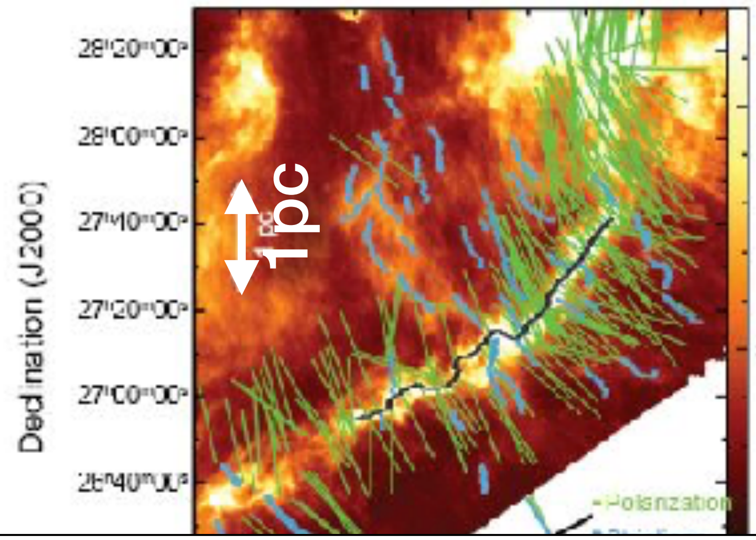
星・惑星形成領域における
サブミリ波偏光観測の展望

Munetake MOMOSE (Ibaraki University)

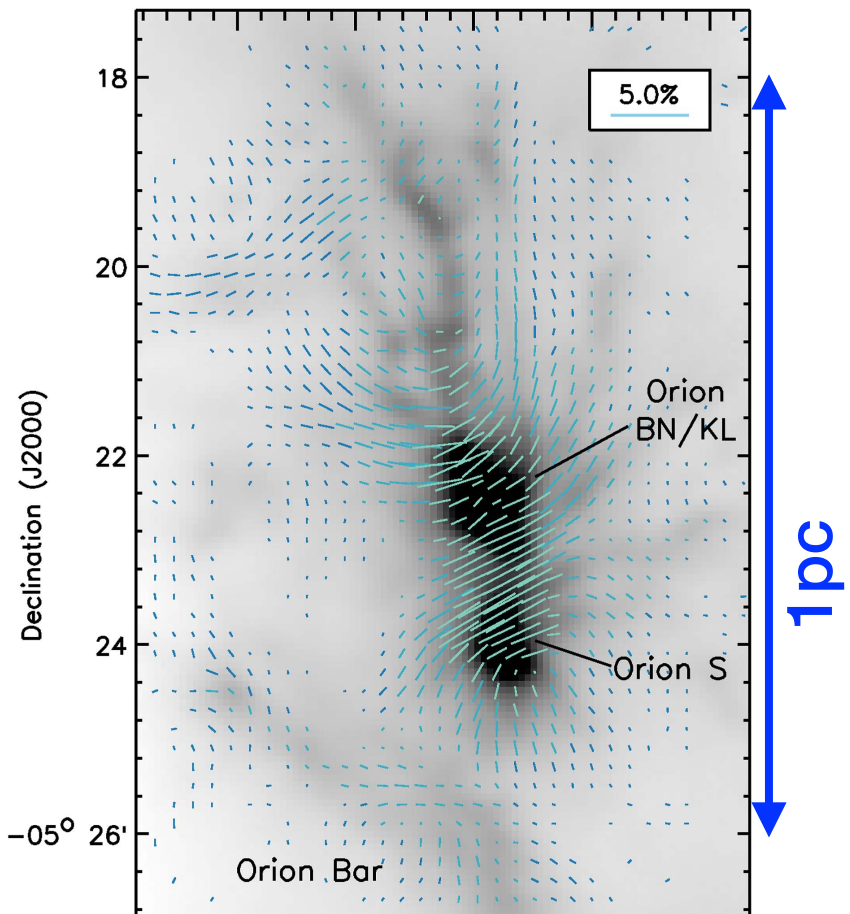
1. Magnetic fields in Star-forming regions
2. Polarization observations of Protoplanetary (& Debris) Disks

~ 0.1pc

B-field



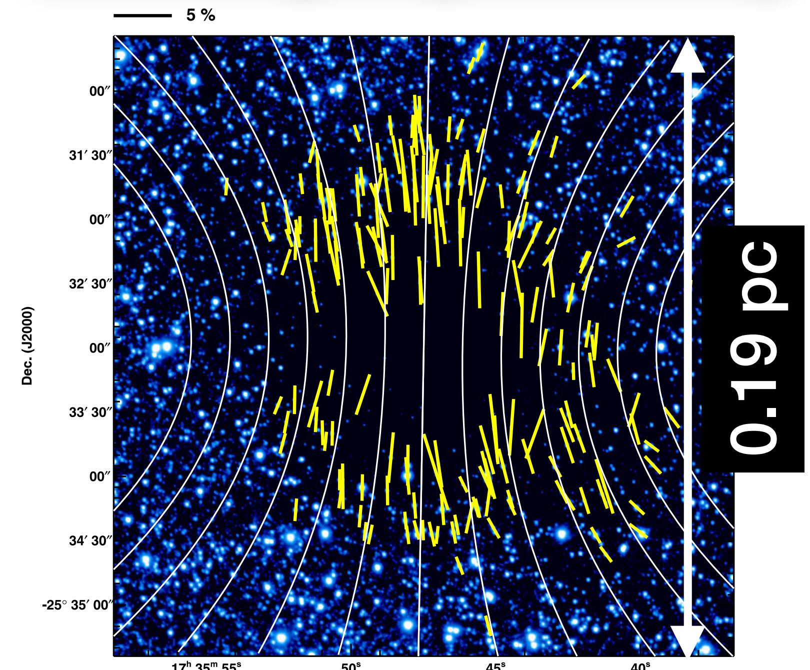
Taurus@250μm + Optical/IR Pol.
(Palmeirim+ 2013; Heyer+ 2008)



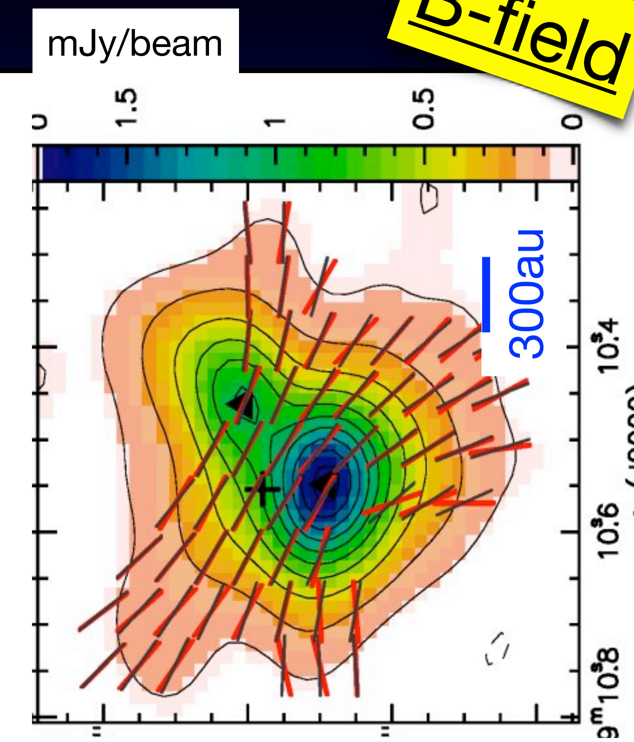
Orion @ 880μm
(*JCMT*; Pattle+ 2017)

~ 0.01pc (2000au)

B-field



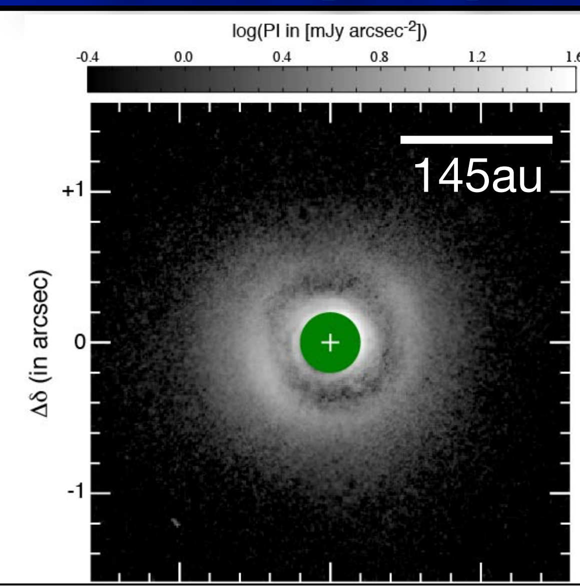
Prestellar Core, FeSt1-457
@1.6μm(*IRSF*; Kandori+2017)



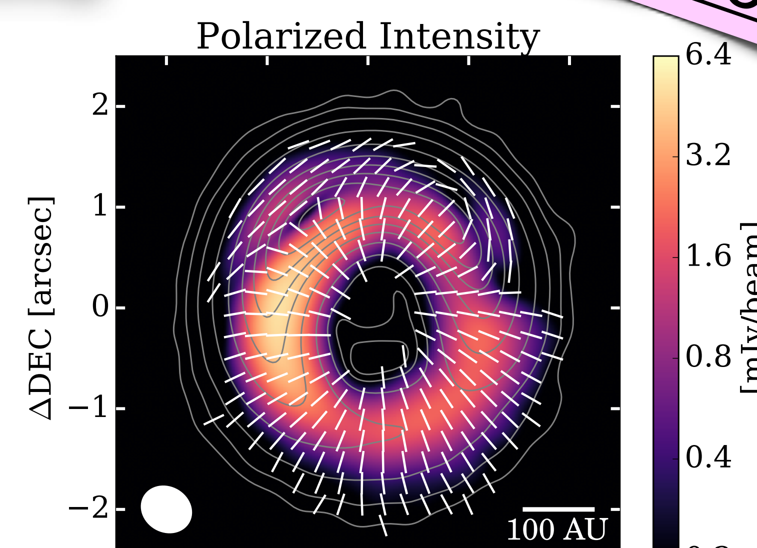
Protobinary, L1333 IRS4A
@880μm(*SMA*; Girart+2006)

~ 0.001pc (200au)

