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Stratospheric Observatory for Infrared Astronomy

On the Curvature, Dynamics, and Magnetic field of the Musca Filament

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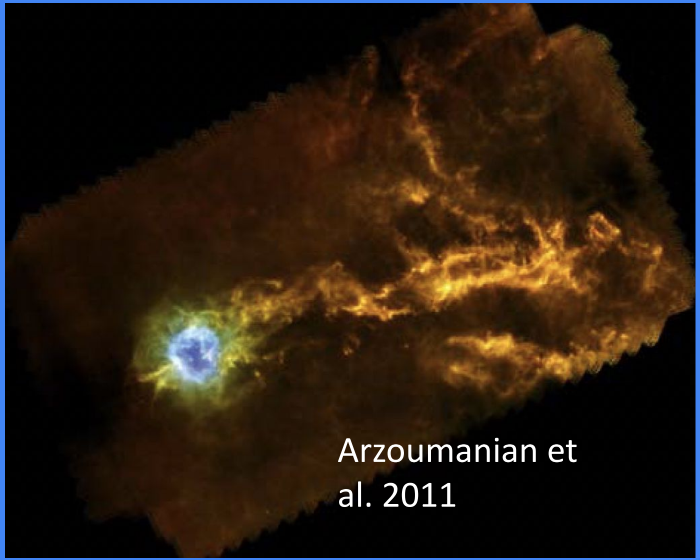
Outline

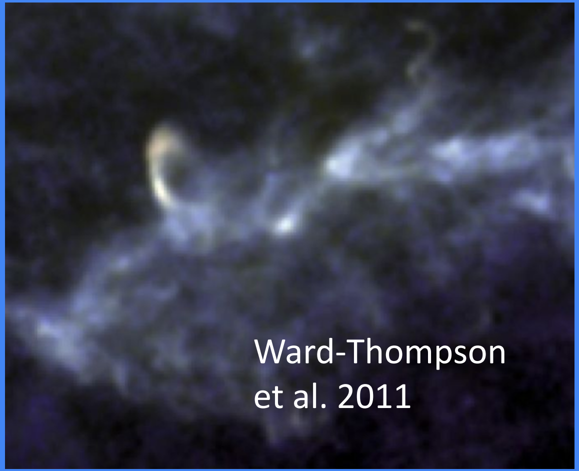
- ❑ About the Musca filament
- ❑ Observations
- ❑ Large-scale Structure, Magnetic field, and Dynamics
- ❑ Magnetic field and Dynamics on small scales

Filamentary Structures in the ISM

- Filaments are ubiquitous in molecular clouds in the ISM (André et al. 2014)
- Observations show core formation in filaments (Hacar et al. 2022, Pineda et al. 2022)
- Magnetic fields on the plane-of-the-sky are usually perpendicular or parallel to the filament crest ⇒ dependent on column densities

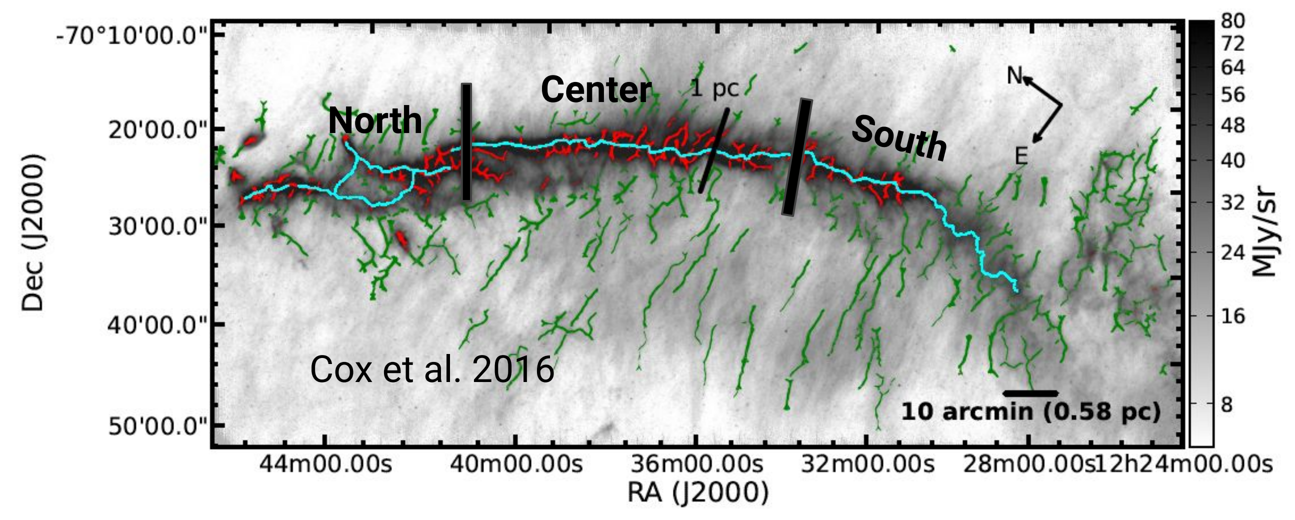
What all of this means: Understanding how filaments form may lead to constraints on star formation mechanisms in the ISM.





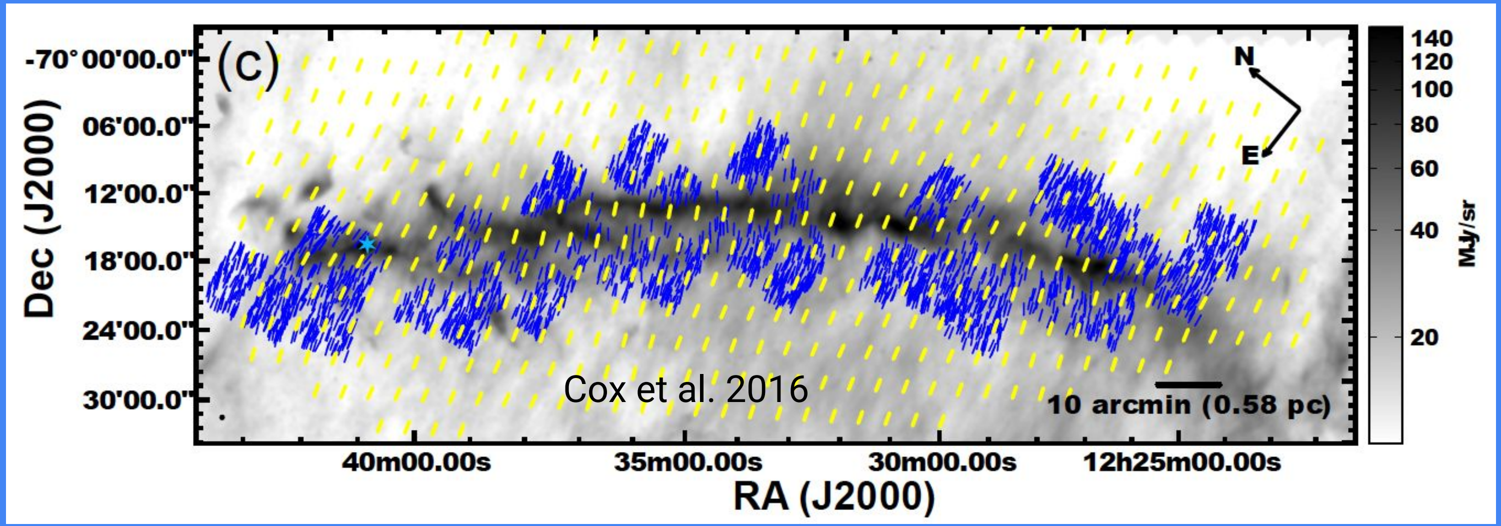
The Musca Filament

- Musca is a rectilinear filament isolated in the POS at ~ 170 pc with almost no confusion along the LOS (Zucker et al. 2021)
- There have been several cores identified at the Northern and Southern ends of the filament, with an unfragmented central region (Kainulainen et al. 2016)
- The Musca filament has a simple velocity structure (Hacar et al. 2016)
- This is an ideal filament to study the early stages of filament formation



