

# Magnetic fields and first results on the ionization fraction in Orion B

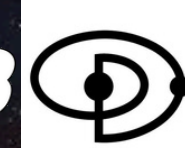
Ivana Bešlić

LERMA, Observatoire de Paris

30/10/2024

PCMI2024 - Bordeaux

DAOISM anr<sup>®</sup> ORION-B



Observatoire  
de Paris



# TALK OVERVIEW

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INTRODUCTION



HOW TO MEASURE?



ORION B AND NGC 2024



1. B-FIELD



2. IONIZATION FRACTION



SUMMARY



# INTRODUCTION

**Molecular ISM is partially ionized.**

**Magnetic (B-) field is spread throughout the Interstellar gas.**

**Electrons are coupled to the B-field and drive chemistry of molecules.**

**Sources of ionization: far-UV radiation, shocks, cosmic rays.**

**Ion-neutral drift, magnetic support against gravitational collapse and star formation.**

# INTRODUCTION

**Molecular ISM is partially ionized.**

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**Ion-neutral drift, magnetic support against gravitational collapse and star formation.**

***MAGNETIC FIELD AND ELECTRON FRACTION ARE FUNDAMENTAL PARAMETERS OF THE ISM.***



# INTRODUCTION

Molecular ISM is partially ionized.

Sources of ionization: far-UV radiation, shocks, cosmic rays.

Magnetic (B-) field is spread through the interstellar gas.

**However, they are not directly observable!**

Ion-neutral drift, magnetic support against gravitational collapse and star formation.

Electrons are coupled to the B-field and drive chemistry of molecules.

***MAGNETIC FIELD AND ELECTRON FRACTION ARE FUNDAMENTAL PARAMETERS OF THE ISM.***



# POS B-FIELD AND HOW TO MEASURE IT



## DUST EMISSION IS POLARIZED



## RADIATIVE ALIGNMENT TORQUES



Polarization is perpendicular to the POS magnetic field.

see Pattle et al., 2023

Compressible nature of the ISM.  
Magneto-hydrodynamic waves. Entropy modes.

$$B_{\text{pos}} \approx 1.8 \cdot \sqrt{n_{\text{H}_2}} \cdot \frac{\Delta v}{\sqrt{\hat{\sigma}_c(\varphi)}} [\mu\text{G}]$$

Skalidis et al., 2021

Skalidis&Tassis et al., 2021



## Measure

1. Gas number density ( $\text{cm}^{-3}$ )
2. Turbulent FWHM (km/s)
3. Spatial dispersion of direction of B-field (deg)

# DERIVING IONIZATION FRACTION



**DEPENDS ON THE MODEL, DENSITY, G<sub>0</sub>, COSMIC IONIZATION, CHEMISTRY, AND TRACER**



Random forest model trained to predict ionization fraction from a tracer (intensity/column density ratio).



see Bron et al., 2021

Analytical approach depends on the visual extinction:

- Dense gas ( $A_v > 6$ )

$$f^{\text{dense}}(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5$$

- Translucent gas ( $A_v$  from 2 to 6 mag)

$$f^{\text{translucent}}(x) = f_{\text{max}} - \log_e \left( 1 + e^{-(a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5)} \right)$$

Bron et al., 2021



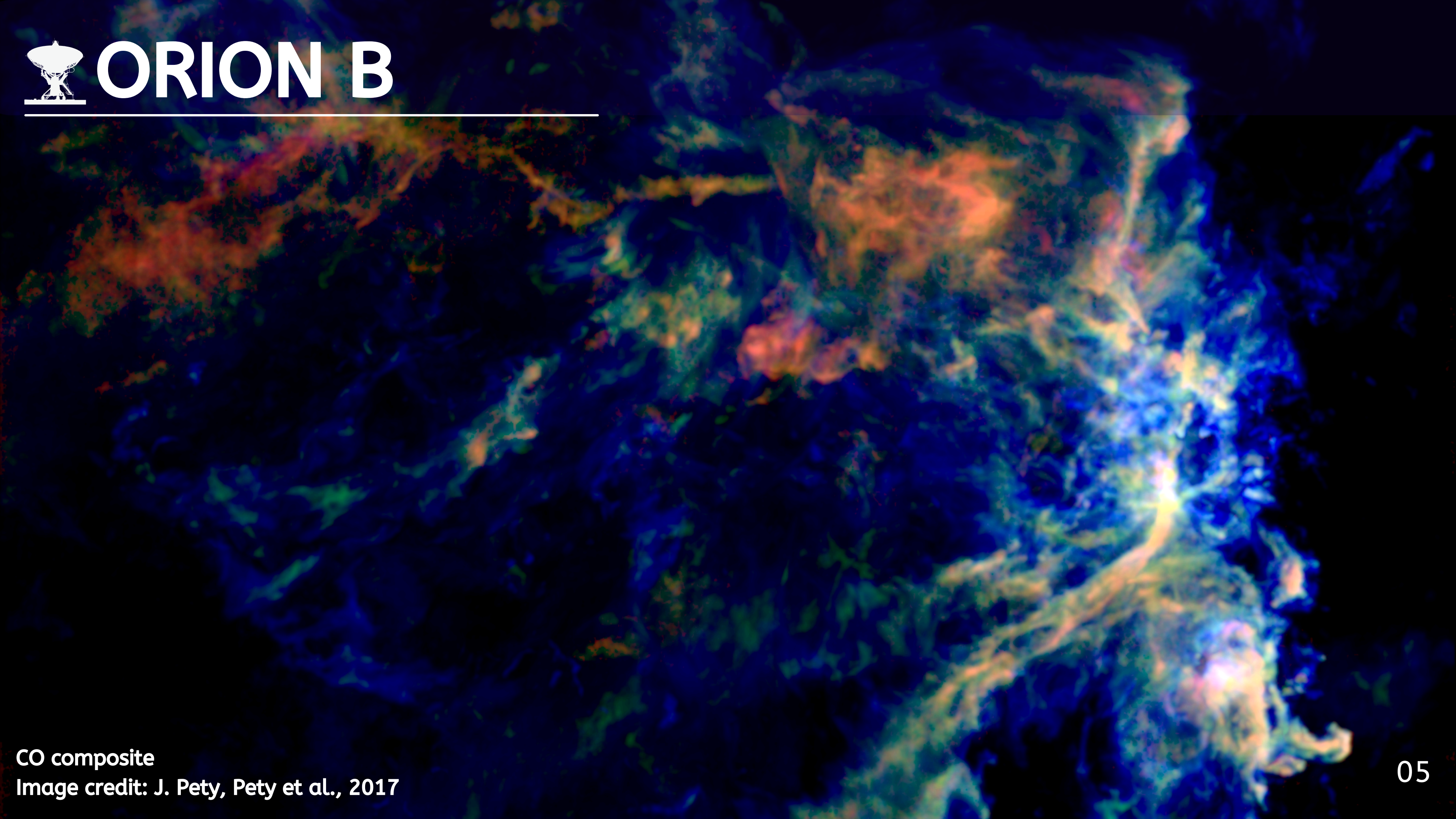
## Measure

1. Integrated intensities
2. Construct line ratios

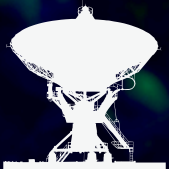


# ORION B

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CO composite  
Image credit: J. Pety, Pety et al., 2017



# ORION B



Team's  
webpage!

## Facts

5 square degrees  
~1000 hours  
0.05 pc,  $10^4$  AU  
30 molecular lines

## Data

~820 000 pixels  
~240 000 spectral channels  
Astronomers and data  
scientists



# ORION B



PIs: J. Pety and M. Gerin

Team's  
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## Team at PCMI2024

**Lucas Einig:** Informativity of  
molecular emission lines

**Leontine Segal:** Sandwich model

**Antoine Zakardjian:** Tracing the sub-  
beam density distribution

**Helena Mazurek:** Chemistry of dense  
cores



# ORION B



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Team's  
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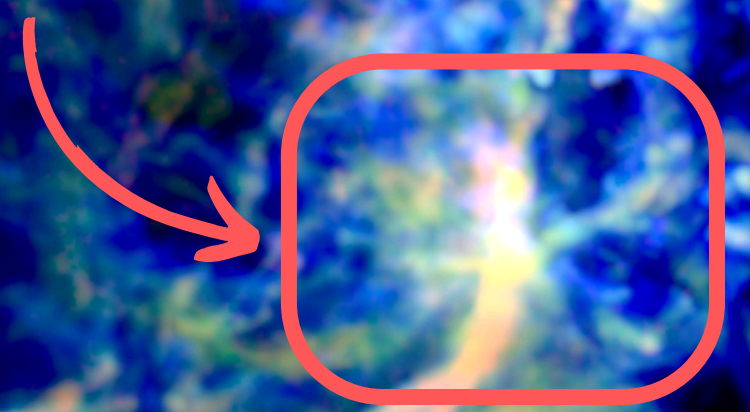
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scientists

The region we  
investigate  
now!



