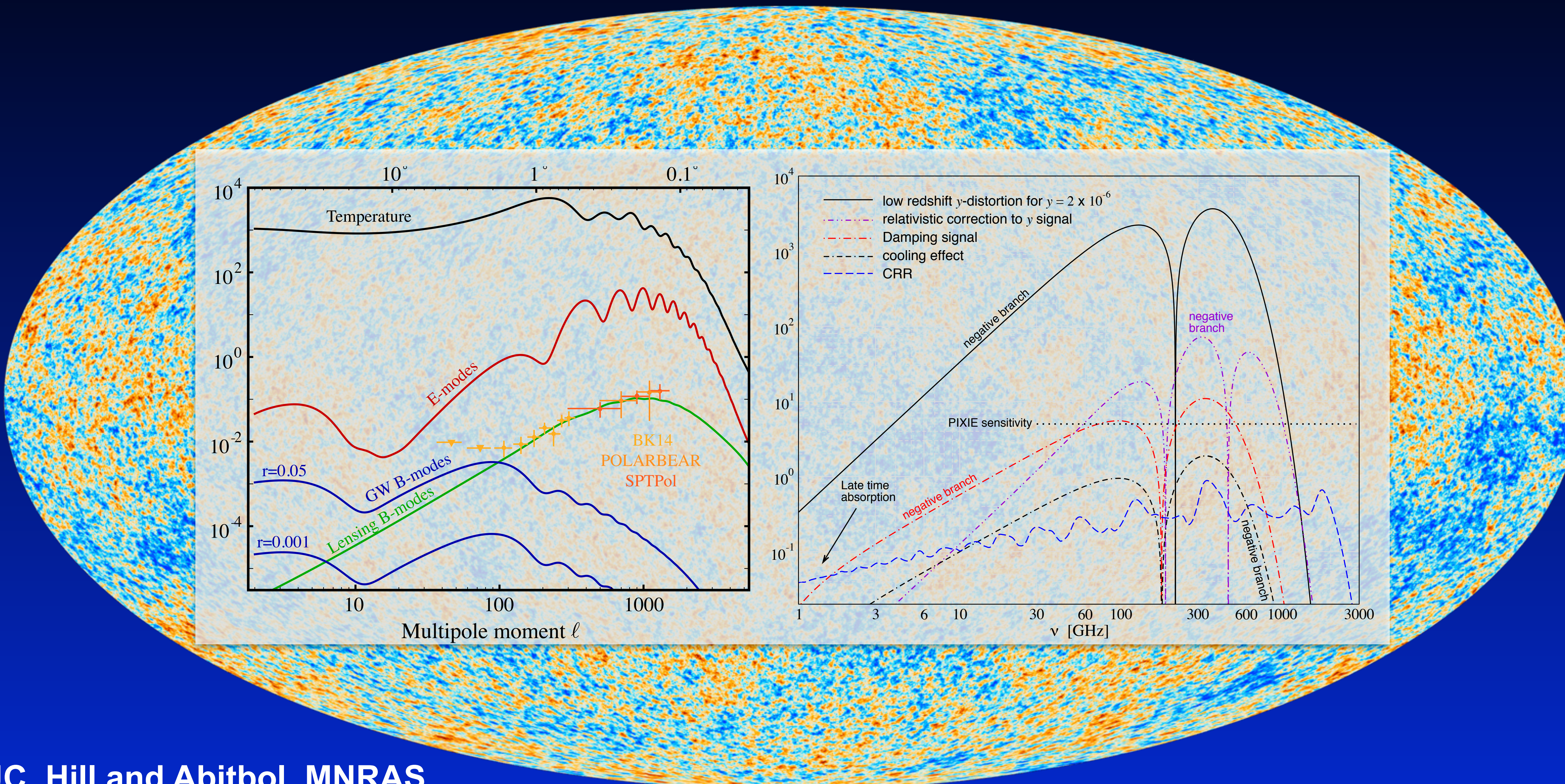
Rethinking CMB Foregrounds: Getting Ready for the Low Signal to Foreground Era



JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

MANCHESTER 1824
The University of Manchester

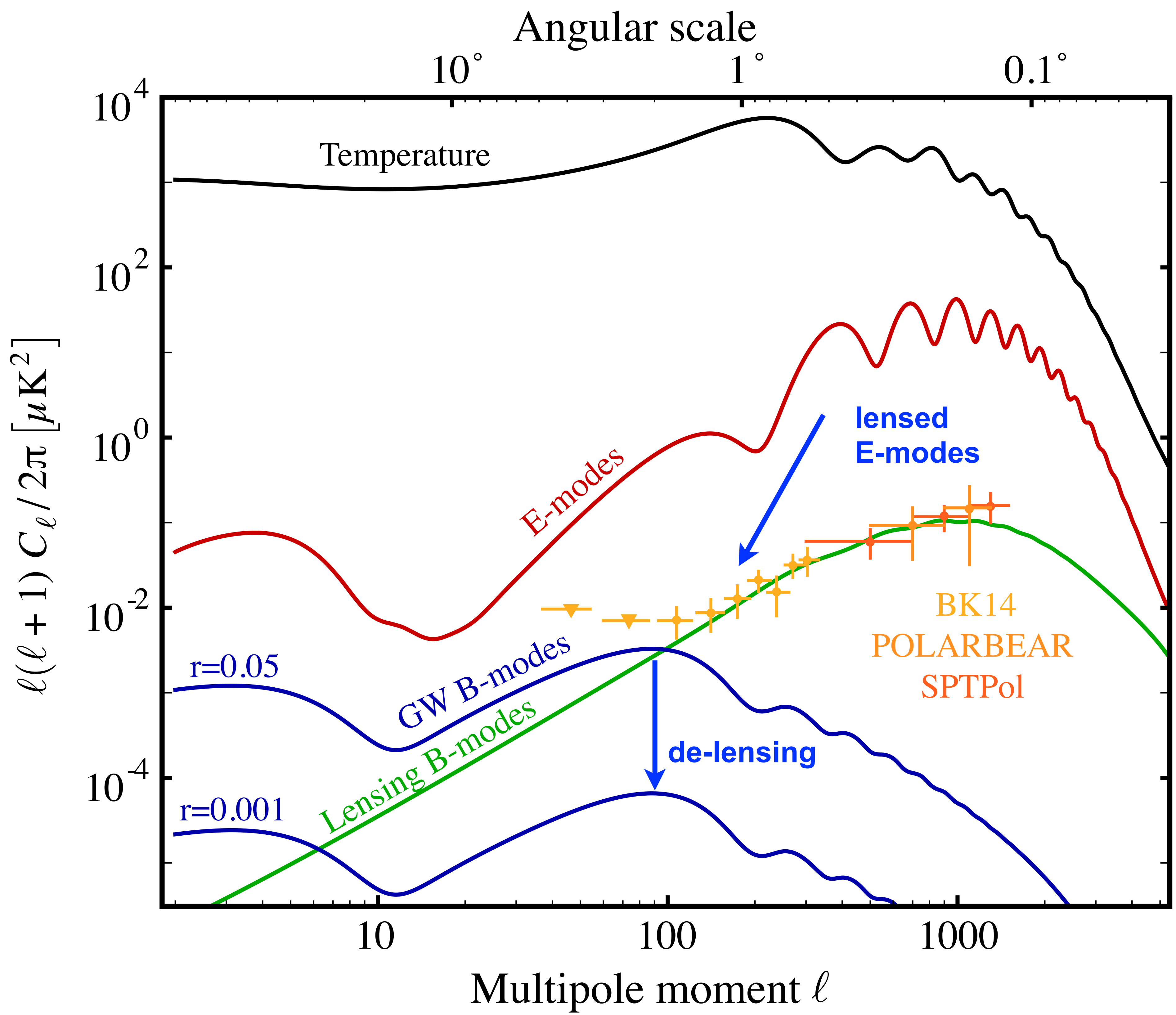
Jens Chluba

CMB Workshop 2017, UC San Diego

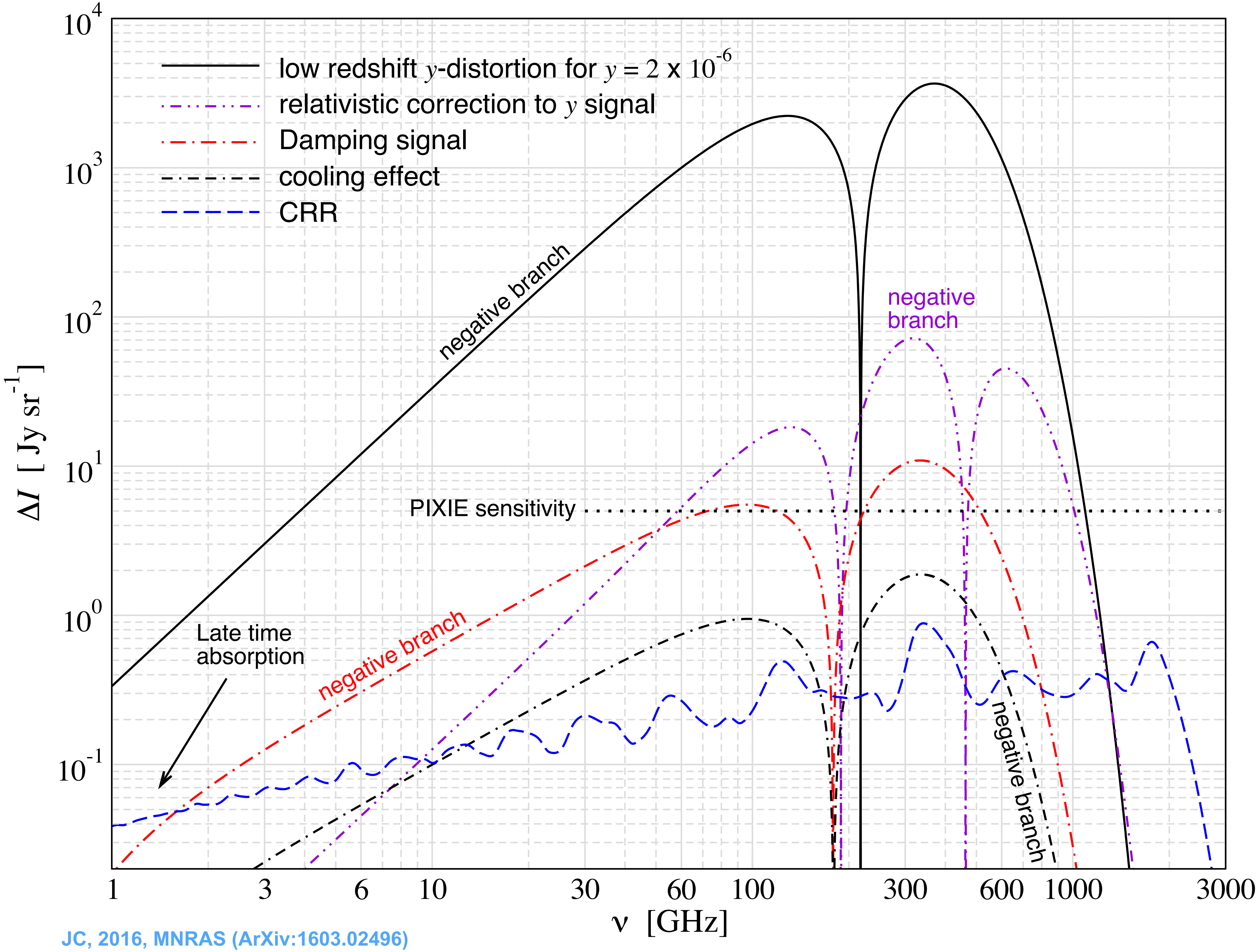
La Jolla, Nov 29th, 2017

erc
THE ROYAL SOCIETY

The E/B-mode signals that we are after



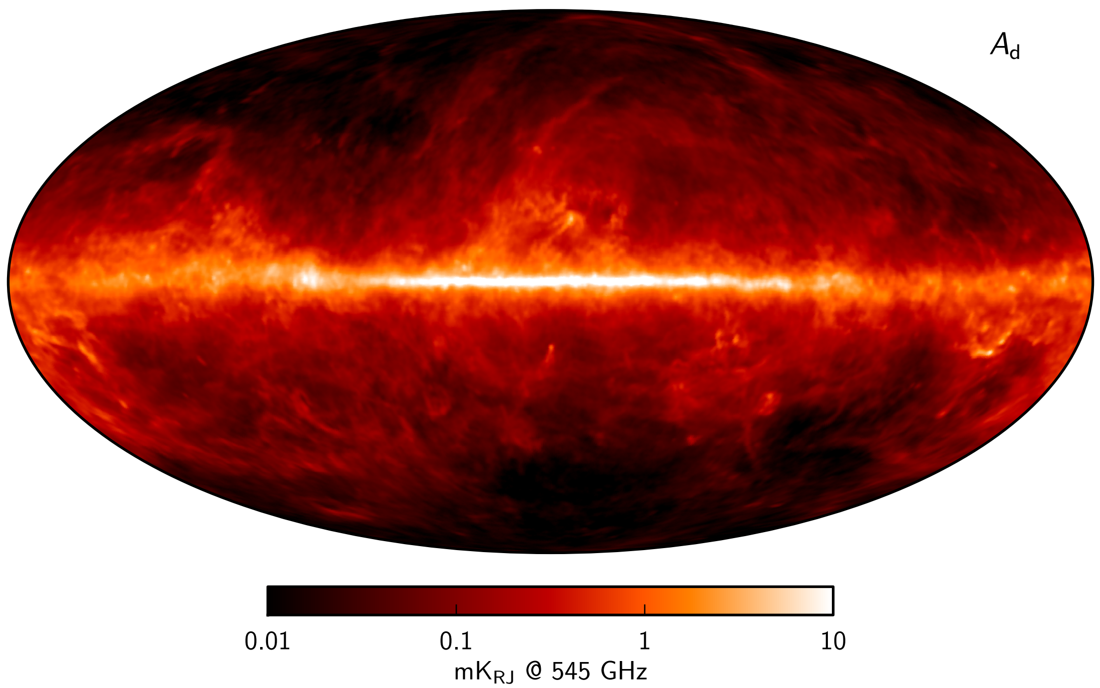
Average CMB spectral distortions



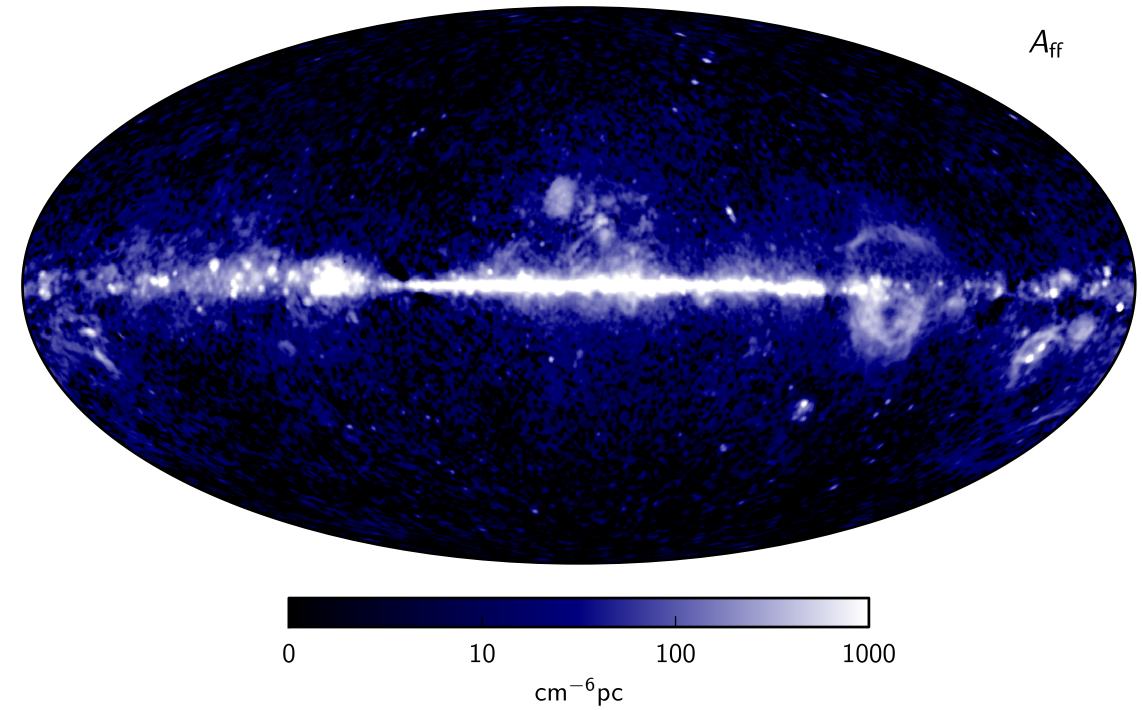
JC, 2016, MNRAS (ArXiv:1603.02496)

Some of the foregrounds that are in the way…

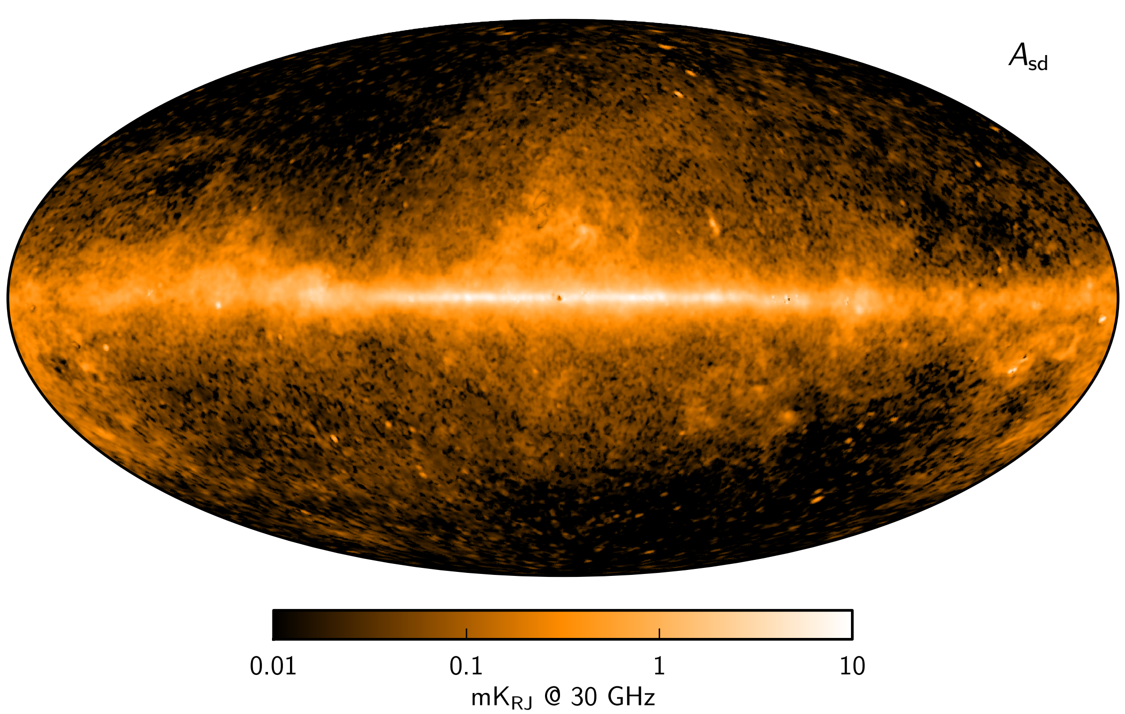
Thermal dust



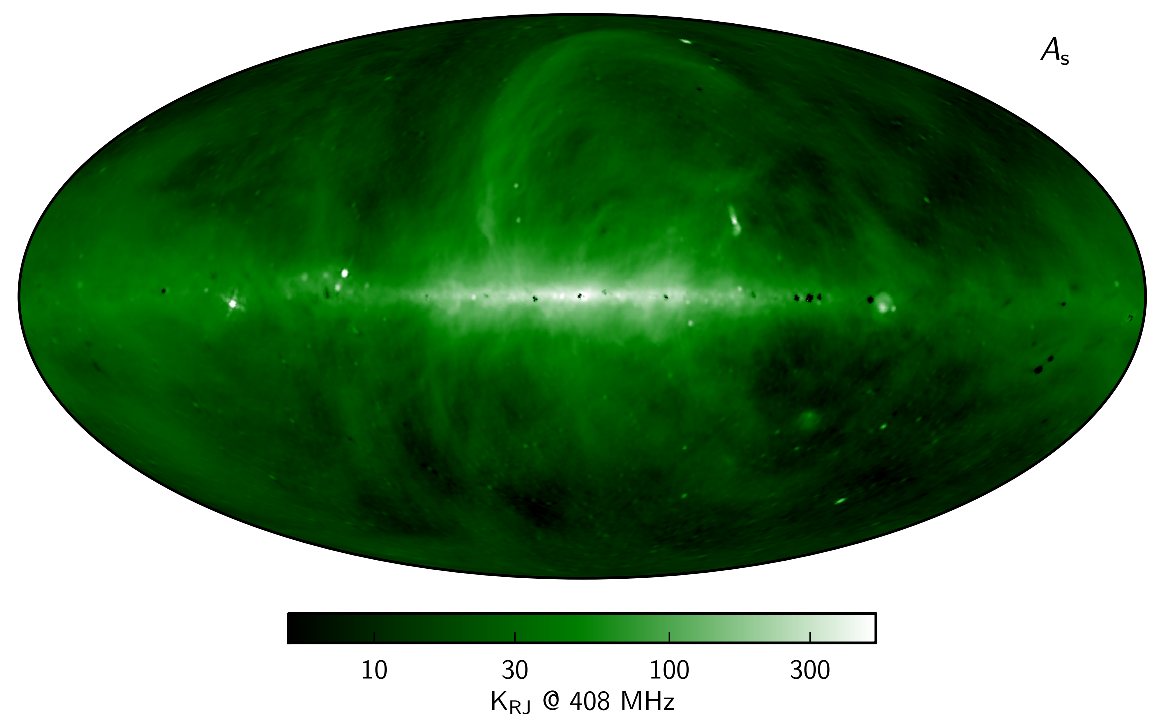
free-free emission



Spinning dust



Synchrotron



Future foreground problem for CMB signals

- B-mode and distortion signals are *quite* small
  - Low signal to ‘noise’ regime with foregrounds dominating in most bands
  - De-lensing required to reach $r \sim 10^{-3}$ or n_T constraint

