James Clerk Maxwell Telescope
East Asian Observatory

Magnetic field properties in molecular clouds and star formation

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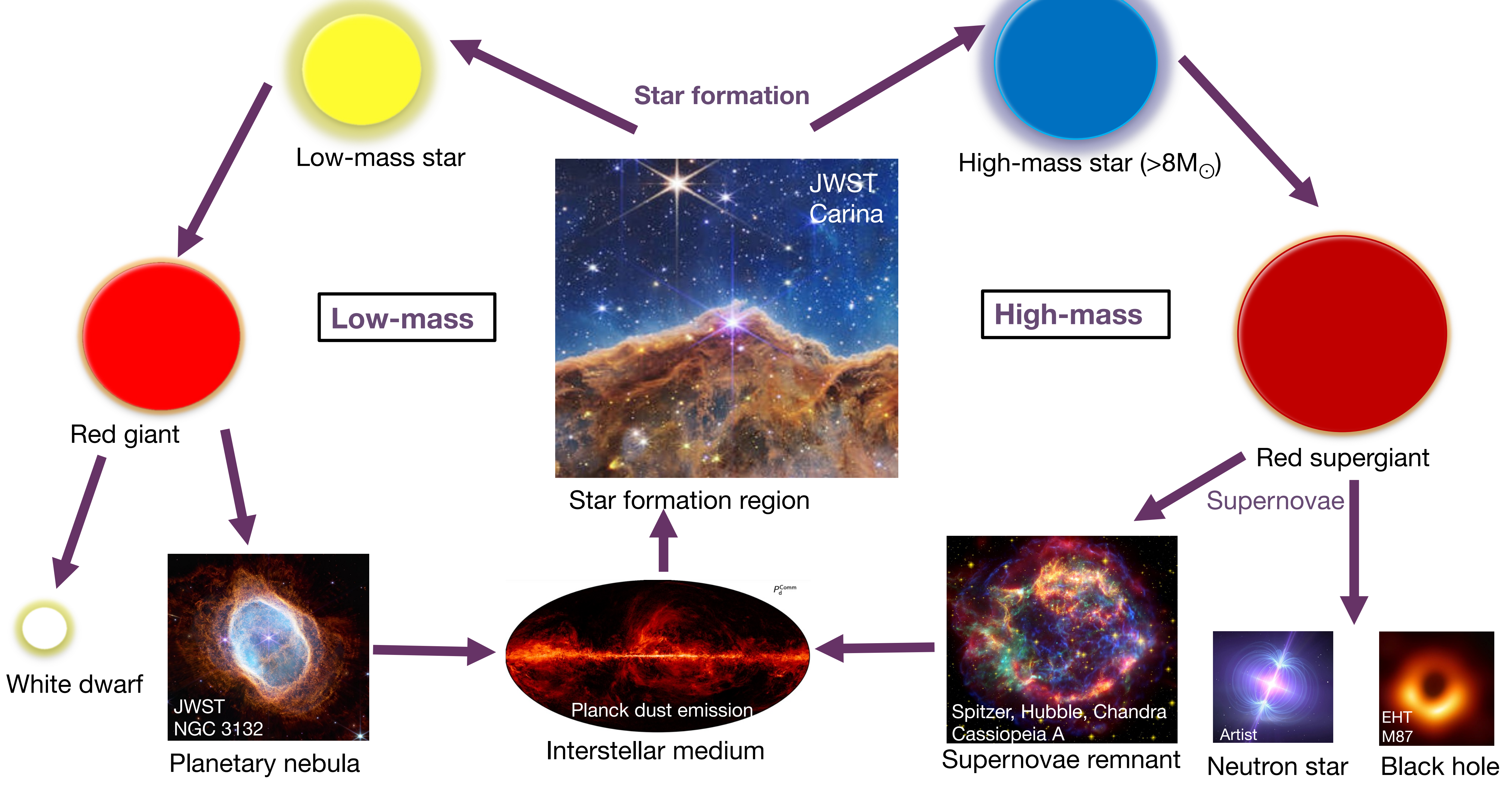
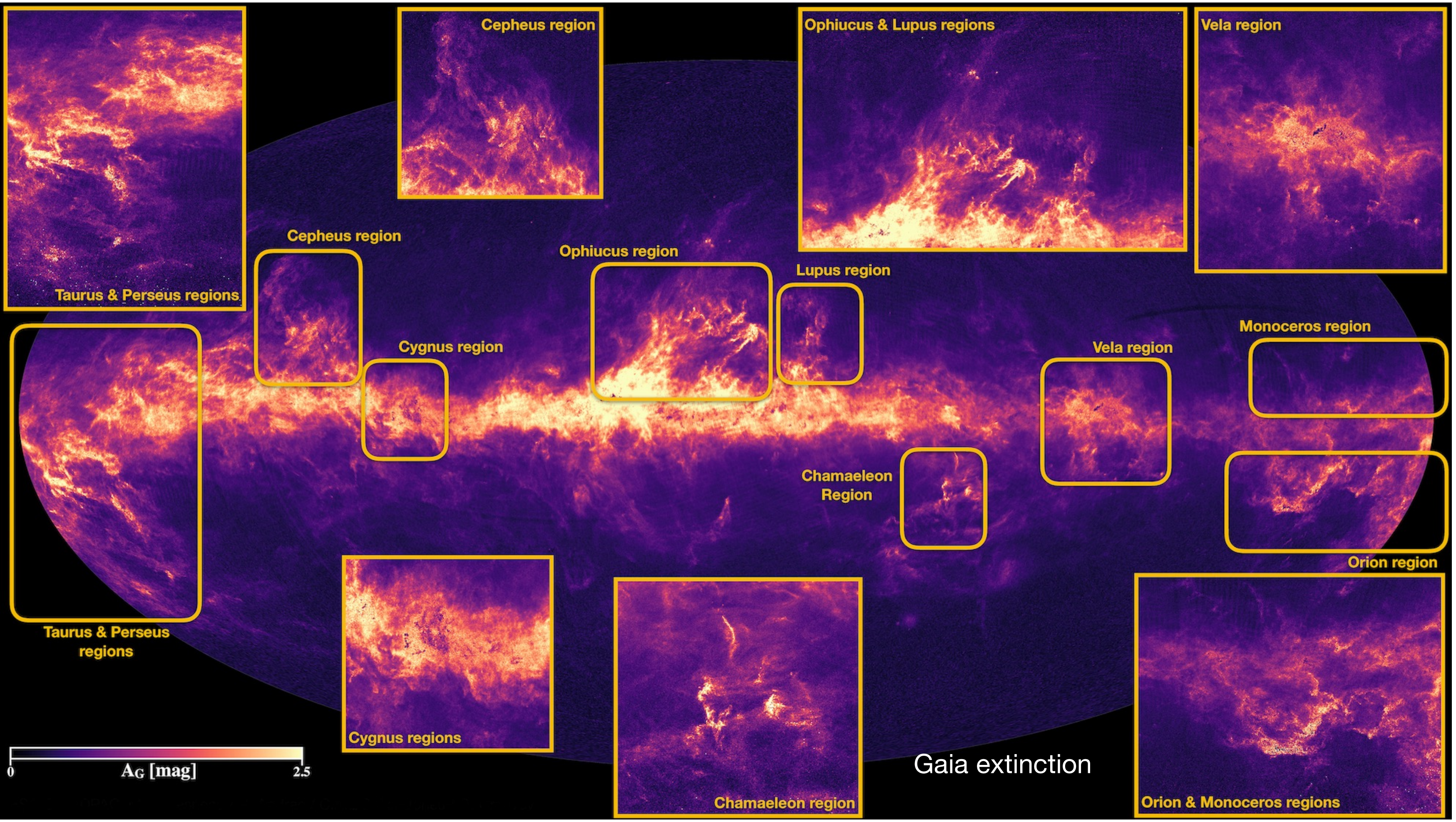
Life cycle of stars and interstellar matter

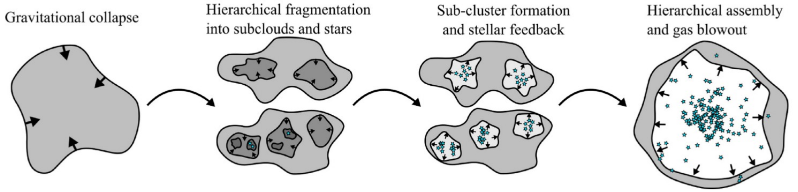


Molecular clouds and star formation (SF)



Hierarchical fragmentation

- ~100 pc cloud complexes
- ~10 pc clouds
- ~1 pc clumps
- ~0.1 pc cores
- ~0.01 pc condensations
- ~100 AU disks
- protostars/young stars