E-vector



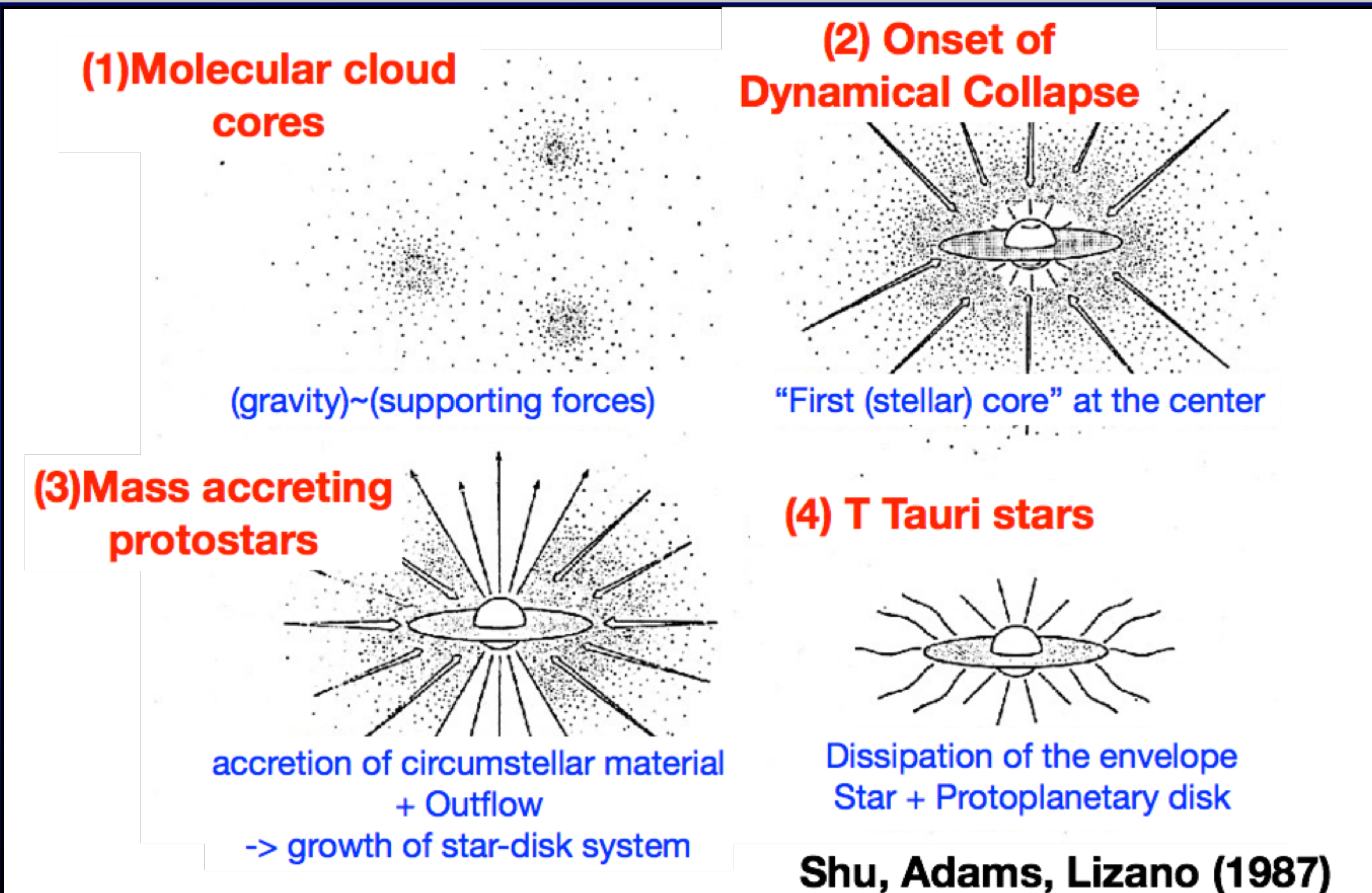
HD169142, PI @1.6μm
(*Subaru*; Momose+ 2015)



HD142527, PI @ 880μm
(ALMA; Kataoka+ 2016)

(1) Magnetic fields in Star-forming regions

Formation of low-mass stars

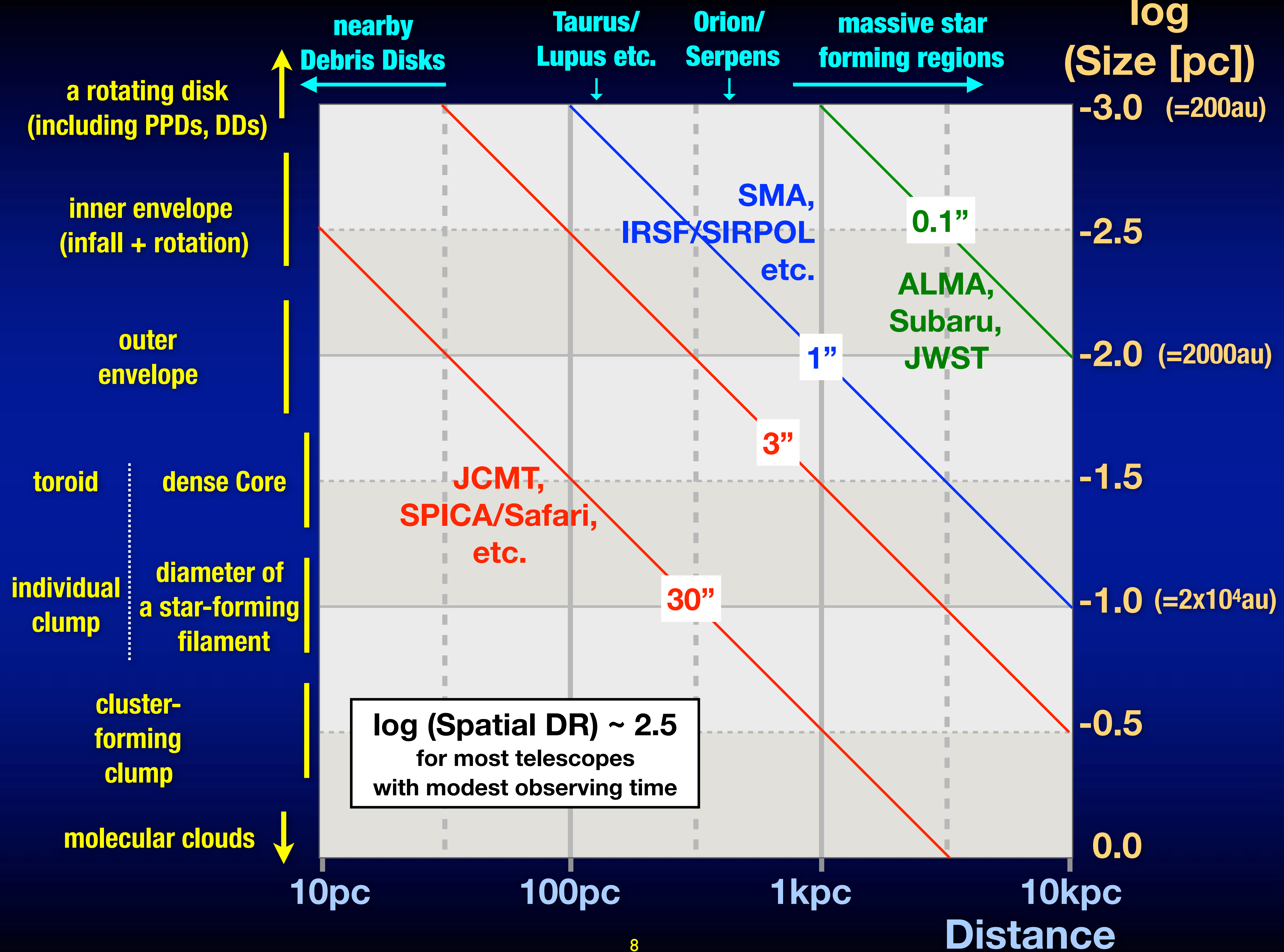


Importance of magnetic (B-)field in formation of stars and planets

- Transportation of angular momentum in a core
  - inevitable during star formation ($L_{core}/M_{core} \gg L_{\star}/M_{\star}$)
  - formation of disks, outflows & jets
- Turbulence by MRI in a disk
  - provide viscosity in an accretion disk
  - hinder the growth of dust grains
- Dissipation of B-field should occur during star formation
  - $B_{core}R_{core}^2 \gg B_{\star} R_{\star}^2$
  - Ambipolar diffusion (Low ρ)→ Ohmic Dissipation (High ρ)

Observational studies on B-field

- B-strength: Zeeman effect
  - OH, CN, (HI)
  - CCS with large SDs and ALMA (at 40 GHz) in near future ?
- B-direction: polarization due to extinction/emission by aligned dichroic dust particles
  - Opt. & nIR: extinction in background stars(**B** ∥ E-vector)
  - fIR - mm*:* thermal emission of dust particles (**B** ⊥ E-vector)
- Millimeter & sub-millimeter wavelengths are unique
  - B-fields in densest & coldest regions
  - Ground-based telescope → high resolution + wide FOVs

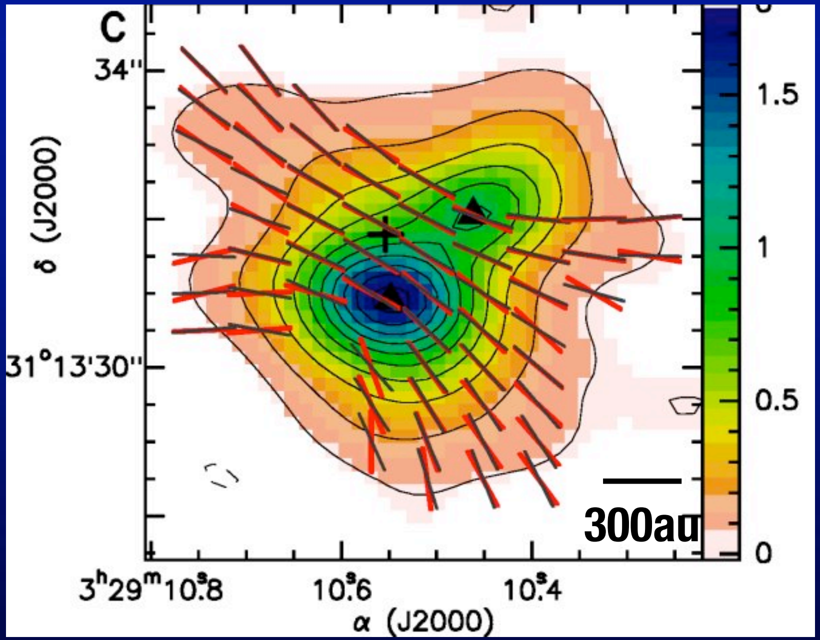


nearby
Debris Disks
Taurus/
Lupus etc.
Orion/
Serpens
massive star
forming regions
log
(Size [pc])
a rotating disk
(including PPDs, DDs)
inner envelope
(infall + rotation)
outer
envelope
toroid
dense Core
individual
clump
diameter of
a star-forming
filament
cluster-
forming
clump
molecular clouds
-3.0 (=200au)
-2.5
-2.0 (=2000au)
-1.5
-1.0 (=2x10^4au)
-0.5
0.0
SMA,
IRSF/SIRPOL
etc.
0.1”
ALMA,
Subaru,
JWST
1”
3”
JCMT,
SPICA/Safari,
etc.
30”
log (Spatial DR) ~ 2.5
for most telescopes
with modest observing time
10pc
100pc
1kpc
10kpc
Distance

