The Planck satellite and cosmic concordance

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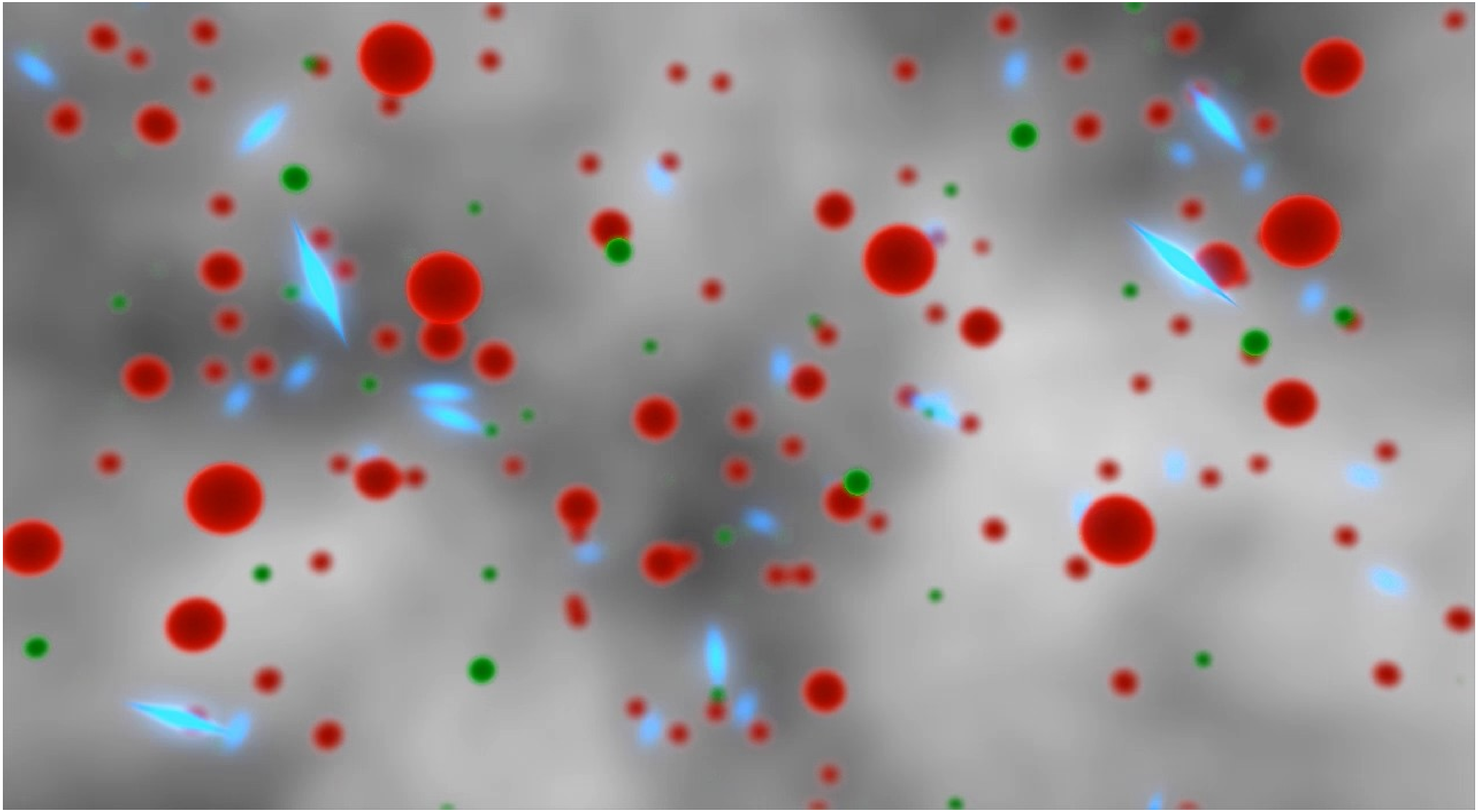
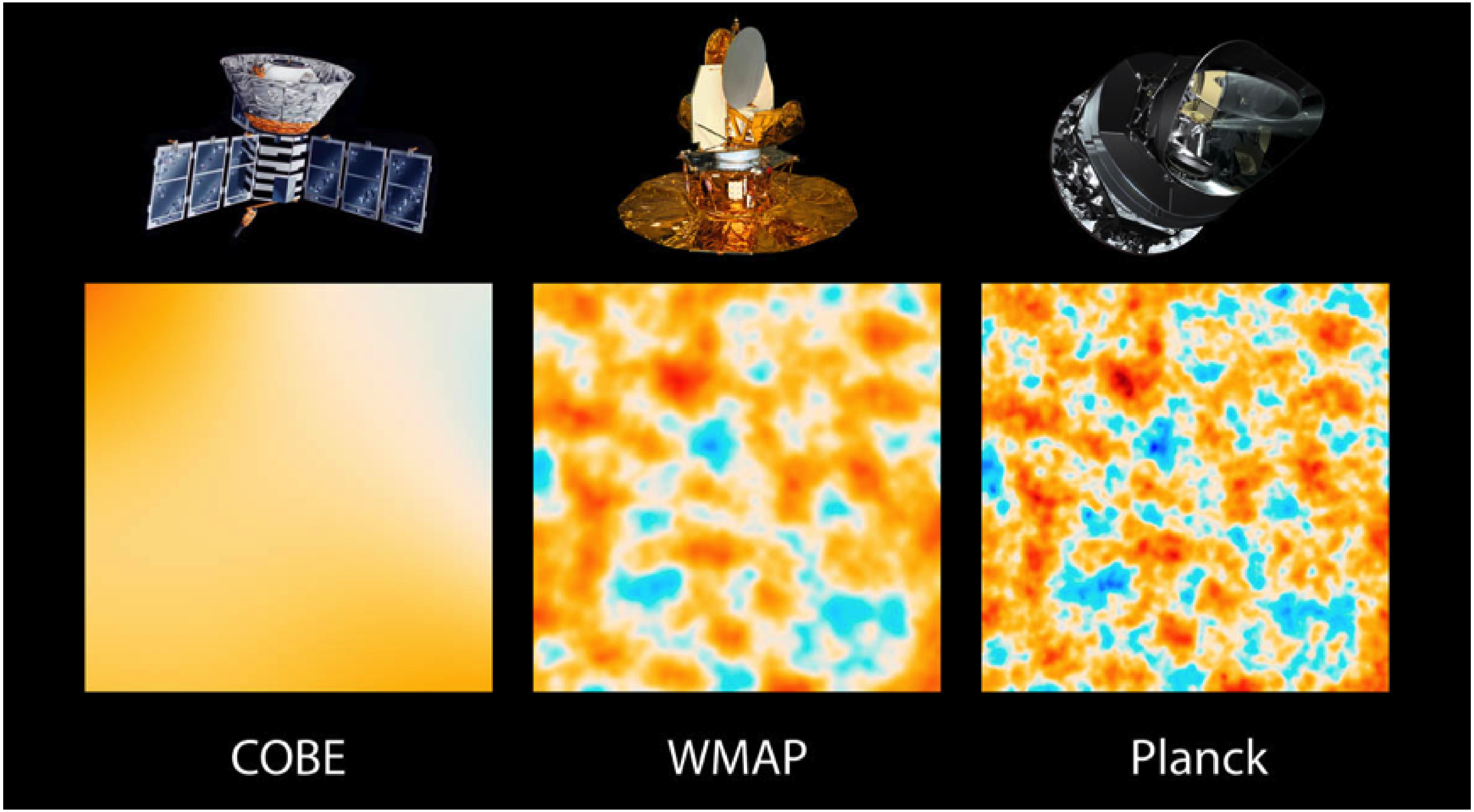
Institut Lagrange de Paris



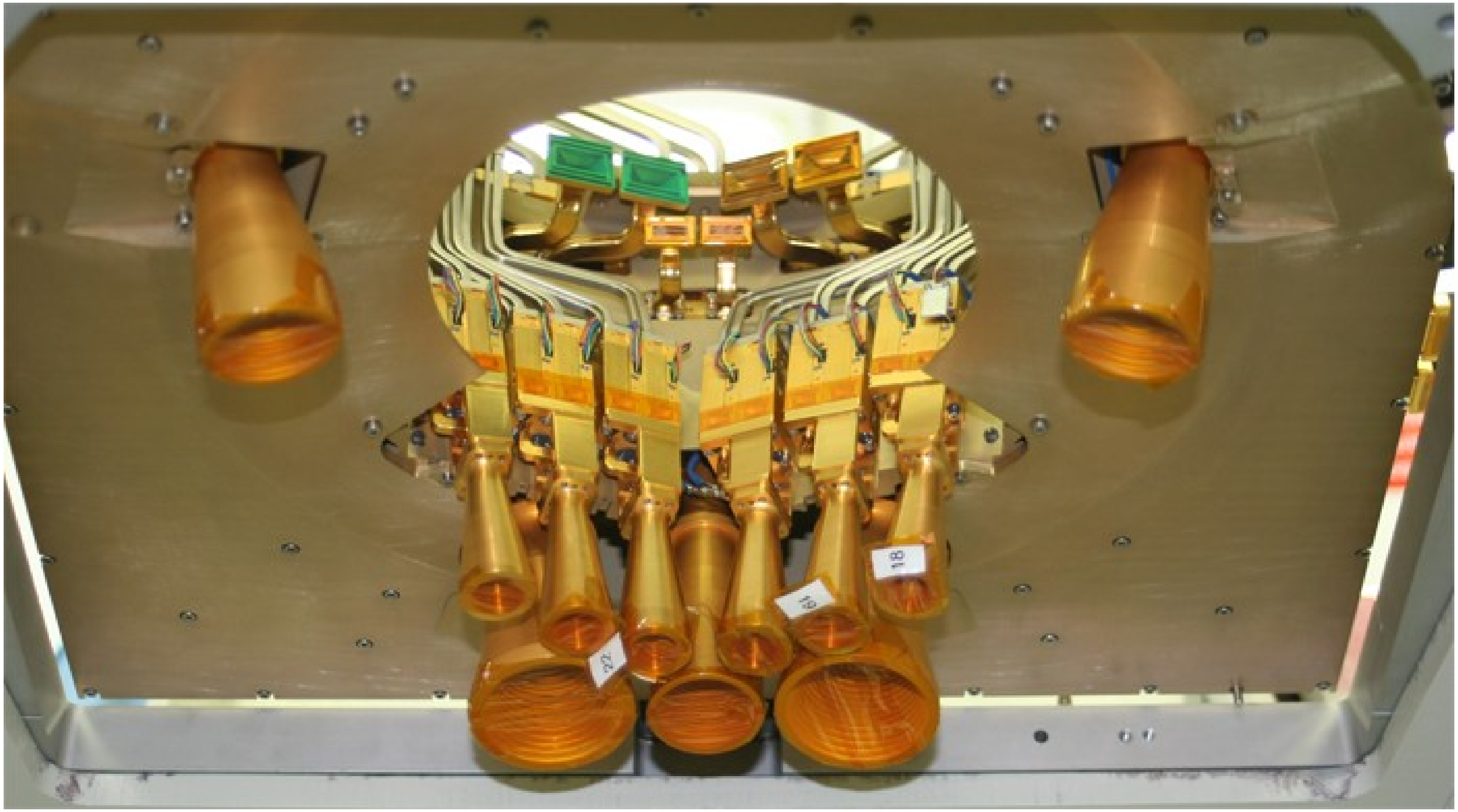
What is Planck?



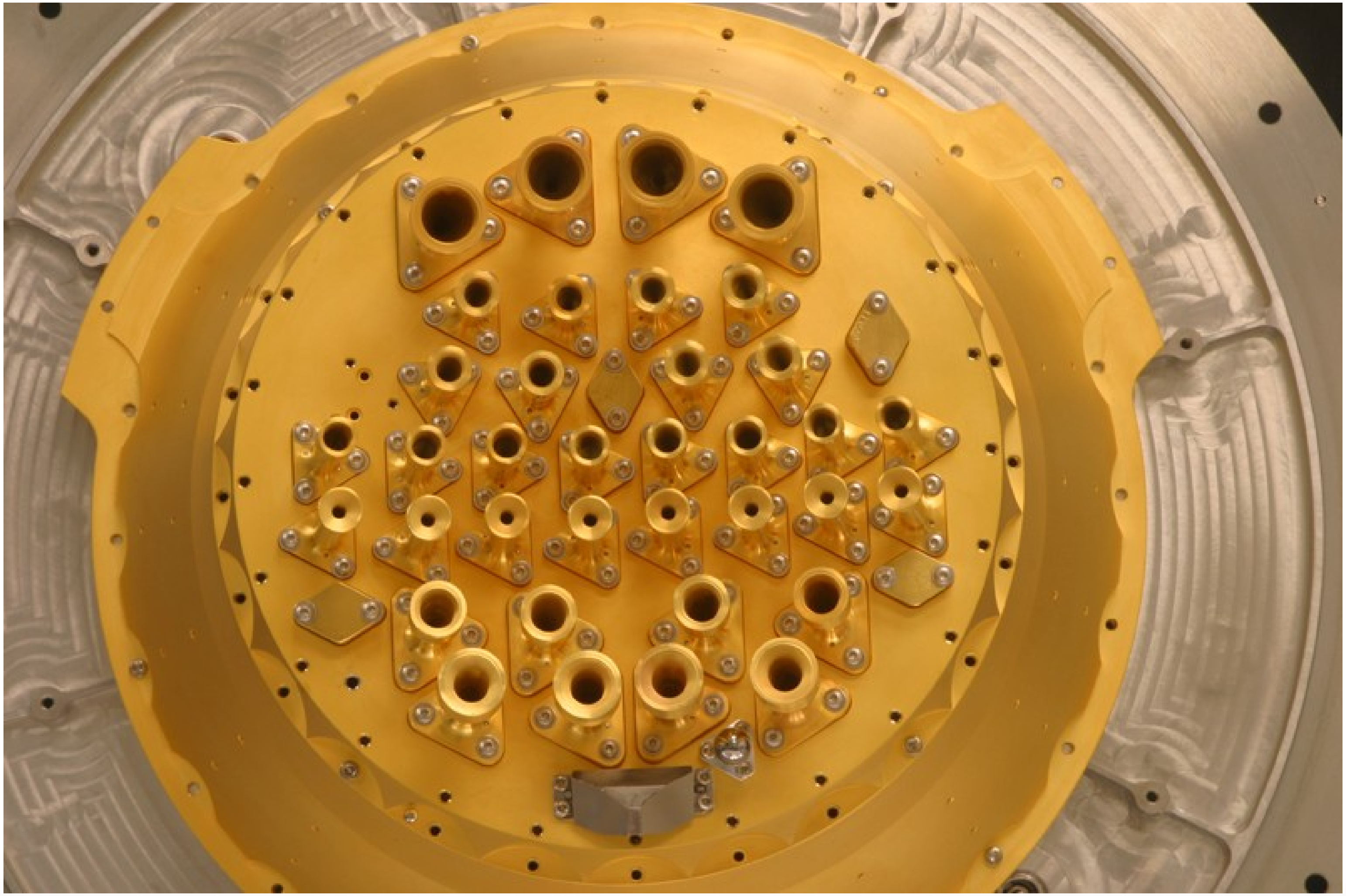
1989 2001 2009

Planck in 2009

Low Frequency Instrument ("LFI")
30, 44, 70 GHz



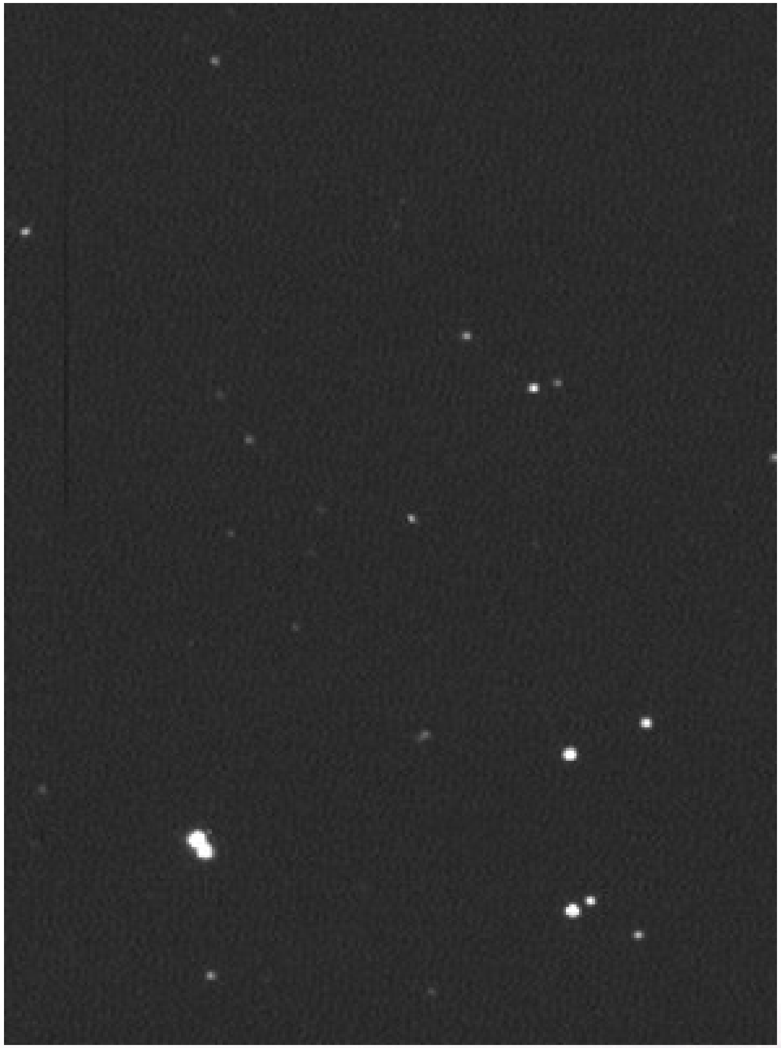
High Frequency Instrument ("HFI")
100, 143, 217, 353, 545, 853 GHZ