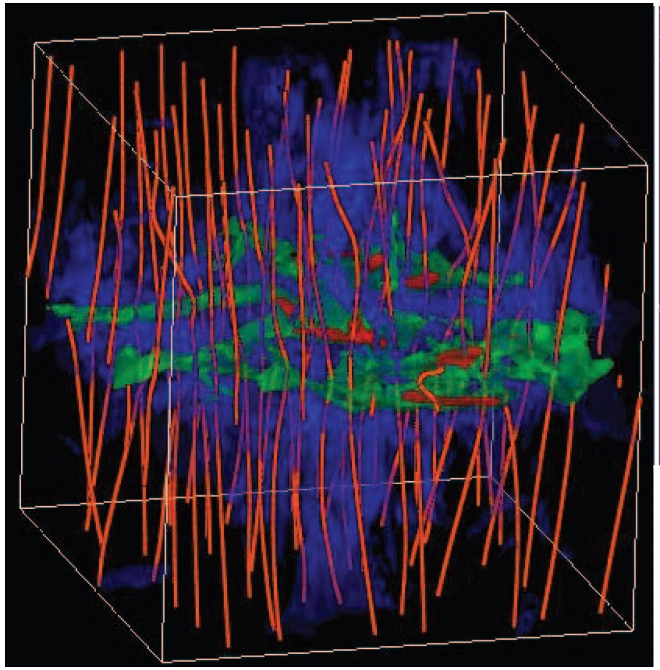
Grudic+ 2018

Inward: **gravity (G)**
Outward: **turbulence, magnetic field (B)**, thermal pressure, rotation, feedback…

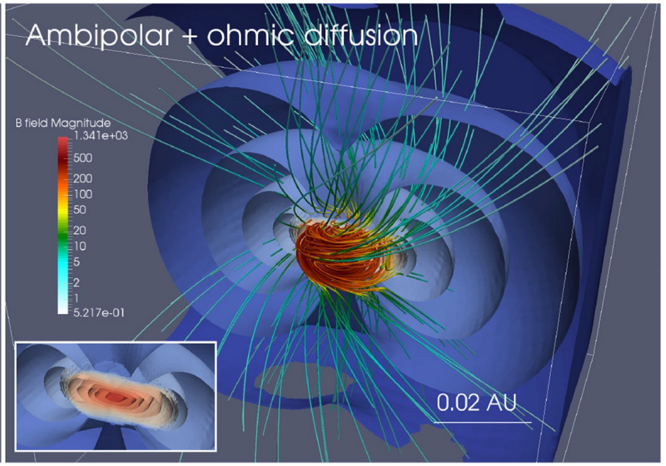
B in molecular clouds and star formation

- **B affect SF**: generate dense structures, guide mass flow, reduce fragmentation, launch outflows, reduce SF rate/efficiency…
- **B affected by SF**: distorted by gravity, disturbed by turbulence and (proto)stellar feedback…
- Two key questions: **B vs. Gravity** (normalized mass-to-flux ratio λ)? **B vs. Turbulence** ($\mathcal{M}_A$)?

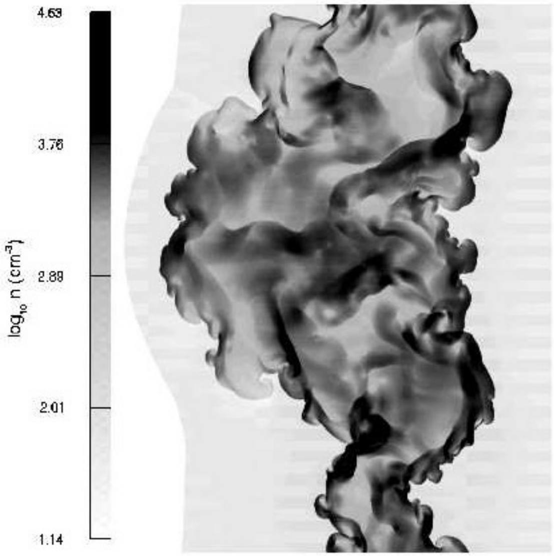
Magnetic field-dominated star formation OR Turbulence-dominated star formation



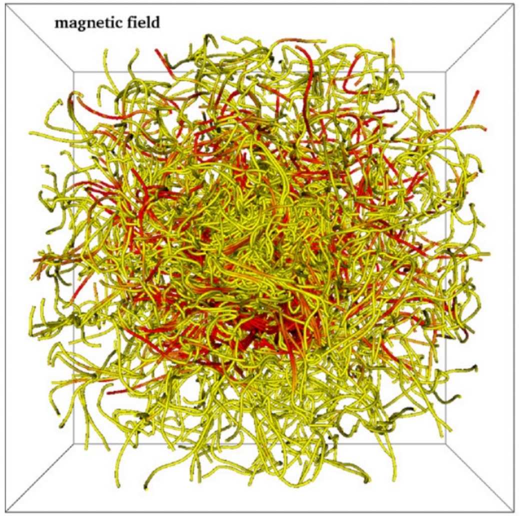
Nakamura & Li 2008



Vaytet+ 2018



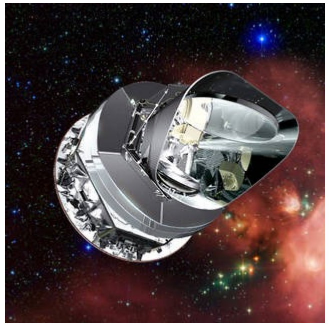
Mac Low & Klessen, 2004



Federrath+ 2011

How to trace B?

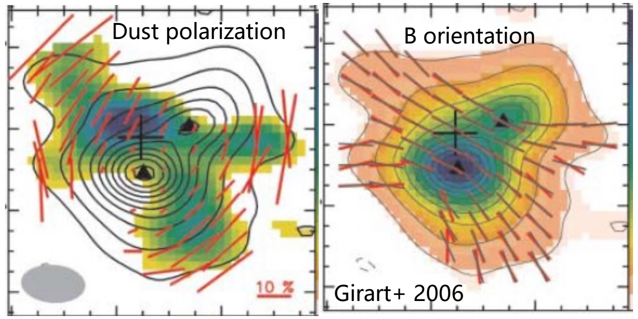
- Tracing $\mathbf{B_{pos}}$: **linearly polarized dust thermal emission** or extinction of starlight (grain alignment), line linear (and circular) polaization (G-K effect), line velocity gradient (VGT)
- Tracing B_{los}: line circular polarization (Zeeman) , ISM polarization (Faraday rotation measure).

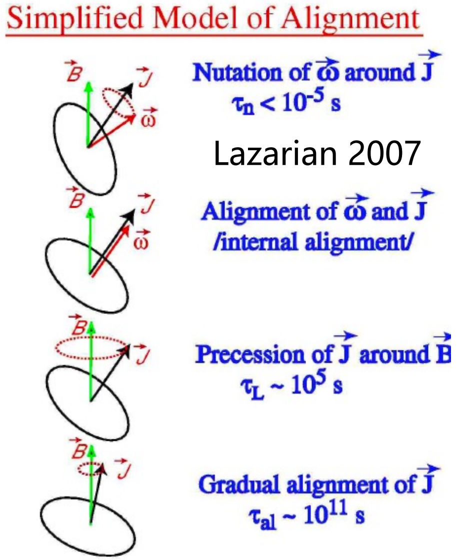


Planck: 5′ at 345 GHz

SOFIA: 5.1′′-18.7′′ at 53-214μm

Dust polarization due to grain alignment: radiative torque (Except for disk polarization.)





