The Planck Mission

Death by Data

The Late Great Universe

The Life and Death of Our Universe

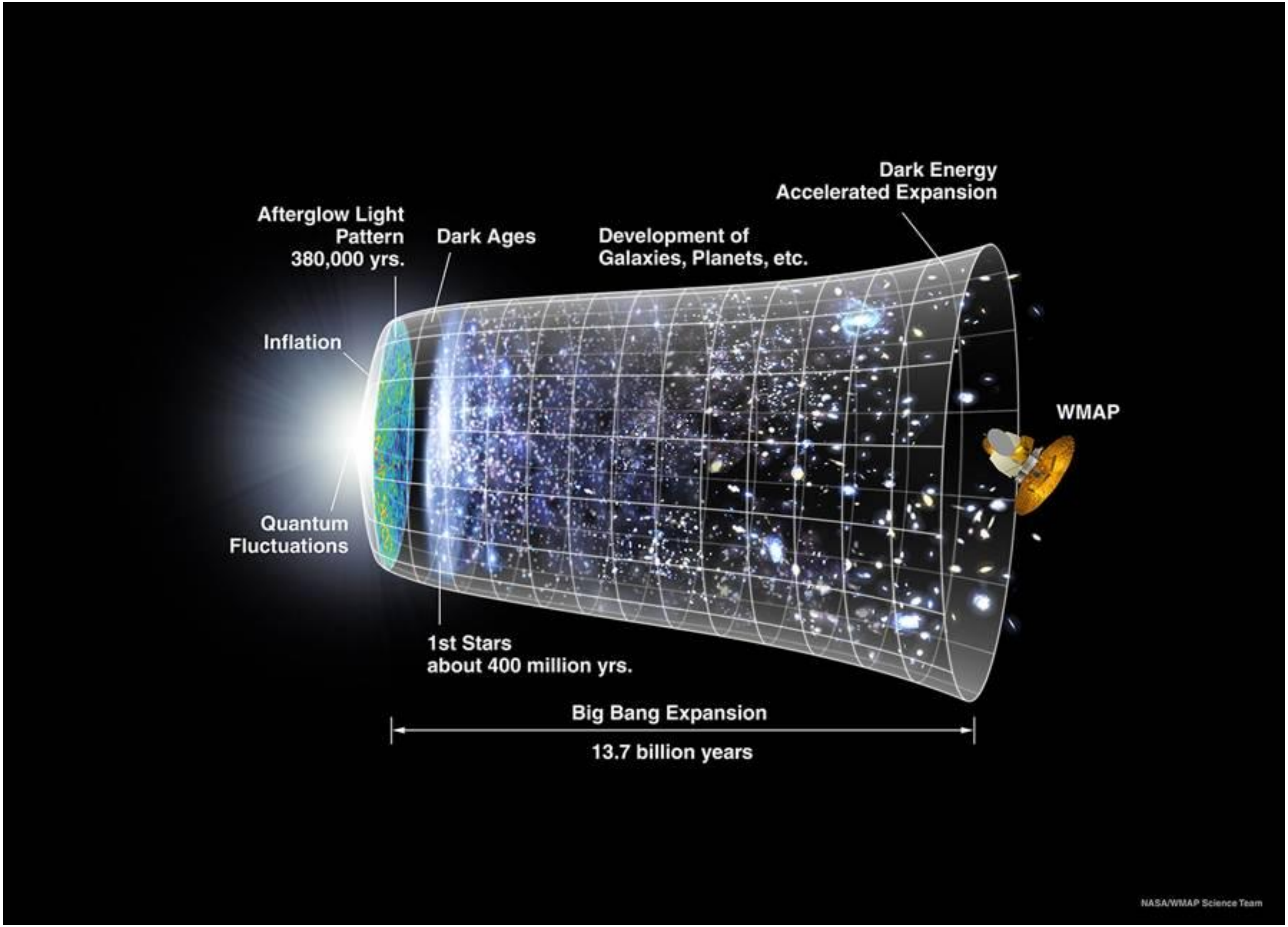
OR

The Eternal Furlough

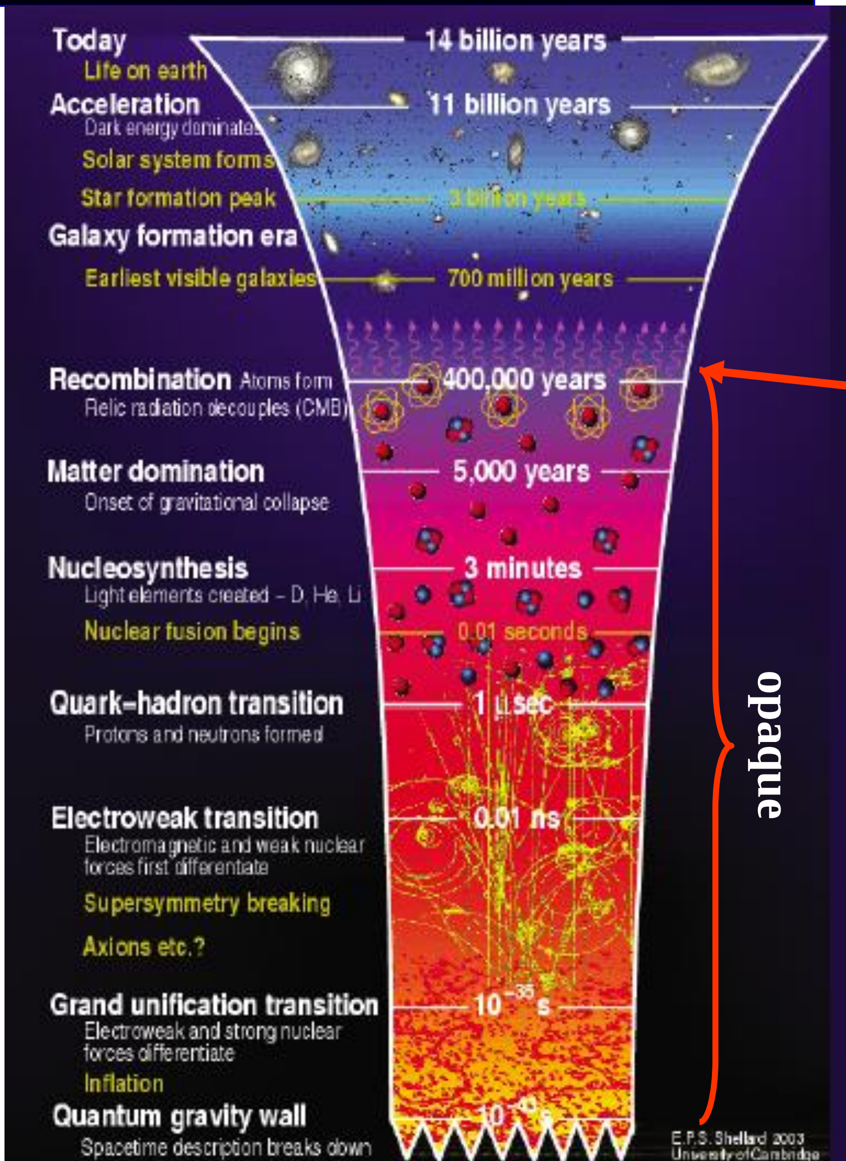
UCSB Experimental Cosmology Group – Planck team
P. Meinhold, A. Zonca, J. van der, P. Lubin + many collaborators –

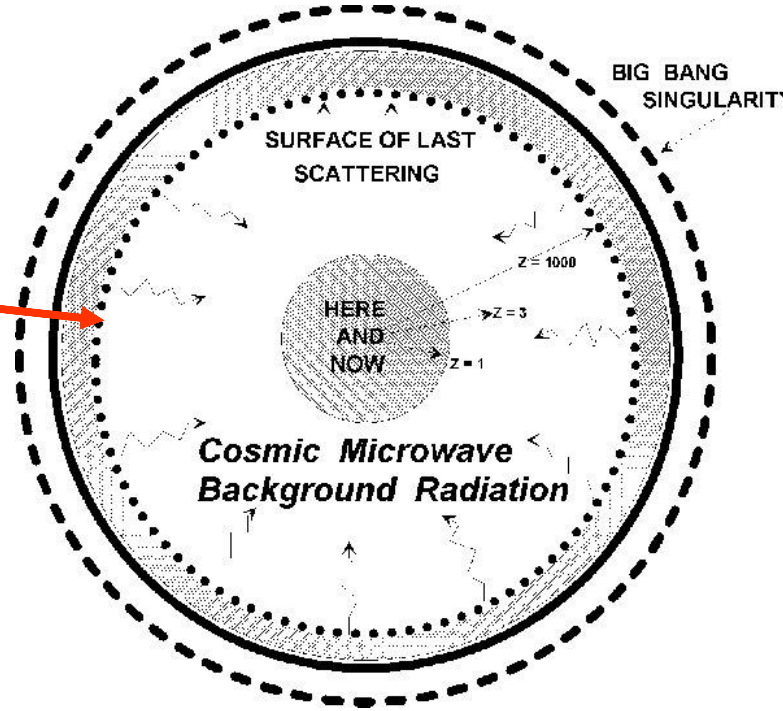
www.deepspace.ucsb.edu

A Brief History of the Universe

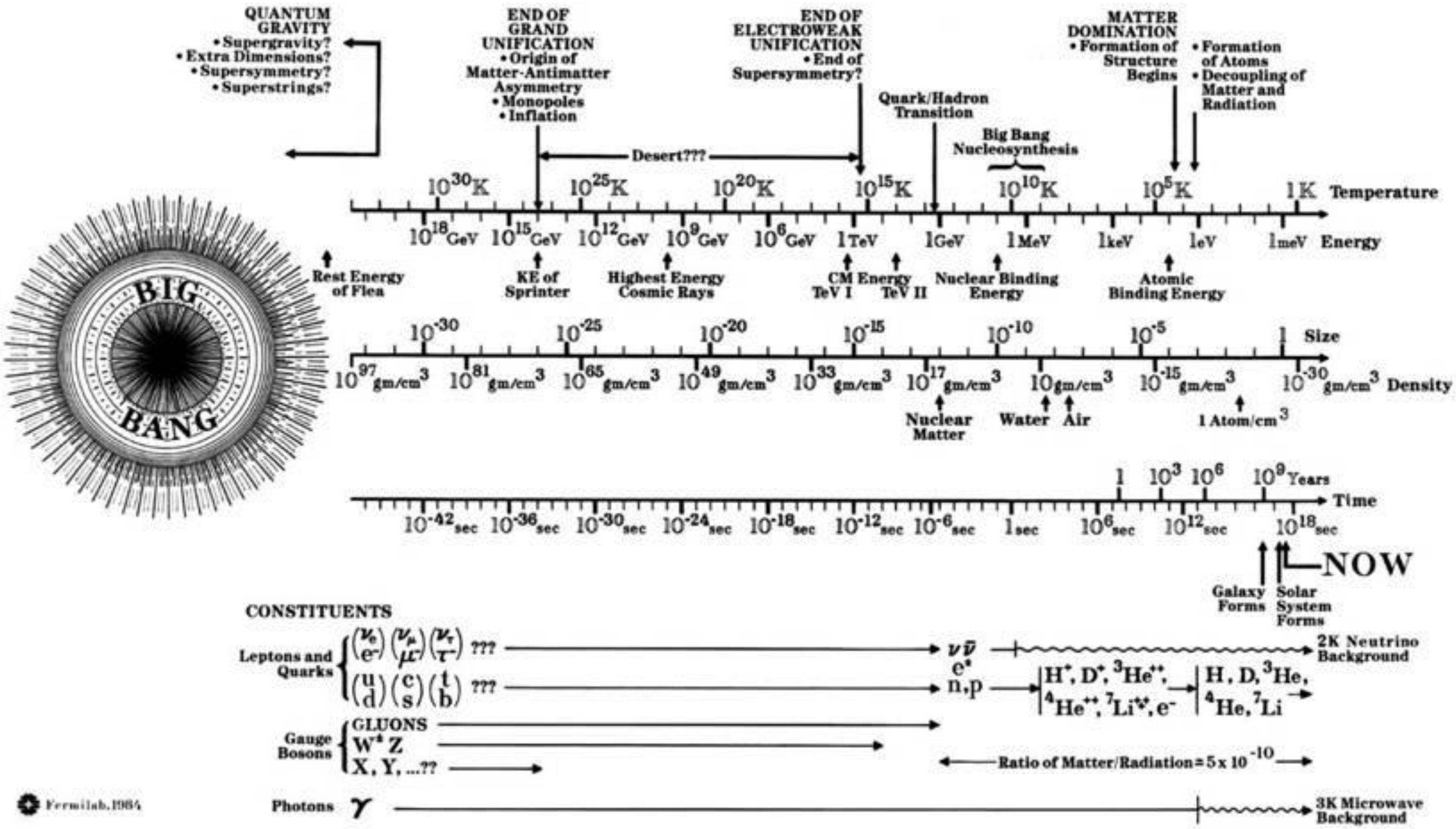


Overview of the CMB:



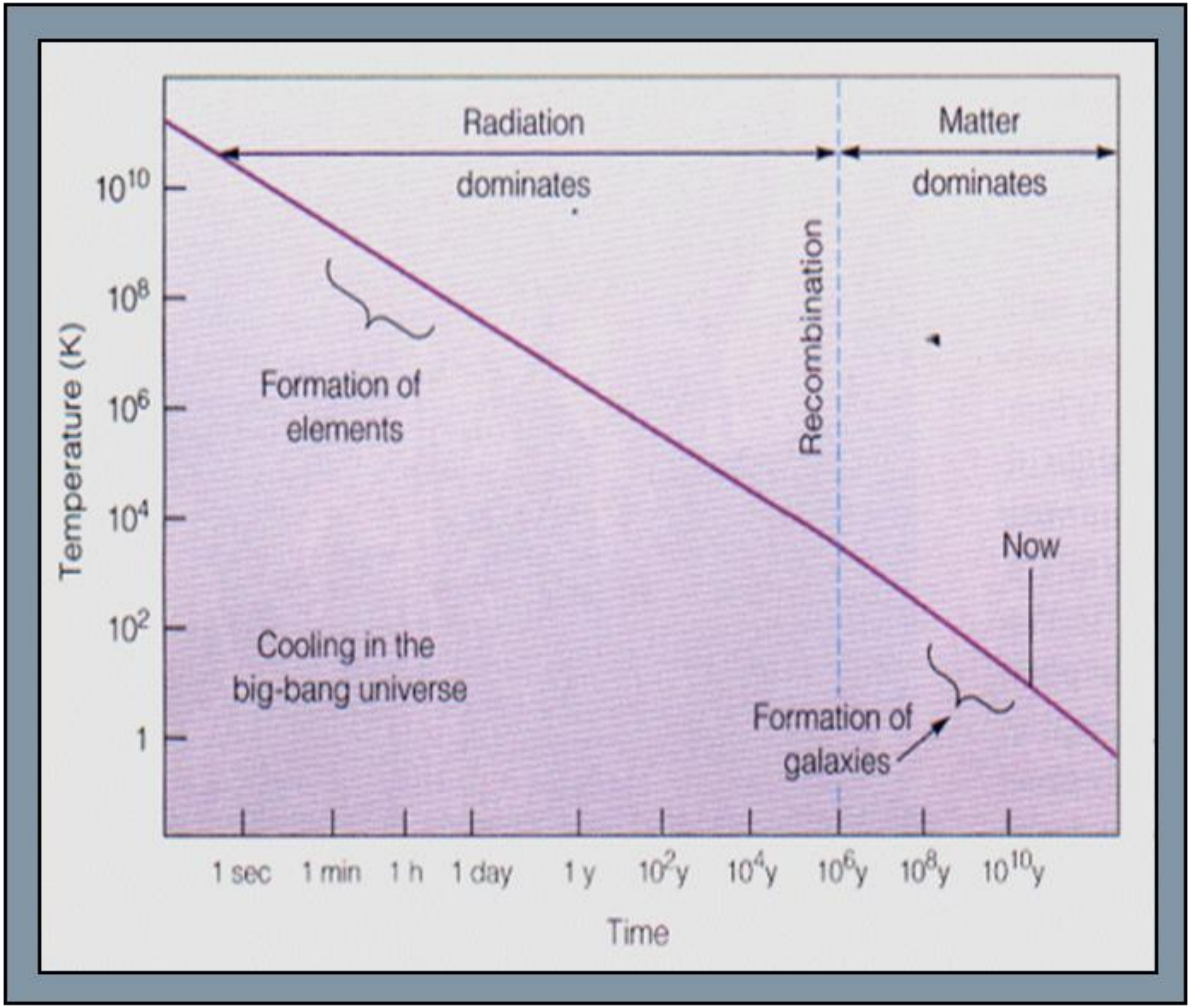


Prior to a red shift of ~1000, the universe was opaque to electromagnetic radiation. Thus, the CMB is the oldest light that we can observe.

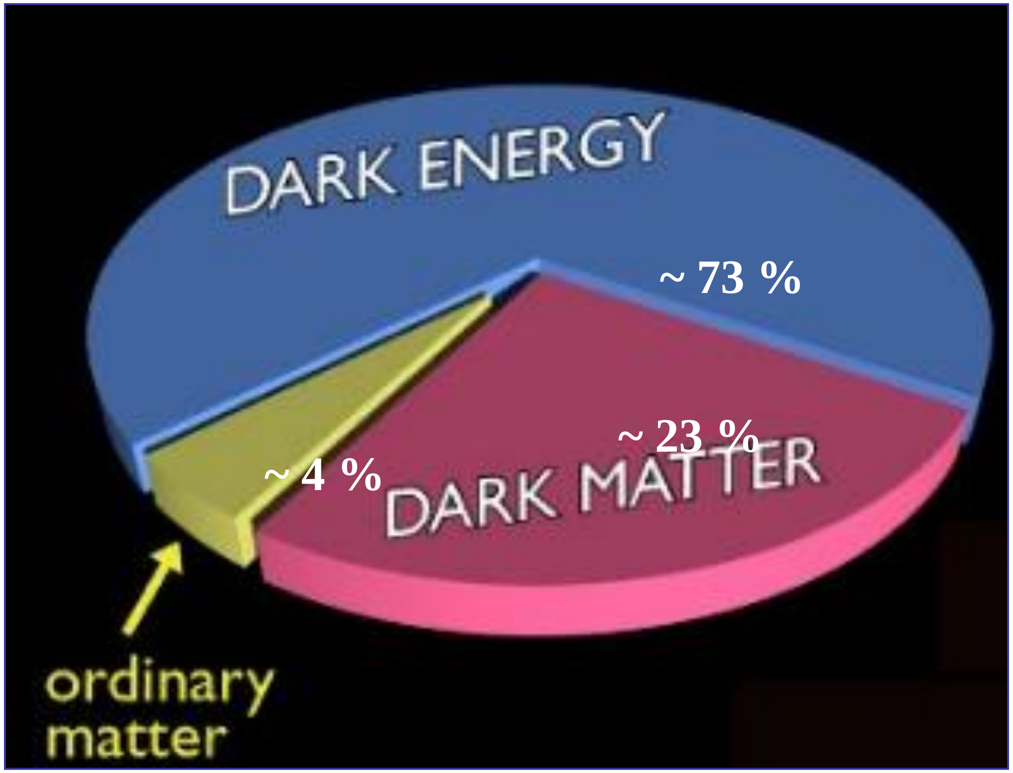


Fermilab Photograph 85-138CN

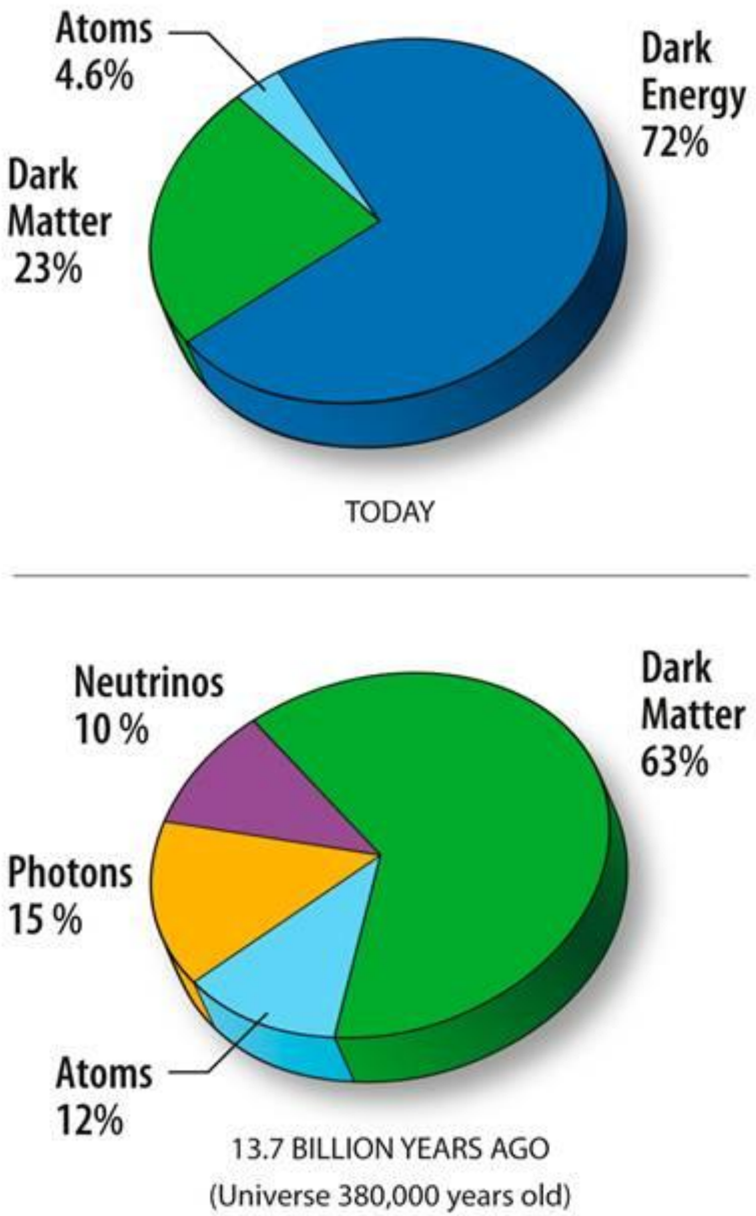
Temperature vs Time



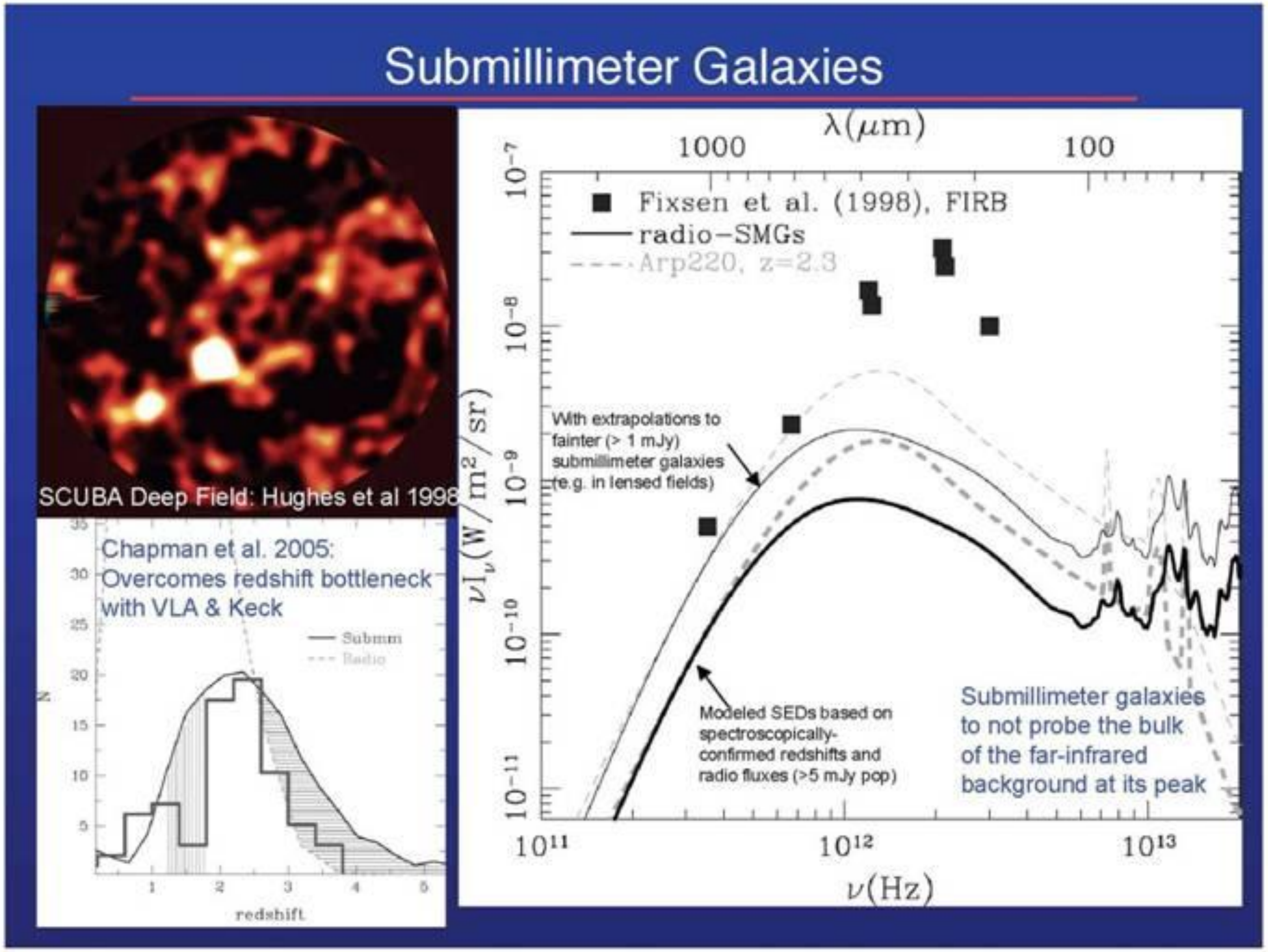
• ***The "dark sector" comprises ~ 96% of our universe...***



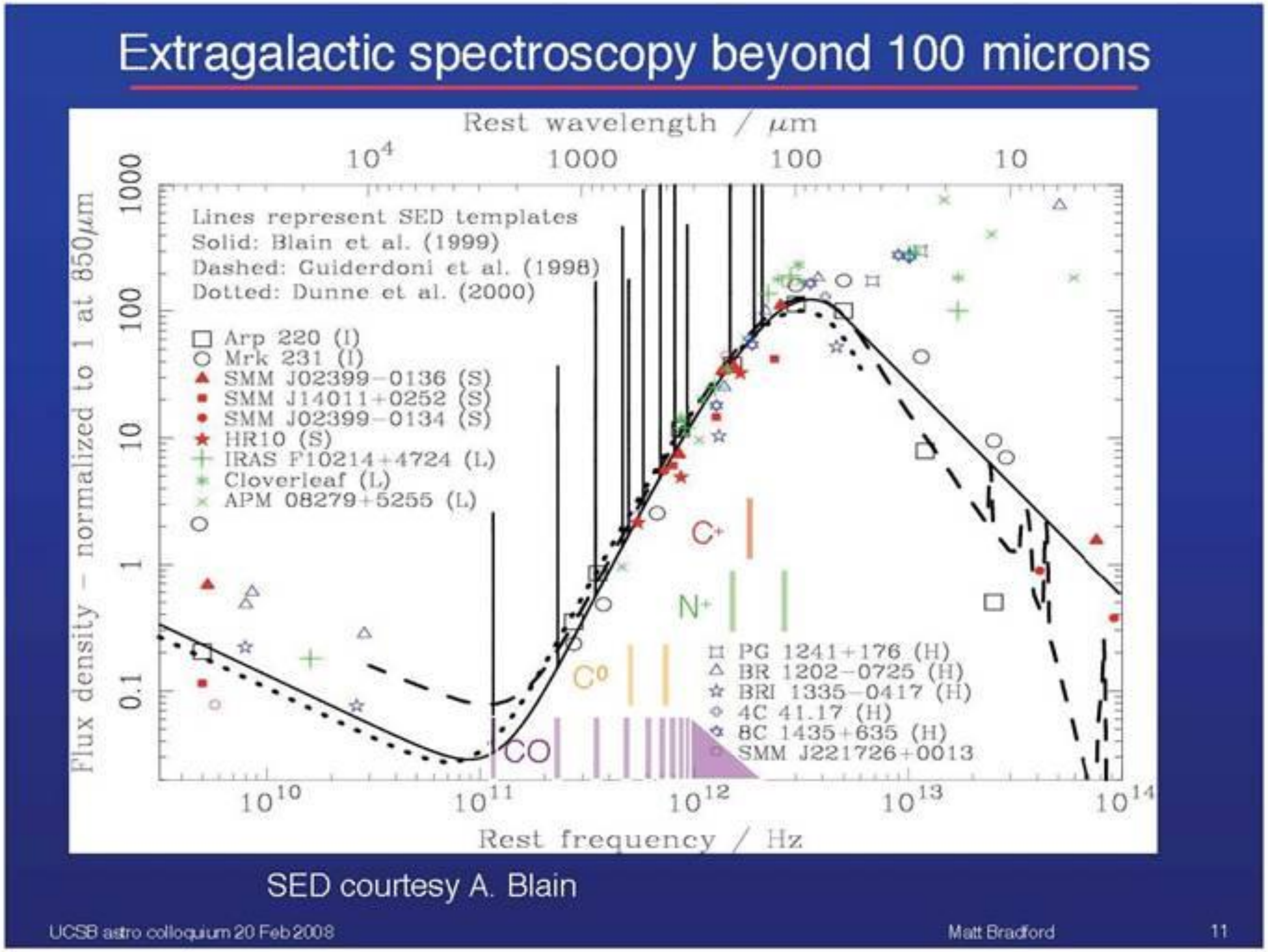
Matter and Energy Distribution Changes with Time



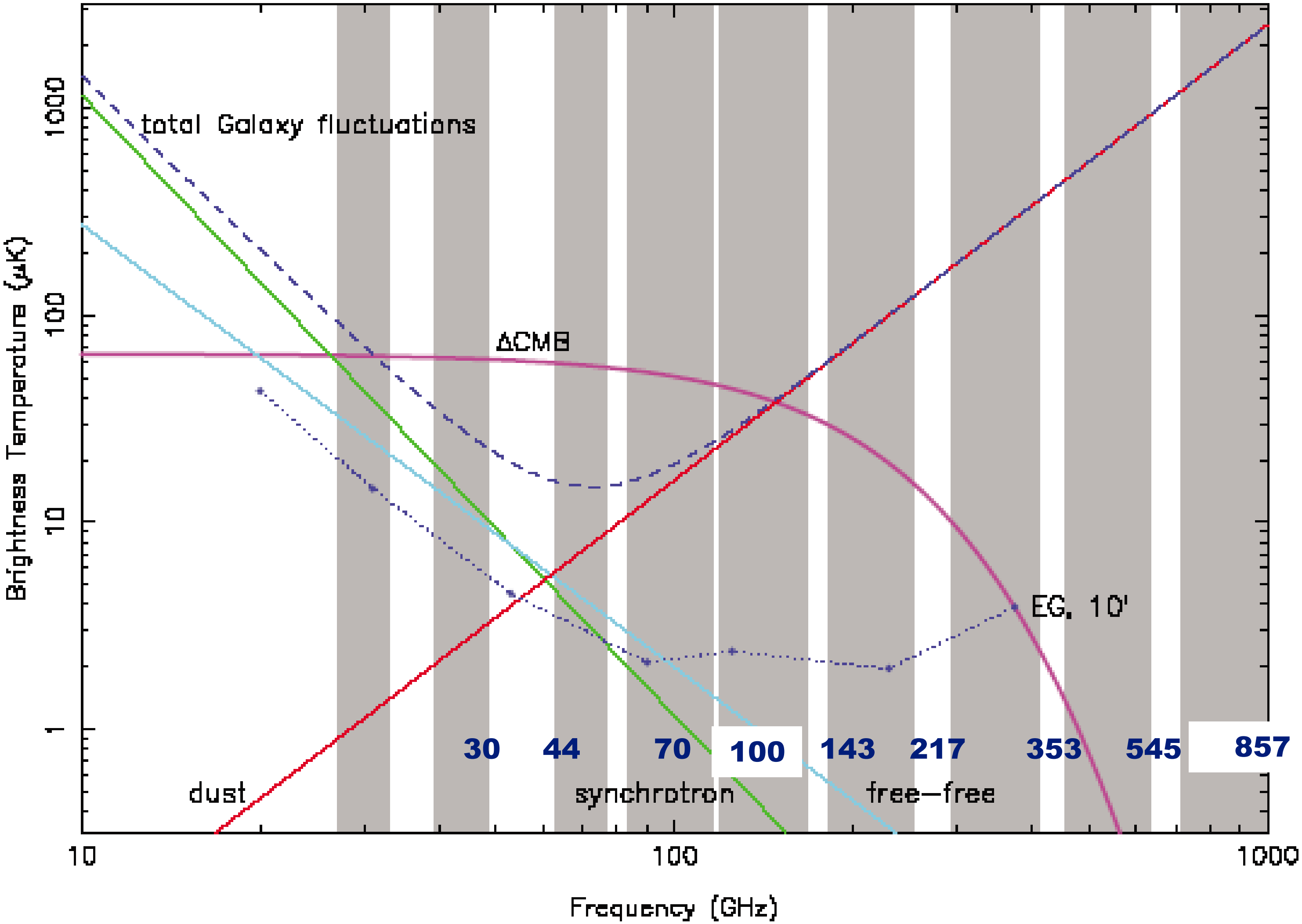
Distant Galaxies in THz



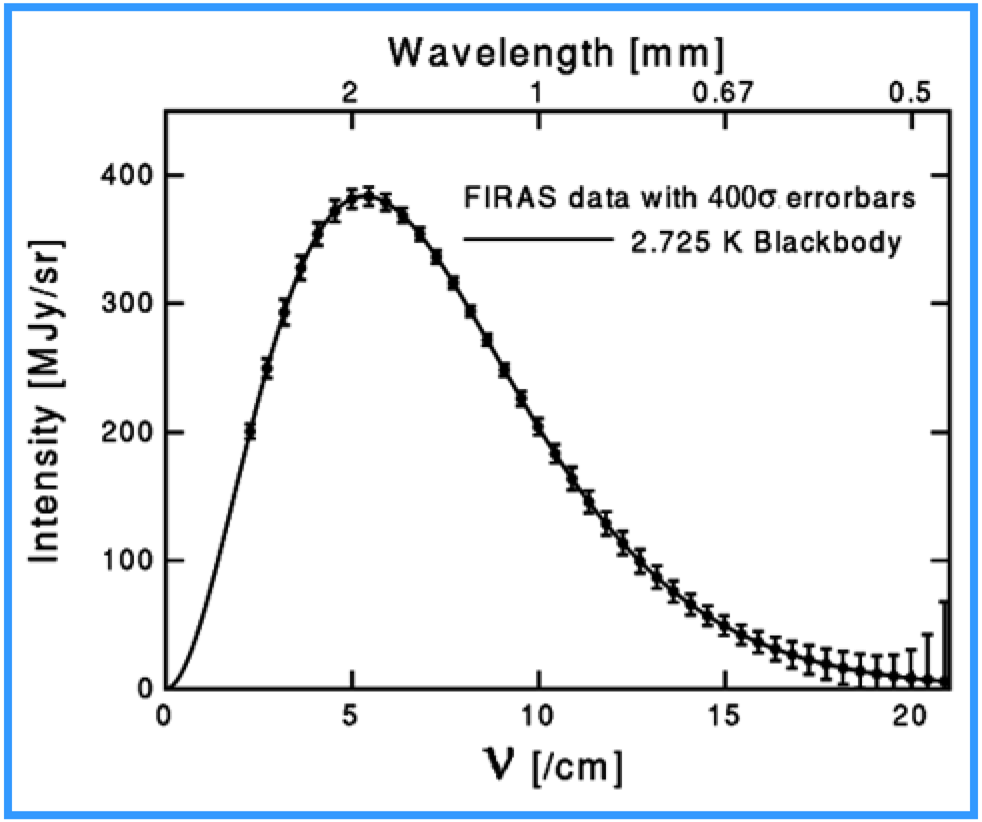
Extragalactic THz Spectroscopy



Planck will measure from 30 GHz (1 cm) to ~ 1 THz (0.3 mm).
Planck cover 10x more freq range than WMAP and we had on COBE
Planck is ~20x more sensitive than WMAP, ~ 200x COBE
Planck has 3x the angular resolution of WMAP and 100x more that we had on COBE

