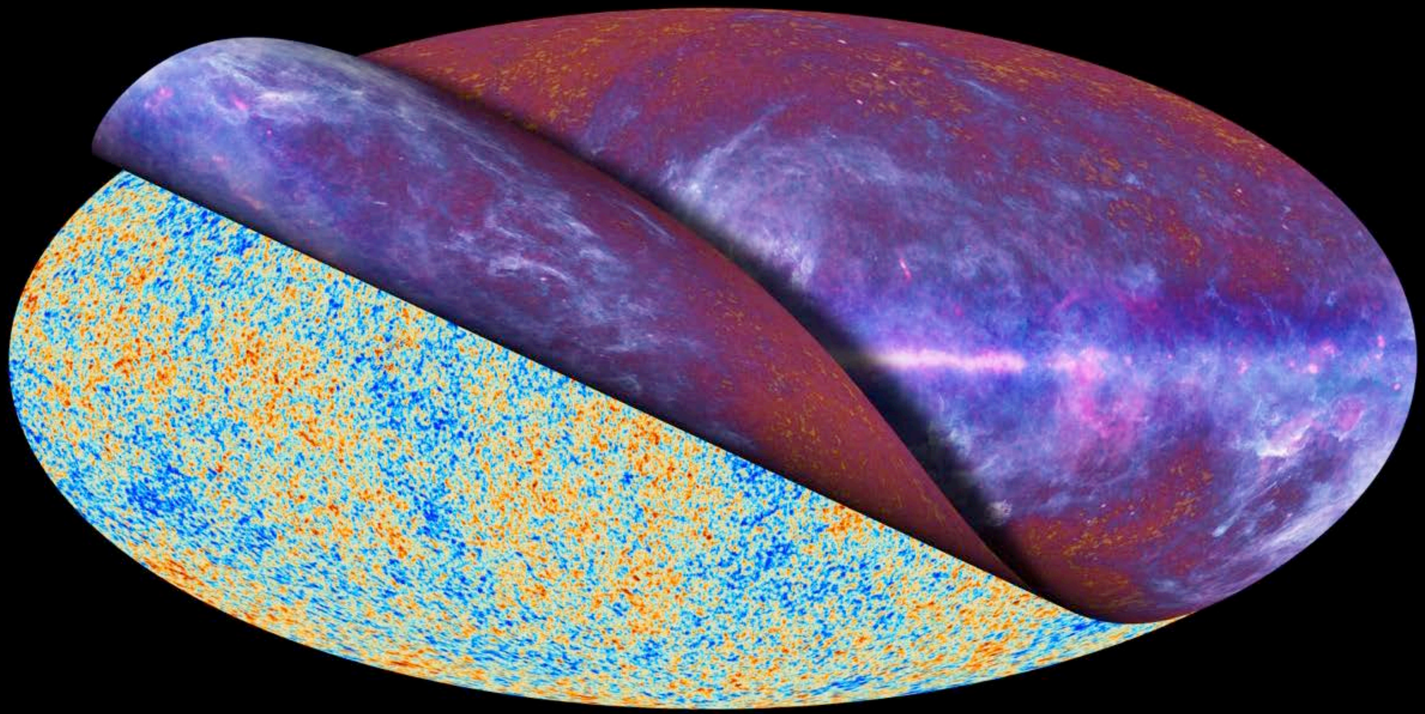
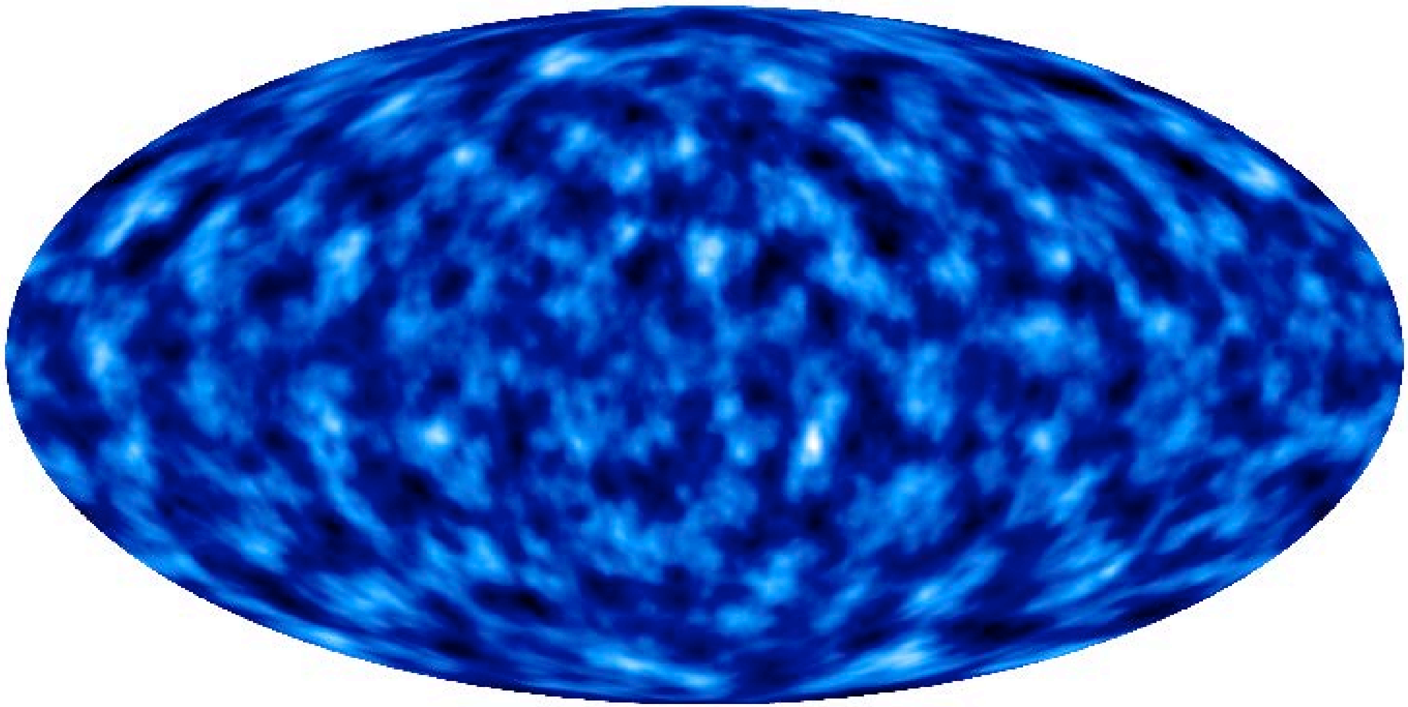


