear structures.



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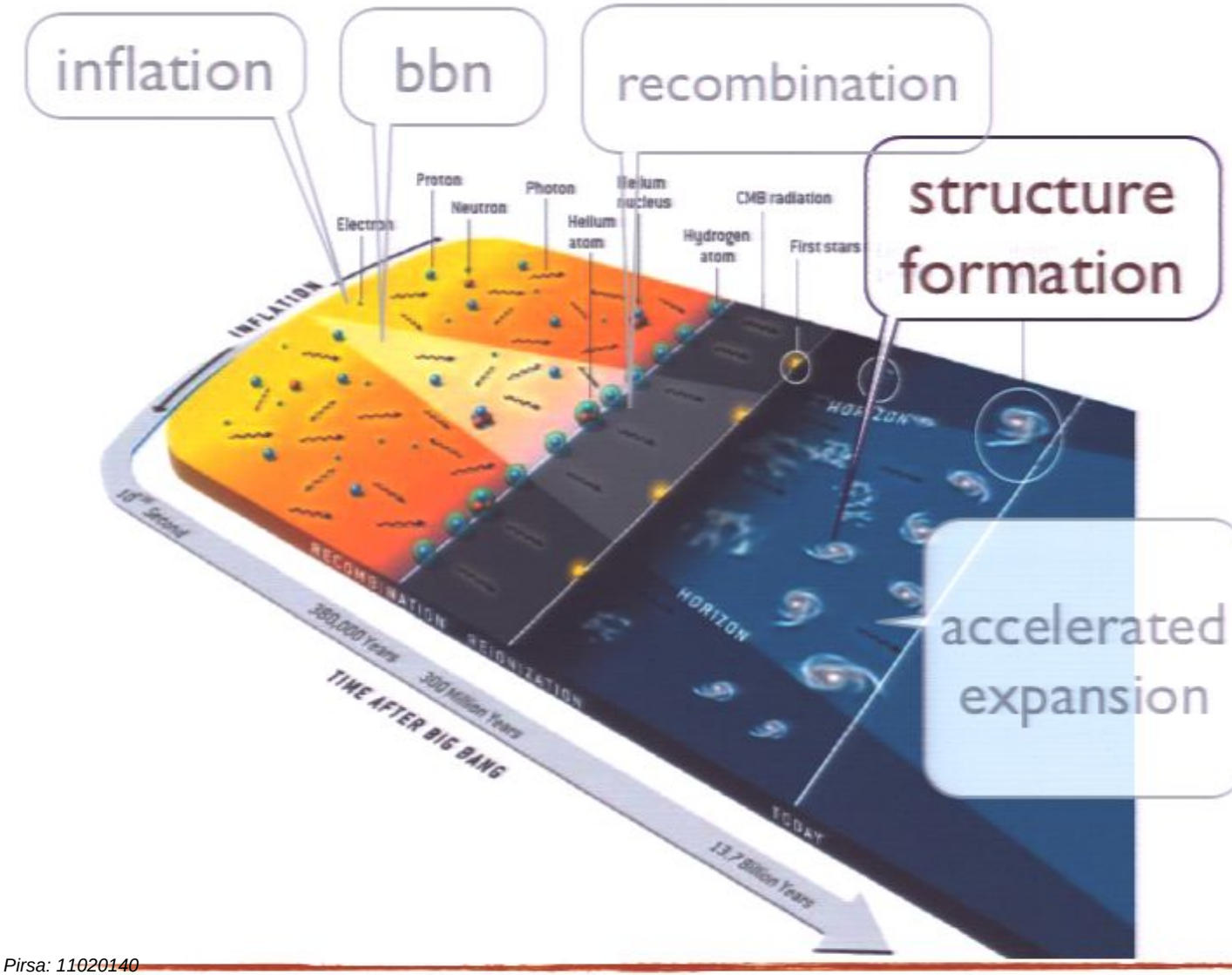

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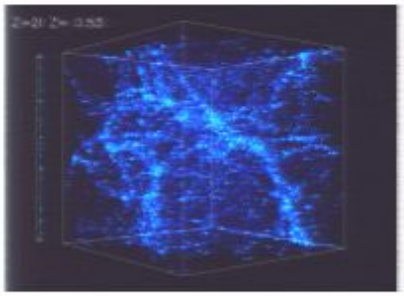

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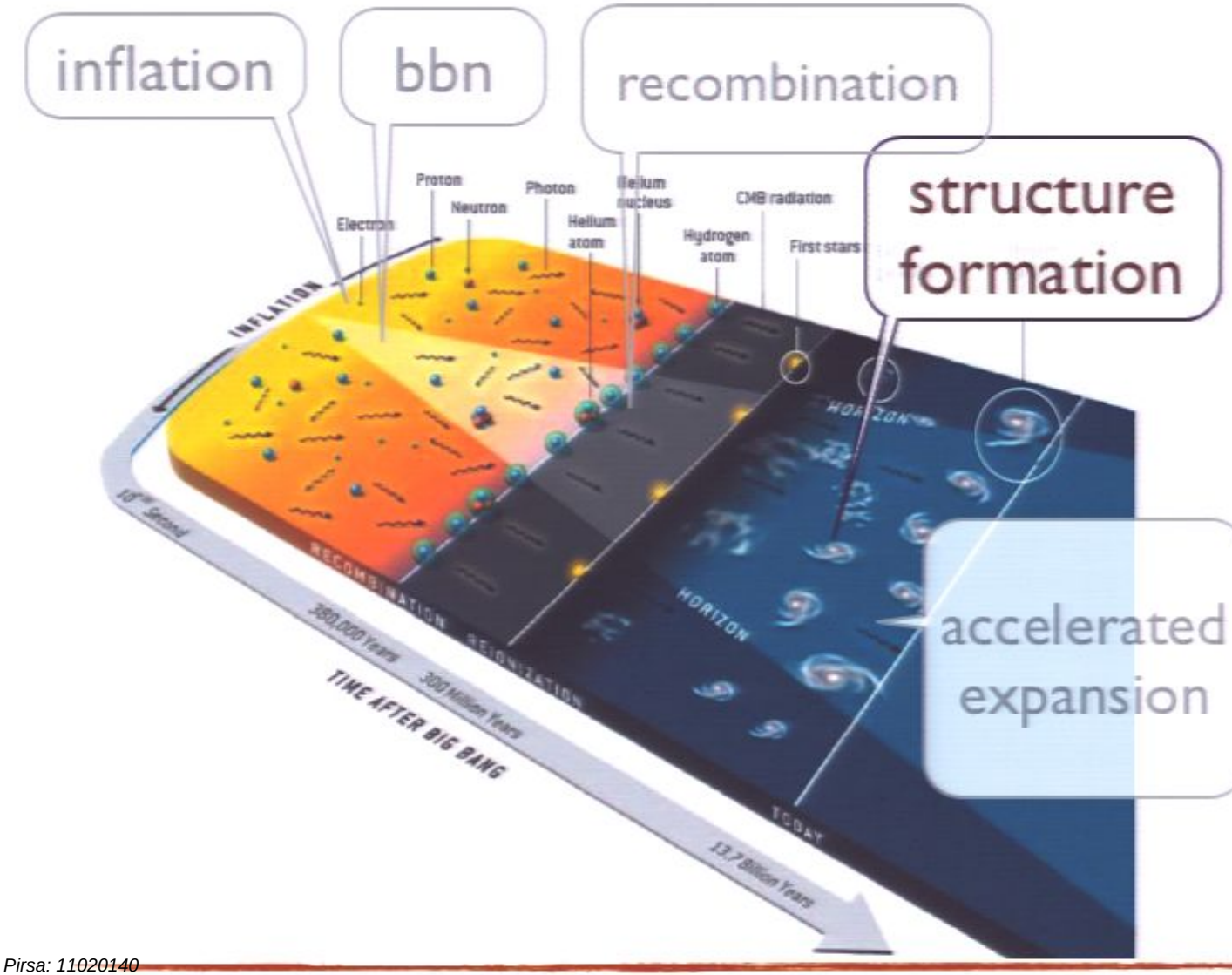

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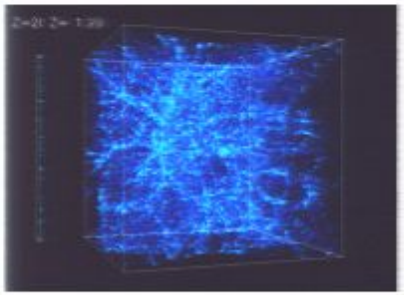

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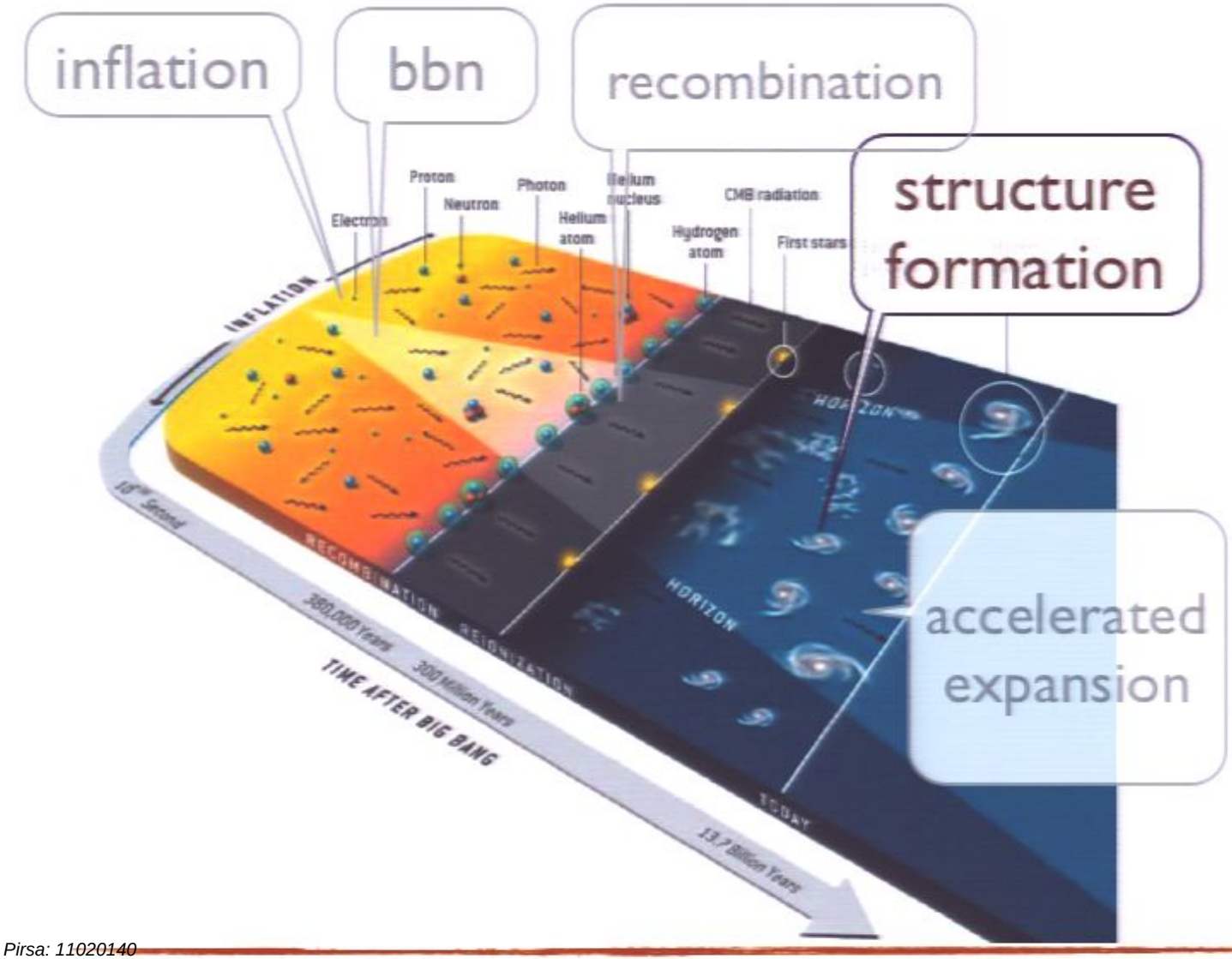

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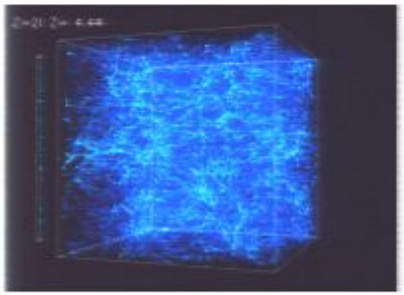

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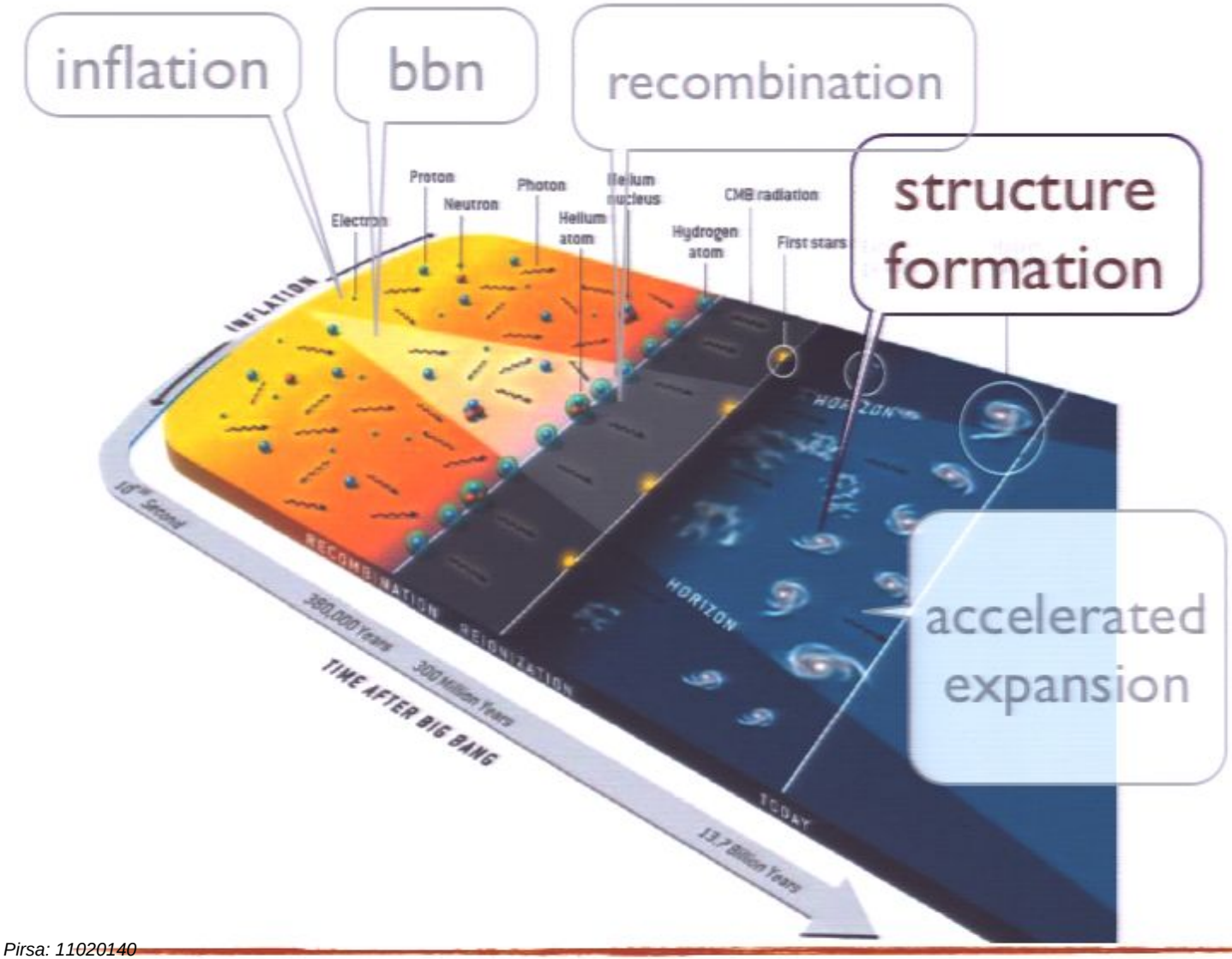

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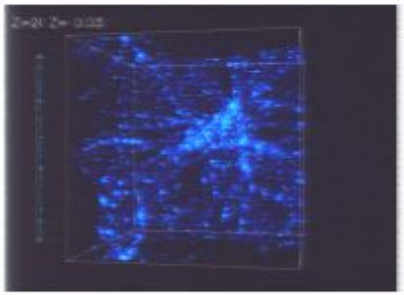

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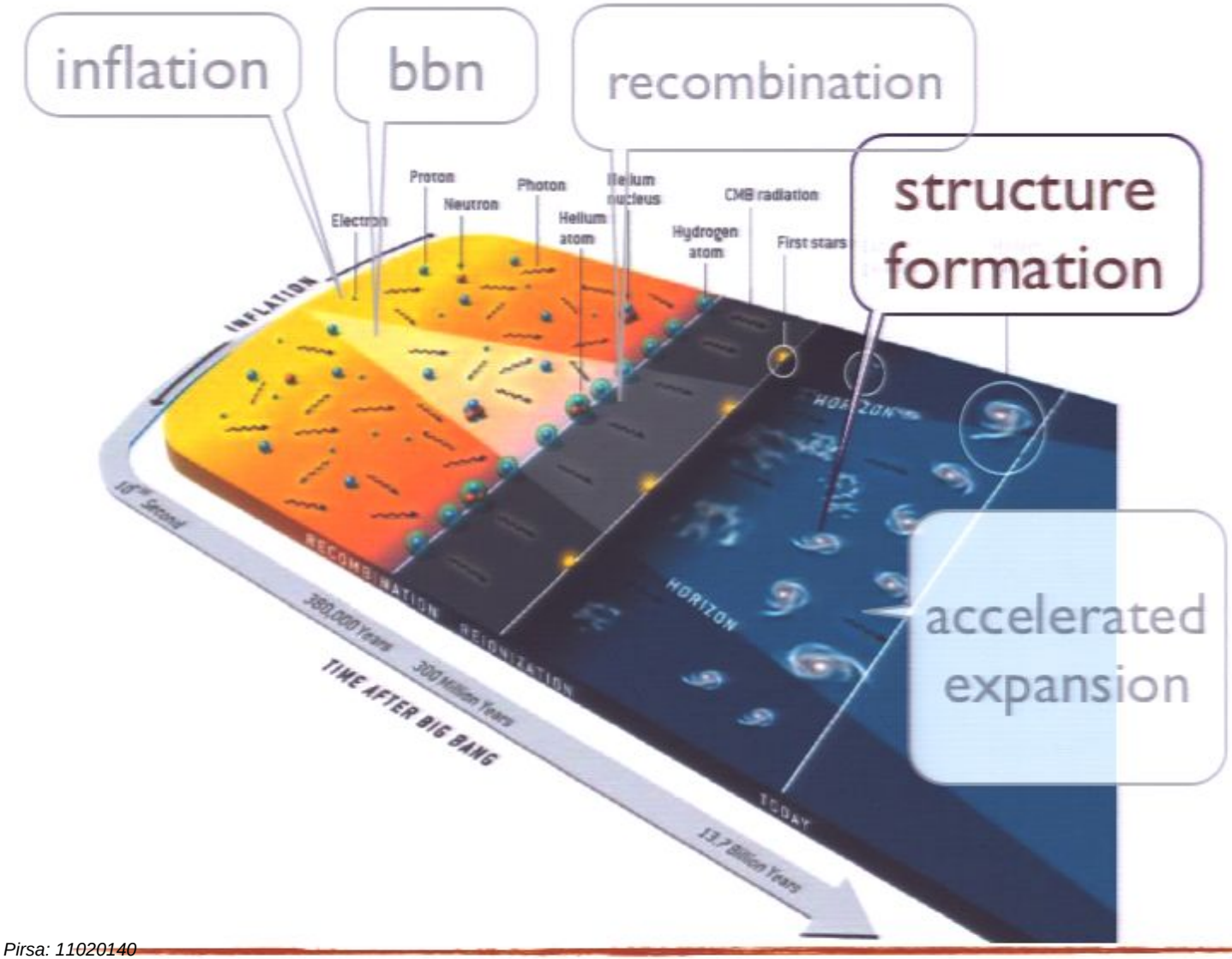

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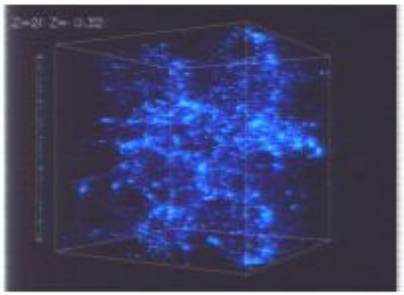

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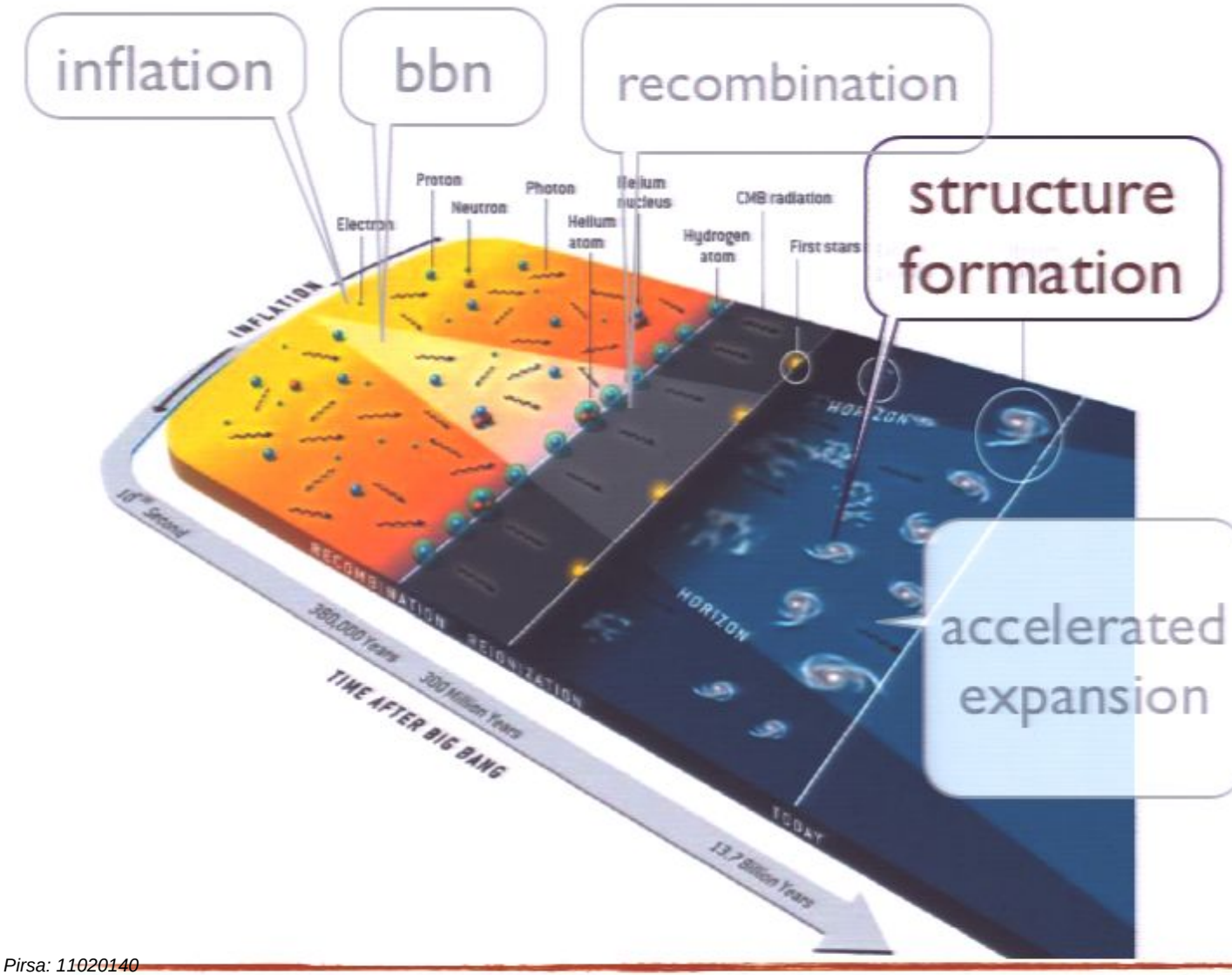

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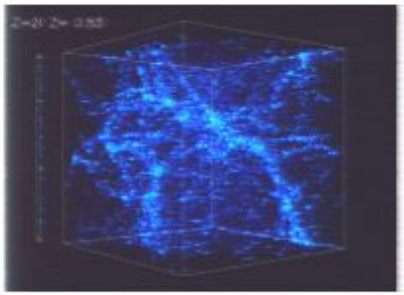
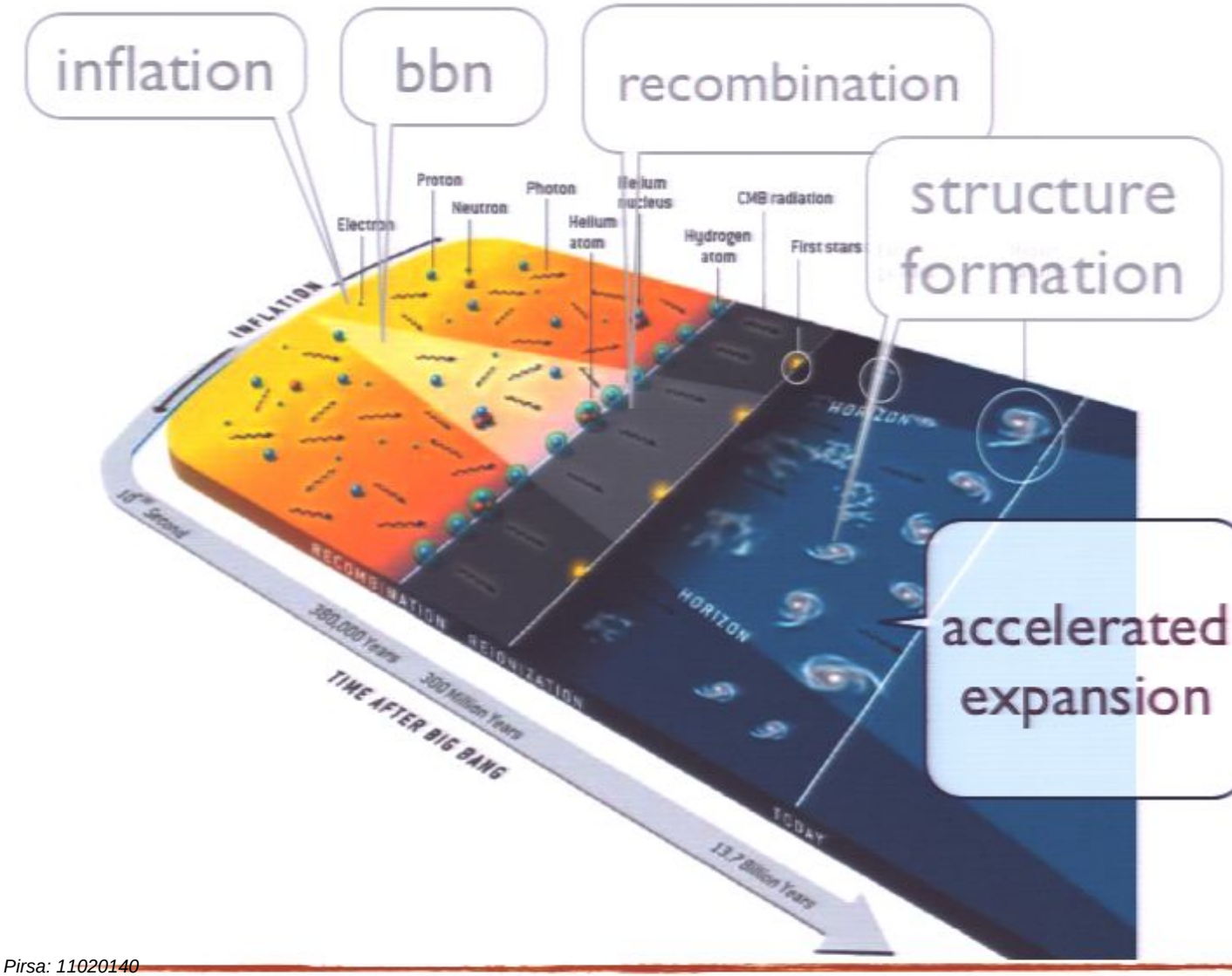


Needs dark matter.

THE UNIVERSE ENTERS A PHASE OF ACCELERATED EXPANSION



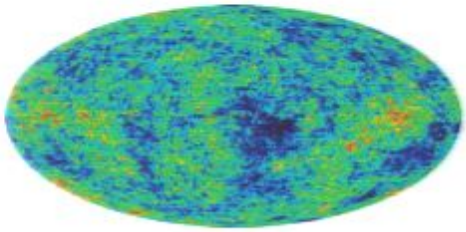
~ 5 Billion years since BB - the present (13.7 billion years)

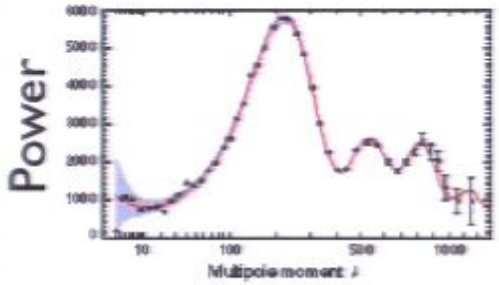
Type-Ia Supernova data shows that the universe is accelerating.

Cosmological Constant/Dark Energy?

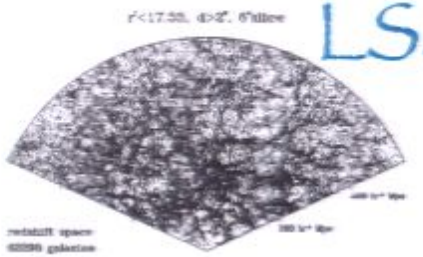
THE ΛCDM MODEL: AN EXCELLENT FIT TO OBSERVATIONS PROBING THESE EPOCHS

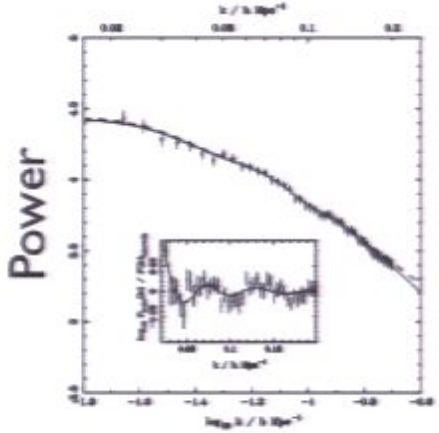
CMB



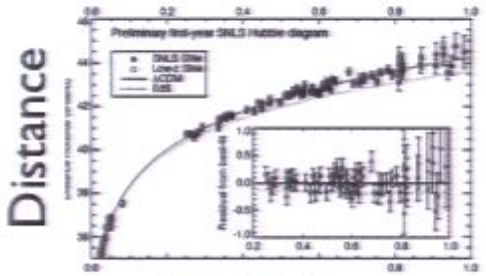


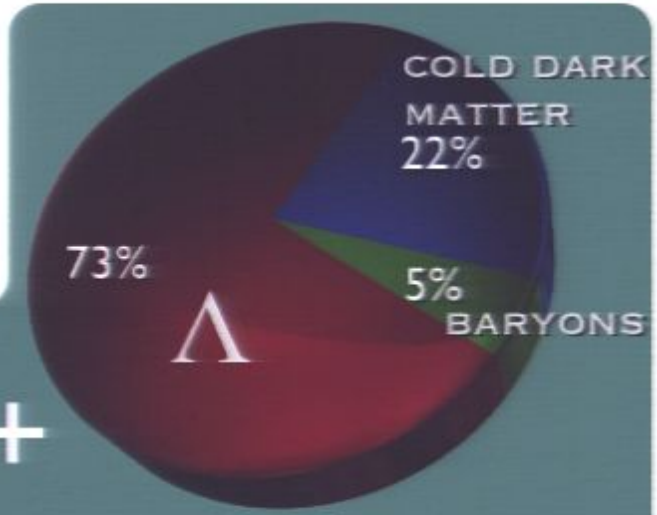
LSS





Supernovae





RECIPE

adiabatic, nearly scale invariant, power law, Gaussian fluctuations + flatness +

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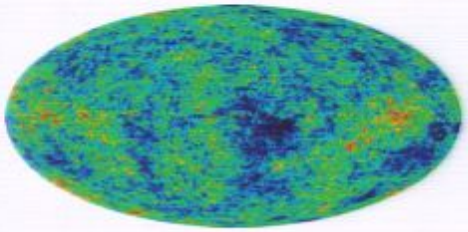

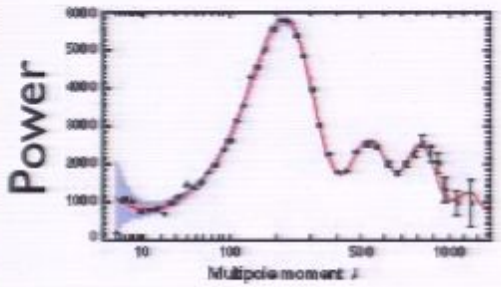

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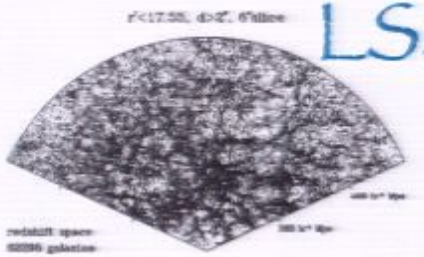

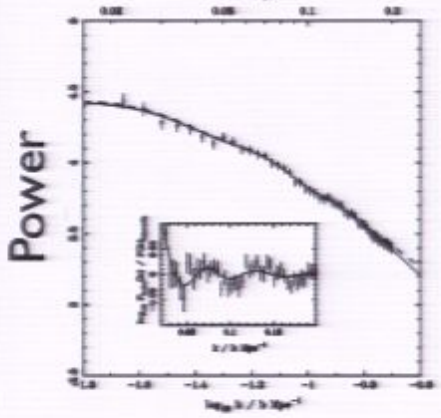

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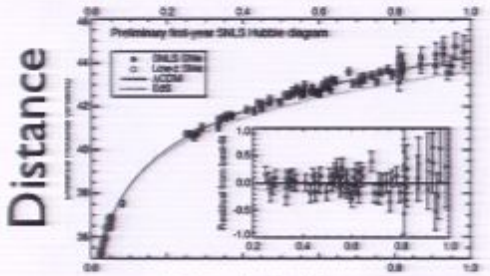

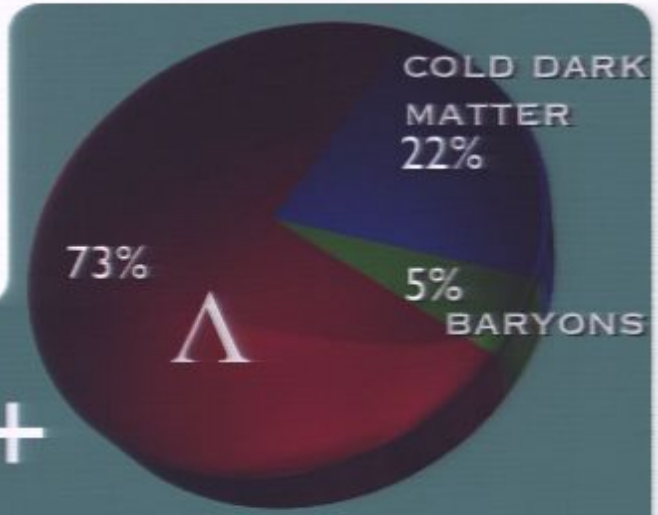

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THERE ARE BIG QUESTIONS WITHIN AND BEYOND THE STANDARD MODEL

inflation

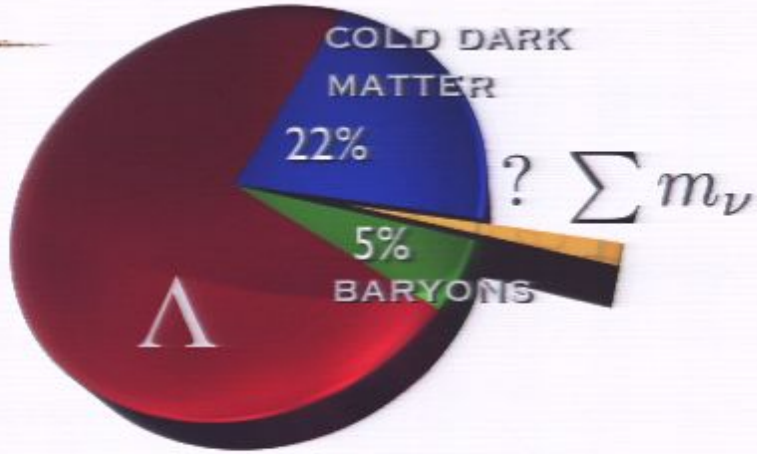
- What is the energy -scale of inflation?
- Which model?

dark sector

- Is Dark Energy a cosmological constant, or a dynamical component?
- What is the nature of Dark Matter?

particle sector

- What are the masses of the neutrinos?
- Physics beyond the Standard Model:
  - excess relativistic species during BBN?
- Sterile neutrinos?



HIGH RESOLUTION CMB OBSERVATIONS ARE OPENING NEW WINDOWS ON ALL THESE EPOCHS

inflation

bbn

structure formation

accelerated expansion/ DE

Higher order peaks in the CMB:

- Tilt and running of the primordial power spectrum.
- Ratio of tensor/scalar modes (r)
- Primordial Helium fraction (Y_p)
- Number of relativistic species (N_{eff})

Gravitational Lensing of the CMB

- Total mass of neutrinos
- Growth of structure
- Dark Energy behavior with redshift
- Geometry of the universe

Also, SZ clusters ...

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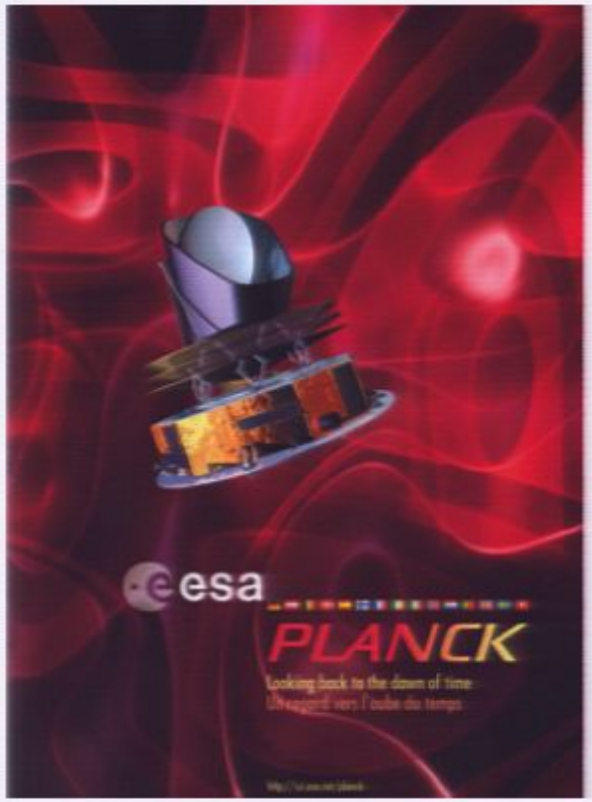
ONGOING EXPERIMENTS ARE PUSHING RESOLUTION AND SENSITIVITY TO NEW LIMITS



Planck

South Pole Telescope (SPT)

Atacama Cosmology Telescope (ACT)

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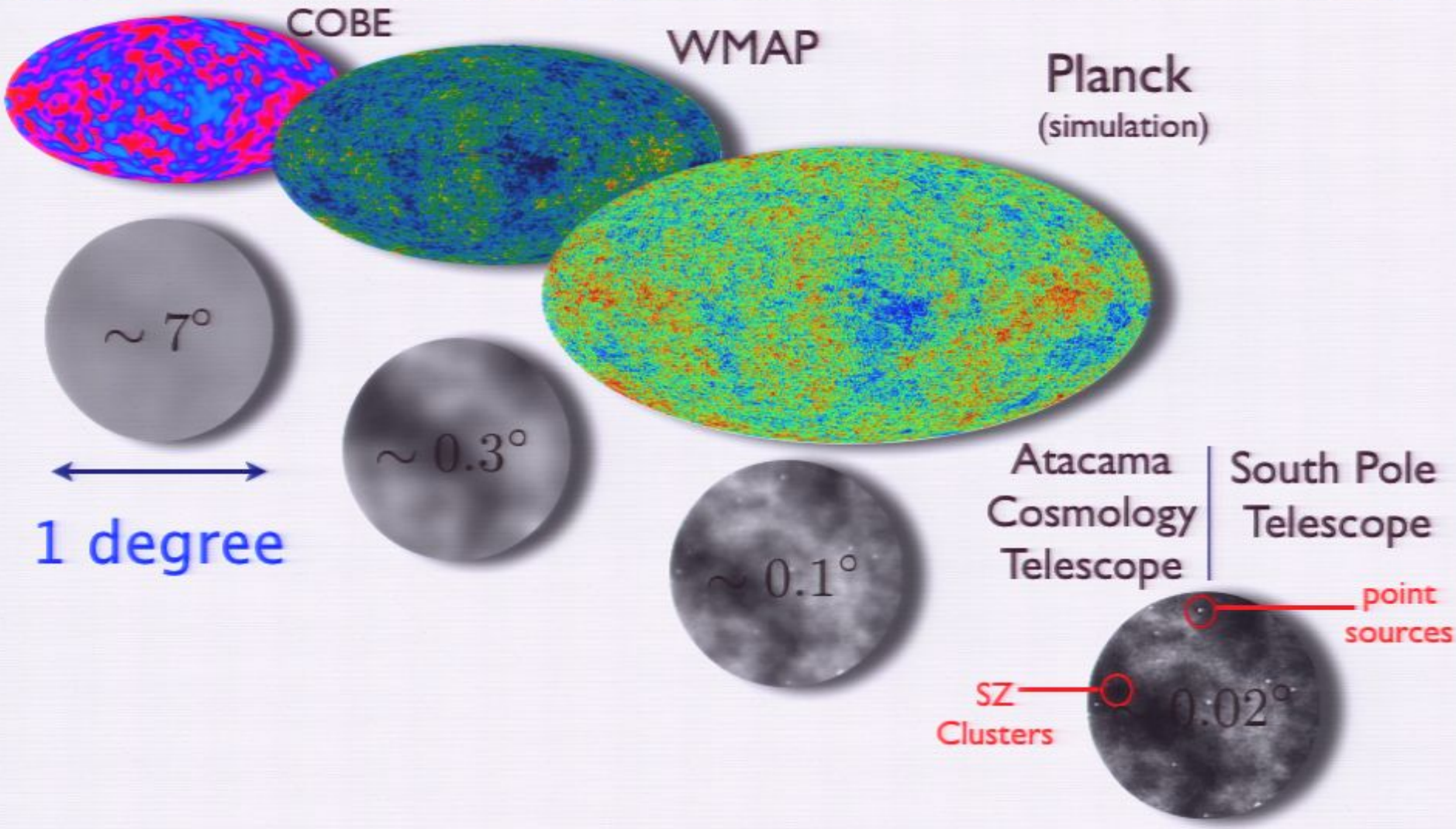
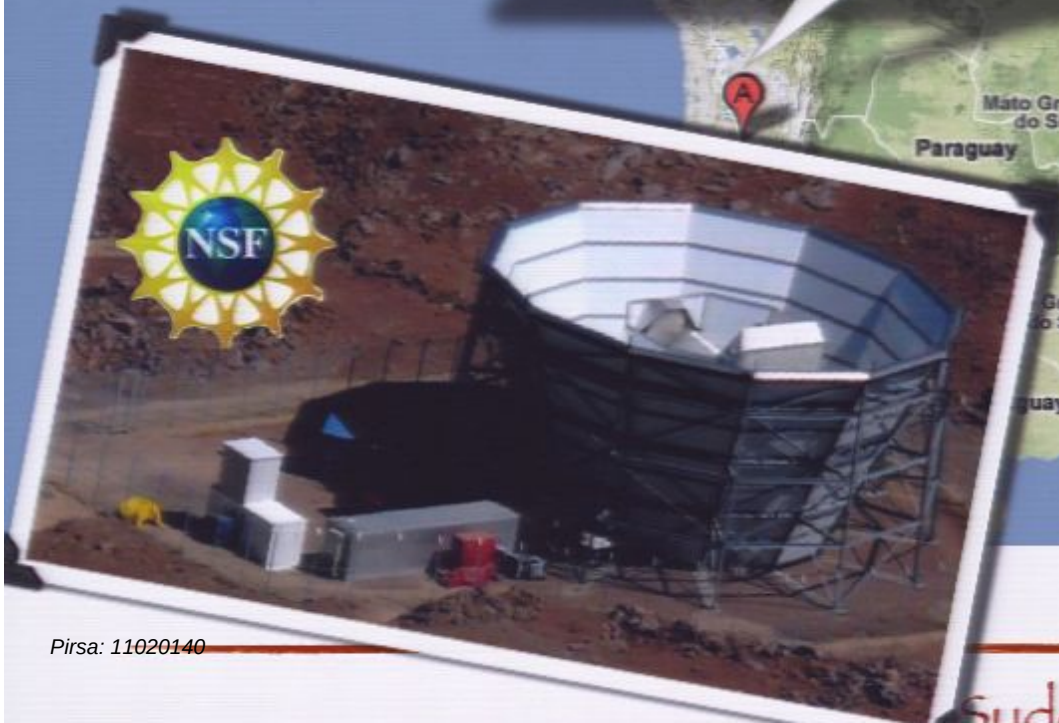


THE ATACAMA COSMOLOGY TELESCOPE

The **Atacama Cosmology Telescope** (**ACT**) is a six-metre telescope on Cerro Toco in the Atacama Desert in the north of Chile. It is designed to make high-resolution, microwave-wavelength surveys of the sky in order to study the cosmic microwave background radiation (CMB). At an altitude of 5190 metres (17030 feet), it is currently the highest permanent, ground-based telescope in the world.



- 6 m primary mirror. Off-axis Gregorian telescope
- ~1 arcmin resolution
- 148, 218, 277 GHz channels
- 3000 detector elements

Sudeep Das, PI, CITA Day, Feb 15, 2011

PUBLICATIONS

Marriage et al 2010 (1007.5256)	'Extragalactic Sources at 148 GHz in the 2008 Survey'
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Sehgal et al 2010 (1010.1025)	'Cosmology from Galaxy Clusters Detected via the Sunyaev-Zel'dovich Effect'
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Das et al 2010 (1009.0847)	'A Measurement of the CMB Power Spectrum at 148 and 218 GHz from the 2008 Southern Survey'
Dunkley et al 2010 (1009.0866)	'Cosmological Parameters from the 2008 Power Spectra'
Hajian, Viero et al. 2010 (1101.1517)	Correlations in the (Sub)millimeter Background from ACTxBLAST

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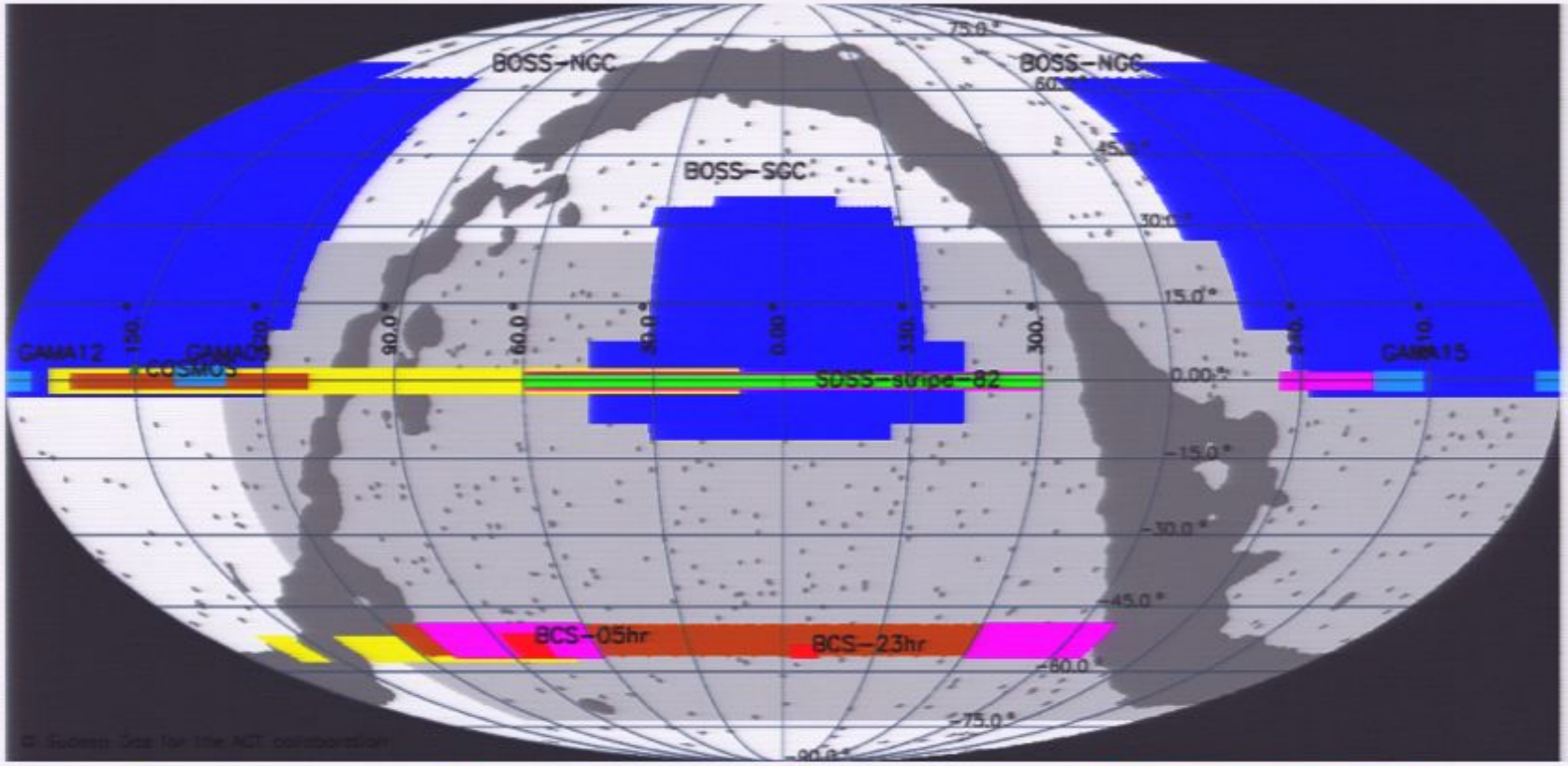
ACT HAS OBSERVED ABOUT 1800 SQ. DEGREES AT ARCMINUTE RESOLUTION!

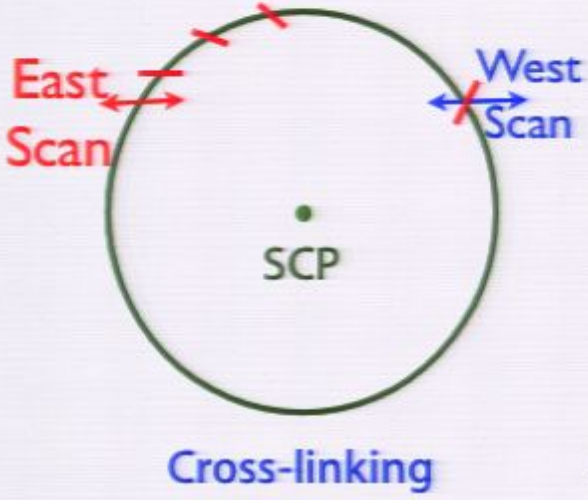


2007 | 2008 | 2009+10 | Stripe 82

BCS | BOSS | GAMA | ACT Range | Mask

Data Reduction and Map Making

- Relative Calibration
- Pointing and Astrometry
- Data Selection
- Map-making: Cross-linked observations help us solve for the maximum-likelihood map: true representation of the sky. Gain back modes suppressed by filtering through iteration. For one season of data, needs 100,000 CPU hours (lead: J. Sievers)



Cross-linking

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

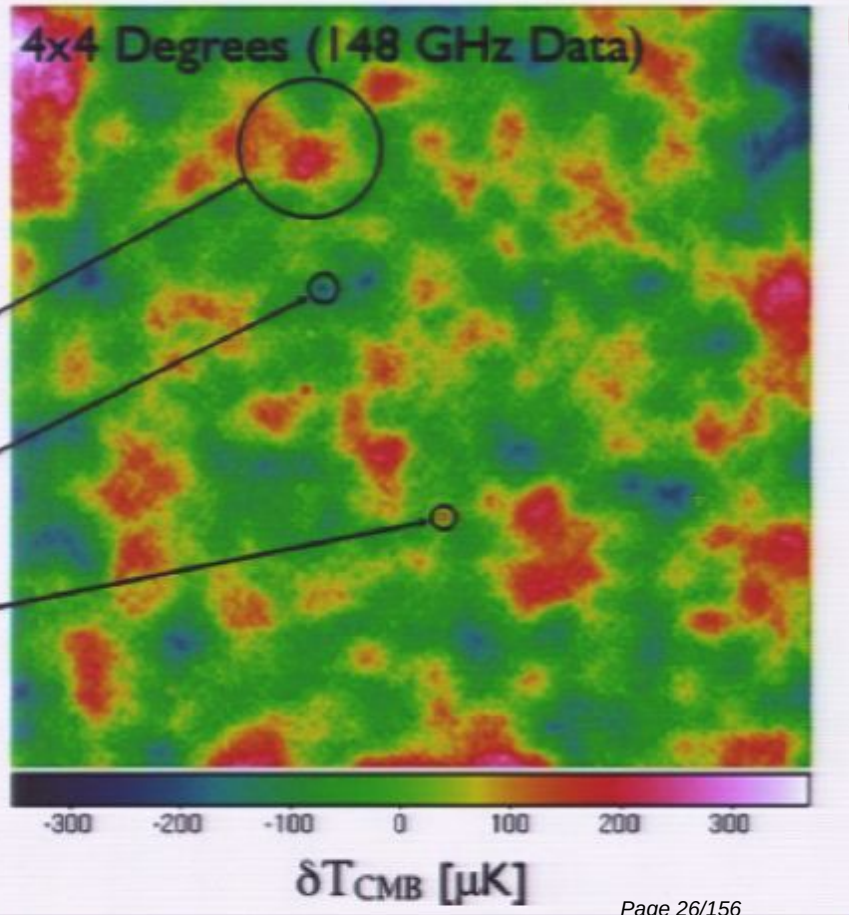
Atmosphere: 2 deg
(Filtered Here)

CMB: 1 deg

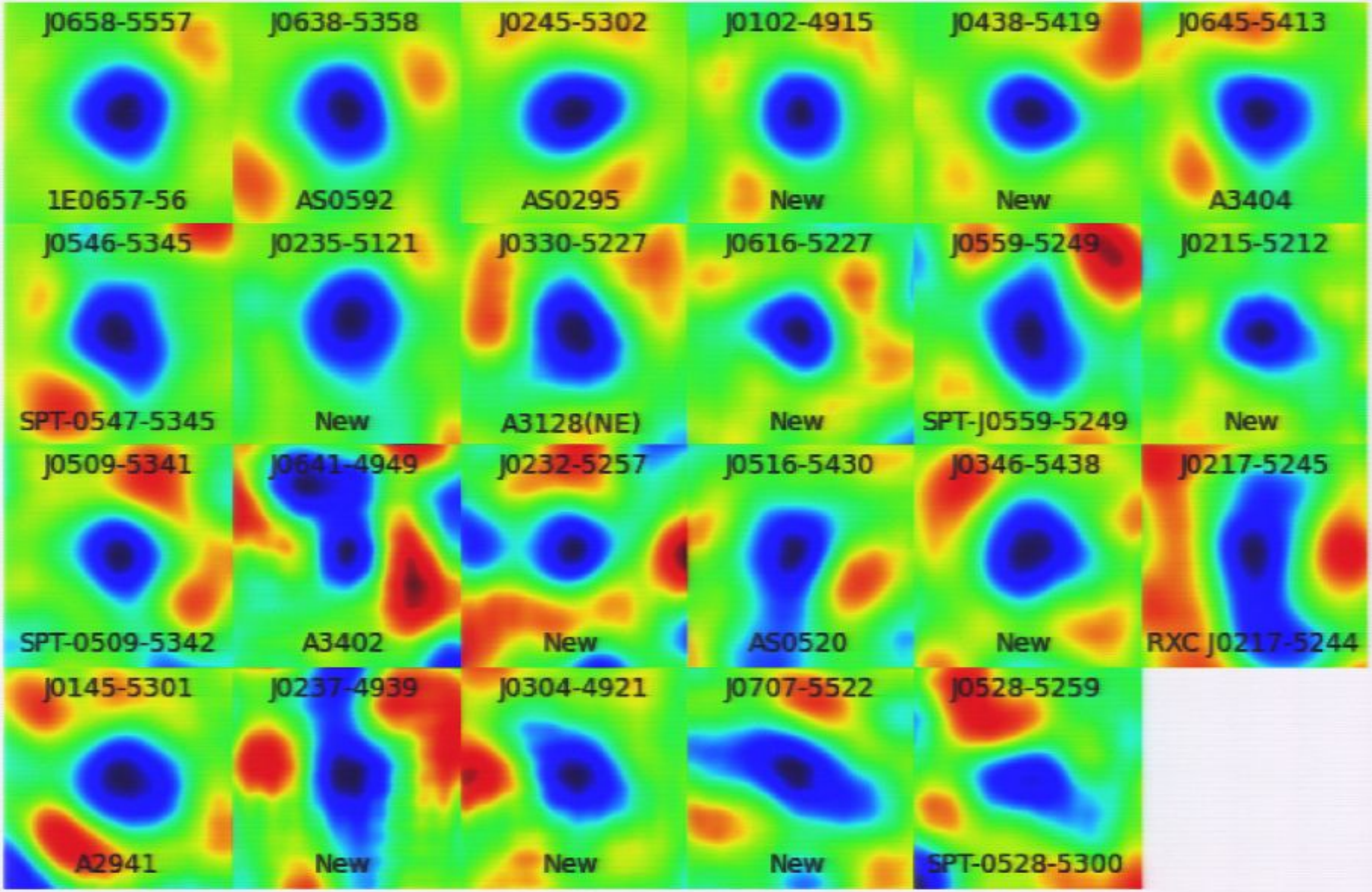
Clusters*: (>1.4')-4'

Sources*: 1.4'

* Minimum size set by beam



Galaxy Clusters @ 148 GHz South



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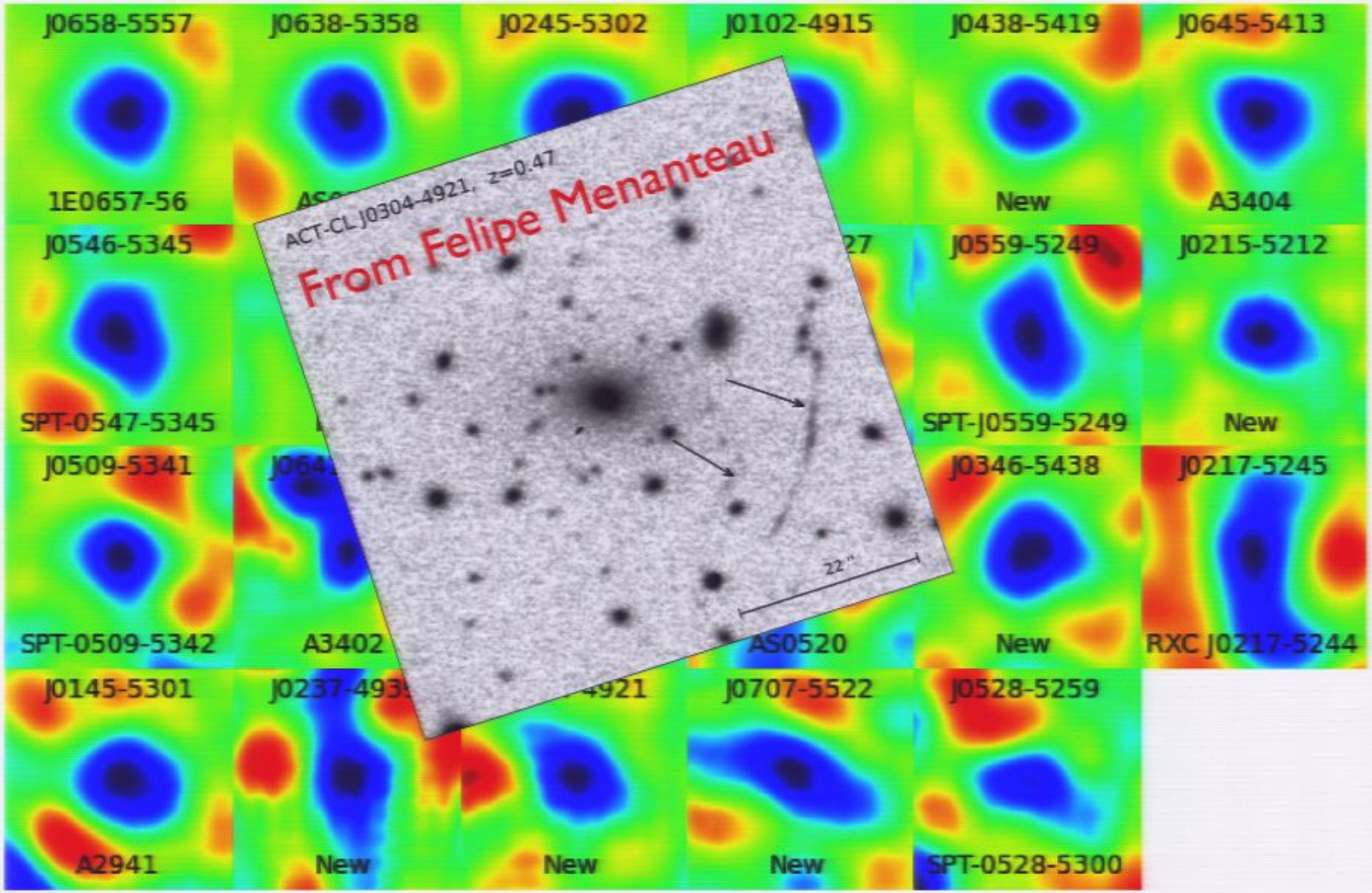

