Multi-scale multi-resolution 3D dust astrocartography of the Milky Way and its molecular clouds

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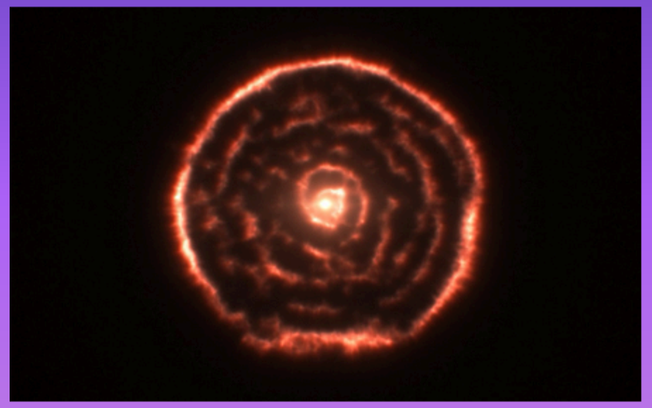
In collaboration with: Blakesley Burkhart (Flatiron/Rutgers), Dan Foreman-Mackey (CCA/Google), Andrew Gordon Wilson (NYU) and Geoff Pleis (UBC), Julianne Dalcanton (CCA), David Hogg (NYU/CCA), Coryn Bailer-Jones (MPIA), Morgan Fouesneau (MPIA), Rene Andrae (MPIA), Thomas Müller (MPIA), Piero Coronica (MPCDF), Timoteo Colnaghi (MPCDF)

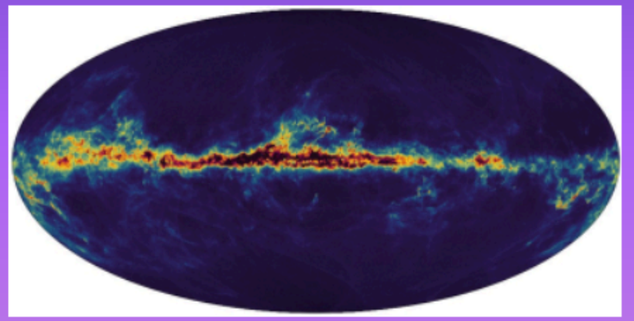
Dust is crucial to galaxy evolution - Life cycle of dust

Ejected by stellar winds, Planetary nebulae and supernovae

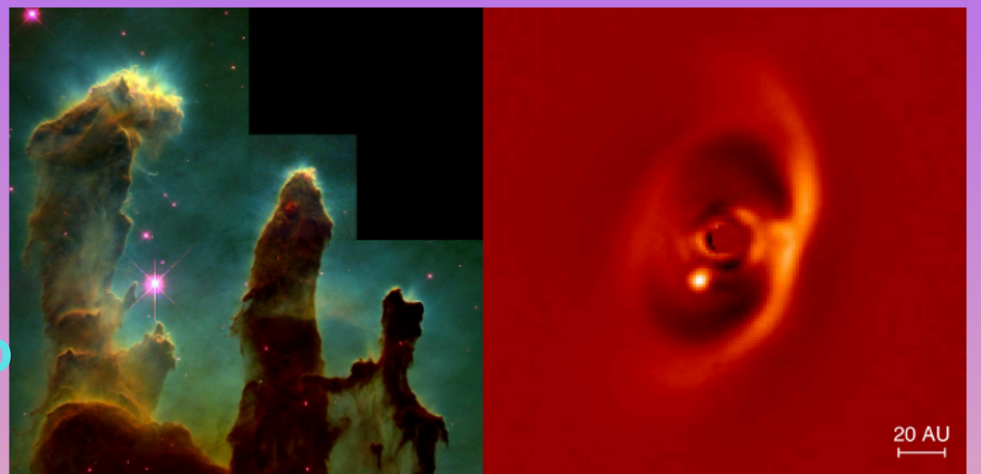
Formed in evolved stars



<1% of total baryonic mass



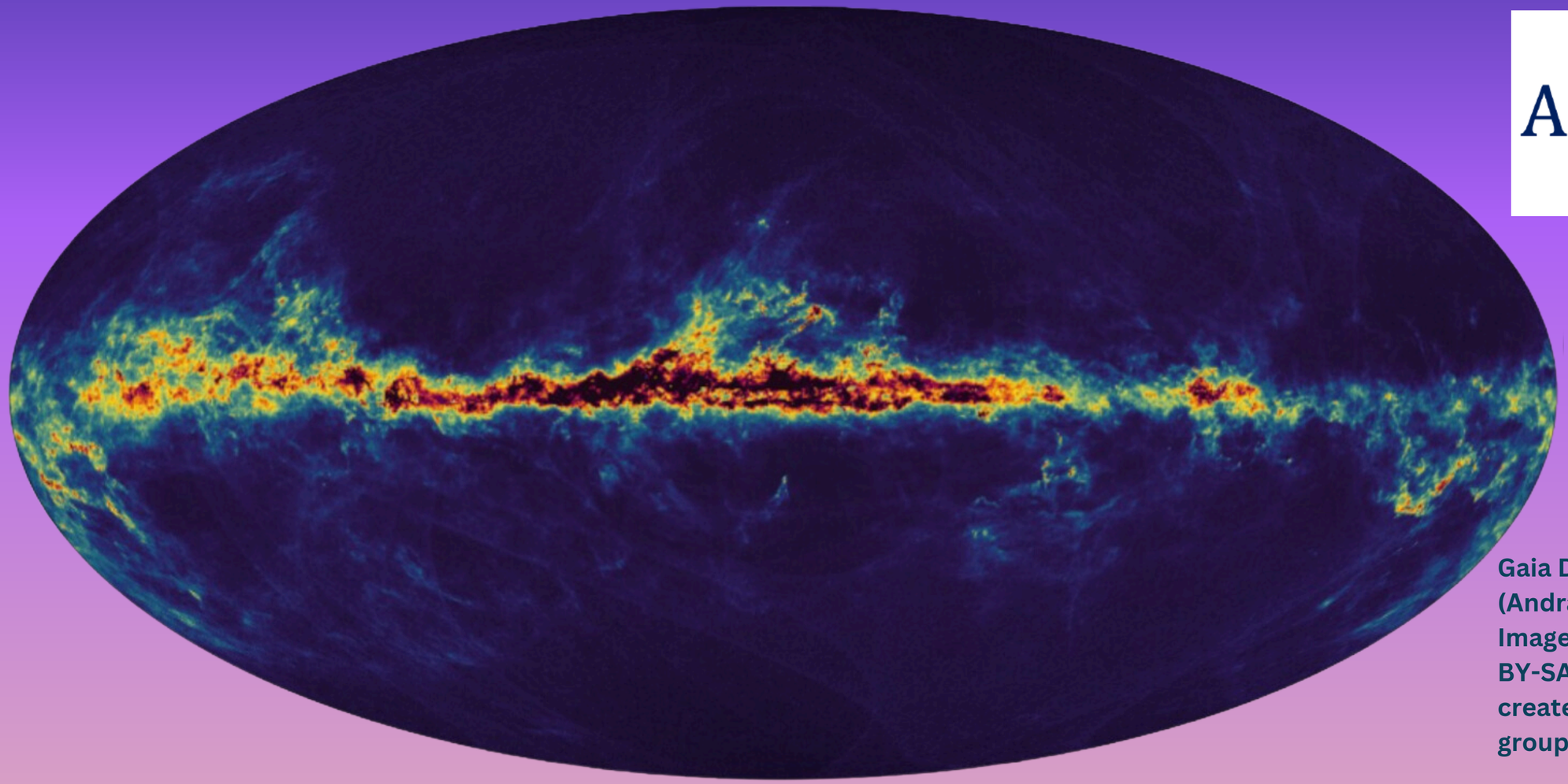
Processed in the ISM



Incorporated back into star and planet formation

Gaia Era - Map dust in 3D

- Precise parallaxes and extinctions to hundreds of millions of stars
- Stellar 3D positions, proper motions and extinctions - 3D Dust density
- 3D dust density - Structure of the Milky Way



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

Gaia DR3 GSPphot extinctions (Andrae et al., 2022).
Image Credits: ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: created by T.E.Dharmawardena, Gaia group @ MPIA

Dust astrocartography

Dustribution - A novel 6D dust astrocartography code

- An open source 6D dust cartography package

- Input (public): Any stellar distance and extinction catalogue
- Input (testing): Add line absorption, velocity catalogues, stellar proper motions

- 3D mapping: Map 3 kpc all sky volume at 0.1-0.7 pc resolution in one week on one H100 GPU [Dharmawardena+2024]

