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3D extinction mapping of the Milky Way with the Besançon Galaxy Model in the Gaia era

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► To cite this version:

Barnabé Déforêt, Julien Montillaud, Annie Robin, Douglas J. Marshall. 3D extinction mapping of the Milky Way with the Besançon Galaxy Model in the Gaia era. European Astronomical society, Jul 2024, Padoue / Padova, Italy. . hal-04706296

HAL Id: hal-04706296

<https://hal.science/hal-04706296v1>

Submitted on 23 Sep 2024

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Context

The structure of the Milky Way (MW) disc remains poorly constrained in spite of numerous studies. The challenge comes from the fact that we are inside the MW disc, which makes all structures overlap along the line of sight. It is then needed to disentangle those structures to get a clear view of our Galaxy. 3D extinction maps aim to characterize the distribution of dust within our Galaxy, as well as to provide information about the structure of the MW. Recent studies^{1,2,3,4} usually provide detailed 3D extinction maps, but that only extend to a few kiloparsecs or that only covers the very local Galactic disc.

The Besançon Galaxy Model

The Besançon Galaxy Model (BGM) is a stellar population synthesis model that simulates the stellar content of the MW. Developed by Robin et al. (2003)⁵, the model has received numerous improvements year after year:

- Implementation of the possibility to use 3D extinction maps⁶.
- New code including binarity generation, new tracks, and based on IMF and SFH hypothesis^{7,8}.
- Implementation of new evolutionary tracks including chemical abundances⁹.
- Implementation of a self-consistent gravitational potential¹⁰.



This model is a tool to constrain evolutionary scenarios of the MW, or to constrain the Galactic structure, such as dust distribution, by comparing model predictions to observations.

Gaia and 2MASS

Several studies have used data from Gaia¹¹ and other surveys to create 3D extinction maps^{1,2,3,4,12}. However, the surveys are often combined with a cross-match, reducing the number of stars in their samples.

Our method uses Gaia DR3¹³ and 2MASS¹⁴ photometric data, as well as Gaia parallaxes, without cross-match, allowing us to benefit from the advantages of each survey to map the 3D dust distribution at different scales.

