Planck CO revisited

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What is CO ?

- The obvious
  - Carbon Monoxide, a molecule that is abundant in the interstellar medium
  - Observable in our galaxy, but also in other galaxies, up to high redshift!

- The rotational emission lines
  - Main "ladder" $^{12}C^{16}O$ *J=1-0*, *J=1-2*, etc... $\nu = n \times 115.27$ GHz
  - Isotopologues $^{13}C^{16}O$, $^{12}C^{17}O$, $^{12}C^{18}O$ at slightly ≠ frequencies ($109.78 - 112.36$ GHz)

- The astrophysical relevance
  - One of the main cooling lines of the ISM (together with C-II)
  - Bright, and hence easily observable
  - A tracer of molecular gas

- The Nuisance
  - One more source of foreground emission for CMB observations !

Why CO *revisited* ???

- Planck collaboration paper :

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Planck 2013 results

Astronomy & Astrophysics
Special feature

Planck 2013 results. XIII. Galactic CO emission

Planck Collaboration: P. A. R. Ade[93], N. Aghanim[62], M. I. R. Alves[62], C. Armitage-Caplan[98], M. Arnaud[77], M. Ashdown[74,6], F. Atrio-Barandela[19], J. Aumont[62], C. Baccigalupi[92], A. J. Banday[101,10], R. B. Barreiro[70], J. G. Bartlett[1,71], E. Battaner[103], K. Benabed[63,100], A. Benoît[60], A. Benoit-Lévy[26,63,100], J.-P. Bernard[101,10], M. Bersanelli[37,53], P. Bielewicz[101,10,92], J. Bobin[77], J. J. Bock[71,11], A. Bonaldi[72], J. R. Bond[9], J. Borrill[14,95], F. R. Bouchet[63,100], F. Boulanger[62], M. Bridges[74,6,66], M. Bucher[1], C. Burigana[52,35], R. C. Butler[52], J.-F. Cardoso[78,1,63], A. Catalano[79,76], A. Chamballu[77,16,62], R.-R. Chary[59], X. Chen[59], H. C. Chiang[30,8], L.-Y. Chiang[65], P. R. Christensen[87,40], S. Church[97], D. L. Clements[58], S. Colombi[63,100], L. P. L. Colombo[25,71], C. Combet[79], F. Couchot[75], A. Coulais[76], B. P. Crill[71,89], A. Curto[6,70], F. Cuttaia[52], L. Danese[92], R. D. Davies[72], P. de Bernardis[36], A. de Rosa[52], G. de Zotti[48,92], J. Delabrouille[1], J.-M. Delouis[63,100], J. T. Dempsey[73], F.-X. Désert[56], C. Dickinson[72], J. M. Diego[70], H. Dole[62,61], S. Donzelli[53], O. Doré[71,11], M. Douspis[62], X. Dupac[42], G. Efstathiou[66], T. A. Enßlin[82],

... etc ...

J. Valiviita[46,28,68], B. Van Tent[80], P. Vielva[70], F. Villa[52], N. Vittorio[39], L. A. Wade[71], B. D. Wandelt[63,100,33], I. K. Wehus[71], H. Yamamoto[29], T. Yoda[67], D. Yvon[16], A. Zacchei[50], and A. Zonca[32]

(Affiliations can be found after the references)

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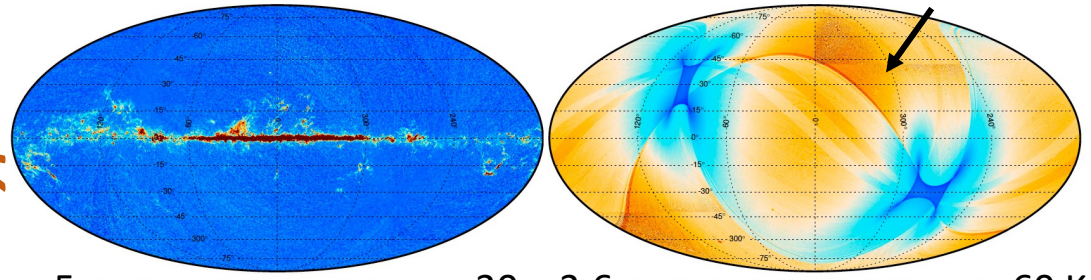
Why CO *revisited* ???

CO J=1-0 (100 GHz channel)

σ_{noise}

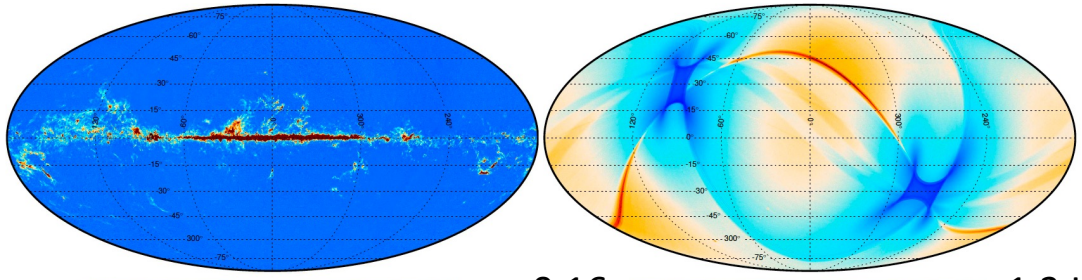
Type 1



-5 30 3.6 60 K km s^{-1}

(a) Type 1 $J = 1 \rightarrow 0$ map (b) Type 1 $J = 1 \rightarrow 0$ stddev

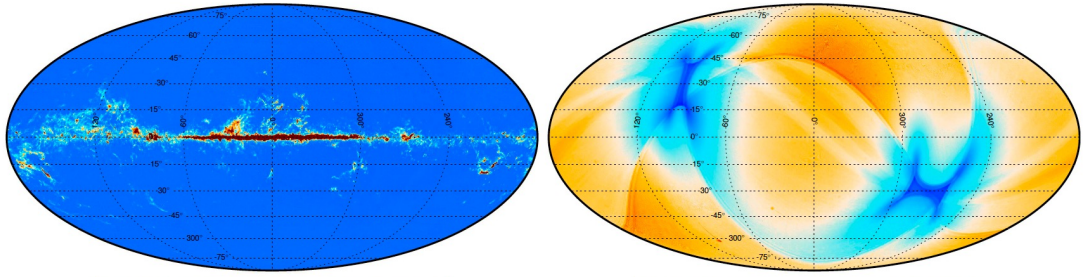
Type 2



-5.0 30.0 0.16 1.3 K km s^{-1}

(c) Type 2 $J = 1 \rightarrow 0$ map (d) Type 2 $J = 1 \rightarrow 0$ stddev

Type 3

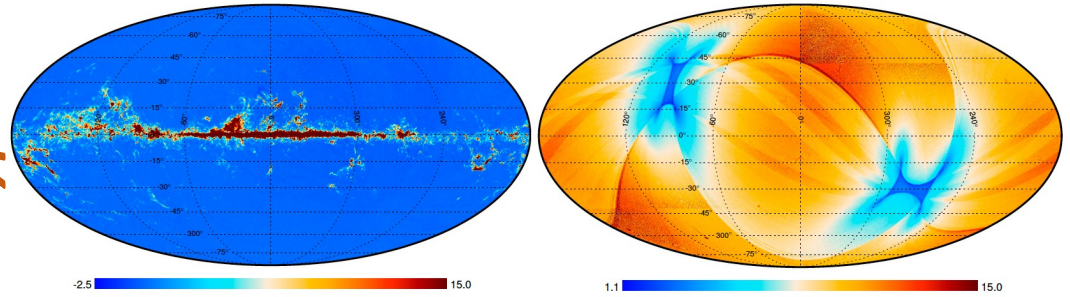


-5.0 30.0 0.37 3.5 K km s^{-1}

(e) Type 3 $J = 1 \rightarrow 0$ map (f) Type 3 $J = 1 \rightarrow 0$ stddev

CO J=2-1 (217 GHz channel)

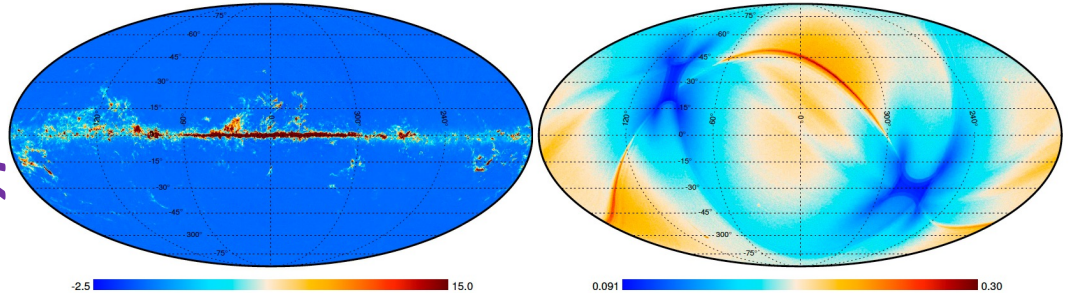
Type 1



-2.5 15.0 1.1 15.0

(a) Type 1 $J = 2 \rightarrow 1$ map (b) Type 1 $J = 2 \rightarrow 1$ stddev

Type 2

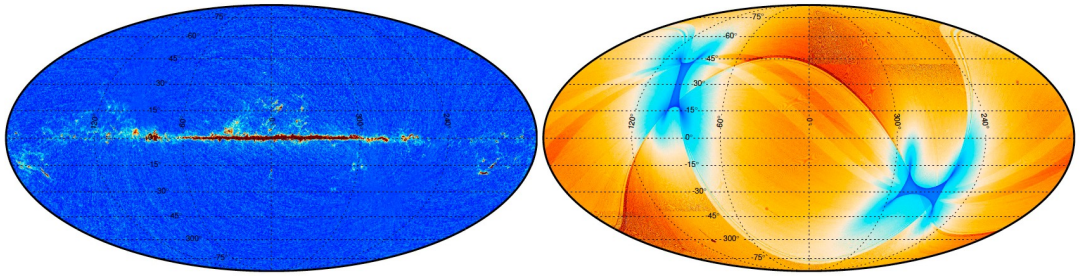


-2.5 15.0 0.091 0.30

(c) Type 2 $J = 2 \rightarrow 1$ map (d) Type 2 $J = 2 \rightarrow 1$ stddev

CO J=3-2 (353 GHz channel)

