

Uma breve história do Universo

(segundo a info da Radiação Cósmica de Fundo)

Armando Bernui

A cosmologia é parte da física, e estuda:

- a origem e evolução do Universo
- conteúdo e suas propriedades
- sua estrutura em grande escala
- sua geometria, sua forma, ...

The cosmological model of the Universe

stands on:

- ▶ Metric theory, e.g., General Relativity
- ▶ Cosmological principle
- ▶ Observational probes

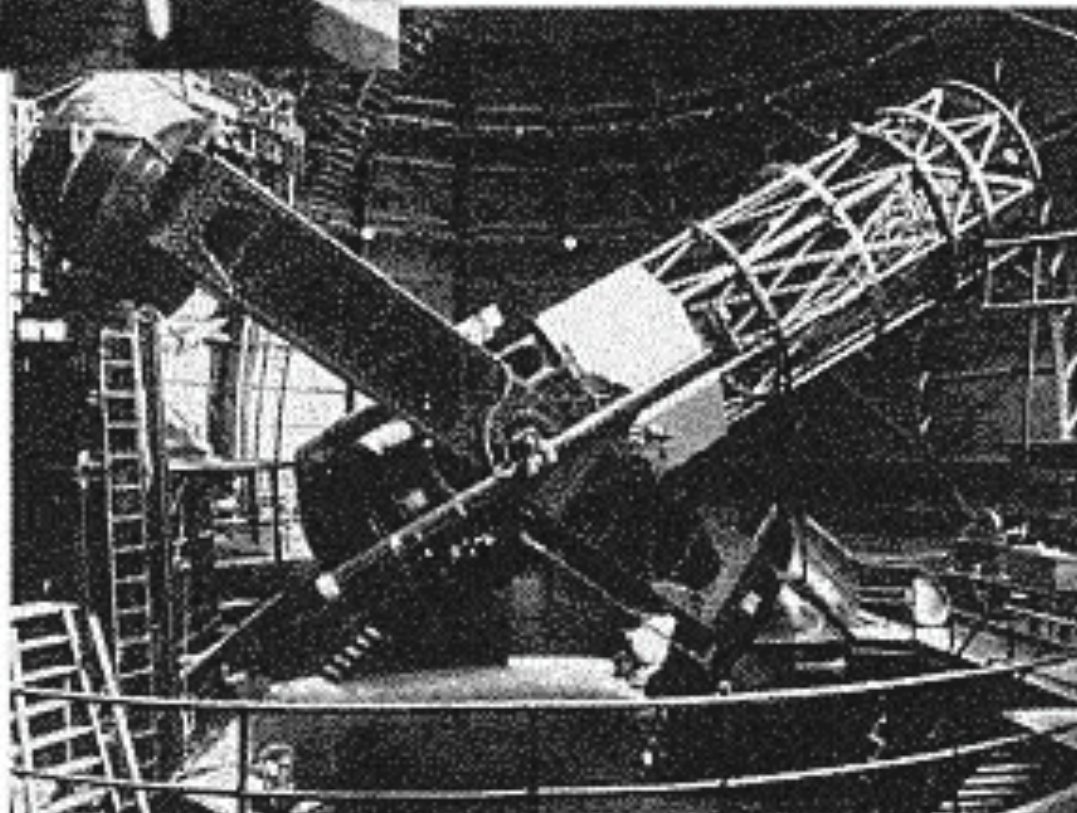
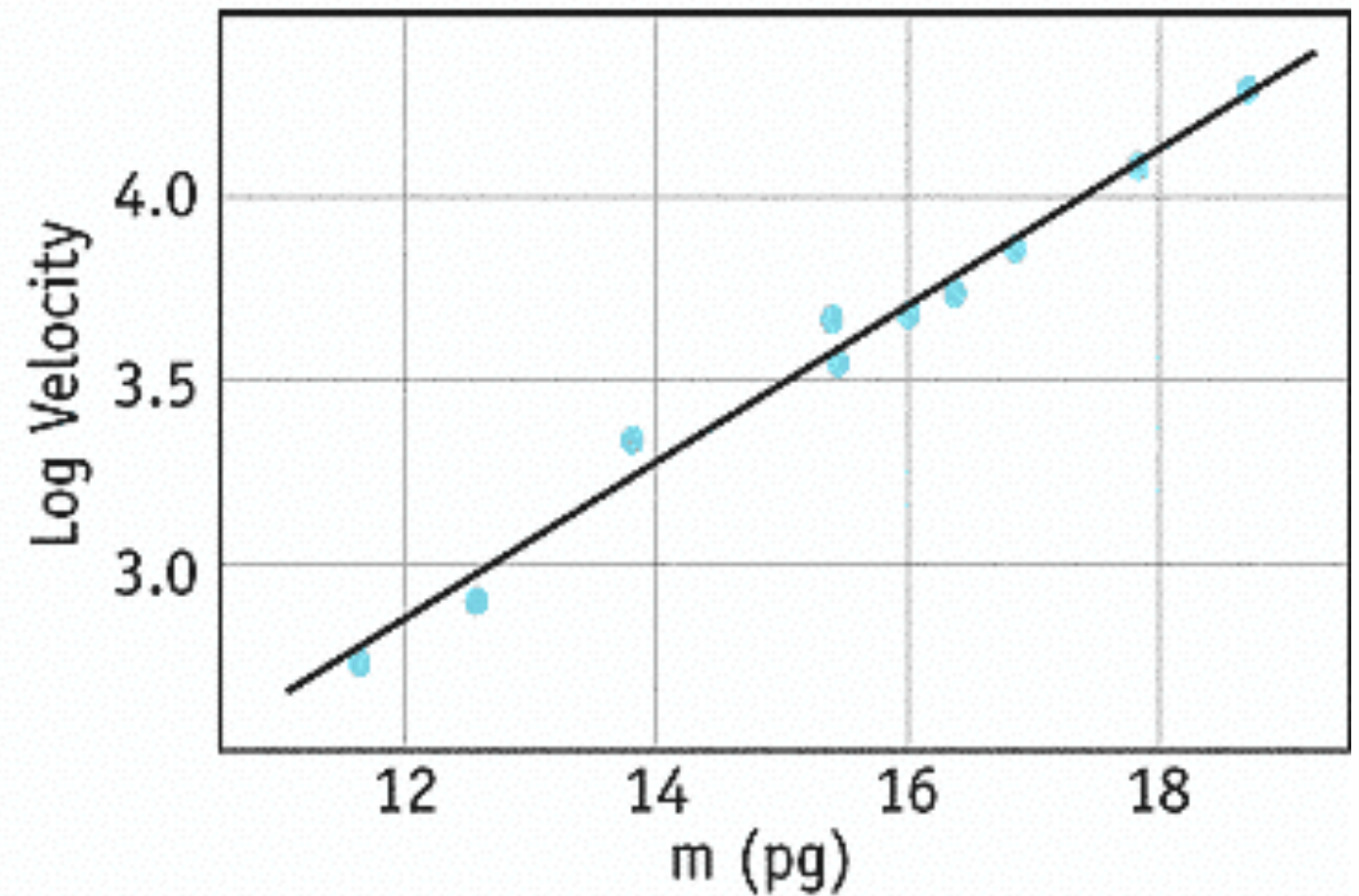
Firsts Observational Probes:

- ▶ **Expansion of the Universe**
- ▶ **Nucleosynthesis of primordial nuclei**
- ▶ **Cosmic Microwave Background Radiation**

► DISCOVERY OF EXPANDING UNIVERSE



Edwin Hubble

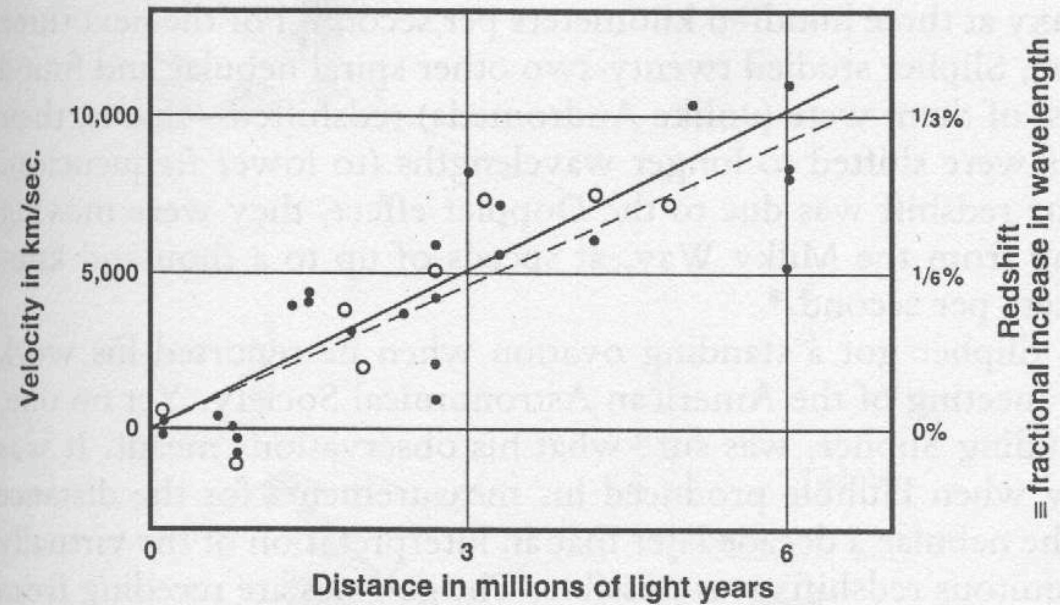


Mt. Wilson
100 Inch
Telescope

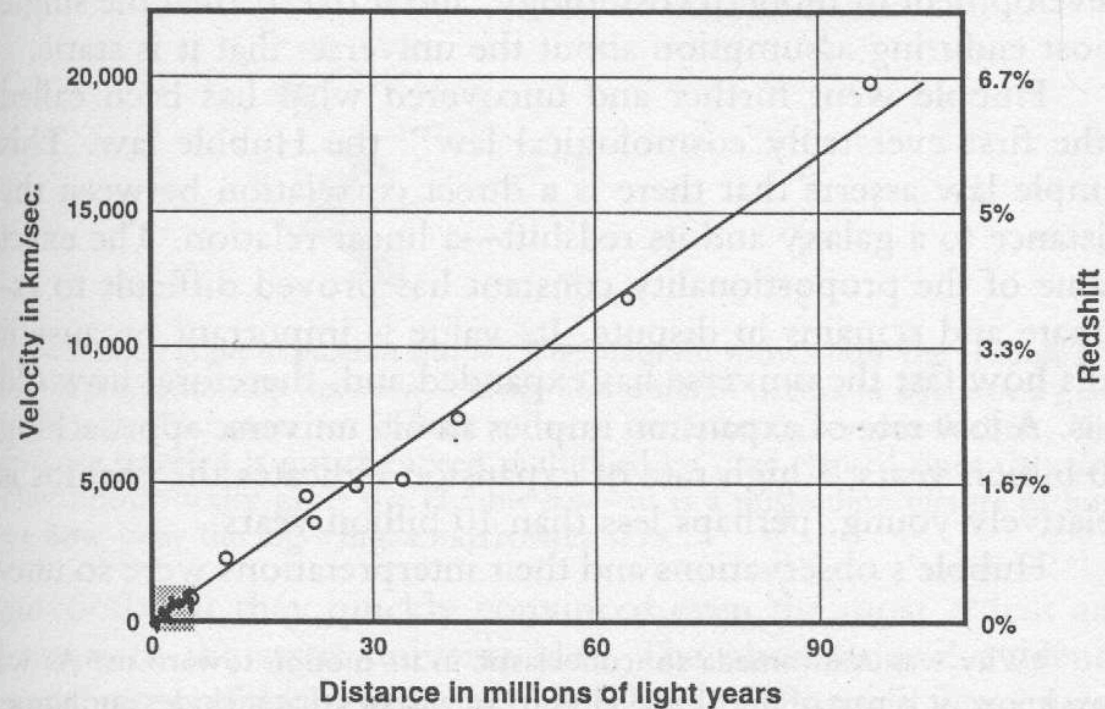
para $z \ll 1$

Hubble's velocity vs. distance plot of 1929.

The black discs and full line represent the Hubble law fitted to the nebulae individually. The circles and broken line represent the solution combining the nebulae into groups.



Hubble and Humason's 1931 velocity vs. distance diagram

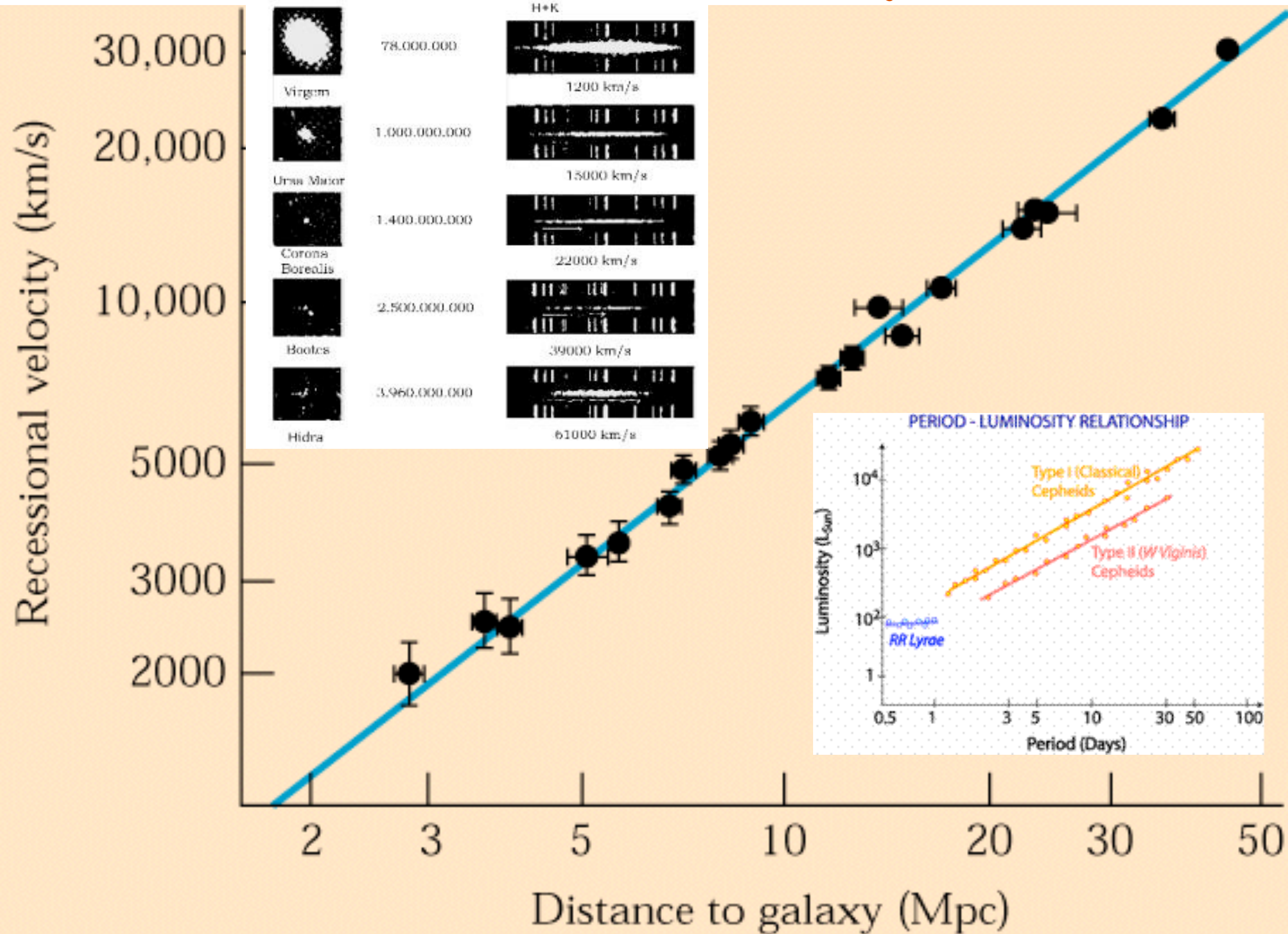


Hubble law data. The upper plot shows Hubble's original data on distance to nebulae (galaxies) and their red shift (or velocity using the Doppler effect relation). The lower plot shows Hubble's original data in the shaded region and the new data collected with Milton Humason. The new data provide a convincing argument for the linear relationship between distance and red shift.

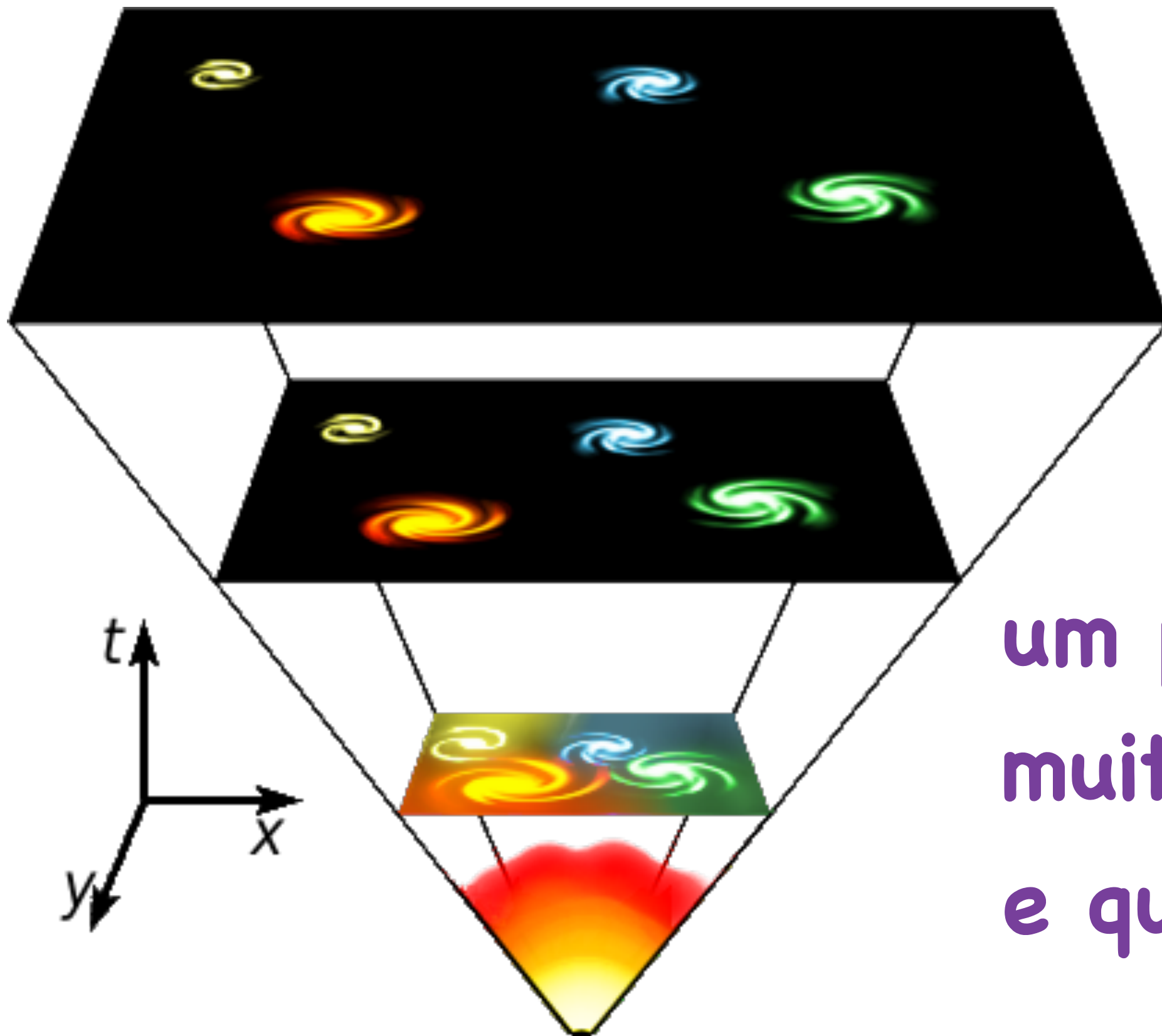
CHRISTOPHER SLYE

$$v \approx cz$$

$$z \ll 1$$

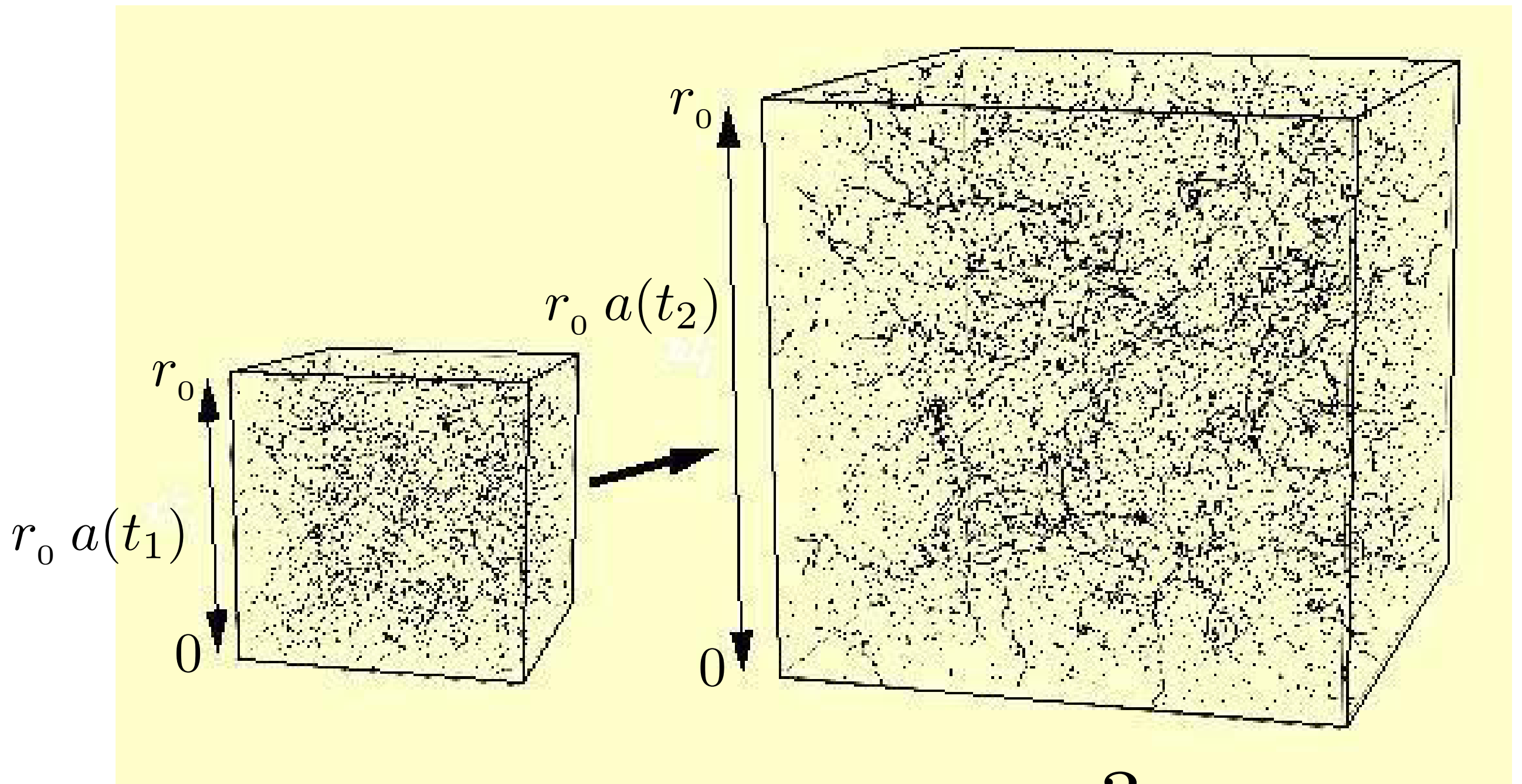


historia termica do Universo



um passado
muito denso
e quente!

o fator de escala: $a=a(t)$



$$V = V_0 a(t)^3$$

Conseqüências da expansão:

os comprimentos de onda de fontes que se afastam aumenta (desvio para o **vermelho**): $\lambda_{\text{obs}}/\lambda_{\text{emi}} = 1 + z_{\text{emi}}$

Time:

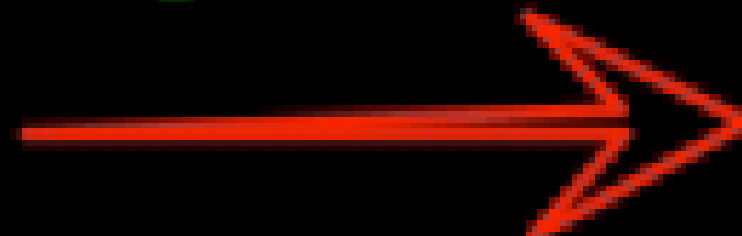
300,000 years after the Big Bang

14 billion years after the Big Bang
(The Present)

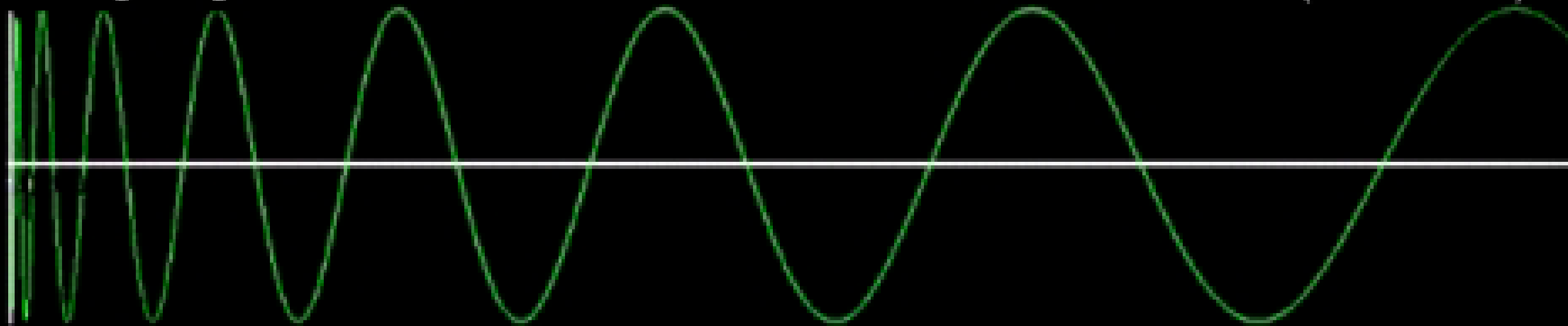
Temperature:

3000 Kelvin

Redshift



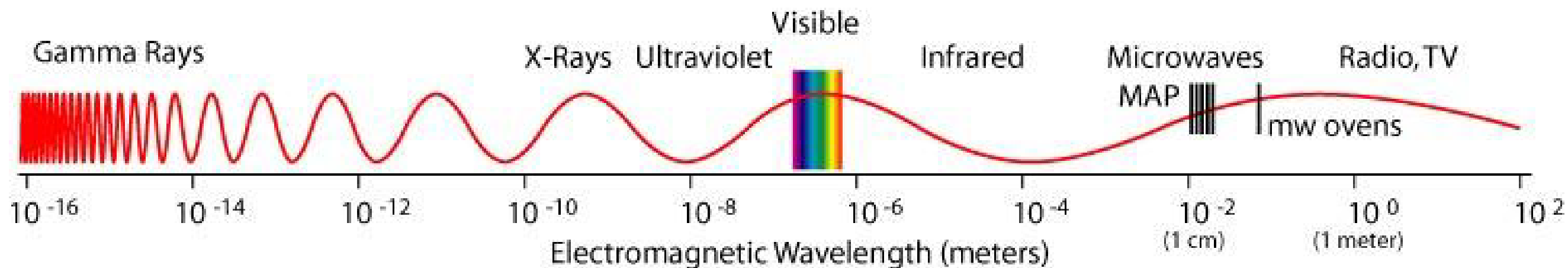
3 Kelvin



Conclusión 1

a expansão do Universo, interpretada como efeito Doppler entre fonte-e-observador, produz (desvio para o **vermelho**):

$$\frac{\lambda_{\text{hoje}}}{\lambda(t)} = 1 + z(t) = \frac{1}{a(t)}$$

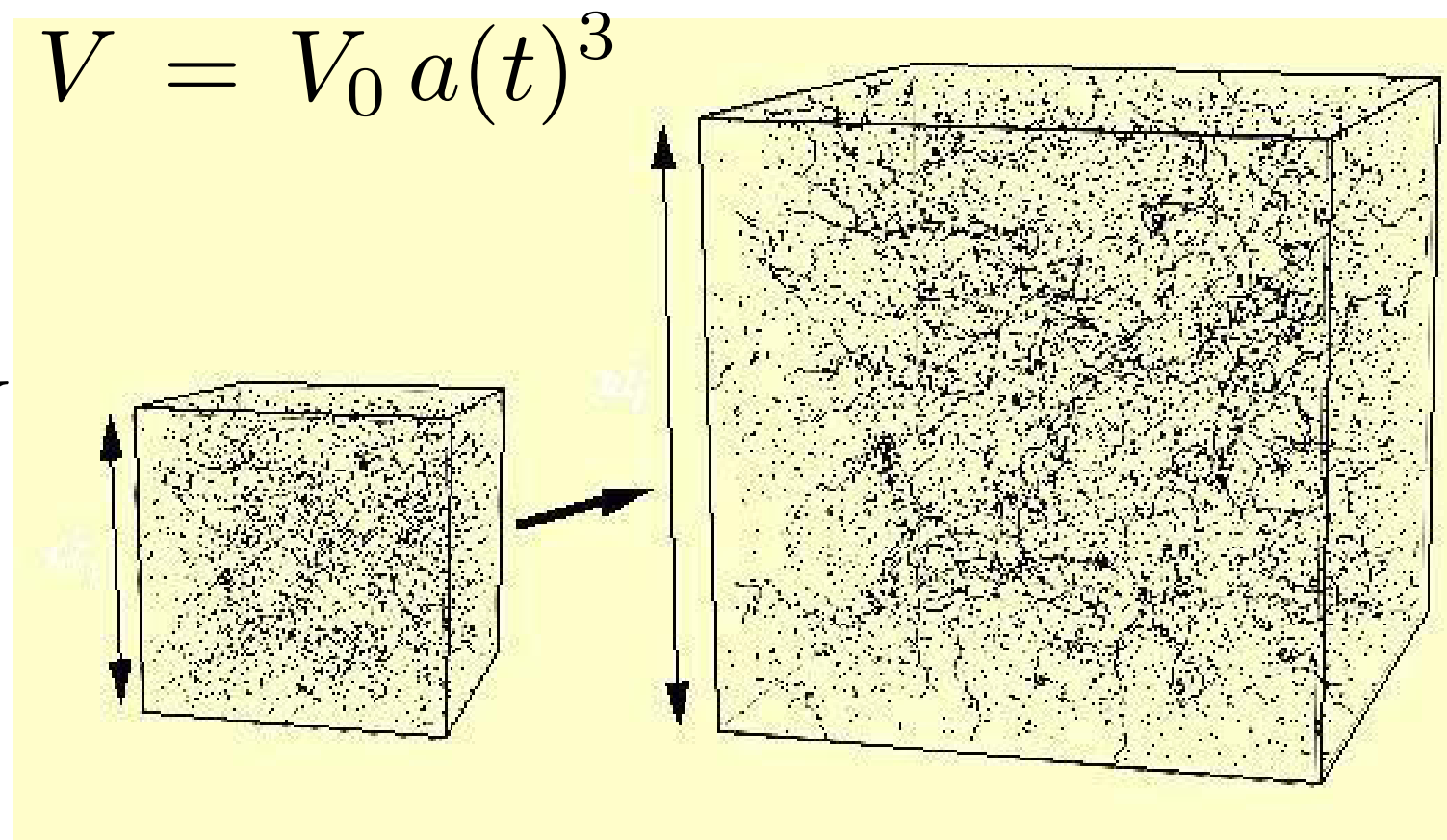


um pouco de termodinâmica

Considere um gas de fótons em equilíbrio termodinâm.
($\varepsilon_\gamma = \sigma T^4$) em um elemento de volume que expande
com o Universo:

$$E = E_\gamma = \varepsilon_\gamma V = \sigma T^4 V$$

$$p = p_\gamma = \sigma T^4 / 3$$



Da 1ra. lei da termodinâmica (+proc. adiabático):

$$dQ = 0$$
$$dQ = dE + p dV \Rightarrow -p_\gamma \frac{dV}{dt} = \frac{dE_\gamma}{dt}$$

Substituindo as relações para p_γ , E_γ na eq. anterior:

$$-\frac{1}{3V} \frac{dV}{dt} = \frac{1}{T} \frac{dT}{dt} \Rightarrow \frac{d}{dt}(\ln a) = \frac{d}{dt}(\ln T^{-1}) \Rightarrow a \propto 1/T$$

Conclusión 2

0 Universo resfria enquanto expande:

$$a(t) = T_0/T(t)$$

por tanto: el pasado fue
muy denso y **muy** caliente!

Conclusión 3

como:

$$a(t) = T_0/T(t)$$

$$a(t) = 1/[1 + z(t)]$$

então:

$$\Rightarrow 1 + z(t) = T(t)/T_0$$

concluimos que podemos contar a história do Universo usando qq um destes parâmetros:

- o tempo cósmico t
- o redshift z
- a temperatura da RCF T (em K ou em eV)

corolário:
$$\left. \begin{array}{l} 1 + z \propto T \\ 1 + z \propto 1/\lambda = \nu/c \end{array} \right\} \Rightarrow T \propto \nu$$

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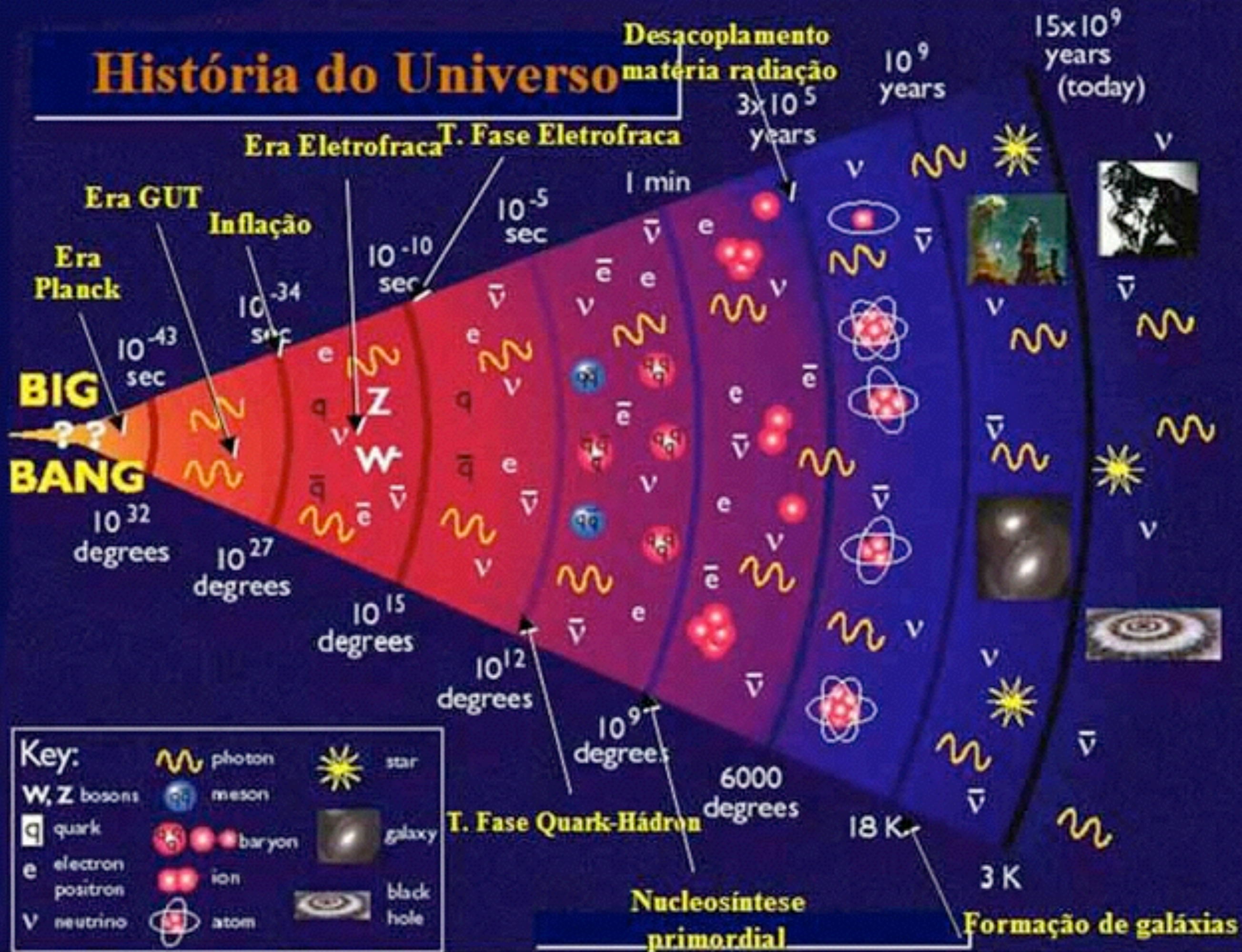
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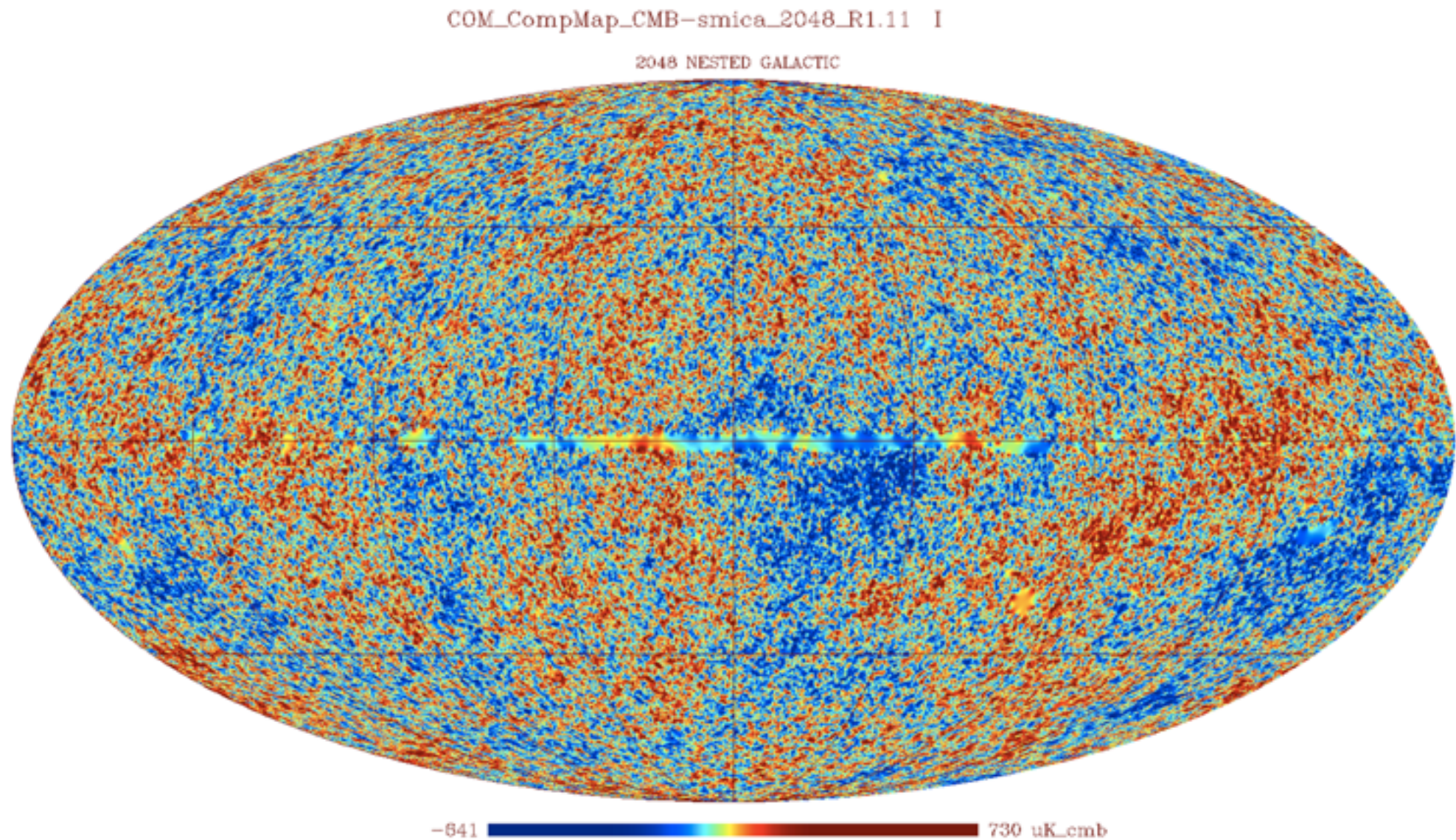
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Thermal history of the Universe

História do Universo



O Universo segundo a RCF



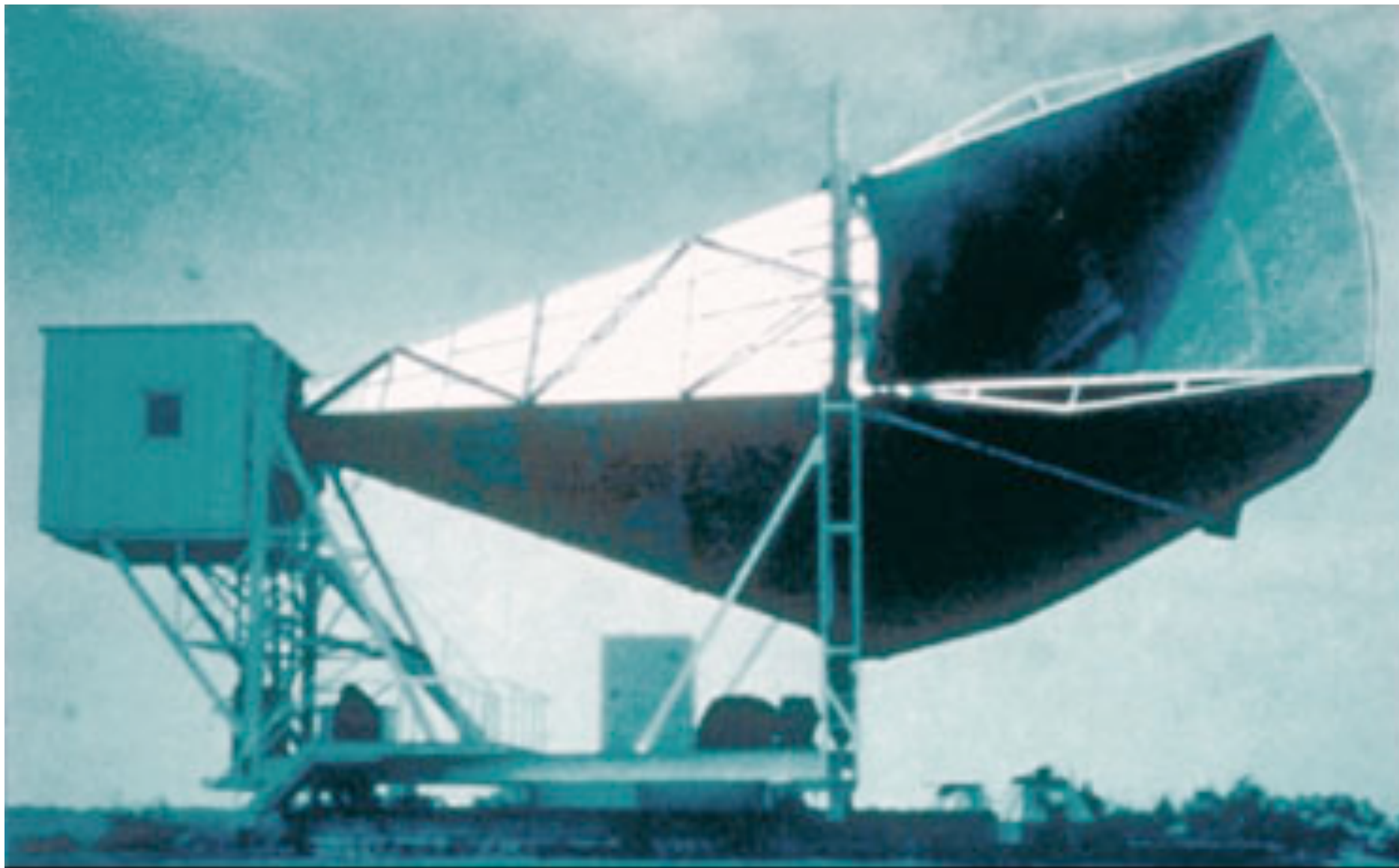
Georgiy Antonovich Gamov... **George Gamow (1948)**

- ▶ 1. Talvez os elementos químicos observados no Universo tenham sido construídos em uma fase do Universo primordial em que a temperatura era elevada ($\simeq 10^9 - 10^{10} \text{ K}$) e matéria e radiação estavam em equilíbrio termodinâmico.
- ▶ 2. A densidade nesta fase devia ser comparável àquela que ocorre no carôço central das estrelas ($\simeq 1 \text{ g/cm}^3$).
- ▶ 3. Como a densidade atual do Universo é da ordem de 10^{-30} g/cm^3 , concluímos que houve uma expansão por um fator da ordem de 10^{10} .
- ▶ 3. O resultado final é que o Universo deve estar preenchido com um fundo de radiação cuja temperatura hoje deve ser da ordem de 1 K.

