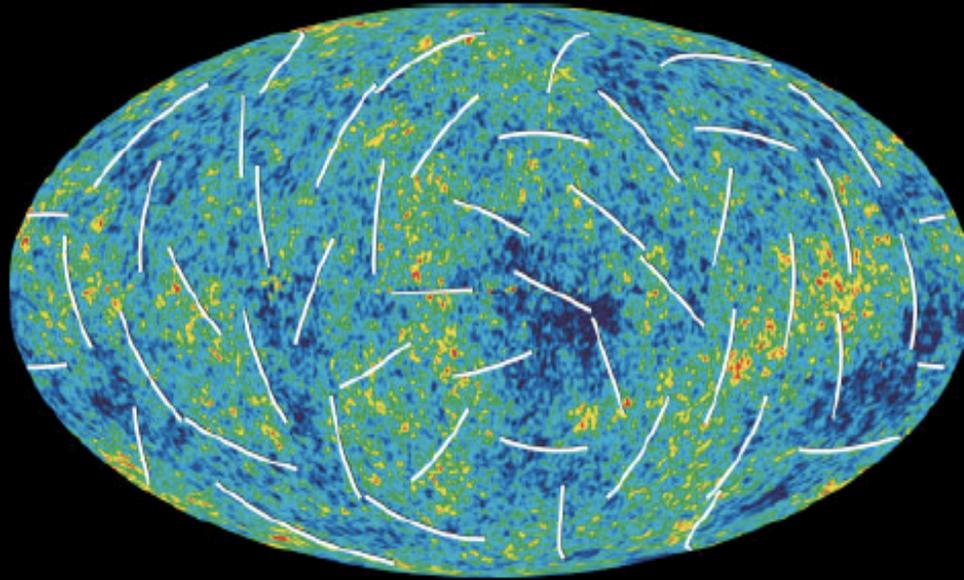


Radiação Cósmica de Fundo: o que ela ainda pode revelar (e o que ela nunca vai responder)

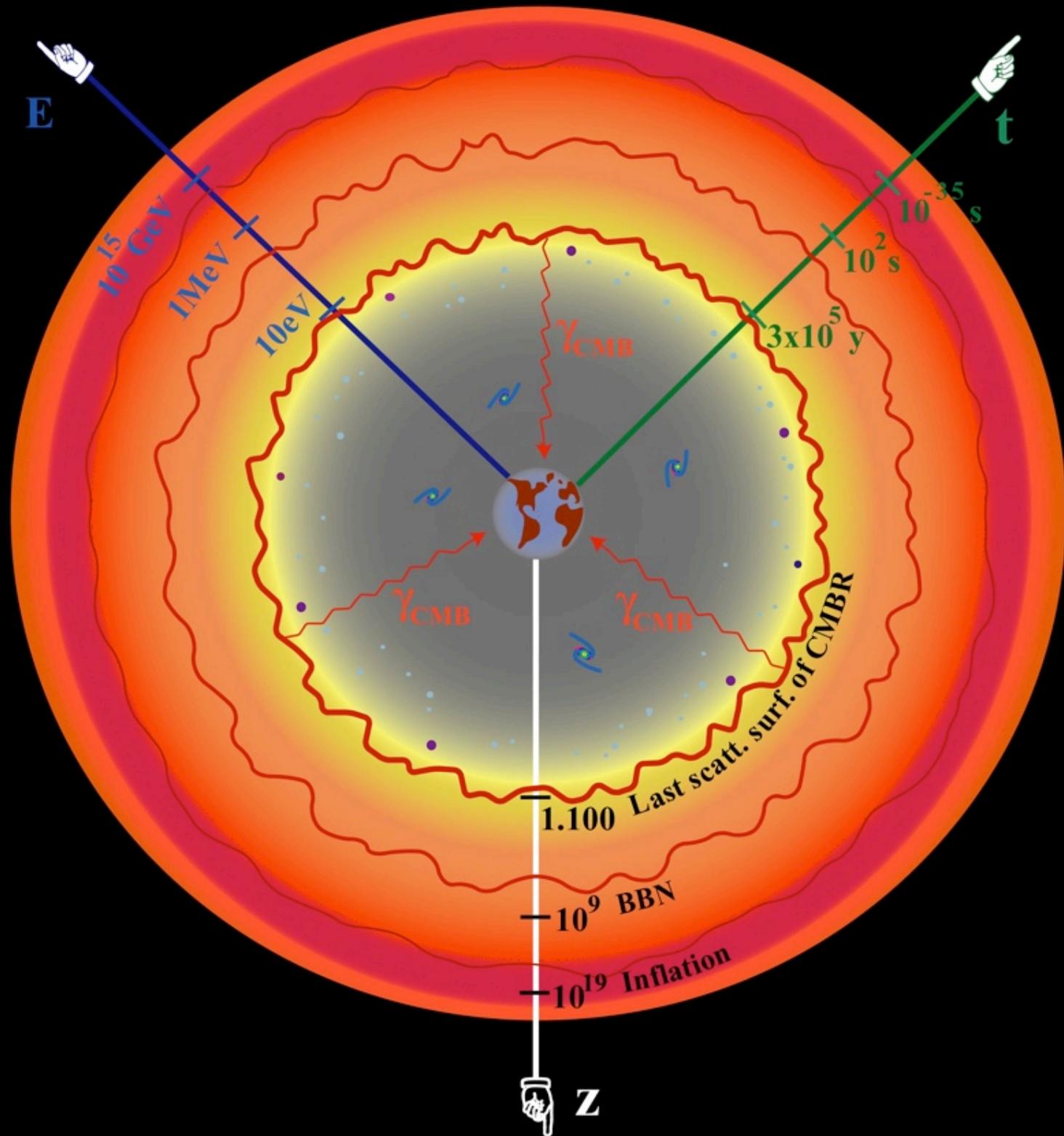


Nova Física no Espaço - fev/2009

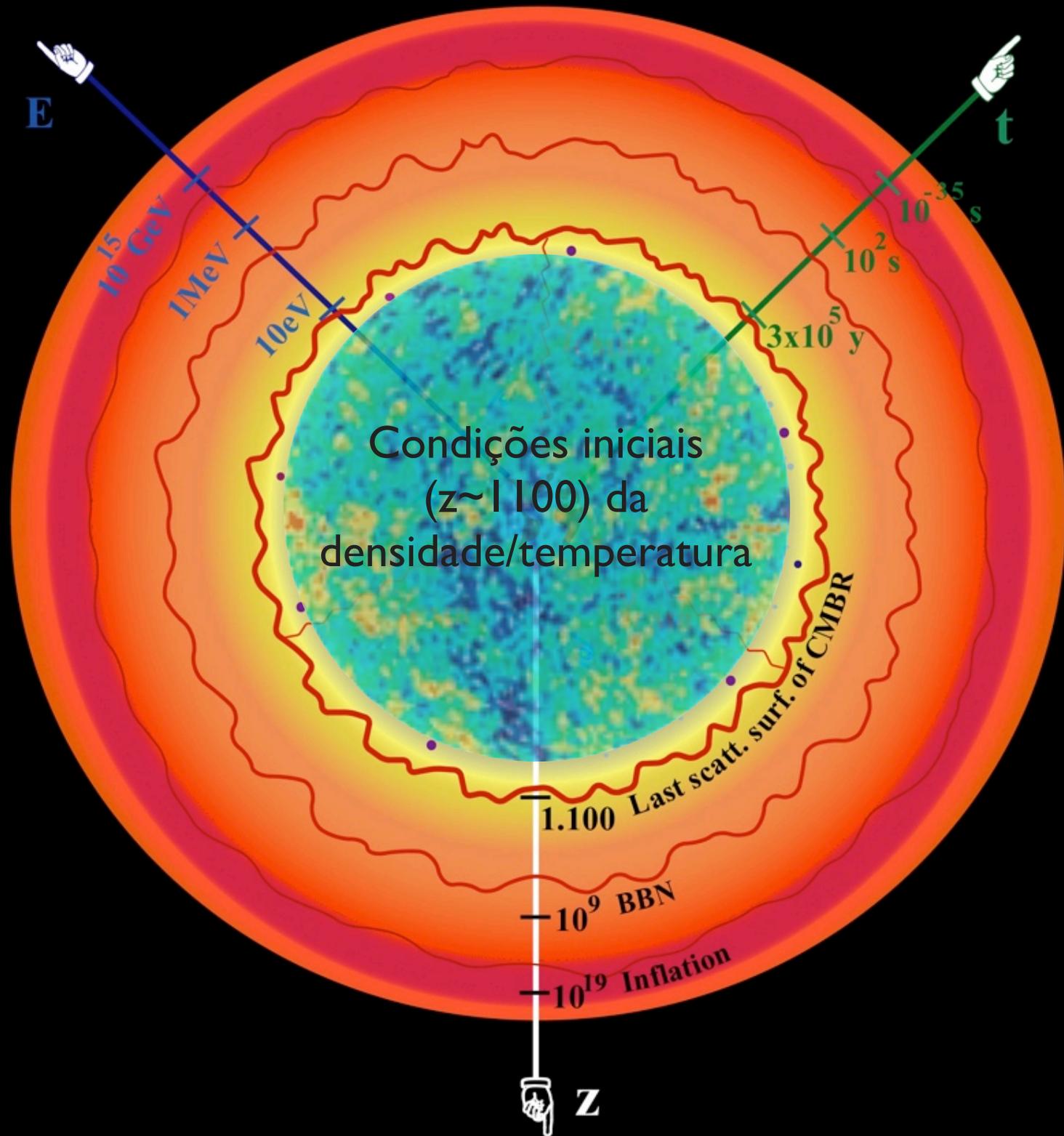
L. Raul Abramo
Instituto de Física
University of Sao Paulo