# NGC 2024



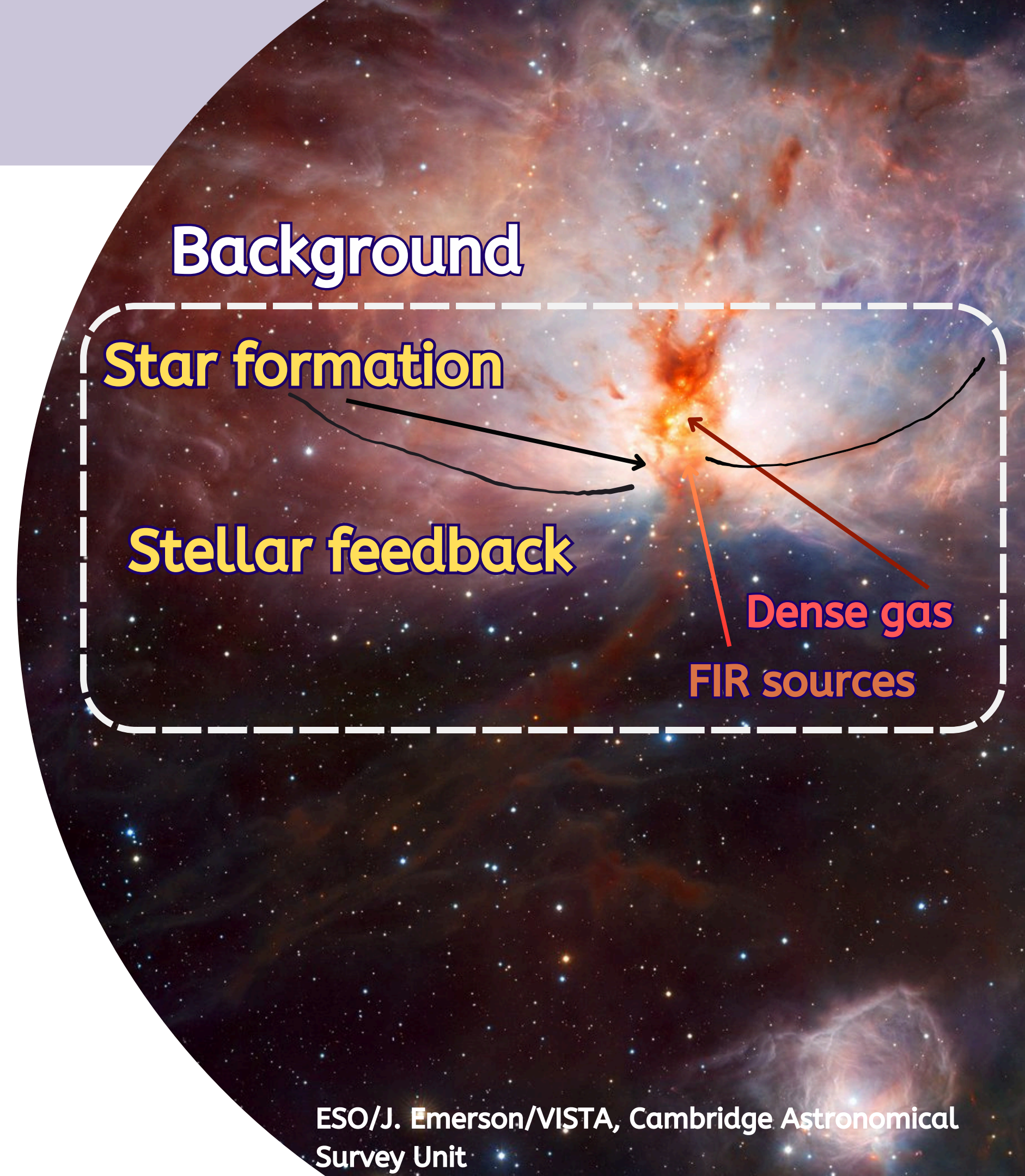
**A massive star-forming region in Orion B.**



**Distance of 410 pc.**

**Contains a filamentary structure and HII region.**

**Turbulent region with the presence of stellar feedback.**



# NGC 2024



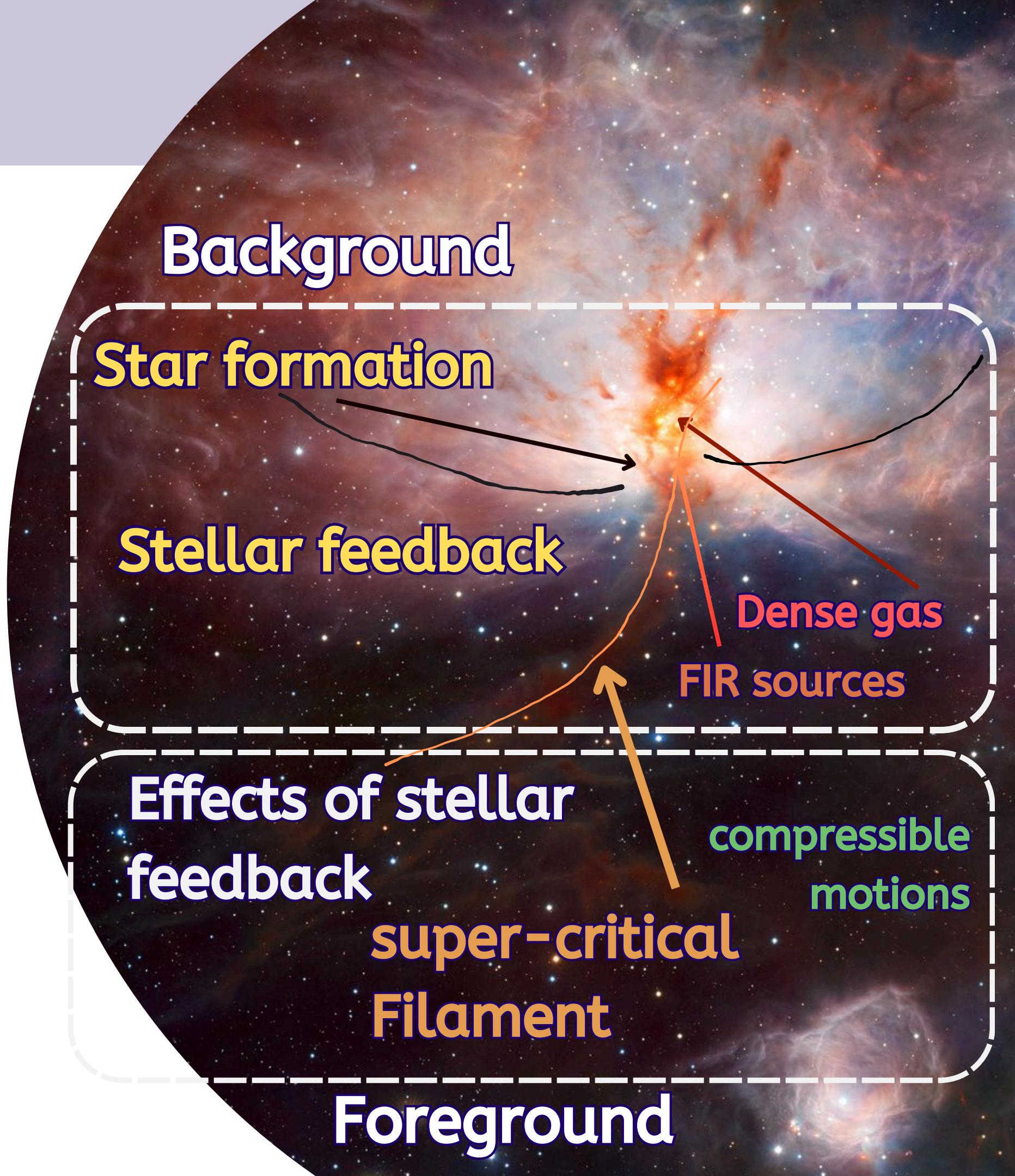
**A massive star-forming region in Orion B.**



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# 1. MAGNETIC FIELD IN NGC 2024

*Astronomy & Astrophysics* manuscript no. NGC2024\_final  
February 8, 2024
















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## GOALS



**Morphology and strength of the B-field in NGC 2024**

### **The magnetic field in the Flame nebula**

I. Bešlić<sup>1</sup> , S. Coudé<sup>2,3</sup> , D. C. Lis<sup>4</sup> , M. Gerin<sup>1</sup> , P. F. Goldsmith<sup>4</sup> , J. Pety<sup>1,5</sup> , A. Roueff<sup>6</sup>, K. Demyk<sup>7</sup> ,  
C. D. Dowell<sup>4</sup>, L. Einig<sup>5,8</sup> , J. R. Goicoechea<sup>9</sup> , F. Levrier<sup>10</sup> , J. Orkisz<sup>5</sup> , N. Peretto<sup>11</sup> , M. G. Santa-Maria<sup>9</sup> ,  
N. Ysard<sup>7,12</sup> , and A. Zakardjian<sup>7</sup> 

