# Dust as a tracer of the ISM in the Gaia Era

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6th Institute of Space Sciences Summer School - Life Cycle of Dust

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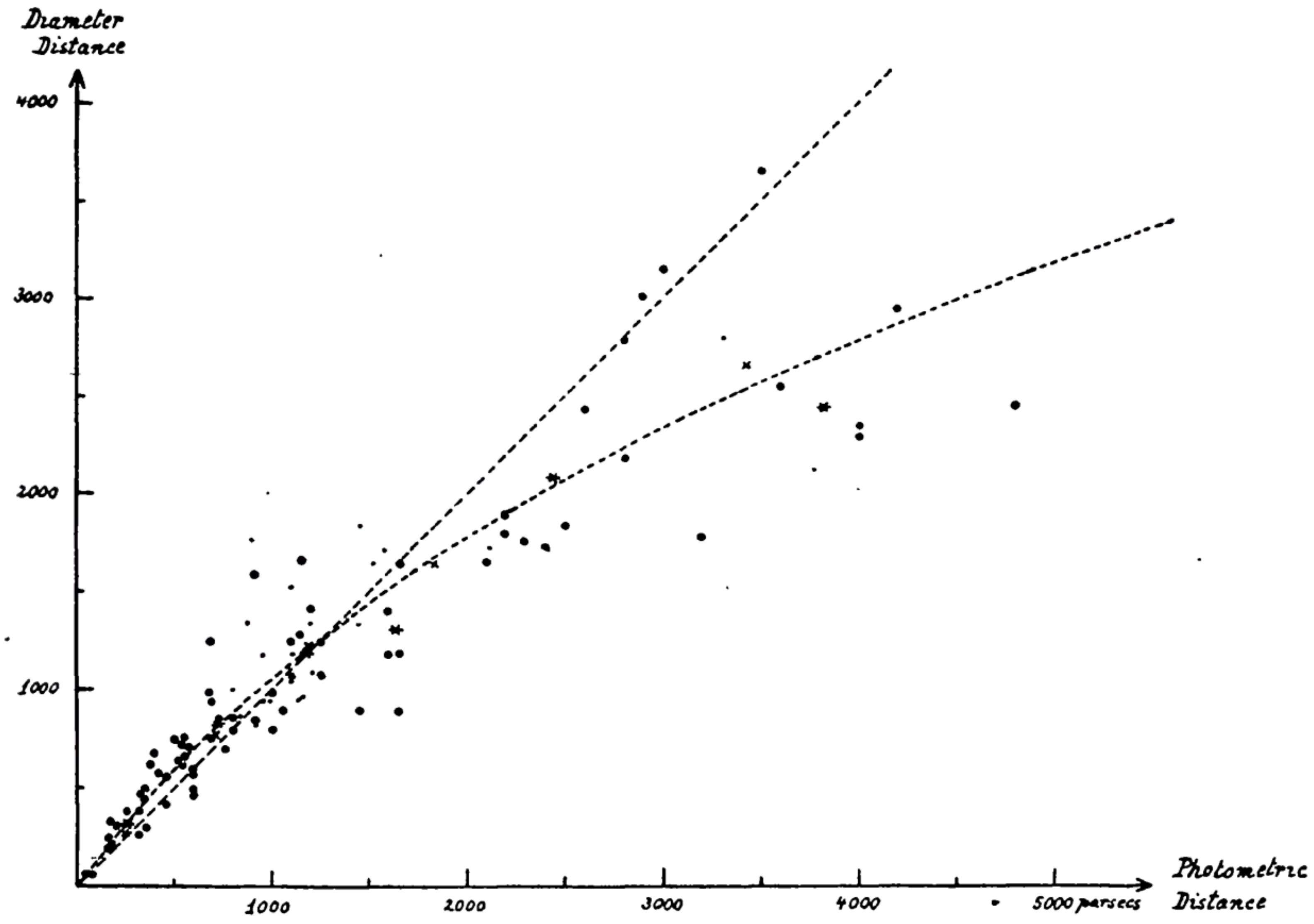
# Part 1:
# Dust as a tracer of the ISM

# Holes in the Sky

Herschel famously noted maybe there's something in the way

EARTHSKY COMMUNICATIONS INC; Amr Abdulwahab. Western desert of Egypt

# Something in the way

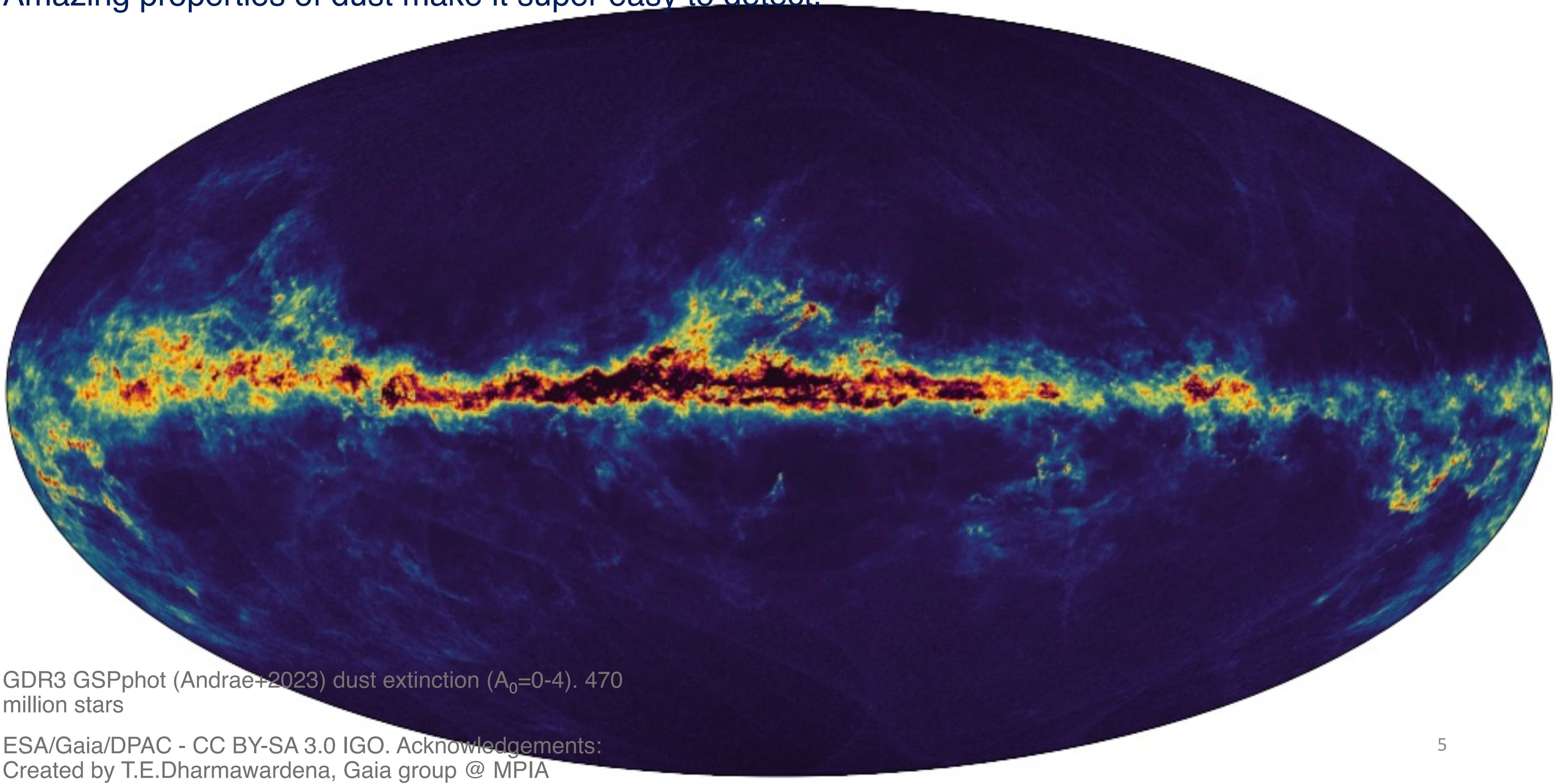



Trumpler 1930 Open clusters: the further they are the dimmer they get and connected it to material in the foreground – Dust!

Trumpler 1930

# < 1% of the total Baryonic matter is dust

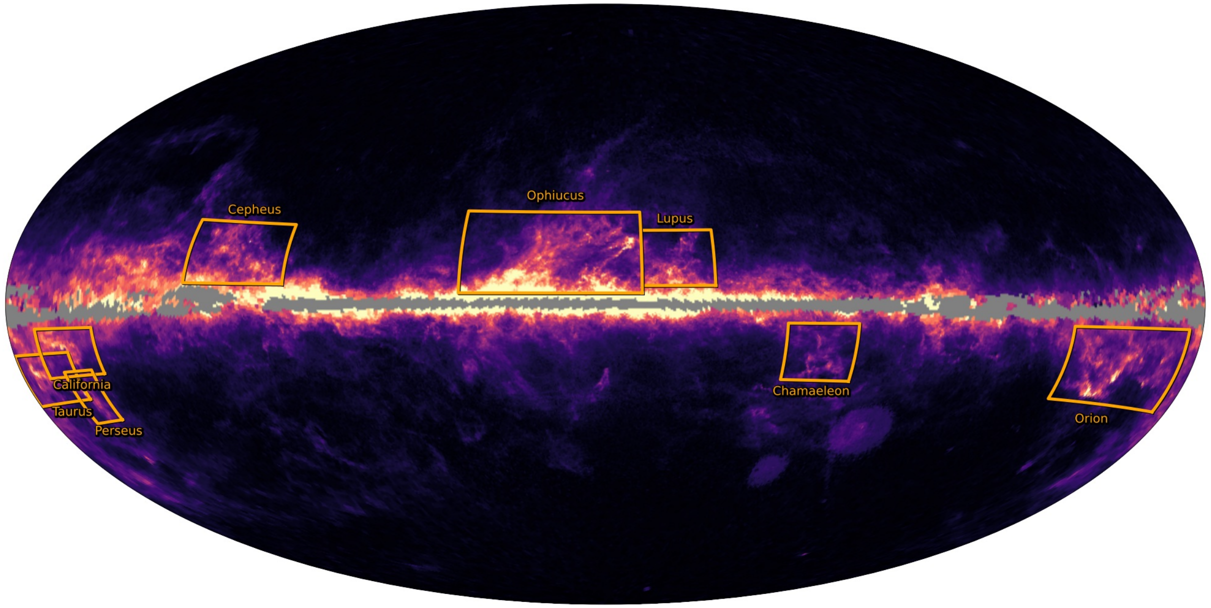
Amazing properties of dust make it super easy to detect.

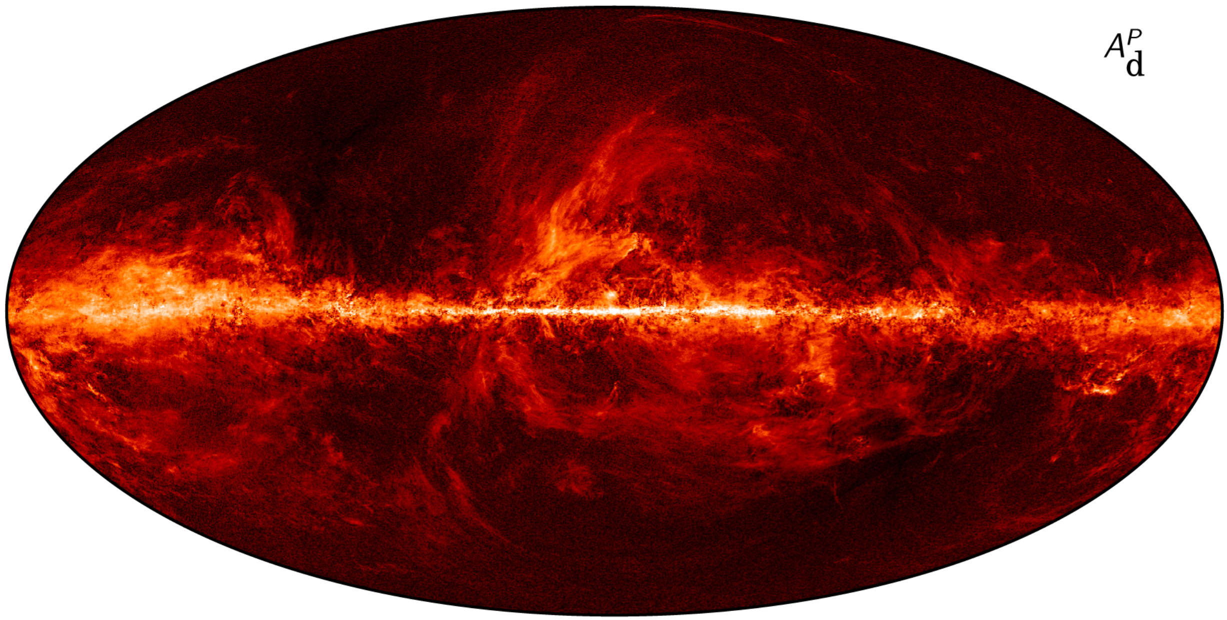


GDR3 GSPphot (Andrae+2023) dust extinction ($A_0$=0-4). 470 million stars

 Acknowledgements: Created by T.E.Dharmawardena, Gaia group @ MPIA

# Two ways to observe dust – Interstellar dust extinction and emission



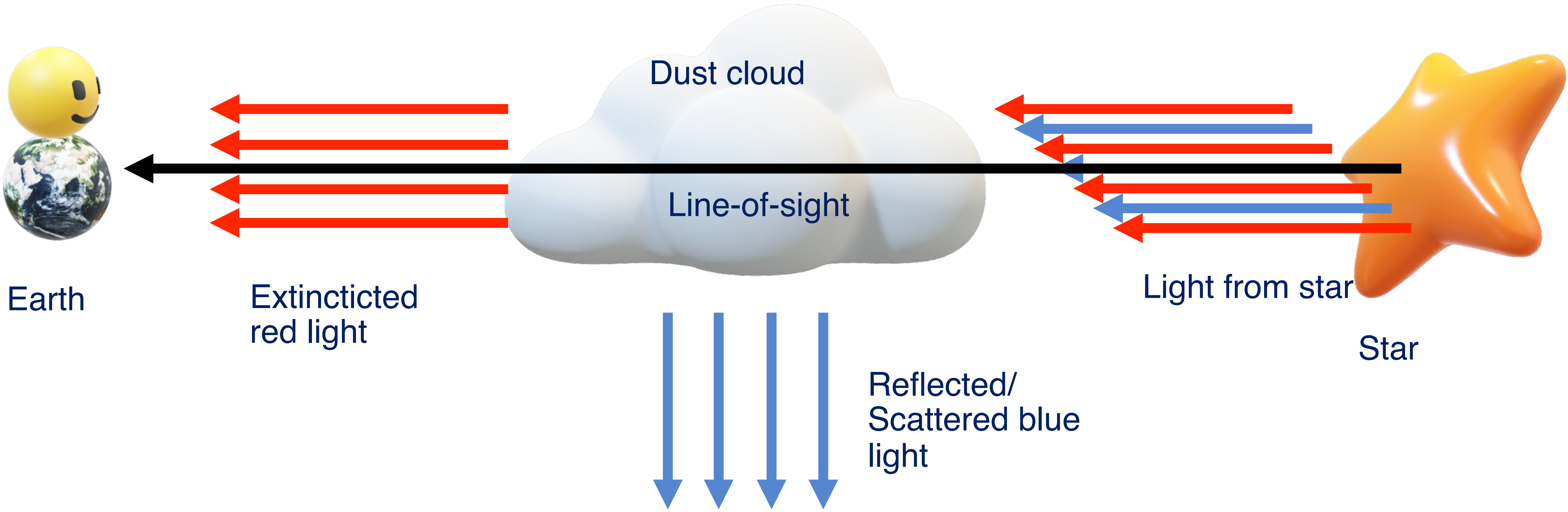




Left: GDR3 total Galactic extinction (Delchambre+2023) ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: Created by T.E.Dharmawardena, Gaia group @ MPIA.

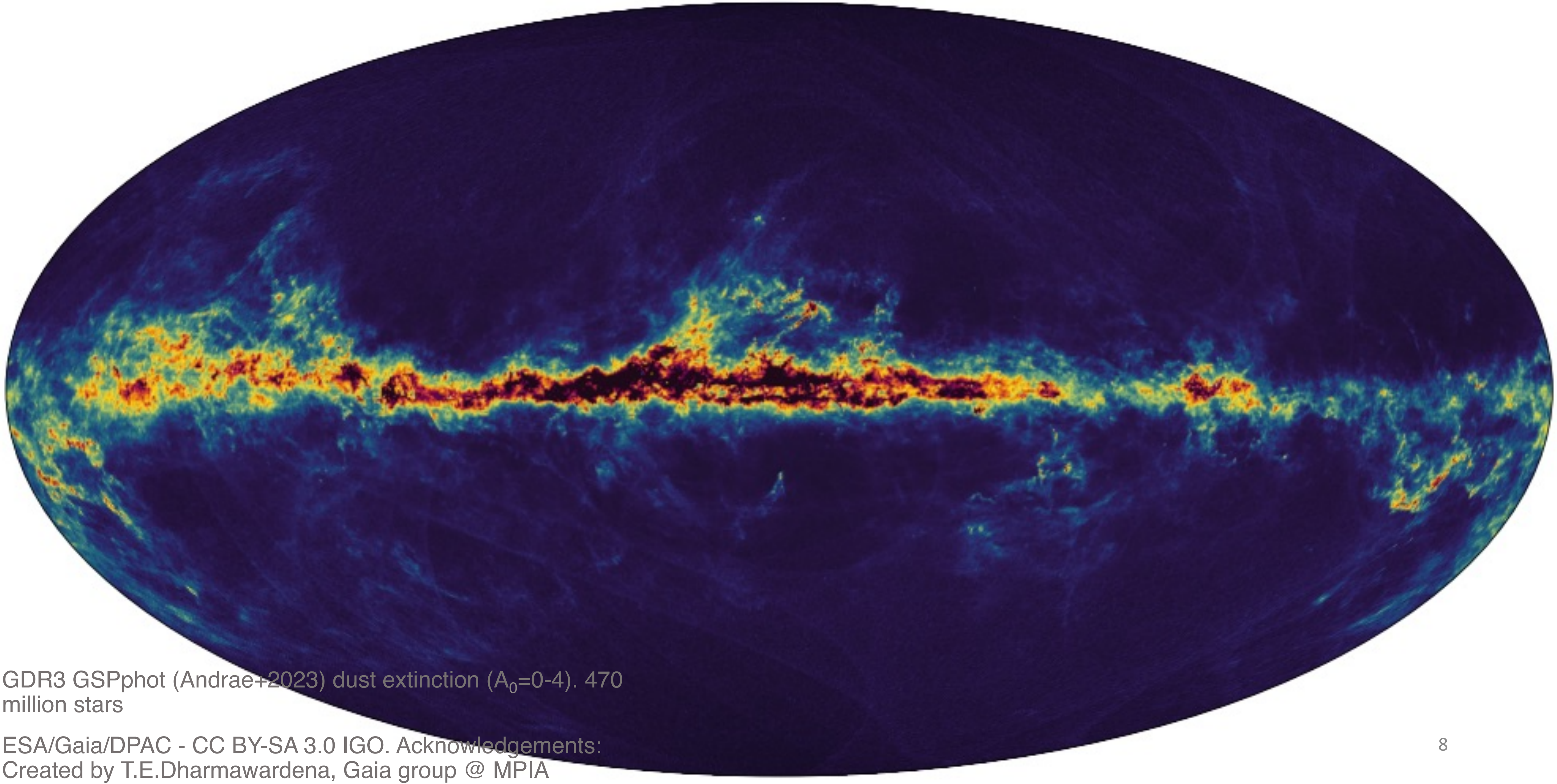
Right: Planck dust distribution in emission. ESA/NASA/JPL-CALTECH.

# Interstellar dust reddening and extinction

Reddening: peak shifts redward; more blue light removed.



# Interstellar dust extinction map of the Milky Way



GDR3 GSPphot (Andrae+2023) dust extinction ($A_0$=0-4). 470 million stars

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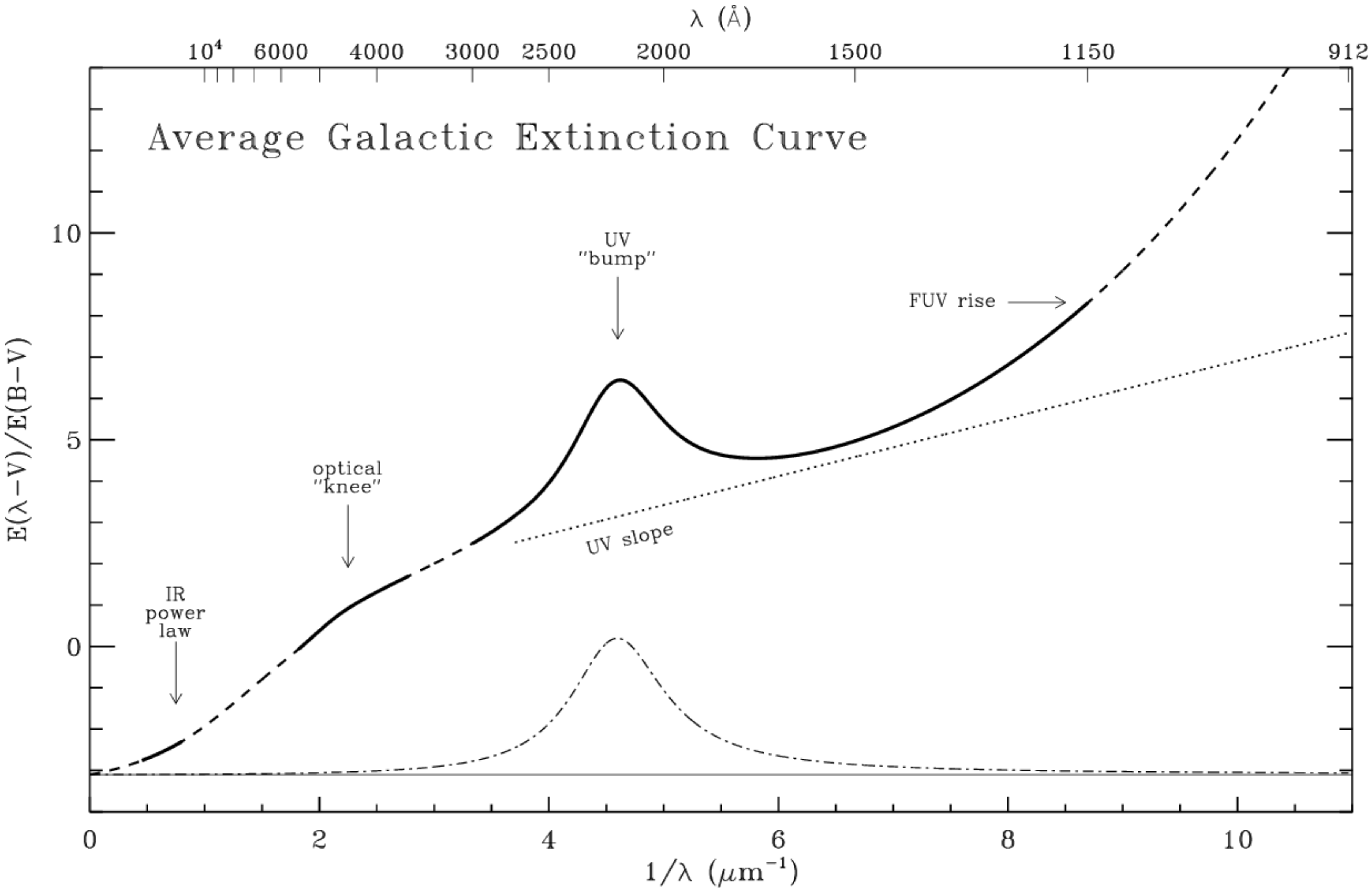
# Interstellar dust extinction curve




Fitzpatrick 2004

Scaling of curve: $A_{\lambda}$.

Slope: $R_V$ – ratio of total to selective extinction

$R_V = A_V/E(B\text{-}V)$ where E(B-V) is reddening.

Rv ~3.1 in Milky Way but it does vary!

# Interstellar dust extinction curve – $R_V$ variations

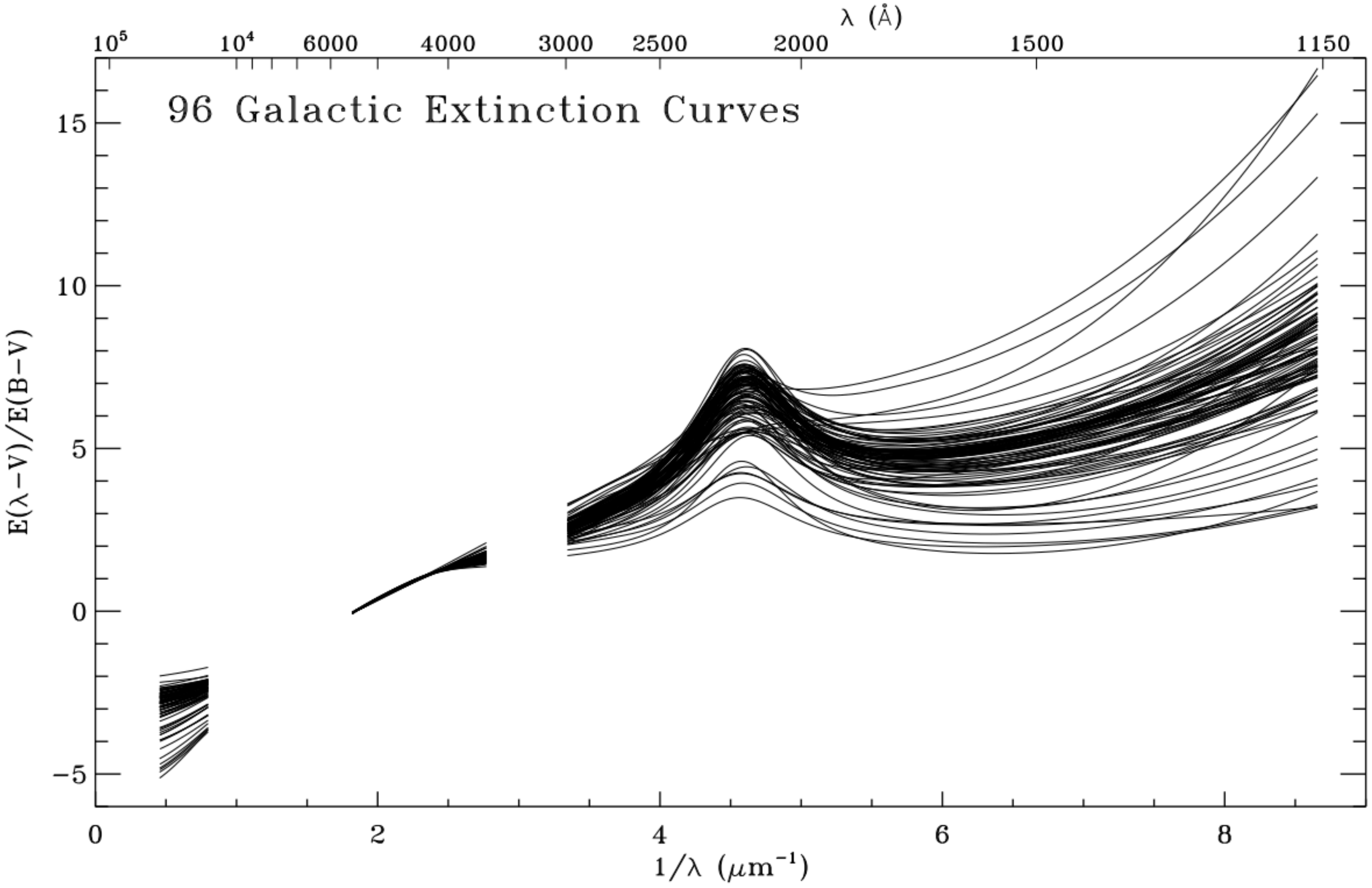
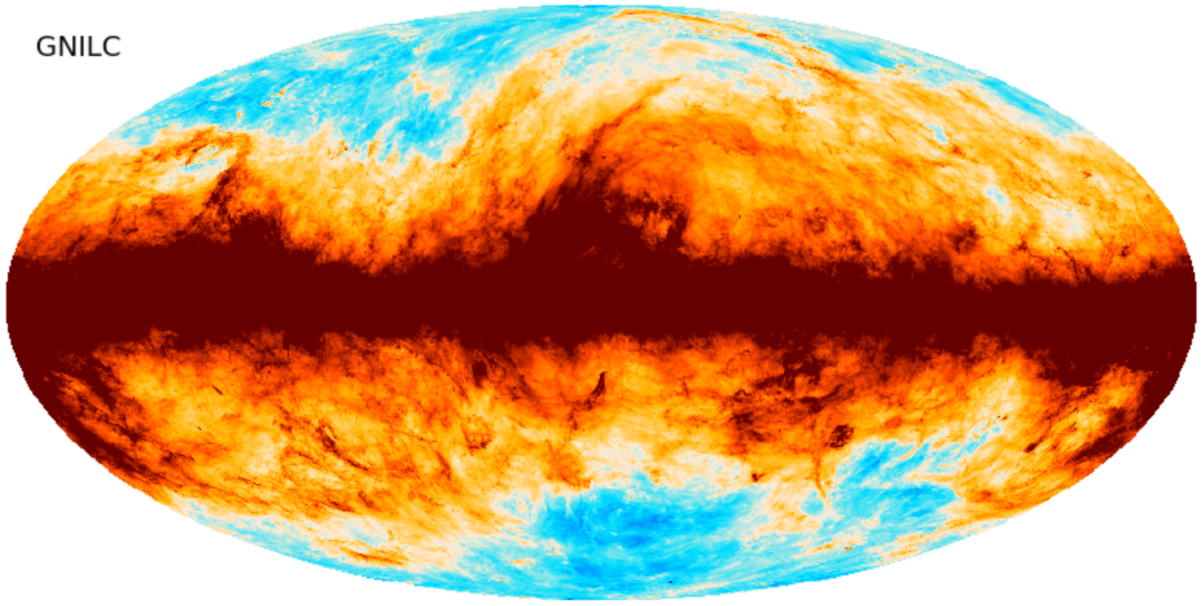


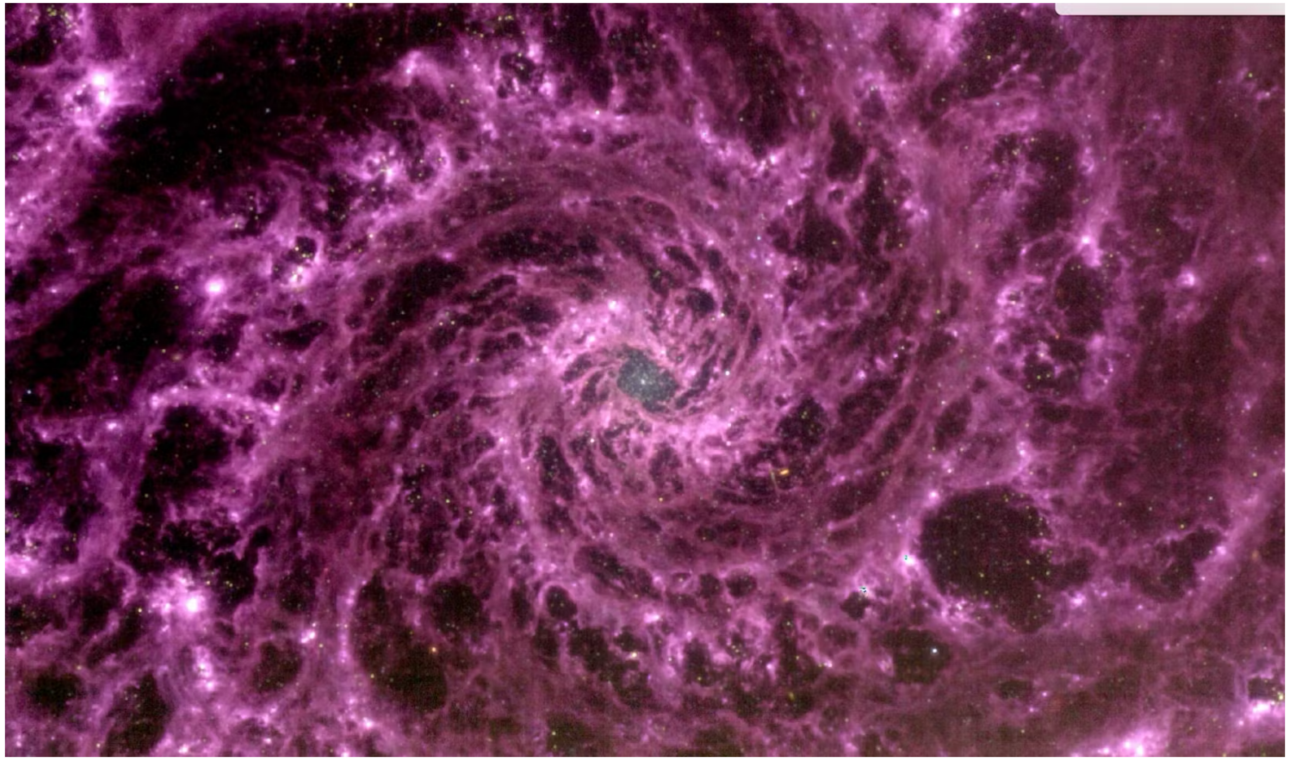

Fig. 3.— Analytical representations of the 96 IR-through-UV extinction curves to be discussed in §4. These illustrate the wide range of extinction properties observed in the Milky Way.

Fitzpatrick 2004

# Interstellar dust emission

IR – far-IR (~ 1 - 300 μm): best



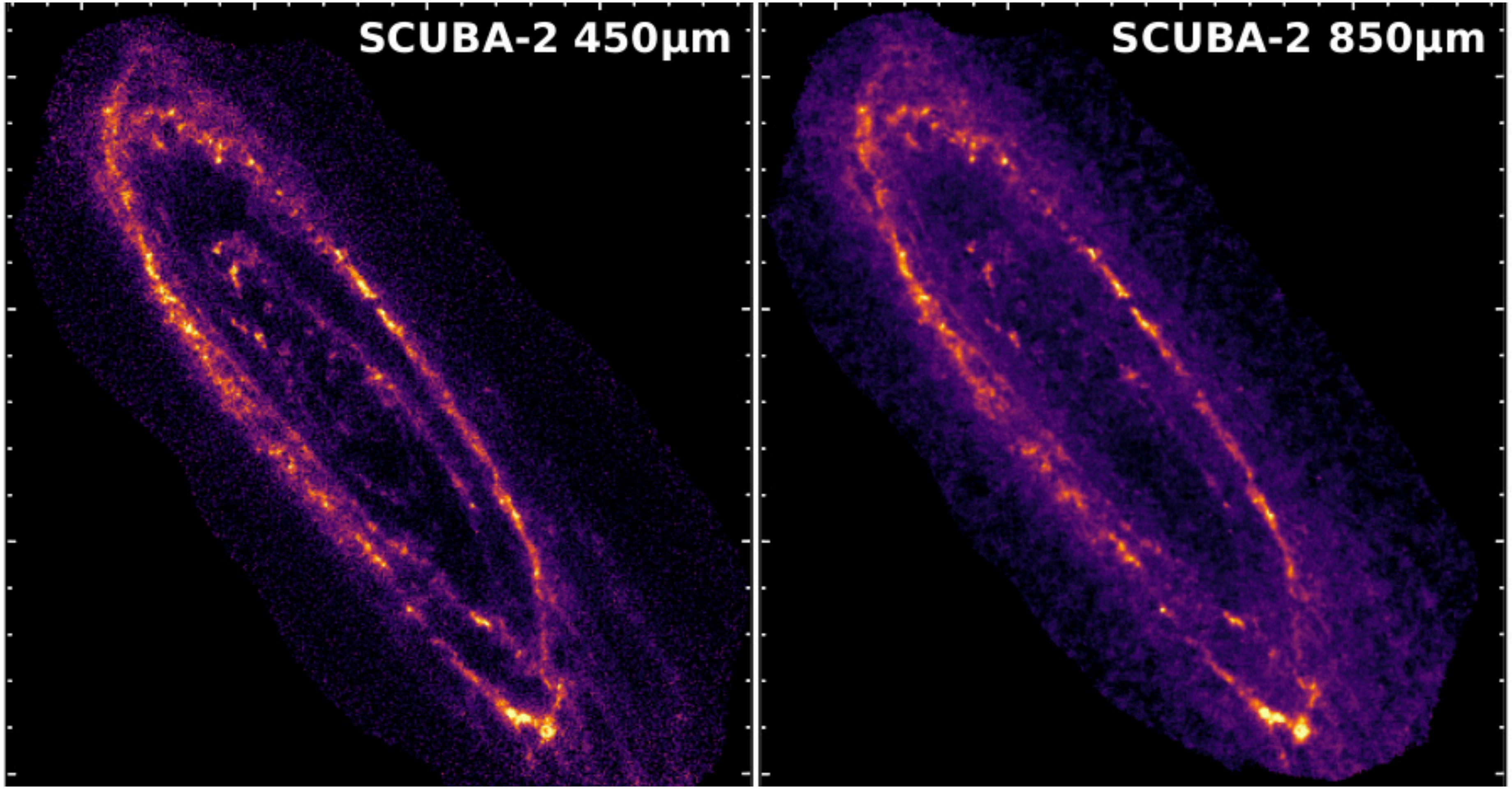



Left: Planck GNILC full-sky map of the Galactic thermal dust emission: Planck 2013 (P13) thermal dust model at 353 GHz and 5 resolution.

