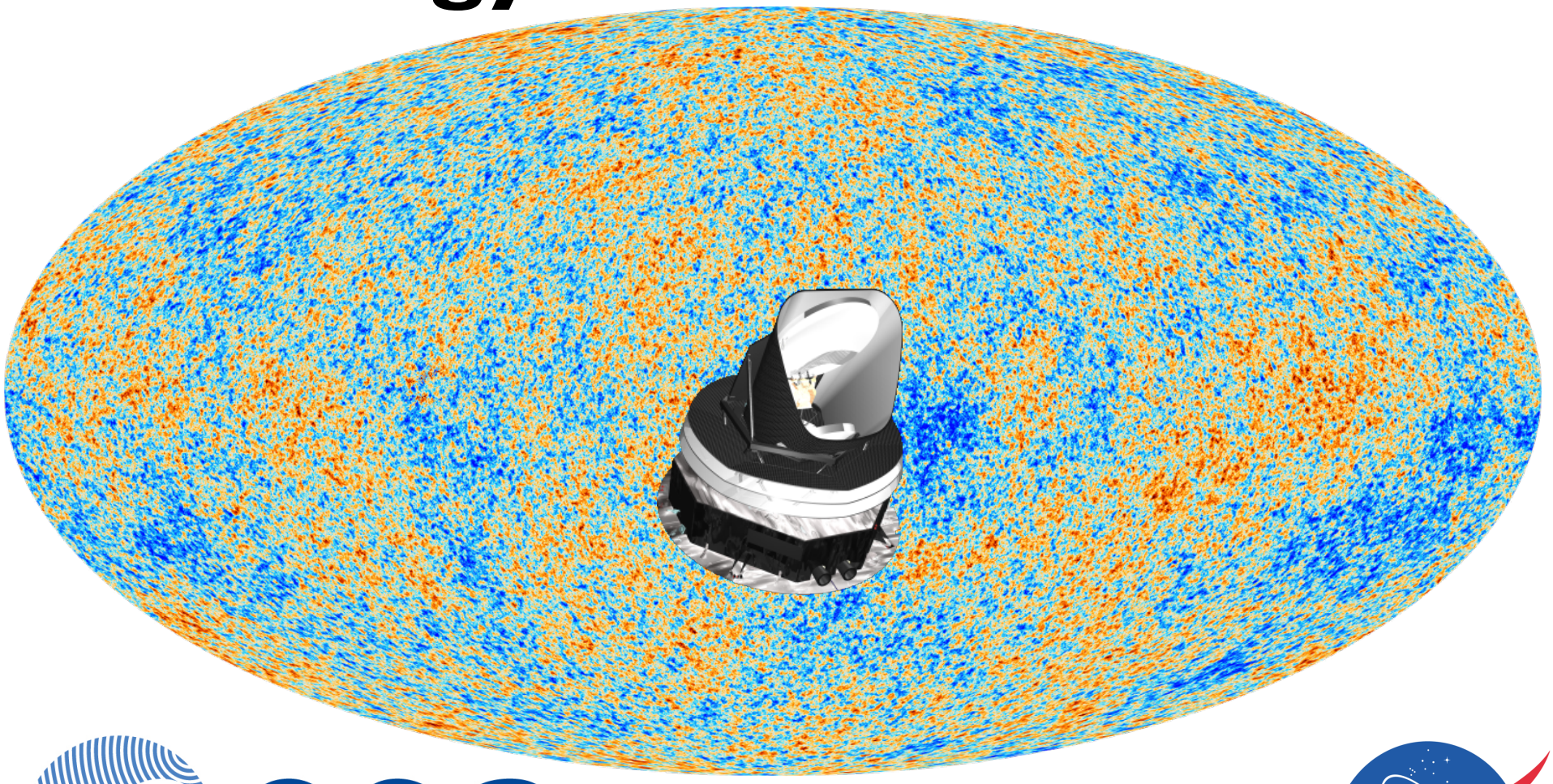
The Universe's Baby Picture: Cosmology Results from Planck

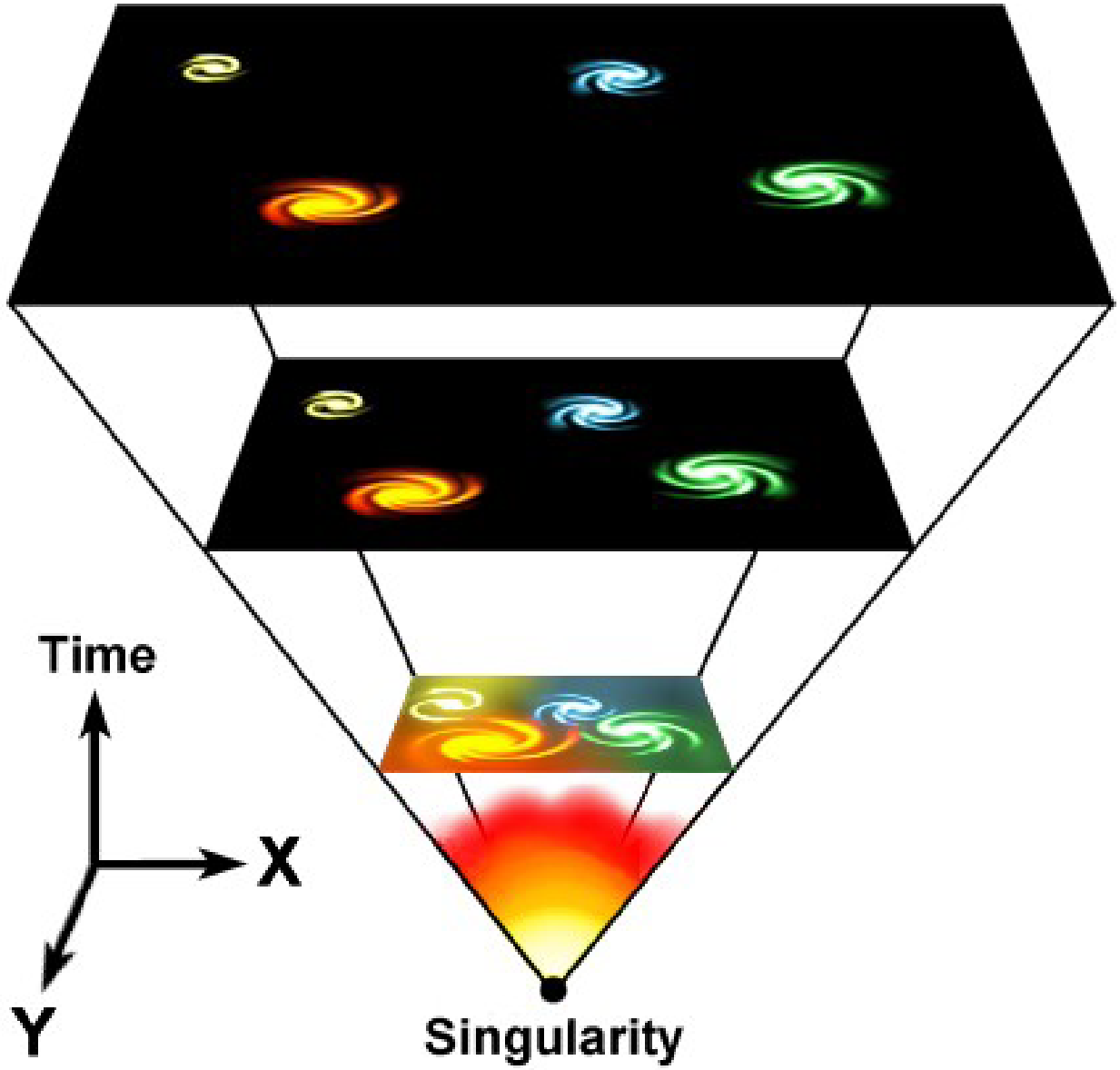


esa

NASA

Kevin Huffenberger, *University of Miami*

Expanding universe & the Big Bang

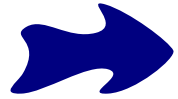


Hot, dense objects glow

Blackbody radiation - Planck Spectrum

Cosmic Microwave Background

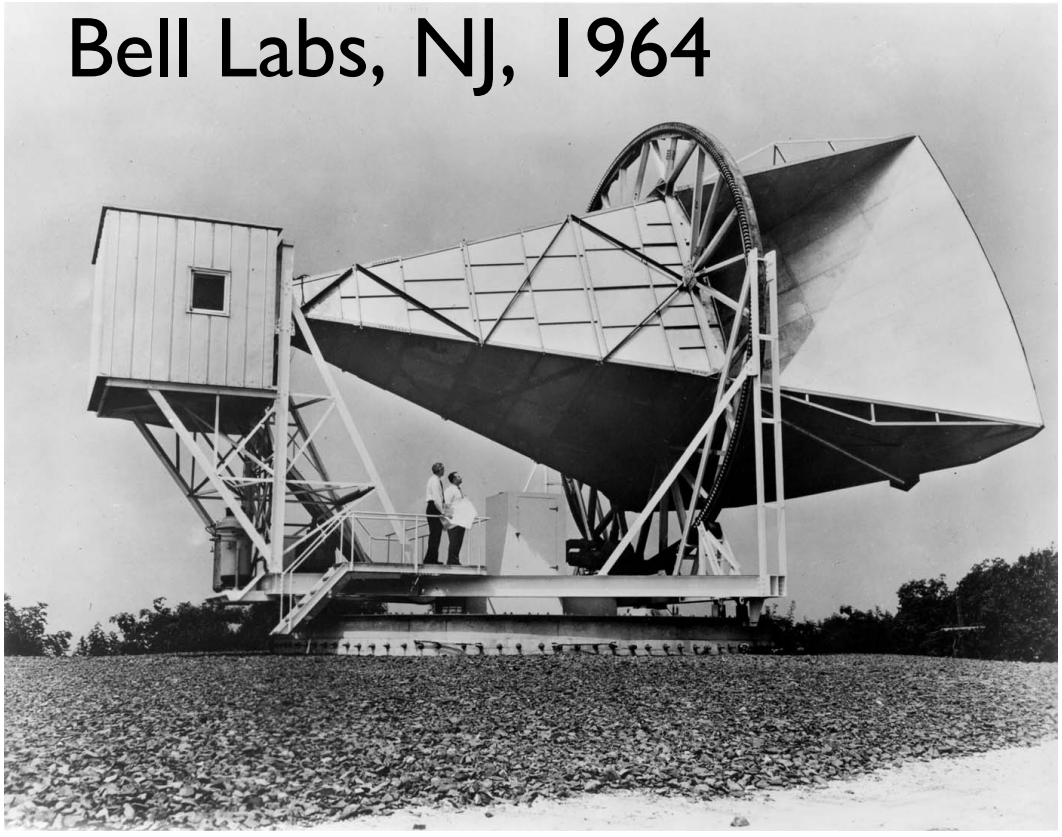
Hot, dense initial state

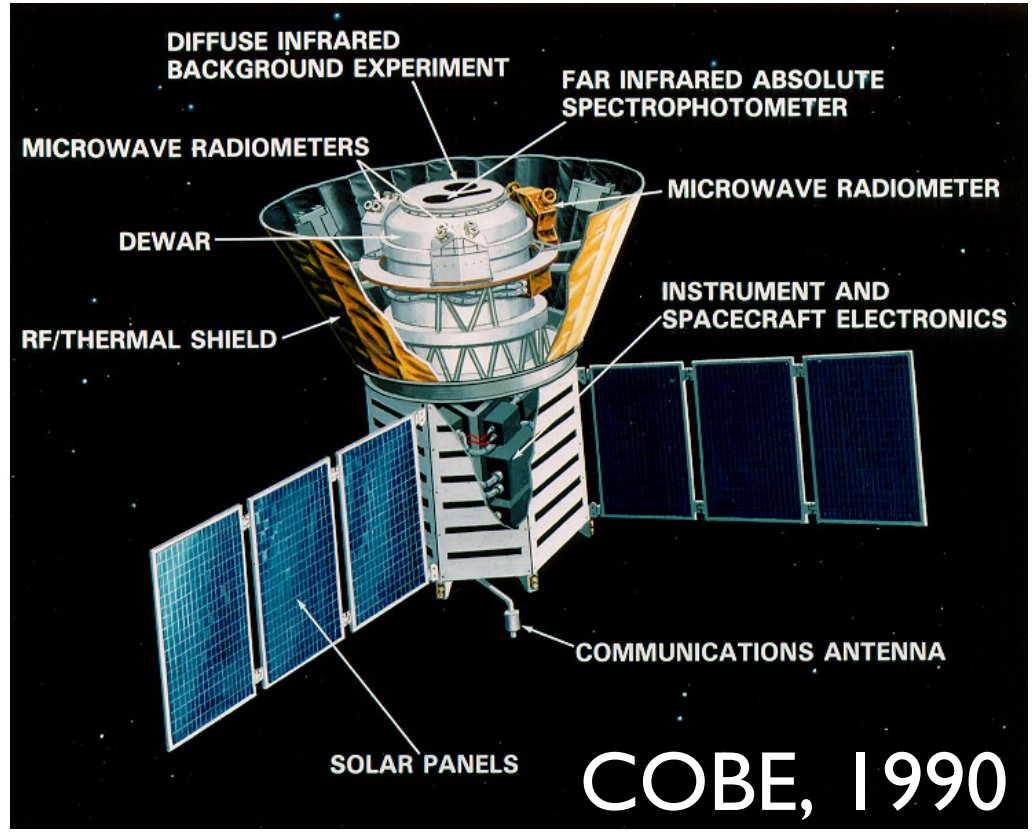


Relic Background Radiation

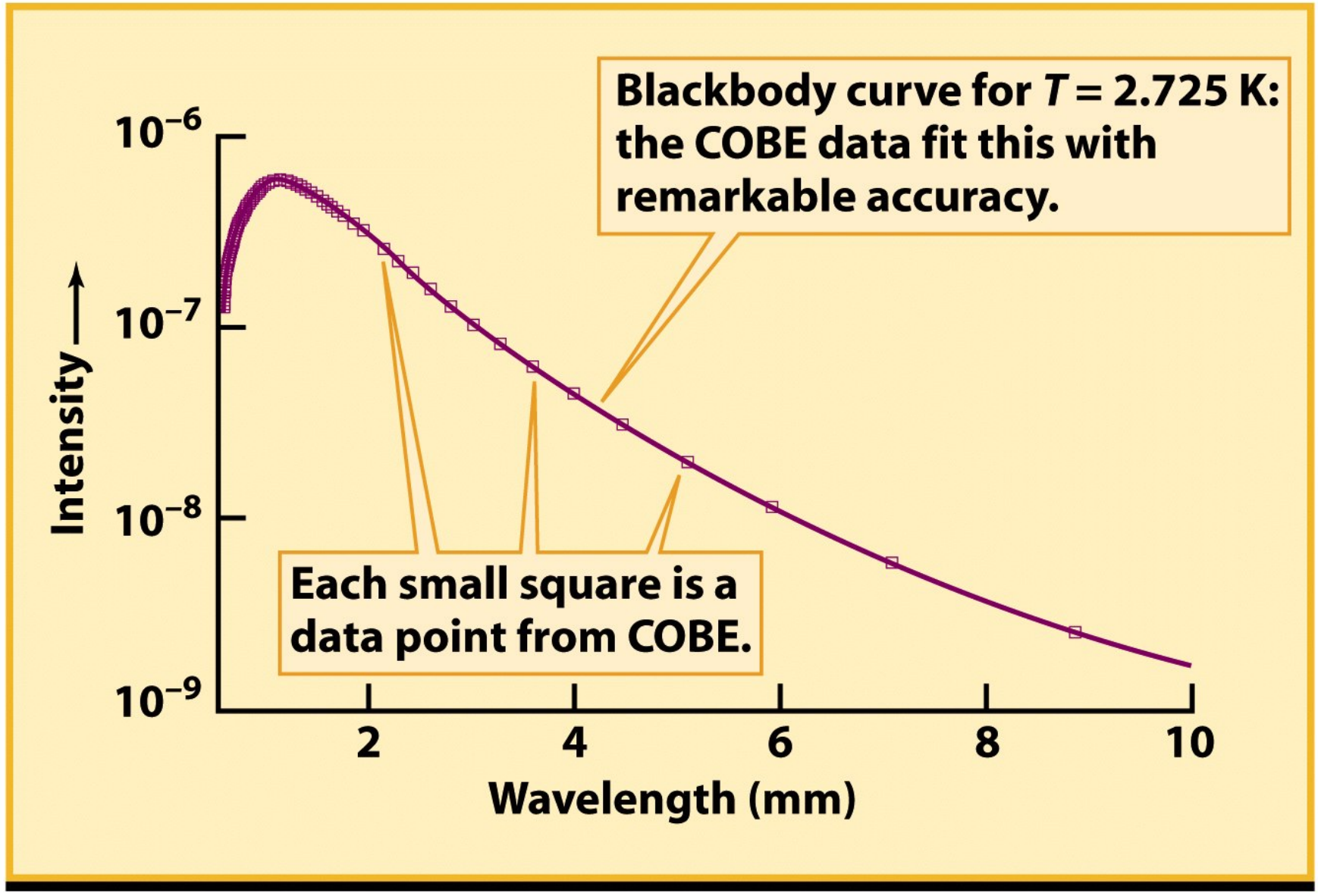
Redshifted to microwaves

Cold: ~3 K above abs. zero





Each resulted in a Nobel prize!



The spectrum of the cosmic microwave background

Figure 26-7b
Universe, Eighth Edition

Big Bang

0

Cosmic inflation
Origin of fluctuations

10^{-32} seconds

Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures

10^{-30} seconds
1 second
100 seconds
1 year
100 years

Recombination
Ordinary matter particles decouple from light and the Cosmic Microwaue Background is released

380 000 years

Dark ages
Ordinary matter particles fall into the structures created by dark matter

200 million years

First stars & galaxies

1 billion years

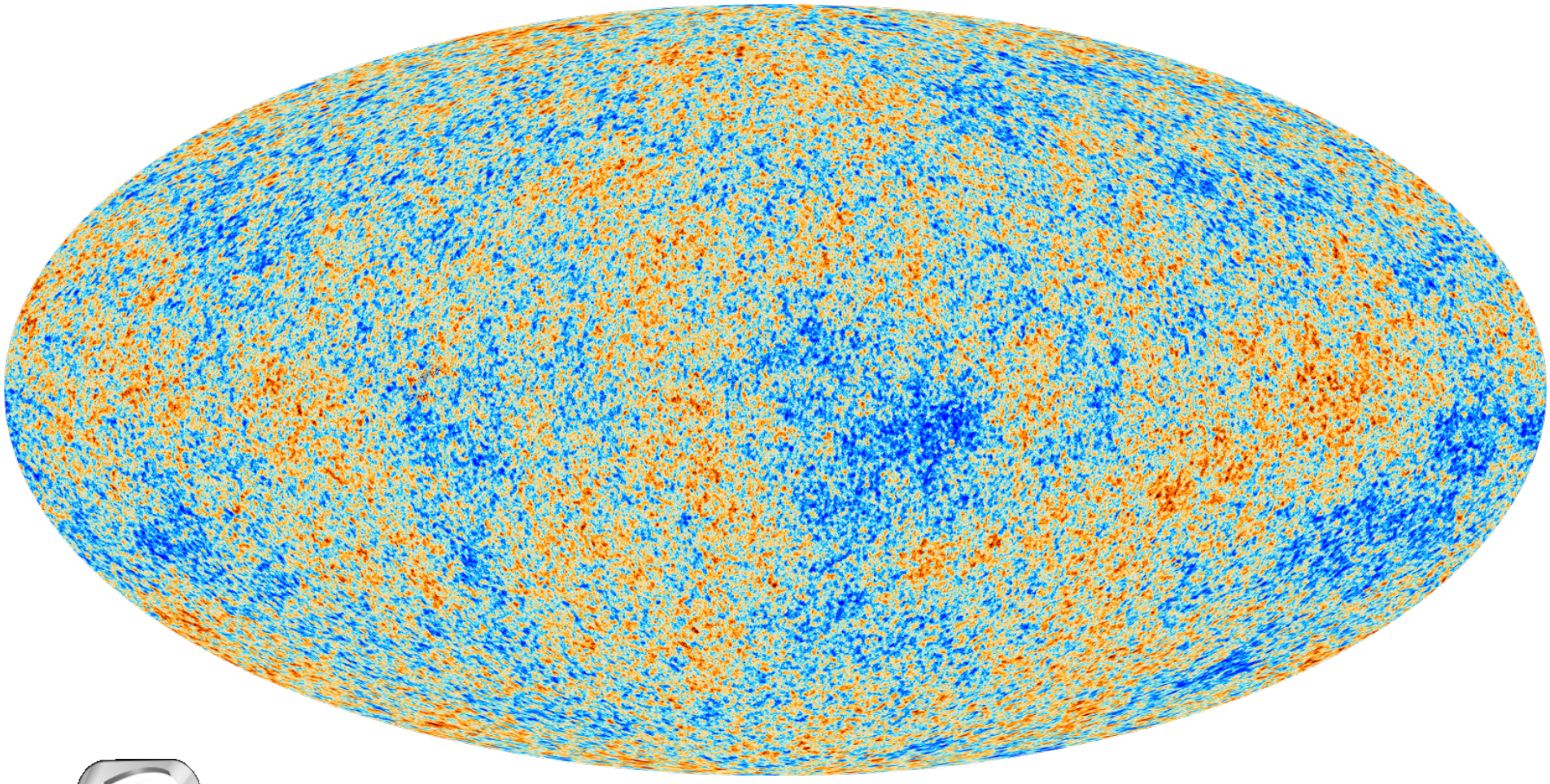
Galaxy euolution
Clusters of galaxies and superclusters form