Planck in 2009

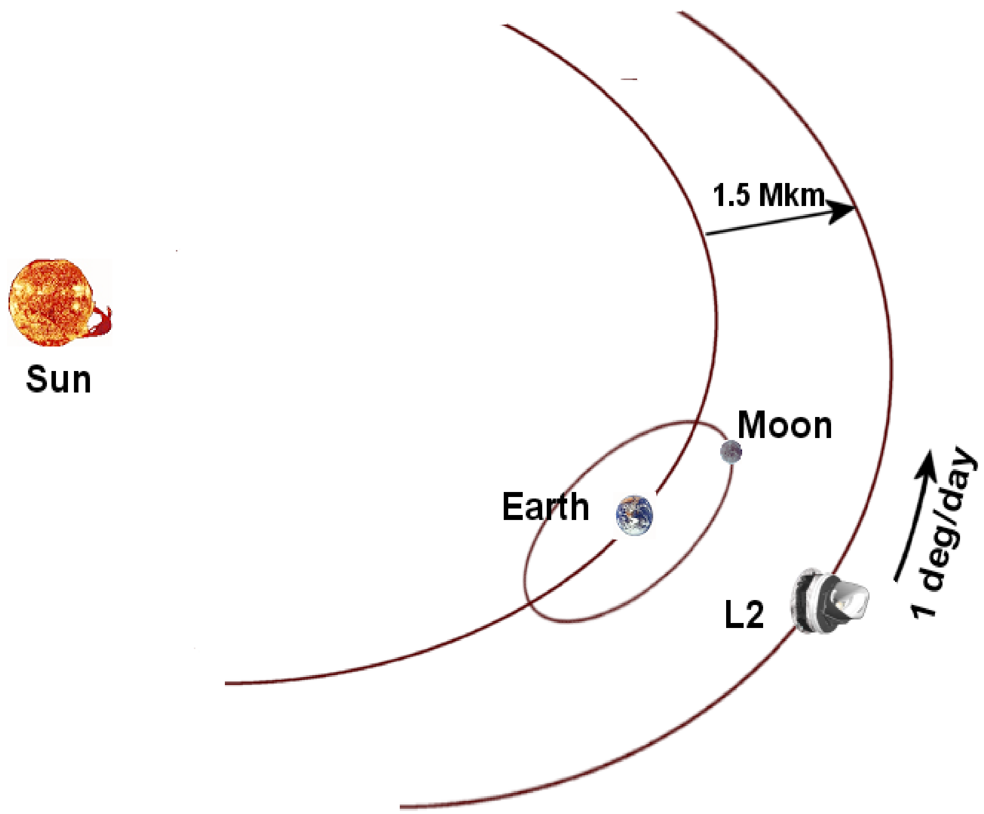
A picture-perfect launch!

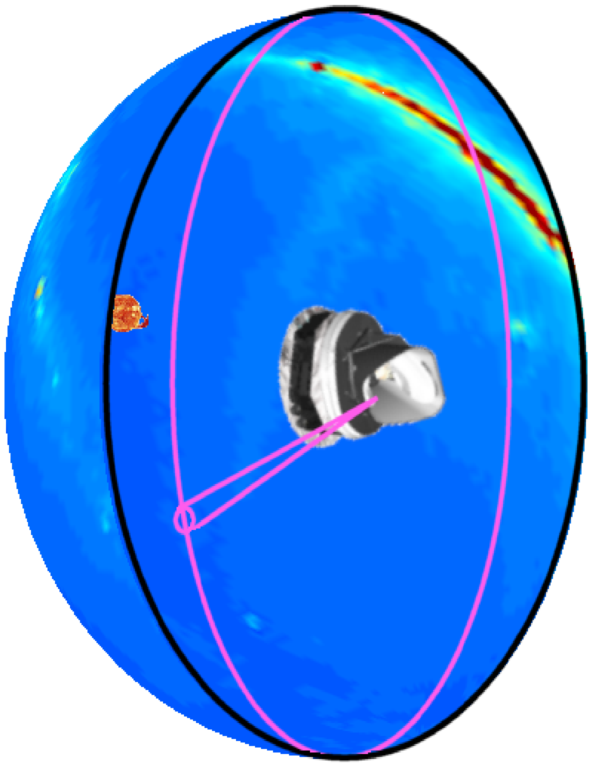
Ariane 5 lifts off with Herschel and Planck on board on 14 May 2009 at 15:12:02 CEST.

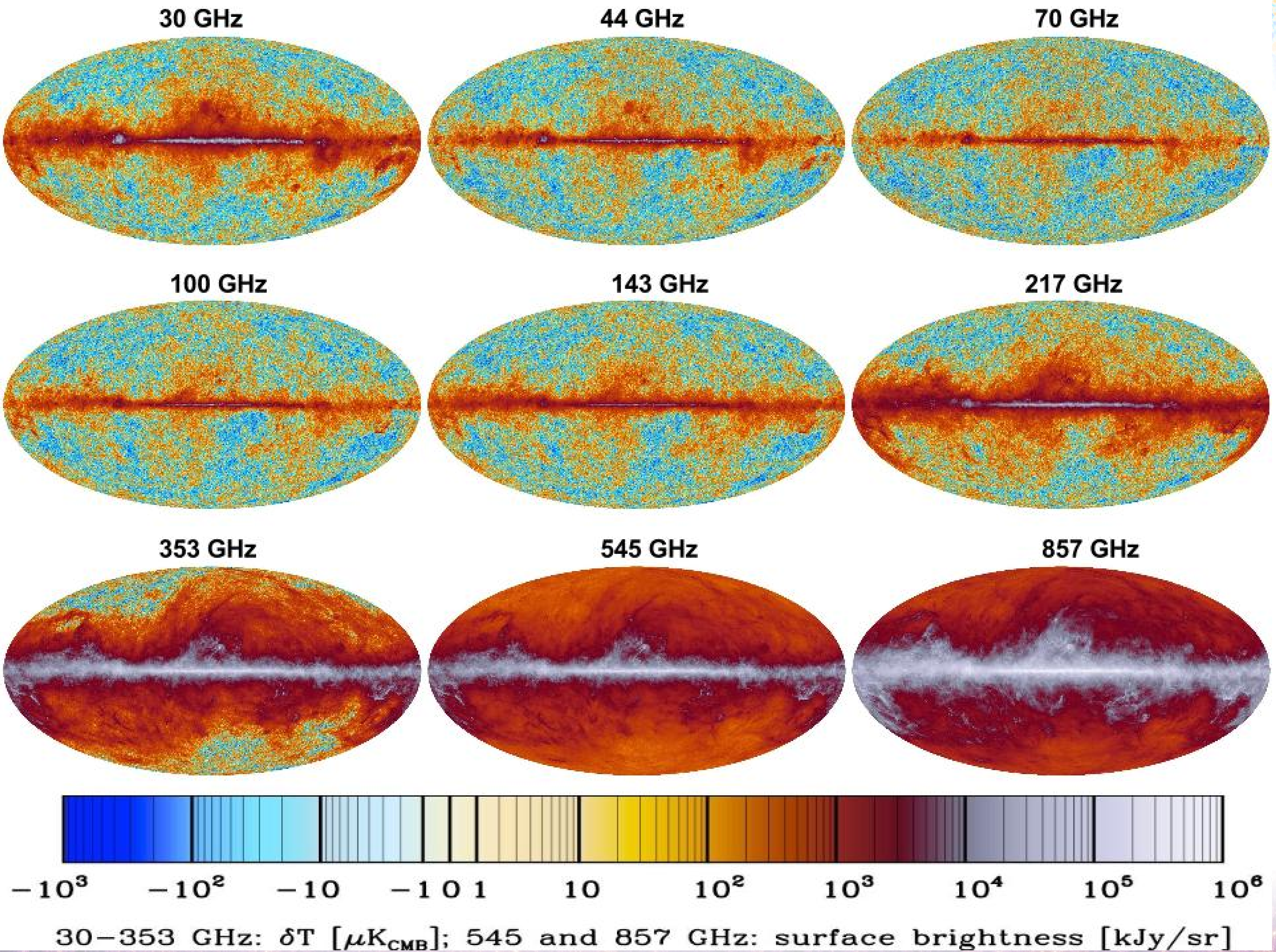


The orbit

Planck makes a map of the full sky every ~6 months.