Right: JWST MIRI observation of M74; Gabriel Brammer. Data from PHANGS collaboration.

# Interstellar dust emission

Sub-mm – mm (~ 300 μm - 1 cm): also great.

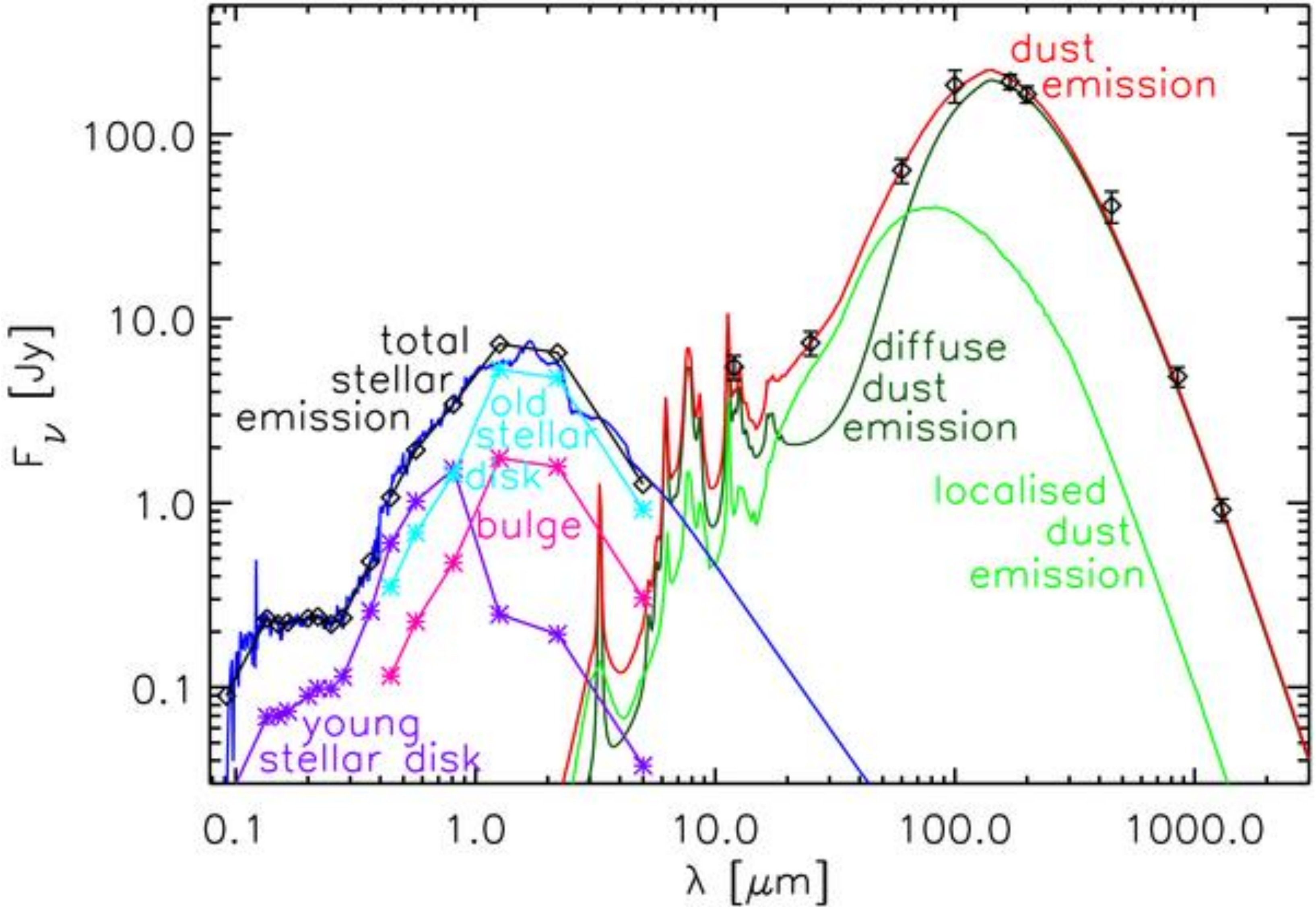



JCMT SCUBA-2 observation of M31. Smith+2021. Data from Hashtag collaboration.

# Why is dust a good tracer of ISM

1. Easy to observe! – dust emission is bright and can outshine the rest of galaxy in mid/far-IR.

You can observe dust to great distances.



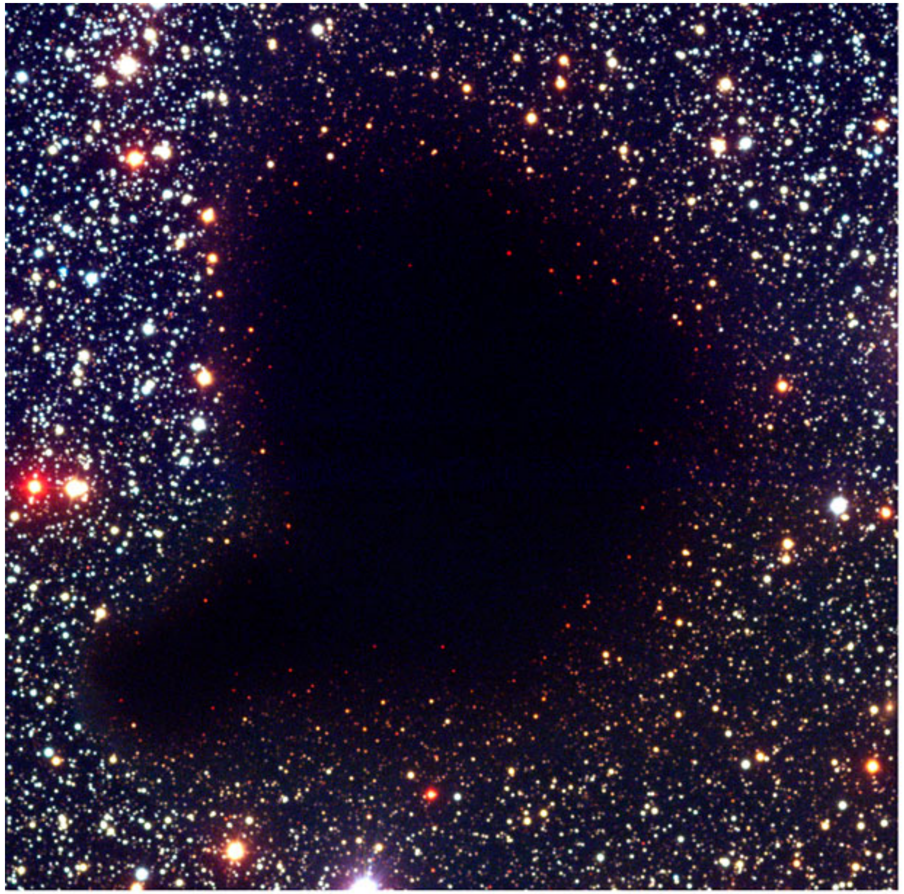

SED showing stellar and dust emission components. Popescu+2010

# Why is dust a good tracer of ISM

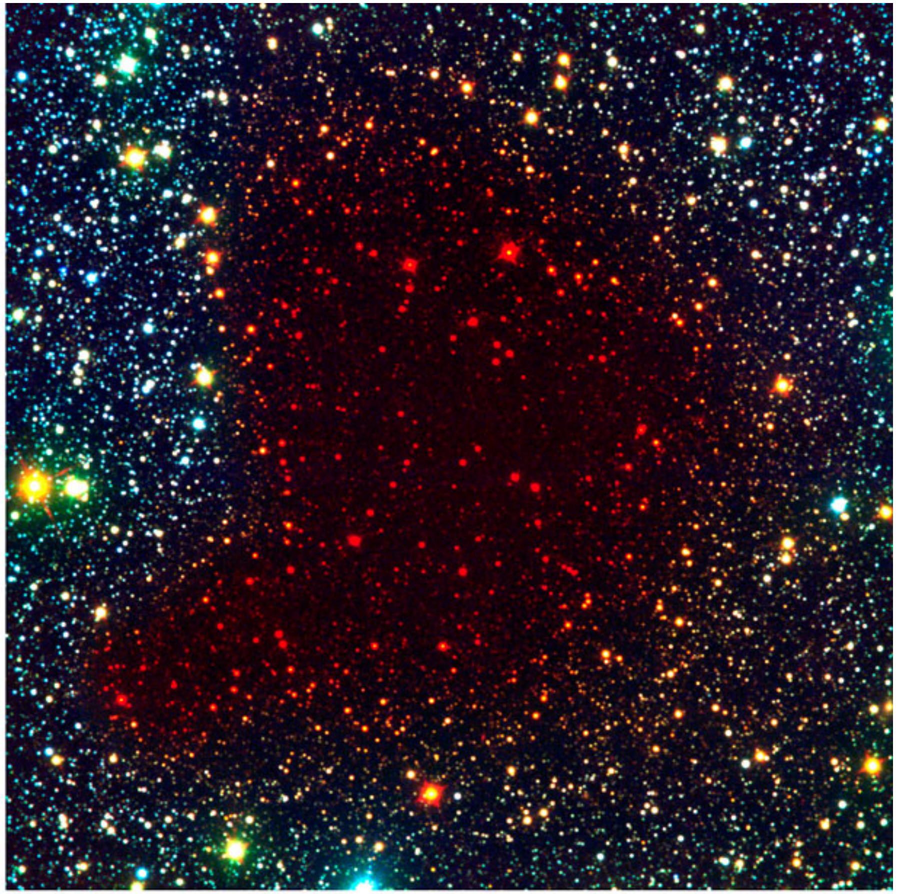
2. Dust extinction always seen as foreground phenomenon.

If we know the distance to the dimmed source, we can derive locations to the dust in front of it.

Gas on the other hand is ppv – need strong assumptions like a Galactic rotation curve and structure to identify locations



B, V, I



B, I, K

Comparison of the central area of globule B68 in a colour composite of visible and near-infrared on the left and a false-colour composite based on a visible (here rendered as blue), a near-infrared (green) and an infrared (red) on the right.

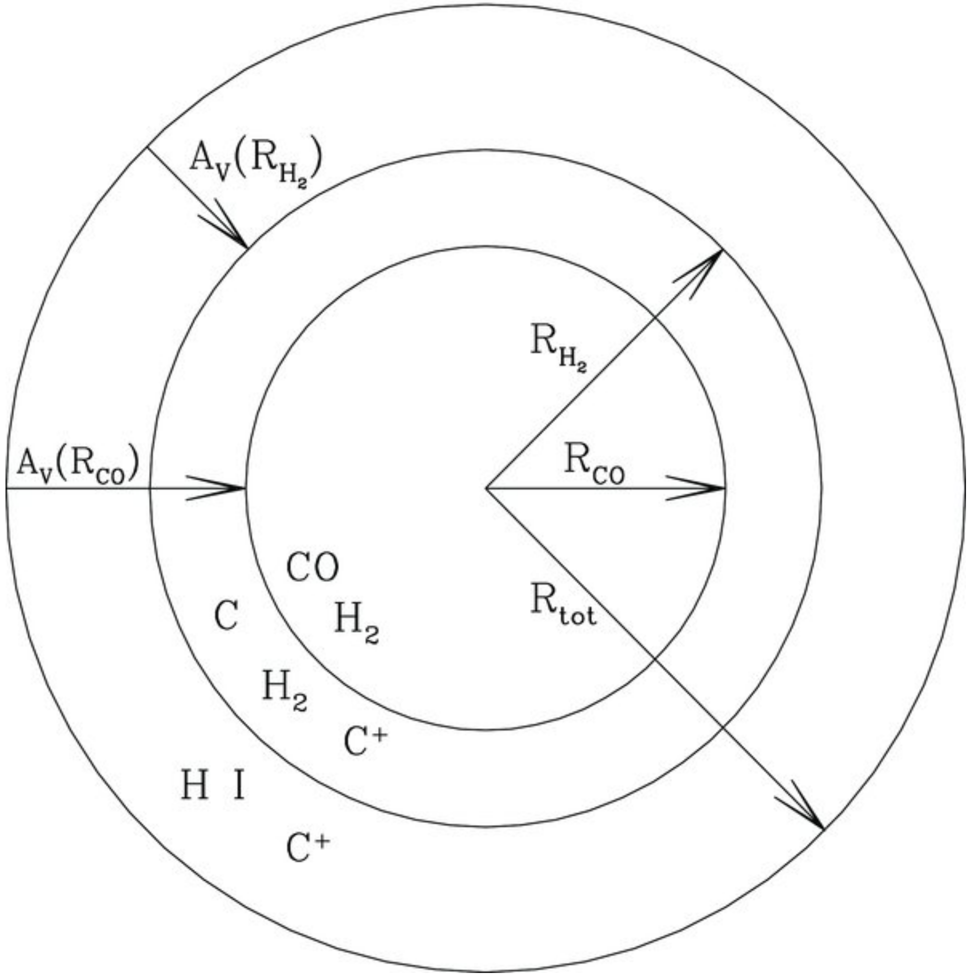
Credit:ESO

# Tracing ISM with Dust

1. Infer gas mass using standard dust:gas ratios  conversions (caution!).

While CO and HI are great tracers for the ISM, there are gaps in gas tracers (e.g: $H_2$) where we can't see gas due to molecular formation and photodissociation.

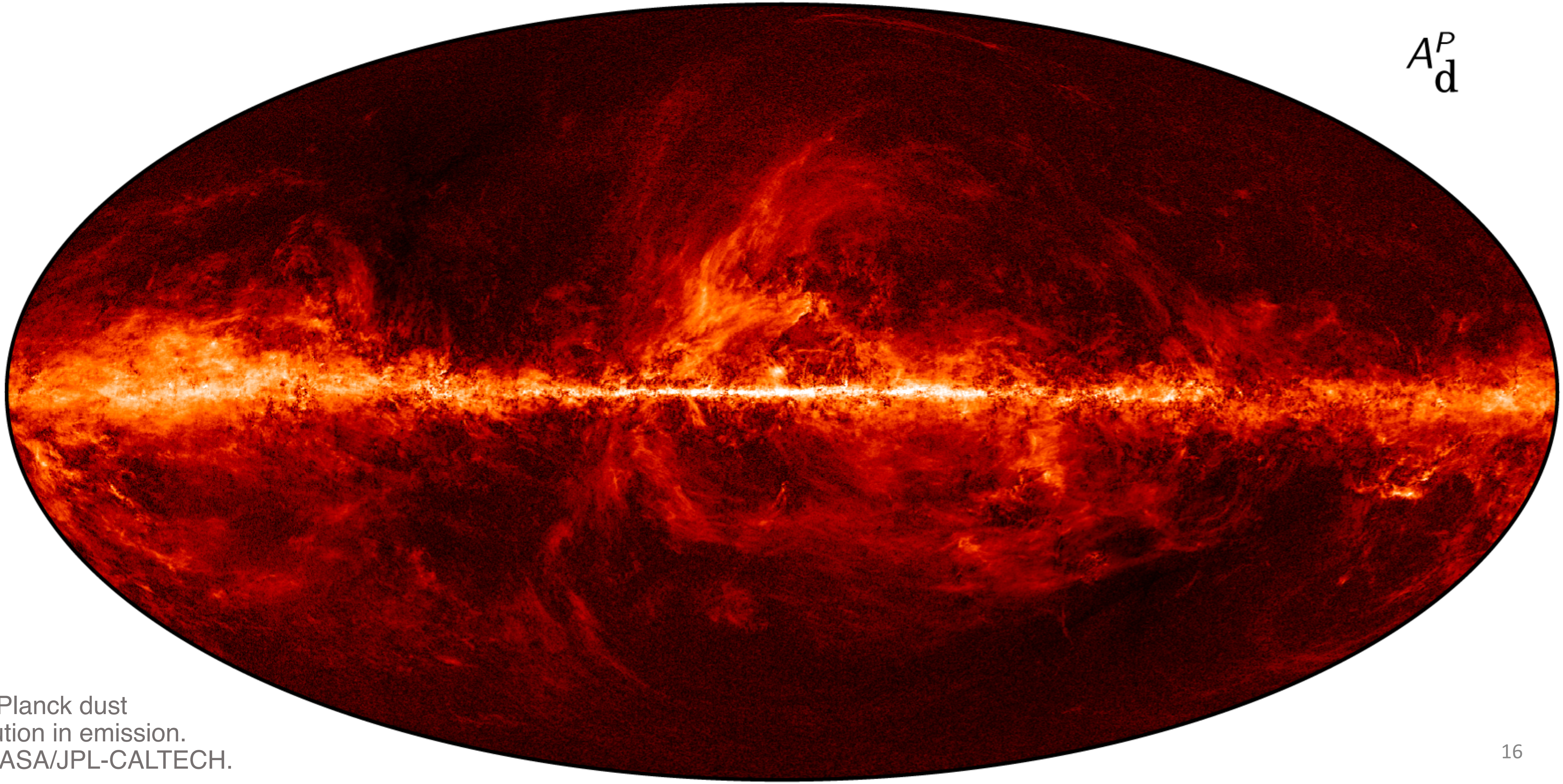
Dust is ubiquitous – dust depends only on density and temp!




Wolfire+2010. When there's lots of UV radiation, gas is atomic because molecules are dissociated, so we can observe HI 21 cm line. When dust has extinguished lots of UV flux, CO can form, which is also easy to observe. But there's an intermediate layer where gas is mostly molecular, but since $H_2$ has not dipole moment it only has high-excitation lines, which makes it hard to observe. But dust is still easy to observe in this regime!

# Tracing ISM with Dust

2. Trace low density areas by simply the absence of dust in emission.

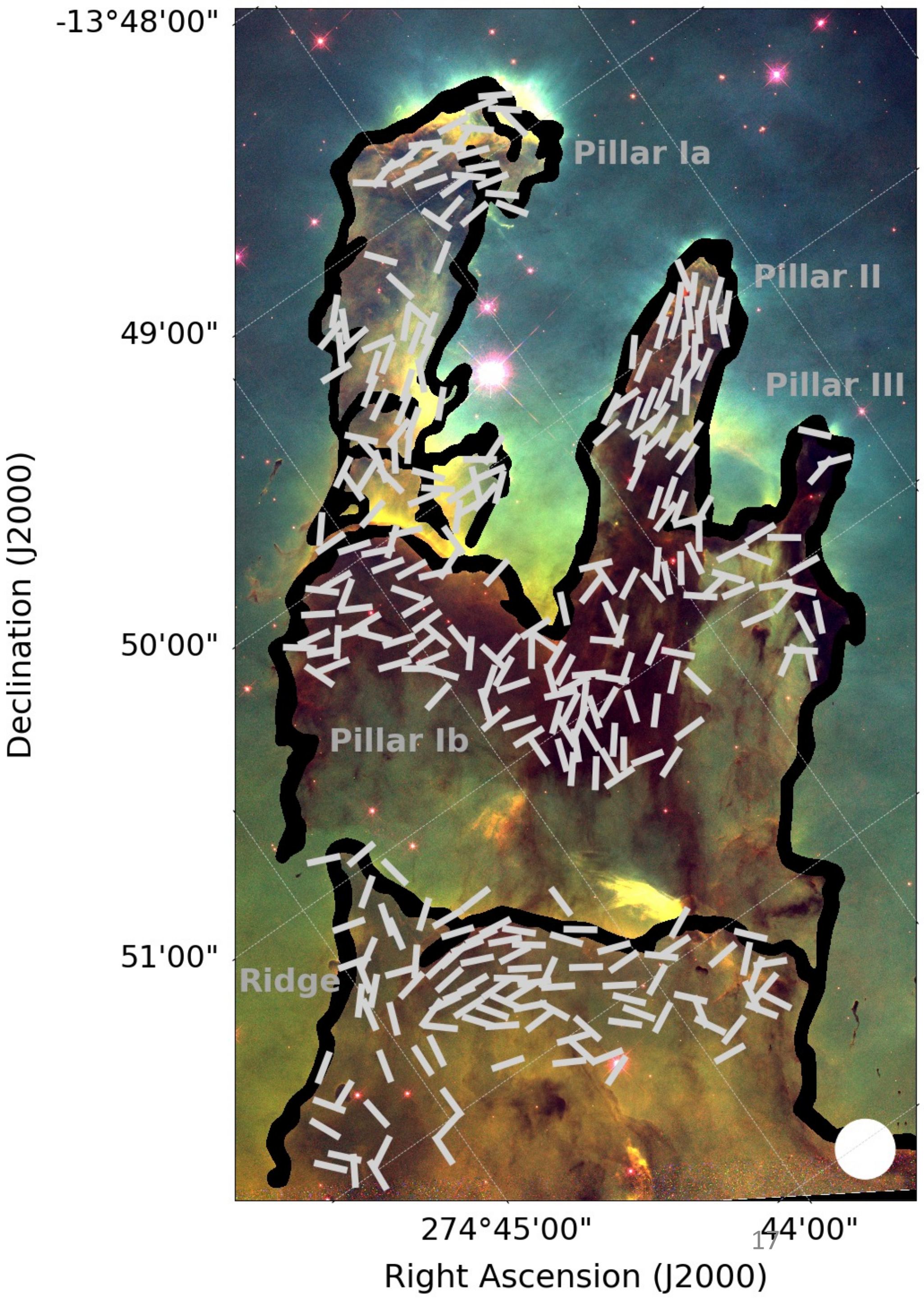



Right: Planck dust distribution in emission. ESA/NASA/JPL-CALTECH.

# Tracing ISM with Dust

3. Use dust to tracer magnetic

In turn trace things like cloud turbulence, etc.



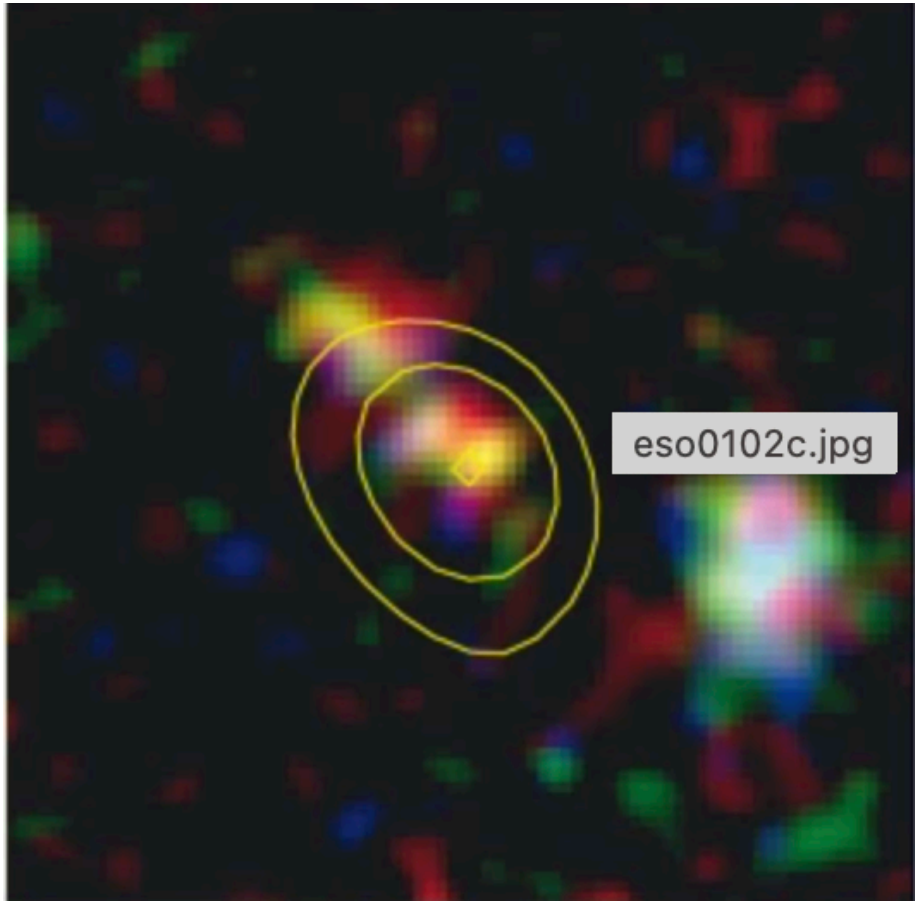

An illustrative figure of the BISTRO magnetic field vectors observed in the Pillars of Creation, overlaid on a HST 502 nm, 657 nm and 673 nm composite – HST imaging from Hester et al. (1996, AJ 111, 2349).

# Tracing ISM with Dust

4. Metal enrichment – Dust is composed of metals and easy to observe!

How much metals are in the ISM . Metals emitted from stars spend time in the ISM before being used up in star formation - measure how much is emitted by different stars and available for star formation.

Particularly useful for high red-shift galaxies where gas is difficult to measure.




Watson+2015; The colour image is composed with Hubble Space Telescope filters: F105W (blue), F125W (green) and F160W (red). The zoomed box (4′′ × 4′′) shows A1689-zD1. Contours indicate far-infrared dust emission detected by ALMA at 3σ, 4σ, and 5σ local rms (yellow, positive; white, negative)

# How do we derive interstellar extinctions

1. Forward model stellar reddened SED+spectra using stellar isochrones and stellar parameter grids.

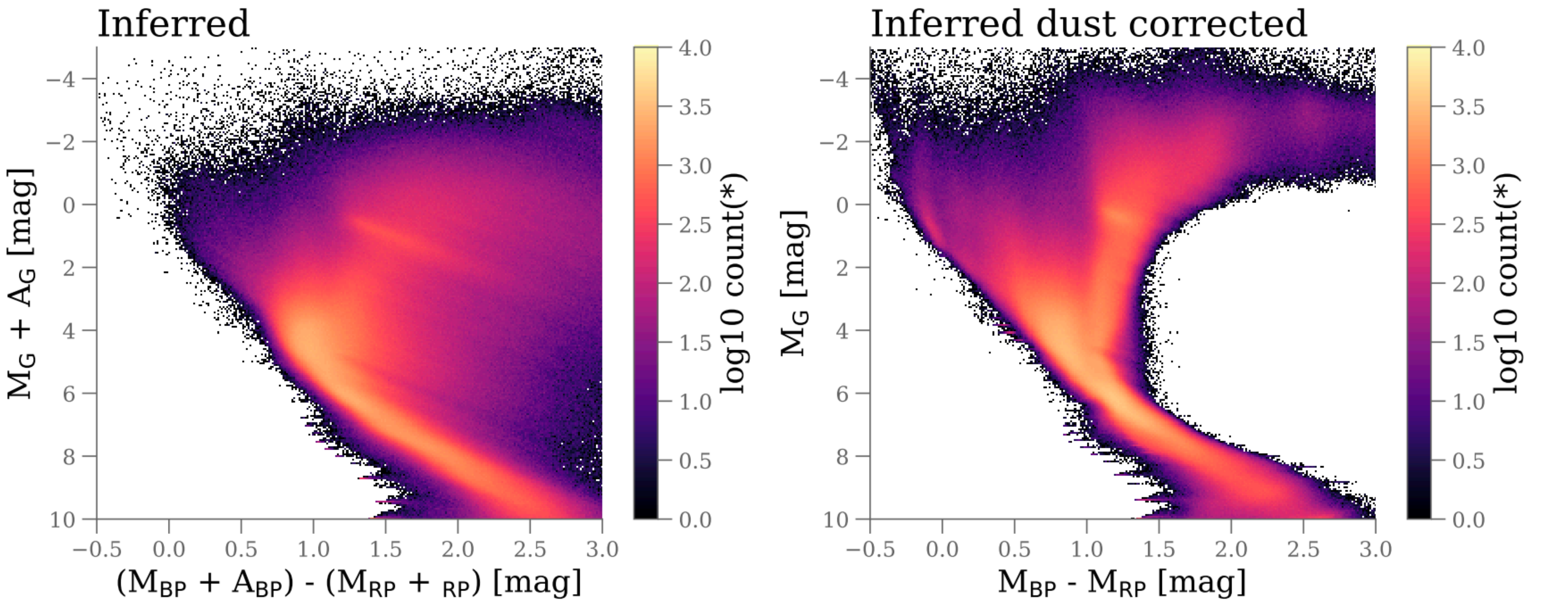



**Fig. B.2.** Inferred color absolute magnitude diagram (CAMD) before (left) and after (right) accounting for the dust extinction for the entire catalog.

Fouesneau+2022

# How do we derive interstellar extinctions

2. Pair method: comparing a reddened star and a dereddened star of the same type

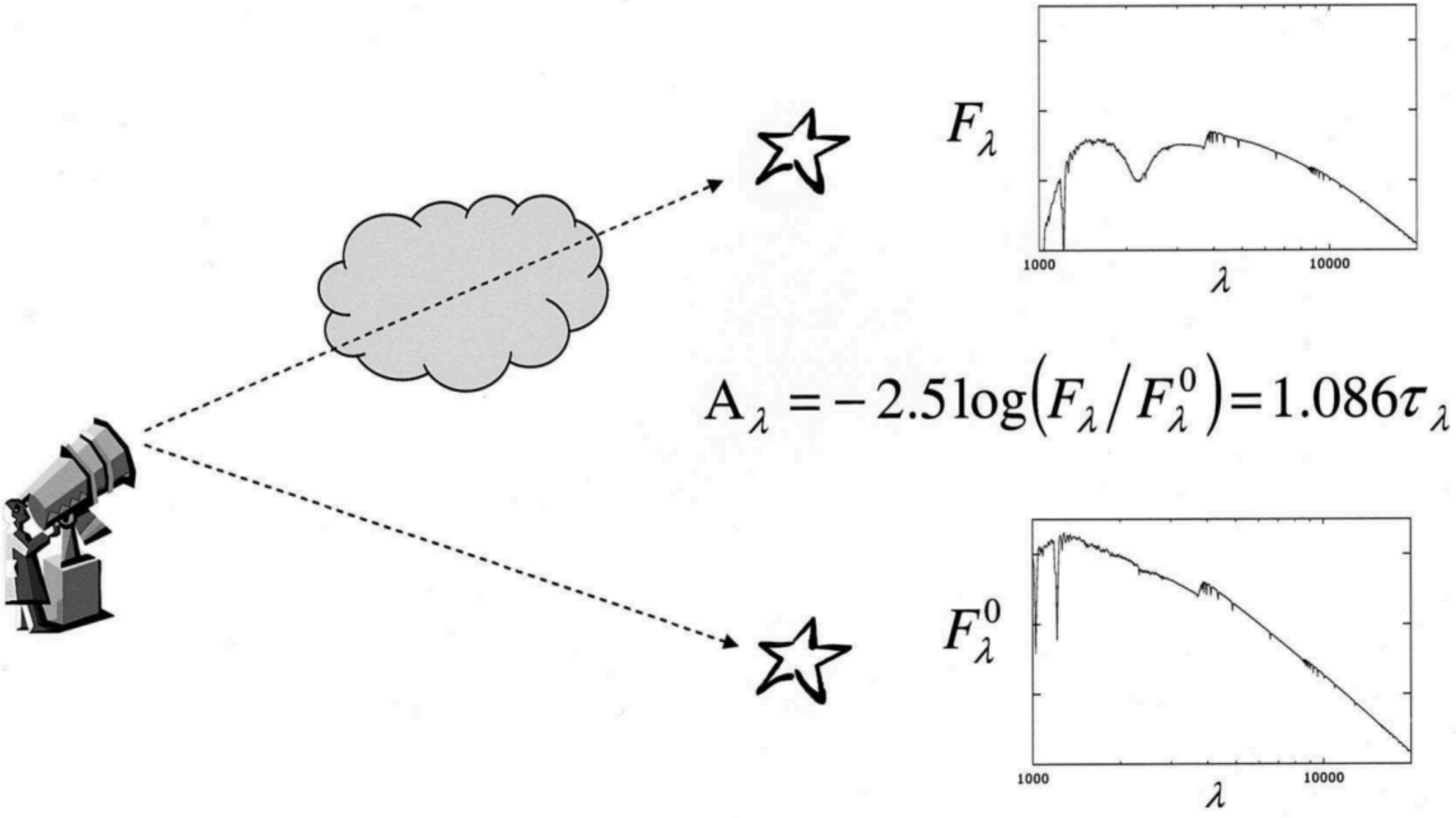
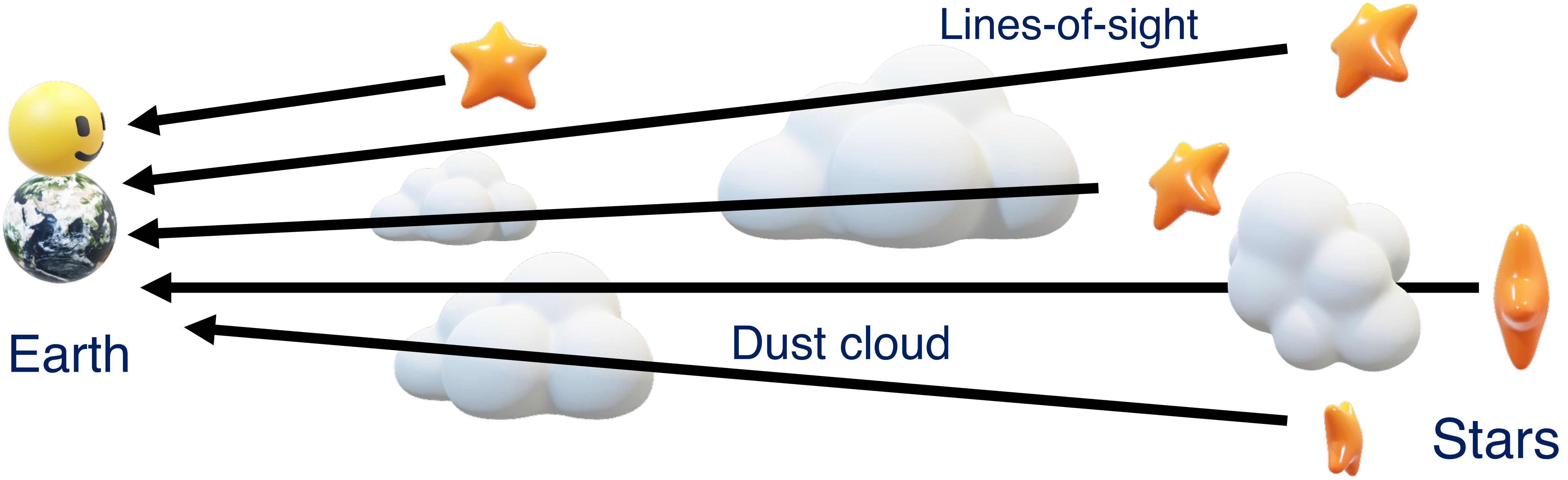



Fig. 1.— A schematic illustration of the "Pair Method," the principal technique used to study Milky Way extinction.

Fitzpatrick 2004

# Leveraging interstellar extinction to create multidimensional dust maps

Once we have enough stars with extinction parameters we can correlate between them to map the material in-between.




Stars passing through clouds will be more extincted and stars in low to no dust regions will be have none to little extinction and we can use this information to infer the amount of matter in between us and the star and what shape it takes.