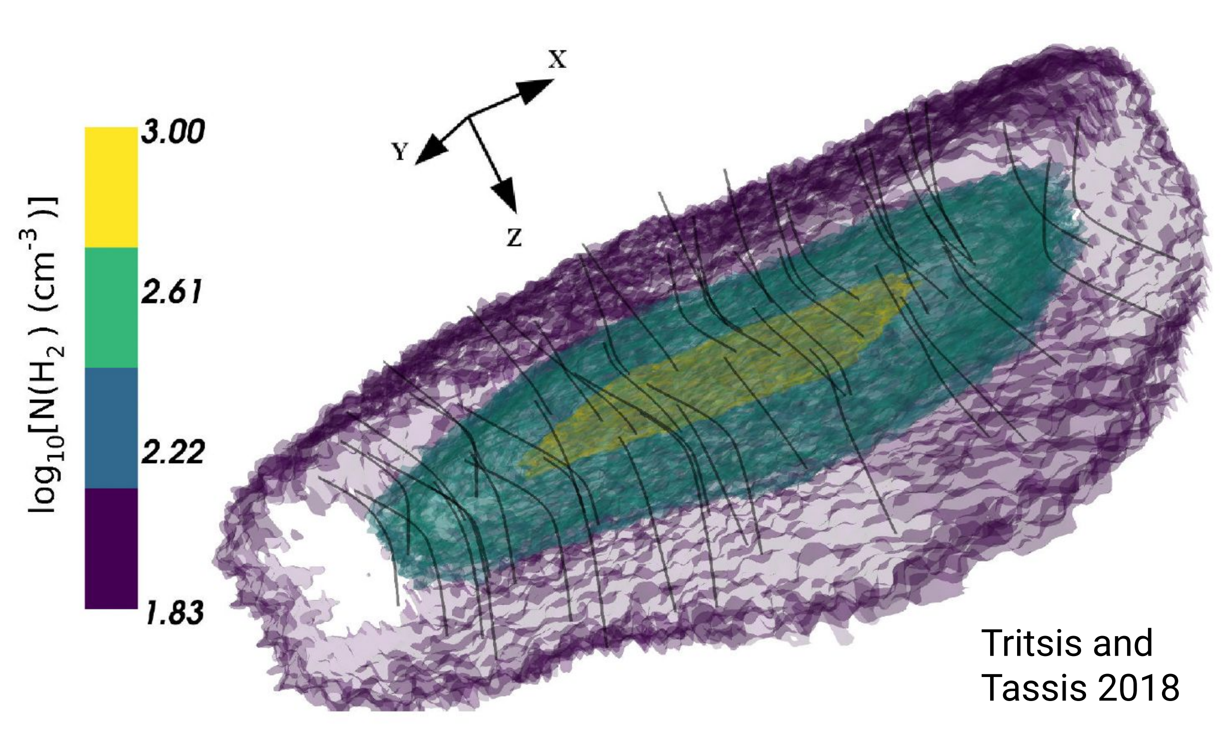
The Magnetic Field Structure of Musca

- Polarized emission and absorption maps show that the magnetic field threading Musca is aligned perpendicular to the filament crest (Pereyra & Magalhães 2004, Planck Collaboration et al. 2016, Cox et al. 2016)
- Magnetic field orientation is consistent with column densities in the region
- Magnetic fields may play an important role in the star formation process by providing supporting against gravitational collapse, however the observational evidence is heavily debated



The True Geometry of Musca: Filament or Sheet?

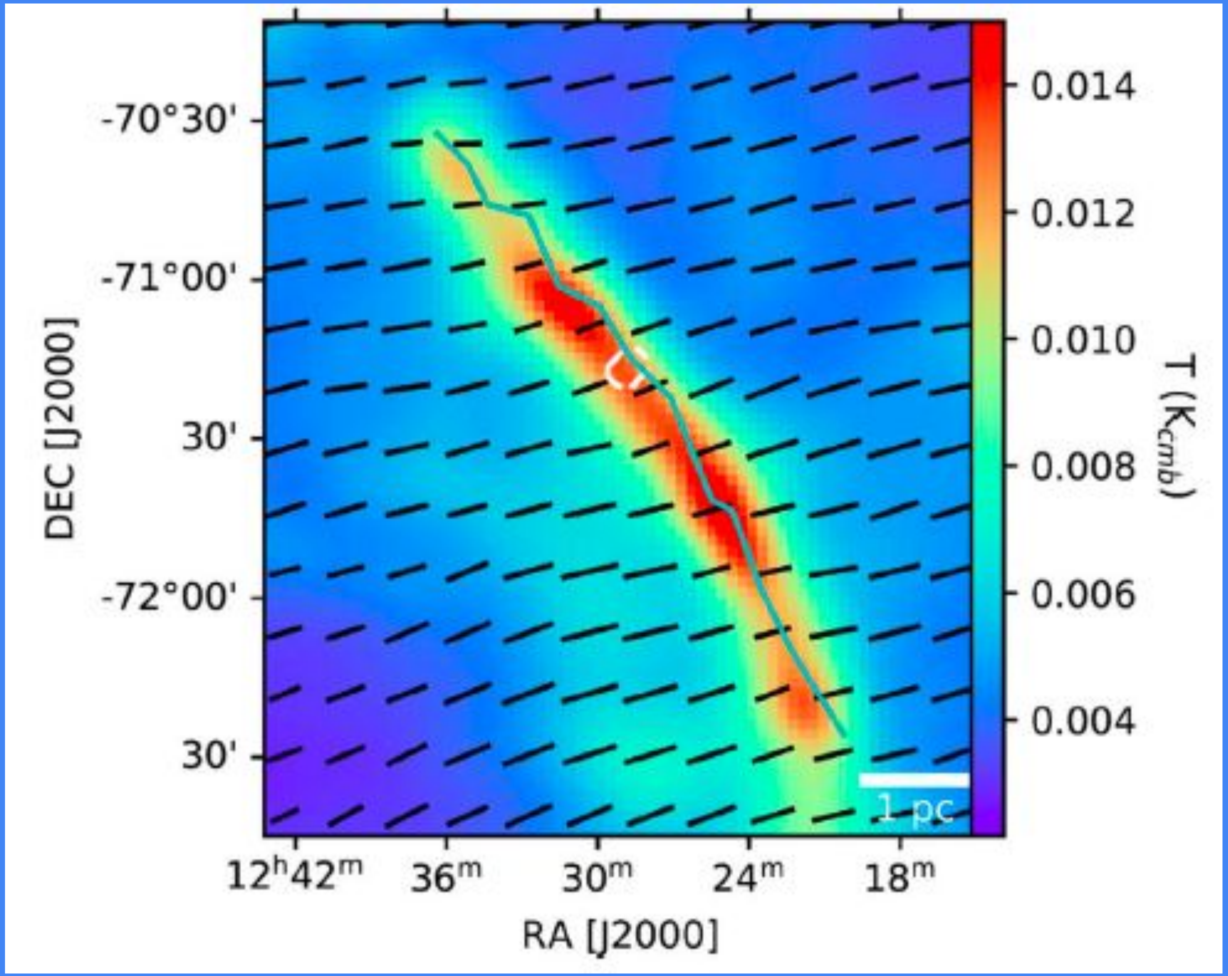
- Tritsis and Tassis (2018) and Tritsis et al. (2022) put forth that Musca is a sheet, and extends ~6 pc along the LOS
- Zucker et al. (2021) proposes that Musca only extends 2 pc along the LOS
- Analysis from Bonne et al. (2020b) found a LOS depth of ~0.1 pc for the high-column density gas (> 2 x 10^{21} cm^{-2}) and results from Cox et al. (2016) show that Musca has a width of ~0.1 pc