Planck unveils the Cosmic Microwave Background

planck

esa

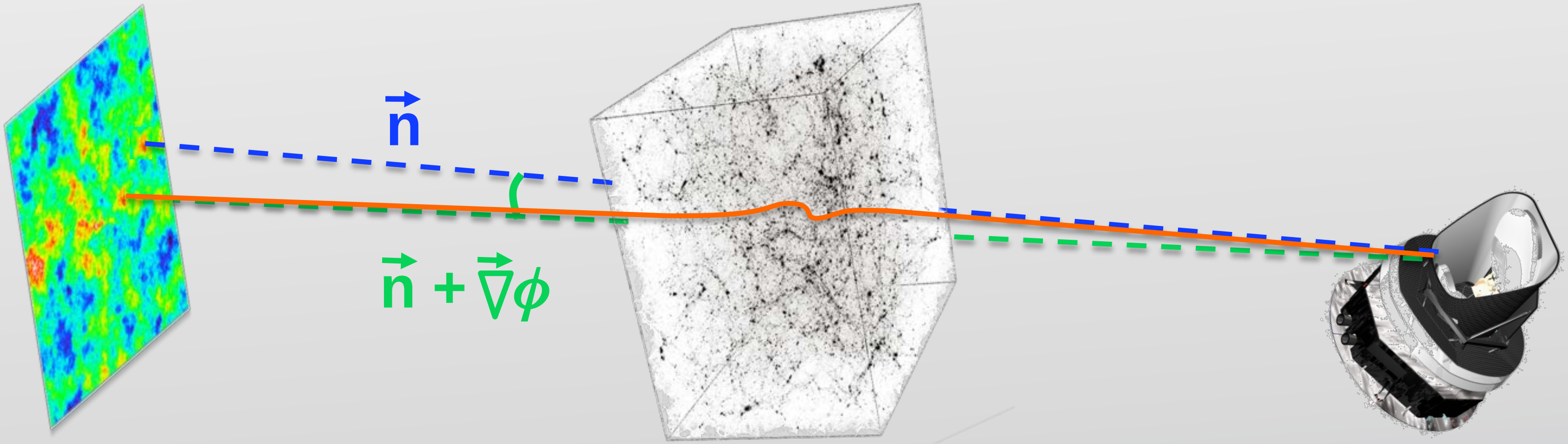


CMB Lensing Reconstruction:
Robustness against foreground residuals & Cosmological impact

Laurence Perotto, LPSC-CNRS, on behalf of the Planck Collaboration

planck esa HFI PLANCK PLANCK LFI LPSC Grenoble

Gravitational Lensing by large-scale Structure



$z \simeq 1090$ | $0.1 < z < 5$ | $z = 0$

Remapping: $T(\hat{\mathbf{n}}) = T^{\mathrm{unlensed}}(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$

Lensing potential:

$$\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_*} d\chi \left(\frac{\chi_* - \chi}{\chi_*\chi}\right) \Psi(\chi\hat{\mathbf{n}}; \eta_0 - \chi)$$

- max. efficiency at z~2
- typical size ~300 Mpc
- linear growth

kernel in a flat universe

conformal distance

lookback conformal time

Observational signature

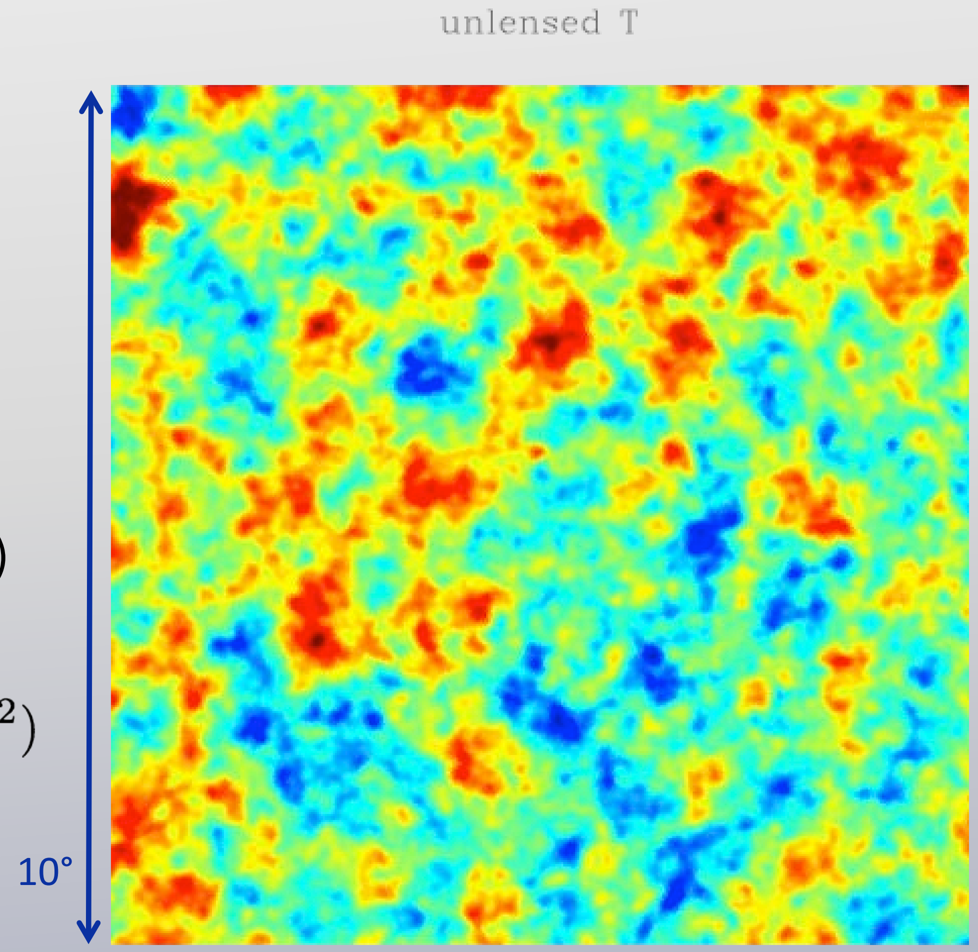
Lensing typical scales:

- deflection scale $\simeq$ 2.5 arcmin (rms)
- correlation length $\simeq$ 2 degrees

Signatures:

- C_ℓ^{TT} smoothing ($\simeq$10% at $\ell = 2000$)
- inducing NG

$$\Delta T(\hat{\mathbf{n}}) \simeq \nabla^i \phi(\hat{\mathbf{n}}) \nabla_i T(\hat{\mathbf{n}}) + \mathcal{O}(\phi^2)$$



Using the NG signature introduced into the T map, the underlying phi potential can be reconstructed

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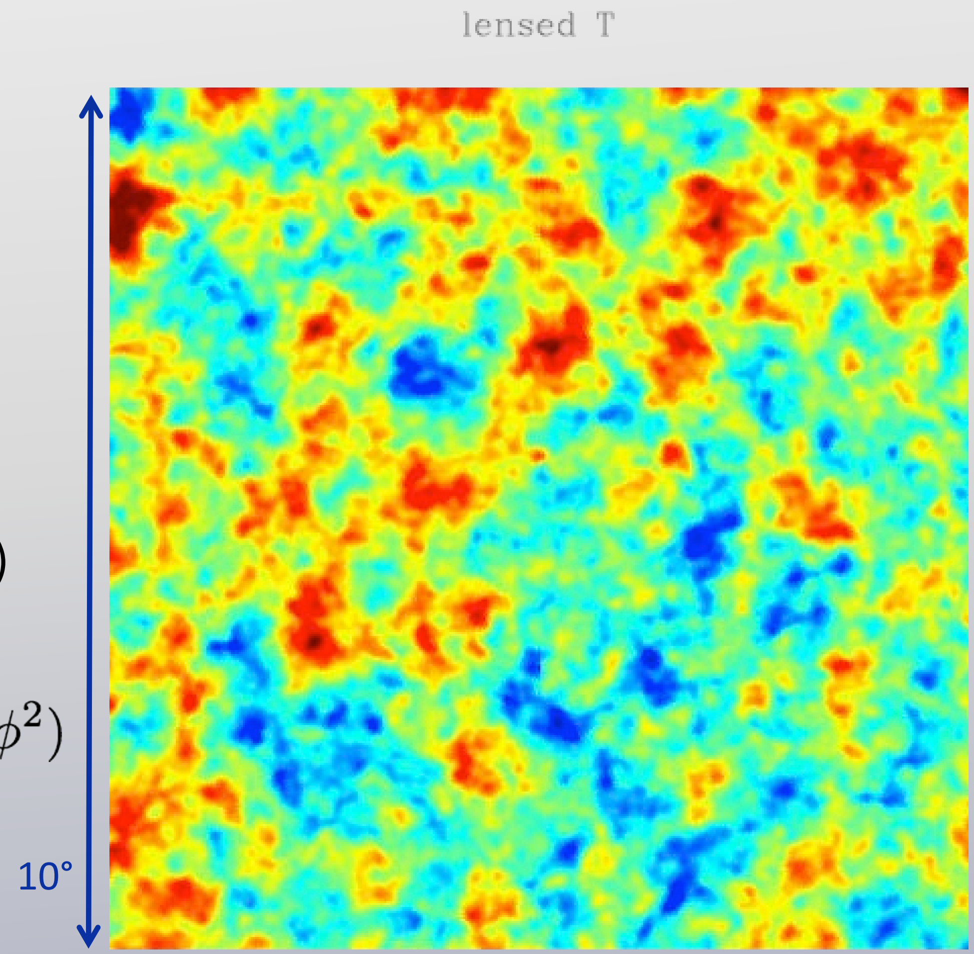


Using the NG signature introduced into the T map, the underlying phi potential can be reconstructed

Reconstruction: methodology

T. Okamoto & W. Hu [astro-ph/0301031]

$\phi(\hat{\mathbf{n}})$ map reconstruction using *quadratic estimators*

$$\hat{\phi}_{LM} = A_L \int d\hat{n}\; \nabla^i Y^*_{LM}(\hat{n})\; \bar{T}(\hat{n}) \nabla_i \bar{T}'(\hat{n})$$

filtered versions of the T map

normalisation and filters optimisation → unbiased, minimum variance estimator

$\hat{C}_L^{\phi\phi}$ reconstruction using the 4-point correlator information

$$\hat{C}_L^{\phi\phi} = \frac{1}{N_{\mathrm{dof}}} \sum_M |\hat{\phi}_{LM}|^2 - N_L^{(0)} - \mathcal{O}(C_L^{\phi\phi})$$

Gaussian bias: disconnected part of the 4-pt correlator

Reconstruction on data: methodology

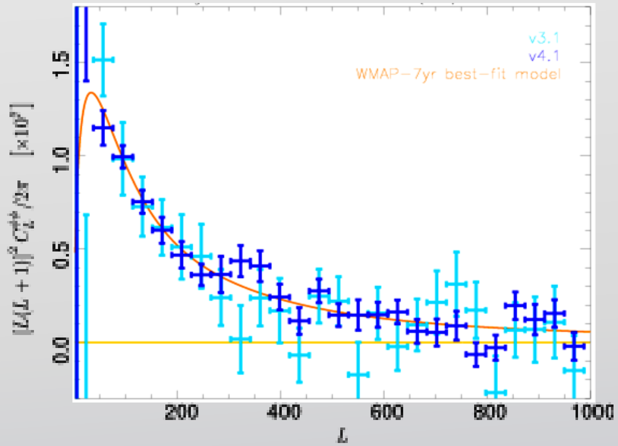
1. data processing steps from timelines to map are critical

- TOI-processing
- Map-making

Planck 2013 results. II, III, IV, V

Planck 2013 results. VI, VII, VIII, IX, X

[archive 2010-11-04]



Early full-sky reconstructions on the same amount of data

- *better model of the time transfert function*
- NL-correction in the V->W
- better SS0 flagging
- improved 4K-lines corr.
- better glitches removal

2. The astrophysical foreground must be dealt with

masking:
- detected point sources
  - radio/IR galaxies using PCCS Planck 2013 results. XXVIII.
  - SZ clusters using PCC Planck 2013 results. XXIX
  - Cold Cores using ECC Planck Early Results. VII
- diffuse emission
  - galactic plane Planck 2013 results. XII
  - CO regions Planck 2013 results. XIII.