# Leveraging interstellar extinction to create multidimensional dust maps

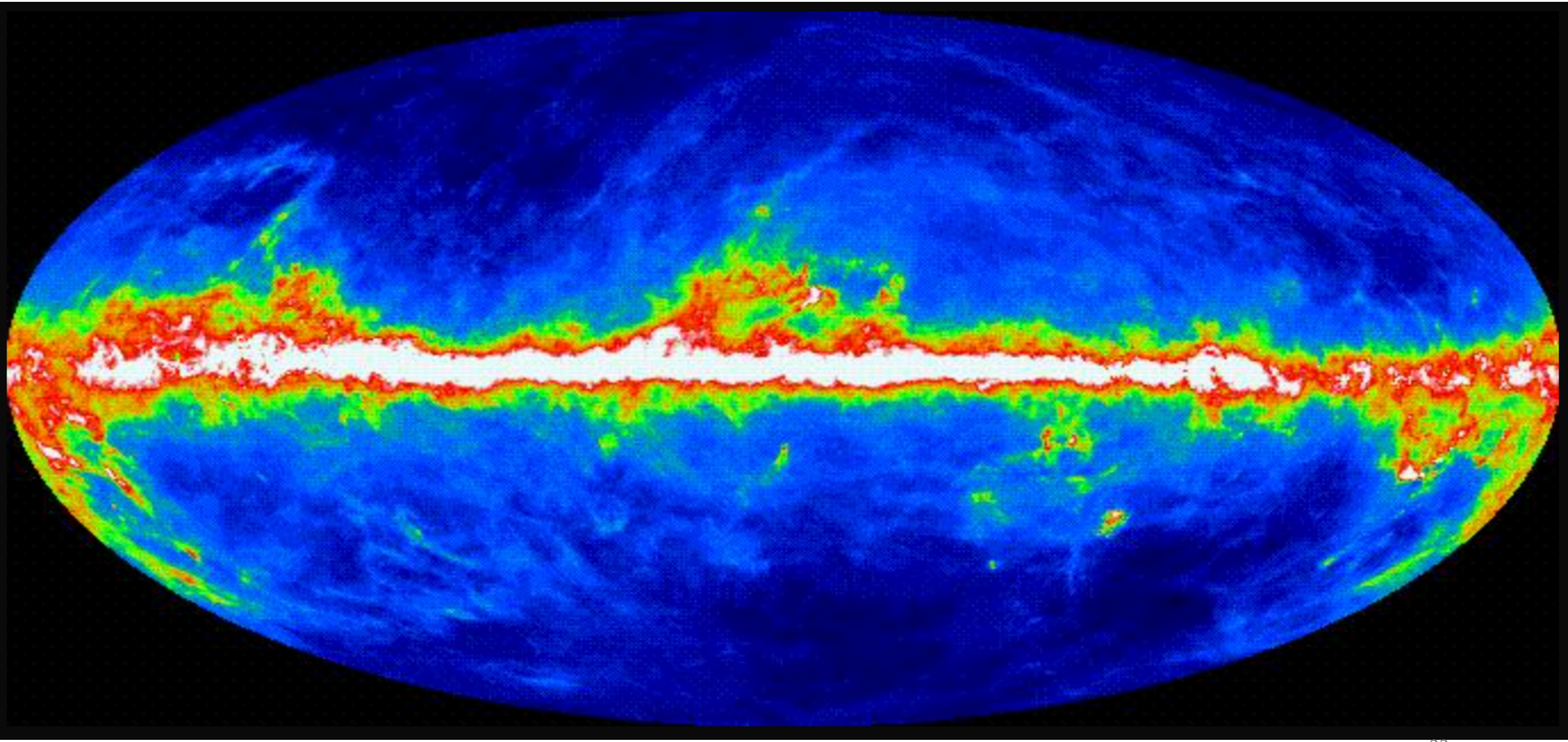
1. 2D dust extinction maps (pp, $A_V$)

2. 3D dust extinction maps (ppp, $A_V$)

3. 3D dust extinction + density maps (ppp, $A_V + \rho$)

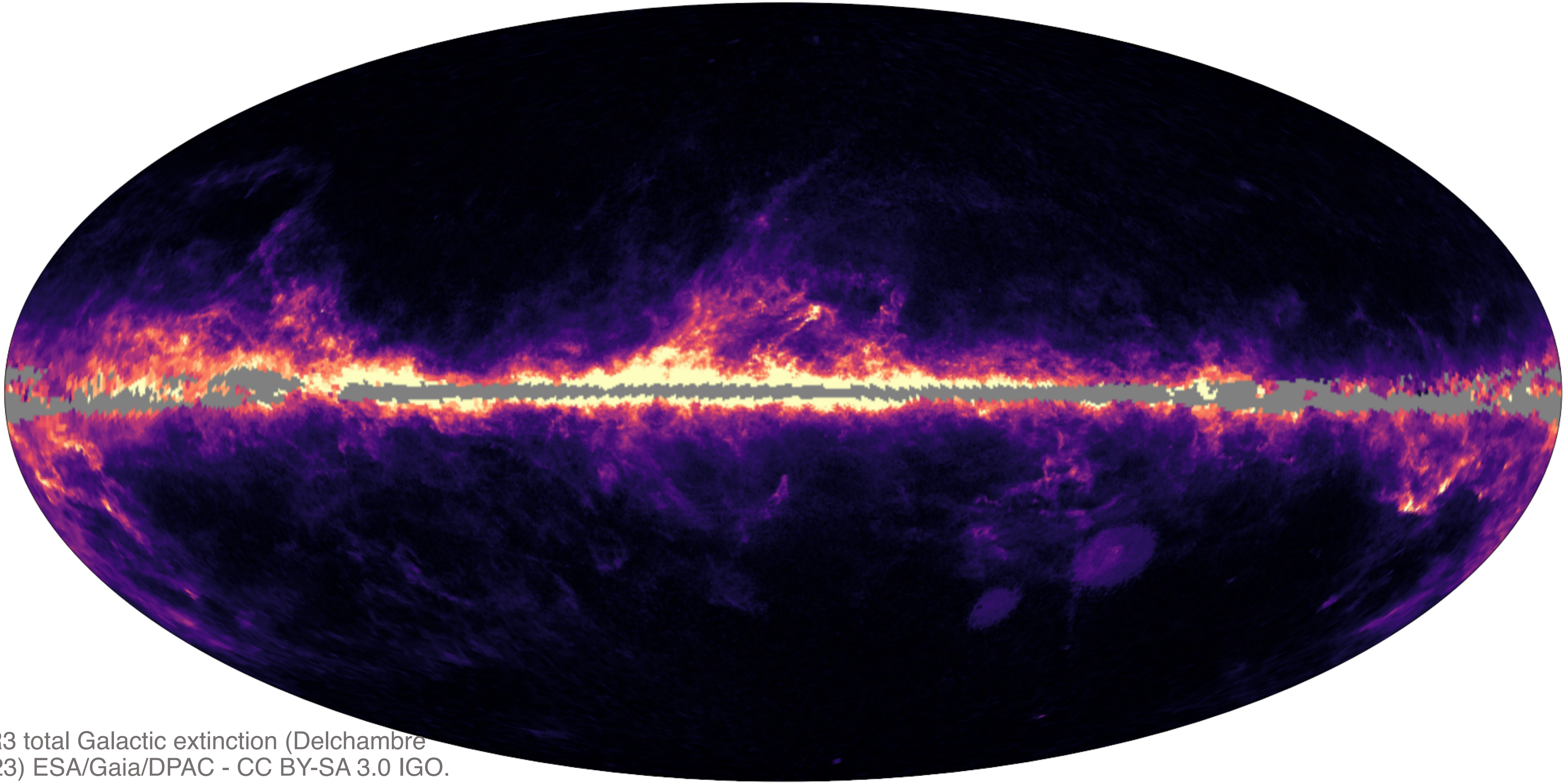
4. 4D dust extinction + density maps (pppv, $A_V + \rho$)

# 1. 2D dust extinction maps (pp: `l,b/ra,dec`)



Schlegel, Finkbeiner & Davis (1998) – COBE/DIRBE + IRAS data

# Important requirement for extragalactic studies: subtract the MW dust effects from observations

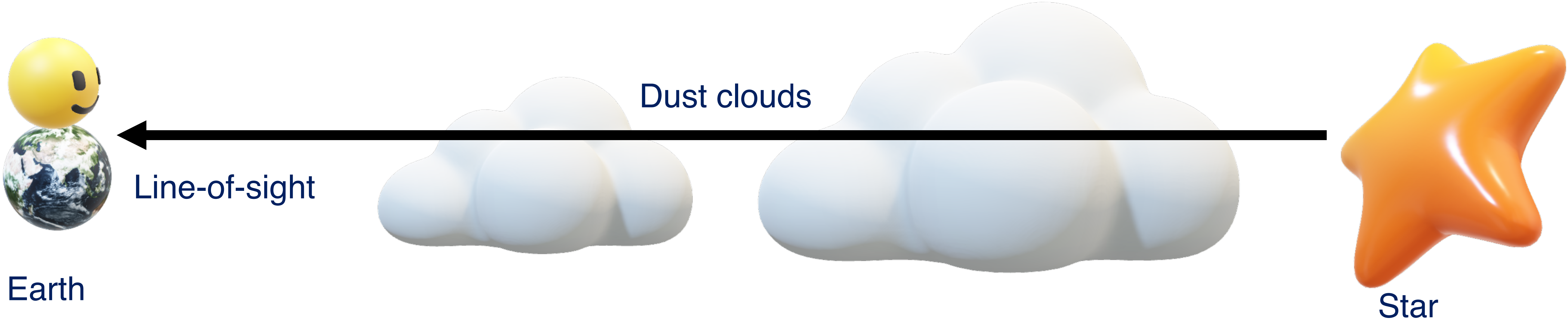


GDR3 total Galactic extinction (Delchambre +2023) ESA/Gaia/DPAC - 
Acknowledgements: Created by T.E.Dharmawardena, Gaia group @ MPIA.

# 2D dust extinction maps for Galactic structure - not great!

2D extinction: Integrated quantity (cumulative as you go along los) – lose information along los!

We can't see behind the wall of extinction.

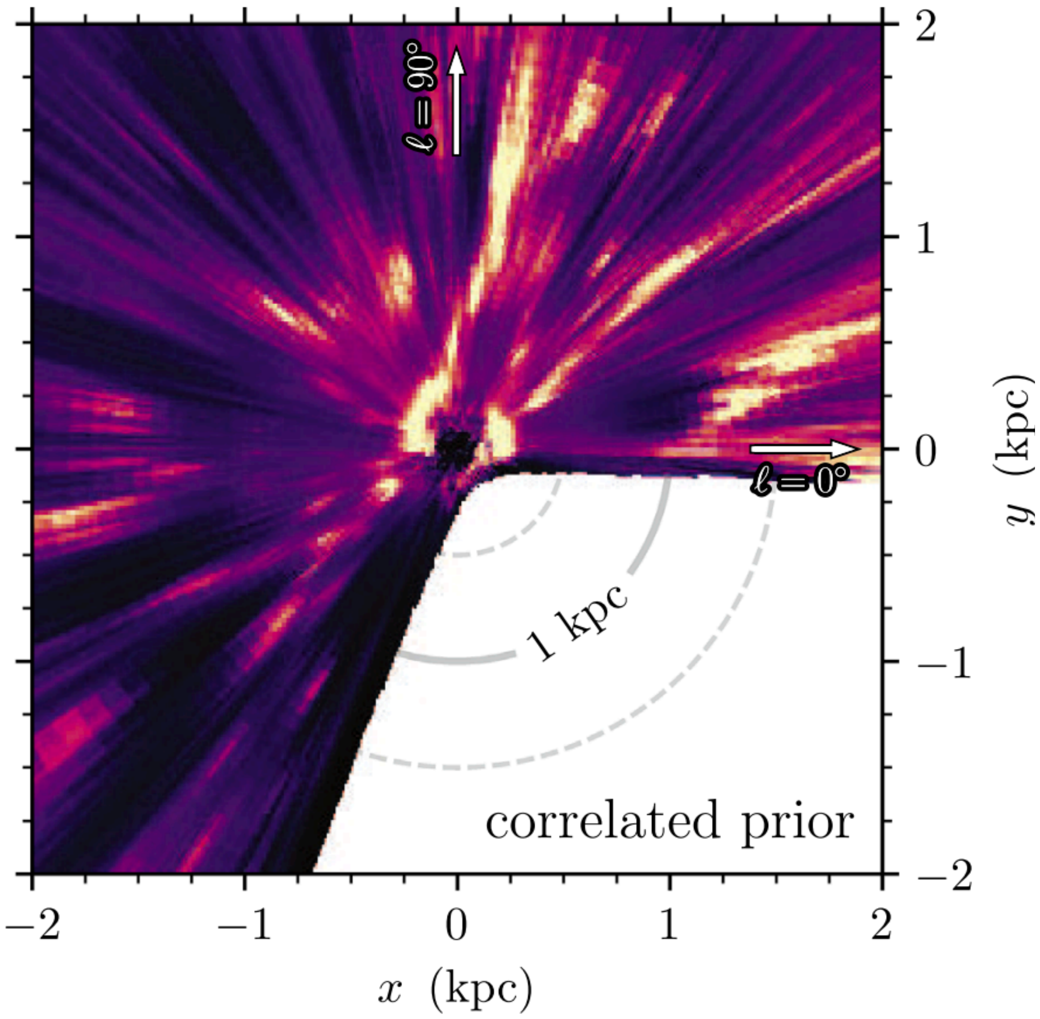


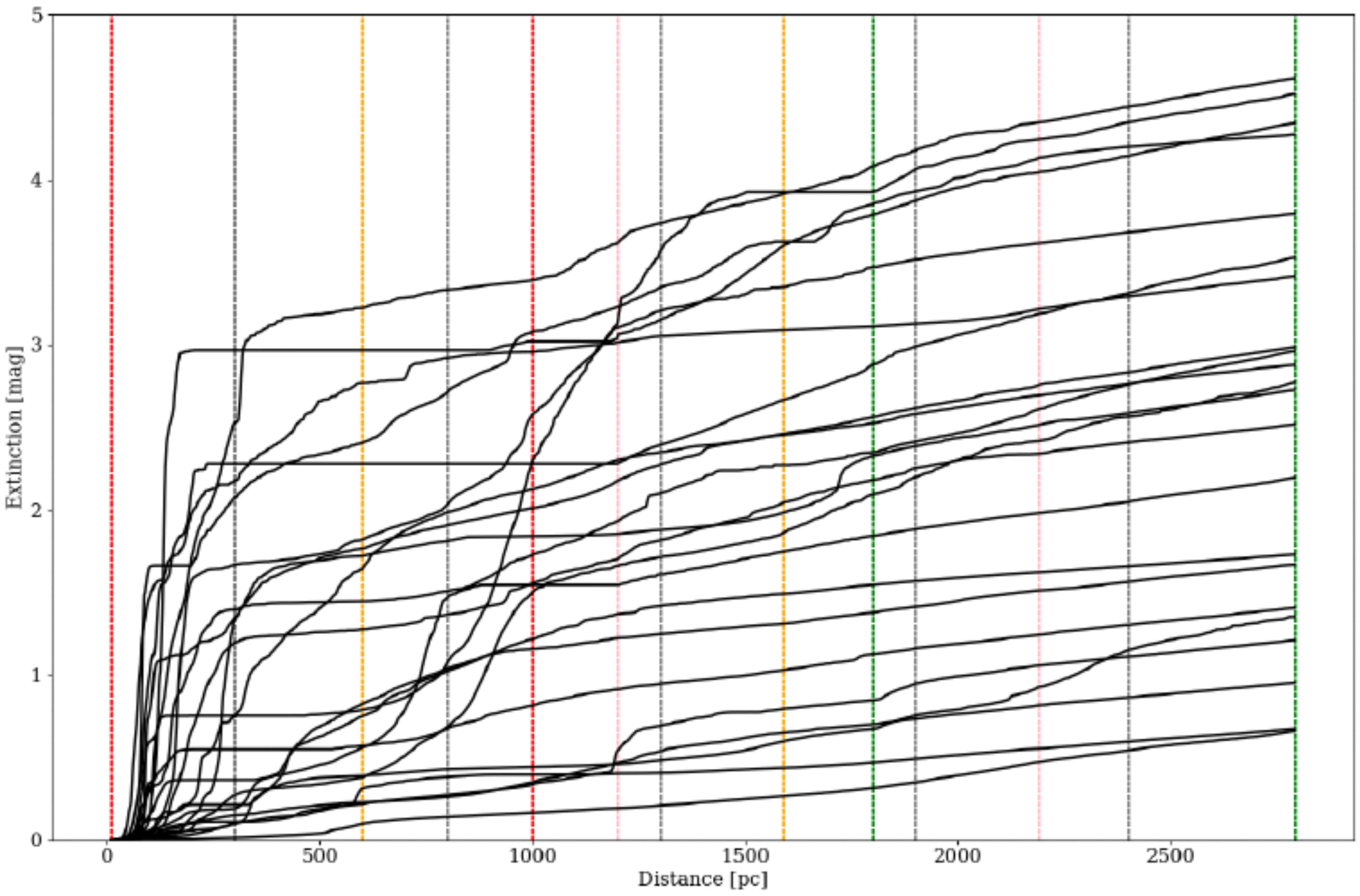

Cumulative (total) extinction = cloud 1 extinction + cloud 2 extinction

# 2. 3D dust extinction maps (ppp, $A_V$: `l,b/ra,dec, d, `$A_V$)

Extinction still integrated – loss of information due to “averaging” out of structure persists.

Extinction is monotonically non-decreasing: can lose small scale and low density regions.




Left: Green+2019 top down view of Milky Way 3D dust extinction



Right: Dharmawardena+subm.,Los extinction of the Milky Way.

# Dust extinction and density relationship

$$A_V = \int_0^s \rho \, ds$$

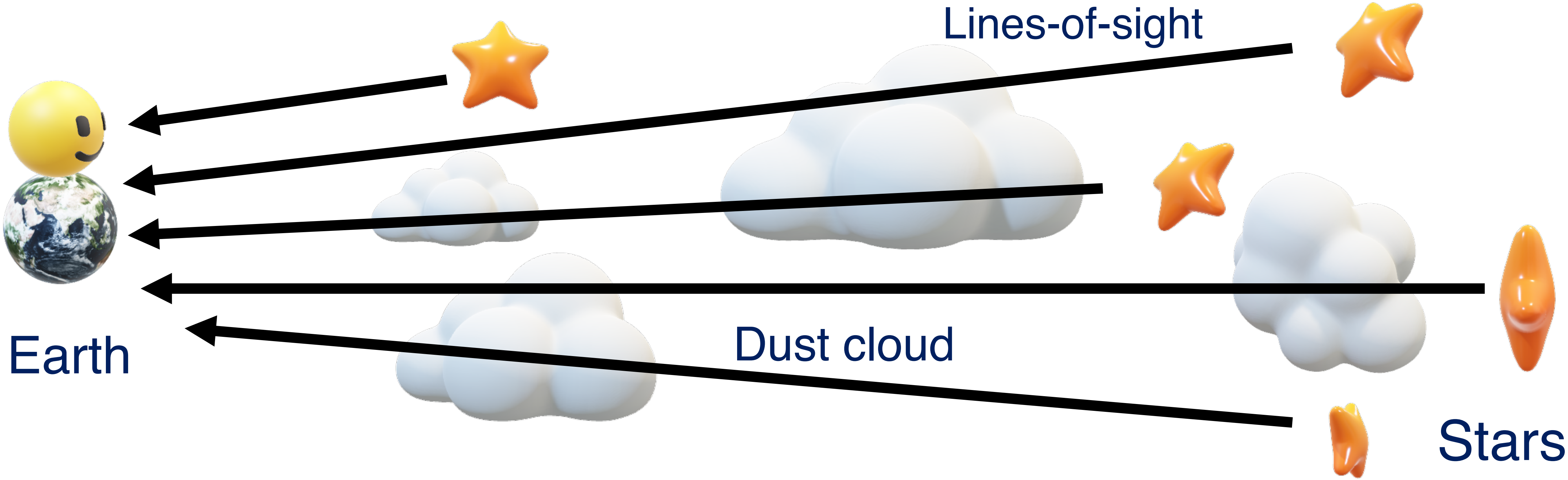
$A_V$ : Dust Extinction (Observed)

$\rho$: Dust density (need to be inferred – can not be directly observed!)

$s$: Distance of emitting source (path length of los)

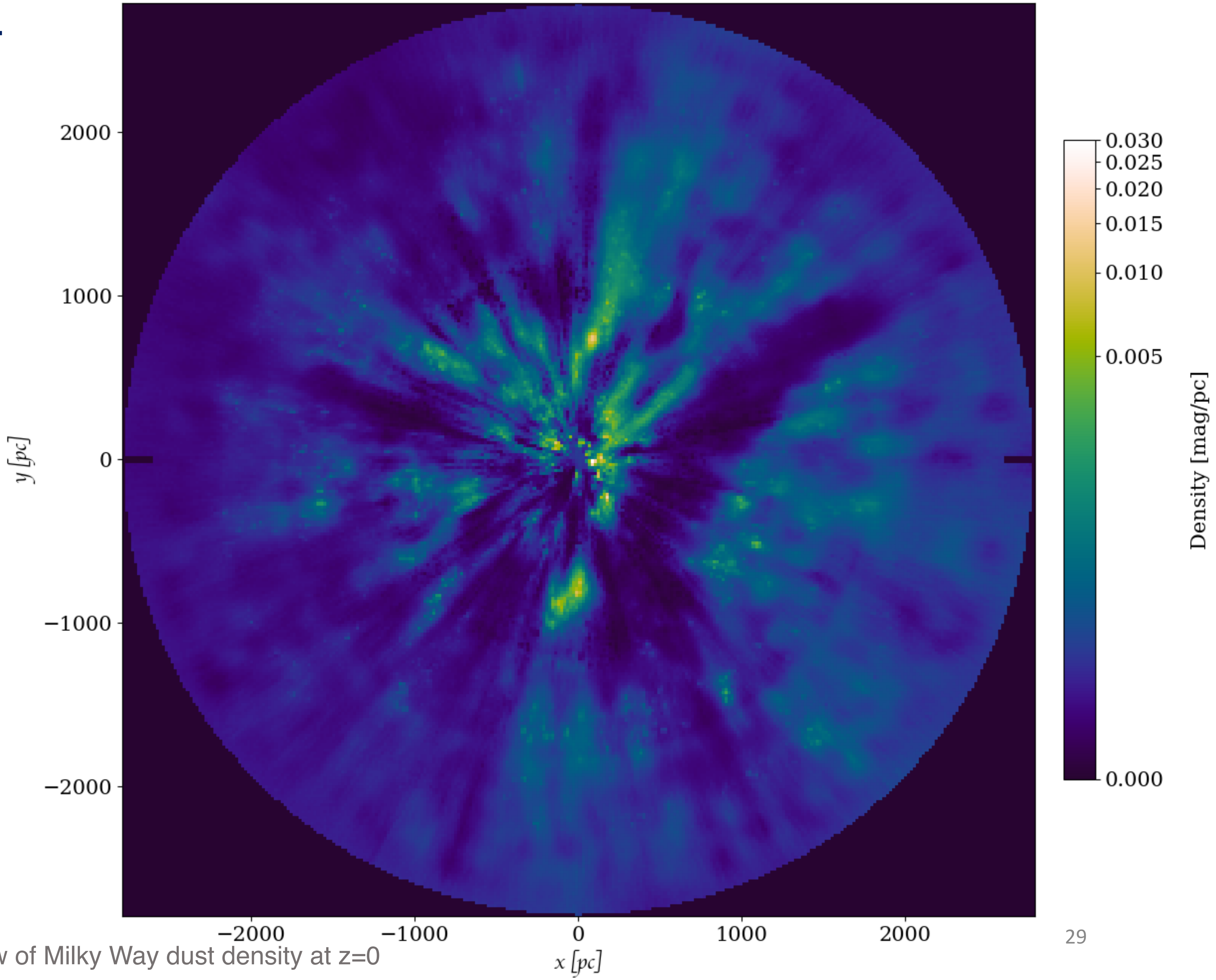
# Dust extinction and density relationship

$$A_V = \int_0^s \rho \, ds$$



# 3. 3D dust extinction + density maps (ppp, $A_V + \rho$: `l,b/ra,dec, d,` $A_V + \rho$)

Expanded on later




Right: Dharmawardena+subm., Top down view of Milky Way dust density at z=0

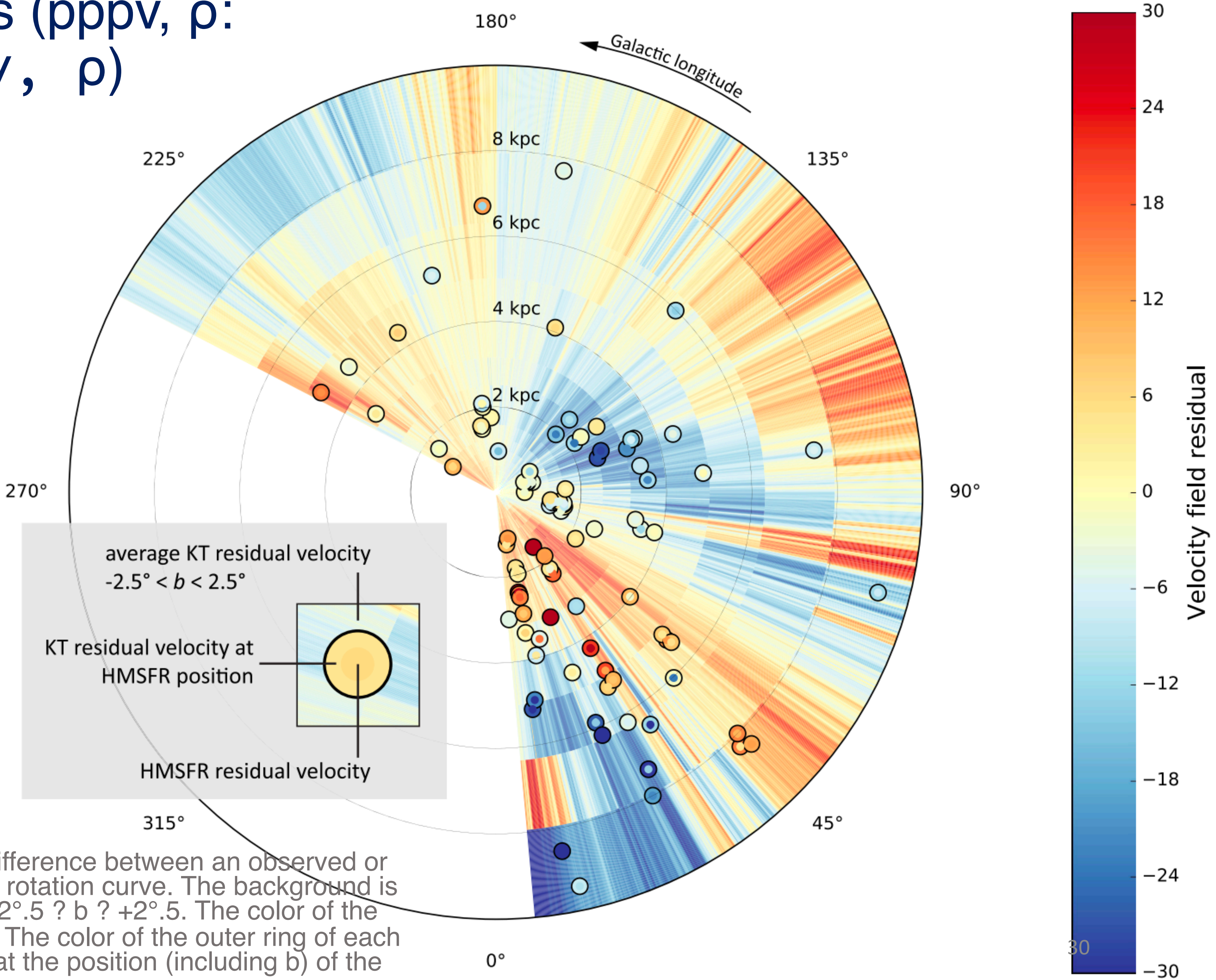
# 4. 4D dust density maps (pppv, ρ: l,b/ra,dec, d, v, ρ)

Dust 3D maps: ppp

Gas maps (CO/HI etc..): ppv

Associate velocity to dust: motion of the dust.

Dust maps constrain the distances which the ppv maps can't.




Tchernyshyov and Peek 2017: Colors show the difference between an observed or estimated vlos and the value predicted from a flat rotation curve. The background is an average of the KT-derived velocity field over –2°.5 ? b ? +2°.5. The color of the inner part of each circle is the vlos of an HMSFR. The color of the outer ring of each circle is the value of the KT-derived velocity field at the position (including b) of the HMSFR

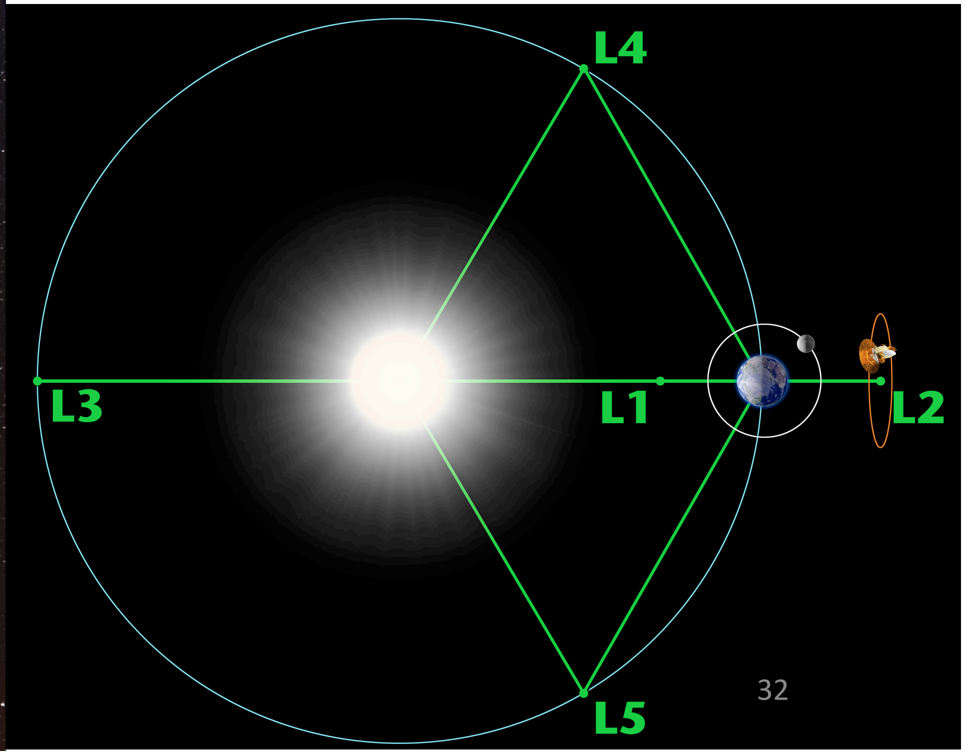
# Part 2:
# The Gaia revolution

Part 2 of 4

# ESA Gaia Mission

Launch: December 2013; located L2

Goal: A global space astrometry mission, building the largest, most precise three-dimensional map of our Galaxy by surveying nearly two billion objects.




Left: ESA/ATG medialab; background: ESO/S. Brunier

Right: NASA/WMAP Science Team

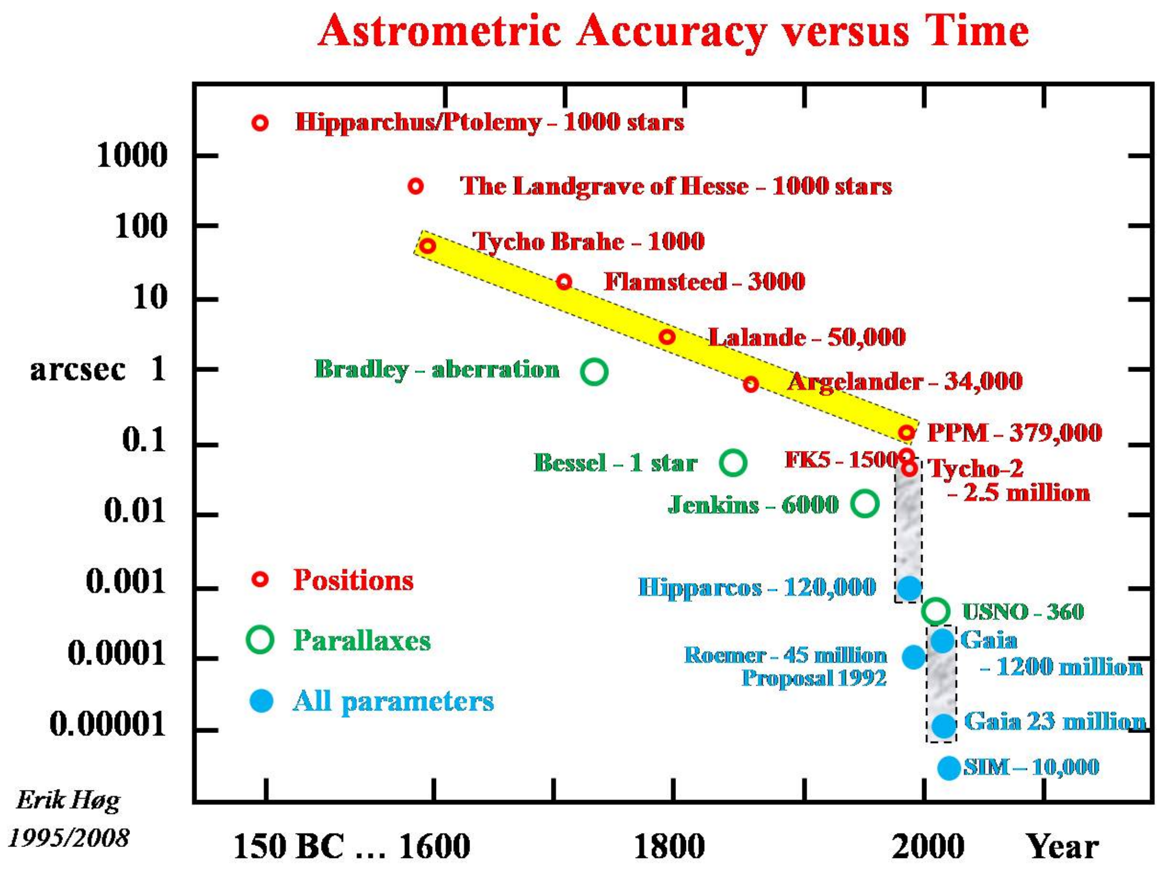
# Gaia Astrometry

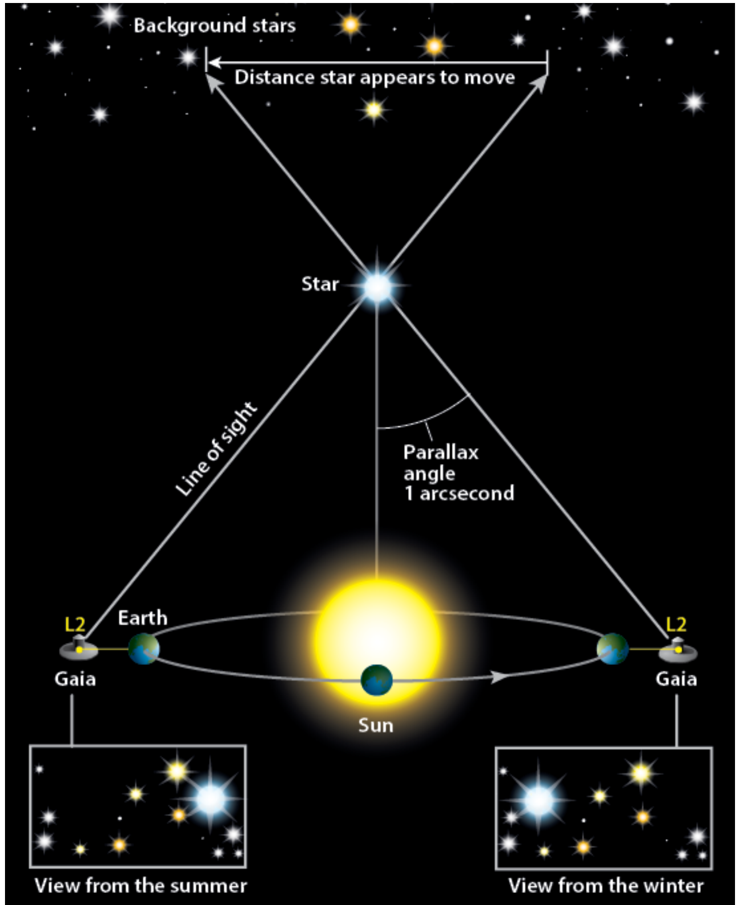
Repeatedly measure: positions, parallax distances, movements, and changes in brightness of all objects down to magnitude 20.

Each star will be measured about 14 times on average.

Objects brighter than magnitude 15: positions accuracy – 24 µas (comparable to measuring the diameter of a human hair at a distance of 1000 km)

Stars near Galactic centre (9 kpc away): distance accuracy 20%.




