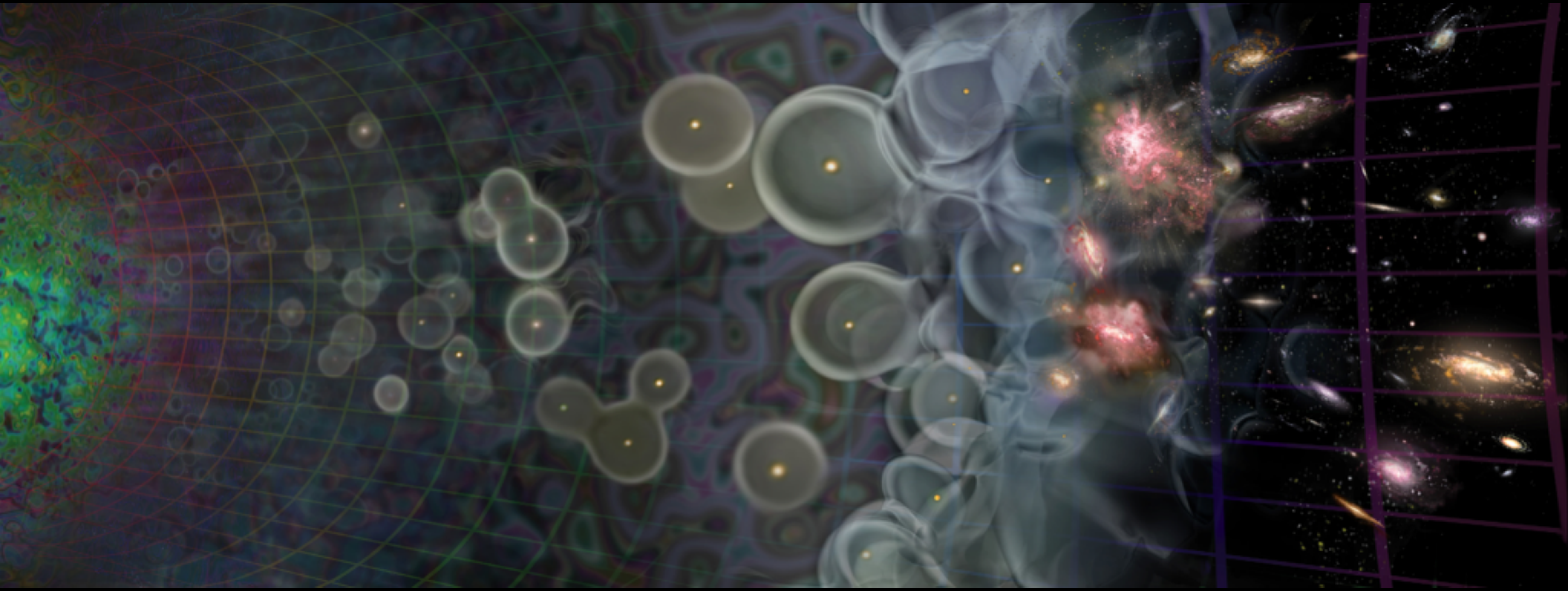
Introdução à Cosmologia Física



Aula 13: A Radiação Cósmica de Fundo

* Revisão sobre o "desacoplamento" da radiação c/ matéria ("recombinação")
* RCF como "fotografia" das condições iniciais do universo
* Física da radiação e matéria durante o desacoplamento

—> Ryder, Cap. 10

Desacomplamento ("recombinação")

A transição entre um universo ionizado e opaco para um **neutro e transparente** é governada pelo processo:

$$p + e^- \rightarrow H + \gamma \quad , \quad B = 13.6\,\mathrm{eV}$$

Vimos nas aulas anteriores que, quando essas reações ocorrem frequentemente (ou seja, a uma taxa alta comparada à taxa de expansão), a fração ionizada $X_e = n_e/n_b$ é dada pela **Equação de Saha**, e obtivemos:

$$\frac{n_p n_e}{n_H n_b} = \frac{X_e^2}{1 - X_e} = \frac{1}{n_b}\left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-B/T} = \frac{\pi^{1/2}}{2^{5/2}\eta_{b\gamma}\zeta(3)}\left(\frac{m_e c^2}{k_B T}\right)^{3/2} e^{-B/k_B T}$$

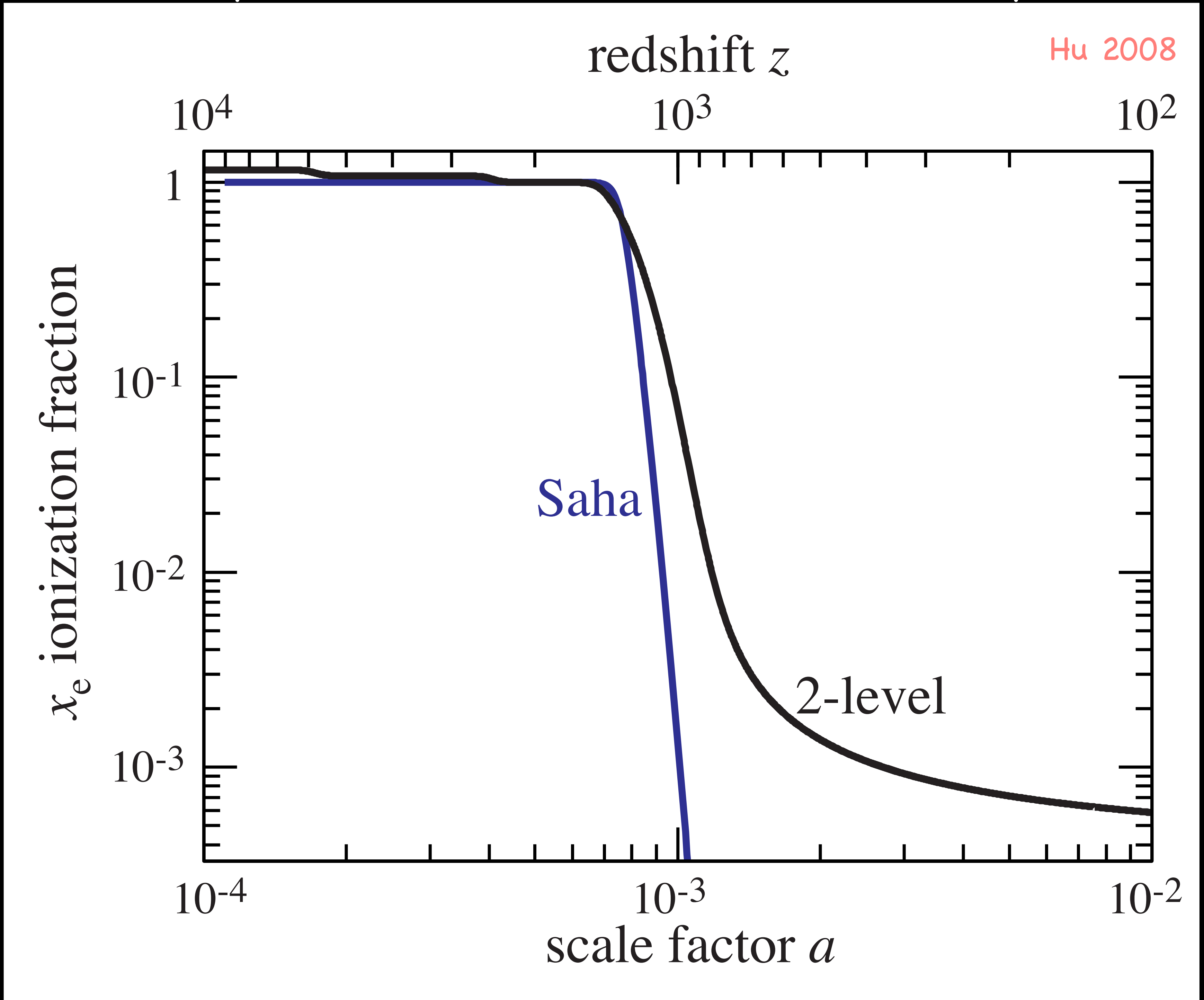
Vivemos num universo com **poucos baryons**!

~10^{-9} !

Fração ionizada

Corrigindo p/ ^{4}He: $$n_e = (1-Y)X_e n_b = x_e \times 1.12 \times 10^{-5} \Omega_b h^2 (1+z)^3 \mathrm{cm}^{-3}$$

O número de e⁻ livres (que são as fontes de espalhamento Thomson/Compton) decai rapidamente quando a temperatura cai abaixo de $T \sim 1$ eV , ou depois de $z \sim 1100$:



E como esses e^- livres afetam os fótons da RCF durante e depois da recombinação?

A **seção de choque** relevante é a do espalhamento Thomson/Compton:

$$\sigma_T = \frac{8\pi\alpha^2}{3m_e^2} = 6.65 \times 10^{-25}\,\mathrm{cm}^2$$

O caminho livre médio ("mean free path") é dado por:

$$\lambda^{mfp}_{phys} = \frac{1}{n_e\sigma_T} = \frac{1}{X_e n_b \sigma_T} \quad \Rightarrow \lambda^{mfp}_c = \frac{1}{X_e n_b \sigma_T a}$$

A **probabilidade normalizada** de que um fóton será espalhado por um e- livre, entre os instantes t_s e $t_s + dt_s$, e **nunca mais depois desse instante**, é :

$$dP = \frac{dt_s}{\lambda(t_s)}\left(1-\frac{dt_1}{\lambda(t_1)}\right)\left(1-\frac{dt_2}{\lambda(t_2)}\right)\ldots\left(1-\frac{dt_N}{\lambda(t_N)}\right)$$

$N \to \infty \downarrow$

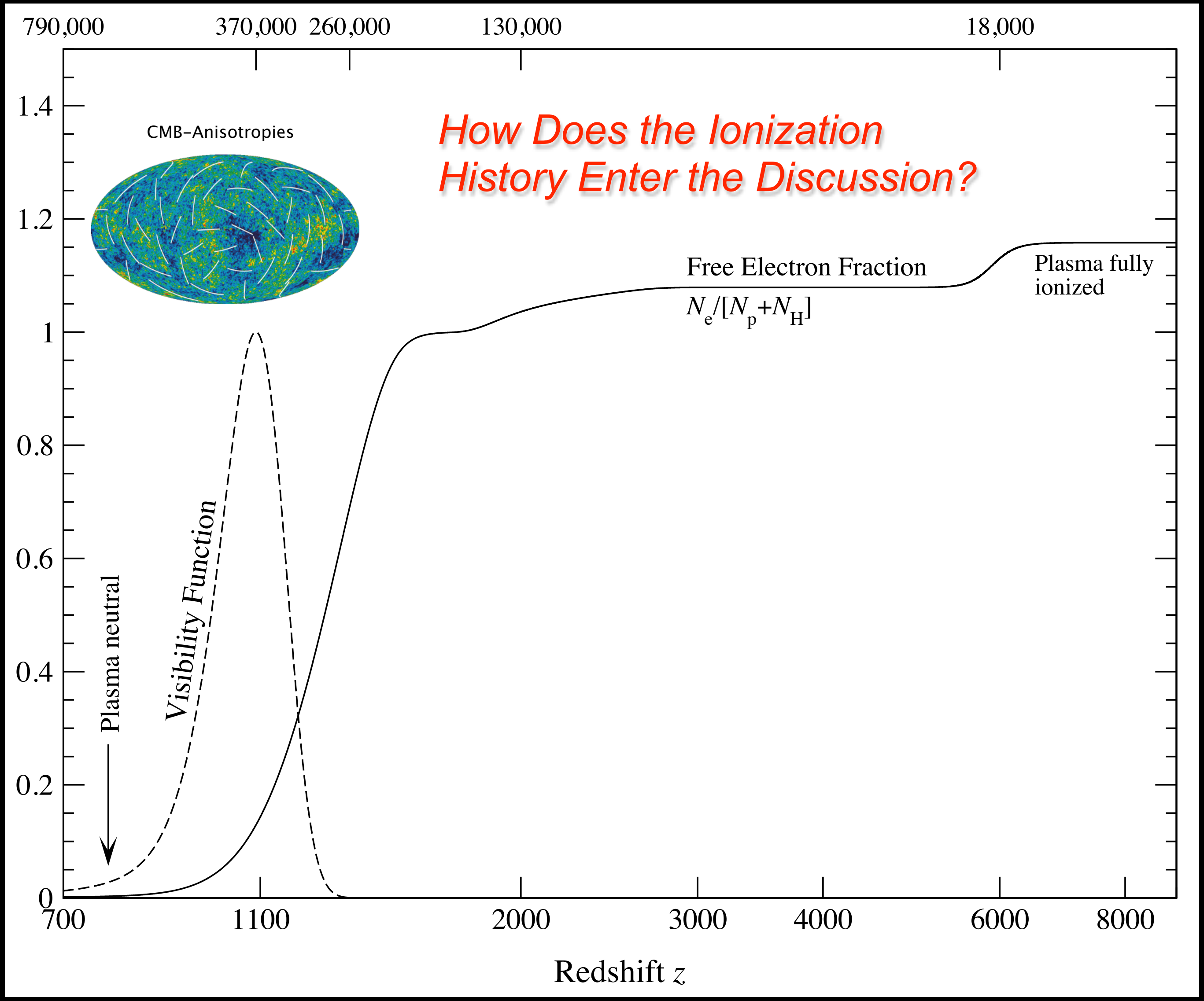
$$\Rightarrow dP = \mu'(\eta_s)d\eta_s \times e^{-\mu(\eta_s)} \quad , \quad \mu(\eta) \equiv \int_\eta^{\eta_f} d\eta'\, X_e(\eta')n_b(\eta')\sigma_T$$

$$P = \int_0^\infty d\mu\, e^{-\mu} = 1$$

Profundidade óptica p/ espalh. Thomson

Essa **probabilidade por unidade de comprimento** de que um fóton **será espalhado** em um instante **t**, mas não depois, é chamada **função de visibilidade:**

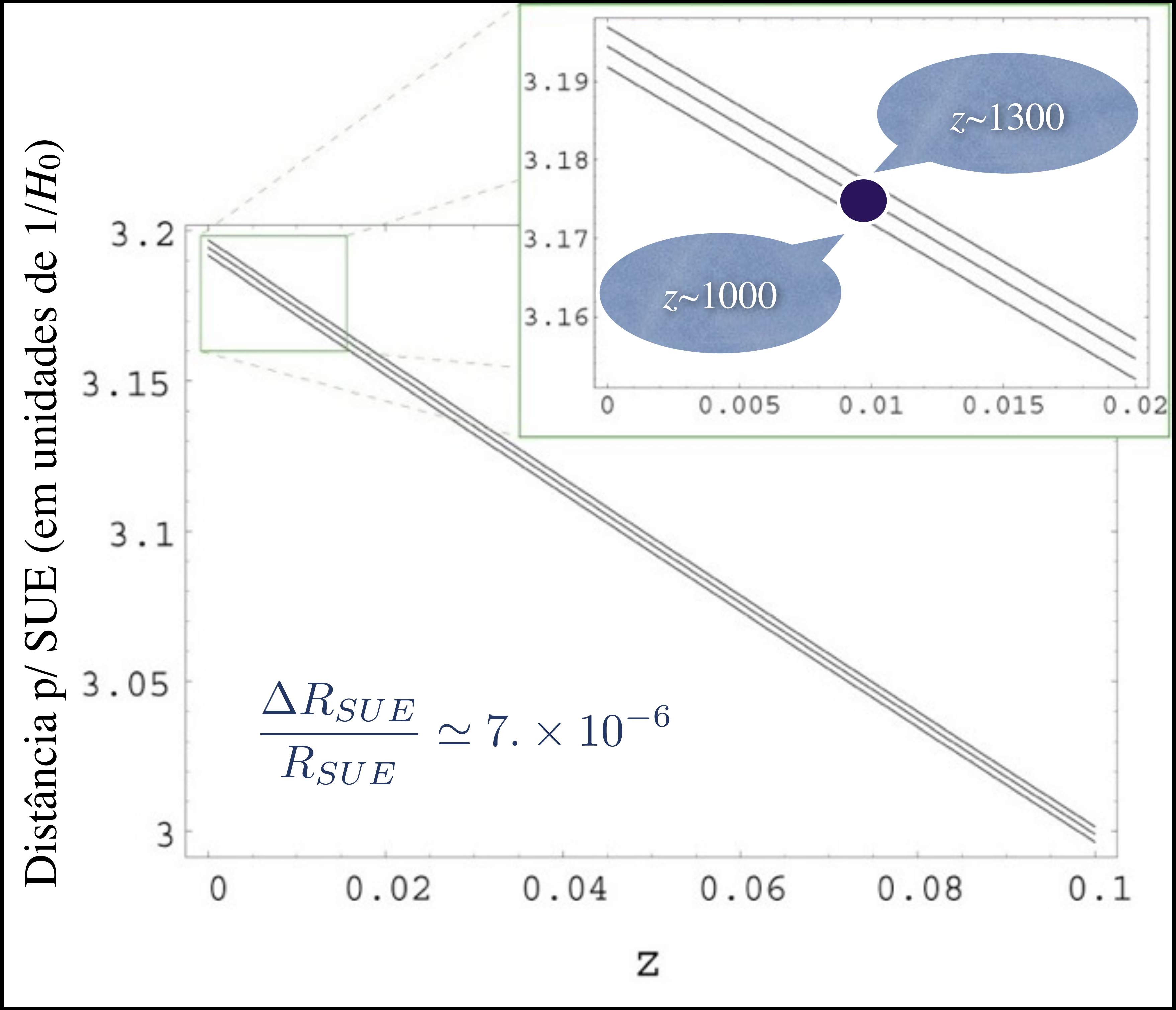
$$g(\eta) = \mu'(\eta)e^{-\mu(\eta)} \;=\; \sigma_T X_e(\eta) n_b(\eta) a(\eta) \times \exp\left[\int_0^\eta d\eta'\, \sigma_T X_e(\eta') n_b(\eta') a(\eta')\right]$$