APEX: 20″ at 345 GHz

JCMT: 14″ at 850μm

SMA: arcsec to sub-arcsec

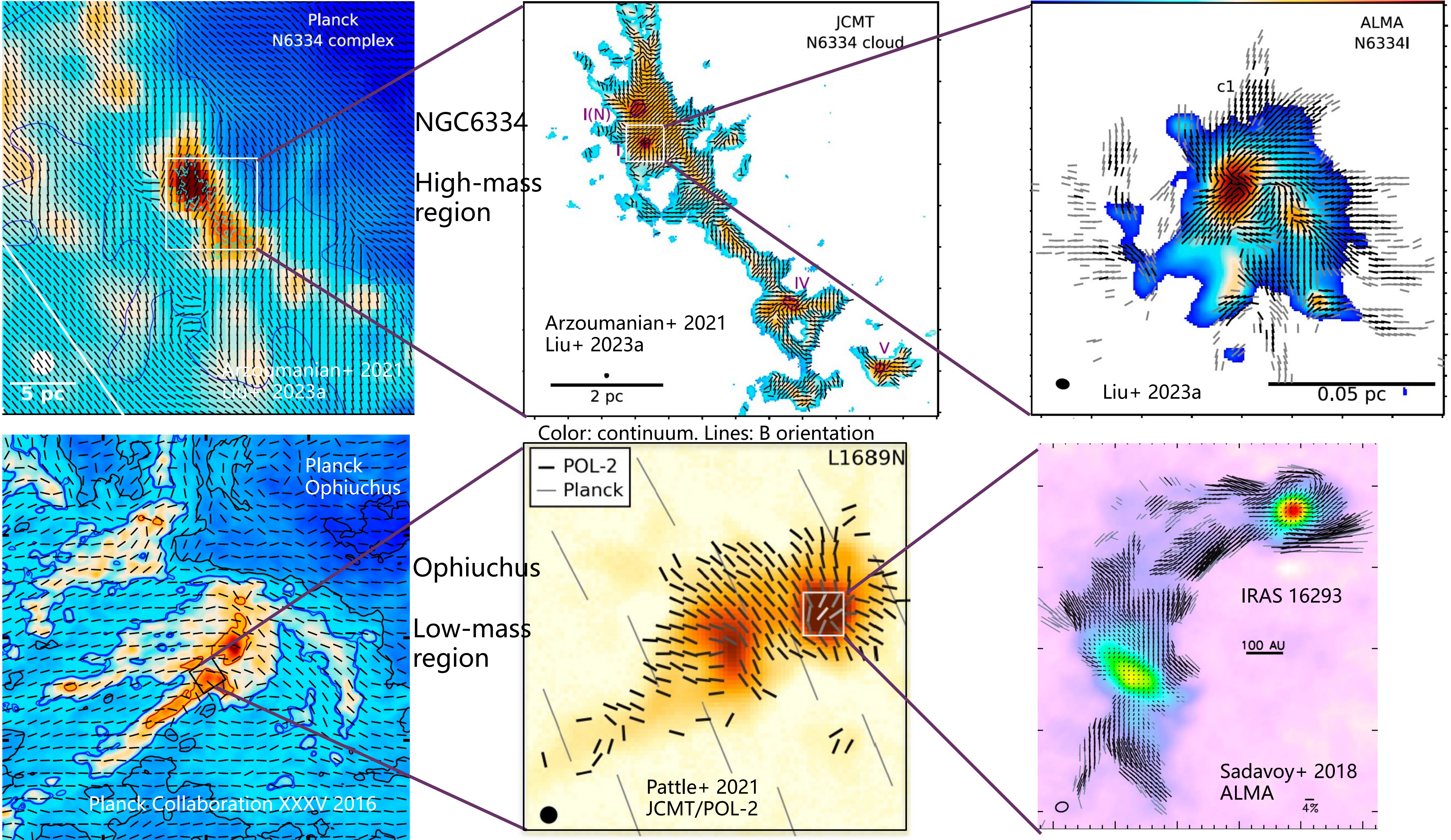
ALMA: arcsec to mas

Active polarimeter: APEX, JCMT(POL2), SMA, ALMA

Finished: Planck, BLASTPol

Decommissioned: CSO, SOFIA, BIMA, CARMA…

Commissioning: IRAM-30m(NIKA2), LMT(TolTEC)…


Planck
N6334 complex
5 pc
Arzoumanian+ 2021
Liu+ 2023a
NGC6334
High-mass
region
JCMT
N6334 cloud
I(N)
I
IV
V
Arzoumanian+ 2021
Liu+ 2023a
2 pc
ALMA
N6334I
c1
Liu+ 2023a
0.05 pc
Color: continuum. Lines: B orientation
Planck
Ophiuchus
Planck Collaboration XXXV 2016
Ophiuchus
Low-mass
region
POL-2
Planck
L1689N
Pattle+ 2021
JCMT/POL-2
IRAS 16293
100 AU
Sadavoy+ 2018
ALMA
4%

How to study B?

- Statistical tool to link observations and simulations
  - **Histogram of relative orientations analysis** (HRO, Soler+ 2013): observations of $\vec{B}_{\text{pos}}$ and N

- Quantitative methods to determine $\vec{B}_{\text{pos}}$ strength.
  - Davis-Chandrasekhar-Fermi method (DCF, Davis 1951, Chandrasekhar & Fermi 1953): needs observations of $\vec{B}_{\text{pos}}$, n, and v
  - Polarization-intensity gradient method (KTH, Koch, Tang, and Ho, 2012): needs observations of $\vec{B}_{\text{pos}}$, n, and N

(Three methods reviewed in Liu+ 2022b)

Histogram of relative orientation (HRO) analysis

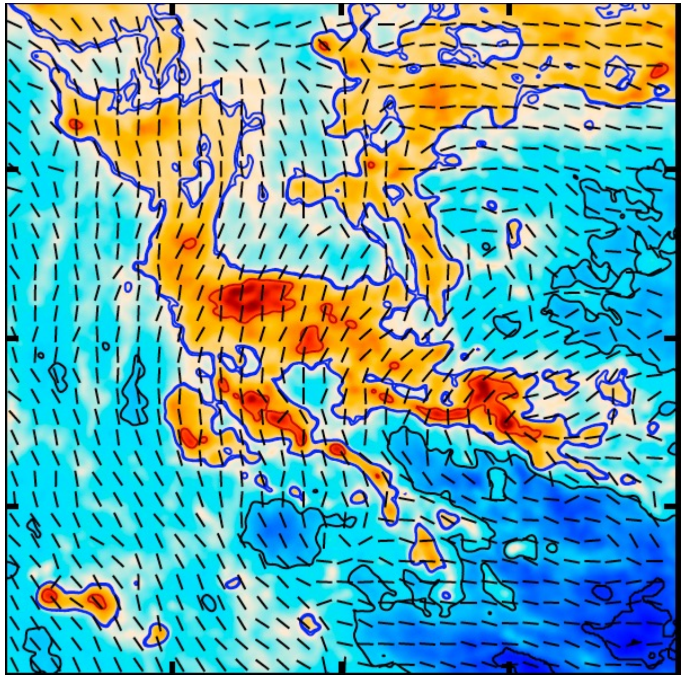
- HRO: characterize the relative orientation between B and N
- HRO shape parameter ξ for an area
  - $\xi>0$: tend to be parallel
  - $\xi<0$: tend to be perpendicular

$$\xi = \frac{A_0 - A_{90}}{A_0 + A_{90}}$$

A_0: $|\phi_{\rm B-N}| < 22.5°$

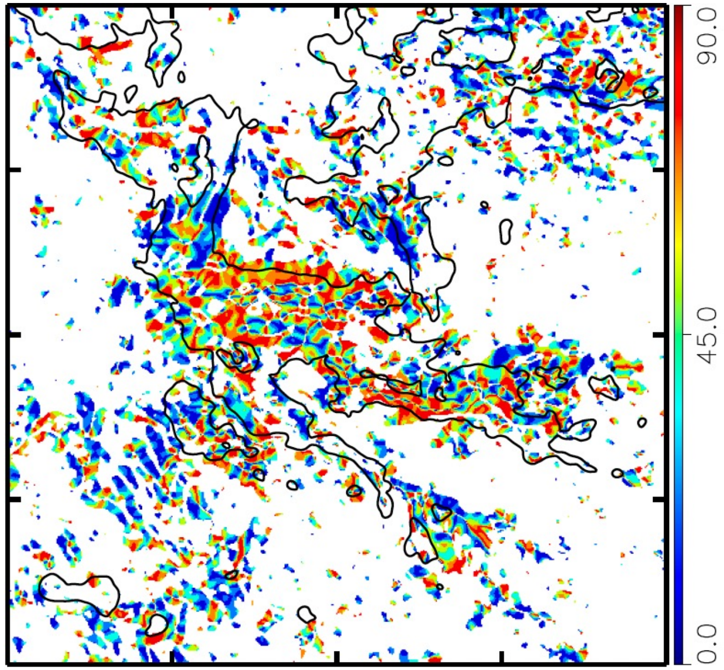
A_{90}: $67.5° < |\phi_{\rm B-N}| < 90°$

- Link properties of observations and simulations



Planck Collaboration XXXV 2016
Taurus

Color: column density (N) structure
Lines: B orientation

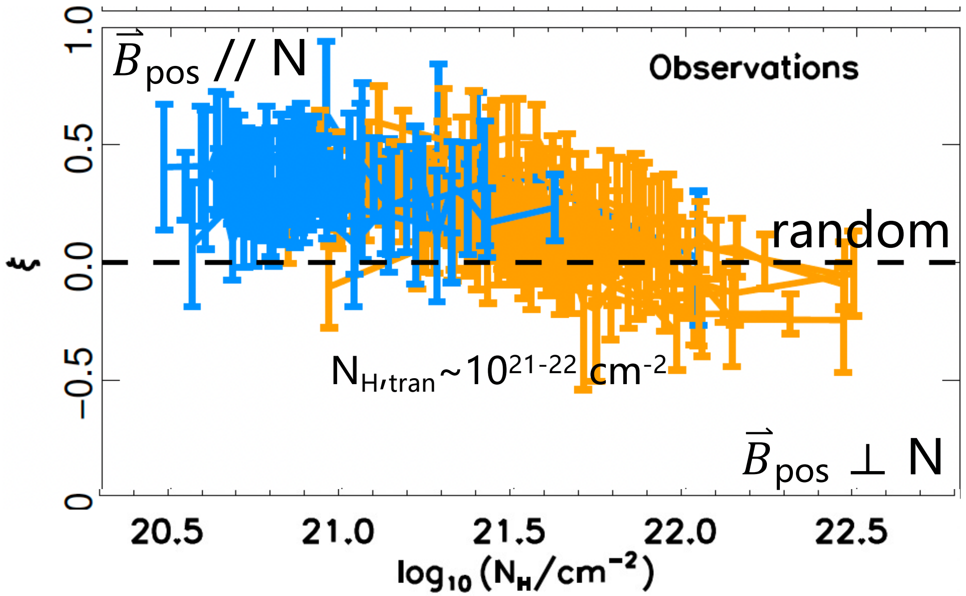


$$\phi_{\rm B-N} = \arctan(|\nabla N \times \boldsymbol{E}|, \nabla N \cdot \boldsymbol{E})$$