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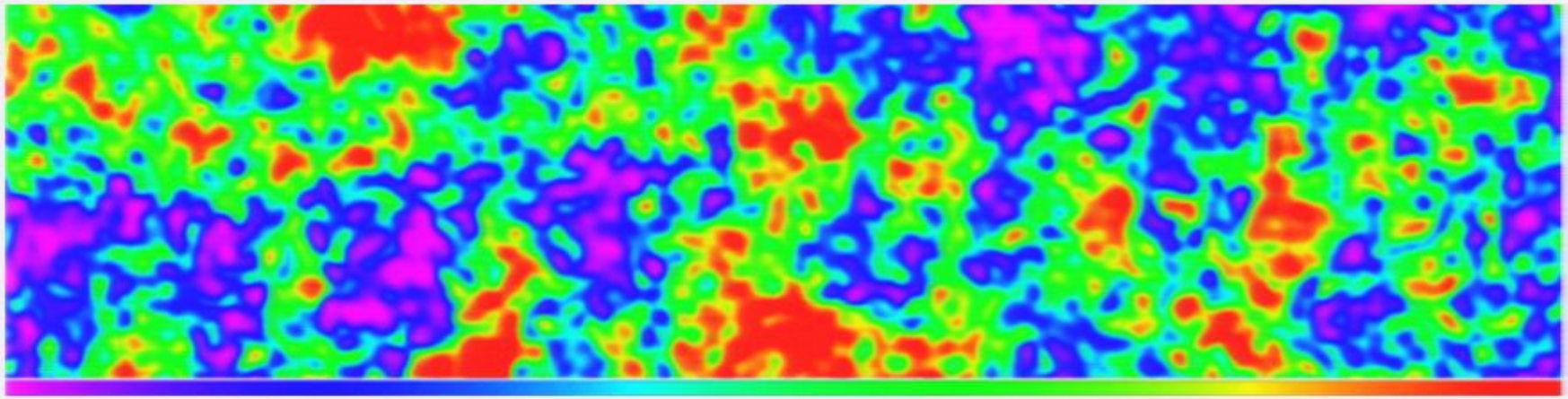

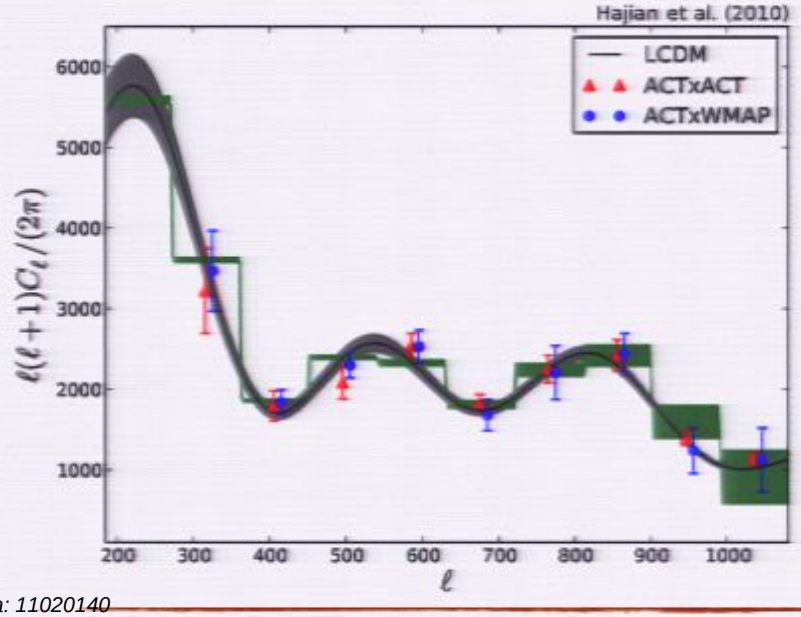

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Hajian et al. (2010) Sudeep Das, PI, CITA Day, Feb 15, 2011

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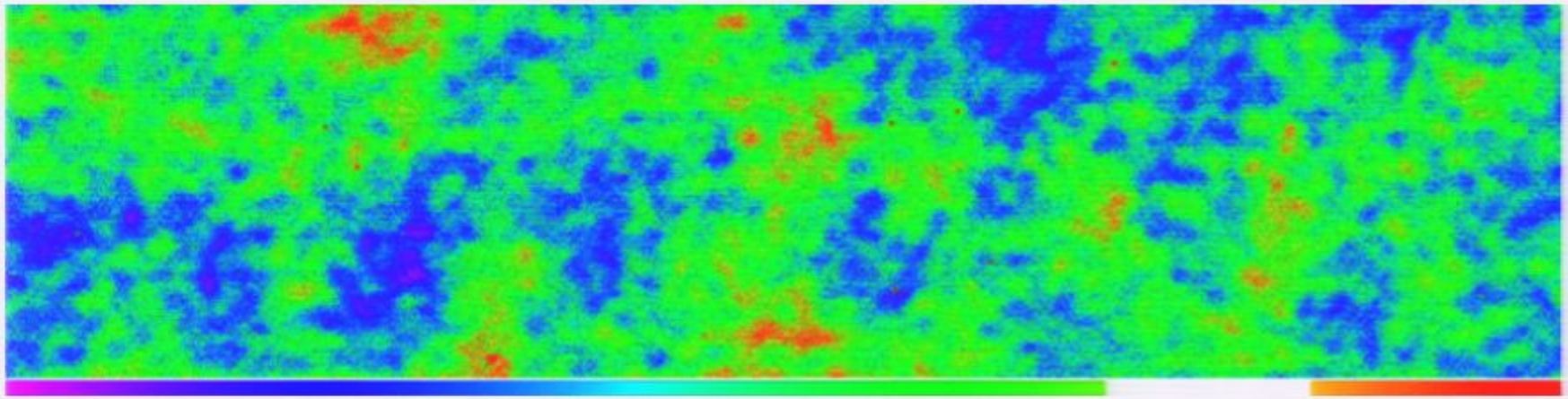

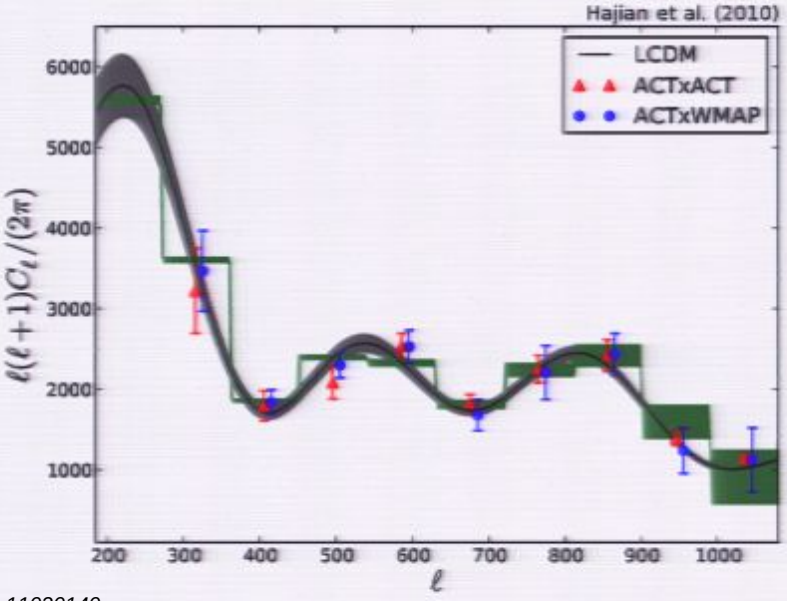

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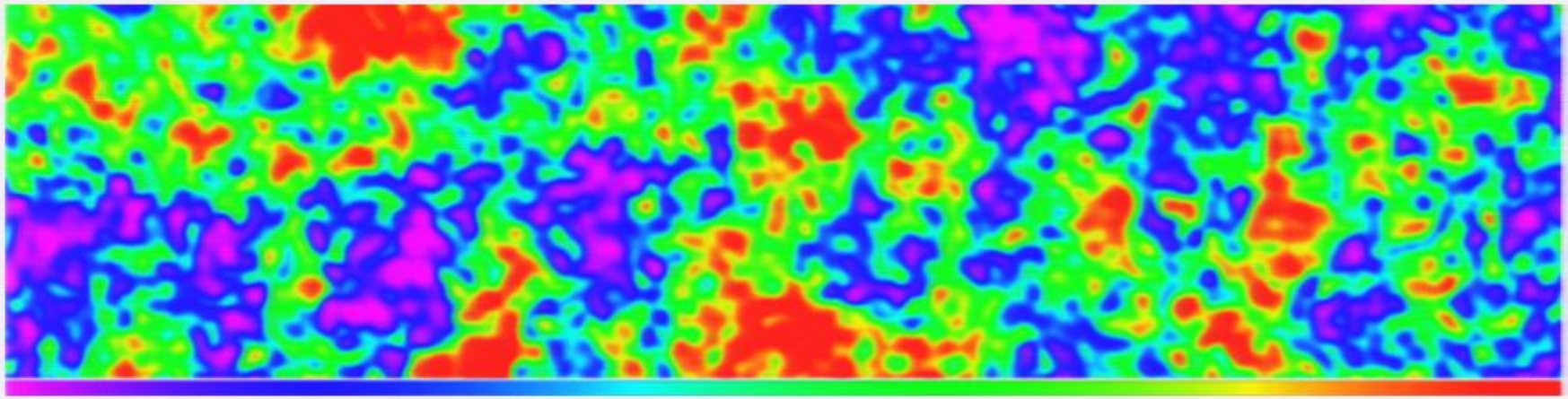

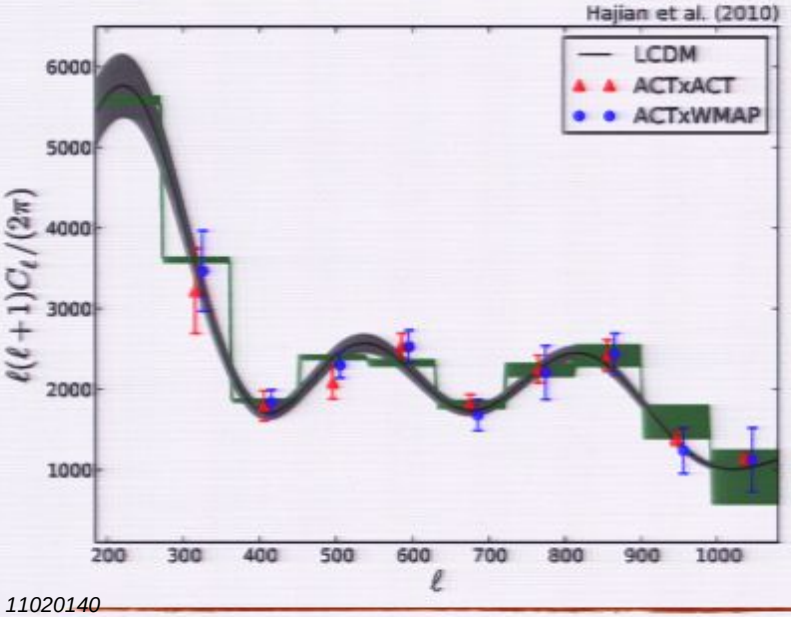

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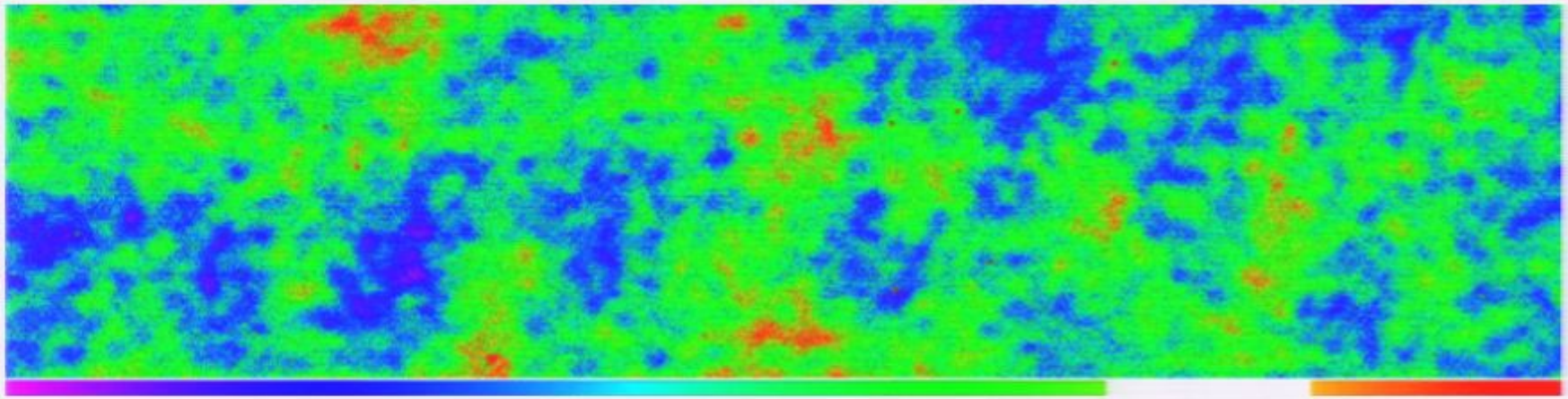

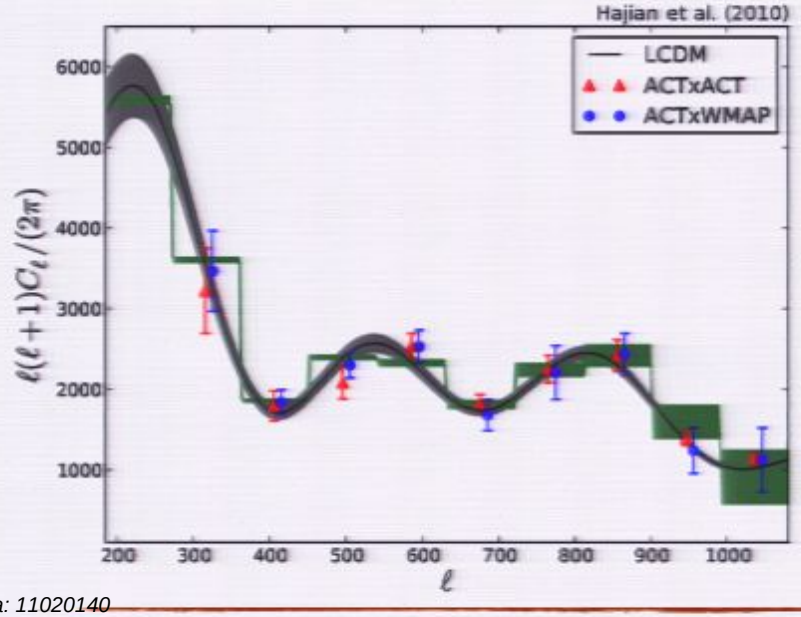

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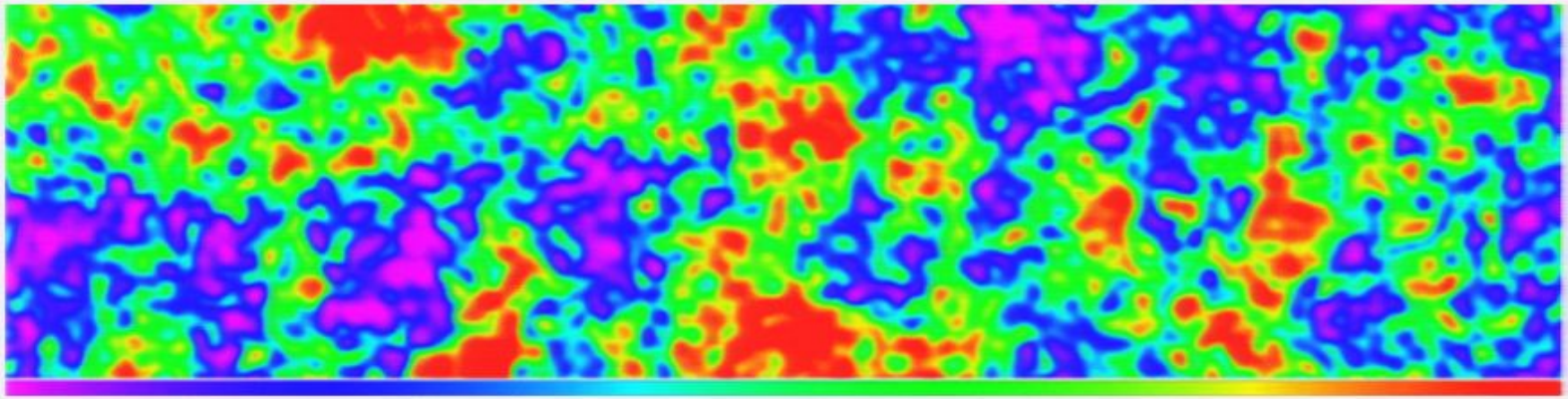

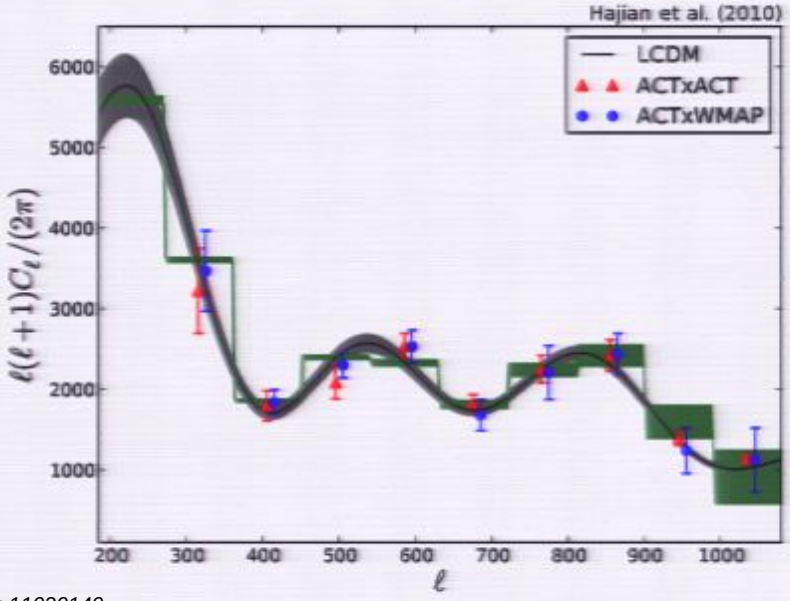

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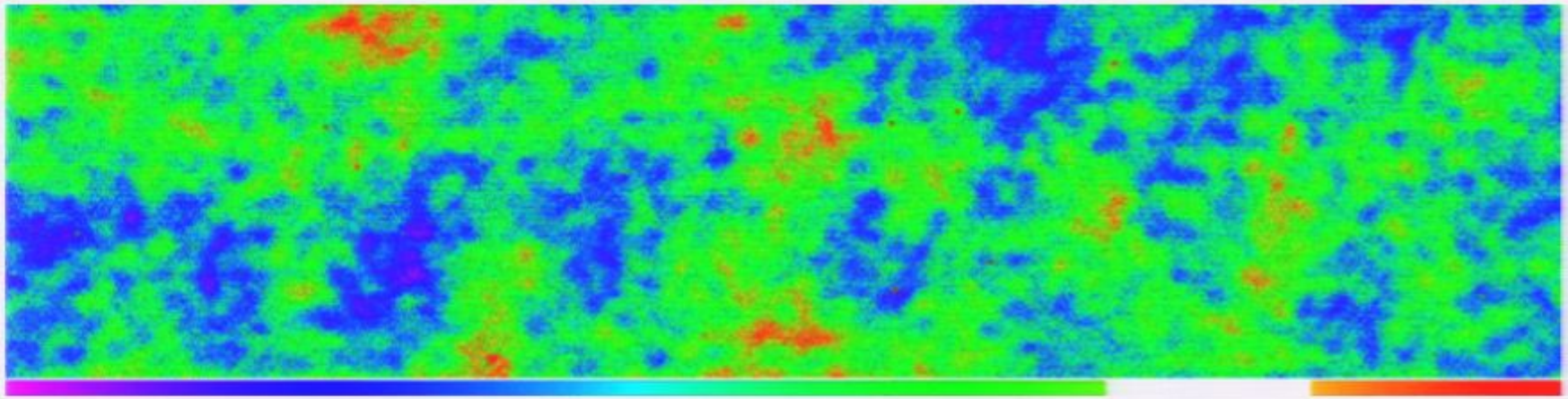

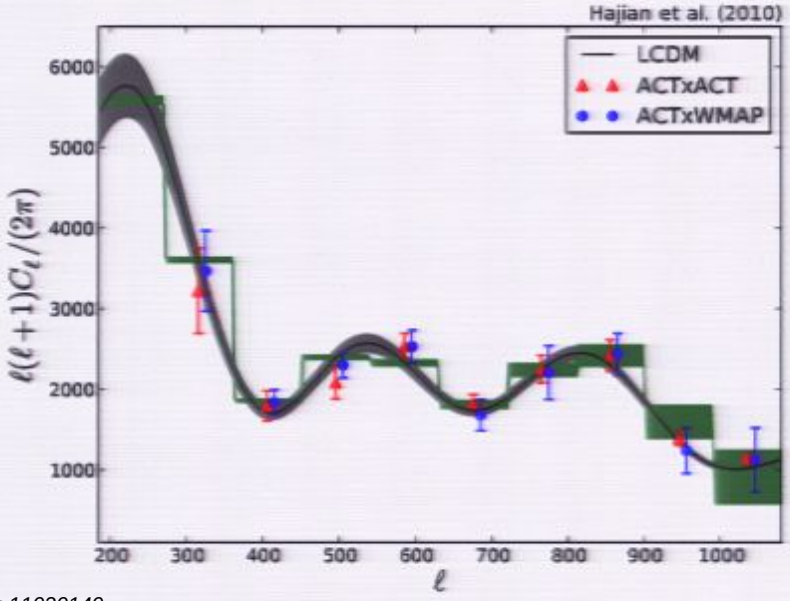

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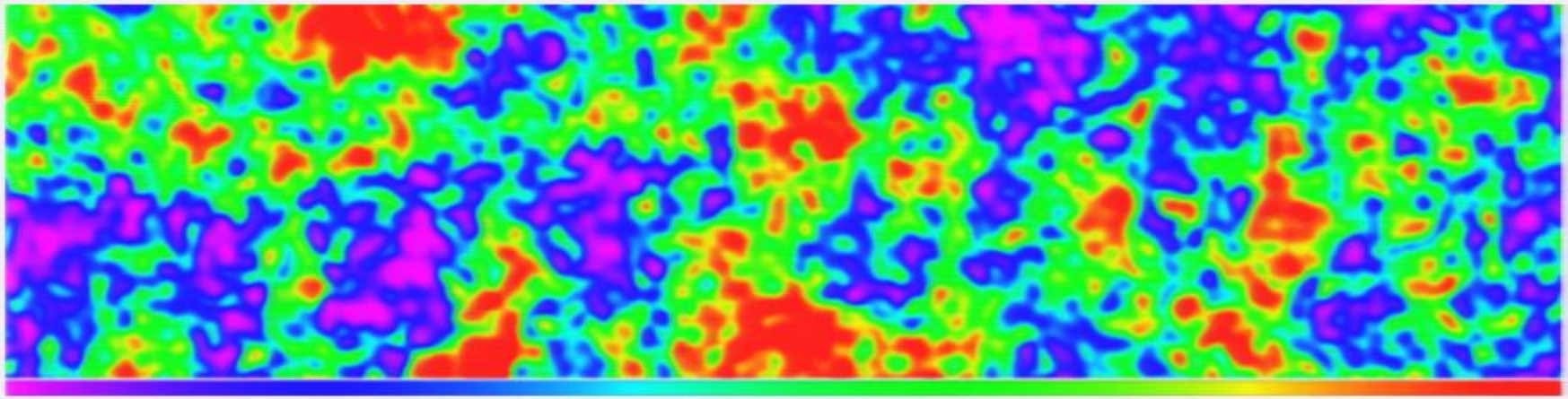

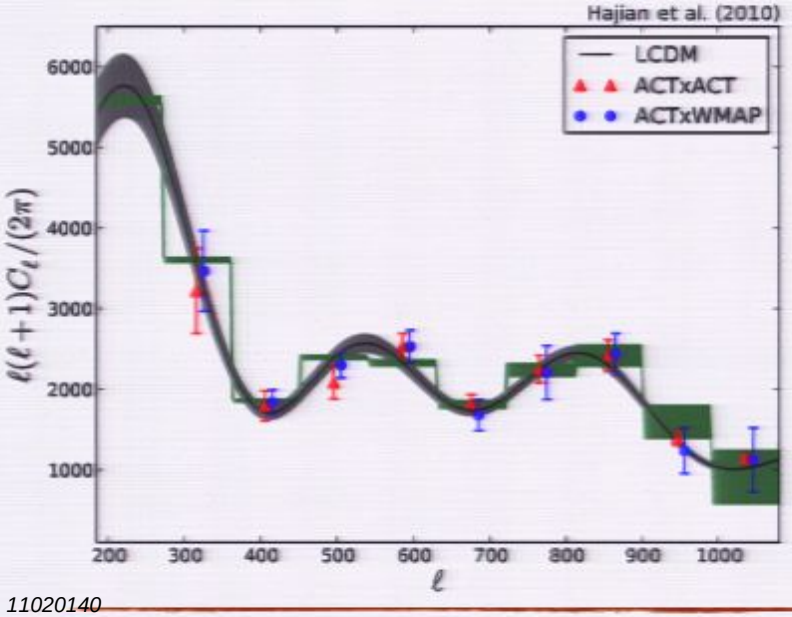

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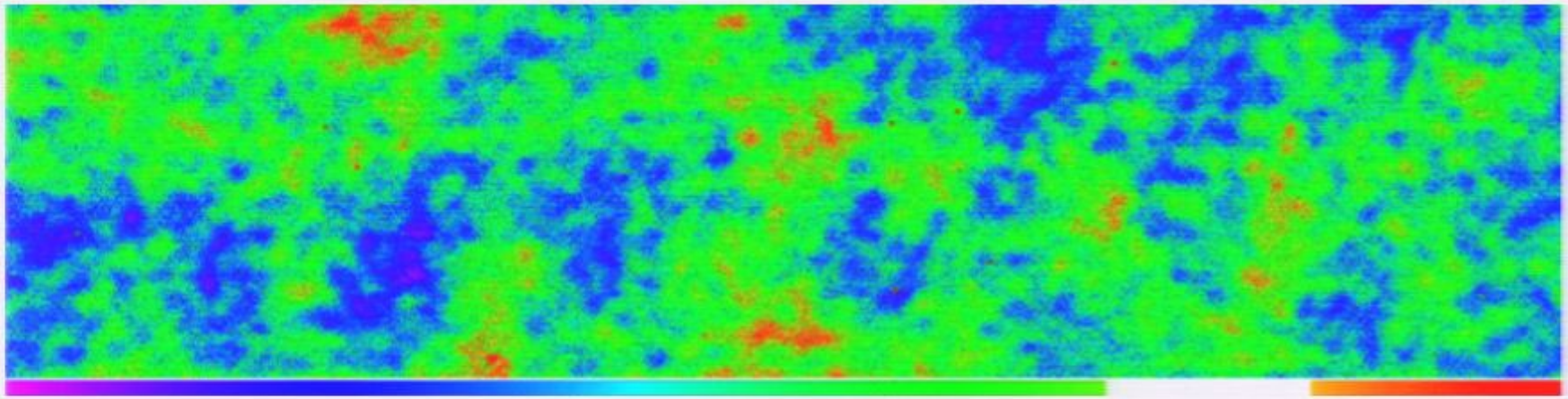

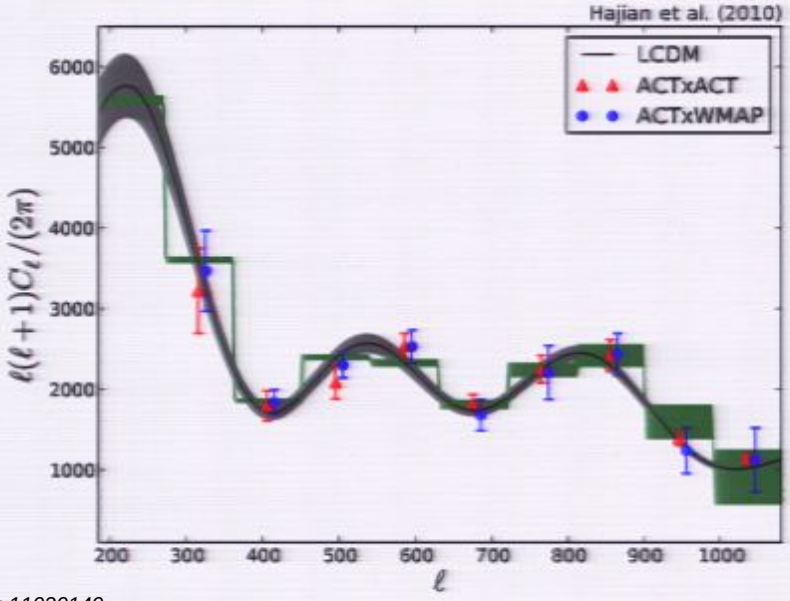

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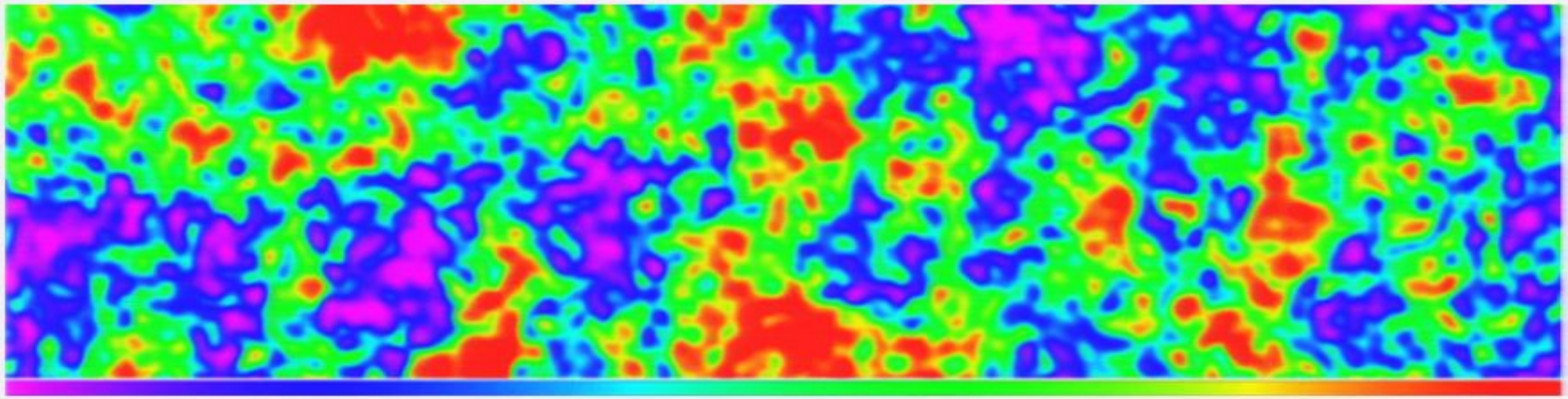

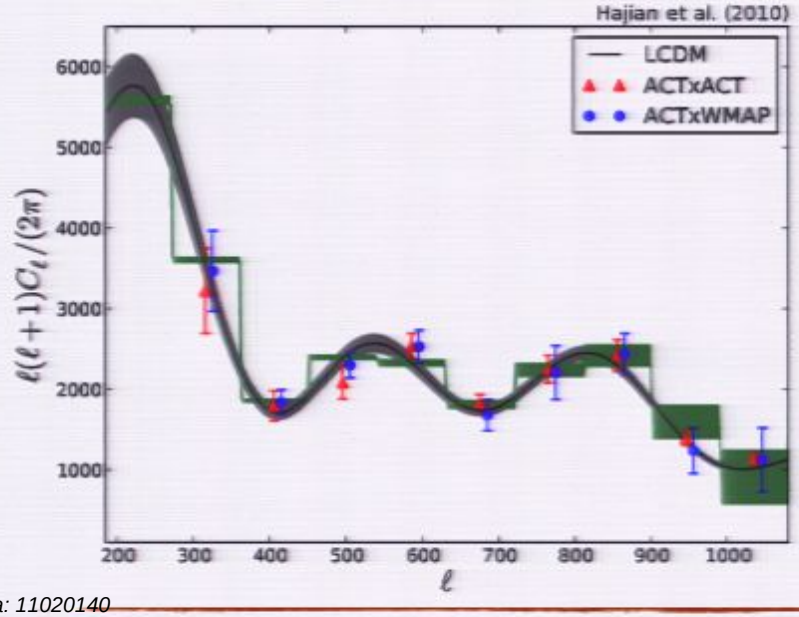

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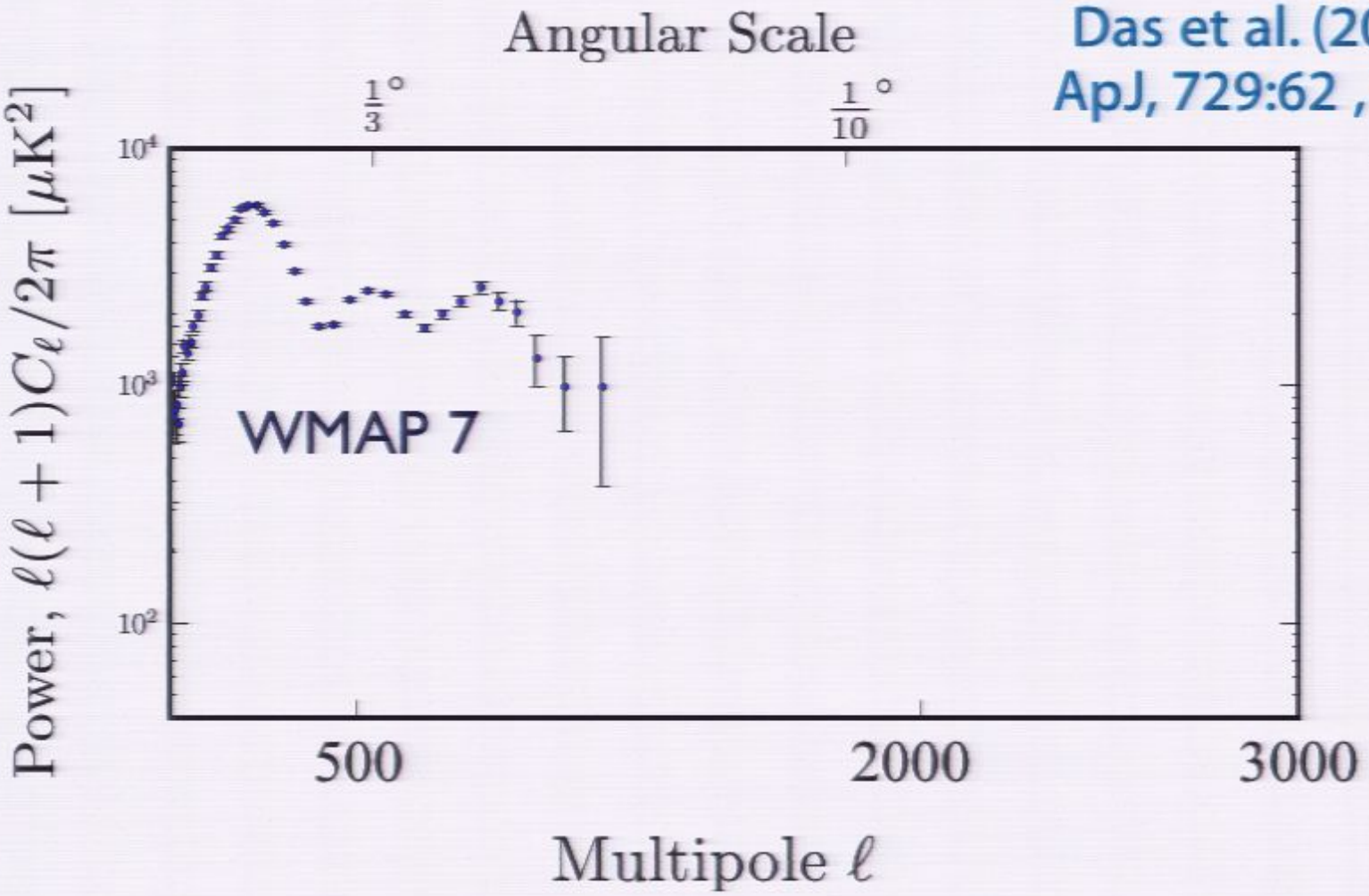
HIGH RESOLUTION POWER SPECTRUM FROM ACT



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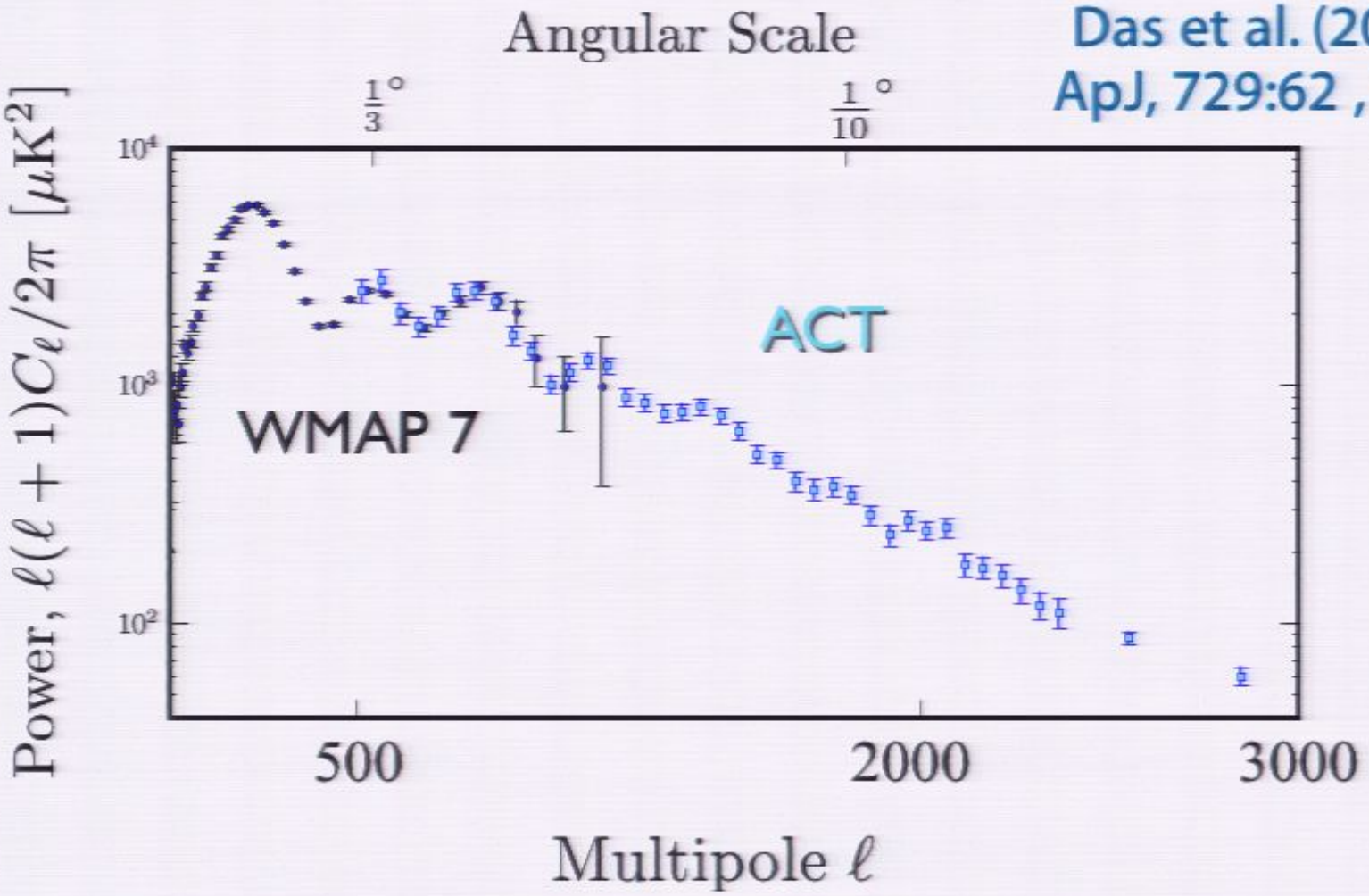

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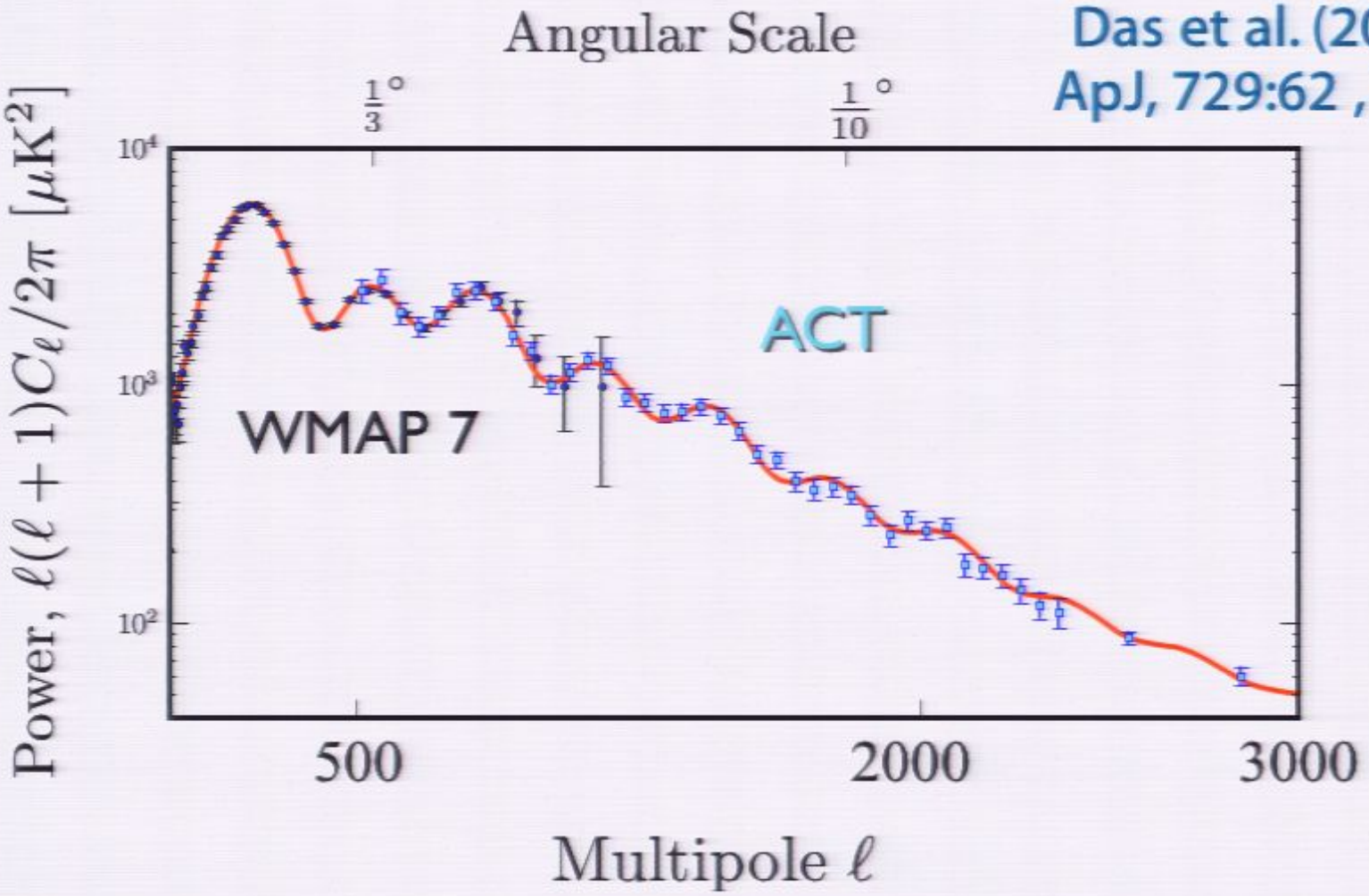

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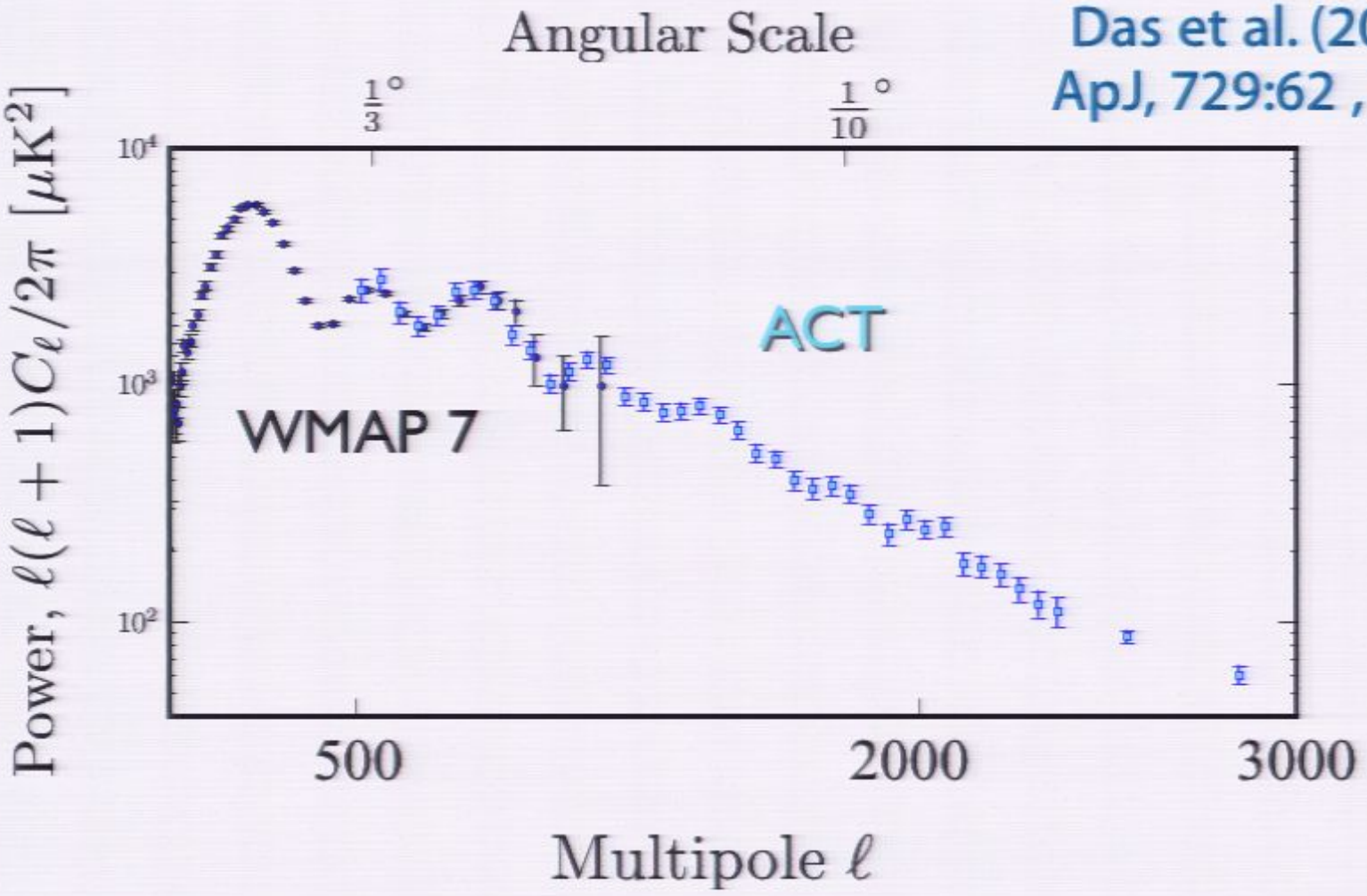

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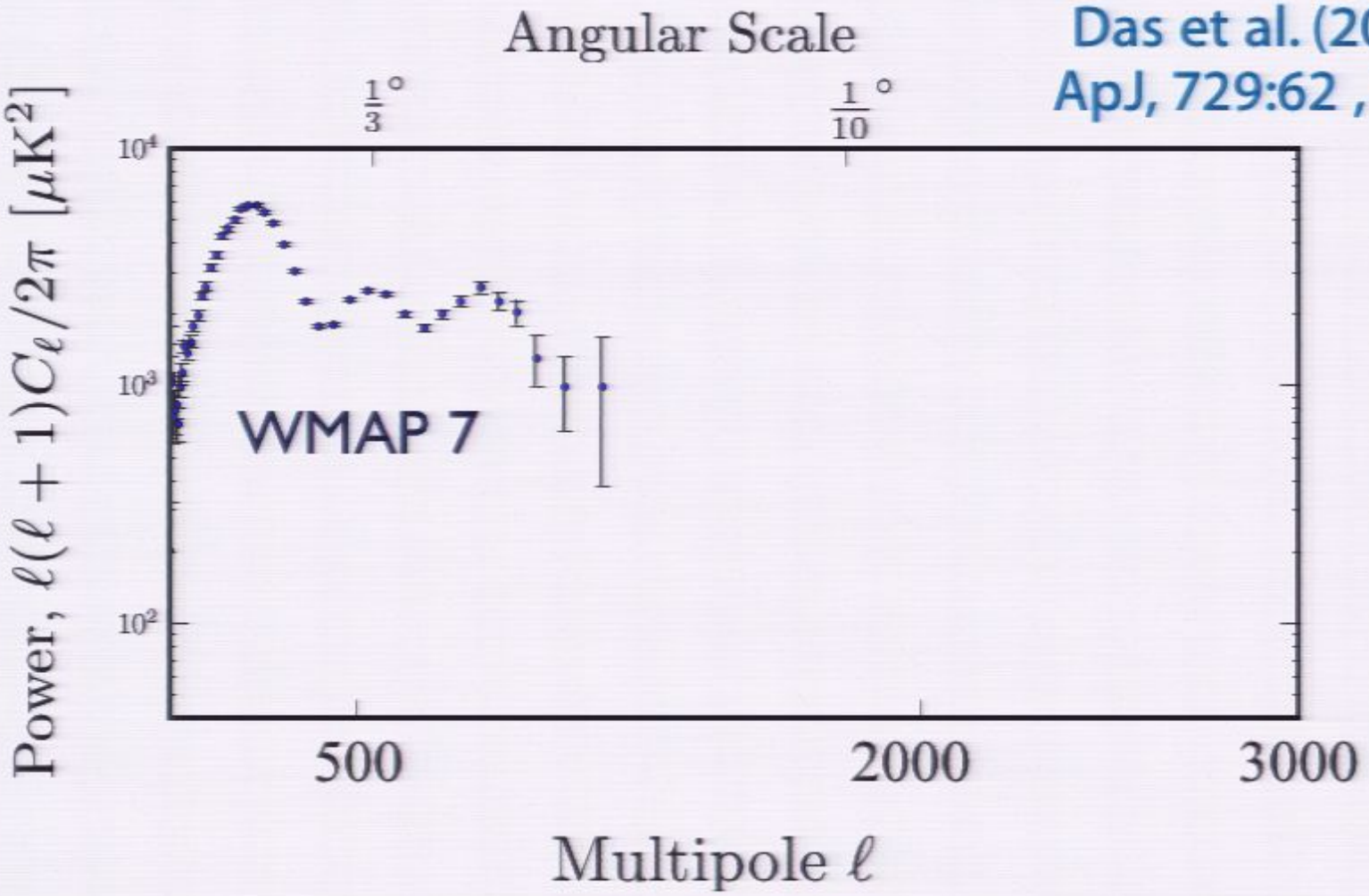

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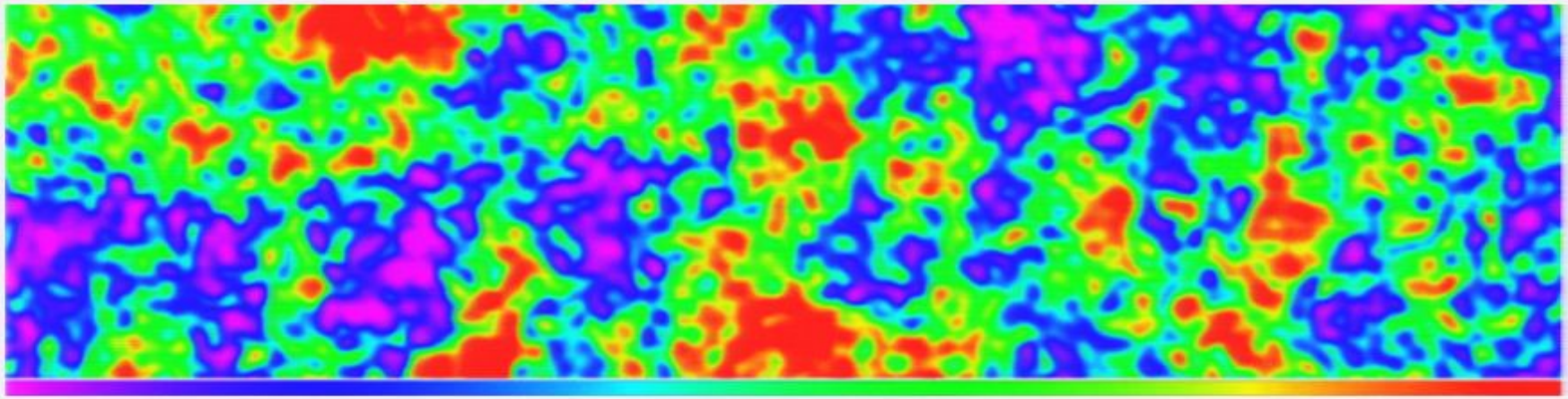

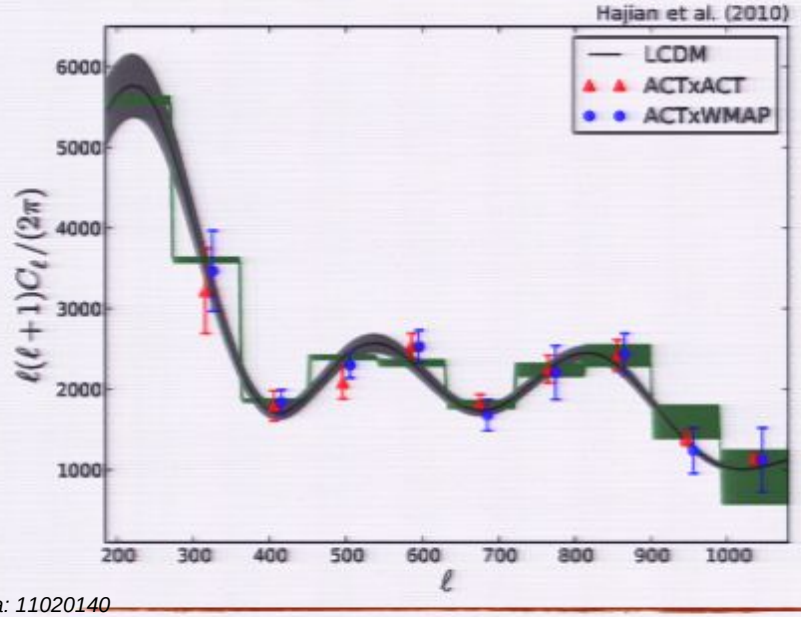

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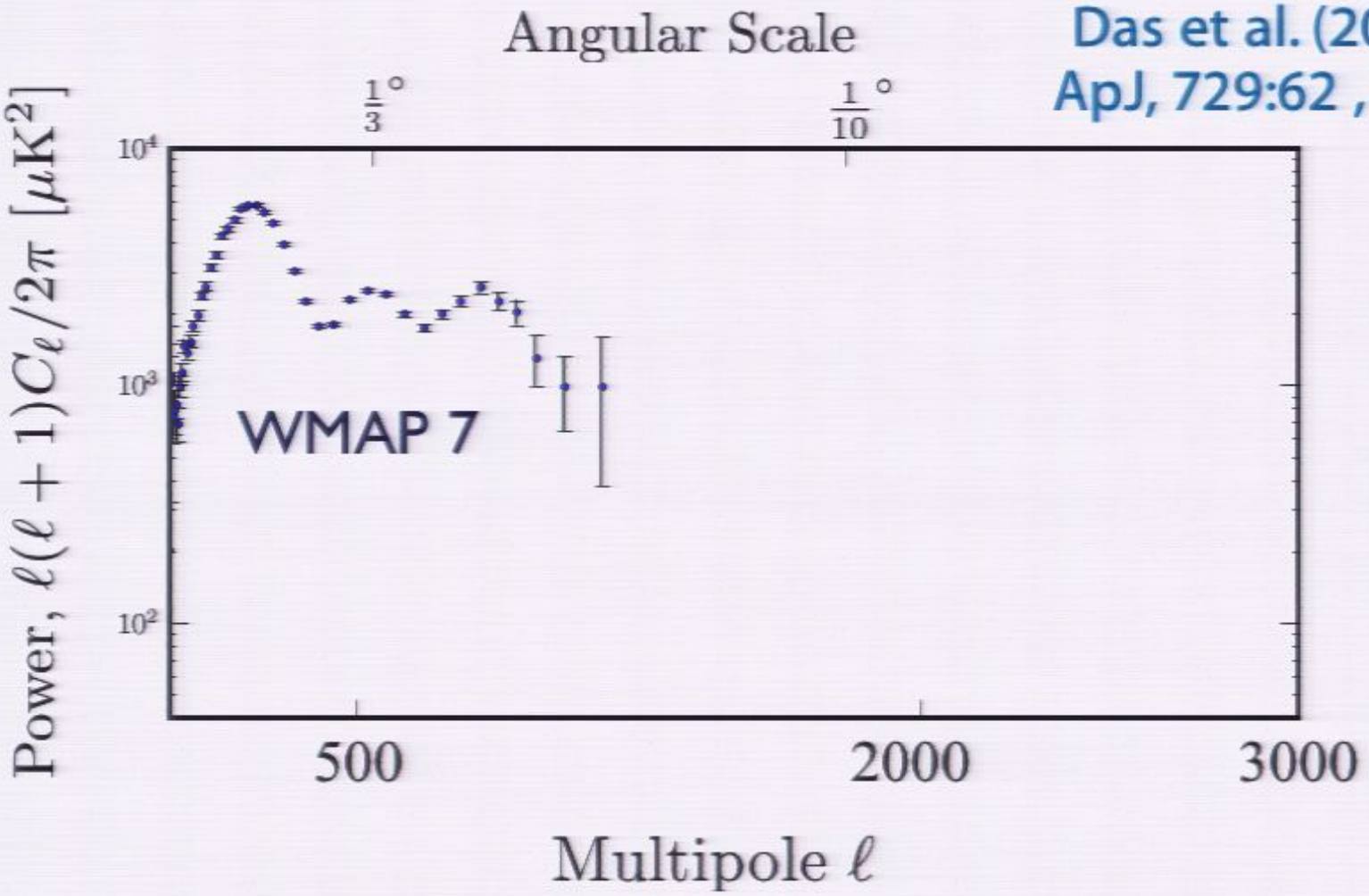

