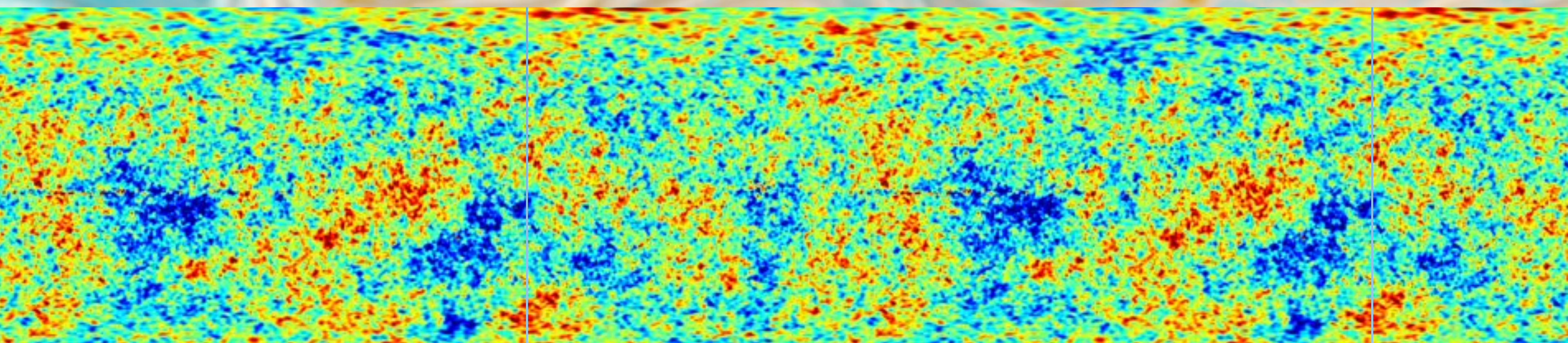
银河系前景扣除和辐射研究



张乐 (中山大学)