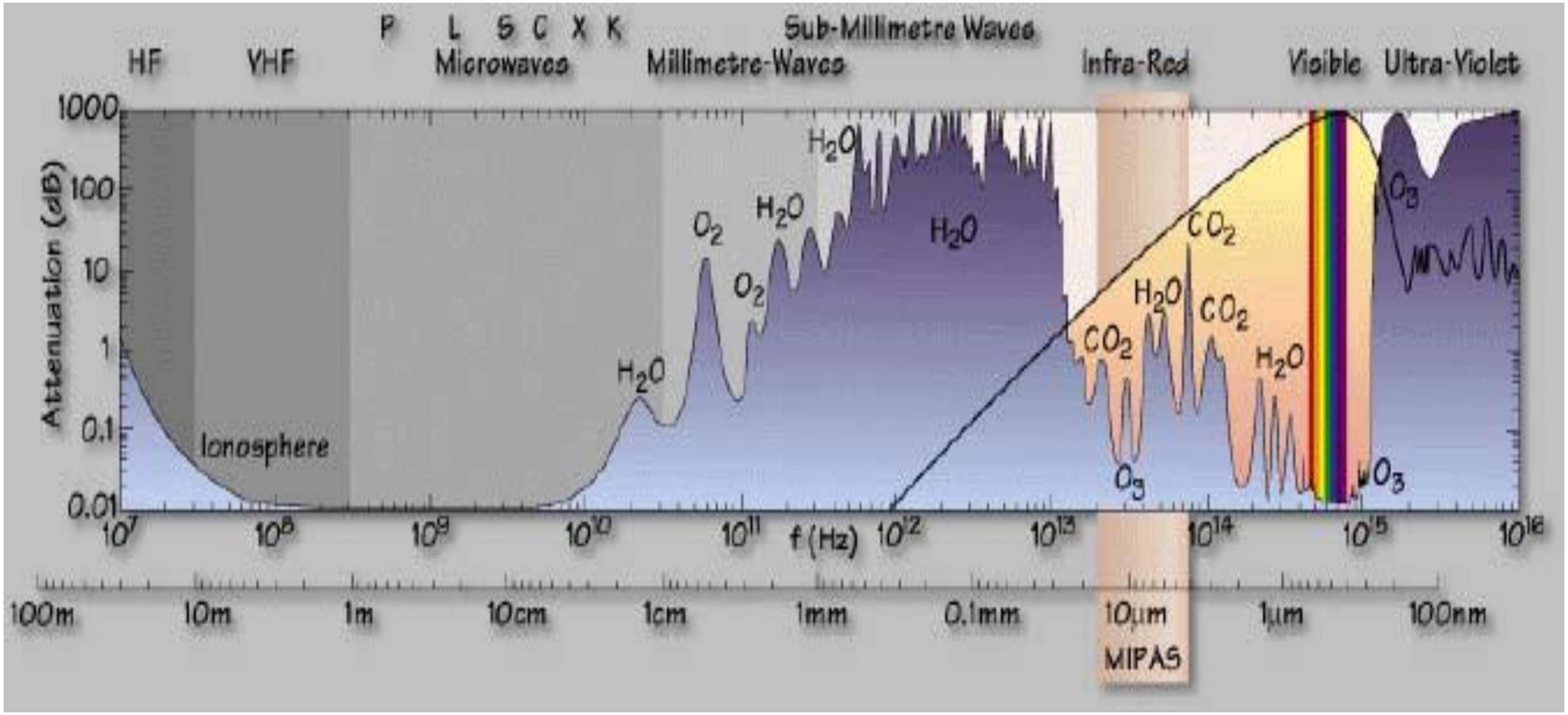


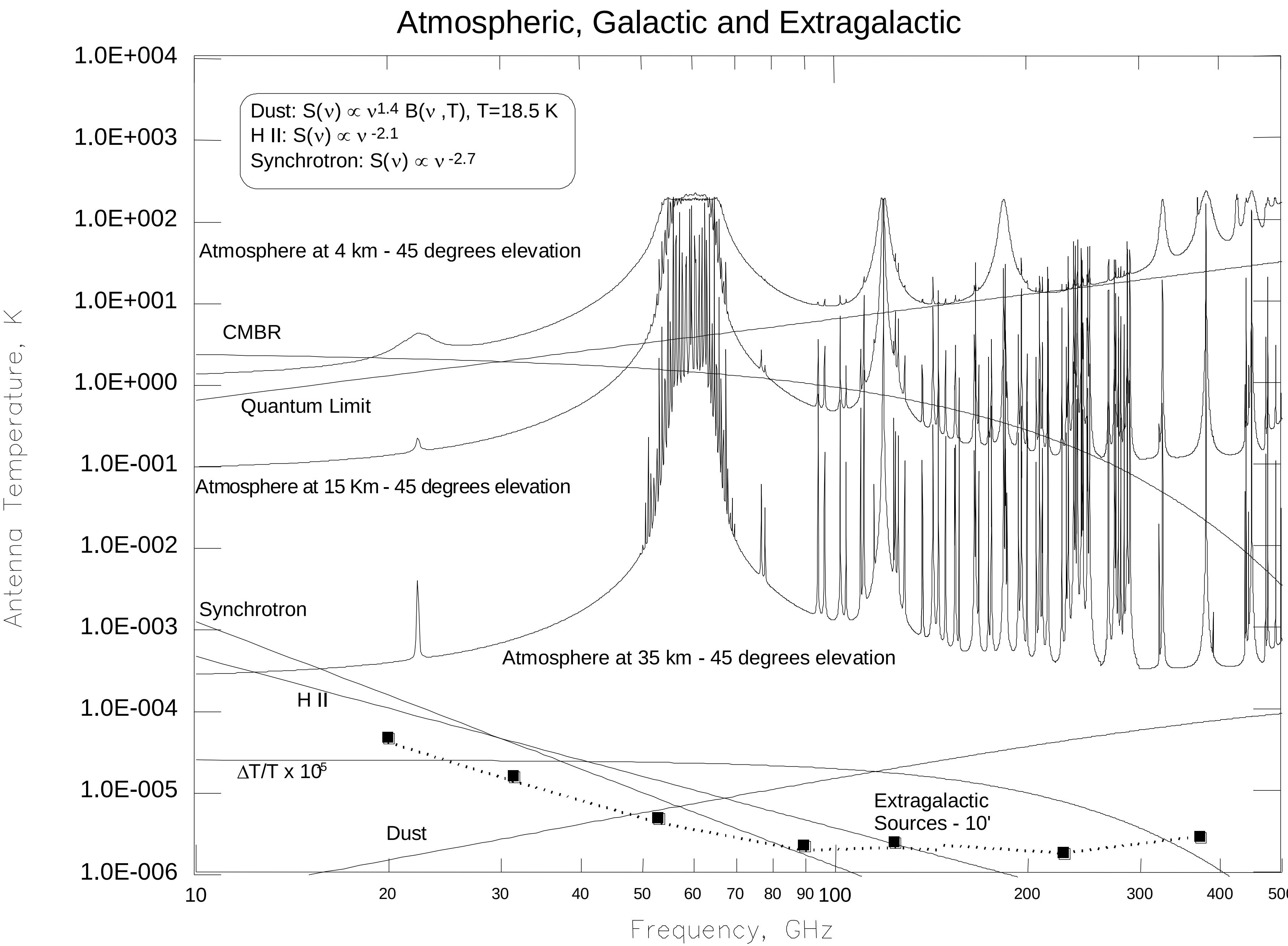
To a first order, the CMB follows a perfect black body, thermal radiation curve which peaks at about 200 GHz.



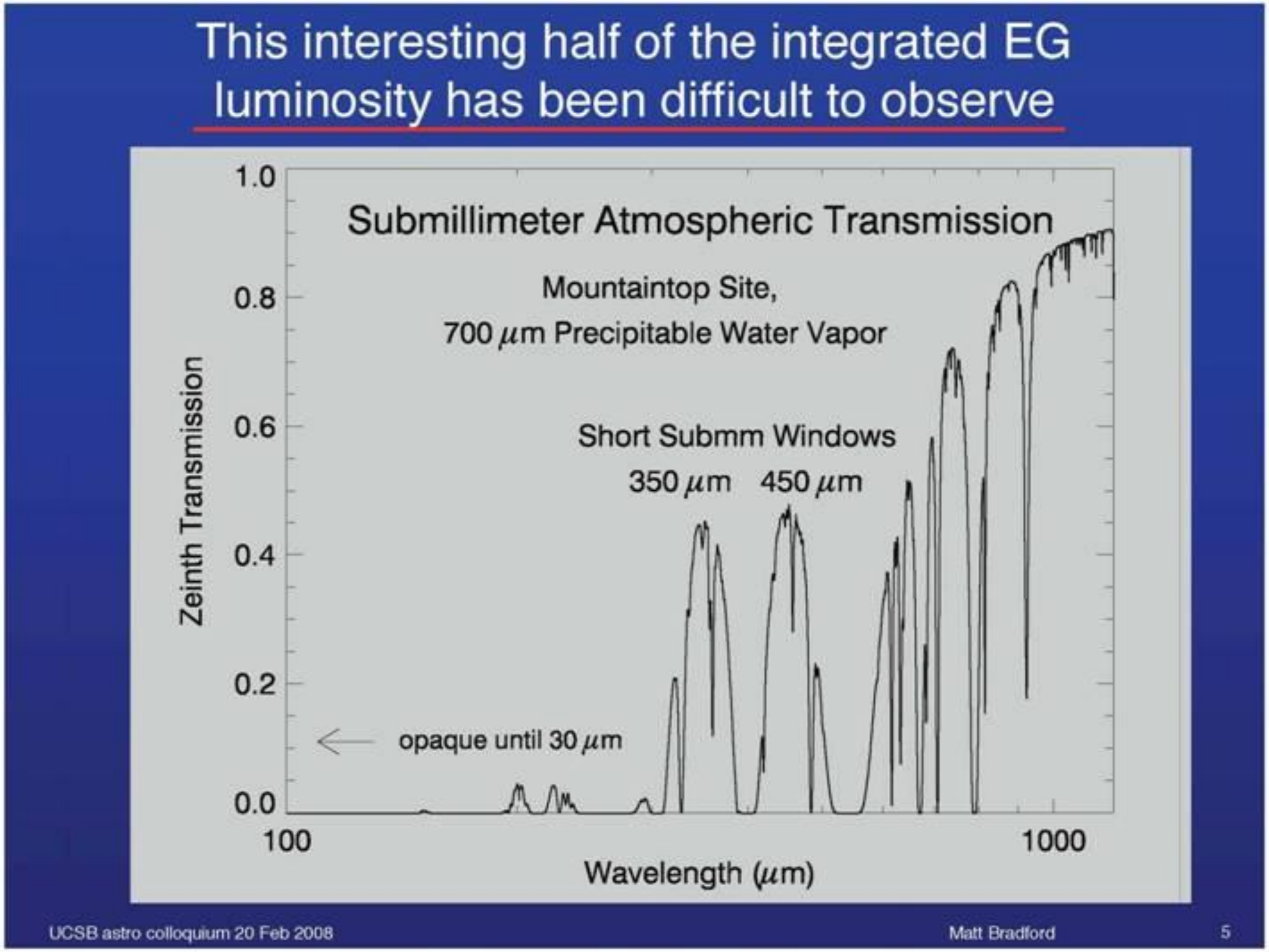
Anisotropies – small-amplitude variations from thermal black body temperature come primarily from two sources: Acausal super horizon (quantum fluctuation) and causal sub horizon from gravitational collapse (influence).

EM spectrum from the Ground

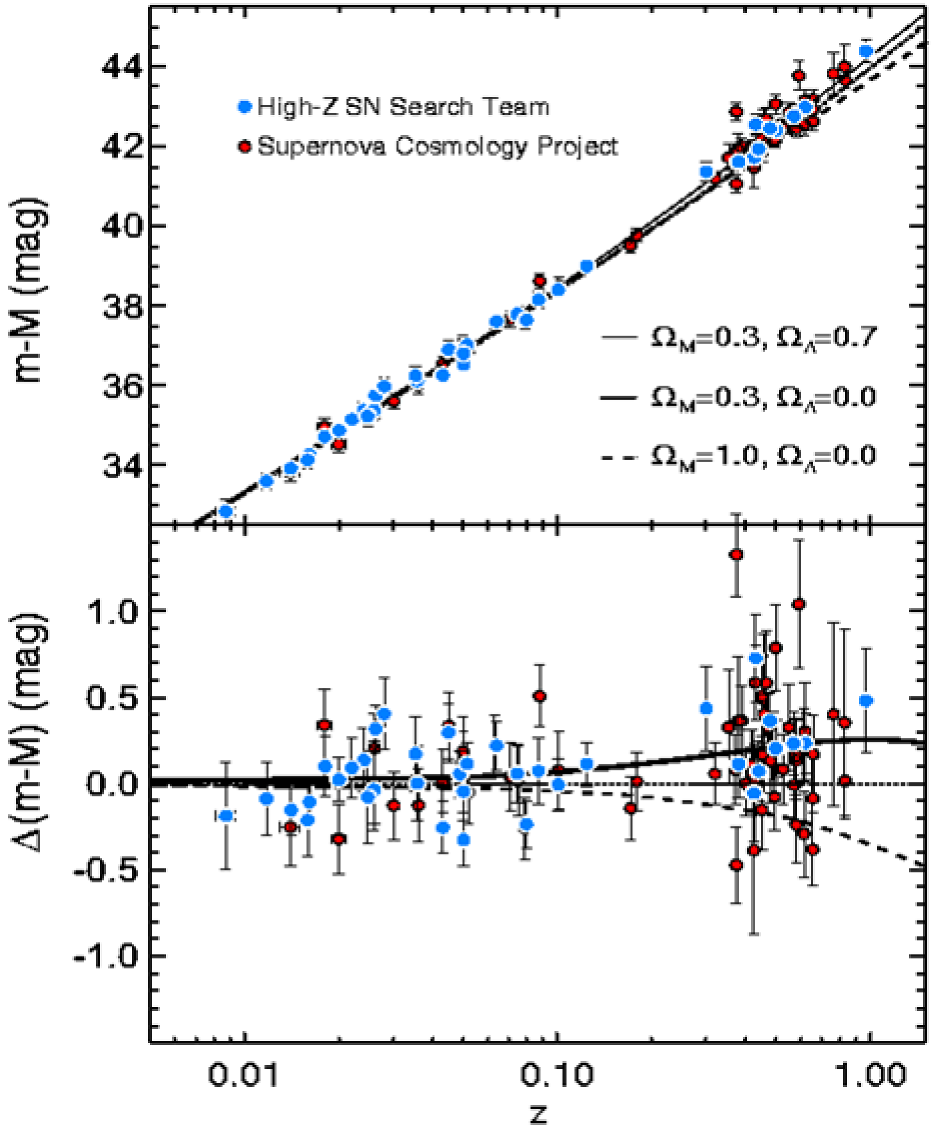



Atmospheric, Galactic and Extragalactic
Dust: S(ν) ∝ ν1.4 B(ν ,T), T=18.5 K
H II: S(ν) ∝ ν -2.1
Synchrotron: S(ν) ∝ ν -2.7
Atmosphere at 4 km - 45 degrees elevation
CMBR
Quantum Limit
Atmosphere at 15 Km - 45 degrees elevation
Synchrotron
Atmosphere at 35 km - 45 degrees elevation
H II
ΔT/T x 105
Dust
Extragalactic
Sources - 10'
1.0E+004
1.0E+003
1.0E+002
1.0E+001
1.0E+000
1.0E-001
1.0E-002
1.0E-003
1.0E-004
1.0E-005
1.0E-006
10
20
30
40
50
60
70
80
90
100
200
300
400
500
Antenna Temperature, K
Frequency, GHz

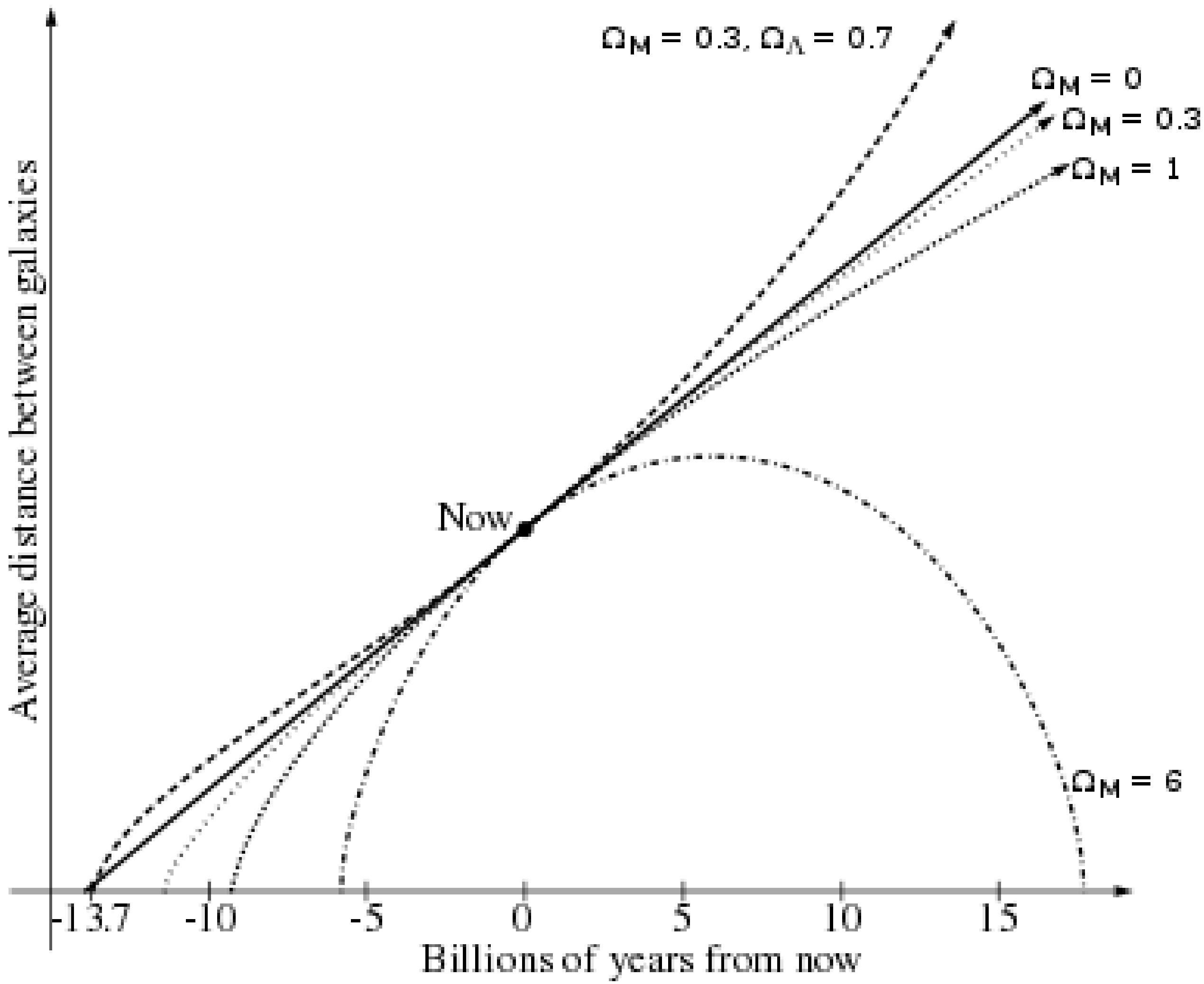
THz Sky from the Ground is Tough



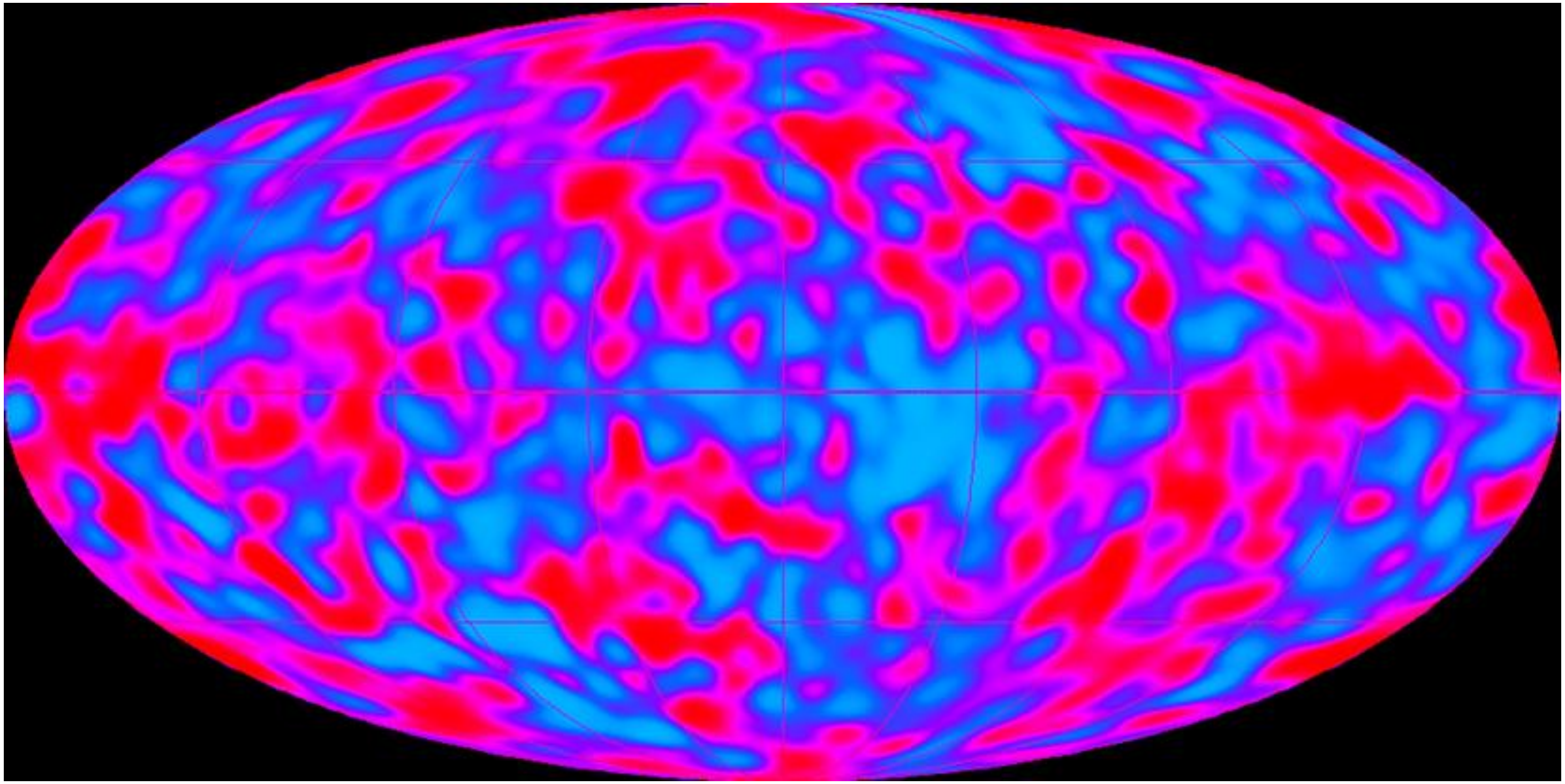
Type Ia Supernovae observations
Suggest the expansion rate of the
Universe began accelerating about 5 billion years ago.
This is bad news for our ultimate fate.
Life will be a passing fad and we will go into an eternal night



Expansion and Dark Matter and Energy

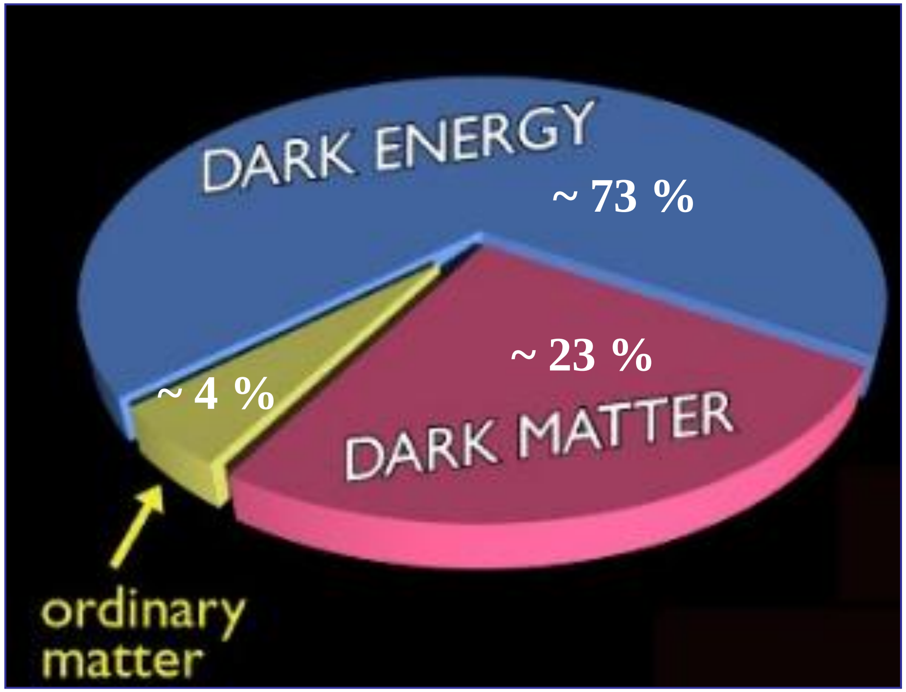


In 1992 data from the Cosmic Background Explorer satellite and from UCSB's South Pole and balloon borne experiments detect evidence for spatial temperature fluctuations (anisotropy) in the CMB at a level of 10^{-5}



The COBE sky at 53 GHz

$$\rho = \rho_{baryon} + \rho_{darkmatter} + \rho_{radiation} + \rho_{\Lambda}$$



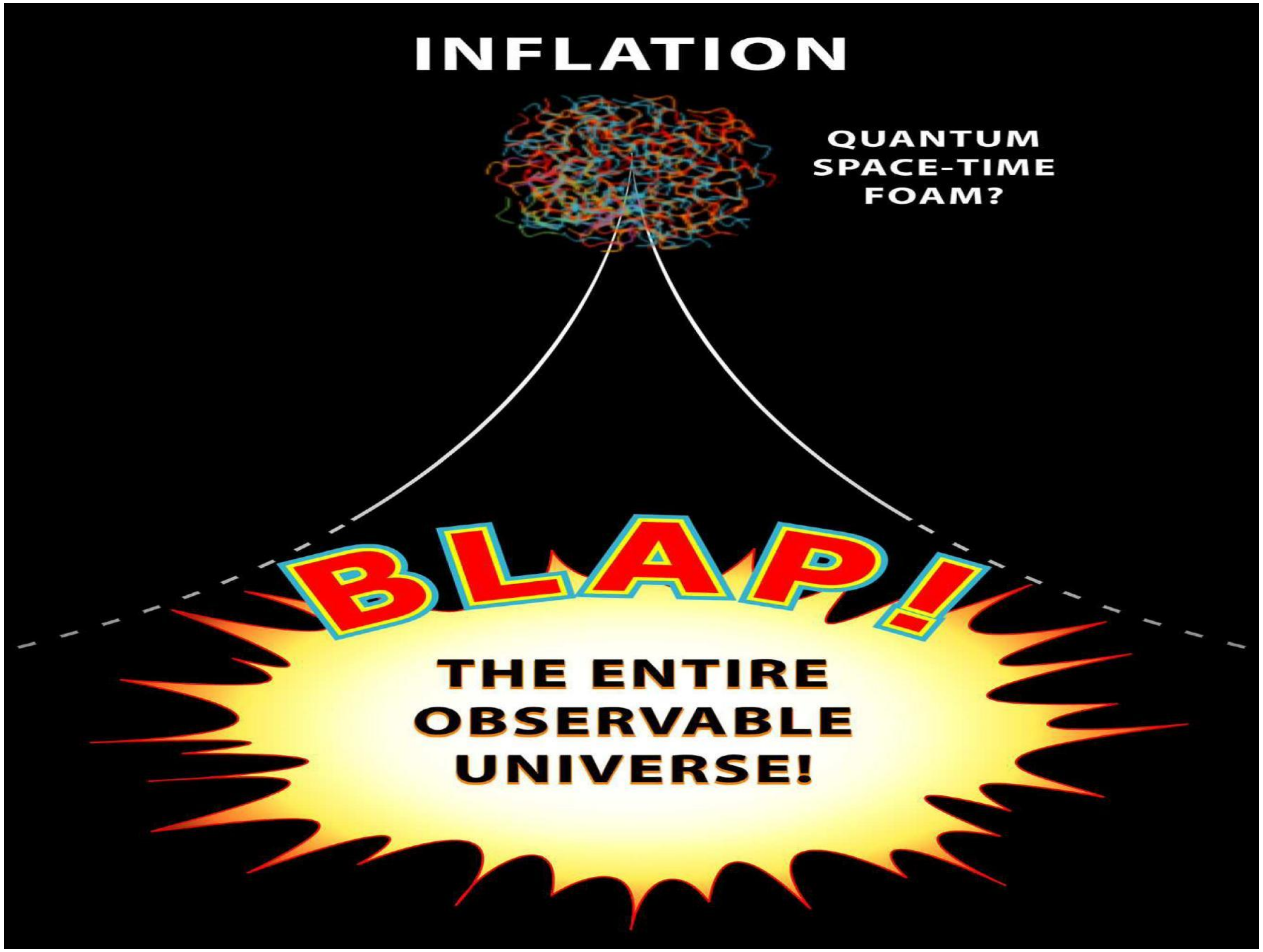
Friend vs Foe

- Dark Matter Sucks but is your friend
- Life exists because of Dark Matter
- Dark Energy Blows and is your enemy
- Life will be Extinguished because of Dark Energy
- Buy Life Insurance Now – It is a good investment
- Unfortunately no one will be around to collect from

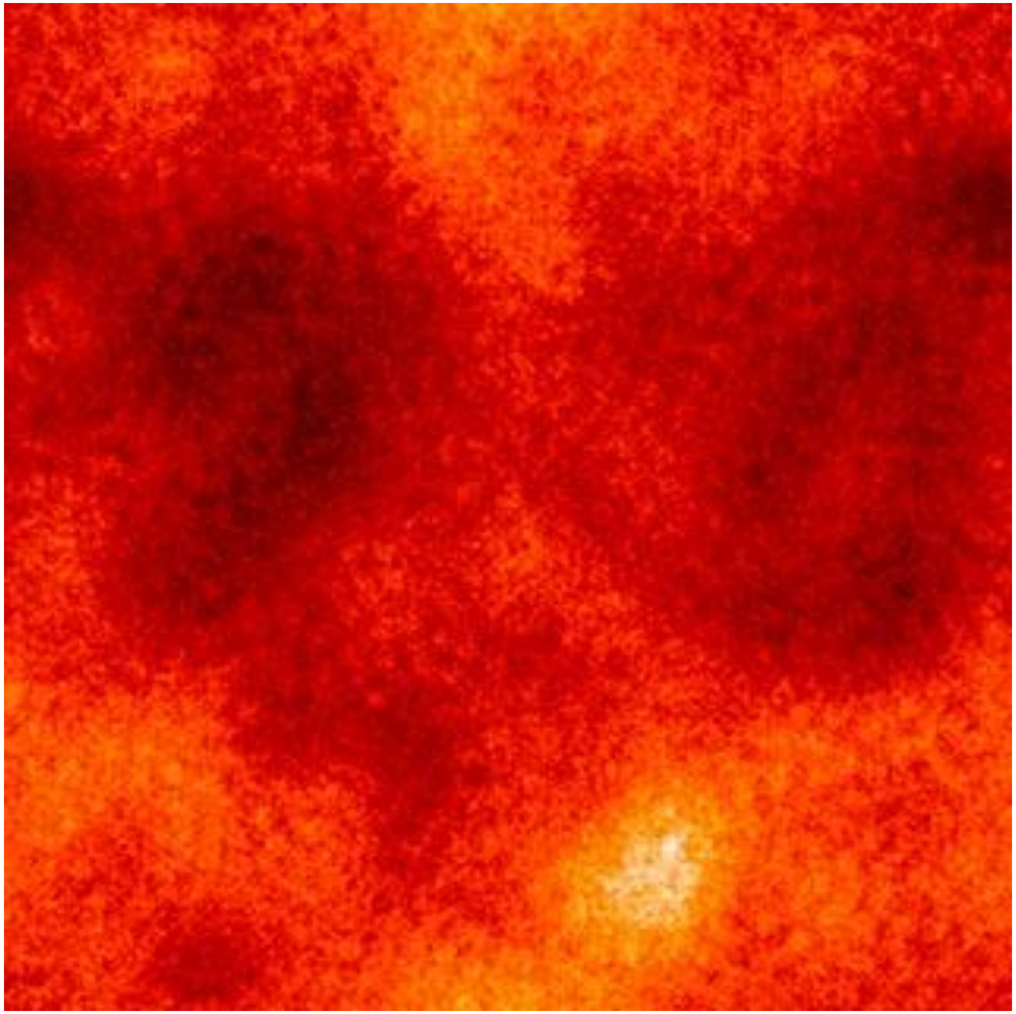
t=0 – "The Big Bang"
Is there a "before"?