Future foreground problem for CMB signals

- B-mode and distortion signals are *quite* small
  - Low signal to 'noise' regime with foregrounds dominating in most bands
  - De-lensing required to reach $r \sim 10^{-3}$ or n_T constraint
- Spatially varying foreground signals across the sky
  - Complex spatial and spectral structure (⟷ non-Gaussian, degeneracies, etc)
  - Foreground SEDs can depend on many parameters
    (e.g., 3 single temperature thermal dust component and AME even more)
  - Intensity and polarization both need to be dealt with

Future foreground problem for CMB signals

- B-mode and distortion signals are *quite* small
  - Low signal to ‘noise’ regime with foregrounds dominating in most bands
  - De-lensing required to reach $r \sim 10^{-3}$ or n_T constraint
- Spatially varying foreground signals across the sky
  - Complex spatial and spectral structure (↔ non-Gaussian, degeneracies, etc)
  - Foreground SEDs can depend on many parameters
    (e.g., 3 single temperature thermal dust component and AME even more)
  - Intensity and polarization both need to be dealt with
- *Many sensitive channels* required to disentangle the different components (probably more than we think…)
- Control of systematics (calibration, beams etc)

Future foreground problem for CMB signals

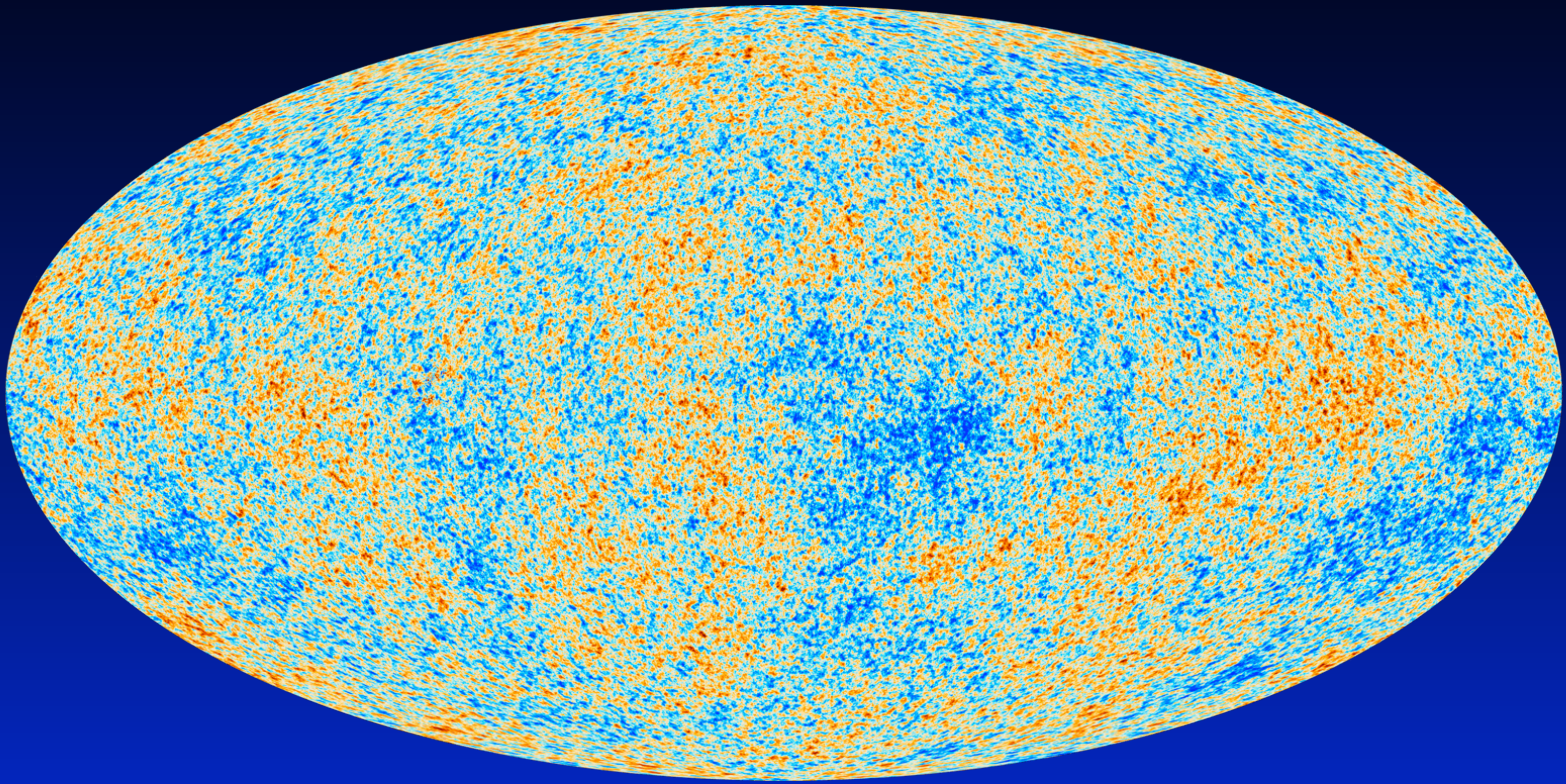
- B-mode and distortion signals are *quite* small
  - Low signal to ‘noise’ regime with foregrounds dominating in most bands
  - De-lensing required to reach $r \sim 10^{-3}$ or n_T constraint
- Spatially varying foreground signals across the sky
  - Complex spatial and spectral structure (⟷ non-Gaussian, degeneracies, etc)
  - Foreground SEDs can depend on many parameters
    (e.g., 3 single temperature thermal dust component and AME even more)
  - Intensity and polarization both need to be dealt with
- *Many sensitive channels* required to disentangle the different components (probably more than we think…)
- Control of systematics (calibration, beams etc)
- *Need* to *model all* the *obvious aspects!*
- *Need* to *prepare for surprises* (redundancies & nulling)!

Future foreground problem for CMB signals

- B-mode and distortion signals are *quite* small
  - Low signal to ‘noise’ regime with foregrounds dominating in most bands
  - De-lensing required to reach $r \sim 10^{-3}$ or n_T constraint
- Spatially varying foreground signals across the sky
  - Complex spatial and spectral structure (↔ non-Gaussian, degeneracies, etc)
  - Foreground SEDs can depend on many parameters
    (e.g., 3 single temperature thermal dust component and AME even more)
  - Intensity and polarization both need to be dealt with
- *Many sensitive channels* required to disentangle the different components (probably more than we think…)
- Control of systematics (calibration, beams etc)
- *Need* to *model all* the *obvious aspects!*
- *Need* to *prepare for surprises* (redundancies & nulling)!