Tritsis and Tassis 2018

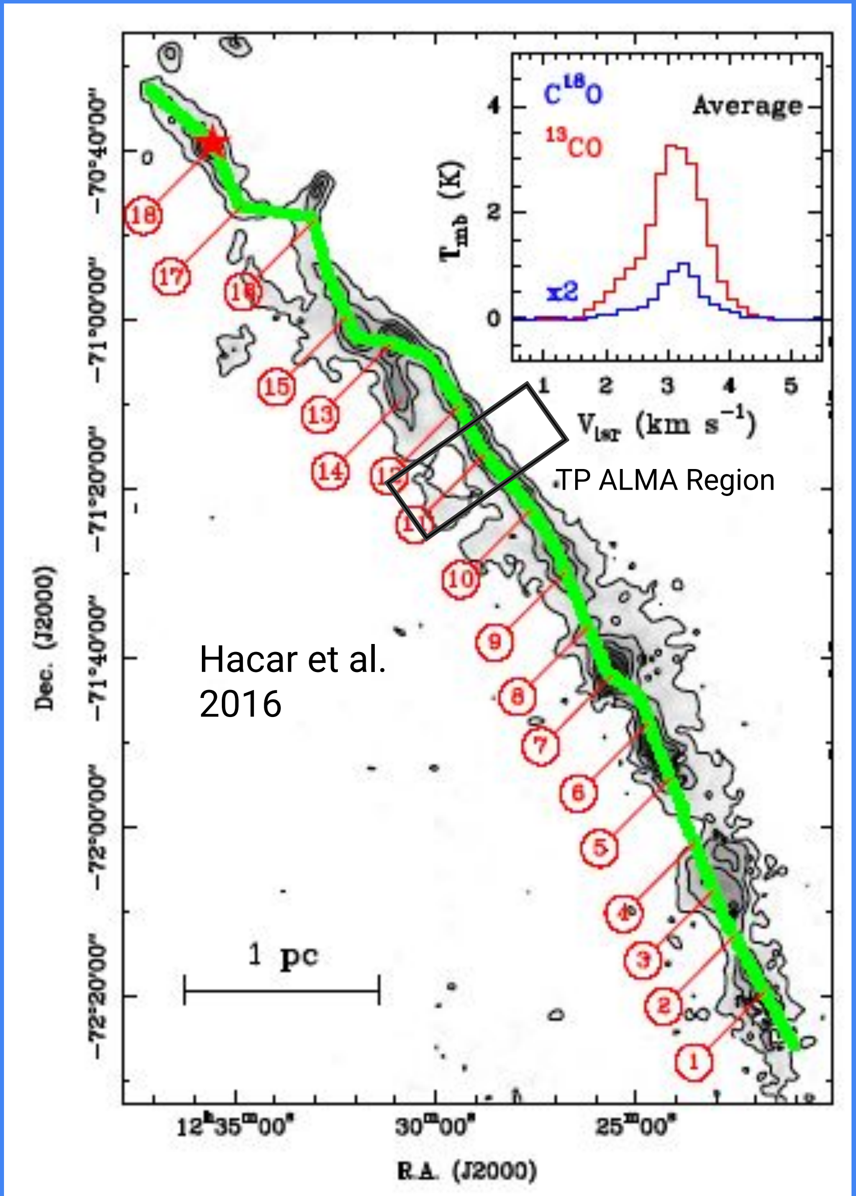
Polarization Measurements of Musca

- In this study we use polarized emission data from both Planck 353 GHz and SOFIA HAWC+ 214 μm maps
  - Planck resolution: 5’ (smoothed to 10’)
  - HAWC+ resolution: 18” (resampled to 28”)
- Both datasets will allow us to analyze both the large- and small-scale magnetic field structure of Musca



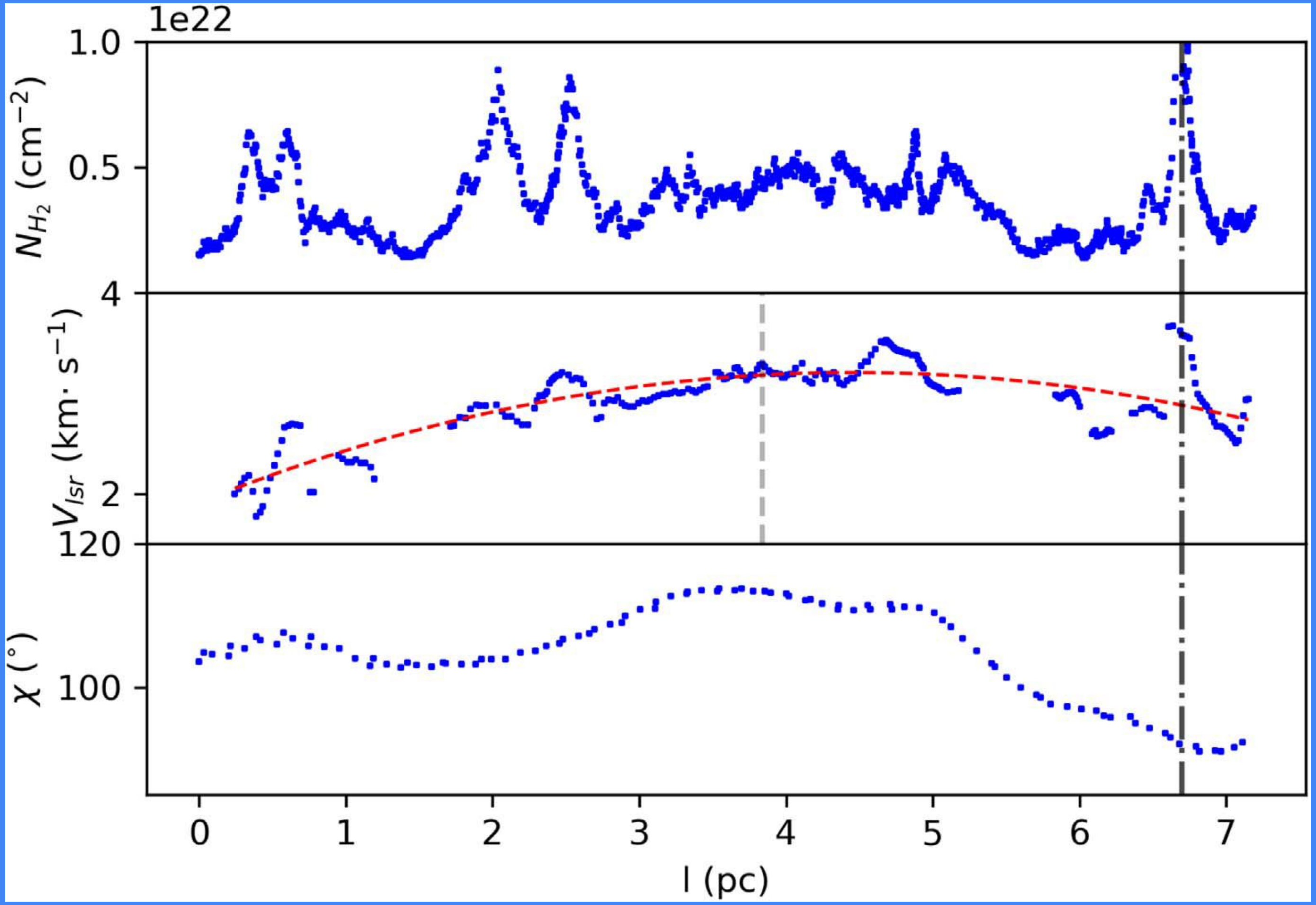
$C^{18}O(2\text{-}1)$ Maps of Musca

- Spectral line observations from both Total Power (TP) ALMA and APEX were analyzed
  - TP ALMA resolution: 28.5”
  - APEX resolution: ~30”
- Hacar et al. (2016) targets 300 highest column density points along filament
- The TP ALMA map covers the same region near the filament crest as the HAWC+ data (PI: D. Arzoumanian)