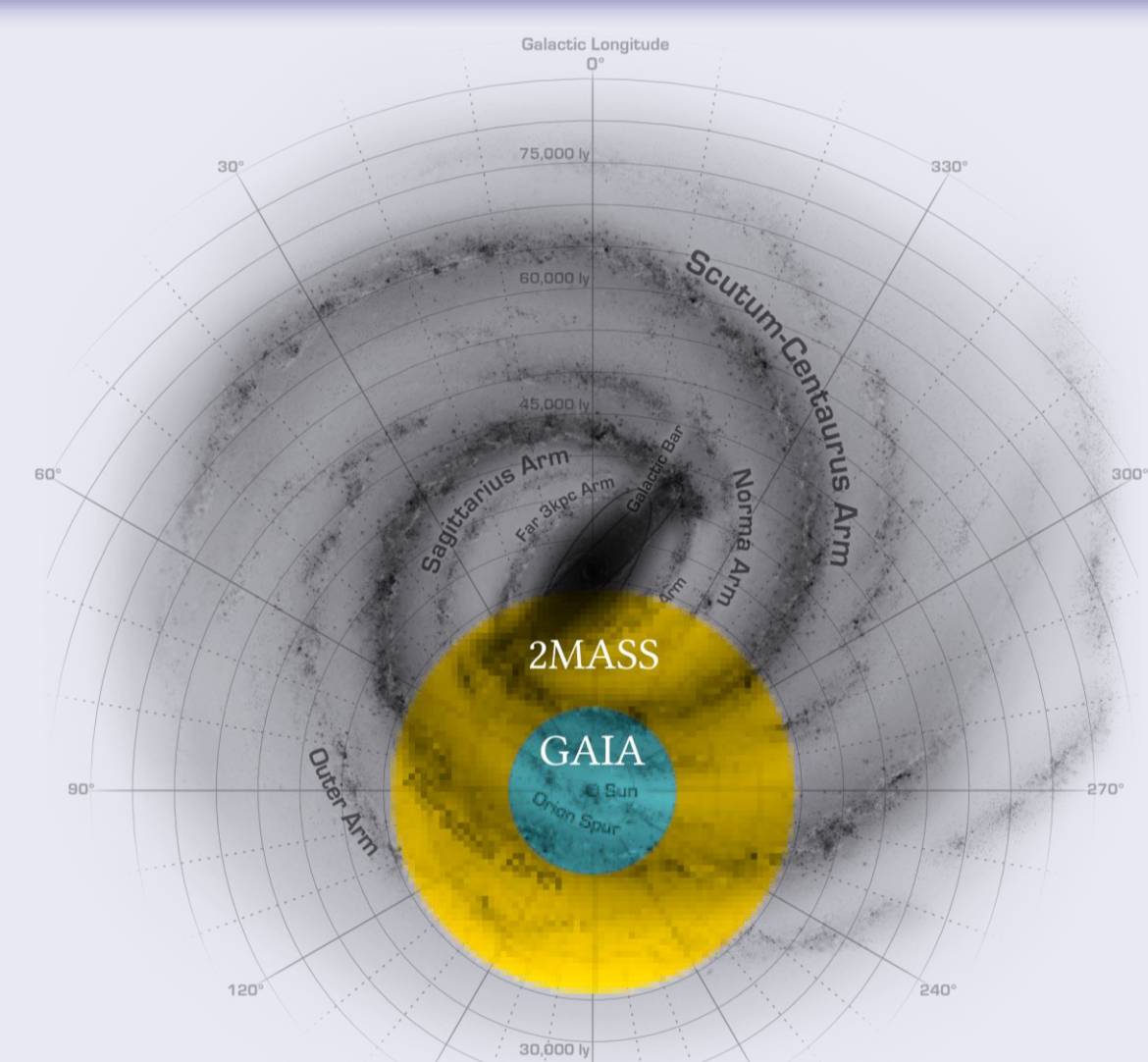


Figure 1: Expected maximum distance range reachable using Gaia or 2MASS. Adapted from ESO.

Method

PyRedLine is a 3D extinction mapping method based on the RedLine method by Marshall et al. (in prep)¹⁵. While RedLine uses only 2MASS data, PyRedLine can use both 2MASS and Gaia data, either separately or together. To estimate the amount of extinction as a function of the distance, we assume that the difference between the BGM and observations is solely due to extinction⁶.



We compare the model and observations using colour histograms. For Gaia, we also compare colour-parallax diagrams. For a given line of sight (LoS), we identify the extinction profile so that the colour distribution of observation and BGM stars are in agreement. The search of the best extinction profile is based on Bayesian theory, where we explore a posterior distribution via MCMC using the emcee¹⁶ Python package:

- Assuming the distribution of stars in each histogram bin follows a Poisson distribution, the (log) likelihood of observing o stars given m stars predicted by the model is¹⁷:

$$\mathcal{L} = \sum_i o_i \left[1 - \frac{m_i}{o_i} + \ln \left(\frac{m_i}{o_i} \right) \right]$$

- The prior on the extinction profile consists in penalising solutions that go beyond unphysical solutions following an exponential probability function.