Include effects of averaging signals

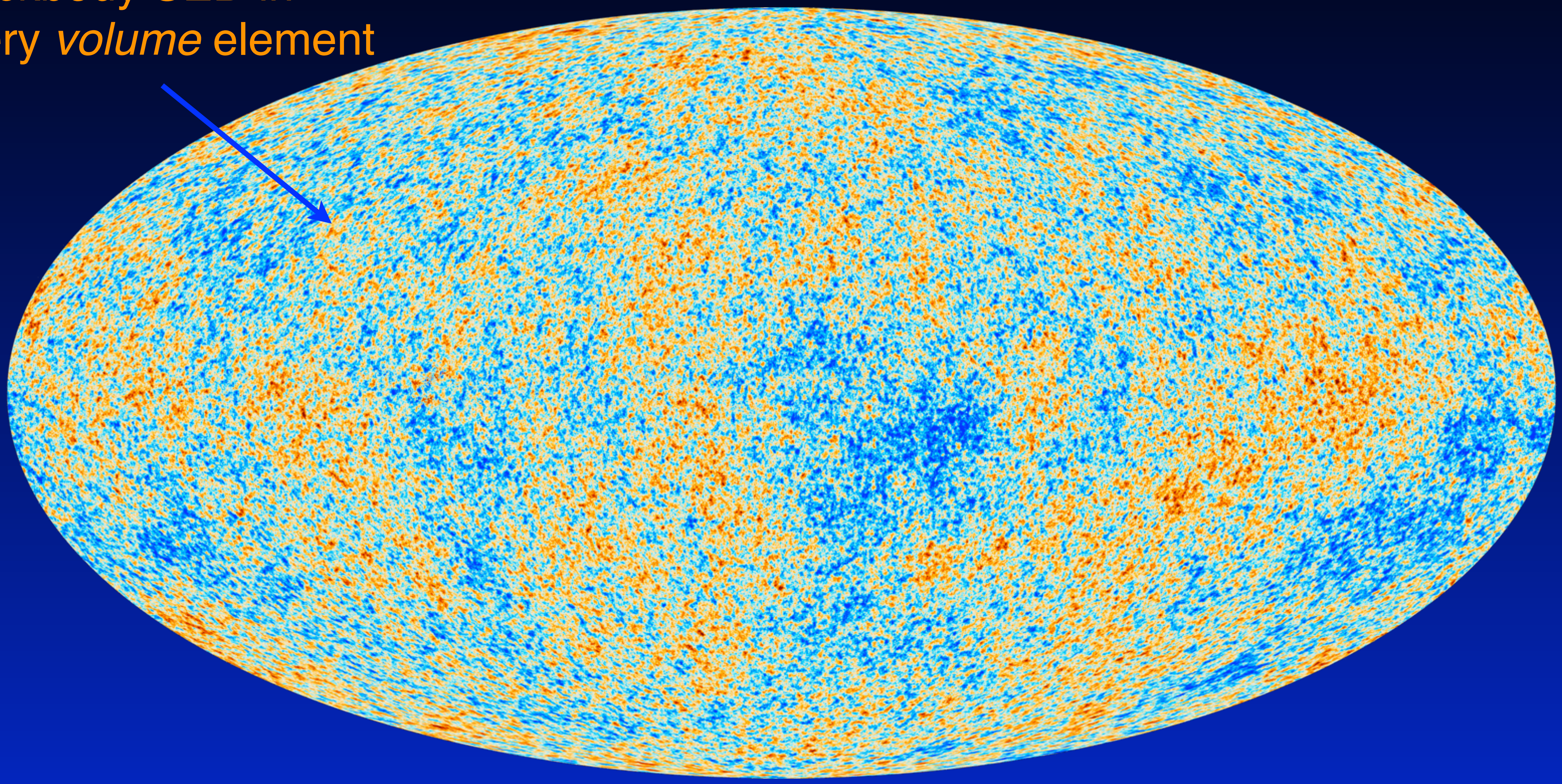
Averaging processes in CMB observations



JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

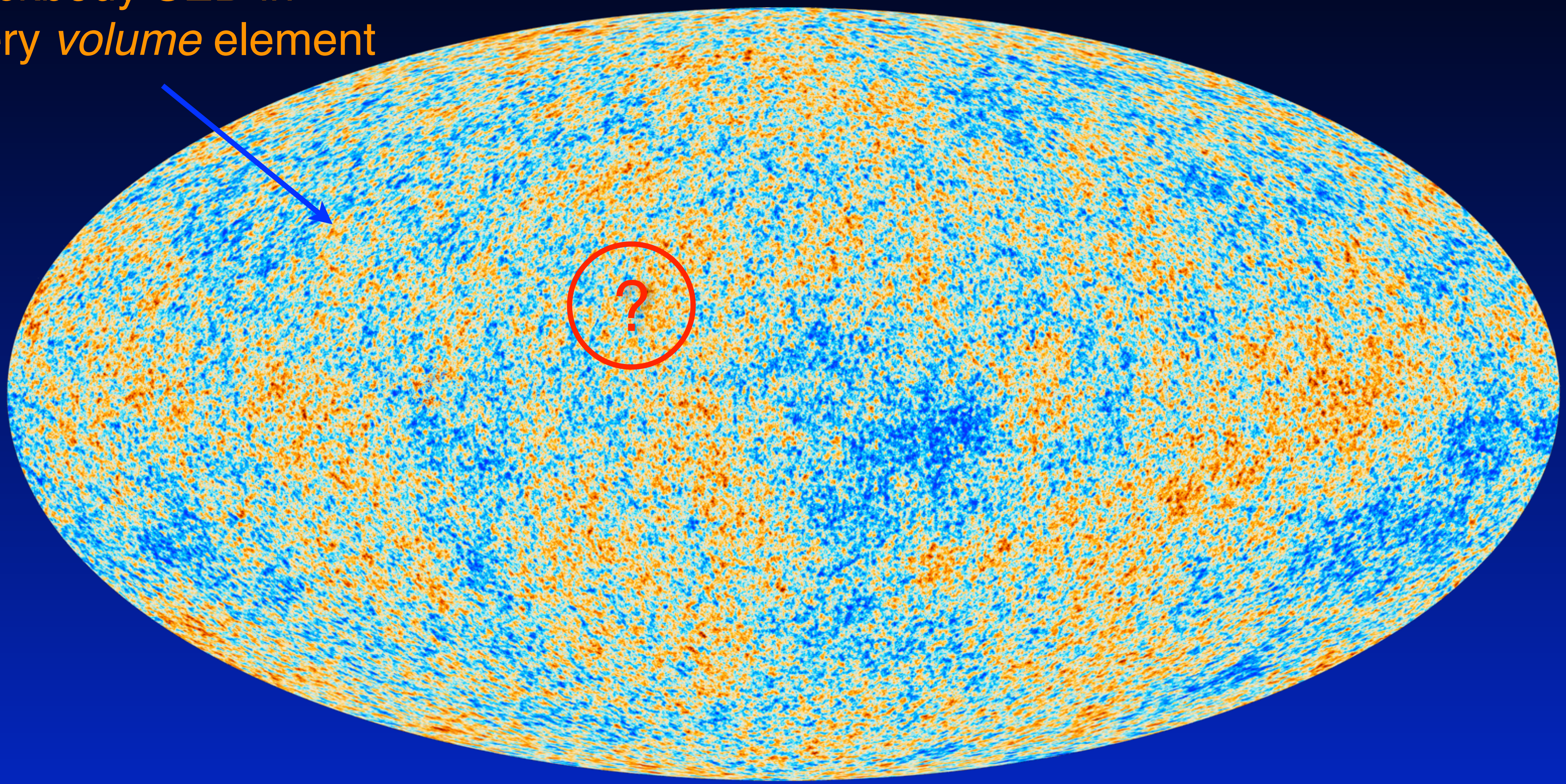
Averaging processes in CMB observations

Blackbody SED in
every *volume* element



JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Averaging processes in CMB observations

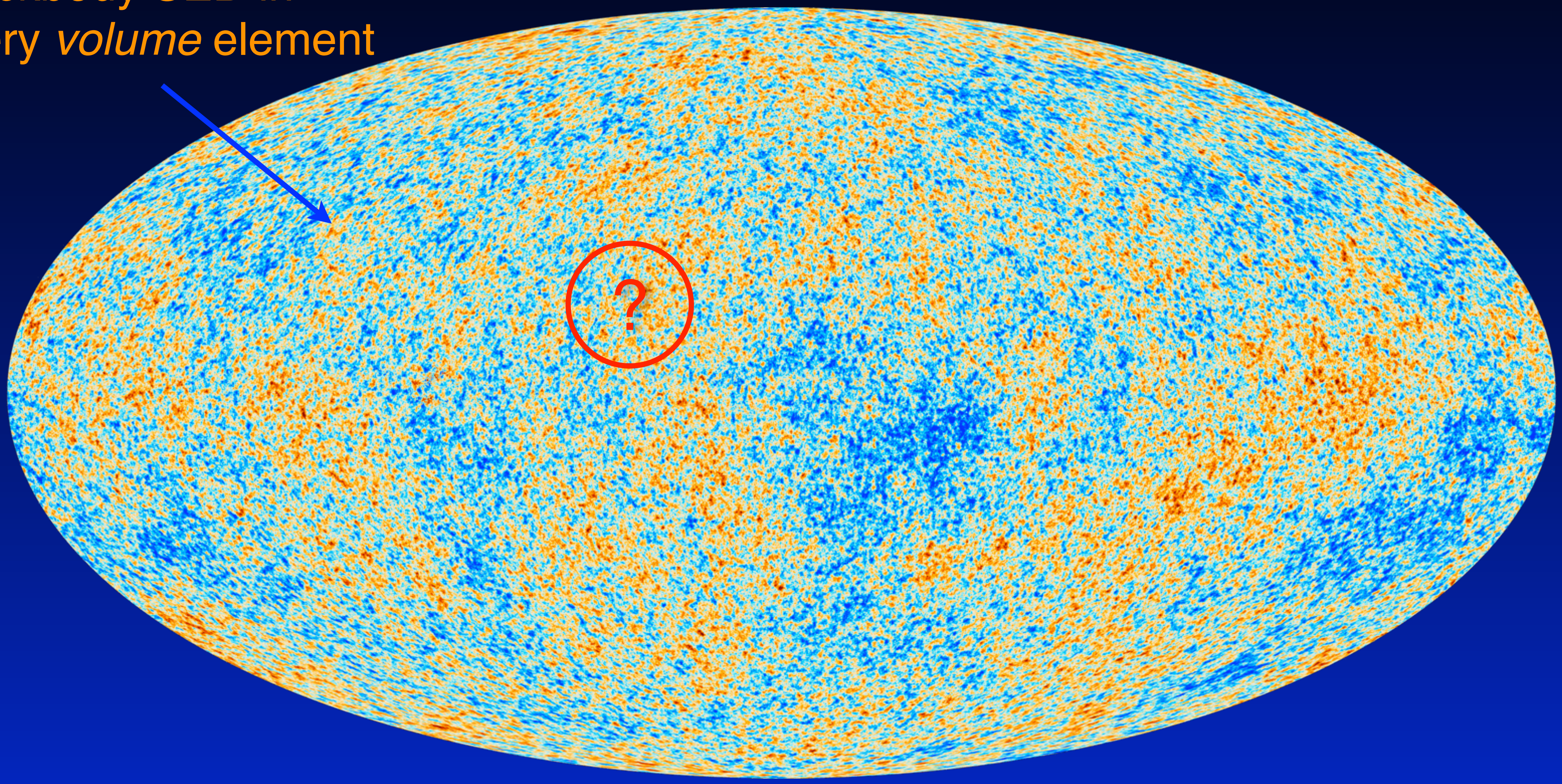


- Beam average *(also in frequency…)*

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Averaging processes in CMB observations