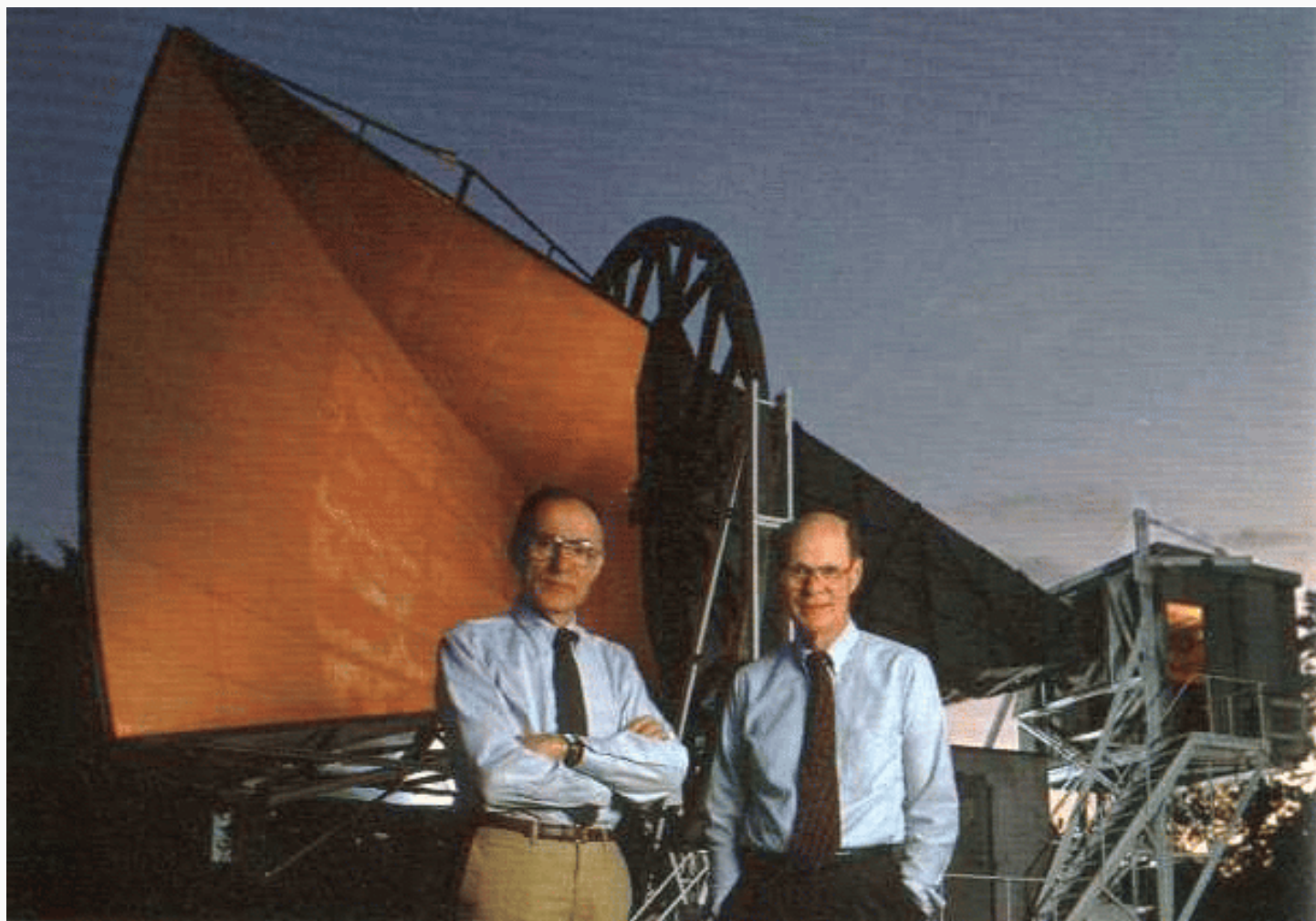


o ingrediente **cultural** que faz a diferença:

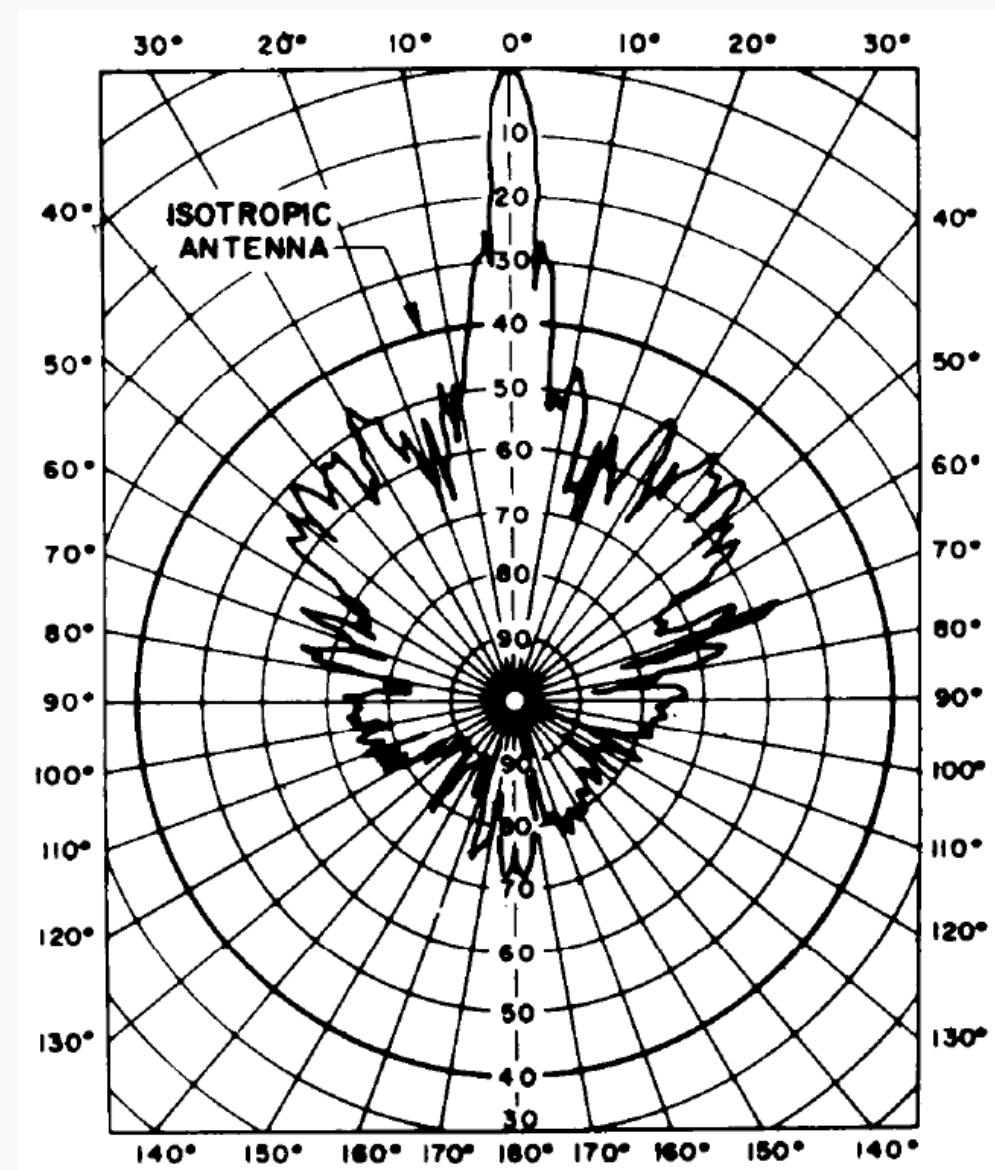
o instrumento de medição



A descoberta da RCF (1964)



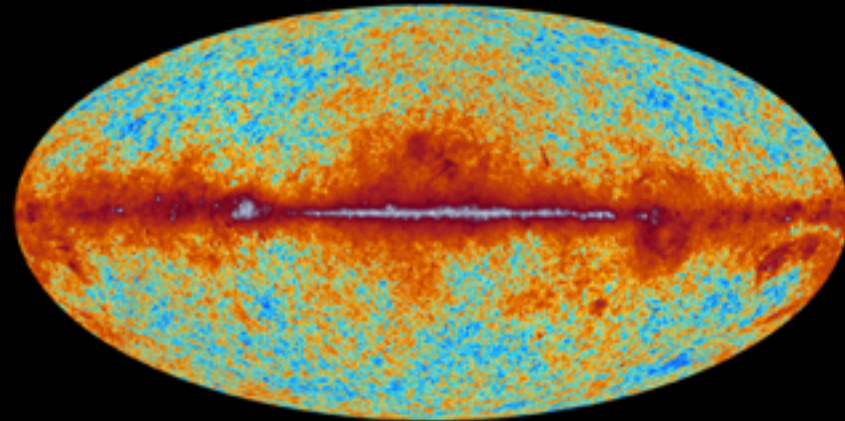
- Antena projetada em 1960 para testes de comunicação de baixo ruído com o satélite echo.
- Sistema direcional de baixo ruído (< 0.05 K) operando em $\lambda = 7.35$ cm.



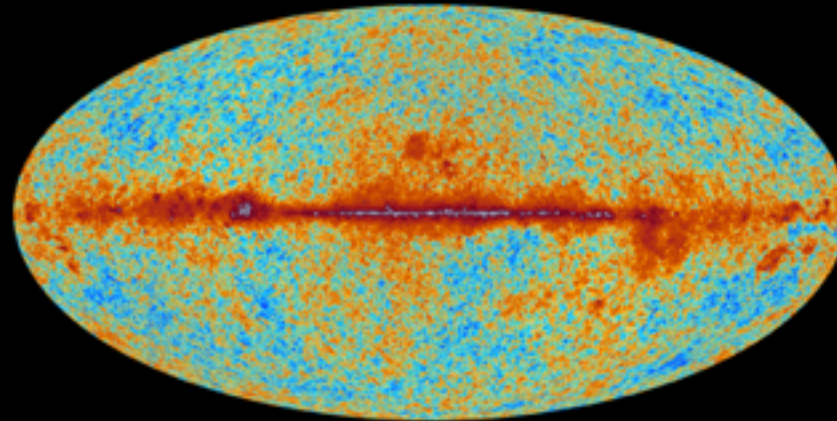


planck

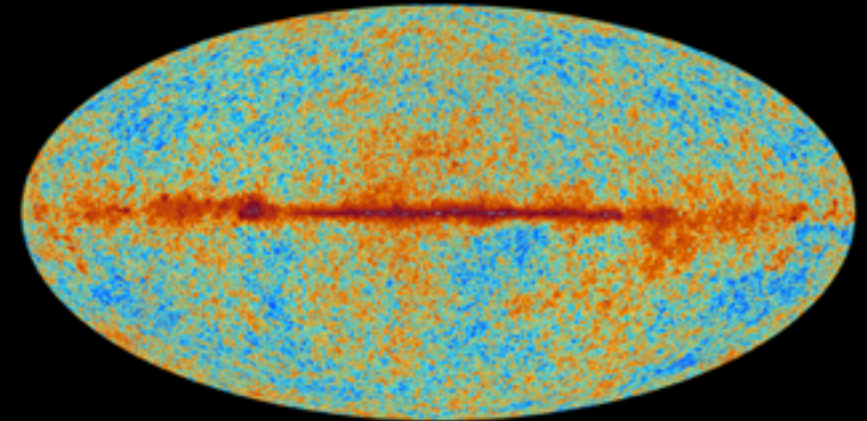
The sky as seen by Planck



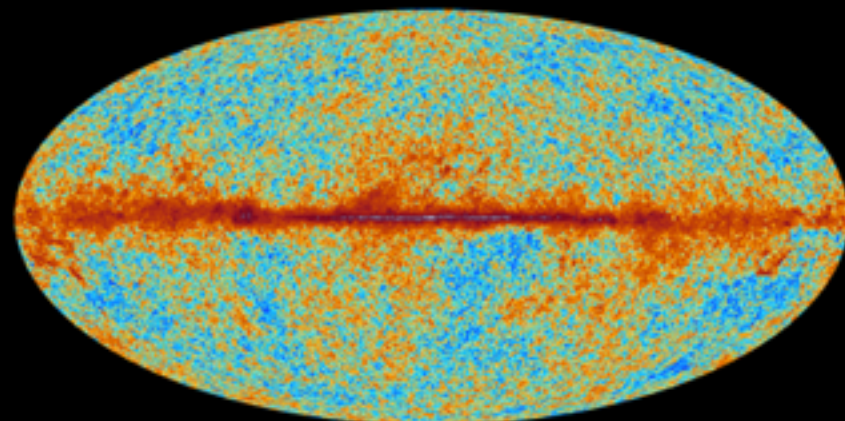
30 GHz



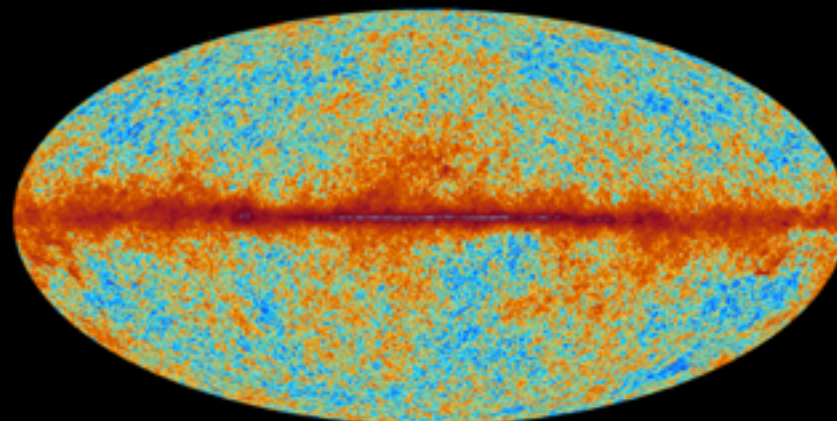
44 GHz



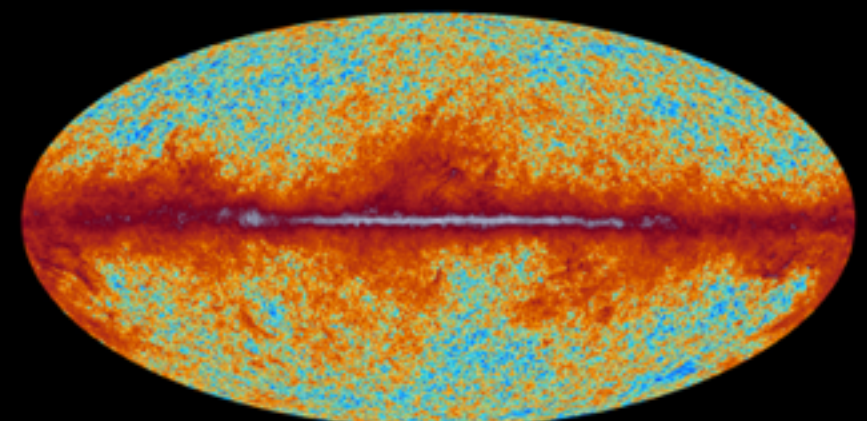
70 GHz



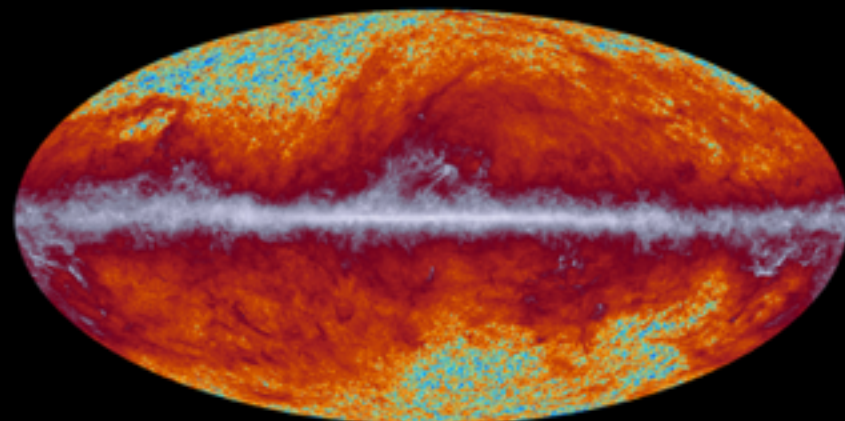
100 GHz



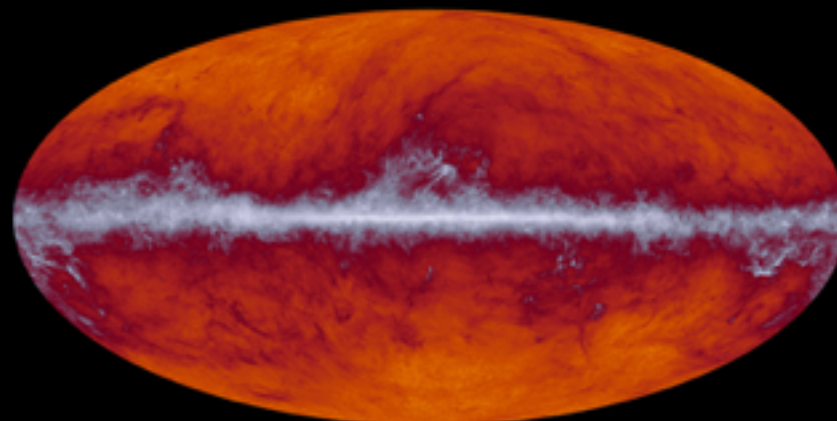
143 GHz



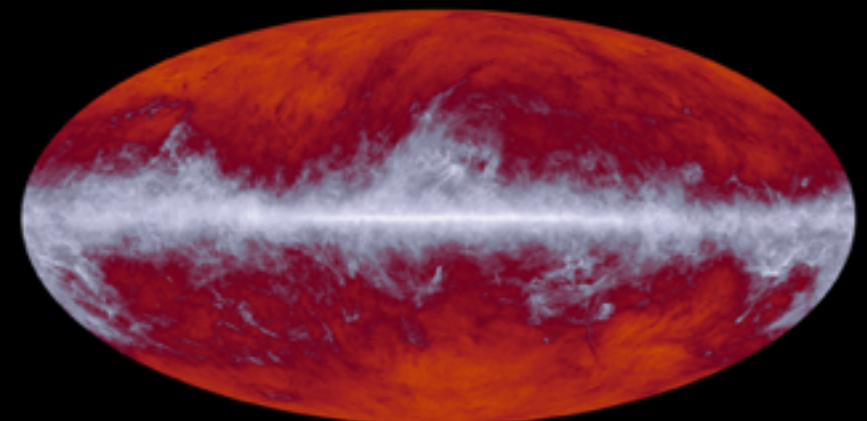
217 GHz



353 GHz



545 GHz



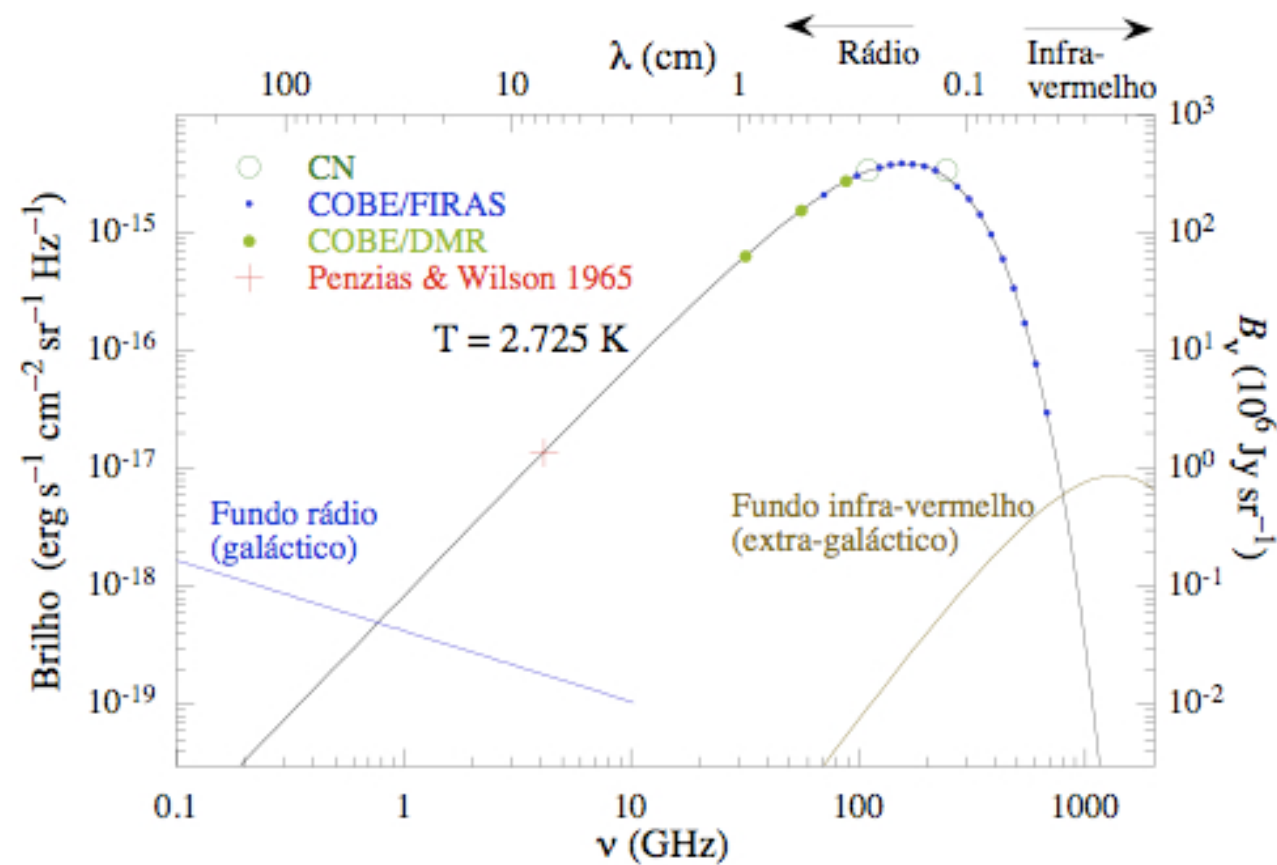
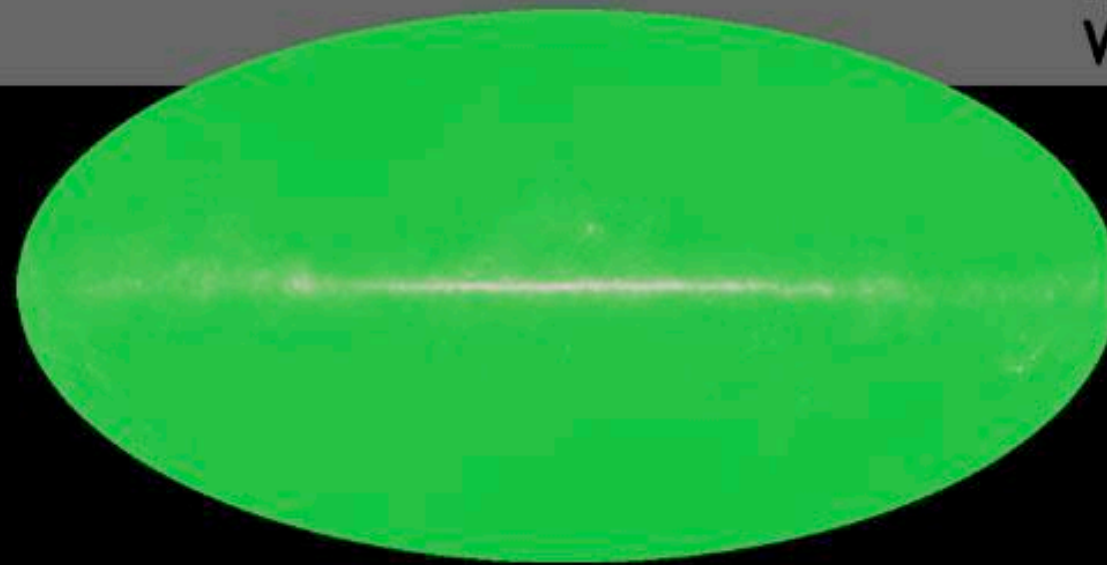
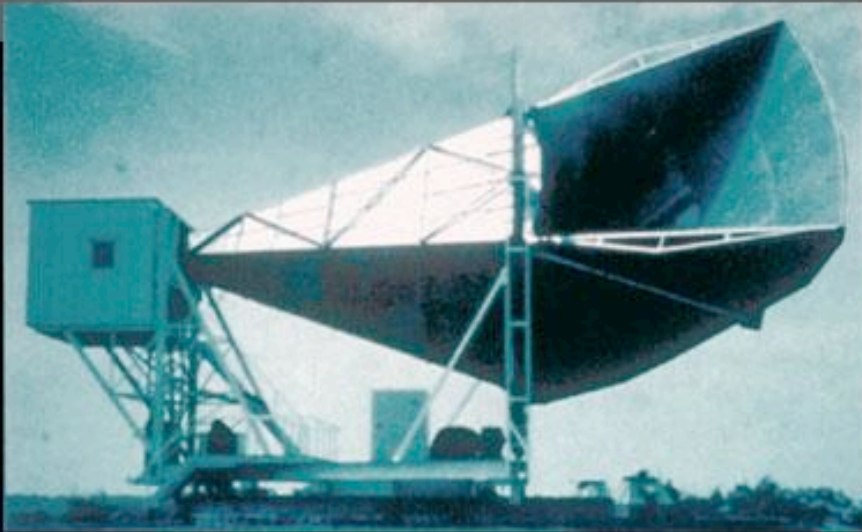
857 GHz



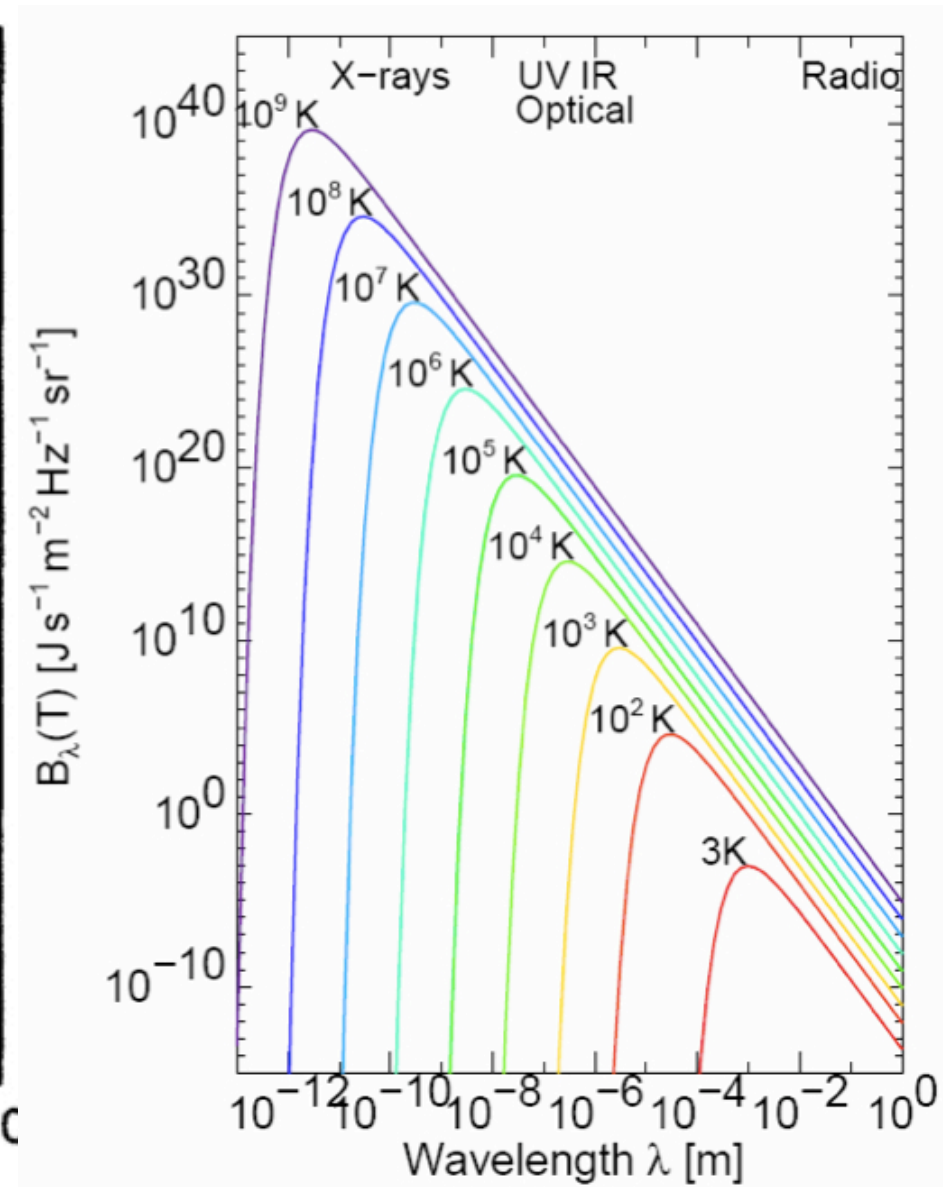
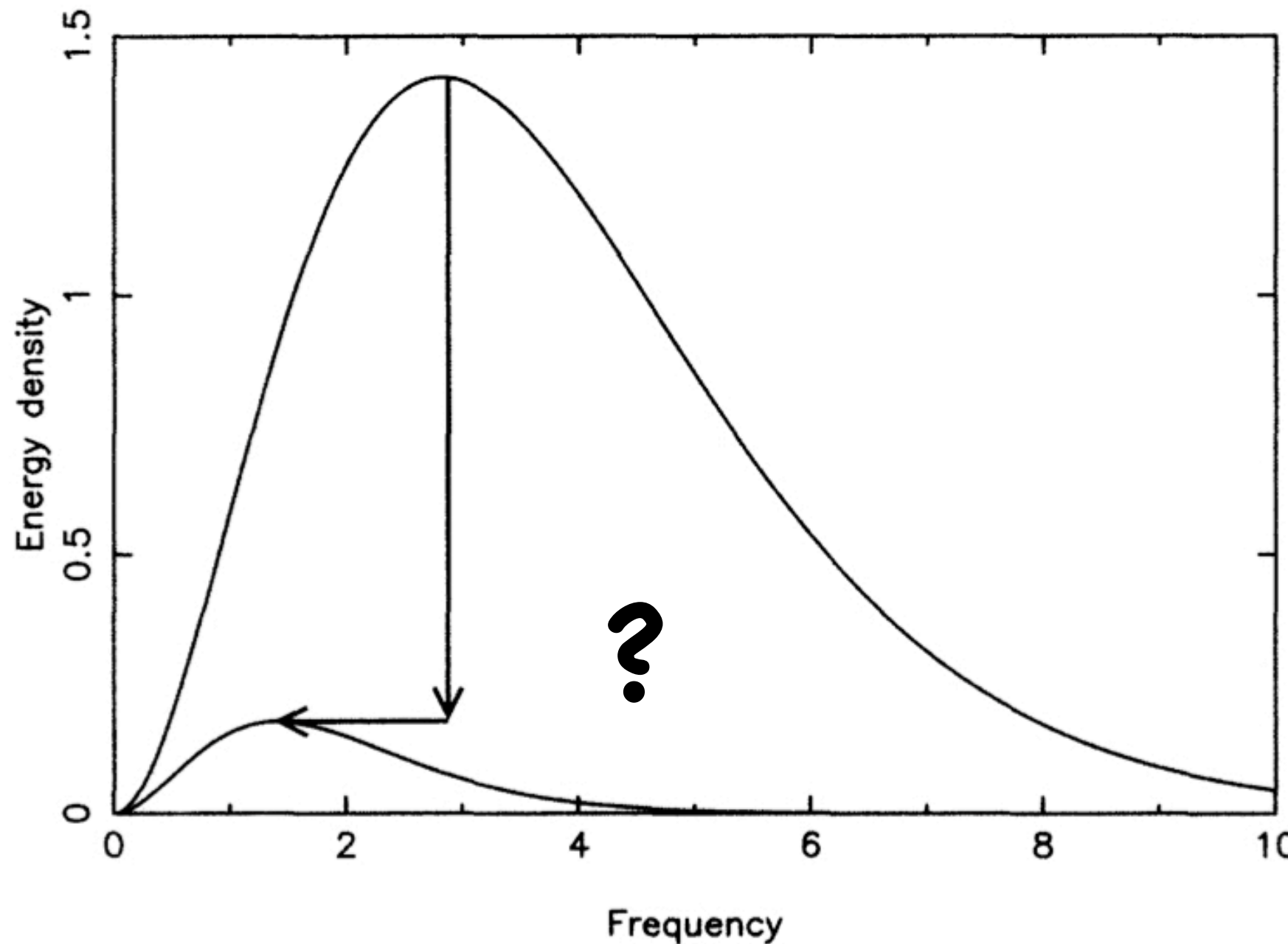
ruído cósmico?

1965

Penzias and Wilson



Cual es el efecto de la expansion?



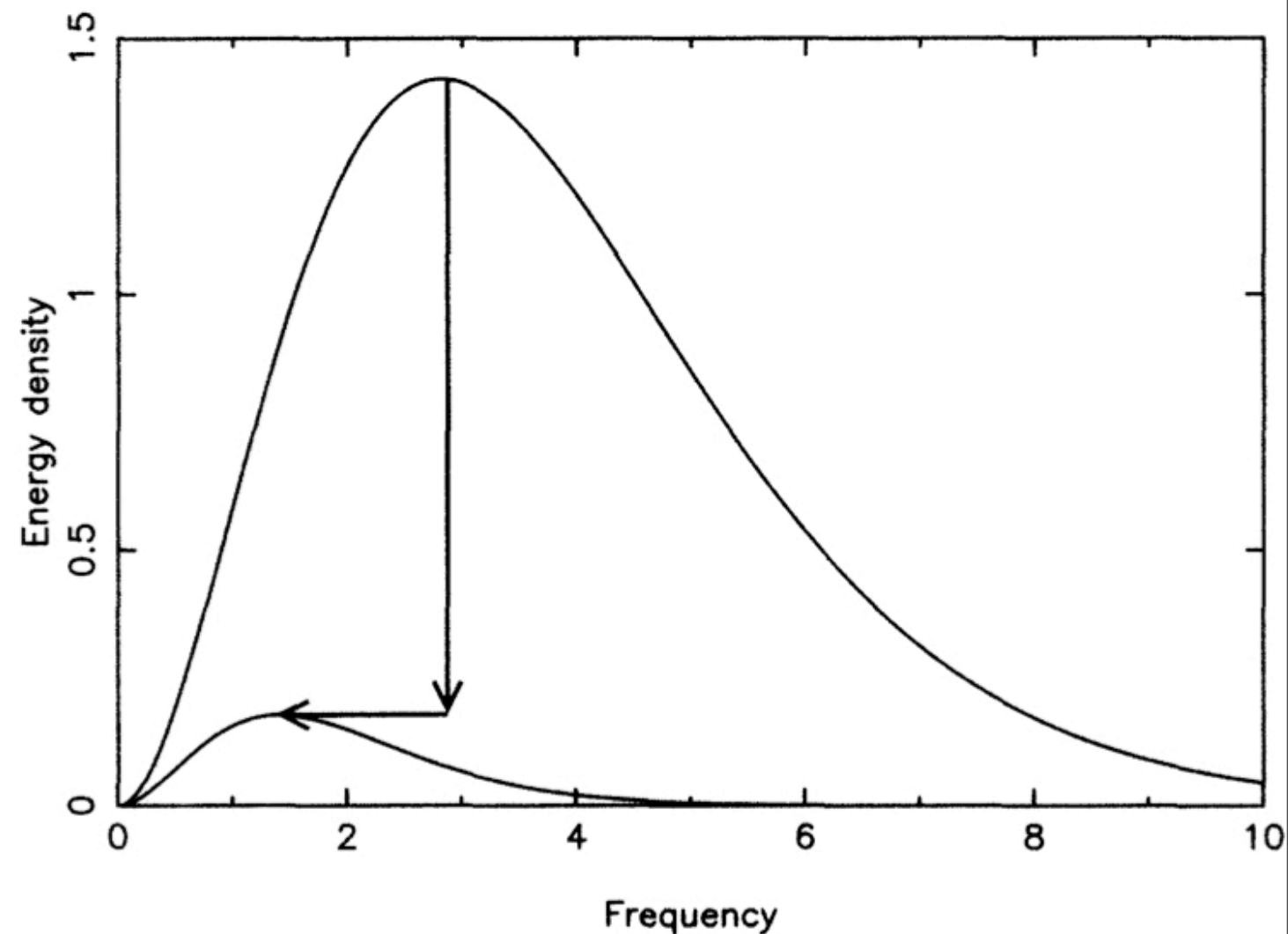
**Invariancia da prop. de CN
pela expansao do Universo**

analisemos a evolução temporal do espectro de corpo negro

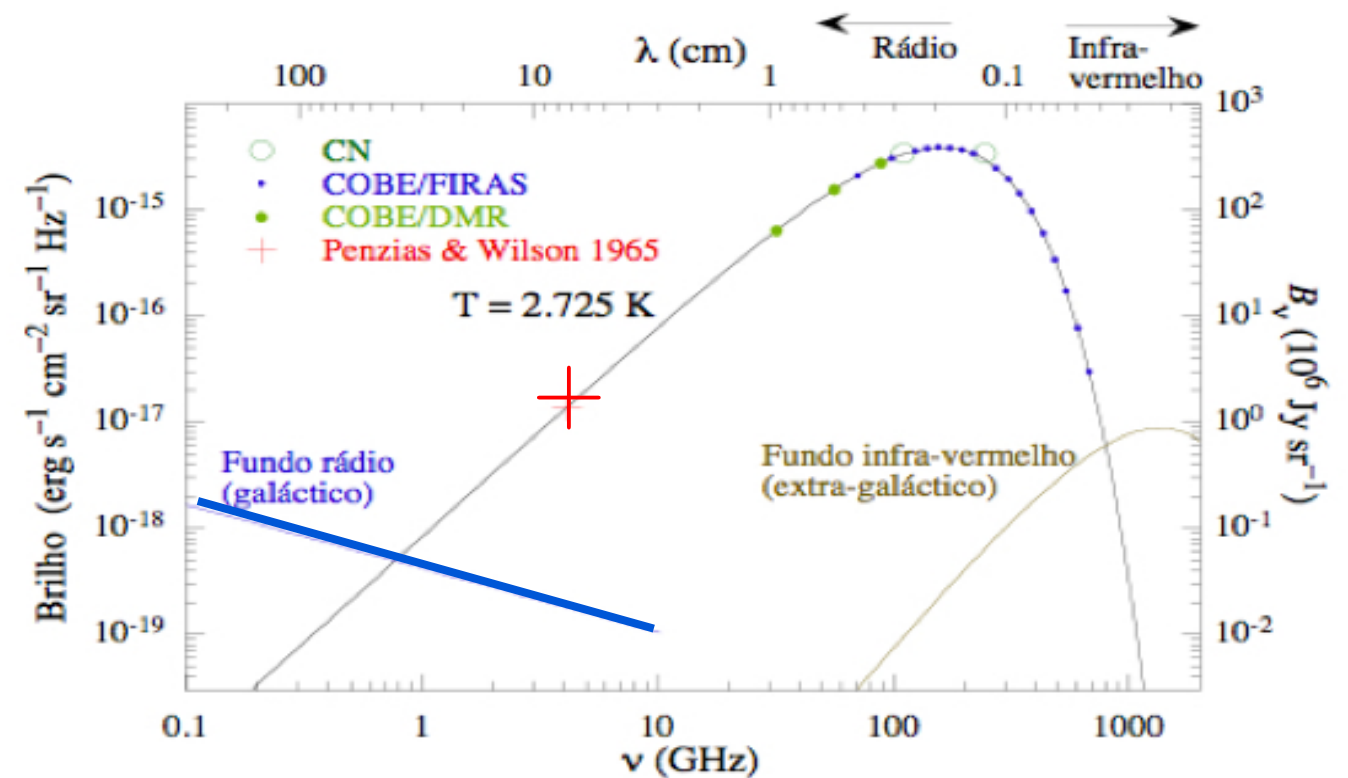
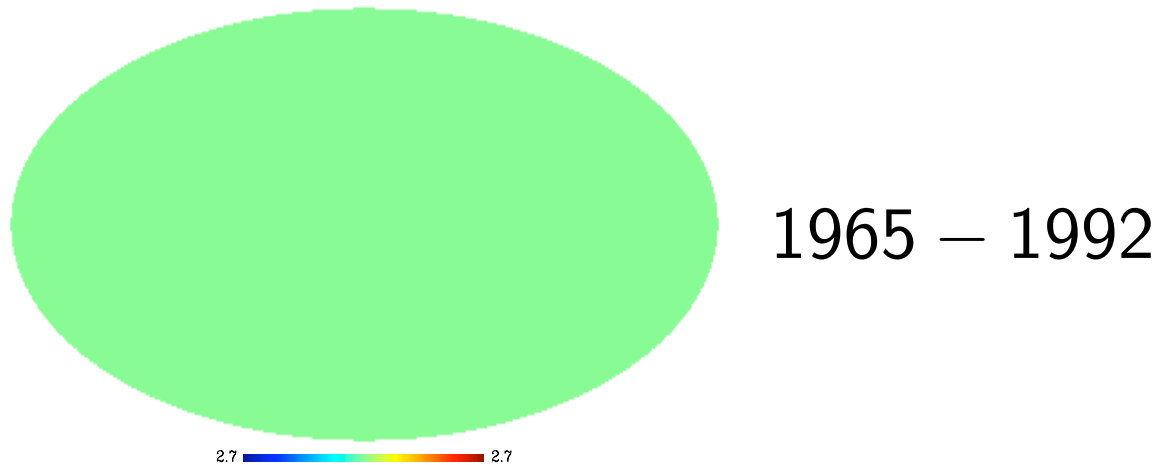
$$\epsilon(f) df = \frac{8\pi h}{c^3} \frac{f^3 df}{\exp(hf/k_B T) - 1}$$

sabemos que:

$$\left. \begin{aligned} T &\propto \nu \equiv f \\ \epsilon(f) &= \frac{E}{V} \propto a^{-3} \\ \nu \equiv f &\propto a^{-1} \end{aligned} \right\}$$



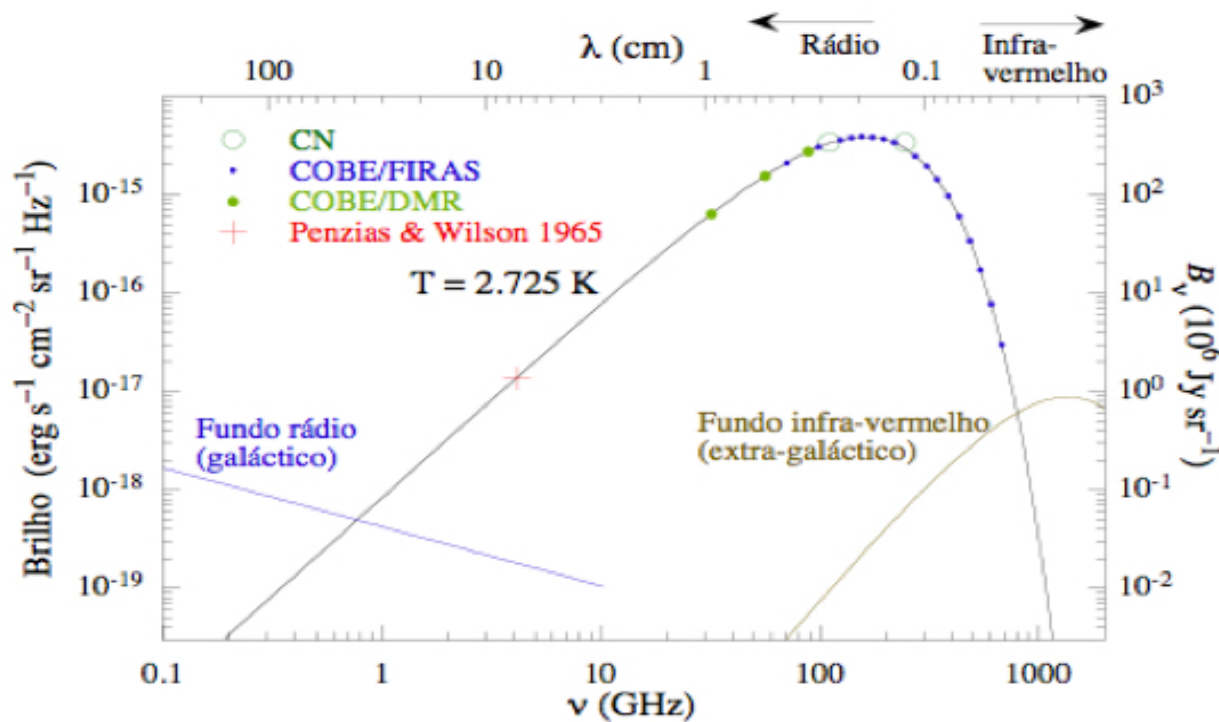
CMB: black-body spectrum at $T_0 = (2.725 \pm 0.001)\text{K}$