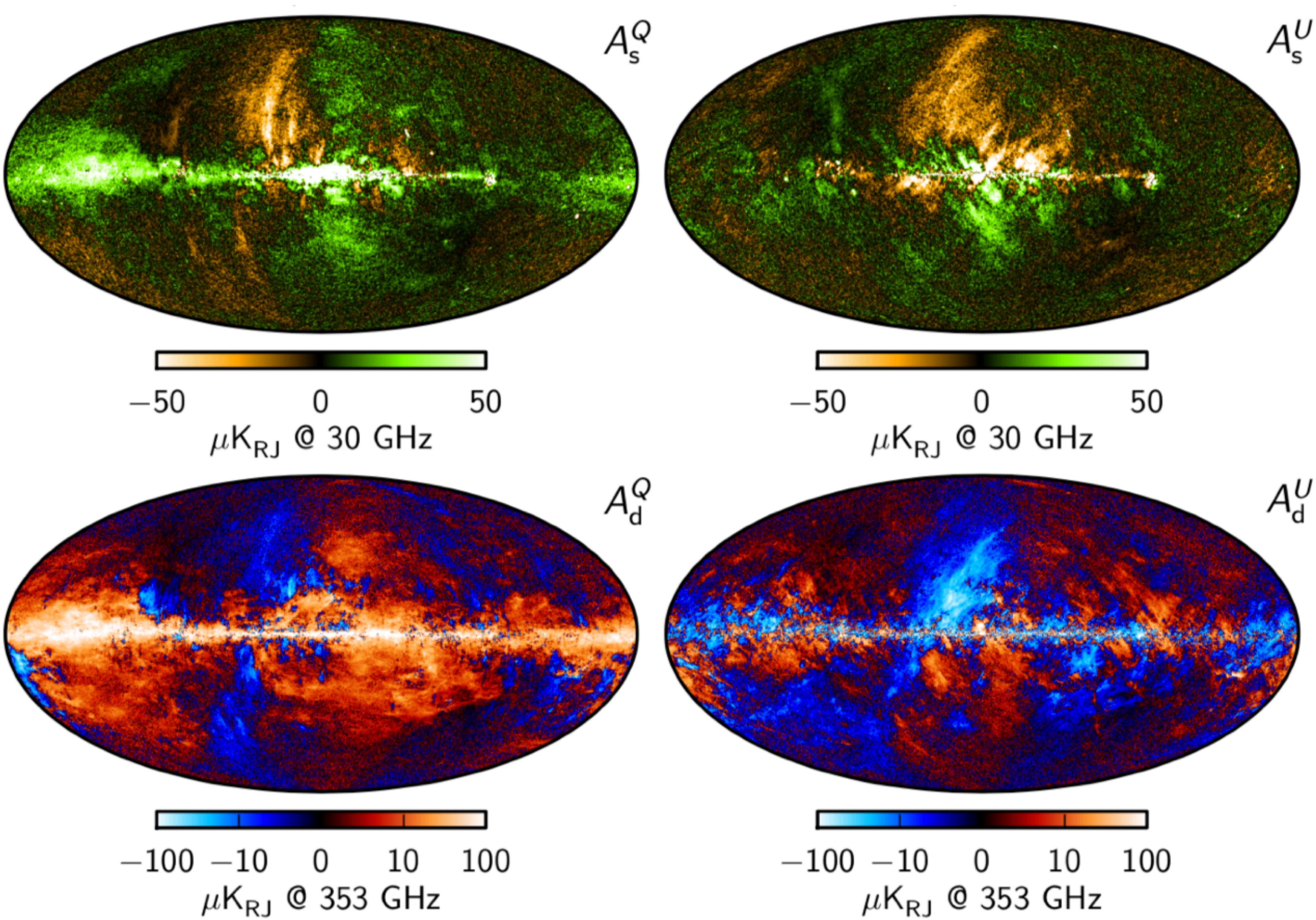
中国高能物理非加速器战略研讨会

2021.05.16

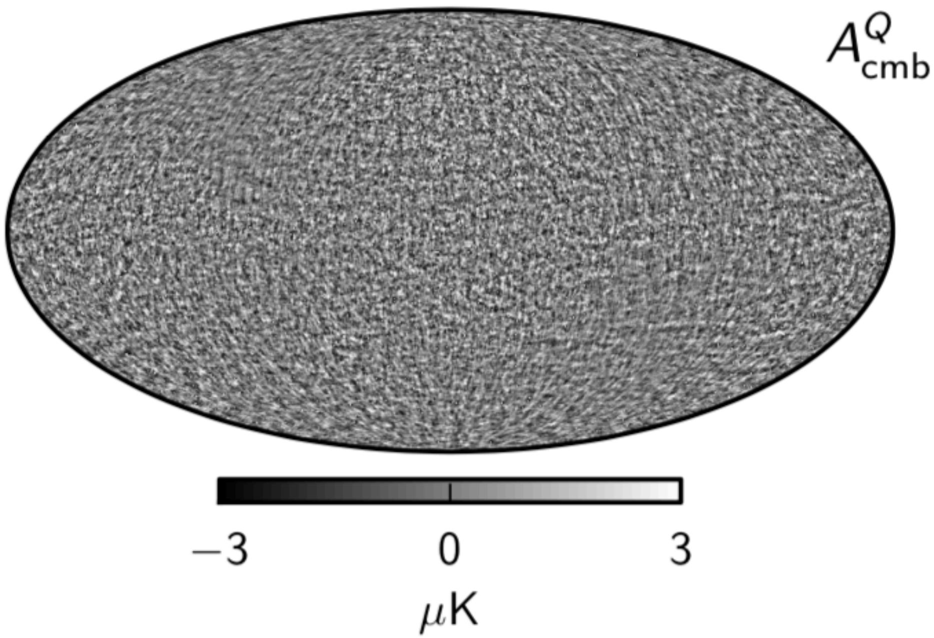
提纲

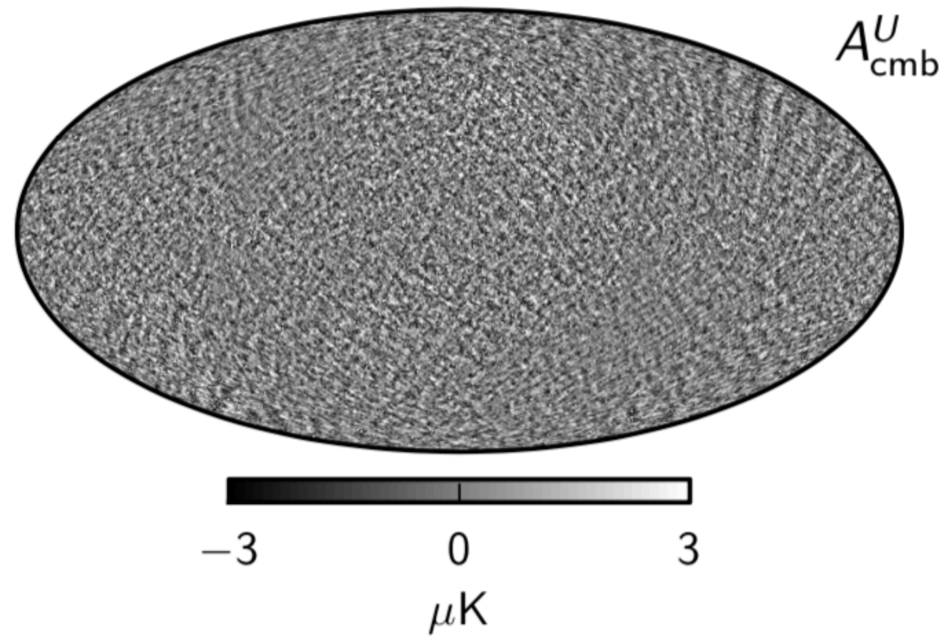
- 前景污染带来的挑战
- 前景扣除方法的总结
- 前景辐射性质的研究
- 总结

Observed polarization maps



Predicted CMB polarization maps



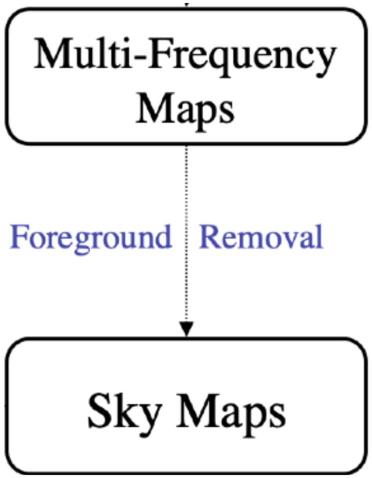


Challenges: foreground contamination

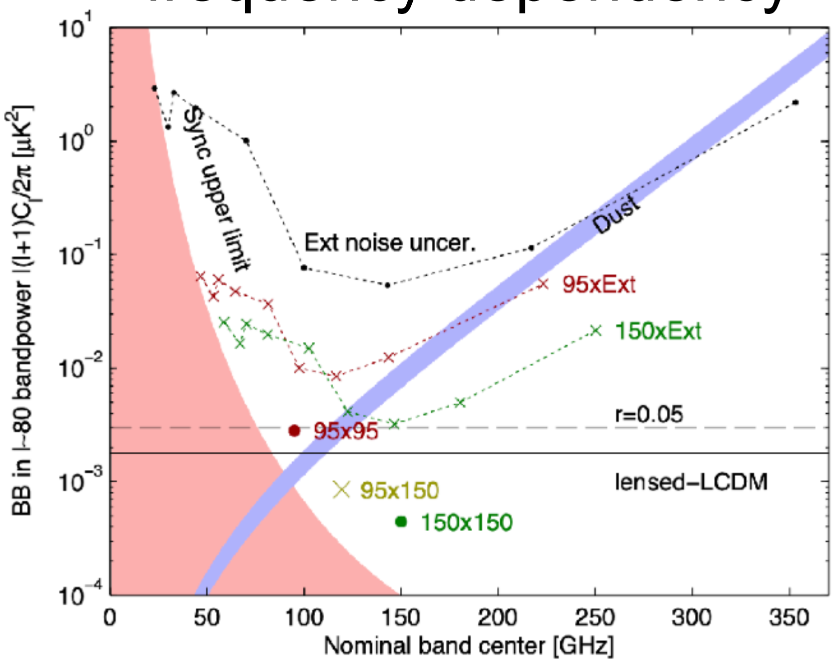
Component	Spectrum	Polarization fraction	References
Synchrotron	Power-law, β~-3.1, possible curvature	~15-20% (up to ~50%)	Page et al. (2007), Kogut et al. (2007), Macellari et al. (2011)
Thermal dust	Modified black-body, flattening at frequencies <300 GHz	~5% (up to ~15+%!)	Ponthieu et al. (2005), Planck CollaboraUon, ESLAB conference (2013).
Magnetic dipole?	Similar to thermal dust, but flatter index at frequencies ~100 GHz	Variable (up to ~35%!?)	Draine & Lazarian (1999), Draine & Hensley (2013)
Spinning dust	**Peaked spectrum ~10-60 GHz.**	<~1%	Lazarian & Draine (2000), Dickinson (2011), Lopez-Caraballo et al. (2011), Macellari et al. (2011), Rubino-Martin et al. (2012)
Free-free	Power-law β~-2.14 with positive curvature (steepening at frequencies >~100 GHz)	<~1%	Rybicki & Lightman (1979), Keating et al. (1998), Macellari et al. (2011)