Blackbody SED in every *volume* element



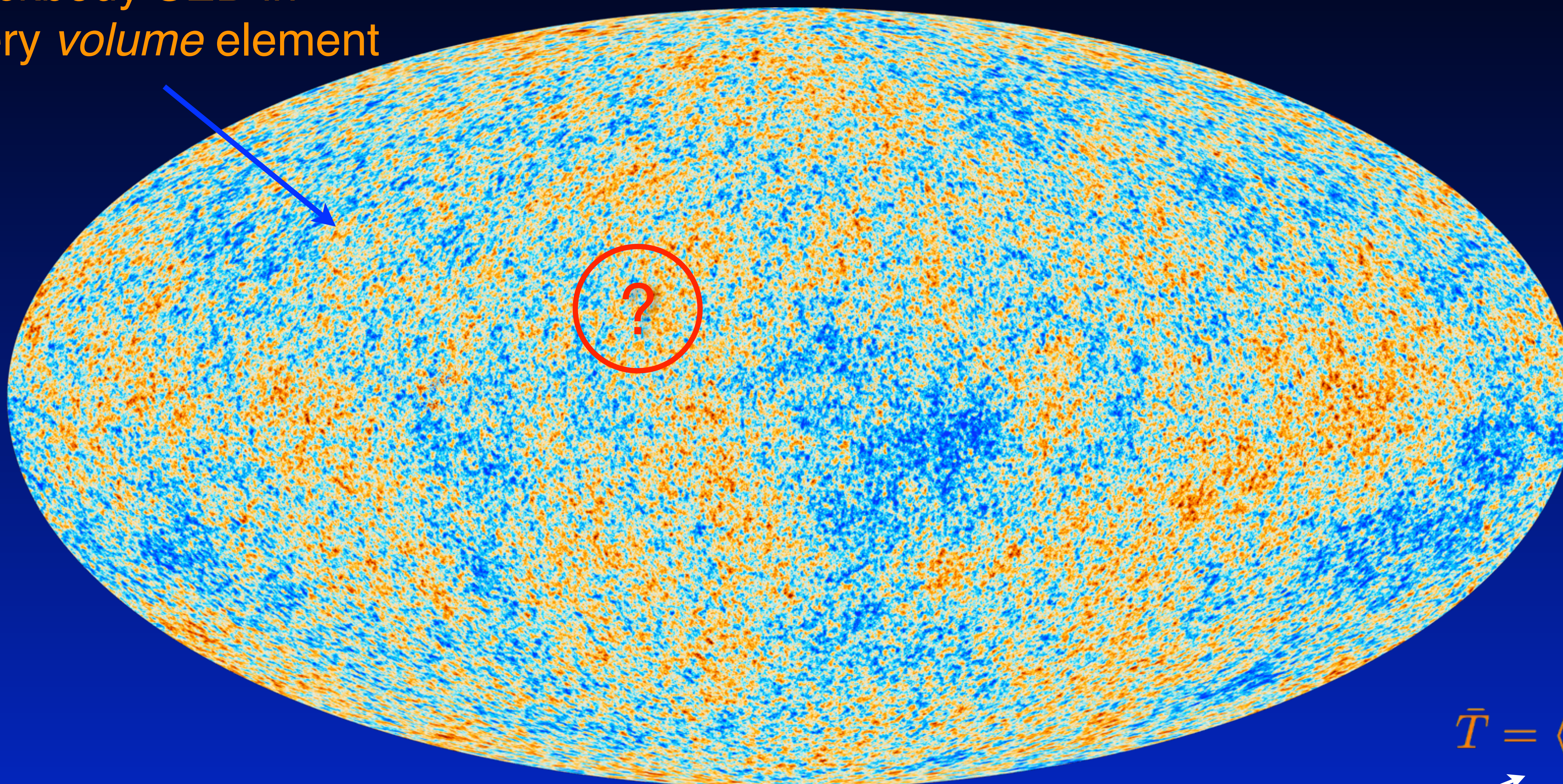
- Beam average *(also in frequency…)*

$$\langle B_\nu(T)\rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle + \frac{1}{2}\bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}}\right)^2 \right\rangle$$

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Averaging processes in CMB observations

Blackbody SED in every *volume* element



$$\bar{T} = \langle T \rangle$$

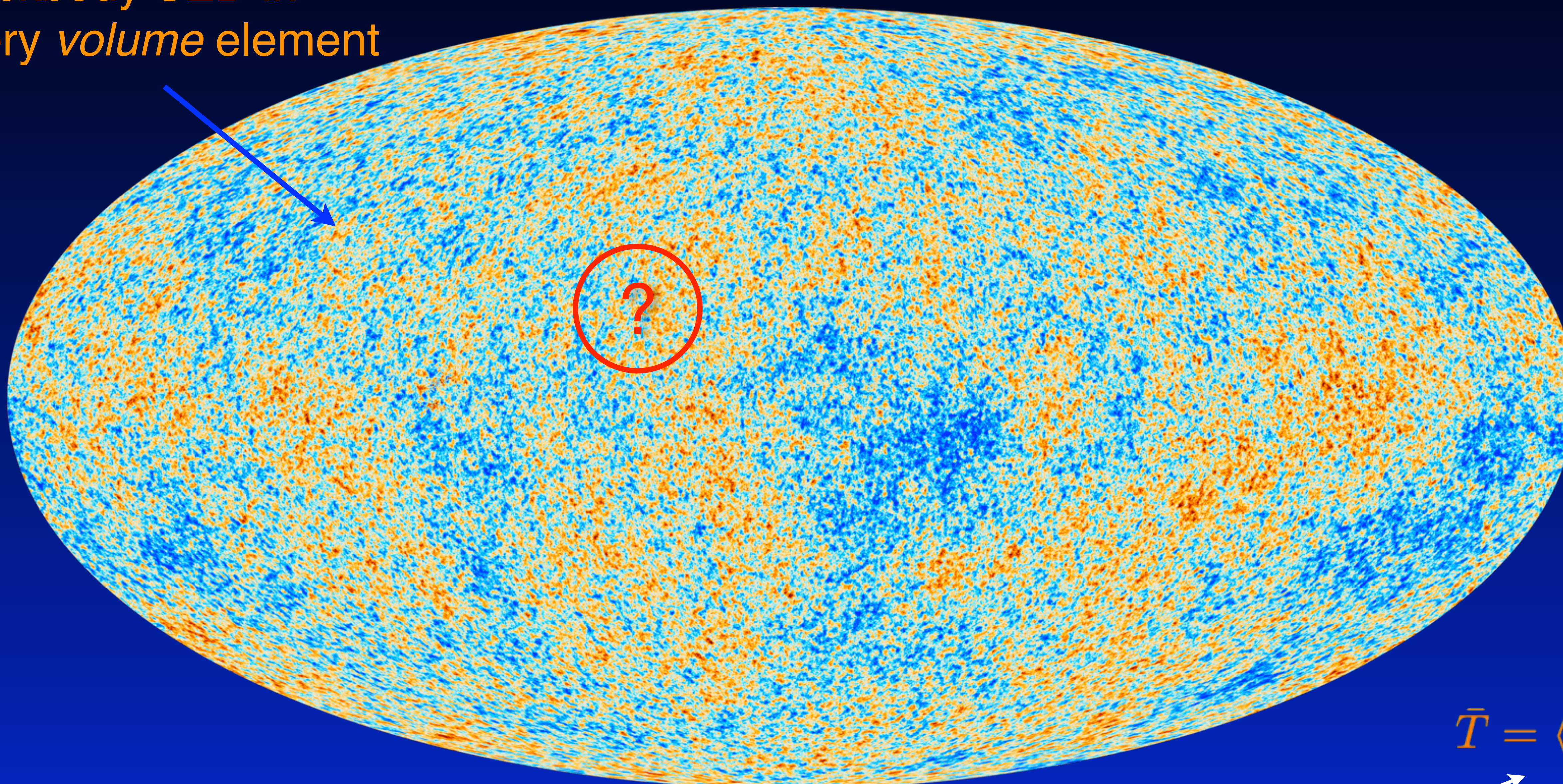
- Beam average *(also in frequency…)*

$$\langle B_\nu(T) \rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle + \frac{1}{2}\bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}}\right)^2 \right\rangle$$

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Averaging processes in CMB observations

Blackbody SED in every *volume* element



- Beam average *(also in frequency…)*

$$\bar{T} = \langle T \rangle$$

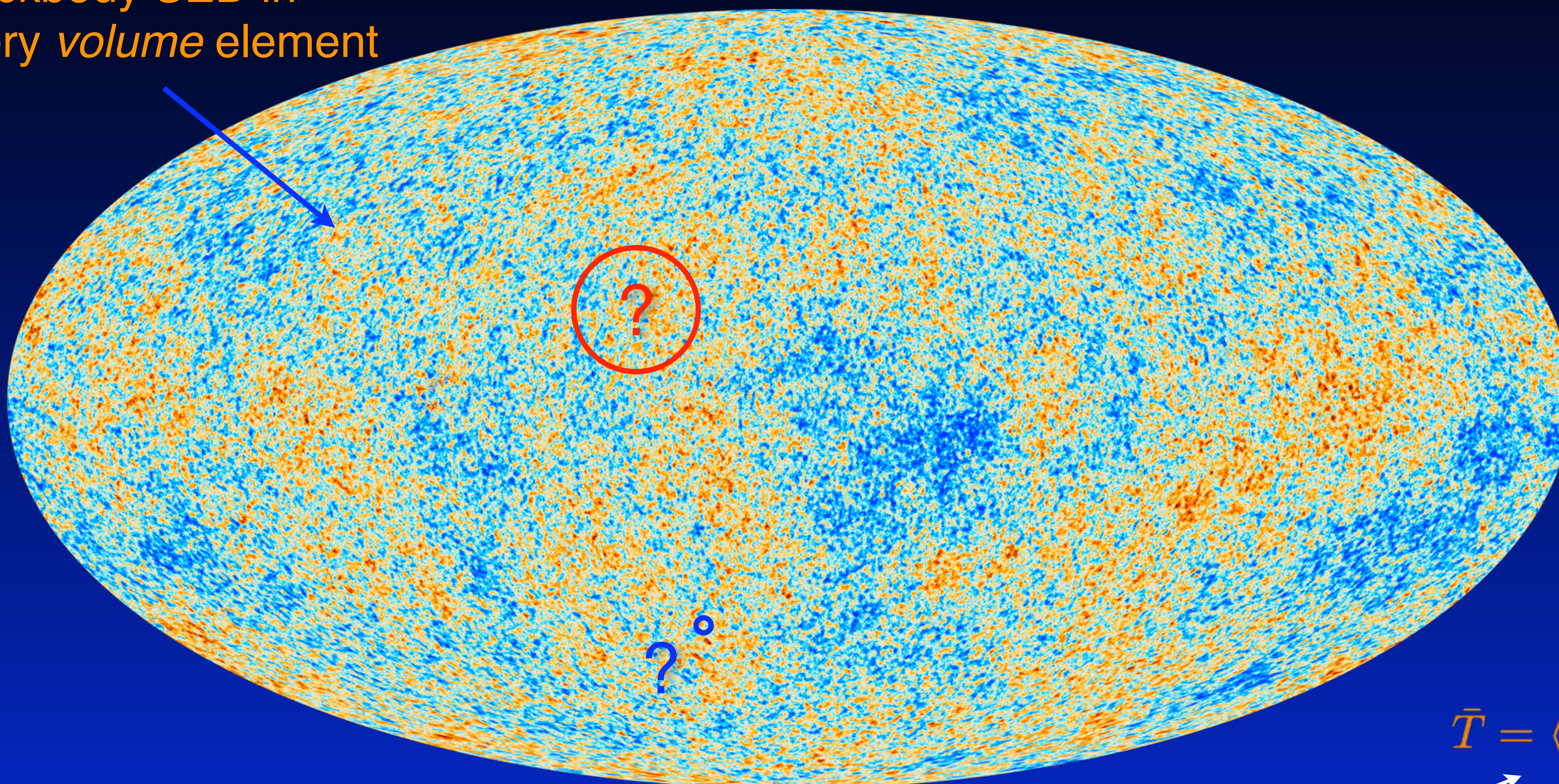
$$\langle B_\nu(T) \rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle + \frac{1}{2}\bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}} \right)^2 \right\rangle$$