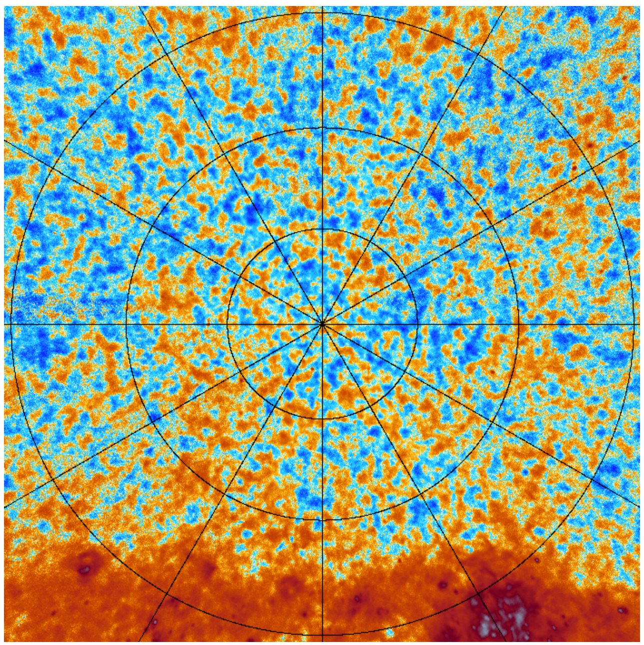




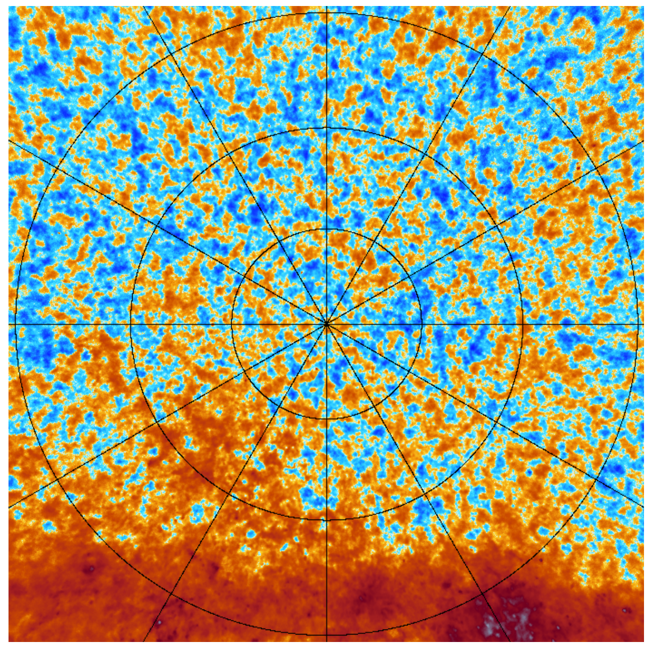

30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

Beautifully Consistent Data

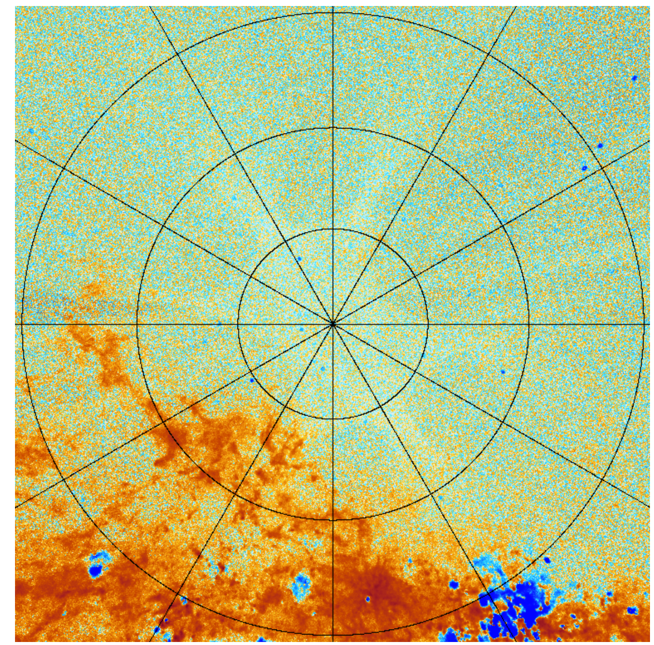
70 GHz



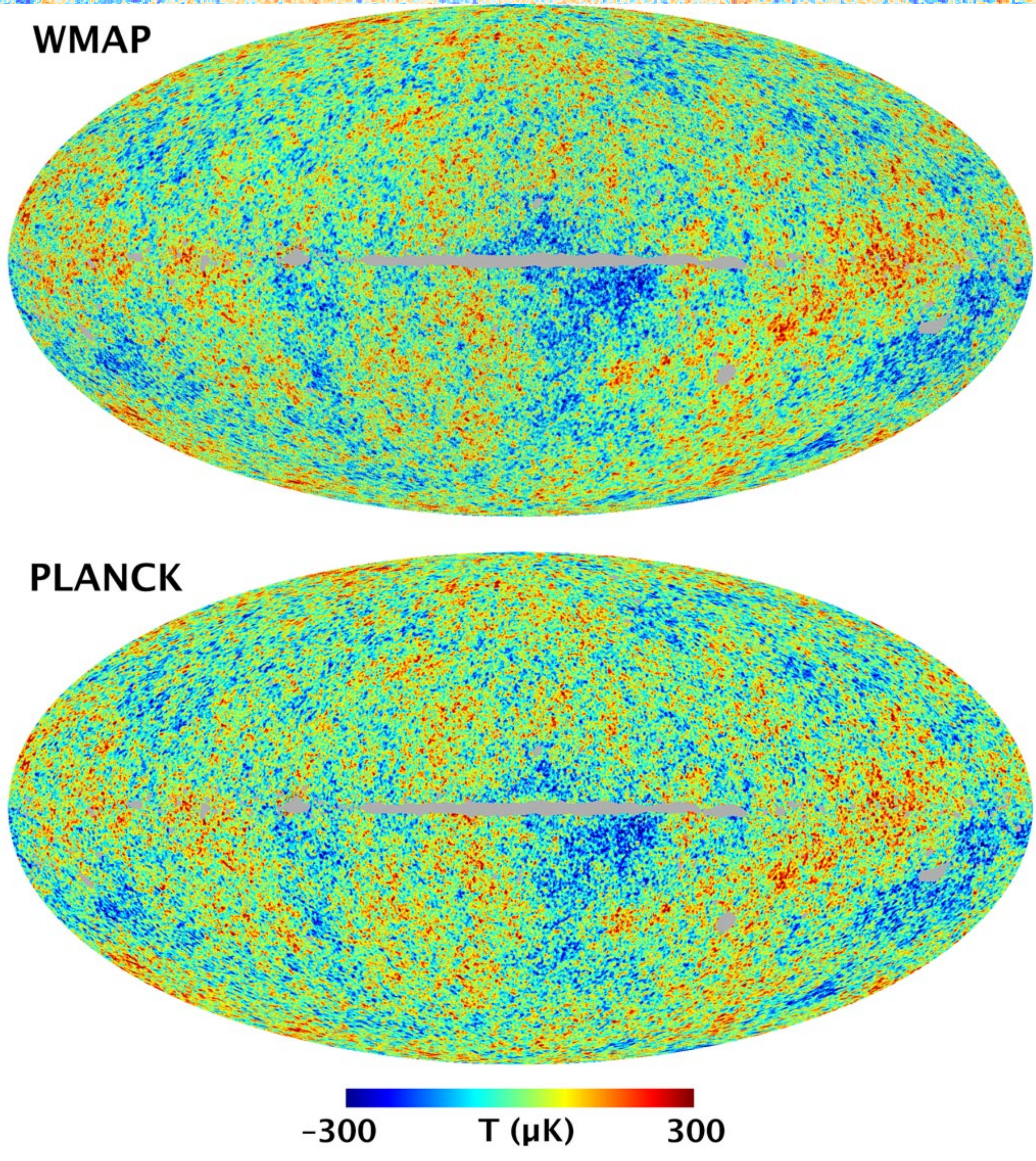
100 GHz

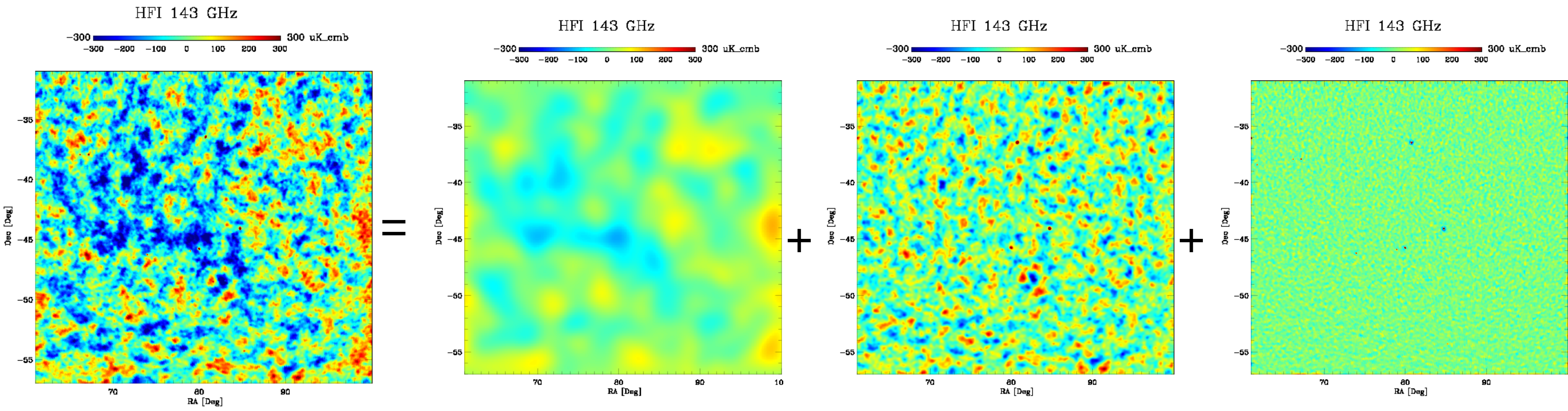


100 GHz – 70 GHz

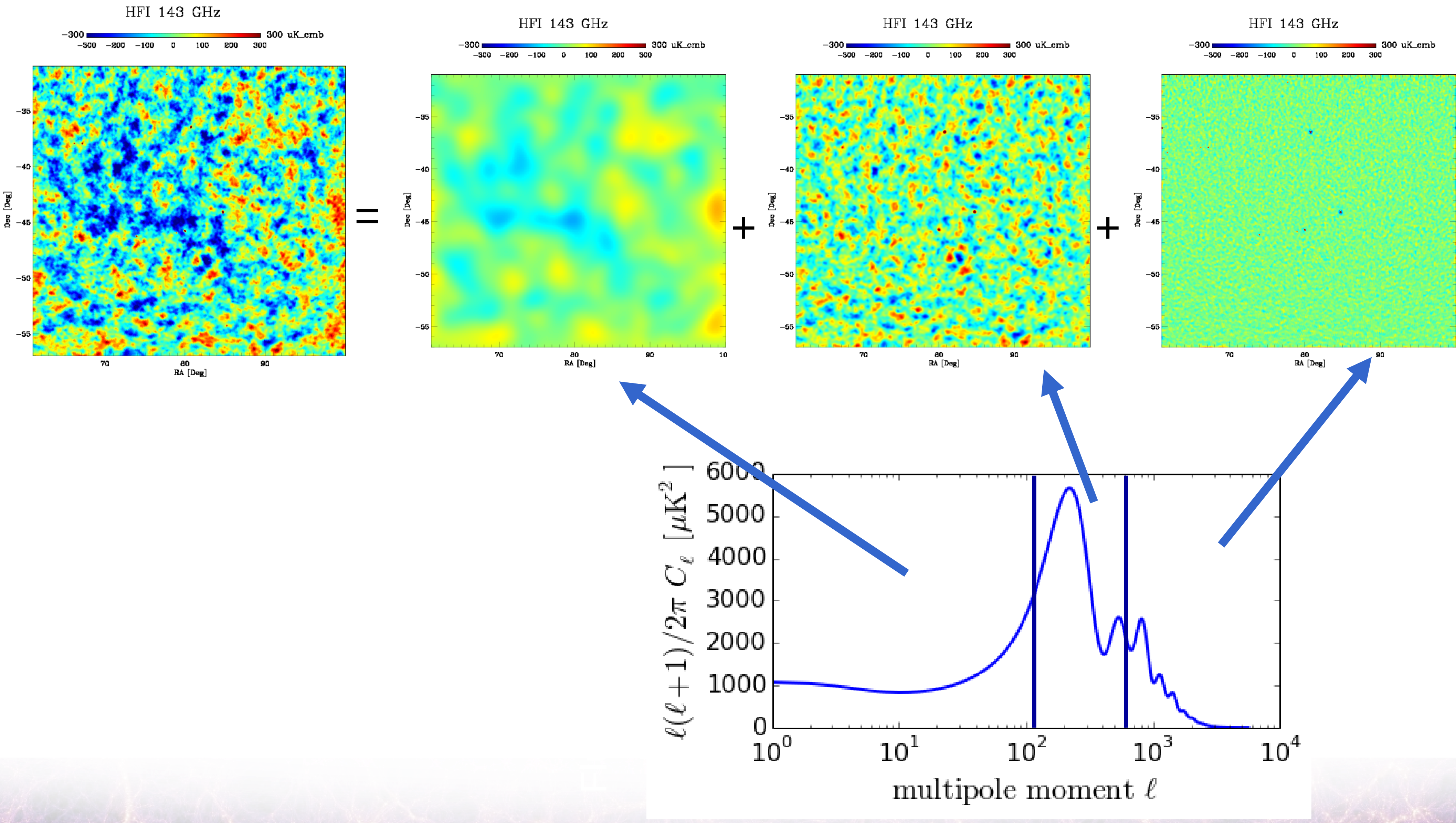


Different detector technologies, different systematics


WMAP
PLANCK
-300
T (μK)
300



To visibly see the difference between Planck and WMAP, let's decompose into band-limited maps

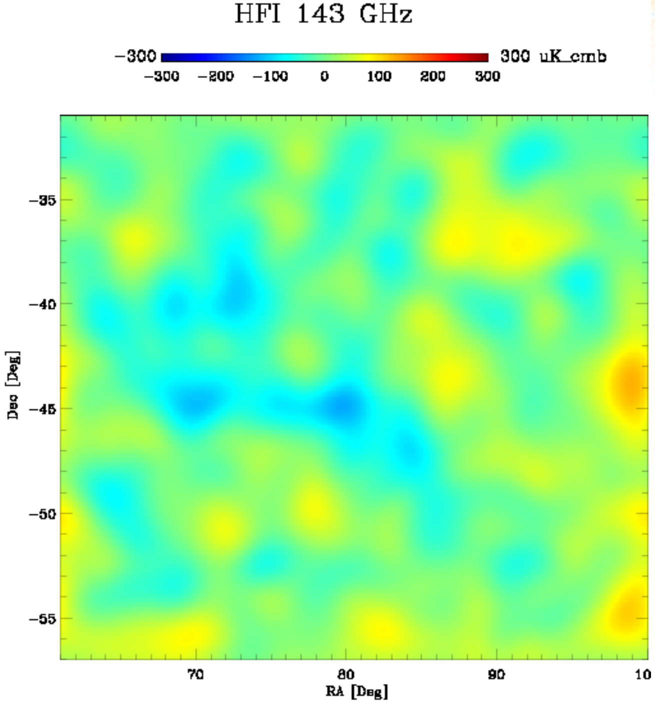


← large-scale modes

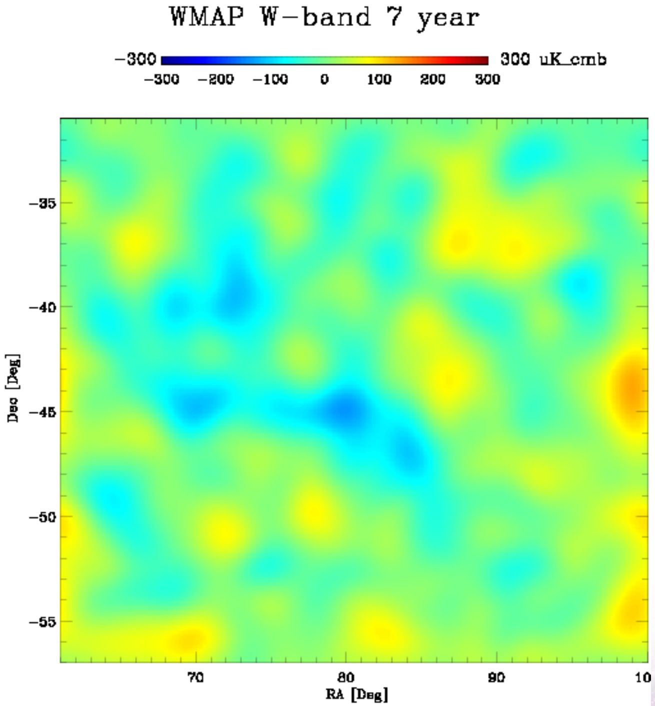
small-scale modes →

Filtered to keep: large scales

Planck 143 GHz

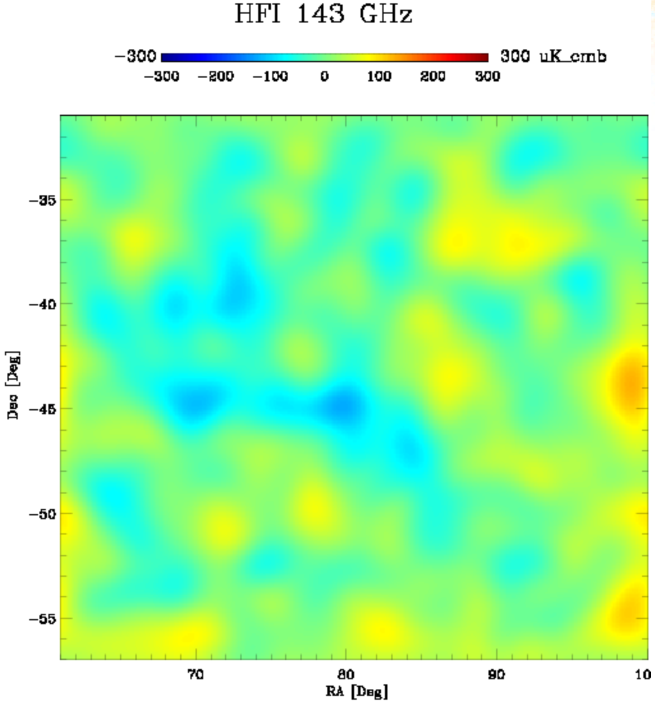


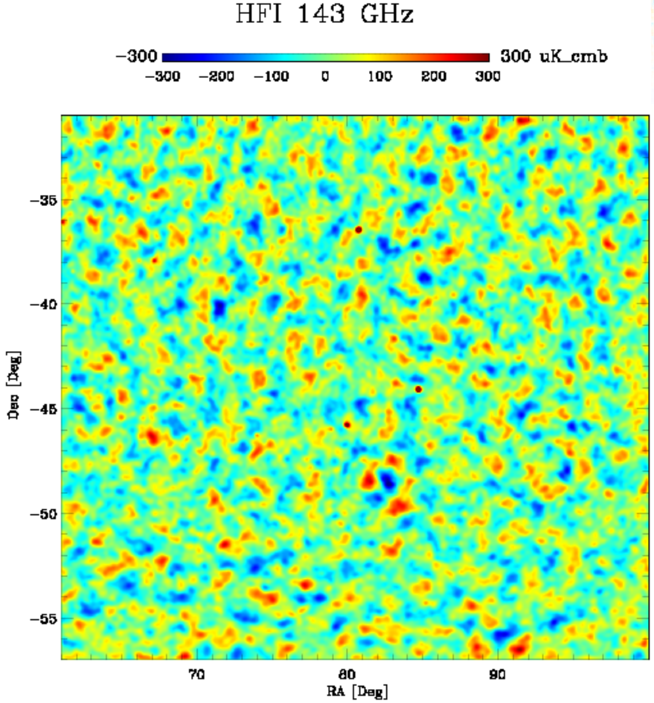
WMAP 94 GHz



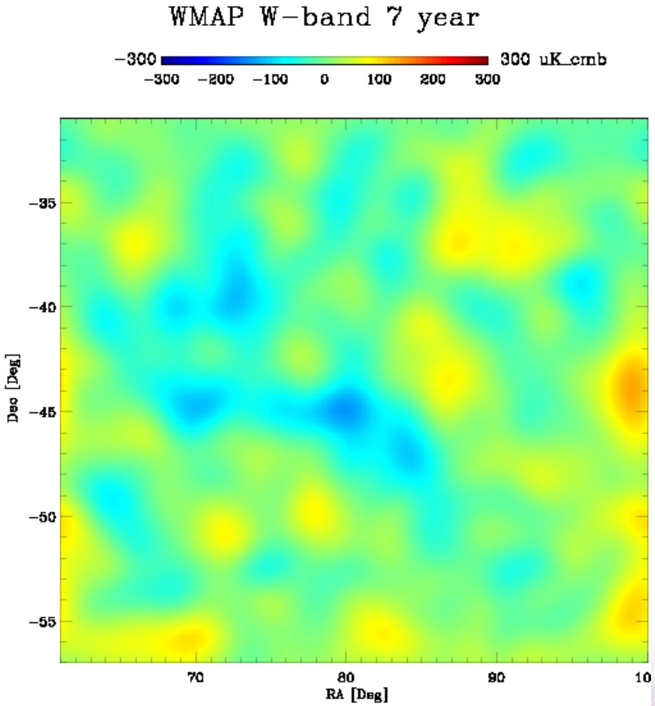
Filtered to keep: large scales intermediate scales

