Relative Orientation of Magnetic Field and Cloud Structure in L1688

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HAWC+/SOFIA Polarimetry in L1688: Relative Orientation of Magnetic Field and Elongated Cloud Structure

Dennis Lee, Marc Berthoud, Che-Yu Chen, Erin G. Cox, Jacqueline A. Davidson, Frankie J. Encalada, Laura M. Fissel, Rachel Harrison, Woojin Kwon, Di Li, Zhi-Yun Li, Leslie W. Looney, Giles Novak, Sarah Sadavoy, Fabio P. Santos, Dominique Segura-Cox, Ian Stephens

Background

Histogram of Relative Orientation Technique

Planck/HAWC+ Combined HRO Analysis of L1688

Transition Density Comparison with Simulations

Background

Histogram of Relative Orientation Technique

Planck/HAWC+ Combined HRO Analysis of L1688

Transition Density Comparison with Simulations

Ingredients of Star Formation

Gravity

Turbulence

Magnetic Field

Ingredients of Star Formation

Gravity

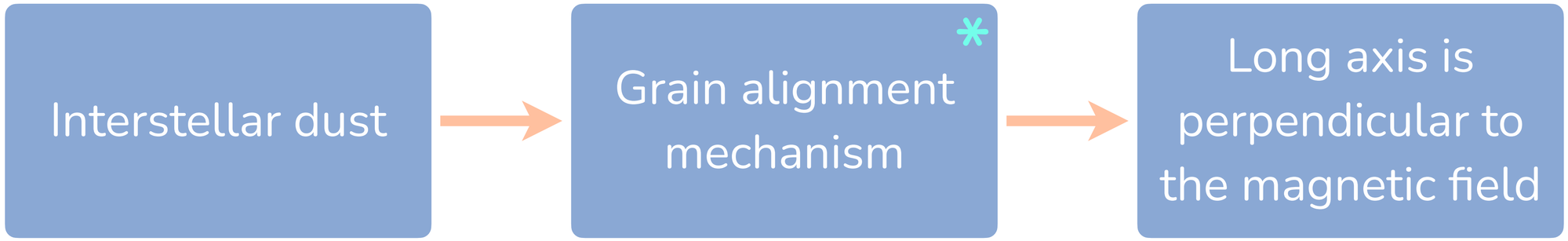
Turbulence

Magnetic Field

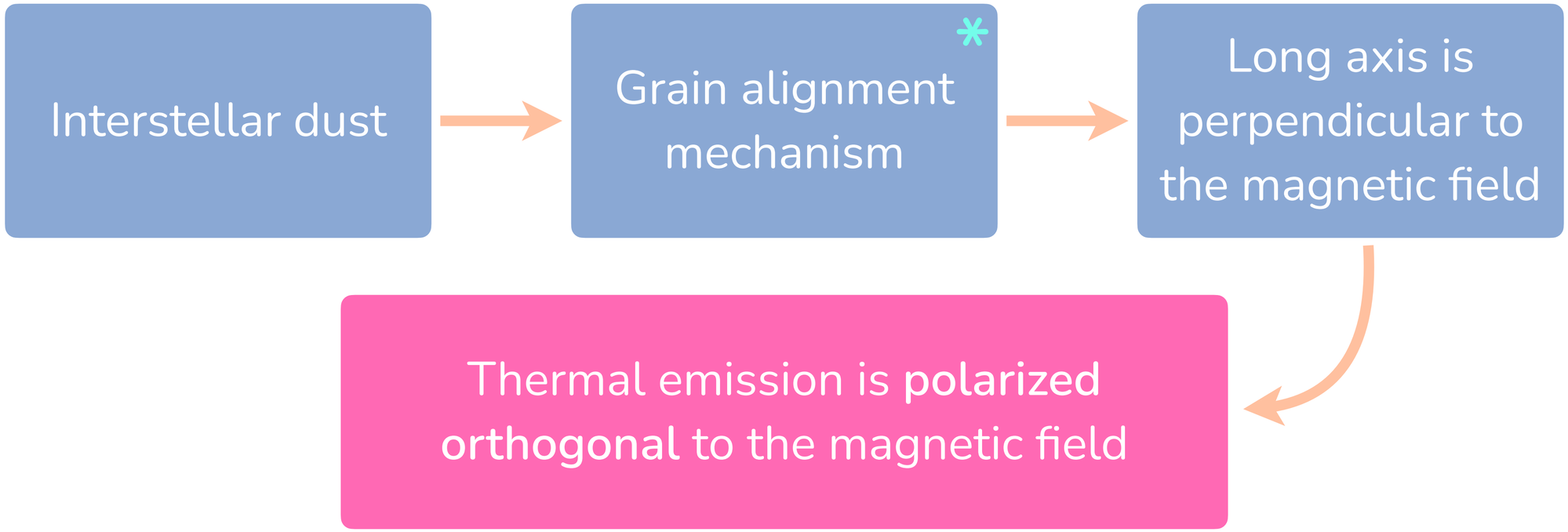
What is the exact role of
the magnetic field in star formation?

Polarization by Emission

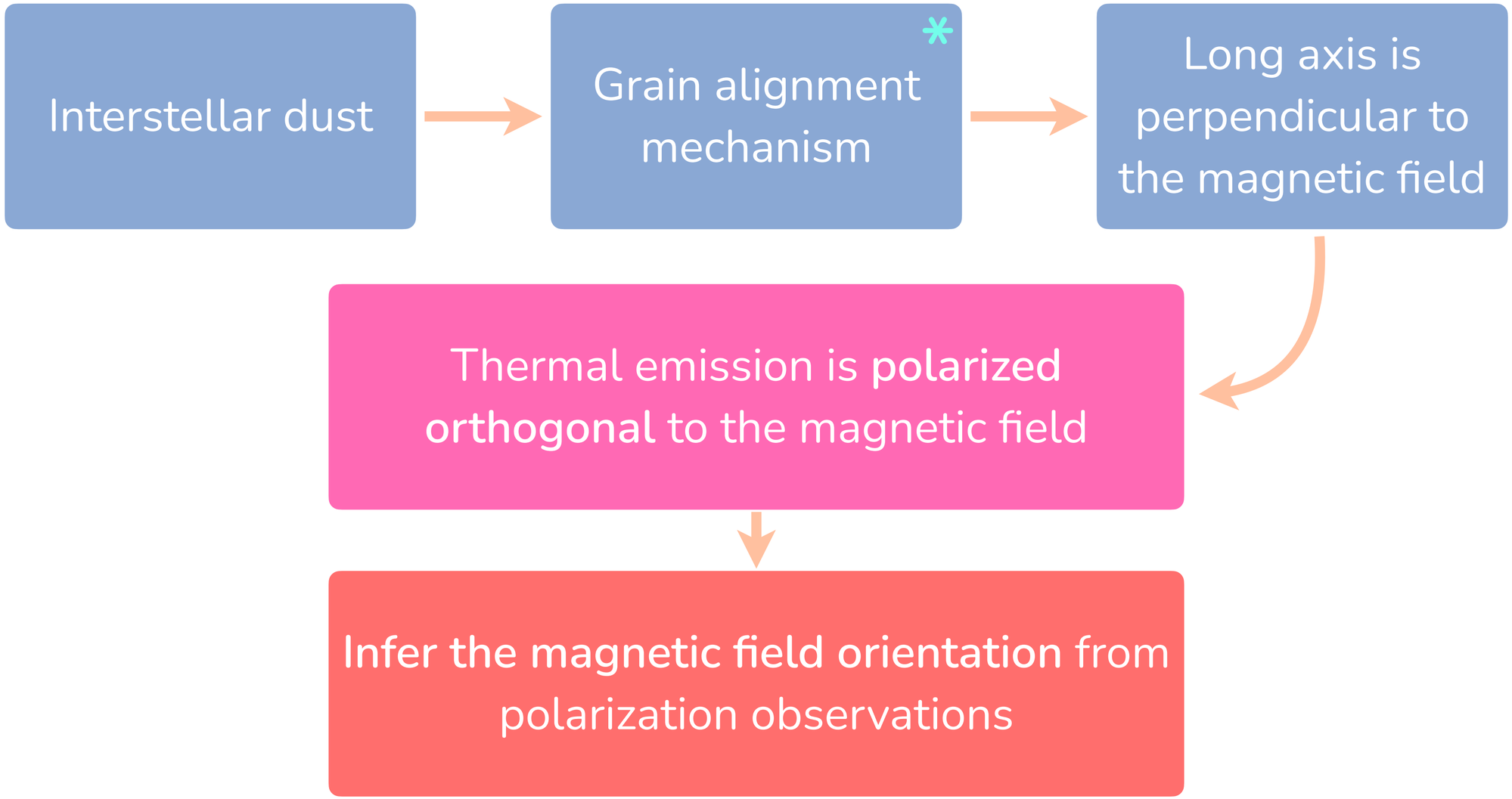
Polarization by Emission



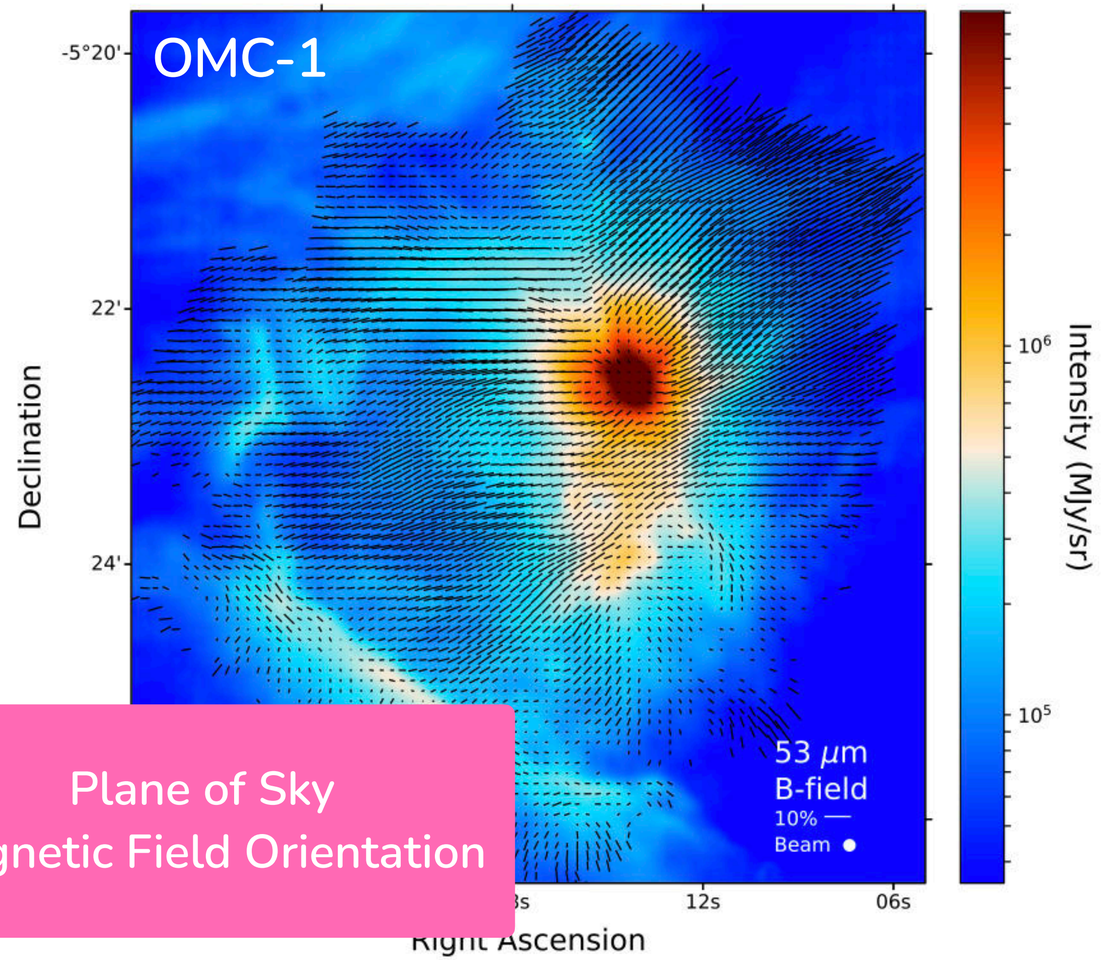
Polarization by Emission

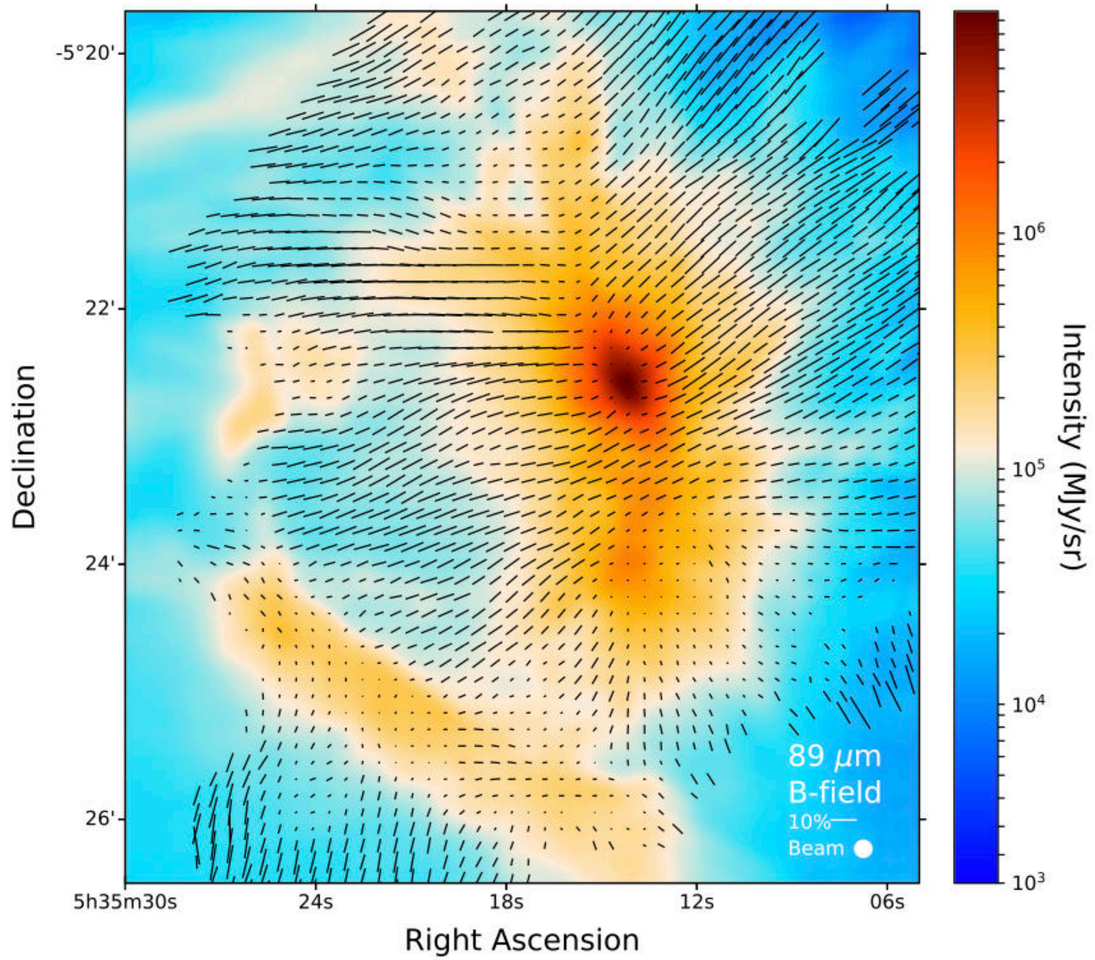


Polarization by Emission



Polarization by Emission





Plane of Sky
Magnetic Field Orientation

Figure 1 — Chuss et al. (2019)

Background

Histogram of Relative Orientation Technique

Planck/HAWC+ Combined HRO Analysis of L1688

Transition Density Comparison with Simulations

Plane of Sky Magnetic Field Orientation

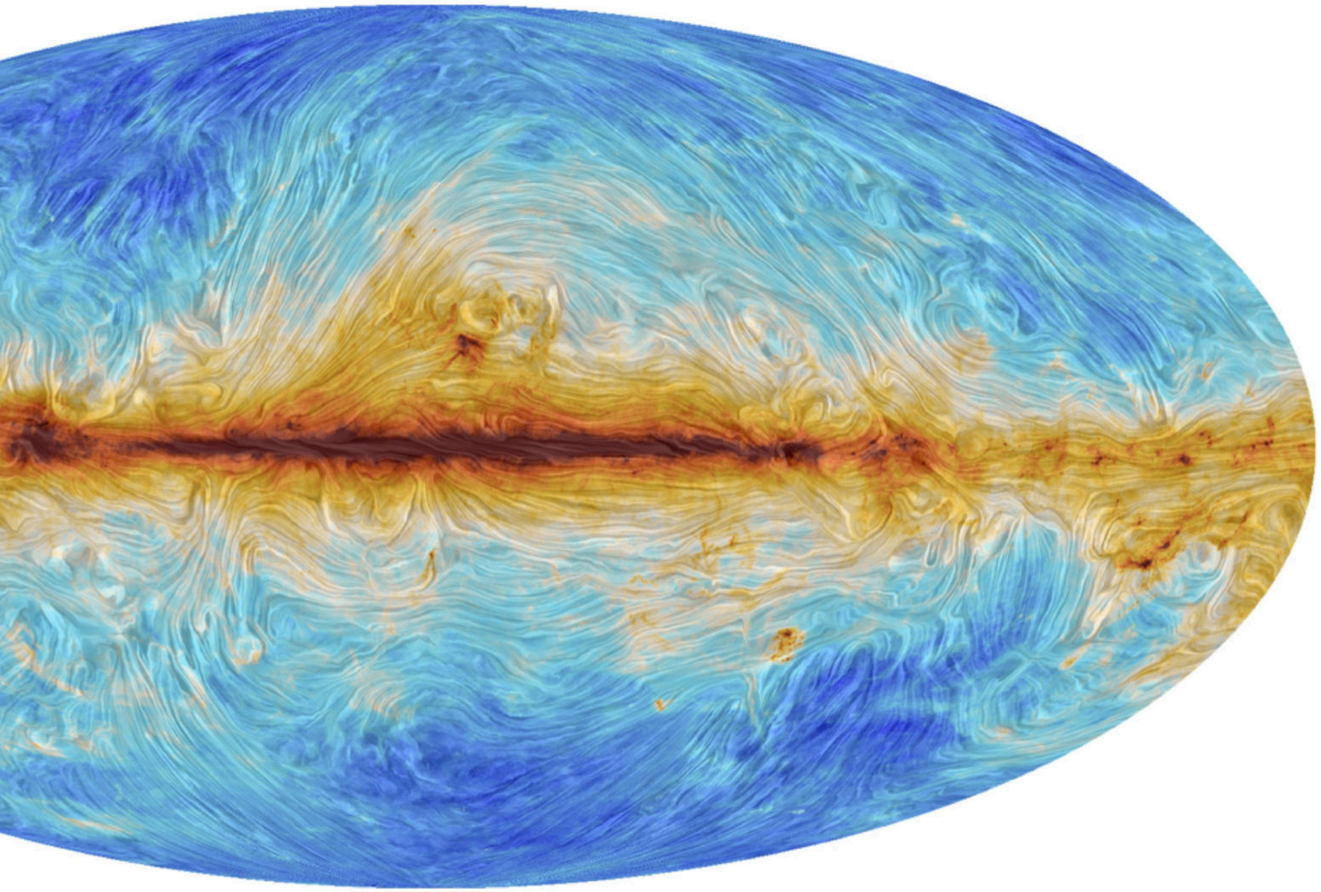


Figure 24 — Planck 2015 I. Results (2016)

