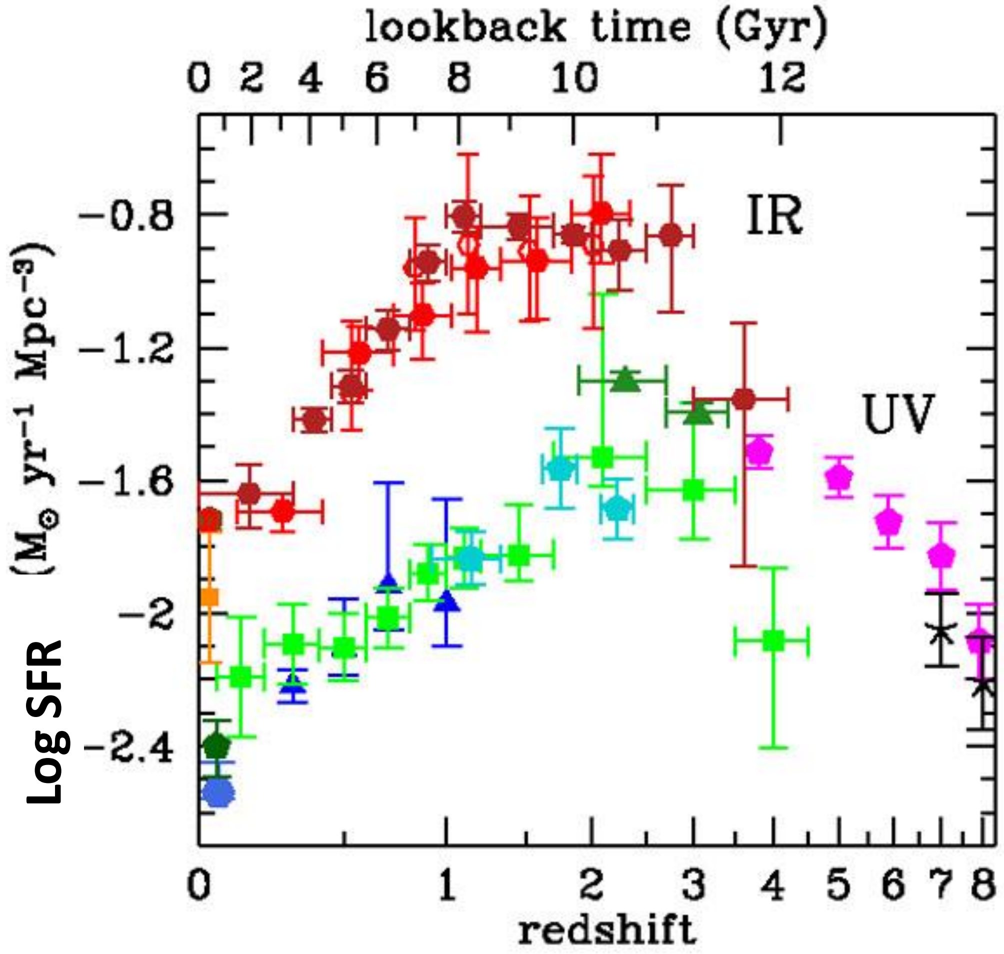
CIB-optical image cross-correlation

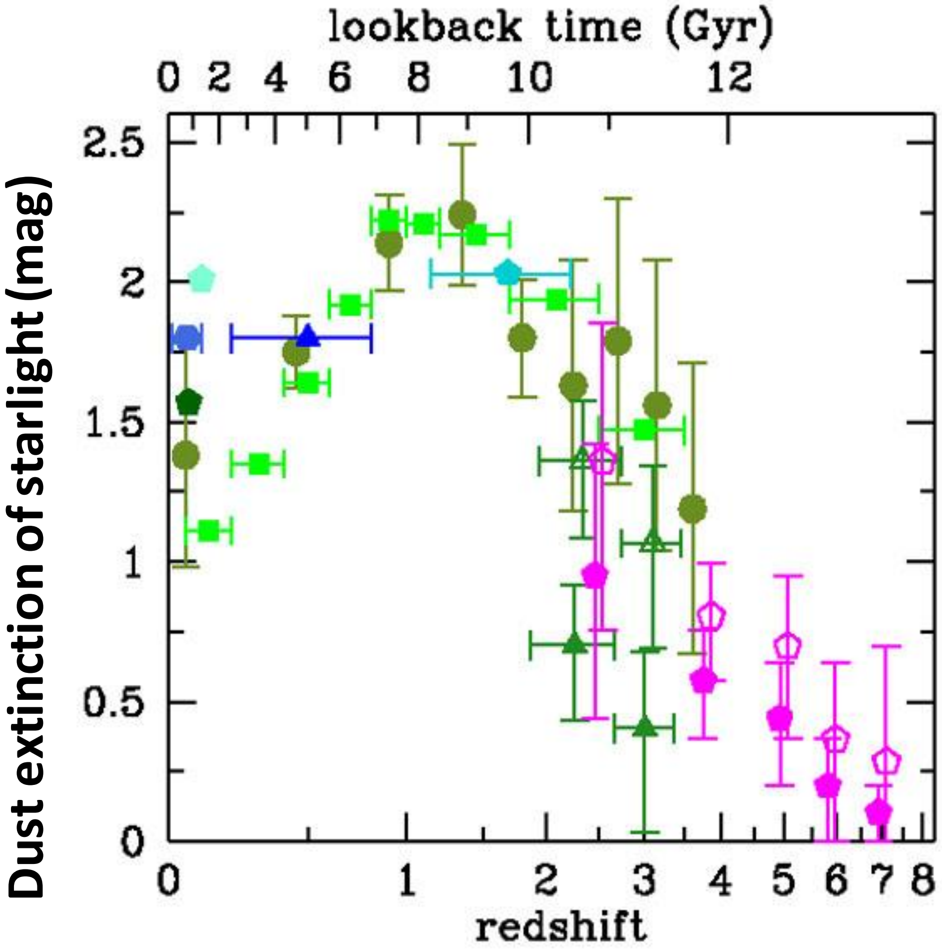
Seunghwan Lim (CITA)

with Douglas Scott, Ryley Hill, Ludo van Waerbeke (UBC), Jean-Charles Cuillandre,
Hervé Aussel, Marc-Antoine Miville-Deschênes (CEA), … in *Euclid* & CFIS-UNIONS (& KiDS?)

CIB-optical image cross-correlation

CIB and optical each has a piece of info about star formation





Madau & Dickinson 2014

CIB-optical image cross-correlation

I am used to leftovers!

- Je-yuk-deop-bob

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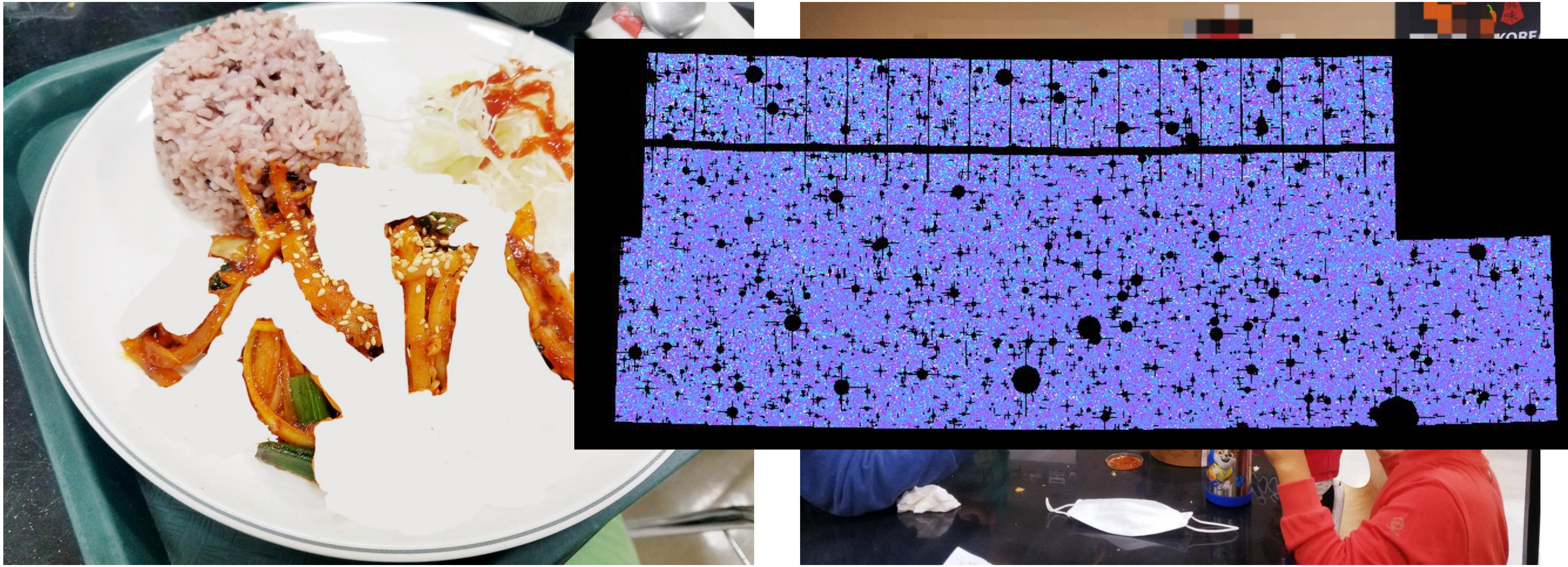
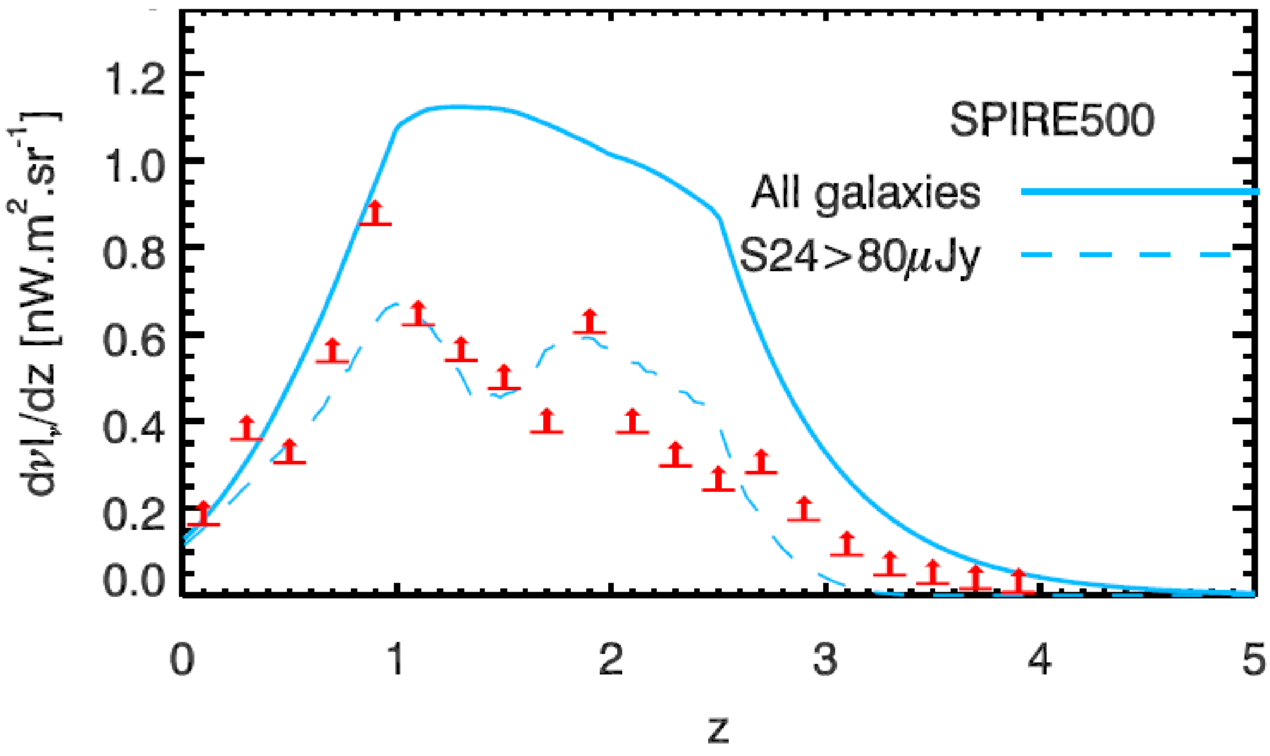
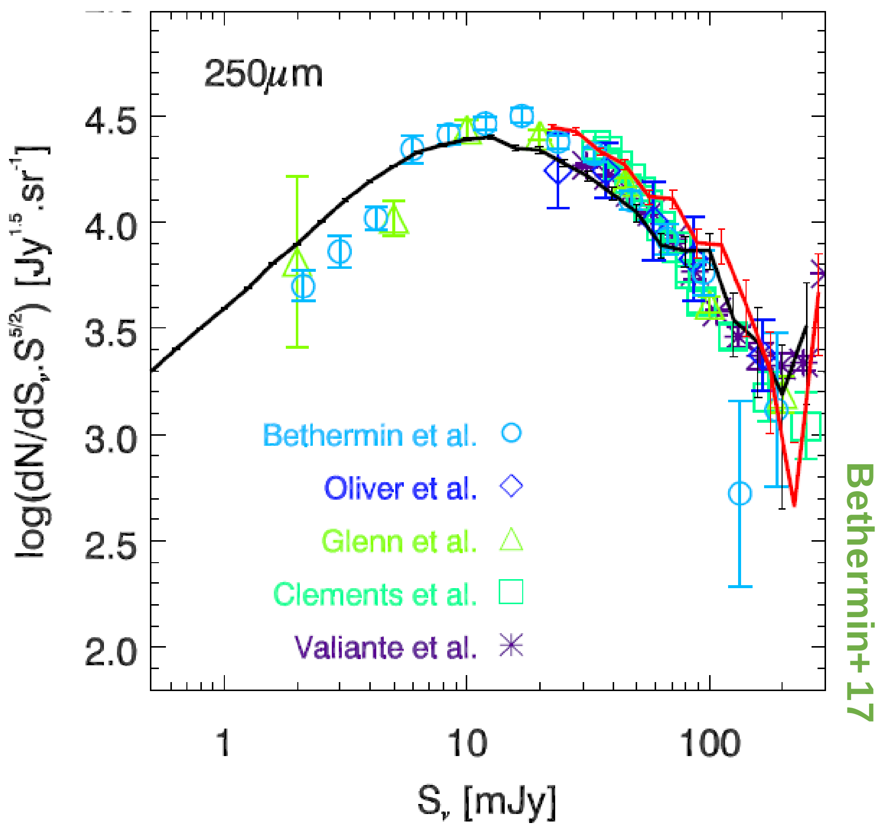


Images contain critical info than identified sources about cosmic noon

- Only <30% of the total flux (<5% of number count) resolved into individual sources



