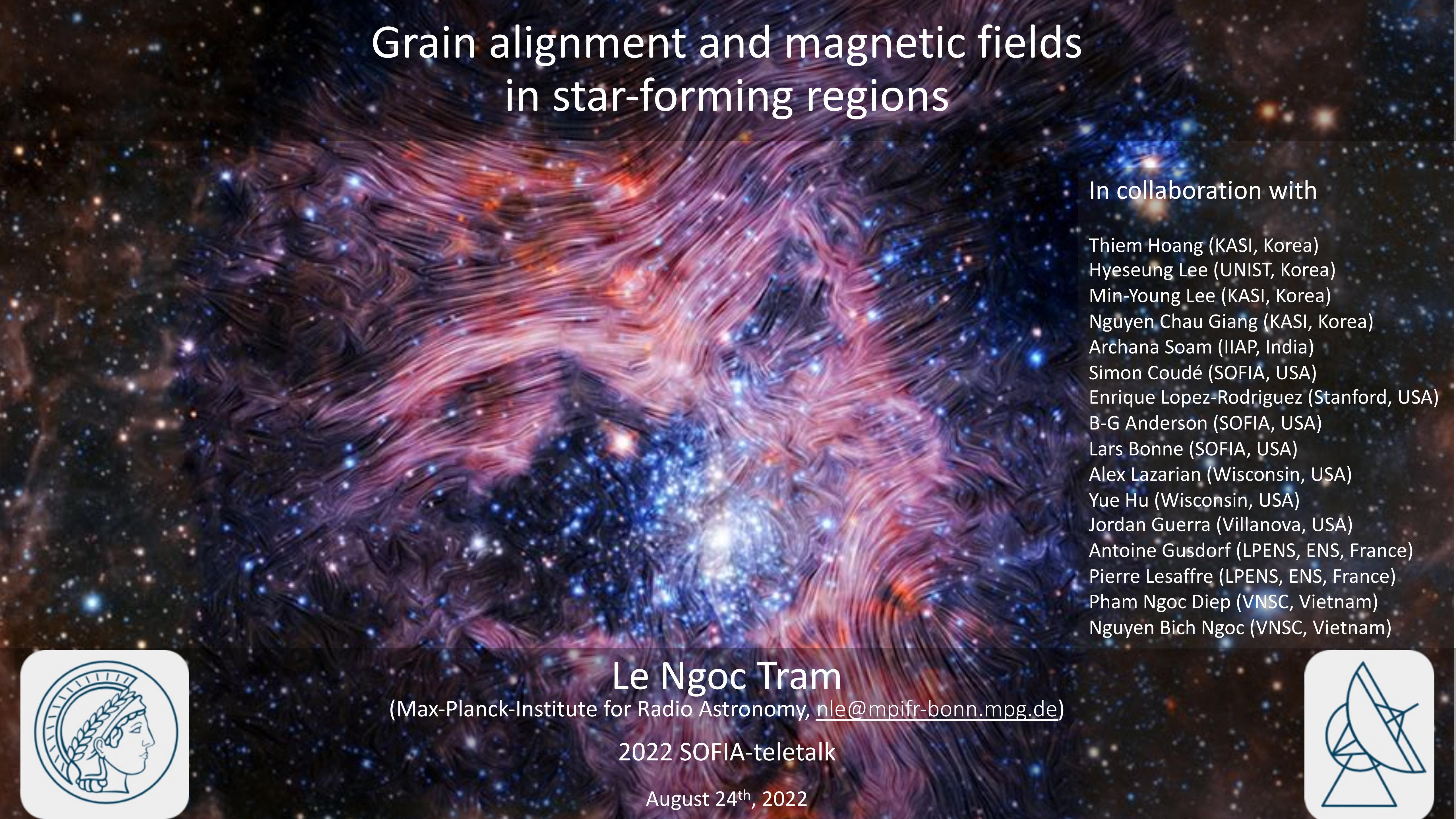


Grain alignment and magnetic fields in star-forming regions

In collaboration with

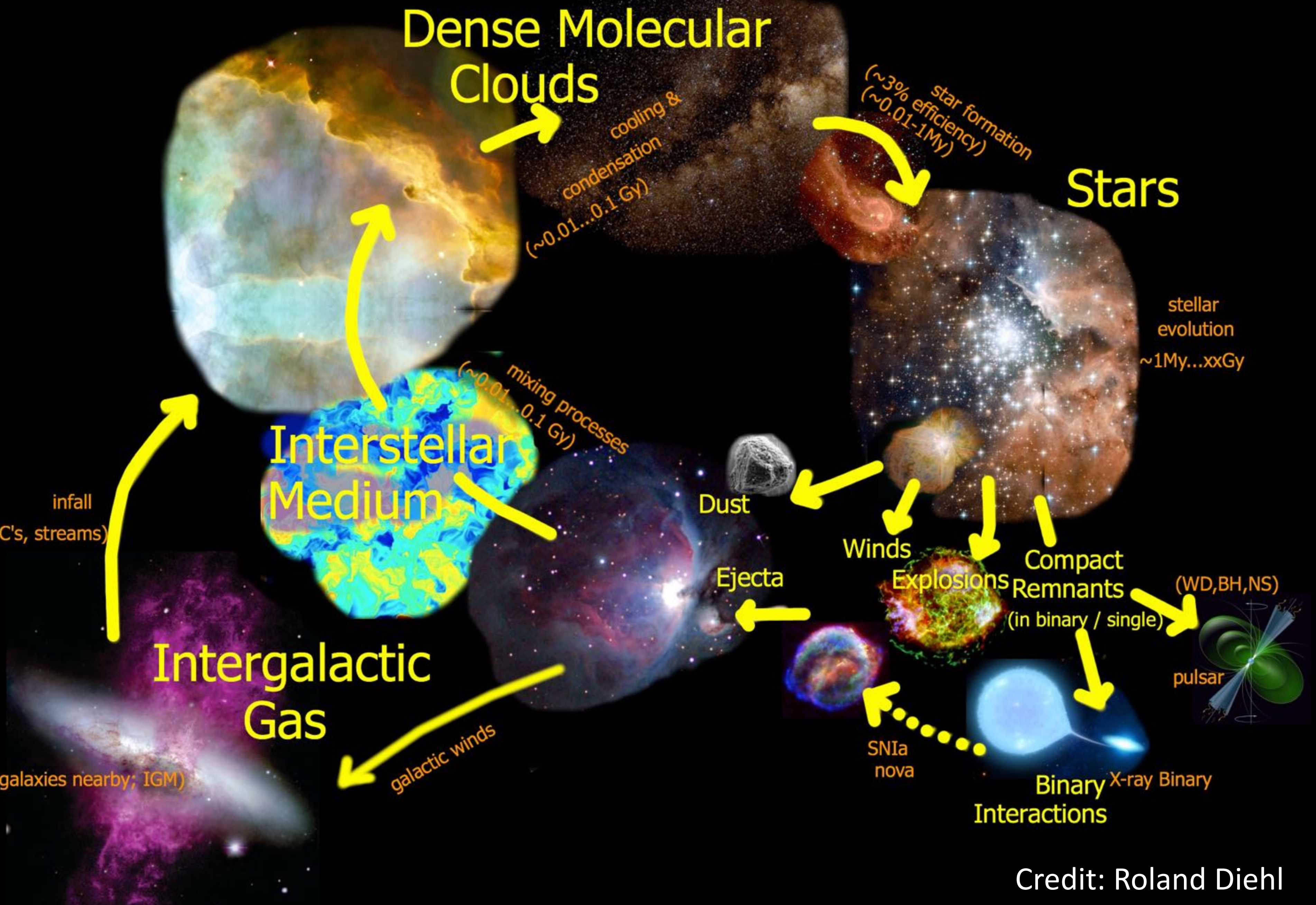
Thiem Hoang (KASI, Korea)
Hyeseung Lee (UNIST, Korea)
Min-Young Lee (KASI, Korea)
Nguyen Chau Giang (KASI, Korea)
Archana Soam (IIAP, India)
Simon Coudé (SOFIA, USA)
Enrique Lopez-Rodriguez (Stanford, USA)
B-G Anderson (SOFIA, USA)
Lars Bonne (SOFIA, USA)
Alex Lazarian (Wisconsin, USA)
Yue Hu (Wisconsin, USA)
Jordan Guerra (Villanova, USA)
Antoine Gusdorf (LPENS, ENS, France)
Pierre Lesaffre (LPENS, ENS, France)
Pham Ngoc Diep (VNSC, Vietnam)
Nguyen Bich Ngoc (VNSC, Vietnam)

Le Ngoc Tram
(Max-Planck-Institute for Radio Astronomy, nle@mpifr-bonn.mpg.de)

2022 SOFIA-teletalk

August 24th, 2022

Stellar evolution and Feedback



Dense Molecular Clouds

cooling & condensation (~0.01...0.1 Gy)

star formation (~3% efficiency) (~0.01-1My)

Stars

stellar evolution ~1My...xxGy

Dust

Winds

Explosions

Compact Remnants (in binary / single)

(WD,BH,NS)

pulsar

Binary Interactions

X-ray Binary

SNIa nova

Ejecta

mixing processes (~0.01...0.1 Gy)

Interstellar Medium

galactic winds

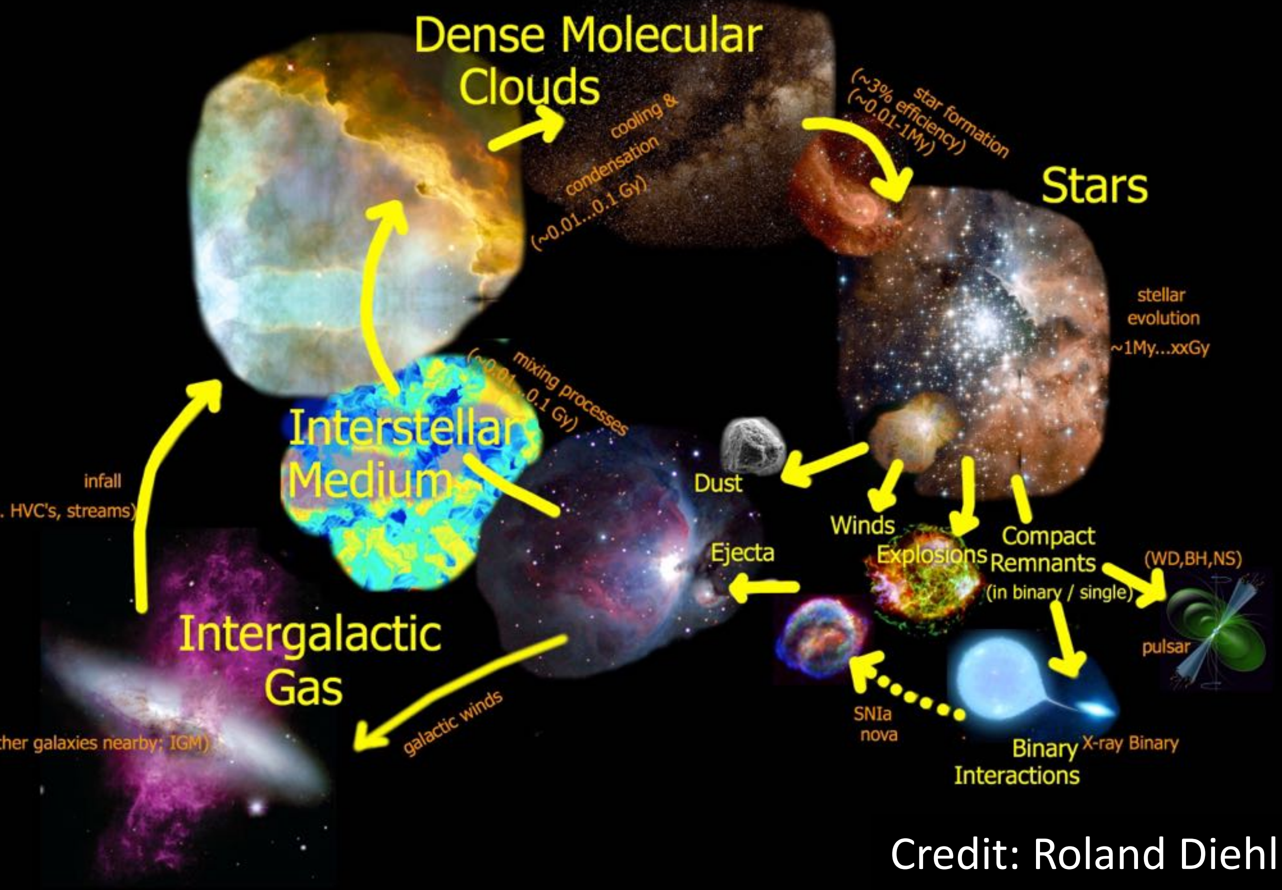
Intergalactic Gas

(other galaxies nearby; IGM)

infall (e.g. HVC's, streams)

Credit: Roland Diehl

Stellar evolution and Feedback



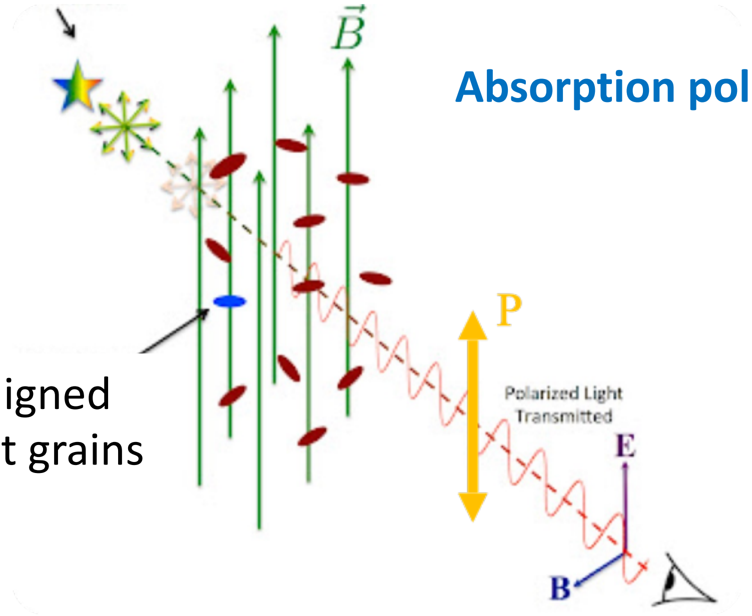
Credit: Roland Diehl

Star is a “bad neighbor”

- Positive feedback
  - Alter physical-chemical stages of nearby/parents clouds
  - Make their properties diversed
  - Falicitate new gen. of stars to form
  - etc …
- Negative feedback
  - Disturb/destroy nearby/parent clouds
  - Halt or slow formation of new star gen.
  - etc …

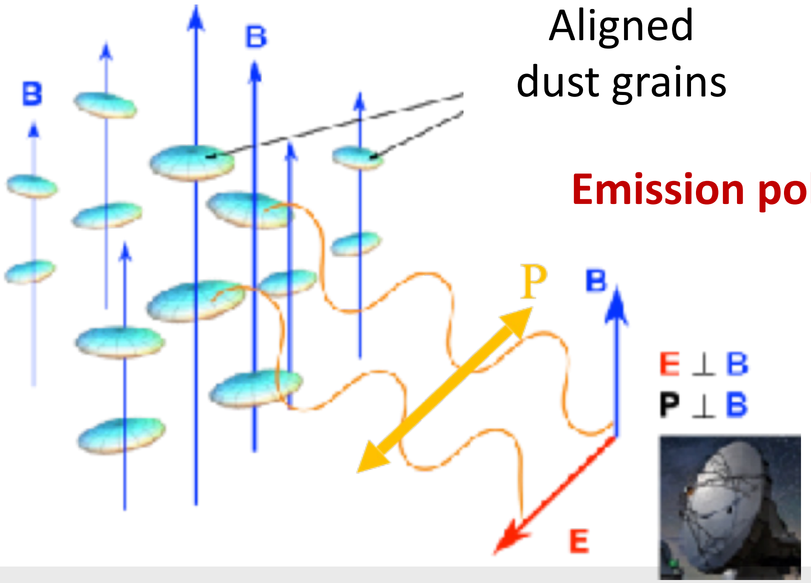
Carina Nebula
Credit: ***NASA, ESA, CSA, and STScI***

Probing magnetic fields via dust polarization



Absorption polarization

Aligned dust grains



Aligned dust grains

Emission polarization

☐ Absorption polarization is parallel to B-fields

➢ Observable at UV-optical-NIR wavelengths

➢ Pol. vectors —> POS morphology

☐ Emission polarizaiton is perpendicular to B-fields

➢ Observable at FIR-Submm wavelengths

➢ Rotating the pol. vectors by 90^o —> POS morphology

☐ B-strength could be estimated by DCF method (Davis 1951; Chandrasekhar-Fermi 1953)

☐ Widely used to probe B-fields in various scales

Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

Probing magnetic fields via dust polarization


Milky Way: Orion Nebula
Credit: SOFIA/NASA


Galaxy: NGC 1068
Credit: SOFIA/NASA

- ☐ Absorption polarization is parallel to B-fields
  - ➢ Observable at UV-optical-NIR wavelengths
  - ➢ Pol. vectors —> POS morphology

- ☐ Emission polarizaiton is perpendicular to B-fields
  - ➢ Observable at FIR-Submm wavelengths
  - ➢ Rotating the pol. vectors by 90^o —> POS morphology