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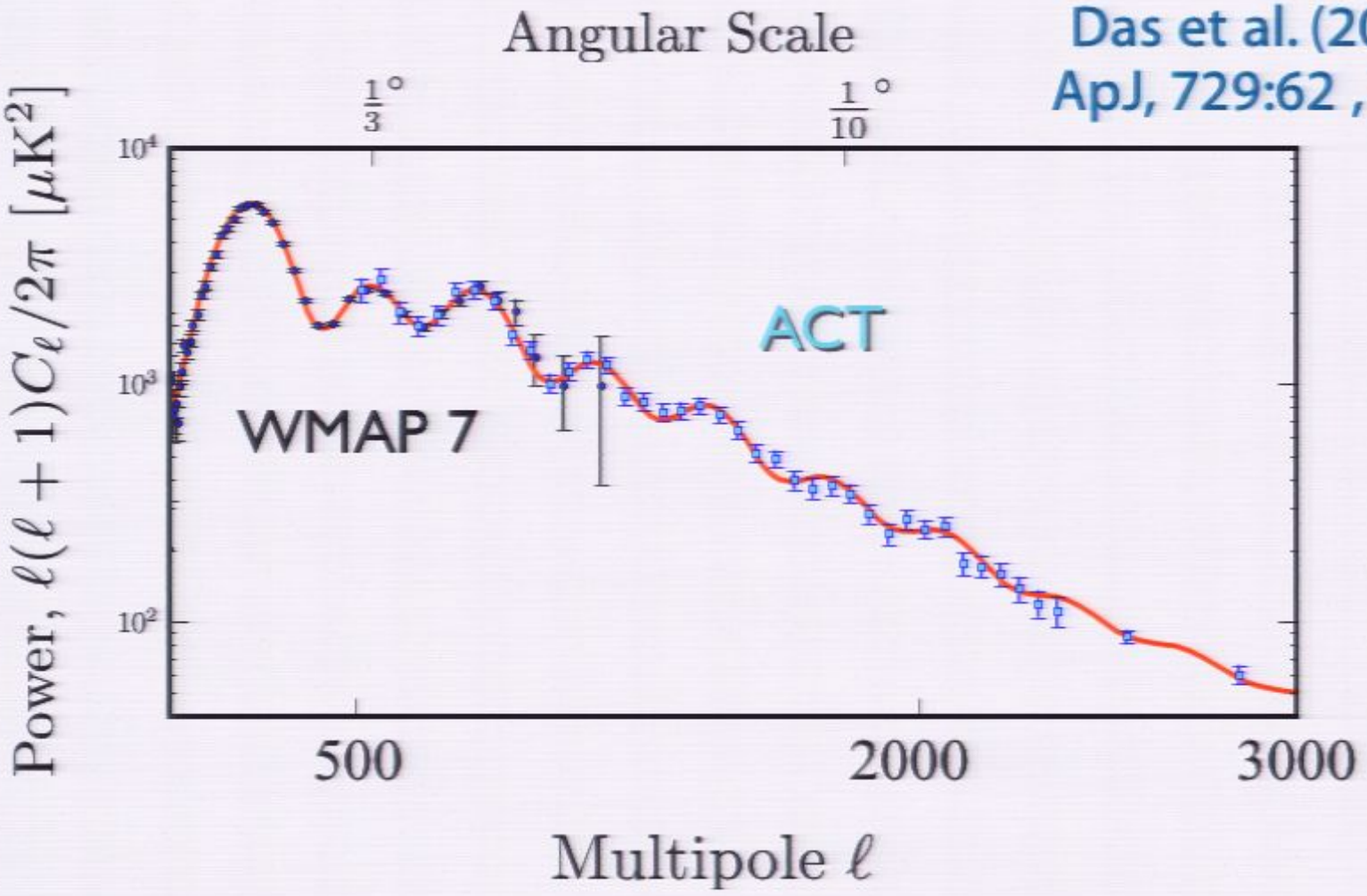

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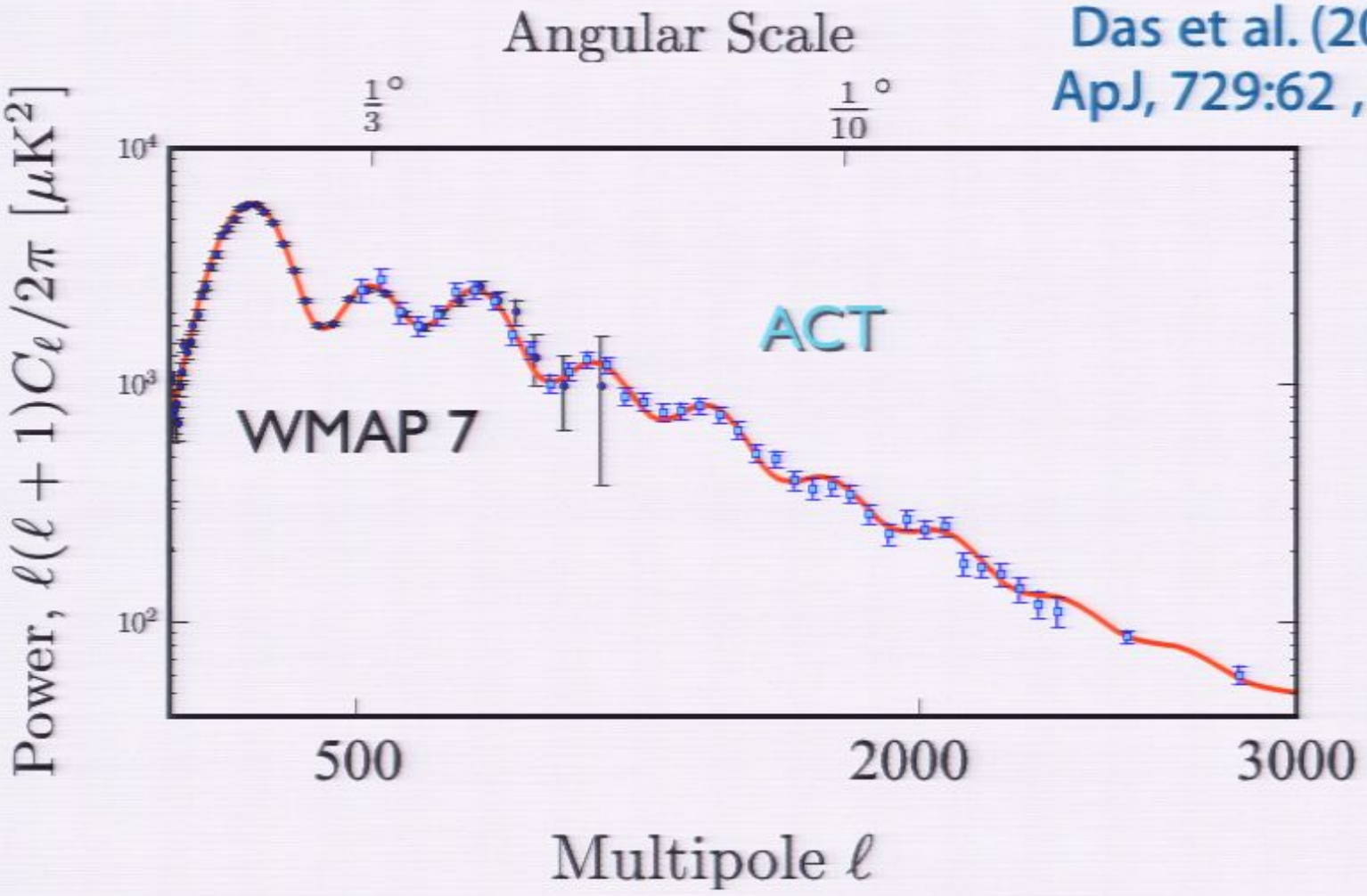

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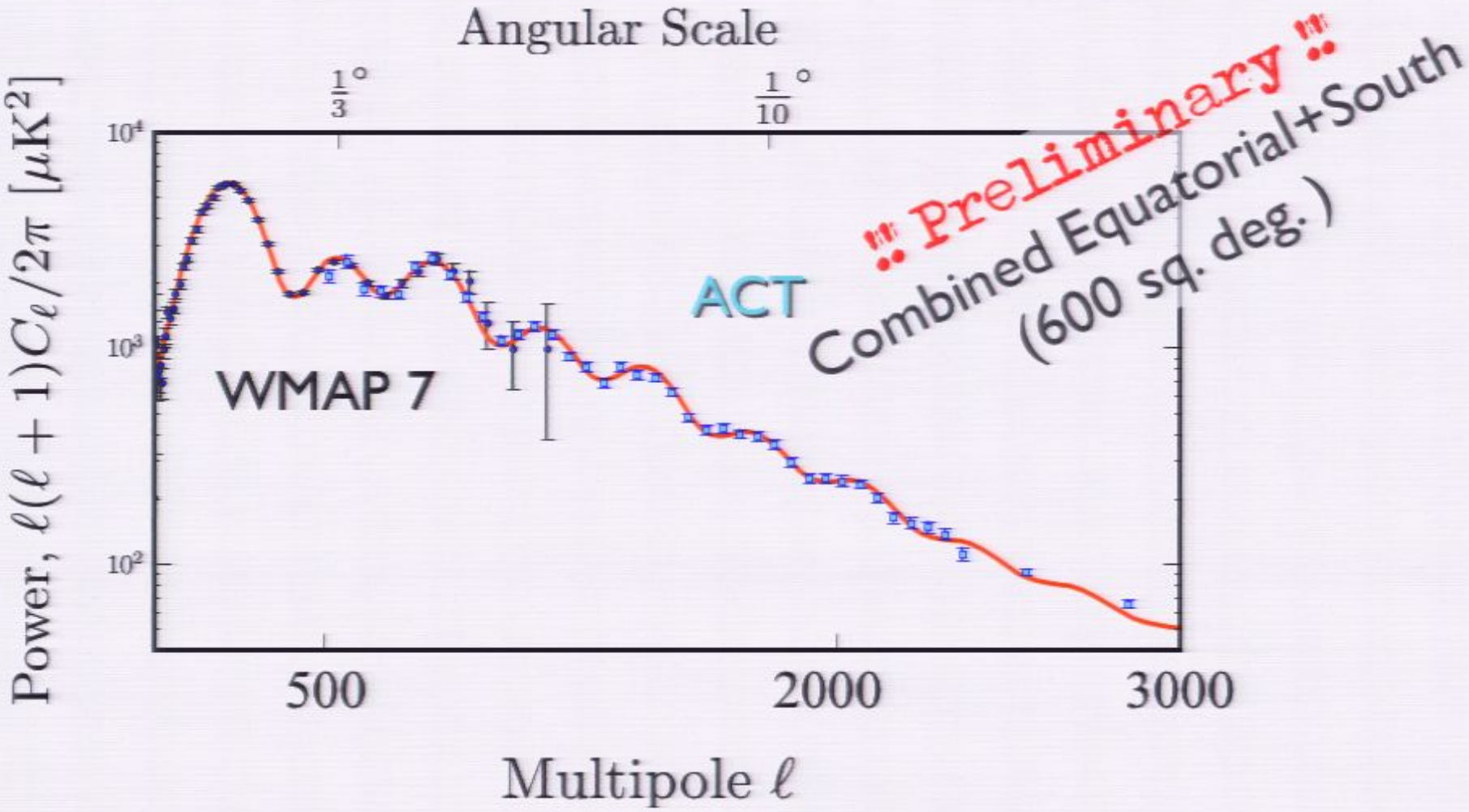
HIGH RESOLUTION POWER SPECTRUM FROM ACT: NEW RESULT!



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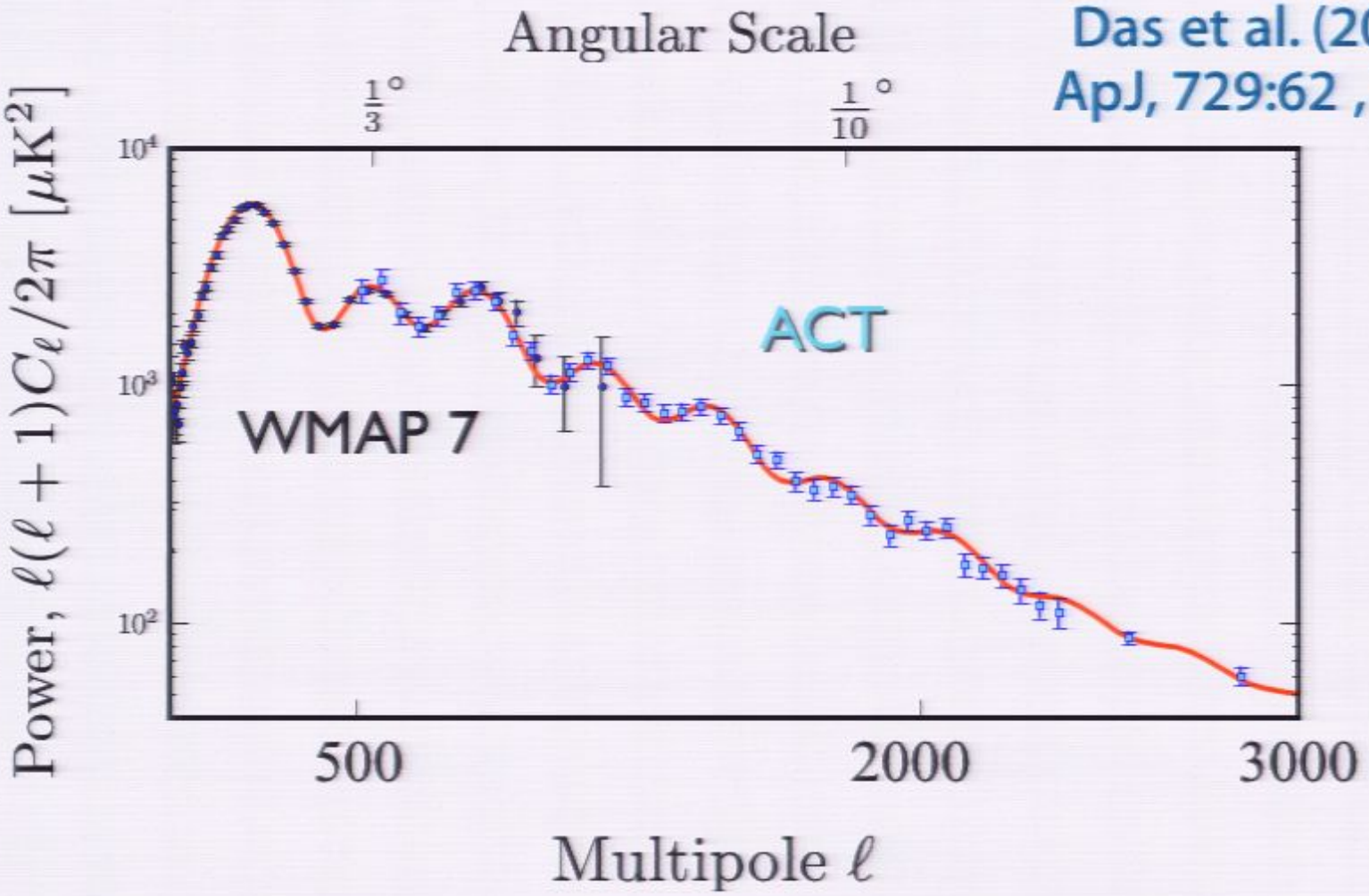

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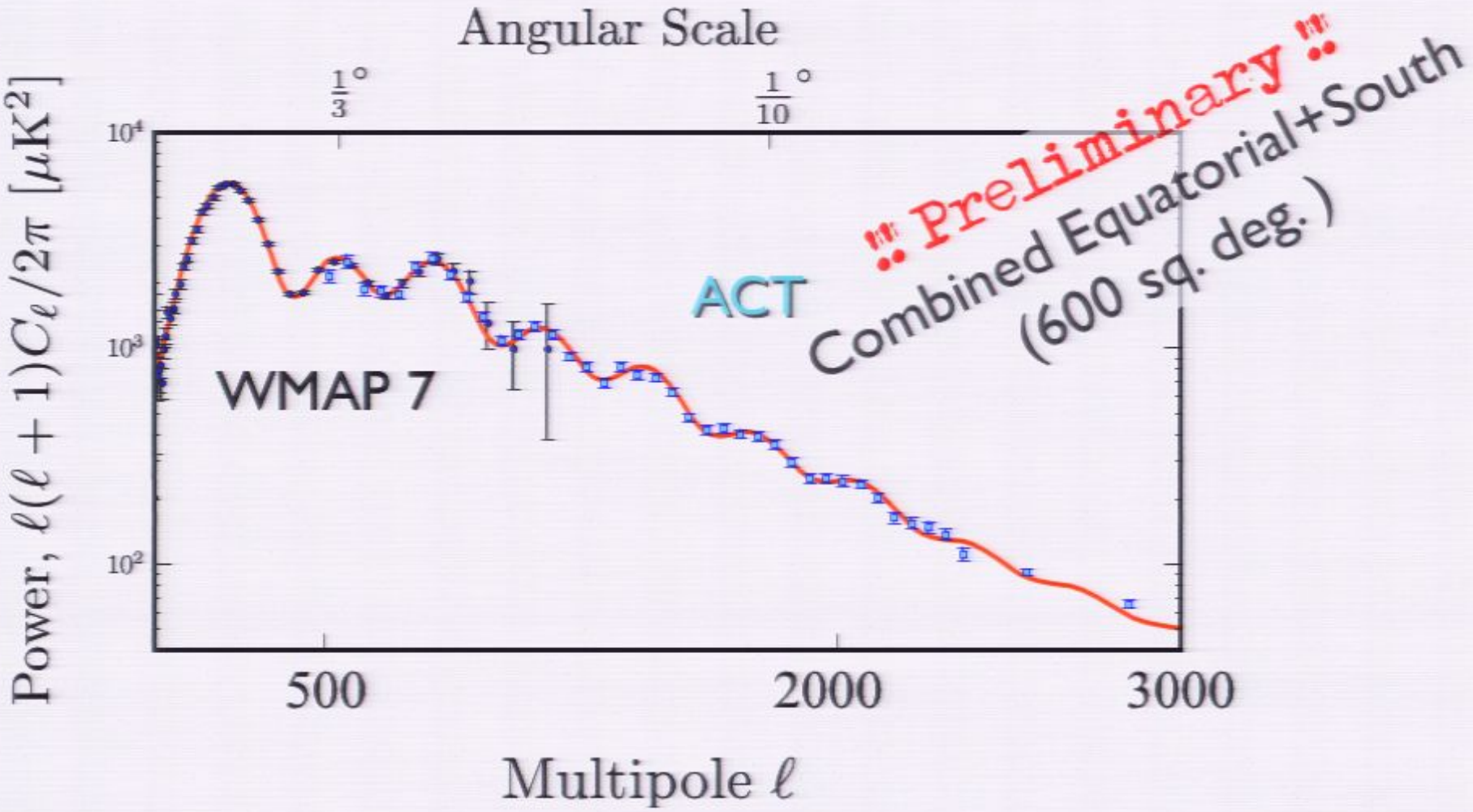
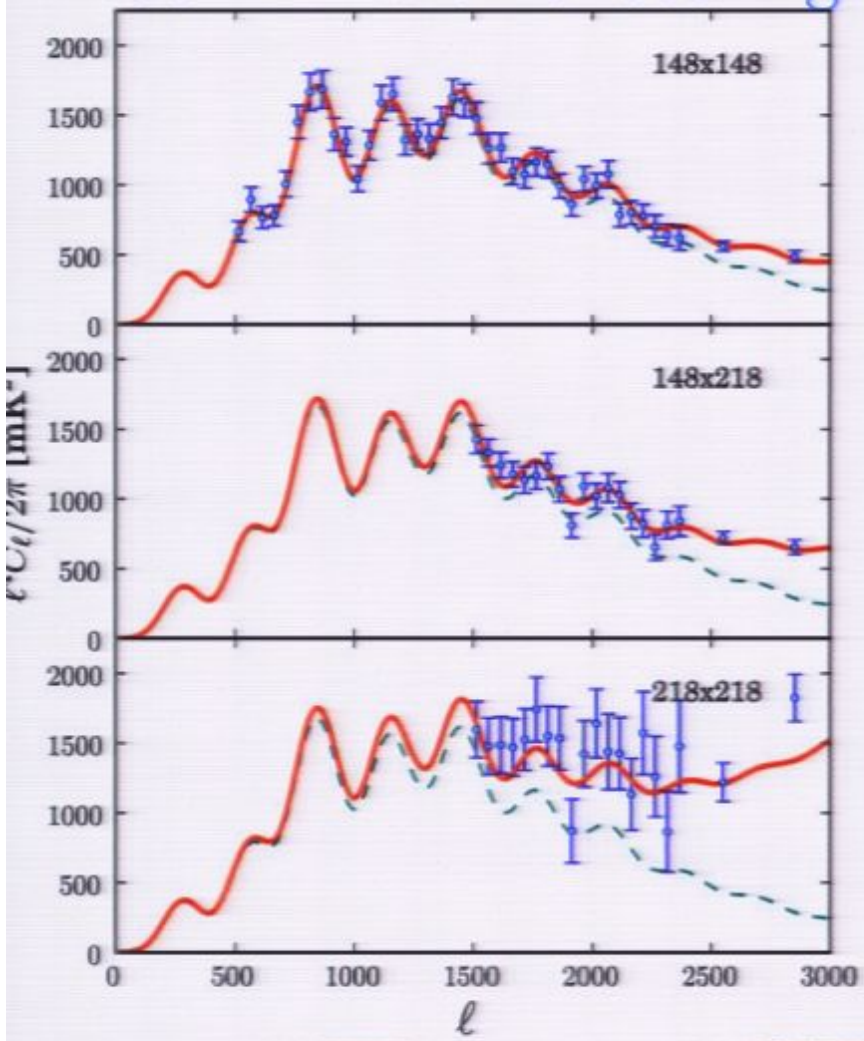


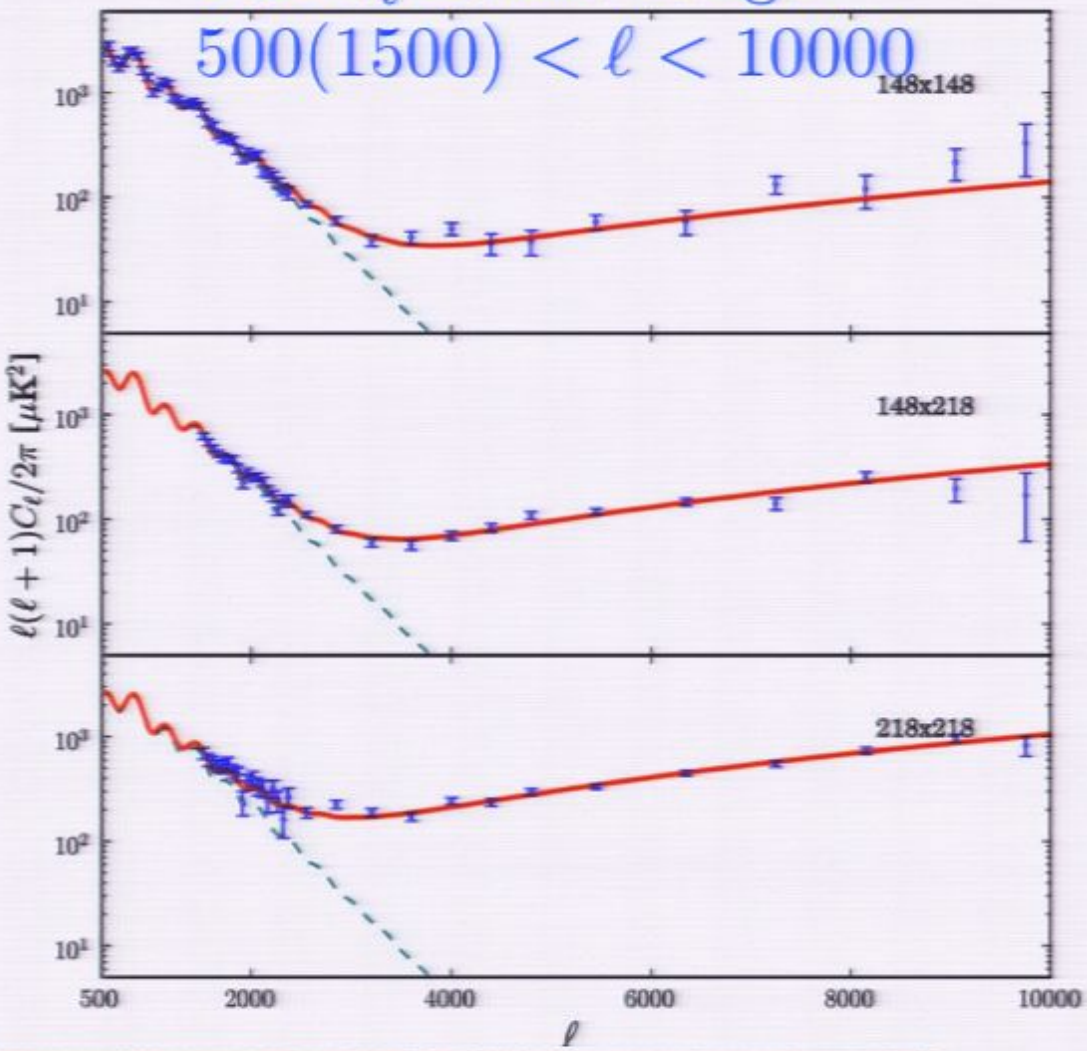
ACT MEASURES POWER SPECTRA IN 3 FREQUENCIES OUT TO L=10,000

Zoom in with ℓ^4 scaling



Full dynamic range

$500(1500) < \ell < 10000$



Das et al. (2011) ApJ, in press

Sudeep Das, PI, CITA Day, Feb 15, 2011

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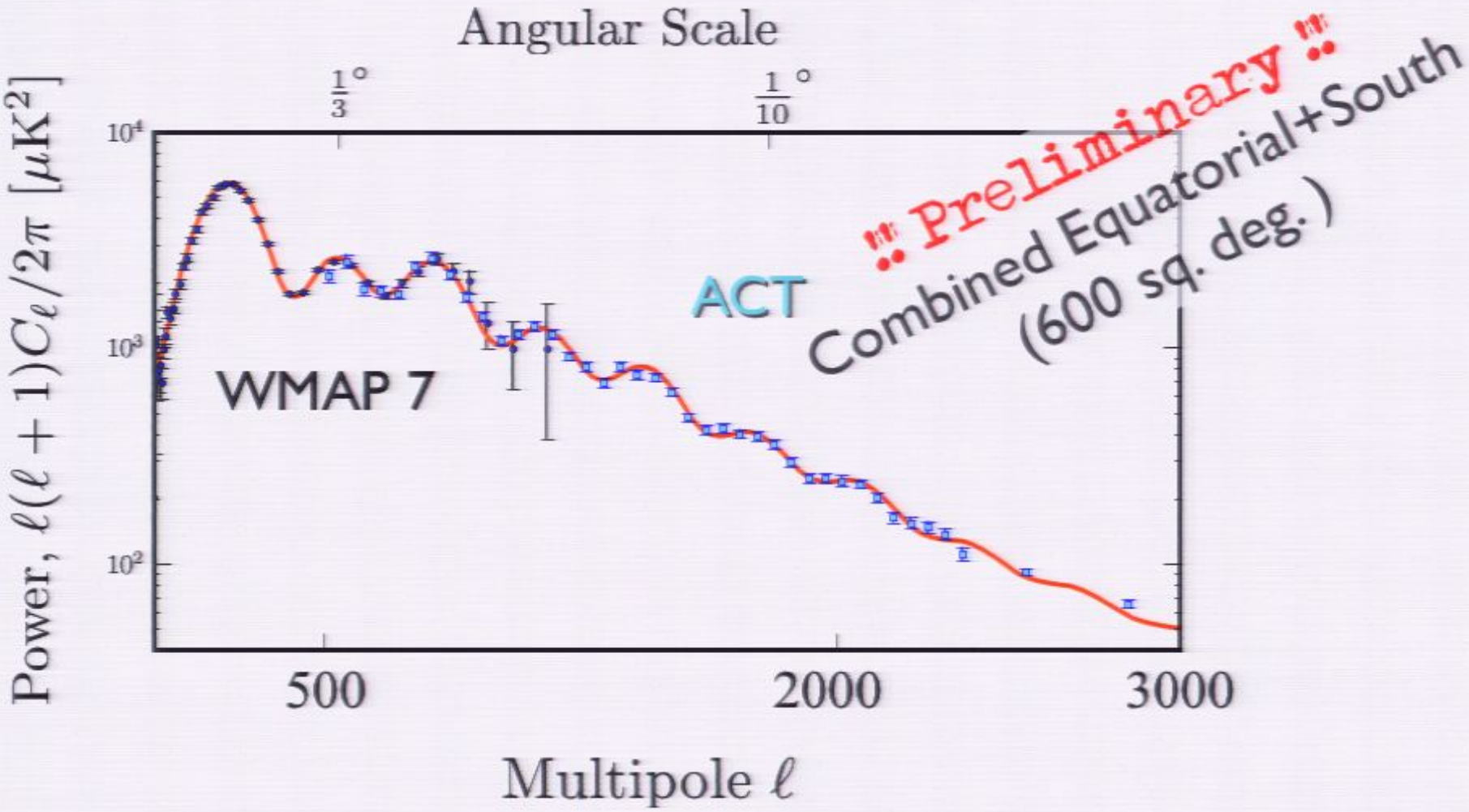

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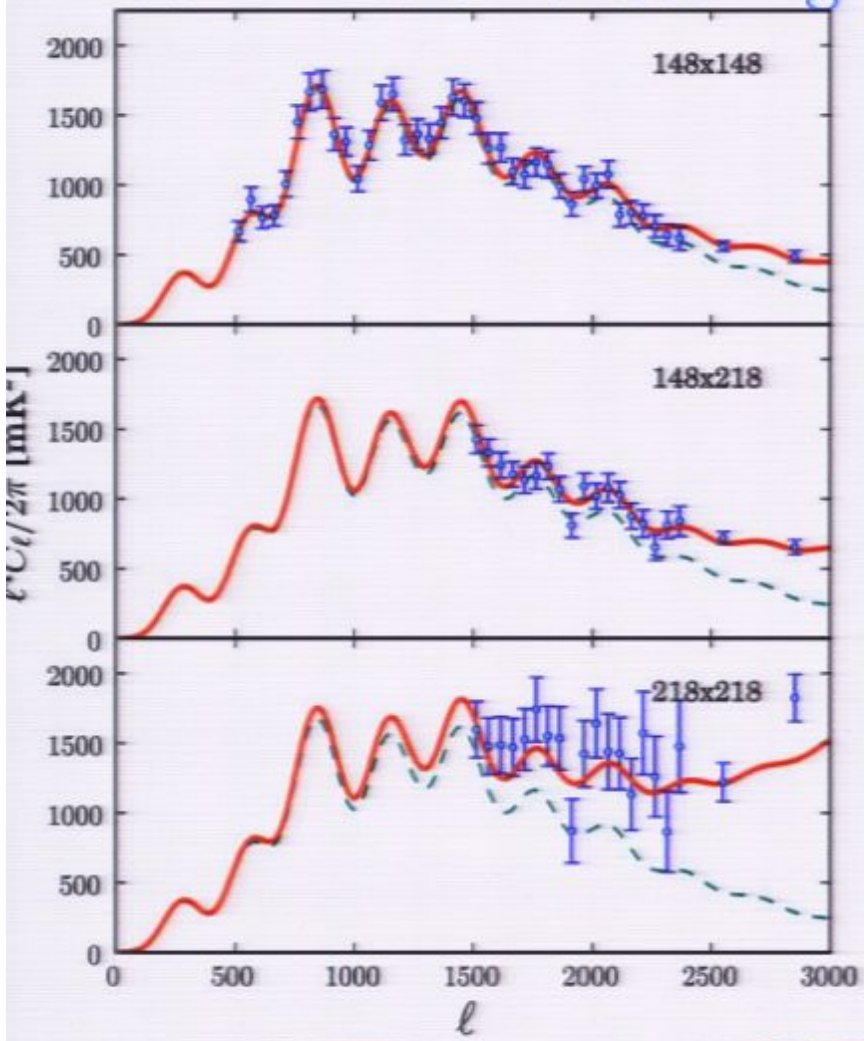

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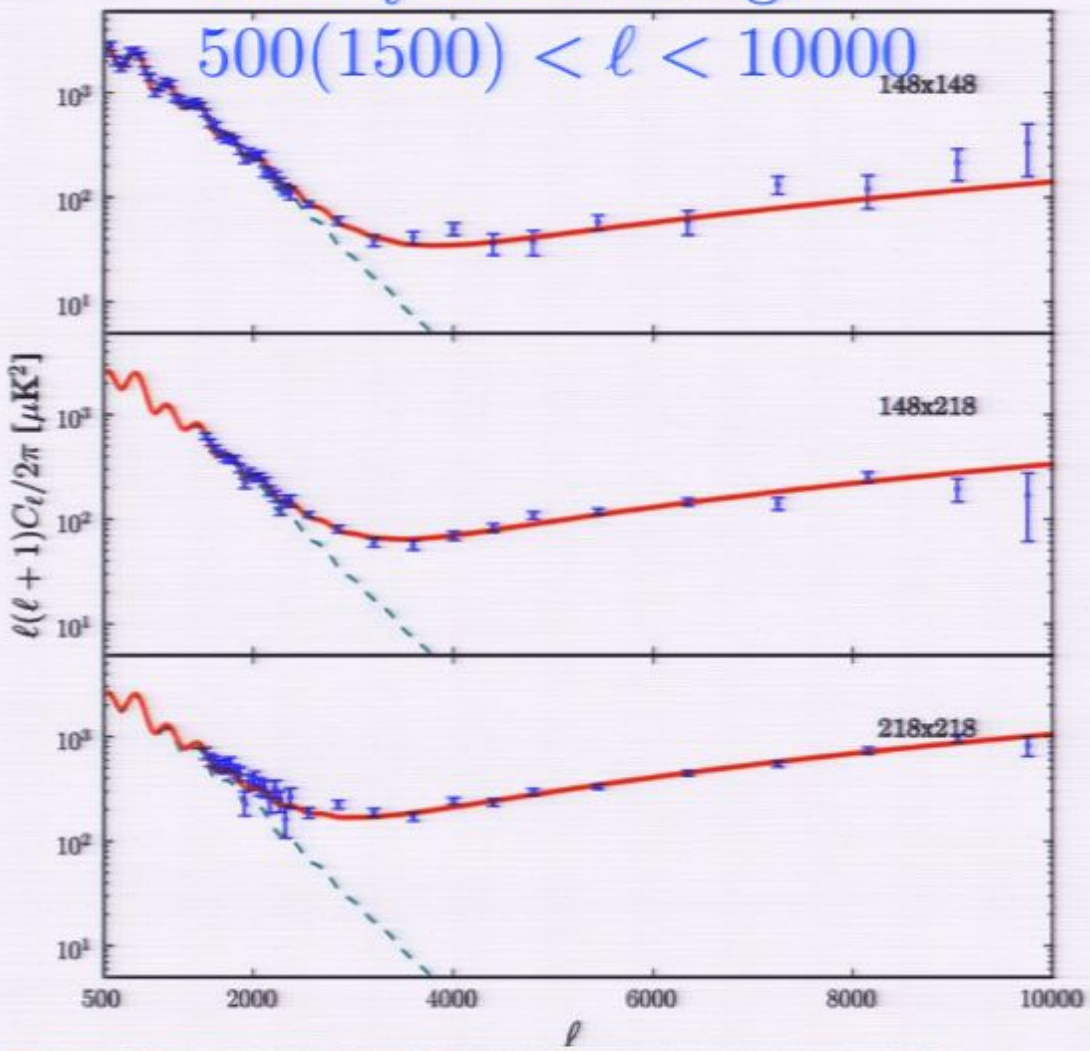

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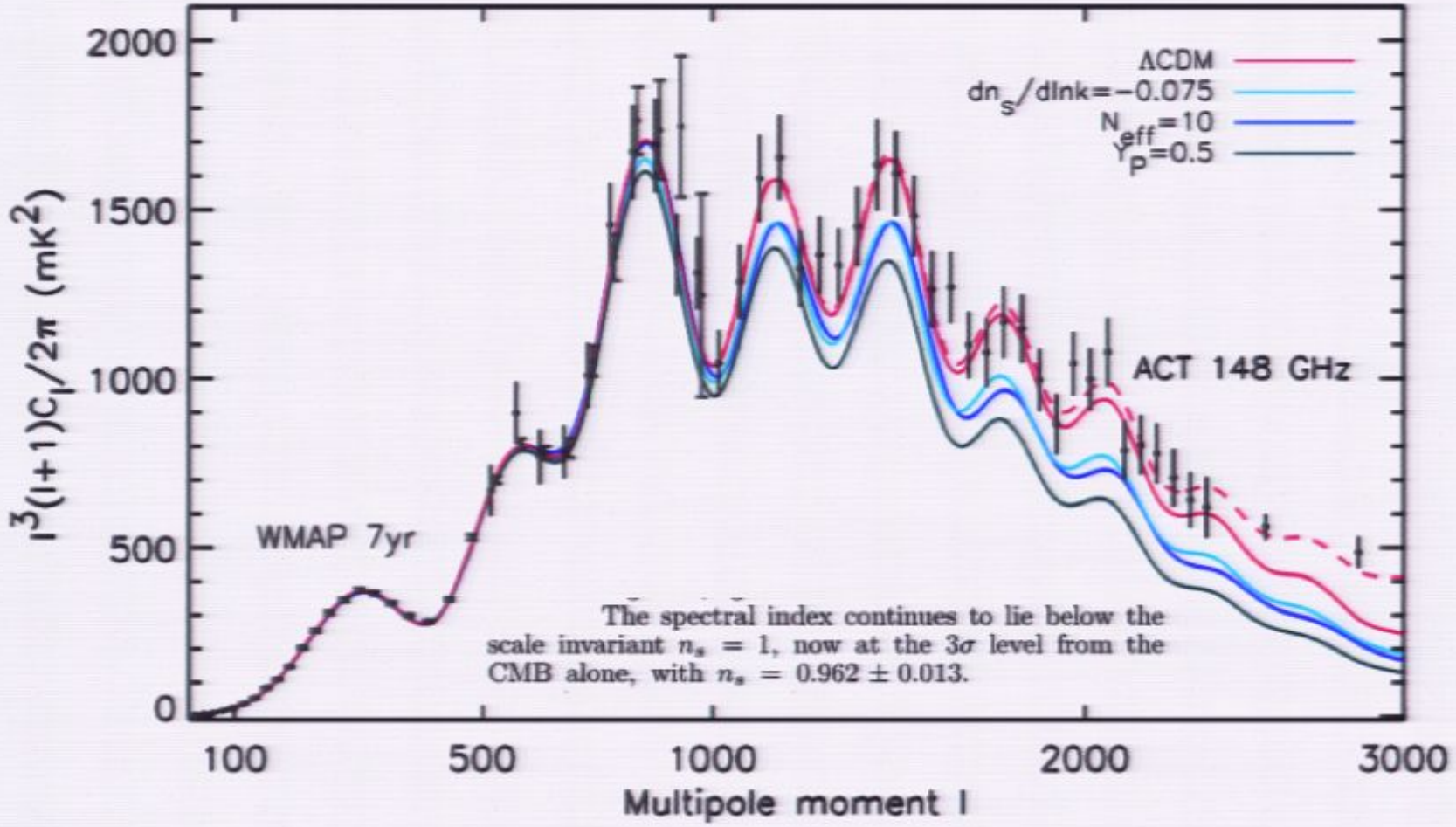
HIGHER ORDER PEAKS HELP CONSTRAIN PARAMETERS BEYOND ΛCDM



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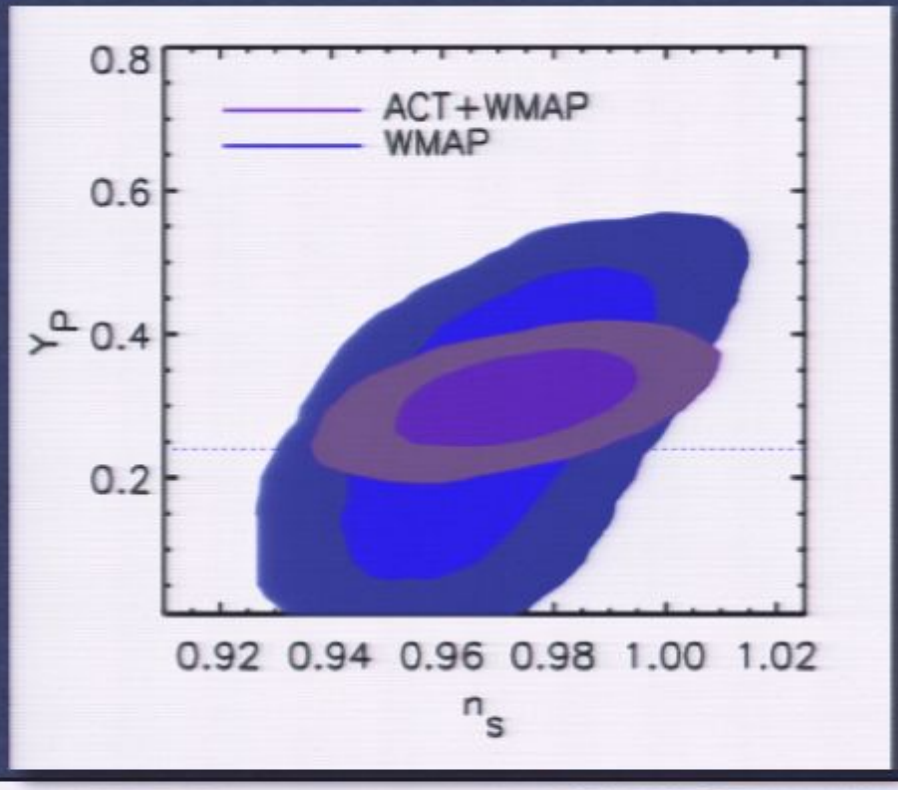
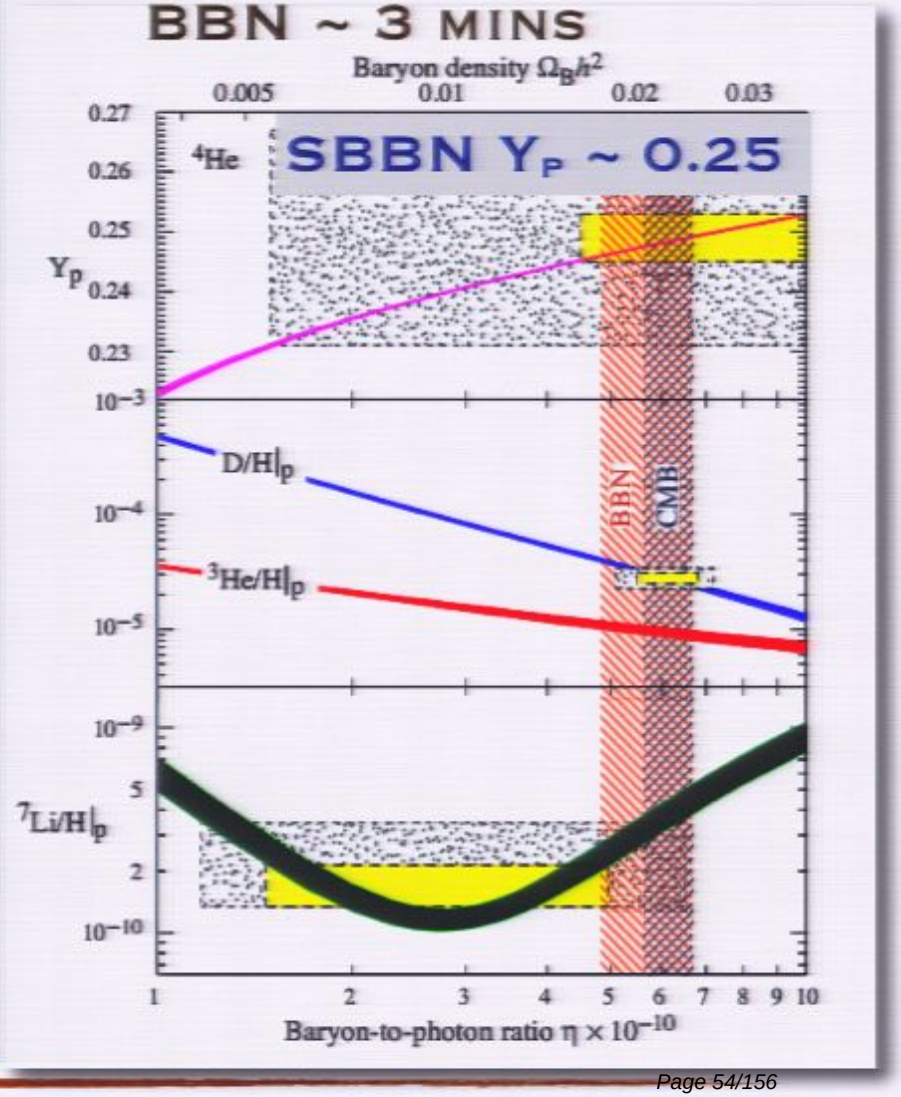
ACT+WMAP MEASURES THE DENSITY OF HELIUM AT 380,000 YEARS AFTER BB

More helium decreases electron density, increasing Silk damping. We find

$Y_p = 0.313 \pm 0.044$ (68% CL, ACT+WMAP)

6-sigma detection from CMB alone.





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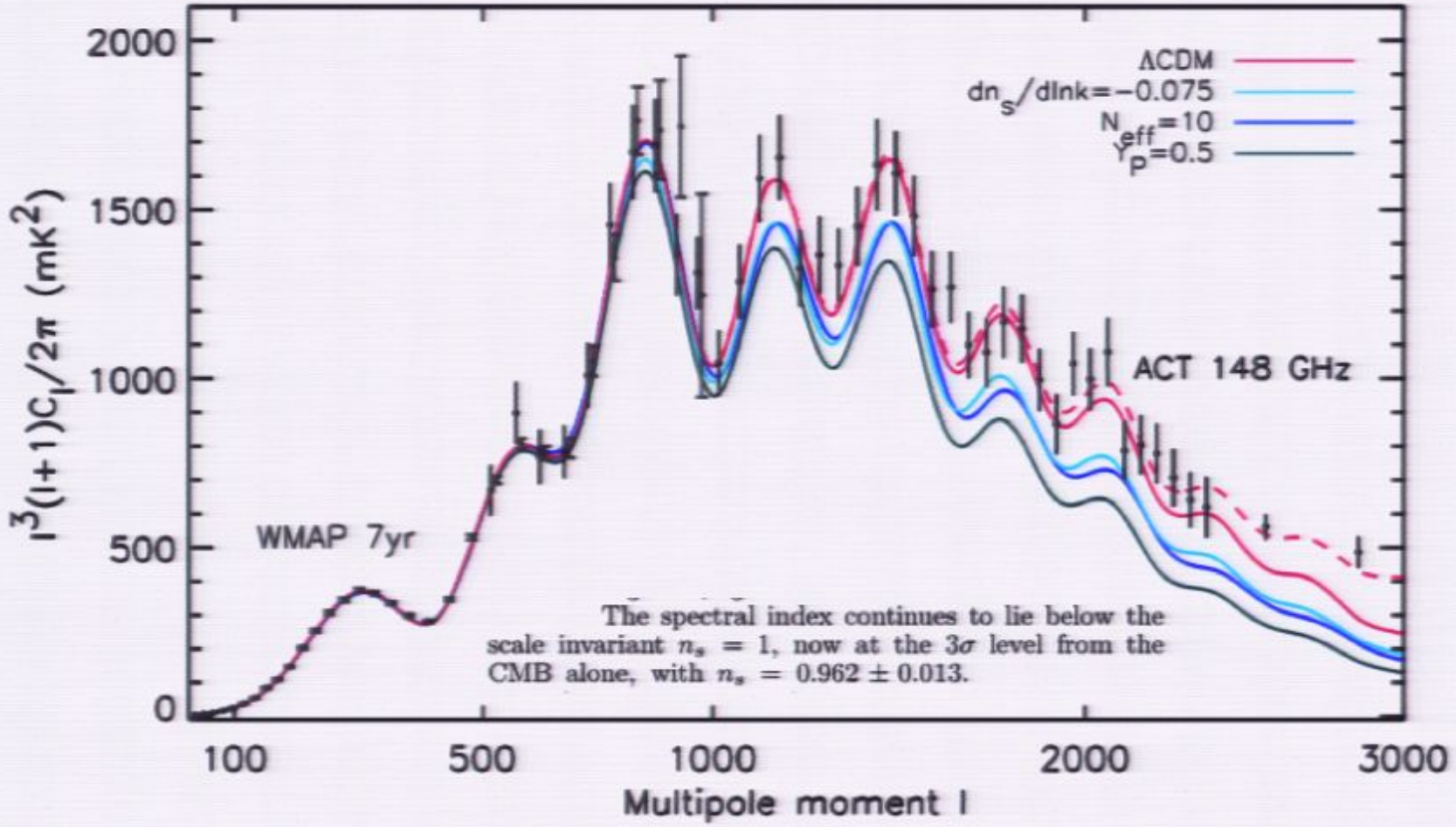

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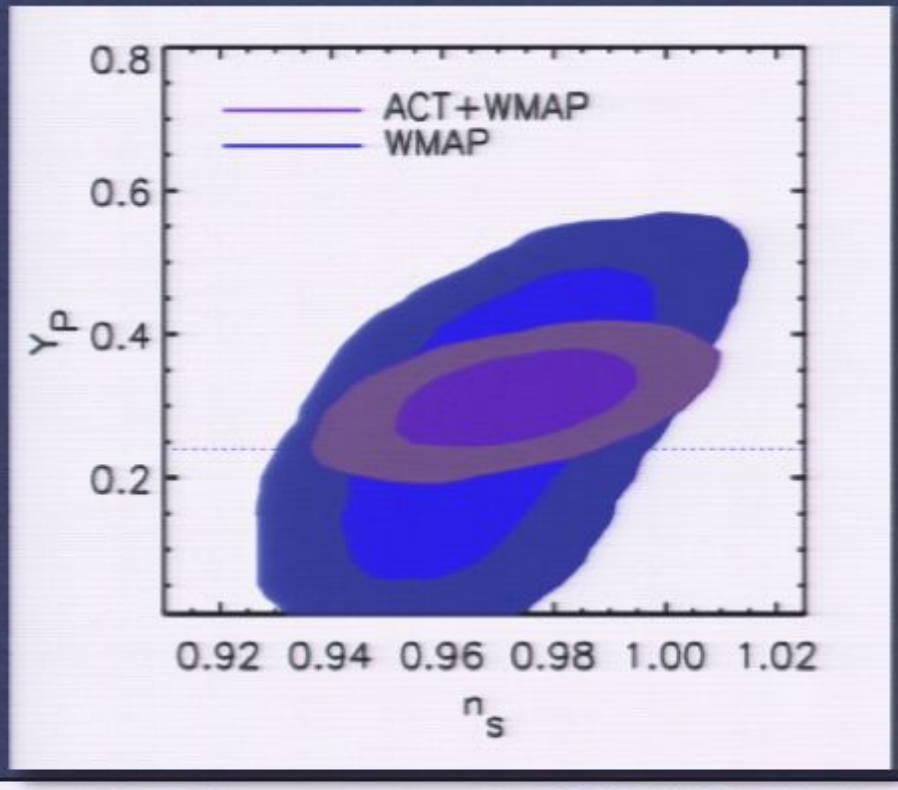

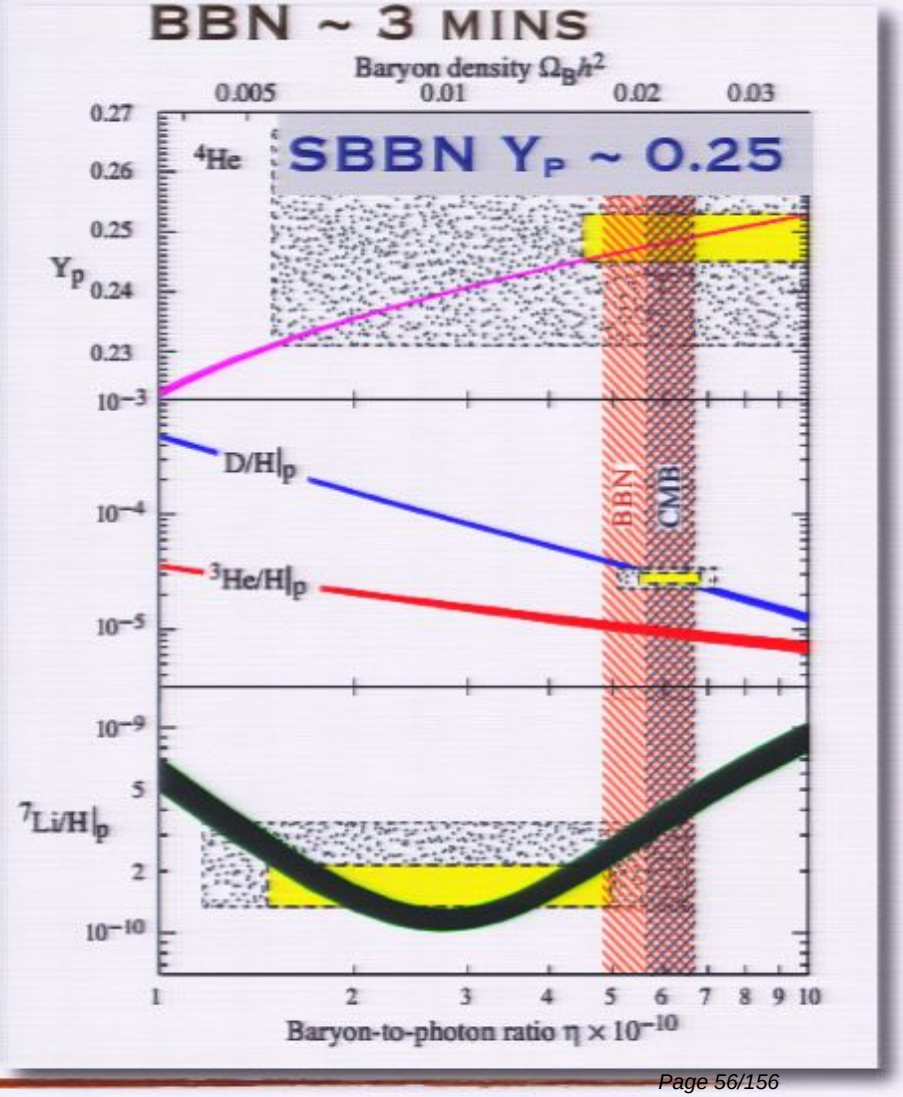

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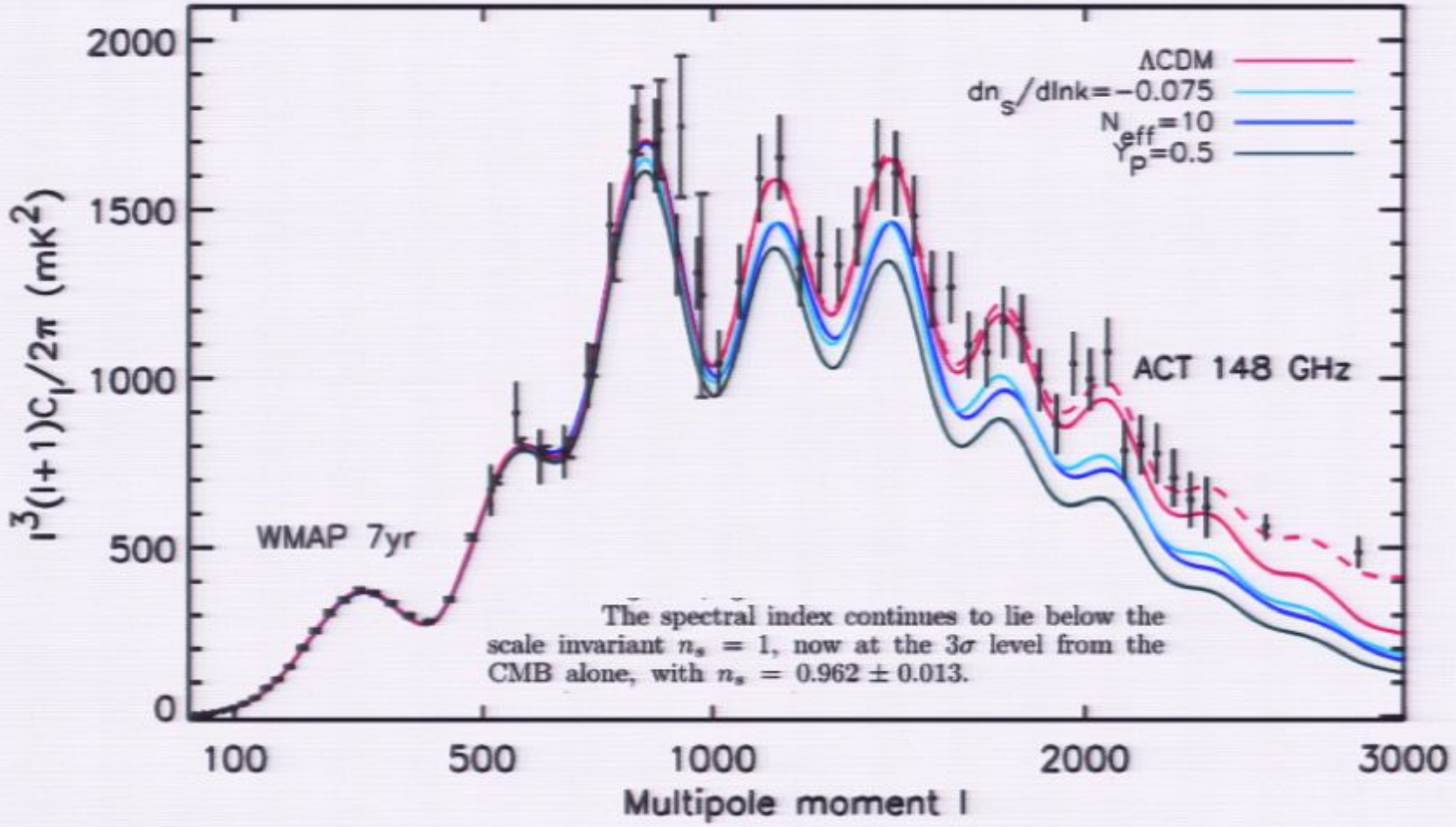

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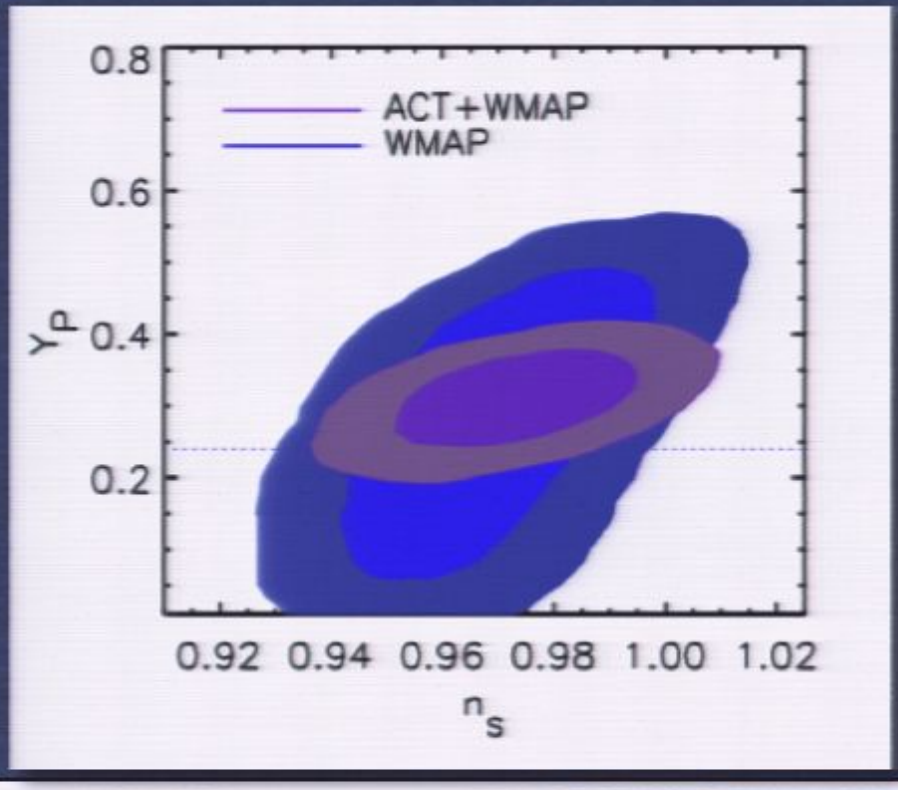

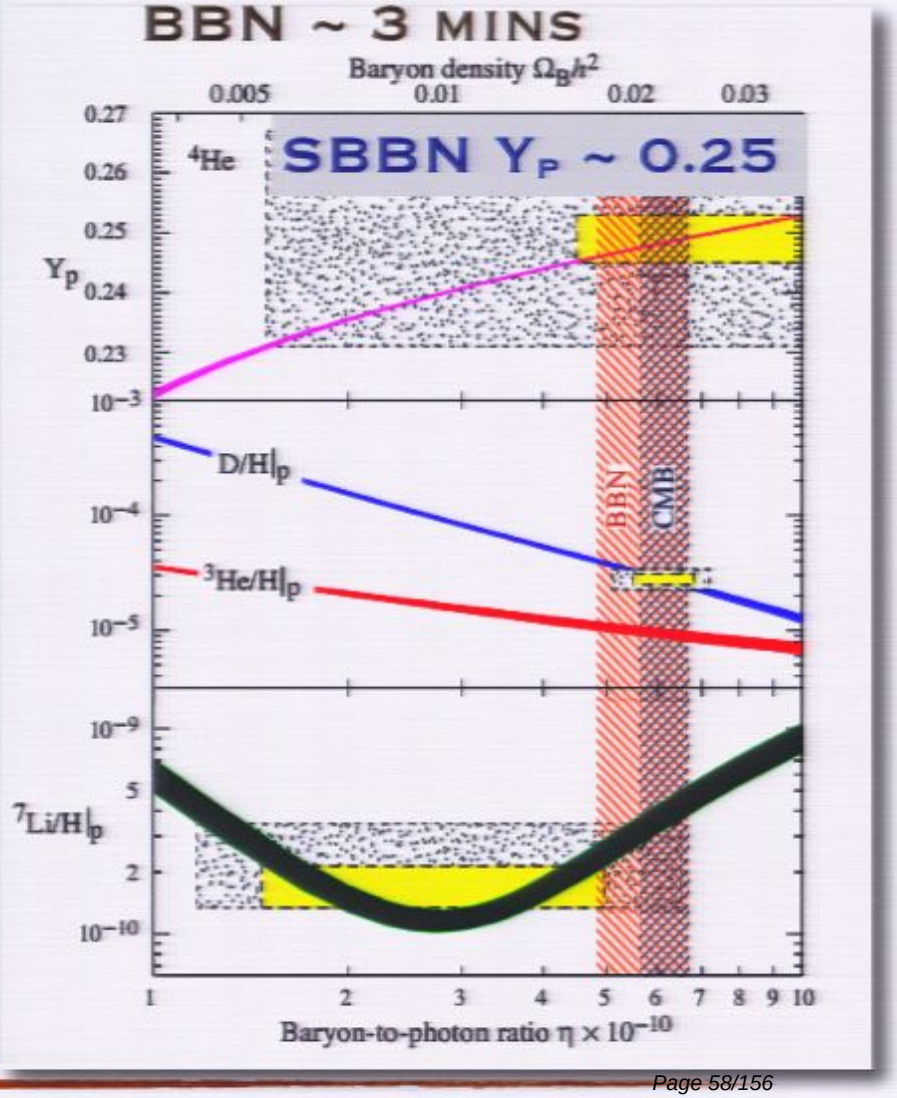

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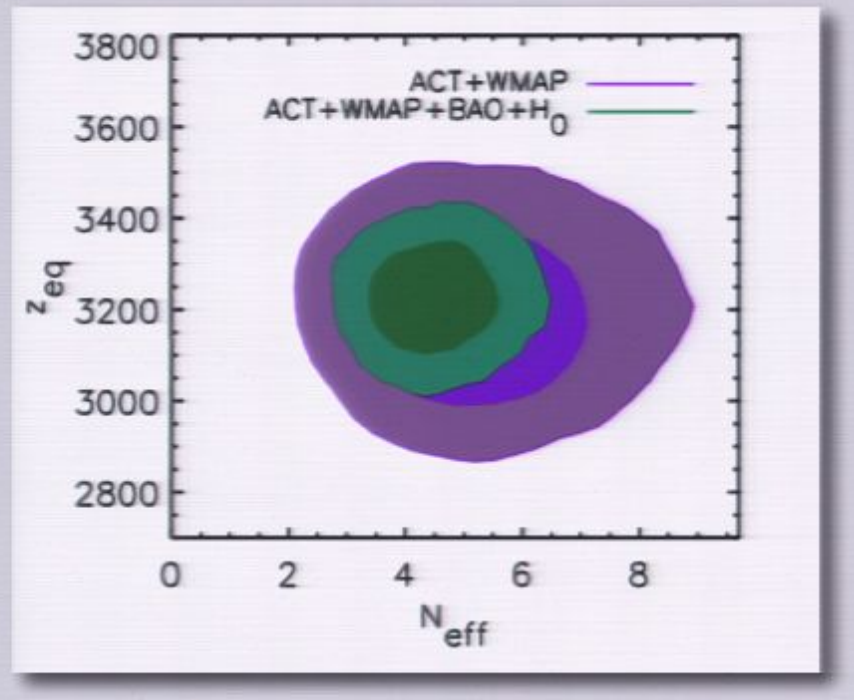
ACT+WMAP CONSTRAINS NUMBER OF RELATIVISTIC SPECIES



Changing N_{eff} changes equality redshift.
Also suppress early acoustic oscillations in primary CMB.
For ACT+WMAP we find N_{eff} = 5.3 ± 1.3
(CMB now constrains it from above !)