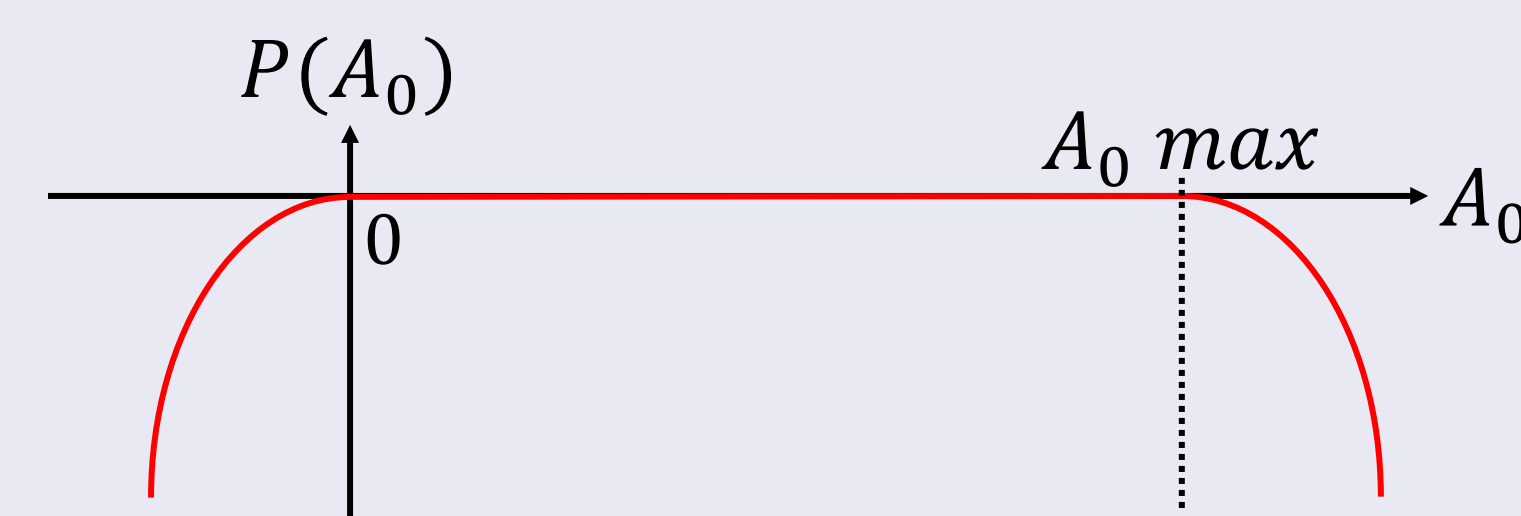


Figure 3: Schematic view of the prior.

