Statistical Analysis of the Relative Orientation Between Filaments and Magnetic Fields in Star Forming Regions

Jonathan Oers, Isabelle Ristorcelli, Katia Ferrière, Ludovic Montier

Collaborators: Mika Juvela, Julien Montillaud, Dana Alina, …

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Université Toulouse III - Paul Sabatier
Institut de Recherche en Astrophysique et Planétologie


WORK IN PROGRESS

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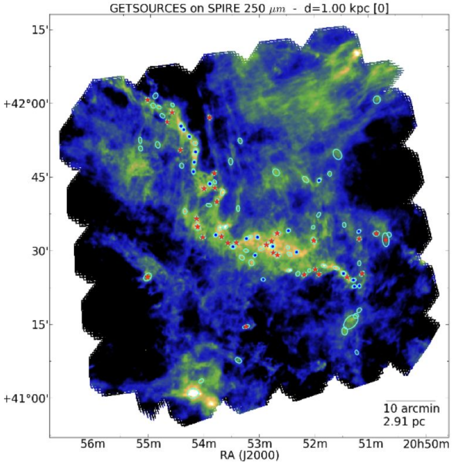
Filaments and Star Formation

Tarantula Nebula, captured using the NIR-Cam.
Credits: NASA, ESA, CSA, STScI, Webb ERO Production Team

Herschel/SPIRE *250 µm dust continuum image of the Polaris flare*
Credits: HGBS survey (André et al., 2010, Miville-Deschênes et al., 2010).

Filaments and Star Formation



Montillaud et al., 2014

Prestellar and protostellar cores are located in the densest filaments (Montillaud et al. 2014)

Early stages of star formation are still poorly understood
-> Link with formation and evolution of filaments

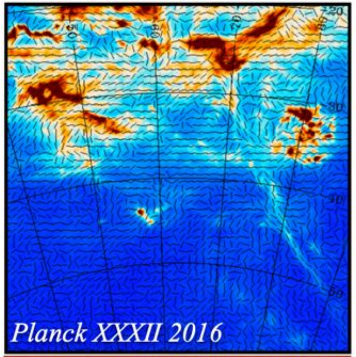
Which interplay between
- gravity
- turbulence
- magnetic fields

at different scales?

Filaments and Star Formation

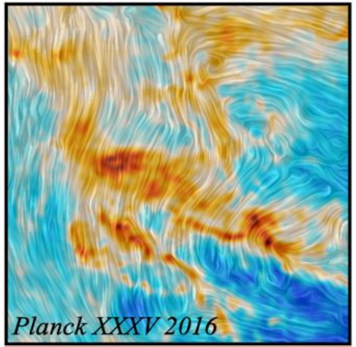
Planck Analyses

Filaments in the diffuse ISM

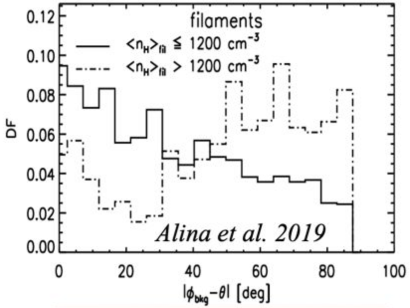


B-fields & filaments mostly //

Nearby molecular complexes

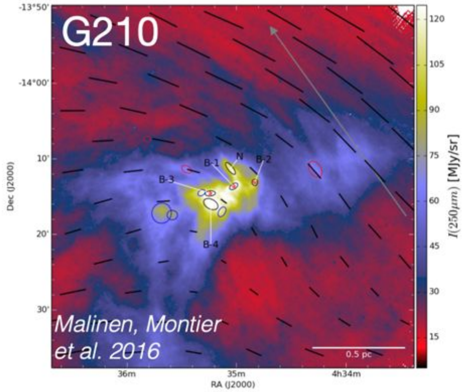


NH transition between // and ⊥ orientations



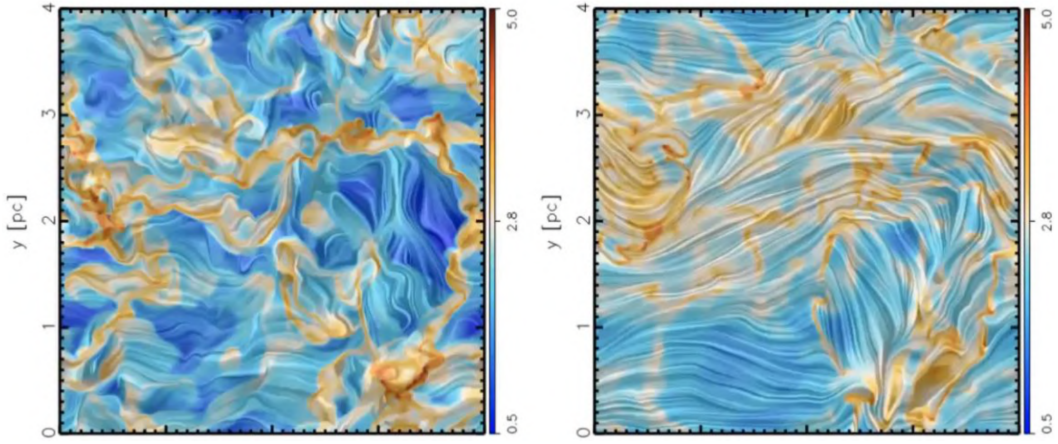
NH transition
+
Influence of B-field in filaments/clumps formation & evolution

First Planck and Herschel combined analysis:
*- transition from filaments // **B** to filaments ⊥ **B** at N_{H2} ~ 1.6×10^{21} cm^{-2}*
(Malinen et al. 2016)



Filaments and Star Formation

Simulations of cloud structure and magnetic field formation



*Weak initial **B** field* *versus* *Strong initial **B** field*
(Soler et al., 2013, and Soler & Hennebelle, 2017)

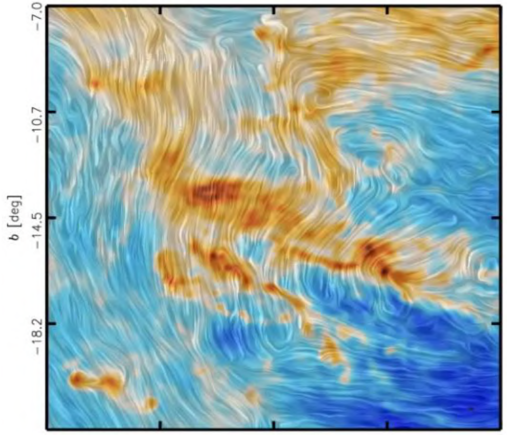
For cloud structure and filament formation:

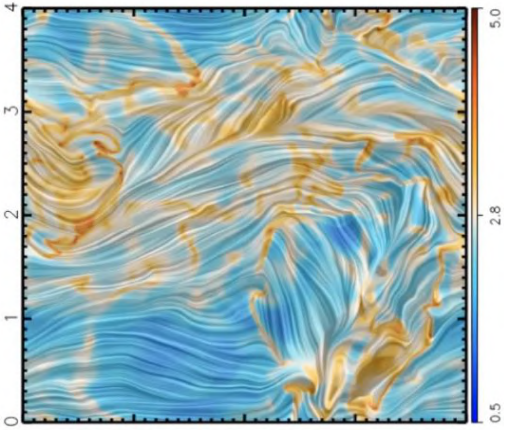
- weak ***B*** field: $\boldsymbol{B}_{\mathrm{PoS}}$ // filamentary structures

- strong ***B*** field: filamentary structures // $\boldsymbol{B}_{\mathrm{PoS}}$ at low N_{H2} and $\perp$ $\boldsymbol{B}_{\mathrm{PoS}}$ at high N_{H2}

Filaments and Star Formation

Simulations of cloud structure and magnetic field formation





Taurus Molecular Cloud *versus* *Strong initial **B** field*

(Planck XXV, 2016) *(Soler et al., 2013, and Soler & Hennebelle, 2017)*

For cloud structure and filament formation:

- weak ***B*** field: $\boldsymbol{B}_{\mathrm{PoS}}$ // filamentary structures

- strong ***B*** field: filamentary structures // $\boldsymbol{B}_{\mathrm{PoS}}$ at low N_{H2} and $\perp$ $\boldsymbol{B}_{\mathrm{PoS}}$ at high N_{H2}

- Transition related to gravitational instability?

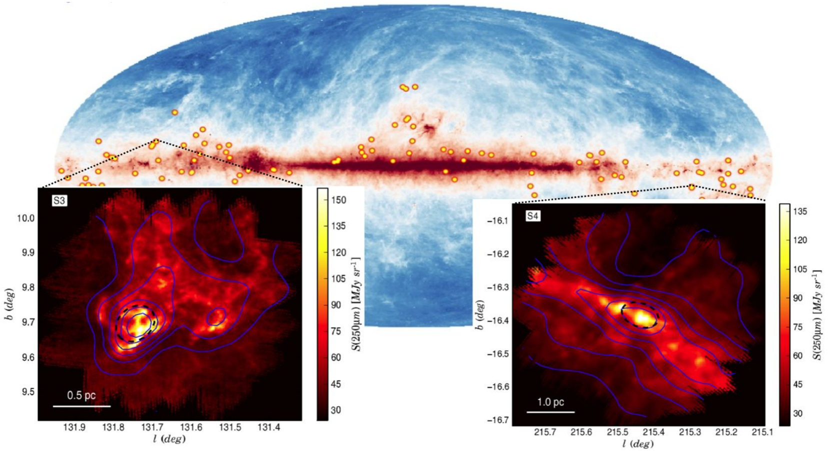
'Galactic Cold Cores' with Herschel and Planck

Herschel (ESA)

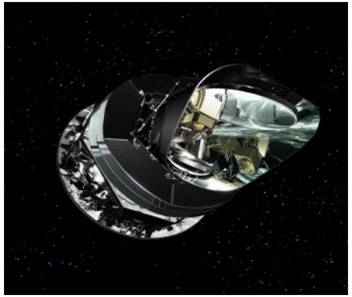
Herschel SPIRE:

Band	250 µm	350 µm	500 µm
FWHM	18"	24.2"	36"

