Revisiting the Crab Nebula's dust and synchrotron radiation — from the infrared to radio domain —

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Abstract: We have fitted the near-infrared to radio images of the Crab Nebula with a Bayesian model that simultaneously reproduces the Crab's synchrotron, interstellar and supernova dust emission. The Herschel images were corrected for interstellar dust emission, with a small contribution ($\lesssim$ 22%) to the Crab's overall infrared (IR) emission. The Crab's supernova dust mass is estimated to be between 0.032 and 0.049 $M_\odot$, with an average dust temperature T_{dust}=41±3K (and a minor contribution from warm 70K dust). The synchrotron power-law spectrum is consistent with a radio spectral index α_{radio}=0.297±0.009, an infrared spectral index α_{IR}=0.429±0.021 with a break at mm/cm wavelengths. We identified an intriguing component of mm excess emission; we discuss possible scenarios that could account for this excess emission.

Crab's dust distribution and mass:

- Our cold (41K)+warm (70K) supernova dust mass of 0.032-0.049 $M_\odot$ (for amorphous carbon grains of size a=1μm, Jones et al. 2012a,b,c) implies that less dust has formed in the Crab Nebula than previously derived (0.11-0.24 $M_\odot$, Gomez et al. 2012), due to our interstellar dust corrections and lower SPIRE 500 μm flux.
- The dust in the Crab is predominantly found in dense filaments south of the pulsar (see Fig. 1). The V-band extinction (A_V =0.20-0.39 mag) inferred from the supernova dust mass maps is consistent with the optical extinction estimates (A_V=0.20-0.34 mag) from Grenman et al. (2017).