→ dominant *mean-field* bias at the ϕ_{LM} level: must be subtracted using MC correction

Foreground cleaning

Baseline T map:

- MV combination of 143 and 217 GHz maps
- corrected for a dust template using the 857GHz map
- $\simeq$ 70% of the sky

Foreground-cleaned T maps: Planck 2013 results. XII

Commander-Ruler

- technique: parametric fg model fit
- 75% of the sky
- resol. $\simeq$ 7 arcmin → lower S/N for lensing

NILC

- technique: needlet-based ILC
- 93% of the sky

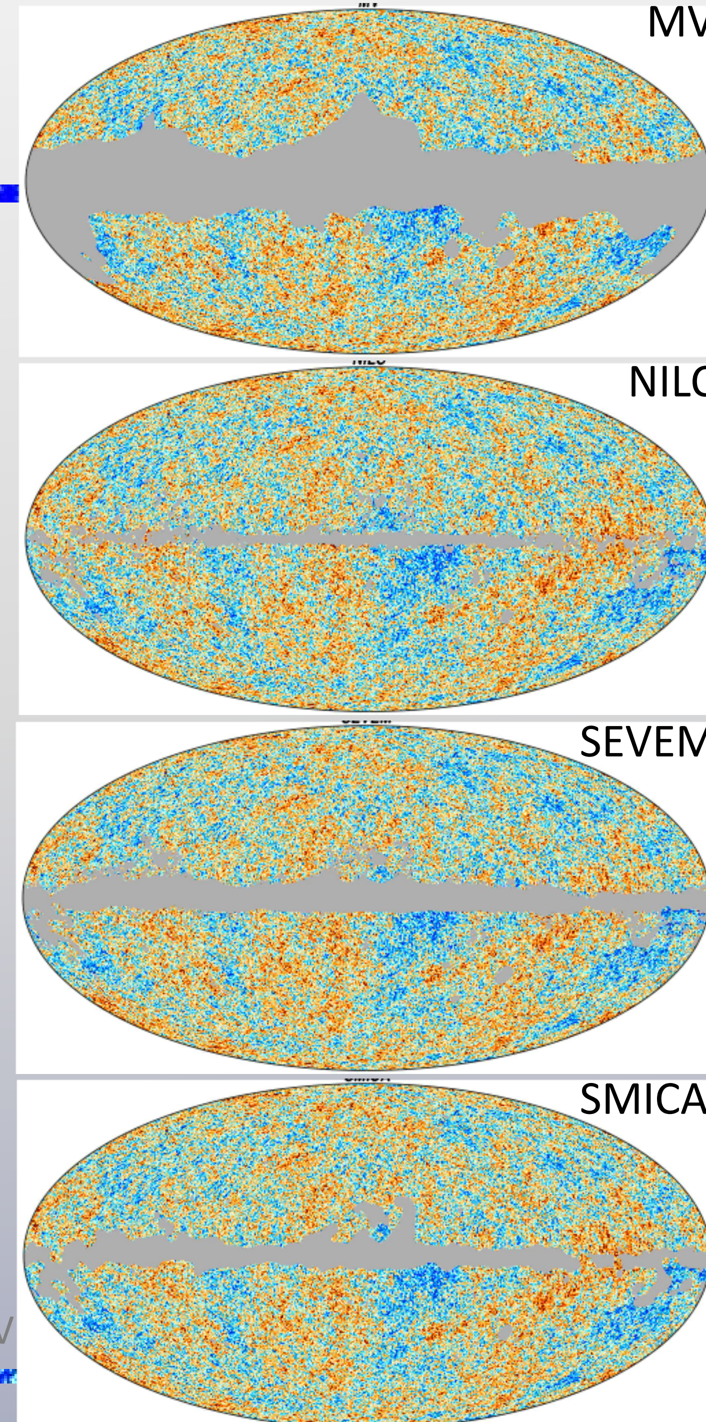
SEVEM

- technique: internal template fitting
- 85% of the sky

SMICA

- technique: ICA in harmonic space
- 89% of the sky

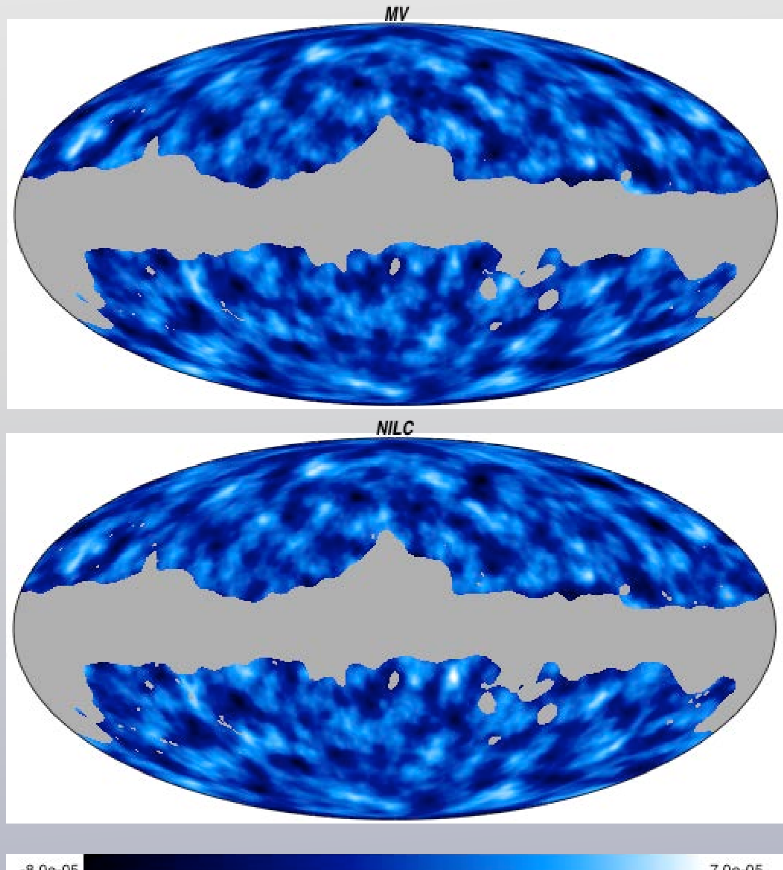
baseline map for NG studies: Planck 2013 Results. XXIV