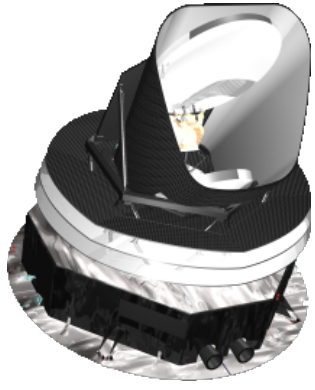
10 billion years

Today

13.82 billion years

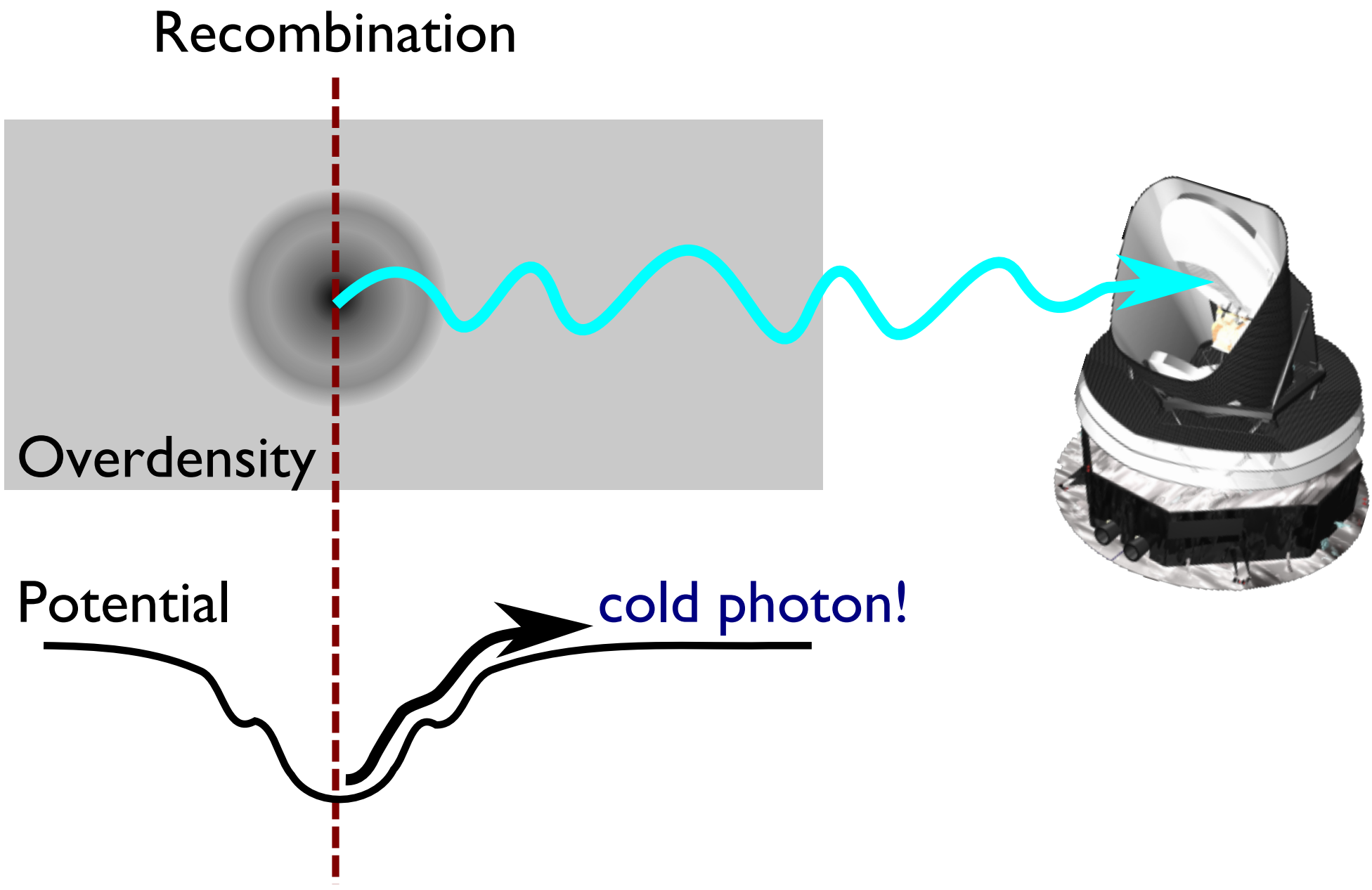
CMB fluctuations





~ few hundred μK around mean *T*

Probing gravitational potential

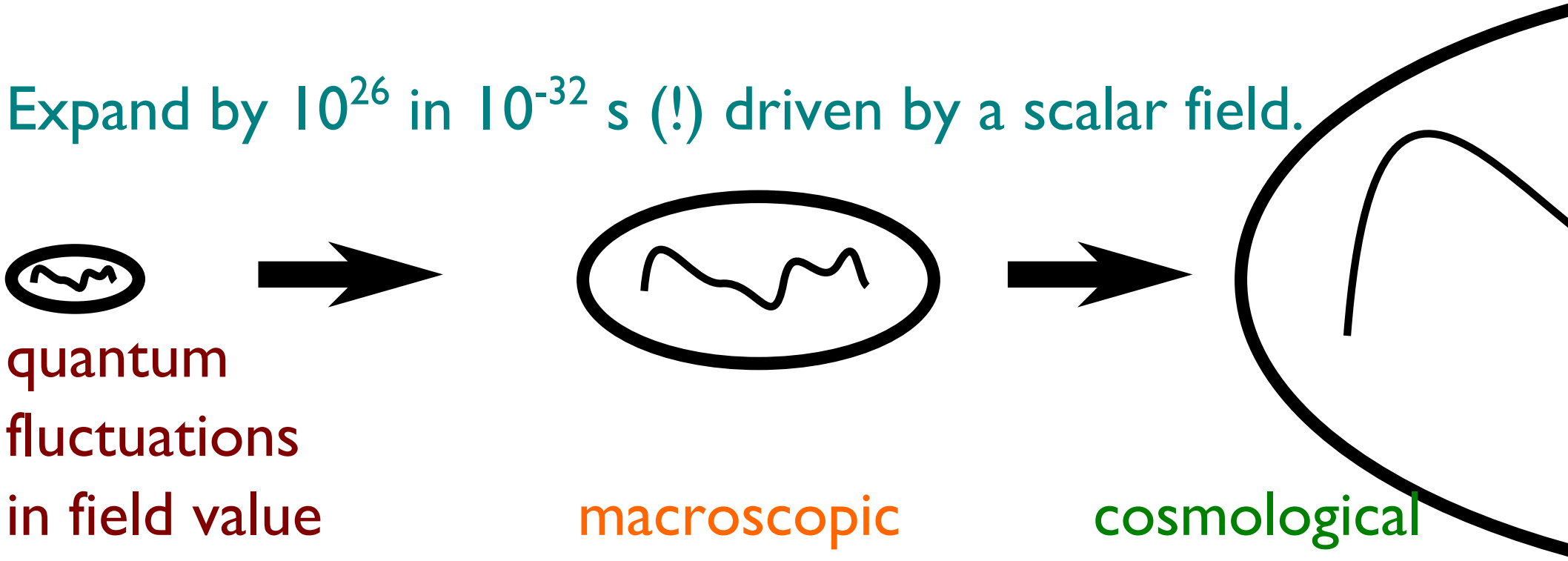


Inflation and initial fluctuations

If new physics at GUT/EW-scale causes exp(60)-fold expansion it explains:

- spatial flatness
- rarity of monopoles
- uniformity of CMB sky

Expand by 10^{26} in 10^{-32} s (!) driven by a scalar field.



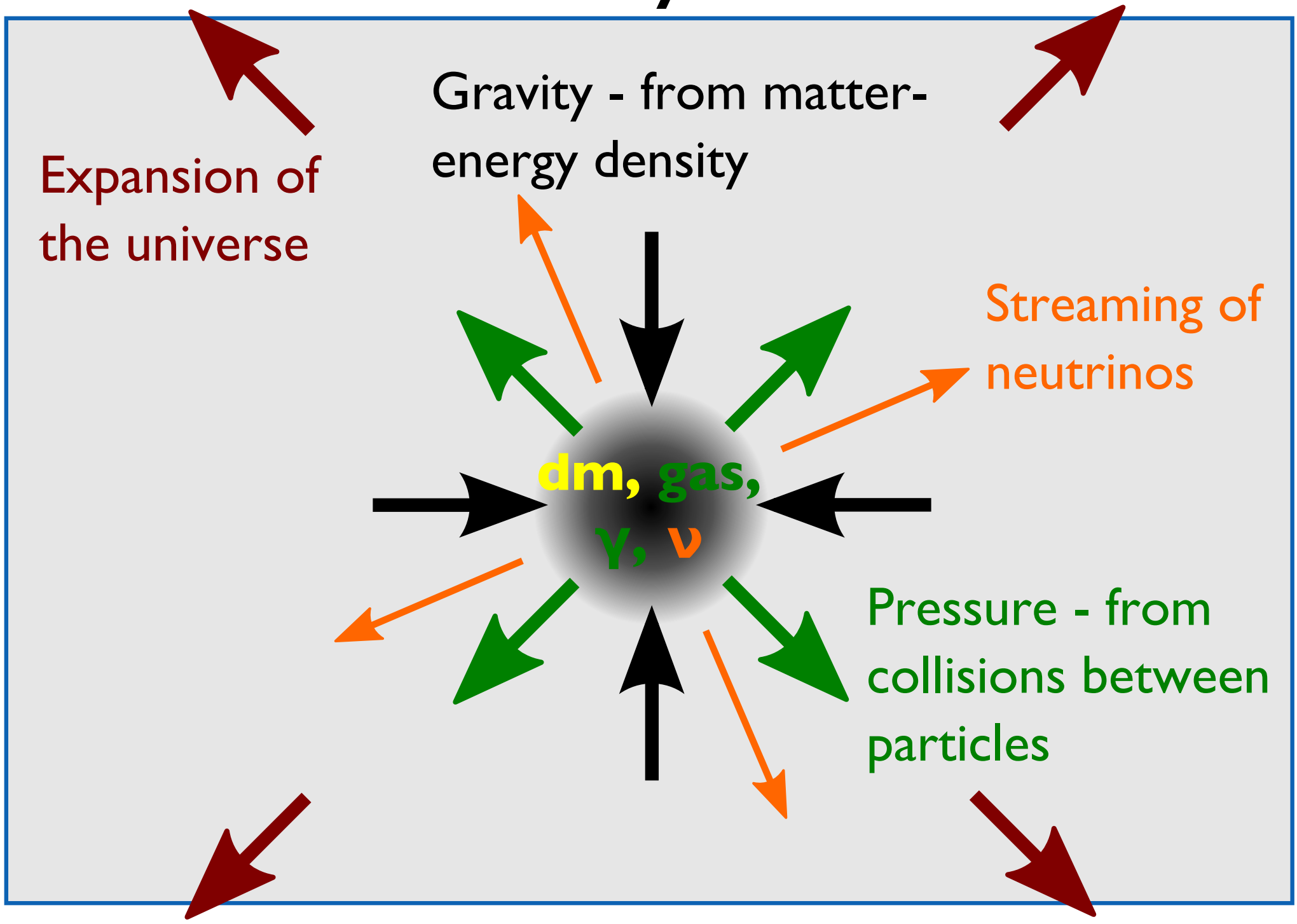
quantum fluctuations in field value

macroscopic

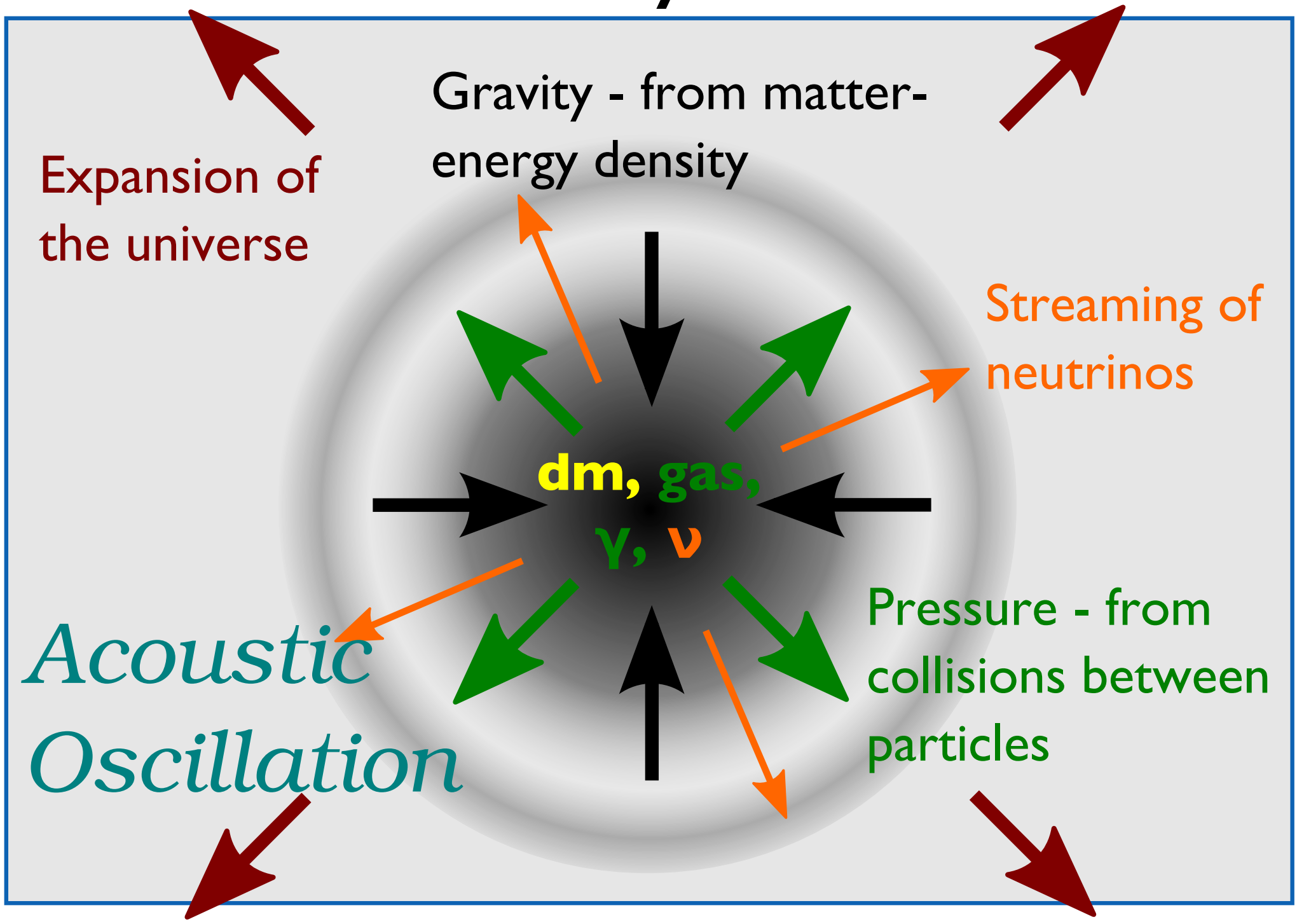
cosmological

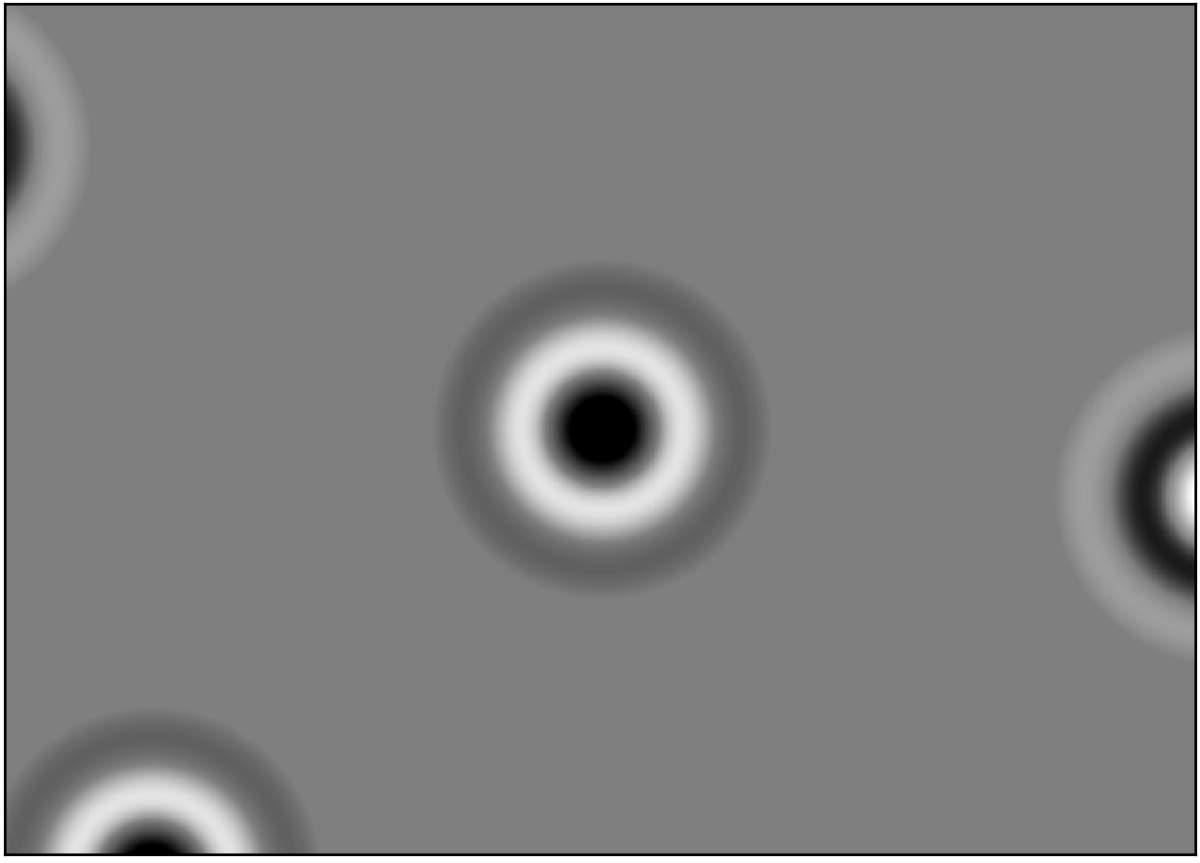
Nearly scale-free spectrum of initial fluctuations