N_{H2} maps -> 36"
- dust emission



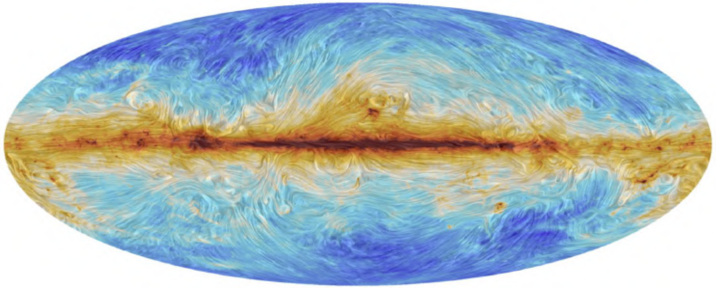
116 Herschel fields of the GCC program (Juvela et al., 2010, 2012)



Planck (ESA)

Planck:

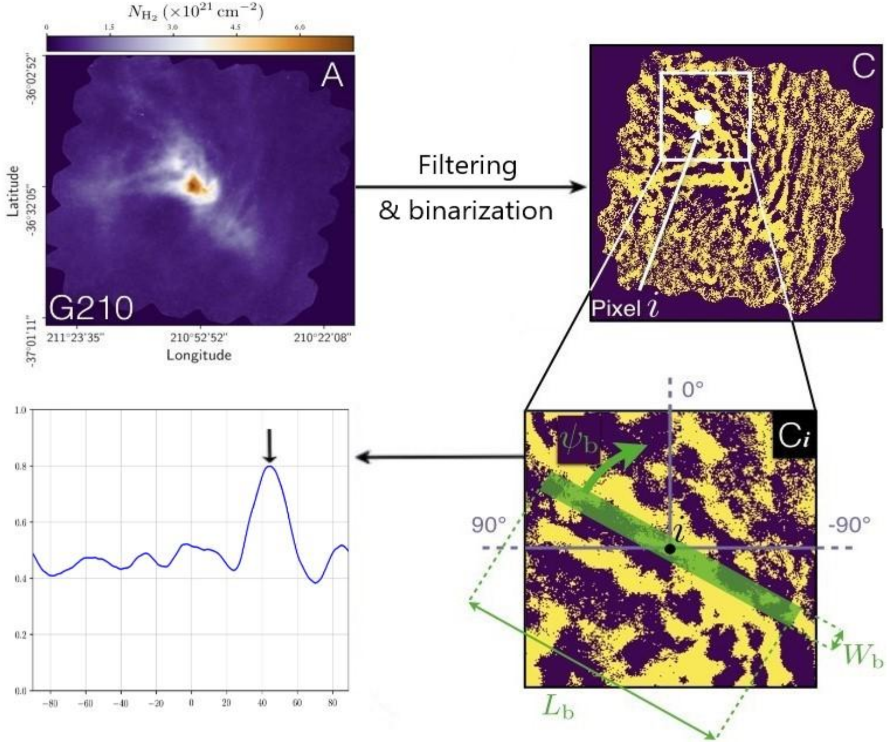
- 353 GHz maps -> 7'
- **polarized** dust emission



Credits: Planck Collaboration

Methodology: filament extraction with FilDReaMS

Filament **D**etection and **Re**construction **a**t **M**ultiple **S**cales (Carrière et al., 2022a)



For a given filament (bar) width W_b:

- Filter and binarize initial map
- Remove structures wider than W_b
- Then, for each pixel *i* of the map:
  - Place a rectangular bar centered on *i* and rotate it
  - Retrieve the bar orientation that matches the map
  - Check the filament relevance using a significance criterion

Repeat this process for a range of W_b

Methodology: filament extraction with FilDReaMS

Filament **D**etection and **Re**construction **a**t **M**ultiple **S**cales (Carrière et al., 2022a)

Main assets of the method:

- ability to detect filaments over a whole range of widths
- estimate of filament widths -> study of relative orientations at multiple scales
- small number of free parameters: bar width W_b, aspect ratio r_b and signal-to-noise ratio S_{fil}
- speed of execution, typically 10 − 20 min to cover the entire range of W_b
- reliability (significance criterion)
- user-friendliness

Methodology: HRO combining Herschel and Planck data

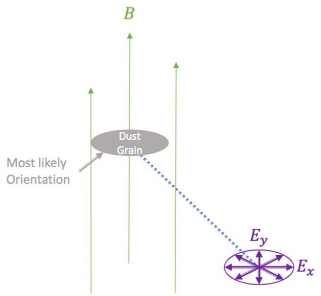
Filament **D**etection and **Re**construction **at** **M**ultiple **S**cales (Carrière et al., 2022a)

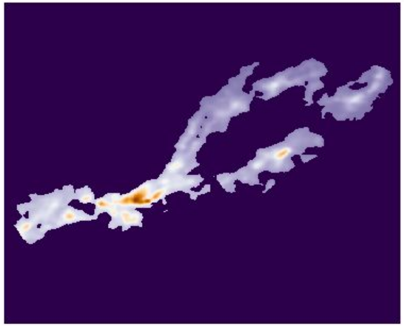
- Extract filaments from Herschel N_{H2} maps

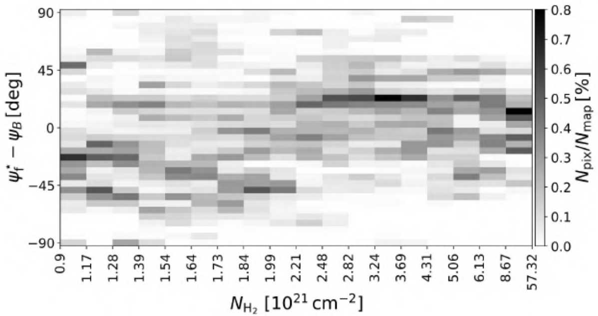
- Infer ***B*** field orientation from Planck polarization data

- Compute relative orientations between extracted filaments and ***B*** field orientations

➔ Build the histogram of relative orientations







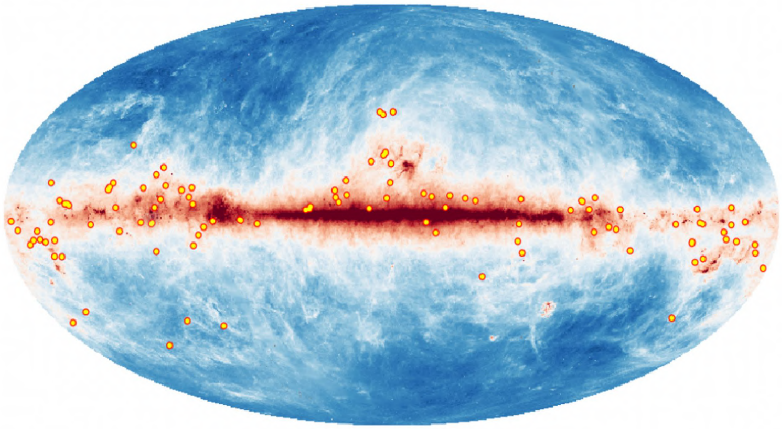
Statistical analysis: first results

I applied FilDReaMS to all 116 Herschel fields of the GCC program:

➔ N_{H2} maps (36”) inferred from SPIRE bands

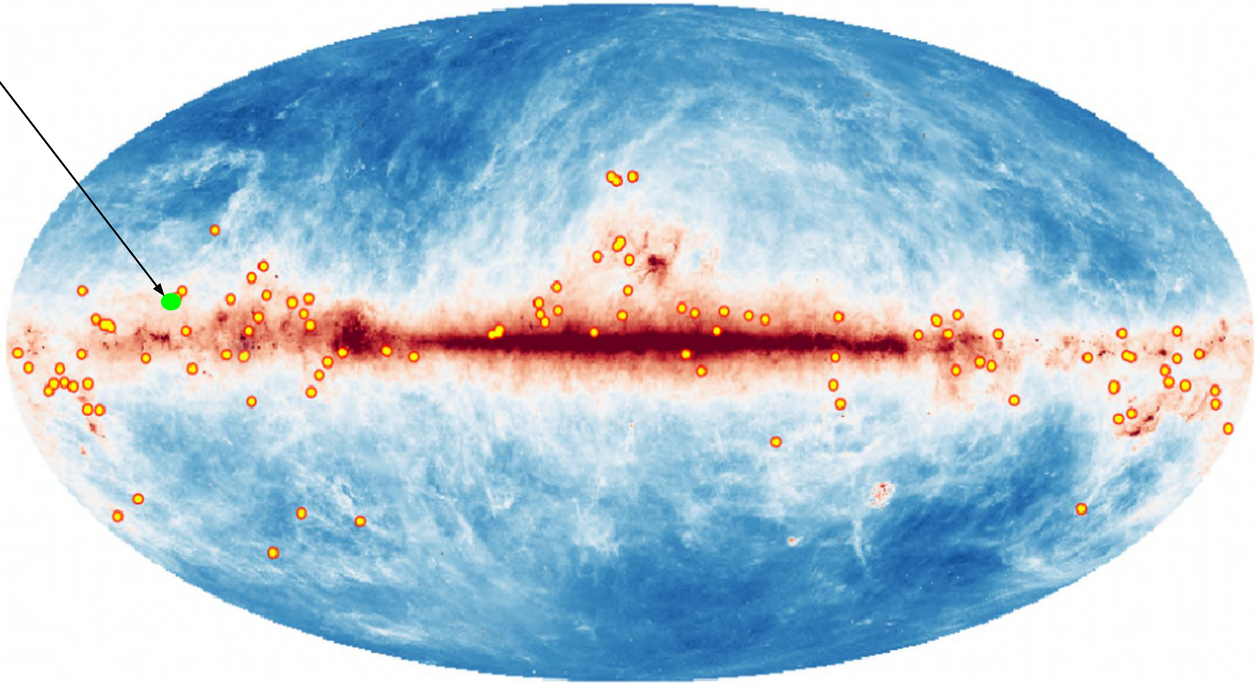
I analyzed the extracted filaments of each map and their orientations relative to $\boldsymbol{B}_{PoS}$

➔ table with key parameters (l, b, d, N_{H2}, p_{MAS}, S_{DISP}, θ_B …)
➔ statistical analyses over the 116 fields