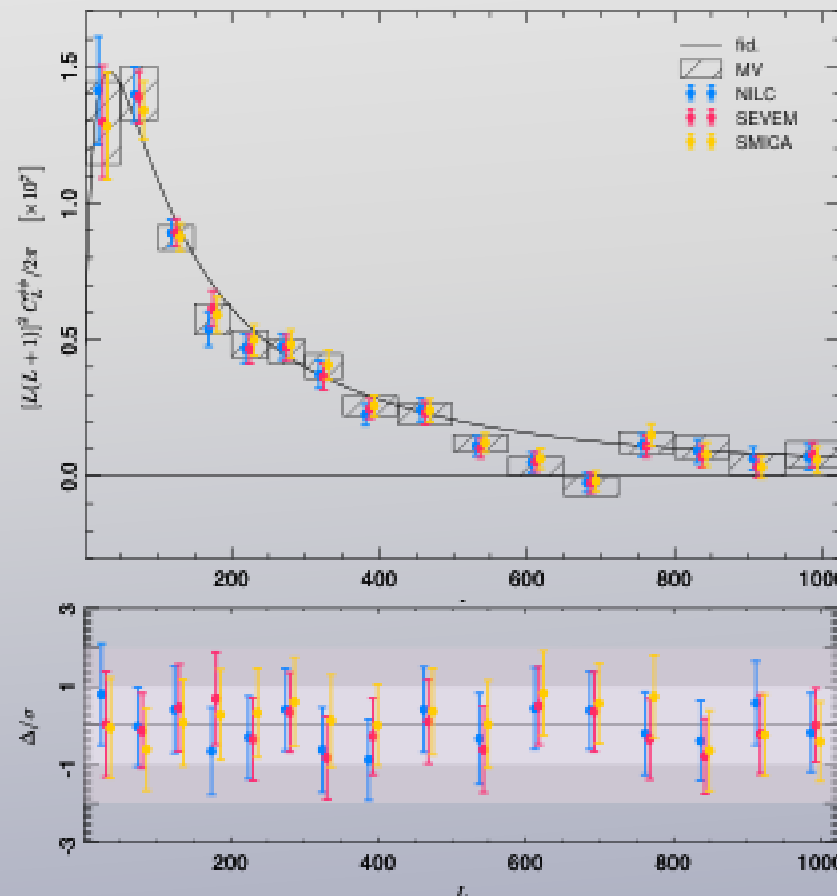


Robustness against foreground residuals

I. Test on the 70% baseline setup to assess the robustness against foreground residuals

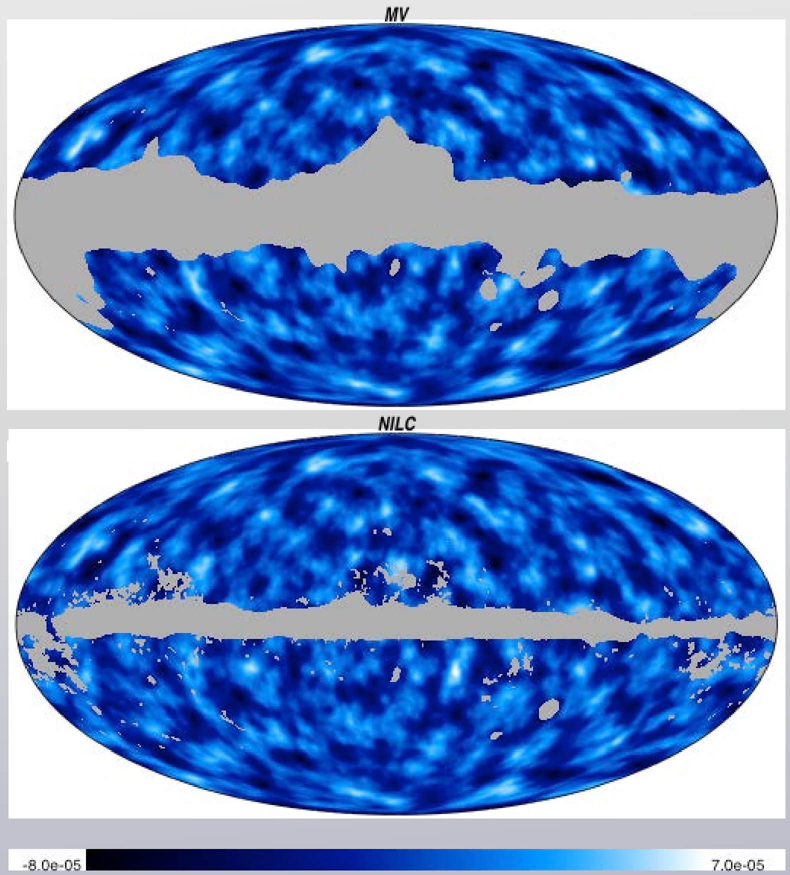
$f_{\rm sky} \simeq 70\%$ → apodization of the diffuse mask mitigating the MF residuals → effective $f_{\rm sky} \simeq 60\%$