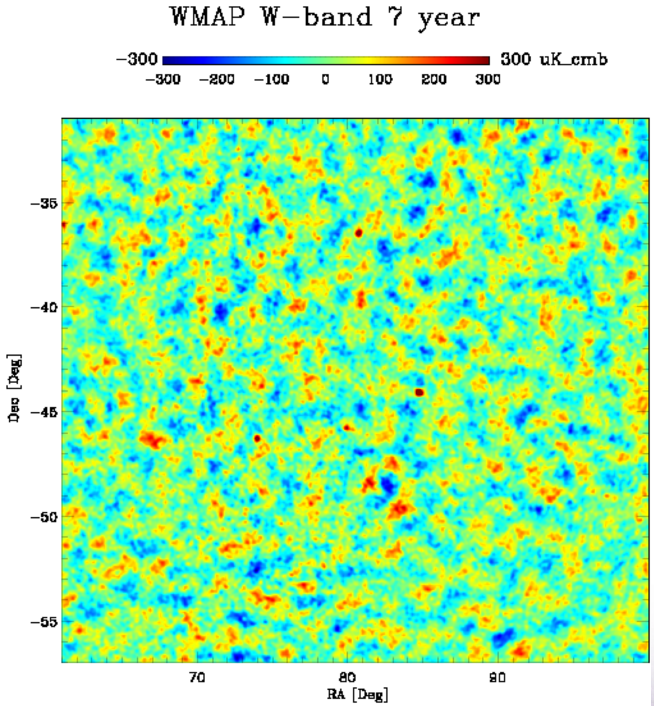
Planck 143 GHz



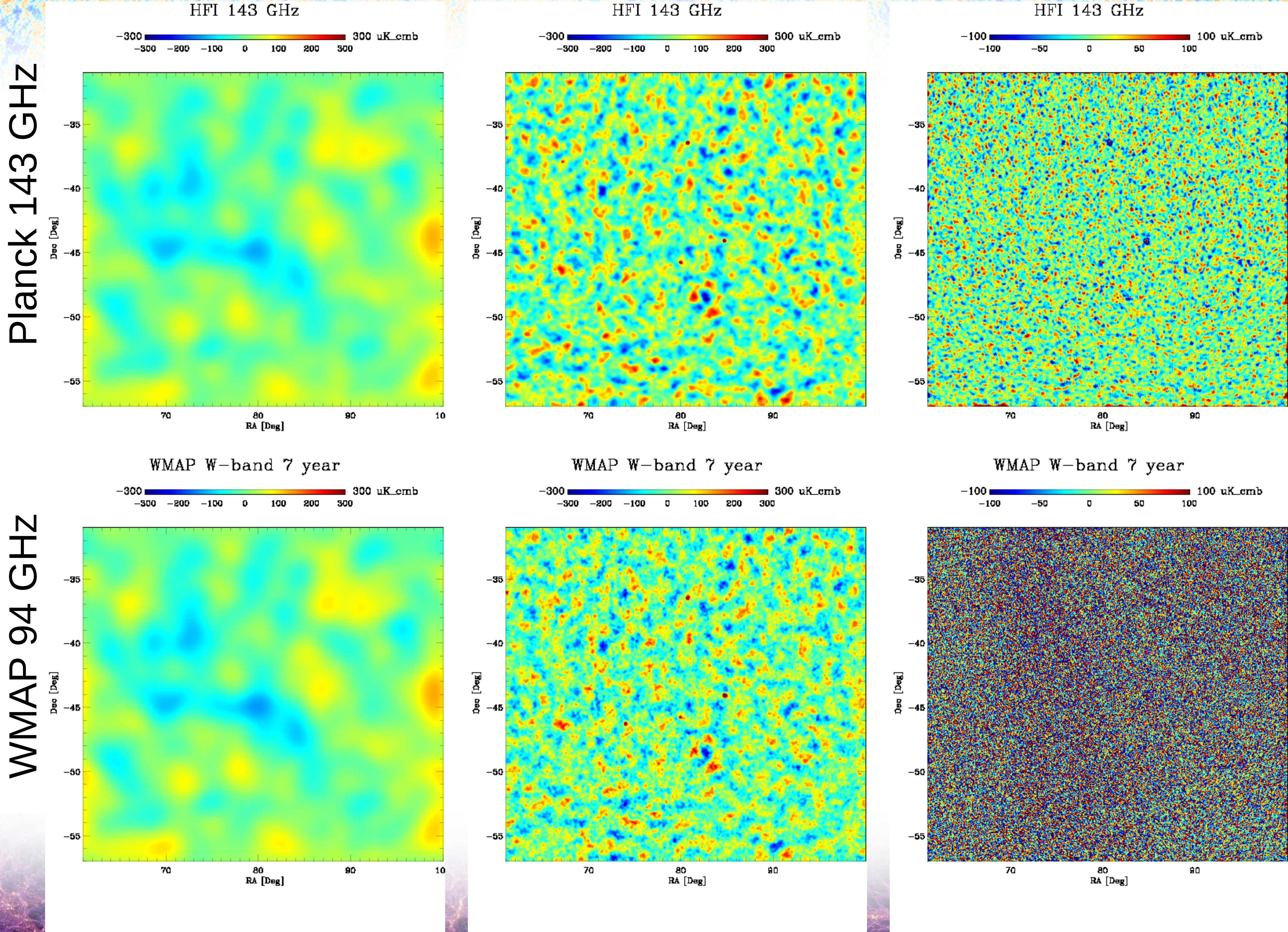


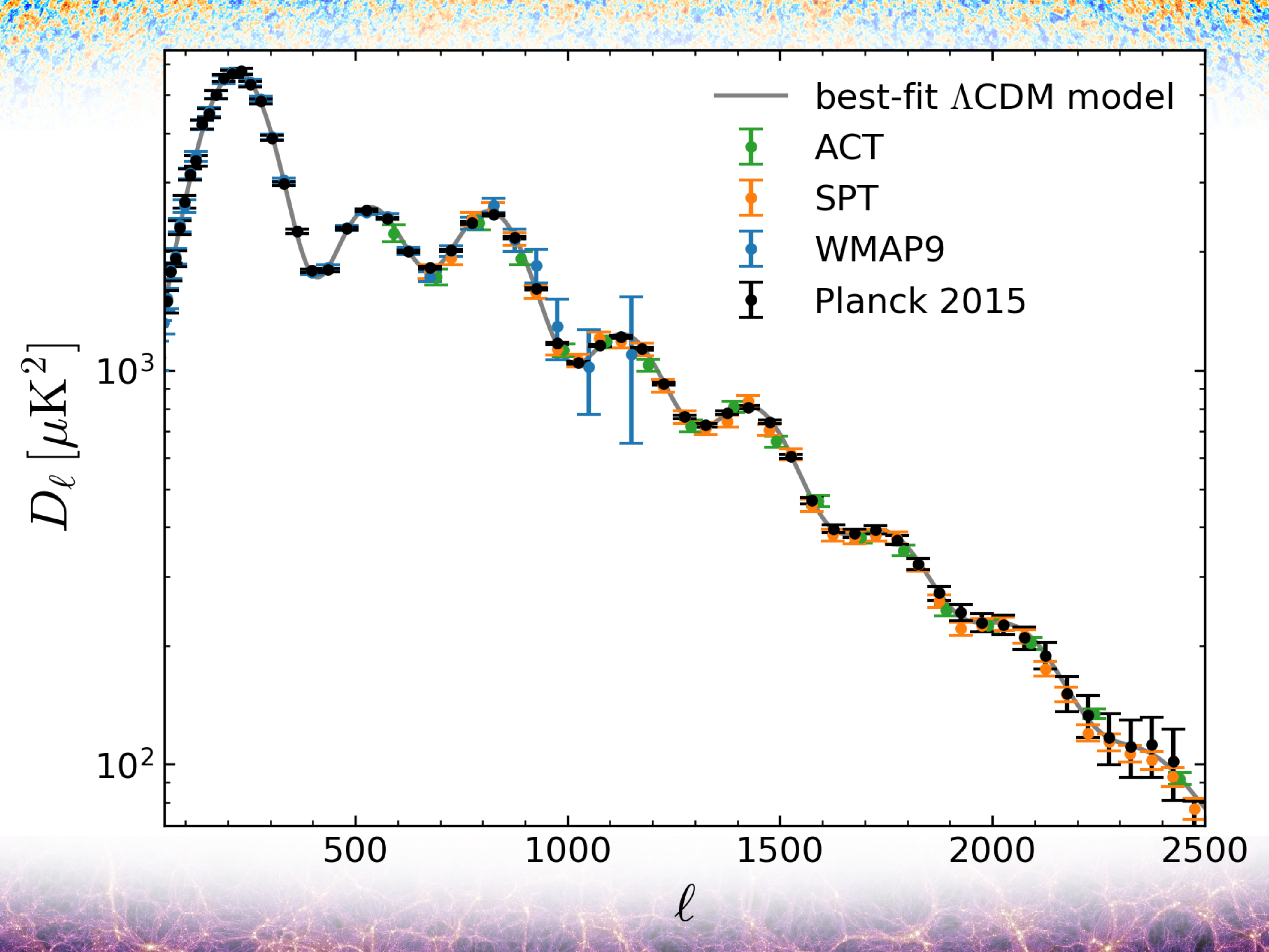
WMAP 94 GHz



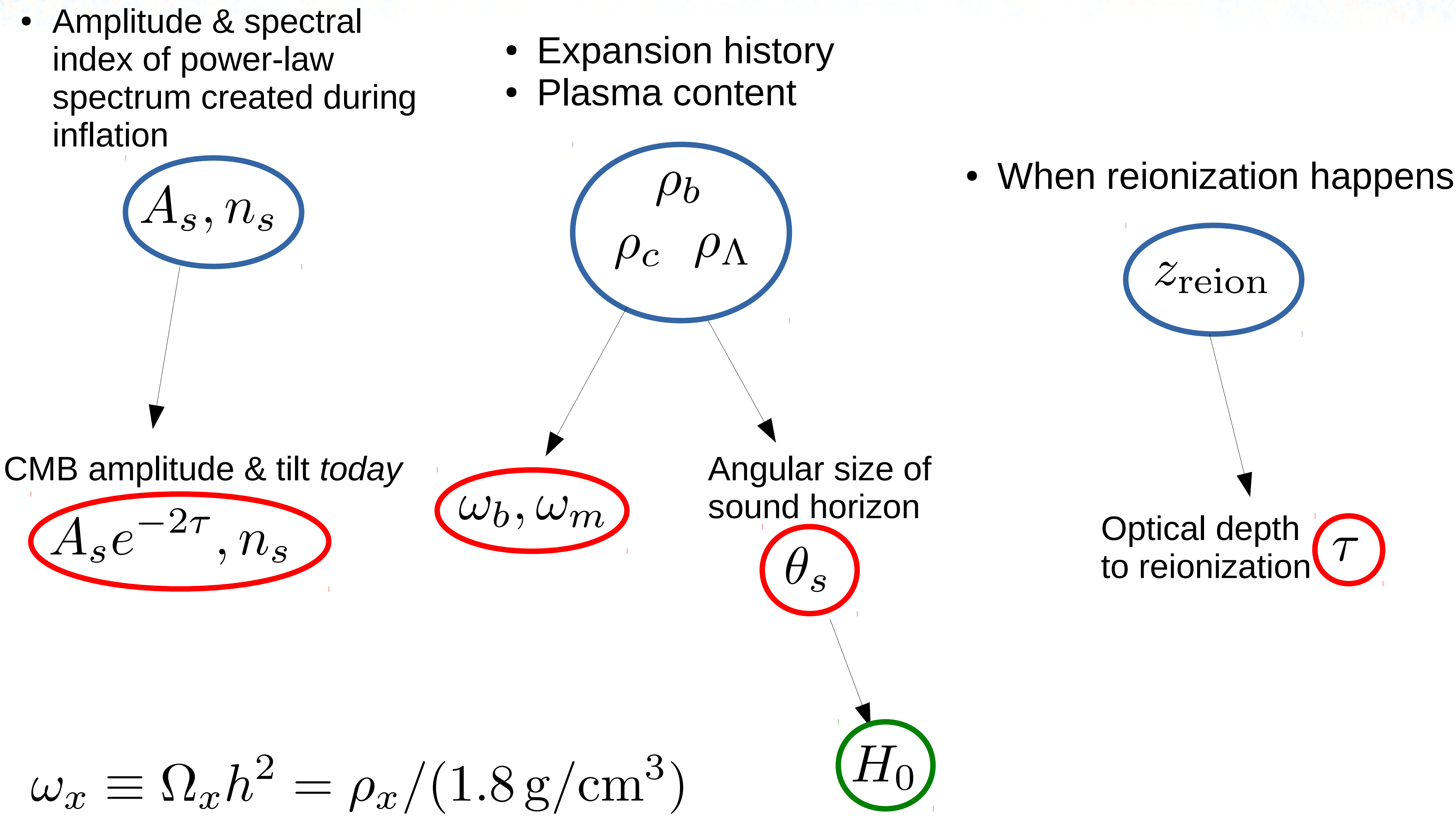


Filtered to keep: large scales intermediate scales small scales




best-fit ΛCDM model
ACT
SPT
WMAP9
Planck 2015
$D_\ell\ [\mu\mathrm{K}^2]$
10^3
10^2
500
1000
1500
2000
2500
ℓ

The 6 Parameter ΛCDM Model



$$\omega_x \equiv \Omega_x h^2 = \rho_x/(1.8\,\mathrm{g/cm^3})$$

In ΛCDM, by definition, other parameters are fixed at their default values:

$w = -1, \Omega_k = 0, N_{\rm eff} = 3.046, \Sigma m_\nu = 0.06\,\mathrm{eV}$, etc...

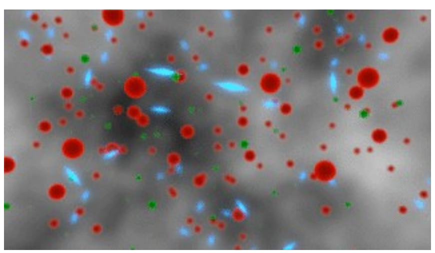
- Universe was very uniform ⇒ linear perturbation theory

External driving force (gravity)

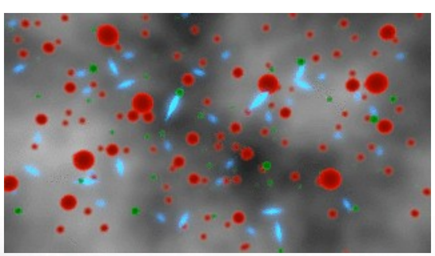
$$\ddot{\Theta}(\vec{x},t) - c_s(t)^2\Theta''(\vec{x},t) = F(\vec{x},t)$$

$$\ddot{\Theta}_{\vec{k}}(t) + k^2 c_s(t)^2\Theta_{\vec{k}}(t) = F_{\vec{k}}(t)$$

