NTU, Dec. 17, 2008

Some Recent Progress in CMB Cosmology

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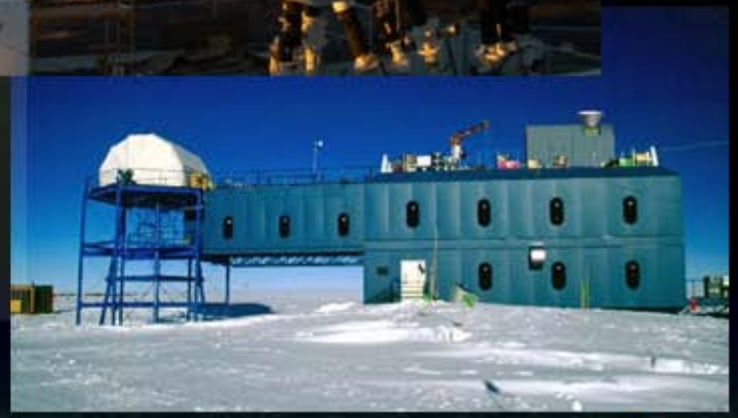
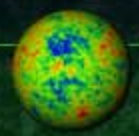
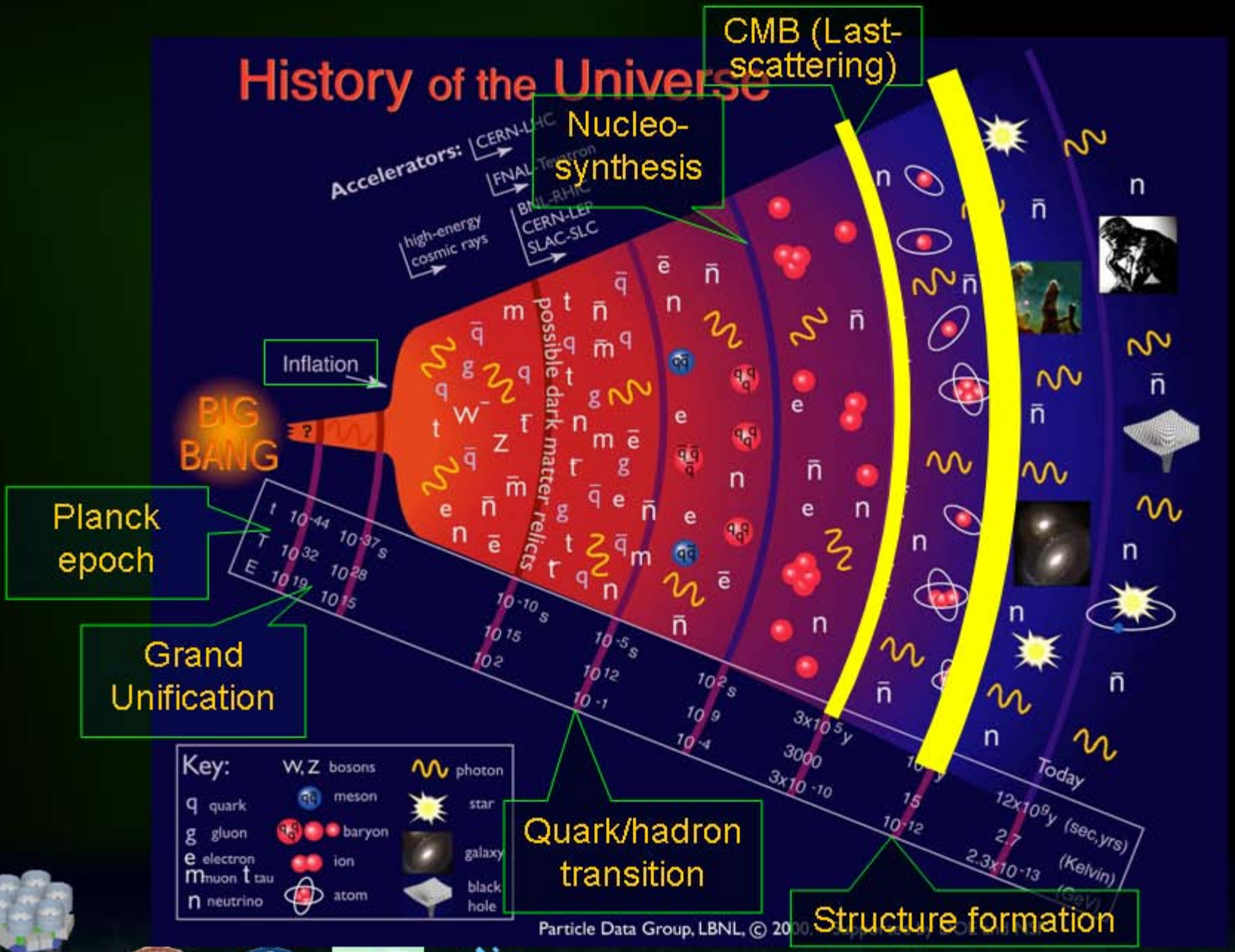
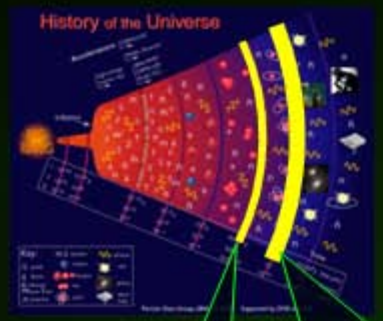
- Introduction
  - CMB Cosmology
  - Current Status, B-mode?
  - Science background
- Experiments & Observations:
  - AMiBA (SZE results, future)
  - MAXIPOL (E-mode polarization result)
  - B-mode Experiment
- Theoretical Studies
  - Sunyaev-Zel'dovich Effects
  - Cosmic Strings
  - Topology & Size of the Universe
- Conclusion





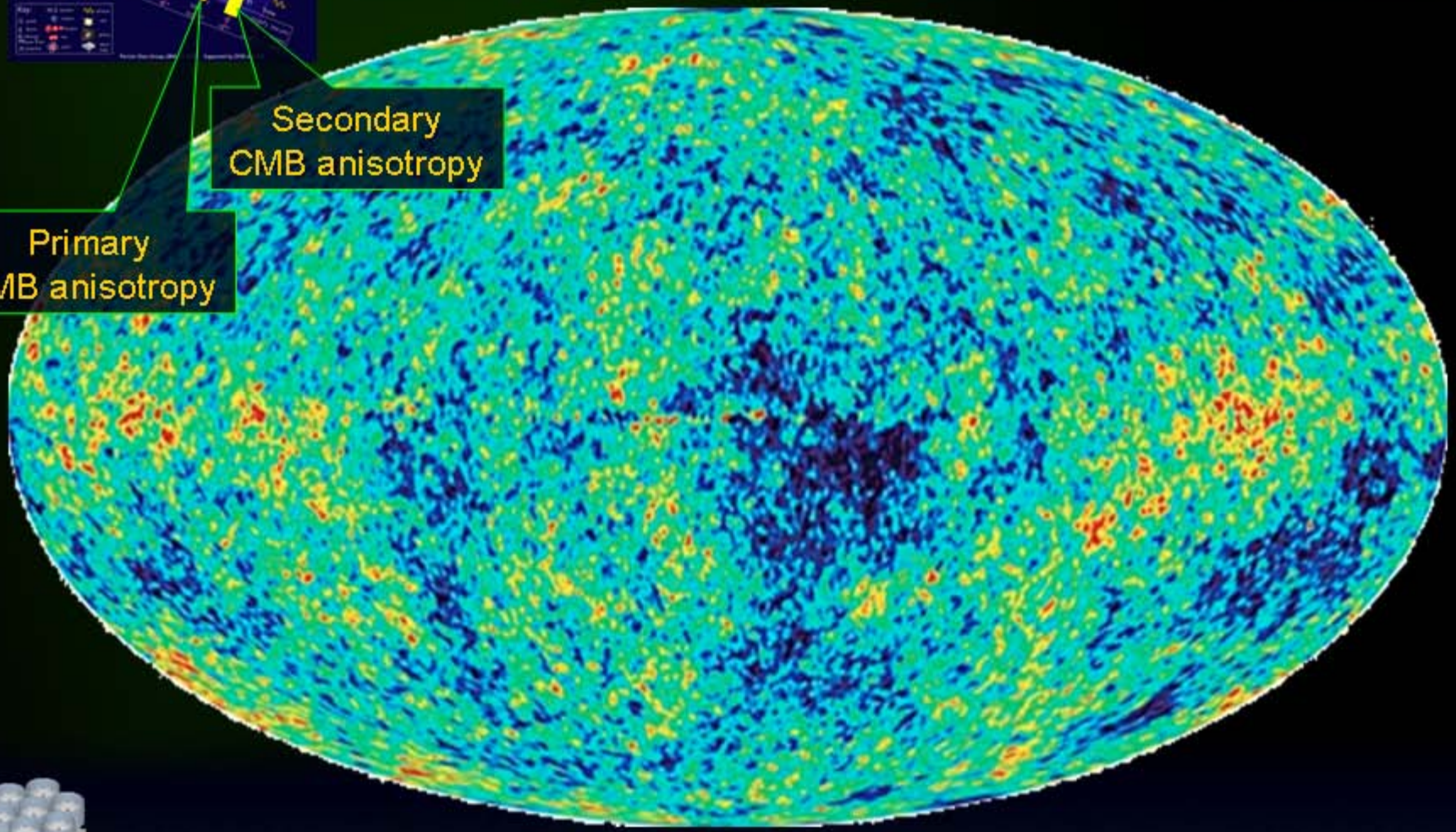

History of the Universe
CMB (Last-scattering)
Nucleo-synthesis
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
Planck epoch
Grand Unification
Quark/hadron transition
Structure formation
Today
Key:
W,Z bosons
photon
quark
meson
star
gluon
baryon
galaxy
electron
ion
muon
tau
atom
black hole
neutrino
Particle Data Group, LBNL, © 2000

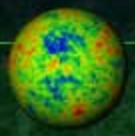


CMB as observed by WMAP (2008)