http://planck.cf.ac.uk/timeline/universe/bigbang

Quantum Space Time -> Inflation - Hyperexpansion? 10^{-35} sec - 10^{60} Times Expansion



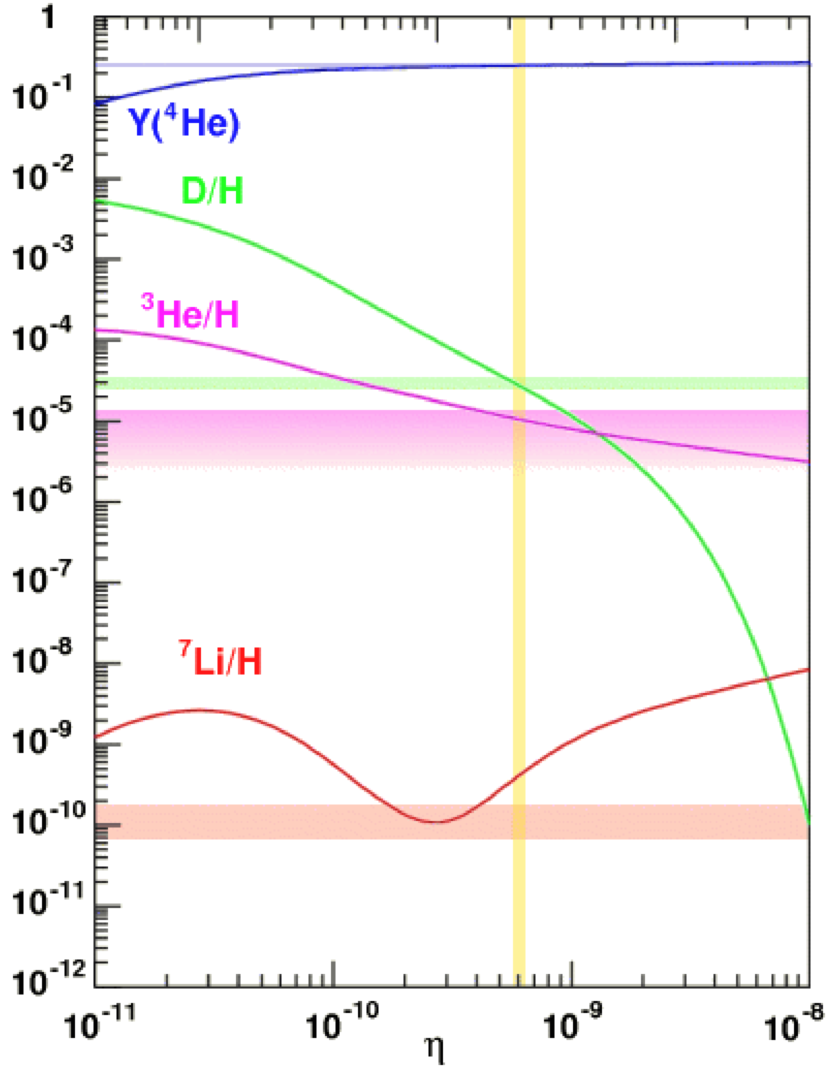
First Three Minutes – Baryogenesis and Nucelosynthsis



Nucleosythesis depends on Proton to Photon ratio ή

(you are alive because there are no stable mass 5 or 8 elements)

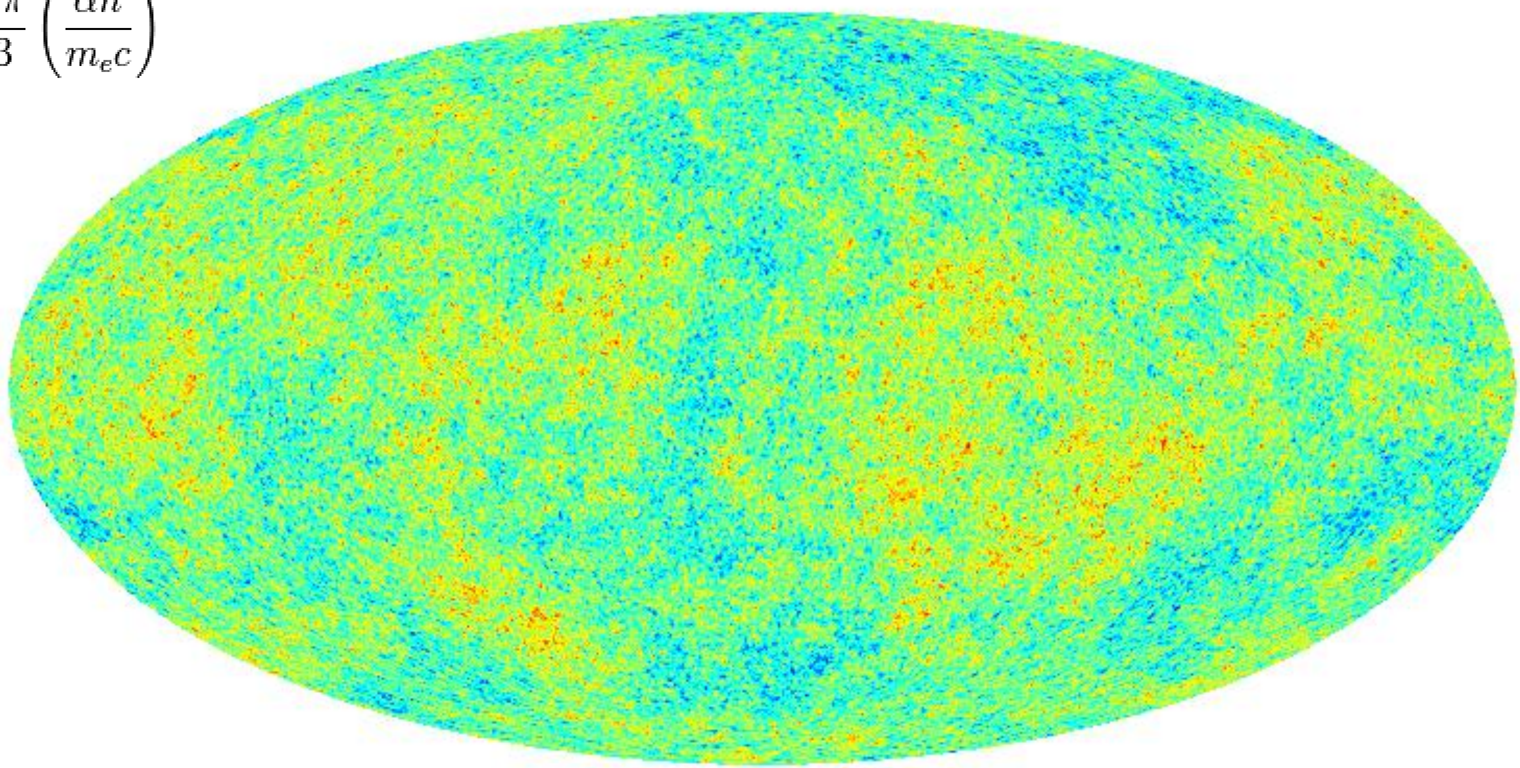
Vertical axis is mass ratio



400 Kyr – Ionized to Neutral – Thomson to Rayleigh Scattering Opaque to Clear - “The CMB”

Thomson – free e scatt cross section ~ 6.7 x 10^{-25} cm^2

$$\sigma_T = \frac{8\pi}{3}\left(\frac{\alpha\hbar}{m_e c}\right)^2$$



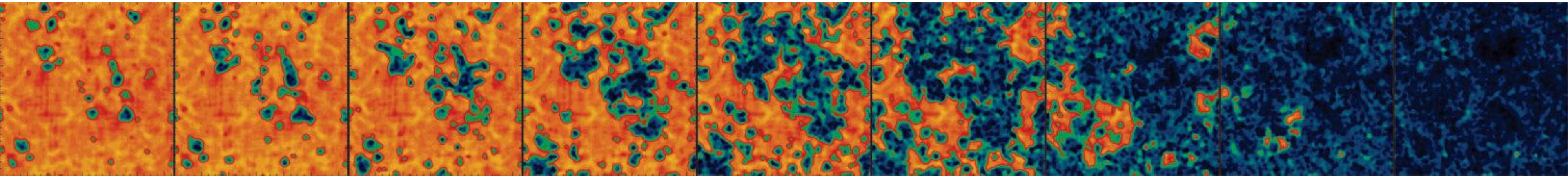
400 Kyr to 400 Myr - The “Dark Ages”

The Universe is largely Neutral but no stars yet – Baryonic collapse in progress

simulation rendition– WMAP team

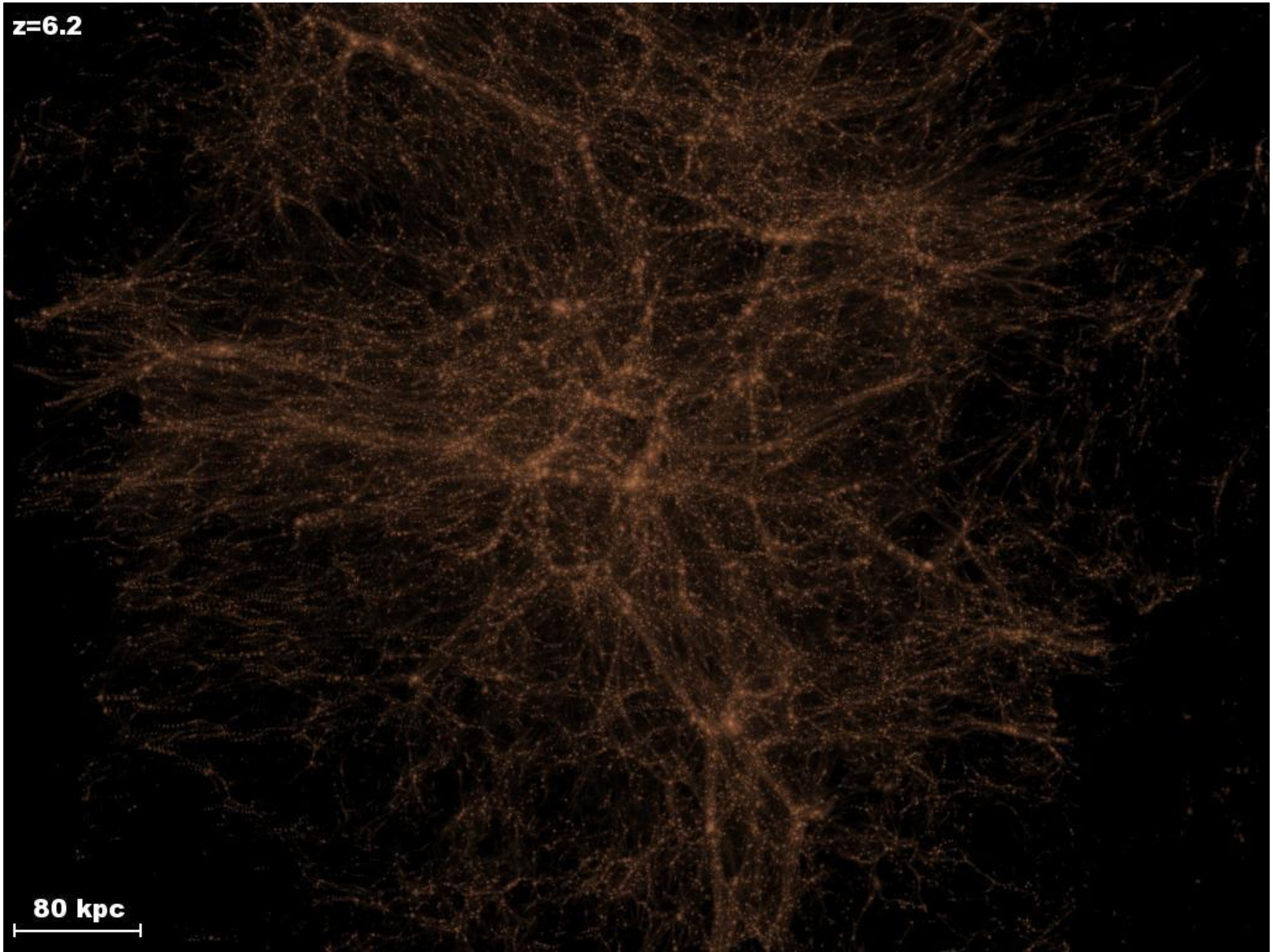
The Universe goes from an Ionized Plasma to Neutral to Ionized
Approx 0.4 Gyr
The First Stars Reionize the Universe

B. Ciardi – Nature 2006 - simulation

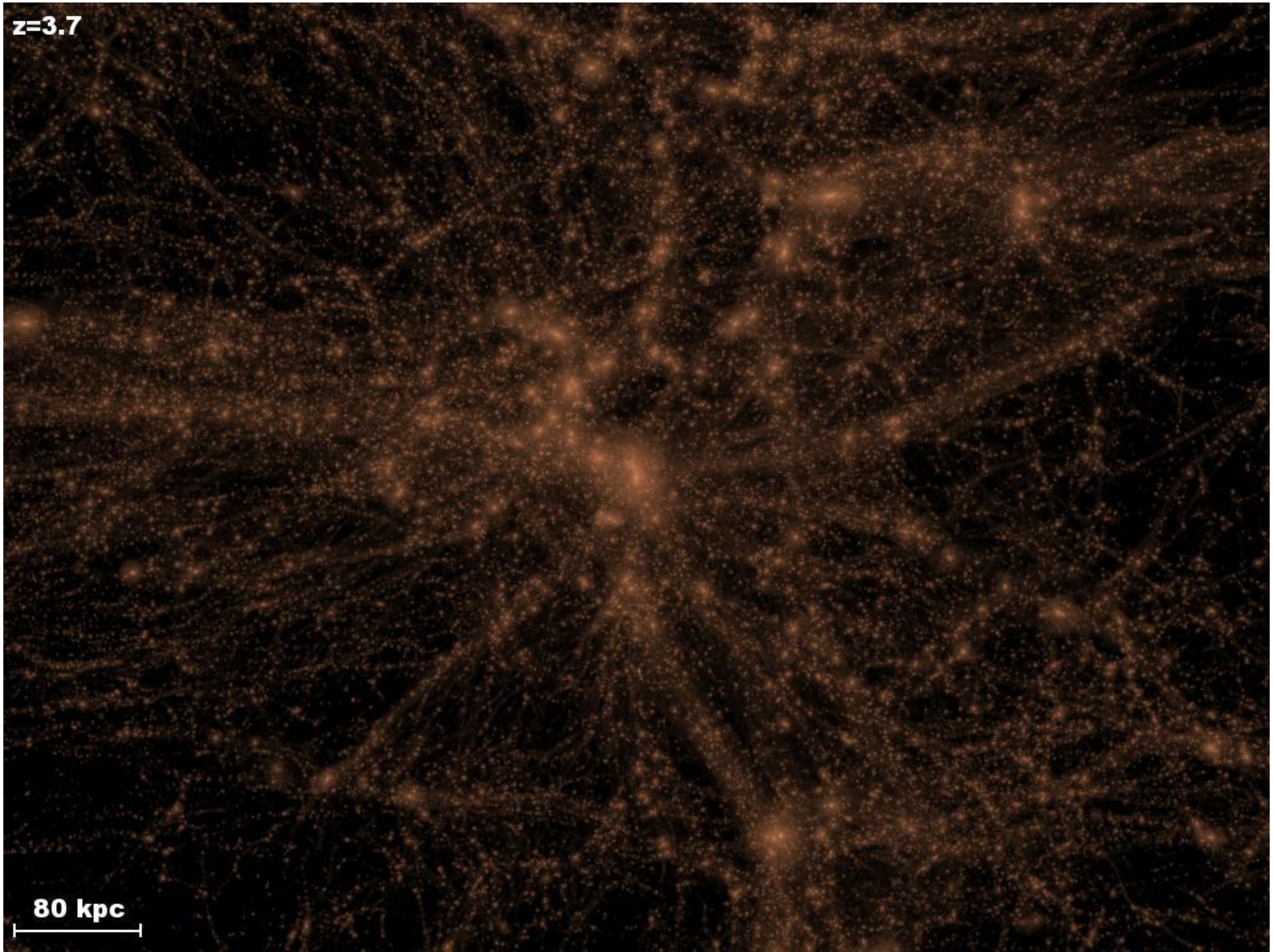


Dark Matter at z=6.2 – 940 Myr

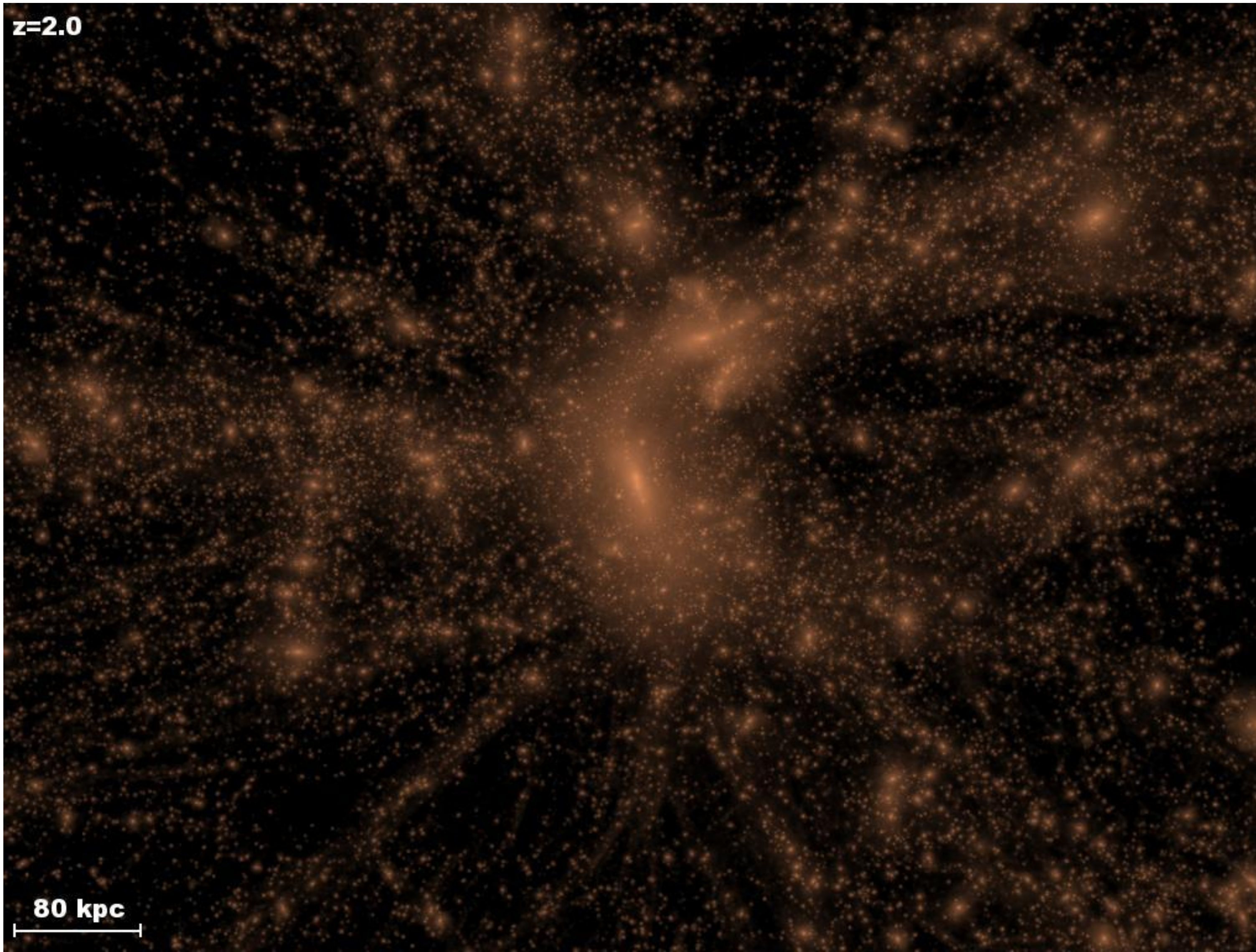
N Body simulation – Via Lactea (lit Milky Way) project