Type 1

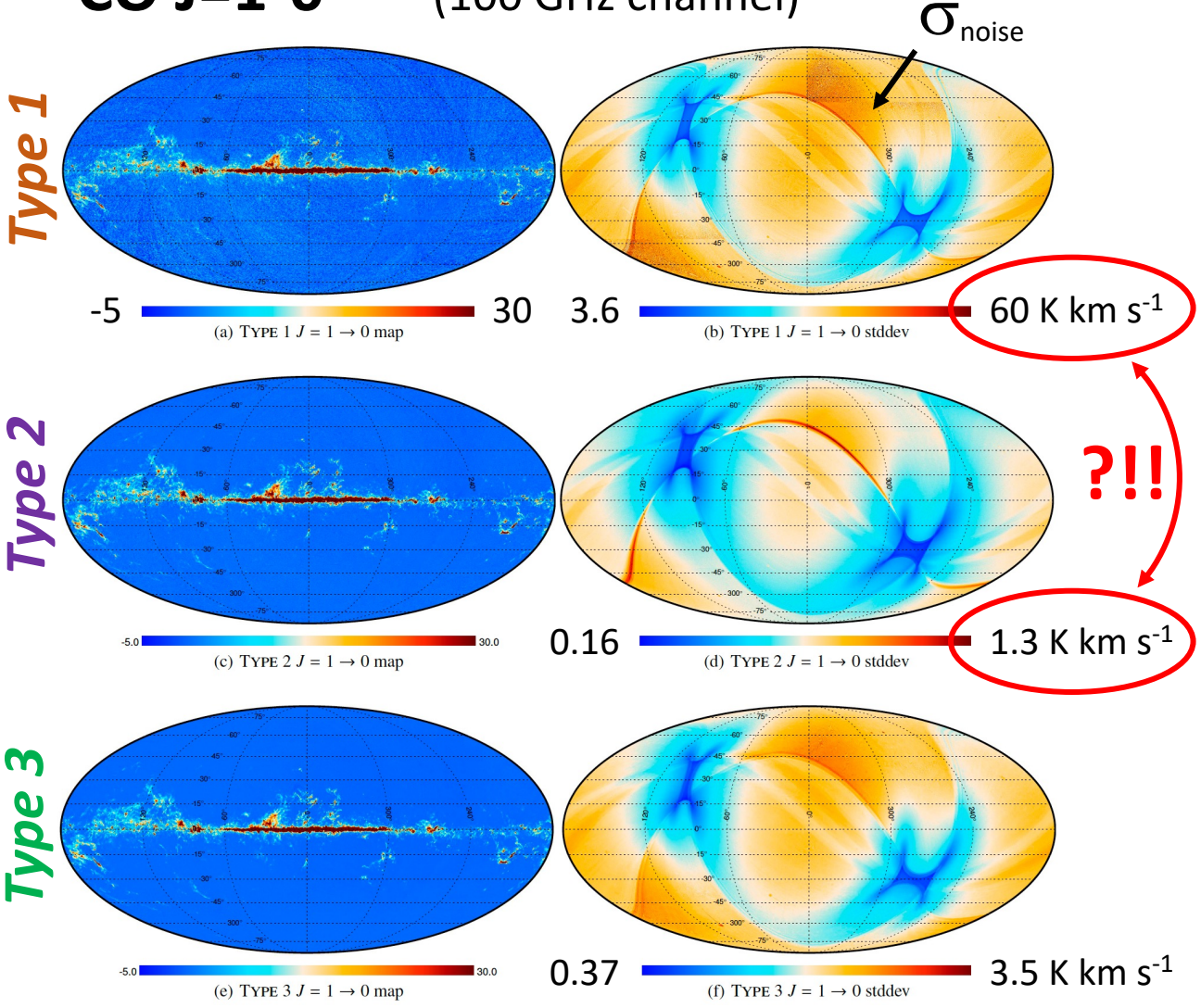


-1.0 10.0 0.8 15.0

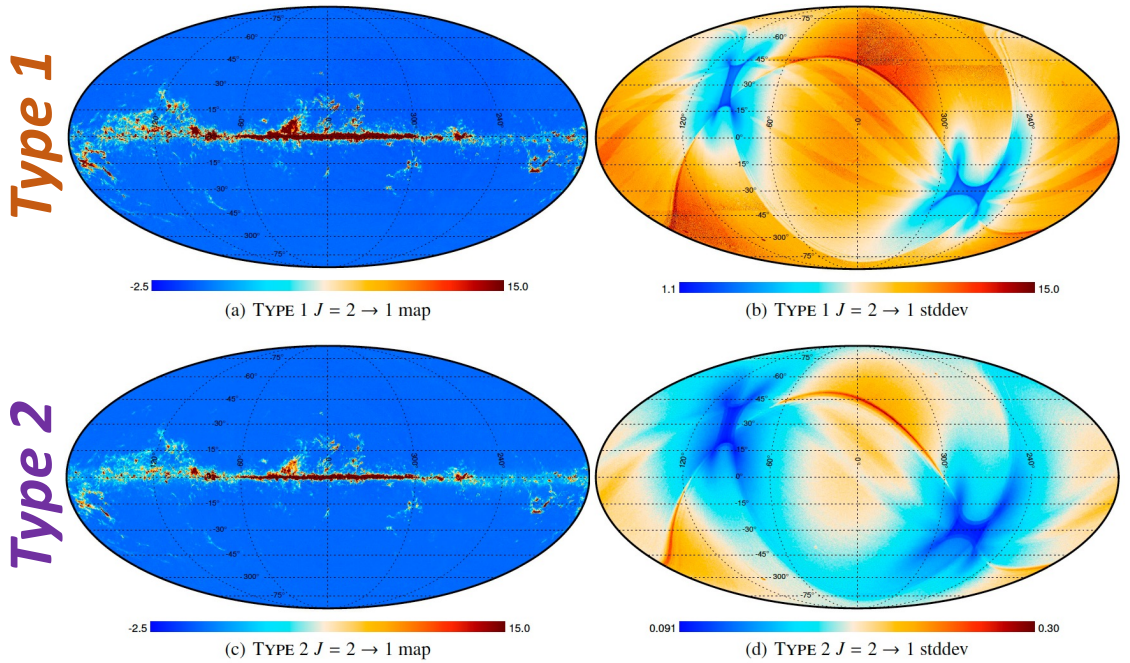
(a) Type 1 $J = 3 \rightarrow 2$ map (b) Type 1 $J = 3 \rightarrow 2$ stddev

Why CO *revisited* ???

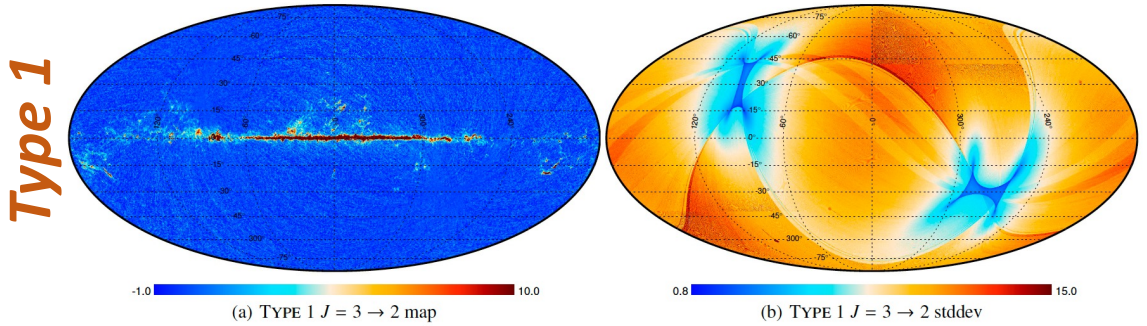
CO J=1-0 (100 GHz channel)



CO J=2-1 (217 GHz channel)



CO J=3-2 (353 GHz channel)

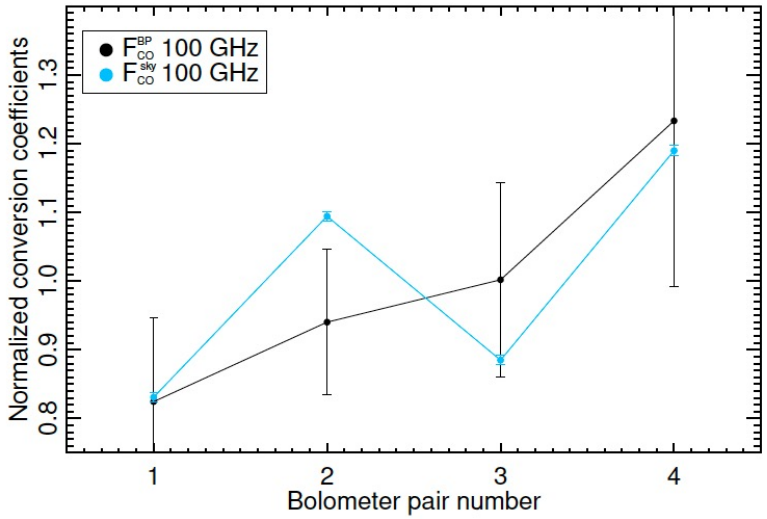


Why *revisit the CO* ???

- **Type 1**

  Exploit differences in the spectral transmission of a given CO line among the bolometers (or pairs) of the same frequency channel. Multi-component fit for in each channel (100, 217, 353 GHz) independently.

Bolometer	$F^{BP}_{^{12}CO}$	$F^{BP}_{^{13}CO}$	F^{sky}_{CO}
$J = 1 \rightarrow 0$			
100-1 (a+b)/2	0.82 ± 0.10	1.03 ± 0.12	0.83 ± 0.01
100-2 (a+b)/2	0.94 ± 0.09	0.97 ± 0.10	1.09 ± 0.01
100-3 (a+b)/2	0.99 ± 0.11	0.87 ± 0.14	0.88 ± 0.01
100-4 (a+b)/2	1.24 ± 0.10	1.13 ± 0.24	1.19 ± 0.01



$$\begin{pmatrix} x_{101\text{-}1} \\ x_{101\text{-}2} \\ x_{101\text{-}3} \\ x_{101\text{-}4} \end{pmatrix} = \begin{pmatrix} 0.83 & 1 \\ 1.09 & 1 \\ 0.88 & 1 \\ 1.19. & 1 \end{pmatrix} \begin{pmatrix} CO \\ CMB+FG \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{pmatrix}$$

$$x = As + n$$

Assuming same noise level σ in all four pairs

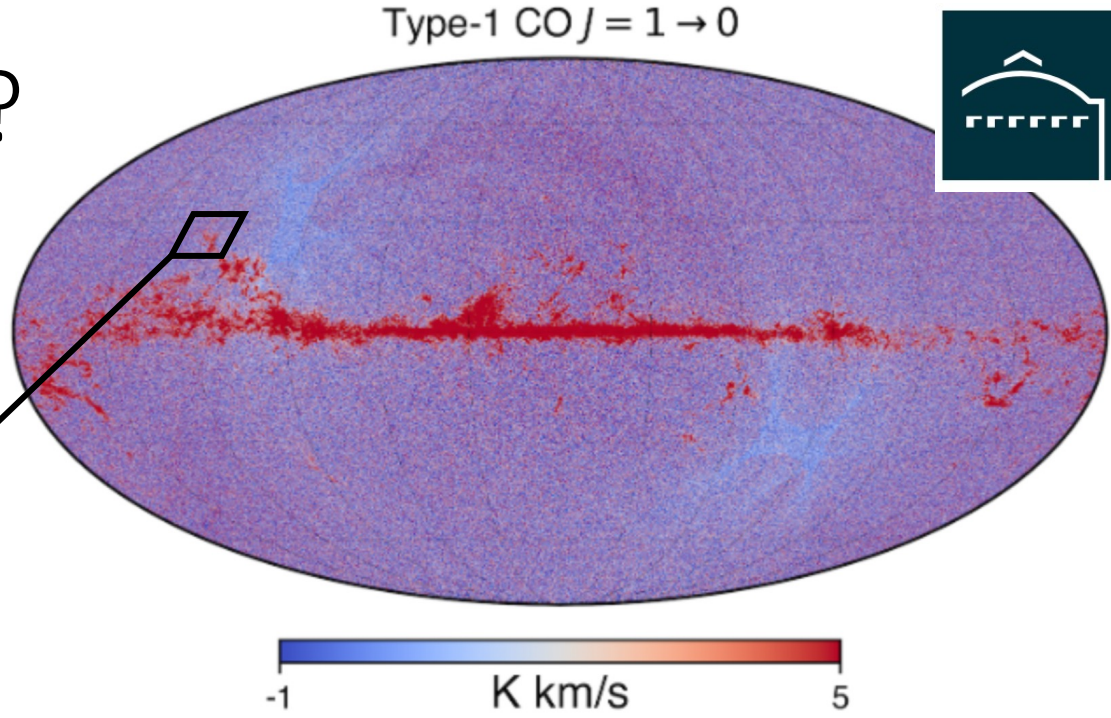
$$\hat{s} = [A^t A]^{-1} A^t x$$

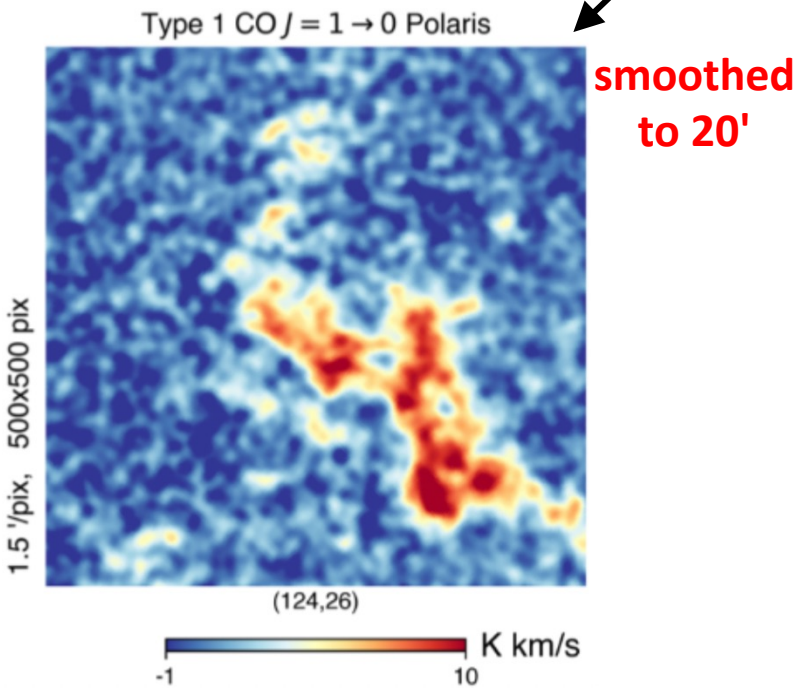
$$\widehat{CO} = 2.16\, x_{101\text{-}1} - 0.80\, x_{101\text{-}1} + 1.59\, x_{101\text{-}1} - 1.95\, x_{101\text{-}1}$$