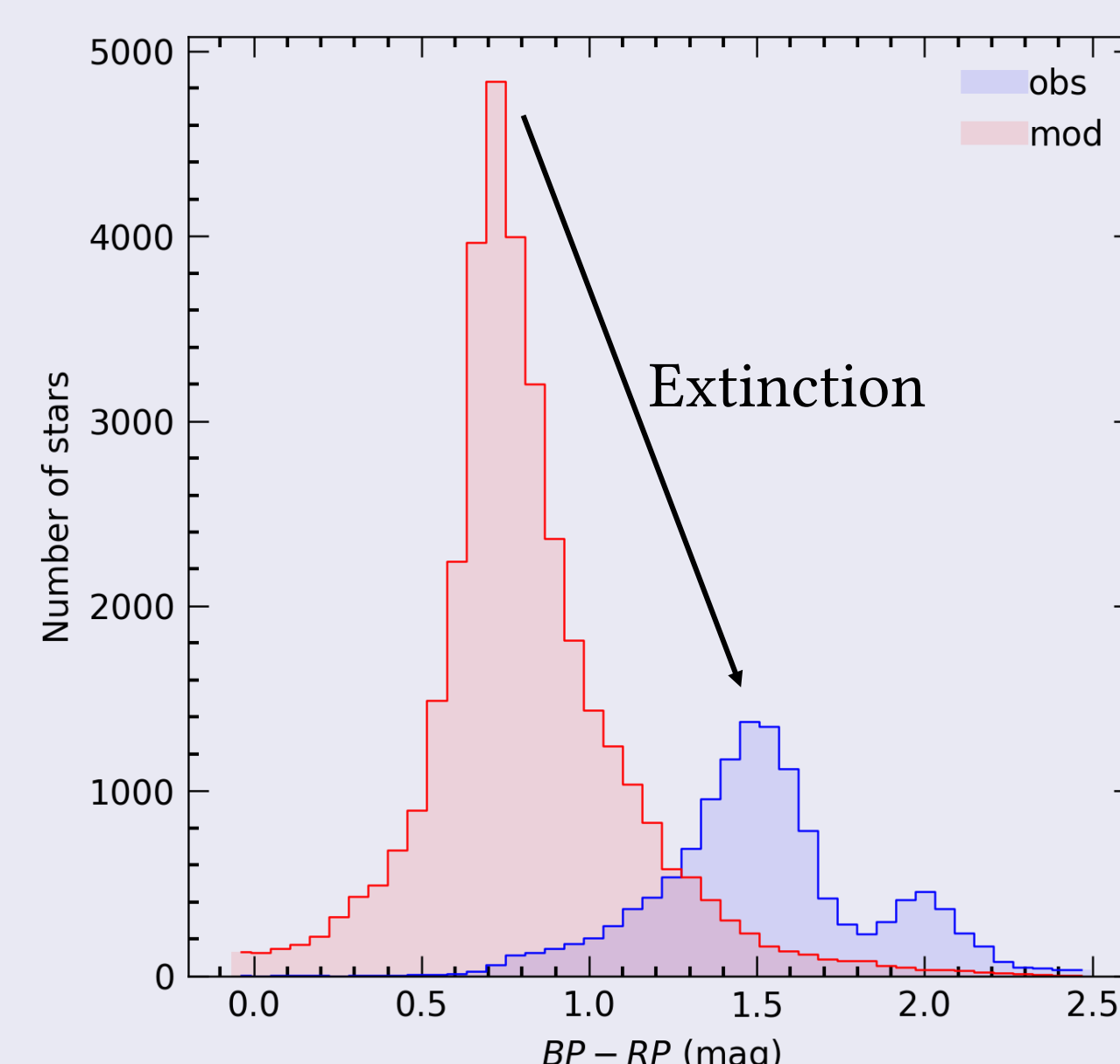


Figure 2: Visualisation of the effect of extinction on a BP-RP histogram.

The MCMC parameters consist in a differential extinction profile of $N \times dA_0/dr$ values arranged onto a regularly spaced grid of distances. To reduce the risk of being stuck in a local maximum of the posterior, we use $M \times N$ walkers, with $M \geq 10$. The Fitzpatrick et al. (2019)¹⁸ extinction law is used to convert from A_0 to A_{BP} , A_G , A_{RP} , A_J , A_H and A_K . This law is parametrised by the total to selective extinction ratio R_V , that we set to its mean value for the MW, i.e. 3.1.

To build a 3D extinction map of the MW, we apply this method on many different LoS.