Visão **causal** do universo **local**

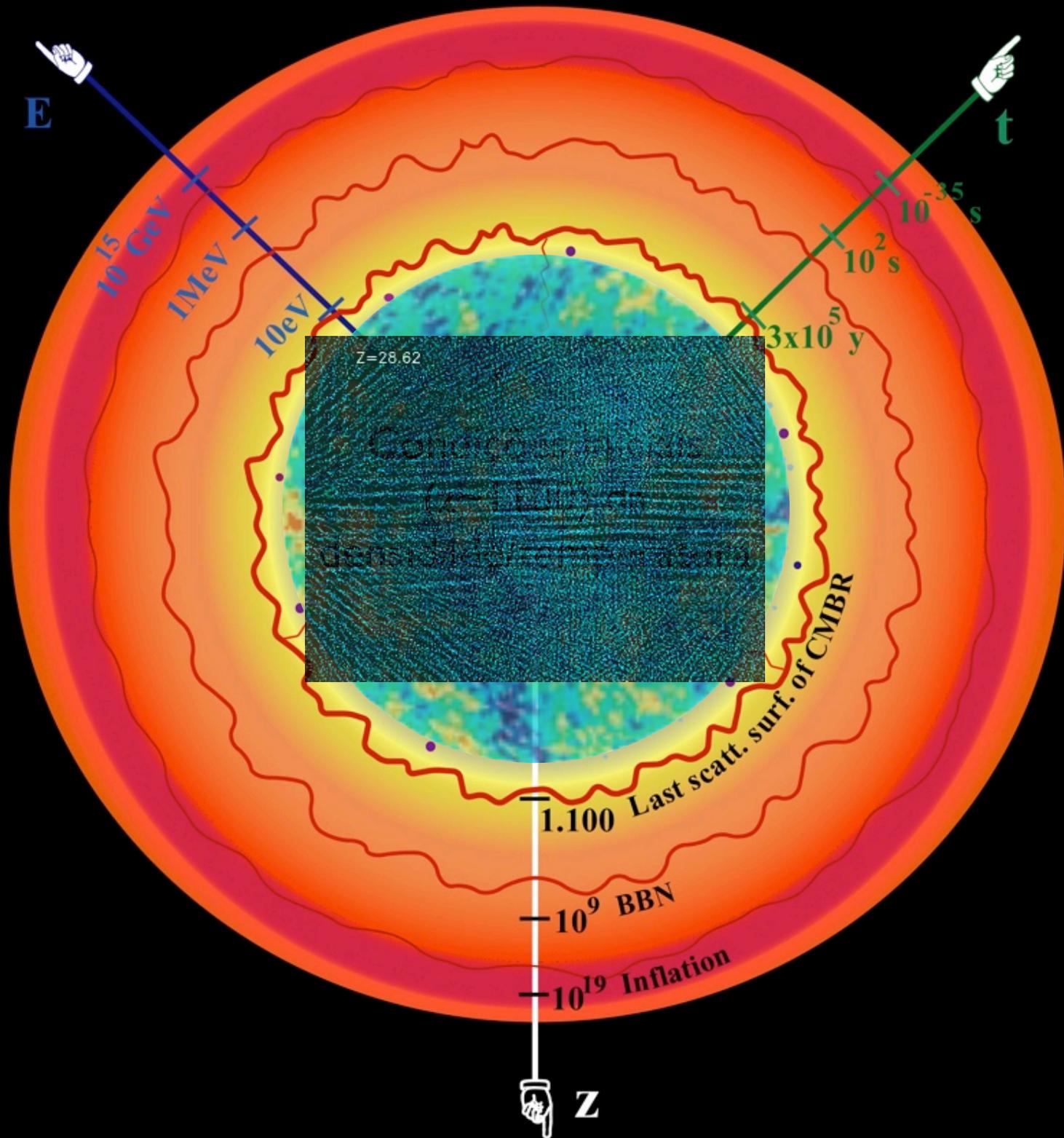
Visão causal do universo local



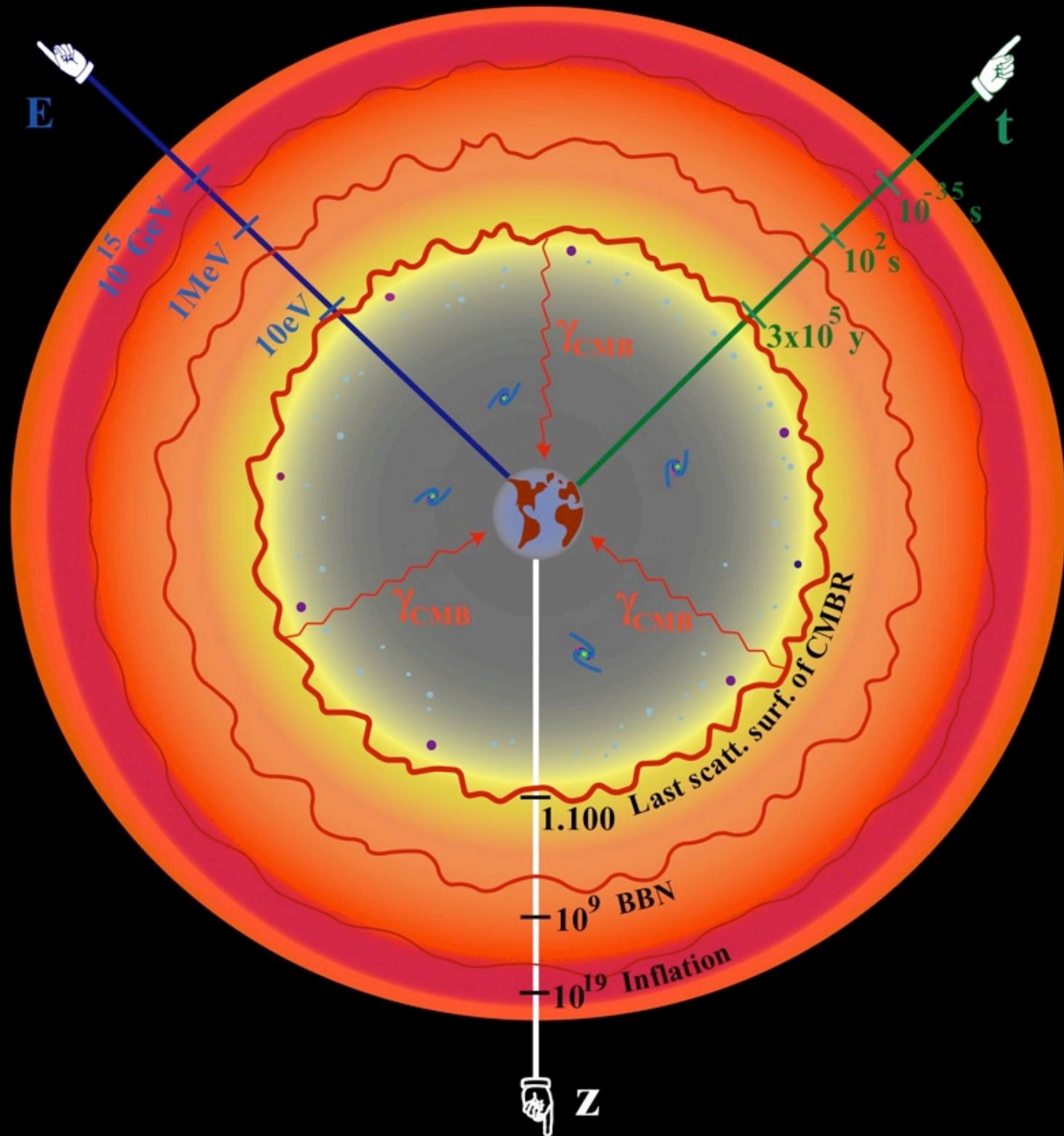
Visão causal do universo local



Visão causal do universo local

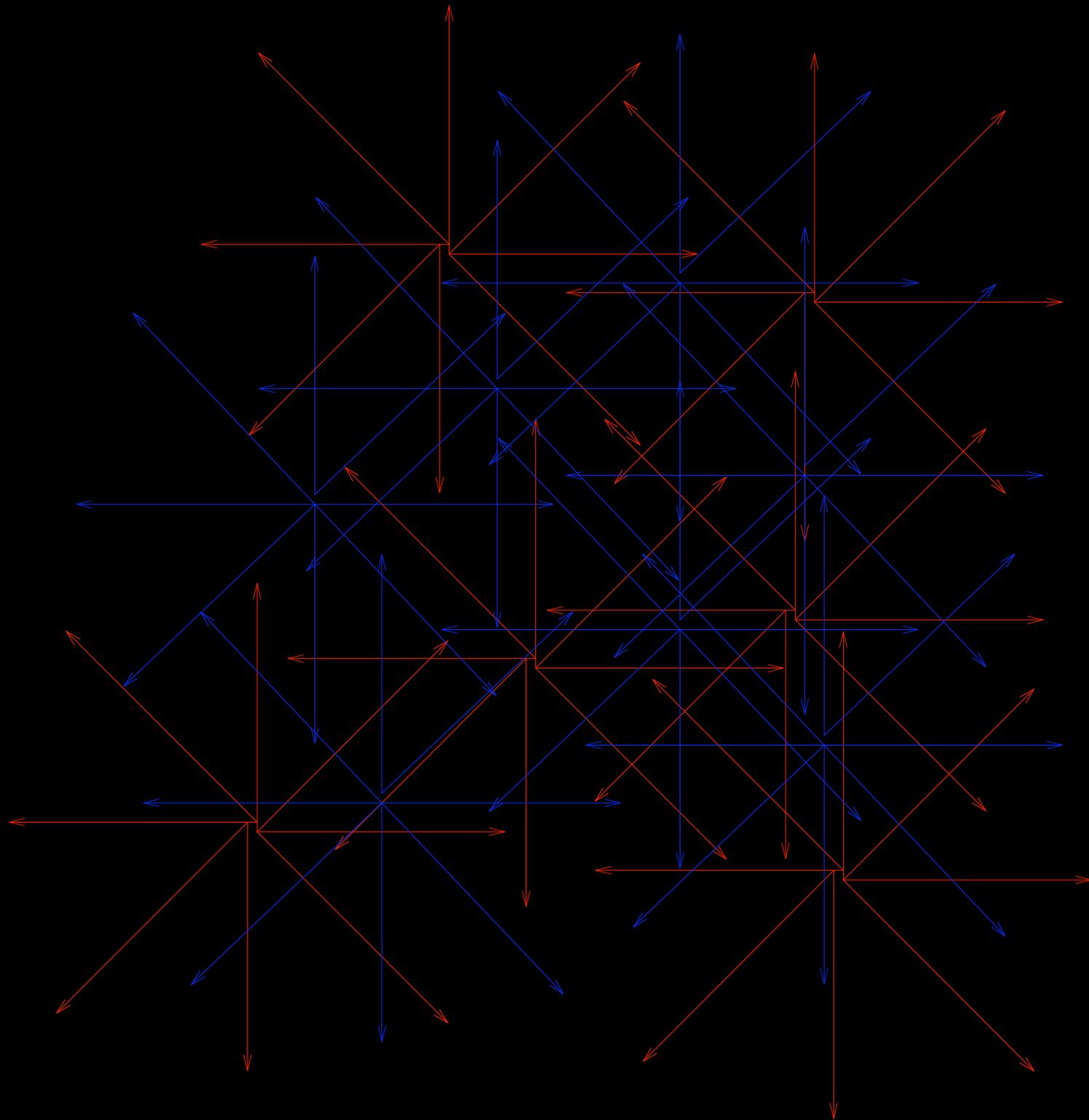


Visão causal do universo local



* $T > 1$ eV: fluido
quase-homogeneo
de barions/fotons,
fortemente
acoplado

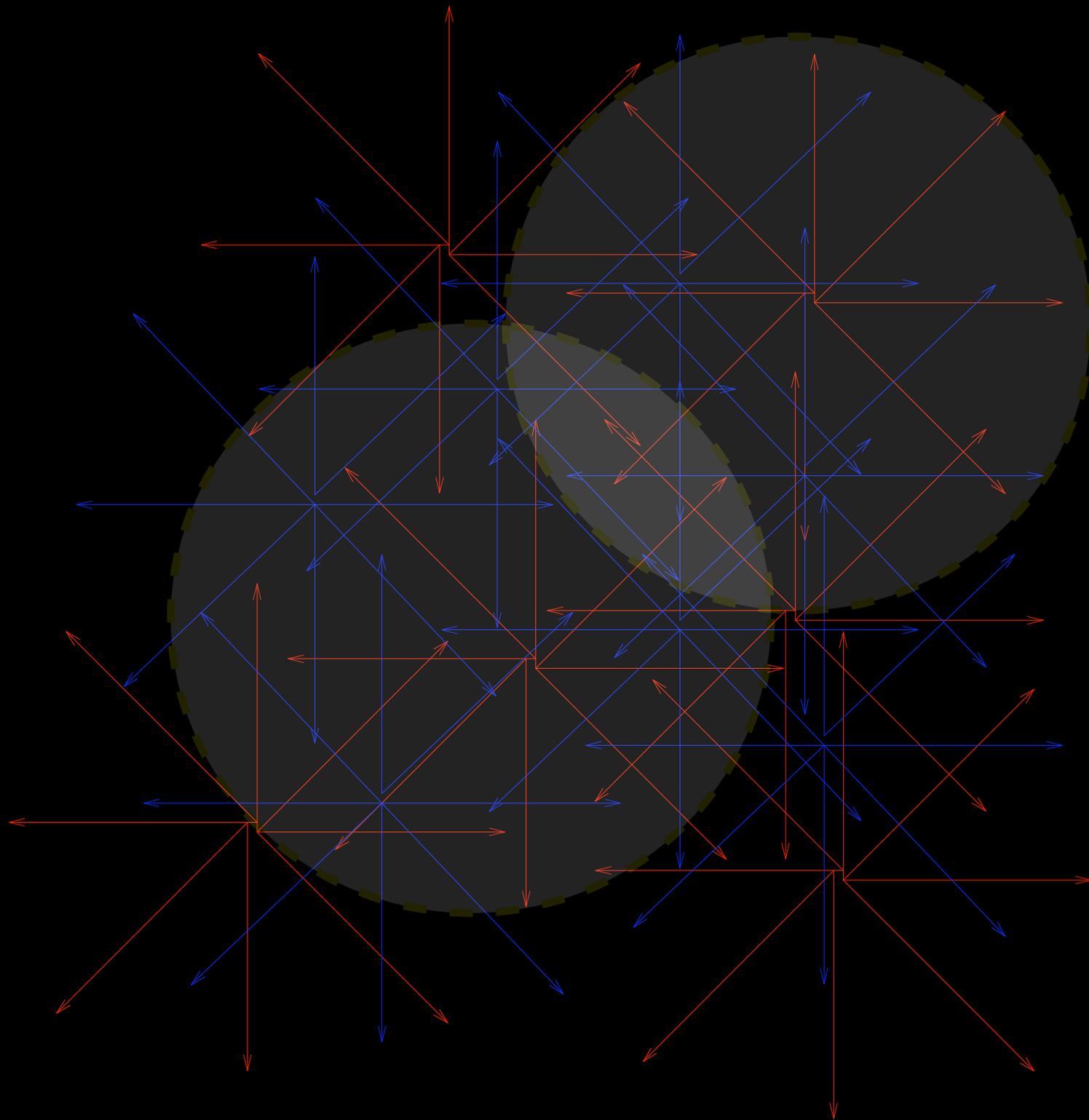
* $T \sim 1$ eV:
desacoplamento



* $T > 1$ eV: fluido
quase-homogeneo
de barions/fotons,
fortemente
acoplado

* $T \sim 1$ eV:
desacoplamento

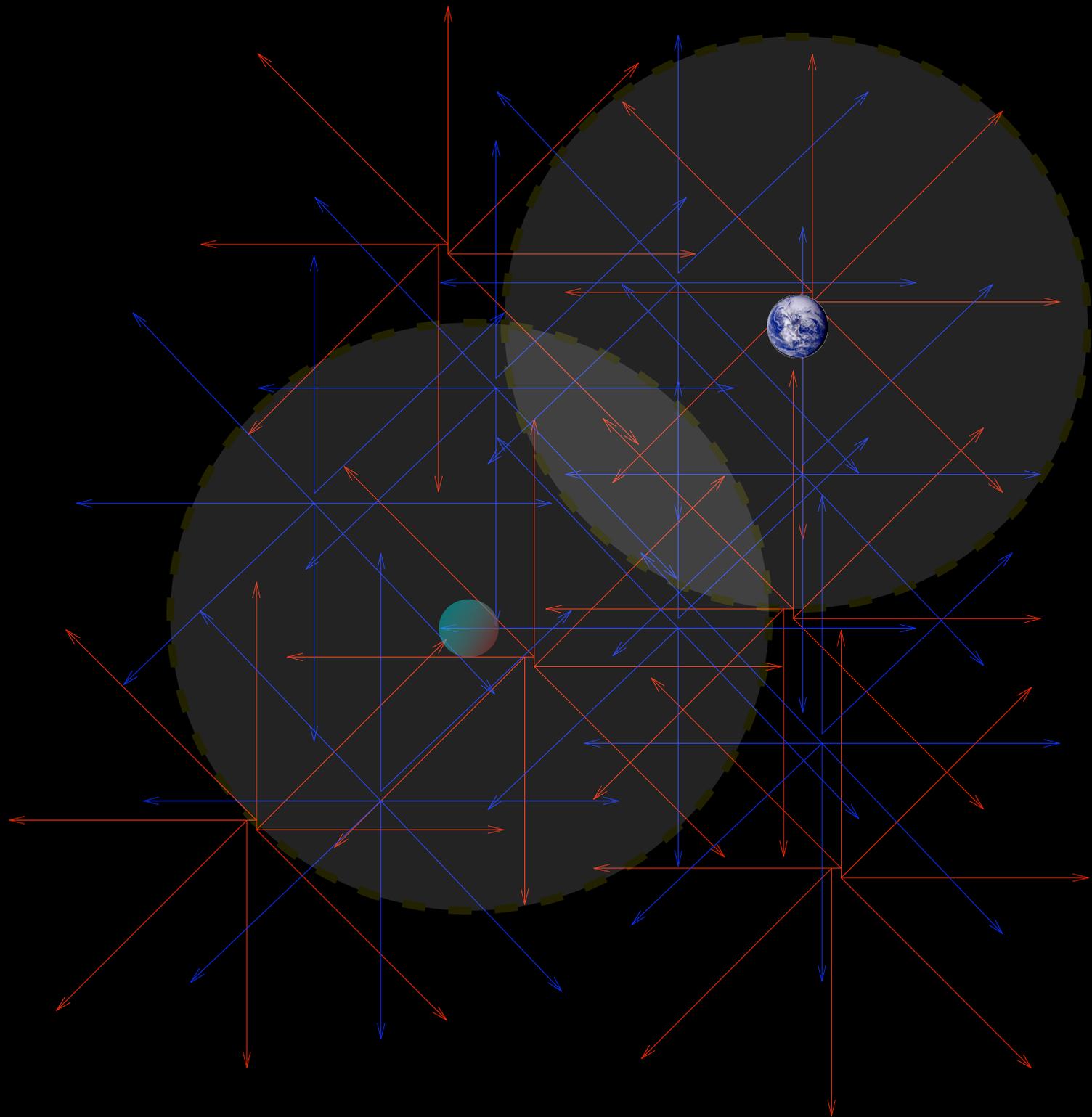
* $T \lesssim 0.2$ eV:
free streaming
(quase nenhum
espalhamento)

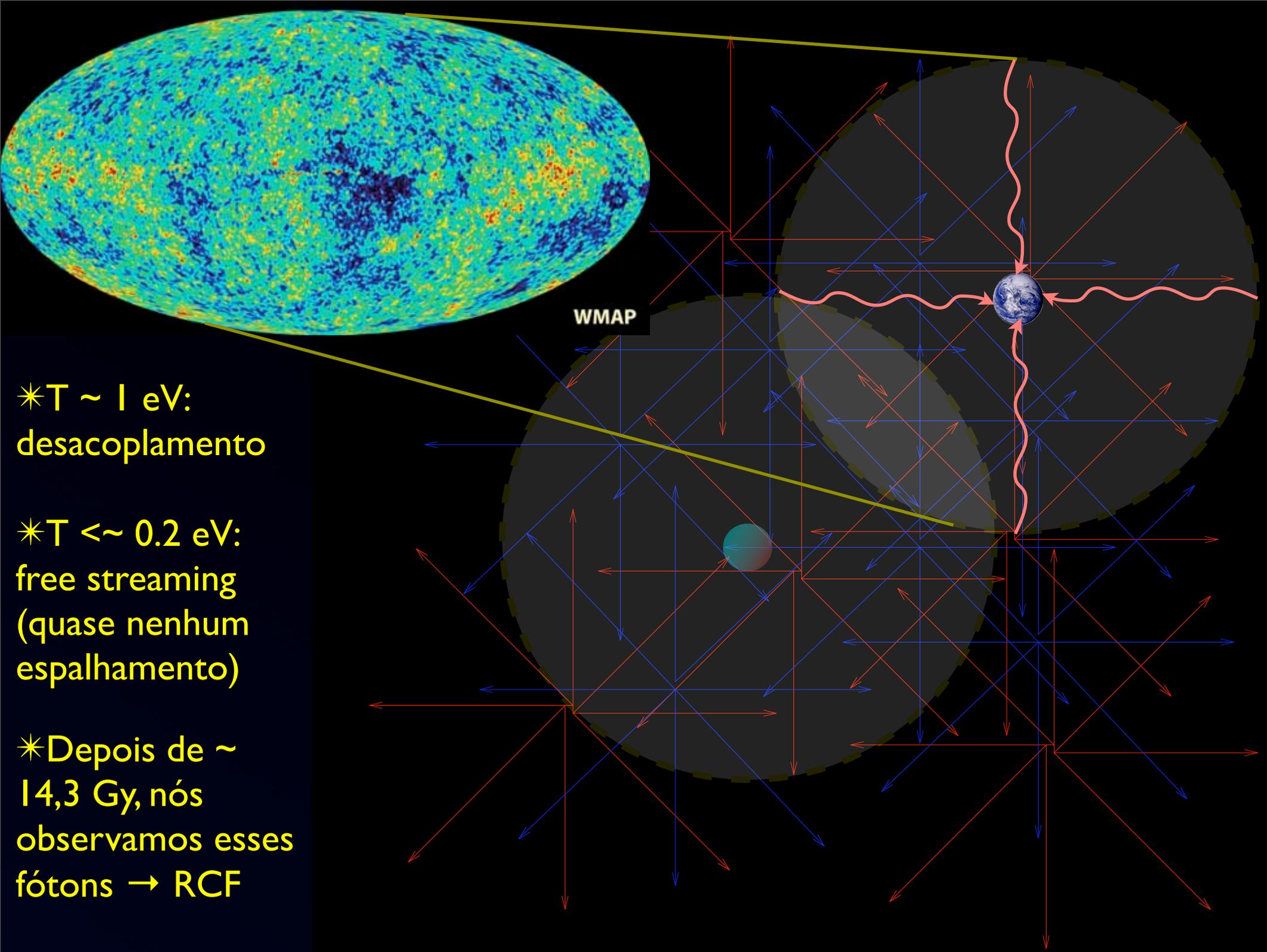


* $T > 1$ eV: fluido
quase-homogeneo
de barions/fotons,
fortemente
acoplado

* $T \sim 1$ eV:
desacoplamento

* $T \lesssim 0.2$ eV:
free streaming
(quase nenhum
espalhamento)

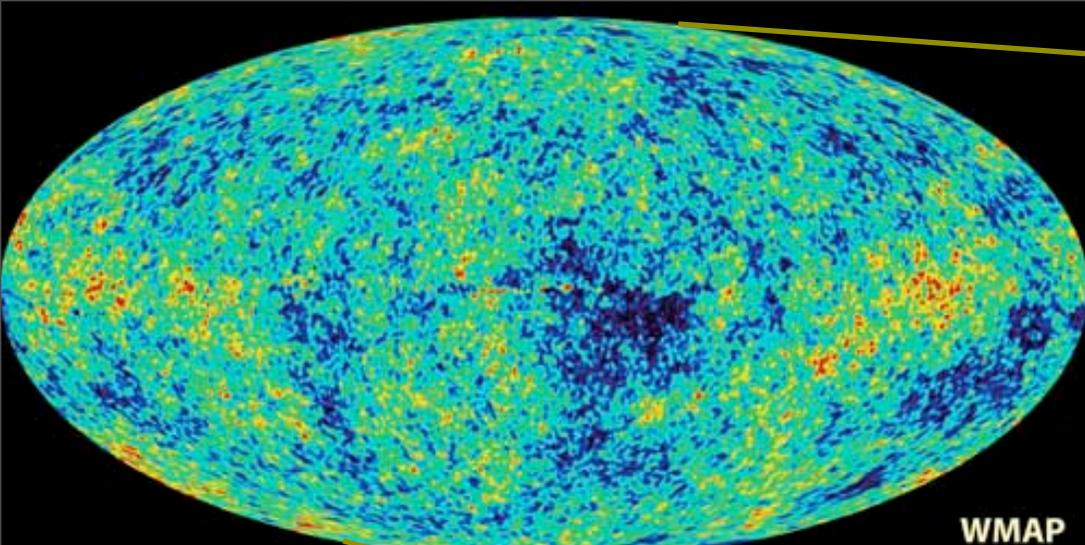




* $T \sim 1 \text{ eV}$:
desacoplamento

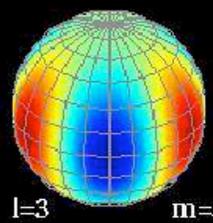
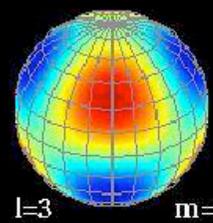
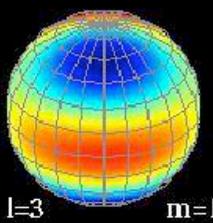
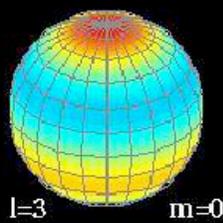
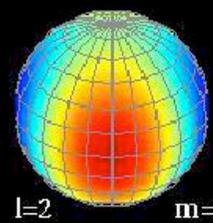
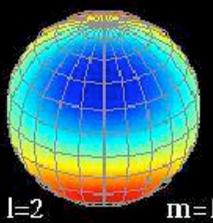
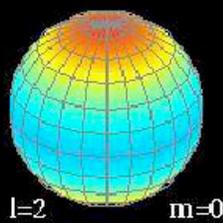
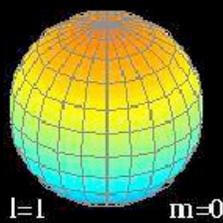
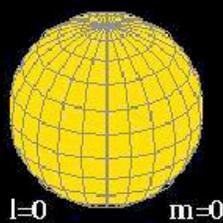
* $T < \sim 0.2 \text{ eV}$:
free streaming
(quase nenhum
espalhamento)

*Depois de $\sim 14,3 \text{ Gy}$, nós
observamos esses
fótons \rightarrow RCF



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

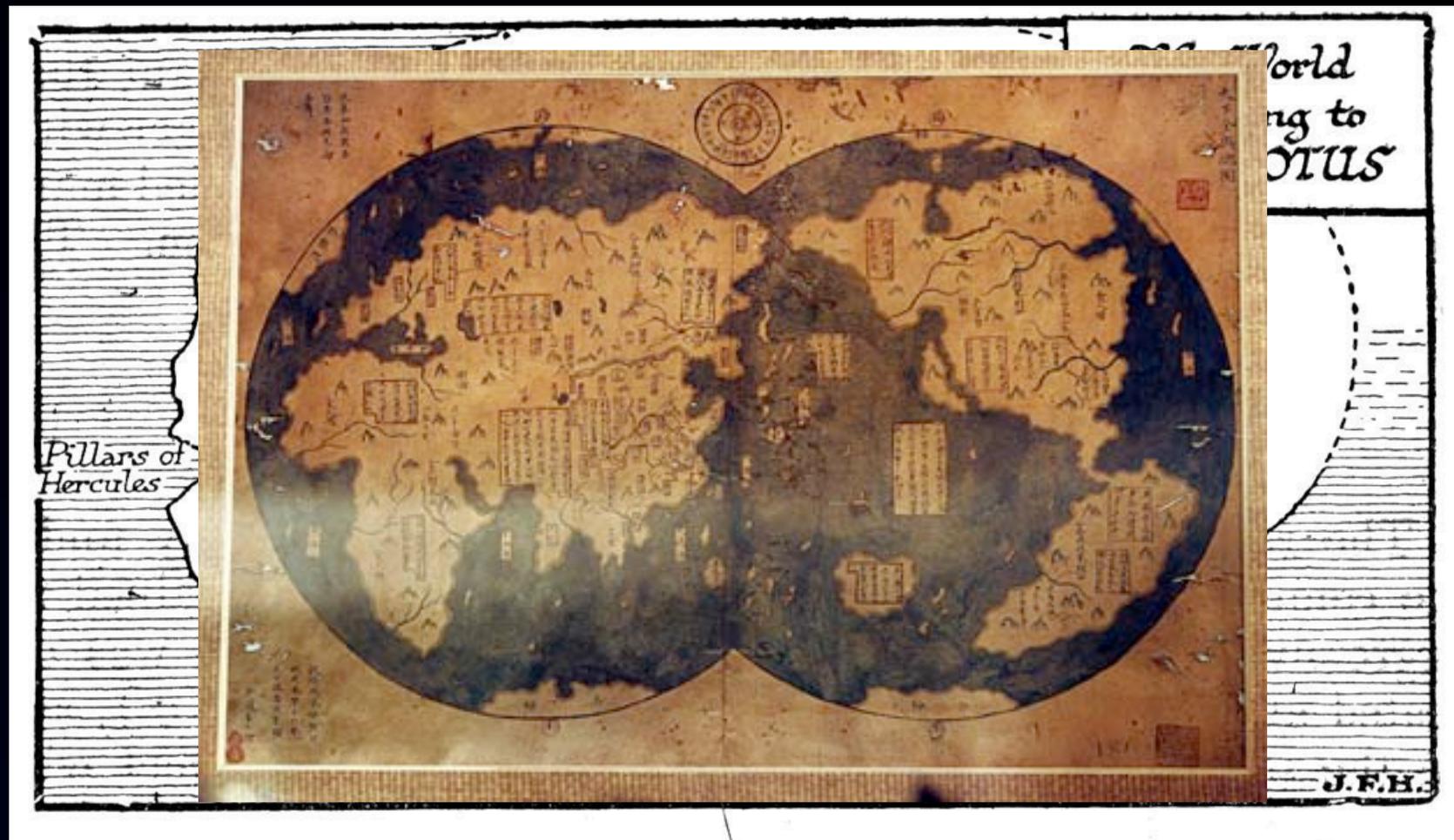
$$C_{\ell} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$



A humanidade levou 100.000 anos para mapear o Planeta Terra...



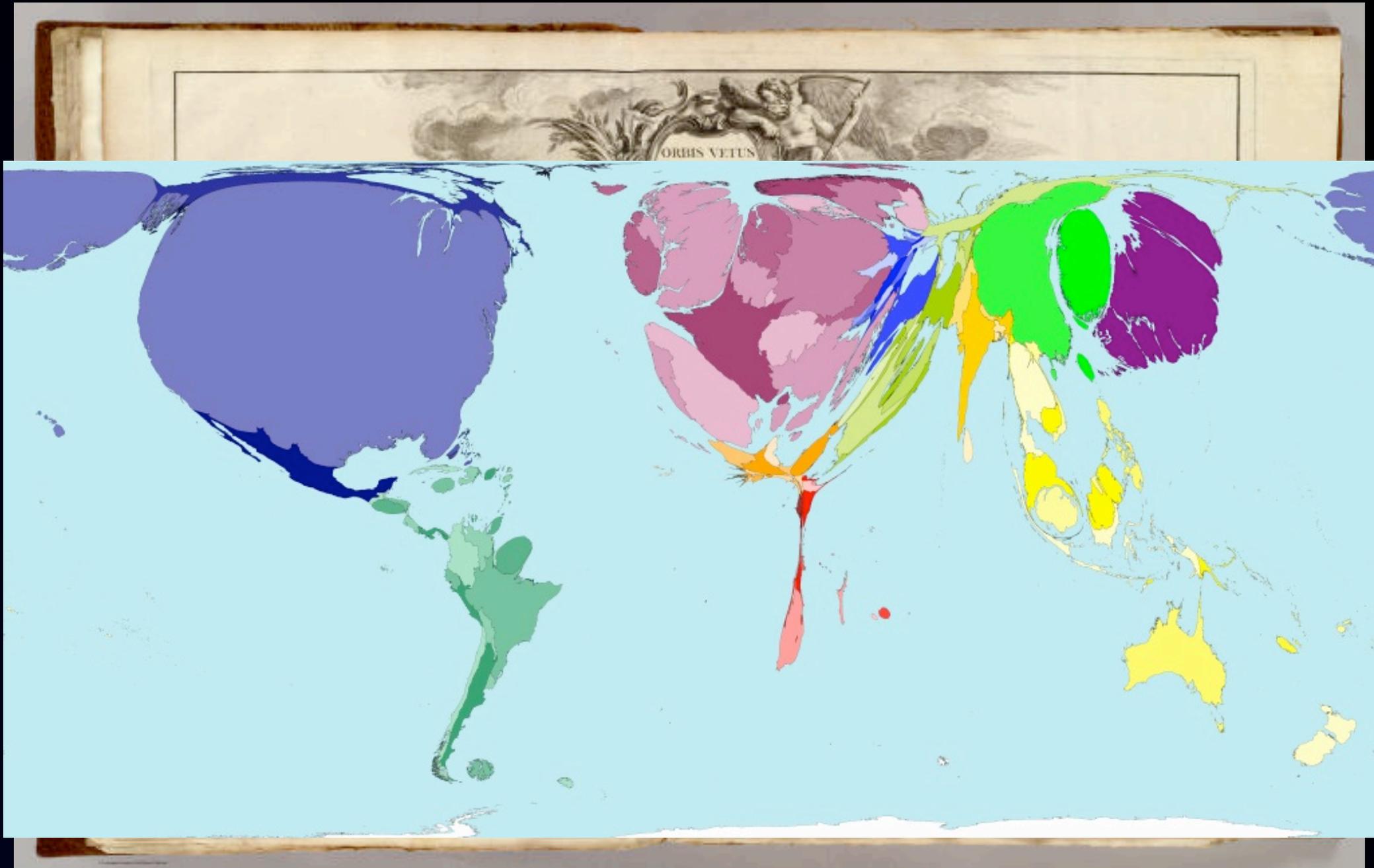
A humanidade levou 100.000 anos para mapear o Planeta Terra...



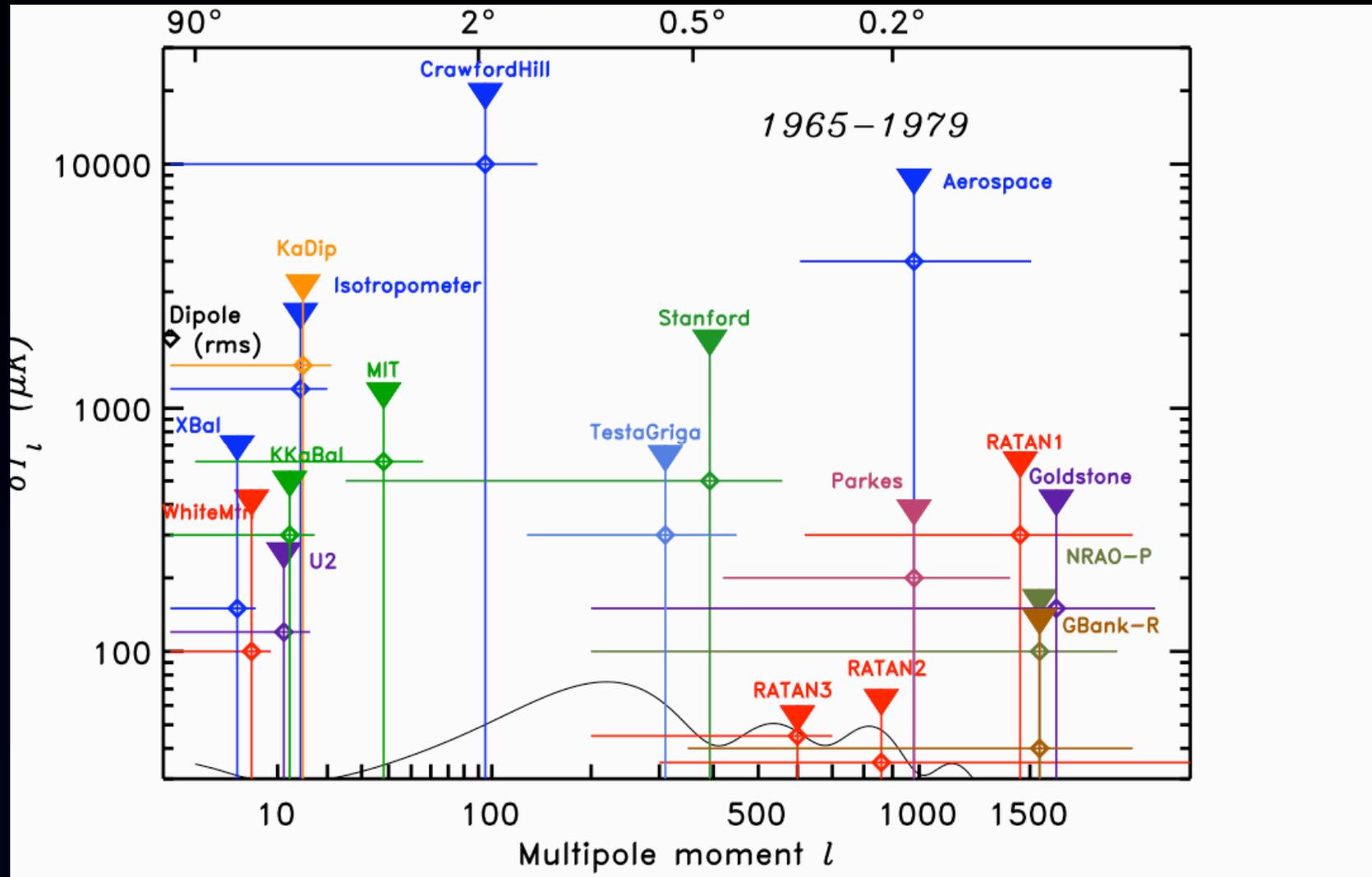
A humanidade levou 100.000 anos para mapear o Planeta Terra...