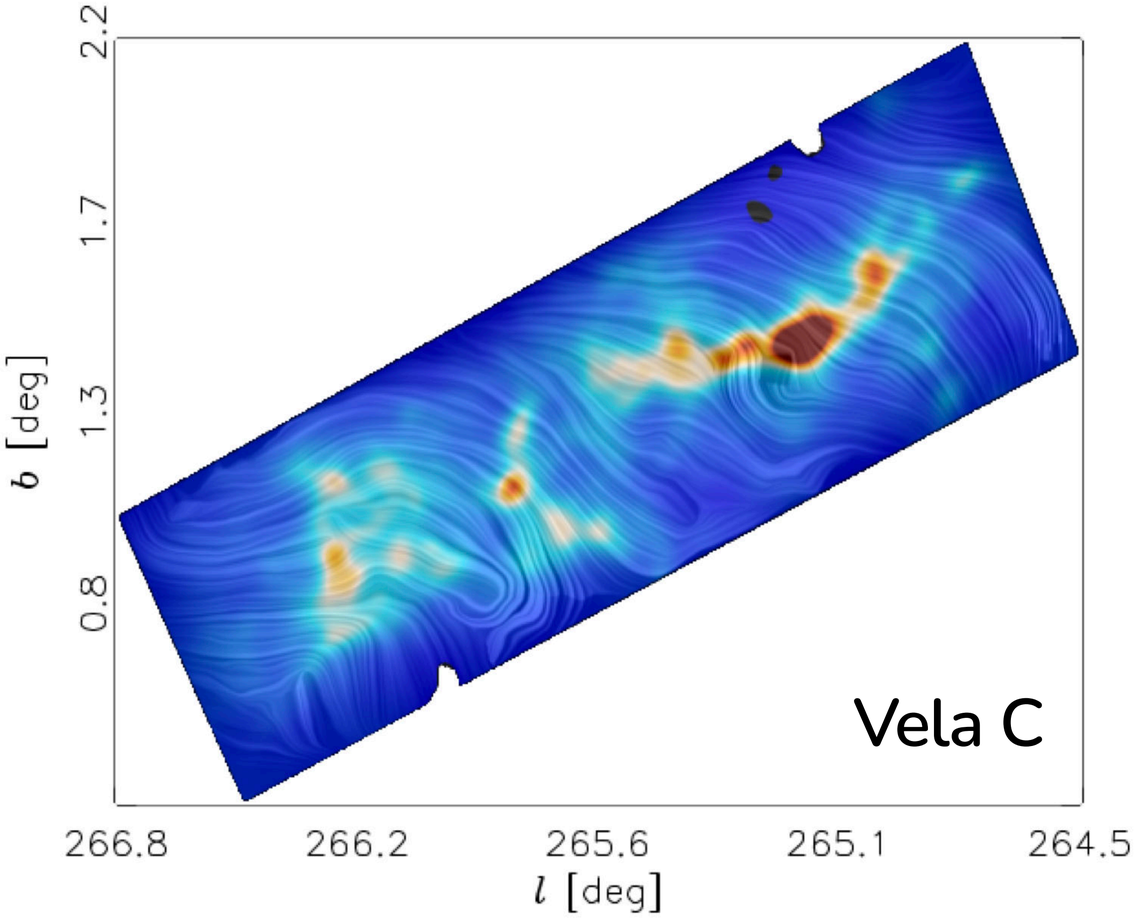


Figure 5 — Fissel et al. (2016)

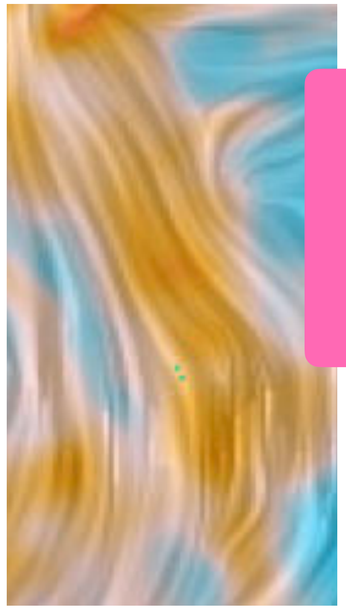
What can we do with this orientation information?

What can we do with this orientation information?

compare with the **cloud structure!**

What can we do with this orientation information?

compare with the **cloud structure!**



preferentially **parallel**

Figure 1 — Planck Int. Results XXXV

preferentially **perpendicular**

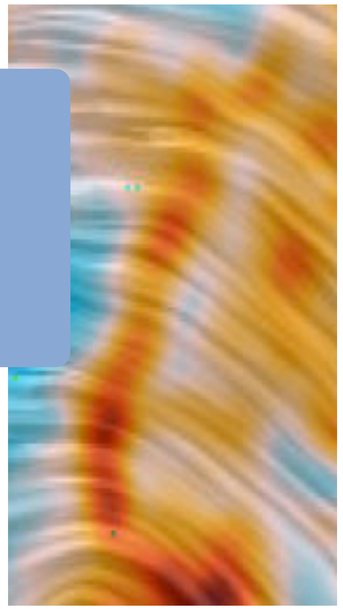
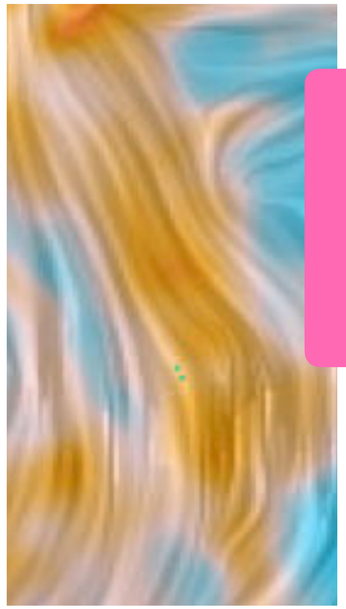


Figure 1 — Planck Int. Results XXXV

What can we do with this orientation information?

compare with the **cloud structure!**



preferentially **parallel**

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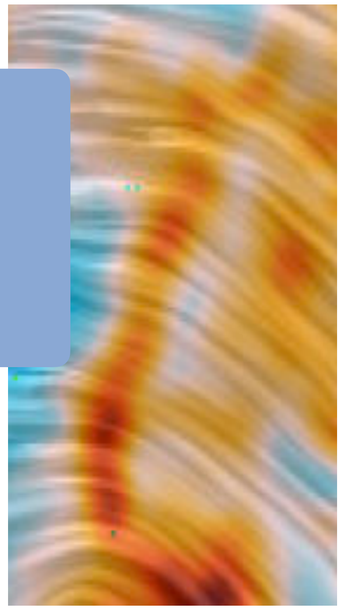


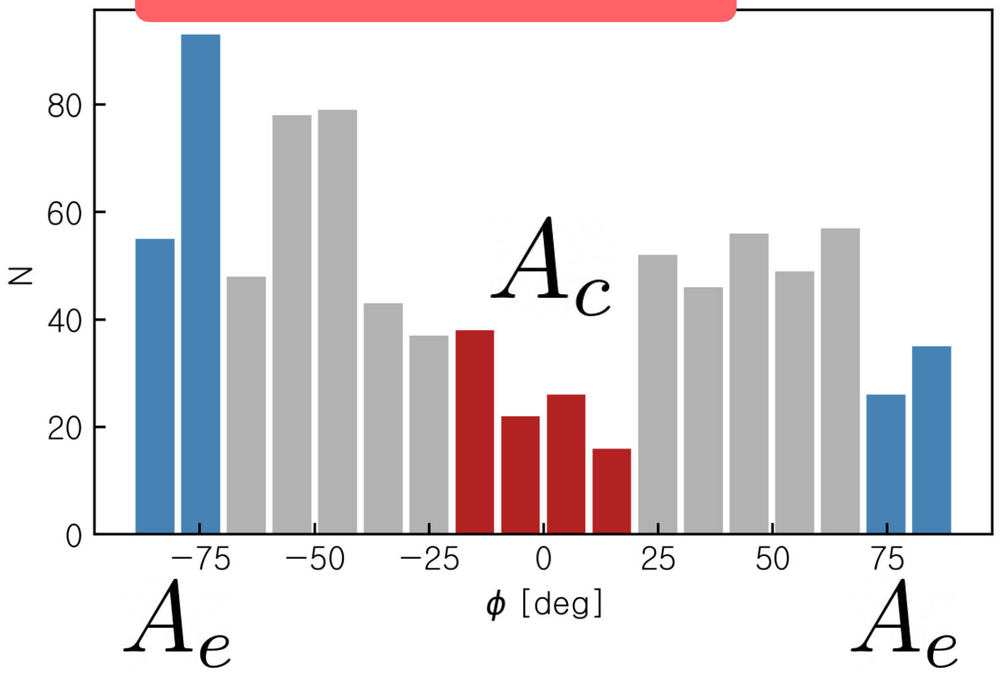
Figure 1 — Planck Int. Results XXXV

How would one **measure** this?

Histogram of Relative Orientations (HROs)

Parameter that quantifies this parallel vs. perpendicular alignment

Create a **histogram(s)** of relative orientations



Calculate the HRO Parameter

$$\xi = \frac{A_c - A_e}{A_c + A_e}$$

Histogram of Relative Orientations (HROs)

Parameter that quantifies this parallel vs. perpendicular alignment

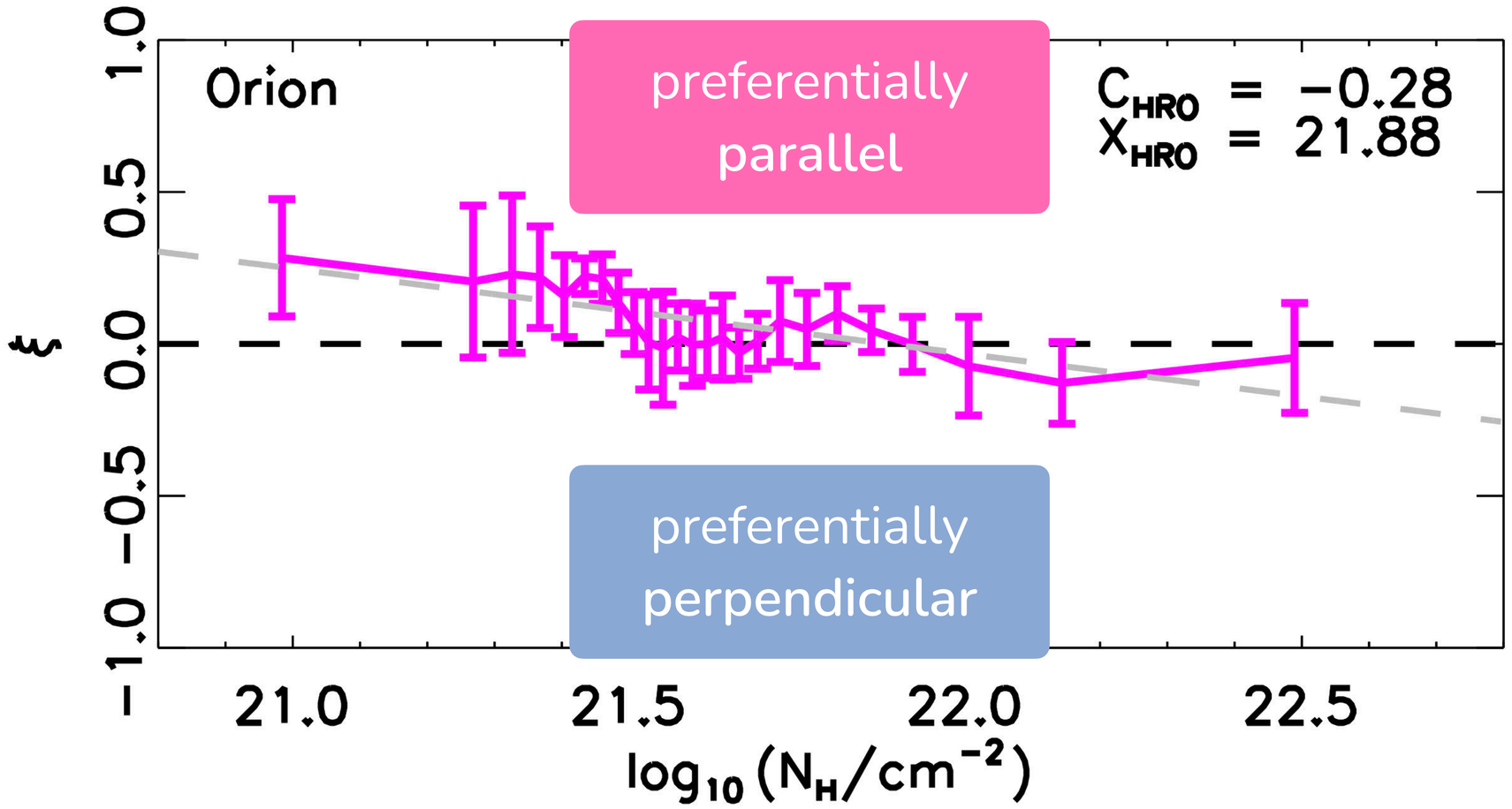


Figure 7 — Planck Int. Results XXXV

Planck Int. Results XXXV

Observations!

Analysis applied to
ten molecular clouds
in the Milky Way.

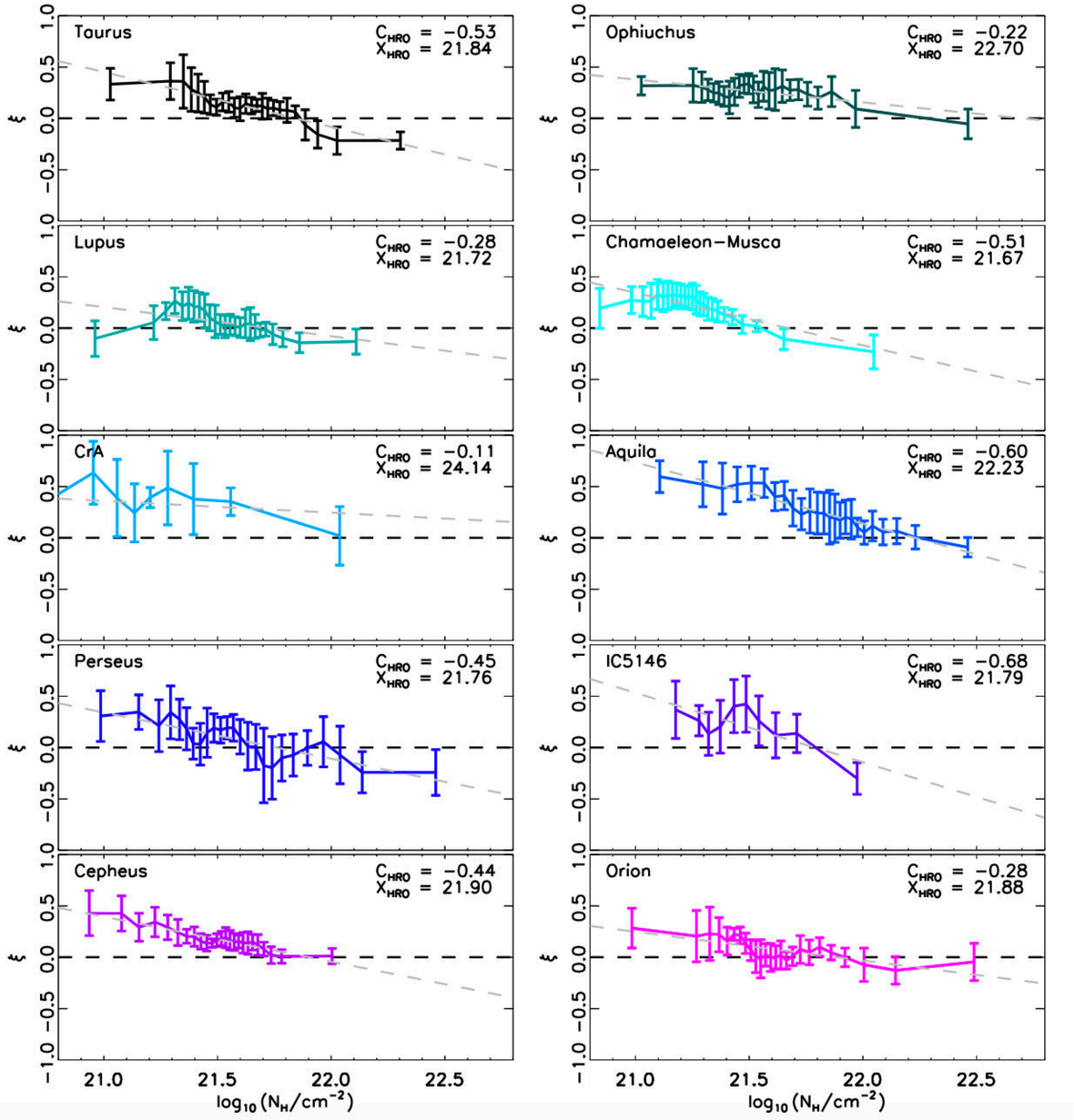


Figure 7 — Planck Int. Results XXXV

Planck Int. Results XXXV

Observations!