To understand the distances between stars, astronomers rely on a method called parallax. By measuring the distances stars appear to move relative to other stars, astronomers can gauge how far away they are from us and from each other. ASTRONOMY: ROEN KELLY

Left: Høg 2011

Right: Astronomy. Roen Kelly

# Gaia Data Releases

DR1: September 2016

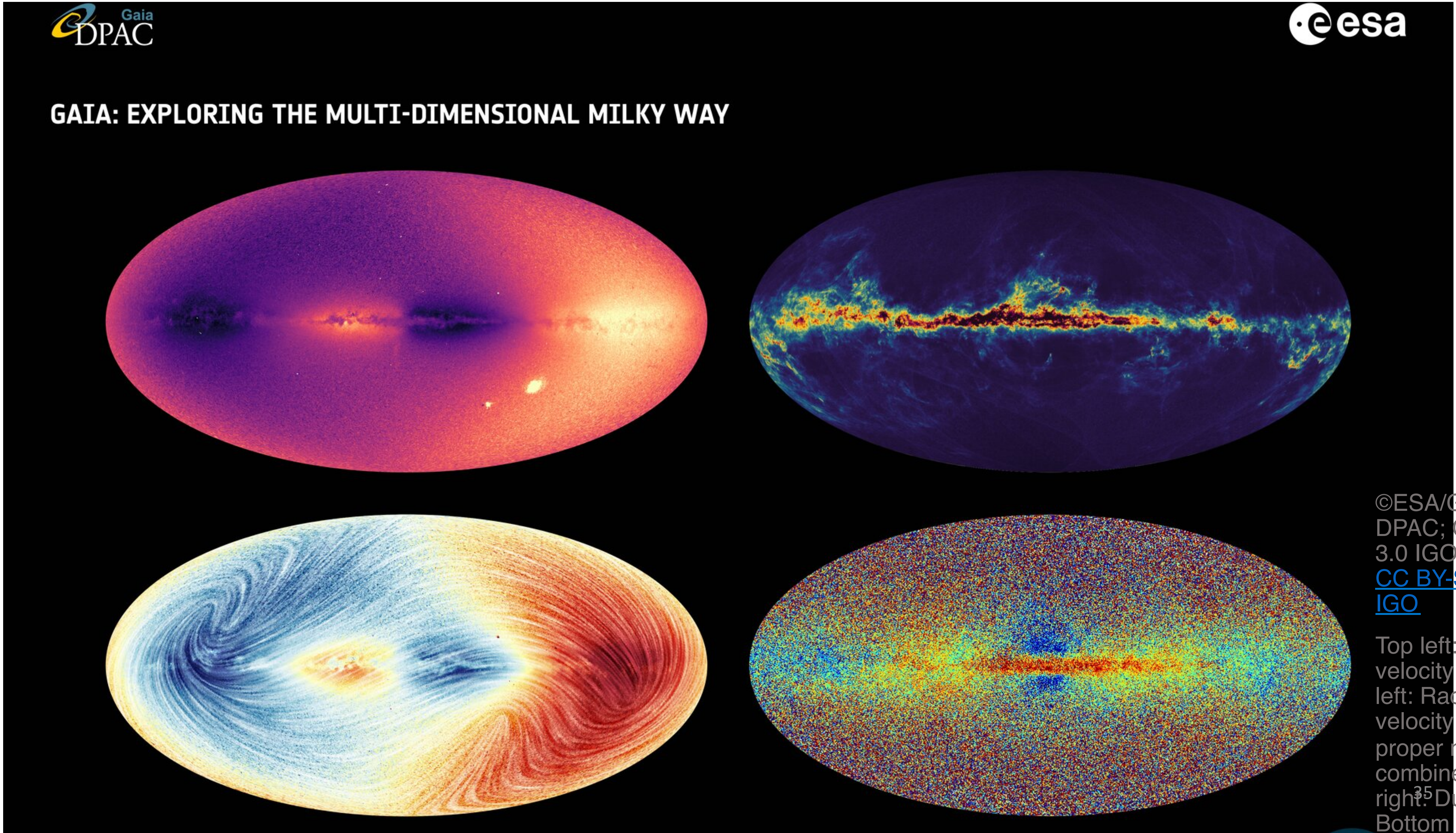
DR2: April 2018

DR3: December 2020 (E-DR3) and June 2022

DR4: not before the end of 2025

DR5: end of 2030

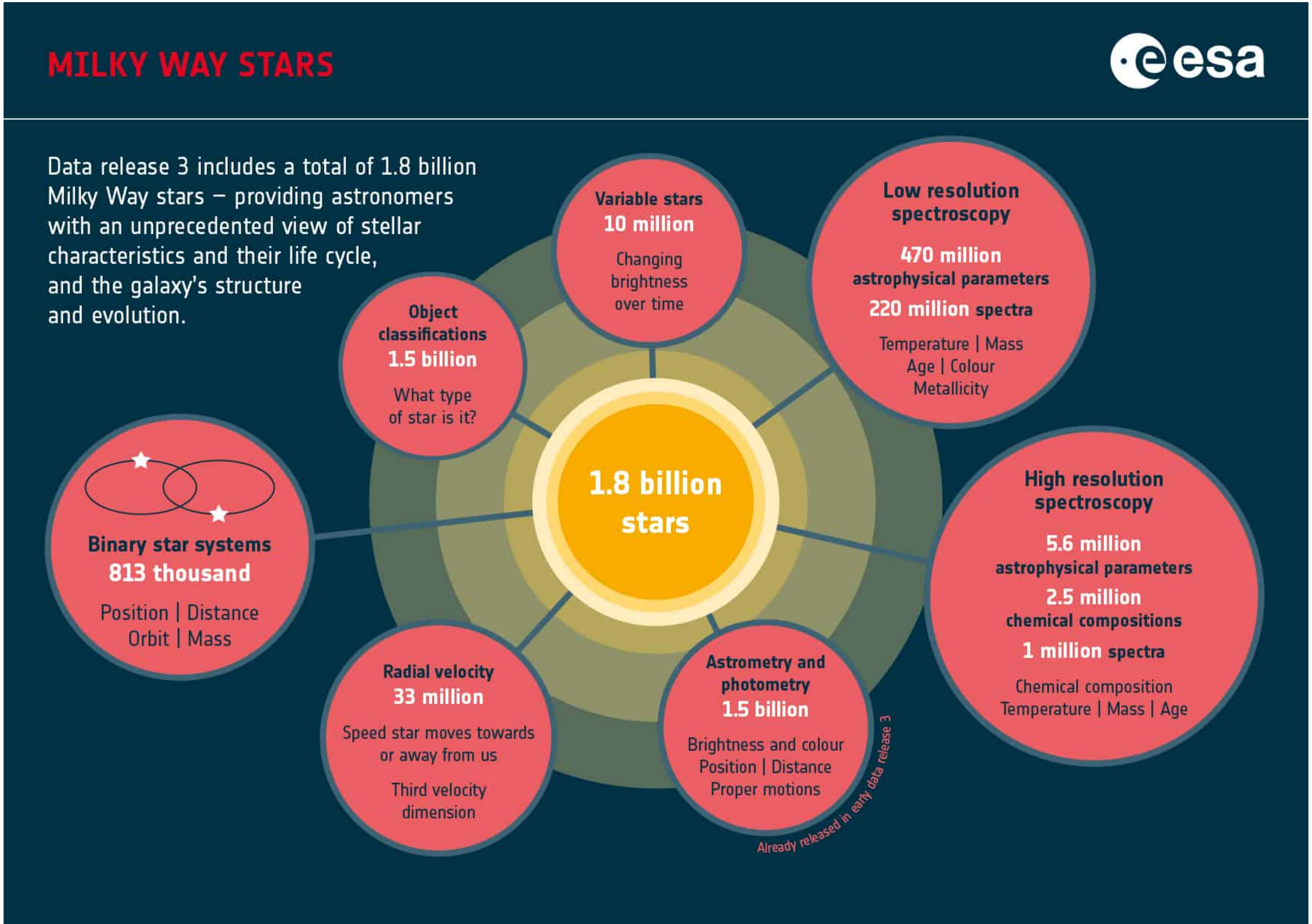
# Gaia Data Release 3 (GDR3) – Multidimensional view of the Milky Way






Top left: Radial velocity; Bottom left: Radial velocity and proper motion combined; Top right: Dust; Bottom right:

# Gaia Data Release 3 (GDR3)

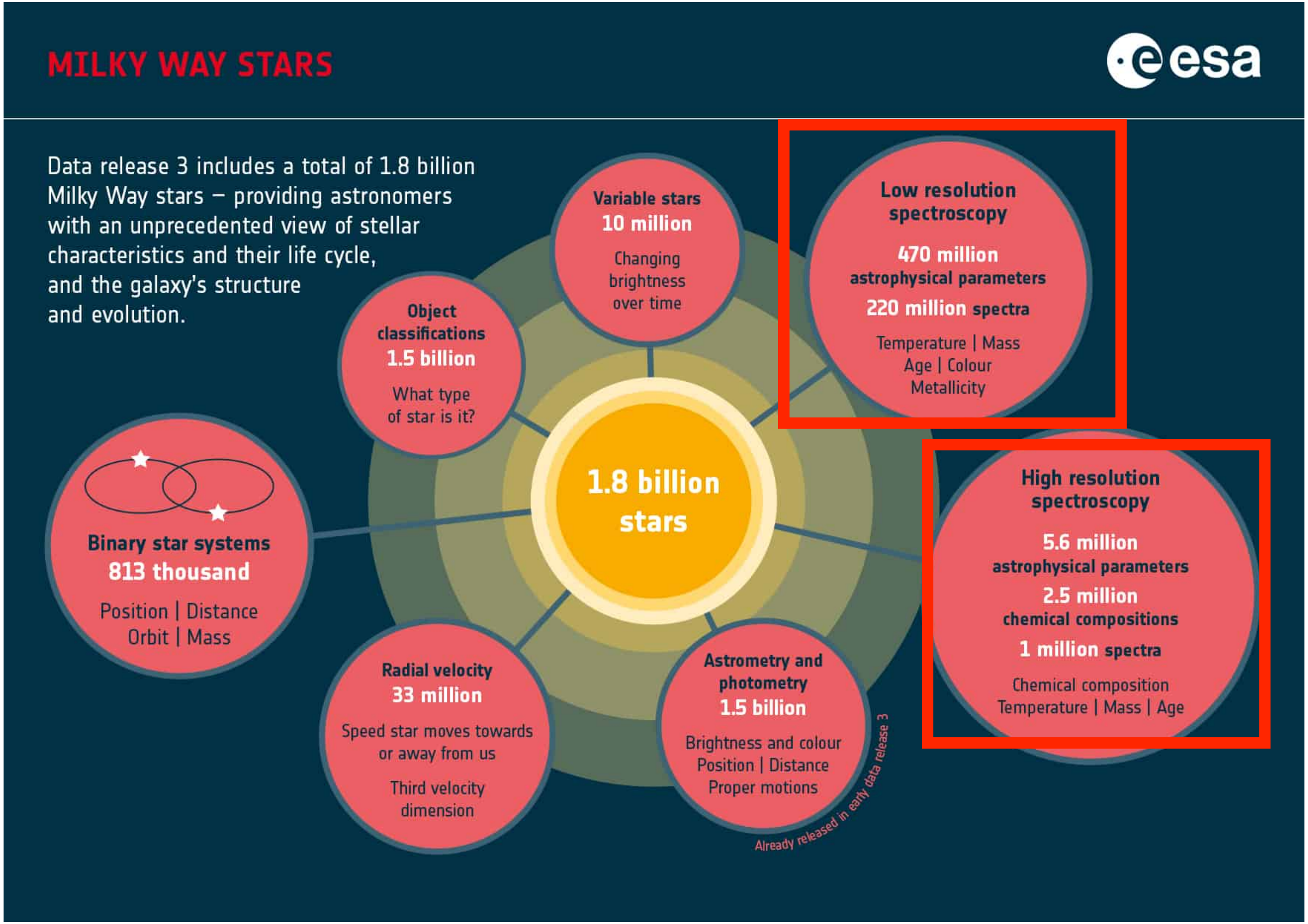



Positions parallax, proper motion: ~1.46 billion sources,

Limiting magnitude: G ≈ 21 and a

bright limit: G ≈ 3.

# Gaia Data Release 3 (GDR3)



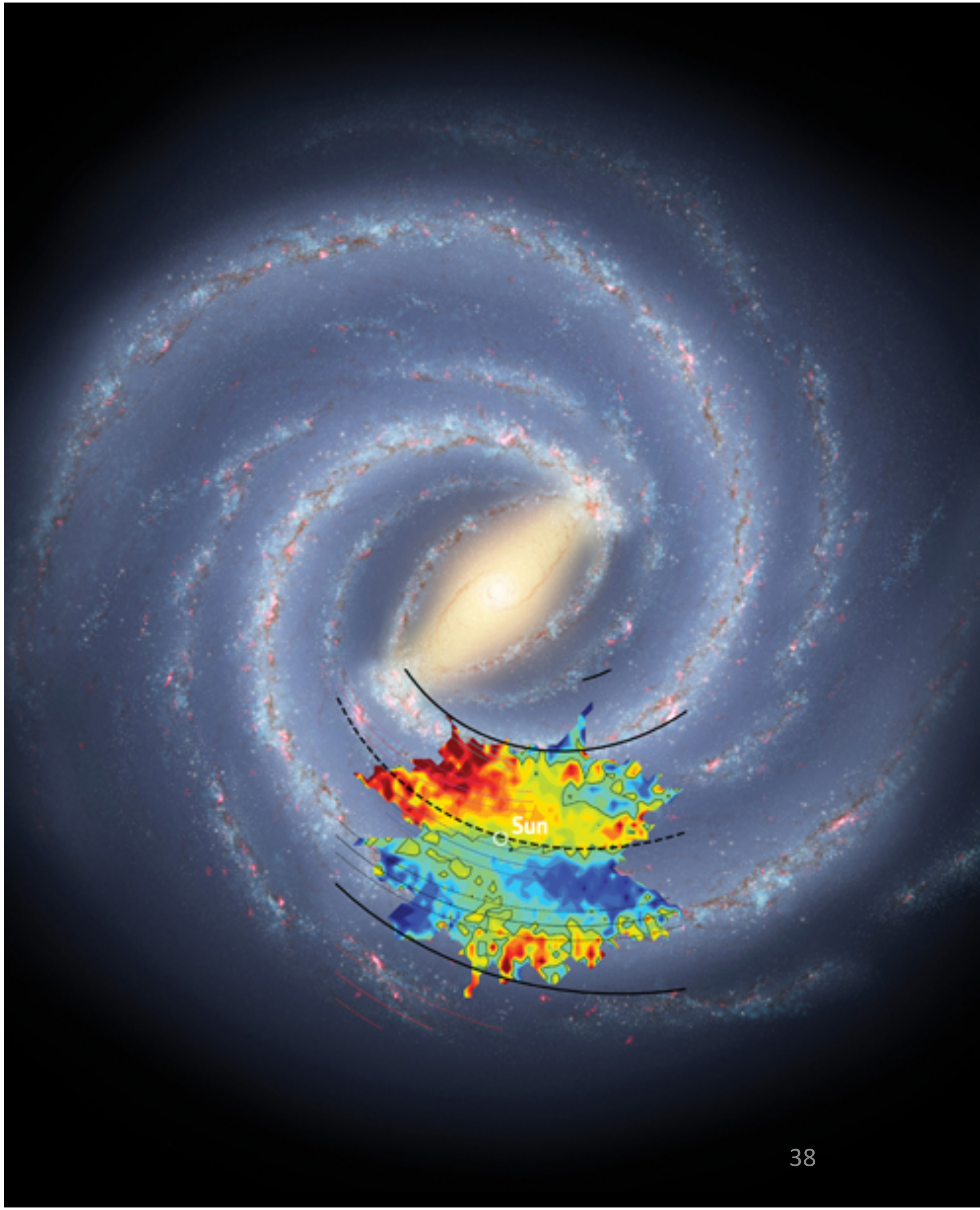

Andrea et al., 2022: Astrophysical parameters ($T_{eff}$, logg, [M/H], $A_V$, distance, etc.) from BP/RP spectra for 470 million objects.

Mean BP/RP spectra for 219 million sources, most with G < 17.6 mag.

Mean RVS spectra for 1 million *well-behaved* objects.

External products (EDR3): Bailer-Jones distances (photo-geometric distances)

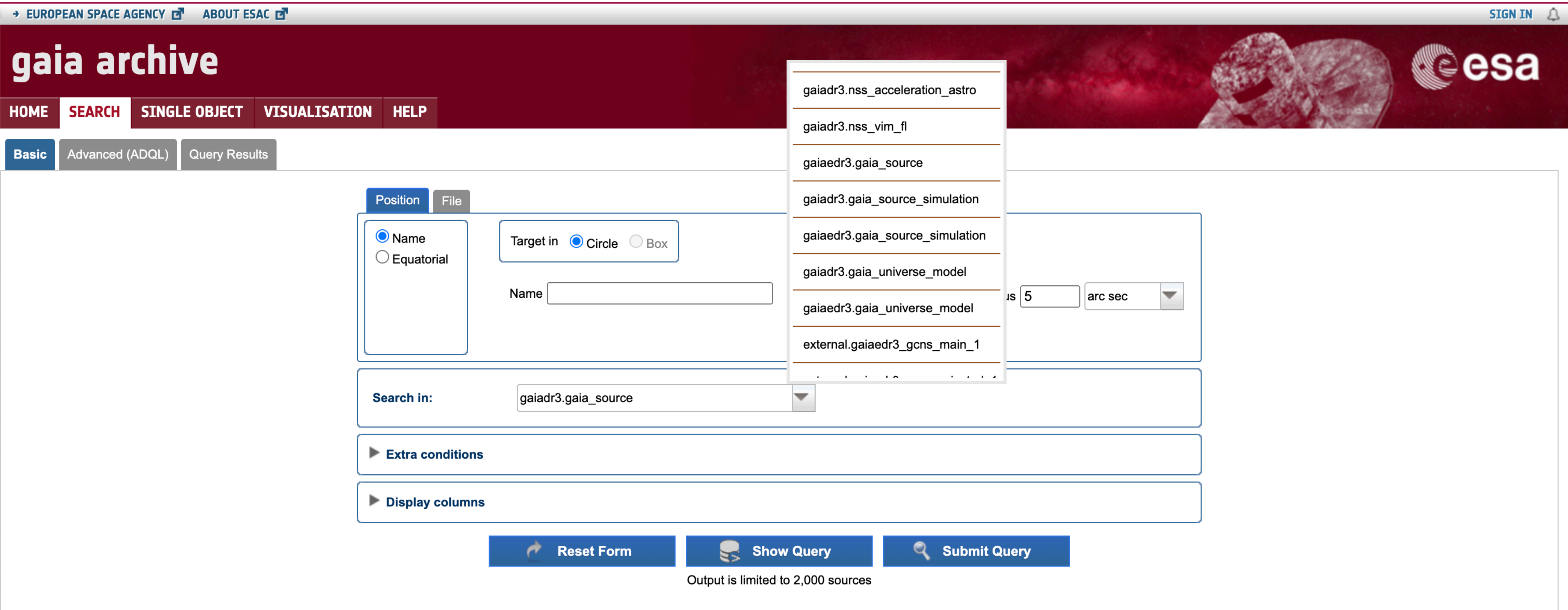
# DR3 footprint




Robert Hurt. Gaia data on stellar velocities is superimposed on a scientifically informed rendering of the Milky Way's spiral arms. The velocity map shows the velocities toward or away from the galactic center, going from 10 kilometers per second away from the galactic center (red), to 10 kilometers per second toward the galactic center (blue).

# DR3 data access: ESA Gaia Archive

https://gea.esac.esa.int/archive/



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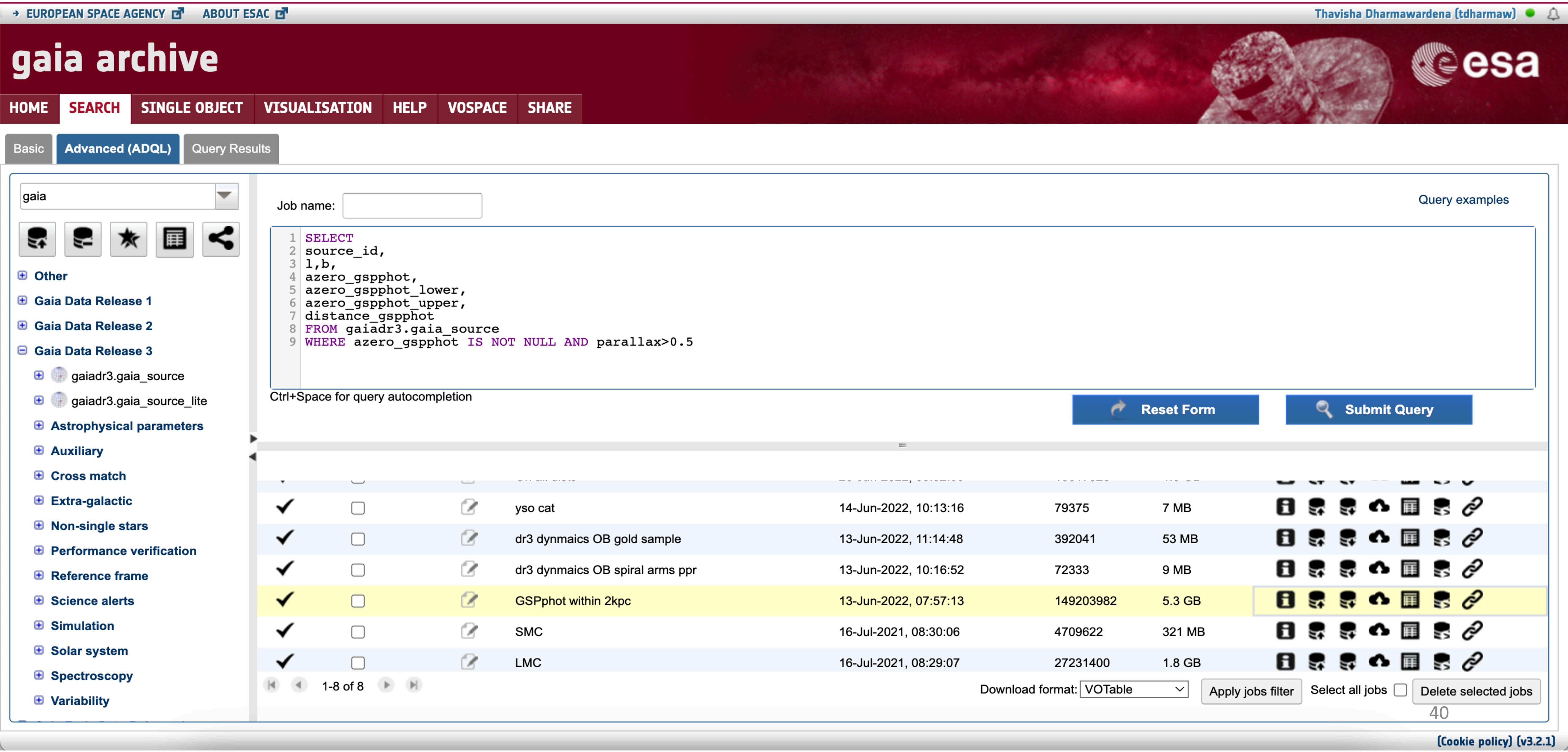


# Gaia low resolution BP/RP (XP) spectra

Two prisms – 2 spectra

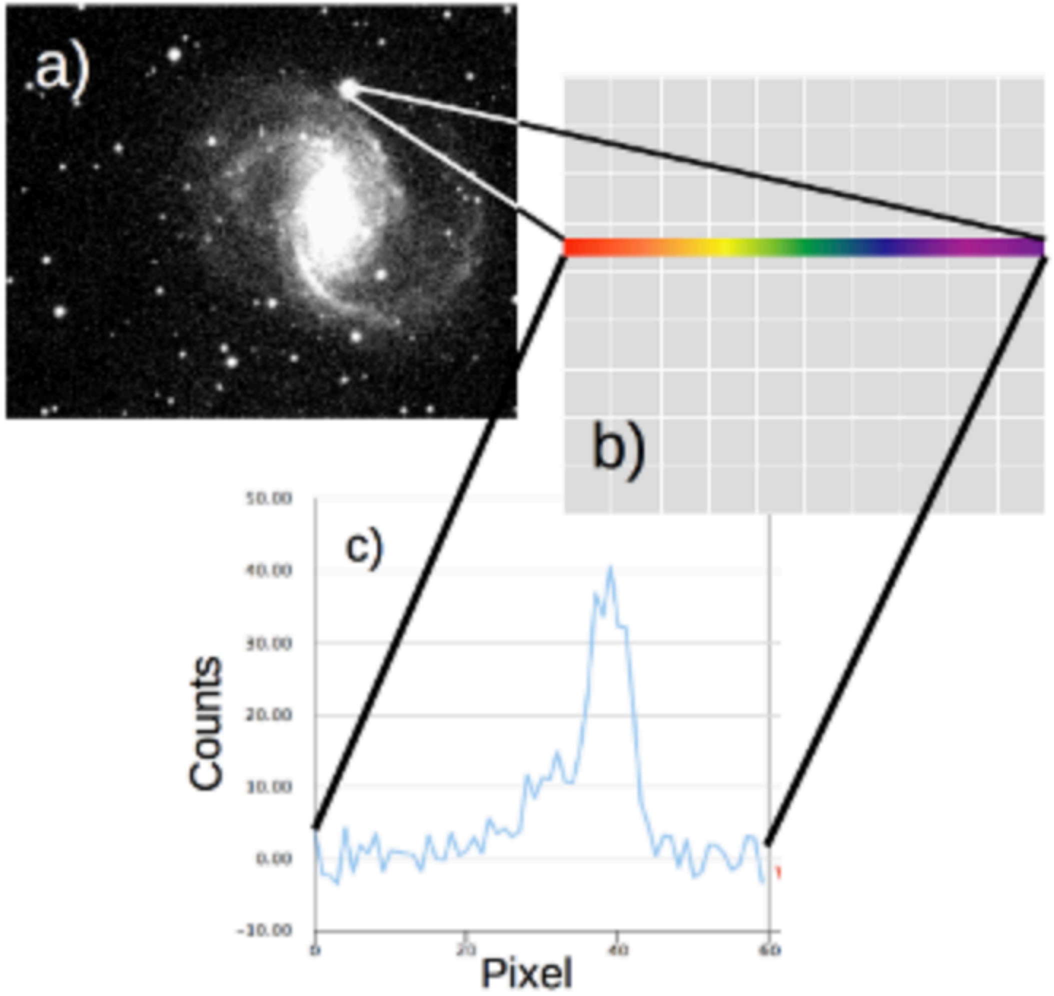
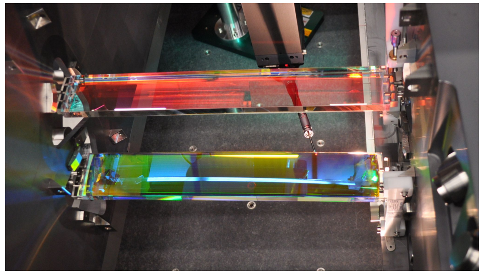
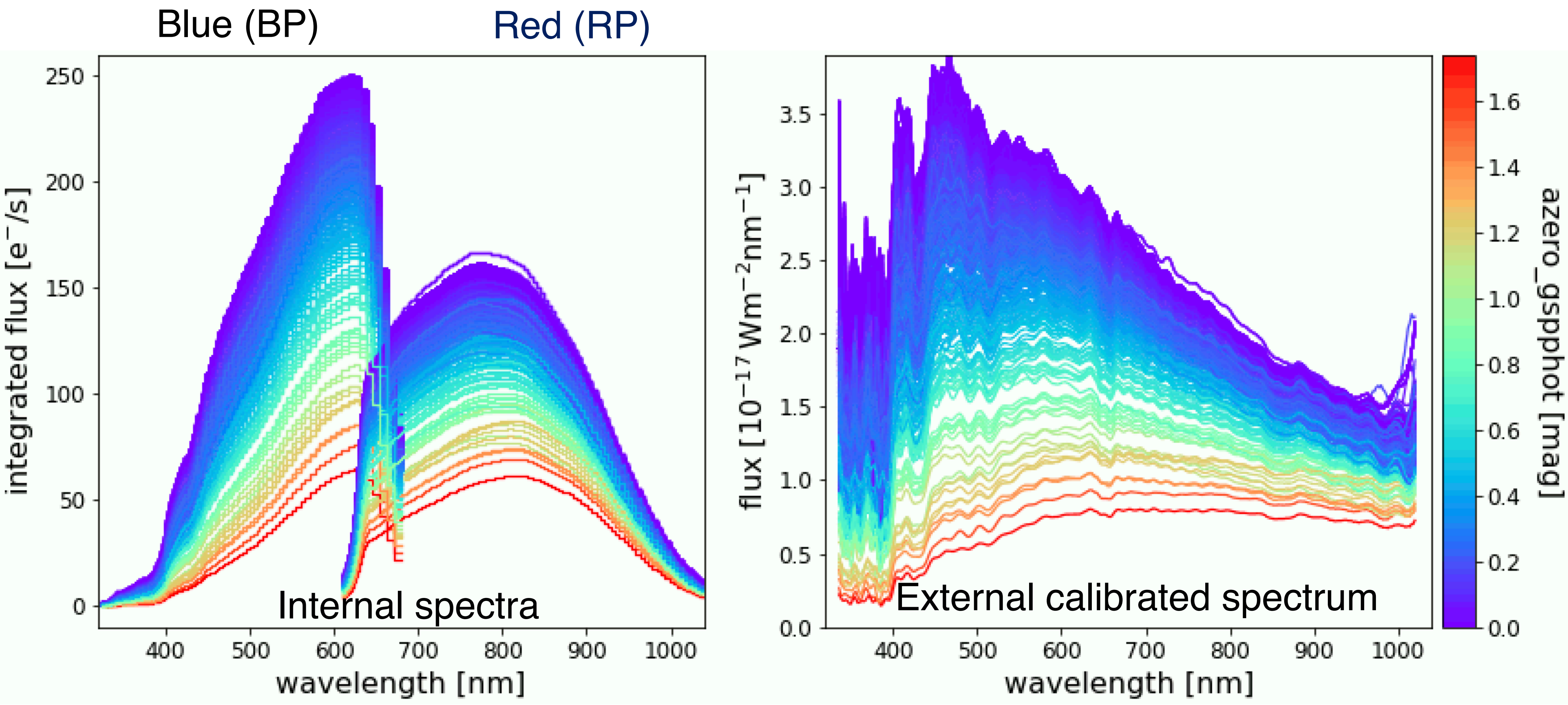



Figure 1 – How spectra are obtained by Gaia. The light from the target (a) is spread out in wavelength, making a spectrum (b). This spectrum is measured by a CCD, and the counts in each pixel are plotted on the Gaia Alerts web pages (c).



2013 Gaia UK, Institute of Astronomy, University of Cambridge.

# Gaia low resolution BP/RP (XP) spectra




Low-resolution: ~20-60.

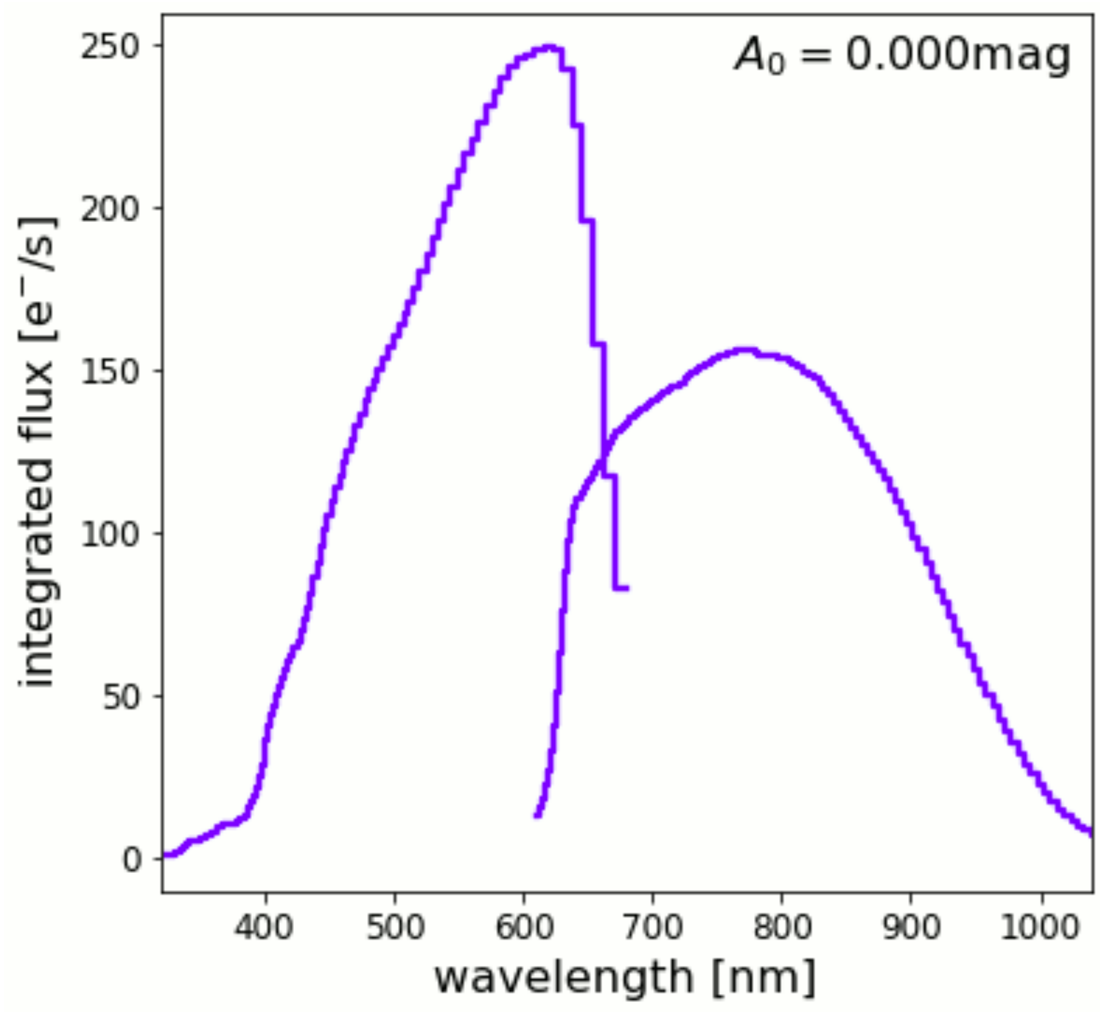
BP: 330 - 680 nm, while the

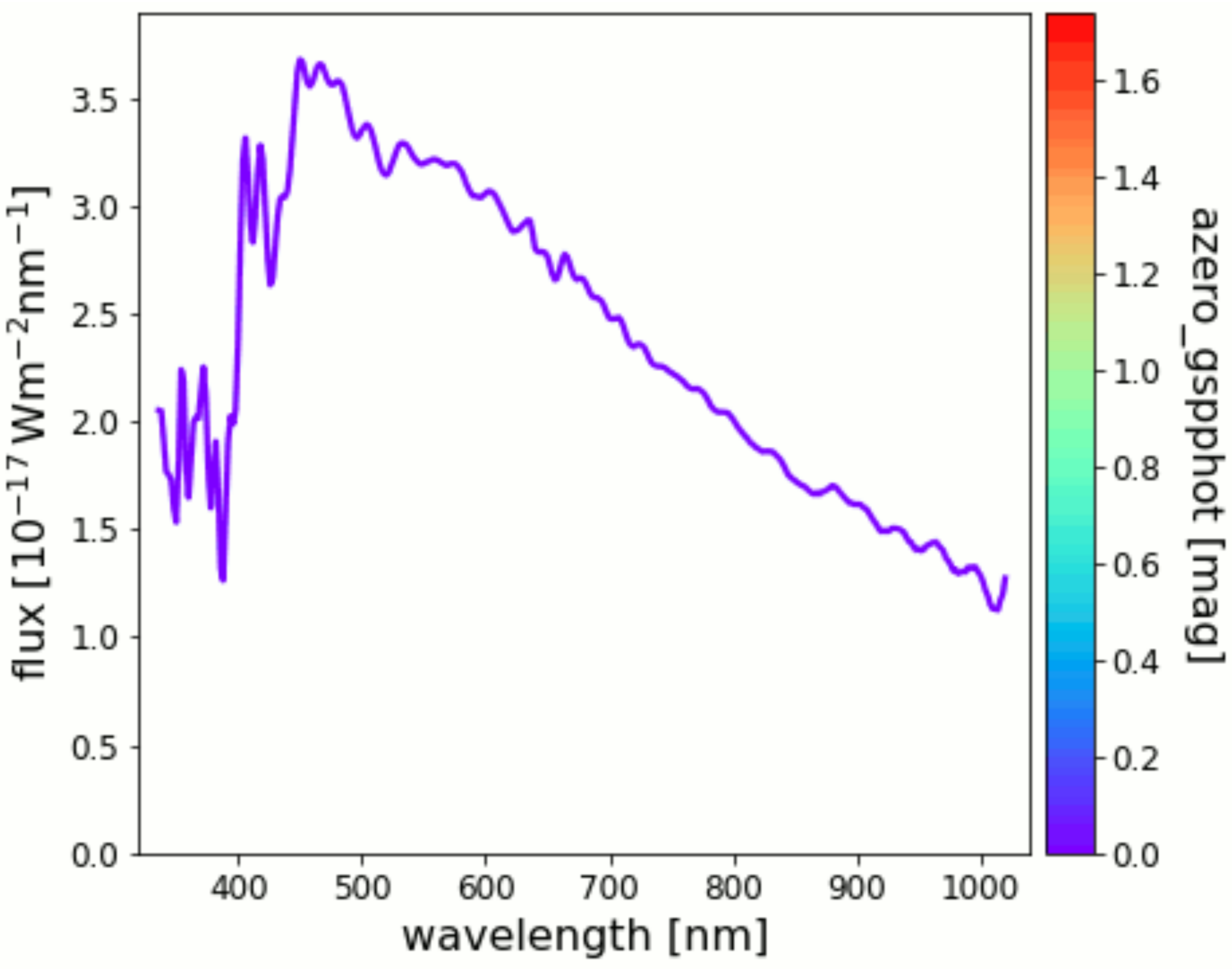
RP 640 - 1050 nm.

Gaia Collaboration, Creevey et al. 2022 A&A. Acknowledgements: Rene Andrae, Andreas Korn, Anthony Brown, Orlagh Creevey.

# Variation of Gaia BP/RP (XP) spectra with Extinction

Despite low resolution - XP spectra contain loads of information: e.g: absorption/emission features.




The images in this animation are adapted from those presented in [Gaia Collaboration, Creevey et al. 2022 A&A](#).
Acknowledgements: Rene Andrae, Andreas Korn, Anthony Brown, Orlagh Creevey.