## 2. IONIZATION FRACTION

# OBSERVATIONS

## FAR INFRARED



**SOFIA**

**HAWC+**

PI: D. Lis

Dust polarization

Stokes parameters

154 and 216 microns

## MILLIMETER



**IRAM 30m**

**EMIR**

ORION B Large Program

PI: J. Pety, M. Gerin

Molecular emission

CN, and HCO<sup>+</sup>

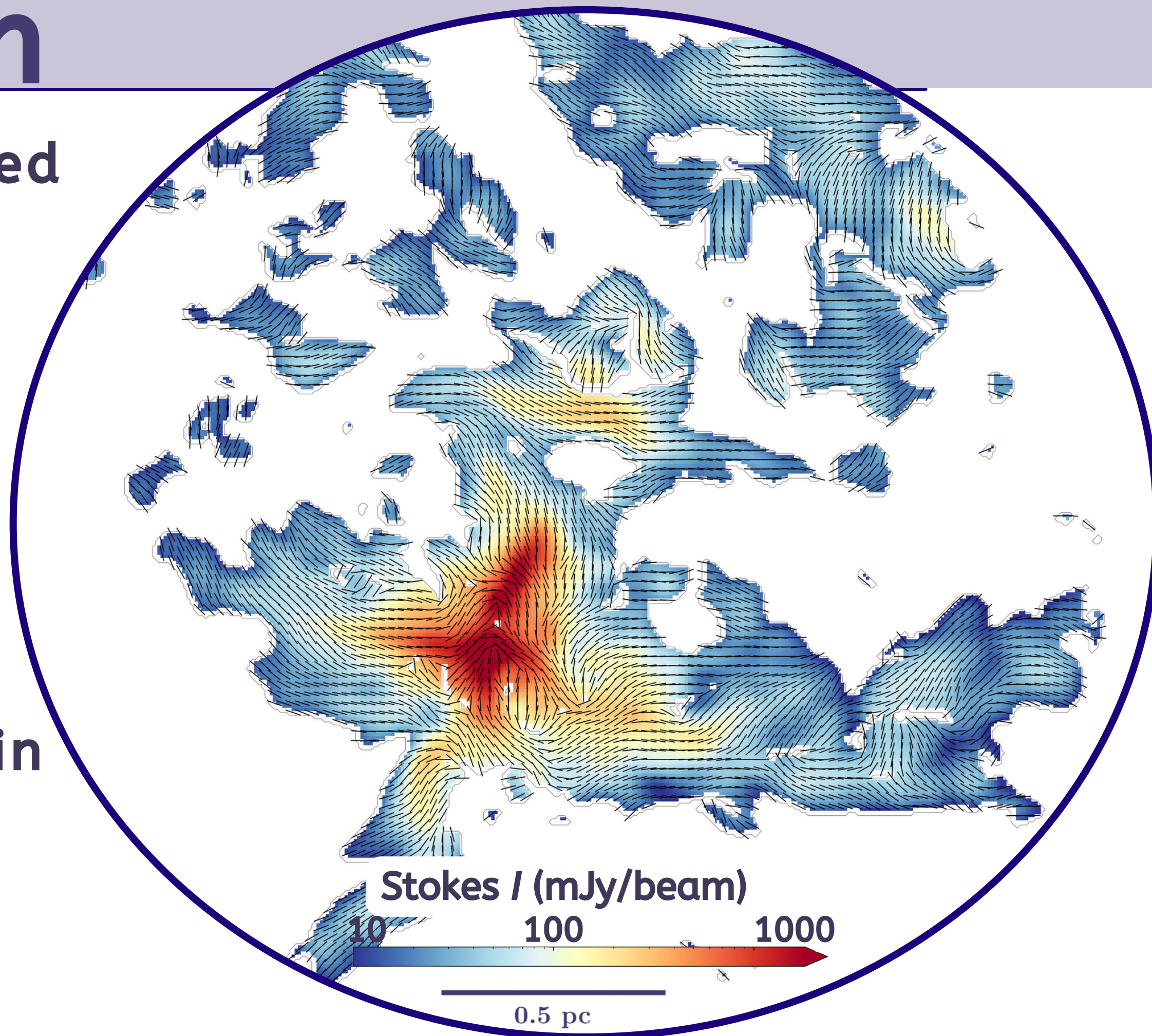
# SOFIA 154 $\mu$ m



**B-field is highly ordered across NGC 2024.**

**B-field follows the morphology of the gas.**

**|| to the edges of HII region, perpendicular in some regions.**



# Molecular gas in NGC 2024



non-LTE radiative transfer  
SpectralRadex (van der Tak  
et al., 2007, Holdship et al.,  
2021)

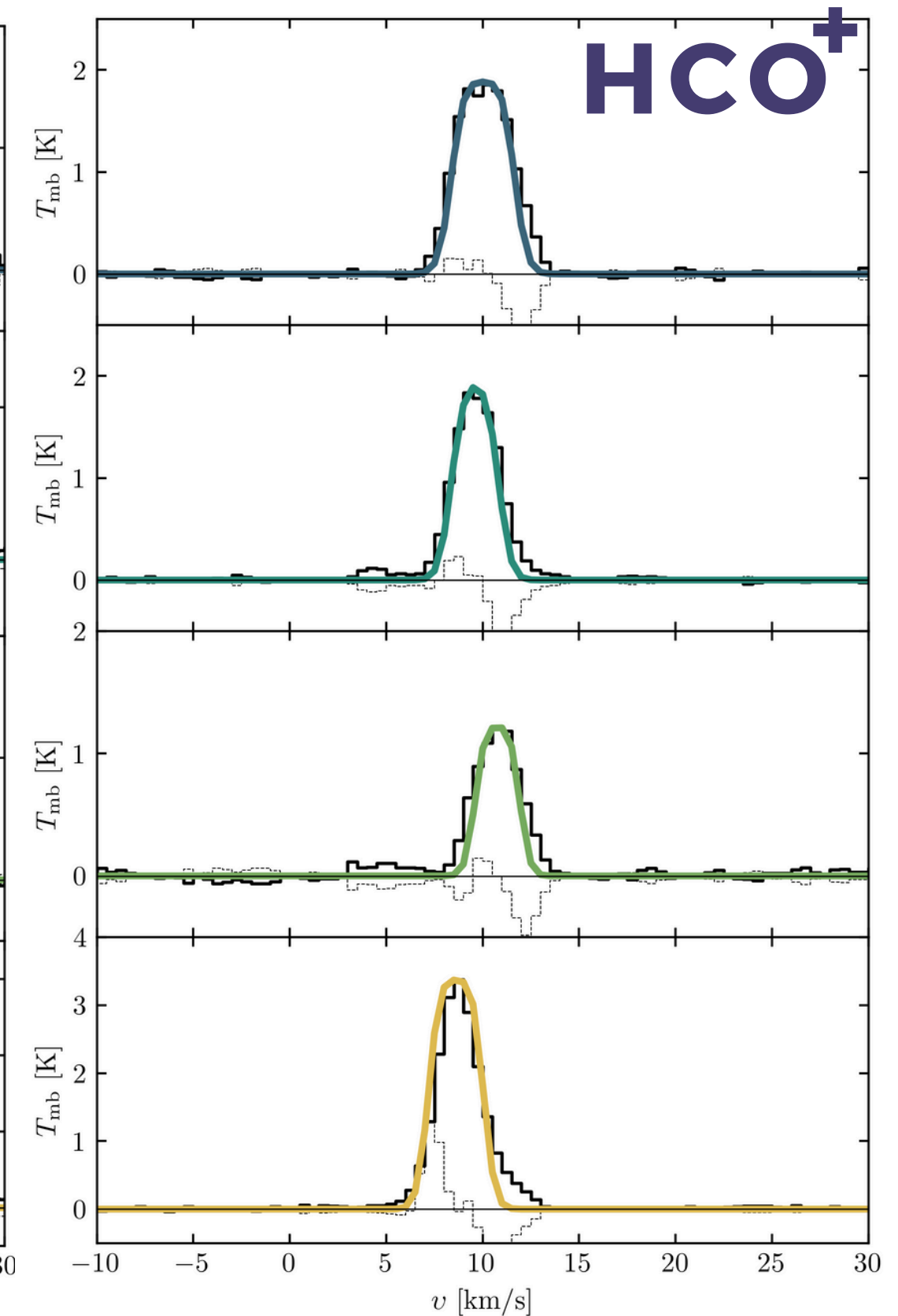
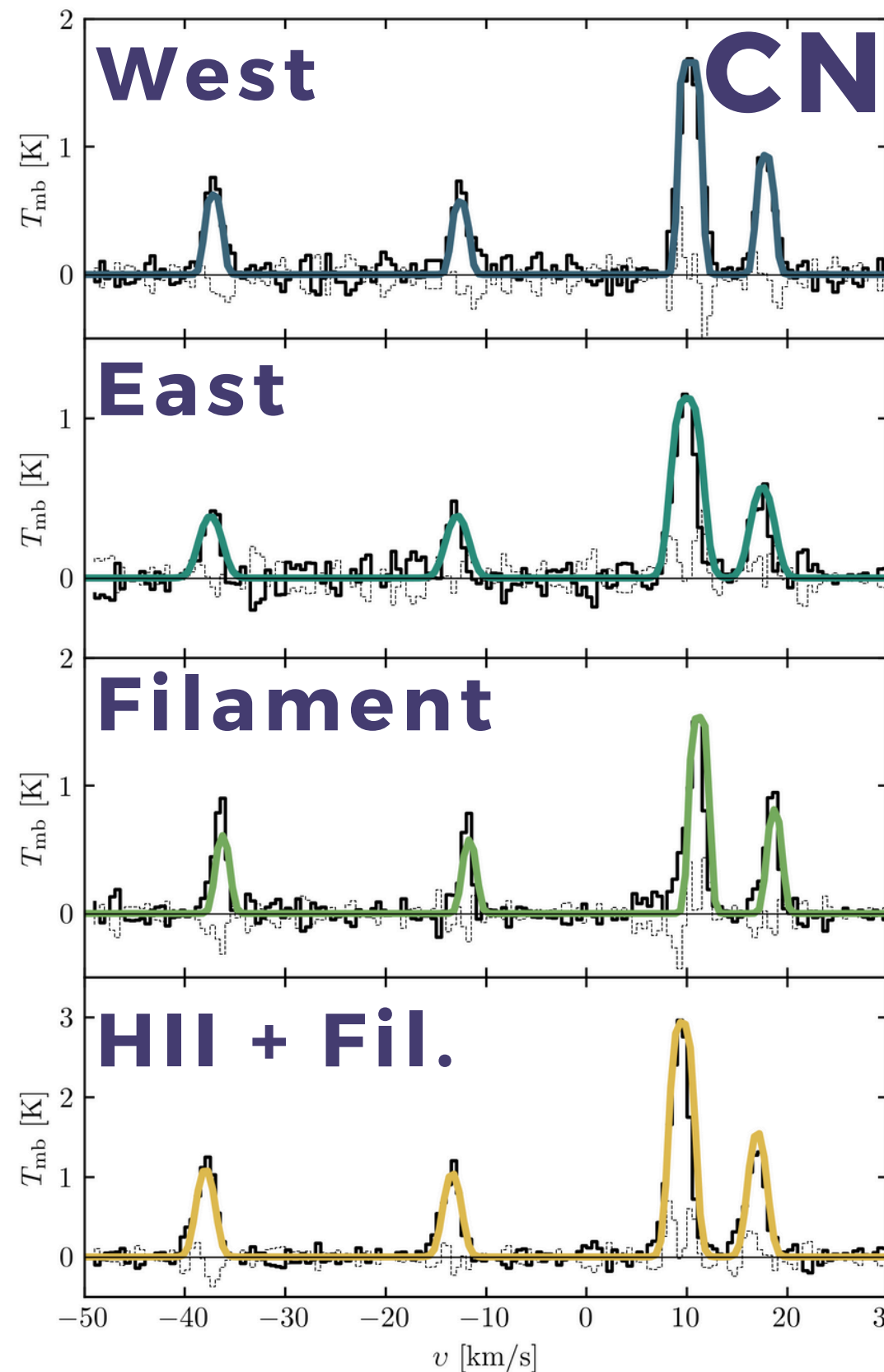


