First Light in the Universe & Cosmic Evolution:

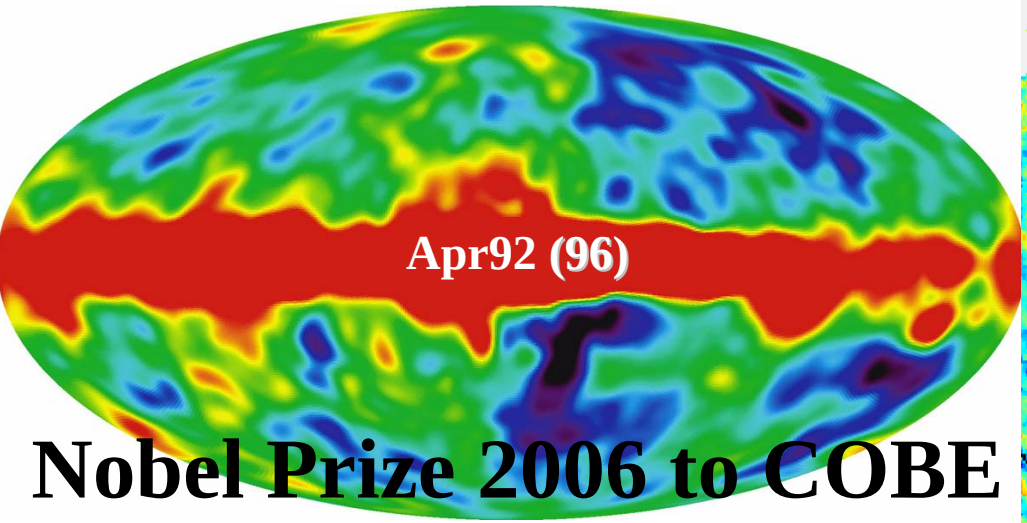
Measuring the Parameters of our Universe

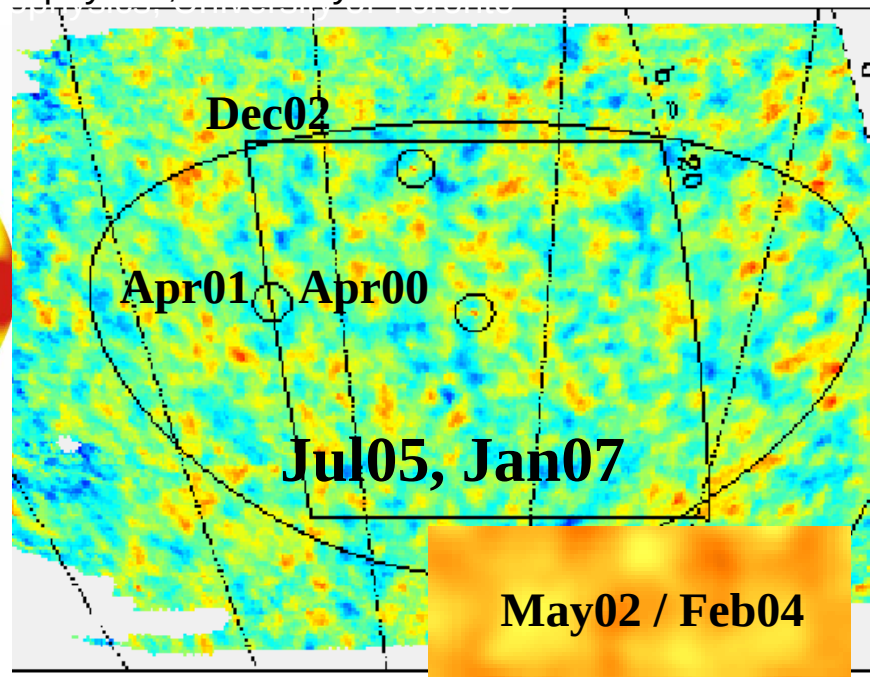
CITA ICAT

Dick Bond

CIAR

Canadian Institute for Theoretical Astrophysics, University of Toronto





Nobel Prize 2006 to COBE

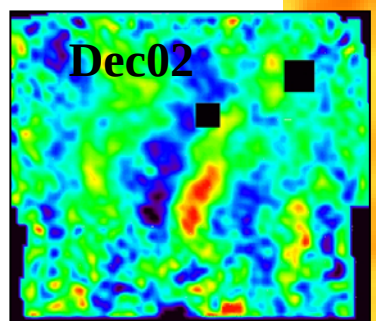
Cosmic history: what is U made of?

Experiment confronts theory: Parameters

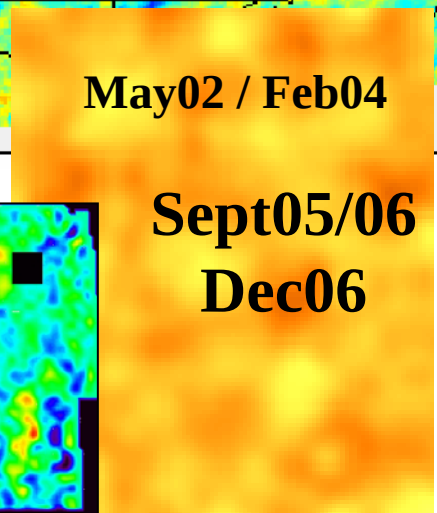
How the Structure of the Universe Arose:

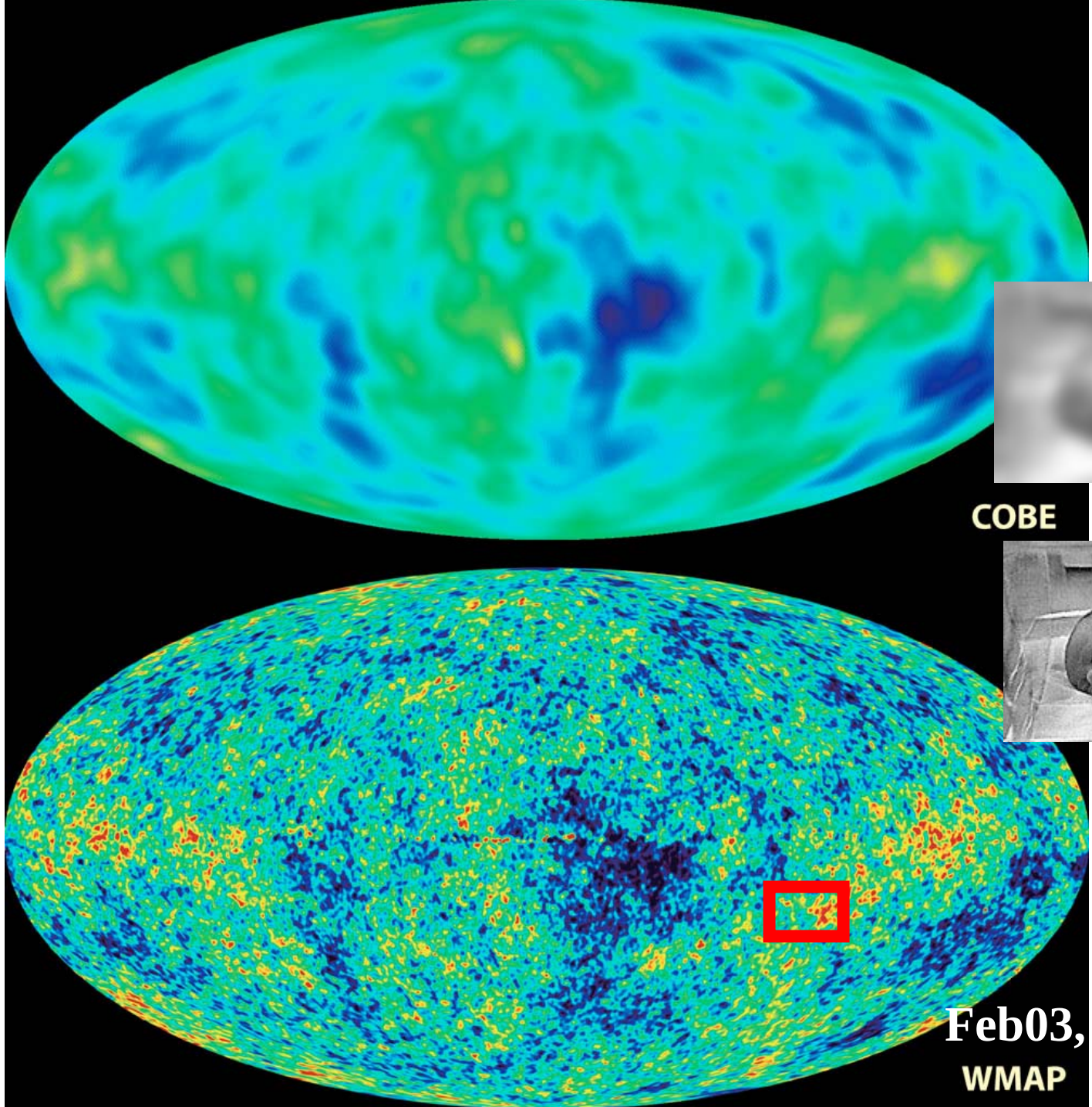
Inflation & the Cosmic Web

(talk link **www.cita.utoronto.ca**)



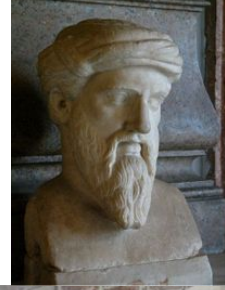
Oct06, Mar07

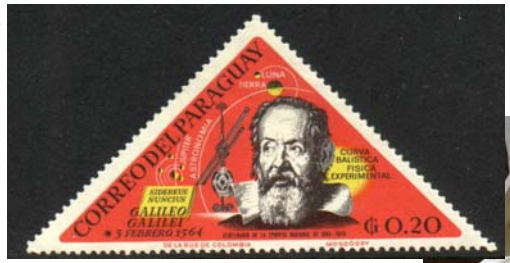


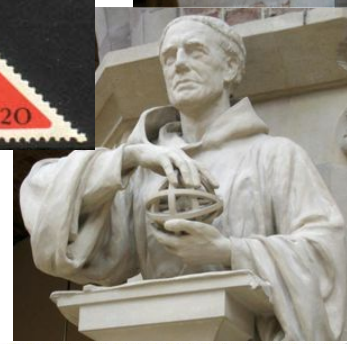

COBE
Feb03, Mar06
WMAP

PYTHAGORAS ~ 550 BCE *The THEORIST*

- ✓ **Cosmos - The Universe as a Mathematical Entity**
- ✓ **Music of the Heavens – Frequency/Wavelength**







ROGER BACON ~ 1260 AD

MARRIAGE: of Experiment to Theory

COPERNICUS/KEPLER/GALILEO et al. ~1600 AD

NEWTON ~ 1660 - 1690 AD *The PHYSICIST*

- ✓ **LAW OF GRAVITATION - Mass Attraction**
- ✓ **Heavenly Objects Arise via Clumping .. *Gravitational Instability***
- ✓ **Thus: the Universe is Infinite**

KANT ~ 1755 AD **Galaxies - 'Island Universes'** **YES! (Early 20s)**

large halo of dark matter 70s/80s relics or remnants?

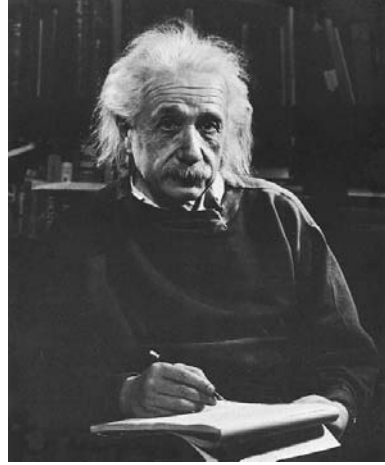
Slipher 1912: redshift, before Hubble expansion, billion solar mass black hole, 9 Mpc away, 0.2 moons across

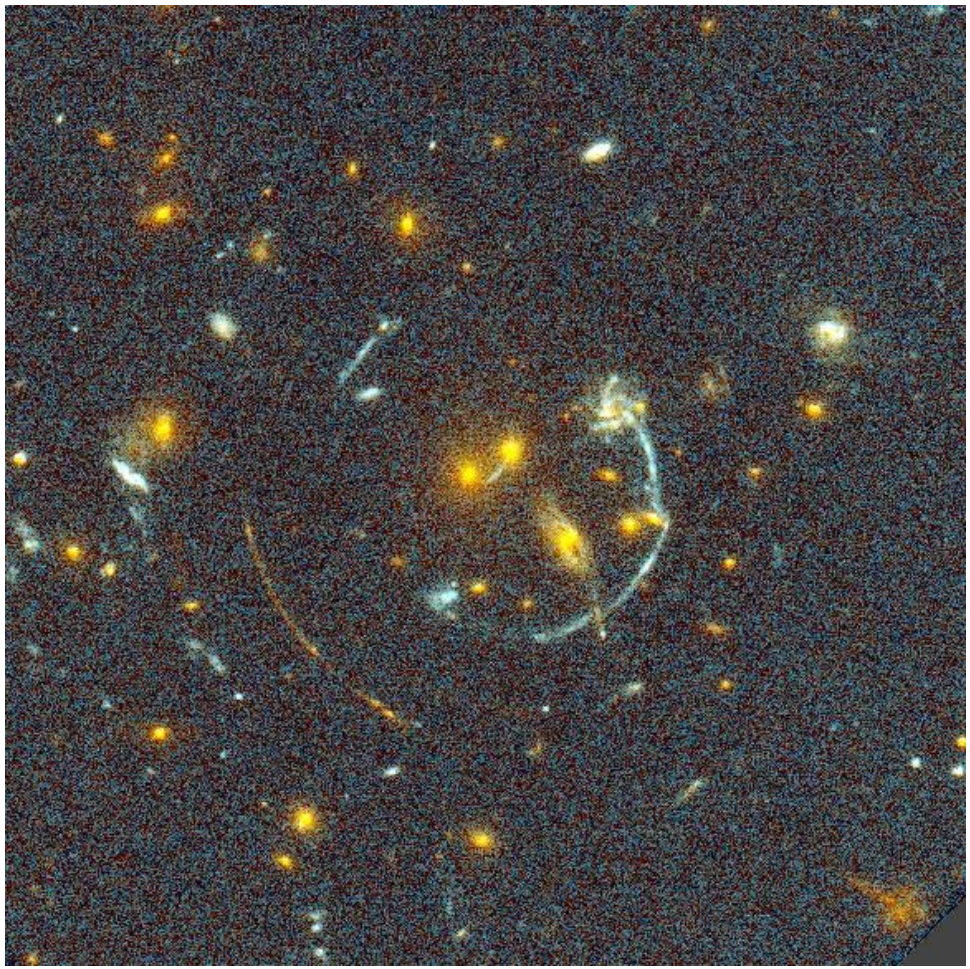
Hubble “Cosmic Evolution Survey”

- 2 deg^2 Hubble Space Telescope data (largest ever Hubble program)
- > 2 million faint galaxies with measurable shapes

EINSTEIN … 1905 international year of physics 2005

- ✓ NEW LAW OF GRAVITATION (1916)
- ✓ speed of light is the ultimate speed ***(HORIZONs)***
- ✓ Space is curved by mass
- ✓ Lightwaves bend, wavelengths change, under gravity





Gravitational lensing of deep galaxies by clusters

Toronto RCS 2001; RCS2 now

CIAR

Hoekstra, Gladders, Yee

Weak lensing via Canada France Hawaii Telescope Legacy Survey 2002-08

Hoekstra, van Waerbeke

CIAR

One of the **most distant galaxies** (Feb 15, 04, very small)

amplified (25X) & sheared (**lensed by the dark matter in a distant cluster**)

Distant Galaxy Lensed by Cluster Abell 2218
Hubble Space Telescope • WFPC2 • ACS
ESA, NASA, J.-P. Kneib (Caltech/Observatoire Midi-Pyrénées) and R. Ellis (Caltech)
CIAR

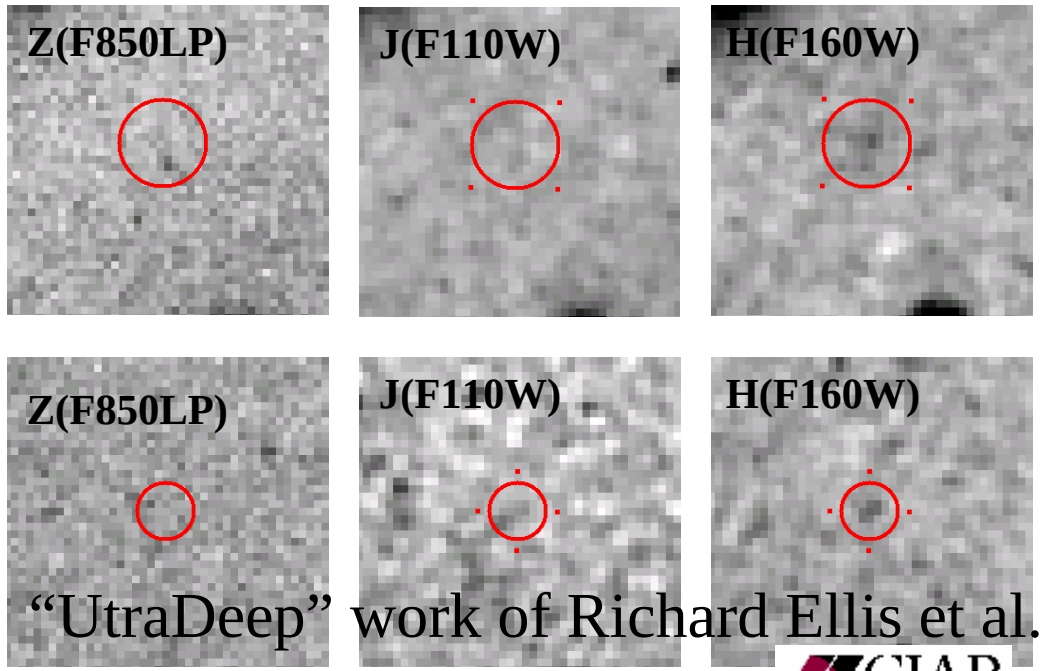
compression factors for **arcs: orange 1.7 blue 2-3.5 red 8 & smudge 11**

DAVE BARRY

Over the years I have been harshly critical of the scientific community for wasting time researching things nobody cares about, such as the universe. I don't know about you, but I'm tired of reading newspaper stories like this:

"Using a giant telescope, astronomers at the prestigious Crudwinkle Observatory have observed a teensy light smudge that they say is a humongous galaxy cluster 17 jillion light years away, which would make it the farthest-away thing that astronomers have discovered this week. However, astronomers at the rival Fendleman Observatory charged that what the Crudwinkle scientists discovered is actually mayonnaise on the lens. Both groups of astronomers say they plan to use these new findings to obtain even larger telescopes."