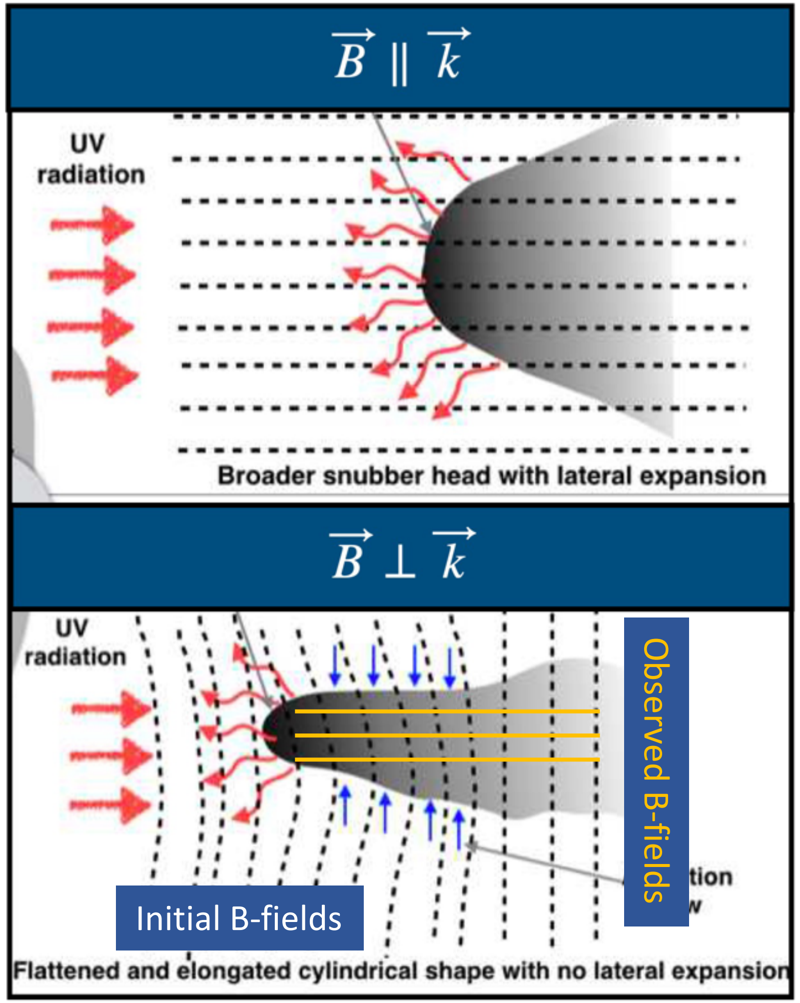
- ☐ B-strength could be estimated by DCF method (Davis 1951; Chandrasekhar-Fermi 1953)

- ☐ Widely used to probe B-fields in various scales

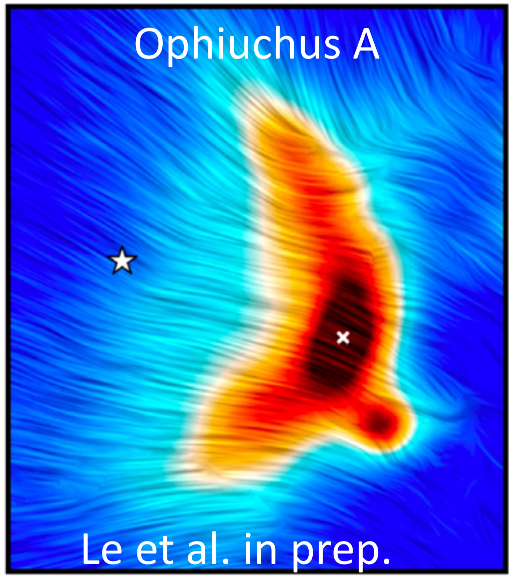
Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

Role magnetic fields in regulating MC evolution

Uniform Bfields

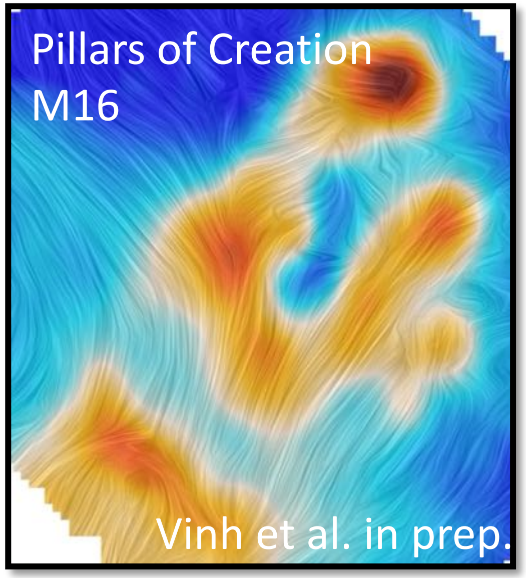


Henney et al. 2009; Mackey & Lim 2011



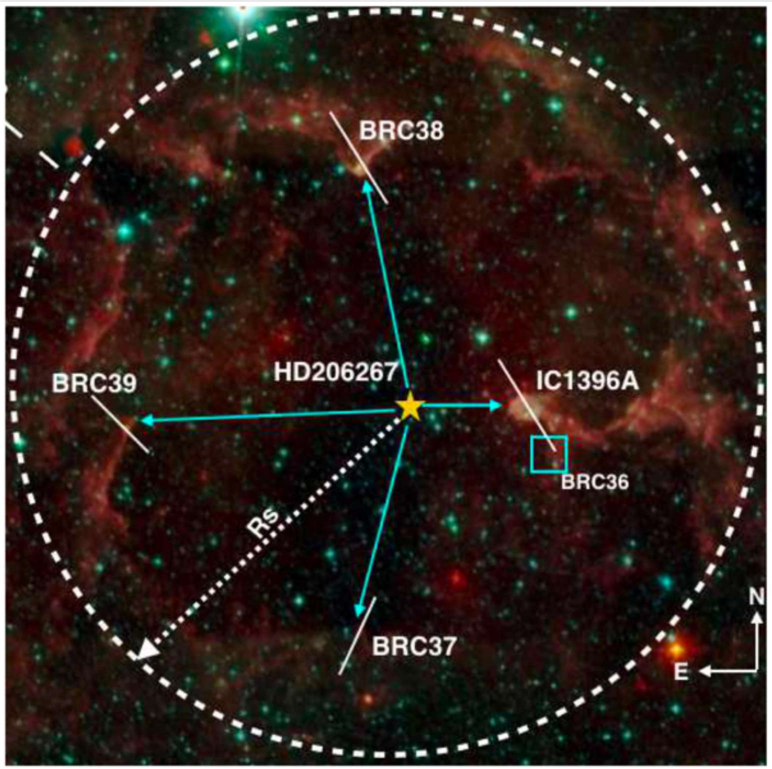
Ophiuchus A

Le et al. in prep.



Pillars of Creation
M16

Vinh et al. in prep.



IC 1396
(Soam et al. 2018)

Role of magnetic fields in star-formation

Starlight pol. Devaraj et al. (2021)

Gravity, **Bfields** and **turbulence** are keys to study star-formation

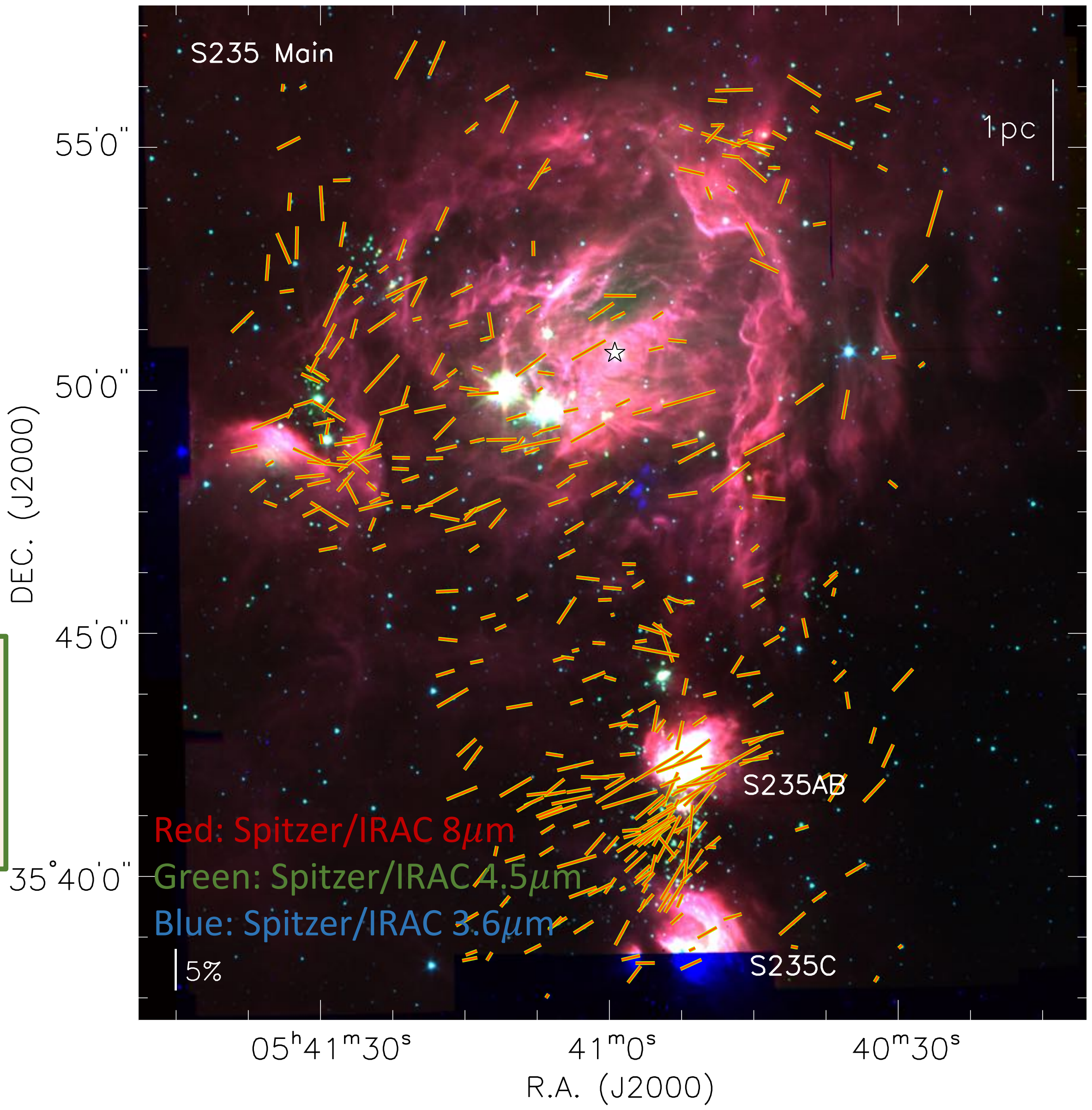
- ☐ Gravity leads to collapse
- ☐ B-field supports against that collapse
- ☐ Turbulences play ”dual role”
  - ➢ Supports against gravitational collapse
  - ➢ Produces local compression

Alfvenic number (“turbulence-to-magnetic ratio”)

- ❖ $M_A>1$: super-Alfvenic (strong turbulence)
- ❖ $M_A<1$: sub-Alfvenic (strong magnetic fields)

Mass-to-flux ratio (“gravity-to-magnetic ratio”)

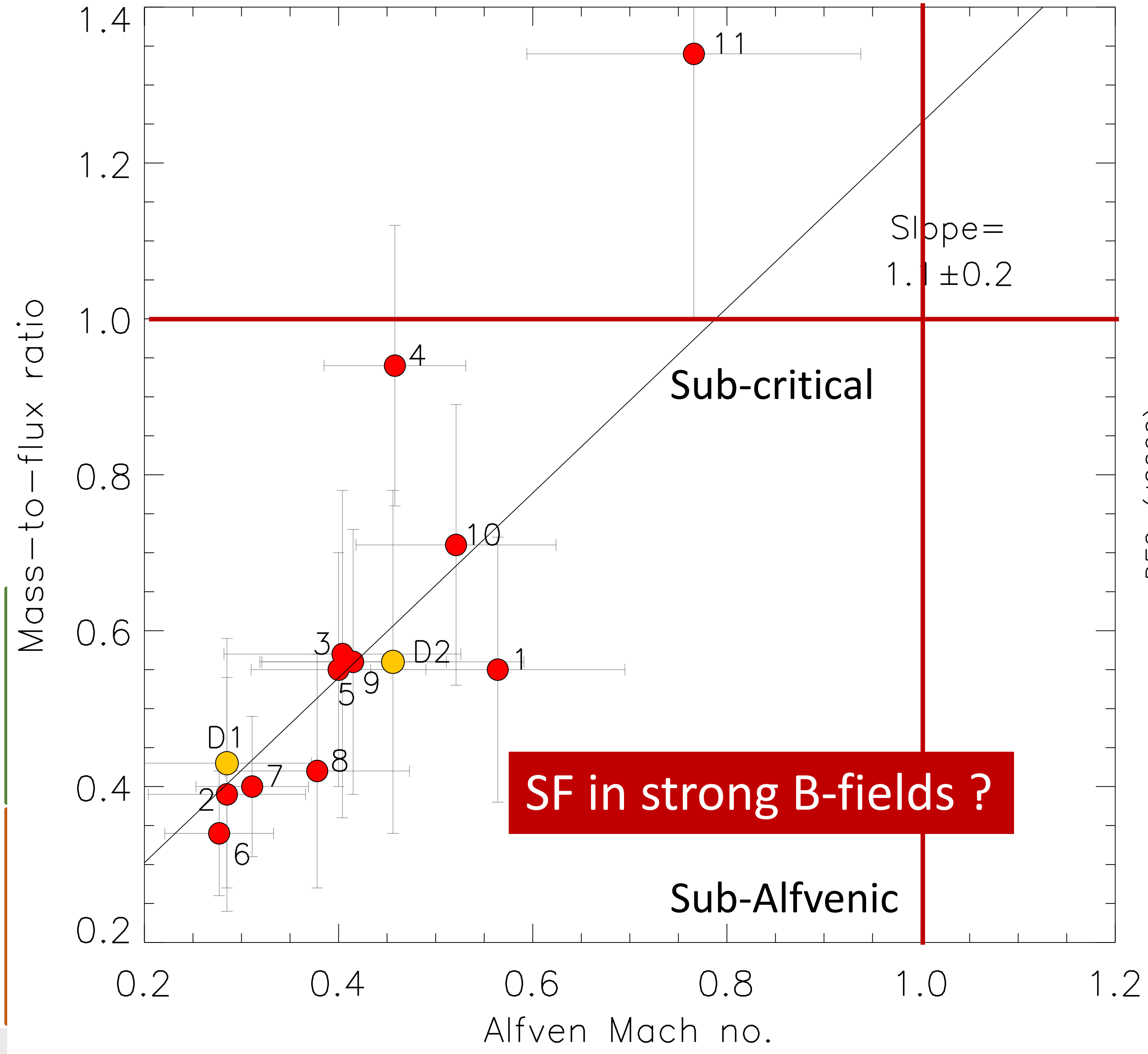
- ❖ $\lambda>1$: super-critical (gravity dominant over)
- ❖ $\lambda<1$: sub-critical (strong magnetic fields)



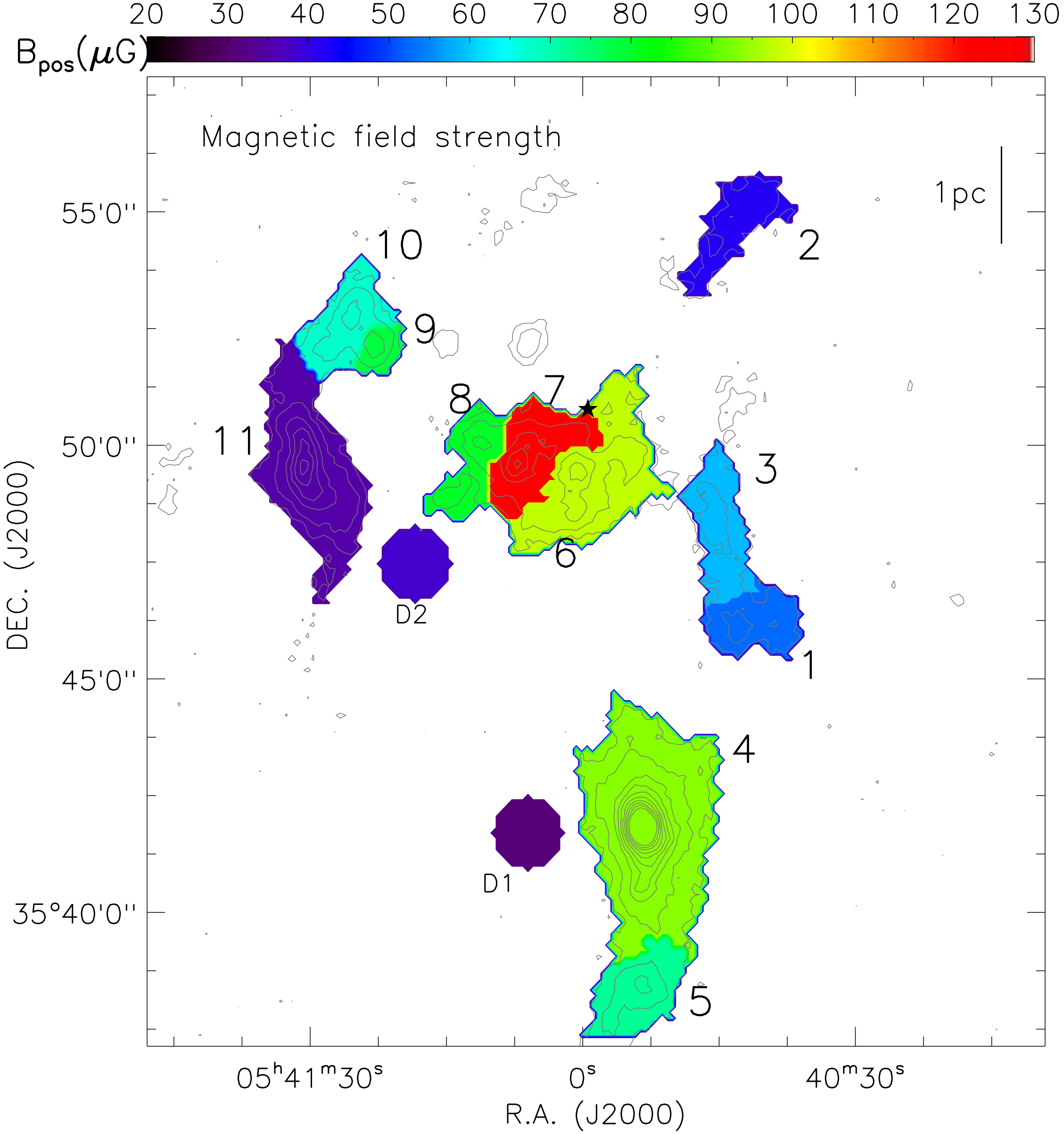
Role of magnetic fields in star-formation

Starlight pol.