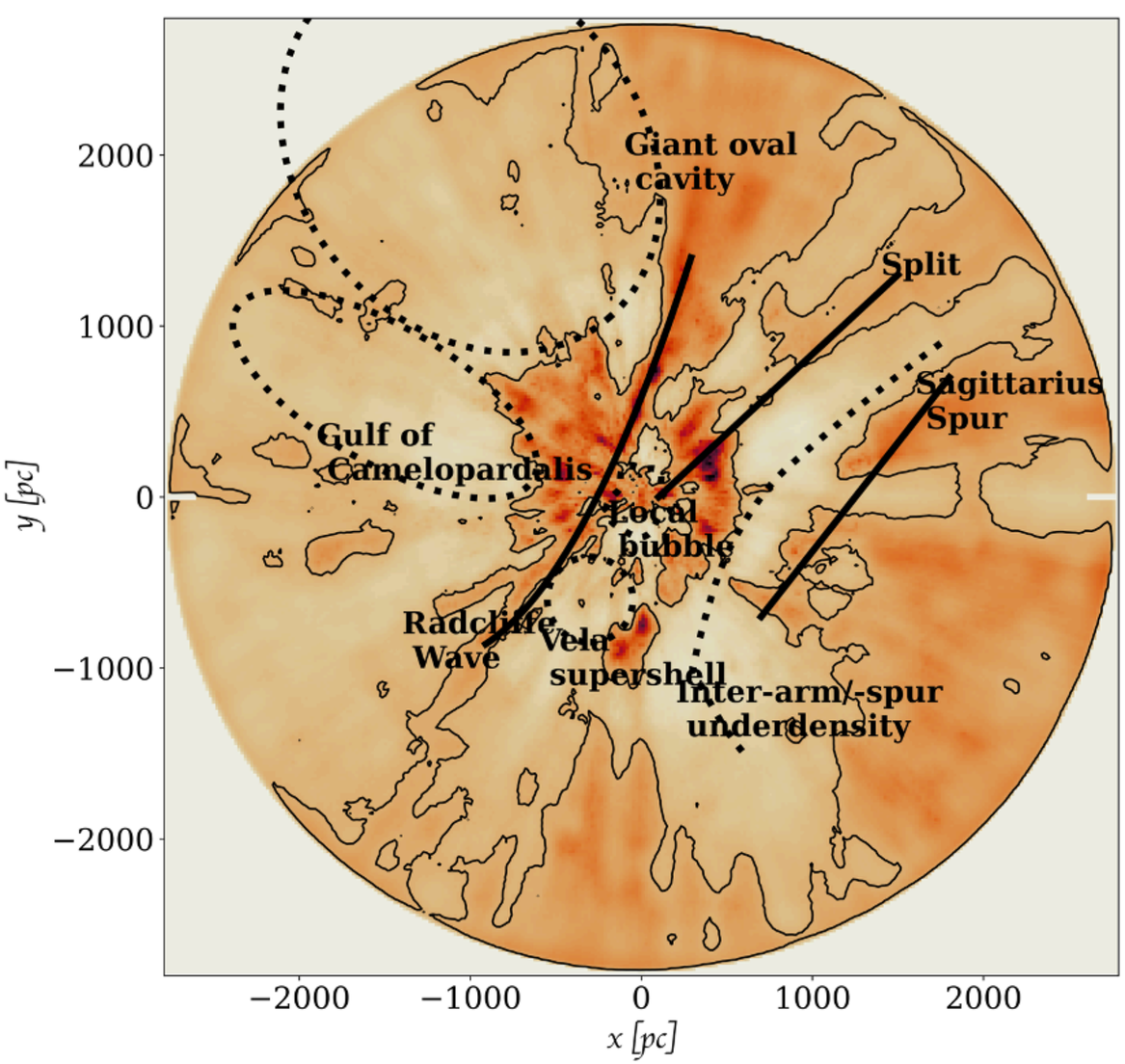
- Latest developments:
  - Latent Variable Nearest Neighbour Gaussian Processes
  - Custom multiscale kernel
  - Deep kernel learning: expand to 6D mapping (testing phase)