Galaxies at compression 10



"UtraDeep" work of Richard Ellis et al.,

CIAR

Caltech & CIAR Associate

TMT: Thirty Metre Telescope CIAR

JWST: James Webb Space Telescope

SKA: Square Kilometre Array

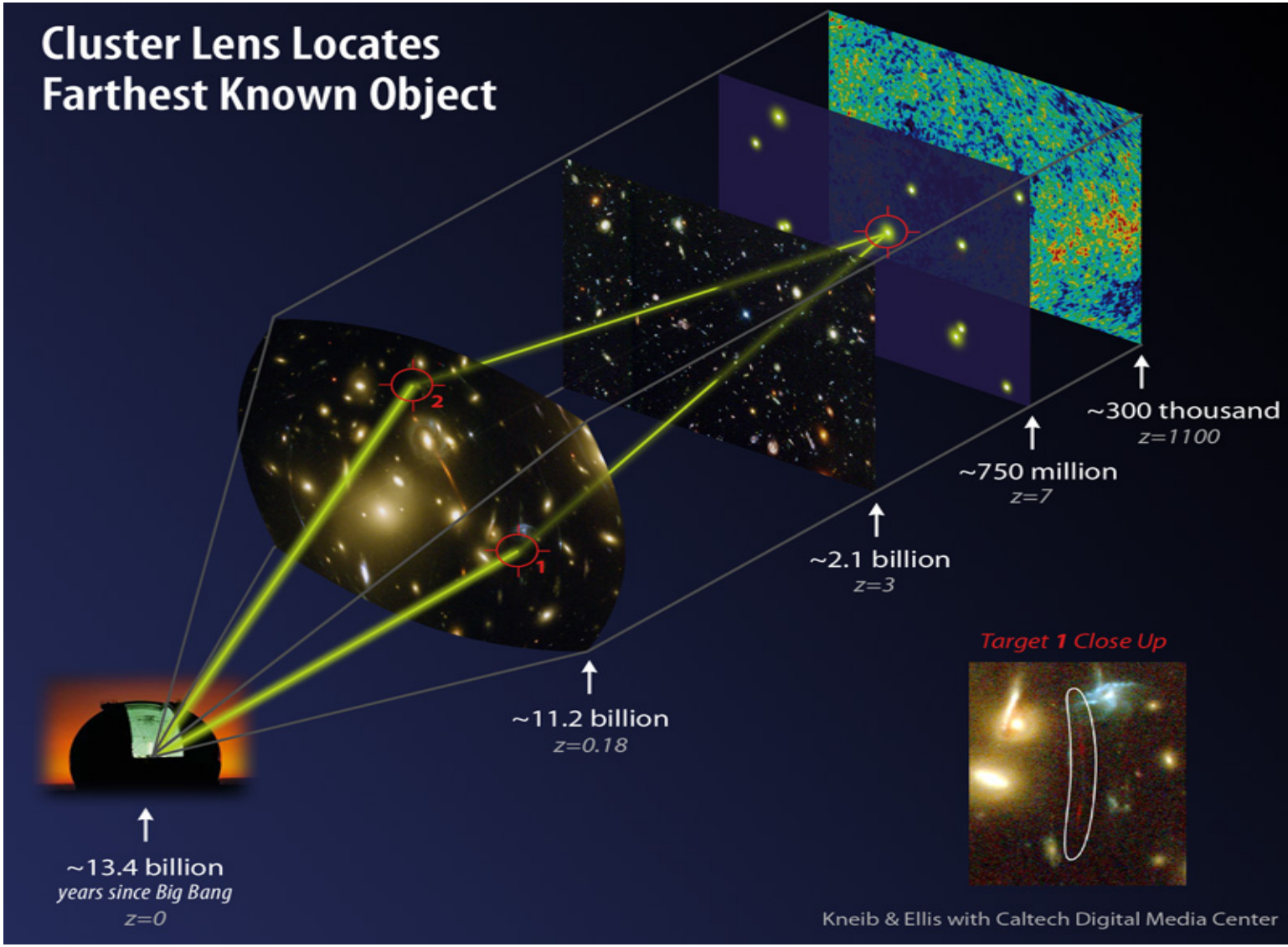
a **starless “dark age”** before the **most distant galaxies**

dwarflets & the 1st stars

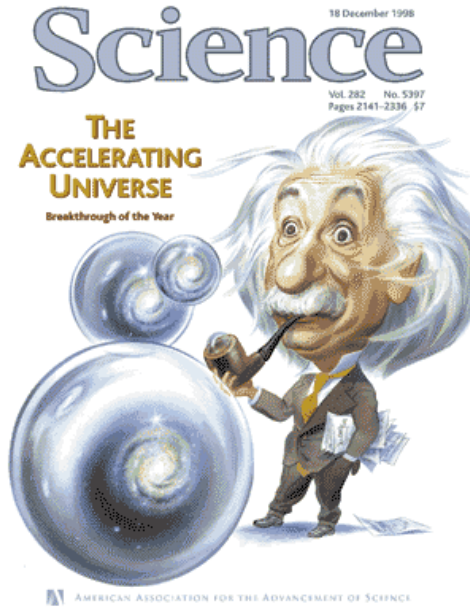
form at compression 13

1st light: Cosmic Microwave Background

released at compression 1100; formed at ~10^{30}



EINSTEIN: SCIENTIFIC COSMOLOGY(1917)



- ✓ Finite universe without a boundary
- ✓ "Cosmological Constant" (~ 1895) Ω_Λ

  Make the Universe Finite via A Repulsive Force

  "My greatest blunder"

Ω_Λ = vacuum energy

(Sakharov ~67)

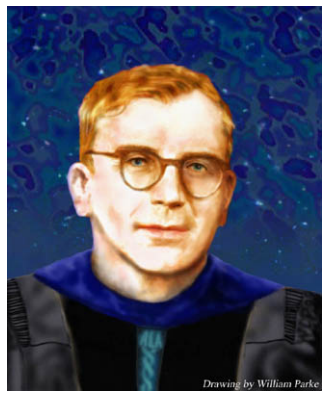
Ω_{cdm} = dark matter

Ω_b = ordinary matter

FRIEDMANN (1922) Evolving (Expanding) Universe

- ✓ YES! Hubble (late 20s)
- ✓ the SINGULARITY (30s,60s), infinite density (!!!???)

- ✓ GAMOW (40s, early 50s) HOT BIG BANG MODEL
- ✓ Hydrogen (75%) & Helium (25%) (Deuterium/Lithium) from the first minutes
- ✓ **Carbon, Oxygen, Iron, … from exploding stars (40s-80s)**



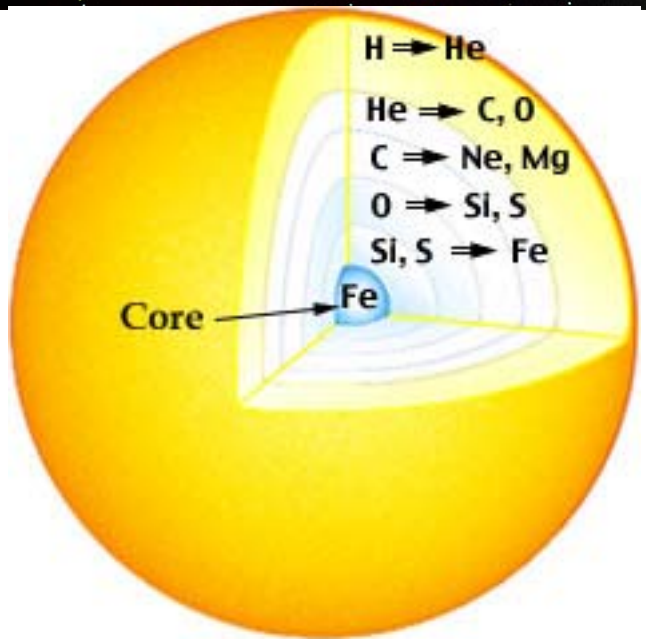
Crab 1054 AD SN + pulsar
i.e. neutron star remnant

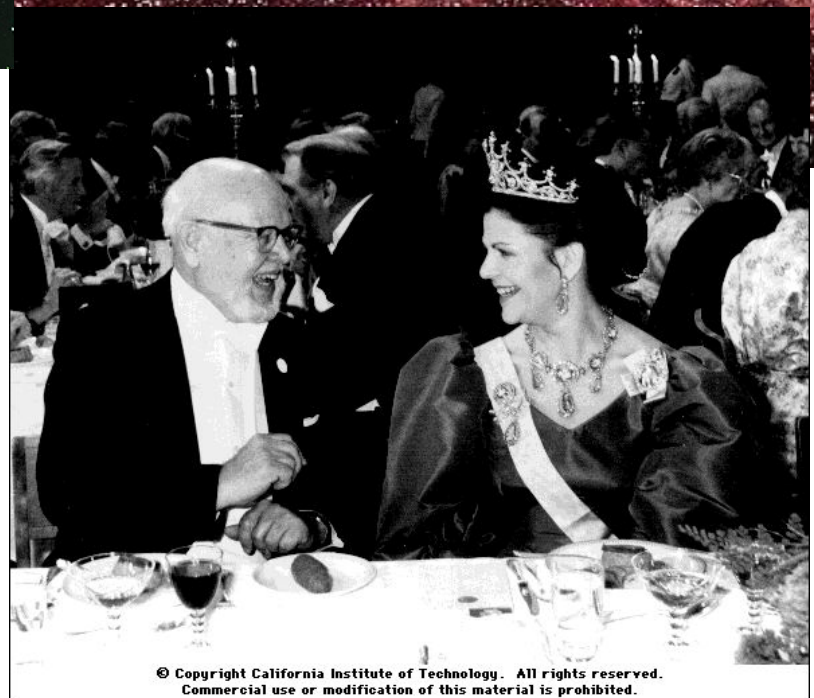
SN1987a @LMC

collapse neutrinos,

no neutron star yet

SN1987a + 17 yrs





Nobel Prize 84 Willy Fowler + Chandra -sekhar

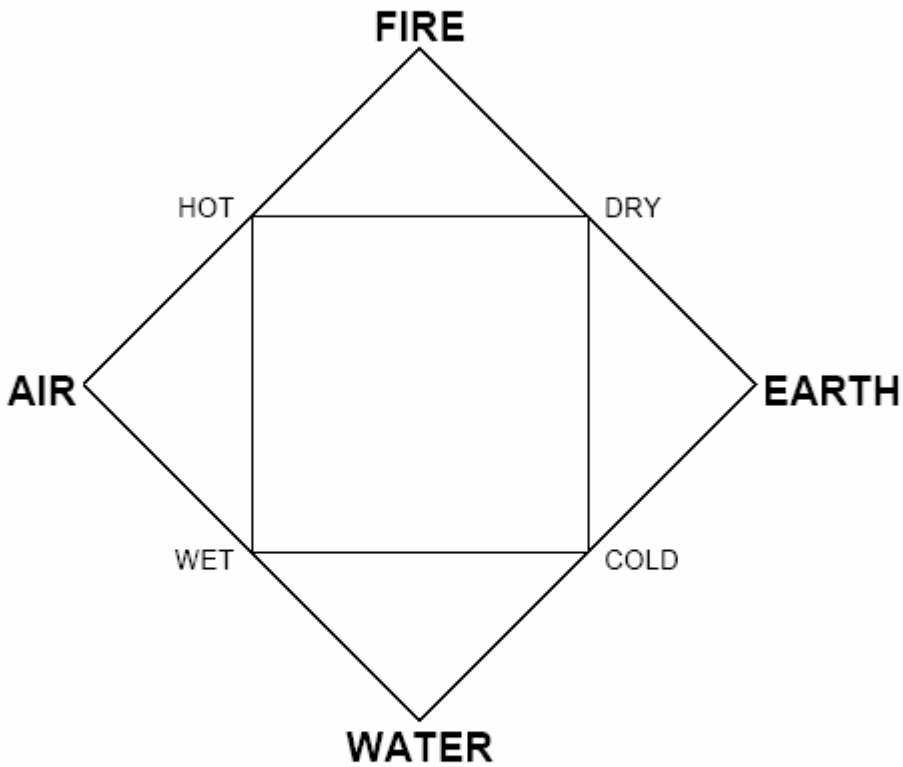
Periodic Table for the *Table of Isotopes** (2001)

1 (IA)	2 (IIA)	3 (IIIB)	4 (IVB)	5 (VB)	6 (VIB)	7 (VIIB)	8 (VIII)	9 (VIII)	10 (VIII)	11 (IB)	12 (IIB)	13 (IIIA)	14 (IVA)	15 (VA)	16 (VIA)	17 (VIIA)	18 (VIIIA)
Hydrogen $^{1}H_{1}$ -259.34° -252.87° -240.18° +1-1 1.00794 91.0%																	**Helium** $^{2}He_{2}$ -272.2° -268.93° -267.96° 0 4.002602 8.9%
Lithium $^{2}_{1}Li_{3}$ 180.5° 1342° +1 6.941 1.86×10^{-7}%	**Beryllium** $^{2}_{2}Be_{4}$ 1287° 2471° +2 9.012182 2.38×10^{-6}%	Group Element K L M N O P Q E_Z M.P.° B.P.° O.S. At.W. Abund%										**Boron** $^{2}_{3}B_{5}$ 2075° 4000° +3 10.811 6.9×10^{-6}%	**Carbon** $^{2}_{4}C_{6}$ 4492° 3642° +2+4-4 12.0107 0.033%	**Nitrogen** $^{2}_{5}N_{7}$ -210.00° -195.79° -146.94° ±1±2±3+4+5 14.00674 0.0102%	**Oxygen** $^{2}_{6}O_{8}$ -218.79° -182.95° -118.56° -2 15.9994 0.078%	**Fluorine** $^{2}_{7}F_{9}$ -219.62° -188.12° -129.02° -1 18.9984032 2.7×10^{-6}%	**Neon** $^{2}_{8}Ne_{10}$ -248.59° -246.08° -228.7° 0 20.1797 0.0112%
Sodium $^{2}_{8}_{1}Na_{11}$ 97.80° 883° +1 22.989770 0.000187%	**Magnesium** $^{2}_{8}_{2}Mg_{12}$ 650° 1090° +2 24.3050 0.00350%						Key to Table					**Aluminum** $^{2}_{8}_{3}Al_{13}$ 660.32° 2519° +3 26.981538 0.000277%	**Silicon** $^{2}_{8}_{4}Si_{14}$ 1414° 3265° +2+4-4 28.0855 0.00326%	**Phosphorus** $^{2}_{8}_{5}P_{15}$ 44.15° 280.5° 721° +3+5-3 30.973761 0.000034%	**Sulfur** $^{2}_{8}_{6}S_{16}$ 115.21° 444.60° 1041° +4+6-2 32.066 0.00168%	**Chlorine** $^{2}_{8}_{7}Cl_{17}$ -101.5° -34.04° 143.8° +1+5+7-1 35.4527 0.000017%	**Argon** $^{2}_{8}_{8}Ar_{18}$ -189.35° -185.85° -122.28° 0 39.948 0.000329%
Potassium $^{2}_{8}_{8}_{1}K_{19}$ 63.38° 759° +1 39.0983 0.0000123%	**Calcium** $^{2}_{8}_{8}_{2}Ca_{20}$ 842° 1484° +2 40.078 0.000199%	**Scandium** $^{2}_{8}_{9}_{2}Sc_{21}$ 1541° 2836° +3 44.955910 1.12×10^{-7}%	**Titanium** $^{2}_{8}_{10}_{2}Ti_{22}$ 1668° 3287° +2+3+4 47.867 7.8×10^{-6}%	**Vanadium** $^{2}_{8}_{11}_{2}V_{23}$ 1910° 3407° +2+3+4+5 50.9415 9.6×10^{-7}%	**Chromium** $^{2}_{8}_{13}_{1}Cr_{24}$ 1907° 2671° +2+3+6 51.9961 0.000044%	**Manganese** $^{2}_{8}_{13}_{2}Mn_{25}$ 1246° 2061° +2+3+4+7 54.938049 0.000031%	**Iron** $^{2}_{8}_{14}_{2}Fe_{26}$ 1538° 2861° +2+3 55.845 0.00294%	**Cobalt** $^{2}_{8}_{15}_{2}Co_{27}$ 1495° 2927° +2+3 58.933200 7.3×10^{-6}%	**Nickel** $^{2}_{8}_{16}_{2}Ni_{28}$ 1455° 2913° +2+3 58.6934 0.000161%	**Copper** $^{2}_{8}_{18}_{1}Cu_{29}$ 1084.62° 2562° +1+2 63.546 1.70×10^{-6}%	**Zinc** $^{2}_{8}_{18}_{2}Zn_{30}$ 419.53° 907° +2 65.39 4.11×10^{-6}%	**Gallium** $^{2}_{8}_{18}_{3}Ga_{31}$ 29.76° 2204° +3 69.723 1.23×10^{-7}%	**Germanium** $^{2}_{8}_{18}_{4}Ge_{32}$ 938.25° 2833° +2+4 72.61 3.9×10^{-7}%	**Arsenic** $^{2}_{8}_{18}_{5}As_{33}$ 817° 614° 1400° +3+5-3 74.92160 2.1×10^{-6}%	**Selenium** $^{2}_{8}_{18}_{6}Se_{34}$ 221° 685° 1493° +4+6-2 78.96 2.03×10^{-7}%	**Bromine** $^{2}_{8}_{18}_{7}Br_{35}$ -7.2° 58.8° 315° +1+5-1 79.904 3.8×10^{-6}%	**Krypton** $^{2}_{8}_{18}_{8}Kr_{36}$ -157.36° -153.22° -63.74° 0 83.80 1.5×10^{-7}%
Rubidium $^{2}_{8}_{18}_{8}_{1}Rb_{37}$ 39.31° 688° +1 85.4678 2.31×10^{-6}%	**Strontium** $^{2}_{8}_{18}_{8}_{2}Sr_{38}$ 777° 1382° +2 87.62 7.7×10^{-6}%	**Yttrium** $^{2}_{8}_{18}_{9}_{2}Y_{39}$ 1522° 3345° +3 88.90585 1.51×10^{-6}%	**Zirconium** $^{2}_{8}_{18}_{10}_{2}Zr_{40}$ 1855° 4409° +4 91.224 3.72×10^{-6}%	**Niobium** $^{2}_{8}_{18}_{12}_{1}Nb_{41}$ 2477° 4744° +3+5 92.90638 2.28×10^{-6}%	**Molybdenum** $^{2}_{8}_{18}_{13}_{1}Mo_{42}$ 2623° 4639° +6 95.94 8.3×10^{-6}%	**Technetium** $^{2}_{8}_{18}_{13}_{2}Tc_{43}$ 2157° 4265° +4+6+7 [98]	**Ruthenium** $^{2}_{8}_{18}_{15}_{1}Ru_{44}$ 2334° 4150° +3 101.07 6.1×10^{-6}%	**Rhodium** $^{2}_{8}_{18}_{16}_{1}Rh_{45}$ 1964° 3695° +3 102.90550 1.12×10^{-6}%	**Palladium** $^{2}_{8}_{18}_{18}Pd_{46}$ 1554.9° 2963° +2+4 106.42 4.5×10^{-6}%	**Silver** $^{2}_{8}_{18}_{18}_{1}Ag_{47}$ 961.78° 2162° +1 107.8682 1.58×10^{-6}%	**Cadmium** $^{2}_{8}_{18}_{18}_{2}Cd_{48}$ 321.07° 767° +2 112.411 5.3×10^{-6}%	**Indium** $^{2}_{8}_{18}_{18}_{3}In_{49}$ 156.60° 2072° +3 114.818 6.0×10^{-6}%	**Tin** $^{2}_{8}_{18}_{18}_{4}Sn_{50}$ 231.93° 2602° +2+4 118.710 1.25×10^{-6}%	**Antimony** $^{2}_{8}_{18}_{18}_{5}Sb_{51}$ 630.65° 1587° +3+5-3 121.760 1.01×10^{-6}%	**Tellurium** $^{2}_{8}_{18}_{18}_{6}Te_{52}$ 449.51° 988° +4+6-2 127.60 1.57×10^{-6}%	**Iodine** $^{2}_{8}_{18}_{18}_{7}I_{53}$ 113.7° 184.4° 546° +1+5+7-1 126.90447 2.9×10^{-6}%	**Xenon** $^{2}_{8}_{18}_{18}_{8}Xe_{54}$ -111.75° -108.04° 16.58° 0 131.29 1.5×10^{-6}%
Cesium $^{2}_{8}_{18}_{18}_{8}_{1}Cs_{55}$ 28.44° 671° +1 132.90545 1.21×10^{-6}%	**Barium** $^{2}_{8}_{18}_{18}_{8}_{2}Ba_{56}$ 727° 1897° +2 137.327 1.46×10^{-6}%	**Lanthanum** $^{2}_{8}_{18}_{18}_{9}_{2}La_{57}$ † 918° 3464° +3 138.9055 1.45×10^{-6}%	**Hafnium** $^{2}_{8}_{18}_{32}_{10}_{2}Hf_{72}$ 2233° 4603° +4 178.49 5.02×10^{-10}%	**Tantalum** $^{2}_{8}_{18}_{32}_{11}_{2}Ta_{73}$ 3017° 5458° +5 180.9479 6.75×10^{-11}%	**Tungsten** $^{2}_{8}_{18}_{32}_{12}_{2}W_{74}$ 3422° 5555° +6 183.84 4.34×10^{-10}%	**Rhenium** $^{2}_{8}_{18}_{32}_{13}_{2}Re_{75}$ 3186° 5596° +4+6+7 186.207 1.69×10^{-10}%	**Osmium** $^{2}_{8}_{18}_{32}_{14}_{2}Os_{76}$ 3033° 5012° +3+4 190.23 2.20×10^{-9}%	**Iridium** $^{2}_{8}_{18}_{32}_{15}_{2}Ir_{77}$ 2446° 4428° +3+4 192.217 2.16×10^{-9}%	**Platinum** $^{2}_{8}_{18}_{32}_{16}_{2}Pt_{78}$ 1768.4° 3825° +2+4 195.078 4.4×10^{-9}%	**Gold** $^{2}_{8}_{18}_{32}_{16}_{1}Au_{79}$ 1064.18° 2856° +1+3 196.96655 6.1×10^{-10}%	**Mercury** $^{2}_{8}_{18}_{32}_{18}_{2}Hg_{80}$ -38.83° 356.73° 1477° +1+2 200.59 1.11×10^{-6}%	**Thallium** $^{2}_{8}_{18}_{32}_{18}_{3}Tl_{81}$ 304° 1473° +1+3 204.3833 6.0×10^{-10}%	**Lead** $^{2}_{8}_{18}_{32}_{18}_{4}Pb_{82}$ 327.46° 1749° +2+4 207.2 1.03×10^{-6}%	**Bismuth** $^{2}_{8}_{18}_{32}_{18}_{5}Bi_{83}$ 271.40° 1564° +3+5 208.98038 4.7×10^{-10}%	**Polonium** $^{2}_{8}_{18}_{32}_{18}_{6}Po_{84}$ 254° 962° +2+4 [209]	**Astatine** $^{2}_{8}_{18}_{32}_{18}_{7}At_{85}$ 302° [210]	**Radon** $^{2}_{8}_{18}_{32}_{18}_{8}Rn_{86}$ -71° -61.7° 104° 0 [222]
Francium $^{2}_{8}_{18}_{32}_{18}_{8}_{1}Fr_{87}$ 27° +1 [223]	**Radium** $^{2}_{8}_{18}_{32}_{18}_{8}_{2}Ra_{88}$ 700° +2 [226]	**Actinium** $^{2}_{8}_{18}_{32}_{18}_{9}_{2}Ac_{89}$ ‡ 1051° 3198° +3 [227]	**Rutherfordium** $^{2}_{8}_{18}_{32}_{32}_{10}_{2}Rf_{104}$ +4 [261]	**Dubnium** $^{2}_{8}_{18}_{32}_{32}_{11}_{2}Db_{105}$ [262]	**Seaborgium** $^{2}_{8}_{18}_{32}_{32}_{12}_{2}Sg_{106}$ [266]	**Bohrium** $^{2}_{8}_{18}_{32}_{32}_{13}_{2}Bh_{107}$ [264]	**Hassium** $^{2}_{8}_{18}_{32}_{32}_{14}_{2}Hs_{108}$ [269]	**Meitnerium** $^{2}_{8}_{18}_{32}_{32}_{15}_{2}Mt_{109}$ [268]	**Element-110** $^{2}_{8}_{18}_{32}_{32}_{16}_{2}110_{110}$ [271]	**Element-111** $^{2}_{8}_{18}_{32}_{32}_{17}_{2}111_{111}$ [272]	**Element-112** $^{2}_{8}_{18}_{32}_{32}_{18}_{2}112_{112}$ [277]					