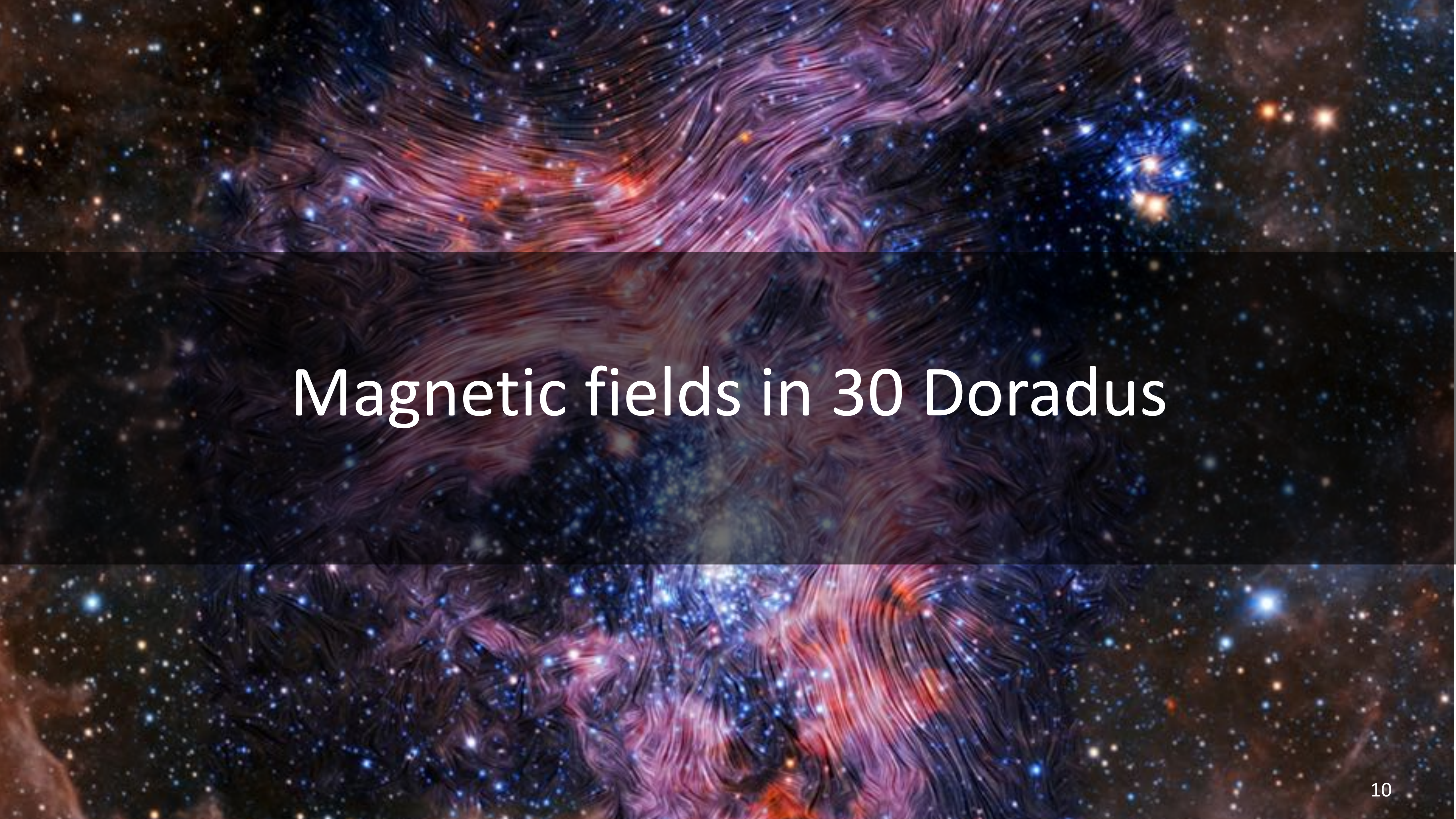
Devaraj et al. (2021)

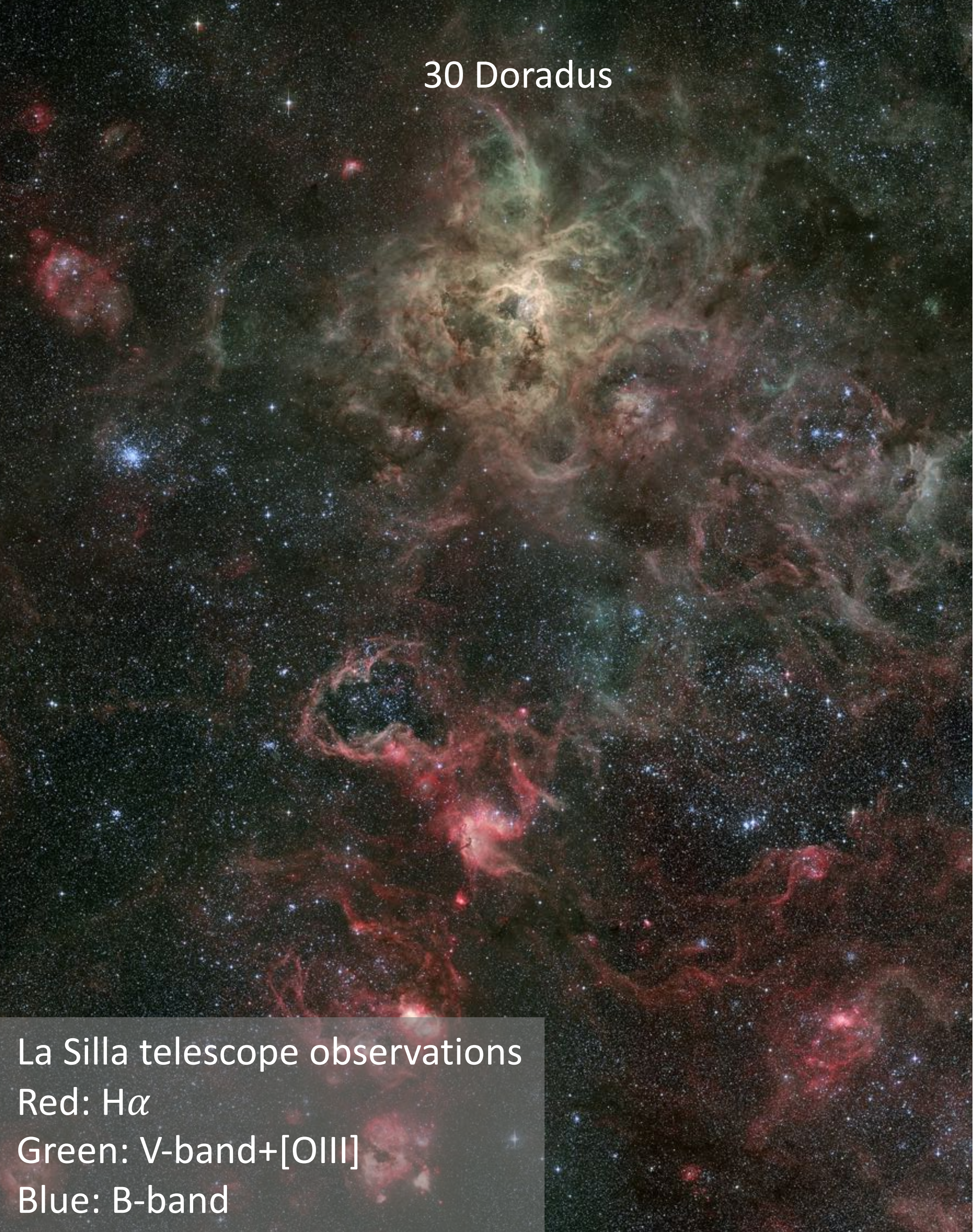


SF in strong B-fields ?