Line width inferred from  
modeling their excitation

Input:  $T_{\text{kin}}$ , Column  
density  
Collision partners:  $e^-$ ,  
ortho and para  $\text{H}_2$ ,  $e^-$   
density



Output: opacity, number  
density, line width, peak  
temperature



# Modeling

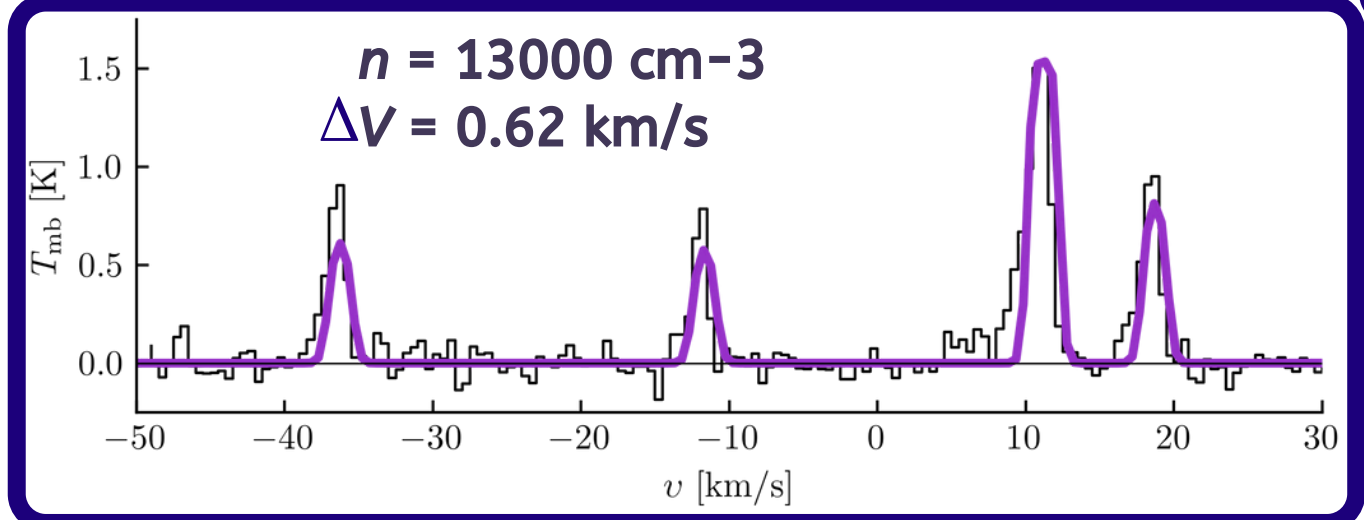
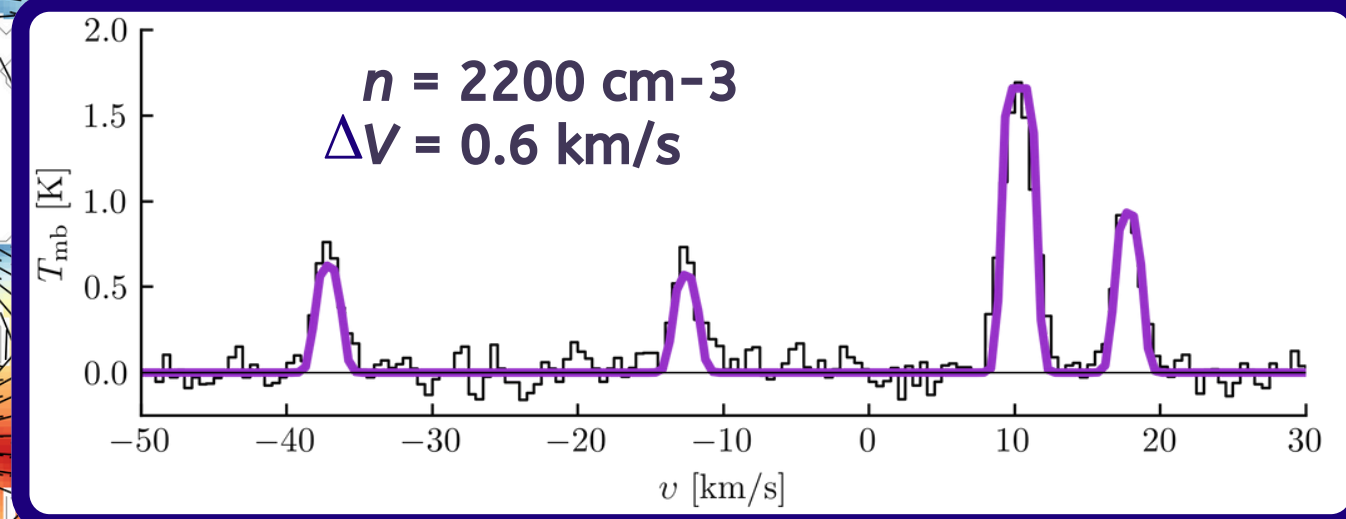
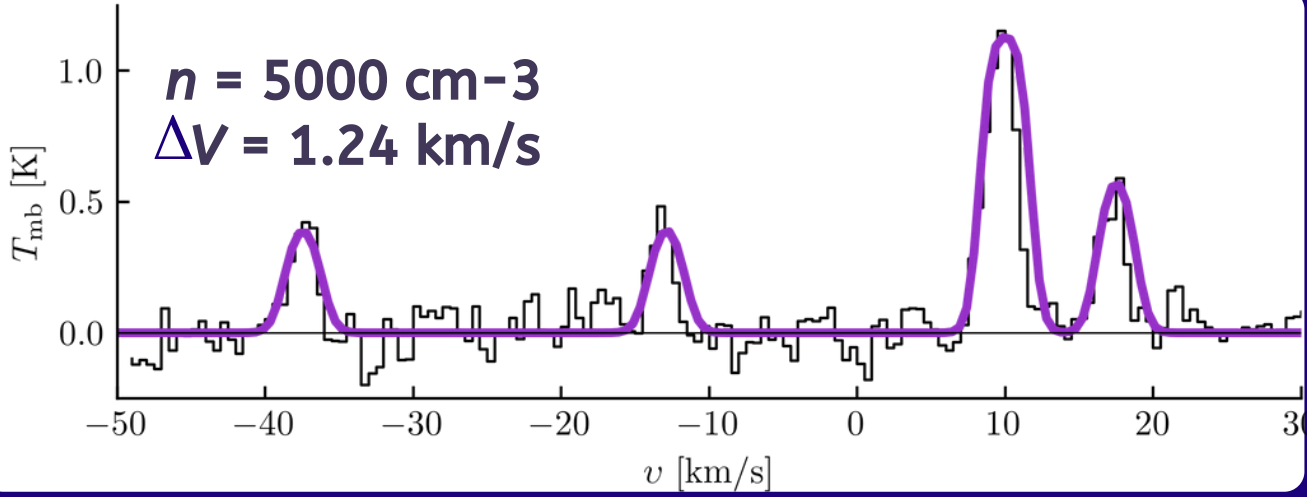
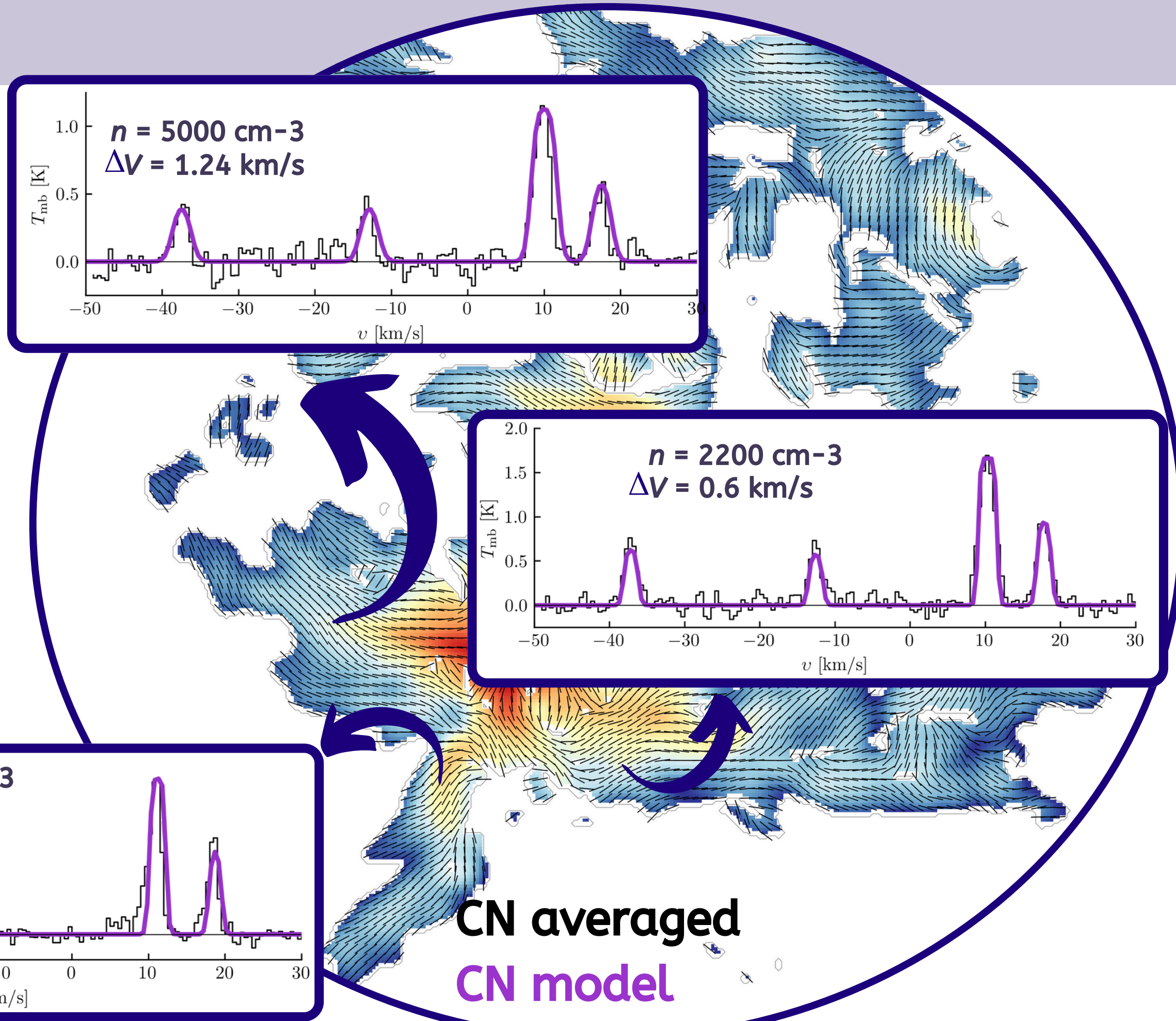


Line widths are generally consistent between CN and HCO<sup>+</sup>.