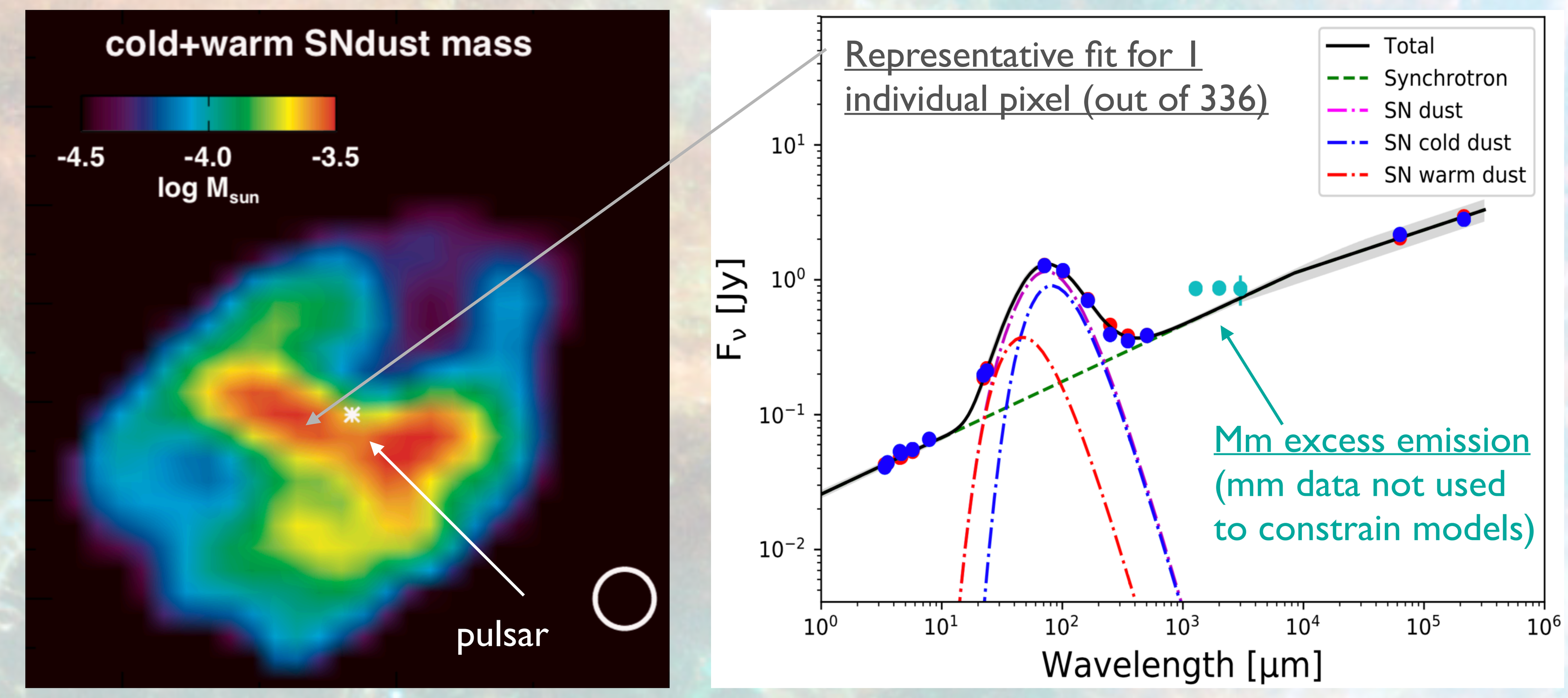

Fig.1: Supernova dust mass map (left) inferred from a Bayesian SED model fit to the near-infrared to radio emission in 336 pixels of size 14x14 arcsec^2 (right). The SPIRE 500 beam (36 arcsec) is overlaid in the bottom right corner (left).

Crab's synchrotron emission:

- The steepening of the IR spectrum (see Fig. 3, middle) towards the outer regions is interpreted in terms of radiative losses, due to electrons having cooling times shorter than the age of the Crab itself. We show in our paper (De Looze et al. 2019) that this fast cooling regime extends to IR/submm wavebands for which α_{radio} (=0.297) < α_{IR} holds.

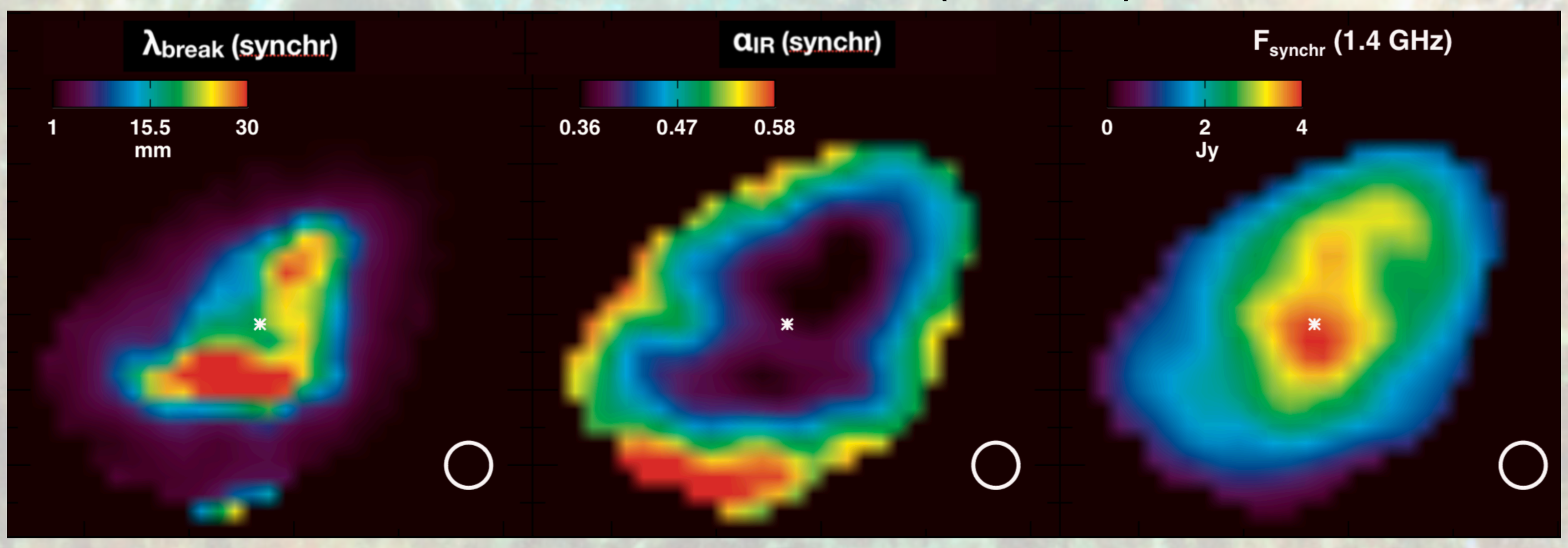

Fig.3: Synchrotron model parameter maps with the wavelength break (left), IR spectral index (middle) and 1.4 GHz (21cm) synchrotron flux density (right). The SPIRE 500 beam (36 arcsec) is overlaid in the bottom right corner.