† Lanthanides	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
	$^{2}_{8}_{18}_{19}_{9}_{2}Ce_{58}$ 798° 3443° +3+4 140.116 3.70×10^{-6}%	$^{2}_{8}_{18}_{21}_{8}_{2}Pr_{59}$ 931° 3520° +3 140.90765 5.44×10^{-6}%	$^{2}_{8}_{18}_{22}_{8}_{2}Nd_{60}$ 1021° 3074° +3 144.24 2.70×10^{-6}%	$^{2}_{8}_{18}_{23}_{8}_{2}Pm_{61}$ 1042° 3000° +3 [145]	$^{2}_{8}_{18}_{24}_{8}_{2}Sm_{62}$ 1074° 1794° +2+3 150.36 8.42×10^{-10}%	$^{2}_{8}_{18}_{25}_{8}_{2}Eu_{63}$ 822° 1596° +2+3 151.964 3.17×10^{-10}%	$^{2}_{8}_{18}_{25}_{9}_{2}Gd_{64}$ 1313° 3273° +3 157.25 1.076×10^{-6}%	$^{2}_{8}_{18}_{27}_{8}_{2}Tb_{65}$ 1356° 3230° +3 158.92534 1.97×10^{-10}%	$^{2}_{8}_{18}_{28}_{8}_{2}Dy_{66}$ 1412° 2567° +3 162.50 1.286×10^{-6}%	$^{2}_{8}_{18}_{29}_{8}_{2}Ho_{67}$ 1474° 2700° +3 164.93032 2.90×10^{-10}%	$^{2}_{8}_{18}_{30}_{8}_{2}Er_{68}$ 1529° 2868° +3 167.26 8.18×10^{-10}%	$^{2}_{8}_{18}_{31}_{8}_{2}Tm_{69}$ 1545° 1950° +3 168.93421 1.23×10^{-10}%	$^{2}_{8}_{18}_{32}_{8}_{2}Yb_{70}$ 819° 1196° +2+3 173.04 8.08×10^{-6}%	$^{2}_{8}_{18}_{32}_{9}_{2}Lu_{71}$ 1663° 3402° +3 174.967 1.197×10^{-10}%

‡ Actinides	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium
	$^{2}_{8}_{18}_{32}_{18}_{10}_{2}Th_{90}$ 1750° 4788° +4 232.0381 1.09×10^{-10}%	$^{2}_{8}_{18}_{32}_{20}_{9}_{2}Pa_{91}$ 1572° +5+4 231.03588	$^{2}_{8}_{18}_{32}_{21}_{9}_{2}U_{92}$ 1135° 4131° +3+4+5+6 238.0289 2.94×10^{-11}%	$^{2}_{8}_{18}_{32}_{22}_{9}_{2}Np_{93}$ 644° +3+4+5+6 [237]	$^{2}_{8}_{18}_{32}_{24}_{8}_{2}Pu_{94}$ 640° 3228° +3+4+5+6 [244]	$^{2}_{8}_{18}_{32}_{25}_{8}_{2}Am_{95}$ 1176° 2011° +3+4+5+6 [243]	$^{2}_{8}_{18}_{32}_{25}_{9}_{2}Cm_{96}$ 1345° +3 [247]	$^{2}_{8}_{18}_{32}_{27}_{8}_{2}Bk_{97}$ 1050° +3+4 [247]	$^{2}_{8}_{18}_{32}_{28}_{8}_{2}Cf_{98}$ 900° +3 [251]	$^{2}_{8}_{18}_{32}_{29}_{8}_{2}Es_{99}$ 860° +3 [252]	$^{2}_{8}_{18}_{32}_{30}_{8}_{2}Fm_{100}$ 1527° +3 [257]	$^{2}_{8}_{18}_{32}_{31}_{8}_{2}Md_{101}$ 827° +2+3 [258]	$^{2}_{8}_{18}_{32}_{32}_{8}_{2}No_{102}$ 827° +2+3 [259]	$^{2}_{8}_{18}_{32}_{32}_{9}_{2}Lr_{103}$ 1627° +3 [262]

Chart of Plato and Aristotle (~400 BC)



Relation of the four elements and the four qualities.

A fifth element was "ETHER" or material of the heavens.
(Dark Matter in early cosmology!)

CFHT

SN

Survey

Carlberg,
Pritchet,

et al.

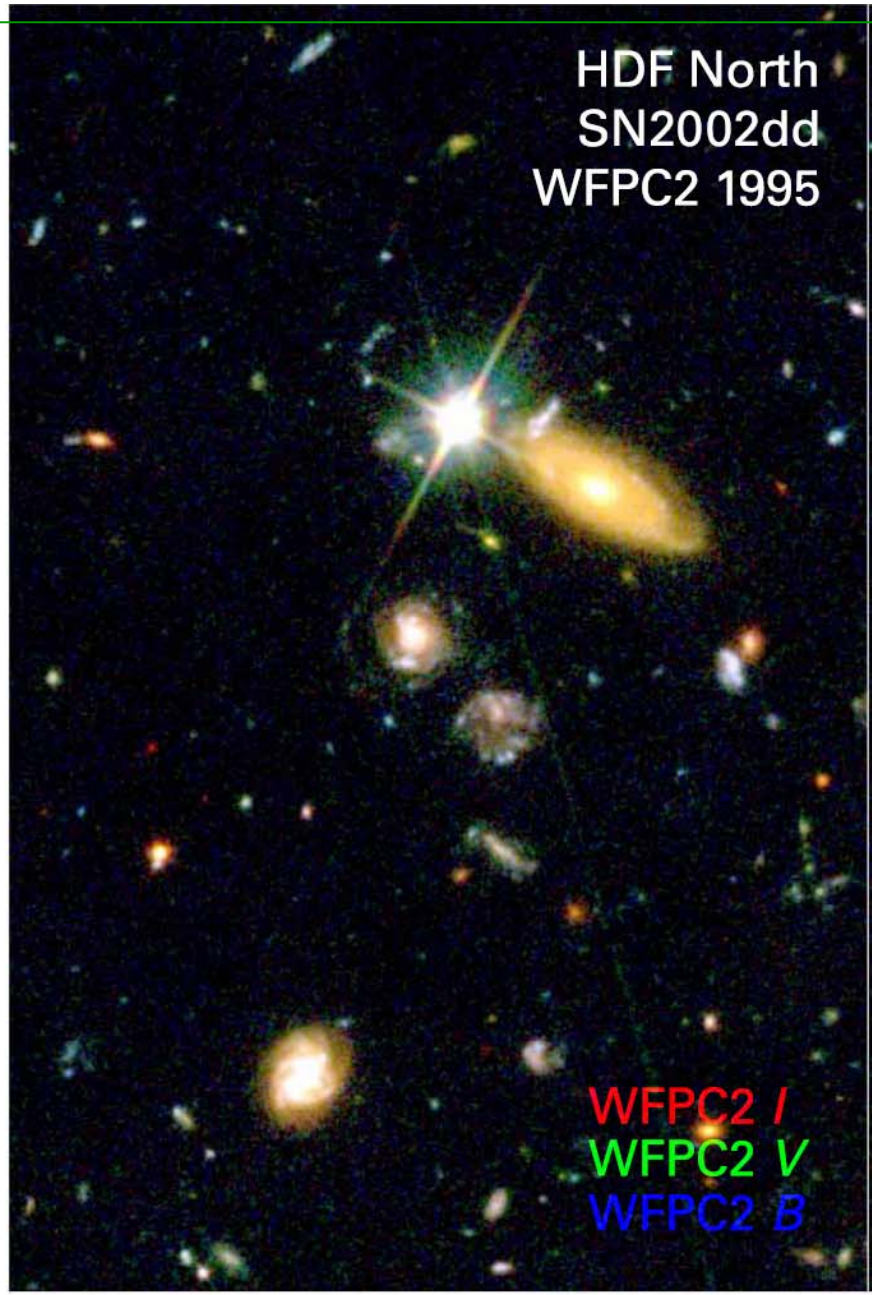
CIAR

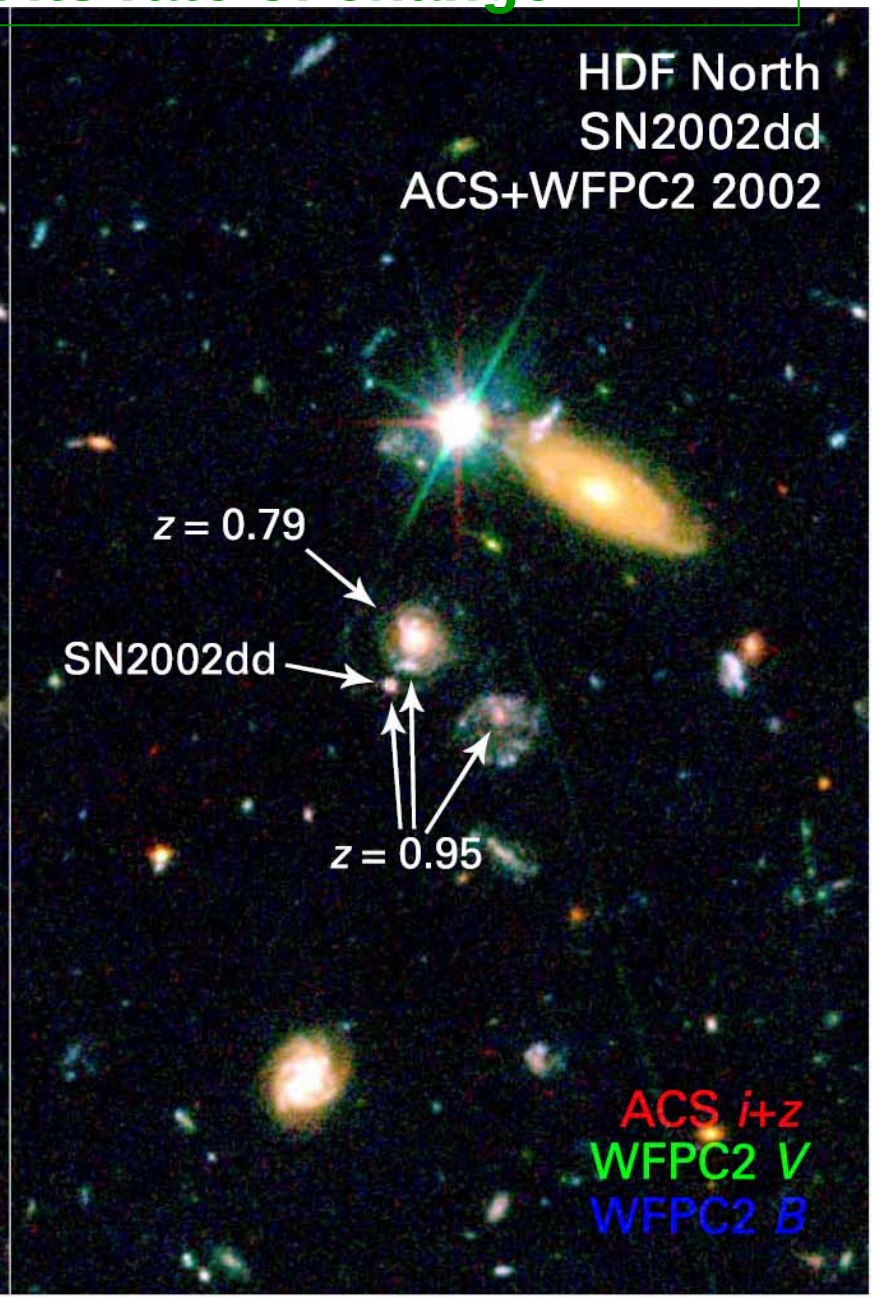
3yr now
300 SN1a

5yr

500

SN determine the acceleration & its rate of change



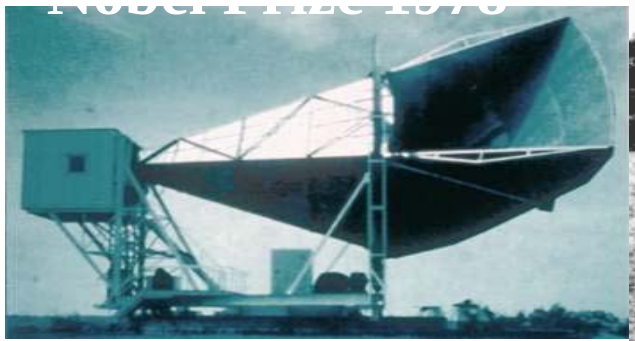


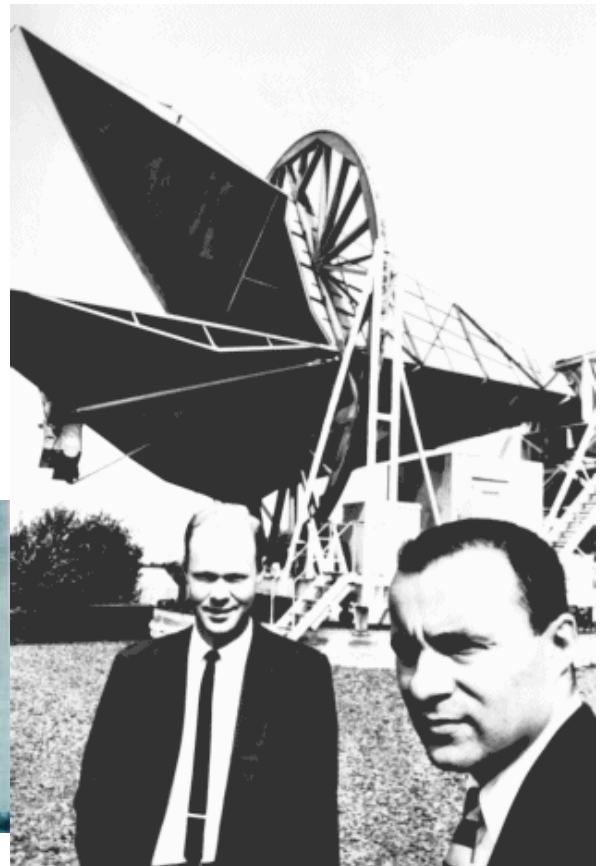
FRIEDMANN (1922) Evolving (Expanding) Universe

- ✓ YES! Hubble (late 20s)
- ✓ the SINGULARITY (30s,60s), infinite density (!!!???)
- ✓ GAMOW (40s, early 50s) HOT BIG BANG MODEL
- ✓ Hydrogen (75%) & Helium (25%) (Deuterium/Lithium) from the first minutes
- ✓ **Carbon, Oxygen, Iron, … from exploding stars (40s-80s)**

✓Thus: THE COSMIC BACKGROUND RADIATION ***AFTERGLOW of the hot period***

Nobel Prize 1978



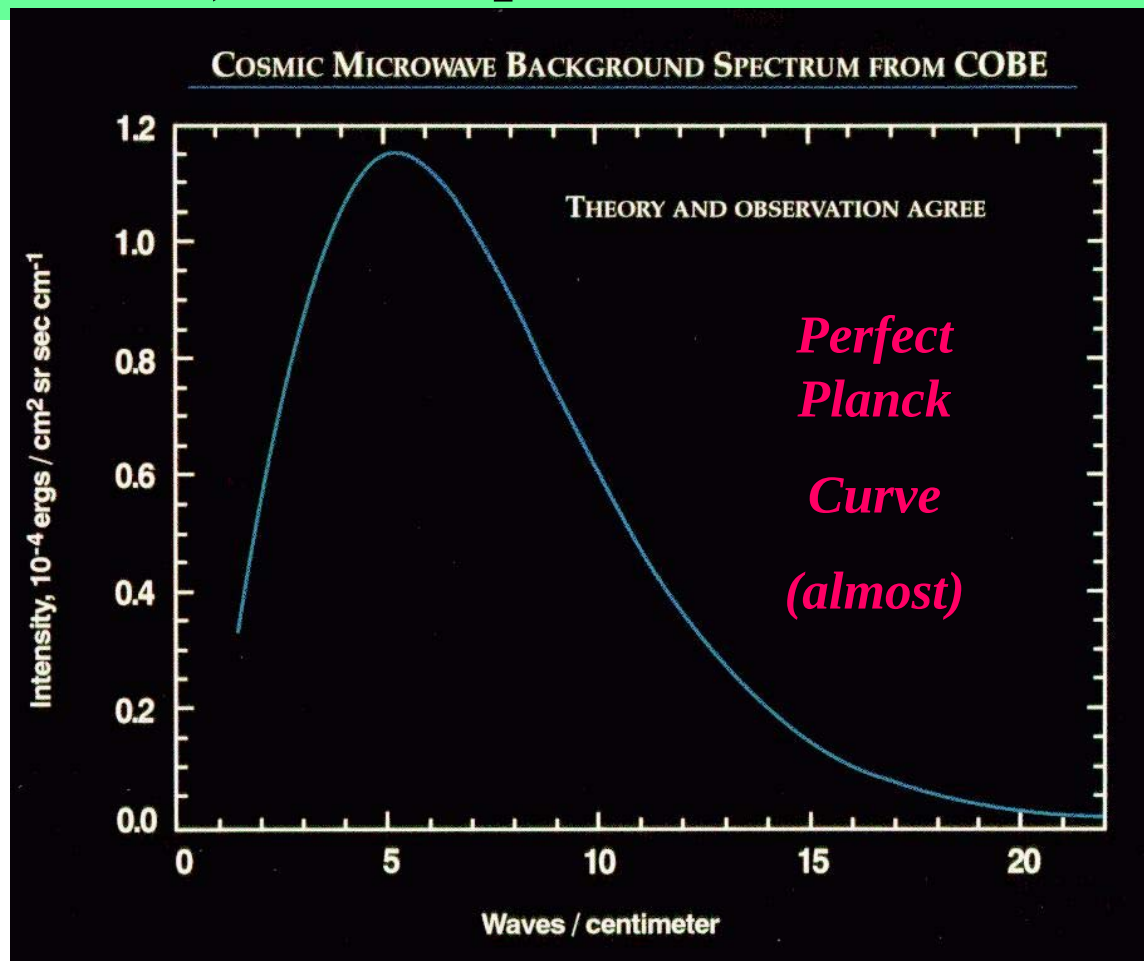


✓YES! Penzias & Wilson (1964)