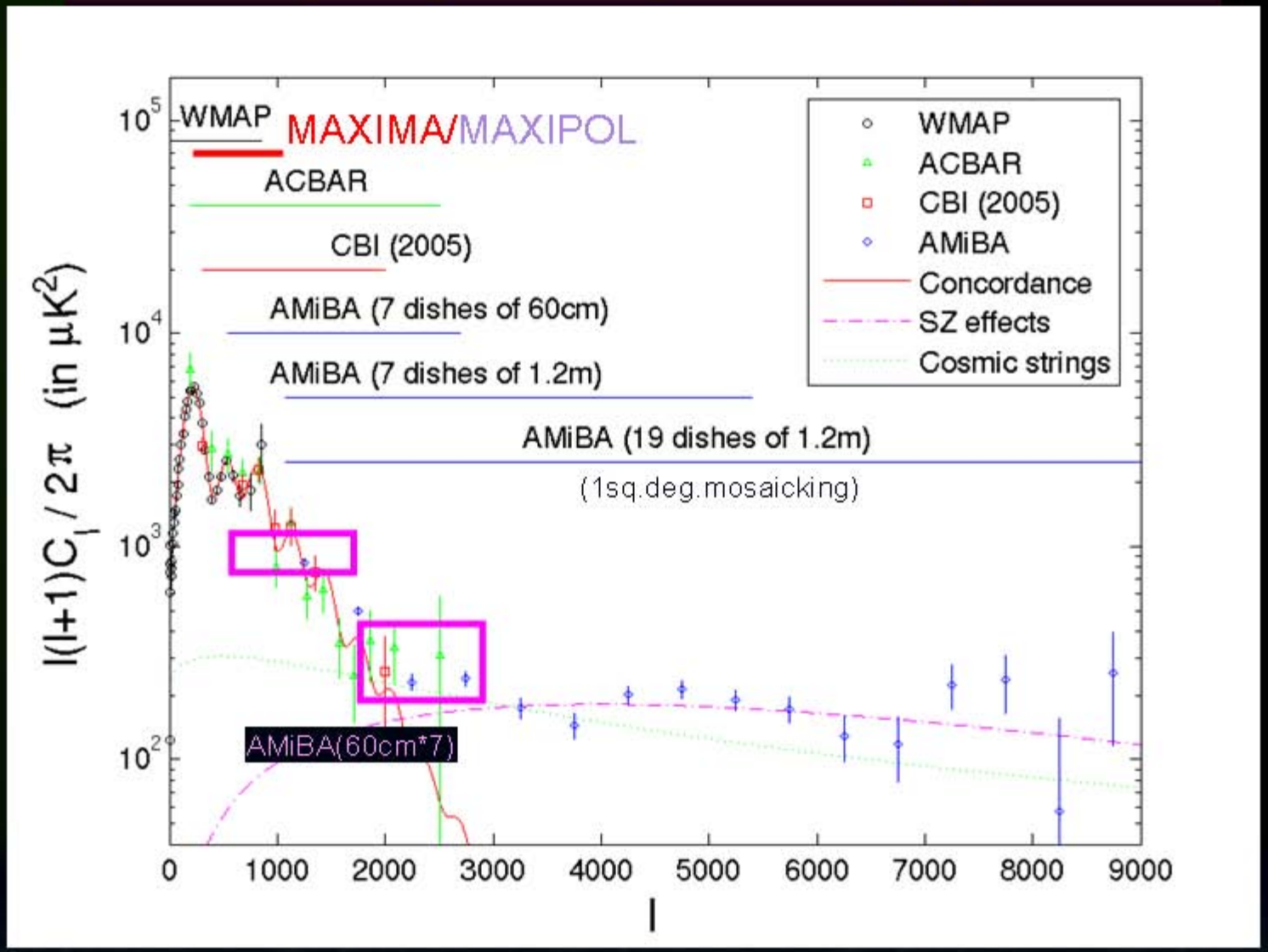
Secondary
CMB anisotropy

Primary
CMB anisotropy





CMB power spectrum (TT)

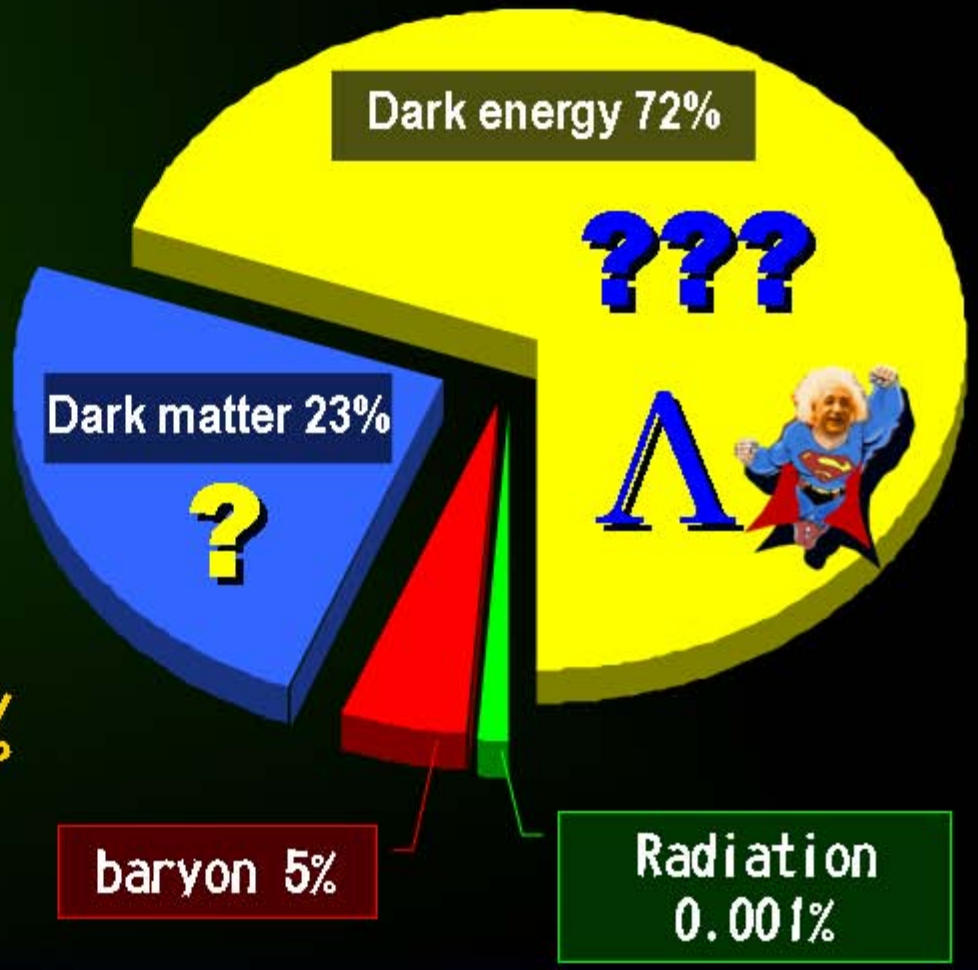


Composition of the Universe

1998 SNa, 2001 CMB
→ accelerated cosmos

compare

Theoretical predictions



Known matter : 5%
Unknown matter : 95%

Nobel prize & astrophysics

Big Bang — 0 yr

Opaque epoch

CMB — 400,000 yr

Dark epoch

Formation of structures — 1 x 10^9 yr

Structure formation epoch

14 x 10^9 yr

Time

B ?

E

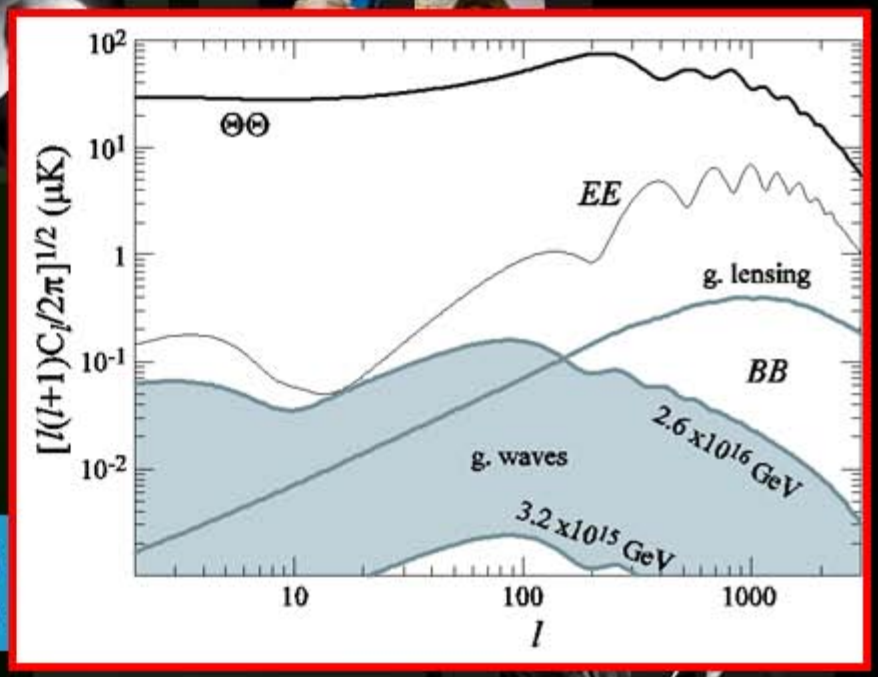
SZ

Gravitational waves (from Inflation, or previous universe, loop gravity, etc.)

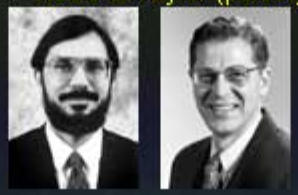
G. lensing -> Dark Energy

1978 Penzias & Wilson (CMB)

2006 Mather & Smoot (CMB)

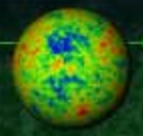


1993 Hulse & Taylor (pulsar)



2002 Davis, Koshiba & Giacconi (Neutrino & X-ray)

NSC

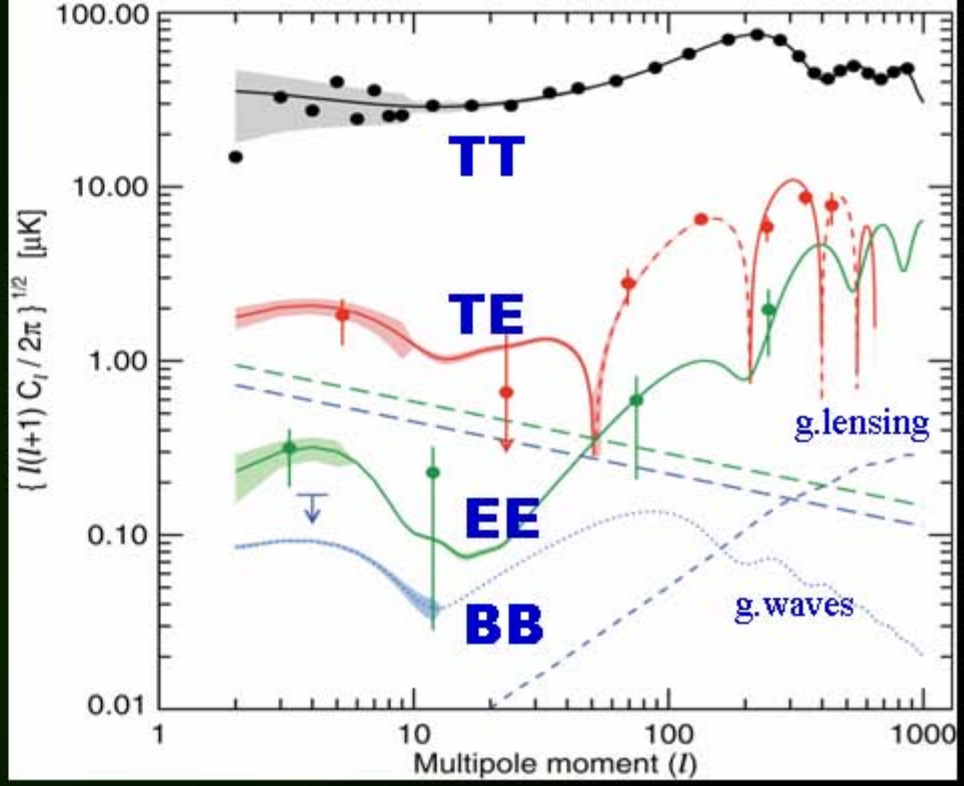


Why polarization?