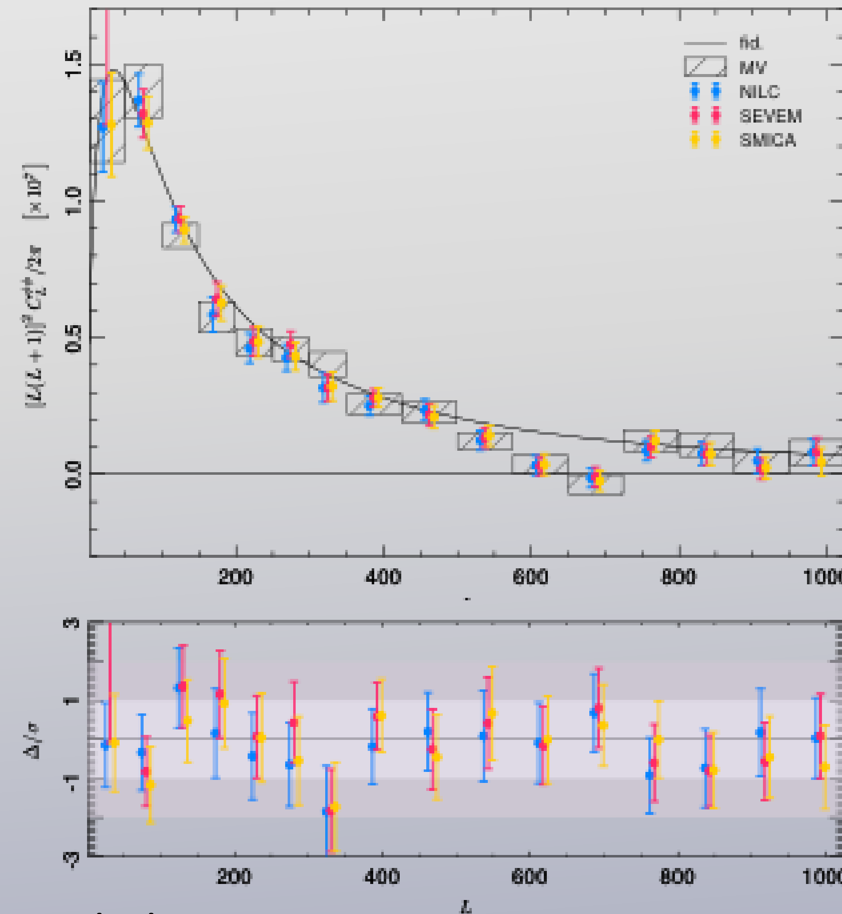




Increasing the sky coverage

$f_{\rm sky} \simeq 85\%$ → effective $f_{\rm sky} \simeq 70\%$





only a maximum <4% improvement of the uncertainties

our nominal products are based on the MV 143-217 combination

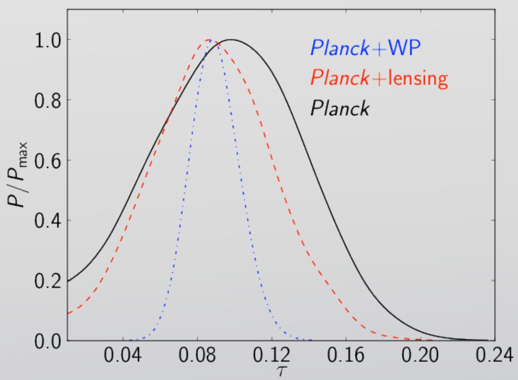
Cosmological impact

Information on the matter up to last-scattering $\Longrightarrow$ constraints on the post-recombination evolution

LCDM6 Planck+WM+highL internal consistency test

$$A_L^{\phi\phi} = 0.99 \pm 0.05 \quad (68\%; \mathrm{Planck} + \mathrm{lensing} + \mathrm{WM} + \mathrm{highL})$$

LCDM6 model: good description of the universe at $z \leq 5$



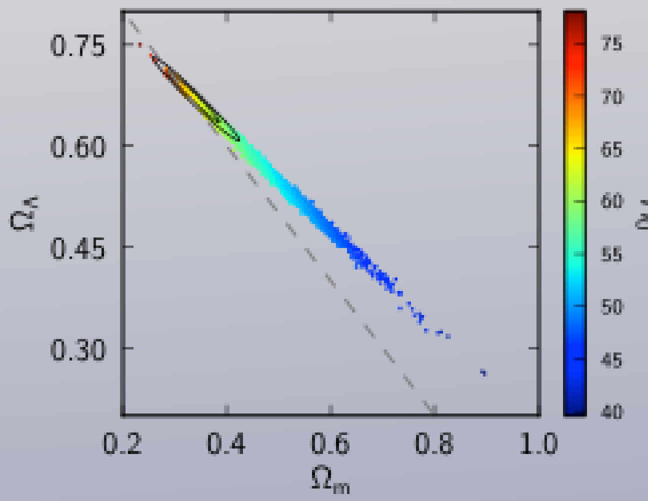
LCDM6 with Planck alone: breaking the A_s-τ degeneracy

$$\tau = 0.097 \pm 0.038 \quad (68\%; \mathrm{Planck})$$
$$\tau = 0.089 \pm 0.032 \quad (68\%; \mathrm{Planck} + \mathrm{lensing})$$

Geometrical degeneracy breaking in a non-flat Universe

CMB alone (Planck+lensing+WP+highL)

- impose a flat-geometry at percent level;
- $\lesssim 3\sigma$ evidence of Dark Energy
- more than x2 improvement of errors over TT alone



ISW-effect: further info on DE

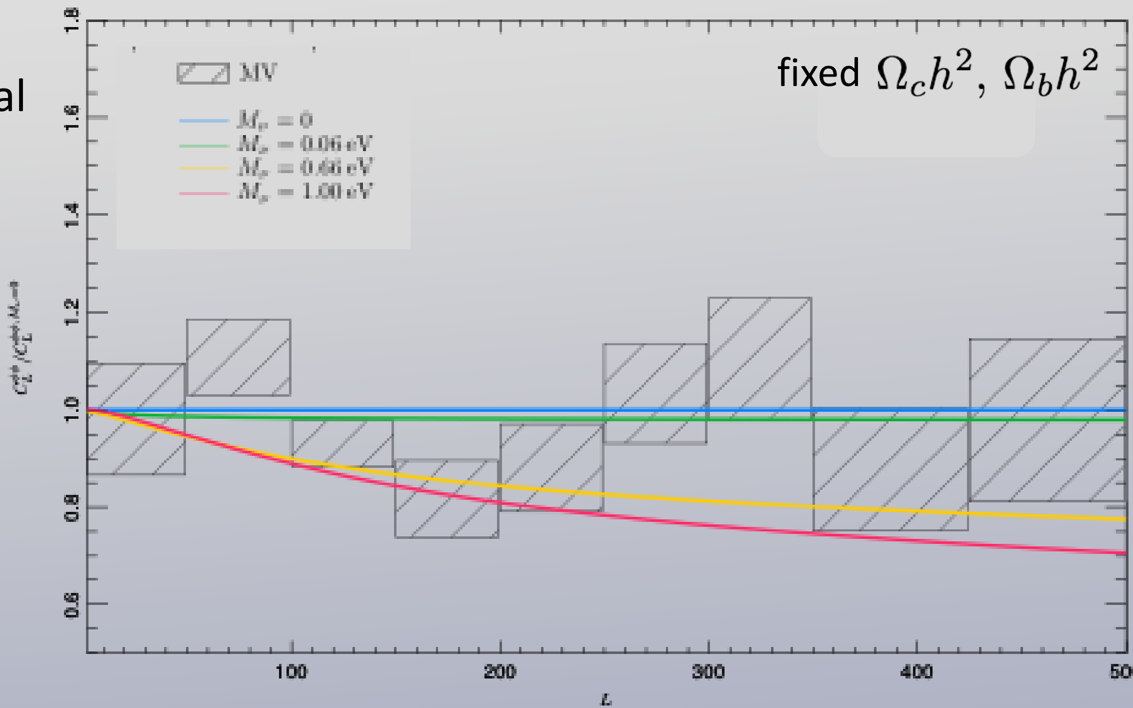
$\lesssim 2.5\sigma$ detection of the lensing-ISW correlation
signature of a late DE domination stage