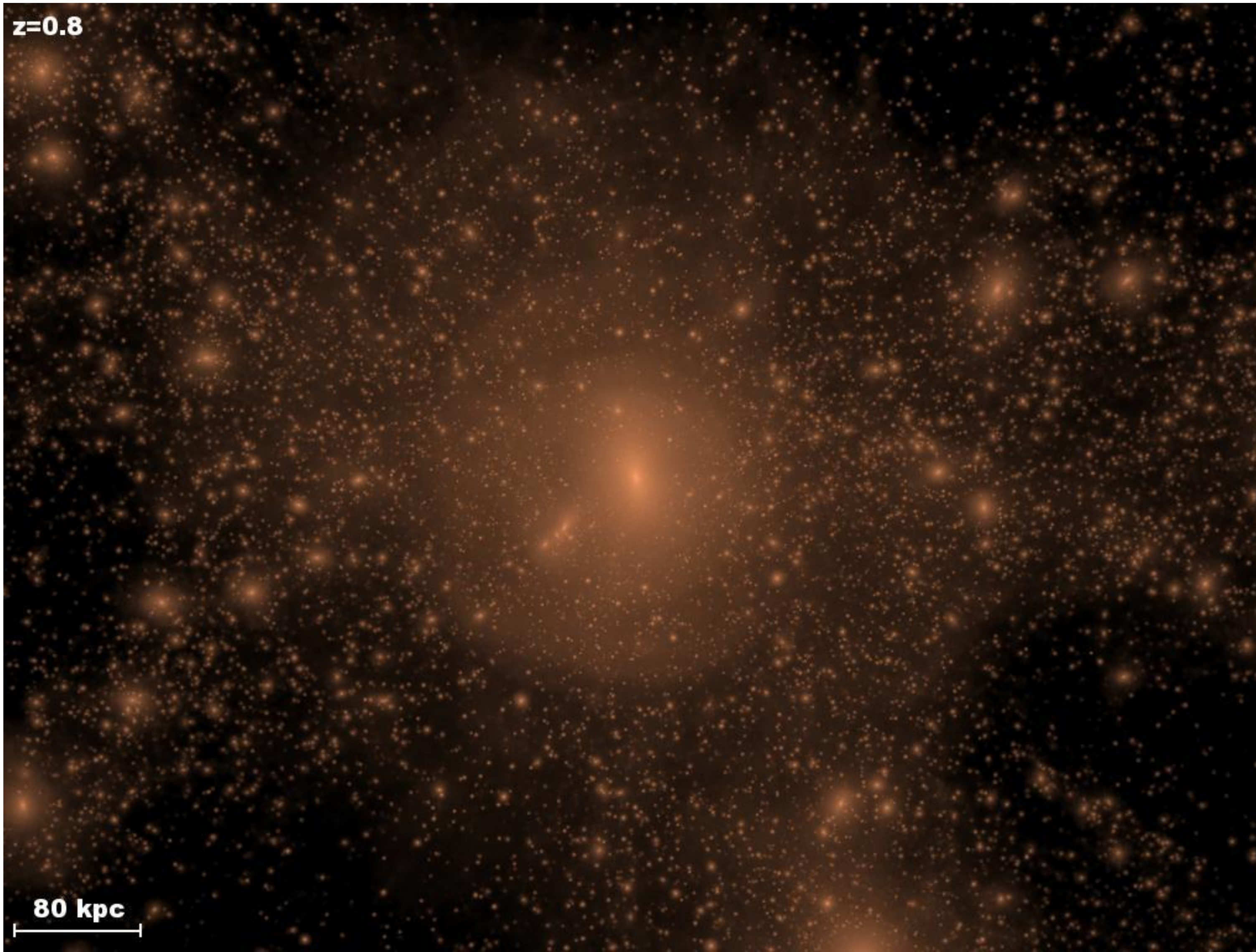
Dark Matter at z=3.7 – 1.8 Gyr



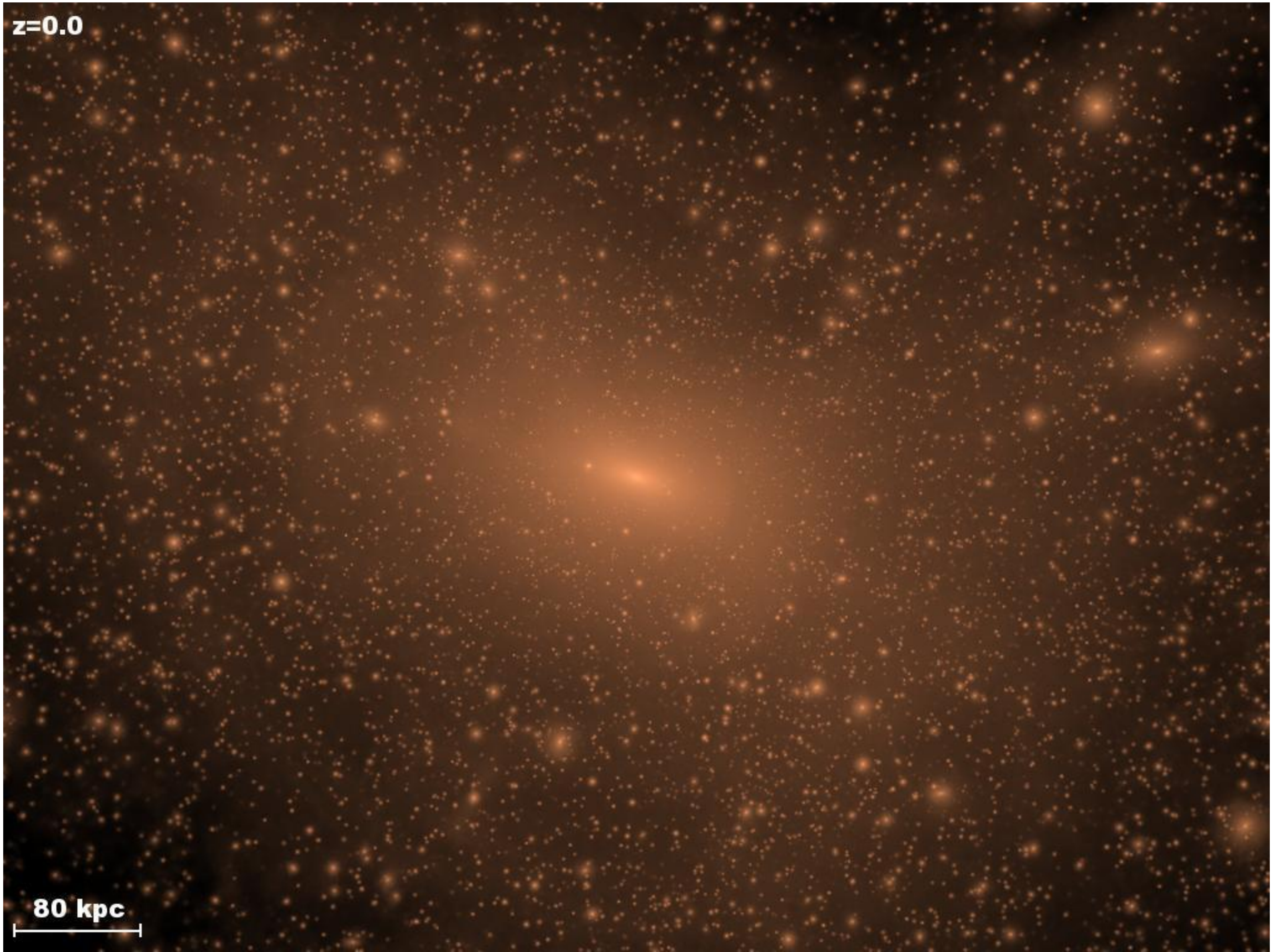
Dark Matter at z=2.0 – 3.5 Gyr



Dark Matter at z=0.8 – 10.4 Gyr

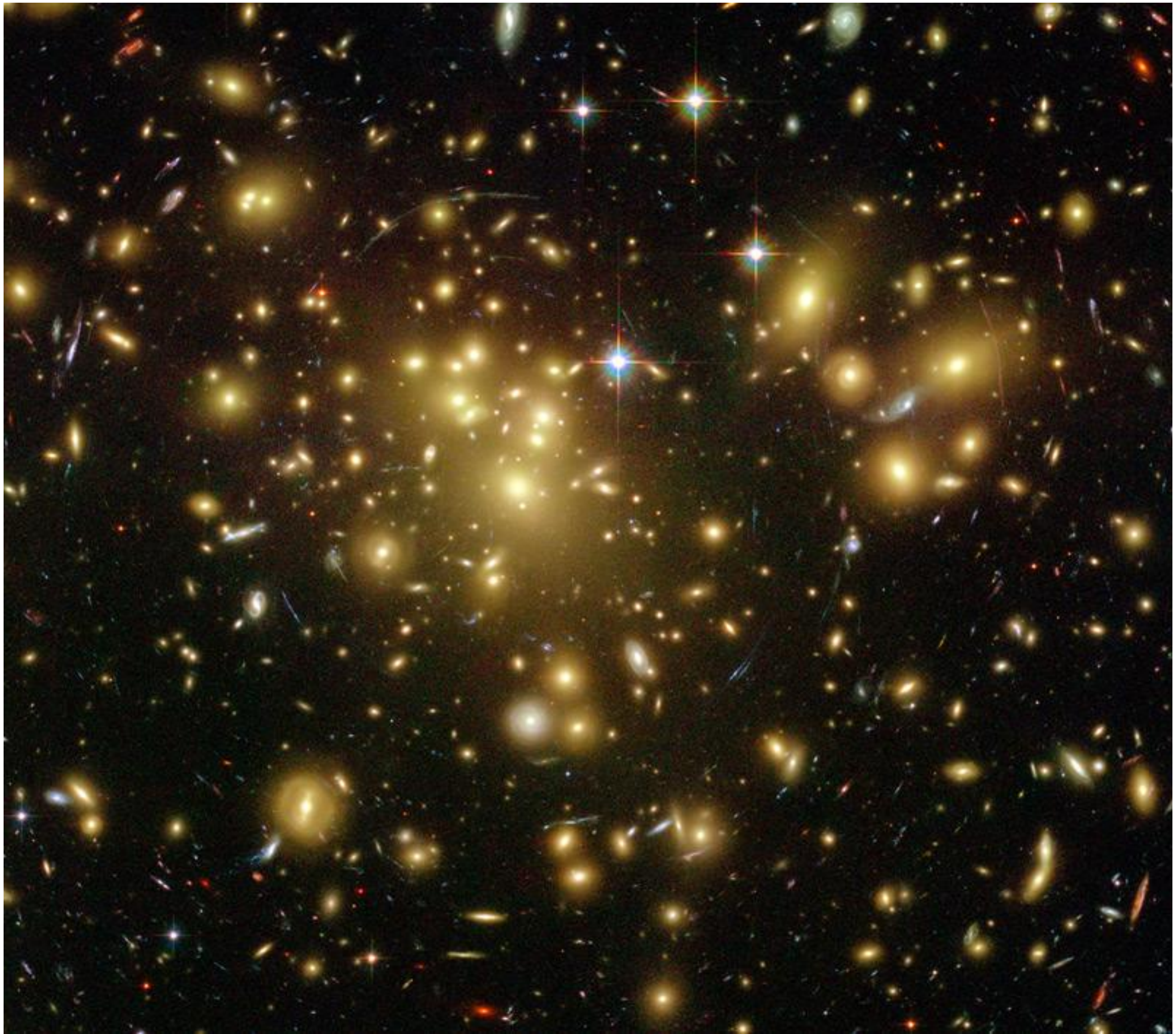


Dark Matter at z=0(now) – 13.7 Gyr

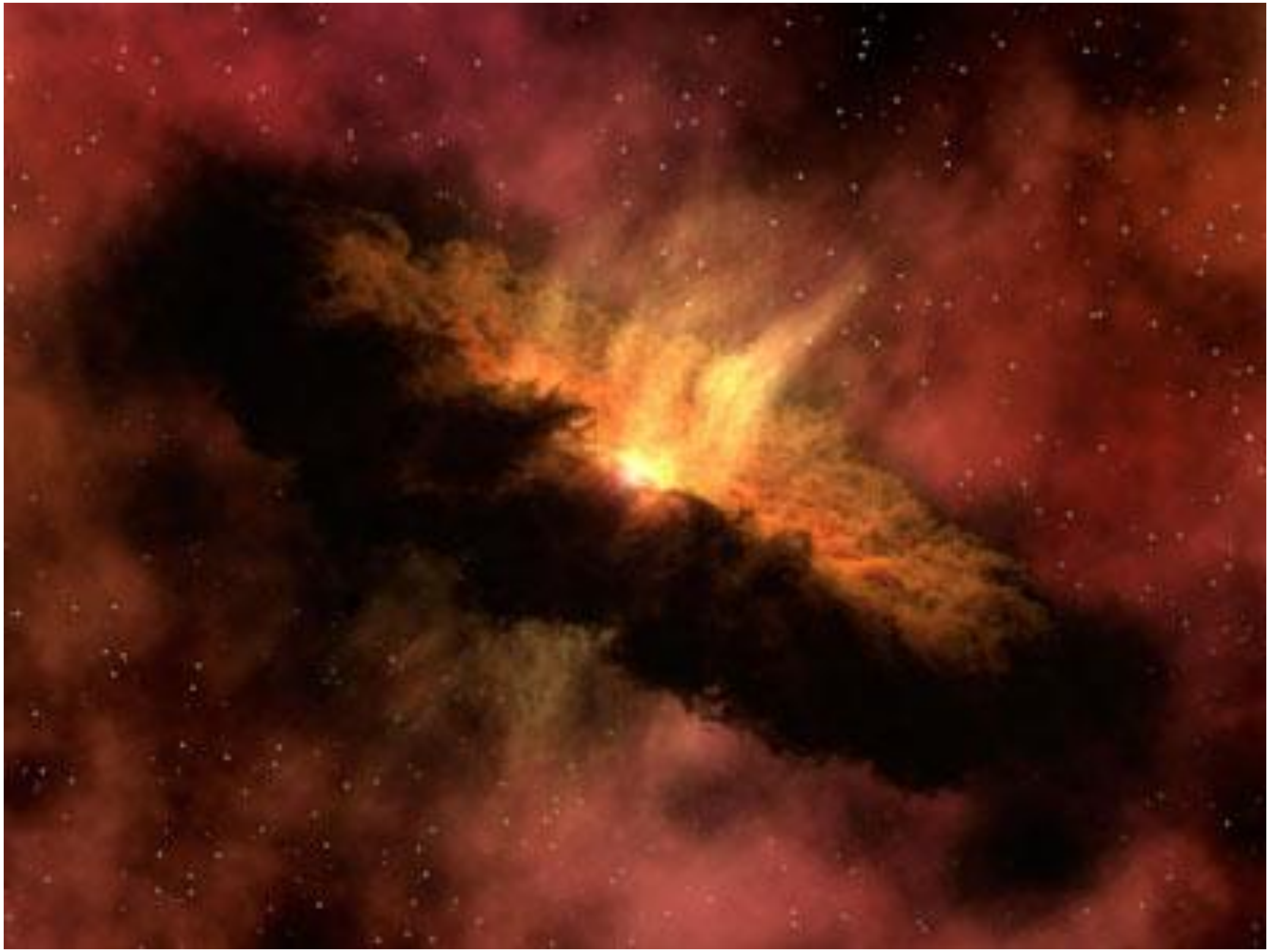


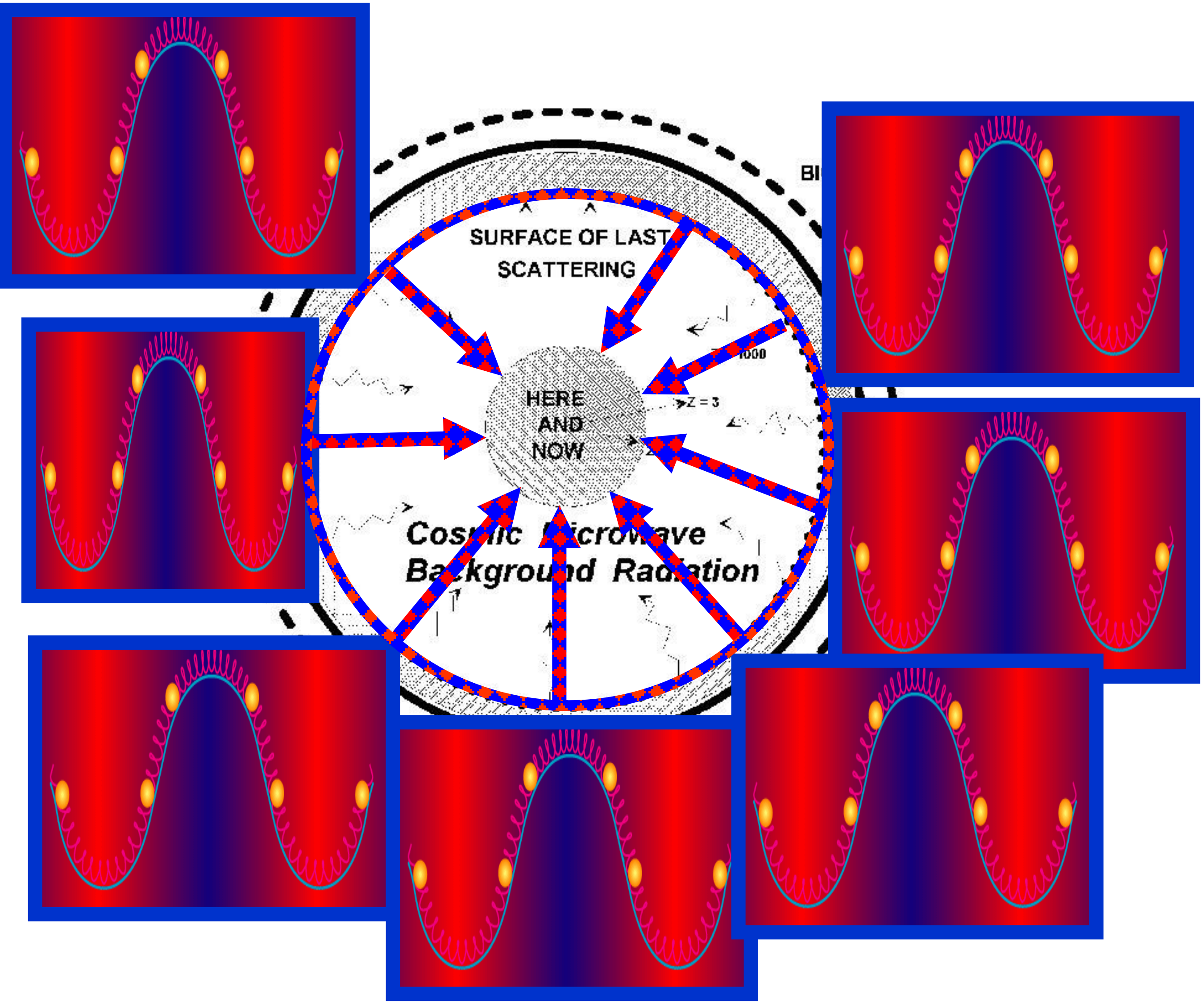
The optical as seen universe today hides the underlying nature of reality – note Grav Lensing

Abell 1689 Hubble Space Telescope



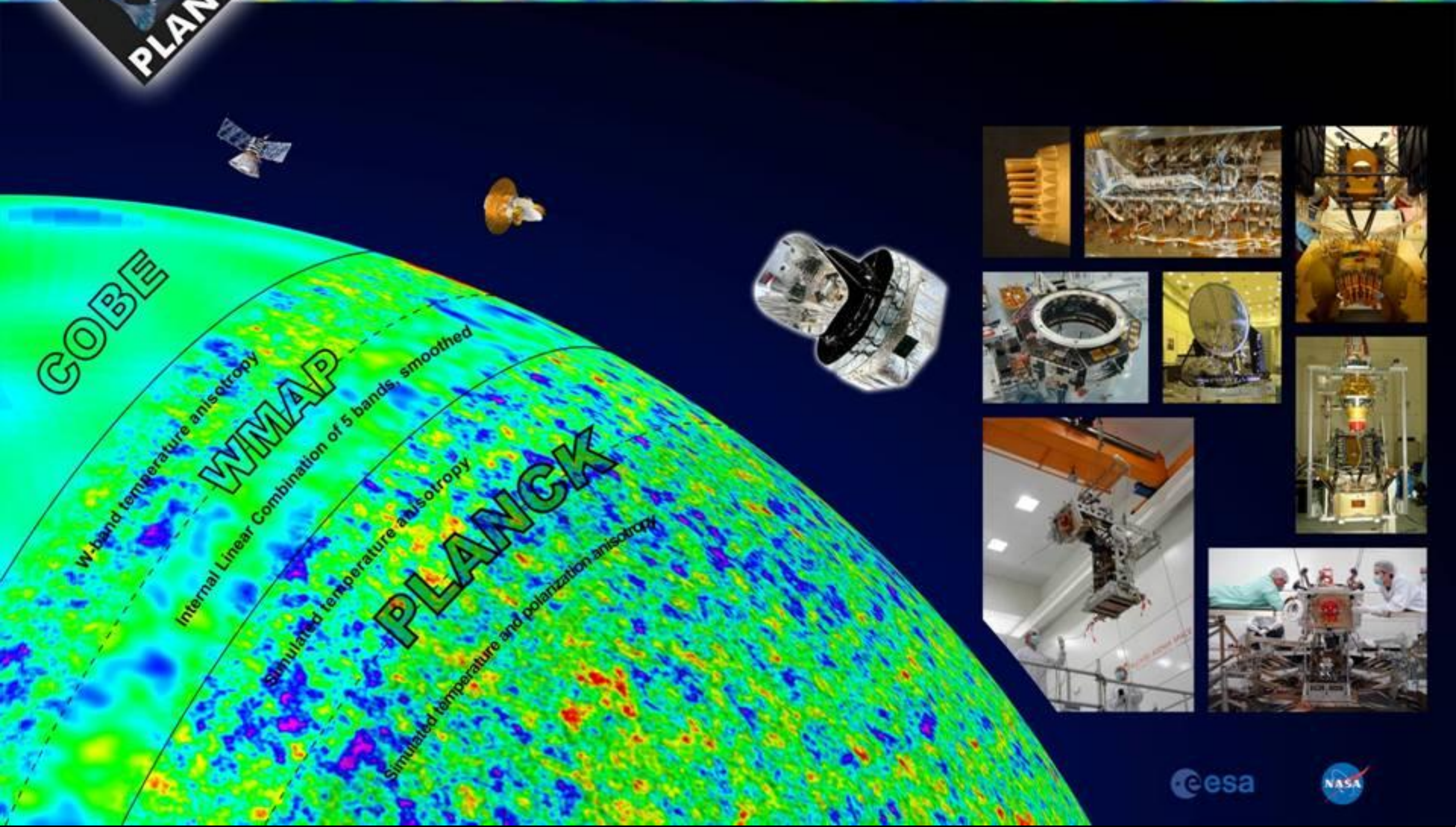
Ultimately Solar Systems form from the debris of dead stars



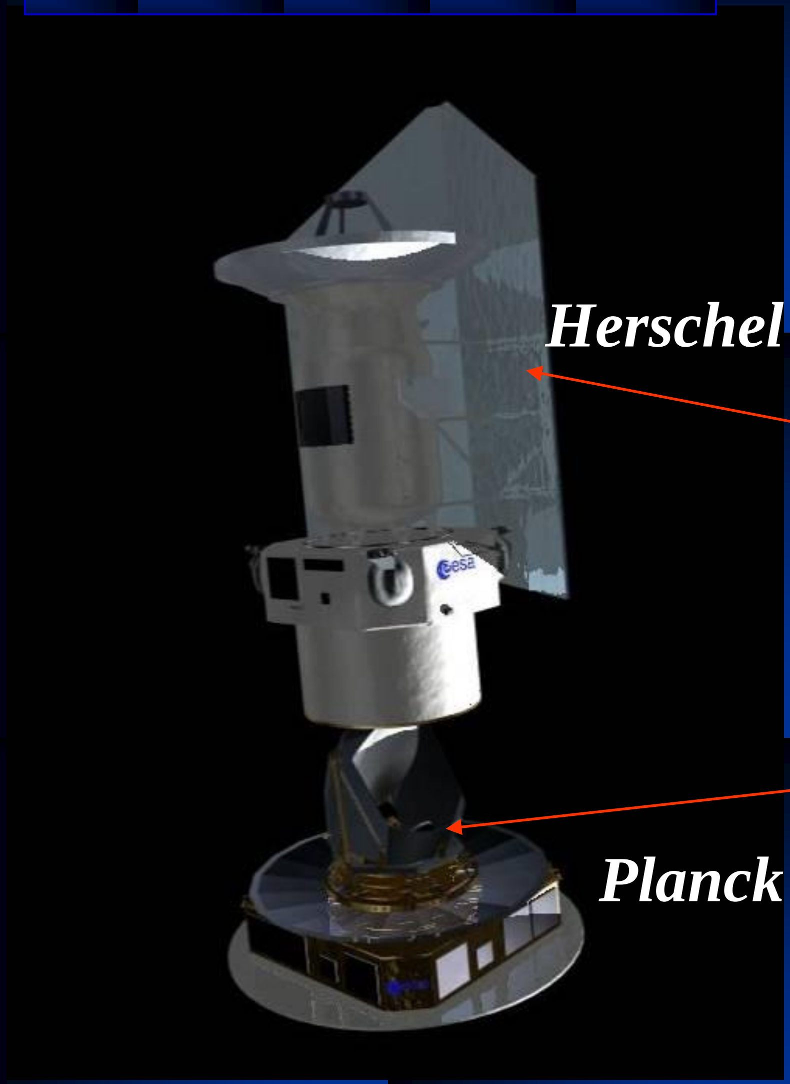


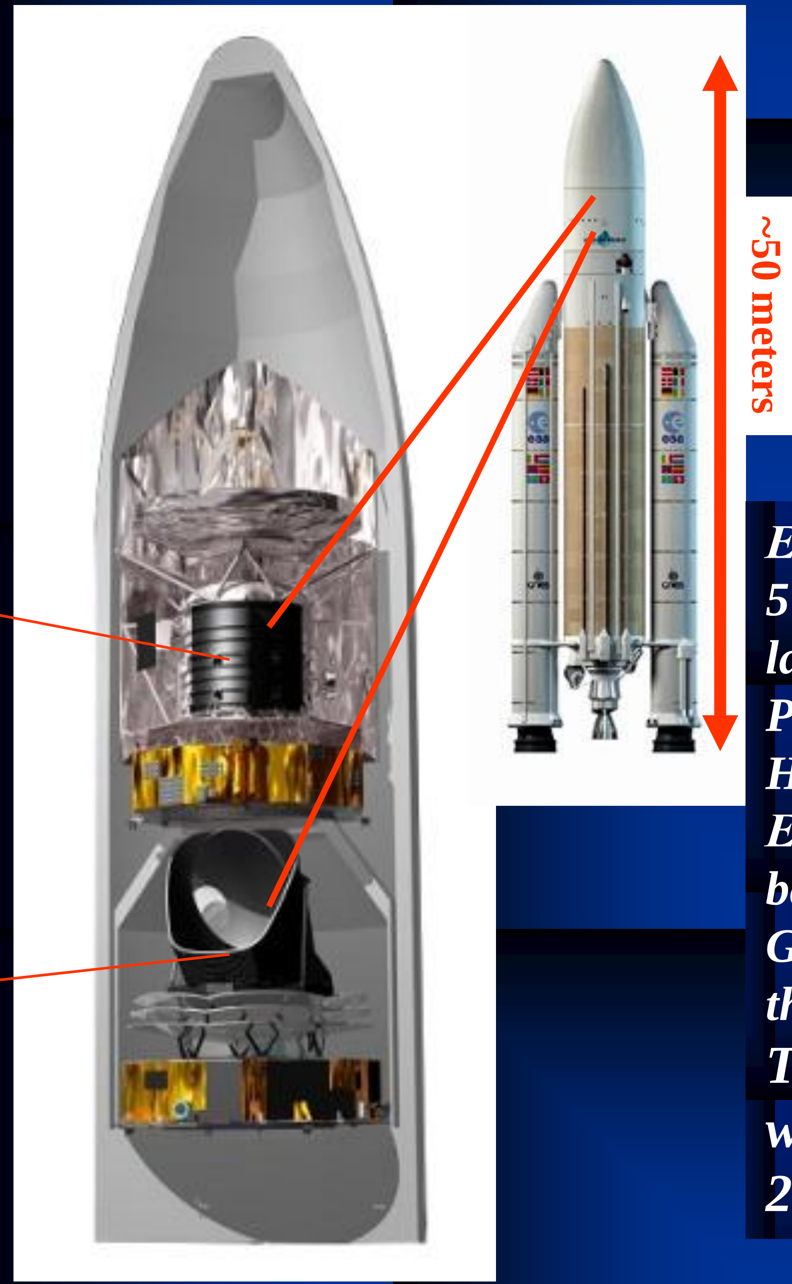
During the short time period when matter condensed out of this fluid, the final imprint of the variations in temperature and density was left as sort of a light echo, which we now see as the CMB, coming towards us from all directions.

Planck, COBE, WMAP



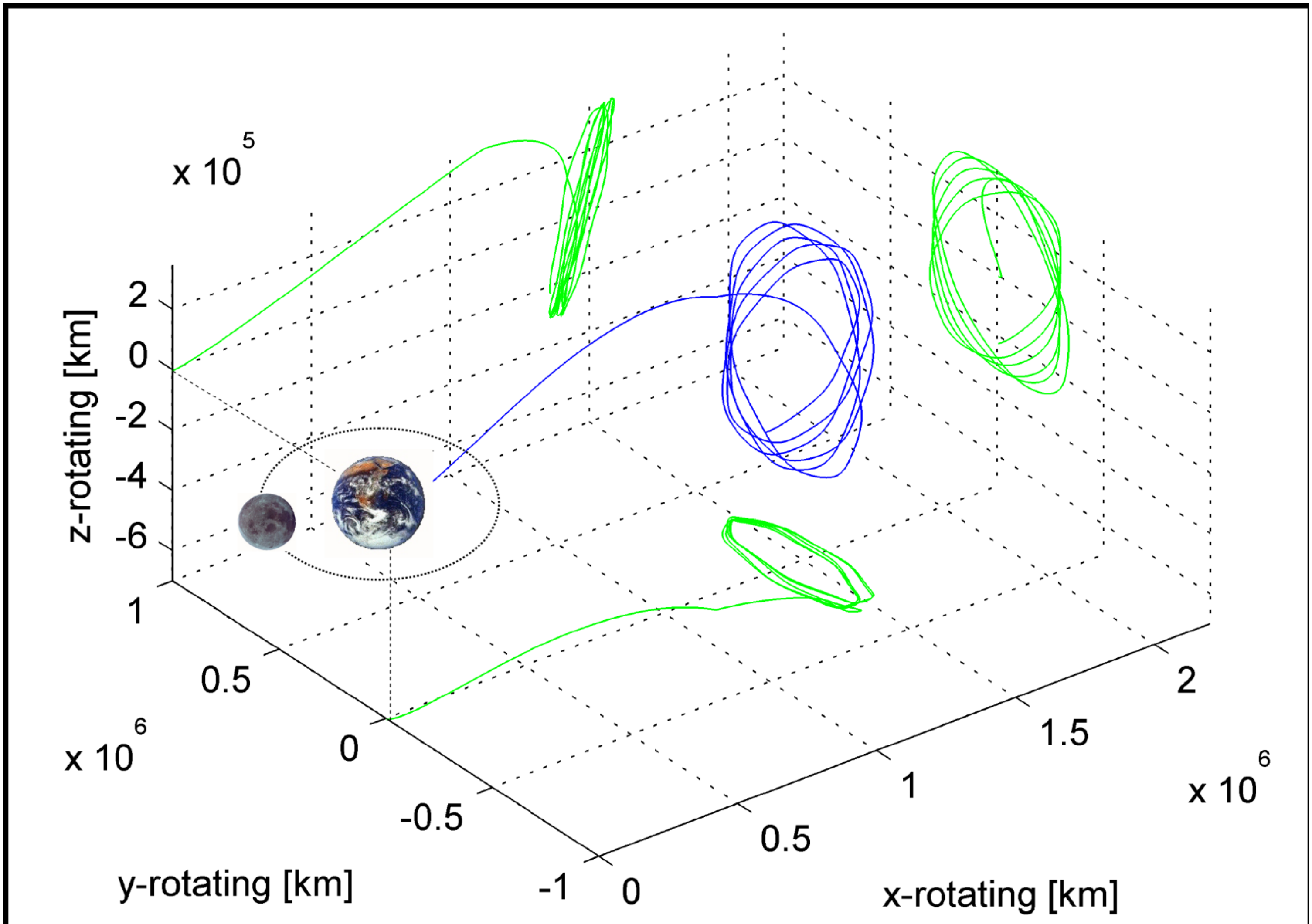
Launch and Orbital Parameters :



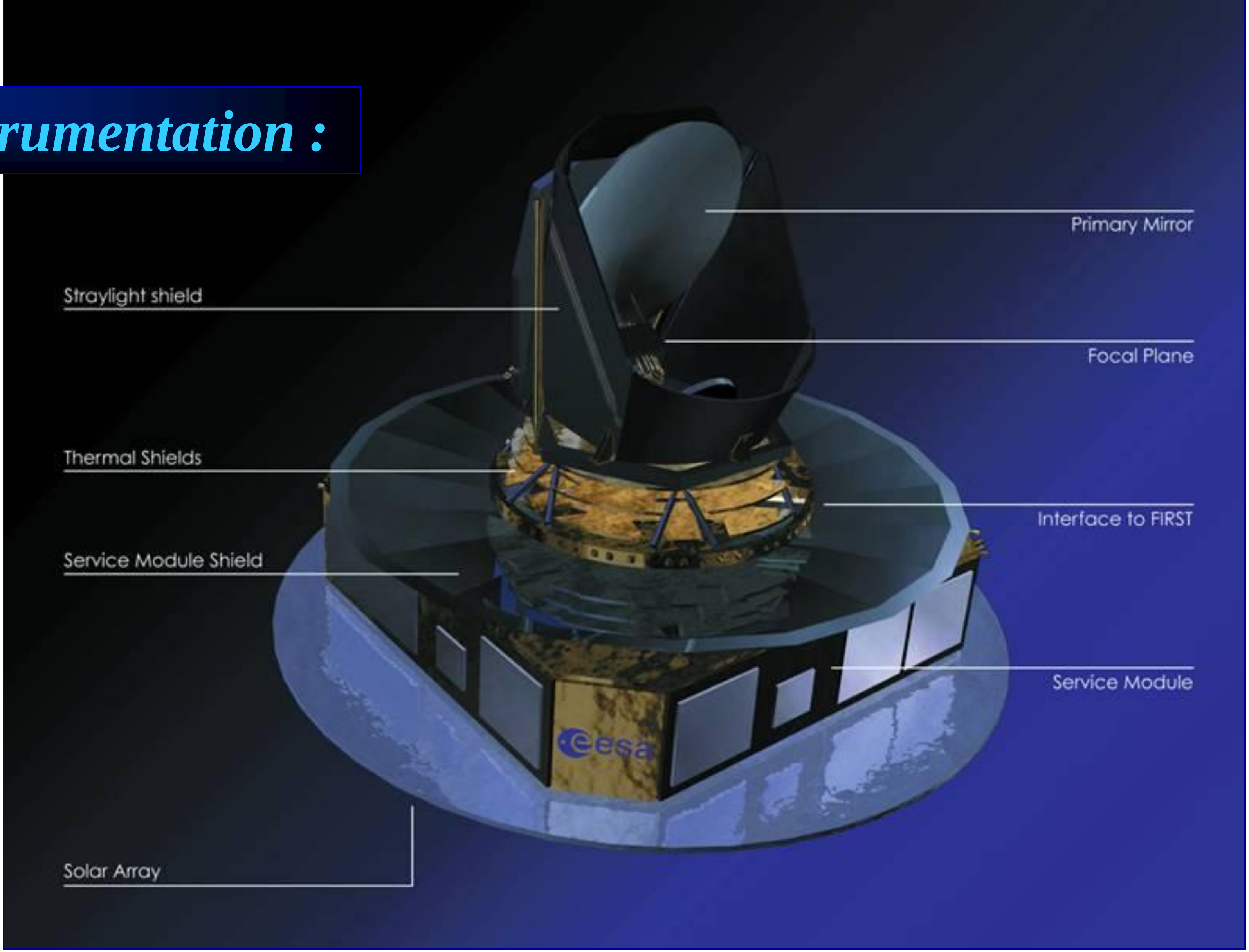


ESA's Arianne 5 Rocket launched both Planck and Herschel from ESA's launch base in French Guiana, near the equator. The launch was May 2009

Orbit is at L2 – Lagrange Point

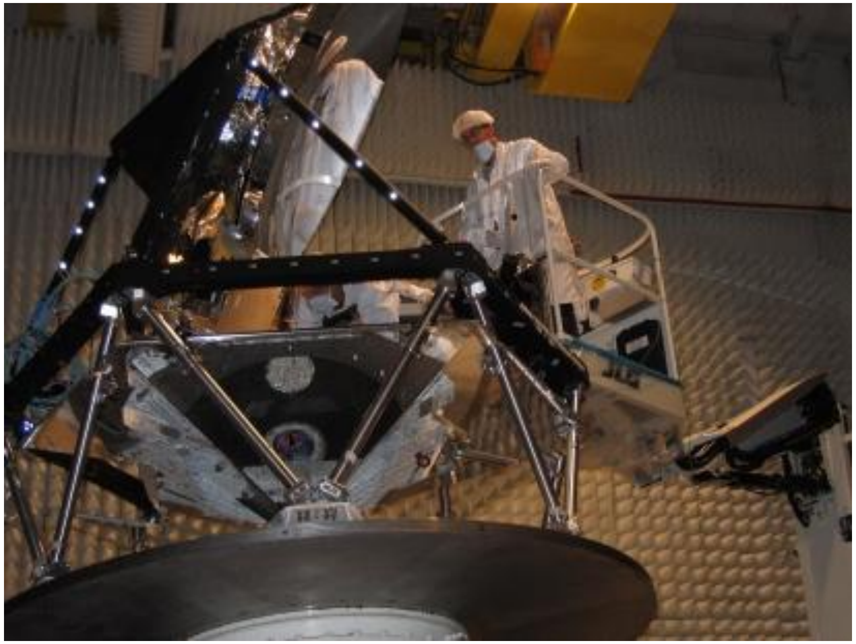


Instrumentation :



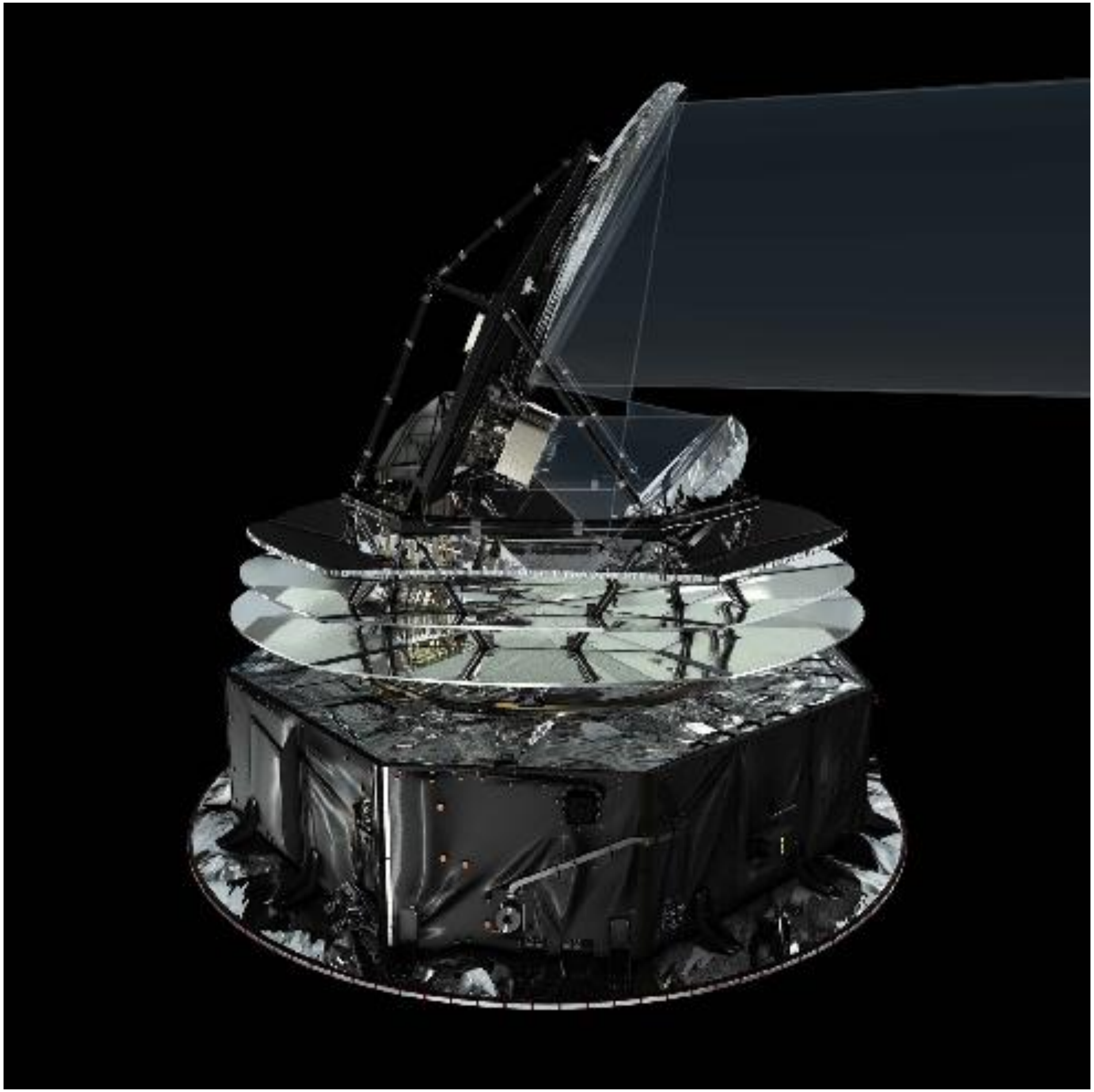
Planck is 4.2 m high with a maximum diameter of 4.2 m. Launch mass is around 900 Kg.

A few days before mating to Ariane 5

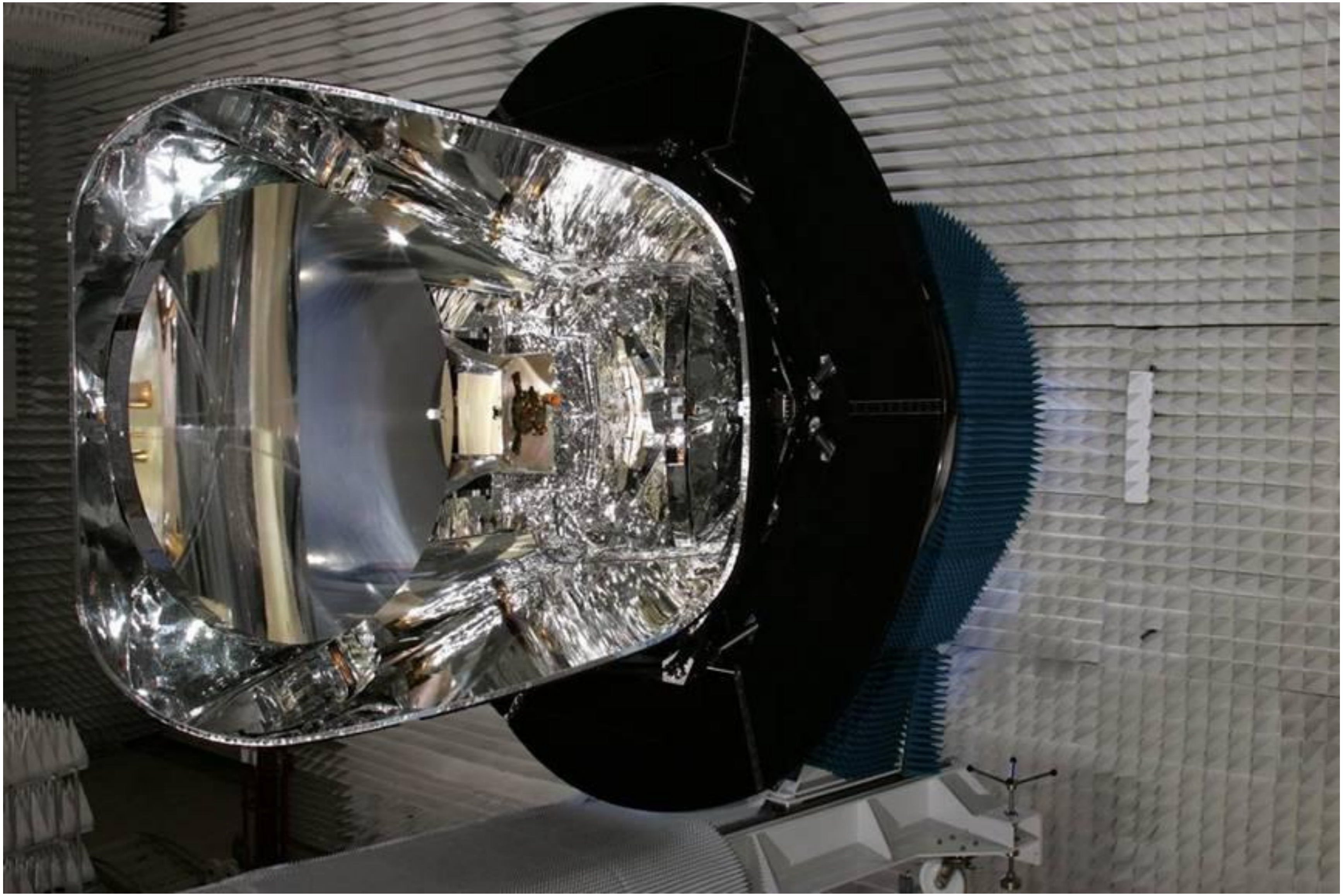


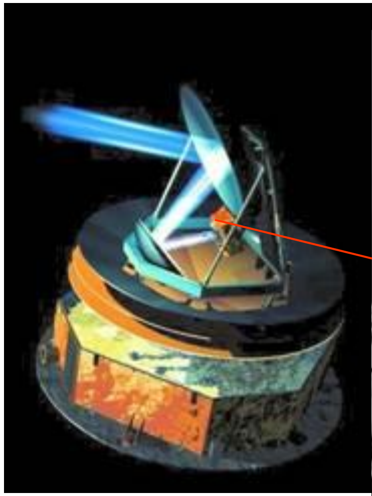
The Planck telescope is an off-axis tilted Gregorian design with a primary mirror 1.75 x 1.5 meters in size.