The noise level in the CO map is about 3.41 σ
i.e. 6.8 times that of the 100 GHz channel (which is $\sigma/2$)

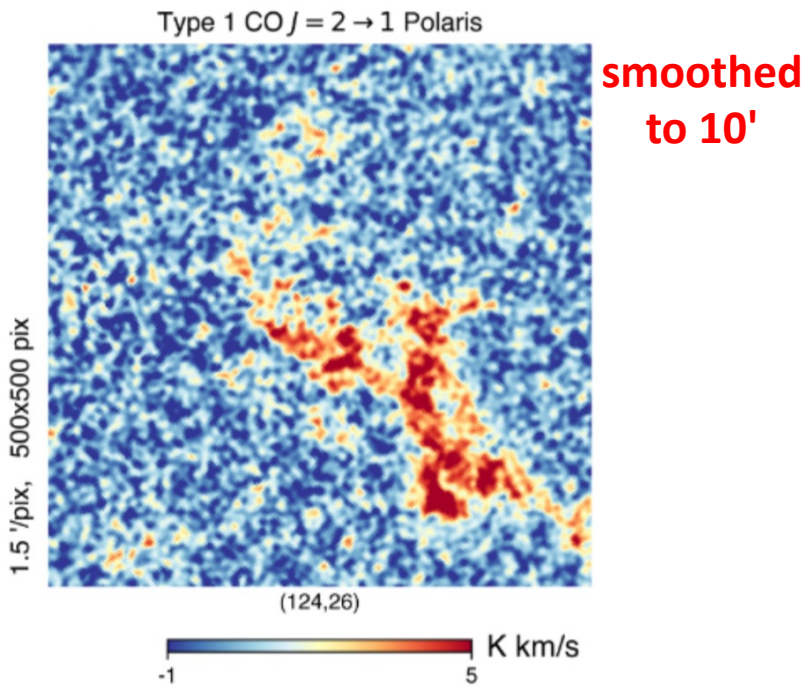
Why *revisit the CO* ???

- **Noisy Type-1 maps**

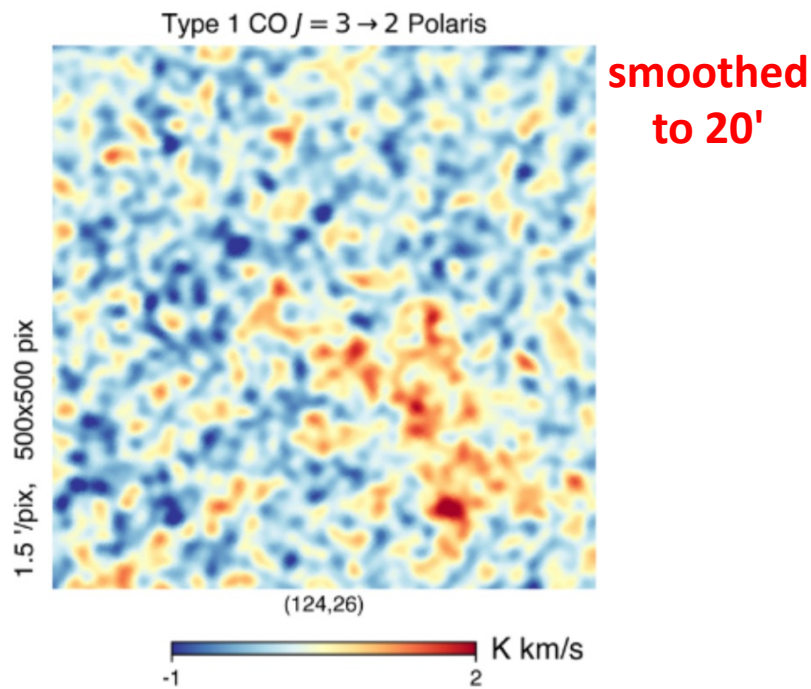




smoothed to 20'



smoothed to 10'



smoothed to 20'

Why *revisit the CO* ???

- **Artefacts in Type-1 J=3-2 map**

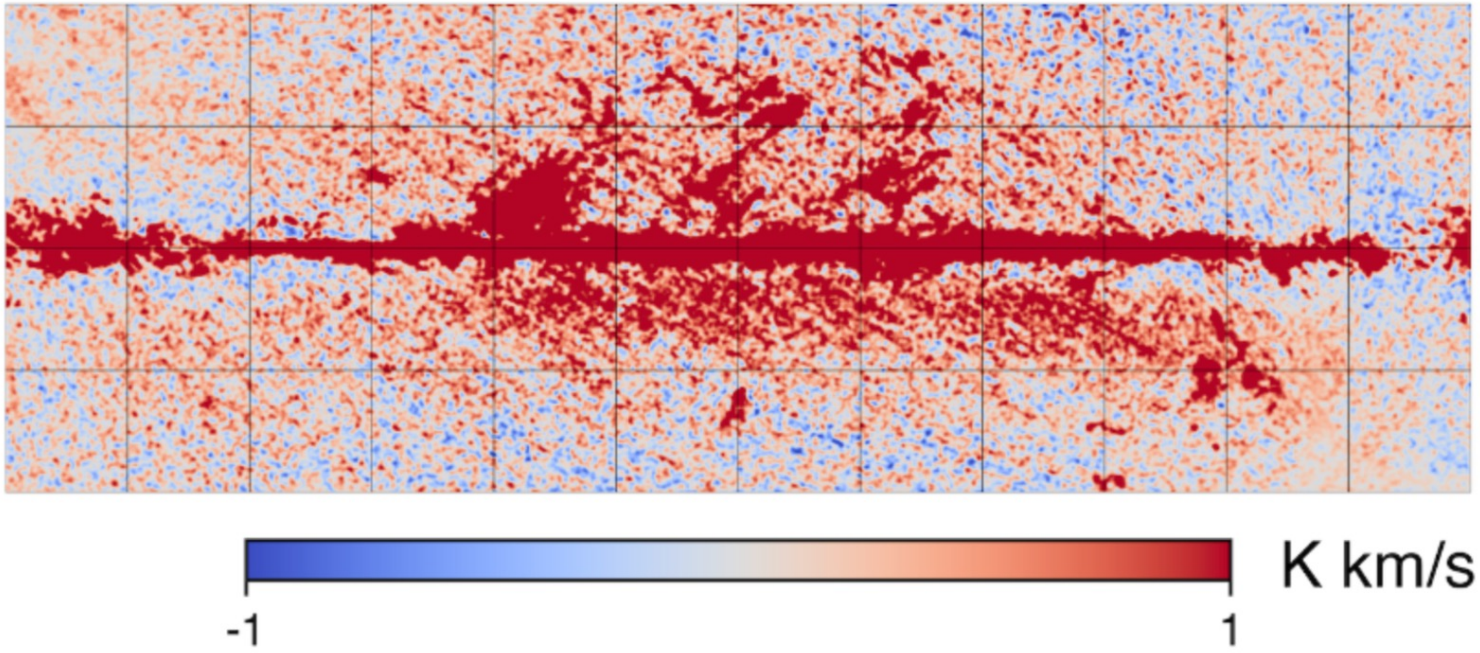


Fig. 3. The TYPE 1 CO $J = 3 \rightarrow 2$ data product from Planck, shown here after smoothing to 30' resolution. We are showing a region ±90° in Galactic longitude and ±30° in Galactic latitude about the Galactic center. Ringing effects and systematic residuals are visible above and below the Galactic ridge.

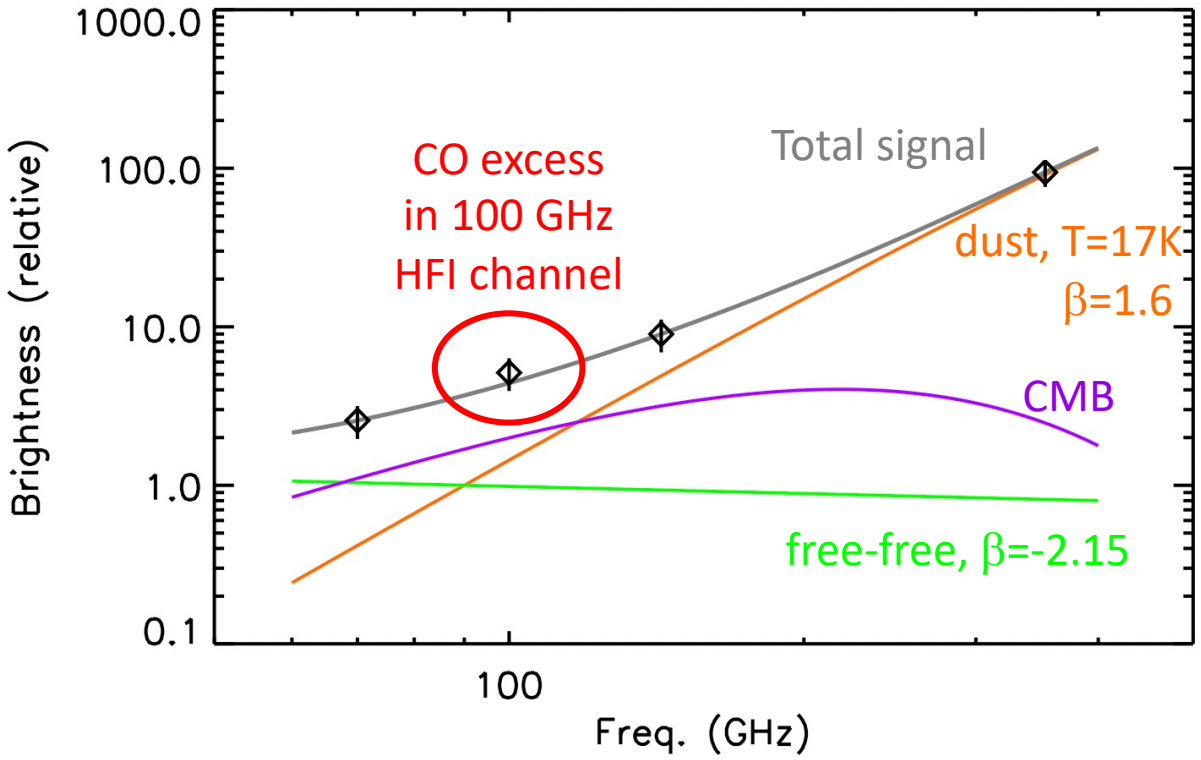
Why *revisit the CO* ???

- **Type-2**

  Assume J=3-2 CO emission is negligible and fit for dust, free-free, CO and CMB across frequencies using additional 70, 143 and 353 GHz channels.