Compared with a set of simulations from Soler et al. (2013)

Molecular clouds consistent with trans- or sub-Alfvénic

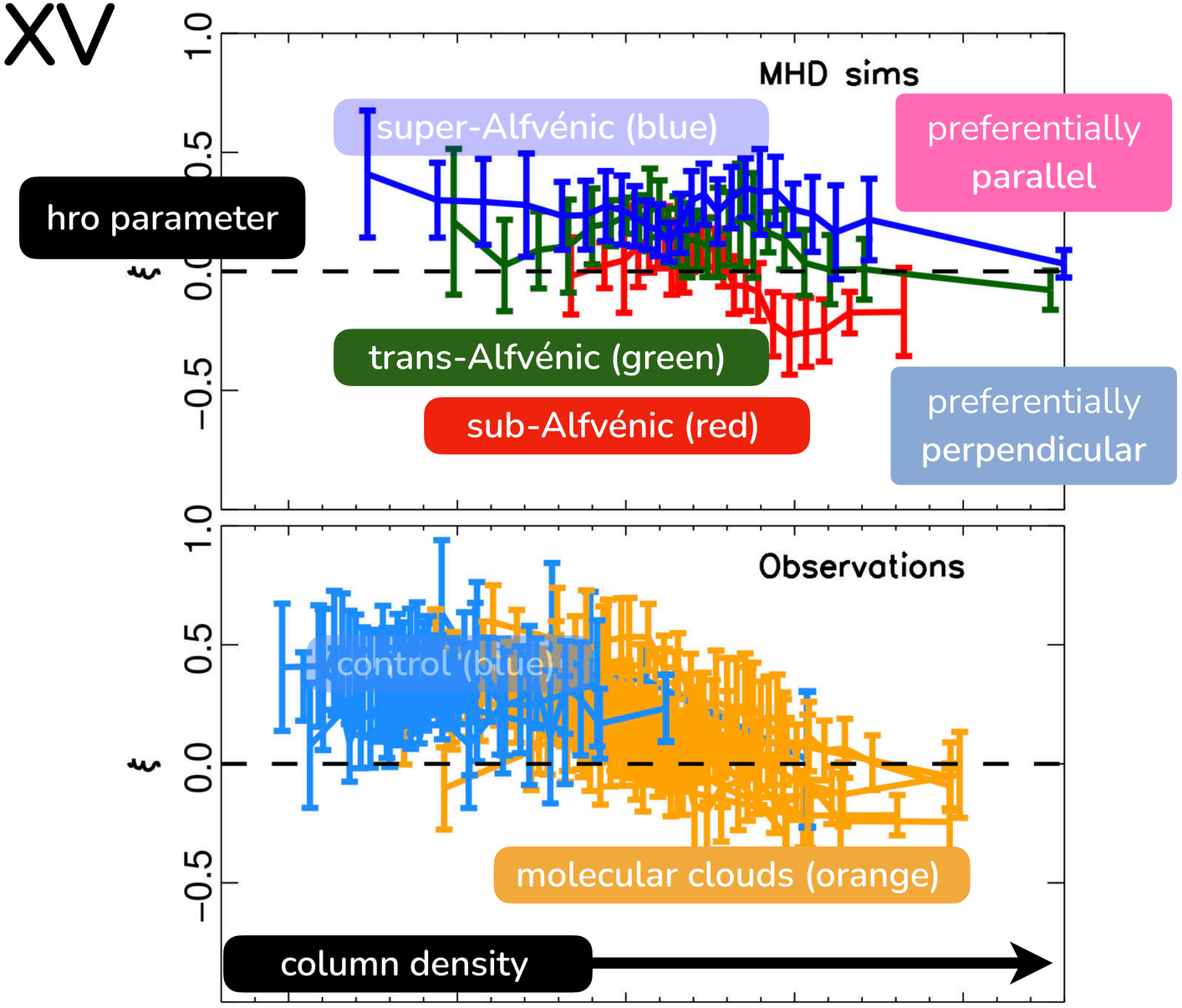


Figure 11 — Planck Int. Results XXXV

Planck Int. Results XXXV

Observations!

Clouds showed varying degrees of crossing from parallel to perpendicular

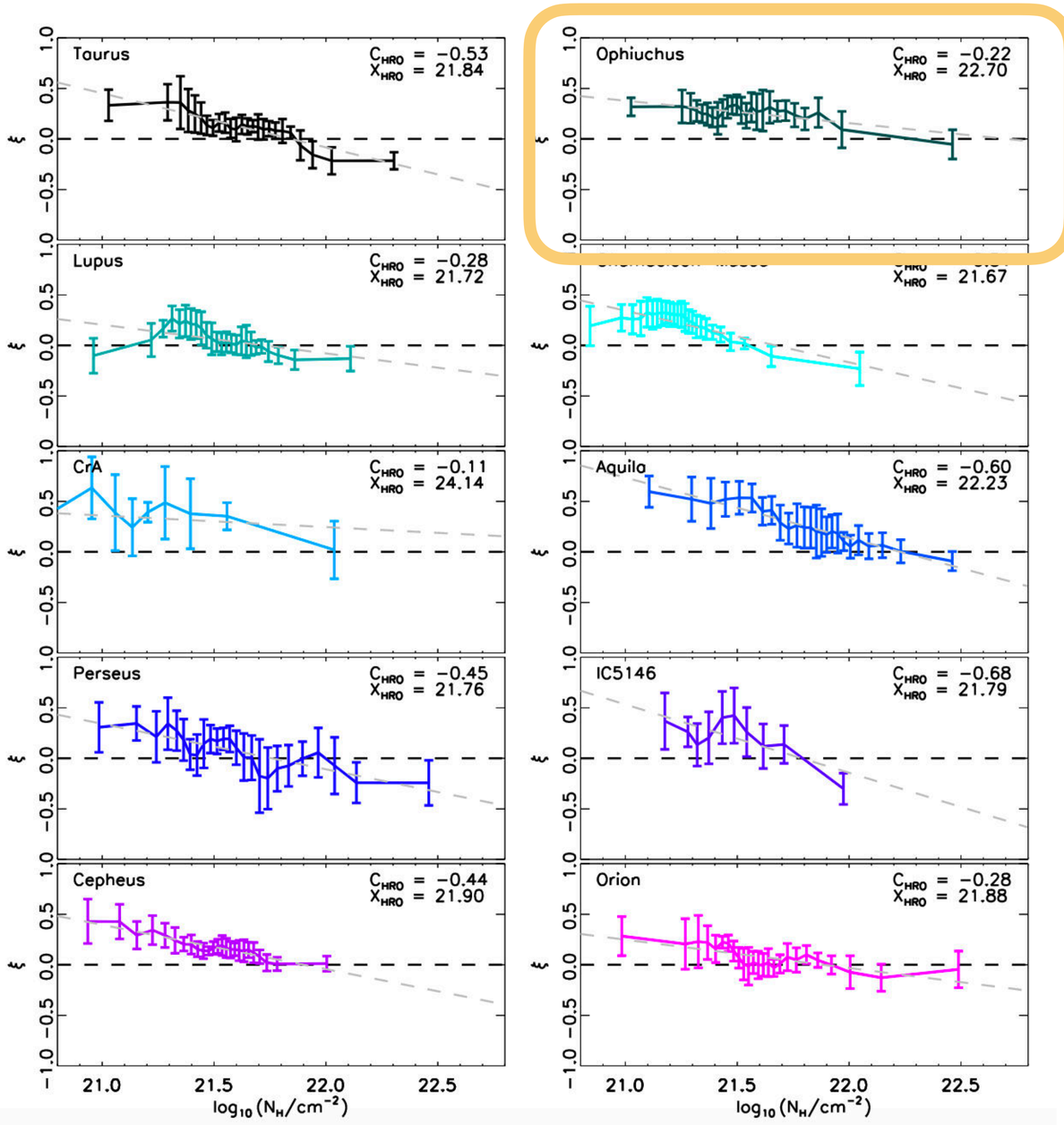
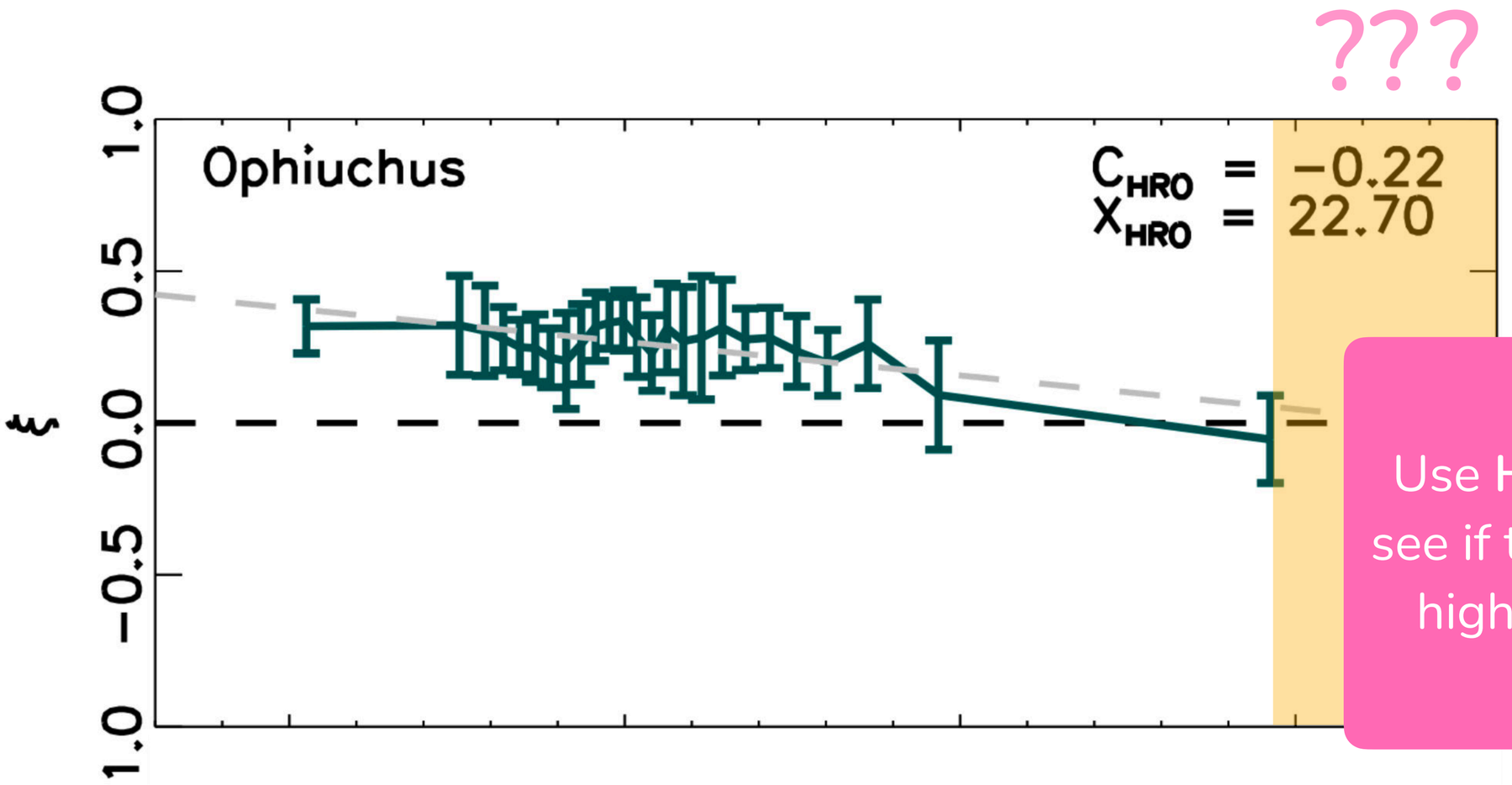


Figure 7 — Planck Int. Results XXXV

Planck Int. Results XXXV



Use HAWC+ on SOFIA to see if the trend continues to higher column densities

Figure 7 — Planck Int. Results XXXV

Background

Histogram of Relative Orientation Technique

Planck/HAWC+ Combined HRO Analysis of L1688

Transition Density Comparison with Simulations

Ophiuchus

One of the closest star-forming region (~137 pc)

Lots and lots of protostars (e.g., Sadavoy et al. 2019)

Focus on L1688 as that is the region that we have available HAWC+ data

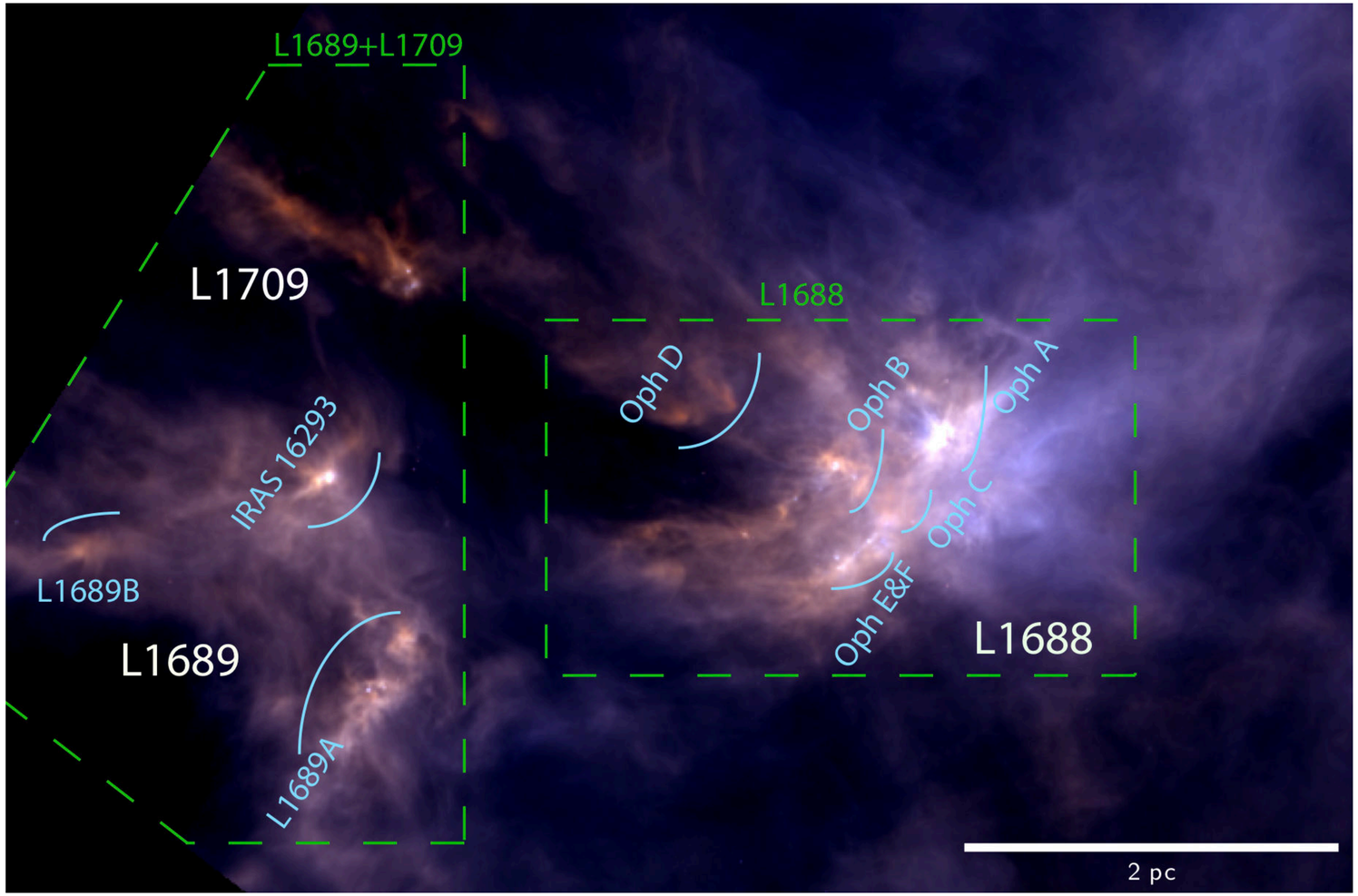
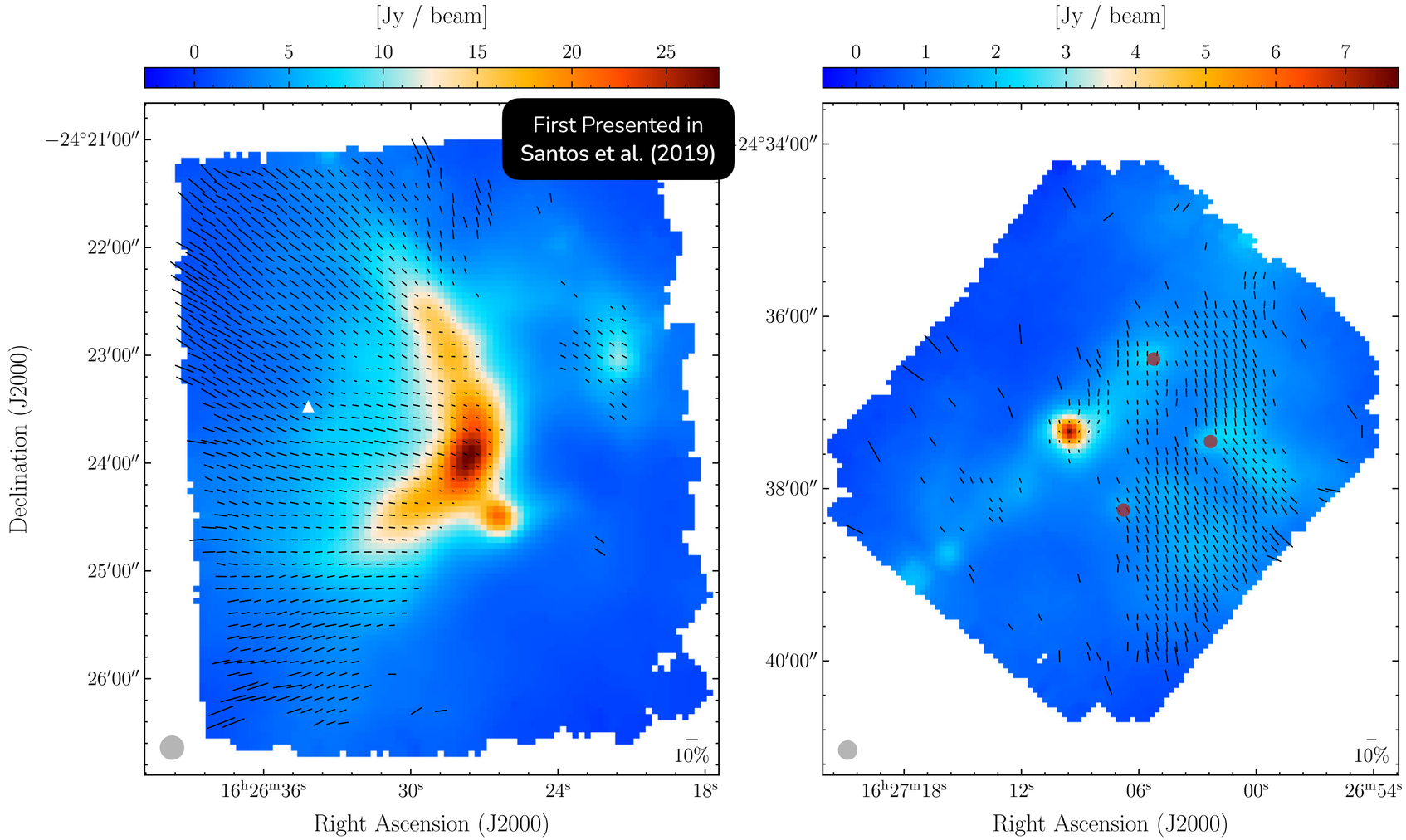