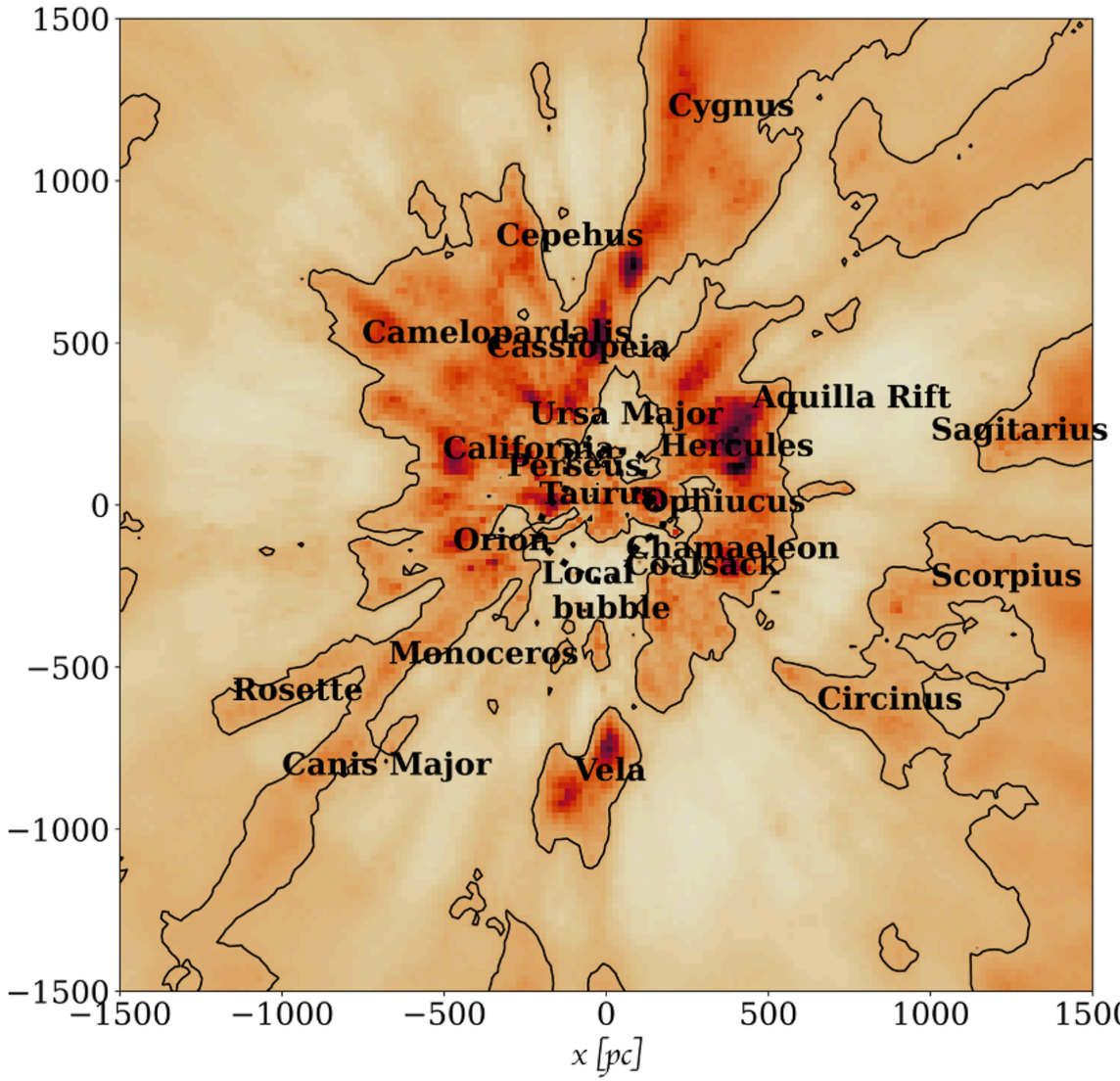
www.mwdust.com

www.github.com/thavisha/dustribution

Dust astrocartography of the Milky Way

The 3D structure of the Milky Way - Large scale





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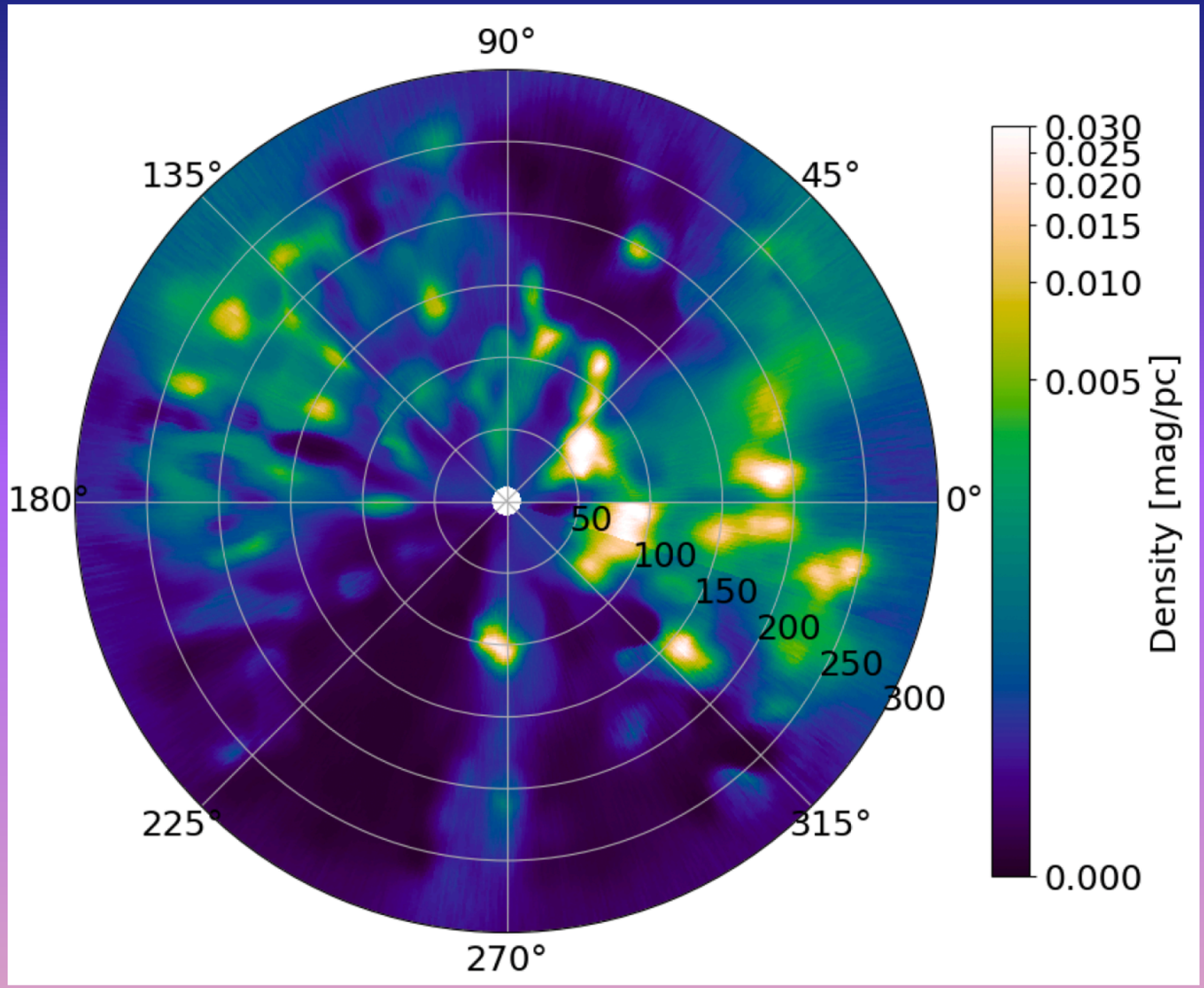
The 3D structure of the Milky Way - Inner 300 pc



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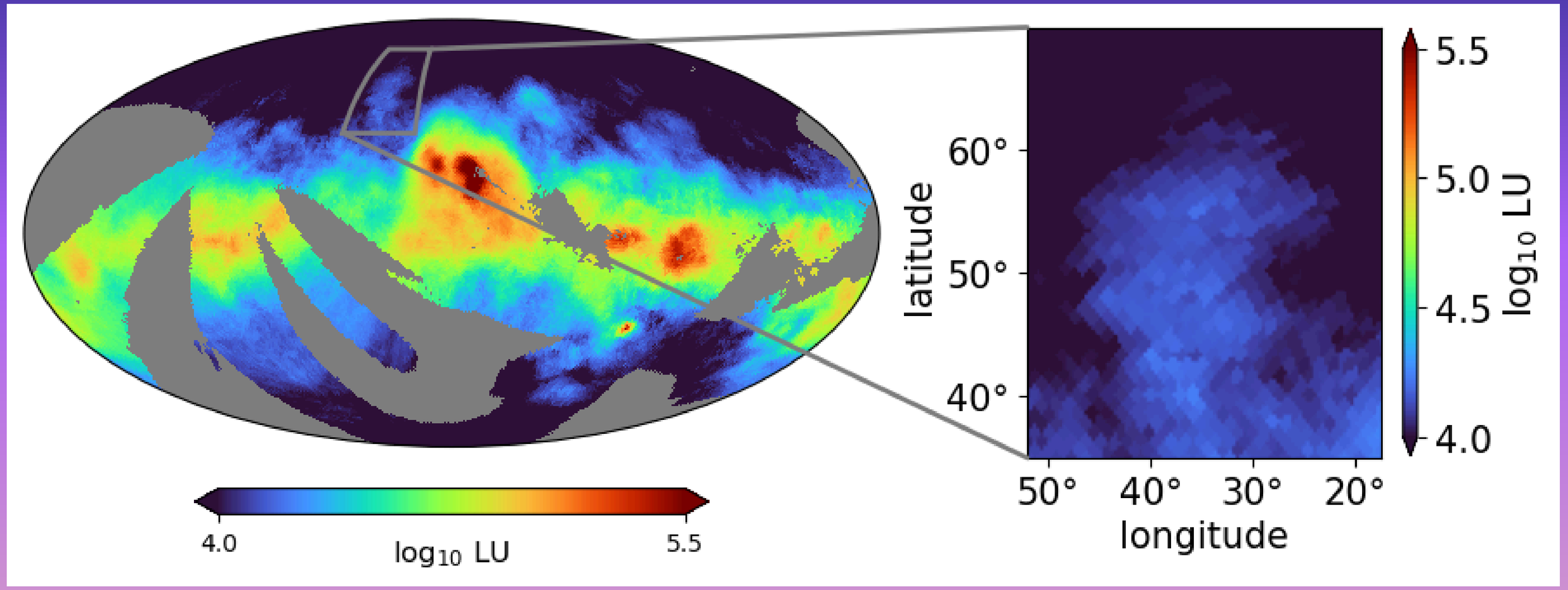
Dust cartography of the newly discovered nearest molecular cloud, Eos

In collaboration with Blakesley Burkhart (Flatiron/Rutgers)

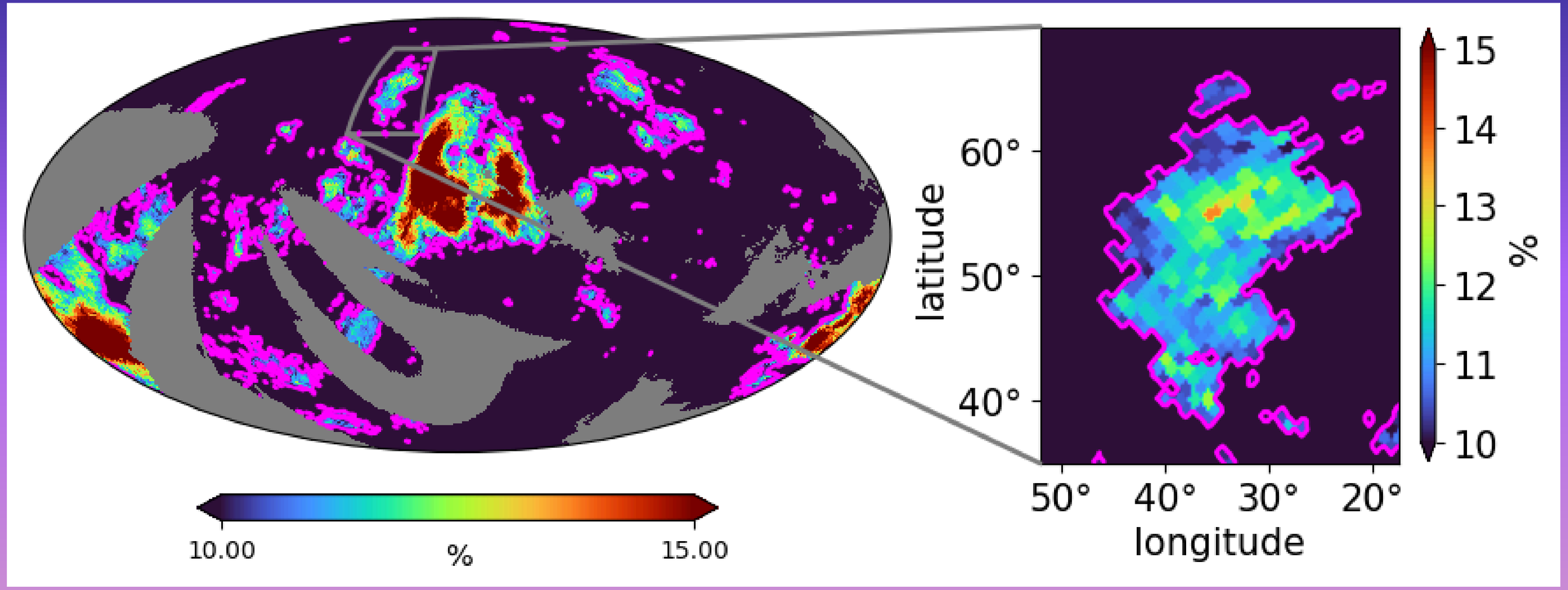
The Eos Cloud - Discovered in H2 fluorescence in the UV

- New large nearby diffuse cloud
- First molecular cloud to be discovered in H2 fluorescence in the UV (FIMS/SPEAR data; Jo+2017)



Burkhart, Dharmawardena + in prep. (shared first author)