Challenges & Solutions

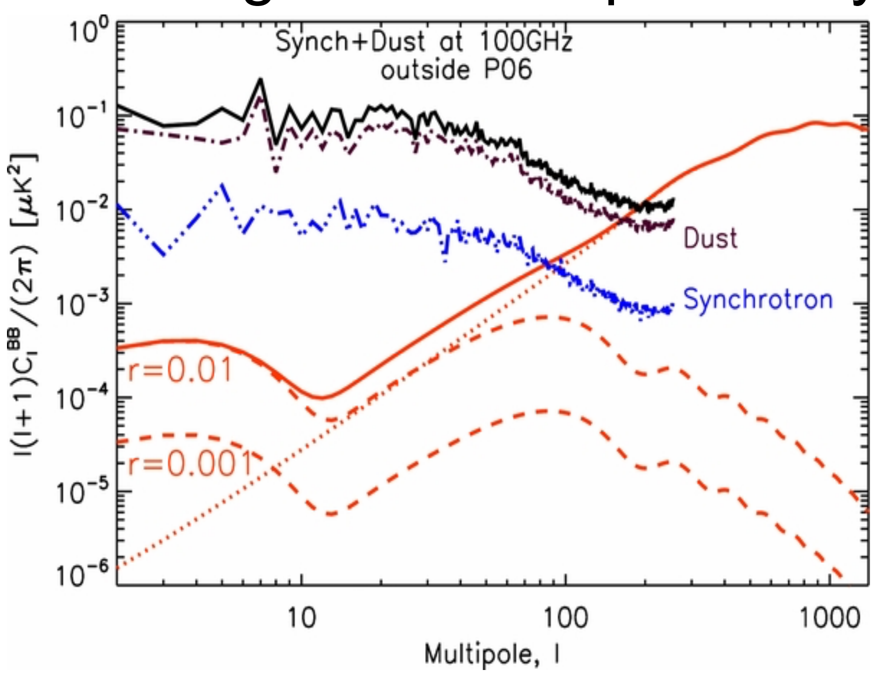
Challenge:
necessary to subtract Galactic foregrounds down to tens of nK for B-mode detection (if r~ 0.01)



frequency dependency



angular size dependency



Science and main tasks

- **Foreground removal:** one of the major challenges in B-mode detection
  - developing pipelines (at least 3) for AliCPT
  - ILC/ABS/template fitting/SMICA/SEVEM
- **Foreground science:**
  - reconstruct magnetic/dusts/electron fields
  - understand the physical origins of foreground components
  - reconstruct DM map for FRB from Q/U maps?
  - low-l C^{EE} may improve tau
  - ……

Existing foreground cleaning methods

Cleaning method:Template fitting

foreground model:

$$D_{\ell,BB}^{\nu_1\times\nu_2} = A_{dust} f_d^{\nu_1} f_d^{\nu_2}\left(\frac{\ell}{80}\right)^{\alpha_d} + A_{sync} f_s^{\nu_1} f_s^{\nu_2}\left(\frac{\ell}{80}\right)^{\alpha_s} + \epsilon\sqrt{A_{dust}A_{sync}}\left(f_d^{\nu_1} f_s^{\nu_2} + f_s^{\nu_1} f_d^{\nu_2}\right)\left(\frac{\ell}{80}\right)^{(\alpha_d+\alpha_s)/2}$$

$$f_d^{\nu} = \left(\frac{\nu}{\nu_0}\right)^{\beta_d-2}\frac{B_{\nu_1}(T_d)}{B_{\nu_0}(T_d)}, \quad f_s^{\nu} = \left(\frac{\nu}{\nu_0}\right)^{\beta_s}$$

- 2. A_d — dust amplitude,at 353 GHz and $l = 71.5$;
- 3. β_d — dust spectral index across frequencies;
- 4. α_d — dust spatial spectral index across ells;
- 5. A_s — sync amplitude, at 23 GHz and $l = 71.5$;
- 6. β_s — sync spectral index across frequencies;
- 7. α_s — sync spatial spectral index across ells;
- 8. ε — synchrotron–dust spatial correlation.

- multi-frequency cross-spectrum likelihood of the data for a given proposed model with a few parameters (dust+synchrotron…)
- using MCMC to estimate posterior values of r and foreground parameters

Hamimeche-Lewis likelihood (l>30)

$$-2\log\mathcal{L}(\{\boldsymbol{C}_l\}|\{\hat{\boldsymbol{C}}_l\}) \approx \mathbf{X}_g^T \boldsymbol{M}_f^{-1}\mathbf{X}_g = \sum_{ll'}[\mathbf{X}_g]_l^T[\boldsymbol{M}_f^{-1}]_{ll'}[\mathbf{X}_g]_{l'}.$$

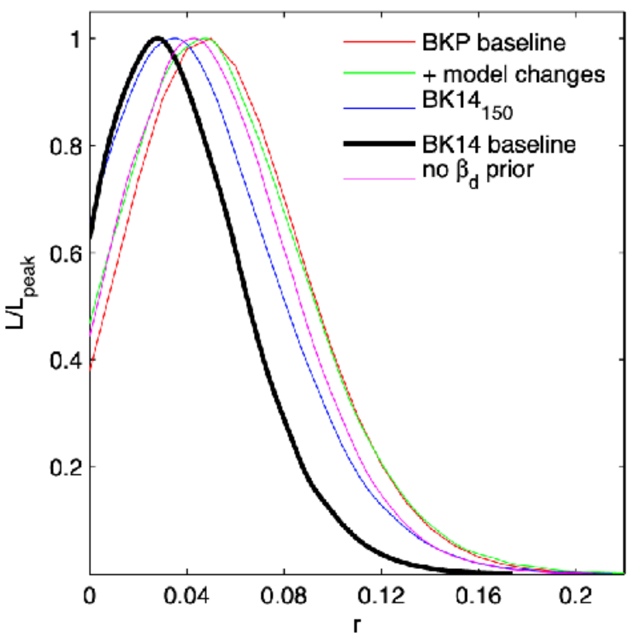
$$g(x) = \mathrm{sign}(x-1)\sqrt{2(x-\ln(x)-1)}$$