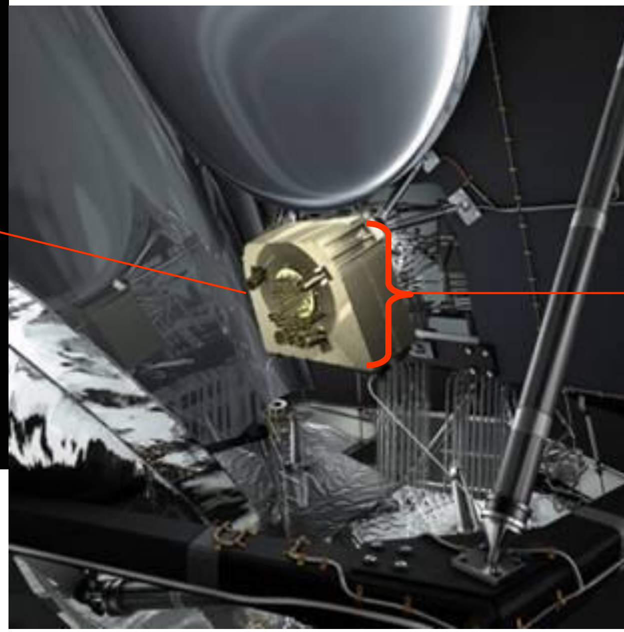
Planck Optical Path – Off axis Gregorian

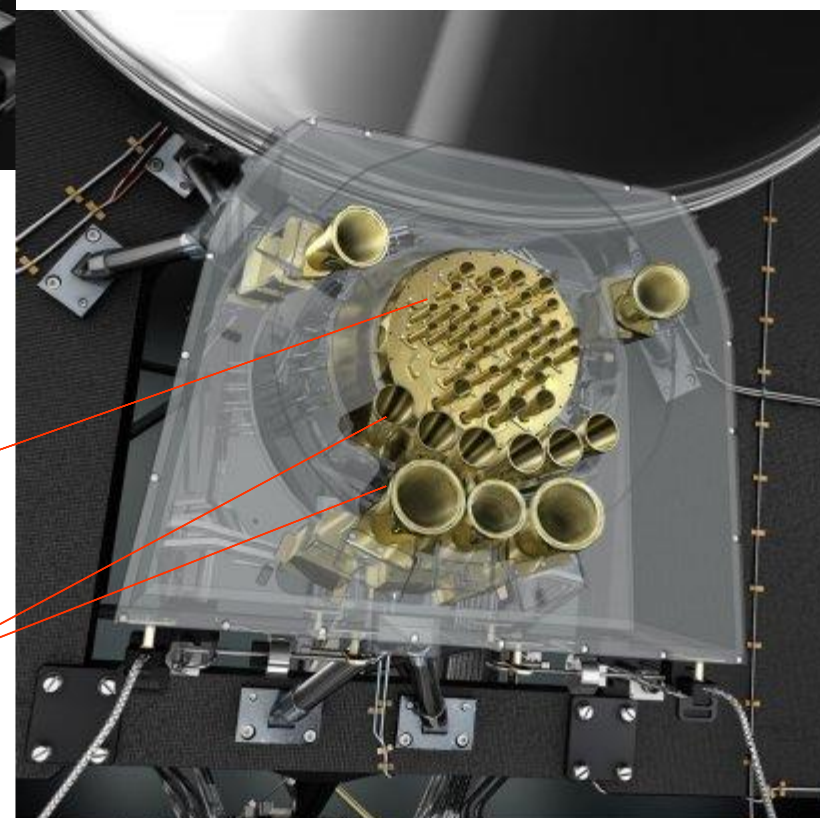


RF Testing in the Anechoic Chamber





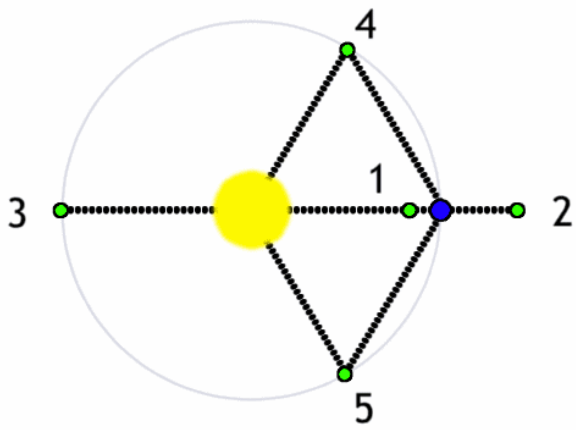


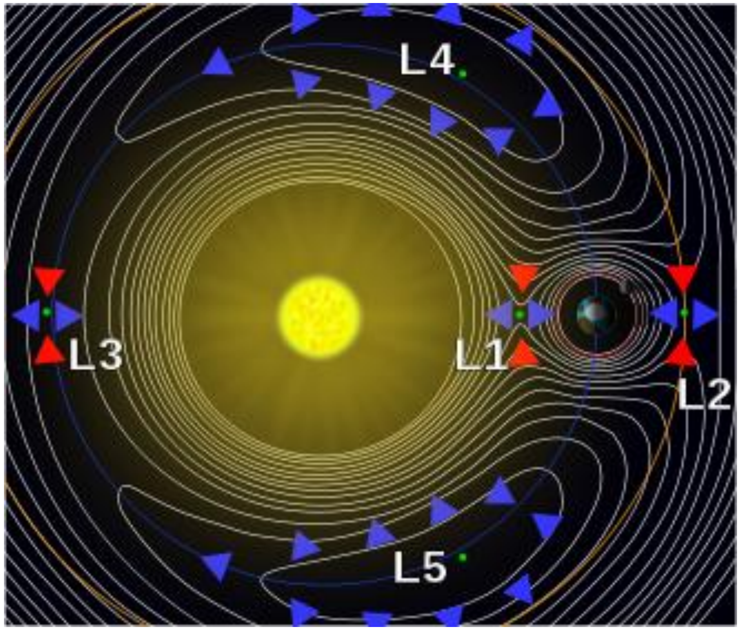


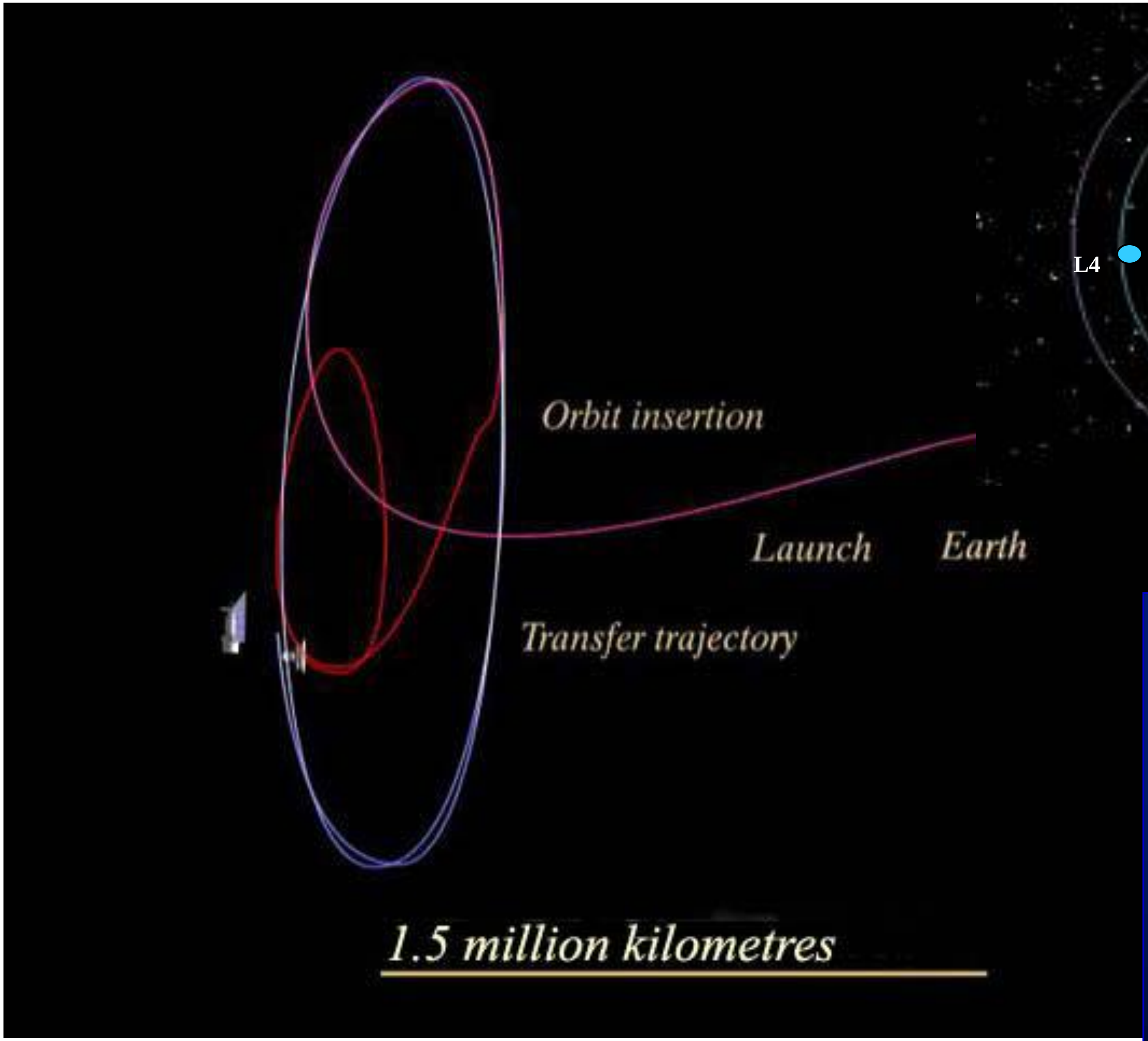
HFI (High frequency Instrument):
array of microwave detectors using spider bolometers, cooled to 0.1 K with open cycle He3-4 dilution fridge.
Approx 2-3 yrs 100-900 GHz
NEP ~ 10 atto-watt/Hz$^{1/2}$

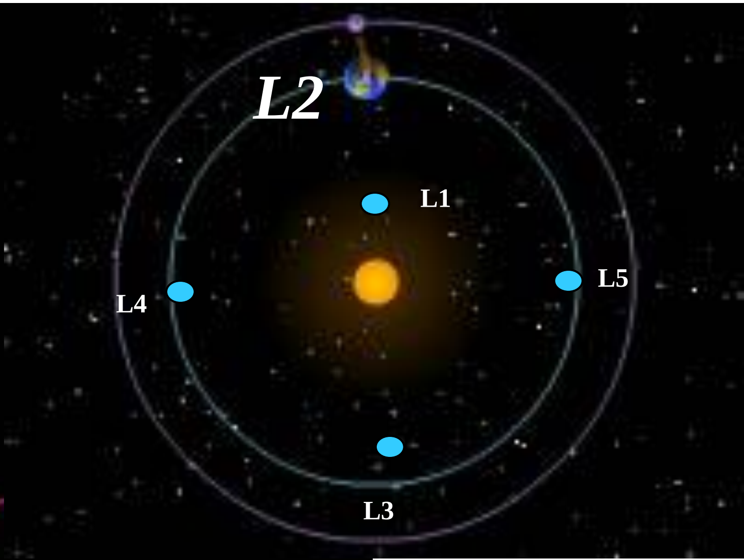
LFI (Low frequency Instrument):
array of radio receivers using HEMT (High Electron Mobility Transistor) amplifiers 30-70 GHz , cooled to 20 K.
T_N ~ 5-10 K ($T_{Q.L.}$ ~ 5K @ 100 GHz)

Lagrange Points



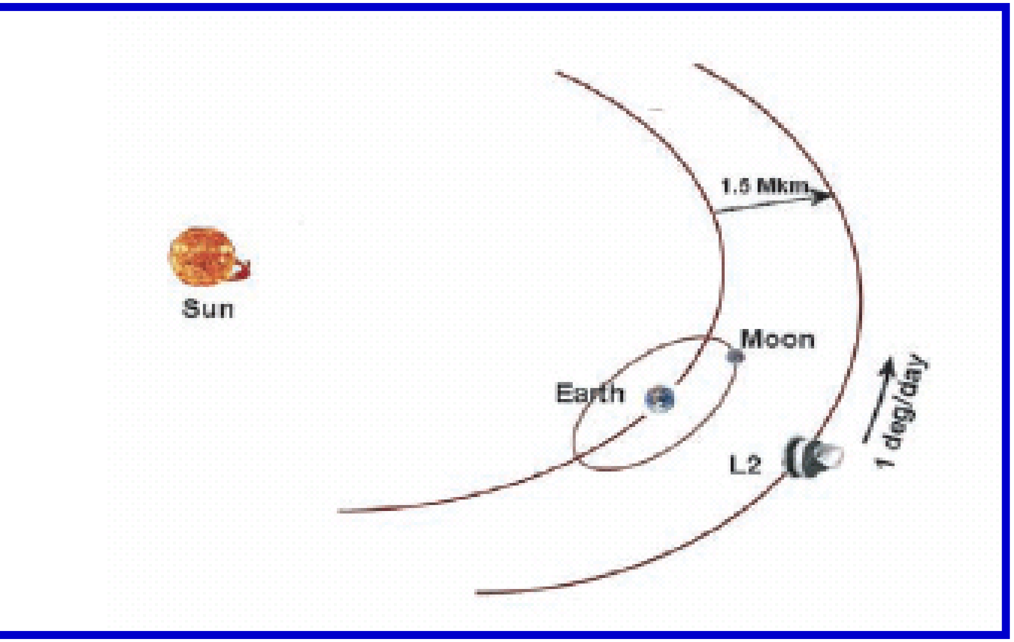


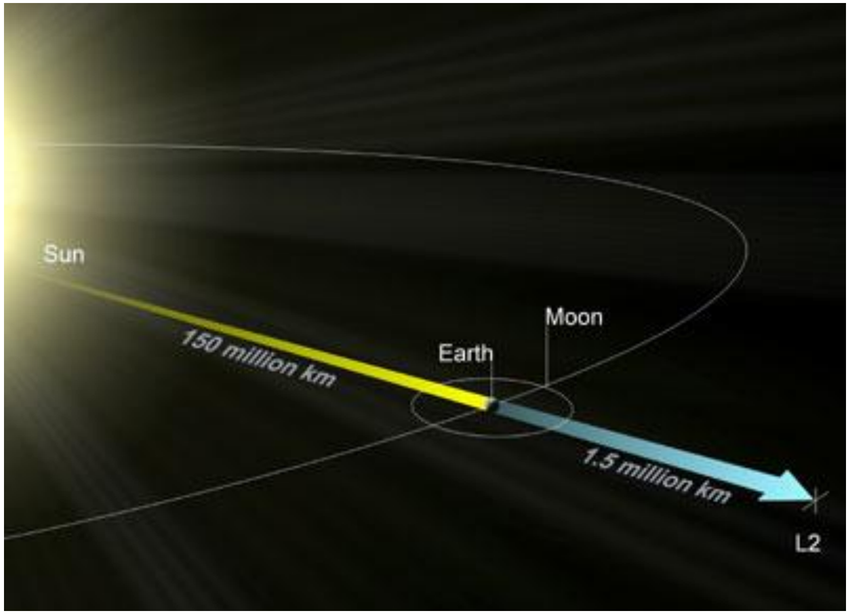


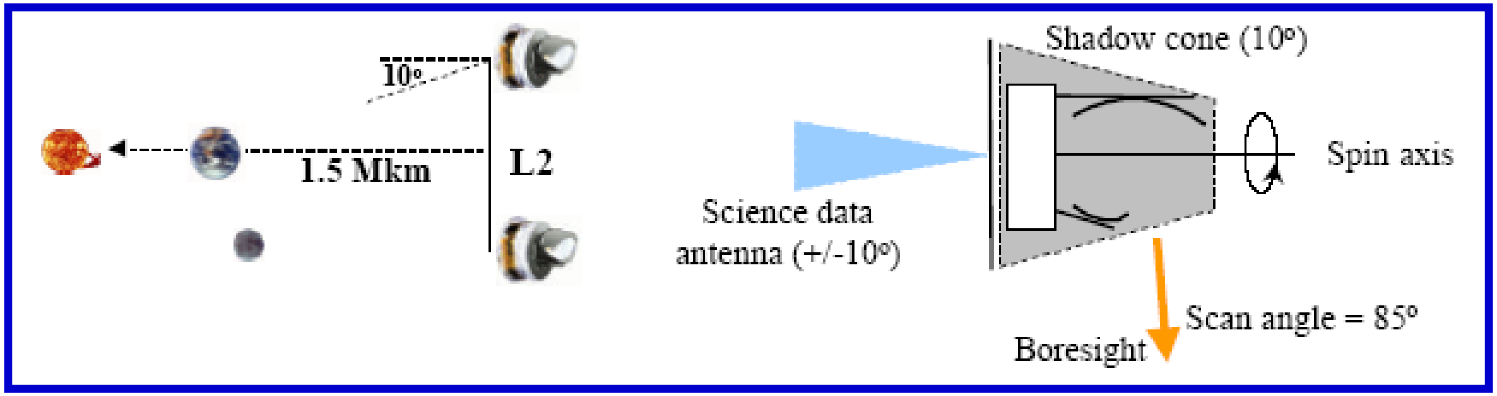


Planck was inserted into an L2 orbit, about 4 times farther from the Earth than the Moon, and on the opposite side from the Sun minimizing effects of going into and out of the Sun's rays. Herschel was inserted into a separate L2 orbit.

The telescope will spin at ~ 1rpm, constantly pointed away from the Sun, moving with the Earth at 1^0/day – LissajousOrbit - unstablerb





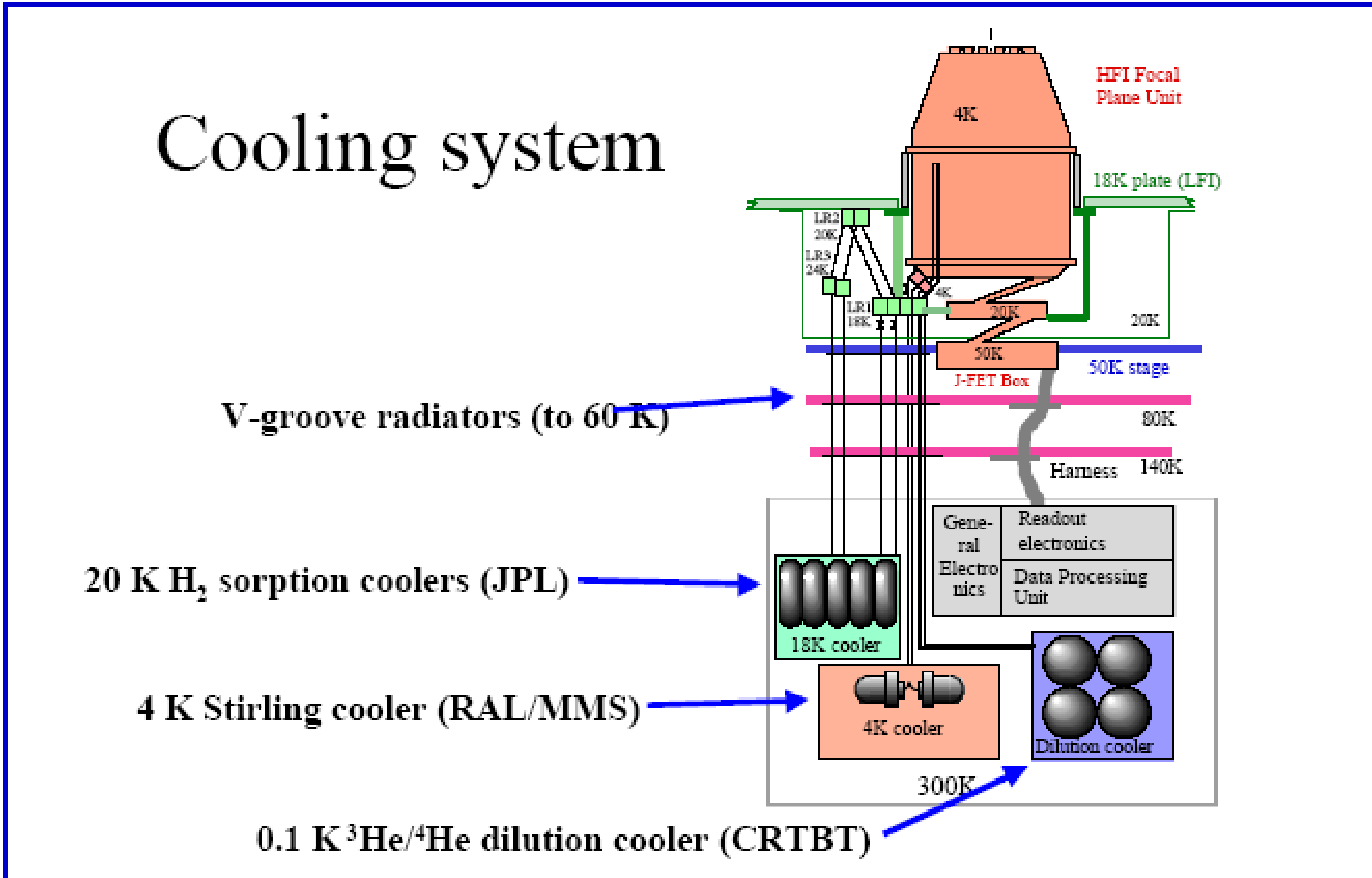


Cryogenics – Passive + 2 x closed cycle + open cycle He-3,4 dilution

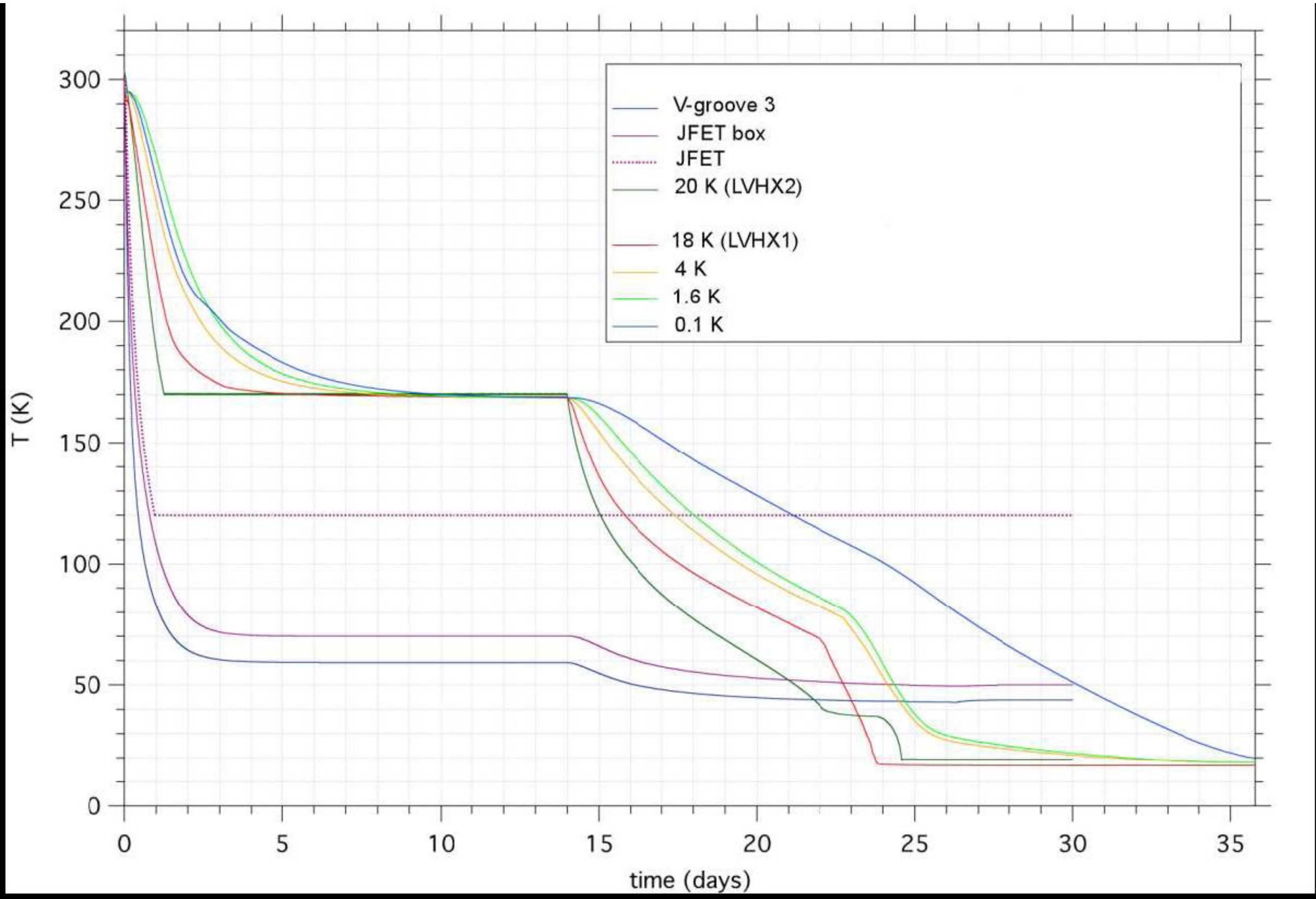
36,000 liters He-3 STP gas + 12,000 liters He-4 gas

Stability – 10 μK (P-P) at 20K and 20 nK/√Hz at 100 mK

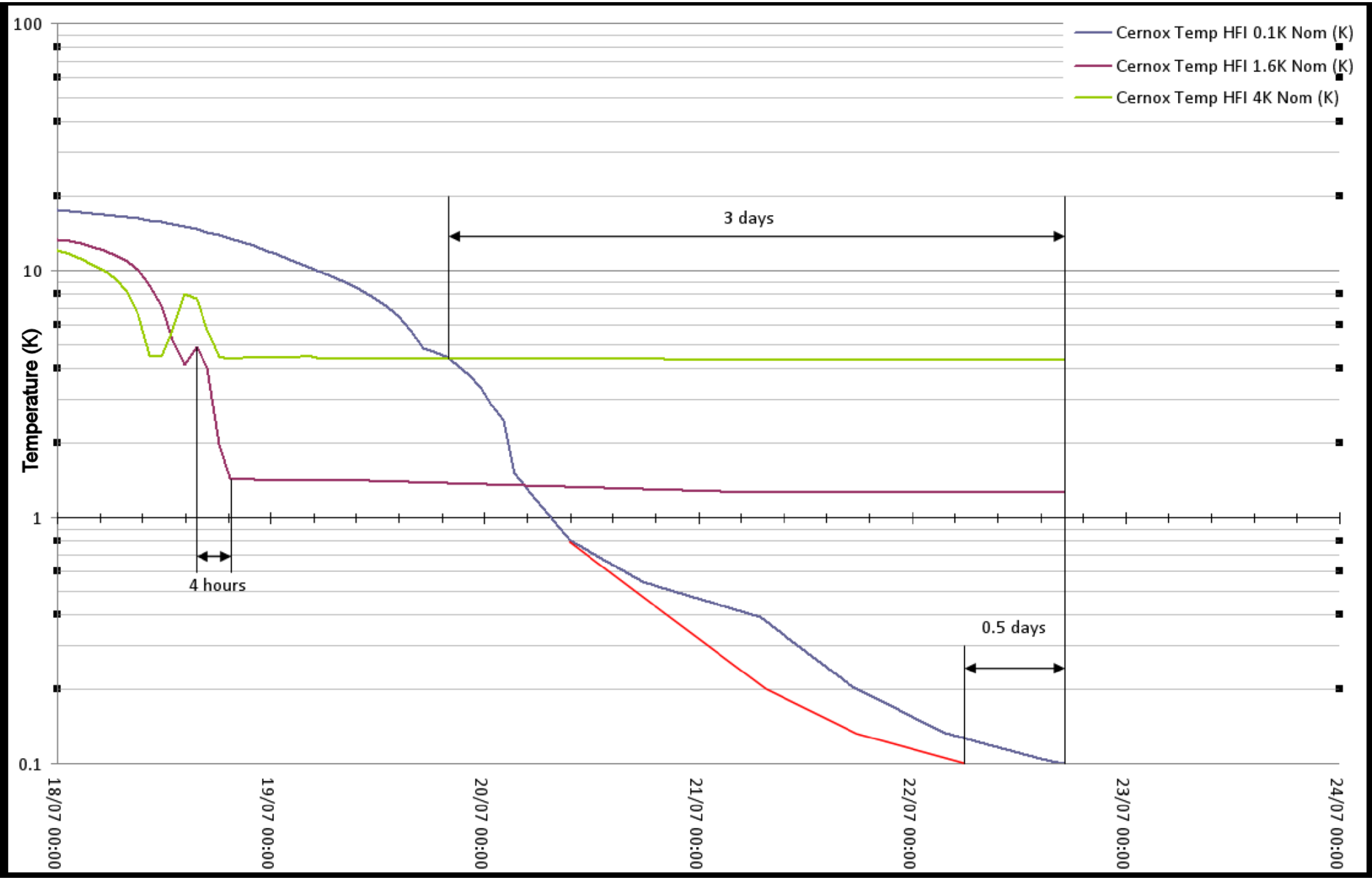
Holmium-Yttrium 100 mK τ ~ hours!