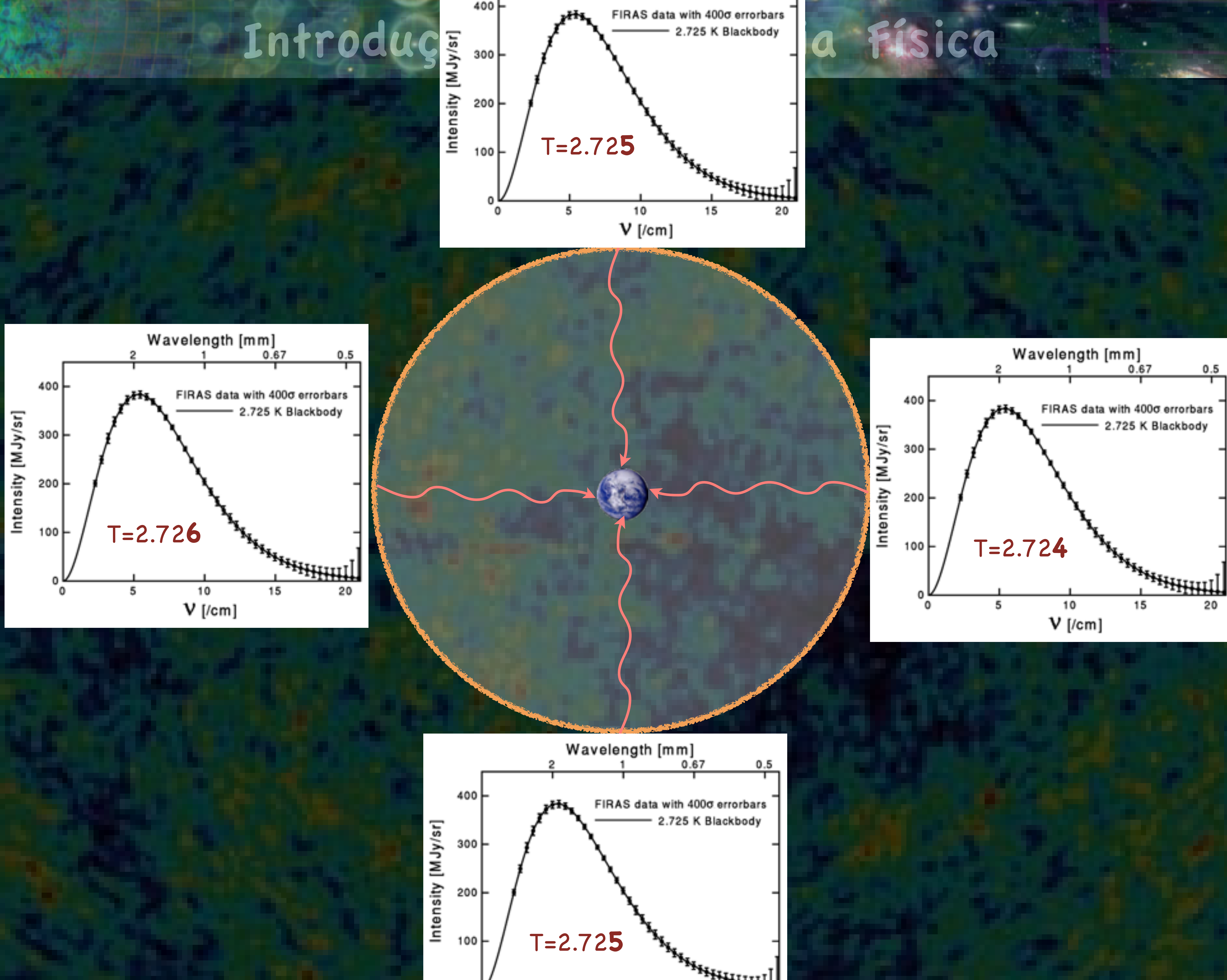
Máxima probabilidade: $$z_* \approx 1089 \left(\frac{\Omega_m h^2}{0.14}\right)^{0.0105} \left(\frac{\Omega_b h^2}{0.024}\right)^{-0.028}$$

Hu 2005

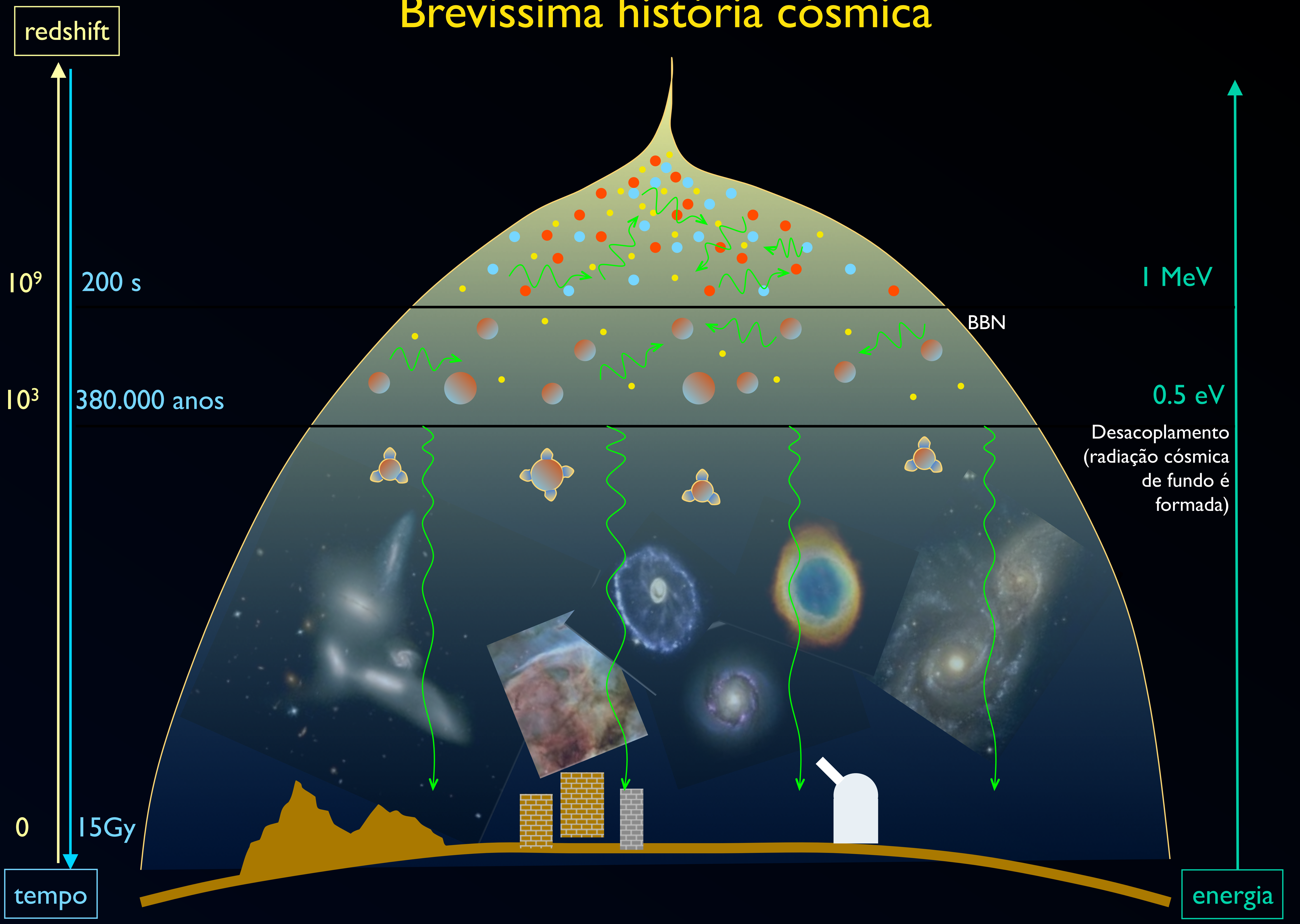
Espessura da Superfície de Último Espalhamento (SUE) observada hoje:



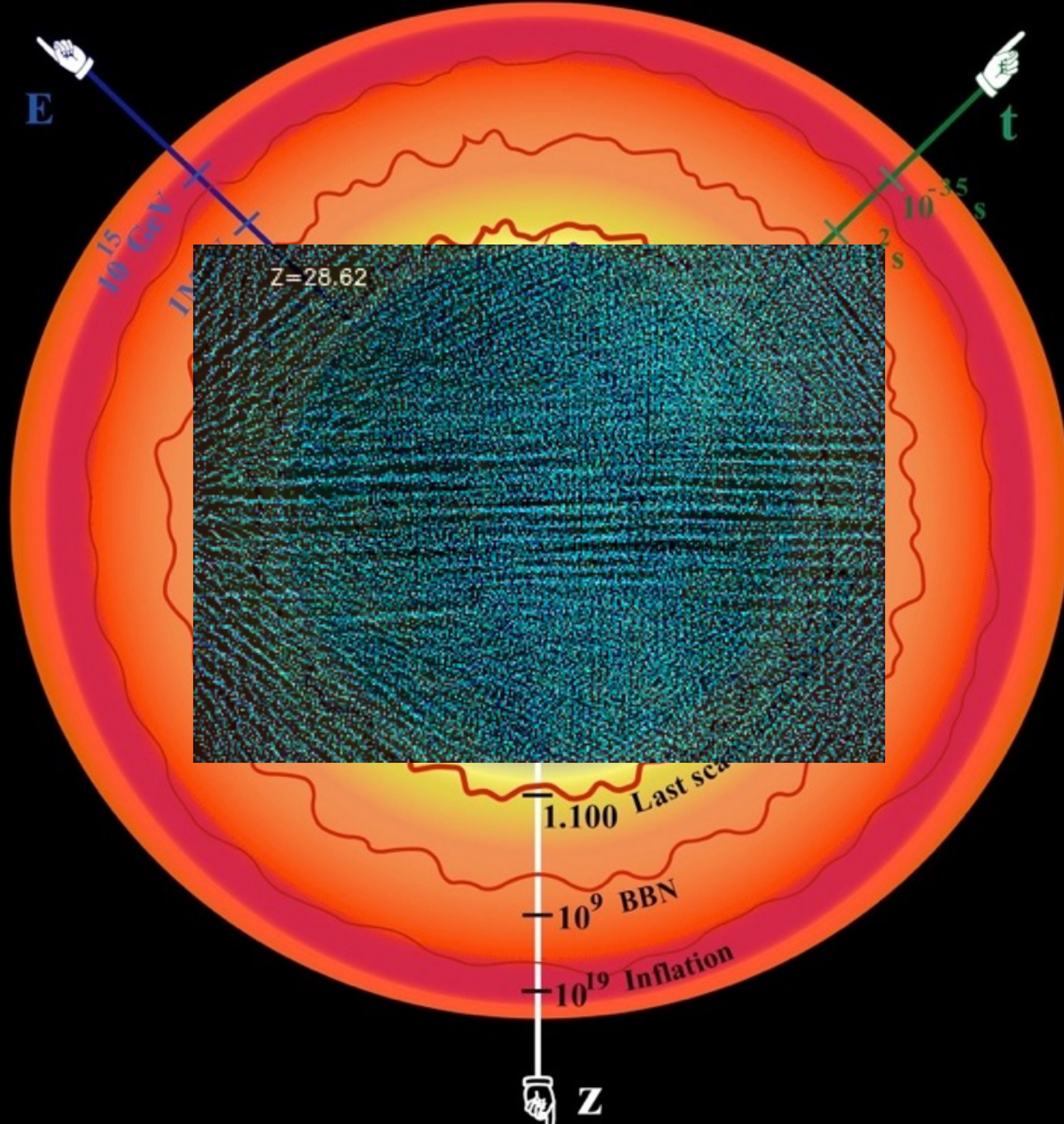
- A RCF **realmente** nos dá uma foto de uma época muito bem determinada, uma casca esférica muito fina, de raio R_{SUE} !


FIRAS data with 400σ errorbars
2.725 K Blackbody
Intensity [MJy/sr]
ν [/cm]
Wavelength [mm]
T=2.725
T=2.726
T=2.724
T=2.725