  Done for 15' maps

  only J=1-0 and J=2-1

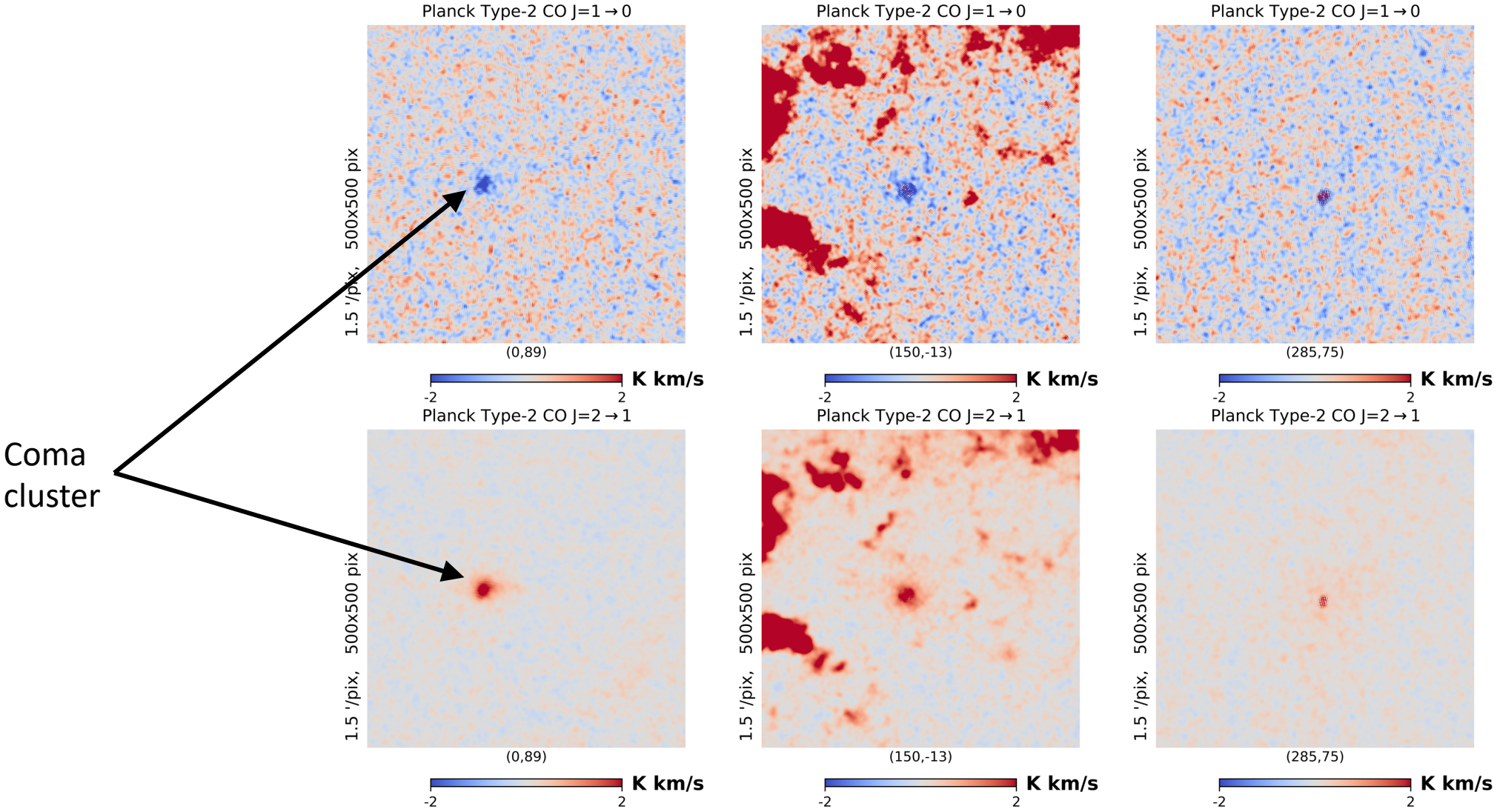


Less noisy than Type-1 (full use of channel sensitivity + smoothing to 15')

Potential foreground contamination

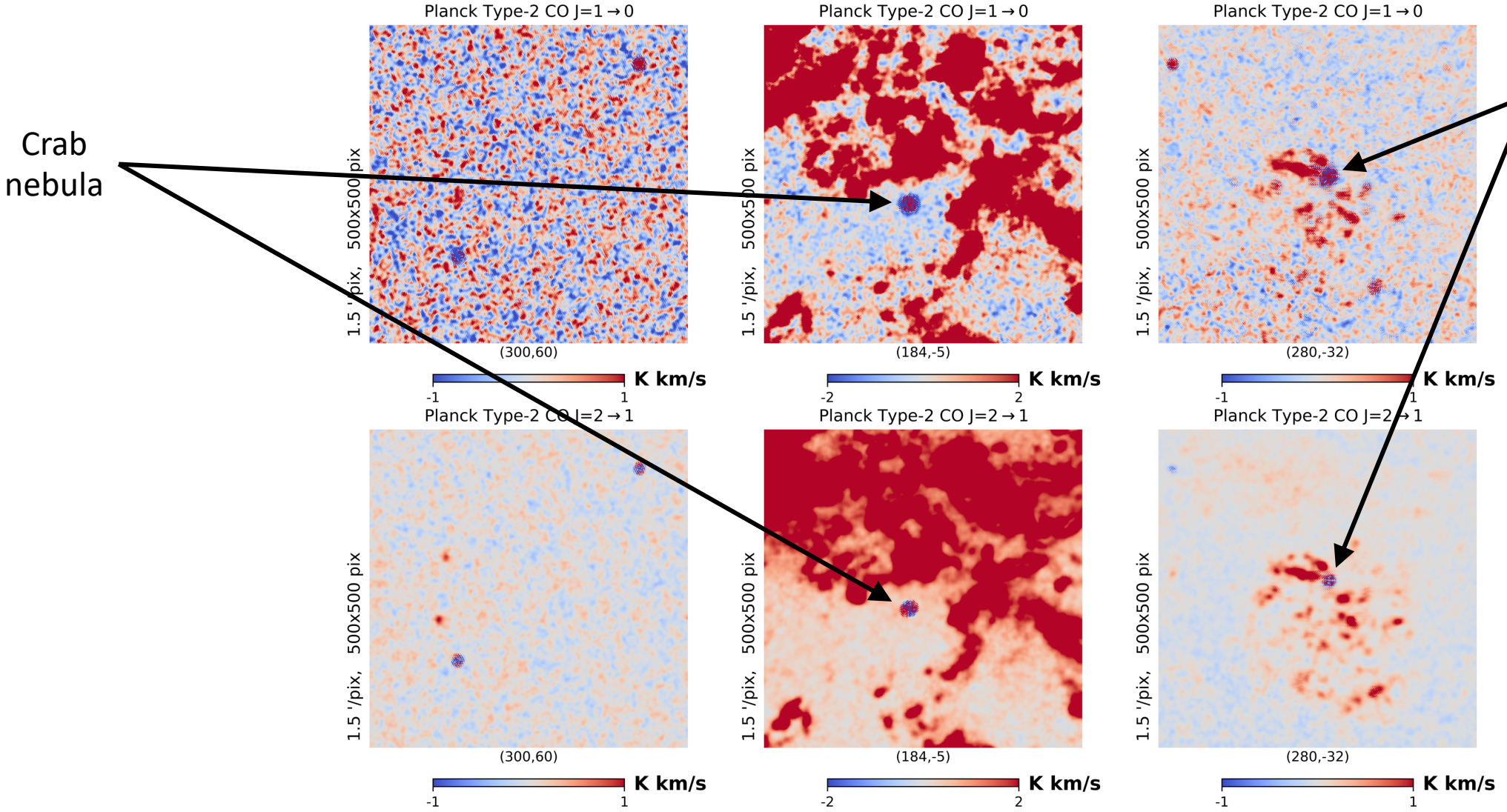
Why *revisit the CO* ???

- **Contamination by thermal SZ effect in Type-2 maps**

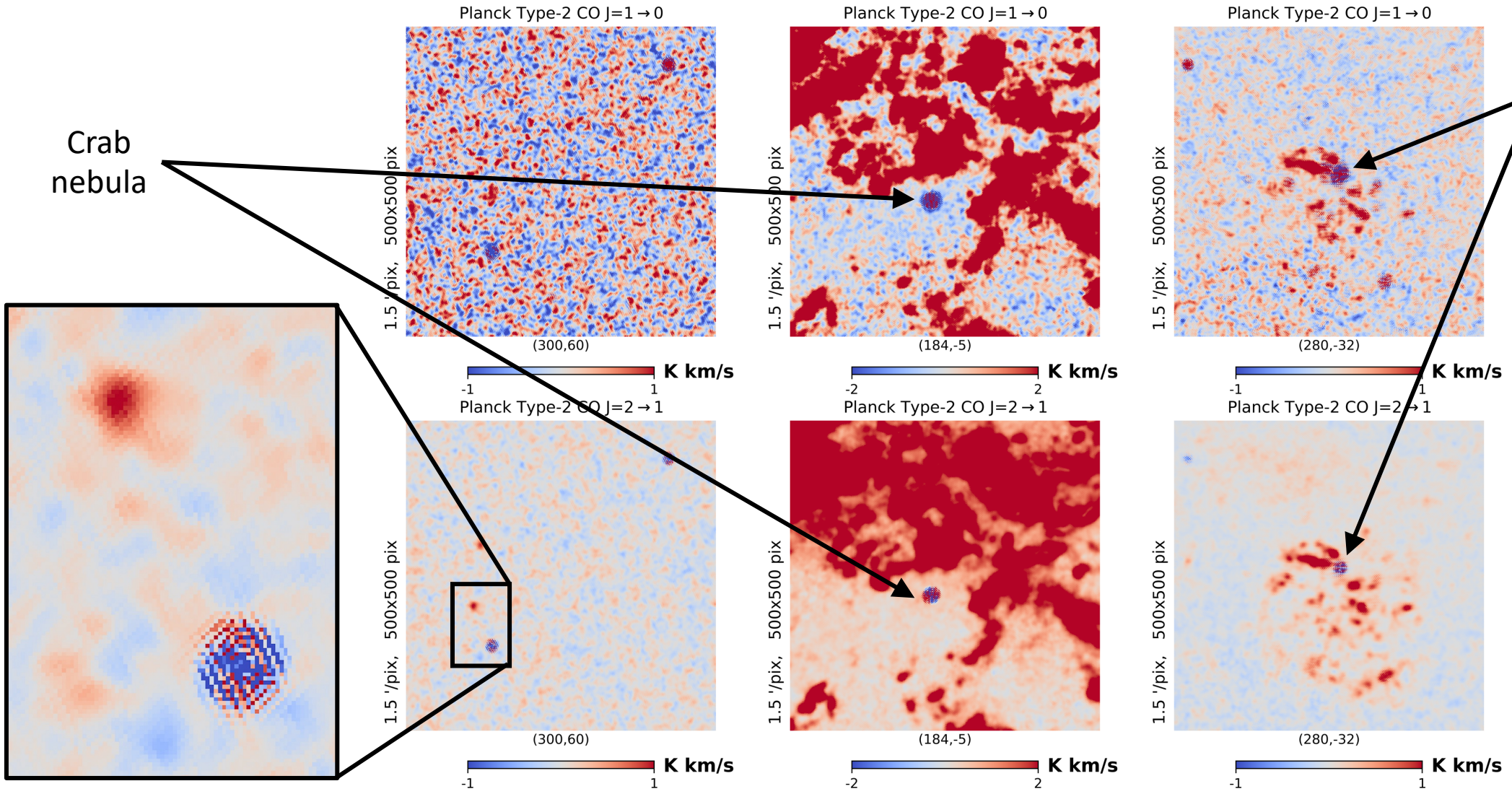


Why *revisit the CO* ???

- **Contamination by other compact sources in Type-2 maps**



Why *revisit the CO* ???



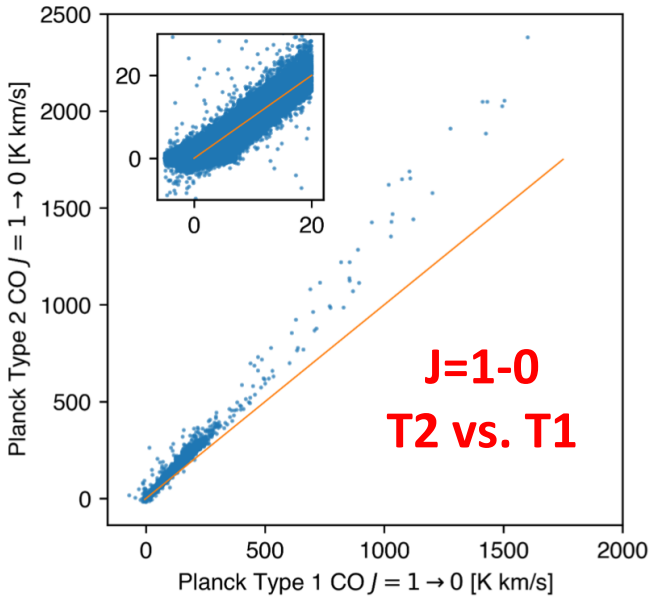
Why *revisit the CO* ???