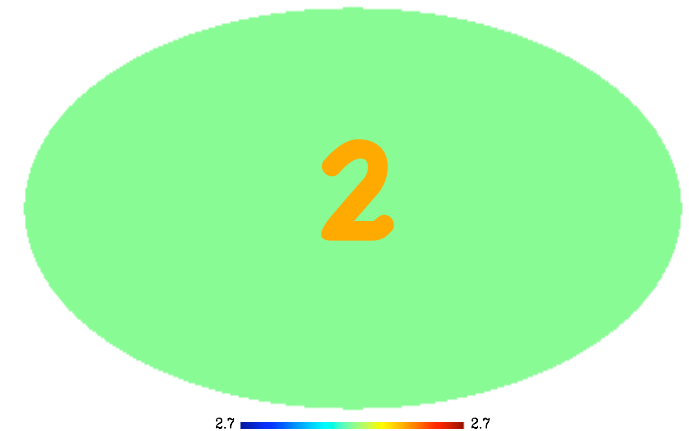
In 1992, **COBE satellite** detected tiny fluctuations around T_0 , of the order of $\frac{\Delta T}{T_0} \sim 10^{-5}$

Resumindo, as pps. da RCF:

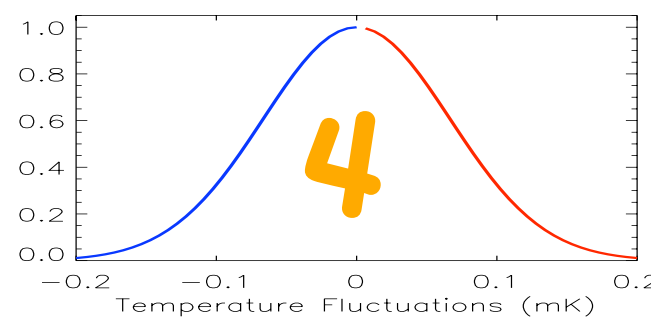
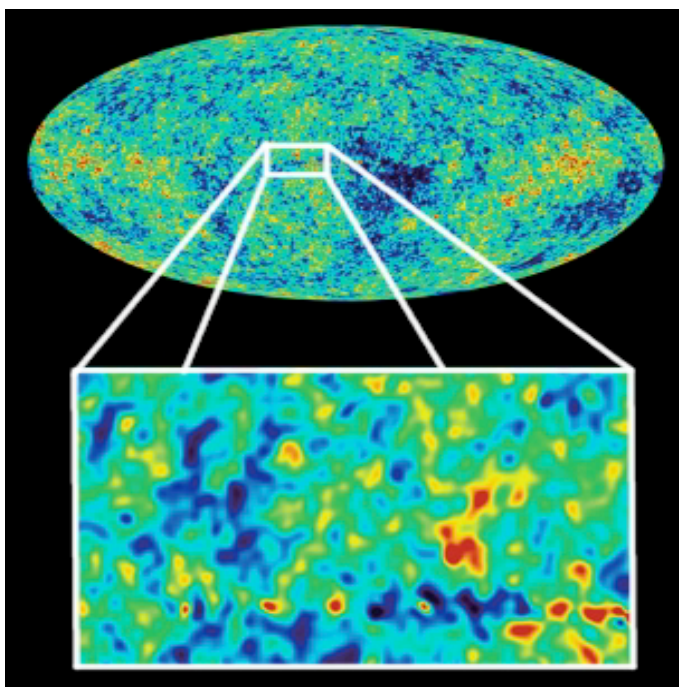
RCF: espectro de corpo negro à temperatura $T_{\text{Planck}} = (2.725 \pm 0.001)\text{K}$



1965 – 1992



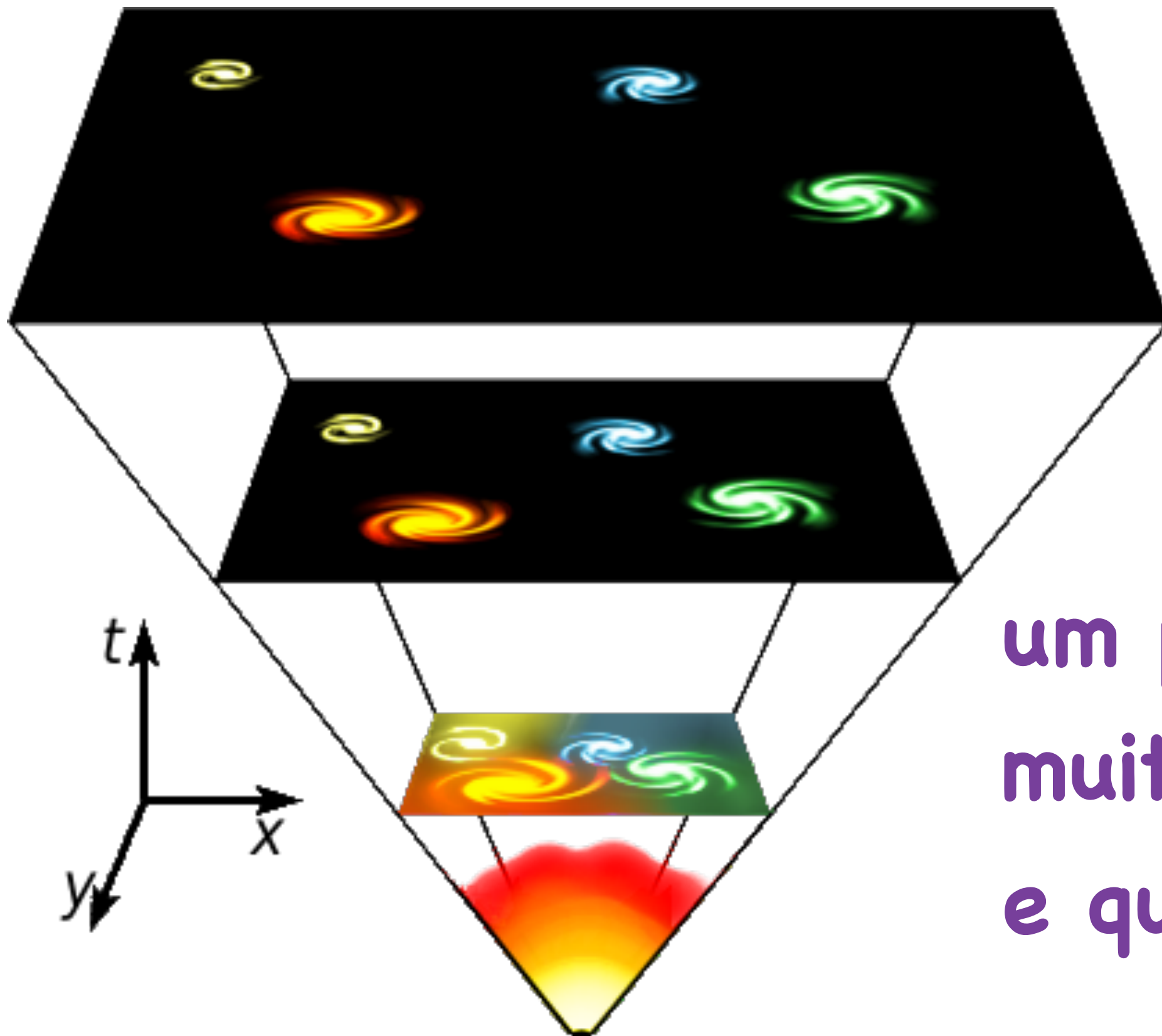
3 Em 1992 verificou-se que ao redor da $T_{\text{Planck}} \exists$ pequenas flutuações positivas $\Delta T > 0$ e negativas $\Delta T < 0$, da ordem $\frac{\Delta T}{T_{\text{Planck}}} \sim 10^{-5}$



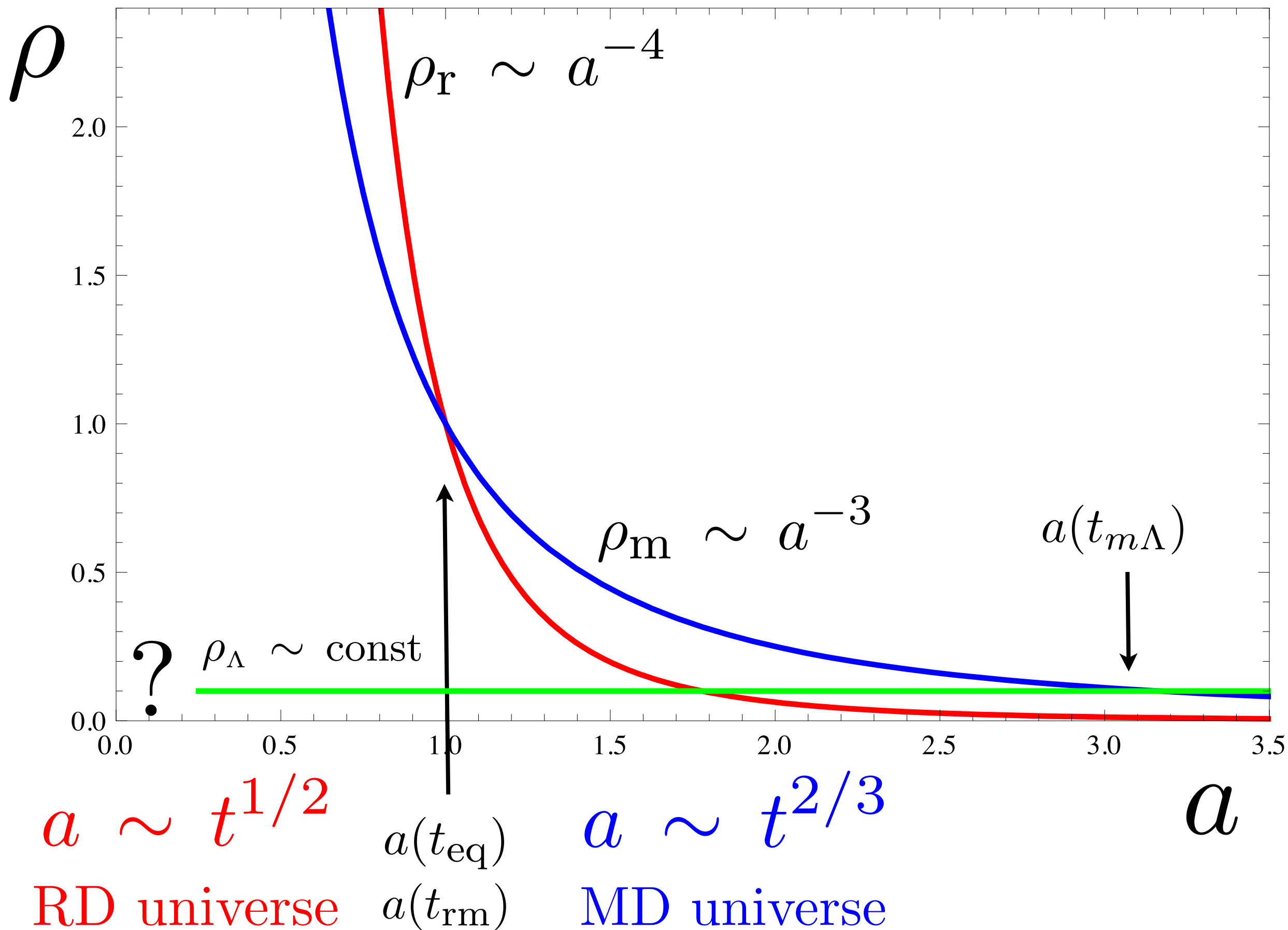
→ $\Delta T \sim (-200\mu\text{K}, 200\mu\text{K})$

Estas flutuações de temp. ΔT ficam visíveis neste mapa depois de retirar da RCF as componentes monopolo (2.725K) e dipolo (3.346mK)

historia termica do Universo

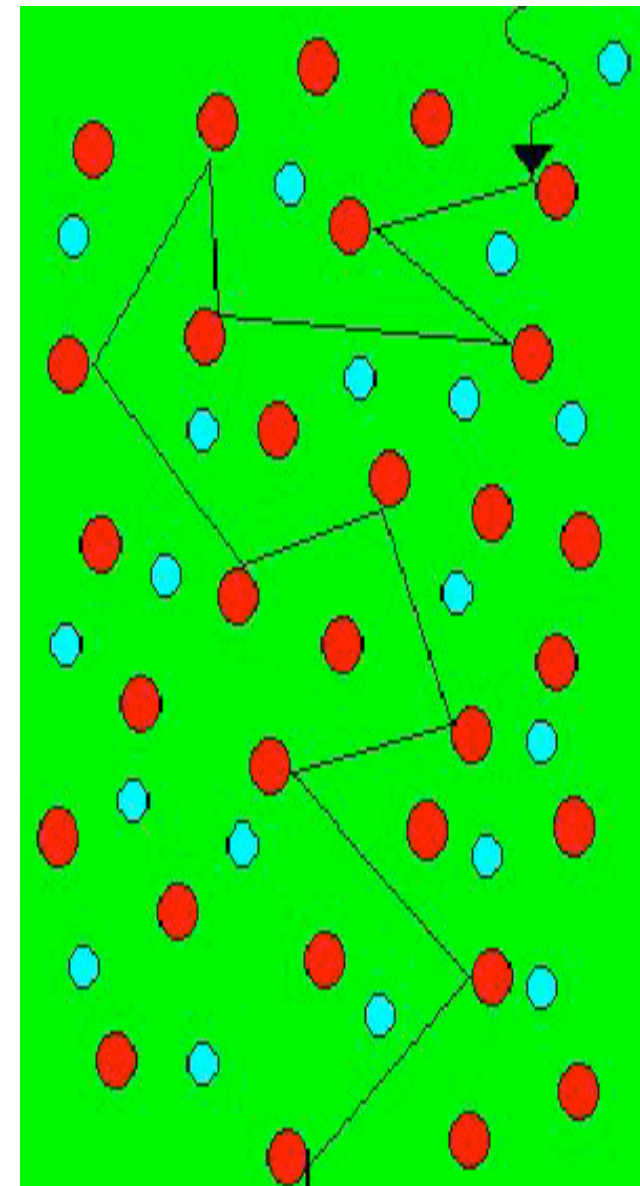


um passado
muito denso
e quente!



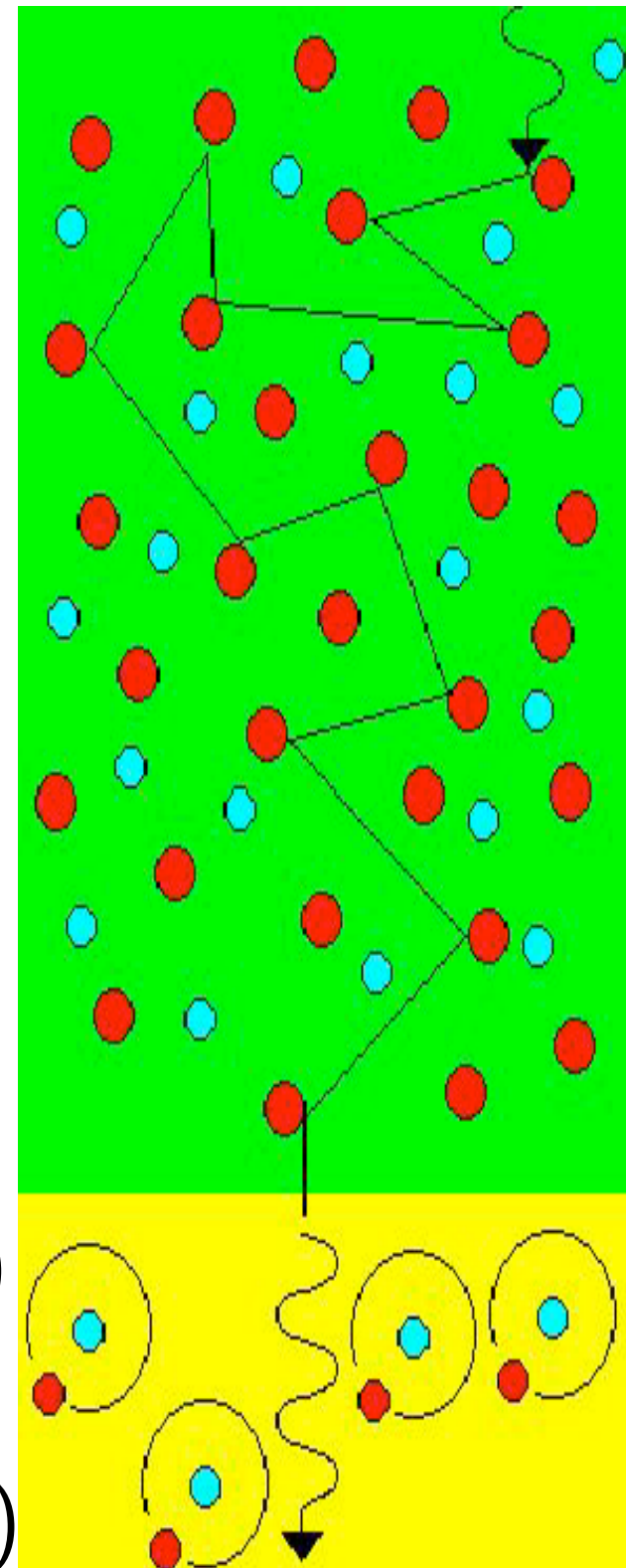
a história do Universo: passado denso e quente

- ▶ Houve uma fase onde o fluido **matéria–radiação** (composto por bárions e fótons interagindo via espalhamento Thomson) estava em **equilíbrio termodinâmico**, e agia como se fosse um fluido só (photon-baryon fluid); $\eta \equiv \frac{n_\gamma}{n_b} \simeq 10^9$.



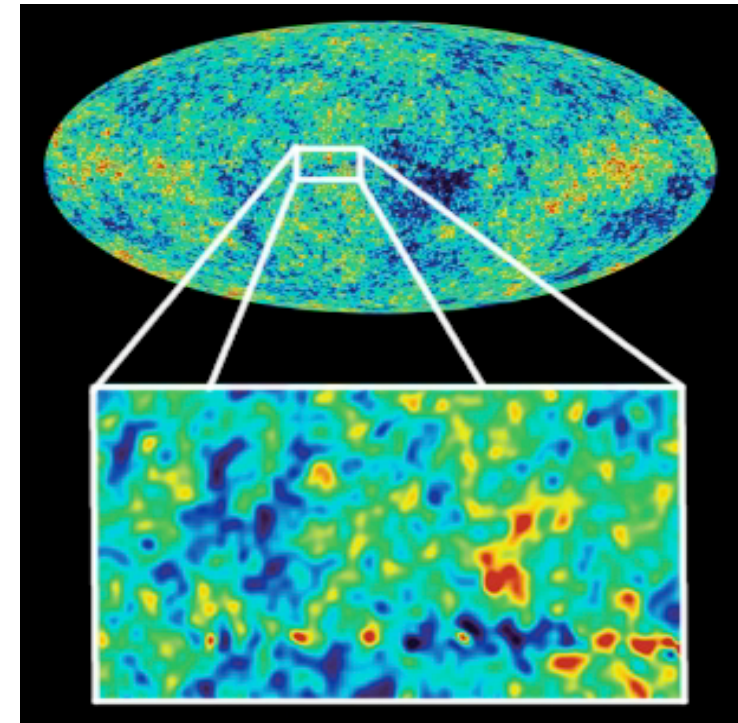
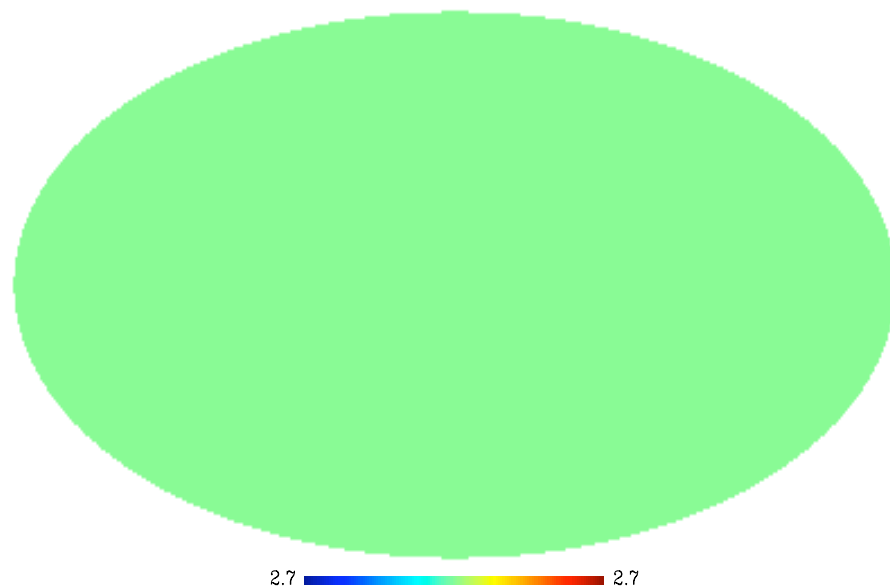
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- ▶ Ao expandir-se o Universo resfria e o fluido alcança uma temperatura crítica que produz o desacoplamento **matéria–radiação**: $T \simeq 3000 \text{ K} \simeq 0.3 \text{ eV}$.
- ▶ Esses fótons livres (de ser espalhados pelos elétrons) constituem uma radiação relíquia do Universo primordial, chamada **Radiação Cósmica de Fundo** (RCF)

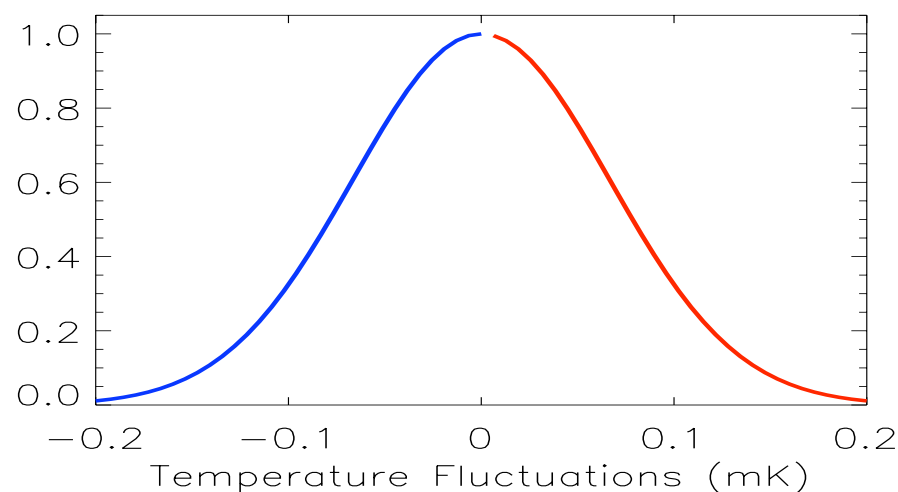


CMB temperature fluctuations?

CMB: temperature fluctuations (**anisotropies**): $\Delta T(\theta, \varphi)$

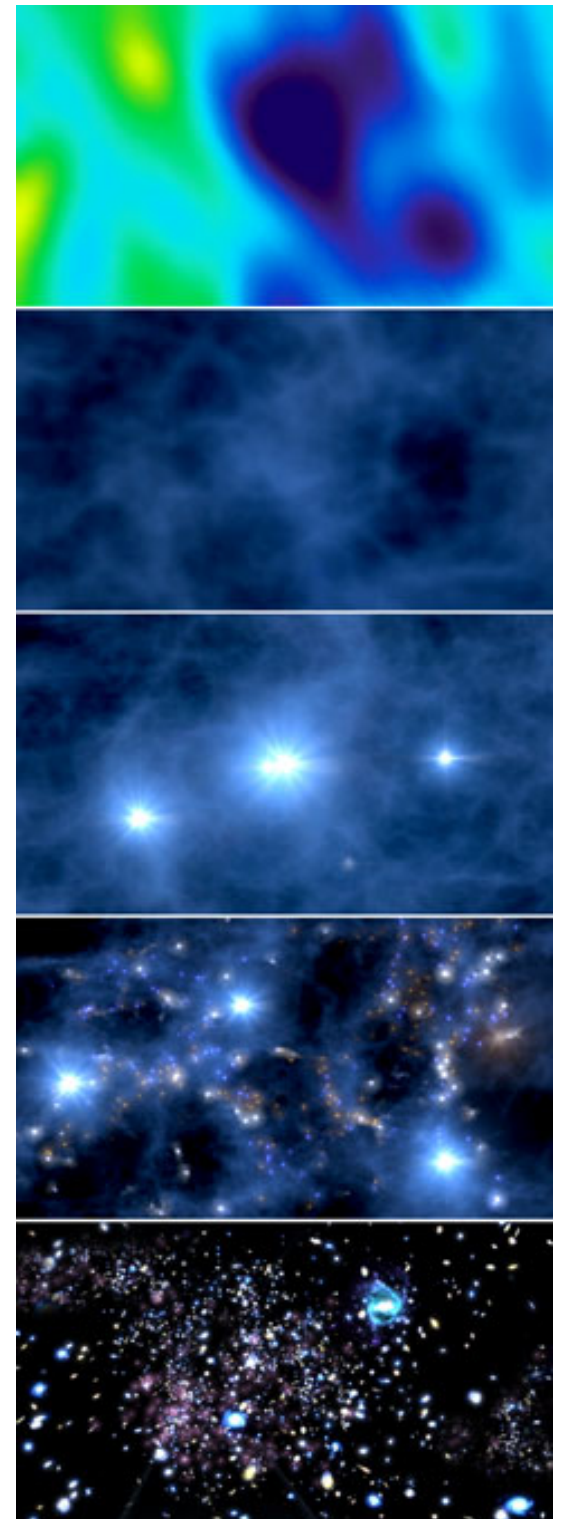
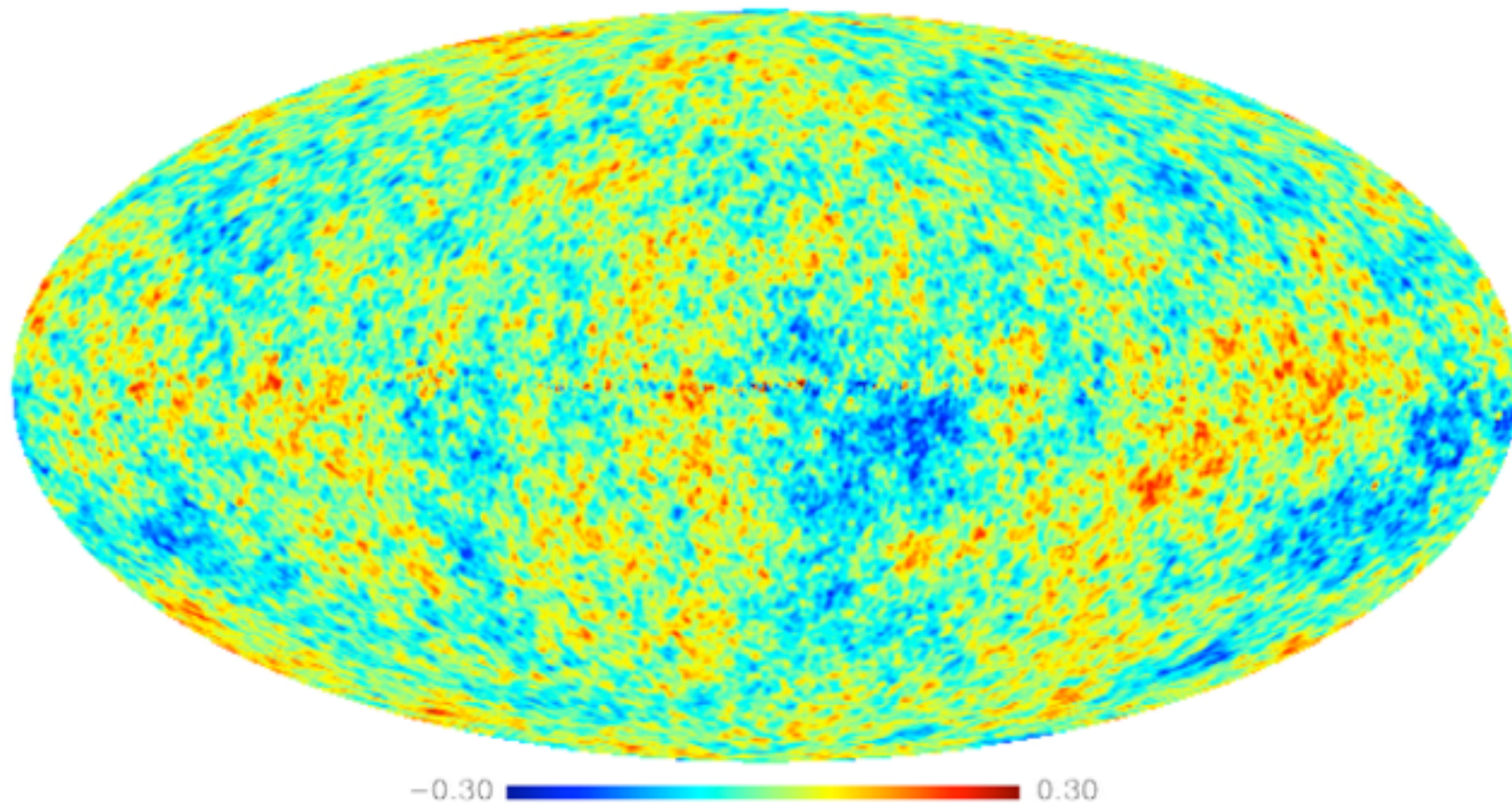


After subtracting the monopole (T_0) and dipole (3.346mK) terms to this map $\Rightarrow$ **positive** $\Delta T > 0$ and **negative** $\Delta T < 0$ flucts. are visible.



$\rightsquigarrow \Delta T \sim (-200\mu\text{K}, 200\mu\text{K})$

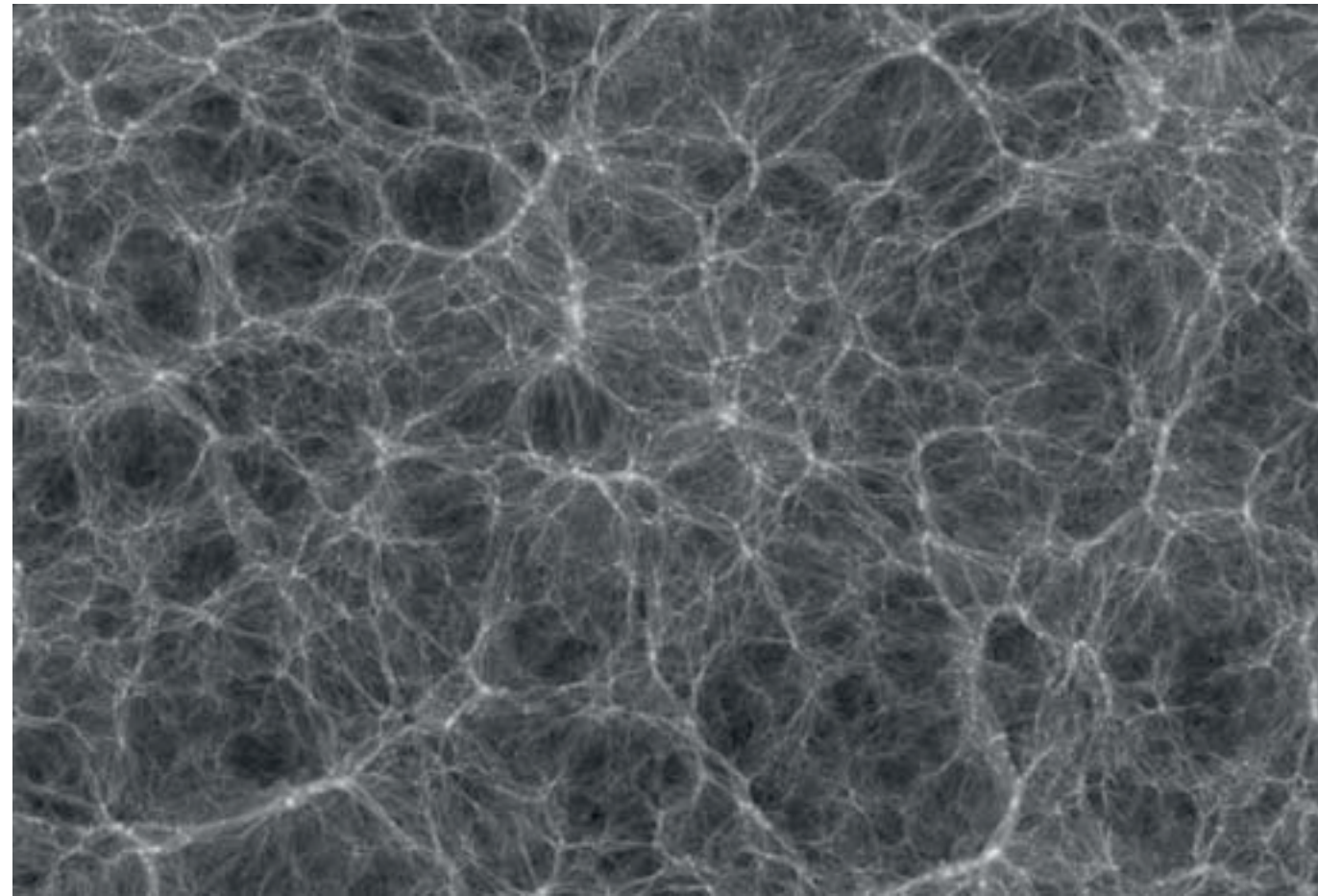
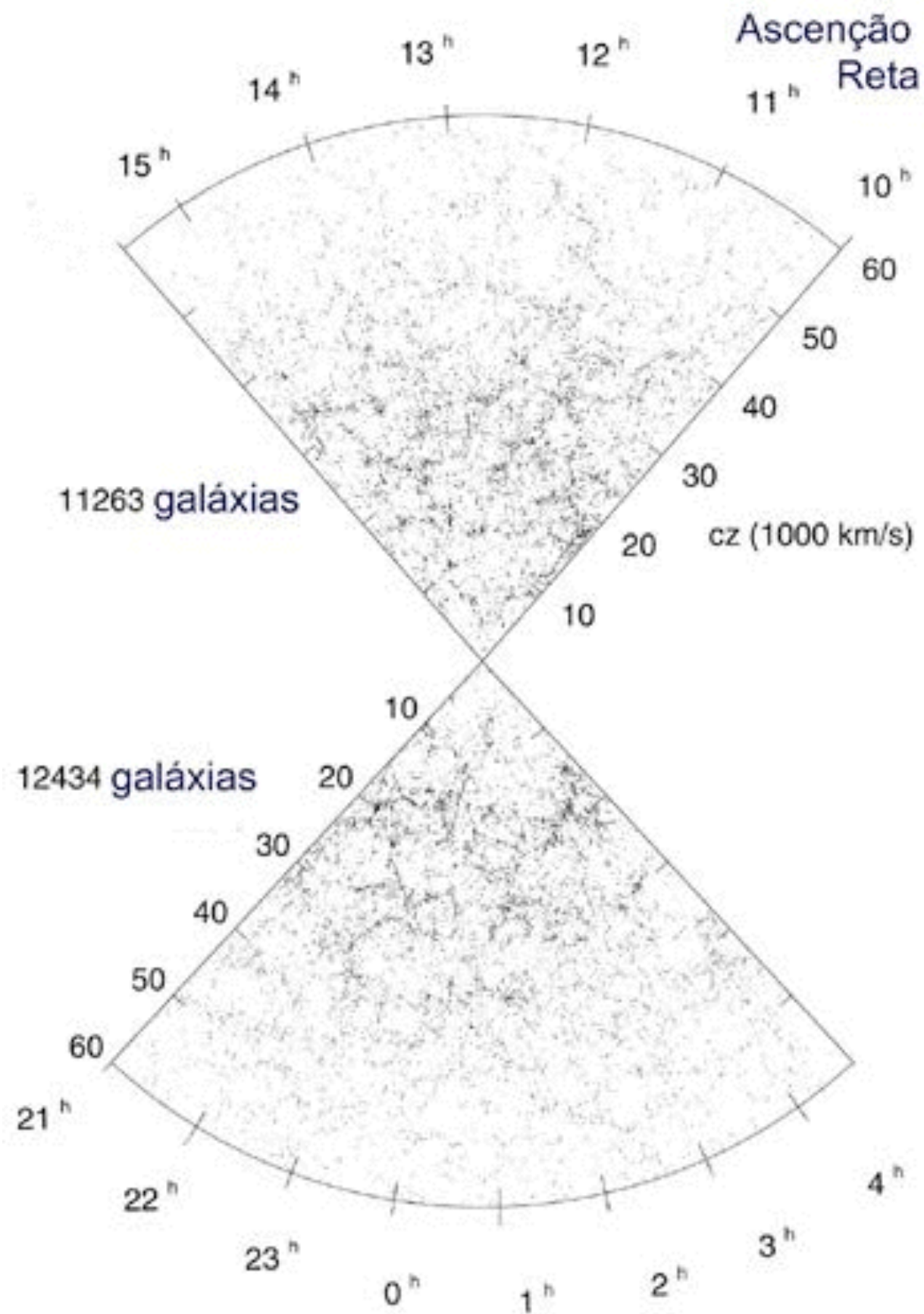
flutuações da RCF e bárions: origem comum



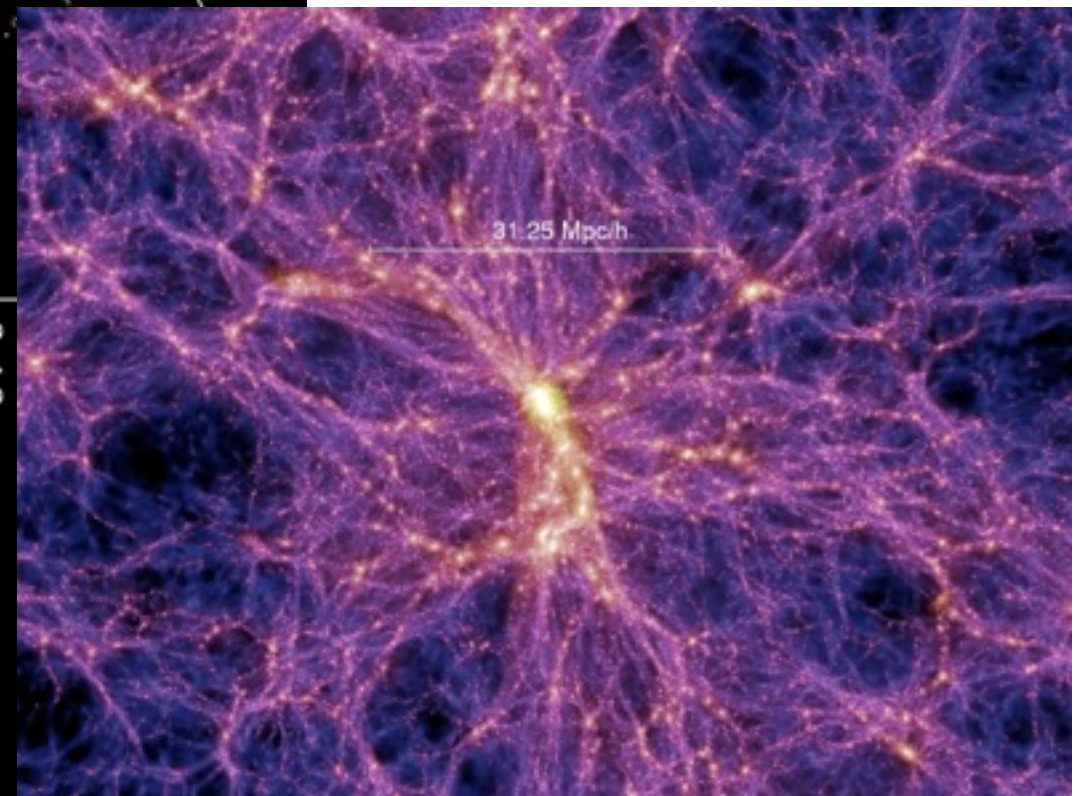
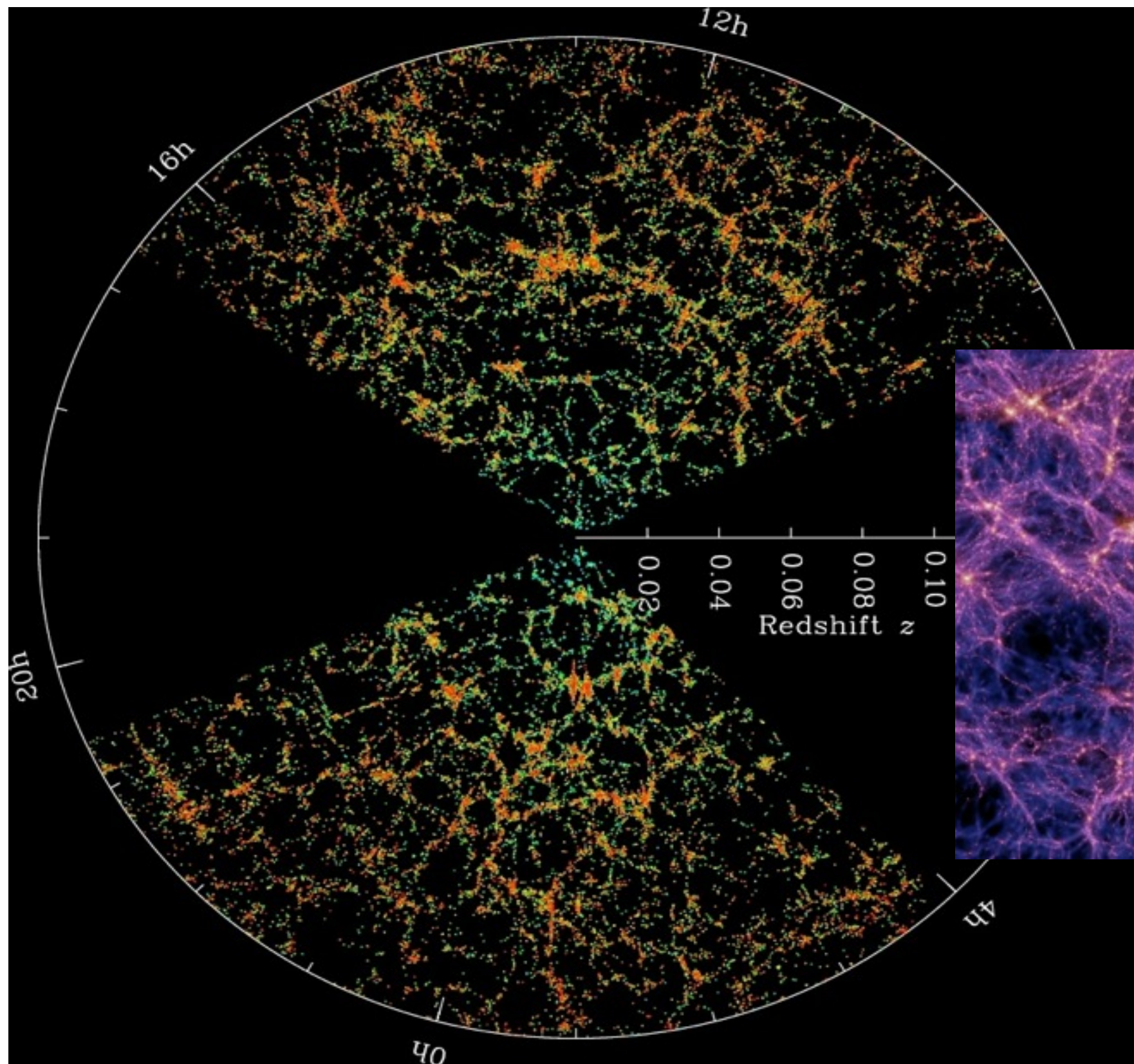
$$\frac{\delta\rho}{\bar{\rho}} \sim \frac{\Delta T}{T_0} \sim 10^{-5}$$