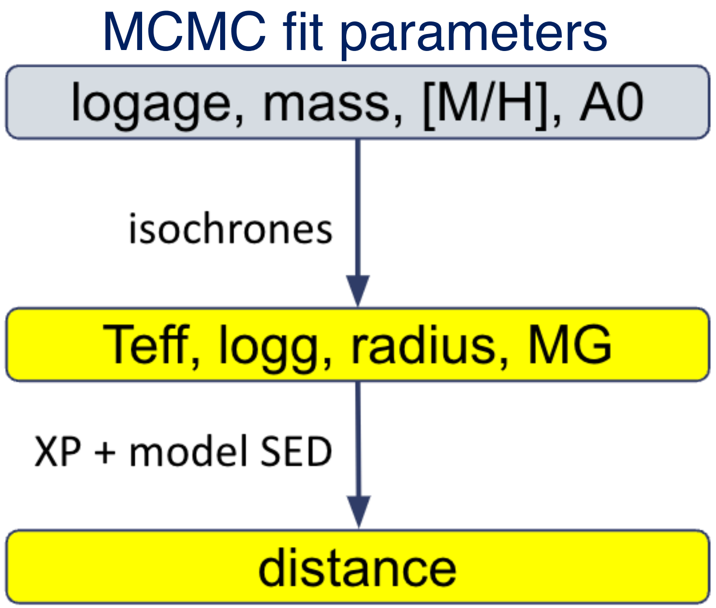
# Spectrophotometric astrophysical parameters – GSPphot (Andrae+2022)

470 million stars

Forward model the XP spectra with stellar isochrones to derive stellar parameters including extinction.

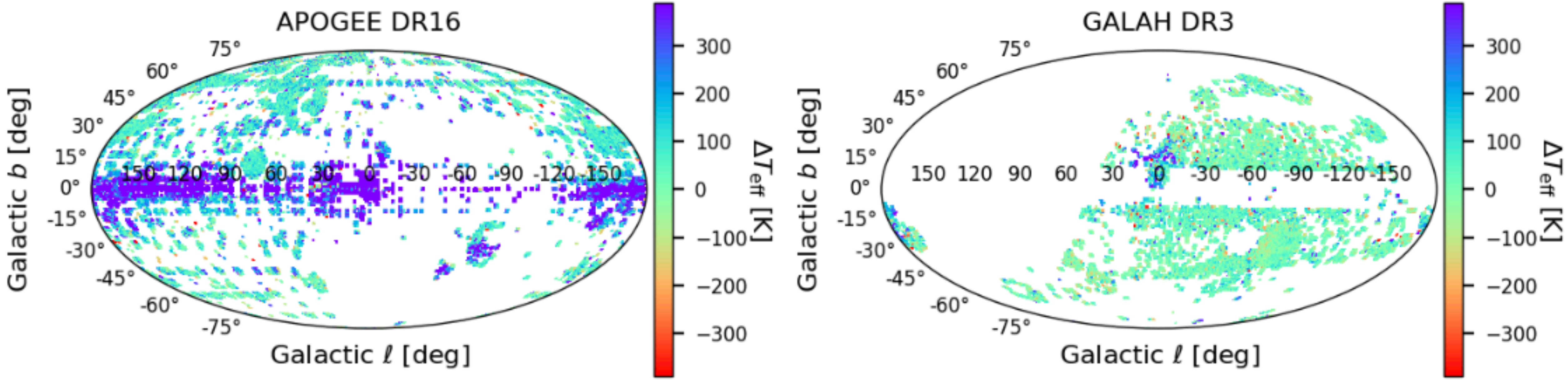
Parameters used: Parallax,  G mag and XP spectrum (all simultaneously forward modelled).

Infer per star: Teff, log*g*, [M/H], Radius, Abs G mag, distance, $A_0$, $A_G$, $A_{BP}$, $A_{RP}$, E(GBP-GRP), $A_{BP}$, $A_{RP}$



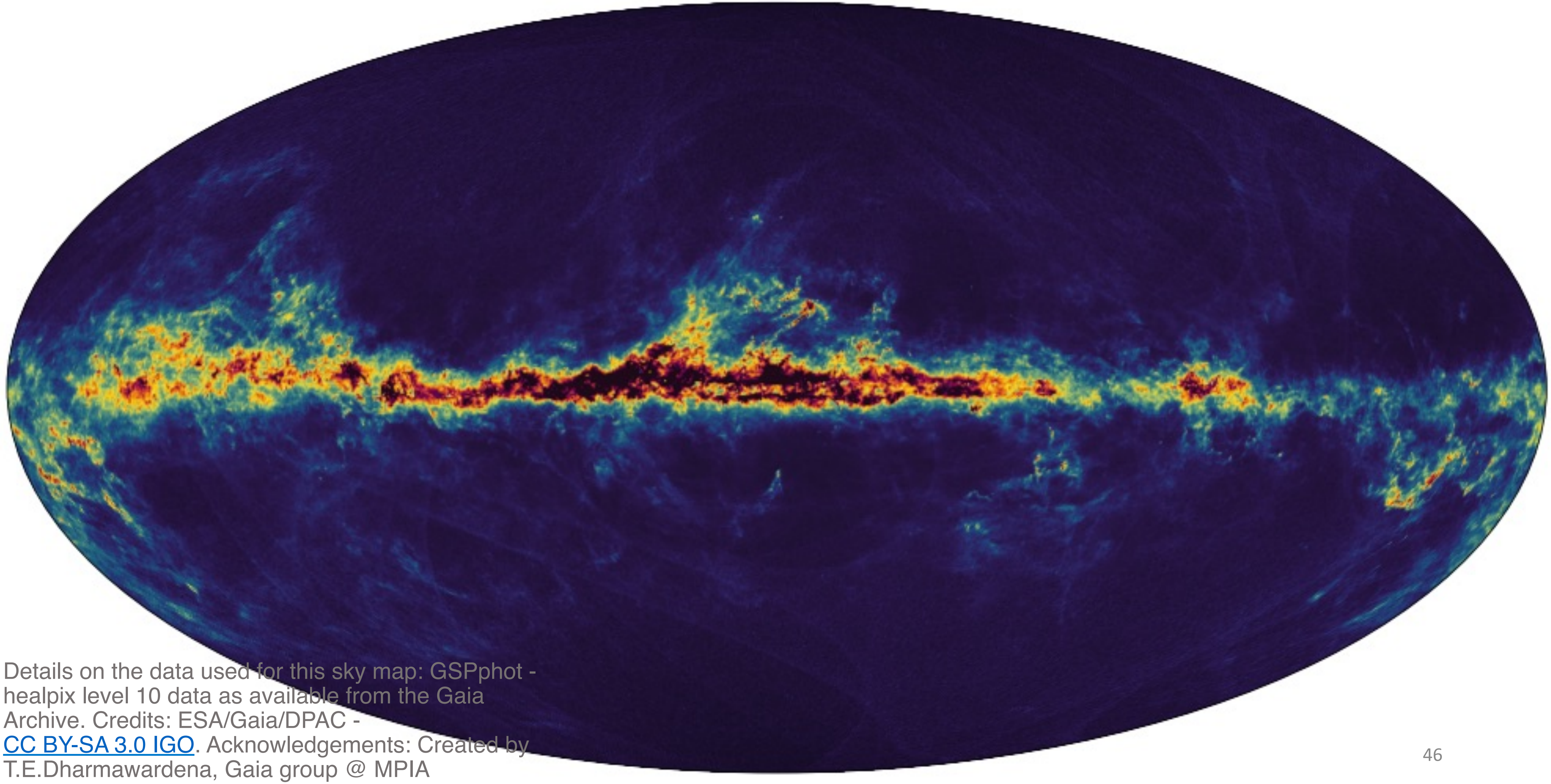

Rene Andrae, priv comm.

# Spectrophotometric astrophysical parameters – GSPphot (Andrae+2022)



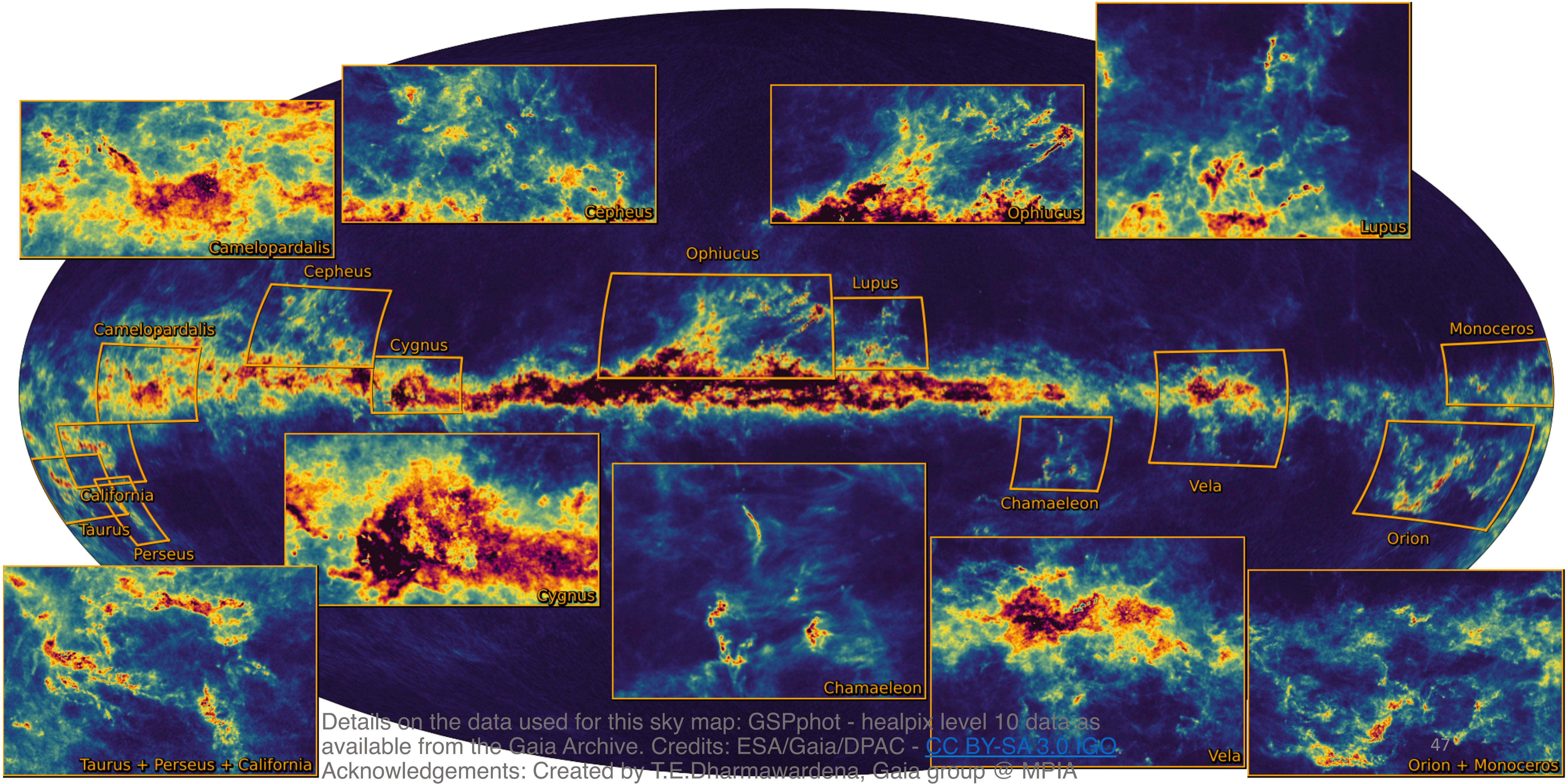

Andrae+2023

# All Sky Extinction map from GSPphot using 470 million stars



Details on the data used for this sky map: GSPphot - healpix level 10 data as available from the Gaia Archive. Credits: ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: Created by T.E.Dharmawardena, Gaia group @ MPIA

# All Sky Extinction map from GSPphot using 470 million stars




Details on the data used for this sky map: GSPphot - healpix level 10 data as available from the Gaia Archive. Credits: ESA/Gaia/DPAC - [CC BY-SA 3.0 IGO](CC BY-SA 3.0 IGO).

Acknowledgements: Created by T.E.Dharmawardena, Gaia group @ MPIA

# All Sky Extinction map from GSPphot using 470 million stars

# Mapping 3D dust density with Gaia

$$A_V = \int_0^s \rho \, ds$$

Observables: $A_V$, parallax (distance), $l, b$

Infer: Dust density

# Commonly used techniques for mapping the 3D dust density

1. Simplest approach: Fit each lines of sight separately

Group stars in nearby lines-of-sight into bins

Bin the line-of-sight into distance bins

Calculate Av as a function distance

Take the derivative of that function for distance).

# Commonly used techniques for mapping the 3D dust density

2. Forward model the dust density and extinction including the 3D correlations

# A few examples of 3D dust extinction and density maps in literature.

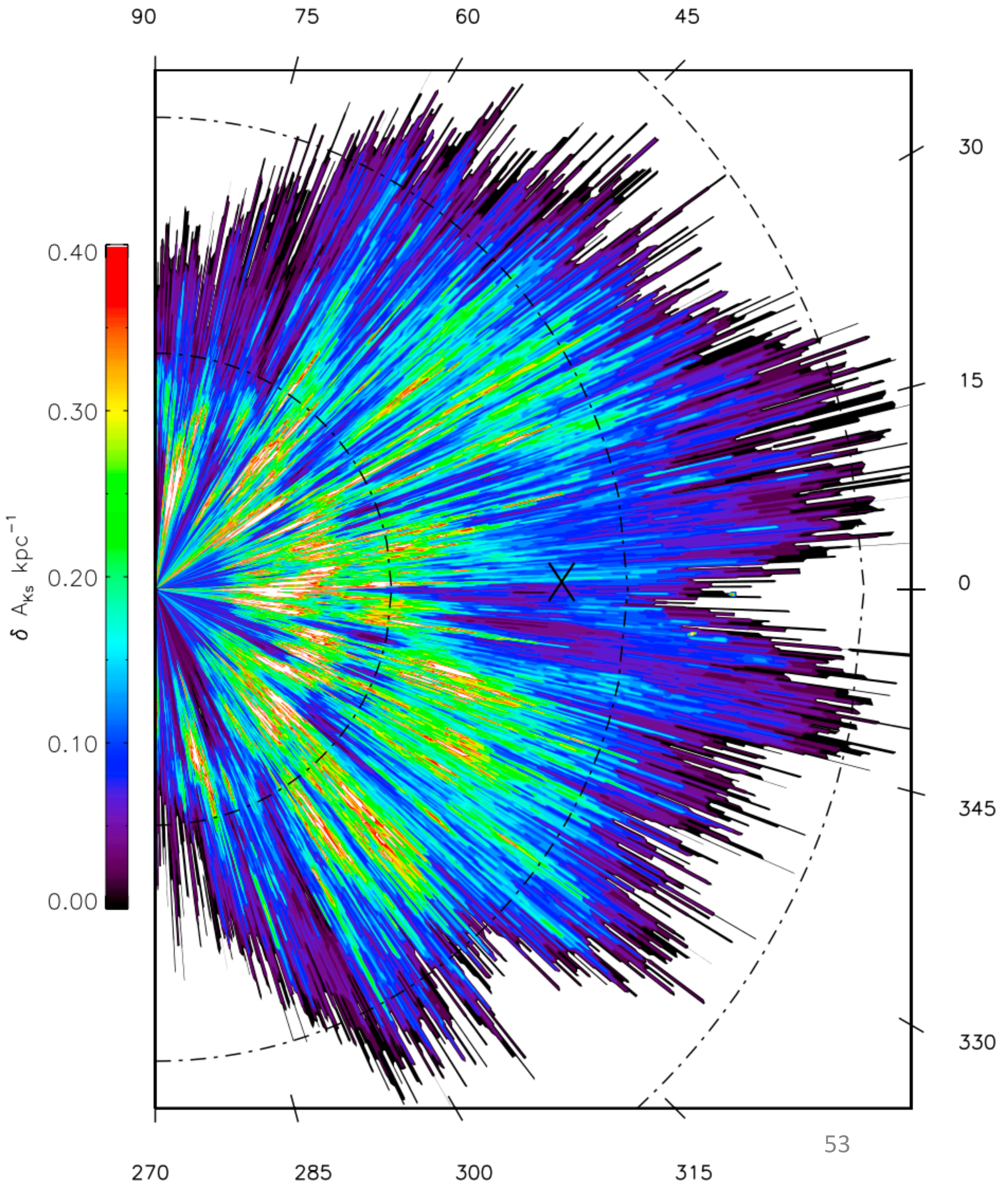
1. Marshall+2006
2. Green+2019
3. Sale and Magorrian 2018
4. Leike and Enßlin 2020
5. Vergely+2022
6. Dharmawardena+2022, 2023, subm. (expanded on later)

This is not an exhaustive list - Many more 3D dust maps are available in literature

# 1. Marshall+2006

Used theoretical Besançon models to derive model CMDs in J,H,K band - add extinction until it matches observed 2MASS colours to derive extinction.

3D dust map derived using the simplest method of binned lines-of-sight and then the distance bins are used to derive the dust density.



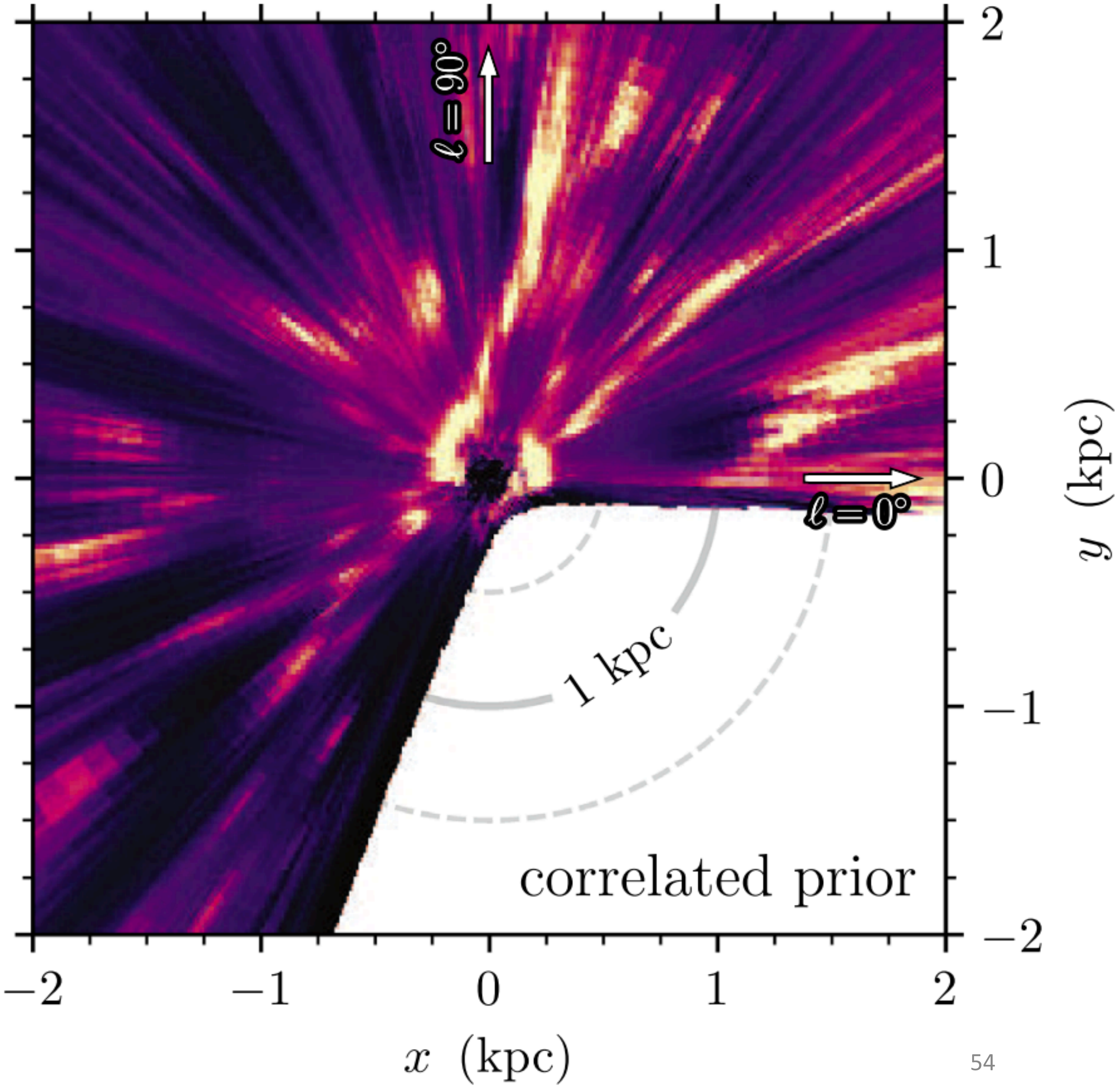
# 2. Green+2019

Used Gaia parallaxes, panSTARRS + 2MASS photometry to derive extinctions to binned line-of-sight.

Binned along distance to get density.

One step further and used a Gaussian process to correlate neighbouring line-of-sight.

The kernel of the GP is a fixed modified exponential kernel.

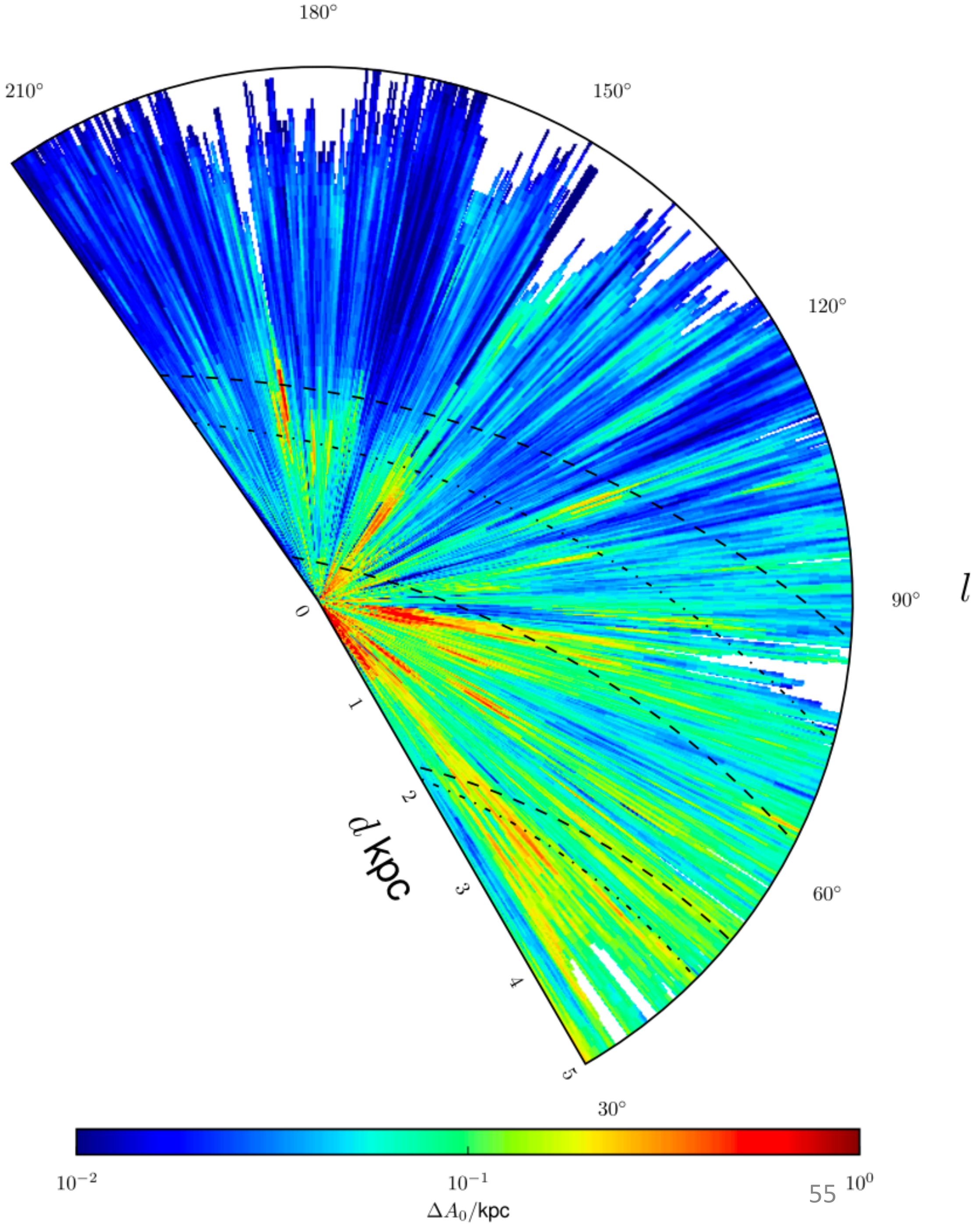


# Sale and Magorrian 2018

Used IPHAS survey extinctions of the Northern Galactic plane.

Applied a forward model Gaussian process to fully correlate all spatial points and model the differential extinction.

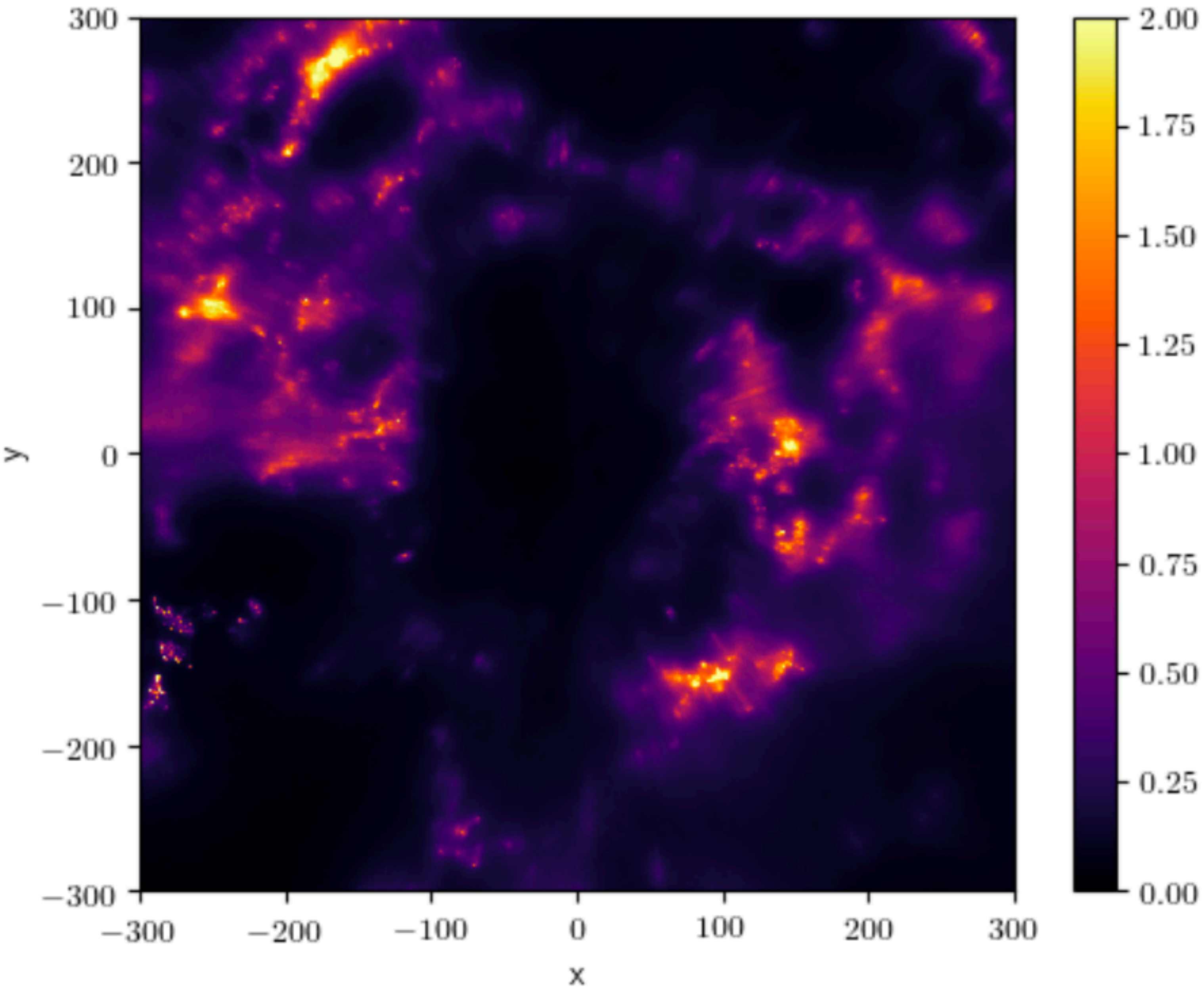
Kernel freely varying with power spectrum of turbulence



# Leike and Enßlin 2020

Full forward model: dust density as a GP which forward models the extinctions derived from 2MASS, WISE and Gaia DR2 photometry.

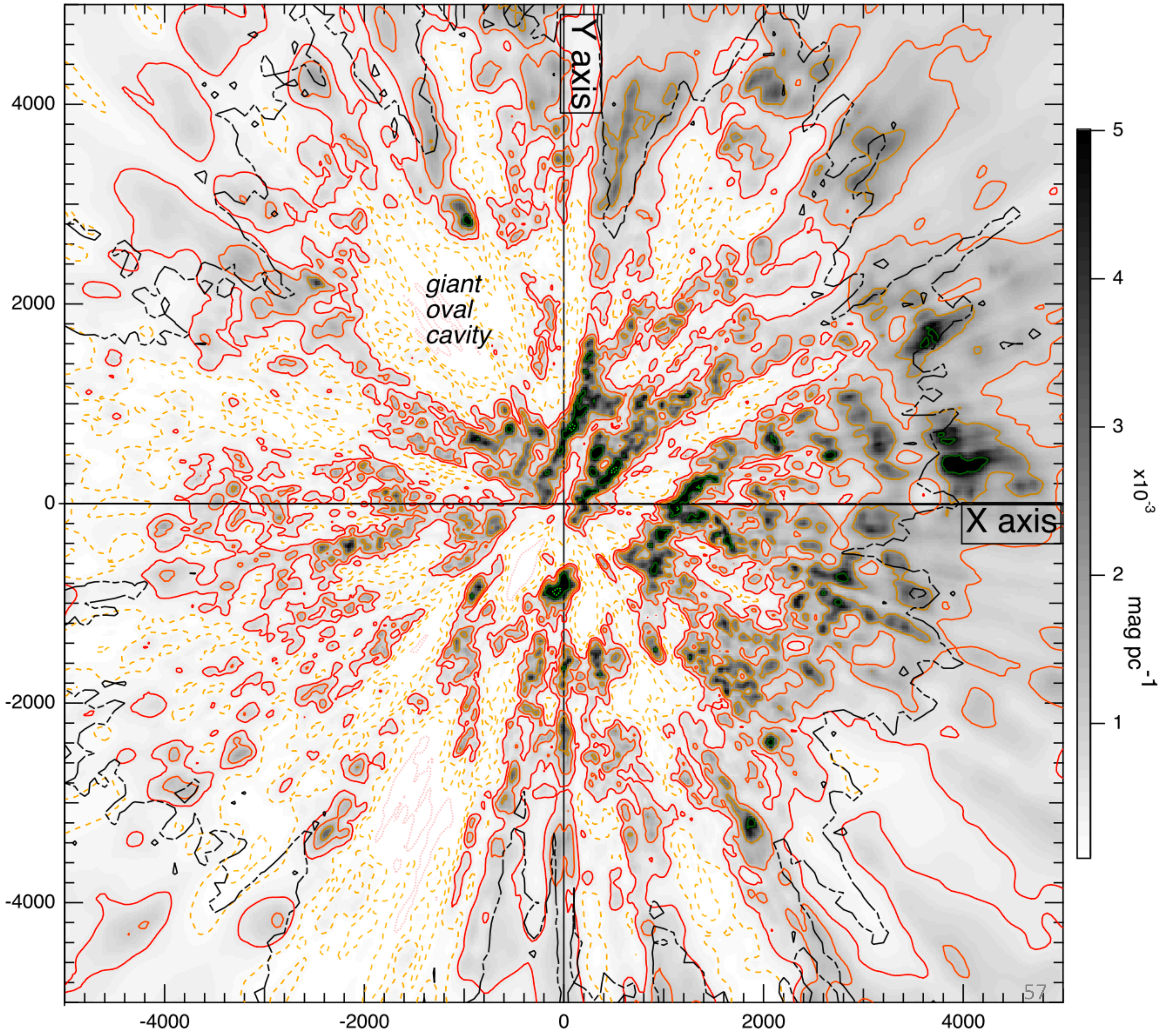
Kernel power spectrum learned along with the GP but not restricted to turbulent profile.



# Vergely+2022

Gaia EDR3+2MASS photometry and Gaia parallaxes.

Approach is similar to Green+2019 but instead of fixing the kernel, they start with a very large kernel, then iteratively reduce the size of the kernel while using the map with the previous kernel as a prior on the new map.



# Mapping 3D dust density – Issues to be tackled

1. Observable vs. required

Want: dust density
Observed: integrated dust density - extinction

$$A_V = \int_0^s \rho \, ds$$

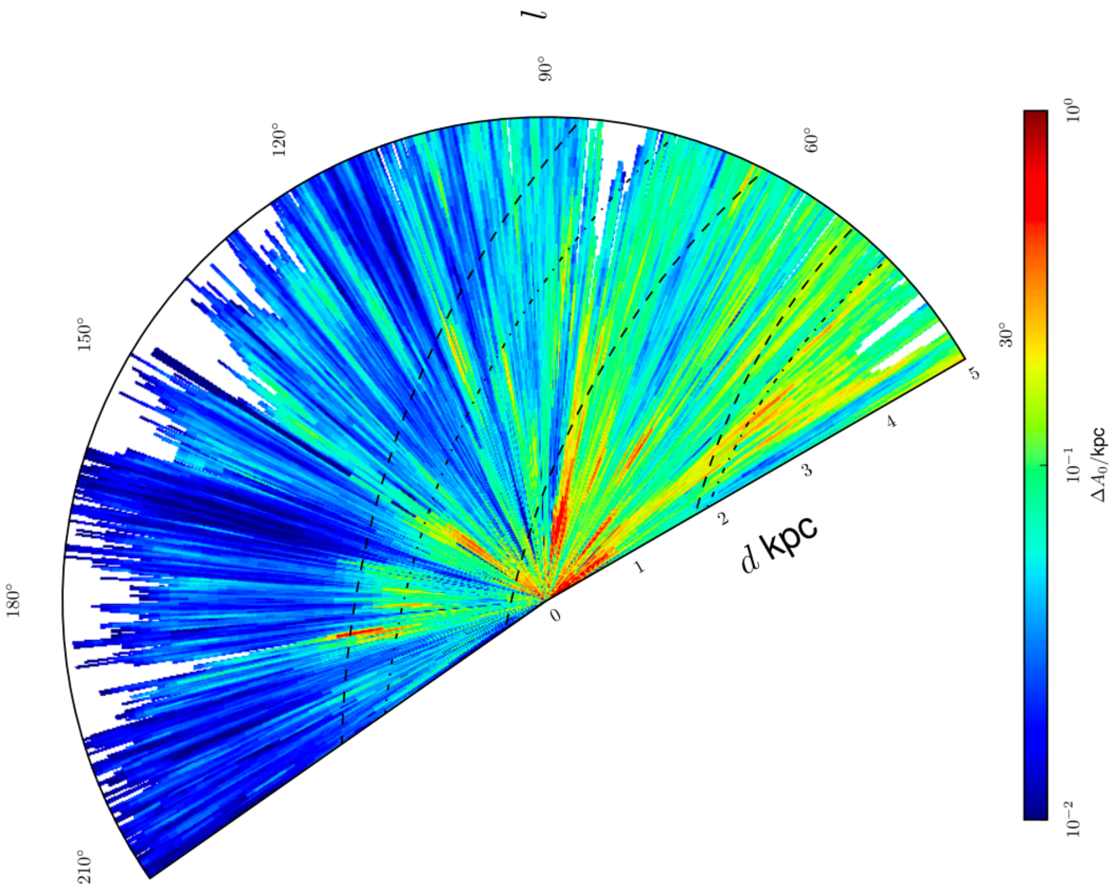
# Mapping 3D dust density – Issues to be tackled

2. Finger-of-god effect

Extended structure along line-of-sight

Consequence of having higher accuracy in plane of sky direction compared to radial ( line-of-sight ).

Correlating spatial points in all directions helps minimise this.