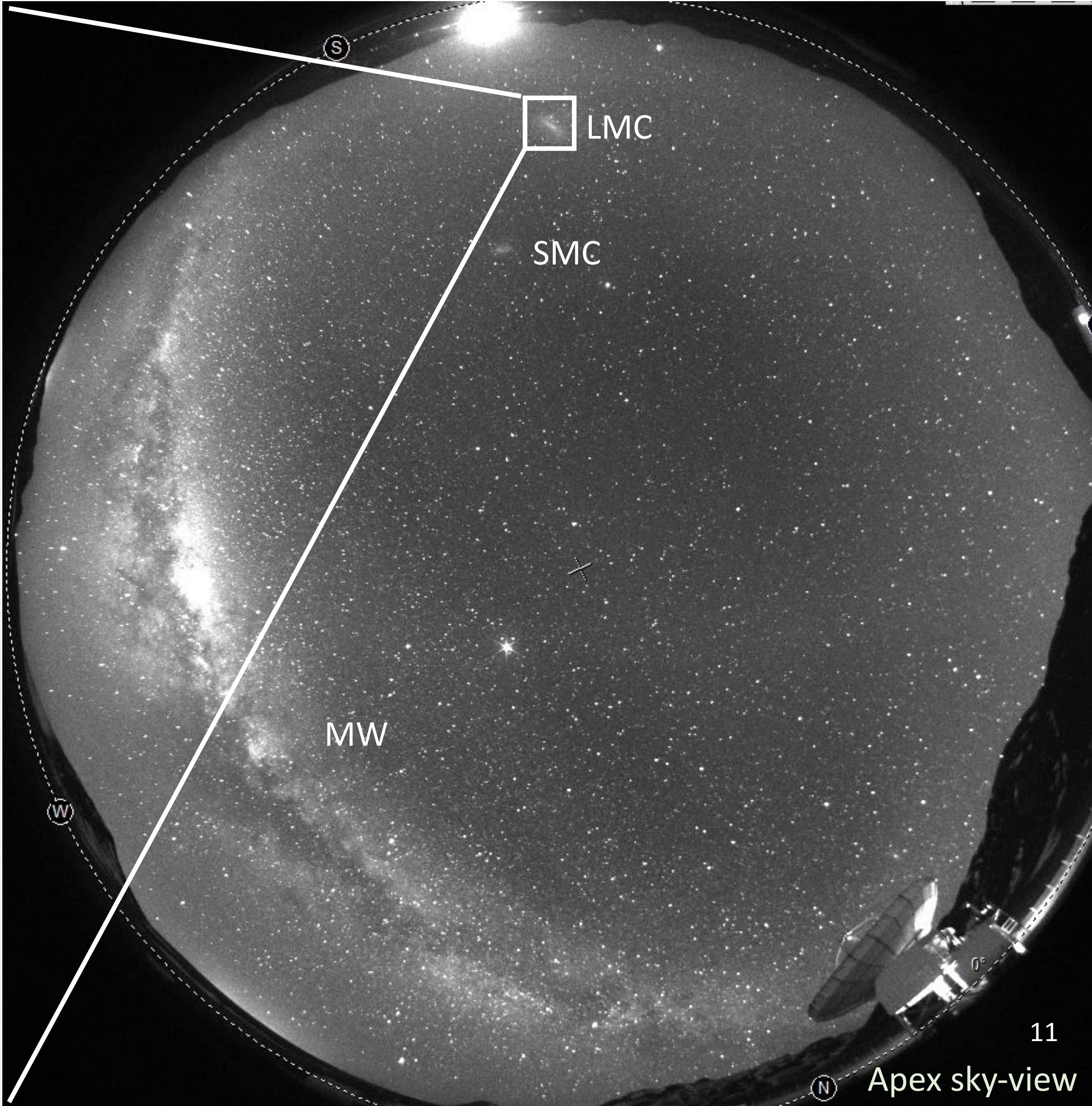


Magnetic fields in 30 Doradus

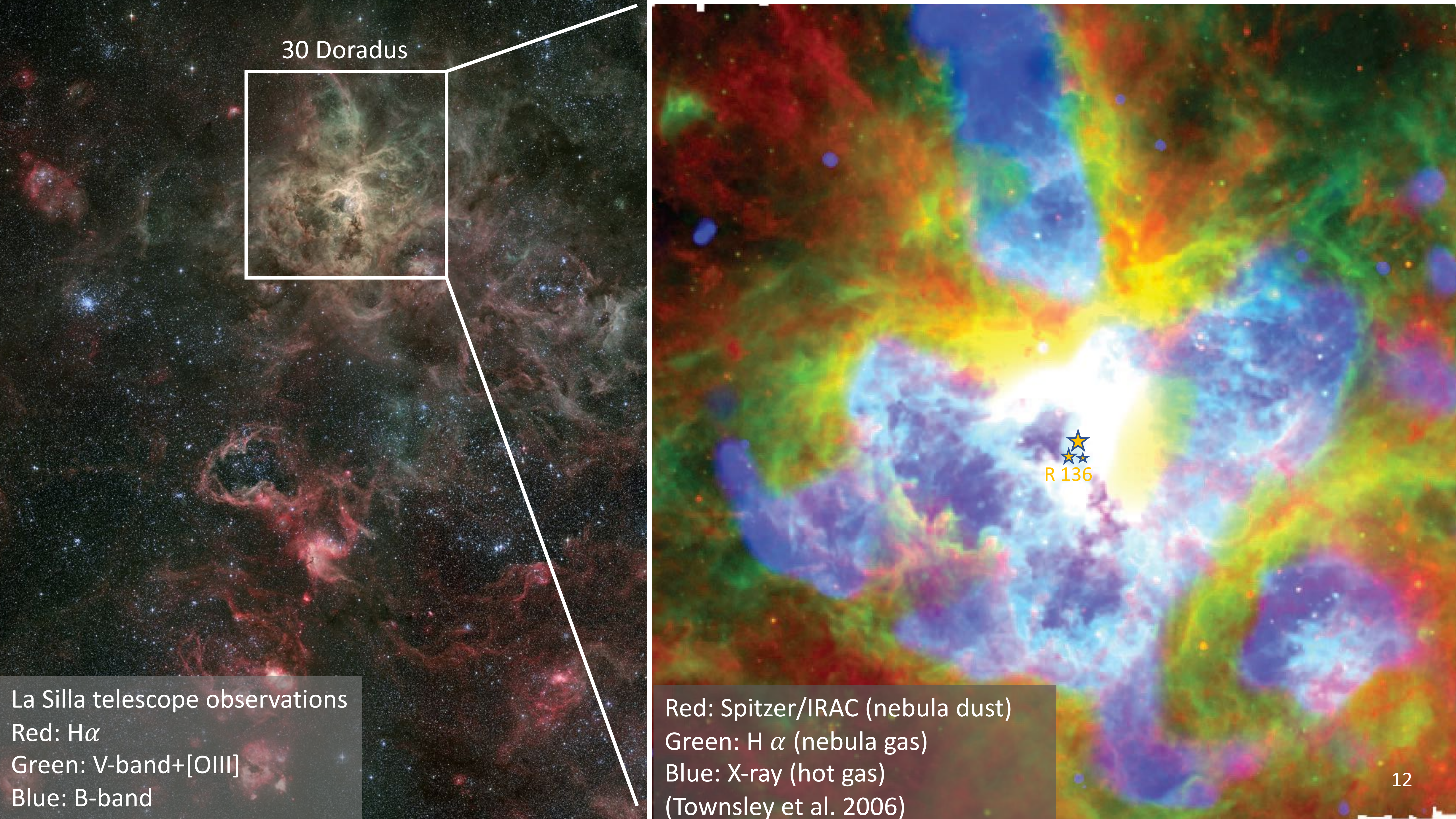




La Silla telescope observations
Red: Hα
Green: V-band+[OIII]
Blue: B-band



Apex sky-view



La Silla telescope observations
Red: Hα
Green: V-band+[OIII]
Blue: B-band

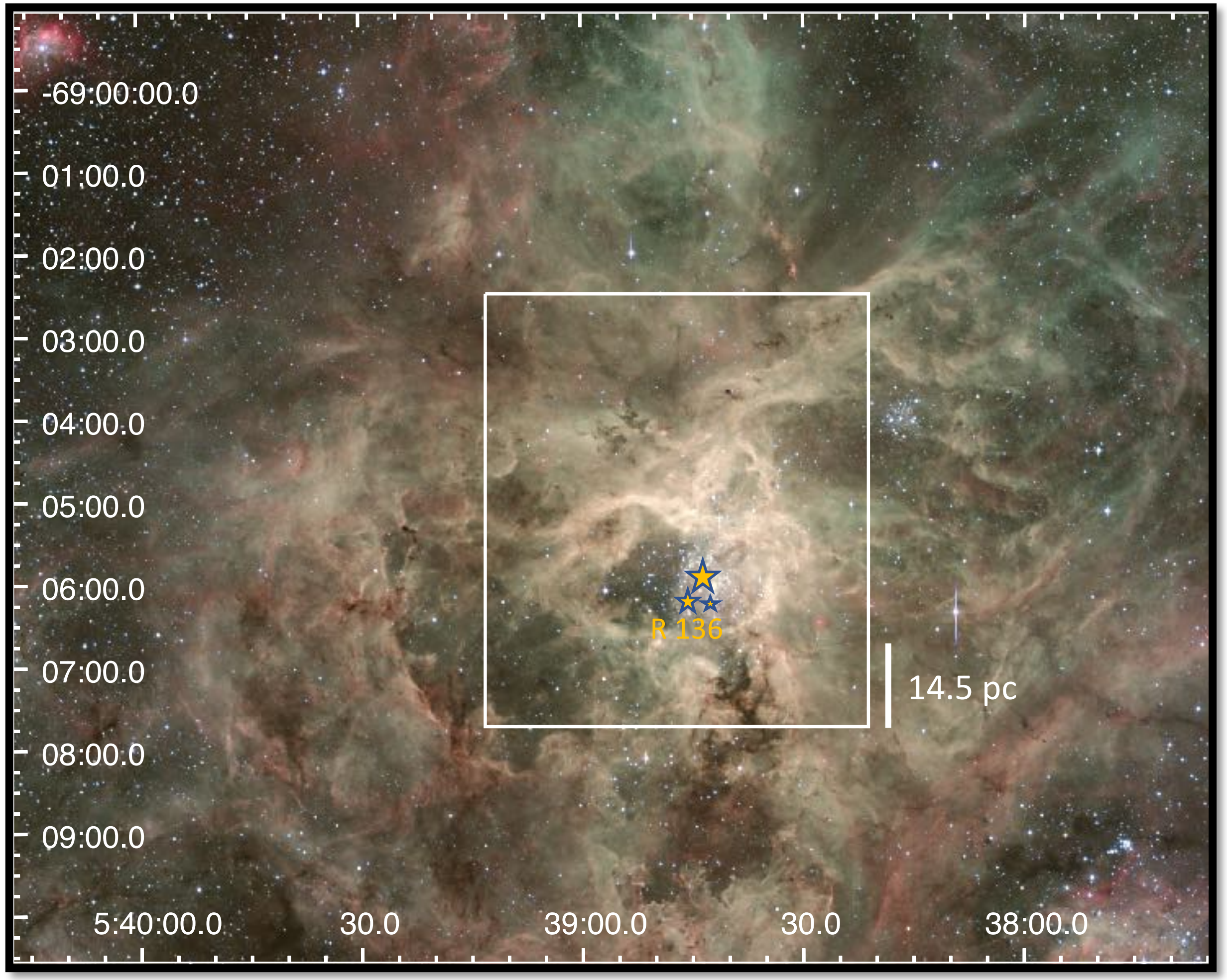
Red: Spitzer/IRAC (nebula dust)
Green: H α (nebula gas)
Blue: X-ray (hot gas)
(Townsley et al. 2006)

30 Doradus facts

- ❖ Distance: 50 kpc (Schaefer 2008)
- ❖ Power source: R 136 ($L_* = 7.8{\times}10^7 L_\odot$)

- ❖ Low shielding effect:
  - ➢ $Z = 0.5 Z_\odot$ (e.g., Galliano et al. 2008)
  - ➢ Av: a fews of mag (e.g., Lee+2019; Chevance+2020)

- ❖ Complex kinematic core-halo structures
  - ➢ R>25 pc: giant HII expanding-shells
    - ❑ Stellar winds or SNRs (Chu & Kennicutt 1994)
    - ❑ Cluster wind (not individual) (Melnick et al. 2021)
  - ➢ R<25 pc: core-nebula
    - ❑ $P_{\rm rad} > P_{\rm thermal}$ (Pellegrini et al. 2011)
    - ❑ $M < M_{\rm virial}$ (Melnick et al. 2021)



1-How could this ”core-nebula” survive?

2-How could this “core-nebeula” host new star-formation?

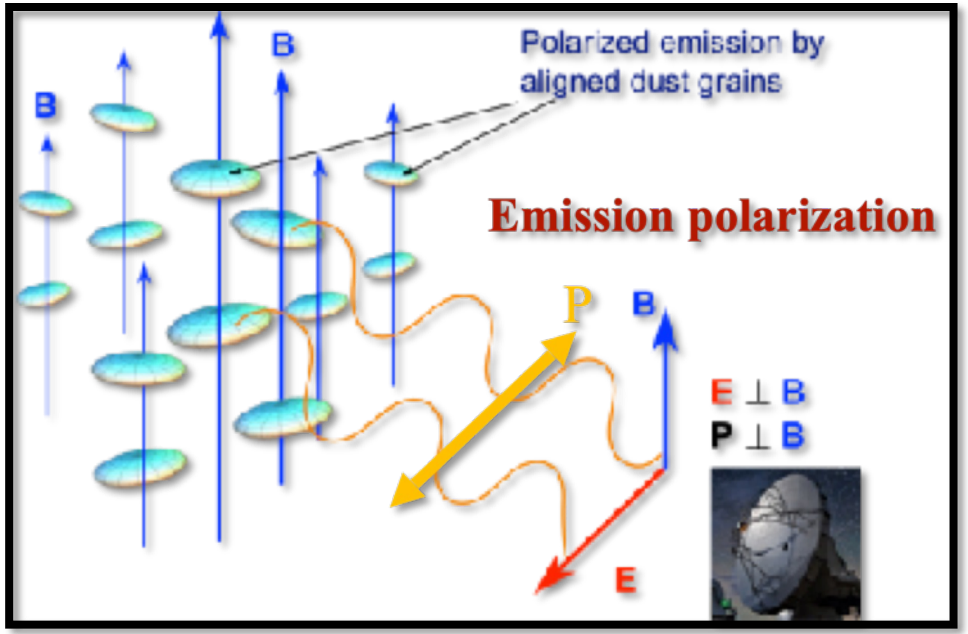
Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

Outline

1. SOFIA/HAWC+ observations: probing magnetic fields
2. Role of magnetic fields
3. Grain alignment mechanisms
4. Conclusion

SOFIA observations of 30 Doradus: Magnetic fields morphology

- Pol. Measurements: 89, 154 and 214 μm
  (DDT - PI: H. Yorke, New Zeeland deployment in 2018)
- B-fields morphology are inferred from pol. vectors
  (rotating E-vectors by 90^o -- verification is discussed later!)



Credit: SOFIA/NASA
Tram et al. (2022)

☐ B-fields' morphology is complex but ordered.
☐ B-fields are bending at the peaked flux intensity.
☐ The "convex points" toward R 136.

SOFIA observations of 30 Doradus: Magnetic fields strength

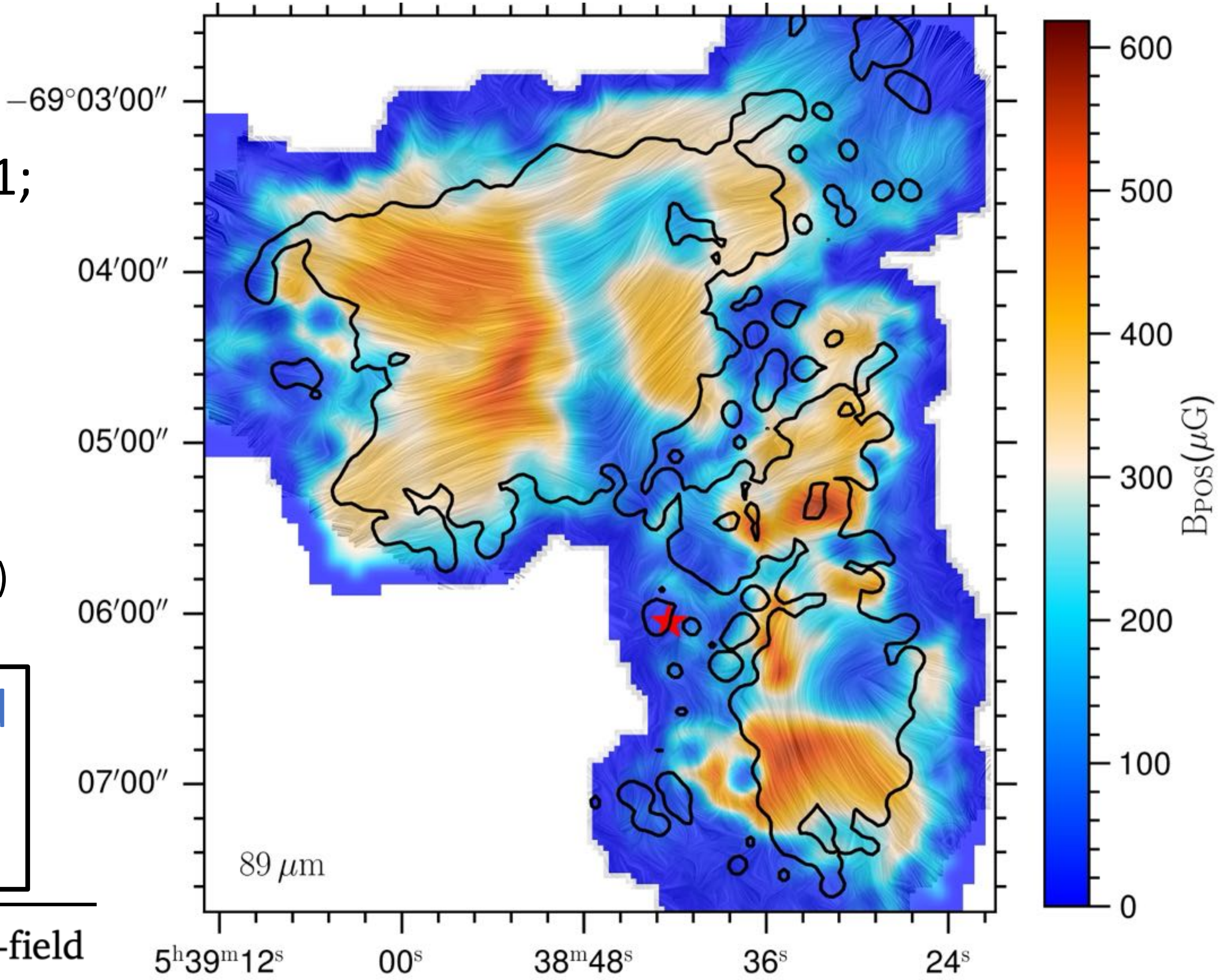
- ❖ Pol. Measurements: 89, 154 and 214 μm
- ❖ Position-of-sky (POS) component is estimated by the DCF method (Davis 1951; Chandrasekhar & Fermi 1953).

$$\frac{1}{2}\rho\sigma_v^2 = \frac{\delta B^2}{8\pi} \longrightarrow B_{POS} = \sqrt{4\pi\rho}\sigma_v \boxed{\left[\frac{\delta B^2}{B_0^2}\right]^{-1/2}}$$

Methodology: “modified DCF” (Houde et al. 2009)
Applicatioin: Guerra +2021

- ❑ B-fields’ strength varies across the cloud
- ❑ Relatively strong field: few hundreds μG
- ❑ Miminal at the peak flux intensity

- ρ: gas mass density
- σ_v: turbulent velocity
- δB: turbulent component of B-field
- B_0: ordered component of B-field

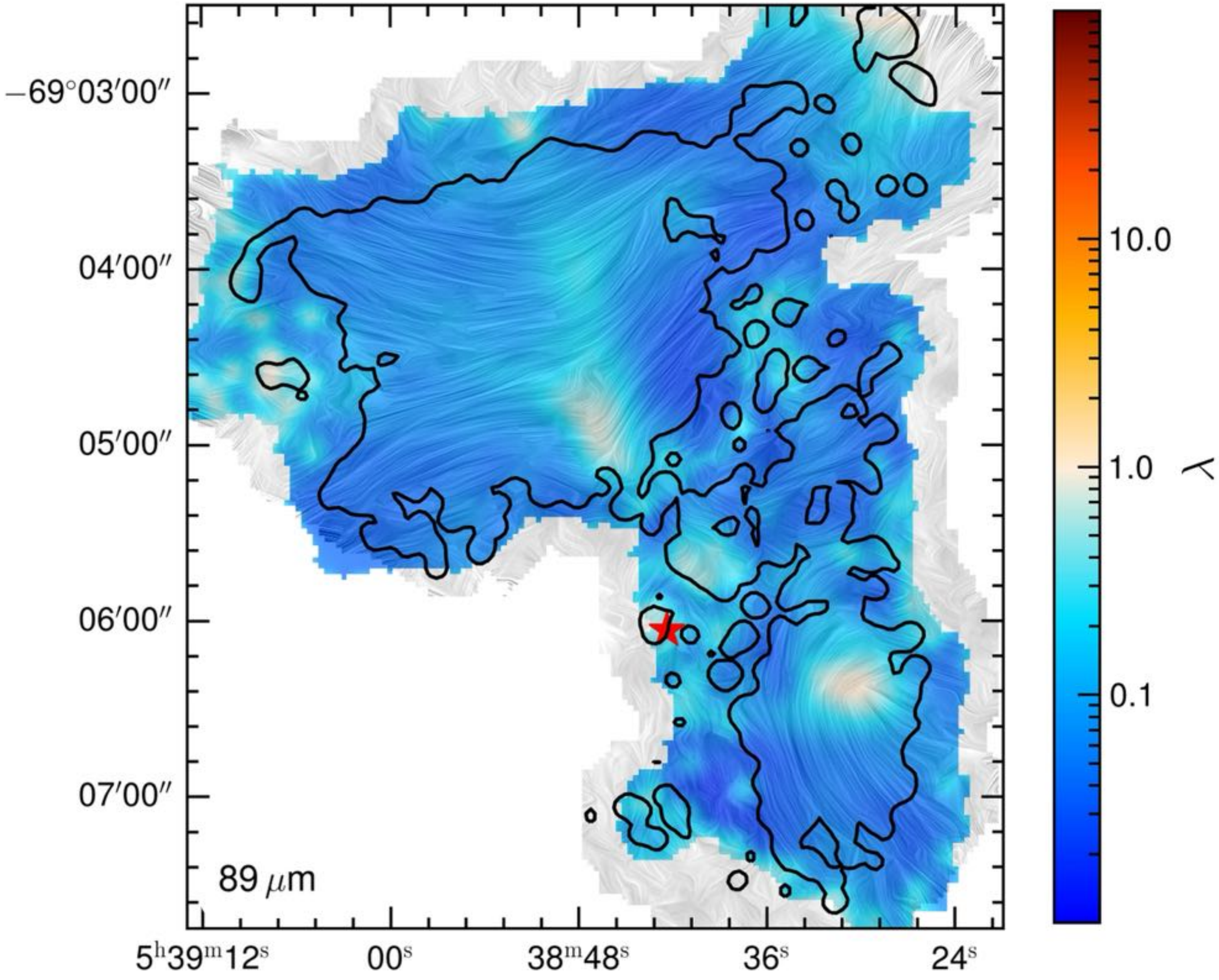


Tram et al. (2022)

Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

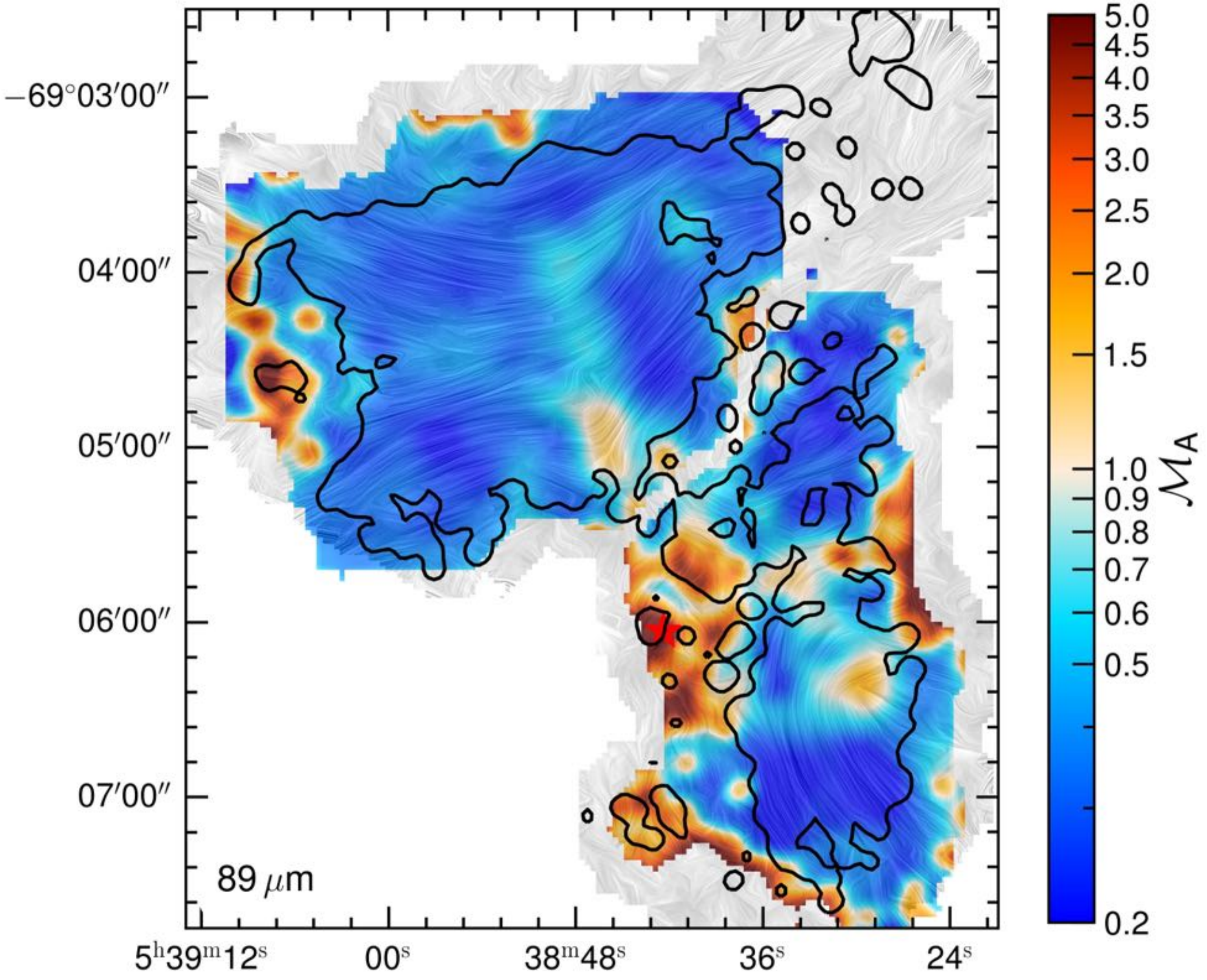
Mass-to-flux ratio

☐ $\lambda < 1$: ”sub-critical”