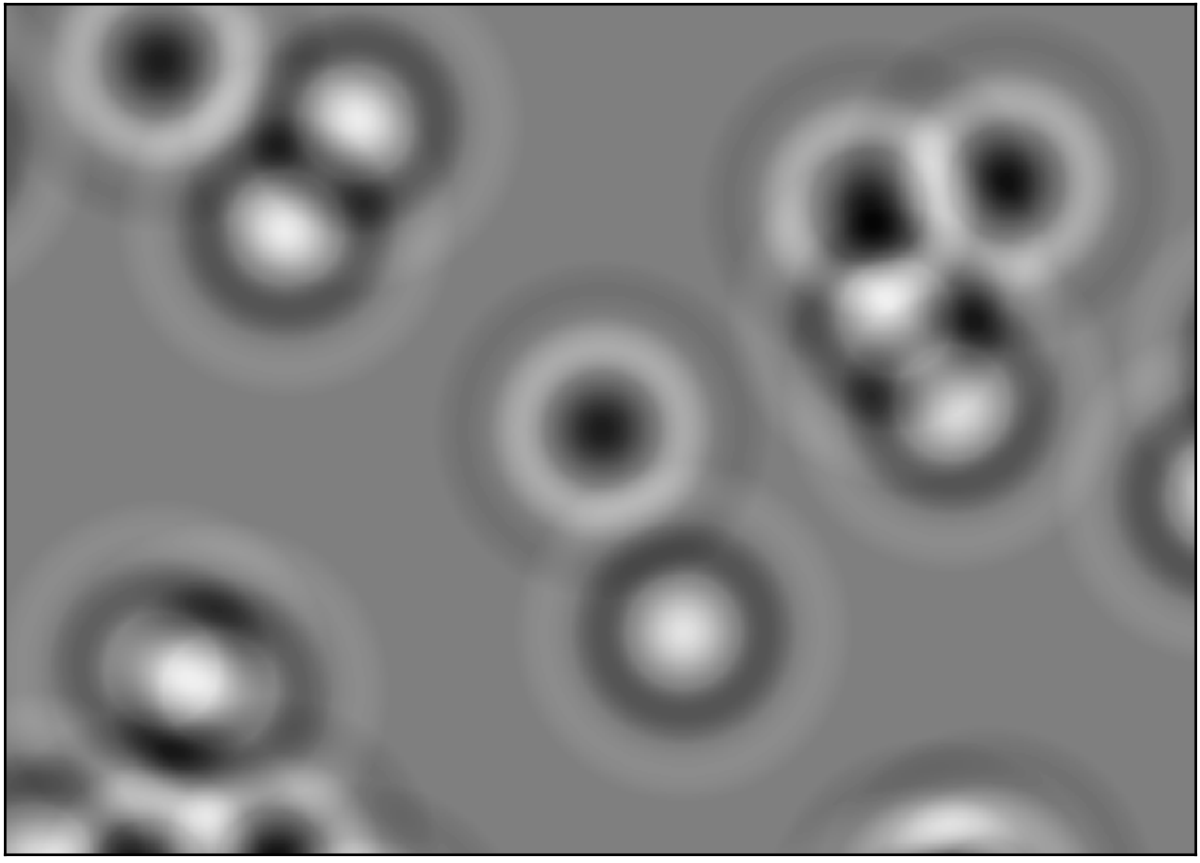
Evolution of overdensity

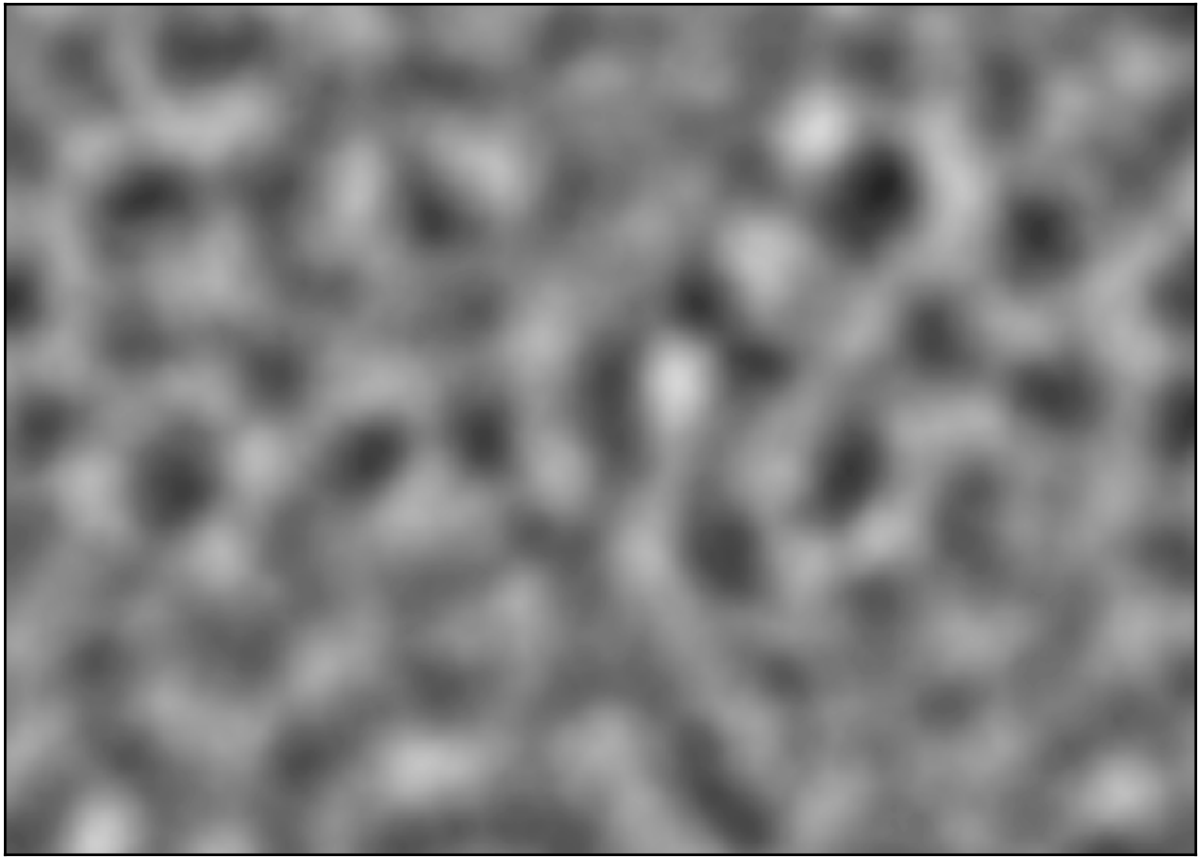


Evolution of overdensity

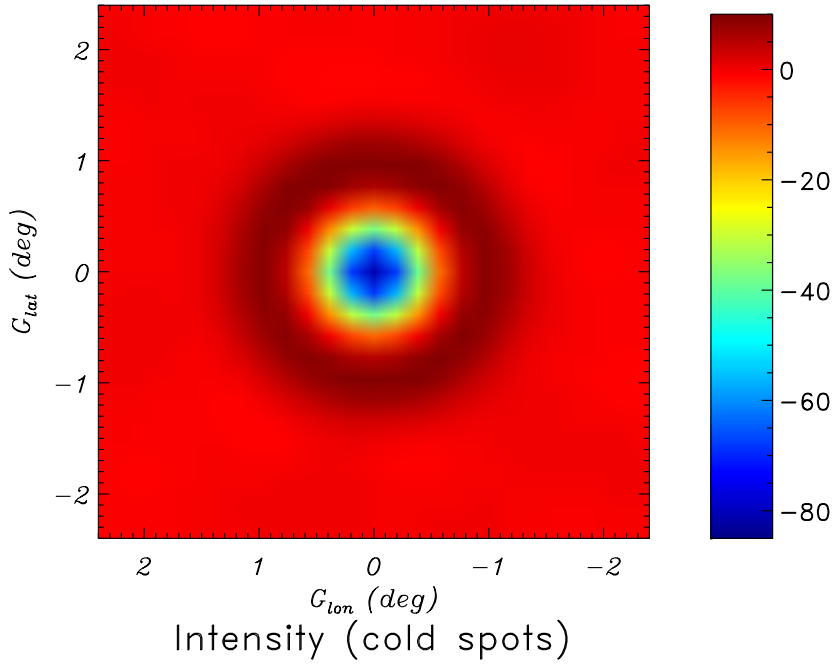




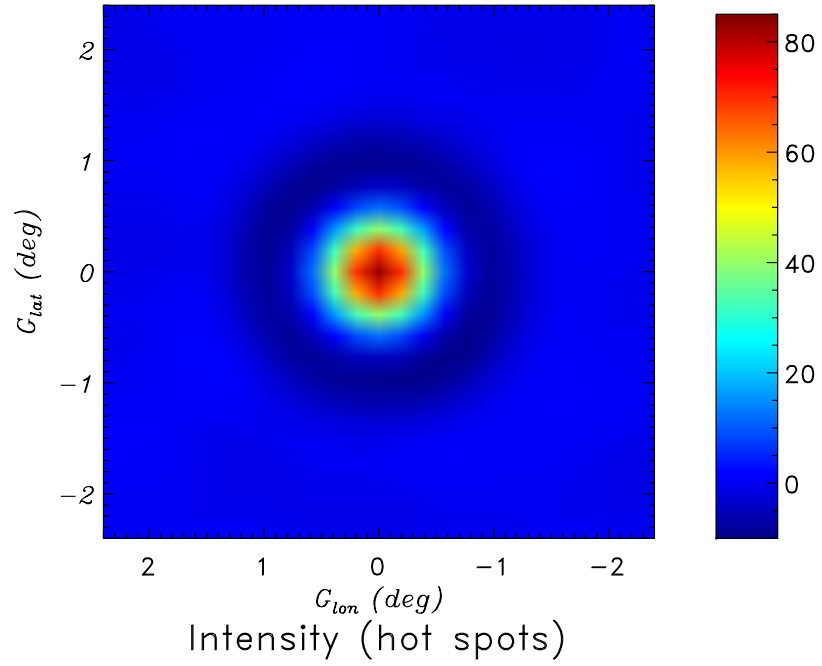




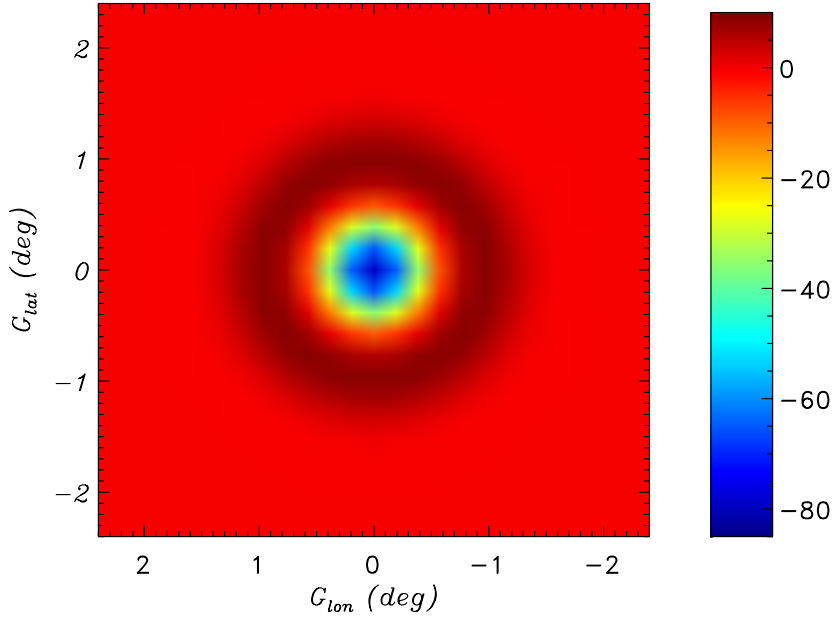
Average Planck map around extrema

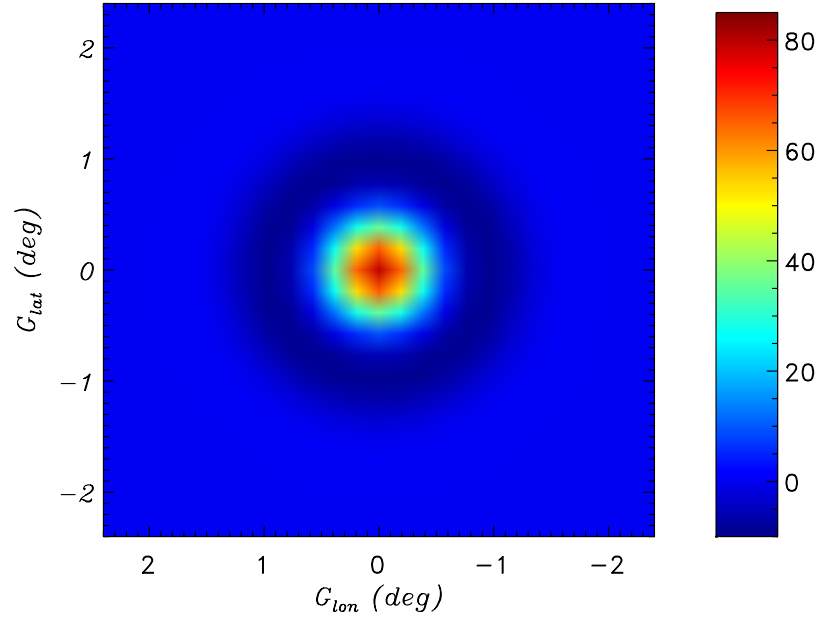


Intensity (cold spots)

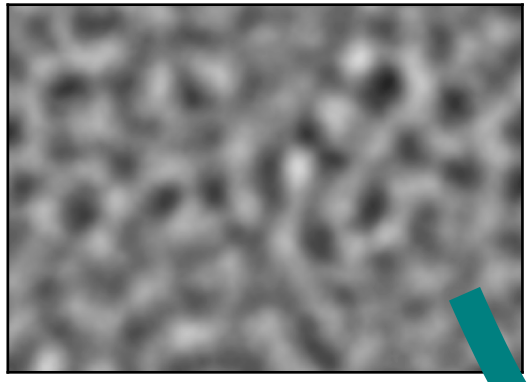


Intensity (hot spots)



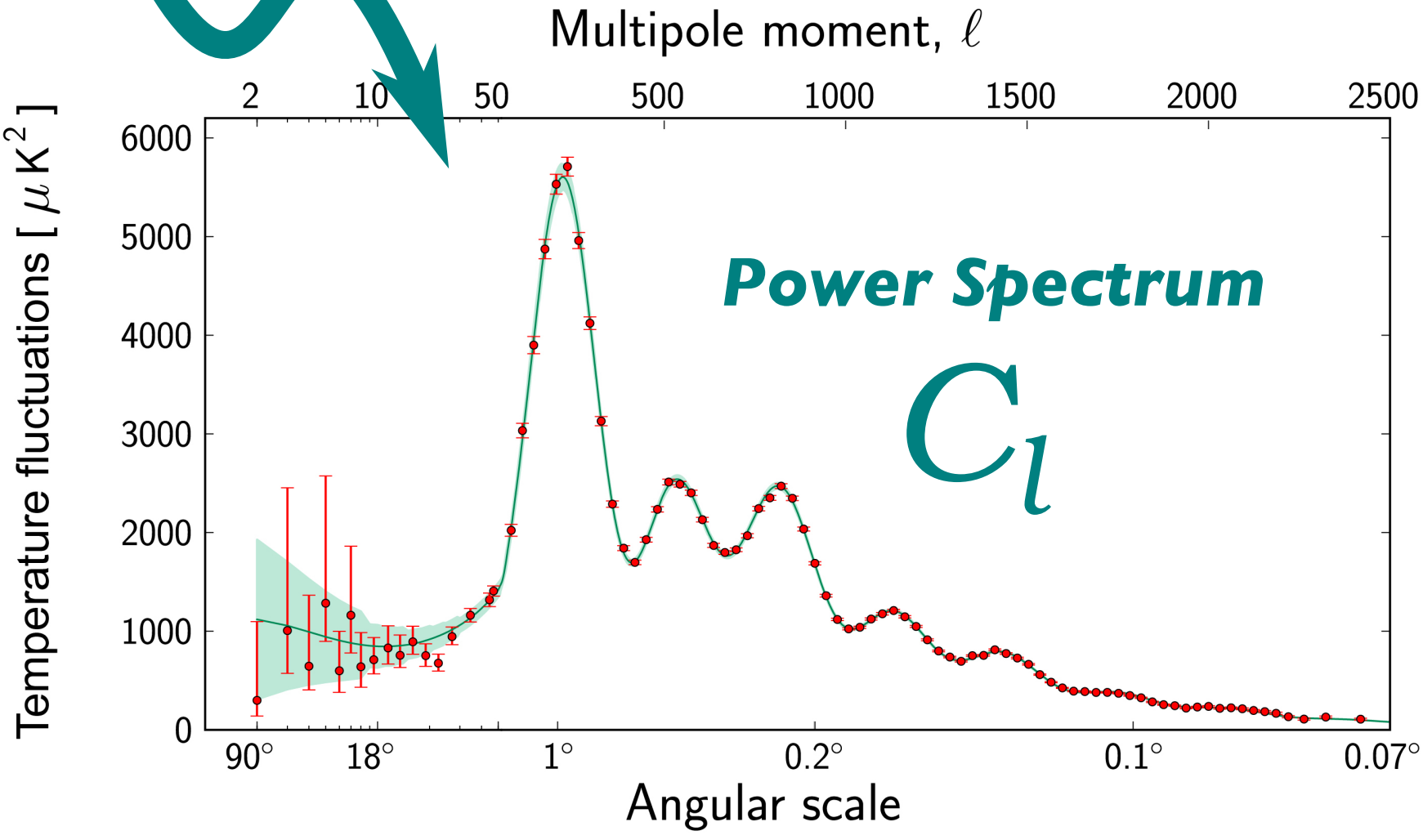


Correlations in harmonic space



$$a_{lm} = \int d\Omega\, T(\theta,\phi) Y^*_{lm}(\theta,\phi)$$

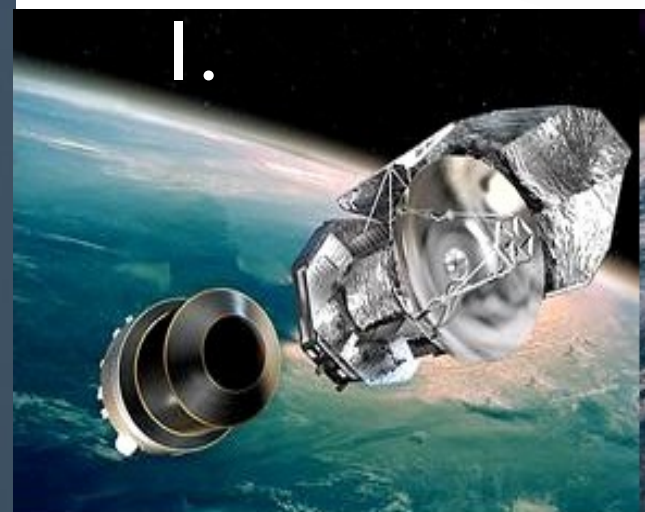
$$\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$