Angular difference between B and N contours (or E and N gradients)

HRO: observations

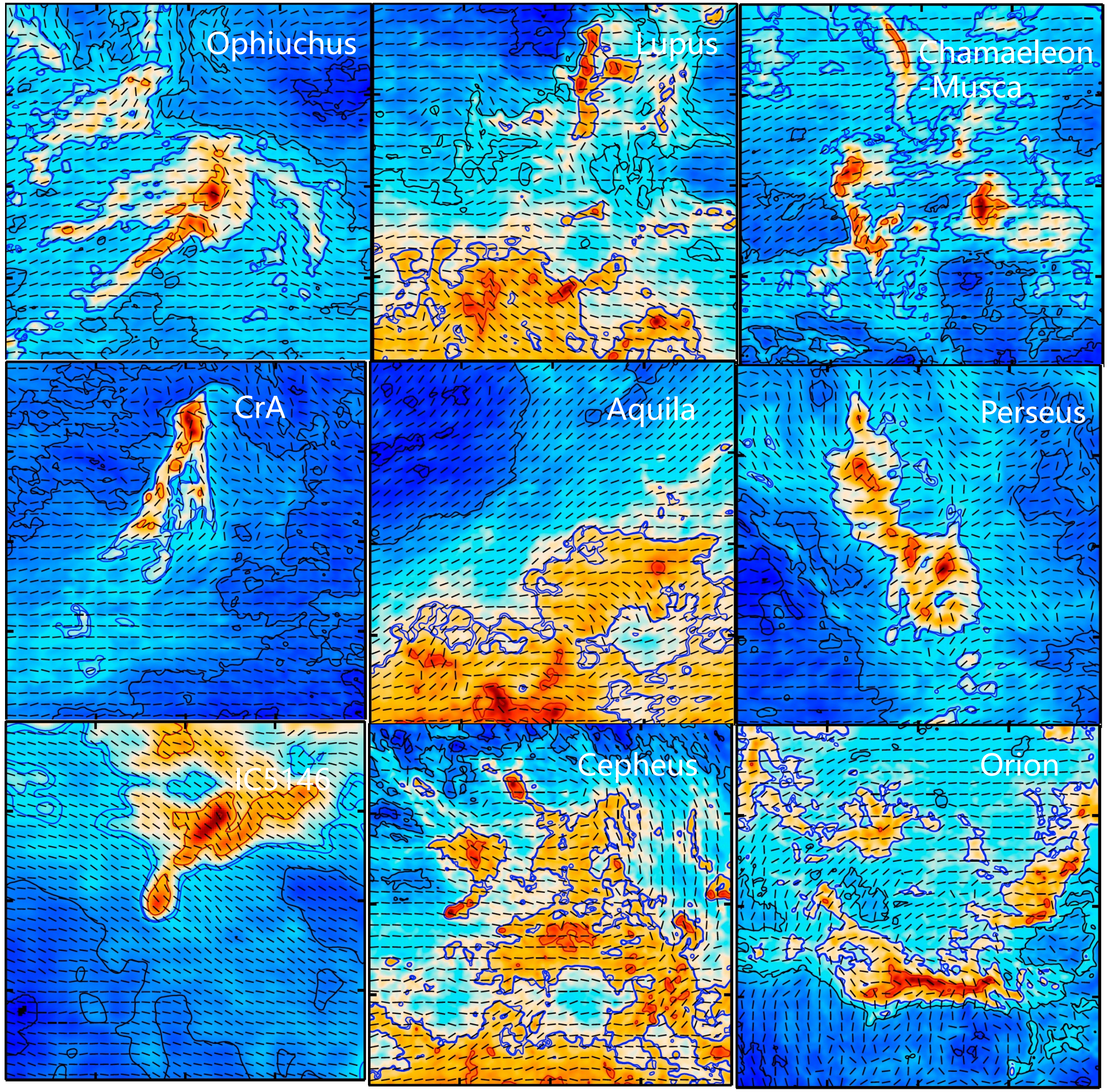
Planck Collaboration XXXV 2016
Gould belt clouds
Planck observations at 5′



Clouds: ξ decreases with increasing N.

Agree with trans-/sub-Alfvenic simulations.

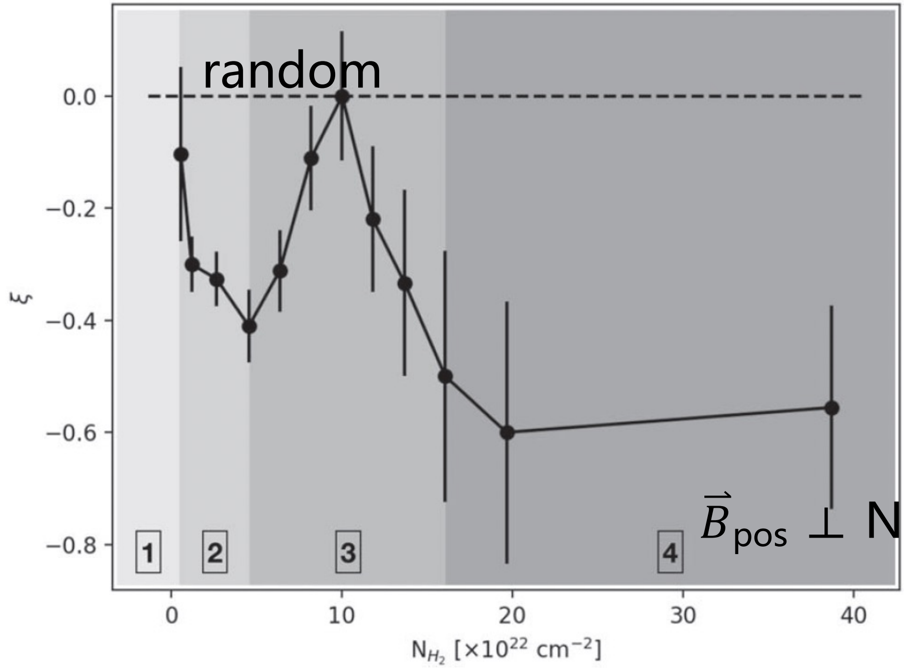
- $\mathcal{M}_A$ **<1**: B>turbulence, sub-Alfvenic
- $\mathcal{M}_A$ >1: B<turbulence, super-Alfvenic