- Probe the origin of the well observed CMB temperature anisotropy (E)
- Provide complementary information to that from CMB temperature observations. (E, B)

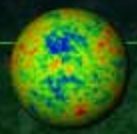
What is CMB polarization?

- Stokes parameters I (T), Q, U, V
- Q,U equivalent to E, B

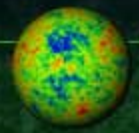


$$(Q \pm iU)(\mathbf{n}) = \sum_{\ell m} \left(a^E_{\ell m} \pm i a^B_{\ell m}\right) {}_{\pm 2}Y_{\ell m}(\mathbf{n})$$

$$C_\ell^{YY'} = \frac{1}{2\ell+1} \sum_m a^Y_{\ell m} a^{Y'*}_{\ell m}$$



AMiBA



AMiBA-7: Sunyaev-Zel'dovich Effect (1972, 1980)

- Fluctuations in CMB intensity:

$$\frac{\Delta I(x)}{I_0} = \Delta I_{thermal}(x, y, T_e) + \Delta I_{kinetic}(x, \tau, v_p)$$
$$= y\left[g(x) + \delta_T(x, T_e)\right] - \beta\tau h(x)$$

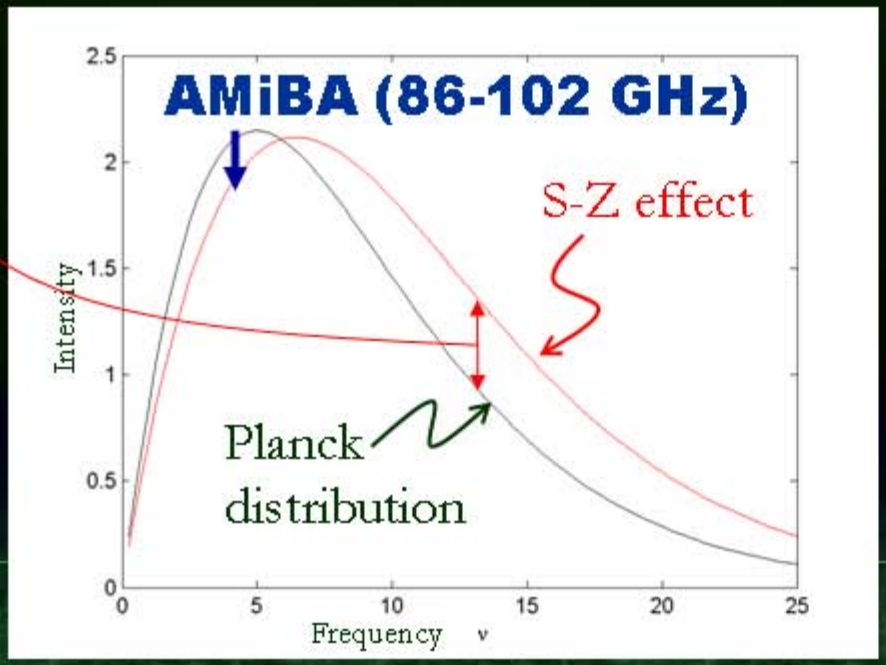
$$x = \frac{h\nu}{kT_{CMB}}, \quad I_0 = \frac{2(kT_{CMB})^3}{(hc)^2}$$

$$y = \frac{k\sigma_T}{m_e c^2}\int T_e n_e dl, \quad g(x) = \frac{x^4 e^x}{(e^x - 1)^2}\left(\frac{x}{\tanh(x/2)} - 4\right)$$

$$\beta = \frac{v_p}{c}, \quad \tau = \sigma_T \int n_e dl, \quad h(x) = \frac{x^4 e^x}{(e^x - 1)^2}$$

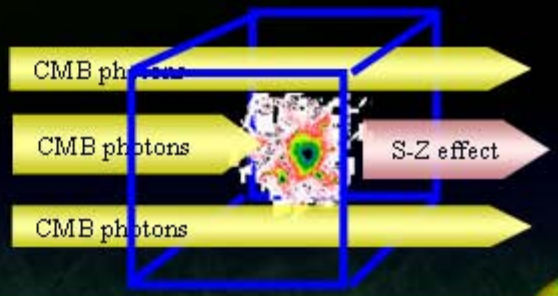
c : speed of light
m_e : electron mass
n_e : electron number density
T_e : electron temperature

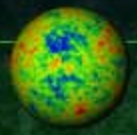
k : Boltzmann constant (erg/K)
h : Planck constant
T : CMB temperature
y : Compton-y parameter
σ_T : Thomson cross section



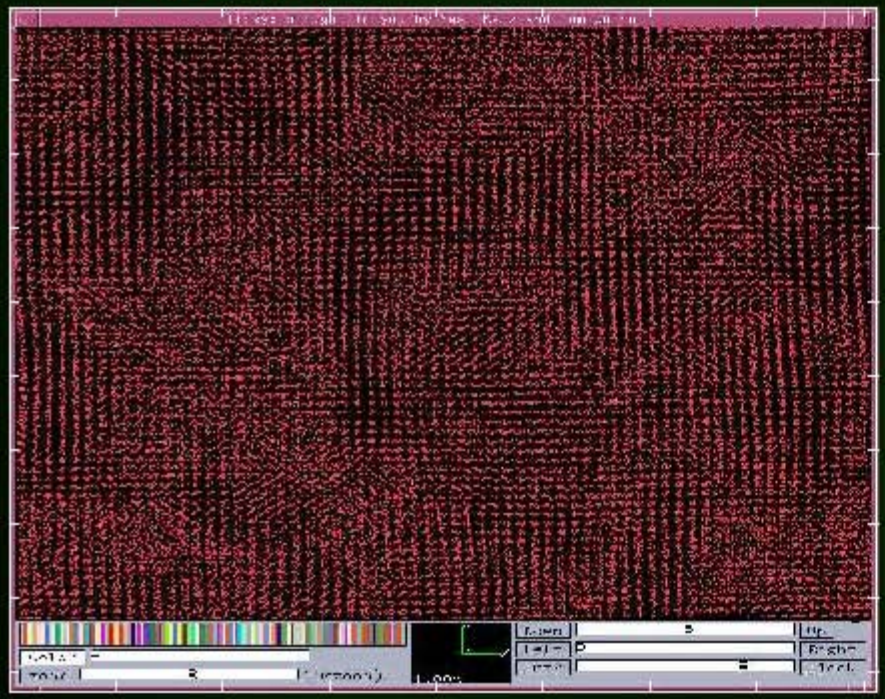
SZE parameters:

$y,\ v_p,\ T_e$



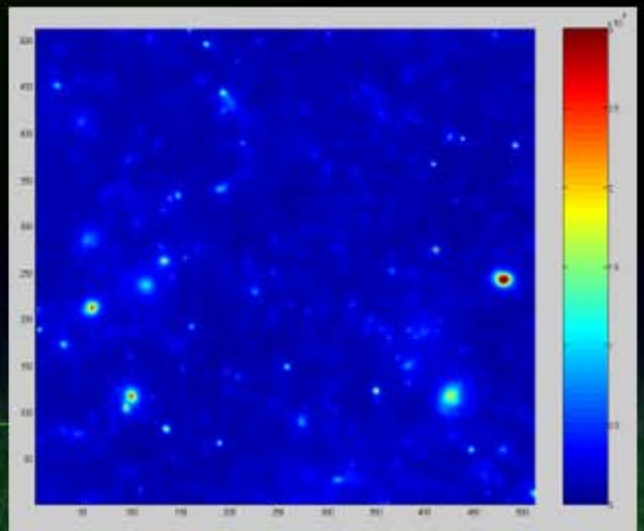


Structure formation:
baryons(red) + CDM(white) +DE



Resulting SZ map:

(Wu, Wang, Tseng, 2005)