1.3mm Survey of Dust Polarization by CARMA

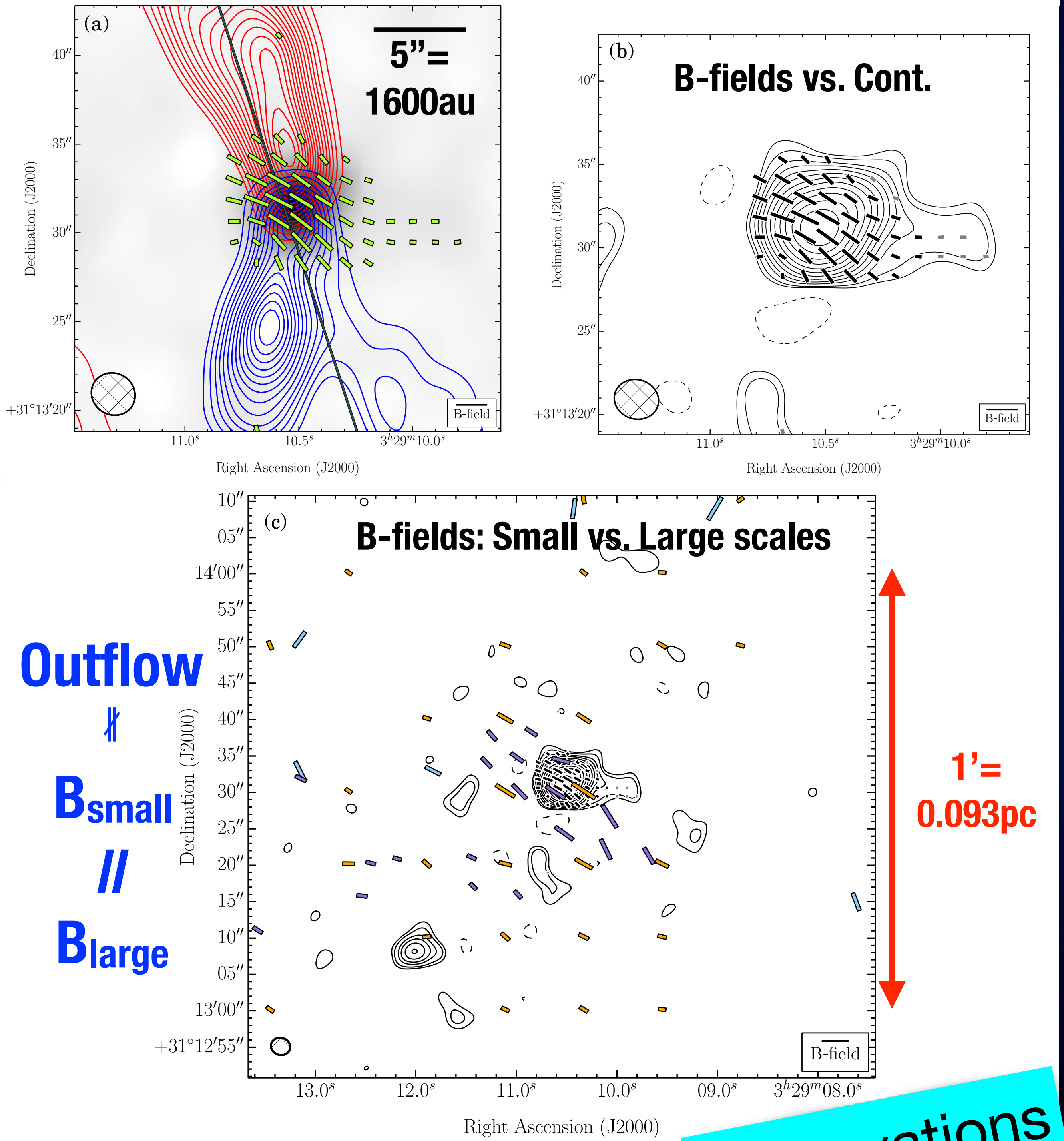
Hull et al. (2014); "TADPOL"-survey

- Pol. towards 30 cores and 8 regions forming stars at 2.5"
  - including low-mass Class 0 & I
- Compare with ≳20" B-fields with JCMT etc. as well as small-scale outflow directions



c.f.) B-vectors derived from λ=877μm Pol. with SMA(red); Girart et al. (2006)

L1333 IRS 4A (Class 0); d=320pc

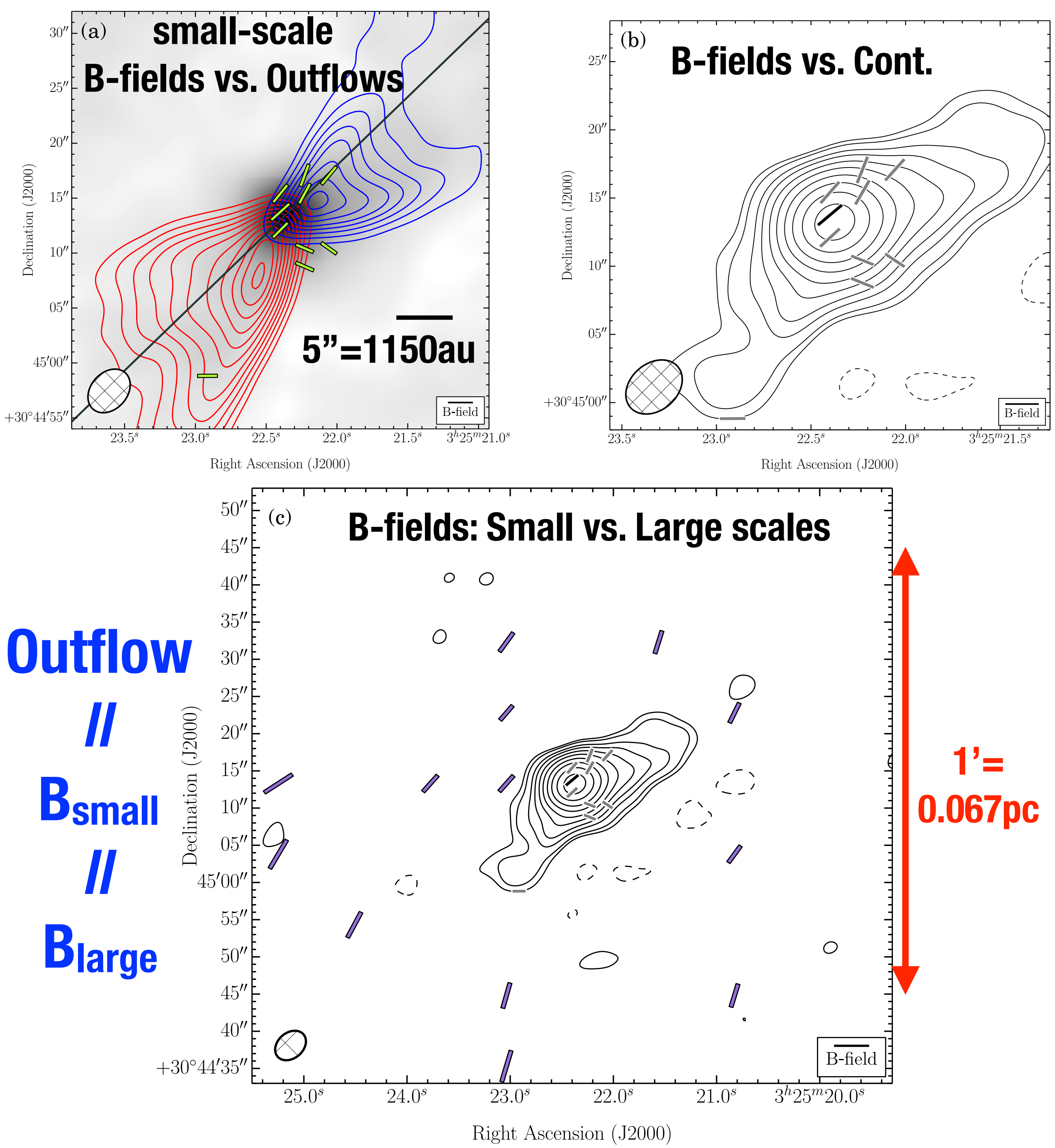


Observations

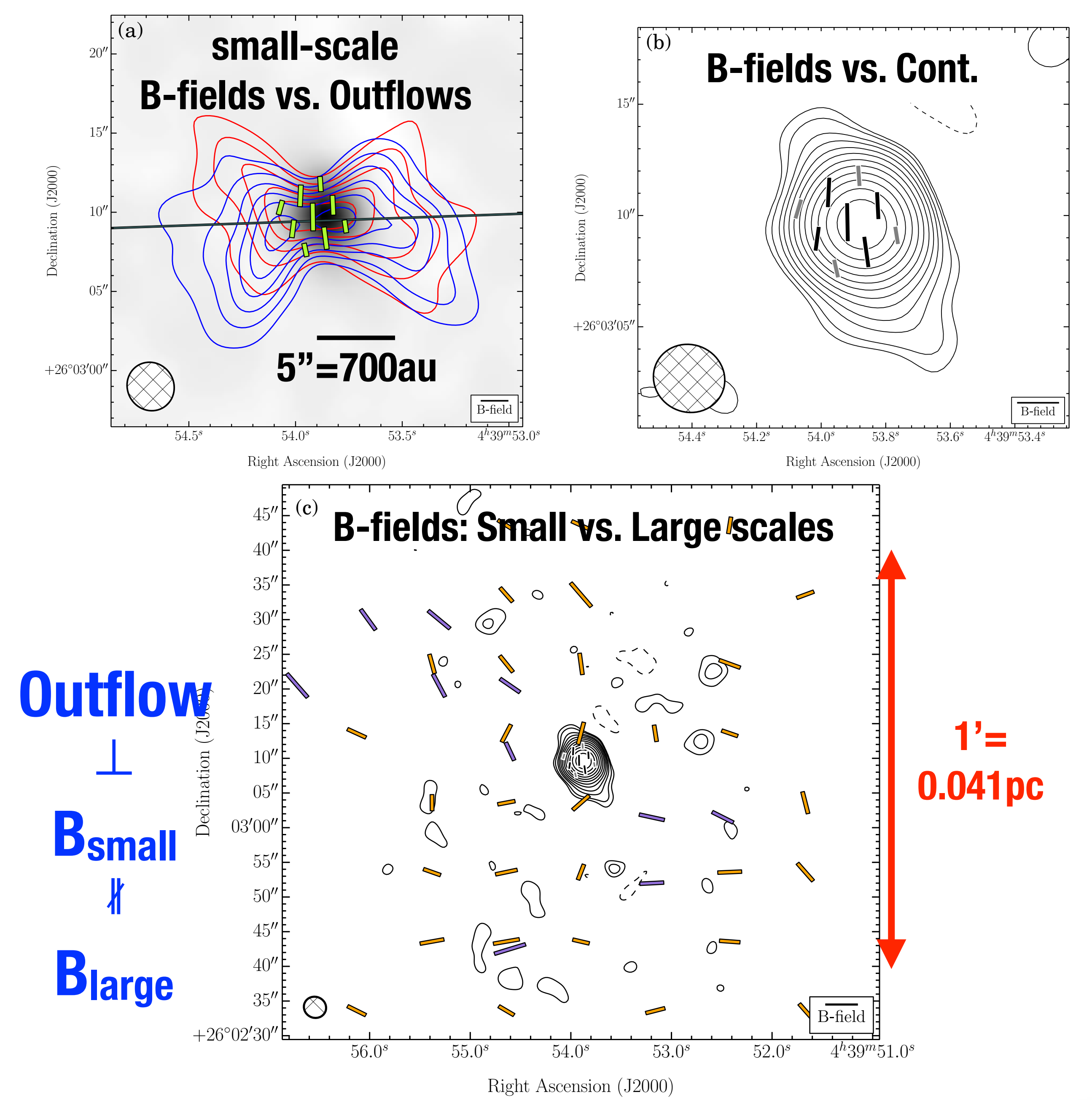
1.3mm Survey of Dust Polarization by CARMA