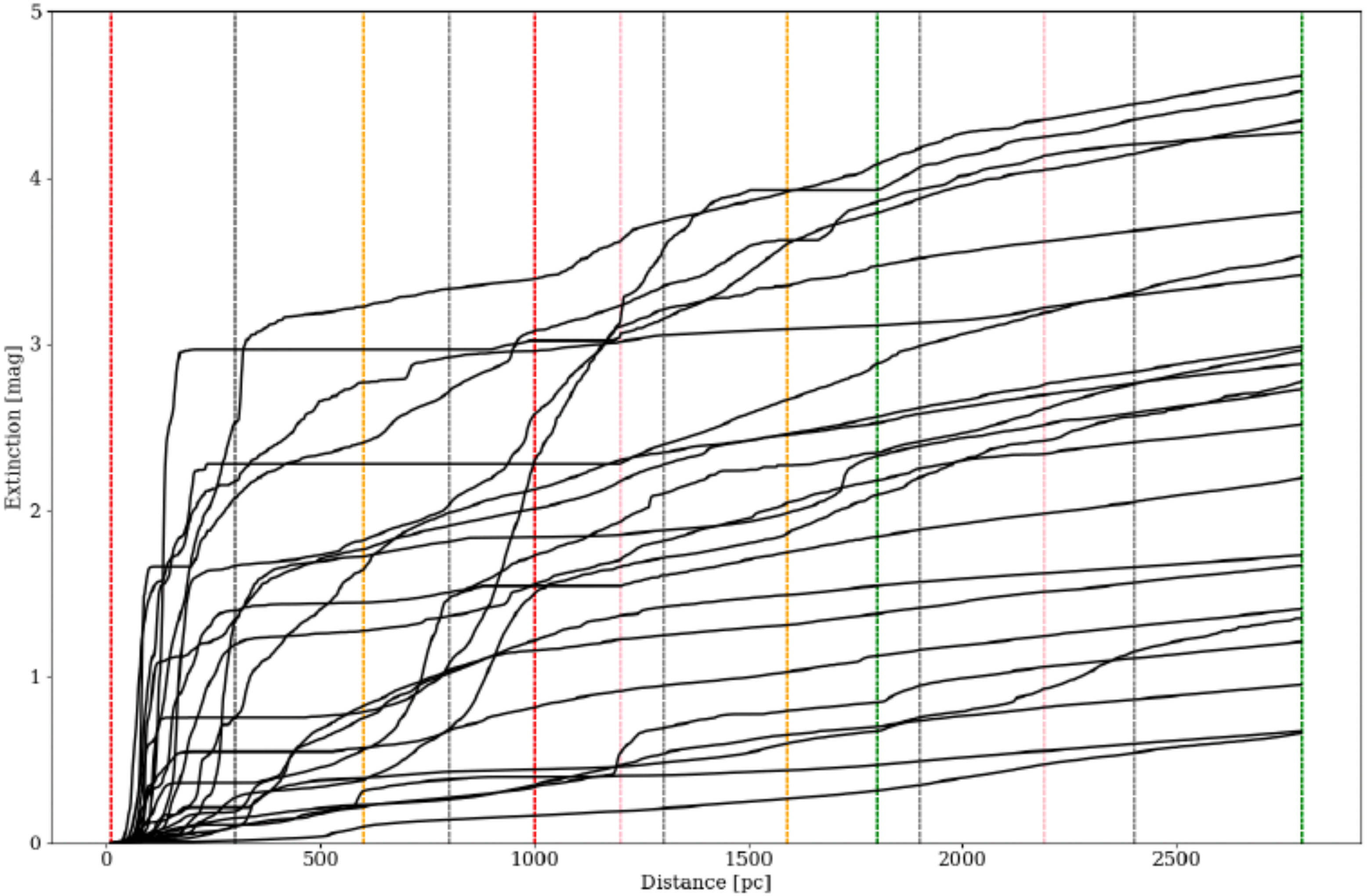



Sale and Magorrian 2018

# Mapping 3D dust density – Issues to be tackled

3. Dust density must be positive definite

Integral - extinction - must not decrease with distance! – Monotonically non-decreasing.

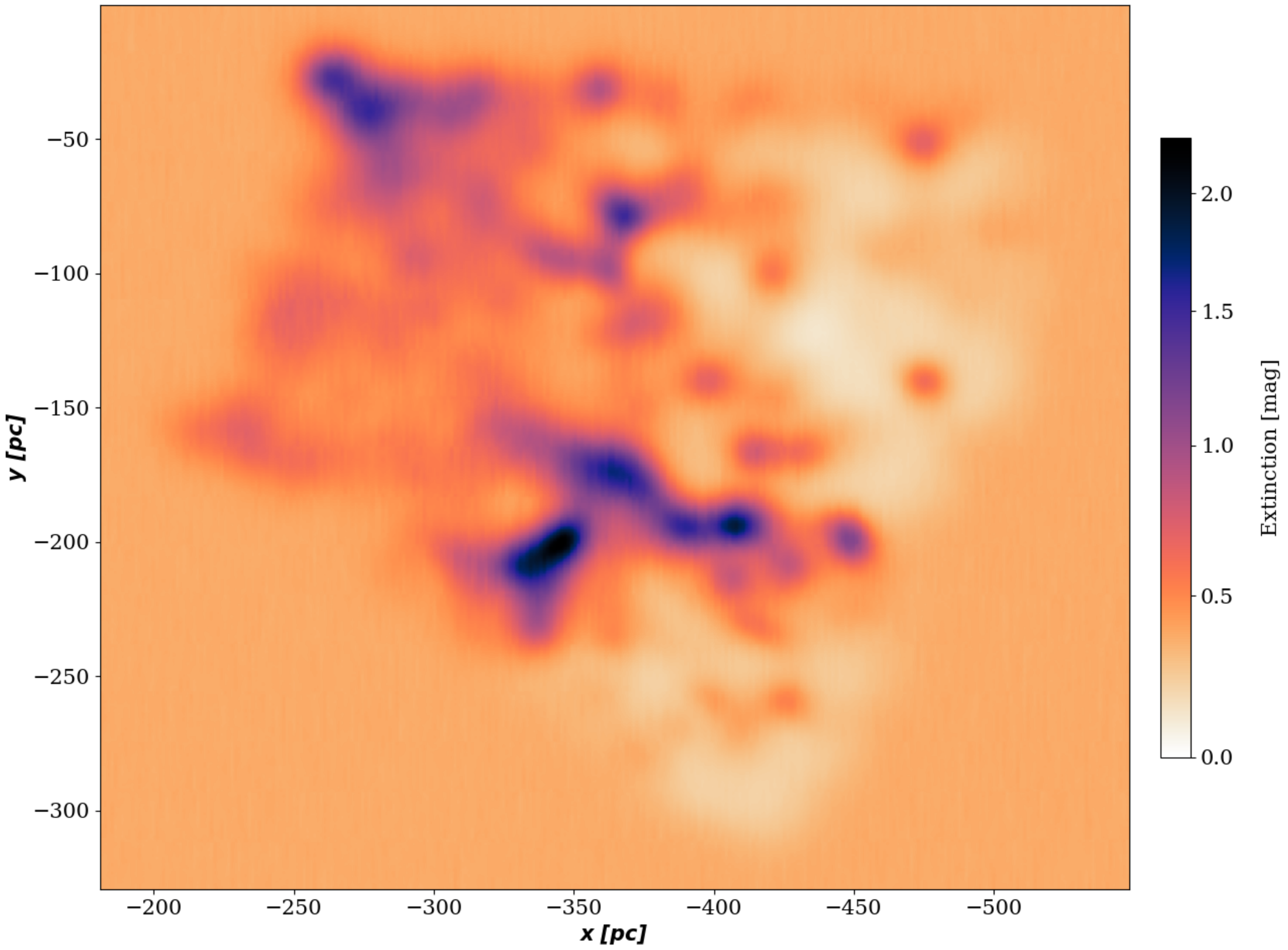



Dharmawardena+subm.,Los extinction of the Milky Way.

# Mapping 3D dust density – Issues to be tackled

4. Dust clouds have varying shapes – single fixed kernels can cause spherical blobs

Using non-fixed kernels can remove this effect.




Dharmawardena+2022. Top down view of Orion GMC

# Mapping 3D dust density – Issues to be tackled

5. Limited by the Gaia Selection function

Can only map the stars bright enough to penetrate the dust clouds

Particularly an issue towards the Galactic center  where it's so dense that we don't have enough stars – therefore we underestimate density

Not because it's low density but because there is too much dust for star light to penetrate.

Can be minimized by combining Gaia with IR surveys such as 2MASS, WISE and VVV

# Mapping 3D dust density – Issues to be tackled

5. Computationally expensive in both memory and run time.

# Part 3:
# 3D dust density with Dustribution

Part 3 of 4

# Dustribution: 3D dust density and extinction mapping tool (Dharmawardena+2022, 2023)

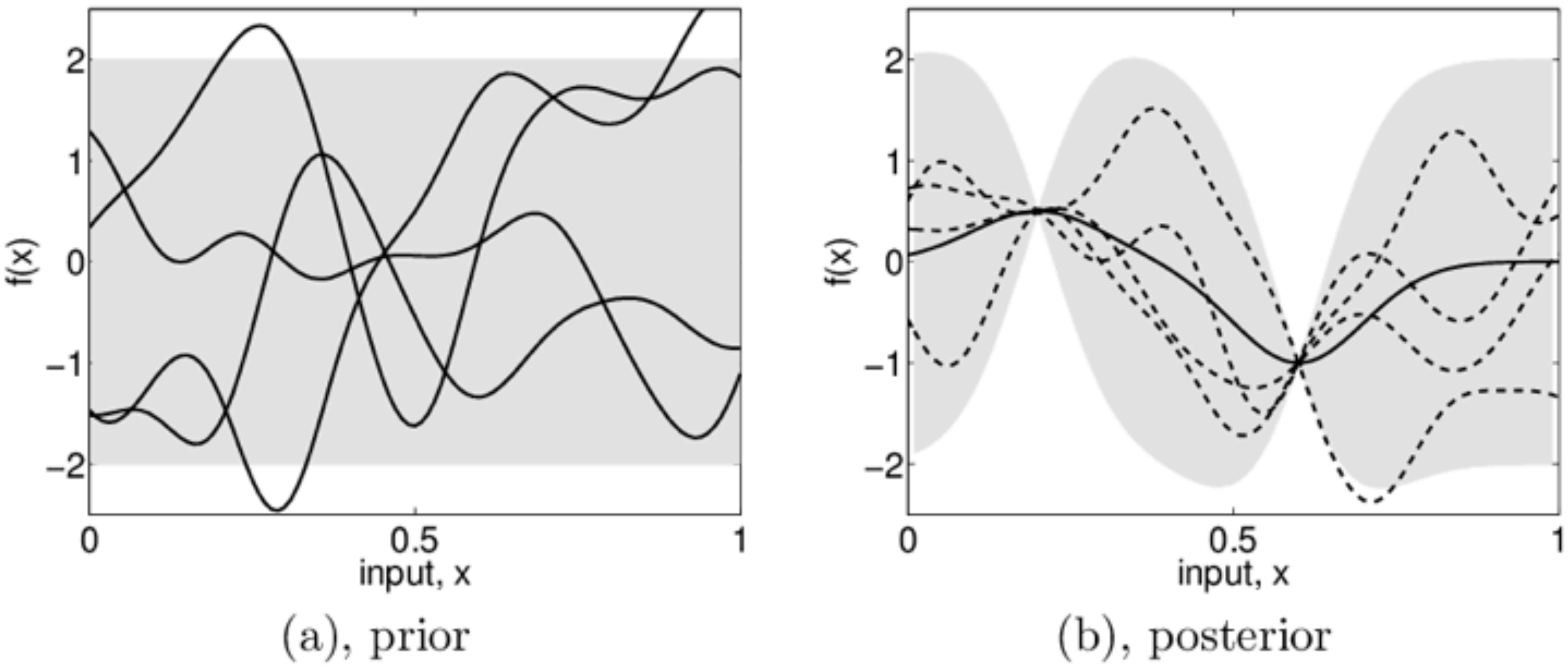
A public tool: Produce 3D dust density and extinction maps using any input catalogue of stellar extinctions and densities for any chosen region and resolution.

Incorporates:

1. Latent variable Gaussian processes – Minimises fingers-of-god effects; maintain positive densities; recovers varying shapes of clouds.

2. Variational inference, inducing points, GPUs –x100 and x200 improvement in memory and speed.

# Gaussian Process



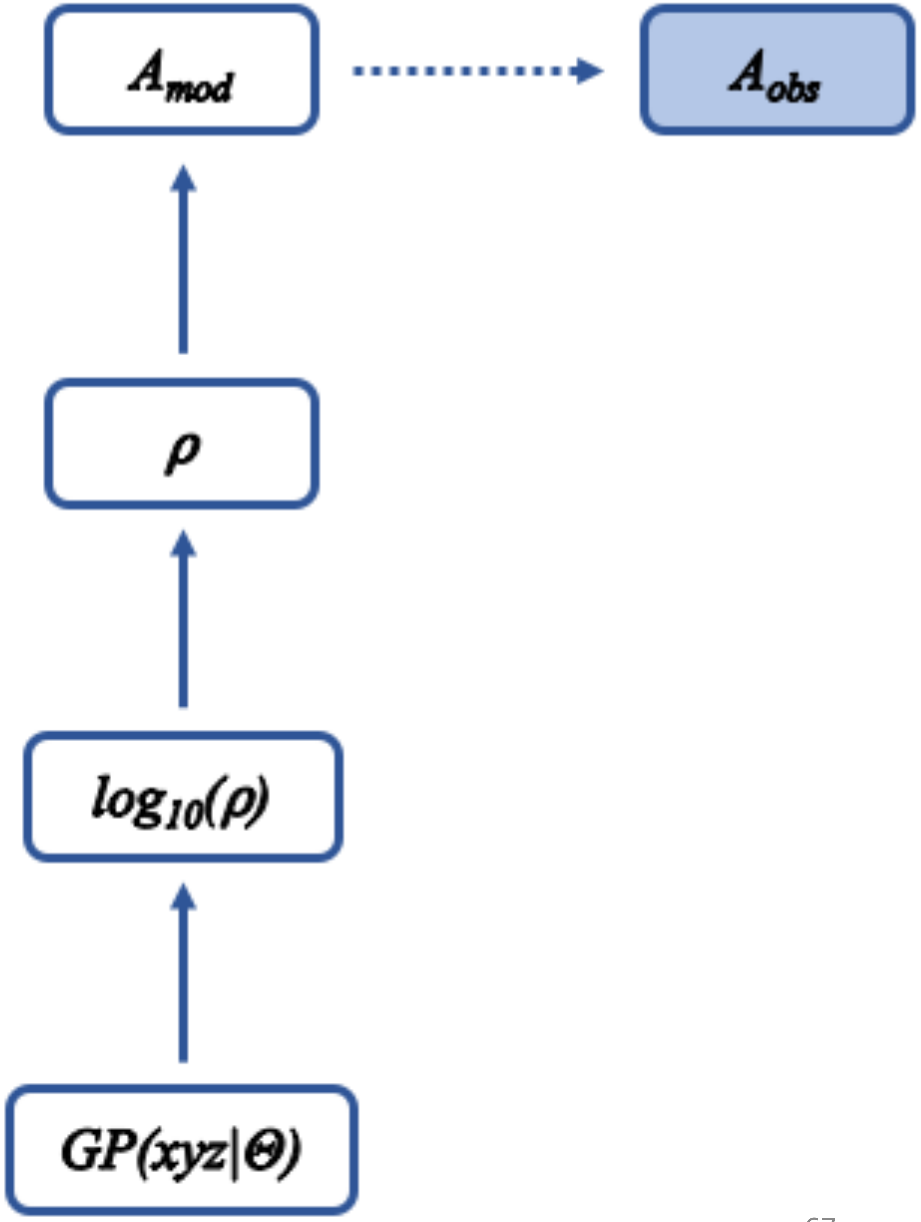

Rasmussen and Williams 2006

A Gaussian process is a distribution of an infinite set of functions described by a covariance function which for ease we describe as a kernel with a set of hyper parameters. With known data points we can condition the process to restrict the set of functions of the posterior or infer the hyper parameters or both. (Rasmussen and Williams 2006)

GP: correlate all the different density points - minimise fingers of god effect.

# Latent Variable Gaussian Process

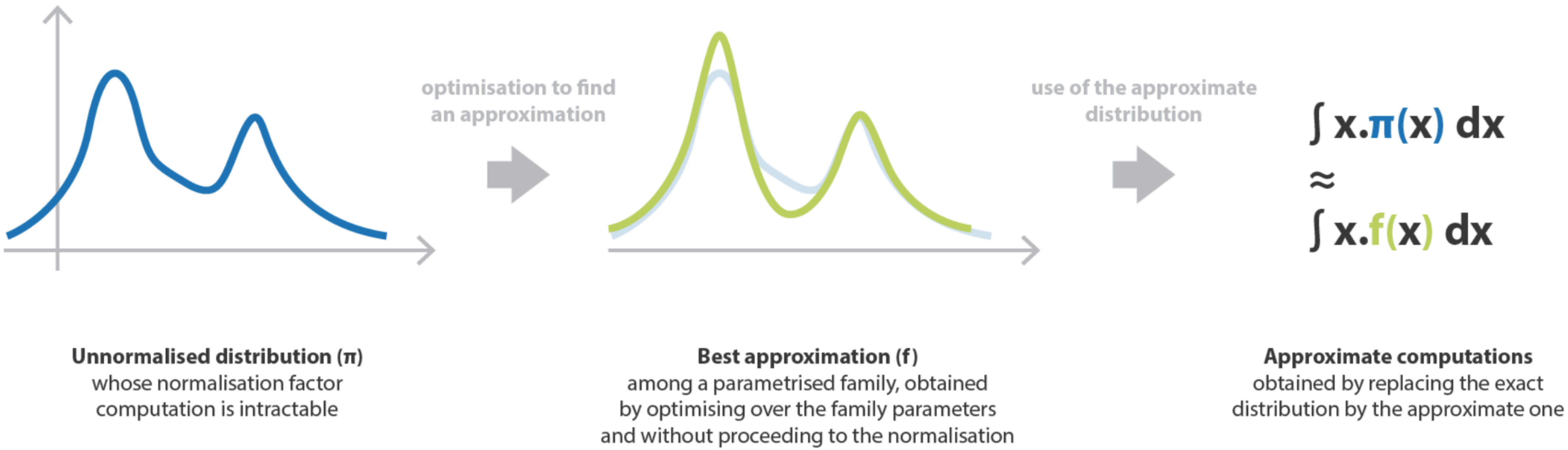
A layered GP applied directly to the unobserved variable: $\log_{10}(\rho)$.



# Variational Inference

GPs scale poorly with the number of points.

VI: replace GP target posterior with an approximate posterior that is easier to work with - optimise parameters for approximation that best reproduce the true posterior.

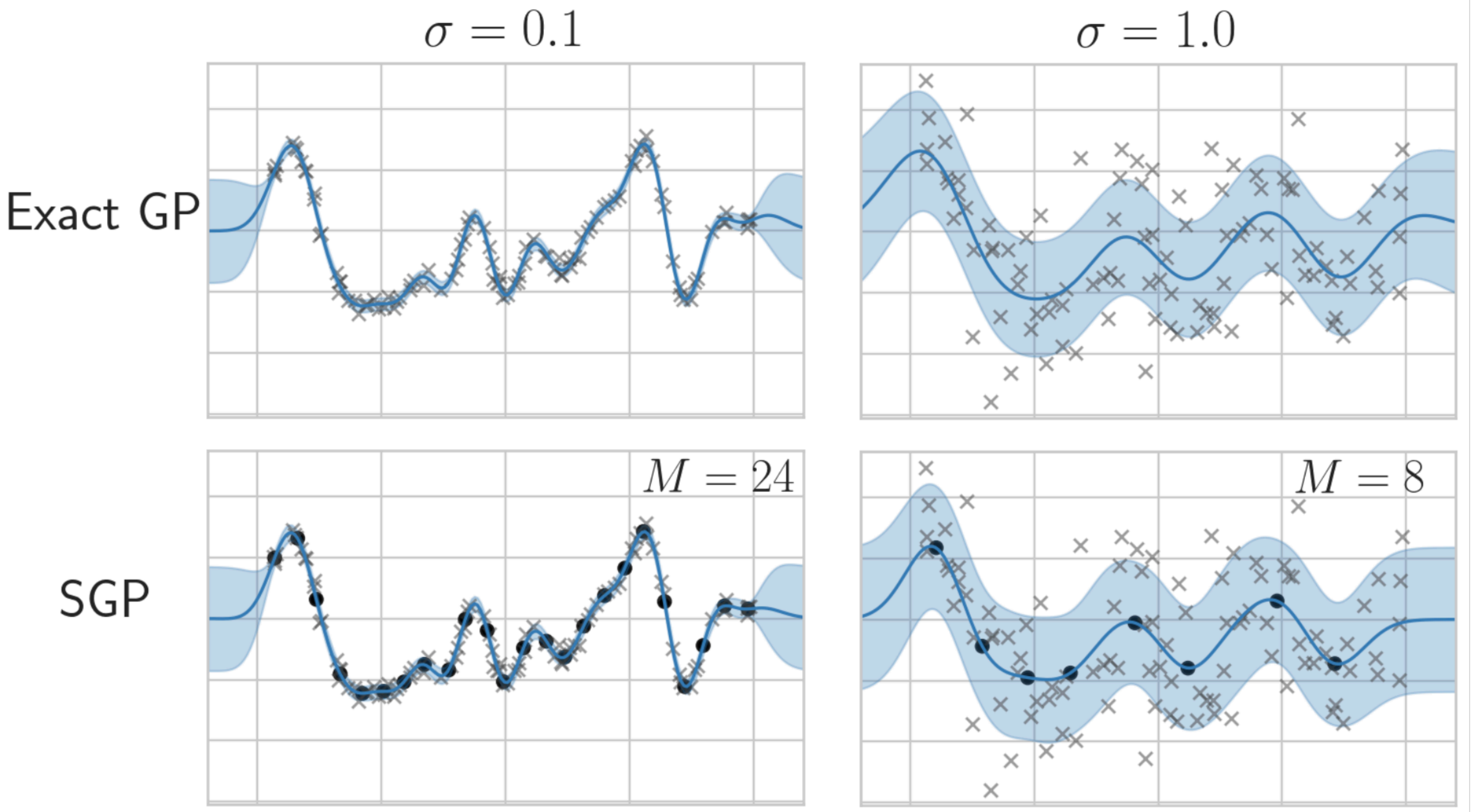



J. Rocca 2019

# Sparse Gaussian process represented by inducing points

Sparse GP described by inducing points ◊ further reduce memory usage and run time.

IPs: Optimize only a subset of points which are representative of the whole distribution.




Uhrenholt+2021

# Dustribution input data

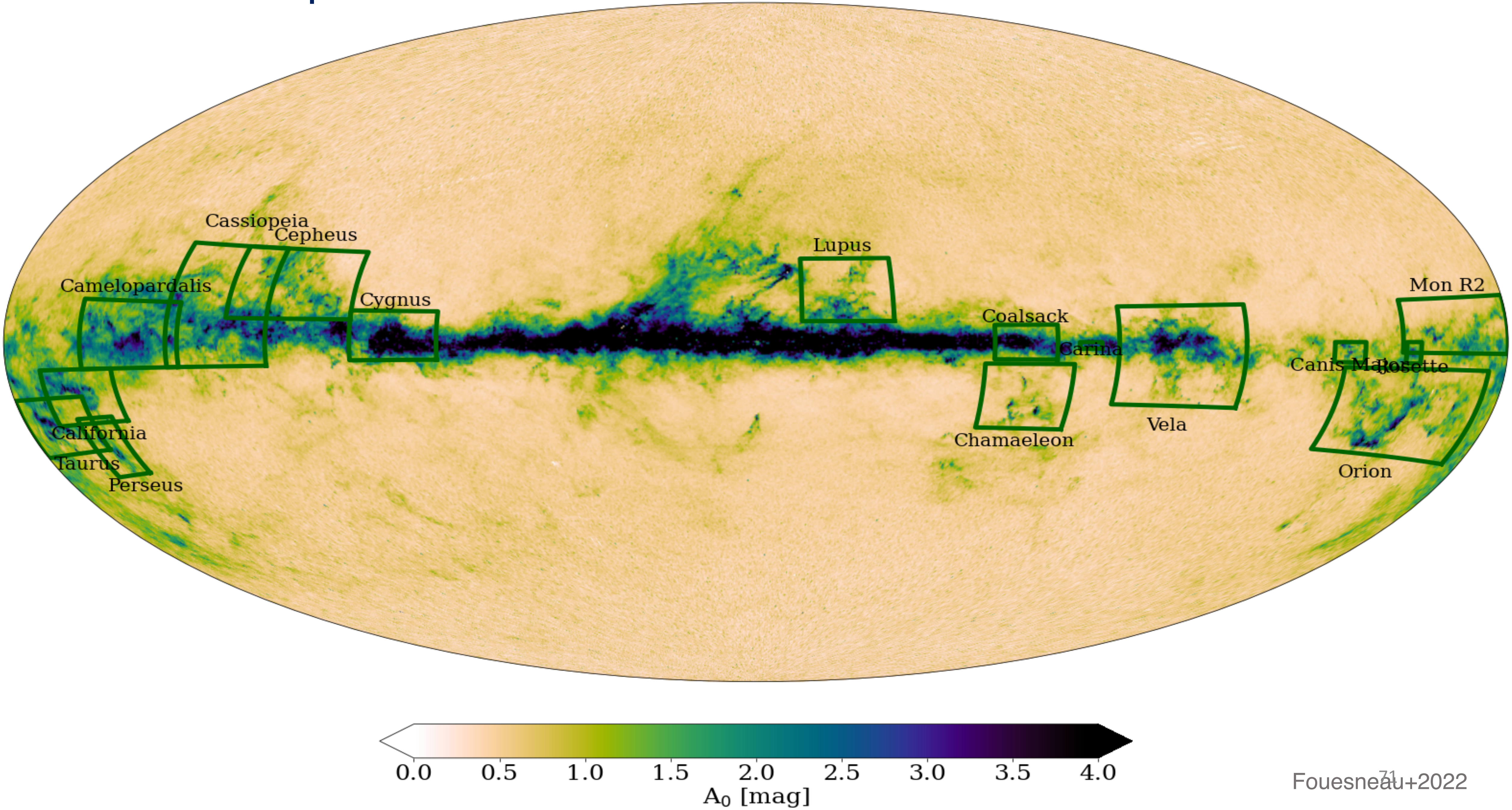
Input $A_0$ and distances: Fouesneau+2022.

Gaia DR2, 2MASS and WISE.

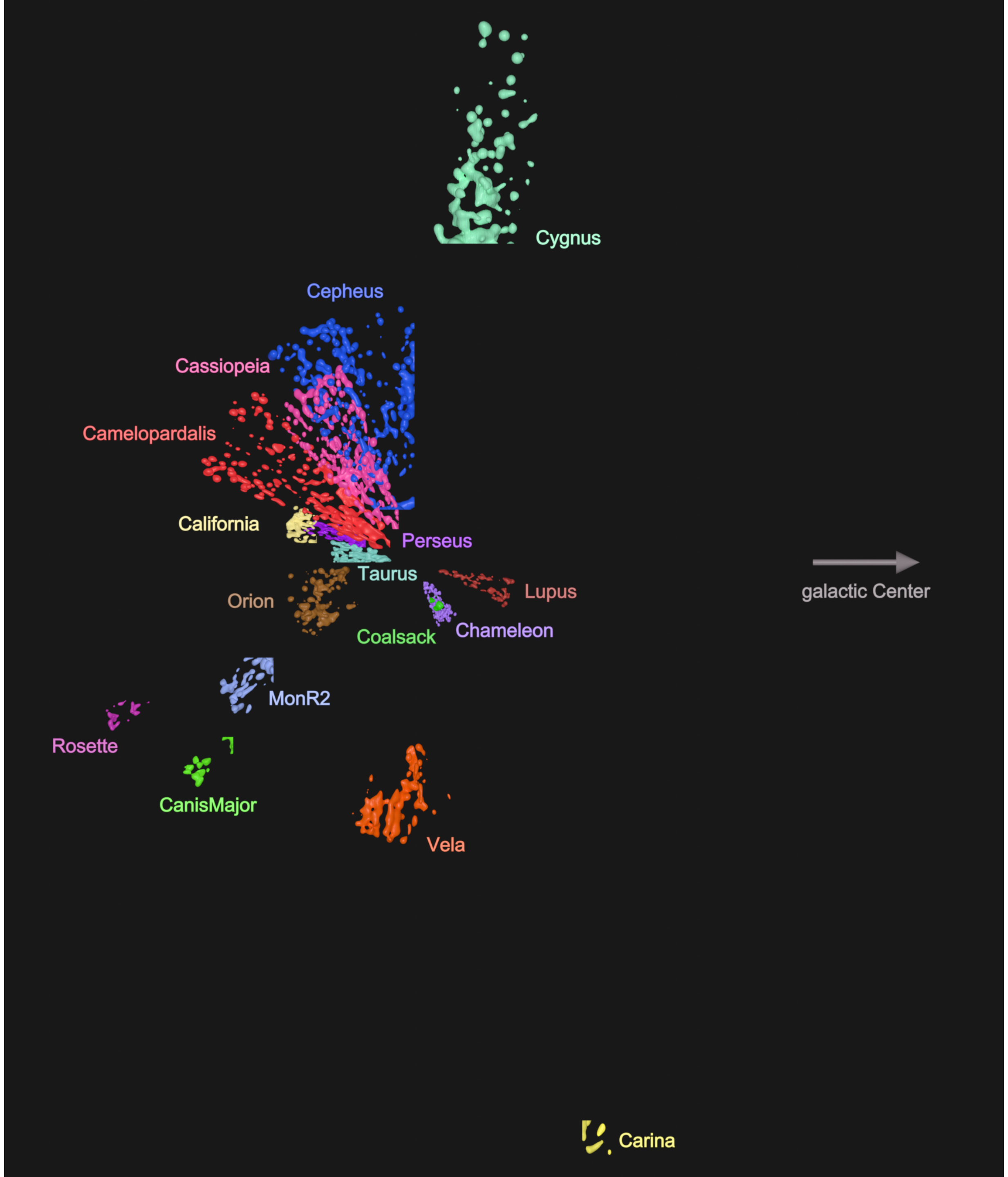
Optical + IR: probe denser dust regions of Milky Way.

Does not assume a Galactic prior - impose a strong shape on the Galaxy, e.g., spiral arms

# Dustribution input data




Fouesneau+2022




# Dustribution derived dust density structure of 16 Galactic molecular clouds

Grid resolution: ≤ 1 pc.

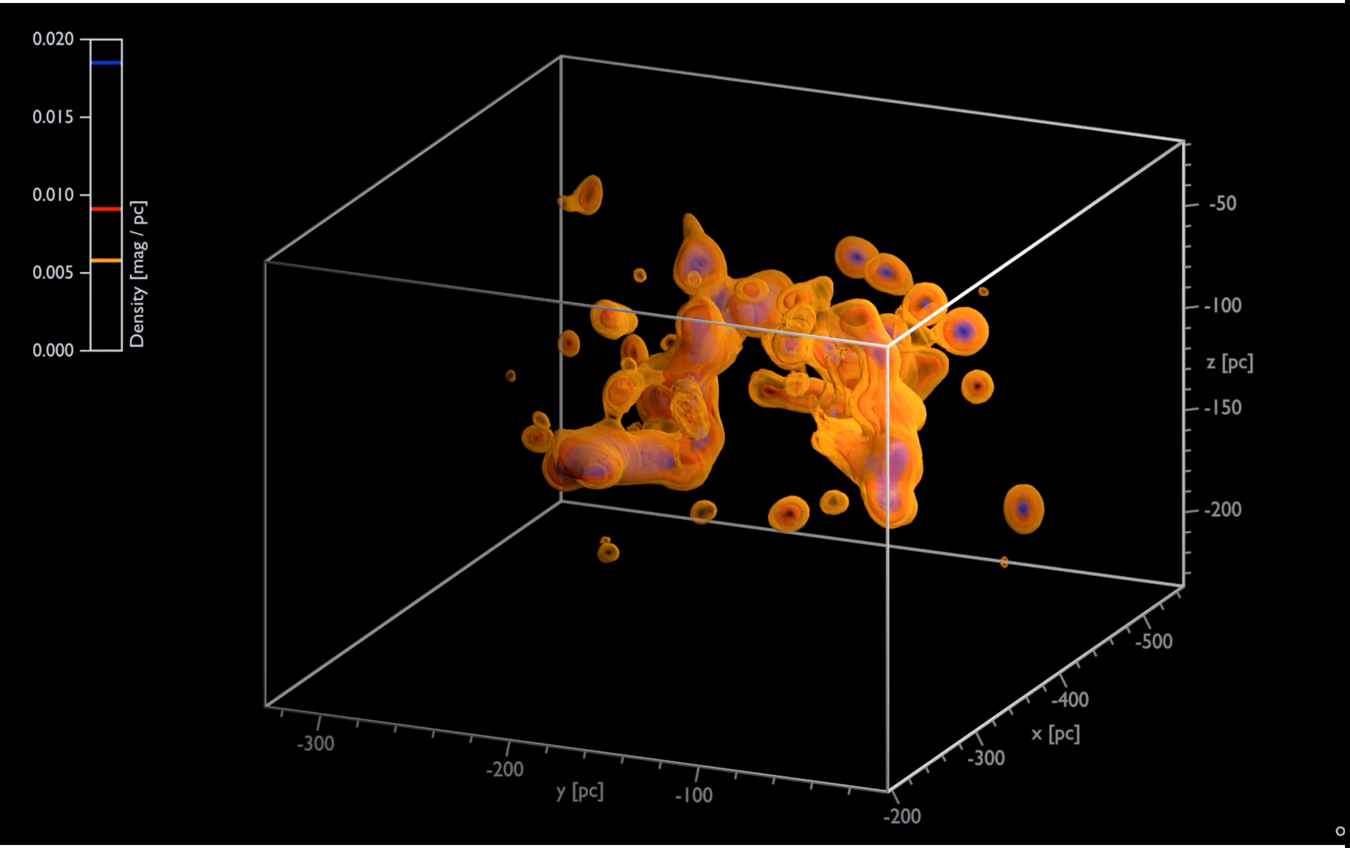
Initial scale length in xyz: 10pc.

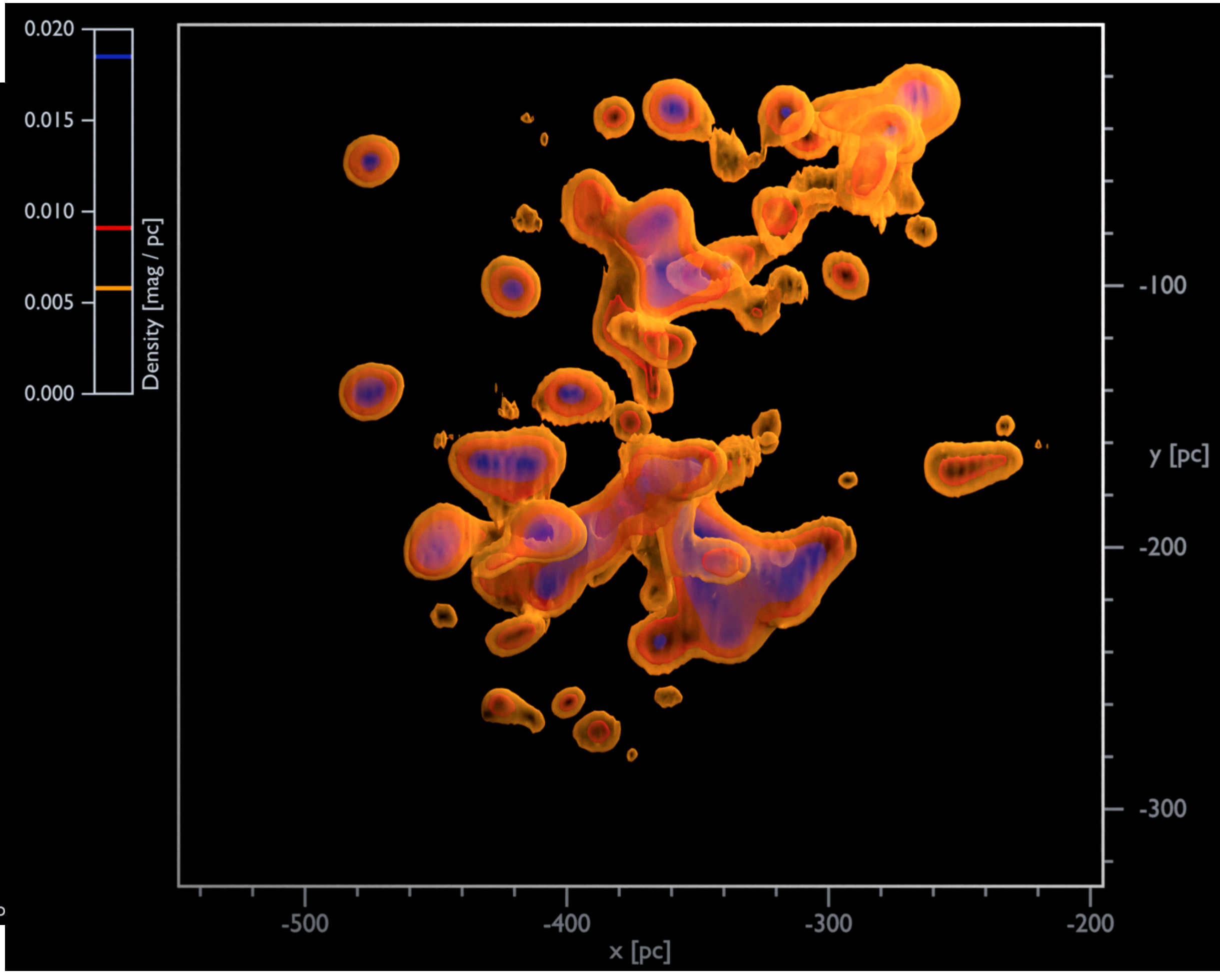
Large variations in shape, size, mass, dust distribution, etc.

Recover filaments, sheets, blobs, cavities.