$$\omega = k\, c_s(t)$$



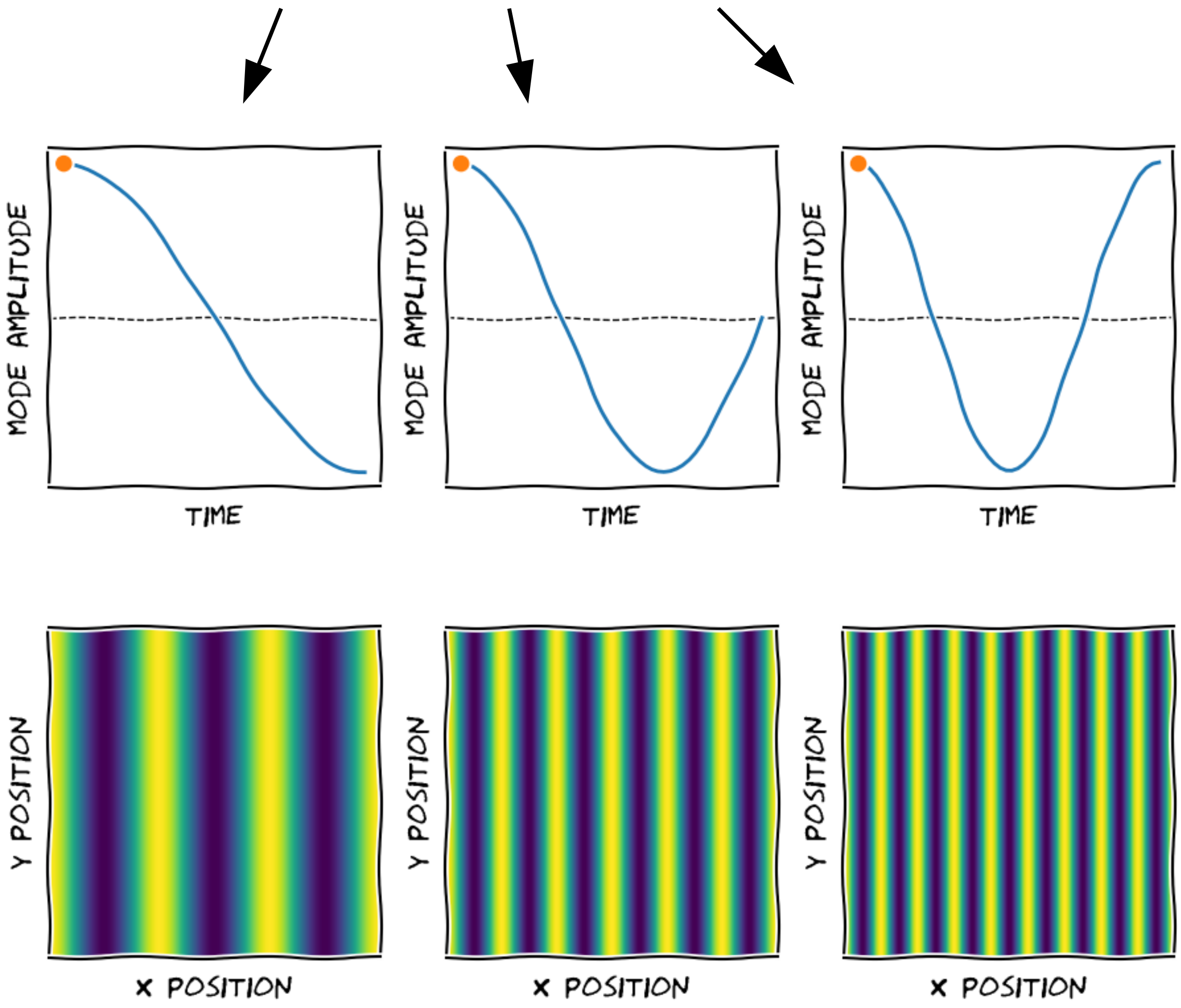
$$c_s = \frac{c}{\sqrt{3}}$$

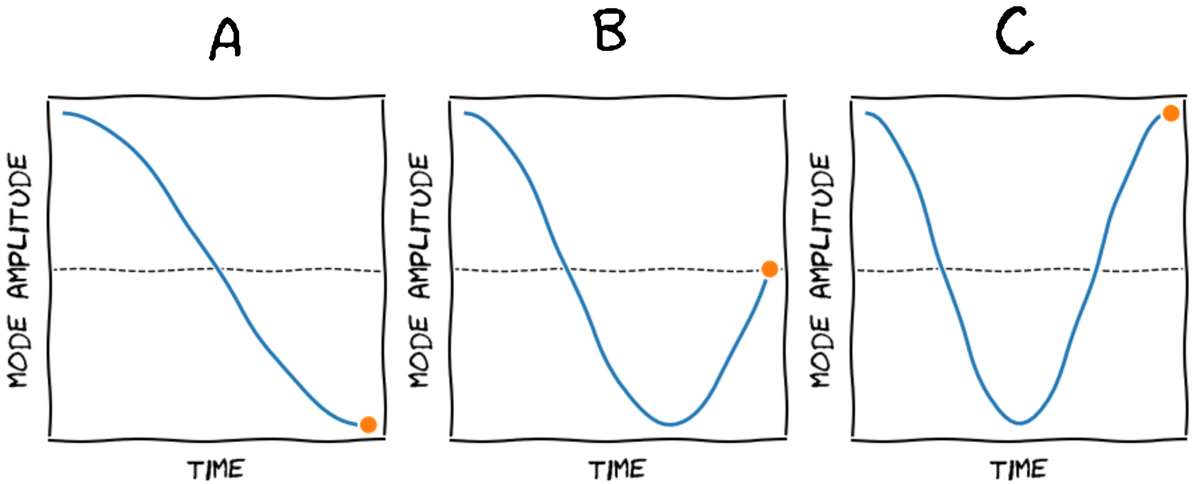


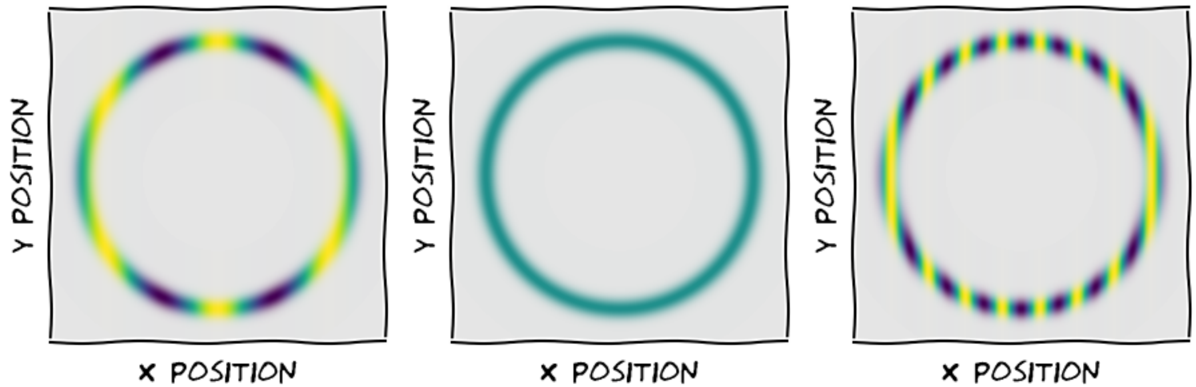
$$c_s \to 0$$

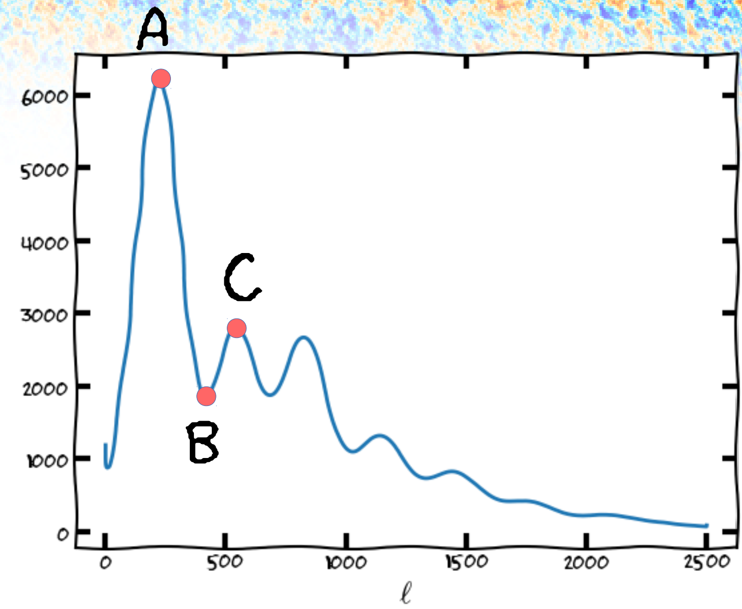
* I’ve neglected a “Hubble drag” term for simplicity in the above equations

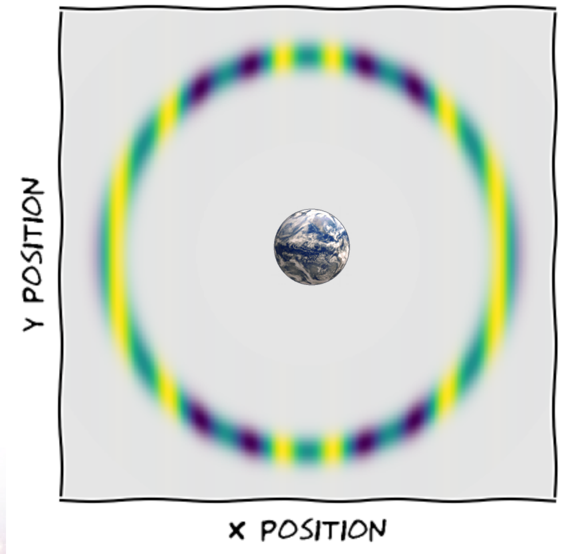
Initial amplitudes set by inflation (A_s, n_s)

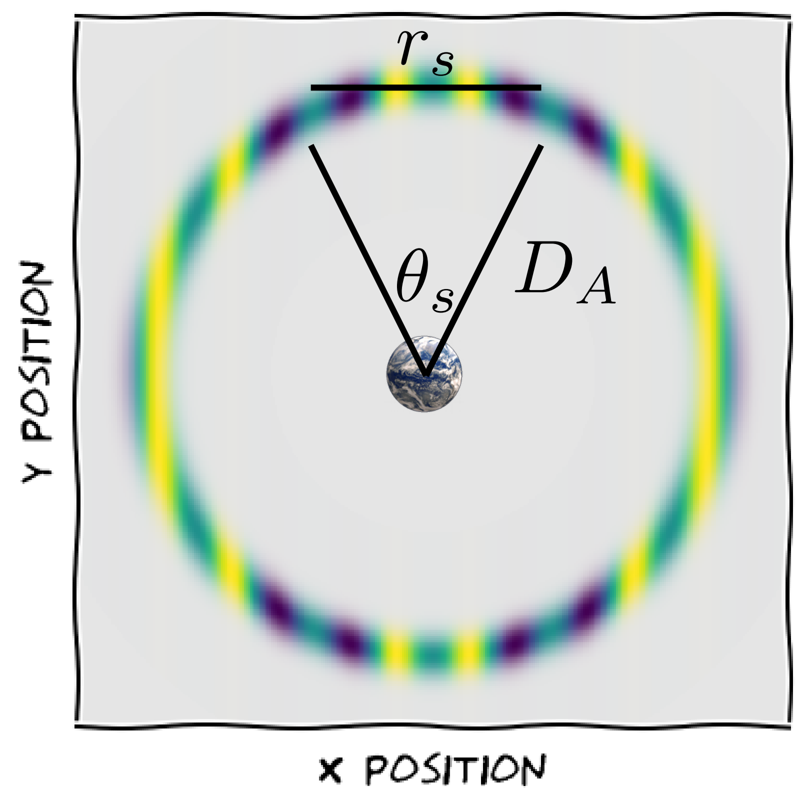



A
B
C
MODE AMPLITUDE
TIME

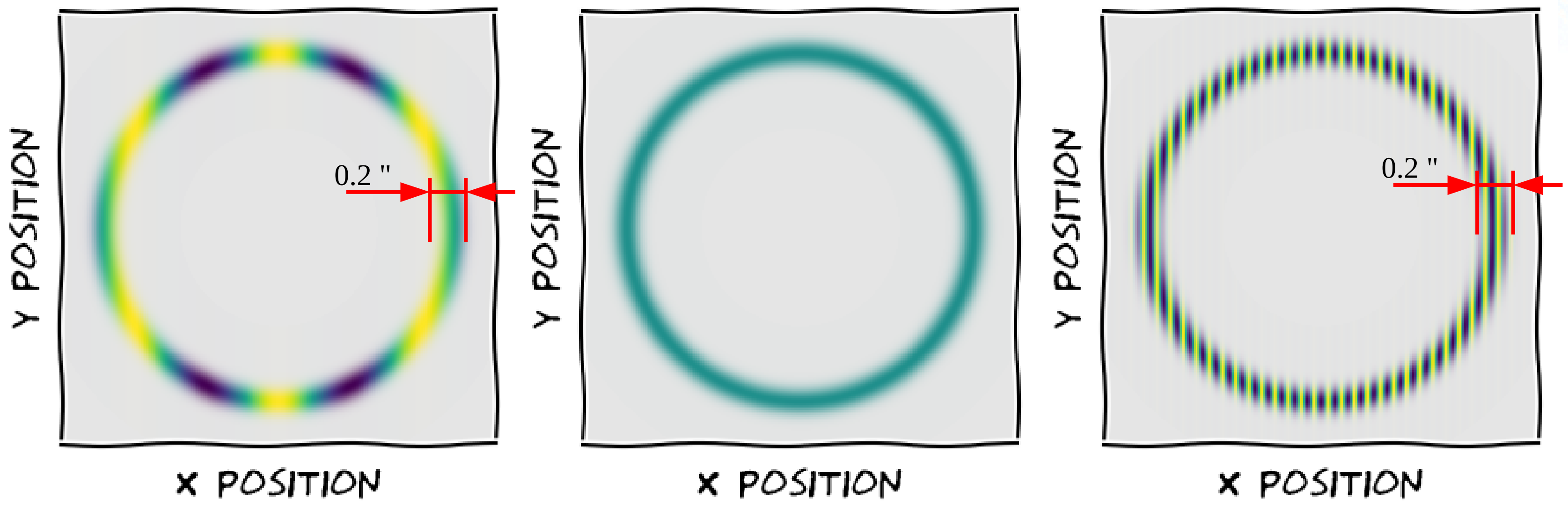

Y POSITION
X POSITION

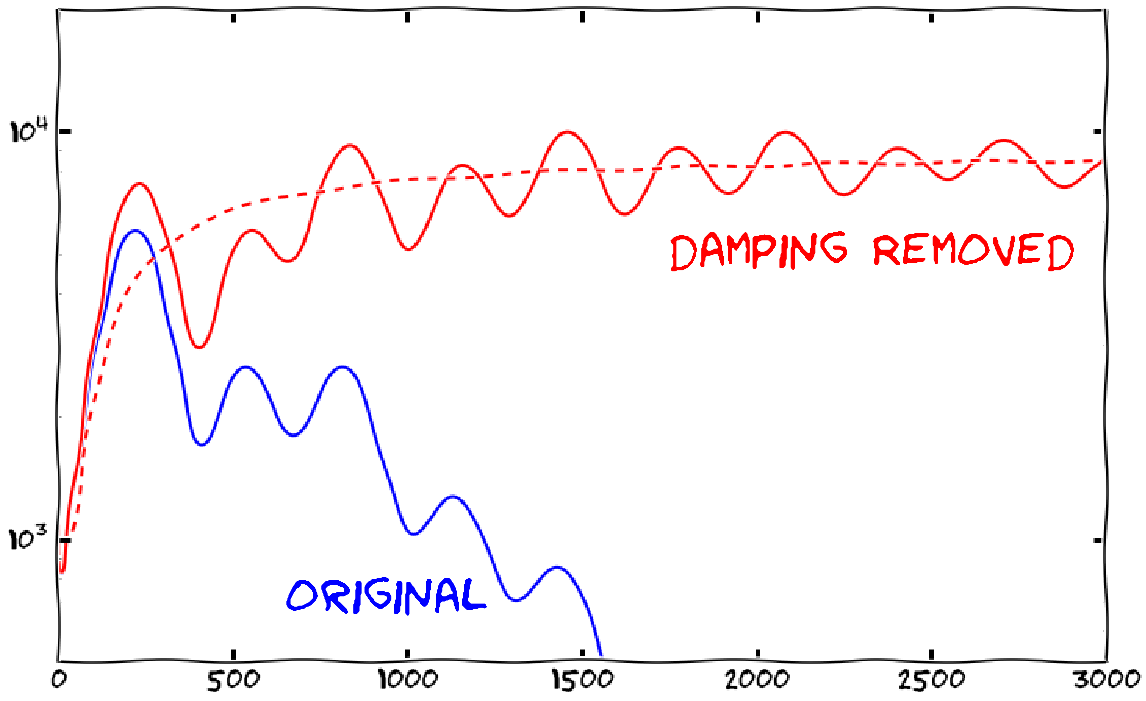

A
B
C
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500
ℓ


Y POSITION
X POSITION



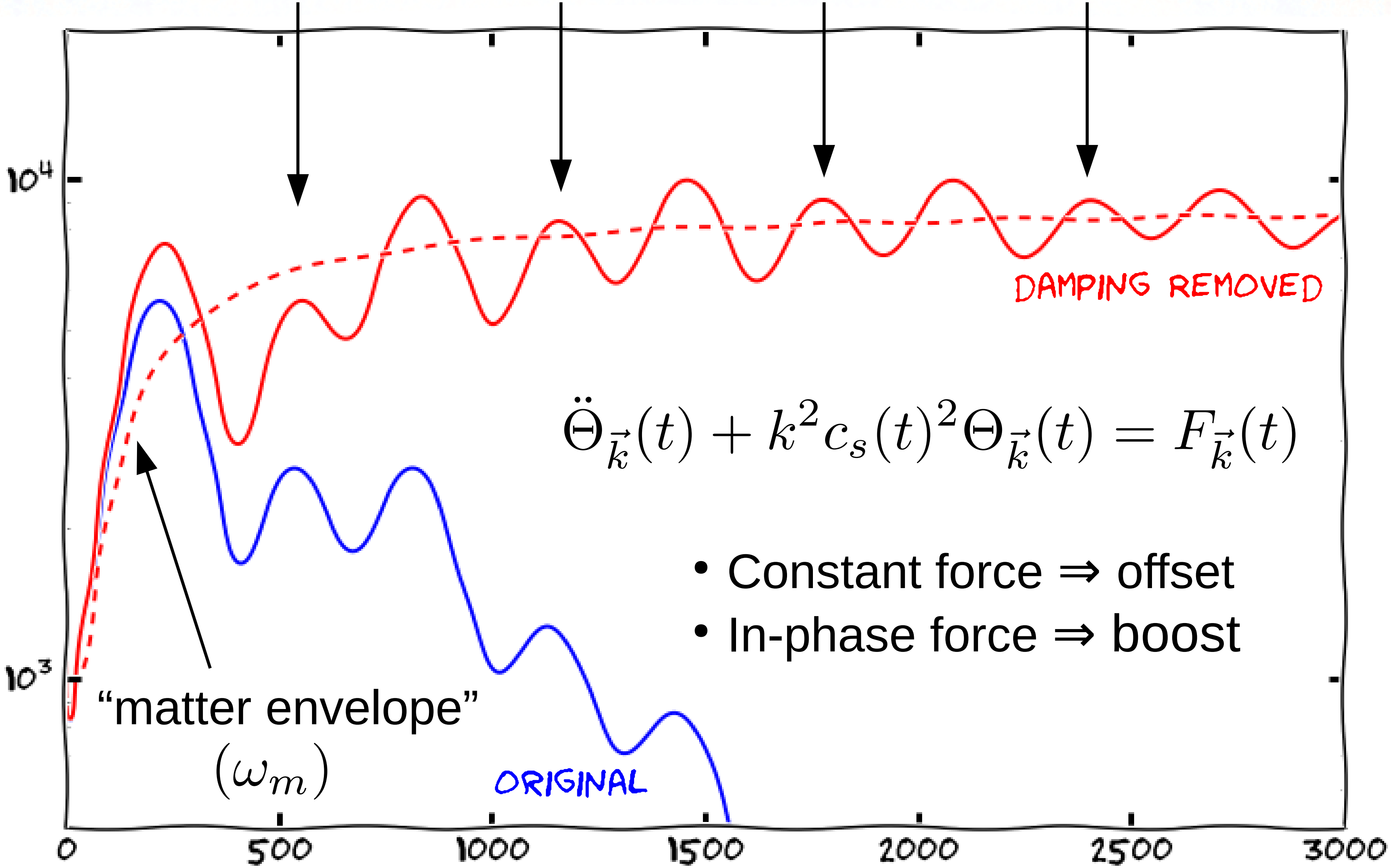
$$\theta_s = \frac{r_s}{D_A} \sim \frac{1/H(\text{recombination})}{1/H(\text{today})} \sim \frac{1/\sqrt{\omega_m}}{1/\sqrt{\omega_\Lambda}}$$