Hull et al. (2014); “TADPOL”-survey

L1448 IRS 2 (Class 0); d=230pc



L1527 (Class 0); d=140pc



Observations

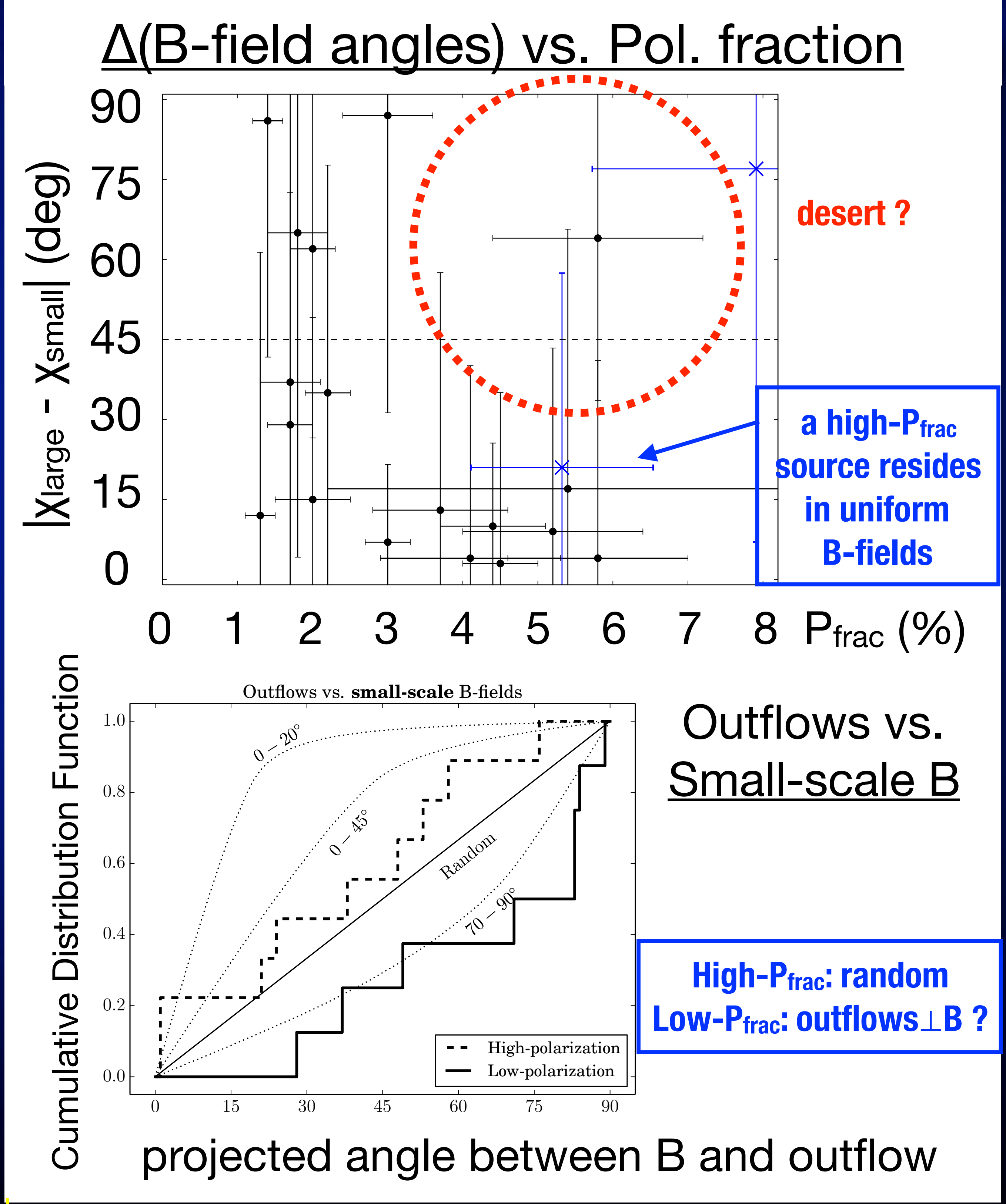
1.3mm Survey of Dust Polarization by CARMA

Hull et al. (2014); "TADPOL"-survey

<u>(Results)</u>

- A subset of objects (high pol.) have consistent B-directions in both size scales, but others do not.

- Outflows seem randomly aligned with B-fields at least for high-P_{frac} sources



- **B-directions (small & large)**
- **Outflows**
- **AM (the axis of rotating disk)**

are not always parallel

Recent progress (1): New large-scale maps

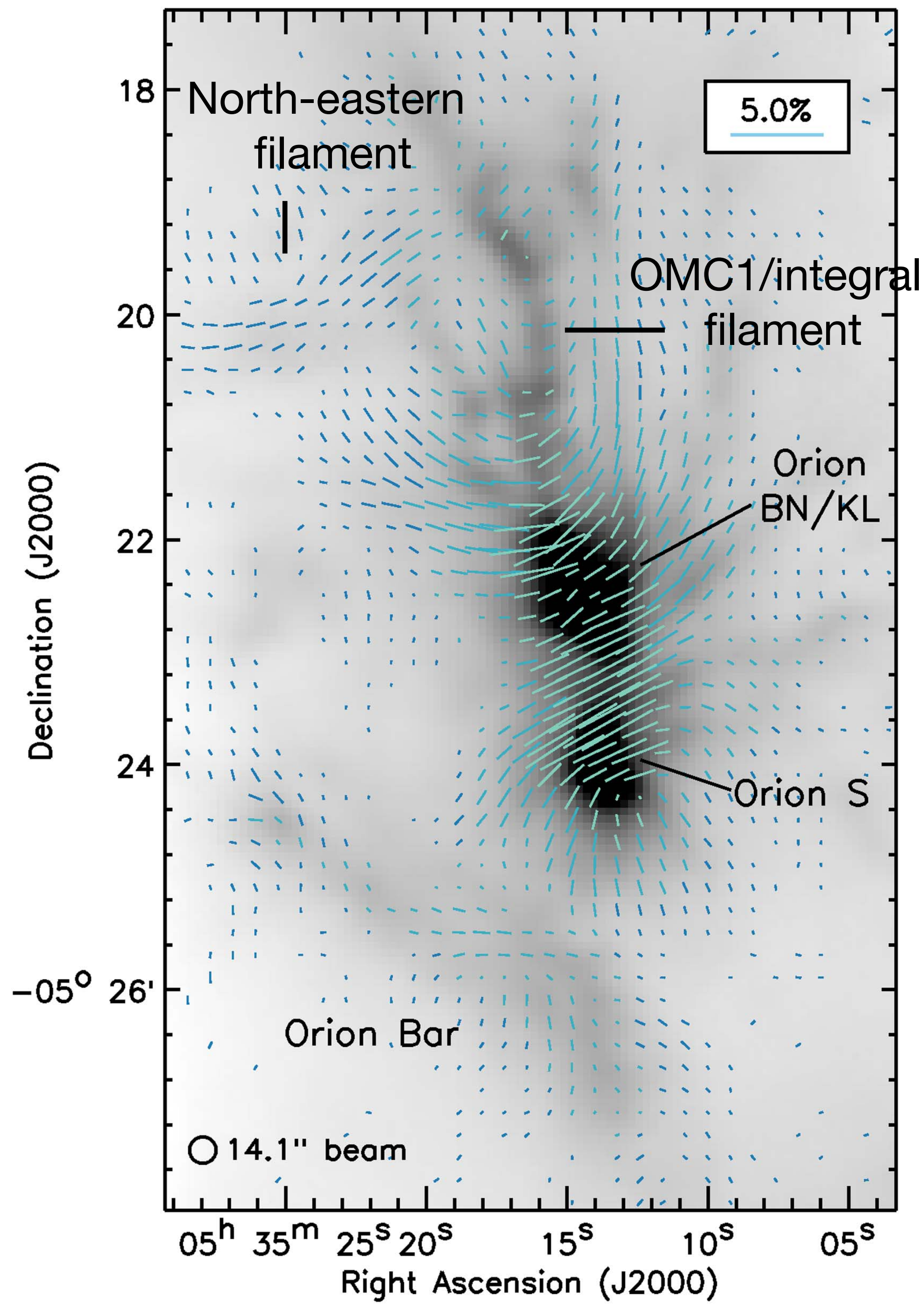
Ward-Thompson+ (2017); Pattle+ (2017); "BISTRO"-team

- JCMT + SCUBA-2/POL-2, 14"-beam at λ=850μm
- B ⊥ filament vs. B || filament
- B-field strength estimated by Chandrasekhar-Fermi method
  - equipartition of energy between B-field & turbulence

$$B_{\rm pos} \propto \frac{\sqrt{n_{\rm H_2}}\Delta V_{\rm turb}}{\langle \sigma_\theta \rangle}$$

  - a systematic method to derive $<\sigma_\theta>$ is also employed (Hildebrand+2009; Pattle+ 2017)