Hot Big Bang

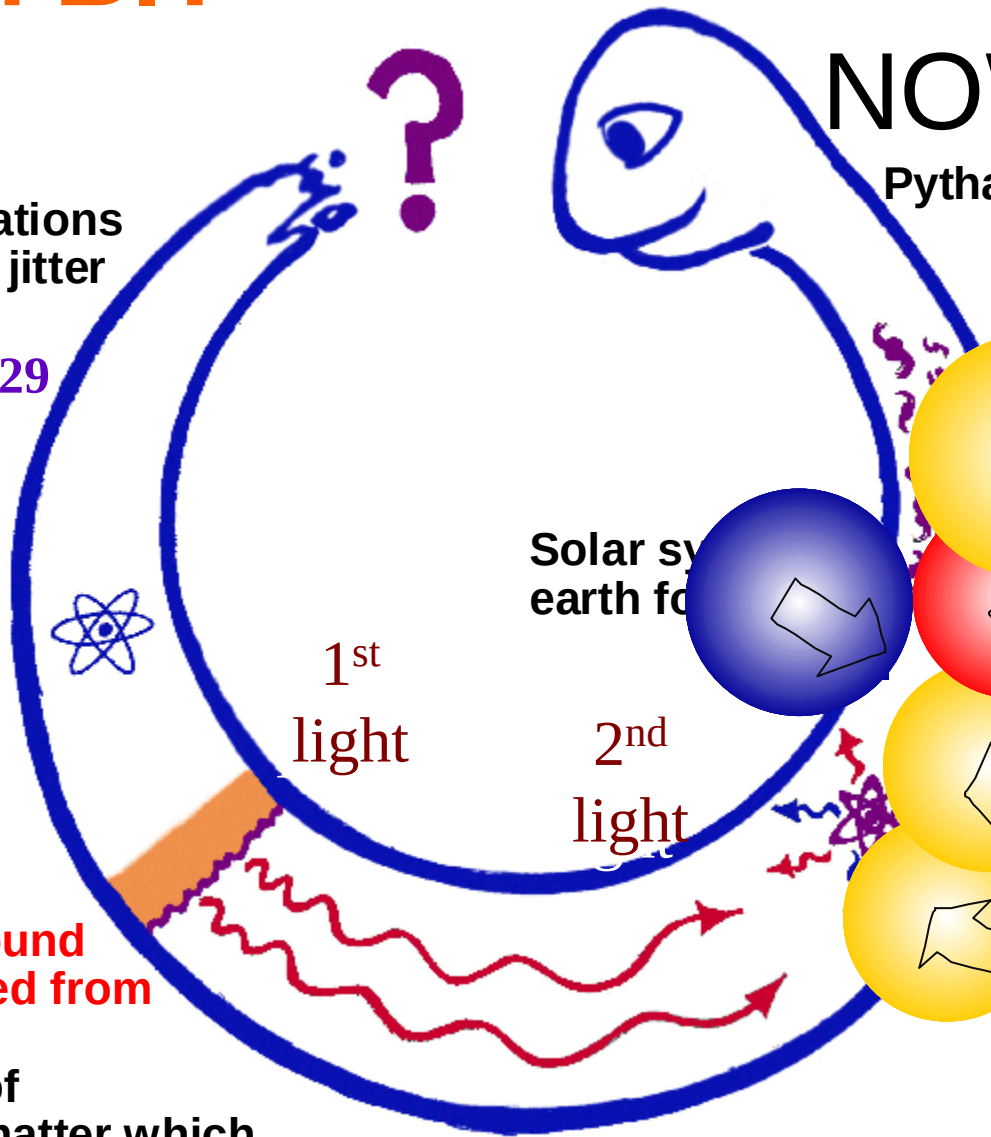
- Picked up as TV ‘snow’ - a few %
- 2.725 ±.001 degrees above absolute zero
- 410 photons per cubic centimetre
- Isotropic (smooth) to one part in 100,000

released as red light 400,000 yrs after the Big Bang, expansion of space stretched the wavelengths to microwave



"IT from BIT"

FATE



NOW 14 Gyr 1

Pythagoras formed

Galaxies Cluster
Cosmic "web" of vast filaments + membranes

Life forms on earth

9 Gyr 1.4

Carbon/oxygen/etc form

Galaxies form

2 Gyr 4

Inflation fluctuations form: quantum jitter

10^{-37}sec 10^{29}

Protons/Neutrons form

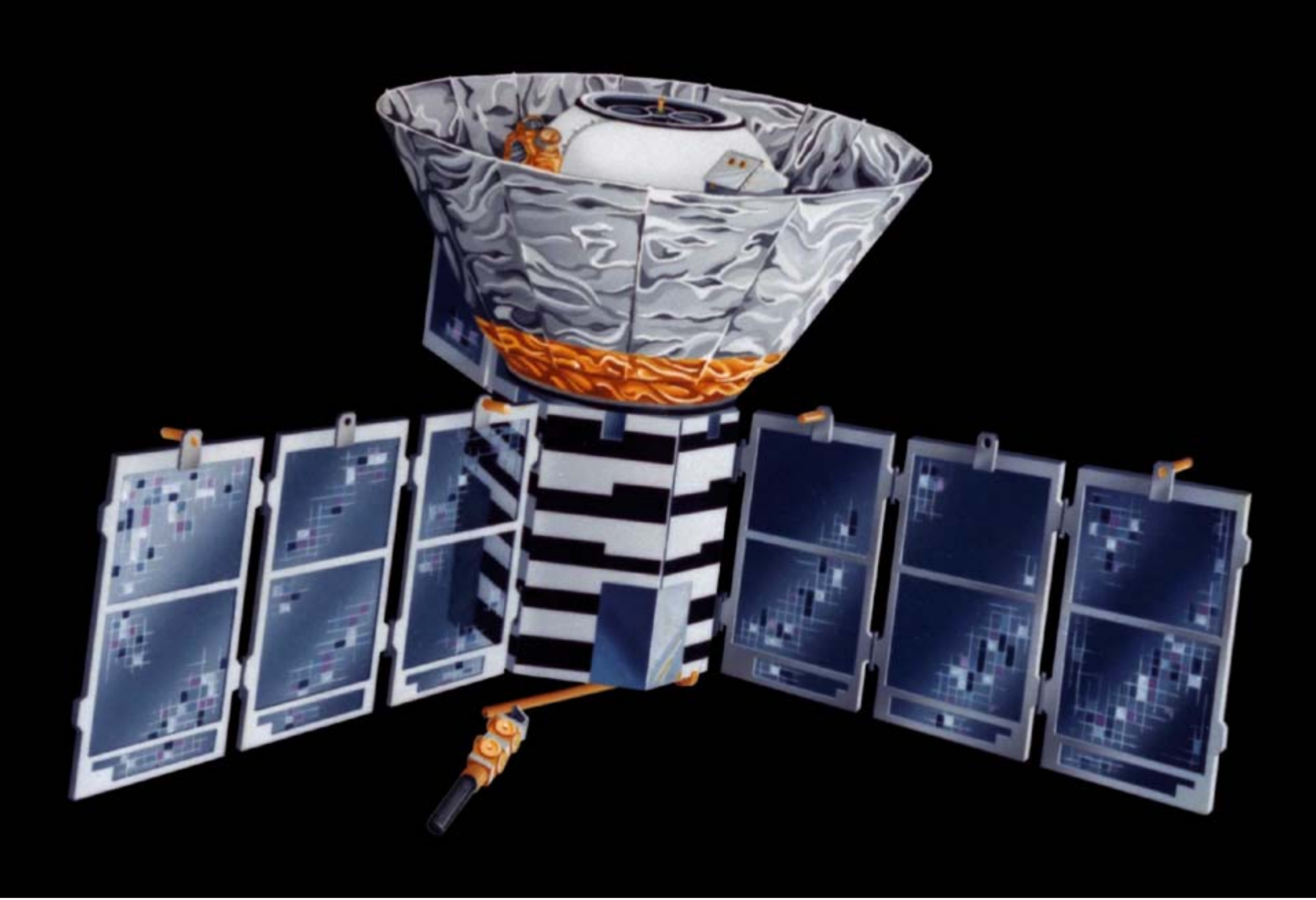
Helium forms

100 sec 10^{9}

Cosmic background radiation released from matter
carries imprint of fluctuations in matter which grow to generate galaxies etc.

0.4 Myr 1100

The 'Meaning' may change
But the facts will remain



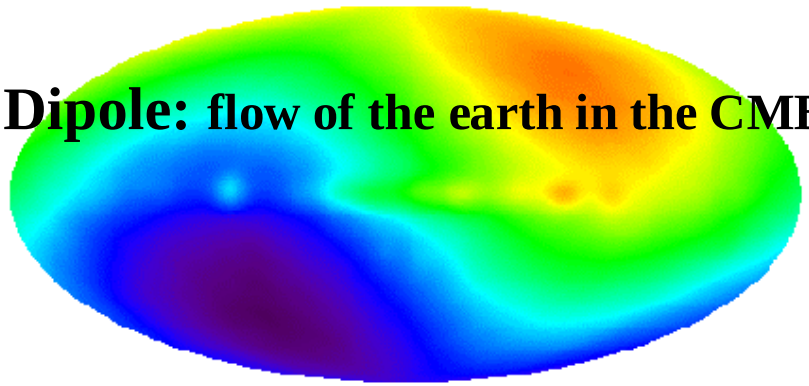
COBE satellite 1989-1994

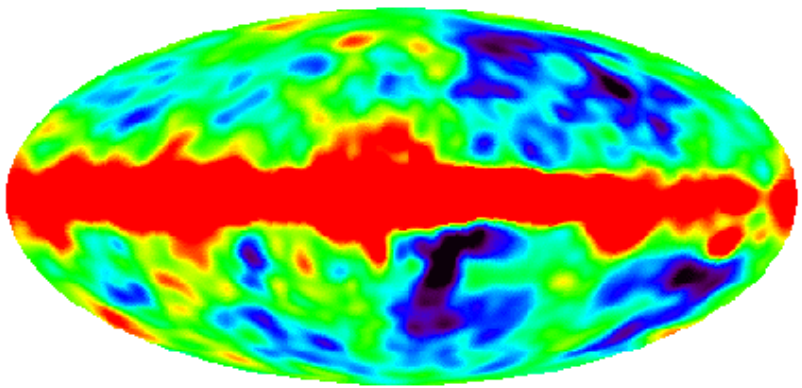
CMB

Nearly Perfect Blackbody

T=2.725 ±.001 K COBE/FIRAS

Dipole: flow of the earth in the CMB





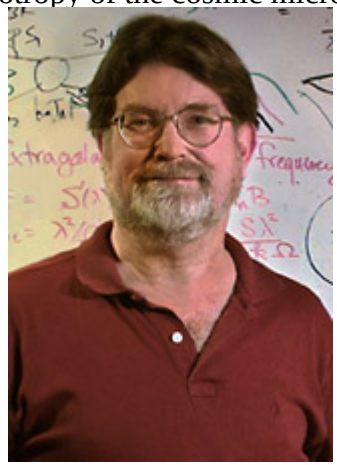
COBE/DMR:

CMB + Galactic @7^{o}

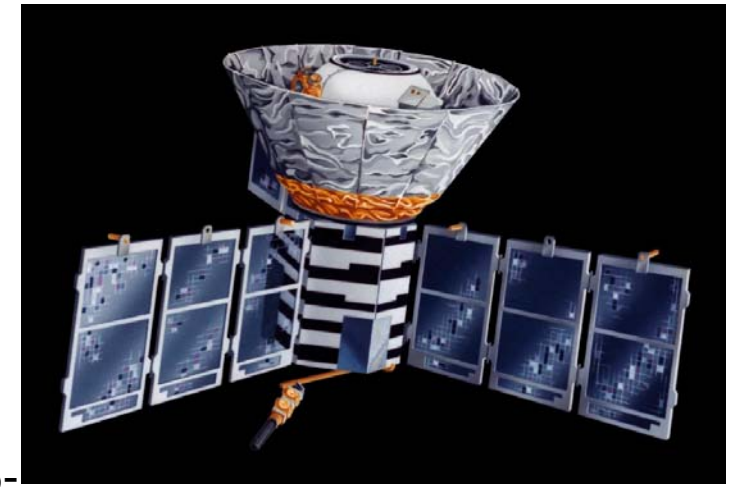
The Nobel Prize in Physics 2006
(also Gruber Prize in Cosmology 2006 for Mather + the COBE team)

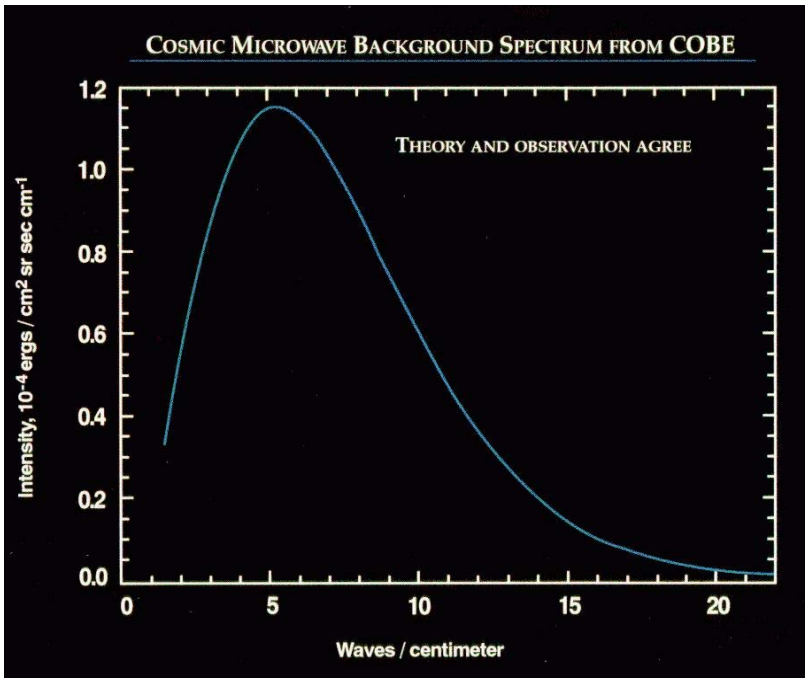
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

John C. Mather 1946-



George F. Smoot 1945-

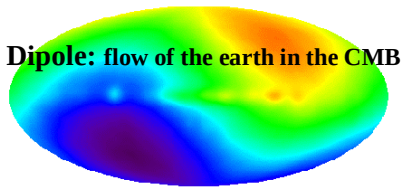




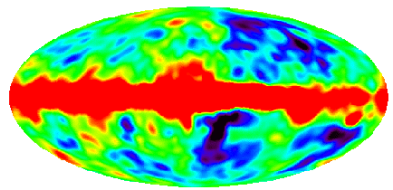
CMB

Nearly Perfect Blackbody

T=2.725 ±.001 K COBE/FIRAS



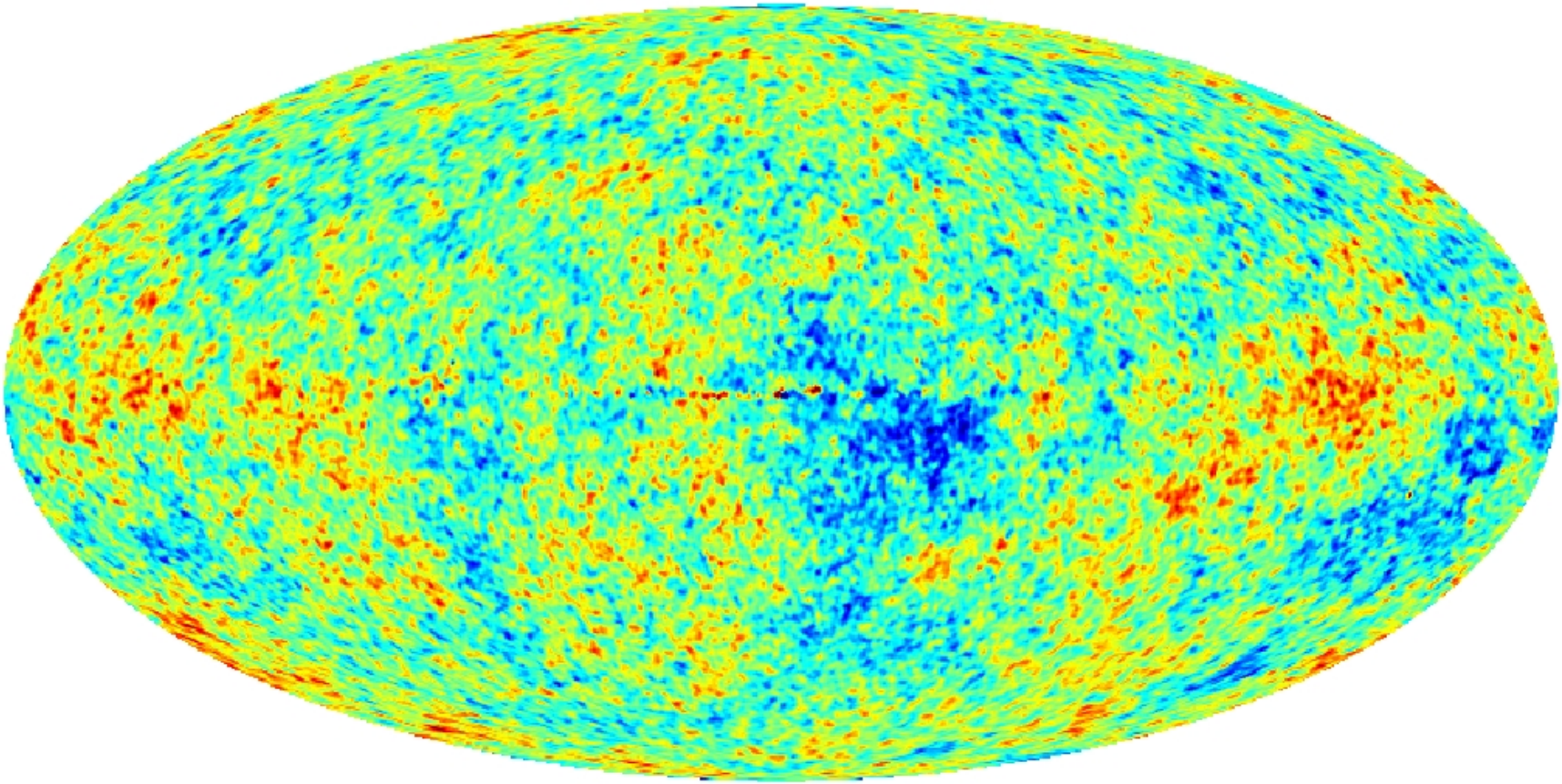
Dipole: flow of the earth in the CMB

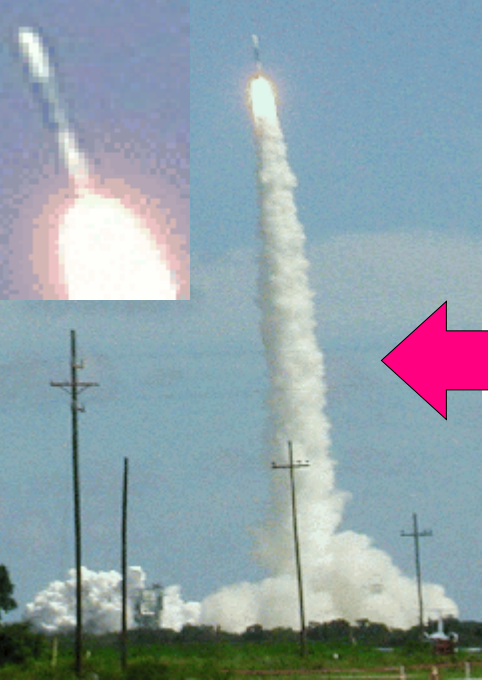


COBE/DMR:

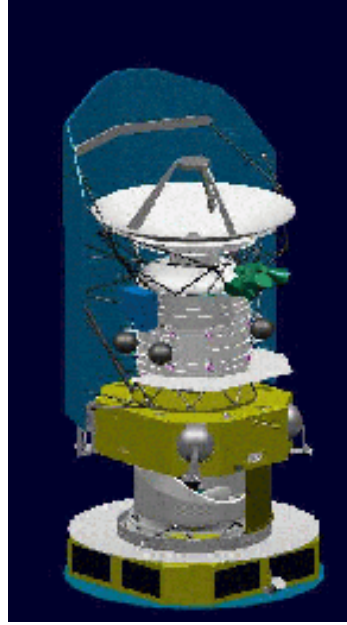
CMB + Galactic @7^{o}

WMAP 2003



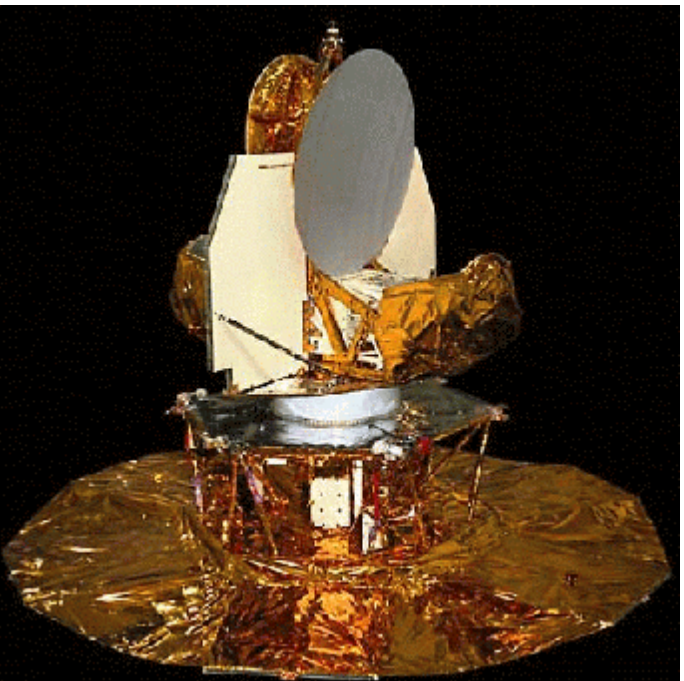


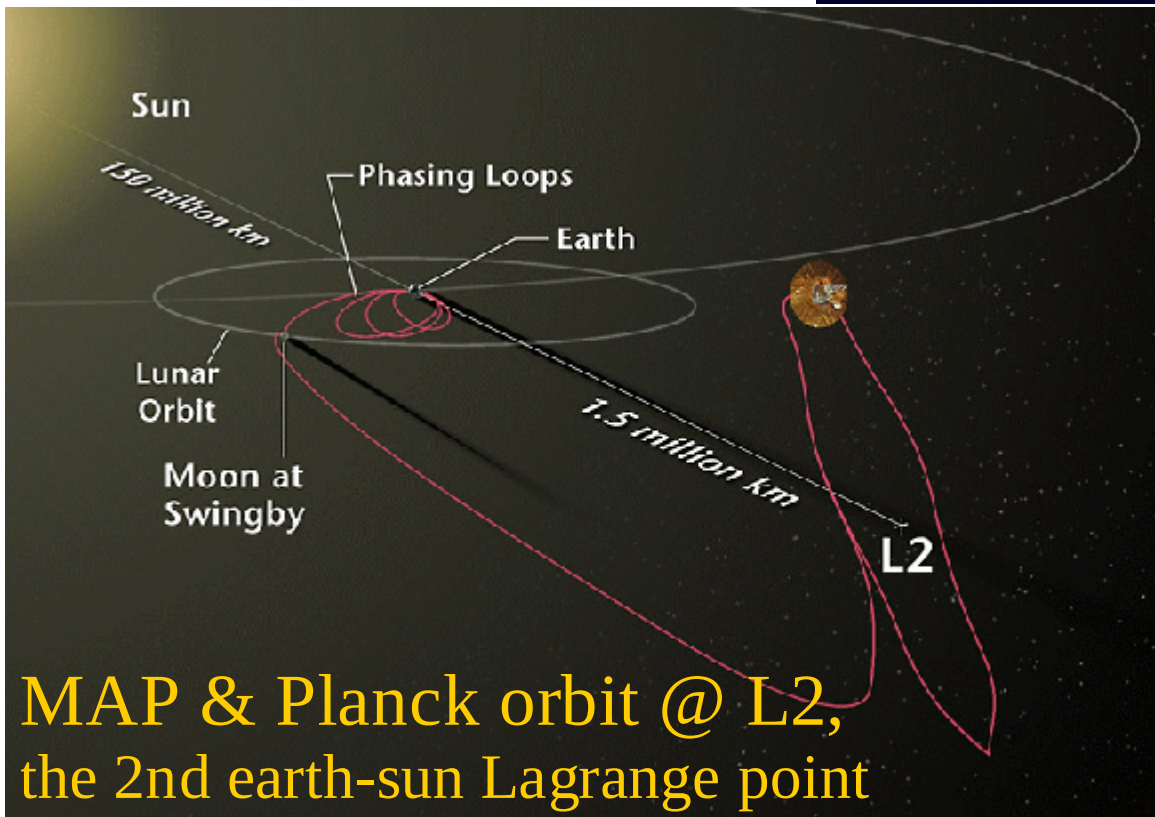
Nasa's WMAP satellite @ L2: launch 2001.5, 1yr data 2003.2, 3yr 2006.3



Planck satellite @ L2: launch 2008.2

ESA+NASA+ Cdn Space Agency

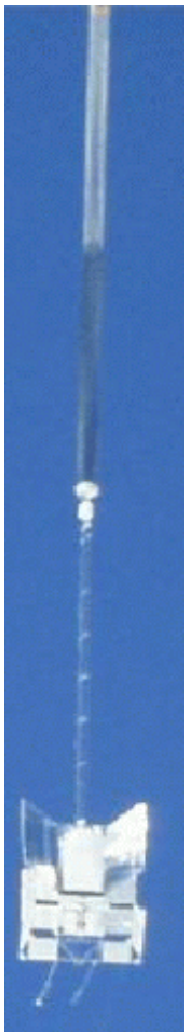




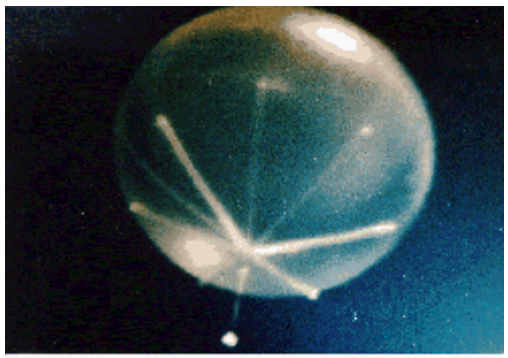
MAP & Planck orbit @ L2,
the 2nd earth-sun Lagrange point

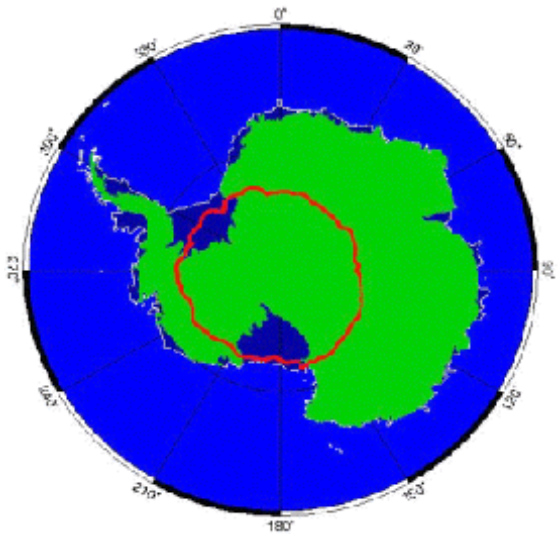
BOOMERanG 98 Netterfield etal 2001

UCSB
K. Coble
P. Farese
T. Montroy
J. Ruhl



UofToronto/CITA
D. Bond
C. Contaldi
B. Netterfield
D. Pogosyan
S. Prunet





Caltech
B. Crill
V. Hristov
B. Jones
A. Lange
P. Mason

IPAC
K. Ganga
E. Hivon

JPL
J. Bock

U. La Sapienza
P. deBernardis
M. Giacometti
A. Iacoangeli
L. Martinis
S. Masi
F. Piacentini
F. Pongetti
F. Scaramuzzi
G. Romeo

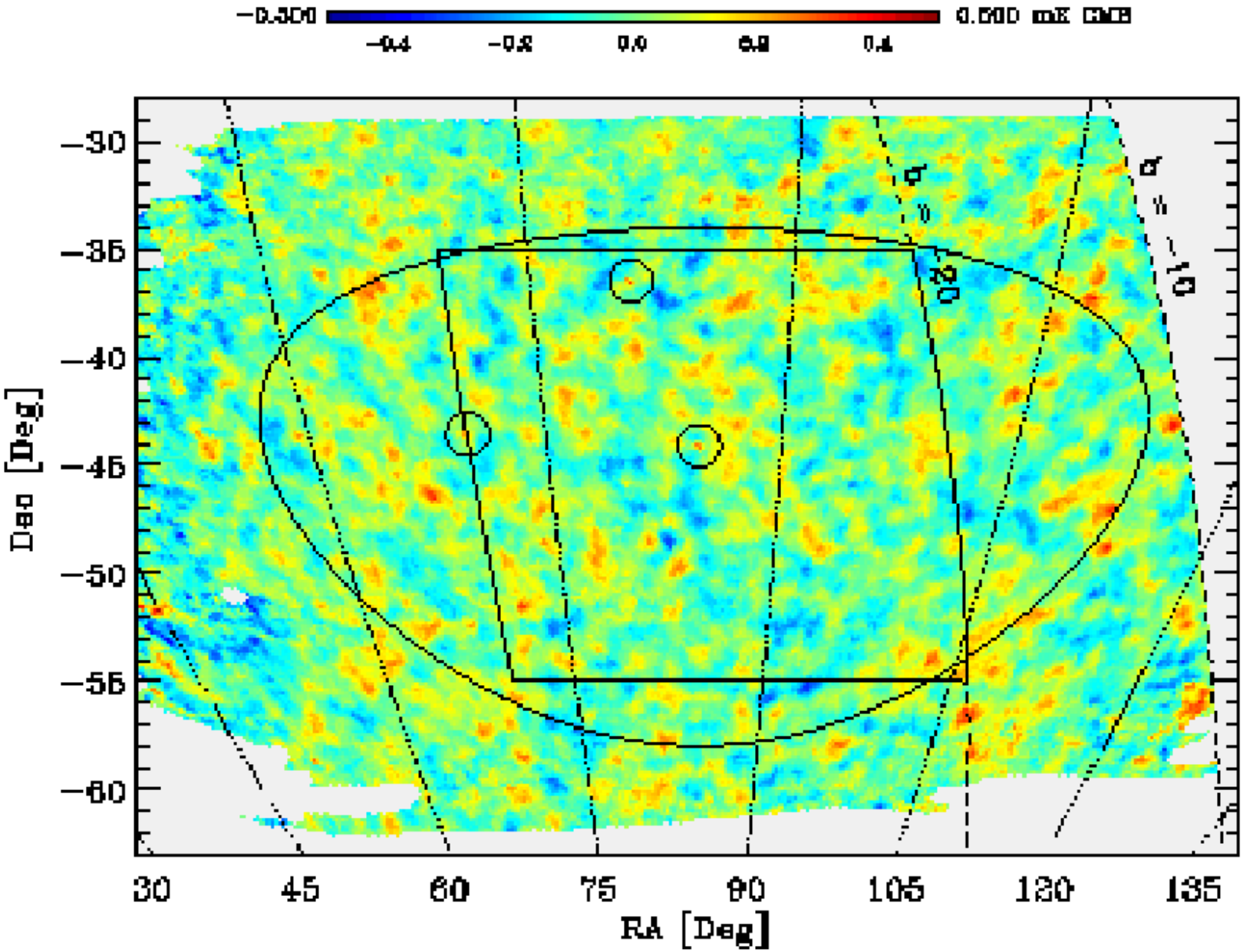
IROE
A. Boscaleri
E. Pascale

Cardiff
P. Mauskopf
P. Ade

Oxford
A. Melchiorri

UCB
J. Borrill
A. Jaffe

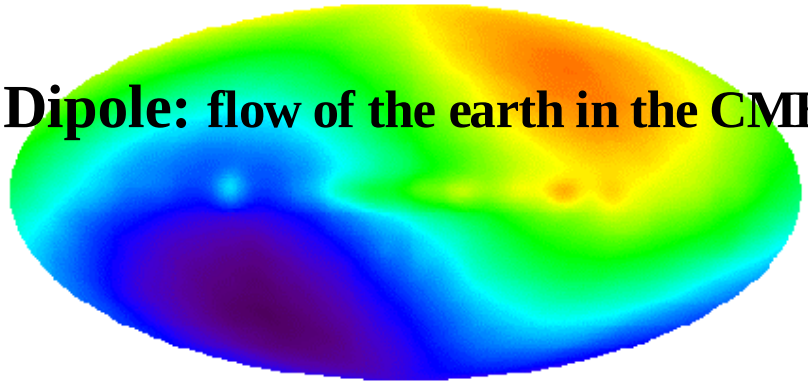
Boomerang B00 440 sq deg, B01 800 sq deg (B02 1200)