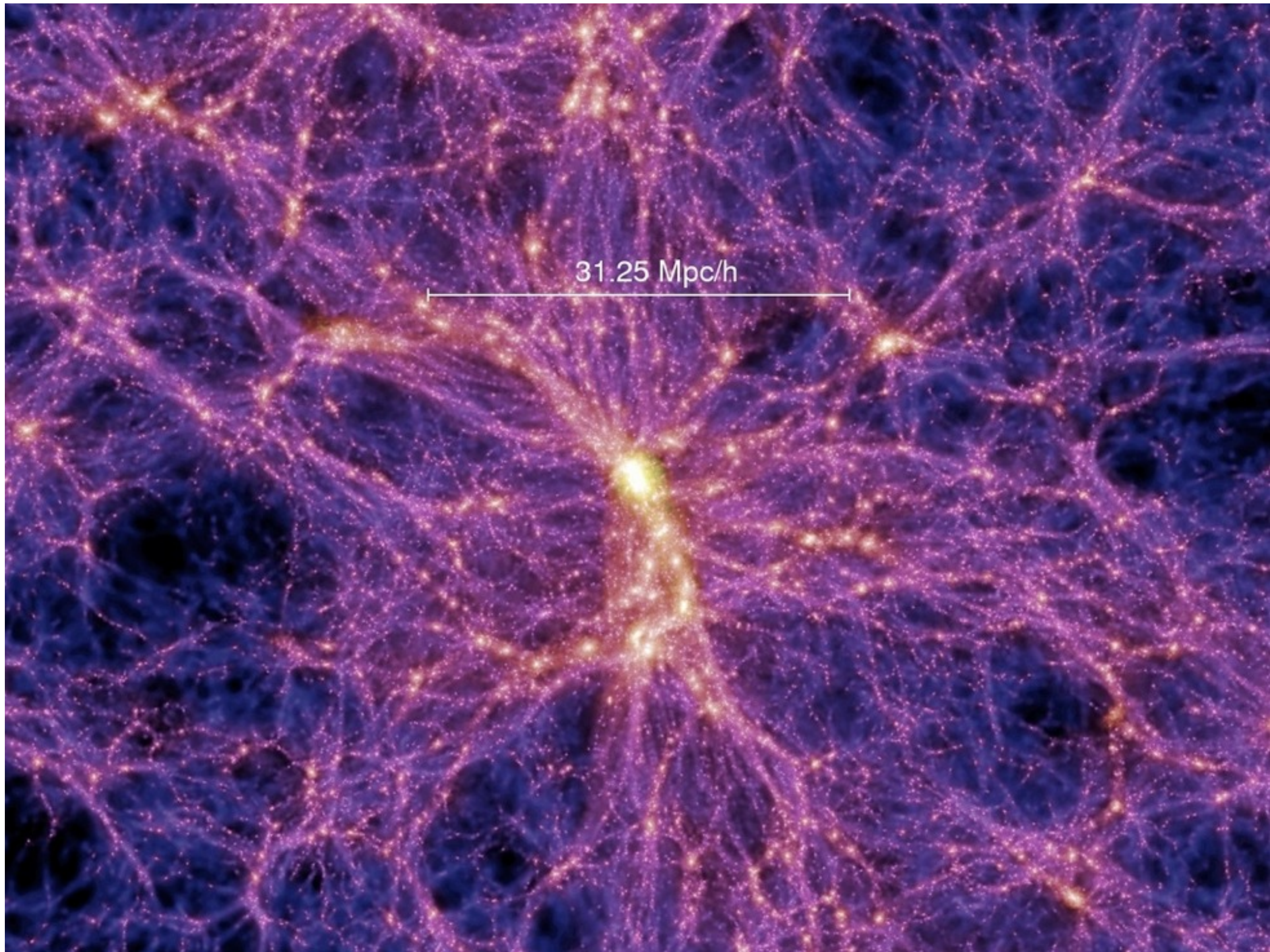
bárions

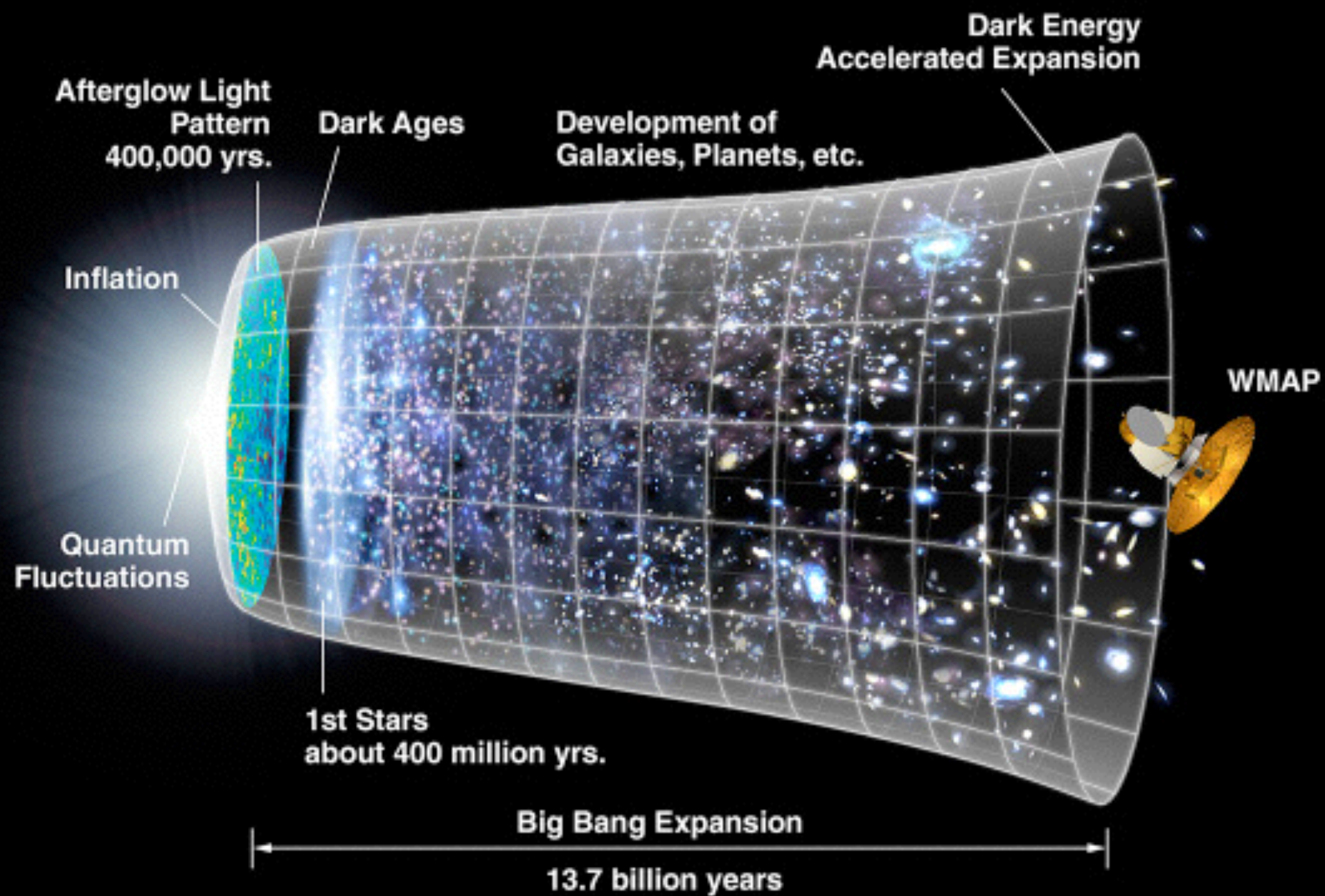
LSS of the Universe



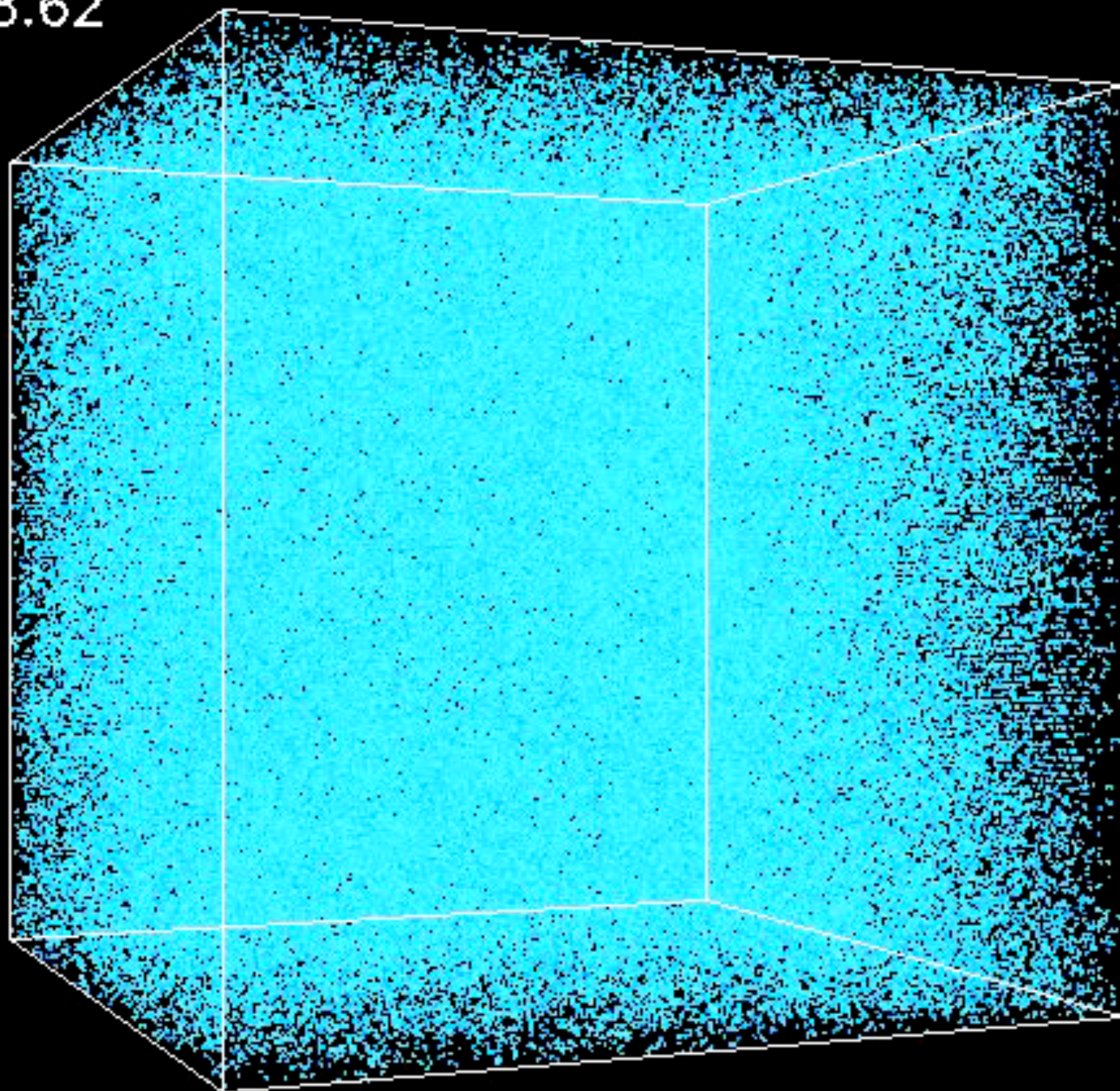
LSS of the Universe







$Z=28.62$



Resumindo, no modelo do BB:

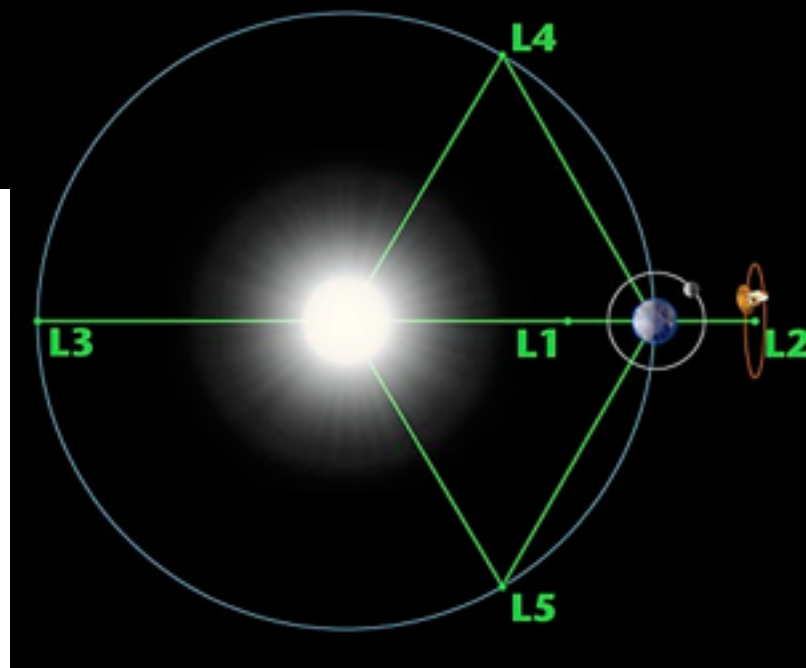
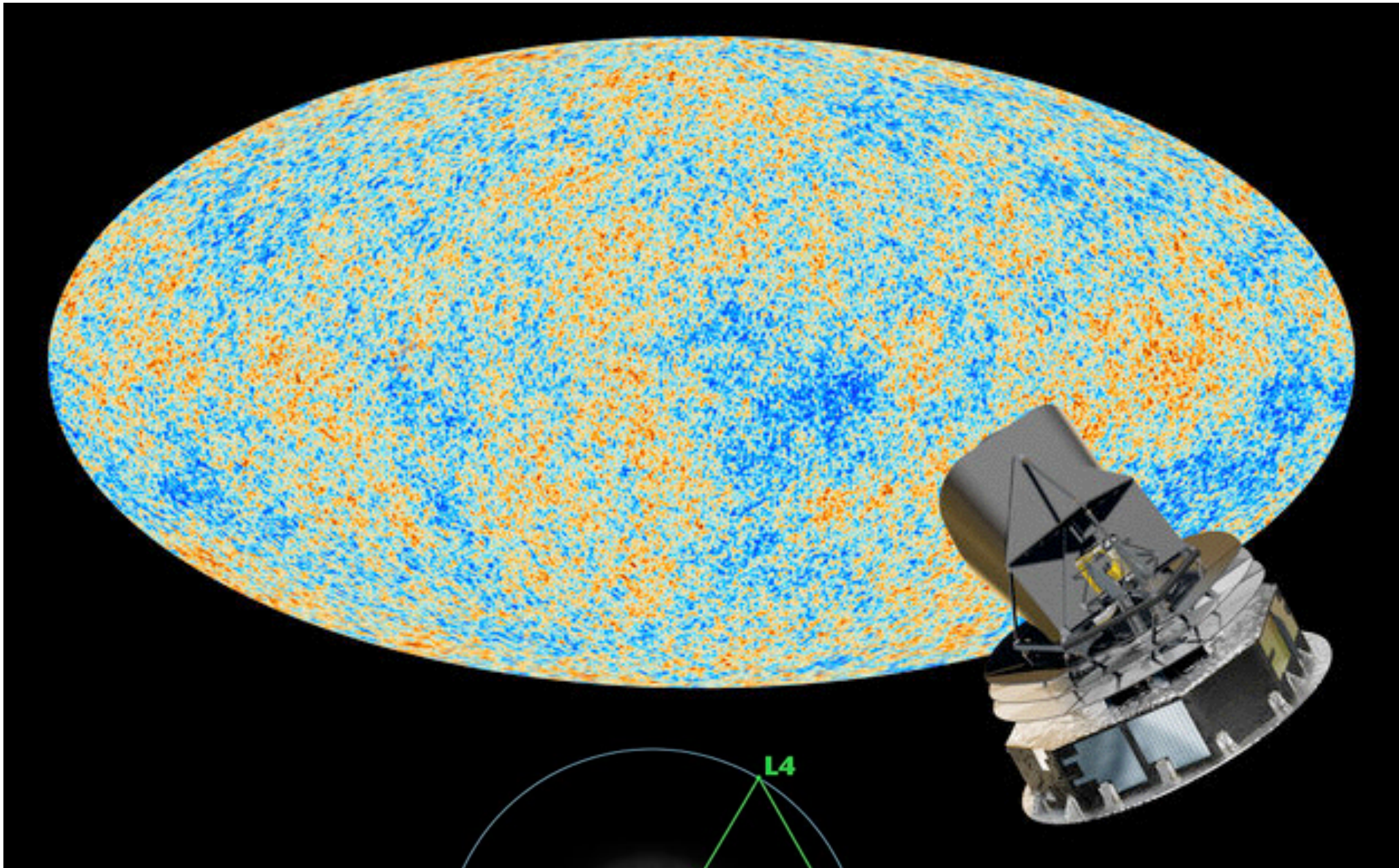
- ▶ O Universo expande e esfria, a tal ponto que matéria e radiação se desacoplam
- ▶ Depois que desacopla da matéria, os fótons (radiação cósmica de fundo) viajam livremente pelo Universo (dizemos que é transparente aos fótons)
- ▶ A matéria forma estruturas por instabilidade gravitacional

CMB temp. fluctuations

Basics on CMB data

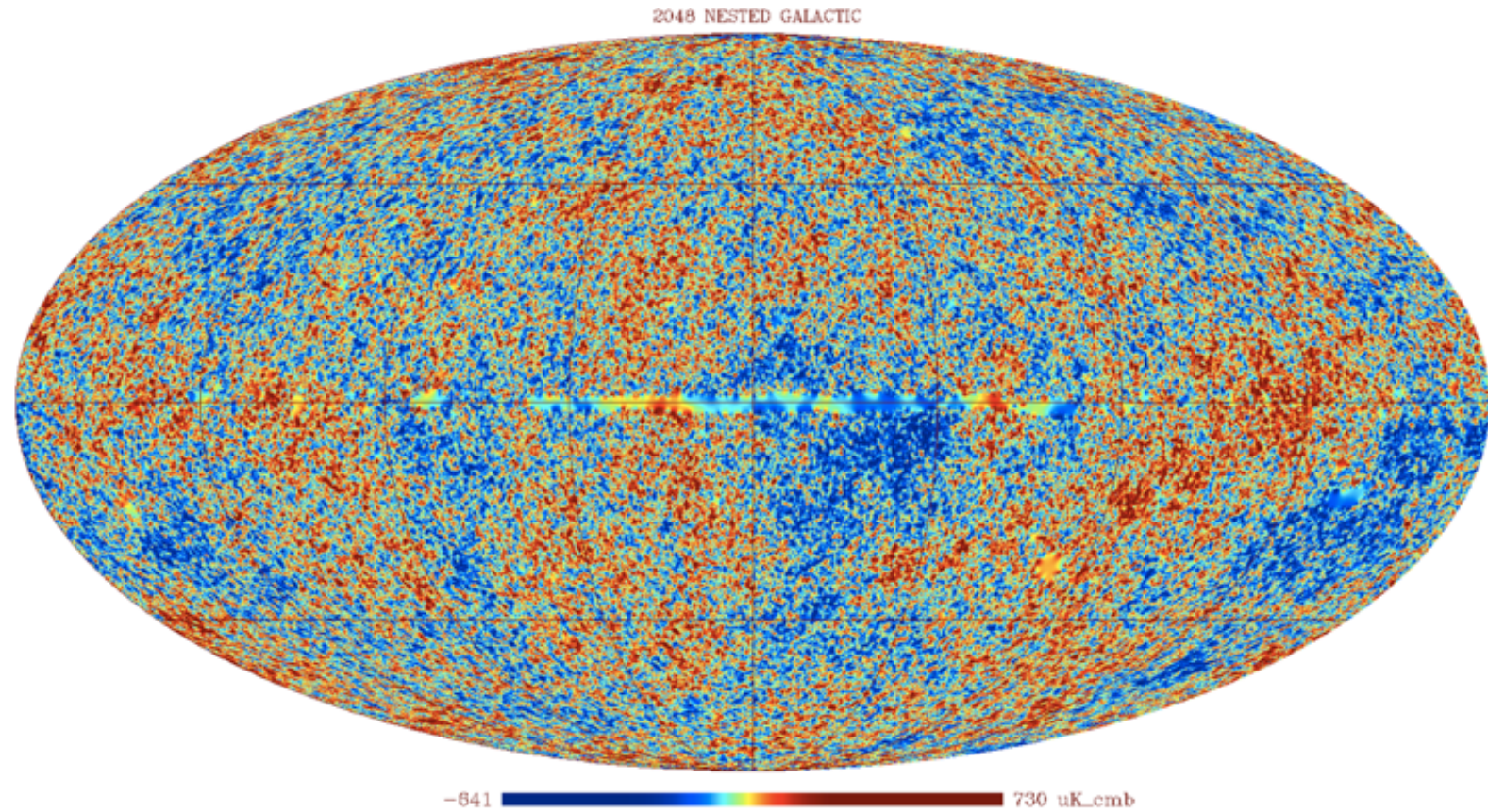
Armando Bernui

2018/Planck CMB data

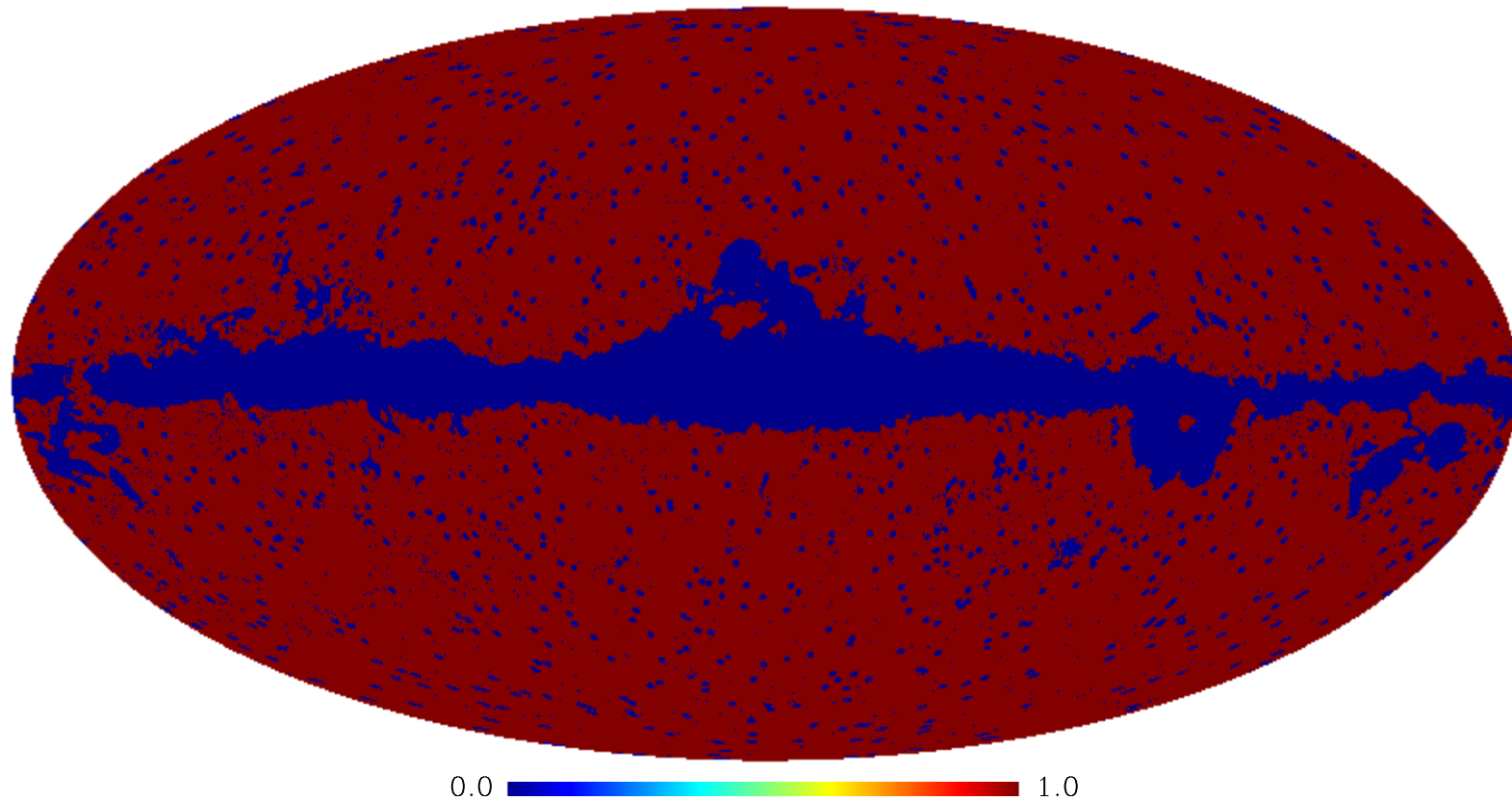


2018/Planck CMB data

SMICA

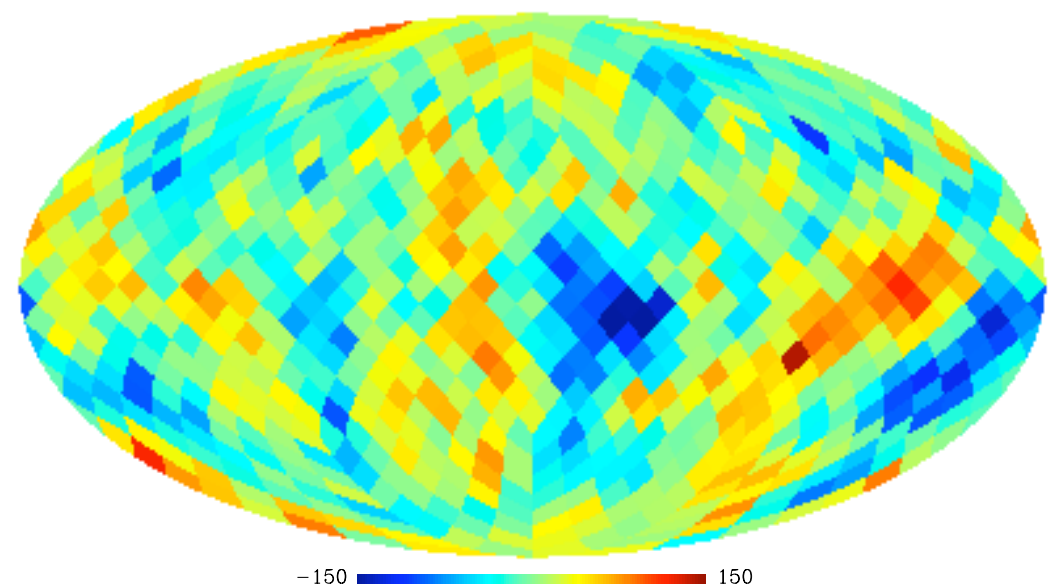
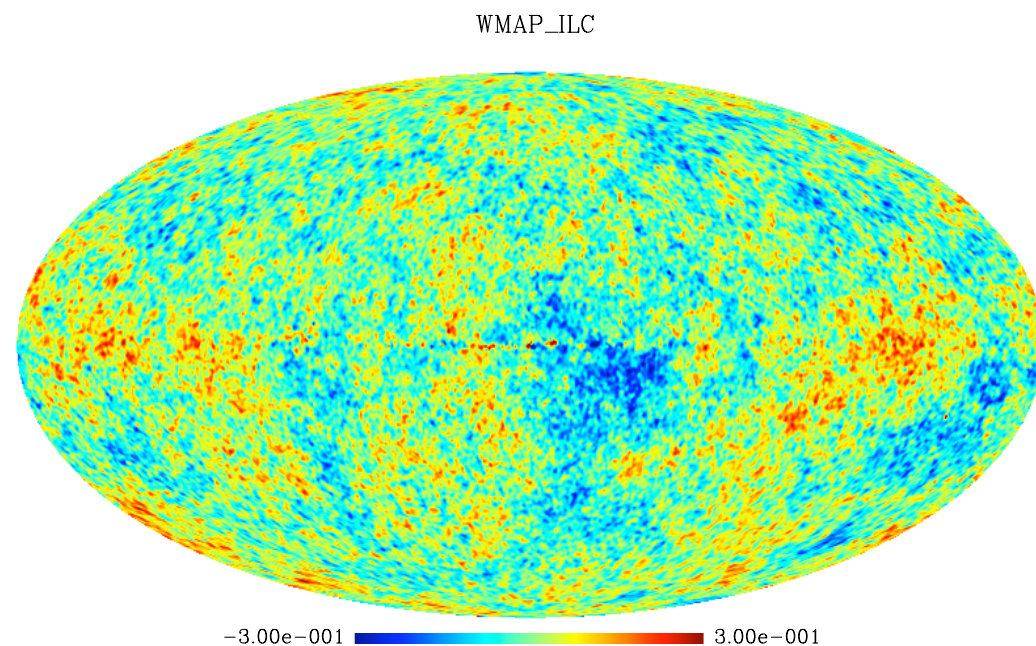


maskara



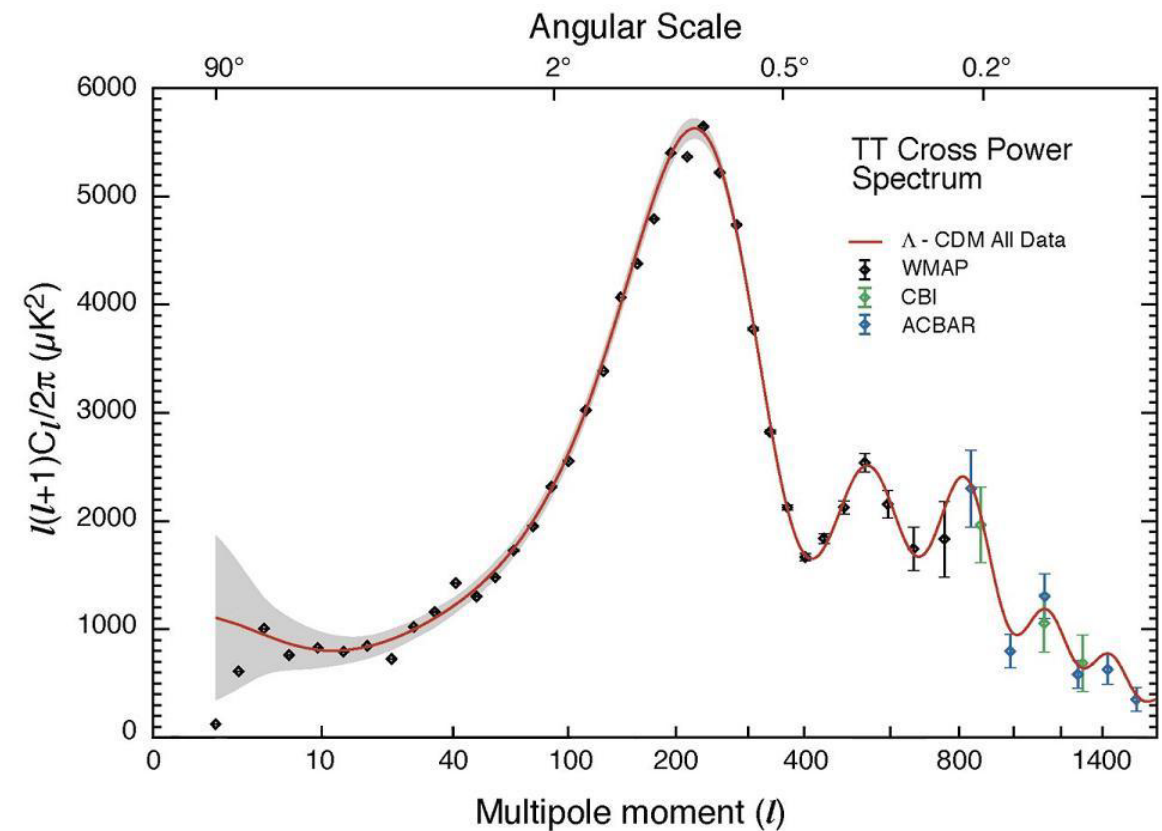
Mapas da Radiação Cósmica de Fundo

- ▶ a esfera celeste é dividida em N pixels da mesma área
- ▶ as flut. de temp. da RCF ΔT representam-se usando uma escala linear de cores: azul (= mín.), verde ($\simeq 0$), e vermelho (=máx.). Representamos: $\frac{\Delta T(\theta, \phi)}{T_{Planck}} = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi)$.
- ▶ os pixels são tão pequenos que os mapas parecem um contínuo de manchas coloridas, mas ... basta degradar o mapa para observar eles:



espectro de potência angular:

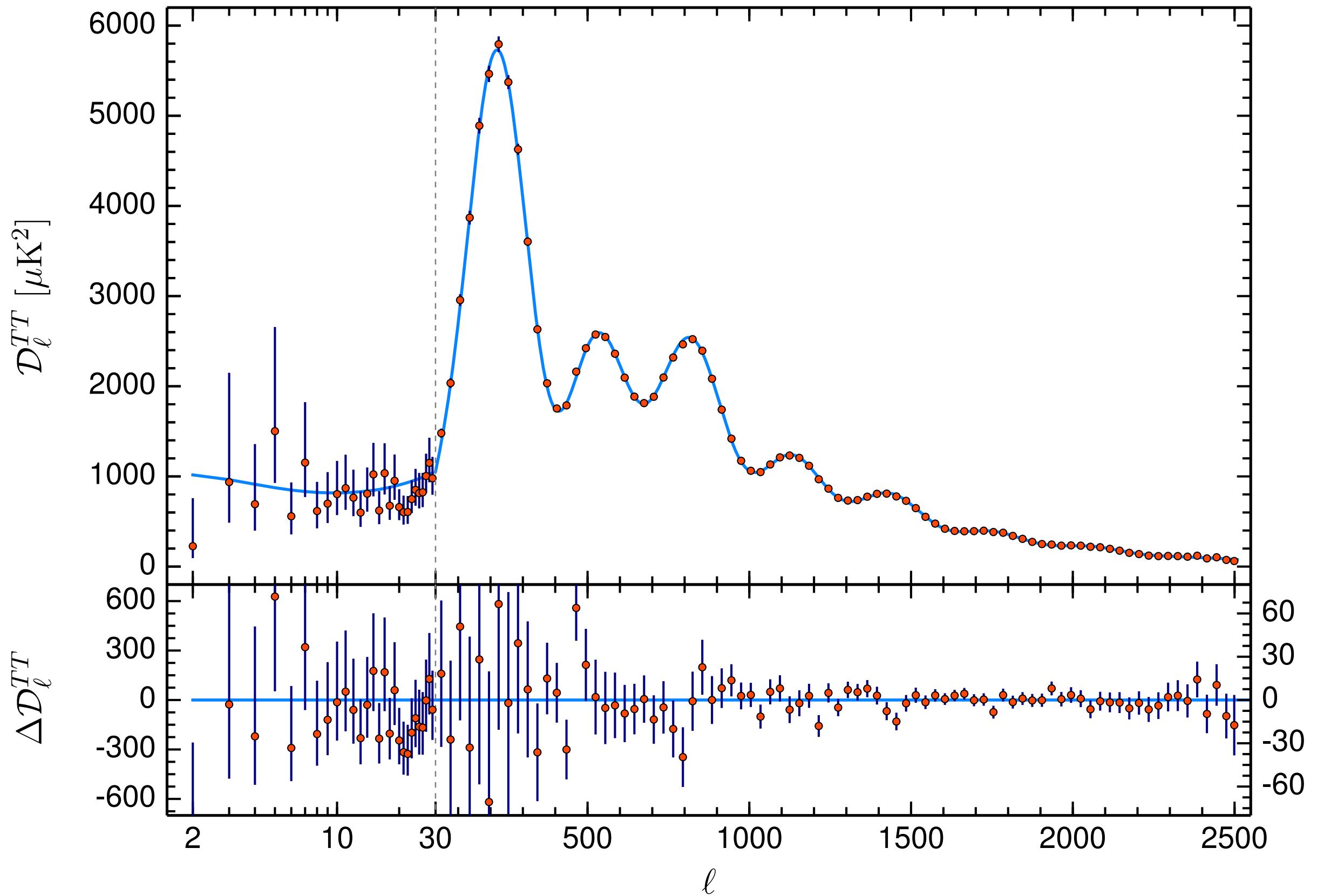
C_ℓ versus ℓ



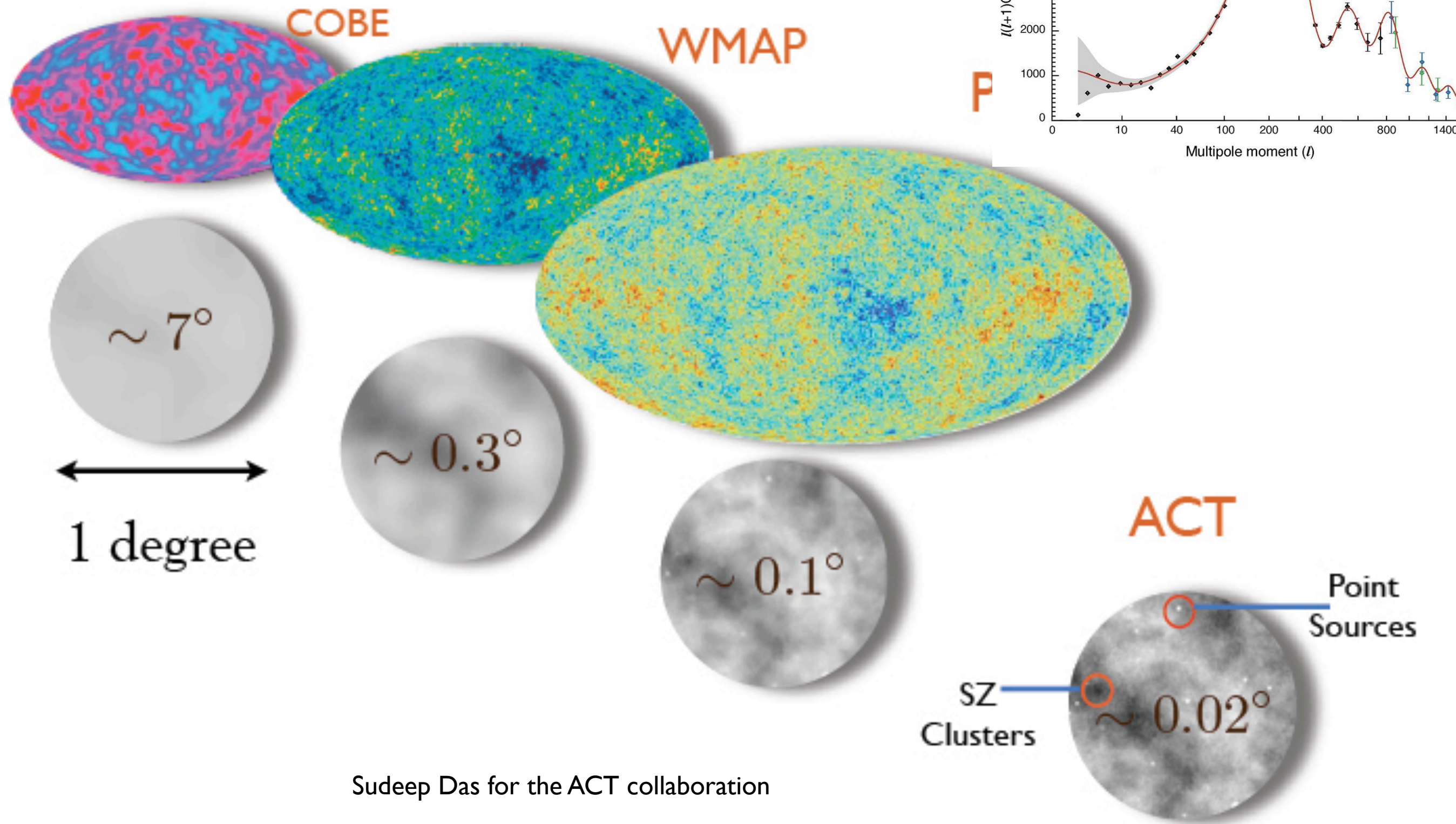
$$\frac{\Delta T}{T_0}(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi) \quad \longrightarrow \quad C_\ell \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |a_{\ell m}|^2$$

assuming estatistical isotropy!

CMB angular power spectrum Planck/18



Going to small scales



Sudeep Das for the ACT collaboration

origem das flutuações de
temp. da RCF

$\frac{\Delta T}{T_0}$: Flutuações de temperatura (**anisotropias**) da RCF

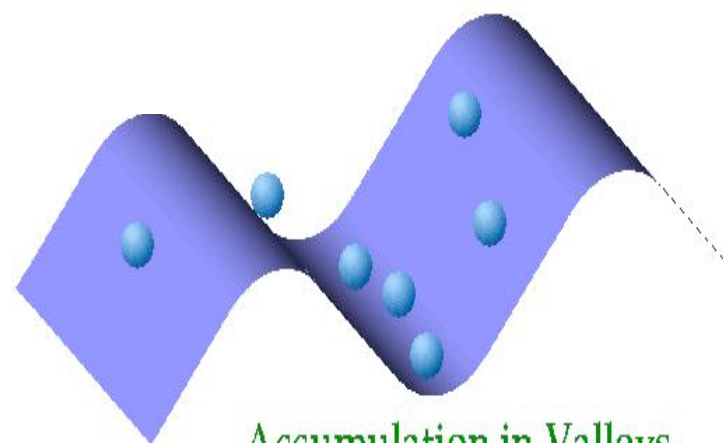
Anisotropias primarias: originadas na SUE

grandes escalas angulares: $\theta > 1^\circ$

- 1) redshift grav.: fótons que escapam do poço de potencial de uma concentração de massa sofrem redshift gravitacional

contraste de densidade:

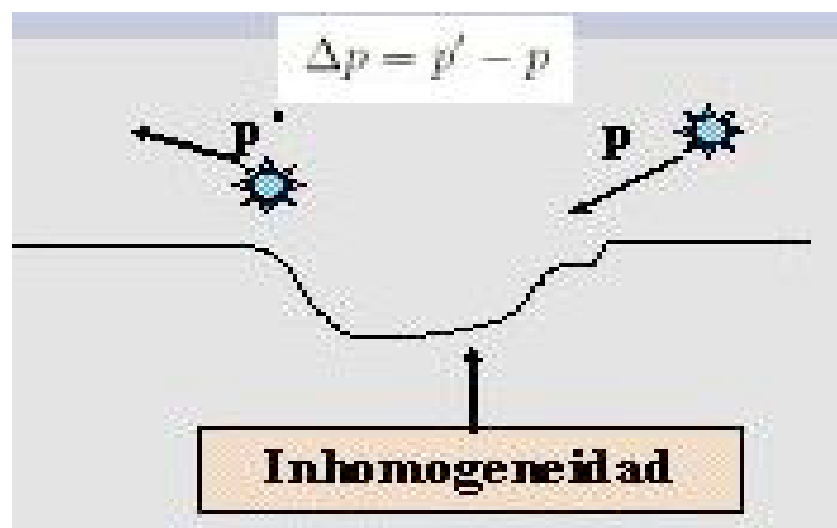
$$\delta\rho \equiv \frac{\rho(x^\mu) - \rho_0}{\rho_0}$$



Accumulation in Valleys



"Top View"



$$\frac{\Delta T(t_{\text{rec}}, \vec{r})}{T} = \frac{\phi(t_{\text{rec}}, \vec{r})}{c^2}$$

$\frac{\Delta T}{T_0}$: Flutuações de temperatura (**anisotropias**) da RCF

Anisotropias primarias: originadas na SUE

grandes escalas angulares: $\theta > 1^\circ$

- ▶ 1) redshift grav.: fótons que escapam do poço de potencial de uma concentração de massa sofrem redshift gravitacional
- ▶ 2) efeito Doppler se a matéria que espalha os fótons tem movimento peculiar em relação ao fluxo de Hubble:

$$\frac{\Delta T(t_{\text{rec}}, \vec{r})}{T} = \frac{\vec{r} \cdot \vec{v}}{c}$$

mas, para grandes escalas angulares: $\langle \vec{r} \cdot \vec{v} \rangle = 0$

$\frac{\Delta T}{T_0}$: Flutuações de temperatura (**anisotropias**) da RCF

Anisotropias primarias: originadas na SUE

grandes escalas angulares: $\theta > 1^\circ$

- ▶ 1) redshift grav.: fótons que escapam do poço de potencial de uma concentração de massa sofrem redshift gravitacional
- ▶ 3) flut. de densidade: fótons que se originam em regiões onde $\delta\rho > 0$ ($\delta\rho < 0$) tem temperatura $+$ ($-$) elevada _(wrm)

$$\frac{\Delta T(t_{\text{rec}}, \vec{r})}{T} = \frac{1}{3} \frac{\delta\rho(t_{\text{rec}}, \vec{r})}{\rho}$$

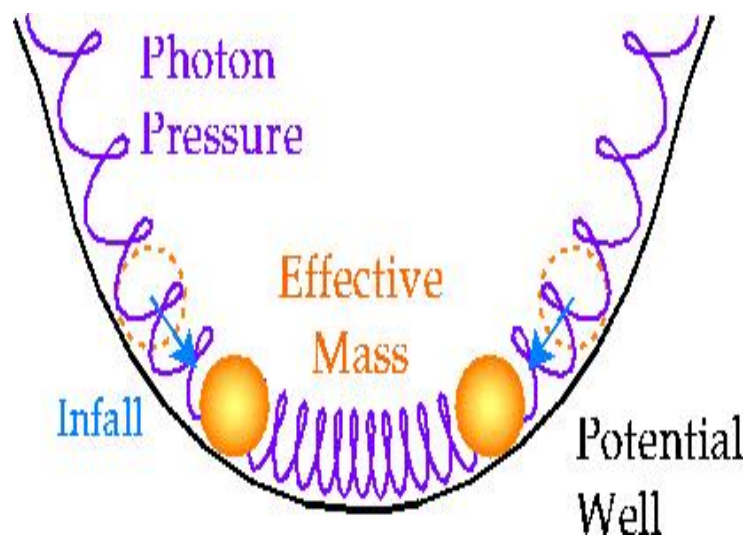
como: $\delta\rho/\rho \simeq -2\phi/c^2 \Rightarrow \frac{\Delta T(t_{\text{rec}}, \vec{r})}{T} \simeq \frac{1}{3} \frac{\phi}{c^2} \simeq -\frac{1}{6} \frac{\delta\rho}{\rho}$

- ▶ $\phi < 0 \Rightarrow \delta\rho > 0$ overdense region $\rightarrow$ **cold** spot
- ▶ $\phi > 0 \Rightarrow \delta\rho < 0$ underdense region $\rightarrow$ **hot** spot

$\frac{\Delta T}{T_0}$: Flutuações de temperatura (**anisotropias**) da RCF

Anisotropias primarias: **peq. escalas angulares:** $0.1^\circ \lesssim \theta \lesssim 1^\circ$

gravidade versus pressão dos fótons: picos acústicos



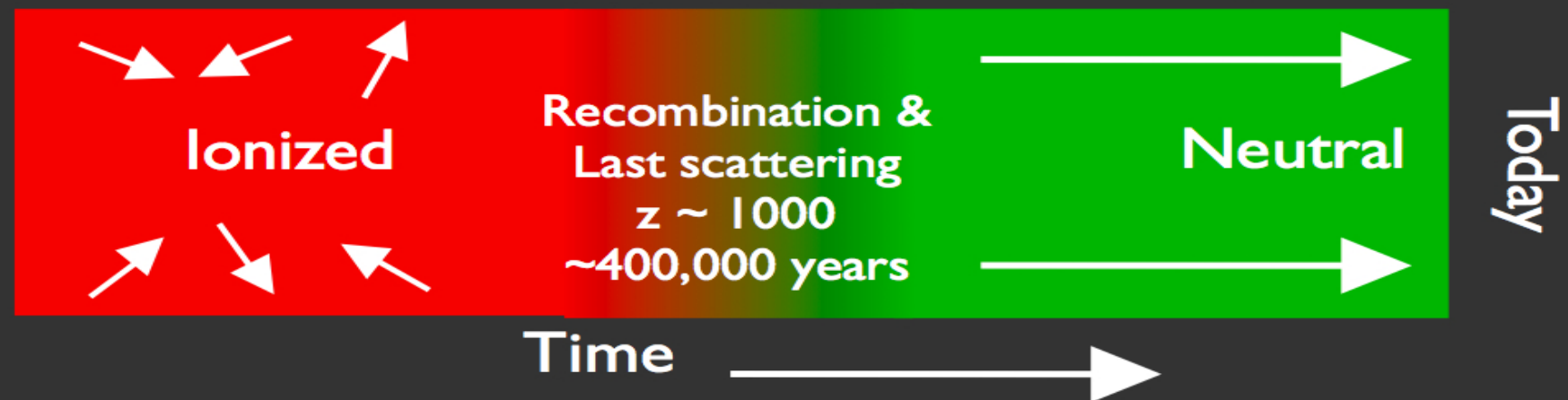
CMB: Sound Waves in the Early Universe

Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Photon-baryon perturbations oscillate as acoustic waves.