B-field map in Orion based on λ=850μm Pol. image



Recent progress (2): ALMA Pol. maps

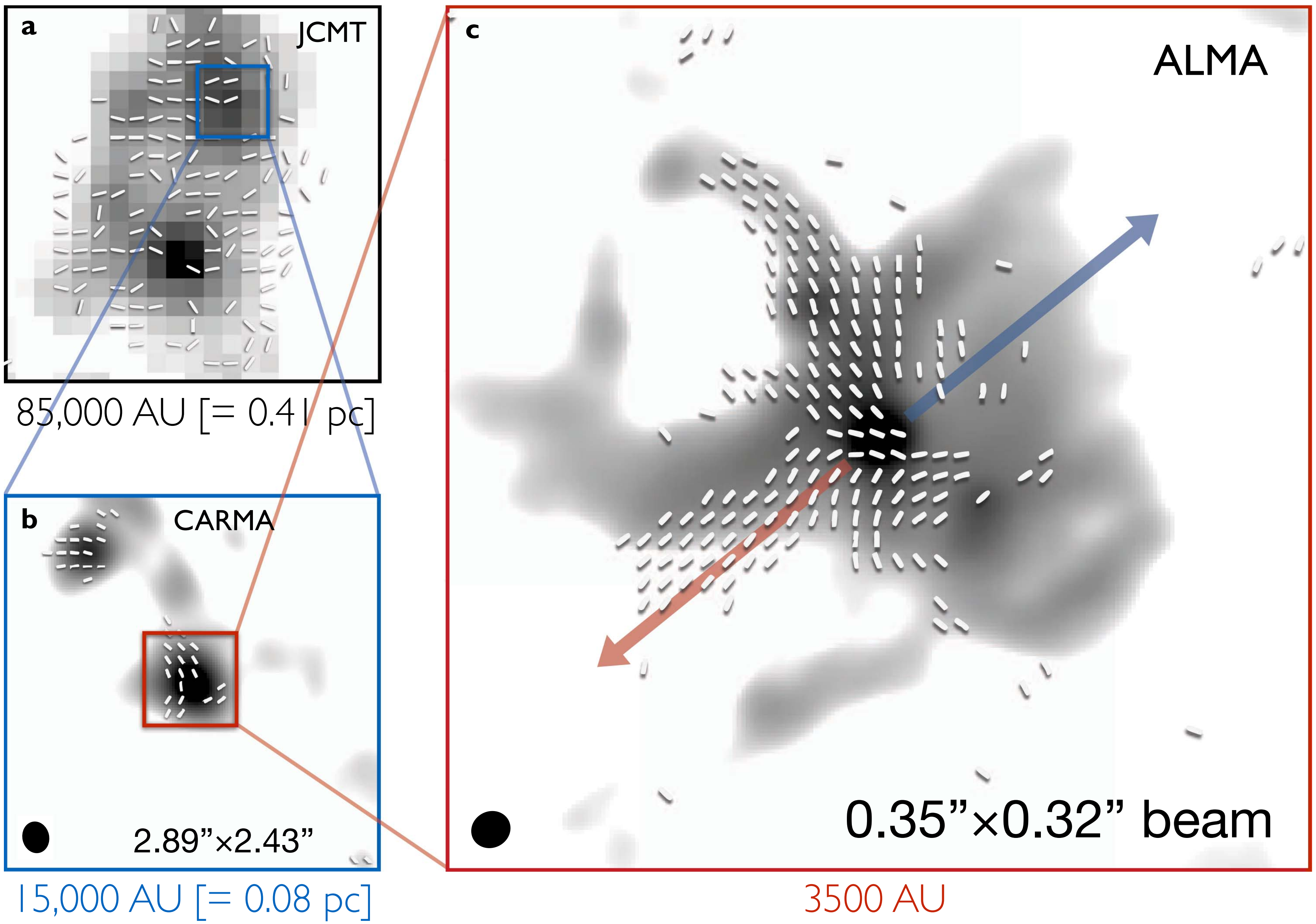
Hull+ (2017)

B-fields around Ser-emb8

d=436±9pc

λ=
870μm

λ=
1.3mm

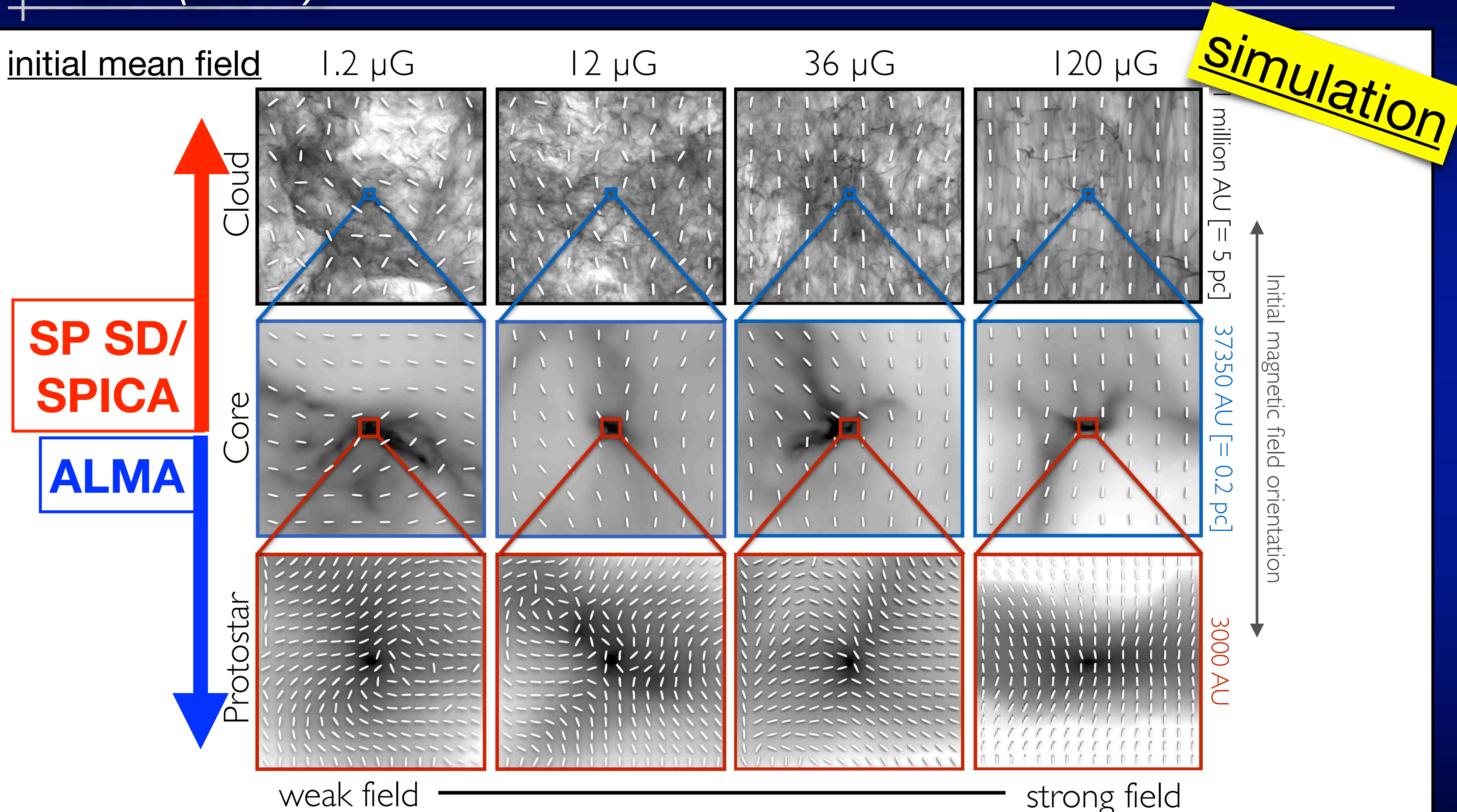


λ=
870μm

No hour-glass morphology (weakly magnetized cloud ?)

Recent progress (2): ALMA Pol. maps

Hull+ (2017)



random alignment, consistent with the “weak-field” case

Nearby Star-forming regions with South-pole Large SD

- B-field structure in size-scale ≳ dense cores
  - change of field directions in smaller size-scales (ALMA)…
    - statistics on protostellar disks
    - outflows' structure
  - field strengths
    - Chandrasekhar-Fermi method
    - Other methods (e.g., Koch+ 2012)
    - need cross-check with Zeeman?
- vs. SPICA/SAFARI
  - wavelength dependence
    - dust characterization,
    - alignment mechanism (environmental effects, etc.)

misalignment between B & AM may produce
<u>Two types of outflows ? (Matsumoto+ 2017)</u>

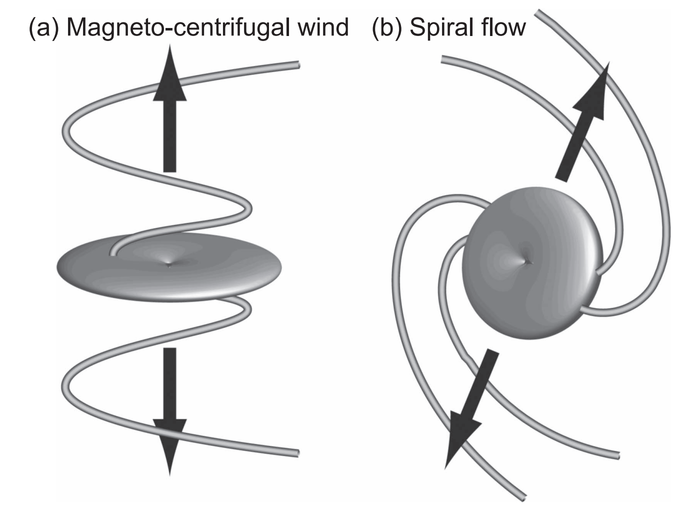
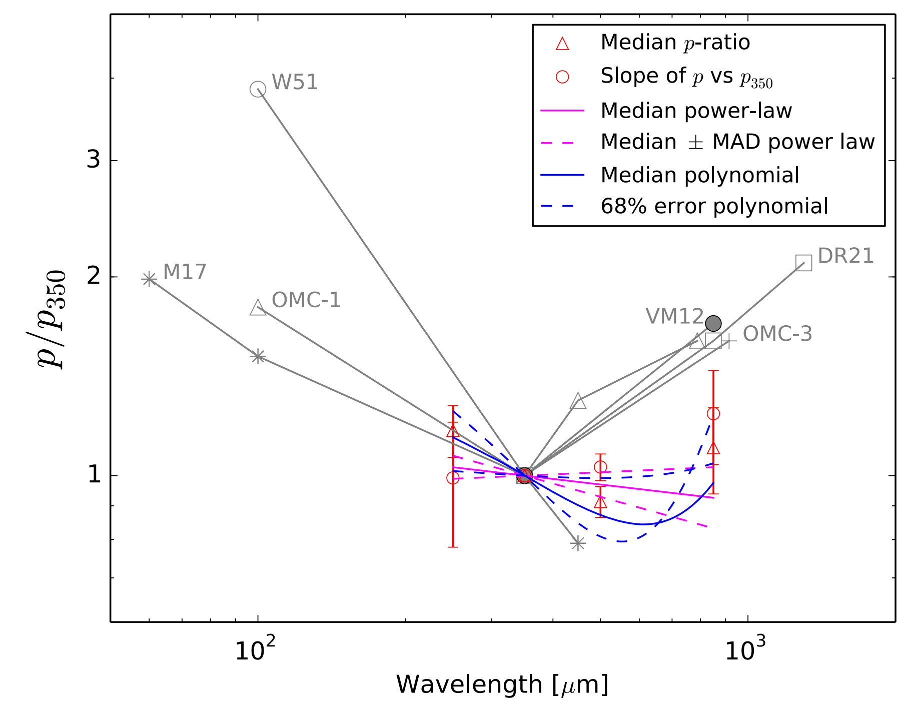


Figure 15. Schematic diagram of two types of outflows: (a) magnetocentrifugal wind, and (b) spiral flow. The surfaces represent isodensity surfaces, and the tubes denote the magnetic field lines. The arrows indicate the direction of the outflow.