Figure 1 — Ladjelate et al. (2020)

High(er) Column Density Polarization

SOFIA/HAWC+
154 μm (Band D)
13.6 arcsecond

Inferred Magnetic Field Orientation



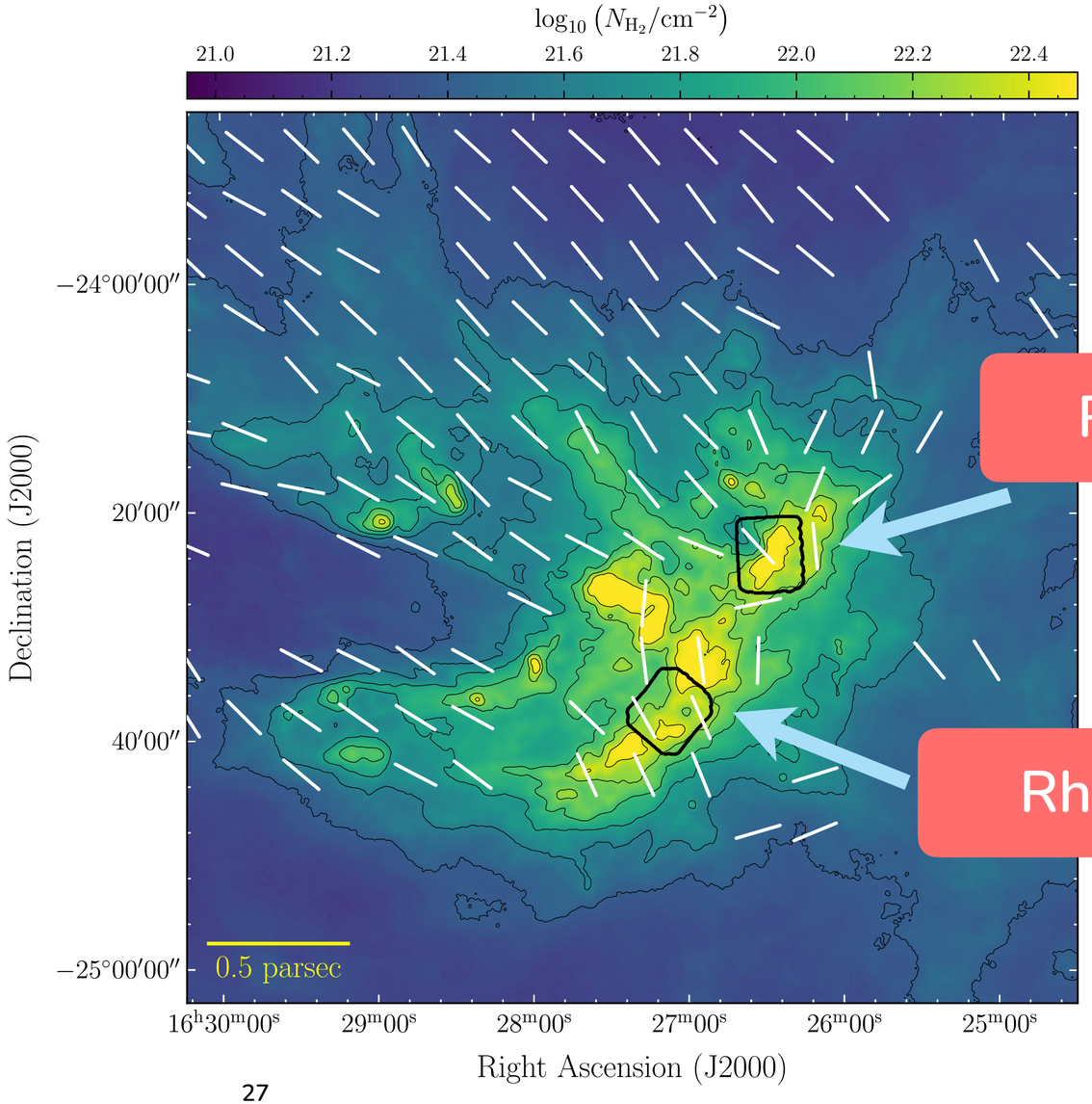
Rho Oph A

Rho Oph E

Low(er) Column Density Polarization

Planck
850 μm (353 GHz)
5 arcminute

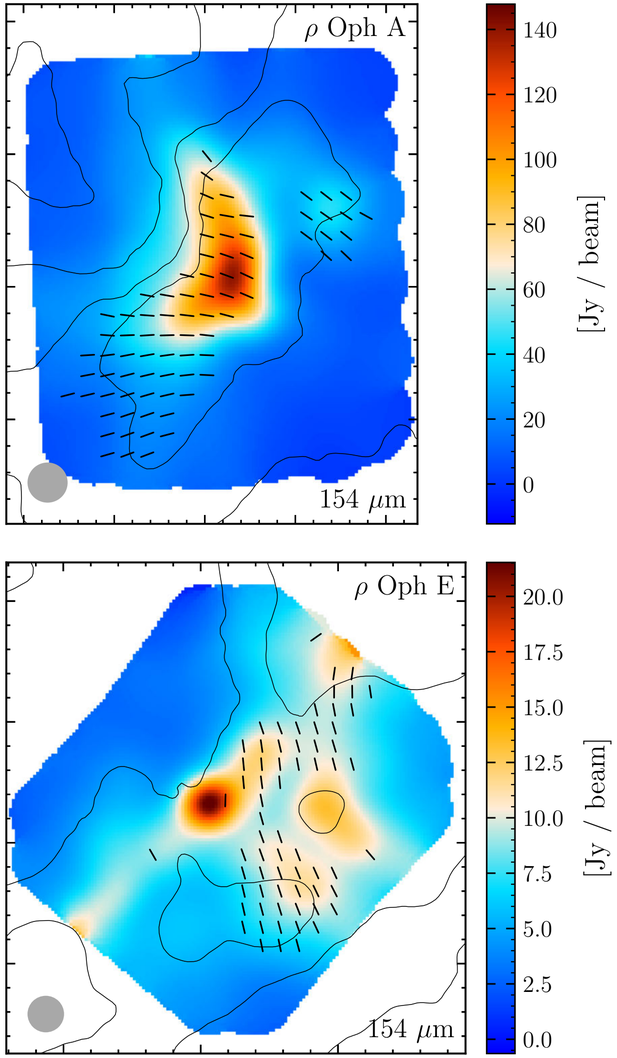
Inferred Magnetic
Field Orientation



Rho Oph A

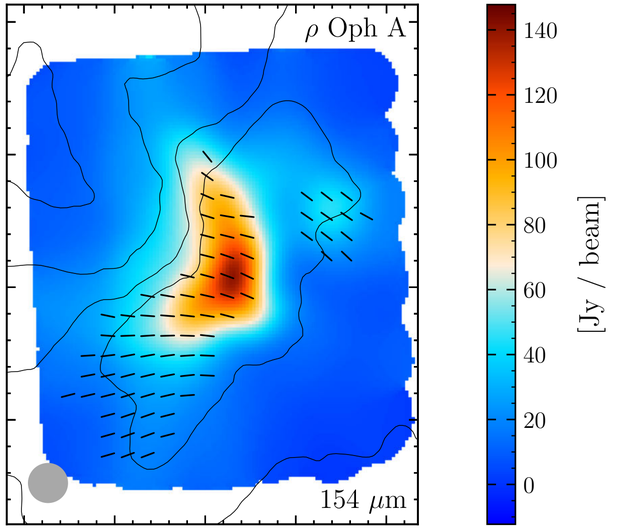
Rho Oph E

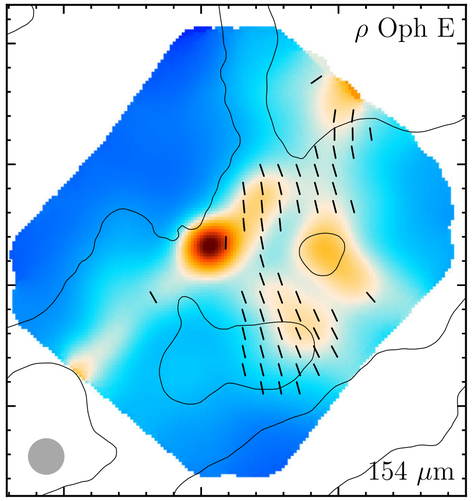
HROs by Subregions of L1688

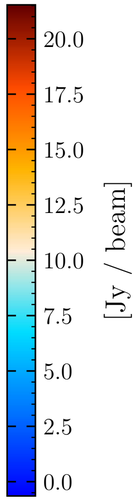


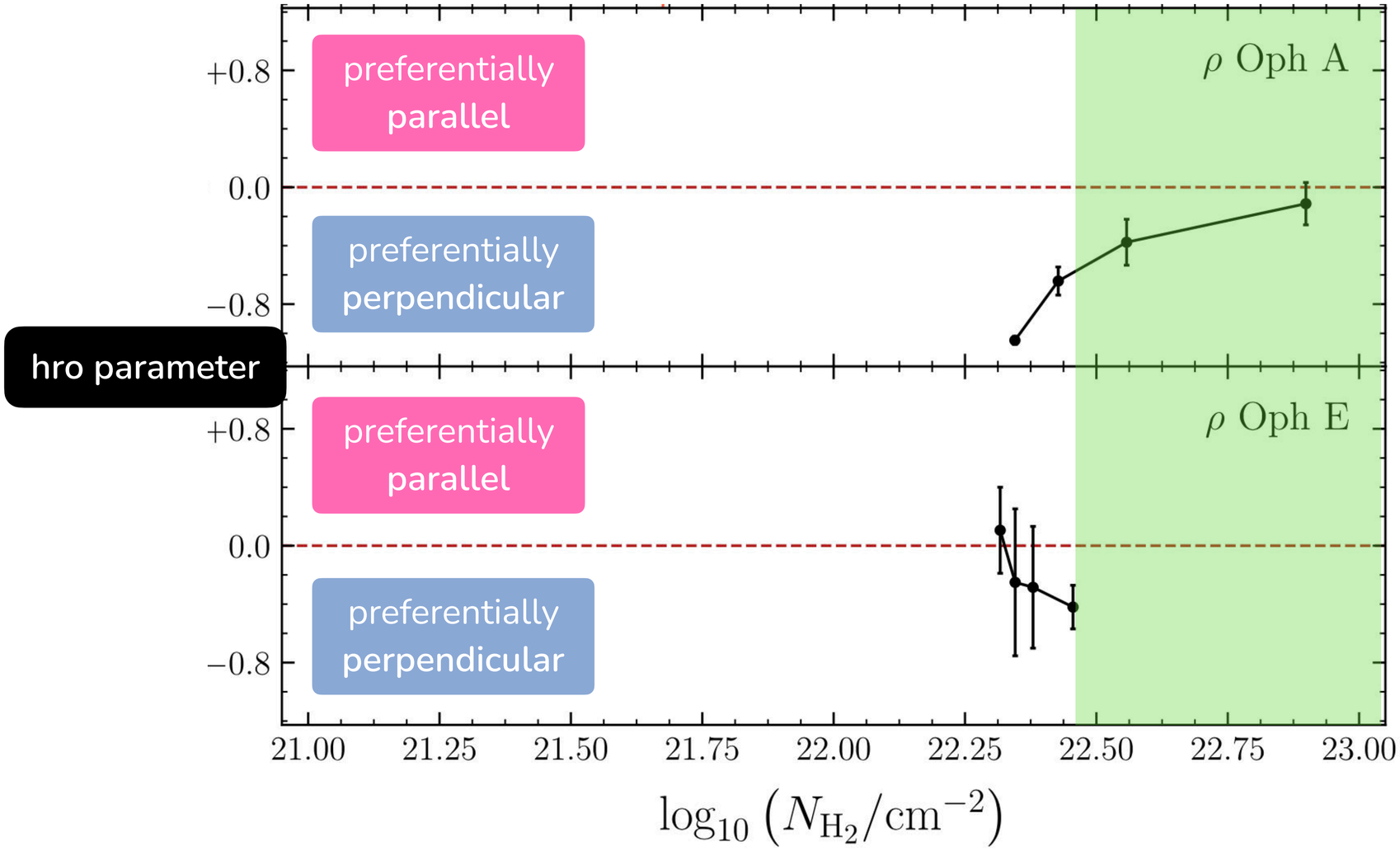
SOFIA/HAWC+
154 μm
33.6 arcsecond
Herschel Column Density