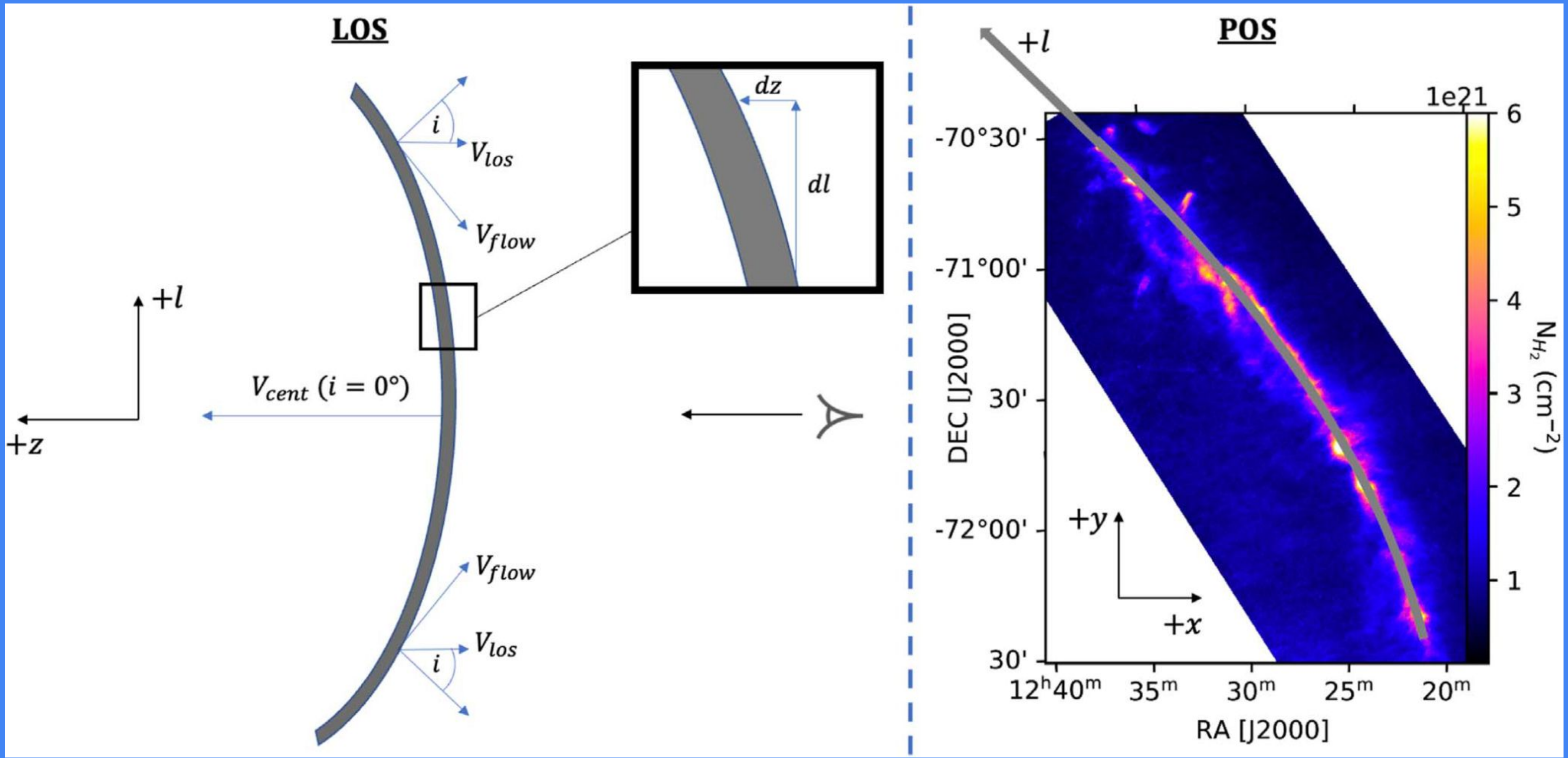
LOS and POS Correlation

- LOS velocity profile is fully consistent with results from Hacar et al. (2016)
- LOS velocity and B-field orientation have similar behavior along the filament



LOS and POS Correlation: Hinting at 3D Curvature

- The similar curvature on the POS and along the LOS ⇒ suggests 3D curved filament
- Magnetic field traces POS curvature, LOS velocity traces LOS curvature
- Assuming velocity field(s) ⇒ derivation of inclination angle and LOS distance



Longitudinal Velocity Fields

- We assume that the velocity profile of Musca is predominantly associated with longitudinal kinematics
- To reconstruct the LOS structure of Musca, we create three different models using several assumptions:
  - **Model 1**: Constant velocity field moving towards filament center
  - **Model 2**: Constant velocity field with a unidirectional flow, either North-to-South or South-to-North
  - **Model 3**: Linear velocity field moving towards filament center

Model 1:

$$V_{\rm lsr} = \begin{cases} V_{\rm cent} - V_{\rm flow}(\sin(\phi) - \sin(\mathrm{i})) & \text{if } \ l < l_{\rm cent} \\ V_{\rm cent} + V_{\rm flow}(\sin(\phi) - \sin(\mathrm{i})) & \text{if } \ l > l_{\rm cent} \end{cases}$$

Model 2:

$$V_{\rm lsr} = \begin{cases} V_{\rm cent} + V_{\rm flow}\sin(i) & \text{for } \ S \rightarrow N \\ V_{\rm cent} - V_{\rm flow}\sin(i) & \text{for } \ N \rightarrow S \end{cases}$$

Model 3:

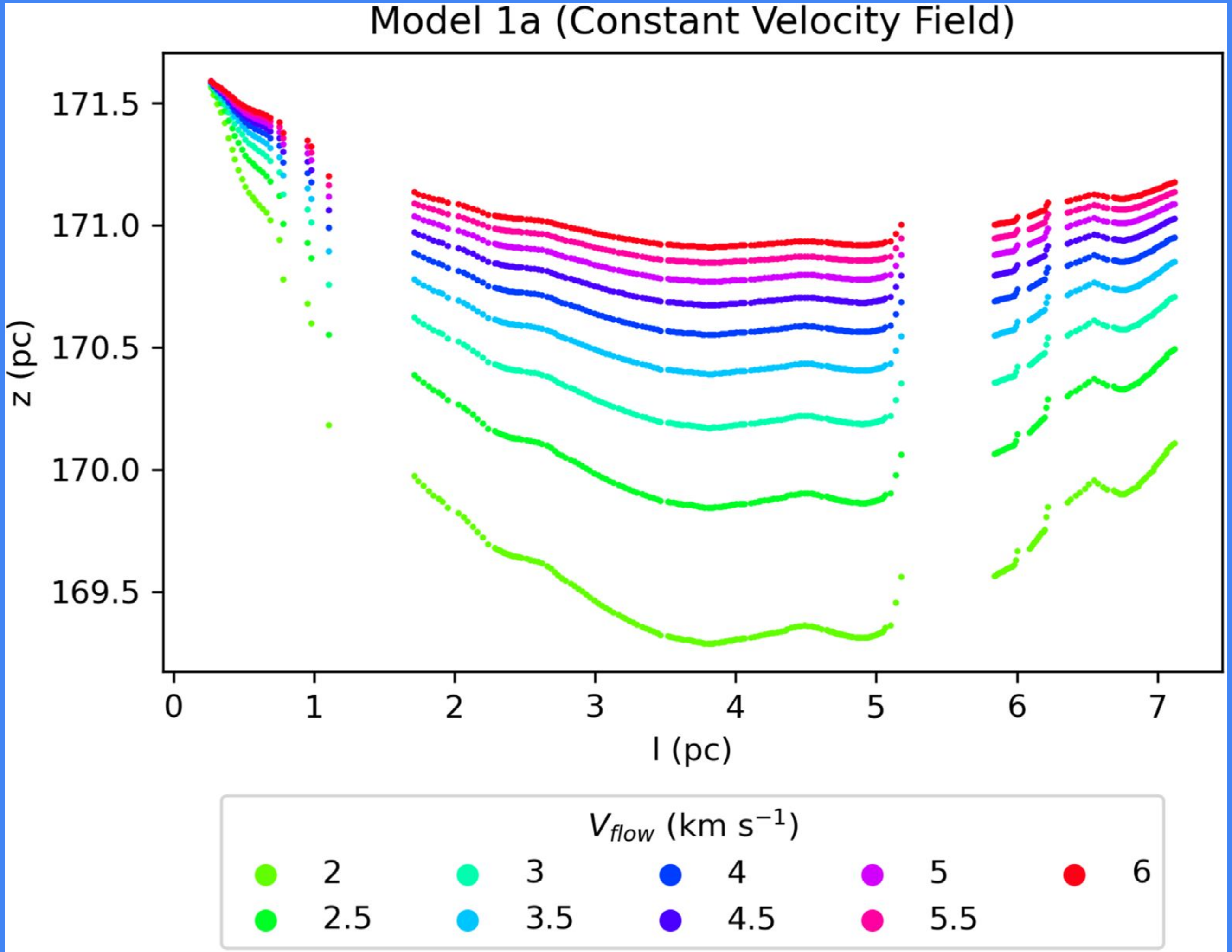
$$V_{\rm lsr} = \begin{cases} V_{\rm cent} - (V_{\rm flow} + b(l_{\rm cent} - l))\sin(\mathrm{i}) & \text{if } \ l < l_{\rm cent} \\ V_{\rm cent} + (V_{\rm flow} + b(l - l_{\rm cent}))\sin(\mathrm{i}) & \text{if } \ l > l_{\rm cent} \end{cases}$$