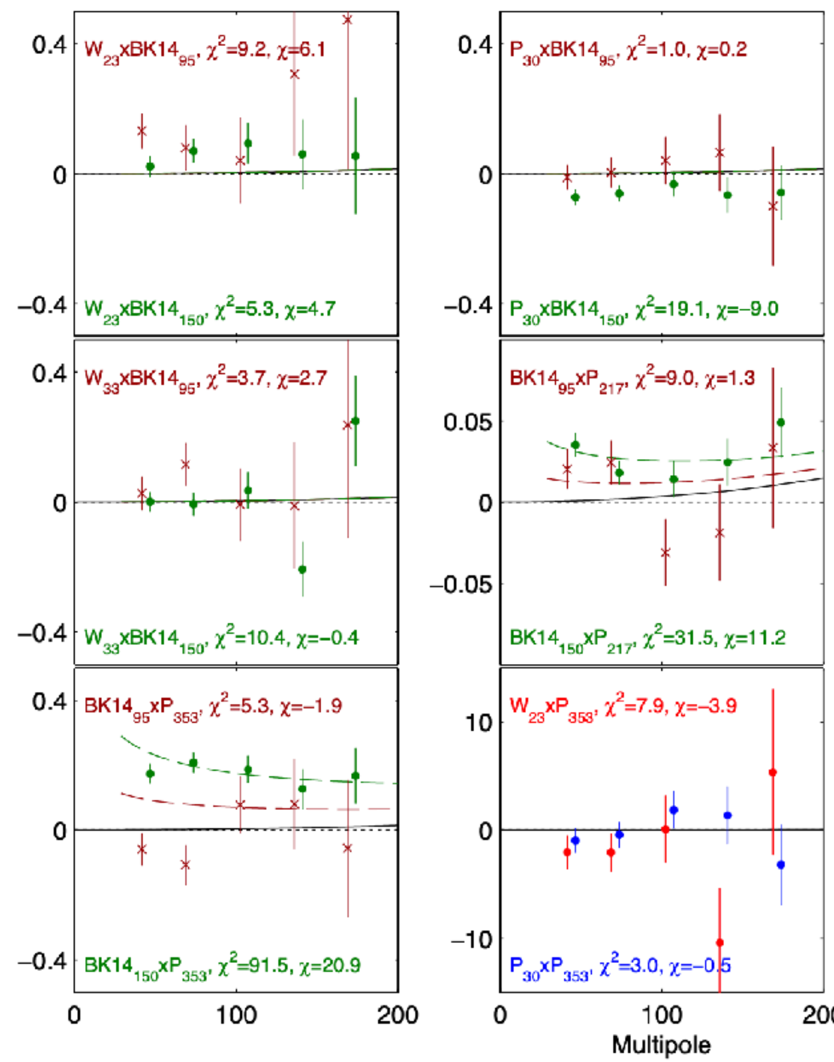
$$[\boldsymbol{M}_f]_{ll'} = \langle(\hat{\mathbf{X}}_l - \mathbf{X}_l)(\hat{\mathbf{X}}_{l'} - \mathbf{X}_{l'})^T\rangle_f$$

$$[\mathbf{X}_g]_l = \mathrm{vecp}(\boldsymbol{C}_{fl}^{1/2}\mathbf{g}[\boldsymbol{C}_l^{-1/2}\hat{\boldsymbol{C}}_l\boldsymbol{C}_l^{-1/2}]\boldsymbol{C}_{fl}^{1/2}),$$

Cleaning method:Template fitting

- cross-spectra between observed maps and all the polarized bands of Planck/WMAP
- Joint analysis based on likelihood analysis (BICEP2/Keck and Planck Collaborations 15&16)





Cleaning method: ILC

Internal Linear Combination: Introducing **a weighting vector "w"** for all frequency maps, but keeping the CMB signal unchanged in sum.

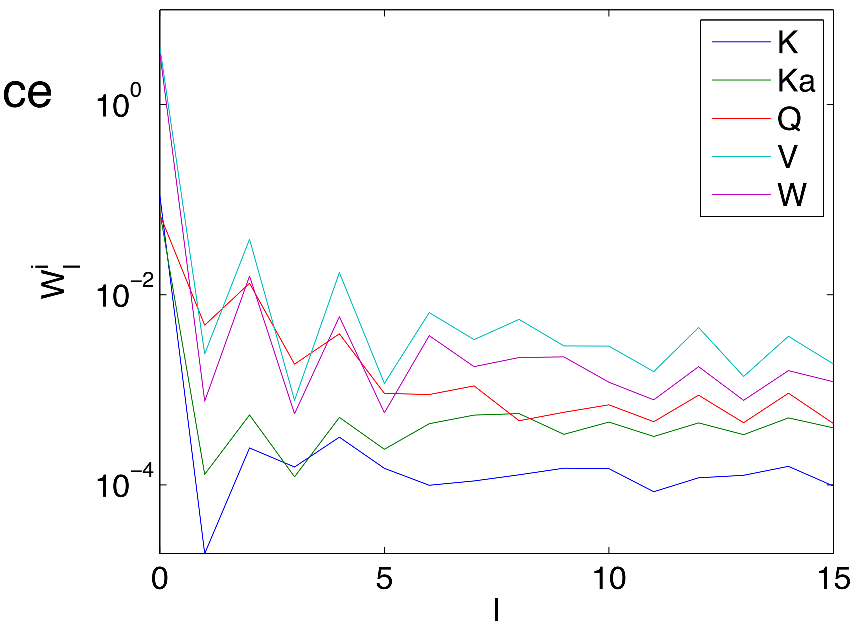
$$\sum_i w_i(\mathbf{x})\, T(\mathbf{x},\nu_i) = T_{\rm cmb}(\mathbf{x}) + \sum_i w_i(\mathbf{x})\, T_{\rm fg}(\mathbf{x},\nu_i). \quad \text{where} \quad \sum_i w_i = 1.$$

- Minimize the variance of the weighted map to analytically derive the best "w"
- The cleaned map is regarded as a pure CMB map

$$\hat{\mathbf{C}}_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} \mathbf{d}_{\ell m}\mathbf{d}^\dagger_{\ell m}.$$ Empirical covariance of data

$$\mathbf{w}^\dagger = \frac{\mathbf{e}^\dagger \hat{\mathbf{C}}_\ell^{-1}}{\mathbf{e}^\dagger \hat{\mathbf{C}}_\ell^{-1}\mathbf{e}}.$$ ILC weighting

$$\tilde{C}_\ell = \frac{1}{\mathbf{e}^\dagger \hat{\mathbf{C}}_\ell^{-1}\mathbf{e}}.$$ CMB estimator



Cleaning method: ABS

We proposed an analytical blind separation method (ABS)

- Goal: to solve for CMB power spectrum without any assumptions on foregrounds; Intuitively, this task seems to be impossible!