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \frac{\pi^2}{15} T_\gamma^4 .$$

In standard BBN
$N_{\rm eff} = 3.04$

ACT's data is comfortably consistent with SBBN. No cause for alarm yet.

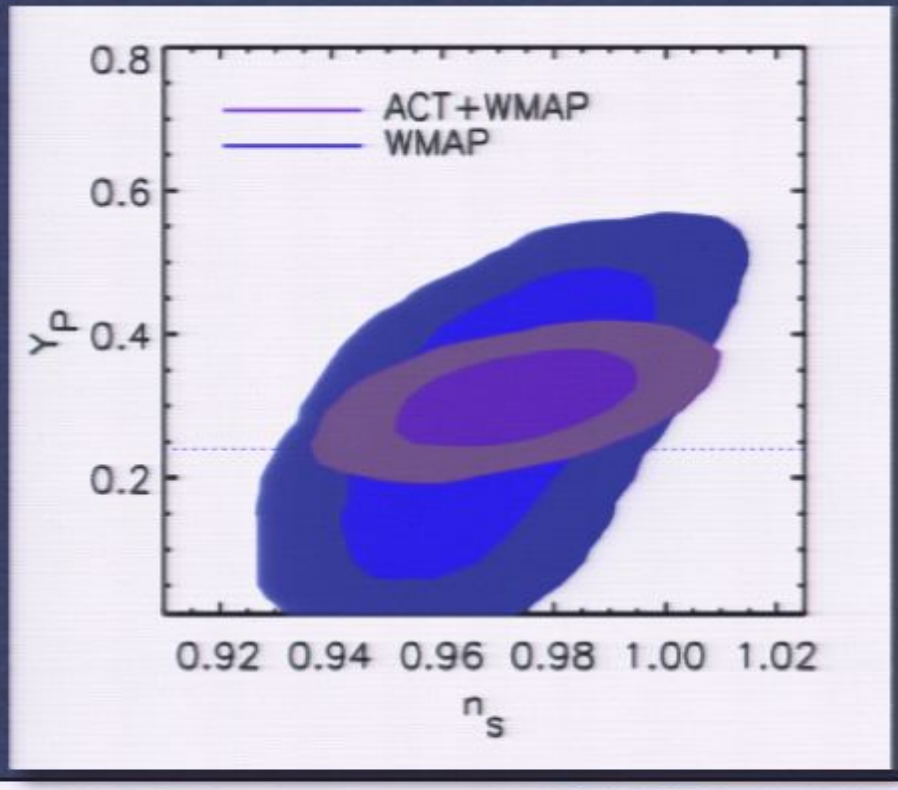
Could these be early hints?

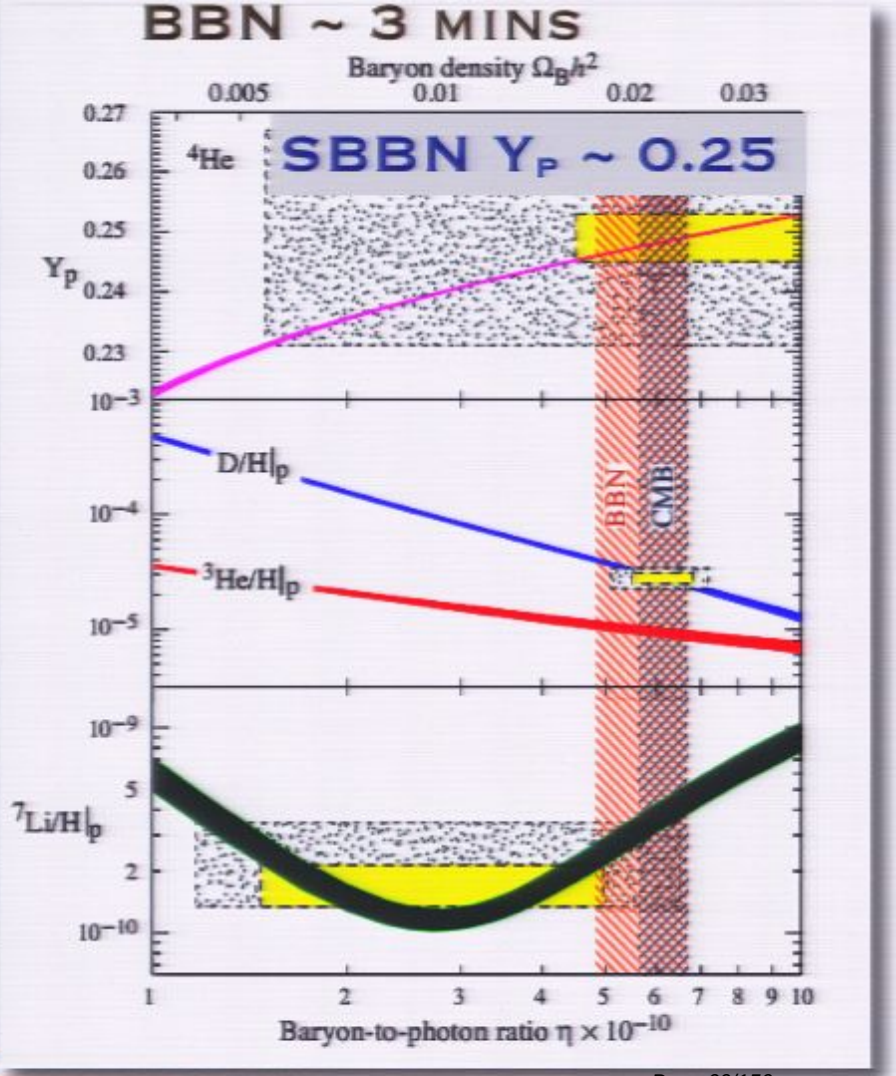
ACT+WMAP MEASURES THE DENSITY OF HELIUM AT 380,000 YEARS AFTER BB

More helium decreases electron density, increasing Silk damping. We find

$Y_p = 0.313 \pm 0.044$ (68% CL, ACT+WMAP)

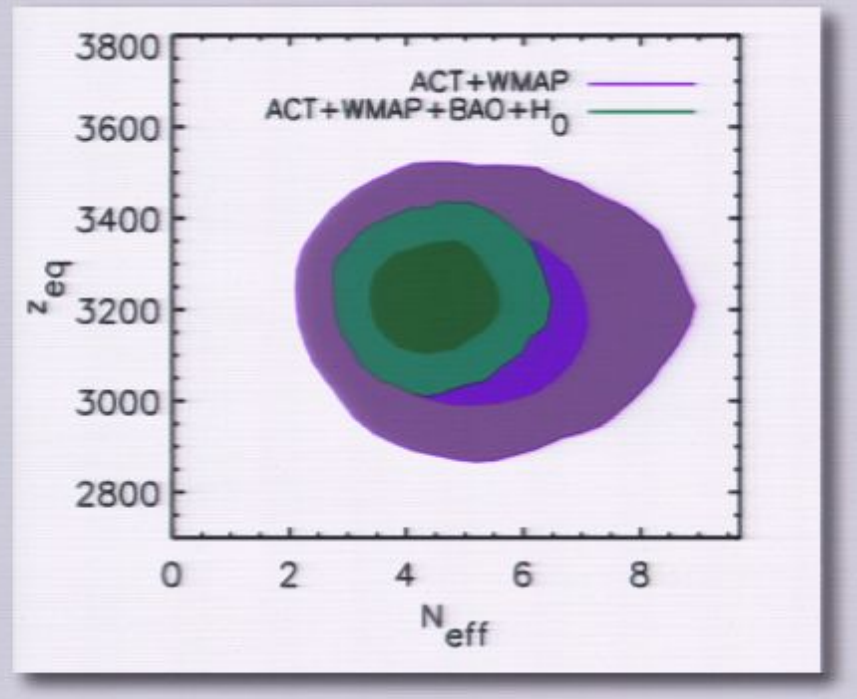
6-sigma detection from CMB alone.





Sudeep Das, PI CITA Day, Feb 15, 2011

ACT+WMAP CONSTRAINS NUMBER OF RELATIVISTIC SPECIES



Changing N_{eff} changes equality redshift.
Also suppress early acoustic oscillations in primary CMB.
For ACT+WMAP we find N_{eff} = 5.3 ± 1.3
(CMB now constrains it from above !)

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \frac{\pi^2}{15} T_\gamma^4 .$$

In standard BBN
$N_{\rm eff} = 3.04$

ACT's data is comfortably consistent with SBBN. No cause for alarm yet.

Could these be early hints?

UPCOMING DATA FROM ACT/POL, SPT/POL AND PLANCK WILL CONSTRAIN BEYOND SM PHYSICS

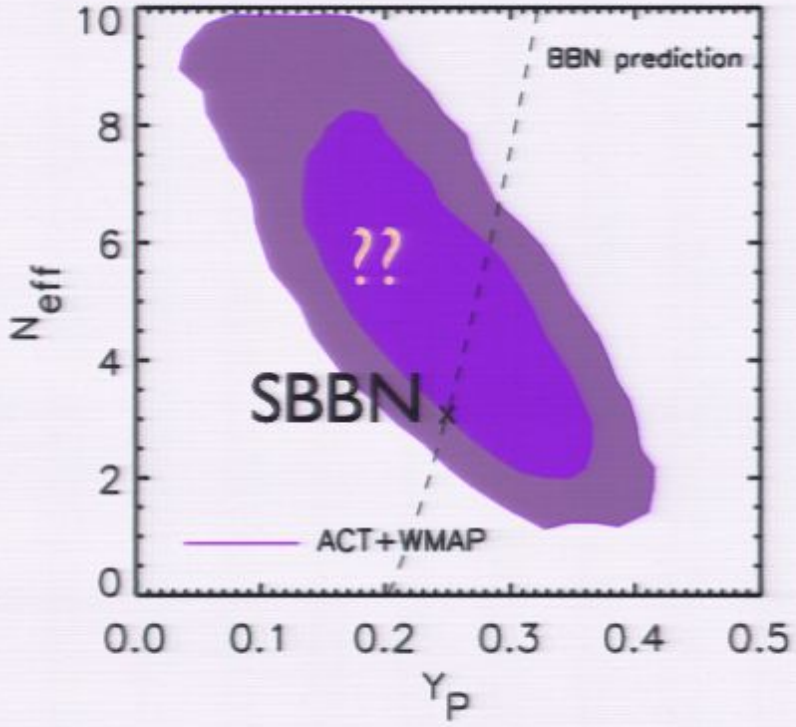
Helium fraction is essentially set by weak interaction freeze-out.

Izotov & Thuan (2010):

$Y_p = 0.2565 \pm 0.0010(\text{stat.}) \pm 0.0050(\text{syst.})$

Higher Helium fraction may mean more radiation during BBN, i.e. higher N_{eff}

$N_{eff} > 3.04$ could mean extra relativistic species (gravitons, axions, sterile neutrinos?) or non-thermal/beyond standard model interactions.

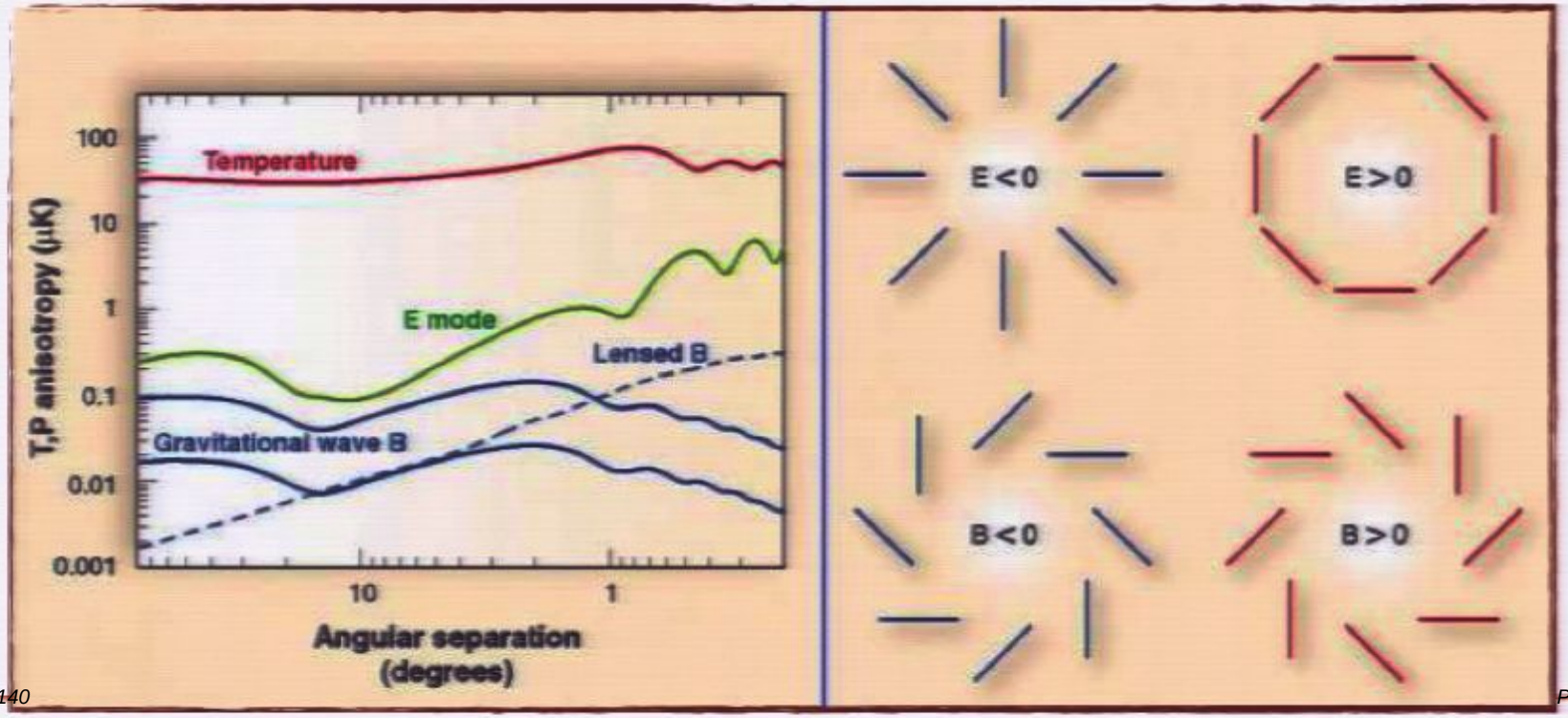


With polarization, where foregrounds and secondaries are lower, we should be able to see deeper into the CMB damping tail .

CMB POLARIZATION CONTAINS COMPLEMENTARY INFORMATION

CMB Polarization is usually decomposed into E (curl-free) and B (gradient-free) modes.

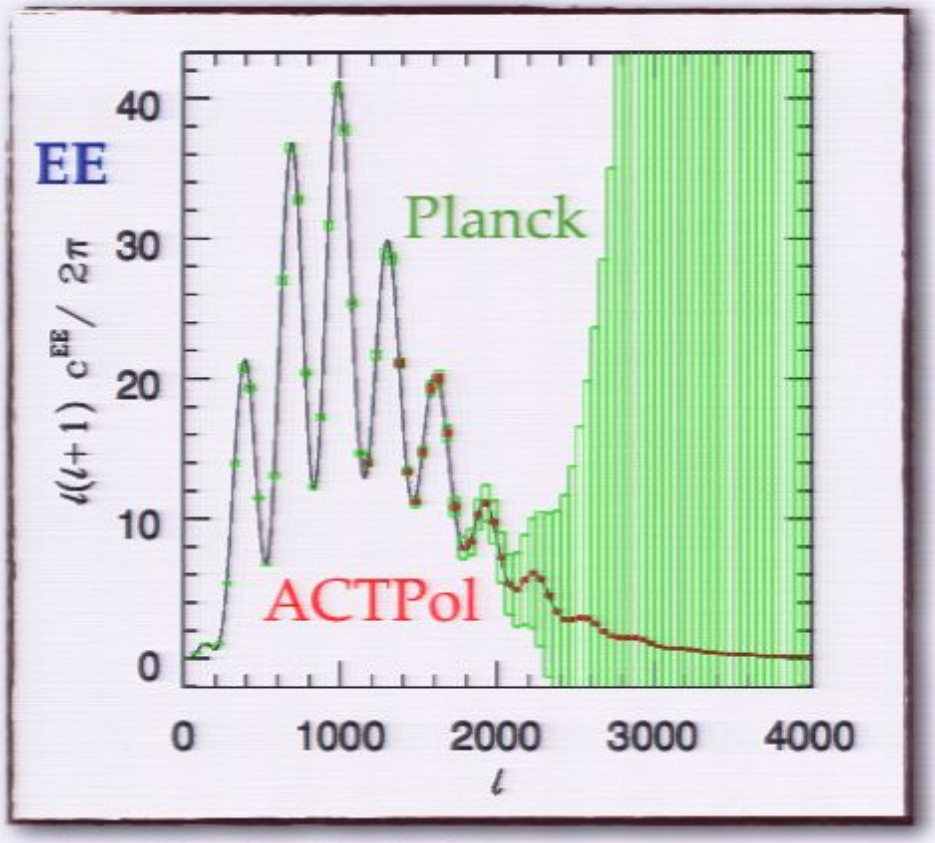
The polarized signals: EE, BB are much weaker than the TT, but foregrounds and secondaries are expected to be much lower.

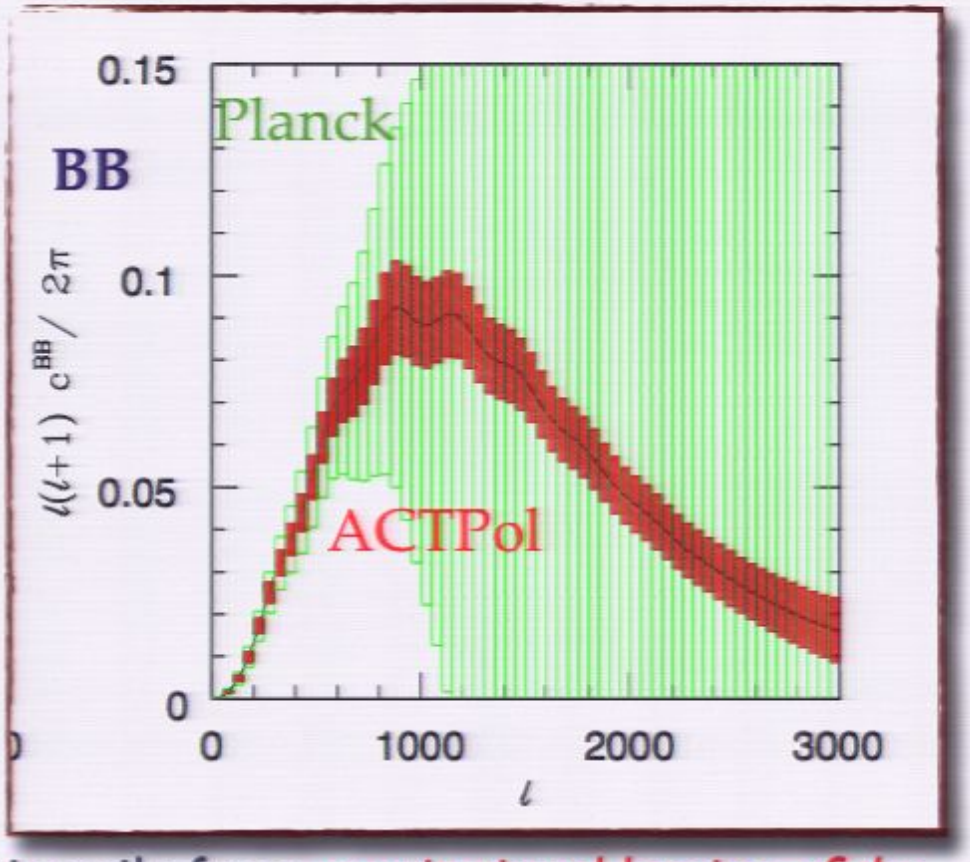


ACTPol: Adding Polarization to ACT

Also upcoming are POLARBEAR and SPTpol

ACTPol will make precise measurements of small scale CMB polarization spectrum. ACTPol is funded, and will start in 2012.



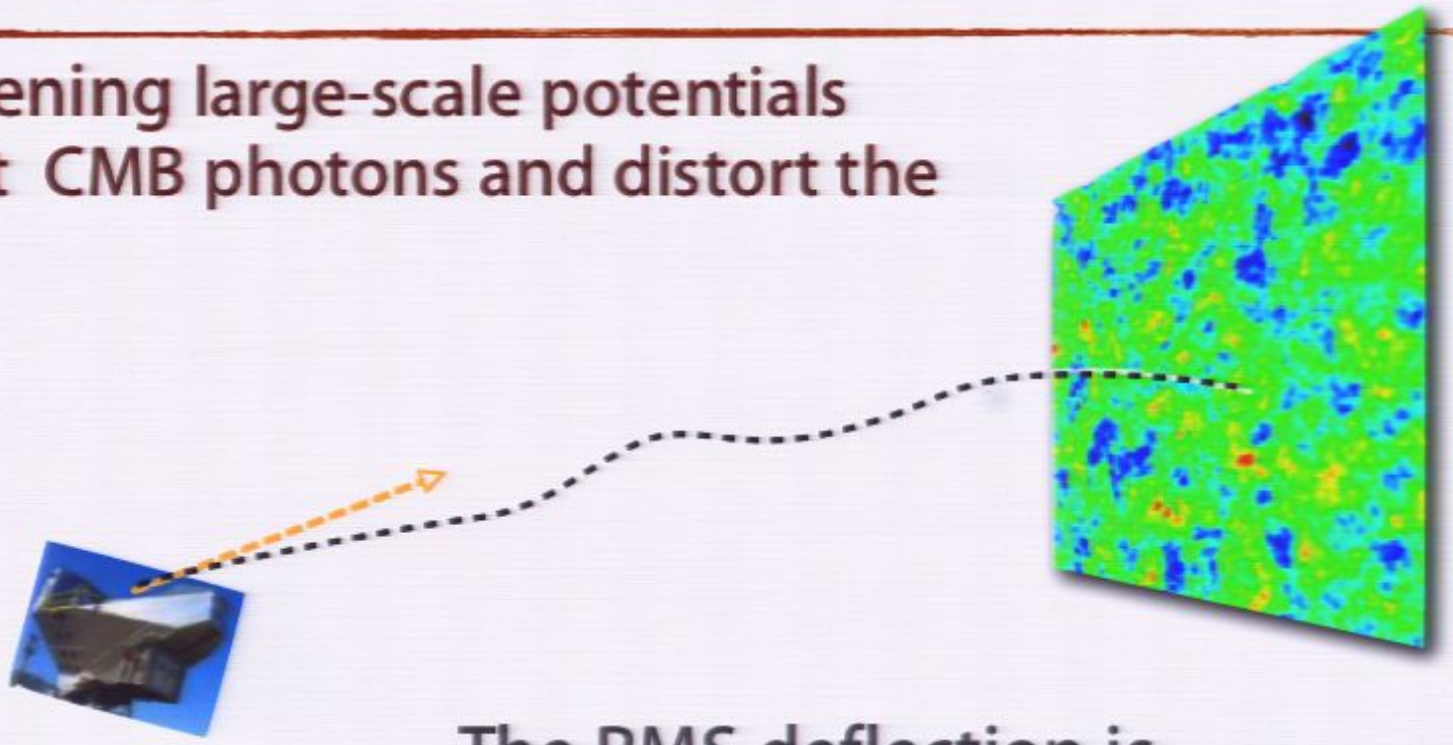


For BB, the high-l spectrum comes primarily from *gravitational lensing of the CMB E-modes*.

See Niemack et al (2010) Sudeep Das, PI CITA Day, Feb 15, 2011

GRAVITATIONAL LENSING OF THE CMB

Intervening large-scale potentials deflect CMB photons and distort the CMB.

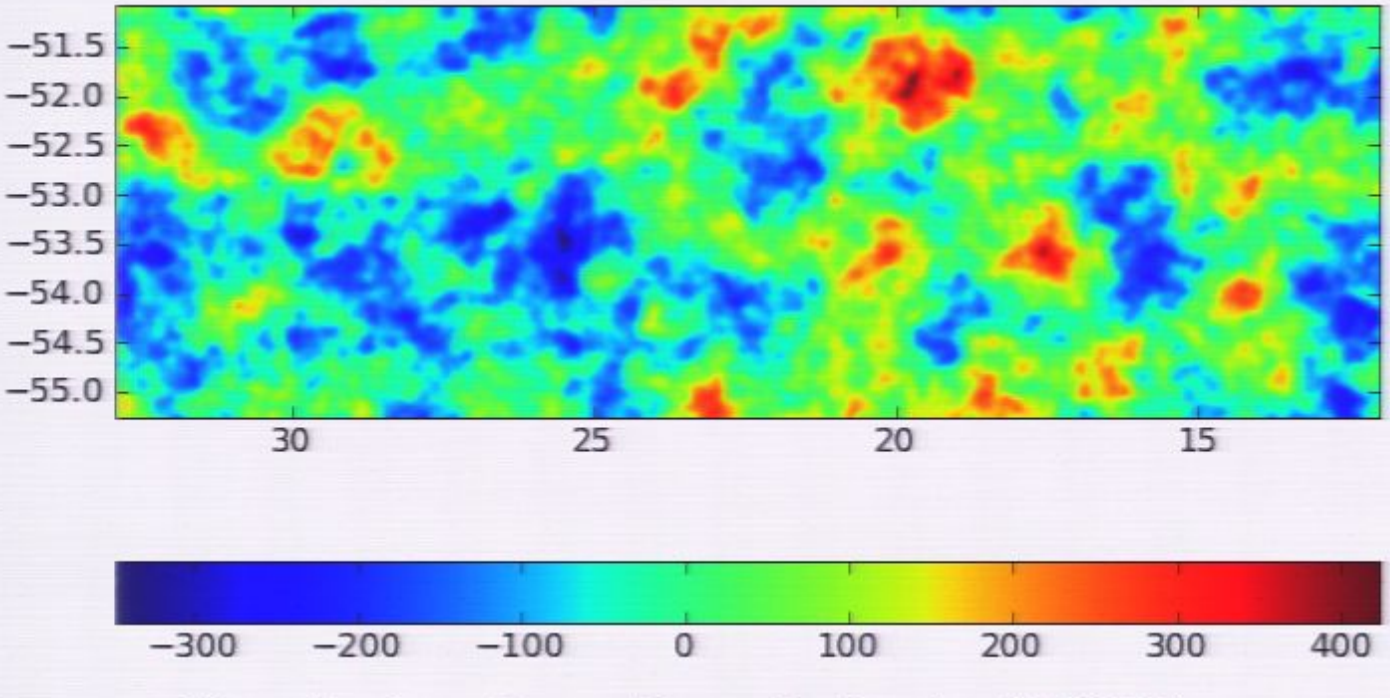


The RMS deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

LENSING REMAPS & MAGNIFIES/DE-MAGNIFIES CMB PATCHES, SMOOTHING OUT PEAKS

$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \nabla\phi)$$

lensed unlensed deflection



Simulation from Das & Bode (2008)

Lens-speak:

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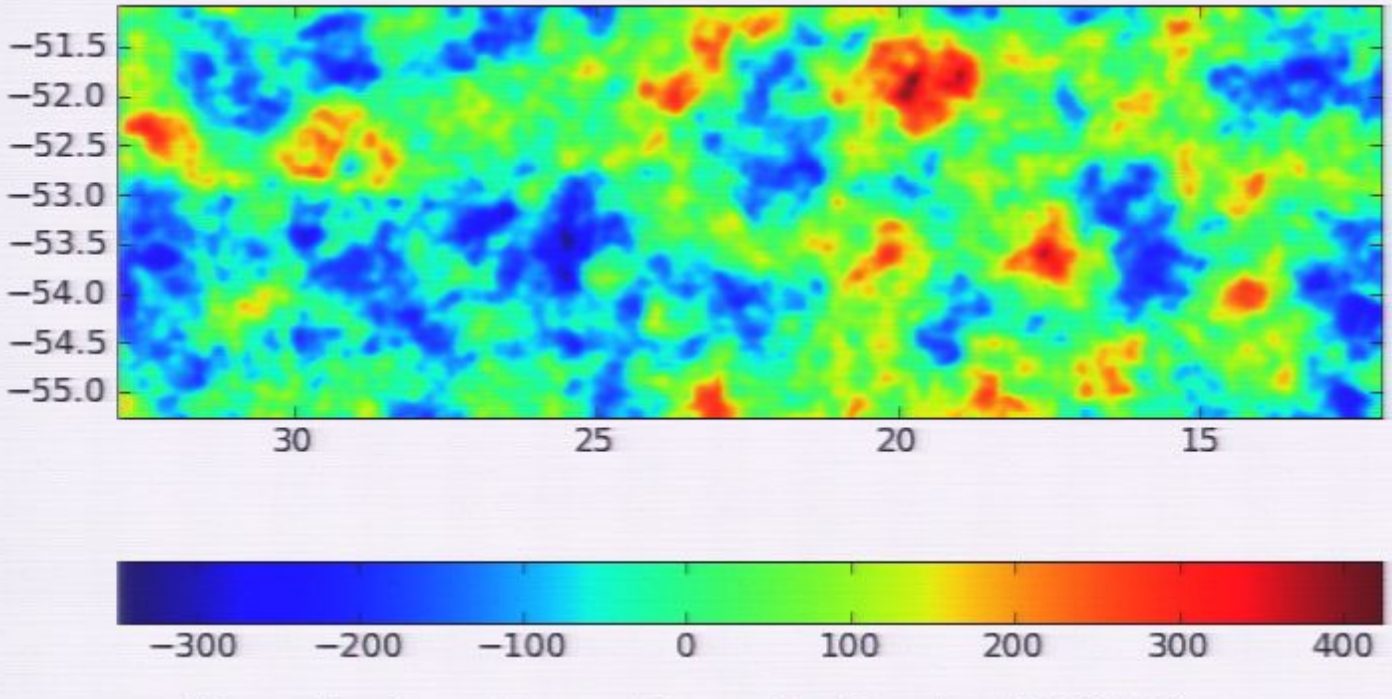

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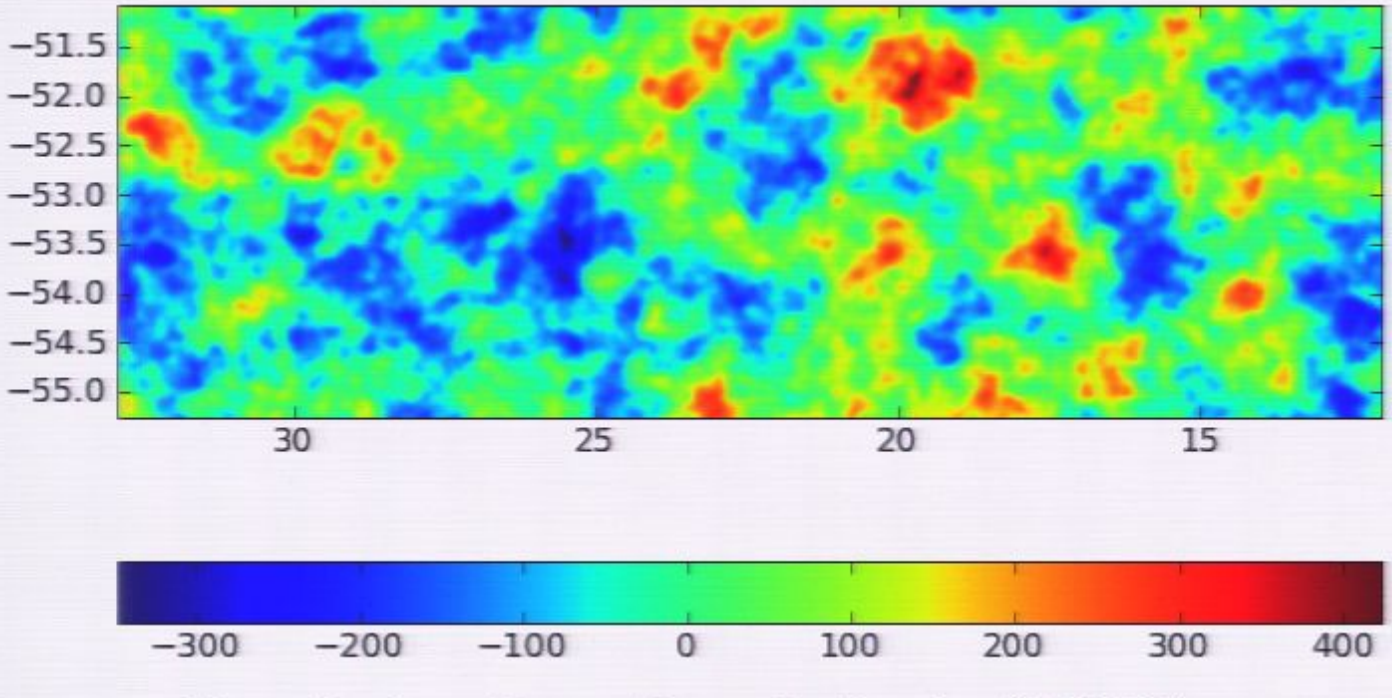

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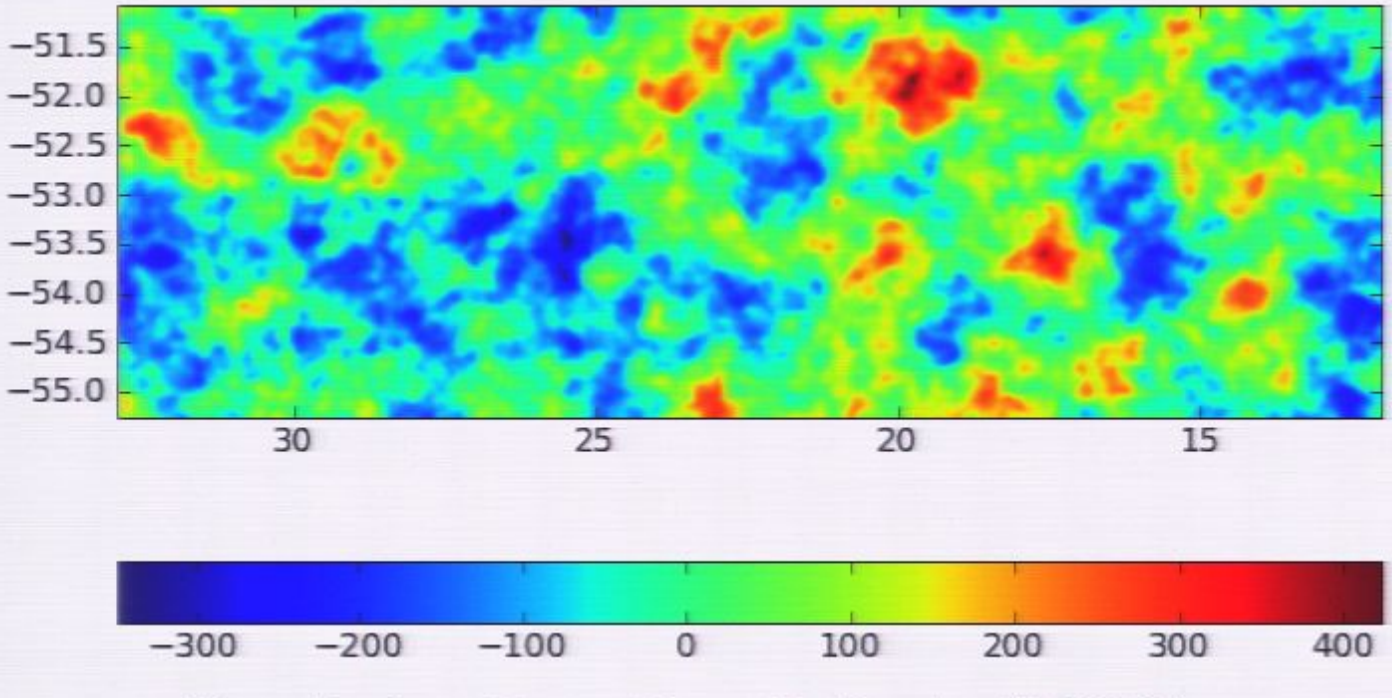

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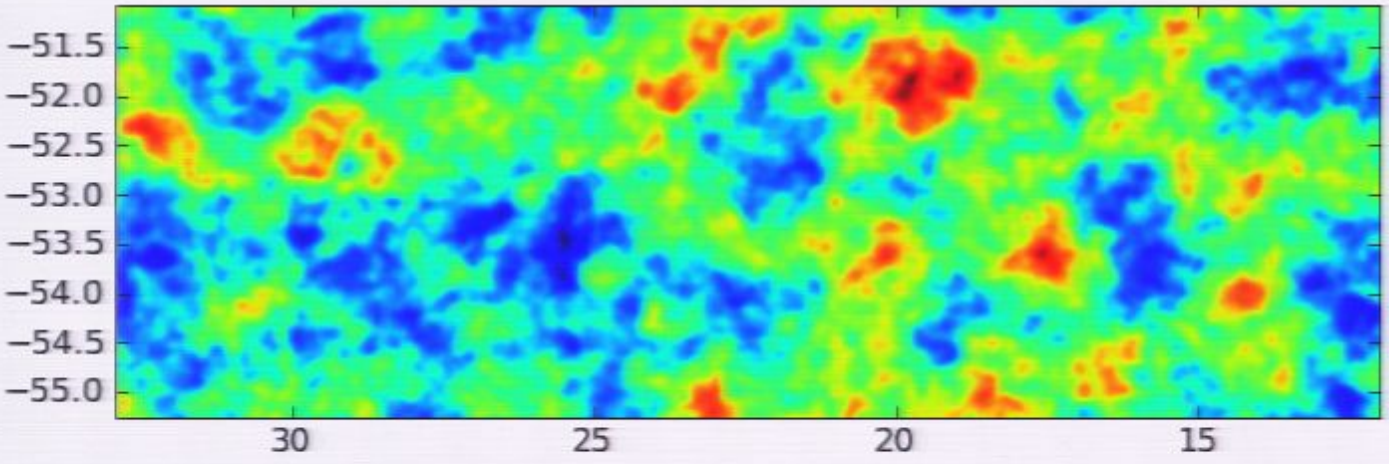

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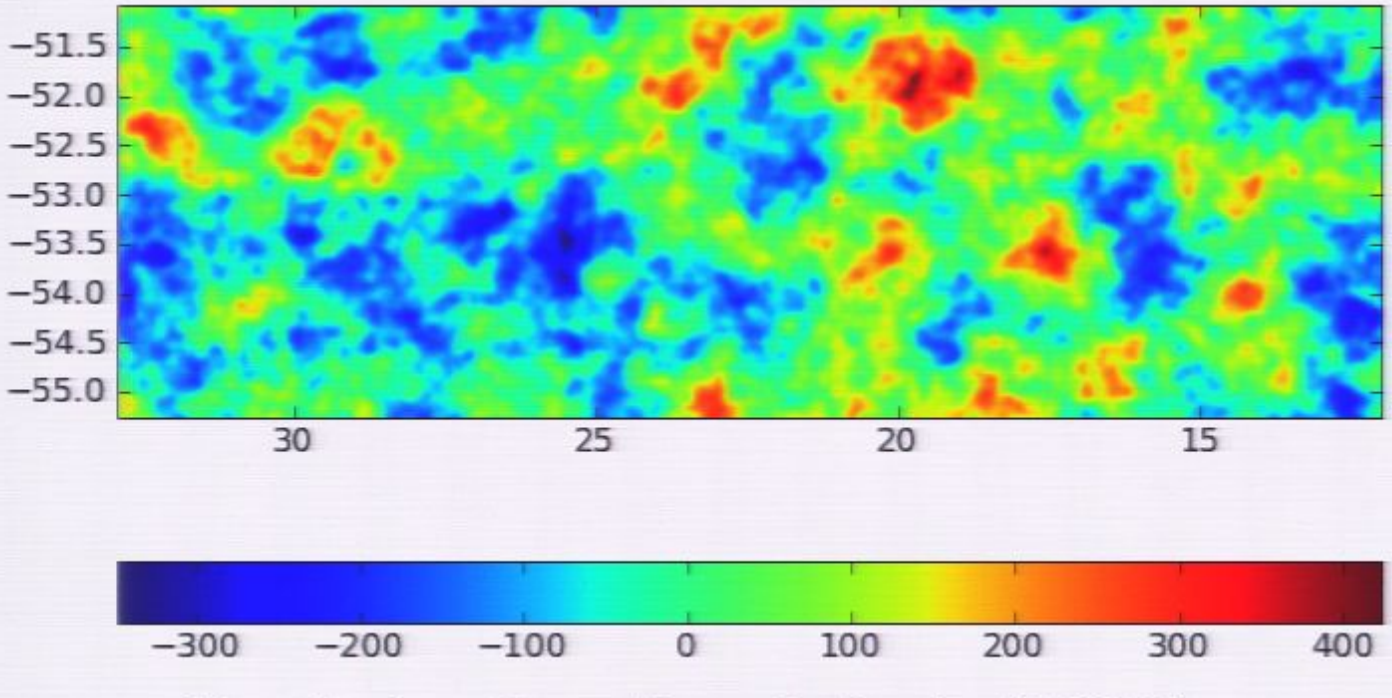

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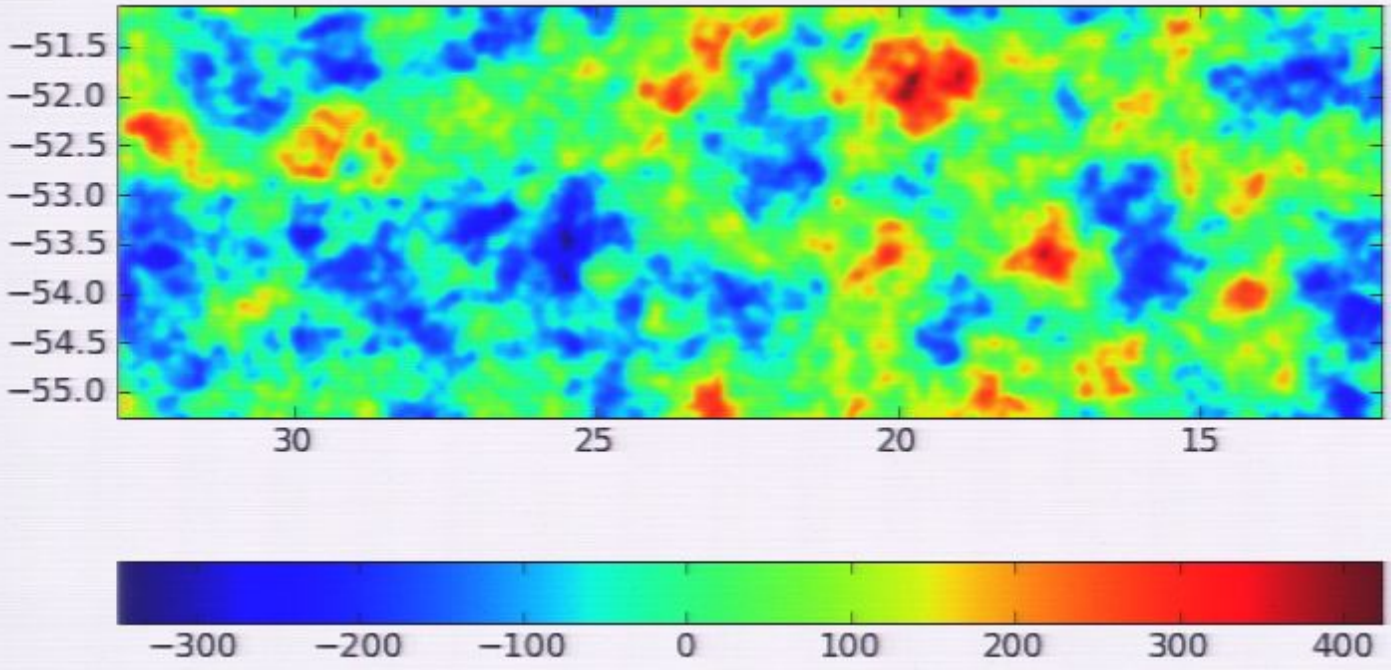

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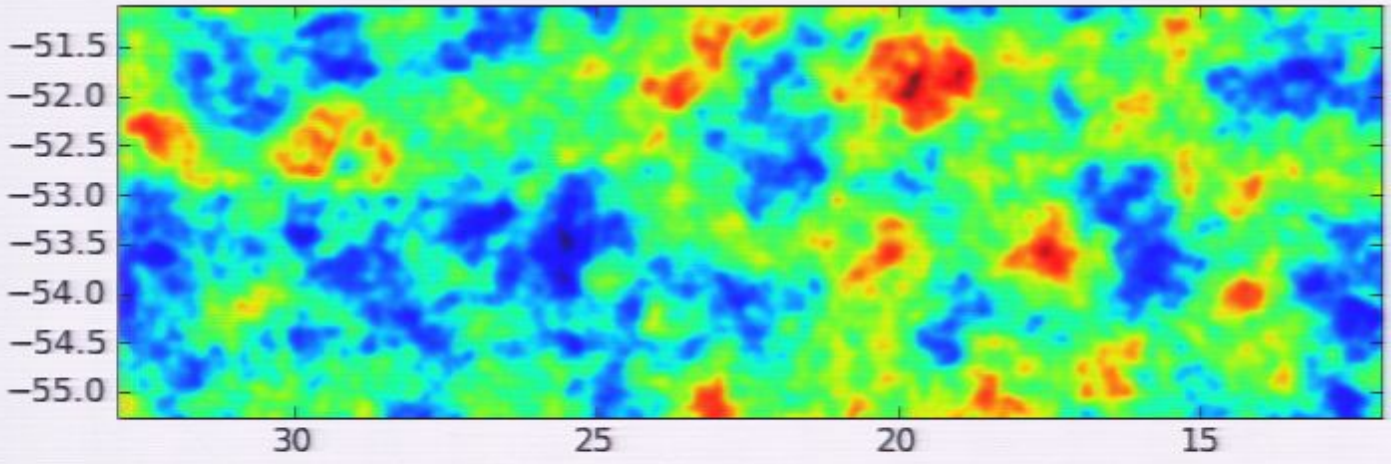

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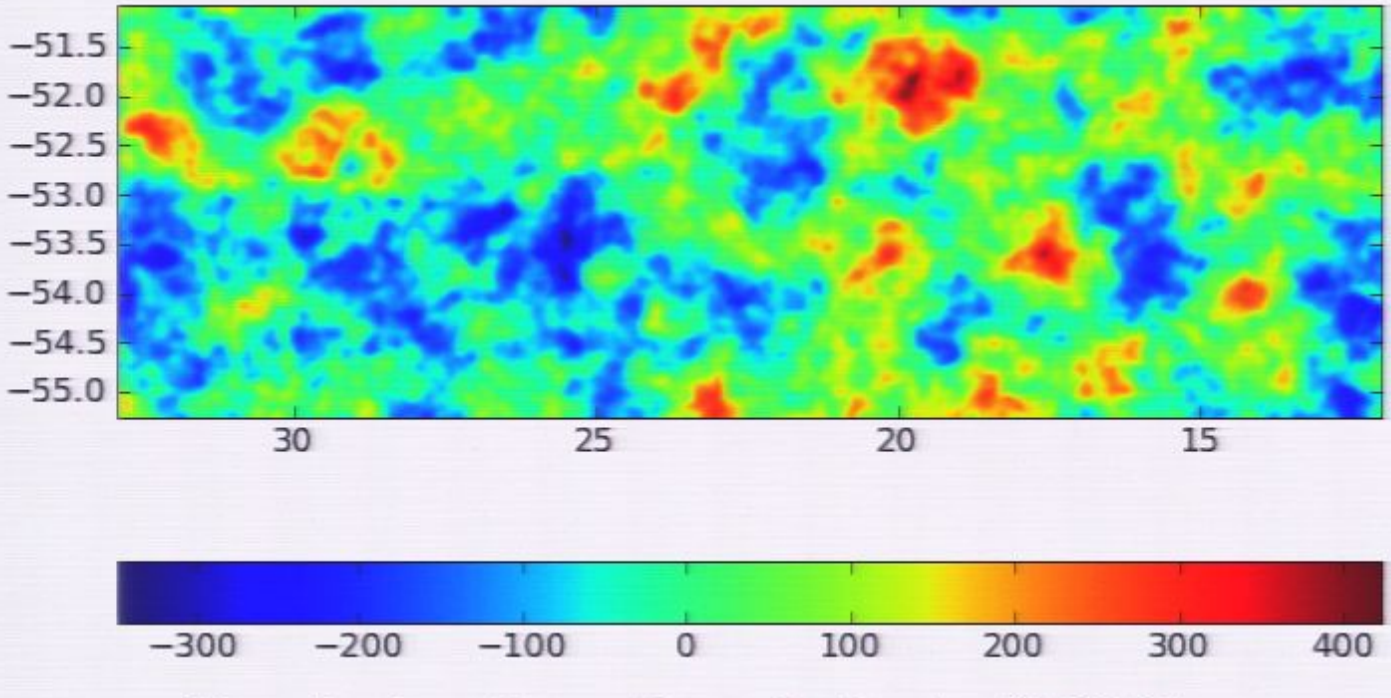

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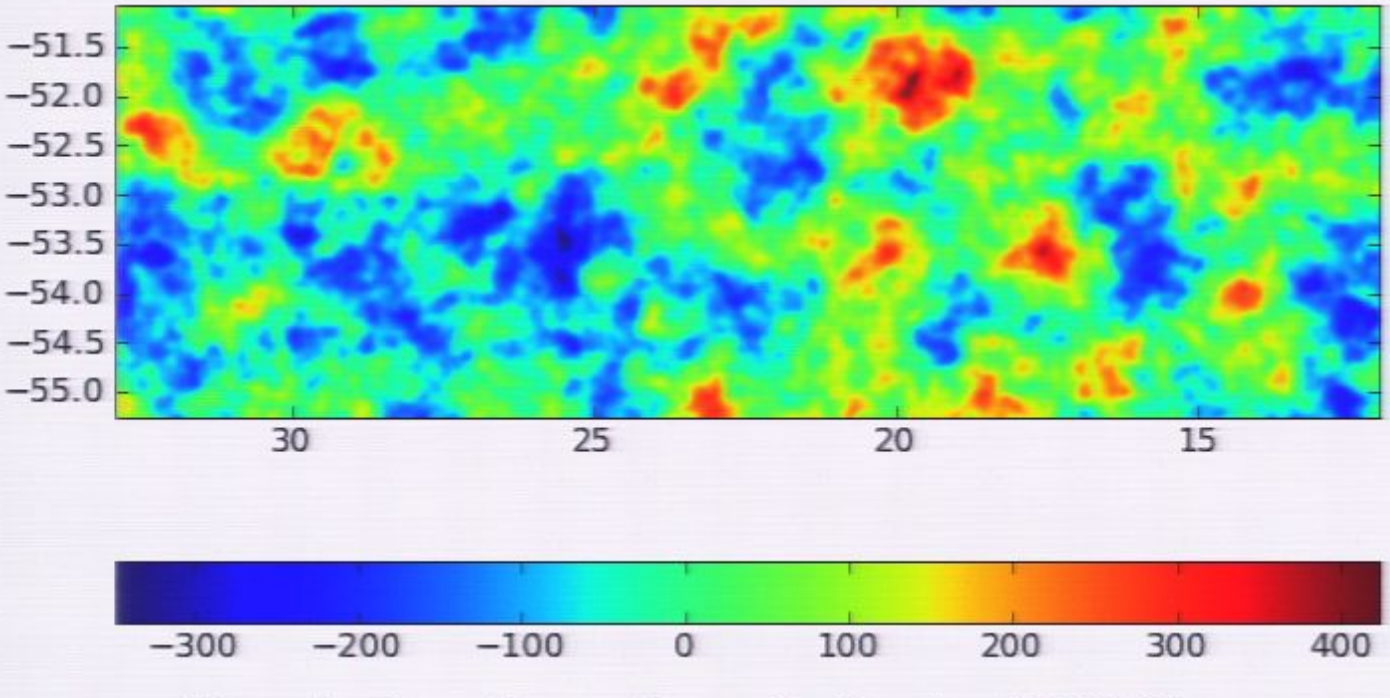

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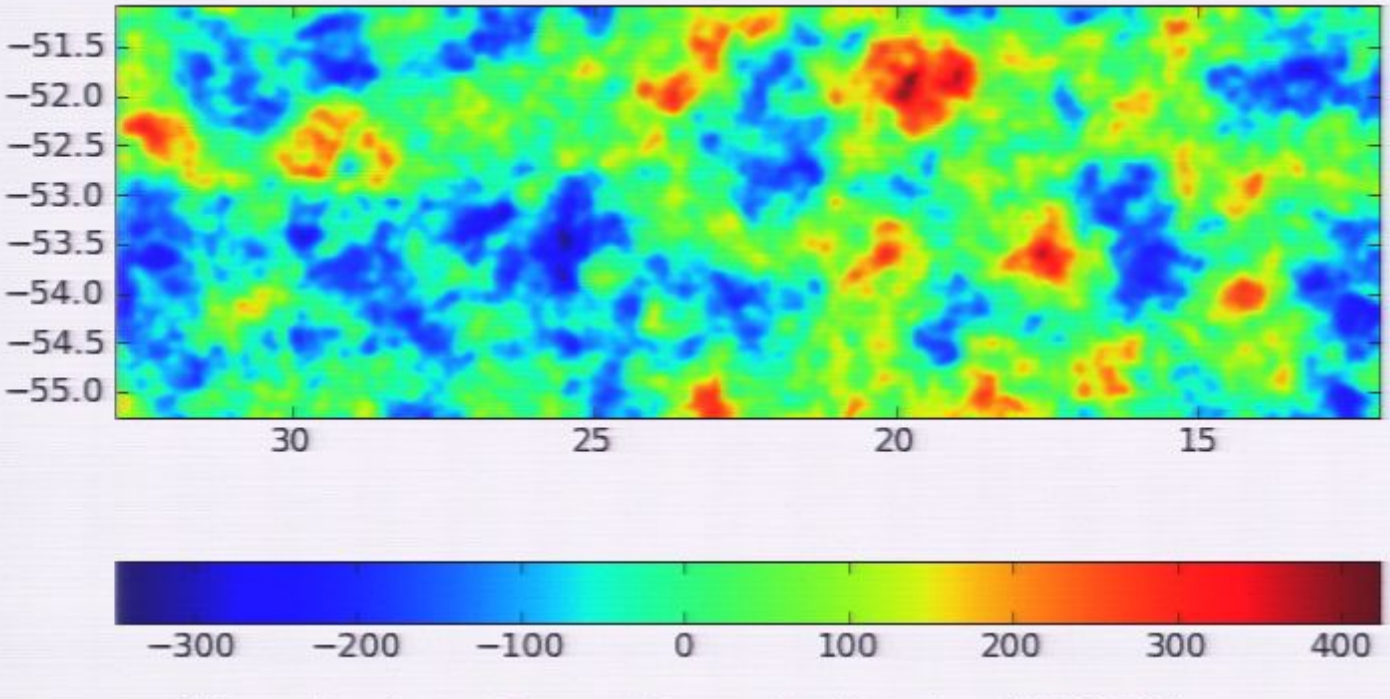

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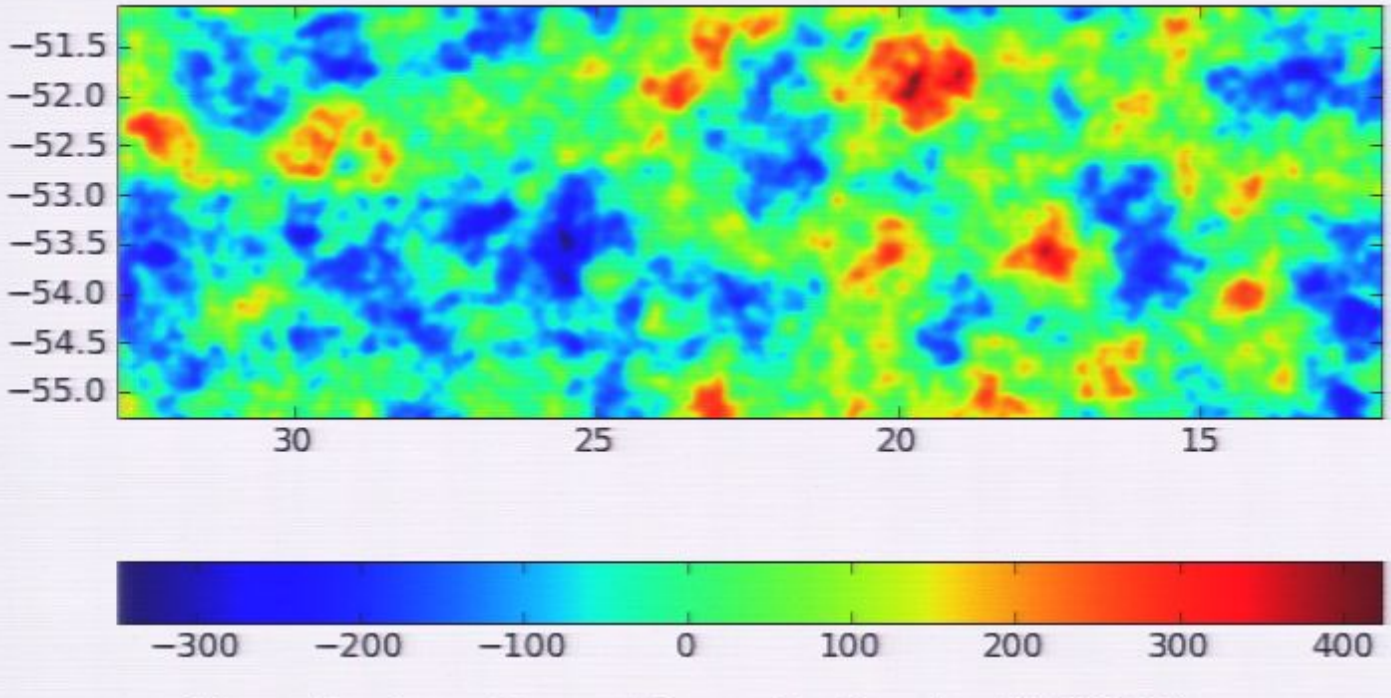