All velocity fields were coupled with the expression to derive the LOS profiles

$$\frac{dz}{dl} = \tan(i)$$

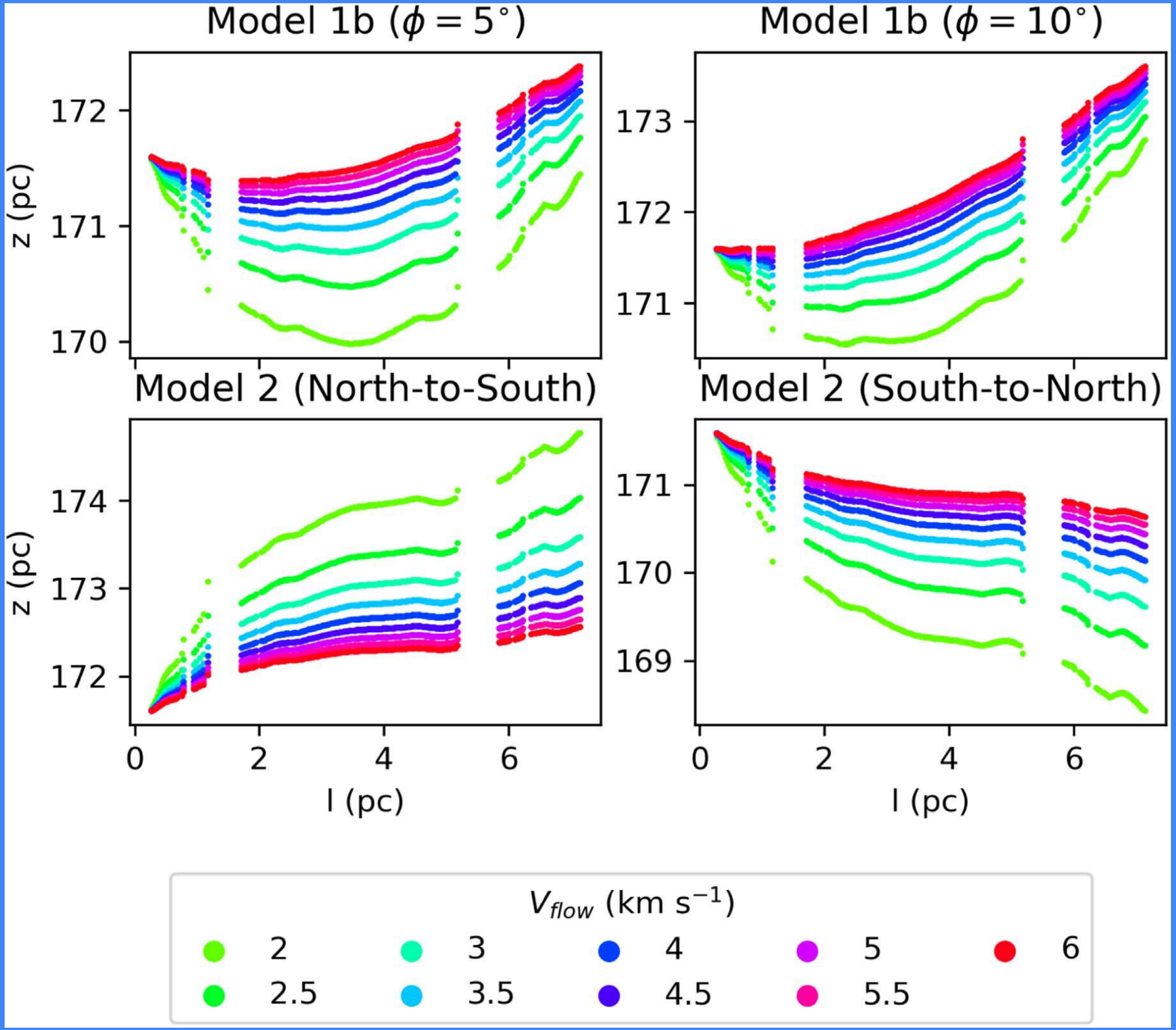
Model 1a

- Model 1a is the special case of Model 1 where the global inclination angle is 0°
- V_{flow} values less than 2 km s^{-1} are not plotted, argument inside $\sin^{-1}()$ blows up
- LOS curvature resembles POS curvature



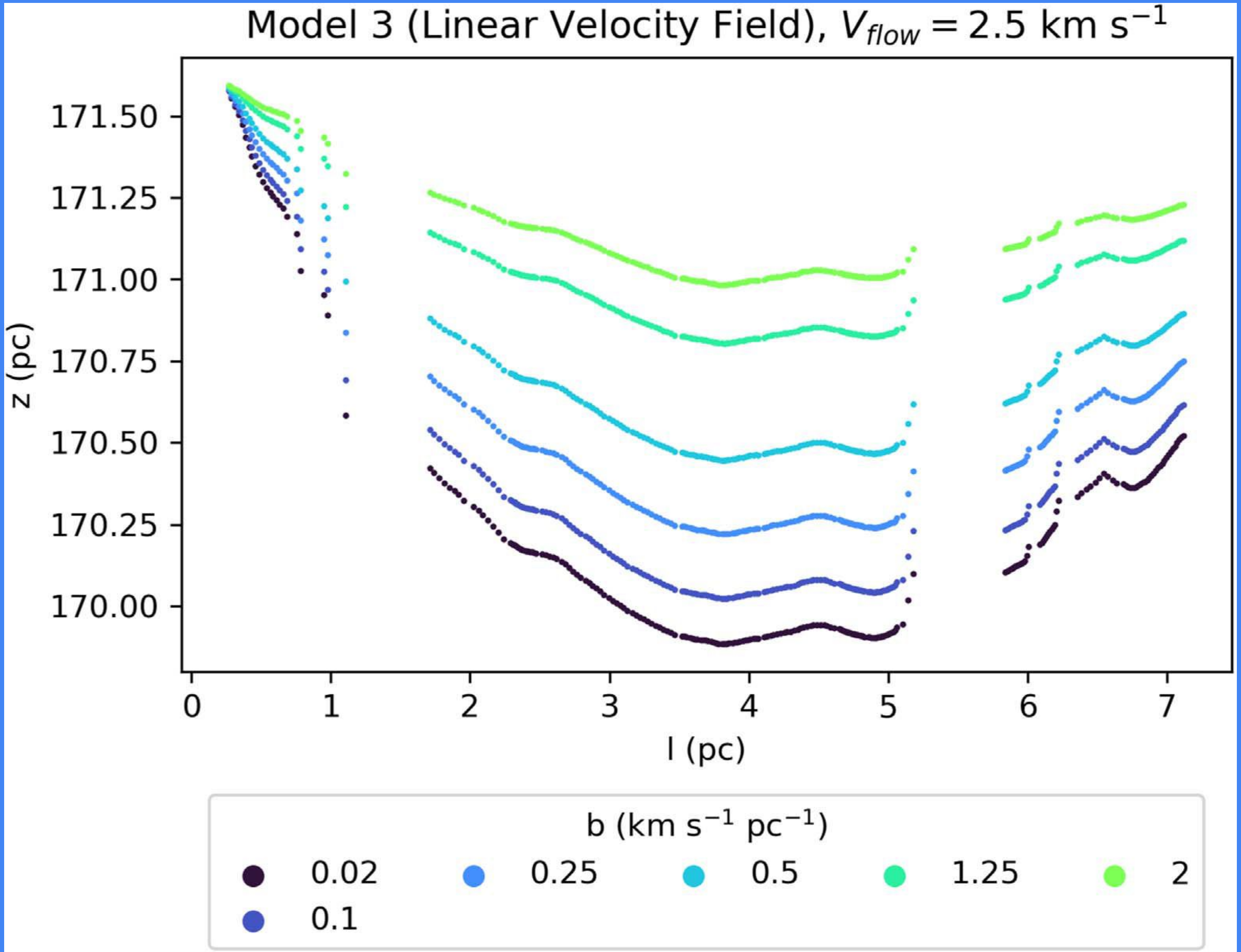
Models 1b and 2

- The same constant velocity parameterization is used for both models
- We expect that Musca will not have a significant inclination along the LOS, so we only test small global inclination angles
- V_{flow} values less than 2 km s^{-1} are not shown for same reasons as Model 1a