<u>λ-dependence</u>

BLAST observations in Vela C molecular clouds (red) do not show "polarization-minimum" at λ~350μm (Gandilo+ 2016; Fissel+ 2016)



An Observation Plan

- Unique if multiple frequencies available (e.g., 400 & 850GHz)
- assuming T=15K, A_V≳20mag., or N(H) ≳ 9.4E22 cm^{-2}
  - to be complimentary to SPICA

表 1.1: ダスト偏光観測に必要な感度 (total intensity×1%に対するもの)

	D=10m		D=30m	
周波数 (GHz)	ビームサイズ (″)	必要感度 (1σ) (mJy/beam)	ビームサイズ (″)	必要感度 (1σ) (mJy/beam)
400	18.6	1.11	6.2	0.123
850	8.7	1.95	2.9	0.216

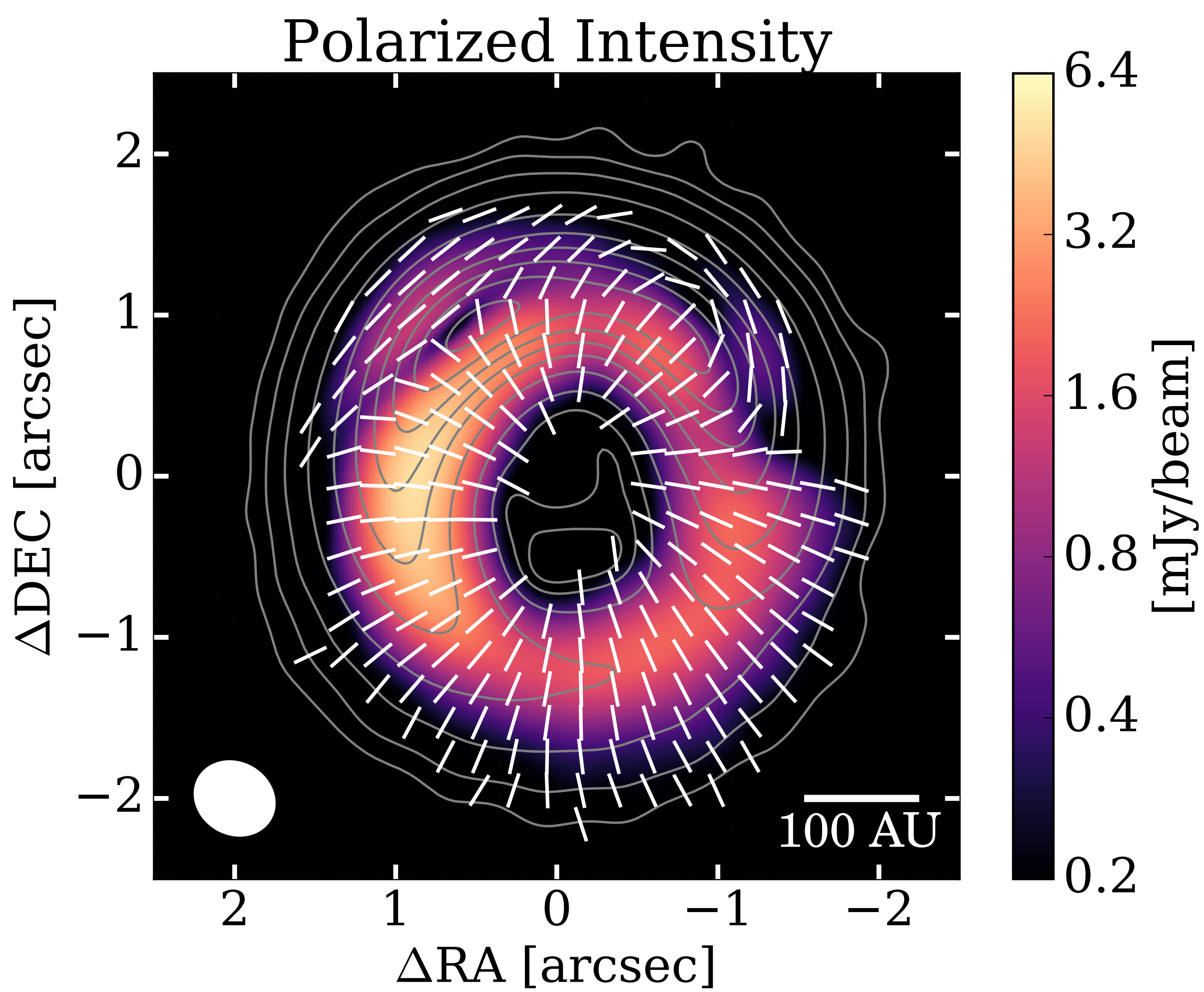
ground-based polarization observations above 850 GHz may be possible only from south pole regions.

(2) Polarization observations of Protoplanetary (& Debris) Disks

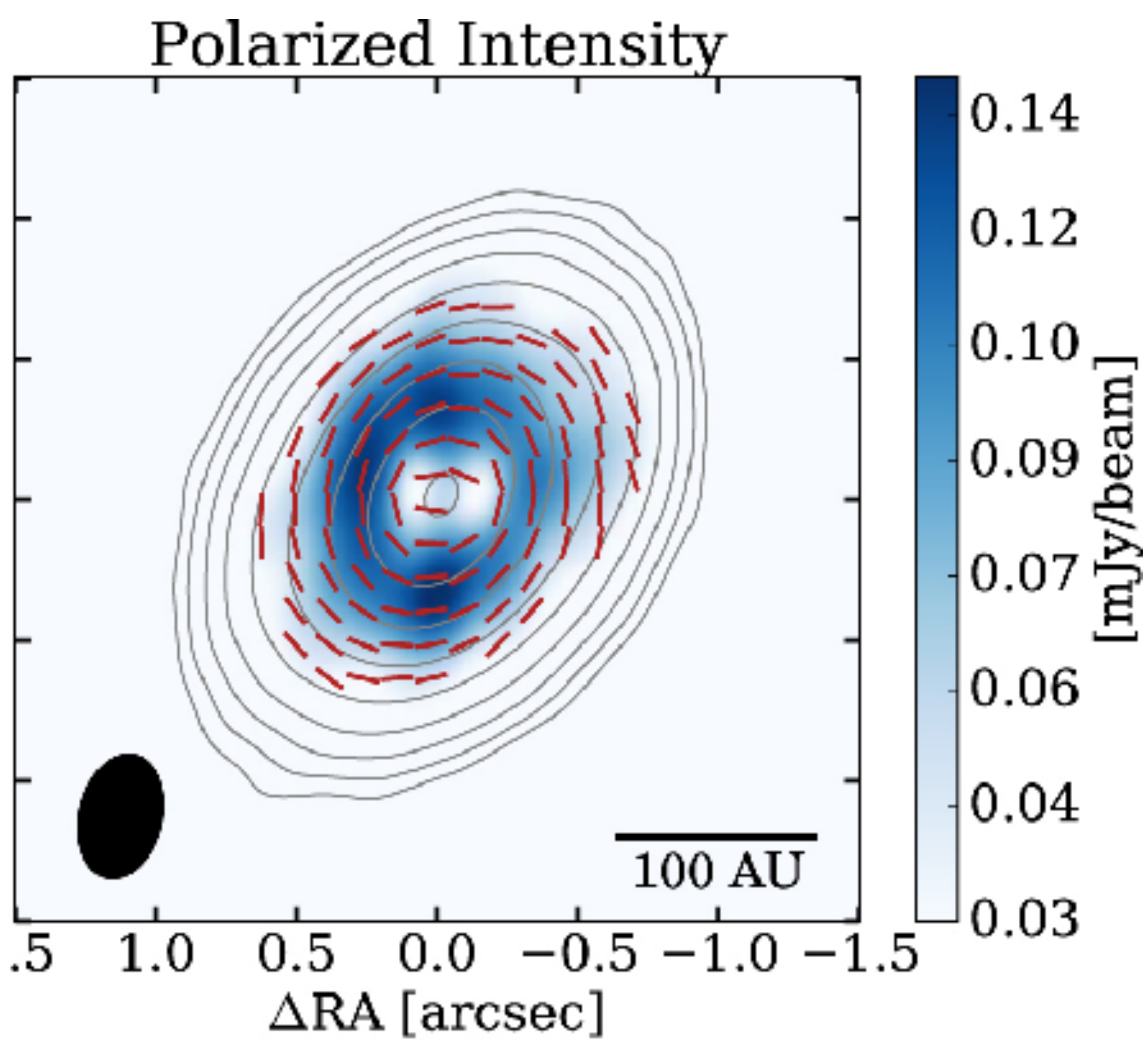
Polarization in a protoplanetary disk

A new window opened by ALMA

HD142527 at λ=874μm



HL Tau at λ=3.1 mm



spatial resolution is critical to reveal small-scale structure of polarization vectors

theoretical background

Origin of dust polarization at mm-submm

1. Thermal emission of “aligned” grains (Tazaki+ 2017)
   - Two alignment mechanisms
     A. ***J // B*** **:** Larmor precession (***B:*** magnetic field)
     B. ***J // k*** **:** Radiative precession (***k:*** net radiation flux)
   - Radiative alignment (***J // k***) seems dominant for a large grains (*a* > 100μm) in a protoplanetary disk
2. Self-scattering of anisotropic radiation fields by dust grains (Kataoka+ 2015, 2016a; Yang+ 2016)
   - High albedo, *and,* High pol. efficiency are required ← prominent only at $\lambda \sim (2\pi)a_{max}$; strong λ-dependence !