Constaint on the neutrino sector

The neutrino masses signature

- for $\sum_\nu m_\nu \lesssim 1.3\,\mathrm{eV}$ (i.e. ν still relativistic at recombinaison): tiny constraints from TT alone
- oscillation measure: $\sum_\nu m_\nu \geq 0.06\,\mathrm{eV}$ at least 2 ν non-relativistic (NR) today
- After the NR transition: contribution to the expansion rate but not to the clustering of small-scale structure.

- Step-like signature in the power spectrum of the potential



Constraint on neutrino masses

In a $\Lambda\mathrm{CDM6} + \sum_\nu \mathrm{m}_\nu$ model with $N_{\mathrm{eff}} = 3$ degenerate massive neutrinos:

$$\sum_\nu m_\nu < 0.66\mathrm{eV} \quad (95\%; \mathrm{Planck} + \mathrm{WM} + \mathrm{highL})$$

Constraint on neutrino masses

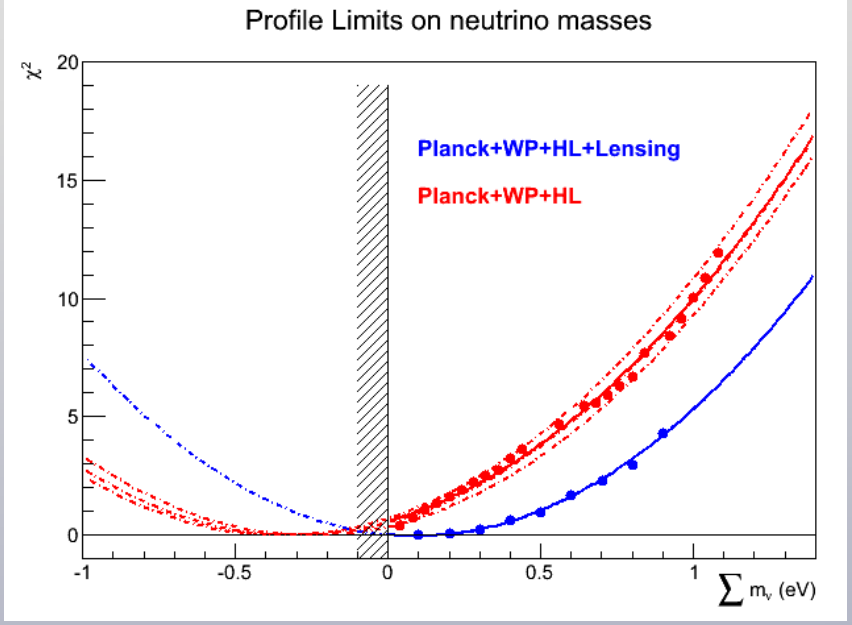
In a $\Lambda\mathrm{CDM6} + \sum_\nu \mathrm{m}_\nu$ model with $N_{\mathrm{eff}} = 3$ degenerate massive neutrinos:

$$\sum_\nu m_\nu < 0.66\mathrm{eV} \quad (95\%; \mathrm{Planck} + \mathrm{WM} + \mathrm{highL})$$
$$\sum_\nu m_\nu < 0.85\mathrm{eV} \quad (95\%; \mathrm{Planck} + \mathrm{lensing} + \mathrm{WM} + \mathrm{highL})$$

- the constraint *is* tigher (smaller σ of the profile-$\mathcal{L}$)
- TT prefers small masses (negative!)

$\sum m_\nu \searrow \;\Rightarrow C_L^{\phi\phi} \nearrow \;\Rightarrow$ more TT smoothing
more level-arm to mitigate the C_ℓ^{TT} low-l/high-l tension

- the lensing information in C_ℓ^{TT} artificially tighten the constraint on $\sum_\nu m_\nu$



more details on Marta Spinelli's poster

Conclusions

- integrated mass distribution on almost the full-sky using Planck (observational performancies + high systematic control in the data-processing)
- Our fiducial lensing is based on a fsky $\simeq$ 70% MV combination of the 143 and 217GHz frequency maps, after dust correction using the 857GHz map as a template
- extensive suite of checks to ensure the robustness againts foreground contamination
- The foreground-cleaned maps were used to obtained a *robust* lensing reconstruction on 90% $\simeq$ of the sky
- Several important cosmological impacts (e.g. As-tau degeneracy breaking, probing the post-recombination history with CMB alone)
  - weaker $\sum_\nu m_\nu$ constraints than expected
- Perspectives with Planck:
  - 2 more surveys: 25% decrease of the Clphi uncertainties + further investigation of possible systematics, reducing the level of conservatism of some choices (multipole cuts, apodisation, …)
  - polarization

Lensing results are a stricking success of the whole collaboration.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Conclusions