Gas number densities consistent between CN and HCO<sup>+</sup> at the edges of HII.

The broadest lines found on the east of NGC 2024.

The densest gas found in the filament.



CN averaged  
CN model

# POS B-field strength



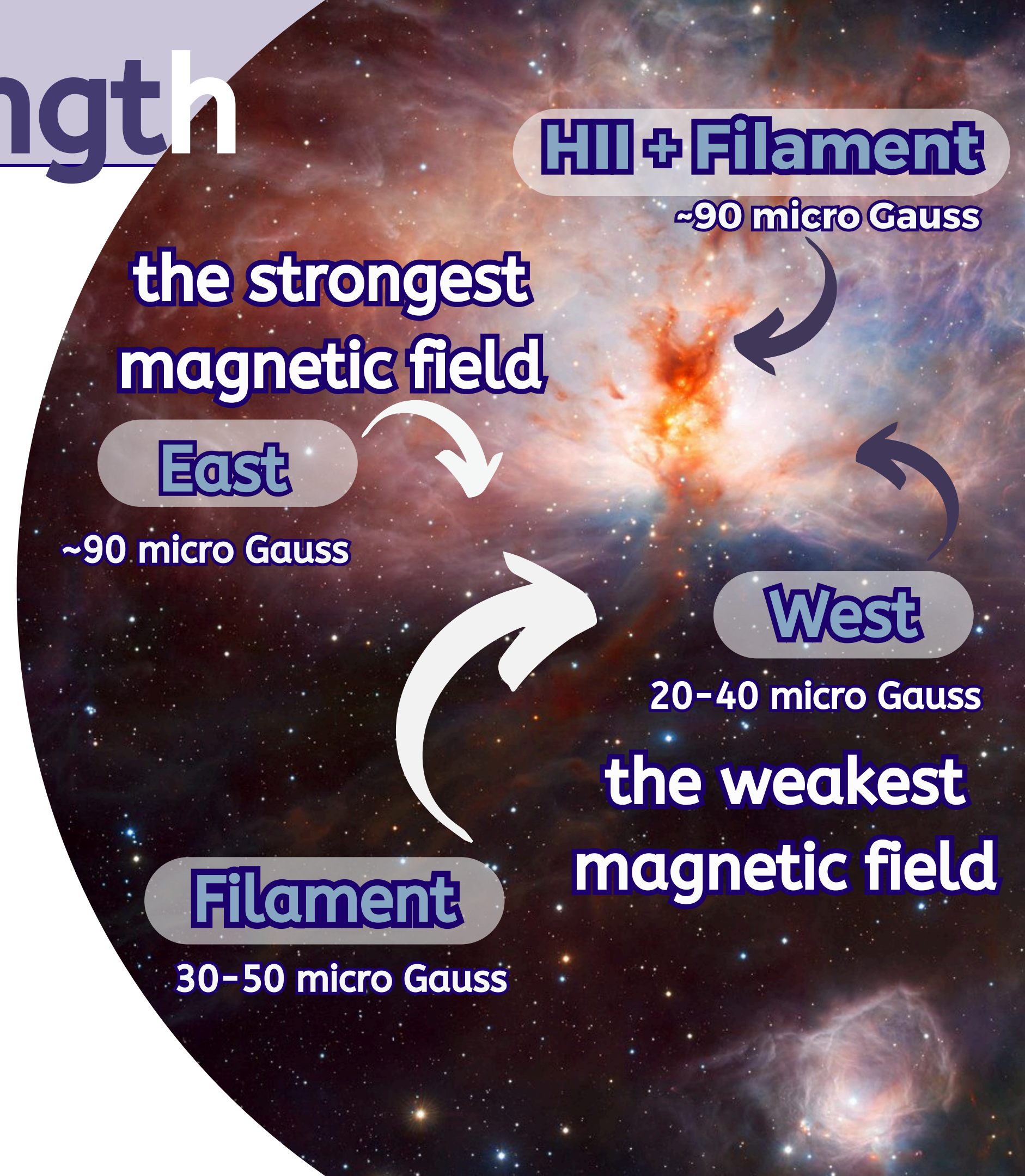
Varies across NGC 2024  
20–90 micro Gauss.

Decreases from east to west.



Possible change of direction  
of B-field?

Gas is highly turbulent in  
NGC 2024.



# 1. MAGNETIC FIELD IN NGC 2024

Astronomy & Astrophysics manuscript no. NGC2024\_final  
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## GOALS



Morphology and strength of the B-field in NGC 2024

## The magnetic field in the Flame nebula

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# 2. IONIZATION FRACTION

## GOALS



Measure  $f_e$  from intensity ratios recommended in Bron et al., 2021 across entire Orion B

**Work in progress!**

MILLIMETER



**IRAM 30m**

**EMIR**

ORION B Large Program

PI: J. Pety, M. Gerin

Molecular emission

Analytical models provided  
by Bron et al., 2021

Translucent gas: CCH and  
HNC

Dense gas: CN,  $N_2H^+$ ,  $C^{18}O$   
and  $HCO^+$

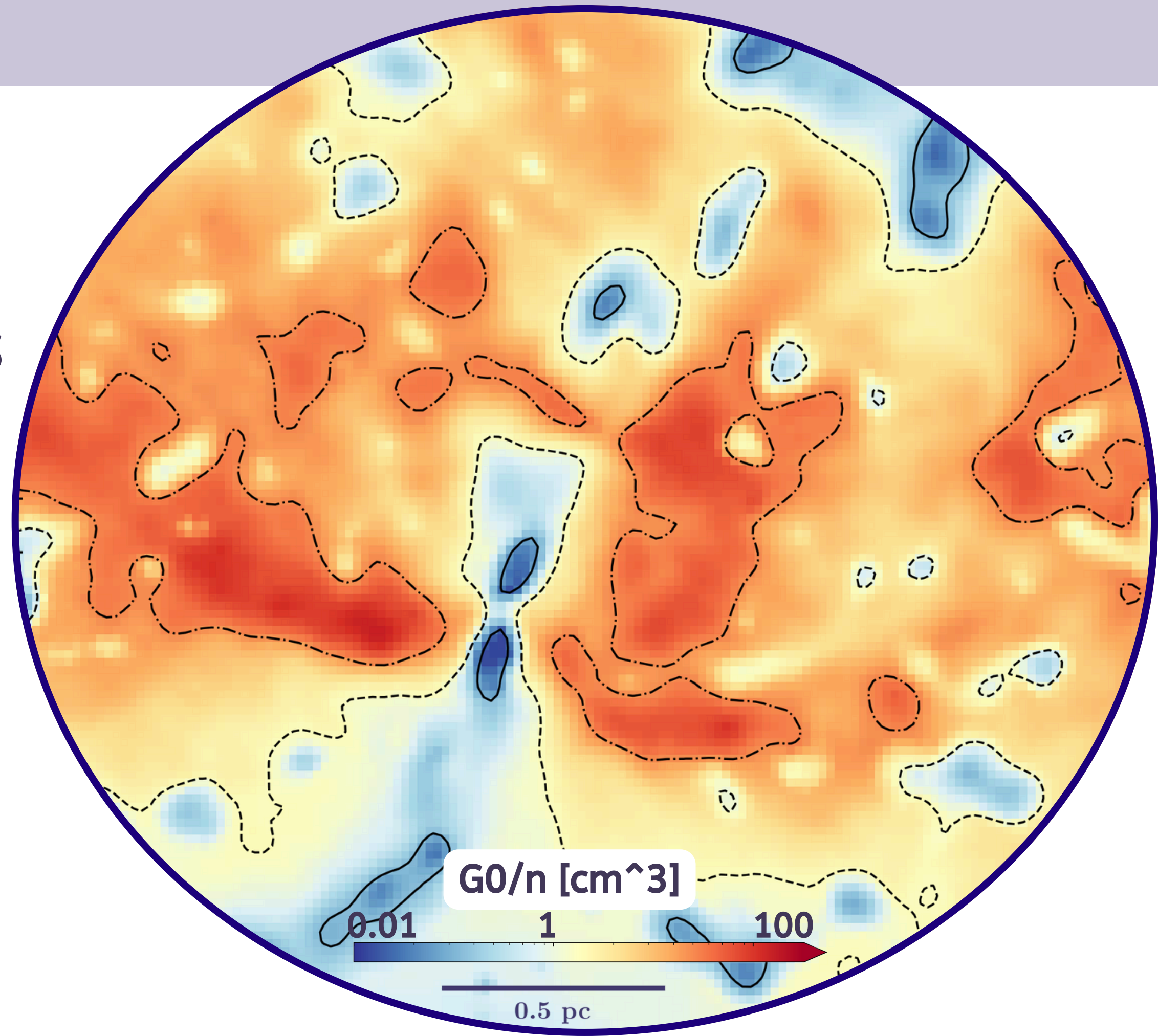
# NGC 2024



**Av contours define regions of corresponding models**

**Dense gas: Filament, dense PDR**

**Translucent gas: surroundings of dense regions**



# IONIZATION FRACTION

💡 *f<sub>e</sub>* in dense gas depends on the selected tracer.