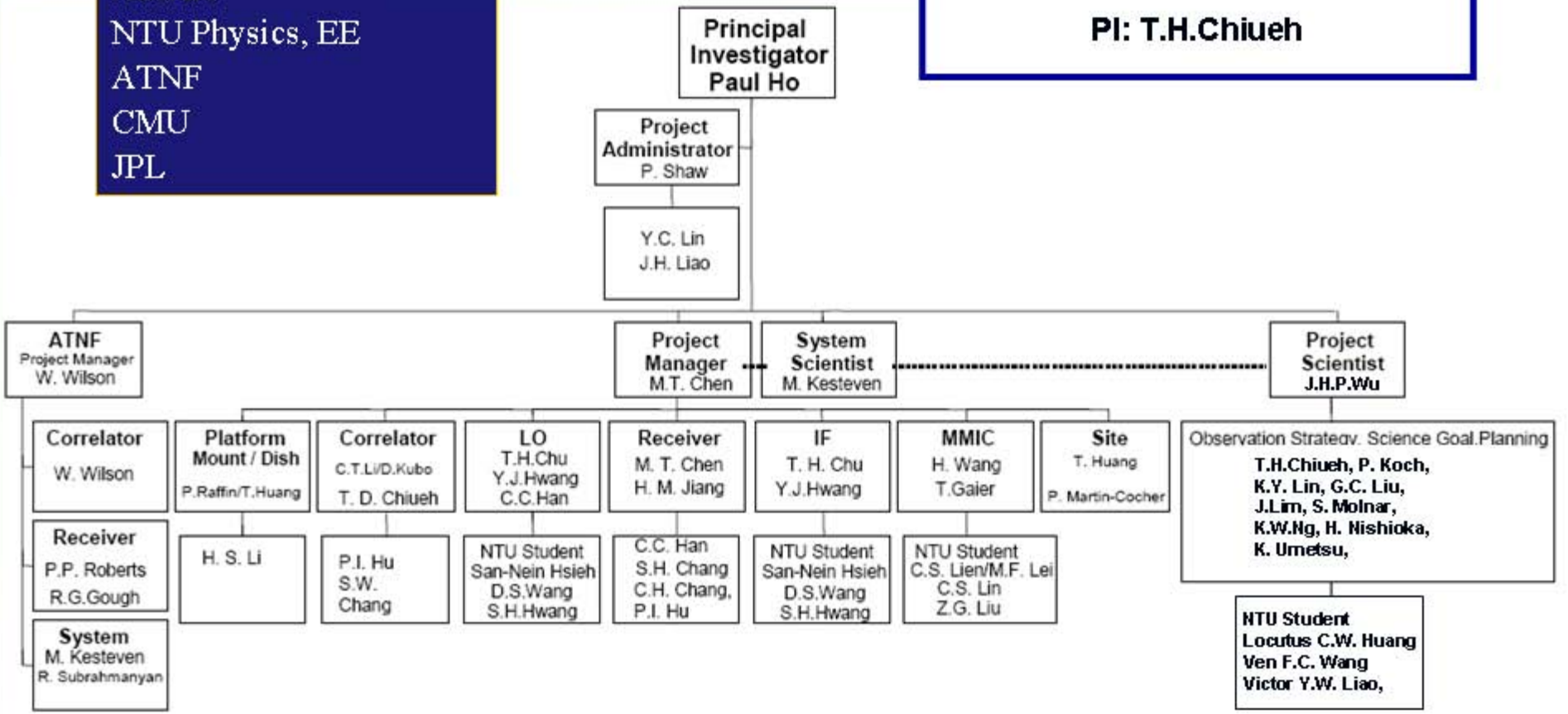


AMiBA Organization

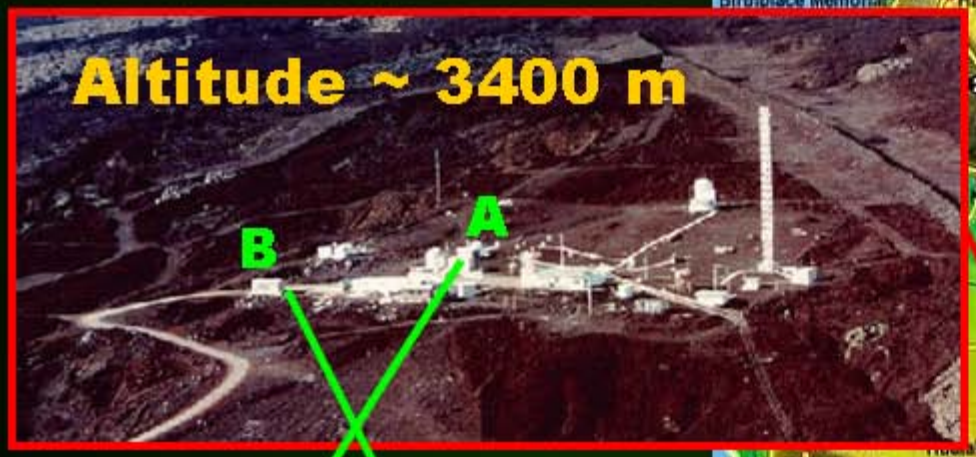
ASIAA
NTU Physics, EE
ATNF
CMU
JPL

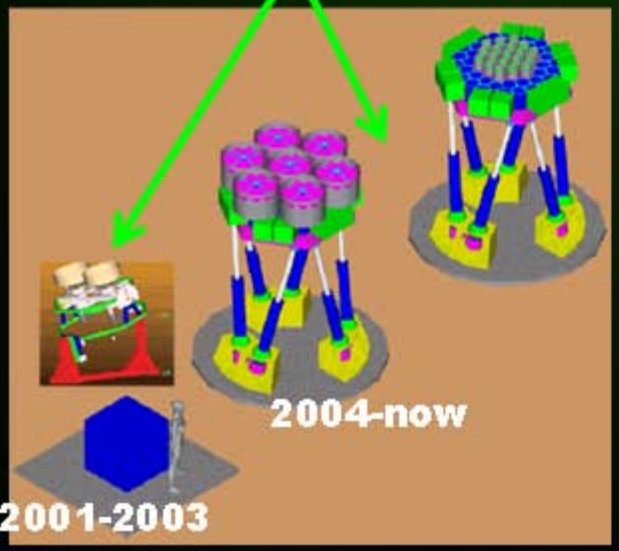
NTU-Array (eAMiBA)
(wide-band digital correlators)

PI: T.H.Chiueh



AMiBA Site – Mauna Loa, Hawaii



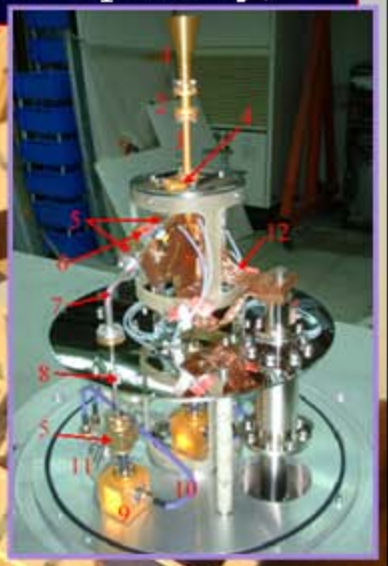


Field of view: **23'**

7 **60**-cm Cassegrain antennas
=> 21 baselines=**12**+**6**+**3**

Resolution: **10'** **6'** **5'**

- Dual-channel 86-102 GHz (94GHz)
  (suppress synchrotron, dust)
  - HEMTs at 20K
  - (Full polarization capability)

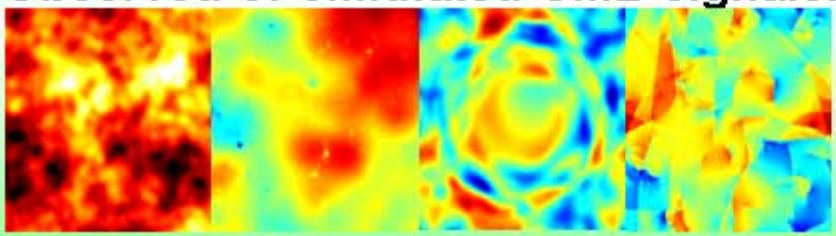


5.6m
1.2'

AMiBA Specifications (current)

Overview of AMiBA Science

Observed or simulated CMB signals:



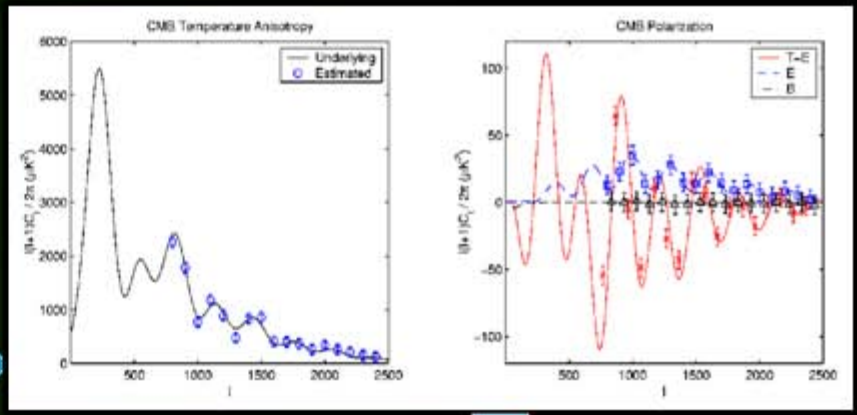
Inflation SZ effects Lensing effects Cosmic strings

Data Taking (with **AMiBA**)

Fringe/lag data (Interferometer)

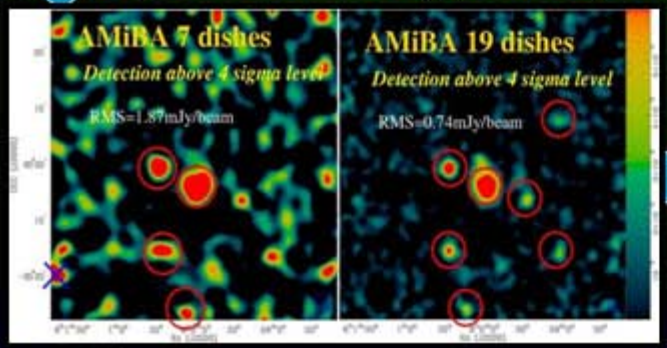
Power-Spectrum Estimation

(maximum-likelihood analysis)



Map Making

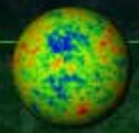
(maximum-entropy method, etc.)



2007

1. SZE science
2. Cosmic defects (monopoles, strings, etc.)
3. Polarization
4. Cosmological Parameters

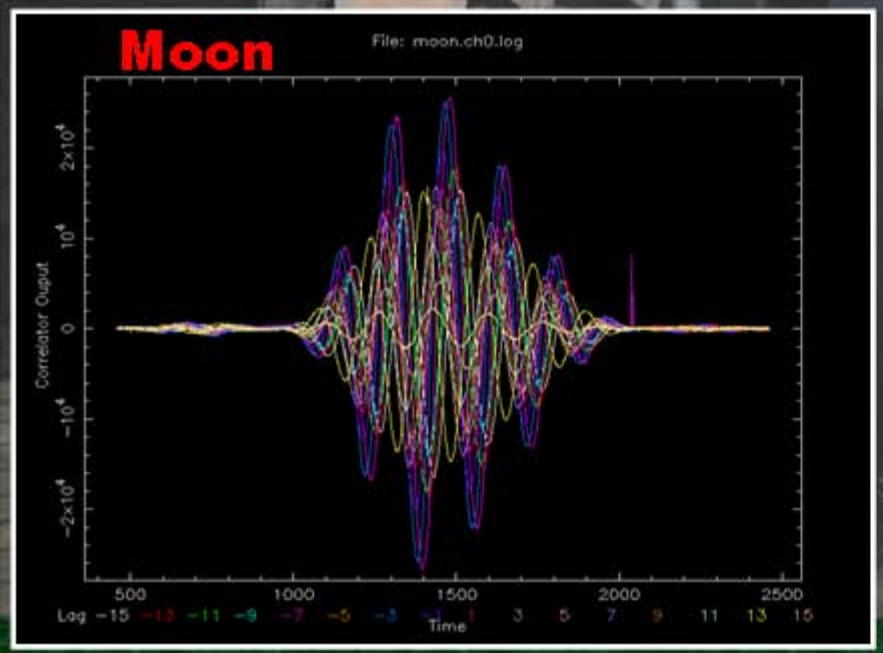
(Ω_t Ω_b Ω_c Ω_Λ H σ_8 w n_s n_T τ_c etc.)

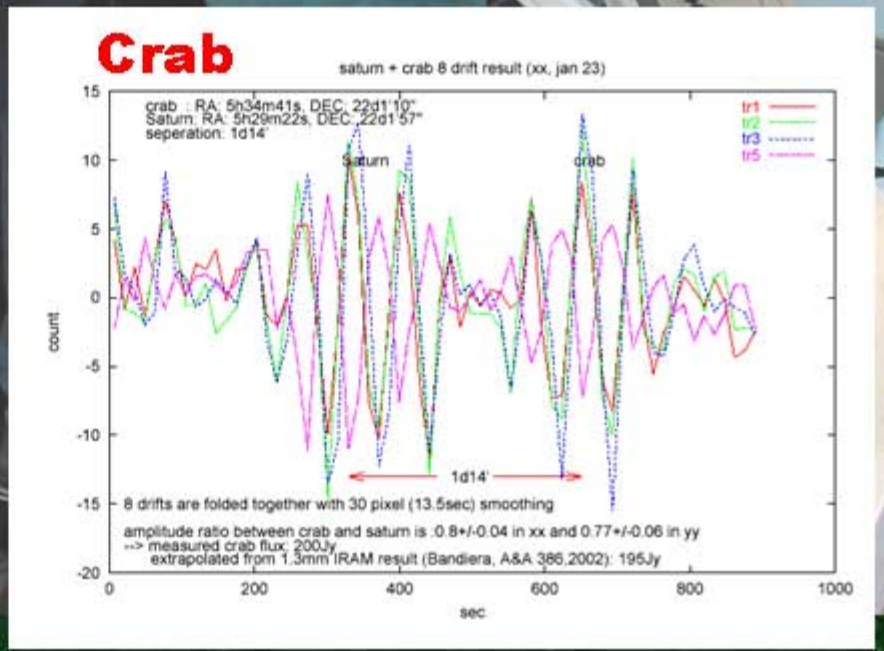


Milestones ....