(Formula to remove damping from Hu & White 1997)

Even / odd peak height modulation (ω_b)



$$\ddot{\Theta}_{\vec{k}}(t) + k^2 c_s(t)^2 \Theta_{\vec{k}}(t) = F_{\vec{k}}(t)$$

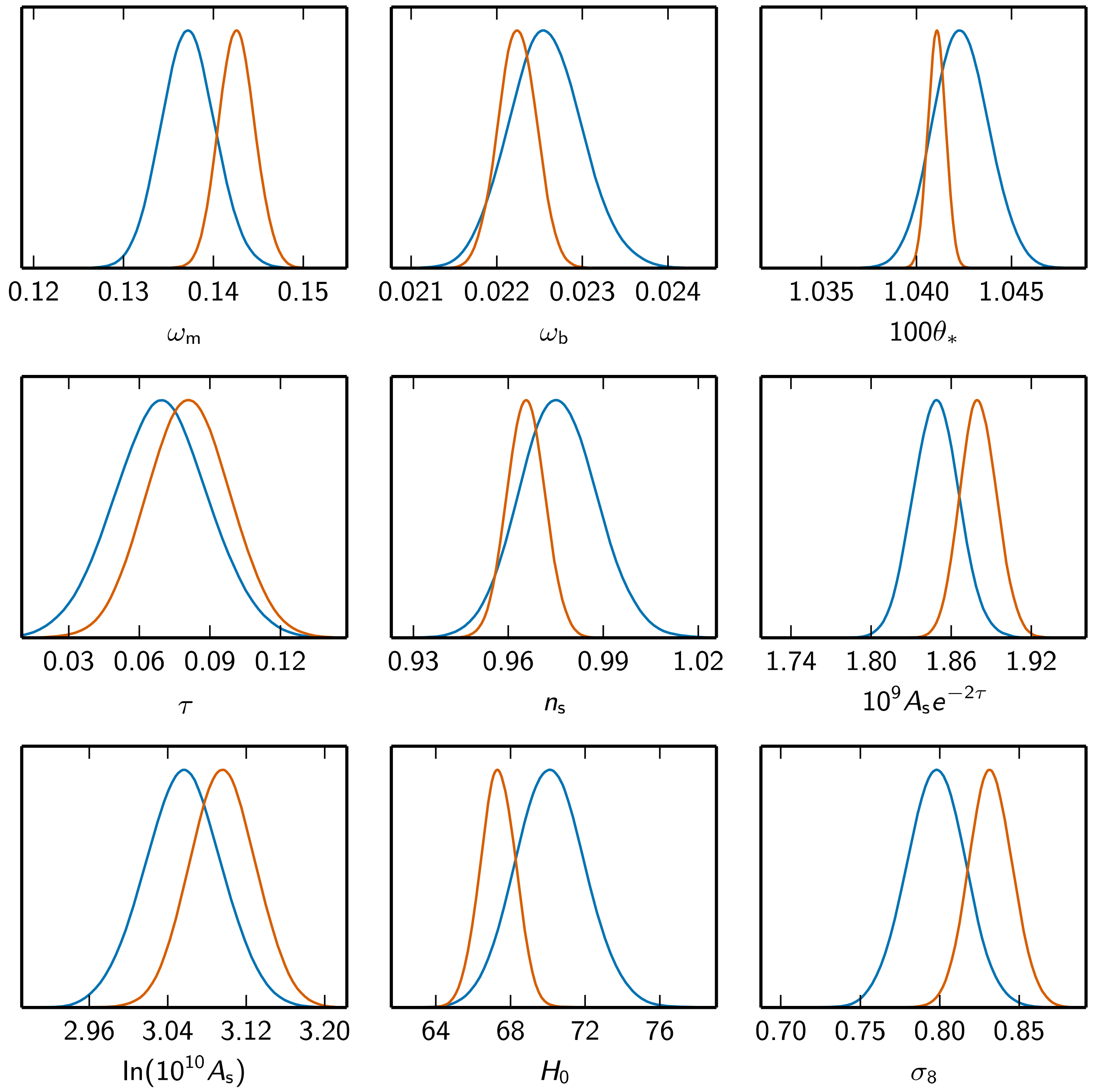
- Constant force ⇒ offset
- In-phase force ⇒ boost

“Primary” 6 LCDM parameters

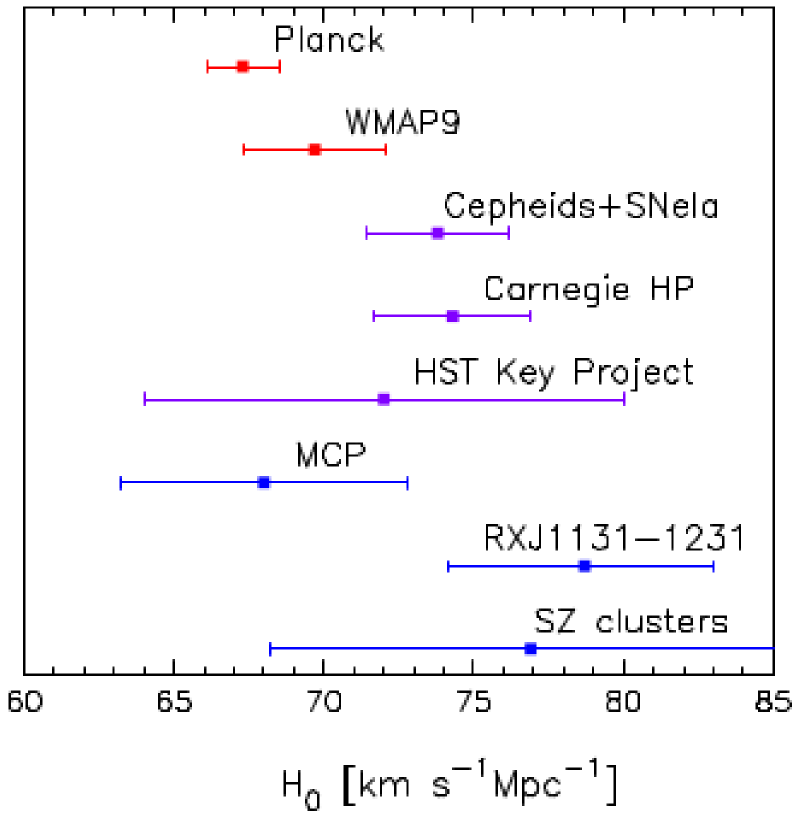
Planck $\ell<800$

Planck $\ell<2500$

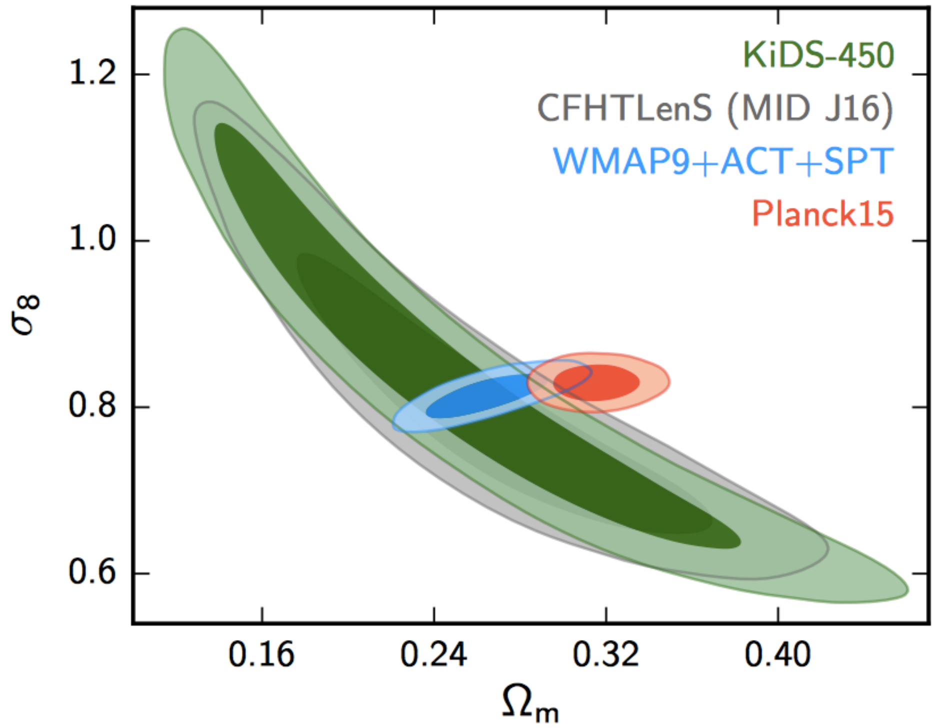
“Derived”



$$H_0 = 70.0 \pm 1.9 \quad \rightarrow \quad H_0 = 67.3 \pm 1.0$$

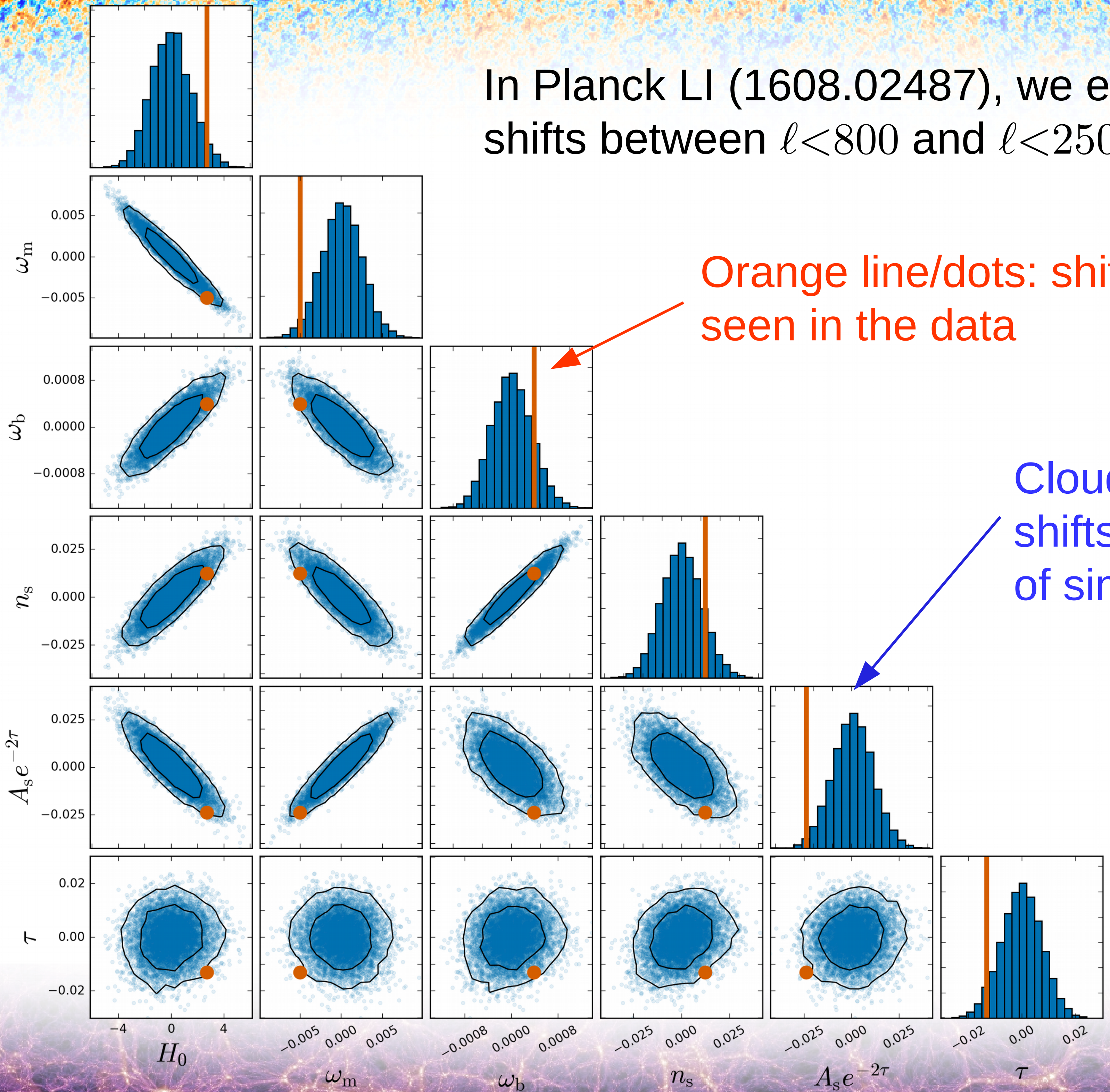


See more about this in talk by Rachel Beaton tomorrow.



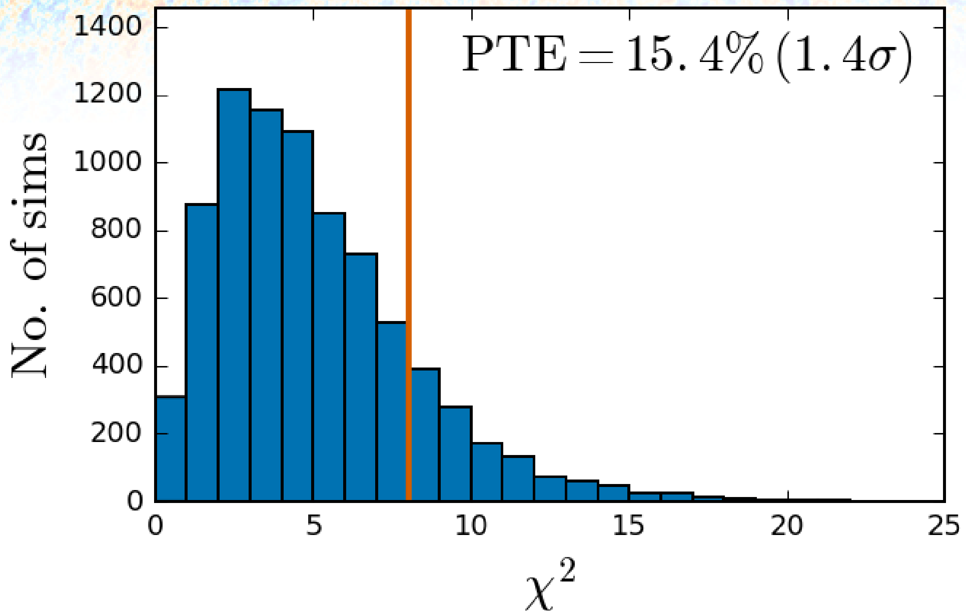
Also some tension with galaxy weak lensing...