- Source-blending due to large beams of submm facilities

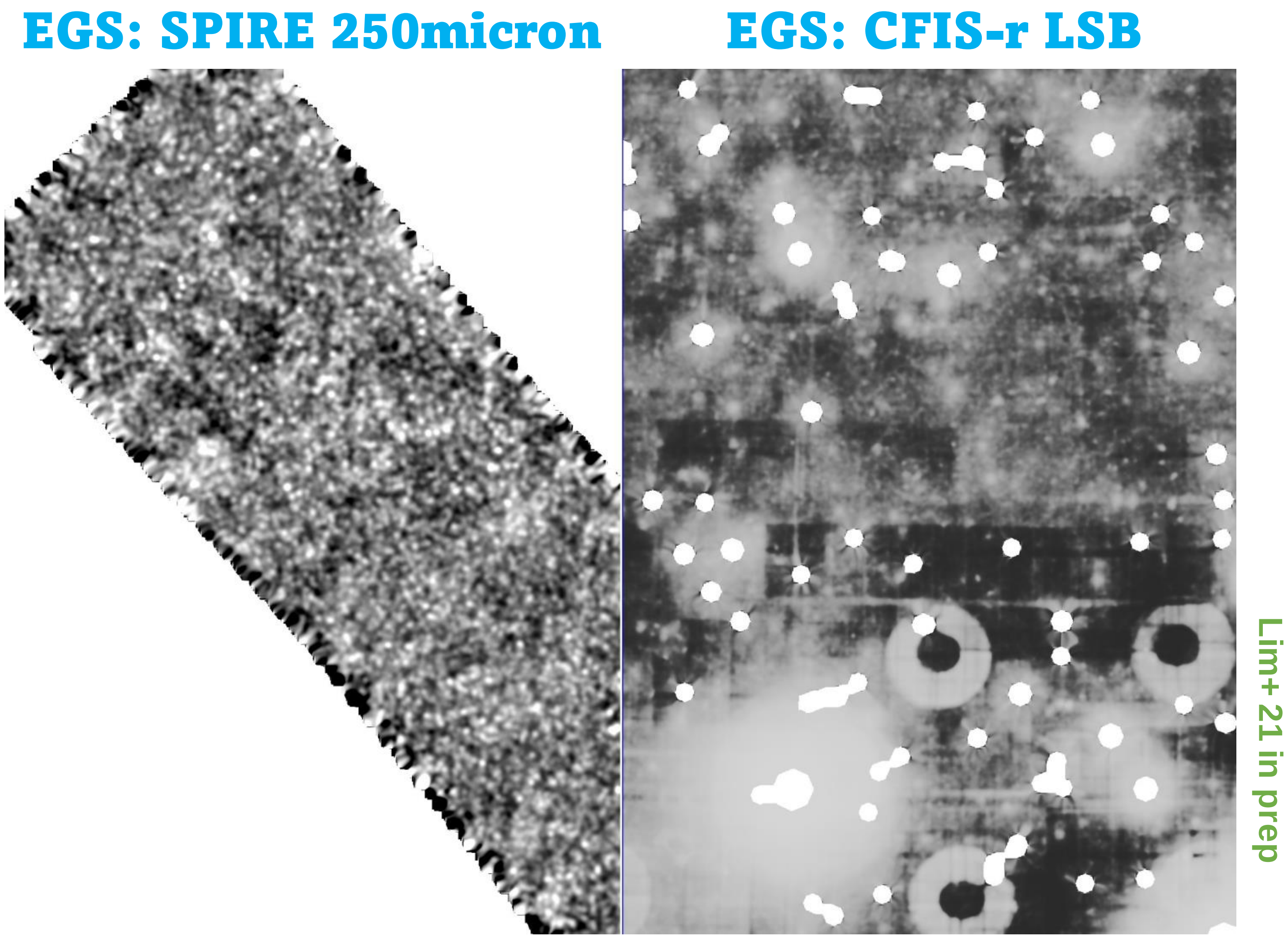


CIB-optical image cross-correlation

Cross-correlation averages out noise and artefacts

- Many (optical) telescopes suffer severely from the atmosphere, stars, and artefacts, inst. noise, any kind of unwanted signal for exgal studies

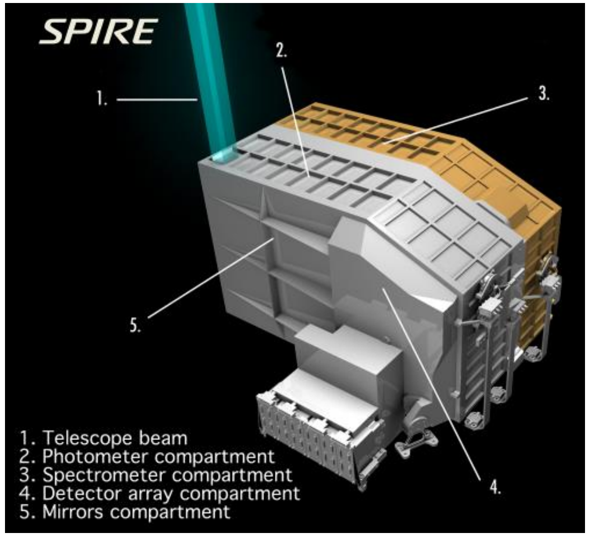
- As not in the same locations, cross-correlation zeroes them out (exception: the MW cirrus)



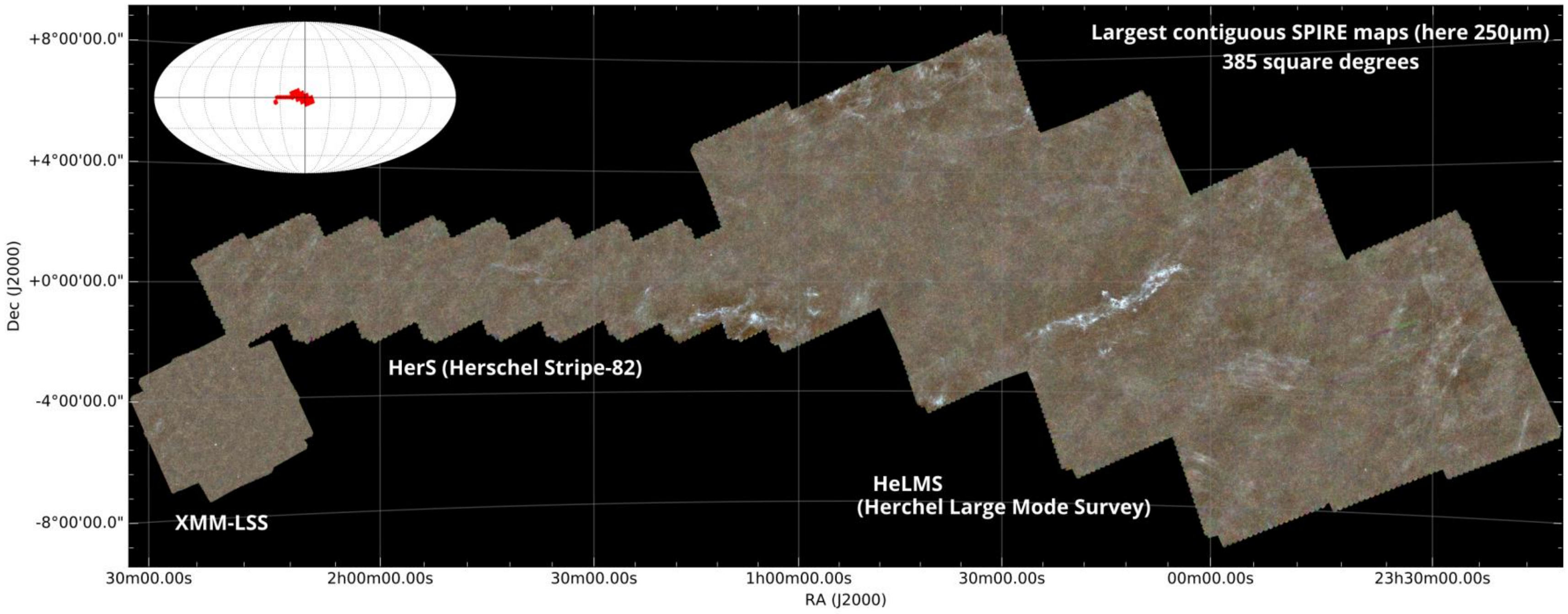
Data

Herschel(SPIRE) captures dust emission at ~20" res

- SPIRE
  - beam: 18, 24, 36" at 250, 350, 500 microns

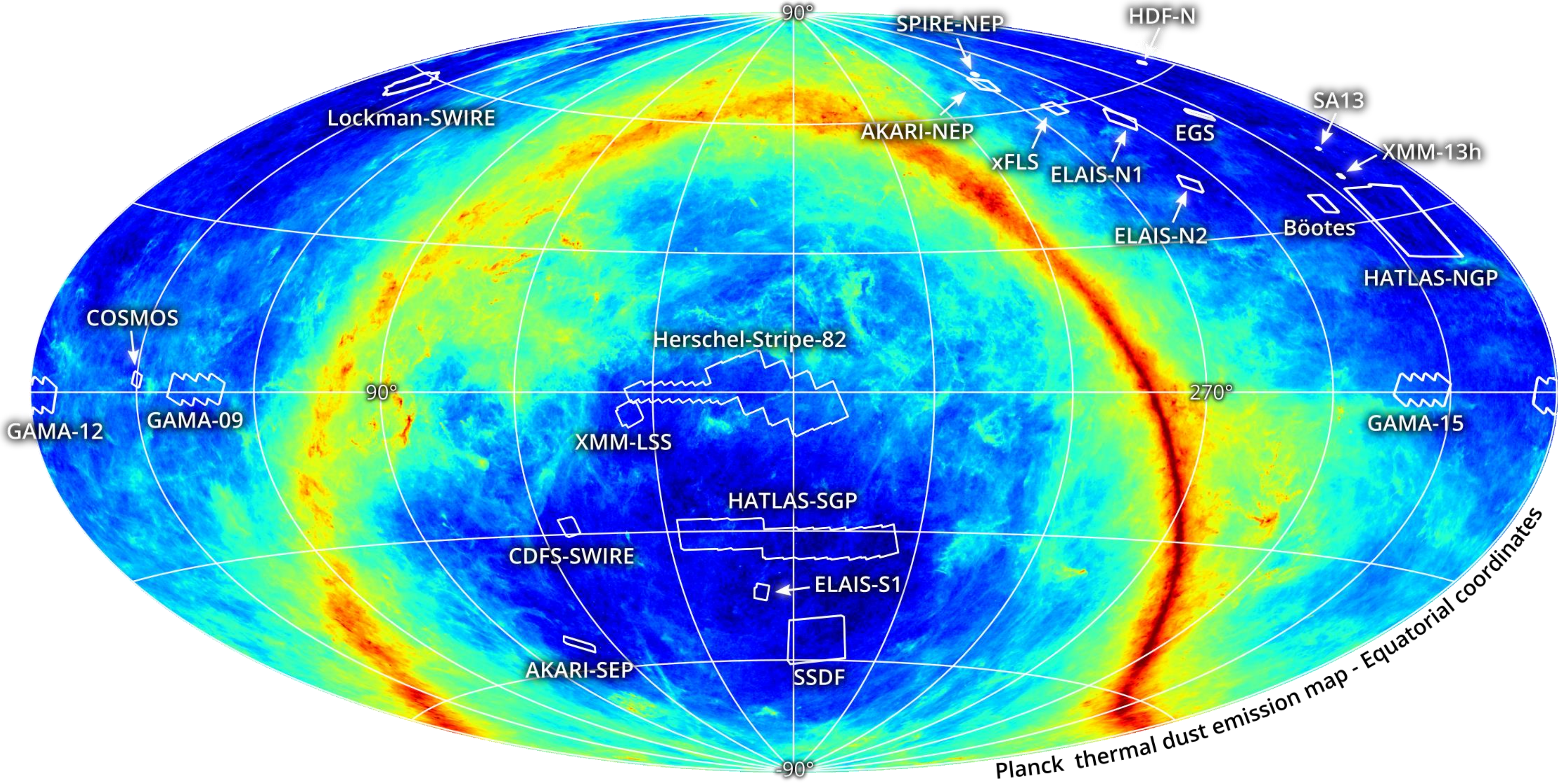


HeLMS_HerS_XMM-LSS: SPIRE view



DR1 of HELP contains 23 fields, ~1300 sq.deg.