- $\text{CN}/\text{N}_2\text{H}^+$ :
  - from  $10^{-7}$  to  $10^{-6.5}$
- $\text{C}^{18}\text{O}/\text{HCO}^+$ :
  - from  $10^{-8}$  to  $10^{-7.5}$



**Dense gas**

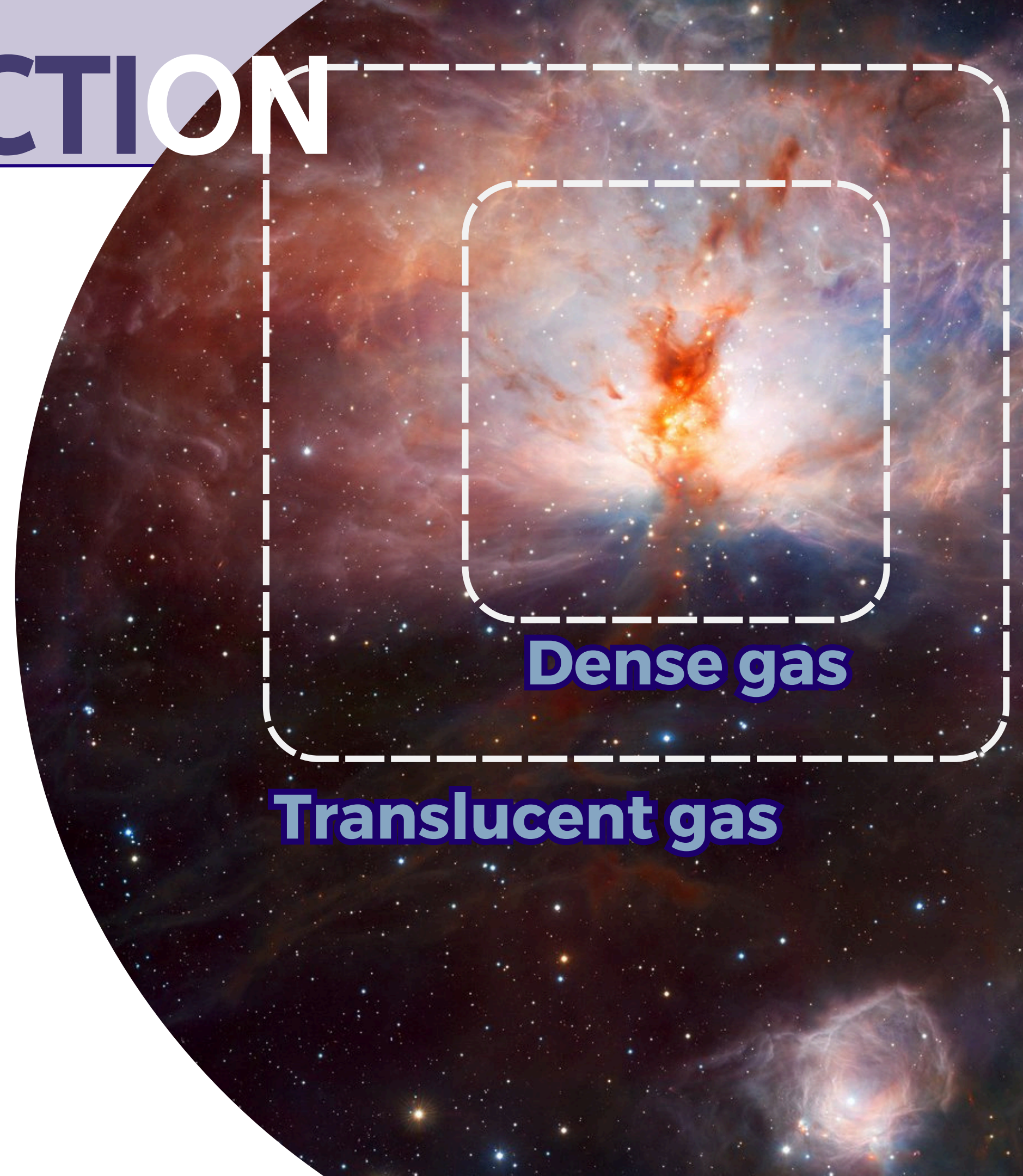
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*f<sub>e</sub>* in translucent gas:

- from  $10^{-5}$  to  $10^{-4.5}$



Dense gas

Translucent gas

# SUMMARY



We investigated magnetic field and ionization fraction in NGC 2024.

B-field shows an ordered structure in NGC 2024, its strength is 20-90 micro Gauss, which regulates star formation.

$f_e$  ranges from  $10^{-8}$  to  $10^{-7.5}$  in dense gas and from  $10^{-5}$  to  $10^{-4.5}$  in translucent medium.

Bešlić+2024



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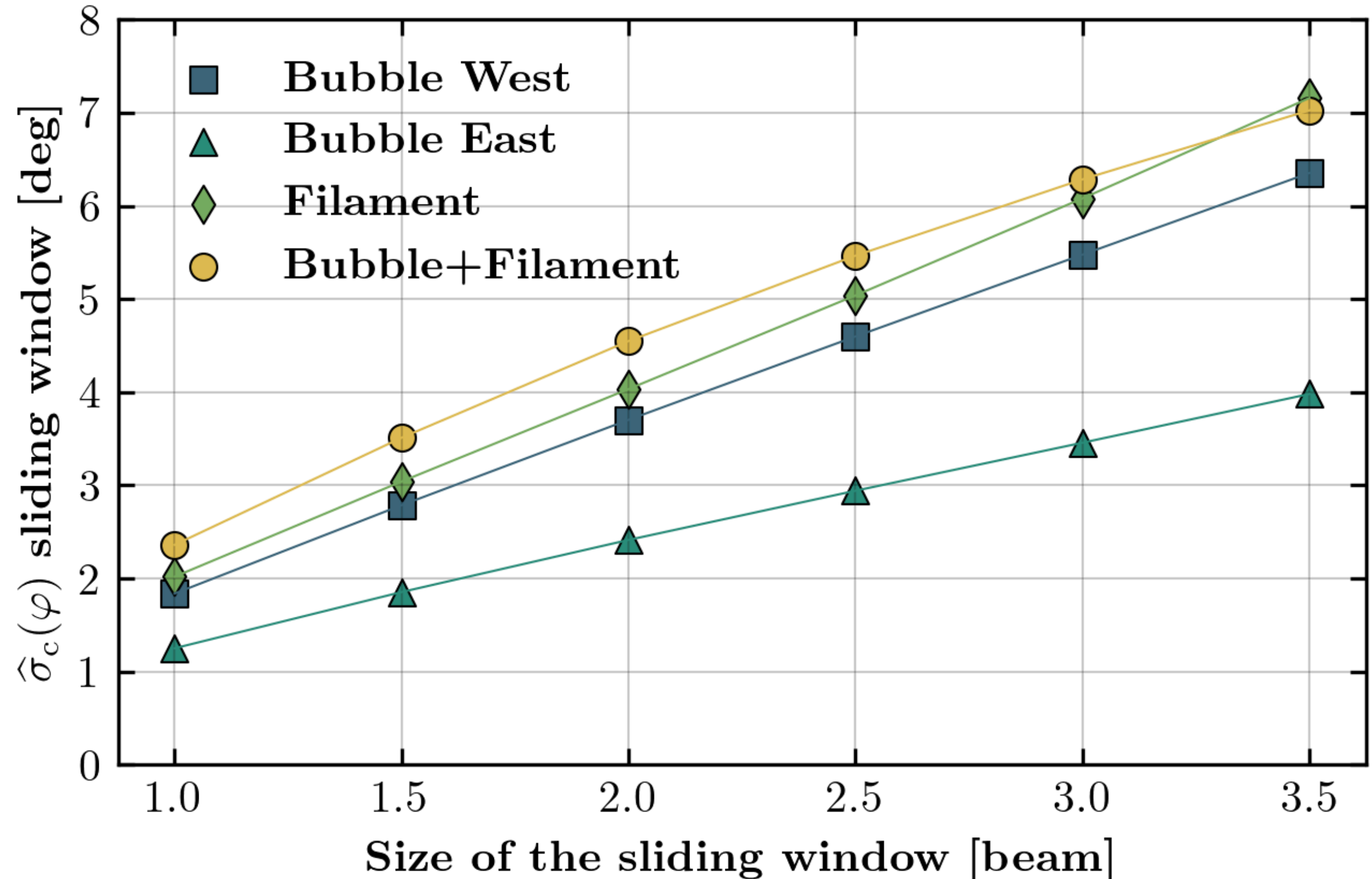
# Sliding window



