NIKA2 maps tracing dust grain evolution in cores of nearby filaments

Carsten Kramer

IRAM/Grenoble

on behalf of the GEMS 30m Large Program team
and the NIKA2 collaboration

Outline

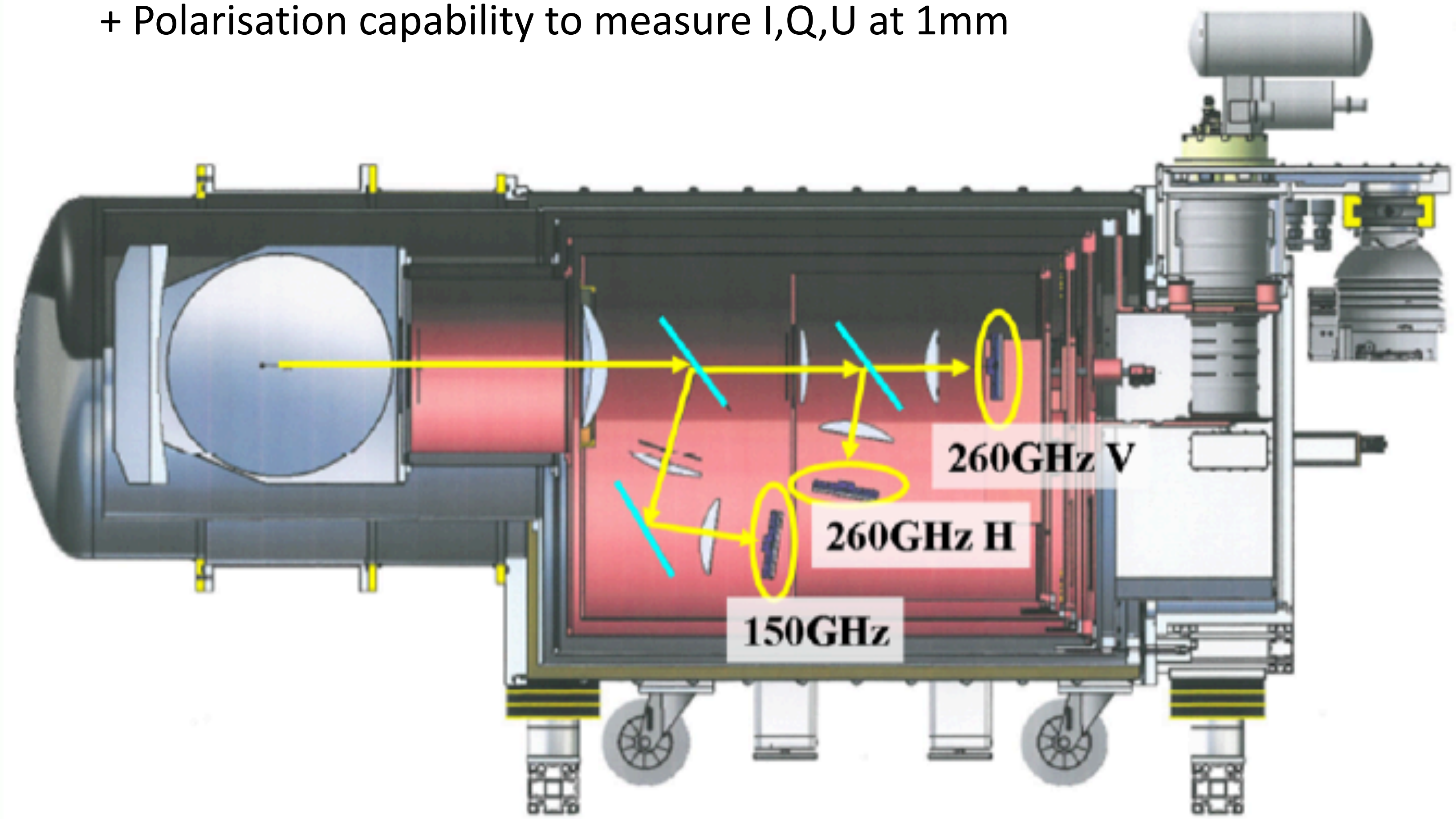
- NIKA2 / IRAM 30-meter telescope
- Starless cores
- **Taurus Molecular Cloud 1 (TMC1)**
  - 1mm/2mm ratio map
  - Beyond Rayleigh Jeans
  - Herschel Gould Belt Survey in Taurus: Av, T_{dust} (Kirk et al. 2024)
  - **Map of dust index $\beta_{1,2}(R_{1,2}, T_d)$**
- Analysis
  - Dust properties
  - **Models of dust opacities** (here: Ossenkopf & Henning 1994)
  - β statistics and possible interpretation
- First results

NIKA2
A continuum camera at the IRAM 30-m telescope

Band	Number of KIDs	Wavelength	Bandwidth	NEFD	HPBW	FoV
NIKA2 2 mm/150 GHz	616	2.00 mm	125-170 GHz	9 ± 1 mJy*s$^{1/2}$	17.6"	6.5'
NIKA2 1 mm/260 GHz	2x1140	1.15 mm	240-280 GHz	30 ± 3 mJy*s$^{1/2}$	11.1"	6.5'

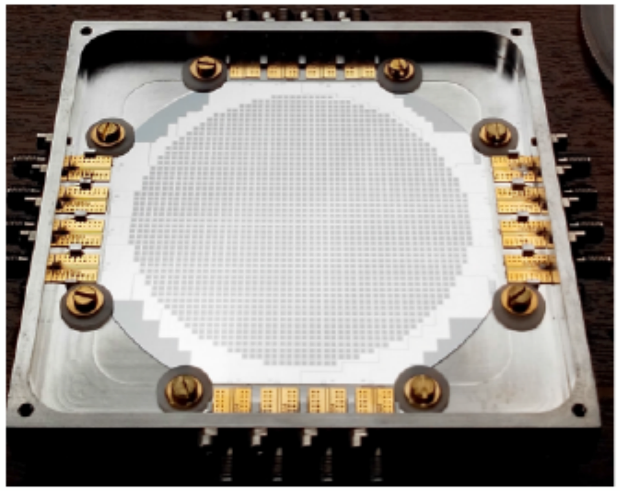
Comments: The half-power beam widths and the NEFDs are taken from Perotto et al. 2020. The NEFDs are extrapolated to a sky opacity of 0 and 90 deg. elevation.