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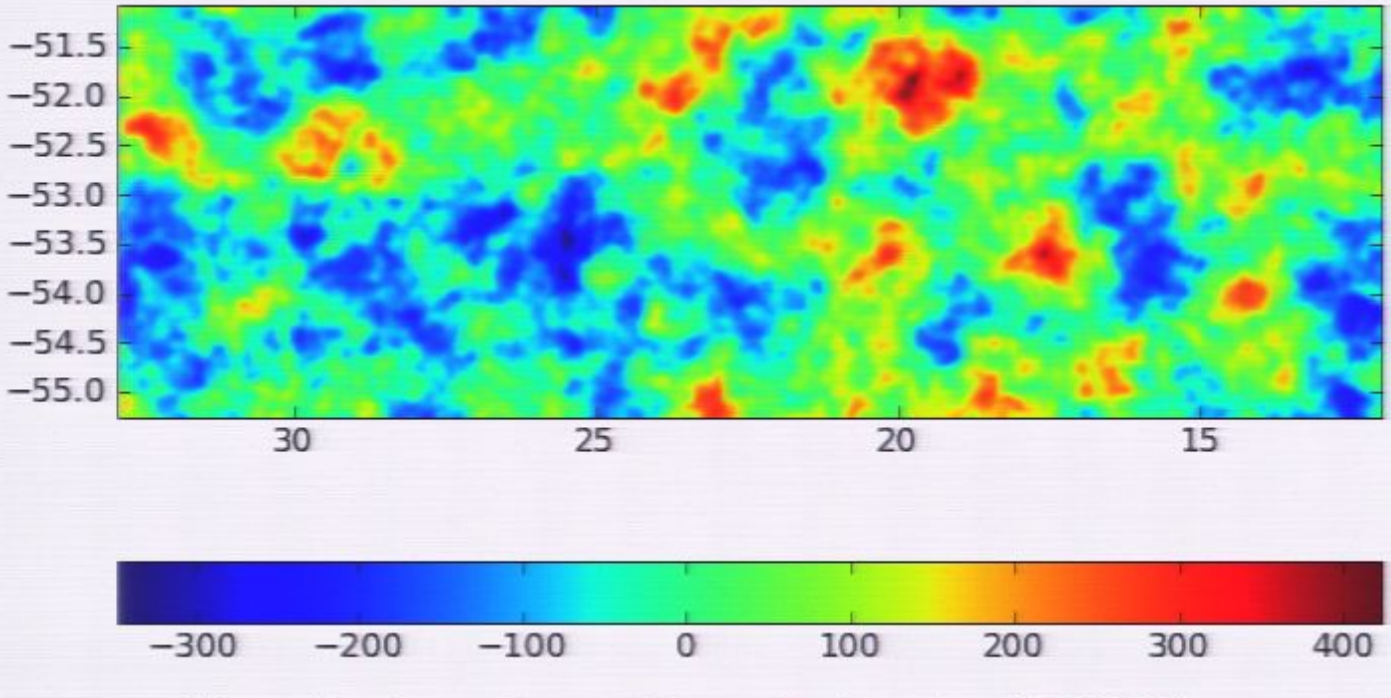

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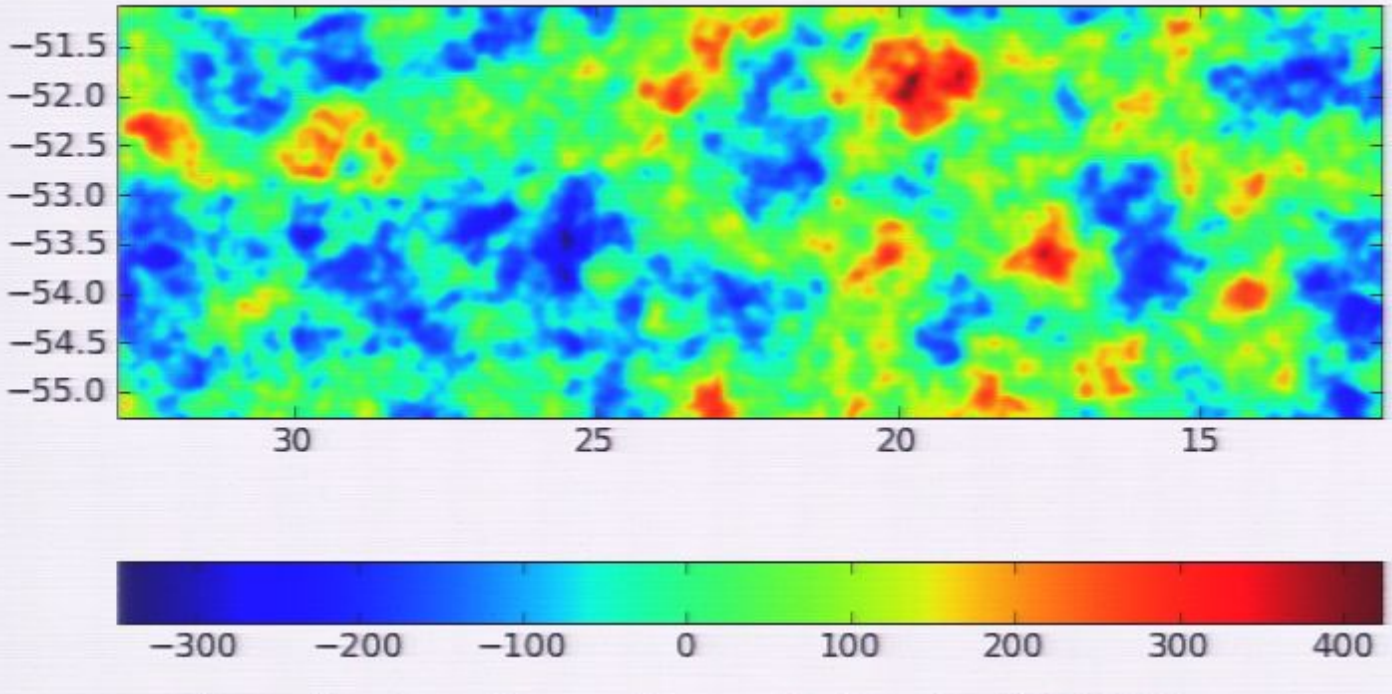

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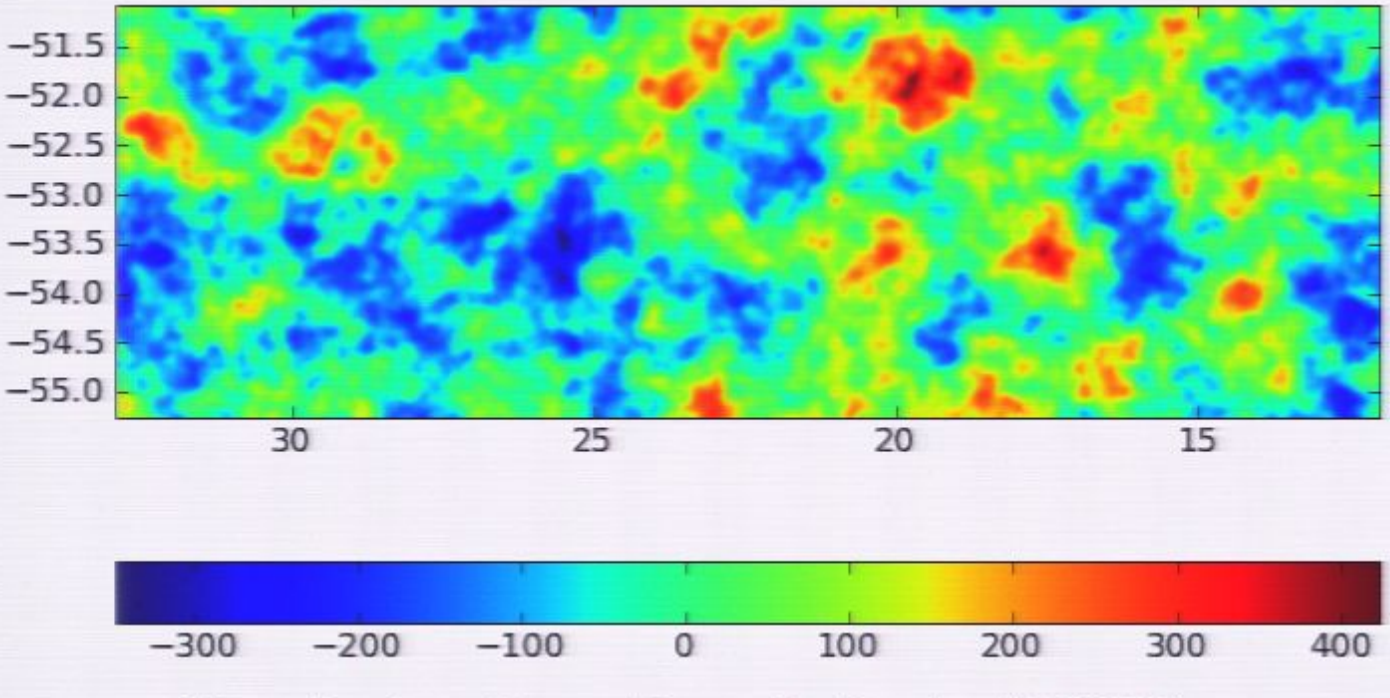

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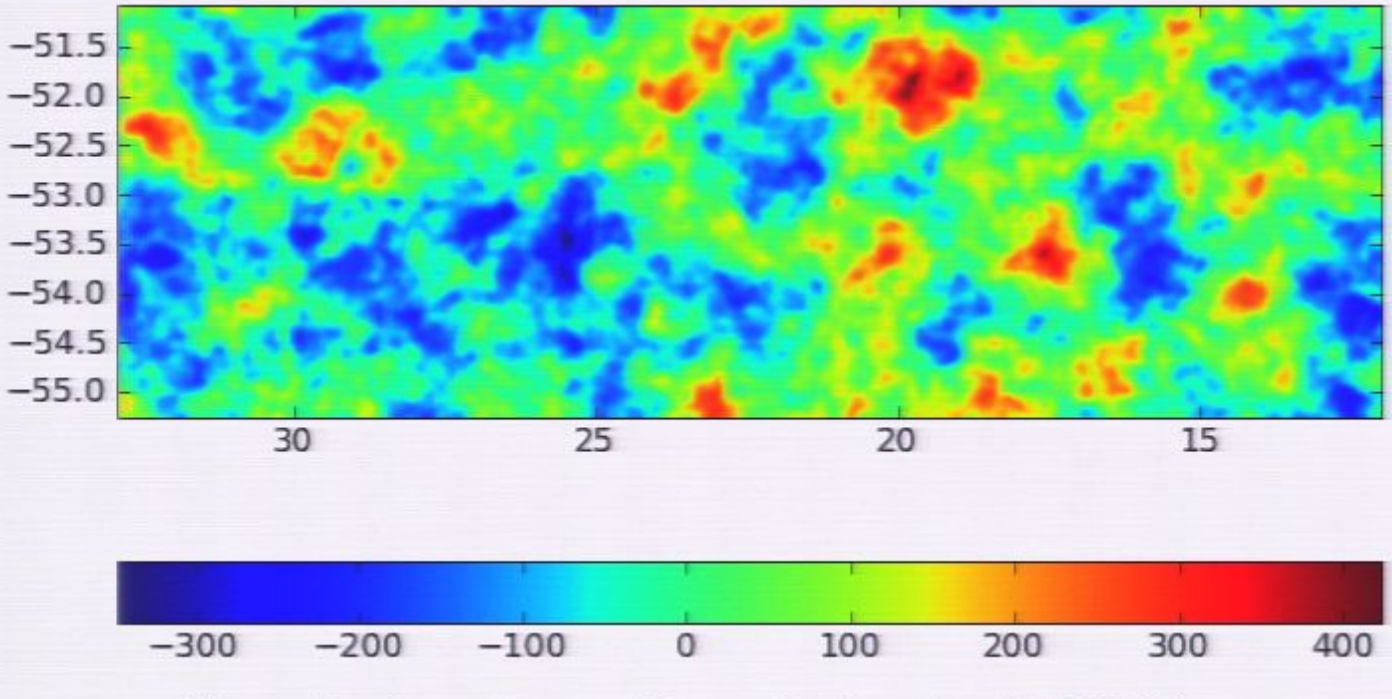

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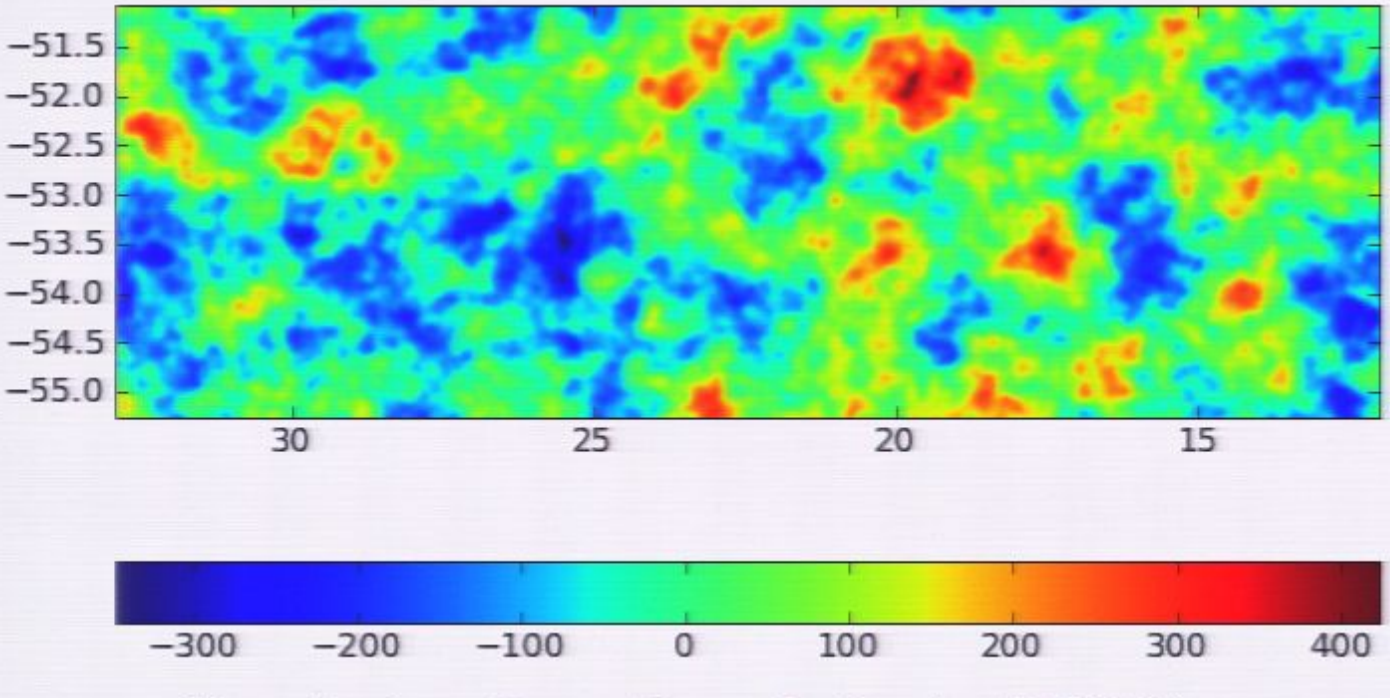

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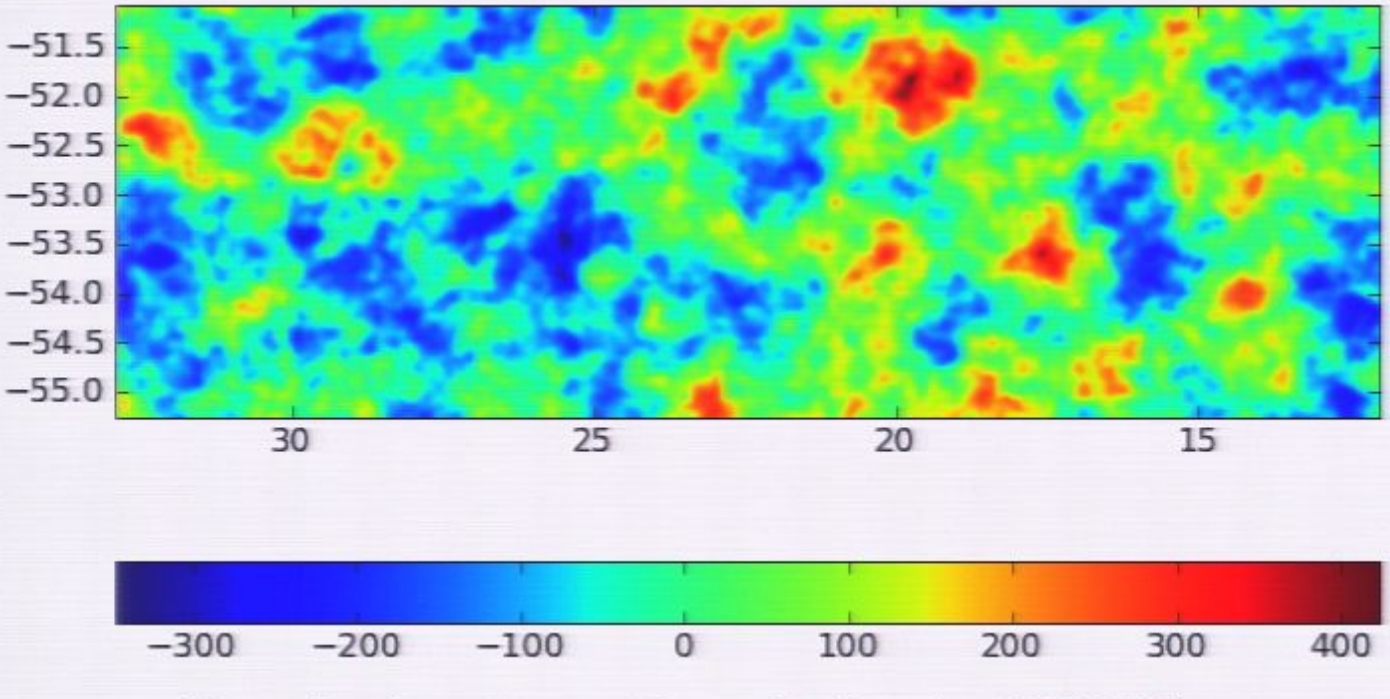

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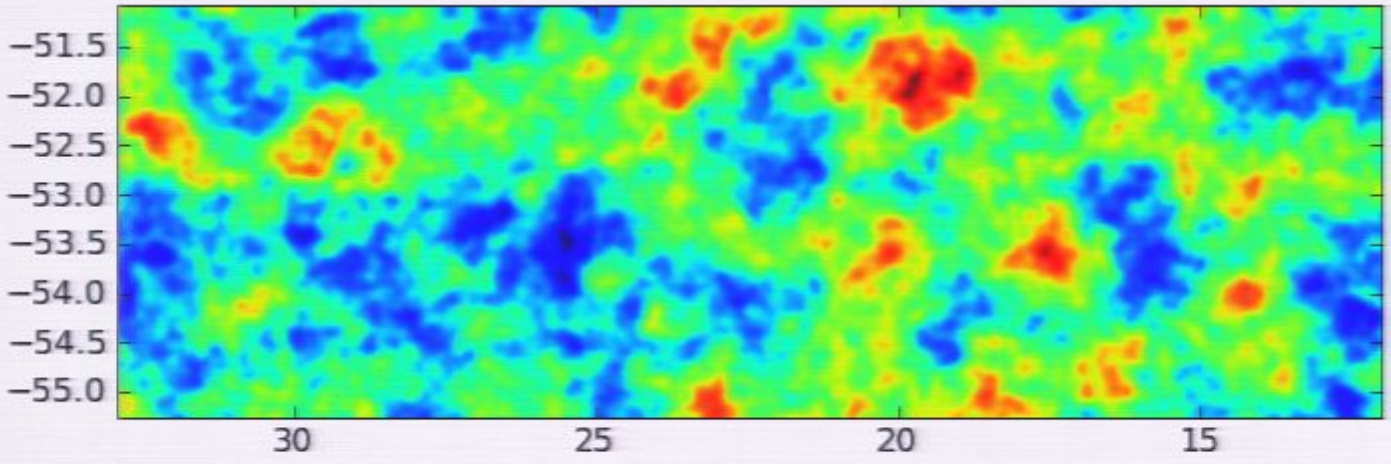

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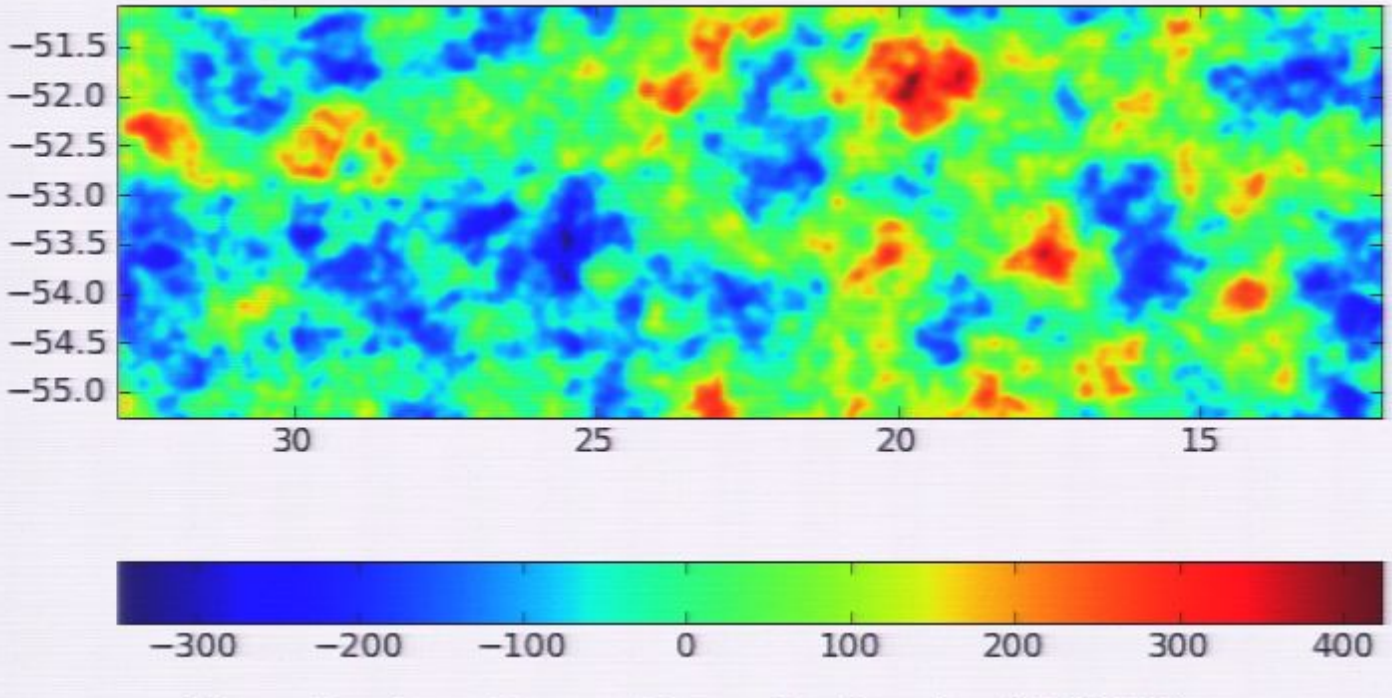

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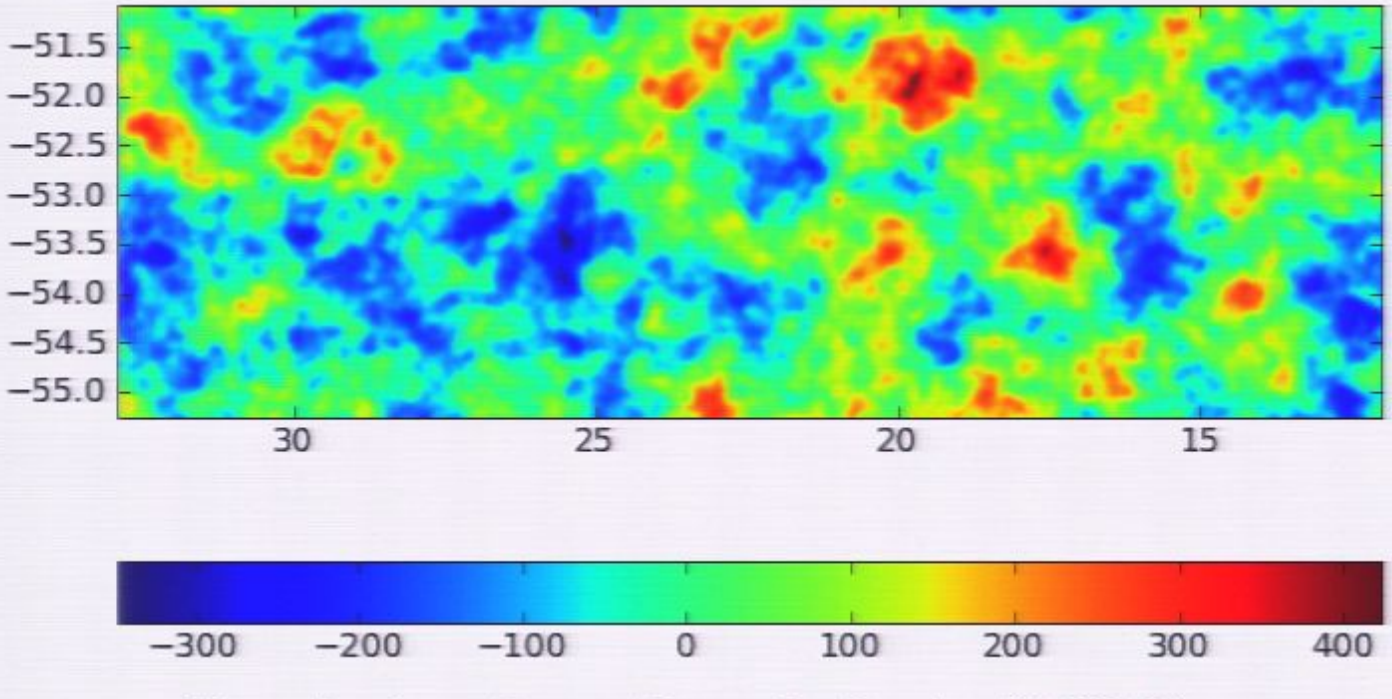

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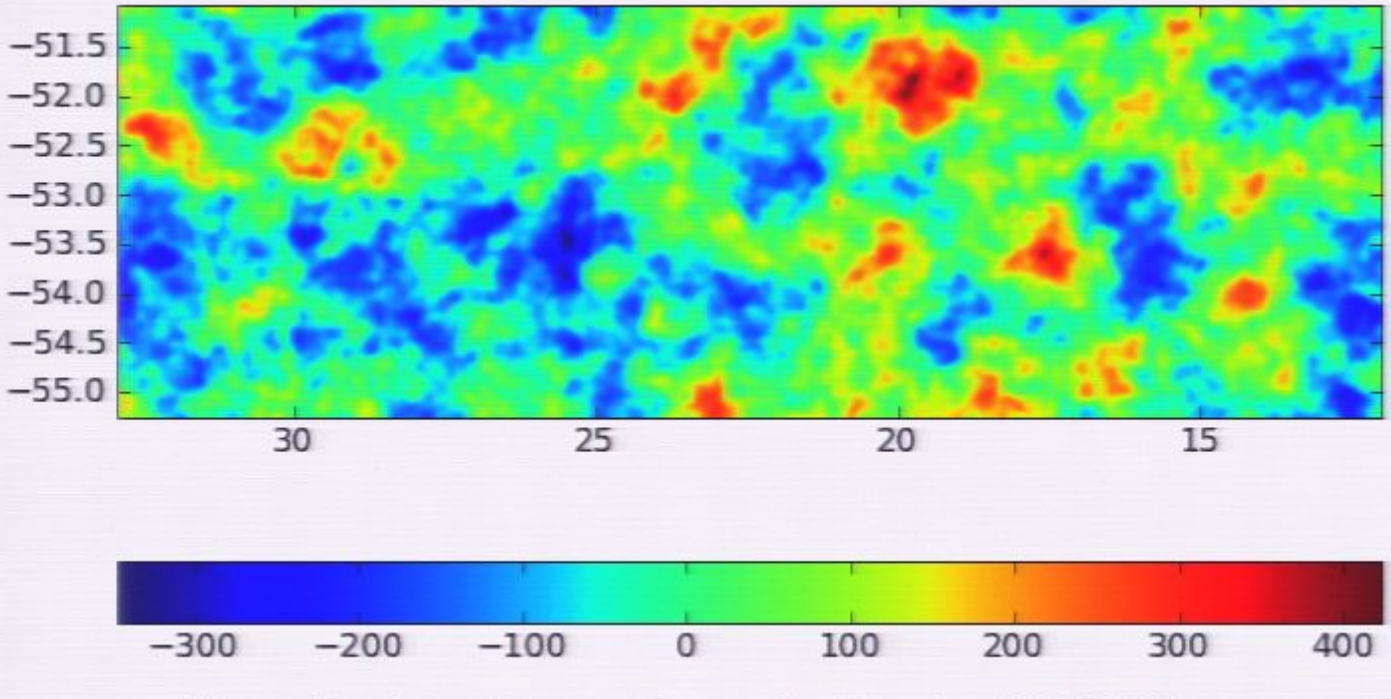

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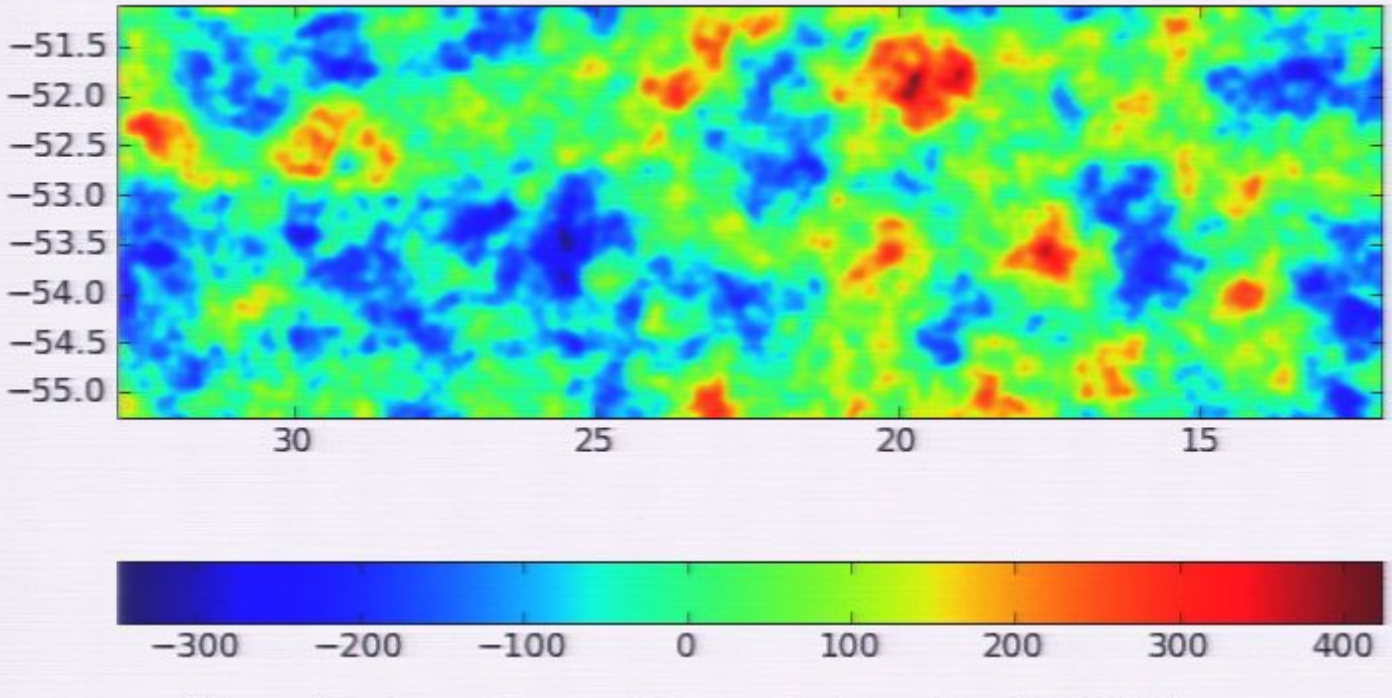

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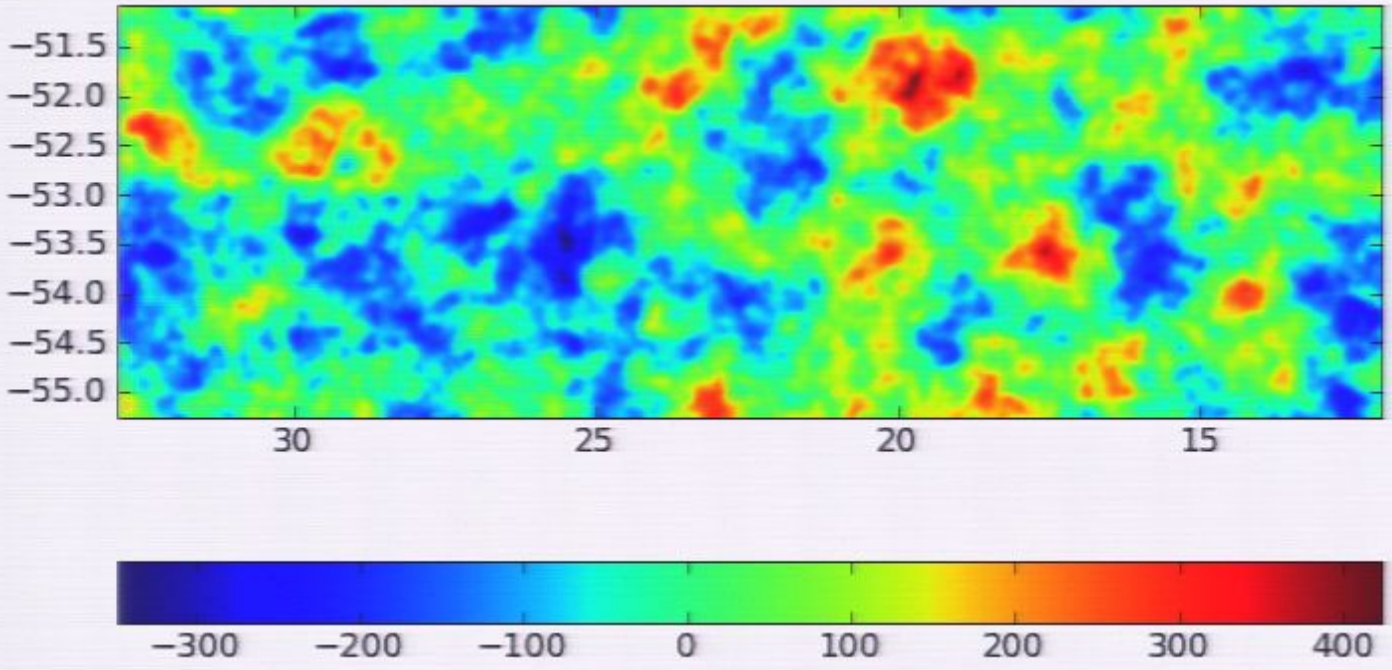

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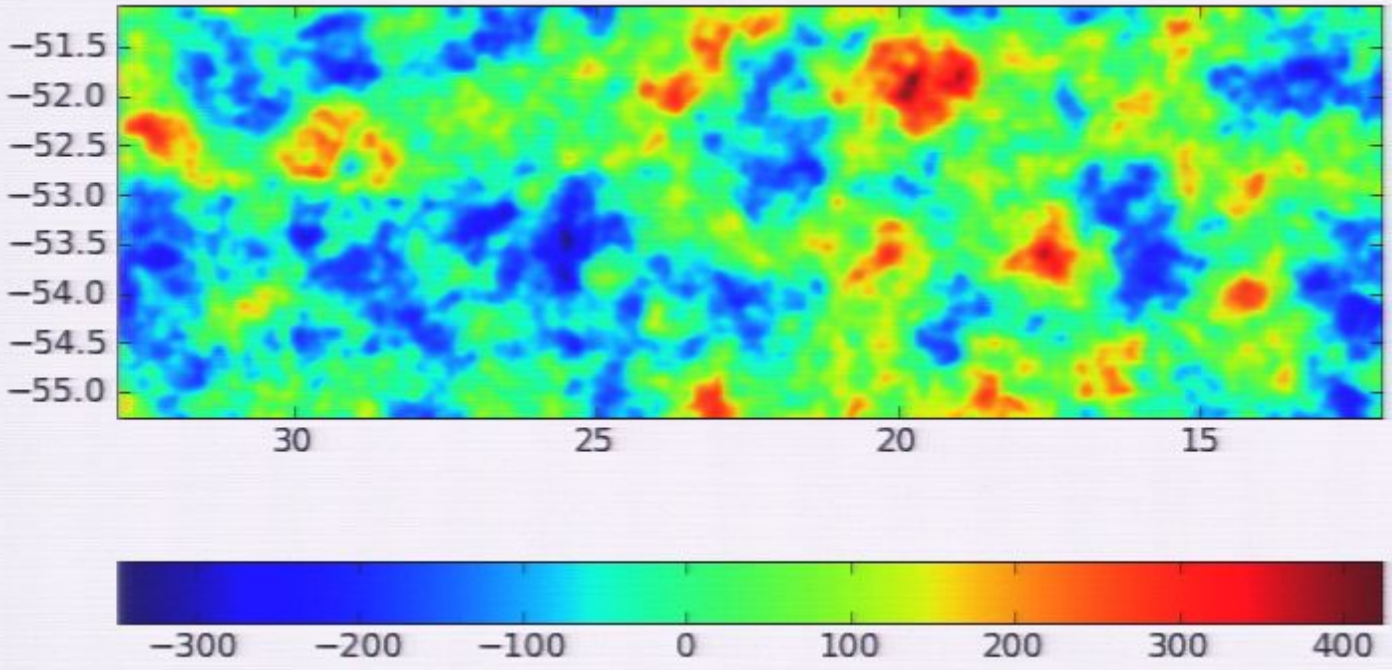

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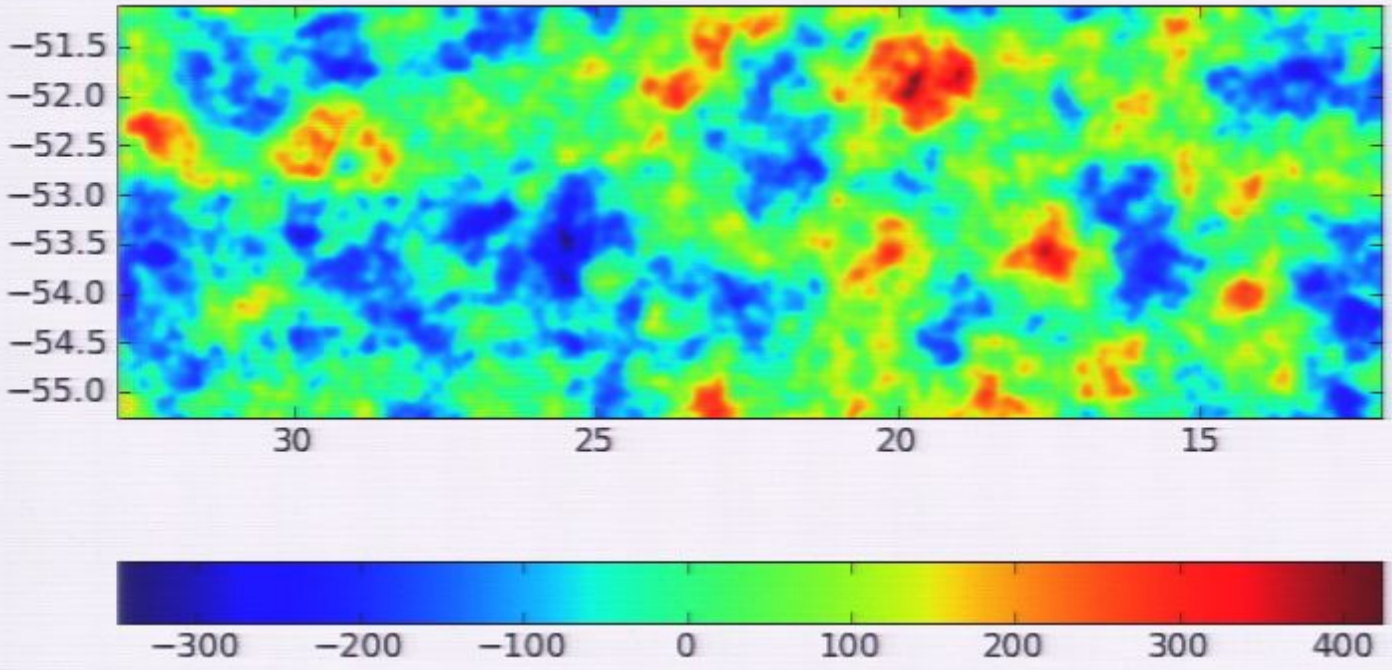

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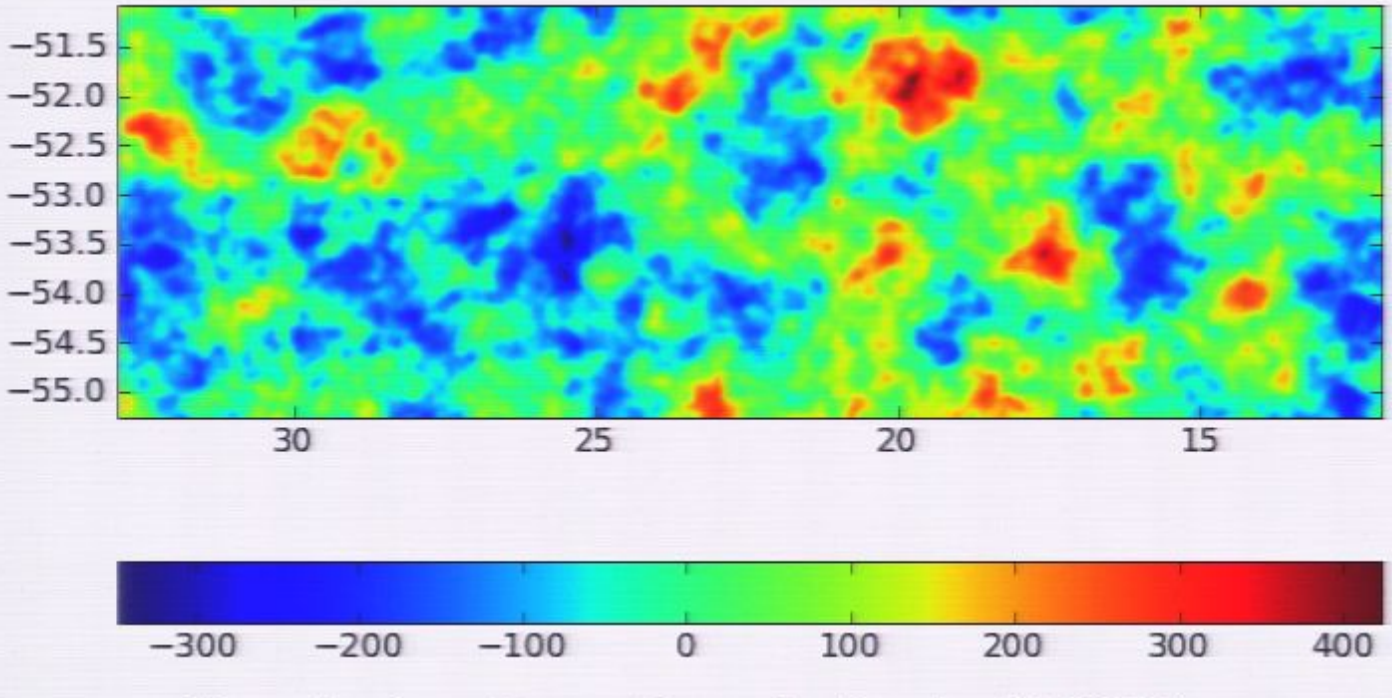

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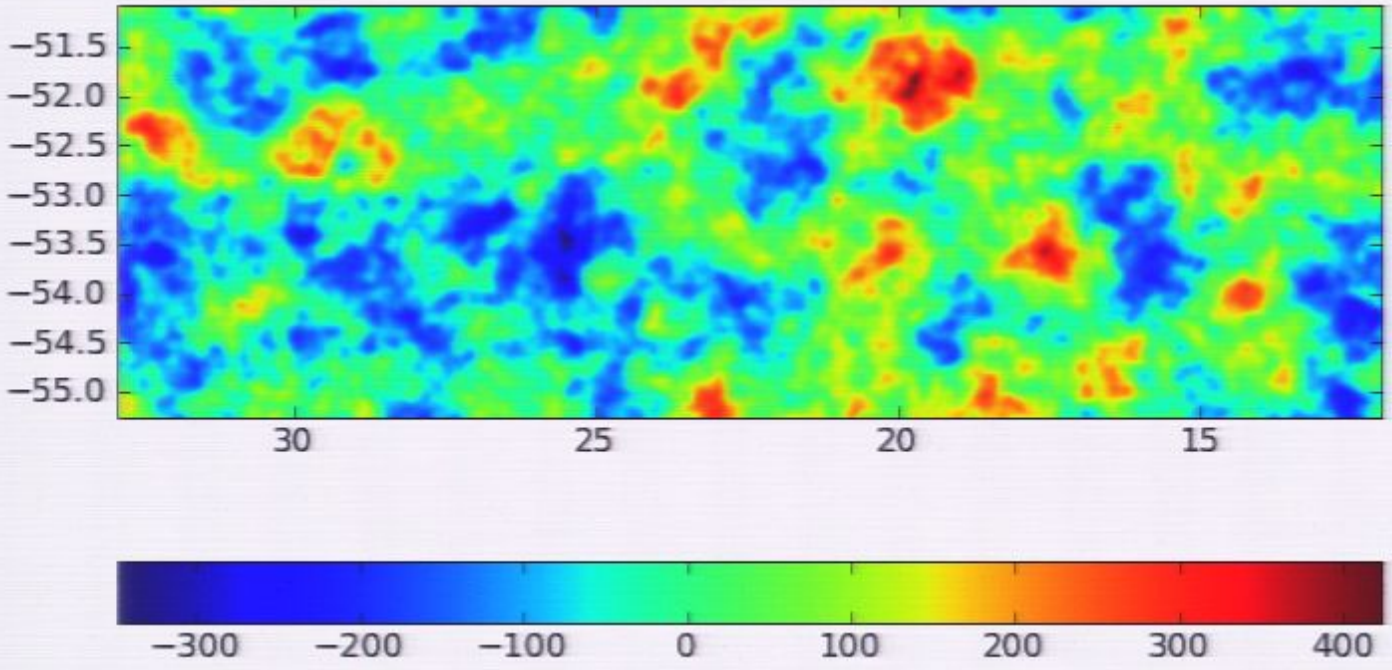

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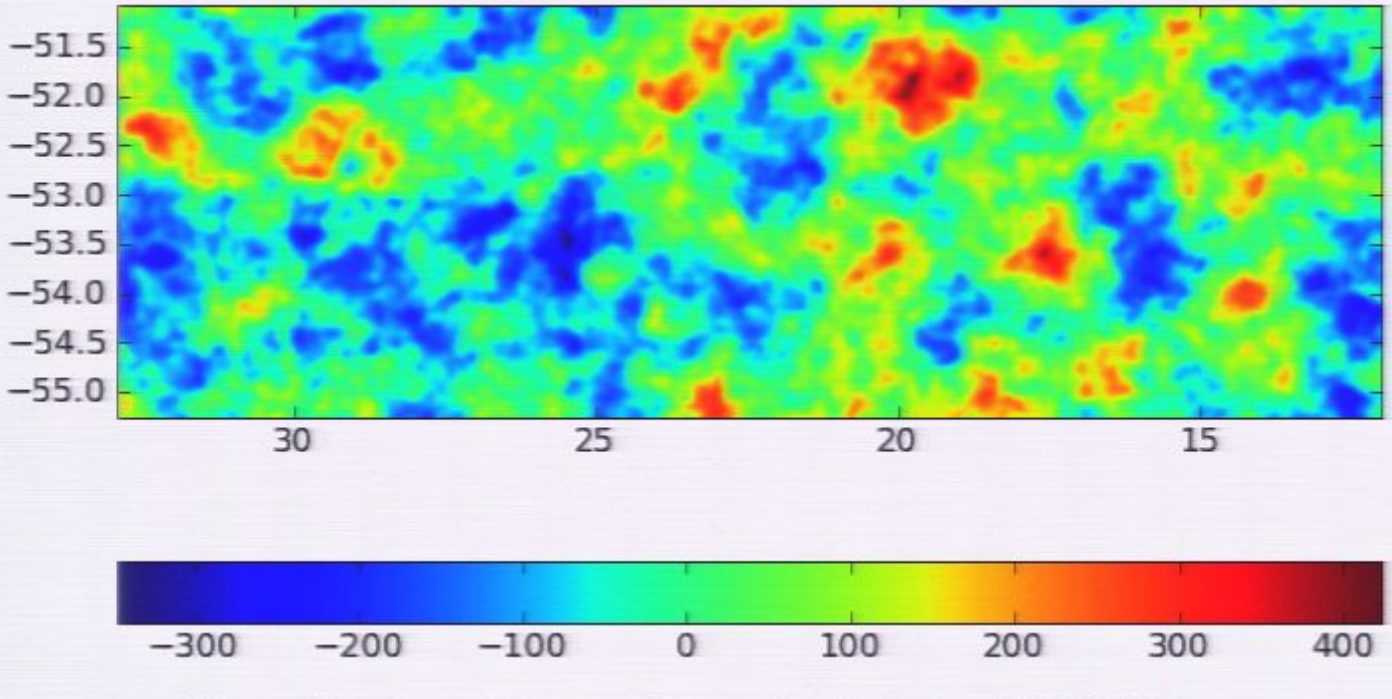

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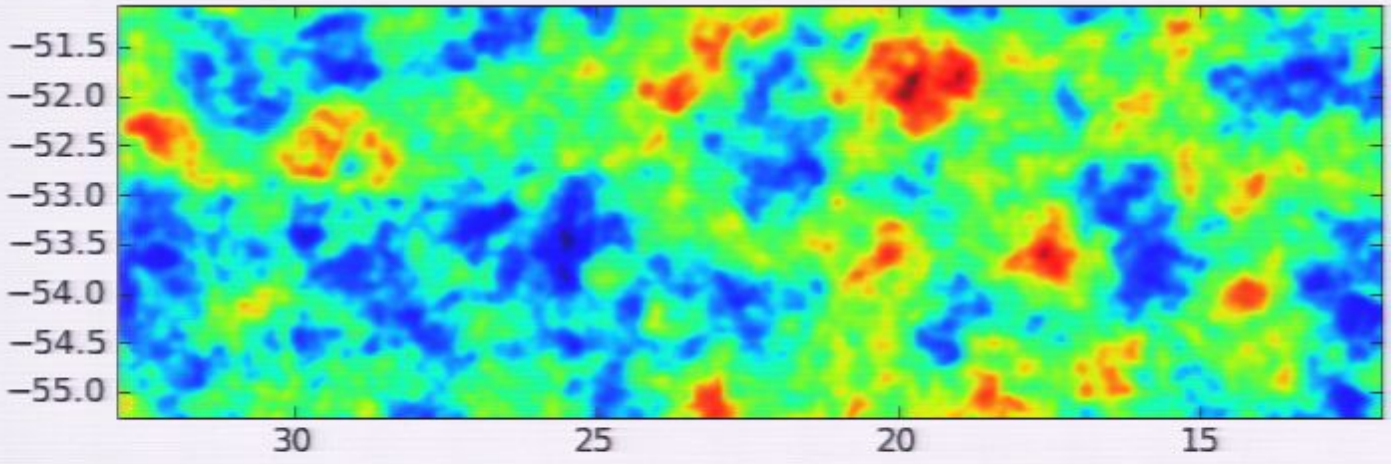

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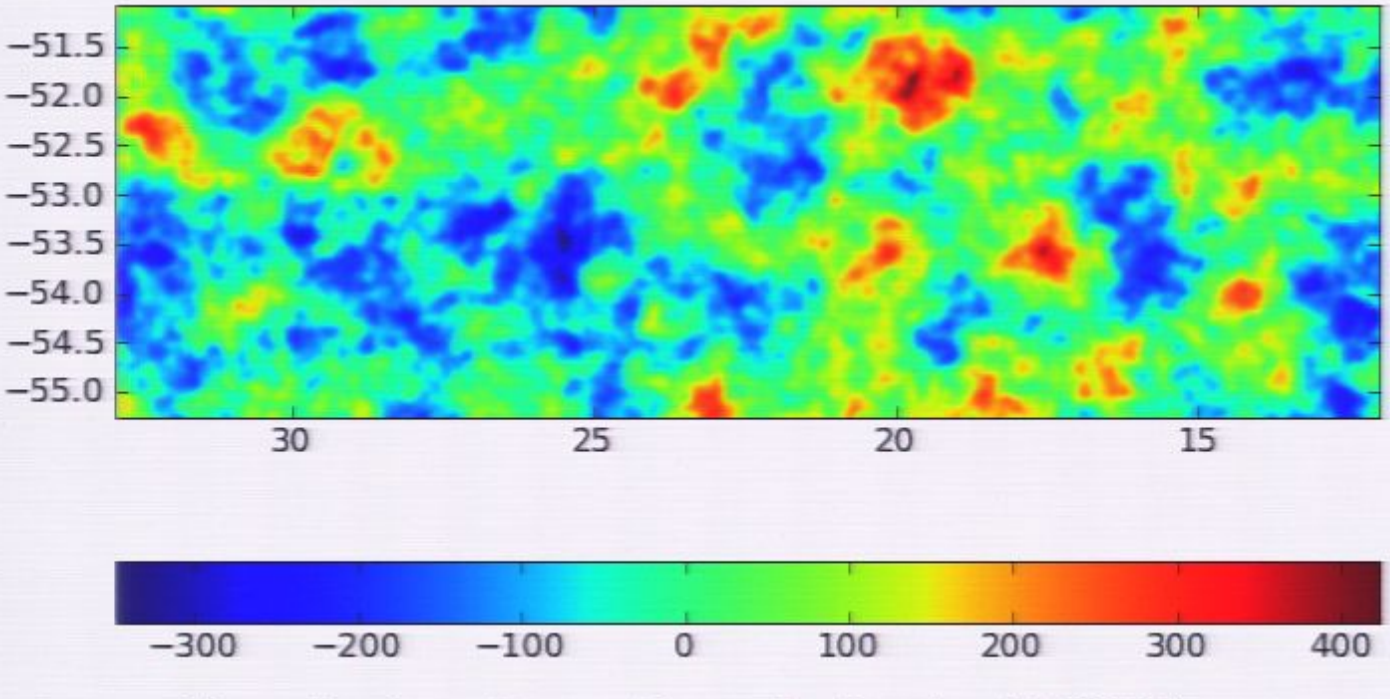

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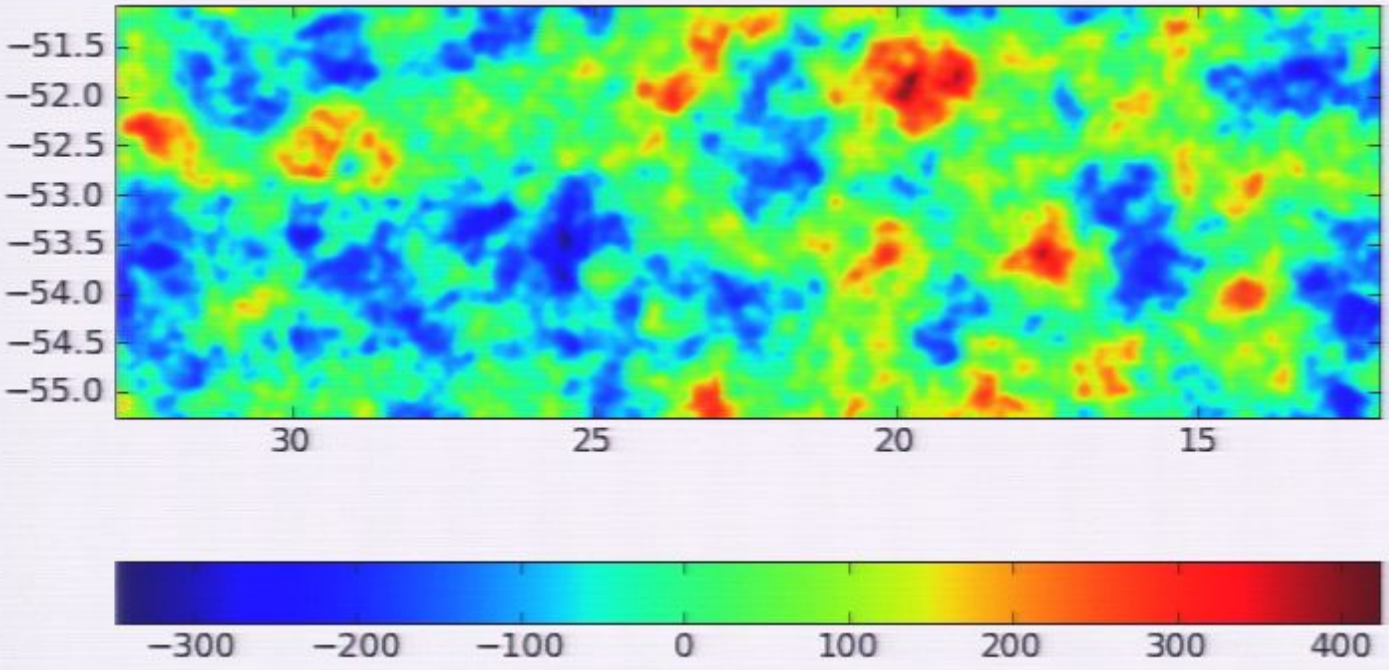

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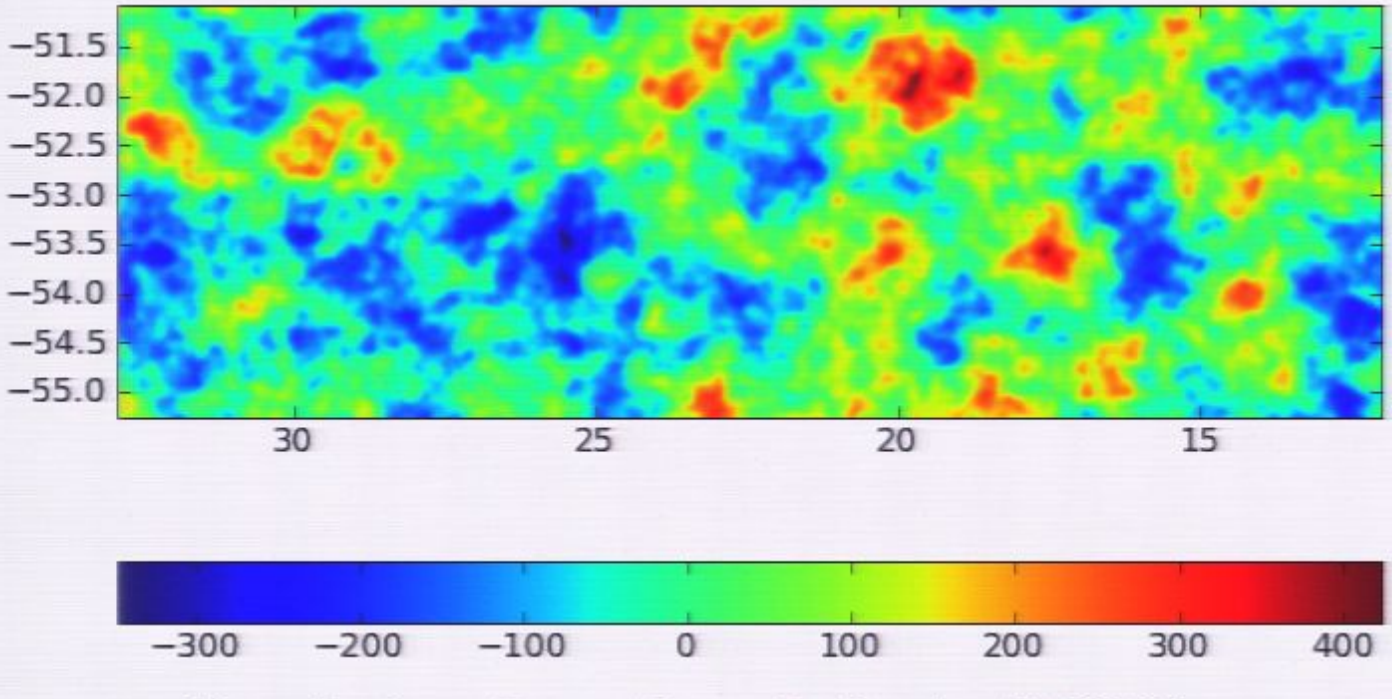