Dec. 2002:

First light for prototype

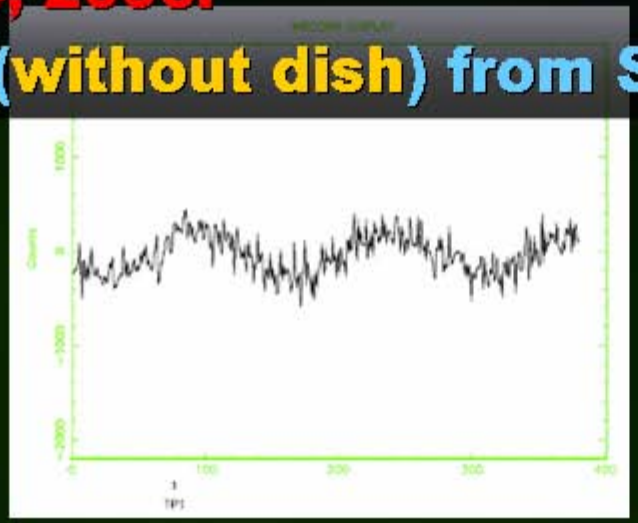




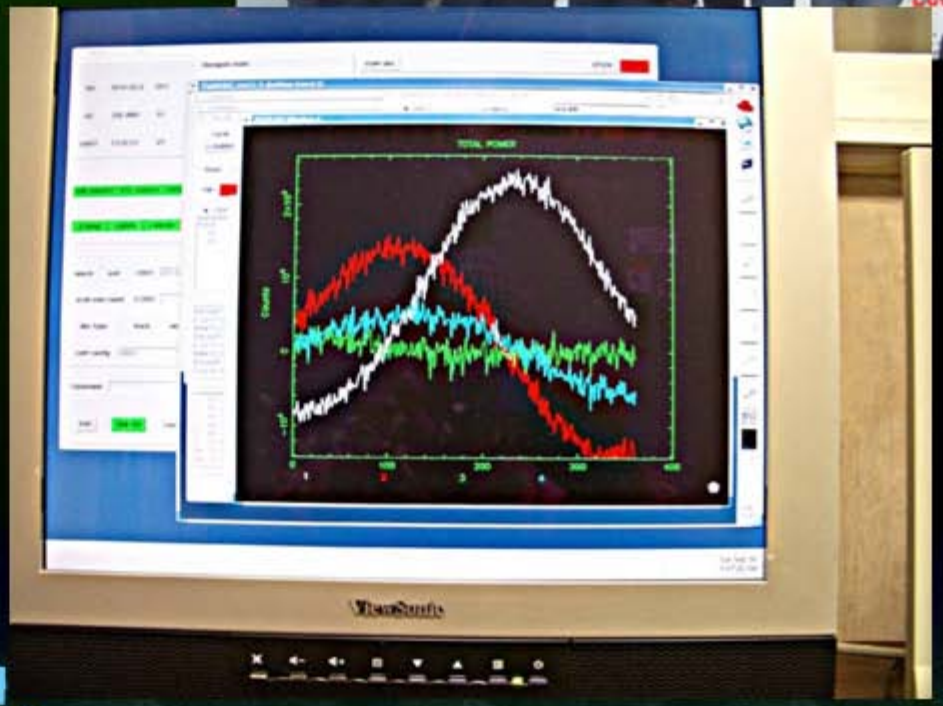
April 16, 2004:
Ground-breaking ceremony

Sept. 2005: Production type

March 14, 2006:
1st light (without dish) from Sun

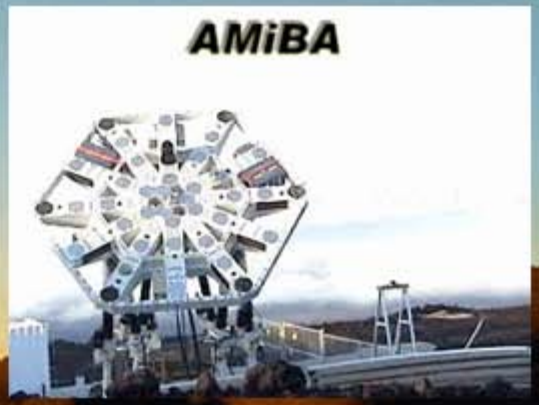


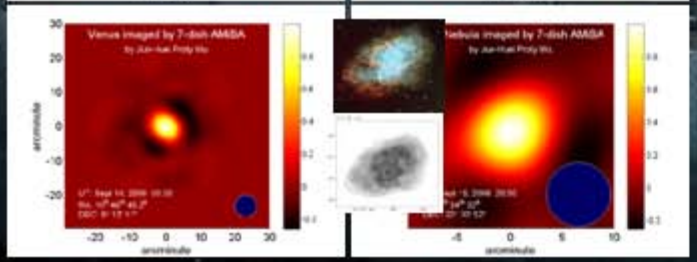
Sept. 6, 2006:
1st light (with dish) from Jupiter



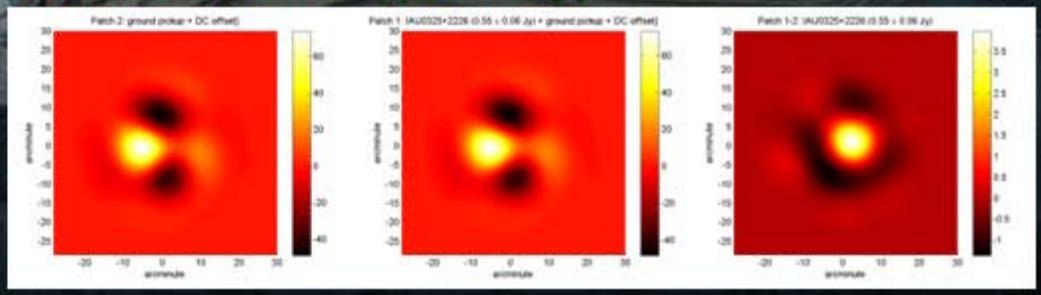
Oct.3, 2006:

Dedication ceremony





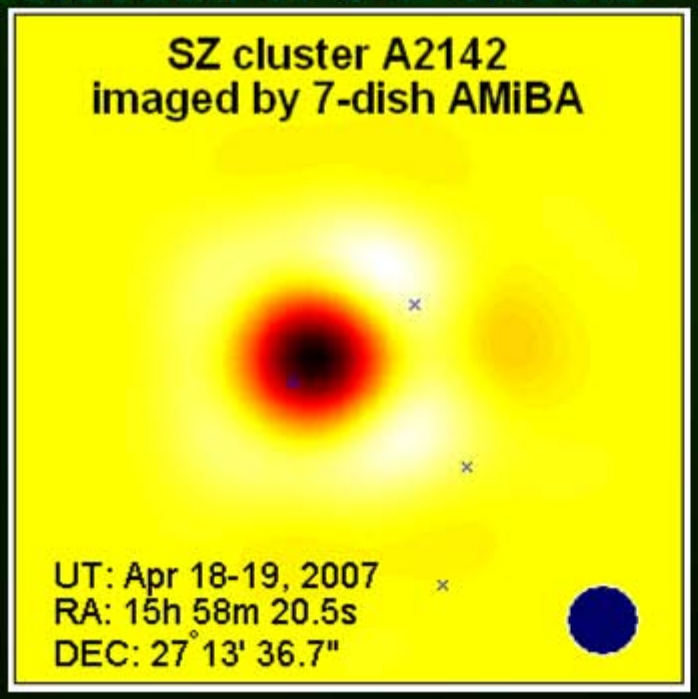
Feb. 07: Quasar (550mJy)



Wu et al. (ApJ. 2009)

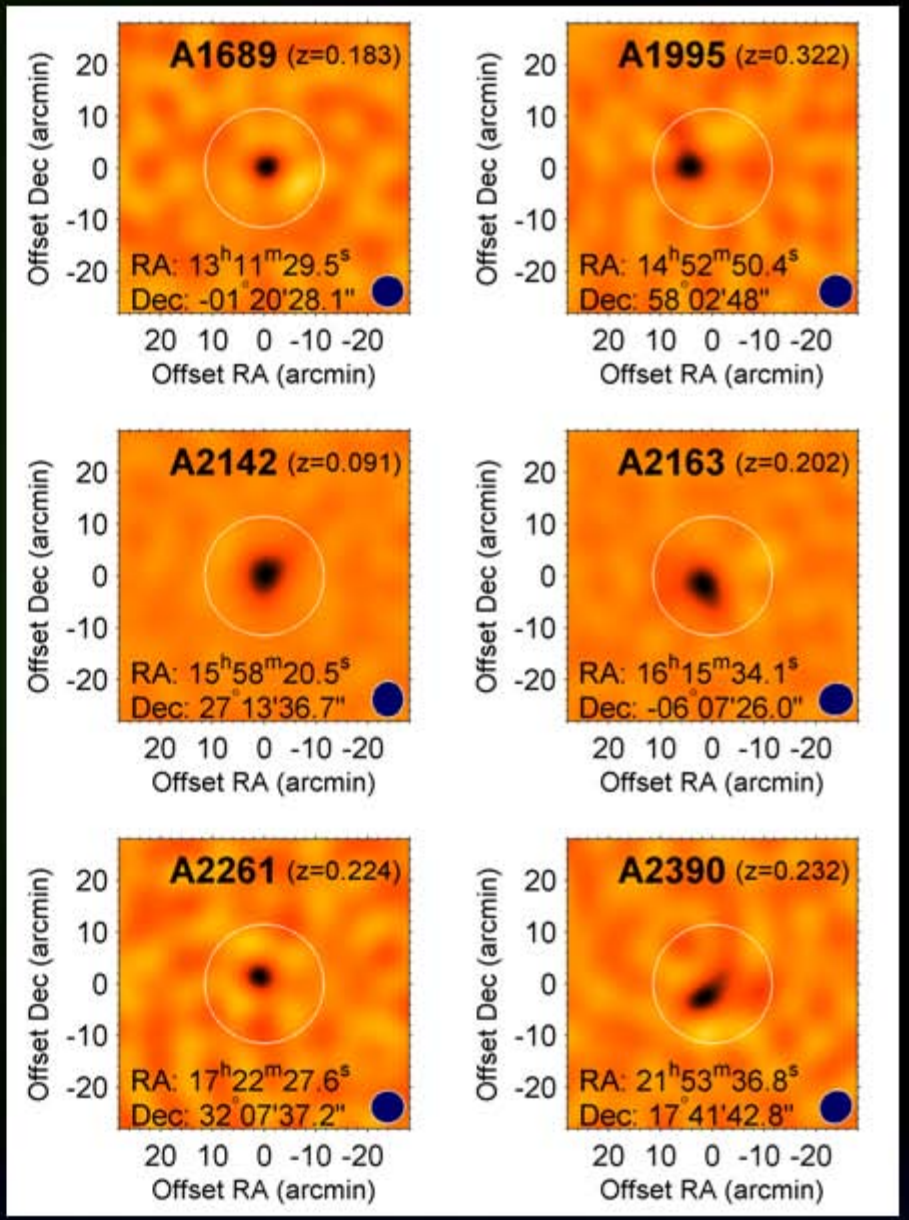
Apr. 18, 2007:

First detection of S-Z effects



2007-2008:

Detected 6 SZE clusters...