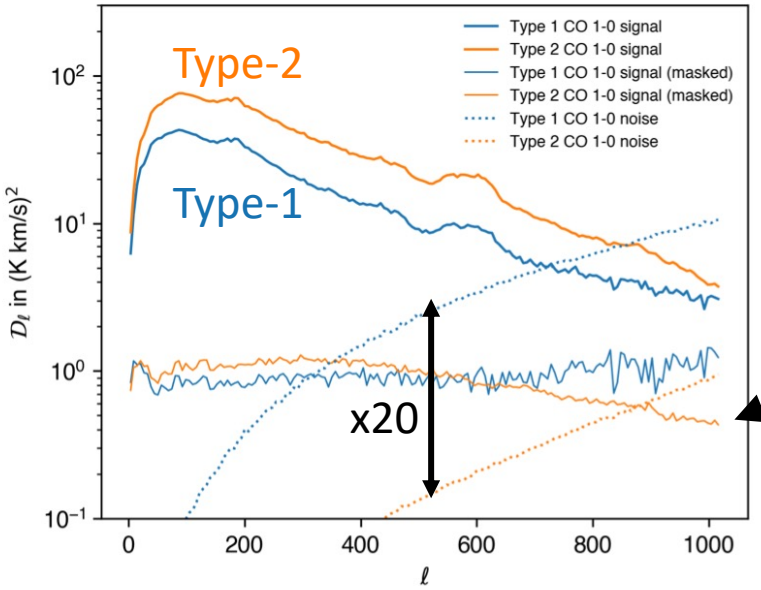
- **Type-3** (Commander)

  - Original Type 3 map at nside = 256 not available on the PLA
  - Superseded by the subsequent Commander map from *Planck Collaboration X. 2016*
  - Global multicomponent fit, 7.5' resolution, J=2-1 line only (line ratio assumed *a priori*)

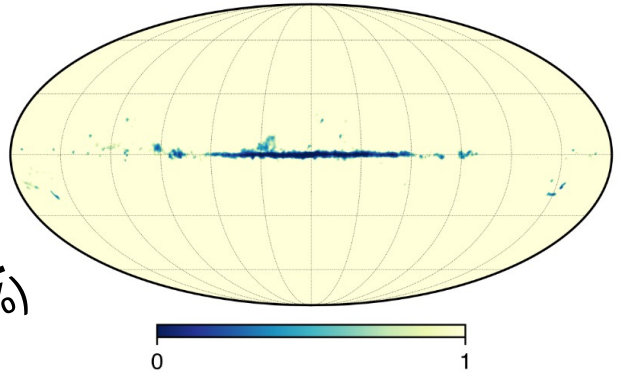
Main limitations :
- One single CO map J=2-1, fixed line ratios
- More noisy than Type-2 *and* also has residual foreground contamination

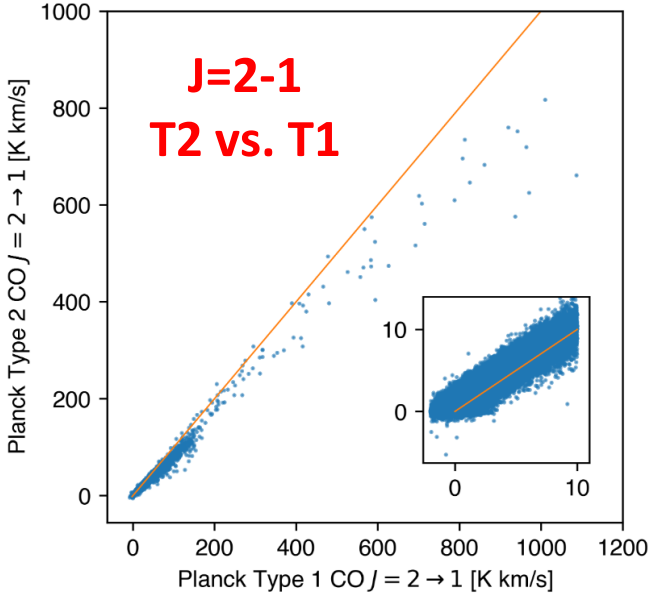
Why *revisit the CO* ???

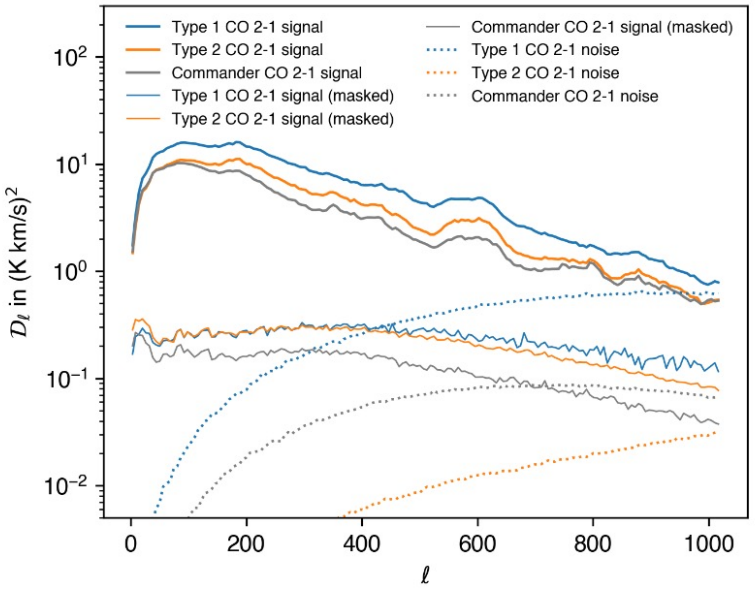




masked (2%)







Methodology

- Start from existing Planck products and post-process them to provide improved final data products
- Guidelines:
  - Trust Type 1 maps more regarding contamination and calibration (3 lines)
  - Exploit the correlation between the 3 CO lines to reduce noise
  - Also use the Type 2 maps for enhanced S/N, but
    - Avoid propagating ISM contamination and CO calibration errors when significant
    - Mask / subtract contamination from strong clusters and point sources
  - Use priors on the line ratio but only where the S/N is very low
  - Validate final products by comparison with independent observations (direct CO line from Dame et al. 2001 and 2022)

A GNILC post-processing pipeline for CO

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GNILC: Remazeilles, Delabrouille, Cardoso, 2011

Consider $x = \mathbf{A}s + n$ with know noise covariance $\mathbf{R}_n$

Then $x' = \mathbf{R}_n^{-1/2} x$ is a linear combination whitening the noise

A GNILC post-processing pipeline for CO

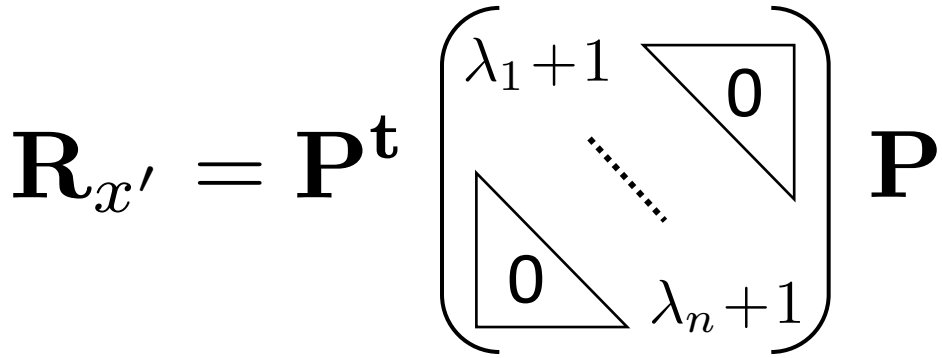
Consider $x = \mathbf{A}s + n$ with know noise covariance $\mathbf{R}_n$

Then $x' = \mathbf{R}_n^{-1/2} x$ is a linear combination whitening the noise

and $$\mathbf{R}_{x'} = [\mathbf{R}_n^{-1/2}\mathbf{A}]\,\mathbf{R}_s\,[\mathbf{A}^{\mathbf{t}}\mathbf{R}_n^{-1/2}] + \mathbf{Id}$$

Orthogonal diagonalization $$\mathbf{R}_{x'} = \mathbf{P}^{\mathbf{t}}\,[\mathbf{\Lambda} + \mathbf{Id}]\,\mathbf{P}$$

A GNILC post-processing pipeline for CO



A GNILC post-processing pipeline for CO

significant : $\lambda_i >> 1$

$$\mathbf{R}_{x'} = \mathbf{P}^{\mathbf{t}} \begin{pmatrix} \lambda_1+1 & & 0 \\ & \ddots & \\ 0 & & \lambda_n+1 \end{pmatrix} \mathbf{P}$$

negligible : $\lambda_i << 1$

Project x' on the "component subspace" spanned by the (few) eigenvectors corresponding to eigenvalues λ_i that are significant, to get an estimate $\widehat{x}'$ of x'

Get back to original space : $\widehat{x} = \mathbf{R}_n^{1/2}\, \widehat{x}'$. We are done !

A GNILC post-processing pipeline for CO

Important details

- Mask clusters and point sources in Type 2 maps and fill gaps
- Mask very strong regions of emission and fill gaps, keep the difference (reinjected in the final maps)
- Reduce artefacts by working at N_{side} = 1024 and apodised 10' beam

- We use 5 input maps (3 x Type-1 and 2 x Type-2) and work in needlet domains (localize both in harmonic and in pixel space)
- Where GNILC finds no significant component, keep one direction, set by a prior on the line ratio (i.e. the matrix A, calibrated on Dame 2001): **xGNILC**
- Filter out systematics in the J=3-2 map as a last cleaning step