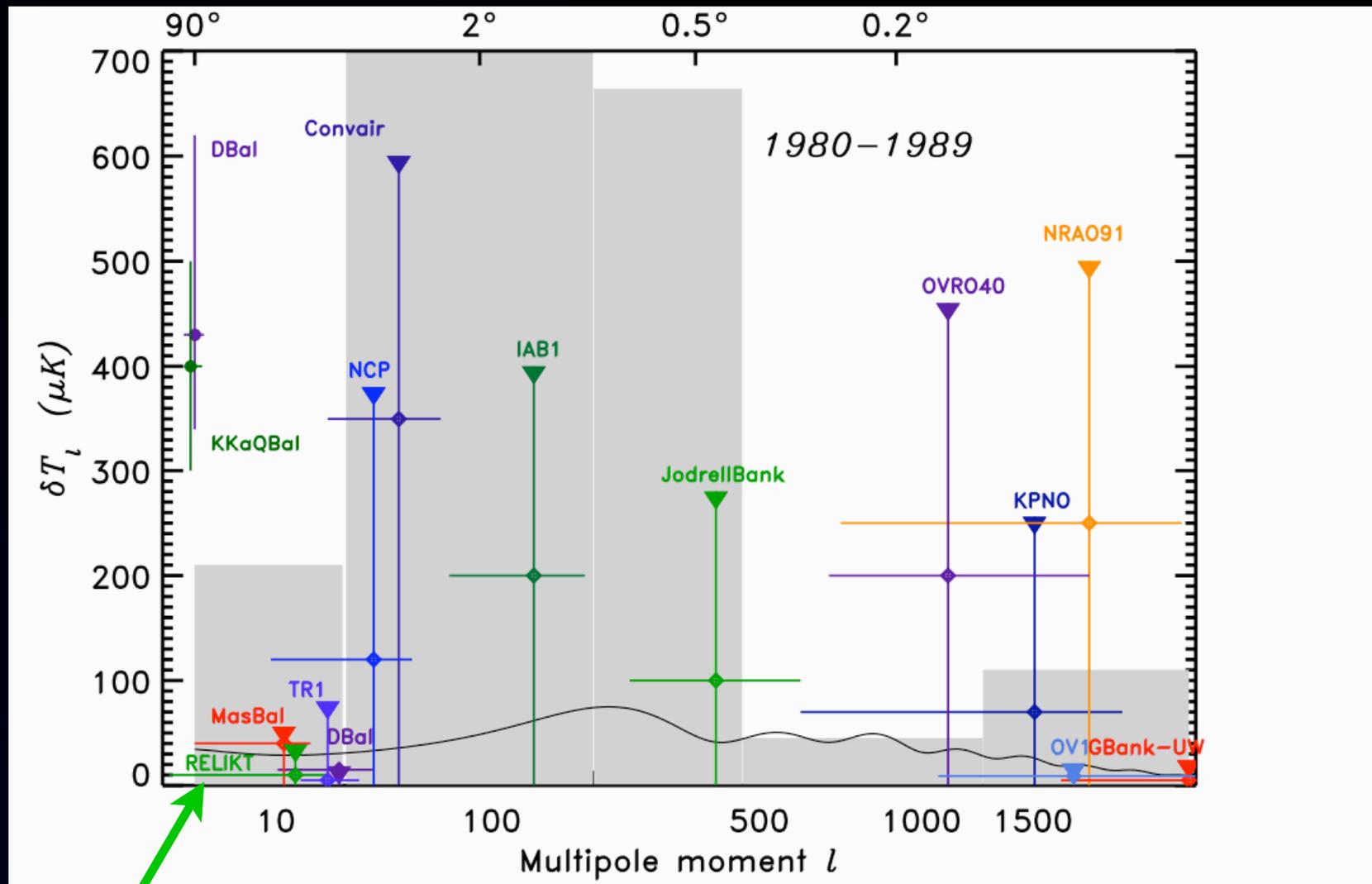
A humanidade levou 100.000 anos para mapear o Planeta Terra...

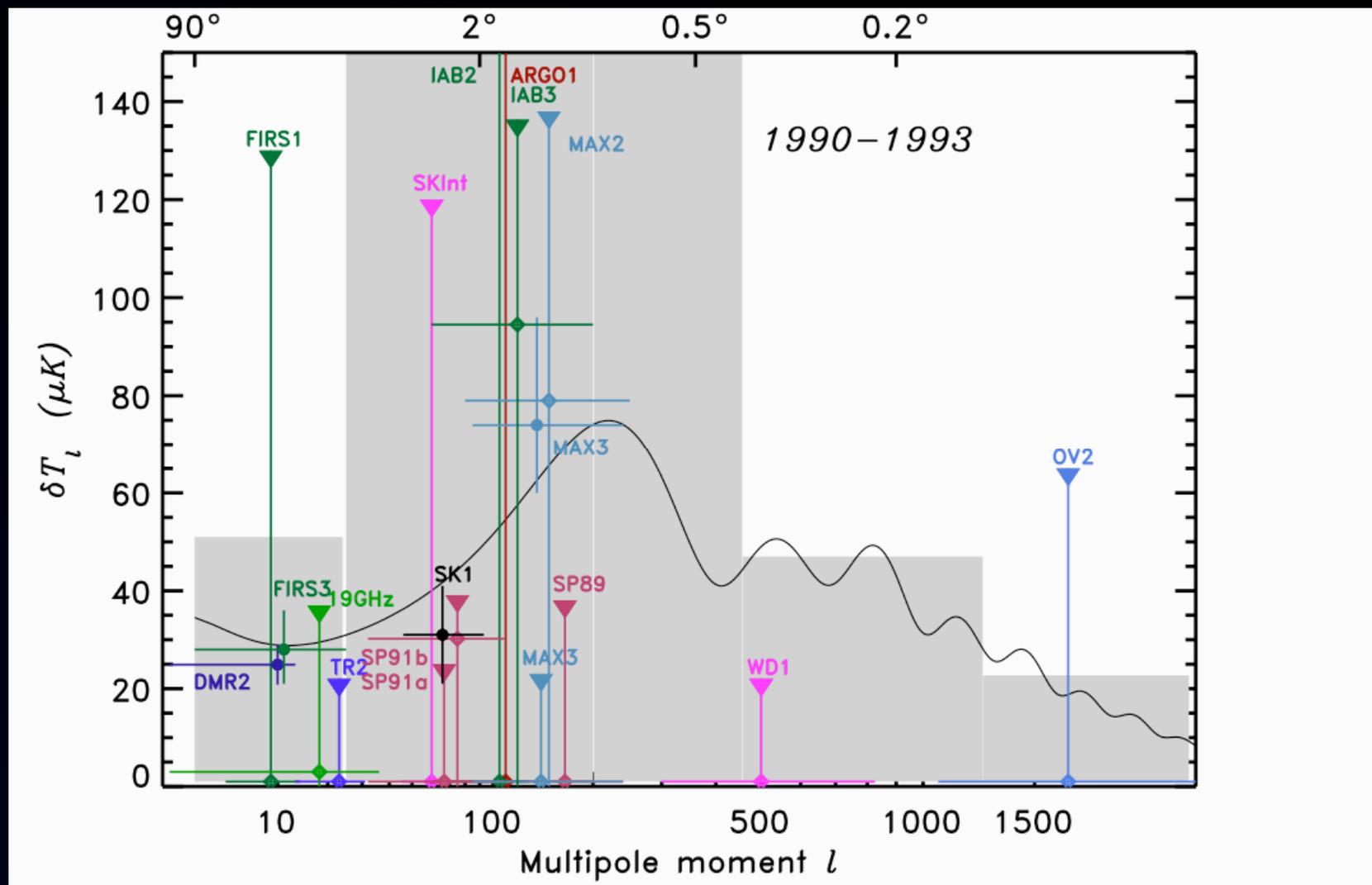


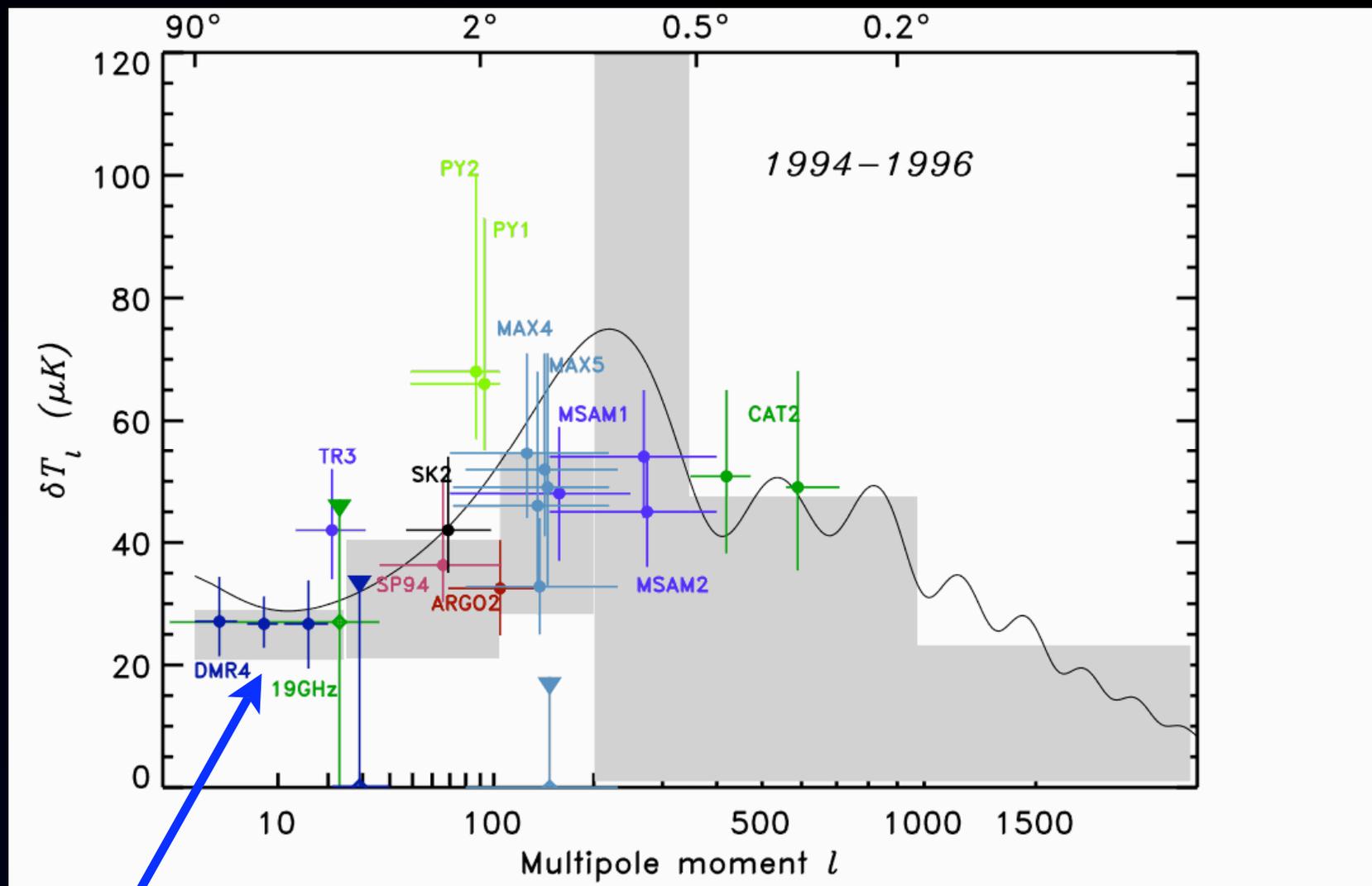
... mas só levou 40 anos para “mapear o universo”
com a radiação cósmica de fundo