Dharmawardena+2022, 2023

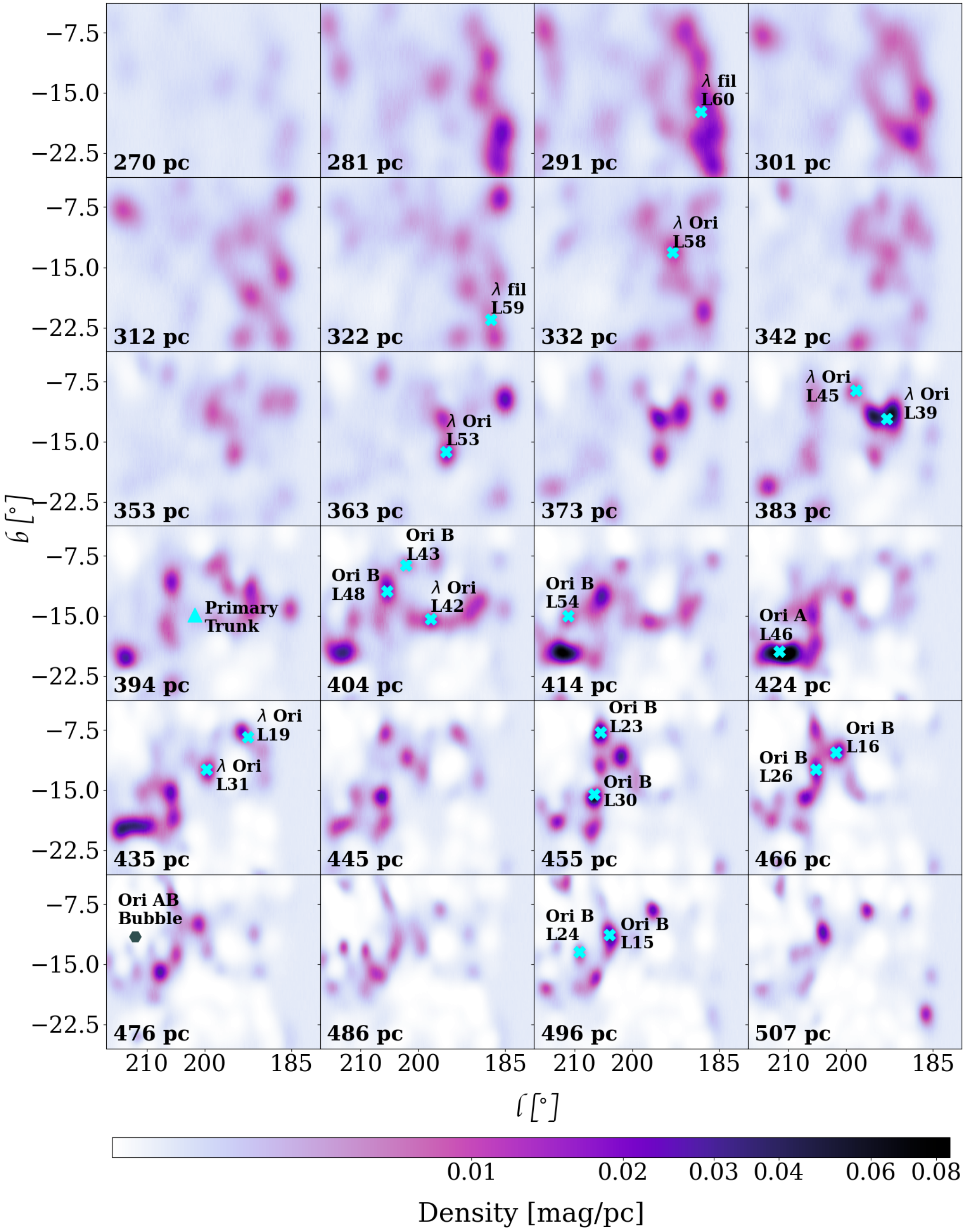
# Tomography of Nearby Molecular Clouds – Orion

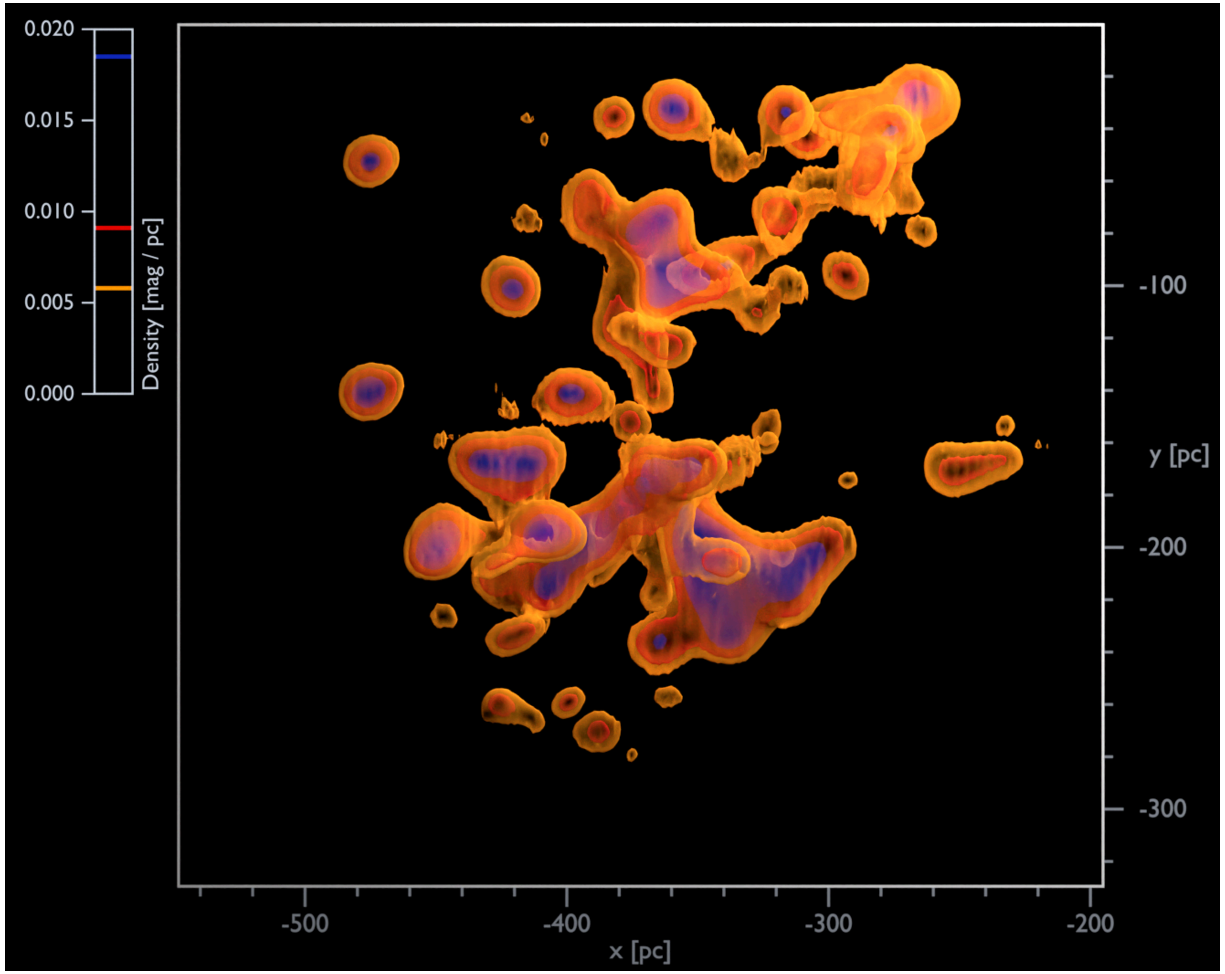



Dharmawardena+2022, 2023. 3D view of Orion from the sun and top down, showing clouds of varying shapes and the previously unrecovered foreground filament.

# Tomography of Nearby Molecular Clouds – Orion: Cavity between Orion A and B

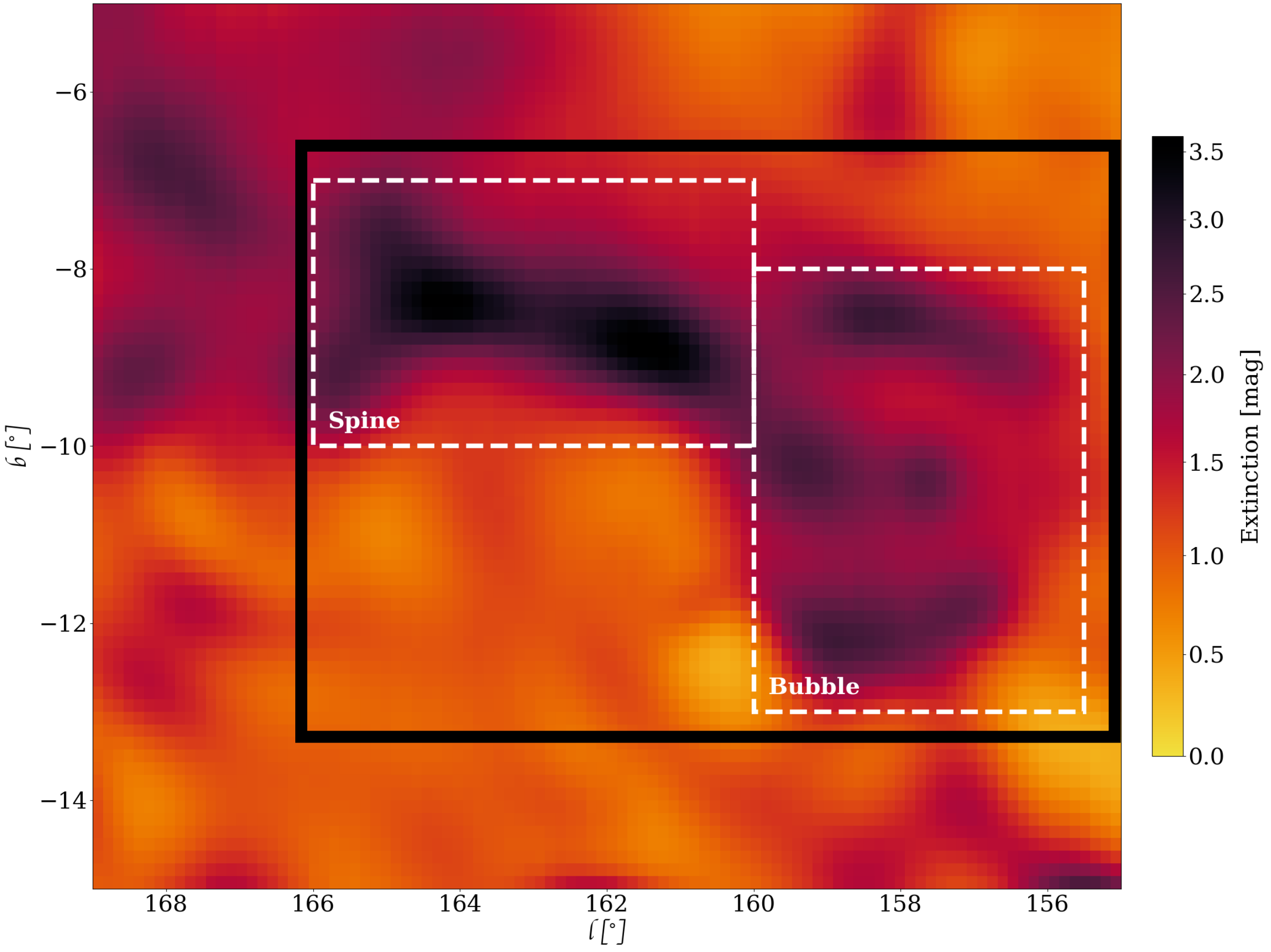


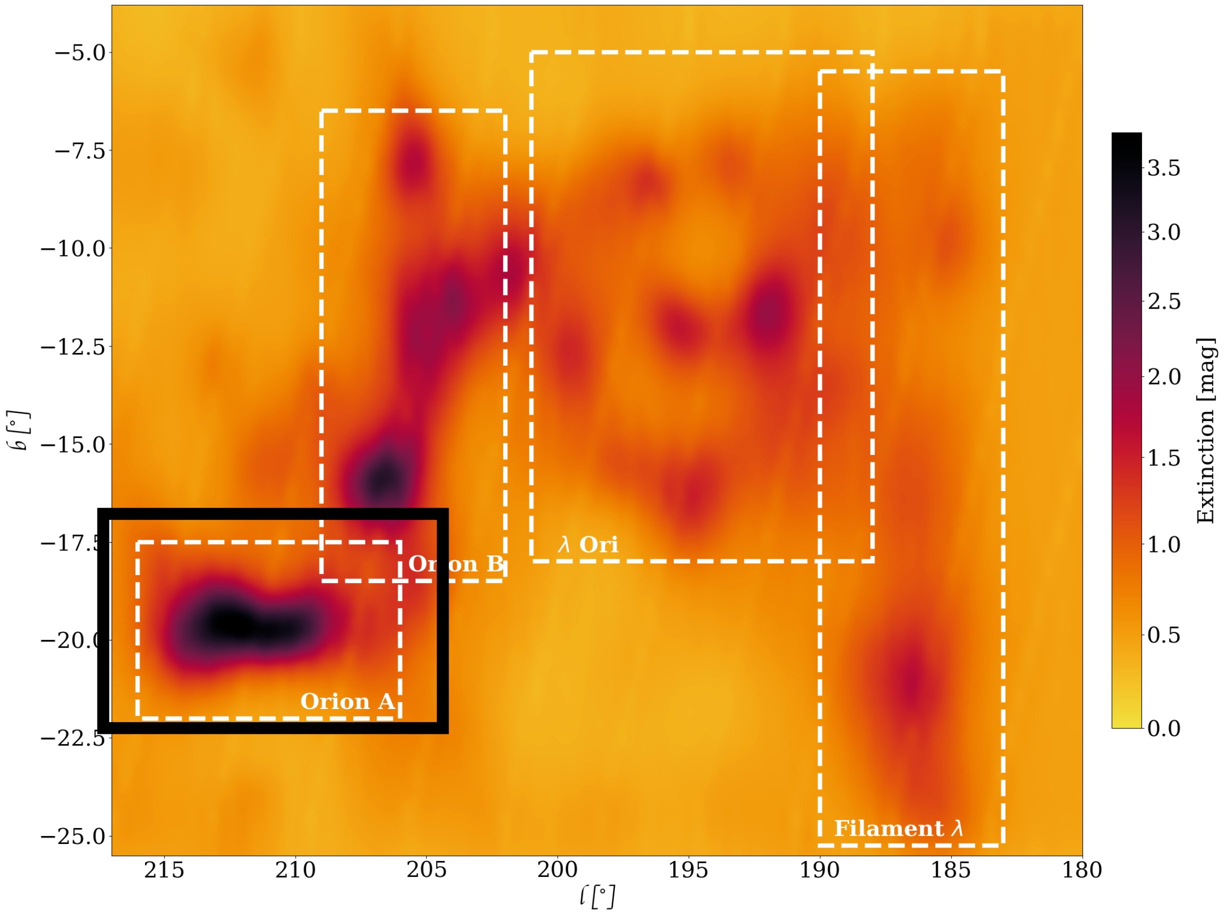




Dharmawardena+2022

# Tomography of Nearby Molecular Clouds – California

## Mystery of California and Orion (Lada et al., 2009)



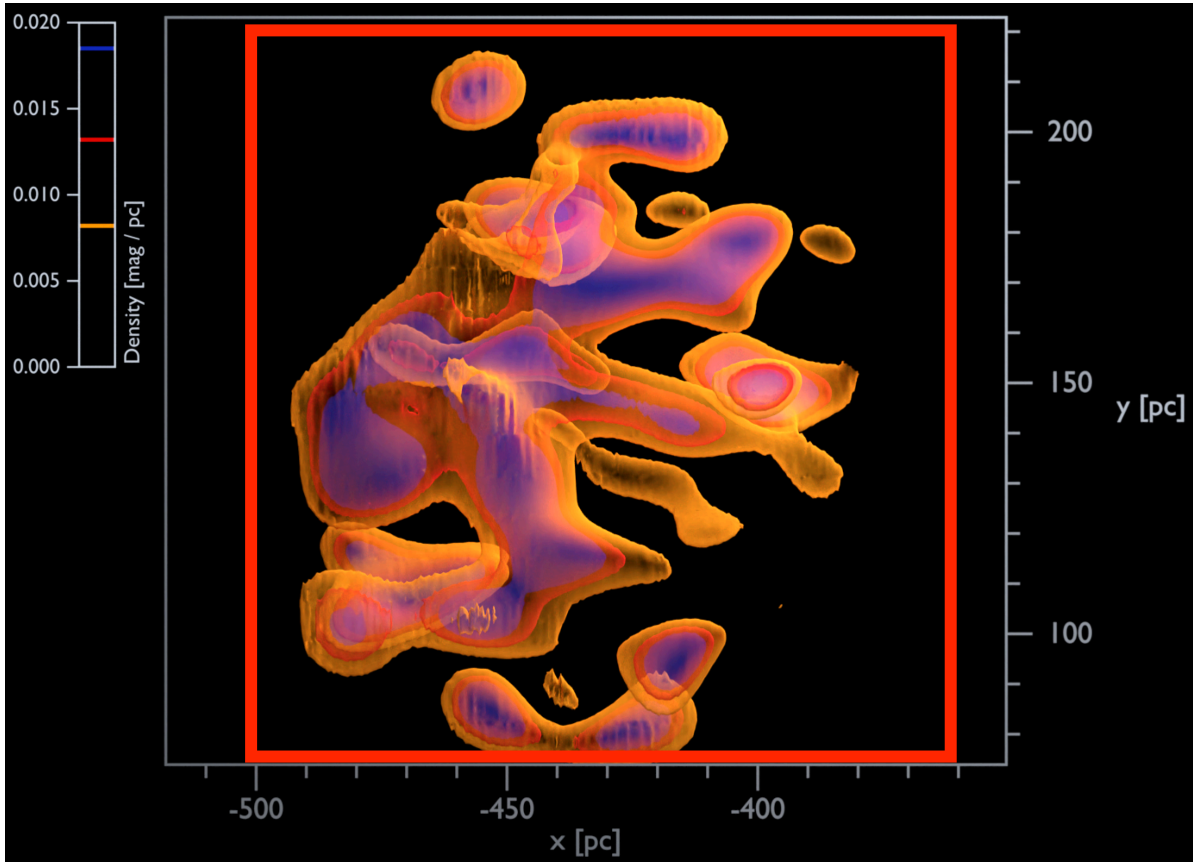



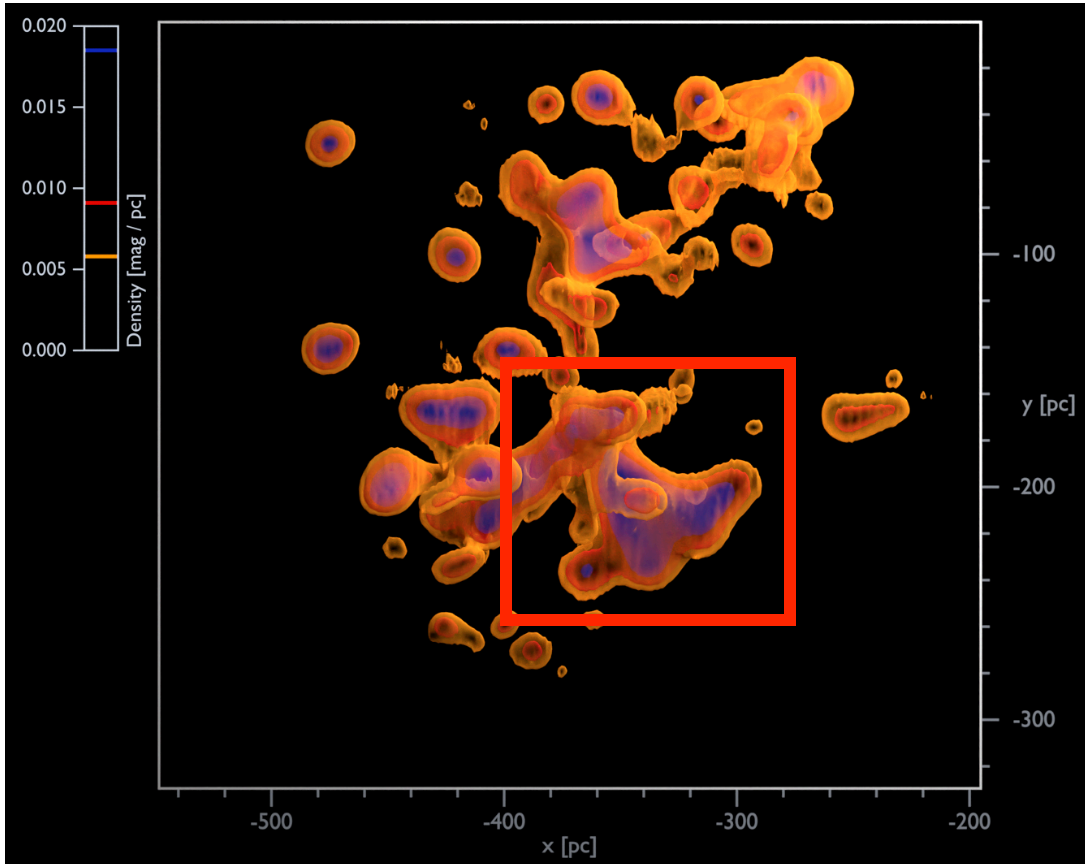

## 2D Extinction view of California (left) and Orion (right)

Dharmawardena +2022, 2023

# Tomography of Nearby Molecular Clouds – California

Mystery solved!: California is about 2 x larger in mass and 7 x larger in volume than Orion A - lower density - combined with the sheet shape this explains the difference in SFR compared to Orion A

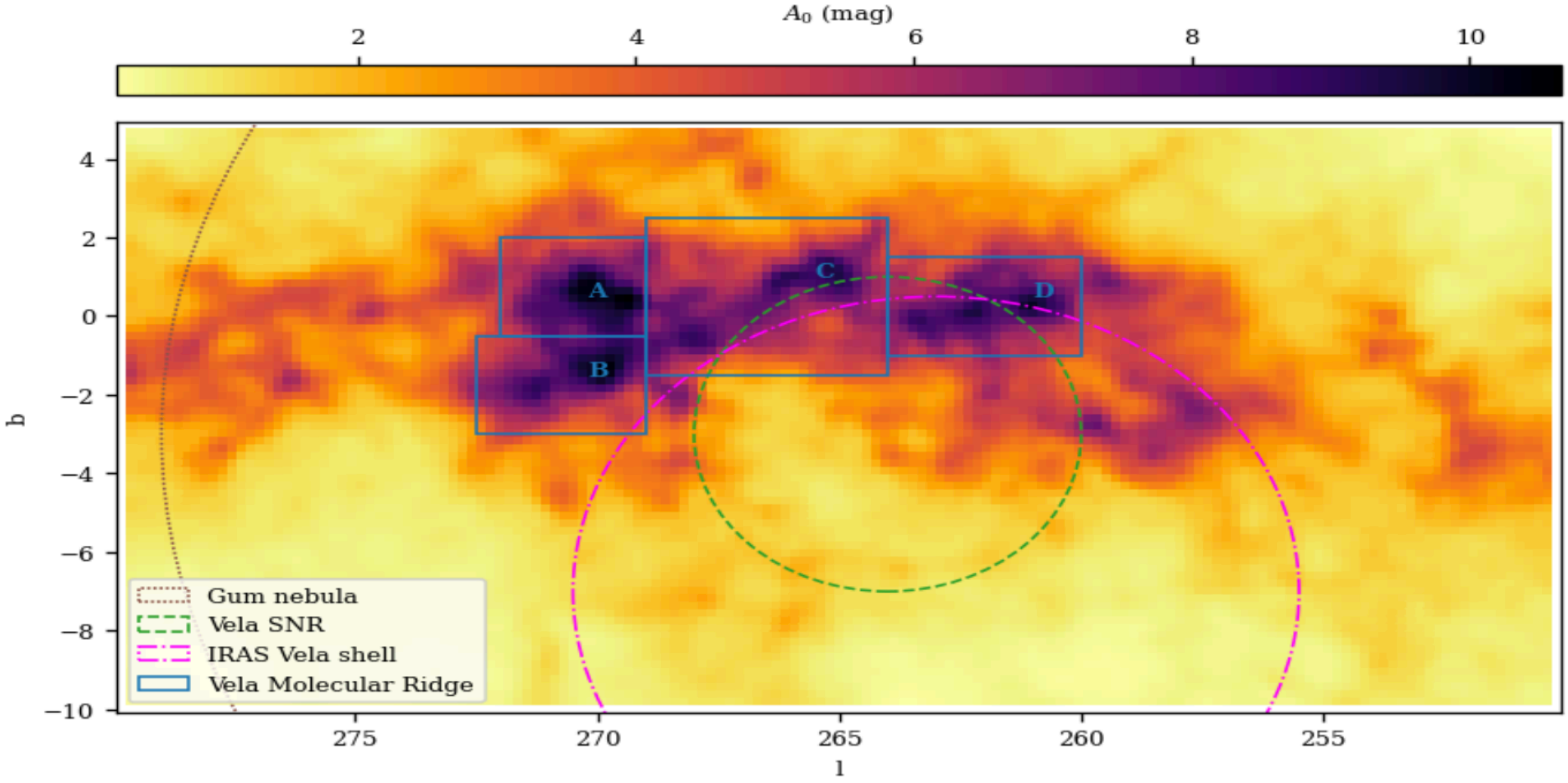



3D view of California top down showing the sheet structure and clouds surrounding cavity

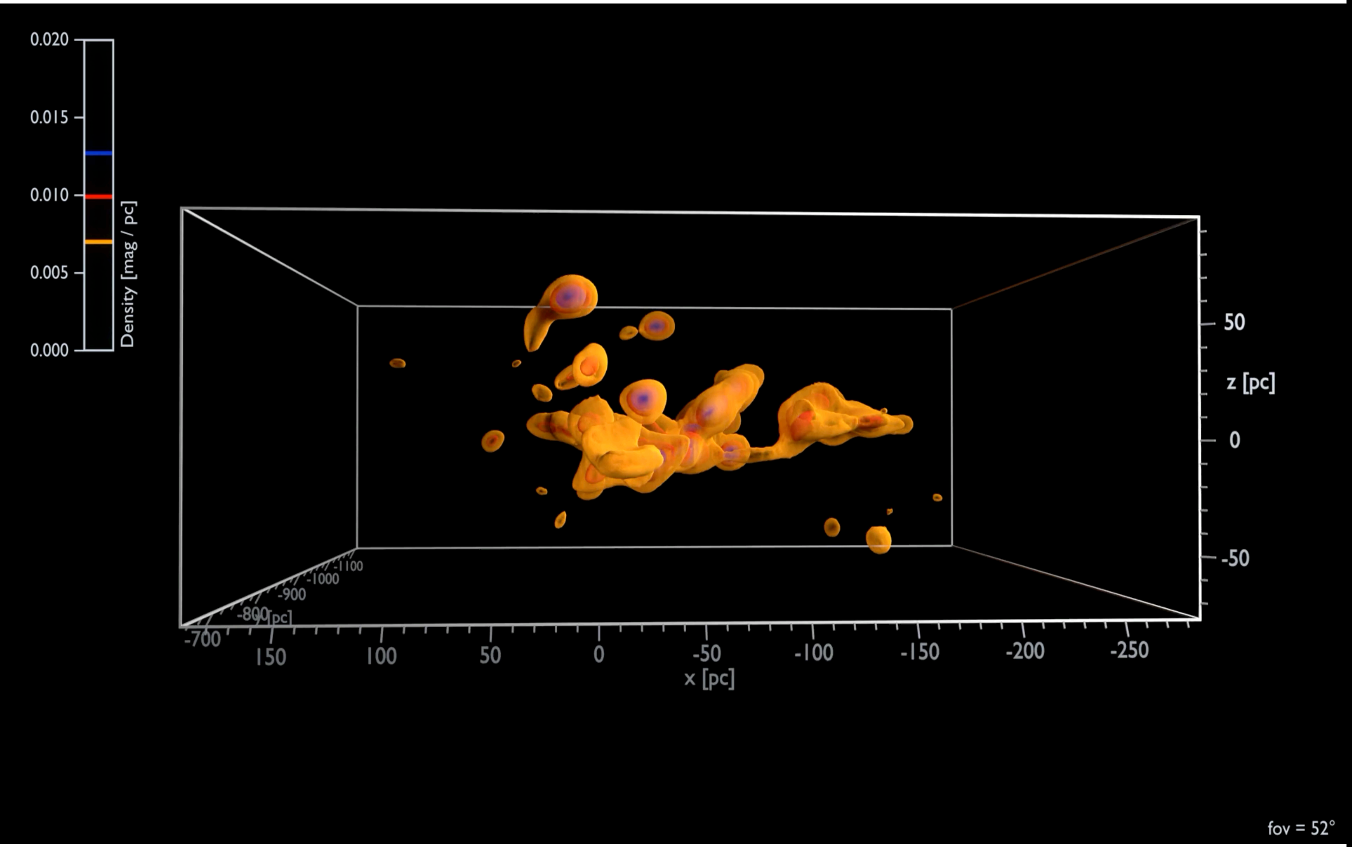
Dharmawardena+2022, 2023

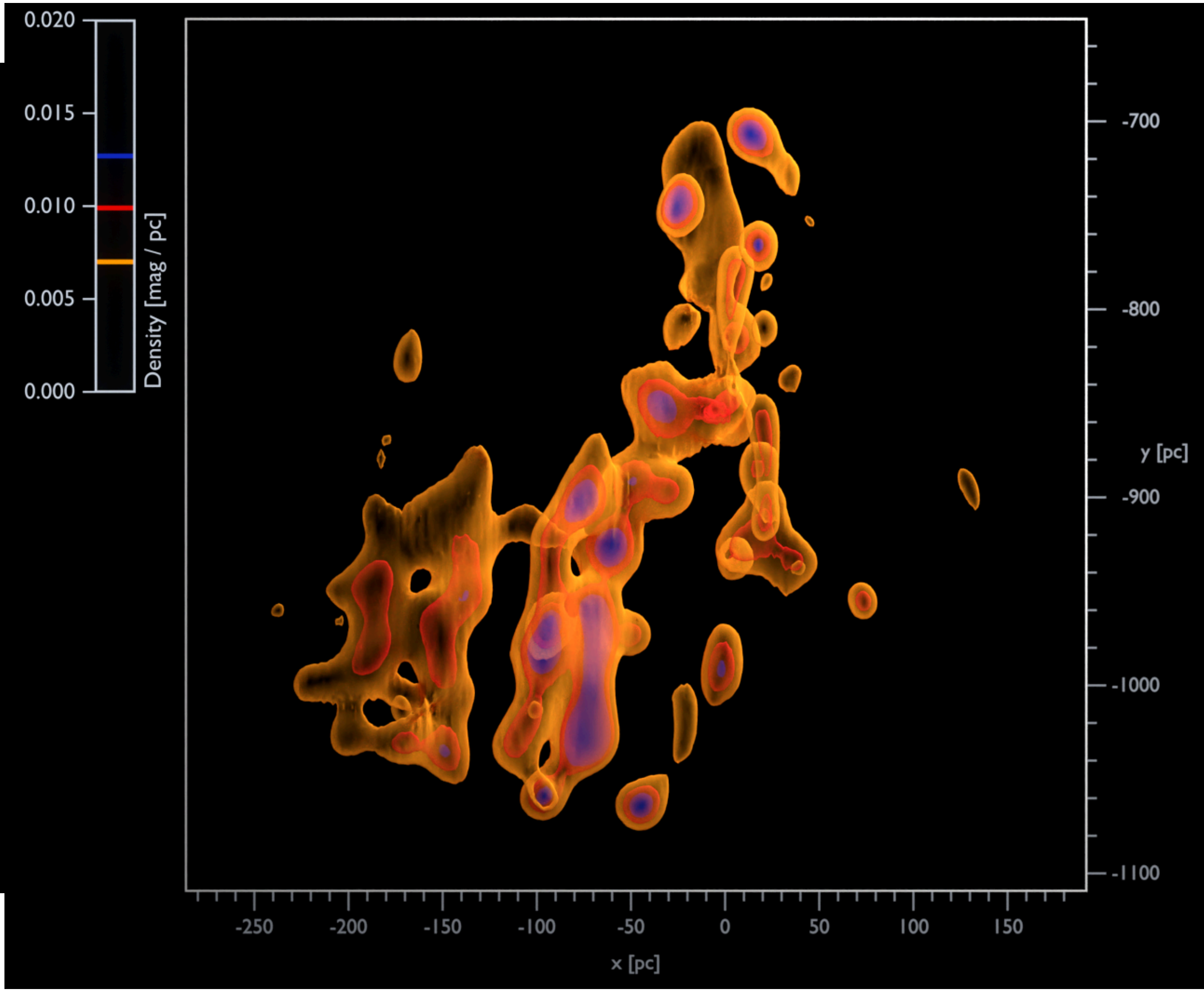
# Tomography of more distant molecular clouds: Vela




Hottier+2021: Extinction map of Vela Molecular Ridge

# Tomography of more distant molecular clouds: Vela



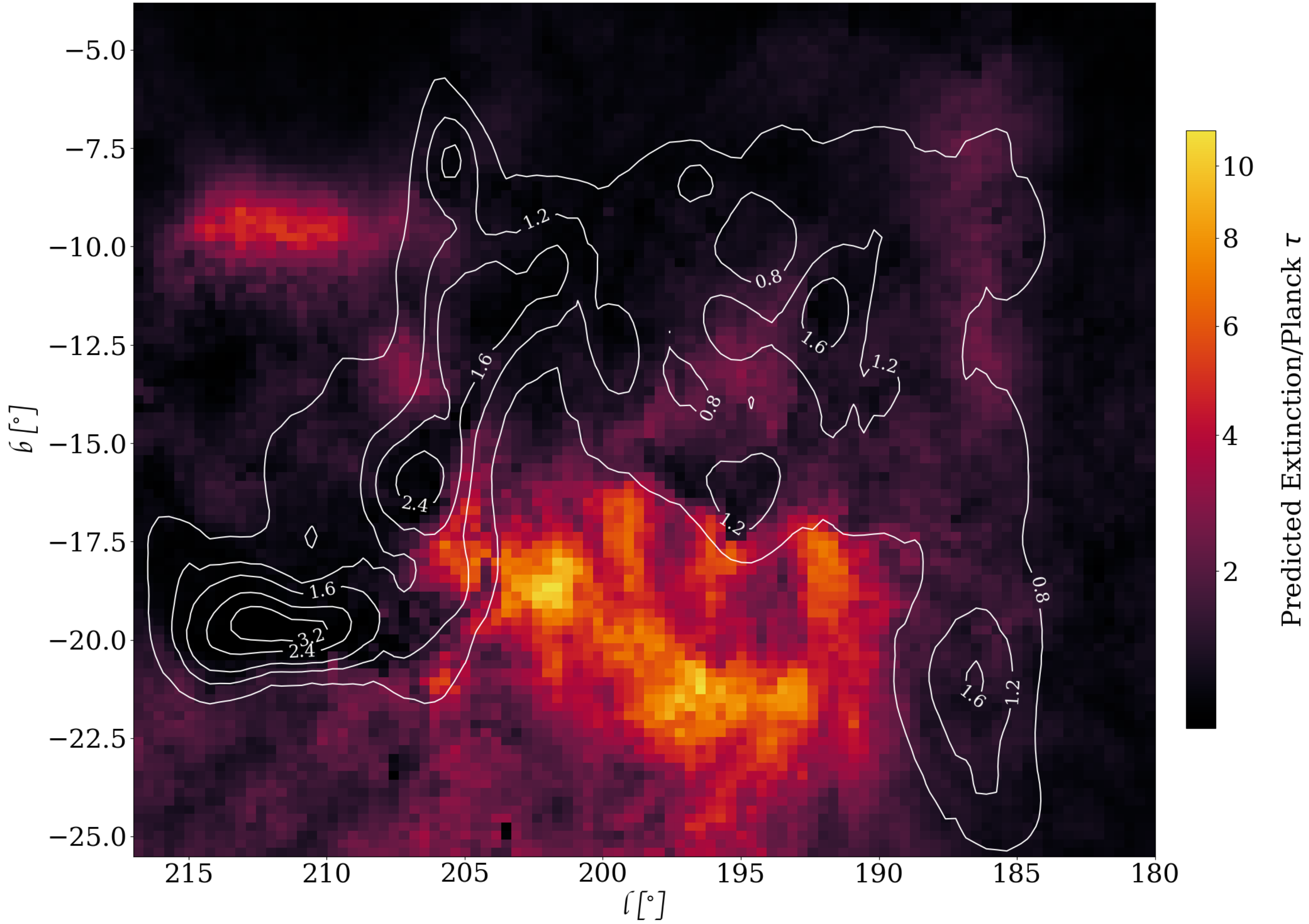




Recover only Vela A,C,D – confirm gas data suggesting Vela B is a seperate cloud at a much further distances.

Vela molecular ridge from sun and top down view: Strong distance gradient in Vela C.

Dharmawardena+2023

# Local variations in dust properties from multi-wavelength data




Dustribution predicted integrated extinction: proxy of dust opacity in optical.