- **HELP** - Herschel Extragalactic Legacy Project

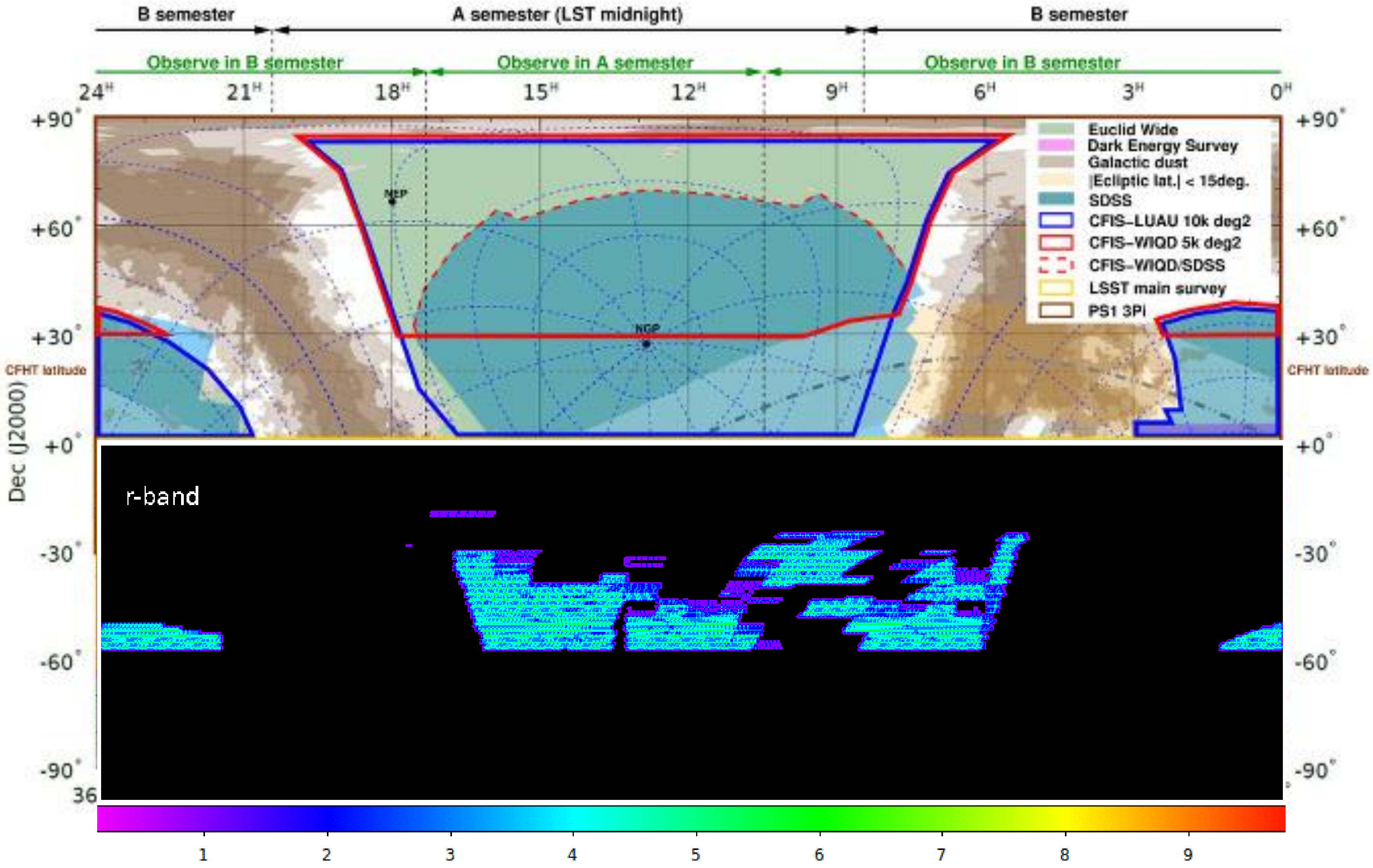


Another data: CFIS r-band ~0.2" res

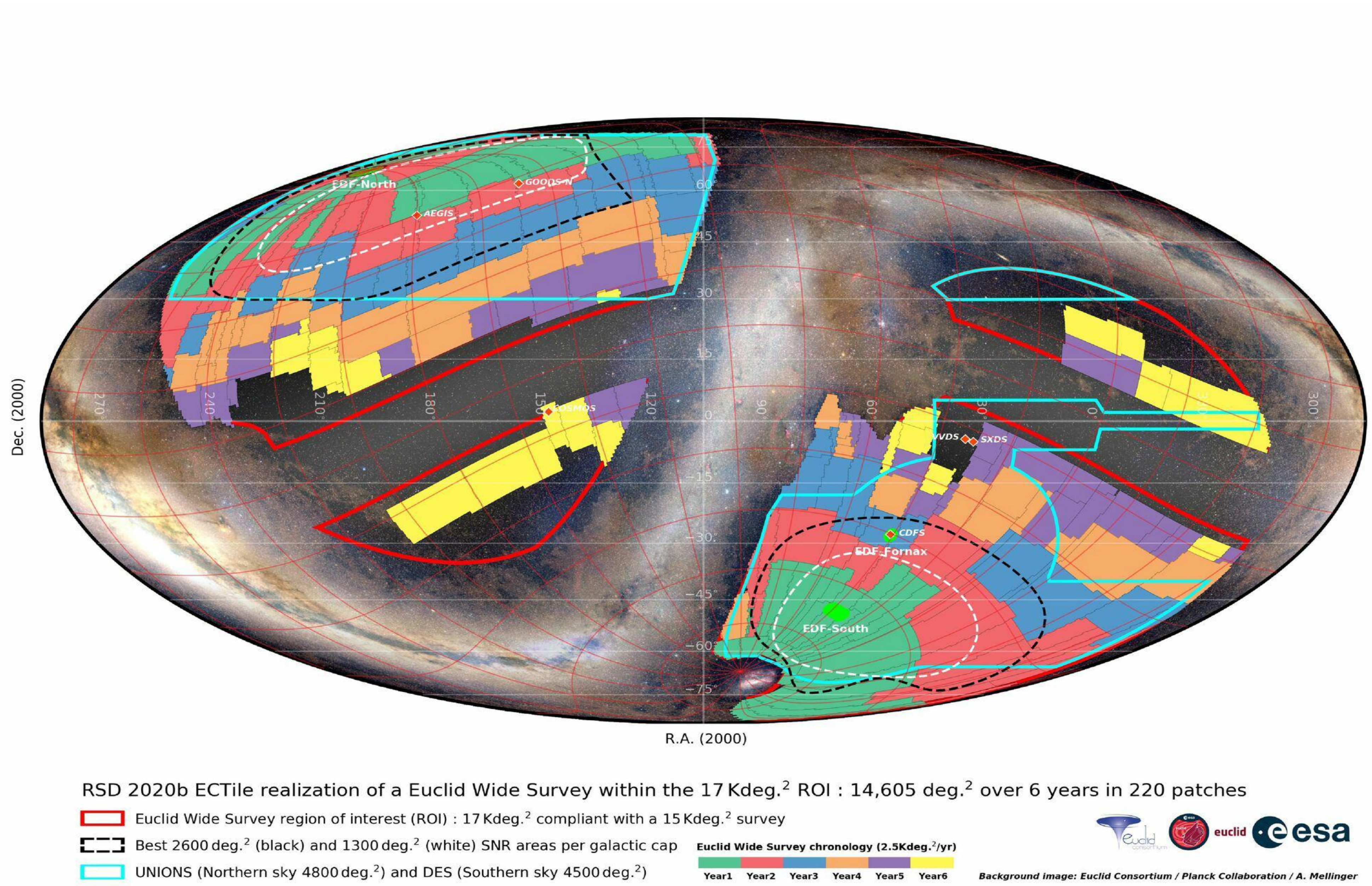
- Canada-France Imaging Survey

  - 5000 sq.deg. Of the northern sky (~60% done; ~2025)

  - part of UNIONS



The study aims for Euclid



Overlap of 5 fields, ~90sq.deg., are used for CIB-optical cross-correlation

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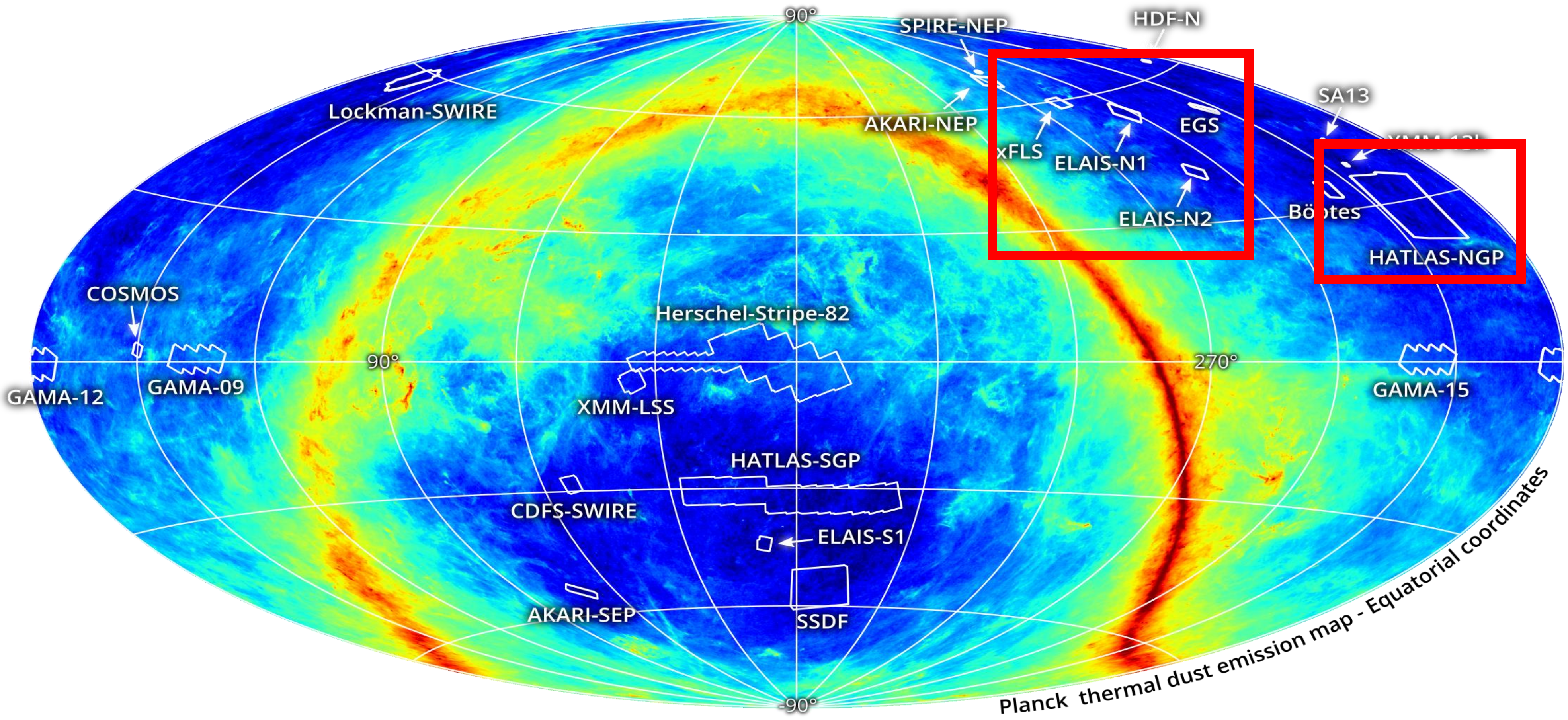

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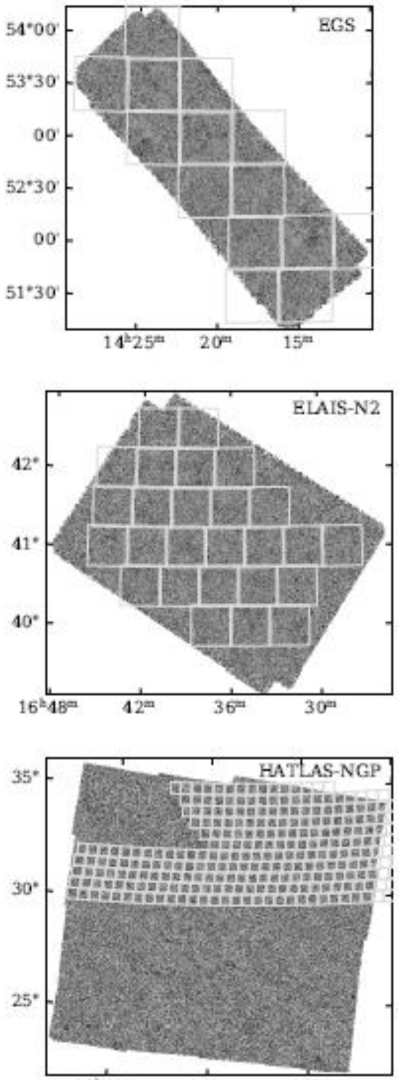
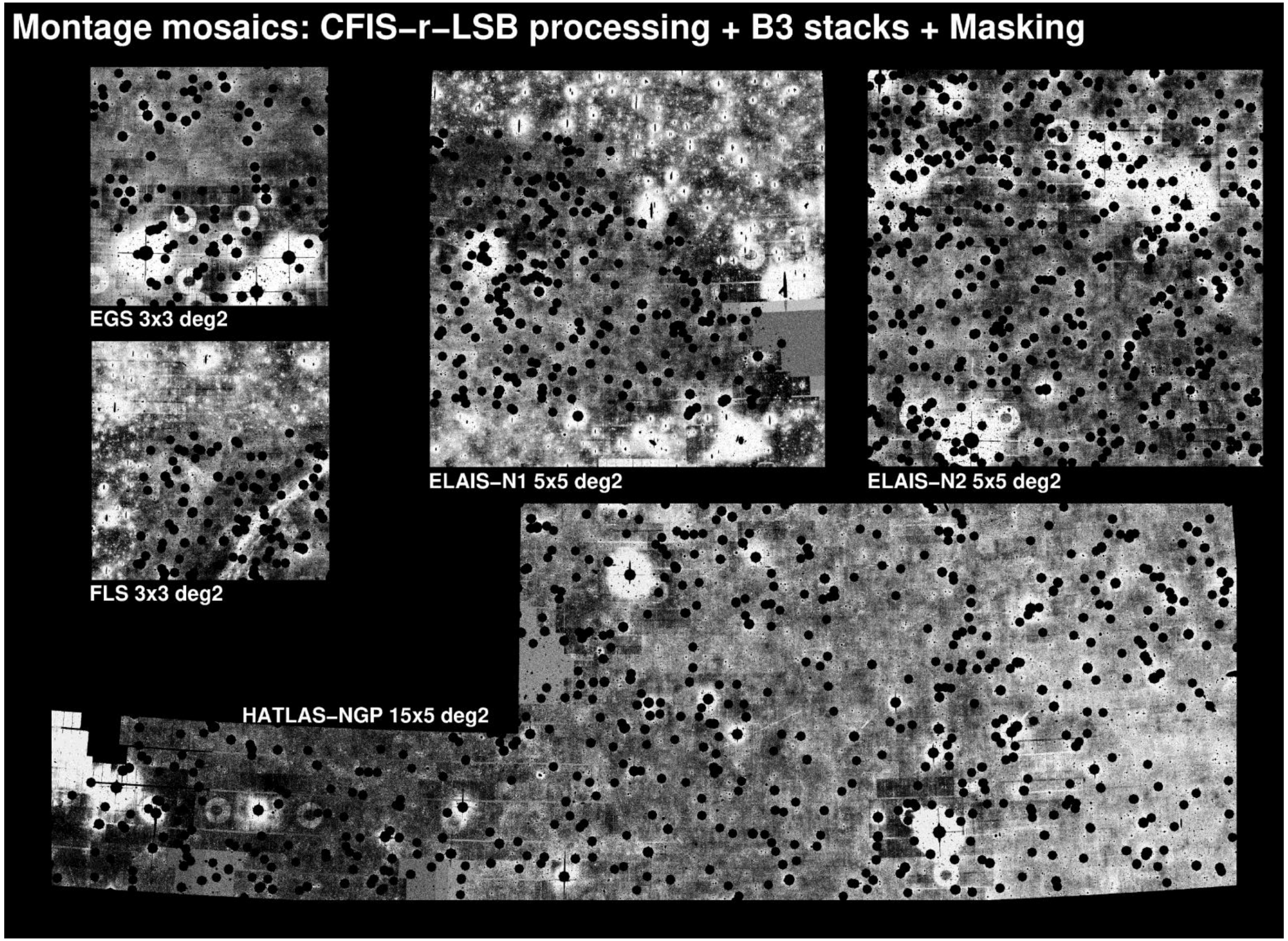
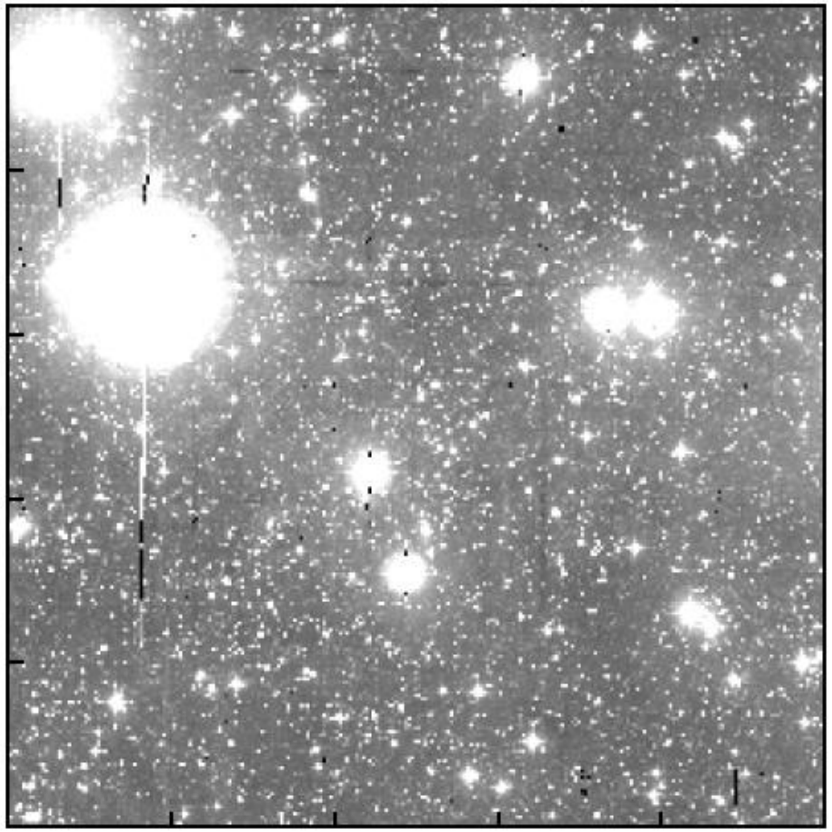




To be LSB or not

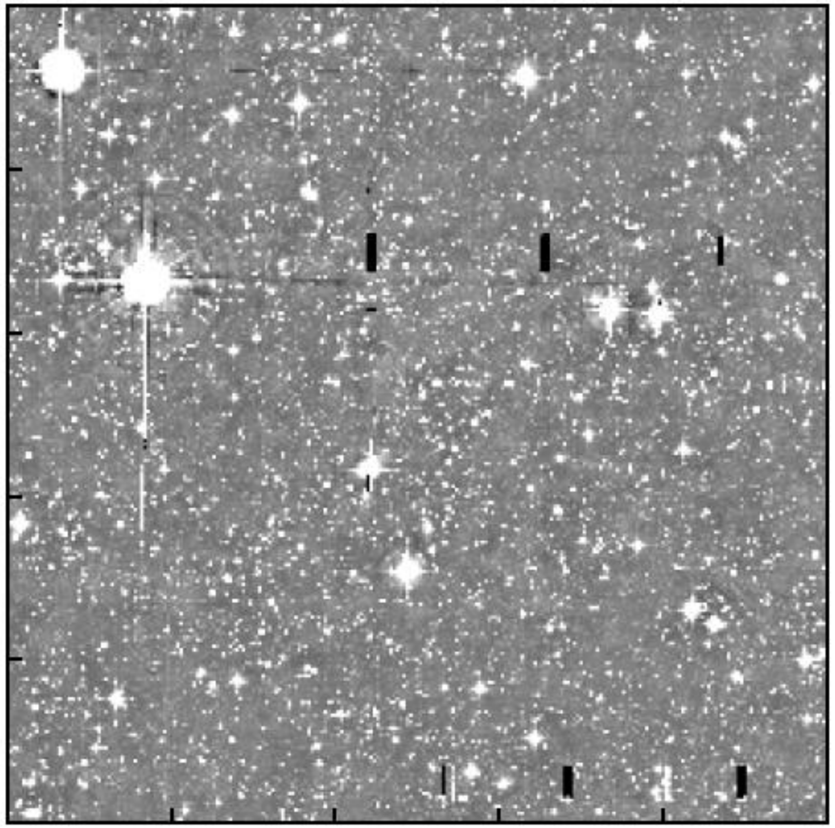
- Low Surface Brightness (LSB) processing