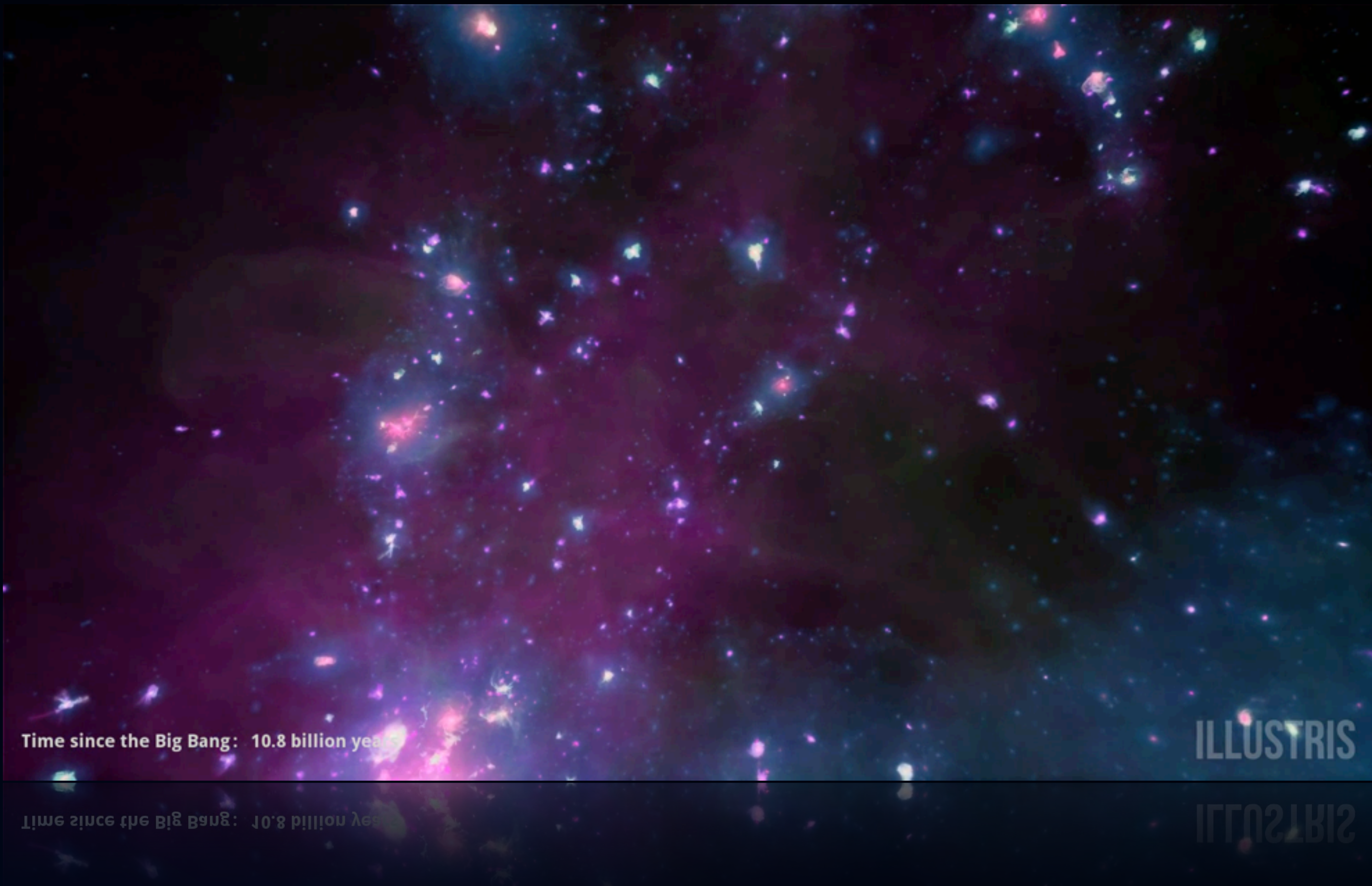
Brevíssima história cósmica



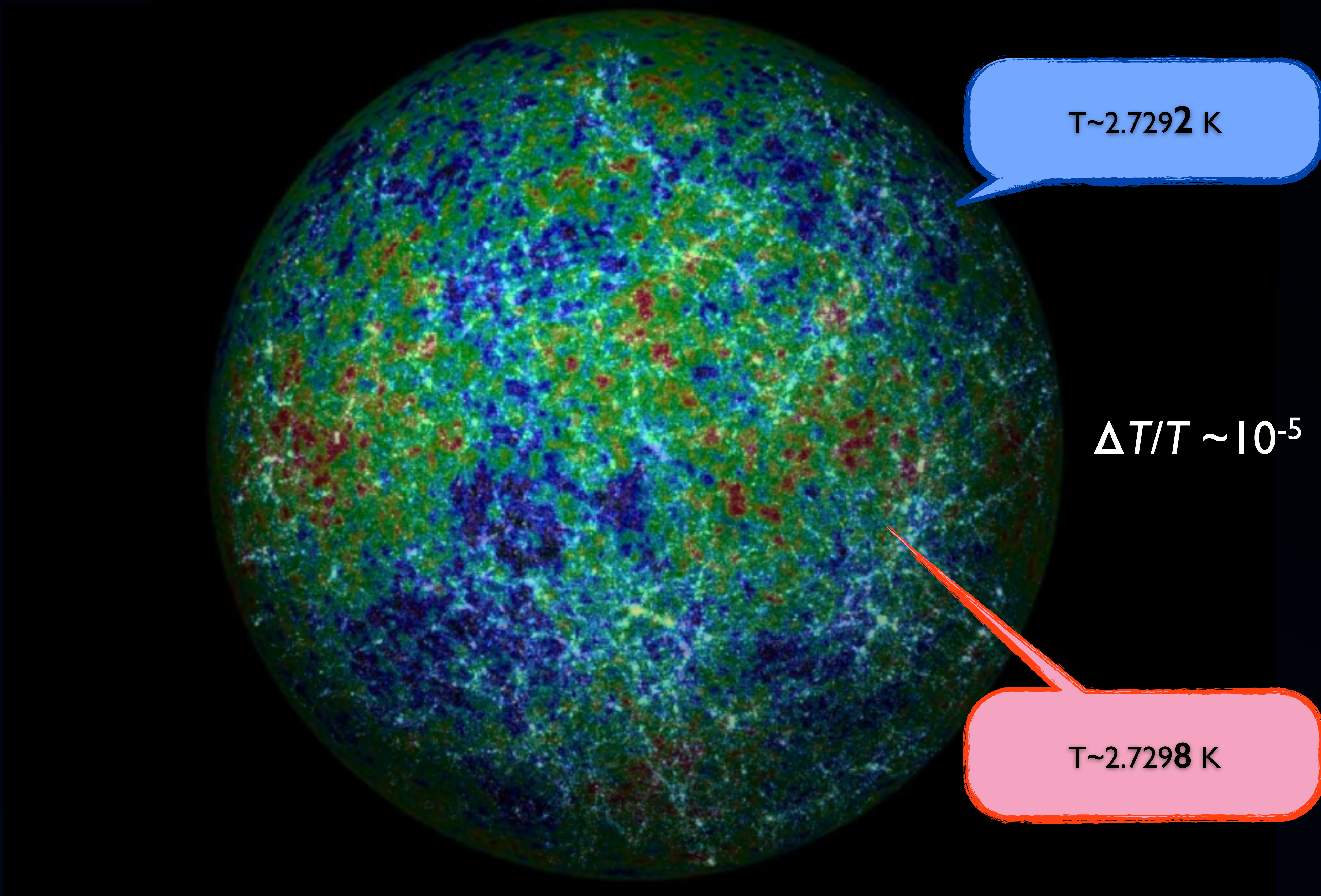
Uma visão causal do nosso universo



Simulação Illustris

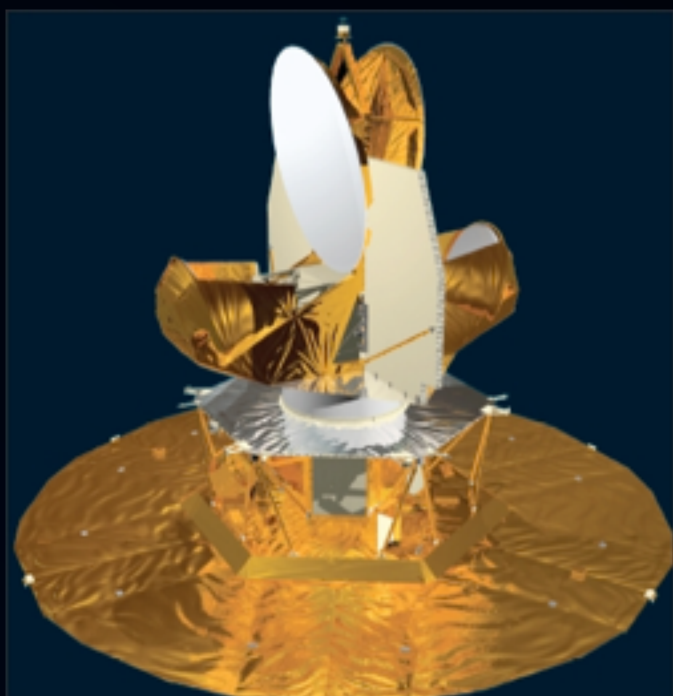


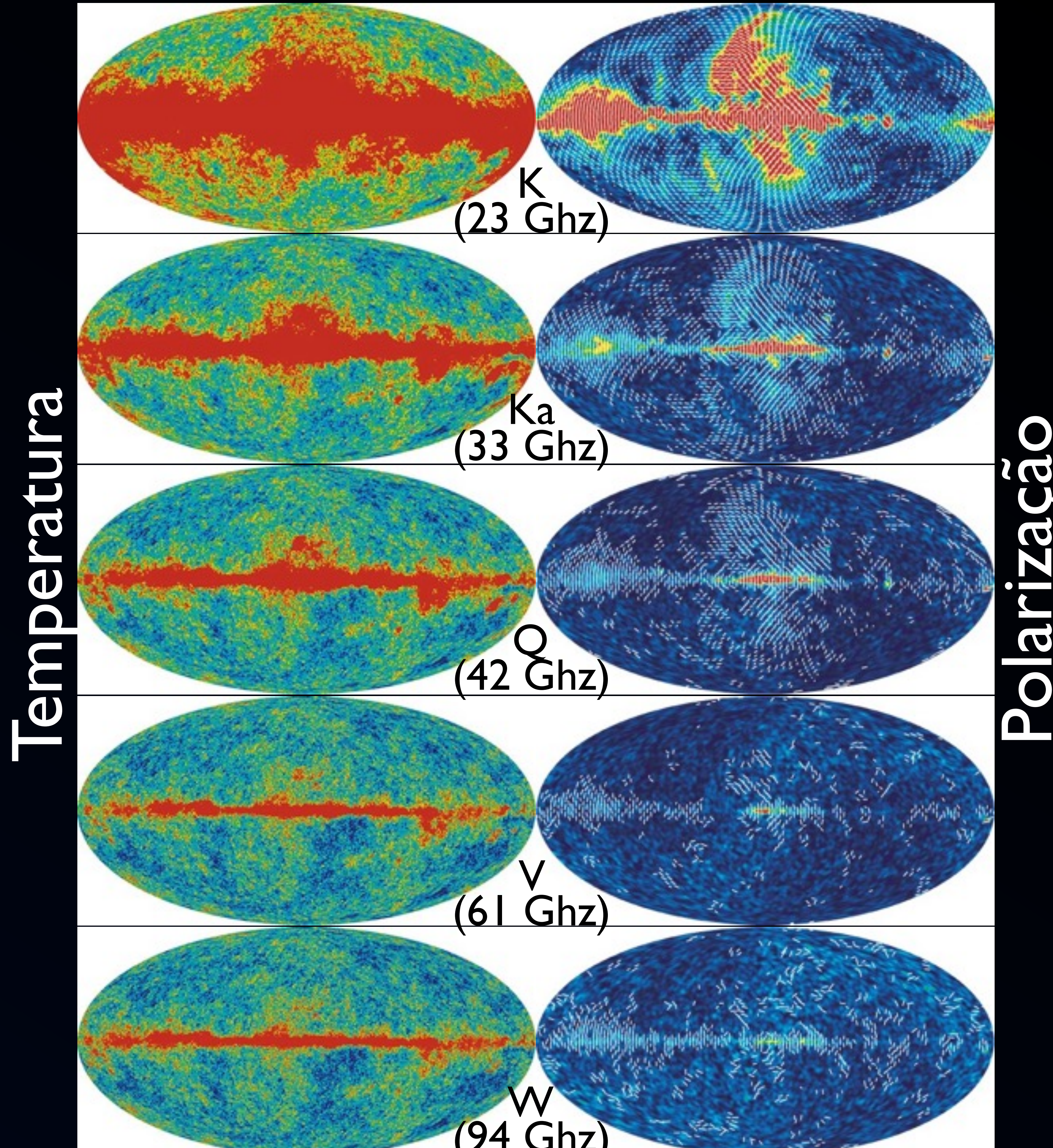
Radiação de fundo: **condições iniciais** para a **rede de estruturas do universo**