HROs by Subregions of L1688

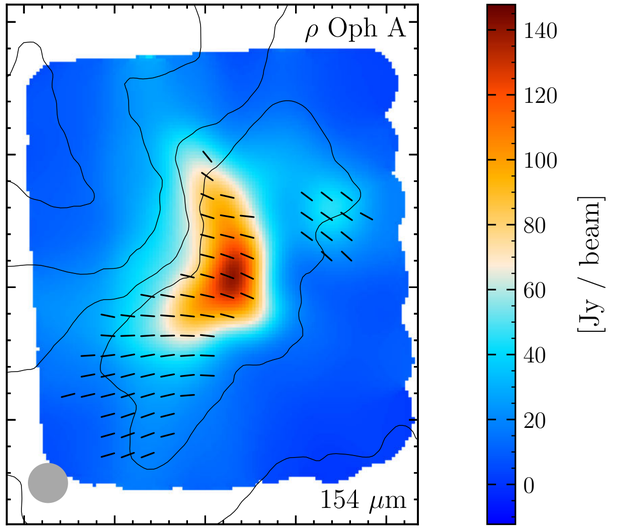


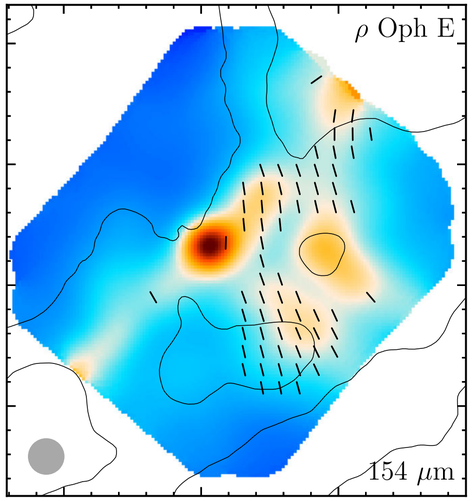


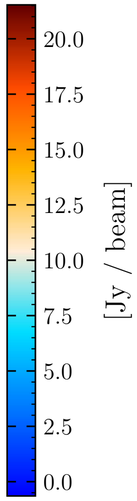


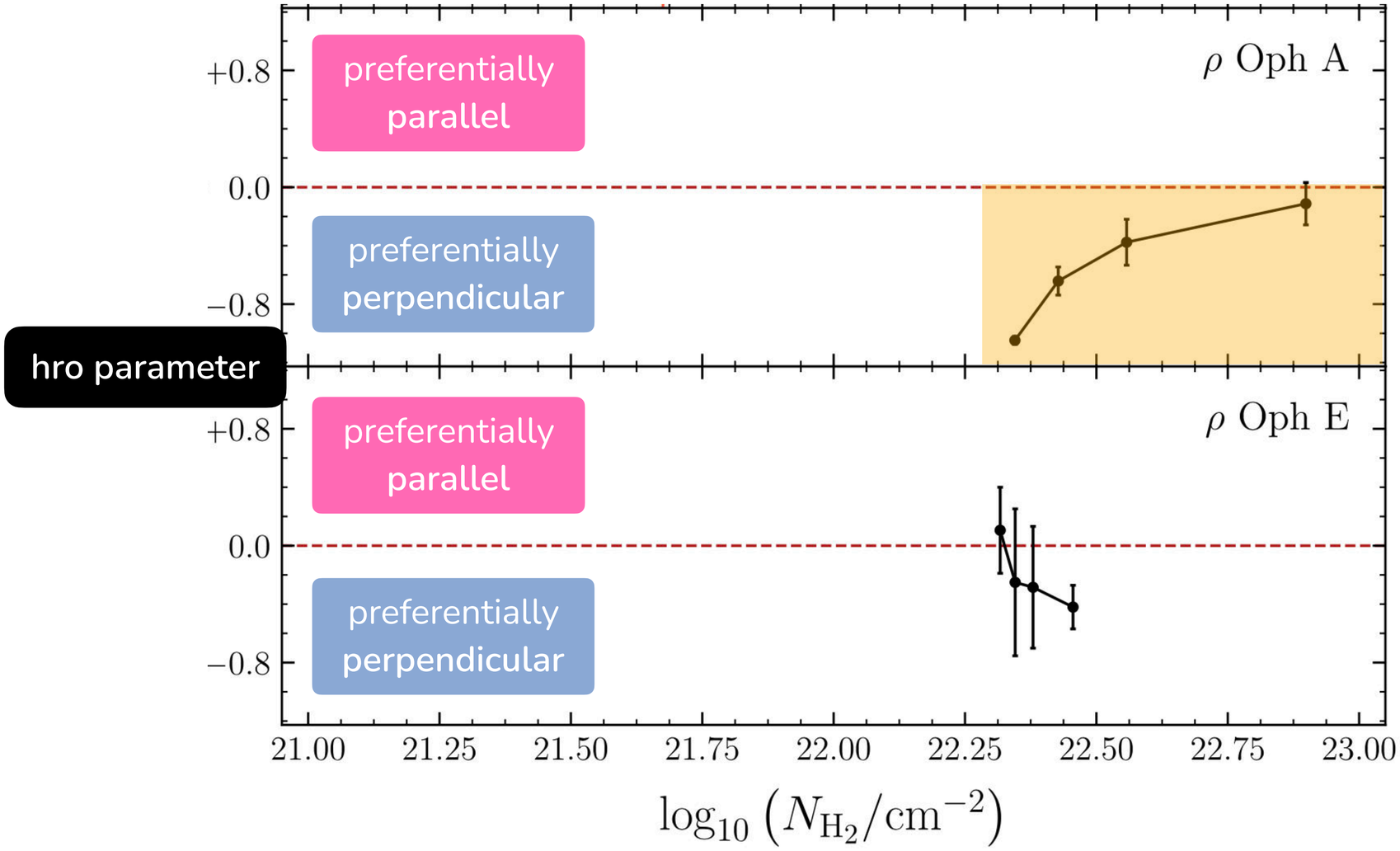


HROs by Subregions of L1688



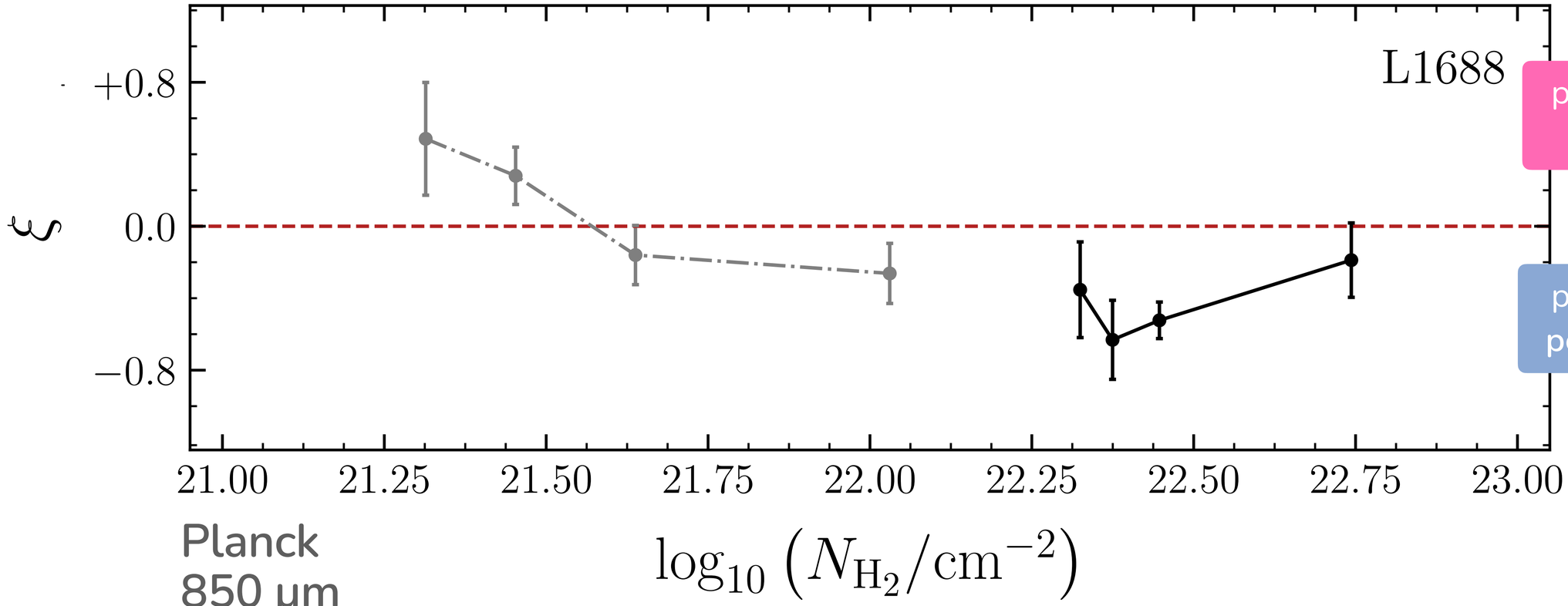






Extending the HRO

SOFIA/HAWC+
154 μm
33.6 arcsecond



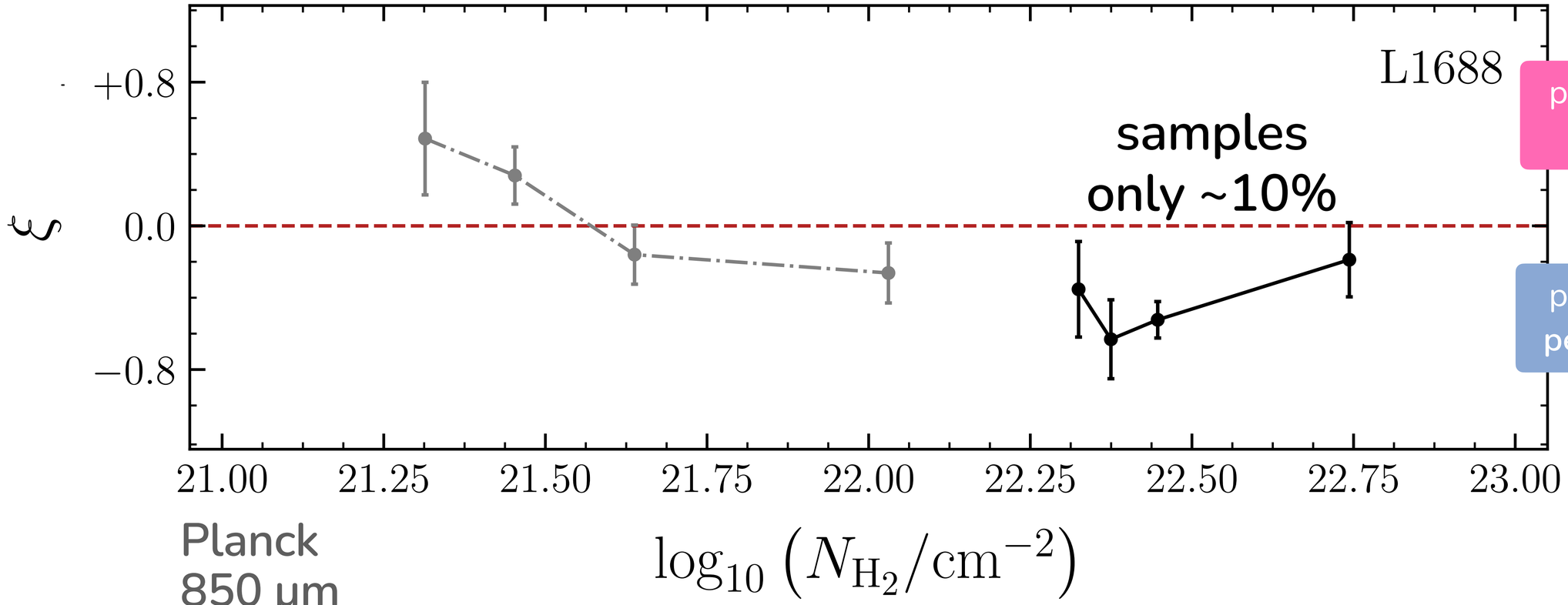
preferentially parallel

preferentially perpendicular

Planck
850 μm
5 arcminute

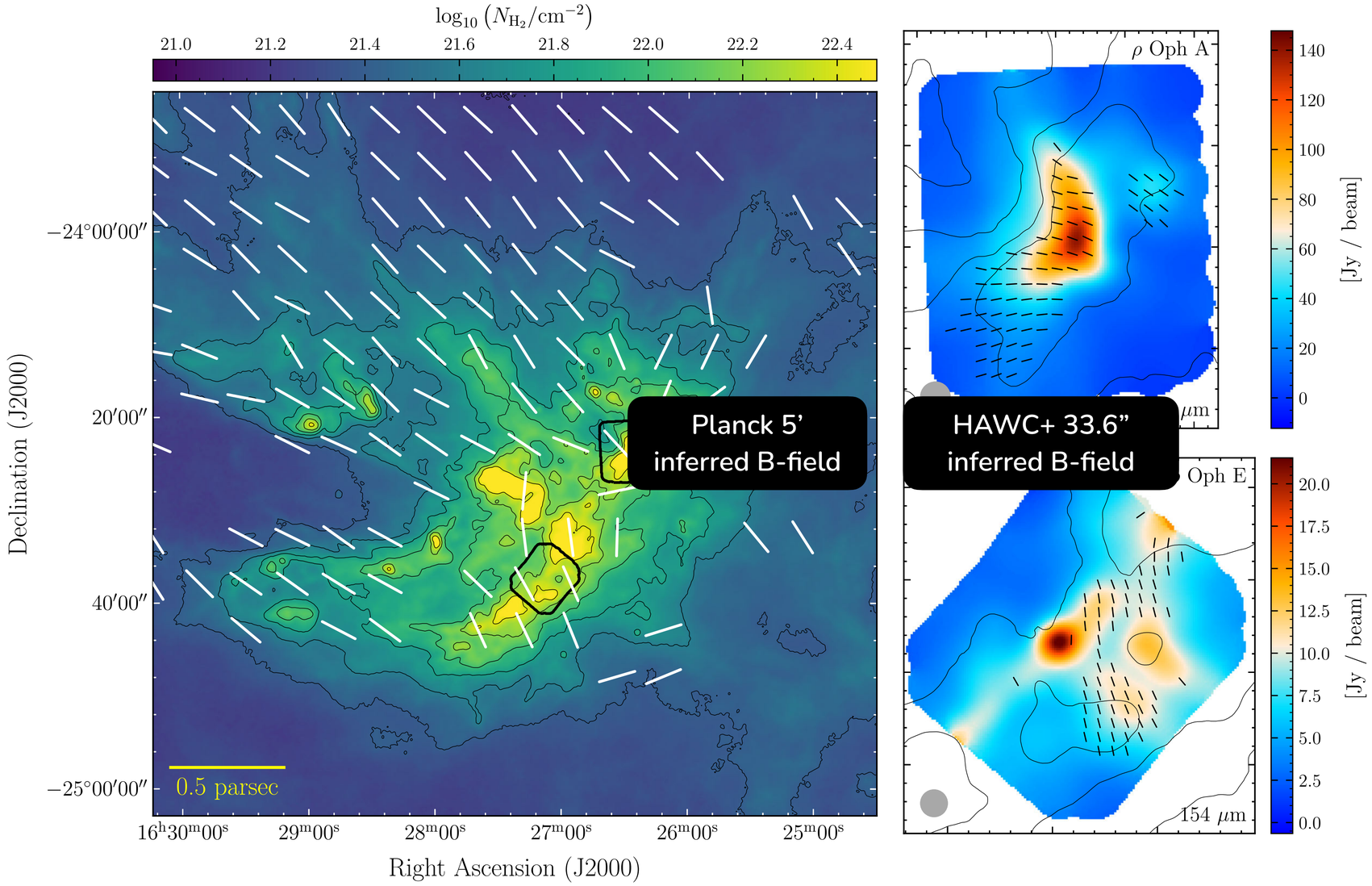
Extending the HRO

SOFIA/HAWC+
154 μm
33.6 arcsecond



Planck
850 μm
5 arcminute

Extending the HRO - Sampling Uncertainty

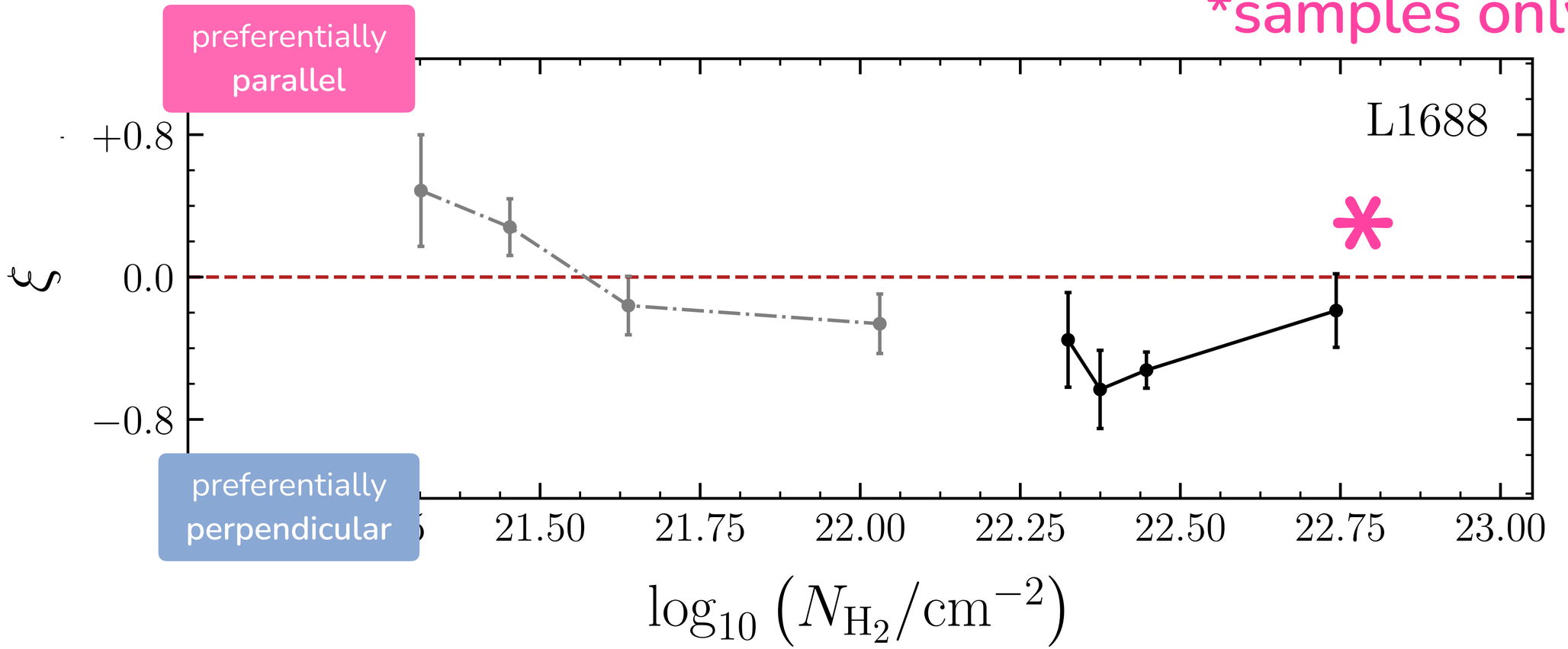


Other regions of L1688 exist

i.e., Rho Oph C

Extending the HRO - Sampling Uncertainty

*samples only ~10%



the transition continues to hold
at these higher column densities

Background

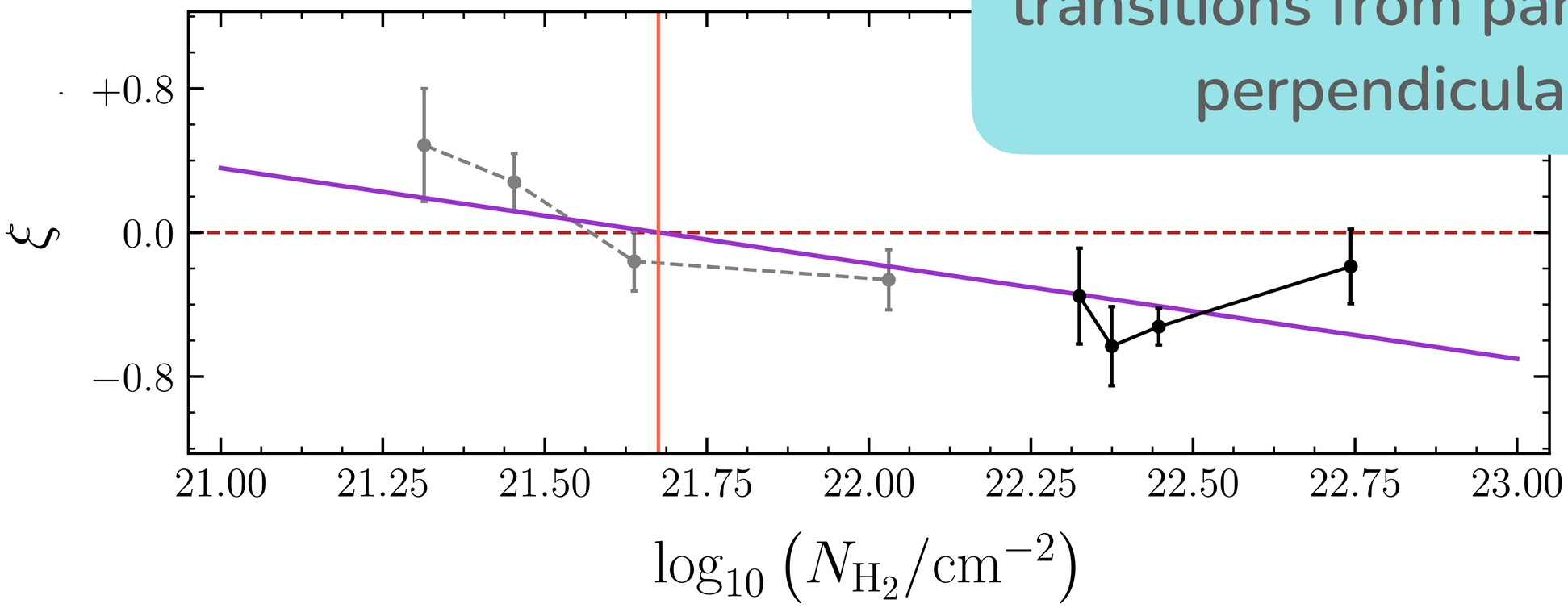
Histogram of Relative Orientation Technique