  - keep all the modes as they are, even including artefacts -> smaller area left



- Non-LSB processing

  - subtract >~arcmin fluctuations, even our signals! -> big area with nothing



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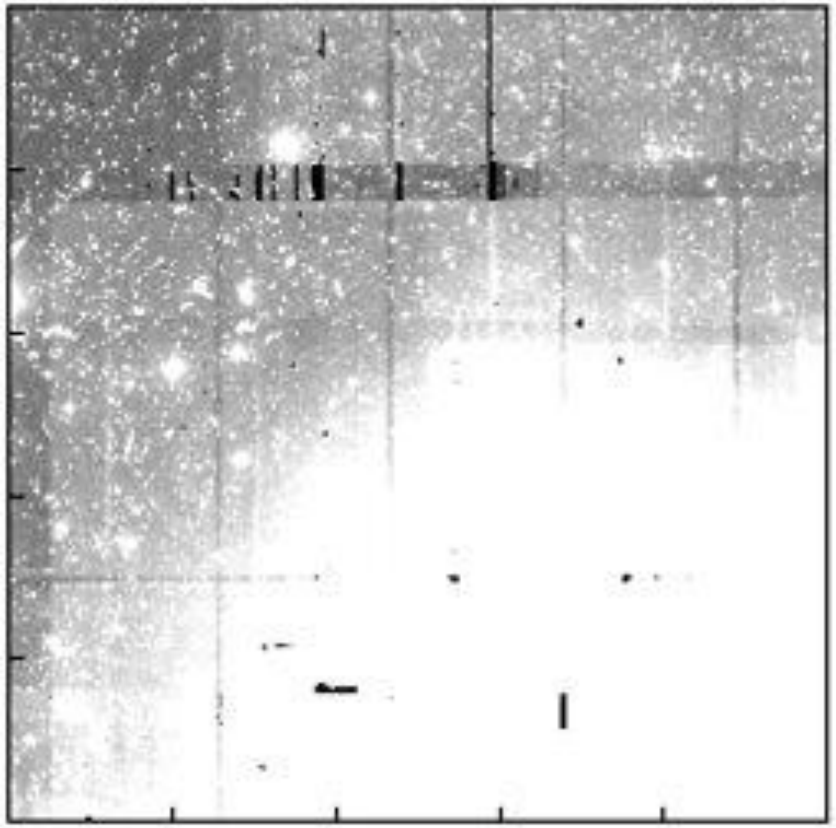

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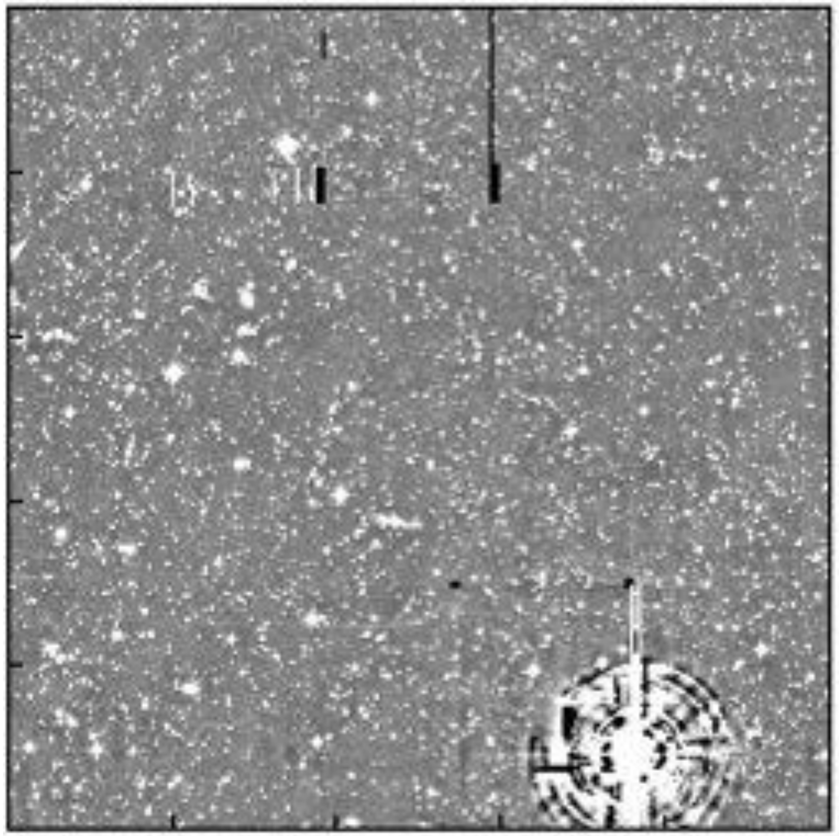

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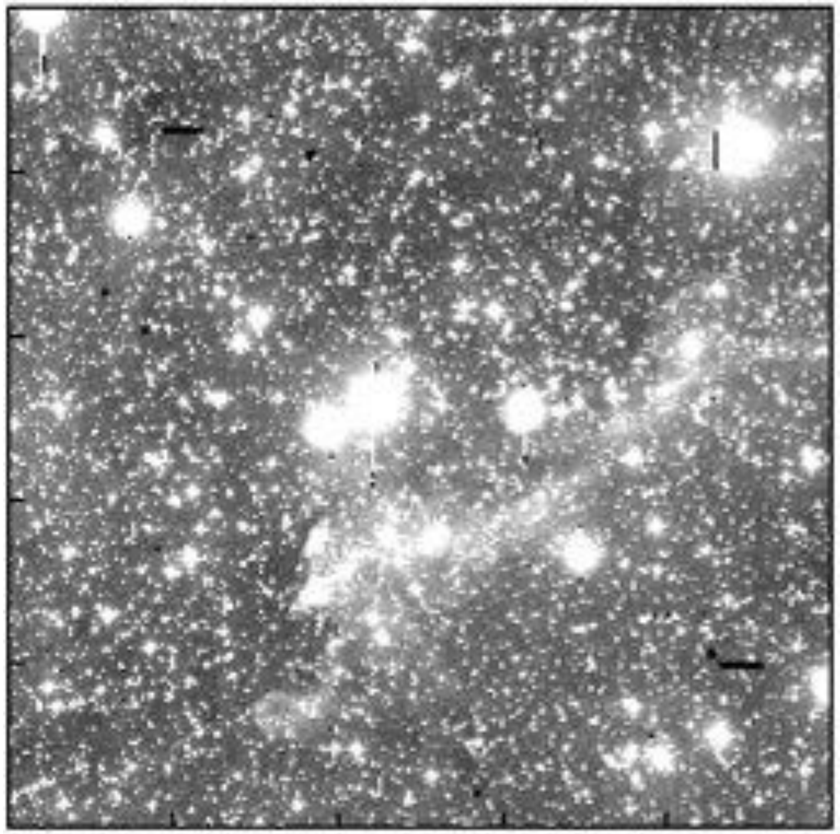

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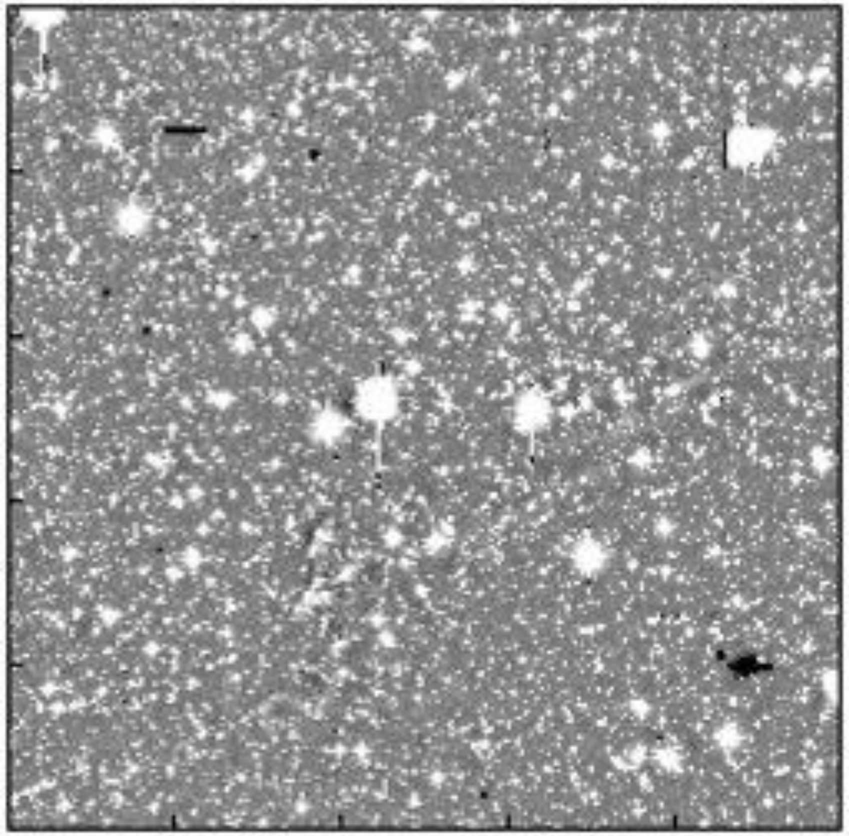
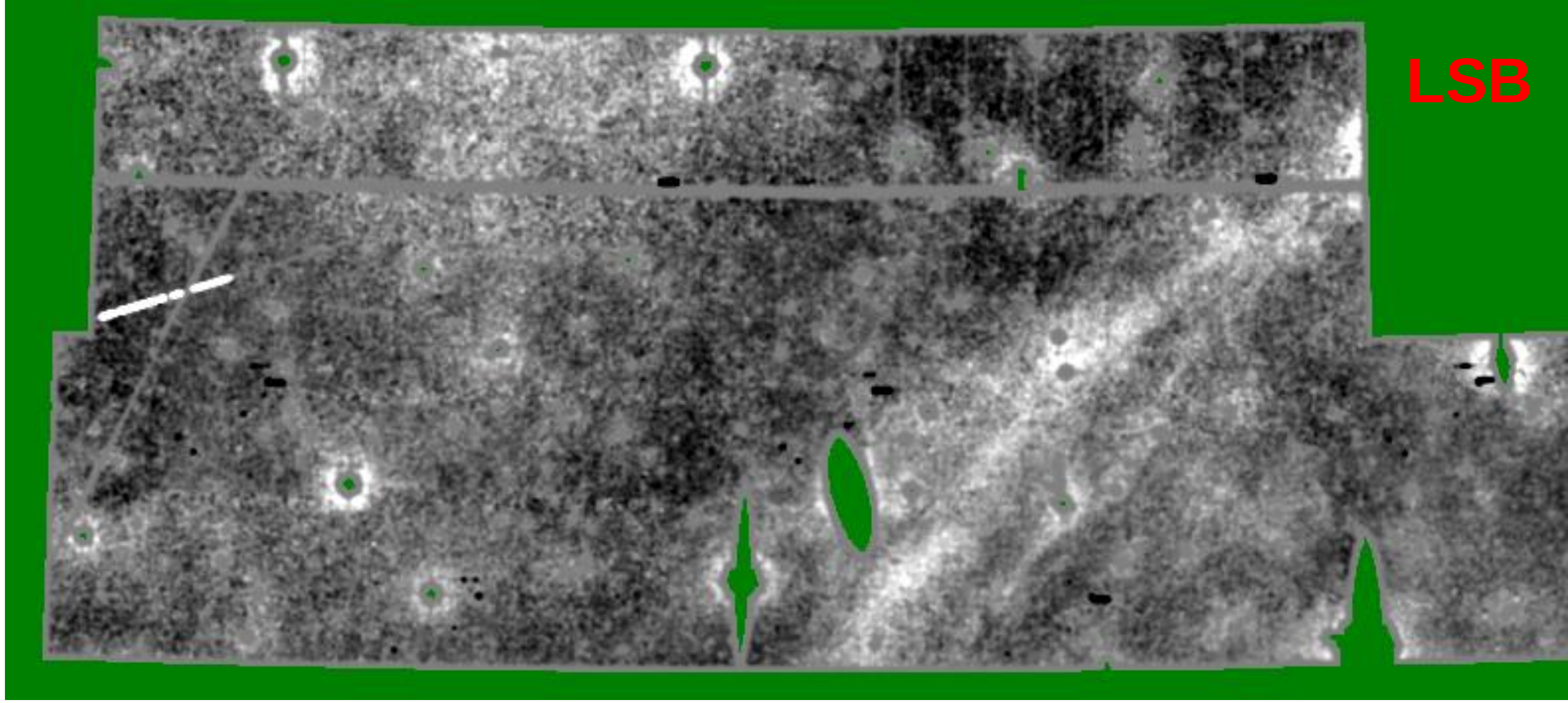
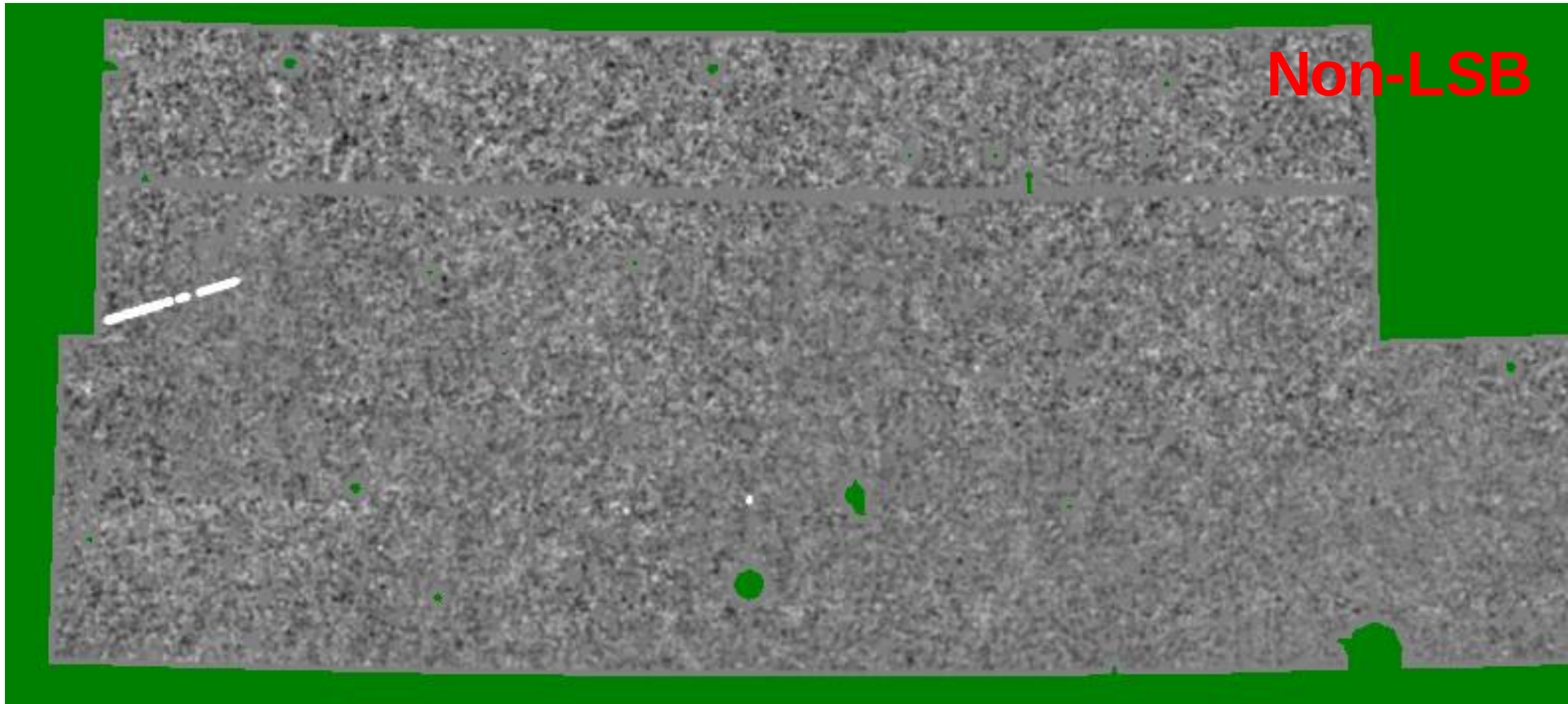