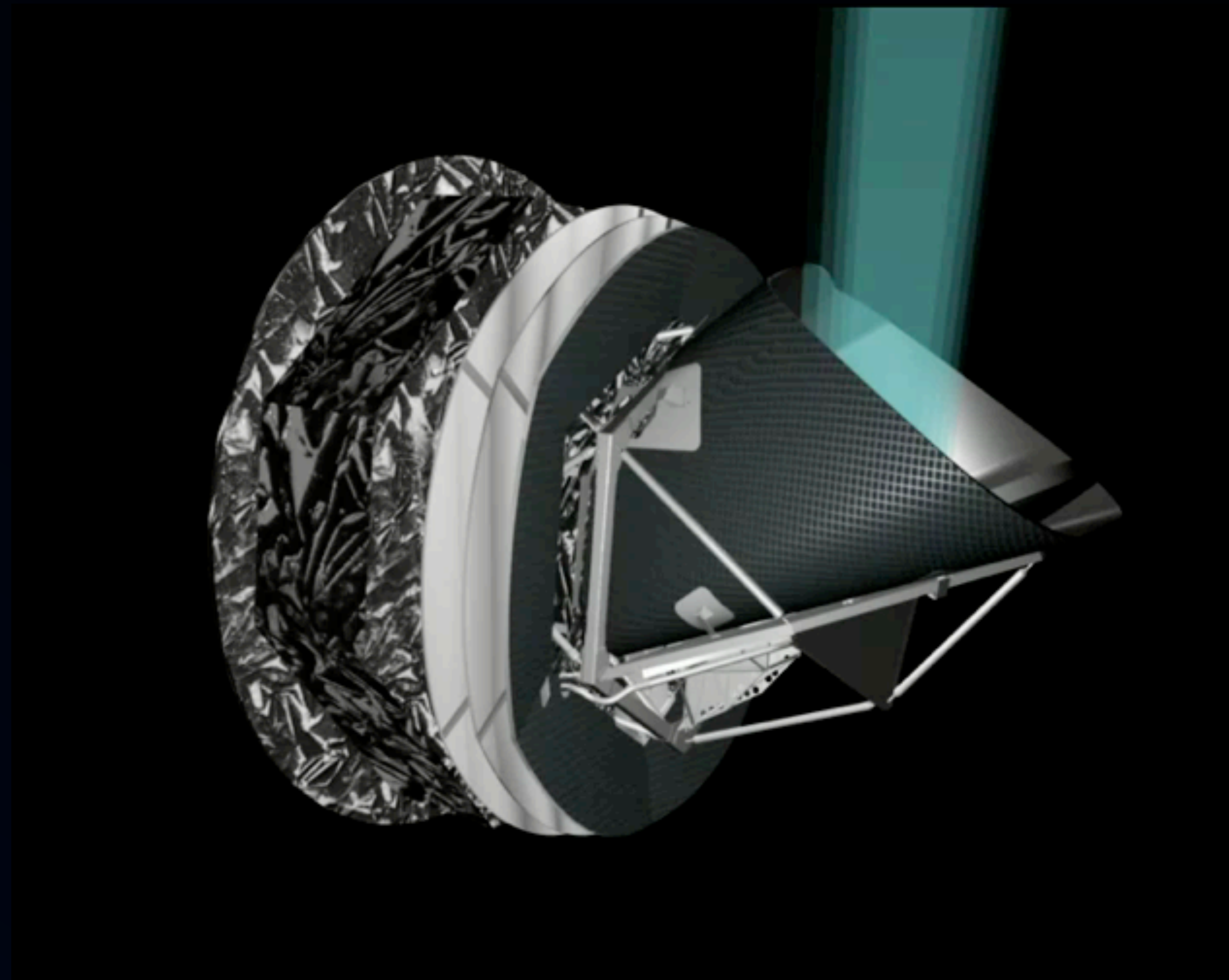
$\Delta T/T \sim 10^{-5}$

WMAP: 2003-2012



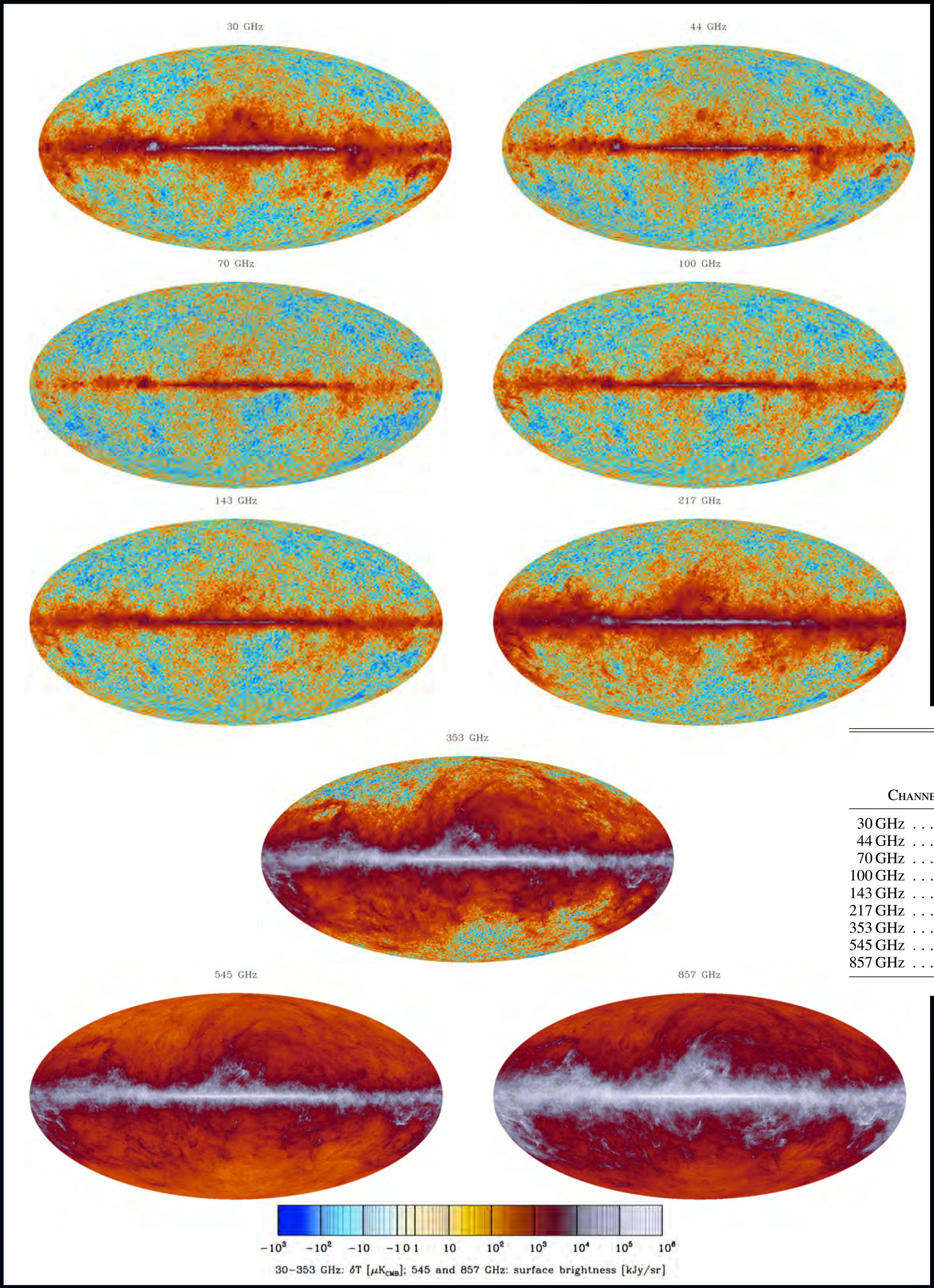


PLANCK



Hu & White

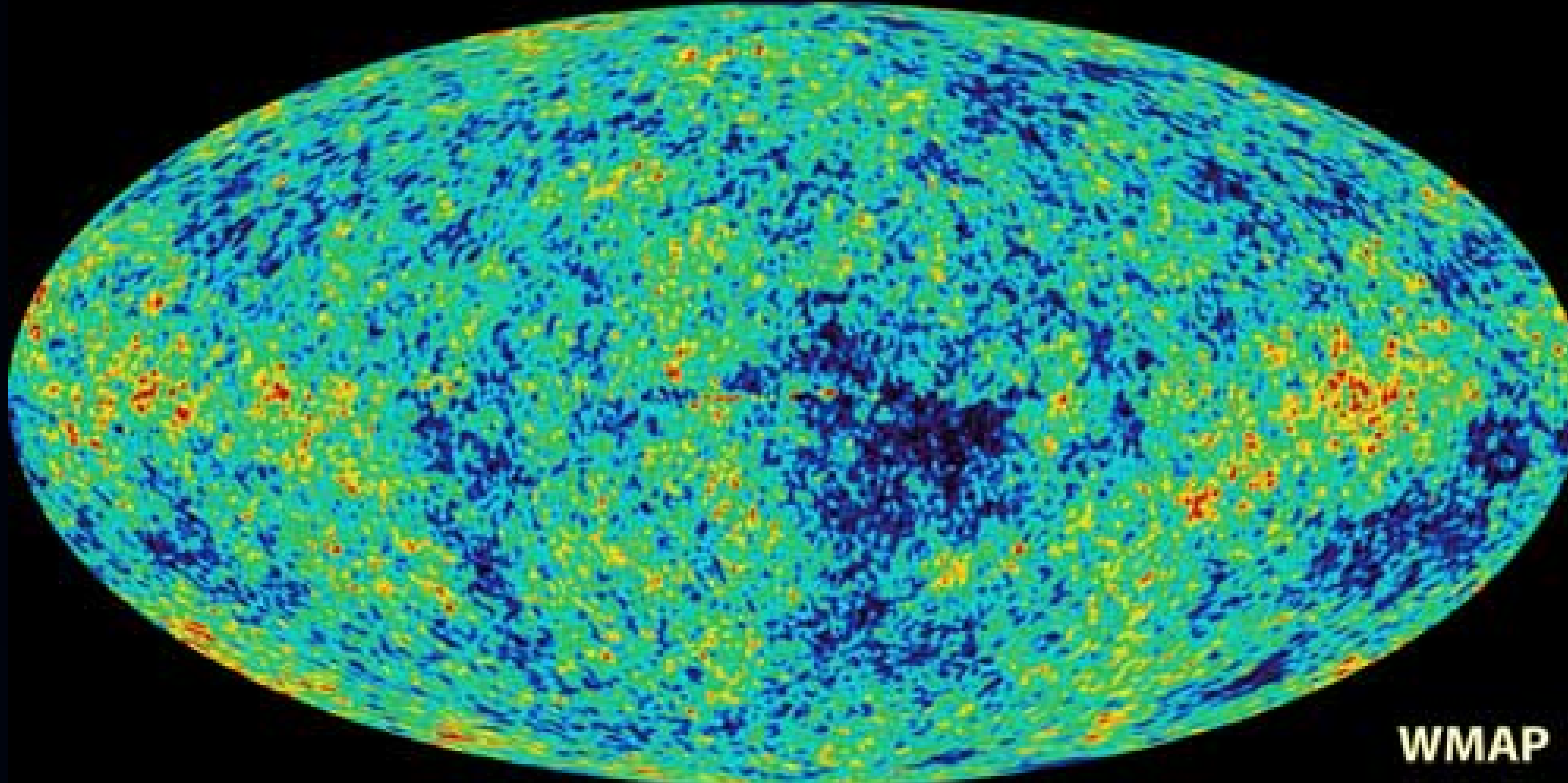
PLANCK canais de frequência

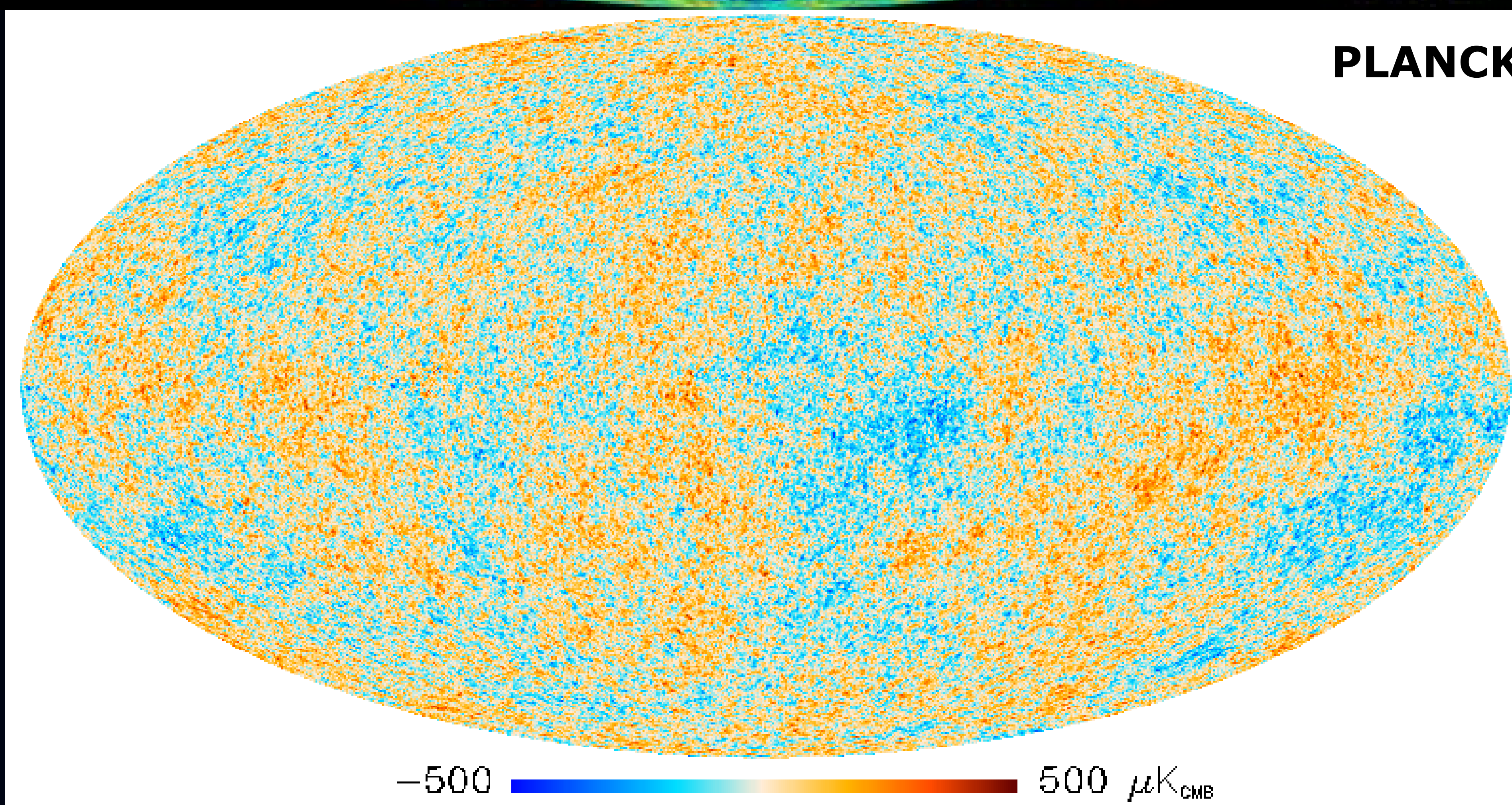


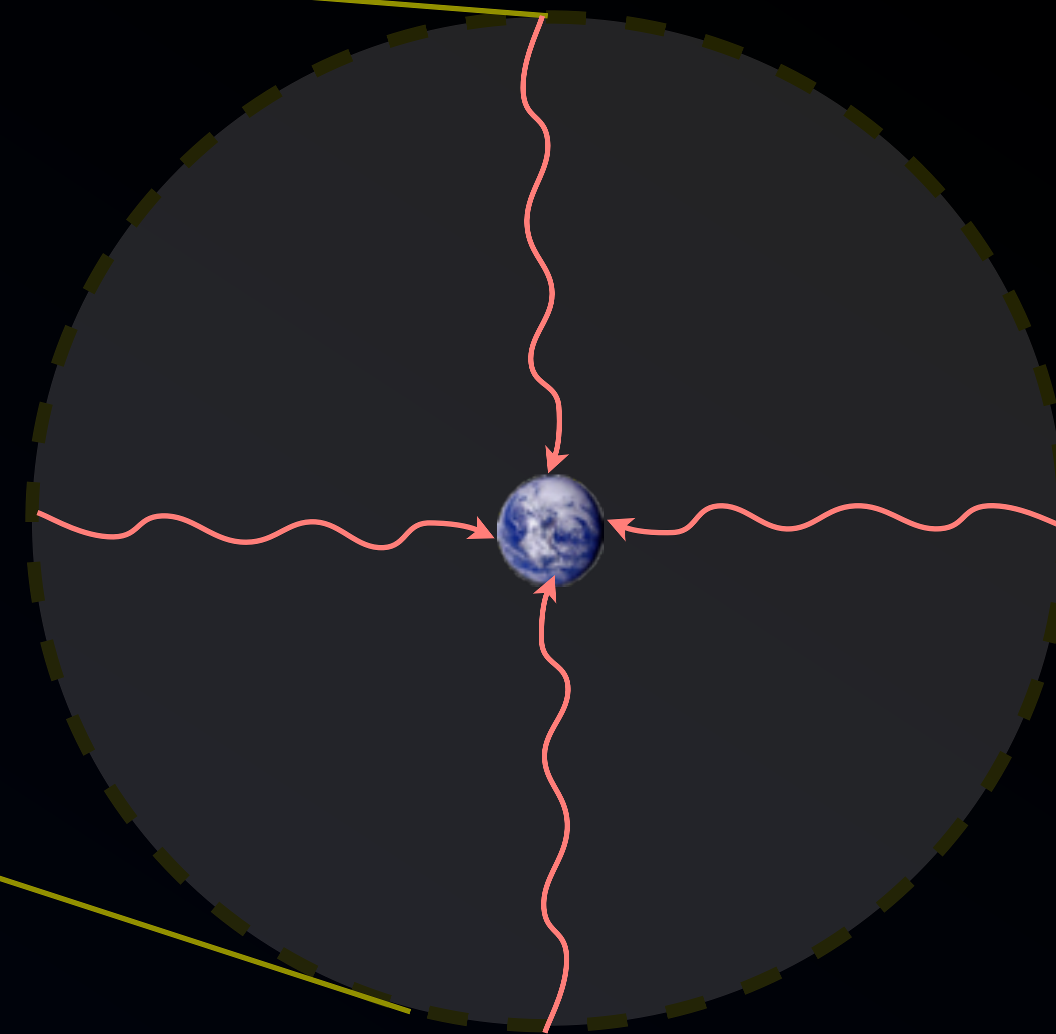
LFI
Low-Frenquency Instrument
Radiômetros: 30, 44 & 70 GHz

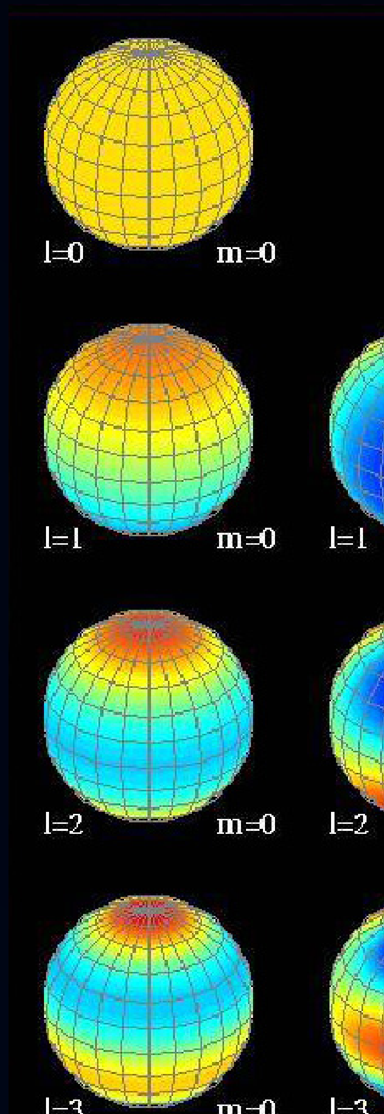
HFI
High-Frenquency Instrument
Bolômetros: 100, ... GHz

Channel	$N_{detectors}$ [a]	ν_{center} [b] [GHz]	Scanning Beam [c] FWHM [arcm]	Scanning Beam [c] Ellipticity	Noise [d] Sensitivity [$\mu K_{RJ}\ s^{1/2}$]	Noise [d] Sensitivity [$\mu K_{CMB}\ s^{1/2}$]
30 GHz	4	28.4	33.16	1.37	145.4	148.5
44 GHz	6	44.1	28.09	1.25	164.8	173.2
70 GHz	12	70.4	13.08	1.27	133.9	151.9
100 GHz	8	100	9.59	1.21	31.52	41.3
143 GHz	11	143	7.18	1.04	10.38	17.4
217 GHz	12	217	4.87	1.22	7.45	23.8
353 GHz	12	353	4.7	1.2	5.52	78.8
545 GHz	3	545	4.73	1.18	2.66	0.0259 [d]
857 GHz	4	857	4.51	1.38	1.33	0.0259 [d]


WMAP


PLANCK
−500
500 μK_CMB





Espectro angular:
decomposição em
"multipolos"