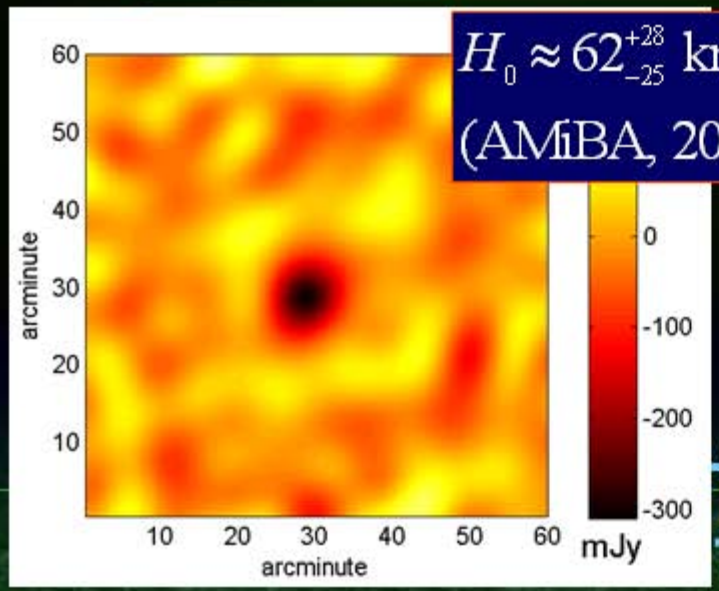
Estimation of Hubble parameter

- S-Z dominated by thermal effect at 94 GHz.
- Cluster model (isothermal β model)

$$\frac{\Delta I(x)}{I_0} \approx \Delta I_{thermal}(x,y,T_e) \approx yg(x) \propto T_e \int n_e dl$$

$$n_e(r) = n_c \left[1+\left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}$$

$$\Delta I(x) \propto T_e n_{ec} \theta_c D_A \left[1+\left(\frac{\theta}{\theta_c}\right)^2\right]^{-3\beta/2+1/2} \propto n_{ec} D_A \propto h^{1/2} h^{-1} = h^{-1/2}$$



$H_0 \approx 62^{+28}_{-25}$ km s^{-1}Mpc^{-1} (AMiBA, 2007)

$H_0 \approx 72 \pm 8$ km s^{-1}Mpc^{-1} (HST, 2001)

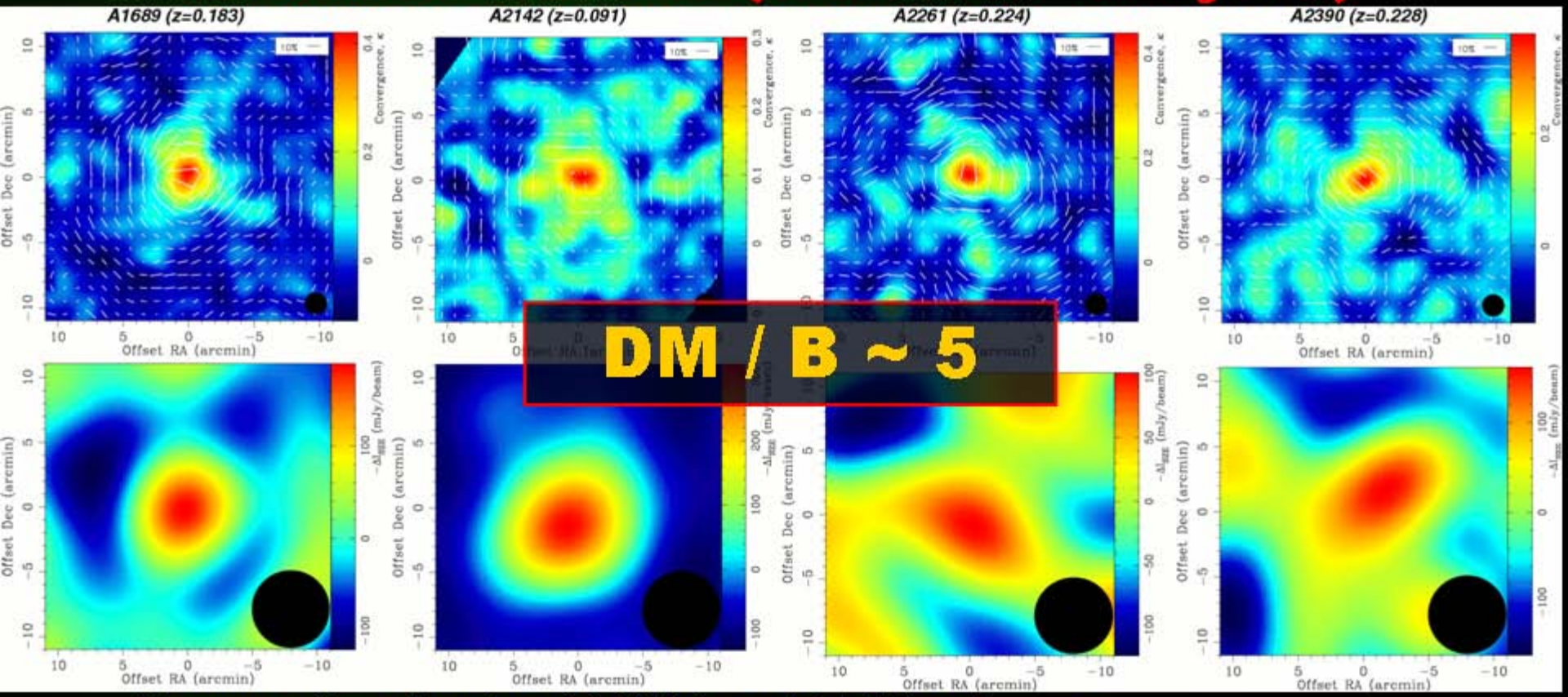
$H_0 \approx 70.1 \pm 1.3$ km s^{-1}Mpc^{-1} (WMAP, 2008)

$H_0 \approx 68^{+21}_{-14}$ km s^{-1}Mpc^{-1} (CBI, 2004)

Koch et al. 2008

Invesitgation for distribution/fraction of baryons and dark matter

Dark Matter distribution (Subaru Weak-Lensing data)



Baryon distribution (AMiBA S-Z Effect)

Umetsu et al. 2008

Scaling relationship (SZE + X-ray)

Huang et al. 2008

Liao et al. 2008

X-ray: X-ray emission measure and spectrum

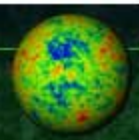
ICM temperature T_{gas}, core radius θ_c, isothermal β, total mass (assuming hydrostatic equil) M_{tot}, etc.

SZE: integrated Compton-y = integrated ICM pressure

$$Y = \frac{\triangle I_{0(SZE)}}{I_{CMB} f(x)} \frac{e^x - 1}{x e^x} \int \left(1 + \frac{\theta^2}{\theta_c^2}\right)^{(1-3\beta)/2} \theta d\theta$$

Quantitative test of "Self-similar model":

$$Y \propto T_e^{5/2} E(z)^{-1}$$
$$Y \propto M_{tot}^{5/3} E(z)^{2/3}$$
$$Y \propto L^{5/4} E(z)^{-9/4}$$



MAXIPOL - to measure CMB Polarization

MAXIMA

retrofit

MAXIPOL

MAXIPOL Collaboration

M. E. Abroe (UMN)
P. A. R. Ade (Cardiff, UK)
J. Bock (JPL)
J. Borrill (LBNL)
A. Boscaleri (IFAC-CNR)
P. de Bernardis (URLS, Italy)
J. Collins (UCB)

S. Hanany (UMN) (P.I.)
A. H. Jaffe (Imperial, UK)
B. R. Johnson (UMN)
T. Jones (UMN)
A. T. Lee (UCB)
L. Levinson (WISR, Israel)
T. Matsumura (UMN)
B. Rabii (UCB)

T. Renbarger (UMN)

Nobel Laureate 2006

G. F. Smoot (UCB)
R. Stompor (UP-7, France)
H. T. Tran (UCB)

Science lead

J. H. P. Wu (NTU, Taiwan)
J. Zuntz (Imperial, UK)

THE ASTROPHYSICAL JOURNAL, 665:55–66, 2007 August 10

MAXIPOL: DATA ANALYSIS AND RESULTS

J. H. P. WU,[1] J. ZUNTZ,[2] M. E. ABROE,[3] P. A. R. ADE,[4] J. BOCK,[5] J. BORRILL,[6,7] J. COLLINS,[8] S. HANANY,[3] A. H. JAFFE,[2] B. R. JOHNSON,[9] T. JONES,[3] A. T. LEE,[7,8,10] T. MATSUMURA,[3] B. RABII,[8] T. RENBARGER,[3] P. L. RICHARDS,[8] G. F. SMOOT,[7,8,9] R. STOMPOR,[6,11] H. T. TRAN,[7,8] AND C. D. WINANT[8]
Received 2006 November 12; accepted 2007 February 21

We present results f
the polarization in the
sults using a rotating
area of 8 deg^2 with 10
timate maps of the Q
frequentist approache
We give results for th
without a prior C_ℓ^{EB} =
systematic tests inclu
leakage from tempera
tematic errors. The B
confidence level for ℓ
prior the probability o
18^{+27}_{-34} and -31^{+31}_{-19} μ

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MAXIPOL: COSMIC MICROWAVE BACKGROUND POLARIMETRY USING A ROTATING HALF-WAVE PLATE

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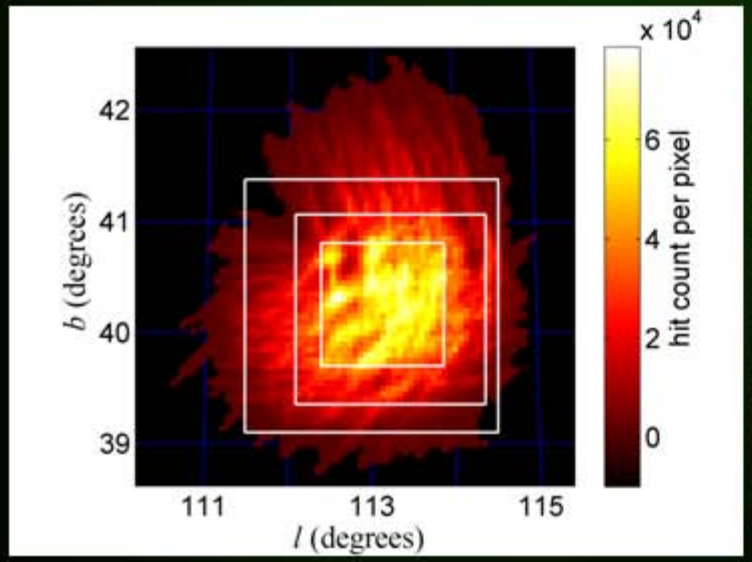
ABSTRACT