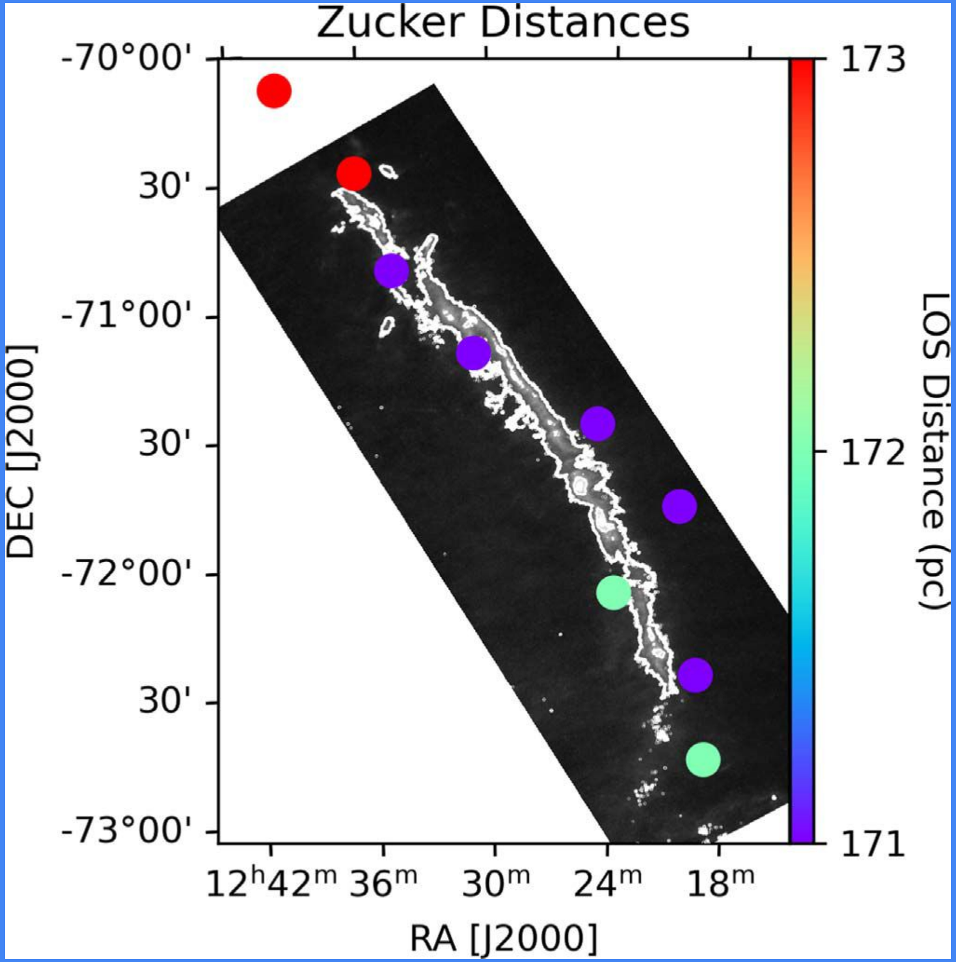
Model 3

- This model uses two different parameters: the zeroth order velocity term and b, the slope of the inflow velocity along the filament
- As b increases, the LOS curvature flattens out



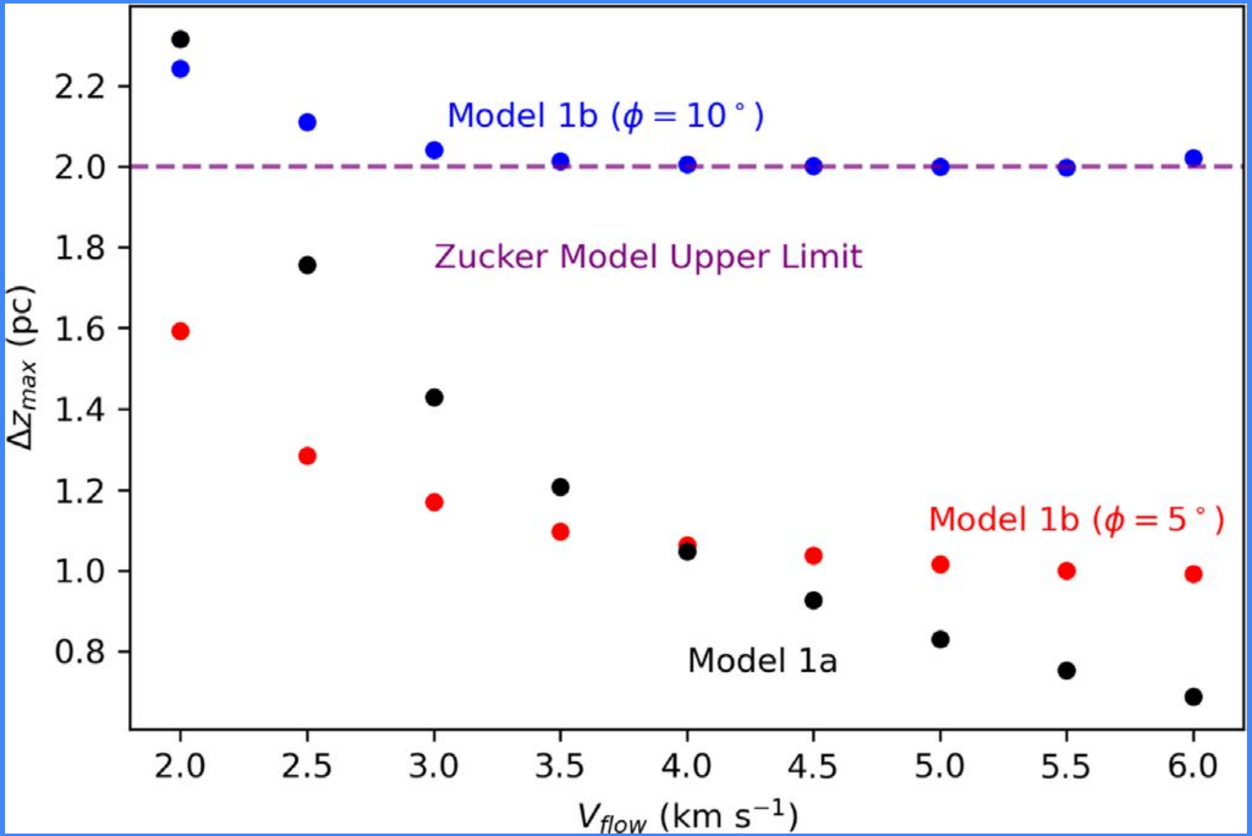
Comparison with Zucker et al. (2021)

- Zucker et al. (2021) used GAIA data and fitted Gaussian distributions to the density to model the profile of Musca
    - The resolution of the data used is ~1 pc
- A curvature along the filament, with a maximum width of 2 pc
    - We use this as an upper limit due to the targeted locations in their study