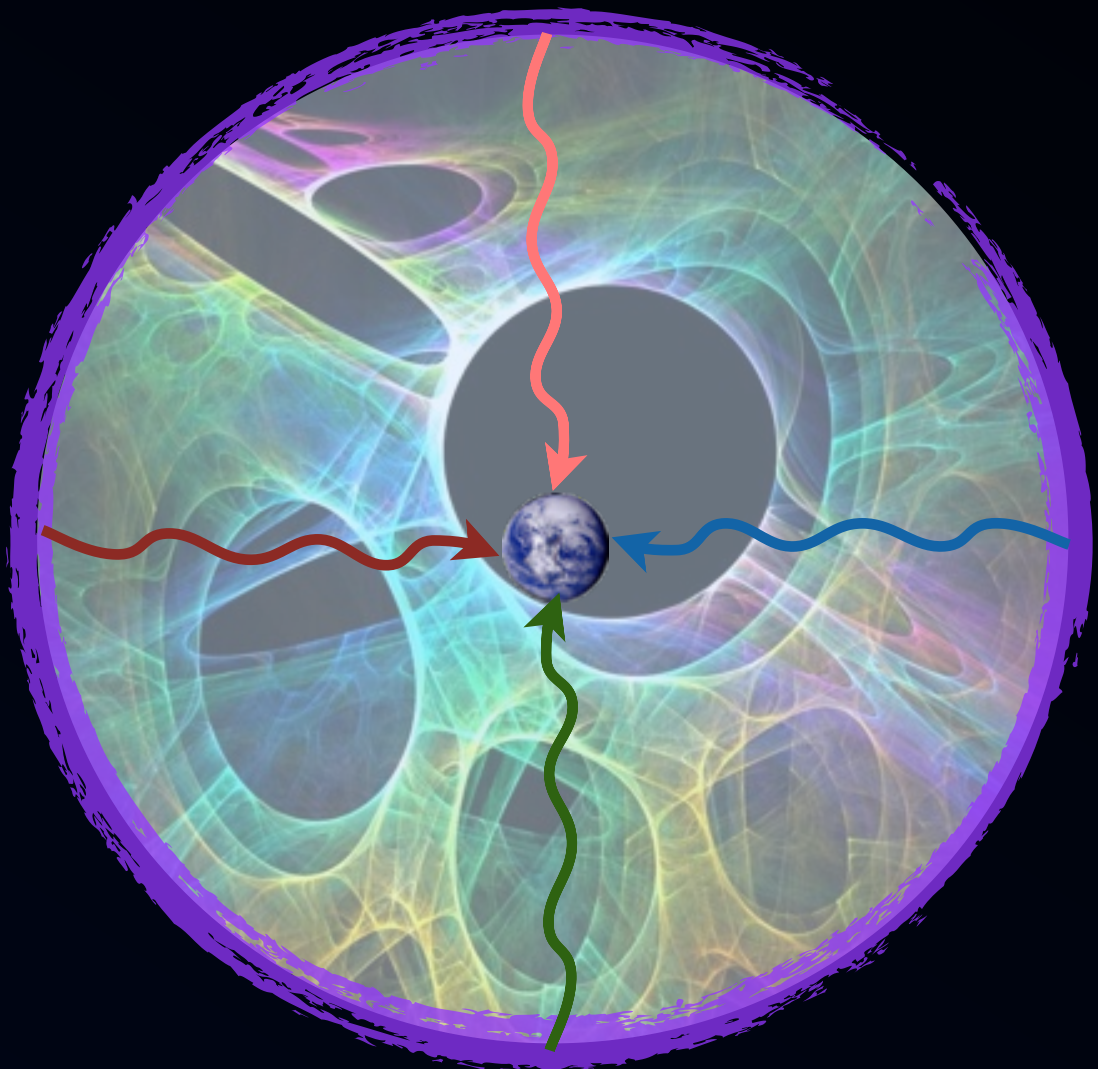
$$\delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_\ell^m(\theta,\varphi)$$

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \left| a_{\ell m} \right|^2$$

Fontes das anistropias da RCF

1) Efeito Sachs-Wolfe

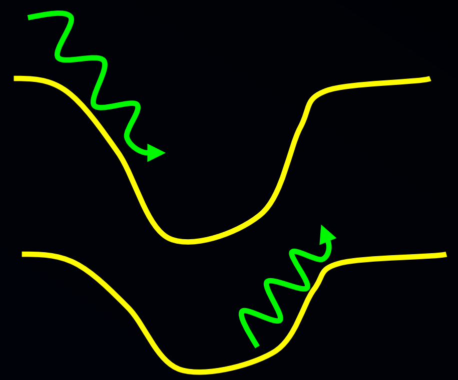
$$\frac{\Delta T(\vec{n})}{T} = -\frac{\Phi(R_{SUE} \cdot \vec{n}, t_{SUE})}{3} \approx \frac{\Delta \rho}{\rho} \approx 10^{-5}$$

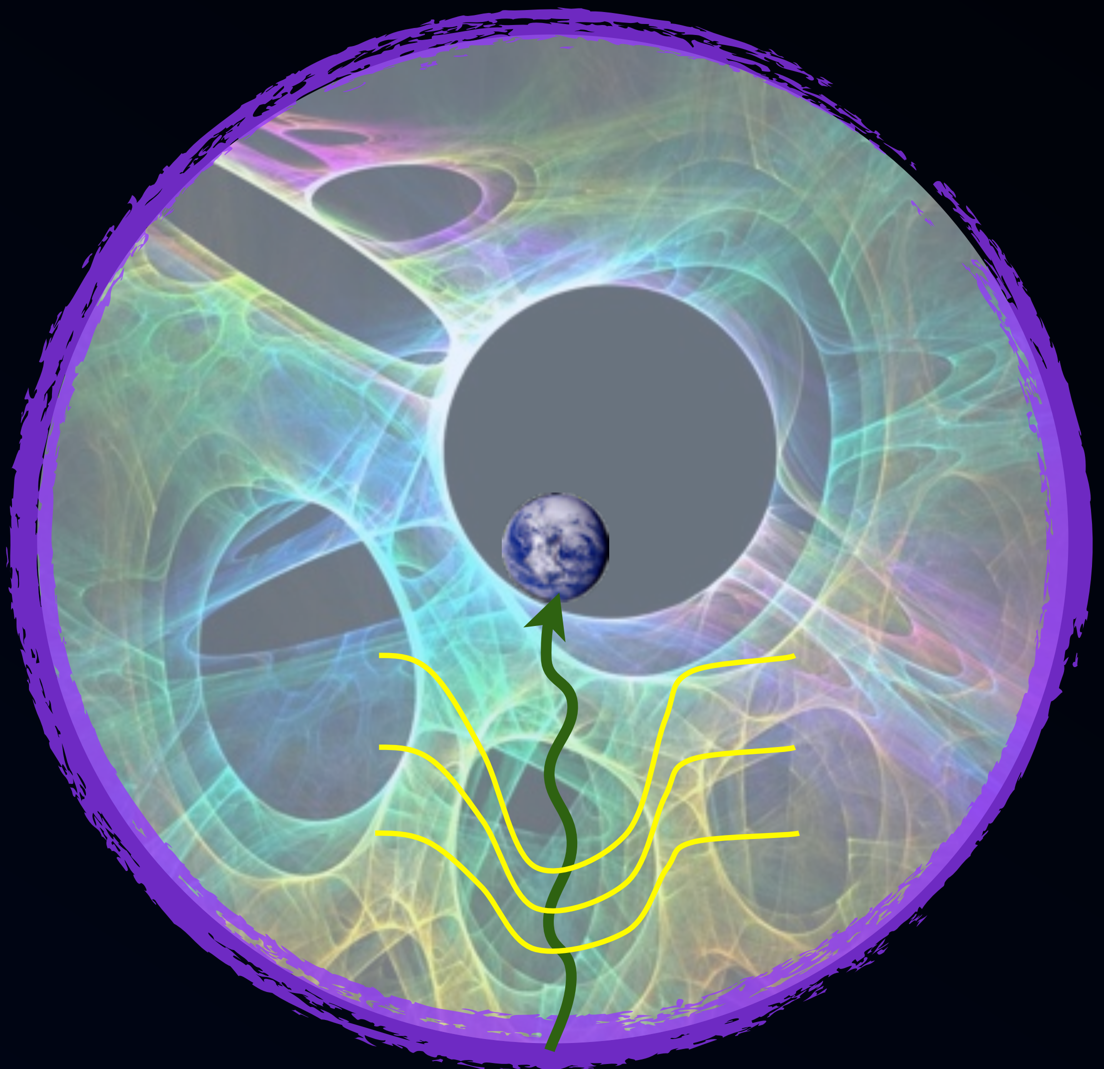


Fontes das anistropias da RCF

2) Efeito Sachs-Wolfe Integrado

$$\frac{\Delta T(\vec{n})}{T} = 2\int_{\vec{n}} d\eta \frac{\partial \Phi(\vec{n}\cdot\eta, \eta)}{\partial \eta}$$

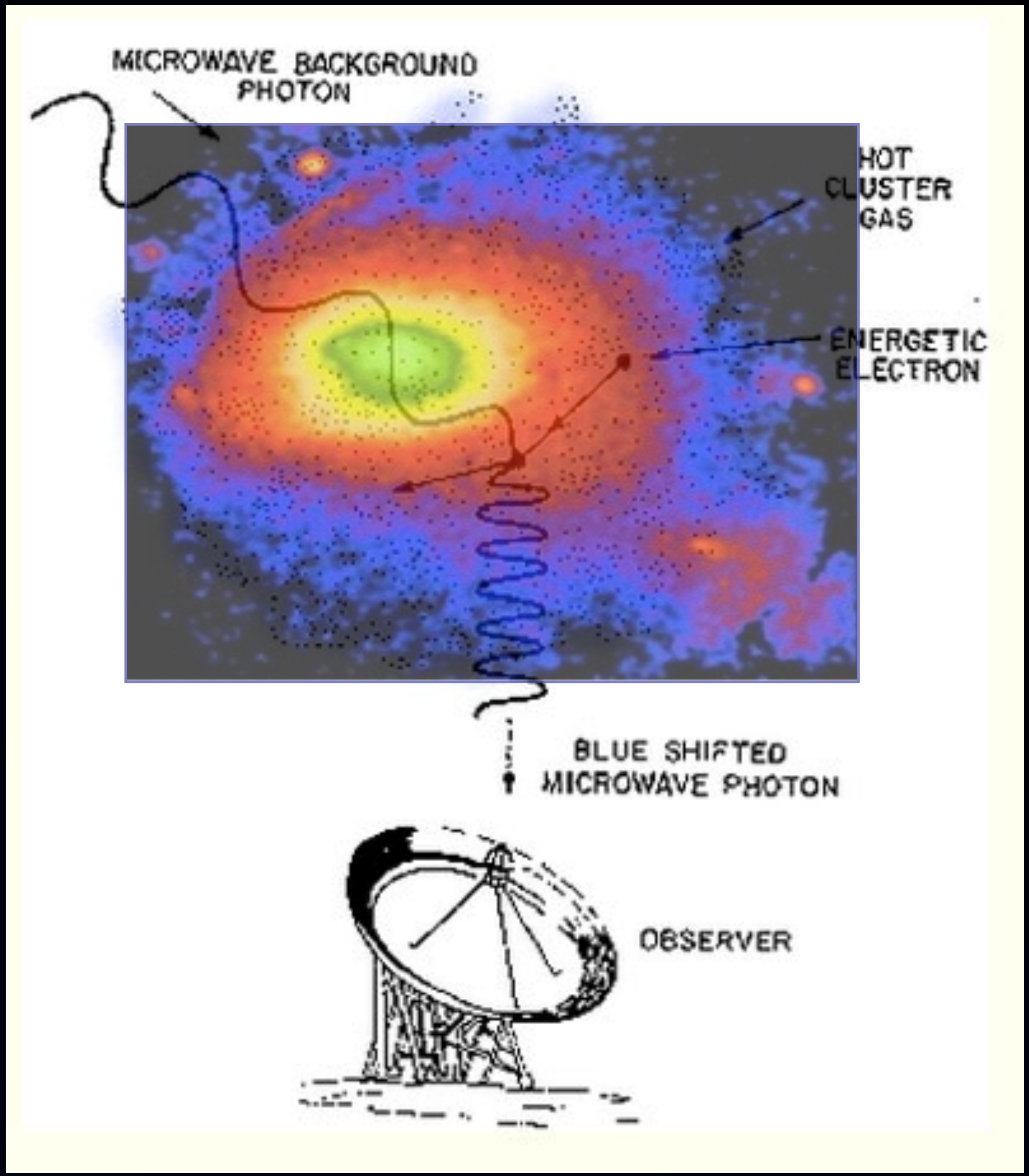




Fontes das anistropias da RCF

3) Efeito Sunyaev-Zel'dovich (SZ)