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

***y*-type distortion appears!**

Averaging processes in CMB observations

Blackbody SED in
every *volume* element



- Beam average *(also in frequency…)*

$$\bar{T} = \langle T \rangle$$

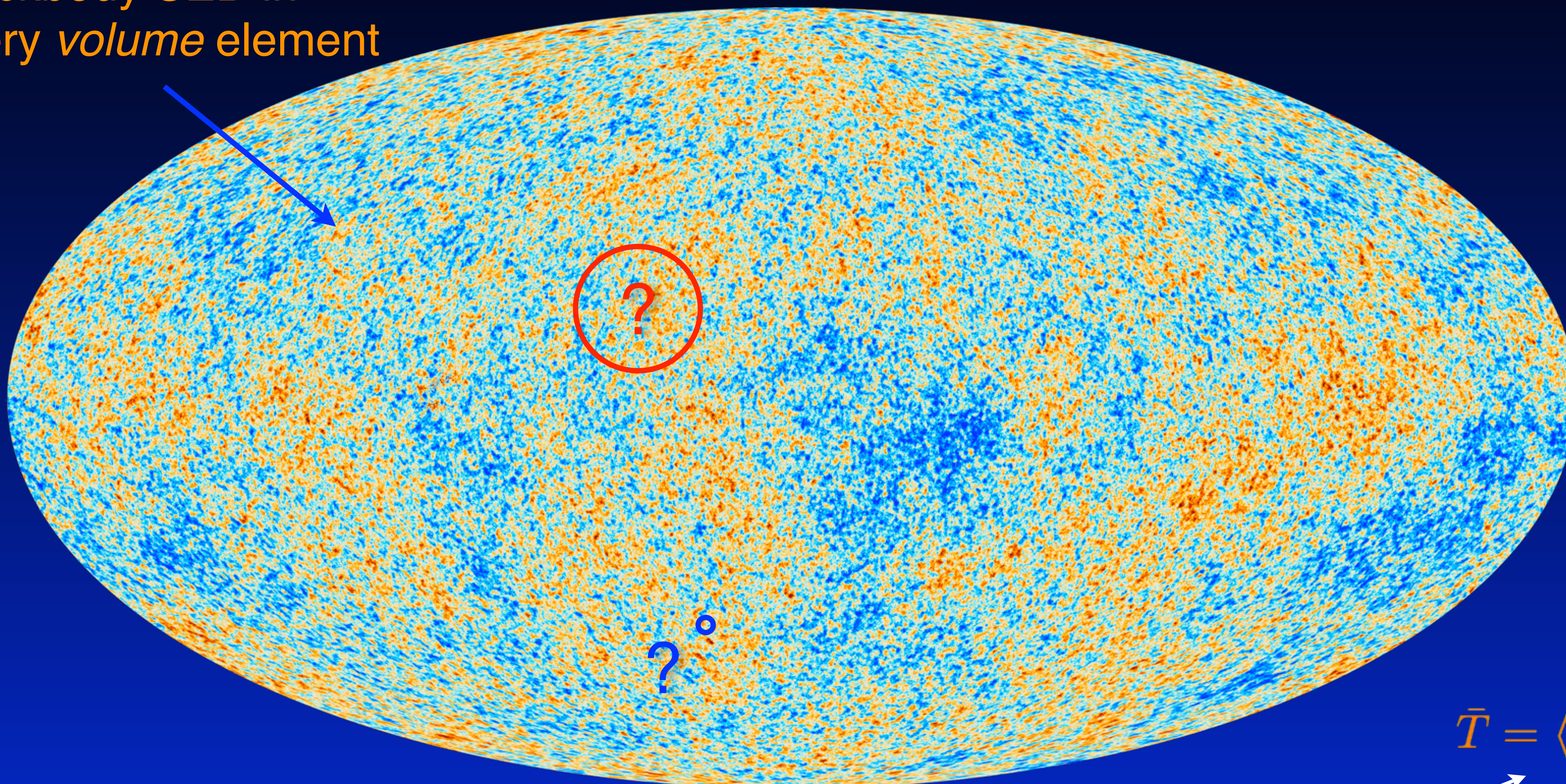
$$\langle B_\nu(T) \rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle + \frac{1}{2}\bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}}\right)^2 \right\rangle$$

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

***y*-type distortion appears!**

Averaging processes in CMB observations

Blackbody SED in every *volume* element



$$\bar{T} = \langle T \rangle$$

- Beam average *(also in frequency…)*
- Line of sight average *(always present!!!)*

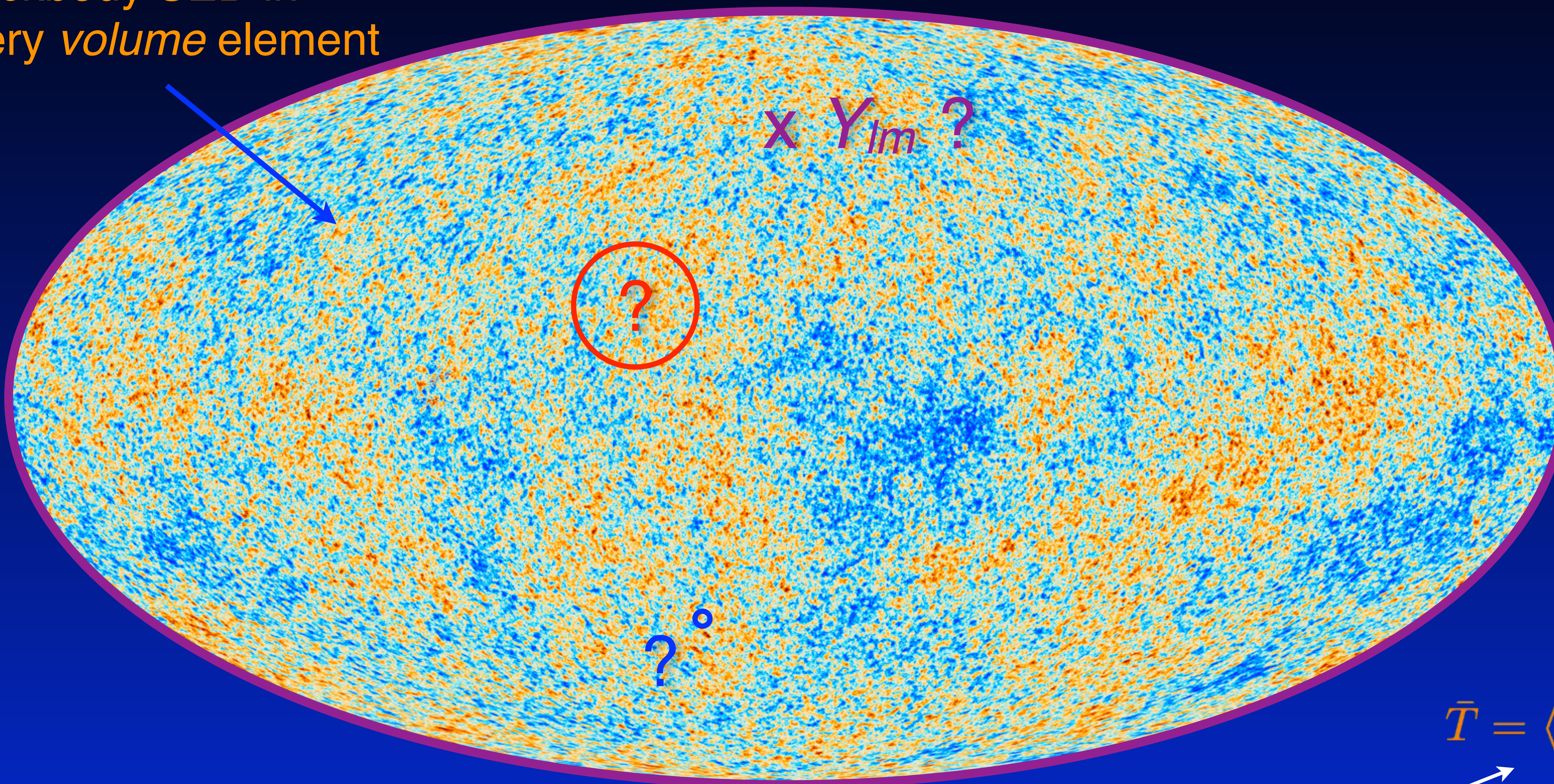
$$\langle B_\nu(T) \rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle + \frac{1}{2}\bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}} \right)^2 \right\rangle$$

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

***y*-type distortion appears!**

Averaging processes in CMB observations

Blackbody SED in
every *volume* element



- Beam average *(also in frequency…)*
- Line of sight average *(always present!!!)*

$$\bar{T} = \langle T \rangle$$

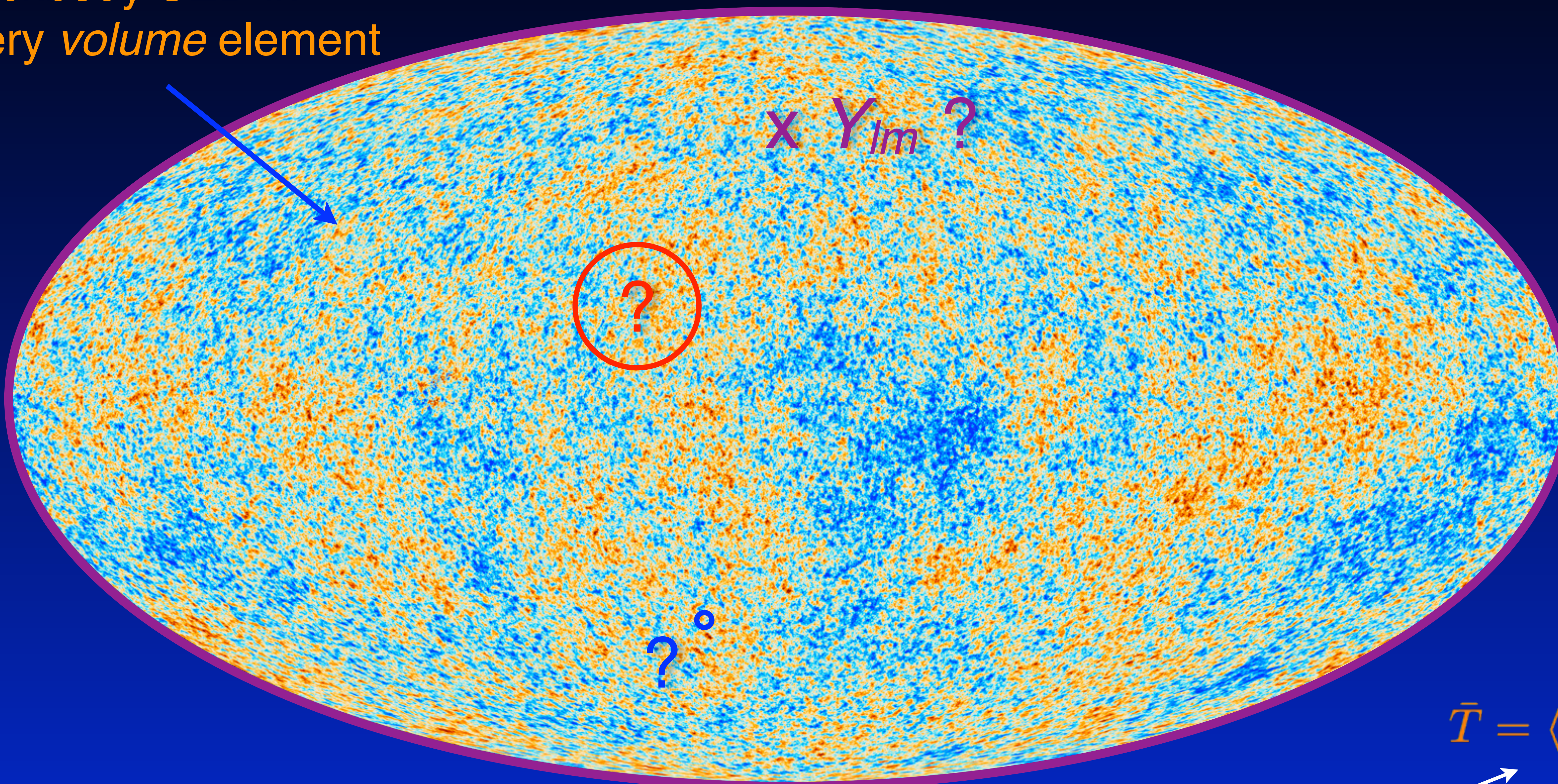
$$\langle B_\nu(T) \rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle + \frac{1}{2}\bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}}\right)^2 \right\rangle$$