- Measured cross band powers between frequency channels

$$\mathcal{D}_{ij}(\ell) = f_i^{\rm B} f_j^{\rm B} \mathcal{D}_{\rm B}(\ell) + \mathcal{D}_{ij}^{\rm fore}(\ell)$$

An analytical unique solution of $D_B(l)$ achieved by the Sylvester's determinant theorem as long as $M< N_f$

M: rank of D^{fore}, M non-zero eigenvalues
N_f: number of frequency channels

the μ-th eigenvector of $\mathcal{D}_{ij}$ is $\mathbf{E}^{(\mu)}$

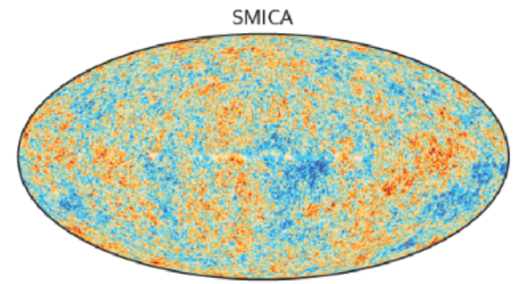
$$G_\mu \equiv \mathbf{f}^{\rm B} \cdot \mathbf{E}^{(\mu)}$$

$$\mathcal{D}_{\rm B} = \left(\sum_{\mu=1}^{M+1} G_\mu^2 \lambda_\mu^{-1} \right)^{-1}$$

PJ Zhang et al, MNRAS 484,1616Z (2019)
Yao et al, ApJS 848,44Z (2018)
L. Santos et al, 2019, accepted by A&A

Cleaning method: SMICA

- **SMICA is a multi-component maximum likelihood spectral estimation method (Delabrouille+ 2003)**



A: mixing matrix - frequency dependance of components
R: angular cross power spectra of components

$$\mathrm{R}_x(\ell) = \mathrm{A}\,\mathrm{R}_s(\ell)\,\mathrm{A}^t + \mathrm{R}_n(\ell)$$

$$\begin{pmatrix} C_\ell^{x_1x_1} & C_\ell^{x_1x_2} & \dots & C_\ell^{x_1x_N} \\ C_\ell^{x_1x_2} & C_\ell^{x_2x_2} & \dots & C_\ell^{x_2x_N} \\ \vdots & \vdots & \ddots & \vdots \\ C_\ell^{x_1x_N} & C_\ell^{x_2x_N} & \dots & C_\ell^{x_Nx_N} \end{pmatrix}$$

$$\widehat{C}_\ell^{x_ix_j} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} x_{i,\ell m}\,\bar{x}_{j,\ell m}$$

OBSERVATIONS

$$\begin{pmatrix} a_1^{\mathrm{CMB}} & a_1^{\mathrm{dust}} & a_1^{\mathrm{sync}} & \dots & a_1^{\mathrm{SZ}} \\ a_2^{\mathrm{CMB}} & a_2^{\mathrm{dust}} & a_2^{\mathrm{sync}} & \dots & a_2^{\mathrm{SZ}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_N^{\mathrm{CMB}} & a_N^{\mathrm{dust}} & a_N^{\mathrm{sync}} & \dots & a_N^{\mathrm{SZ}} \end{pmatrix}$$

$$\begin{pmatrix} C_\ell^{\mathrm{CMB}} & 0 & 0 & \dots & 0 \\ 0 & C_\ell^{\mathrm{dust}} & X_\ell & \dots & 0 \\ 0 & X_\ell & C_\ell^{\mathrm{sync}} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & C_\ell^{\mathrm{SZ}} \end{pmatrix}$$

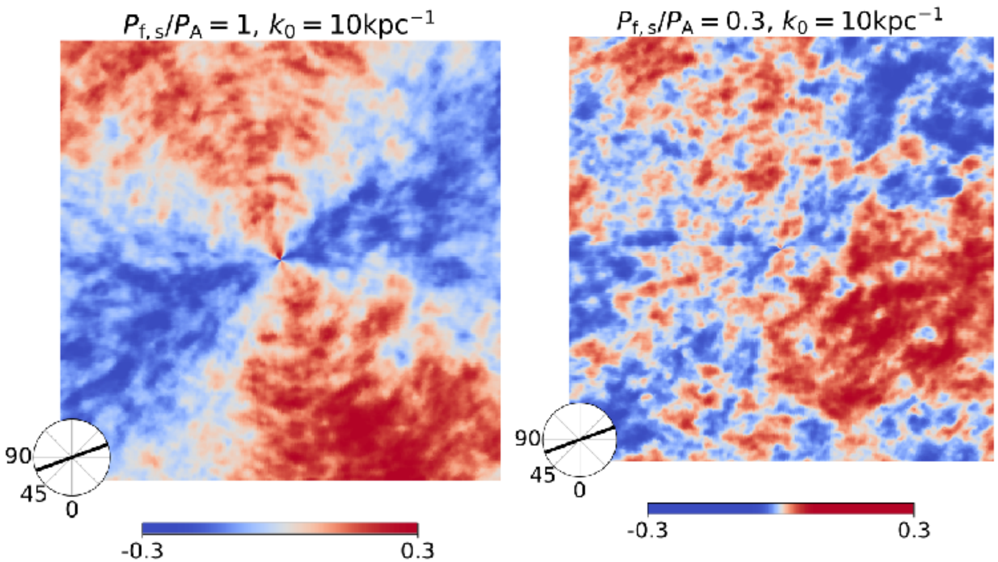
$$\begin{pmatrix} C_\ell^{n_1n_1} & 0 & \dots & 0 \\ 0 & C_\ell^{n_2n_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & C_\ell^{n_Nn_N} \end{pmatrix}$$

MODEL

non-linear optimization problem

New foreground emulator

Hammurabi X — the Galactic emission simulator (JX Wang+)



simulated synchrotron Stokes Q maps with locally parameterized MHD magnetic turbulence

Hammurabi X (*ApJS 247 18, JOSS 01889*)

- Simulating Galactic emissions from physical Galactic component modelings
- Numerically verified MHD turbulence as plausible explanation of synchrotron E/B ratio
- Hammurabi X + IMAGINE can pin down model parameters with given Galactic foreground maps, improving the understanding of foregrounds