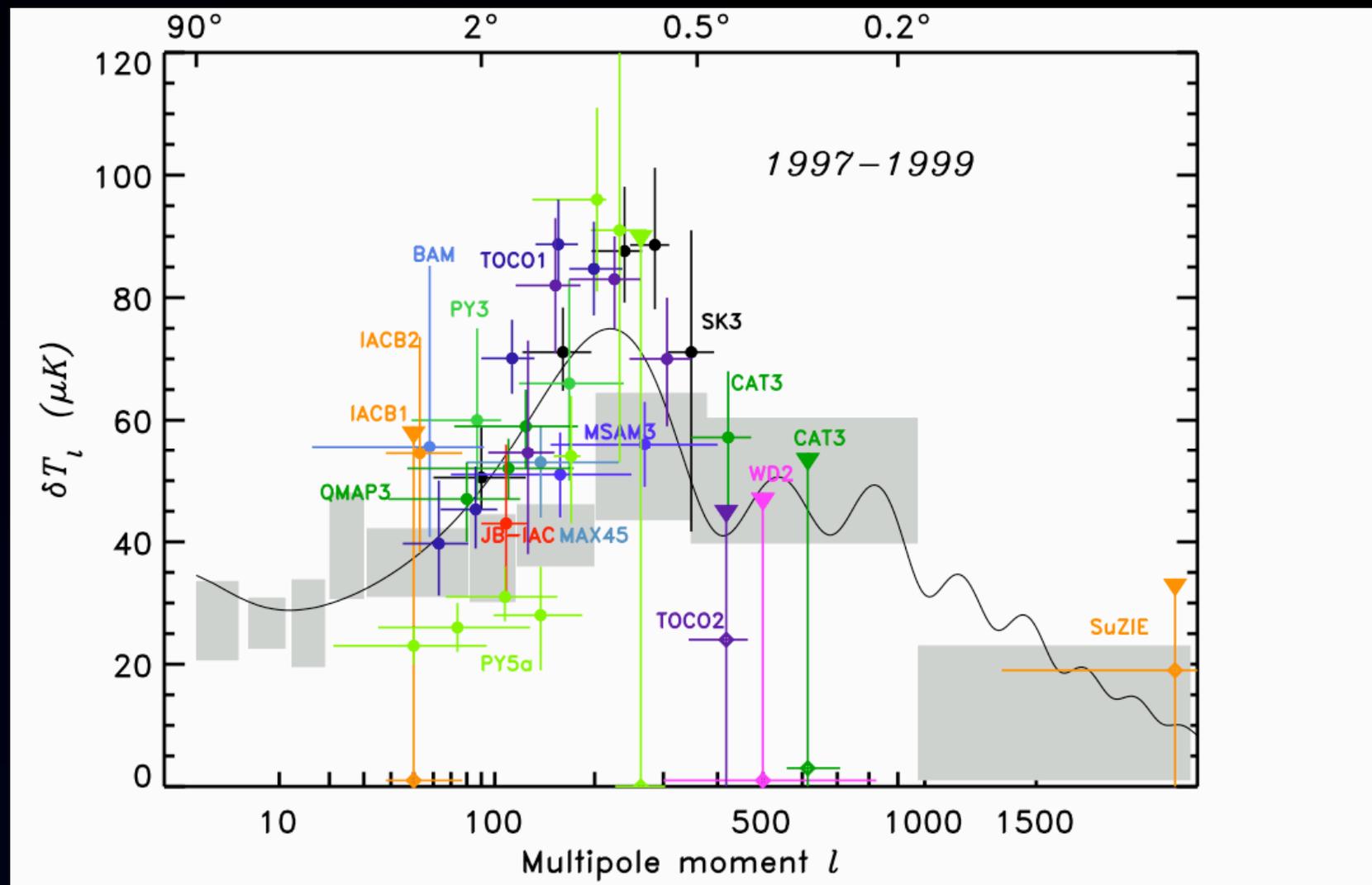


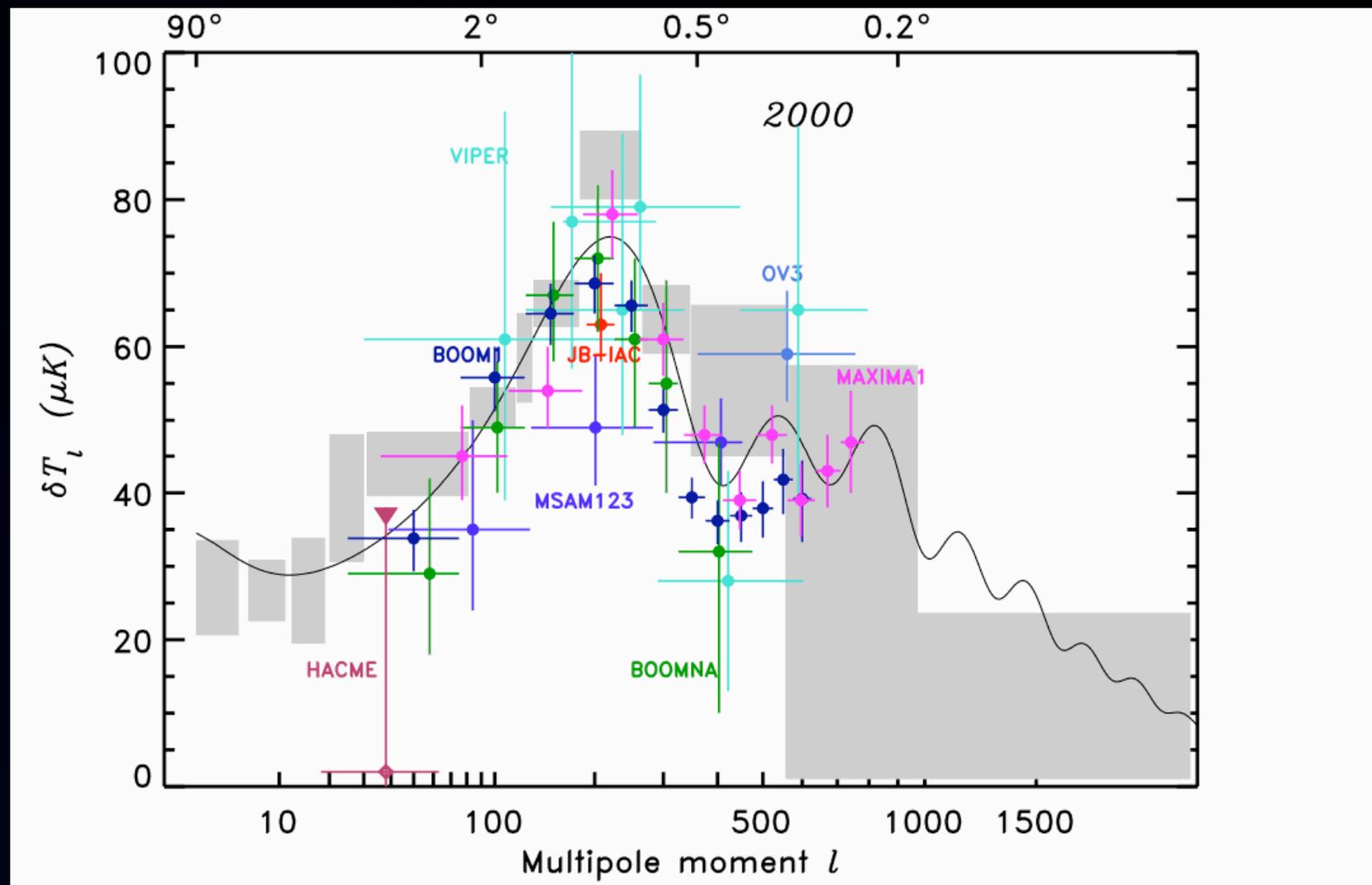
Figuras: Lyman Page

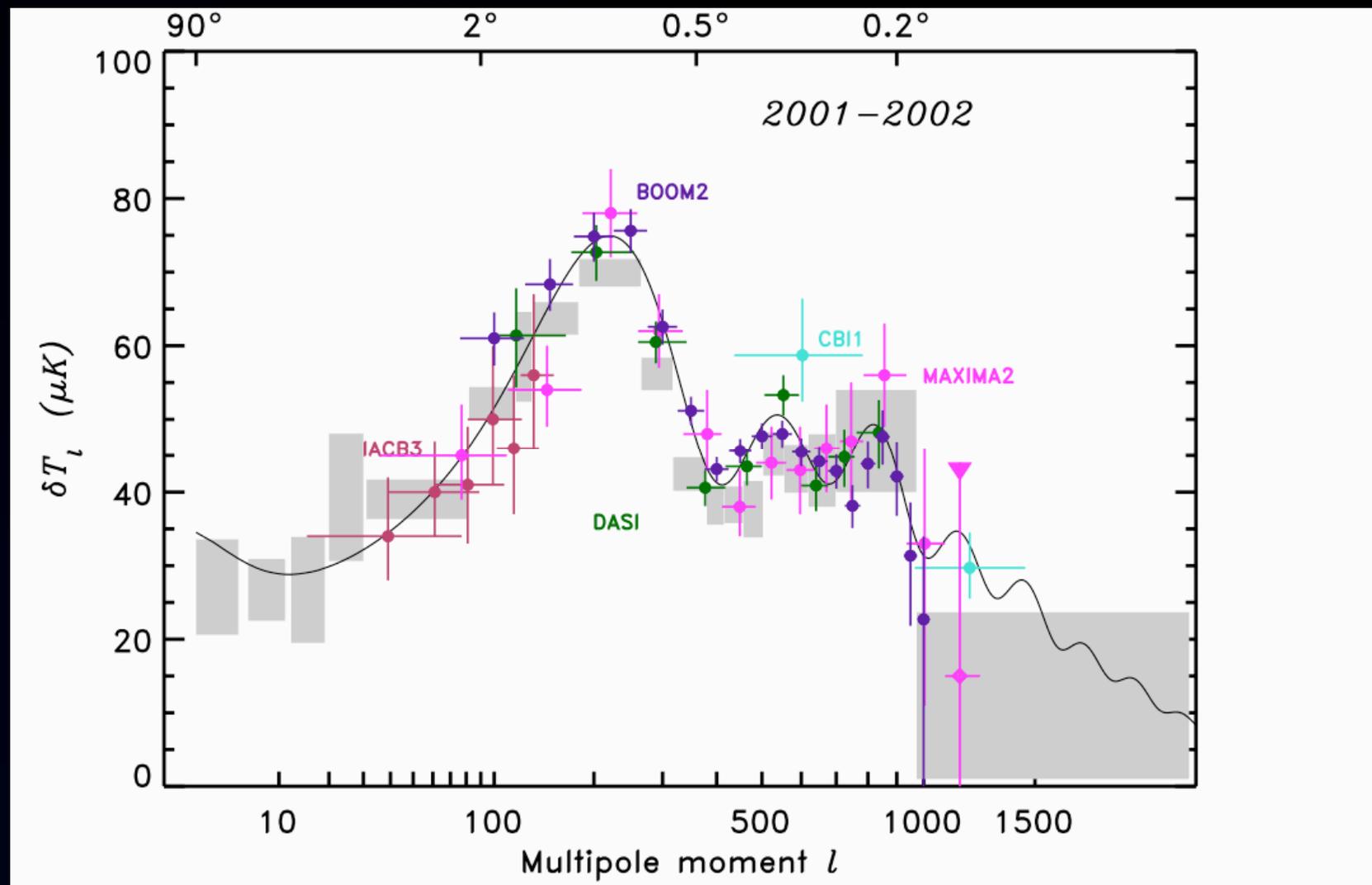


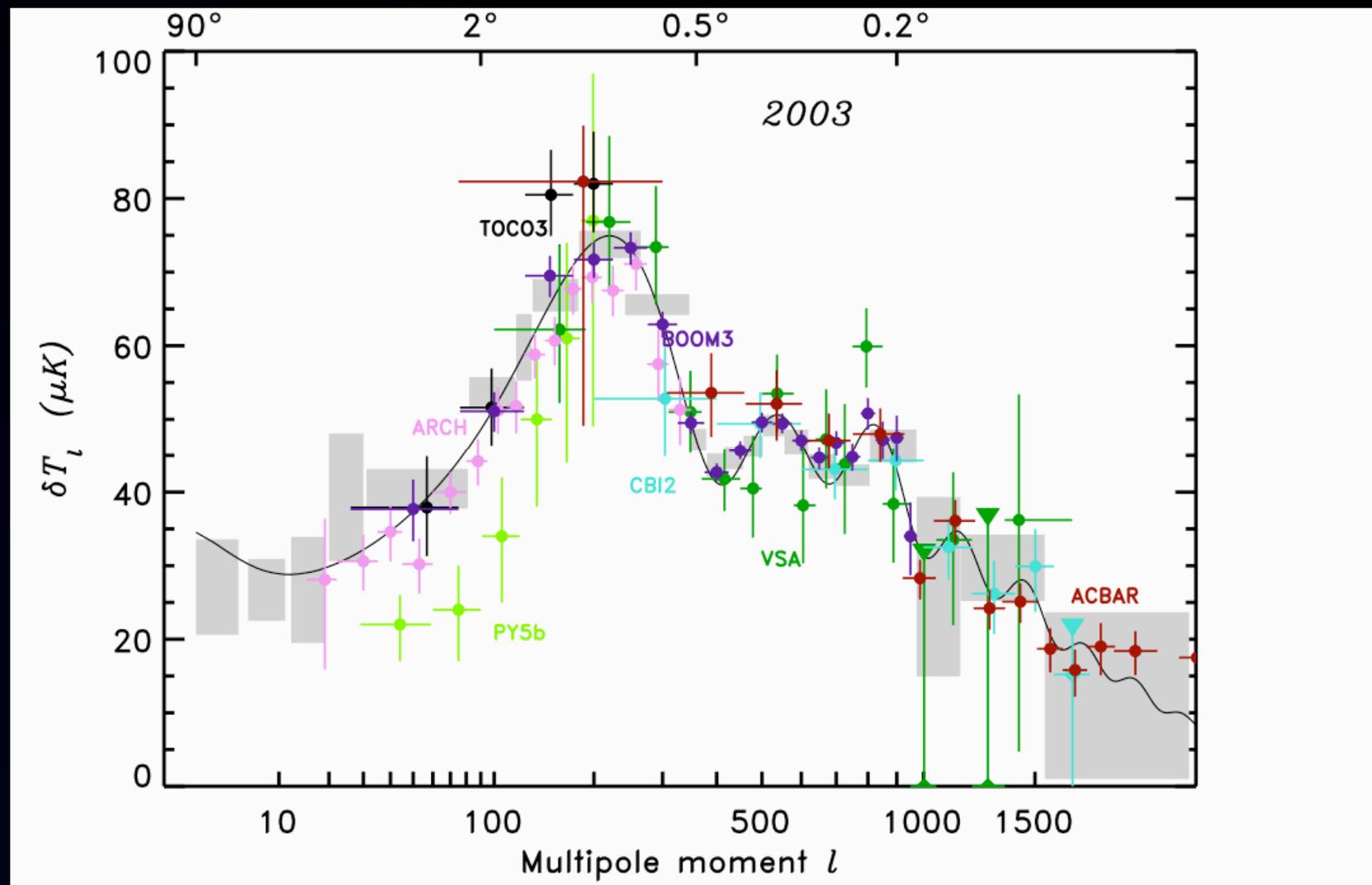


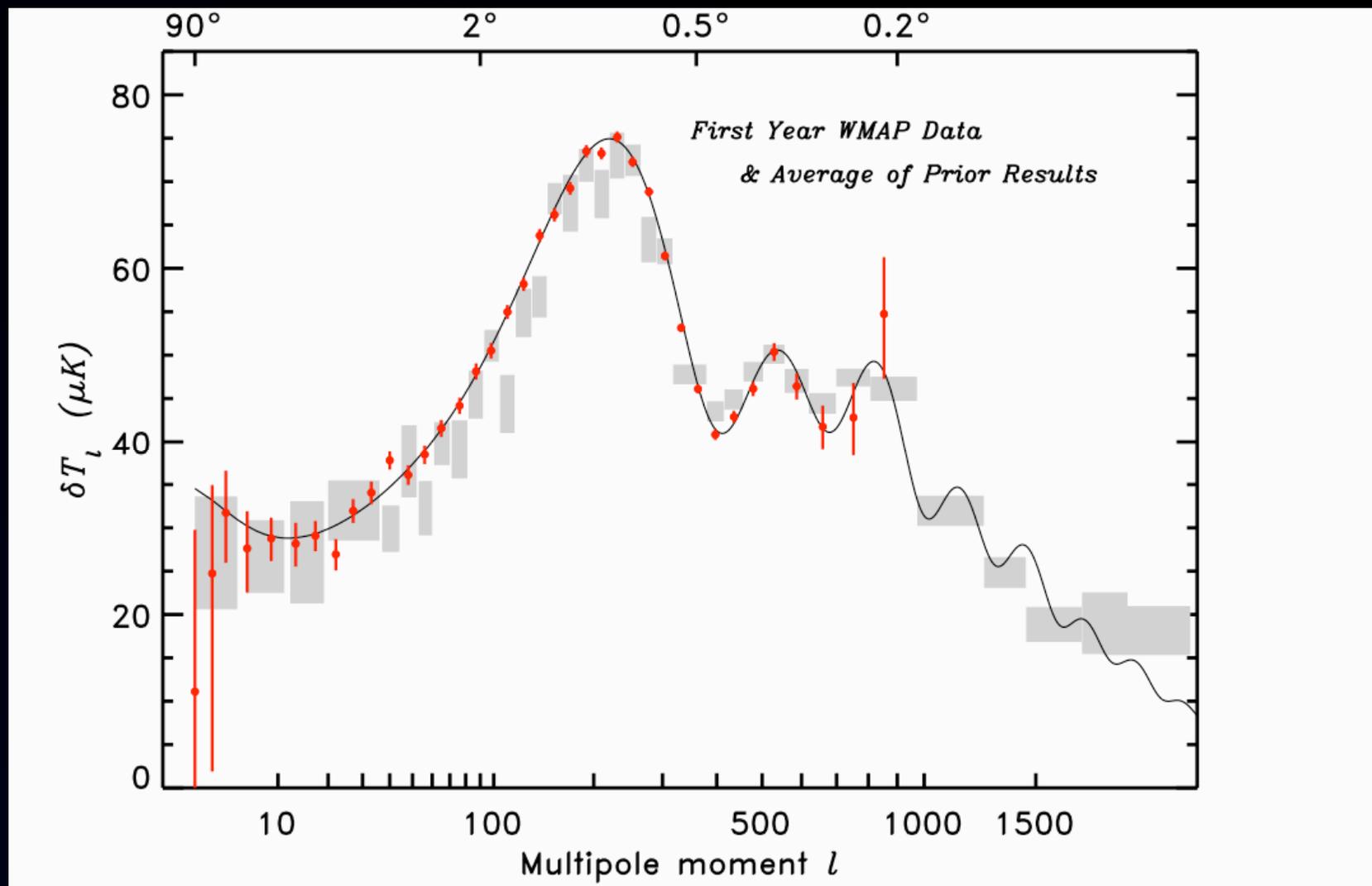




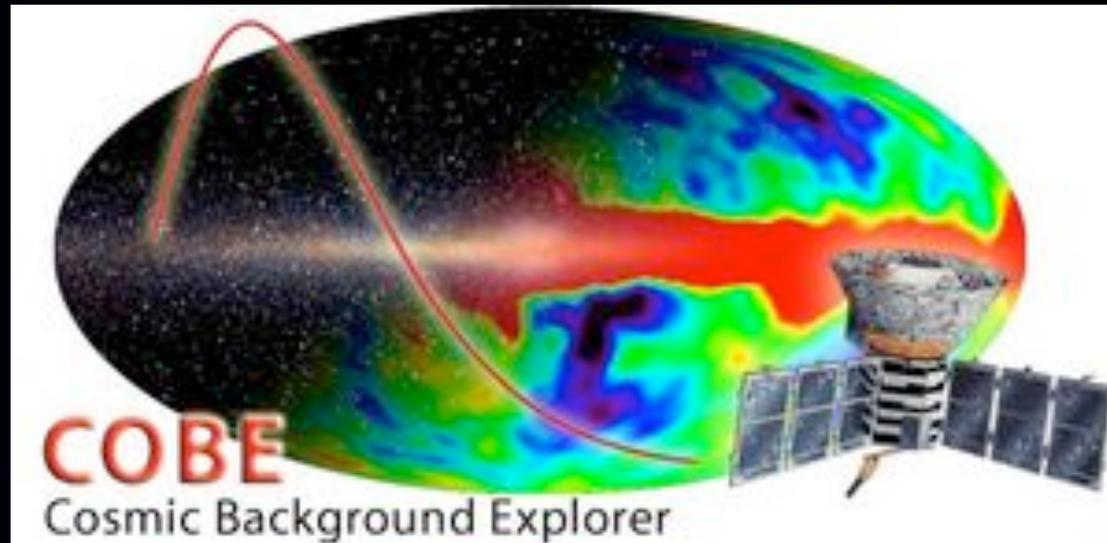




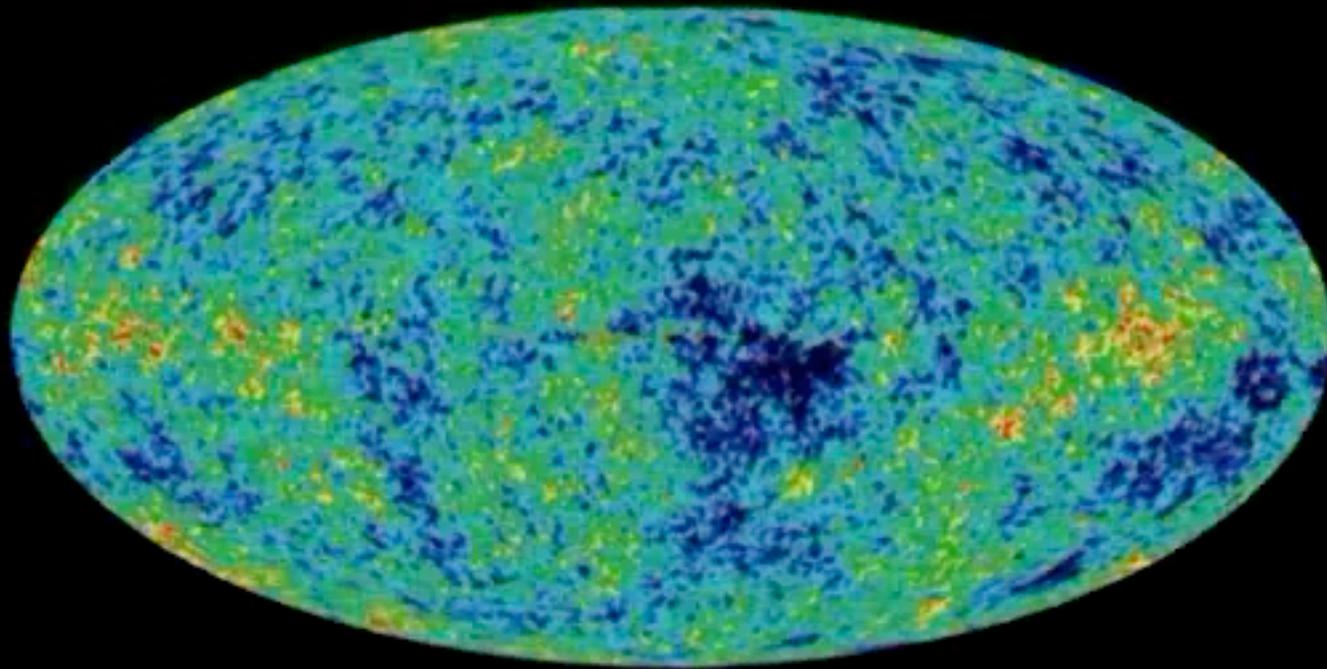




COBE-DMR/FIRAS



WMAP



South Pole Telescope

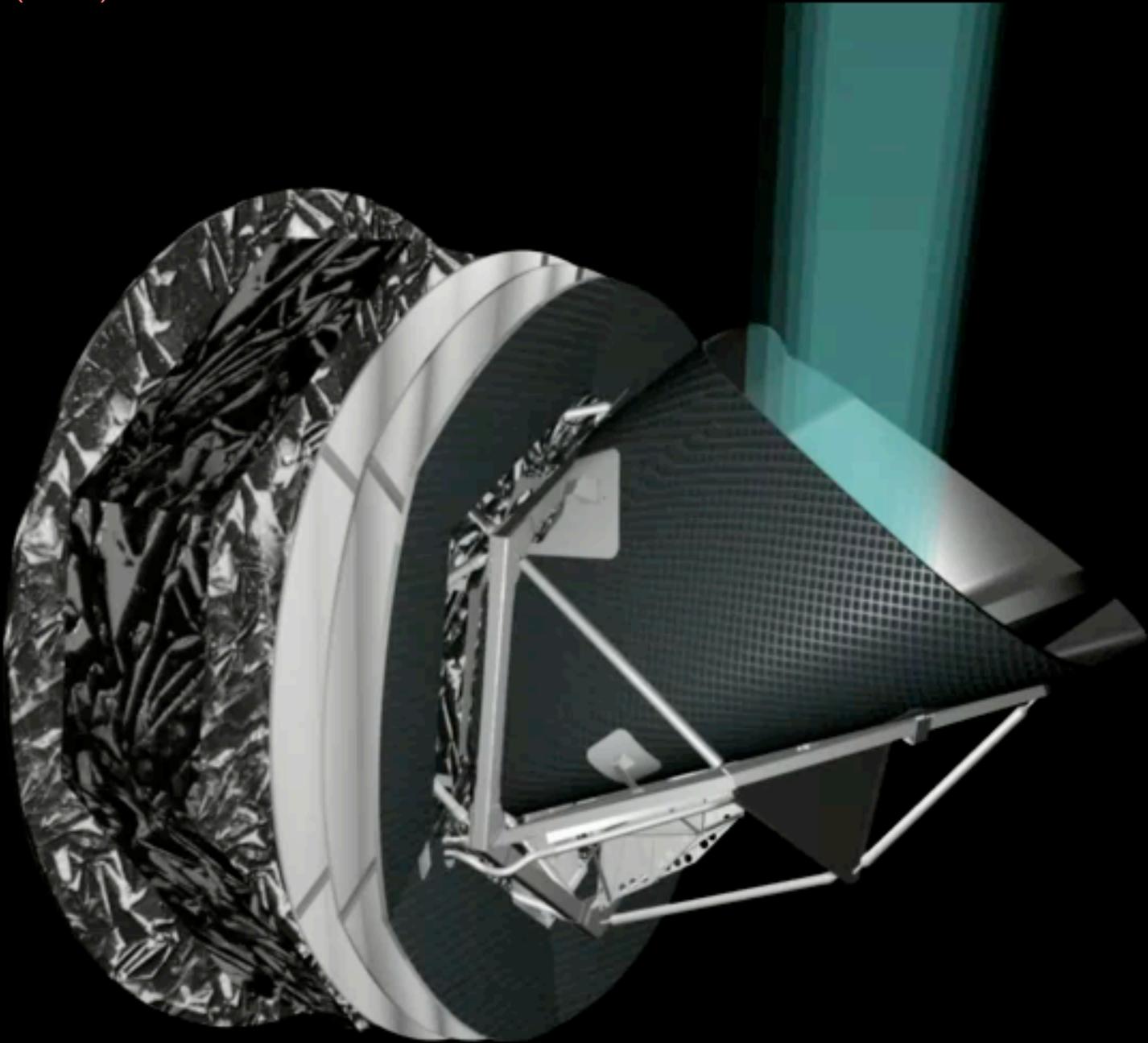
Anisotropias \sim arcmin
Aglomerados de galáxias
(Efeito Sunyaev-Zel'dovich térmico)

4000 deg² \rightarrow 1000 deg² !

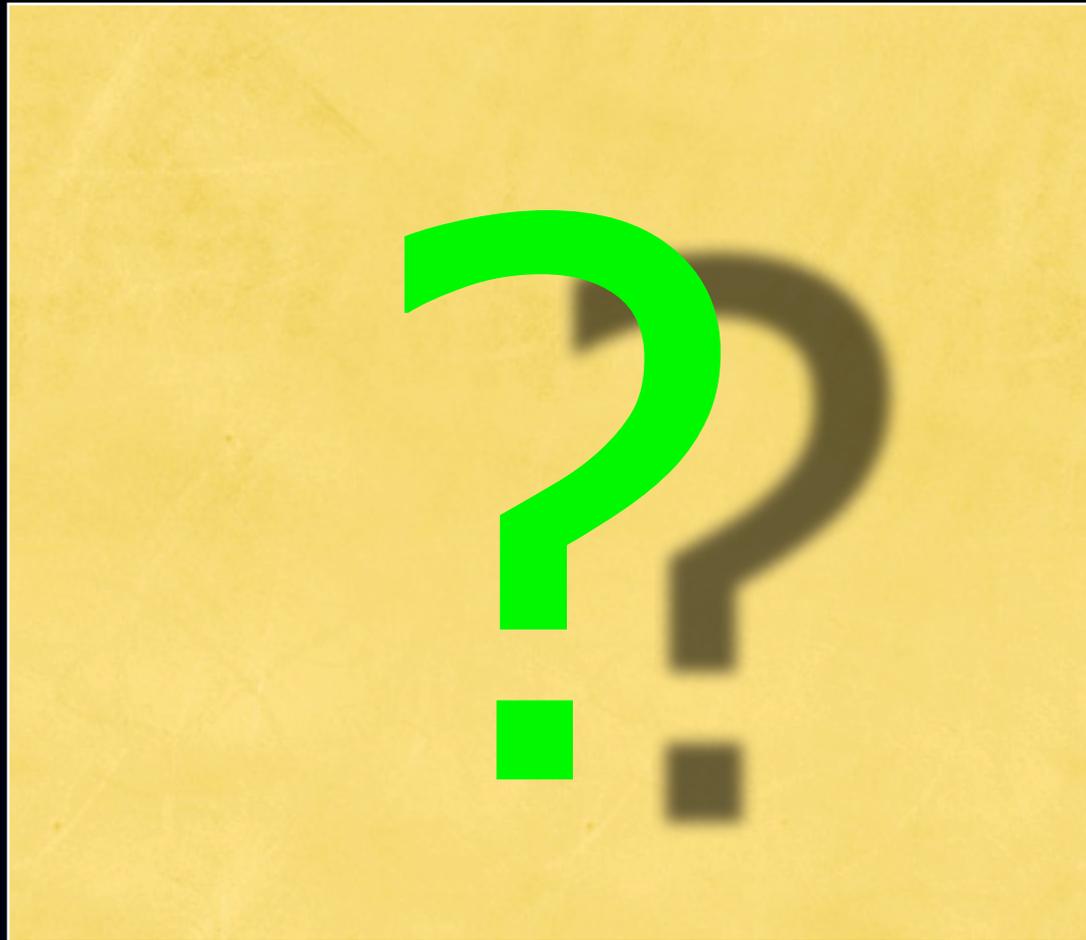


Atacama Cosmology Telescope

Anisotropias \sim arcmin
Aglomerados de galáxias
(Efeitos Sunyaev-Zel'dovich
térmico e cinético)

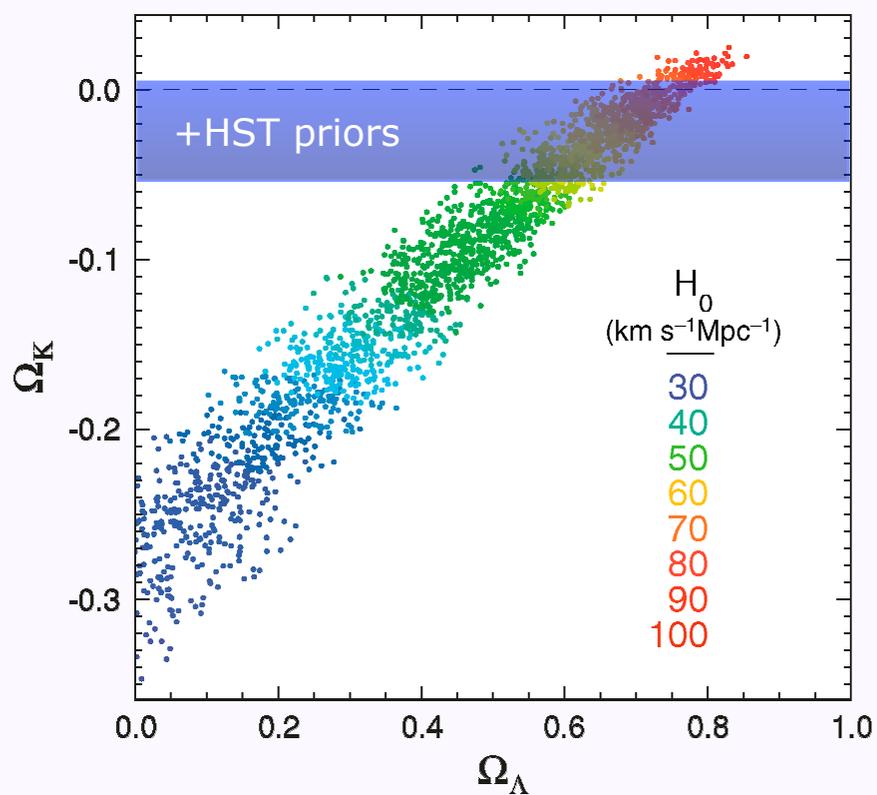
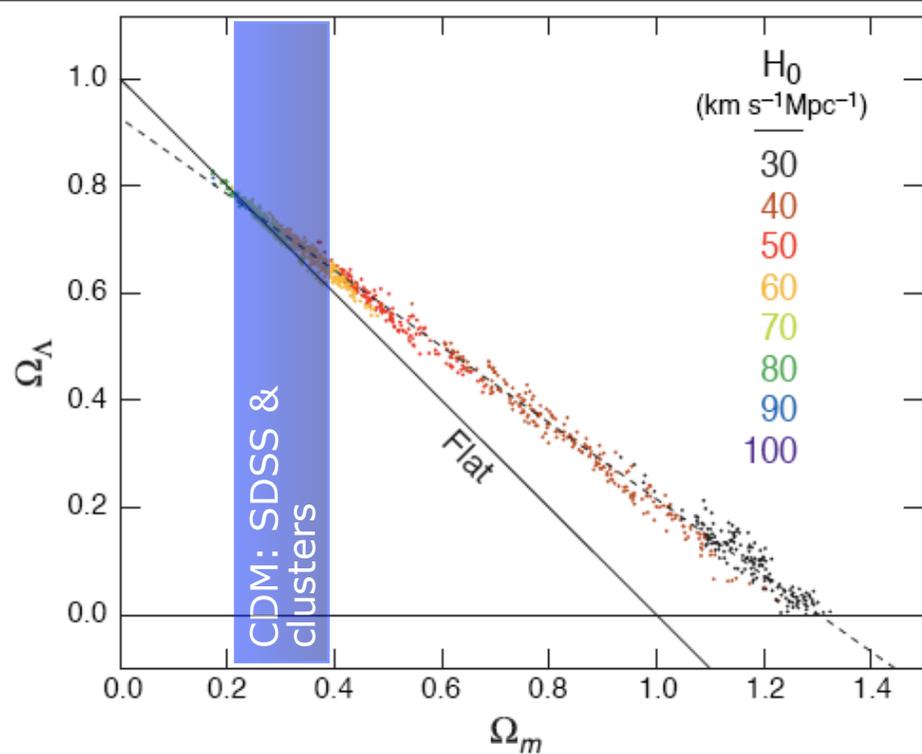
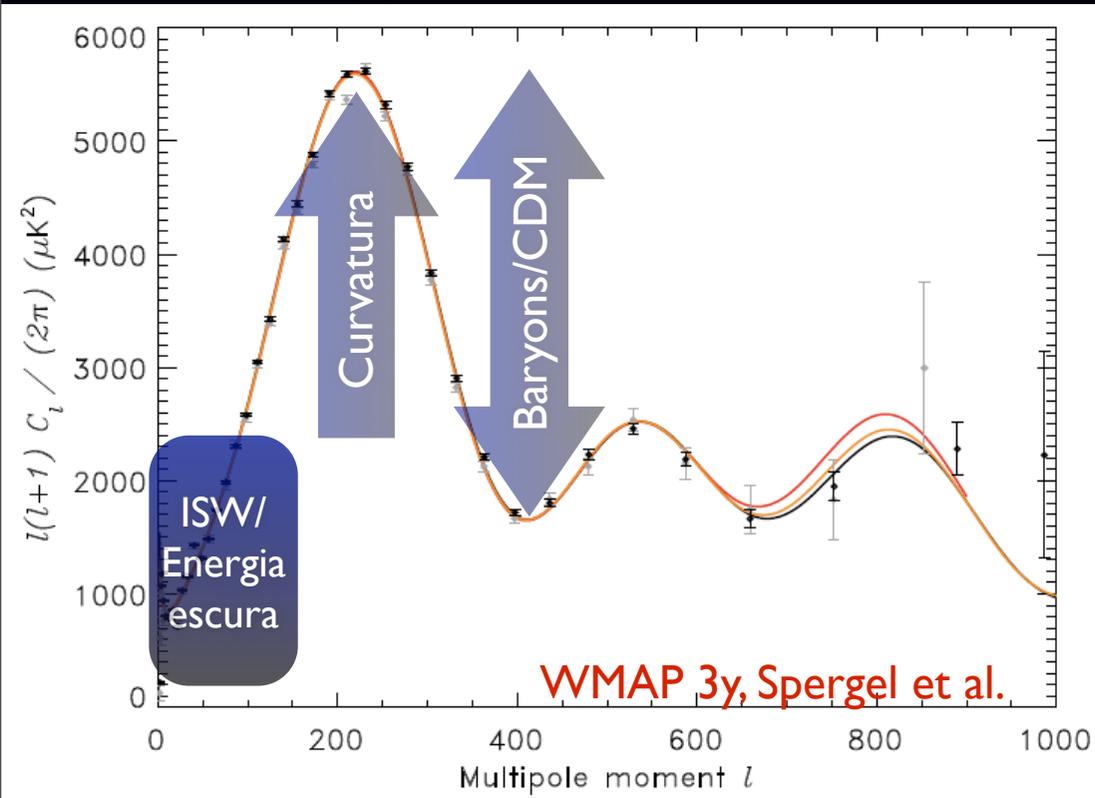


...e o futuro distante:
CMBPol (?)