***y*-type distortion appears!**

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Averaging processes in CMB observations

Blackbody SED in every *volume* element



$$\bar{T} = \langle T \rangle$$

$$\langle B_\nu(T)\rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle + \frac{1}{2}\bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}}\right)^2 \right\rangle$$

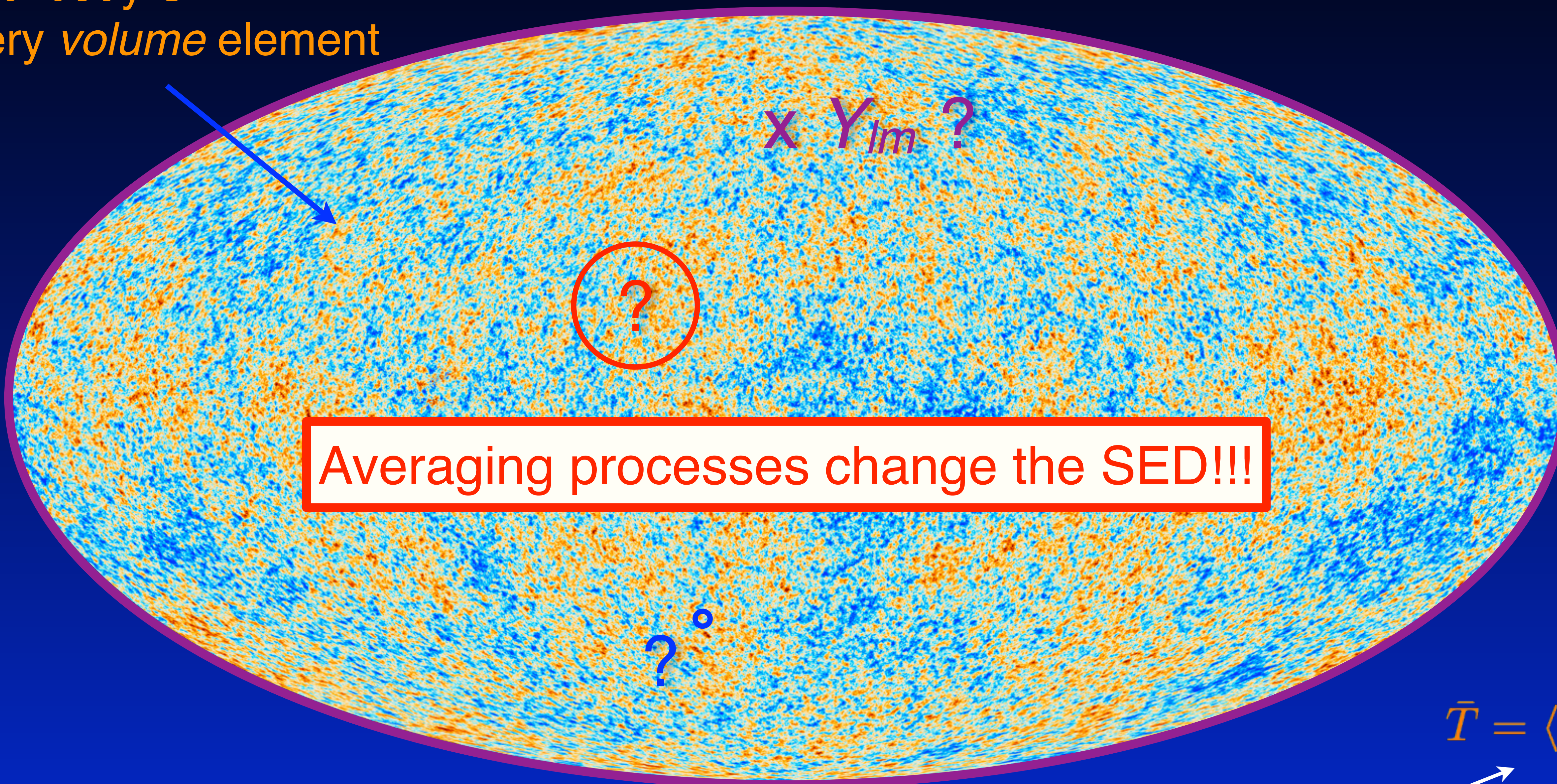
- Beam average (*also in frequency…*)
- Line of sight average (*always present!!!*)
- Map operations (e.g., *spherical harmonic expansion*)

y-type distortion appears!

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Averaging processes in CMB observations

Blackbody SED in every *volume* element



$$\bar{T} = \langle T \rangle$$

$$\langle B_\nu(T) \rangle \approx B_\nu(\bar{T}) + \bar{T}\partial_{\bar{T}} B_\nu(\bar{T}) \left\langle \frac{\Delta T}{\bar{T}} \right\rangle$$

$$+ \frac{1}{2} \bar{T}^2 \partial^2_{\bar{T}} B_\nu(\bar{T}) \left\langle \left(\frac{\Delta T}{\bar{T}} \right)^2 \right\rangle$$

- Beam average (*also in frequency…*)
- Line of sight average (*always present!!!*)
- Map operations (e.g., *spherical harmonic expansion*)

y-type distortion appears!

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Obvious statements about averaging processes

- SED no longer described by averaged parameters

$$\langle I_\nu(\boldsymbol{p})\rangle \neq I_\nu(\langle \boldsymbol{p}\rangle)$$

- SED shape becomes *scale-dependent*

$$\langle B_\nu(T)\rangle \approx B_\nu(T_0) + T_0 \partial_{T_0} B_\nu(T_0) \left\langle \frac{\Delta T}{T_0} \right\rangle + \frac{1}{2} T_0^2 \partial_{T_0}^2 B_\nu(T_0) \left\langle \left(\frac{\Delta T}{T_0}\right)^2 \right\rangle$$

- New *morphologies* introduced by new SED shapes

Obvious statements about averaging processes

- SED no longer described by averaged parameters

$$\langle I_\nu(\boldsymbol{p})\rangle \neq I_\nu(\langle \boldsymbol{p}\rangle)$$

- SED shape becomes *scale-dependent*

$$\langle B_\nu(T)\rangle \approx B_\nu(T_0) + T_0 \partial_{T_0} B_\nu(T_0) \left\langle \frac{\Delta T}{T_0} \right\rangle + \frac{1}{2} T_0^2 \partial_{T_0}^2 B_\nu(T_0) \left\langle \left(\frac{\Delta T}{T_0}\right)^2 \right\rangle$$

- New *morphologies* introduced by new SED shapes

How can we capture these effects?

Obvious statements about averaging processes

- SED no longer described by averaged parameters

$$\langle I_\nu(\boldsymbol{p})\rangle \neq I_\nu(\langle \boldsymbol{p}\rangle)$$

- SED shape becomes *scale-dependent*

$$\langle B_\nu(T)\rangle \approx B_\nu(T_0) + T_0\partial_{T_0}B_\nu(T_0)\left\langle \frac{\Delta T}{T_0}\right\rangle + \frac{1}{2}T_0^2\partial_{T_0}^2 B_\nu(T_0)\left\langle \left(\frac{\Delta T}{T_0}\right)^2\right\rangle$$

- New *morphologies* introduced by new SED shapes

$\boxed{\textit{How can we capture these effects?}}$

One possibility is (Taylor)-Moment expansions!

(JC, Hill & Abitbol, 2017, ArXiv: 1701.00274)

Moment expansions of simple SEDs

- **Power-law distribution** ($\leftrightarrow$ synchrotron)

$$\langle I_\nu \rangle = A\,(\nu_{\rm c}/\nu_0)^{\alpha}\left[1 + \tfrac{1}{2}\,\beta\ln^2(\nu_{\rm c}/\nu_0) + \tfrac{1}{6}\,\gamma\ln^3(\nu_{\rm c}/\nu_0) + \tfrac{1}{24}\,\delta\ln^4(\nu_{\rm c}/\nu_0) + \dots\right]$$

  - Also works as representation for *free-free*!
  - More general than simple curvature ($\leftrightarrow$ gaussian moments)

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Moment expansions of simple SEDs

- **Power-law distribution** (↔ synchrotron)

$$\langle I_\nu \rangle = A\,(\nu_{\rm c}/\nu_0)^\alpha \left[1 + \tfrac{1}{2}\,\beta \ln^2(\nu_{\rm c}/\nu_0) + \tfrac{1}{6}\,\gamma \ln^3(\nu_{\rm c}/\nu_0) + \tfrac{1}{24}\,\delta \ln^4(\nu_{\rm c}/\nu_0) + \ldots\right]$$

  - Also works as representation for *free-free*!
  - More general than simple curvature (↔ gaussian moments)

- **Modified blackbody distribution** (↔ thermal dust, CIB and integrated extra-galactic dust)
  - Longish expressions given in moment paper
  - Second order expansion has six parameters like two temperature mBB case but is more general
  - Third order expansion has 10 parameters

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Moment expansions of simple SEDs

- **Power-law distribution** (↔ synchrotron)

$$\langle I_\nu \rangle = A\,(\nu_\mathrm{c}/\nu_0)^\alpha \left[1 + \tfrac{1}{2}\,\beta \ln^2(\nu_\mathrm{c}/\nu_0) + \tfrac{1}{6}\,\gamma \ln^3(\nu_\mathrm{c}/\nu_0) + \tfrac{1}{24}\,\delta \ln^4(\nu_\mathrm{c}/\nu_0) + \dots\right]$$