10 – 1 pc scales

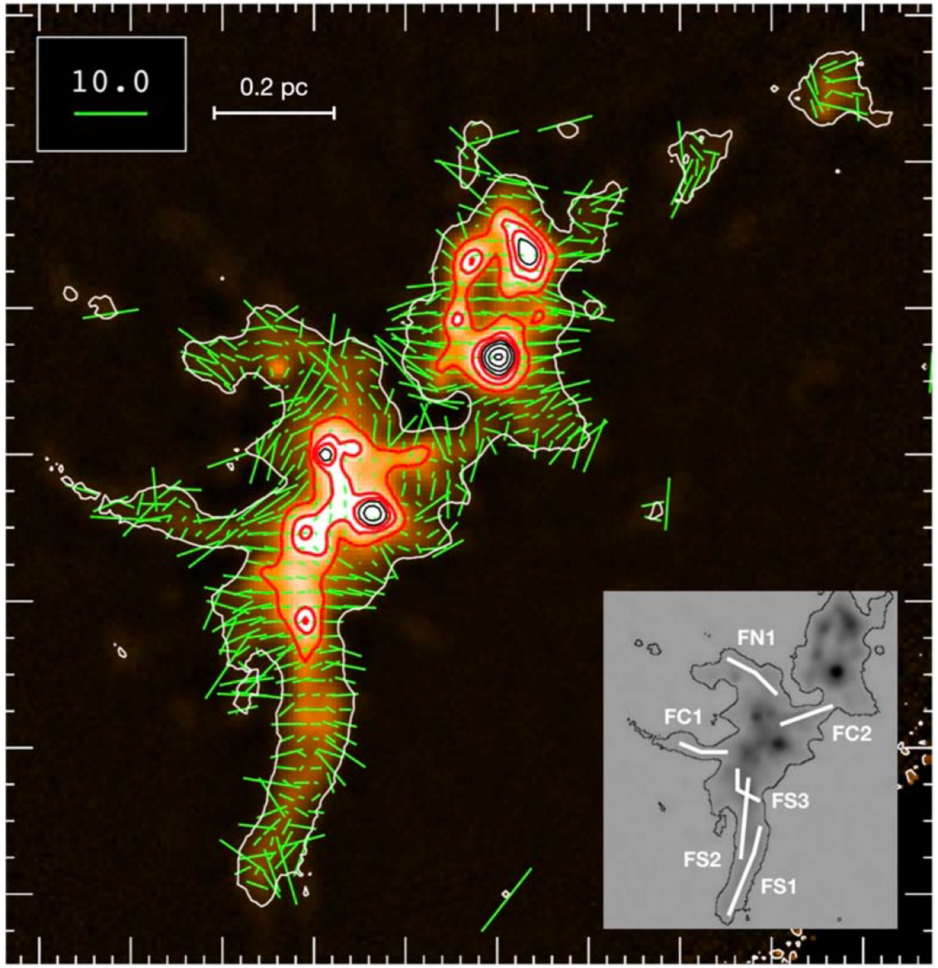
HRO: observations

Kwon, BISTRO+ 2022
Serpens Main
JCMT observations at 14″



Filaments/clumps: ξ decreases with increasing N

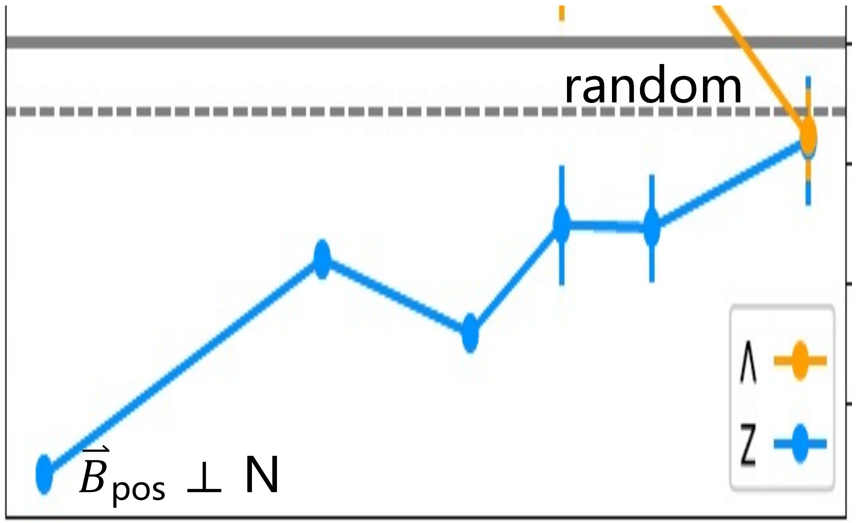
Transition back to random alignment at intermediate N, possibly due to accreting gas flows



1 – 0.1 pc scales

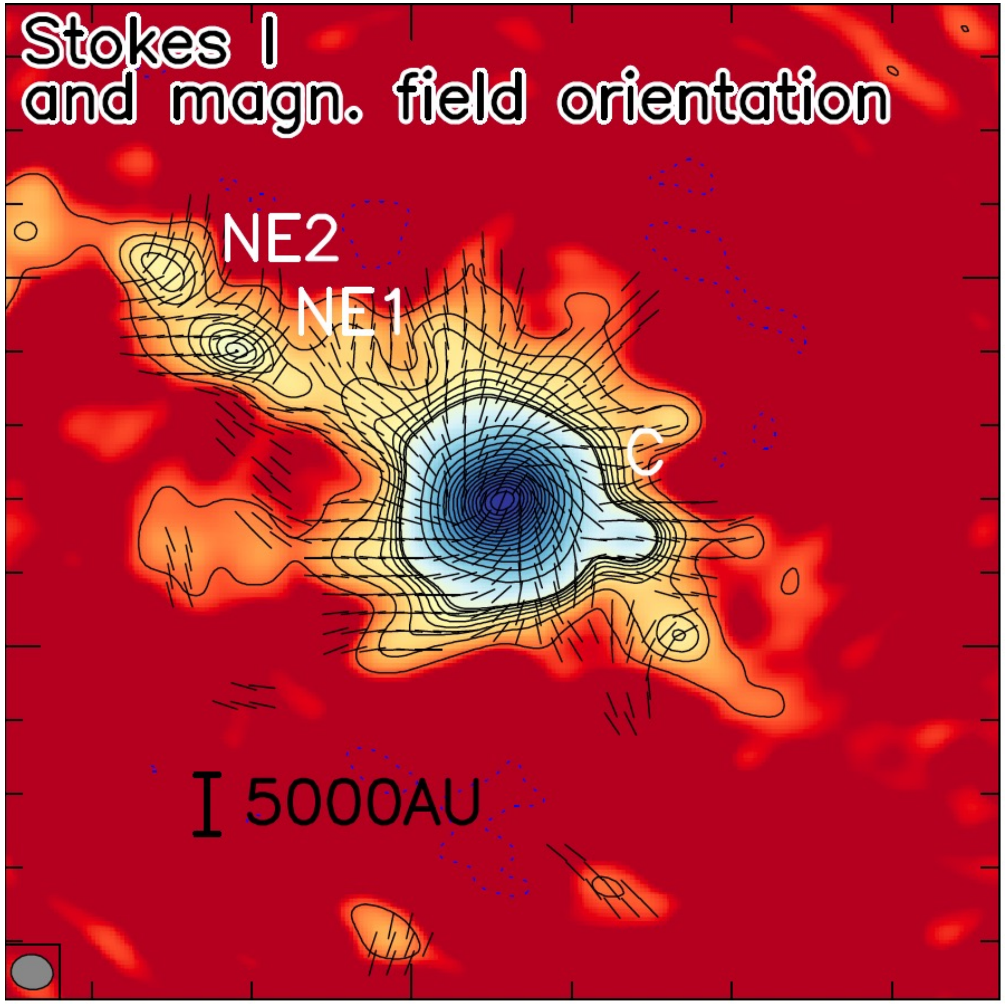
HRO: observations

Beuther+ 2020
G327.3
ALMA observations at 1″



(N)

Dense cores: Zx (similar to ξ) increases with increasing N. Possibly due to core/disk rotation



0.1 – 0.01 pc scales

HRO: simulations

Liu+ 2022b

$\mu = \lambda$

Size (pc)	Gravity	μ_0	$\mathcal{M}_{A0}$	μ	$\mathcal{M}_A$	$\xi > 0^d$	$\xi < 0^d$	Reference[e]
4	Yes	4.52-14.3	3.16-10	...	$\lesssim 1$	$A_{23} < 0$	$A_{23} > 0$, $\mathcal{M}_A > 1$, $\nabla \boldsymbol{v} < 0$	1,2,3
1	Yes	...	2.2-8.8	...	0.78-0.84	$\mathcal{M}_A < 1$	$\mathcal{M}_A > 1$	4
32[a]	Yes	...	0.6-0.8	0.54-0.72	...	$A_1 + A_{23} < 0$	$A_1 + A_{23} > 0$,$\mathcal{M}_A > 1$	5
10	No	...	0.5	...	...	...	$A_1 + A_{23} > 0$	6
10[b]	Yes	...	...	...	...	$\mu < 1$	$\mu > 1$	7
10	No	...	0.7	...	...	...	...	8
10	Yes	...	0.6	...	...	...	...	8
100[c]	Yes	...	0.6	...	...	...	$\mathcal{M}_A > 1$	9

[e] References: (1) Soler et al. (2013); (2) Planck Collaboration et al. (2016b); (3) Soler et al. (2017); (4) Chen et al. (2016); (5) Seifried et al. (2020); (6) Körtgen and Soler (2020); (7) Girichidis (2021); (8) Barreto-Mota et al. (2021); (9) Ibáñez-Mejía et al. (2022).

$$A_1 = \frac{\partial_i (\partial_j v_j)}{(R_k R_k)^{1/2}} r_i,$$

$$A_{23} = \frac{1}{2}(\partial_i v_j + \partial_j v_i)[r_i r_j - b_i b_j]$$

- $\vec{B}_{\rm pos}$ // N at low-N: (1). Initially super-Alfvenic turbulence stretch density? (2). Intrinsic properties of sub-Alfvenic MHD turbulence?

- $\vec{B}_{\rm pos} \perp$ N at higher-N: (1). Supersonic gas compression of local sub-Alfvenic turbulence? (2). Magnetized gravitational collapse? (3). Sub-Alfvenic large-scale B?

- $\vec{B}_{\rm pos}$ // N change to $\vec{B}_{\rm pos} \perp$ N: only found in **trans-/sub-Alfvenic environment**. Direct reason for transition may be related to local $\mathcal{M}_A > 1$, $A_1 + A_{23} > 0$, $\mu > 1$, and/or $\nabla v < 0$

- Needs investigation: transition back to random alignment at intermediate-N and high-N.