14 May 2009

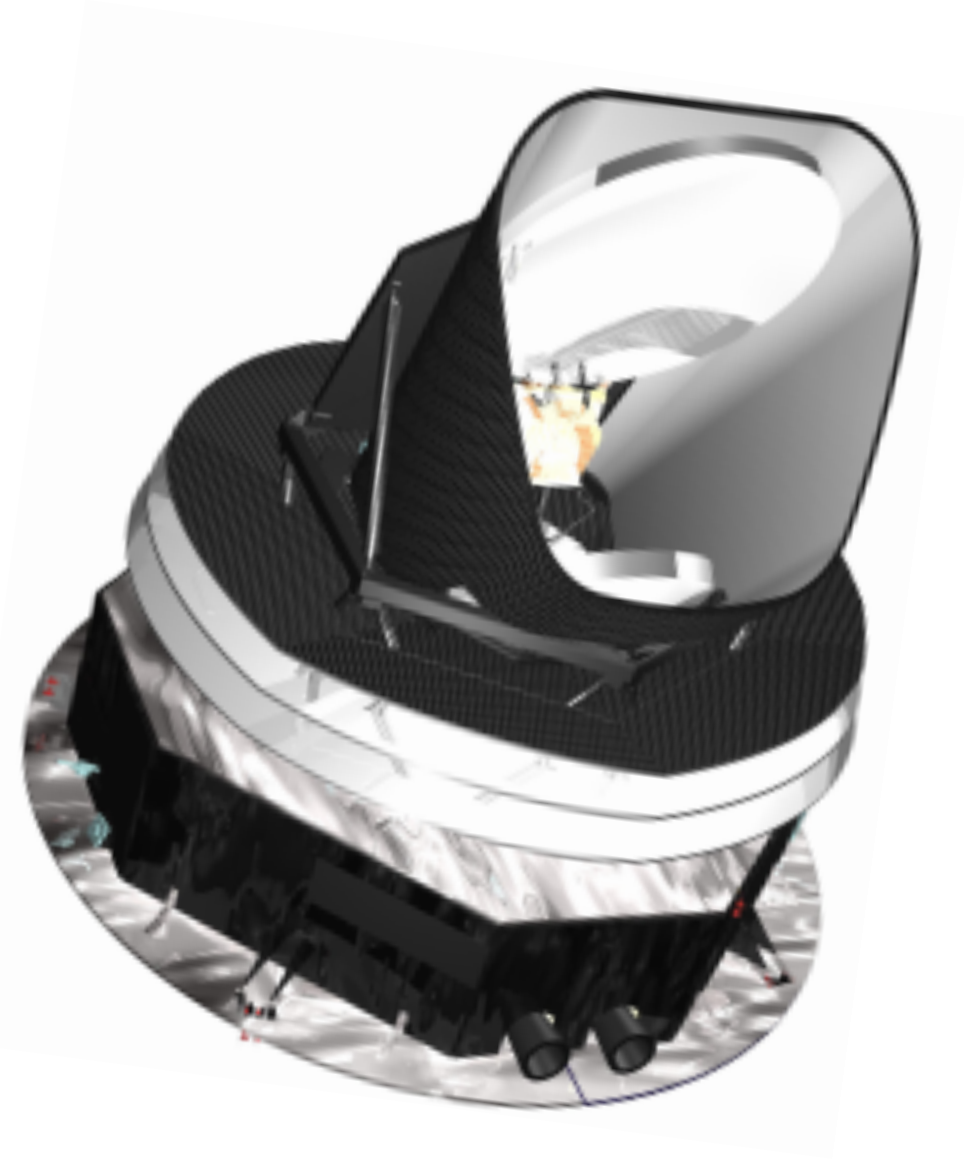
Herschel

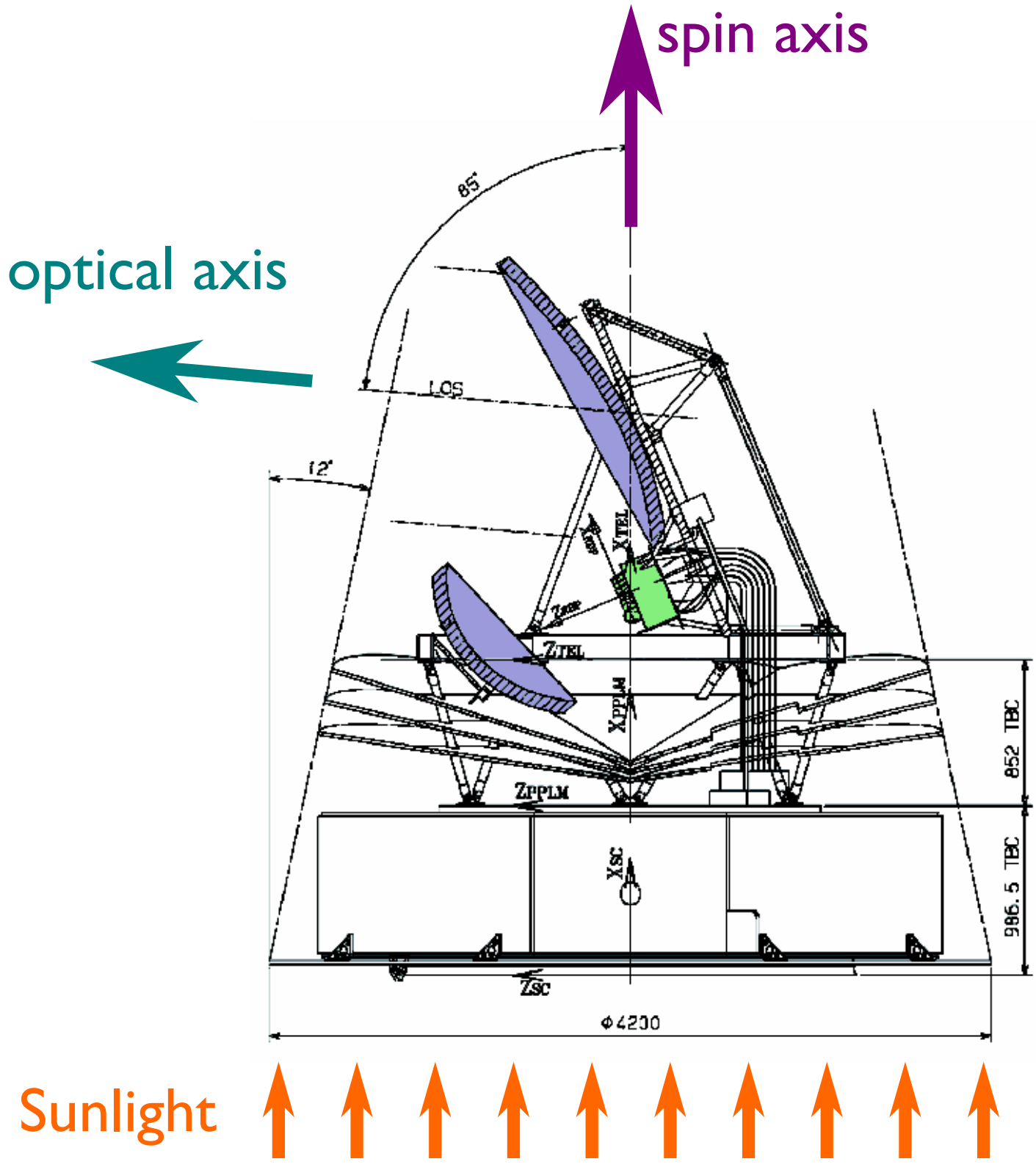
Planck

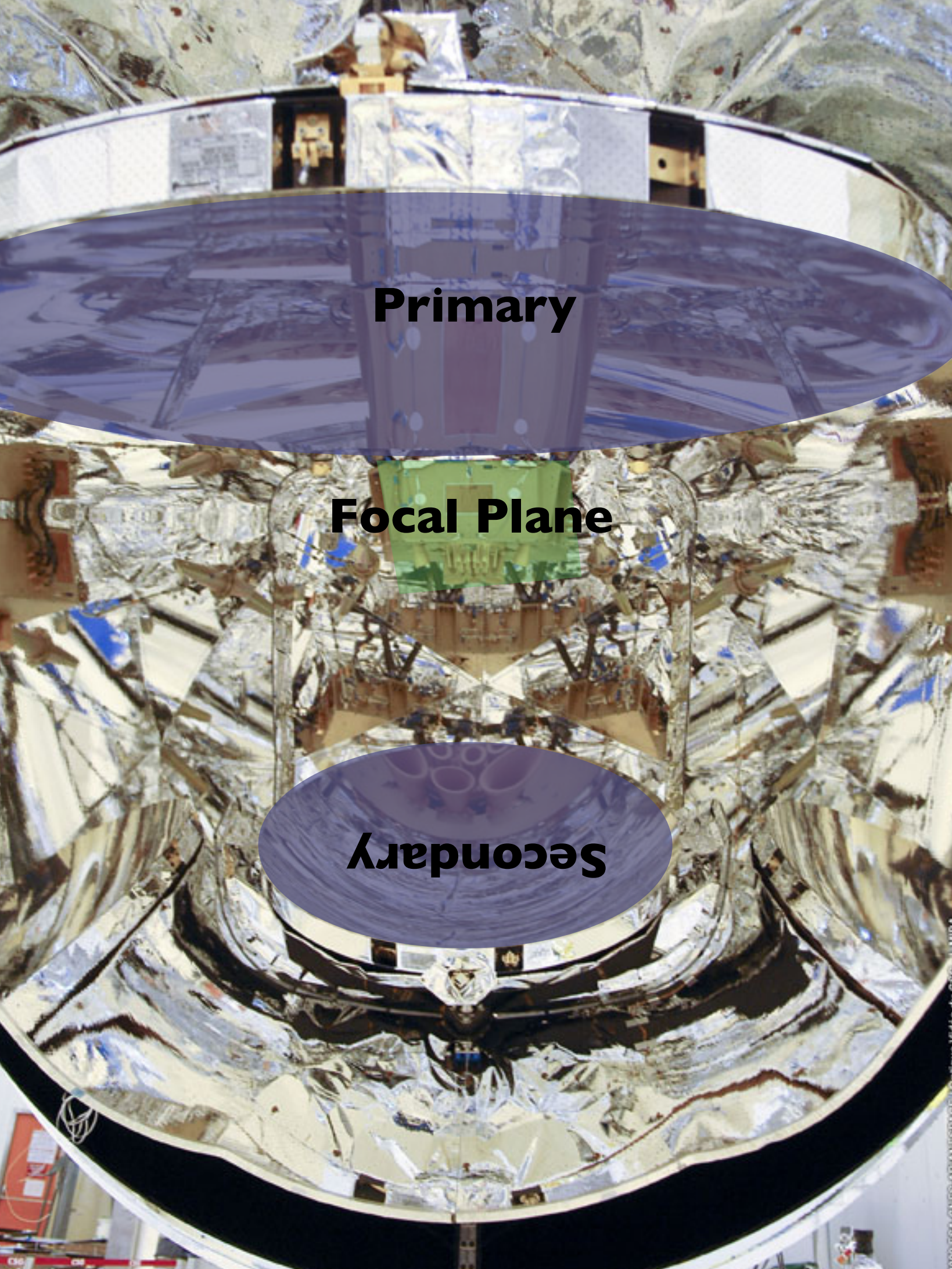


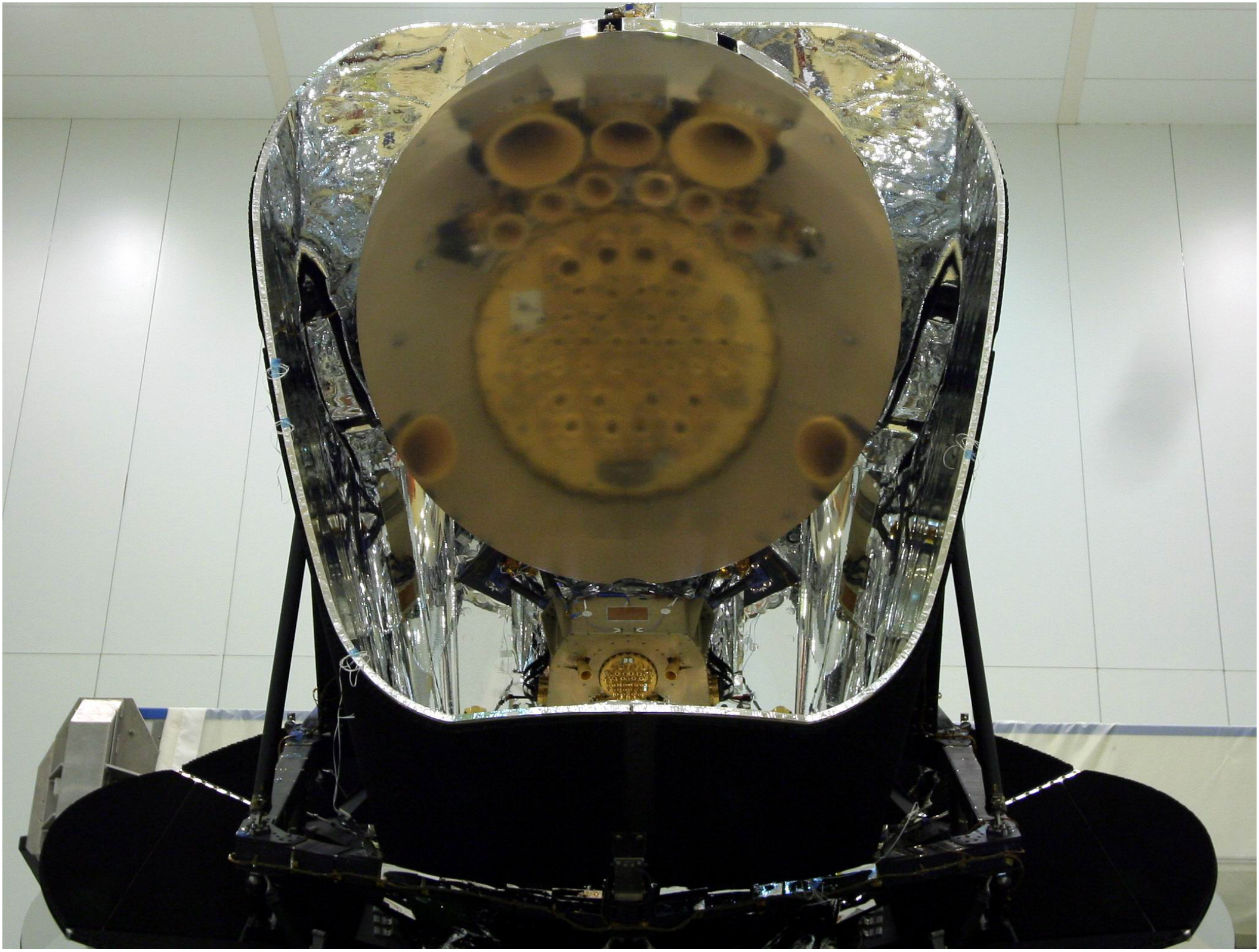
1.5 million km away at L2

(movies)

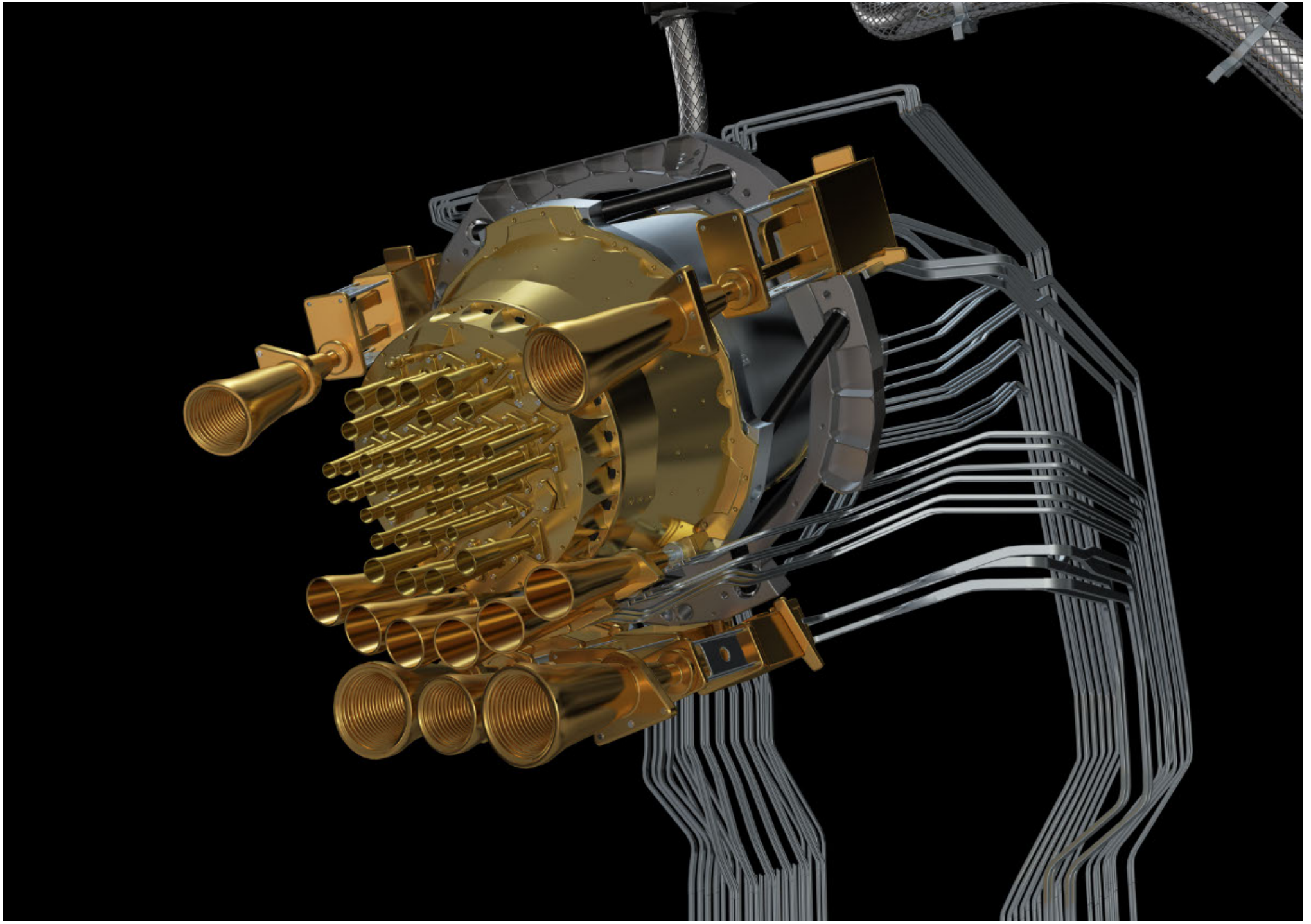



spin axis
optical axis
85°
LOS
12°
XTEL
ZTEL
XPPLM
ZPPLM
XSC
ZSC
852 TBC
986.5 TBC
Φ4230
Sunlight

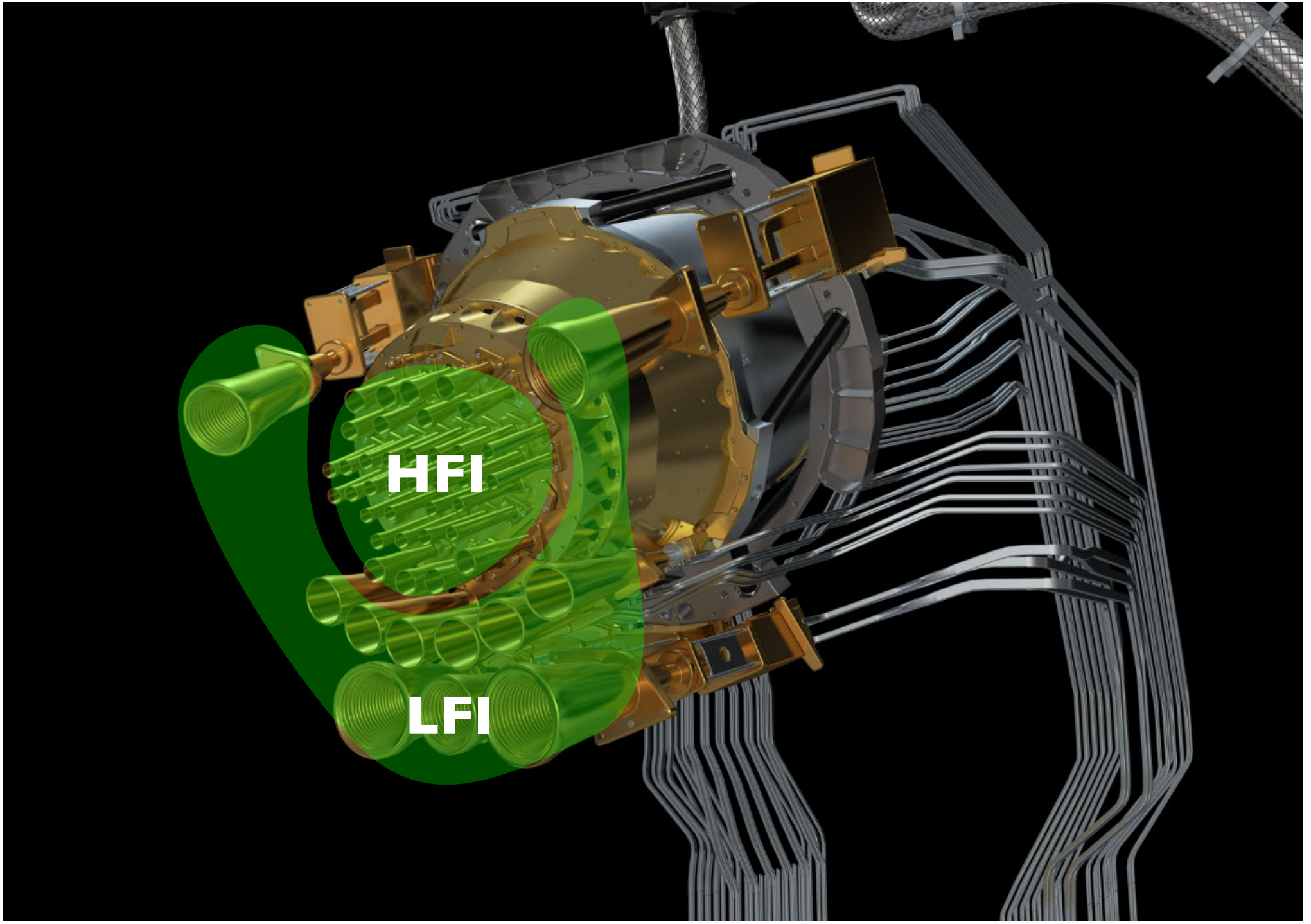

Primary
Focal Plane
Secondary



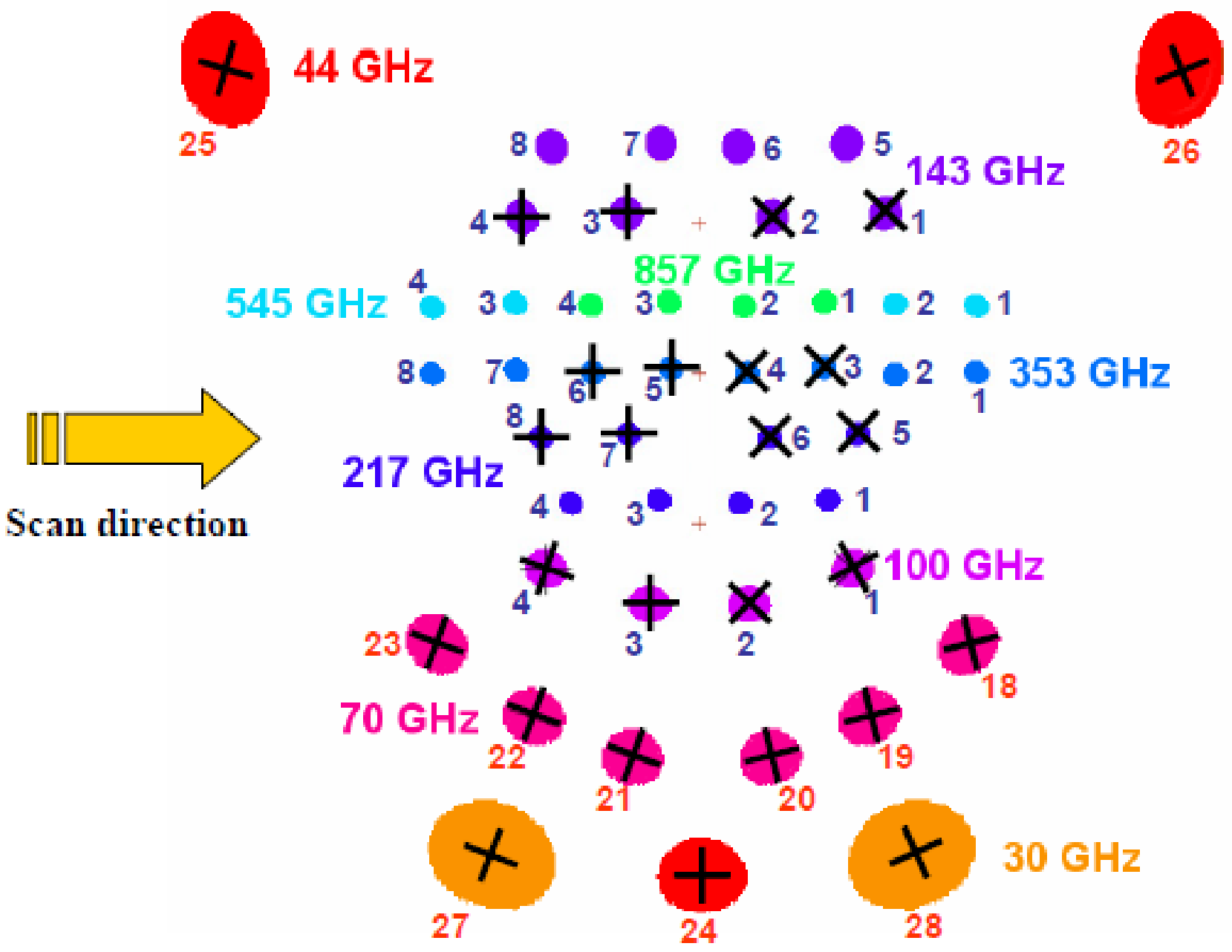
Focal plane



Focal plane



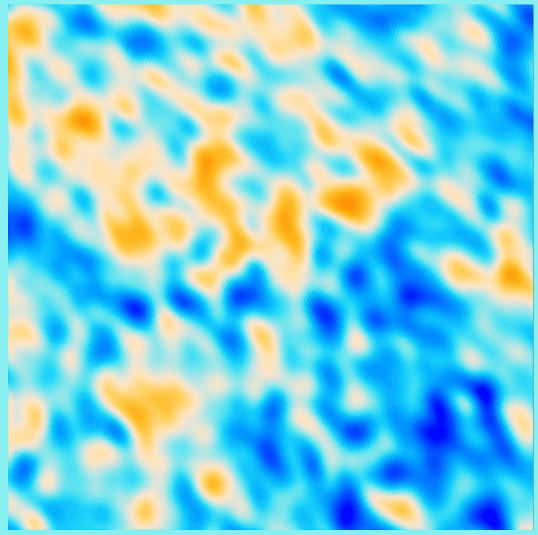
Planck focal plane

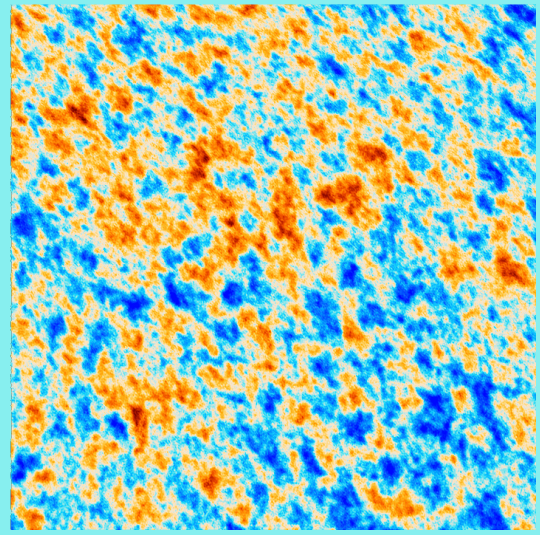


Capabilities

"3 times better resolution
&
10 times lower noise than WMAP"

WMAP





Planck

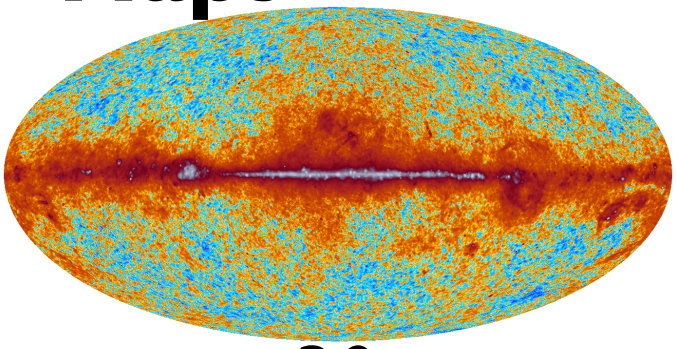
Planck: 9 channels

30 44 70 100 143 217 353 545(I) 857(I) GHz

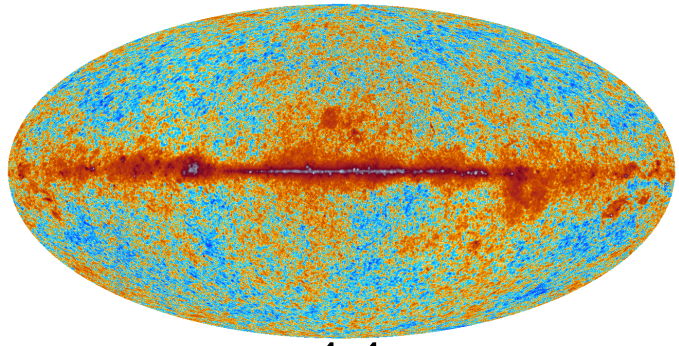
LFI HFI

(20-30% bandwidth)

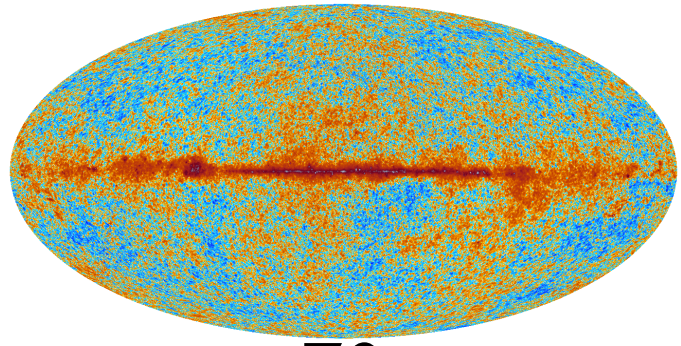
Maps



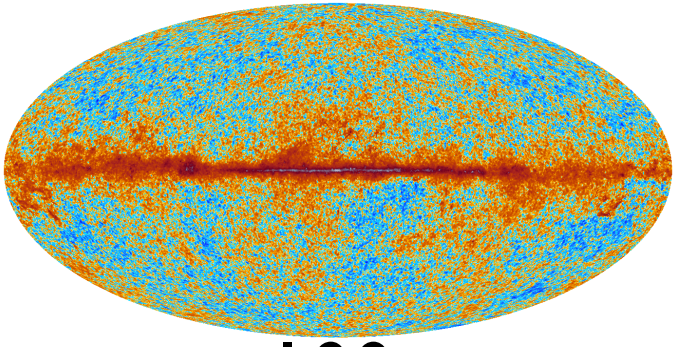
30



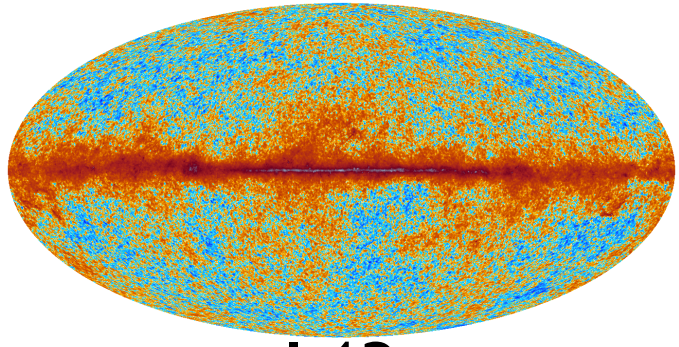
44



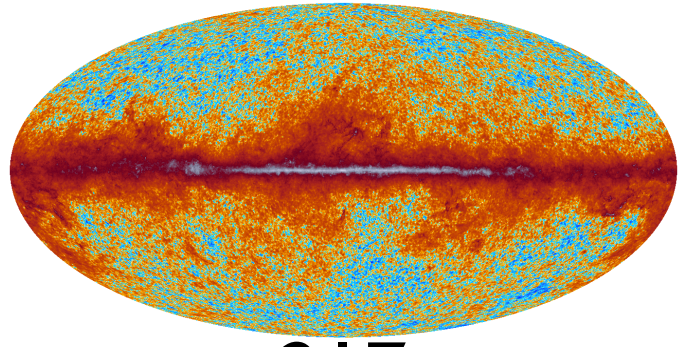
70



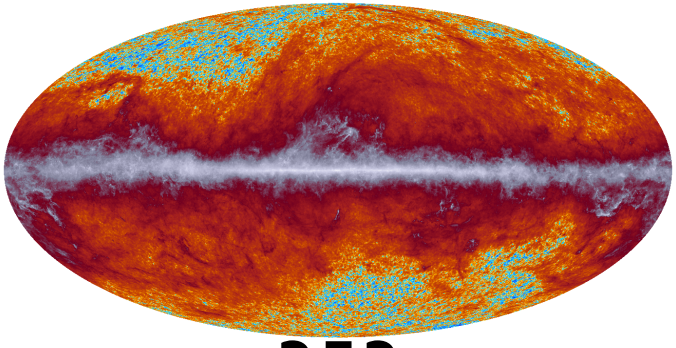
100



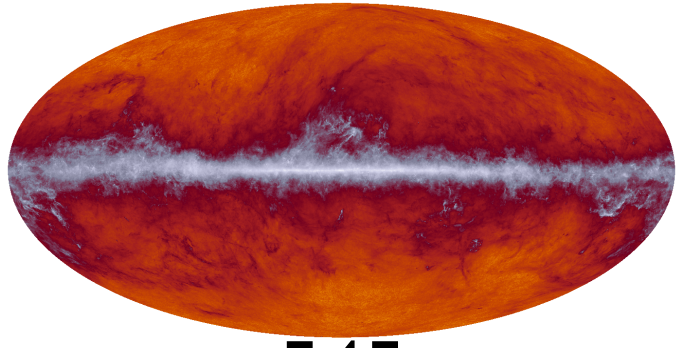
143



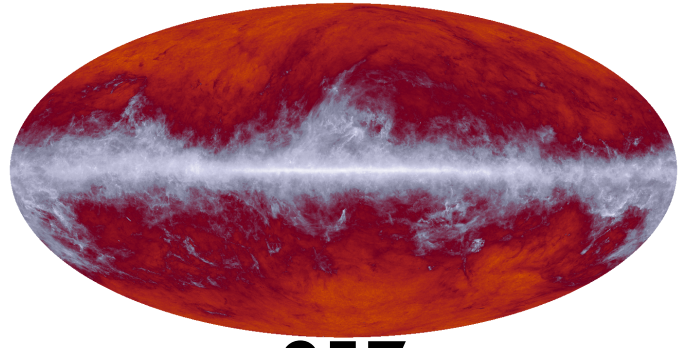
217



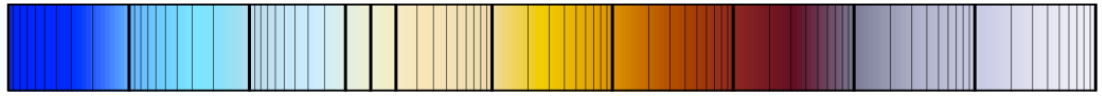
353



545



857



30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

"All the News That's Fit to Print"