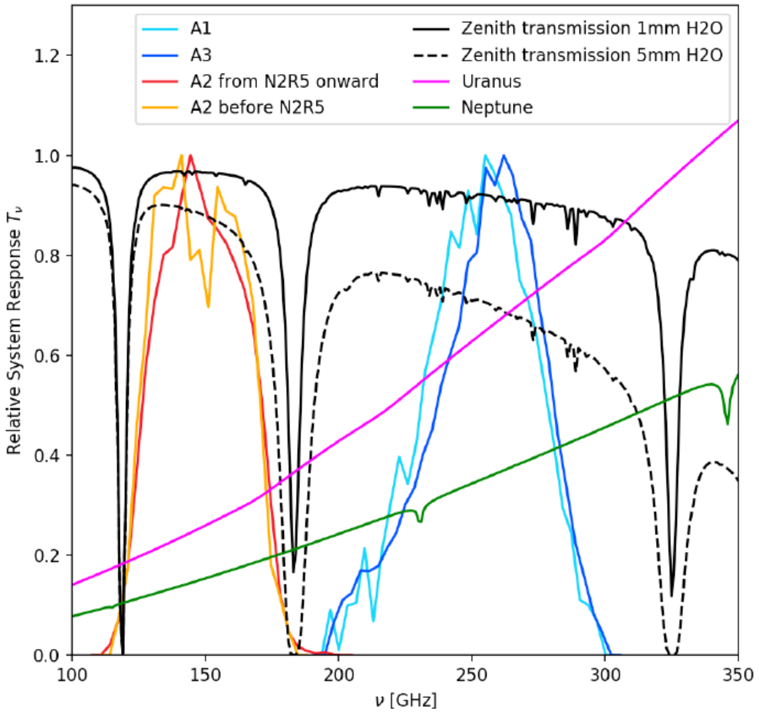
+ Polarisation capability to measure I,Q,U at 1mm



NIKA2 LEKID ARRAY
~ thousands of pixels

at 150mK





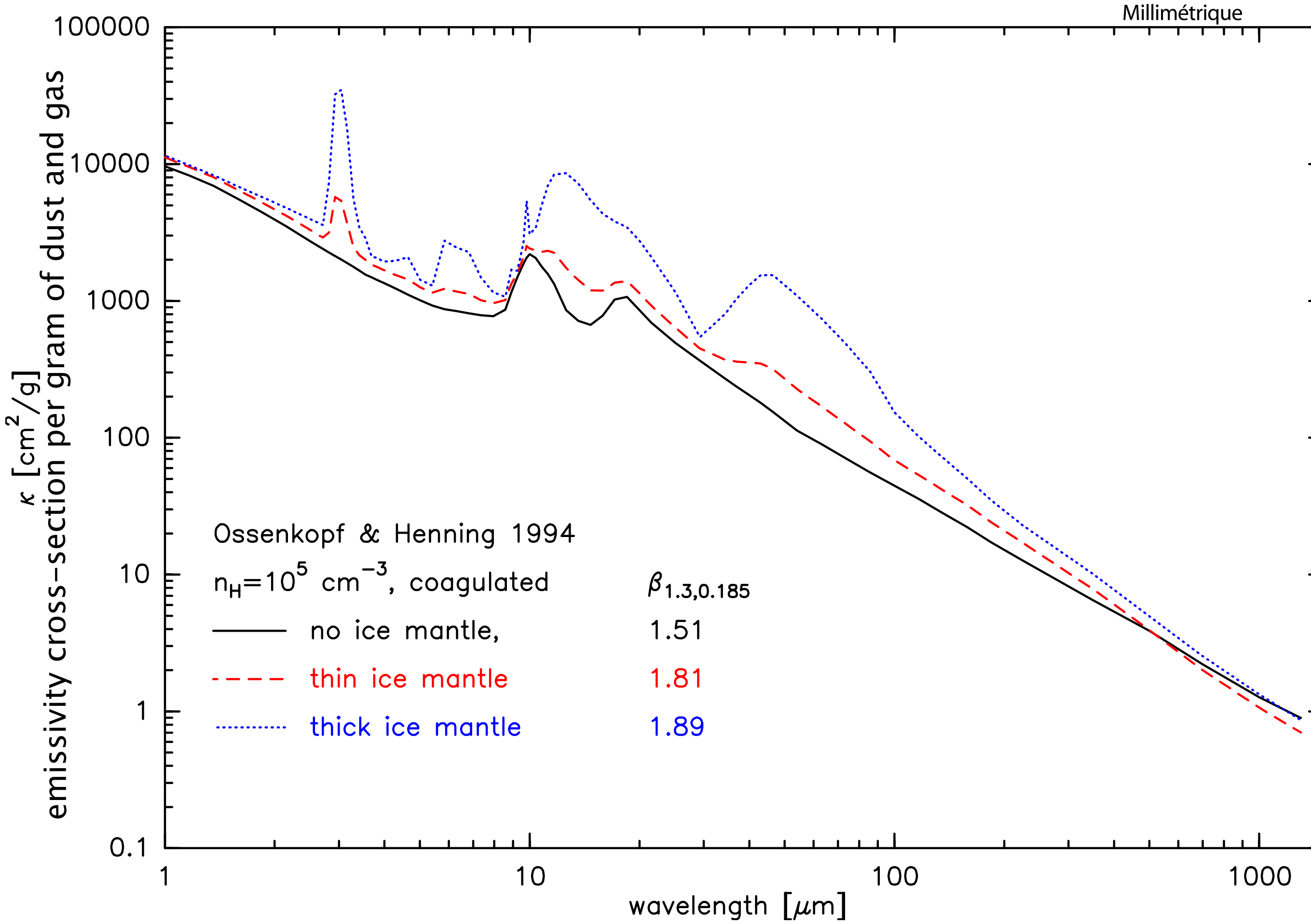
+ Offered to the community since October 2017
+ Upgrade of 30m drive system and surface paint in 2023/2024
+ Upgrade of NIKA2 in 3/2025: new 1mm arrays, new dichroic, …
+ https://publicwiki.iram.es/Continuum/NIKA2/Main

Starless cores

- Starless cores allow to study the **initial phases of star formation**: no shocks or outflows, no internal heating source, shielding from FUV (A_v > 10mag), low temperatures ($T_d <$ 20K), dense n>10^4cm^{-3}, self-gravitating.