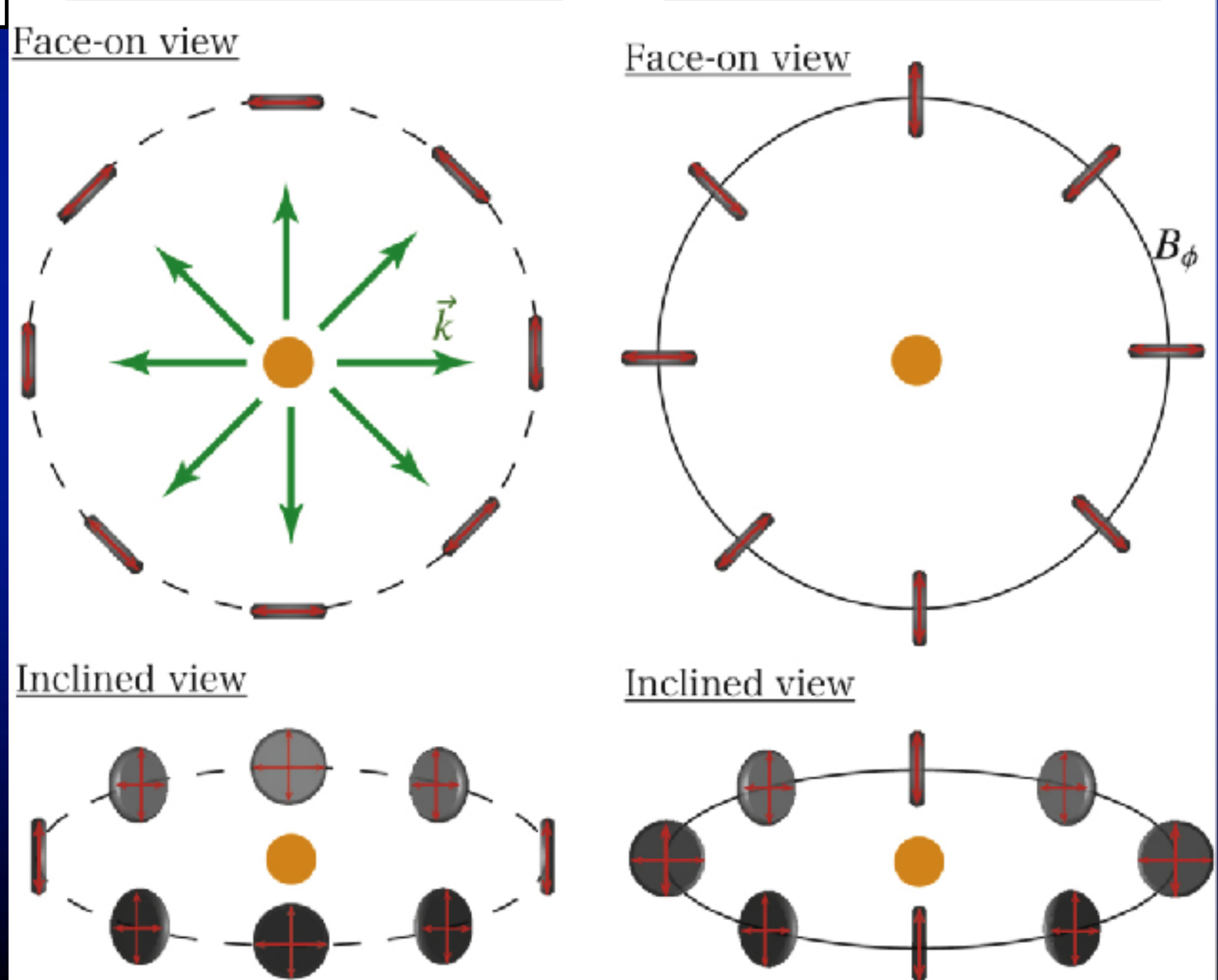
Two external alignment mechanisms

$\vec{J} \parallel \vec{k}$

with radiation flux

with toroidal B-field

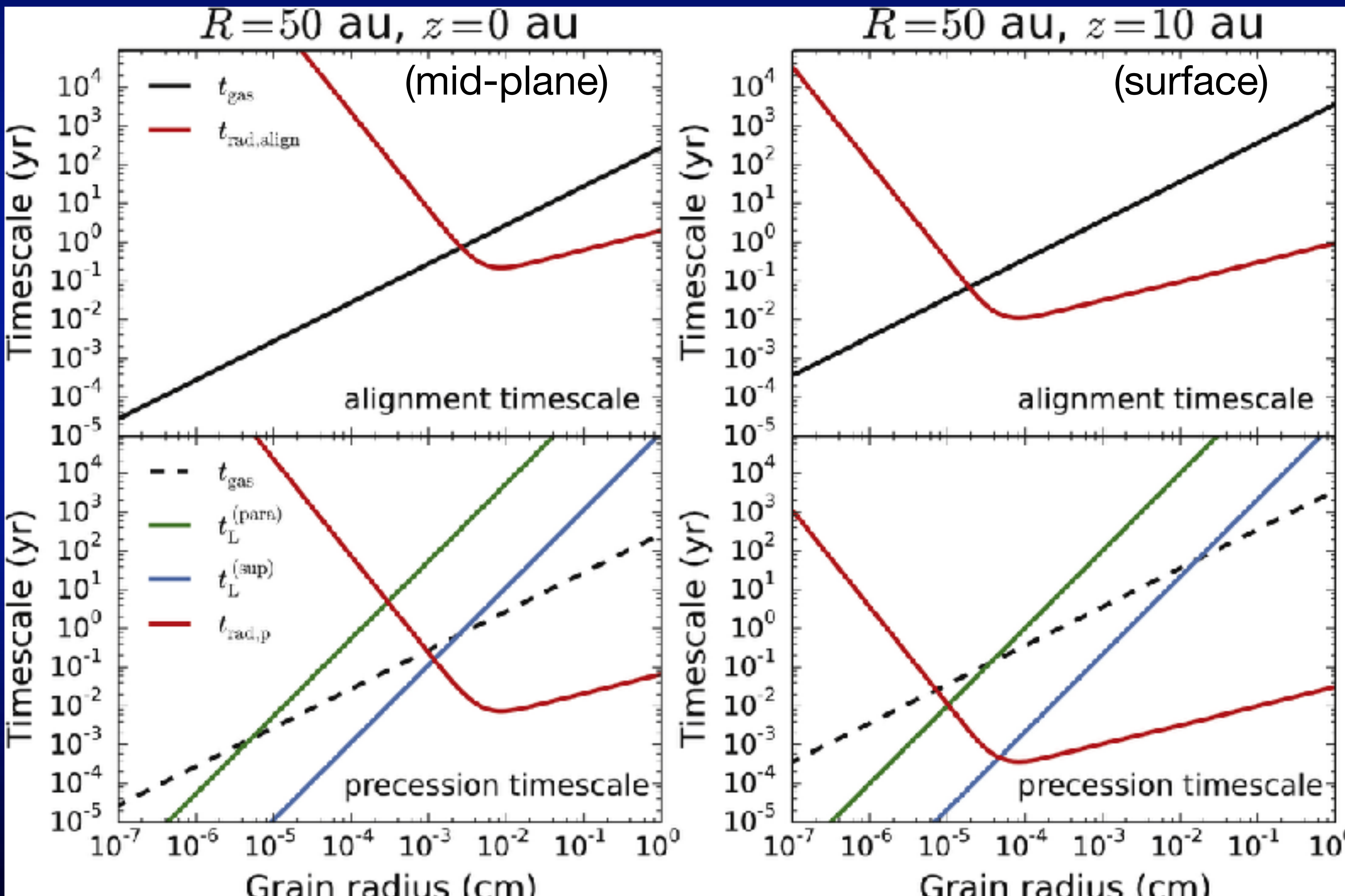
$\vec{J} \parallel \vec{B}$



Tazaki et al. (2017)

Various timescales of related processes in a protoplanetary disk *(Tazaki et al. 2017)*

Timescale : the shorter is more important



(black)
gaseous damping

(red)
radiation alignment

magnetic precession
(green)
10% paramagnetic inclusion
(blue)
10% super-paramagnetic inclusion

(red)
radiation precession

theoretical background

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Condition for polarization due to scattering

Kataoka, Muto, MM et al. (2015)