The Eos Cloud - On-sky boundary in H2 intensity/Total FUV intensity



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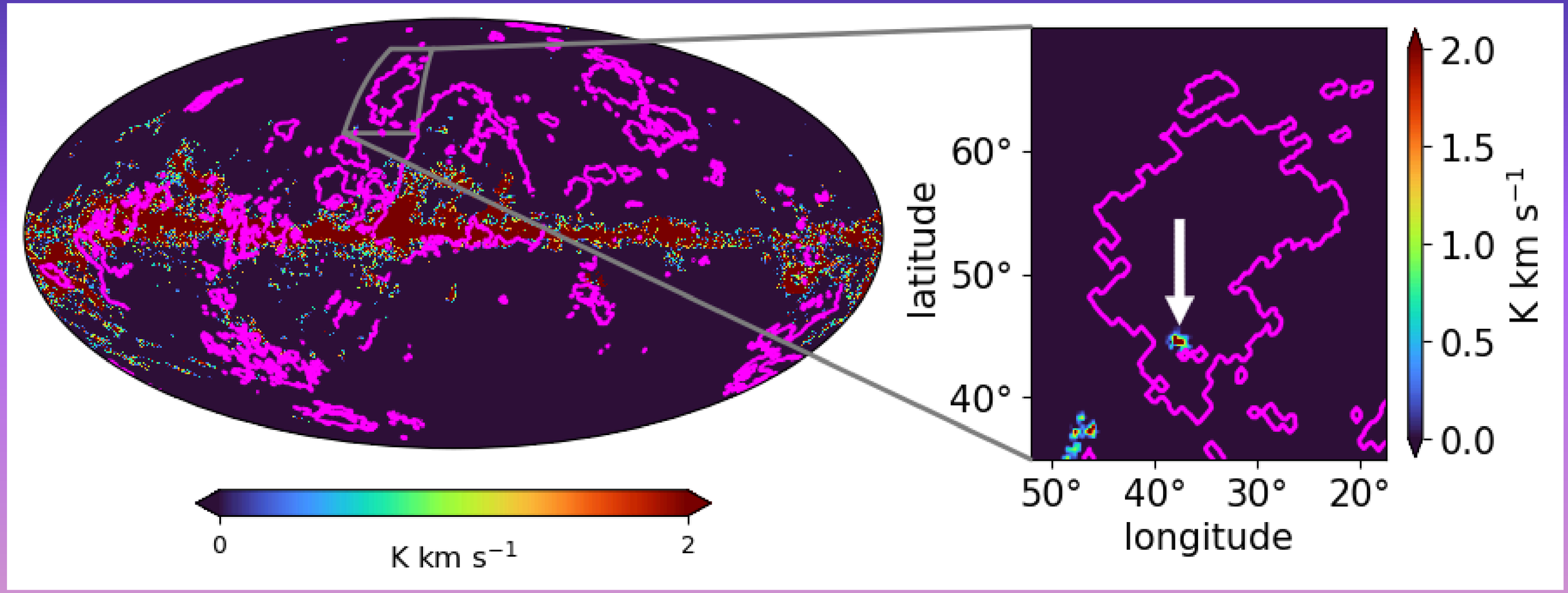
The Eos Cloud - CO dark

- CO emission - Very little CO present (data from Dame+2020) - matches Planck CO maps
- CO-dark molecular gas
- Kinematic distance to CO clump: 280 (+180/-210)



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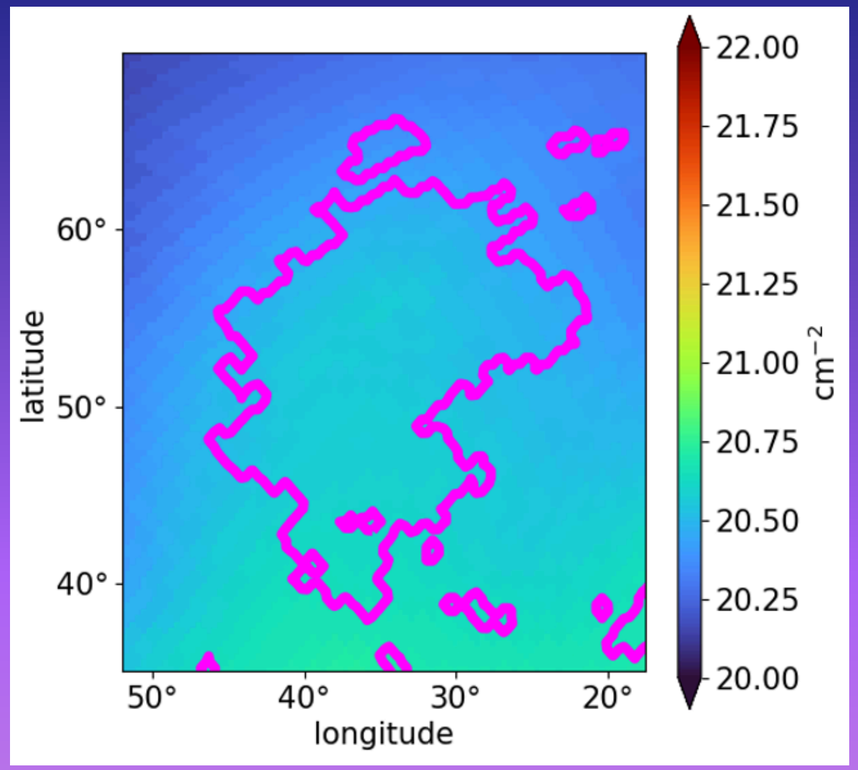
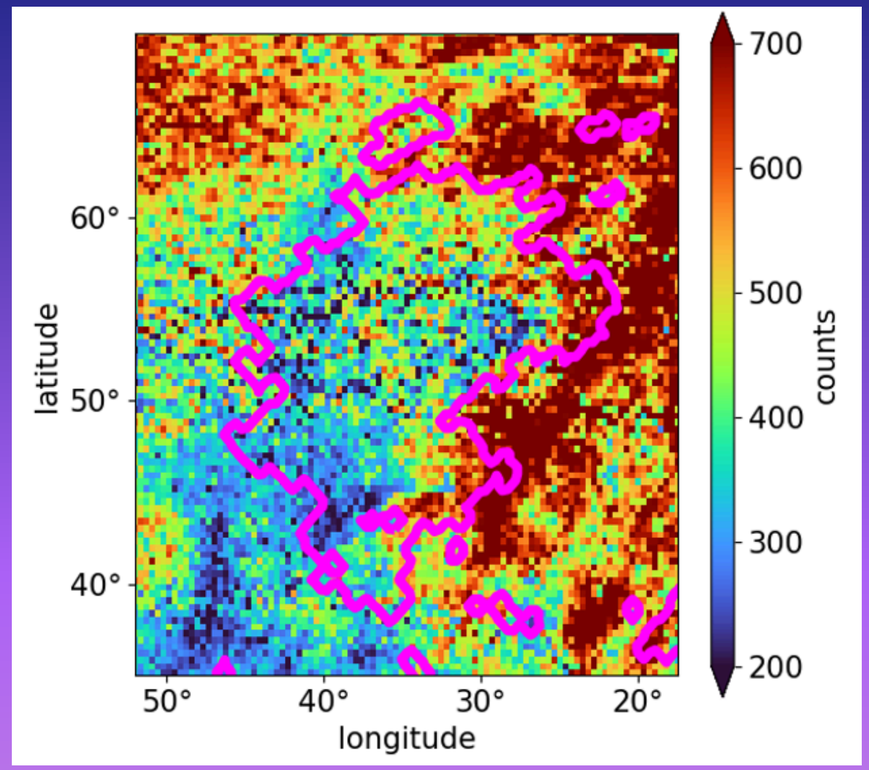
The Eos Cloud - Other tracers



- HI - diffused in atomic gas (data from H4PI)
- Formed of molecular gas and not atomic



- 1/4 KeV soft x-ray - clear gap (data from Rosat)
- Absorbing background Galactic xray emission