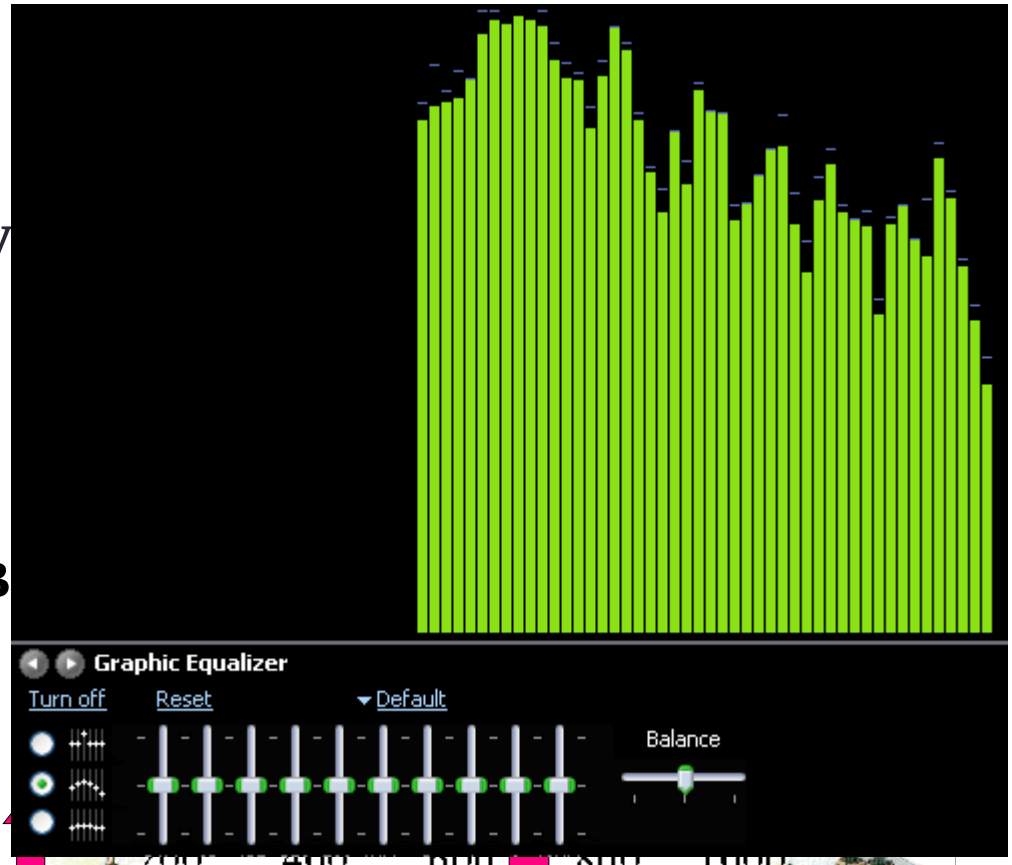
CMB

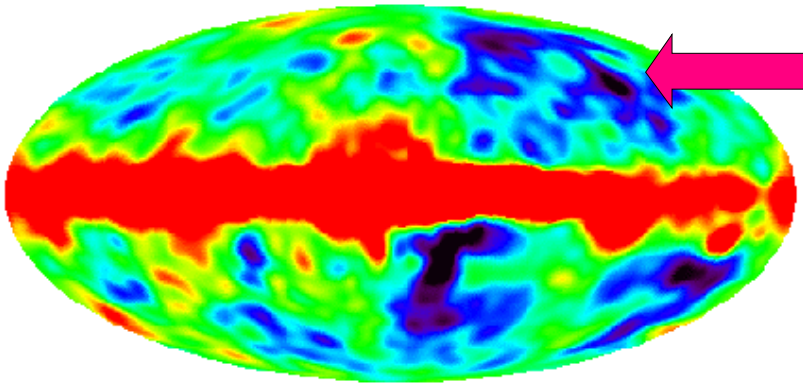
Nearly Perfect Blackbody

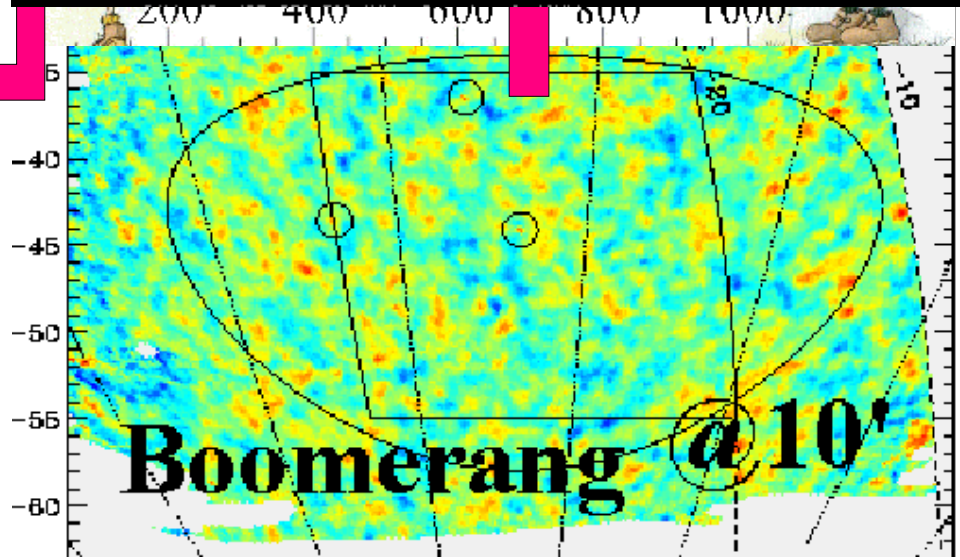
T=2.725 ±.001 K COBE/FIRAS



Dipole: flow of the earth in the CMB

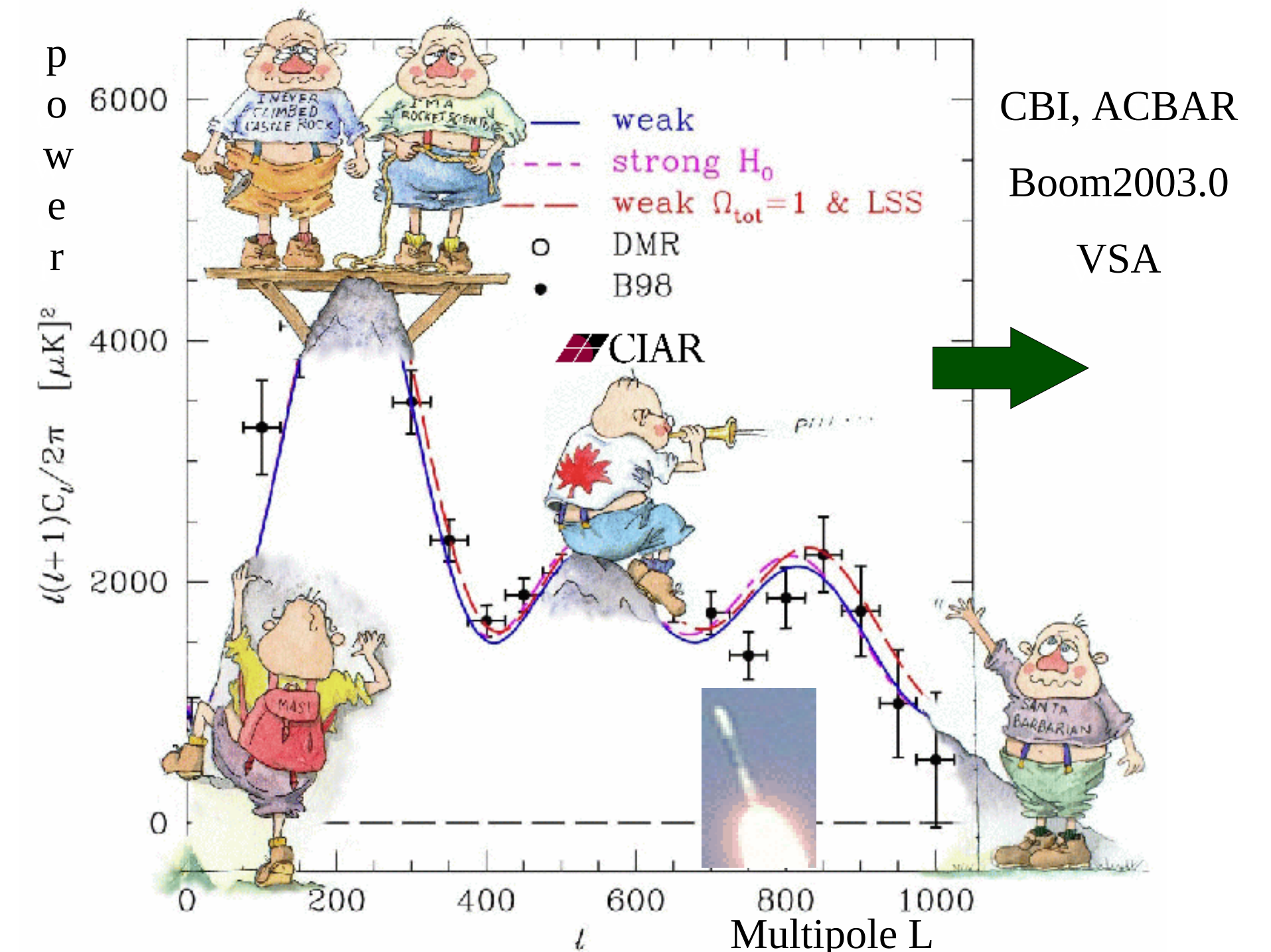






COBE/DMR:

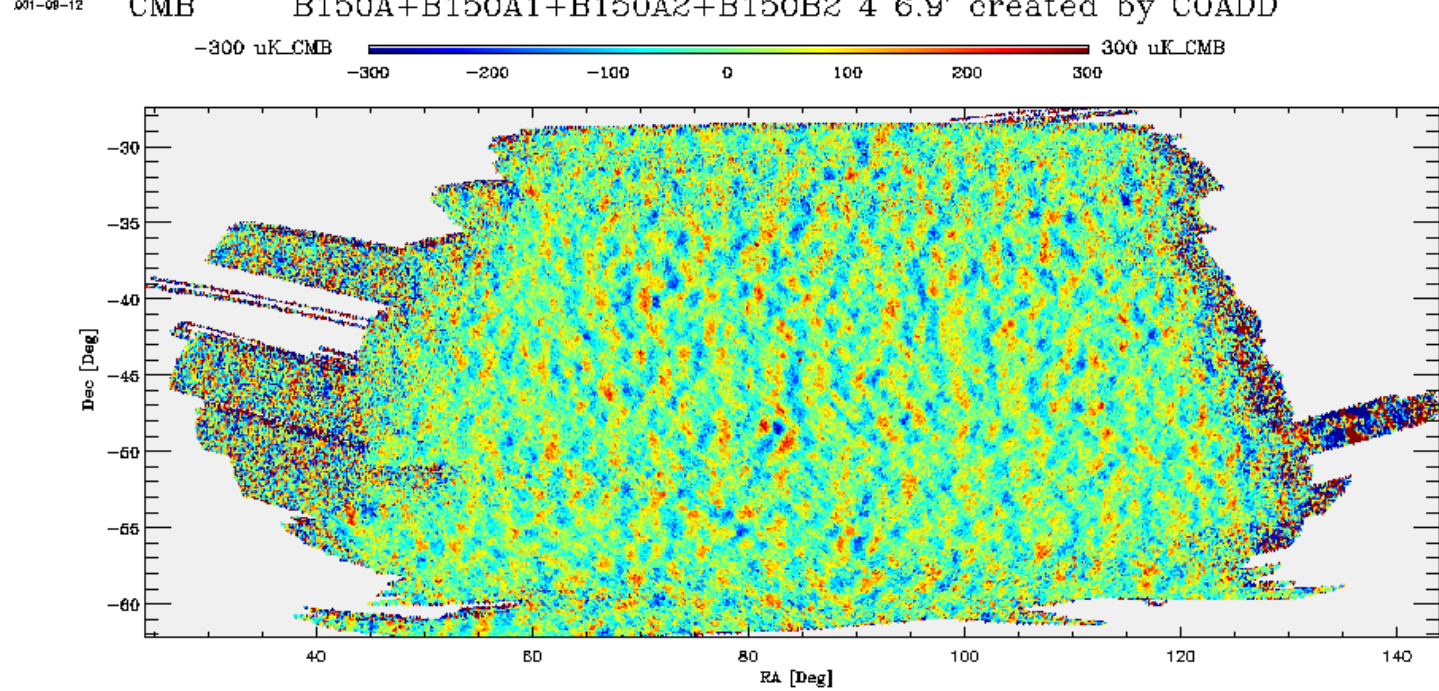
CMB + Galactic @7^{o}

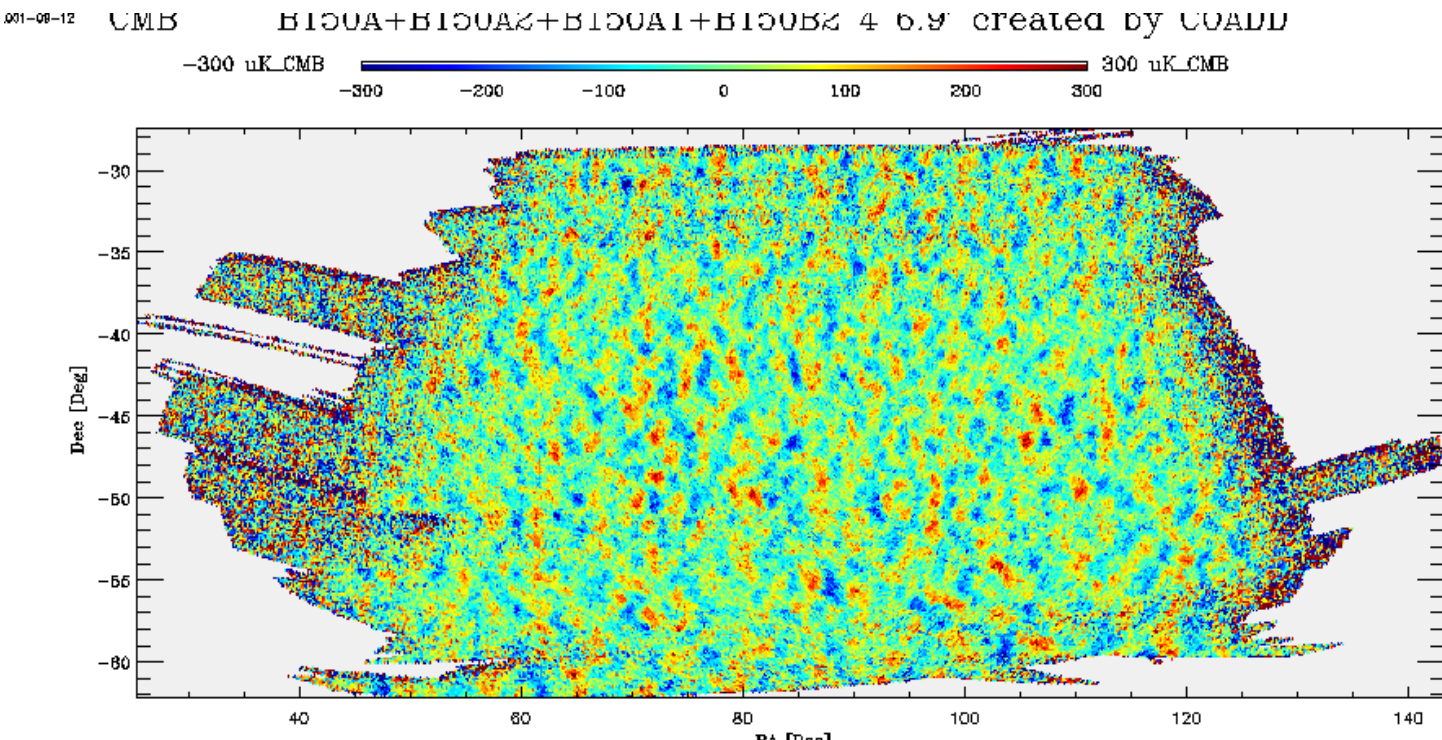

power
$\ell(\ell+1)C_\ell/2\pi$ $[\mu K]^2$
6000
4000
2000
0
weak
strong H_0
weak $\Omega_{tot}=1$ & LSS
DMR
B98
CIAR
CBI, ACBAR
Boom2003.0
VSA
0
200
400
600
800
1000
ℓ
Multipole L

Boomerang @150GHz

Simulated Theory *vs* Real Data

looks the same



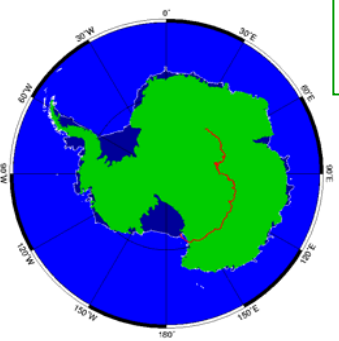


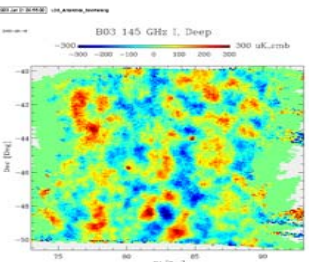

Balzan Prize 2006 (1M Swiss Francs)

Paolo de Bernardis, Italy and Andrew Lange, USA

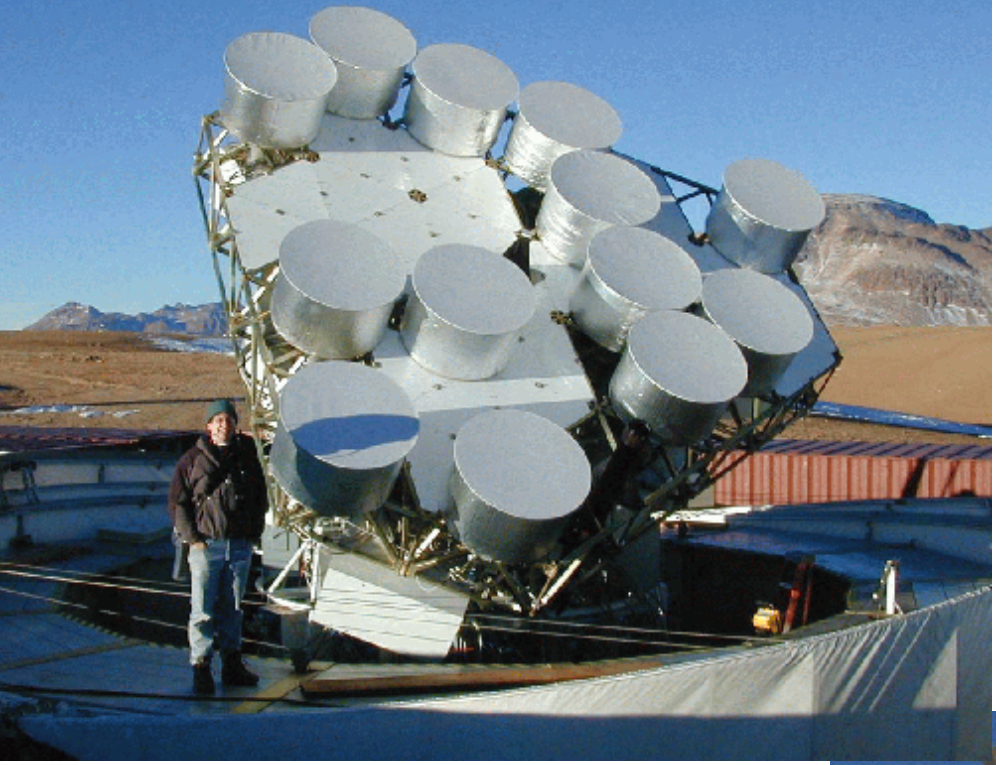
Observational astronomy and astrophysics

Motivation of the Prize Committee: "For their contributions to cosmology, in particular the Boomerang Antarctic balloon experiment."
team: Toronto/Caltech/JPL/CaseWestern/Italy/Cardiff