After recombination:

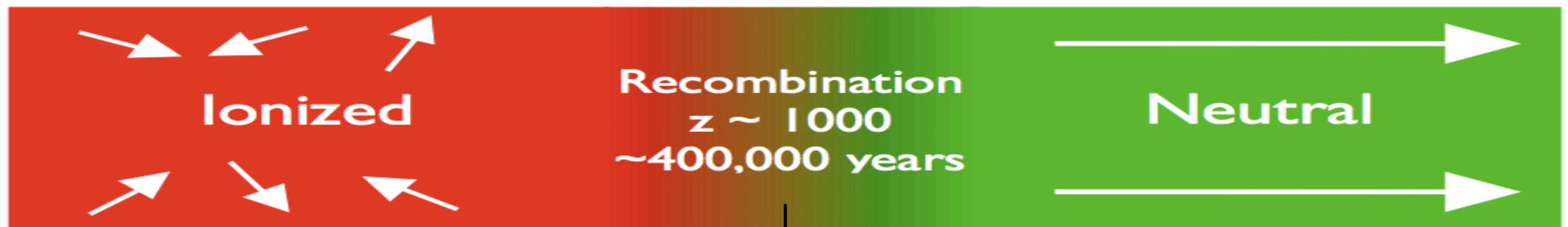
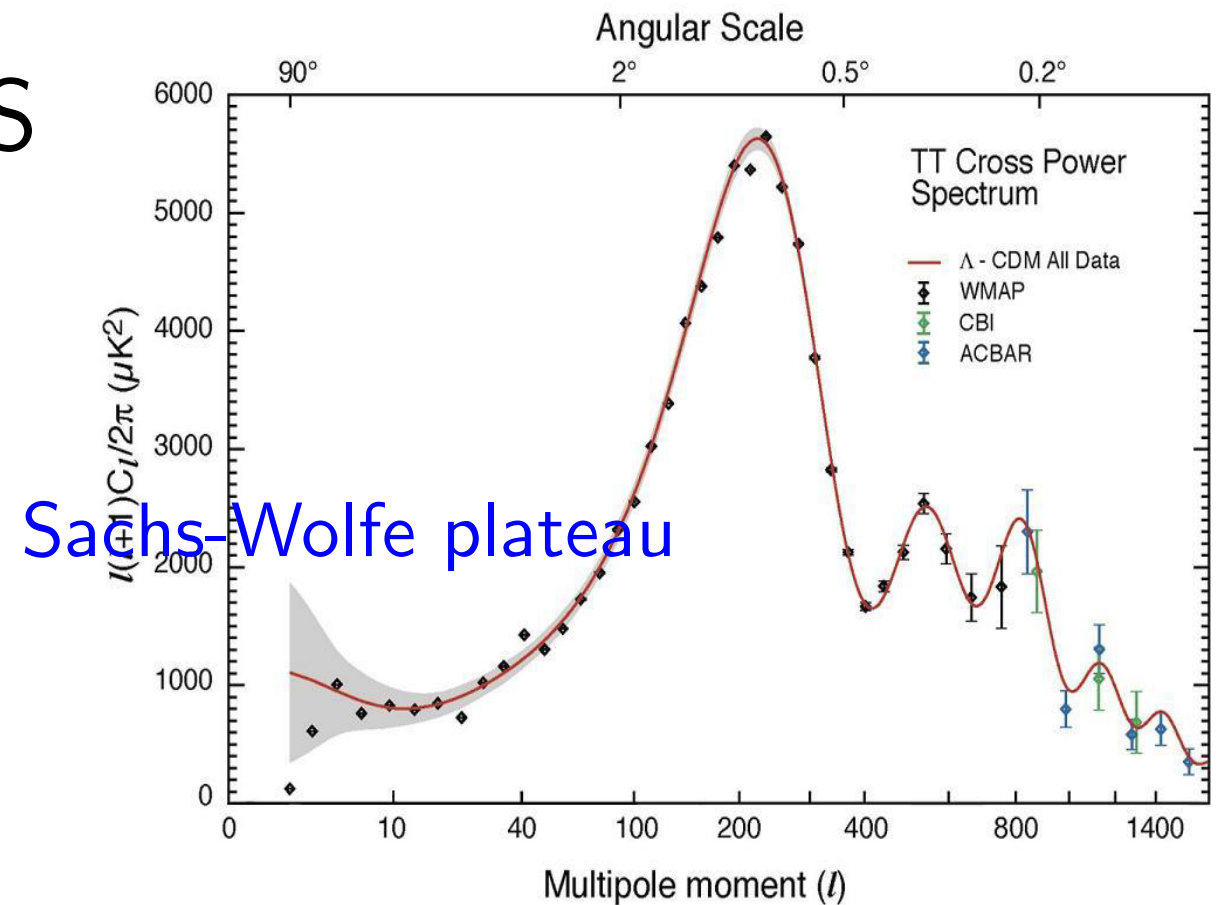
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.



CMB temperature fluctuations:

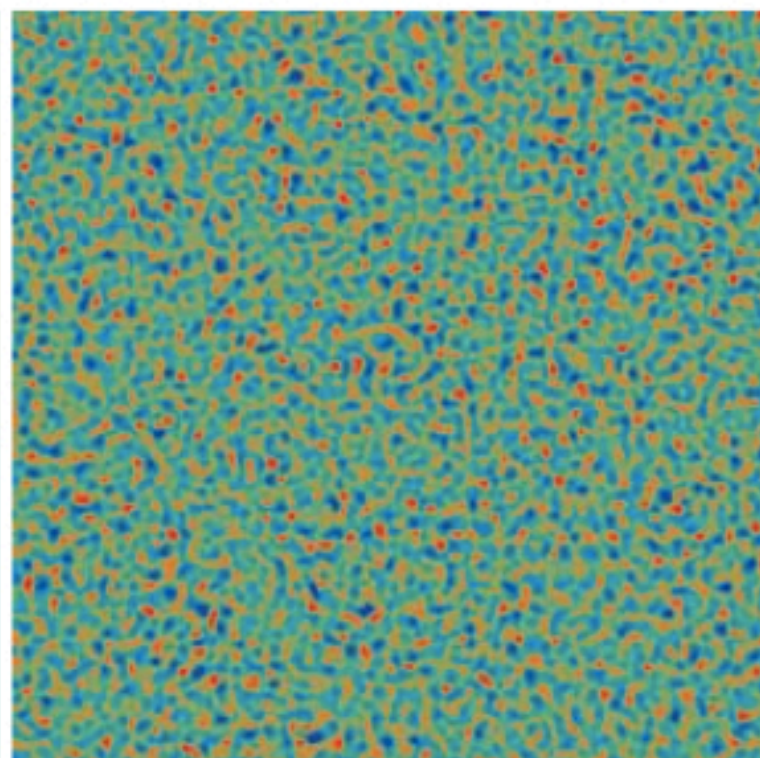
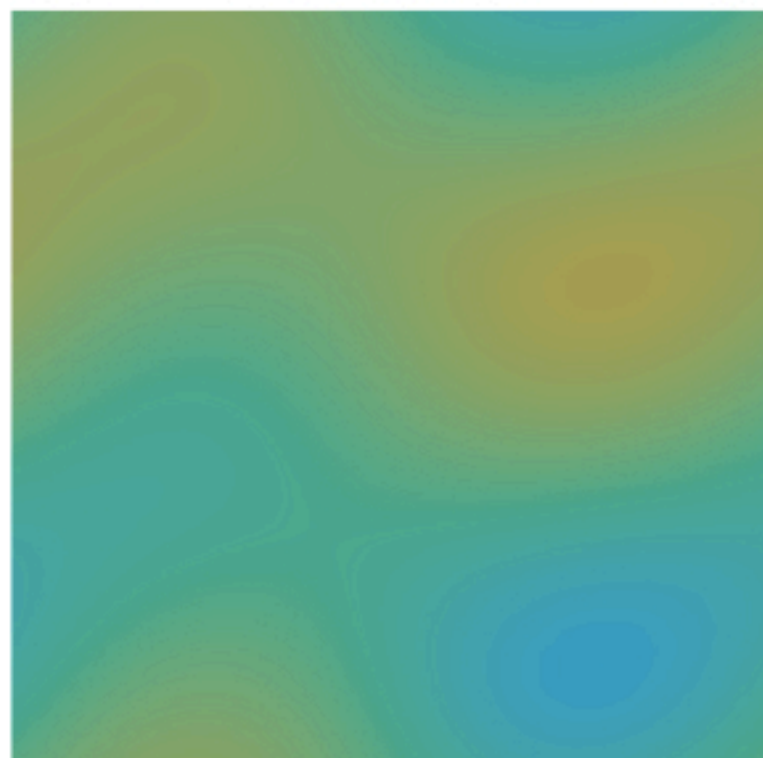
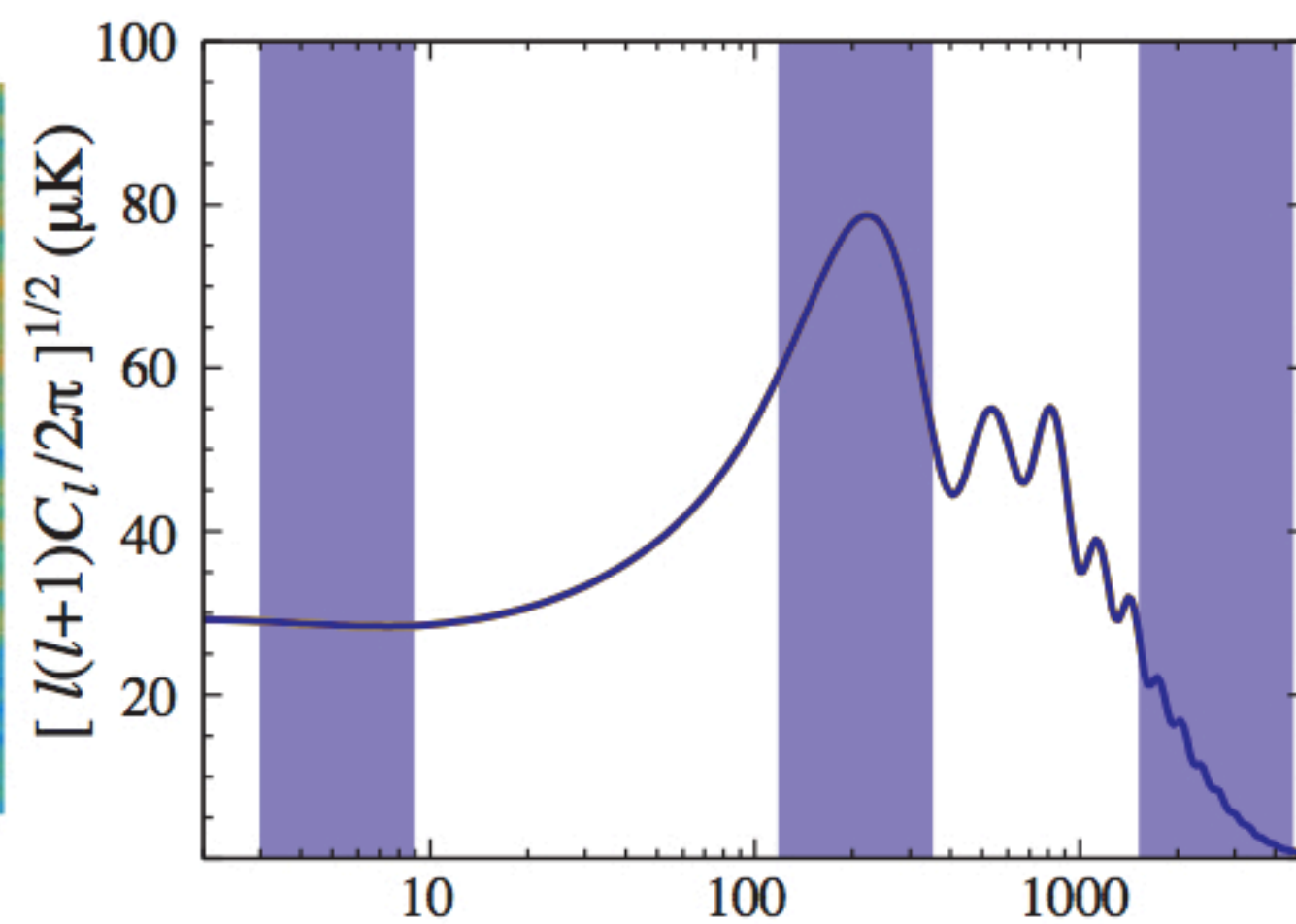
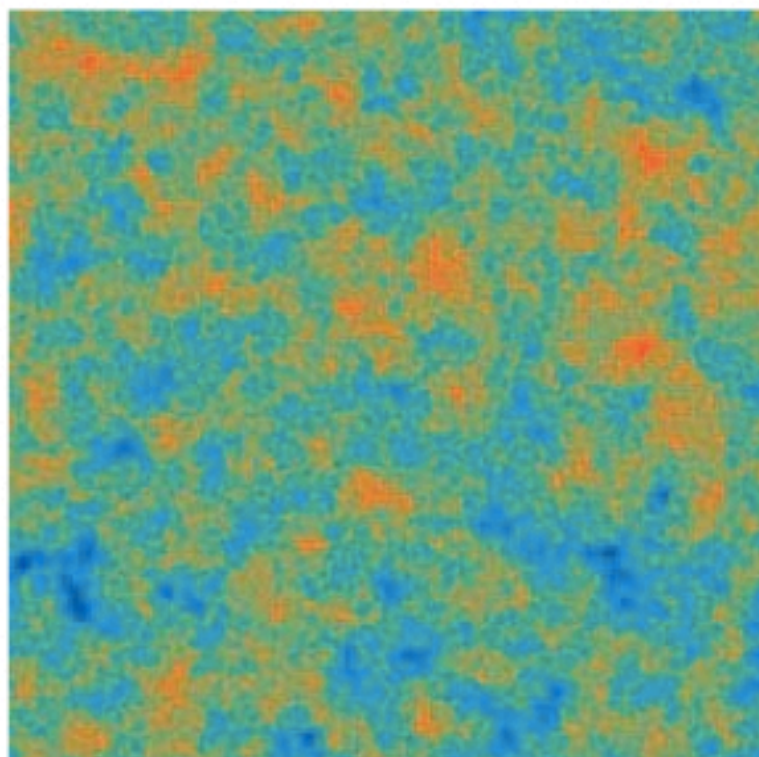
$$\Delta T = \Delta T(\theta, \varphi)$$

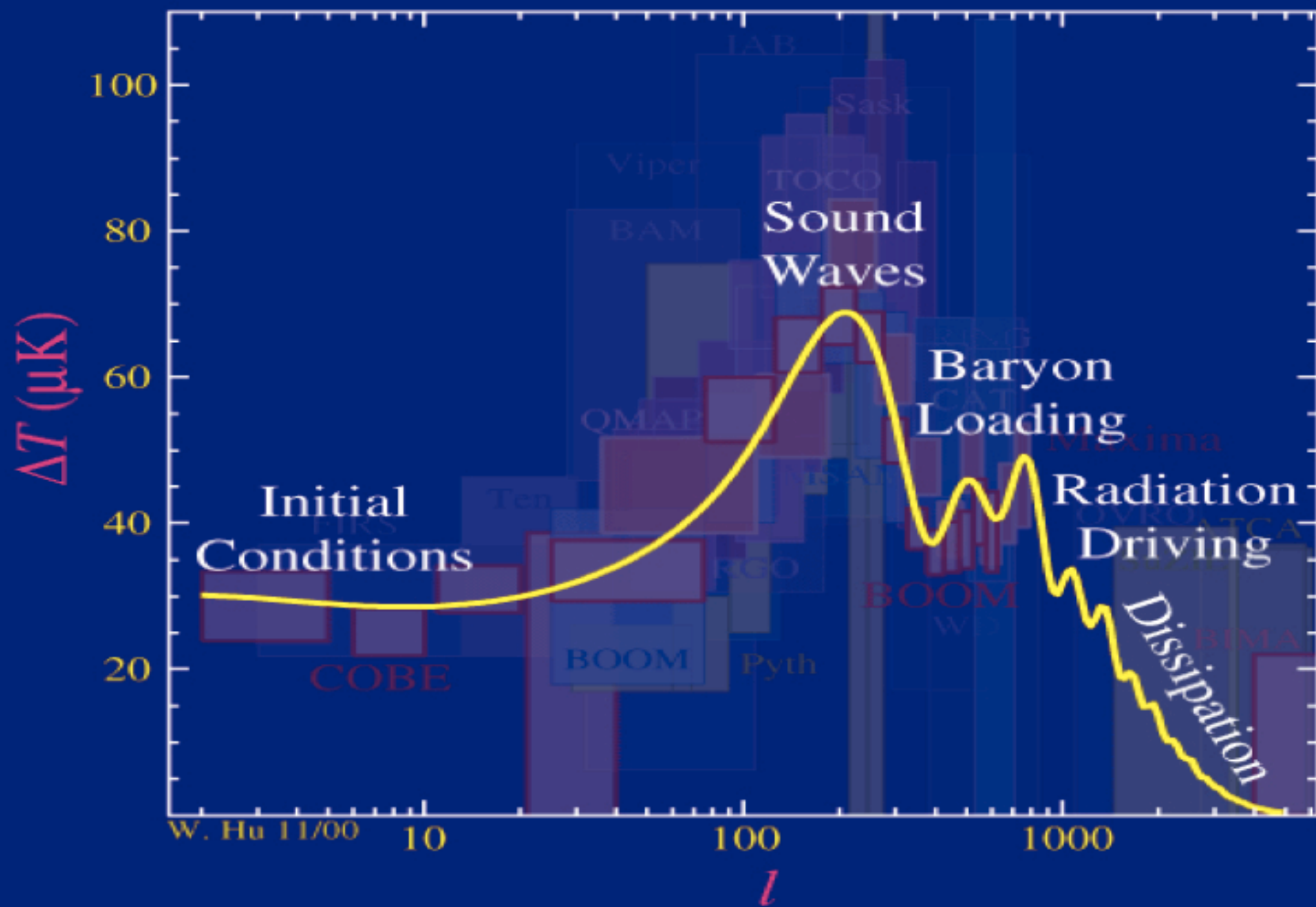
- Primary anisotropies: at LSS

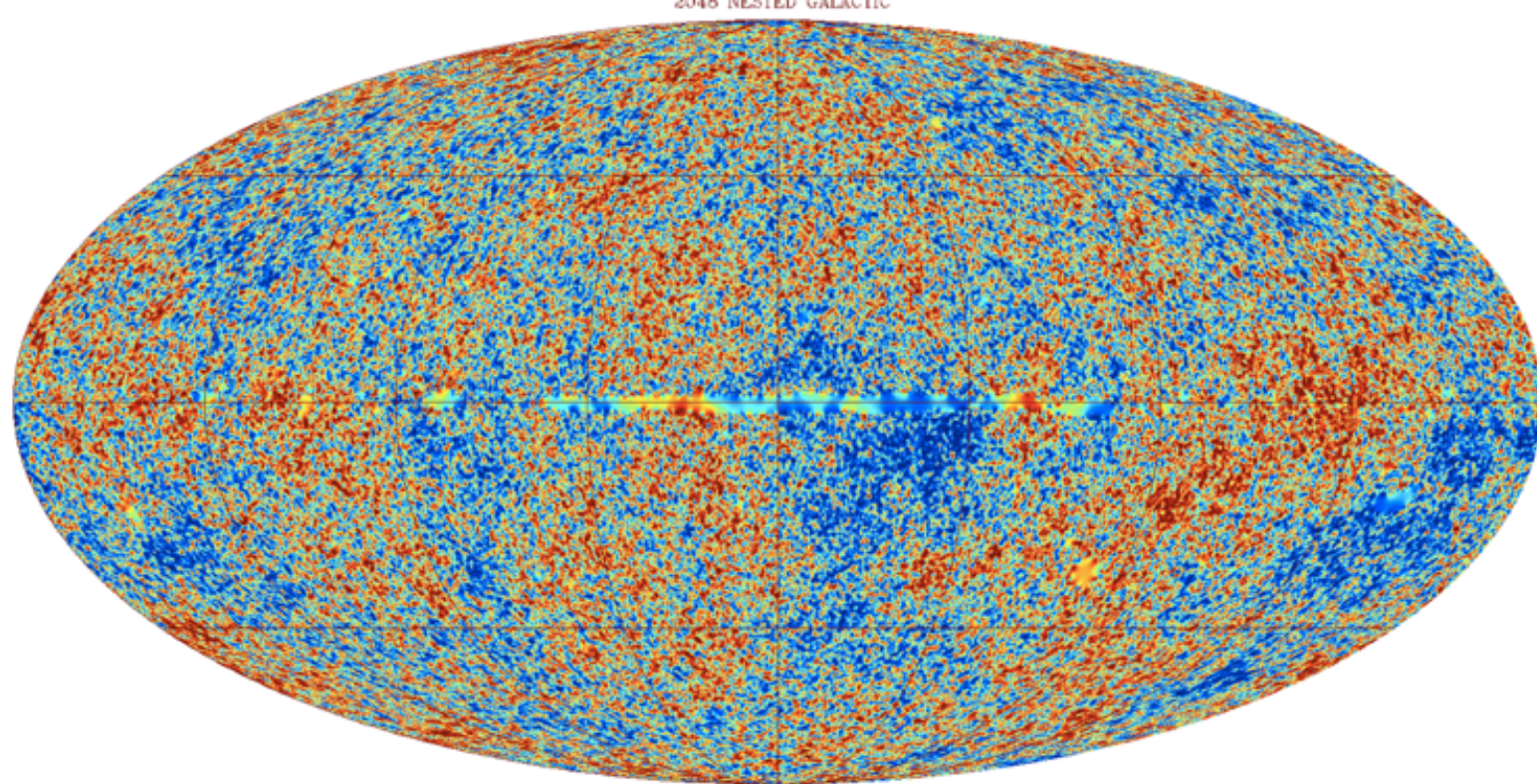


LSS = Last Scattering Surface, i.e., Universe at $t = t_{\text{rec}}$

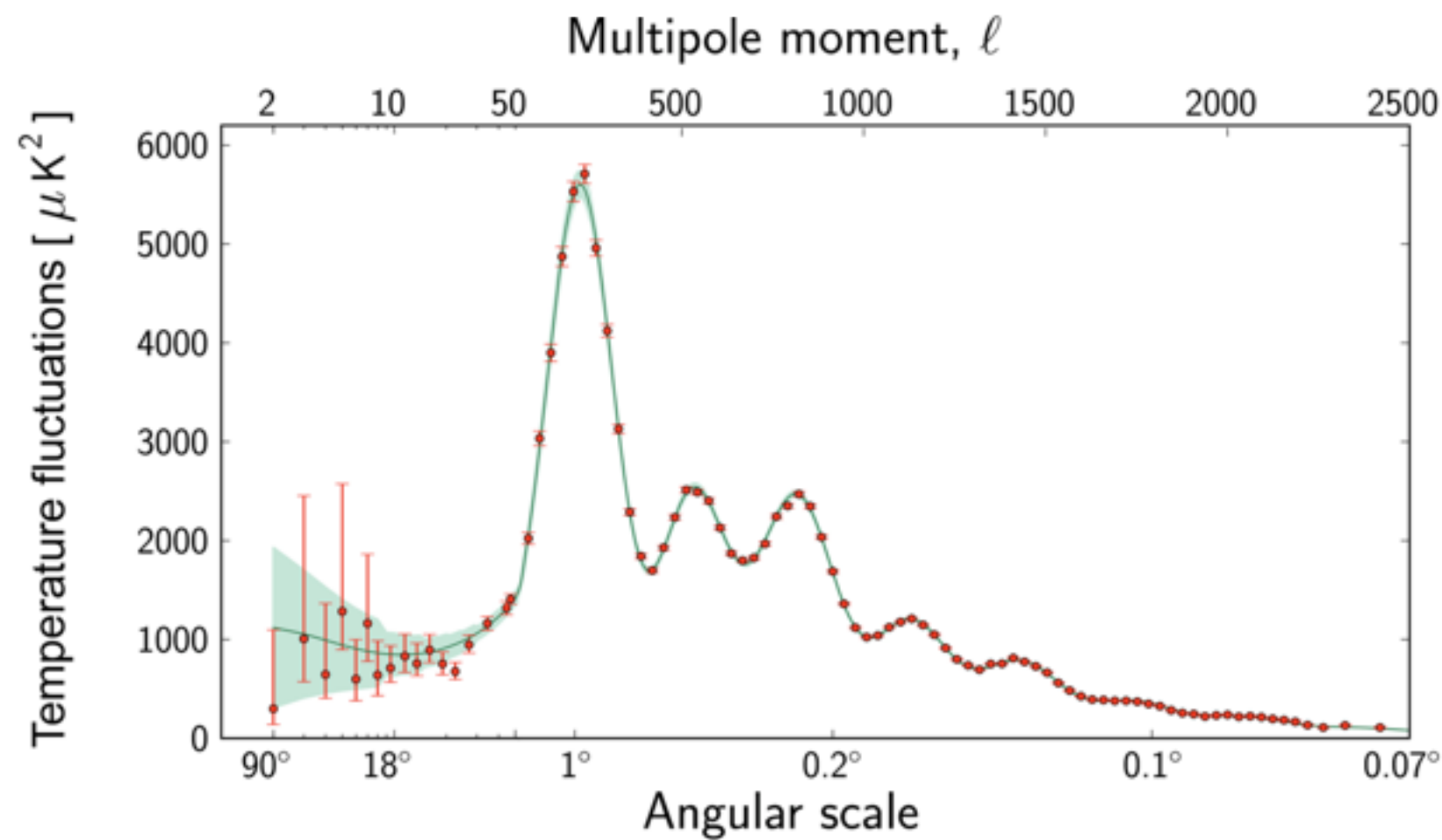
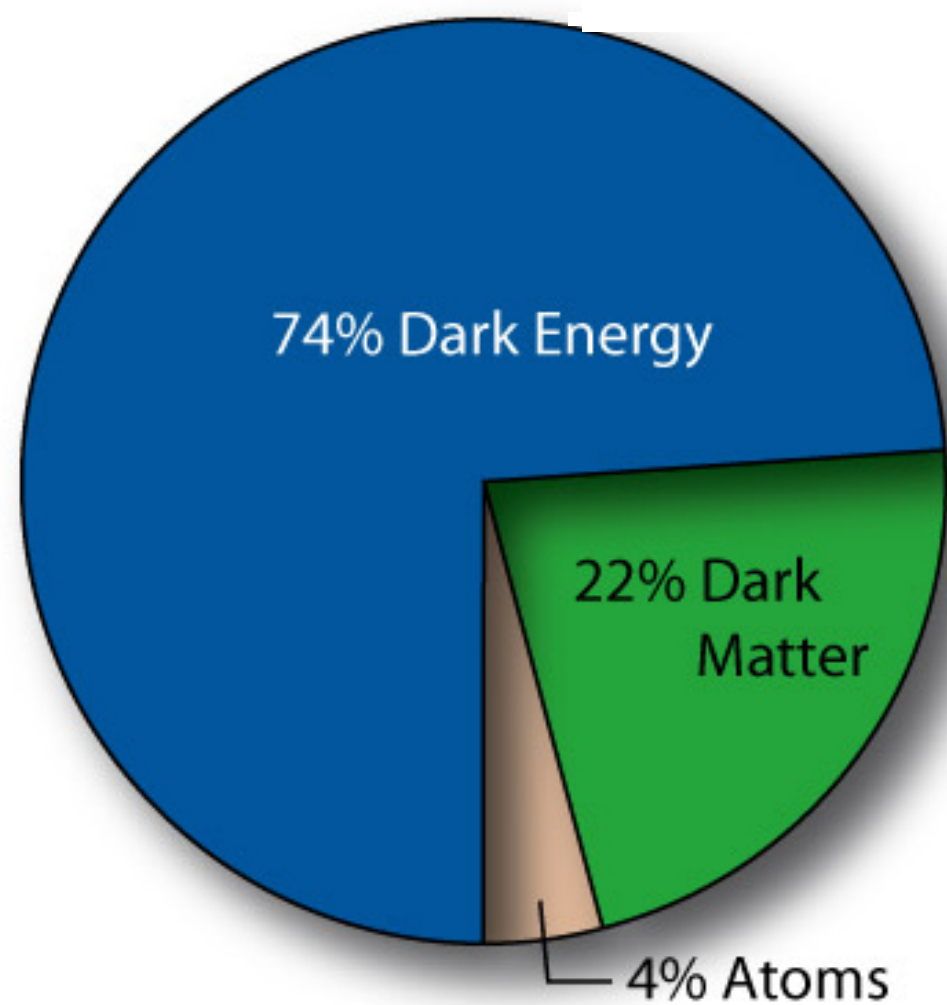
64°







-841 730 uK_{emb}



$$E = E_{\Lambda} + E_{\text{ME}} + E_b + E_{\gamma} + E_c$$

3 geometrias
são possíveis:



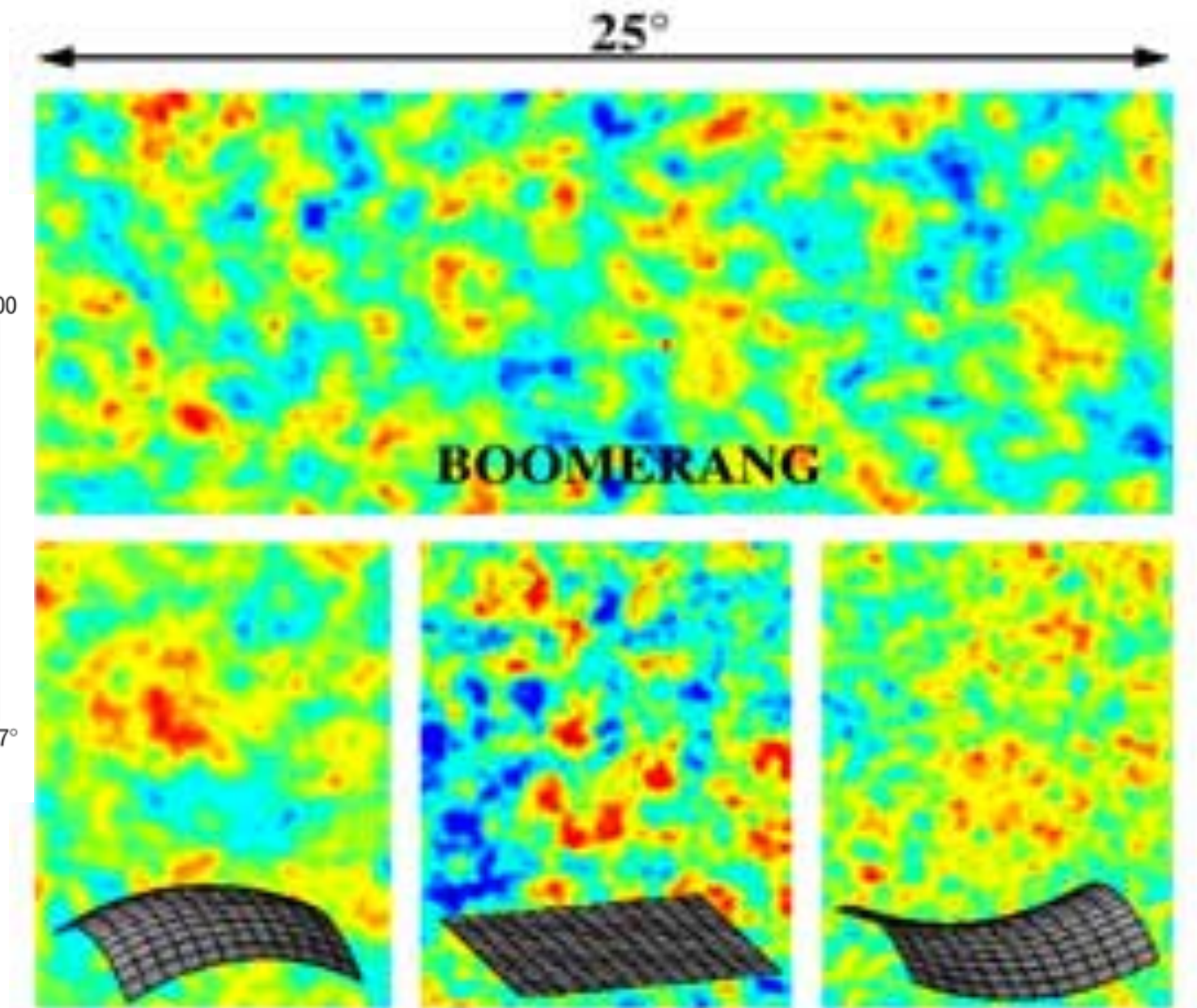
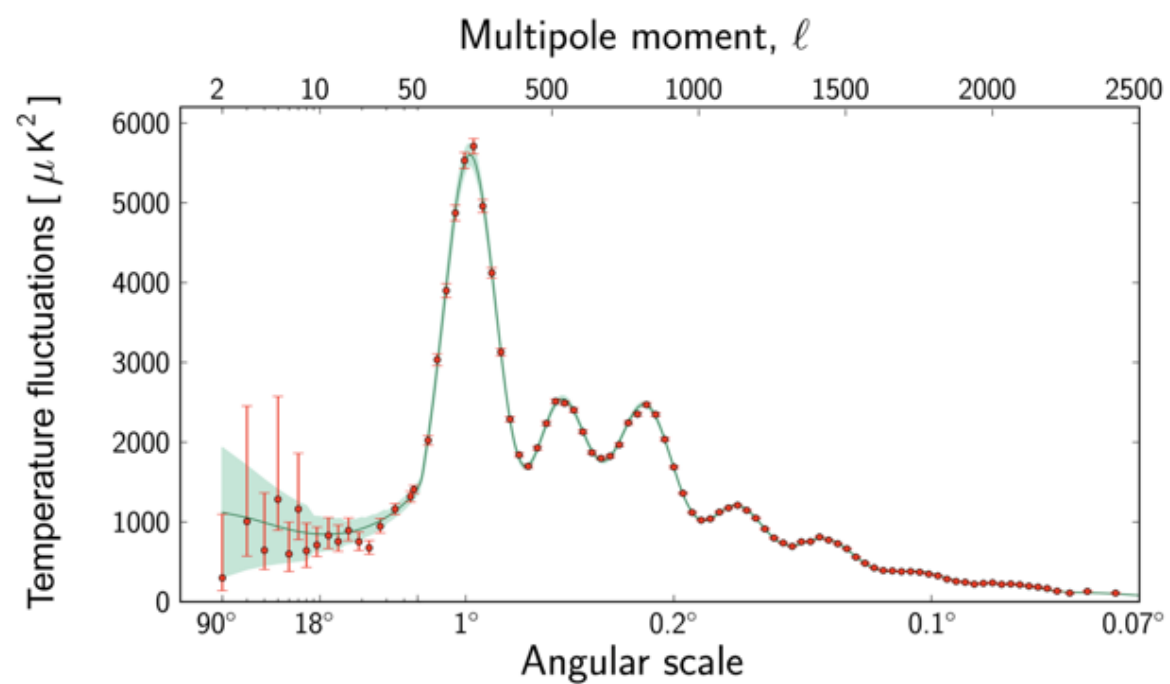
esférica



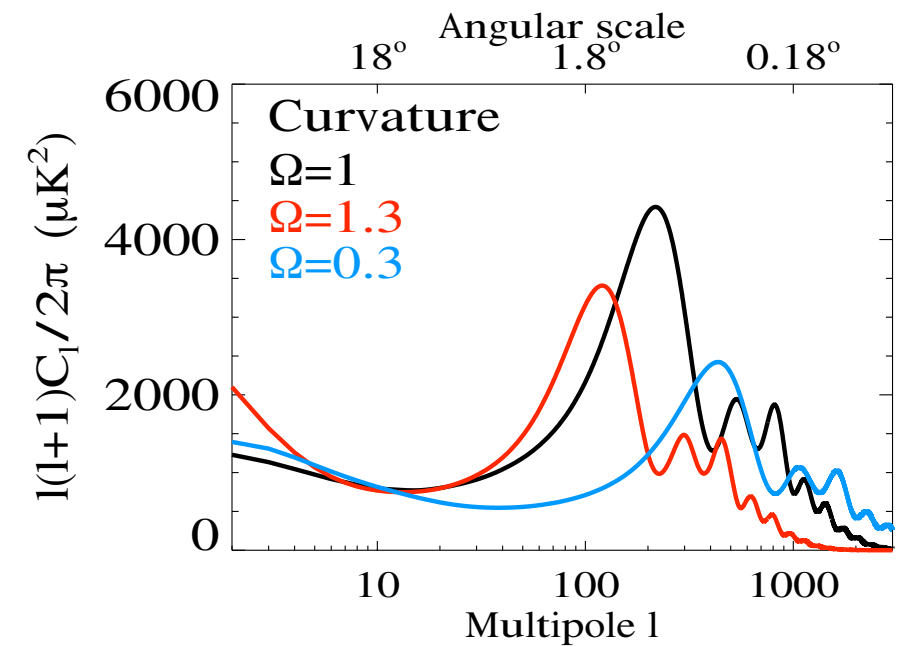
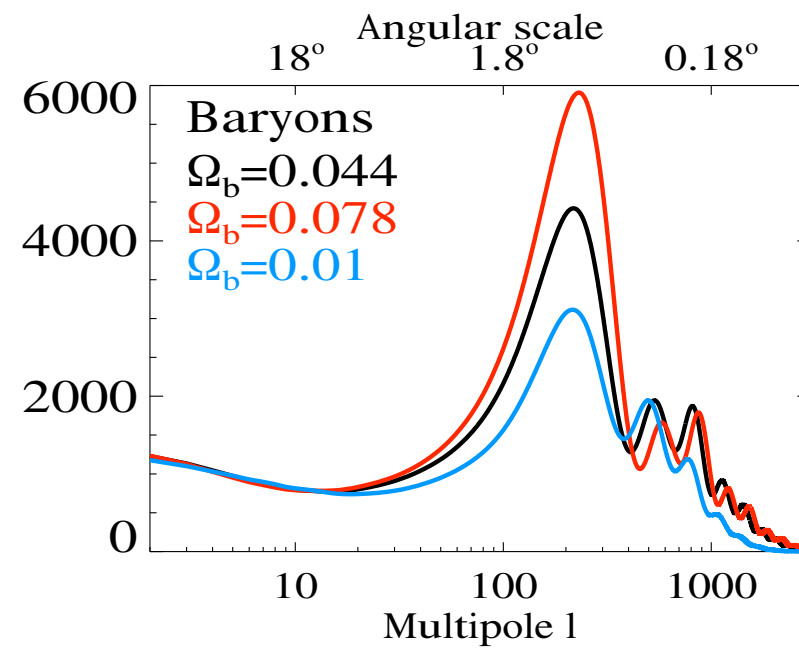
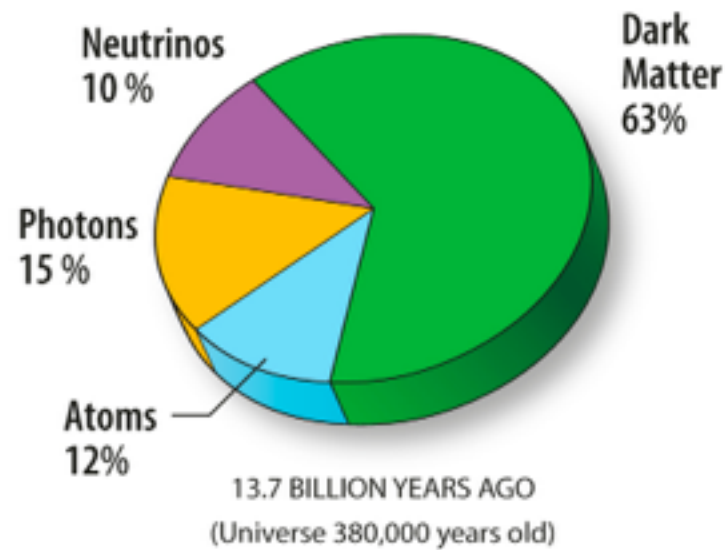
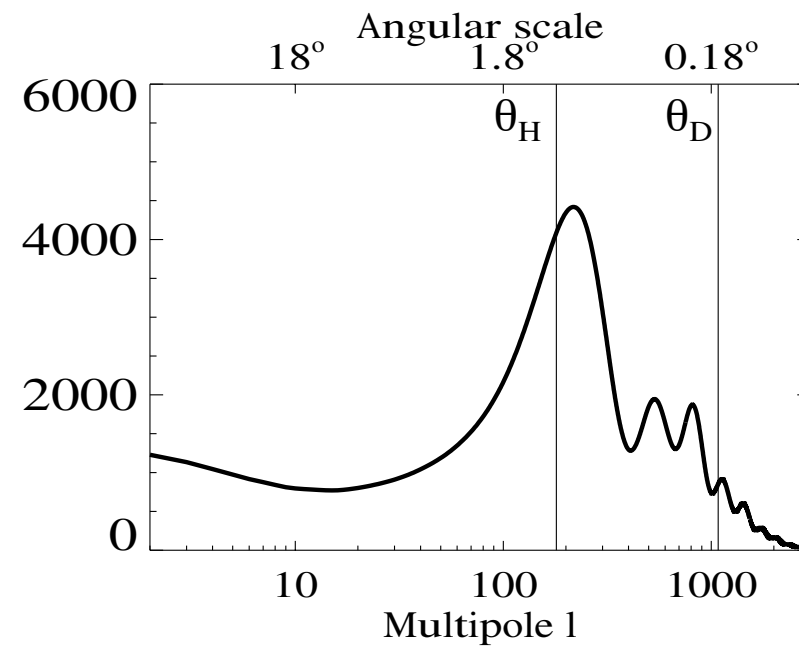
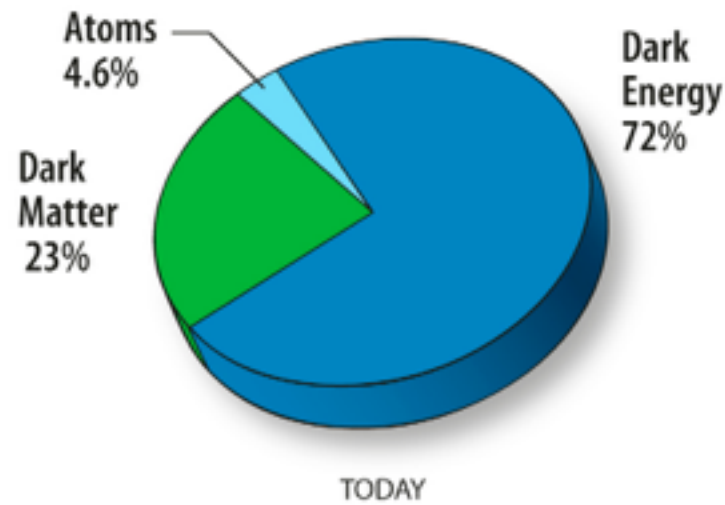
hiperbólica