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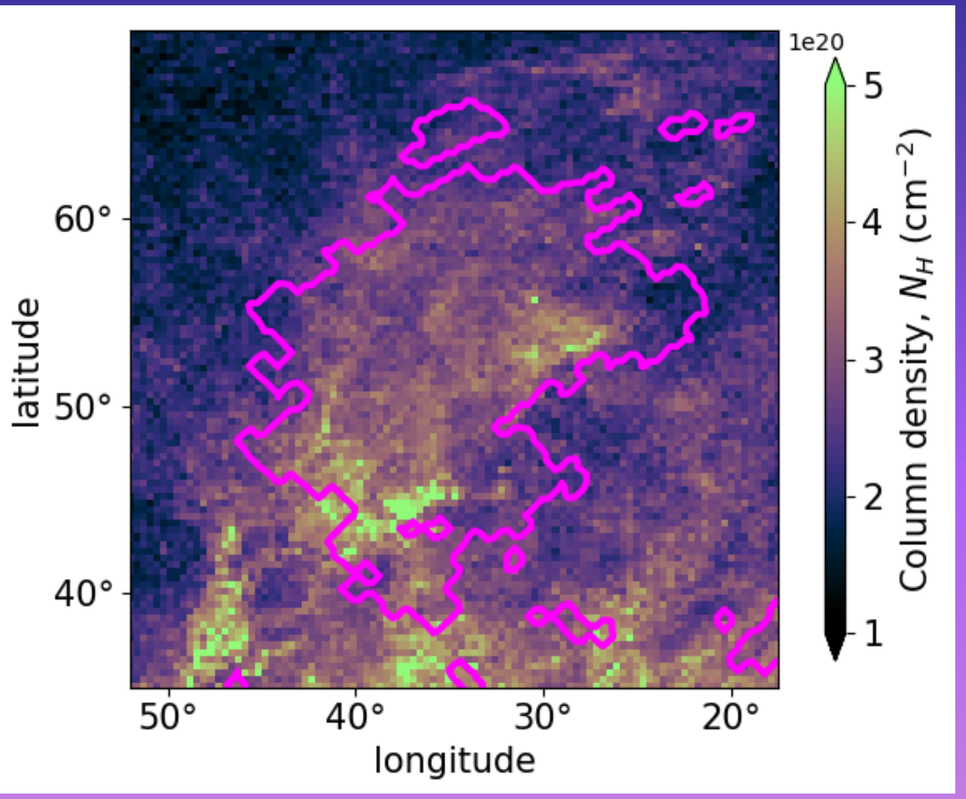
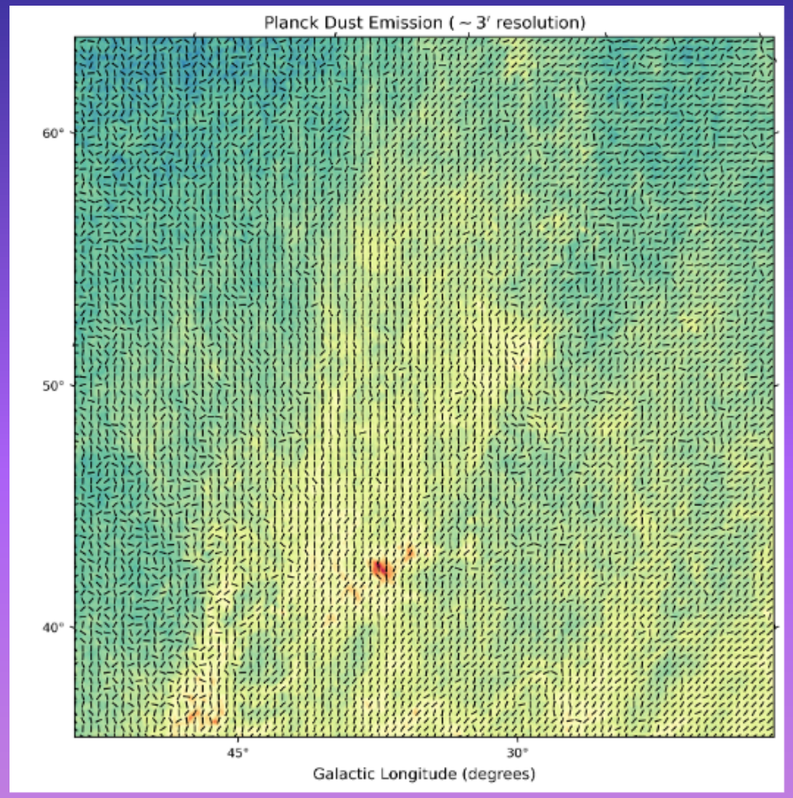
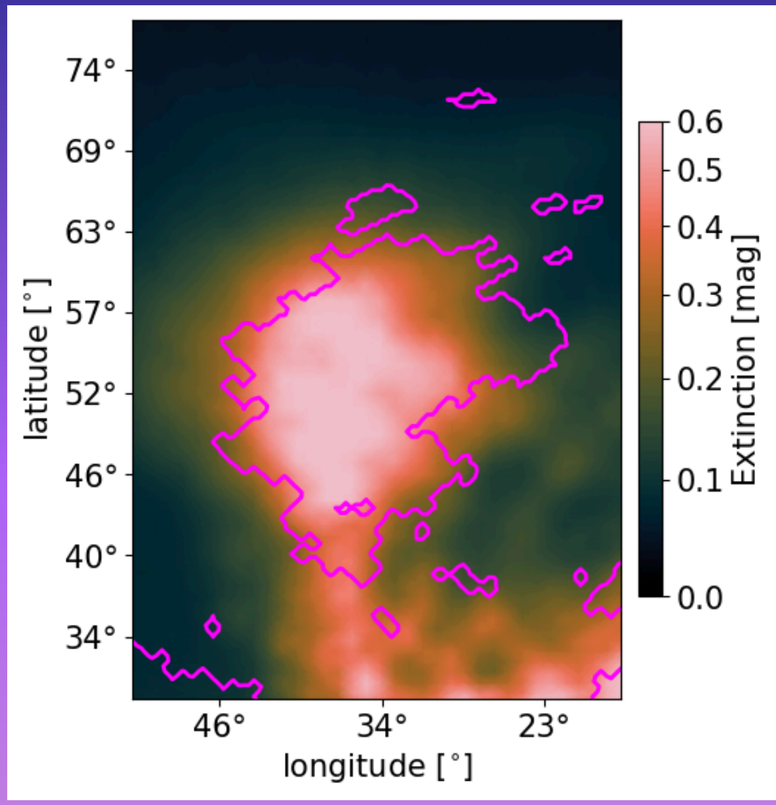
The Eos Cloud - Other tracers



- Planck column density from 545 GHz map



- Dust polarisation - Planck magnetic field from 545 GHz map
- Magnetic feilds ordered in Eos cloud and disordered outside



- Integrated dust extinction with Dustribution

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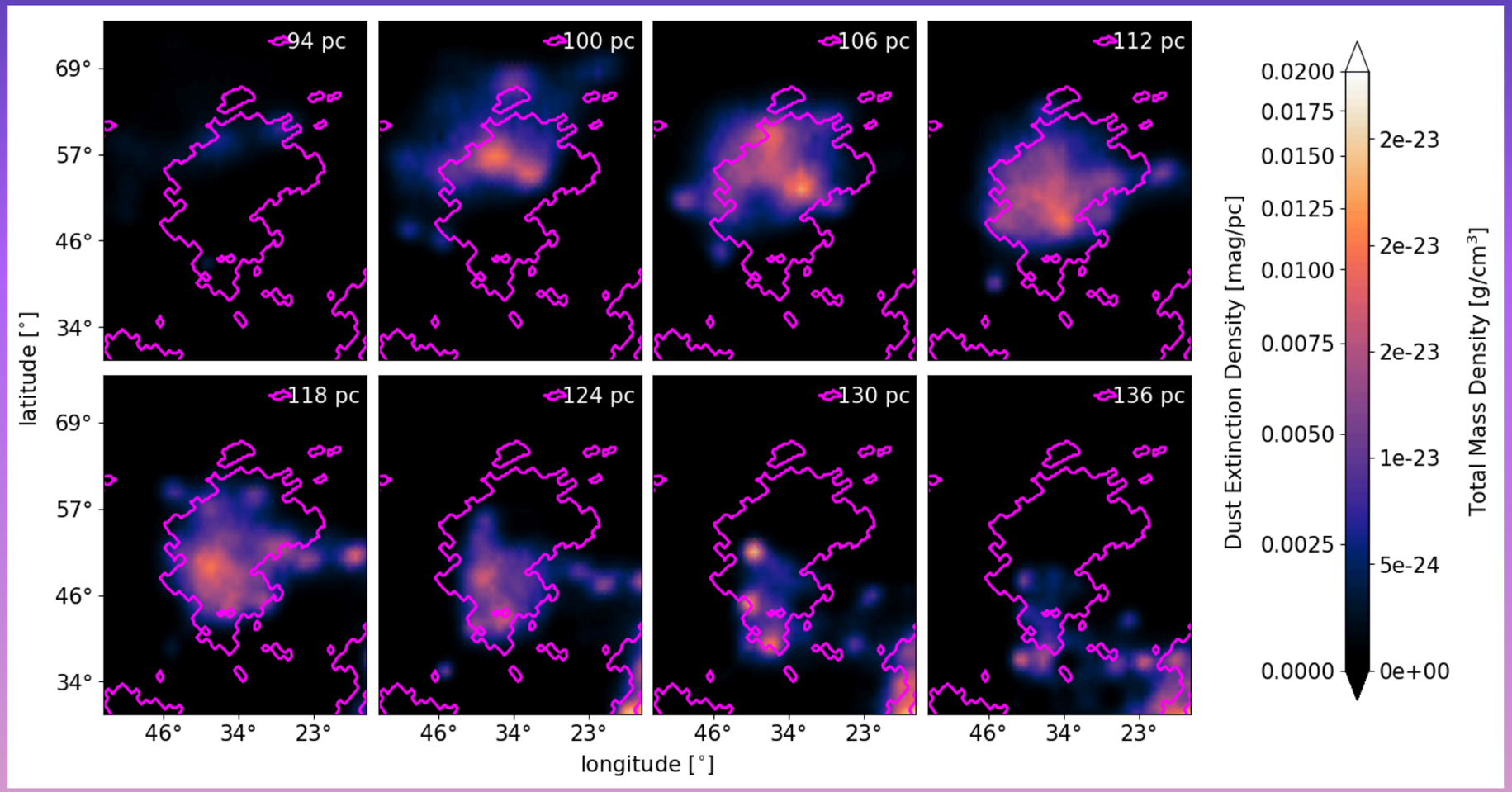
The Eos Cloud - Confirming size and position with 3D dust cartography