Alfvenic Mach number

☐ $\mathcal{M}_A < 1$: ”sub-Alfvenic”



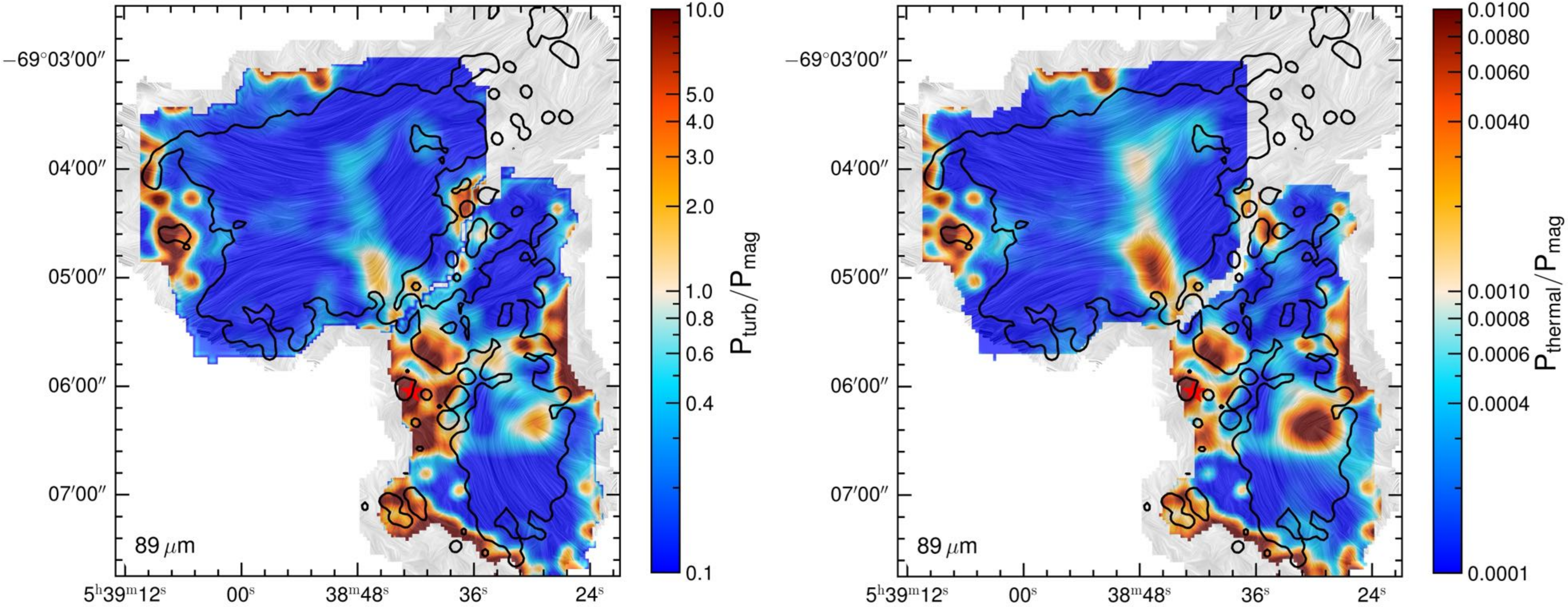
Tram et al. (2022)

Magnetic vs. turbulent vs. thermal pressures

❑ $P_{\text{mag}} > P_{\text{turb}}$

Strong B-fields in 30 Doradus

❑ $P_{\text{mag}} \gg P_{\text{thermal}}$



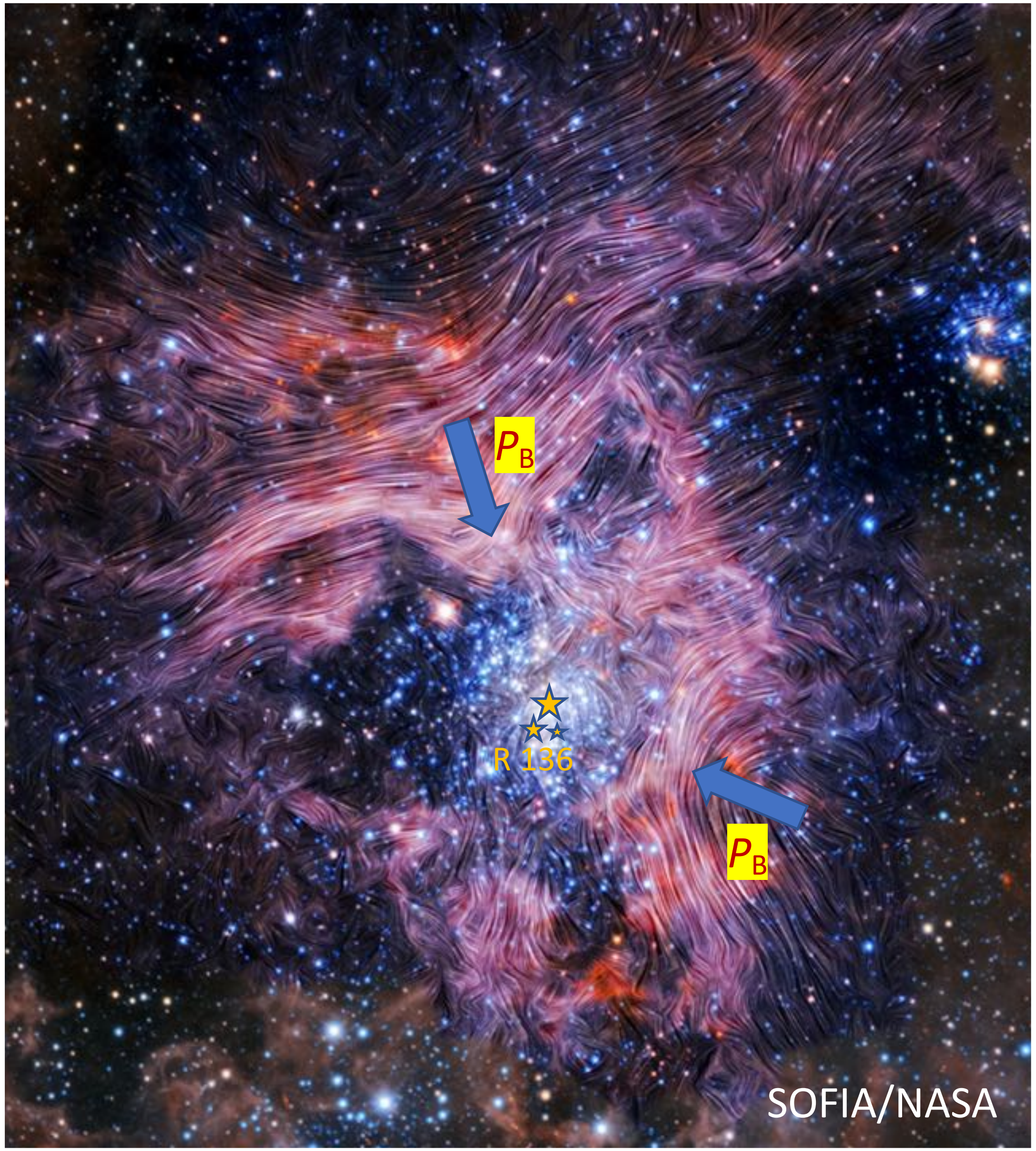
Tram et al. (2022)

Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

Magnetic fields are key to hold the 30 Doradus structure

- ☐ $P_{\text{hot-gas}} < P_{\text{thermal}}$ (Pellegrini et al. 2011)
- ☐ $P_{\text{thermal}} < P_{\text{rad}}$ (Pellegrini et al. 2011)
- ☐ $P_{\text{rad}} \sim 10^{-9}$ dyn cm^{-2} (Pellegrini et al. 2011)
- ☐ $P_{\text{B}} \sim 10^{-9} - 10^{-8}$ dyn cm^{-2} for B=200-500 μG
  → $P_{\text{B}} \geq P_{\text{rad}}$
- ☐ $P_{\text{B}} > P_{\text{turb.}}$

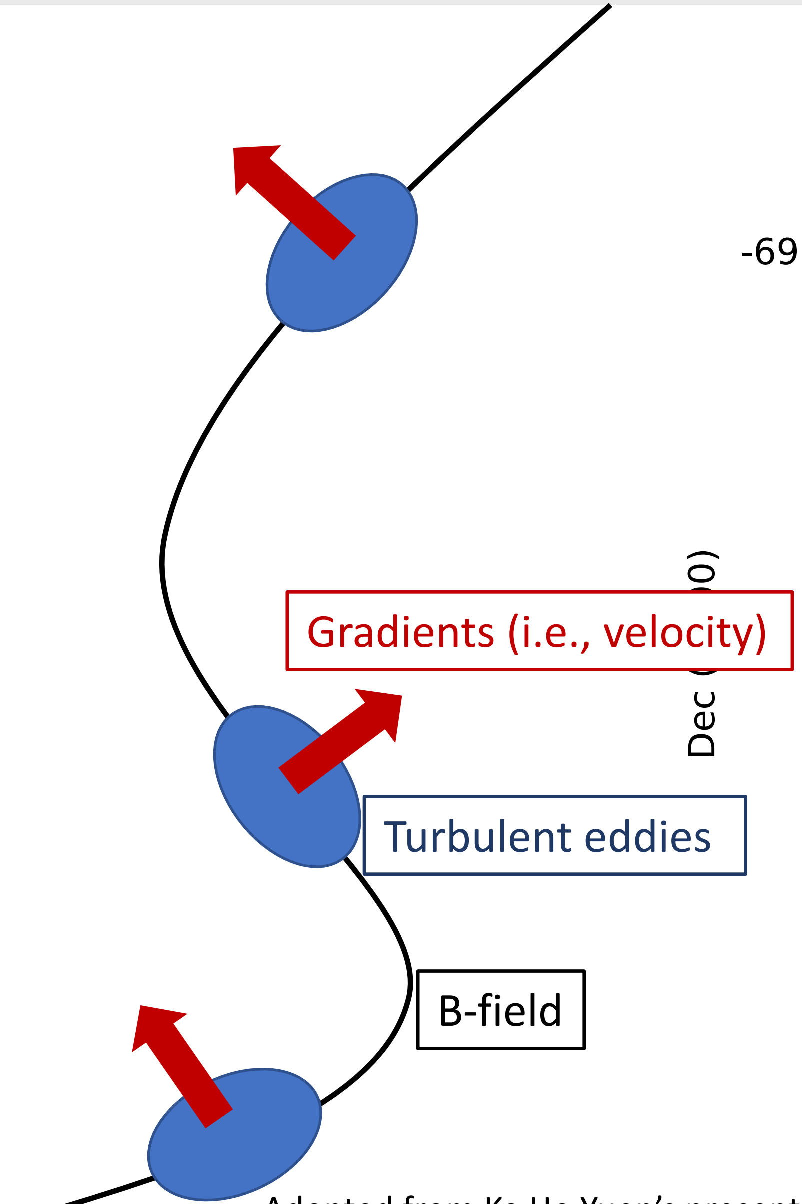
- ☐ $E_{\text{K}} \sim 5 \times 10^{50}$ ergs (Melnick et al. 2021)
- ☐ $E_{\text{turb.}} \sim 10^{51}$ ergs (Melnick et al. 2021)
- ☐ $E_{\text{B}} \sim 10^{51} - 10^{52}$ ergs for B=200-500 μG
  → $E_{\text{B}} > E_{\text{turb.}} \geq E_{\text{K}}$



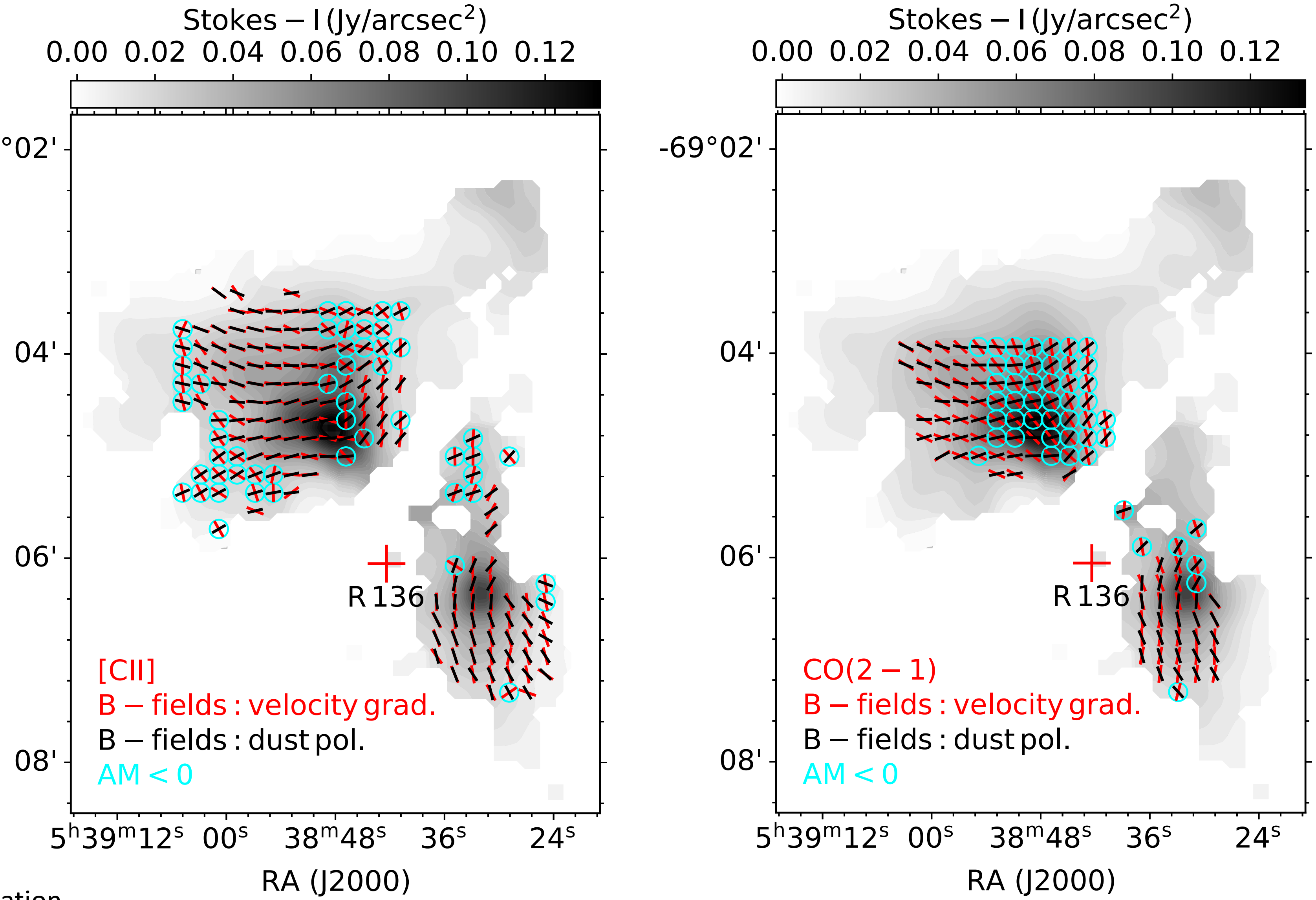
SOFIA/NASA

Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

Gas kinematics vs. magnetic fields



Adopted from Ka Ho Yuen's presentation



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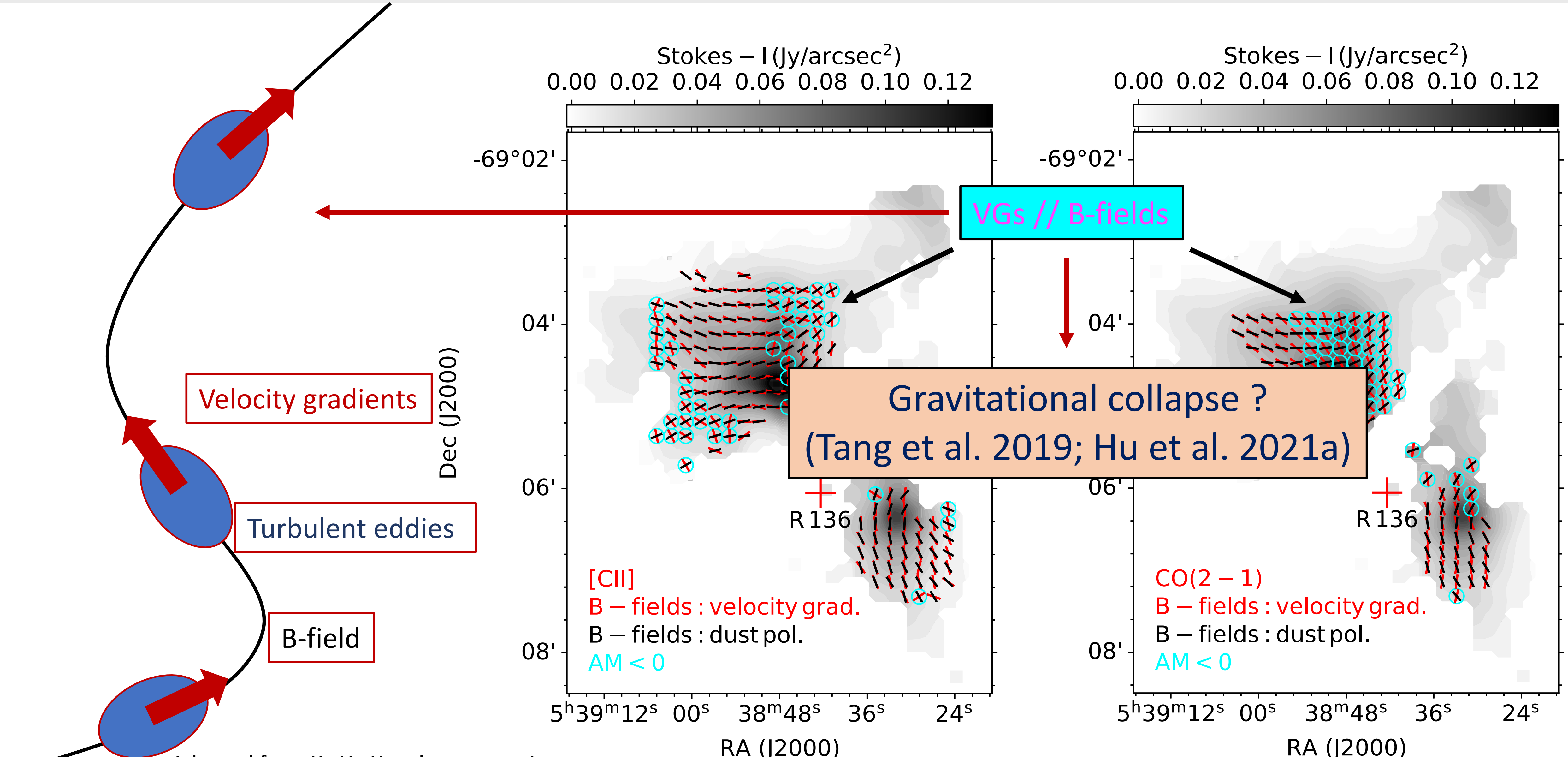
Gas kinematics vs. magnetic fields