Temperatura da RCF: “Cosmologia de Precisão”

H_0 ,
 Ω_{cdm} , Ω_{b} , Ω_{Λ} , Ω_{K} ,
 n_s , σ_8 ,
 etc.



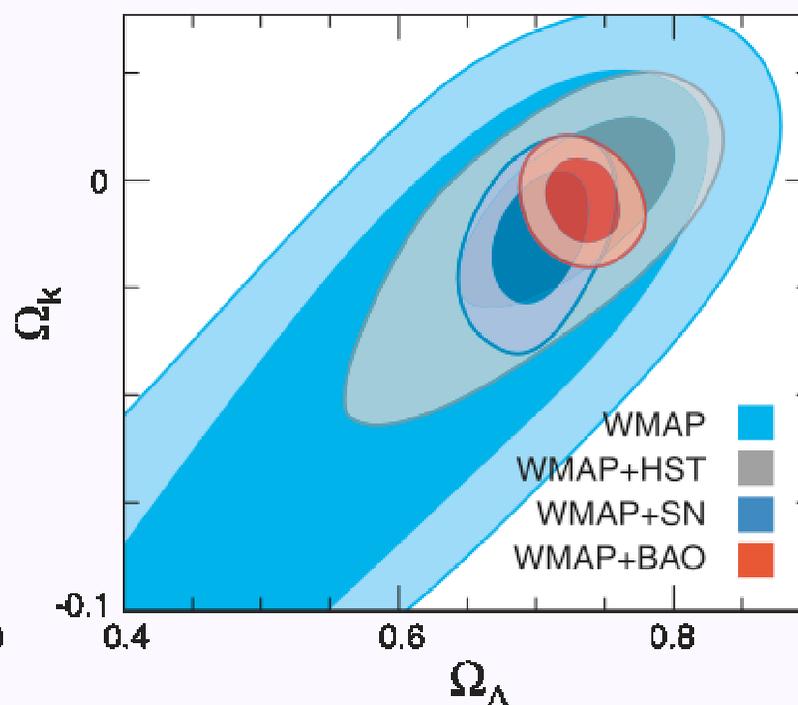
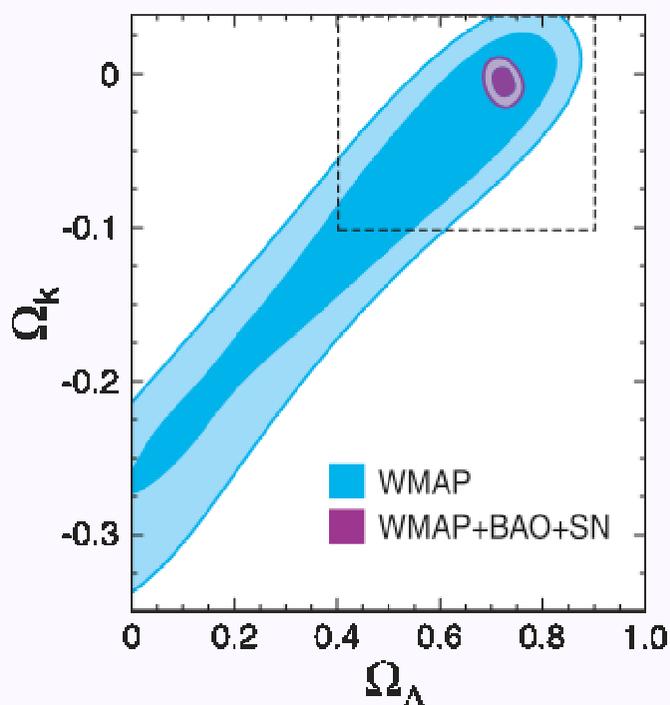
Situação atual (WMAP 5y)

Apenas WMAP-5y

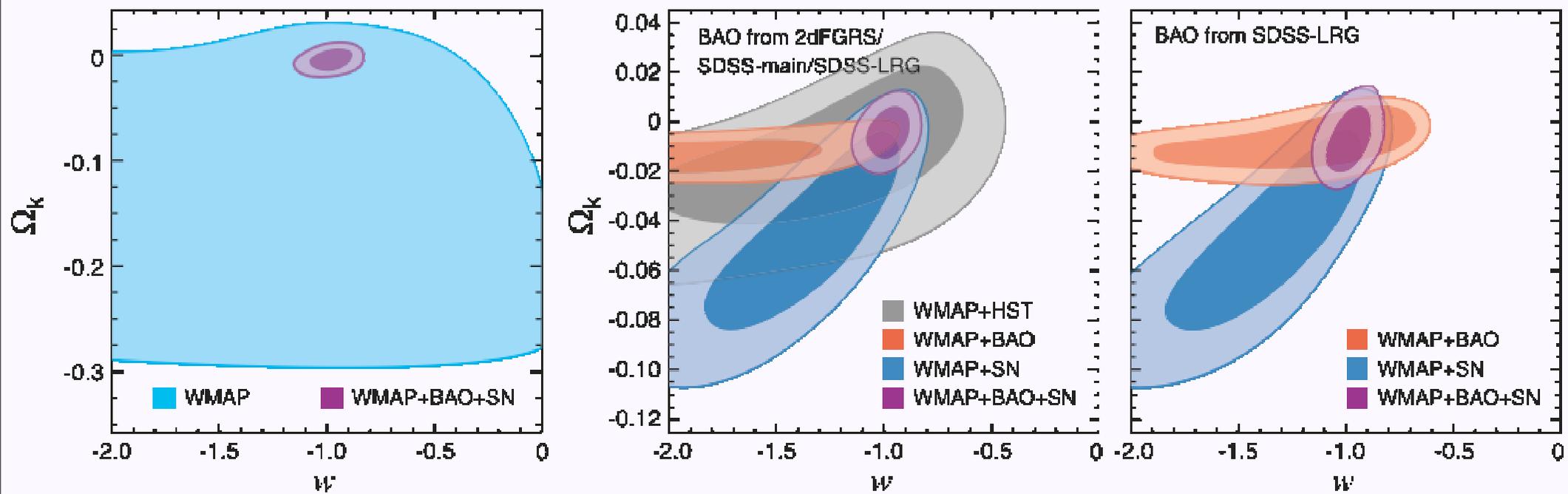
$$\begin{aligned}\Omega_b h^2 &= 0.02273 \pm 0.00062 \\ \Omega_c h^2 &= 0.1099 \pm 0.0062 \\ h &= 0.719 \pm 0.027 \\ \sigma_8 &= 0.796 \pm 0.036 \\ \tau &= 0.087 \pm 0.017 \\ n_s &= 0.963 \pm 0.015\end{aligned}$$

WMAP-5y + SN + BAO

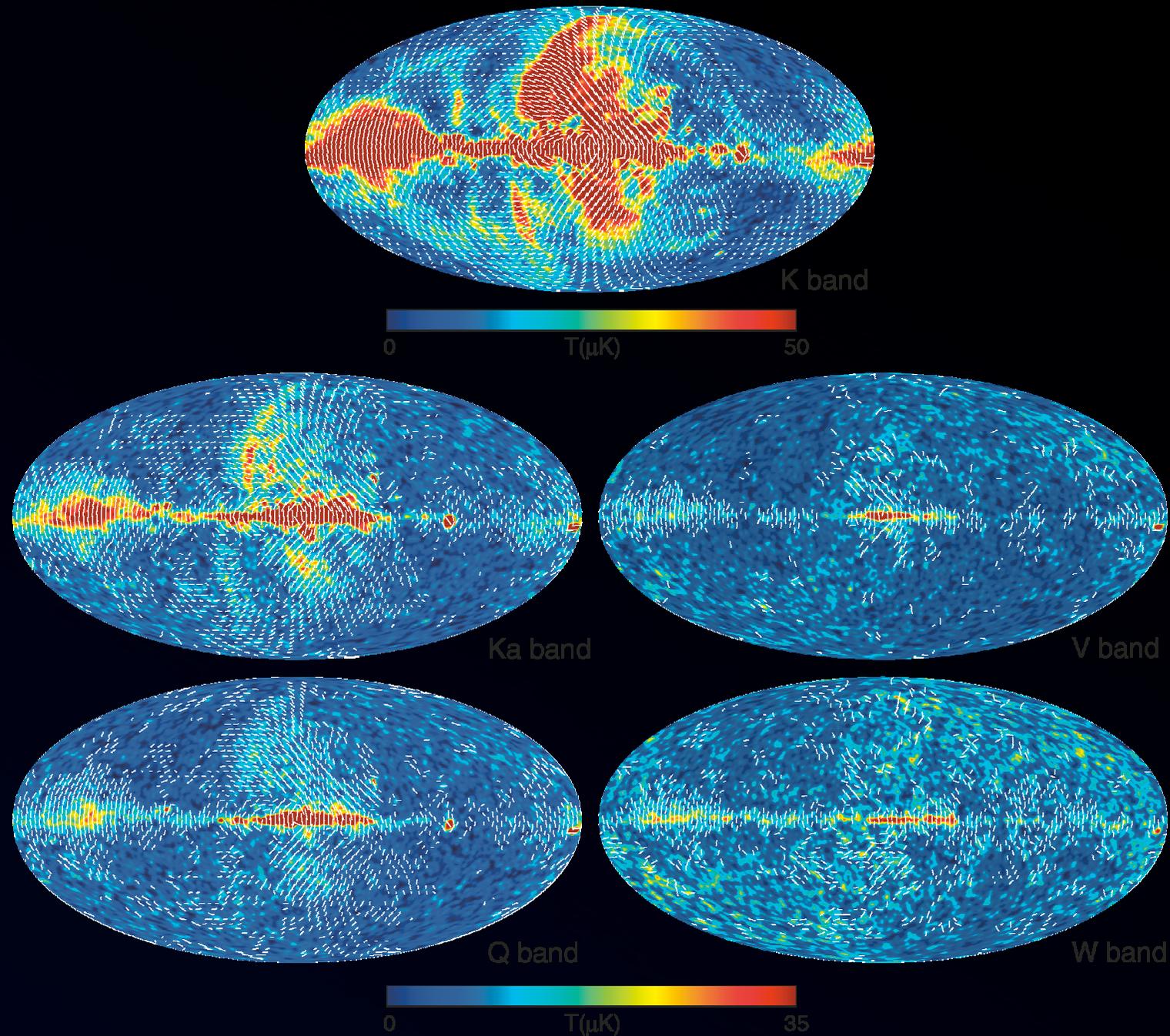
$$\begin{aligned}\Omega_b h^2 &= 0.02265 \pm 0.00059 \\ \Omega_c h^2 &= 0.1143 \pm 0.0034 \\ h &= 0.701 \pm 0.013 \\ \sigma_8 &= 0.776 \pm 0.031 \\ \tau &= 0.084 \pm 0.016 \\ n_s &= 0.96 \pm 0.0135\end{aligned}$$



RCF, por si só, não diz **quase nada** sobre energia escura:



Mas até o momento quase todos esses limites se devem apenas à **temperatura**, já que a polarização...



- Polarização ~linear: modos **Q** (N-S, E-W) e **U** (SW-NW, SW-NE):

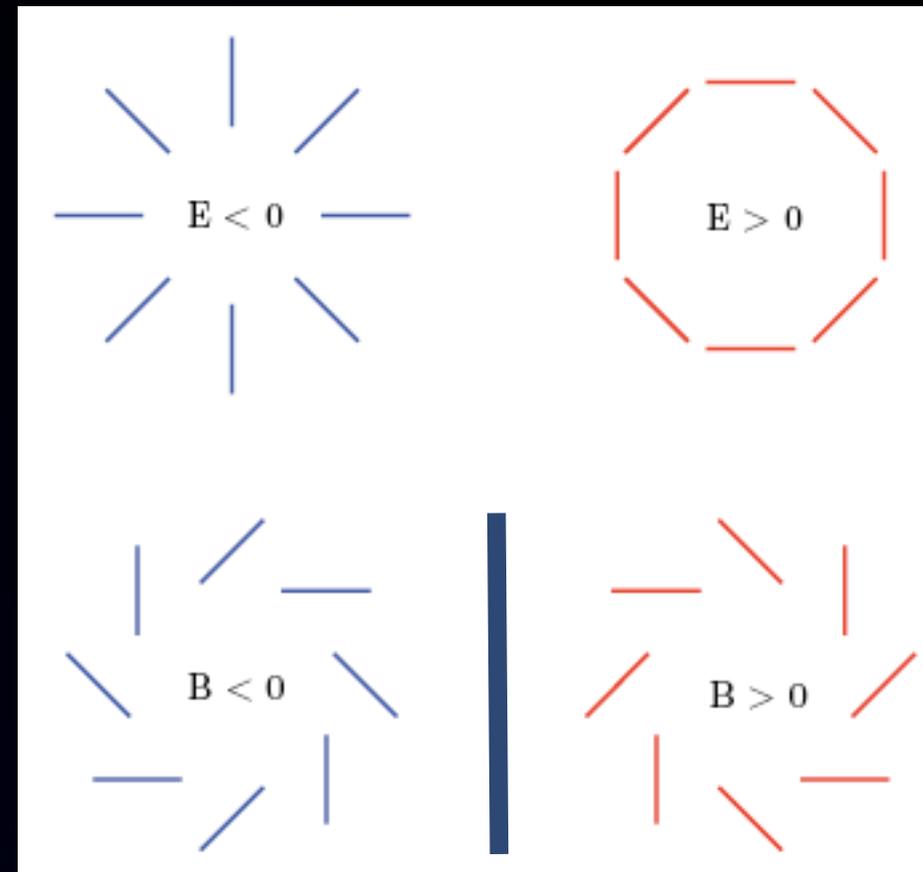


- Os parâmetros de Stokes dizem respeito a um sistema de referência explícito

- Muitas vezes é mais útil representar a polarização em termos do modo GRADIENTE (“elétrico”, E) e ROTACIONAL (“magnético”, B)

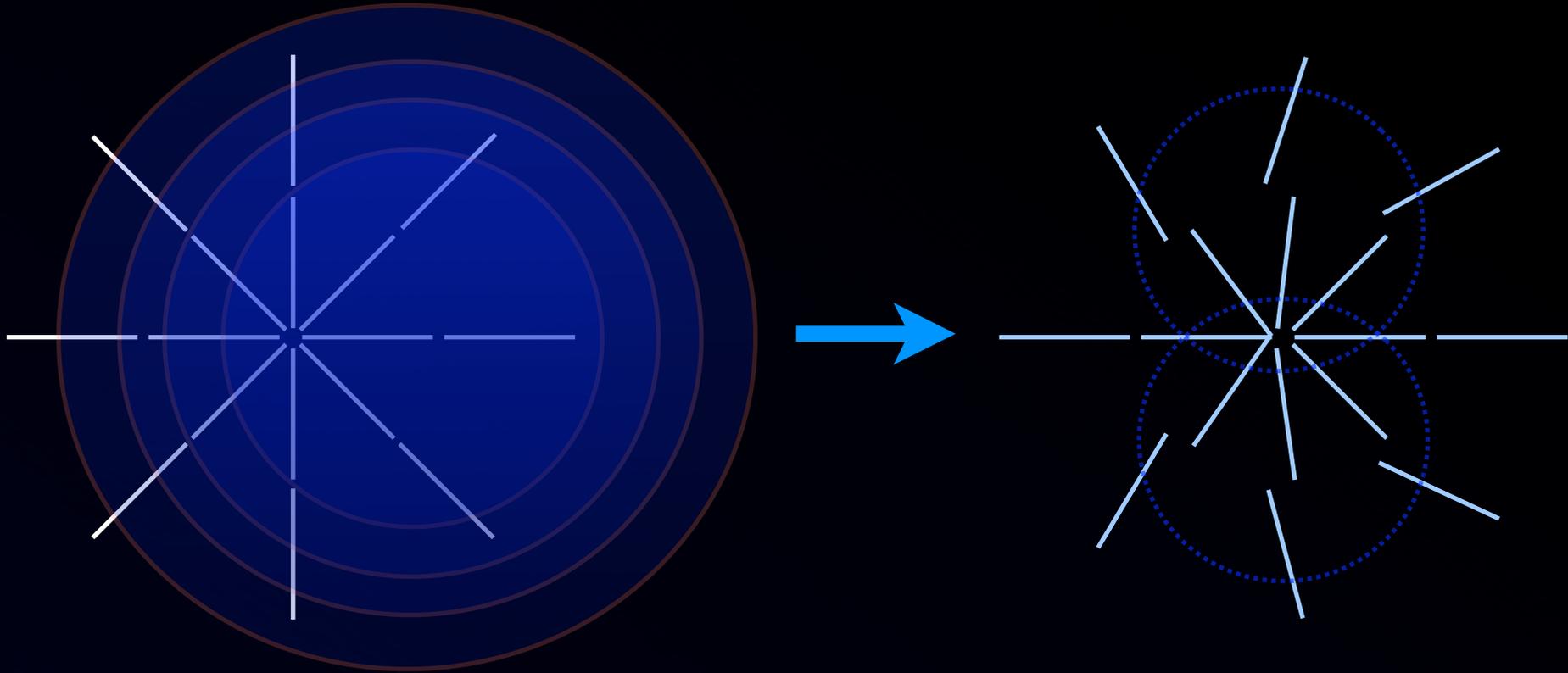
- O modo E não muda sob paridade (espelhamento)

- O modo B muda de sinal (roda de 90°) sob paridade



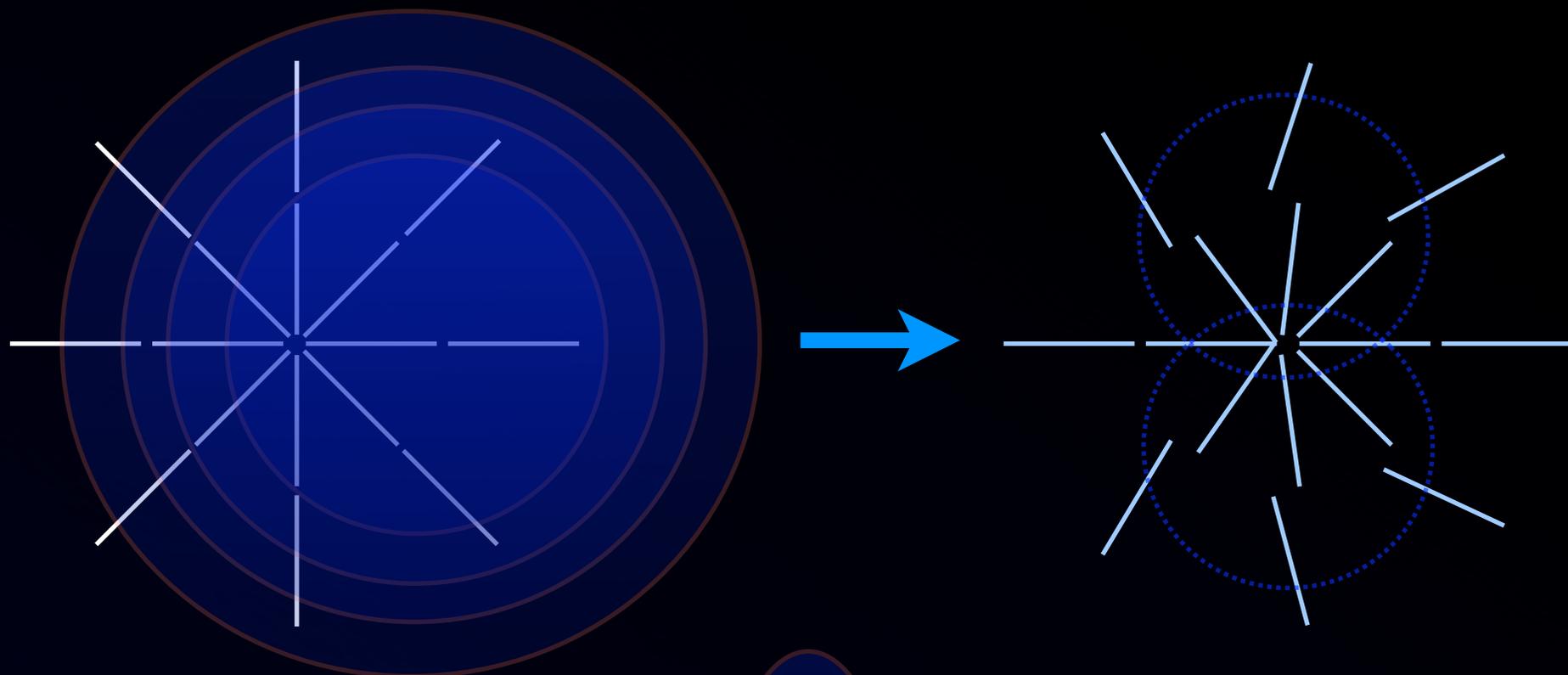
Modo B da polarização:

- Lente fraca sobre modo E

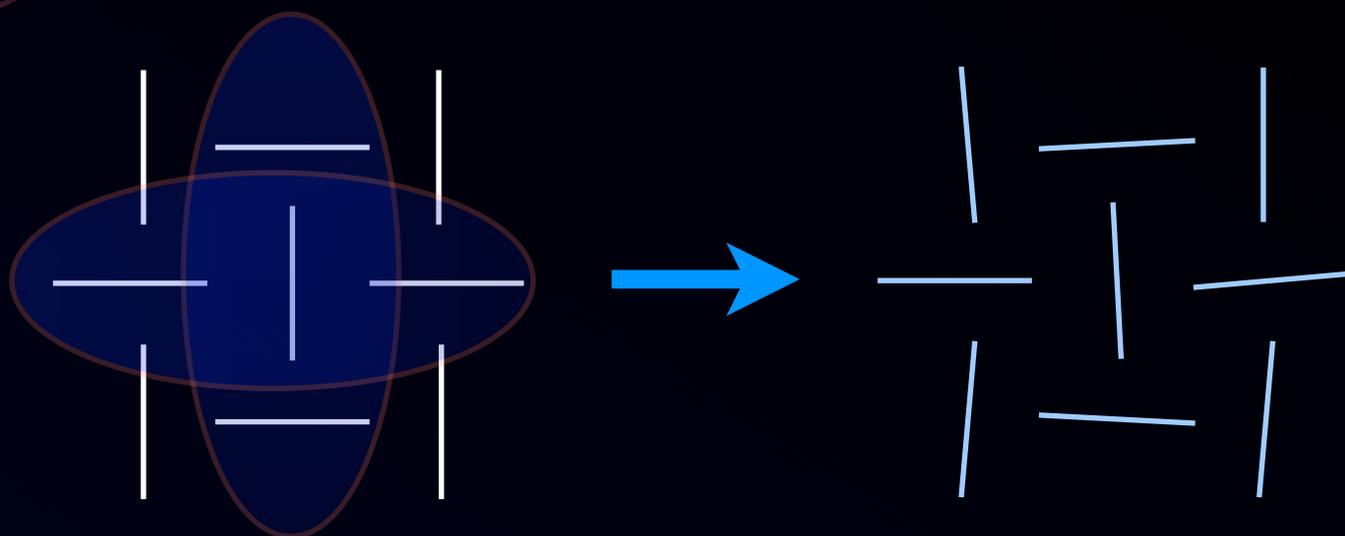


Modo B da polarização:

- Lente fraca sobre modo E

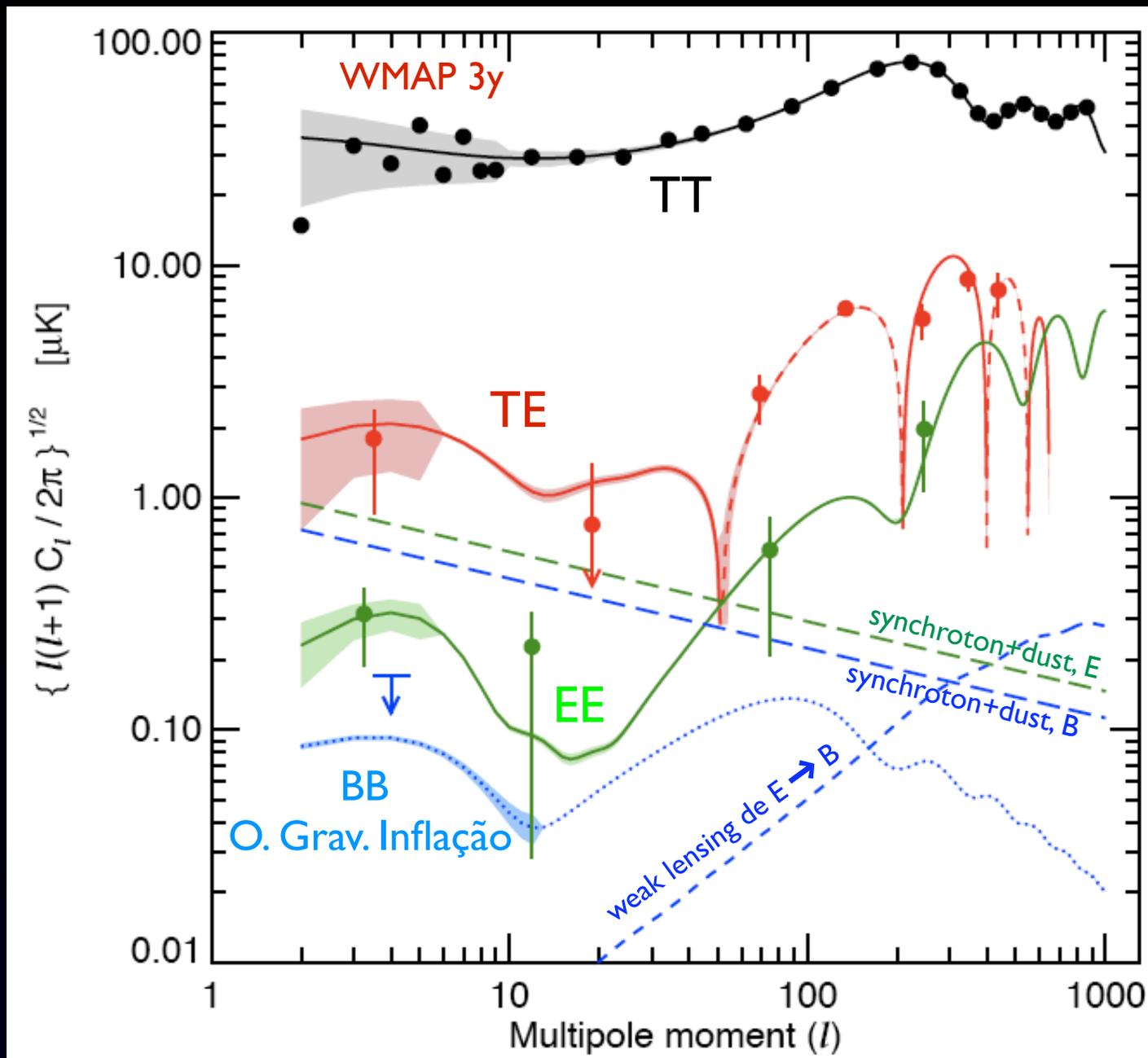


- Ondas gravitacionais



Polarização da RCF:

Tudo que já sabemos
+
ondas grav. inflacion.
inflação v. defeitos
reionização
campos magnéticos
adiabat./isocurvatura
etc. etc. etc.

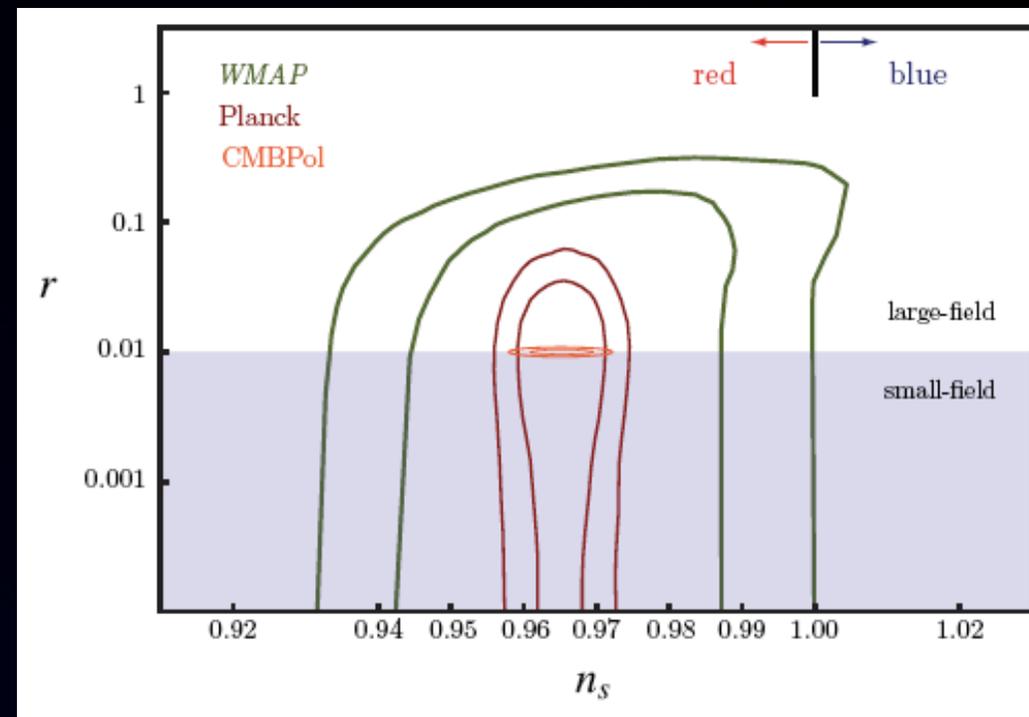
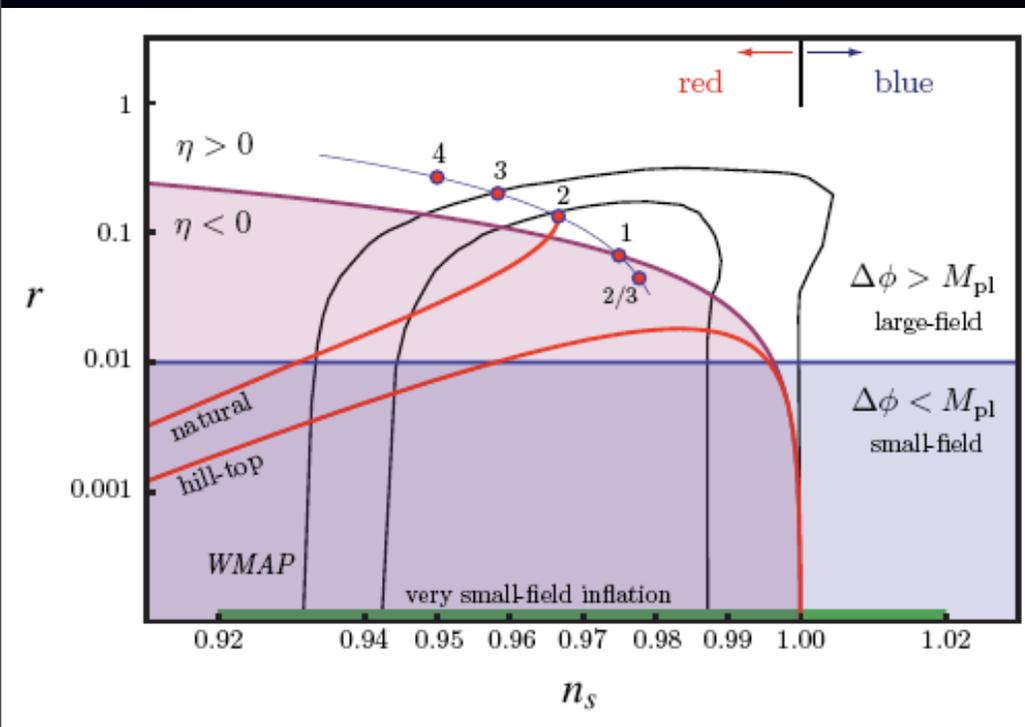
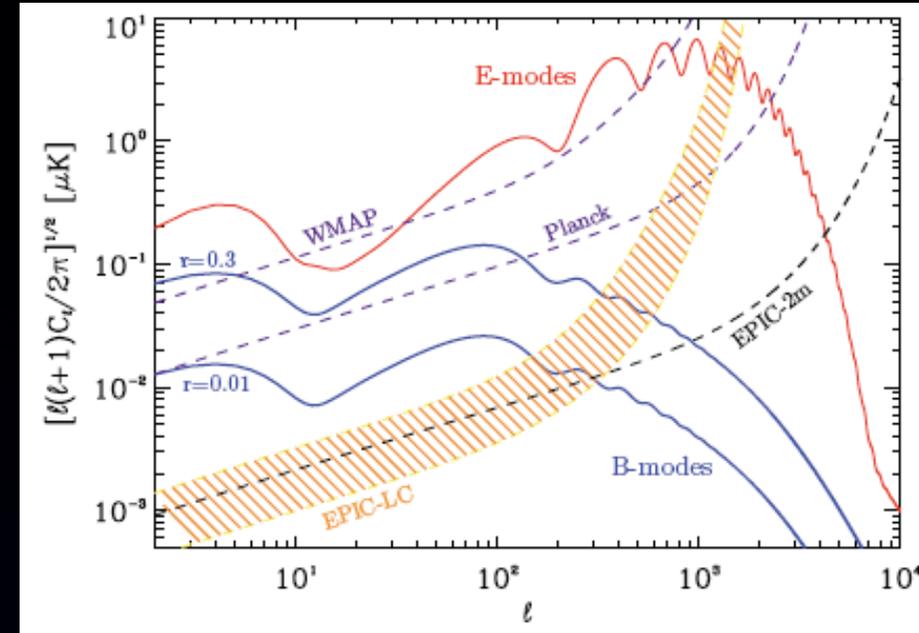


CMBPol etc.: para quê?

CMBPol Mission Concept Study -
D. Baumann et al., 0811.3919

I. Descobertas que o CMBPol poderia fazer:

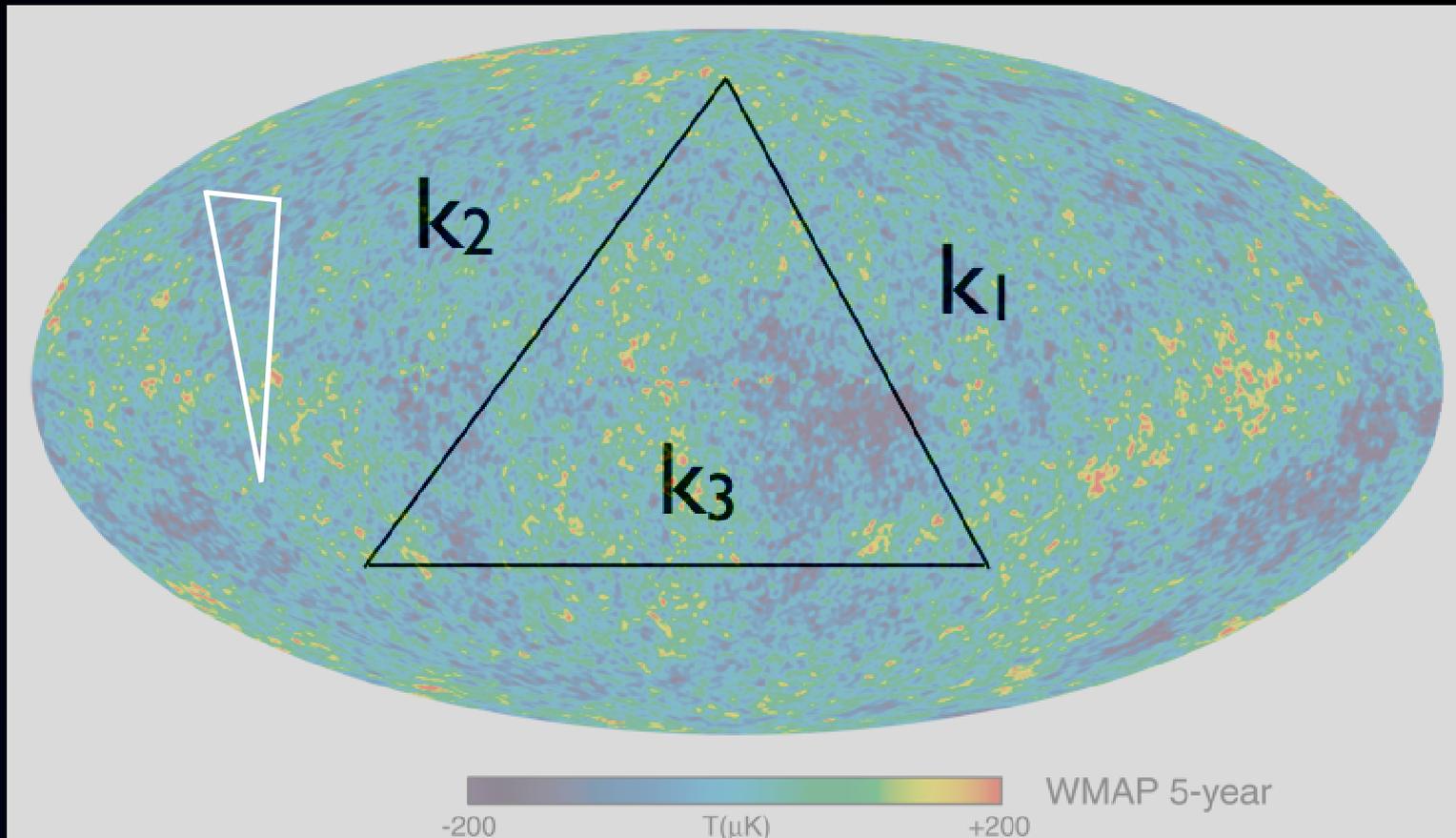
- Ondas gravitacionais (modo B):
Inflação, ricochete, pre-big-bang,
string gas, ekpirose, ...
- OBSERVAÇÃO DE UMA NOVA
ESCALA DE ENERGIA: 10^3 GeV,
 10^9 GeV, 10^{12} GeV, 10^{15} GeV ???...



- Não-gaussianidades

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) f_{\text{NL}} F(k_1, k_2, k_3)$$

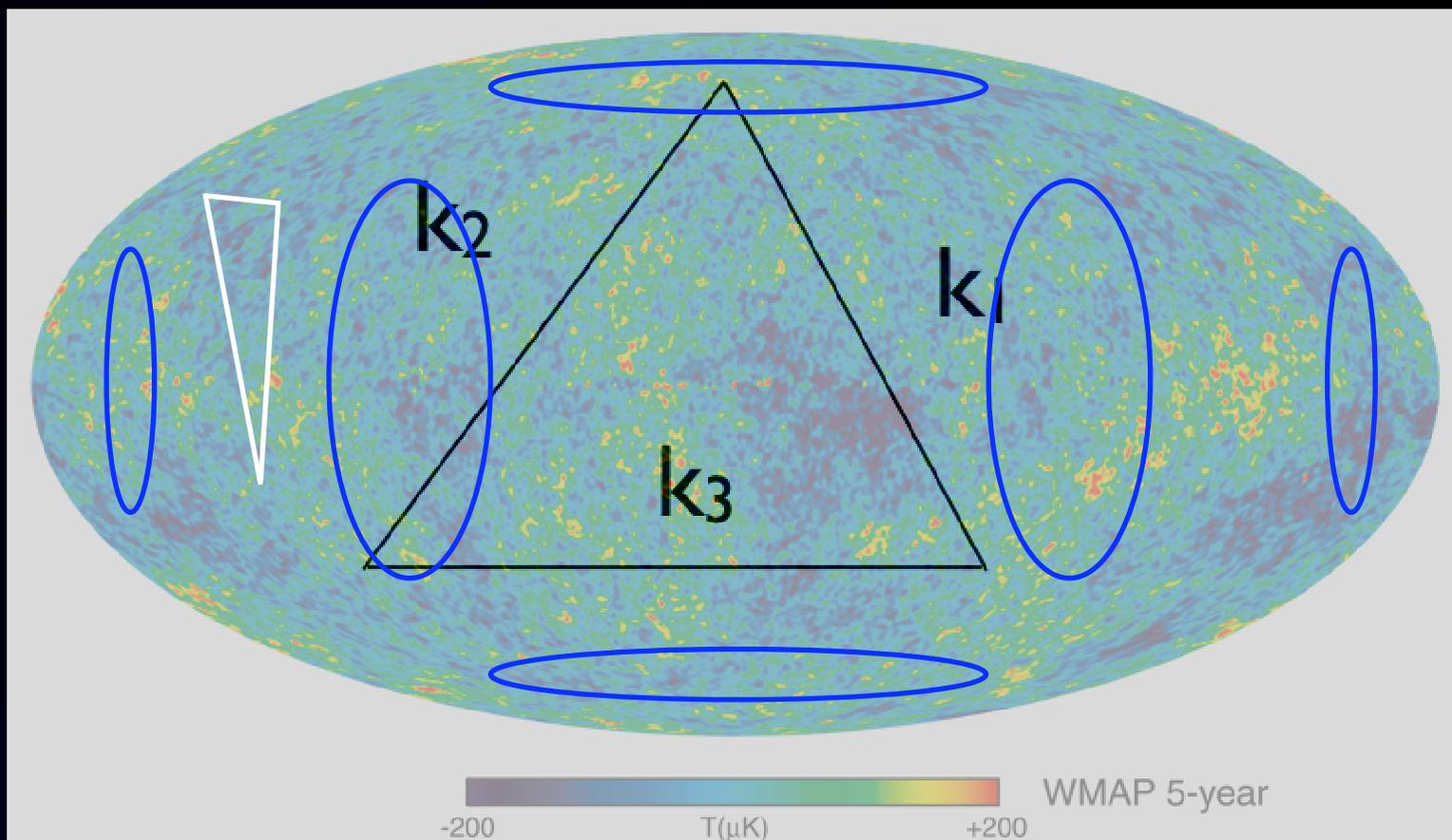
$$\zeta(\mathbf{x}) = \zeta_G(\mathbf{x}) + f_{\text{NL}}^{\text{local}} (\zeta_G(\mathbf{x})^2 - \langle \zeta_G(\mathbf{x})^2 \rangle)$$



- Não-gaussianidades

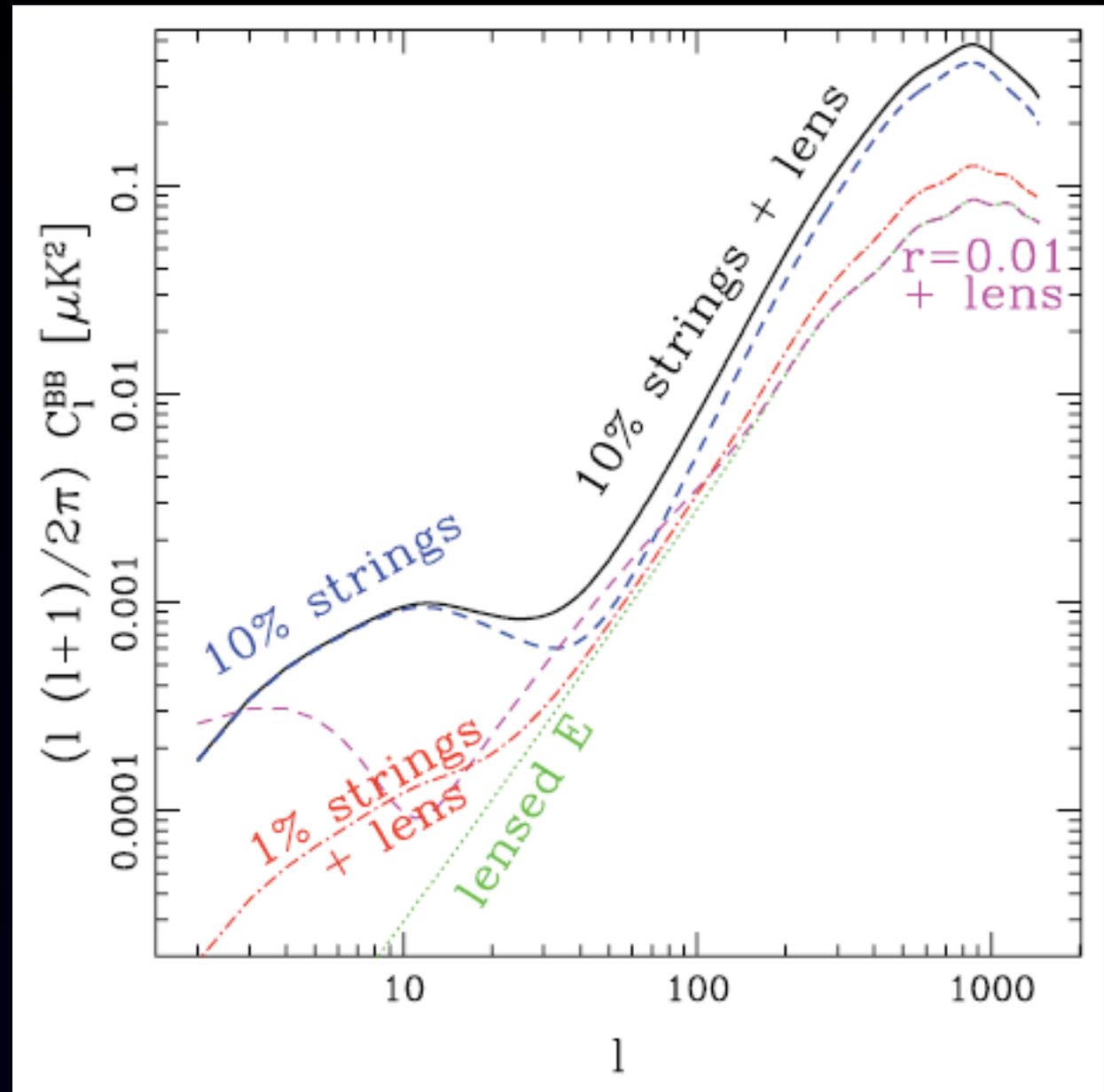
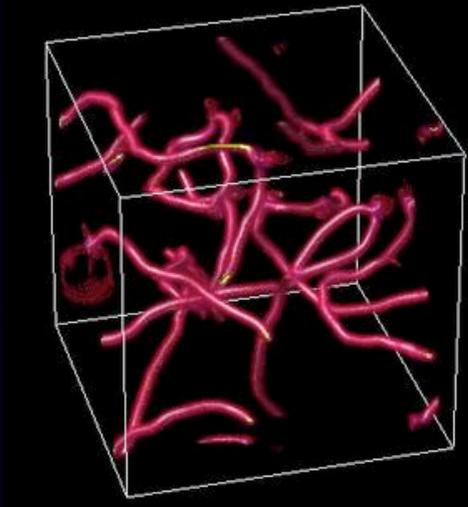
$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) f_{\text{NL}} F(k_1, k_2, k_3)$$

$$\zeta(\mathbf{x}) = \zeta_G(\mathbf{x}) + f_{\text{NL}}^{\text{local}} (\zeta_G(\mathbf{x})^2 - \langle \zeta_G(\mathbf{x})^2 \rangle)$$



- Topologia

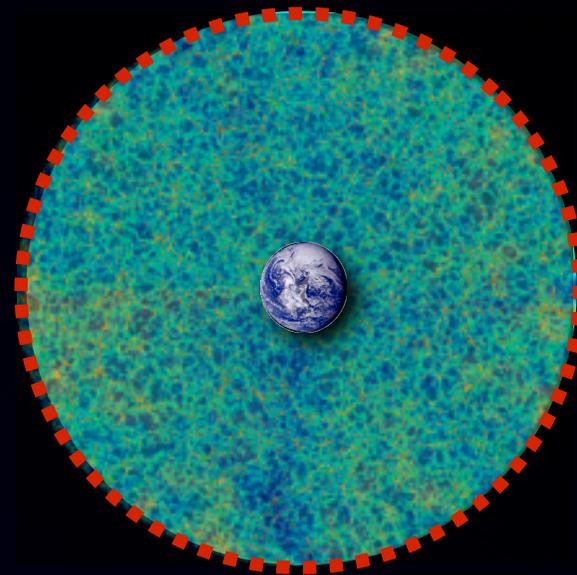
- Defeitos topológicos: cordas cósmicas, texturas (frustradas ou não)...