We discuss MAXIPOL, a bolometric balloon-borne experiment designed to measure the E-mode polarization

Observations



MAXIPOL-0: Sept. 2002

MAXIPOL-1: May 2003 (Beta Ursae Minoris)

l = 110.69° - 114.98°

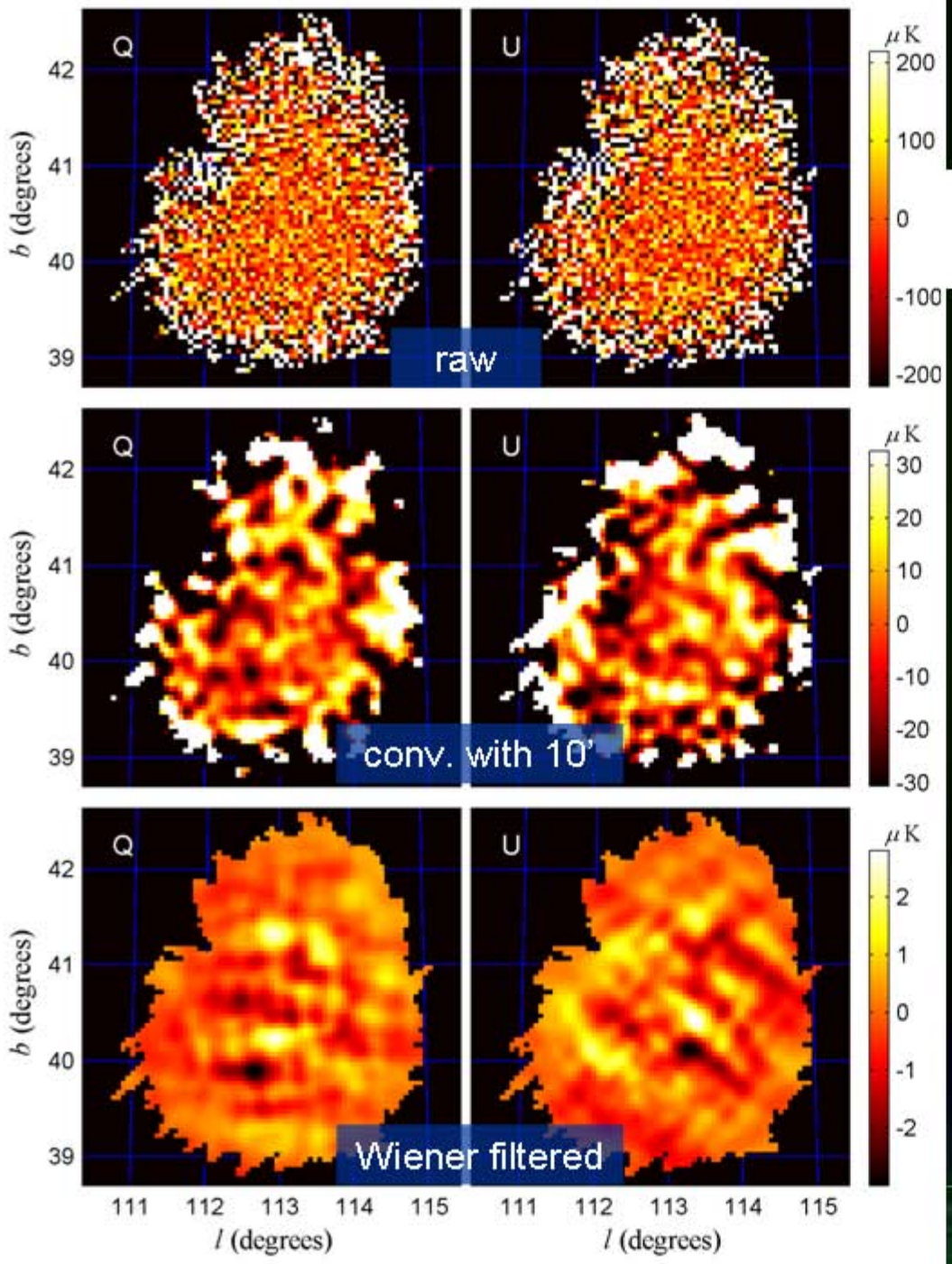
b = 38.75° - 42.49°

7.6 hours (5.6 hours)

All work needs to be done on supercomputers….

Formosa II HPC cluster
National Center for High-performance Computing, Taiwan
IBM e326 320 CPU-Cores

Seaborg: world ranking 14 (National Energy Research Scientific Computing Center at Lawrence Berkeley Naitonal Laboratory)
IBM SP Power3 375 MHz 16 way / 6656 CPU / 9984 GFlops

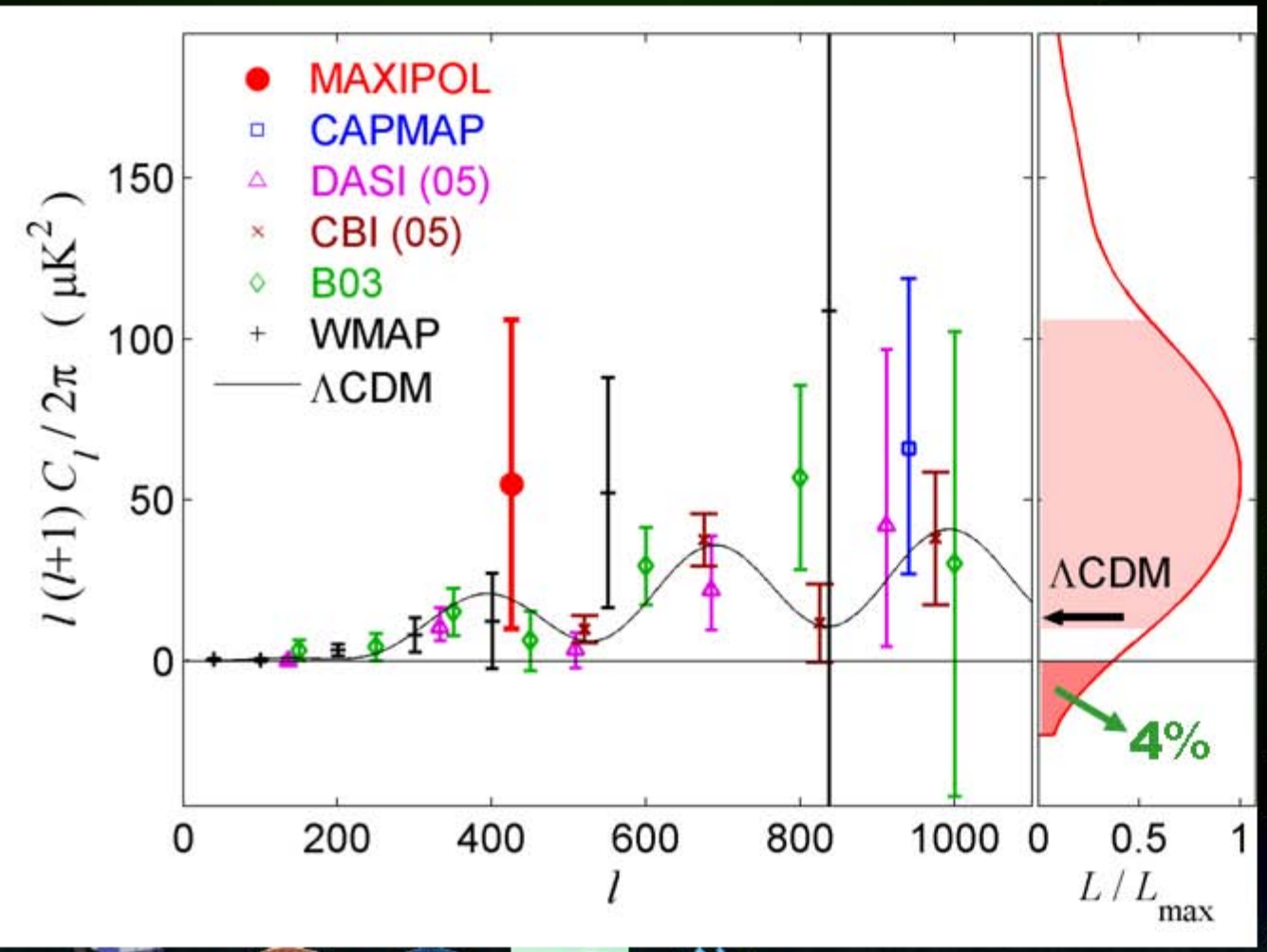


$$(Q \pm iU)(\mathbf{n}) = \sum_{\ell m} \left(a^{E}_{\ell m} \pm i a^{B}_{\ell m}\right) {}_{\pm 2}Y_{\ell m}(\mathbf{n})$$

$$C_{\ell}^{YY'} = \frac{1}{2\ell+1} \sum_{m} a^{Y}_{\ell m} a^{Y'*}_{\ell m}$$

EE spectrum

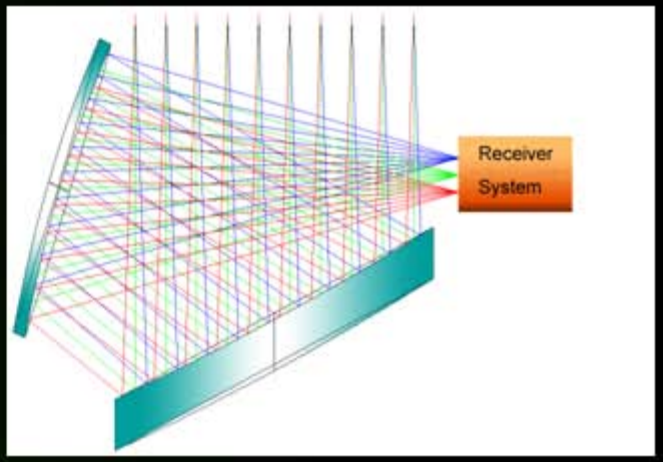
Shape $D_\ell^{(n)}$	No Prior	$C_\ell^{EB} = C_\ell^{BB} = 0$
$1/[\ell(\ell+1)]$	96%	83%
ΛCDM	94%	-
$1/(2\ell+1)$	98%	92%
1	98%	-



Shape $D_\ell^{(n)}$	Mode	68%	95%
Bayesian $C_\ell^{EB} = C_\ell^{BB} = 0$			
$1/[\ell(\ell+1)]$	12	$^{+40}_{-21}$	$^{+83}_{-38}$
$1/(2\ell+1)$	41	$^{+59}_{-38}$	$^{+130}_{-71}$
Bayesian $C_\ell^{EB} = C_\ell^{BB} = 0$ (inc. σ_{cal})			
$1/[\ell(\ell+1)]$	12	$^{+41}_{-22}$	$^{+94}_{-38}$
$1/(2\ell+1)$	49	$^{+56}_{-48}$	$^{+144}_{-80}$

B-mode Experiment

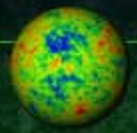
- Detectors, readout: TES polarimeters, SQUID readout system
  Receivers, cryostat
- Mount, drive
- Telescope: 1.5-2m
- Manpower: grads, postdocs
- Operation: **South Pole** (NSF-OPP)
- Analysis, shipping



Why interested in Cosmic Strings?