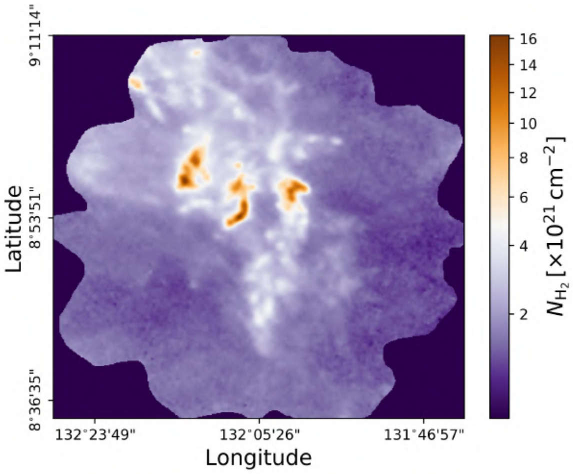
Analysis of the G132 field

G132.12+8.95
d ~ 0.85 kpc

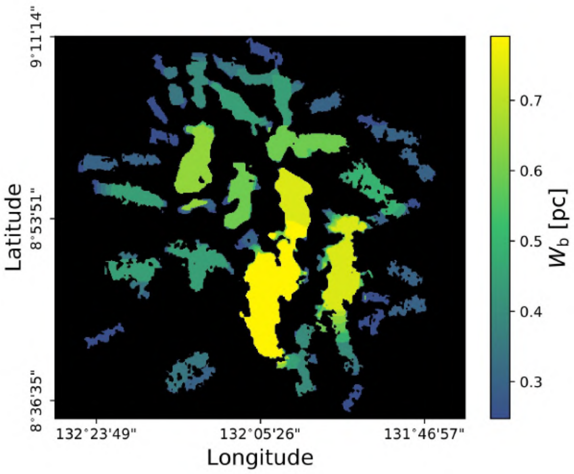


G132: filament extraction from N_{H2} map

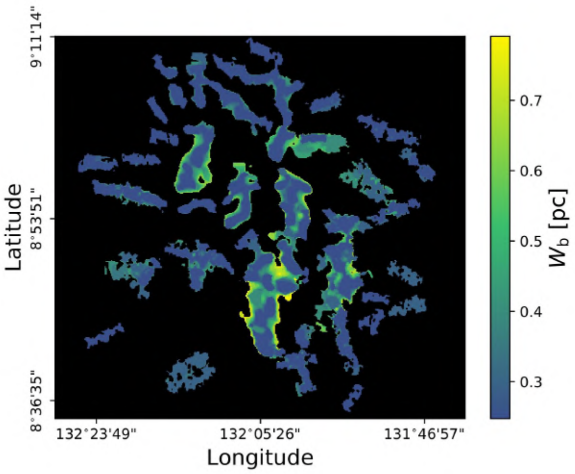
Original Herschel map

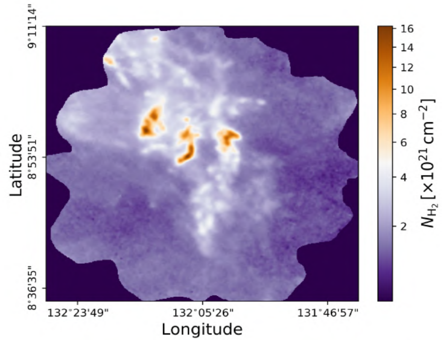


Large filaments in foreground



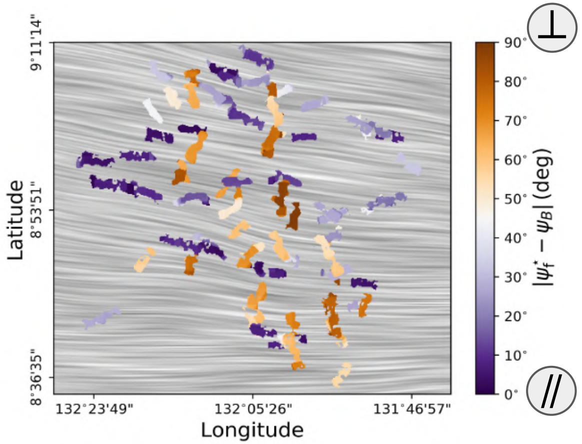
Small filaments in background



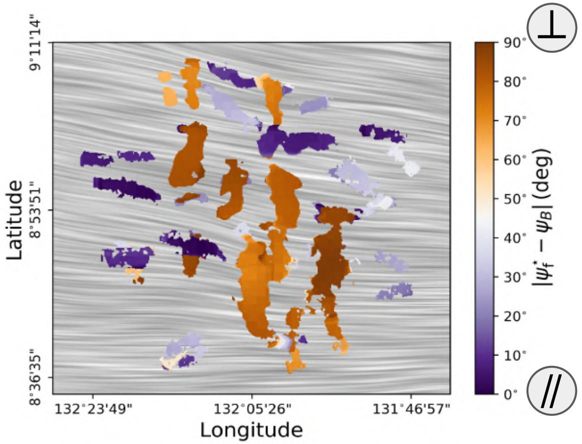


G132: spatial distribution of filaments in 3 ranges of size

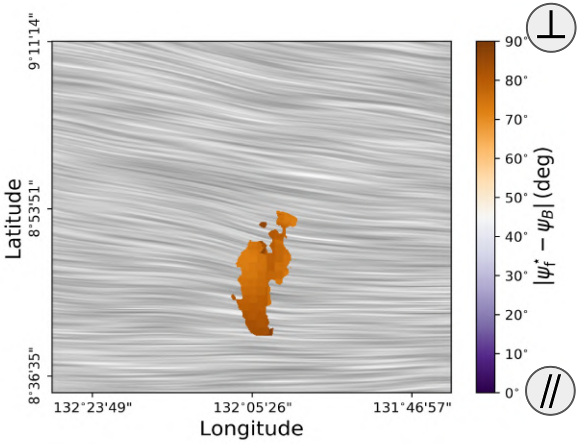
S



M



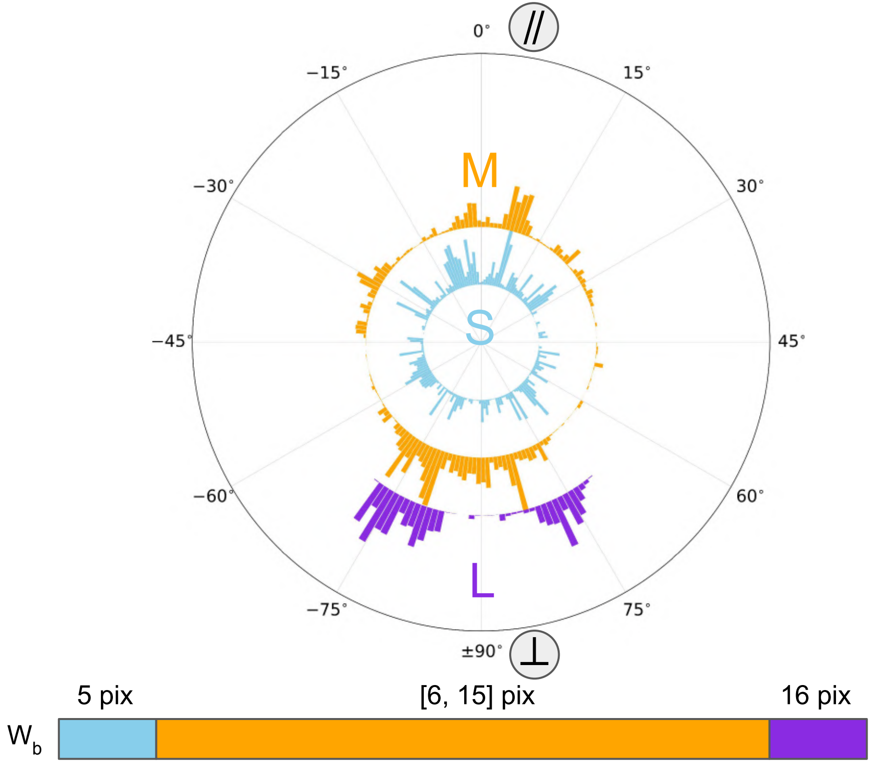
L

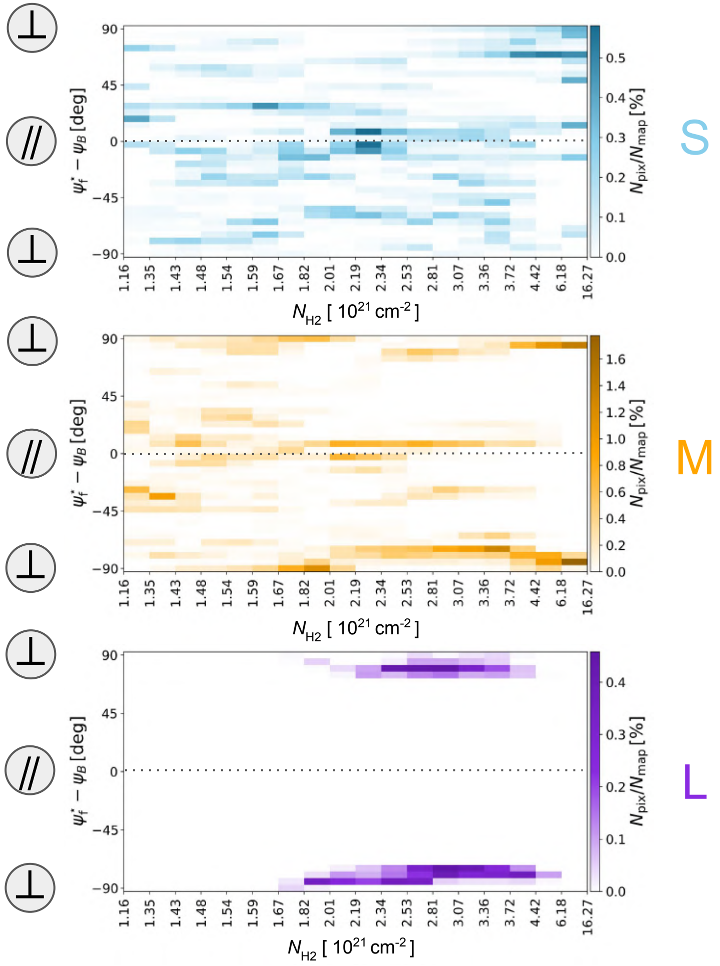


5 pix | [6, 15] pix | 16 pix

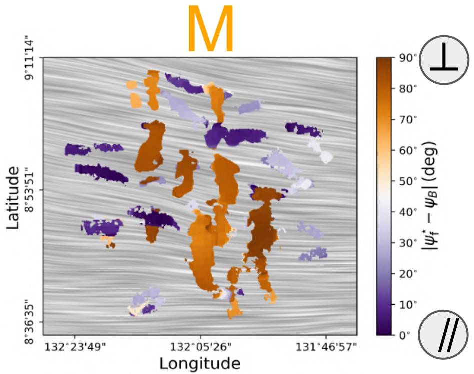
W_b

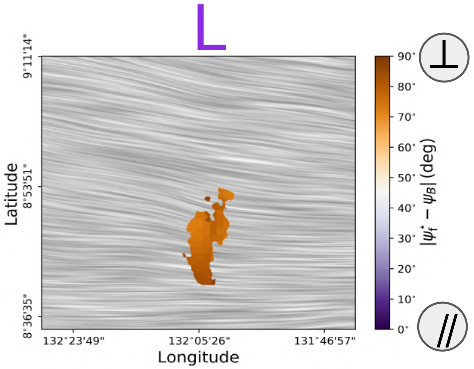
G132: HRO decomposition

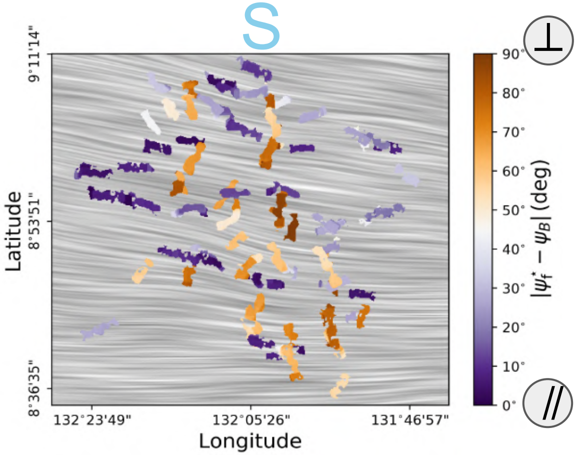


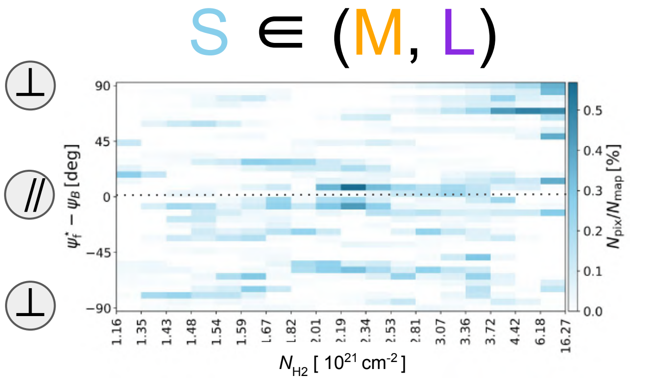


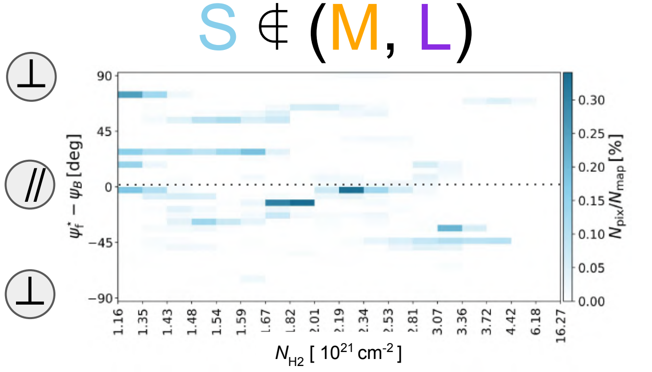
G132 HRO: 2 types of S filaments

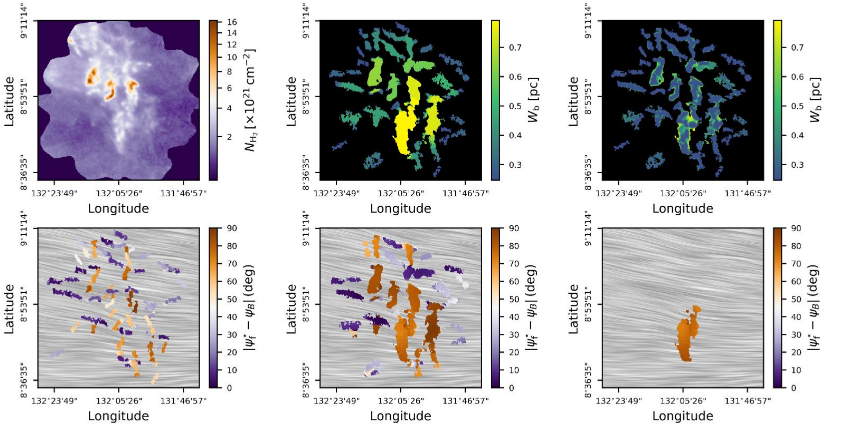




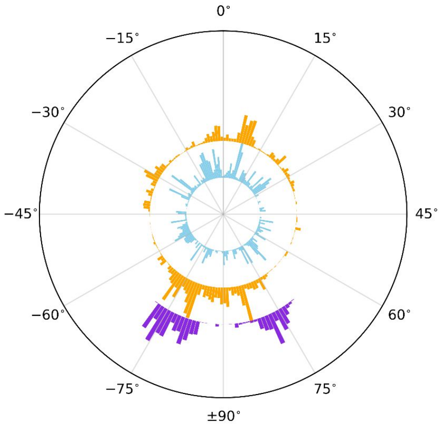