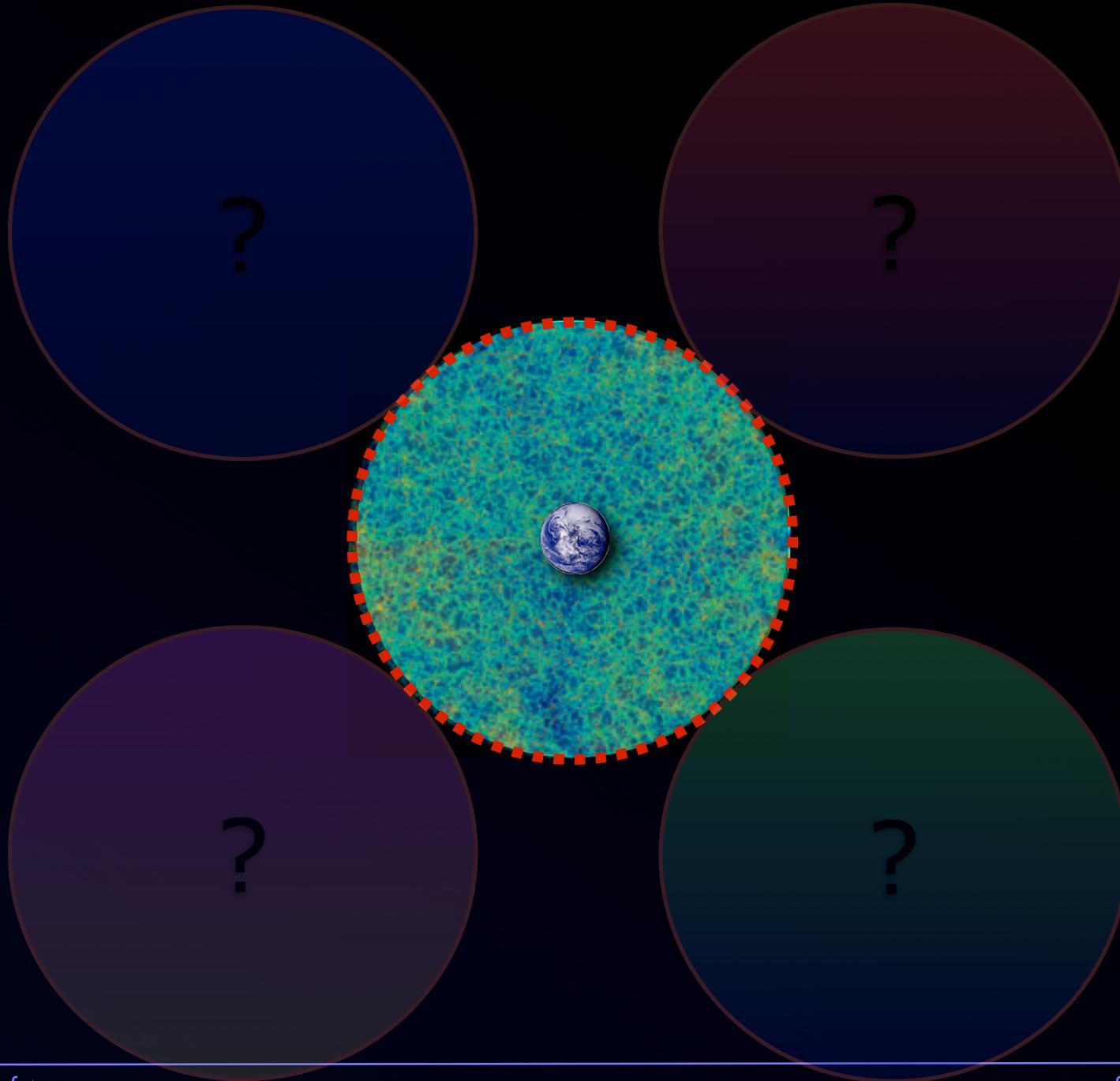
O que a RCF
nunca vai poder
responder...



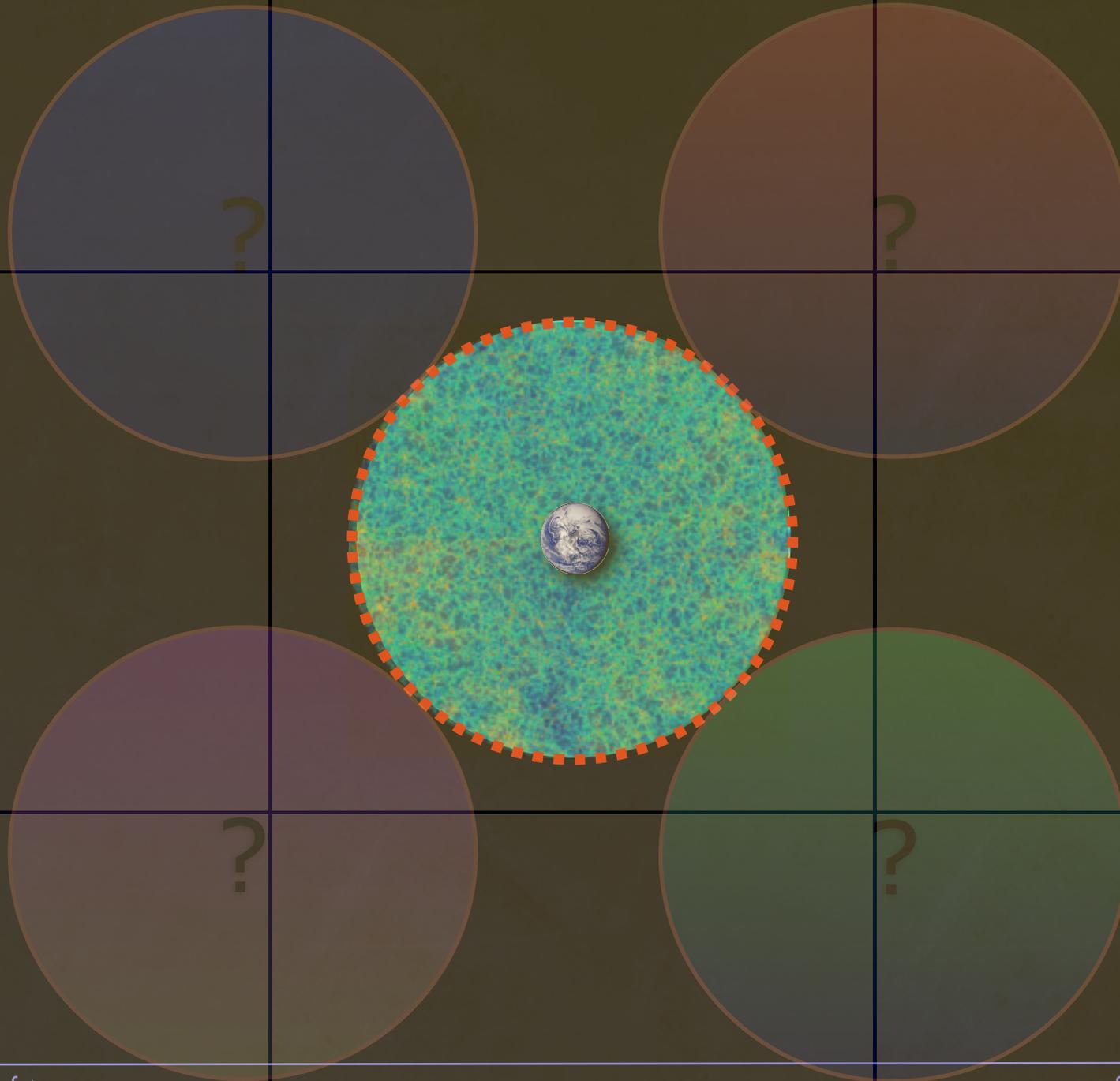
Causalidade limita o alcance da radiação de fundo: só podemos enxergar até um certo horizonte - a superfície de último espalhamento



Causalidade limita o alcance da radiação de fundo: só podemos enxergar até um certo horizonte - a superfície de último espalhamento



Causalidade limita o alcance da radiação de fundo: só podemos enxergar até um certo horizonte - a superfície de último espalhamento



Causalidade limita o alcance da radiação de fundo: só podemos enxergar até um certo horizonte - a superfície de último espalhamento



Lições

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- A RCF é o nosso mais poderoso “farol” iluminando o passado

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Lições

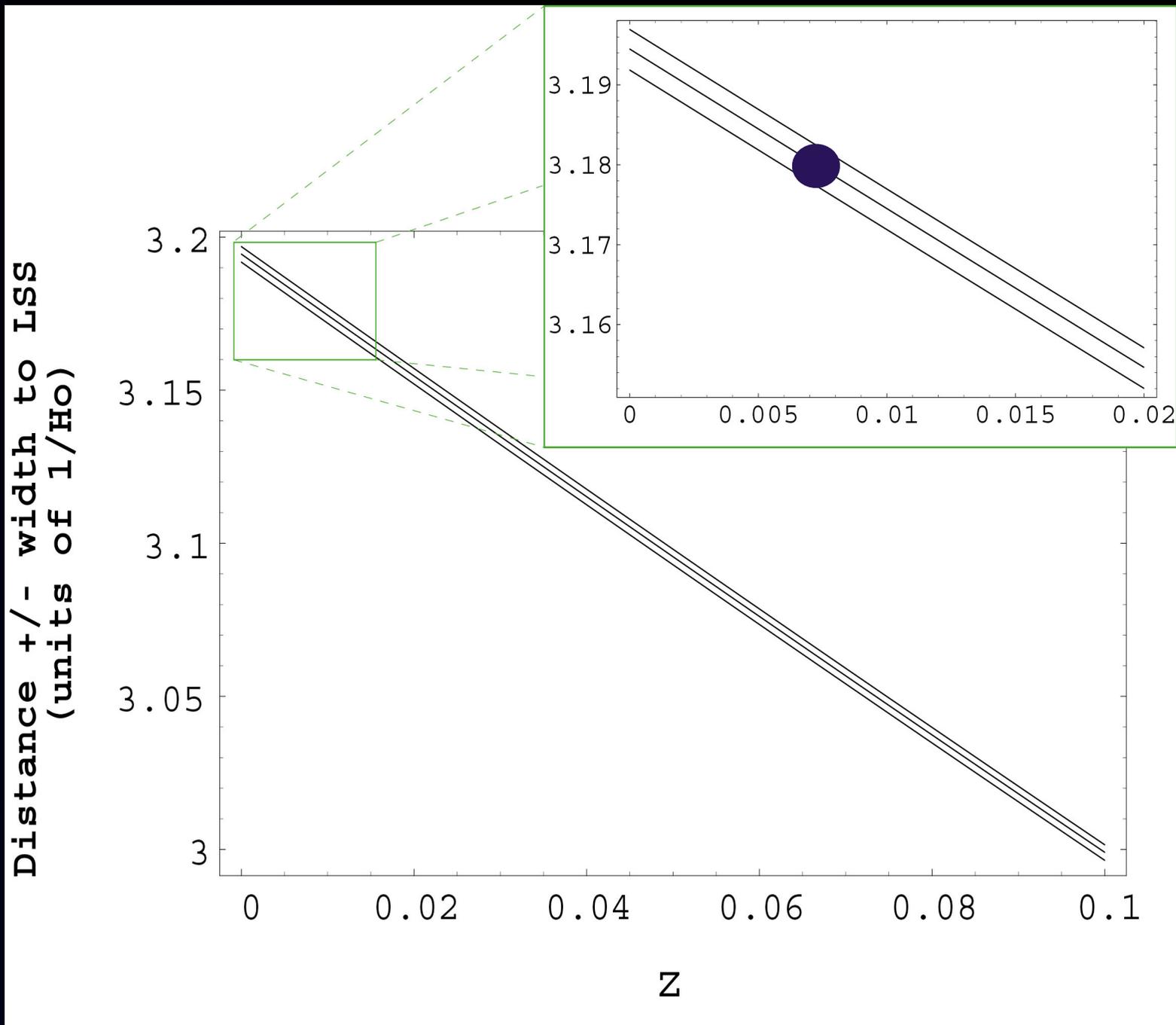
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Lições

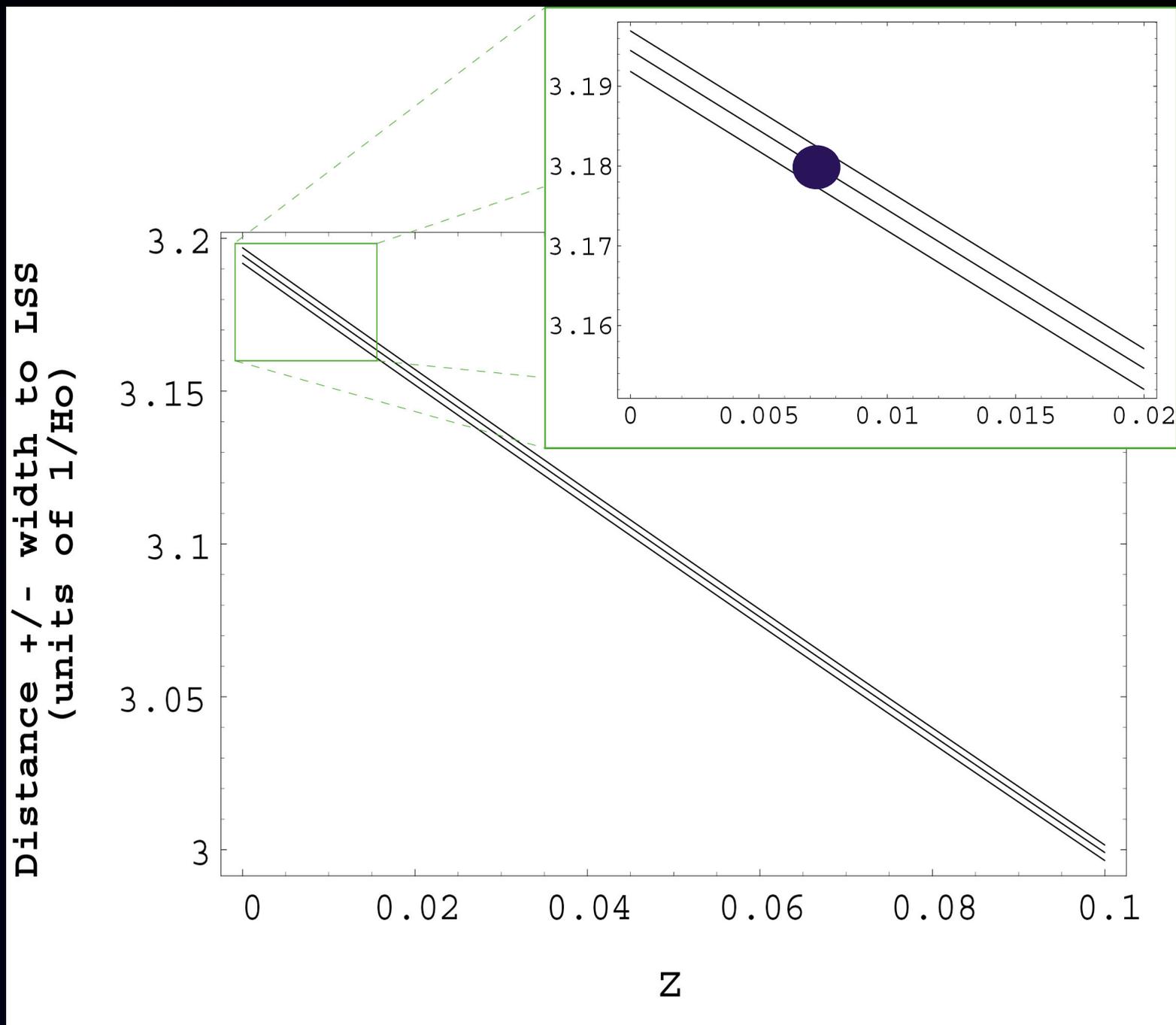
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- Com as futuras observações poderemos espiar **diretamente** o que aconteceu nas primeiras frações de segundo de vida do universo! (Escala de energia **inimagináveis!**) **SPT, ACT, Planck, CMBPol**

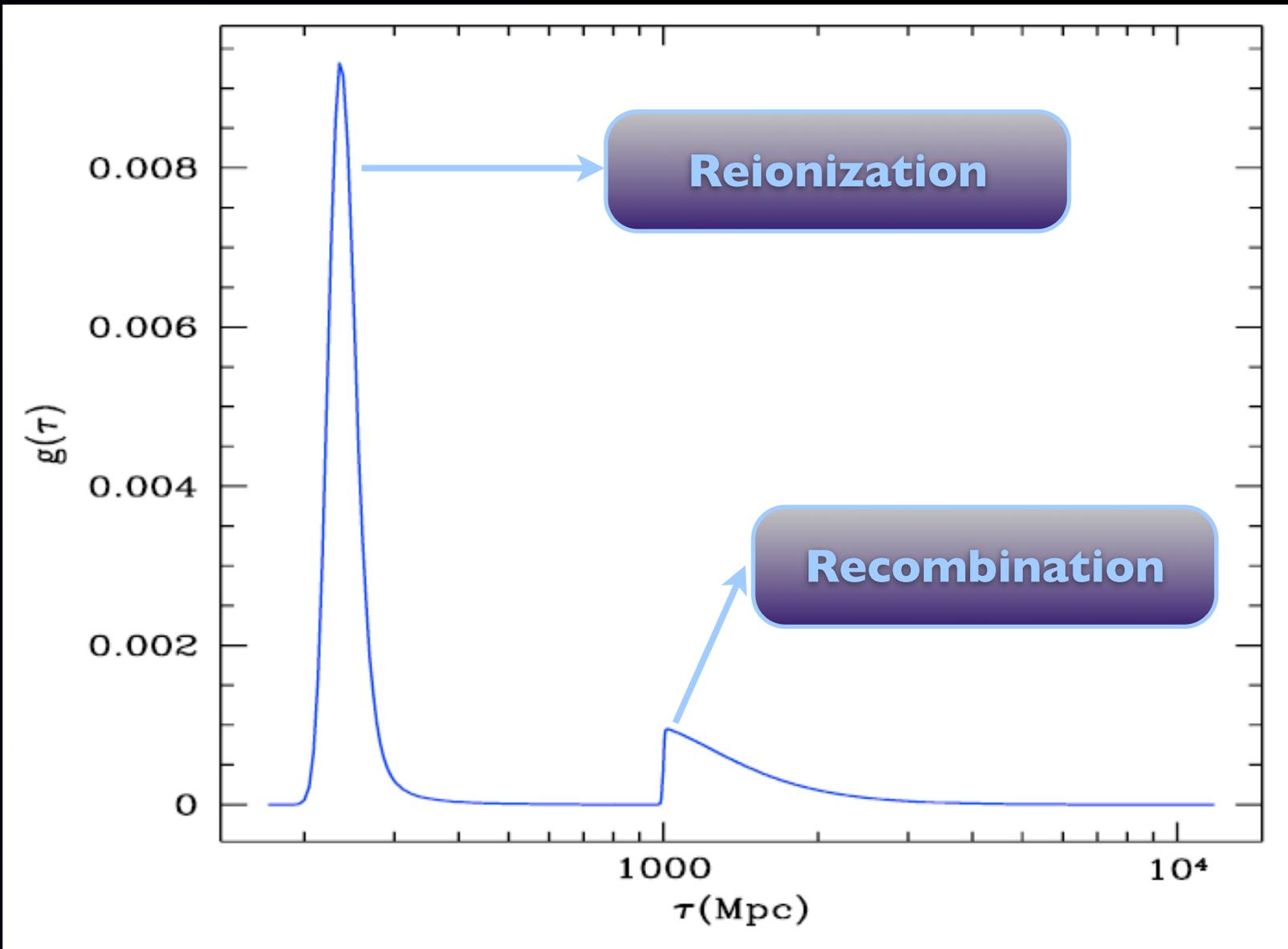
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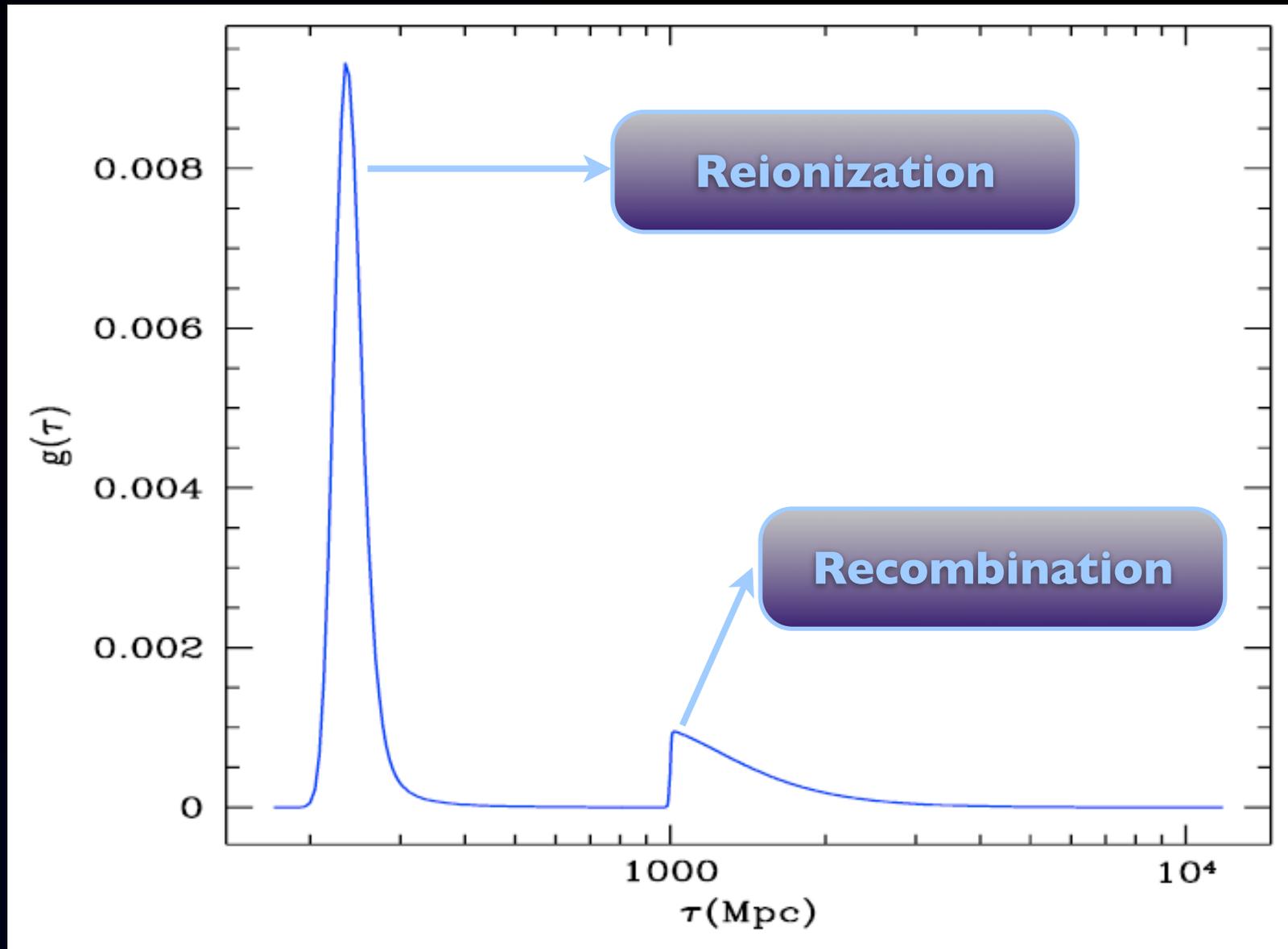
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- ... Mas em última análise, a **causalidade** das leis da Física frustram nossa ambição de conhecer o todo: temos que nos contentar com a visão do **universo local**. E além disso.....?