- Why studying starless cores ?
  - influence of environment
  - turbulence, ionization fraction
  - gas elemental abundances, depletions
  - dust grain chemistry
  - magnetic fields
  - **grain coagulation and formation of ice mantles from gas depletion**

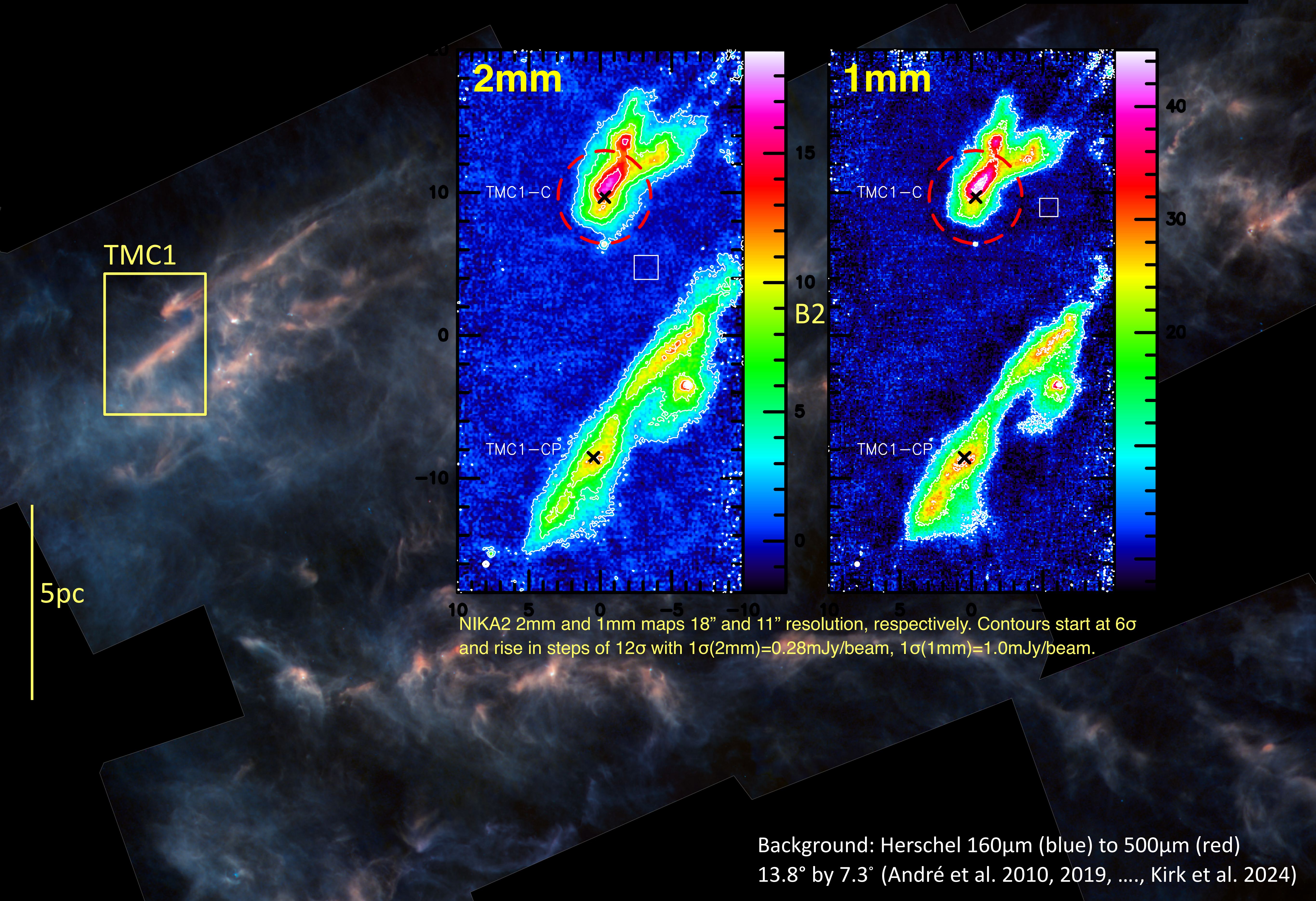
- Here: NIKA2 observations following-up on EMIR Large Program on gas phase molecular abundances in starless cores (GEMS) by Asuncion Fuente et al..
- This presentation: Taurus Molecular Cloud 1 (TMC1) at 135pc distance (12", 1620au, 0.008pc).



Models of dust opacity spectra (Ossenkopf & Henning 1994) for coagulated grains and a gas density of 10^5 cm^{-3} in proto-stellar cores, **varying the ice thickness** (cf. e.g. Ormel et al. 2011). The **mm-slope**, i.e. **Beta, changes with grain properties,** increasing with ice thickness.

Most molecules freeze-out onto dust grains in the central part of dense cores with A_v>10mag (CO-depletion: Kramer et al. 1999; Caselli et al. 1999; Nagy, Spezzano, Caselli et al. 2019).

TMC1: NIKA2 maps and Herschel Gould Belt Survey



NIKA2 2mm and 1mm maps 18” and 11” resolution, respectively. Contours start at 6σ and rise in steps of 12σ with 1σ(2mm)=0.28mJy/beam, 1σ(1mm)=1.0mJy/beam.

Background: Herschel 160µm (blue) to 500µm (red)
13.8˚ by 7.3˚ (André et al. 2010, 2019, …., Kirk et al. 2024)

β - the dust emissivity index

$$I_\nu = \tau_\nu B_\nu(T_\mathrm{d}) = \kappa_\nu \Sigma B_\nu(T_\mathrm{d}) \qquad \kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta$$

- T_d, β are weighted averages along the line of sight.

with the emissivity cross-section per gram of dust and gas and the gas surface density.

- Convolve 1mm map to 18” resolution using Gaussian kernel. Create maps of $R_{1,2}$ at 18” resolution. To first order, in the Rayleigh-Jeans limit, hν<<kT, the NIKA-2 1mm/2mm flux ratio $R_{1,2}$ is solely a function of β, the dust emissivity index.

$$\beta_\mathrm{RJ} = \frac{\log R_{1,2}}{\log\left(\nu_{1\ \mathrm{mm}}/\nu_{2\ \mathrm{mm}}\right)} - 2$$

Here, the 1mm/2mm ratio is a rather robust quantity, as observations are done simultaneously, i.e. with the same instrument under the same conditions.

β - the dust emissivity index

$$I_\nu = \tau_\nu B_\nu(T_\mathrm{d}) = \kappa_\nu \Sigma B_\nu(T_\mathrm{d}) \qquad \kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta$$

- T_d, β are weighted averages along the line of sight.