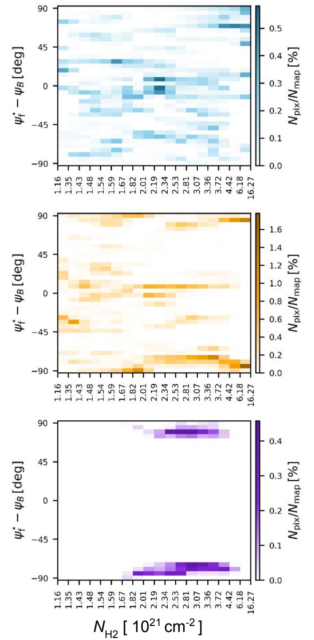






G132: summary ID card





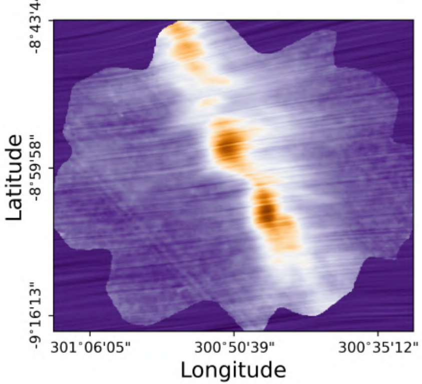
Statistical analysis of all 116 GCC fields

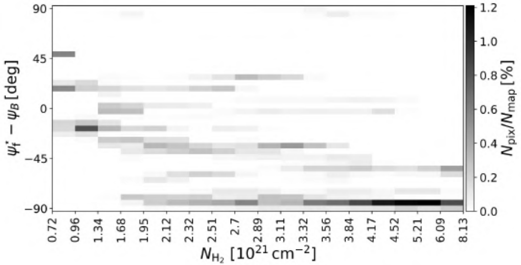
- General trends:
  - -> smaller filaments at lower N_{H2} mostly // $\boldsymbol{B}_{PoS}$
  - -> filaments at higher N_{H2} mostly $\perp$ $\boldsymbol{B}_{PoS}$
  - -> transition from // to $\perp$ for $N_{H2} \in [0.8\ ,\ 2] \times 10^{21}$ cm^{-2}

- Over 30% of maps show:
  - -> no transition from // to $\perp$,
  - -> // at all scales
  - -> opposite transition, from $\perp$ to //
  - -> complex matter morphology
  - -> fluctuating $\boldsymbol{B}$ field

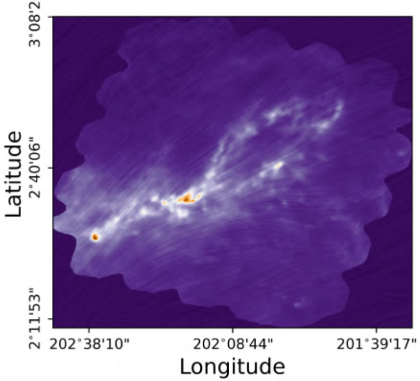
A variety of behaviours

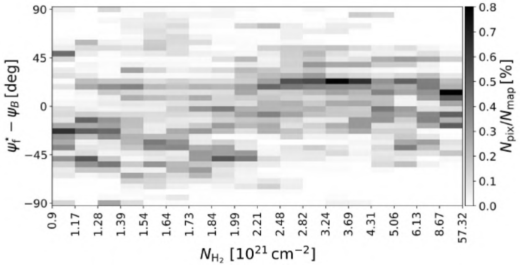
G300.86-9.00



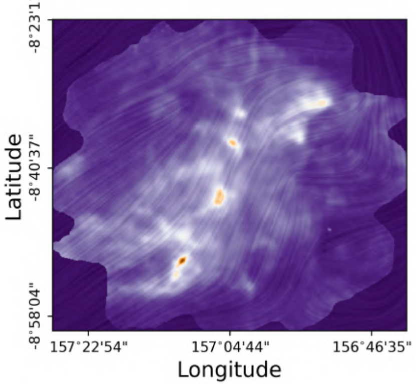


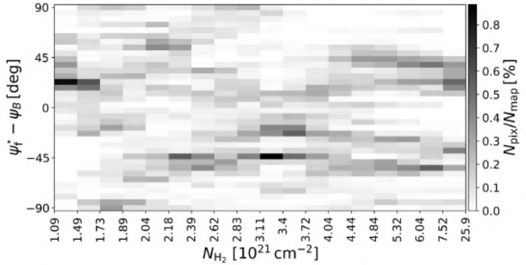
G202.02+2.85





G157.08-8.69





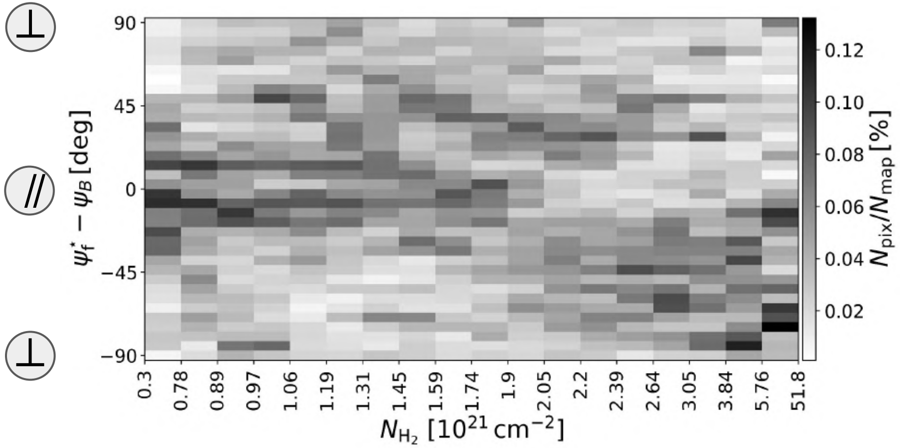
Statistical analysis of all 116 GCC fields