Orion and Vela C

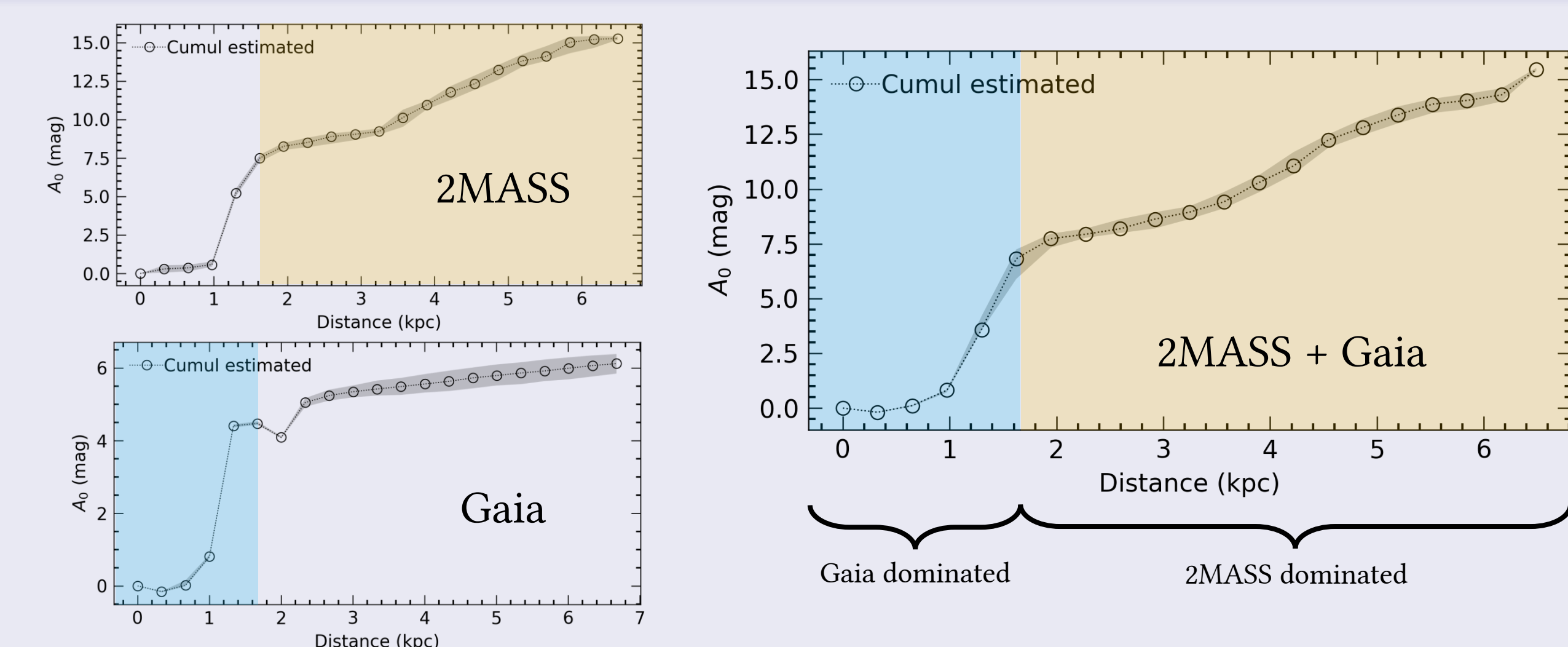


Figure 4: Single extinction profile in the direction of Vela C (~ 917 pc¹⁹), at $l = 266.1^\circ$ and $b = 1^\circ$.

Fig. 4 shows the complementarity of Gaia and 2MASS, where Gaia constrains the extinction profile at short distances while 2MASS constrains it at larger distances.

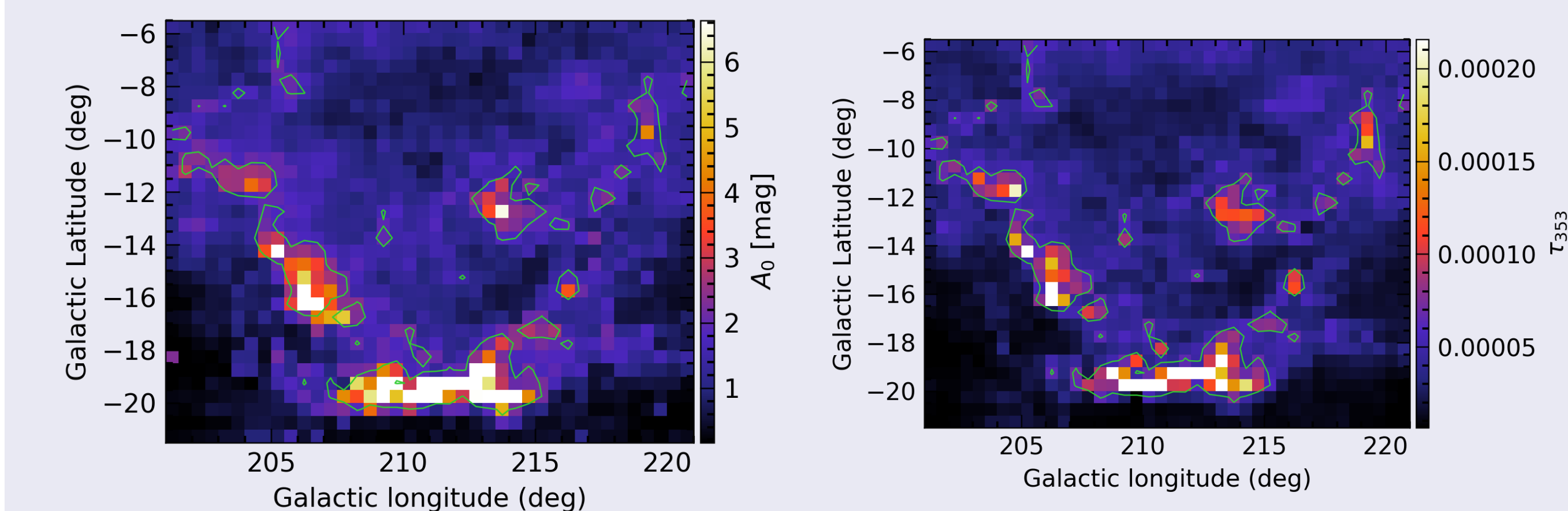


Figure 5: Results for the Orion region (~ 400 pc¹⁹) up to 2 kpc. *Left*: PyRedLine integrated map. *Right*: Planck dust opacity at 353 GHz. Green contours correspond to $\tau_{353} = 0.00006$.

The method can retrieve the position of Vela C for a single LoS and the overall 2D dust distribution of Orion. 3D mapping is then the next step. Improvements can be obtained in the near future by, for example, increasing the spatial resolution in regions where the extinction varies rapidly, or considering the fractal structure of the ISM.

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