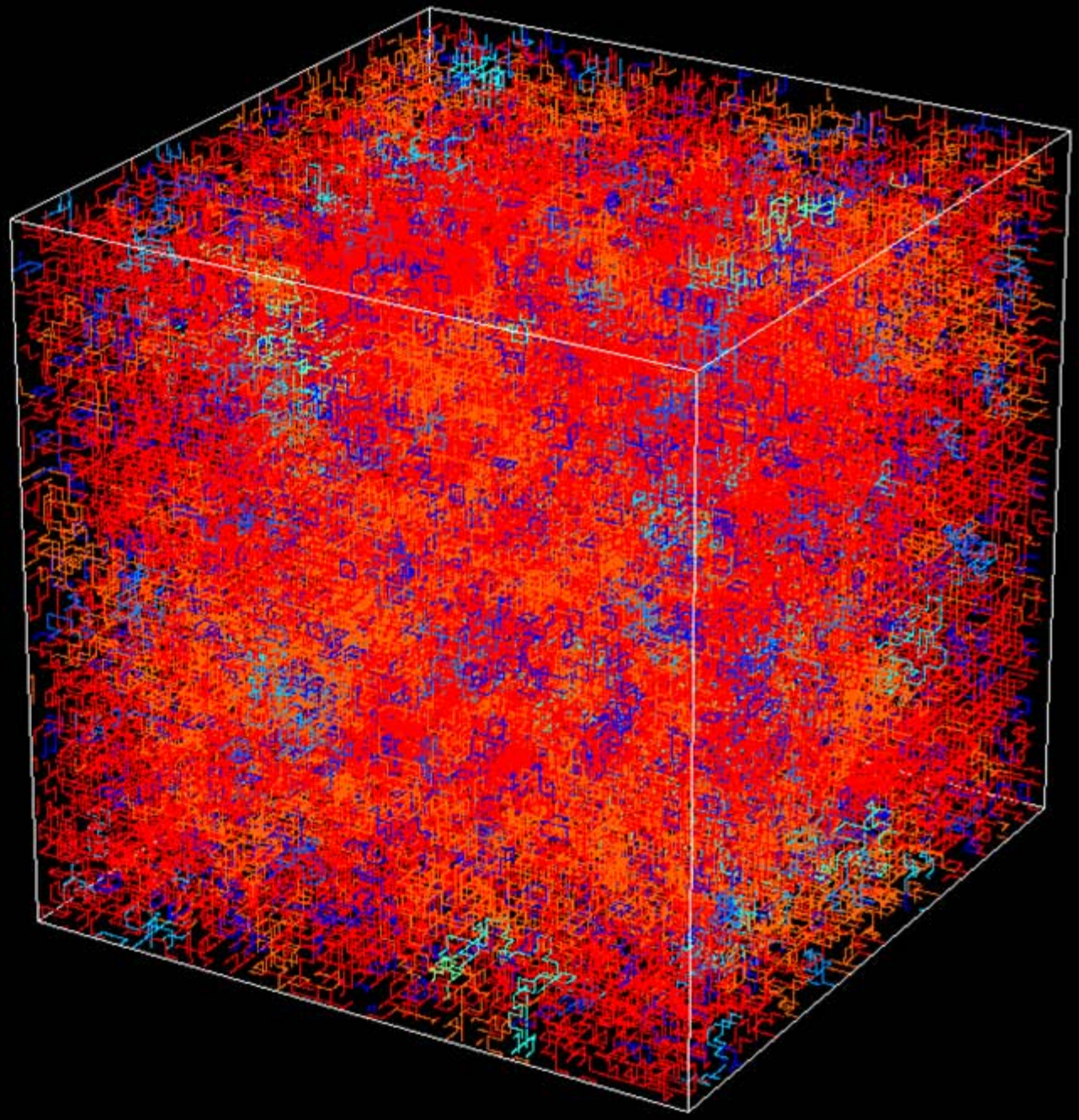
1. In general, when Hybrid inflation ends
   > various defects
   (Copeland et al. 1994)
2. String theory: colliding branes
   > cosmic strings
   (Sarangi & Tye 2002;
   Dvali & Vilenkin 2004)
3. SUSY GUTs: when Hybrid inflation ends
   > cosmic strings
   (Jeannerot,Rocher,Skellariadou 2003;
   Rocher & Sakellariadou 2005)
4. GUT, EW....



String Evolution

(J.H.P. Wu, 2002-2008)

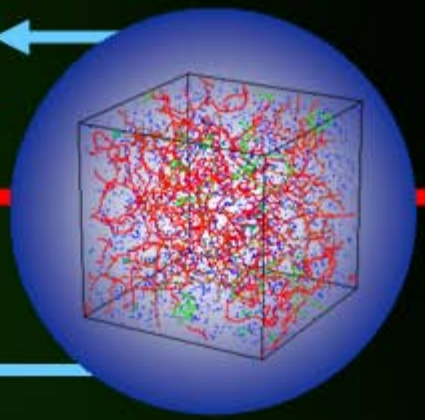


String production

(SUSY GUT, Inflation, String theory, etc)

Einstein-Boltzmann eq.

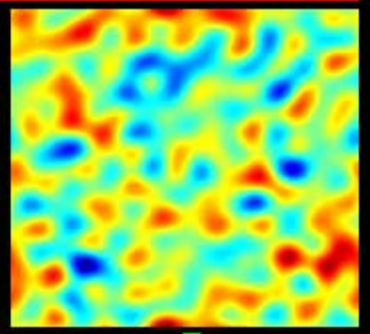
$$F_{\mu\nu}(\delta_{cdm}, \delta_b, \delta_\gamma, \delta_\nu; \mathbf{x}, t) = \Theta_{\mu\nu}(\mathbf{x}, t)$$



Last scattering

Einstein eq.

$$G_{\mu\nu}(\delta_\gamma, \delta_\nu; \mathbf{x}, t) = \Theta_{\mu\nu}(\mathbf{x}, t)$$



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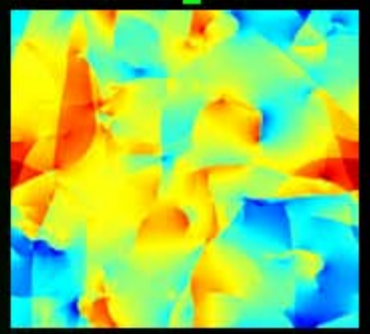

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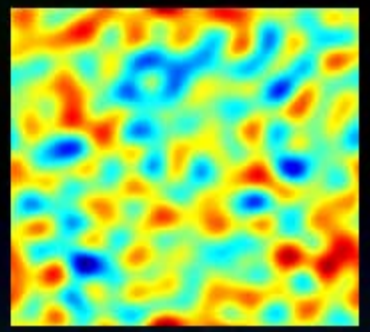
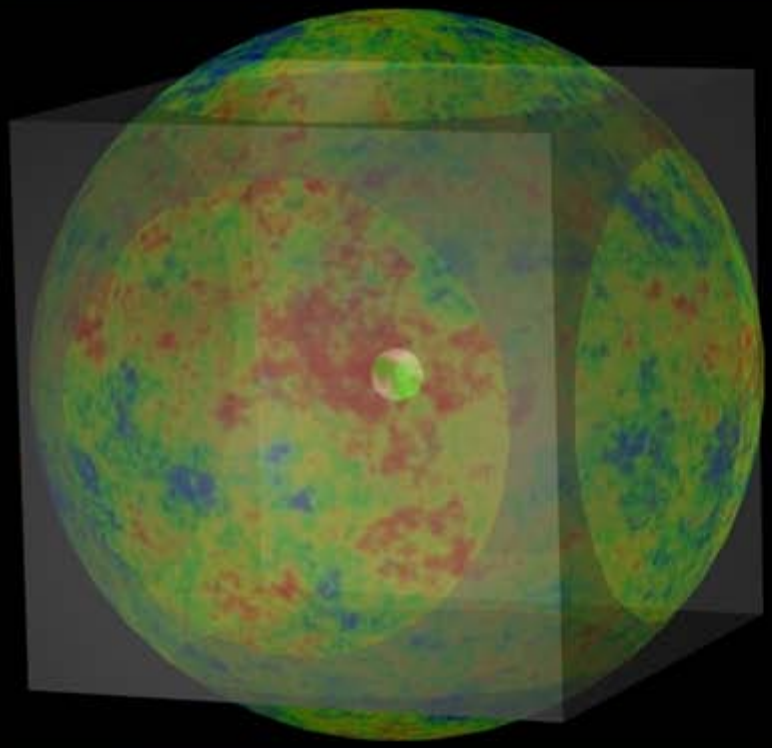
Today

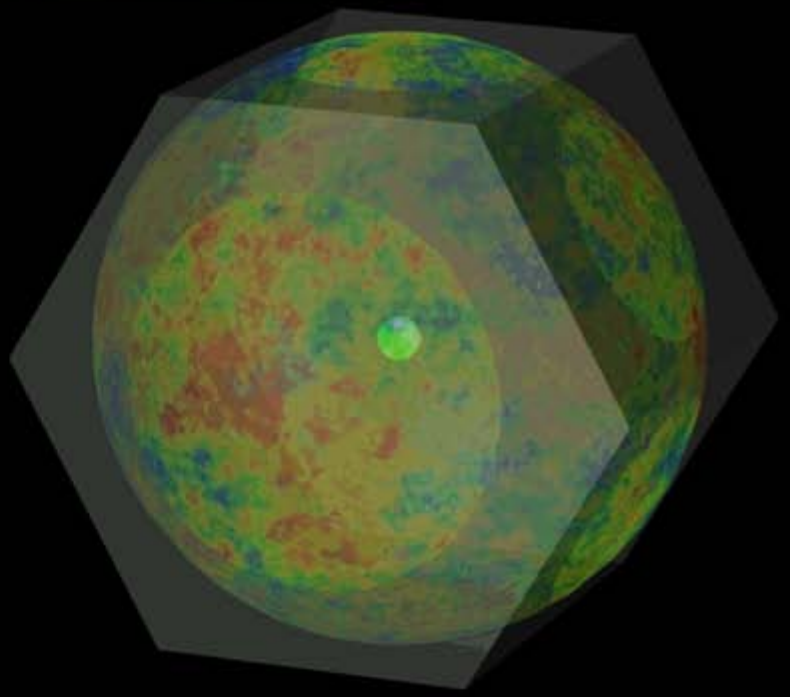


String-induced CMB

Time

Topology & Size of the Universe





Liao & Wu, 2009

Conclusion

- Observations & Experiments:
  - AMiBA, MAXIPOL/EBEX, B-mode Exp.
- Theoretical Studies:
  - Sunyaev-Zel'dovich Effects
  - Cosmic Strings
  - Topology of the Universe
  - (Gravitational Lensing Effects)

You are welcome to join!