Largura da superfície de último espalhamento (como f. de z)







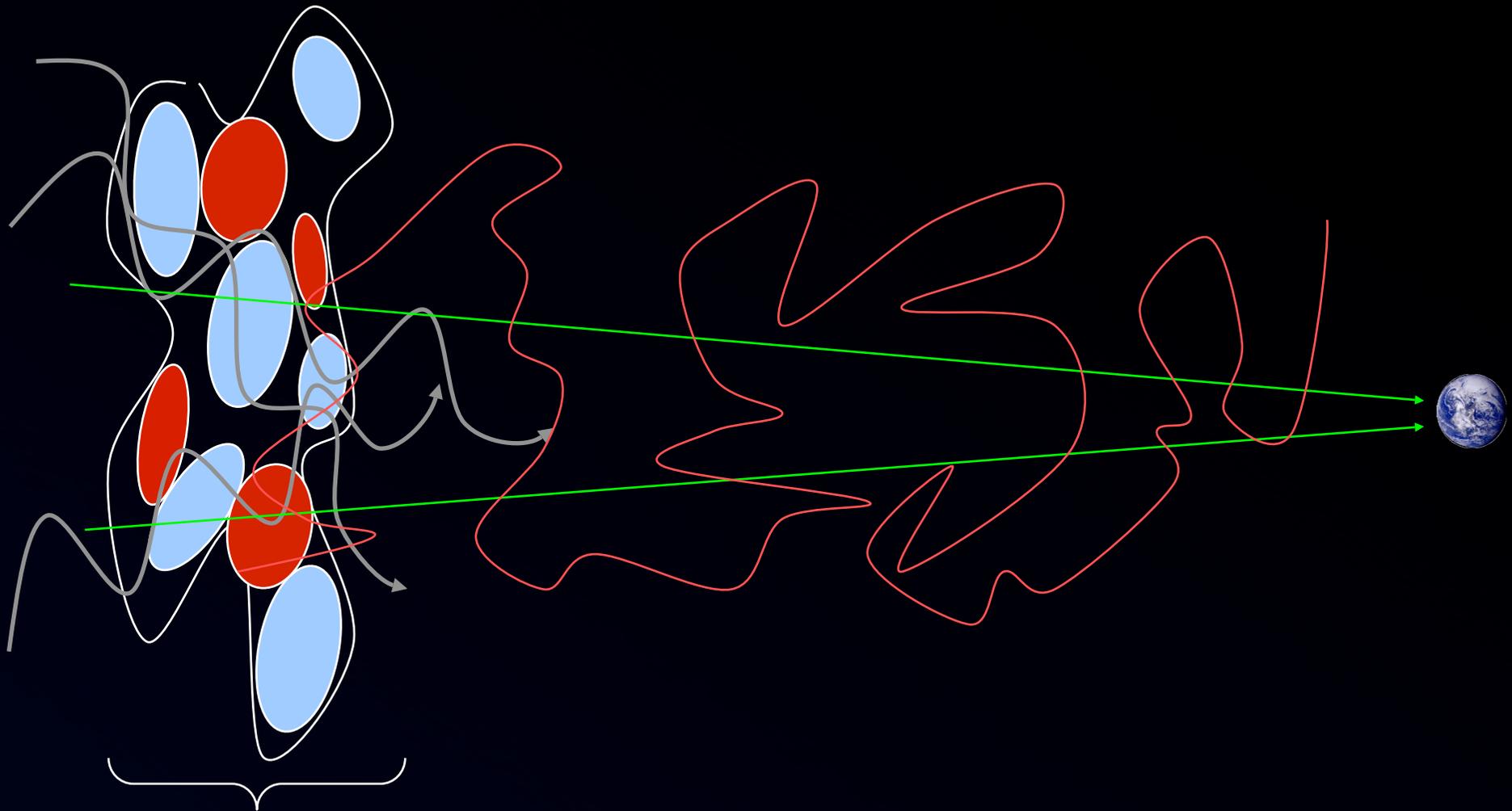
Principais fontes de polarização primárias ($z \sim 1100$) e secundárias ($z < \sim 900$): elétrons livres

$$d\tau = \sigma_T n_e d\eta$$



Principais fontes de polarização primárias ($z \sim 1100$) e secundárias ($z < \sim 900$): elétrons livres

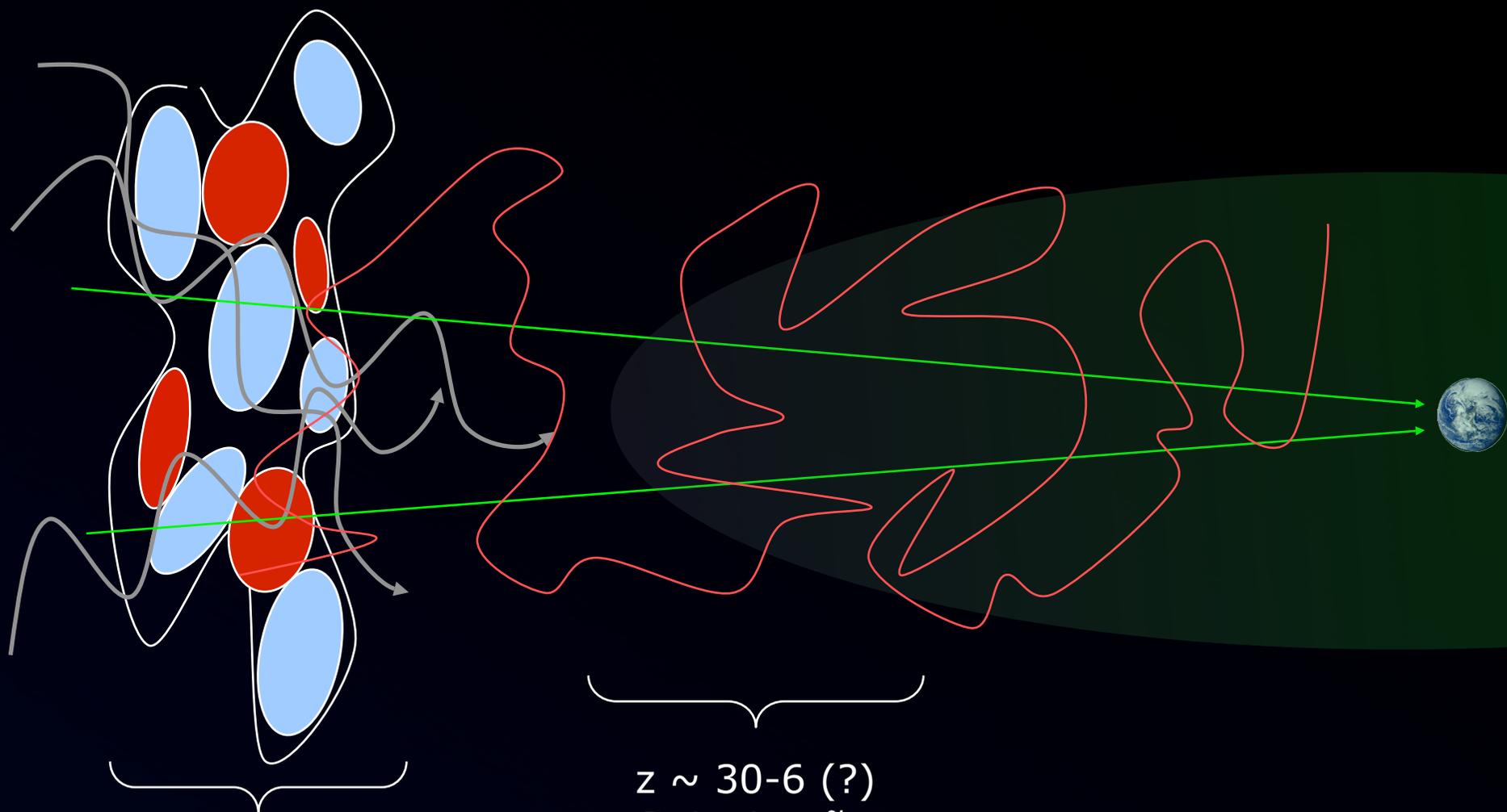
$$d\tau = \sigma_T n_e d\eta$$



Primárias:
 $z \sim 1100$
@ SUE

Principais fontes de polarização primárias ($z \sim 1100$) e secundárias ($z < \sim 900$): elétrons livres

$$d\tau = \sigma_T n_e d\eta$$

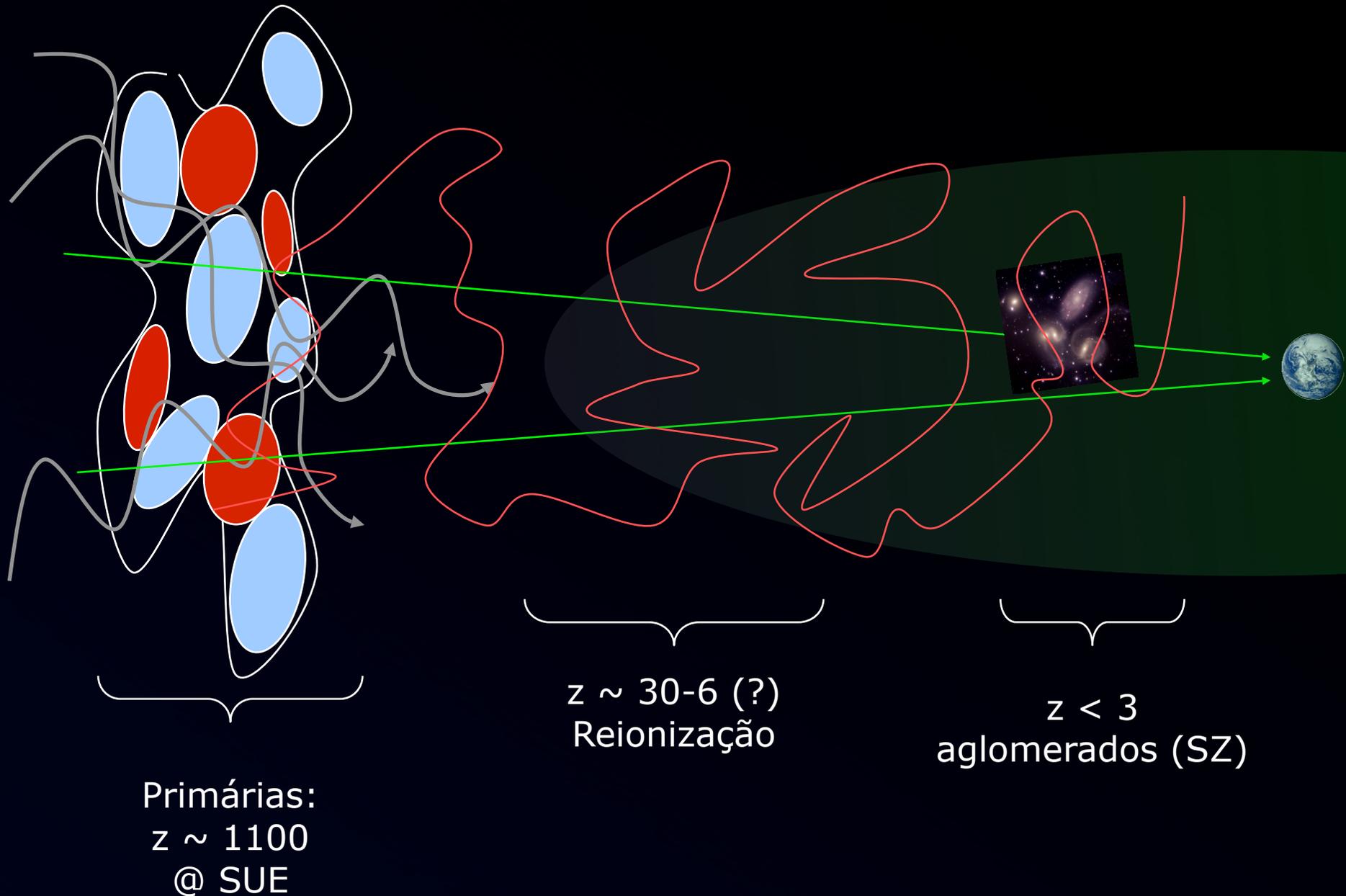


Primárias:
 $z \sim 1100$
@ SUE

$z \sim 30-6$ (?)
Reionização

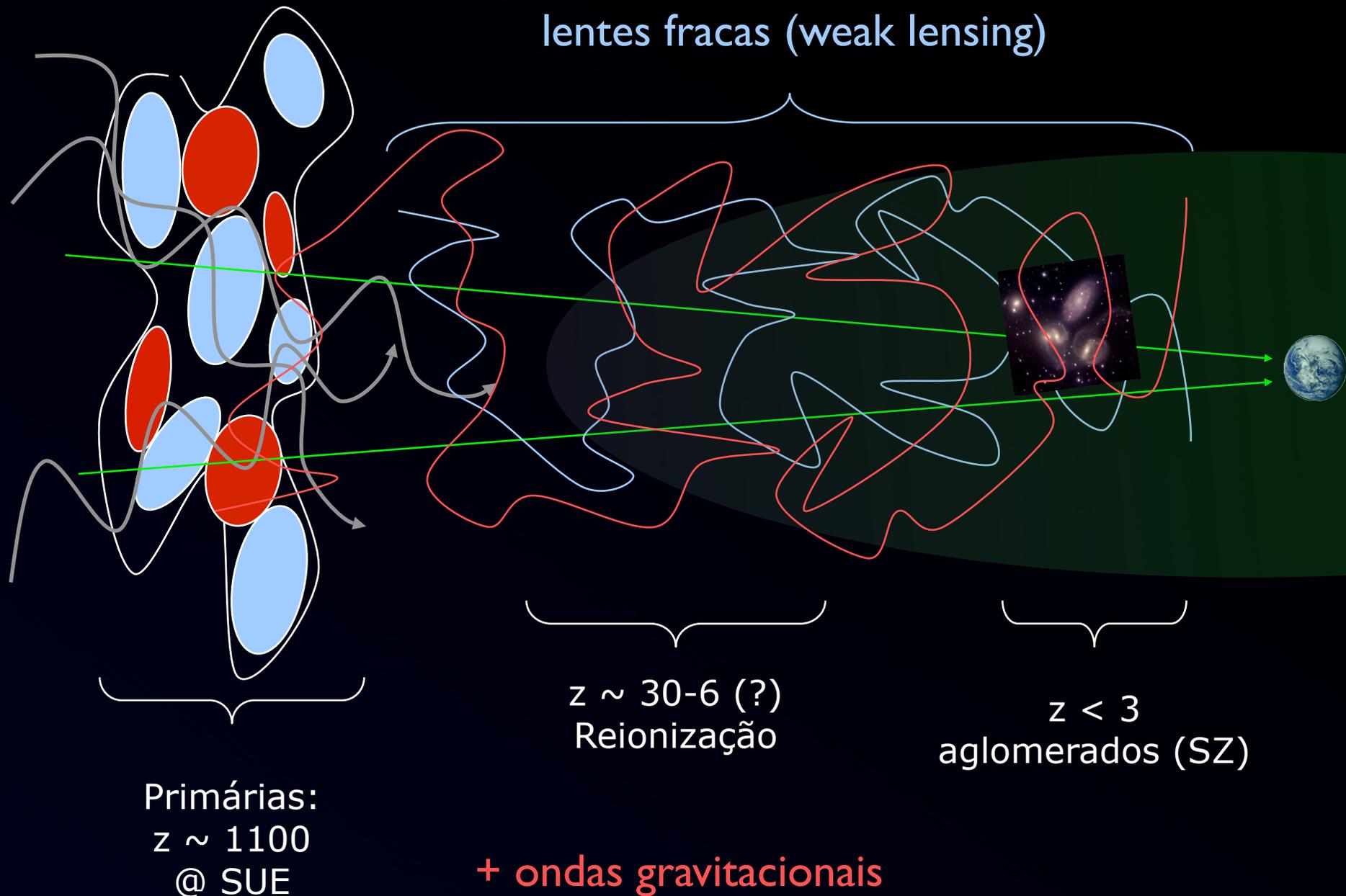
Principais fontes de polarização primárias ($z \sim 1100$) e secundárias ($z < \sim 900$): elétrons livres

$$d\tau = \sigma_T n_e d\eta$$

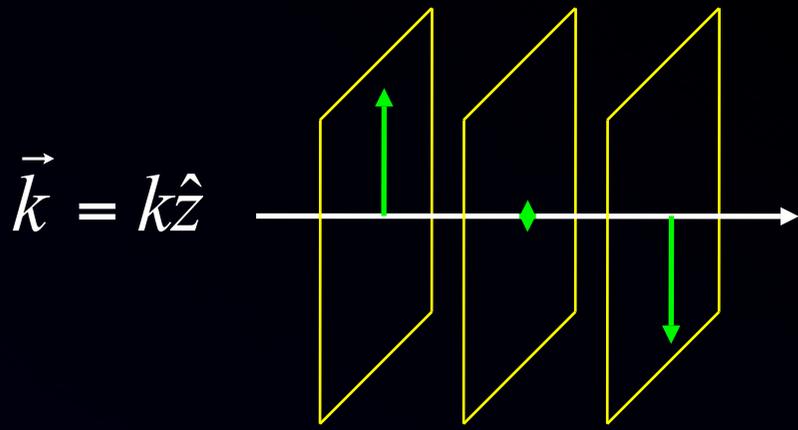


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Polarization: brief overview I

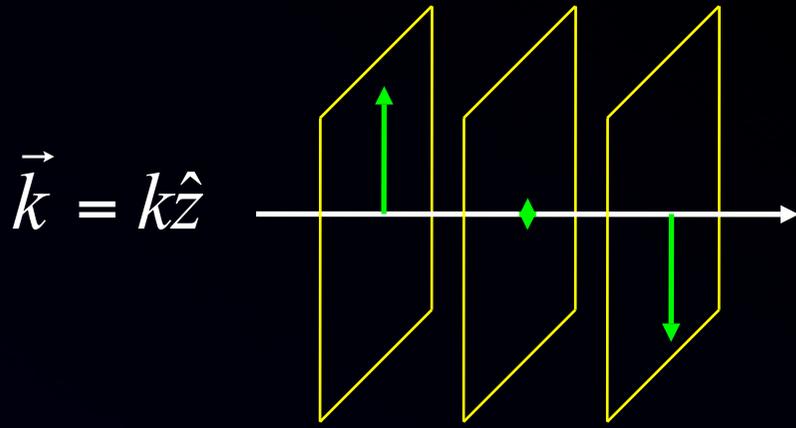


- Individual photons possess fixed linear polarization, given by the direction of the electric field:

$$\vec{E} = E_x\hat{i} + E_y\hat{j}$$

$$E_x = a_x \cos(\omega t) \quad E_y = a_y \cos(\omega t)$$

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- A generic radiation field is a multi-photon state \Rightarrow mix of linear polarizations
- For a beam propagating in the direction z the **Stokes parameters** are:

$$I = E_x^2 + E_y^2$$

$$Q = E_x^2 - E_y^2$$

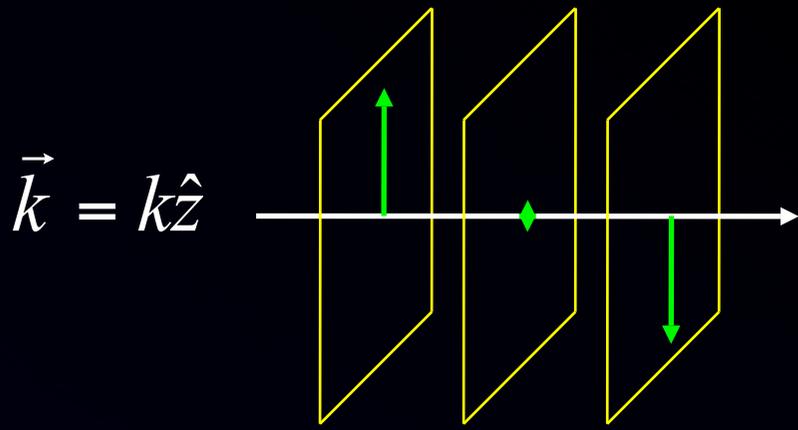
$$E_x = a_x \cos(\omega t)$$

$$E_y = a_y \cos(\omega t + \psi)$$

$$U = 2E_x E_y \cos \psi$$

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- For a beam propagating in the direction z the **Stokes parameters** are:

$$I = E_x^2 + E_y^2 \quad \rightarrow \text{Intensity}$$

$$E_x = a_x \cos(\omega t)$$

$$Q = E_x^2 - E_y^2 \quad \rightarrow \text{Polarizations } - - |$$

$$E_y = a_y \cos(\omega t + \psi)$$

$$U = 2E_x E_y \cos \psi \quad \rightarrow \text{Polarizations } / - \backslash$$

$$V = 2E_x E_y \sin \psi \quad \rightarrow \text{Circular polarization}$$

$$I^2 \geq Q^2 + U^2 + V^2 \quad (= \text{f/ monochromatic wave})$$

CMB polarization: brief overview II

- Prior to decoupling ($z > 1100$), radiation was unpolarized: $\langle I_i \rangle \neq 0$, $\langle Q_i \rangle = \langle U_i \rangle = \langle V_i \rangle = 0$

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Polnarev 1985

Kosowski 1996

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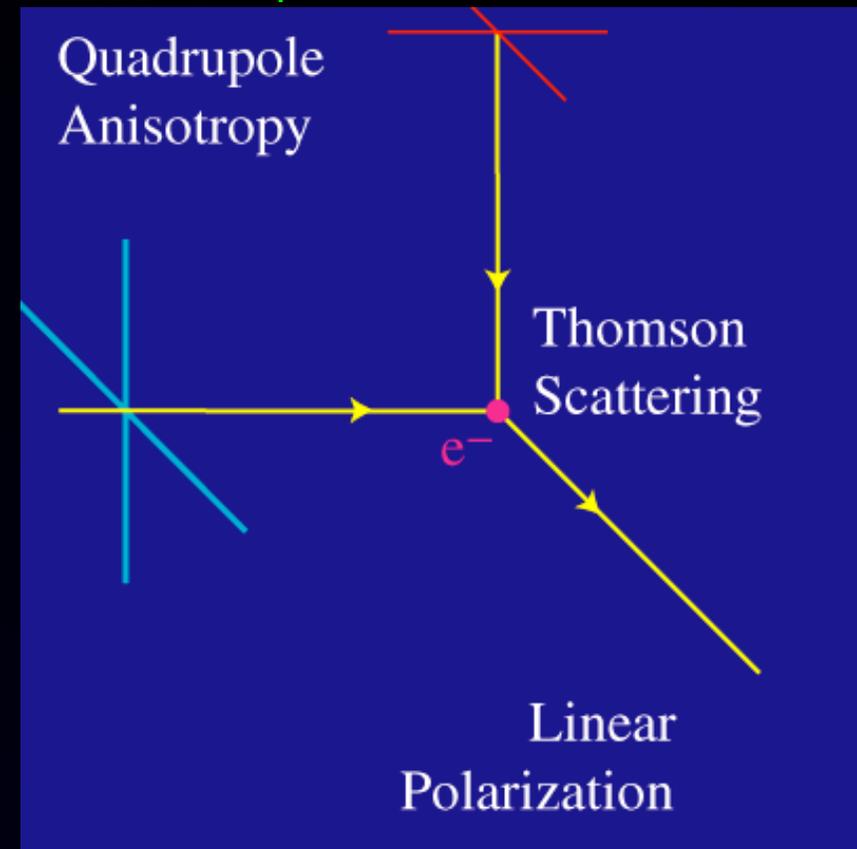
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$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} |\hat{\epsilon}_i \cdot \hat{\epsilon}_f|^2$$

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- Integrating over incident radiation field I_i gives the polarization of final state:

$$\left. \begin{aligned} Q_f &= \frac{3\sigma_T}{16\pi} \int d\Omega \sin^2 \theta \cos 2\varphi I_i(\theta, \varphi) \\ U_f &= -\frac{3\sigma_T}{16\pi} \int d\Omega \sin^2 \theta \sin 2\varphi I_i(\theta, \varphi) \end{aligned} \right\} Q - iU \sim \int d\Omega Y_{22}(\theta, \varphi) I(\theta, \varphi)$$

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Polarization \Leftrightarrow quadrupole

of incident radiation