- Convolve 1mm map to 18” resolution using Gaussian kernel. Create maps of $R_{1,2}$ at 18” resolution. To first order, in the Rayleigh-Jeans limit, hν<<kT, the NIKA-2 1mm/2mm flux ratio $R_{1,2}$ is solely a function of β, the dust emissivity index.

$$\beta_\mathrm{RJ} = \frac{\log R_{1,2}}{\log\left(\nu_{1\ \mathrm{mm}}/\nu_{2\ \mathrm{mm}}\right)} - 2$$

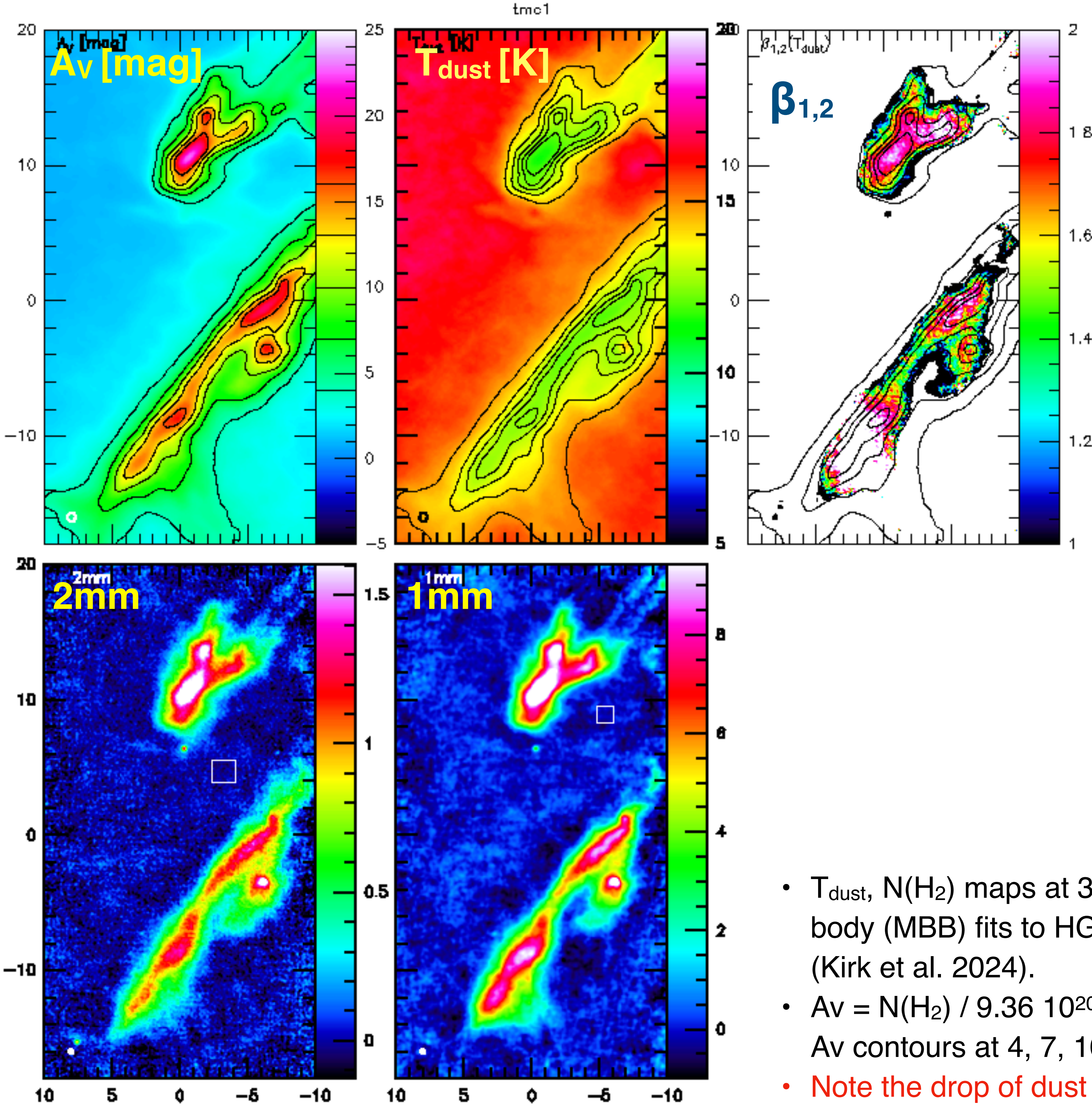
  Here, the 1mm/2mm ratio is a rather robust quantity, as observations are done simultaneously under the same conditions with the same instrument and through the same atmosphere.

- However, at the low temperatures of pre-stellar cores of ~10K, the RJ limit doesn’t hold and the flux ratio is a **function of β and also of the dust temperature T_d** :

$$\boxed{R_{1,2} = \frac{B_{\nu_{1.2mm}}[T_d]}{B_{\nu_{2.0mm}}[T_d]} \left(\frac{\nu_{1.2mm}}{\nu_{2.0mm}}\right)^\beta}$$

- Here, dust temperatures were estimated from fits of modified black-bodies to PACS/SPIRE Herschel 160, 250, 350, 500μm data from the Herschel Gould Belt Survey (HGBS, André et al. 2010; Kirk et al. 2024).

  This allows to create maps of $\beta_{1,2}$ at 18” resolution.