Fractional contributions in different wavebands:

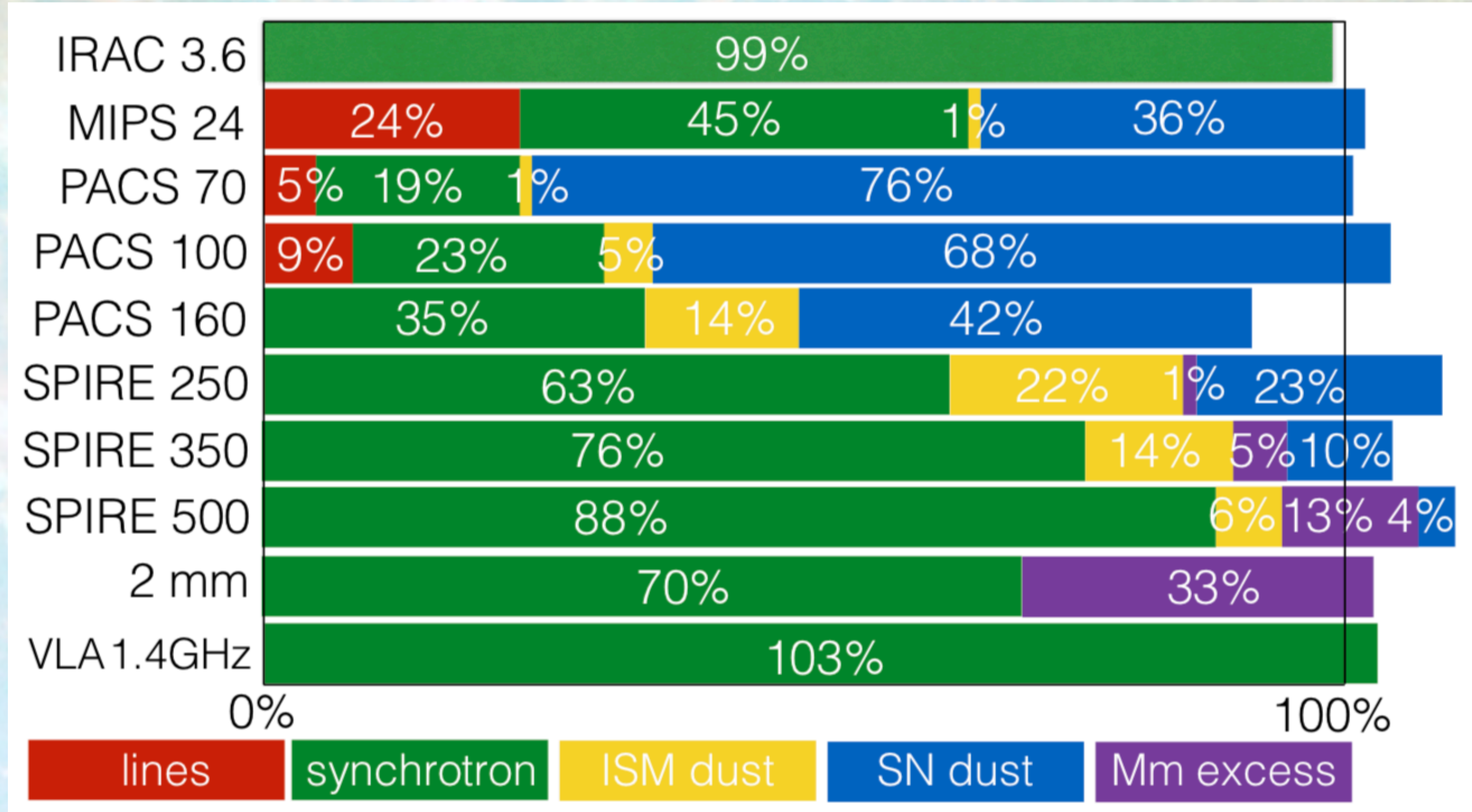

Fig.2: Overview of the contributions of different model components to the observed flux densities in each waveband. Because the Bayesian model is fitting the observed flux densities within the limits of uncertainty, the fractional contributions do not always exactly add up to a 100%.