  - Also works as representation for *free-free*!
  - More general than simple curvature (↔ gaussian moments)

- **Modified blackbody distribution** (↔ thermal dust, CIB and integrated extra-galactic dust)
  - Longish expressions given in moment paper
  - Second order expansion has six parameters like two temperature mBB case but is more general
  - Third order expansion has 10 parameters

- **SZ effect with relativistic correction** (JC, Switzer, Nagai & Nelson, 2012)

JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Moment expansions of simple SEDs

- **Power-law distribution** ($\leftrightarrow$ synchrotron)

$$\langle I_\nu \rangle = A\,(\nu_{\rm c}/\nu_0)^\alpha \left[1 + \tfrac{1}{2}\,\beta\ln^2(\nu_{\rm c}/\nu_0) + \tfrac{1}{6}\,\gamma\ln^3(\nu_{\rm c}/\nu_0) + \tfrac{1}{24}\,\delta\ln^4(\nu_{\rm c}/\nu_0) + \dots\right]$$

  - Also works as representation for *free-free*!
  - More general than simple curvature ($\leftrightarrow$ gaussian moments)

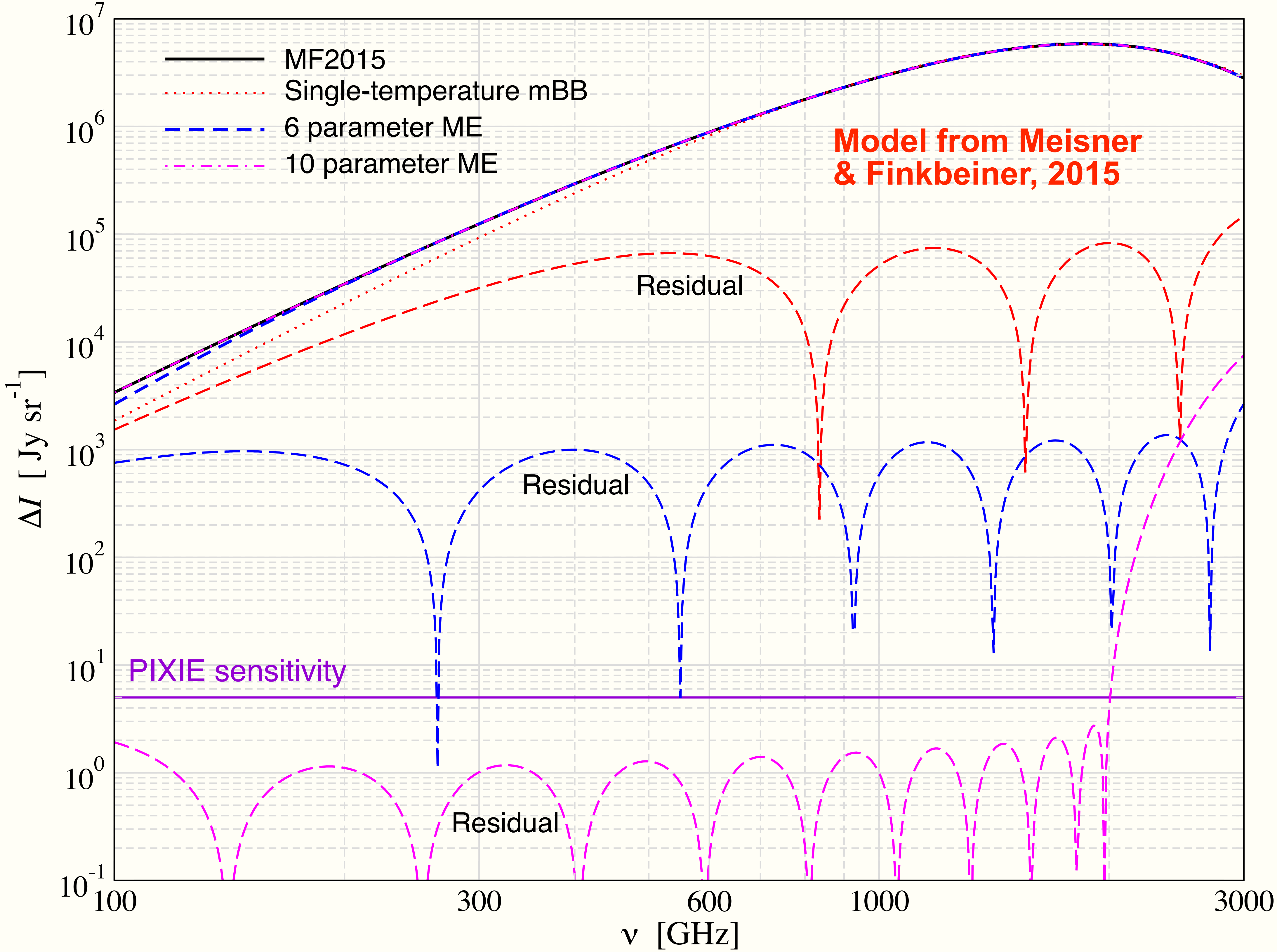
- **Modified blackbody distribution** ($\leftrightarrow$ thermal dust, CIB and integrated extra-galactic dust)
  - Longish expressions given in moment paper
  - Second order expansion has six parameters like two temperature mBB case but is more general
  - Third order expansion has 10 parameters

- **SZ effect with relativistic correction** (JC, Switzer, Nagai & Nelson, 2012)

- ***Can be easily generalized to polarization case!!!***

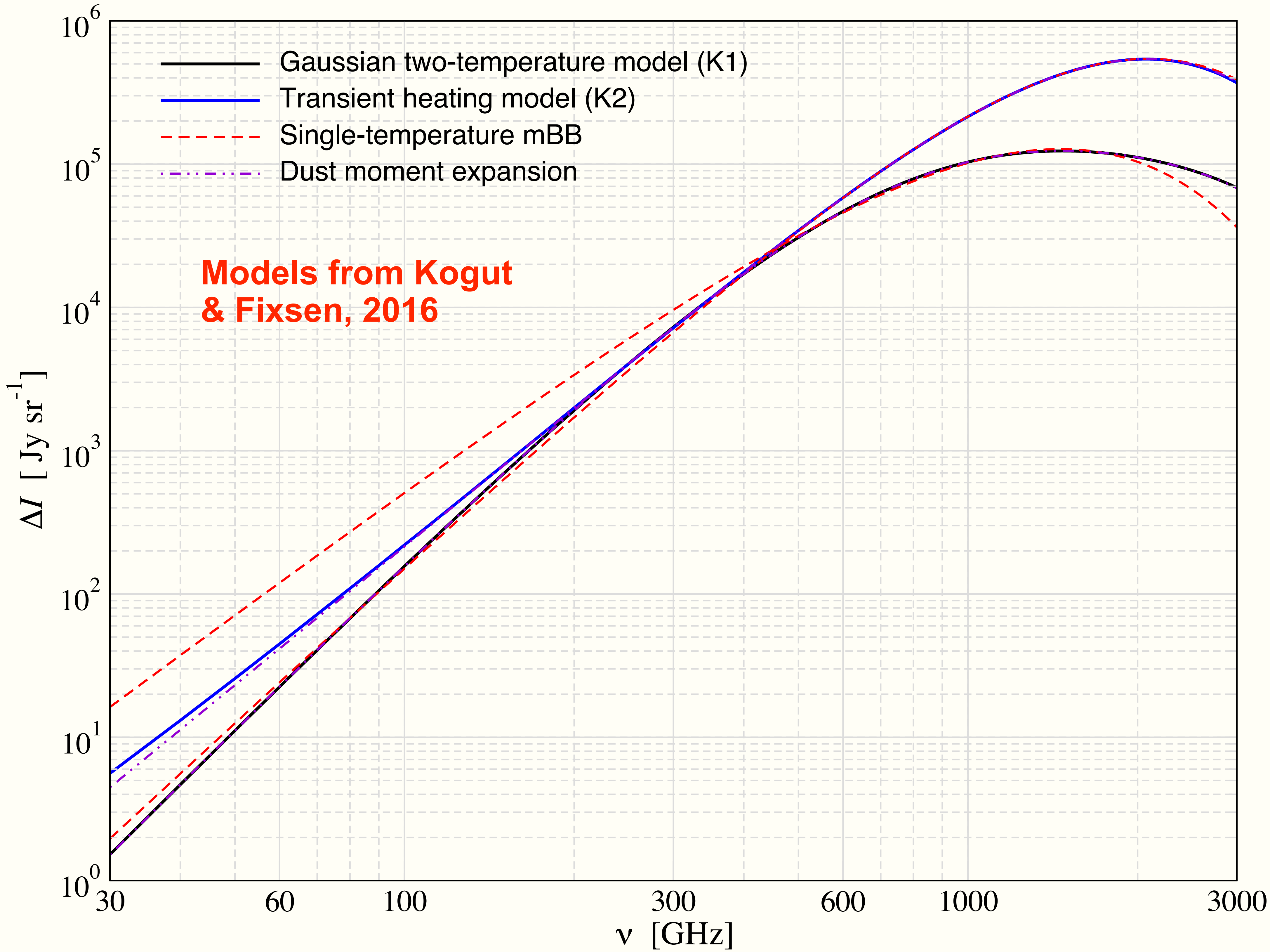
JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Application to dust spectra (two-temperature case)



JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

Application to dust spectra (blind)



JC, Hill and Abitbol, MNRAS, 2017 (ArXiv: 1701.00274)

What could the moment expansion method achieve?

- *Natural extension* of the simple SED shapes
  - The averaging of SEDs *is a physical* process
- *Factorization* of spatial and spectral terms (*linear operations!*)
  - Moments are new parameters with new morphologies / maps
- *Compression* of the information
  - Could even think about orthogonalization schemes to reduce # of pars
  - Allows combining constraints from different methods
- Useful for *simulations* of dust and other foregrounds
  - Assessment of possible *biases* due to foreground residuals
  - *Risk* assessment (*how large could the problem maximally be?*)!
- *Propagation* of effects across scales
  - Describes frequency de-correlation effects
  - Scale-dependent SED effects and propagation of noise

What could the moment expansion method achieve?

- *Natural extension* of the simple SED shapes
  - The averaging of SEDs *is a physical* process
- *Factorization* of spatial and spectral terms (*linear operations!*)
  - Moments are new parameters with new morphologies / maps
- *Compression* of the information
  - Could even think about orthogonalization schemes to reduce # of pars
  - Allows combining constraints from different methods
- Useful for *simulations* of dust and other foregrounds
  - Assessment of possible *biases* due to foreground residuals
  - *Risk* assessment (*how large could the problem maximally be?*)!
- *Propagation* of effects across scales
  - Describes frequency de-correlation effects
  - Scale-dependent SED effects and propagation of noise

We need to check that things are going to work out!