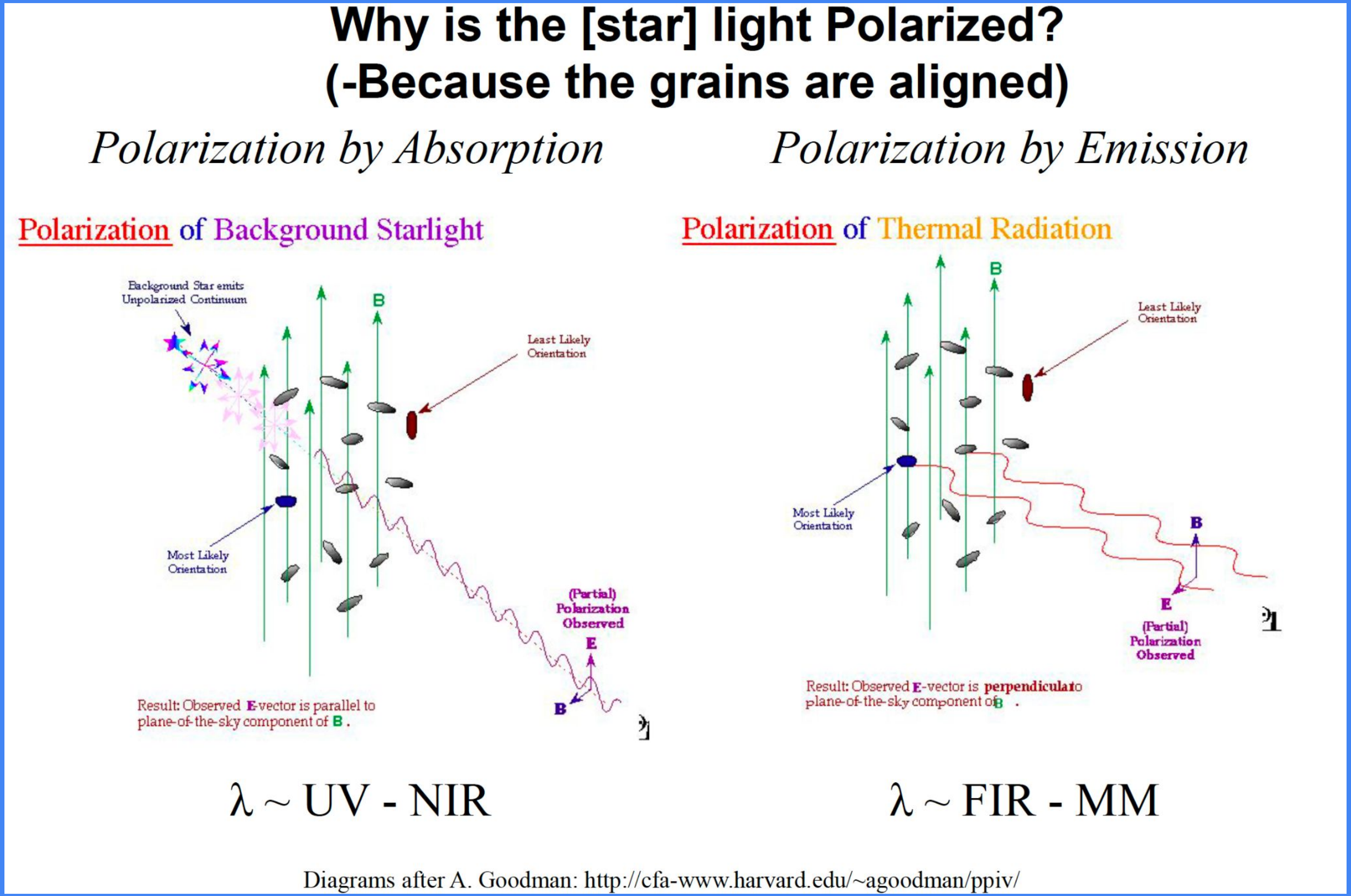
Comparison with Zucker et al. (2021) Continued

- Models 1a and 1b show a very similar structure along the LOS as the Zucker distances
- The LOS profile generated using Model 2 does not have an LOS curvature similar to the Zucker distances ⇒ likely to be ruled out
- Model 3 has a similar LOS structure to Model 1
    - For V_{flow} = 2 - 3 km s^{-1}, lies between 1 -2 pc



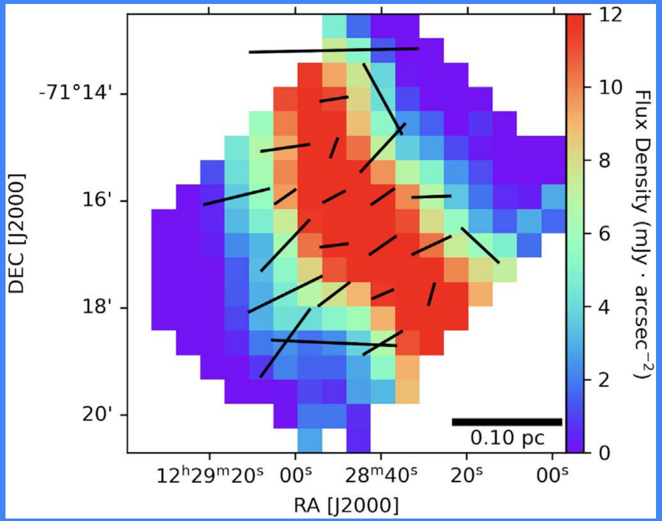
Moving from large to small scales…

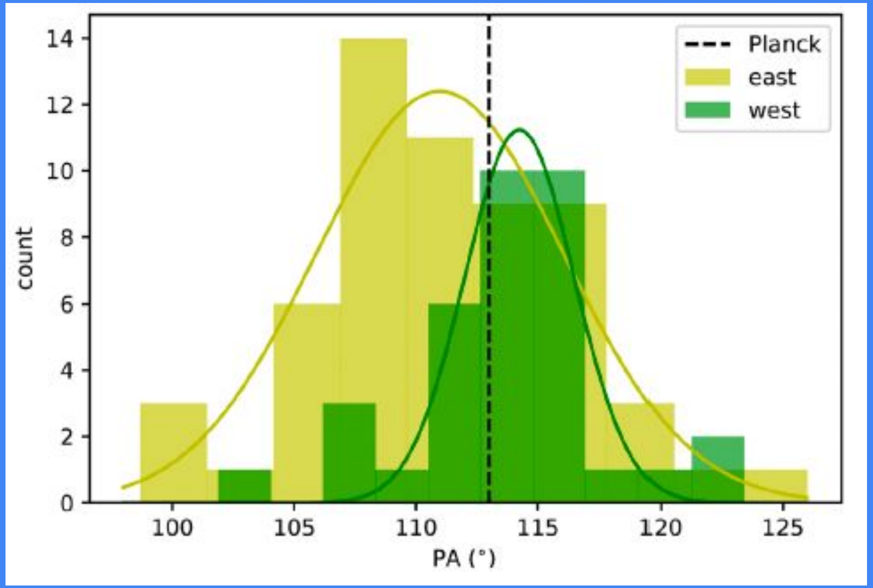
Polarization of Interstellar Dust Grains



Small-scale Dynamics of Musca

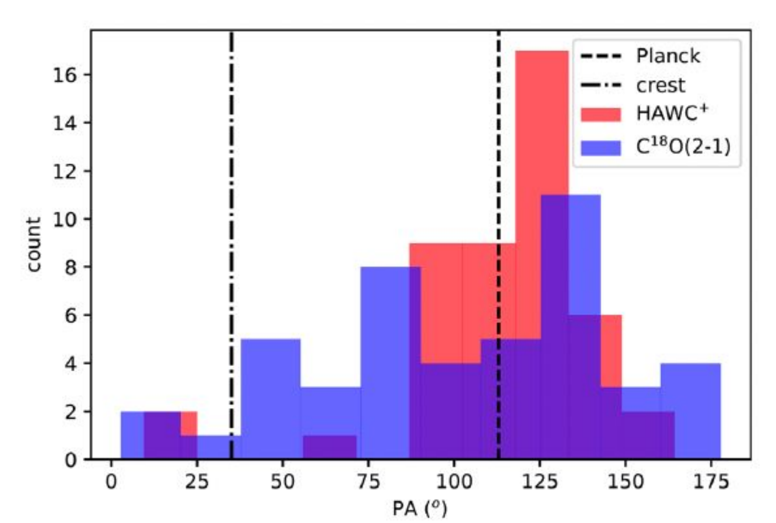
- Magnetic field is aligned perpendicular to the filament crest
  - The mean position angle is 116° ± 15°, which is very close to the local Planck measurement of 113°
- Optical polarization data from Pereyra and Magalhães (2004) shows a reorientation of the POS magnetic field structure across the filament crest of 3.3° ± 0.4°

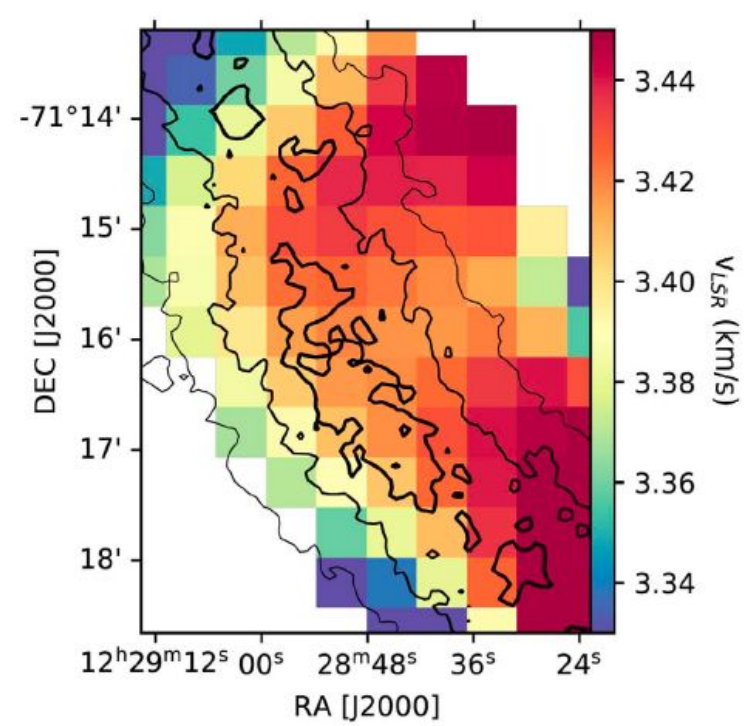




Small-scale Dynamics of Musca Continued

- Small-scale velocity field has a dominant component perpendicular to the filament crest, although with a longitudinal component
  - This component may be associated with the proposed large-scale mass inflow towards the filament center