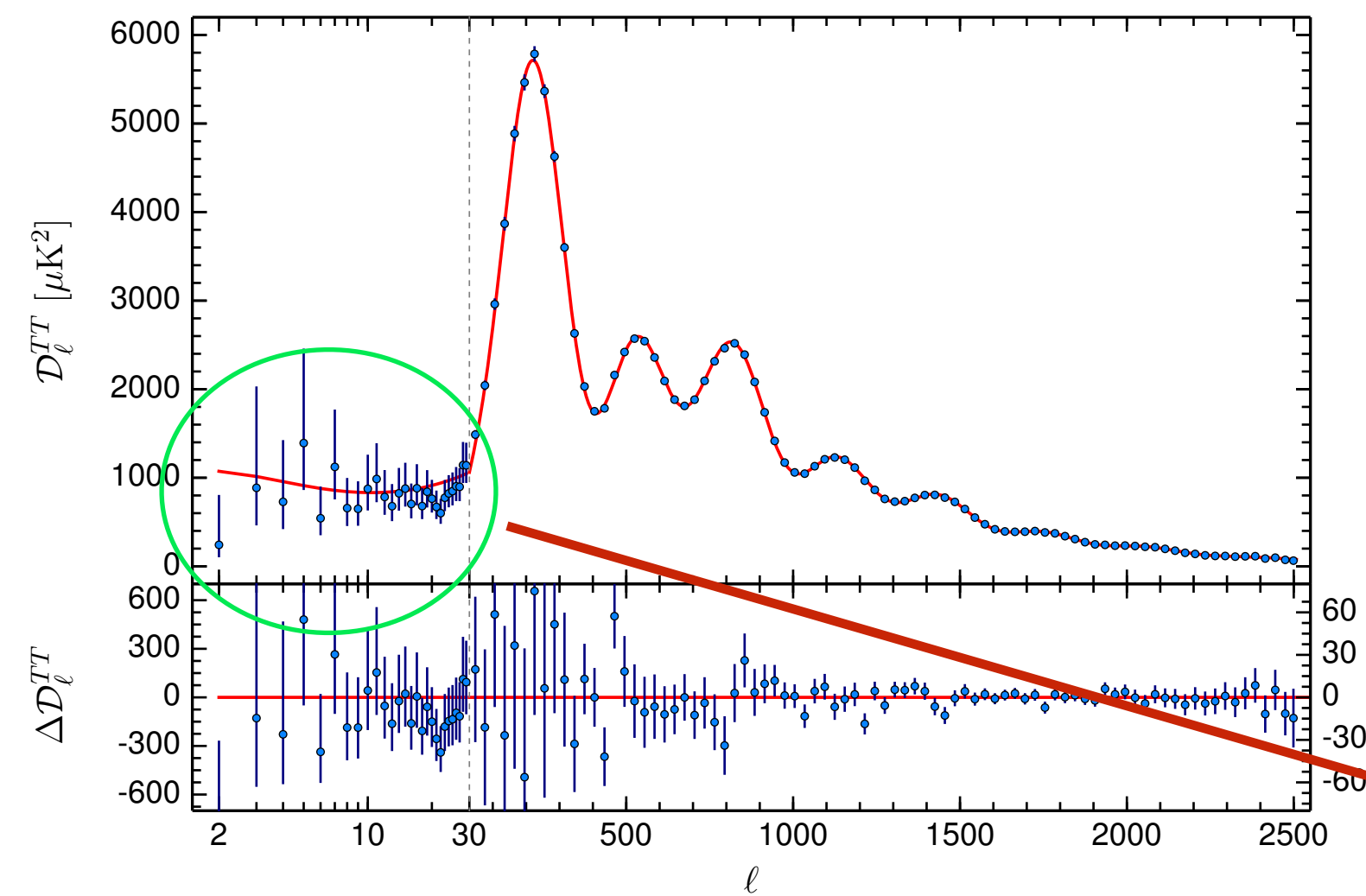


plana



Parameter dependence





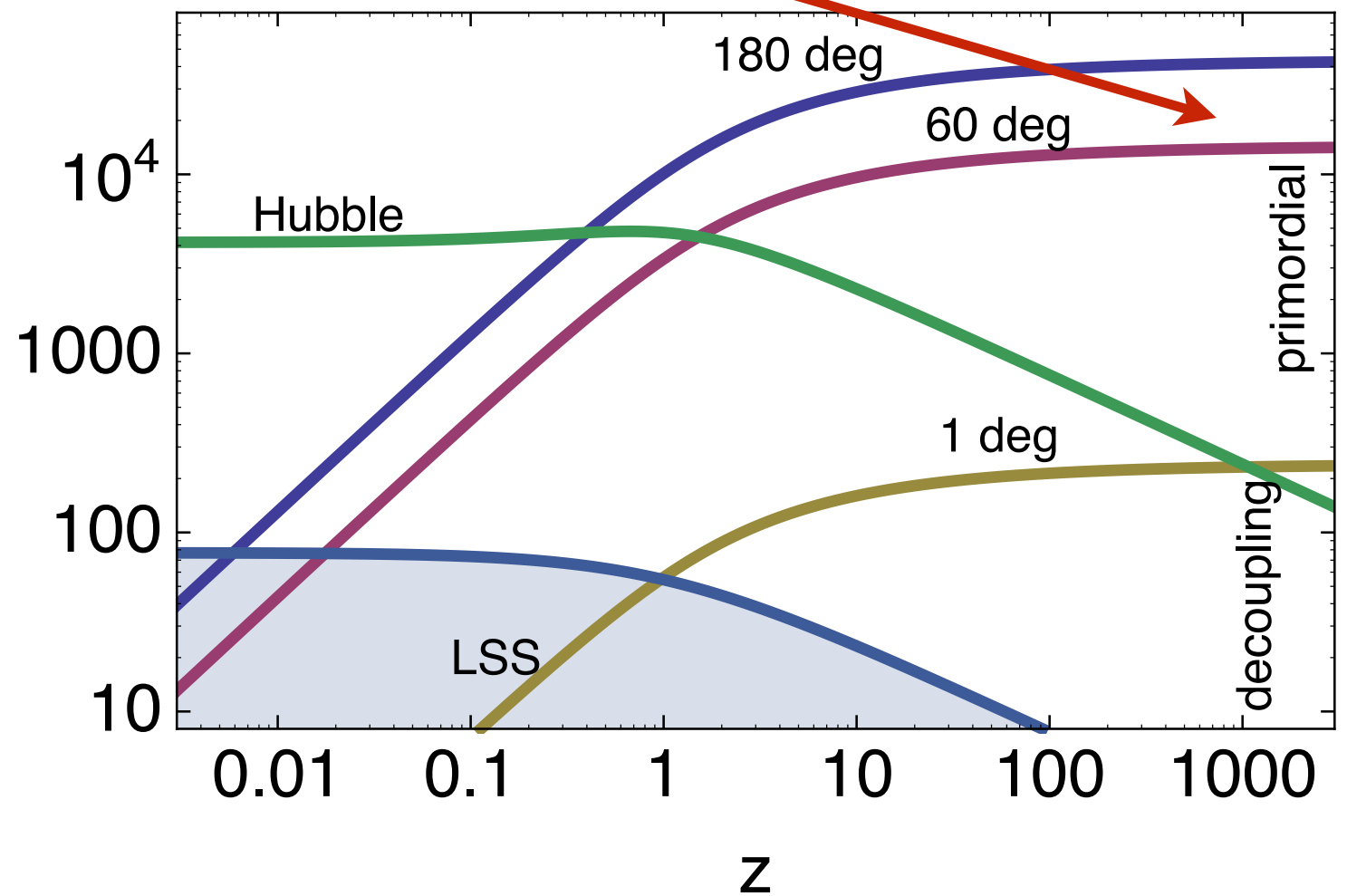
Unexpected
primordial
features

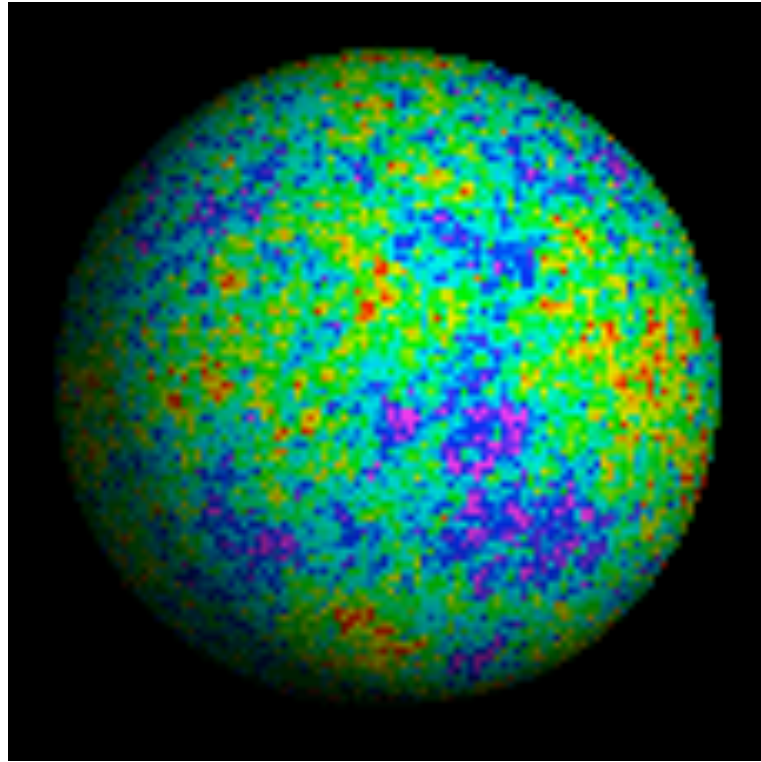
ΛCDM



grandes escalas
guardan info. del
Univ. primordial

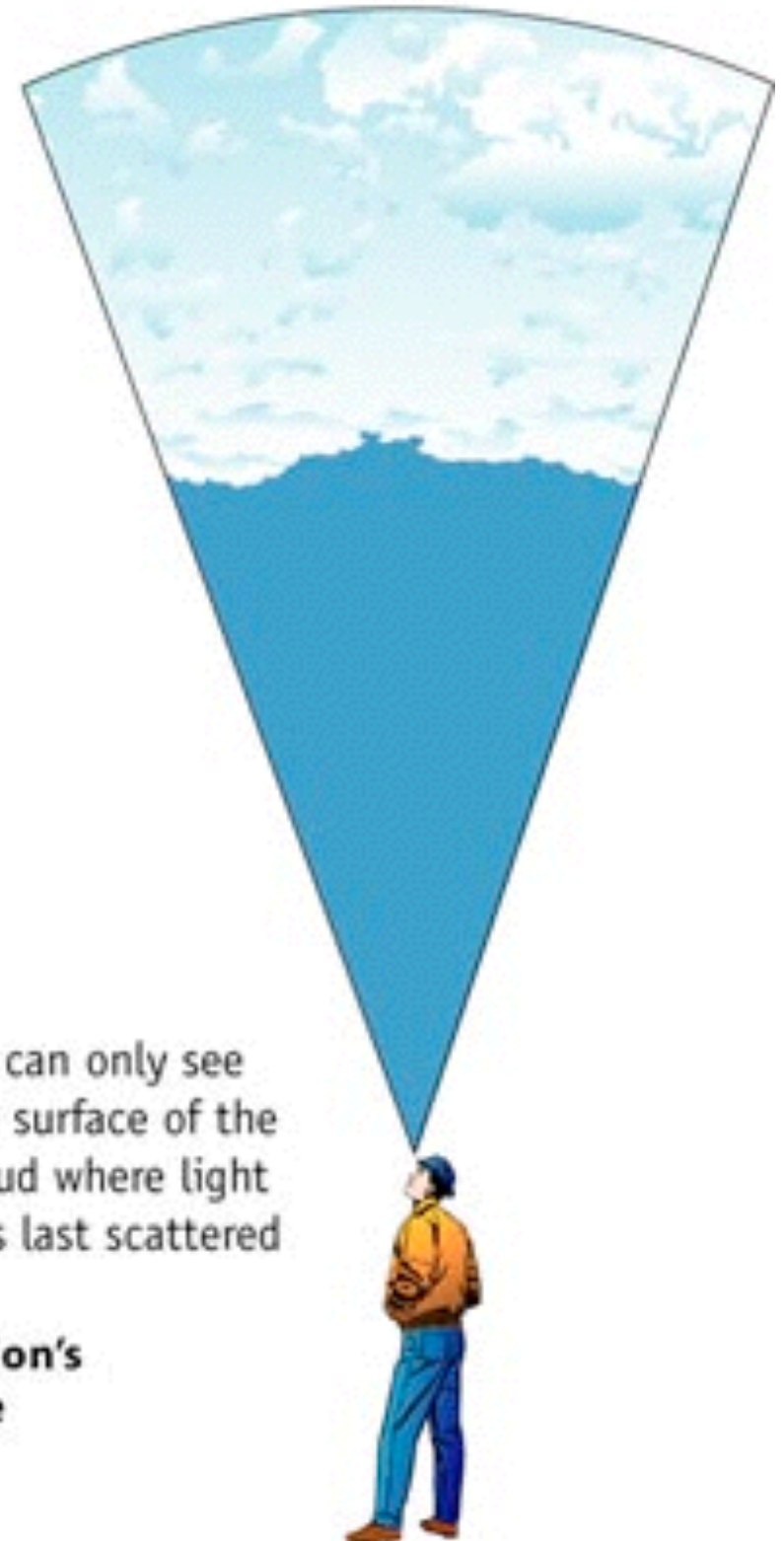
comoving scale [Mpc]



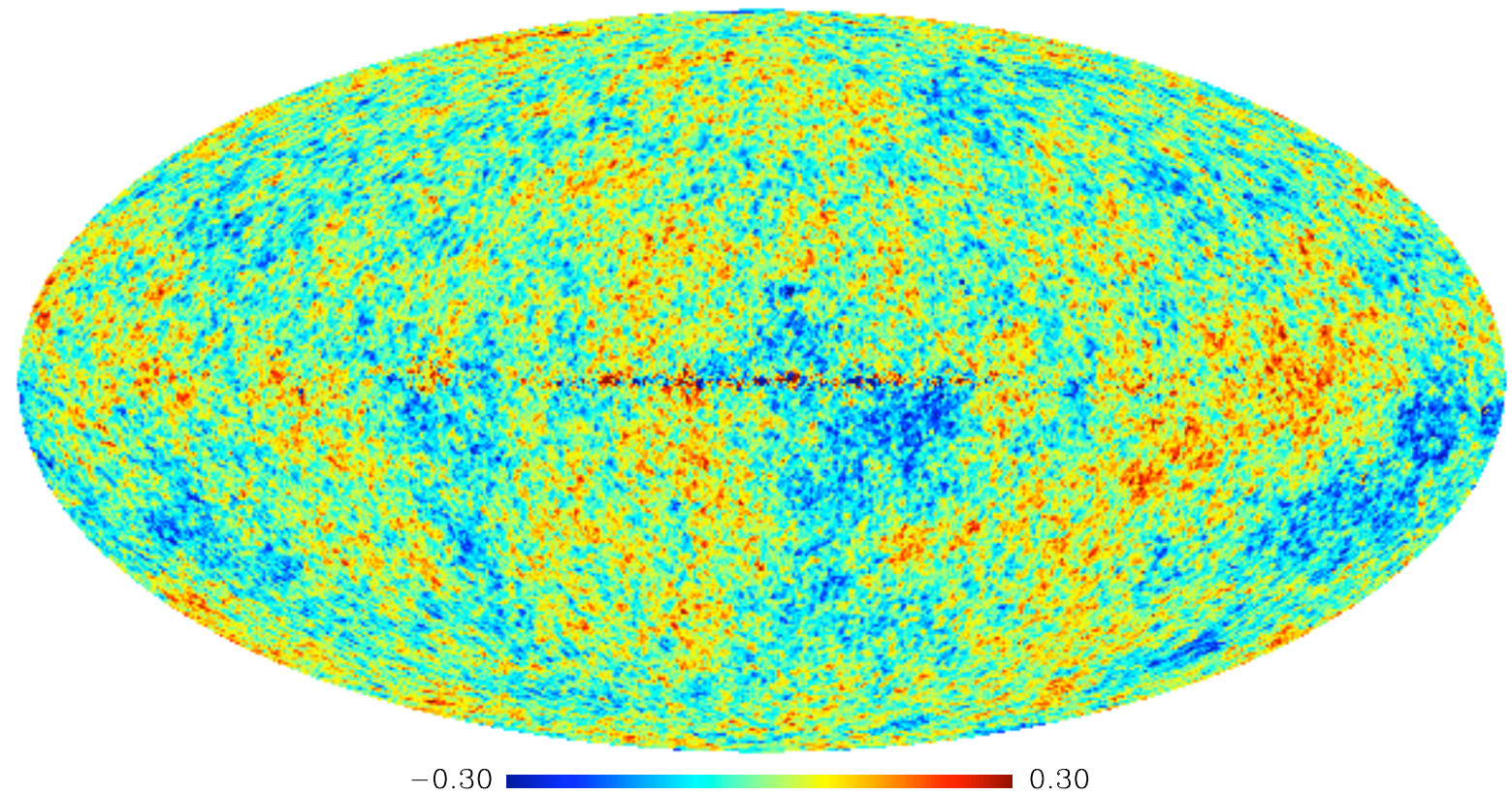


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

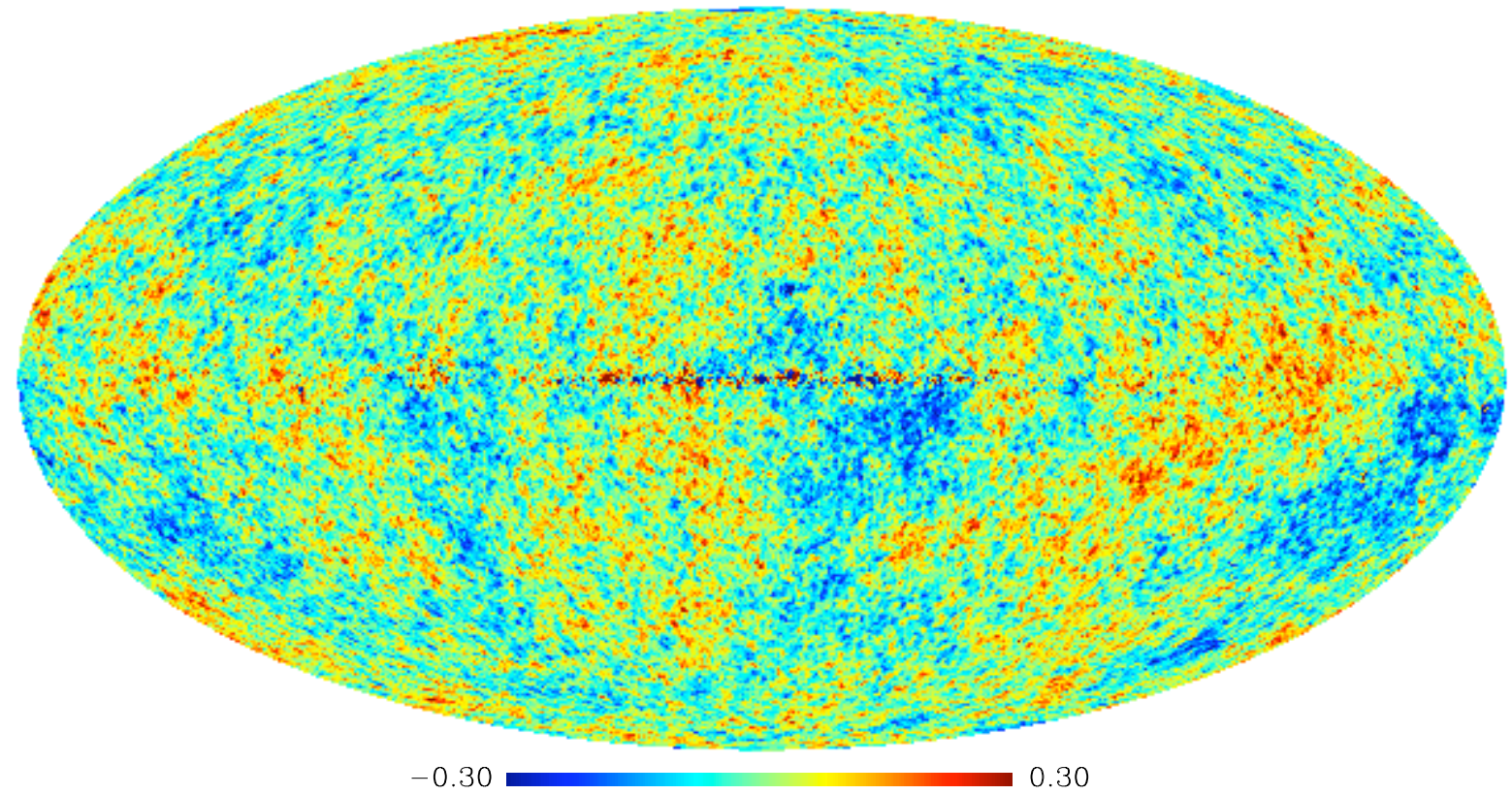
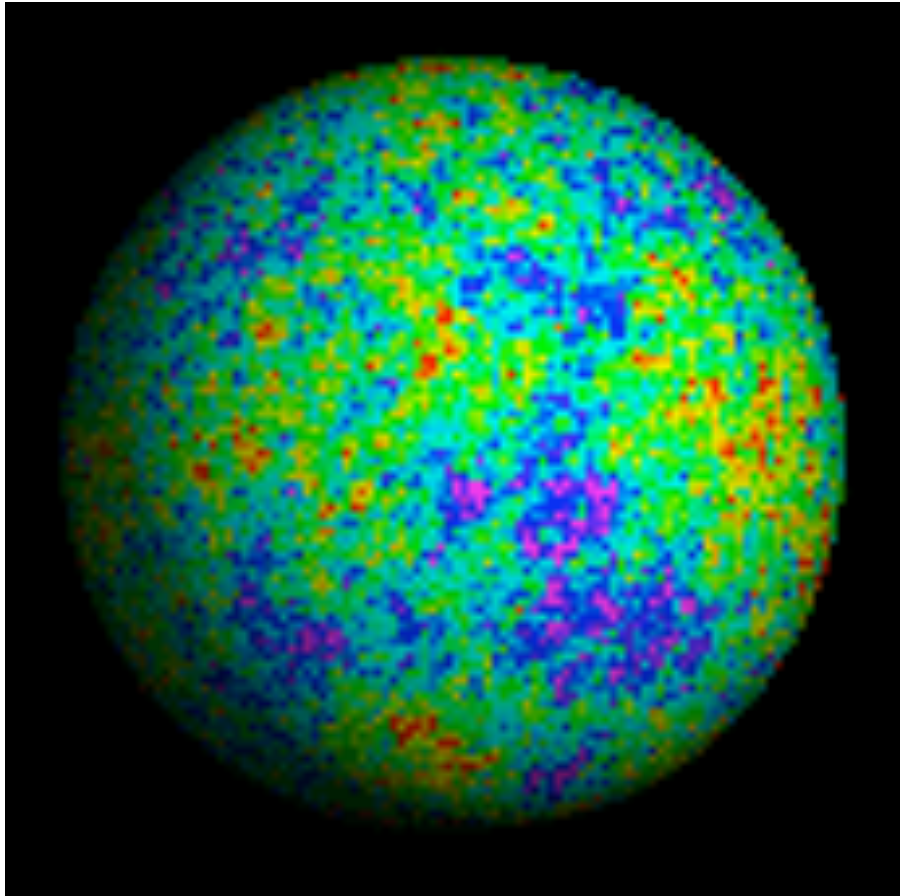
We can only see the surface of the cloud where light was last scattered



CMB sphere?



CMB sphere?



Esfera S^2

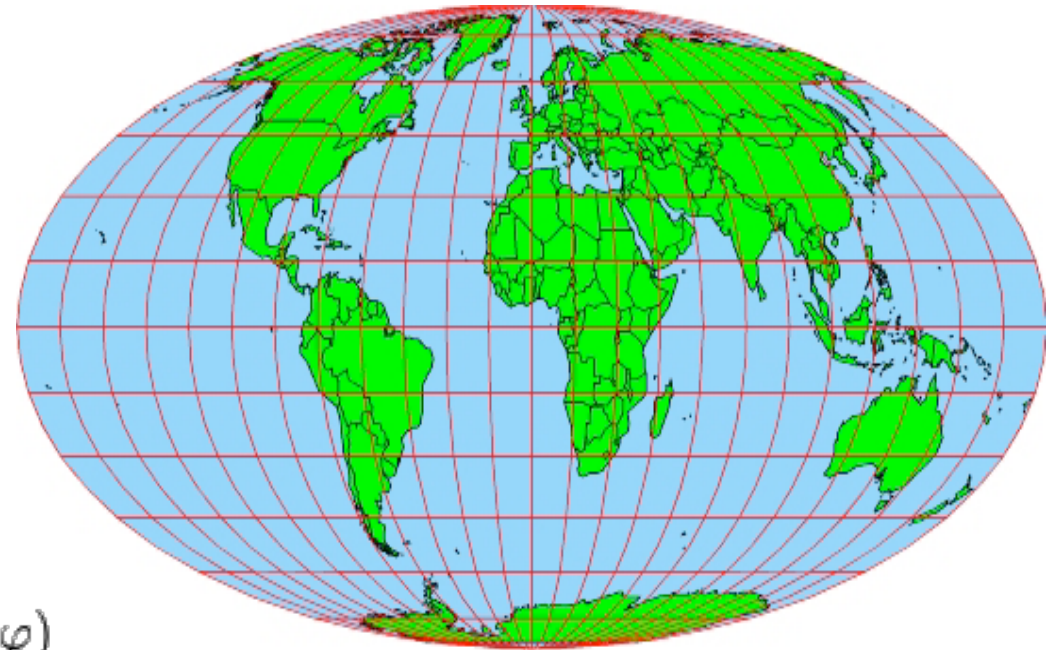
Projeção Mollweide sobre um plano



$$x = \frac{2\sqrt{2}}{\pi} \lambda \cos(\theta),$$

$$y = \sqrt{2} \sin(\theta),$$

$$2\theta + \sin(2\theta) = \pi \sin(\varphi)$$



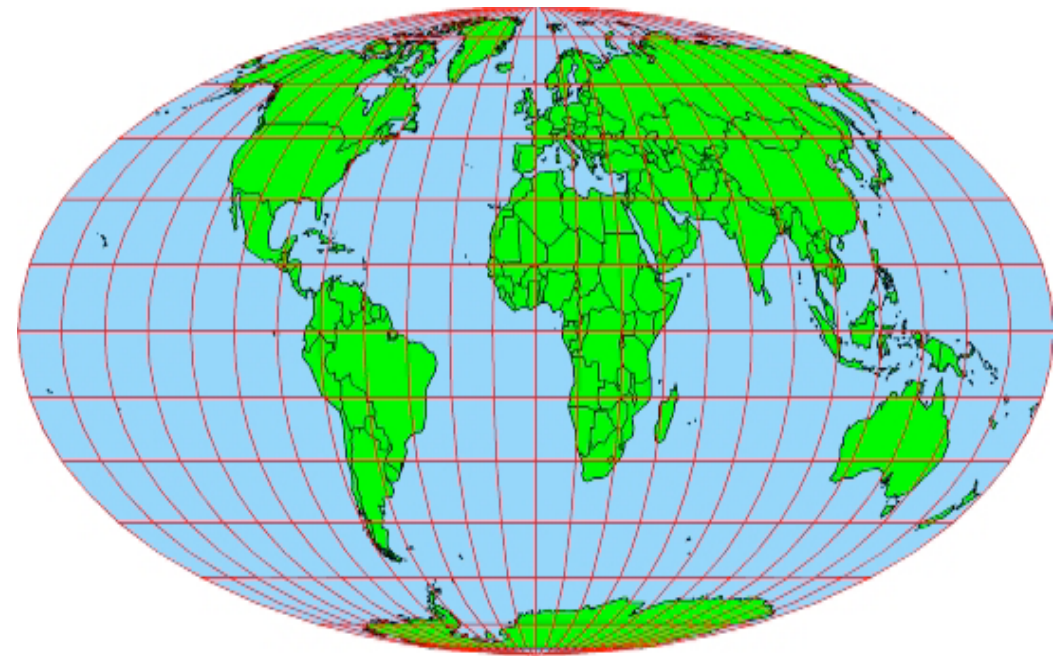
K. Mollweide (1774-1825)

Matemático

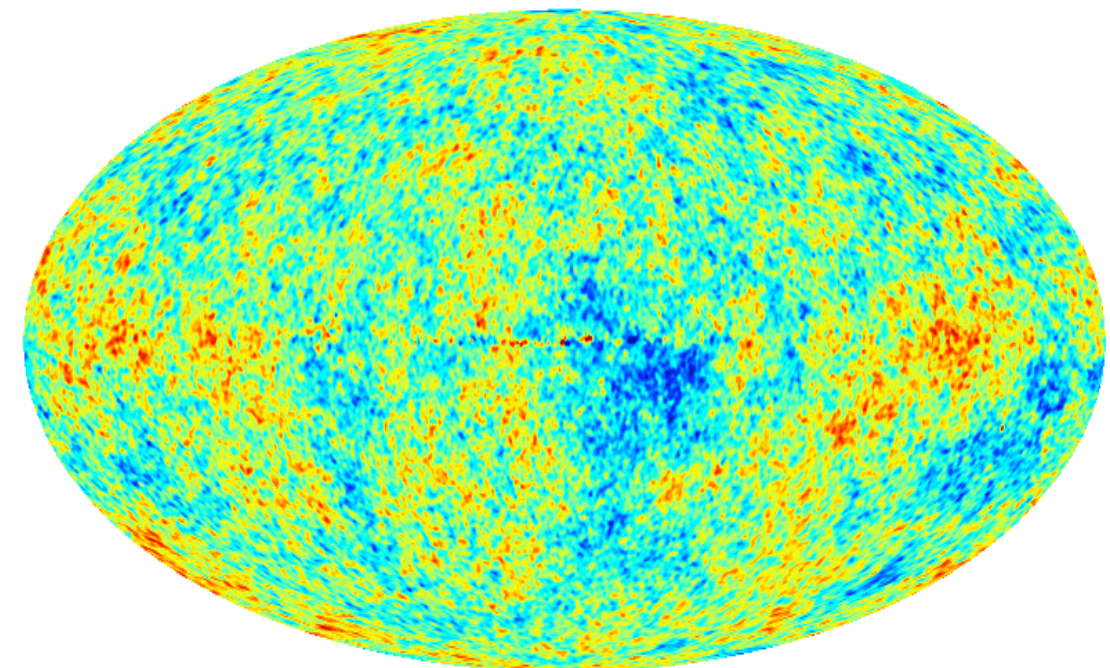
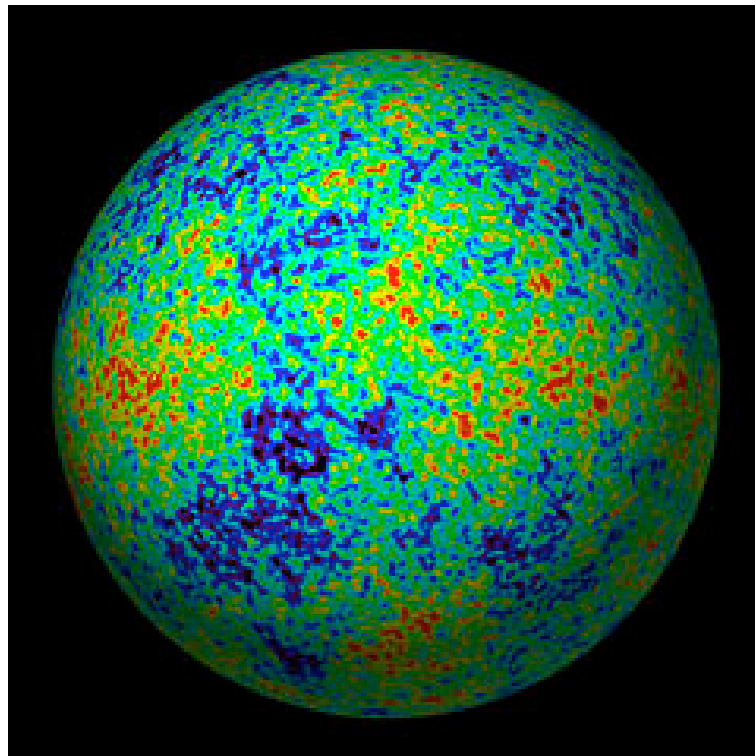
Esfera S^2



Projeção Mollweide sobre um plano



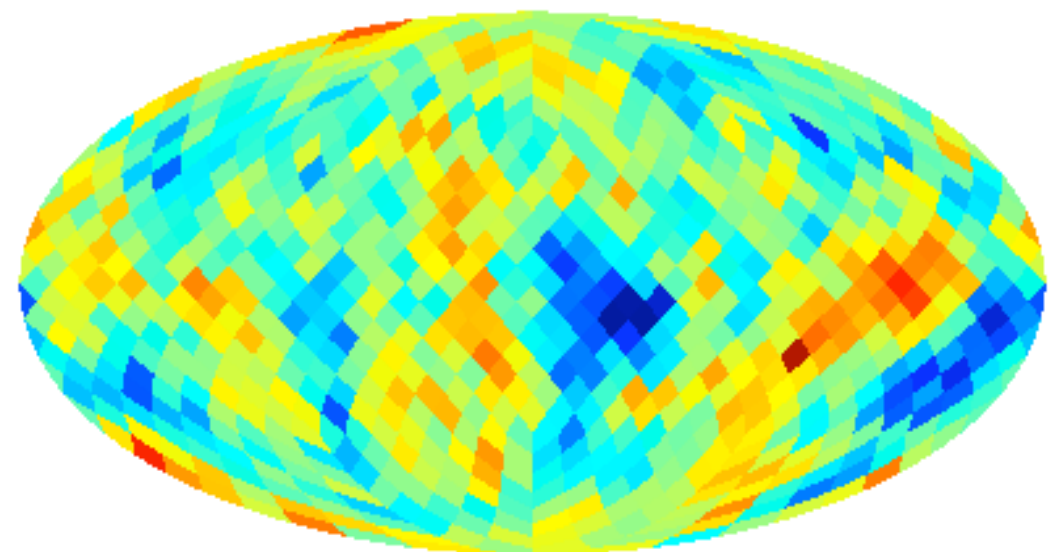
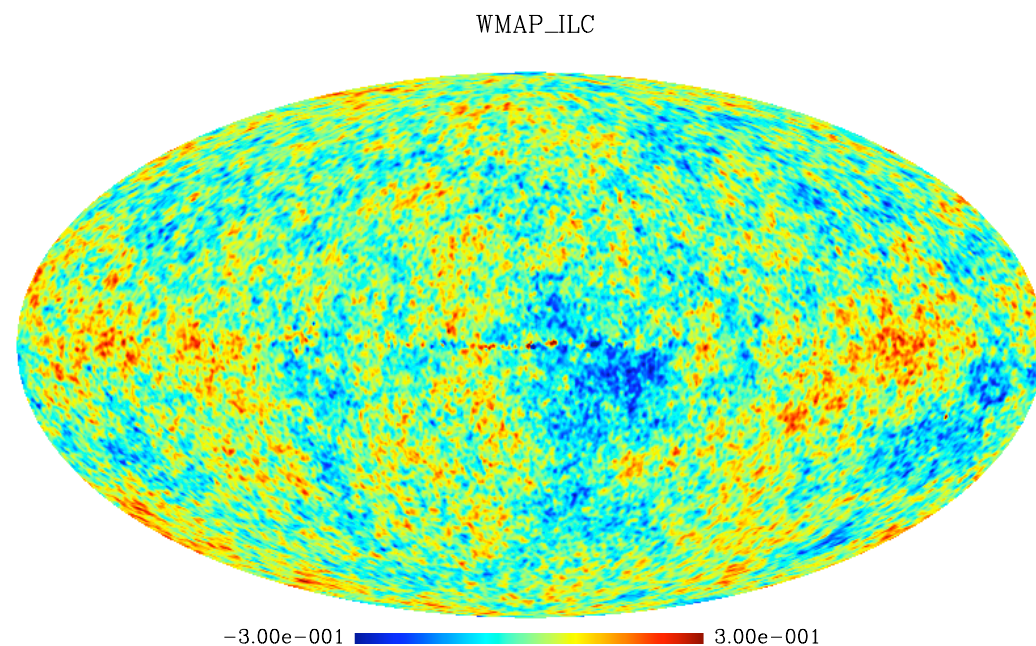
WMAP_ILC



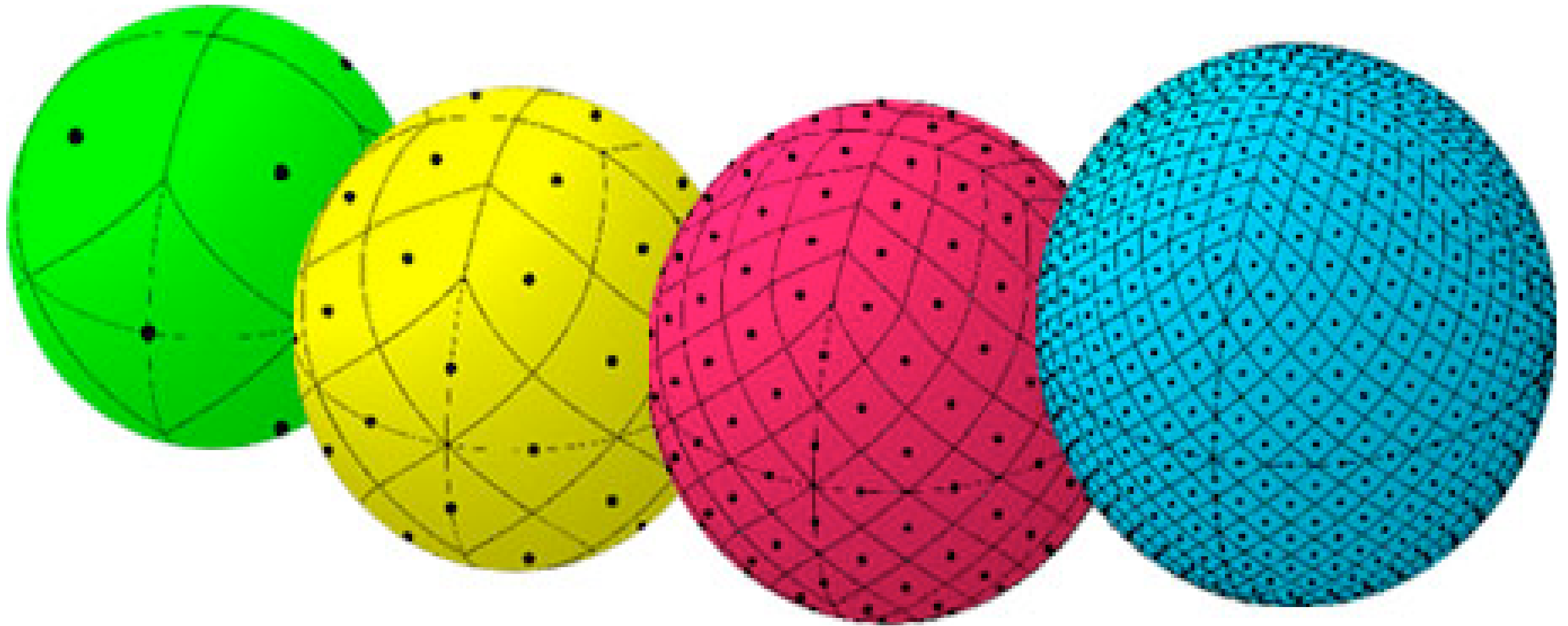
-3.00e-001 3.00e-001

Mapas da Radiação Cósmica de Fundo

- ▶ a esfera celeste é dividida em N pixels da mesma área
- ▶ as flut. de temp. da RCF ΔT representam-se usando uma escala linear de cores: azul (= mín.), verde ($\simeq 0$), e vermelho (=máx.). Representamos: $\frac{\Delta T(\theta, \phi)}{T_{Planck}} = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi)$.
- ▶ os pixels são tão pequenos que os mapas parecem um contínuo de manchas coloridas, mas ... basta degradar o mapa para observar eles:

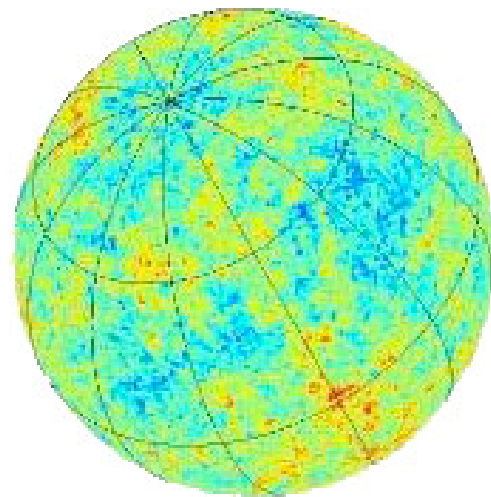


- ▶ a esfera celeste é dividida em N pixels, todos de igual área, seguindo o esquema de pixelização (HEALPIX)



Harmonic analyses in 2-d

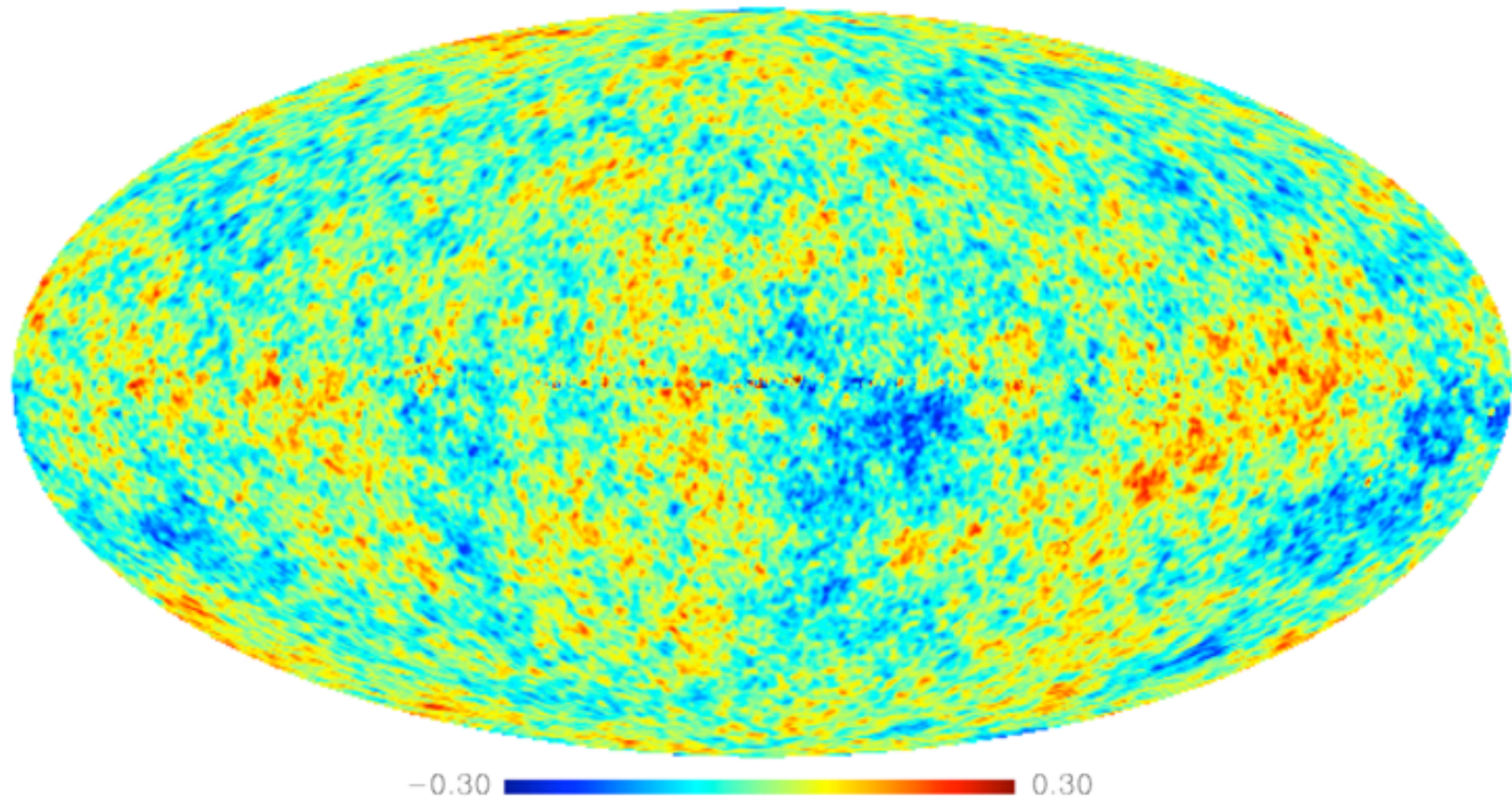
Analogously, on the spherical surface S^2 any function $\Delta T = \Delta T(\theta, \varphi)$ can be represented as a combination of the spherical harmonics $Y_{\ell m}$



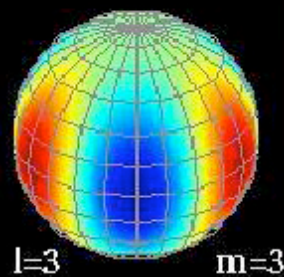
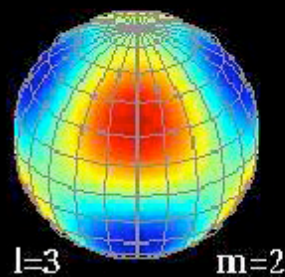
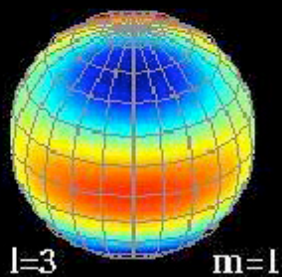
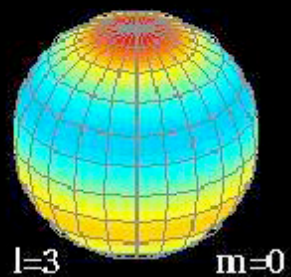
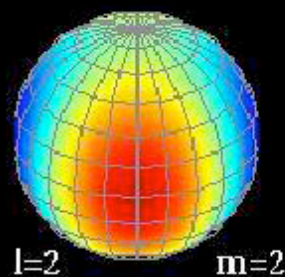
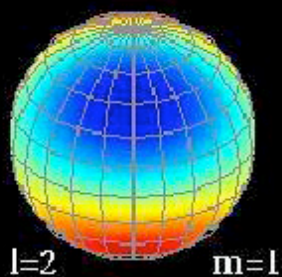
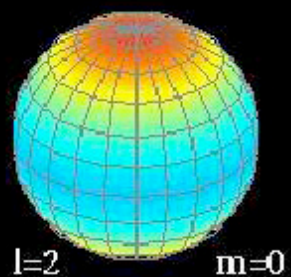
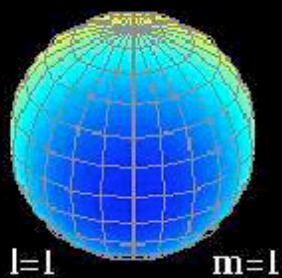
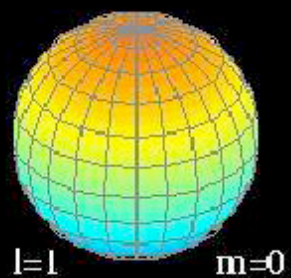
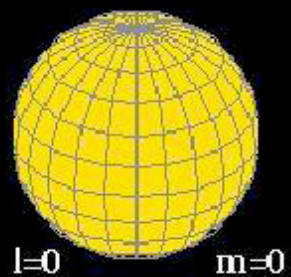
$$= \frac{\Delta T(\theta, \phi)}{T_o} = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

where the coefficients $a_{\ell m}$ have the complete information about the spectrum perturbation ΔT , where the variable ℓ (also called multipole order) is associated to the angular scale θ ($\sim \pi/\ell$) and the variable m is associated to the angular scale φ .