Millimetre excess emission !?!:

- We identify a millimetre excess that accounts for 33% of the total integrated emission at 2 mm. On resolved scales, the excess emission peaks in the centre, and follows the structure of the torus and jet as seen in radio images (see Fig. 4). We therefore argue that a synchrotron origin for the mm-excess emission is most likely.

- The synchrotron radiation is thought to originate from two different synchrotron components (Atoyan & Aharonian 1996; Bandiera et al. 2002; Meyer et al. 2010; Schweizer et al. 2013; Porth et al. 2014a; Lyutikov et al. 2018), which spatially correlate with the particles emitting at radio and optical wavelengths, with a transition at mm wavelengths.

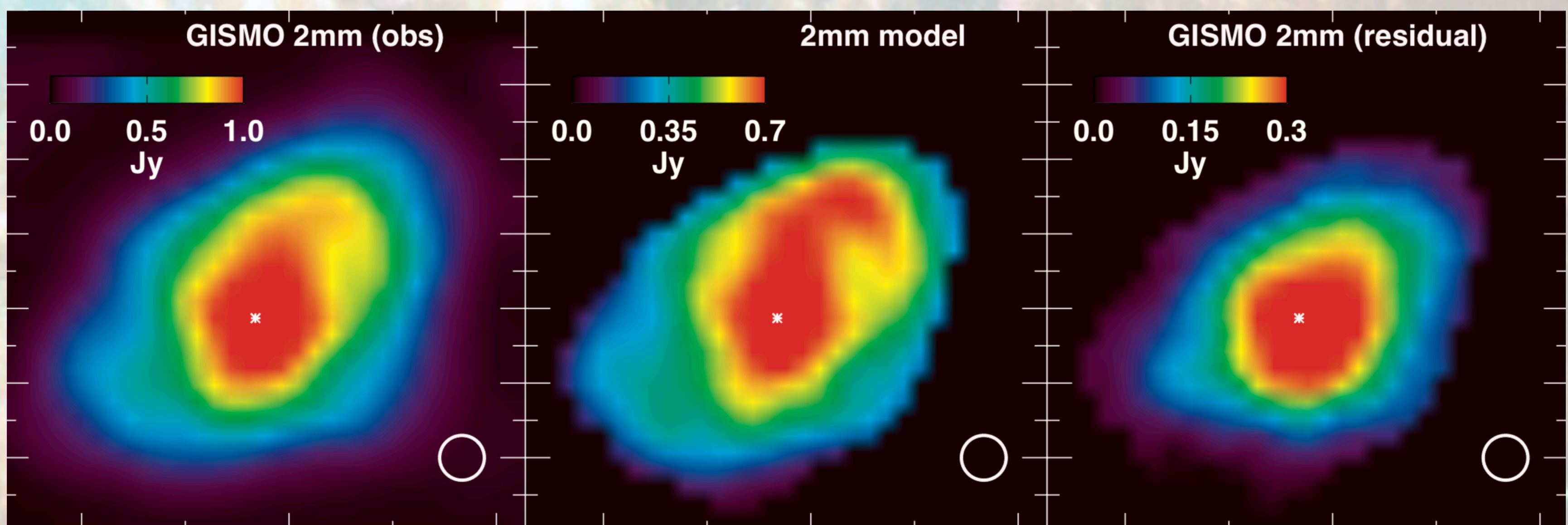

Fig.4: Resolved maps of the observed (left column), modelled (middle column), and residual (i.e., observations-model, right column) emission in the GISMO 2mm waveband. The residual excess mm emission follows the distribution of the Crab's synchrotron radiation (see Fig. 3, right panel). The SPIRE 500 beam (36 arcsec) is overlaid in the bottom right corner of each panel.

Conclusions: In our recent study, De Looze et al. 2019 (resubmitted), we have revised the dust mass (0.032-0.049 $M_\odot$) condensed in the Crab Nebula. In line with recent studies of other SNRs, we conclude that the Crab's efficient dust condensation (8-12%) provides further evidence for a scenario whereby supernovae could provide considerable contributions to the interstellar dust budgets in galaxies.

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