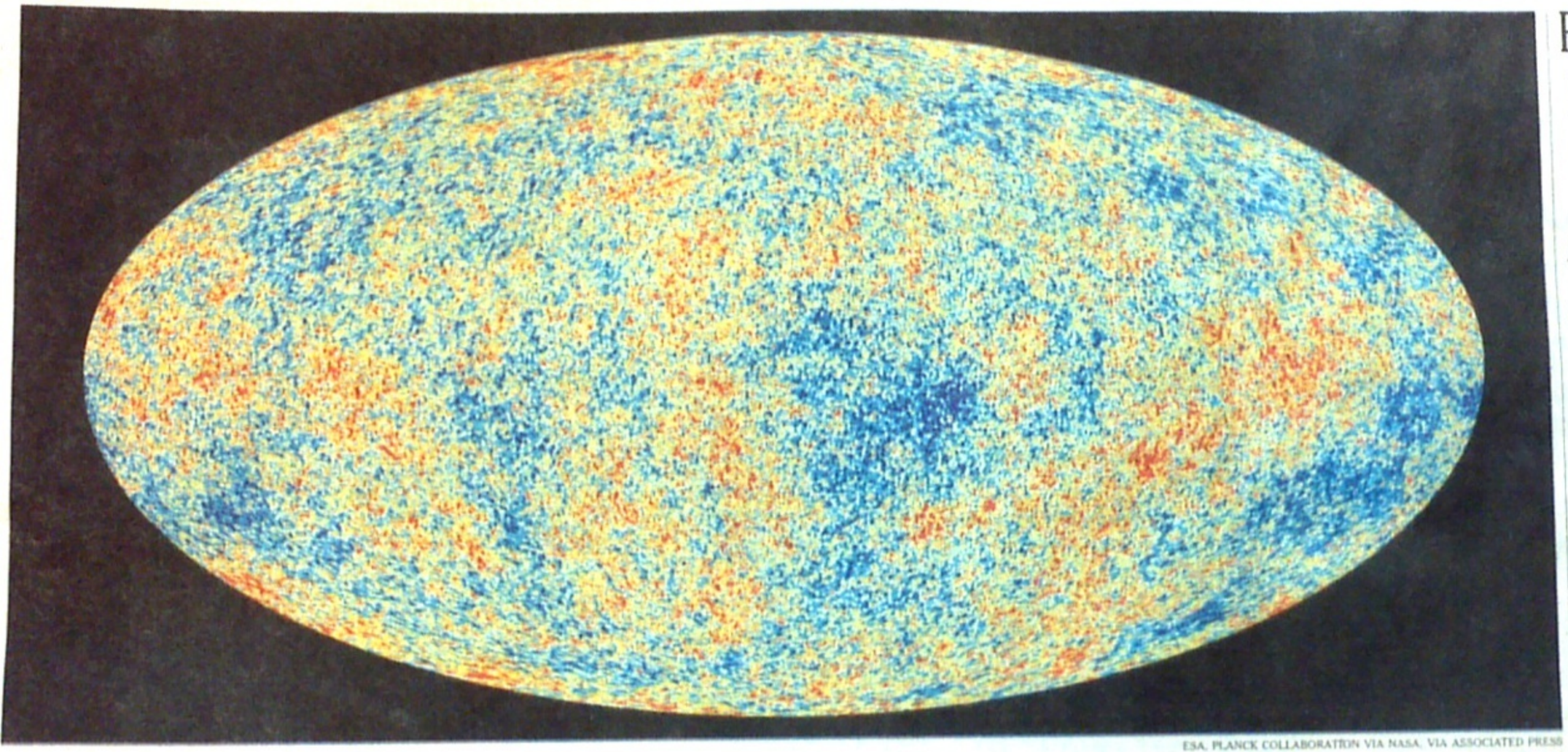
The New York Times

National Edition

Florida. A mix of sun and clouds. Afternoon showers. Highs 70s to near 80. Showers central and north tonight. Partly cloudy south. Lows 50s to 70s. Weather map, Page B10.

VOL. CLXII .... No. 56,083 FRIDAY, MARCH 22, 2013

Printed in Deerfield Beach $2.50



ESA, PLANCK COLLABORATION VIA NASA, VIA ASSOCIATED PRESS

The Cosmos, Back in the Day
An image from data recorded by a European Space Agency satellite shows a heat map of the universe as it appeared 370,000 years after the Big Bang. Page A10.

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases Stance on Settlement Halt Before Talks

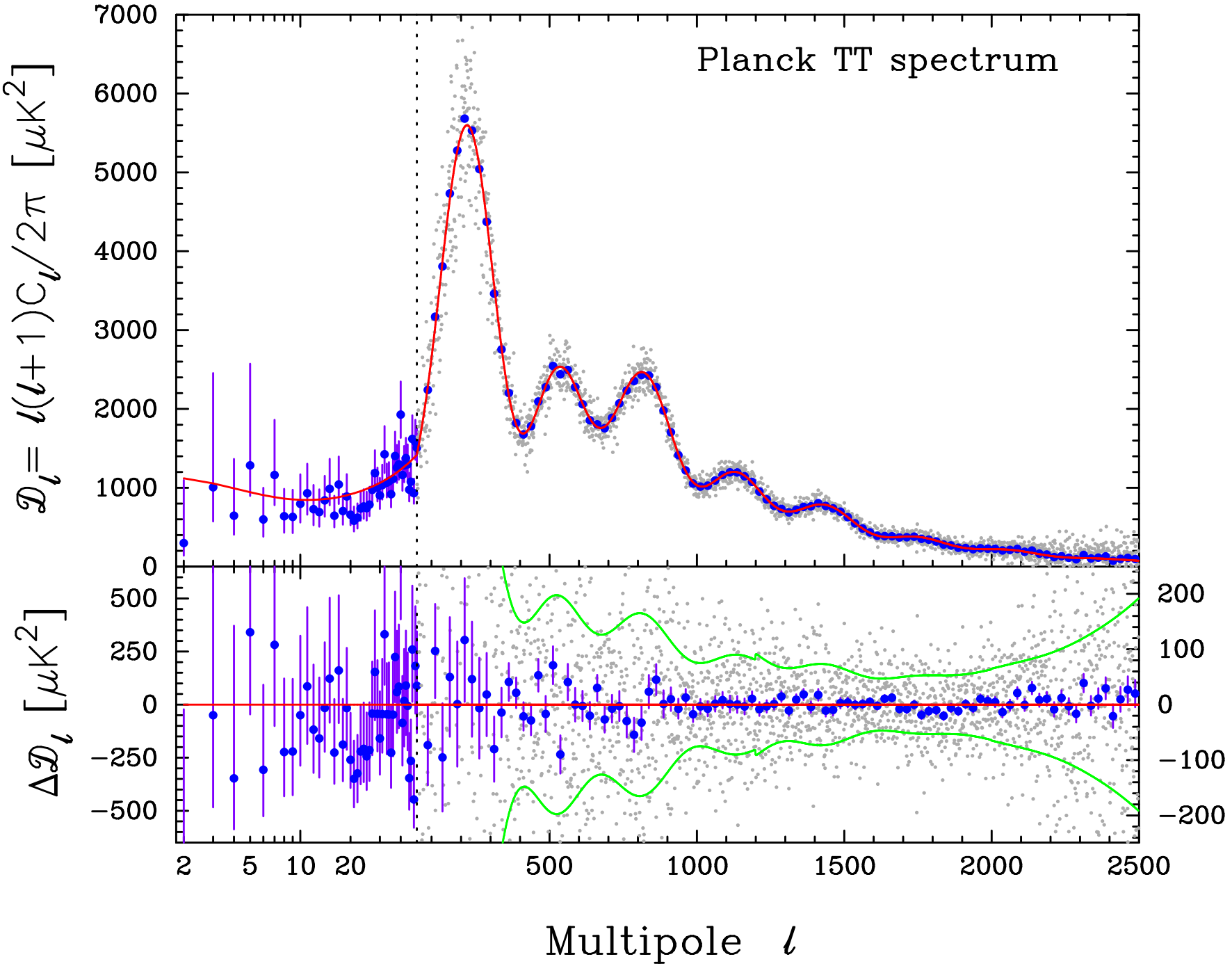
By MARK LANDLER

JERUSALEM — President Obama, appealing to very disparate audiences to solve one of the world's thorniest problems, moved closer on Thursday to the Israeli government's position on resuming long-stalled peace talks with the Palestinians, even as he passionately implored young Israelis to get ahead of their own leaders in the push for peace.

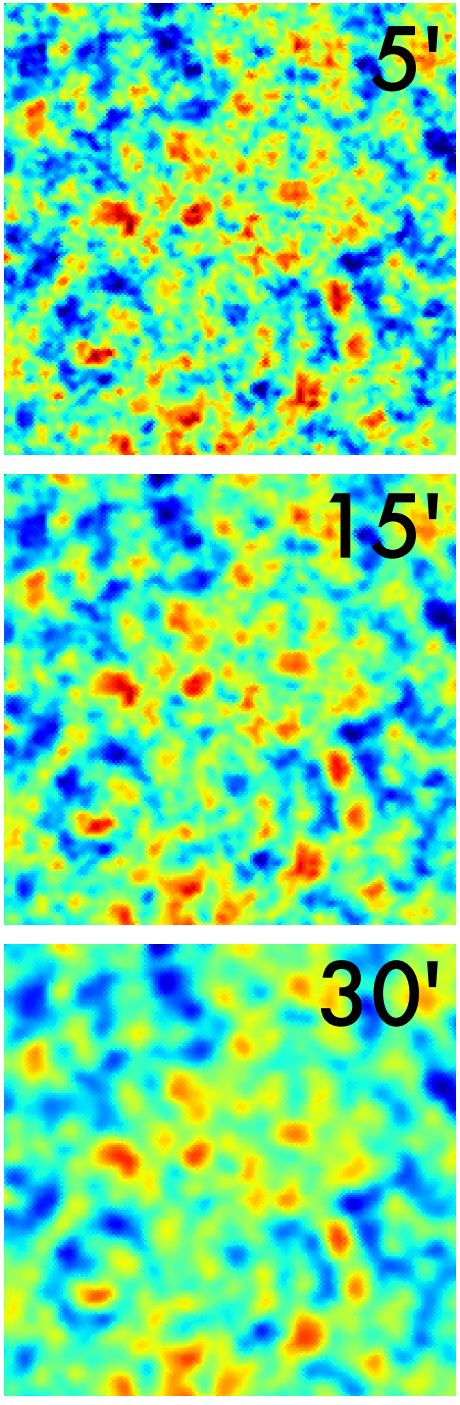
Addressing an enthusiastic crowd of more than 2,000, Mr. Obama offered a fervent, unsparing case for why a peace agreement was both morally just and in Israel's self-interest. Younger Israelis, Mr. Obama said, should empathize with their Palestinian neighbors living under occupation — or, as he put it, "look at the world through their eyes."

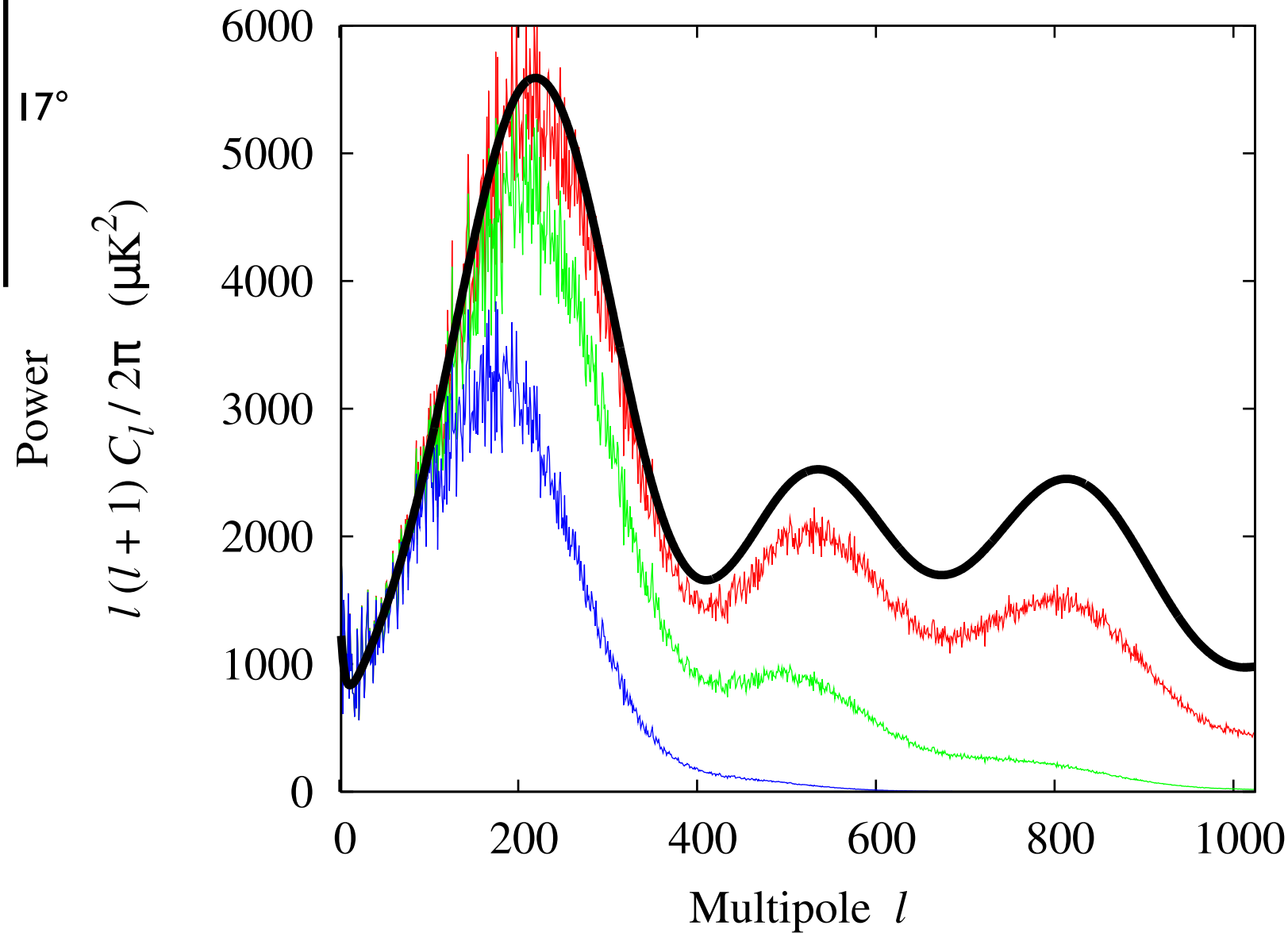
As Pollution Worsens in China,

Once Few, Women Hold More Power in Senate


Planck TT spectrum
$\mathcal{D}_l = l(l+1)C_l/2\pi$ [μK^2]
$\Delta\mathcal{D}_l$ [μK^2]
Multipole l
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

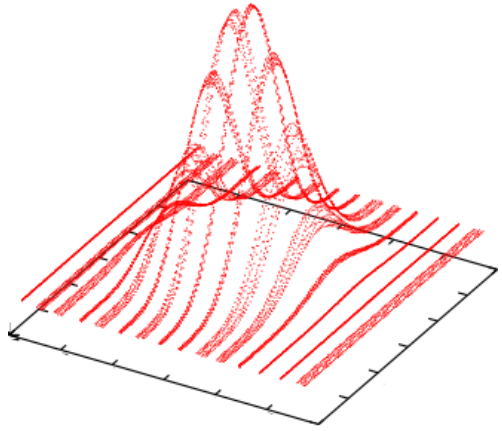
Finite resolution damps small scale power



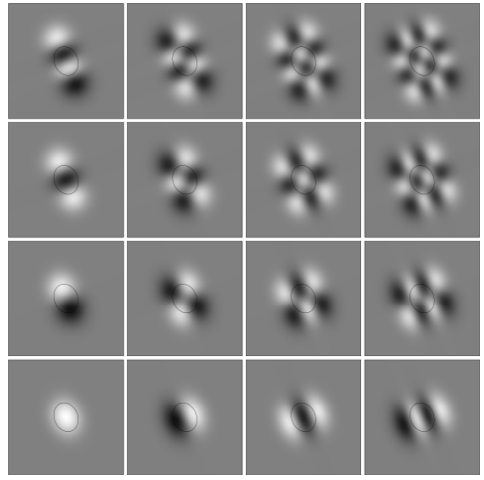


Must know beam well to unbias spectrum.

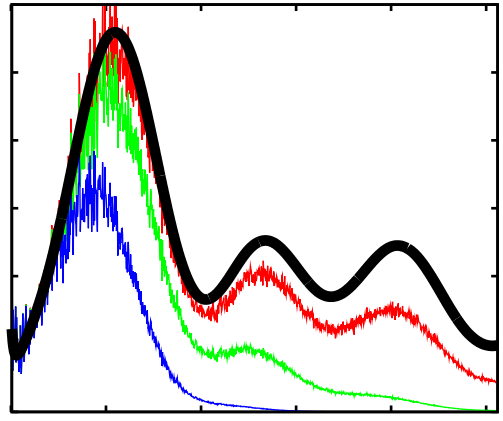
Pipeline to reconstruct beam

1. 

sparse signal, noise, electronics, etc.

2. 