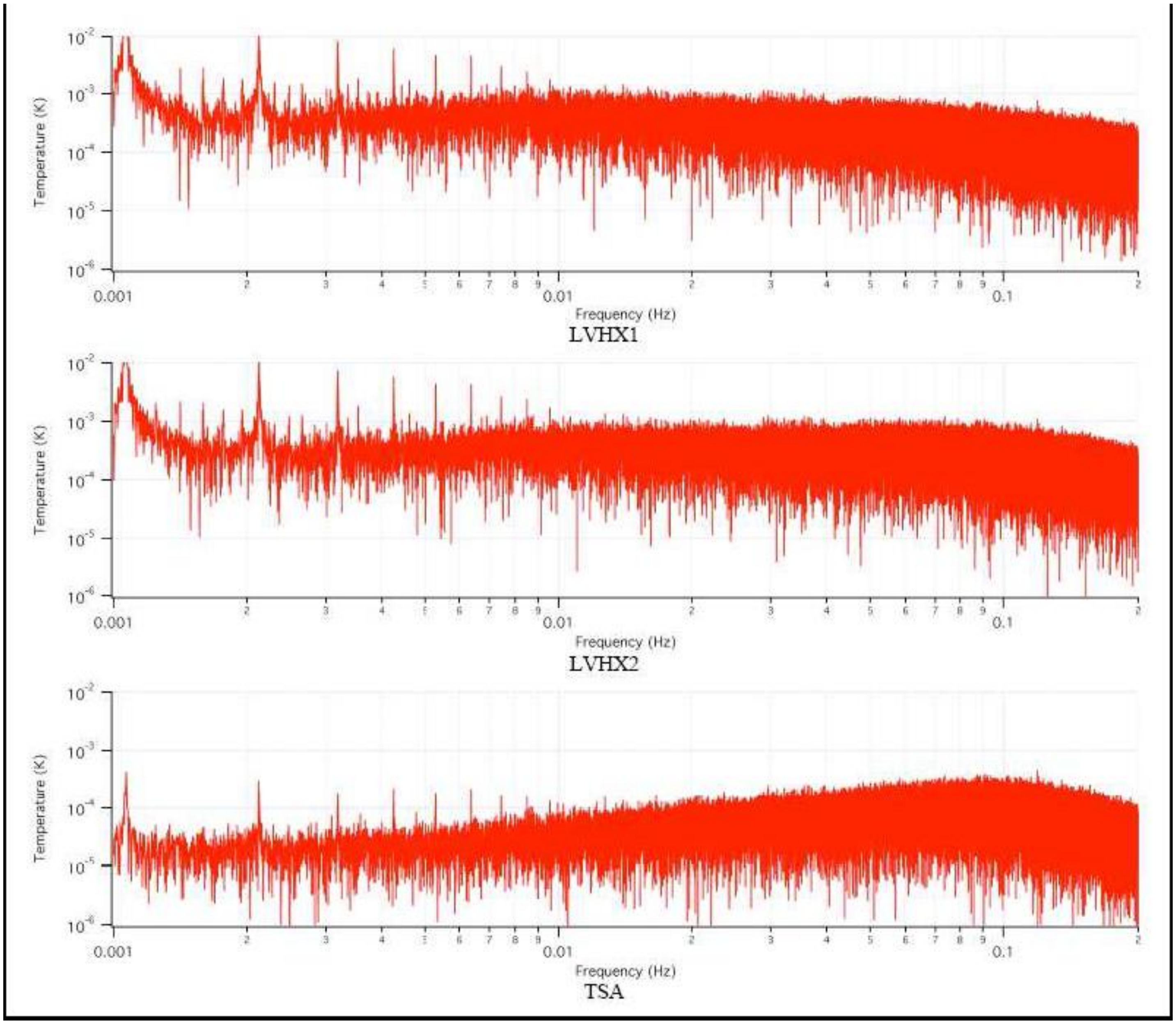
Cool down on way out



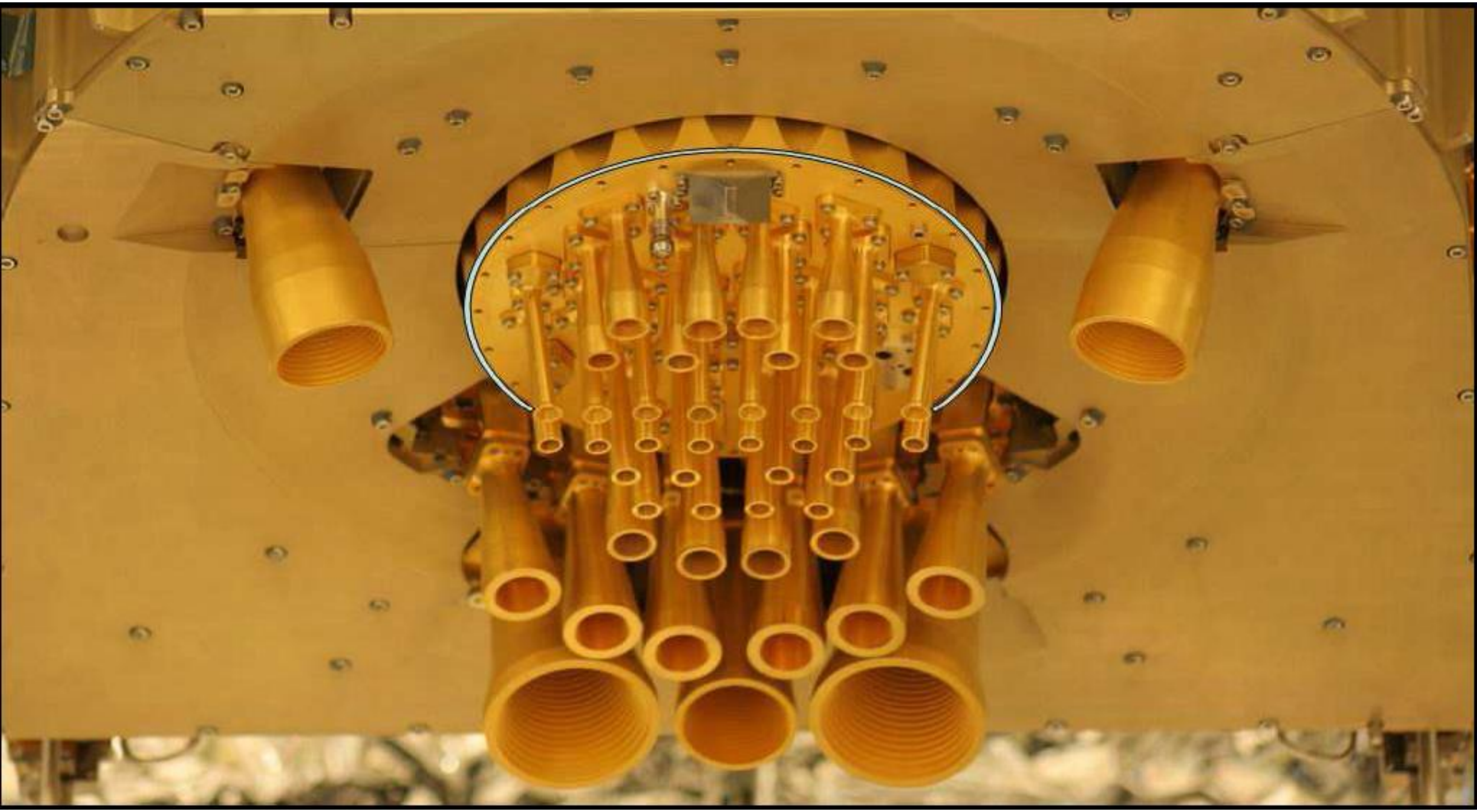
Cooling to 4K and 0.1 K



20 K H2 Sorption Cooler temperature power spectrum



Focal Plane – 100 mK bolometers + 20 K HEMTS



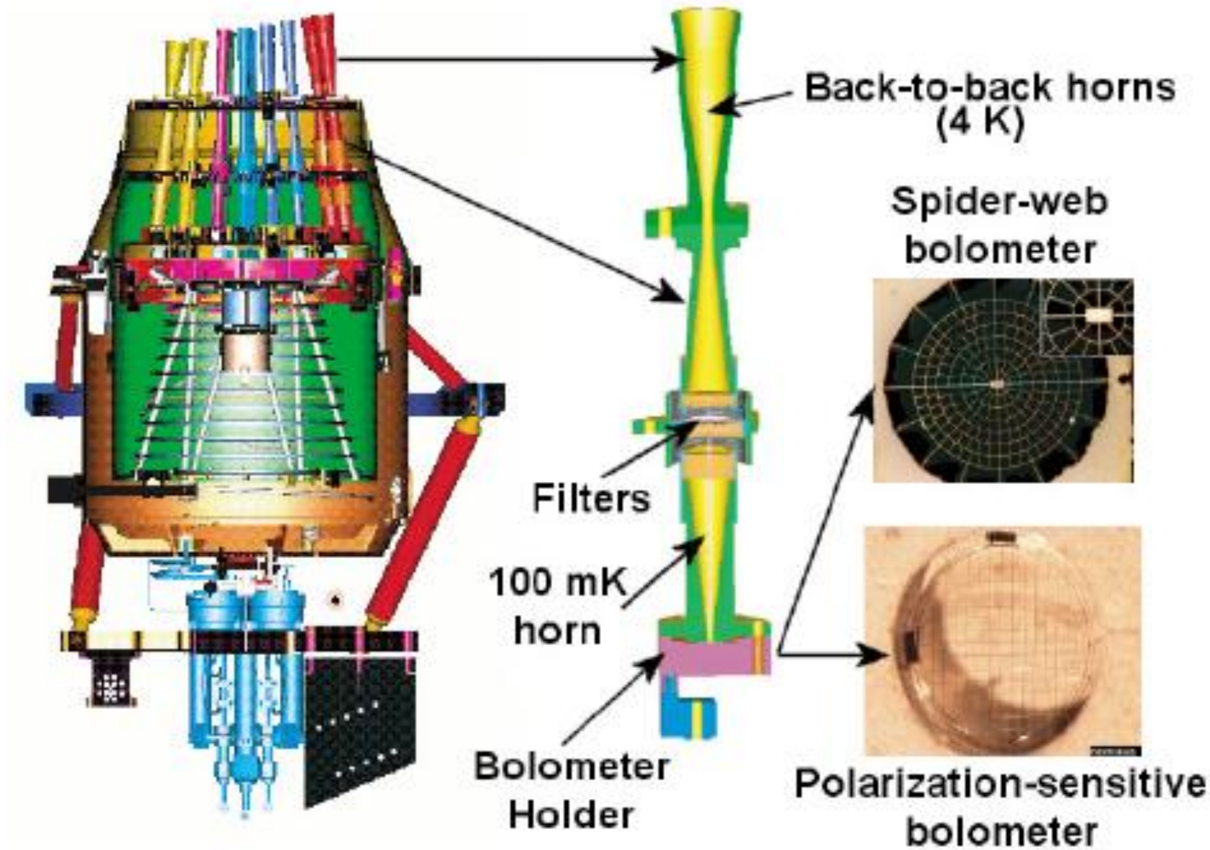
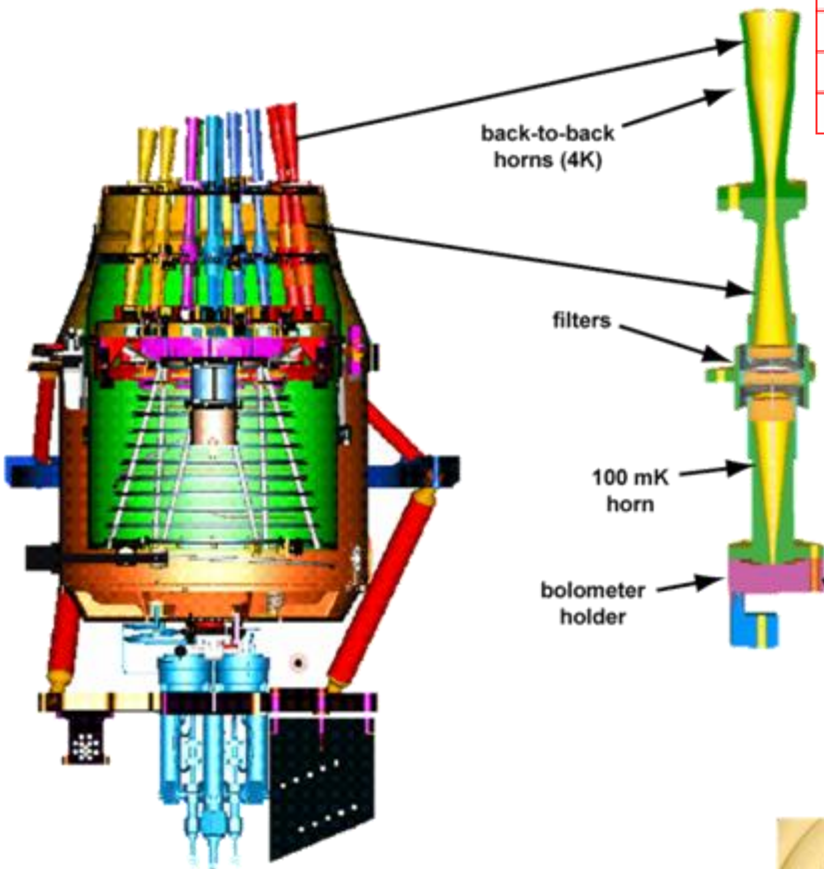


FIG 1.8.—Cutaway view of the HFI focal plane unit. Corrugated back-to-back feedhorns collect the radiation from the telescope and deliver it to the bolometer cavity through filters which determine the bandpass. The bolometers are of two kinds: (a) "spider-web" bolometers, which absorb radiation via a spider-web-like antenna; and (b) "polarisation-sensitive" bolometers, which absorb radiation in a pair of linear grids at right angles to each other. Each grid absorbs one linear polarization only. The absorbed radiant energy raises the temperature of a thermometer located either in the center of the spider-web, or at the edge of each linear grid.

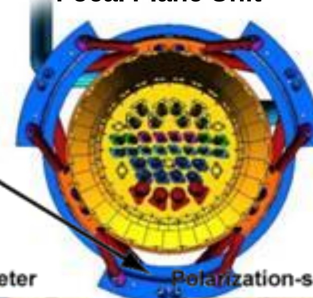
HFI Performance Goals

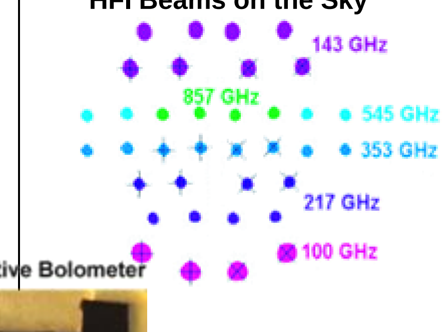
Center Frequency (GHz)	No. of Polarized Detectors	No. of Unpolarized Detectors	Angular Resolution (FWHM in arcmin)	ΔT/T Intensity (μK/K per beam)	ΔT/T Polarization
100	8	0	9.5	2.5	4
143	8	4	7.1	2.2	4.2
217	8	4	5	4.8	9.8
353	8	4	5	14.7	29.8
545	0	4	5	147	-
857	0	4	5	6700	-

(a) Average 1σ sensitivity per square pixel whose side is the beam FWHM, in thermodynamic units, after 14 months integration time (2 full sky surveys).

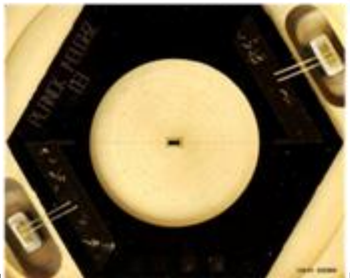


Focal Plane Unit





Spider-web Bolometer



Polarization-sensitive Bolometer

Planck/HFI uses Jet Propulsion Laboratory (JPL) spider-web and polarization-sensitive bolometers cooled to 0.1 K to map the sky in 6 frequency bands from 100 GHz to 857 GHz (3 mm to 350 mm). **36 feed horns, 52 bolometers – ~Photon (BLIP) noise limited**

Secondary Science with HFI

The primary science goal of Planck is to map temperature and polarization anisotropies in the Cosmic Microwave Background, but the instruments on Planck will also see other sources during Planck's full-sky surveys.

HFI will see clusters of galaxies in the Sunyaev-Zeldovich effect. The full sky maps will contain an unbiased survey for clusters of galaxies allowing measurement of the Hubble constant and study of the history of large scale structure formation.

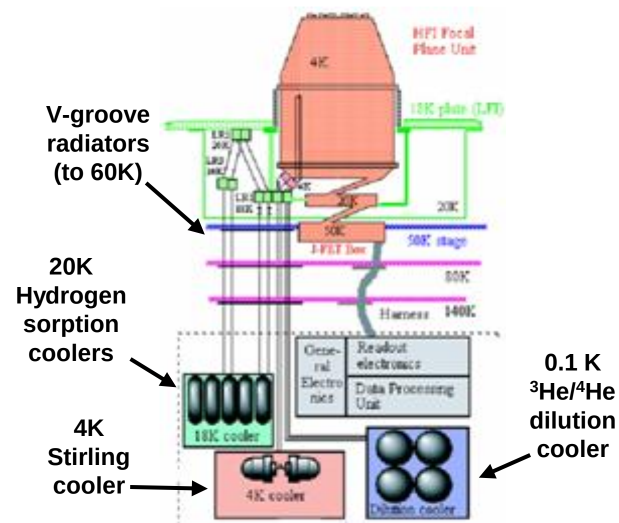
Dusty galaxies at high redshift are expected to be very bright in the submillimeter. Planck/HFI will survey the entire sky in 6 wavelength bands and should detect many of these galaxies. Number counts of young dusty galaxies at high redshift will provide insight into the history of structure formation in the universe, as well as providing information about the composition of the universe itself.

HFI will map the brightness and intensity of interstellar dust in our own galaxy, allowing the investigation of galactic magnetic fields, the structure of the Milky Way, and the early stages of star formation.

HFI Point Source Survey Properties

Center Frequency (GHz)	Confusion Limit (3σ, mJy)	All Sky Average Intensity (3σ, mJy)	Deep Survey Sensitivity (3σ, mJy)	Predicted No. of Galaxy Detections
143	6.3	26	10	570
217	14.1	37	18.4	860
353	44.7	75	49	1,700
545	112	180	170	4,400
857	251	300	280	35,000

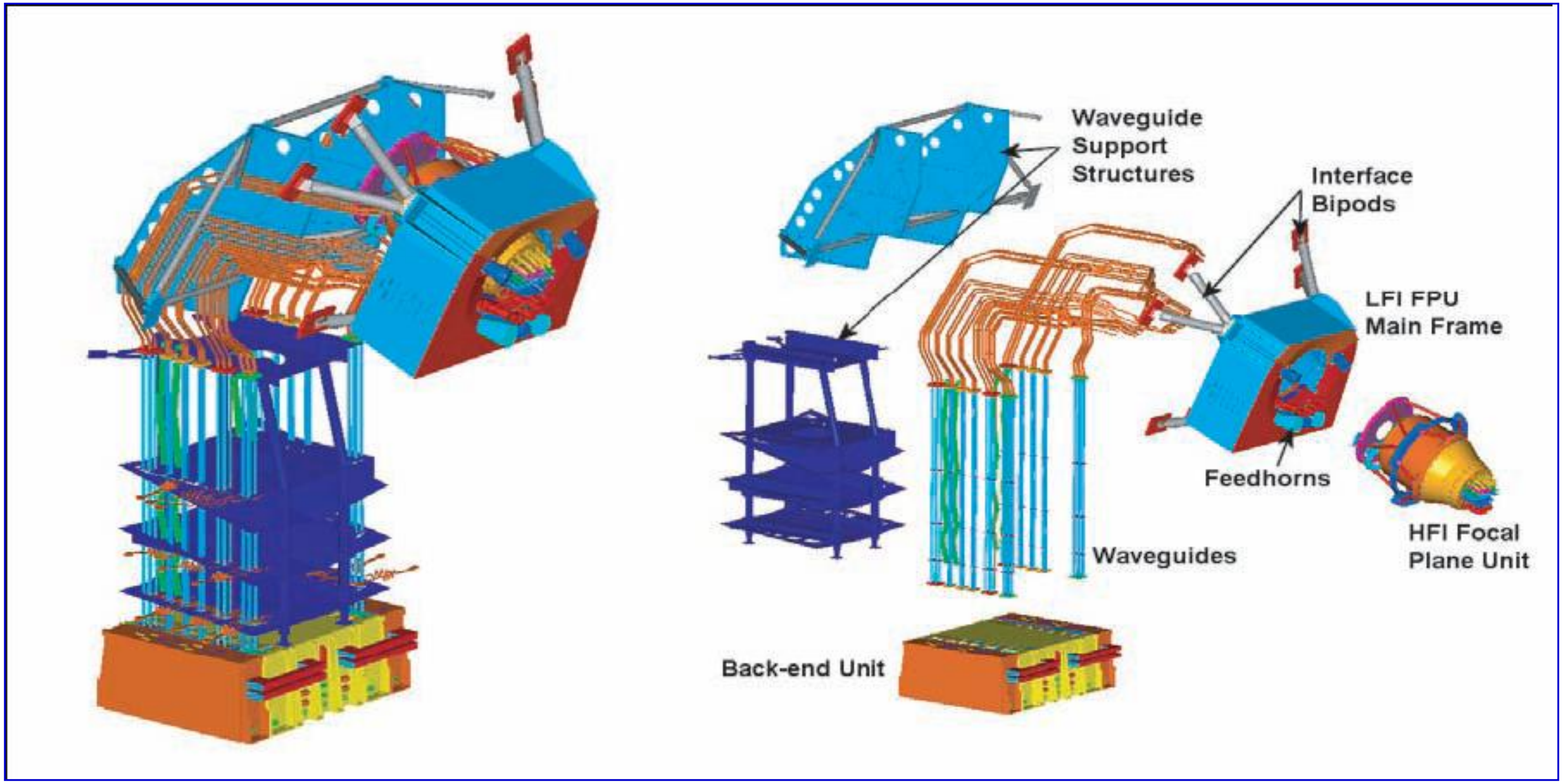
Cooling System



HFI Flight Focal Plane Instrument

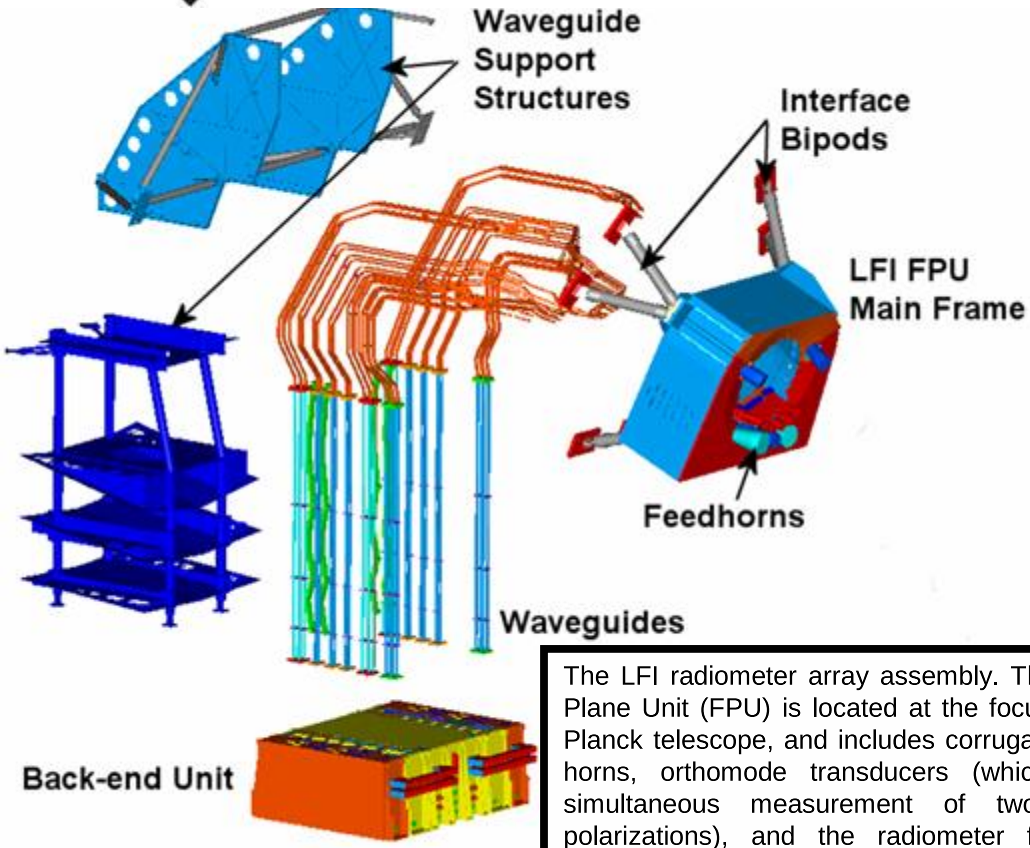
The HFI is being designed and built by a Consortium of scientists led by Jean-Loup Puget (PI) of the Institut d'Astrophysique Spatiale in Orsay (France), and Francois Bouchet (Deputy PI) of the Institut d'Astrophysique de Paris. The other main institutes involved in the HFI Consortium are Caltech (Pasadena,USA), Canadian Institute for Theoretical Astrophysics (Toronto, Canada), Cardiff University (Cardiff, UK), Centre d'Etudes Spatiales des Rayonnements (Toulouse, France), Centre de Recherche sur les tres Basses Temperatures (Grenoble, France), College de France (Paris, France), Commissariat a l'Energie Atomique (Gif-sur-Yvette, France), Danish Space Research Institute (Copenhagen, Denmark), Imperial College (London, UK), Institut des Sciences Nucleaires (Grenoble, France), Institute of Astronomy (Cambridge, UK), Jet Propulsion Laboratory (Pasadena, USA), Laboratoire de l'Accelerateur Lineaire (Orsay, France), Laboratoire d'Etude du Rayonnement et de la Matiere en Astrophysique (Paris, France), Max-Planck-Institut fuer Astrophysik (Garching, Germany), Mullard Radio Astronomy Observatory (Cambridge, UK), National University of Ireland (Maynooth, Ireland), Rutherford Appleton Laboratory (Chilton, UK), Space Science Dpt of ESA (Noordwijk, Netherlands), Stanford University (Palo Alto, USA), Universite de Geneve (Geneva, Switzerland), Universidad de Granada (Granada, Spain), and University La Sapienza (Rome, Italy).

For more information on HFI, see “The Planck High Frequency Instrument, a 3rd generation CMB experiment, and a full sky submillimeter survey” in the proceedings of the workshop “The Cosmic Microwave Background and its Polarization”, (eds., S. Hanany and R.A. Olive), New Astronomy Reviews 47, 877 (2003) [astro-ph/0308075].



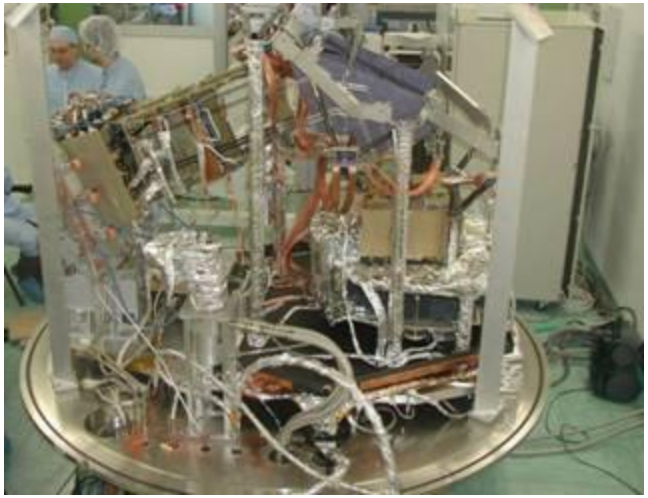
Array of differential microwave radiometers (DMRs) designed to measure the CMB at 30, 44, and 70 GHz using High Electron Mobility Transfer (HEMT) technology, cooled to 20K using hydrogen sorption coolers

Low Frequency Instrument (LFI)

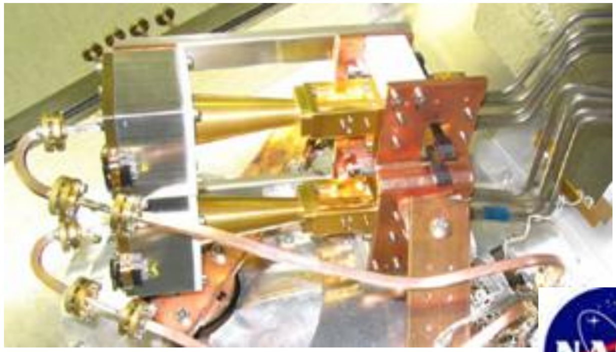


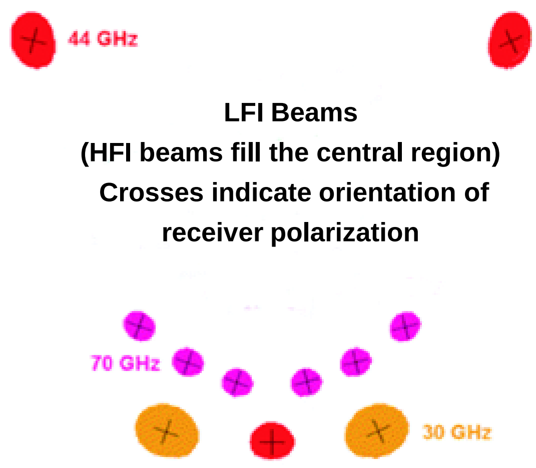
The LFI radiometer array assembly. The Focal Plane Unit (FPU) is located at the focus of the Planck telescope, and includes corrugated feed horns, orthomode transducers (which allow simultaneous measurement of two linear polarizations), and the radiometer front-end modules with hybrids, cryogenic low noise amplifiers and phase switches. The waveguides simultaneously meet complex radiometric, thermal and mechanical requirements. The radiometer back-end units are located on top of the Planck service module at 300 K and provide further amplification and detection.

The Qualification Model LFI after integration into the Alenia-Spazio cryogenic test facility in Italy.



A flight model 70 GHz Radiometer Chain Assembly under test at Electro-Bit Microwave in Finland.

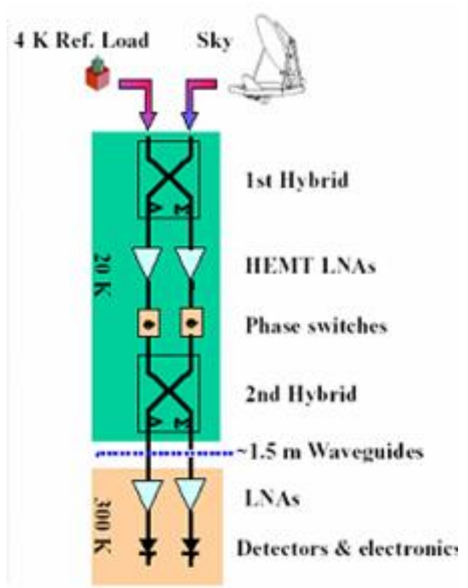




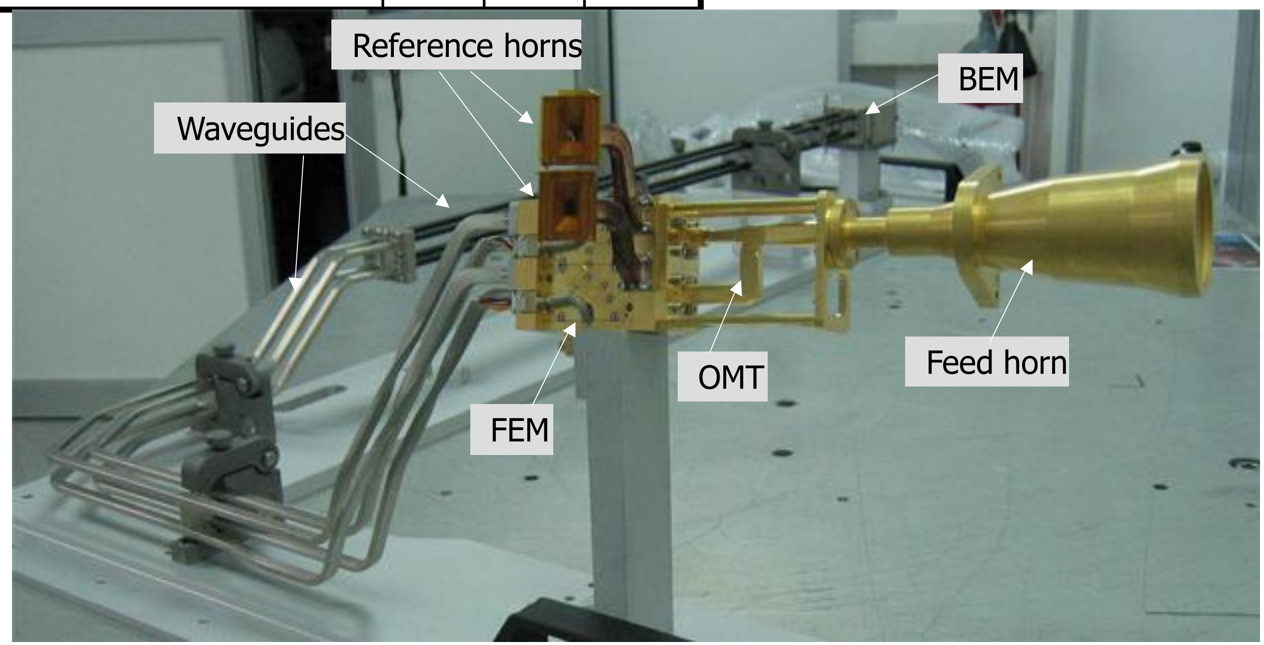
Main LFI flight performance specifications

Center Frequency (GHz)	30	44	70
Number of Feeds	2	3	6
Number of detectors	8	12	24
Angular Resolution (arcmin)	33	23	13
Effective Bandwidth (GHz)	6	8.8	14
Sensitivity (mK/√Hz)	0.24	0.29	0.41
Noise per 0.5° pixel (micro-K)	8	8	8
1/f knee frequency (Hz)	50	50	50
Systematic error per pix (micro-K)	<3	<3	<3
FEM power dissipation (mW)	27	34	24

The LFI is being designed and built by a Consortium of scientists led by Reno Mandolesi of the Istituto Fisica Spaziale e Fisica Cosmica (IASF) in Bologna (Italy). The other main institutes involved in the LFI Consortium are: Chalmers University of Technology,(S),Danish Space Research Institute (DK), Instituto de Astrofisica de Canarias,(E), Instituto de Fisica de Cantabria (E), Istituto CAISMI(I), Istituto IASF (CNR)(I), Istituto di Fisica del Plasma IFP (CNR)(I), Istituto IFSI(I), Jet Propulsion Laboratory,(USA), Max-Planck-Institut fuer Astrophysik(D), Millimetre Wave Laboratory(FI) Jodrell Bank Observatory(UK), Osservatorio Astronomico di Padova(I), Osservatorio Astronomico di Trieste, SISSA(I), Space Science Dpt of ESA(NL), Theoretical Astrophysics Center(DK), University of California (Berkeley)(USA), University of California (Santa Barbara)(USA), Universite de Geneve(CH), University of Oslo(N), Universita Tor Vergata(I)

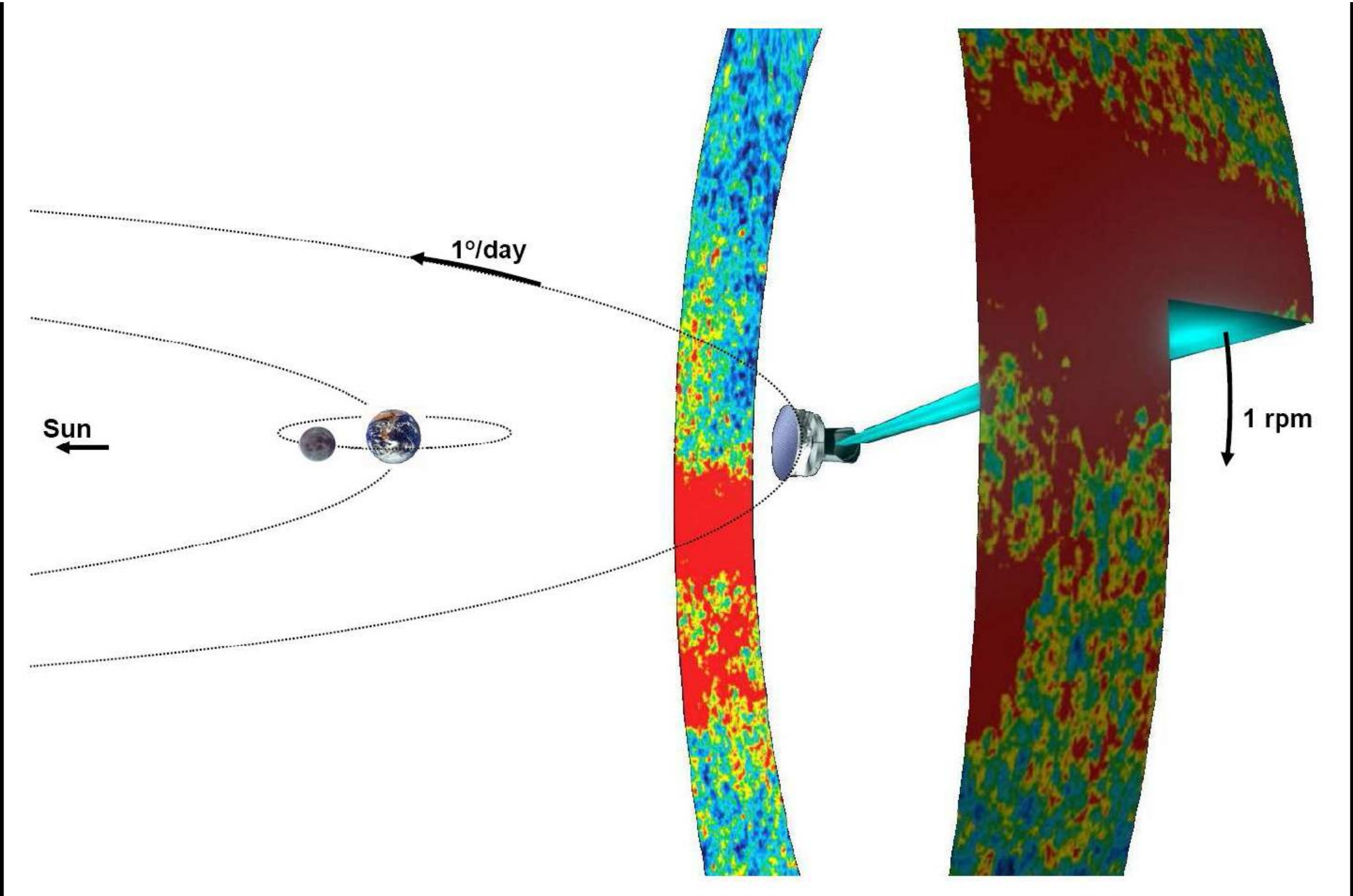


LFI "Continuous Comparison" Pseudo-correlation receiver. One phase switch switches at 8192 Hz, providing alternately 'Sky' and 4 K 'Reference' outputs at each diode. Differencing these states effectively removes 1/f noise from the data.