$$\frac{\Delta T(\vec{n}_c, nu)}{T} \approx f(\nu)\Delta\tau_T(\vec{n}_c)$$

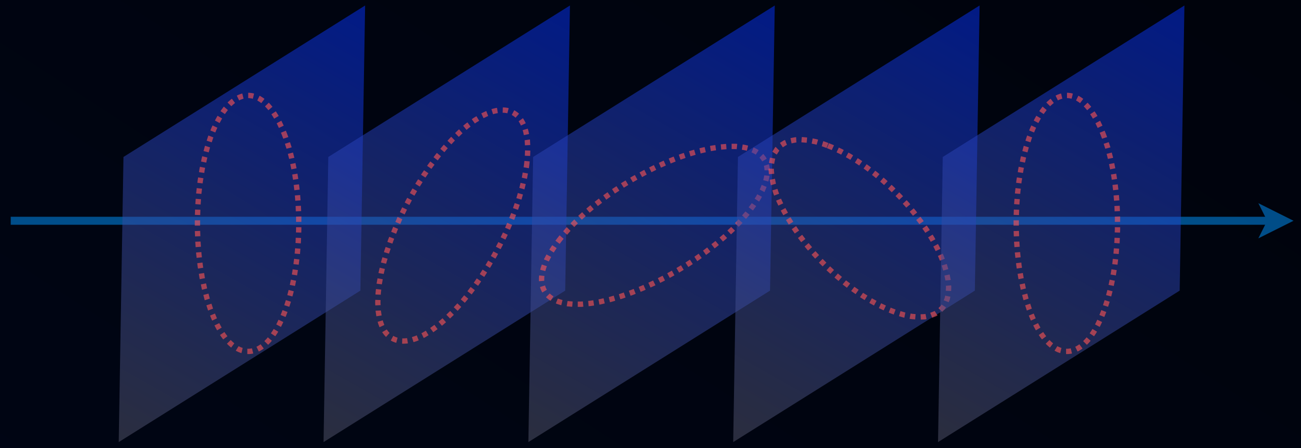


Fontes das anistropias da RCF

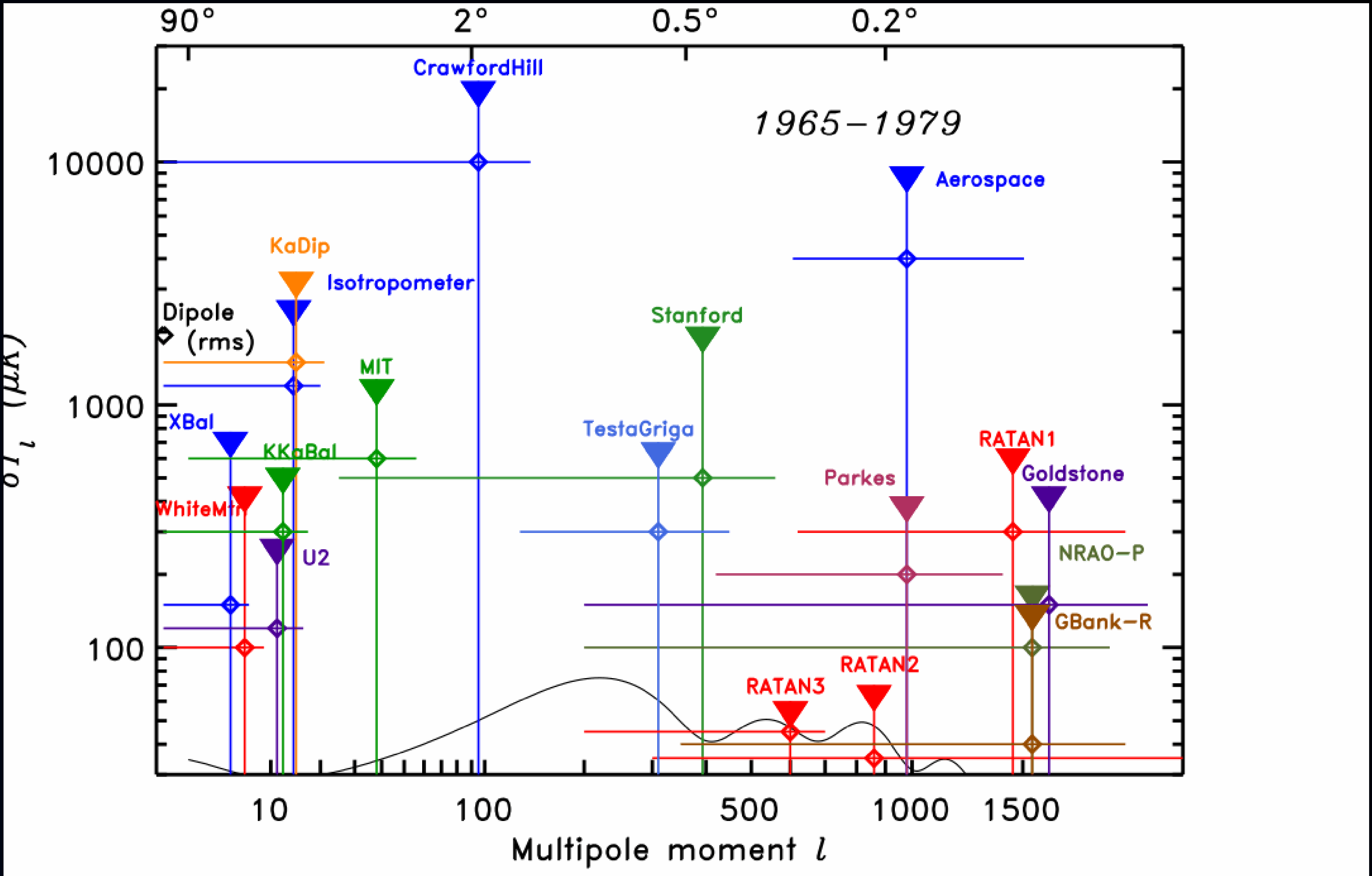
4) Lentes gravitacionais

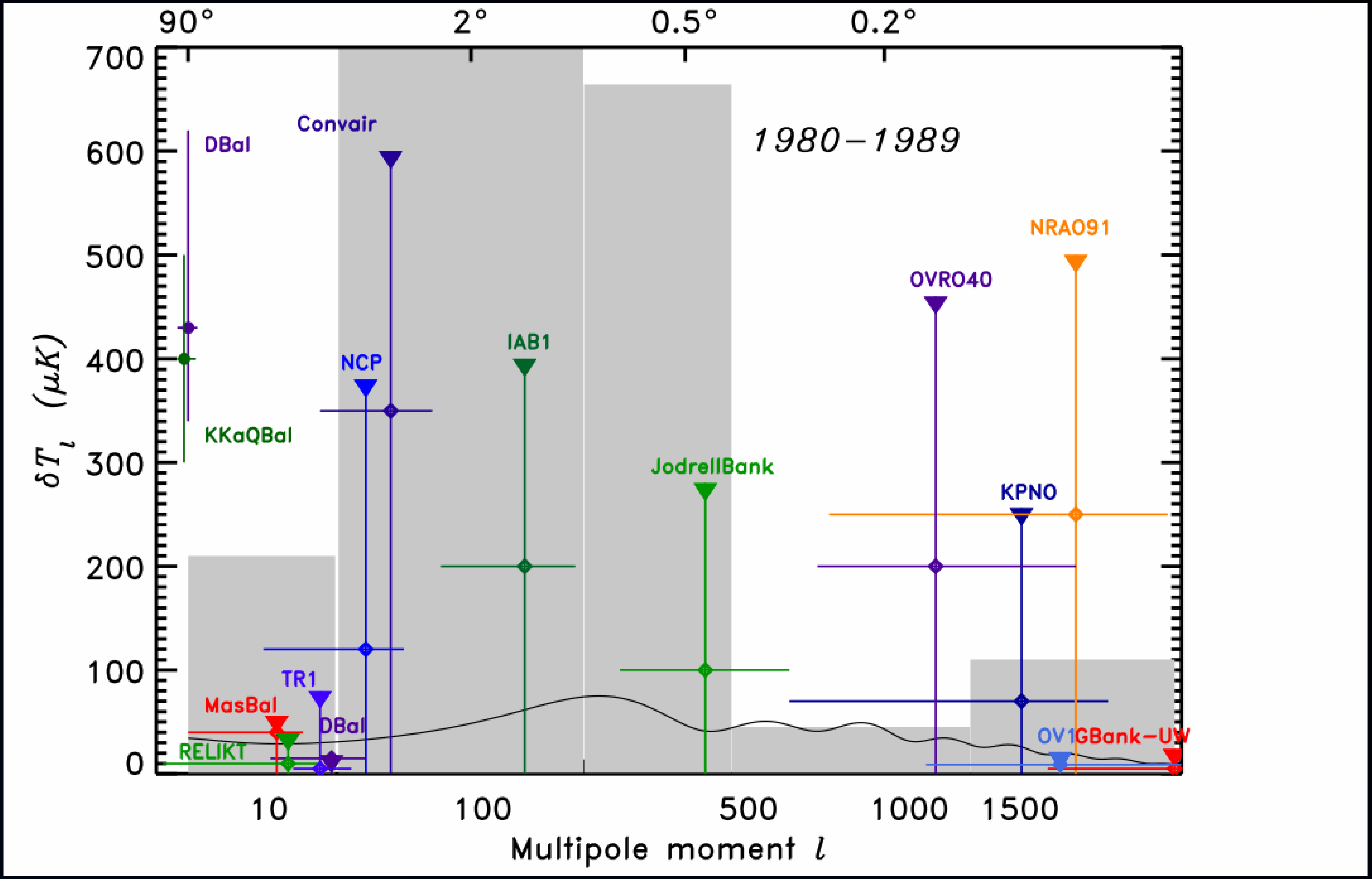
$$n^a \rightarrow \tilde{n}^a = M^a_b n^b$$

4) Ondas gravitacionais

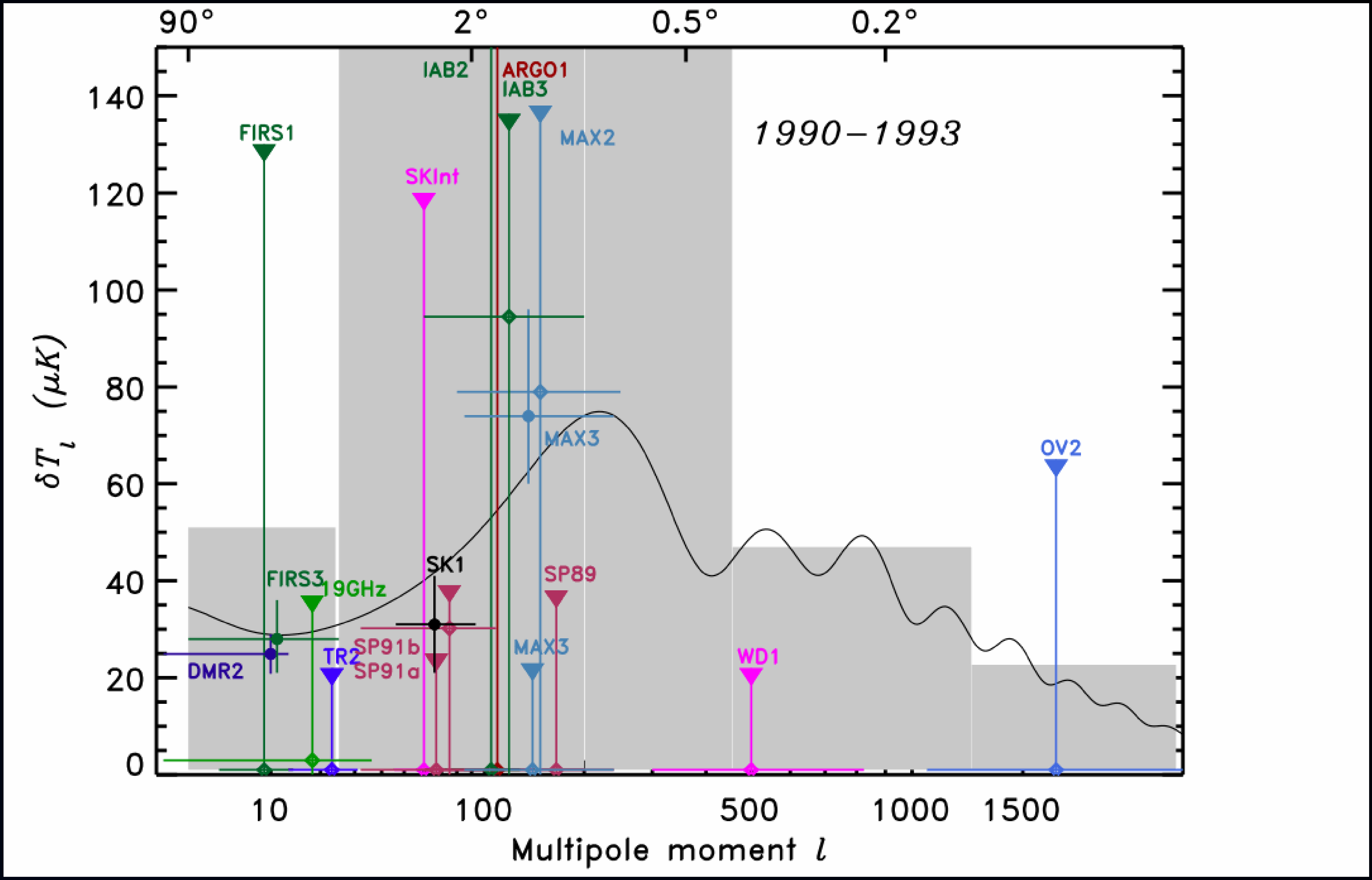


40 anos de pesquisas em RCF

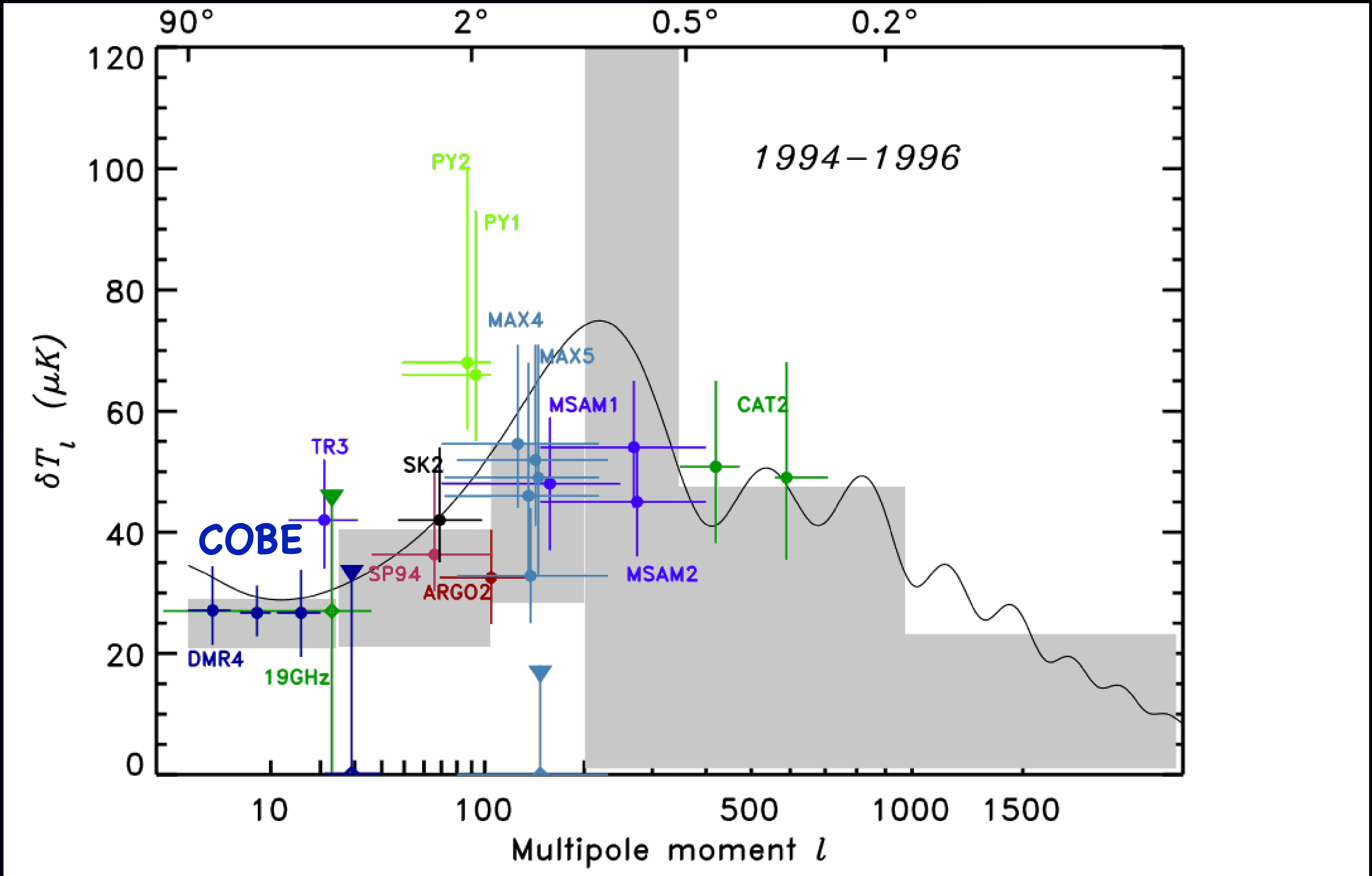


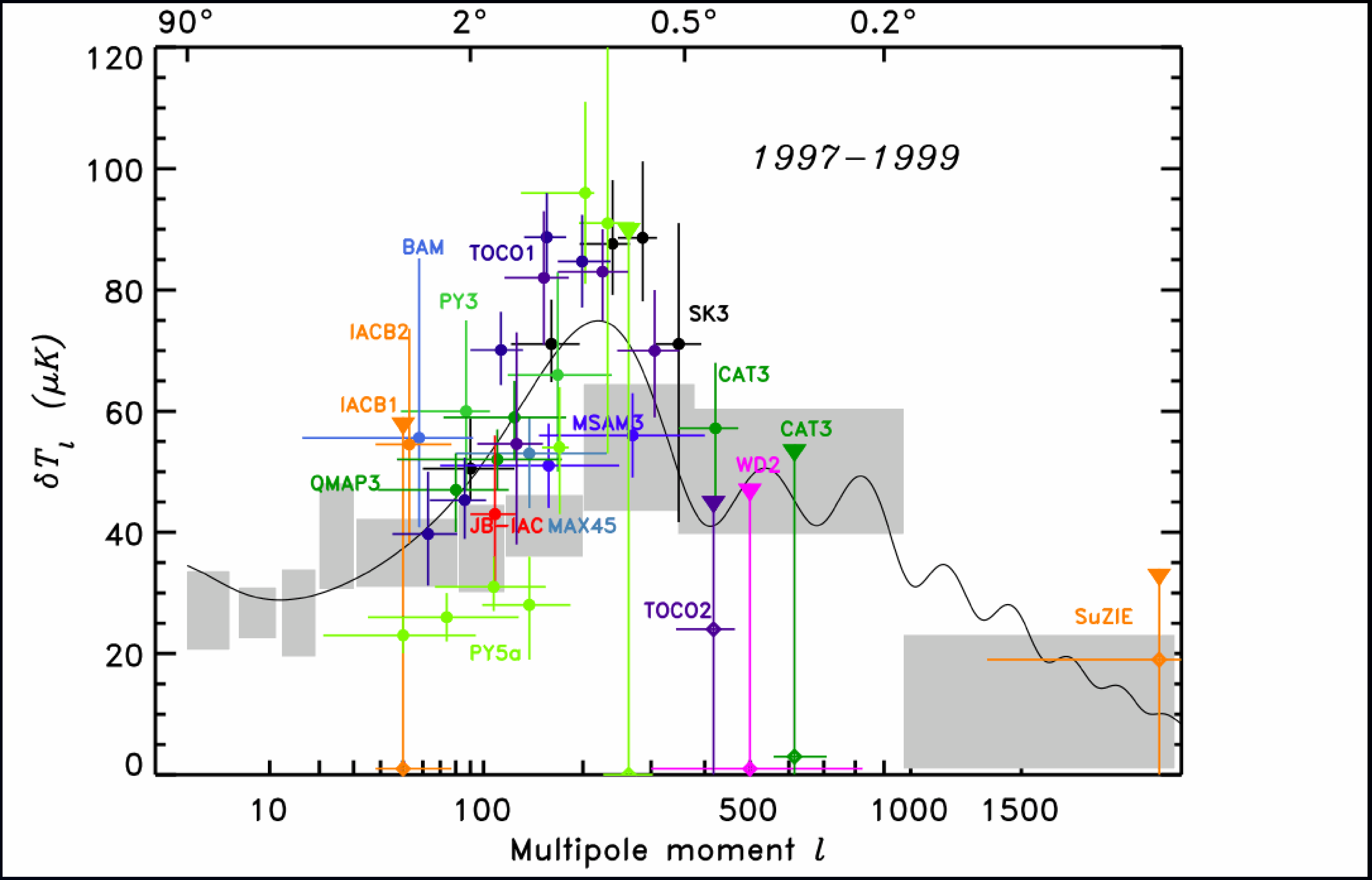


90°
2°
0.5°
0.2°
1980−1989
DBal
Convair
KKaQBal
NCP
IAB1
JodrellBank
OVRO40
NRAO91
KPNO
TR1
MasBal
DBal
RELIKT
OV1
GBank−UW
700
600
500
400
300
200
100
0
10
100
500
1000
1500
δT_l (μK)
Multipole moment l