TMC1 region

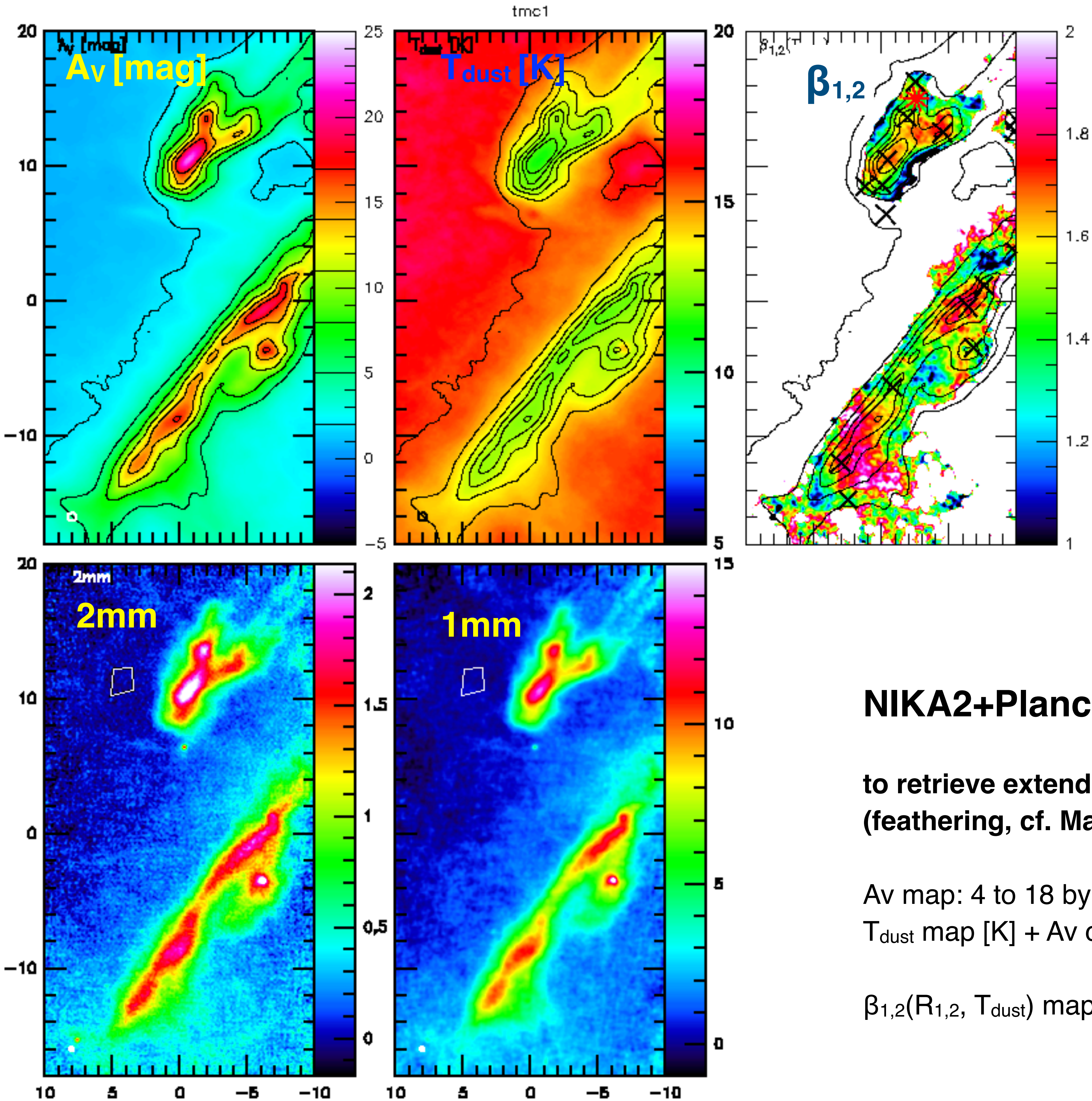
NIKA2 2mm map [MJy/sr]
NIKA2 1mm map [MJy/sr]

Av map: 4, 7, 10, … mag
T_{dust} map [K] + Av contours

$\beta_{1,2}(R_{1,2}, T_{dust})$ map + Av contours

Crosses: HGBS cores
(unbound, starless)

- T_{dust}, $N(H_2)$ maps at 36” resolution. From modified black body (MBB) fits to HGBS Herschel data with beta = 2 fixed (Kirk et al. 2024).
- Av = $N(H_2)$ / 9.36 10^{20} (Bohlin, Savage, Drake 1978)
  Av contours at 4, 7, 10, 13, 16mag.
- Note the drop of dust temperatures in the dense interiors of the filaments and cores from ~14K to 11-12K (averaged along the lines of sight).



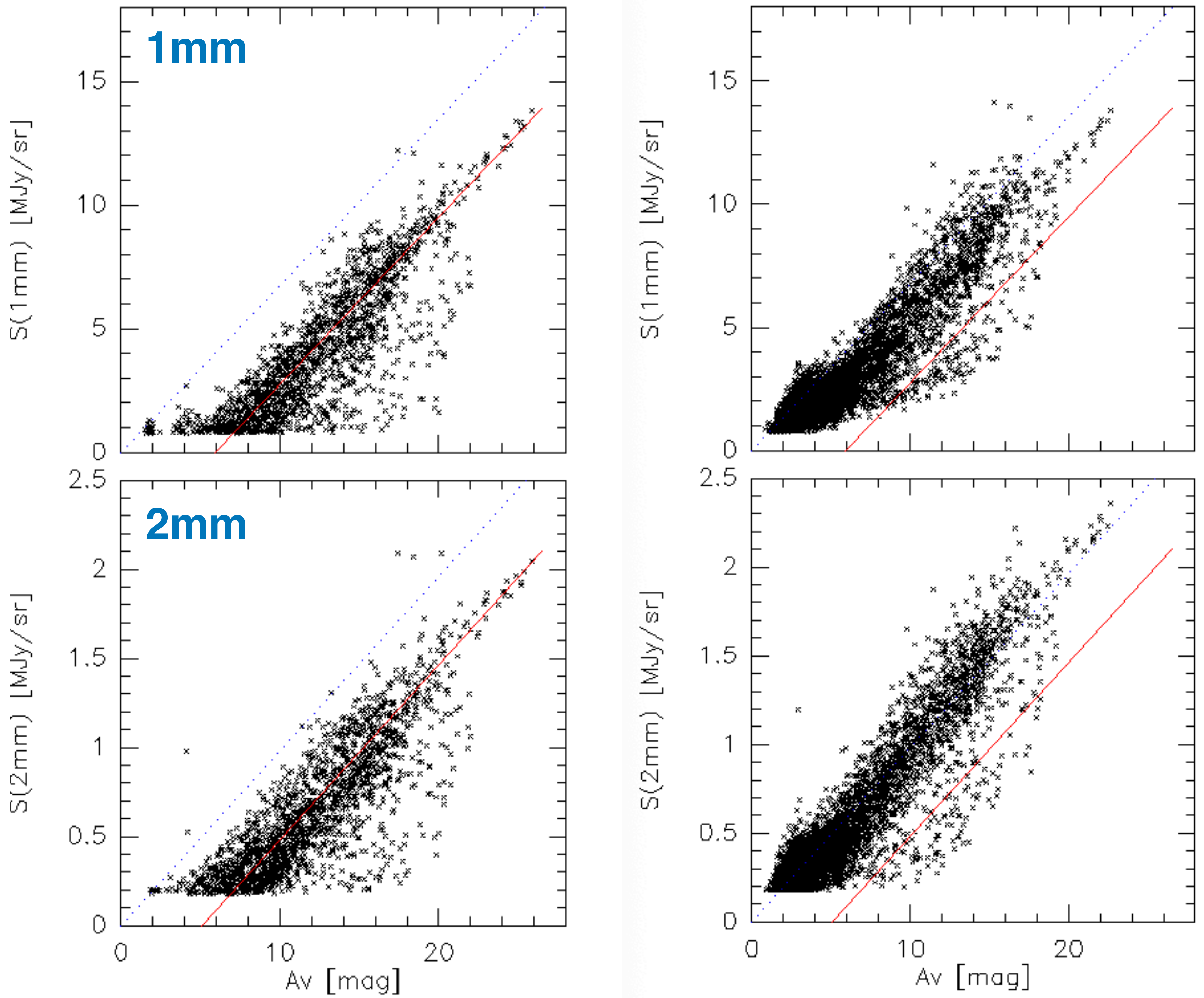
NIKA2+Planck maps

to retrieve extended emission missed by NIKA2 (feathering, cf. Matt Smith et al. 2021)