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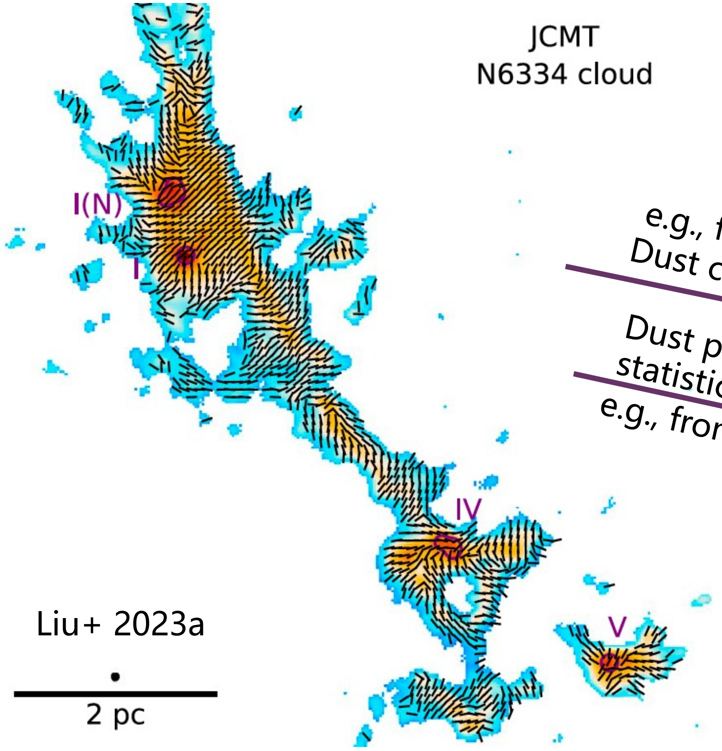
(Three methods reviewed in Liu+ 2022b)

Davis-Chandrasekhar-Fermi (DCF) method

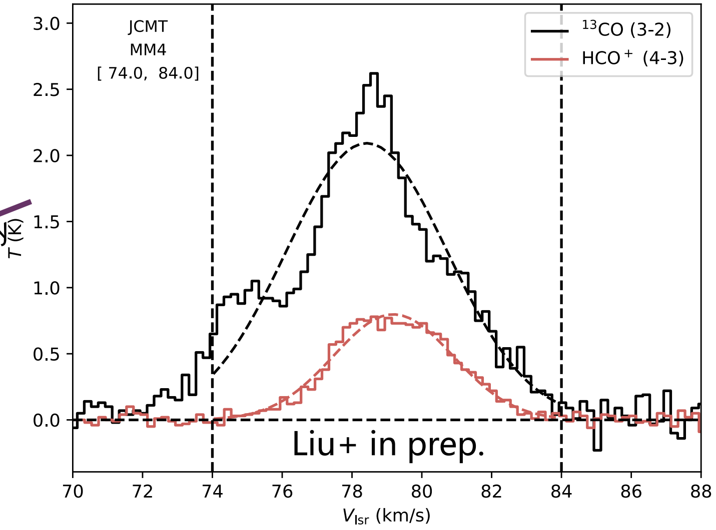


e.g., from SCUBA-2
Dust continuum -> gas density

Dust polarization ->
statistics of polarization angle
e.g., from POL-2

e.g., from HARP
Molecular line ->
statistics of velocity

$$B_{pos} \sim Q_c \frac{\sqrt{4\pi\rho}\,\delta v}{\delta\varphi}$$



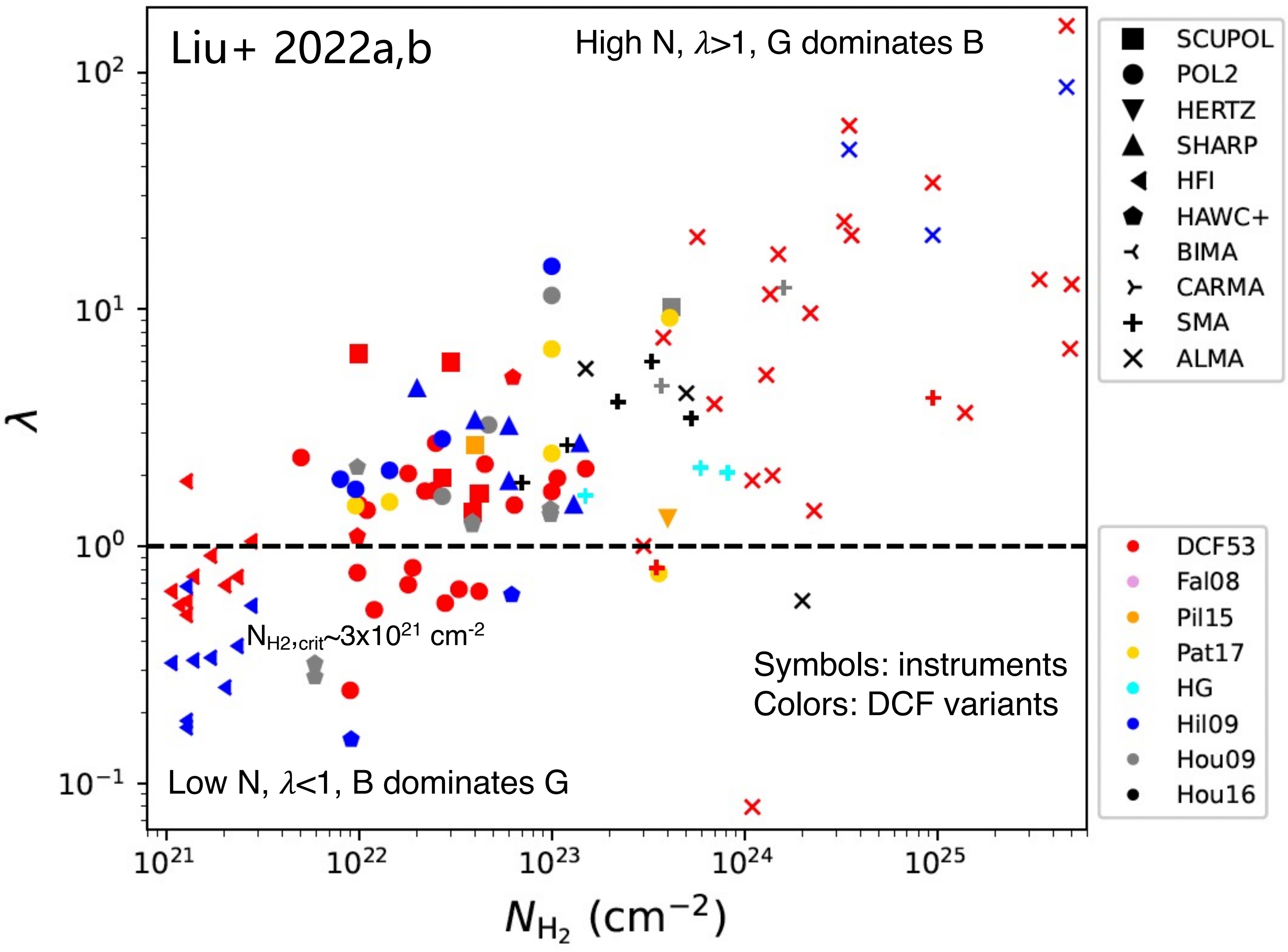
Uncertainties in basic assumptions and statistics of $\vec{B}_{pos}$ -> Correction factor Q_c

- Basic assumptions (Liu+ 2022b review)
  - Energy Equipartition
  - Isotropic turbulence.
  - Prominent underlying field
  - B^t/B^u and B^t/B^{tot} traced by statistics of observed $\vec{B}_{pos}$

- Factors affecting the statistics of $\vec{B}_{pos}$ (Liu+ 2022b)
  - Ordered field
  - Turbulent correlation
  - Line-of-sight signal integration
  - Beam smoothing and interferometer filtering
  - Projection effects

B vs. gravity (G): DCF compilation

- Liu+ 2022a,b: a **complete DCF compilation**. Correction factors for DCF variants from Liu+ 2021
- Normalized mass-to-flux ratio λ
- **λ gradually increases with column density (N).**
  - Loss of magnetic flux at high N
    - Ambipolar diffusion
    - Magnetic reconnection
  - Mass accumulation along B lines.
- High-mass SF region more gravity dominant than low-mass region