$$z = \frac{1}{L} \sum_{l=1}^L e^{2i\varphi(l)}$$

$$\hat{m}_c(\varphi) = \frac{1}{2} \arctan \frac{b}{a},$$

$$\hat{\sigma}_c(\varphi) = \sqrt{\frac{1}{2} (1 - |z|)}.$$



# Sliding window



**Angle**

**Circ mean**

**Circ standard deviation**

-50

0

50

-50

0

50

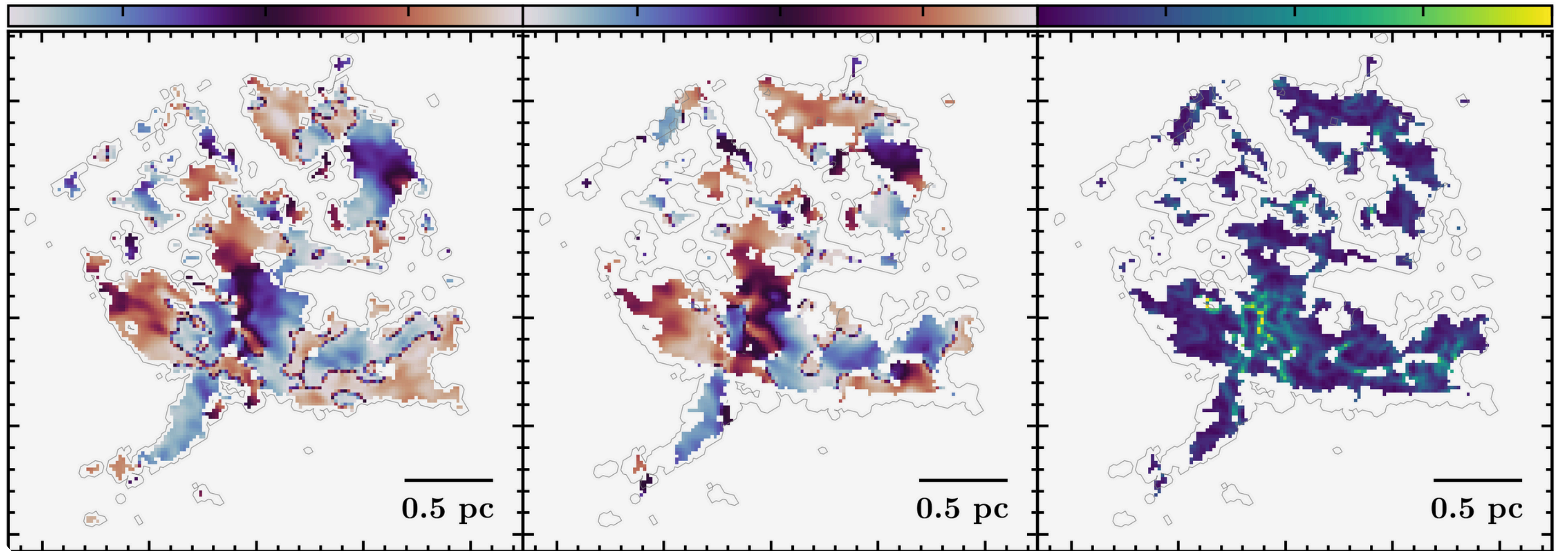
0

5

10

15

20



20m 20s 00s 41m 40s 20s 00s 5h 42m 20s 00s 41m 40s 20s 00s 5h 42m 20s 00s 41m 40s 20s 00s

# POS B-FIELD AND HOW TO MEASURE IT



## DUST EMISSION IS POLARIZED



## RADIATIVE ALIGNMENT TORQUES



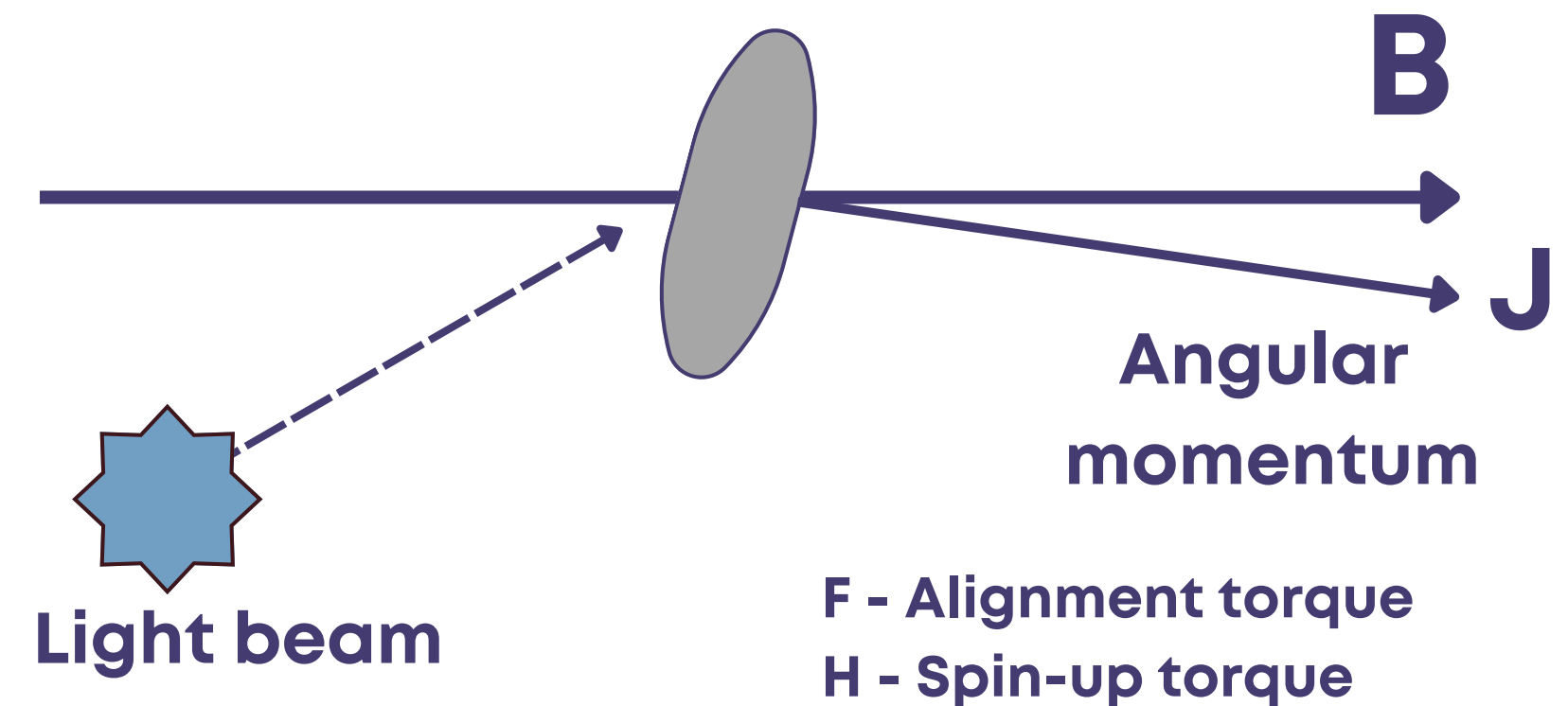
Polarization is perpendicular to the POS magnetic field.

see Pattle et al., 2023

Sketch adapted from Andersson et al., 2015

Magnetic field

Dust grain



Hoang & Lazarian et al., 2014;  
Andersson et al., 2015

# POS B-FIELD AND HOW TO MEASURE IT

Small-scale turbulence impacts direction of the B-field.

$$B_{\text{pos}} \approx 9.3 \cdot \sqrt{n_{\text{H}_2}} \cdot \frac{\Delta v}{\widehat{\sigma}_c(\varphi)} [\mu\text{G}]$$

Davis & Greenstein et al., 1951;  
Chandrasekhar & Fermi et al., 1953

Compressible nature of the ISM.  
Magneto-hydrodynamic waves.  
Entropy modes.

$$B_{\text{pos}} \approx 1.8 \cdot \sqrt{n_{\text{H}_2}} \cdot \frac{\Delta v}{\sqrt{\widehat{\sigma}_c(\varphi)}} [\mu\text{G}]$$

Skalidis et al., 2021  
Skalidis&Tassis et al., 2021



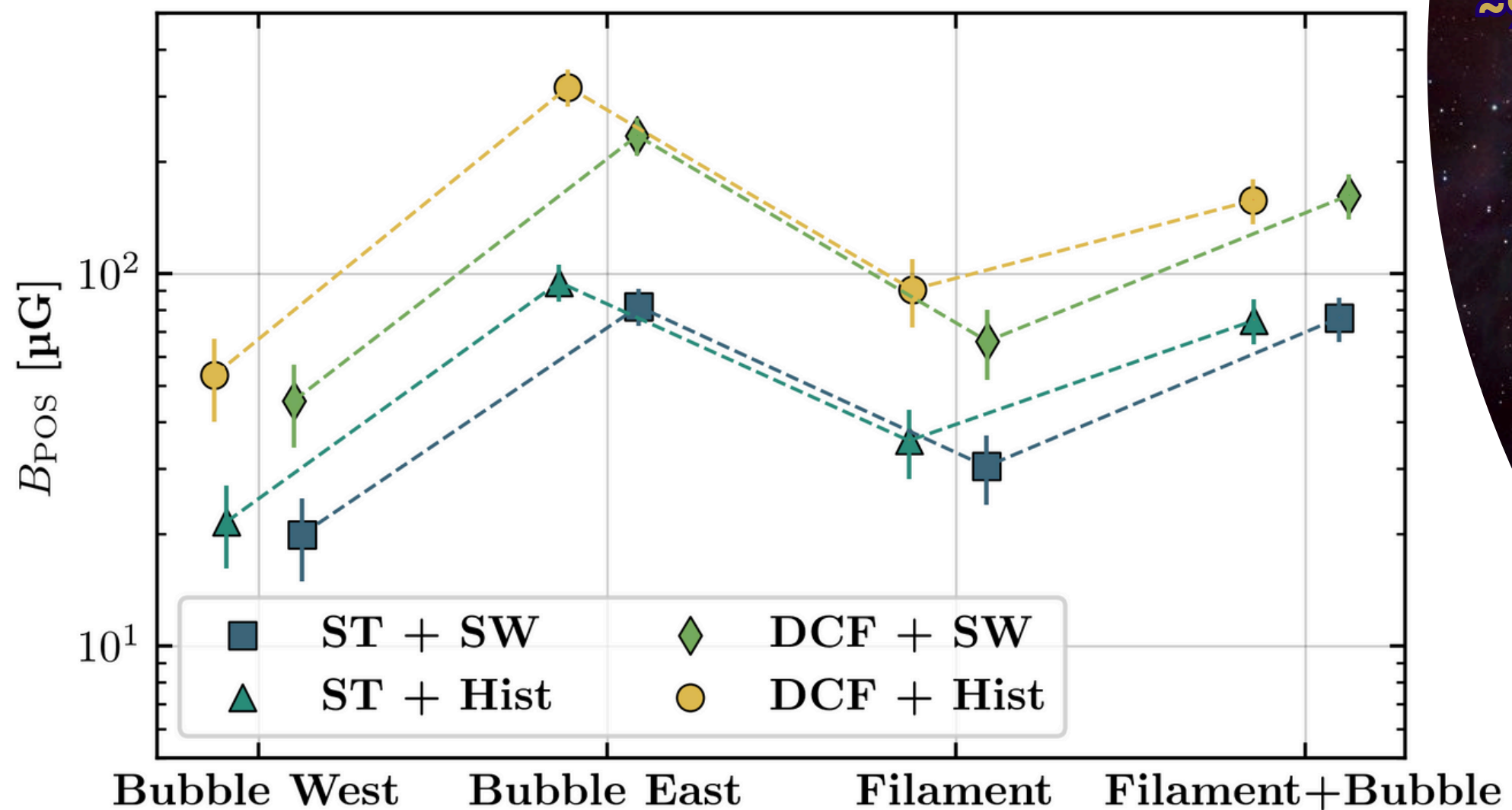
## Measure

1. Gas number density (cm<sup>-3</sup>)
2. Turbulent FWHM (km/s)
3. Spatial dispersion of direction of B-field (deg)

# POS B-field strength



B-field strength derived from ST is generally lower than the DCF. Angle dispersion measurements consistent between sliding window and histogram analysis.