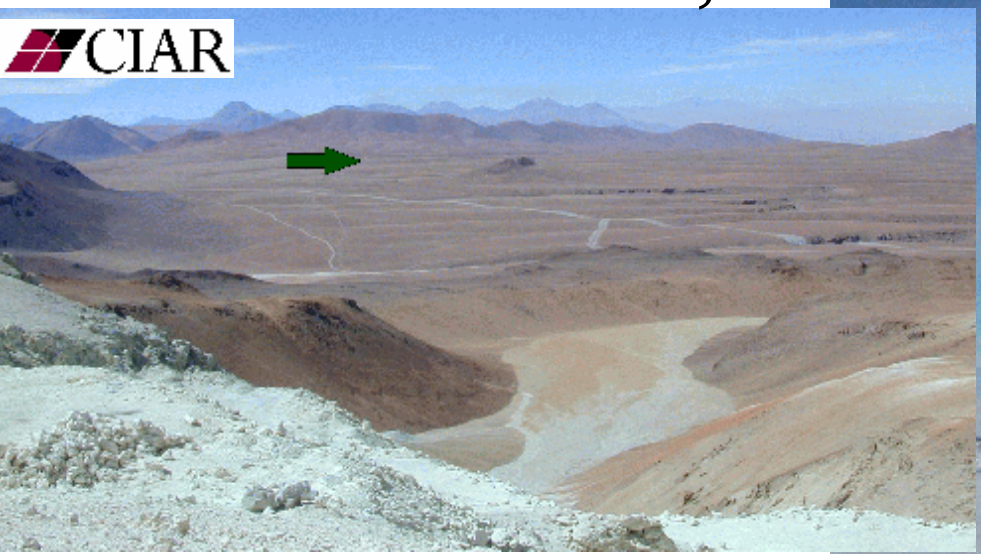
B03



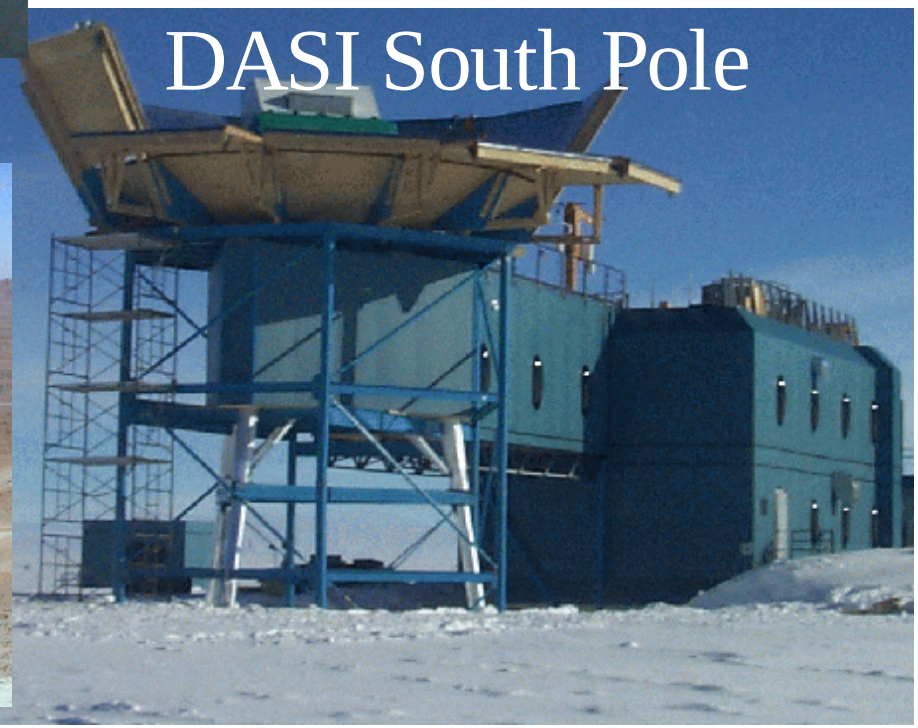
CIAR

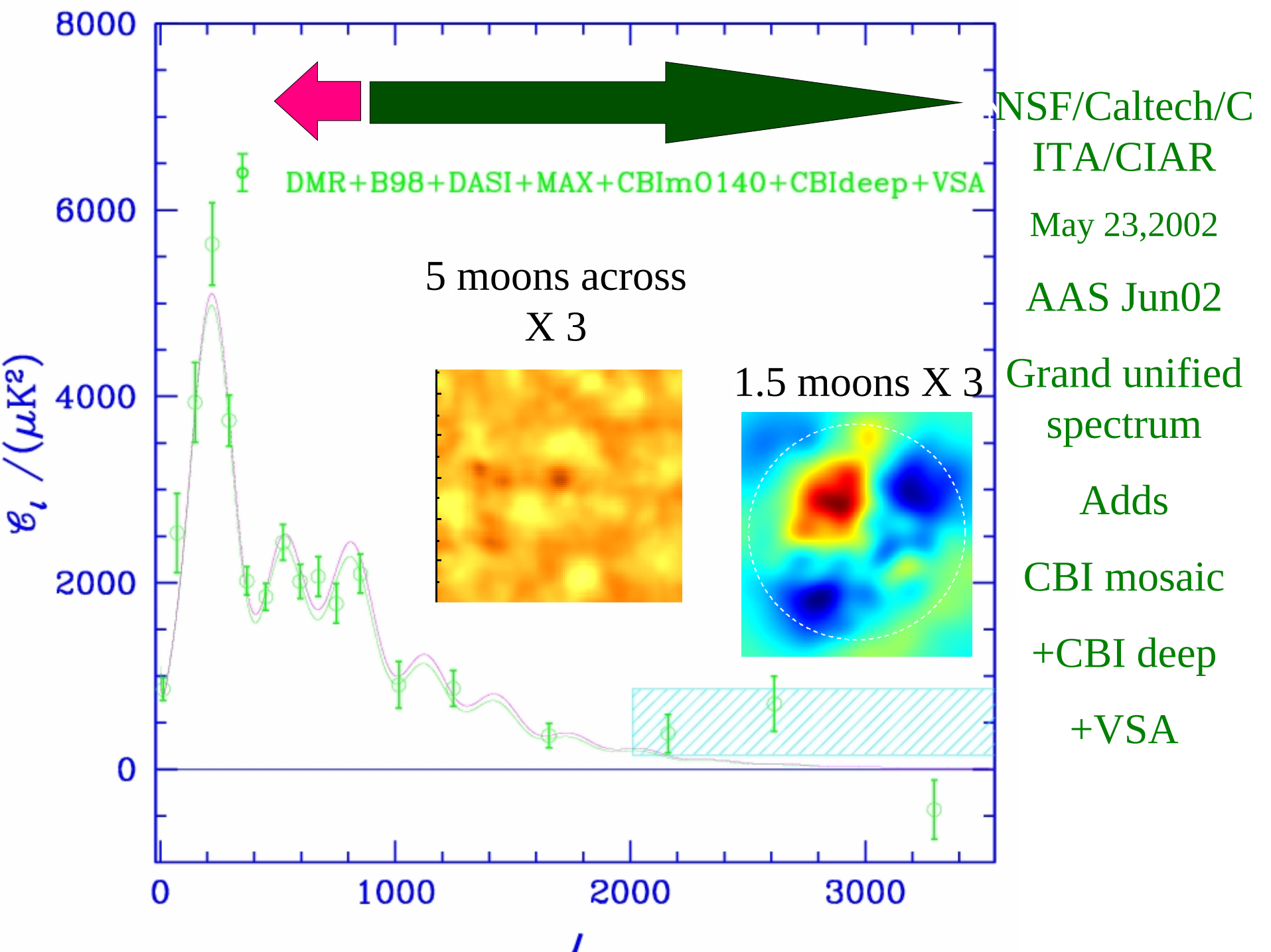
CBI Atacama desert, Chile

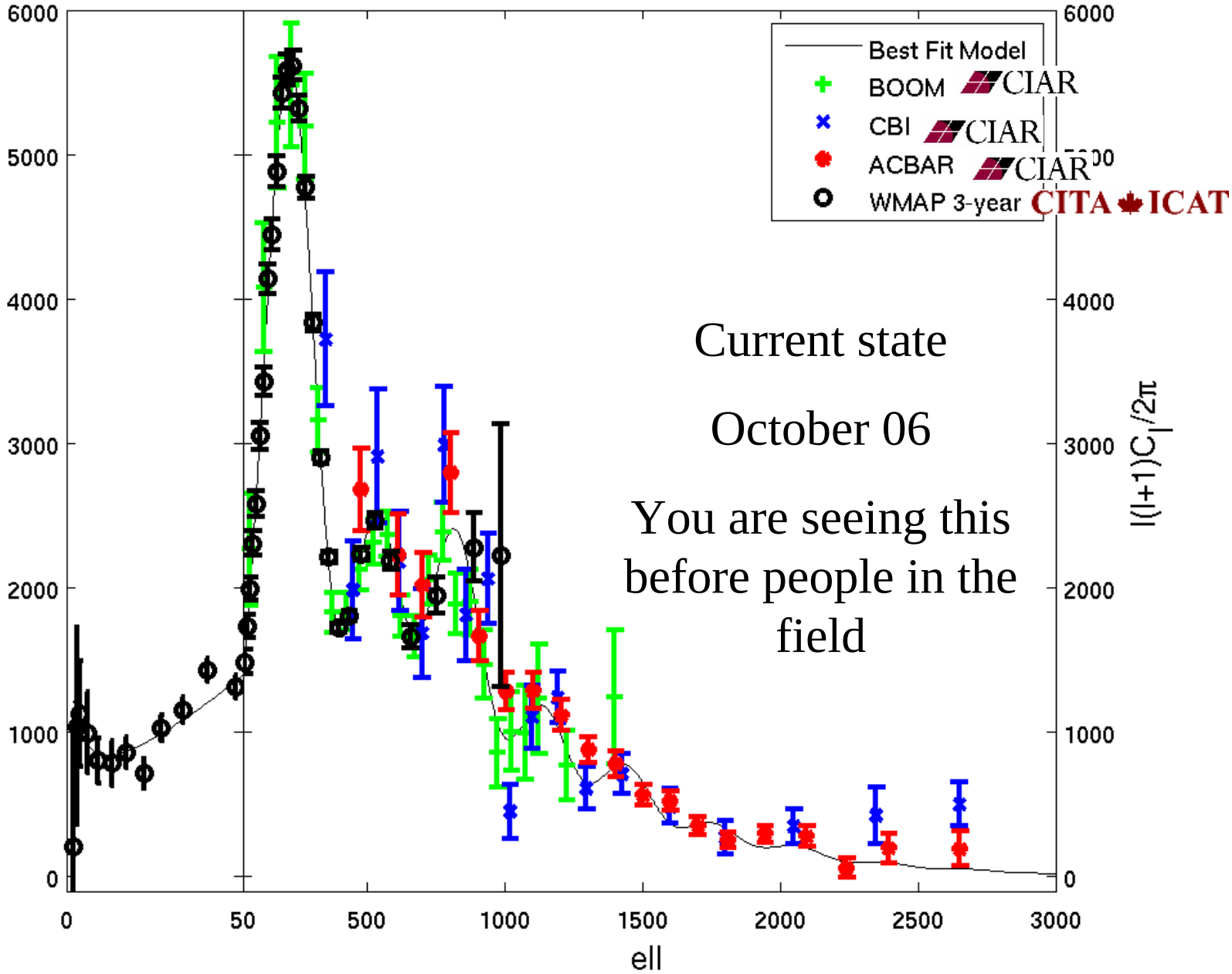
CIAR



DASI South Pole




8000
6000
4000
2000
0
$\mathcal{C}_l$ /(μK^2)
0
1000
2000
3000
l
DMR+B98+DASI+MAX+CBIm0140+CBIdeep+VSA
5 moons across
X 3
1.5 moons X 3
NSF/Caltech/C
ITA/CIAR
May 23,2002
AAS Jun02
Grand unified
spectrum
Adds
CBI mosaic
+CBI deep
+VSA

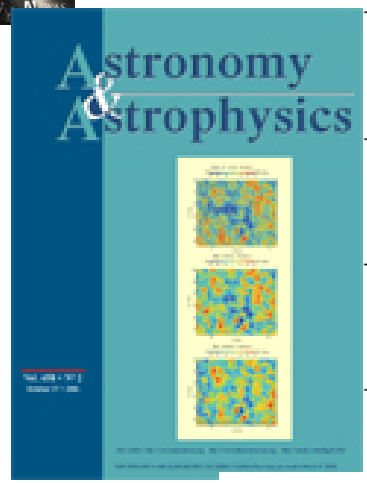

Best Fit Model
BOOM
CBI
ACBAR
WMAP 3-year
CIAR
CIAR
CIAR
CITA
ICAT
Current state
October 06
You are seeing this before people in the field
ell
l(l+1)C_l/2π
0
50
500
1000
1500
2000
2500
3000
1000
2000
3000
4000
5000
6000

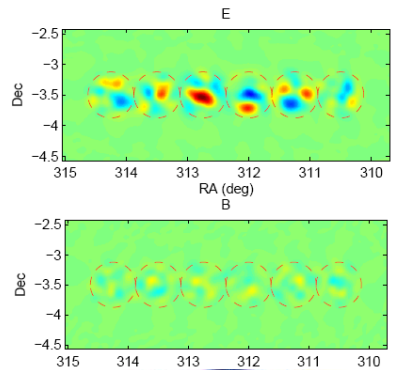
Current state

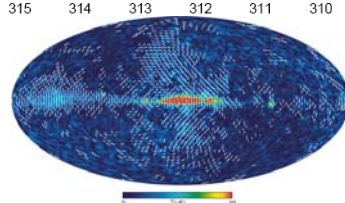
October 06

Polarization

a Frontier







Measuring Cosmological Parameters (7++) from Data+Theory

how much ordinary matter in U? $\Omega_b = 0.045 \pm 0.003$

agrees with Big Bang Nucleosynthesis

how much dark matter which clusters in U? Big Bang relics $\Omega_{cdm} = 0.225 \pm 0.03$

how much dark energy which does not cluster in U? $\Omega_\Lambda = 0.73 \pm 0.03$

greatest mystery in physics. dynamics?

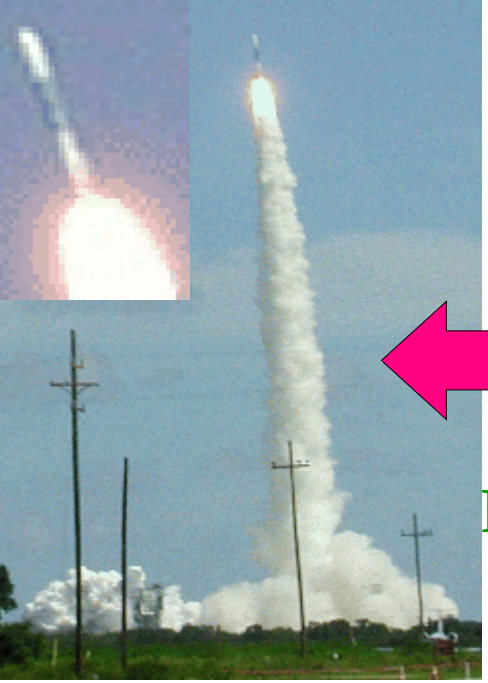
how curved are U?

$$\Omega_{tot} = \Omega_b + \Omega_{cdm} + \Omega_\Lambda = 1.02 \pm .02$$

1.0000 simple inflation

how old are U? **13.7 ± 0.1 billion yrs**

how big are U? > Horizon (?)

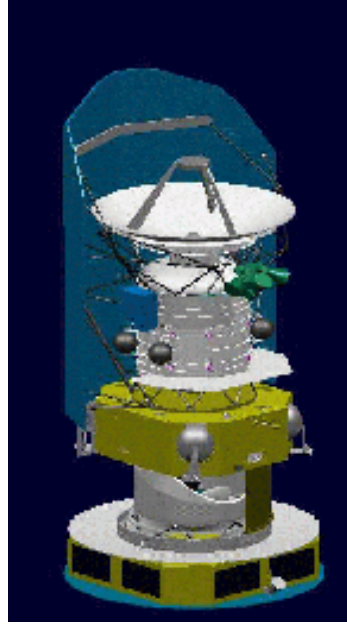


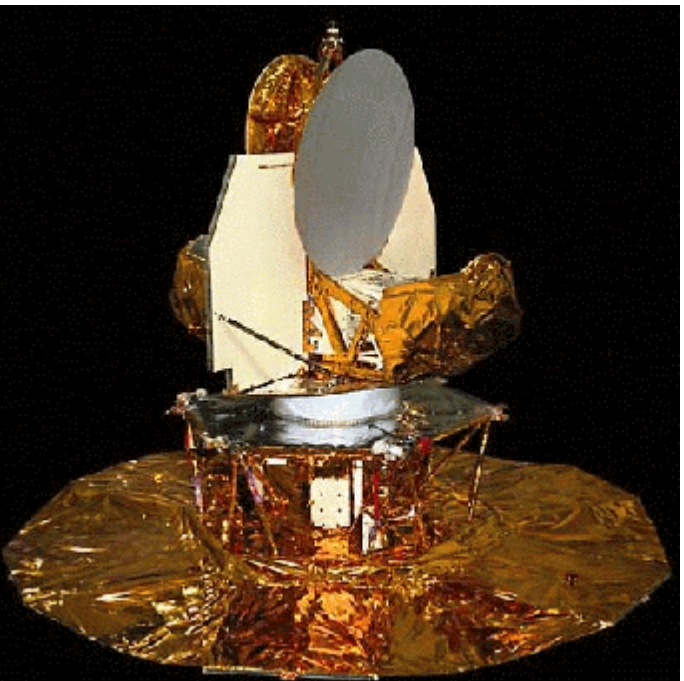
Forecasts of precision on 9 "standard model" parameters