- **3D dust density distribution with Dustribution**
- **Size: Height: 35 pc; Width: 52 pc; los: 45 pc**
- **Largest single molecular cloud on sky (45 moons)**



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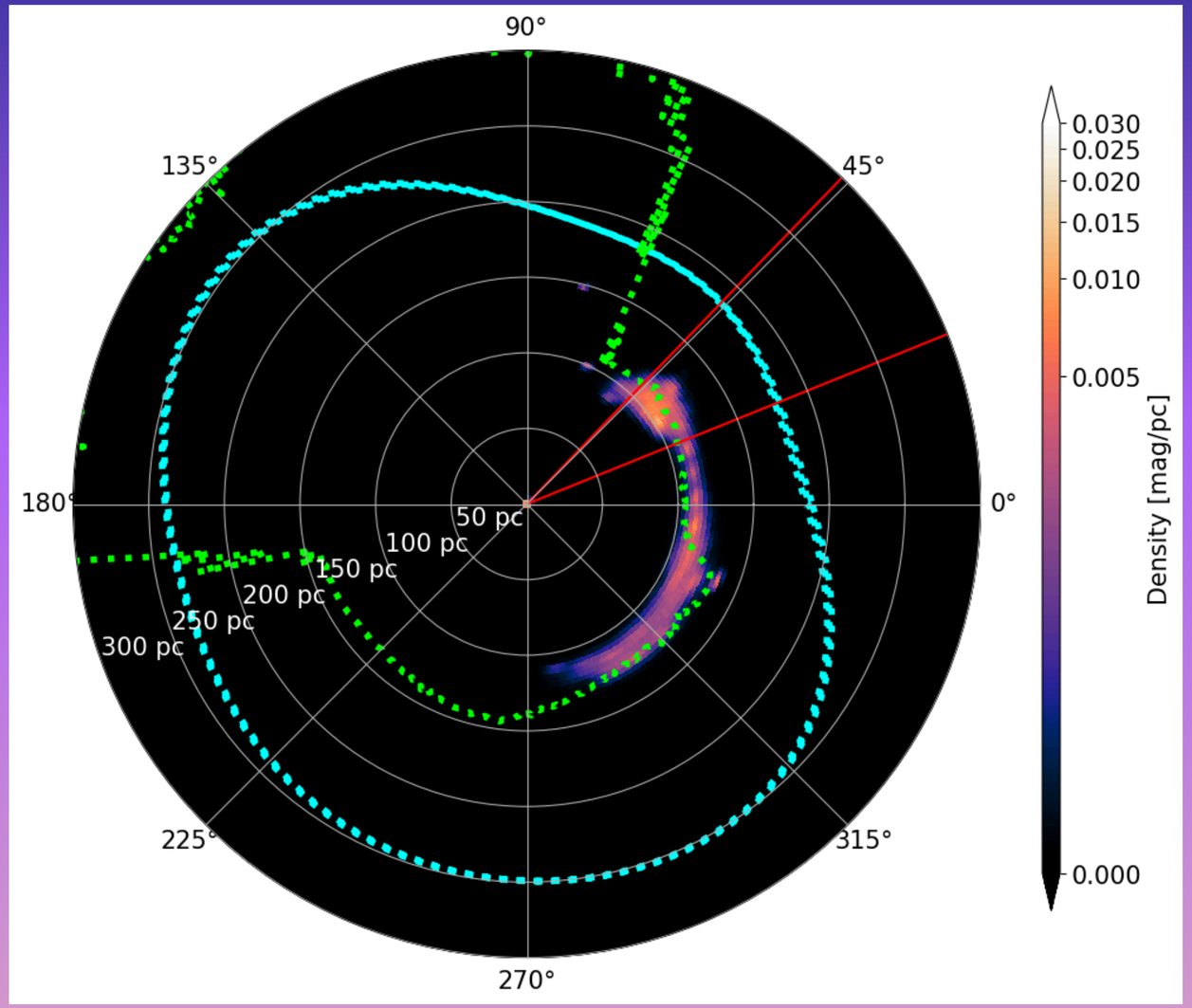
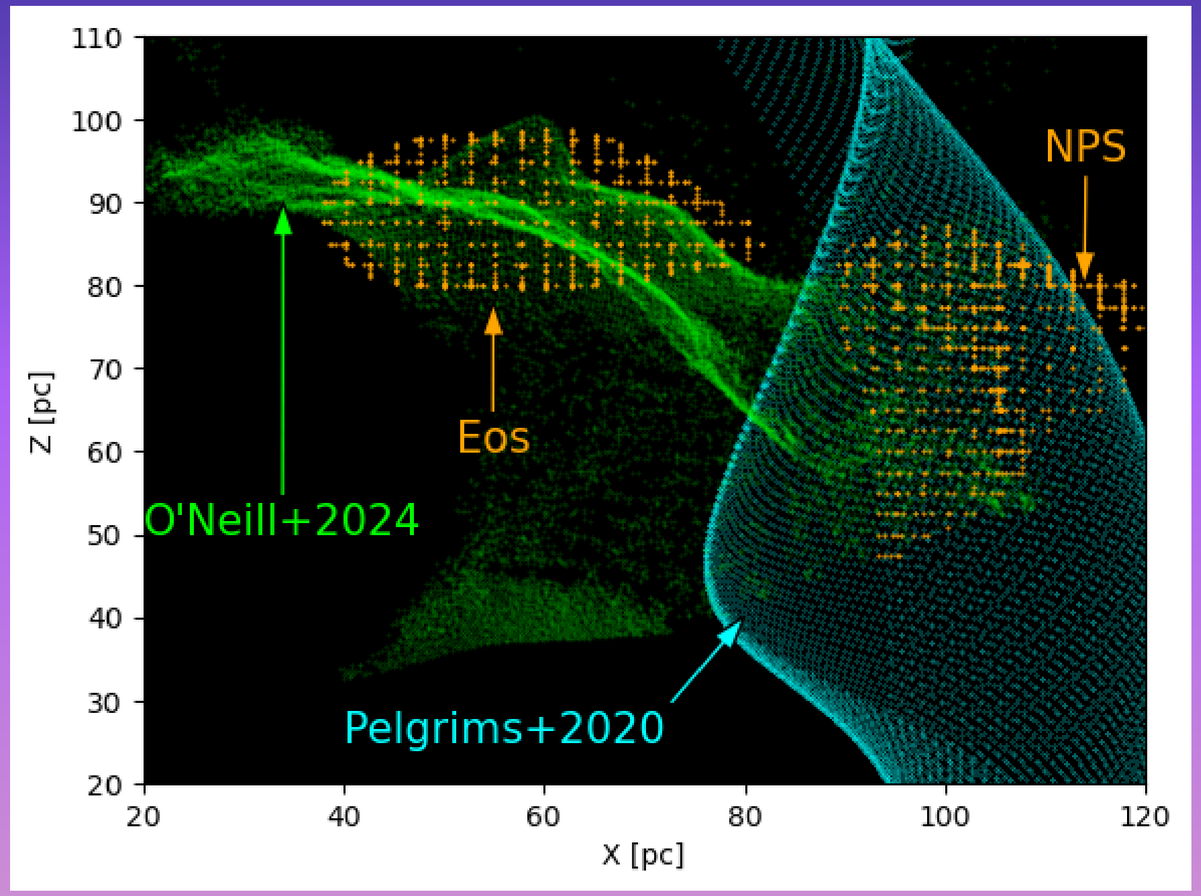
The Eos Cloud - Confirming size and position with 3D dust cartography

- **Relationship to the local bubble**
- **UV fluorescence - excited by the x-ray emission from North Polar Spur**