To be LSB or not

- FLS mosaic maps with LSB (upper) / non-LSB (lower) processing of CFIS





Analysis
: cross-power spectra

We recover the true spectra from the measurements

- Cross-power spectra

$$P_{\mathrm{C}\times\mathrm{S}}(k_i) = \left| \frac{\sum_{\boldsymbol{k}\in k_i} F_{\mathrm{C}}(\boldsymbol{k}) F^*_{\mathrm{S}}(\boldsymbol{k})}{N_{\boldsymbol{k}\in k_i}} \right| = \left| \left\langle C_{\mathrm{C}}(\boldsymbol{k}) C_{\mathrm{S}}(\boldsymbol{k}) e^{i\Theta(\boldsymbol{k})} \right\rangle_{\boldsymbol{k}\in k_i} \right|$$

- Map-making

$$I_{\mathrm{map}} = (T \otimes [I_{\mathrm{sky}} \otimes B + N\,])M$$

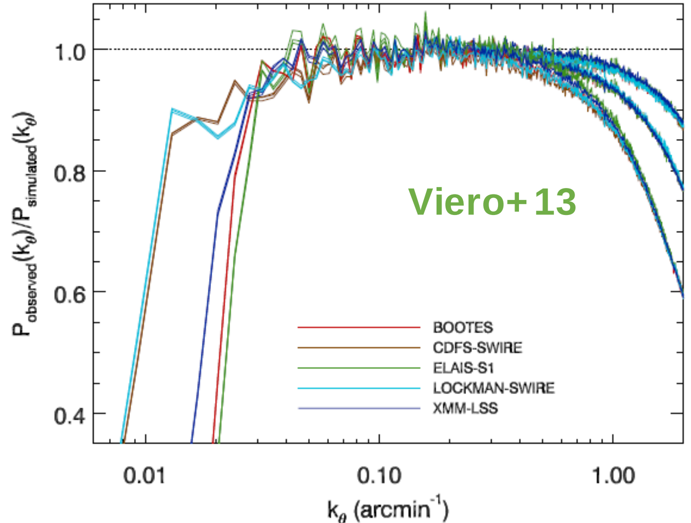
(B- beam, T- transfer function, N- noise, M- masking)

- Recovery of underlying signal

$$P_{\mathrm{measured}}(k) = \sum_{k'} M_{kk'} T(k') B(k') P_{\mathrm{true}}(k')$$

$$M_{kk'} = \sum_{\boldsymbol{k}\in k} \sum_{\boldsymbol{k}\in k'} \langle w^{\mathrm{C}}_{kk'} w^{*\mathrm{S}}_{kk'} \rangle / N_{\boldsymbol{k}\in k}$$

- *T(k)*

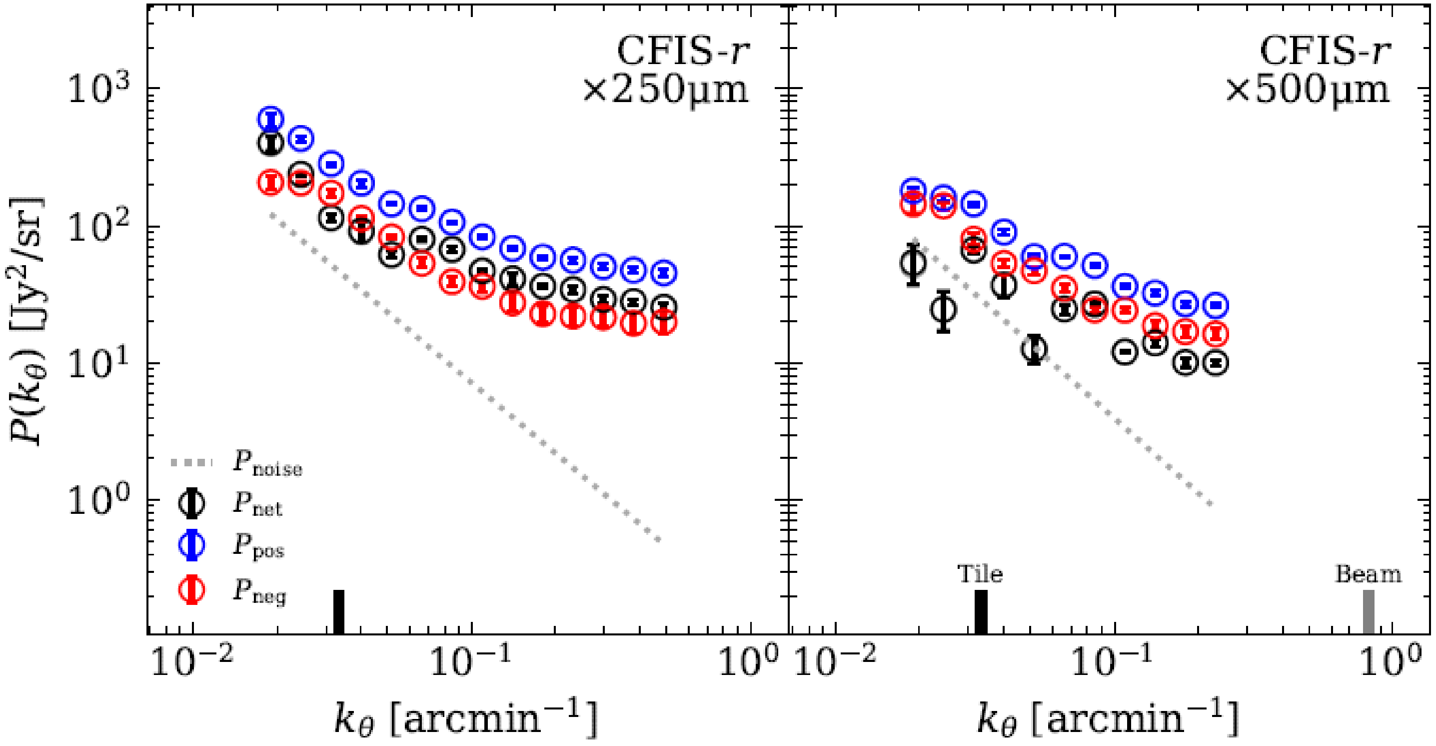


Clearly, strong signals are present

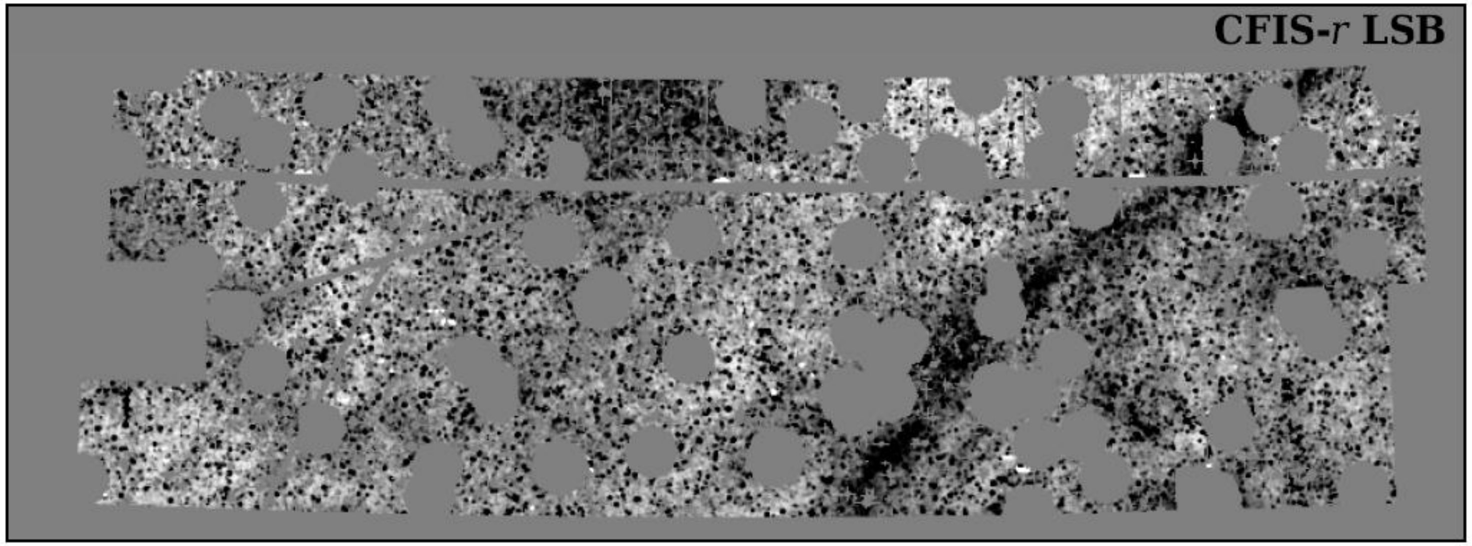
- In- and out-of-phase separation

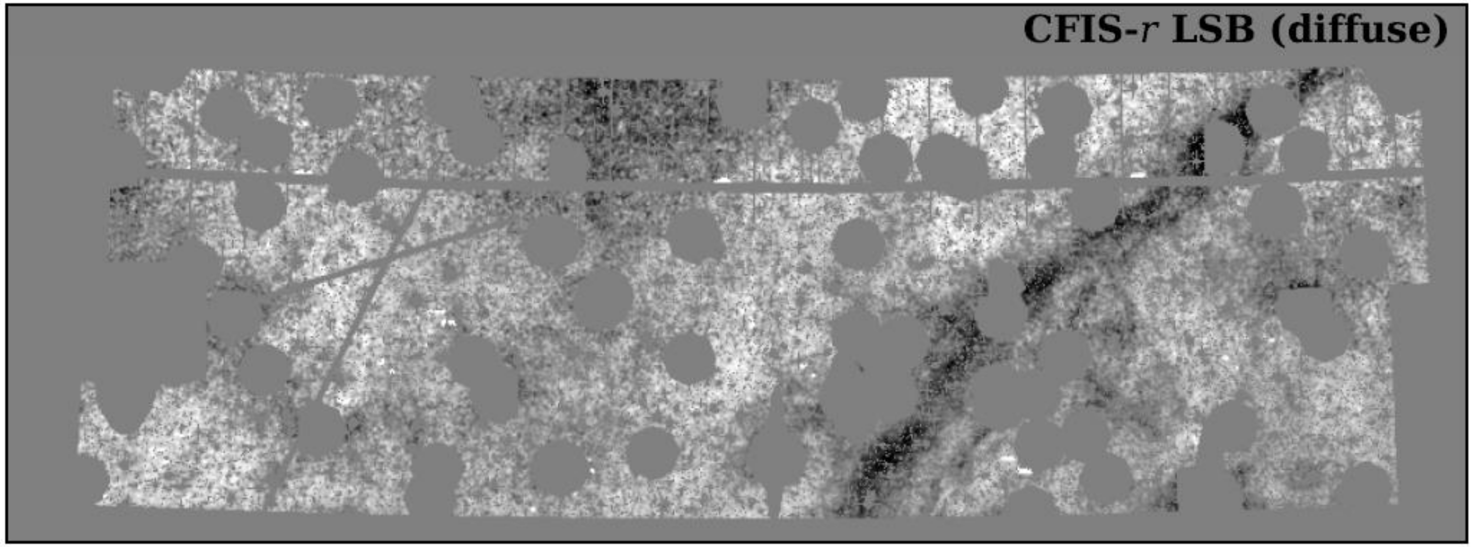
$$P_{\rm pos}(k_i) = \left| \frac{\sum_{\boldsymbol{k}\in k_i,\ |\Theta|\leqslant\pi/2} C_{\rm C}(\boldsymbol{k}) C_{\rm S}(\boldsymbol{k}) e^{i\Theta(\boldsymbol{k})}}{N_{\boldsymbol{k}\in k_i}} \right|,$$

$$P_{\rm neg}(k_i) = \left| \frac{\sum_{\boldsymbol{k}\in k_i i,\ |\Theta|\geqslant\pi/2} C_{\rm C}(\boldsymbol{k}) C_{\rm S}(\boldsymbol{k}) e^{i\Theta(\boldsymbol{k})}}{N_{\boldsymbol{k}\in k_i}} \right|,$$