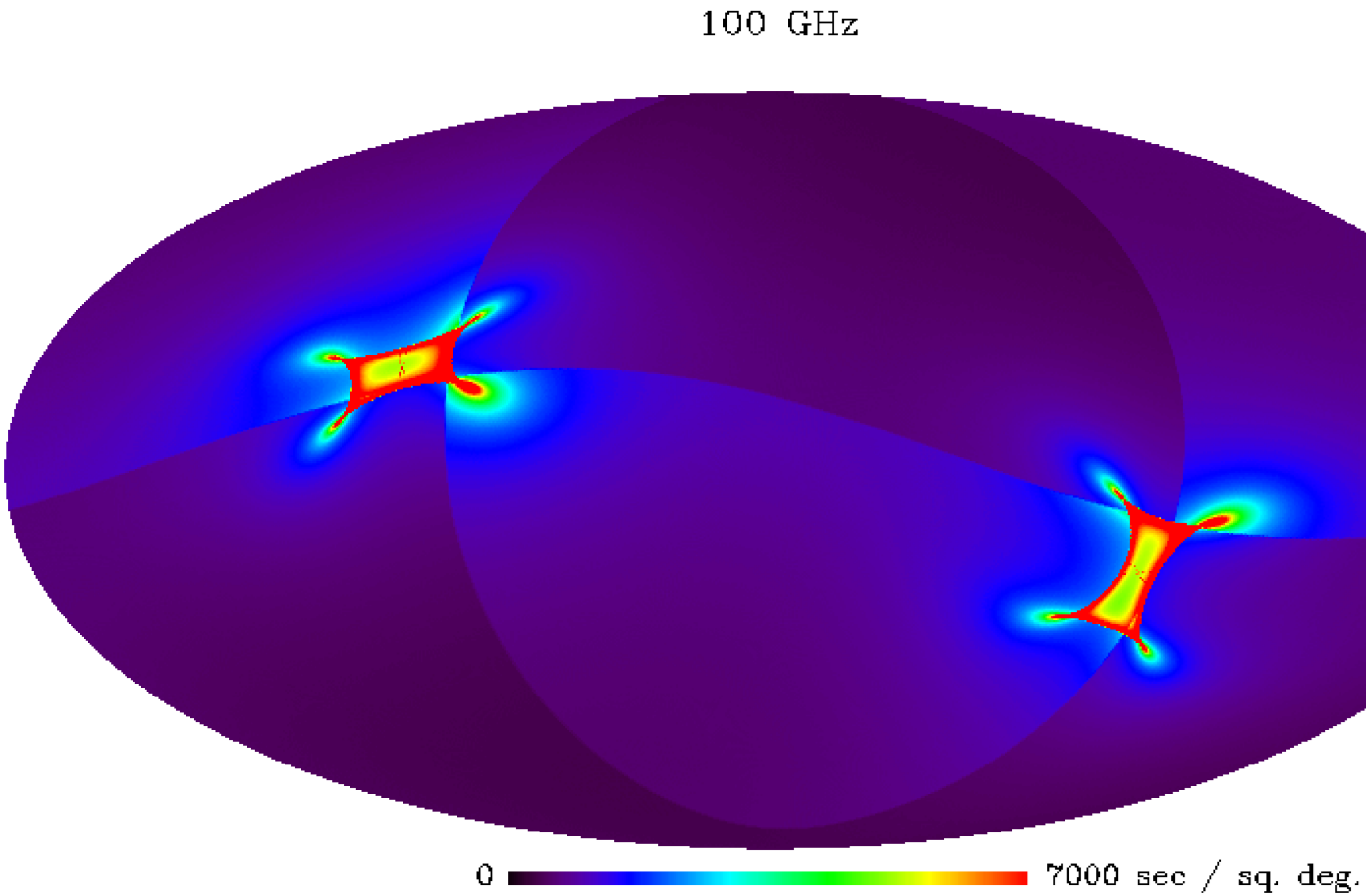


Picture of the 30 GHz Radiometer Chain Assembly being mounted in the RCA cryo testchamber at Alenia Spazio, Italy. The four waveguides are visible, the twisted copper section connected to the 20 K Front End Module, and the straight stainless steel section connecting to the 300 K Back-End Module. The horn feeds two radiometers, each carrying one of the linearly polarised components provided by an orthomode Transducer. **11 feeds**.

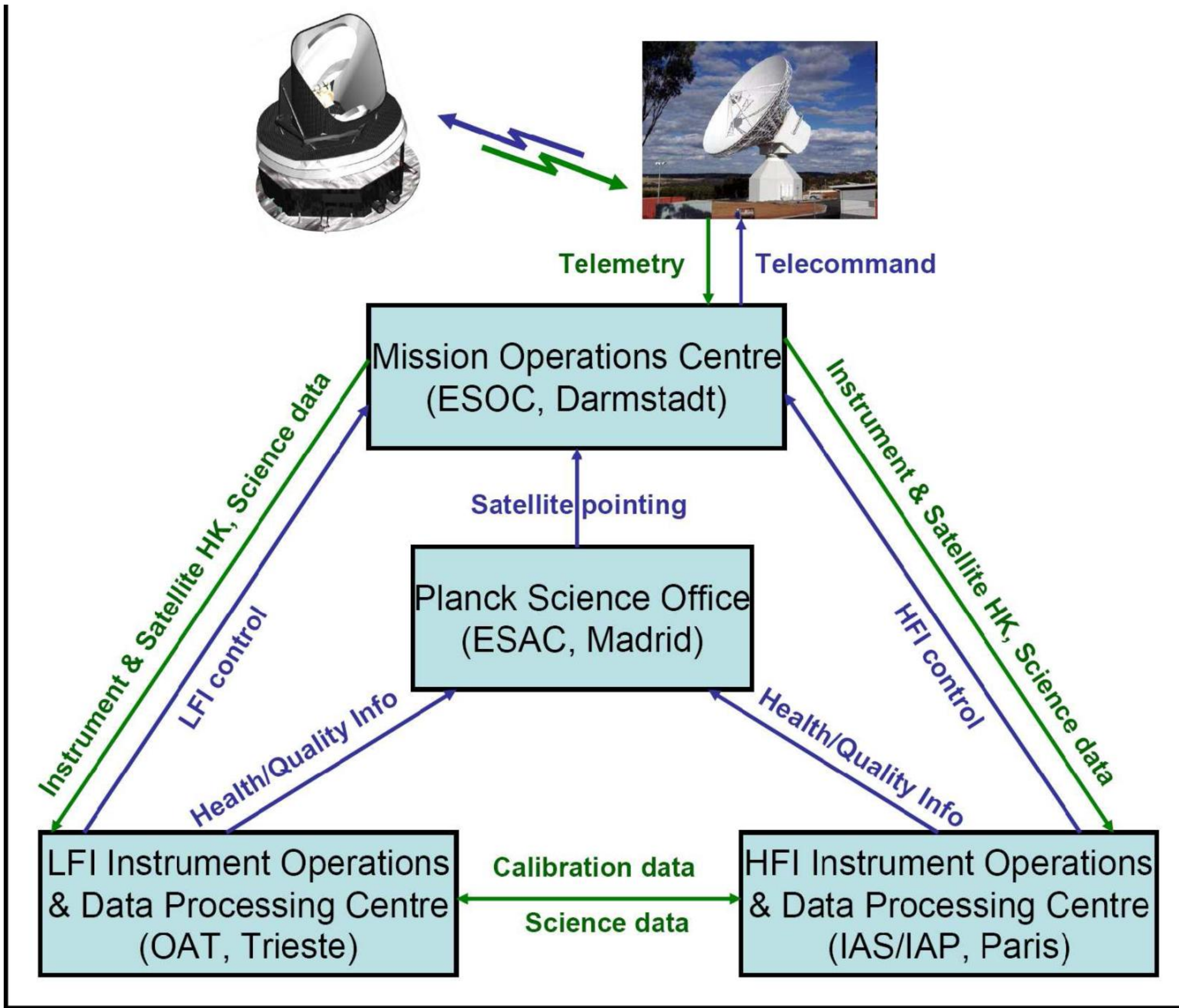
Mapping Strategy



Sky Coverage at 100 GHz – 15 month Mission (30+ possible)
Galactic Coordinates – Note Ecliptic Poles

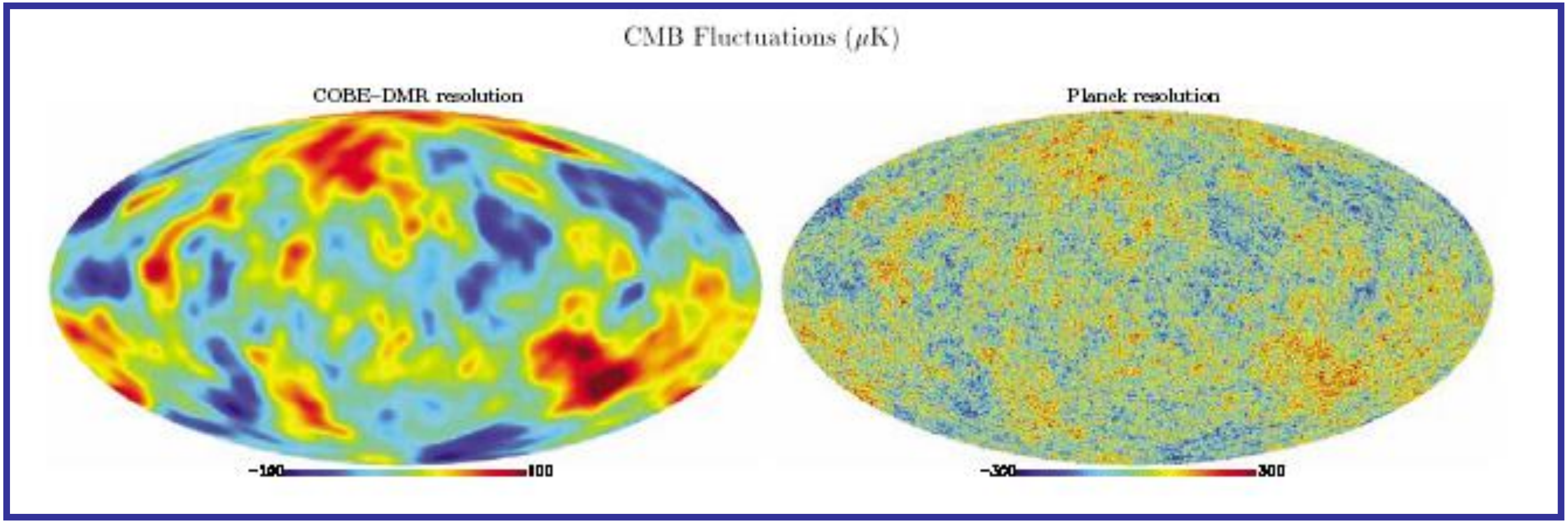


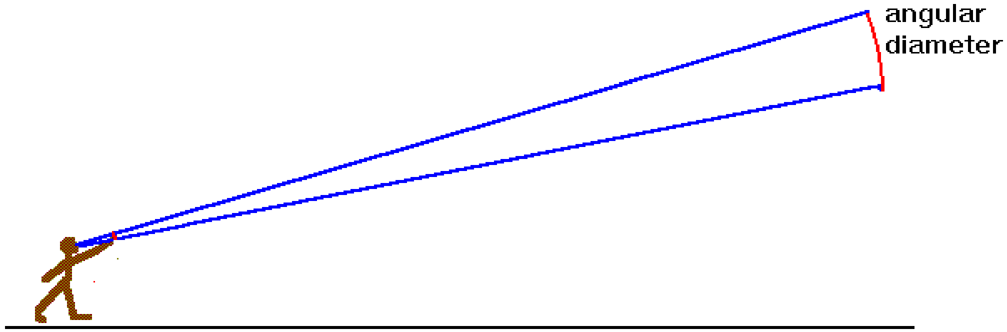
How data gets to us

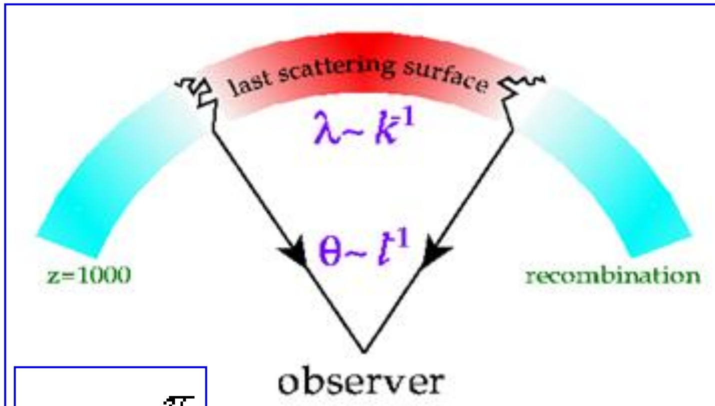


Scientific Objectives of Planck:

• To map the small temperature variations in the Cosmic Microwave Background with a resolution of 5 arc minutes and sensitivity of 10^{-6} Kelvin to determine our cosmological parameters and search for inflationary features, reionization, early structure formation, …





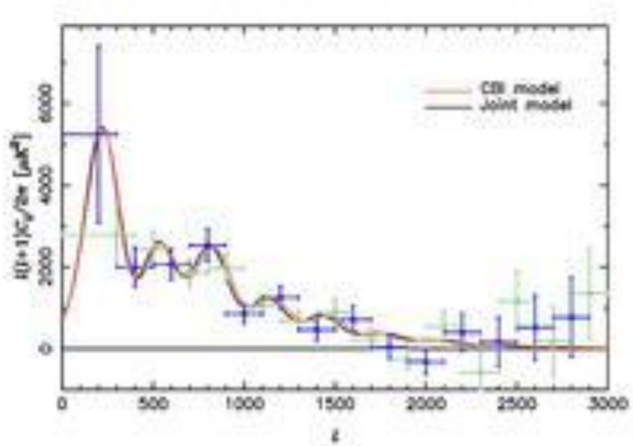


$$\Delta\theta \approx \frac{\pi}{l}$$

$$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi).$$

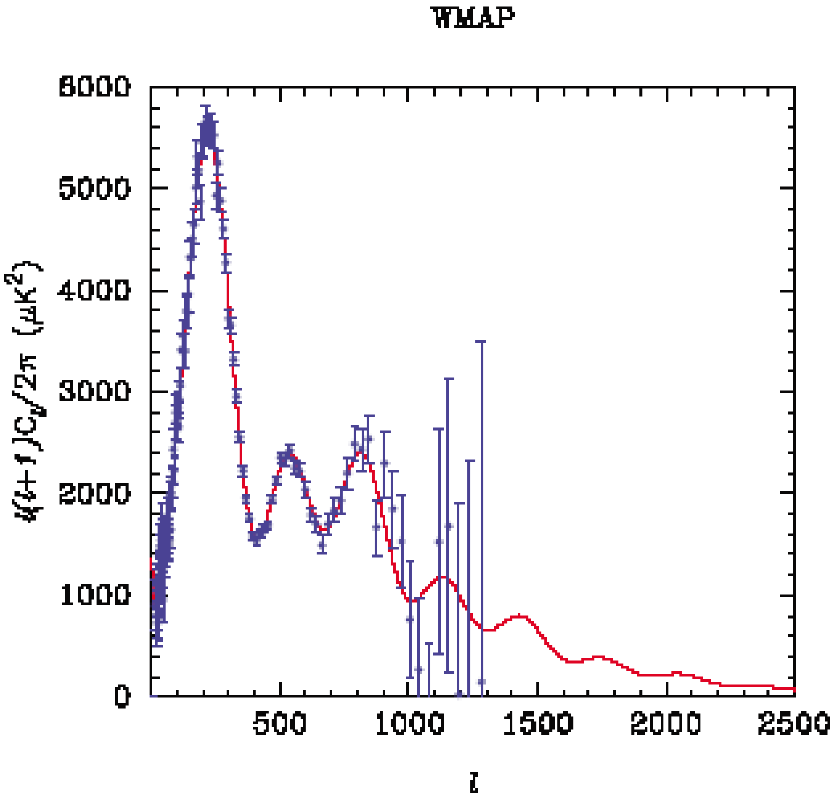
$$Y_{l,m} = \sqrt{\frac{2l+1(l-m)!}{4\pi(l+m)!}}\, P_l^m(\cos\theta)e^{im\phi}$$

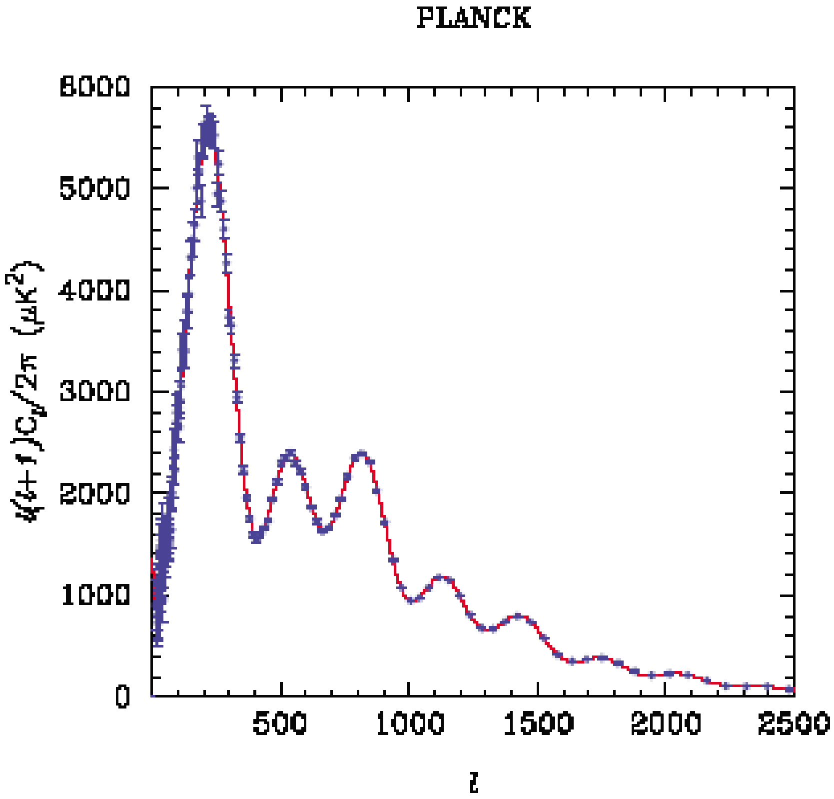
$$C_\ell^T = \langle |a_{\ell m}|^2 \rangle.$$



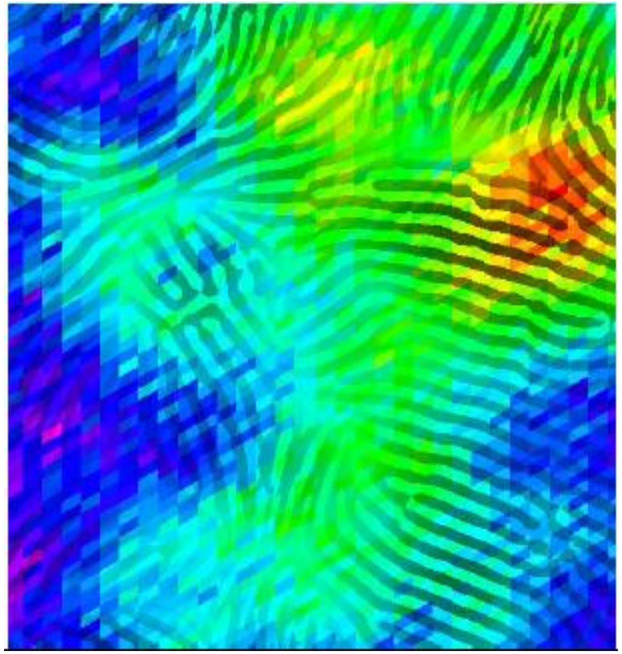
The power spectrum of the temperature variations can be predicted and depend on the detailed model of the universe. Measuring the power spectrum determines these details. The peaks in the spectrum are controlled by the density of matter, the expansion rate of among other things.

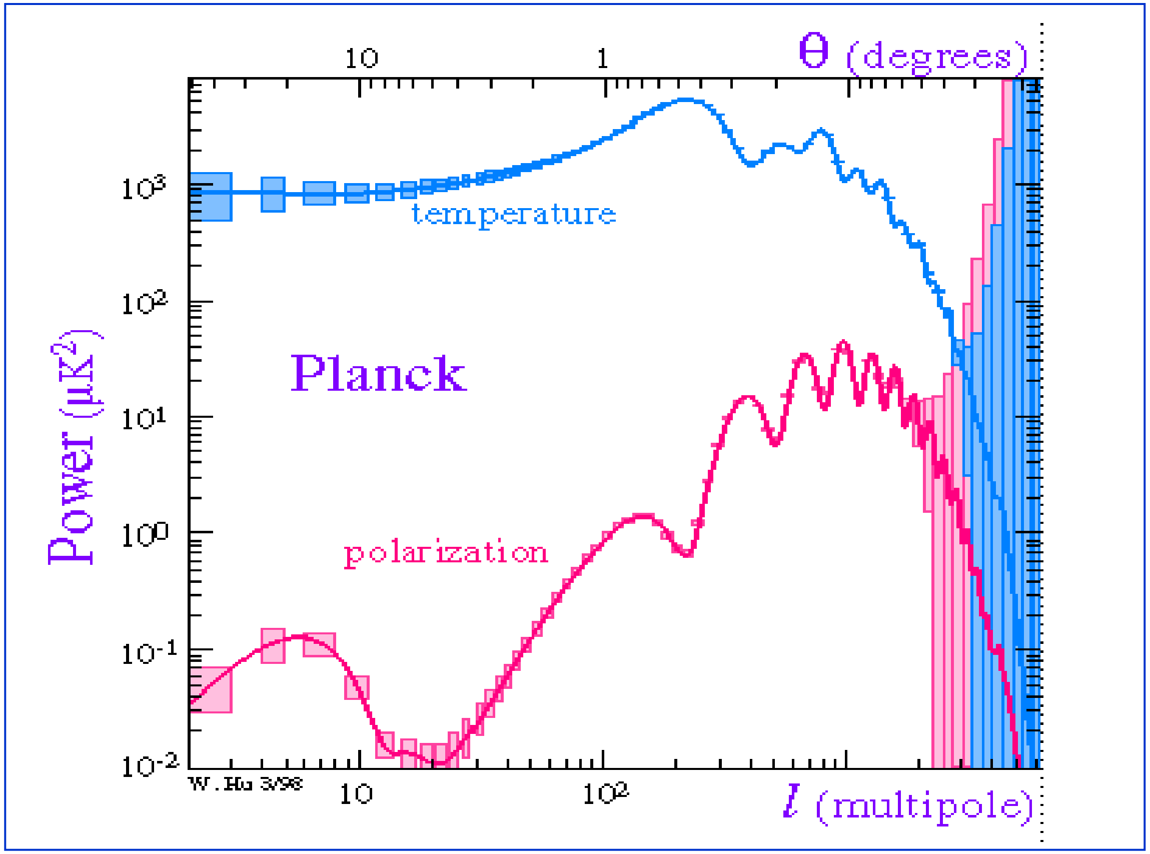
• *Constraining the power spectrum of the CMB at small scales*





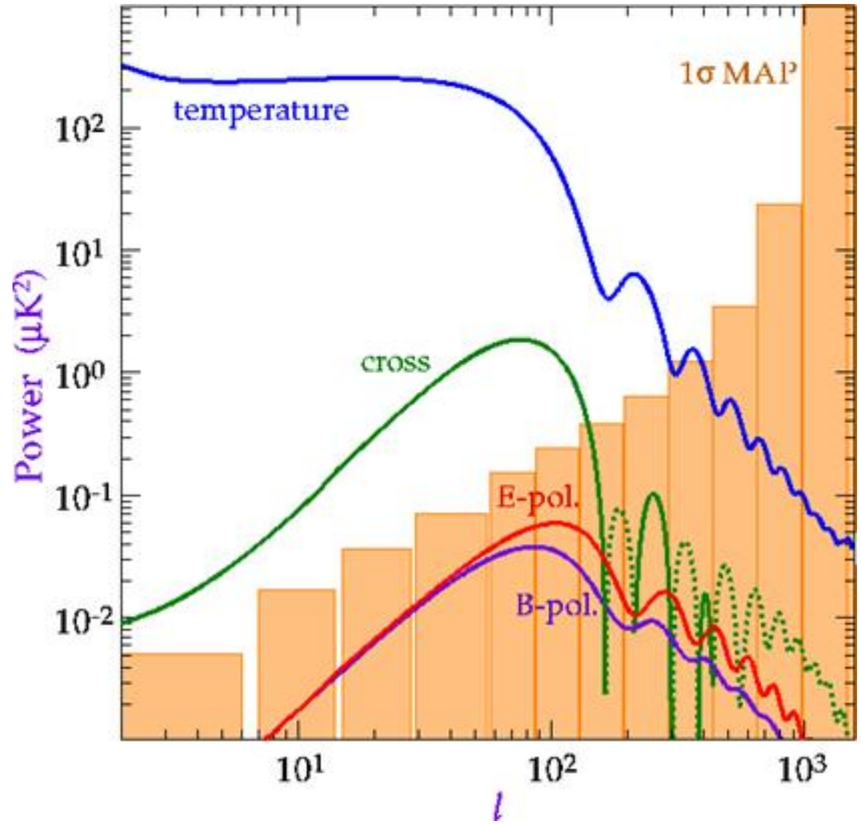
• *To map the polarization of the CMB and derive the polarization power spectrum of the CMB at high resolution ...*



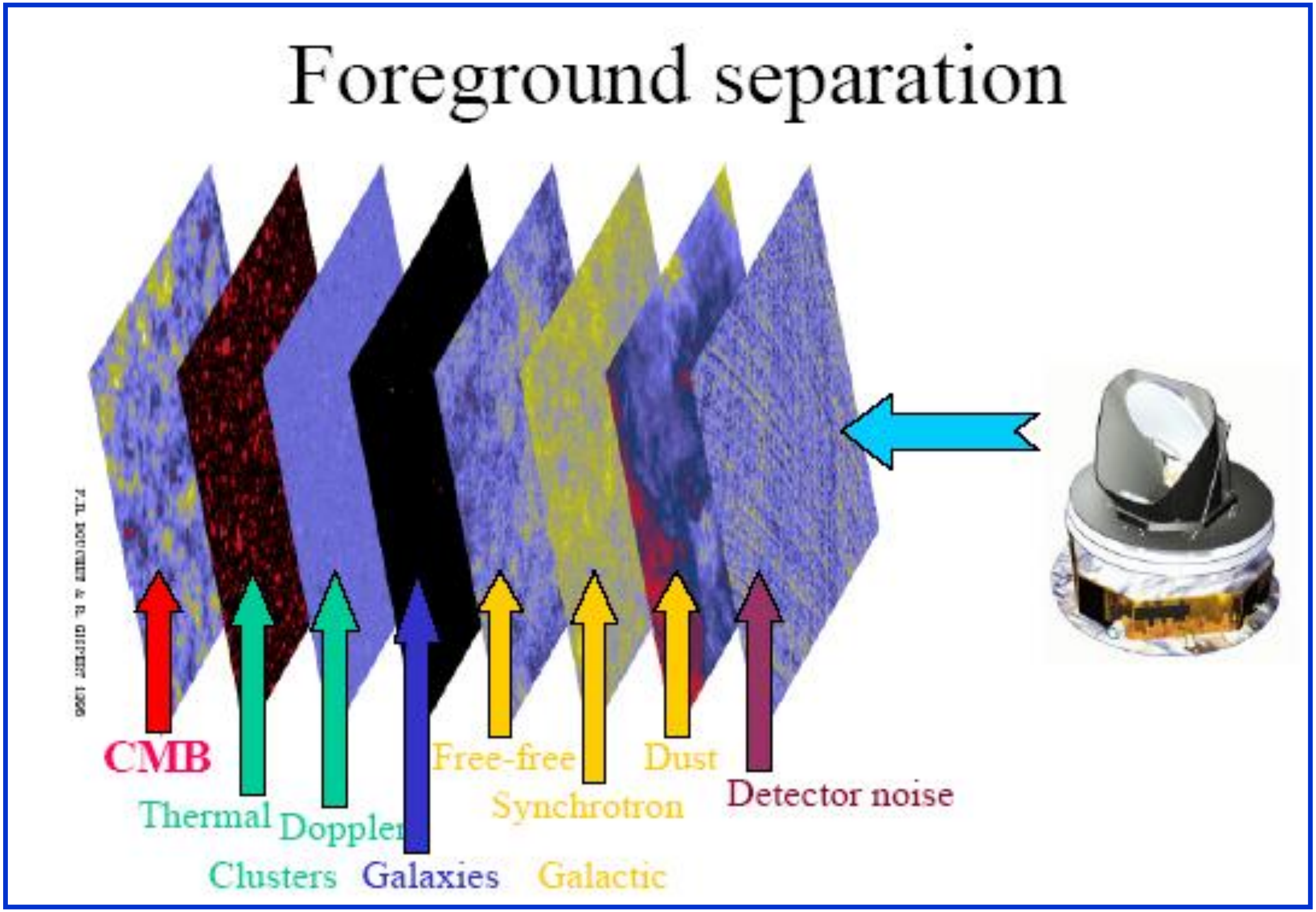


Each of these polarization patterns on the sky can be separated into a gradient``electric'' (E) and a curl ``magnetic'' (B) components. Any "nice" vector field can be decomposed this way.

E-modes arise primarily from density variations prior to recombination. B-modes are sensitive to the depth of re-ionization of the CMB after recombination, thus B-polarization can yield information about the ionization history of the Universe.



• Measure foreground sources accurately so as to separate the foreground signals from the CMB signal

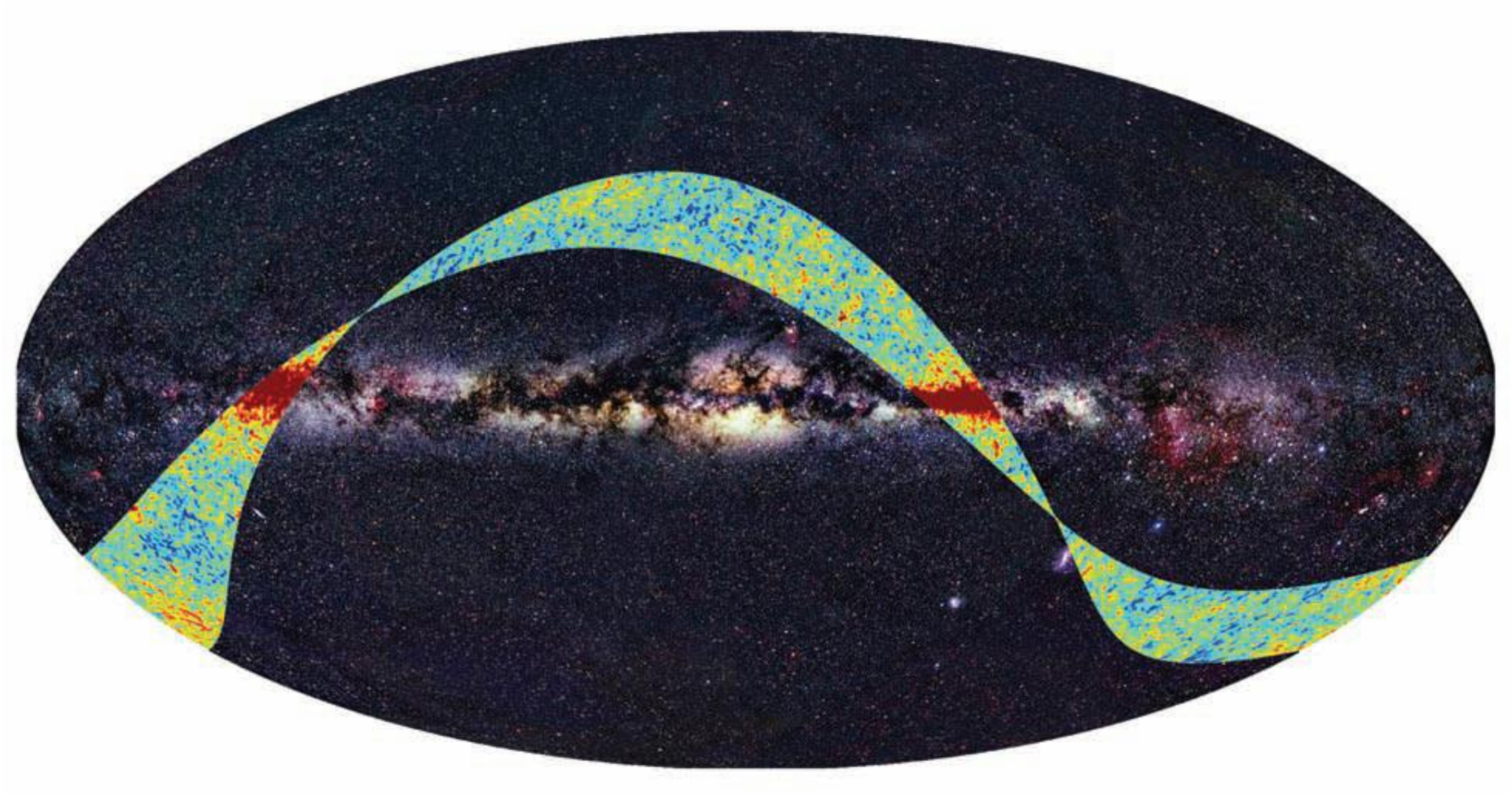


…which will permit better estimates of cosmological parameters:

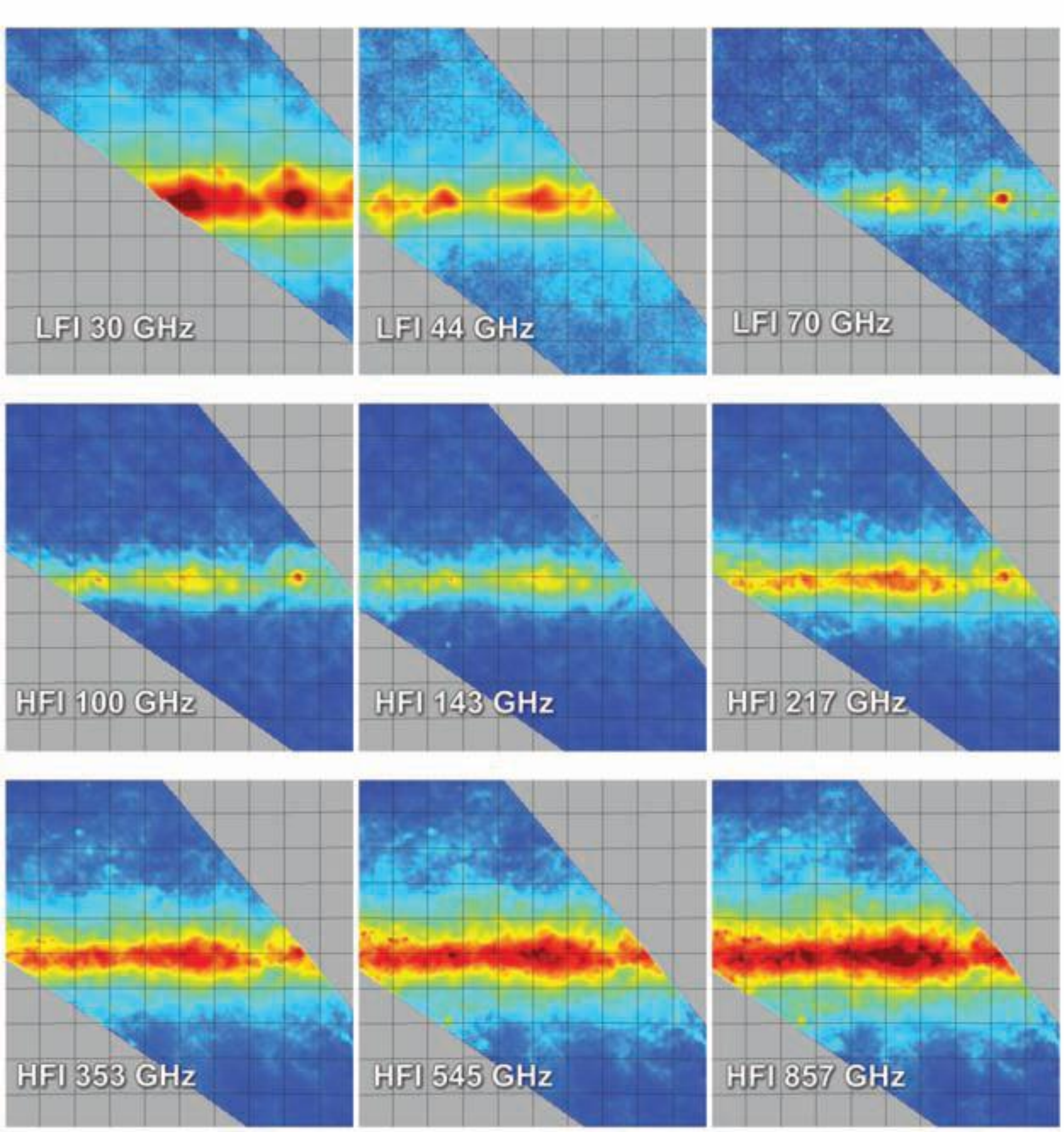
Main Cosmological Parameters

- Ω_o Cosmological total density parameter
- H_o Hubble constant
- Ω_b Baryon density
- Ω_c Cold dark matter density
- Λ Cosmological constant
- n_s Spectral index of scalar perturbations
- Q Amplitude of fluctuation spectrum
- r Ratio of Gravitational wave to density perturbations
- τ_r Residual optical depth due to reionisation