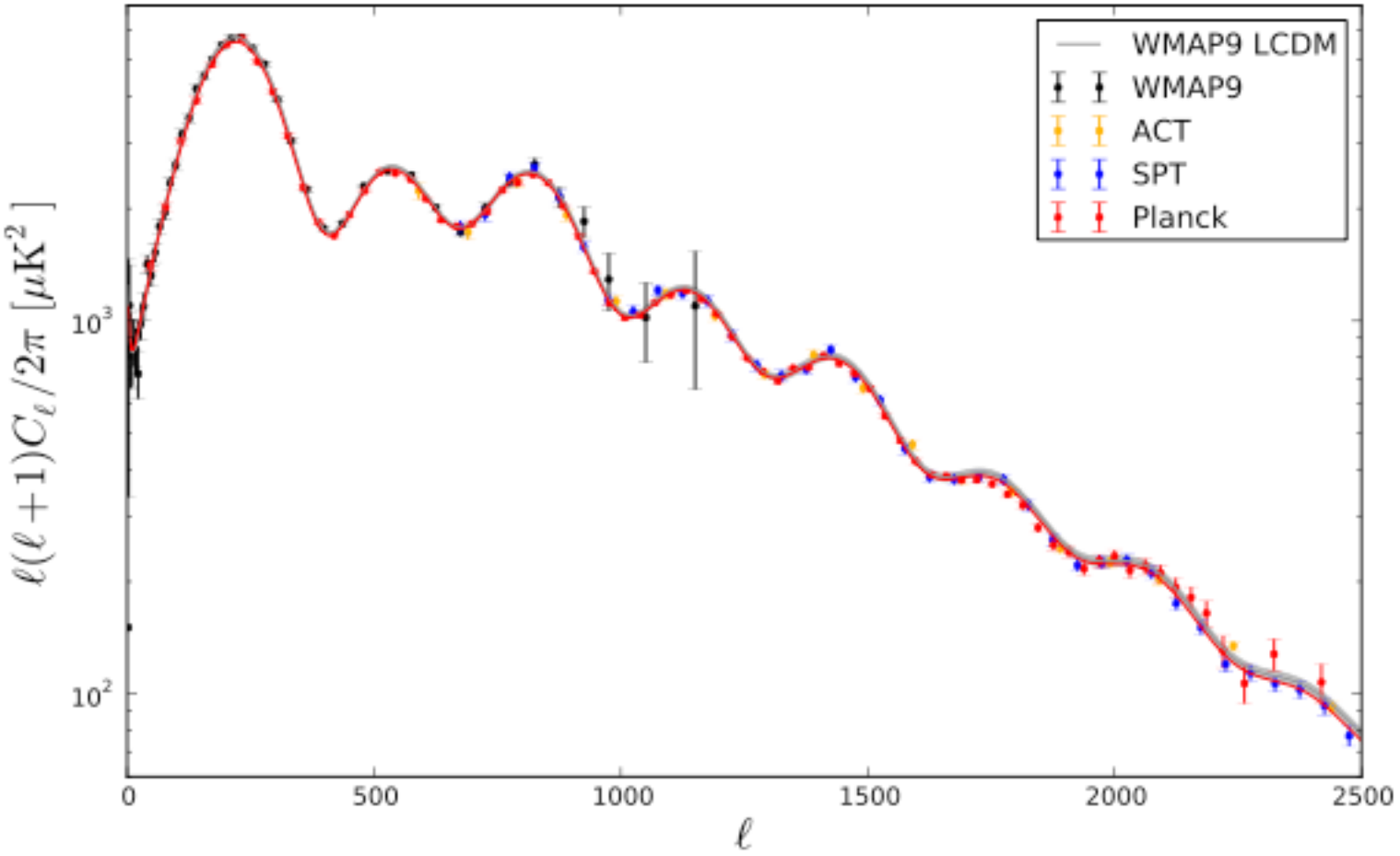
reconstruct beam

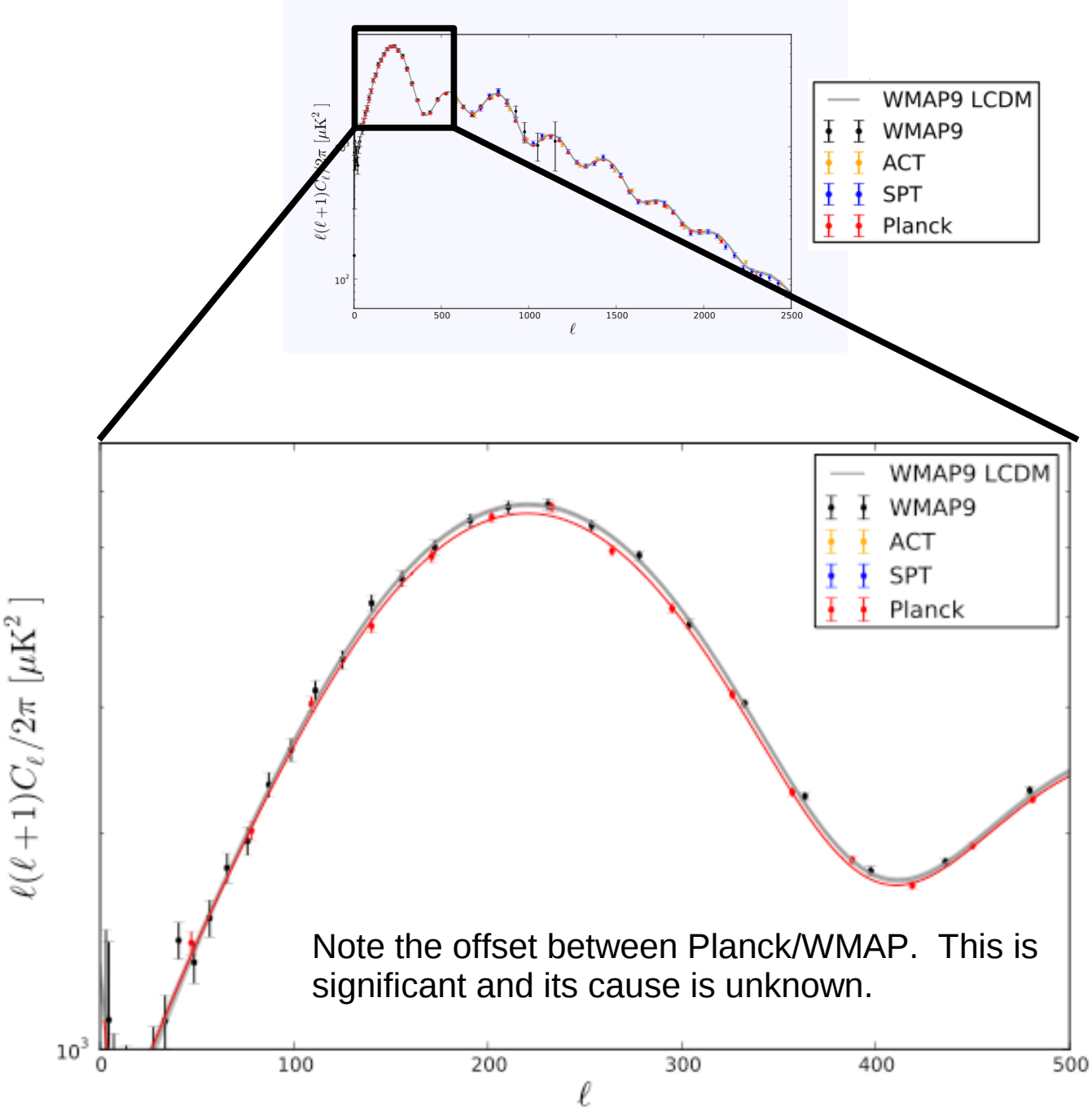
3. 

repair spectrum

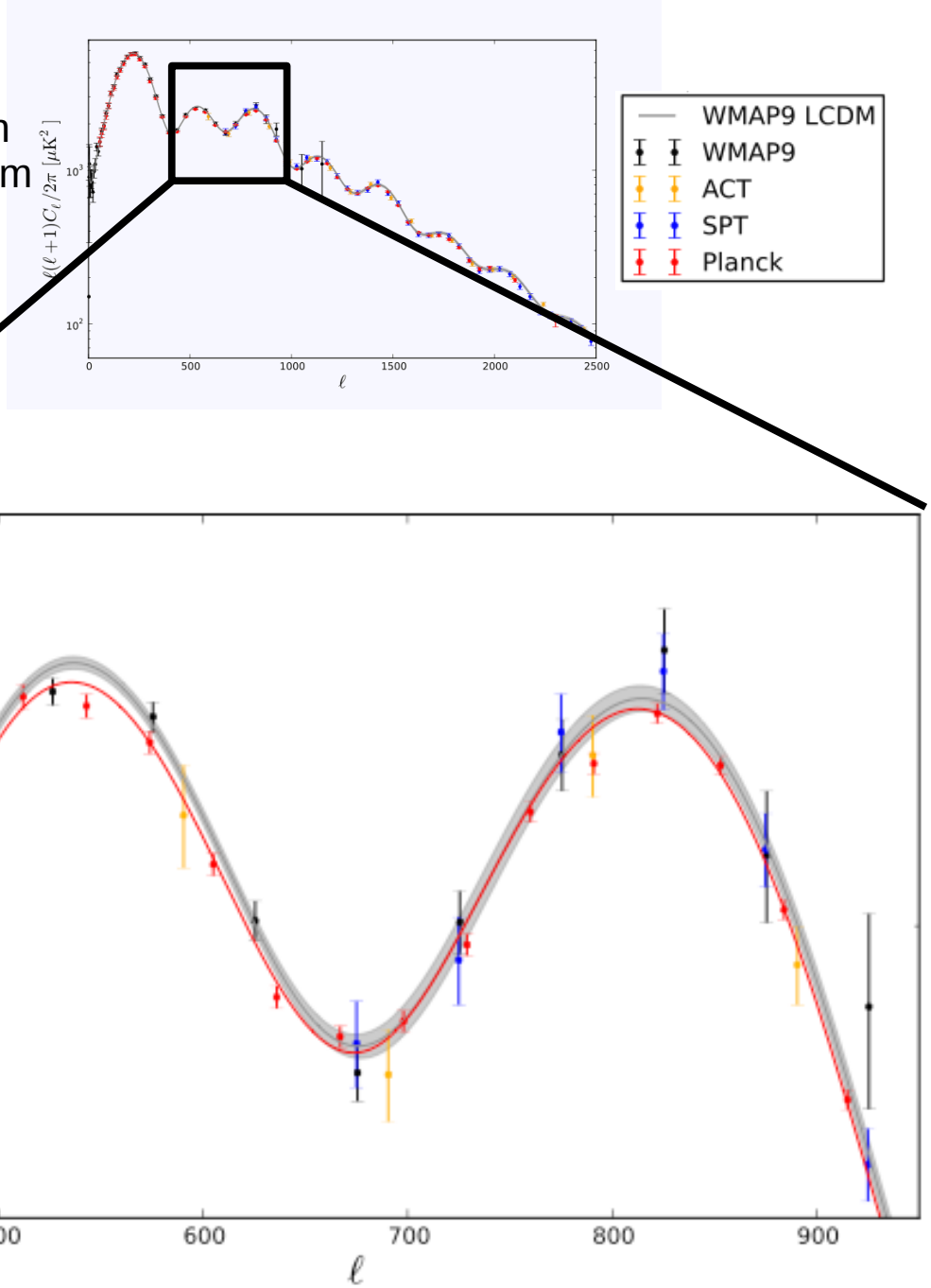
Characterize with Monte Carlo

Huffenberger et al., A&A 510 (2010)

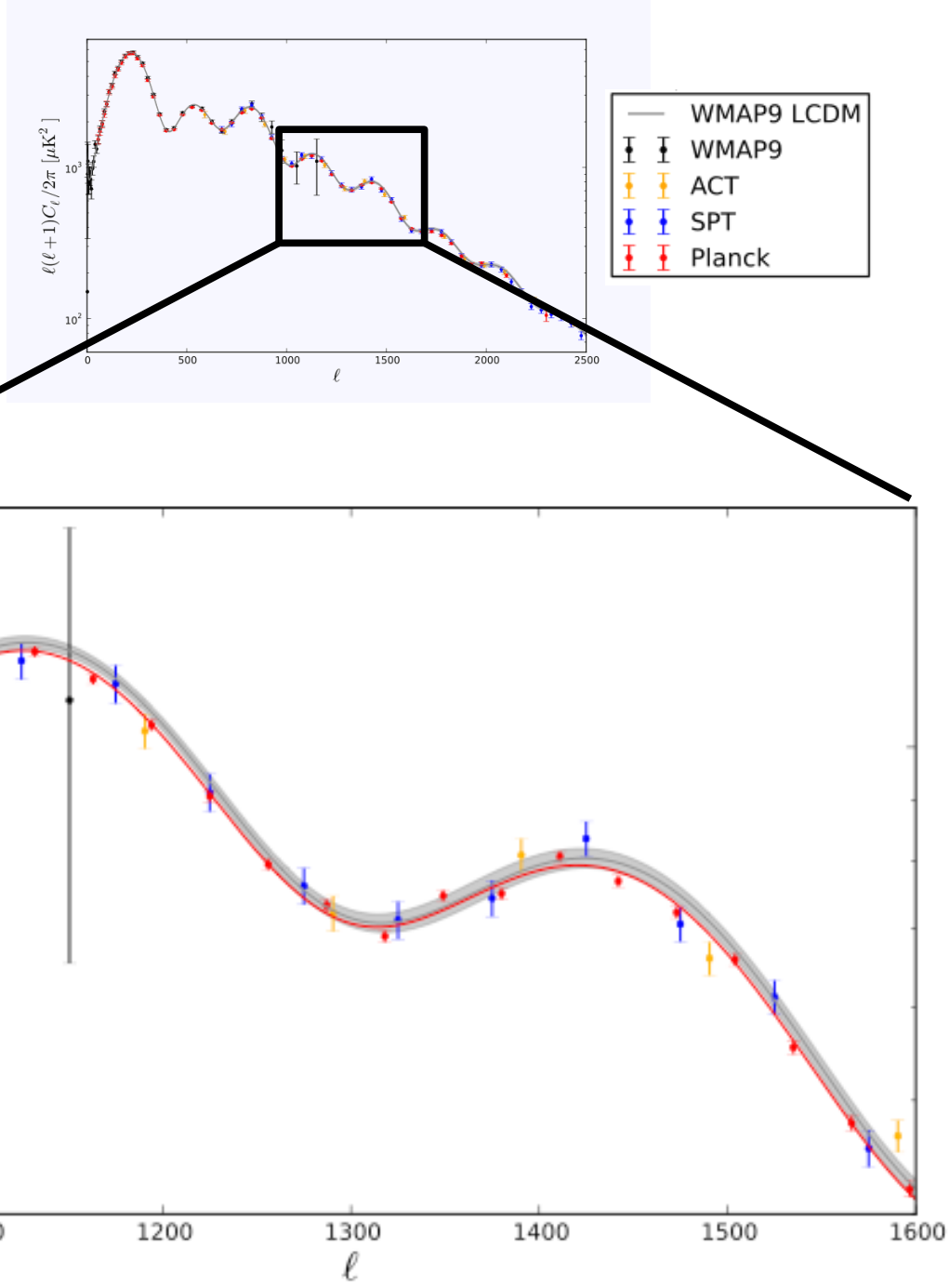

WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ


WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
ℓ
Note the offset between Planck/WMAP. This is significant and its cause is unknown.

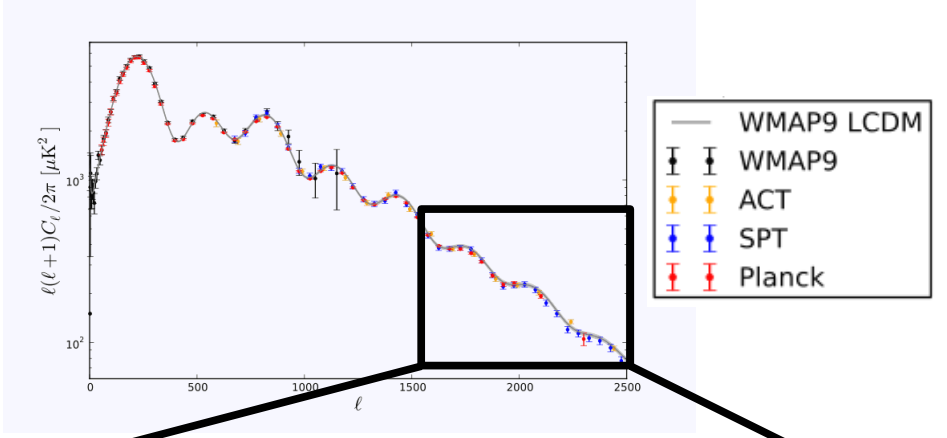
- WMAP errors start to get large because we're now on the scale of the WMAP beam

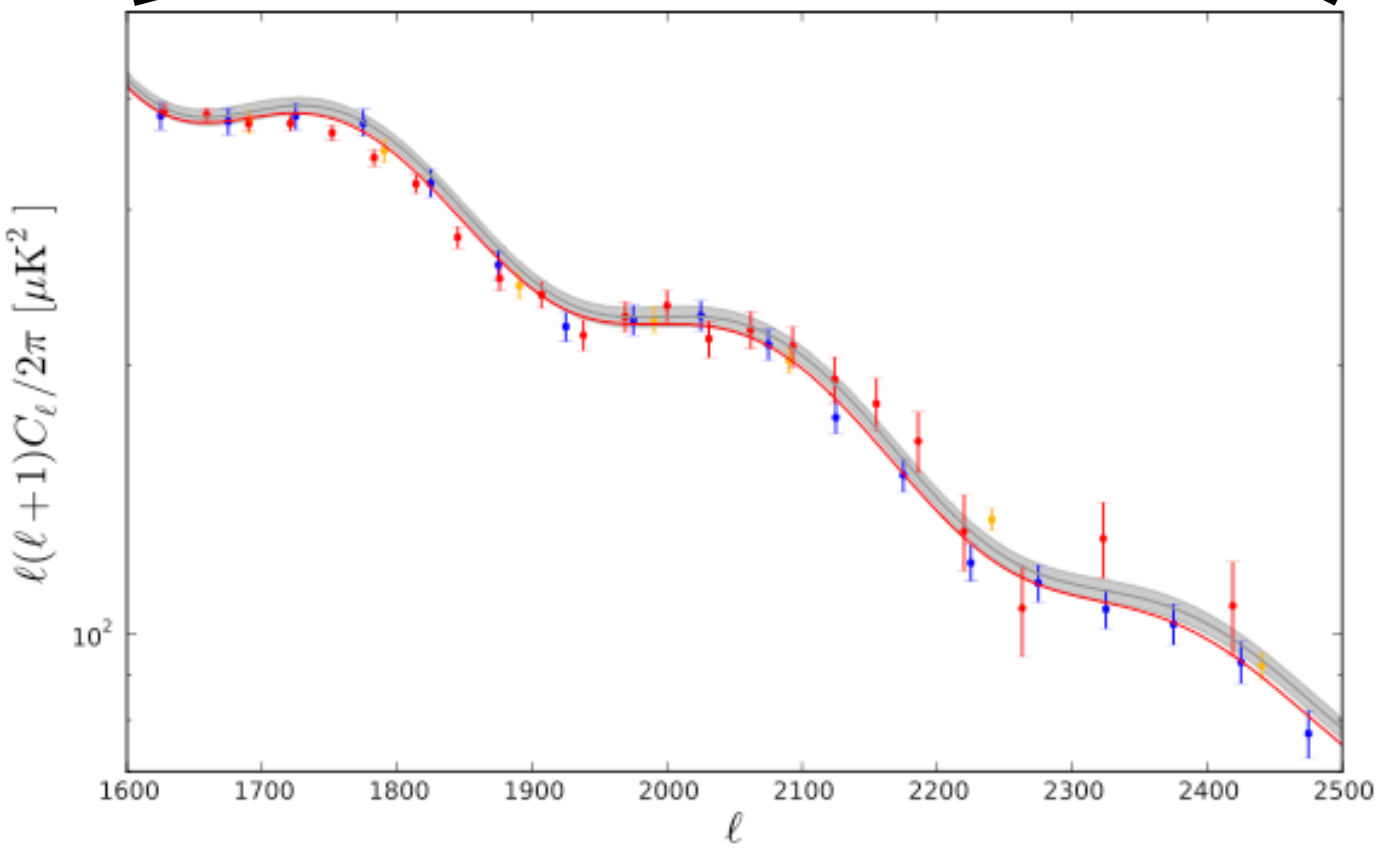


- Here ACT/SPT/Planck are all sample variance limited but Planck has much larger sky coverage



- Finally, at around l=2000, ACT/SPT become a tighter constraint because their beams are smaller





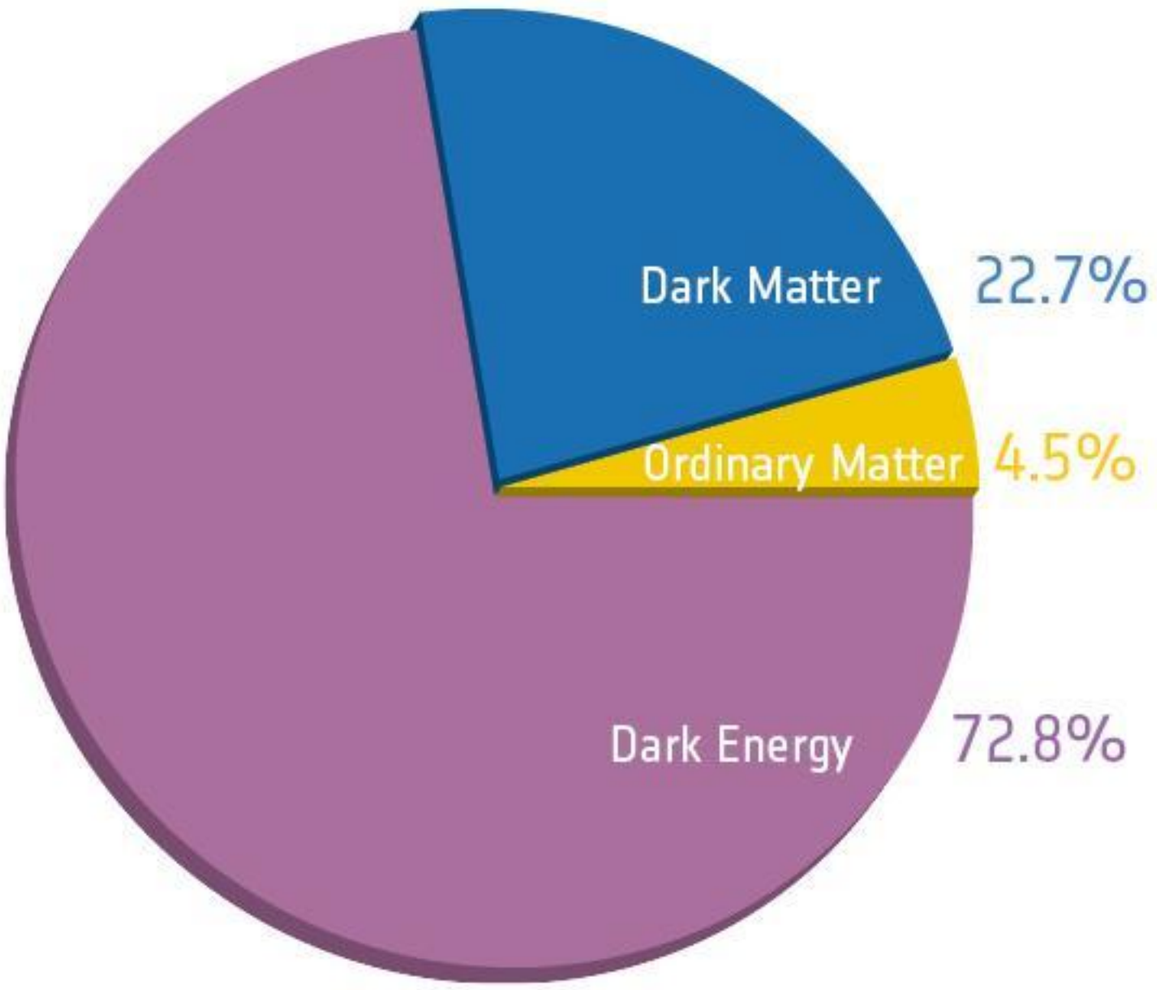
Parameters

Basic

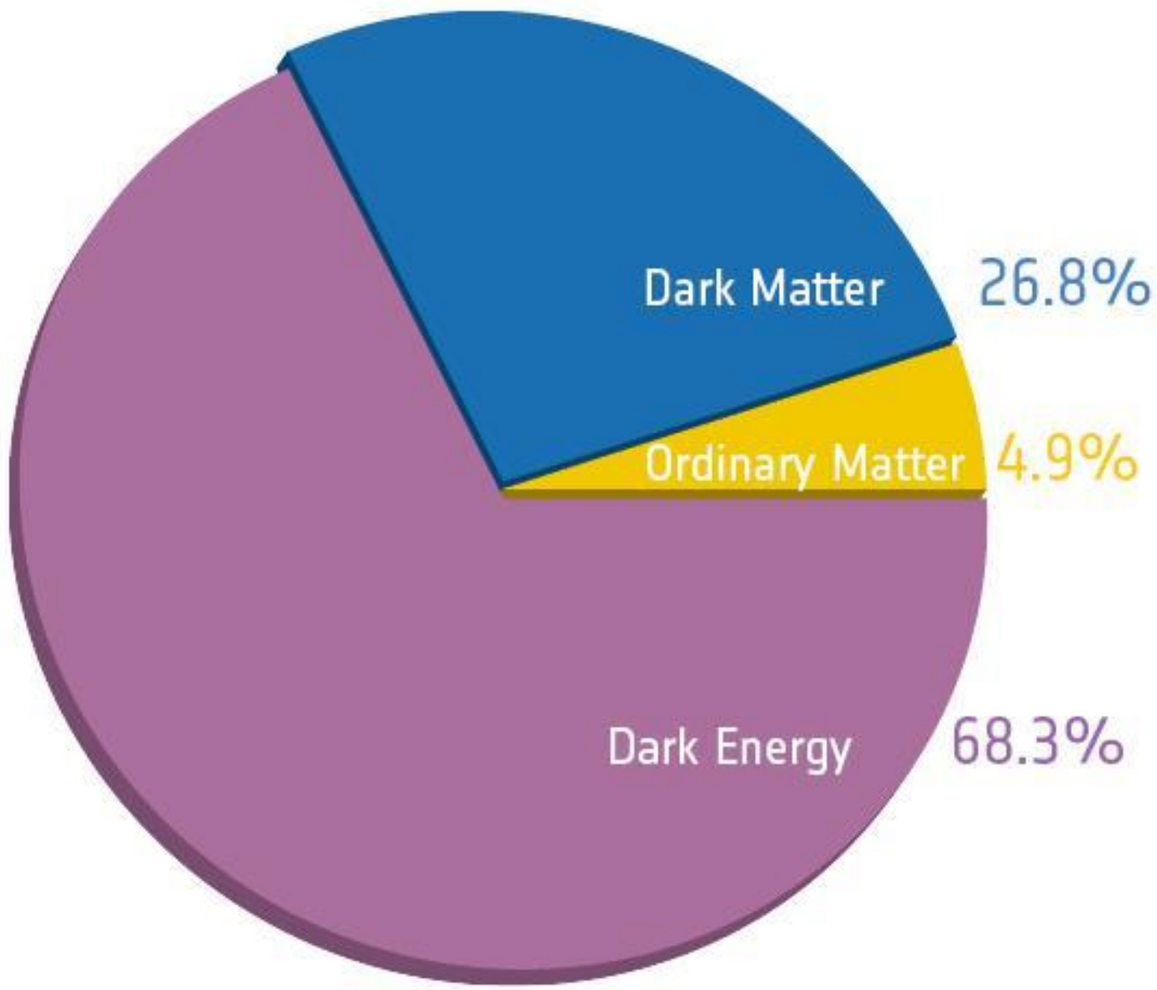
Nuisance (Marginalized)

Derived

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45



Before Planck



After Planck

Universe Older, Wider Than Previously Thought

AMERICAN VOICES · Opinion · ISSUE 49•12 · Mar 22, 2013

Astronomers determined that the universe is actually 13.8 billion years old, about 80 to 100 million years older than previously believed, and that it is also a bit wider than once thought. What do *you* think?