Planck/HAWC+ Combined HRO Analysis of L1688

Transition Density Comparison with Simulations

Transition Column Density

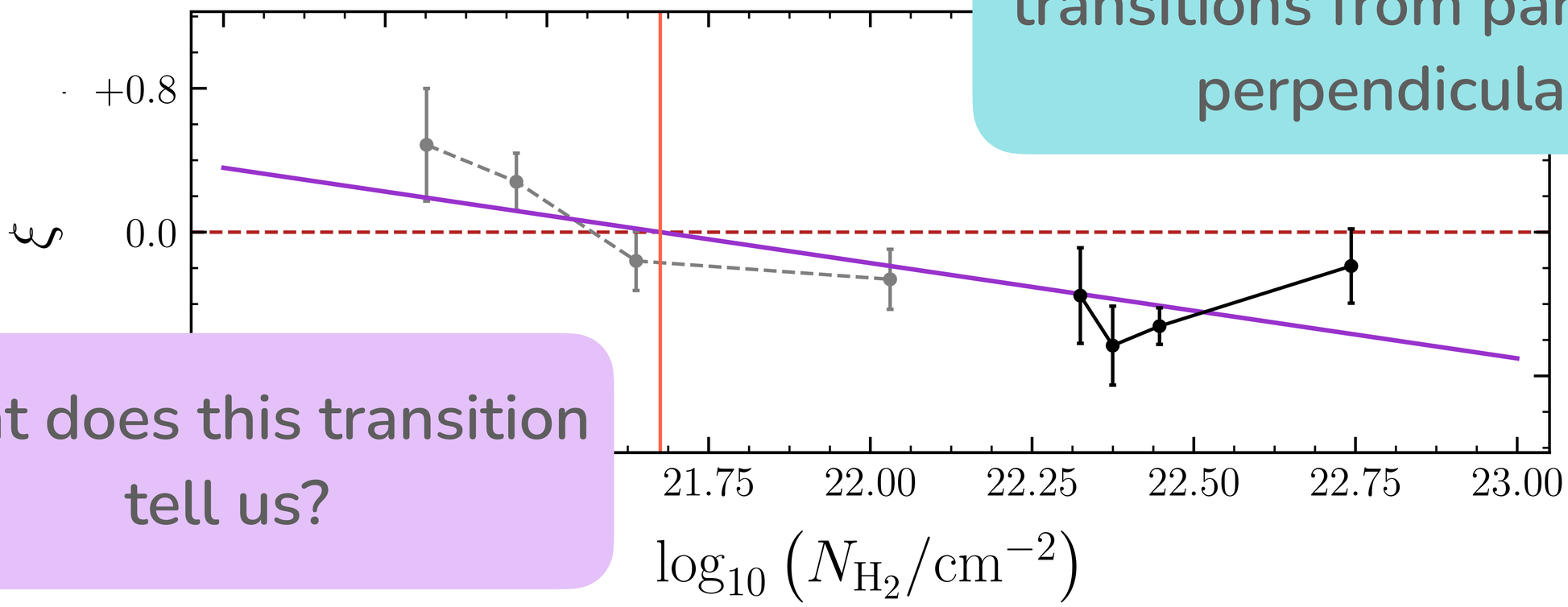
Where the column density transitions from parallel to perpendicular



$$N_{\mathrm{H_2,tr}}/\mathrm{cm}^{-2} = 10^{21.7}$$

Transition Column Density

Where the column density transitions from parallel to perpendicular



What does this transition tell us?

$$N_{\mathrm{H_2,tr}}/\mathrm{cm}^{-2} = 10^{21.7}$$

Zeeman Measurements

Crutcher et al. (2010)
scaling transition volume/number density

When the magnetic field can no longer support against gravitational collapse

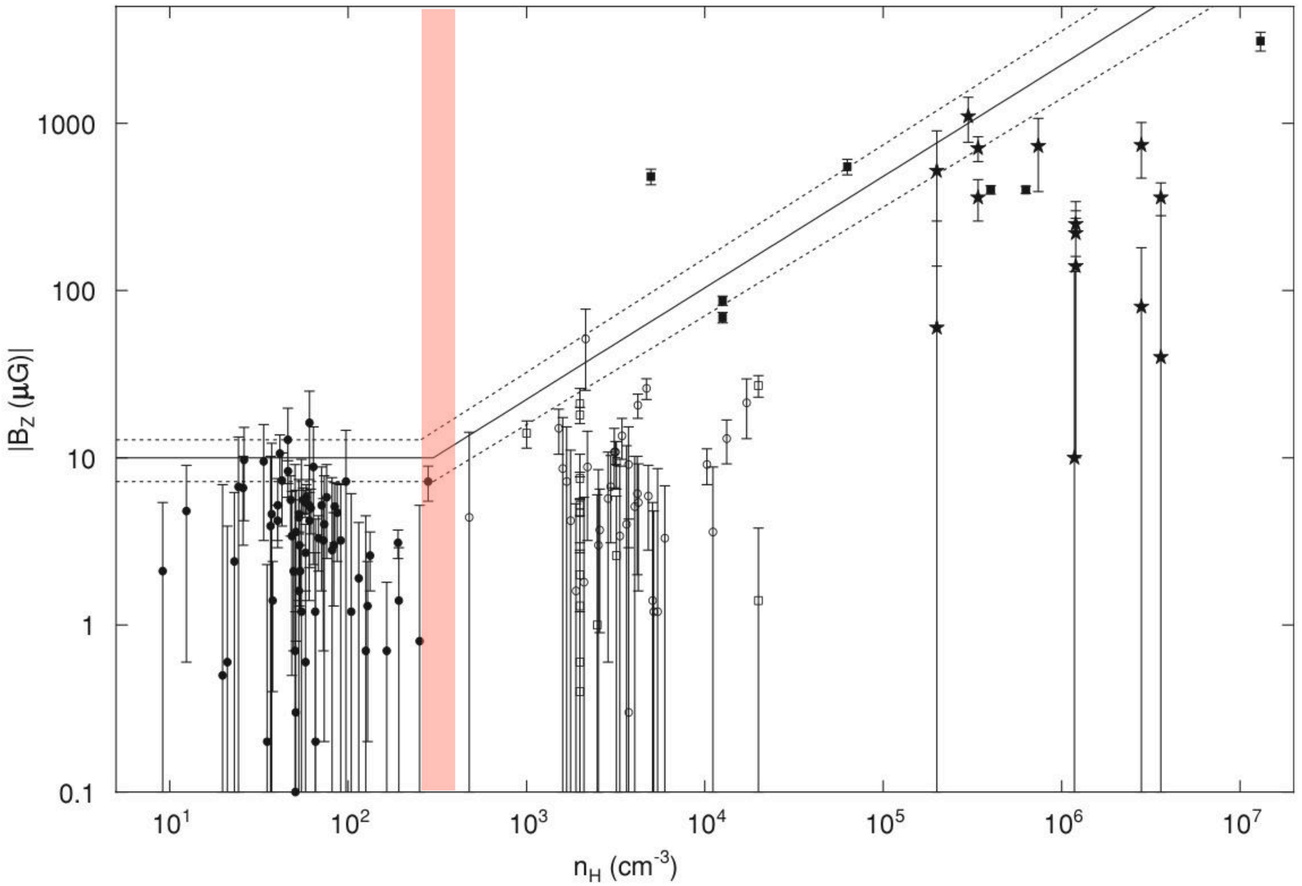


Figure 1 — Crutcher et al. (2010)

Simulations — Chen et al. (2016)

Colliding flow simulations
Chen & Ostriker (2015)

Isothermal

Initial magnetic field at an oblique angle

Three different inflow Mach numbers

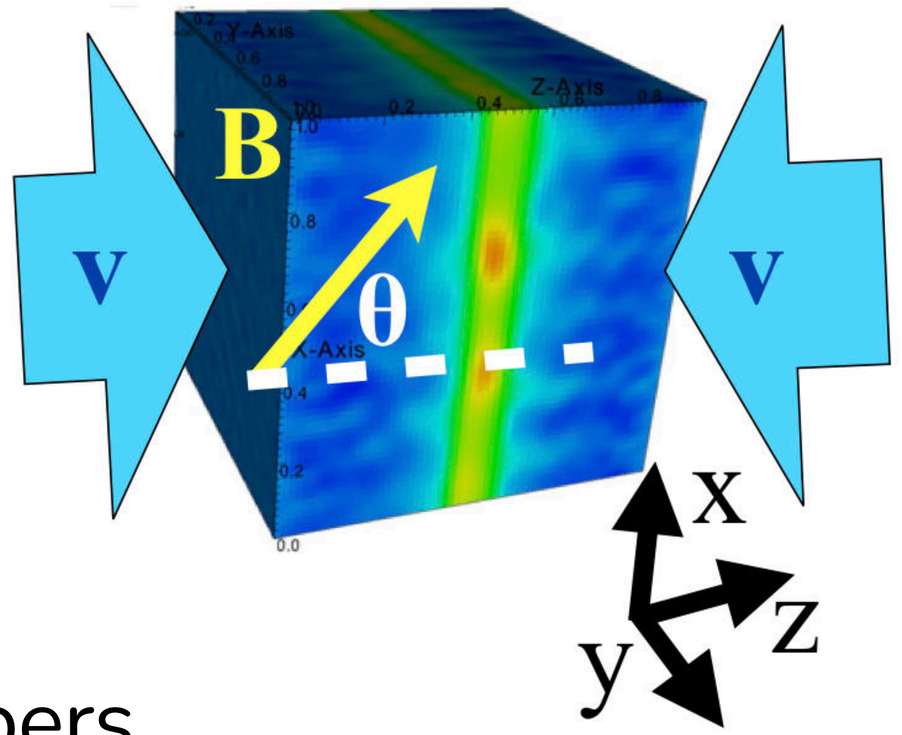


Figure 2 — Chen & Ostriker (2014)

Simulations — Chen et al. (2016)

At scaling transition volume/ number density

Comparing energy densities shows that equipartition between kinetic and magnetic.

Kinetic becomes more dominant after this point moving toward higher densities.

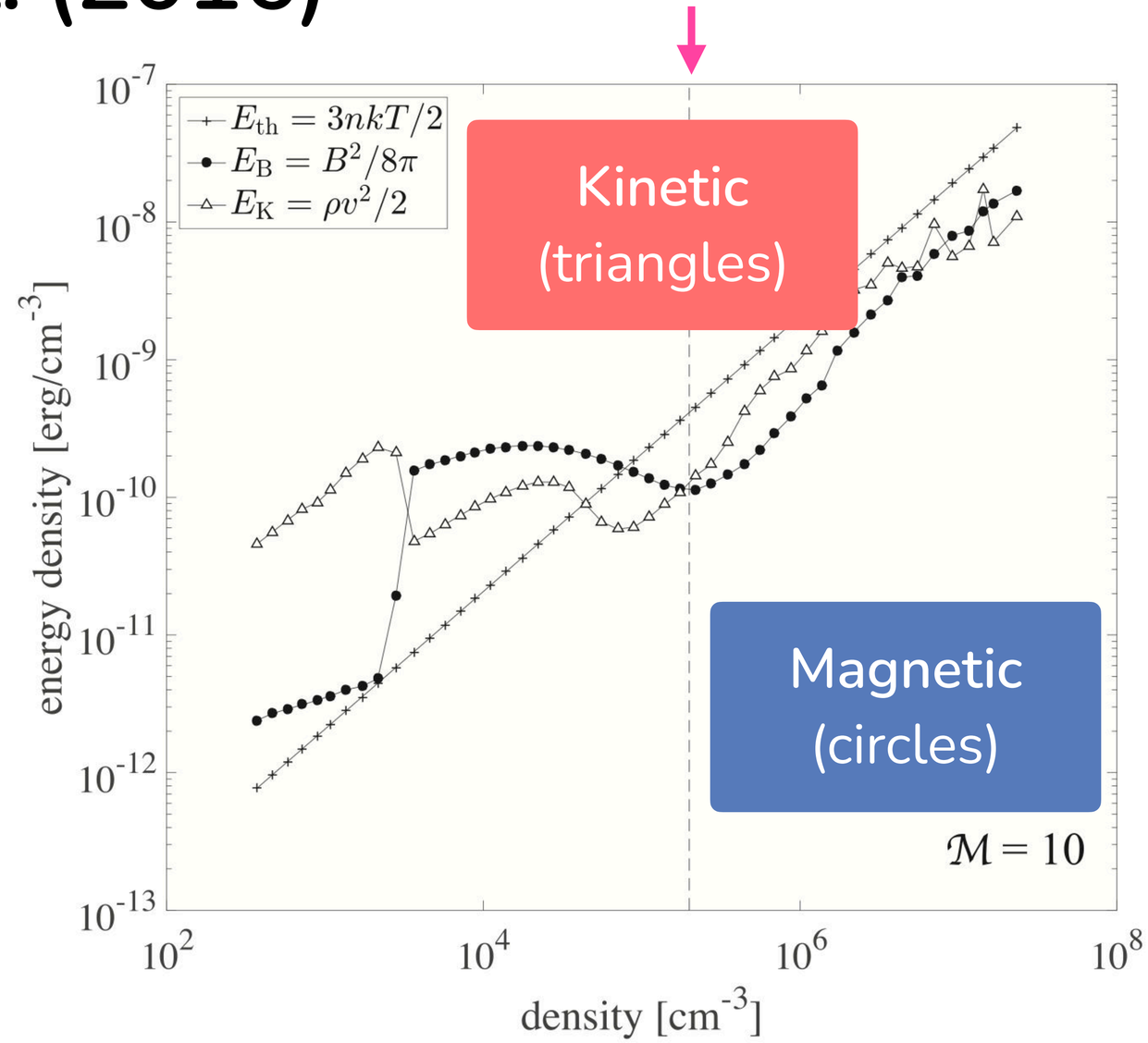


Figure 5 — Chen et al. (2016)

Simulations — Chen et al. (2016)

Scaling transition density is coincident with the transition density in 3D HROs.

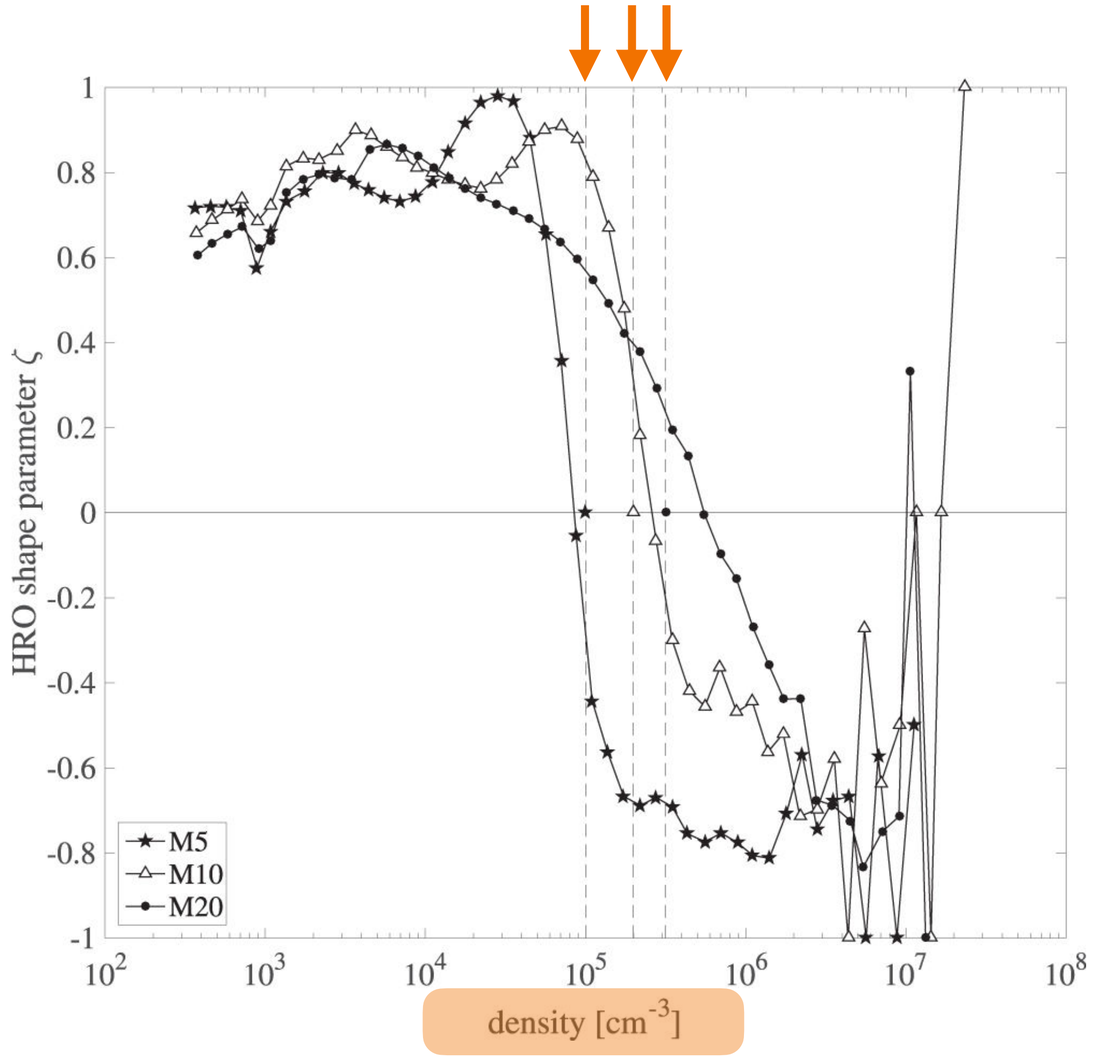


Figure 4 — Chen et al. (2016)

Simulations — Chen et al. (2016)

Scaling transition density is **coincident** with the transition density in 3D HROs.