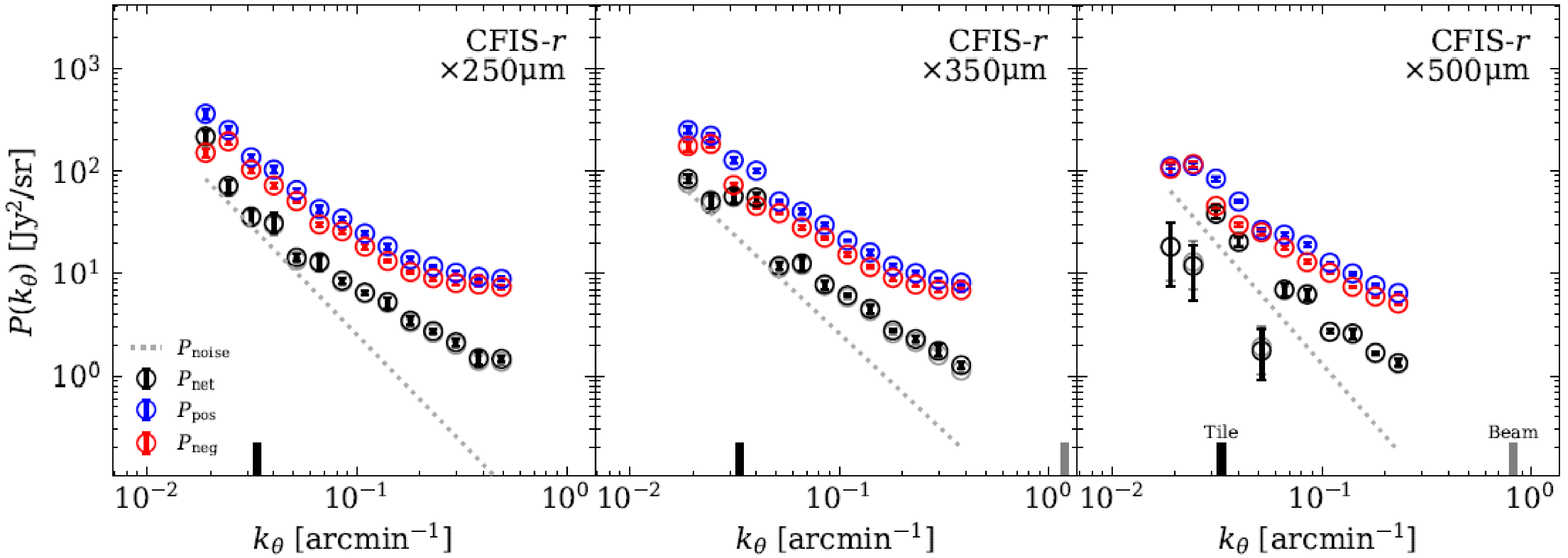


Galaxy maps vs. Diffuse(bkg) maps

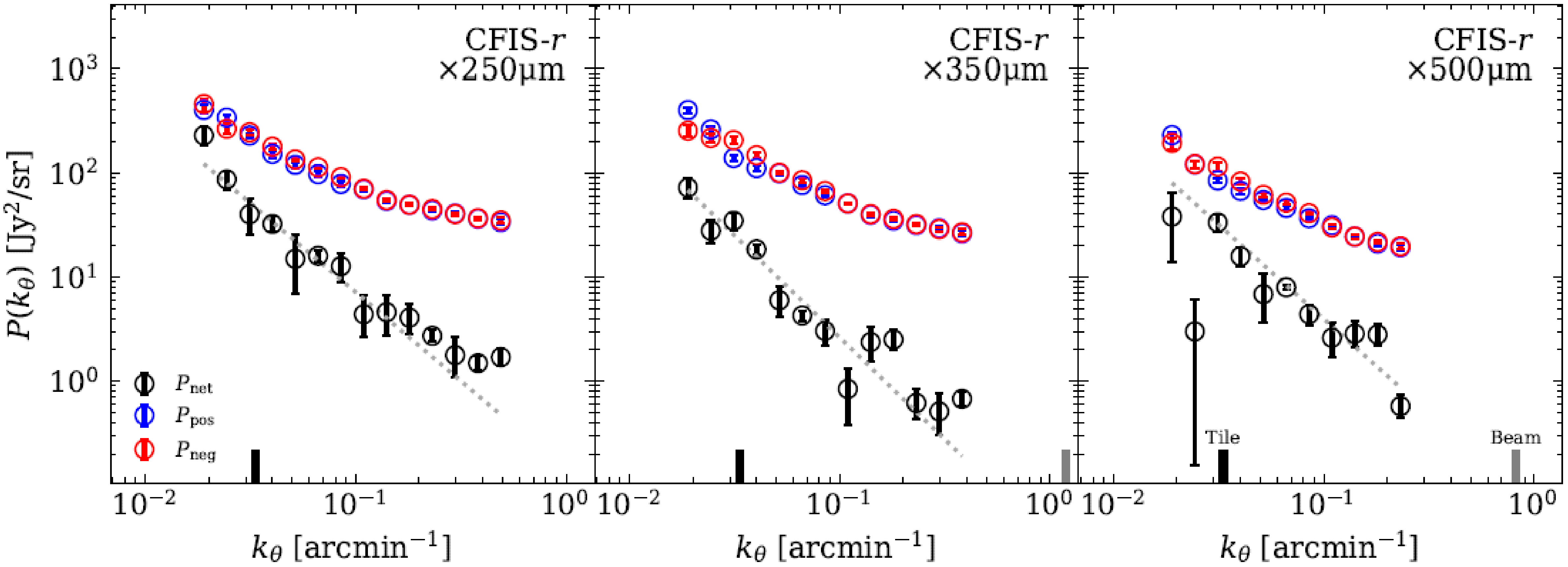




Signals are strong even in the bkg (galaxy-masked) maps



Null tests show our method is not biased

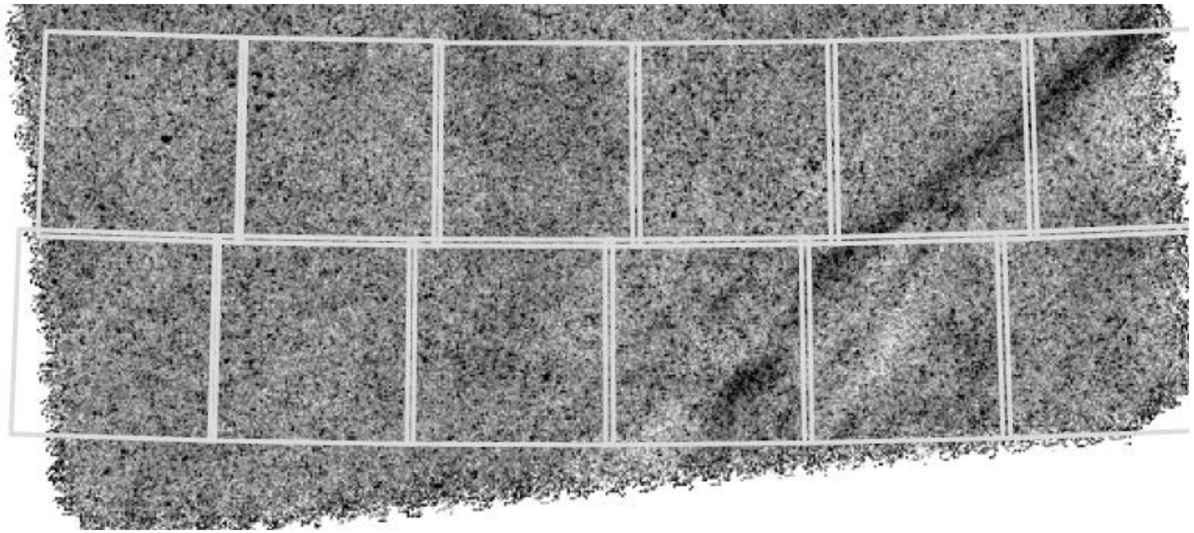


Systematics

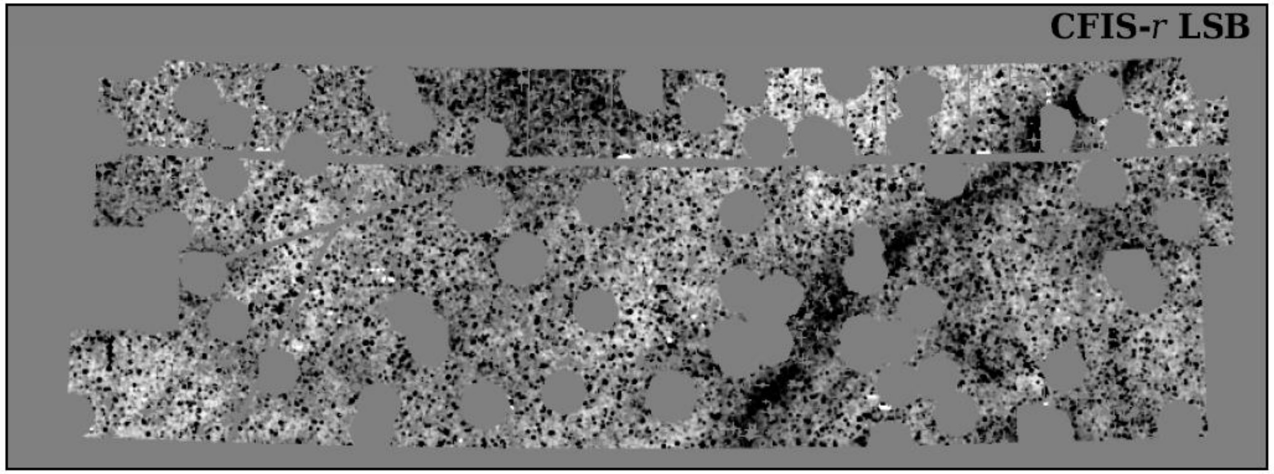
: the MW contamination

Are we detecting the MW signal, instead of ex-gal signal?

- SPIRE map of FLS

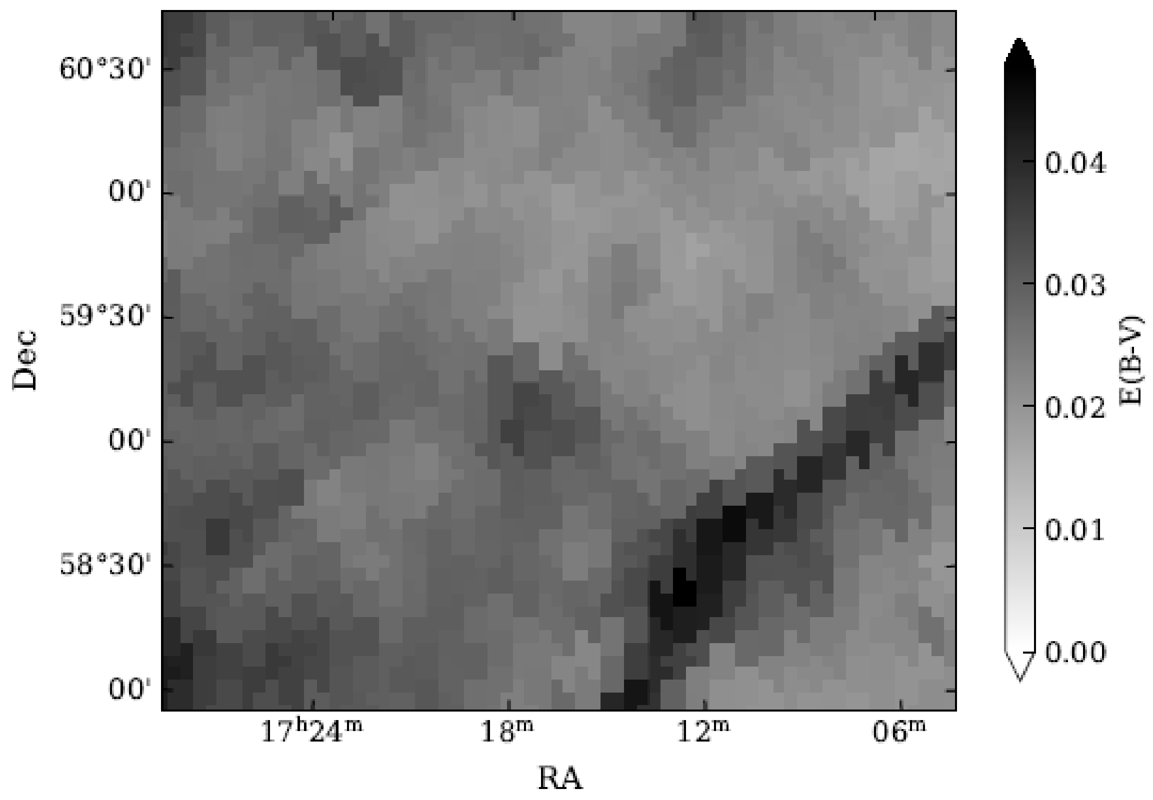


- CFIS map of FLS

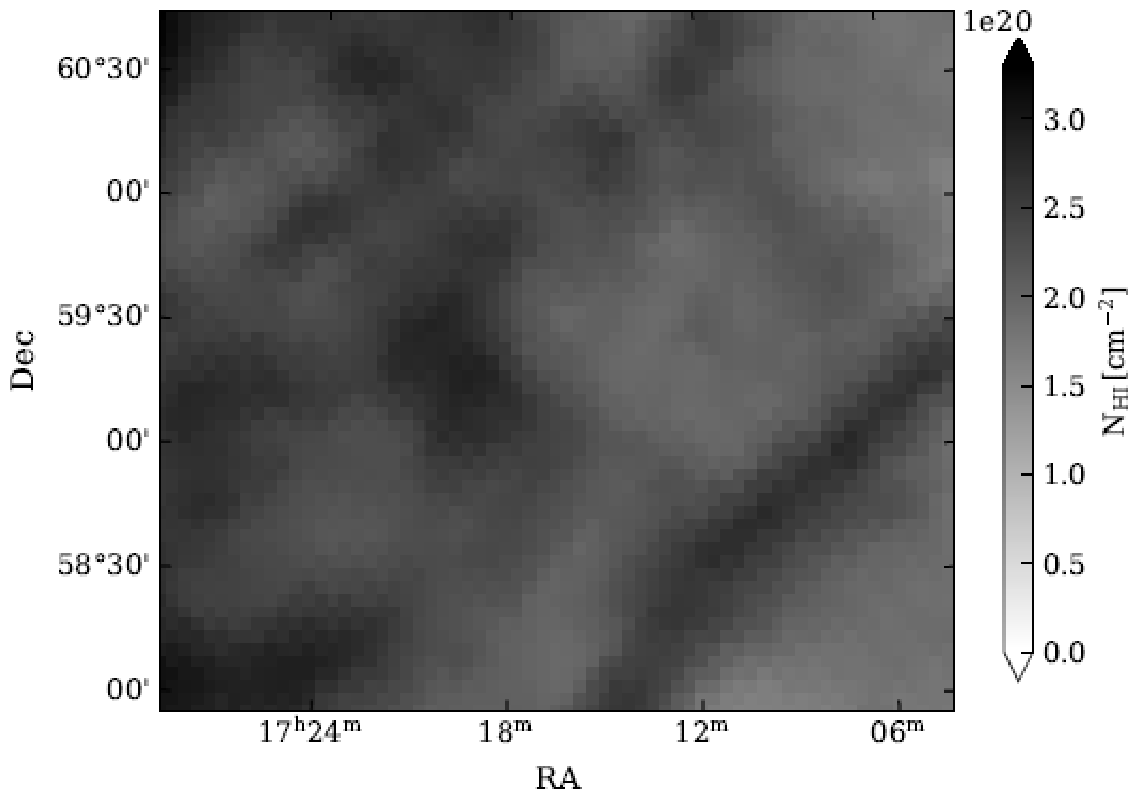


We subtract the MWG using other dust/HI maps

- Schlegel+ 98 dust map of FLS



- Effelsberg-Bonn HI Survey (EBHIS)