230 DCF estimations from 75 papers in the literature

B vs. turbulence: DCF compilation

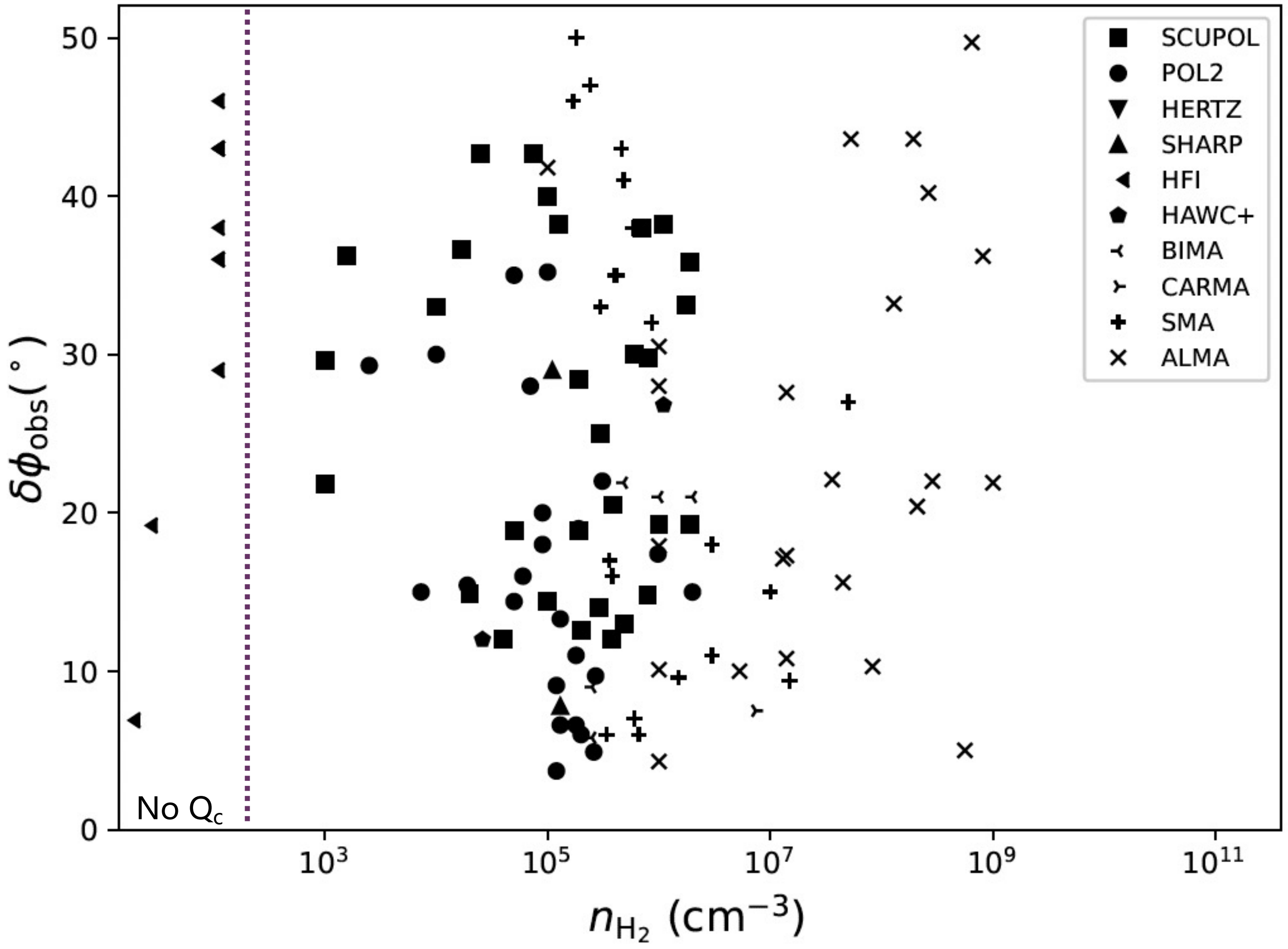
- Alfvenic Mach number
  - $\mathcal{M}_A$<1: B>turbulence, sub-Alfvenic
  - $\mathcal{M}_A$>1: B<turbulence, super-Alfvenic

$$\mathcal{M}_A \sim (f_t/f_u/Q_c/f_o)\delta\phi_{\rm obs}$$

- Cloud sub-structures $\overline{\mathcal{M}_A}$~0.9, averagely trans-Alfvenic?

- If DCF assumptions not satisfied, $\overline{\mathcal{M}_A} \gg 1$ (super-Alfvenic?)

Liu+ 2022a,b



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(Three methods reviewed in Liu+ 2022b)

Koch-Tang-Ho (KTH) method

- ψ: angle between intensity gradient (IG) and Local gravity (LG)
- α: angle between intensity structure and B
- Estimate B with ideal MHD equation

$$B = \sqrt{\frac{\sin\psi}{\sin\alpha}(\nabla P + \rho\nabla\phi_G)4\pi R_B},$$

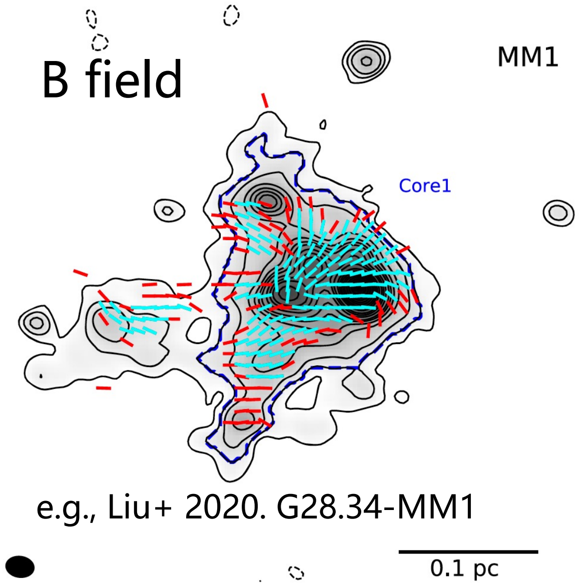
- B significance parameter Σ_B

$$\Sigma_B = \frac{\sin\psi}{\sin\alpha} = \frac{F_B}{|F_G + F_P|}$$

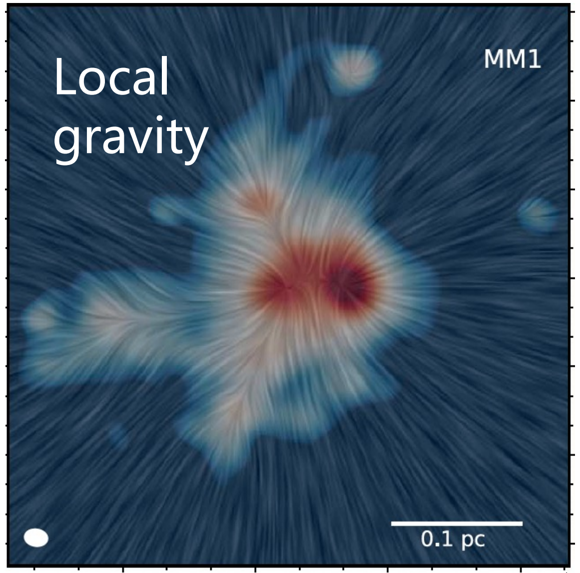
- Normalized mass-to-flux ratio λ_{KTH}

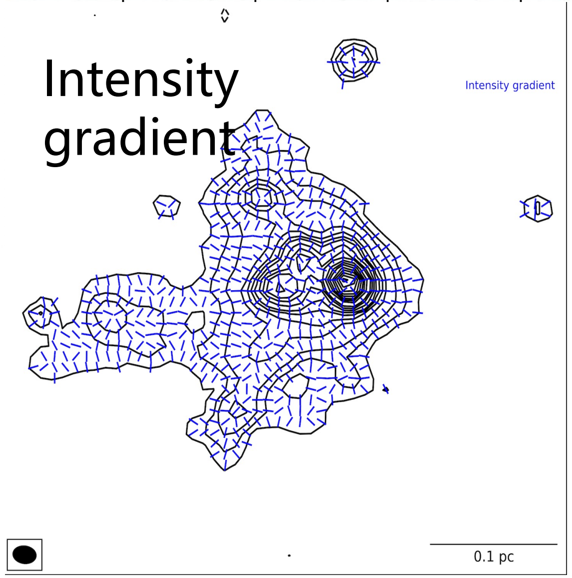
$$\lambda_{\rm KTH} = \langle \Sigma_B^{-1/2} \rangle \pi^{-1/2},$$

- Uncertainty not investigated with simulations yet.
- Observational KTH studies agree with HRO and DCF studies.



e.g., Liu+ 2020. G28.34-MM1

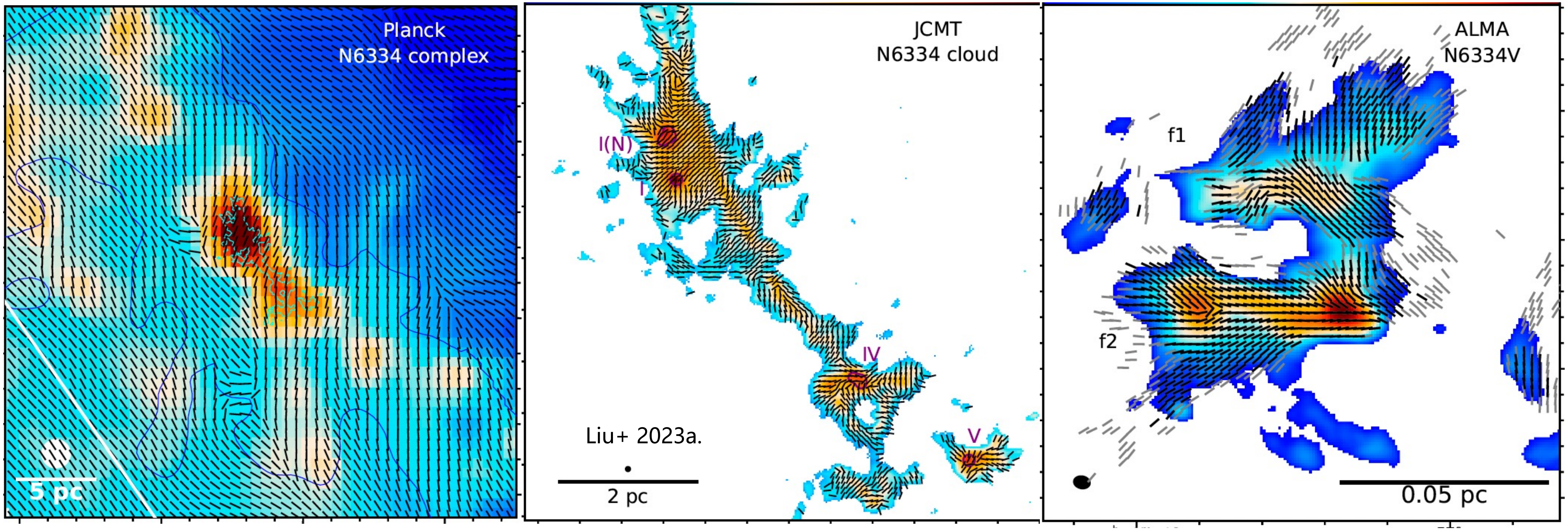




Combination of HRO and KTH methods

- A unified relative orientation analysis between B, column density gradient (NG), local gravity (LG), and velocity gradient (VG).