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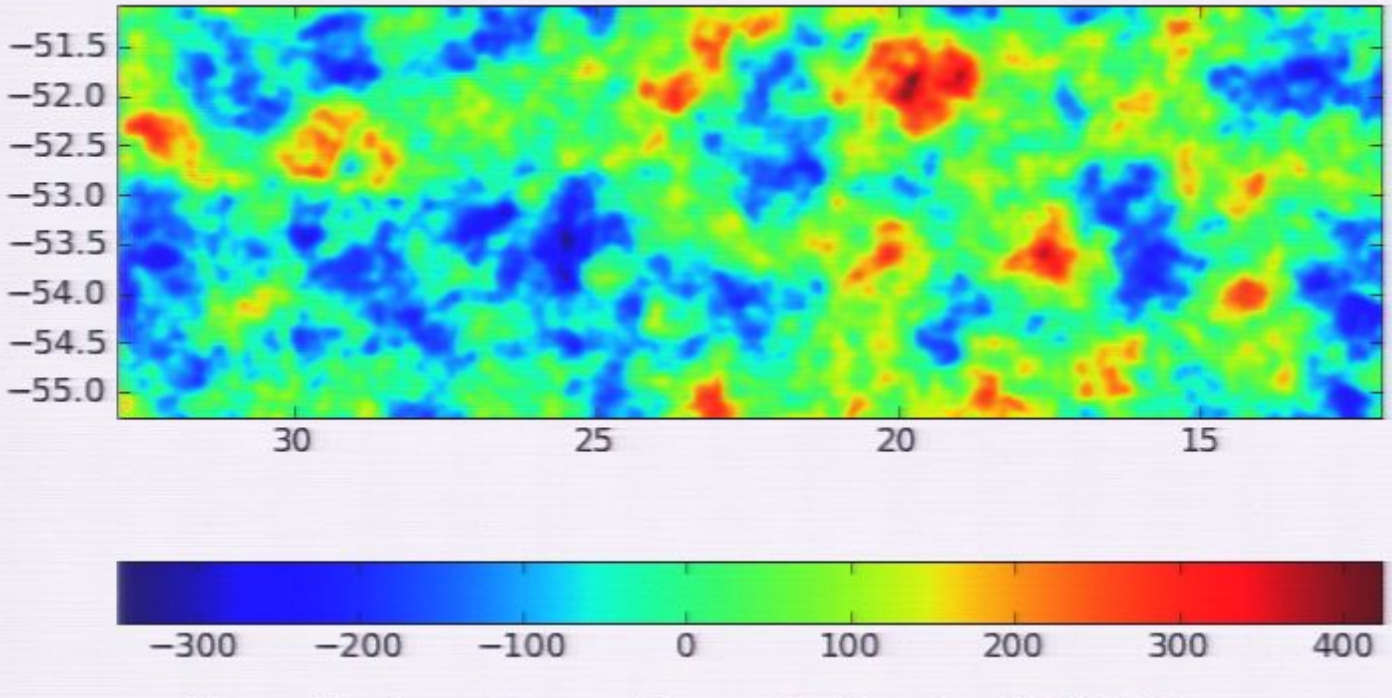

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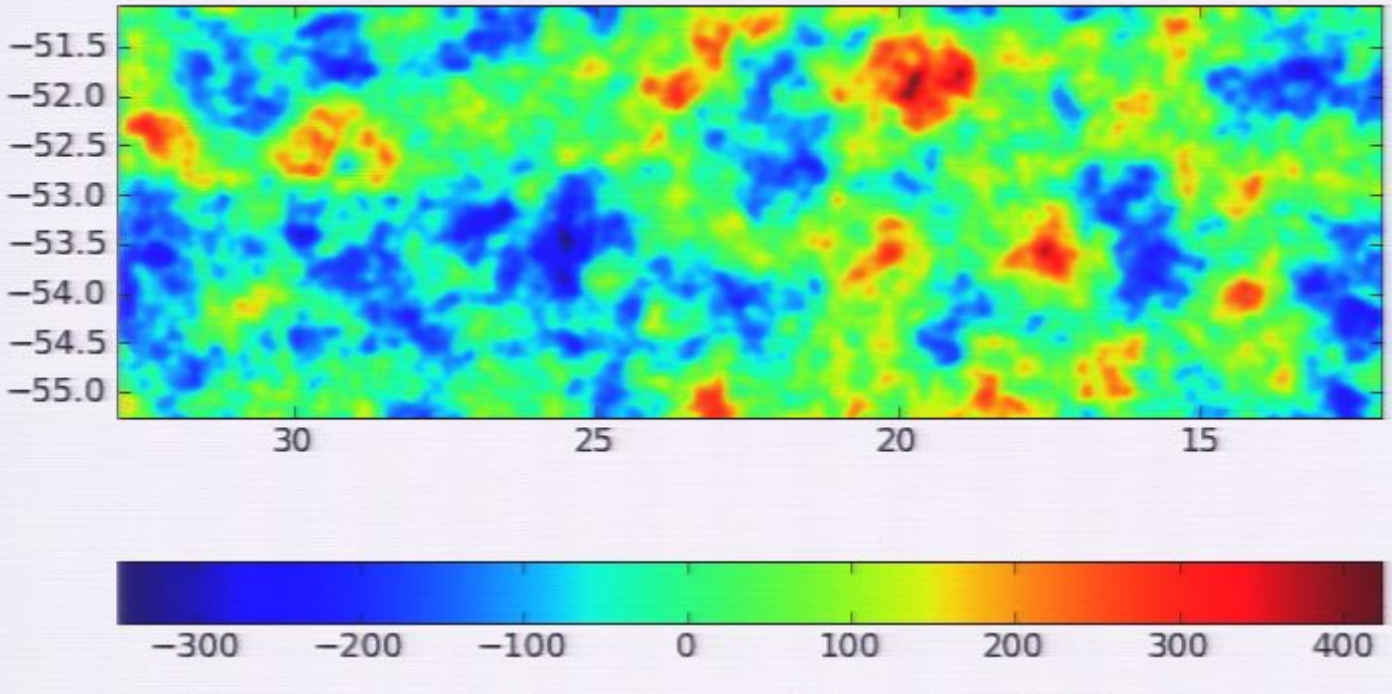

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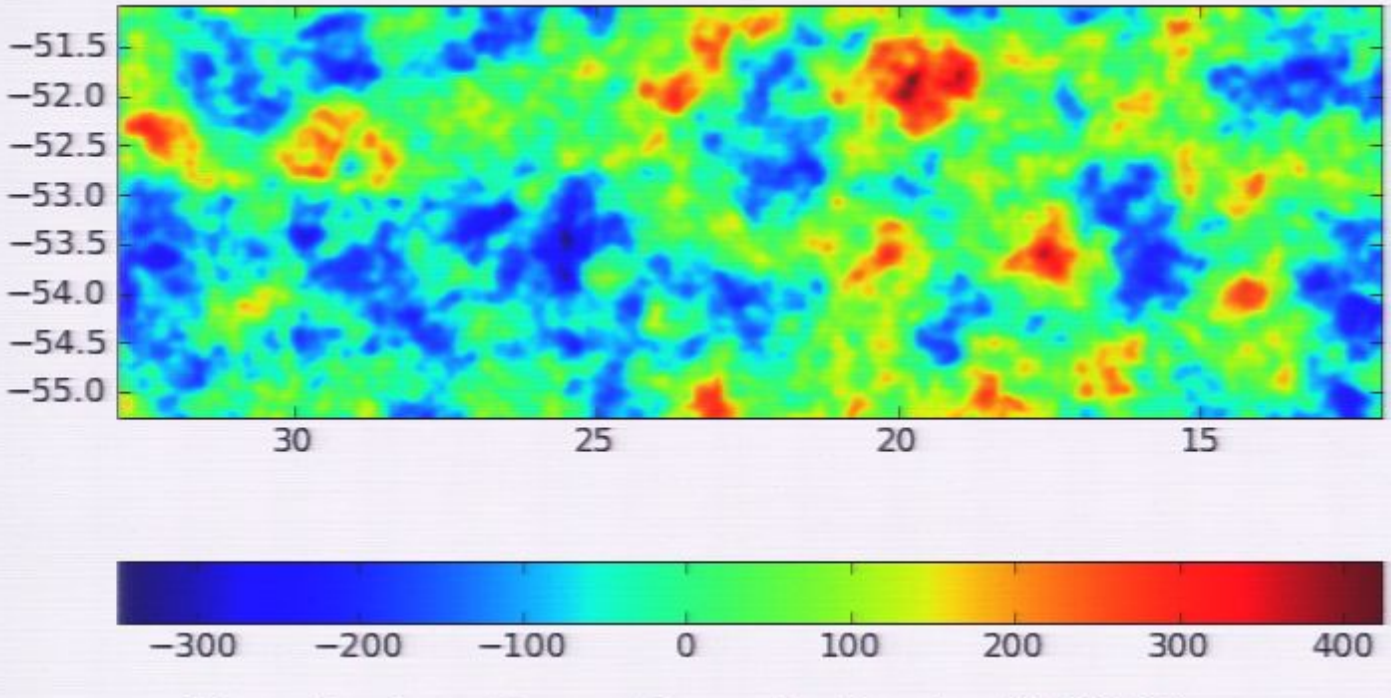

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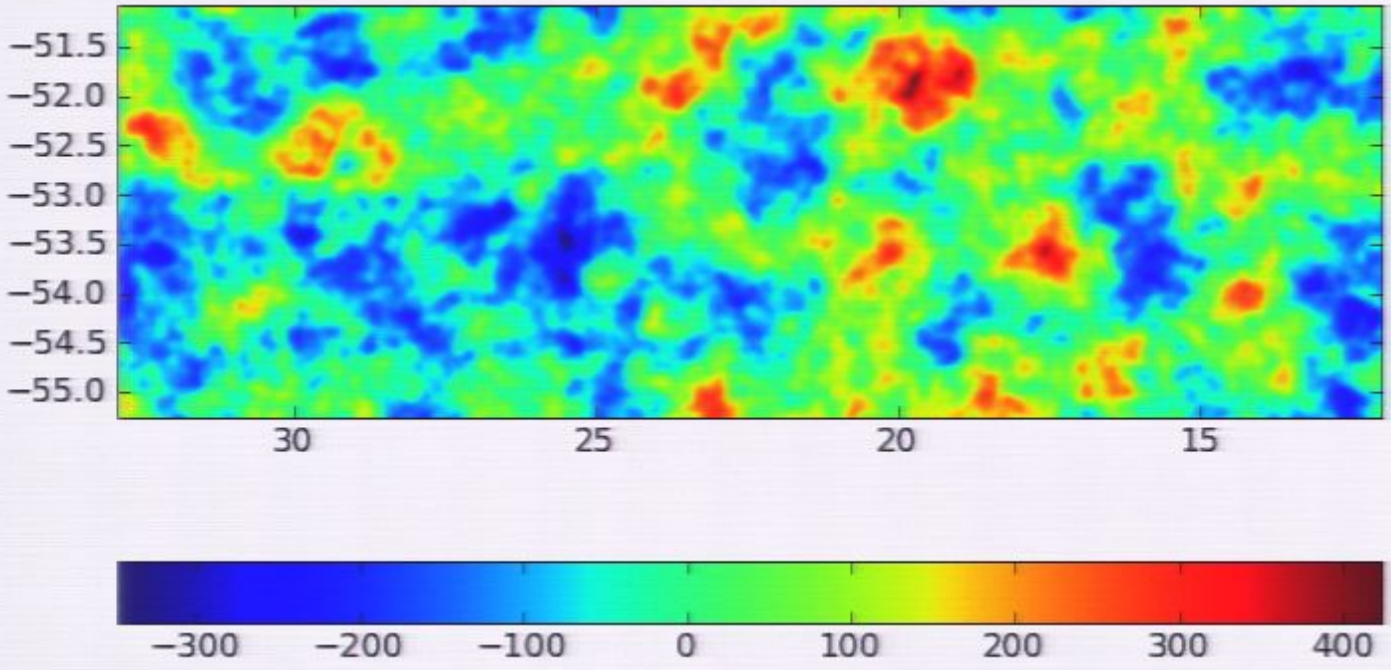

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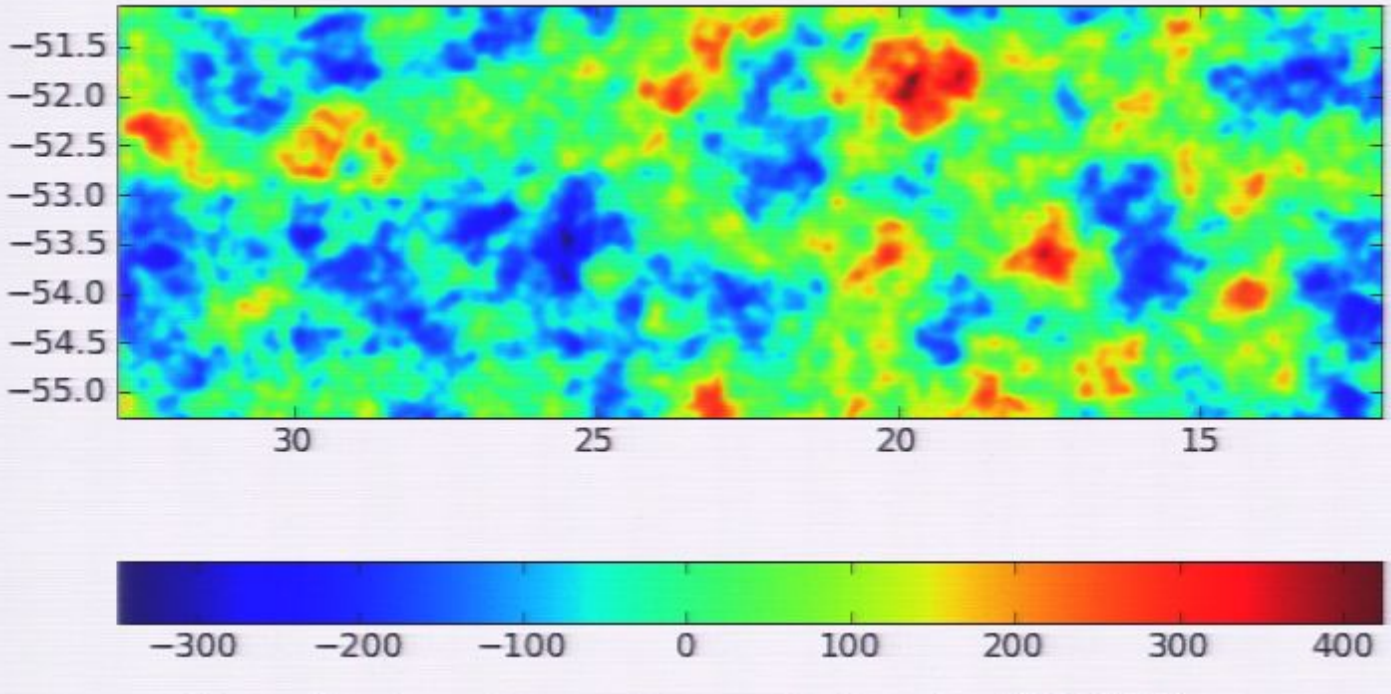

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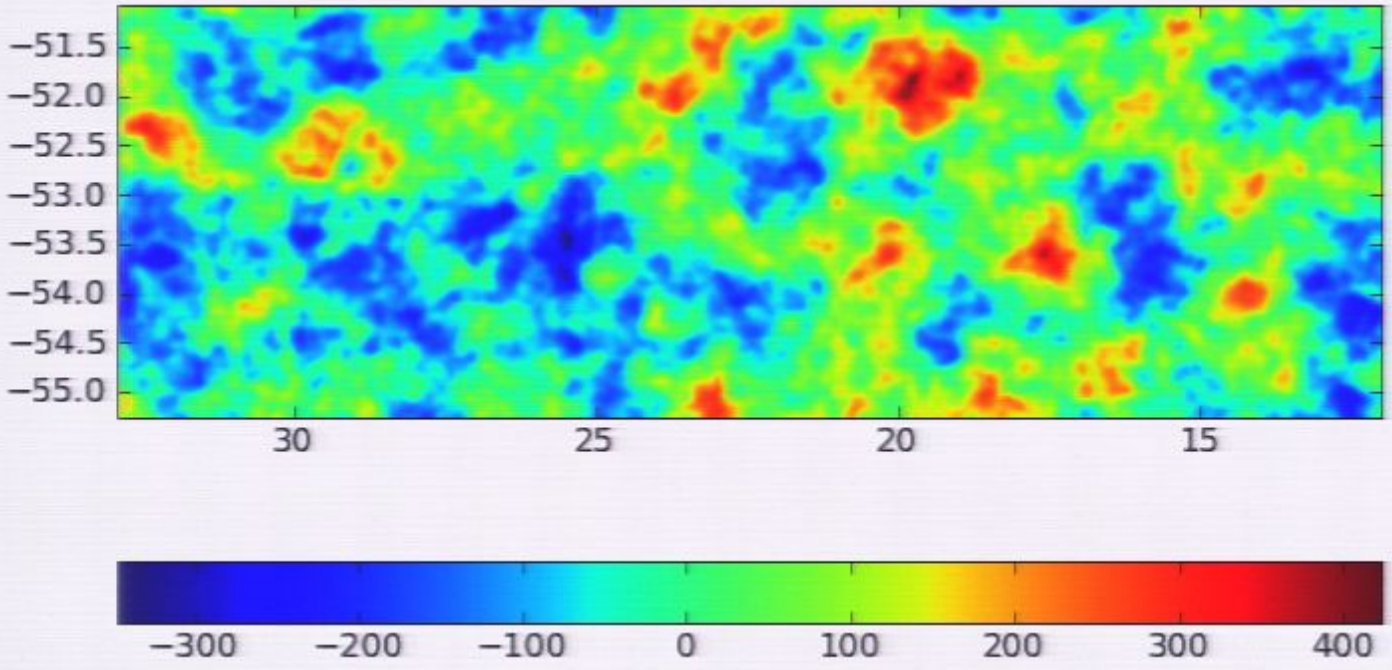

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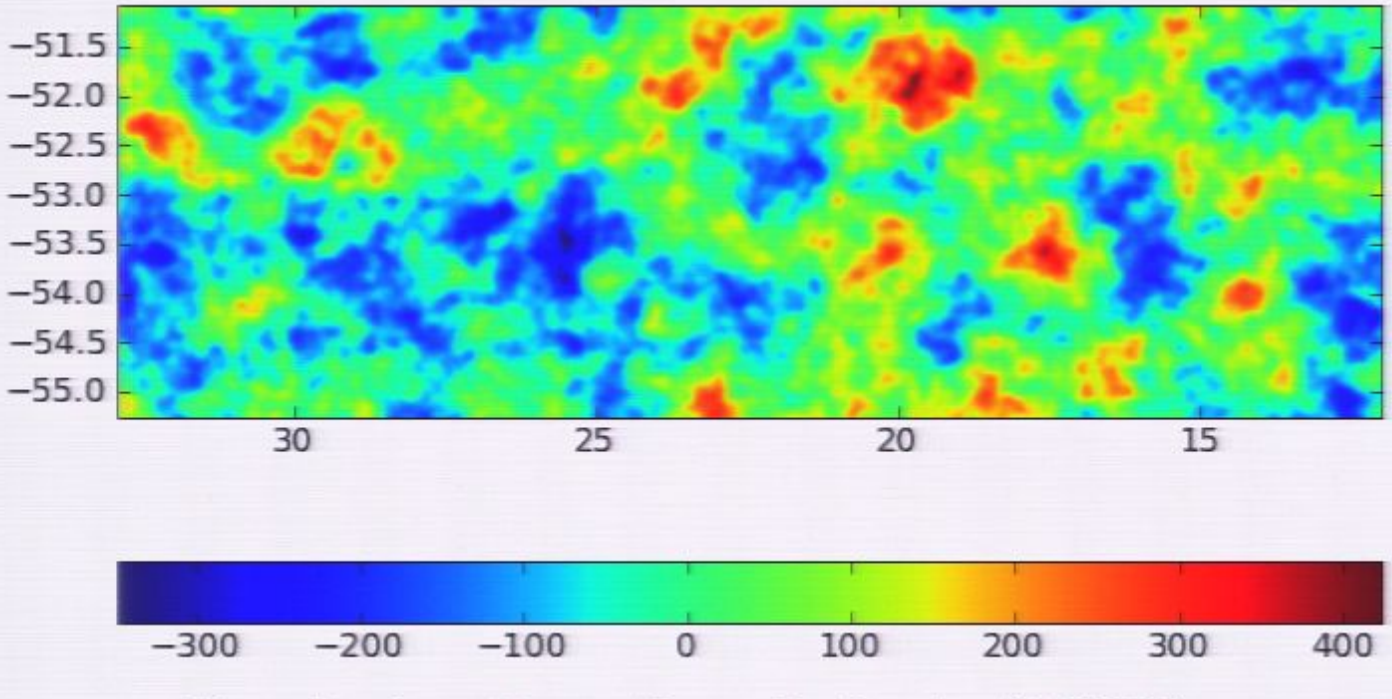

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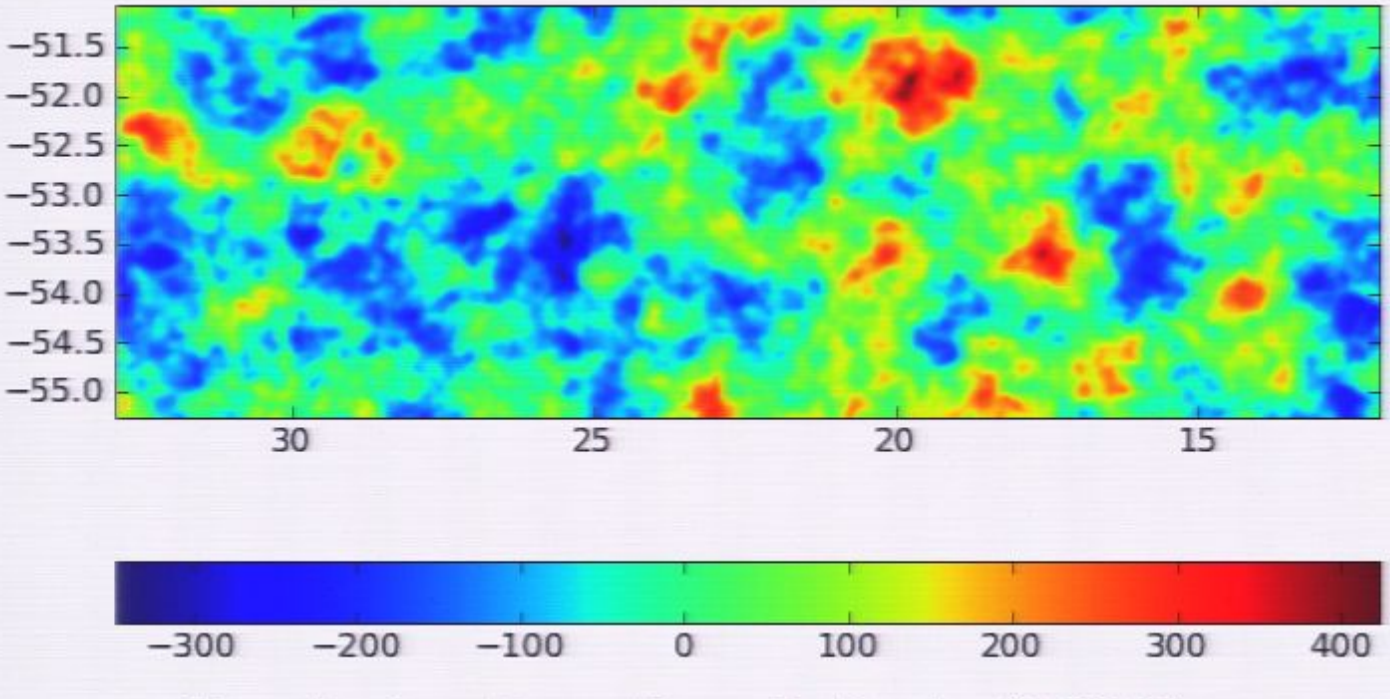

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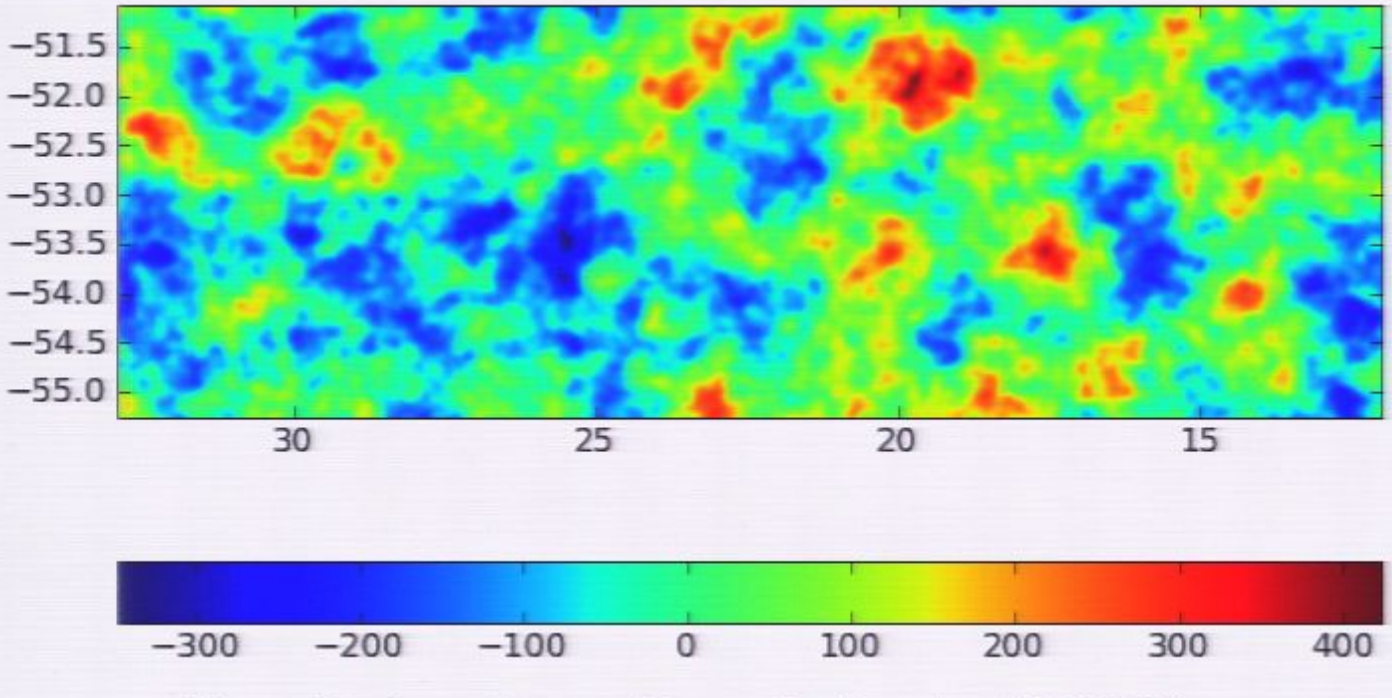

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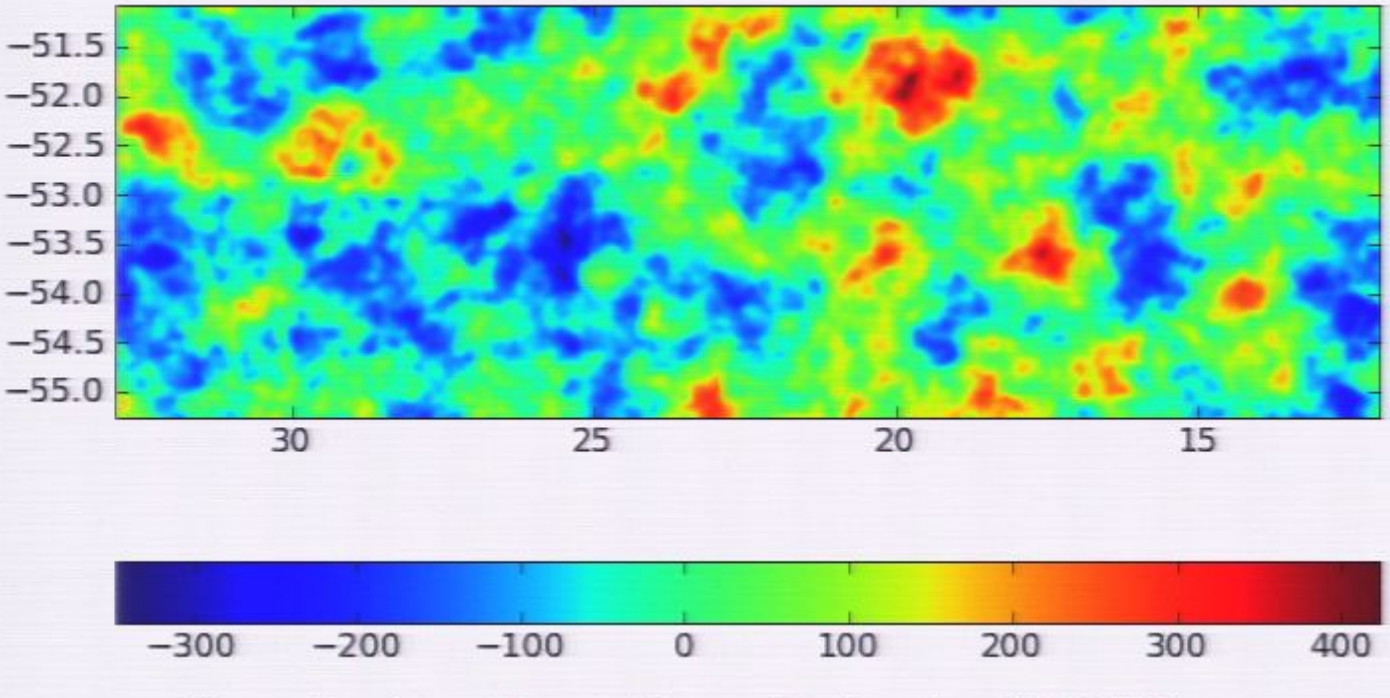

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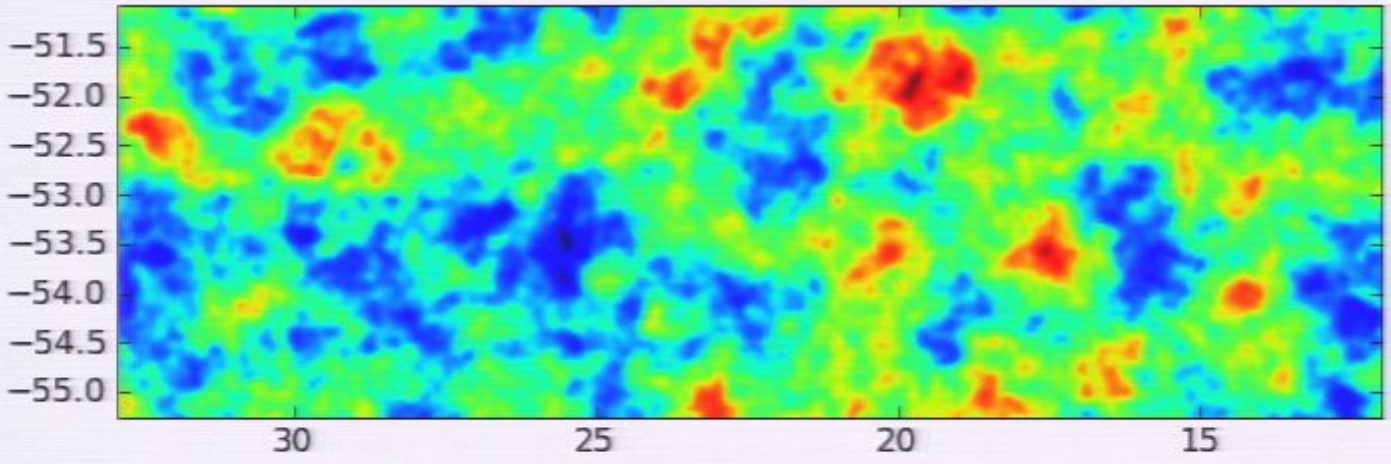

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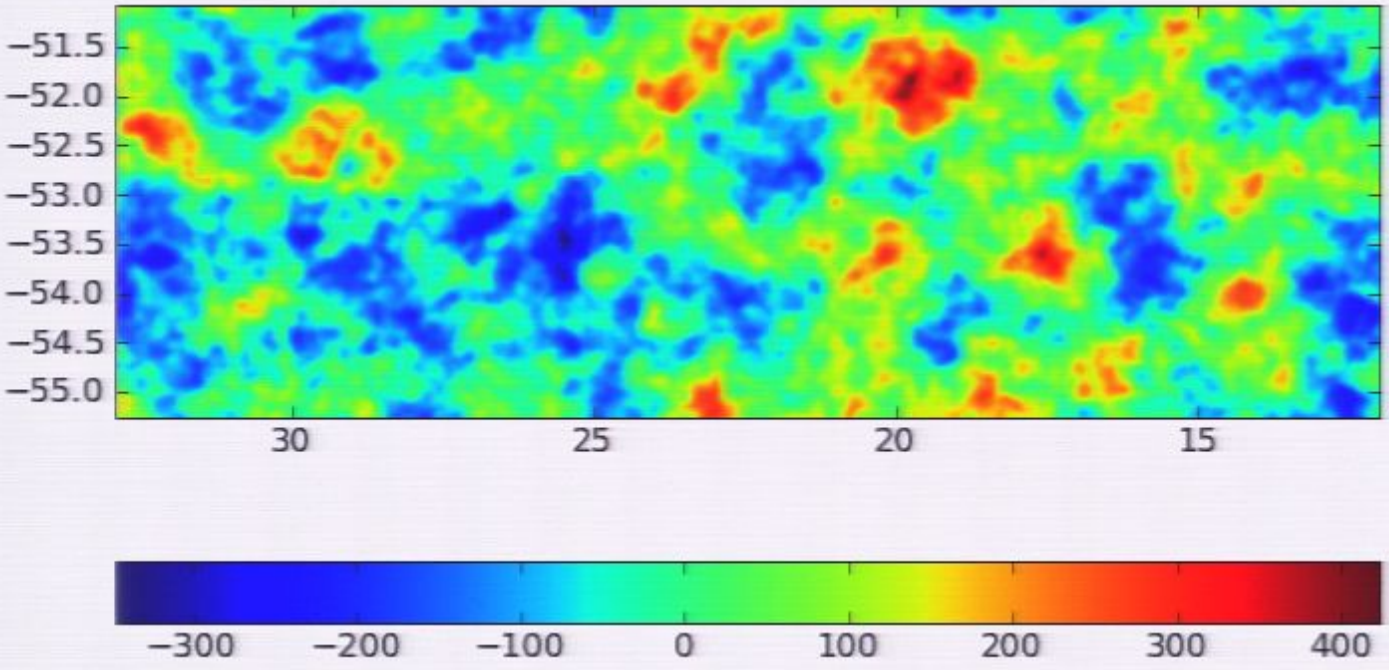

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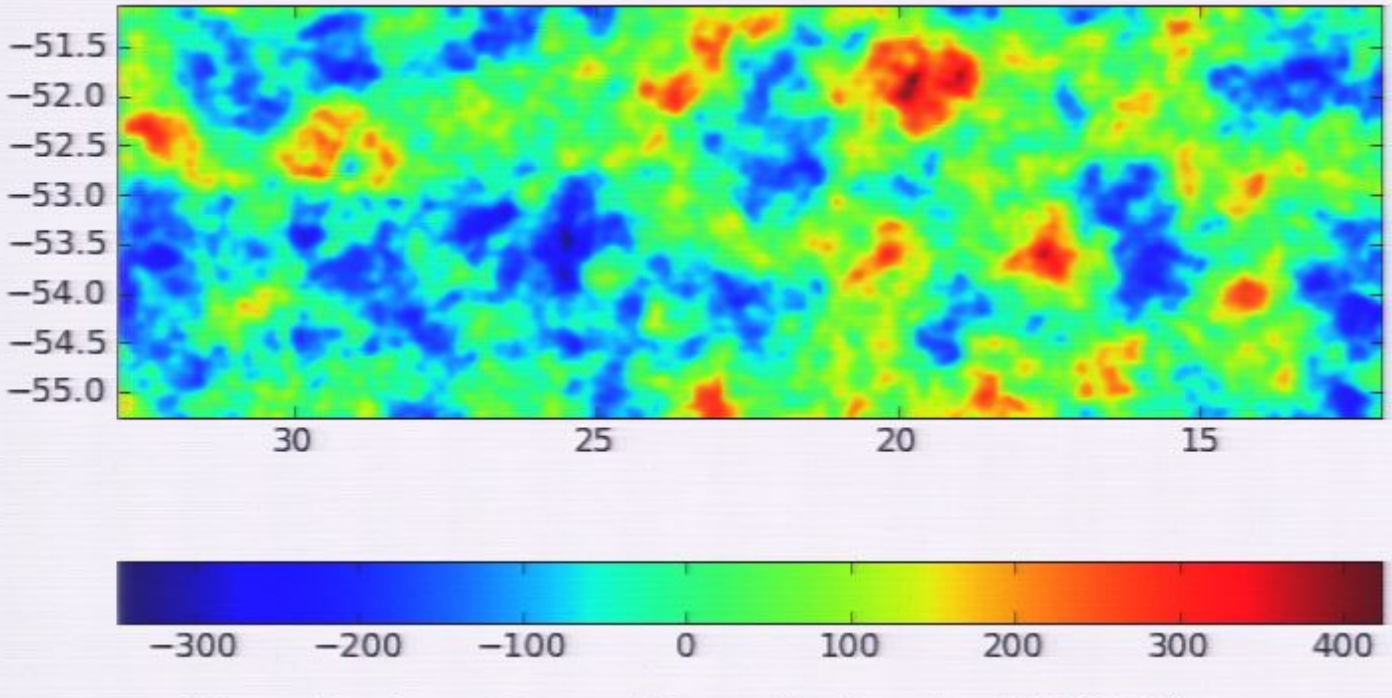

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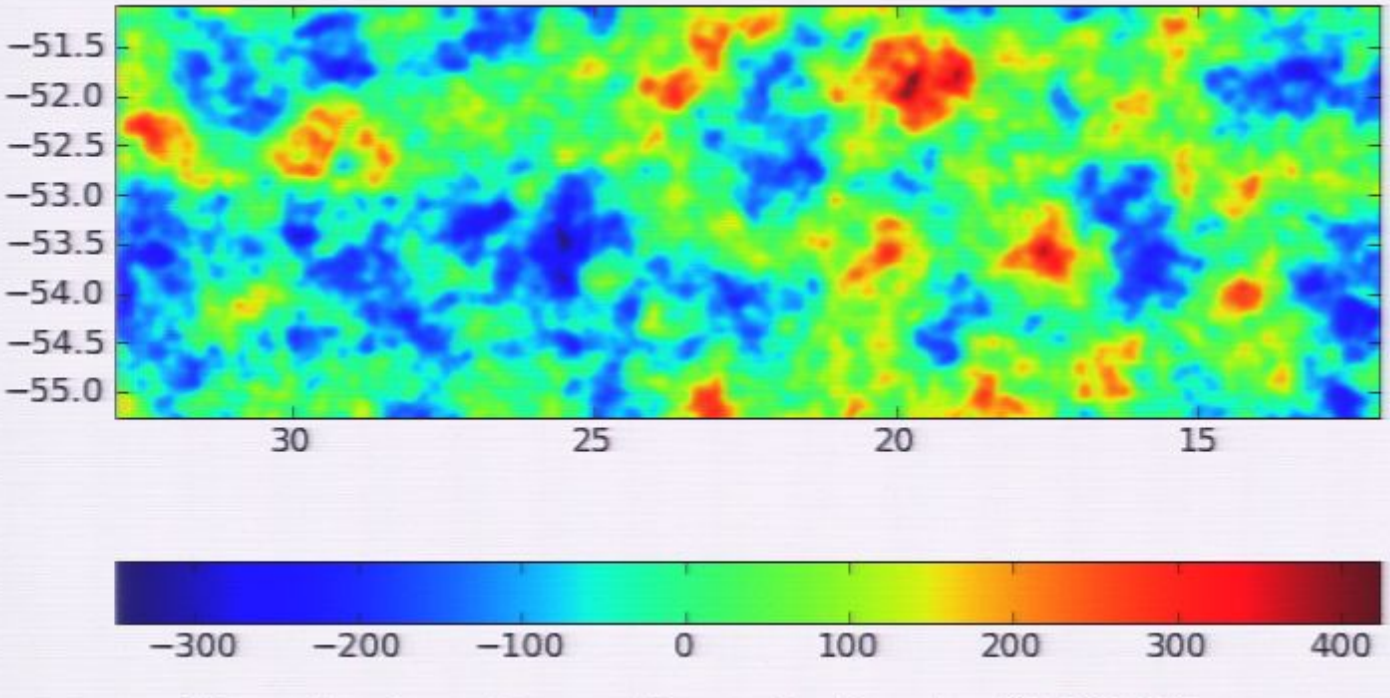

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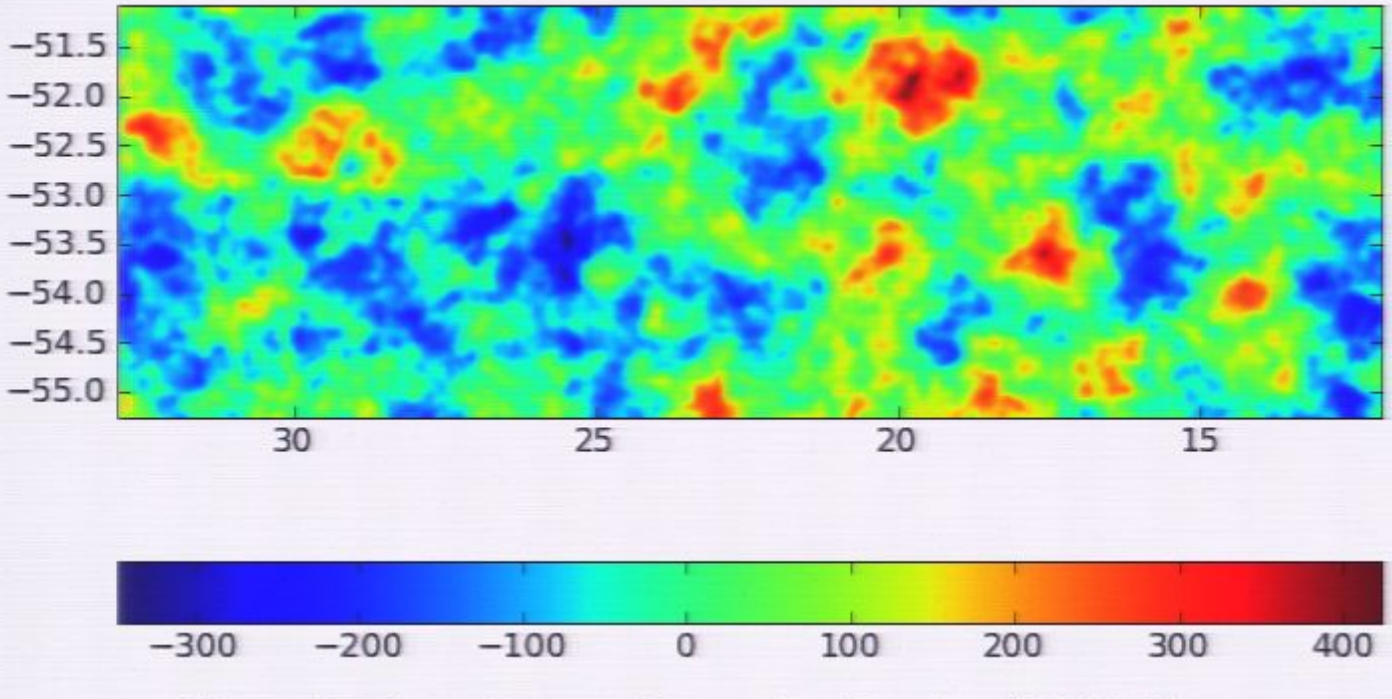

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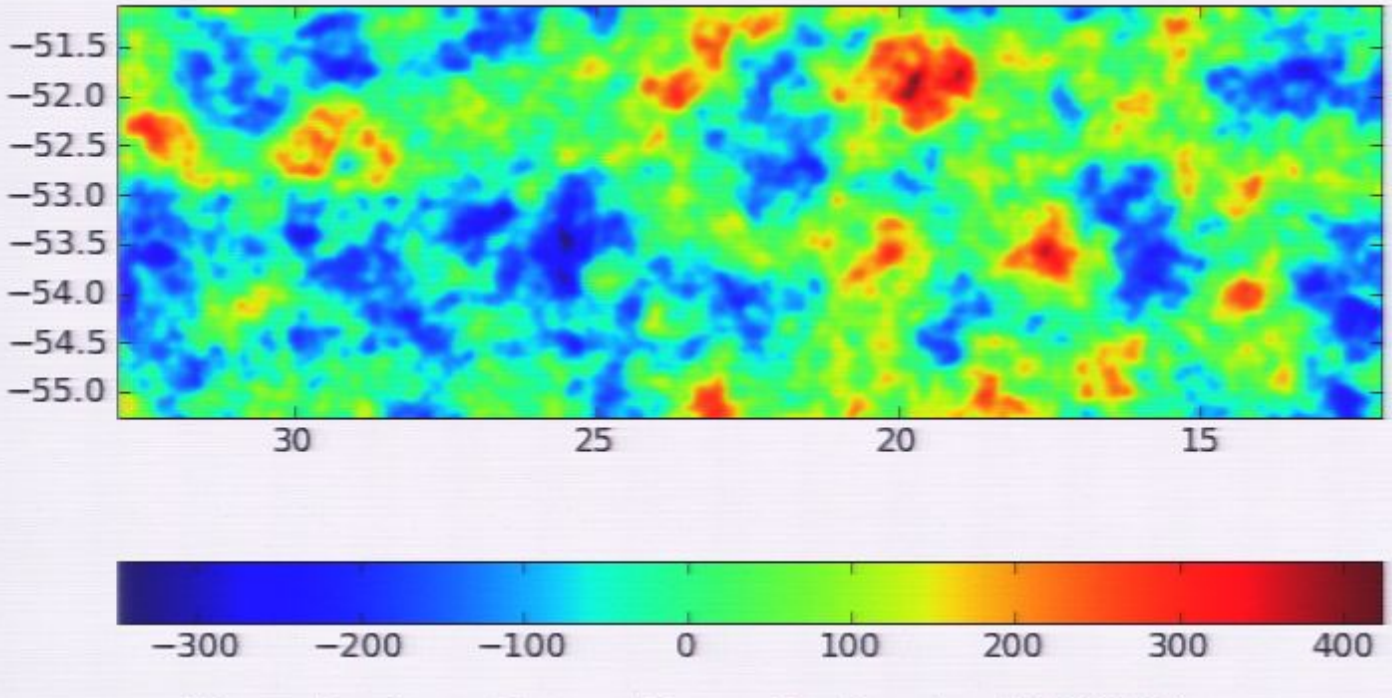

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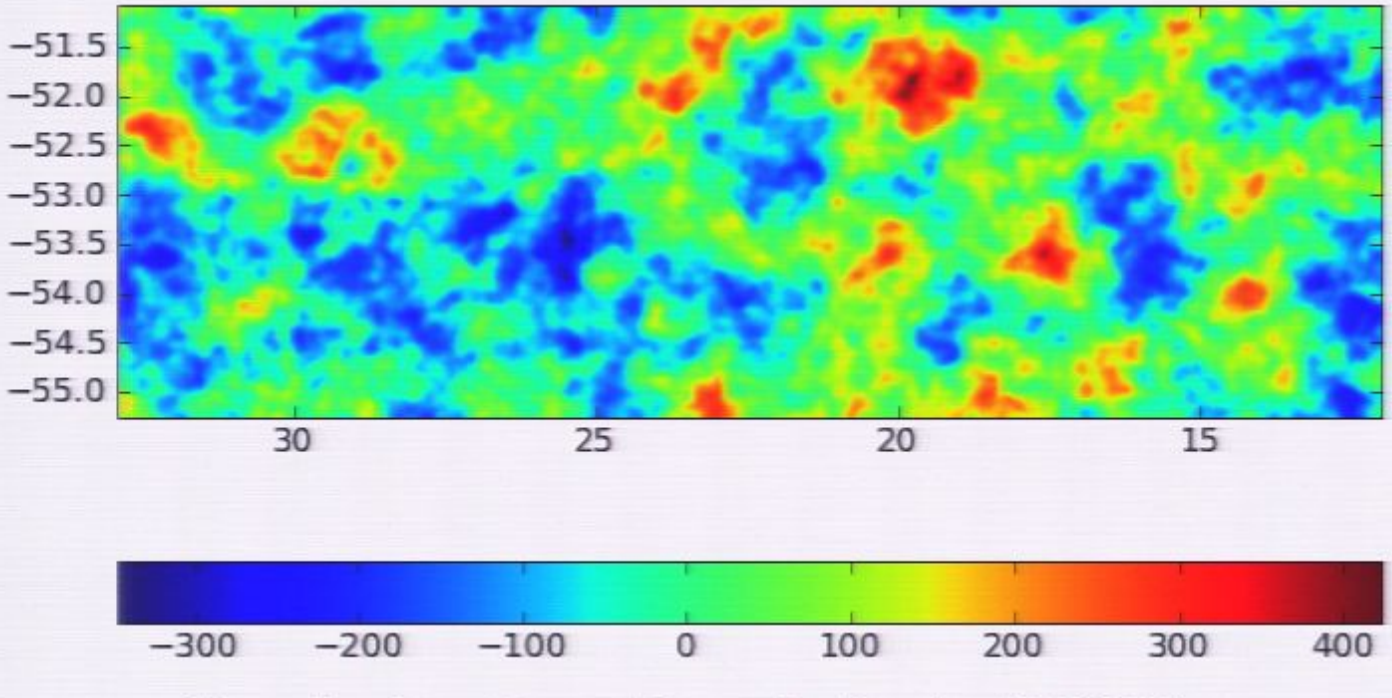

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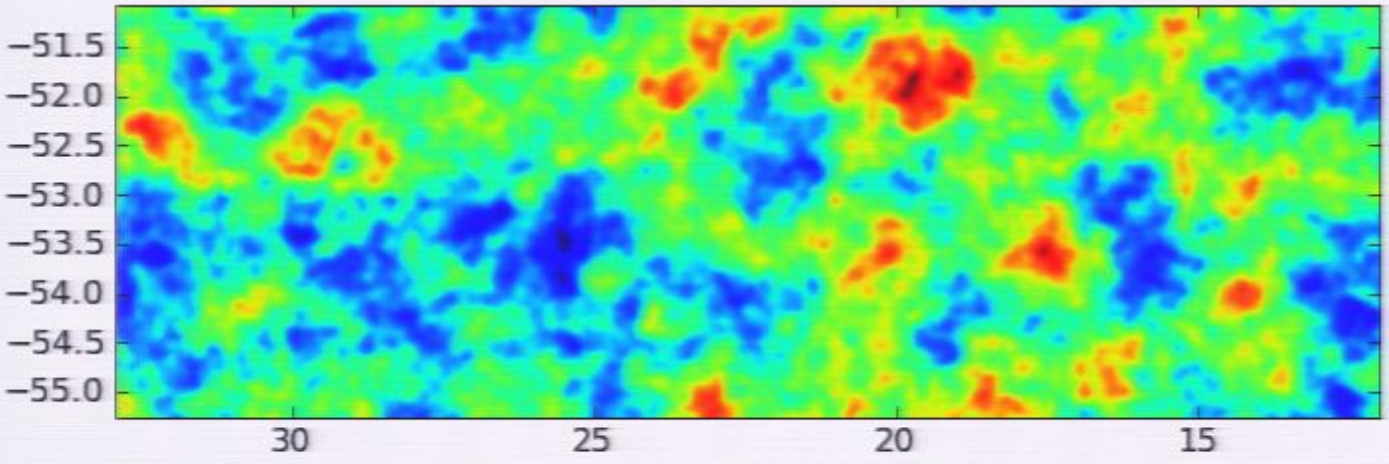

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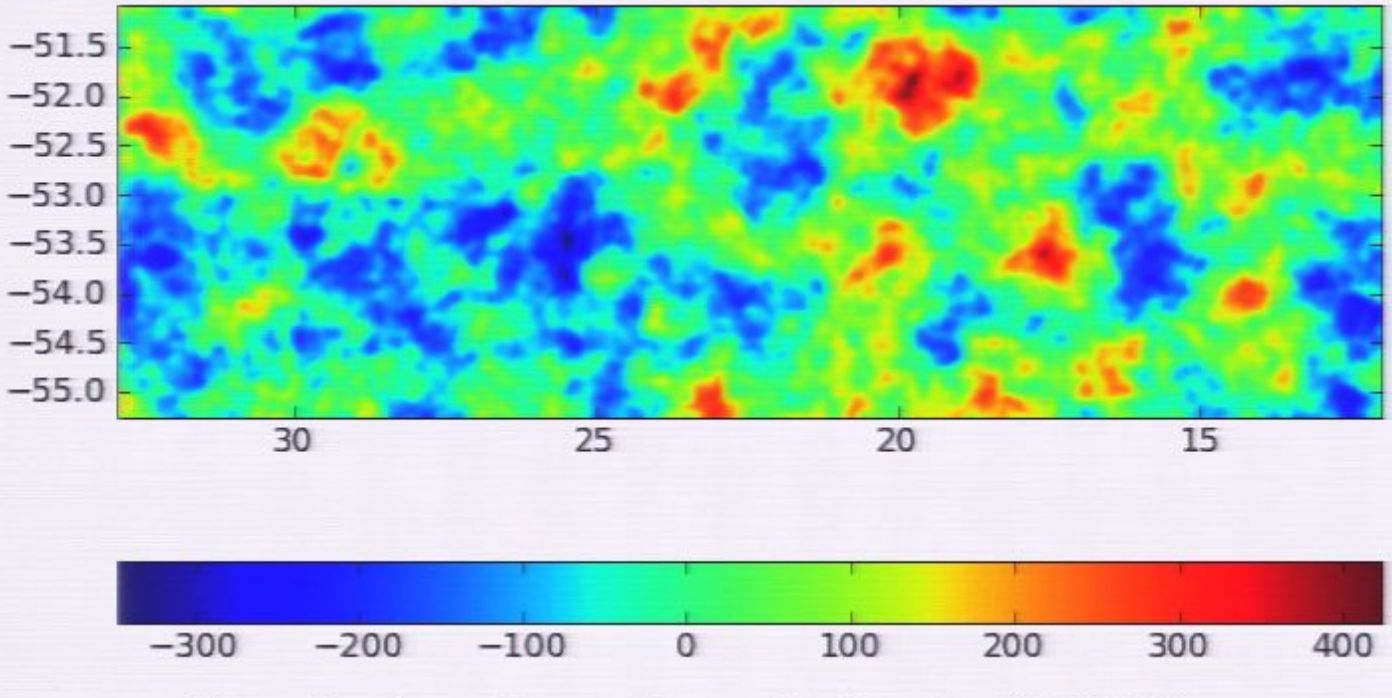

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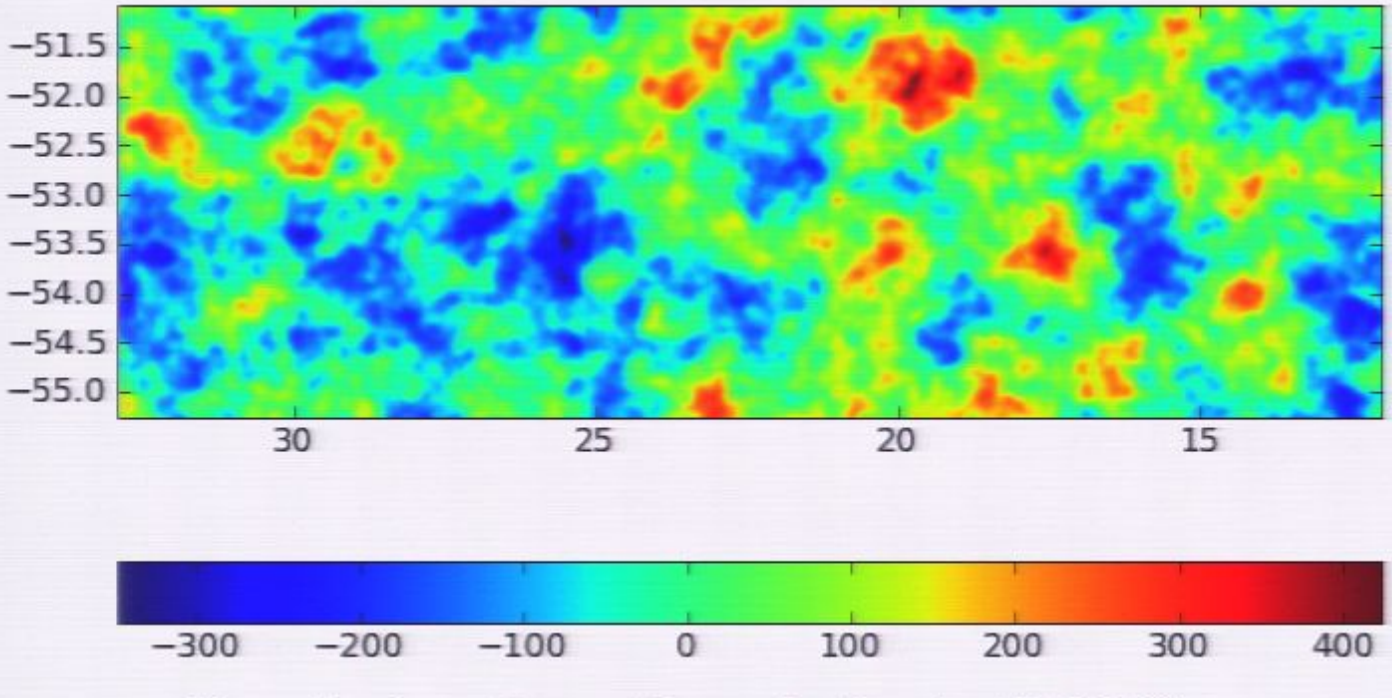

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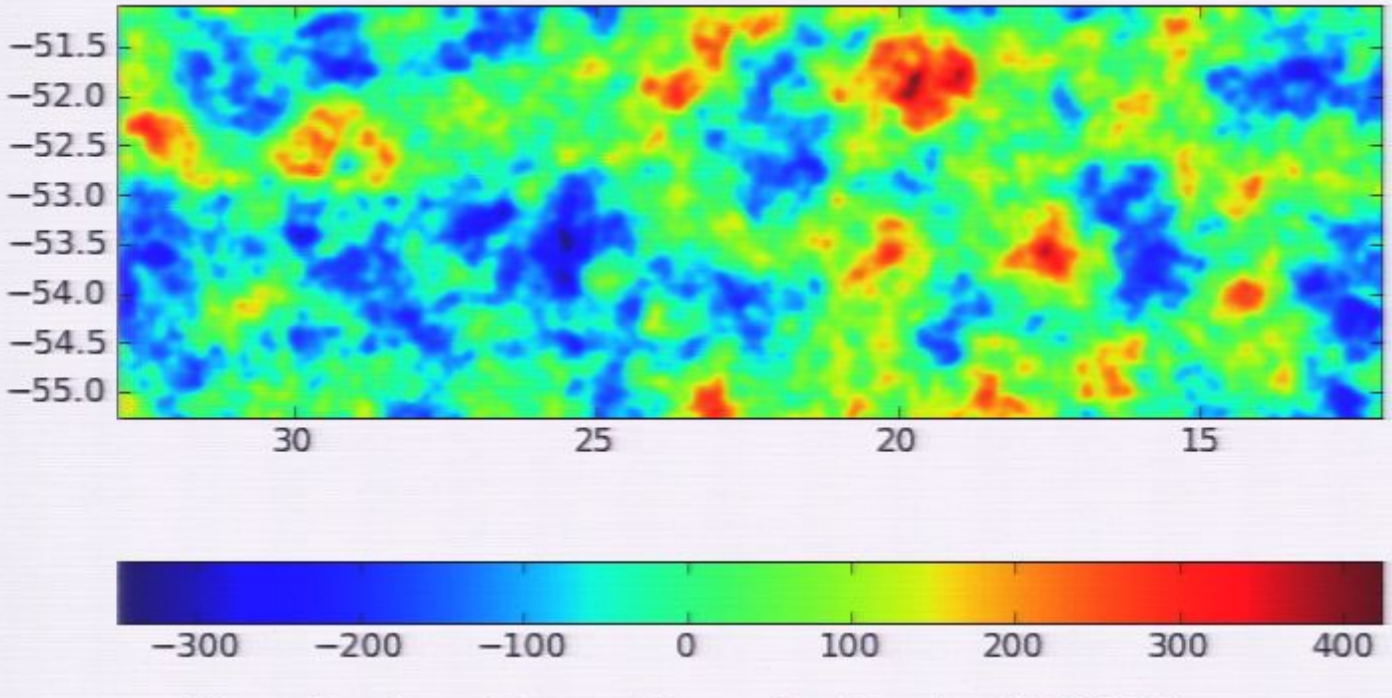

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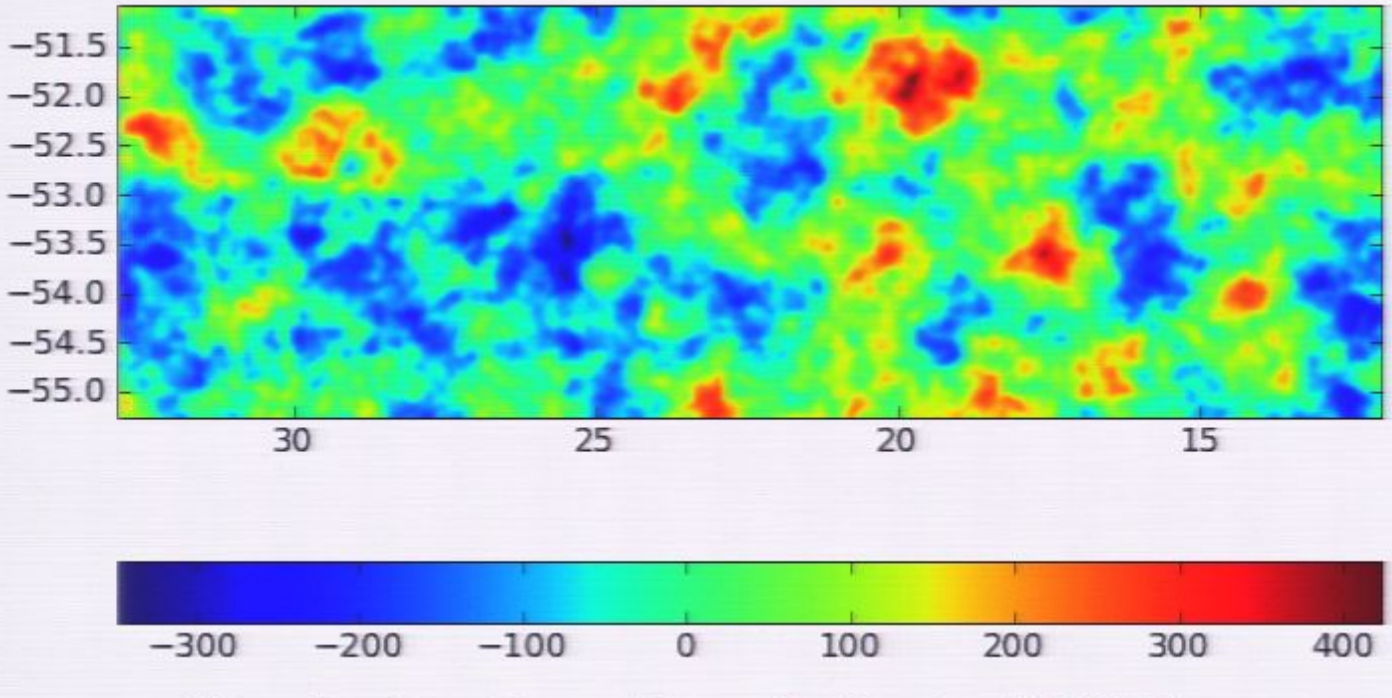