Behavior can be also be found in 2D HROs

Compute a transition number density value from our HROs for comparison

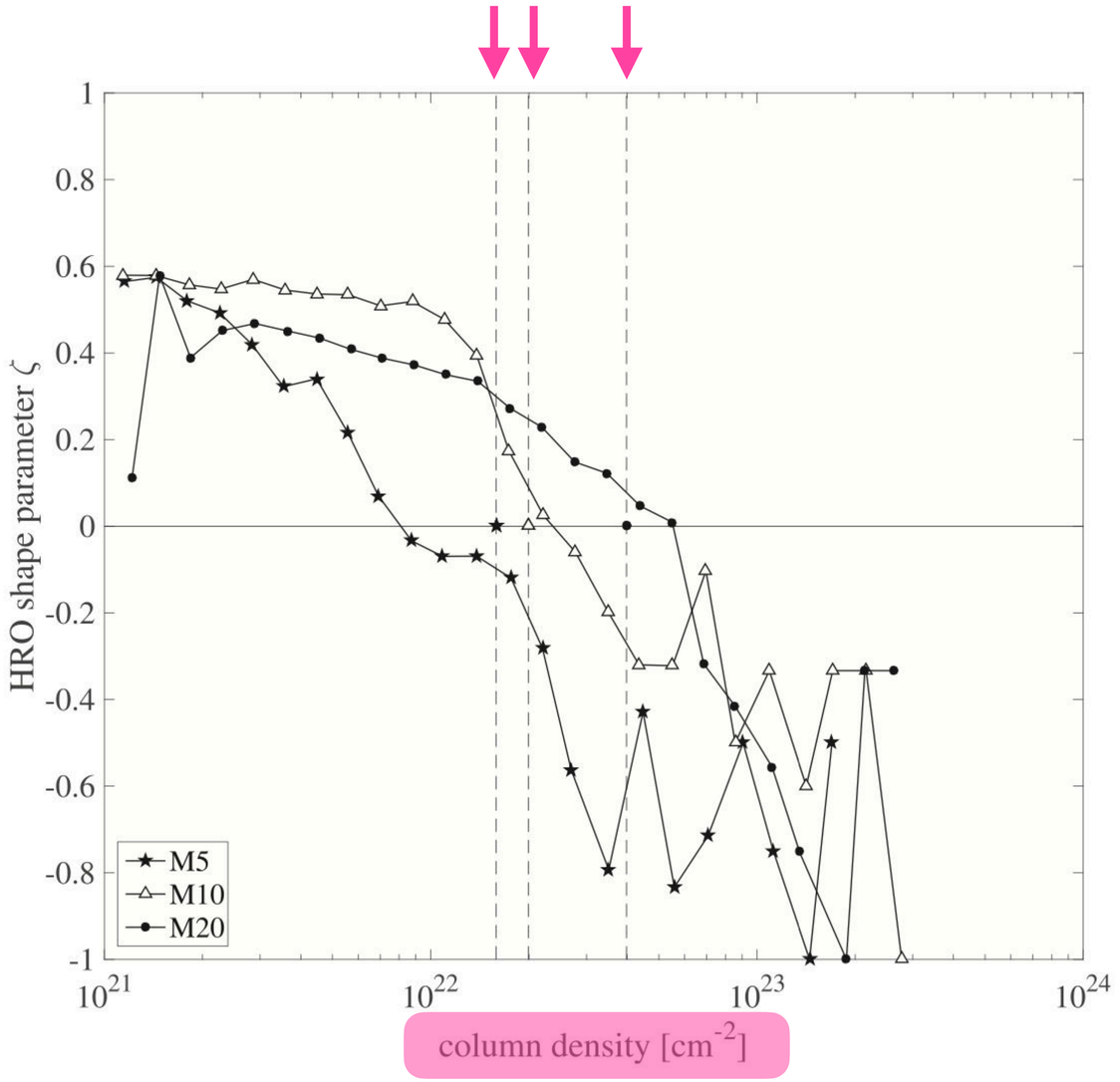


Figure 8 — Chen et al. (2016)

Transition Density

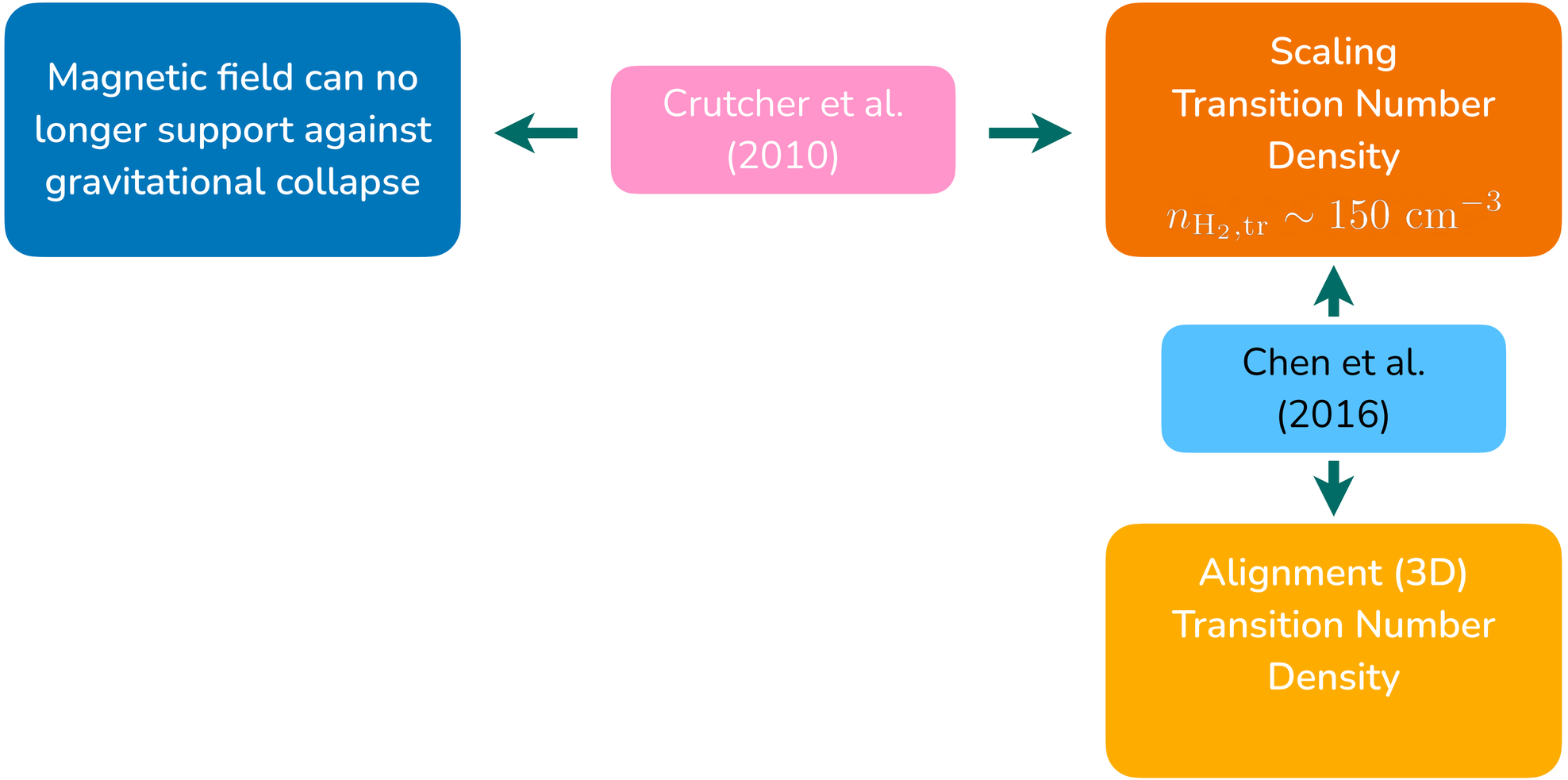
Magnetic field can no longer support against gravitational collapse