In Planck LI (1608.02487), we examined the shifts between $\ell < 800$ and $\ell < 2500$ parameters

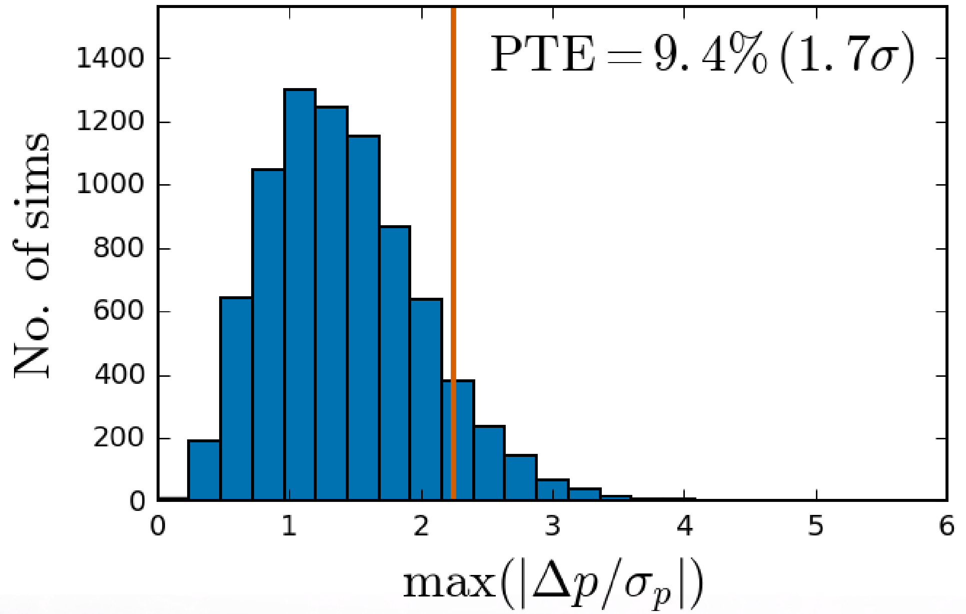


Orange line/dots: shifts seen in the data

Cloud of points: shifts from a suite of simulations



The overall significance of those shifts across 6 parameters is 1.4σ.



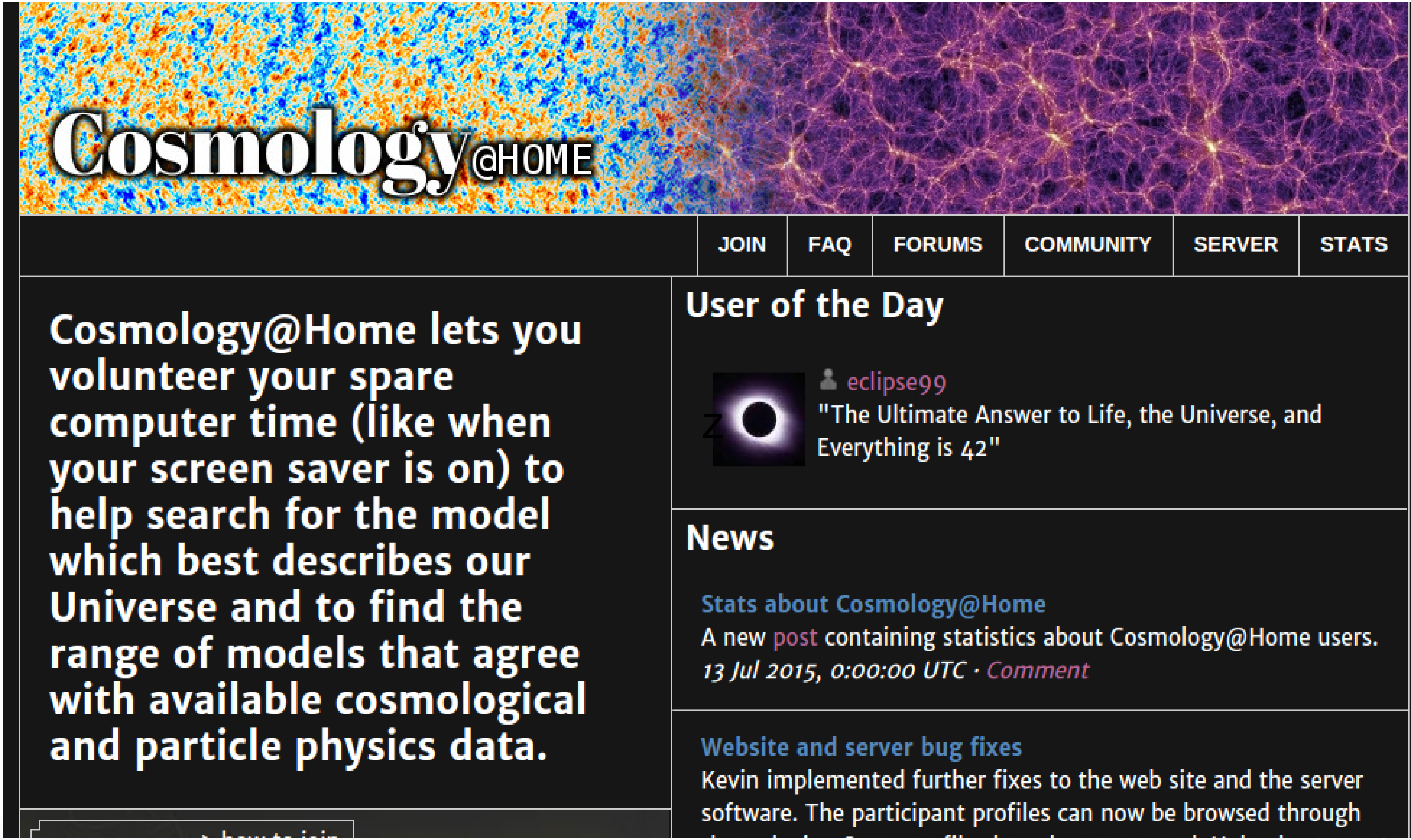
This significance of finding a biggest outlier as big as the one we found ($A_s e^{-2\tau}$).

What about splitting at a different ℓ or comparing low-ℓ vs high-ℓ?

		Test	
Data set 1	Data set 2	χ^2	`max-param`
$\ell < 800$	$\ell < 2500$	$1.4\,\sigma^\dagger$	$1.7\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.6\,\sigma$	$2.1\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.8\,\sigma^\dagger$	$1.5\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell > 1000$	$1.6\,\sigma$	$1.6\,\sigma$ (ω_m)

← The numbers from previous slide

www.cosmologyathome.org



Your personal background.

I was born in 1970 in the est of France. I live actually in Paris. I like soccer, cars racing and share computing.

Your personal background.

Sou brasileiro tenho 18 anos sou técnico em eletrônica e desde pequeno tenho uma admiração pelo universo,penso em futuramente fazer faculdade de astronomia física engenharia aeroespacial.

Your opinions about Cosmology@Home

Entrei nesse projeto por motivos de estudo conhecimento sobre o cosmo minha curiosidade em estudar e descobrir cada vez mais sobre o universo e seus mistérios.

Your personal background.

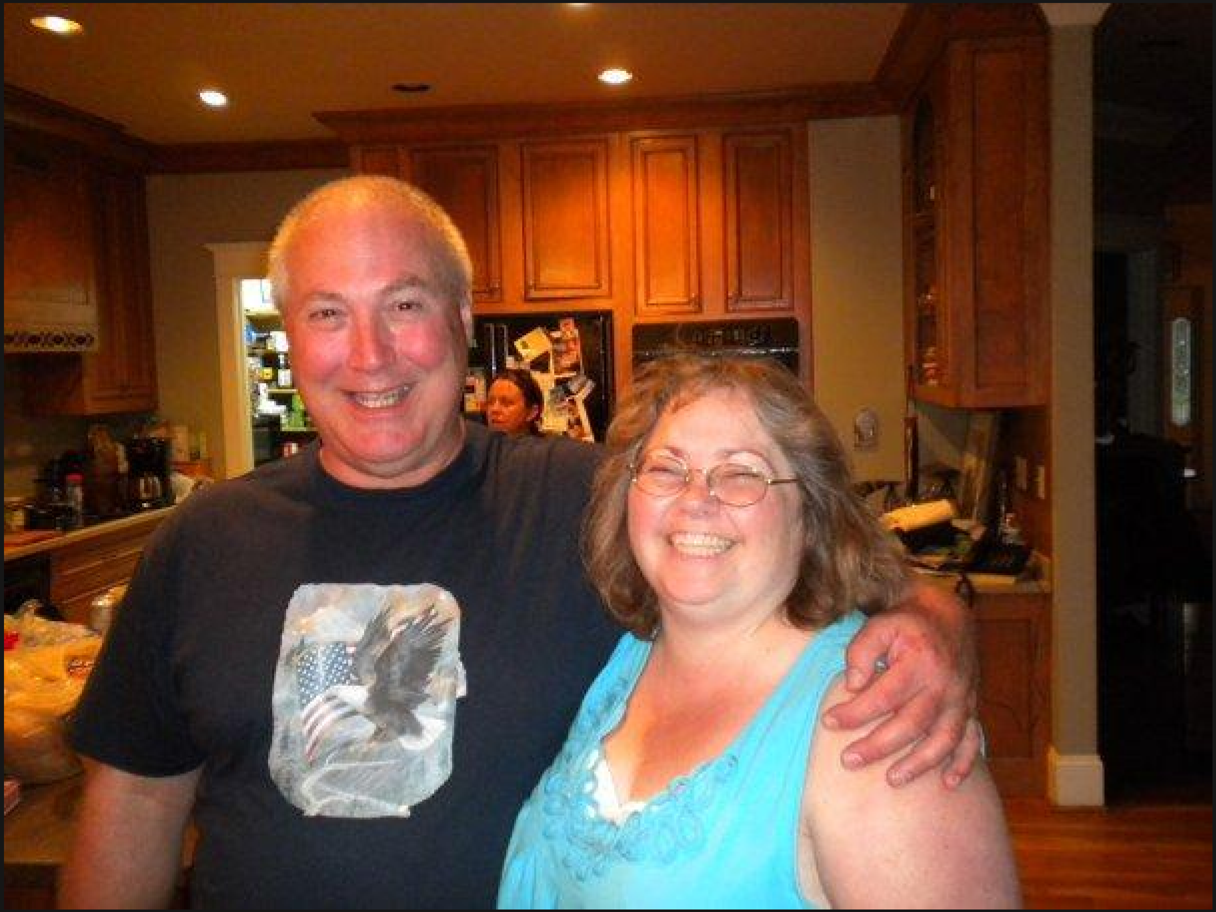
25 y/o Mommy of 1 and 1 on the way:)

Your personal background.

Located in southeastern,Illinois and soon to hit age 50. Enjoy running various science and medical projects to benefit mankind in his quest to improve the world. Been in retail most my life and like spending time with my three cherished grandchildren. Hopefully doing all of these will help to improve their future on earth.

Your opinions about Cosmology@Home

I run cosmo for hopefully the future of mankind as I believe it is a worthy project. Go Illini



Your personal background.

I believe that man has made great strides in understanding the cosmos in the last 100 years. We now know a little bit about the 4% of regular matter and energy that makes up the universe and very little to nothing about that 96% known as Dark Matter and Dark Energy. Maybe the next 100 years will prove to be as enlightening, only time will tell.

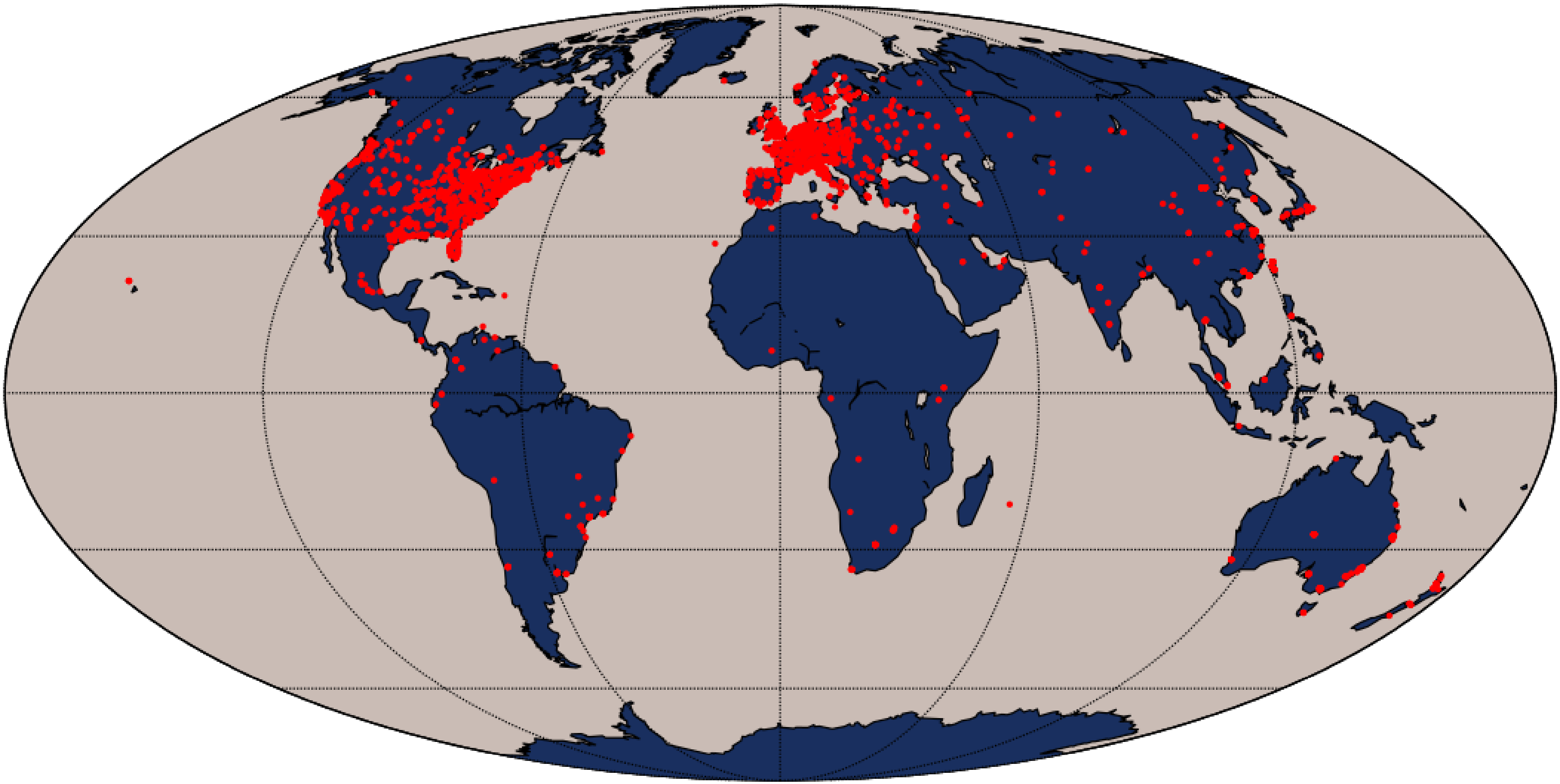
Your opinions about Cosmology@Home

I love any strivings to better understand fact from fiction. The more we humans know about our universe hopefully the better off we will be and can better adapt to it - or it to us.

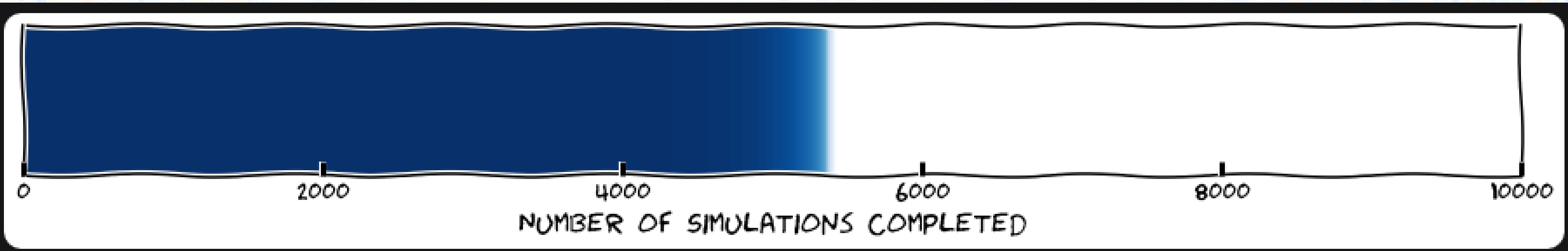
Your personal background.