**the strongest magnetic field**

**HII + Filament**

~90 micro Gauss

**East**

~90 micro Gauss

**West**

20-40 micro Gauss

**the weakest magnetic field**

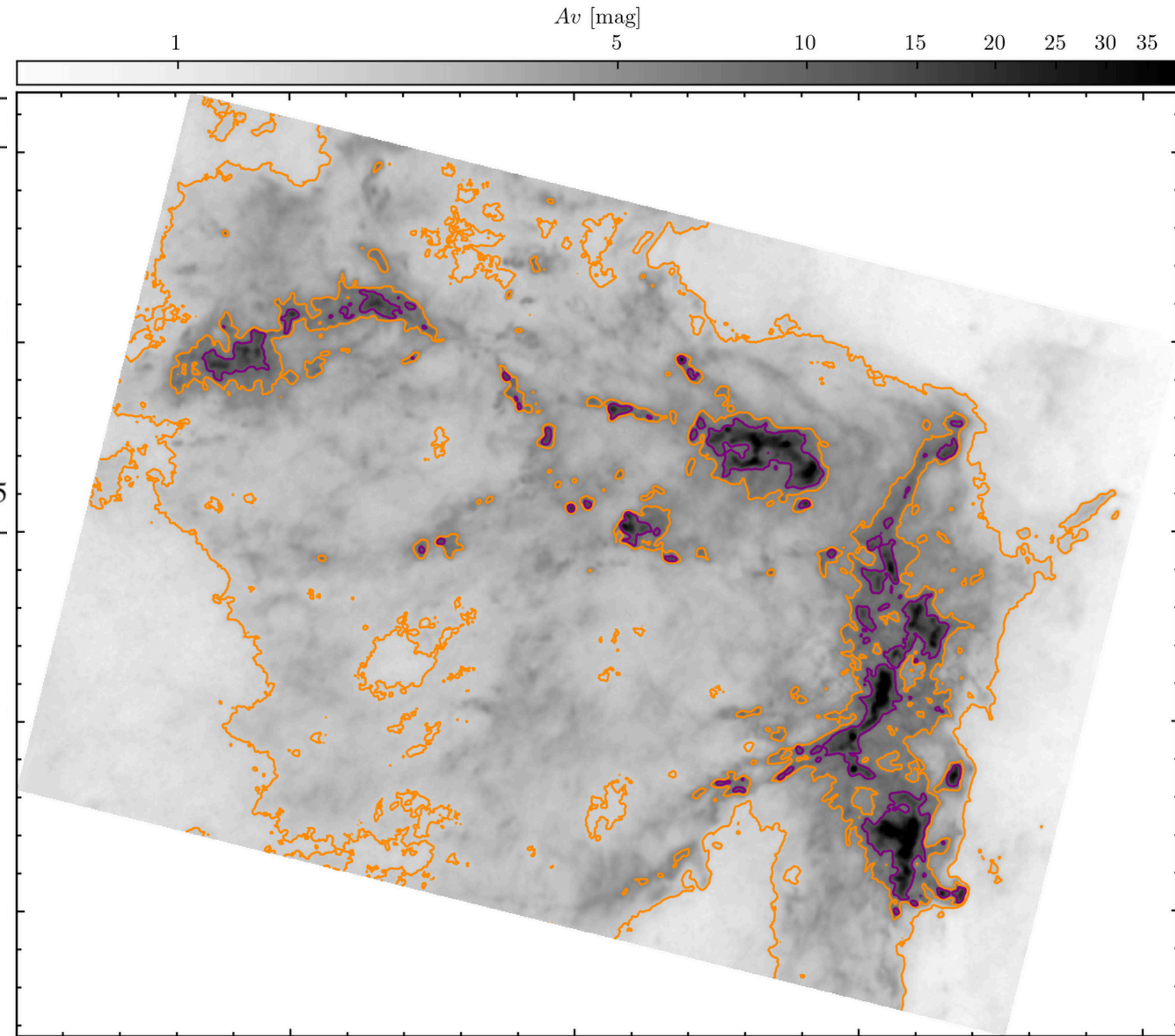
**Filament**

30-50 micro Gauss

# Ionization fraction

Bron et al., 2021

	translucent medium	cold dense medium
$n_{\text{H}} [\text{cm}^{-3}]$	$3 \times 10^2 - 3 \times 10^3$	$10^3 - 10^6$
$T_{\text{gas}} [\text{K}]$	15 – 100	7 – 20
$G_0$	1 – 1000	1
$A_{\text{V}}$	2 – 6	5 – 20
$\zeta [\text{s}^{-1}]$	$10^{-17} - 10^{-15}$	$10^{-17} - 10^{-16}$
$\text{OPR}_{\text{H}_2}$	0.1 – 3	$10^{-4} - 10^{-1}$
depletion factor	1	1 – 10
[S]	$1.86 \times 10^{-8} - 1.86 \times 10^{-5}$	$1.86 \times 10^{-8} - 1.86 \times 10^{-5}$

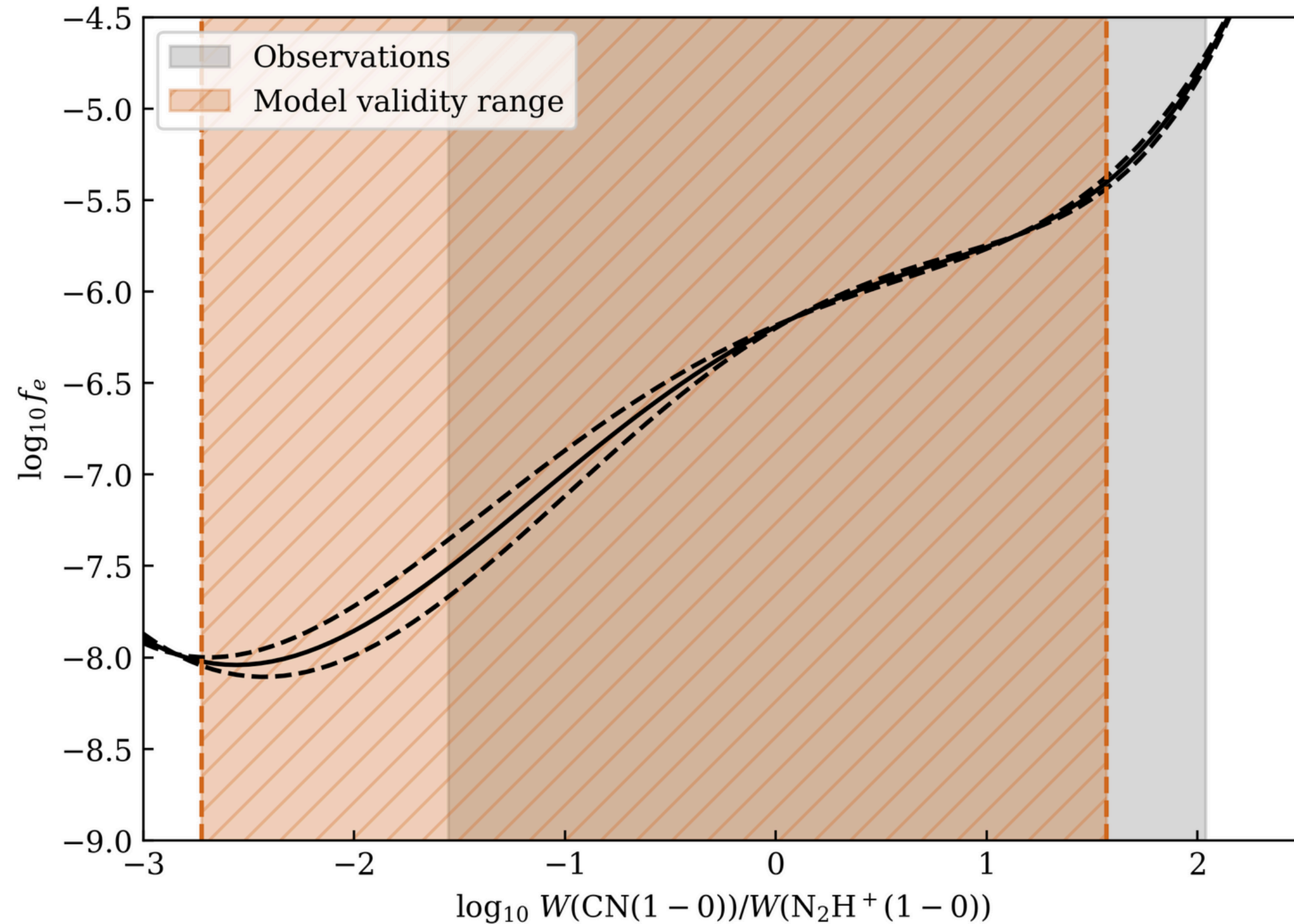


# Validity range

Bron et al., 2021 provided for each tracer of ionization fraction a validity range.

The uncertainties of the model within this validity range is smaller than 2 per cent.

More than 98 per cent of  $\text{CN}/\text{N}_2\text{H}^+$  pixels are found within the validity range.



# CN/N<sub>2</sub>H<sup>+</sup>