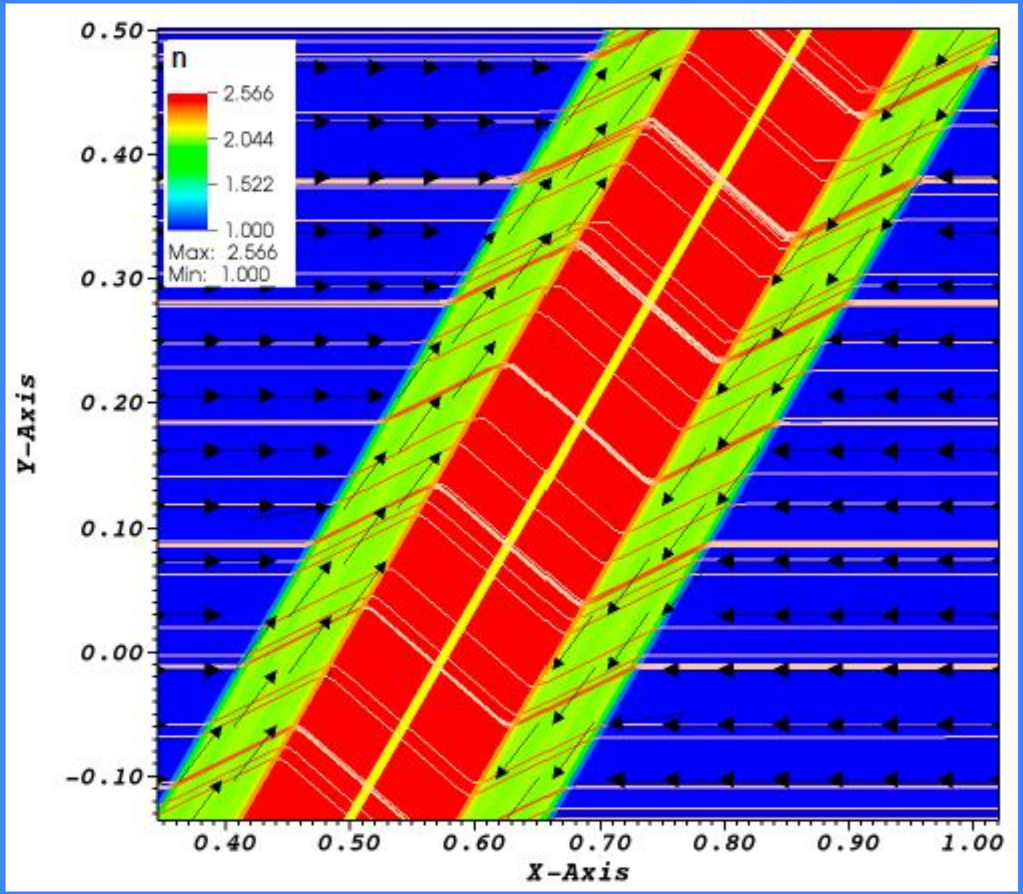


Evolution of Musca

- Using the 3D curvature reconstructed with Models 1 and 3:
    - LOS structure is consistent with the accretion flow prediction made by Bonne et al. (2020a)
    - The velocity field is far stronger than predicted gravitationally-driven fields with terminal velocities of ~0.4 km s^{-1} (Pon et al. 2012, Clarke & Whitworth 2015, Hoemann et al. 2023)
    - Unlikely for Musca to have formed via hierarchical collapse ⇒ no evidence for strong accelerated velocity fields (Gómez & Vázquez-Semadeni et al. 2014, Vázquez-Semadeni et al. 2019, Naranjo-Romero et al. 2022)

Evolution of Musca Continued

- A possible explanation for the velocity fields in Models 1 and 3 are oblique shocks which reorient the velocity and magnetic fields, seen in Fogerty et al. (2017)
- The reorientation of the velocity field radially is much stronger than that of the magnetic field ⇒ further observations are required to investigate this

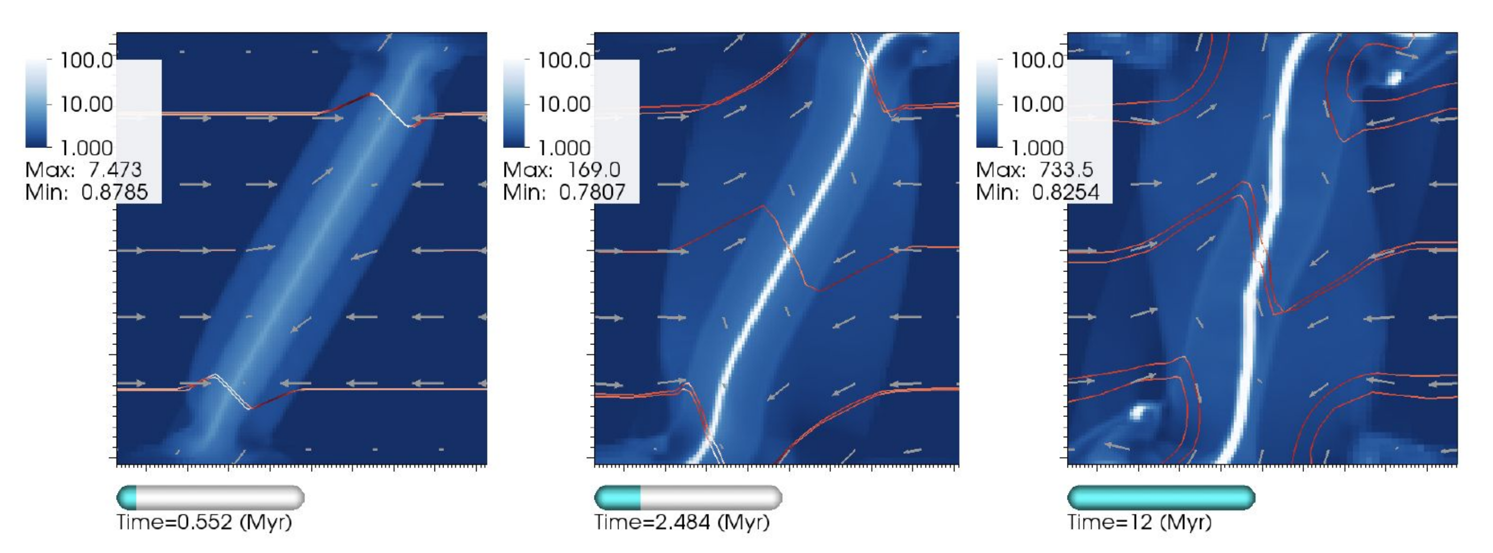


Fogerty et al. 2017

Evolution of Musca Continued

- Results from Fogerty et al. (2017) show a reorientation of the magnetic field with motions along the filament axis
- This scenario is consistent with the tentative detection of filament accretion shocks in Bonne et al. (2020a)

- Further questions regarding this scenario:
  - Simulations include ideal MHD ⇒ Musca is likely weakly ionized
  - The filament accretion shock detection was tentative
  - The B-field reorientation of 3° is really small



Fogerty et al. 2017

Conclusion

- LOS velocity profile along the Musca filament suggest a velocity coherent structure
  - The correlation between the longitudinal velocity and magnetic field orientation profiles suggest that Musca has a 3D curvature
- LOS profiles of Musca were reconstructed using APEX $C^{18}O$ data, and show a LOS curvature similar to the results of Zucker et al. (2021)
- The assumed velocity fields are relatively high and are inconsistent with gravitational-collapse models
  - The velocity fields can possibly be explained by flows originating outside the filament, a small global inclination angle, or a linearly increasing velocity field
- On small scales, both the velocity field and magnetic field experience a reorientation, although the former is much more complex
- Link to the paper: https://iopscience.iop.org/article/10.3847/1538-4357/acc462