"How embarrassing."

Victoria Rosegard –
Street Cleaner

"Typical. You give birth to a few trillion galaxies and then people just talk about how old and fat you've gotten."

Francois Jenevein –
Hide Trimmer

"Just like it says in Leviticus."

Chris Vanderhorst –
Systems Analyst

‹ Ian McKellen Officiating Patrick Stewart's Wedding

CDC: 1 In Every 50 U.S. Schoolchildren ... ›

RECENT NEWS

Future Christian Drinking And Doing Drugs And Thinking It's One Big Joke

Fast-Talking Computer Hacker Just Has To Break Through Encryption Shield Before Uploading Nano-Virus

JCPenney CEO's Severance Package Includes 34,000 Pea Coats

Kim Jong-Un Wonders If Nuclear Threats Distracting Him From Real Goal Of Starving Citizenry

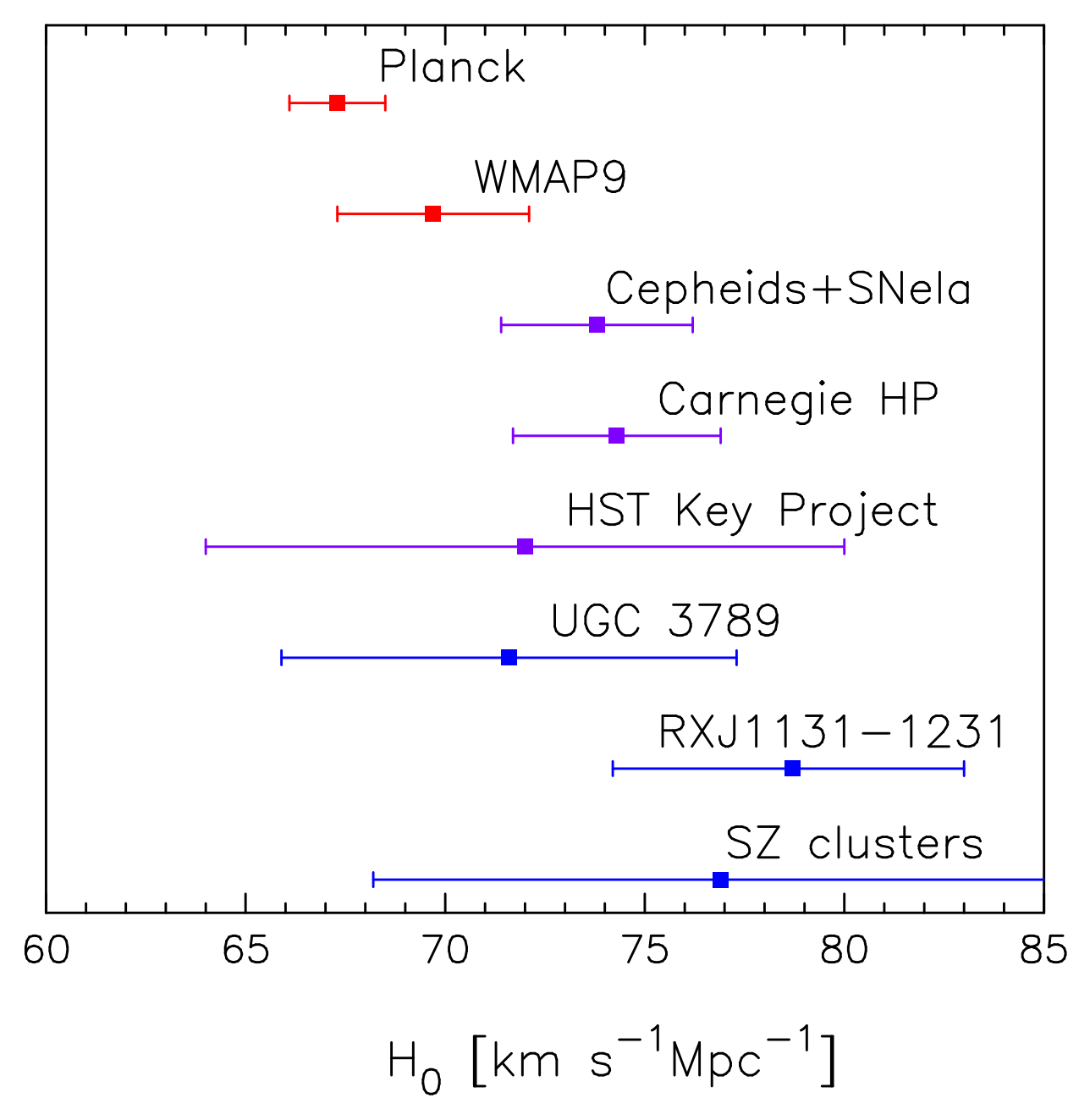
China Announces Plans To Build International Space Prison

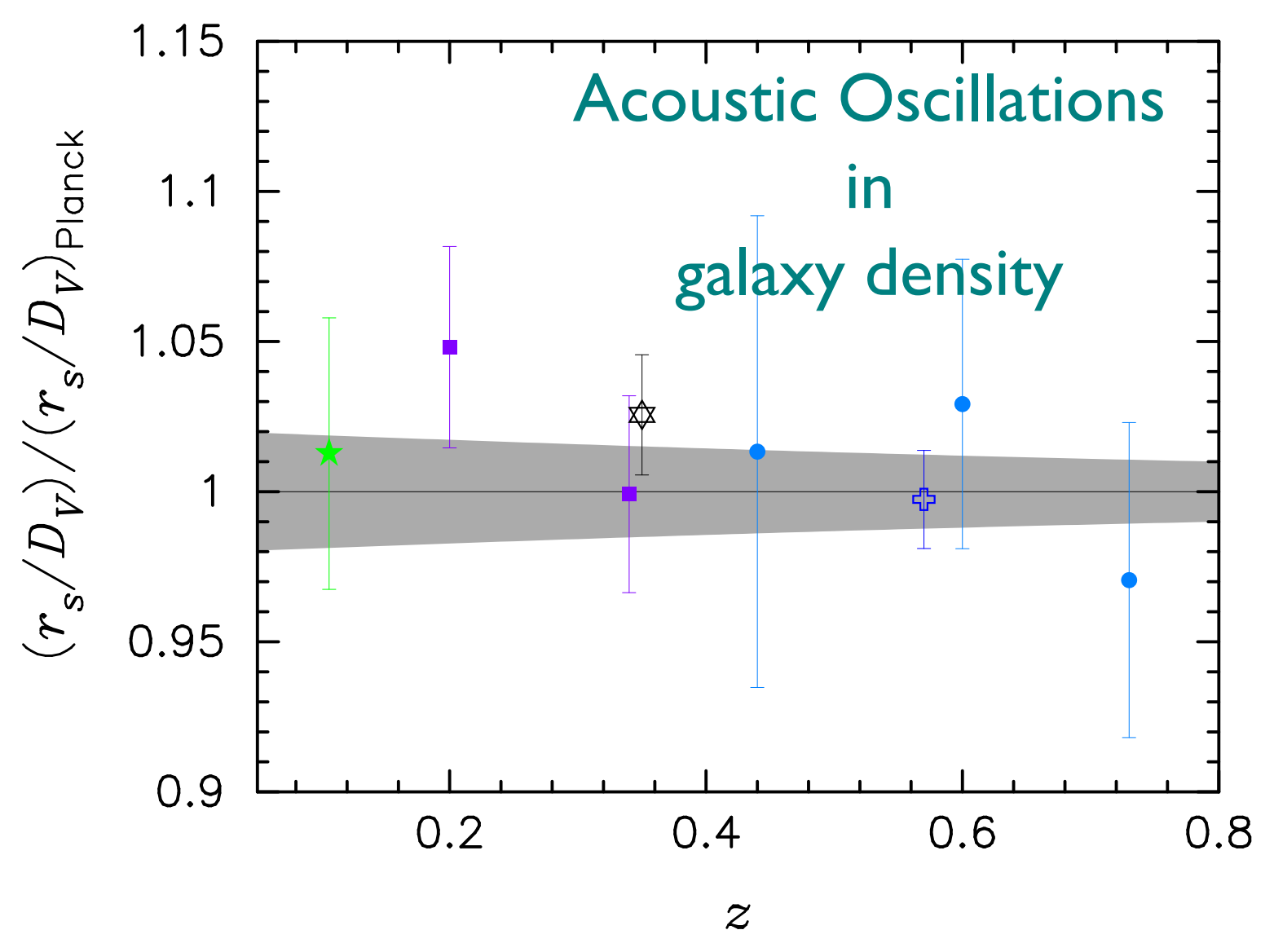
Man Not Certain What Any Of His Coworkers' Names Are

NATO Airstrike Destroys Key Taliban Day Care Center

RECENT VIDEOS

Popular Children's Book Author Reveals The 'Spooky Truth' About Creepy Conspiracy Theories


Planck
WMAP9
Cepheids+SNeIa
Carnegie HP
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
H_0 [km s^{-1}Mpc^{-1}]


Acoustic Oscillations
in
galaxy density
1.15
1.1
1.05
1
0.95
0.9
0.2
0.4
0.6
0.8
z
$(r_s/D_V)/(r_s/D_V)_{\rm Planck}$

Parameter extensions to base model

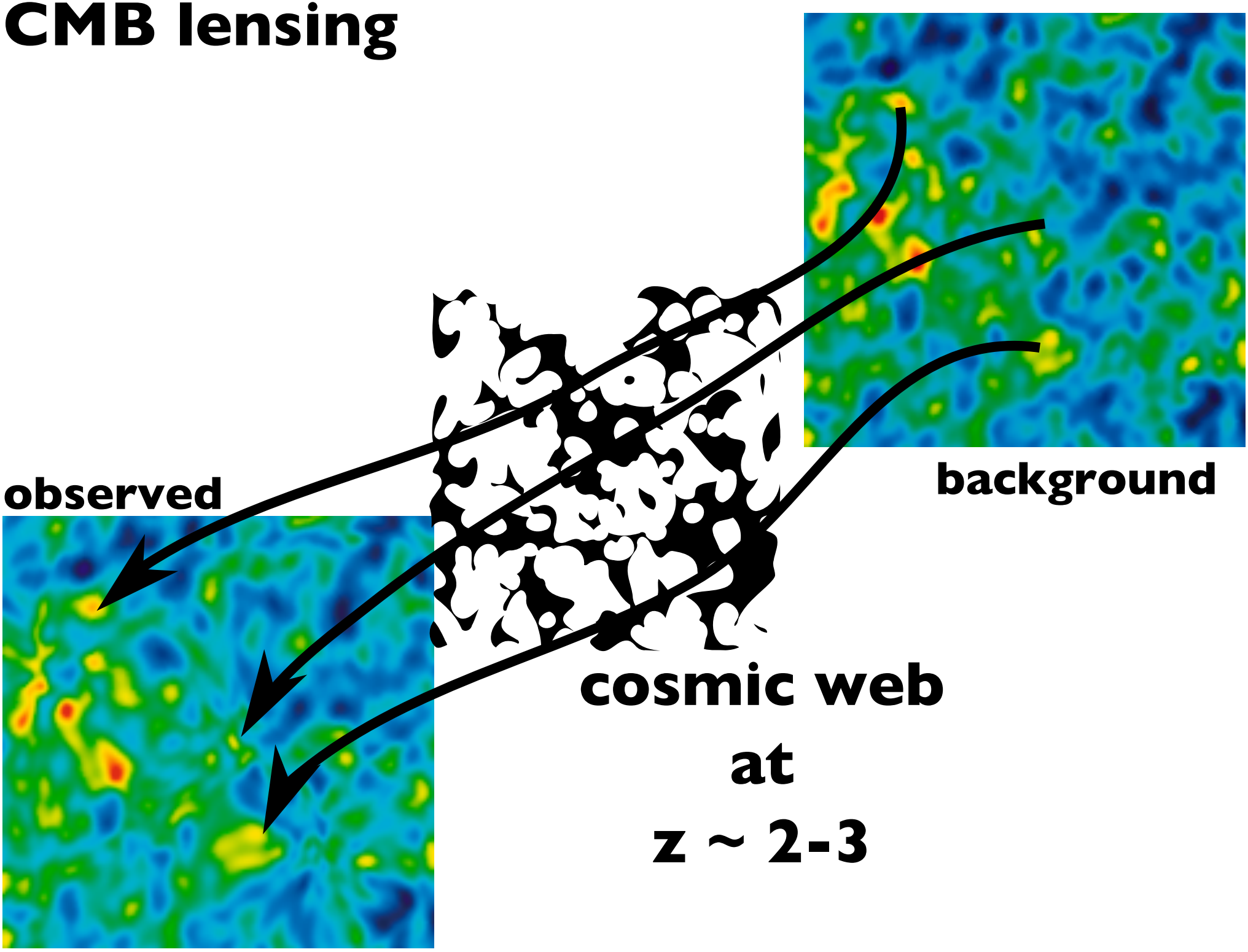
	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	−0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	−0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	−0.0090	$-0.013^{+0.018}_{-0.018}$	−0.0102	$-0.013^{+0.018}_{-0.018}$	−0.0106	$-0.015^{+0.017}_{-0.017}$	−0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	−1.20	$-1.49^{+0.65}_{-0.57}$	−1.076	$-1.13^{+0.24}_{-0.25}$	−1.20	$-1.51^{+0.62}_{-0.53}$	−1.109	$-1.13^{+0.23}_{-0.25}$

Spatially flat to 1%

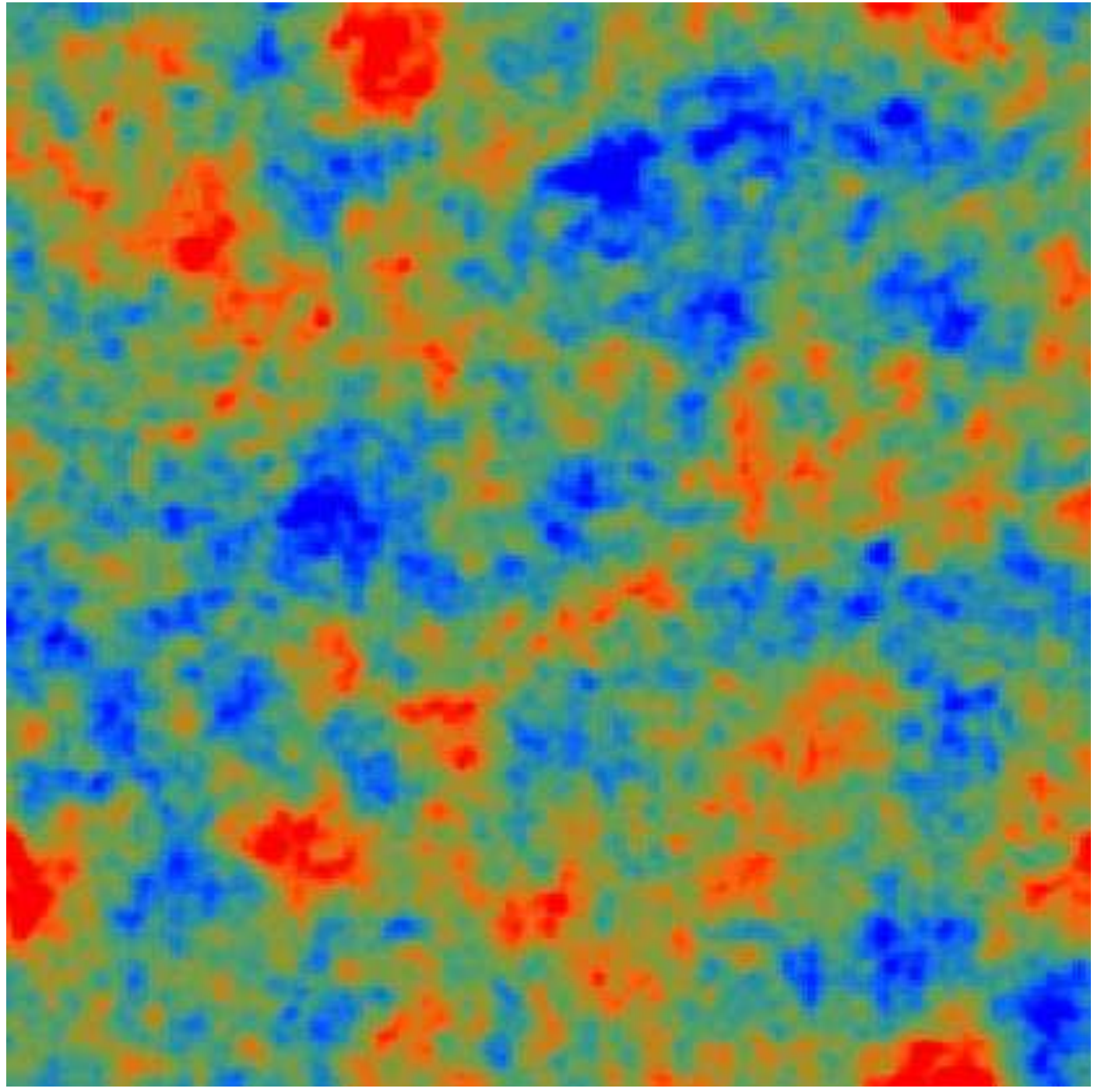
Tight limit on sum of neutrino mass... (osc: m > 0.05 eV)

No extra relativistic species. Standard Helium abundance.

CMB lensing

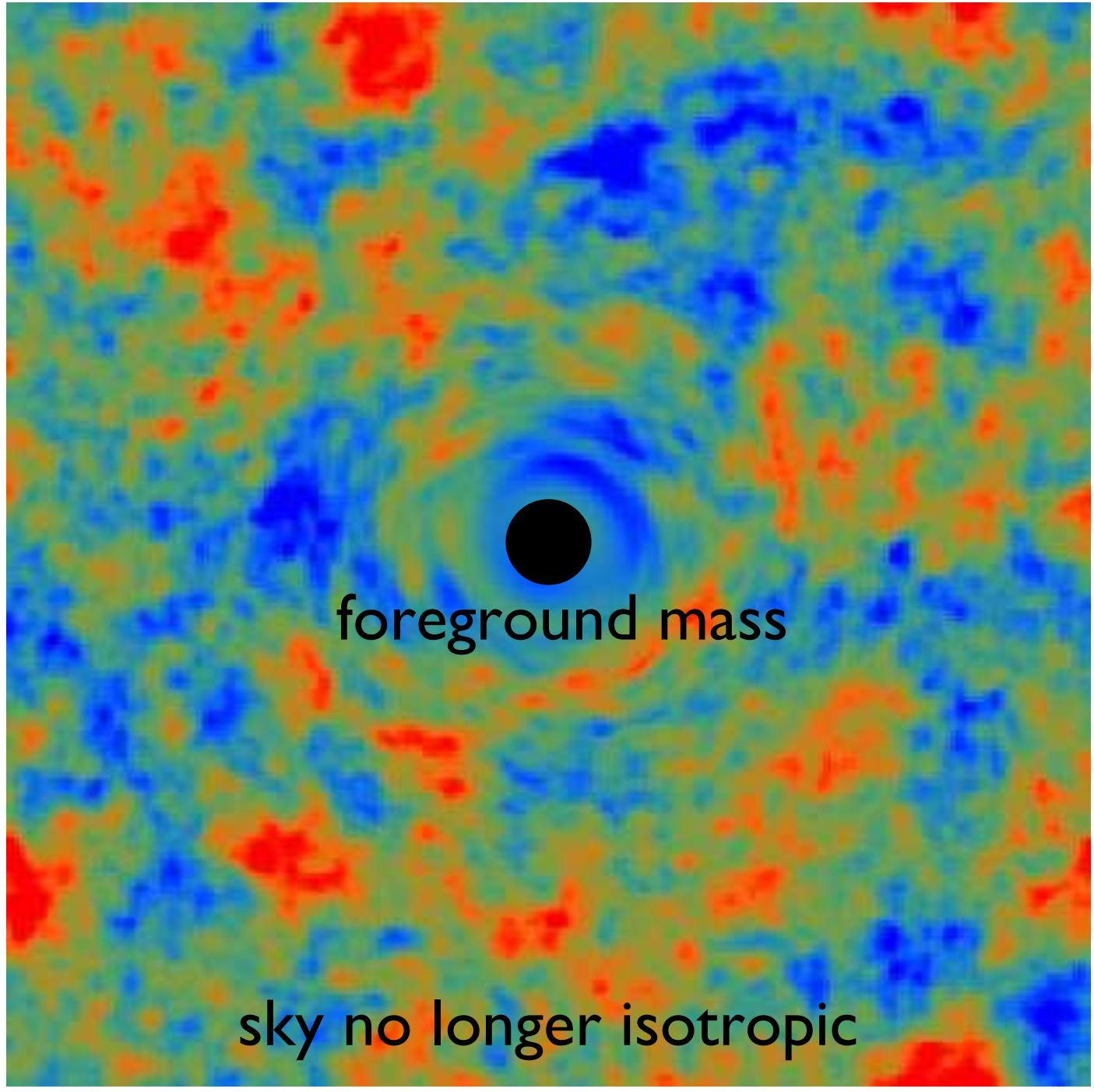


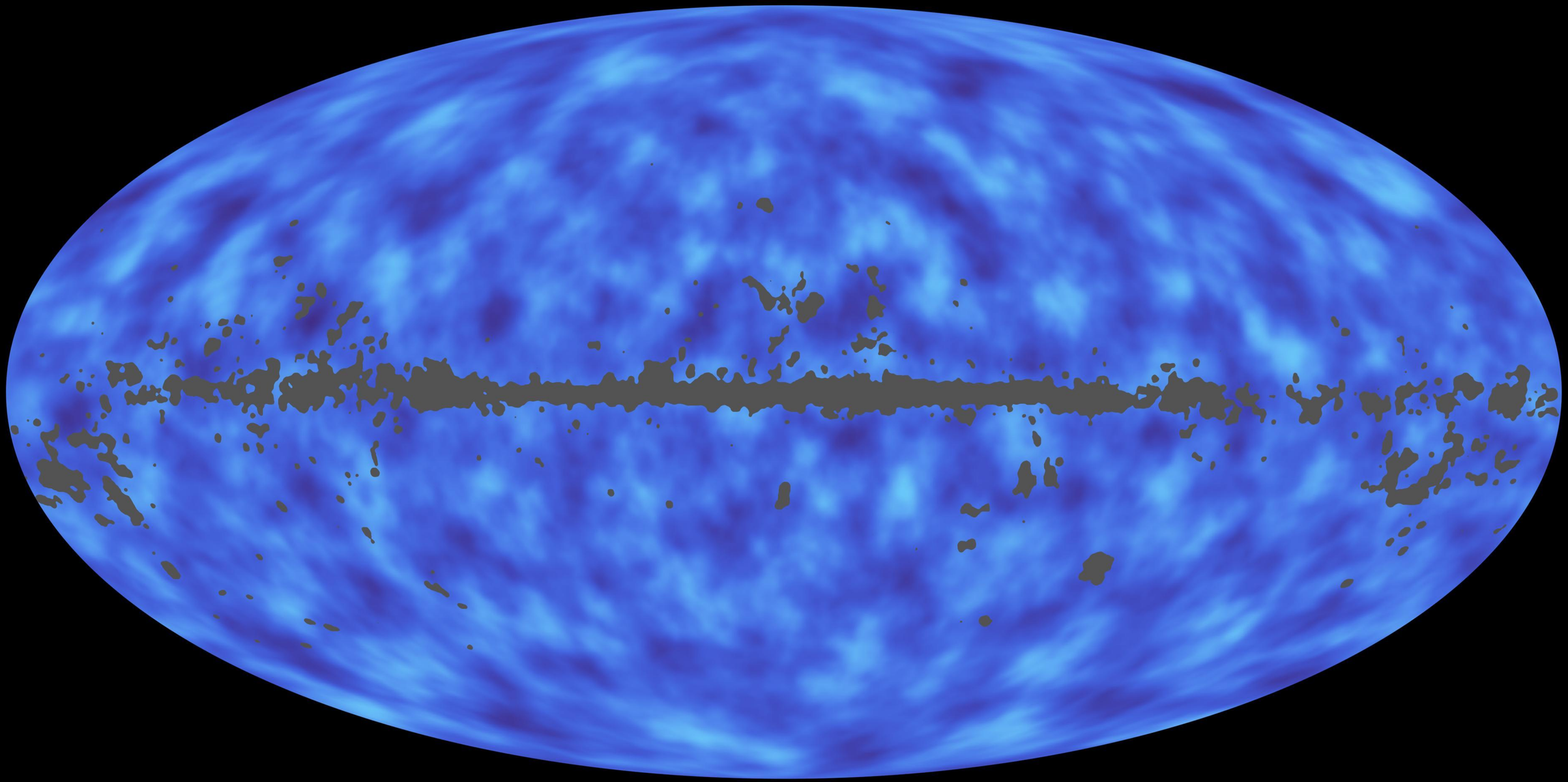
CMB (Hu & Okamoto 2001)