- Need for statistics to study the trends, but different factors have an impact

- Determine dependency of filament orientation on key parameters
  -> longitude, latitude, distance
  -> low N_{H2} or high N_{H2} region
  -> galactic environment properties
  -> strength of ***B*** field
  -> orientation of large-scale ***B*** field to LoS
  -> evolutionary stage
  -> confusion along LoS

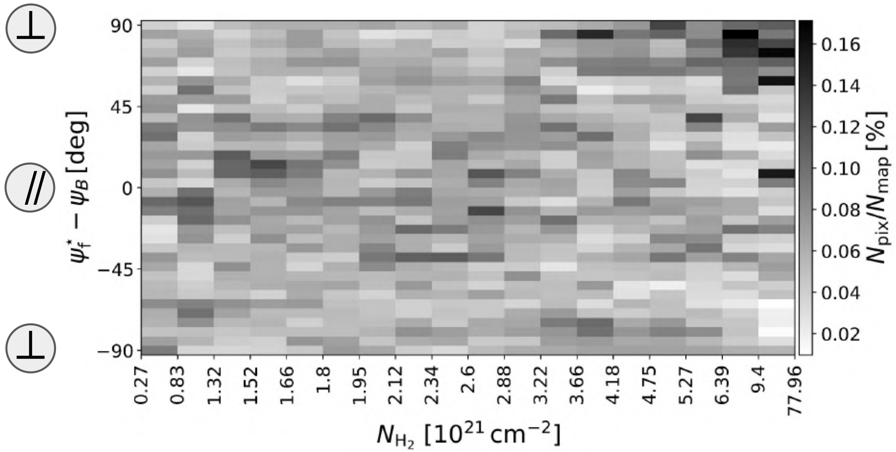
- Investigate correlations with and between parameters (l, b, d, N_{H2}, p_{MAS}, S_{DISP}, θ_B …)

Statistical analysis: field distance



d < 200 pc
Number of GCC fields: 18

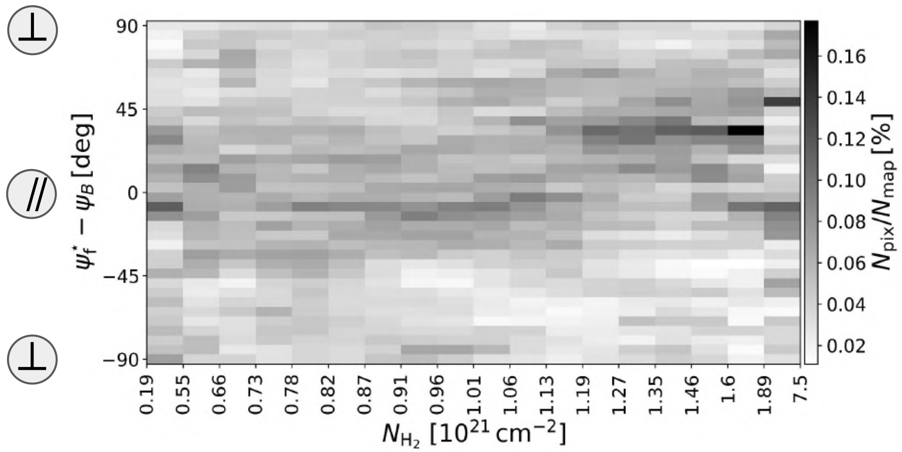
Trends: - filaments mostly // for low N_{H2}
- filaments ~⊥ for high N_{H2}

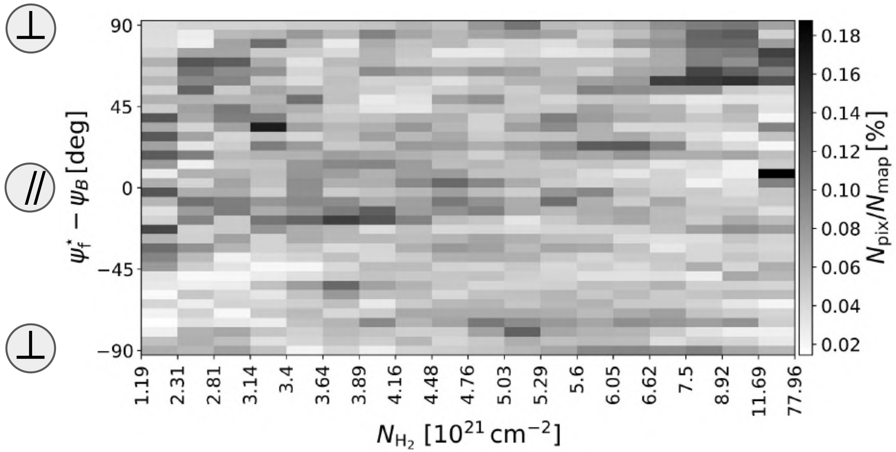


800 pc < d < 1200 pc
Number of GCC fields: 23

Trends: - no preferred orientation for low N_{H2}
- filaments ~⊥ for high N_{H2}

Statistical analysis: N_{H2}





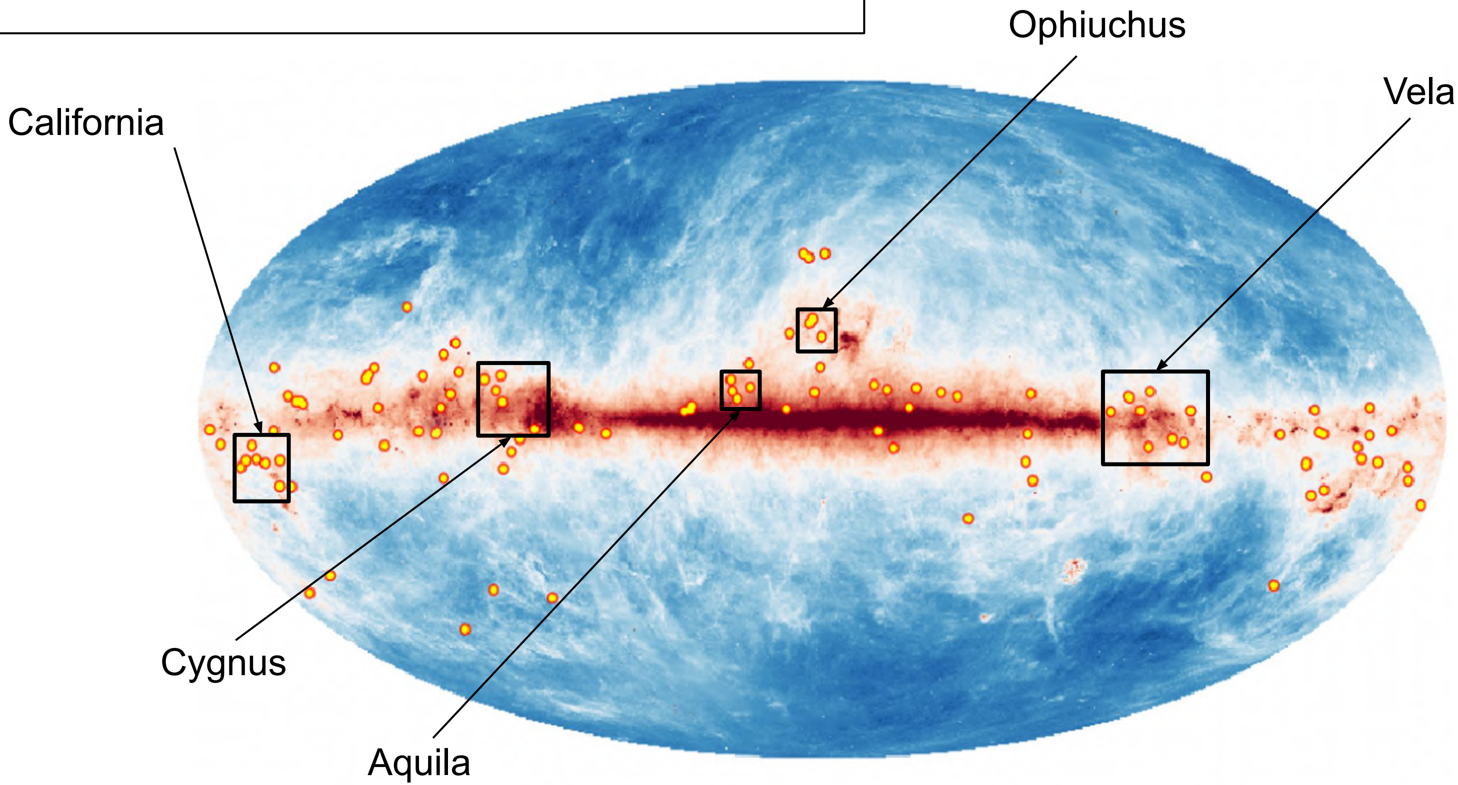
$N_{H2} < 10^{21}$ cm^{-2}
Number of GCC fields: 21