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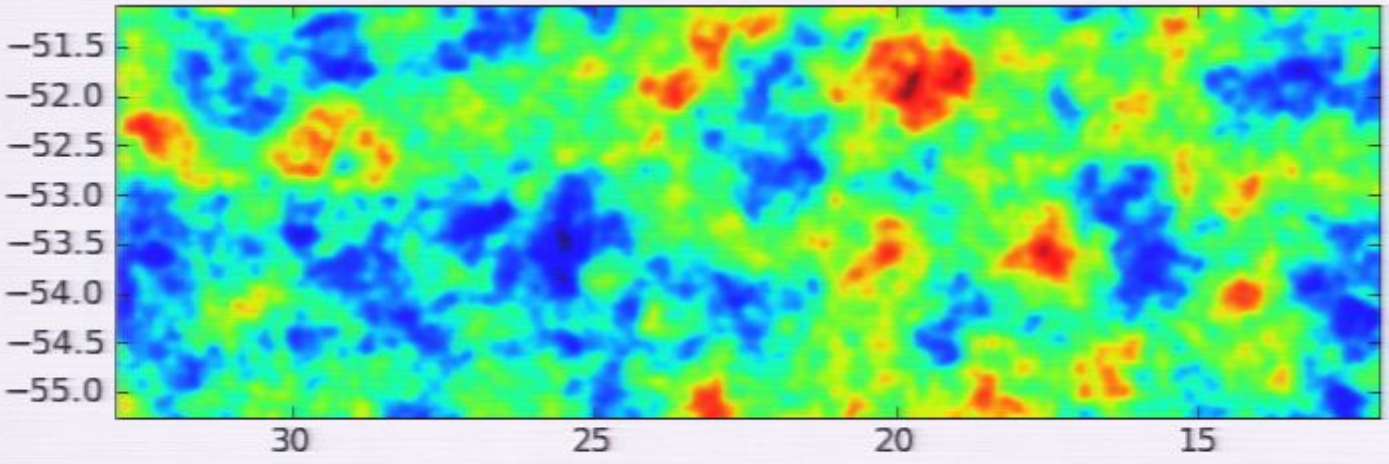

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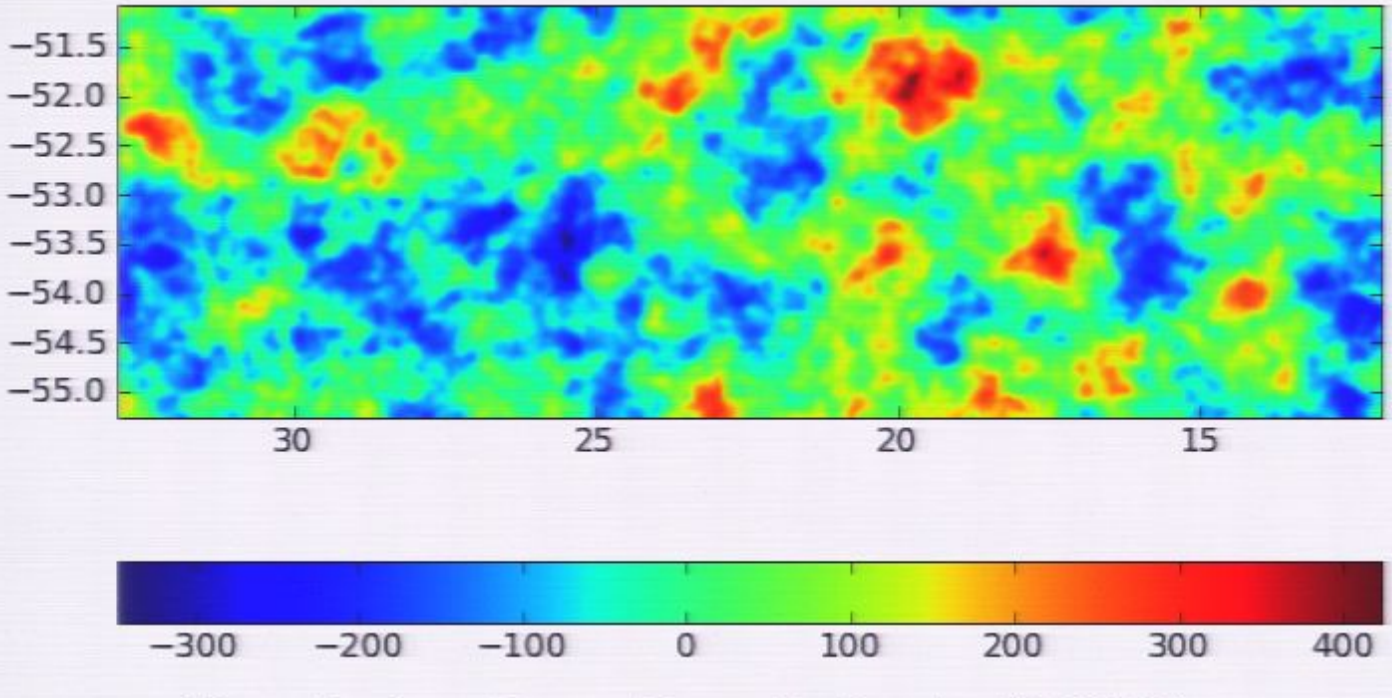
LENSING REMAPS & MAGNIFIES/DE-MAGNIFIES CMB PATCHES, SMOOTHING OUT PEAKS

$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \nabla\phi)$$

lensed unlensed deflection



Simulation from Das & Bode (2008)

Lens-speak:

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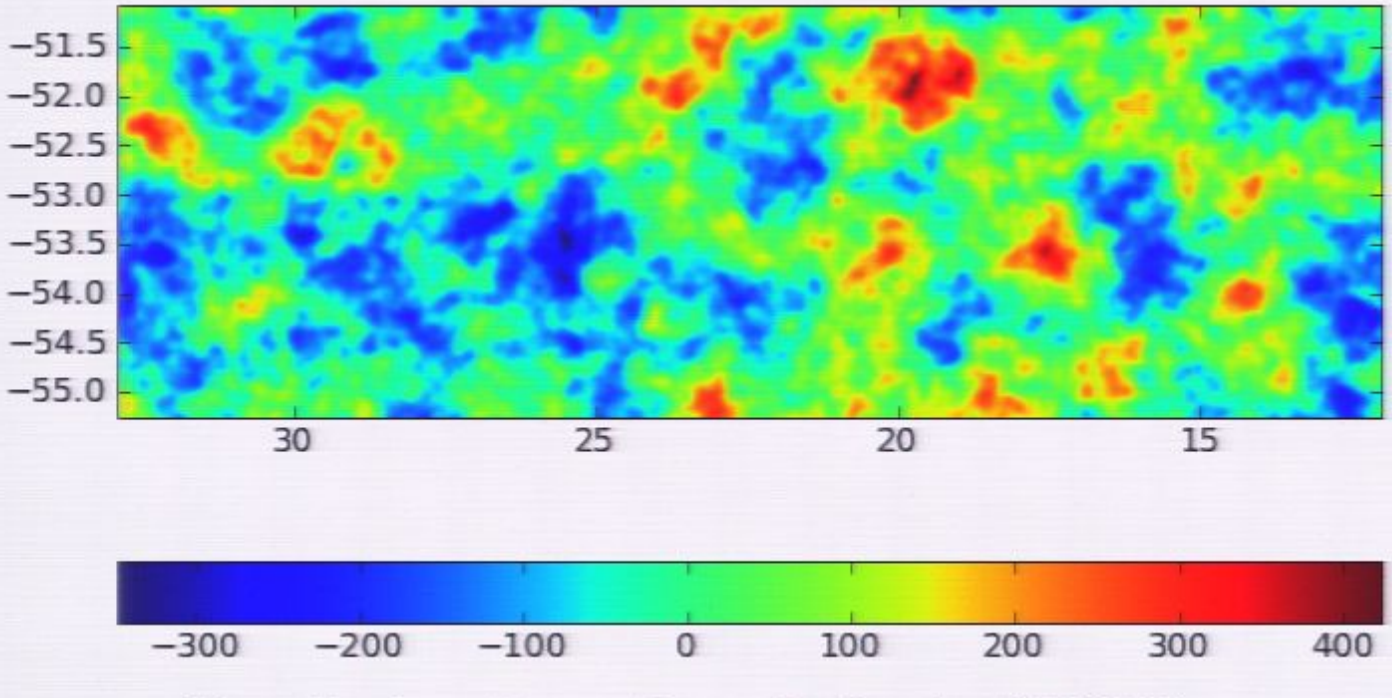

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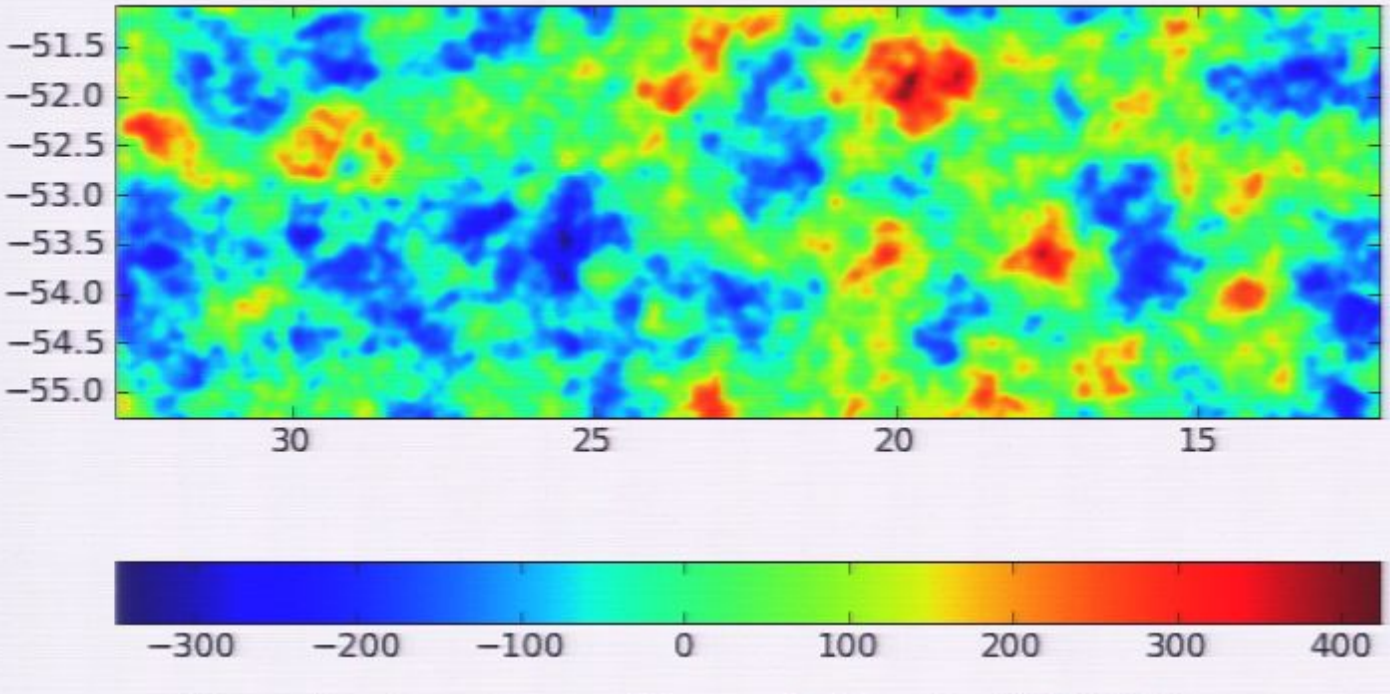

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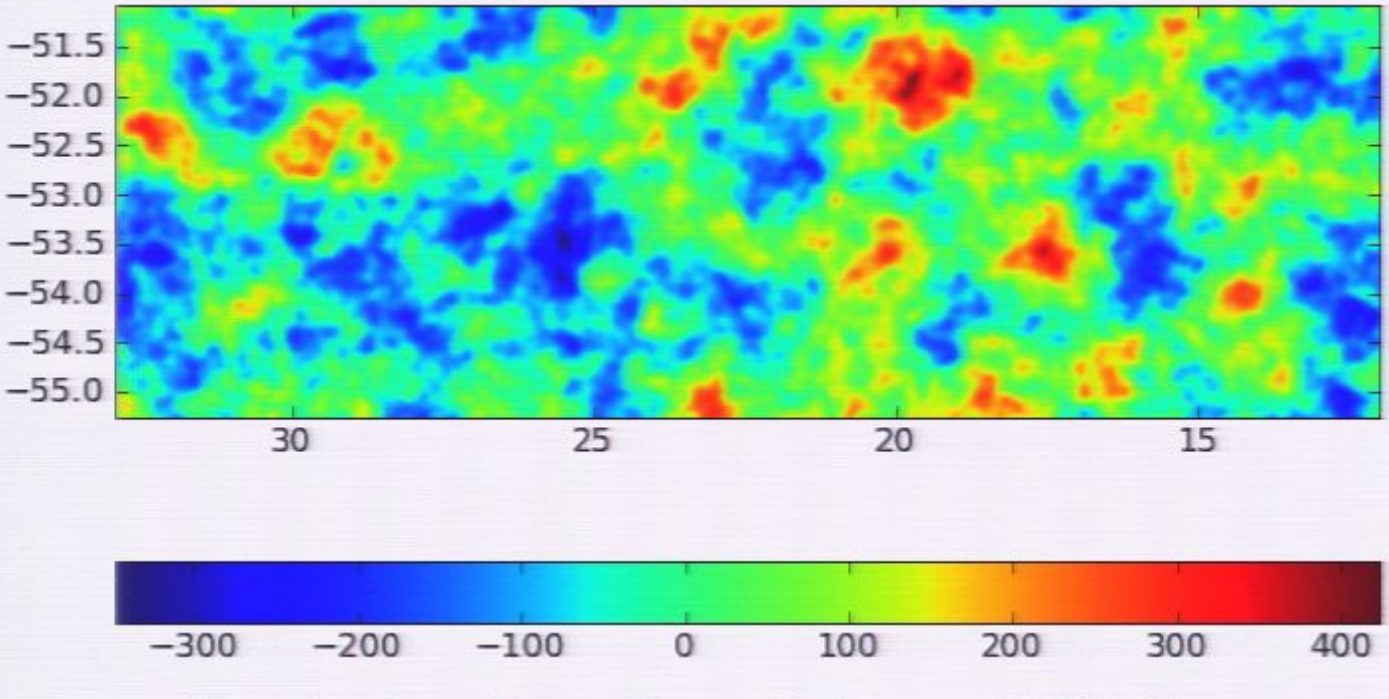

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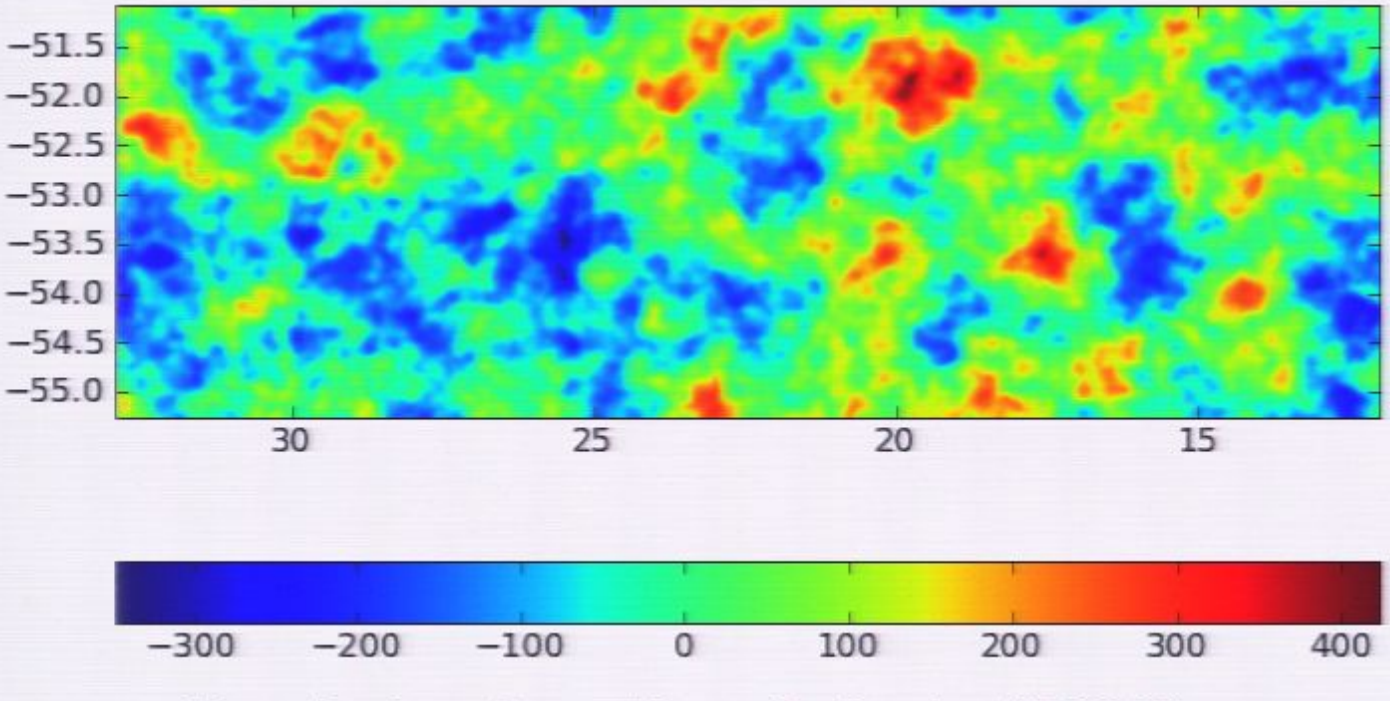

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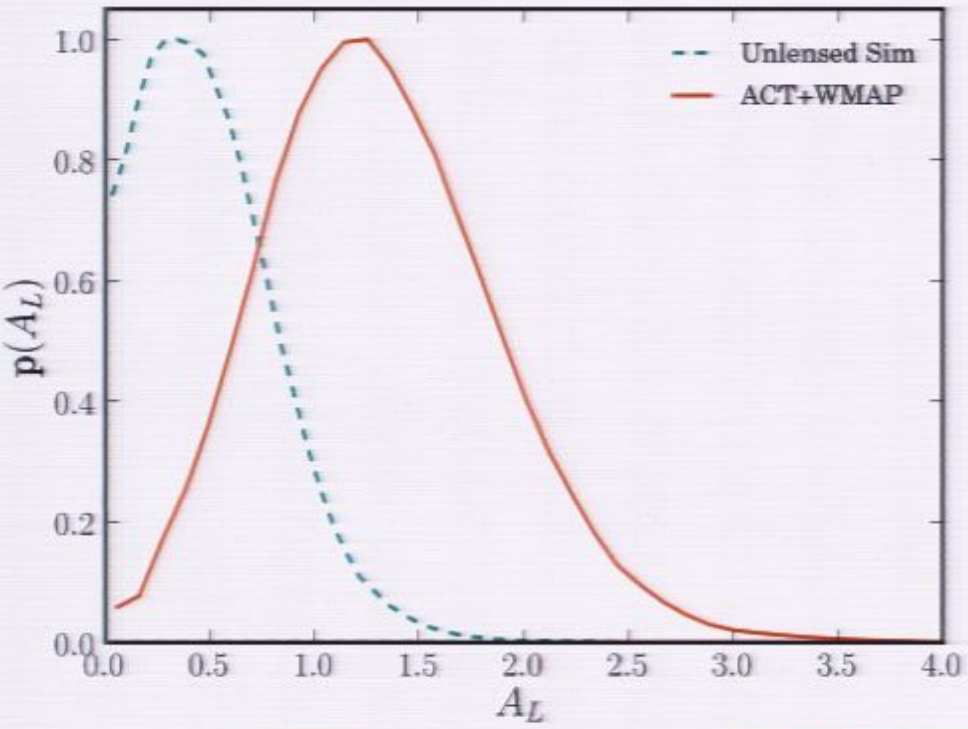
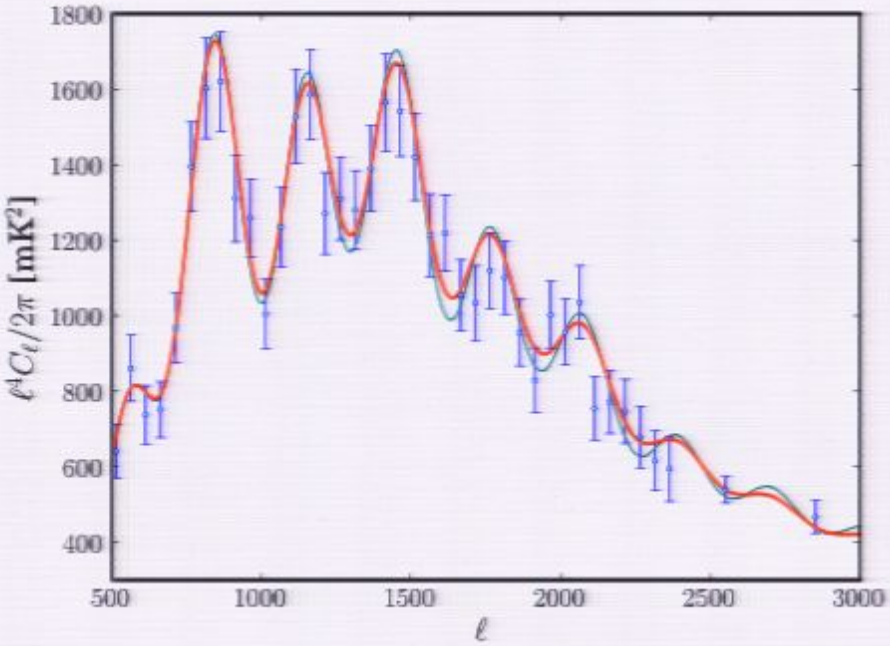
SMEARING OF ACOUSTIC PEAKS IN ACT'S SPECTRUM LETS US SEE LENSING AT ~ 3σ

Das et al. (2011), ApJ, in press

$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$





- Test for lensing in spectrum by marginalizing over (unphysical) parameter A_L, scaling lensing potential. [Calabrese et al 2008]

- Expect $A_L = 1$, and unlensed has $A_L = 0$. See lensing at almost 3σ level.

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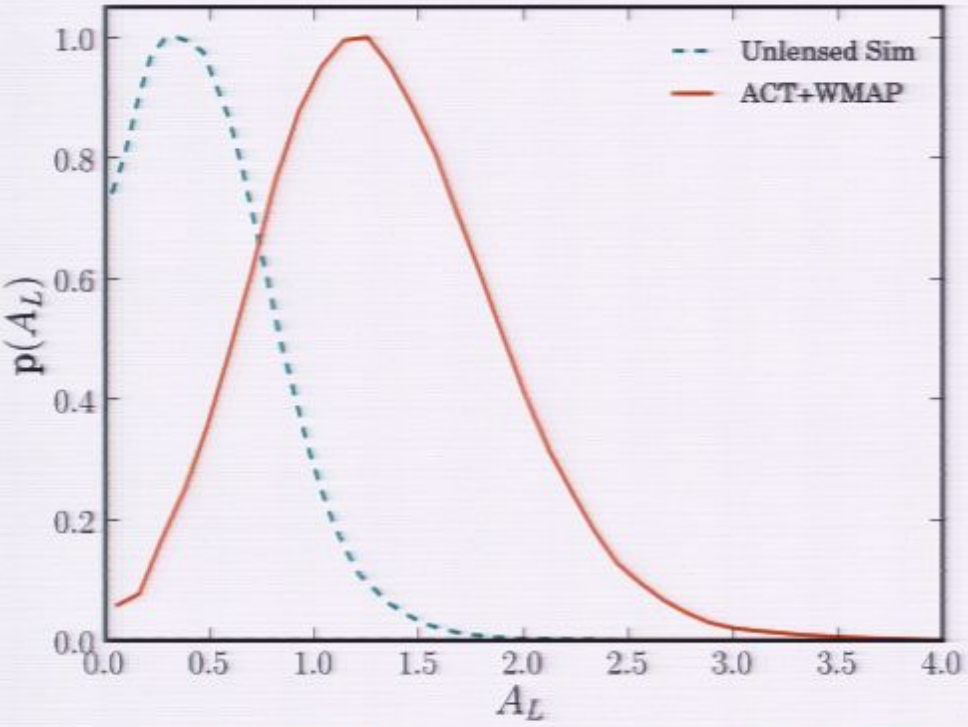

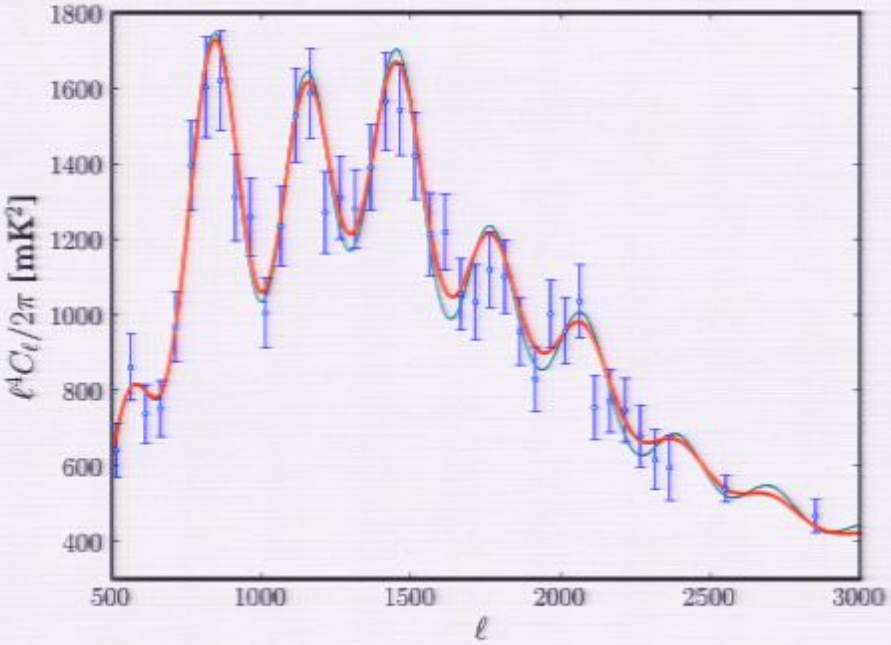

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LENSING MAKES THE CMB UNIQUELY SENSITIVE TO GEOMETRY AND STRUCTURE

CMB lensing can be fully described via the deflection field:

$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$

Lensed — Unlensed — Deflection Field

$$\phi = -2 \int \frac{d_A(\eta_0 - \eta)}{d_A(\eta) d_A(\eta_0)} \Phi(\eta\hat{n}, \eta)$$

Effective Lensing Potential — Geometry — Matter potential

Affected by parameters that affect distance scales and growth of structure in the late universe.

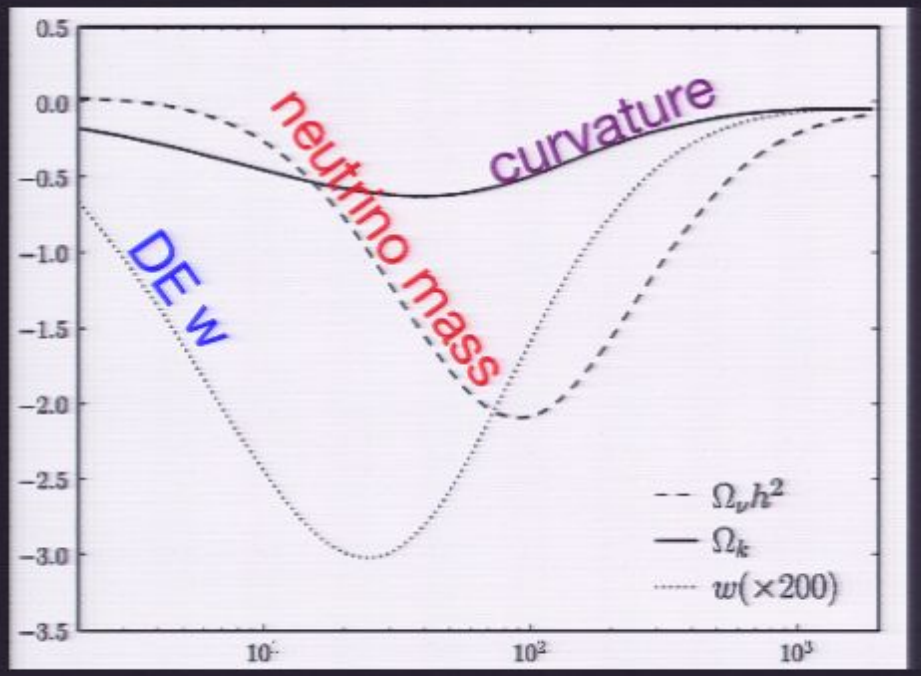
For high z lenses (clusters, galaxies) CMB is the only source !

LENSING MAKES THE CMB UNIQUELY SENSITIVE TO GEOMETRY AND STRUCTURE

The primary CMB can be kept nearly unchanged under variations of neutrino mass, dark energy equation of state or curvature. But the deflection field cares about these:

Lensing breaks the angular diameter distance degeneracy!

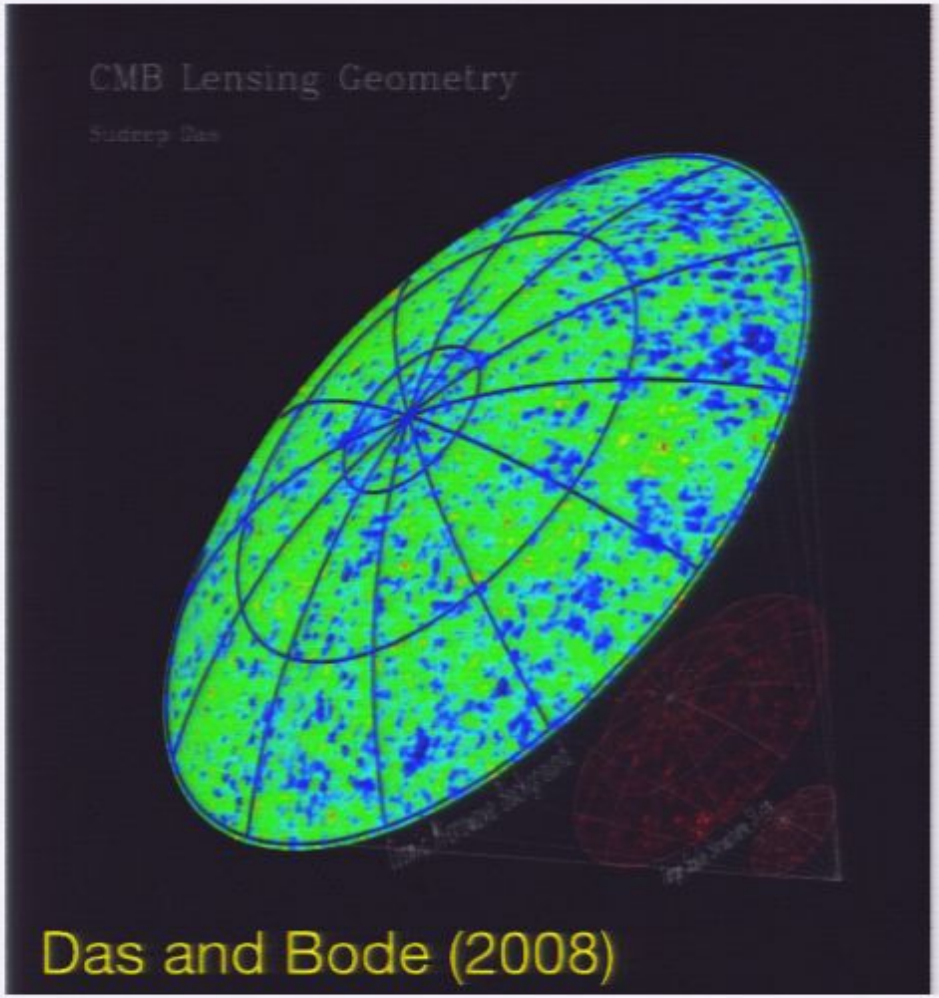
$\ell^2 \partial C_\ell^{dd} / \partial x$



ℓ

Smith, Cooray, Das, Dore et al., CMBPOL Lensing White Paper (2009)

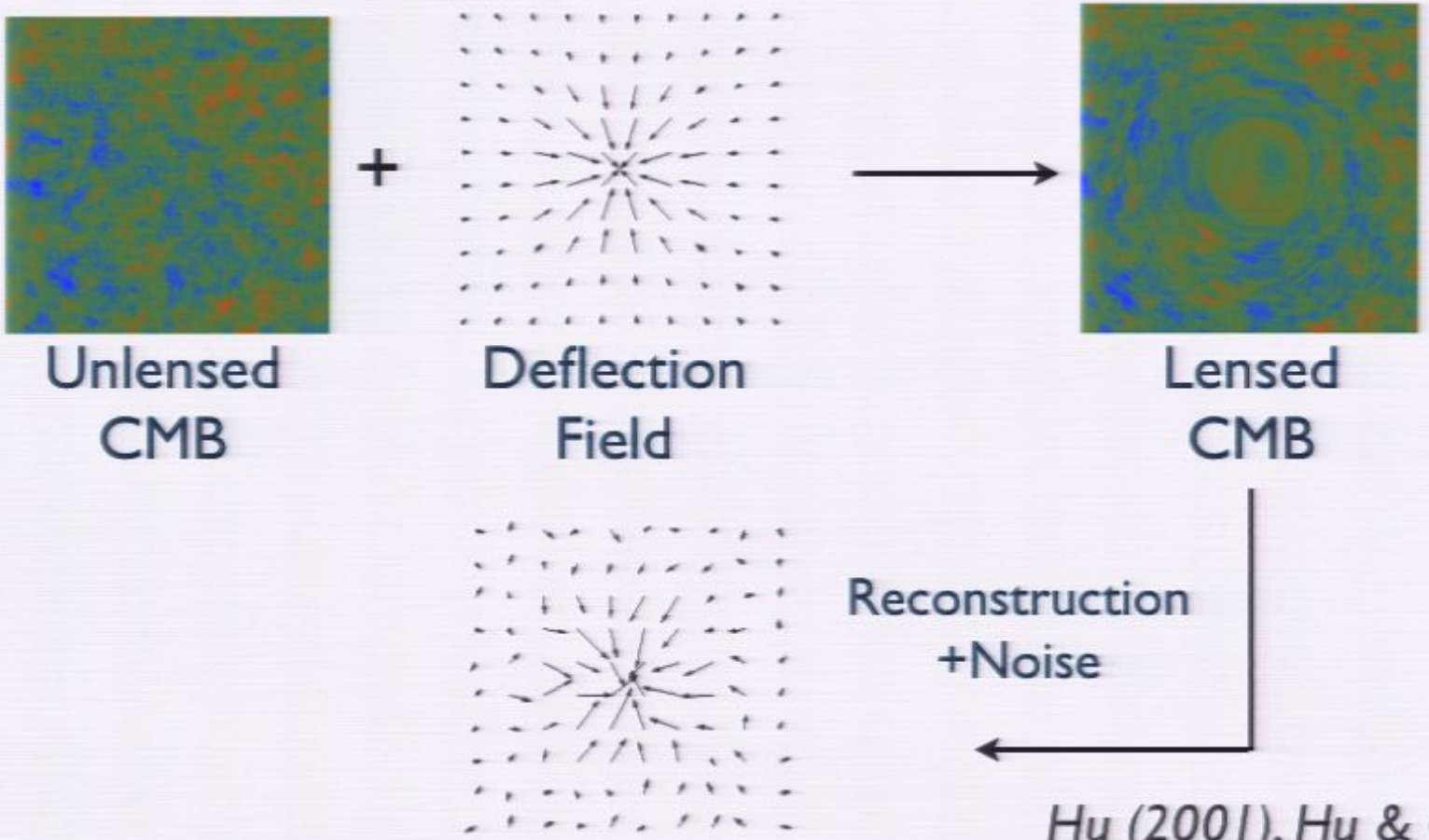
LENSING INDUCES NON-GAUSSIANITY



Difference between lensed and unlensed CMB

LENSING RECONSTRUCTION

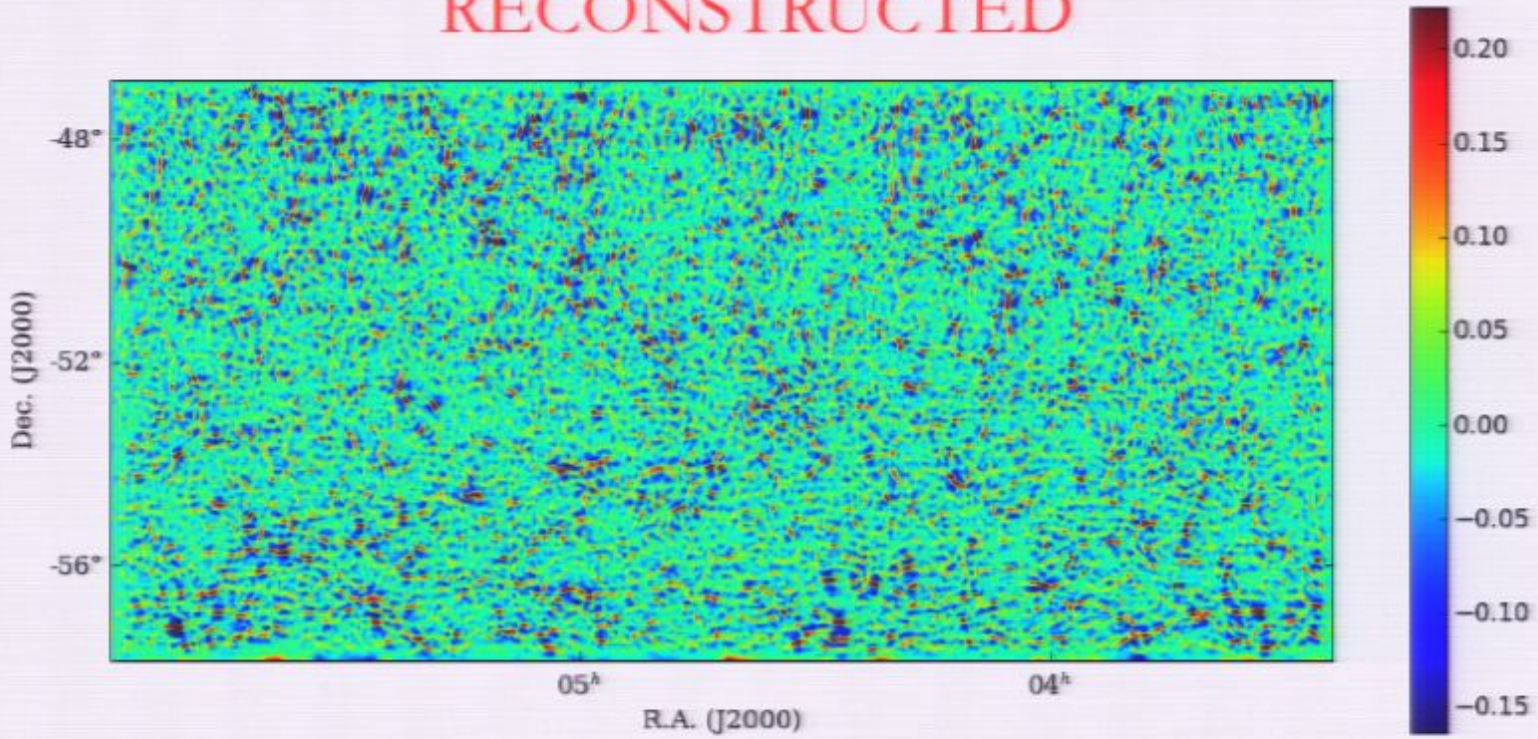
Given only the lensed CMB sky, can we estimate the deflection field?



Hu (2001), Hu & Okamoto (2002)

Simulated reconstruction
A worked example

RECONSTRUCTED



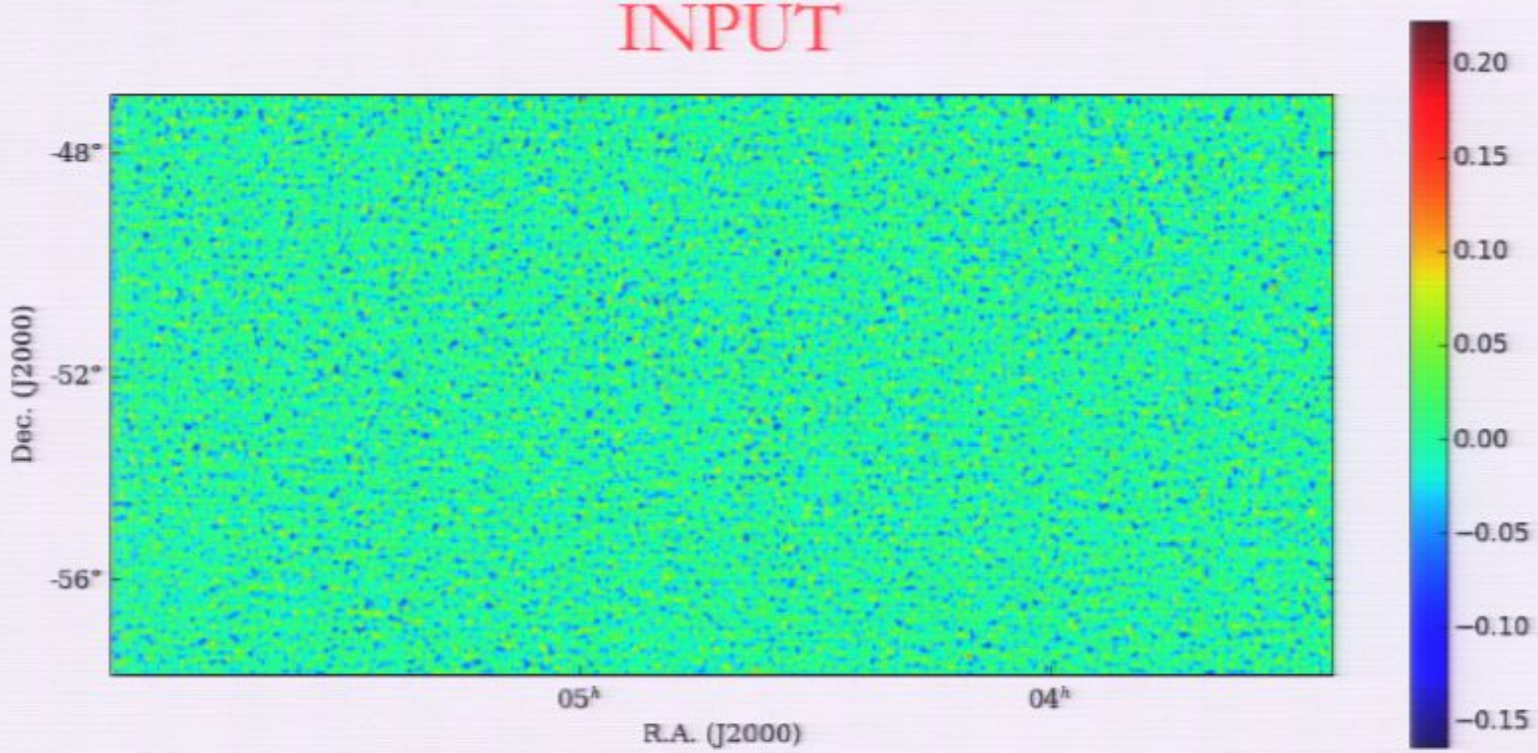
$$\mathbf{d} = \nabla\phi$$

$\hat{\mathbf{d}} \times \hat{\mathbf{d}}$

$\hat{\mathbf{d}} \times \text{Stuff}$

Simulated reconstruction
A worked example

INPUT



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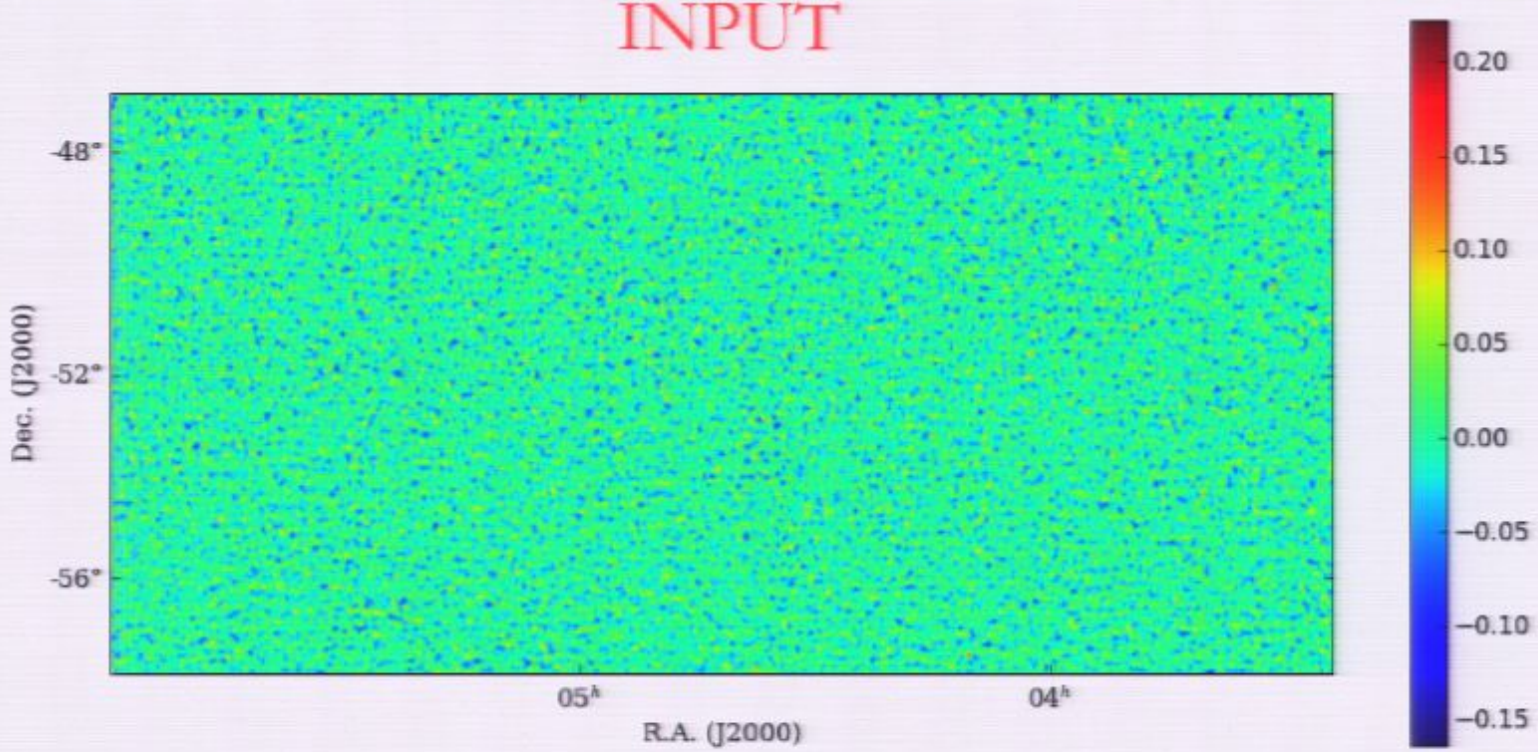

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SIMULATED RECONSTRUCTION
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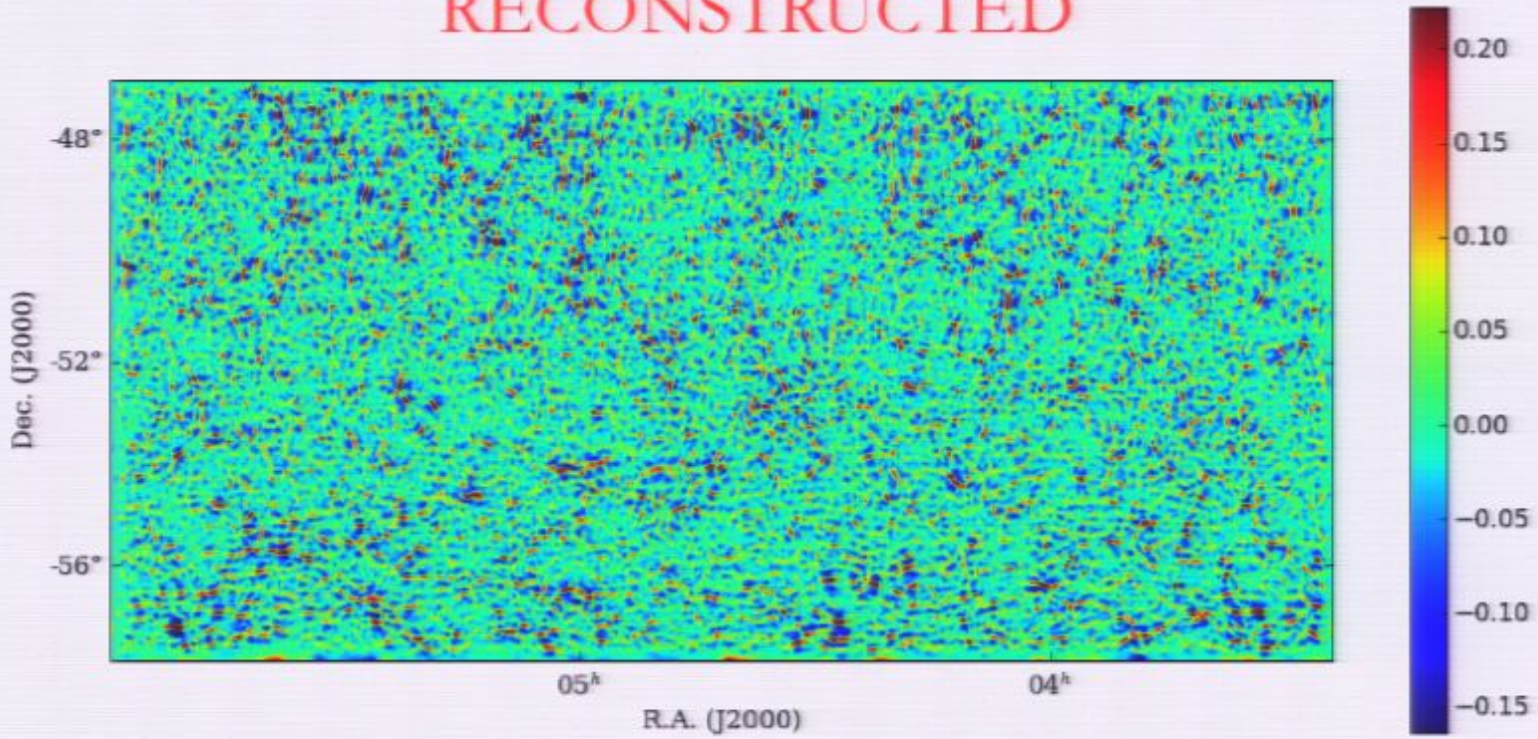

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Sudeep Das, PI, CITA Day, Feb 15, 2011

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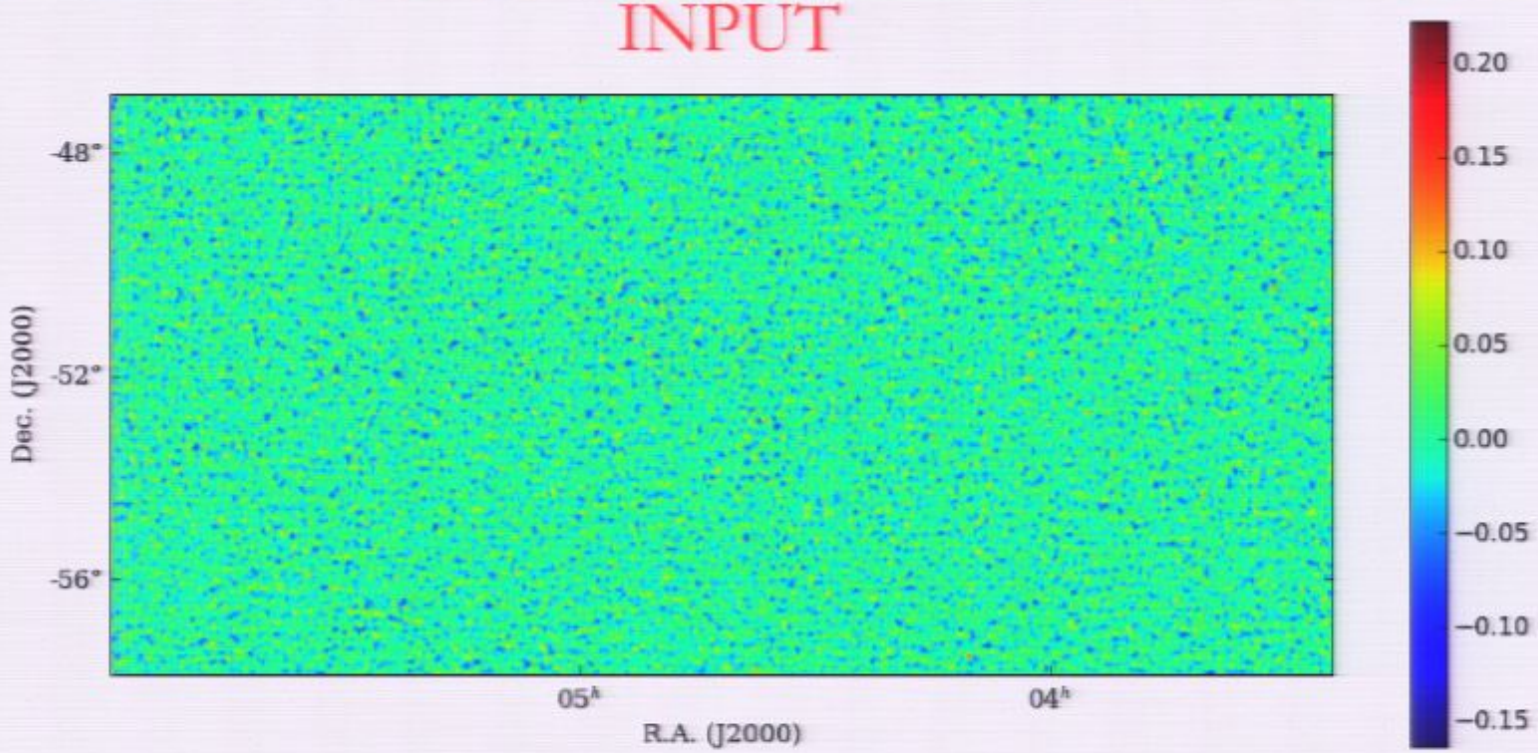

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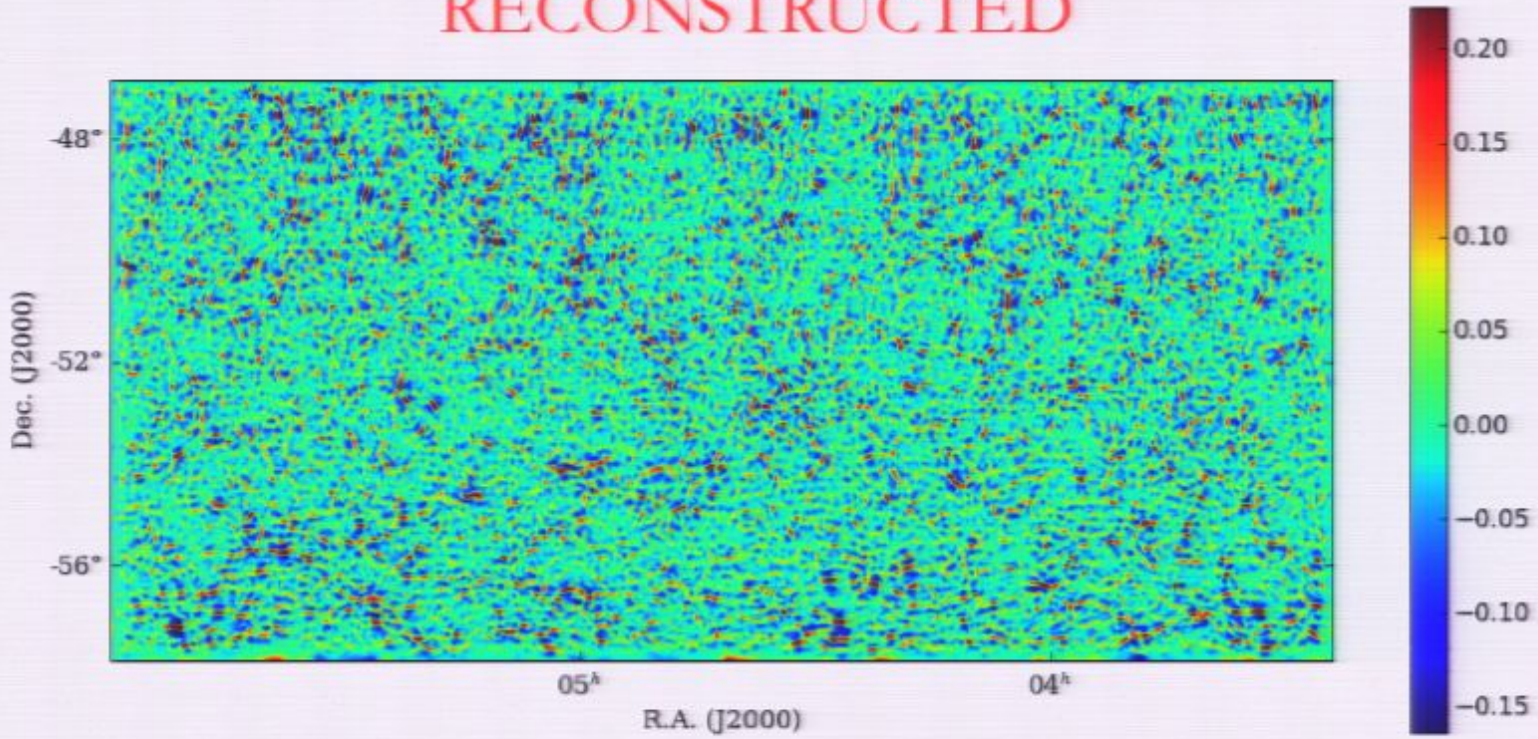

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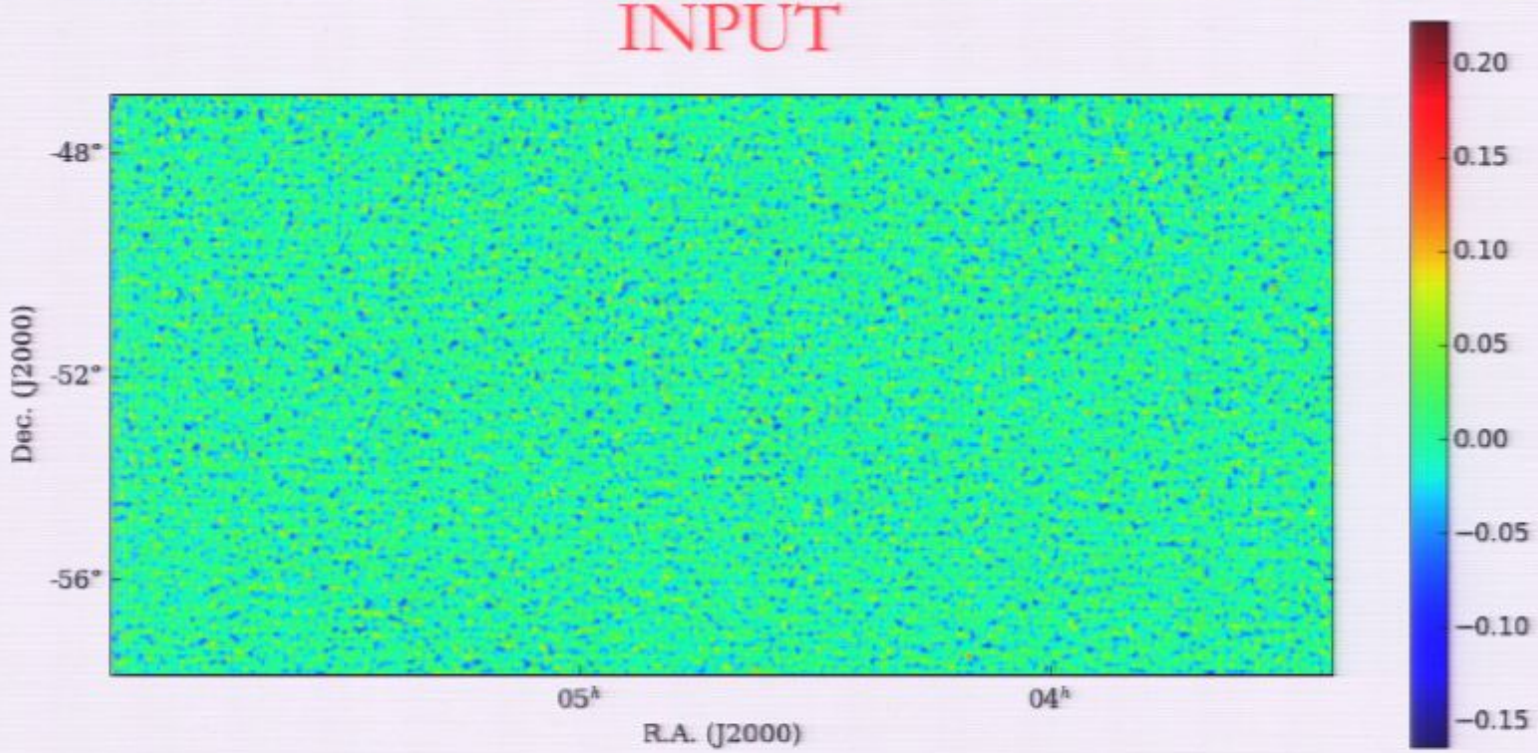