Planck Tau$_{365\ GHZ}$: proxy of dust opacity in sub-mm.

Ratio ∝ Ratio of the optical to the sub-mm dust cross-section.

Variation in grain sizes between the dense molecular clouds and the surrounding diffuse ISM at pc resolution.

Dharmawardena+2022. Ratio of Dustribution predicted extinction/Planck Tau365 GHz for Orion; contours: Dustribution predicted extinction.

# 3D dust density of the Milky Way

GP Scale lengths: 10pc and 100pc merged

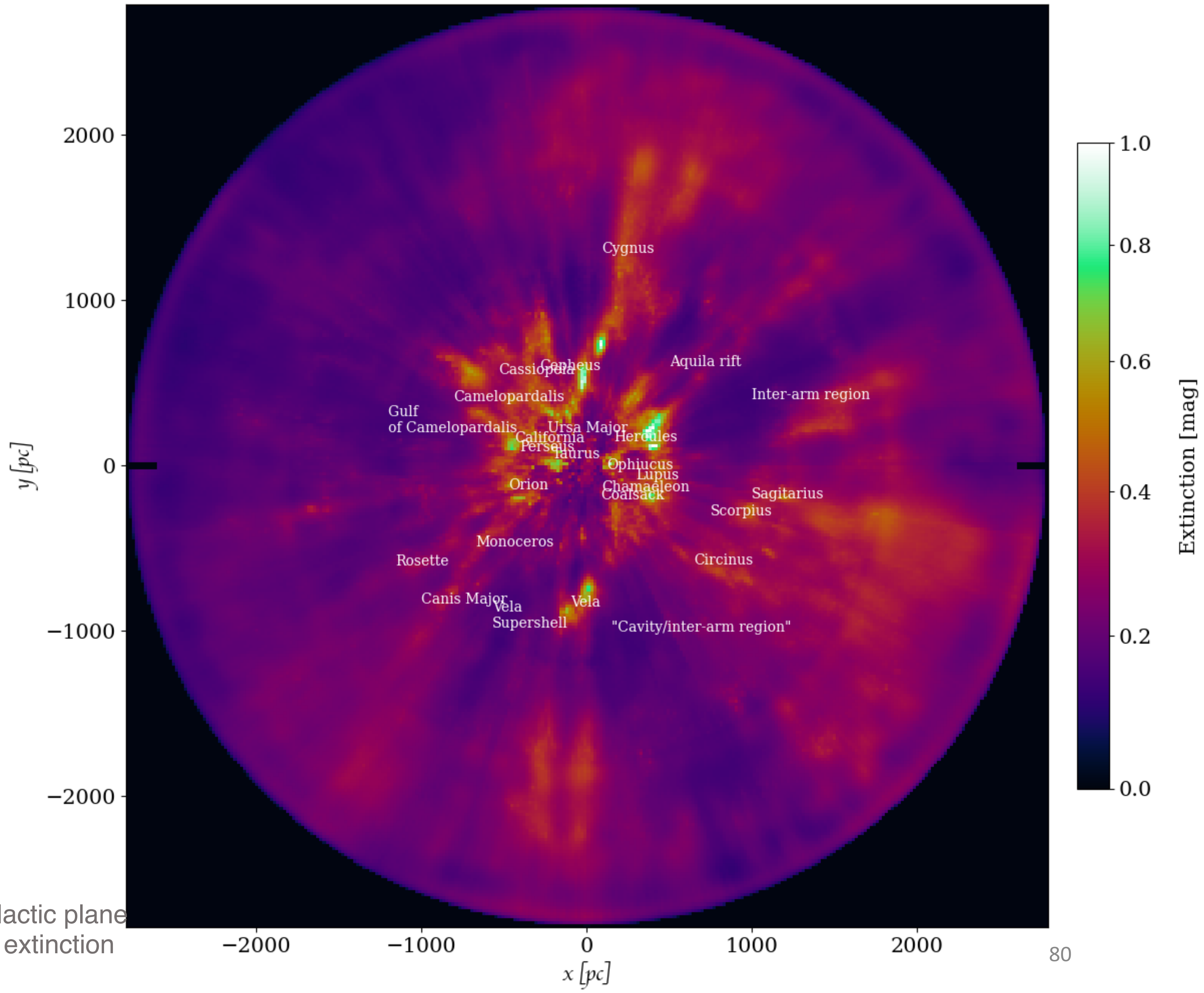
Distance: 2.8 kpc

Grid Sampling: 1.7 pc

Split MW in LBD chunks

Smooth edge: no information - GP falls to mean - Removed with more distance layers.

Ring structure at 1800-1900 pc: Merging artefact



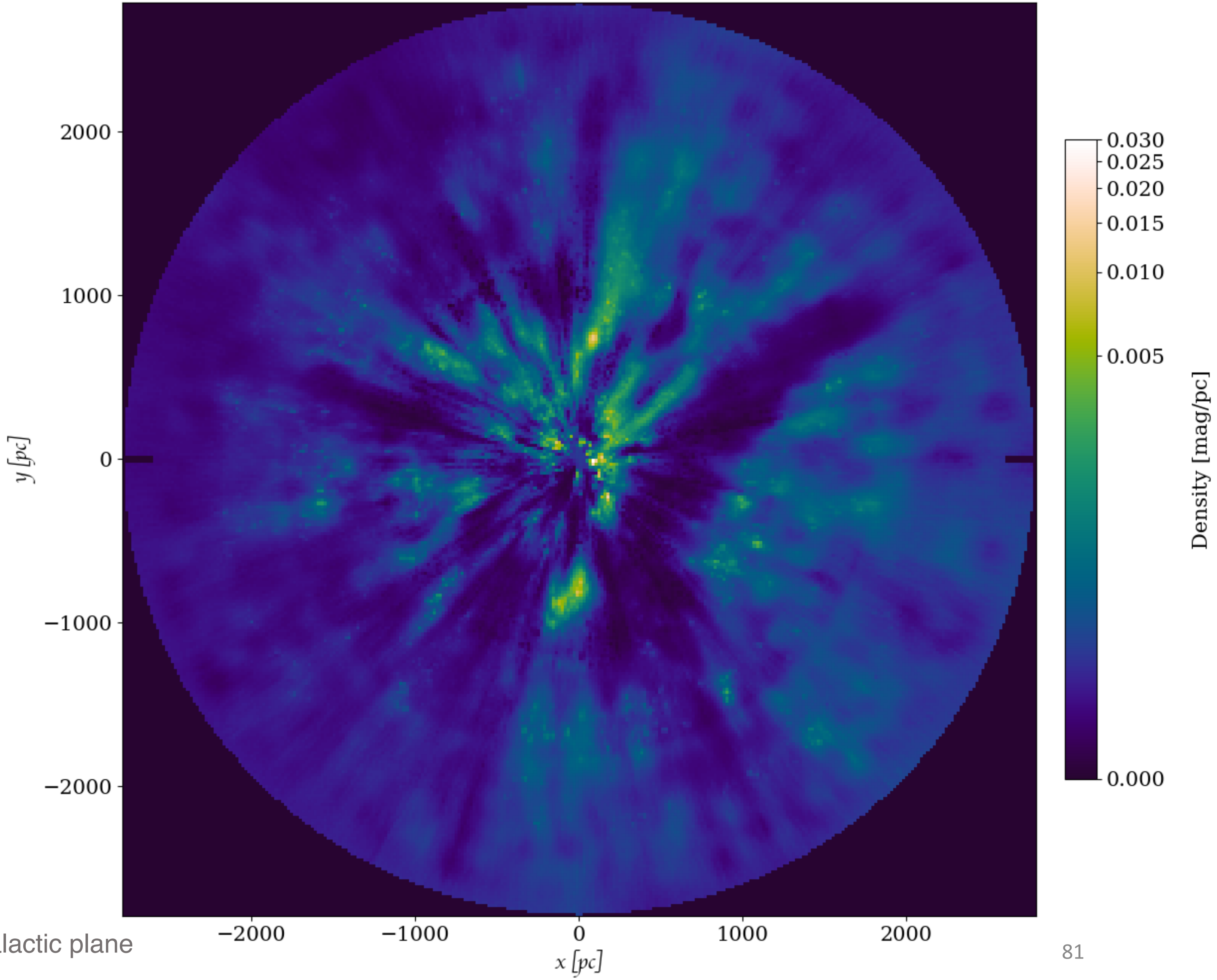

Dharmawardena+subm. Top down view of the Galactic plane with dust density integrated along z to derive dust extinction in the z direction.

# 3D dust density of the Milky Way

GP Scale lengths:
10pc and 100pc
merged

Distance: 2.8 kpc

Grid Sampling: 1.7 pc



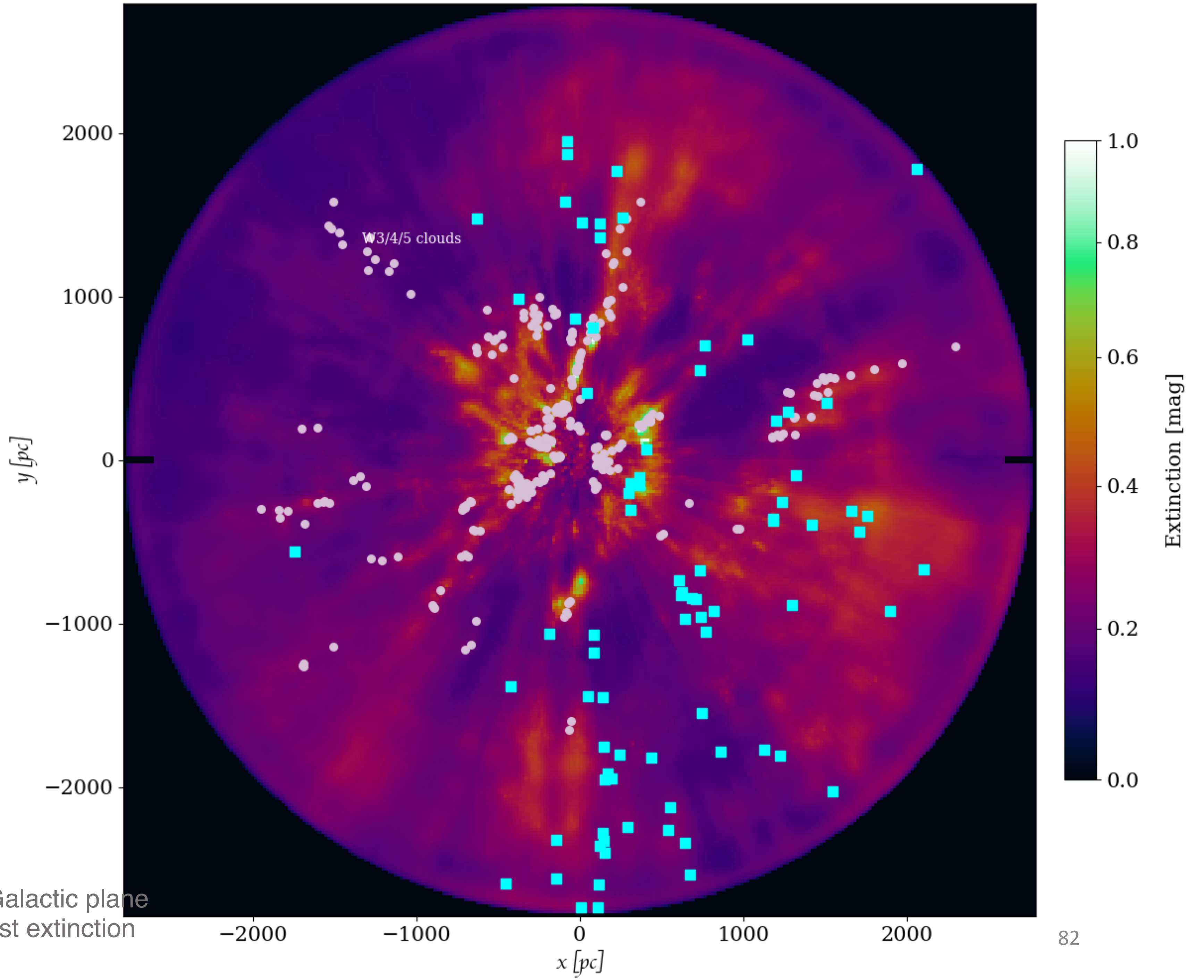

Dharmawardena+subm. Top down view of the Galactic plane with dust density at z=0 slice

# 3D dust density of the Milky Way – Tracing SFRs in the ISM with dust

Comparison to SFRs and Masers:

Violet triangles: Zucker+2021.

Blue squares: Reid+2018



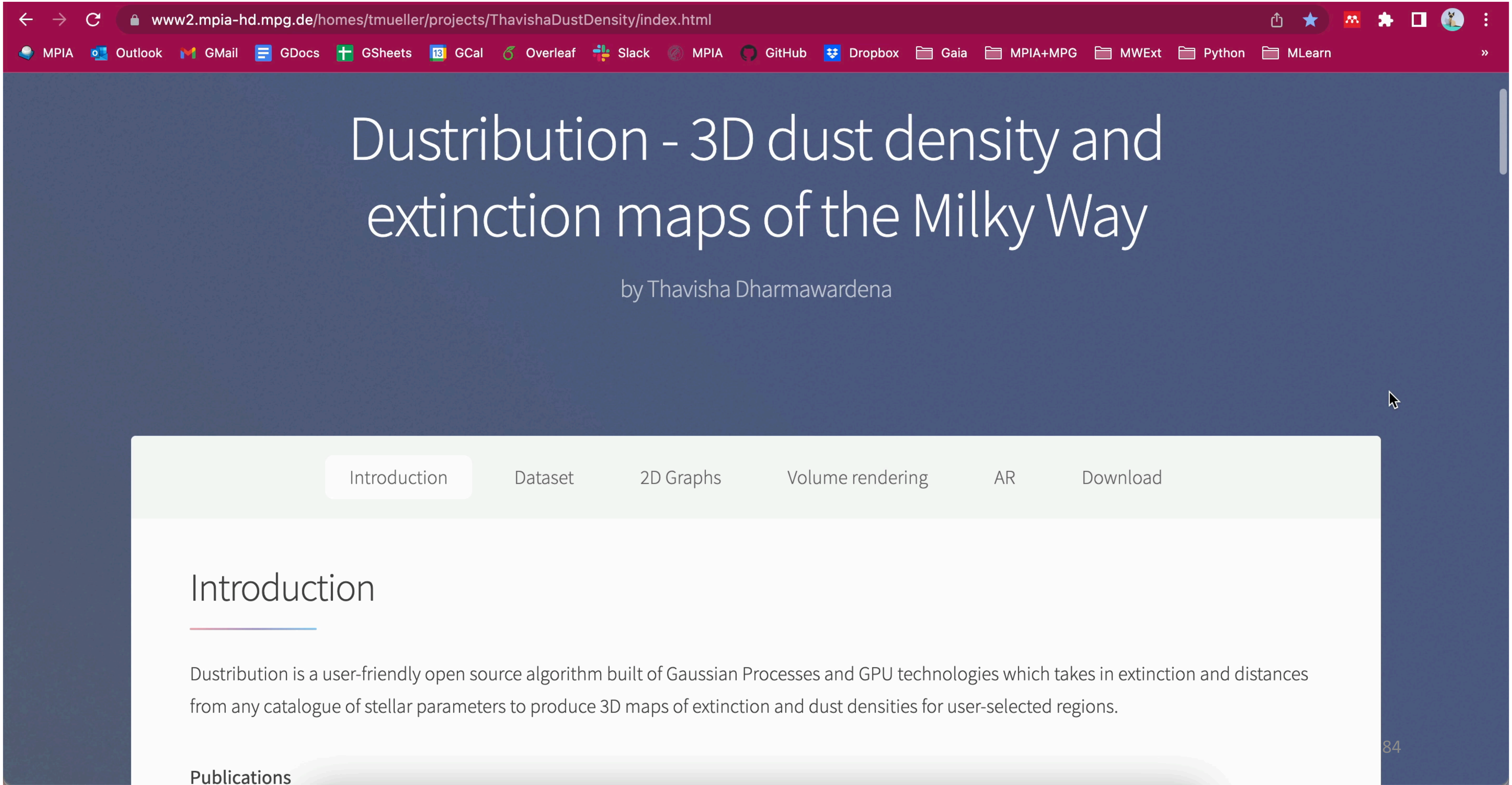

Dharmawardena+subm. Top down view of the Galactic plane with dust density integrated along z to derive dust extinction in the z direction.

# Dustribution: Fully public code and results

Results:
www.mwdust.com

Code:
www.github.com/thavisha/dustribution

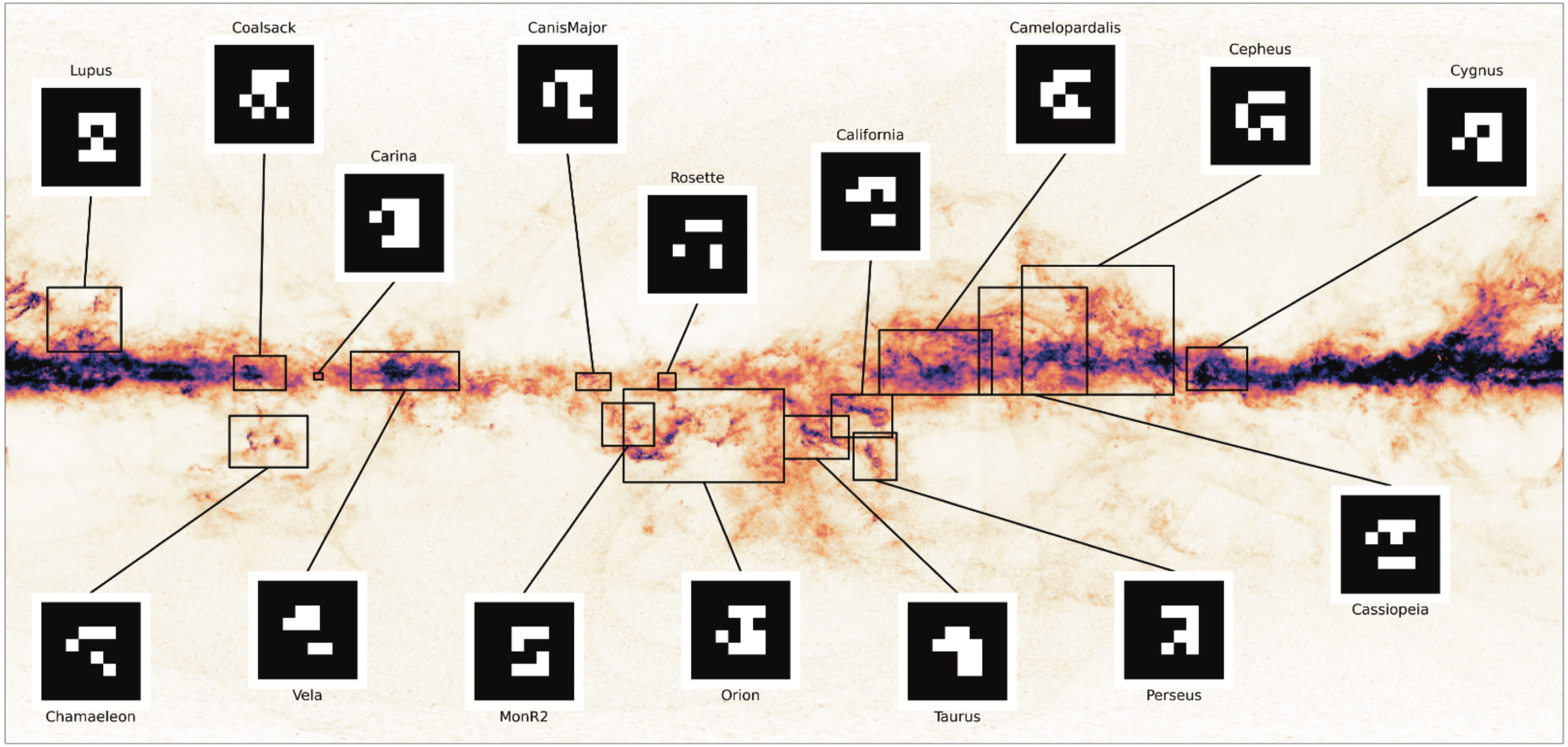
# Interactive website for Dustribution: www.mwdust.com



# Augmented Reality: Galactic molecular clouds

## The three-dimensional Structure of Galactic Molecular Cloud Complexes out to 2.5 kpc

Augmented-Reality view of Dust Contours



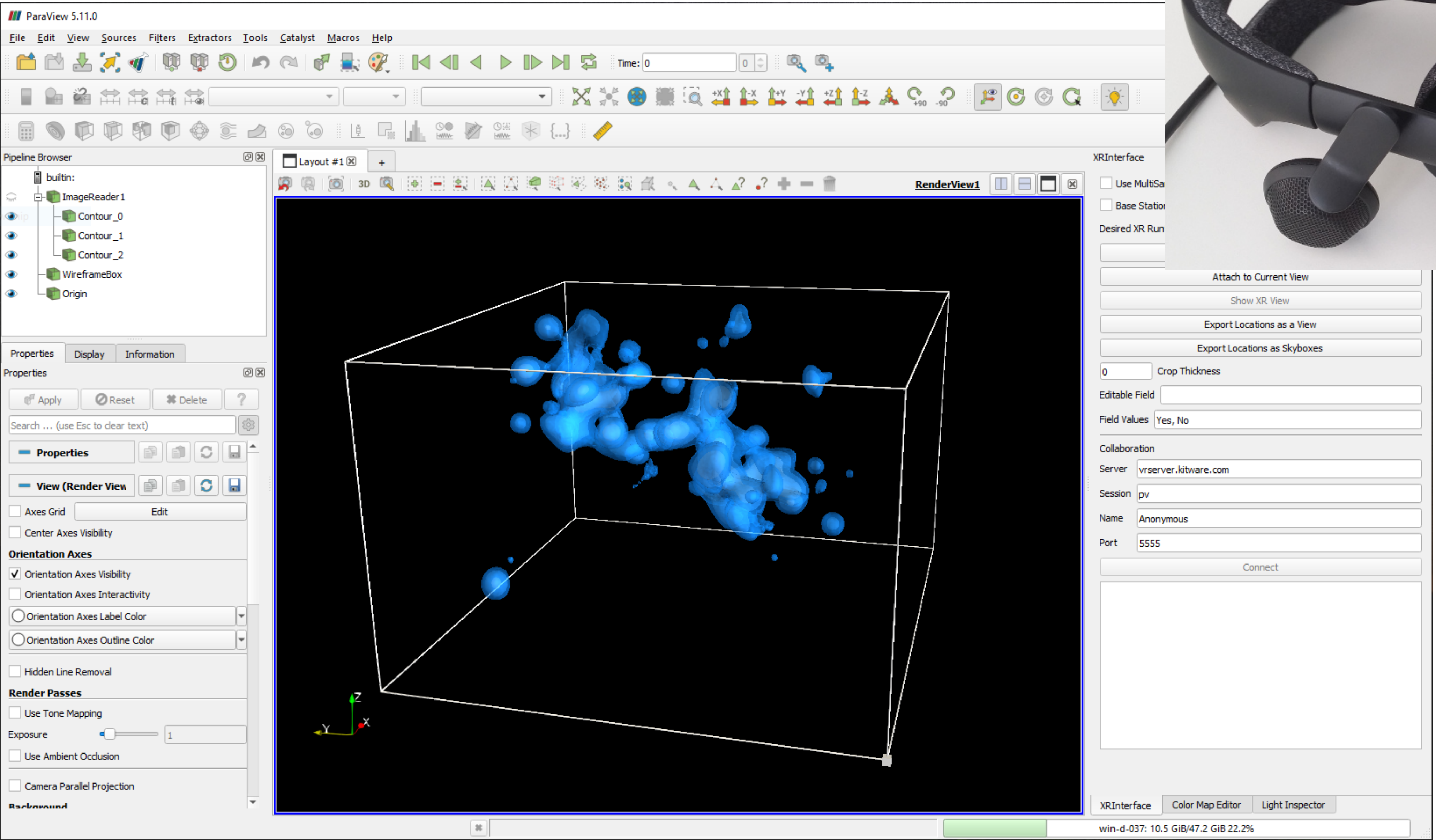

Interstellar dust encompasses less than 1% of the total baryonic matter in the universe and yet plays a crucial role in key processes such as Hydrogen catalyzation and star and planet formation. Further, interstellar dust is key to understanding the structure of the Milky Way. This dust absorbs, scatters and reemits star light which is known as an effect called reddening. Using this reddening along with accurate distances to stars using ground breaking mission such as Gaia and novel machine learning techniques we are able to trace the structure of Milky Way all the way from small scale star-formation regions to massive spiral arm structure. In this poster we use the **Dustribution** algorithm (Dharmawardena et al., 2022a) which maps the 3D density structure of the Milky way along with extinction and distance data from the Fouesneau et al., 2022 catalogue to map the 3D structure of the extended environments of sixteen Galactic molecular clouds.

**How-To**

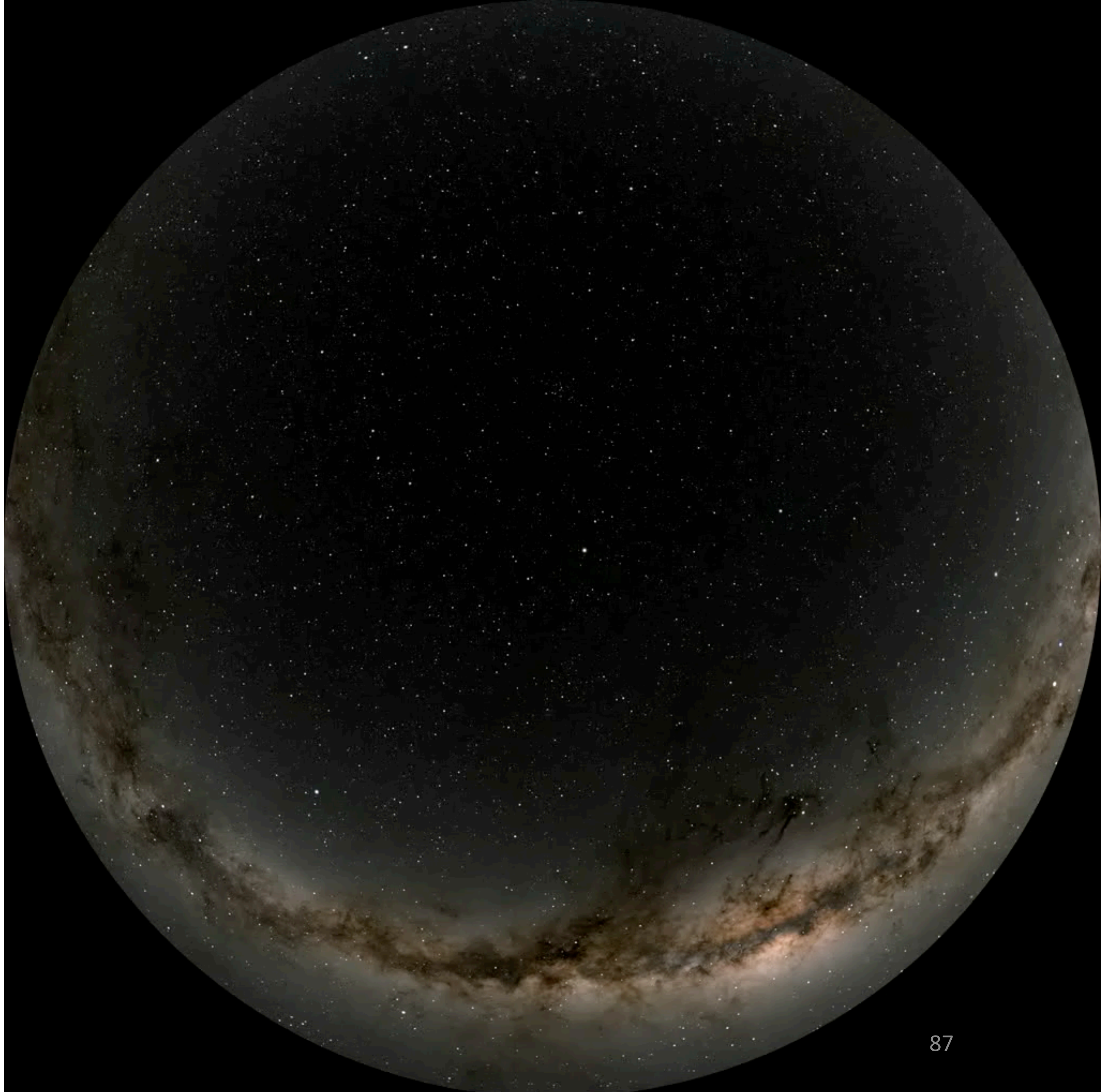
1. Scan the QR-Code in the lower right corner. This will open the corresponding website: (www.mpia-hd.mpg.de/homes/tmueller/projects/ThavishaAR).
2. Hold the camera of your tablet or mobile phone for one of the barcode markers to view the 3D structure of the dust cloud. Note that your camera always has to see the complete marker to work.
3. To increase or decrease a cloud use the config menu in the upper left corner. At this point you can also set some other parameters.

**Credit:** Data and code used to map the 3D structure of sixteen Galactic molecular clouds: Dharmawardena et al., 2022a, Dharmawardena et al., 2022b and Fouesneau et al., 2022 / Background image: Gaia DR3 extinction ($A_0$) map using data from Andrae et al., 2022 / Developed: Thomas Müller (HdA/MPIA)

# Augmented Reality: Galactic molecular clouds




# Galactic Molecular Clouds on Planetarium dome



# Part 4:
# Looking ahead

# 1. Improved data sets

Gaia DR3+IR; SDSS-V; LSST; Gaia DR4

GDR4: not before the end of 2025

Full astrometric, photometric, and radial-velocity catalogues.

All available variable-star and non-single-star solutions.

Source classifications (probabilities) plus multiple astrophysical parameters (derived from BP/RP, RVS, and astrometry) for stars, unresolved binaries, galaxies, and quasars. Some parameters may not be available for faint(er) stars.

An exo-planet list.

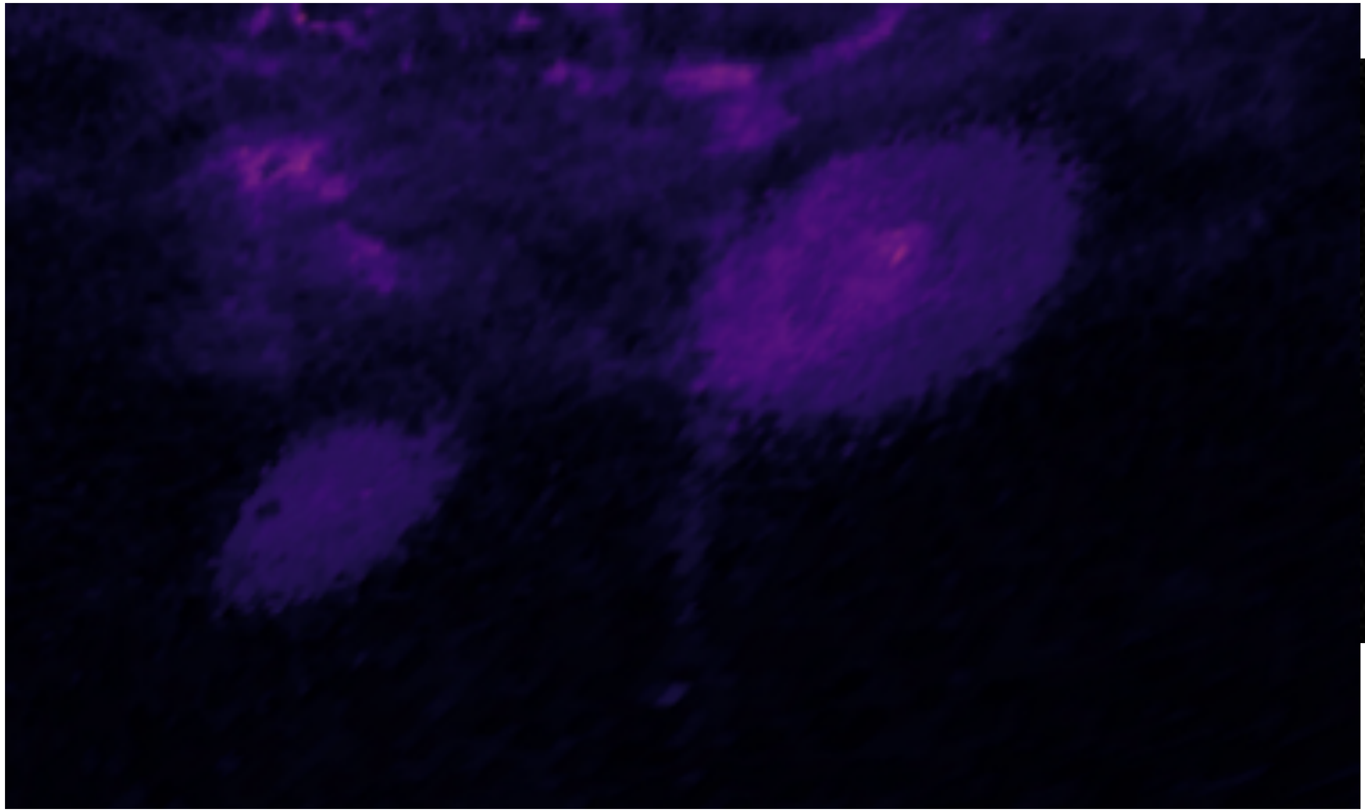
All epoch and transit data for all sources.

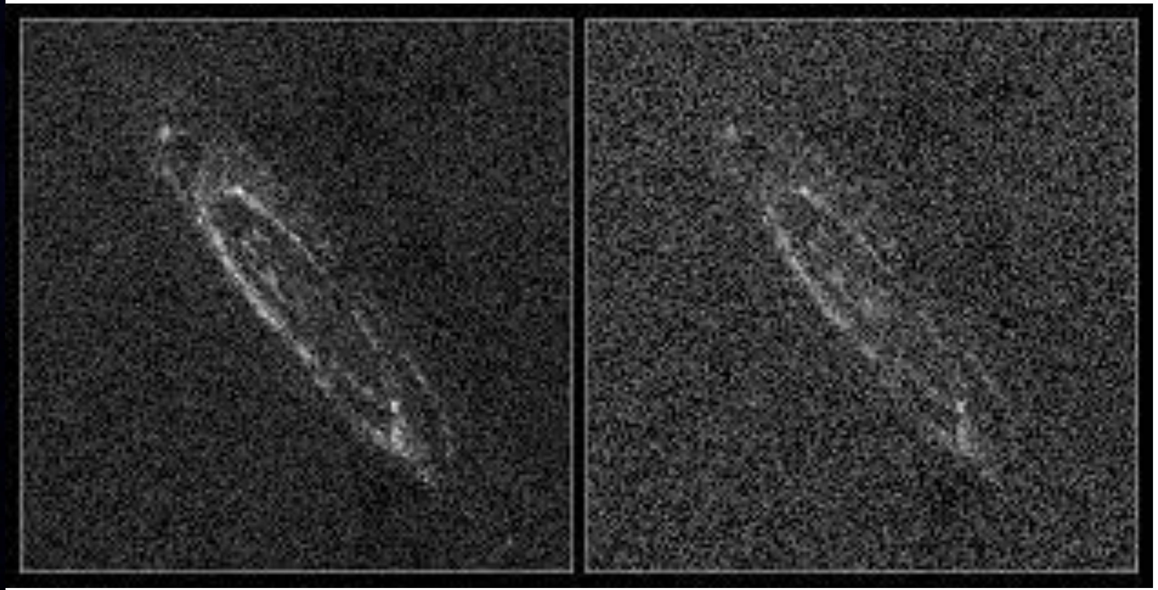
GDR5: end of 2020

Complete Gaia Legacy Archive of all data.

# 2. LMC+SMC and M31

3D dust density and extinction maps of LMC/SMC and M31
Itterative distance improvement maybe needed





Left: LMC/SMC cutout from Total Galactic Extinction map - optimised healpix map based on the DR3 table total_galactic_extinction_map_opt. This sky map has not been smoothed. See Delchambre et al. 2022 for more details. Credits: ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: Created by T.E.Dharmawardena, Gaia group @ MPIA.



Right: M31 stellar and flux density with Gaia EDR3. ESA/Gaia/DPAC

# 4. Advancing 4D dust density maps

Simultaneously map the dust and the gas together to get a full correlated view of the ISM

4D dust density maps: pppv, $A_V + \rho$: l,b/ra,dec, d, v, $A_V + \rho$

# Some useful links

- https://iopscience.iop.org/article/10.1088/1742-6596/6/1/001/pdf
- https://articles.adsabs.harvard.edu/pdf/1930PASP...42..214T
- https://www.youtube.com/watch?v=2Zg8aEkDYa8
- https://www.gaia.ac.uk/alerts/what-and-why/gaia-spectra
- https://www.cosmos.esa.int/web/gaia/dr3
- https://gaussianprocess.org/gpml/chapters/RW.pdf
- https://gea.esac.esa.int/archive/documentation/GDR3/Data_analysis/chap_cu8par/sec_cu8par_apsis/ssec_cu8par_apsis_gspphot.html
- https://www.youtube.com/watch?v=2Zg8aEkDYa8
- www.mwdust.com
- www.github.com/thavisha/dustribution