Trends: - filaments mostly // over all N_{H2}
- filaments ~⊥ for high N_{H2}

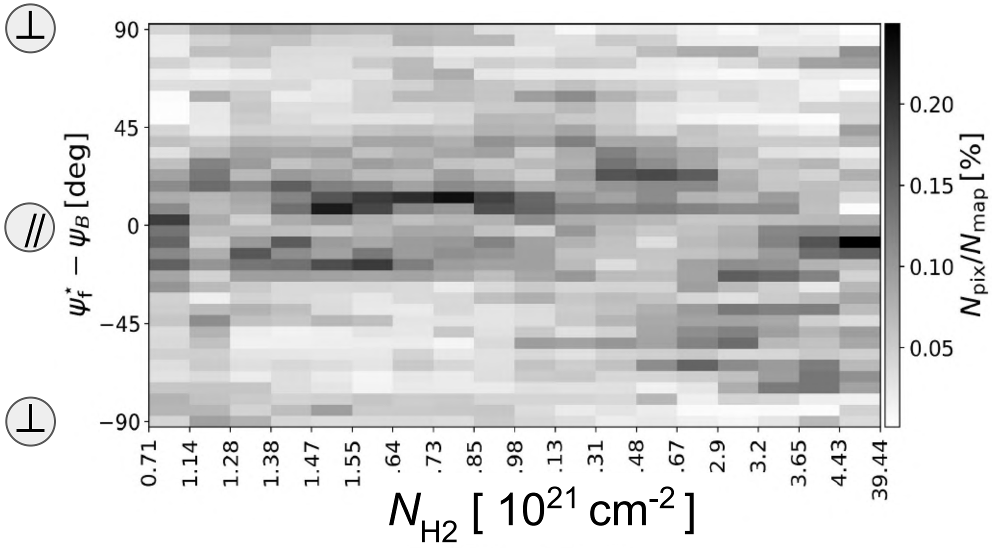
3×10^{21} cm^{-2} pc $< N_{H2} < 10^{22}$ cm^{-2}
Number of GCC fields: 16

Trends: - no preferred orientation for low N_{H2}
- filaments ~⊥ for high N_{H2}

Statistical analysis: molecular complex



Molecular complex study: California



Trends: - filaments mostly // over all N_{H2}
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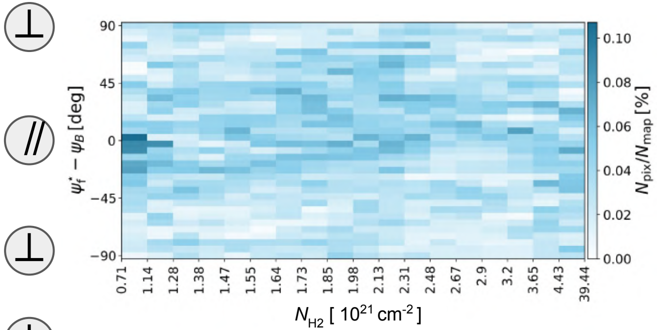

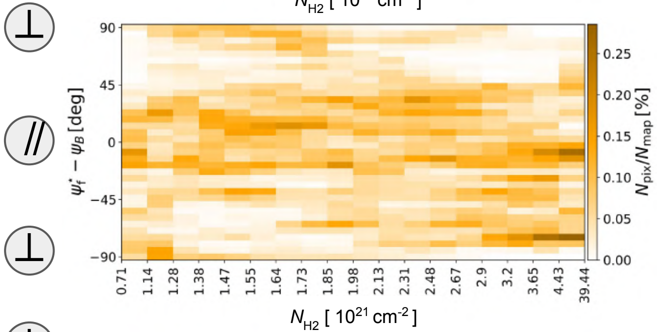

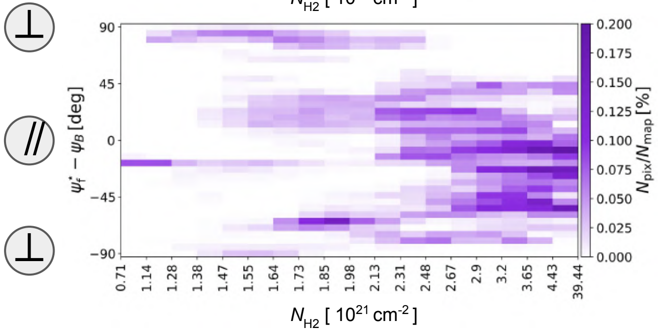

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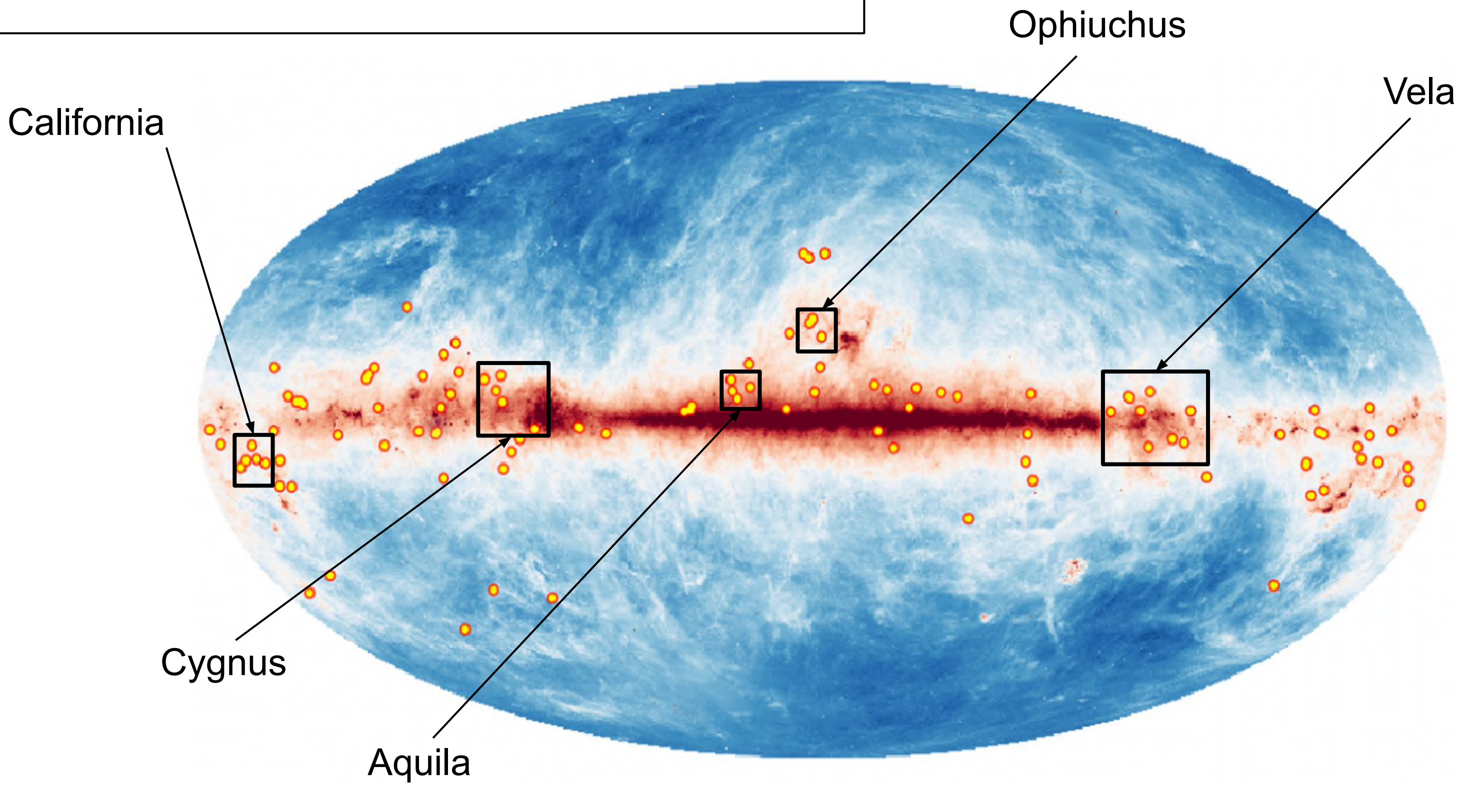
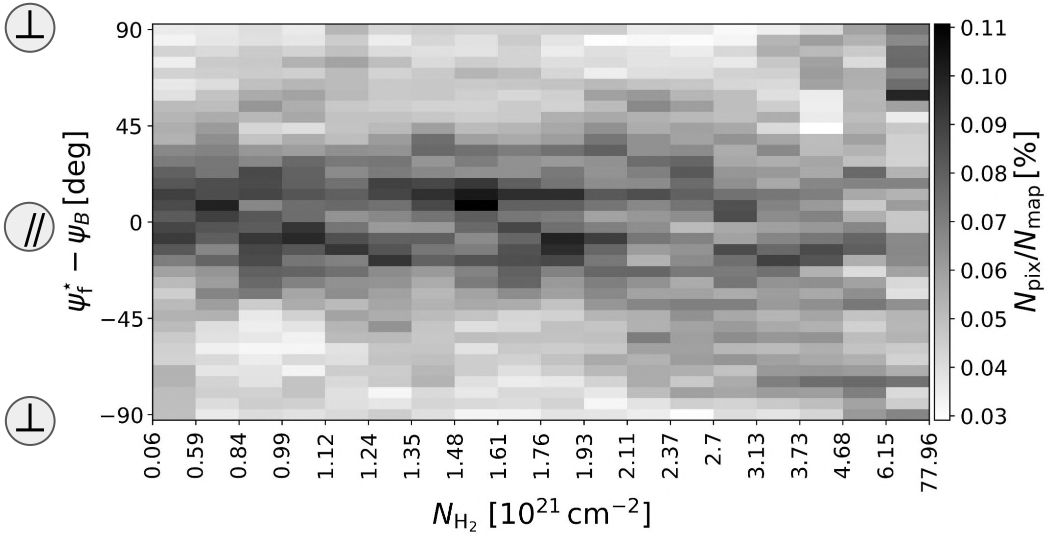


Conclusion

Statistical analysis of all 116 GCC fields:

- Usual trends identified in most maps



Conclusion

Statistical analysis of all 116 GCC fields:

- Usual trends identified in most maps

- no transition from // to ⊥,
- // at all scales
- opposite transition, from ⊥ to //

~ different physical conditions

Combined HROs:

- Trends are either reinforced or lost in the noise

- Useful to compare combined HRO with individual HRO for chosen GCC fields

Perspectives

- Improve constrain on key parameters (Herschel distances, Gaia distances, …)