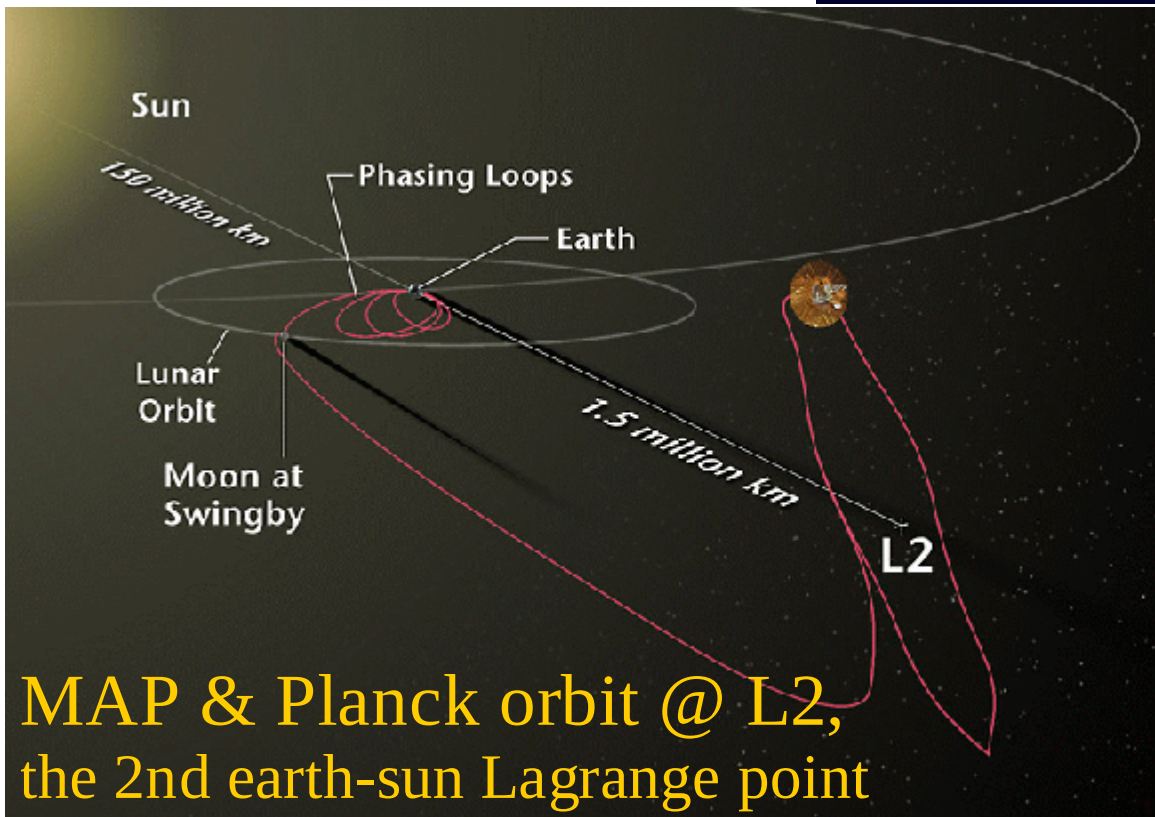
WMAP4 3/9 to ±0.01, 7/9 to ±0. 1

WMAP4+gnd 6/9 to ±0.01, 9/9±0. 1

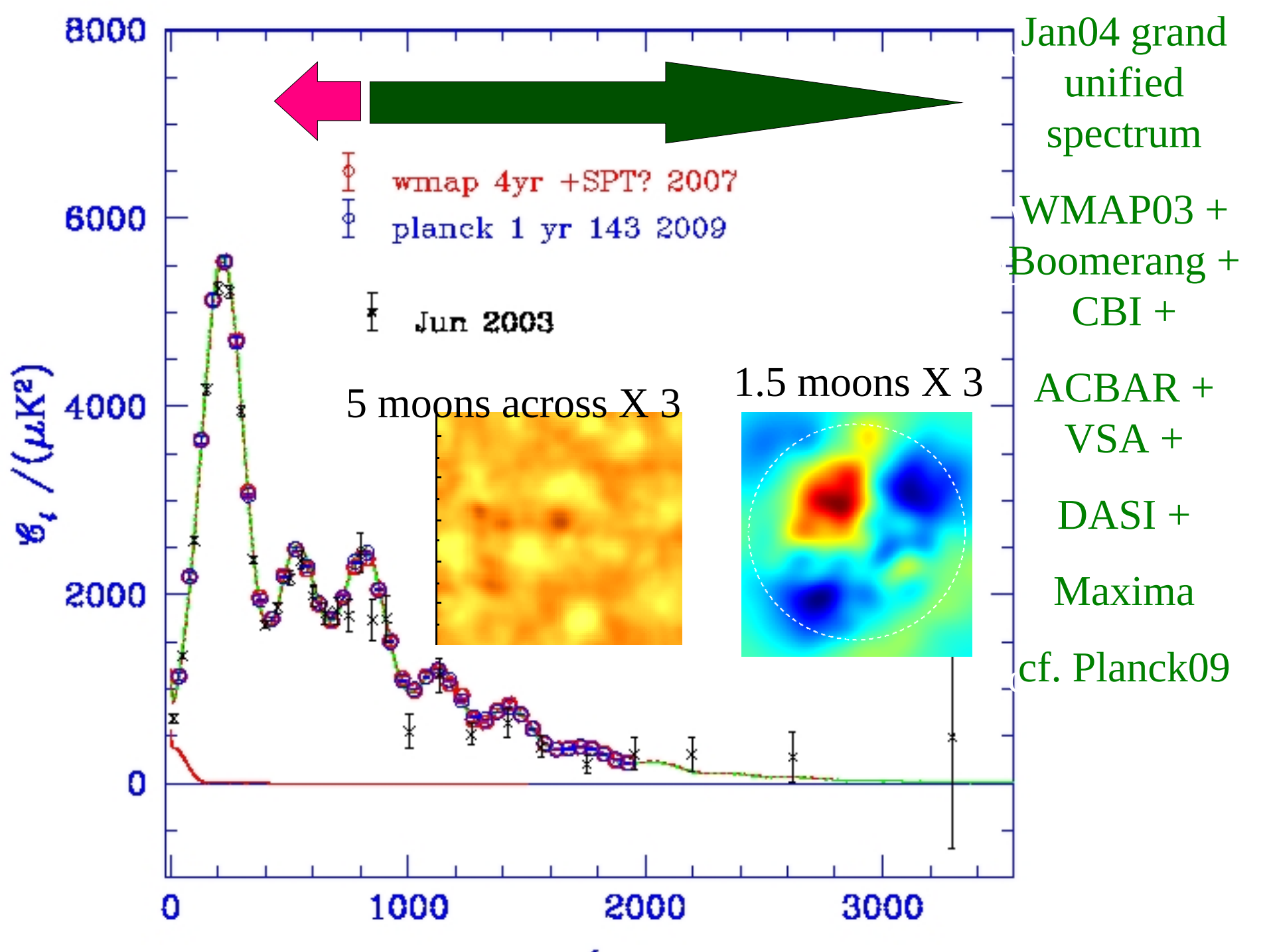
Planck1 2008+ 7/9 to ±0.01, 9/9





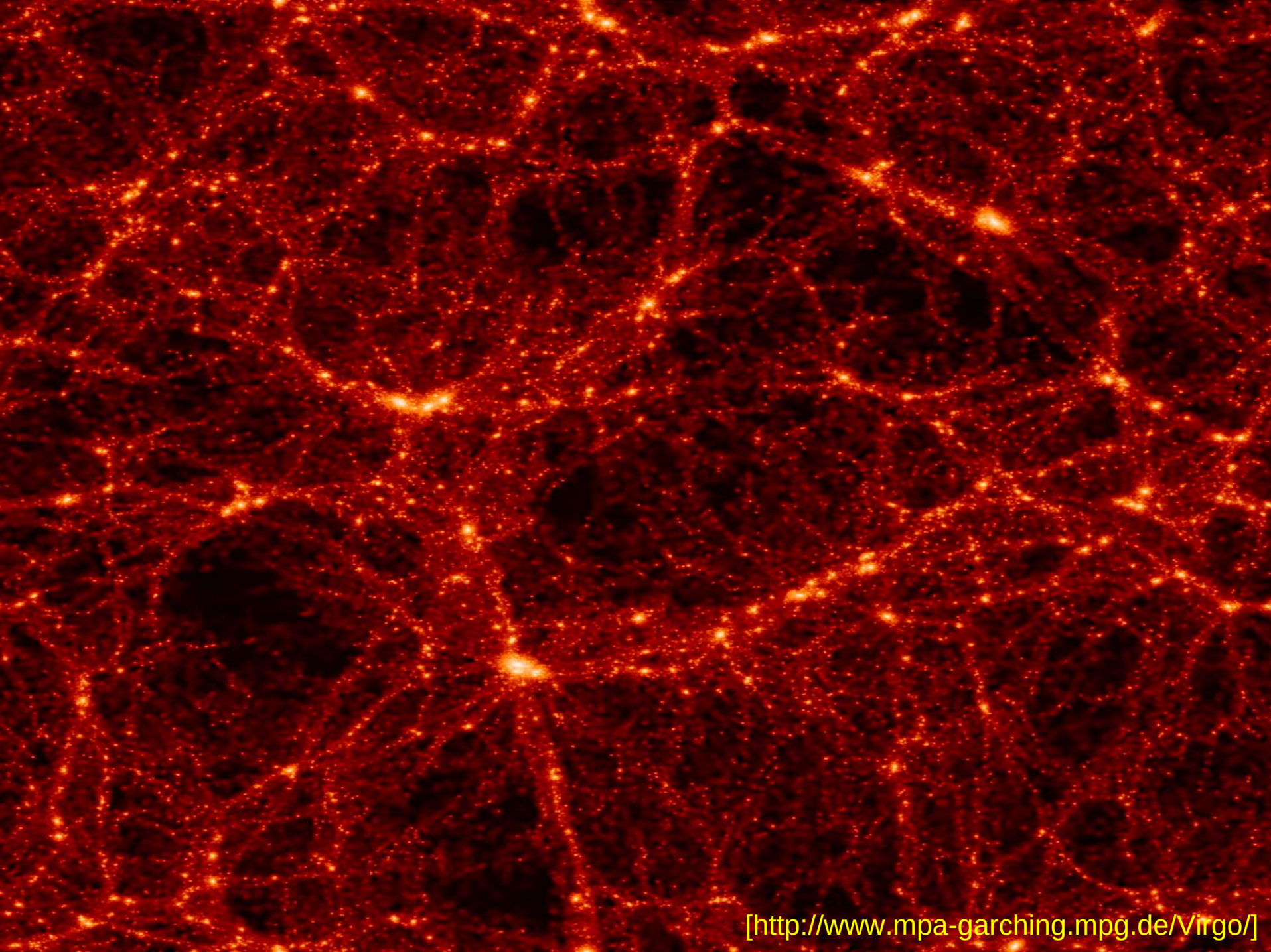


MAP & Planck orbit @ L2,
the 2nd earth-sun Lagrange point

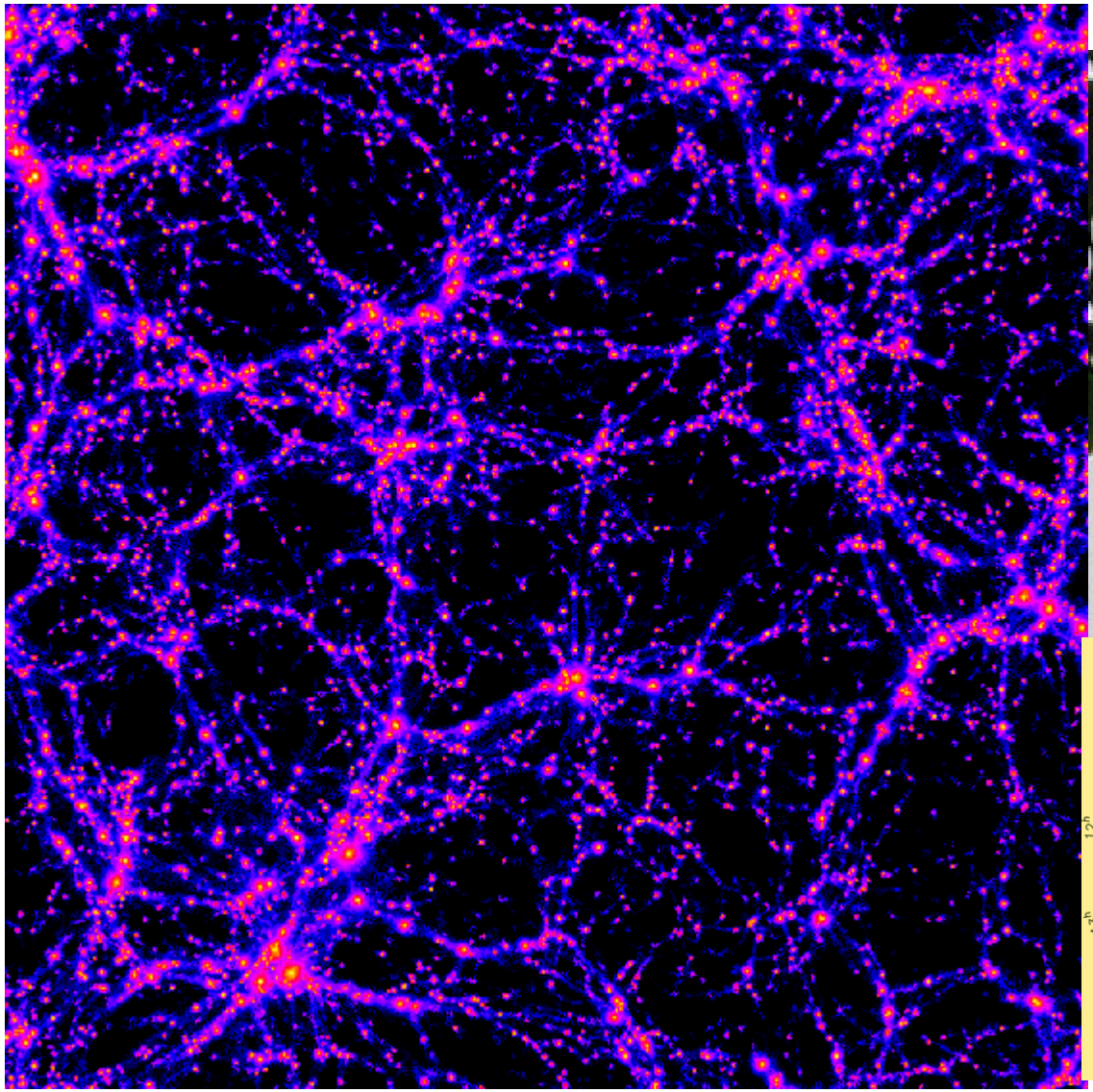

8000
6000
4000
2000
0
0
1000
2000
3000
$\mathcal{C}_\ell$ /(μK^2)
wmap 4yr +SPT? 2007
planck 1 yr 143 2009
Jun 2003
5 moons across X 3
1.5 moons X 3
Jan04 grand unified spectrum
WMAP03 + Boomerang + CBI +
ACBAR + VSA +
DASI +
Maxima
cf. Planck09

massively parallel computations in Canada @CITA

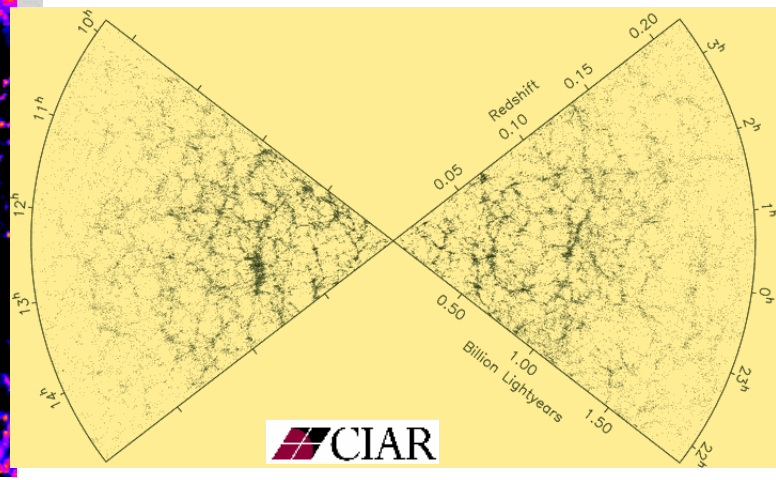
Bob+Doug Mackenzie beowulf cluster: 536 Intel processors.
Jun03, 38th in the world. Simulation of theory / analysis of data

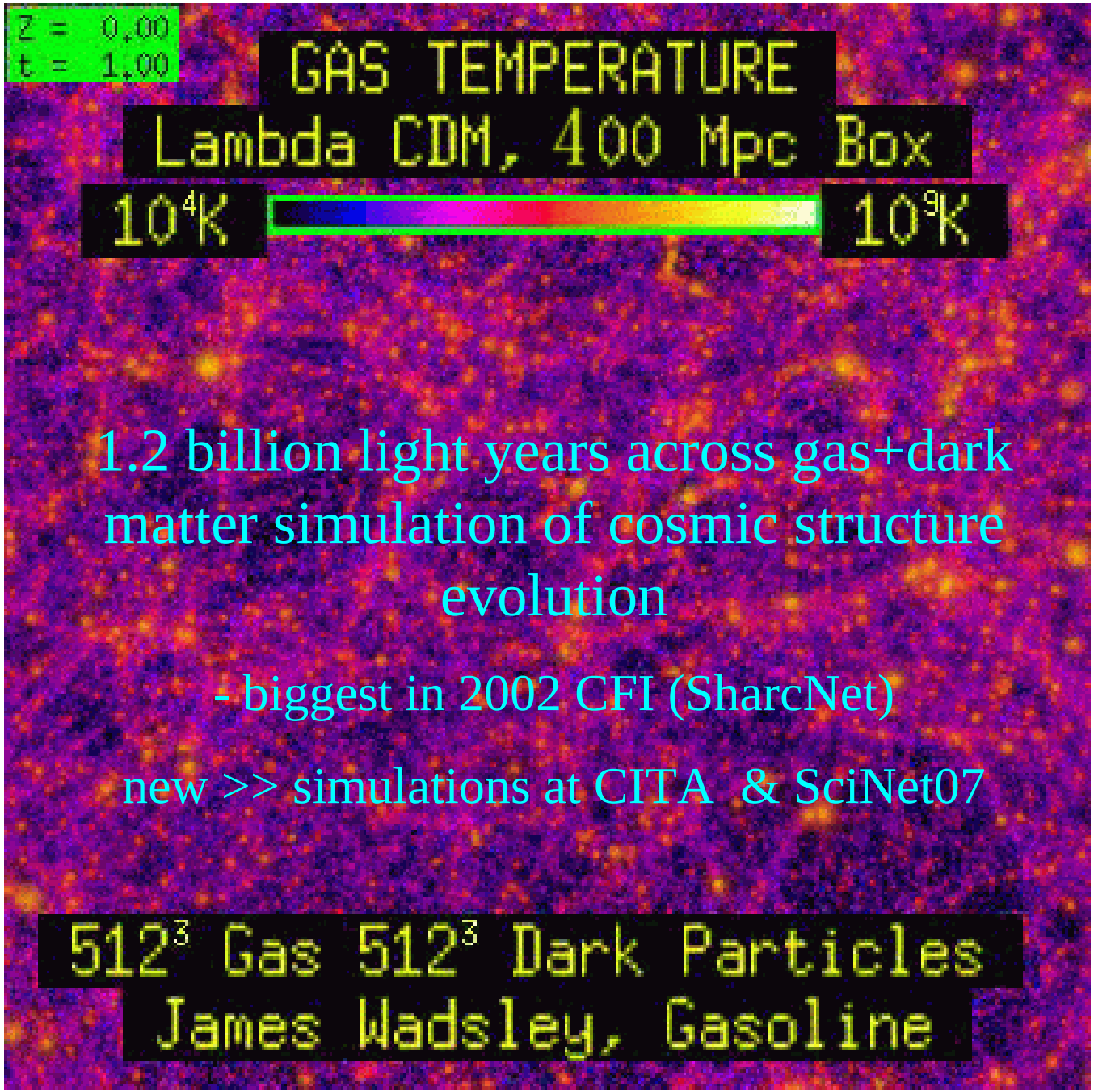

[http://www.mpa-garching.mpg.de/Virgo/]

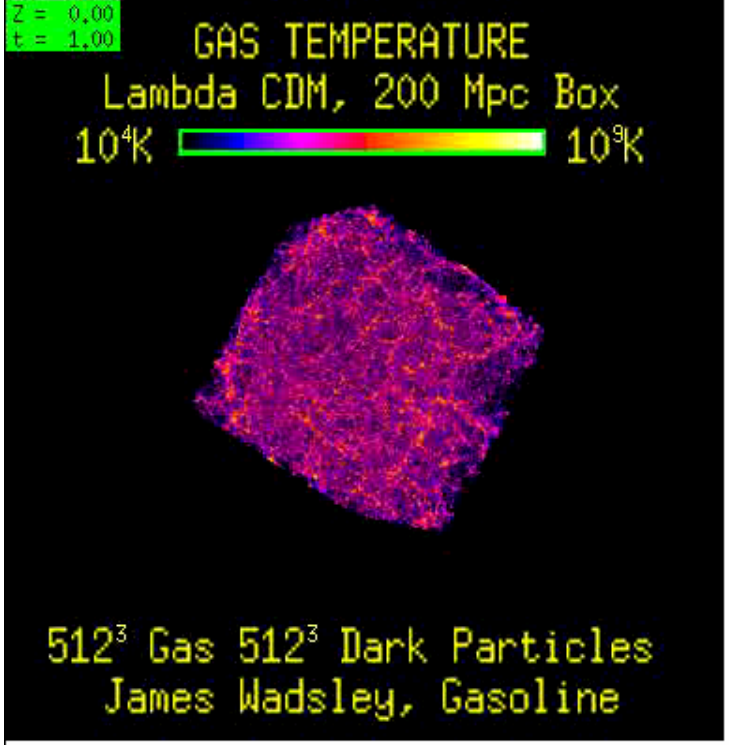
Cosmic Web & Superclustering: a natural consequence of the gravitational instability of a hierarchical Gaussian random density field



clusters,
filaments,
membranes
& voids




z = 0.00
t = 1.00
GAS TEMPERATURE
Lambda CDM, 400 Mpc Box
10⁴K
10⁹K
1.2 billion light years across gas+dark matter simulation of cosmic structure evolution
- biggest in 2002 CFI (SharcNet)
new >> simulations at CITA & SciNet07
512³ Gas 512³ Dark Particles
James Wadsley, Gasoline



LCDMSZ512Temp_fullmovie384.mpg

"IT from BIT"

FATE U inflate (again)

a cold death? reheat/rebirth?

NOW **14 Gyr 1**

Pythagoras formed

Galaxies Cluster
Cosmic "web" of vast filaments + membranes

Life forms on earth

9 Gyr 1.4

Carbon/oxygen/etc form

Galaxies form

2 Gyr 4

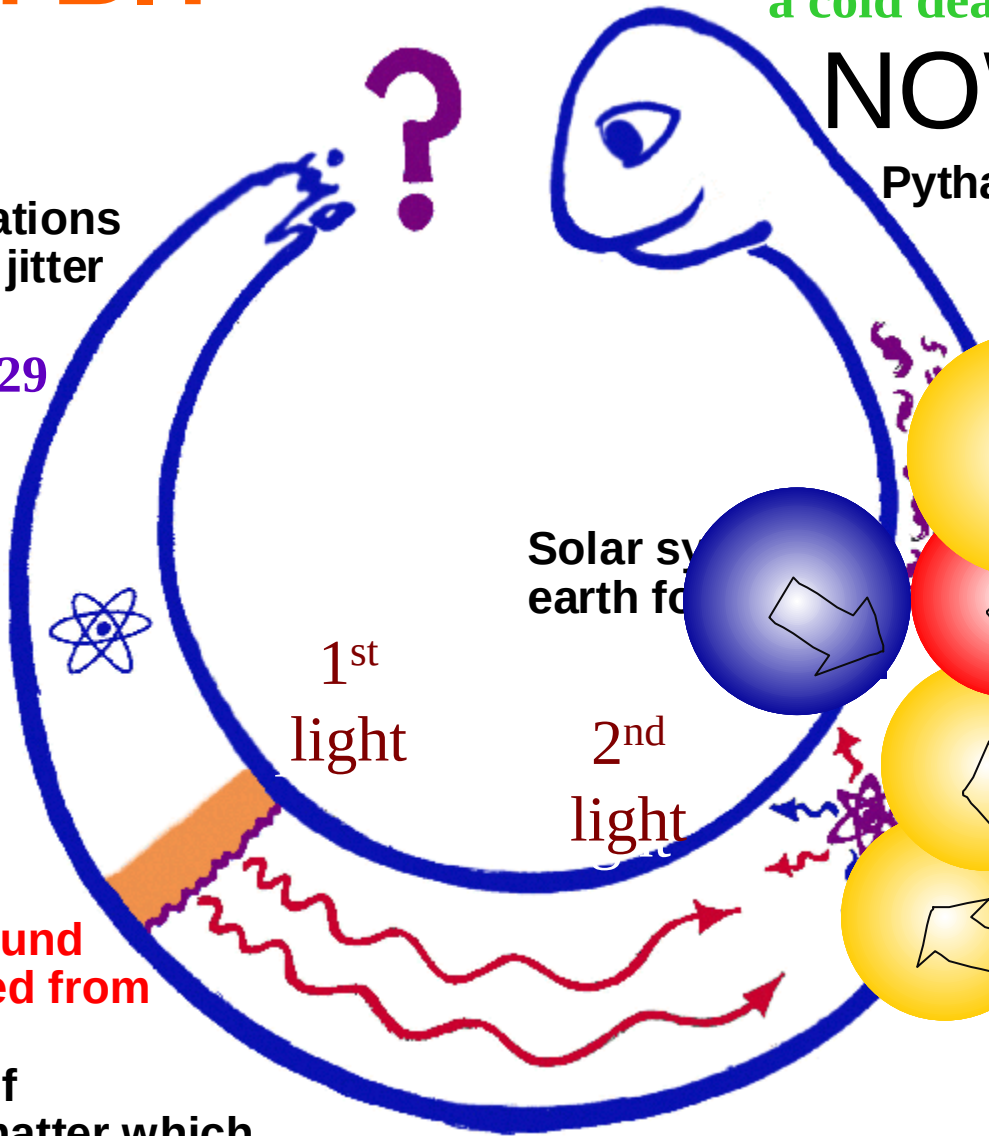
Inflation fluctuations form: quantum jitter

10^{-37} sec 10^{29}

Protons/Neutrons form

Helium forms

100 sec 10^{9}



Cosmic background radiation released from matter
carries imprint of fluctuations in matter which grow to generate galaxies etc.

0.4 Myr 1100

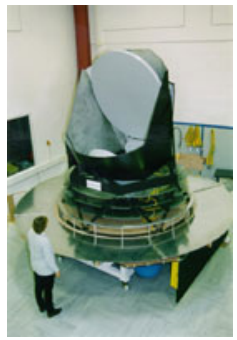
The 'Meaning' may change
But the facts will remain

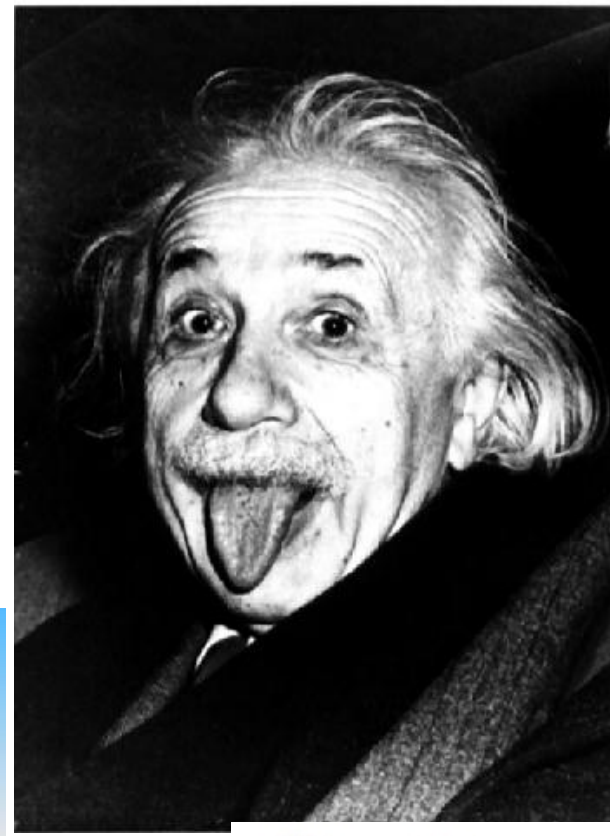
Ω_Λ (time,space)

Then (10^{-37}s) inflation &

Now (13.7×10^{-37}yr)

dark energy mystery





our UofT/CITA/CIAR future:

to the early & late Universe

thru Experiment + Theory

(CMB+Lens+SN+clusters)