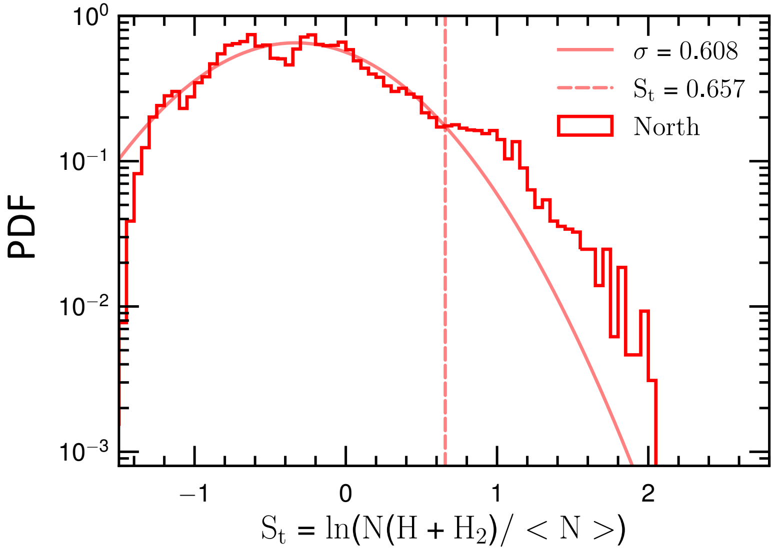


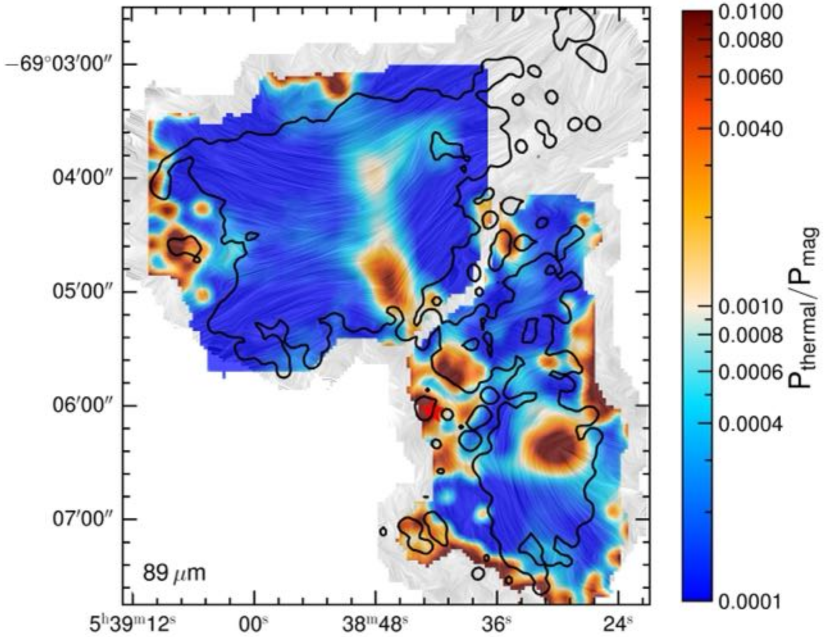
VGs // B-fields

Gravitational collapse ?
(Tang et al. 2019; Hu et al. 2021a)

Adopted from Ka Ho Yuen's presentation

Turbulence driving mode





❑ Power law-tail: gravitational collapse (as seen by VGTs)

(e.g., Klessen 2000; Federrath & Klessen 2013; Kainulainen et al. 2014; Girichidis et al. 2014; Schneider et al. 2013, 2015).

❑ Turbulence driving parameter: b ~ 1

→ Compressive turbulence (Federrath et al. 2010)

❑ $P_{\text{mag}} \gg P_{\text{thermal}} \Rightarrow \mathcal{M}_s \gg 1$

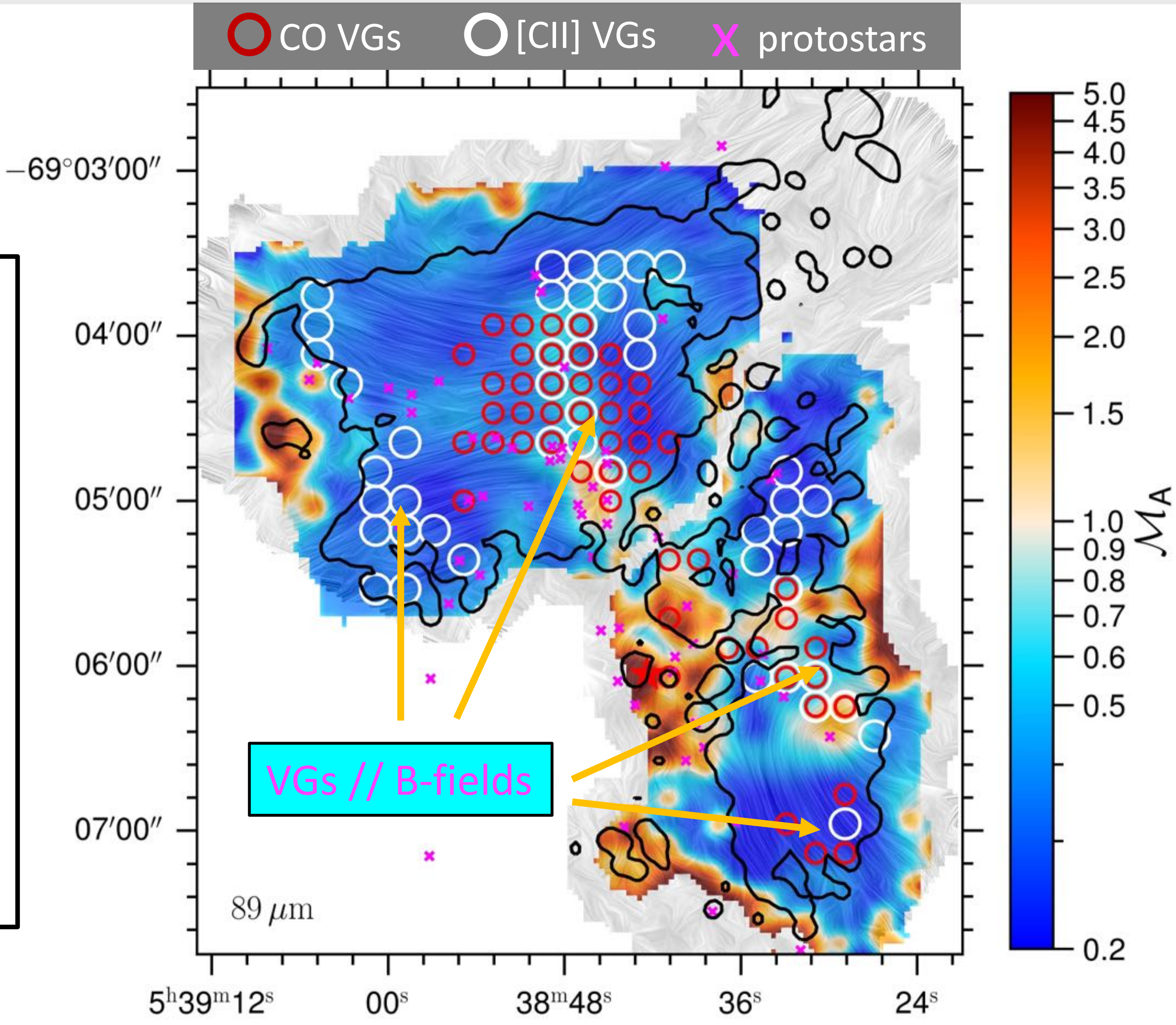
→ Super-sonic turbulence

(in agreement with Chu & Kennicutt 1994 and Melnick et al. 2021)

Turbulence and star-formation in 30 Doradus

We propose

- ☐ At certain locations in 30 Doradus (unfilled-circles), super-sonic compressive turbulence drives material parallel to B-field lines,
- ☐ This process could accumulate material that is sufficient to trigger new gen. of stars to form,
- ☐ This process is not affected by magnetic pressure.



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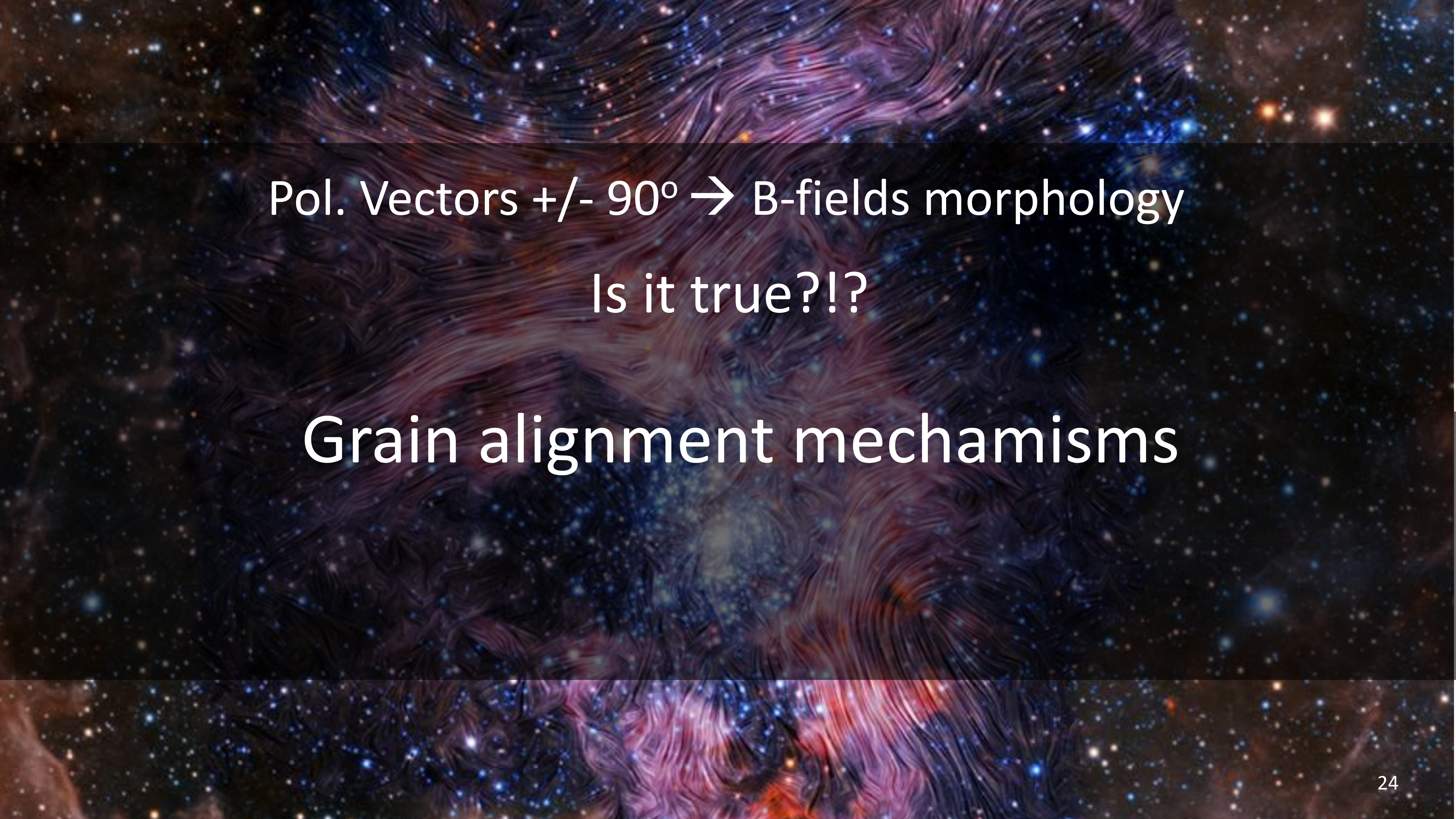


Pol. Vectors +/- 90° → B-fields morphology

Is it true?!?

Grain alignment mechamisms

Iron depletion vs. metalicity

Higher metallicity → higher iron depletion factor

For Galactic HII region and PNe:

- ➢ Depletion factor = [-1.3, -2.0]
- ➢ Iron is mostly locked in dust grains!

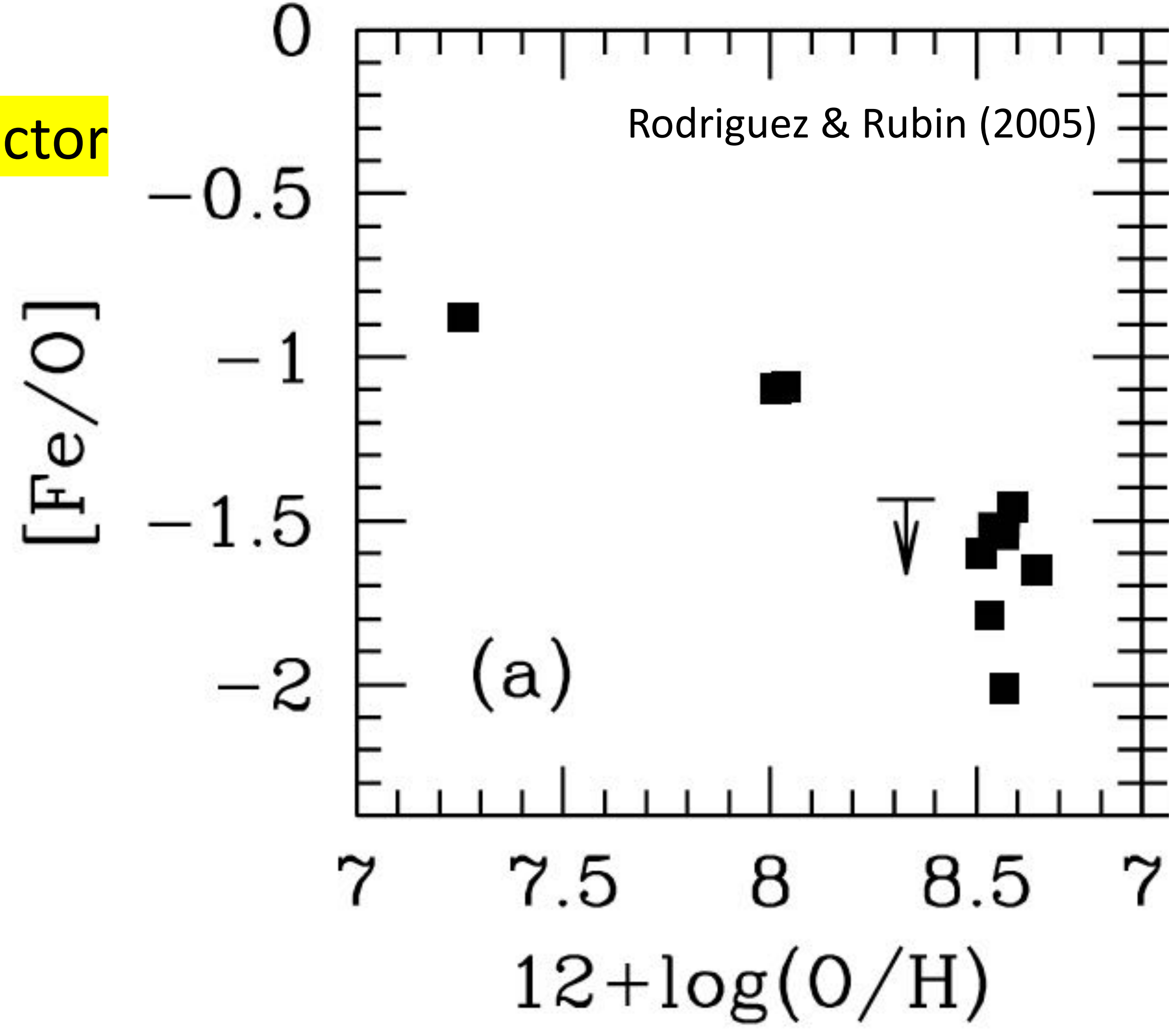
For LMC:

- ➢ **Depletion factor is ~ -1.4**

For SMC:

- ➢ Depletion factor is ~ [-0.5, -1.1]

$[Fe/O] = \log(Fe/O) - \log(Fe/O)_{sun}$



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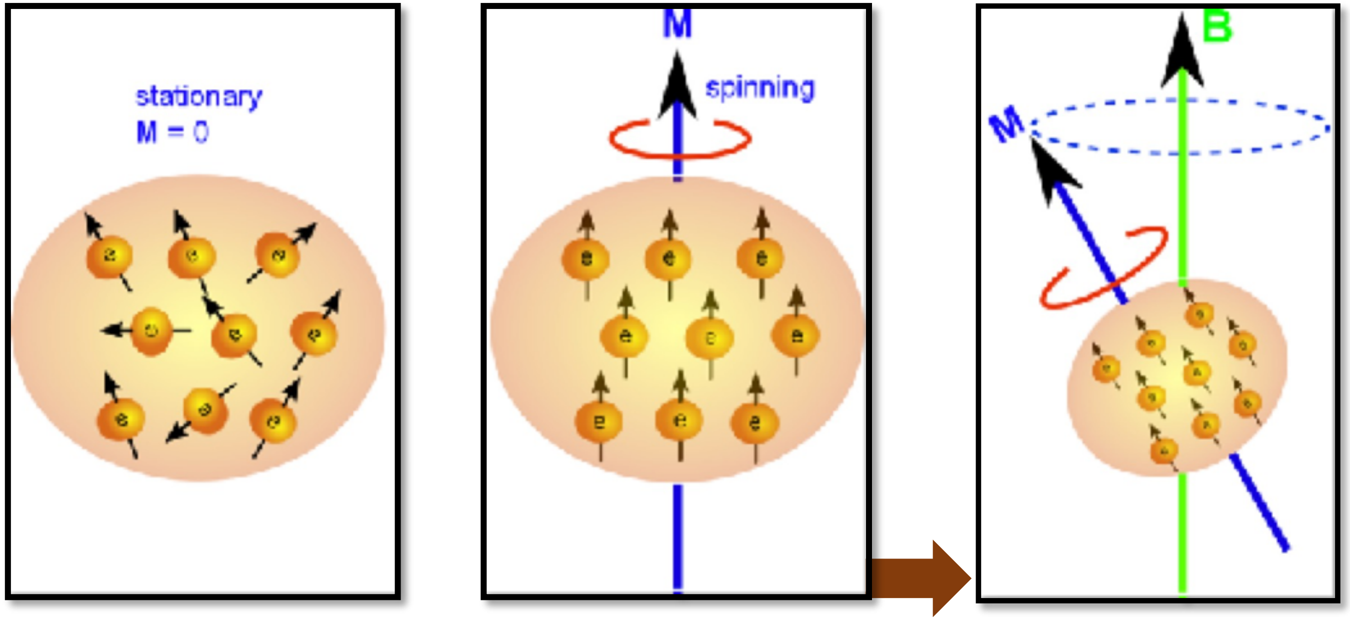
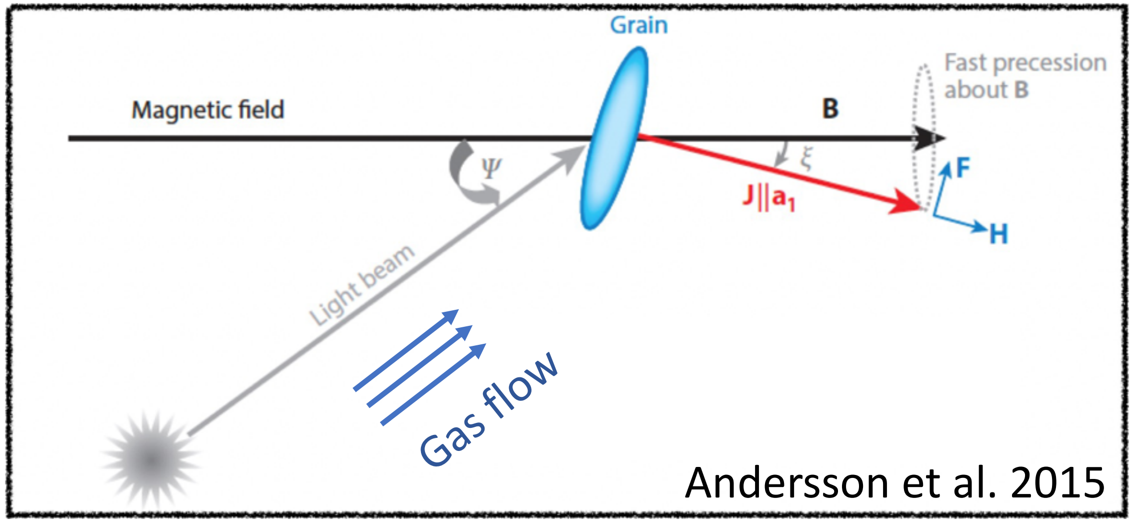
Principle of grain alignment

Paramagnetic grains (pm; iron inclusion)

Super-paramagnetic grains (spm; iron formed in cluster)





Andersson et al. 2015

Spin-up

Internal alignment

External alignment

- Internal align.: ***J*** vs. short-axis
- External align.: ***J*** vs. ambient B-fields

Dia-magnetic grains are not considered here

Spin-up process

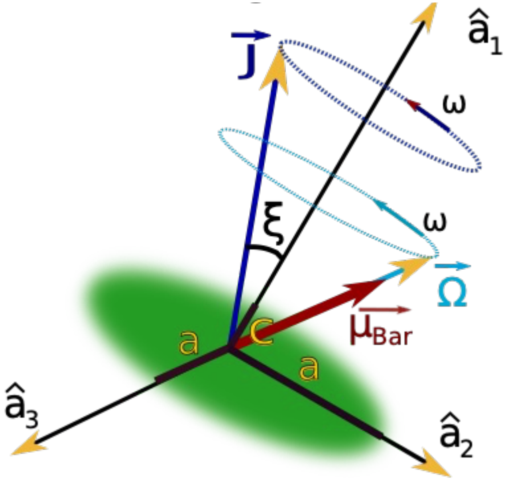
Randomization: Gas collision (reducing alignment efficiency)

Anisotropic radiation field

Radiative Torque (RAT)

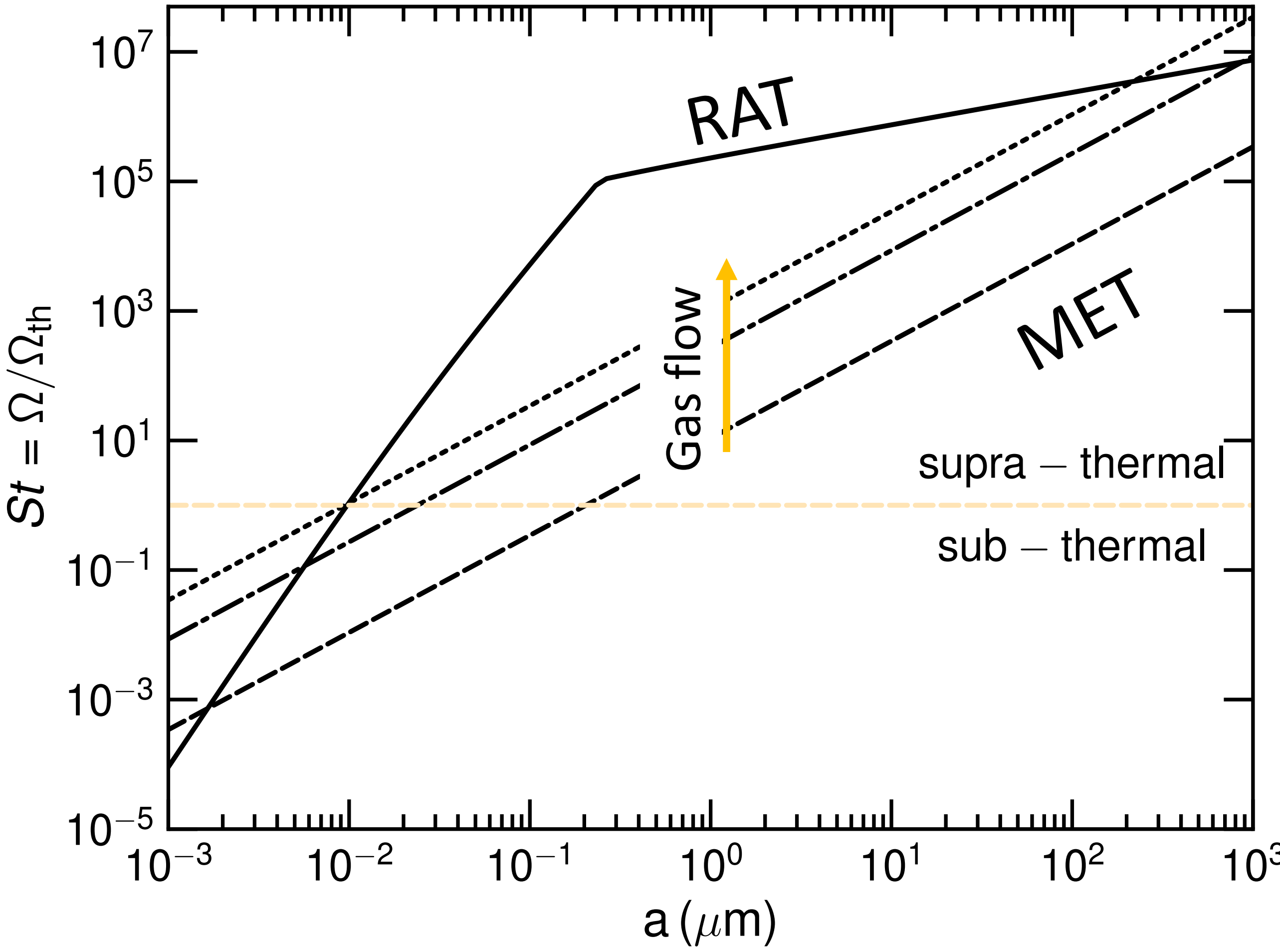
Mechanical Torque (MET)

Gas flow



Grain's body frame

30 Doradus condition – MCs conditions

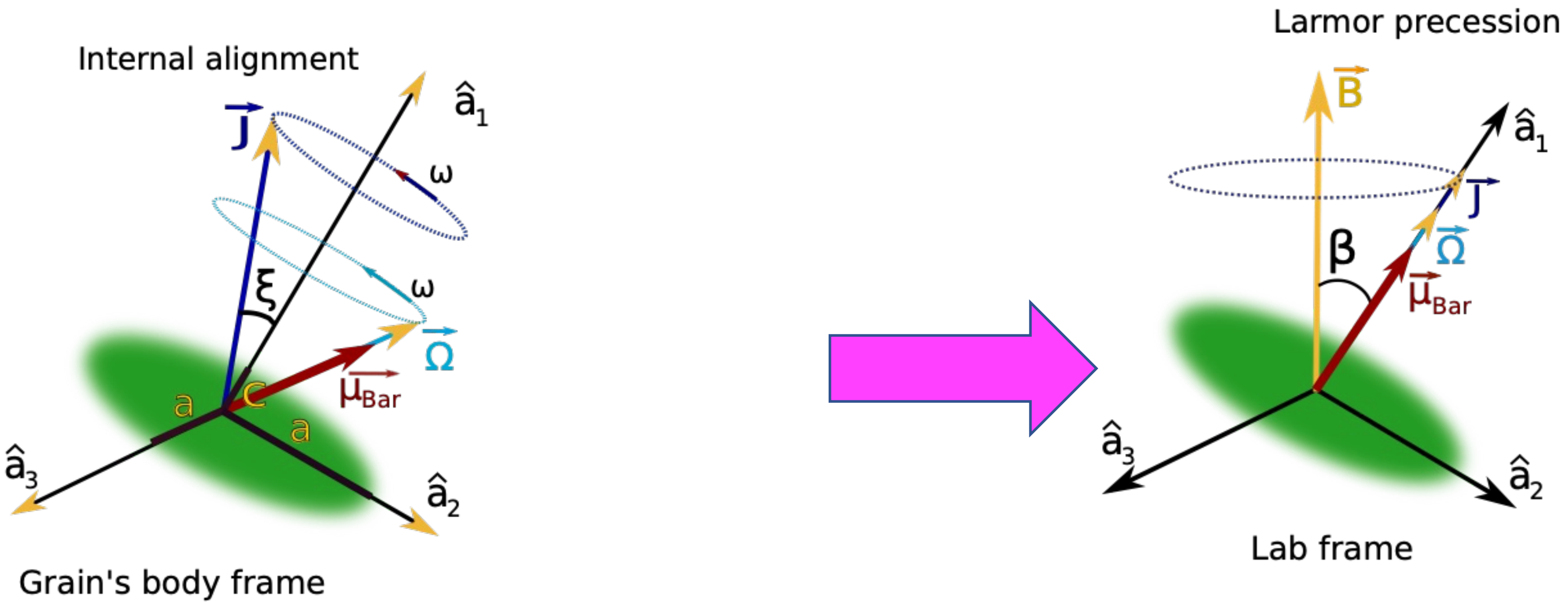


- **For MCs:** (Tram & Hoang 2022; Tram et al. in prep.)
  RAT is the main cause to spin-up grains
- **For prostellar cores and disks**:
  Complicated RAT vs. MET (not shown)
  (Hoang et al. 2022; Giang et al. in prep.)

Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

Internal vs. External alignments

Radiative Torque alignment (RAT-A) is the leading theory describing grains alignment (reviewed in e.g., Lazarian & Hoang 2007a, 2021; Andersson et al. 2015)



Giang et et al. in prep.

Review in Tram & Hoang (2022)

Internal vs. External alignments

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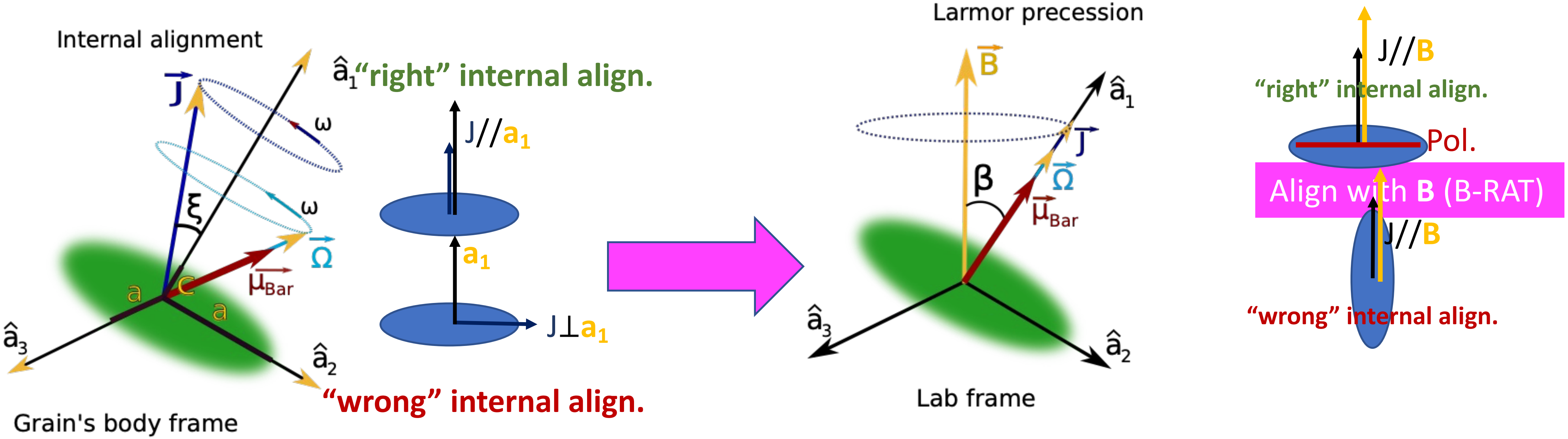


Giang et et al. in prep.