- Determine dependency of filament orientation on key parameters

- Examine correlations between parameters

- Remove confusion along the LoS
  -> spectral HI / CO observations

- Increase sample size

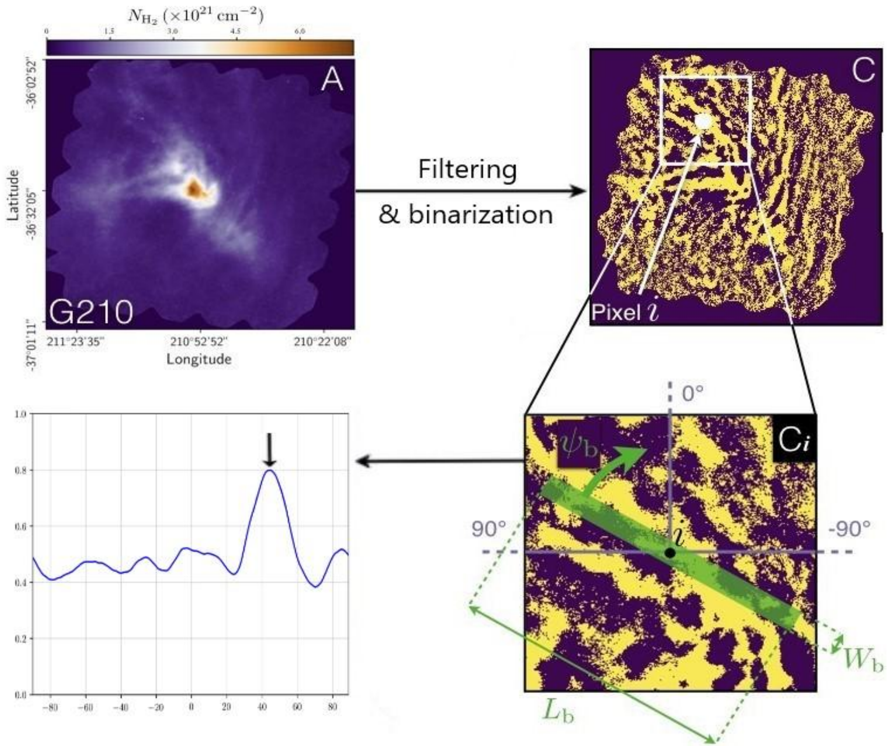
- Improve statistical analyses
  -> insight on filamentary evolution


WORK IN PROGRESS

THANK YOU FOR YOUR ATTENTION

FilDReaMS: filament detection

Filament **D**etection and **Re**construction **a**t **M**ultiple **S**cales
(Carrière et al., 2022a)



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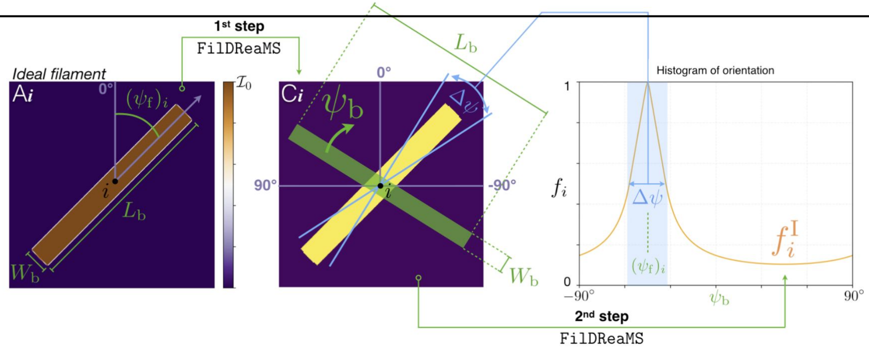
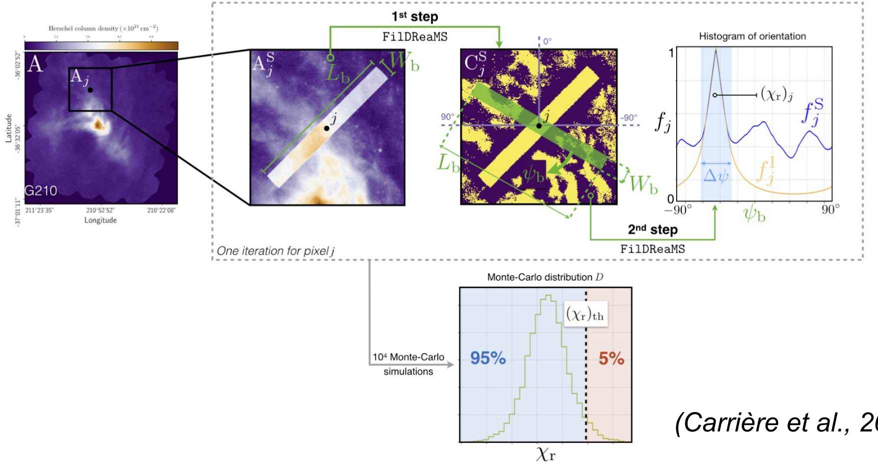
  - Verify filament relevance using a significance criterion

Repeat this process for a range of W_b

FilDReaMS: filament validation





(Carrière et al., 2022a)

Filament **D**etection and **Re**construction **a**t **M**ultiple **S**cales (Carrière et al., 2022a)

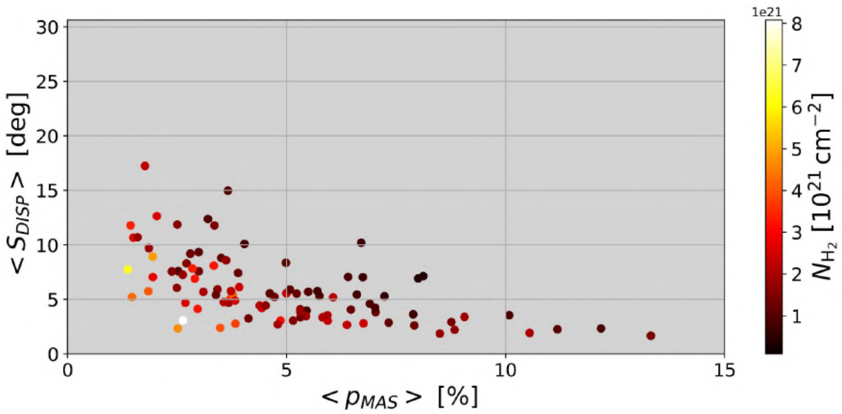
Mieux développer/ plusieurs slides?

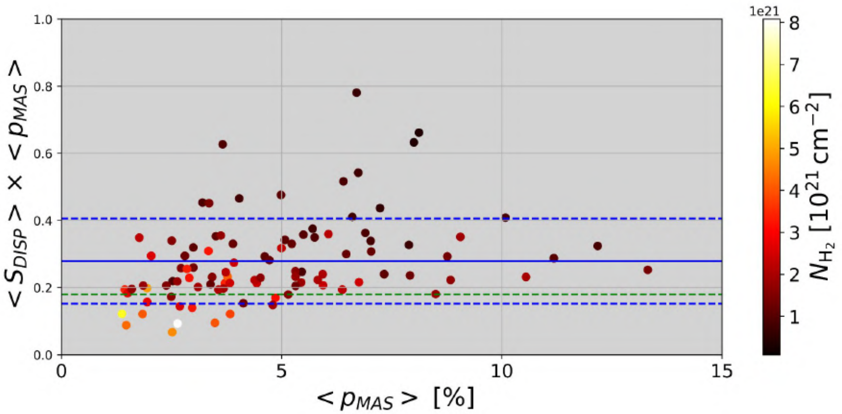
For a given filament (bar) width W_b, and for each pixel where a filament was detected:

- Identify a filament in an ideal case
  -> compare the detected filament with the ideal filament
  -> reduced $\square_i$ quantifying the likeness of the potential filament to a bar
- Identify a filament in a synthetic case
  -> compare the synthetic filament with the ideal filament
  -> reduced $\square_{th}$ quantifying the effects of the background on filament detection
- S = $\square_{th}$ / $\square_i$. S > 1 confirms the potential filament detected at a given position and orientation

Repeat this process for a range of W_b

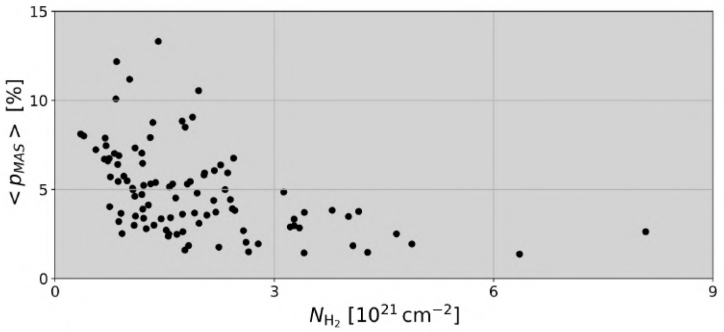
First step into perspectives

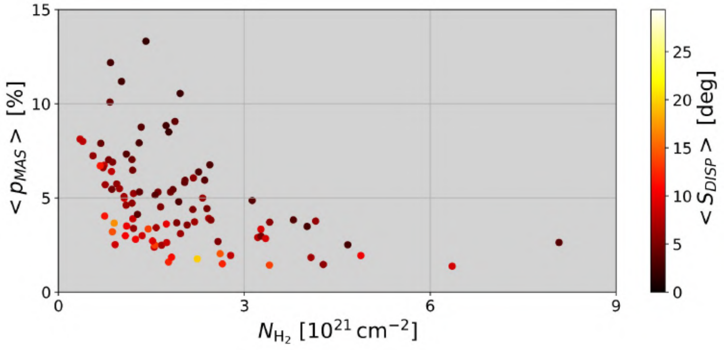


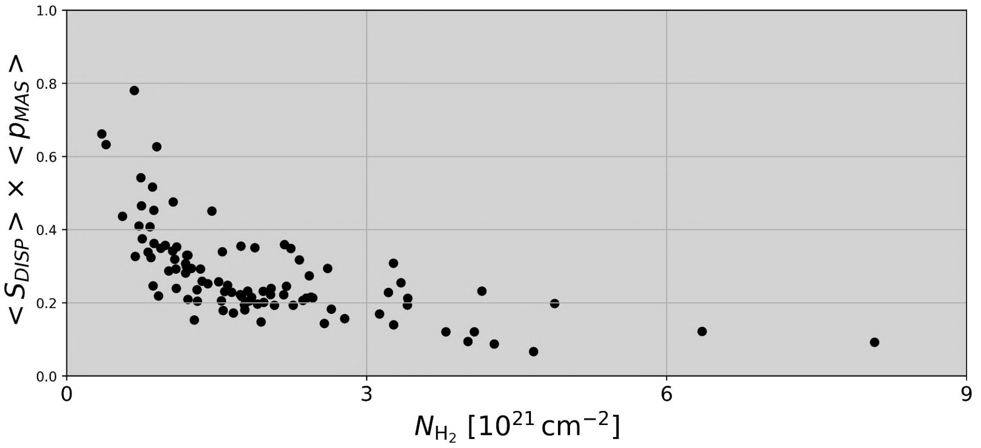


Introduire le travail fait sur la corrélation entre p, S et NH?