Constrain foreground parameters

Component	Free parameters and priors	Brightness temperature, s_ν [μK_{RJ}]	Additional information
CMB[a]	$A_{cmb} \sim \mathrm{Uni}(-\infty,\infty)$	$x = \frac{h\nu}{k_B T_{CMB}}$ $g(\nu) = (\exp(x)-1)^2/(x^2\exp(x))$ $s_{CMB} = A_{CMB}/g(\nu)$	$T_{CMB} = 2.7255\,\mathrm{K}$
Synchrotron[a]	$A_s > 0$ $\alpha > 0$, spatially constant	$s_s = A_s\left(\frac{\nu_0}{\nu}\right)^2 \frac{f_s(\frac{\nu}{\alpha})}{f_s(\frac{\nu_0}{\alpha})}$	$\nu_0 = 408\,\mathrm{MHz}$ $f_s(\nu) =$ Ext template
Free-free	$\log \mathrm{EM} \sim \mathrm{Uni}(-\infty,\infty)$ $T_e \sim N(7000 \pm 500\,\mathrm{K})$	$g_{ff} = \log\left\{\exp\left[5.960 - \sqrt{3}/\pi \log(\nu_9\ T_4^{-3/2})\right] + e\right\}$ $\tau = 0.05468\ T_e^{-3/2}\ \nu_9^{-2}\ \mathrm{EM}\ g_{ff}$ $s_{ff} = 10^6\, T_e\,(1-e^{-\tau})$	$T_4 = T_e/10^4$ $\nu_9 = \nu/(10^9\,\mathrm{Hz})$
Spinning dust	$A^1_{sd}, A^2_{sd} > 0$ $\nu^1_p \sim N(19 \pm 3\,\mathrm{GHz})$ $\nu^2_p > 0$, spatially constant	$s_{sd} = A_{sd}\cdot\left(\frac{\nu_0}{\nu}\right)^2 \frac{f_{sd}(\nu\cdot\nu_{p0}/\nu_p)}{f_{sd}(\nu_0\cdot\nu_{p0}/\nu_p)}$	$\nu^1_0 = 22.8\,\mathrm{GHz}$ $\nu^2_0 = 41.0\,\mathrm{GHz}$ $\nu_{p0} = 30.0\,\mathrm{GHz}$ $f_{sd}(\nu) =$ Ext template
Thermal dust[a]	$A_d > 0$ $\beta_d \sim N(1.55 \pm 0.1)$ $T_d \sim N(23 \pm 3\,\mathrm{K})$	$\gamma = \frac{h}{k_B T_d}$ $s_d = A_d\cdot\left(\frac{\nu}{\nu_0}\right)^{\beta_d+1} \frac{\exp(\gamma\nu_0)-1}{\exp(\gamma\nu)-1}$	$\nu_0 = 545\,\mathrm{GHz}$
SZ	$y_{sz} > 0$	$s_{sz} = 10^6\, y_{sz}/g(\nu)\, T_{CMB}\left(\frac{x(\exp(x)+1)}{\exp(x)-1} - 4\right)$	
Line emission	$A_i > 0$ $h_{ij} > 0$, spatially constant	$s_i = A_i h_{ij} \frac{F_i(\nu_j)}{F_i(\nu_0)} \frac{g(\nu_0)}{g(\nu_j)}$	$i \in$ {CO $J=1\to0$, CO $J=2\to1$, CO $J=3\to2$, 94/100} $j =$ detector index $F =$ unit conversion

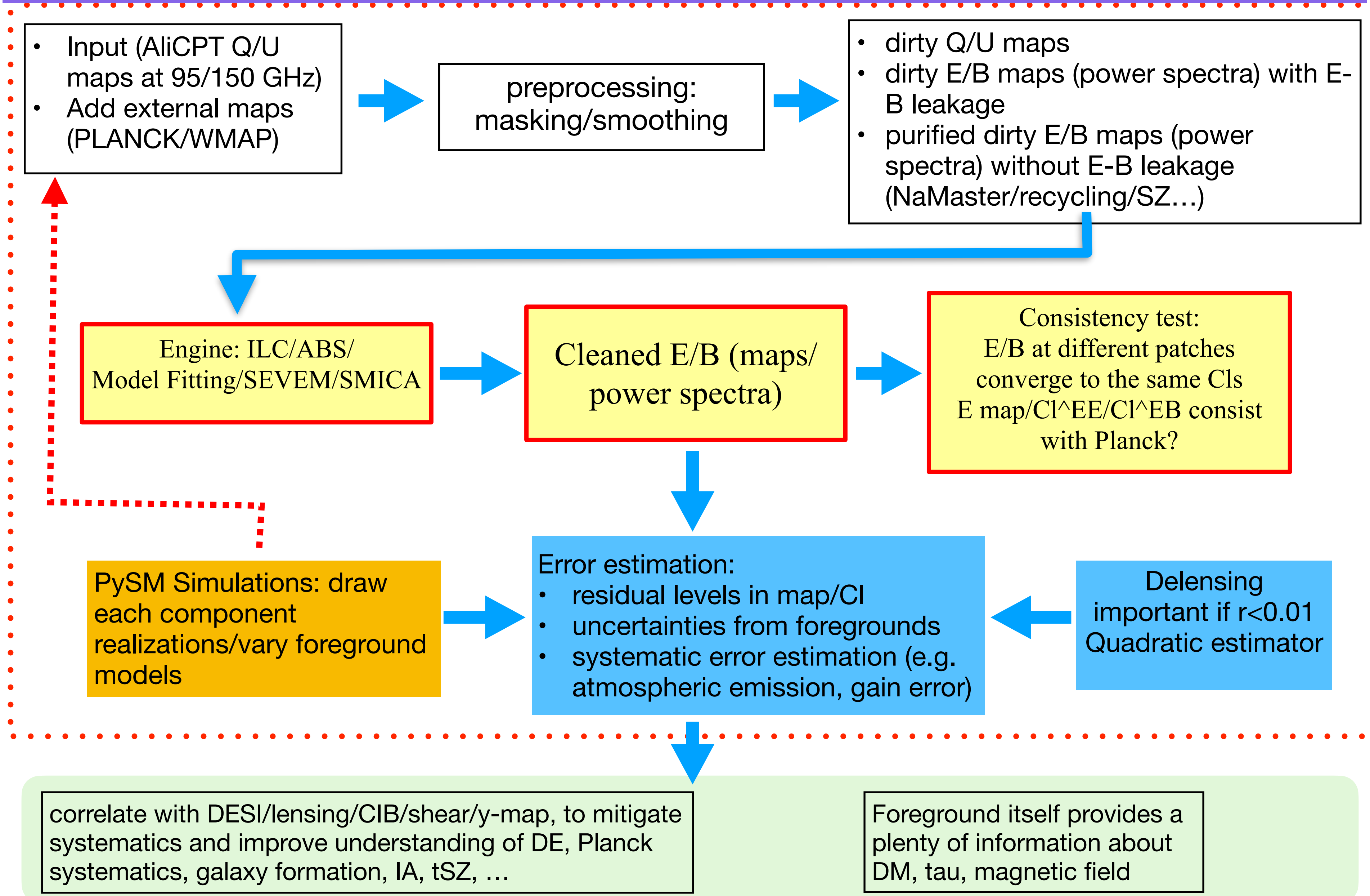
[a] Polarized component.