CMB temperature fluctuations:

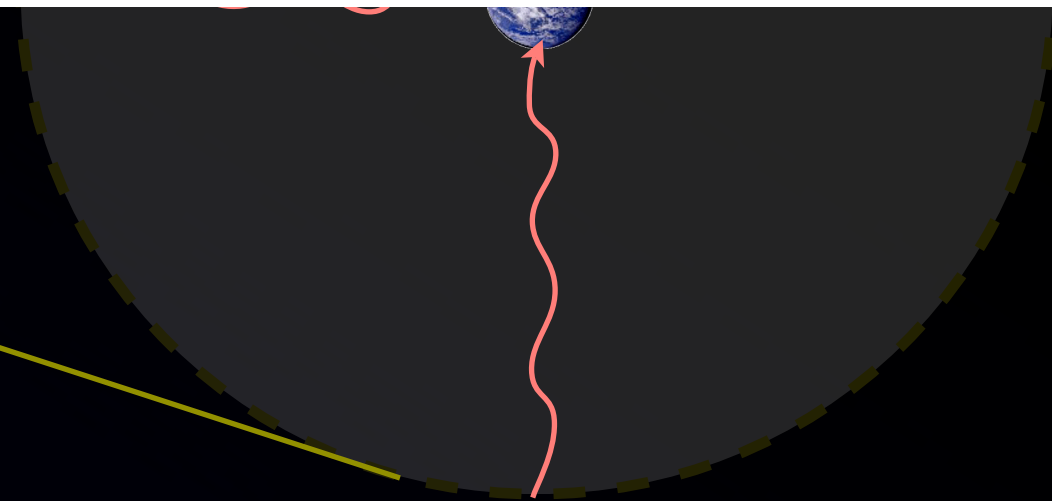


$$\frac{\Delta T}{T_0} = \frac{\Delta T}{T_0}(\theta, \phi) \quad \rightarrow \quad \frac{\Delta T}{T_0}(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

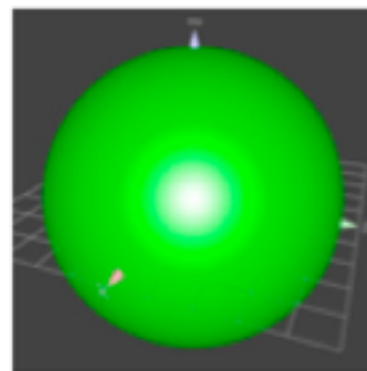


$$\delta T(\theta, \varphi) = \sum_{\ell, m} a_{\ell m} Y_{\ell}^m(\theta, \varphi)$$

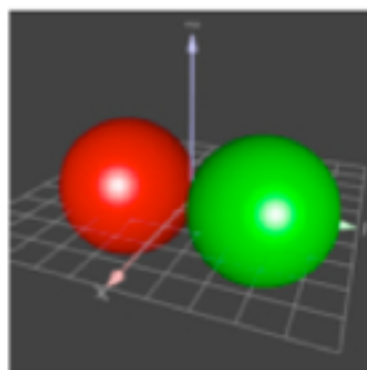
$$C_{\ell} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$



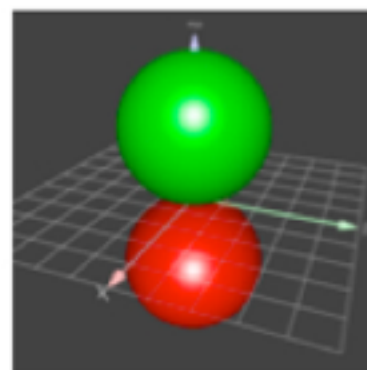
$Y_{\ell m}$



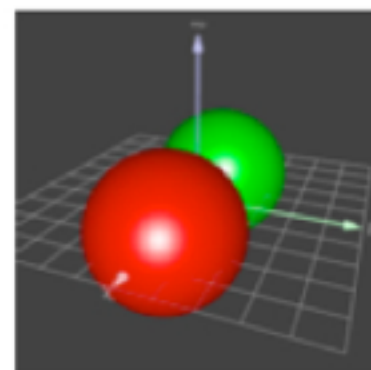
L0 M0



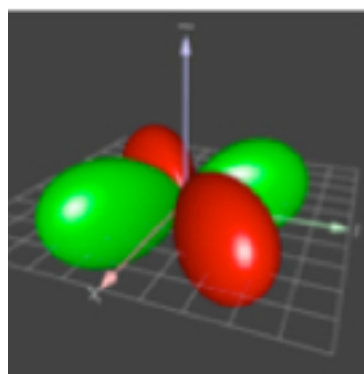
L1 M-1



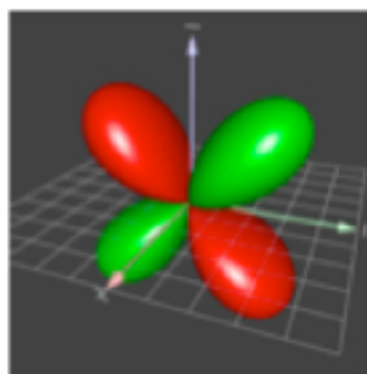
L1 M0



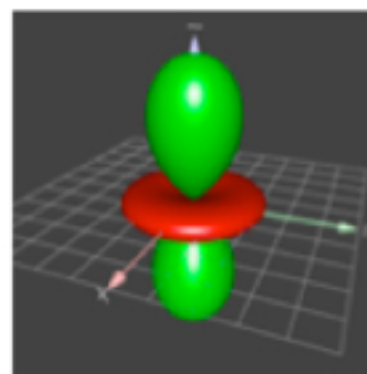
L1 M1



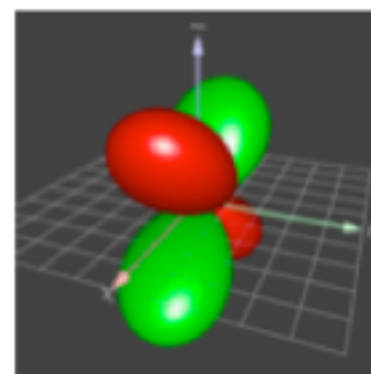
L2 M-2



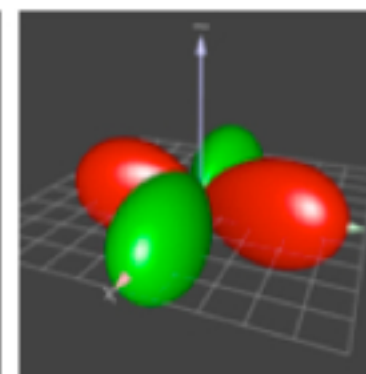
L2 M-1



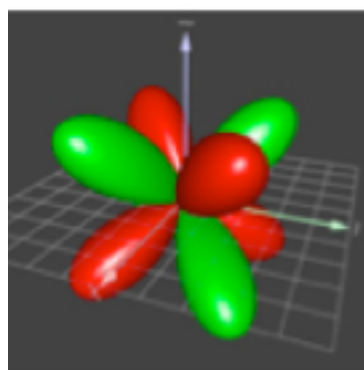
L2 M0



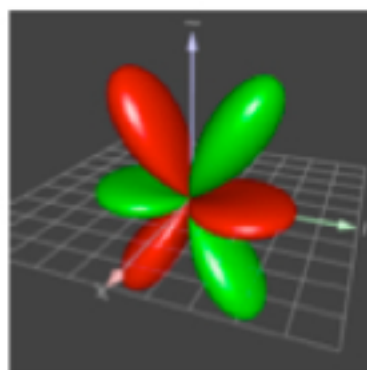
L2 M1



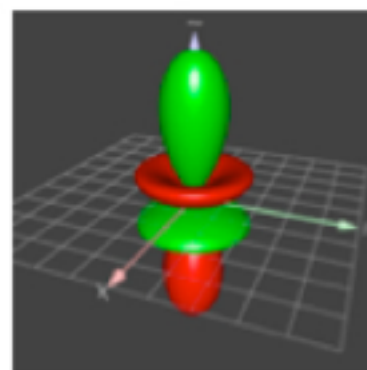
L2 M2



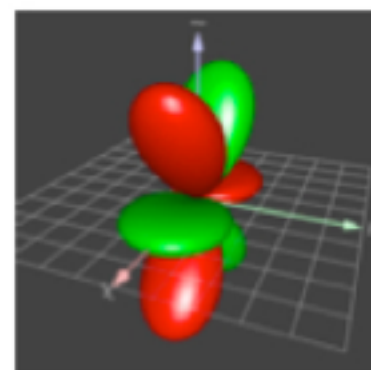
L3 M-2



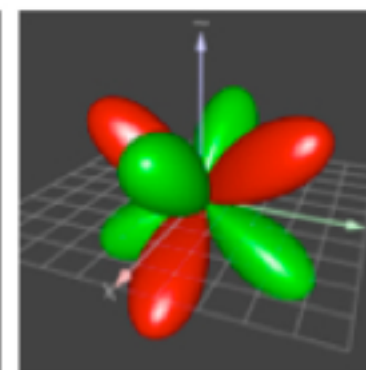
L3 M-1



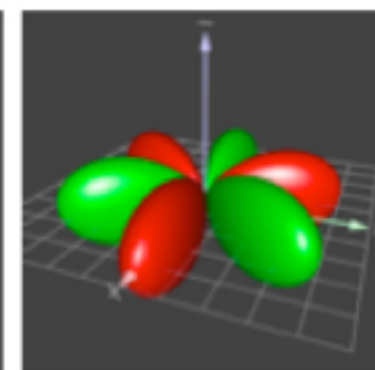
L3 M0



L3 M1



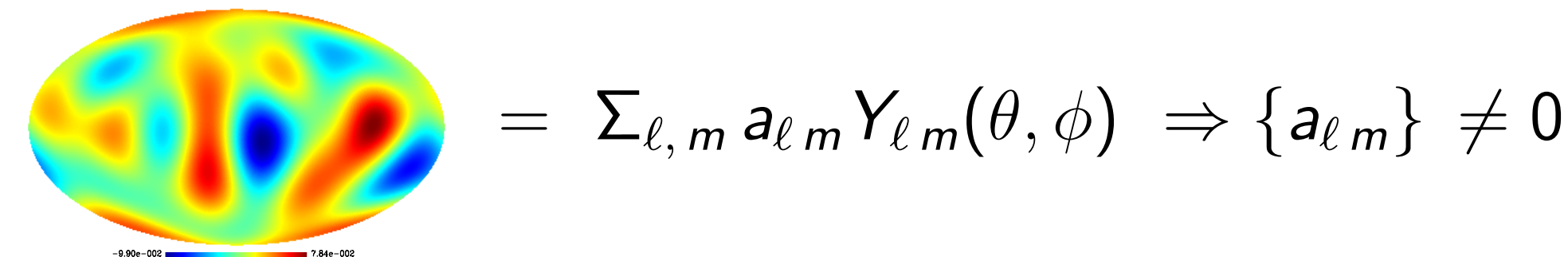
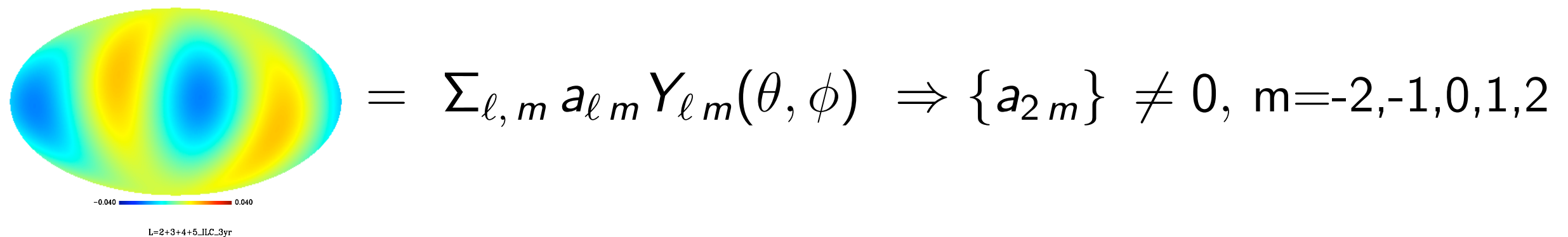
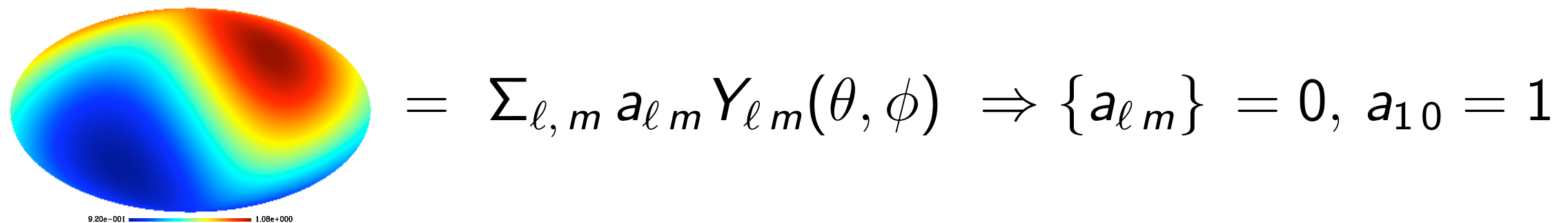
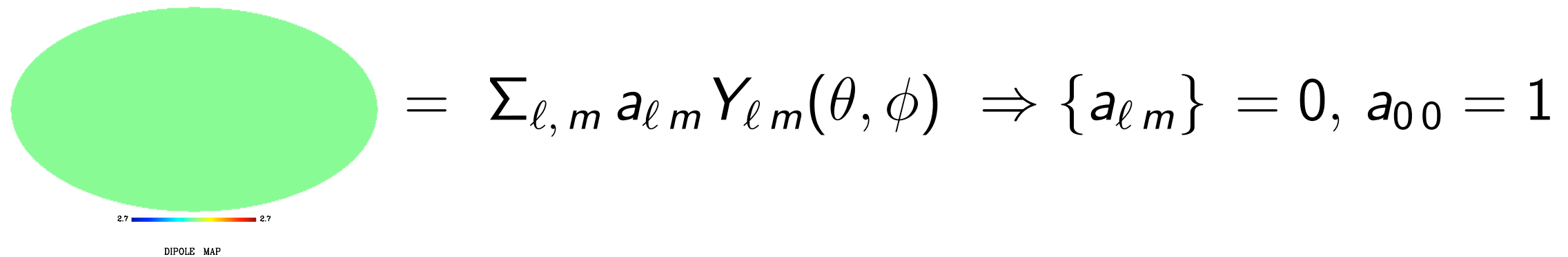
L3 M2



L3 M3

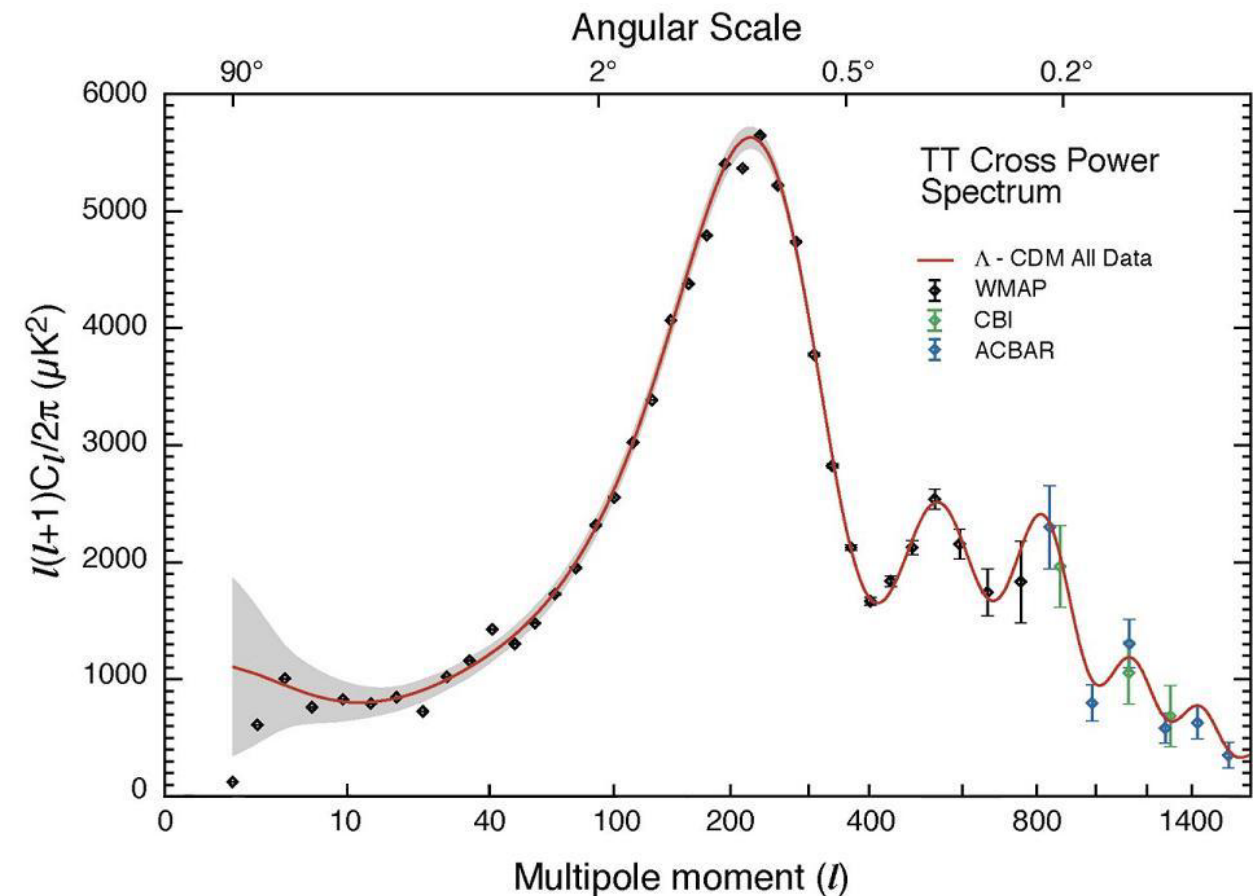
Harmonic analyses in 2-d

The coefficients $a_{\ell m}$ have the complete information:



espectro de potência angular

C_ℓ versus ℓ



$$\frac{\Delta T}{T_0}(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi) \quad \longrightarrow \quad C_\ell \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |a_{\ell m}|^2$$

assuming estatistical isotropy!

Em um universo estatisticamente isotrópico

$$\langle a_{\ell m} a_{\ell' m'}^* \rangle = C_{\ell} \delta_{mm'} \delta_{\ell\ell'} \longrightarrow C_{\ell} \equiv \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$

Em um universo estatisticamente anisotrópico

$$\langle a_{\ell m} a_{\ell' m'}^* \rangle = C_{\ell m}^{\ell' m'} \not\rightarrow C_{\ell} \equiv \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$

Como analisar dados sem assumir IE?

espectro de potência angular

C_ℓ versus ℓ

$$\frac{\Delta T}{T_0}(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi) \quad C_\ell \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |a_{\ell m}|^2$$

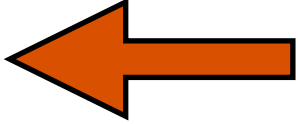
função de correlação angular de dois pontos: 2PACF

$C(\gamma)$ versus γ

$$C(\gamma) \equiv \left\langle \frac{\Delta T}{T_0}(\varphi) \frac{\Delta T}{T_0}(\varphi + \gamma) \right\rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_\ell P_\ell(\cos \gamma)$$

The cosmological model of the Universe

stands on:

- ▶ Metric theory, e.g., General Relativity
- ▶ Cosmological principle  can be test!
- ▶ Observational probes

Properties expected for the cosmic background radiation (CMB):

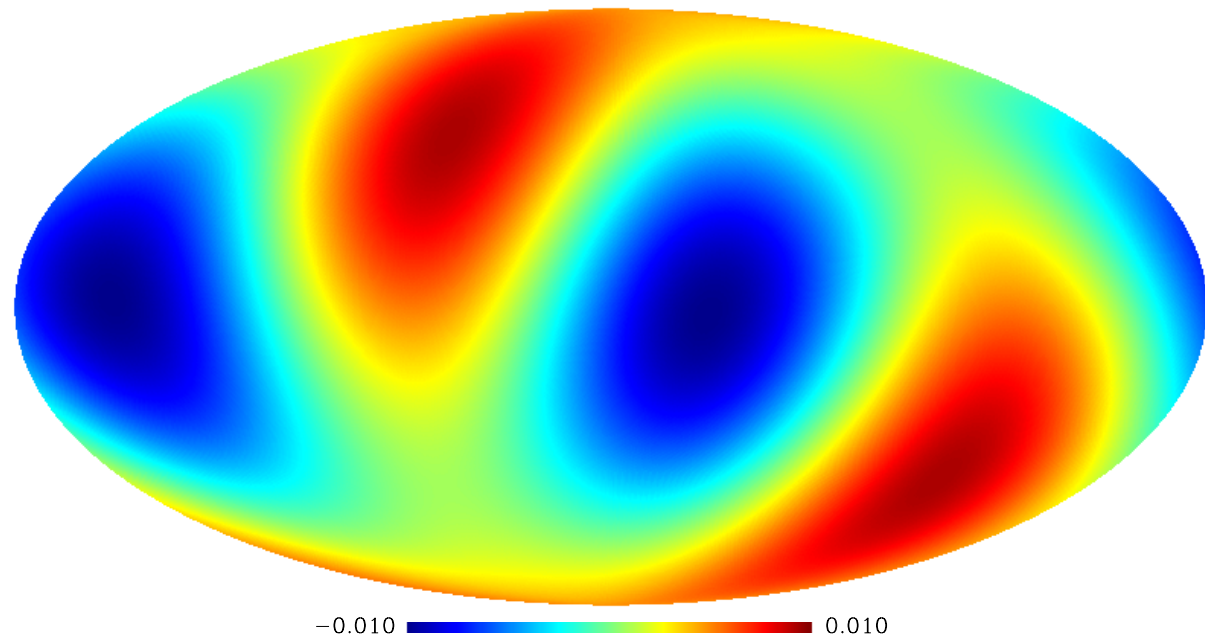
- CMB is statistically isotropic
- CMB is statistically Gaussian

CMB hemispherical asymmetry:

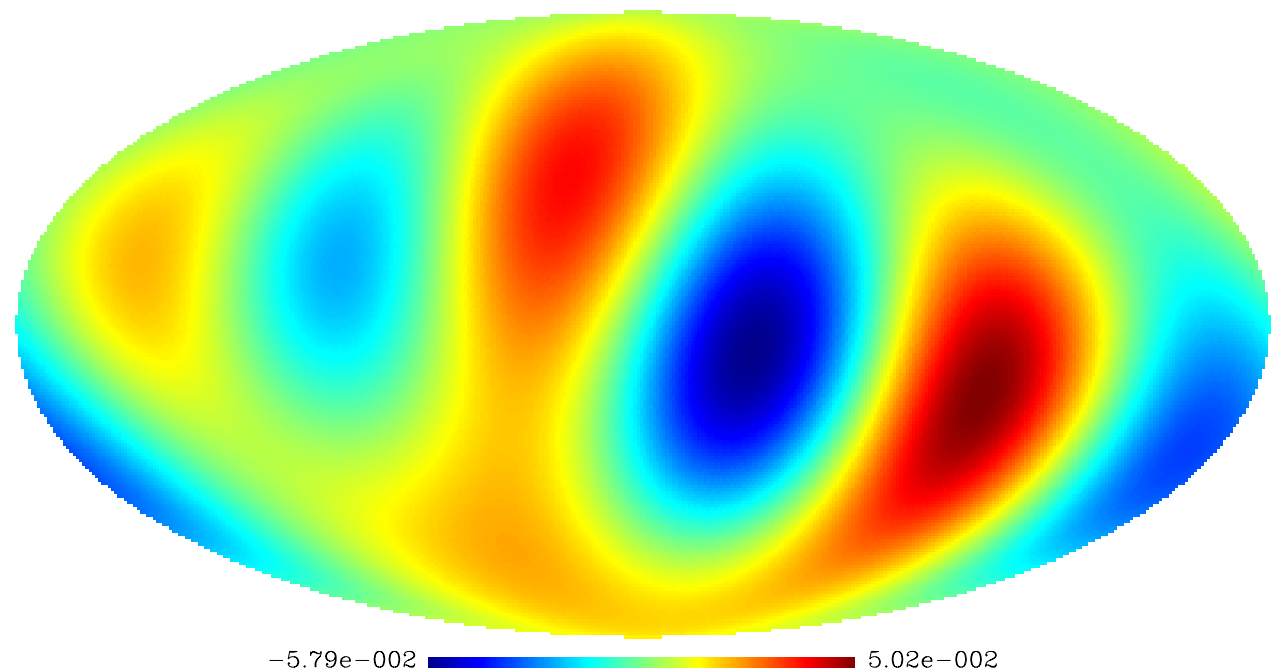
intuitively... step by step

Summing up the multipoles (large-scales)

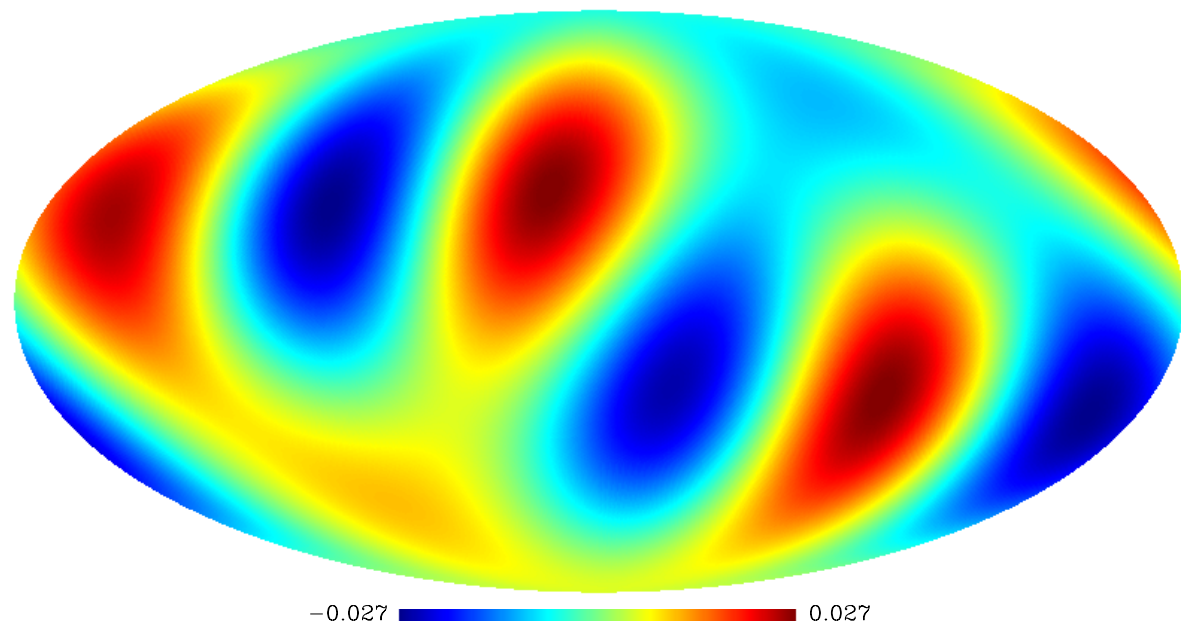
$$\ell = 2$$



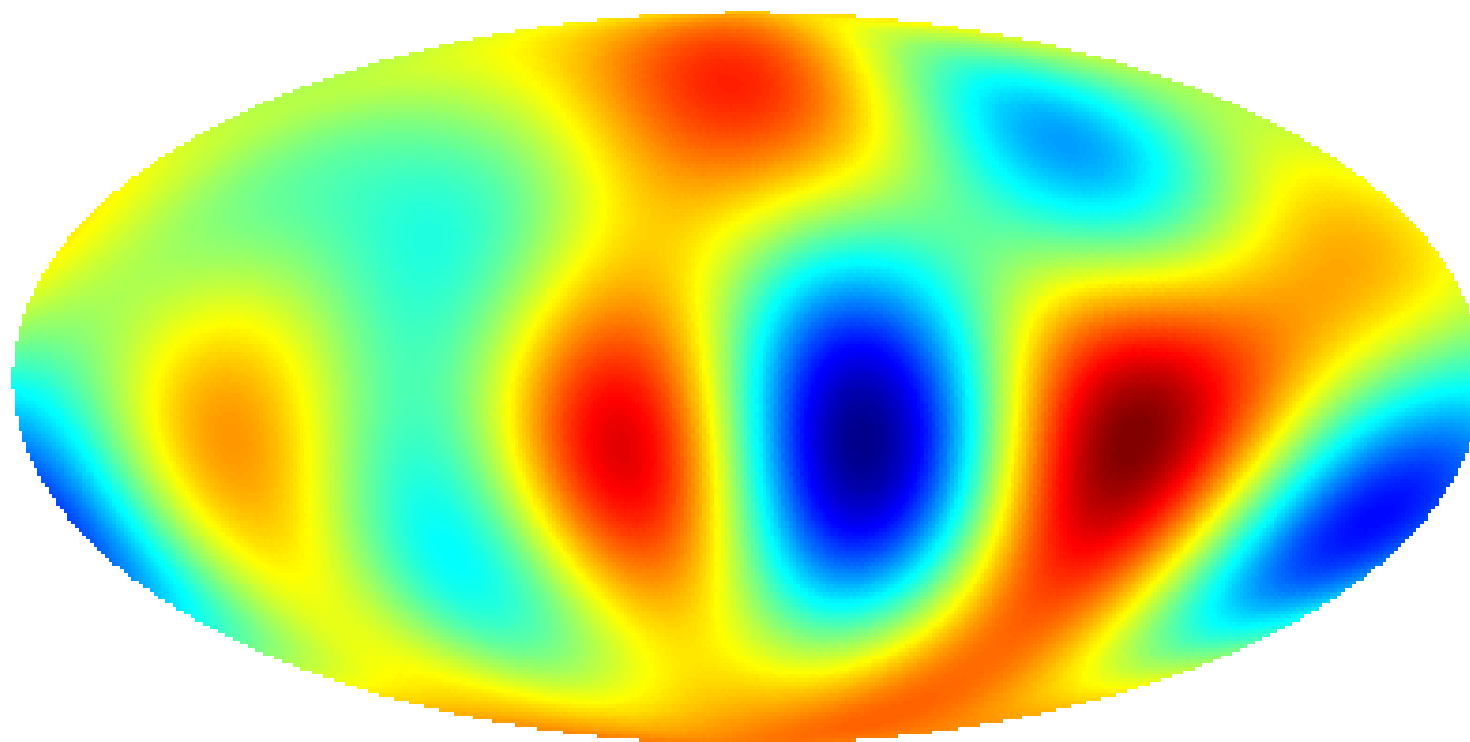
$$\ell = 2 + 3$$



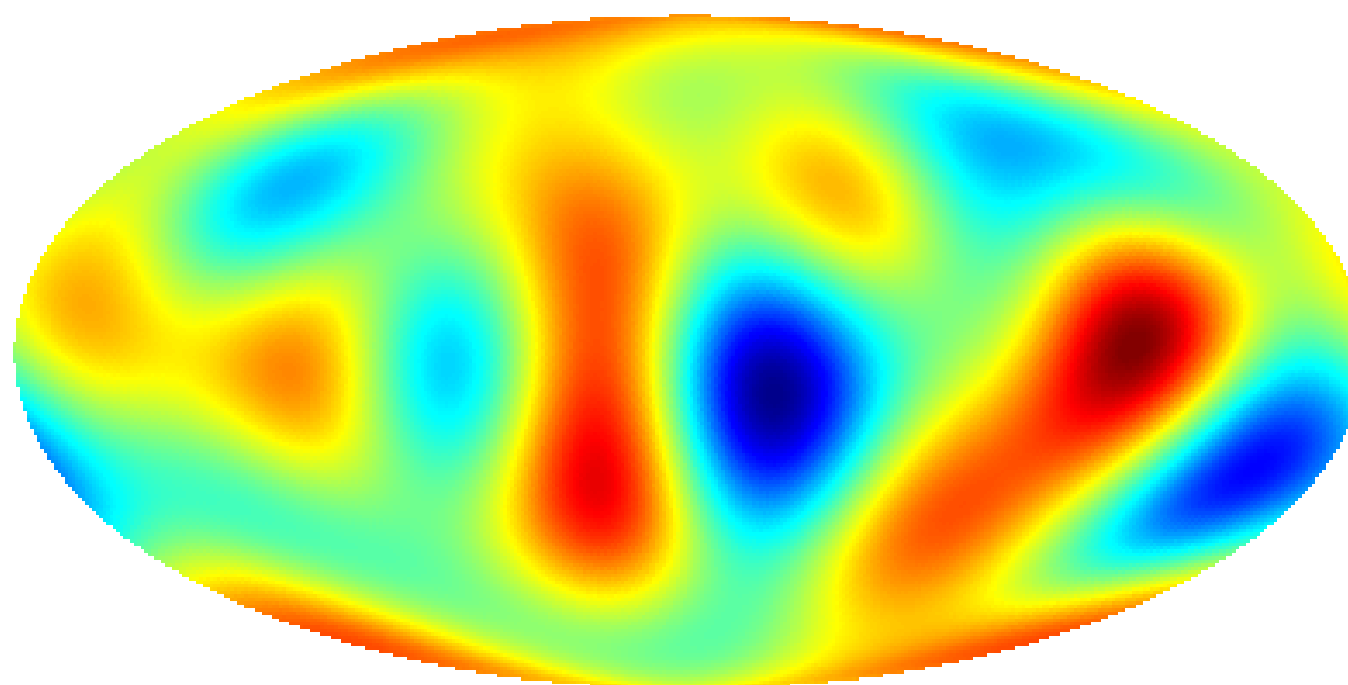
$$\ell = 3$$



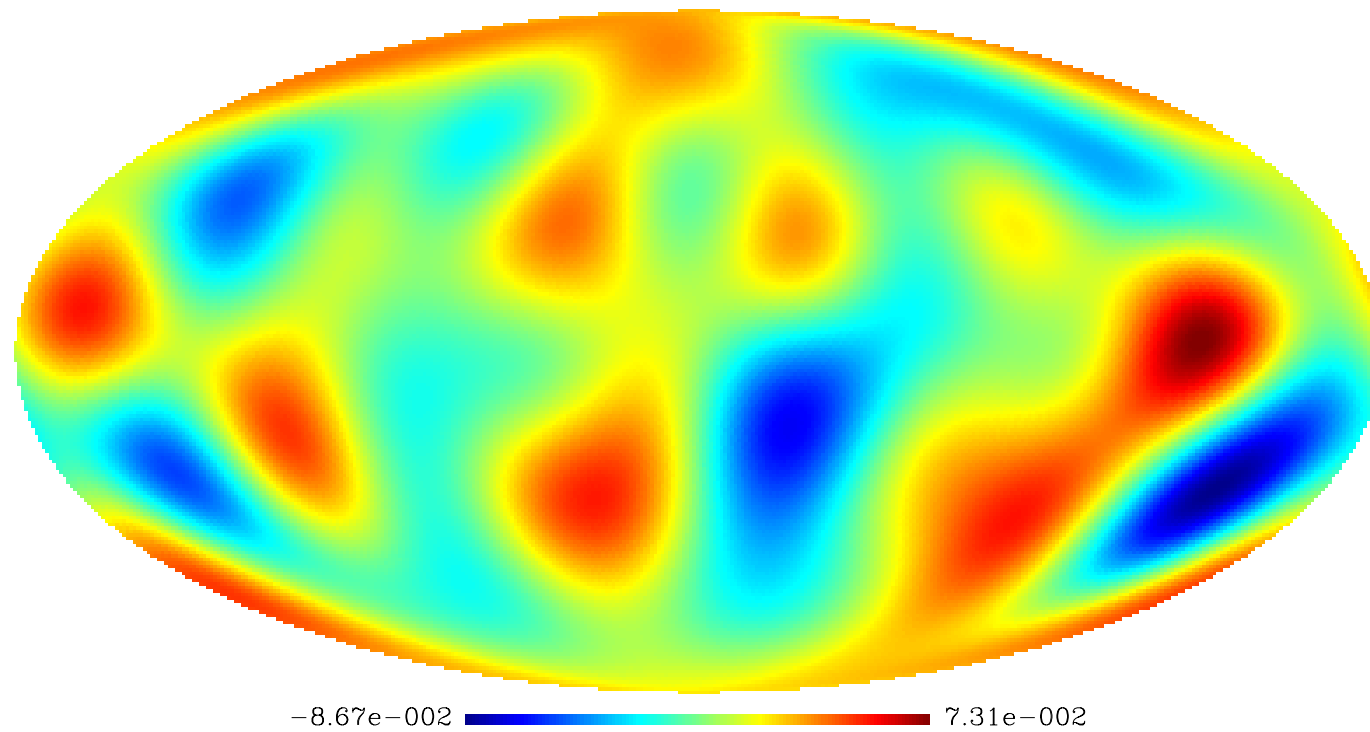
and ... $\ell = 2 + 3 + 4$?