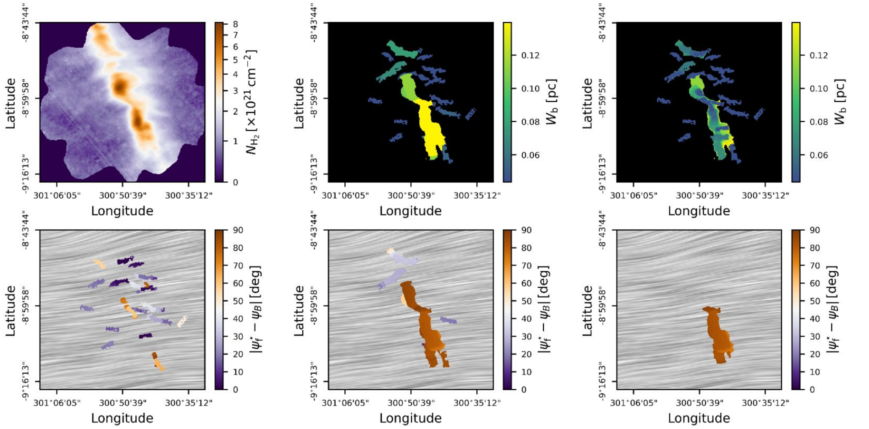
First step into perspectives



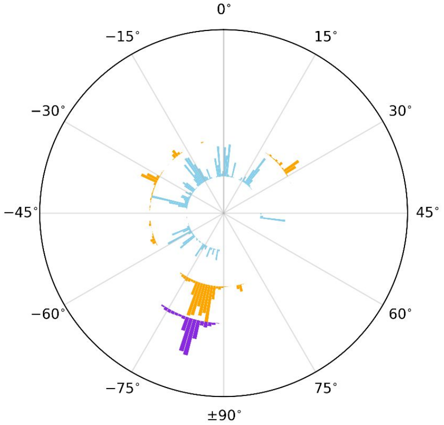


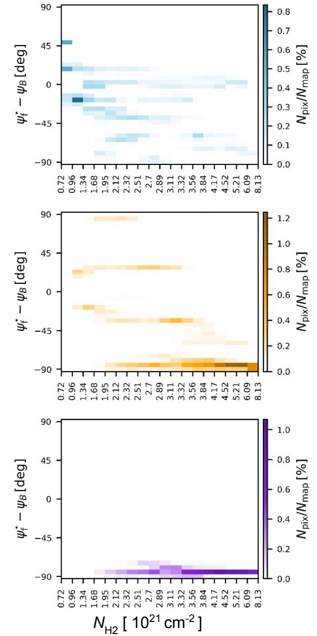


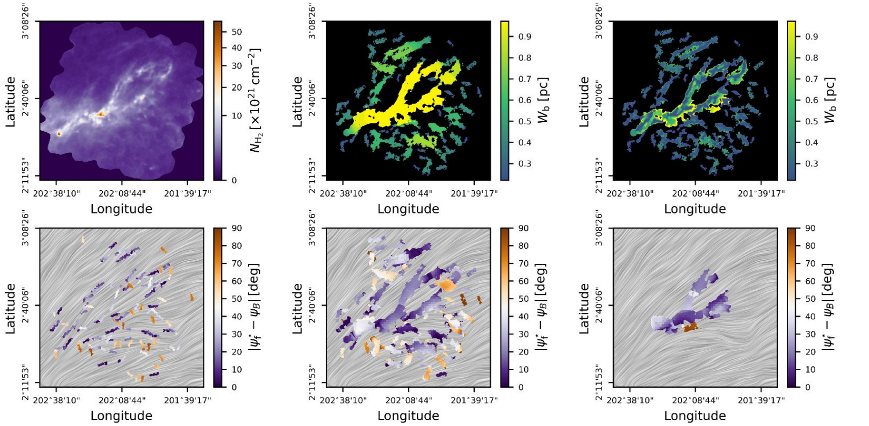
Introduire le travail fait sur la corrélation entre p, S et NH?



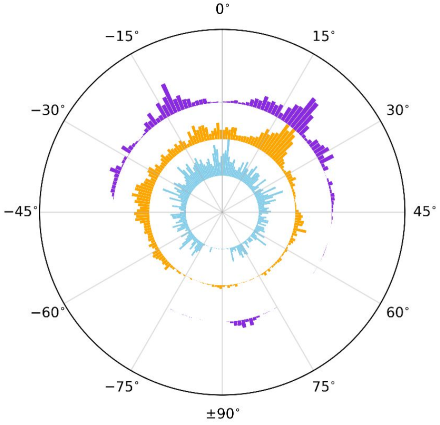
G300.86: summary ID card

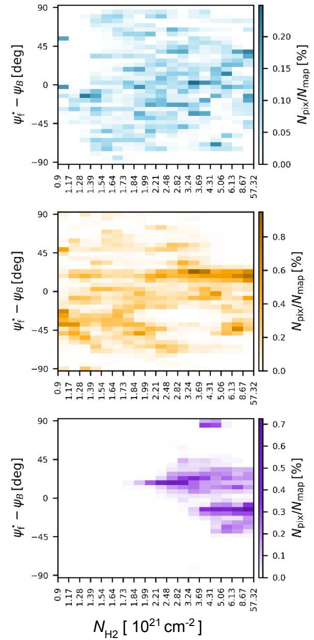


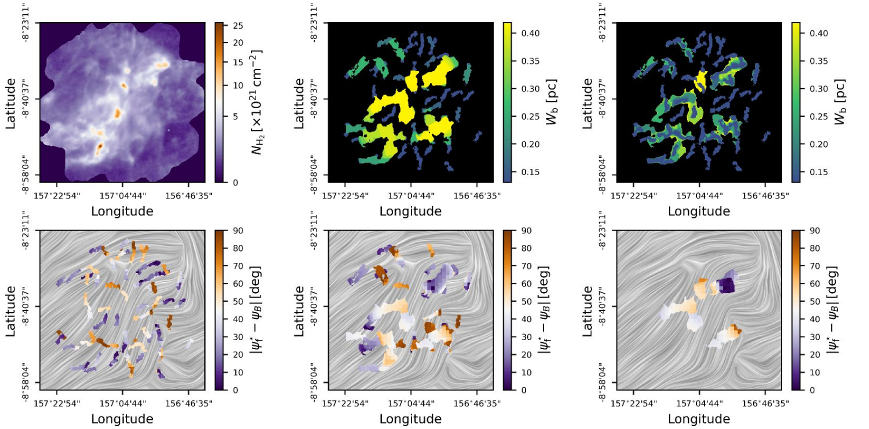




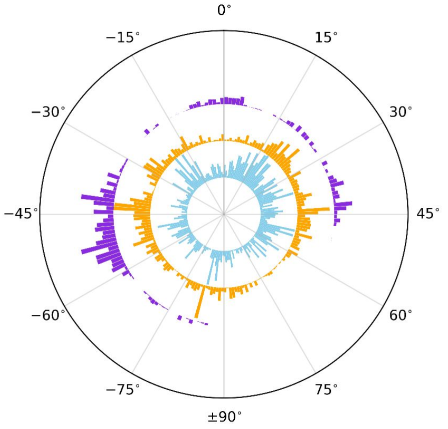
G202.02: summary ID card

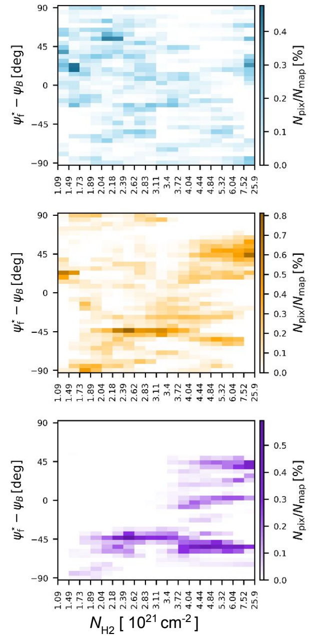


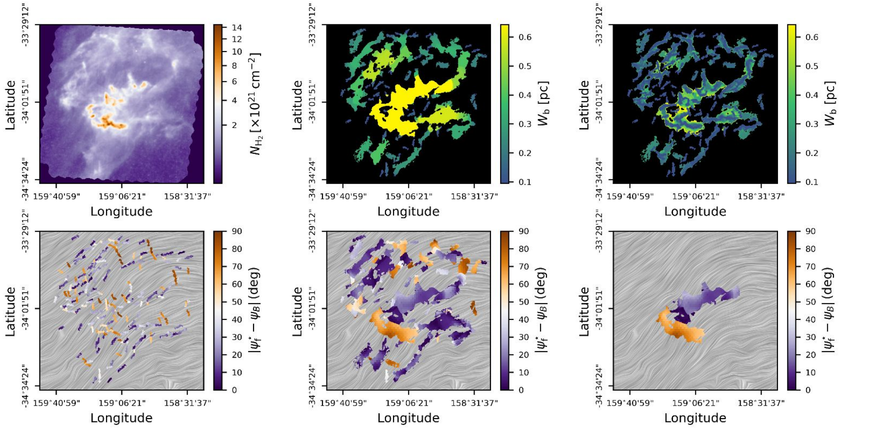




G157.08: summary ID card







G159.23: summary ID card