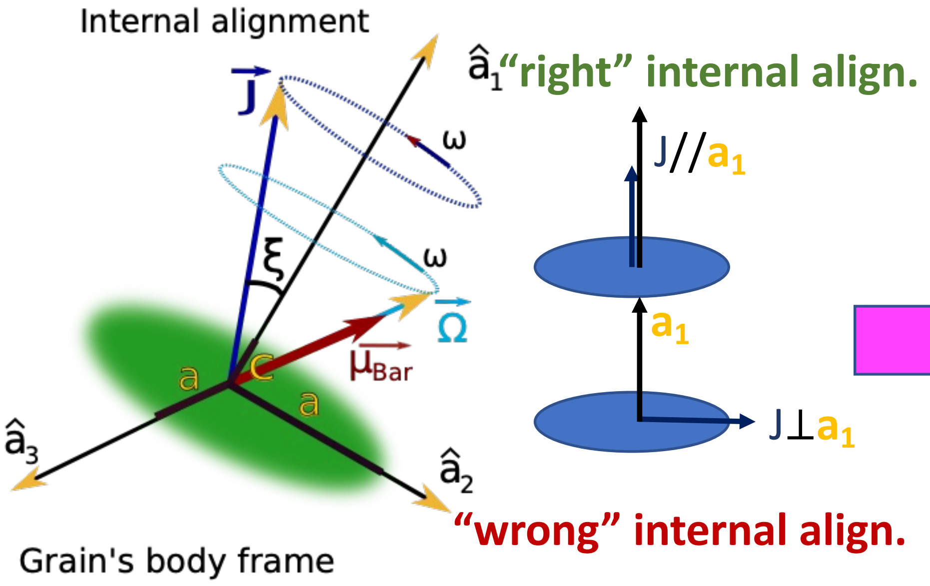
Review in Tram & Hoang (2022)

Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

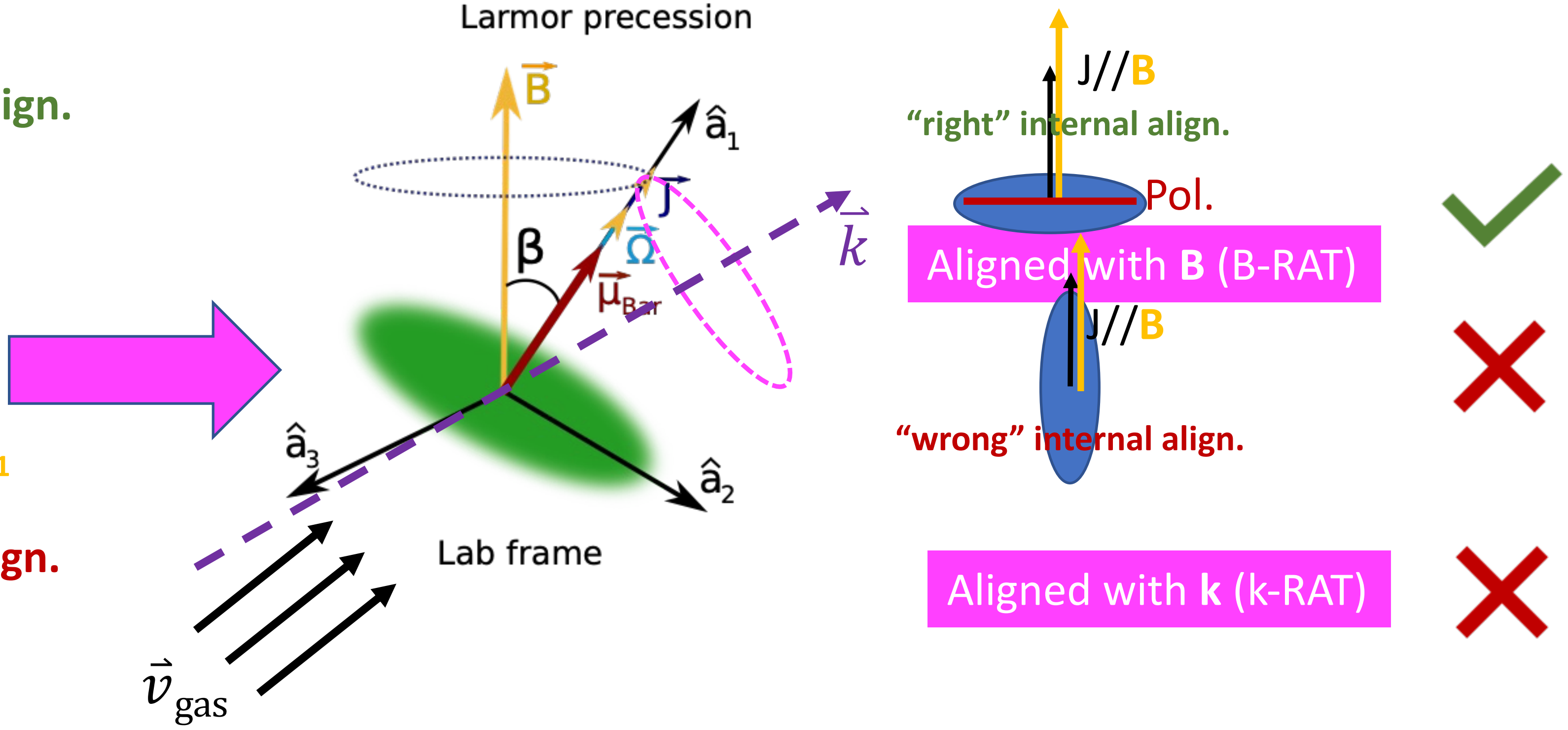
Internal vs. External alignments

Radiative Torque alignment (RAT-A) is the leading theory describing grains alignment (reviewed in e.g., Lazarian & Hoang 2007a, 2021; Andersson et al. 2015)

B-fields by rotating pol. vectors by 90°



Giang et et al. in prep.



Aligned with **B** (B-RAT) ✓

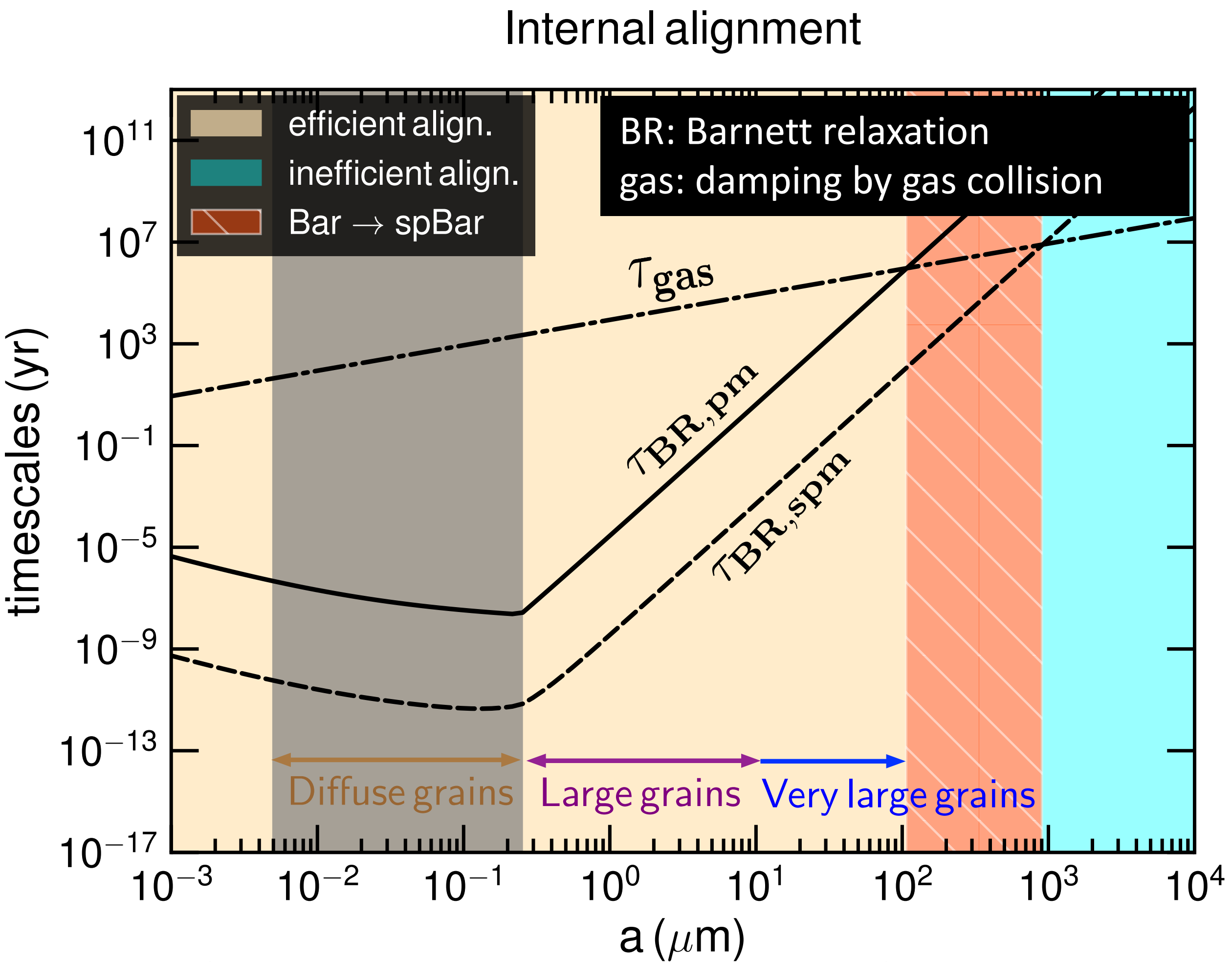
Aligned with **k** (k-RAT) ✗

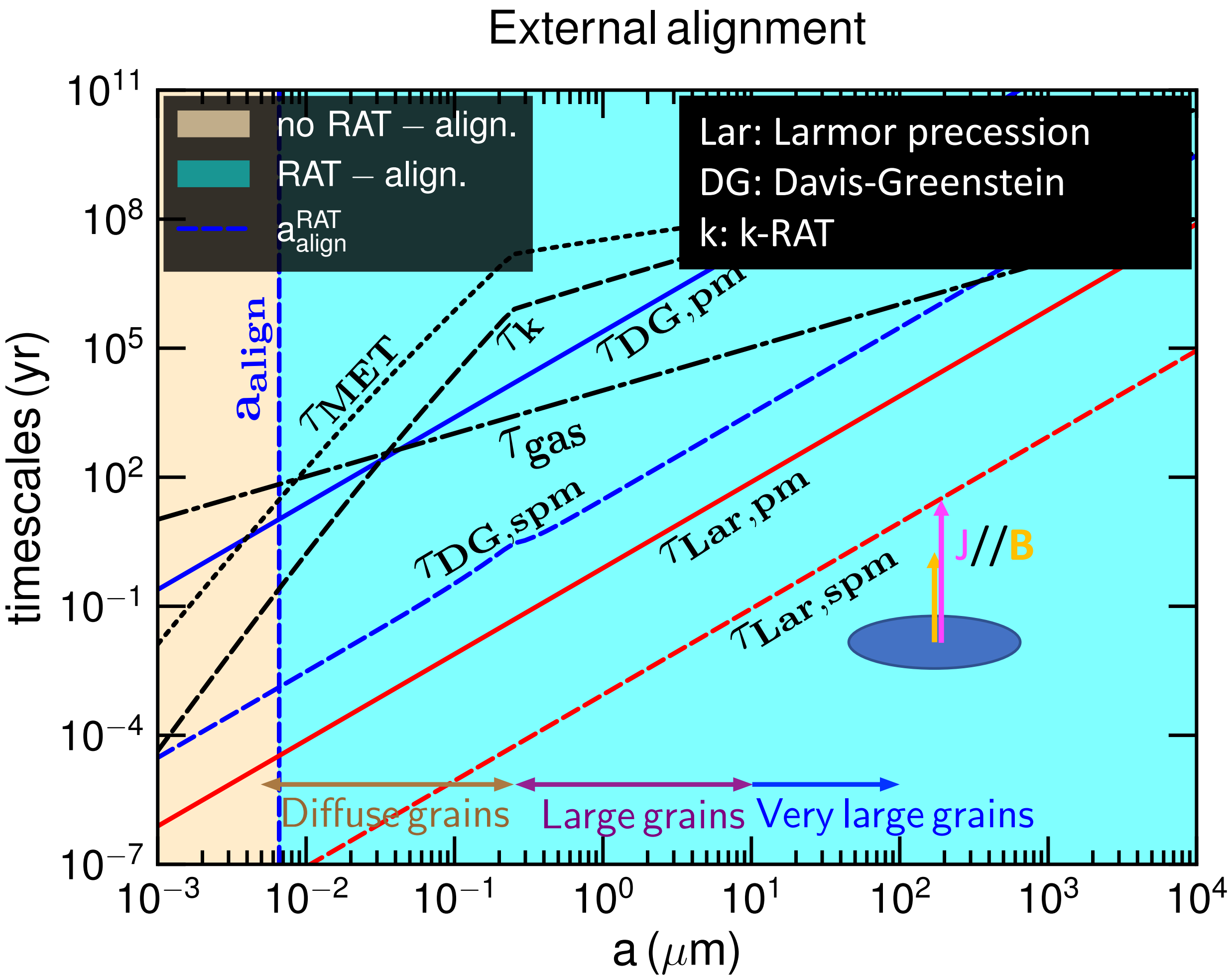
Review in Tram & Hoang (2022)

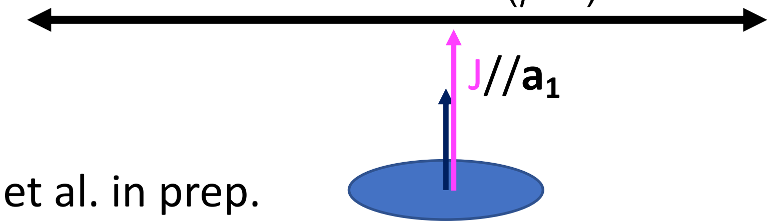
Aligned with mechanical torques (METs) ✗

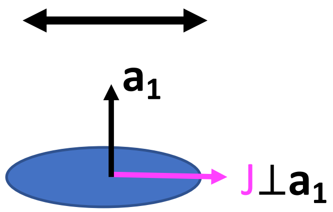
Le Ngoc Tram (nle@mpifr-bonn.mpg.de)

Internal vs. External alignments for 30 Doradus







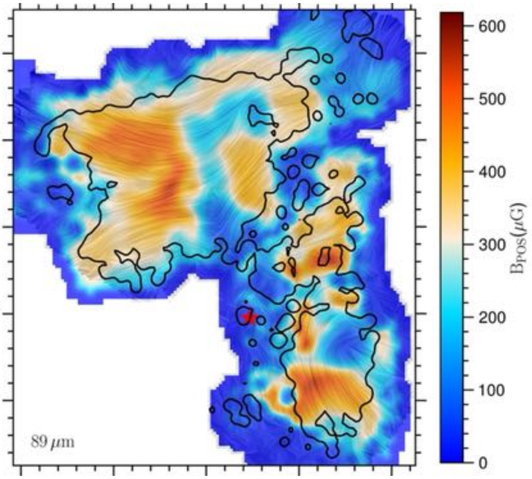


Rotating pol. Vectors by 90° could infer to B-fields within 30 Doradus conditions

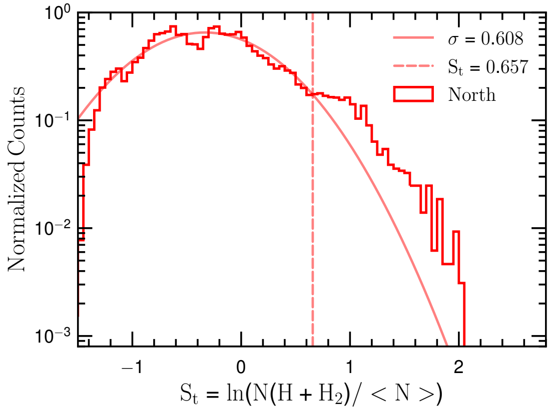
Tram et et al. in prep.

Conclusion (1)

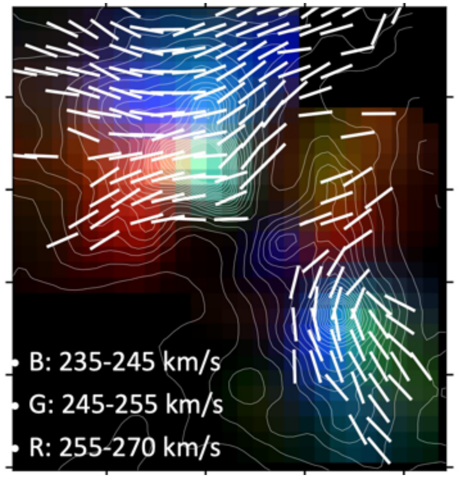
- ❑ B-field lines are complex but ordered,
- ❑ B-field is sufficient strong to hold the structure integrity of cloud.



- ❑ Compressive supersonic turbulence,
- ❑ Turb. helps stars to form in strong B-fields.

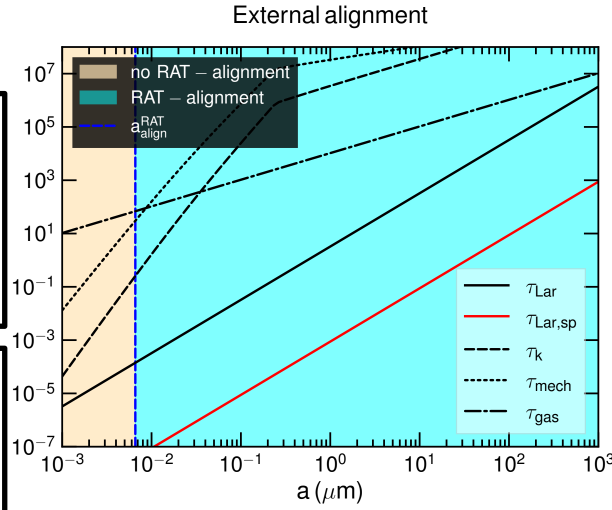


- ❑ Complex structure of gas kinematic,
- ❑ Multiple expanding-shells,
- ❑ Cloud structure has been suffered by R136 feedback.



- ❑ B-RAT is likely the main mechanism to align dust grains.

Note: It's not always true in protostellar cores or disks.



Conclusion (2)

For a given polarimetry dataset, we suggest

1. We could study the basic physical properties of dust grains (e.g., shape, mineralogy, helicity, internal structure, size-distribution) (e.g., 30 Dor: Tram et al. 2021c),
2. We could investigate the role of magnetic fields (e.g., 30 Dor: Tram et al. 2022)
3. But, we must verify the B-RAT assumption (pol. vectors → B-vectors)
   - In "cloud scale", B-RAT is likely the case (e.g., 30 Dor: Tram et al. in prep.),
   - In "core" and "disk" scales, the picture is far more complicated.

   (Giang et al. in prep.; Hoang et al. 2022) – new version of POLARIS code

Thank you very much for your attention!

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