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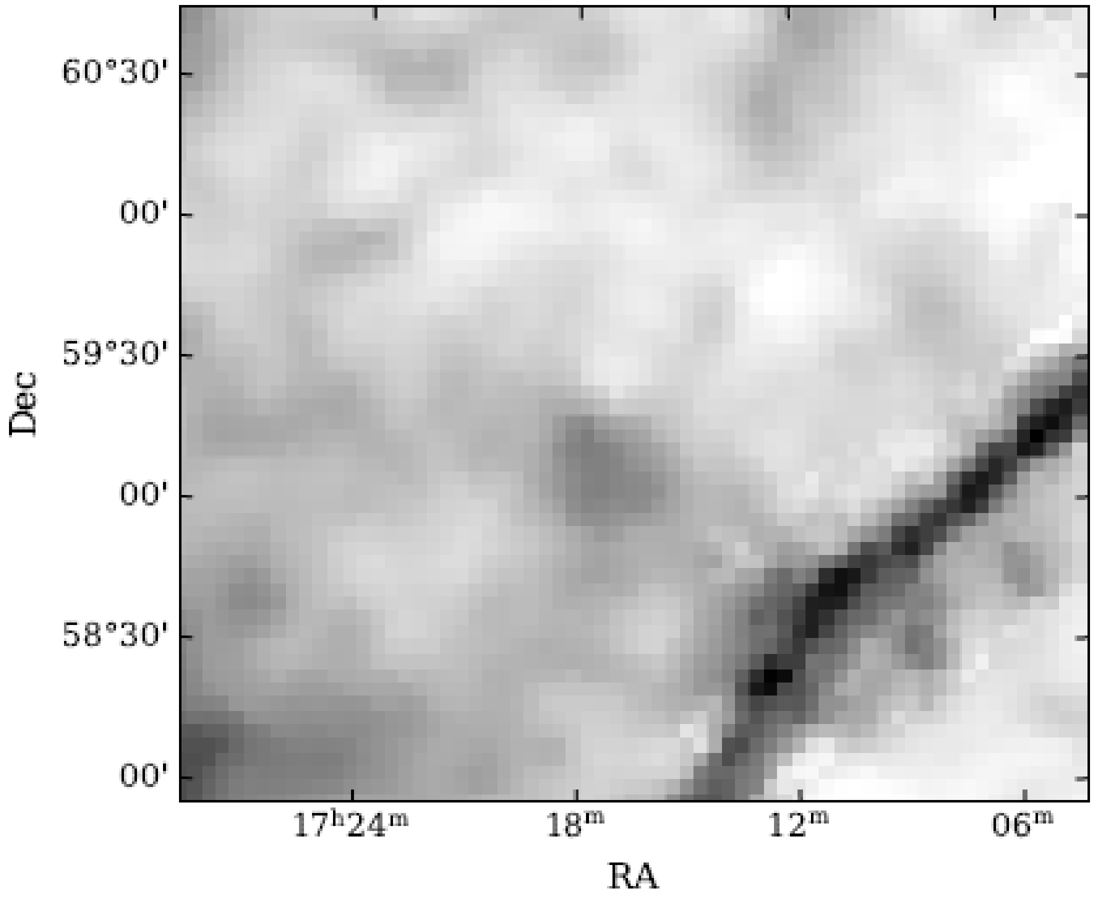
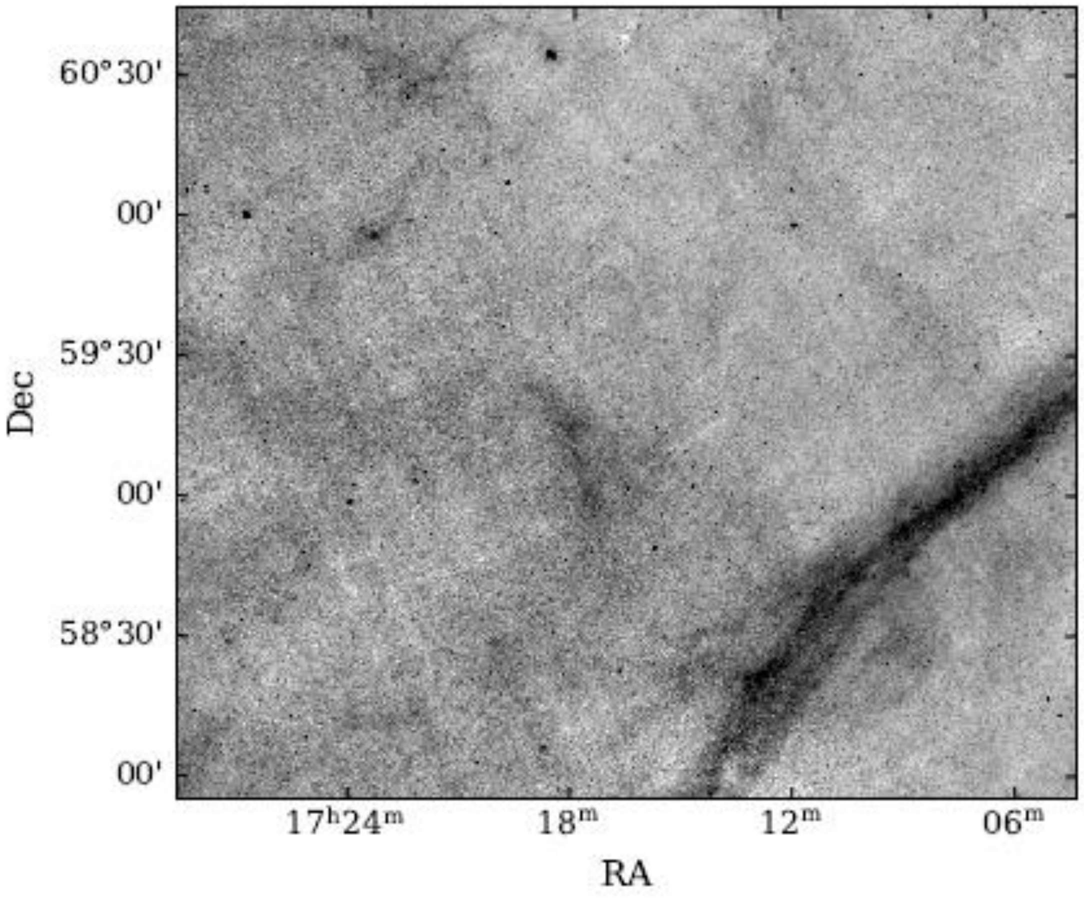
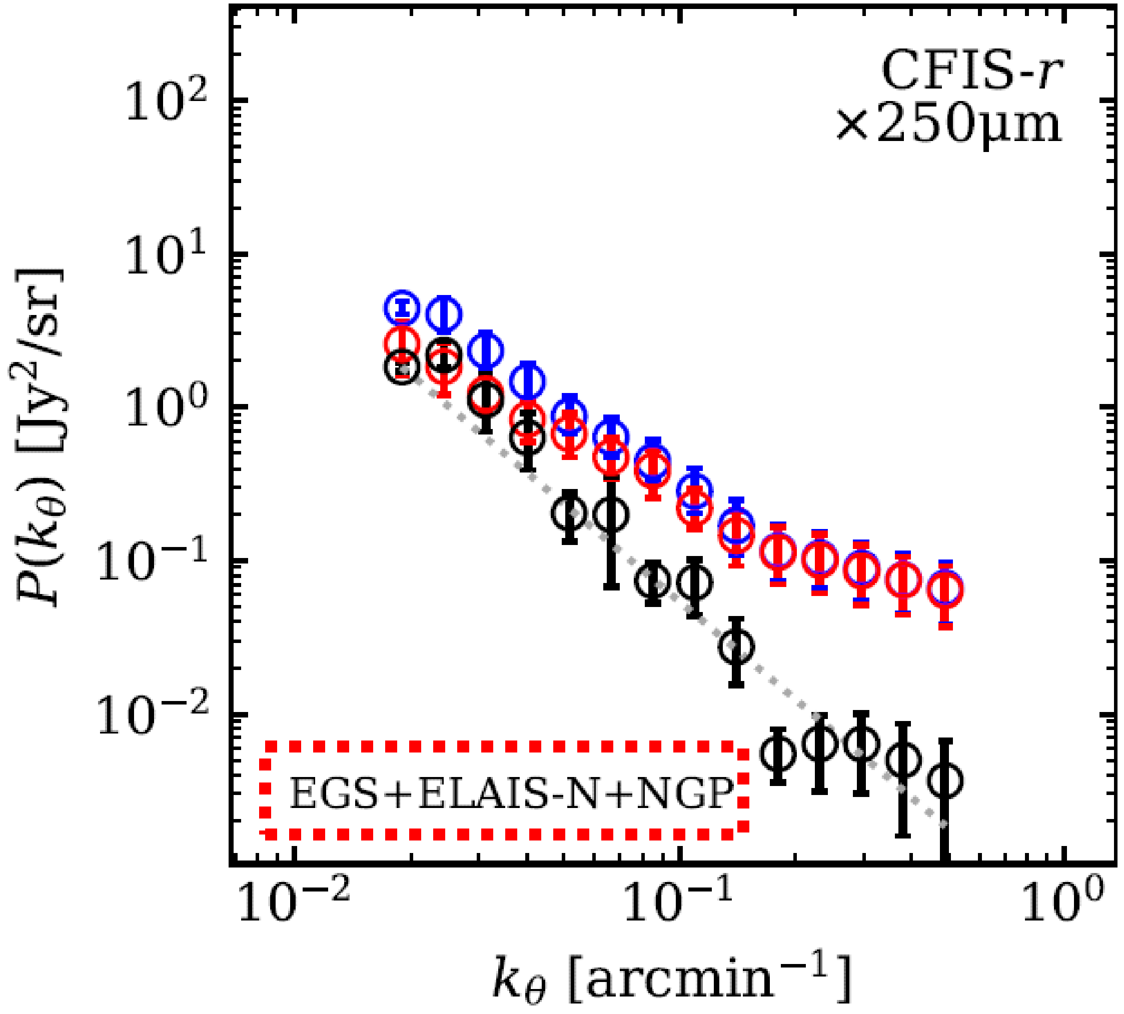
- Planck GNILC (2016; res=5~10')



- WISE (PAH) map (M&F 2014; ~15")



The residual MW is insignificant but for FLS



- Cross-correlation between the (ideally) Galaxy-only and the Galaxy-free maps, shows a bit of positive correlation on the large scale possibly from residual Galaxy, but more or less consistent with zero correlation on the smaller scales.

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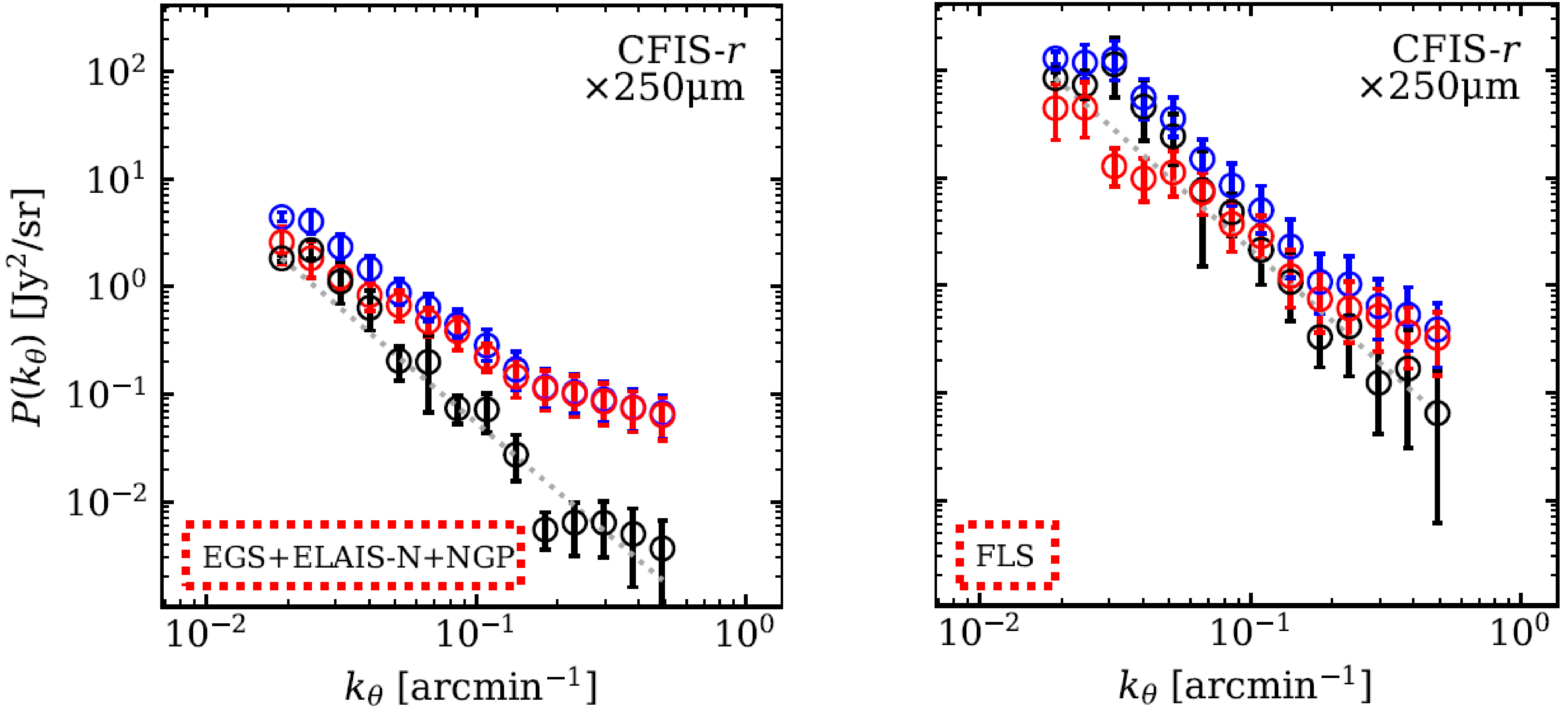
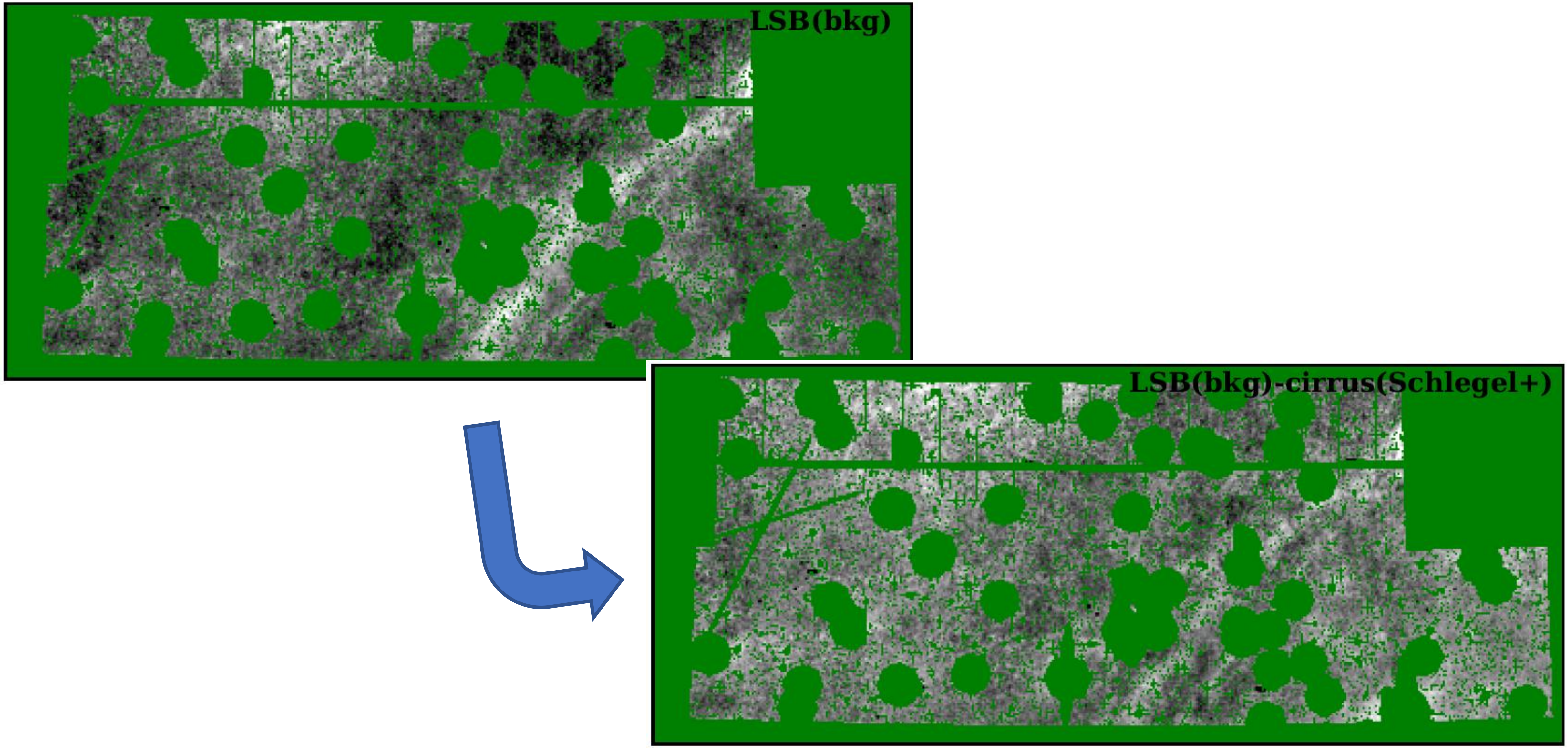
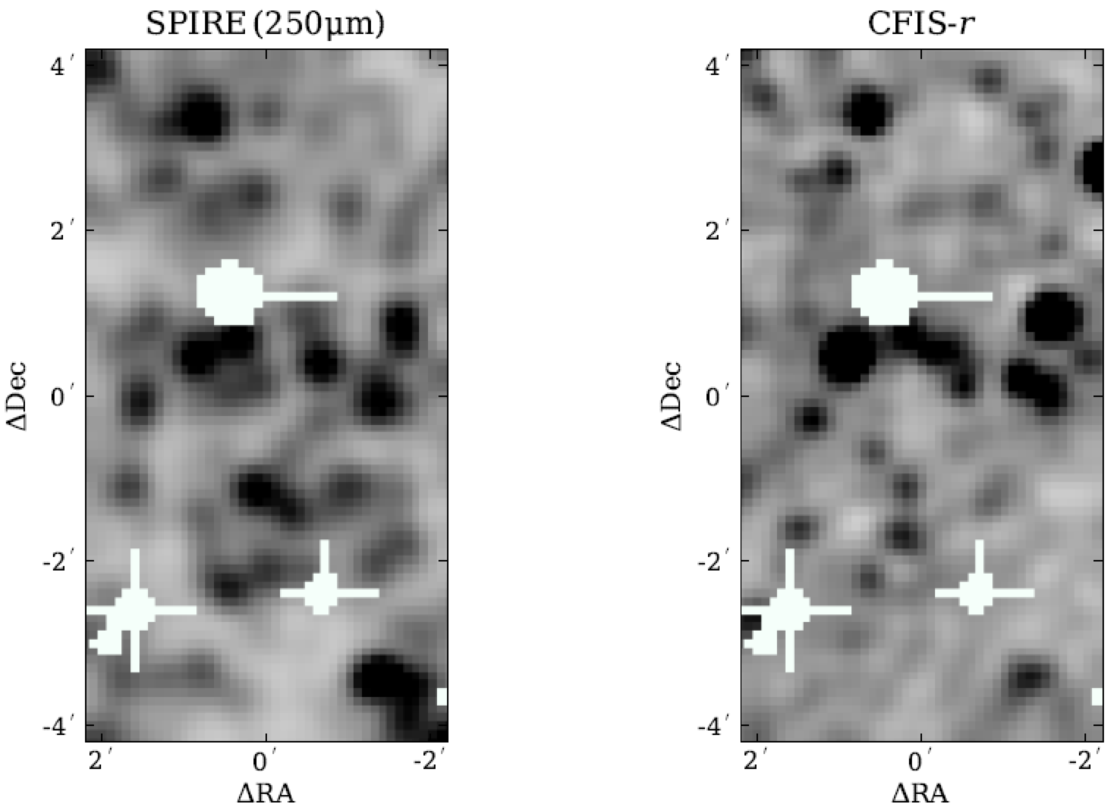