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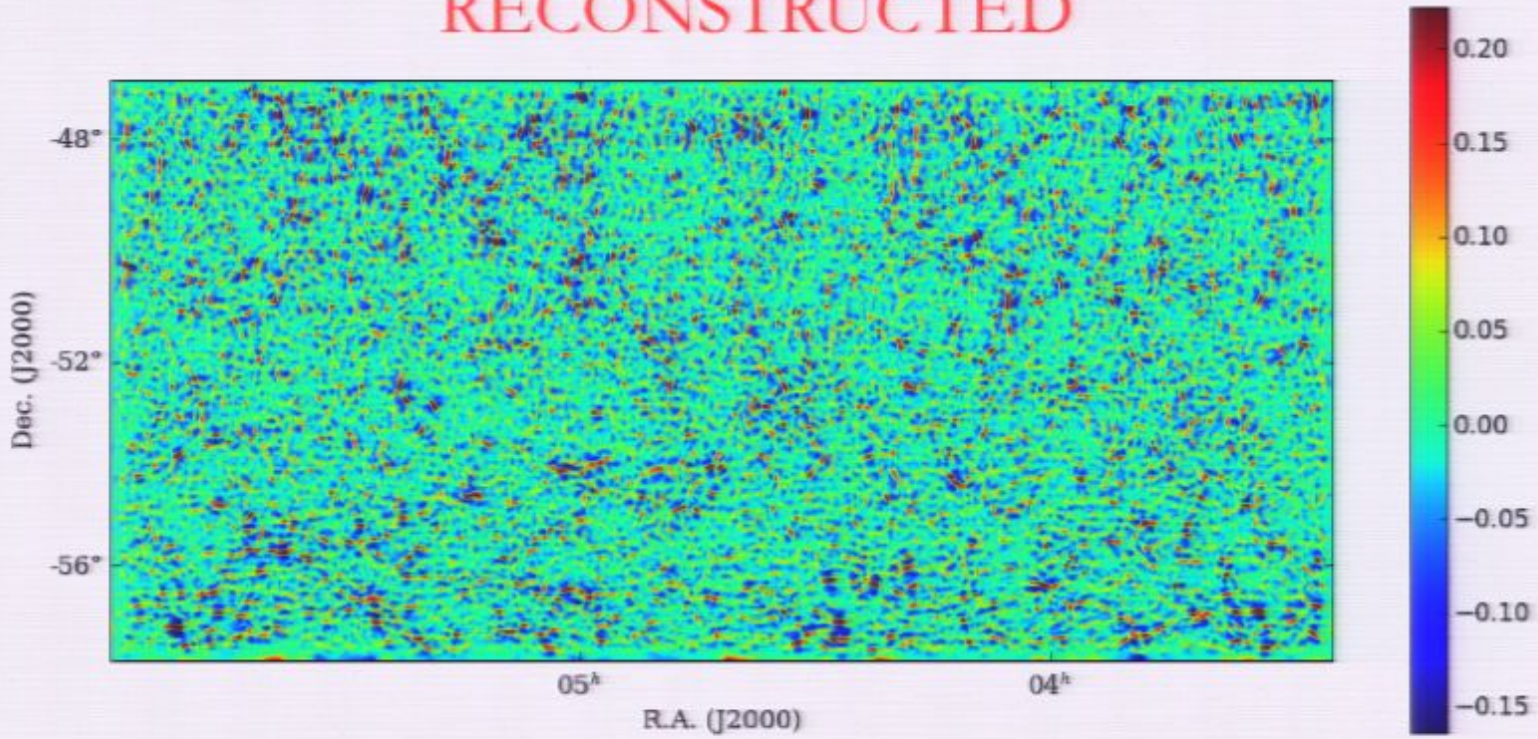

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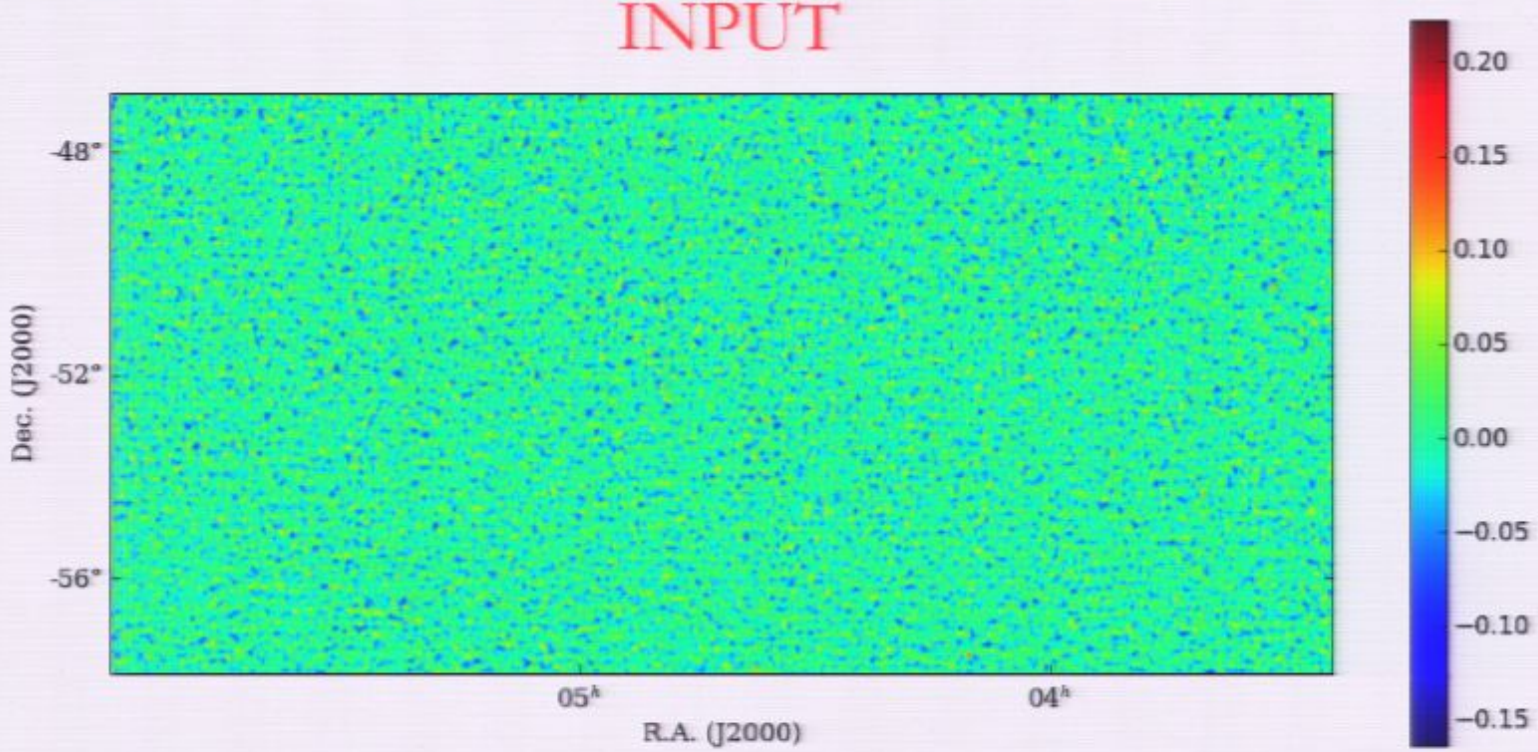

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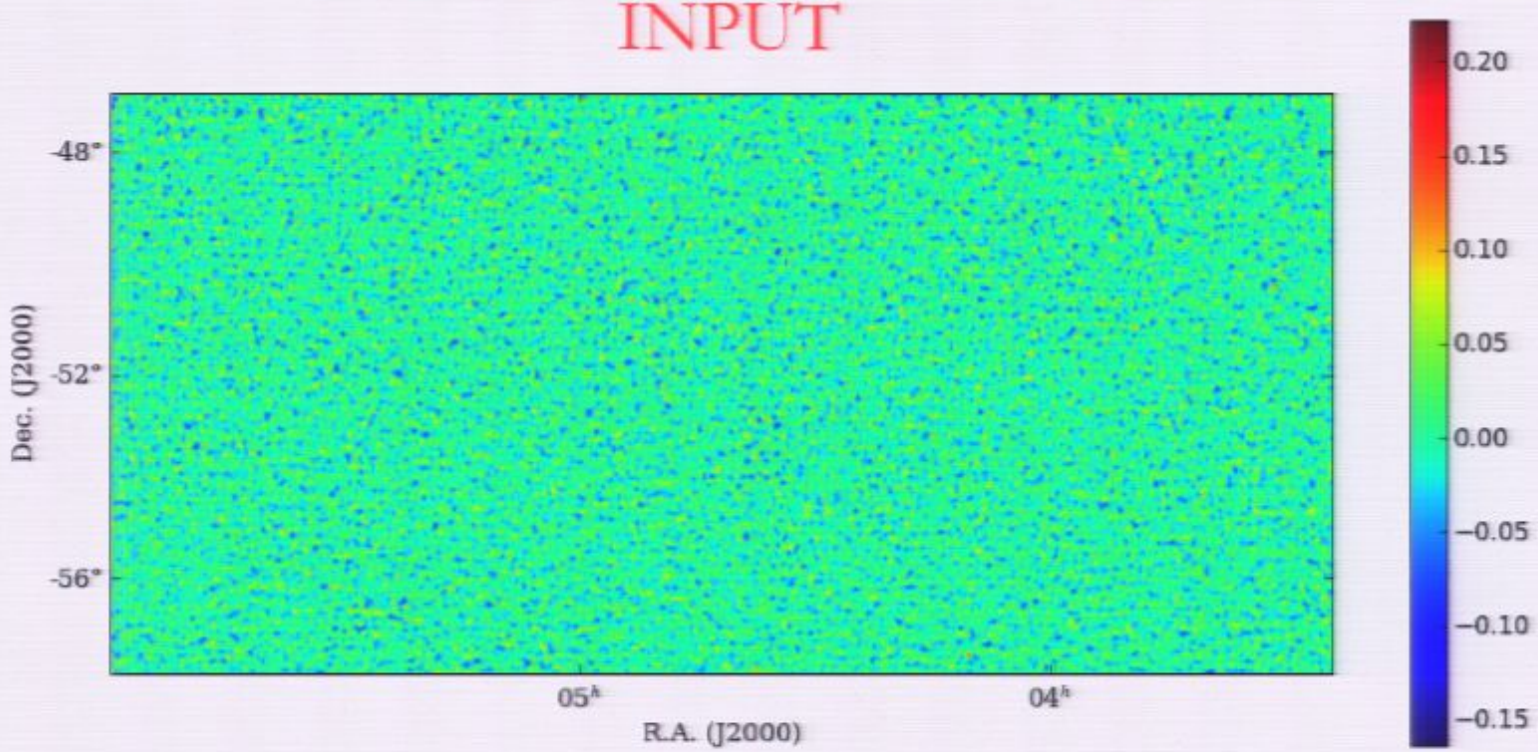

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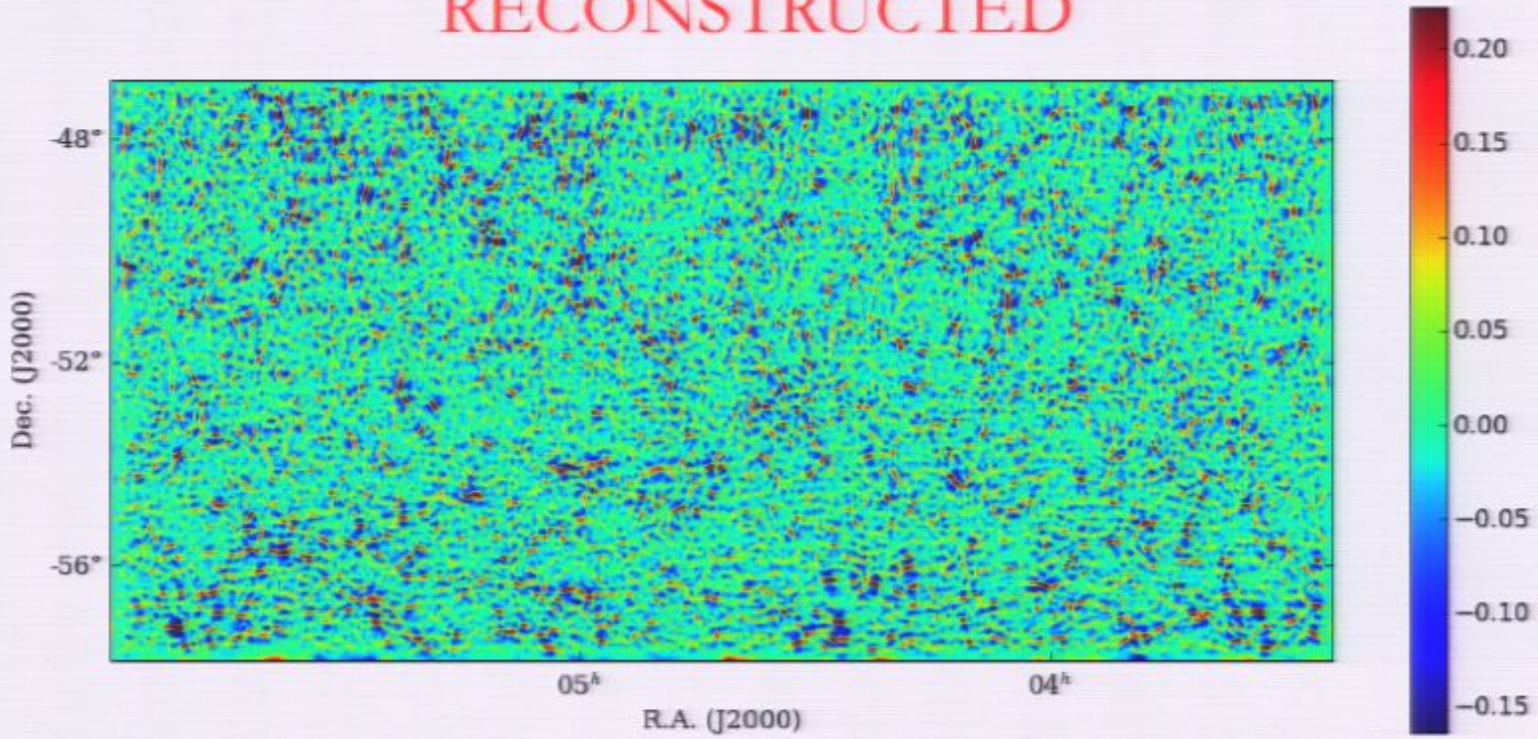

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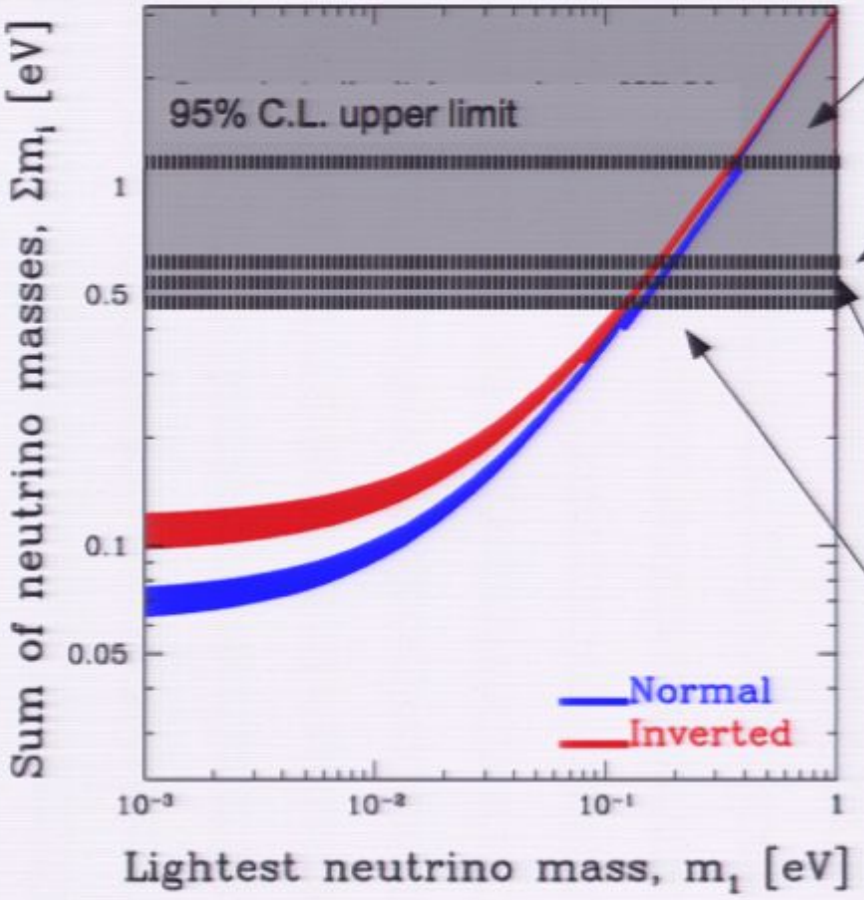
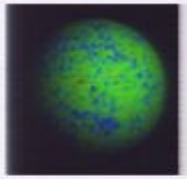
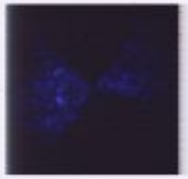
ACTPOL CAN HELP CONSTRAIN NEUTRINO HIERARCHIES!

Present status...

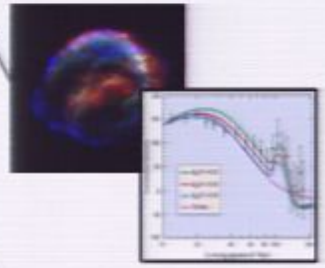




WMAP7 only
Komatsu et al. 2010



+ Galaxy clustering
Reid et al. 2009



+ Galaxy + SN + HST
Reid et al. 2009

Break degenercies

+ Weak lensing
Tereno et al. 2008
Ichiki et al. 2008

... and many more.

Graphic from Y. Wong

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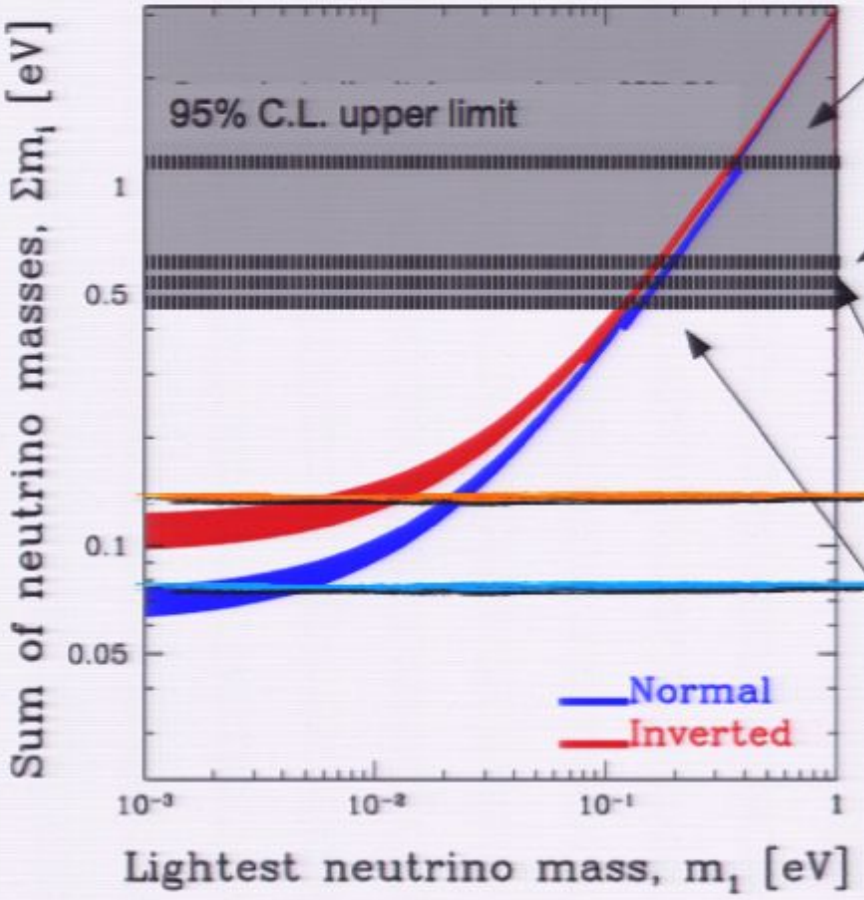

WMAP7 only
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+ Galaxy clustering
Reid et al. 2009

+ Galaxy + SN + HST
Reid et al. 2009

Planck

Planck + ACTPol

$\Delta \sum m_\nu \sim 0.06$ eV

+ Weak lensing
Ichiki et al. 2008

... and many more.

Graphic from Y. Wong

PLANCK, ACTPOL AND SPTPOL WILL CONSTRAIN FUNDAMENTAL PHYSICS

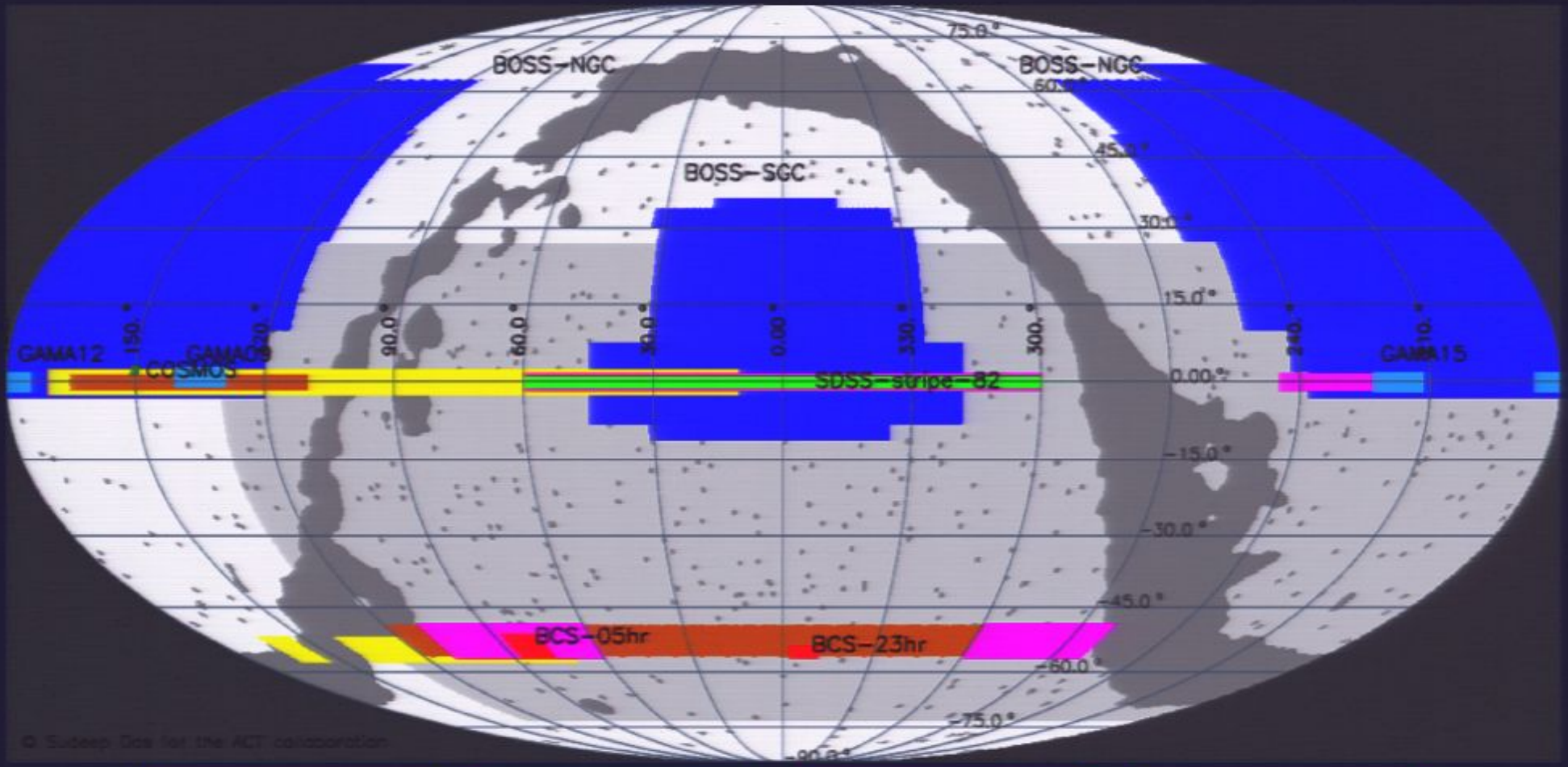
	WMAP5	WMAP9 + ACTPol	Planck	Planck + ACTPol
$\Omega_b h^2$	6×10^{-4}	1.9×10^{-4}	2×10^{-4}	1.3×10^{-4}
$\Omega_m h^2$	6×10^{-3}	3.7×10^{-3}	2.2×10^{-3}	1.7×10^{-3}
n_s	0.014	0.008	0.007	0.006
m_ν	-	0.15	0.1	0.06
τ	0.017	0.010	0.004	0.004
Y_{He}	-	0.007	0.01	0.005

Systematics?

Currently exploring systematics with Jeff McMahon, Oliver Zahn, and their effect on parameters with Silvia Galli.

Preliminary analysis shows that all major systematics can be controlled.

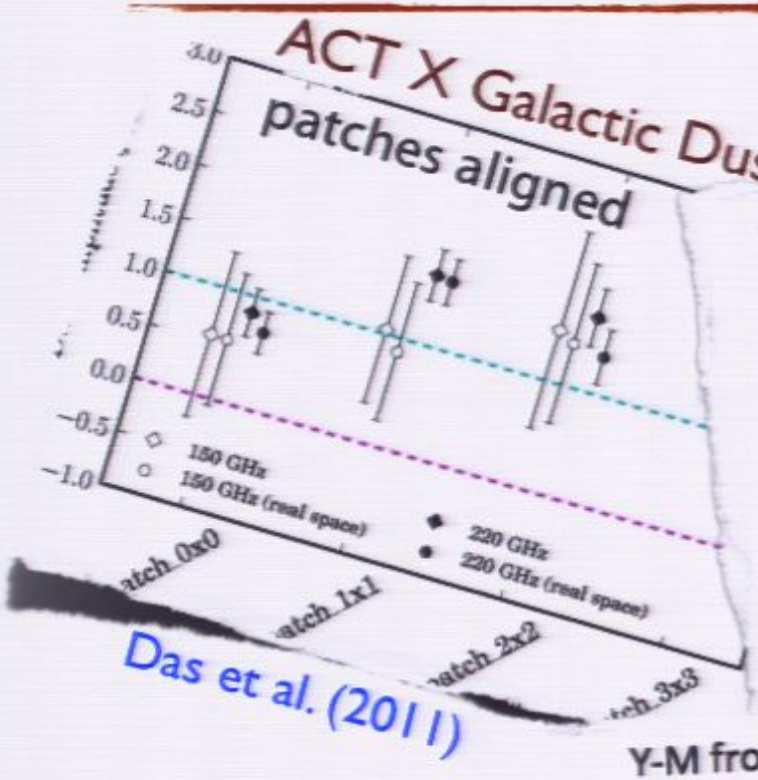
Cross Correlation Science

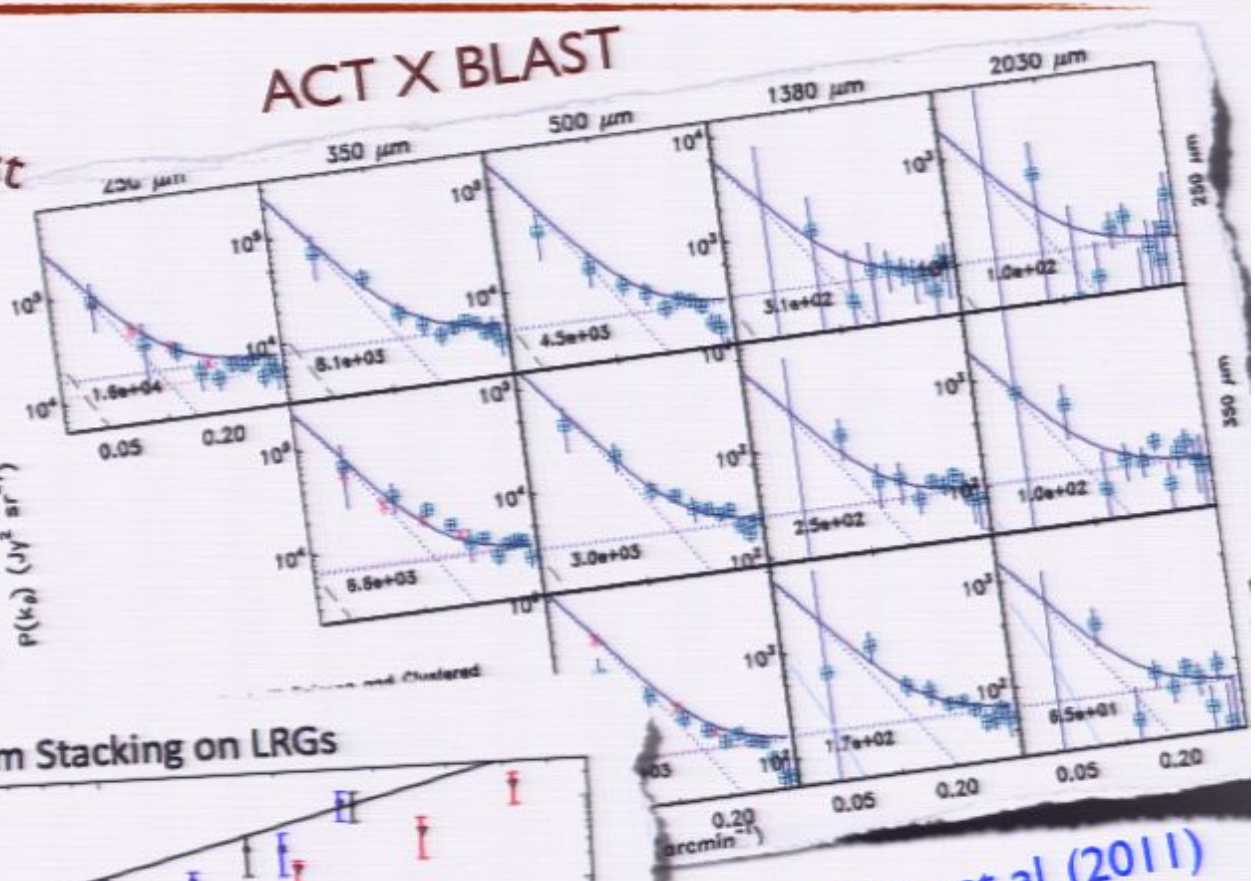


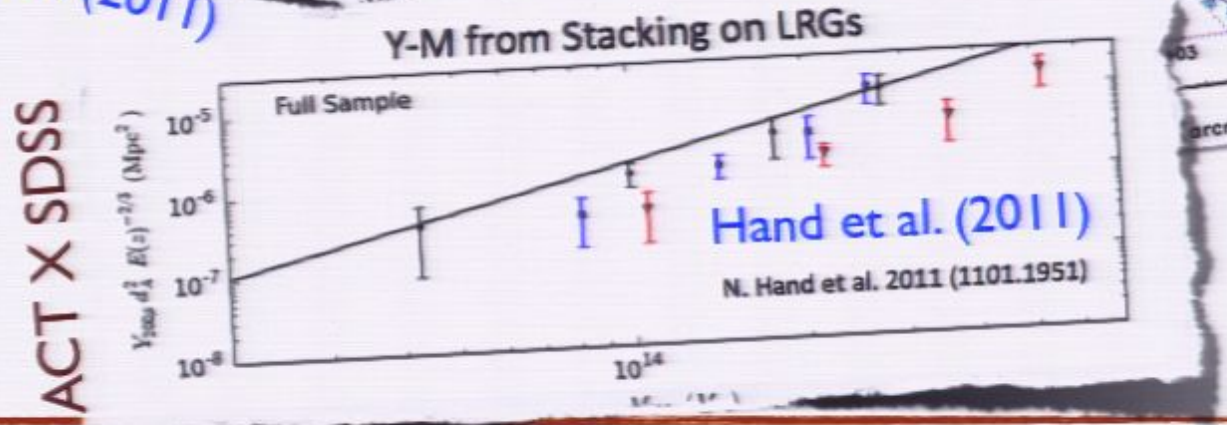
2007 | 2008 | 2009 | Stripe 82

BCS | BOSS | GAMA | ACT Range | Mask

ACT MAPS ARE PROVING SENSITIVE ENOUGH FOR CROSS CORRELATION STUDIES!







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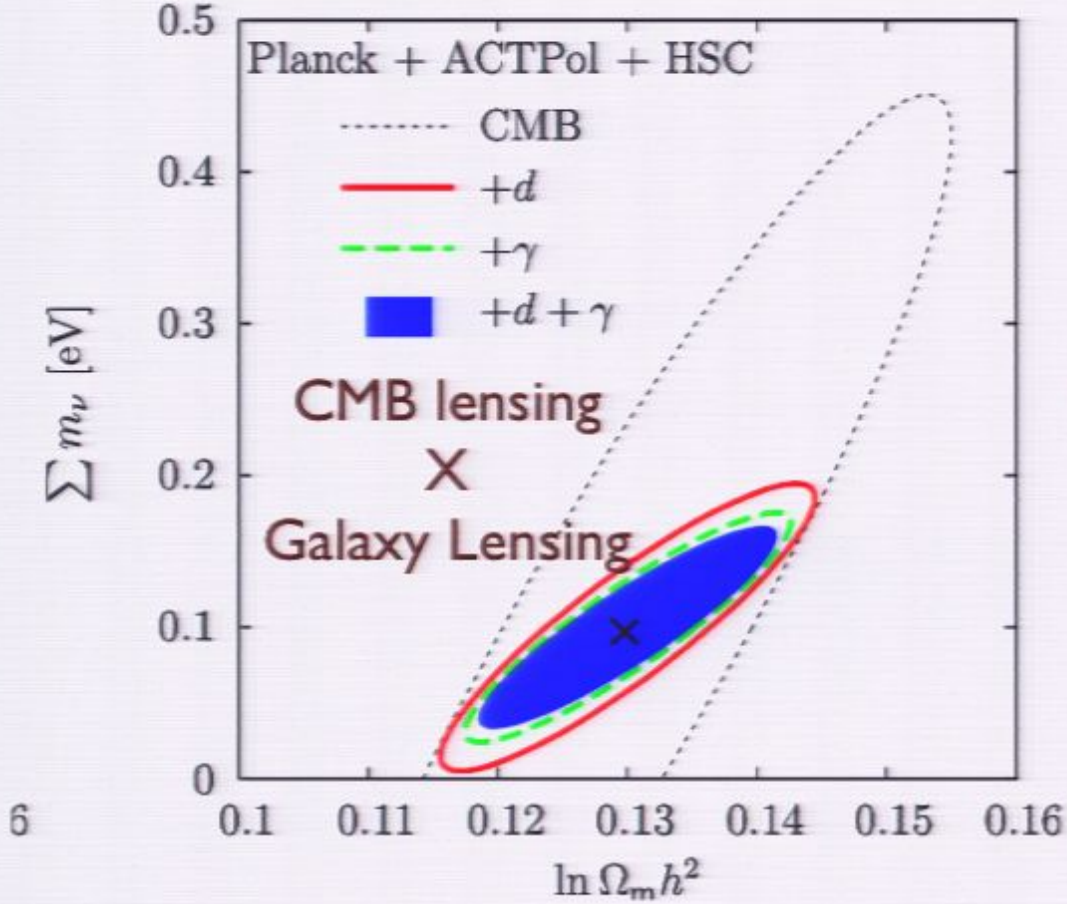
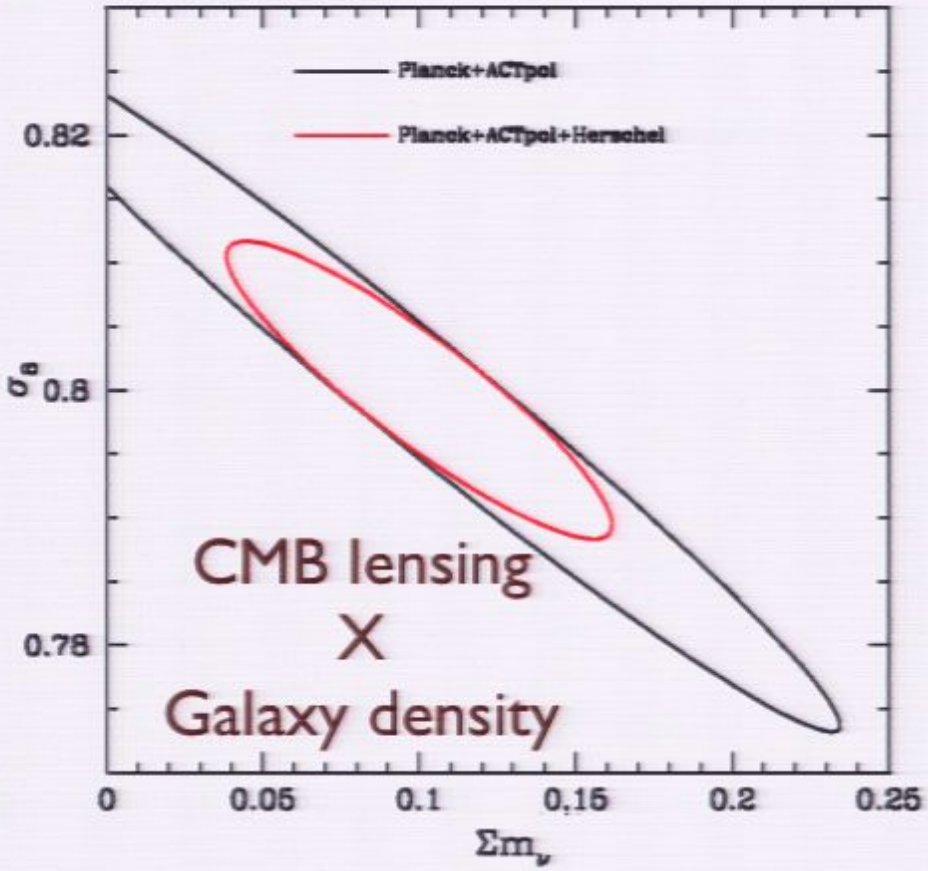
CMB LENSING: SYNERGY WITH GALAXY AND WEAK LENSING SURVEYS (BIGBOSS, DES, LSST)





Namikawa et al (2010)

Das & De Putter, in prep.

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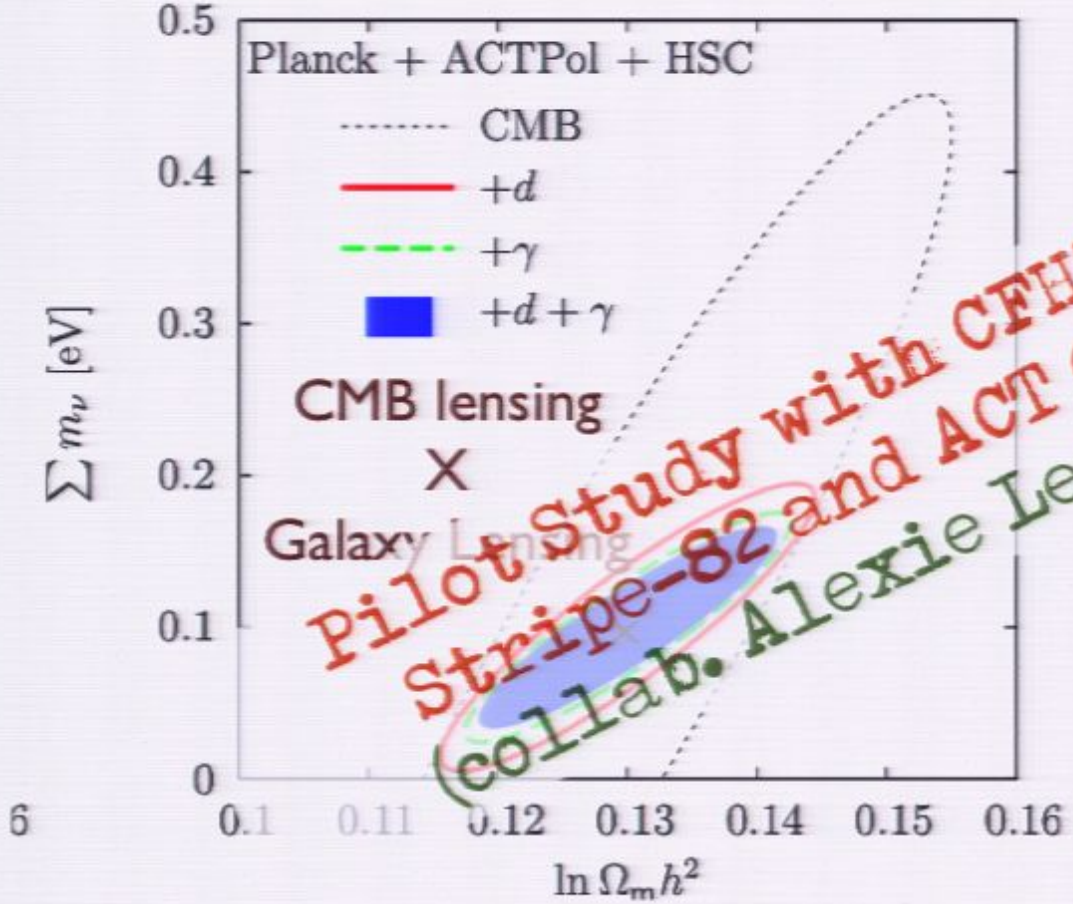

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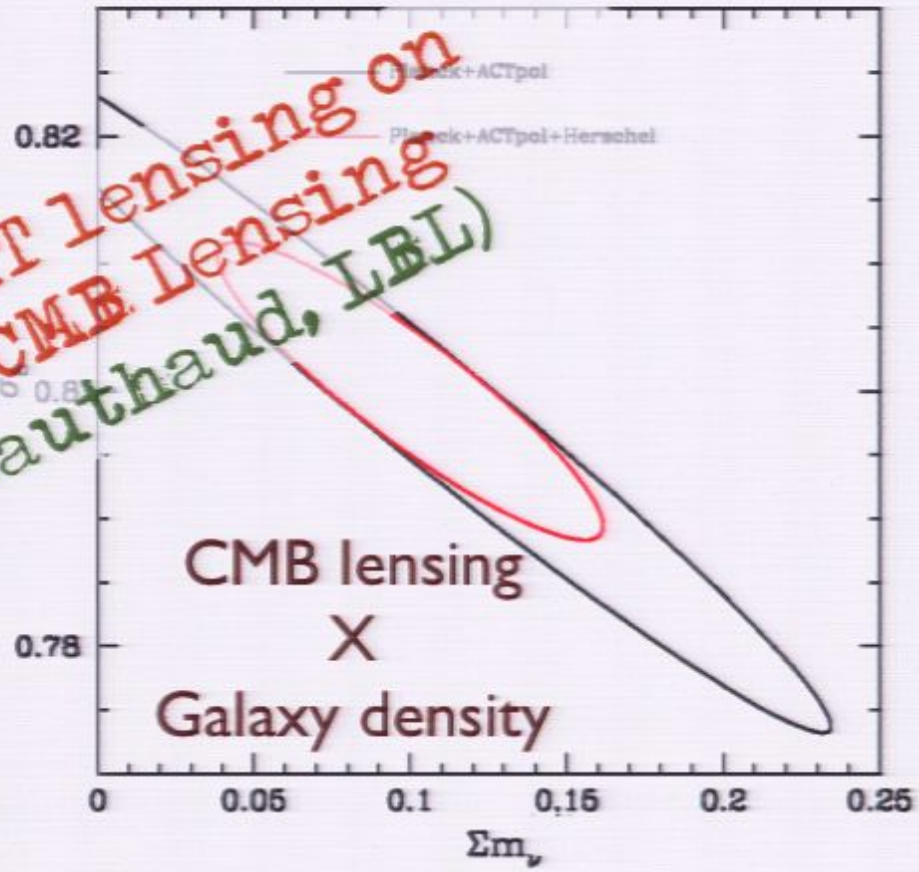
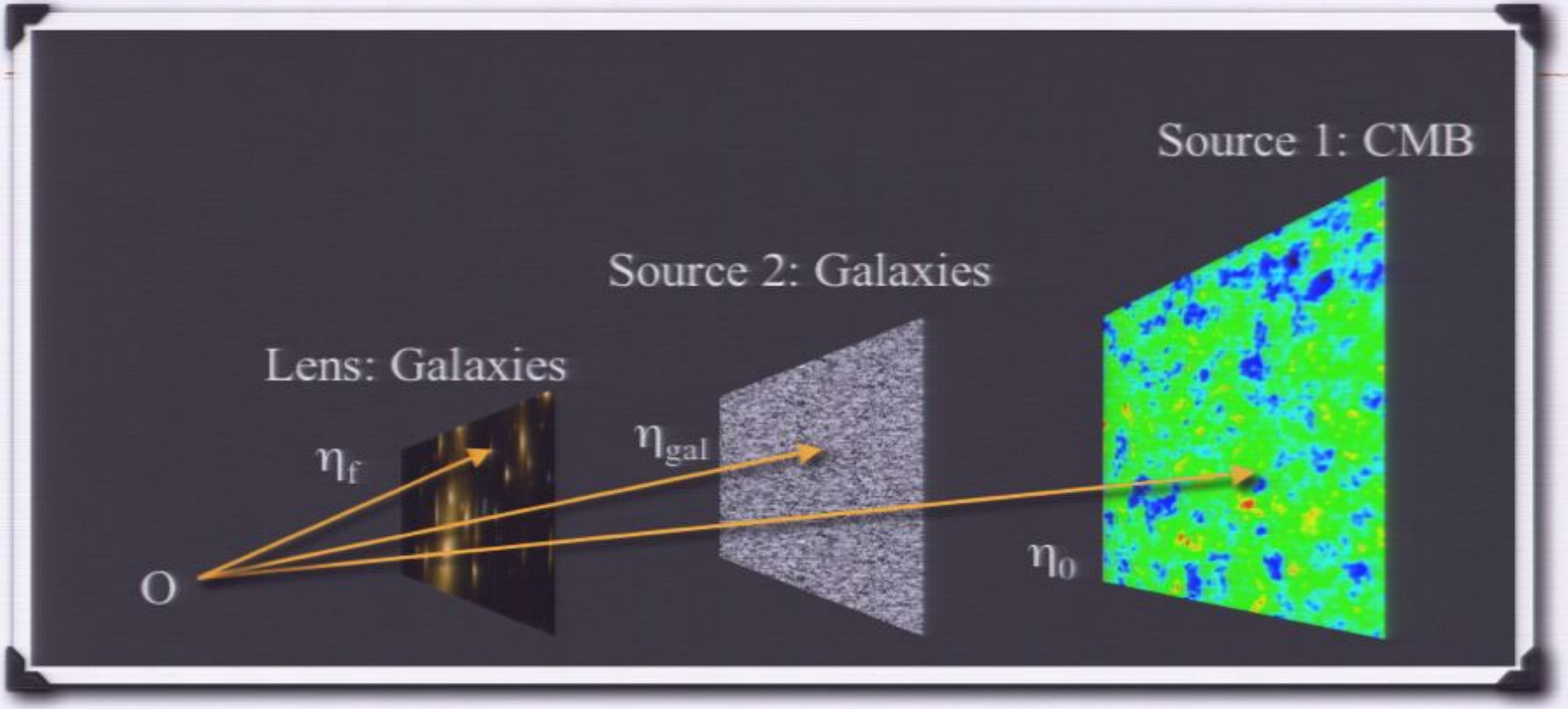


Das & De Putter, in prep.

Pilot Study with CFHT lensing on Stripe-82 and ACT CMB Lensing (collab. Alexie Leauthaud, LBL)

MEASURING GEOMETRY



$$r \equiv \frac{C_\ell^{\kappa_{\rm CMB}\Sigma}}{C_\ell^{\kappa_{\rm gal}\Sigma}} \qquad \frac{d_A(\eta_0-\eta_f)d_A(\eta_{\rm gal})}{d_A(\eta_{\rm gal}-\eta_f)d_A(\eta_0)}.$$

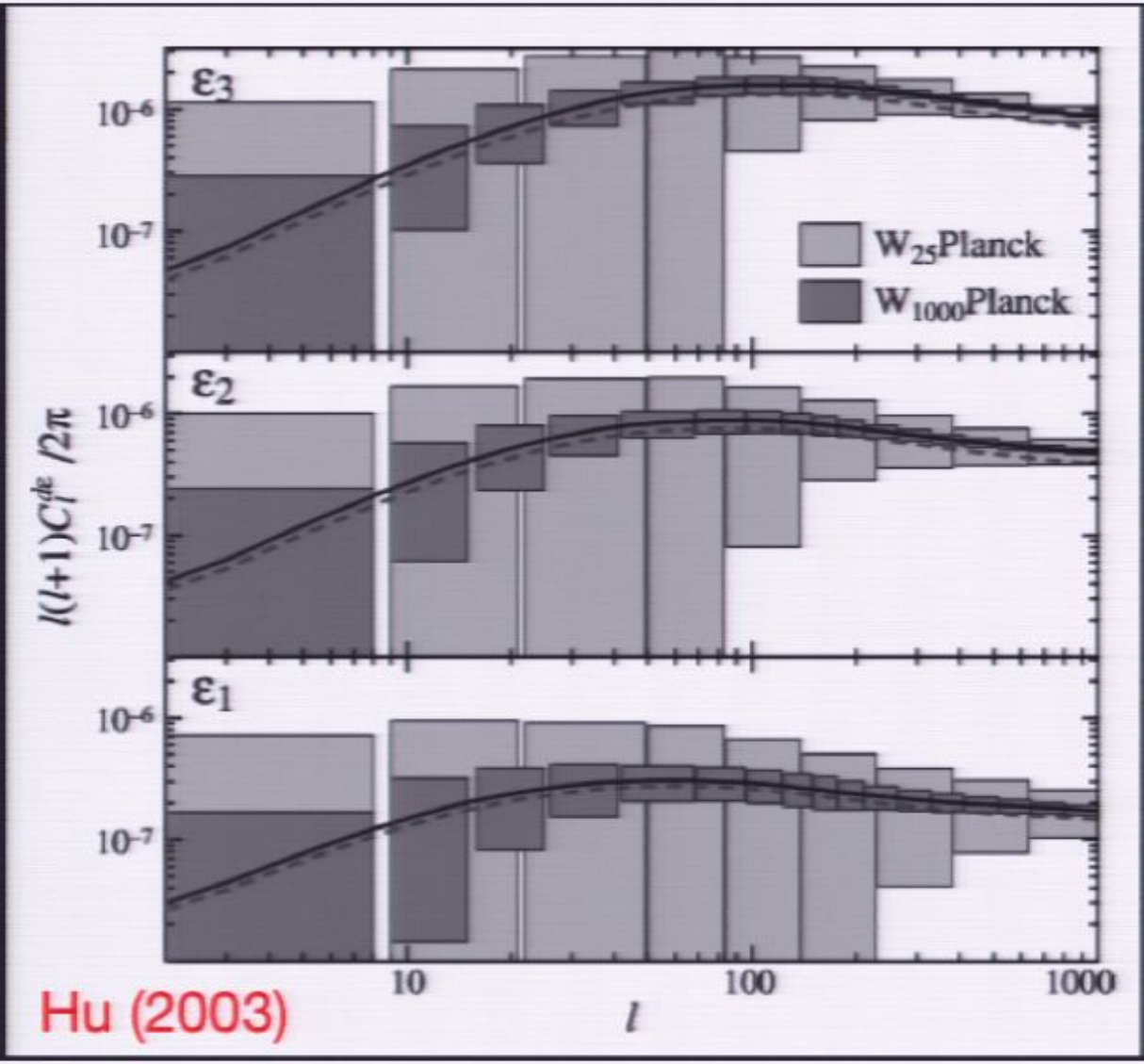
Sudeep Das, PI CITA Day, Feb 15, 2011

Measuring DM Growth, and early DE

Cross-correlating CMB lensing with cosmic shear in redshift slices will probe growth of structure directly!

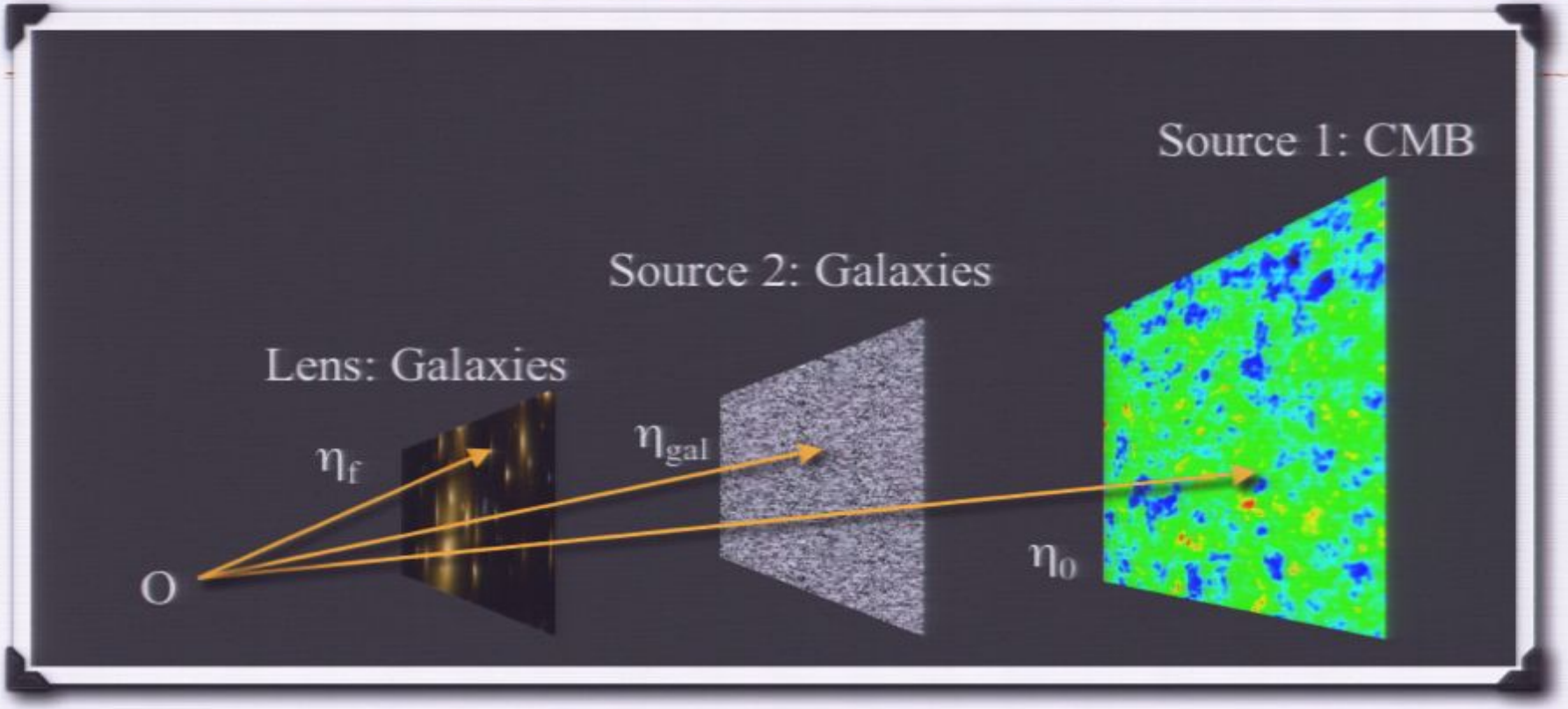
Deviations from GR?

Das, de Putter, et al in prep



Hu (2003)

MEASURING GEOMETRY



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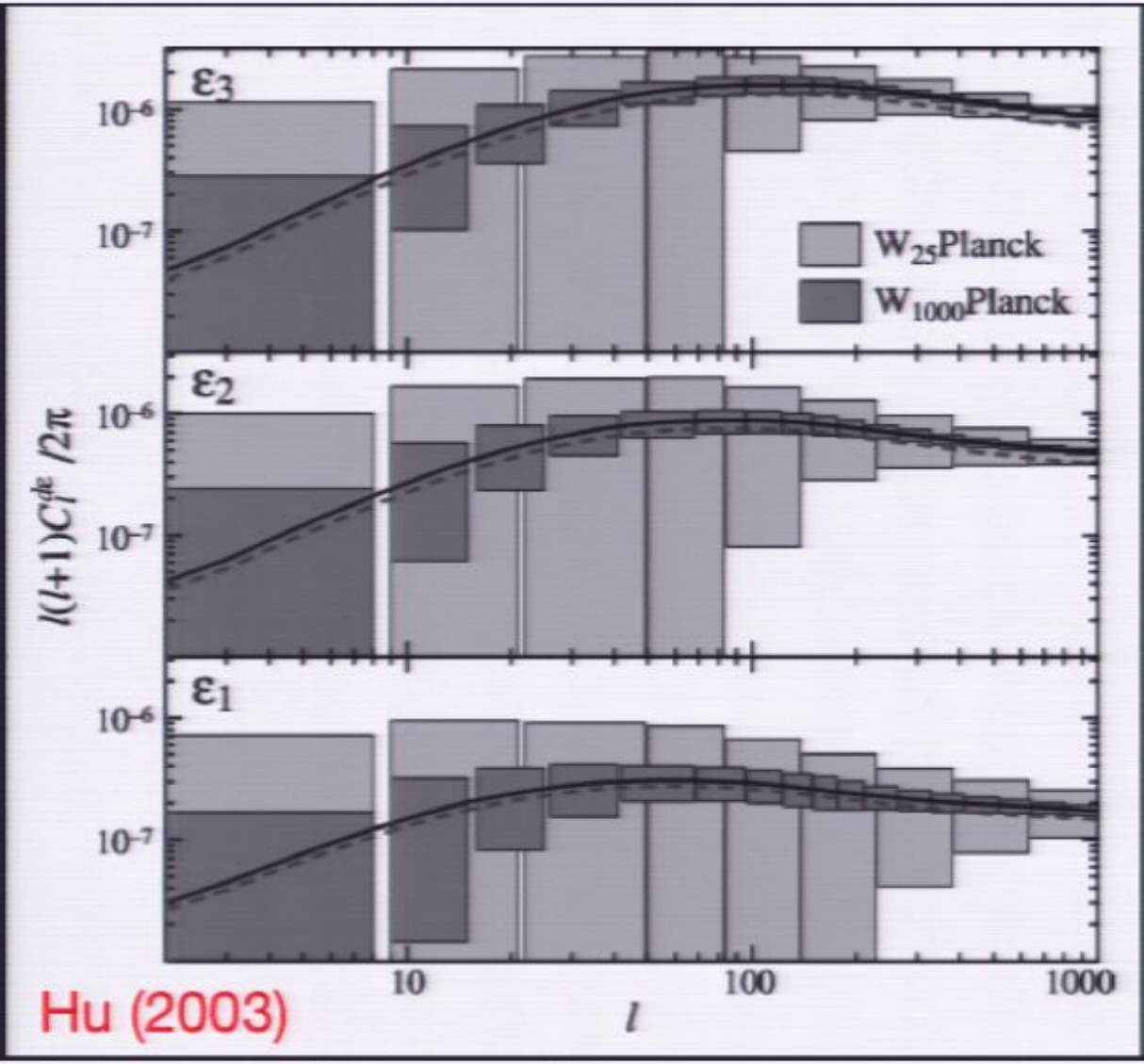
Deviations from GR?

Das, de Putter, et al in prep



Hu (2003)

LOOKING AHEAD ... EXCITING TIMES IN CMB PHYSICS!

- Two keywords in the future of CMB: high resolution, polarization
- ACT is a working example, and is already probing fundamental physics.
- CMB lensing is a new and powerful tool.
- Small-scale polarization experiments like PolarBeaR, ACTPol and SPTPol will be primarily CMB lensing machines.
- CMB lensing will provide new constraints on neutrino mass, dark energy, and deviations from GR.
- A large array of cross-correlation projects are possible with the wealth of data in multiple frequencies.
- Be prepared to witness a very productive interplay of CMB, fundamental physics, and astrophysics in the coming years!


No Signal
VGA-1