总结

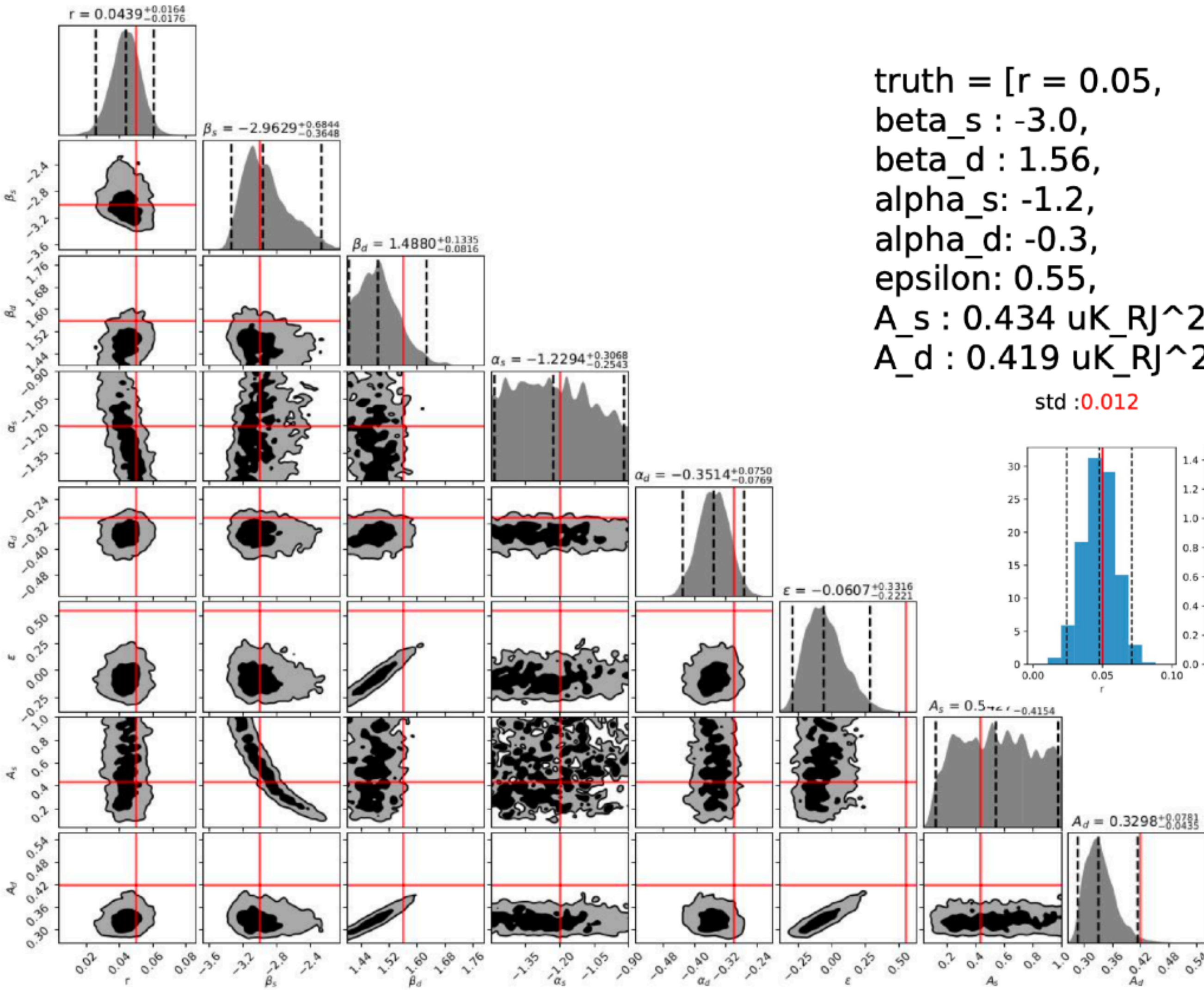
多频段、高信噪比的极化观测对理解和扣除前景至关重要！

Backup

Pipeline of foreground removal



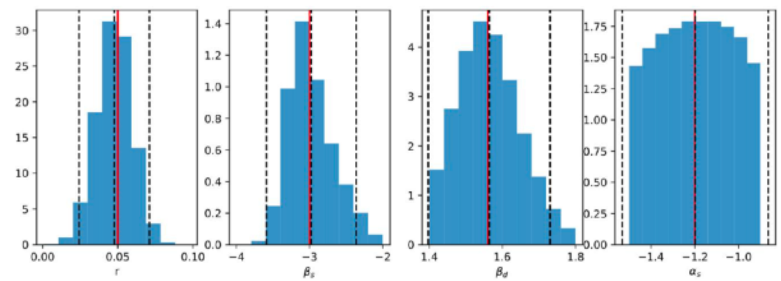
算法测试 – Model fitting



truth = [r = 0.05,
beta_s : -3.0,
beta_d : 1.56,
alpha_s: -1.2,
alpha_d: -0.3,
epsilon: 0.55,
A_s : 0.434 uK_RJ^2,
A_d : 0.419 uK_RJ^2]