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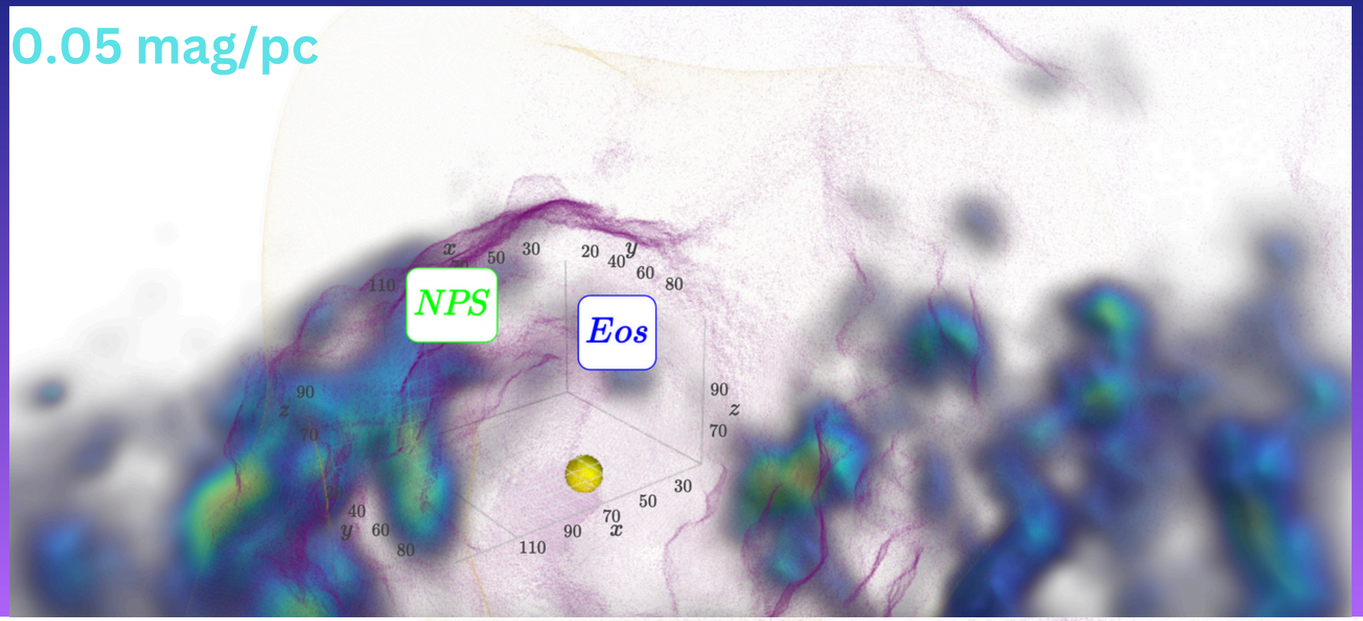
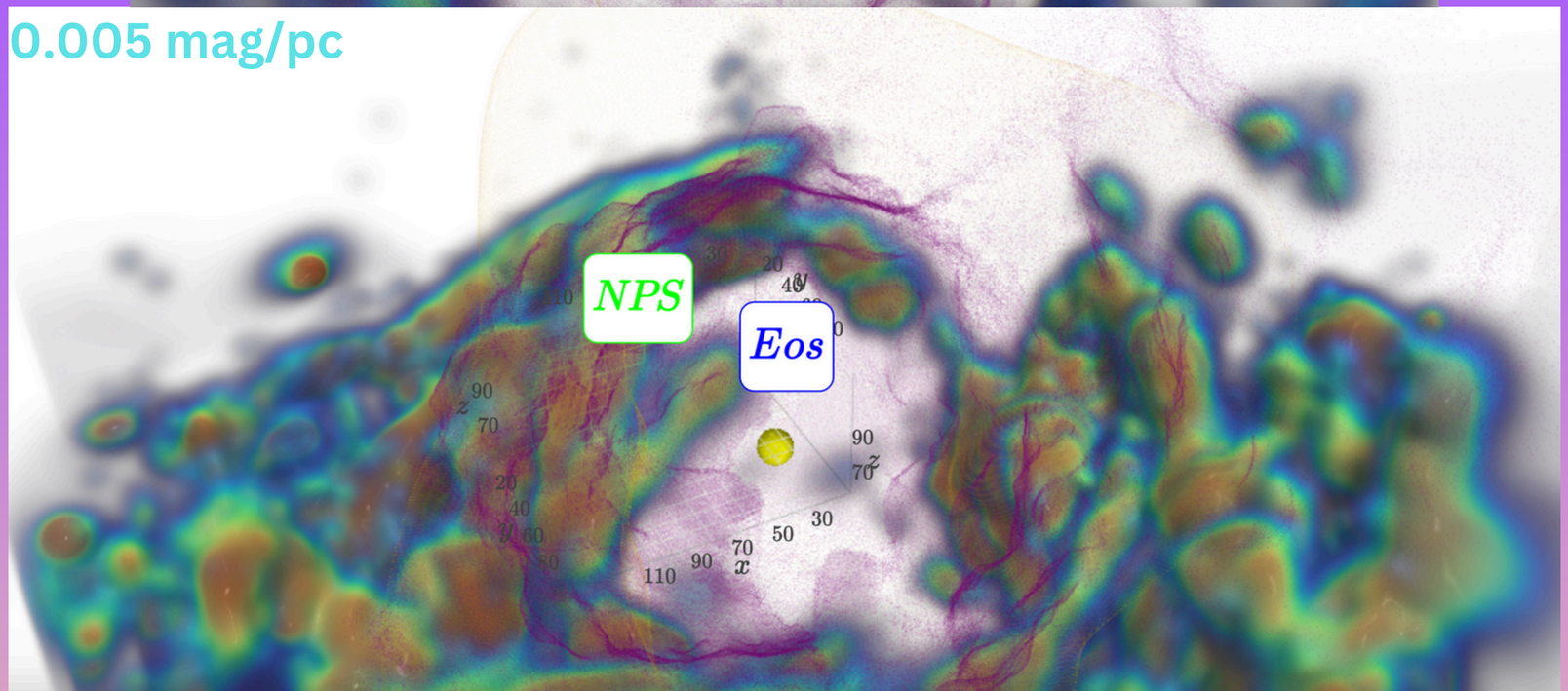
The Eos Cloud - Confirming size and position with 3D dust cartography

- **Density scales**





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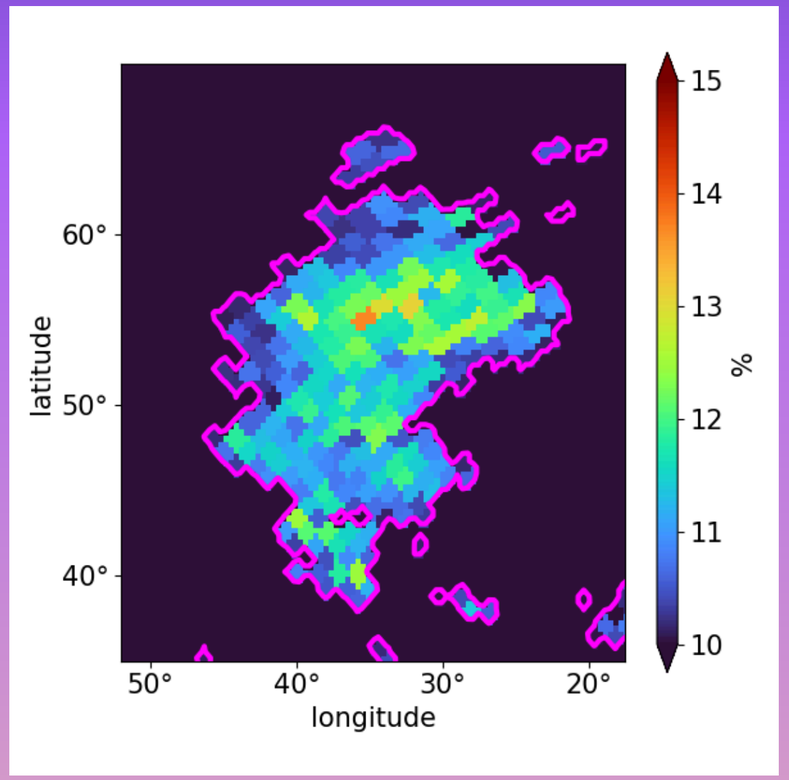
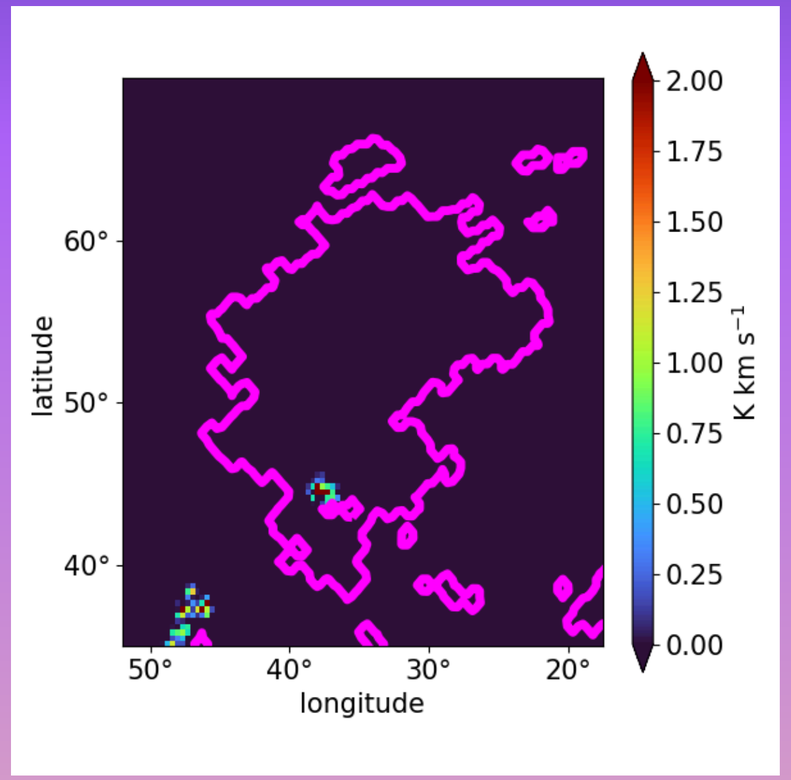
The Eos Cloud - Missing mass for star formation