Av map: 4 to 18 by 3 mag
T_{dust} map [K] + Av contours

$\beta_{1,2}(R_{1,2}, T_{dust})$ map + Av contours

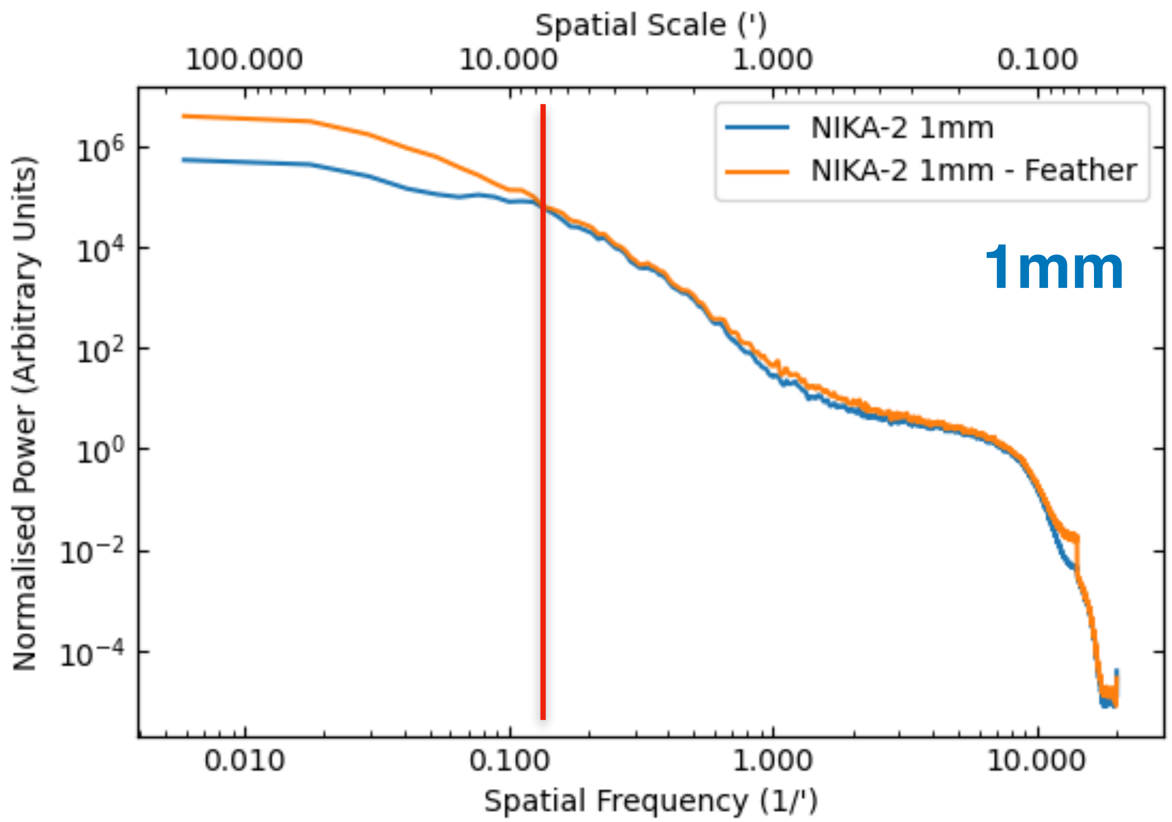
Retrieving the extended emission

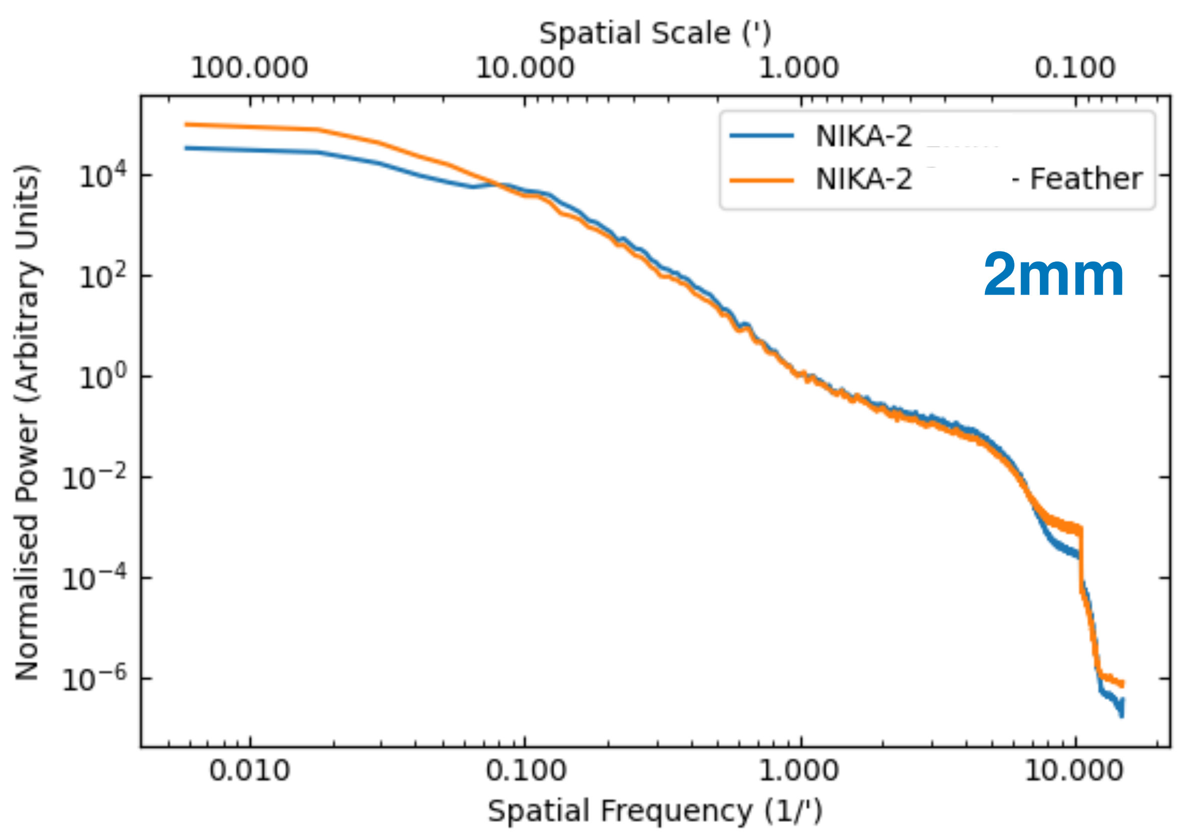


Flux of original NIKA2 maps vs. Av

feathered maps combining NIKA2 and Planck (cf. Matt Smith et al. 2021)