100 realizations

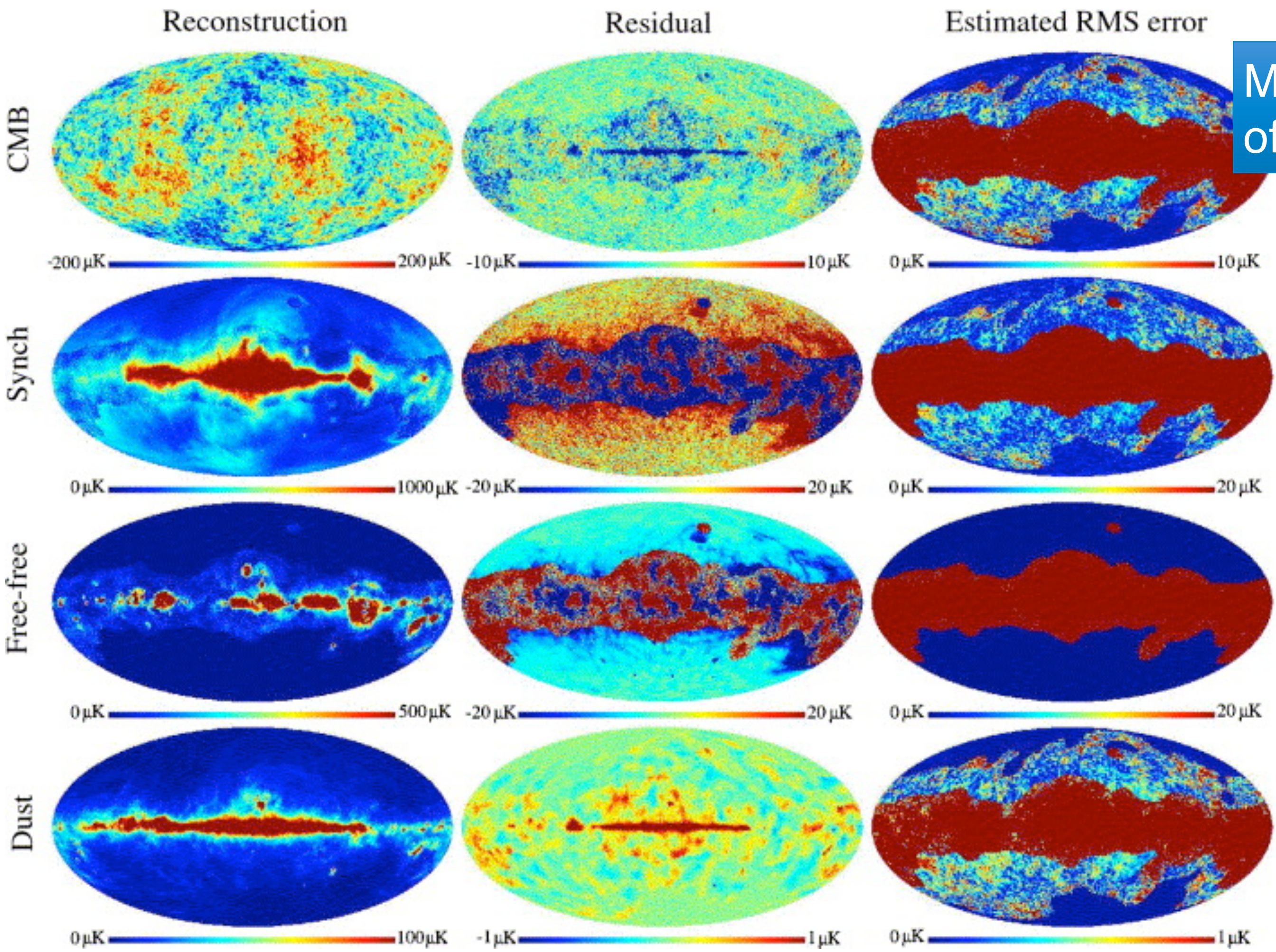
std :0.012



- **Validation: blind test by mock data with unknown components & frequency scalings**
- **propagate systematics into the error estimation**

Cleaning method: Model fitting (II)

Commander (Gibbs sampling technique) Eriksen+ 2008



MCMC-based estimation of physical parameters θ

$$\mathbf{s}^{i+1} \leftarrow P(\mathbf{s}|C_\ell^i, \theta^i, \mathbf{d})$$
$$C_\ell^{i+1} \leftarrow P(C_\ell|\mathbf{s}^{i+1}, \mathbf{d})$$
$$\theta^{i+1} \leftarrow P(\theta|C_\ell^{i+1}, \mathbf{s}^{i+1}, \mathbf{d}).$$

Cleaning method: SMICA

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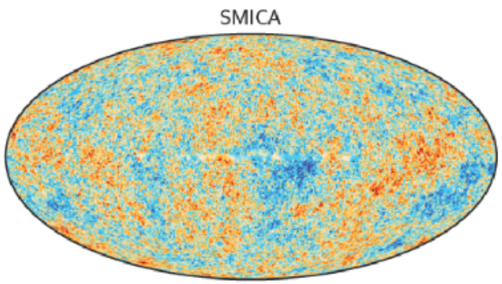

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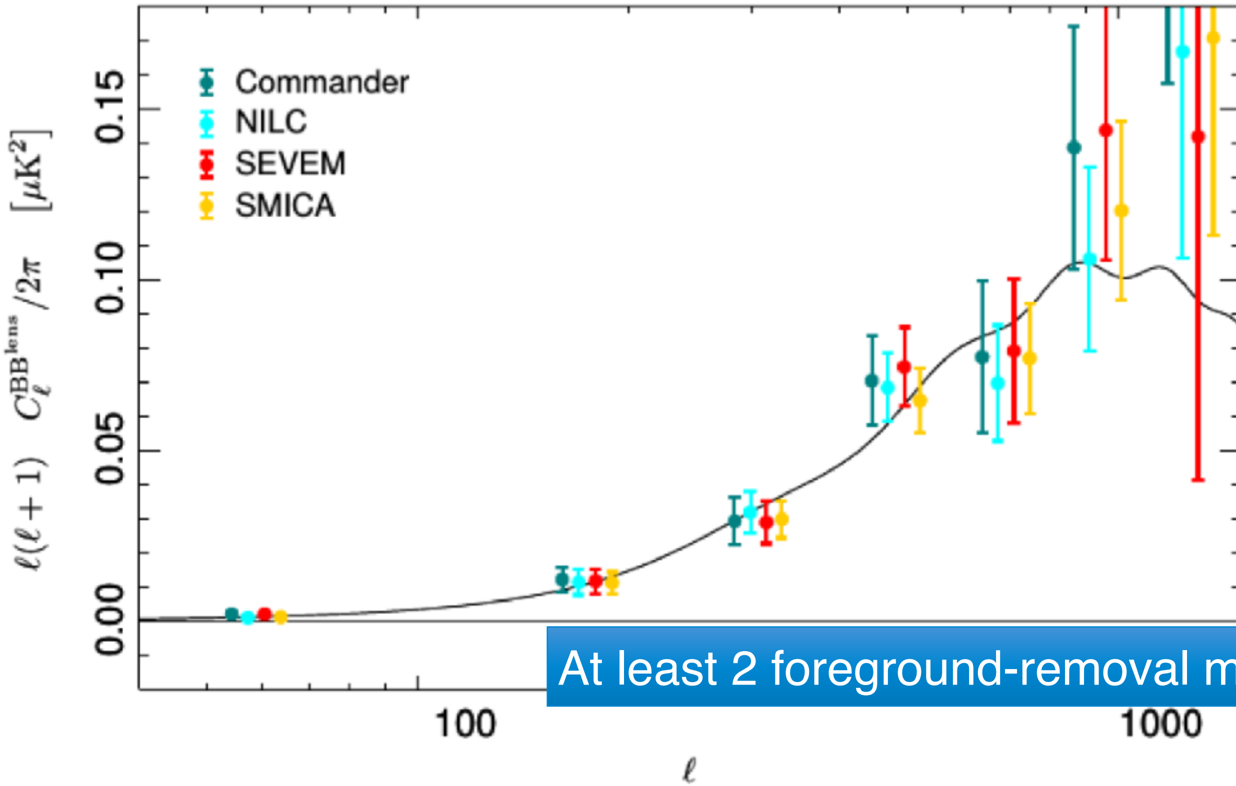
$$\begin{pmatrix} C_\ell^{\mathrm{CMB}} & 0 & 0 & \dots & 0 \\ 0 & C_\ell^{\mathrm{dust}} & X_\ell & \dots & 0 \\ 0 & X_\ell & C_\ell^{\mathrm{sync}} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & C_\ell^{\mathrm{SZ}} \end{pmatrix}$$

$$\begin{pmatrix} C_\ell^{n_1n_1} & 0 & \dots & 0 \\ 0 & C_\ell^{n_2n_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & C_\ell^{n_Nn_N} \end{pmatrix}$$

MODEL

non-linear optimization problem

Consistency check



Cross-check is important for validation!

At least 2 foreground-removal methods to be used in AliCPT

- parametric/non-blind - model fitting
  - COMMANDER (Gibbs sampling)

- non-parametric/blind - data driven
  - SMICA, ILC, SEVEM