- Cloud mass based on Dustribution 3D dust density maps
  - Total mass: 5.4e+03 M⊙ (few % in CO clump)
  - Density: 7.8e-2 M⊙ pc^-3

- Large mass of CO dark gas - Matches expections from theory - >50% of mass for star formation is hidden

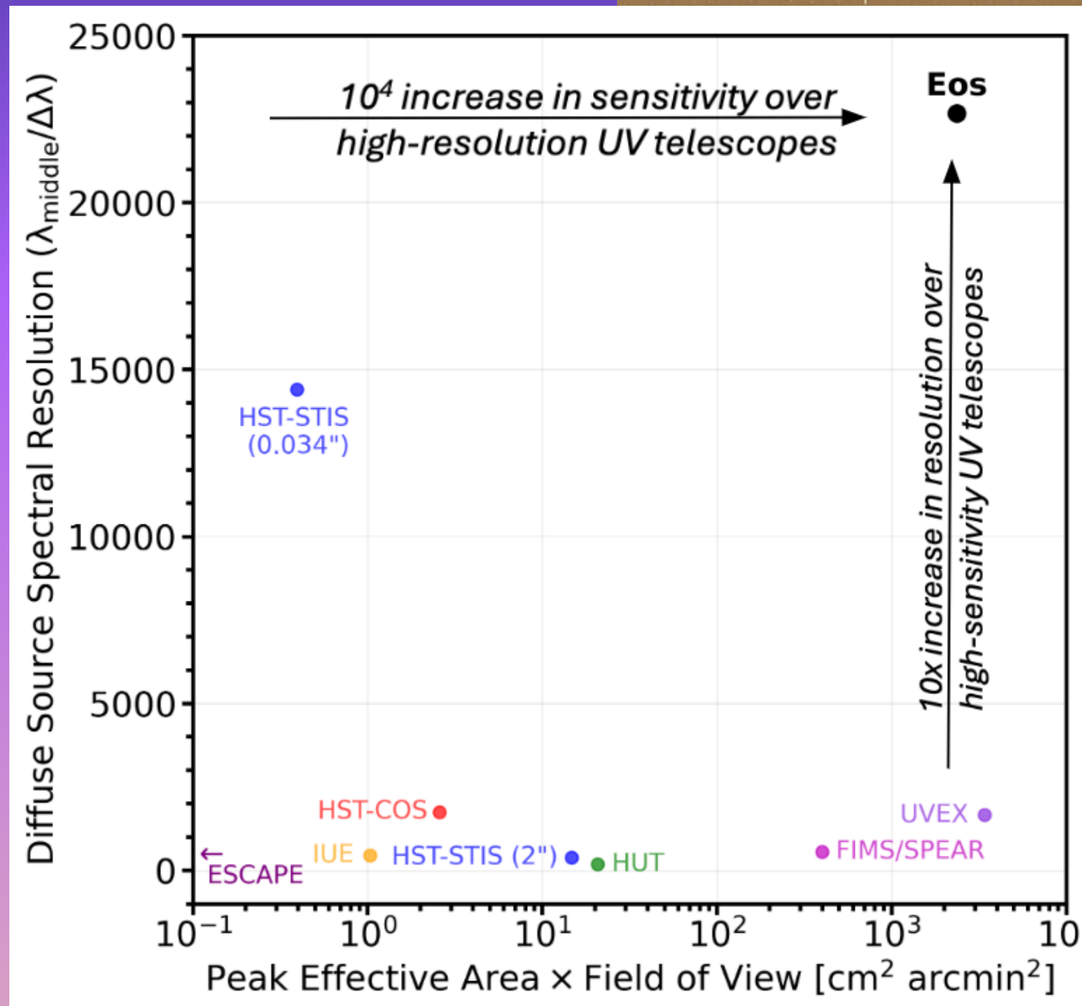




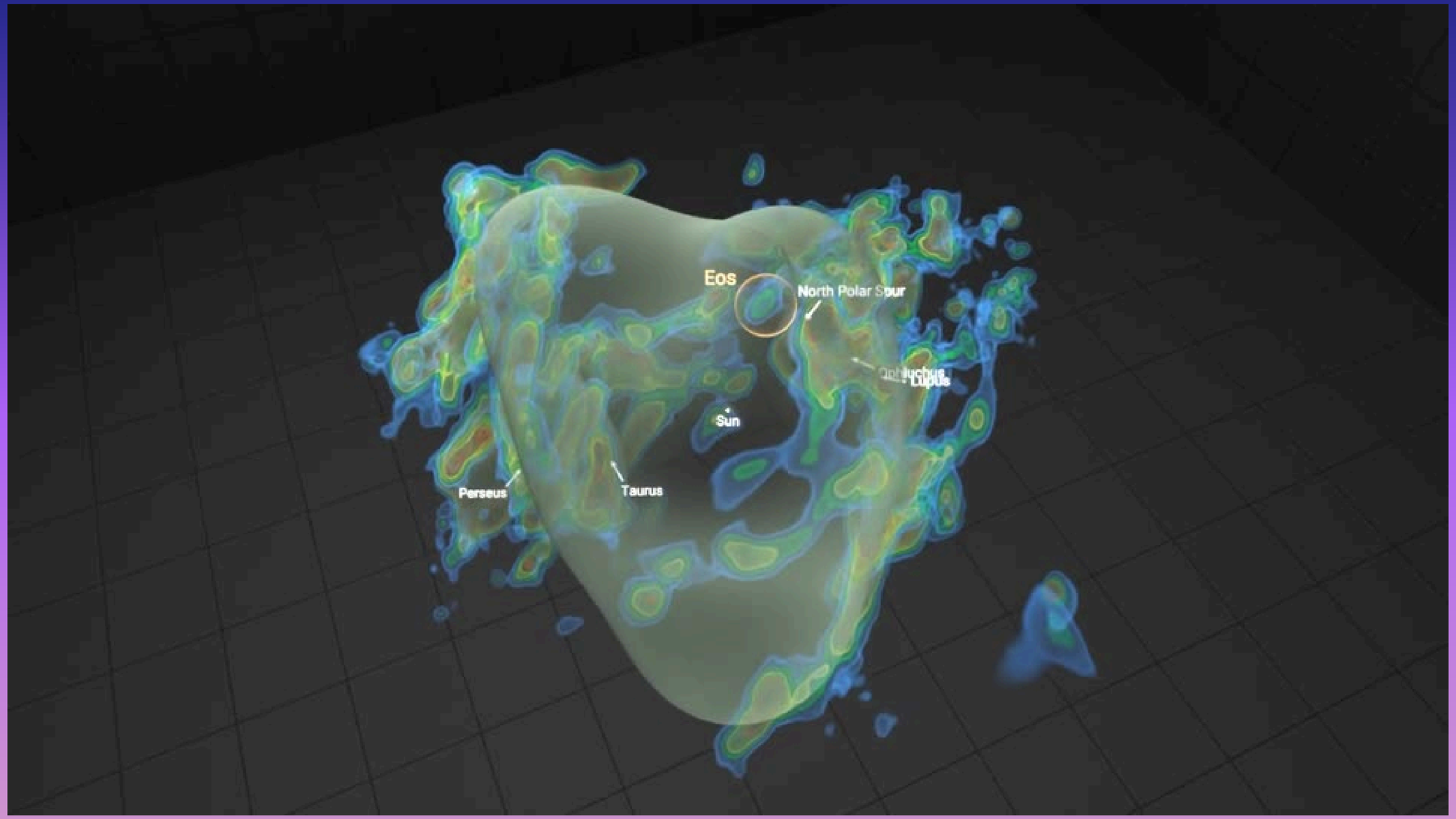
Burkhart, Dharmawardena + in prep. (shared first author)

The Eos Mission - Proposed NASA SMEX mission

- **Where is the hidden gas for star formation?**
- **Require a mission to map molecular clouds in far-UV in high resolution**
- **Eos mission - PI: Erika Hamden (University of Arizona)**
- **R > 20,000**
- **Wavelength range: 135 nm - 170 nm**
- **An industrial-scale, high-resolution spectroscopic census of all observable Galactic molecular clouds for the FIRST TIME in the UV**



The Eos Cloud - Interactive view



Burkhart, Dharmawardena + in prep. (shared first author)

To conclude....

- 3D dust cartography is crucial to determine the structure and parameters of molecular clouds and the Milky Way
- Dustribution - An open source 3D dust density and extinction cartography package
  - www.mwdust.com
  - www.github.com/thavisha/dustribution
- Recover a wide range of features from small parsec scale to massive kilo parsec scale filaments, sheet, bubbles to voids
- The local bubble is not a complete void and has diffuse material in within it.
- The Eos cloud - Discovery of the nearest diffused molecular cloud (formed nearly entirely of CO-dark molecular gas) - Burkhart, Dharmawardena + in prep.
- Upcoming
  - Simultaneous 3D gas maps with gas absorption and emission - 6D momentum maps
  - 3D structure of the LMC/SMC with GDR4
  - Eos telescope mission
  - .....