Results

J=1-0 xGNILC

J=1-0 Type-1

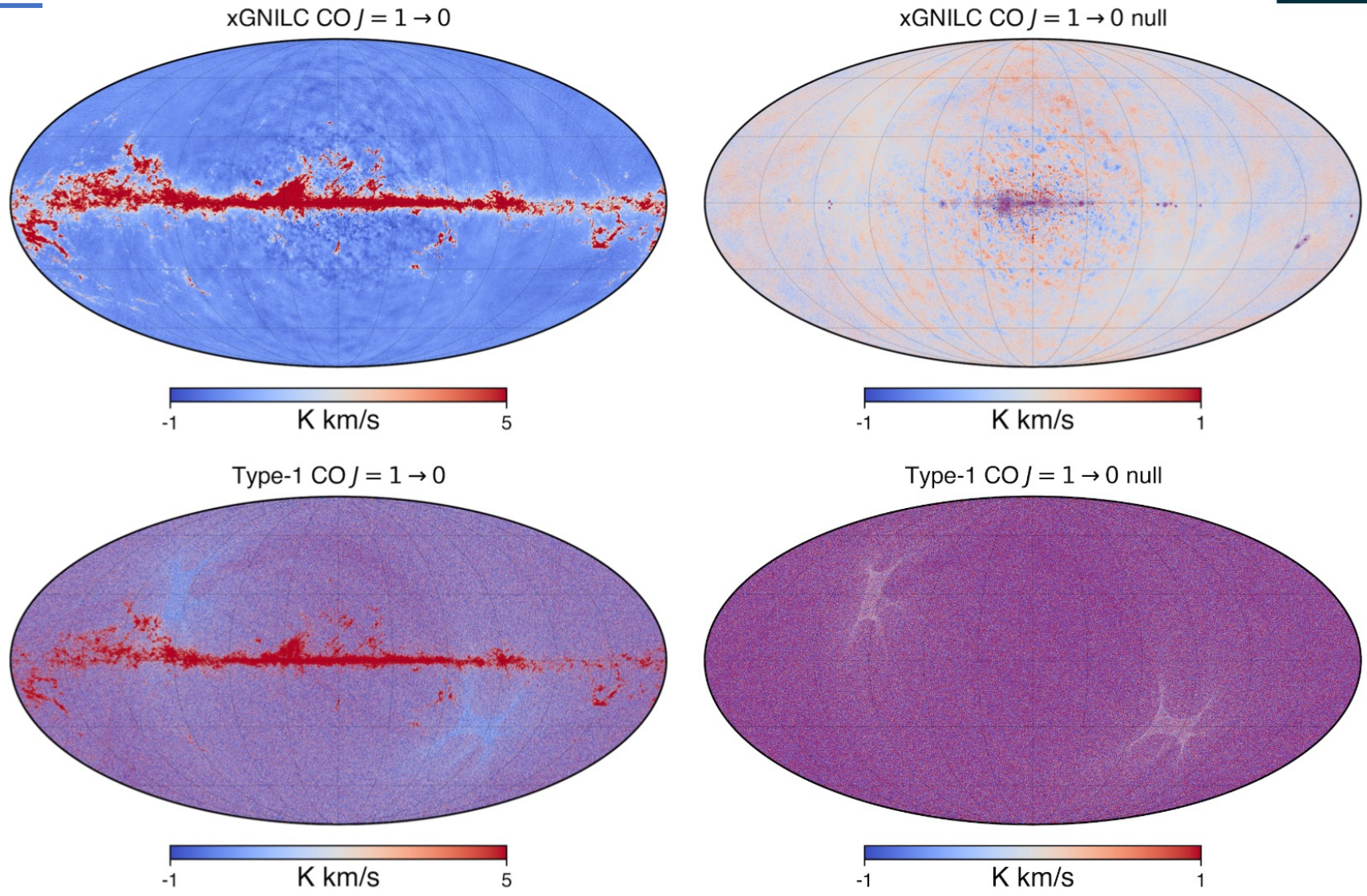
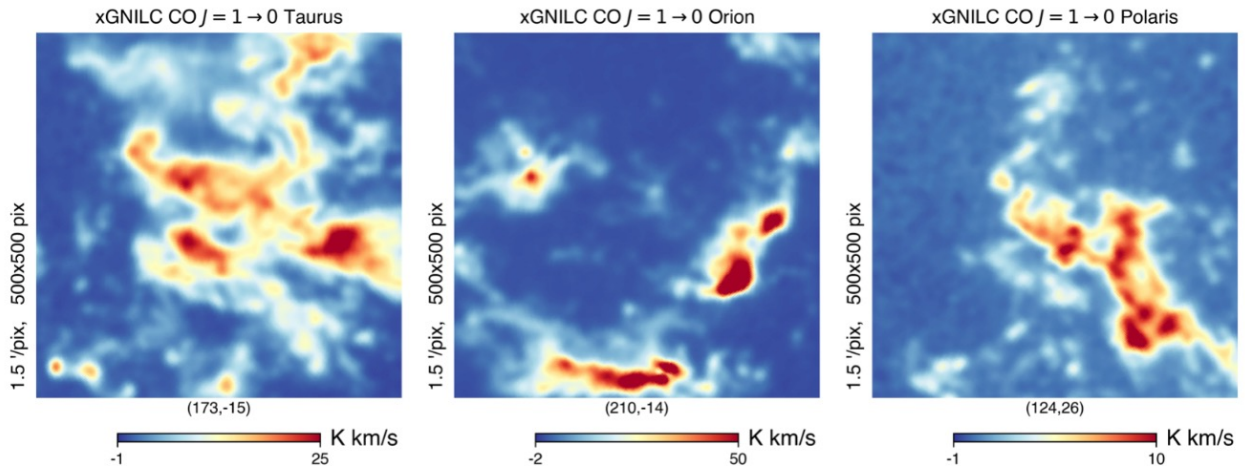


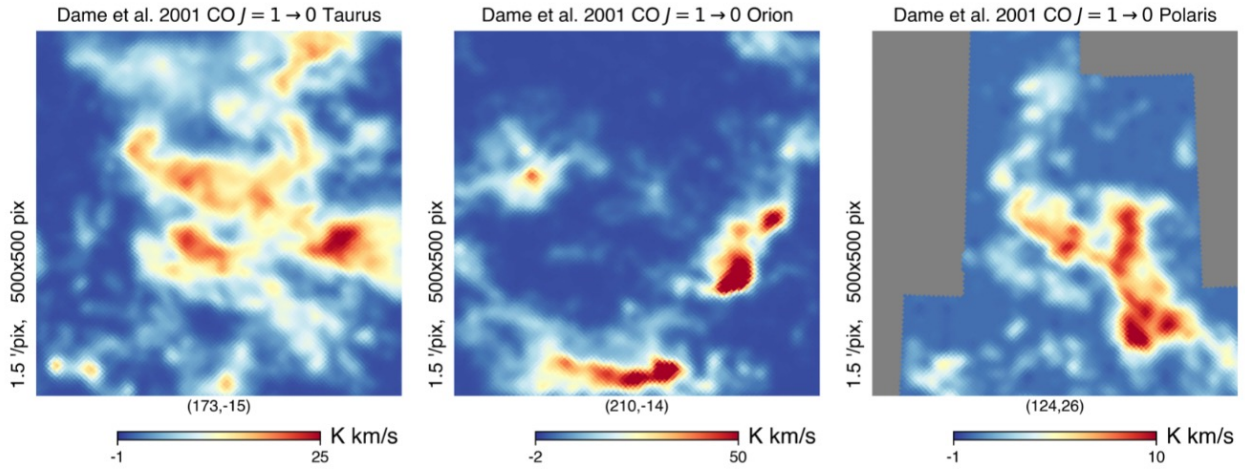
Fig. 8. Top: the xGNILC CO $J = 1 \rightarrow 0$ map, at output resolution of 10′, and the corresponding jackknife noise map. Bottom: Similar maps for the Planck Type 1 CO $J = 1 \rightarrow 0$ data product, and the jackknife noise of the Planck Type 1 CO $J = 1 \rightarrow 0$ map, both smoothed to 10′ resolution.