Hello, i am Gattorantolo from the Boinc Italy team.

Active Cosmology@Home Computers as of July 2015



Today, about 10,000 active computers per month



These results will be used in a forthcoming paper from the Planck collaboration. In the paper, we will thank by name the top 3 users and top team who have crunched the most on the planck_param_sims application. Below are the current standings. We will give a two week notice before picking the winners.

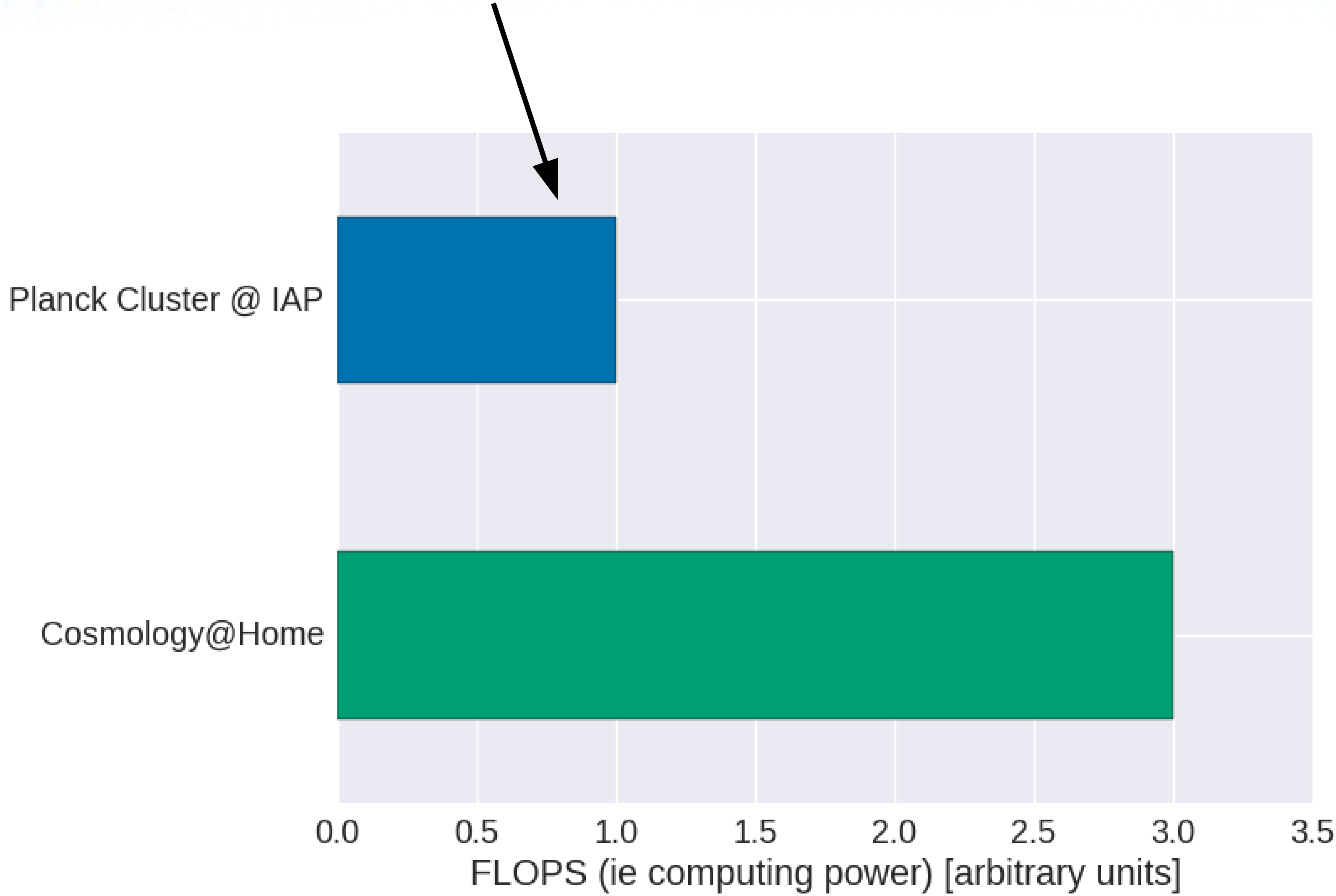
Users

Rank	Name	Credit
1	MaDdCoW	3,673,650
2	Rally1965	2,844,150
3	25000ghz [Lombardia]	2,559,100
4	Phil1966	1,734,650
5	Skywalker TSBT	1,656,550
6	McPaste	1,584,000
7	zioriga	1,413,900
8	RoSi	1,349,650
9	Mumps [MM]	1,117,000
10	Bart Simpson	1,061,000
11	[VENETO] sabayonino	975,850
12	Sebastian*	940,700
13	tyler	898,150

Teams

Rank	Name	Credit
1	BOINC.Italy	7,484,450
2	SETI.Germany	4,685,750
3	Gridcoin	4,186,750
4	Team Norway	2,924,200
5	Overclock.net	1,874,800
6	France	1,812,300
7	The Scottish Boinc Team	1,711,000
8	SETI.USA	1,689,300
9	USA	1,448,600
10	SETI@klamm.de	1,361,300
11	Sicituradastra.	1,099,100
12	Czech National Team	722,250
13	SETIKAH@KOREA	685,600

130 node (8 CPU / node) cluster shared by ~10 active people at my institute working on Planck

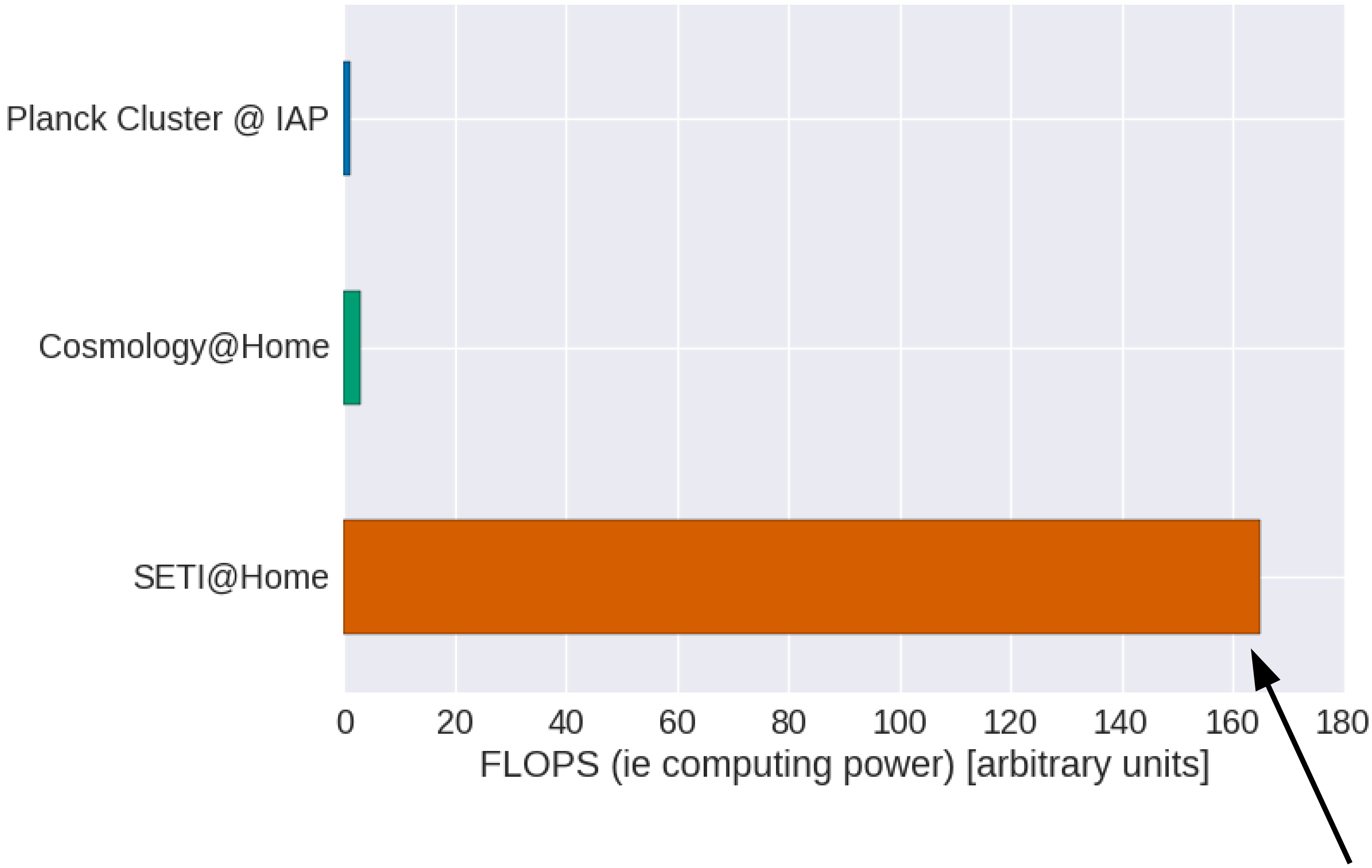


There's a lot of room to grow….

Project stats info

Project name	Users	last day	Hosts	last day	Teams
BOINC combined	3,590,362	2,984	13,470,462	15,843	104,469
SETI@Home	1,620,852	438	3,984,976	988	63,579
NFS@Home	11,355	3	2,643,083	10,969	741
World Community Grid	503,807	69	2,600,749	449	24,650
Rosetta@Home	810,385	2,424	1,725,294	2,122	10,812
Einstein@Home	429,838	79	1,519,891	730	11,364
POEM@HOME	55,778	16	1,130,829	34	1,795
Malaria Control	205,916	0	783,133	0	2,480
Climate Prediction	289,696	0	612,087	0	7,903
MilkyWay@home	201,429	54	453,511	102	4,139
Collatz Conjecture	58,053	34	379,793	514	1,633
LHC@Home Classic	133,372	21	358,530	52	5,077
theSkyNet POGS	43,320	45	307,785	68	758
PrimeGrid	90,606	13	264,201	50	2,931
Moo! Wrapper	31,002	57	222,613	434	631
Cosmology@Home	66,194	12	153,369	41	2,041
Asteroids@home	78,030	82	133,444	125	1,342
yoyo@home	62,107	39	132,745	59	986
Enigma@Home	56,343	33	120,011	61	1,533
SZTAKI Desktop Grid	39,363	3	110,975	21	1,651
FiND@Home	52,349	0	78,178	0	599

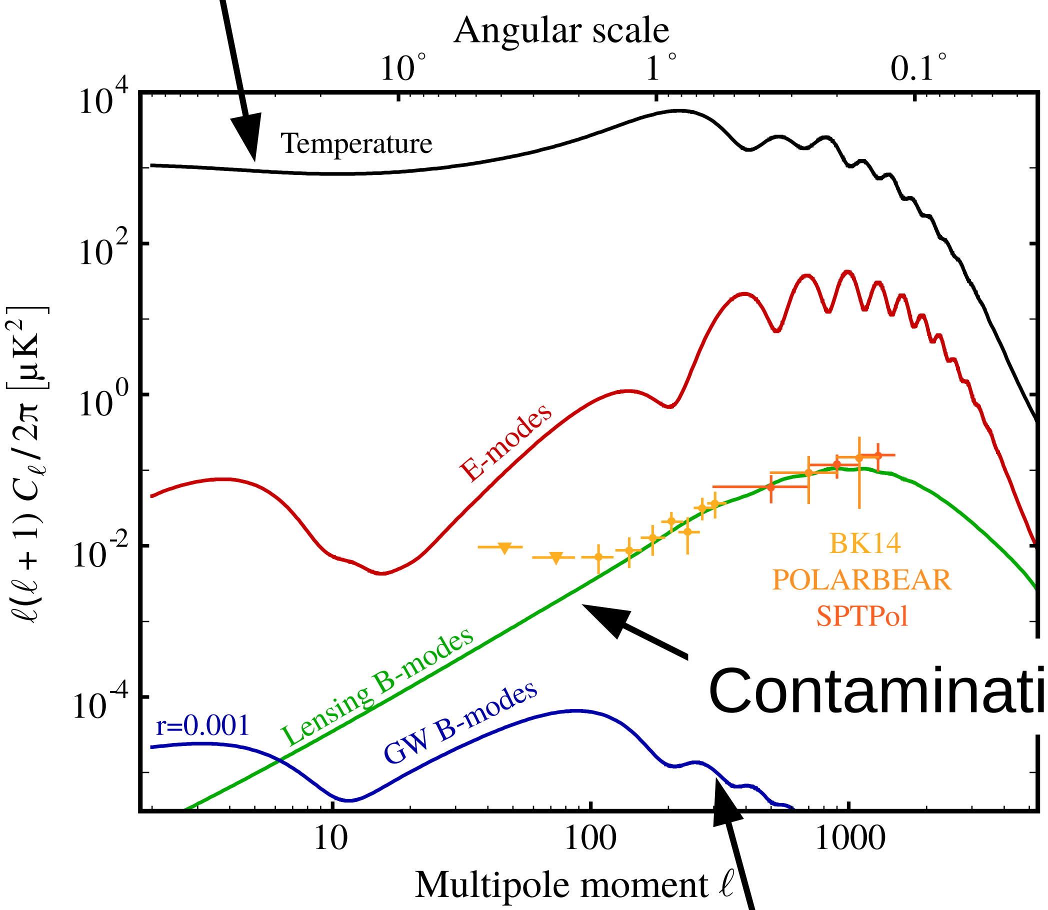
+hundreds more...



One of the biggest projects, SETI@Home

What's to come from the CMB?

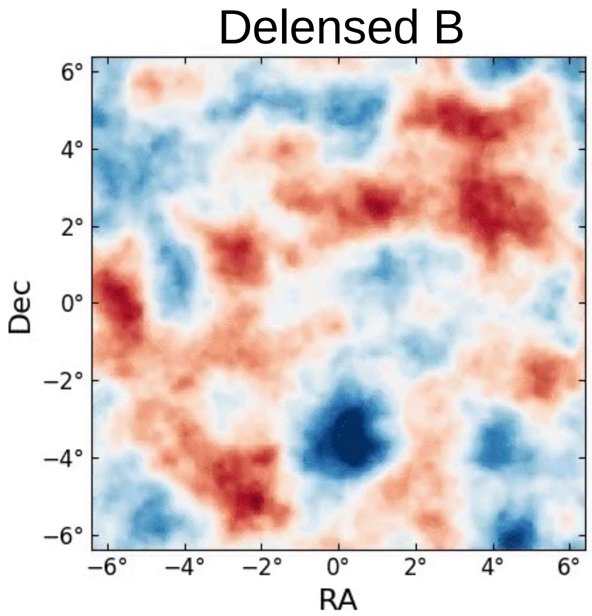
This talk

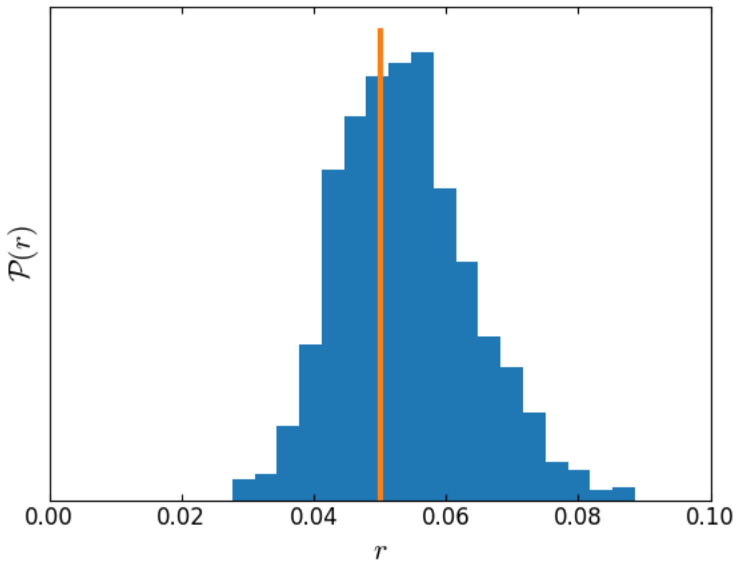


Contamination

(r) Signature of gravitational waves from inflation

Much ongoing work in optimally removing this lensing contamination, e.g. MM, Anderes, & Wandelt 2017 (1708.06753)





Conclusion

- The Planck mission
  - Planck agrees very well with simple 6 parameter LCDM model
  - Planck is internally consistent
- Cosmology@Home is a big and useful computing resource
- Lots of interesting CMB work looking forward

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

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