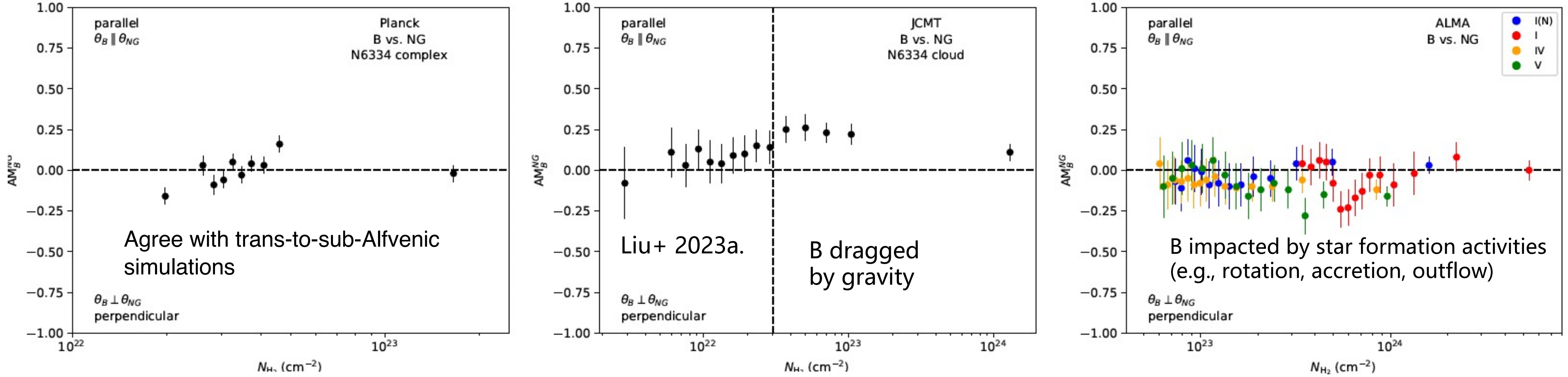
Color: dust continuum. Line: B orientation

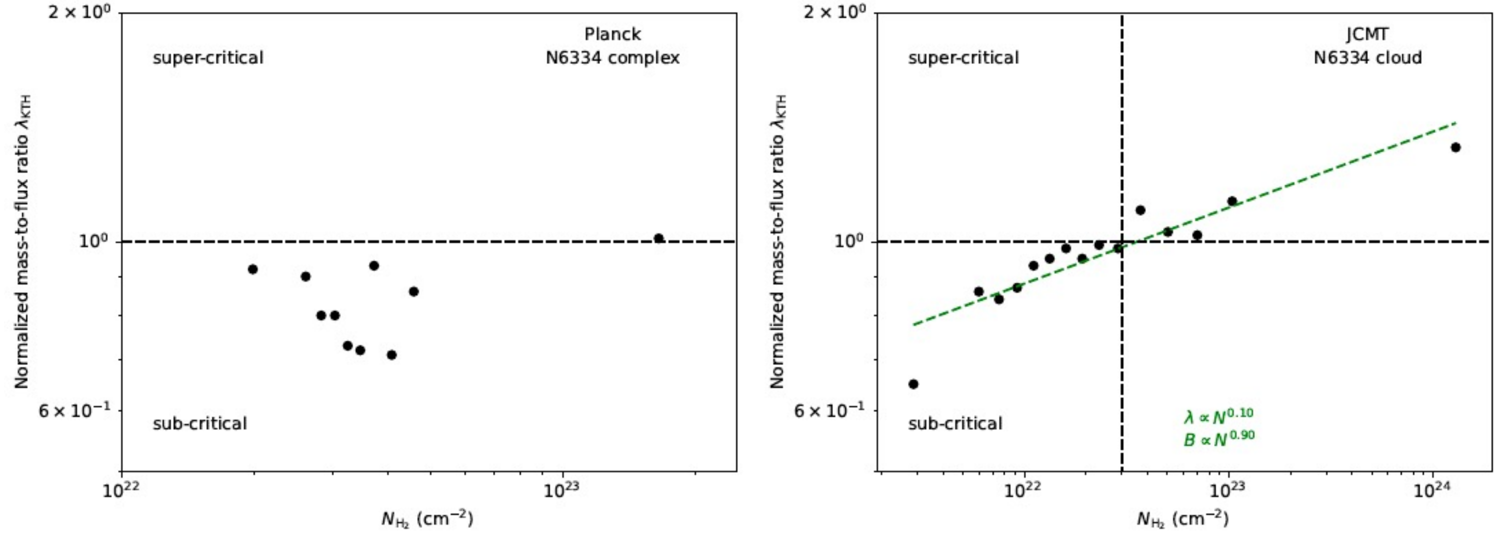


Liu+ 2023a: multi-scale (30 pc – 0.003 pc) B survey in massive star formation region NGC 6334

$$AM = \langle \cos(2\phi_{o1}^{o2}) \rangle$$

- Alignment measure (AM). AM>1: more parallel alignment. AM<1: more perpendicular alignment.
- AM-N relation. λ_{KTH}–N relation

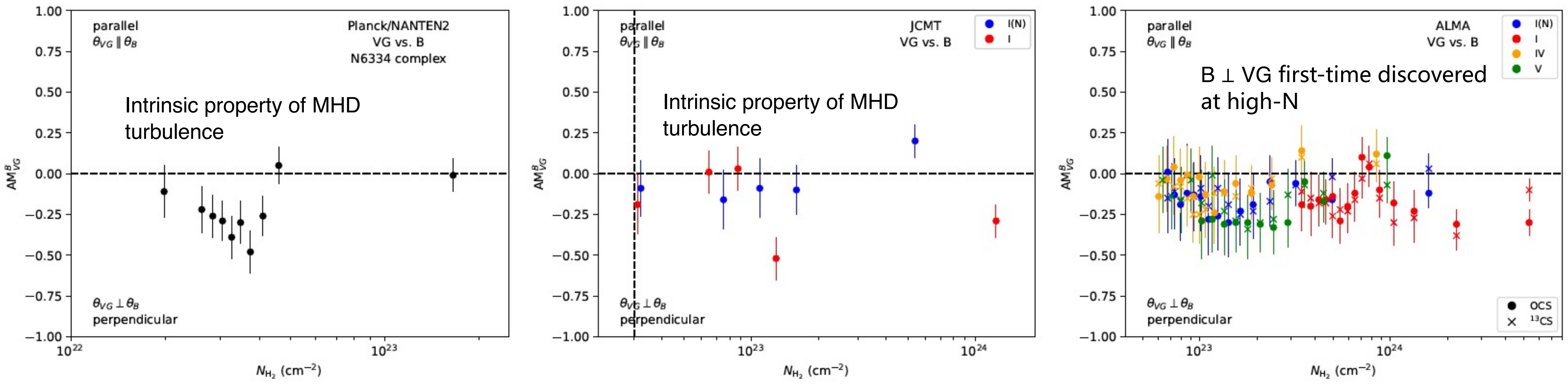




λ gradually increases with N.
Agree with DCF compilation in Liu 2022a,b

- B ⊥ velocity gradient (VG): sub-Alfvenic turbulence?

- Theoretical/numerical predictions: B ⊥ VG at low-N, reflecting MHD turbulence; B//VG at high-N, both dragged by gravity.



Summary

Thanks!

- DCF method
  - Energy equipartition under debate
  - B>G at low-N; B<G at high-N. $N_{H2,crit}$~$3x10^{21}$ cm^{-2}. Ambipolar diffusion, magnetic reconnection, or mass accumulation along B lines.
  - Cloud substructures are averagely trans-to-super-Alfvenic
  - High-mass regions are more gravity dominant
- HRO analysis
  - $\vec{B}_{pos}$ // N at low-N; $\vec{B}_{pos} \perp$ N at high-N. $N_{H,tran}$~10^{21-22} cm^{-2}, agrees with $N_{H2,crit}$ from DCF. Transition back to random alignment at higher N.
  - Reasons for alignment & transition to be investigated.
  - Clouds are trans-to-sub-Alfvenic.
- KTH method
  - Uncertainty to be investigated by simulations.
  - Observational results agree with the DCF and HRO studies.

General trend of B	B VS gravity	B VS turbulence
Low-N, large-scale, ~clouds	Sub-critical (B>G)	trans-/sub-Alfvenic (B≳turb)
Intermediate N and scale, ~clumps/cores	Super-critical (B<G)	averagely trans-/super-Alfvenic (B≲turb)?
High-N, small-scale, ~near protostars	B impacted by star formation activities (rotation, outflow, accretion…)	

My publications at EAO

- Liu+ 2022a: Compilation of B estimations from DCF in the literature
- Liu+ 2022b: Review of DCF, HRO, and KTH methods
- Liu+ 2023a: Multi-scale relative orientation analysis in NGC 6334
- Liu+ 2023b: turbulence cascade in NGC 6334 (not introduced)