Results

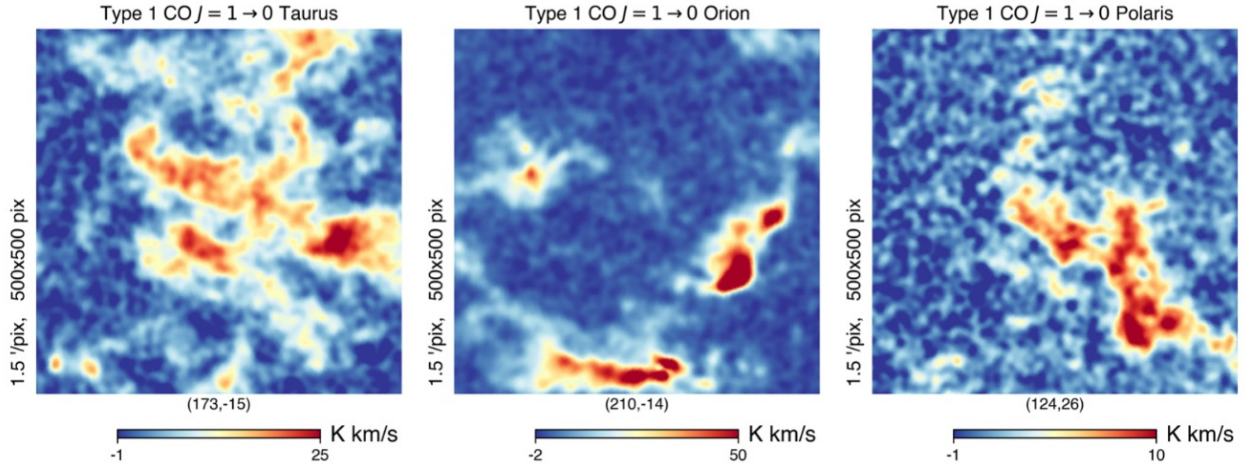
J=1-0
xGNILC



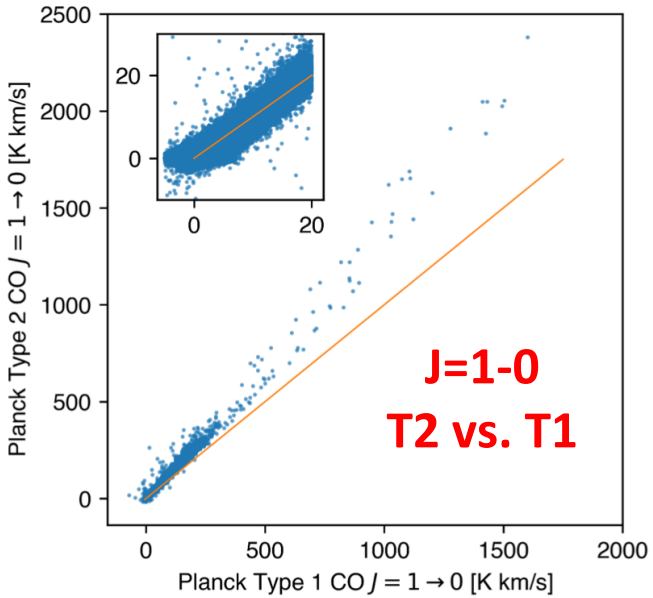
J=1-0
Dame et al. 2001

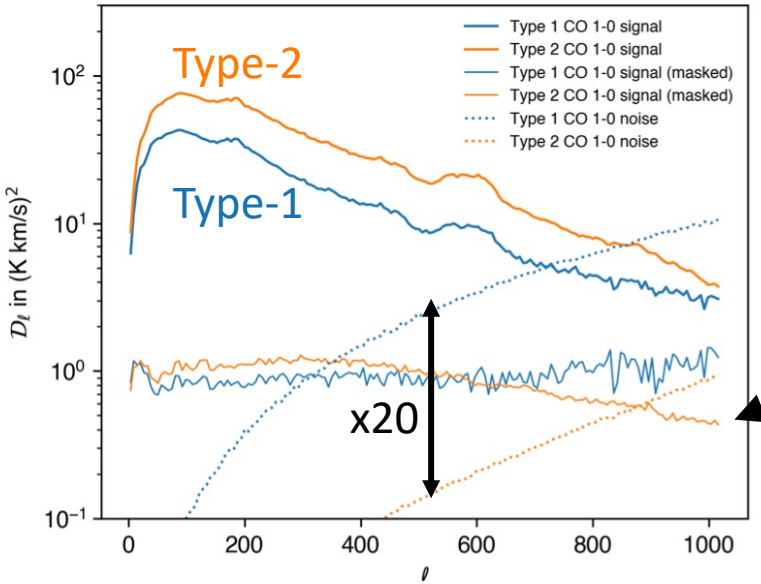


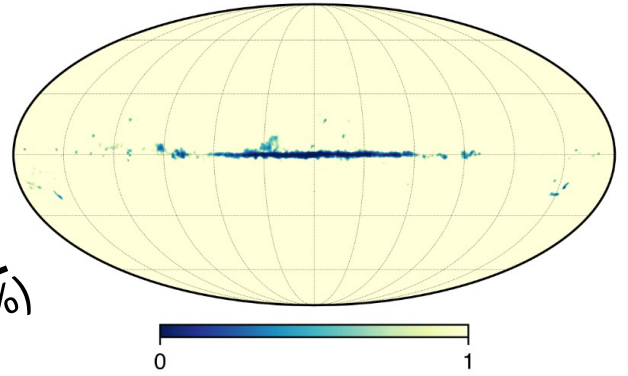
J=1-0
Type-1

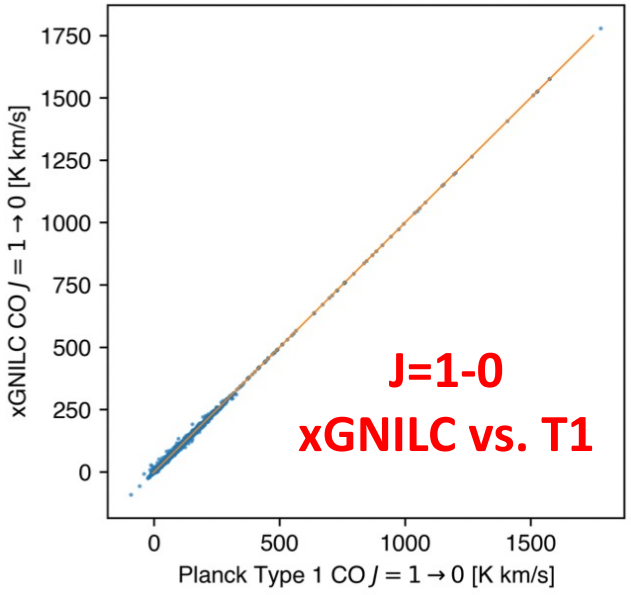


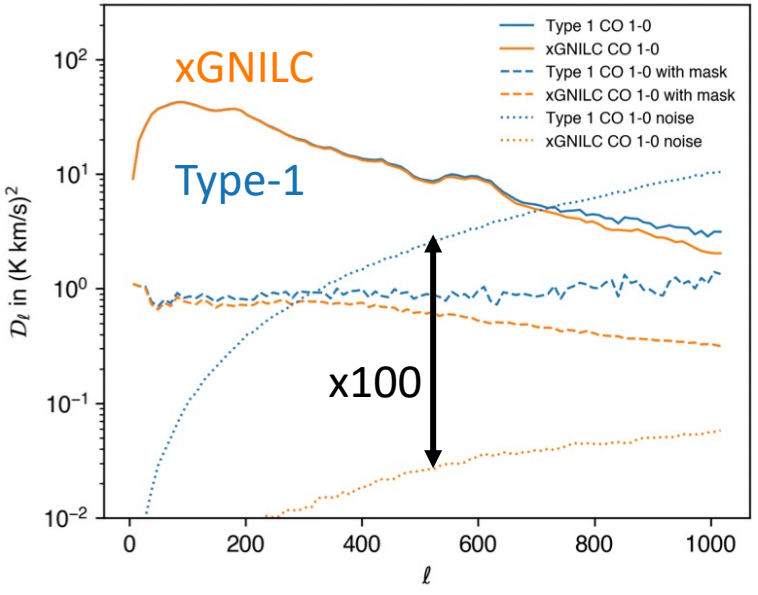
Comparison with Type-1 for J=1-0





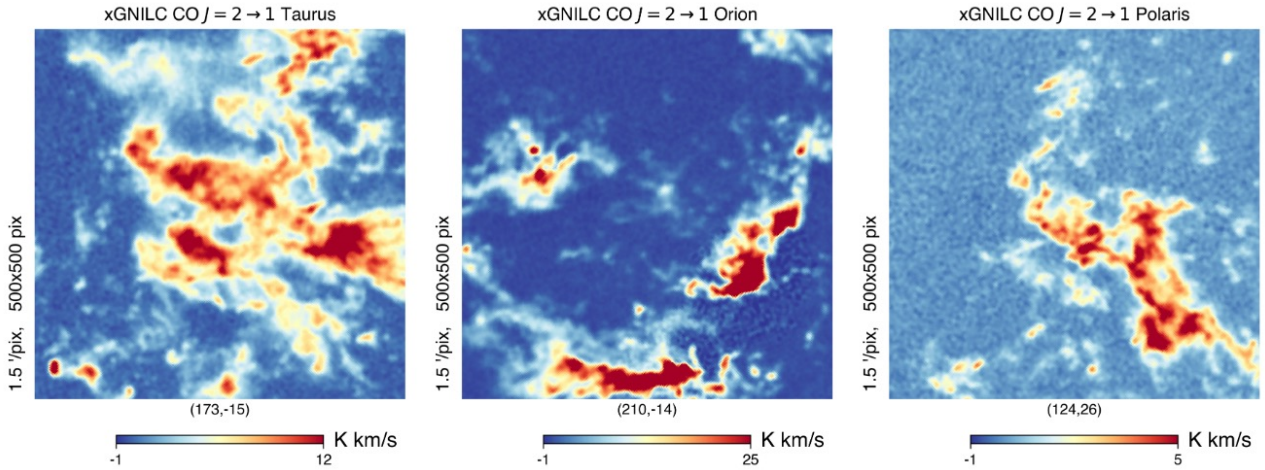




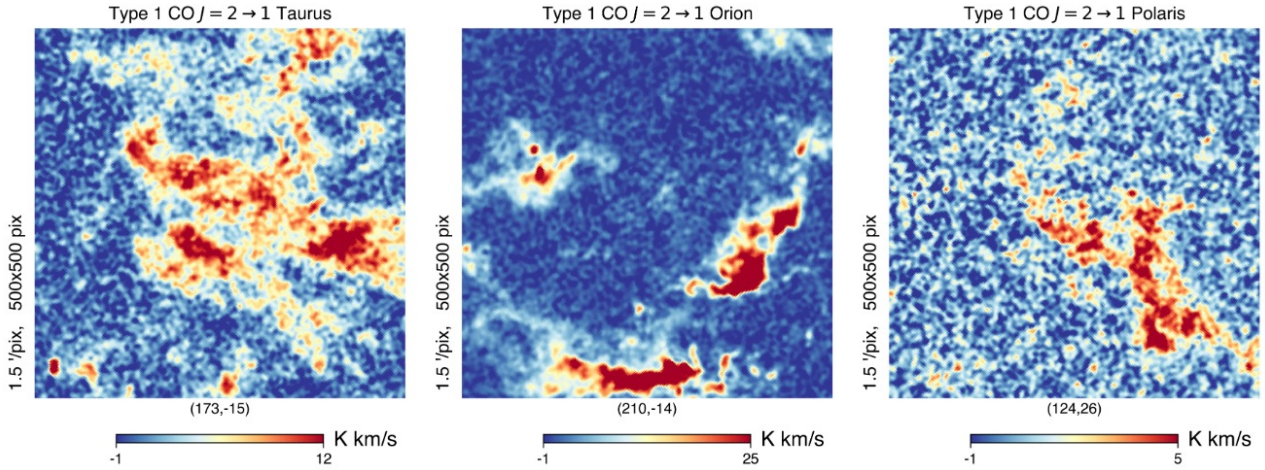


Results

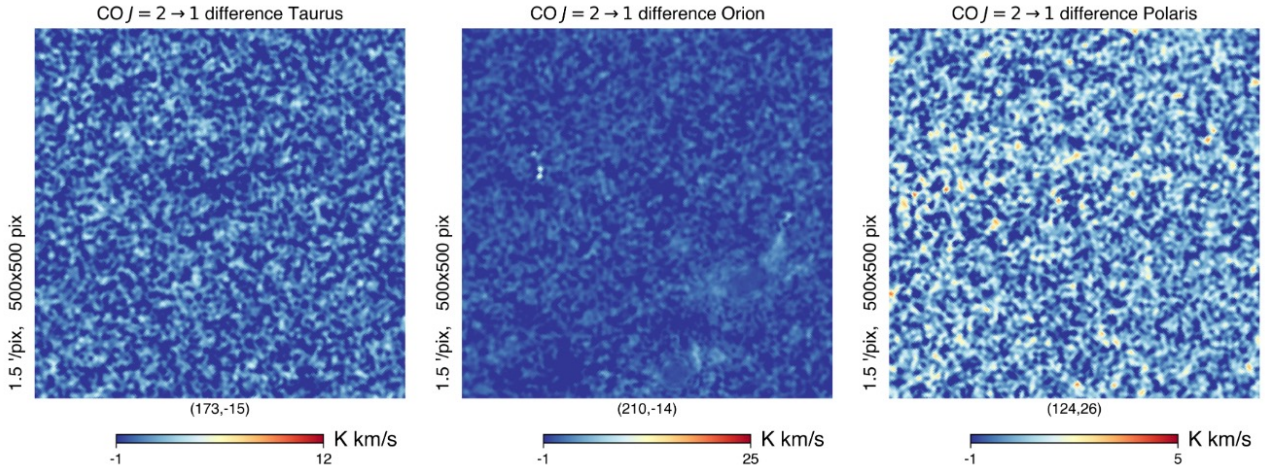
J=2-1 xGNILC



J=2-1 Type-1

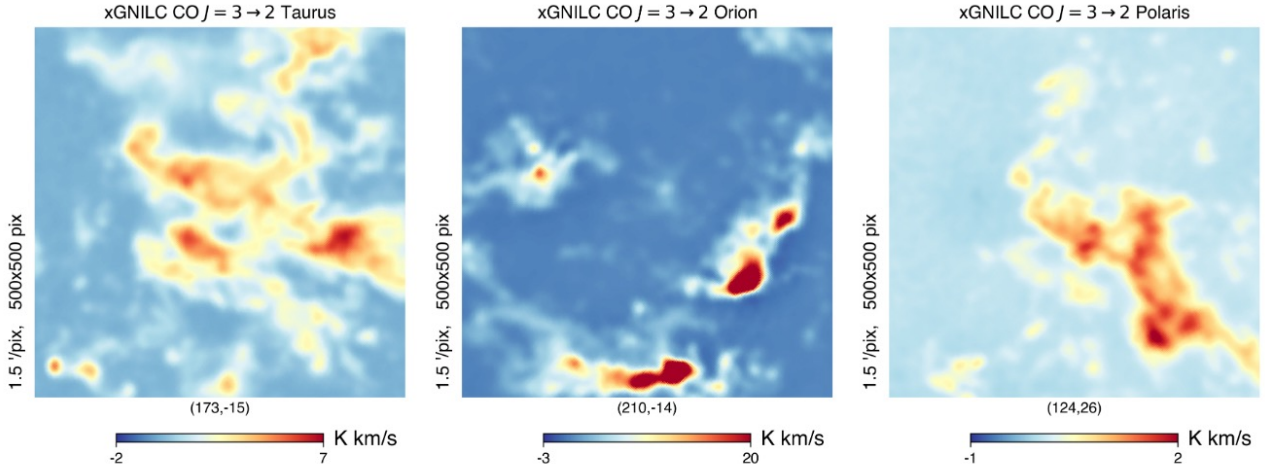


Difference Type-1 - xGNILC

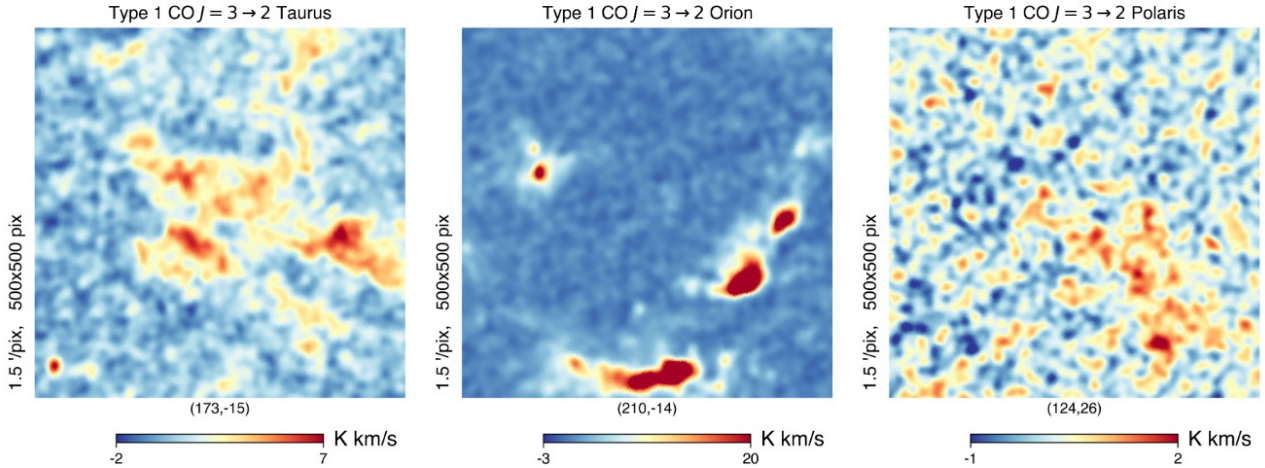


Results

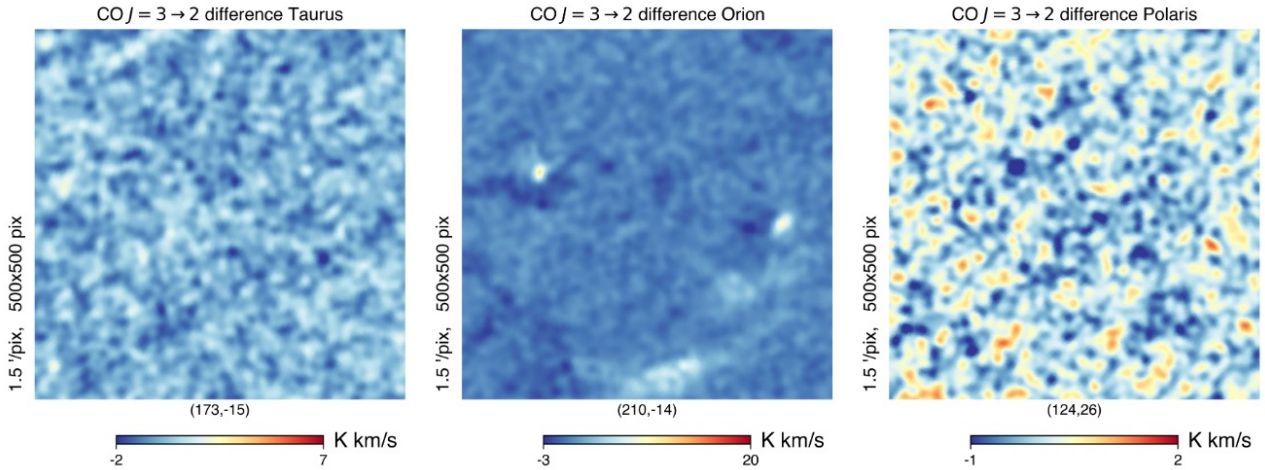
J=3-2 xGNILC



J=3-2 Type-1



Difference Type-1 - xGNILC

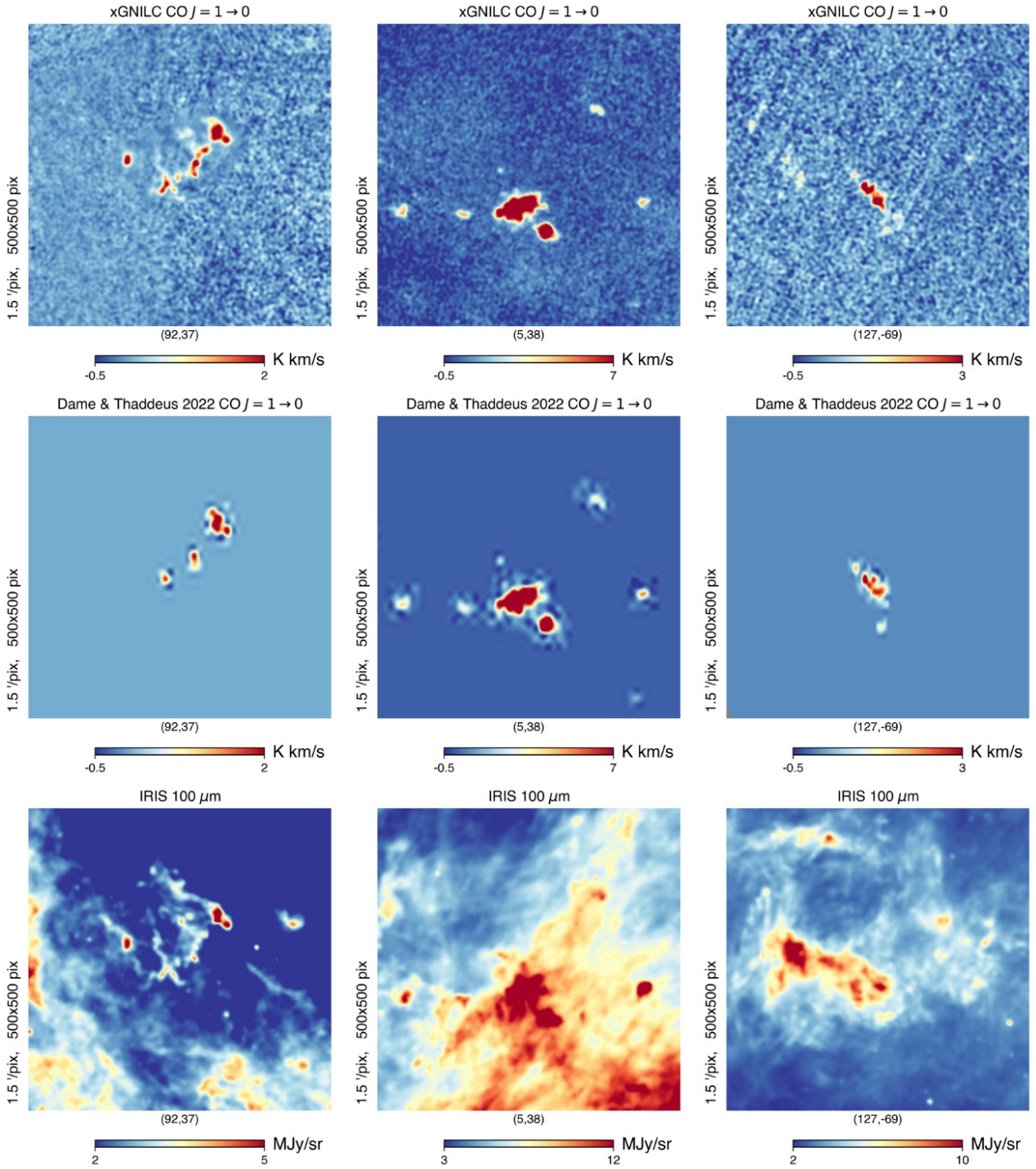


Results

J=1-0 xGNILC

Dame et al 2022

IRAS (IRIS)