CMB lensed

(Hu & Okamoto 2001)

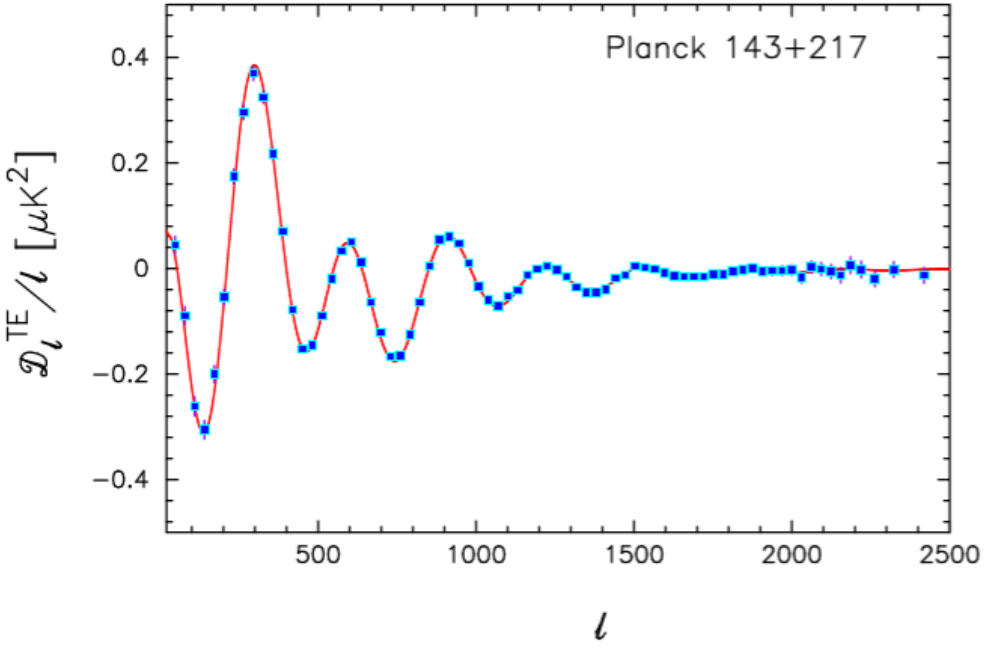


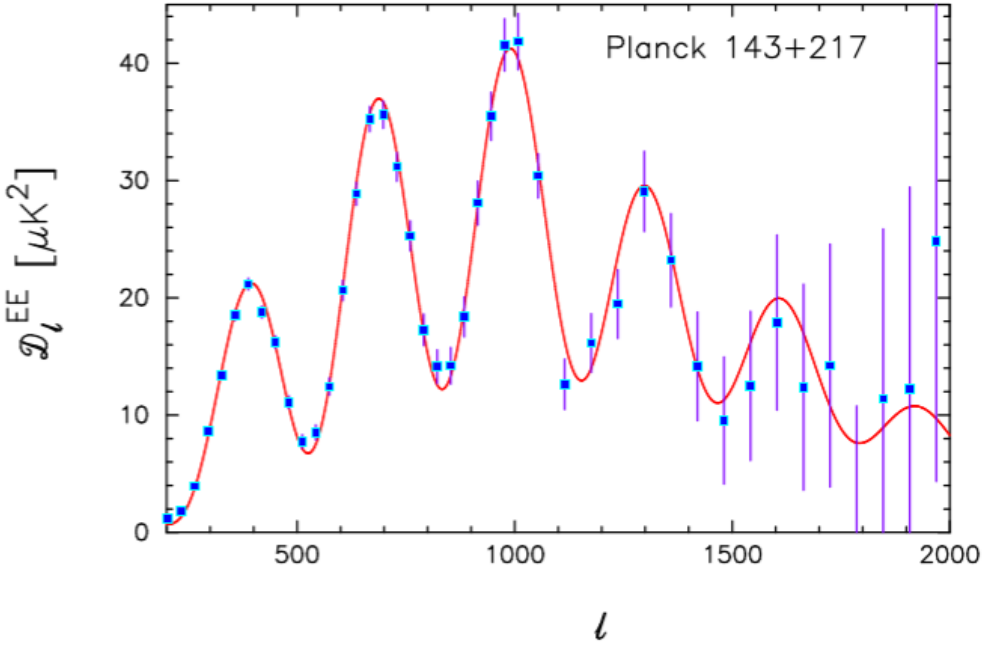


Conclusions

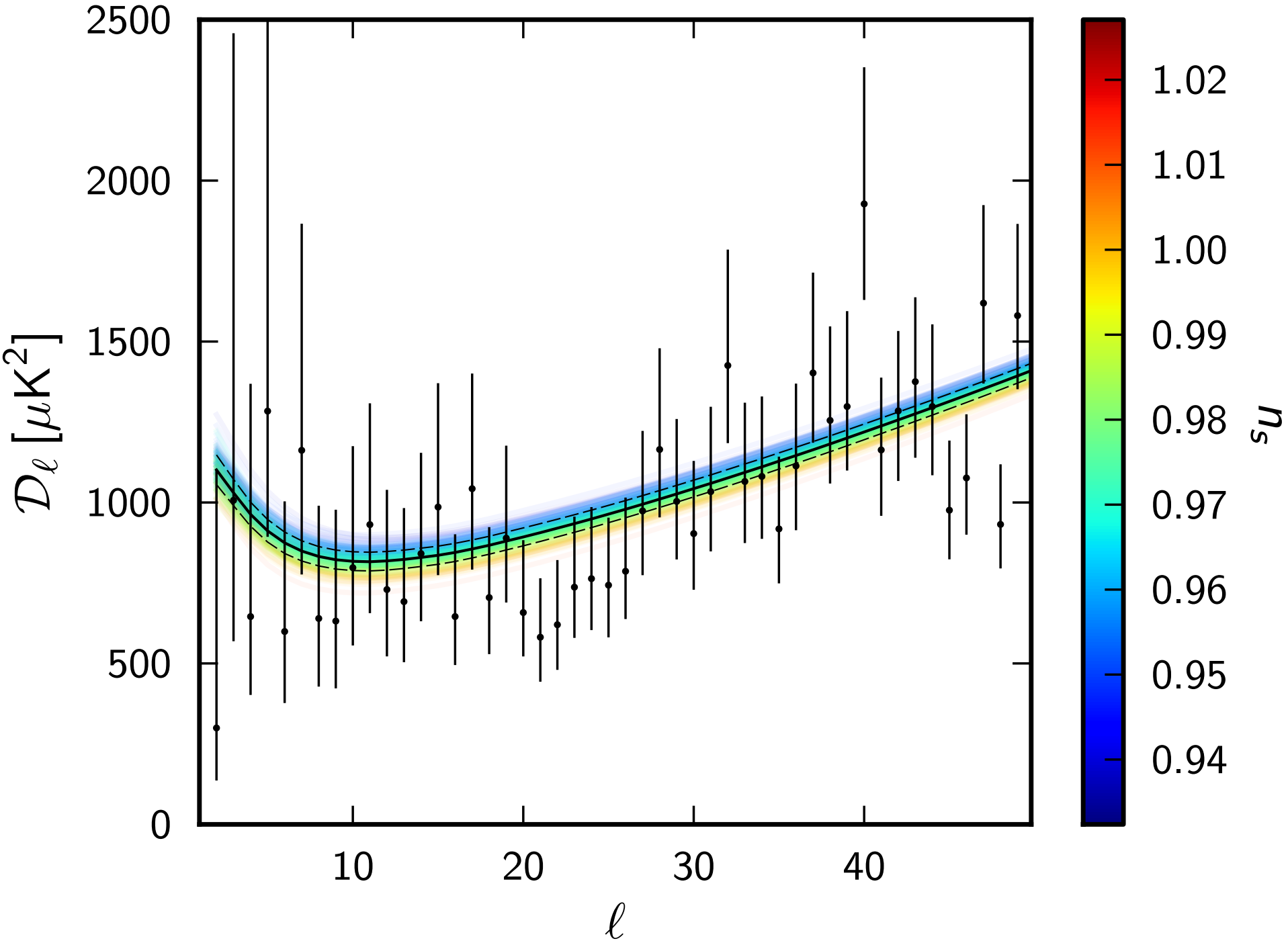
Planck has produced a rich store of data and cosmological results.

Next: Polarization

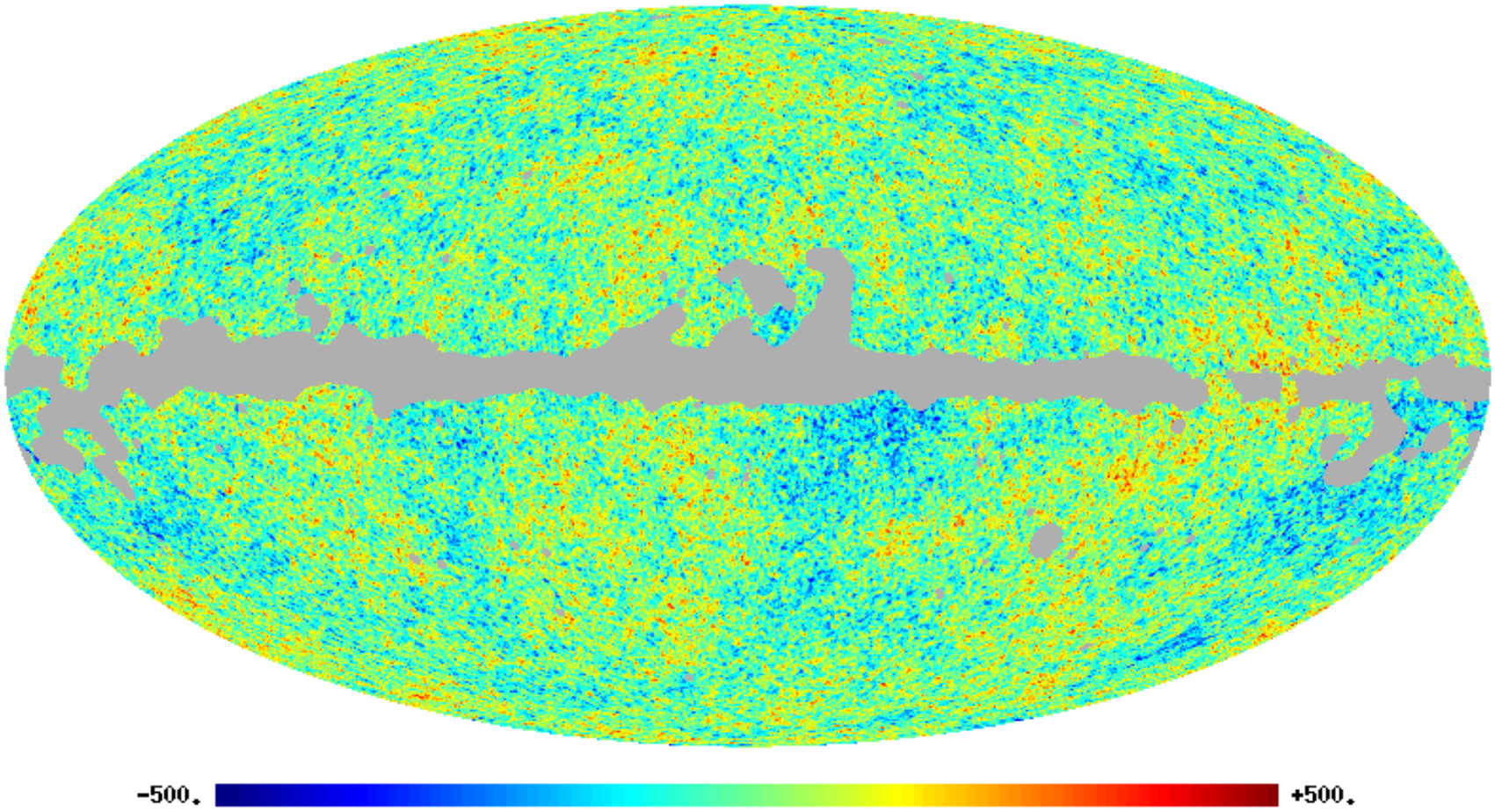




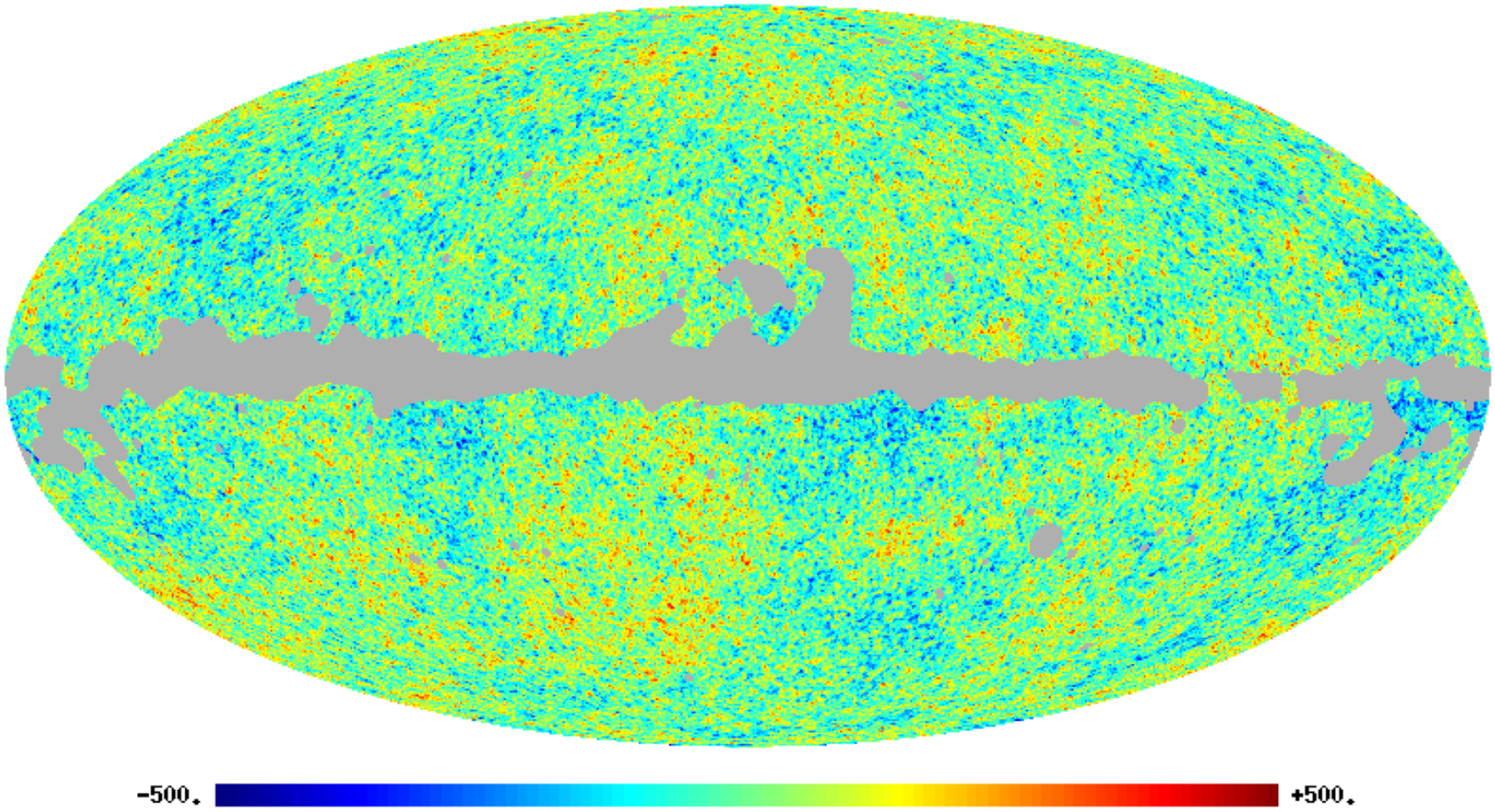
Large scale anomalies?


2500
2000
1500
1000
500
0
$\mathcal{D}_\ell\ [\mu\mathrm{K}^2]$
10
20
30
40
ℓ
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
s_u

The Observed CMB Sky



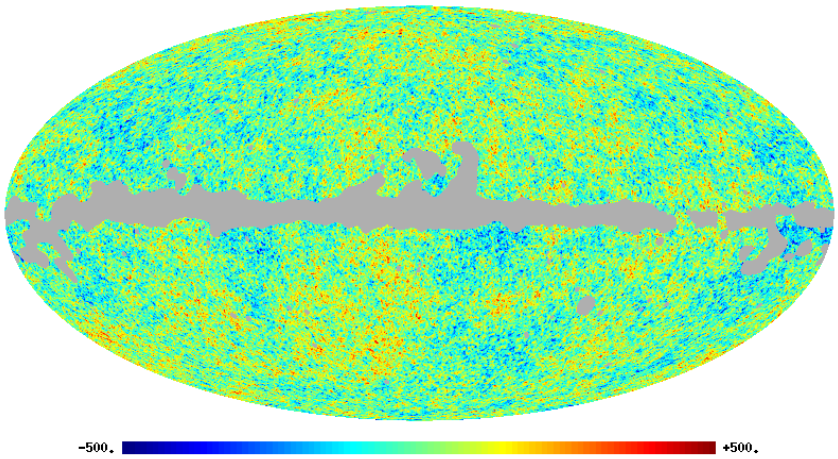
The Corrected, More Manifestly Isotropic CMB Sky



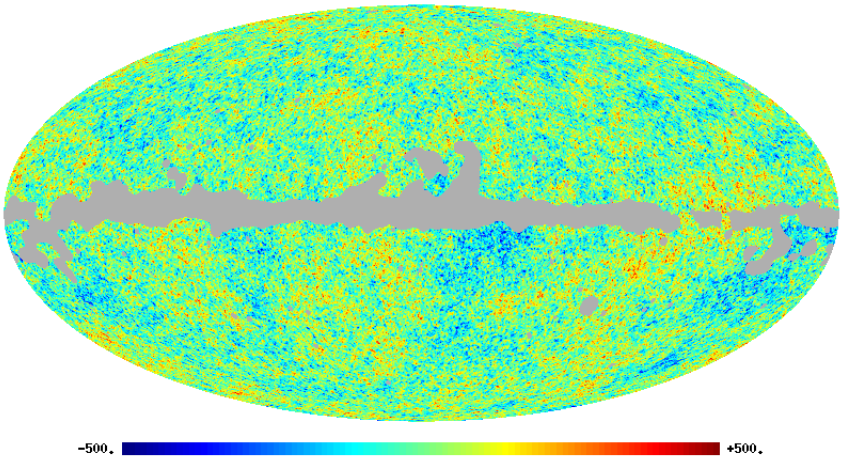
A Paradoxical "solution" to the Idiosyncratic Appearance of Our CMB Sky

The Bianchi model **must be open** to fit the data, and cannot be merged with the overall flat cosmology that describes the observed universe

Corrected CMB Sky



Real CMB Sky



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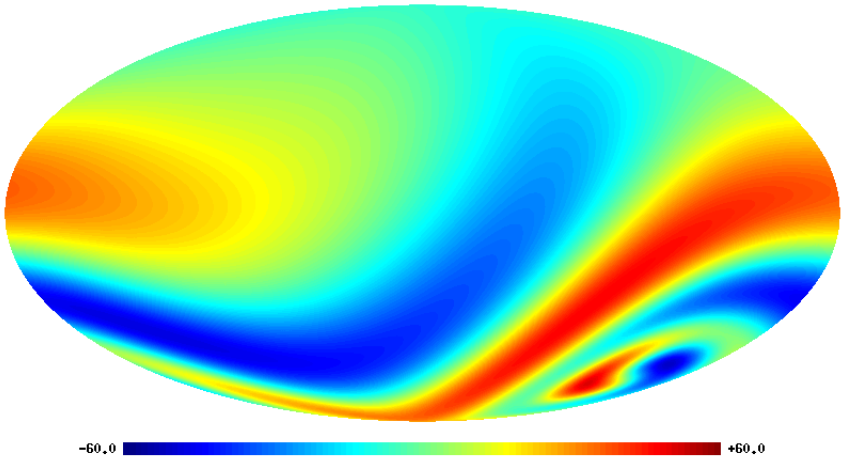

Correction that fits the sky:
a homogeneous, anisotropic Bianchi VII_h model