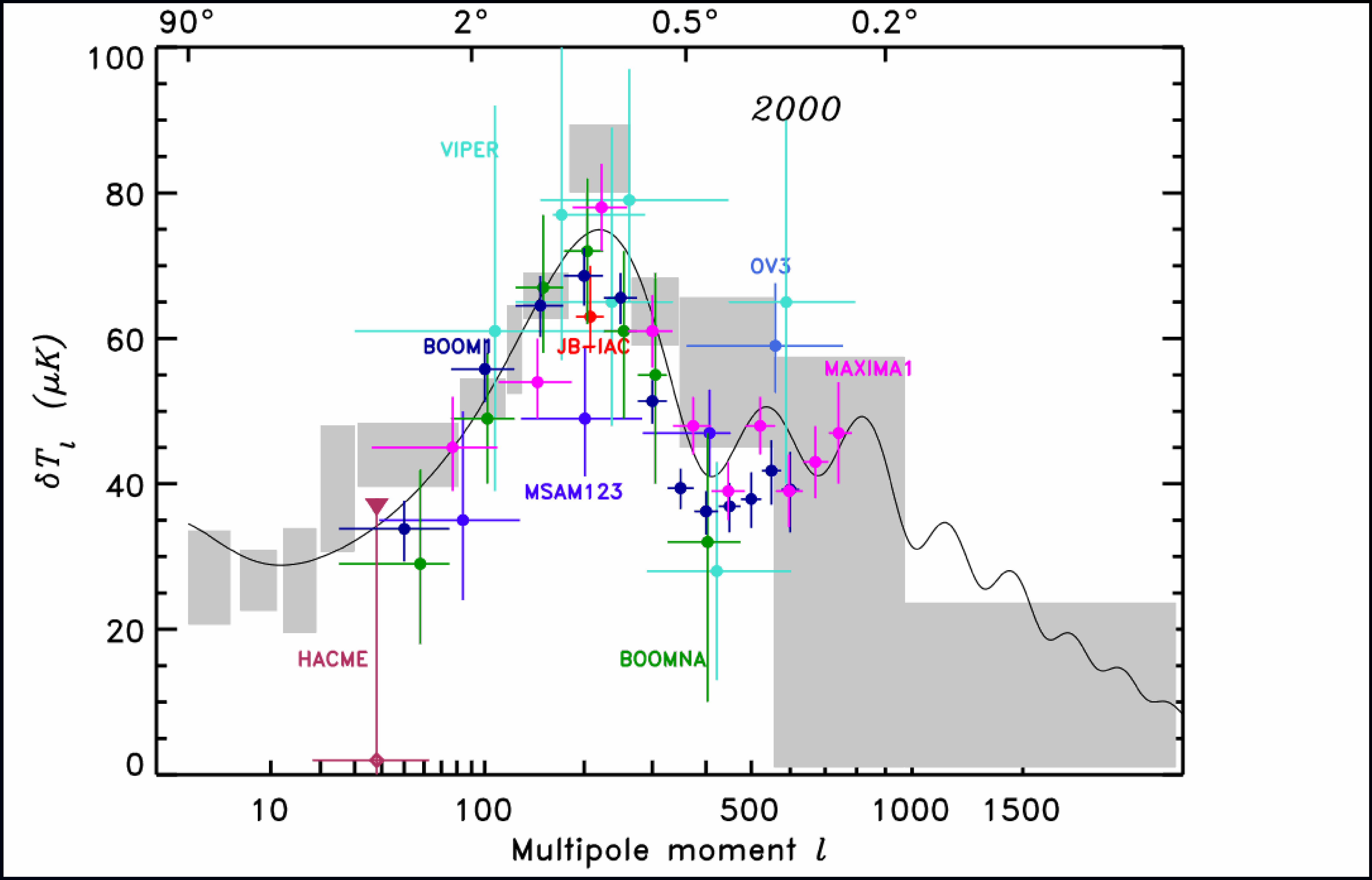


90°
2°
0.5°
0.2°
1990–1993
IAB2
ARGO1
IAB3
FIRS1
MAX2
SKInt
MAX3
OV2
SK1
SP89
FIRS3
19GHz
SP91b
SP91a
MAX3
WD1
TR2
DMR2
140
120
100
80
60
40
20
0
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

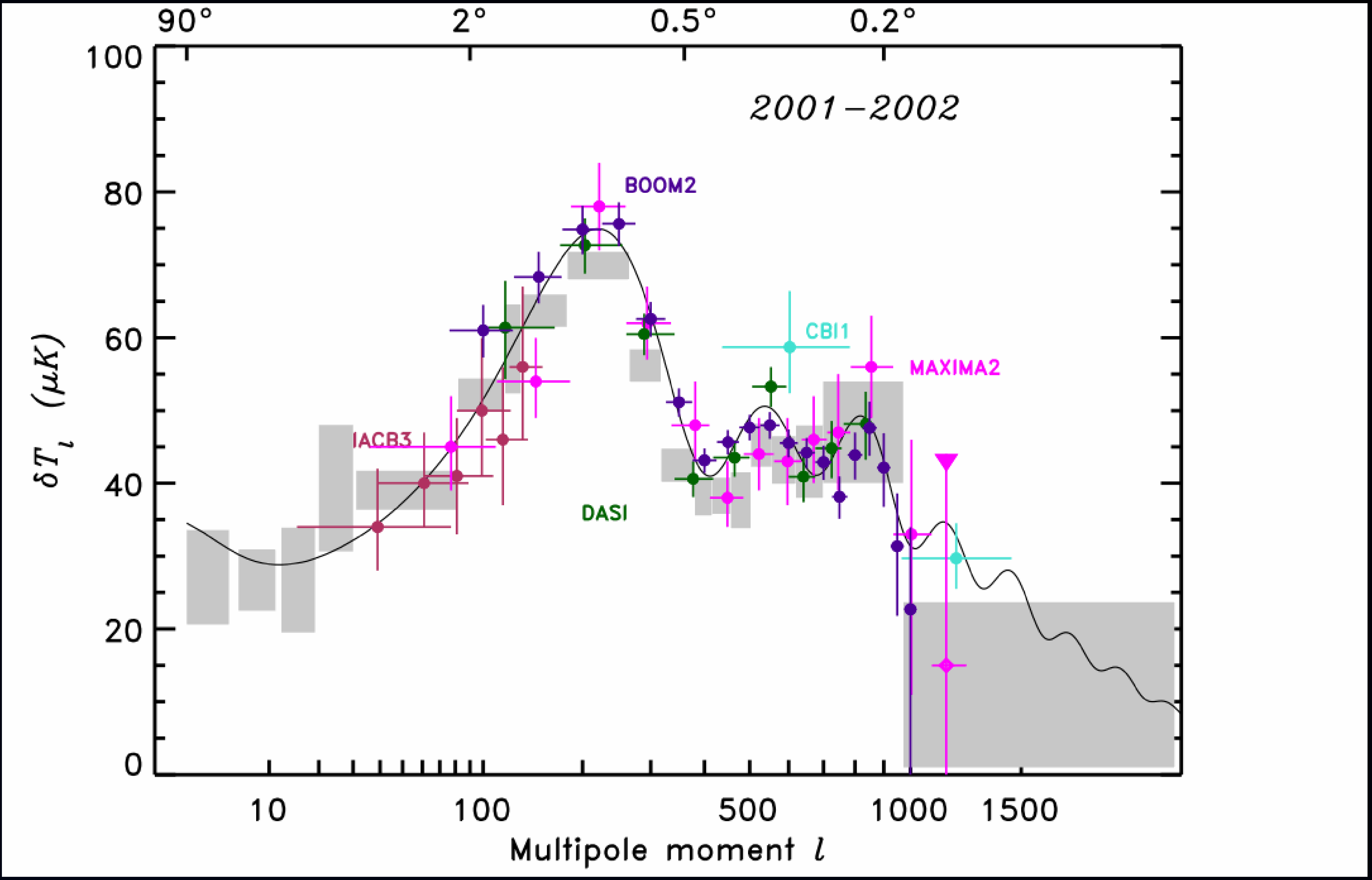

90°
2°
0.5°
0.2°
1994–1996
PY2
PY1
MAX4
MAX5
MSAM1
CAT2
TR3
SK2
COBE
SP94
ARGO2
MSAM2
DMR4
19GHz
120
100
80
60
40
20
0
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

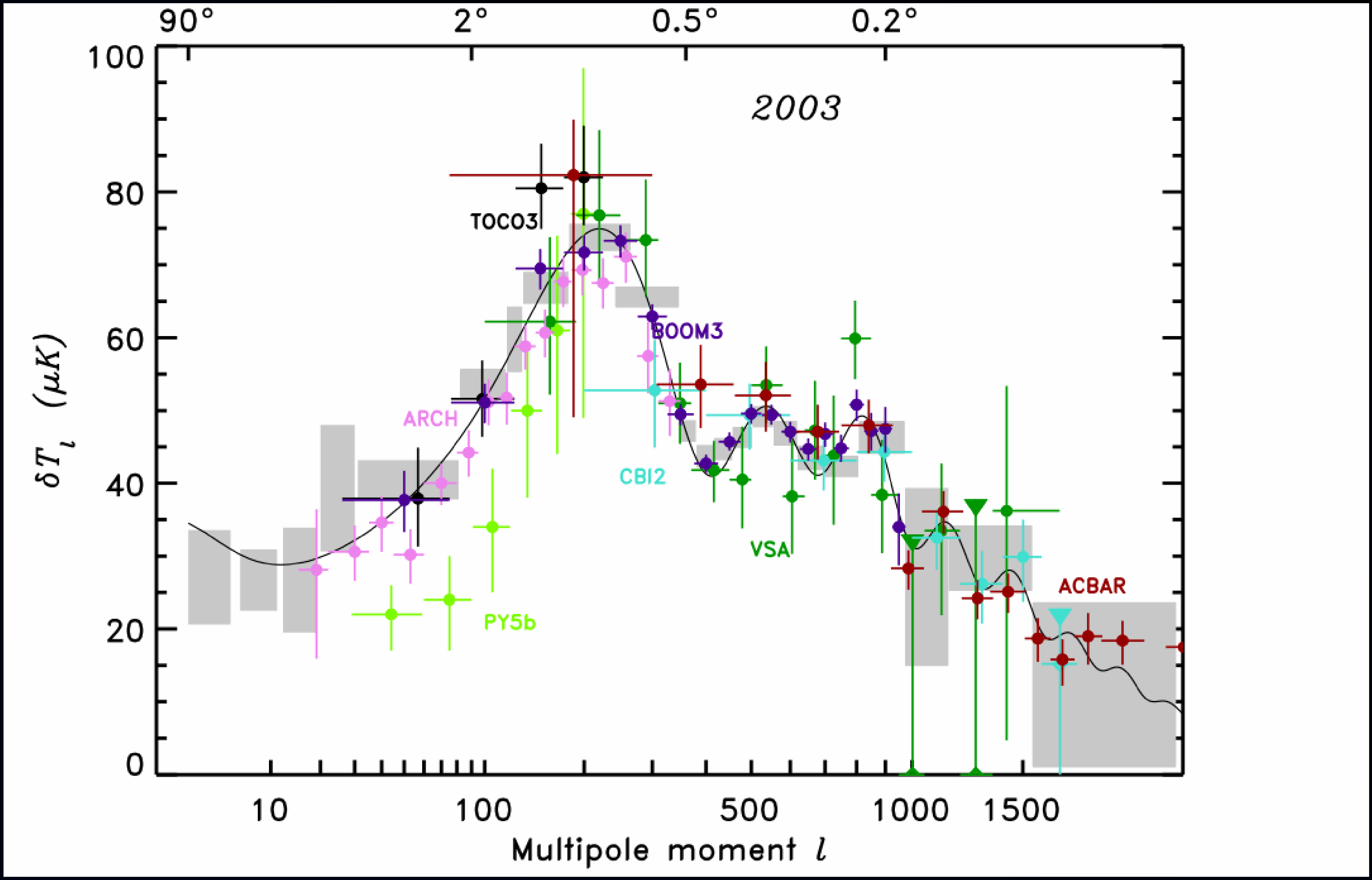


90°
2°
0.5°
0.2°
1997–1999
δT_l (μK)
BAM
TOCO1
PY3
IACB2
SK3
CAT3
IACB1
MSAM3
CAT3
WD2
QMAP3
JB–IAC
MAX45
TOCO2
SuZIE
PY5a
Multipole moment l



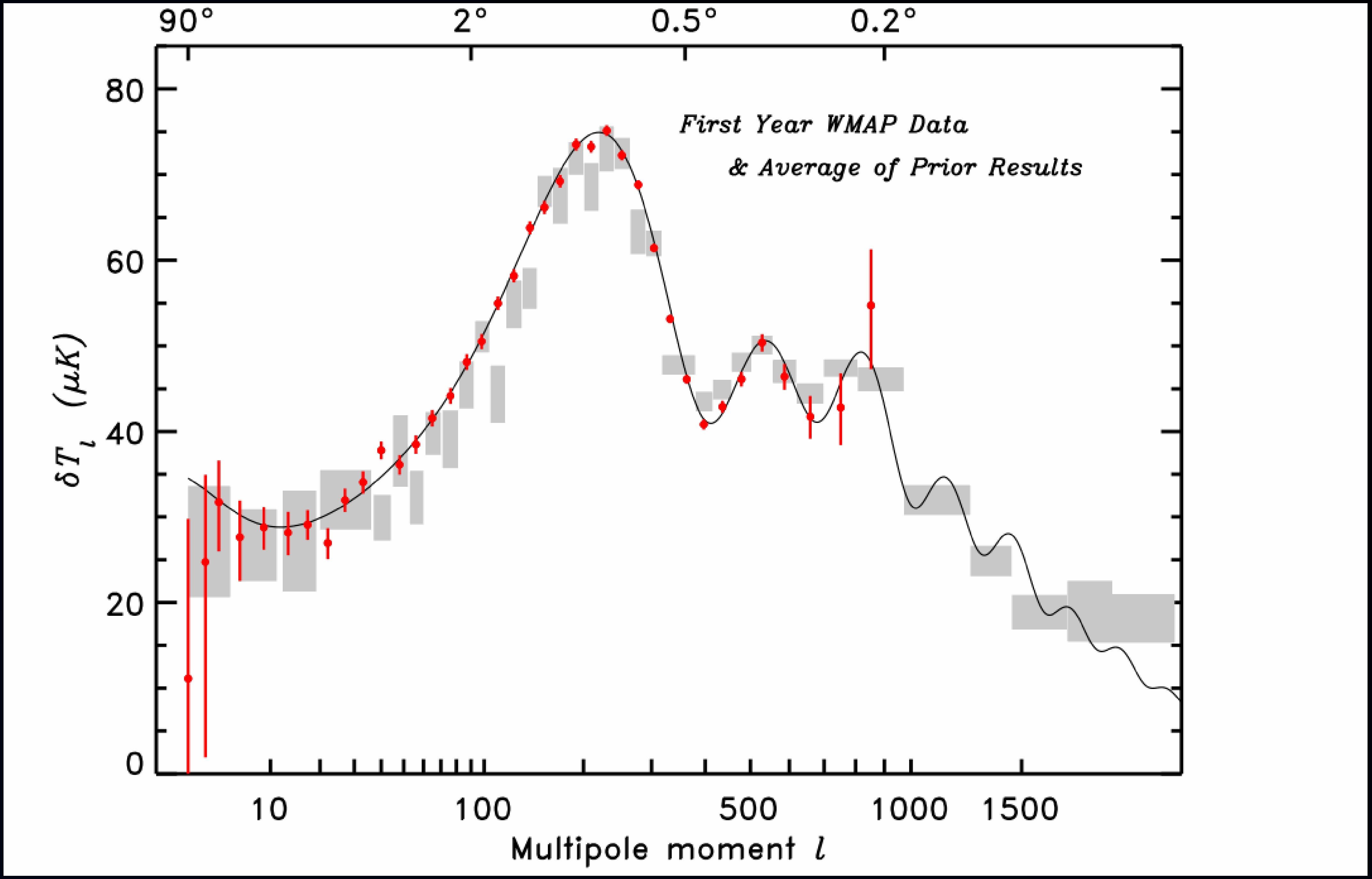
90°
2°
0.5°
0.2°
2000
100
80
60
40
20
0
δT_l (μK)
VIPER
BOOM1
JB+IAC
OV3
MAXIMA1
MSAM123
HACME
BOOMNA
10
100
500
1000
1500
Multipole moment l