← Crutcher et al. (2010) →

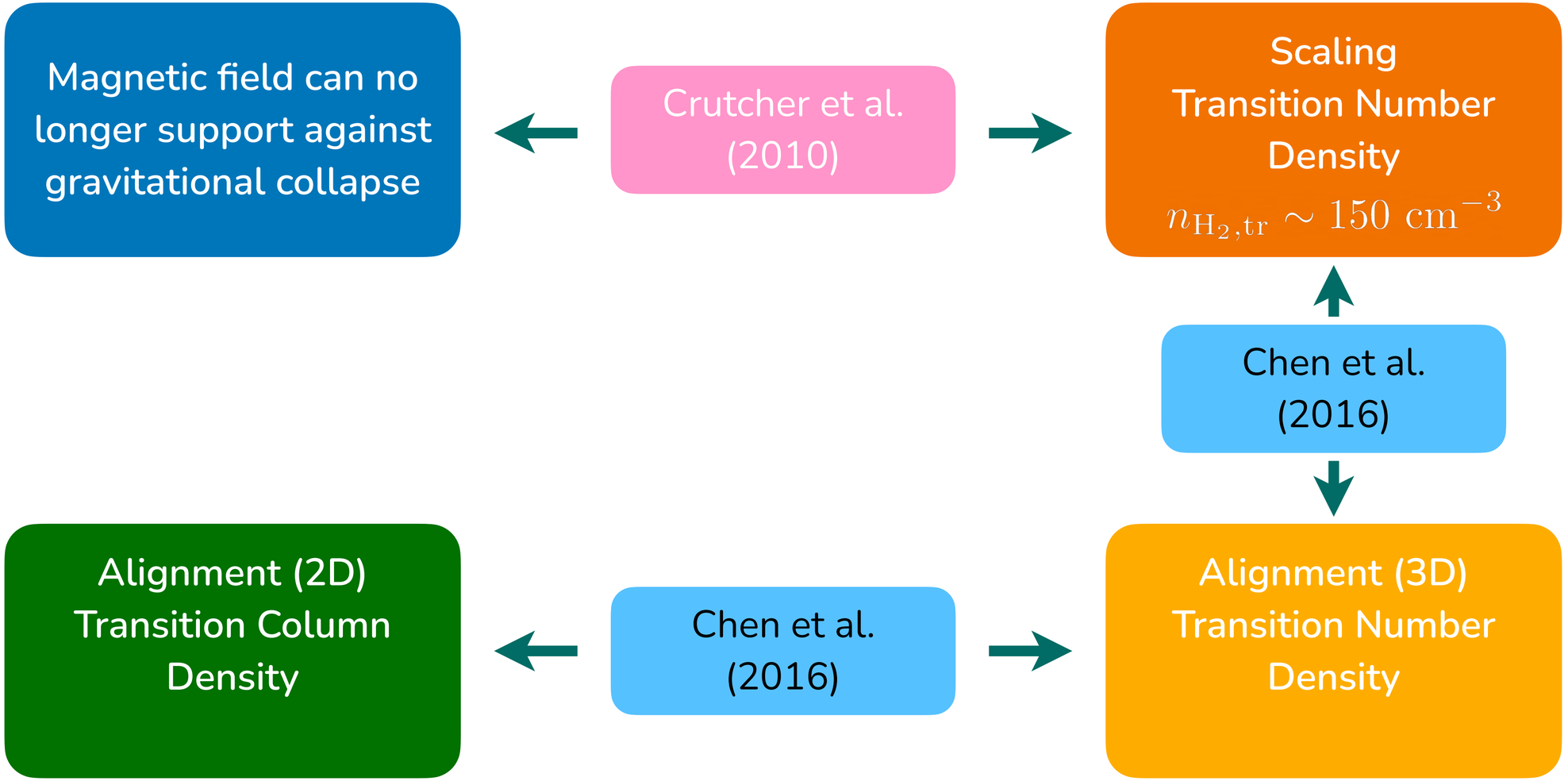
Scaling Transition Number Density

$n_{\mathrm{H_2,tr}} \sim 150\ \mathrm{cm}^{-3}$

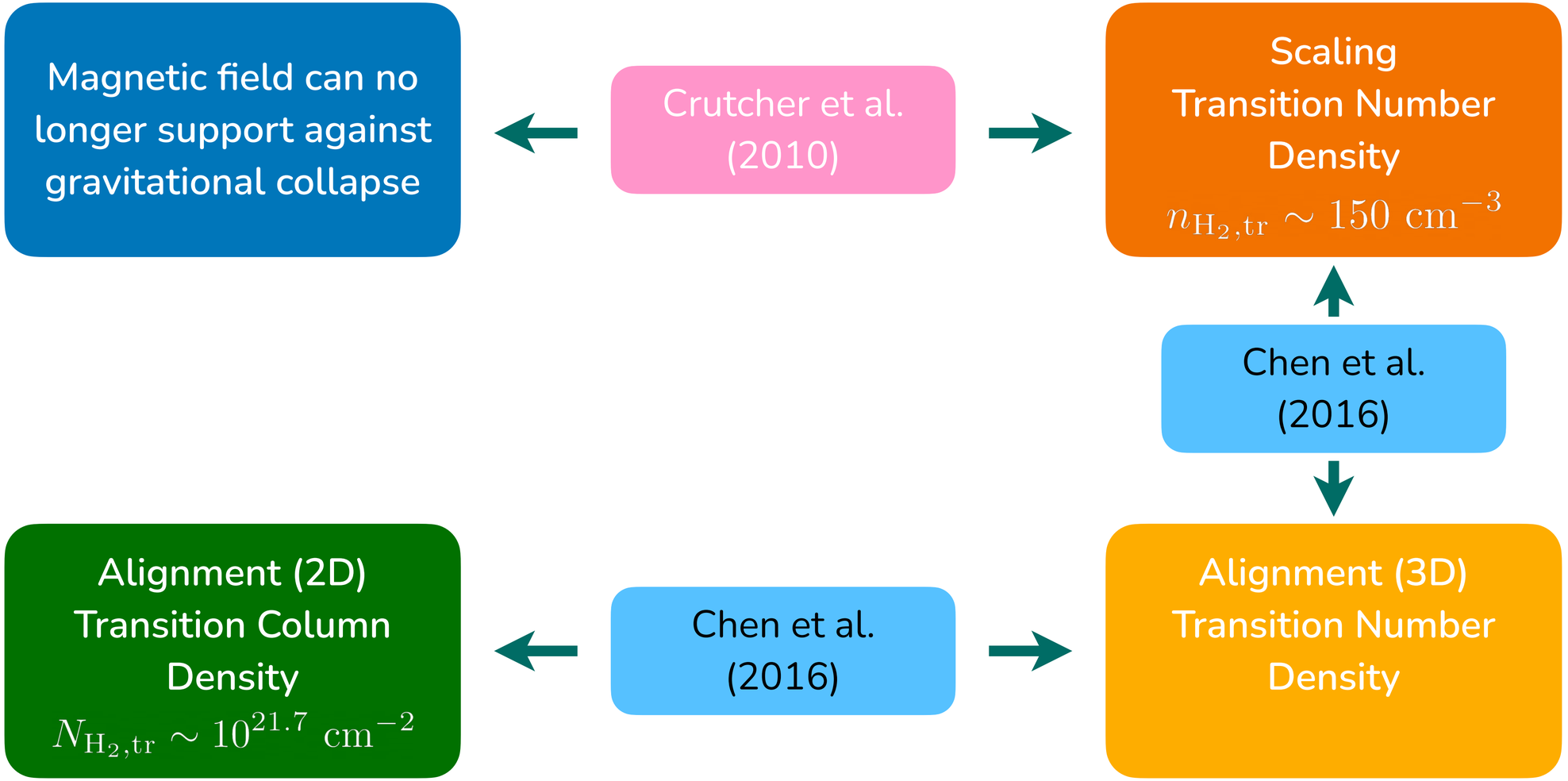
Transition Density



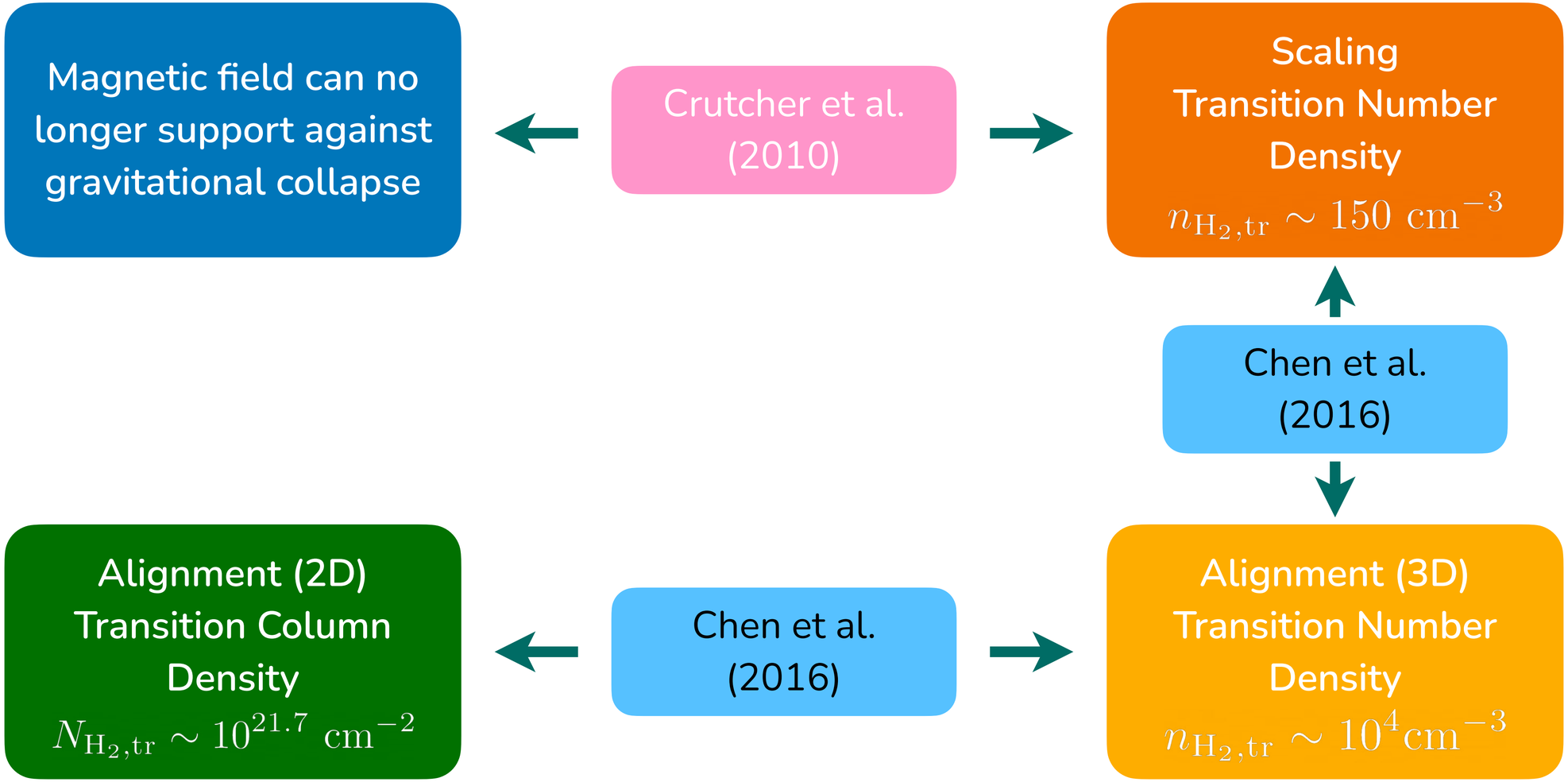
Transition Density



Transition Density



Transition Density



Comparison of Values

$n_{\mathrm{H_2,tr}}/\mathrm{cm}^{-3}$

~ 150

Crutcher et al. (2010)
Zeeman measurements

$\sim 10^4$

from the HRO analysis of L1688 here

Comparison of Values

$n_{\mathrm{H_2,tr}}/\mathrm{cm}^{-3}$

~ 150 Crutcher et al. (2010) Zeeman measurements

$\sim 10^3$ Fissel et al. (2016) Vela C, Molecular Line

$\sim 10^4$ from the HRO analysis of L1688 here

Comparison of Values

$n_{\mathrm{H_2,tr}}/\mathrm{cm}^{-3}$

Sampling of L1688

~ 150

Crutcher et al. (2010)
Zeeman measurements

$\sim 10^3$

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Vela C, Molecular Line

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from the HRO analysis of L1688 here

Comparison of Values

$n_{\mathrm{H_2,tr}}/\mathrm{cm}^{-3}$

Sampling of L1688

Particular configuration of simulations

~ 150 **Crutcher et al. (2010)** Zeeman measurements

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$\sim 10^4$ from the HRO analysis of L1688 here

Comparison of Values

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Sampling of L1688

Particular configuration of simulations

Viewing angles for the simulation

~ 150

Crutcher et al. (2010)
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from the HRO analysis of L1688 here

Comparison of Values

$n_{\mathrm{H_2,tr}}/\mathrm{cm}^{-3}$

Sampling of L1688

Particular configuration of simulations

Viewing angles for the simulation

~ 560 Jiang et al. (2020) Zeeman measurements

$\sim 10^3$ Fissel et al. (2016) Vela C, Molecular Line

$\sim 10^4$ from the HRO analysis of L1688 here

Physical Properties

Equipartition of energy at this point

$$E_{\mathrm{K}} = E_{\mathrm{B}}$$

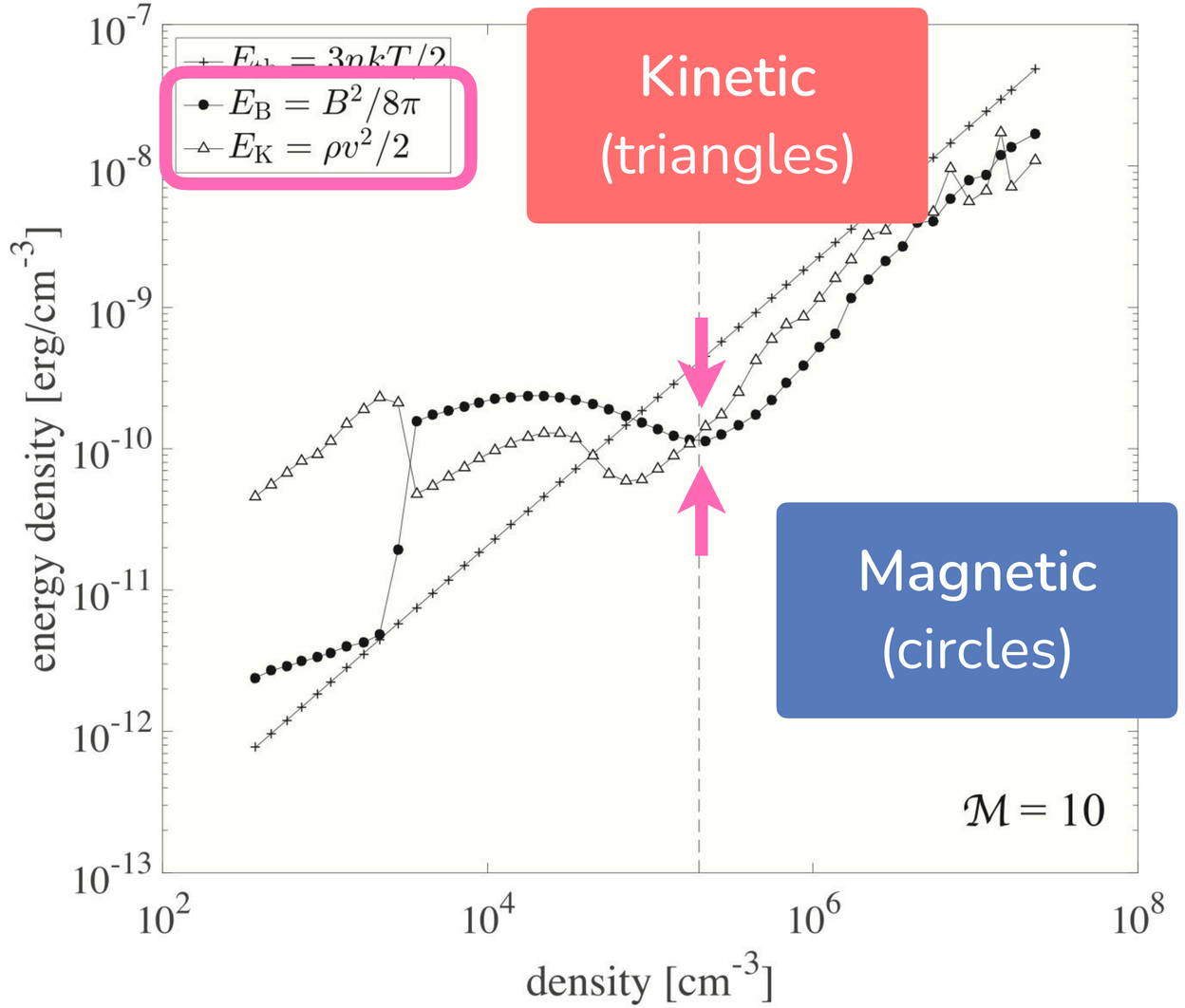


Figure 5 — Chen et al. (2016)

Physical Properties

Equipartition of energy at this point

$$E_{\rm K} = E_{\rm B}$$

$$\frac{\rho v^2}{2} = \frac{B^2}{8\pi}$$

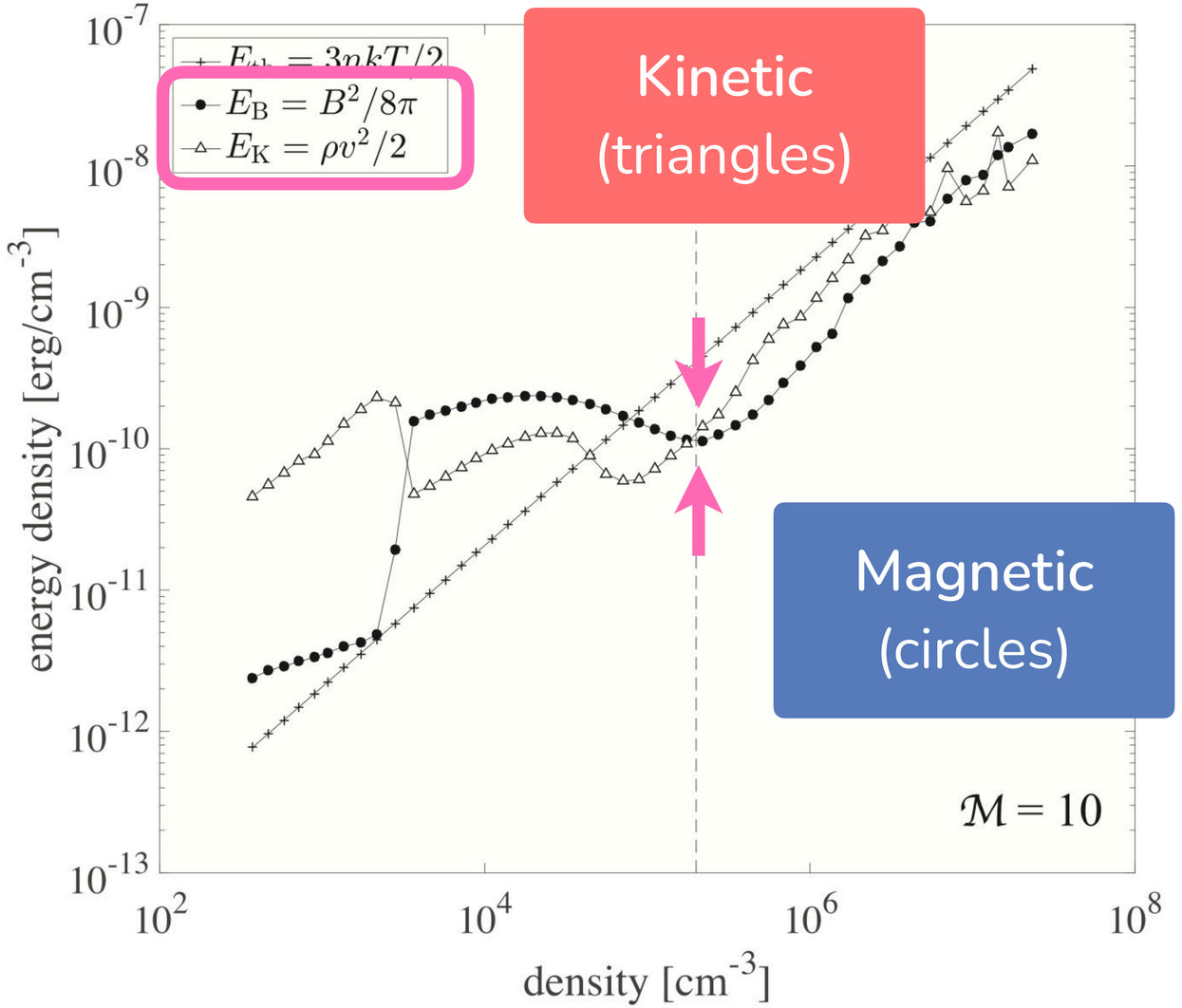


Figure 5 — Chen et al. (2016)

Physical Properties

Equipartition of energy at this point

$$E_{\mathrm{K}} = E_{\mathrm{B}}$$

$$\frac{\rho v^2}{2} = \frac{B^2}{8\pi}$$

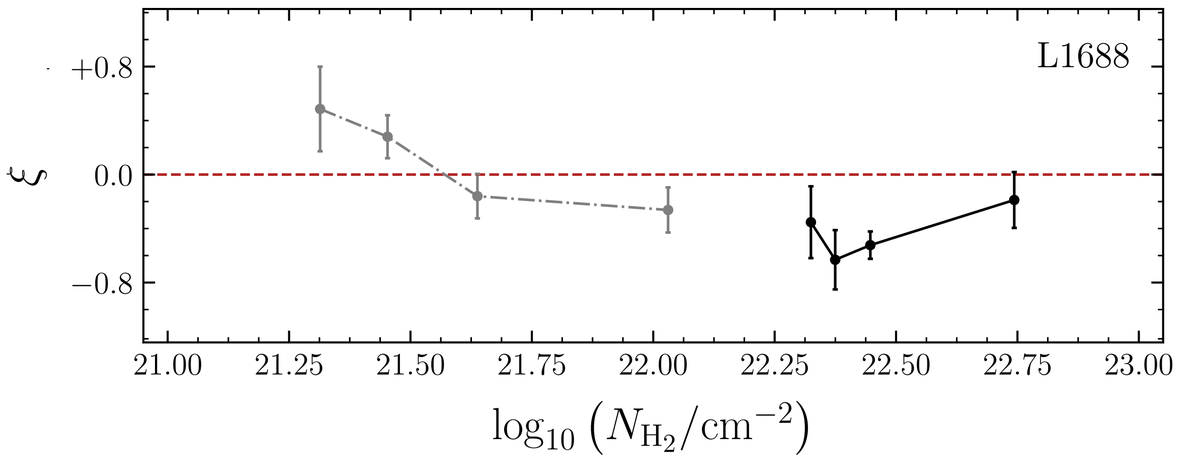
$n_{\mathrm{H_2,tr}} \sim 10^4\ \mathrm{cm}^{-3}$

$v = 0.5\ \mathrm{km/s}$

Friesen et al. 2017

$B_{\mathrm{tr}} \sim 30\ \mu\mathrm{G}$

Summary



Parallel to perpendicular trend seen in Planck Int. Results XXXV appears to **continue** for L1688

Demonstration of using relative orientation to **obtain** magnetic field properties

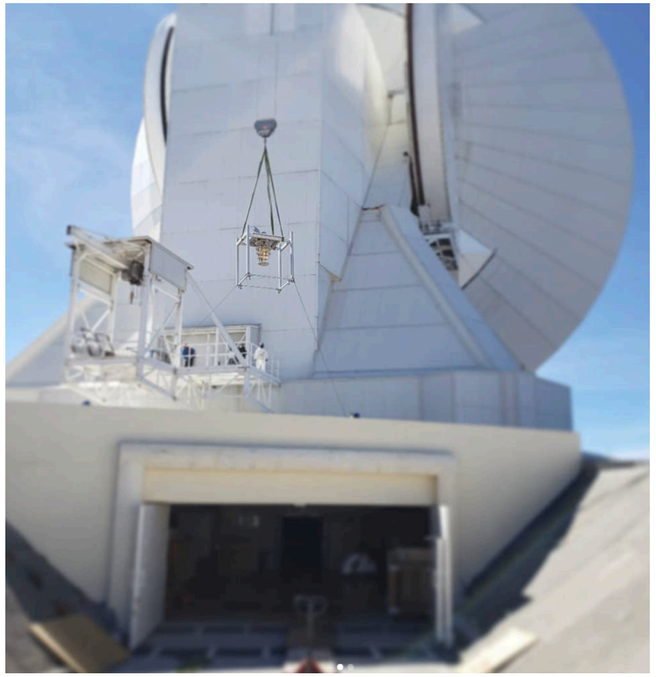
Calculation of transition density is **higher** than that suggested by previous work

Sampling uncertainty needs to considered and can be improved with more SOFIA observations

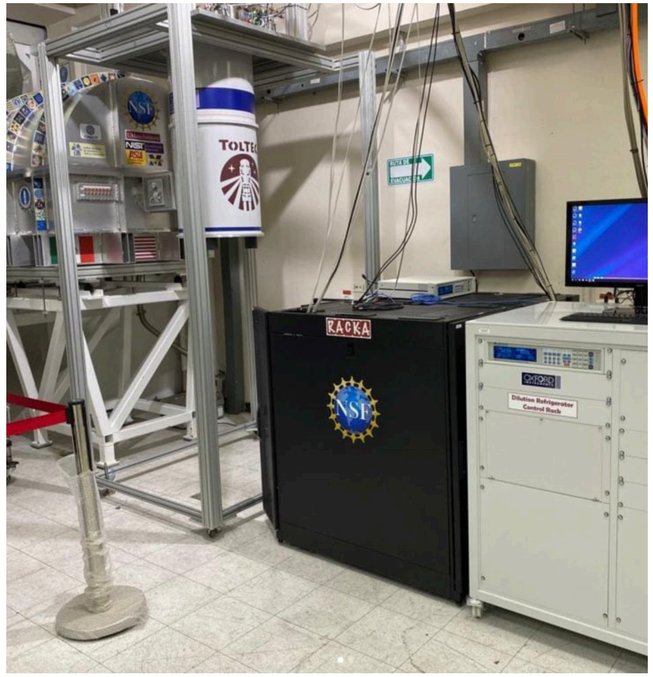
TolTEC
Large Millimeter Telescope

1.1 mm
1.4 mm
2.1 mm

5” fwhm @ 1.1 mm



UMass/TolTEC



UMass/TolTEC

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