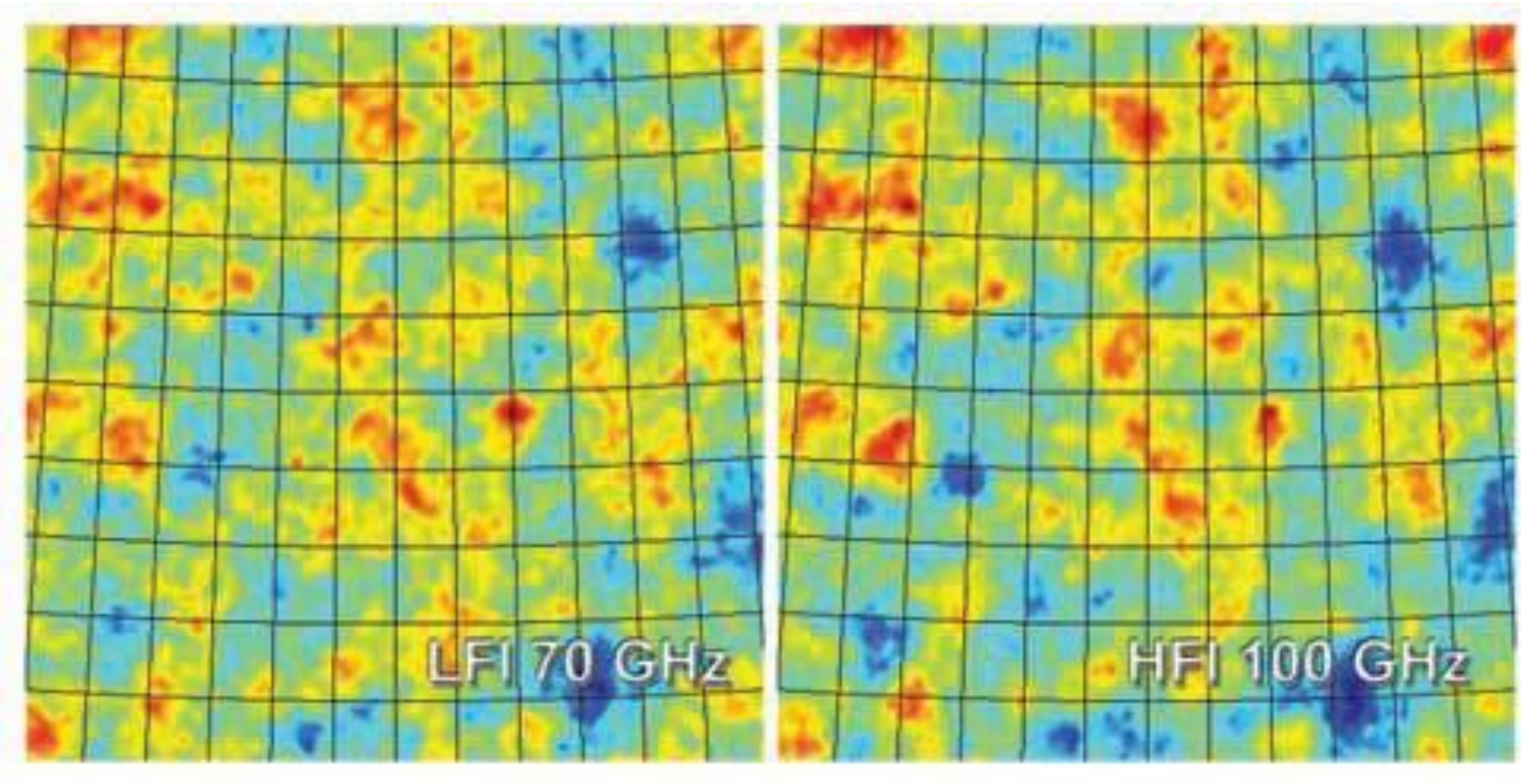
First two weeks of data



Galactic Plane Crossing from 0.03 to 0.86 THz

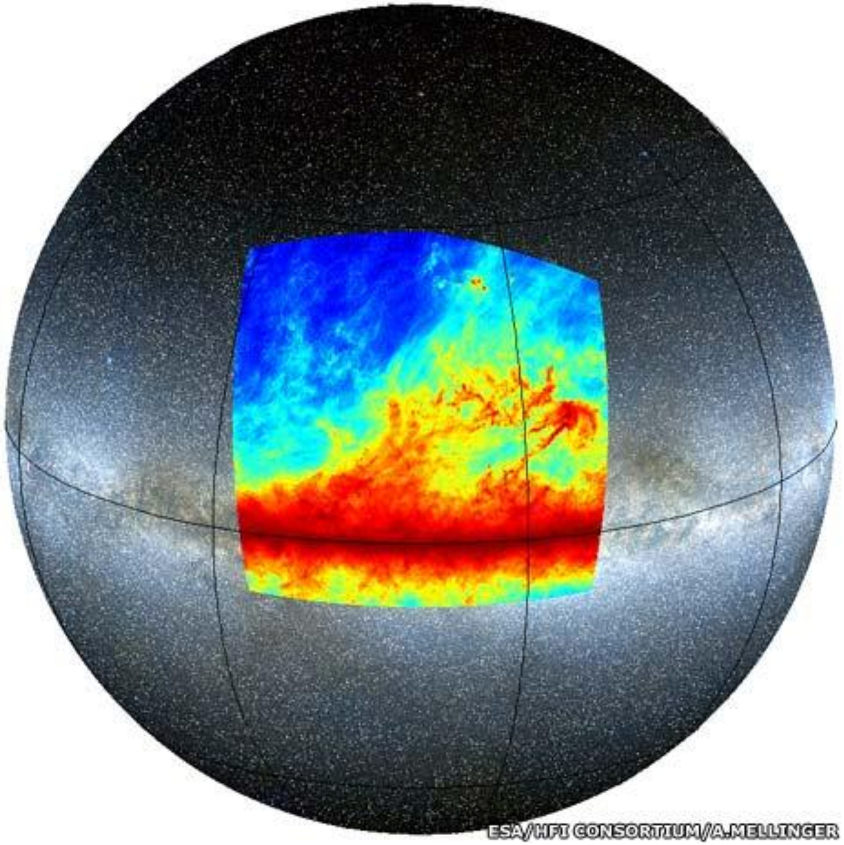


High Galactic Latitude at least galactic contamination and most sensitive frequencies

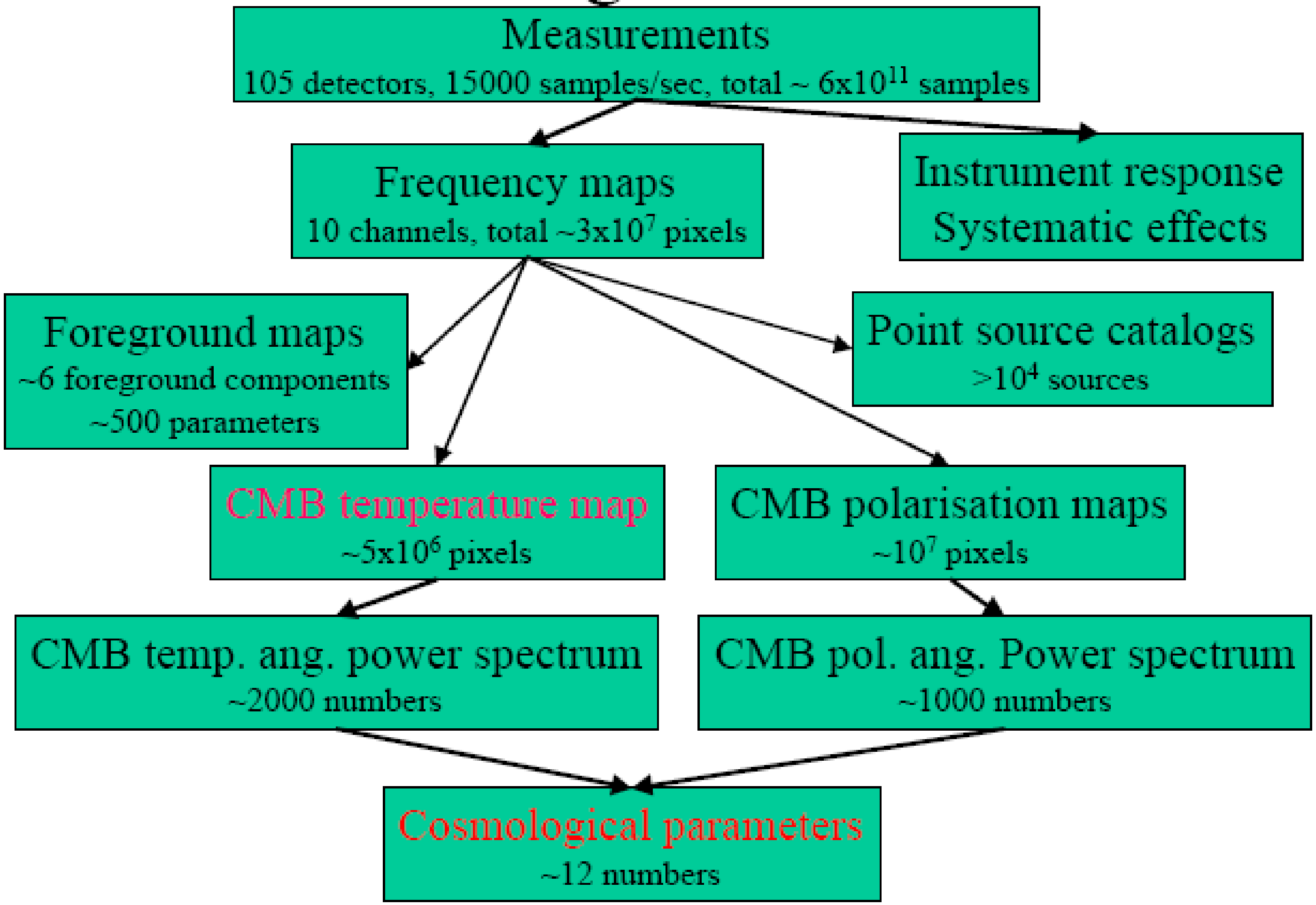


Star Dust – data release 3-17

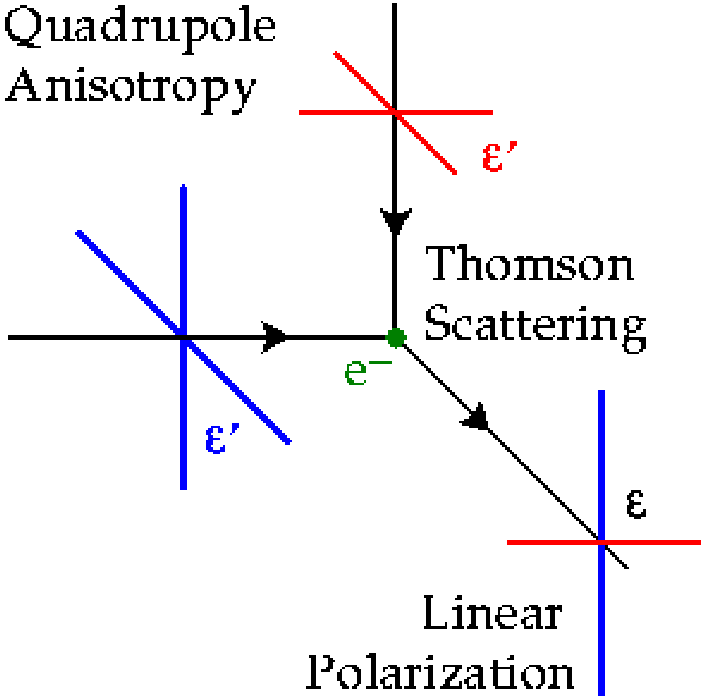
Planck spies massive dust clouds - BBC

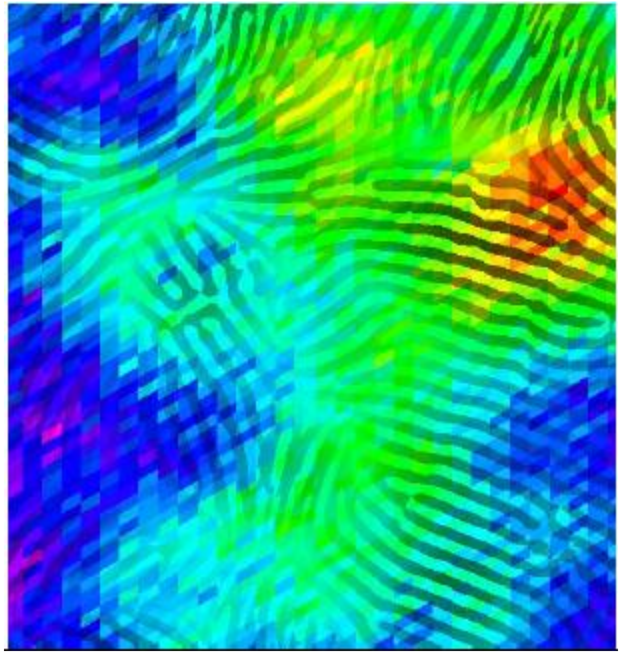


Extracting the science

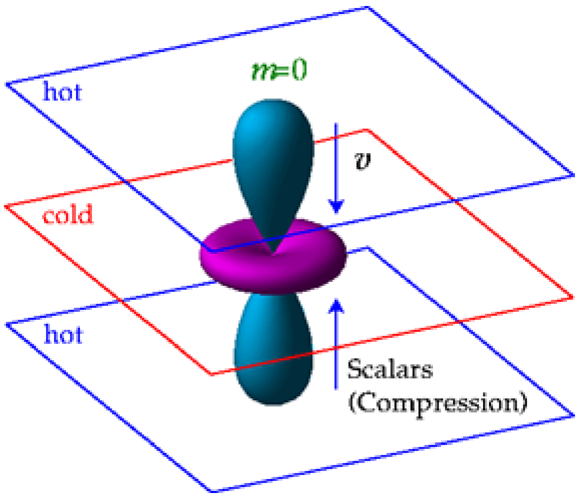


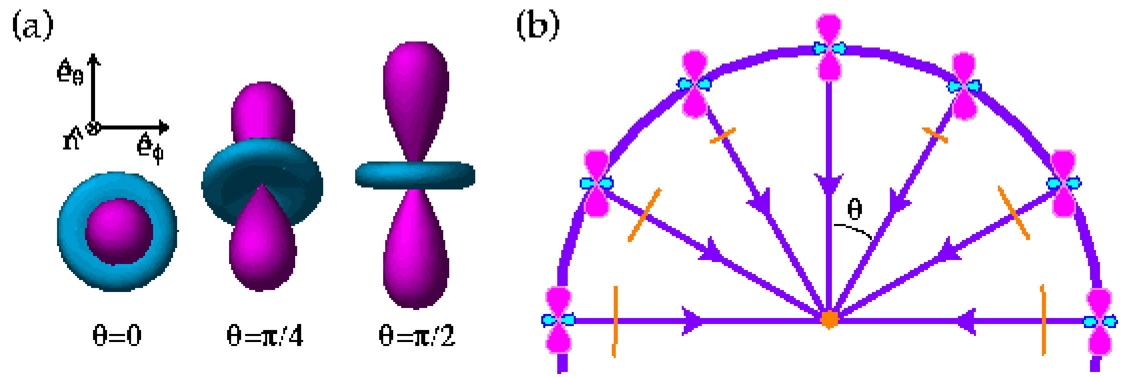
Polarization of the CMB can hopefully resolve some of these questions…

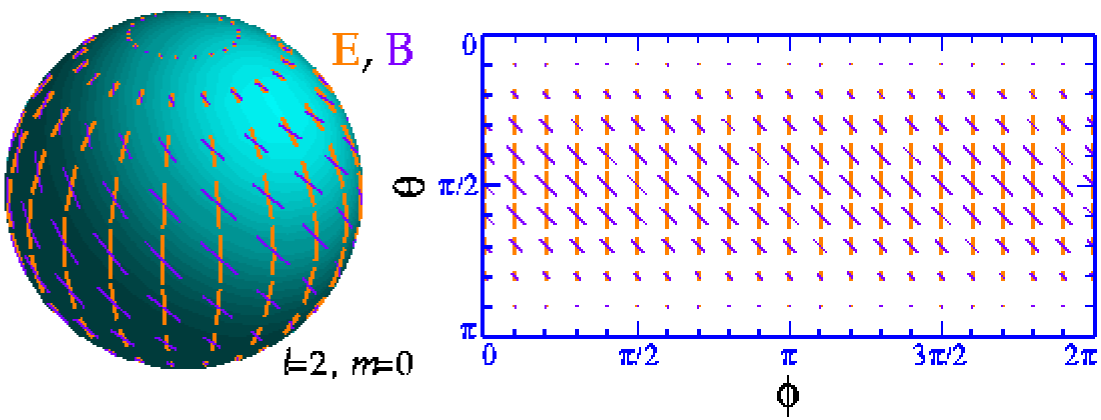




The most commonly considered and familiar types of perturbations are scalar modes. These modes represent perturbations in the (energy) density of the cosmological fluid at last scattering and are the only fluctuations which can form structure though gravitational instability.

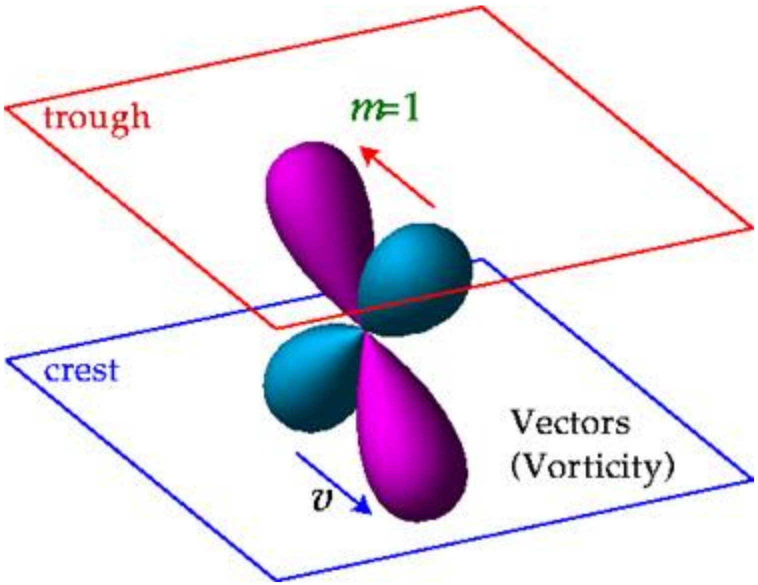


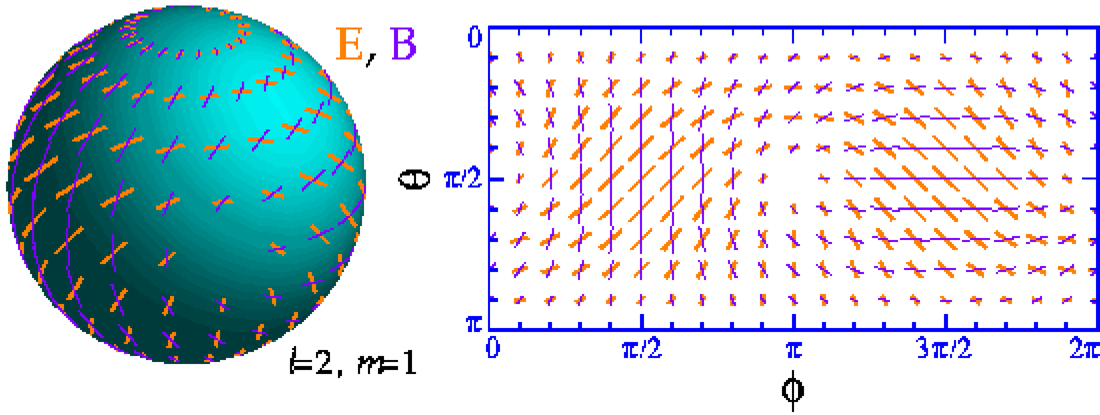




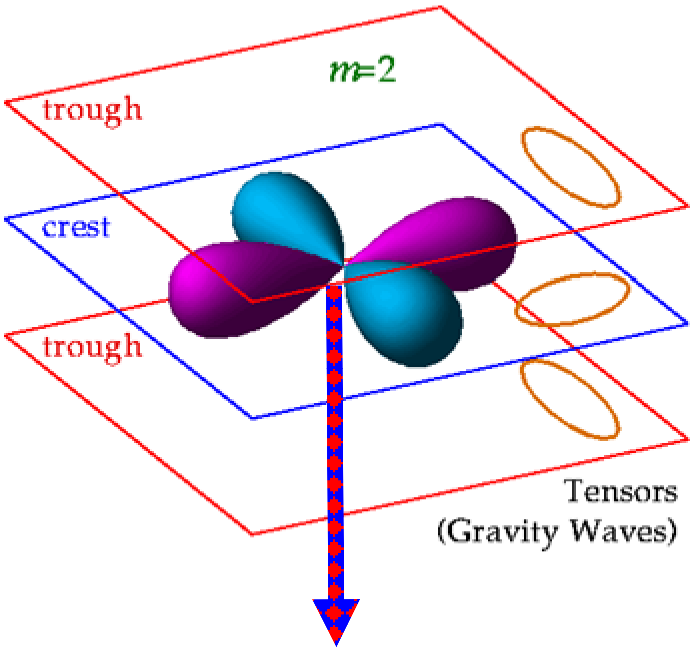
Wayne Hu, http://background.uchicago.edu/.

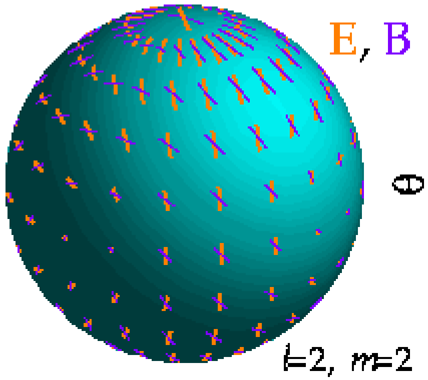
Vector perturbations represent vortex motions of the matter, similar to ``eddies" in water. There is no associated density variation, and these modes are not expected to be observable in the CMB.

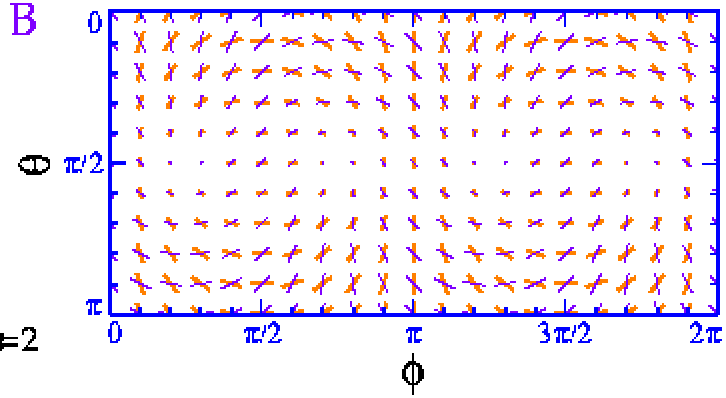




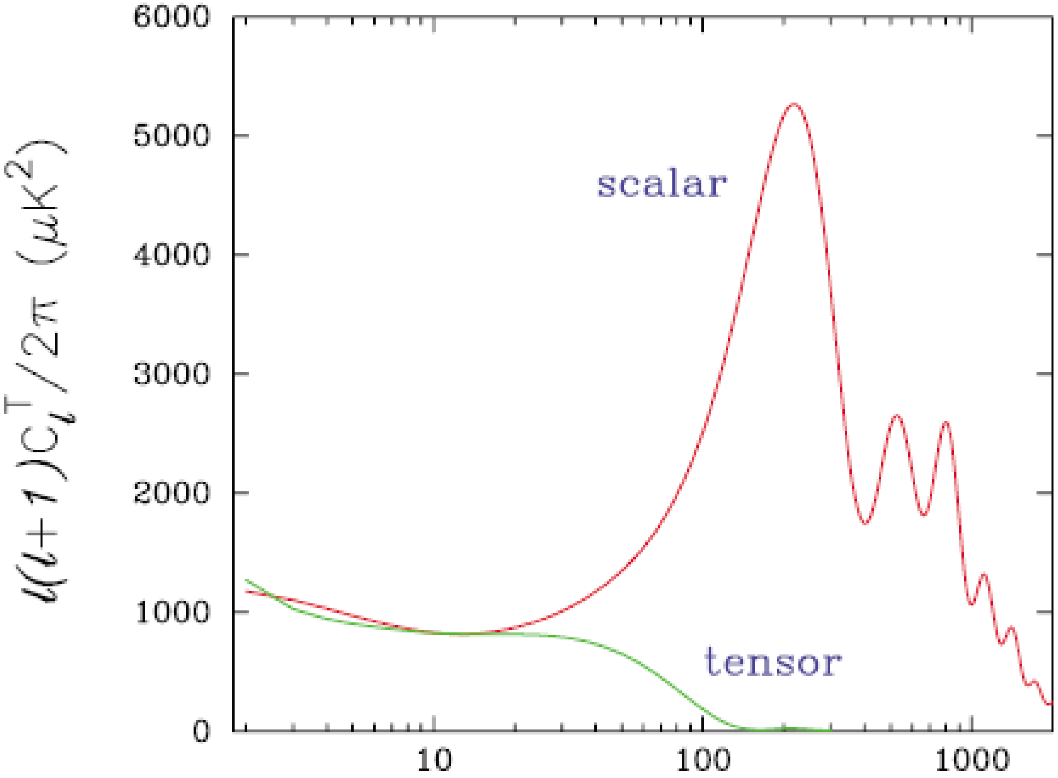
Tensor fluctuations in the CMB should come from gravitational waves in the early universe. If we can detect these polarization states In the CMB, then we can possibly probe the era of time BEFORE recombination!







Tensor fluctuations from possible gravity waves generated during the inflationary era are much more difficult to detect, but Planck might be able to detect them. Gravity waves (spin 2) impart Curl or Vorticity (B mode) topological structure on the linear polarization of the CMB photons (spin 1)



$$P_S(k) \simeq \left(\frac{H^2}{16\pi^3\dot{\phi}^2}\right)_{(k=aH)} \quad \text{(scalar perturbations)},$$

$$P_T(k) \simeq \left(\frac{H^2}{4\pi^2 m_{Pl}^2}\right)_{(k=aH)} \quad \text{(tensor perturbations)},$$

Cosmological Parameter Estimates WMAP-4 yr vs Planck 1 yr

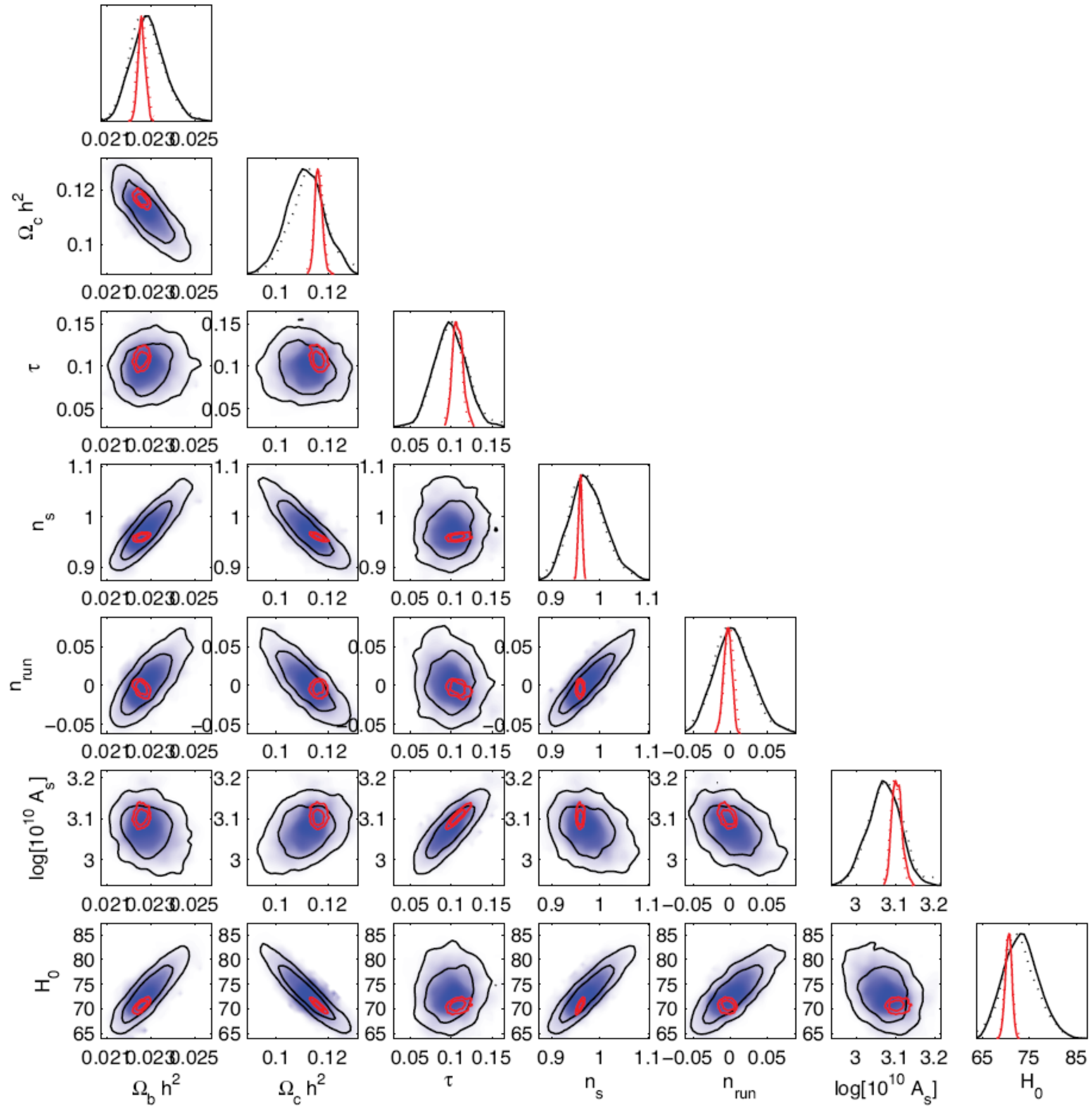
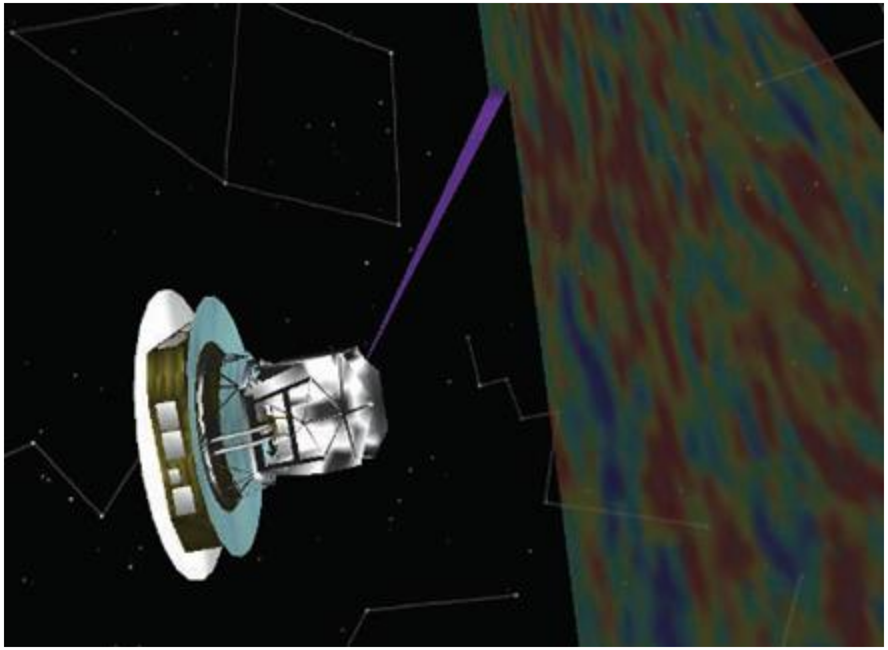


FIG 2.18.—Forecasts of 1 and 2σ contour regions for various cosmological parameters when the spectral index is allowed to run. Blue contours show forecasts for *WMAP* after 4 years of observation and red contours show results for *Planck* after 1 year of observations. The curves show marginalized posterior distributions for each parameter.

Planck THz Outreach – J van der Veen lead – UCSB Collaboration with CNSI – Allosphere group amomg others



Where are we 3-23-2010

- One full sky survey finished
- One full sky survey every 7 months
- Hopefully we will get 4+ more sky surveys
- Vote YES on Prop P – “leave the lights on”
- If only I could show you – how many beers would it take?
- Planck is even more sensitive than expected
- Planck ~ 20 x more sensitive than WMAP
- 1 Year Planck =~ 400 years WMAP (even more as beam size is smaller on Planck) – 2.5 year mission ~ 1000 WMAP years!
- Planck ~ 200 x more sensitive than we had on COBE
- 1 Year Planck =~ 40,000 years of COBE
- Planck is ~ Photon statistics limited – can’t do better per detector

What is coming

- How low do we need to go?
- If we are ~ random phase then cosmic variance limited …
- BUT the sky is much more complex
- What about foregrounds, non Gaussian structures
- Lensing
- 2,4,6,8 how many peaks do you appreciate?
- Is n_s different from 1? Planck will give <1% error
- Scientific papers will appear in 2011
- Data will be released in 2012
- BUT 2012 may never come – Mayans knew it all along