90°
2°
0.5°
0.2°
2001–2002
BOOM2
CBI1
MAXIMA2
IACB3
DASI
100
80
60
40
20
0
δT_l (μK)
10
100
500
1000
1500
Multipole moment l



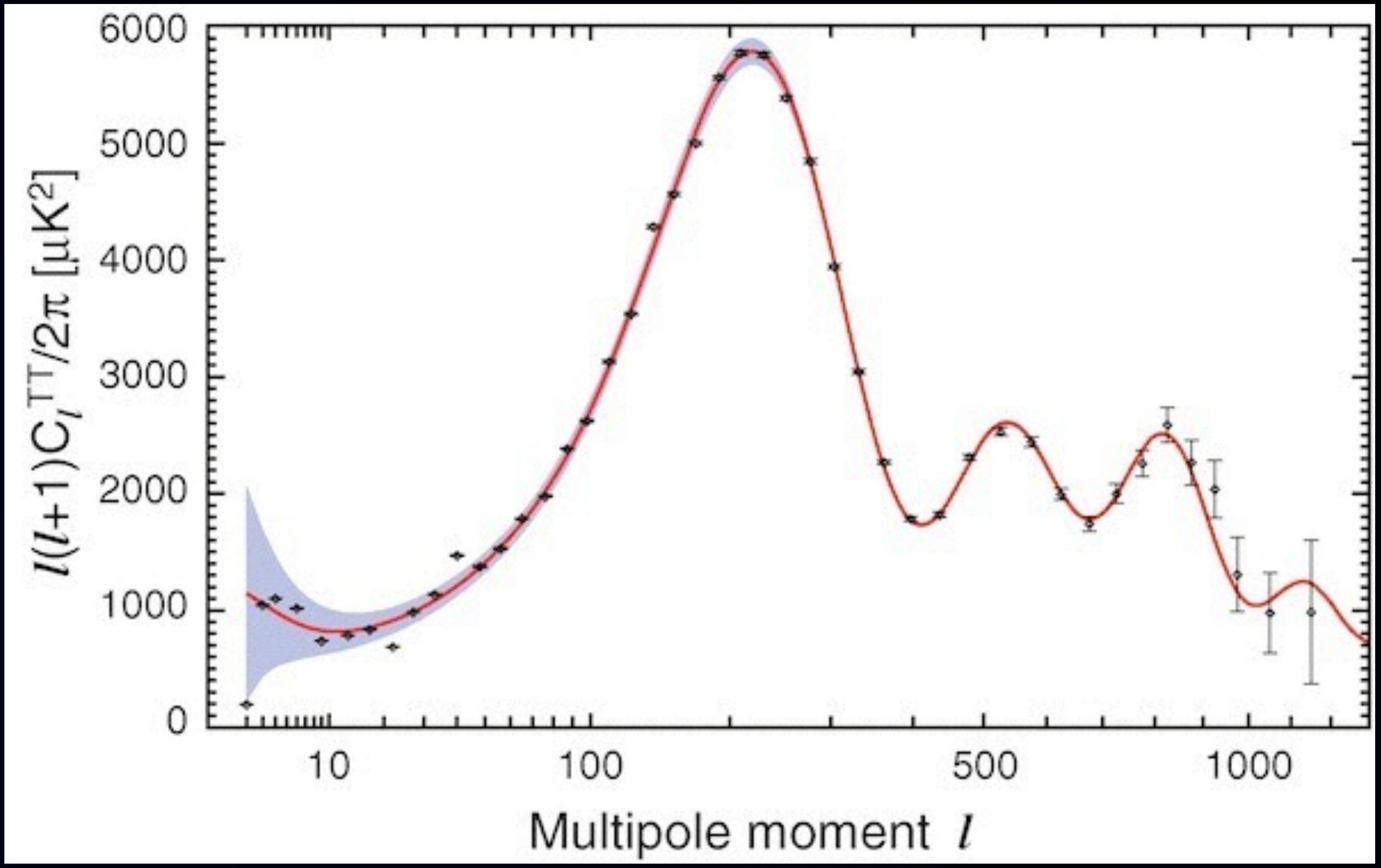
90°
2°
0.5°
0.2°
2003
TOCO3
BOOM3
ARCH
CBI2
VSA
ACBAR
PY5b
δT_l (μK)
100
80
60
40
20
0
10
100
500
1000
1500
Multipole moment l

WMAP @ 2003



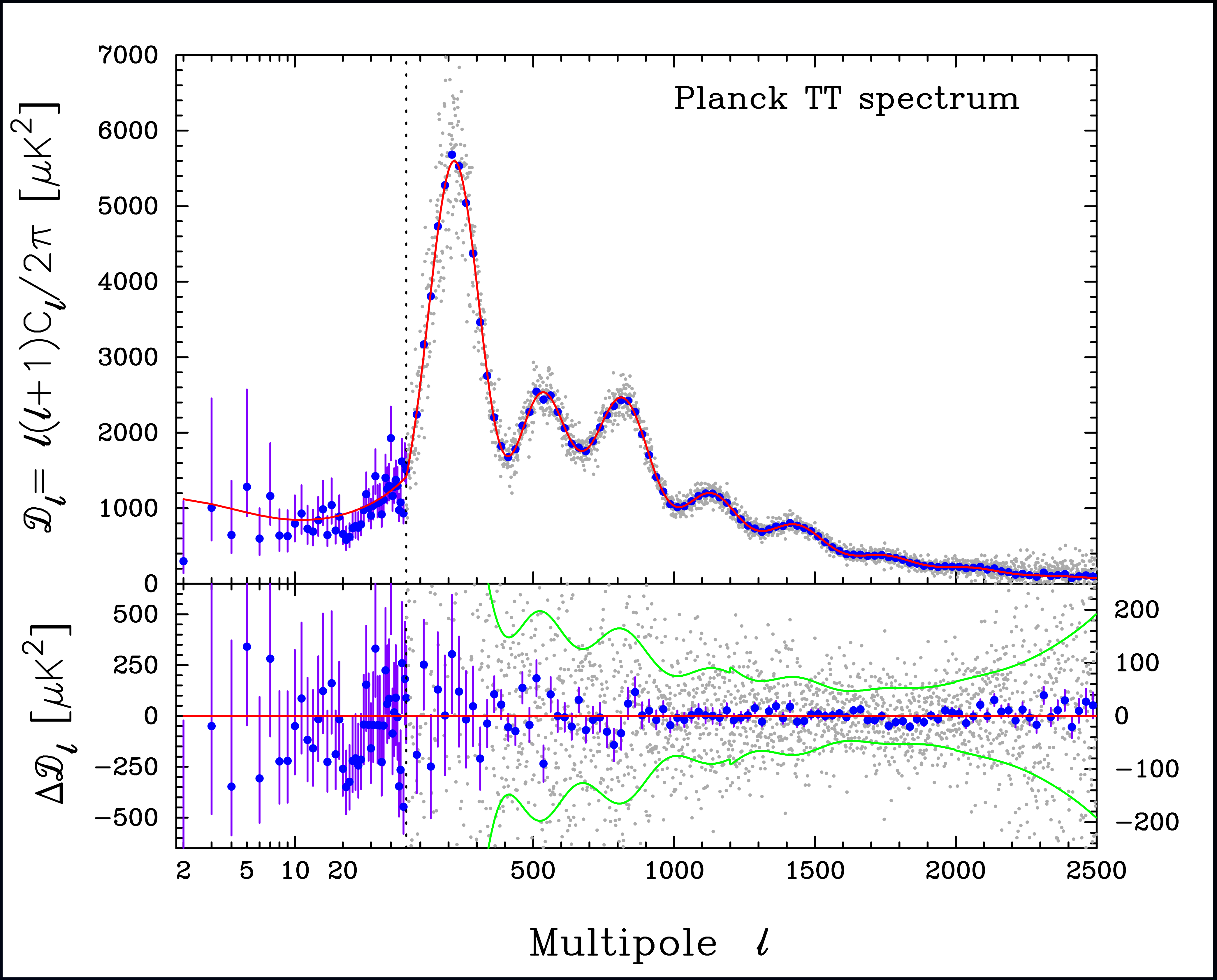
90°
2°
0.5°
0.2°
80
60
40
20
0
First Year WMAP Data
& Average of Prior Results
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

WMAP @ 2009



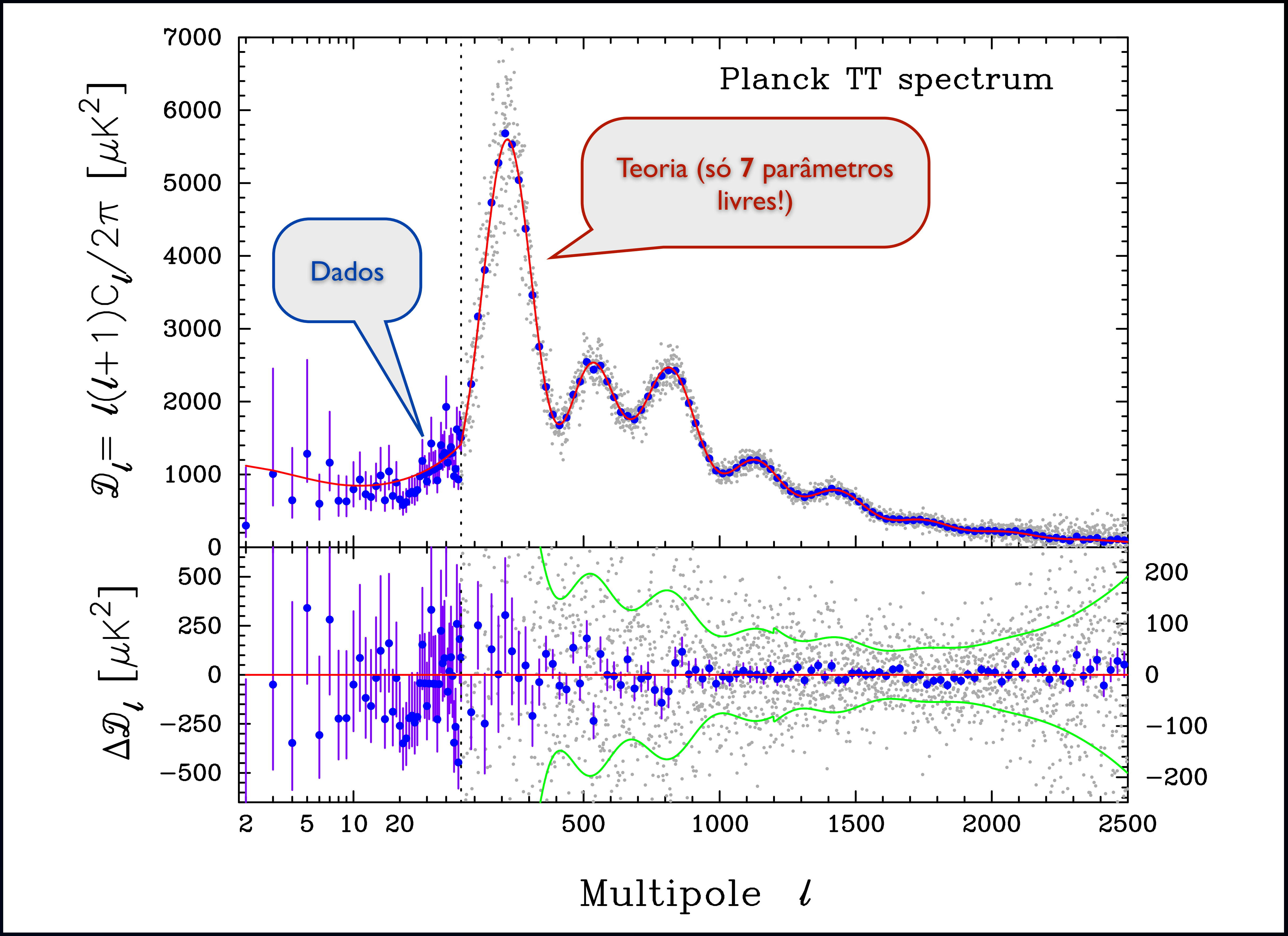
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
Multipole moment l

PLANCK @ 2013

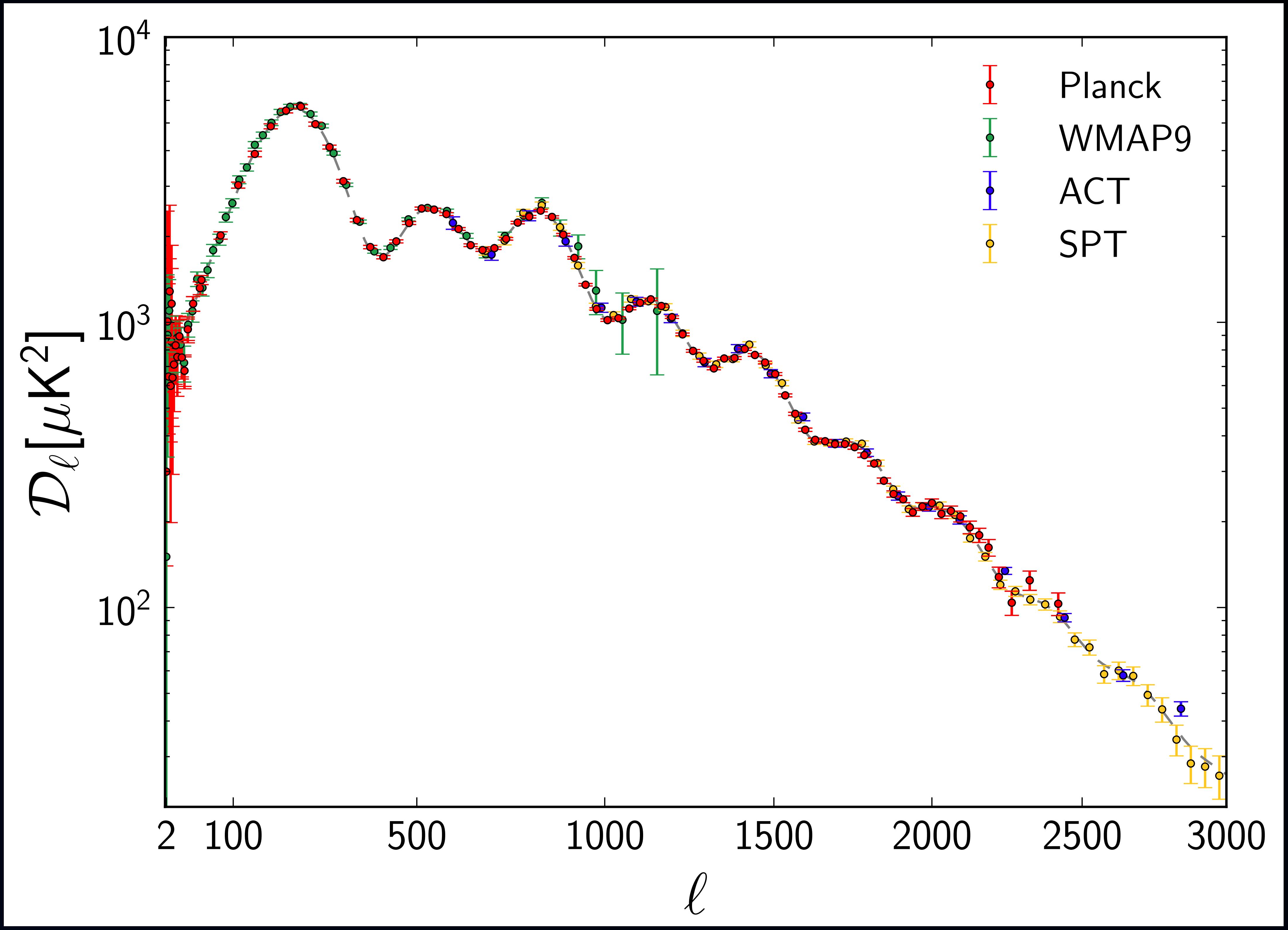


Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

Teoria *v.* dados (temperatura)



Estado-da-arte em 2014



Radiação cósmica de fundo: “Cosmologia de precisão"

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Origem física da RCF: ondas de pressão ("ondas acústicas")