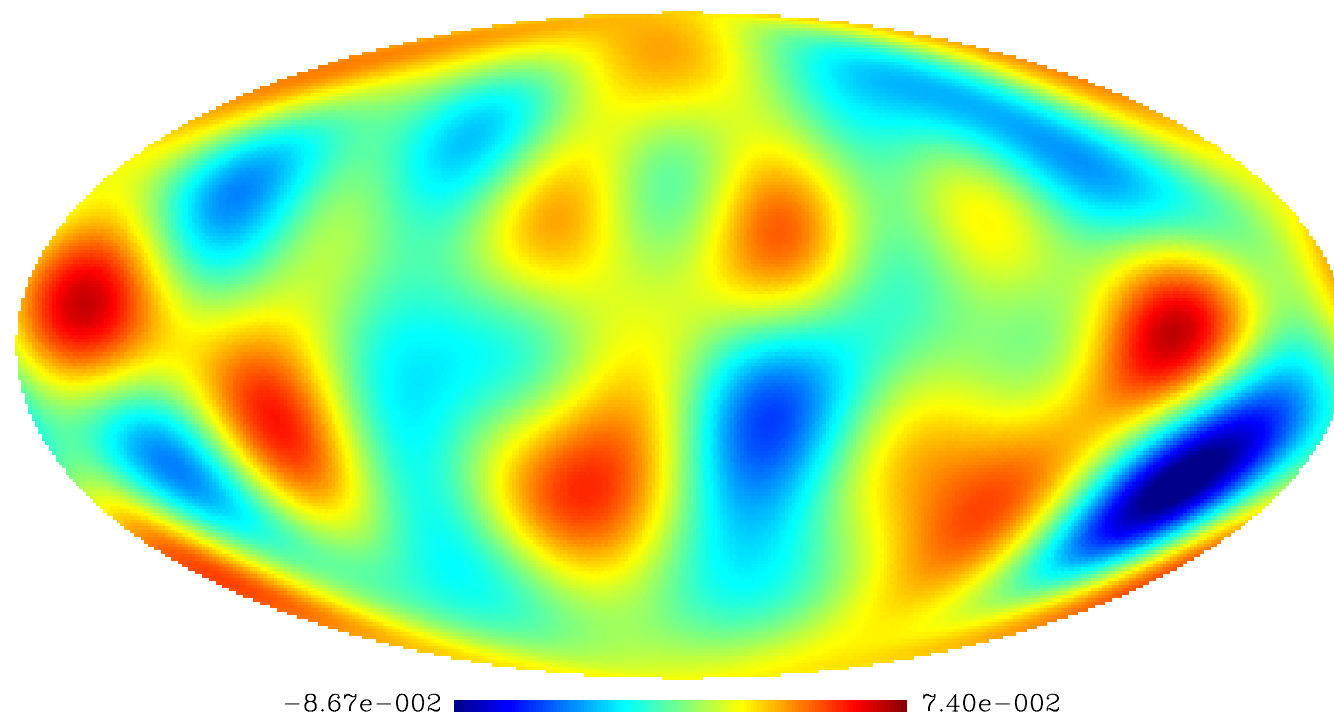
$\ell = 2 + 3 + 4 + 5$



$$\ell = 2 + 3 + 4 + 5 + 6 + 7$$



$$\ell = 3 + 4 + 5 + 6 + 7$$



CMB hemispherical asymmetry:

funcion de correlacion angular
de 2-puntos (2PACF)

Função de correlação angular de dois pontos

Seja um mapa de flut. de temperaturas $\Delta T_i = \Delta T(\theta_i, \phi_i)$ com N pixels: $\Delta T_1, \Delta T_2, \dots, \Delta T_N$. A pixelização da esfera determina que as distâncias angulares são discretas: entre o centro do pixel i com coordenadas (θ_i, ϕ_i) e o centro do pixel j com coordenadas (θ_j, ϕ_j) . A **função de correlação angular de dois pontos** (**2PACF**, em inglês) é

$$C(\gamma_{ij}) \equiv \langle \Delta T(\theta_i, \phi_i) \Delta T(\theta_j, \phi_j) \rangle,$$

$$\gamma_{ij} \equiv \cos^{-1}[\cos(\theta_i) \cos(\theta_j) + \sin(\theta_i) \sin(\theta_j) \cos(\phi_i - \phi_j)],$$

a média $\langle \rangle$ é obtida usando todos os valores t.q. $\gamma_{ij} \in [(k-1)\delta, k\delta]$, $\forall k = 1, \dots, N_{\text{bins}}$; tal média dá o valor de C no k -ésimo bin:



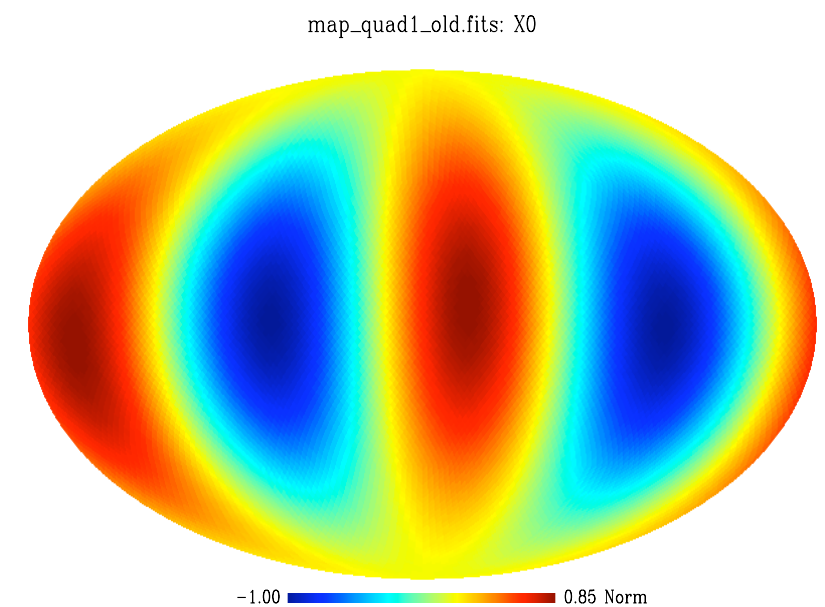
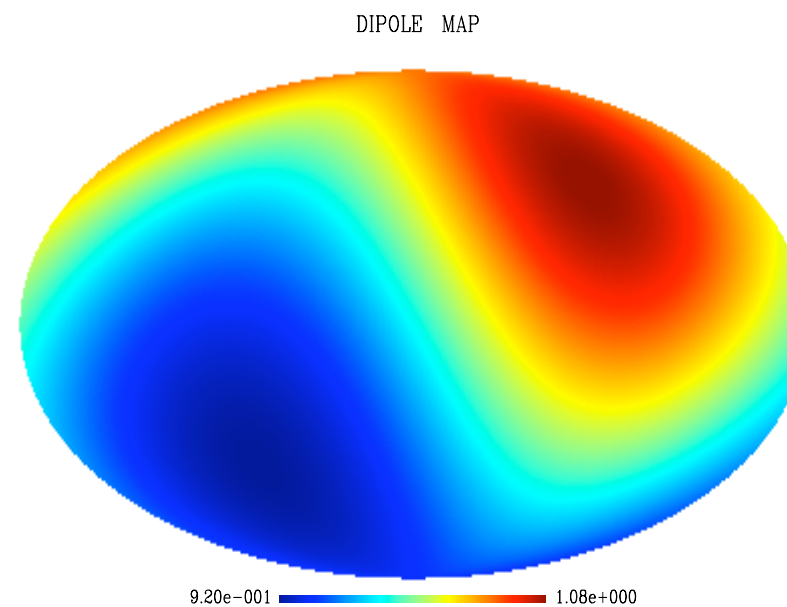
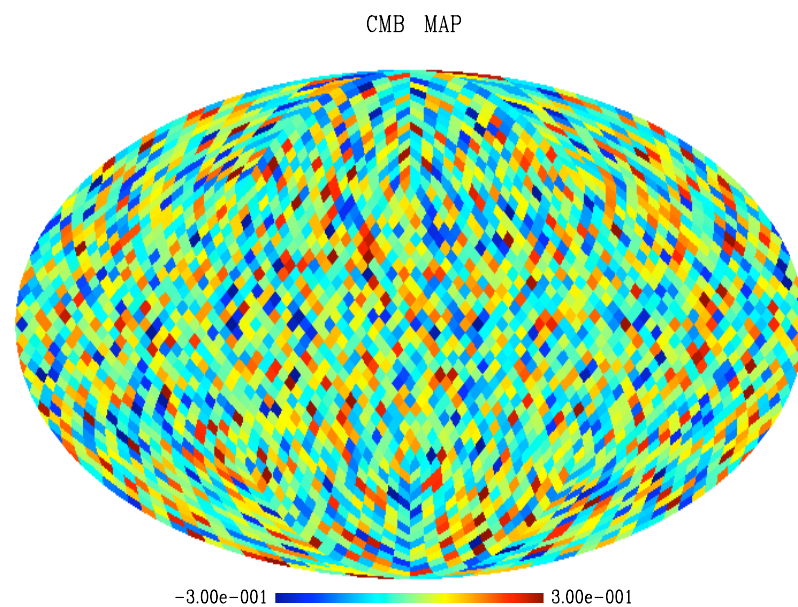
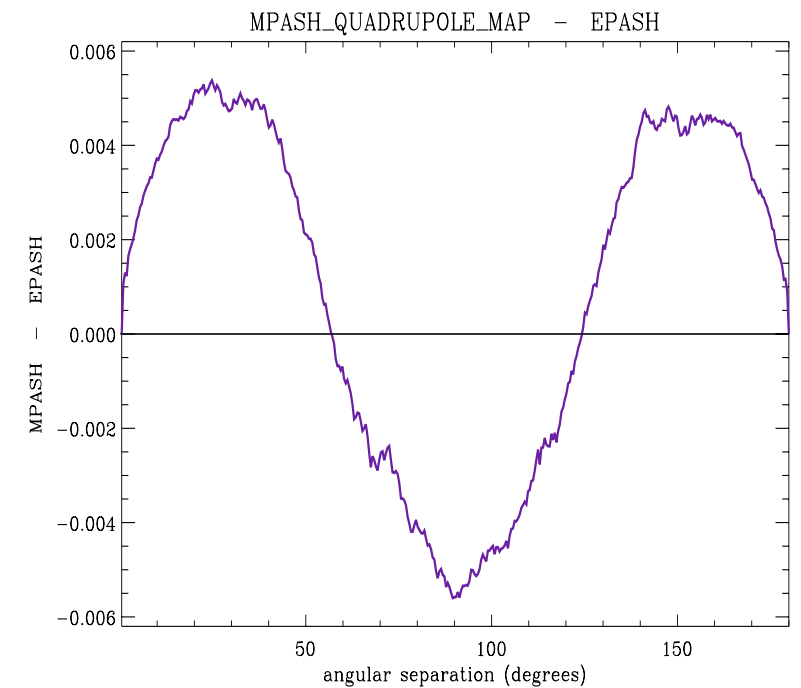
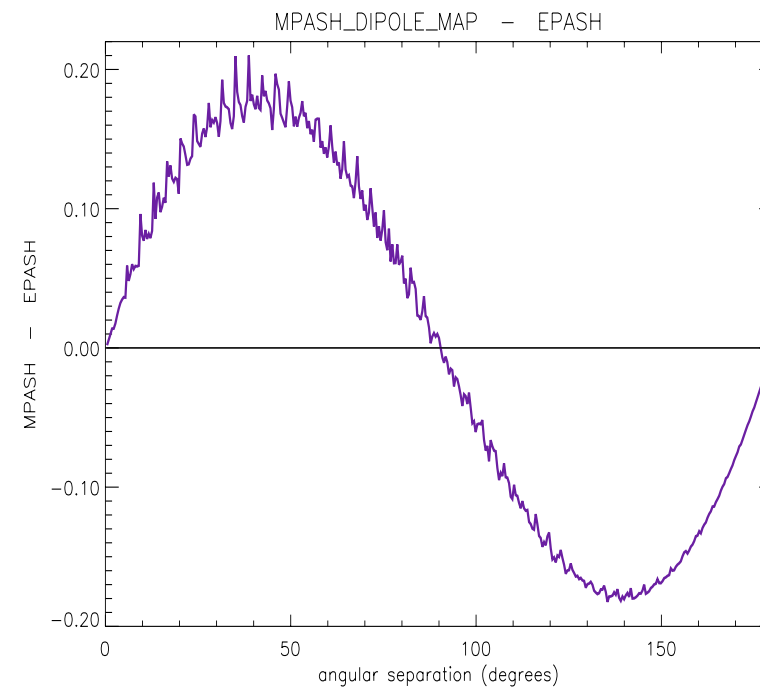
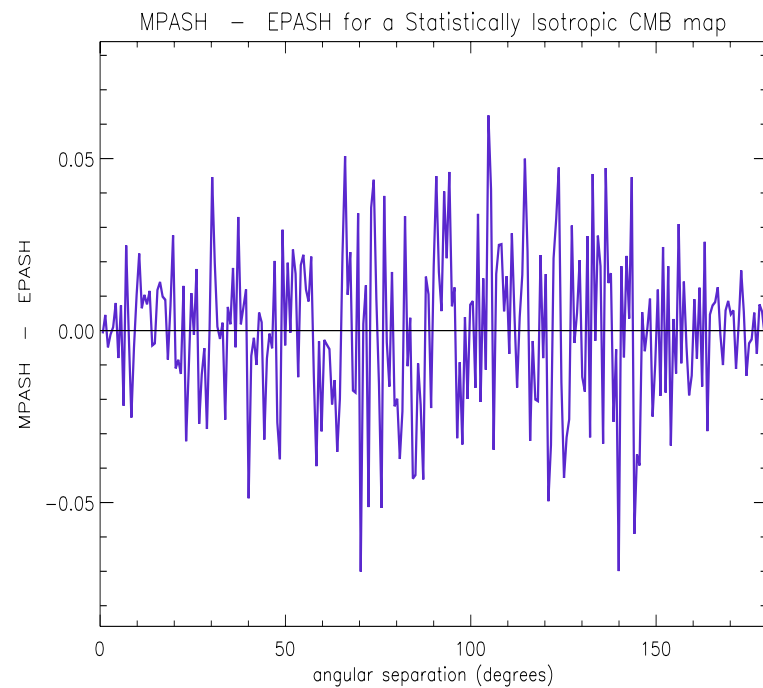
δ é o tamanho do bin

Revelando assinaturas nas curvas **2PACF**

assinatura-zero,

assinatura-dipolar,

assinatura-quadrupolar,..

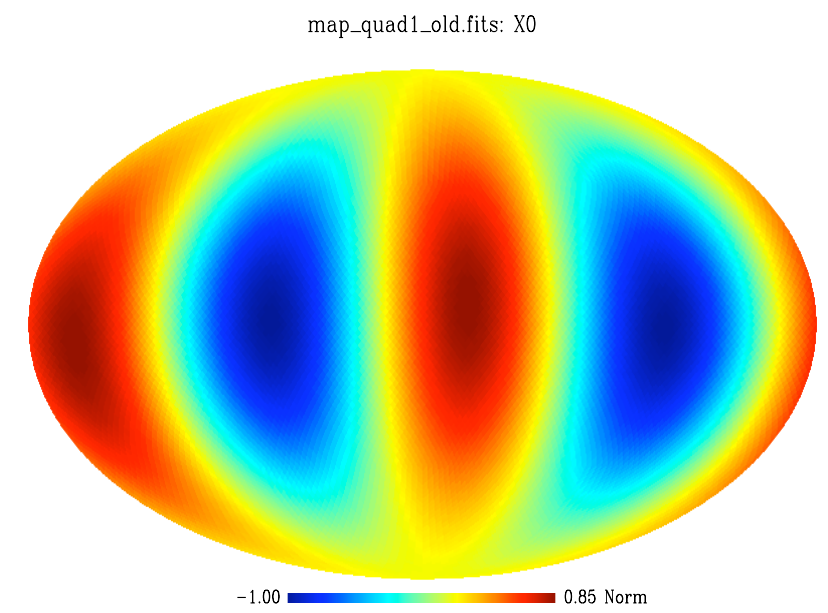
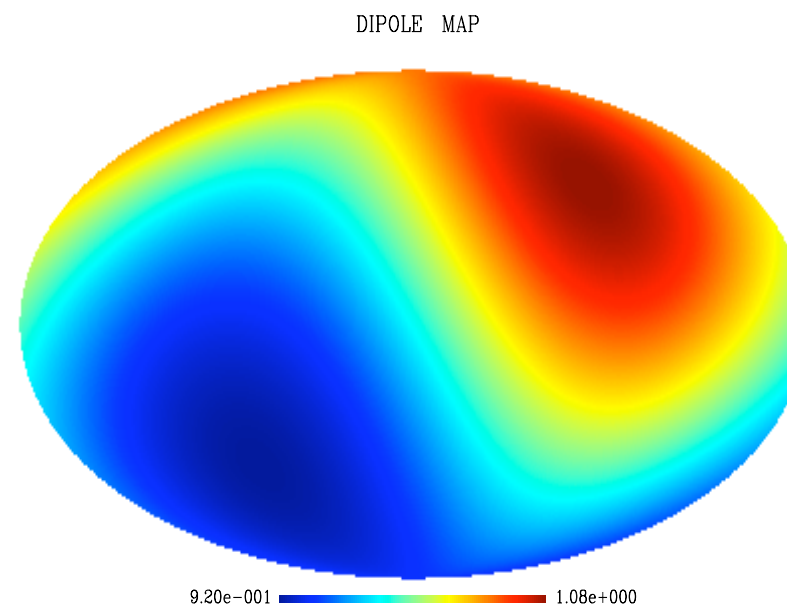
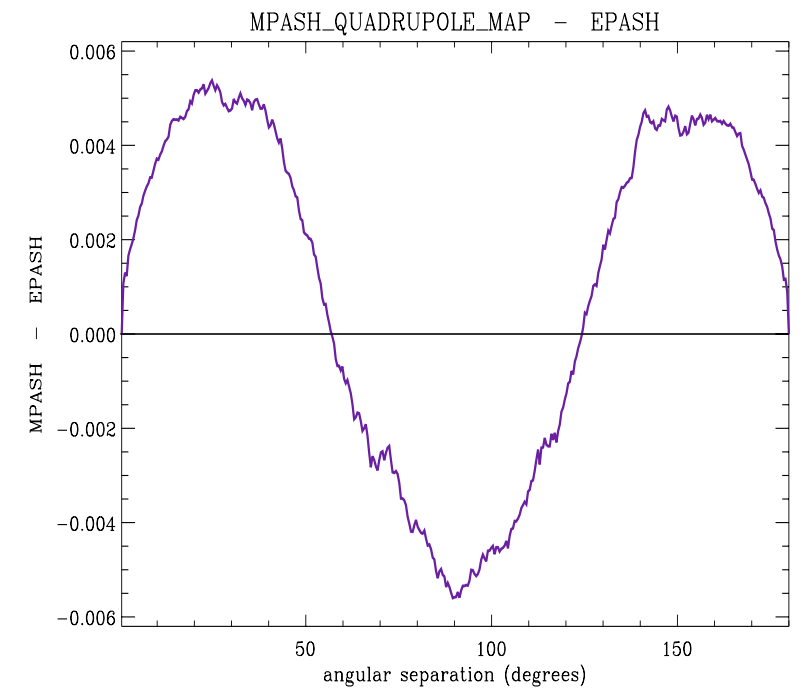
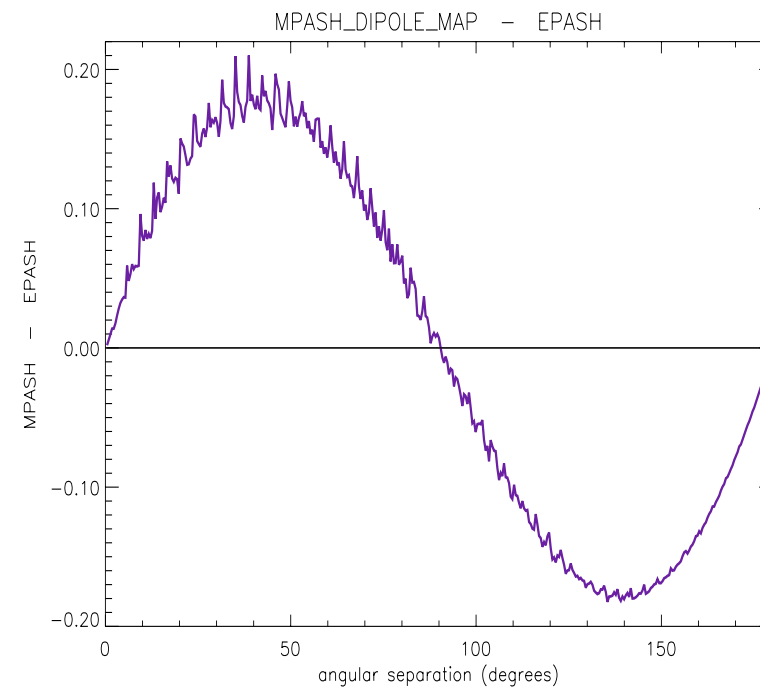
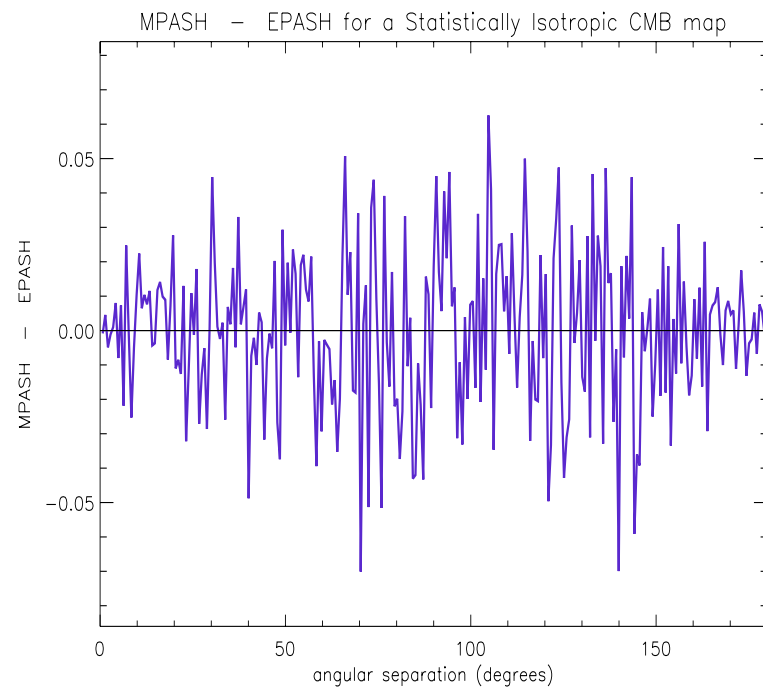


Revelando assinaturas nas curvas **2PACF**

assinatura-zero,

assinatura-dipolar,

assinatura-quadrupolar,..



espectro de potencia angular

C_ℓ versus ℓ

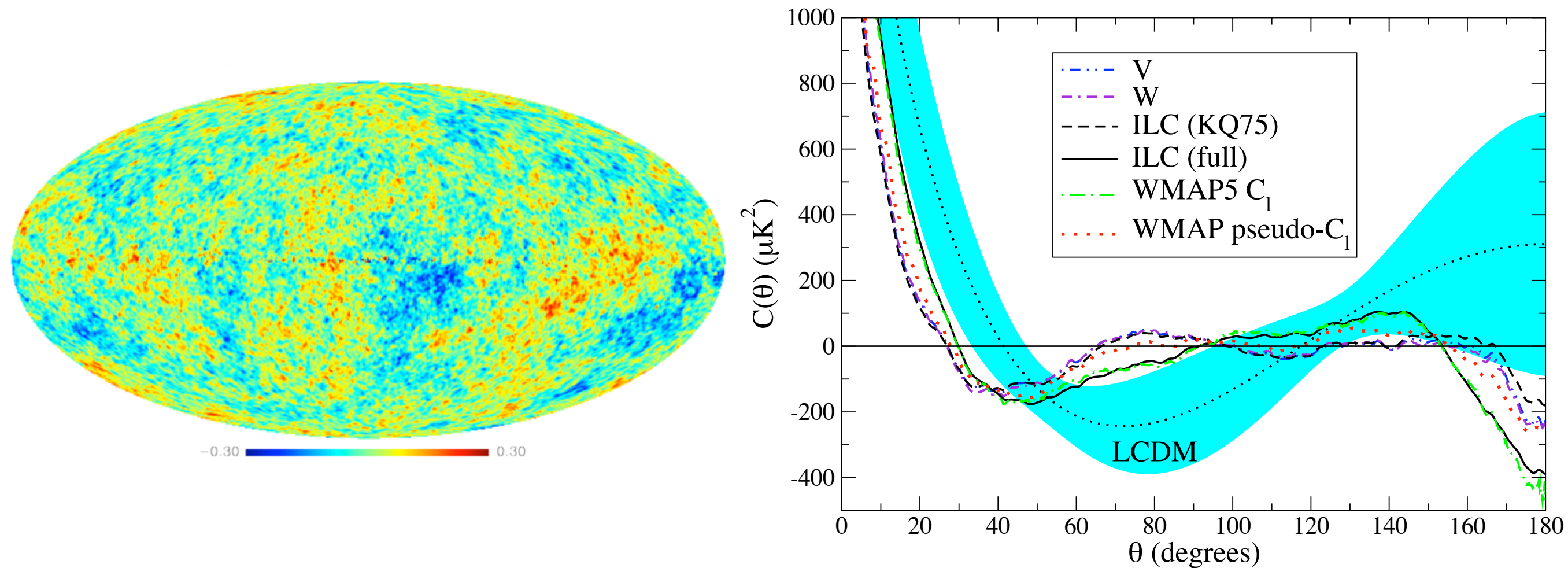
$$\frac{\Delta T}{T_0}(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi) \qquad C_\ell \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |a_{\ell m}|^2$$

funcion de correlacion angular de dos puntos: 2PACF

$C(\gamma)$ versus γ

$$C(\gamma) \equiv \left\langle \frac{\Delta T}{T_0}(\varphi) \frac{\Delta T}{T_0}(\varphi + \gamma) \right\rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_\ell P_\ell(\cos \gamma)$$

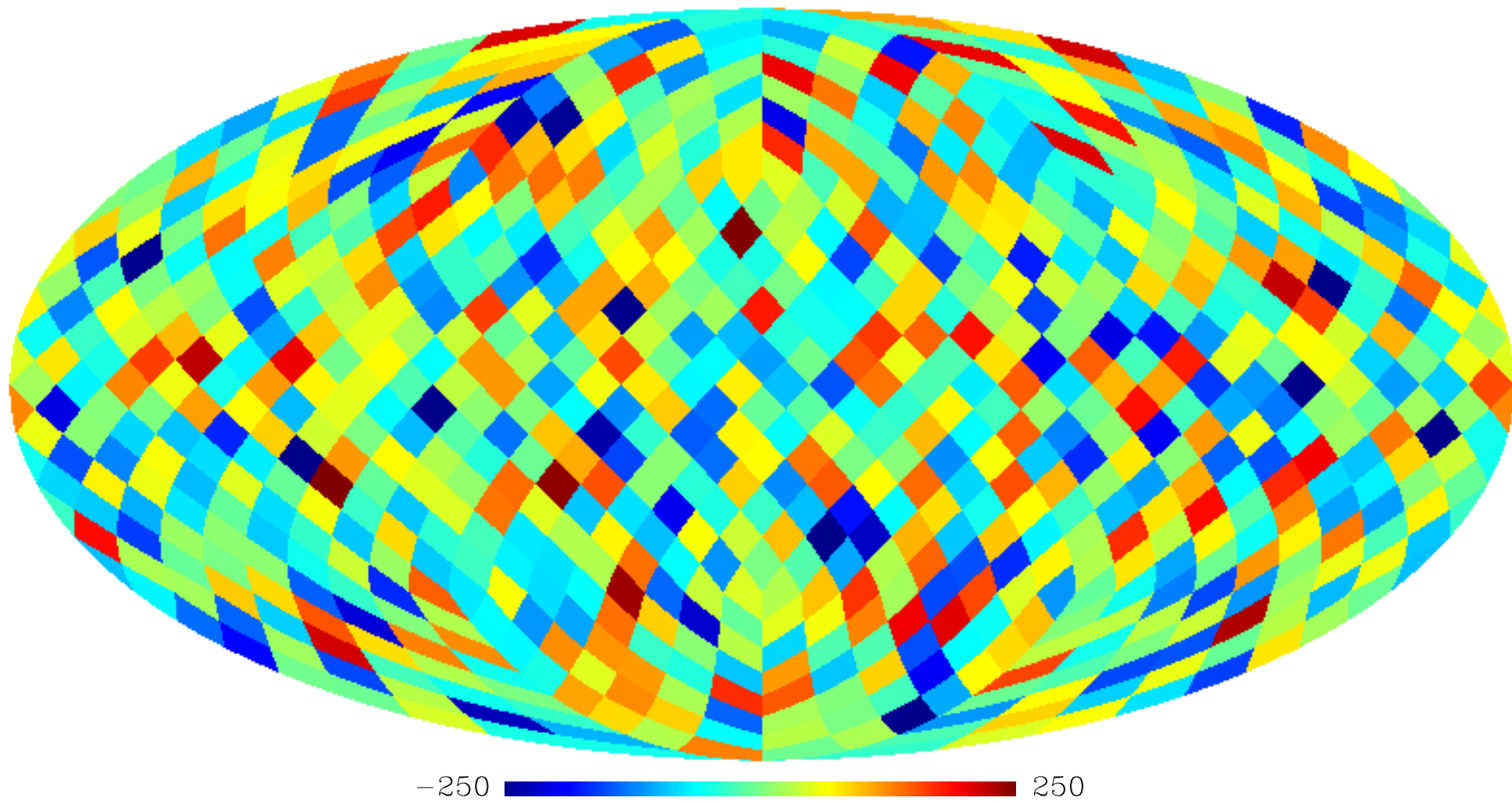
2-Point Angular Correlation Function



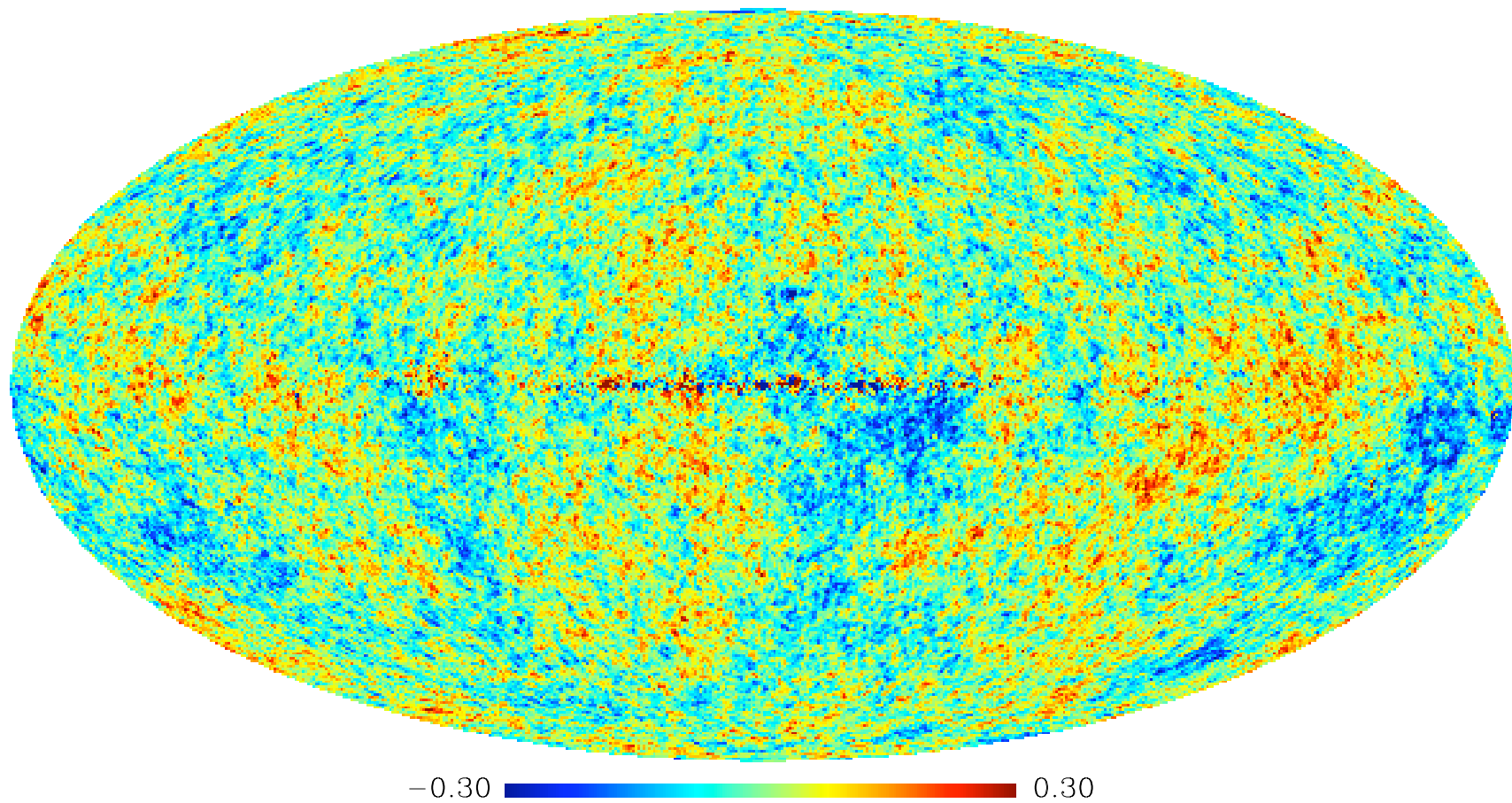
$$C(\gamma) \equiv \left\langle \frac{\Delta T}{T_0}(\varphi) \frac{\Delta T}{T_0}(\varphi + \gamma) \right\rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_{\ell} P_{\ell}(\cos \gamma)$$

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

A Statistically Isotropic Gaussian CMB

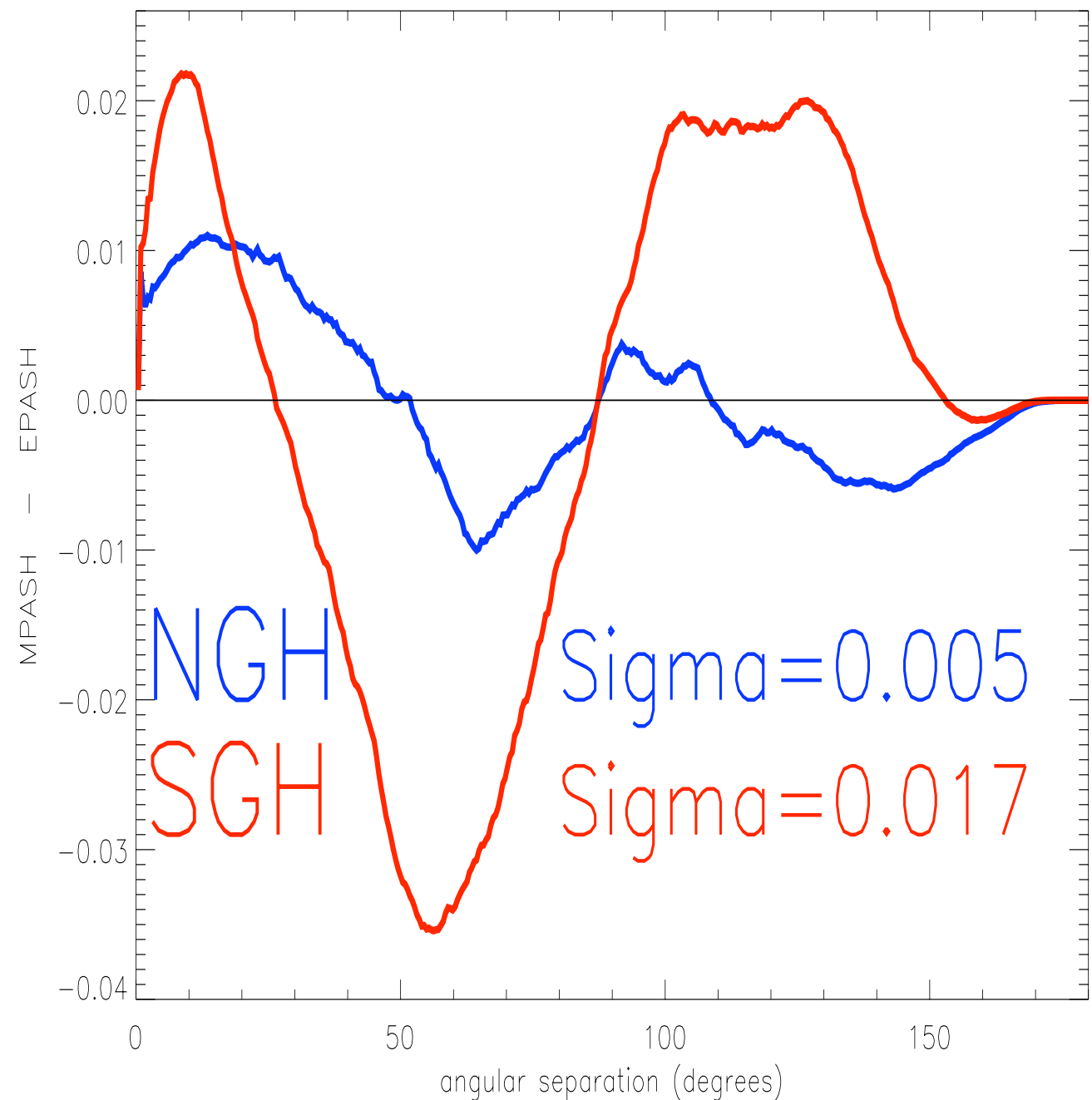
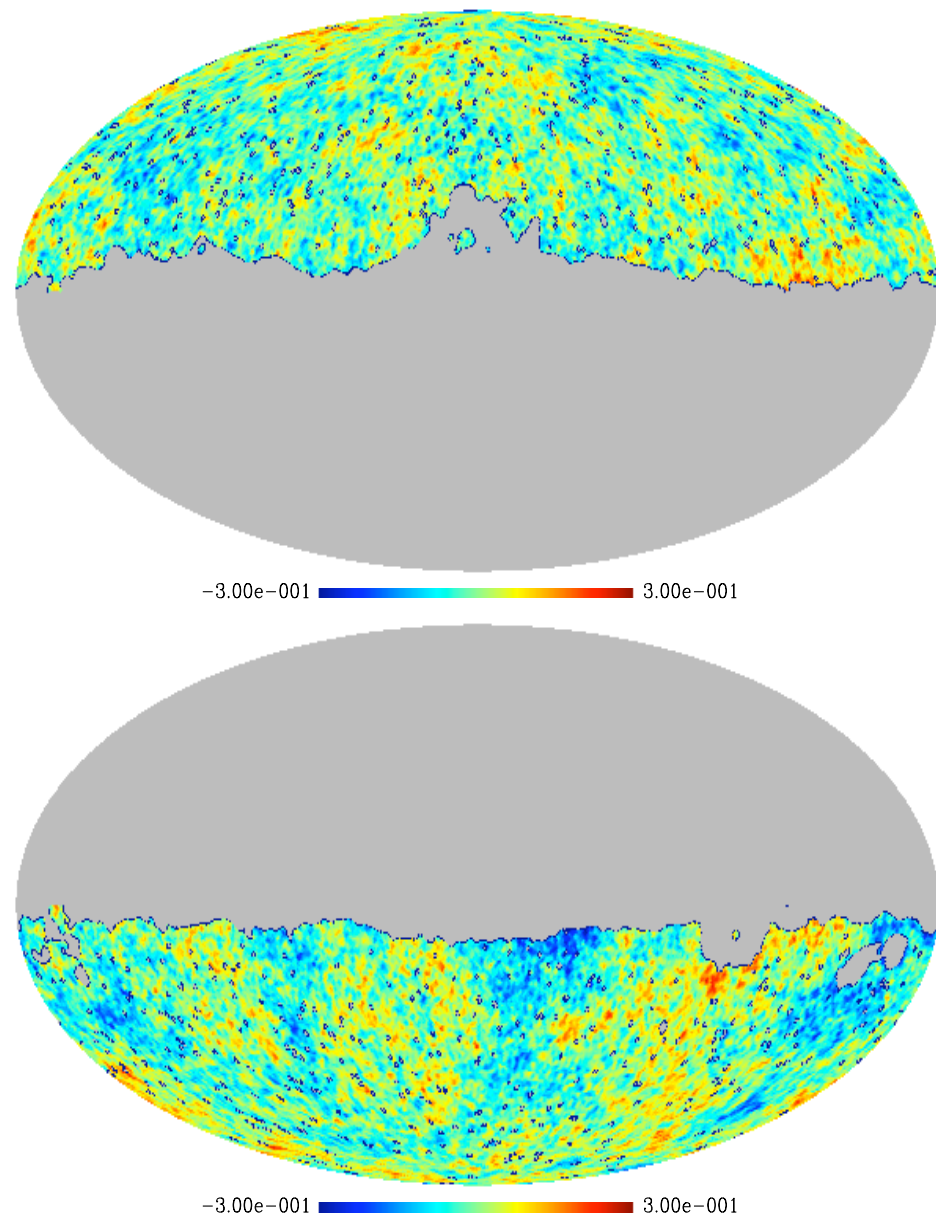


Is the CMB statistically isotropic?



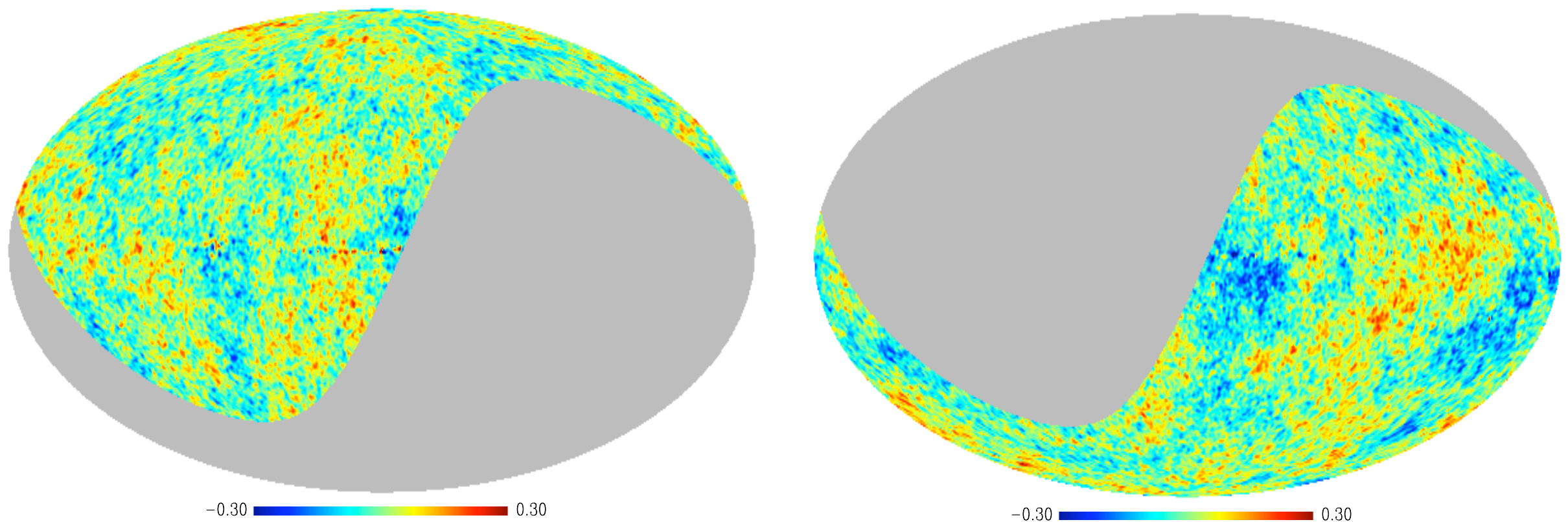
Anomalias na RCF: assimetria Norte-Sul

Primeiro detectada, por Eriksen et al. (2003), nos hemis. Galác. *



* AB, T. Villela, C.A. Wuensche, R. Leonardi, I. Ferreira, A&A 2006

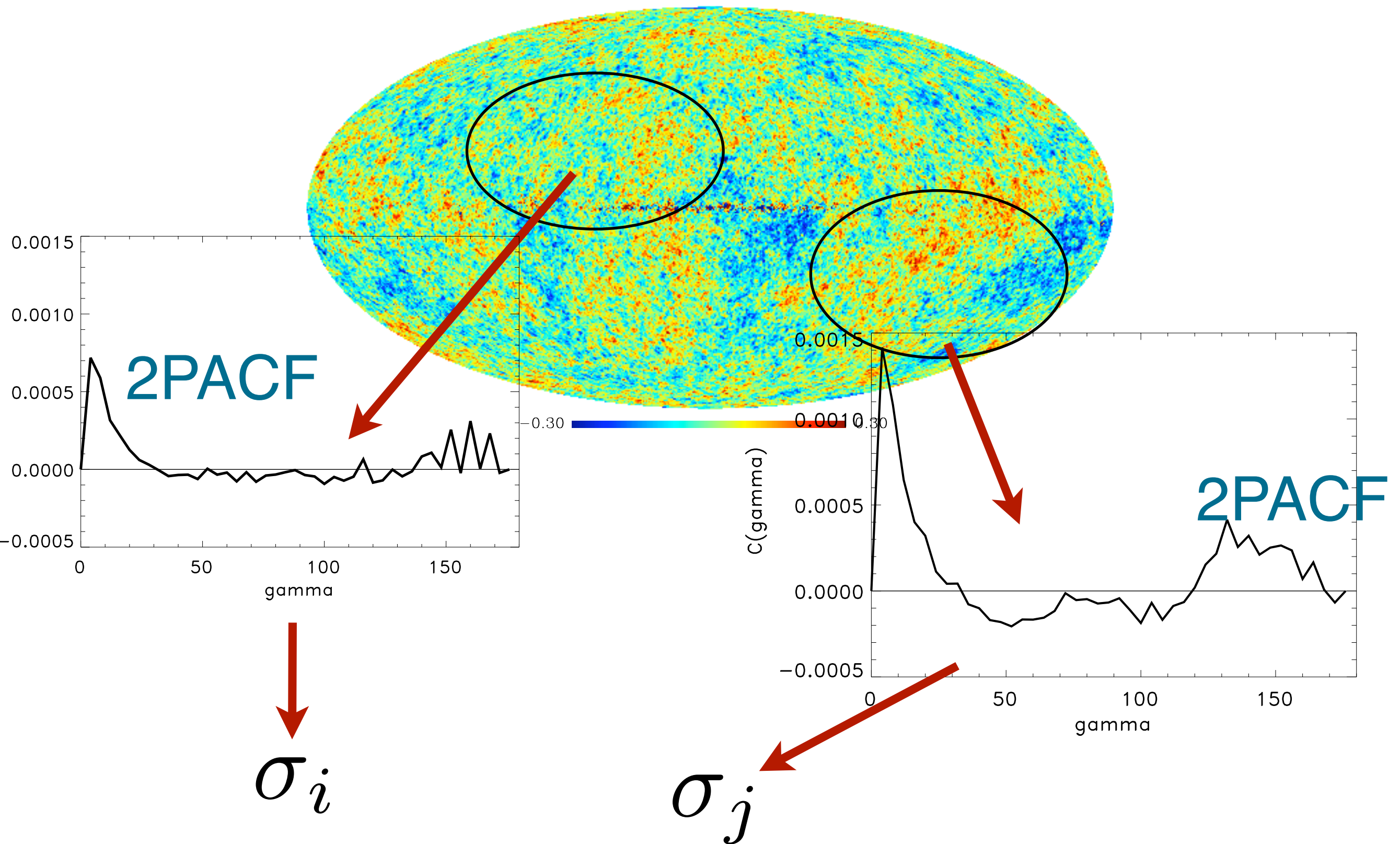
However, NS-asymmetry is maximal in the hemispheres:



How one can find the asymmetric hemispheres?

AB, B. Mota, R. Tavakol, M.J. Rebouças, A&A 2007

Is the CMB isotropic?



σ -map