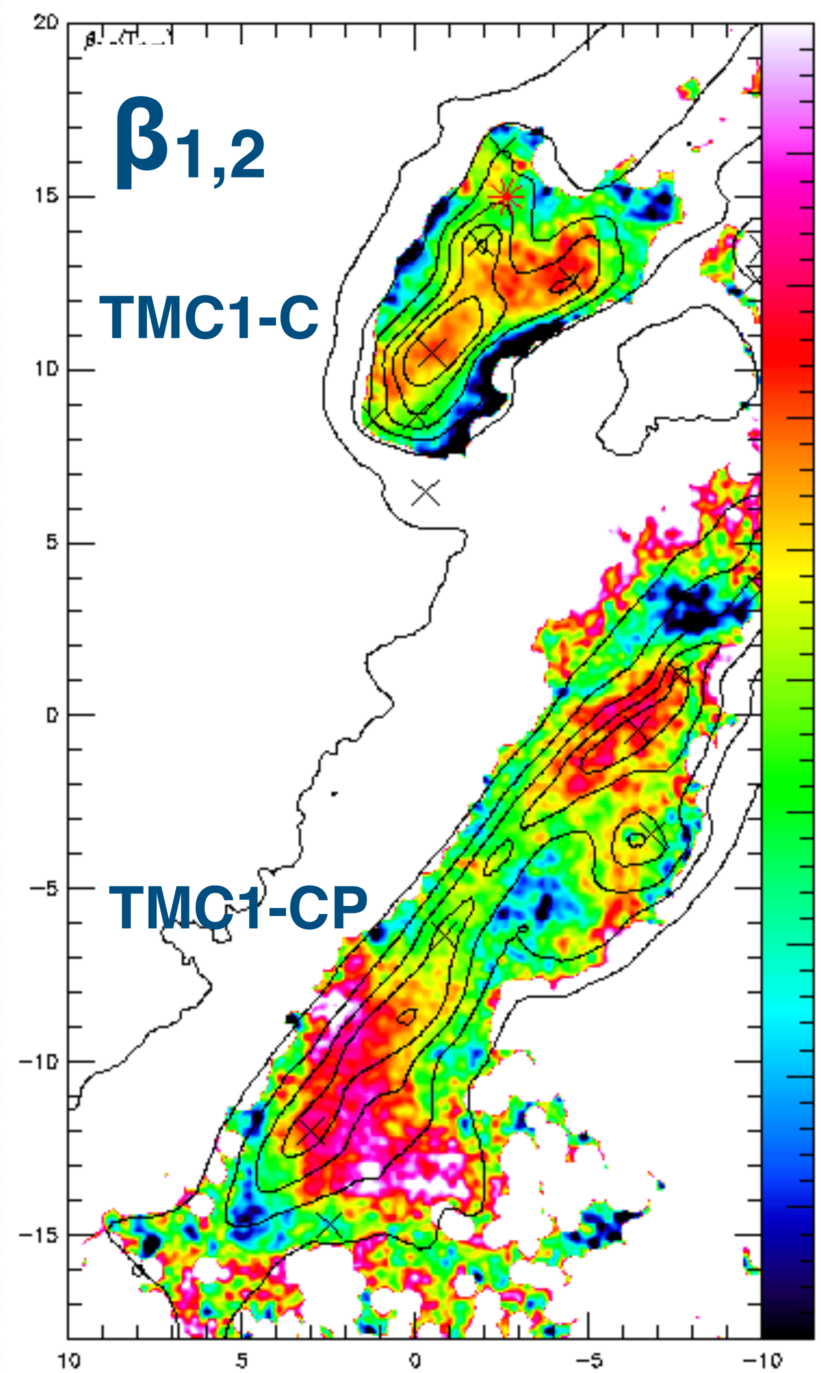
Retrieving the extended emission



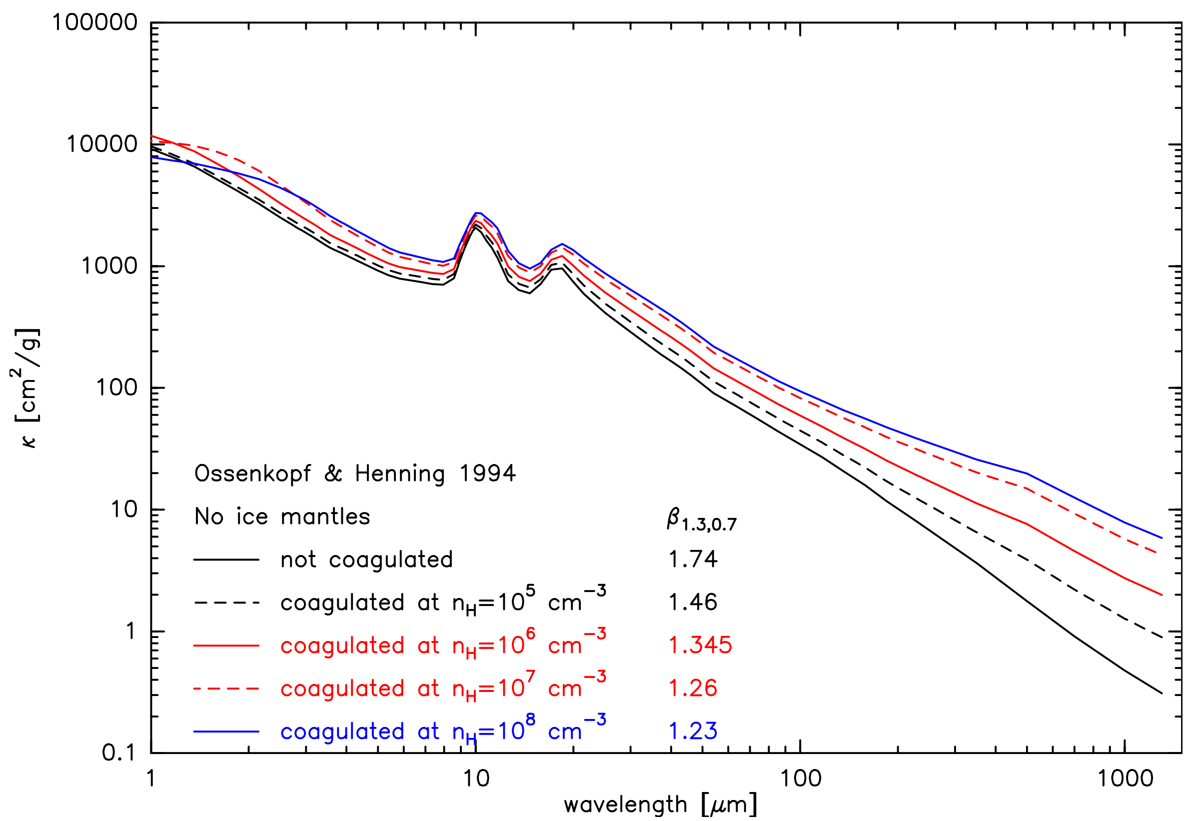


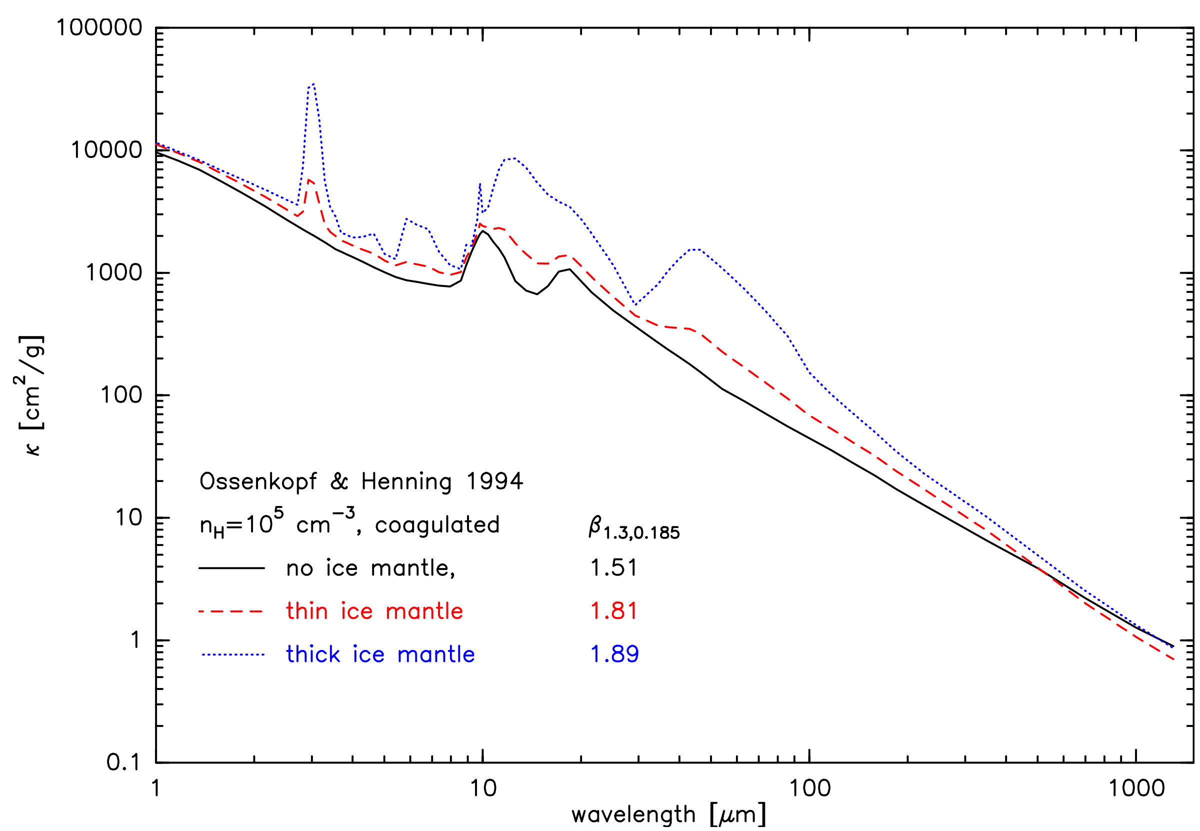
NIKA2 power spectra
before and
after feathering with Planck data
(cf. Matt Smith et al. 2021)

Map of dust emissivity index in TMC1



After feathering, β is often high in the core centers, increasing **from β~1.4 in the outskirts at Av~7mag to β~1.8 at Av~18mag**.





No ice mantles:

long wavelength slope flattens with **density** (and grain size).

However, we observe the slope to steepen with Av and density, i.e. β to rise.

Ice mantles:

β increases with **thickness of ice layer**.

This interpretation is consistent with observations in TMC1-C.

Cores in Taurus: First results (1)

Literature for Taurus & Perseus:

β=1.2-1.9±0.1 NGC1333-C7 by Navarro-Almaida et al. 2022 (MUSTANG-2, SCUBA, SPIRE/PACS)
β=2.1±0.1 TMC1-C also by Navarro-Almaida et al. 2022
β=2.0±0.5 B10 covering B213-C6 by Scibelli et al. 2023 (NIKA2)
β=2.4±0.3 B213 by Bracco et al. 2017 (NIKA)
β=1.6-2.0±0.4 L1544 by Chacon-Tanarro et al. 2019 (MUSTANG-2, AzTEC) [cf. 2017 paper with NIKA]

- Results obtained here:
  - Combining NIKA2 and Planck maps (“feathering”) is important to retrieve the emission at scales larger than the NIKA2 field-of-view. This lowers the beta index.
  - In general, the mm/submm slopes are steepening towards the TMC1 cores. Cuts shown an increase of beta from $\beta_{1,2} \sim 1.4$ at 7 mag to $\beta_{1,2} \sim 1.8$ at 20 mag.

Cores in Taurus: First results (2)

- Grain models show that the mm slope of the SED, i.e. the β index, is a strong function of grain properties e.g. coagulation and/or ice mantles.

- Possible interpretation of the observed β variation:

  β increases with ice layer thickness (Ossenkopf & Henning 1994, OH94), i.e. with evolutionary stage. This has implications for e.g. the efficiency of chemical desorption.

OH94: Ossenkopf & Henning 1994 Models
with $n_H=10^5$ cm^{-3}, coagulated
β=1.51 no ice
β=1.81 thin ice mantle
β=1.89 thick ice mantle