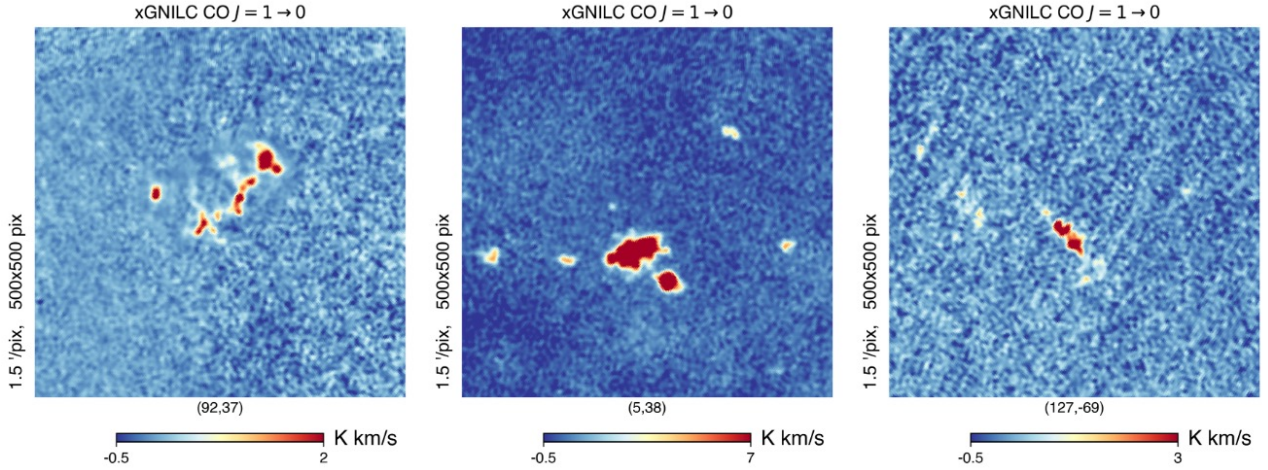
Clear detection of high galactic latitude clouds

Confirmed by comparison with Dame+ 2022

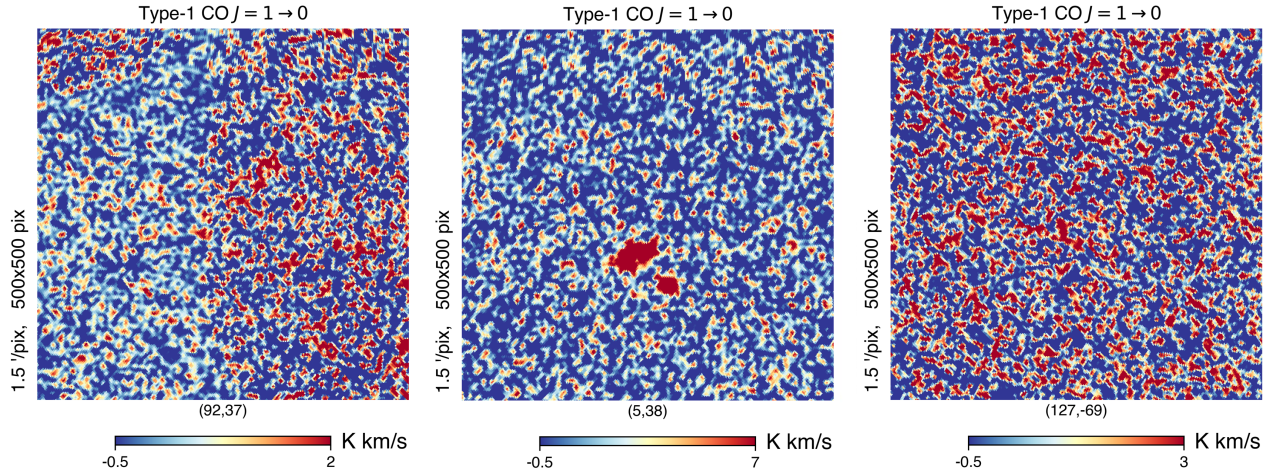
Do not seem to be due to confusion with dust

Results

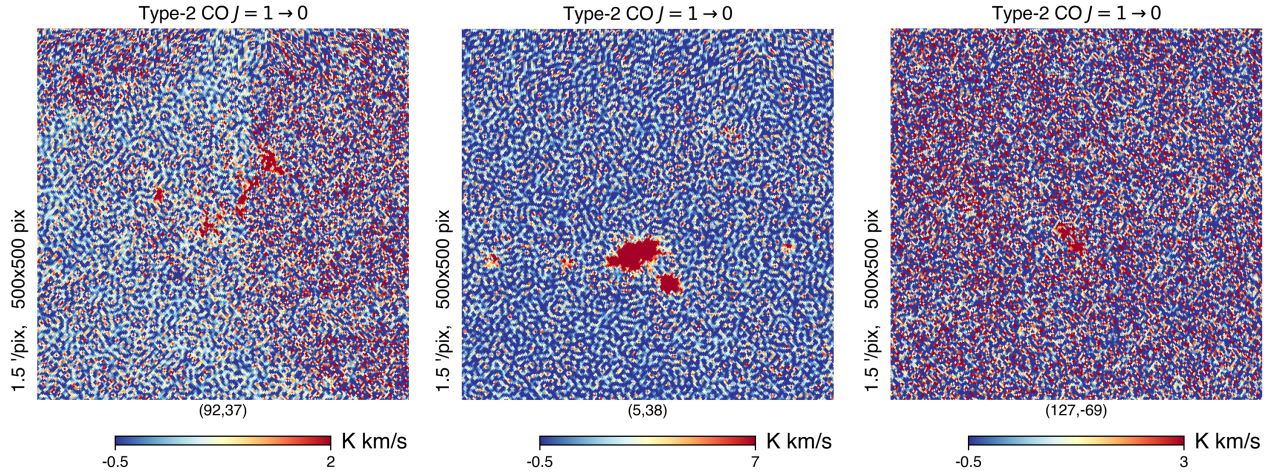
J=1-0
xGNILC



J=1-0
Type-1



J=1-0
Type-2



Clear detection of high galactic latitude clouds

Confirmed by comparison with Dame+ 2022

Do not seem to be due to confusion with dust

Some faint clouds are real and hard to see in the original Planck maps.

Summary

New low-noise, low contamination CO maps from Planck

- Publication ready, to be posted on arXiv and submitted to A&A in the coming days (probably this week)
- Data will be available online (PLA and/or NERSC and/or LAMBDA)
- Implementation of new CO models in PSM and PySM scheduled for next releases