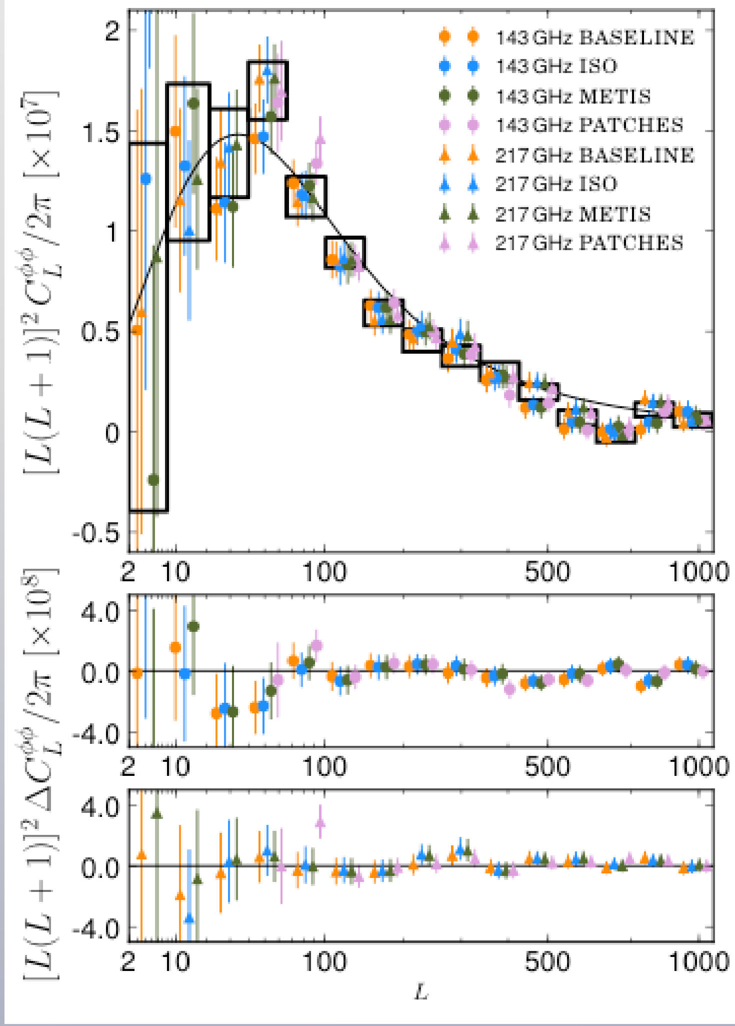
- The subtle lensing effect can be reconstructed using Planck, thanks to its data quality and the low-systematic early stages of data-processing.
- Our fiducial lensing is based on a fsky~70% MV combination of the 143 and 217GHz frequency maps, after dust correction using the 857GHz map as a template
- The robustness against foreground contamination was assessed by comparing to results from properly cleaned CMB maps using component separation technique.
- The foreground-cleaned maps were used to obtained a *robust* lensing reconstruction on ~90% of the sky -> Although leading to a marginal decrease of the uncertainties, this map is a stricking success of the whole collaboration.
- The lensing reconstruction has important cosmological impact:
  - breaking of the As-tau degeneracy
  - probing post-recombination history with CMB alone: e.g. more than x2 improvement on the curvature/DE
  - Note: tension between Clphi and ClT in LCDM model -> weaker mnu constraint
- Perspectives with Planck:
  - 2 more surveys: 25% decrease of the Clphi uncertainties + further investigation of possible systematics, reducing the level of conservatism of some choices (lmax,Lmax, apodisation, …)
  - polarization

Results based on single frequency maps

reconstruction based on the 143 and 217GHz channel maps:

dust template subtraction using the 857GHz map

mask cutting $\simeq$30% of the sky



4 methods which deals differently with the mask:

BASELINE the sky cut is accounted for at the T filtering stage: $N^{-1}_{pp'} = 0$ for masked p, p' pixels

ISO
- inpainting of the source mask (constr. Gaussian sim.)
- apodization of the galactic mask

see A. Benoit-Lévy's poster

METIS
- *sparse*-inpainting of mask (source+galaxy)

Perotto et al. (arXiv:1201.5779);
Abrial et al. (arXiv:0804.1295)

PATCHES
- local method (flat-sky approximation)
- inpainting of the source mask
- galactic mask avoided

Plaszczynski et al. (arXiv:1201.5779)

excellent agreement

same performances (note: patches l>35)

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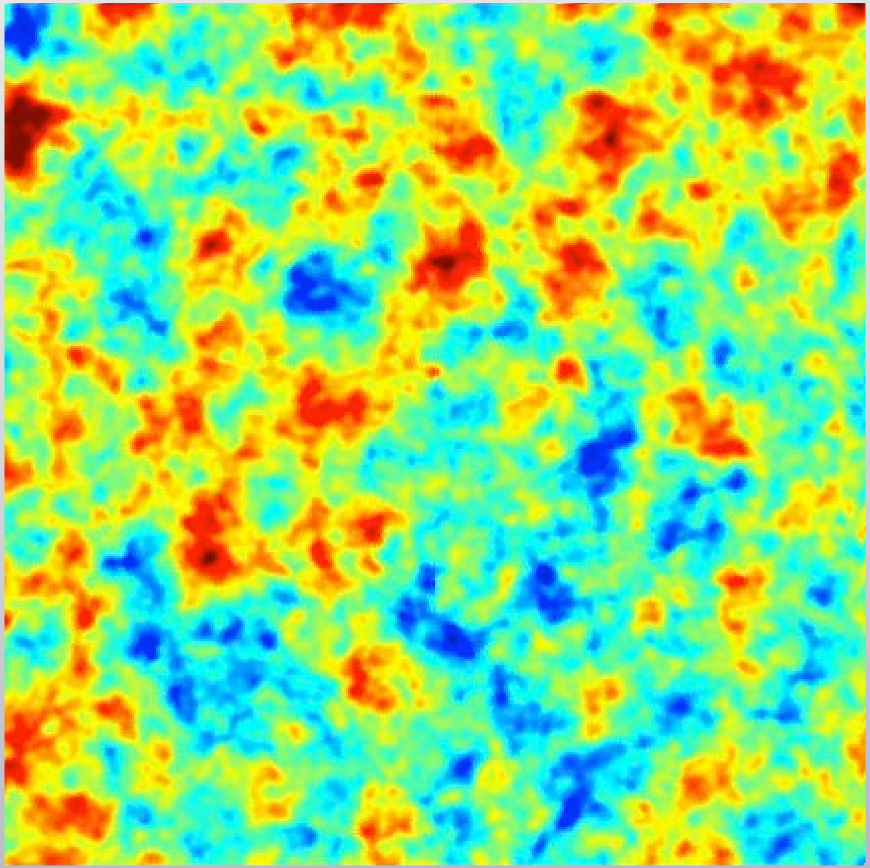

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