The MW is not removed well from FLS

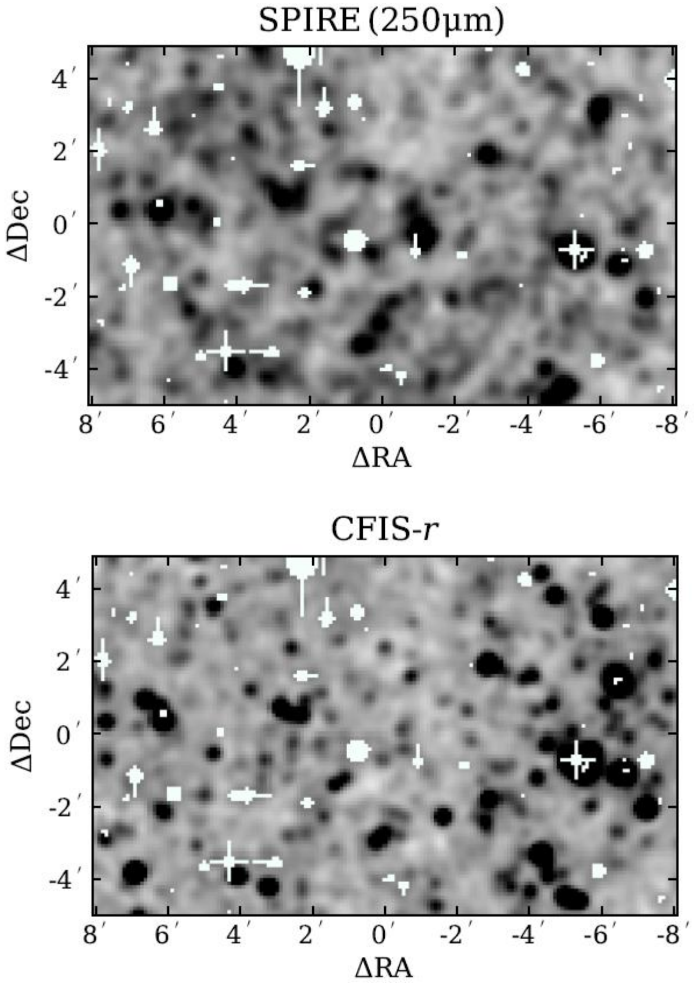


The **correlations** are clear even **by eyes**

- Part of the EGS field



- Part of the ELAIS-N1 field



Results can be interpreted within halo model framework

$$C_\ell^{\nu\nu'} = C_\ell^{\nu\nu';1\mathrm{h}} + C_\ell^{\nu\nu';2\mathrm{h}} + C_\ell^{\nu\nu';\mathrm{shot}}$$

$$\begin{aligned} C_\ell^{\nu\nu';1\mathrm{h}} &= \int dz \frac{d\chi}{dz}\chi^2 \int dM_\mathrm{h} \frac{dn_\mathrm{h}}{dM_\mathrm{h}} \\ &\times \Big\{ \overline{S}_{\nu,\mathrm{cen}} \overline{S}_{\nu',\mathrm{sat}} u_{\mathrm{gal},k}(M_\mathrm{h}, z) \\ &+ \overline{S}_{\nu,\mathrm{sat}} \overline{S}_{\nu',\mathrm{cen}} u_{\mathrm{gal},k}(M_\mathrm{h}, z) \\ &+ \overline{S}_{\nu,\mathrm{sat}} \overline{S}_{\nu',\mathrm{sat}} u_{\mathrm{gal},k}^2(M_\mathrm{h}, z) \Big\} \end{aligned}$$

$$\begin{aligned} C_\ell^{\nu\nu';2\mathrm{h}} &= \int dz \frac{d\chi}{dz}\chi^2 \int dM_\mathrm{h} \frac{dn_\mathrm{h}}{dM_\mathrm{h}} \int dM'_\mathrm{h} \frac{dn_\mathrm{h}}{dM'_\mathrm{h}} \\ &\times \Big\{ \overline{S}_{\nu,\mathrm{cen}} + \overline{S}_{\nu,\mathrm{sat}} u_{\mathrm{gal},k}(M_\mathrm{h}, z) \Big\} \\ &\times \Big\{ \overline{S}_{\nu',\mathrm{cen}} + \overline{S}_{\nu',\mathrm{sat}} u_{\mathrm{gal},k}(M'_\mathrm{h}, z) \Big\} \\ &\times b_\mathrm{h}(M_\mathrm{h}, z) b_\mathrm{h}(M'_\mathrm{h}, z) P_\mathrm{m}(\ell/\chi, z). \end{aligned}$$

$$\begin{aligned} C_\ell^{\nu\nu';\mathrm{shot}} &= \int dz \frac{d\chi}{dz}\chi^2 \int dM_\mathrm{h} \frac{dn_\mathrm{h}}{dM_\mathrm{h}} \\ &\times \Big\{ \overline{S_{\nu,\mathrm{cen}} S_{\nu',\mathrm{cen}}} + \overline{S_{\nu,\mathrm{sat}} S_{\nu',\mathrm{sat}}} \Big\} \end{aligned}$$

Results can be interpreted within halo model framework

$$\overline{S}_{\nu,\mathrm{cen}}(M_\mathrm{h}, z) = \frac{\mathcal{S}_\mathrm{MS}(M_*, z)}{K} \times (1 - f_\mathrm{Q}(M_*, z)) \times \overline{f}_{\text{IR-to-}\nu}$$

$\mathcal{S}_{MS}$: the avg SFR of MS gals
K: SFR-to-L_{TIR} conversion
$f_{\text{IR-to-nu}}$: L_{TIR}-to-S_{nu} conversion
f_Q : Quenched fraction at M_*

$$\log \frac{\mathcal{S}_\mathrm{MS}(M_*, z)}{\mathrm{M}_\odot\ \mathrm{yr}^{-1}} = m - m_0 - a_1 \left[\max(0, m - m_1 - a_2\eta)\right]^2 + a_0\eta - 0.1 \times \frac{0.5 - \min(0.5, z)}{0.5 - 0.22}, \quad (25)$$

where $\eta = \log(1+z)$, $m = \log(M_*/10^9\mathrm{M}_\odot)$

$$\overline{S}_{\nu,\mathrm{sat}}(M_\mathrm{h}, z) = \int dm_\mathrm{sub} \frac{dN_\mathrm{sub}}{dm_\mathrm{sub}}(m_\mathrm{sub}|M_\mathrm{h}) \times \frac{\mathcal{S}_\mathrm{MS}(M_{*,\mathrm{sub}}, z)}{K} \times \left[1 - f_\mathrm{Q}(M_{*,\mathrm{sub}}, z)\right] \overline{f}_{\text{IR-to-}\nu},$$

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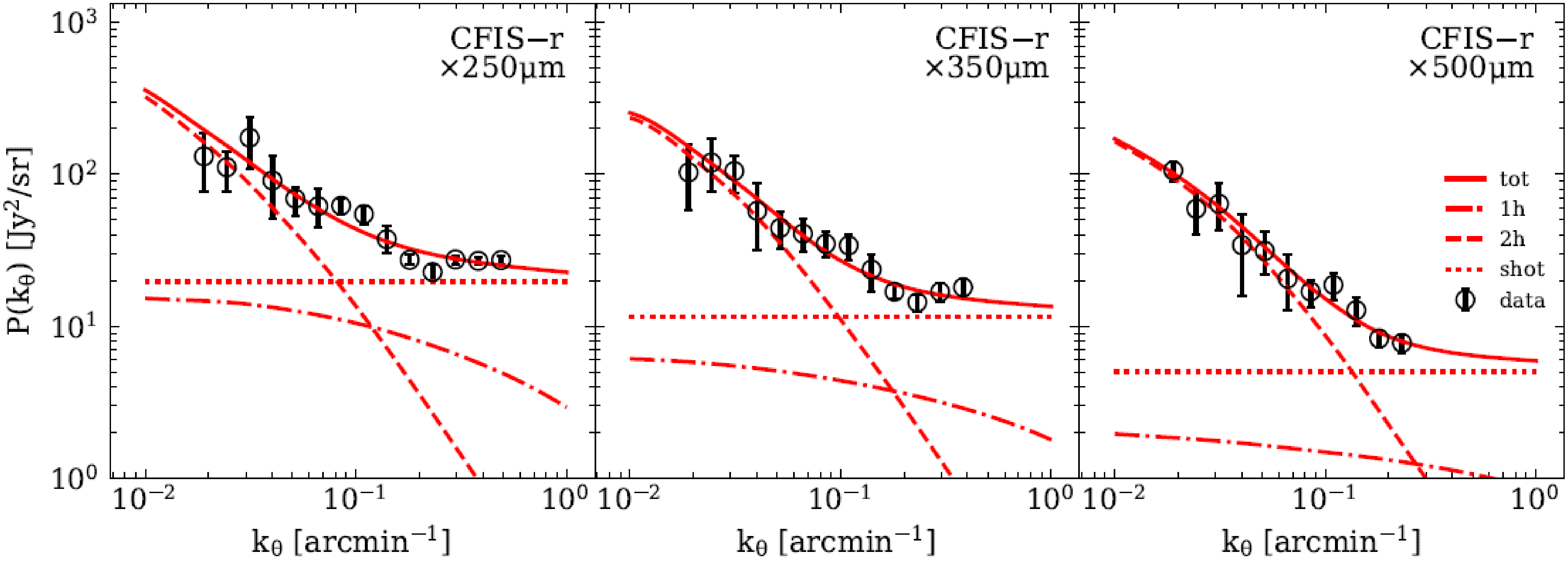
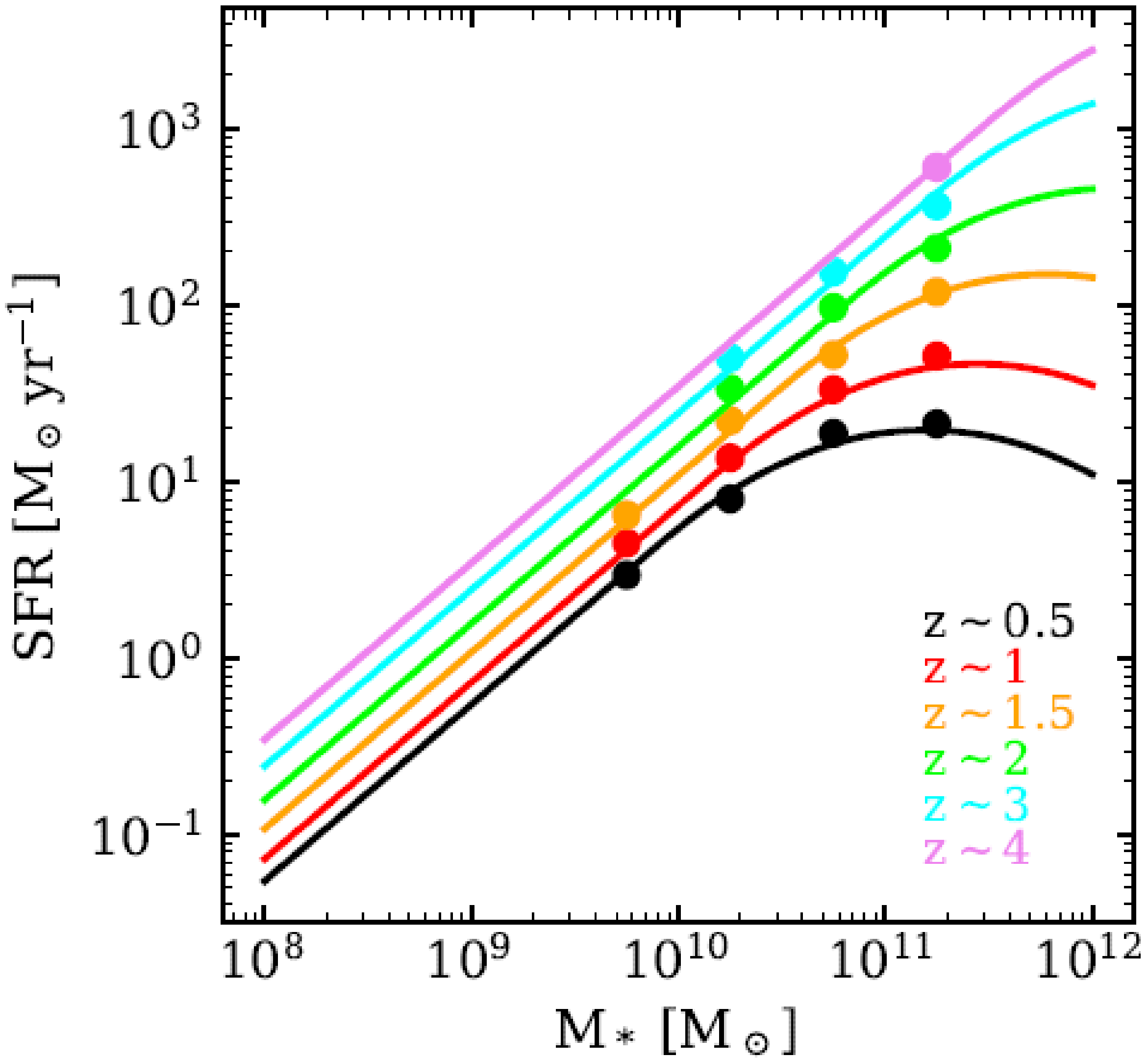


The model constraints agree well with independent obs



Summary

CIB-optical image cross-correlation is a promising tool to study galaxy formation, especially with the upcoming surveys like Euclid

Strong signals are detected after carefully treating:

- contamination from stars and artefacts by aggresive masking
- preserving a wide range of modes by using LSB processing
- separation of in- and out-of-phase cross-power and noise-level estimate
- contribution from individually detected sources
- the Galactic contamination
- consistency check by checking the correlations by eyes