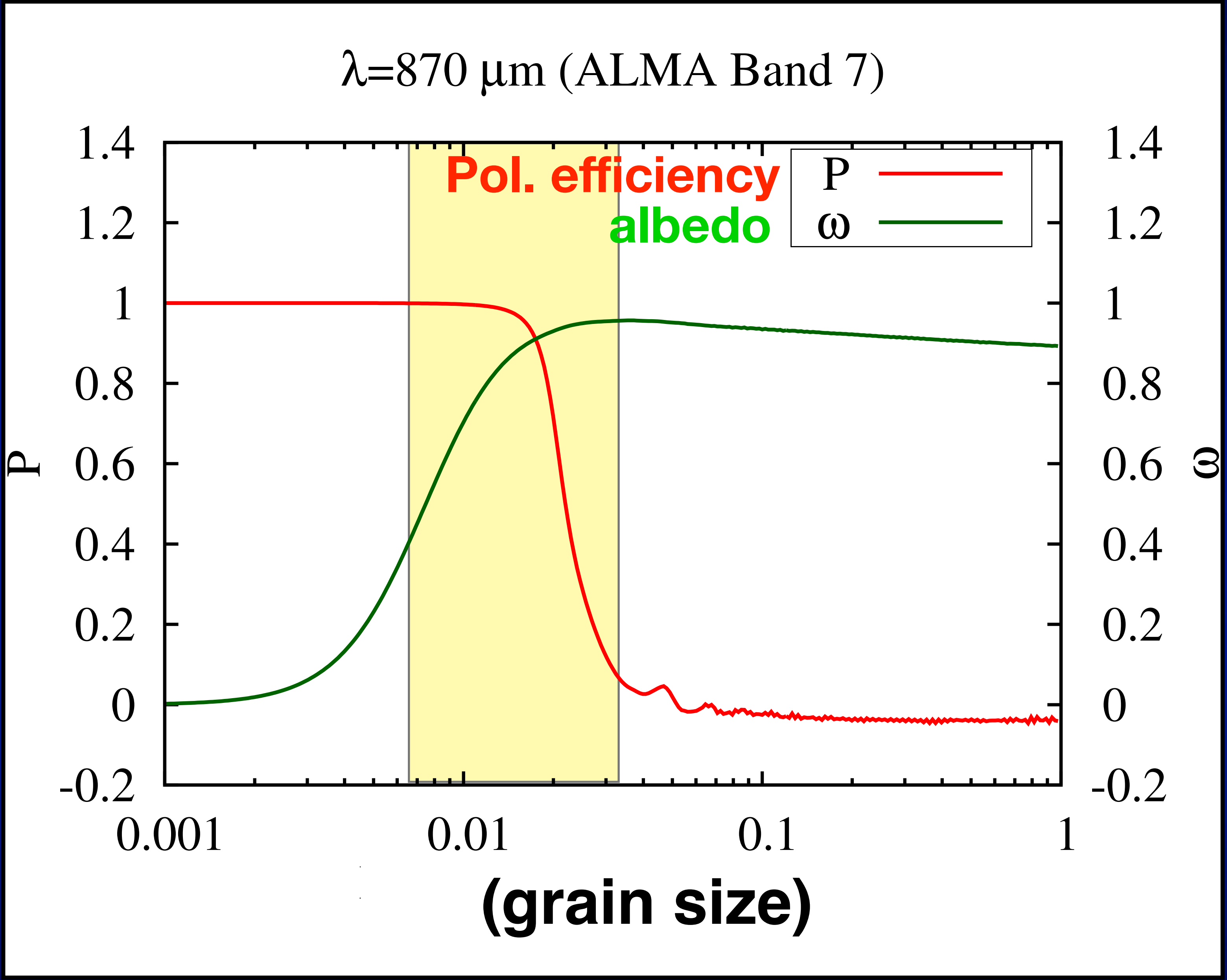
- For efficient scattering

  (grain size) ≳ λ/2π

- For efficient polarization

  (grain size) ≲ λ/2π

There is a grain size which contributes most to the polarized emission

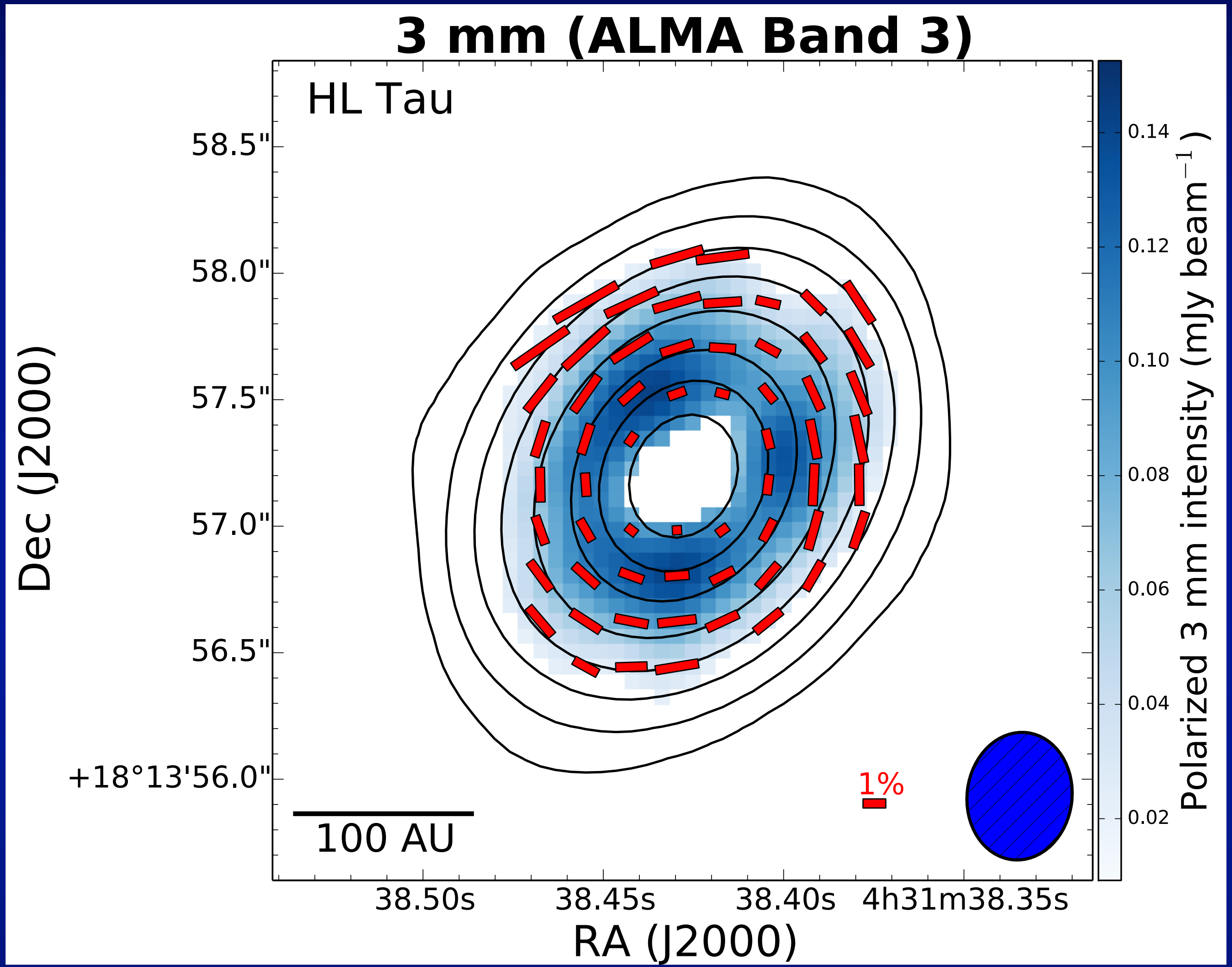


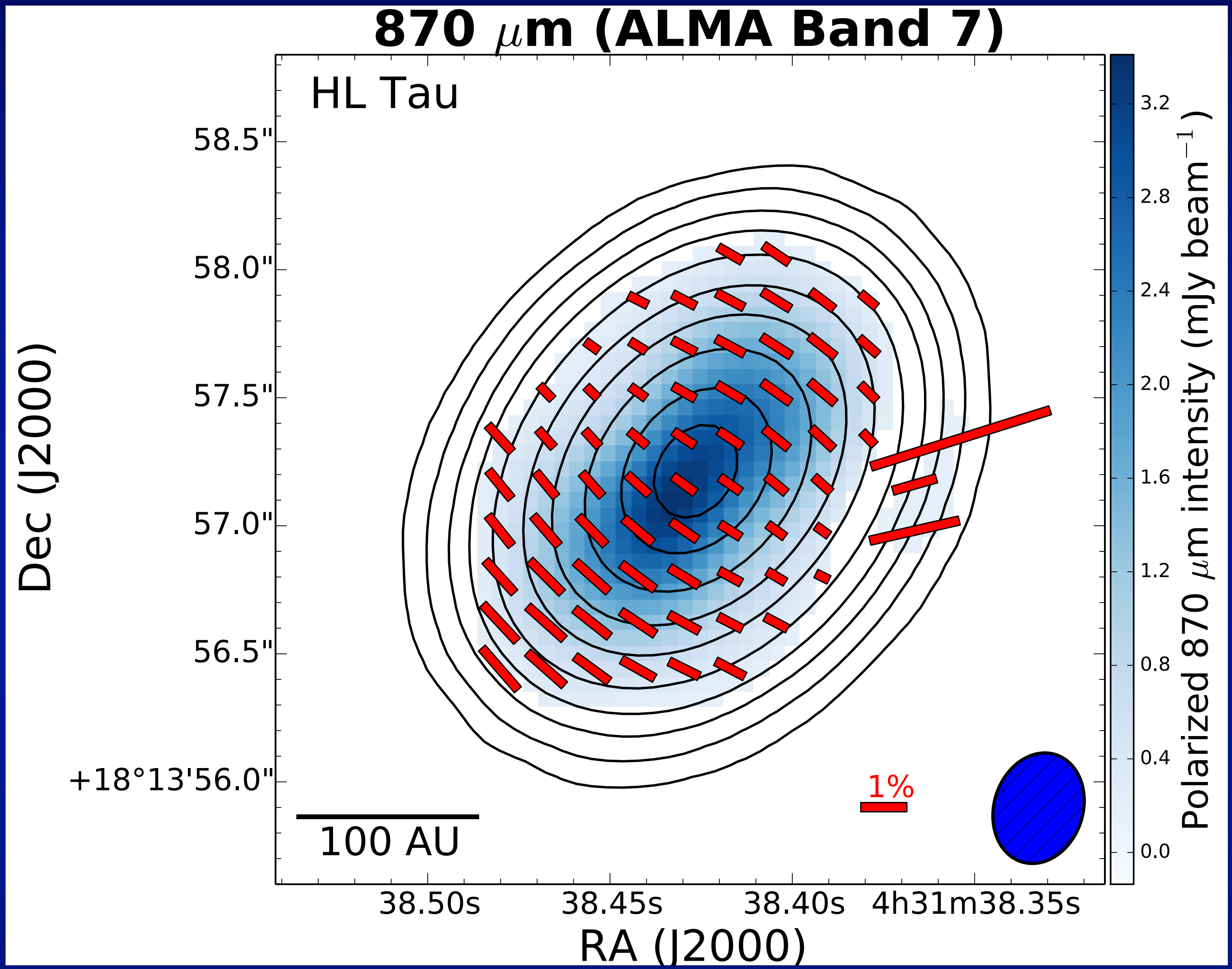
If (grain size) ~ λ/2π, the polarized emission due to dust scattering is strongest

HL Tau: Strong λ-dependence

Kataoka et al. (2017, 2015); Stephans et al. (2017; 2014)

observations





Polarization directions

- λ=3.1mm: azimuthal ← radiative alignment (i.e., ***J // k***)
- λ=0.87mm: parallel to the minor axis ← self-scattering
- consistent with the case of $a_{max} \approx 100\mu m$ with $n(a) \propto a^{-3.5}$

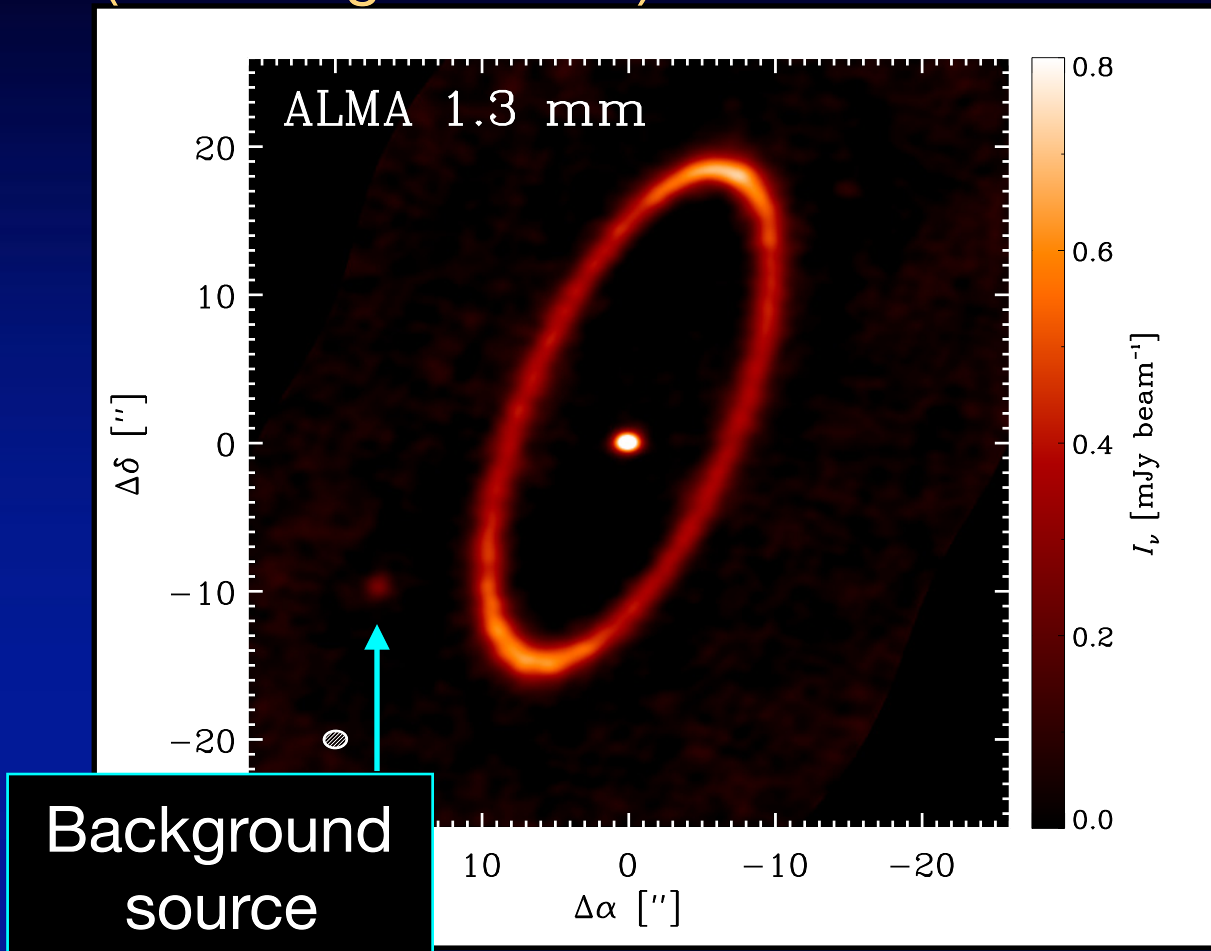
Protoplanetary Disks/Debris Disks with a South-Pole Single Disk at THz

- protoplanetary disks seem sufficiently bright to make polarization observations at THz
  - HL Tau: ~10Jy @ λ=450μm (Andrews & Williams 2005)
  - DM Tau: ~ 1.08 Jy @ λ=350μm (Andrews & Williams 2005)
- will not be able to spatially resolve them, but …
  - polarization will be detected only when the polarization directions in the disk are rather uniform
  - λ-dependence of polarization detection — scattering ?
- nearby debris disks: Pol may be difficult, but..
  - β Pic, Fomalhaut, ε Eri (Vega) : "The Fabulous Four", Pol.?
  - τ Cet : 5.8mJy at λ=850μm(JCMT) r_{out} = 52au at d=3.65 pc, can be imaged in Total intensity with better sensitivity

Fohmalhaut

(MacGregor+ 2017)

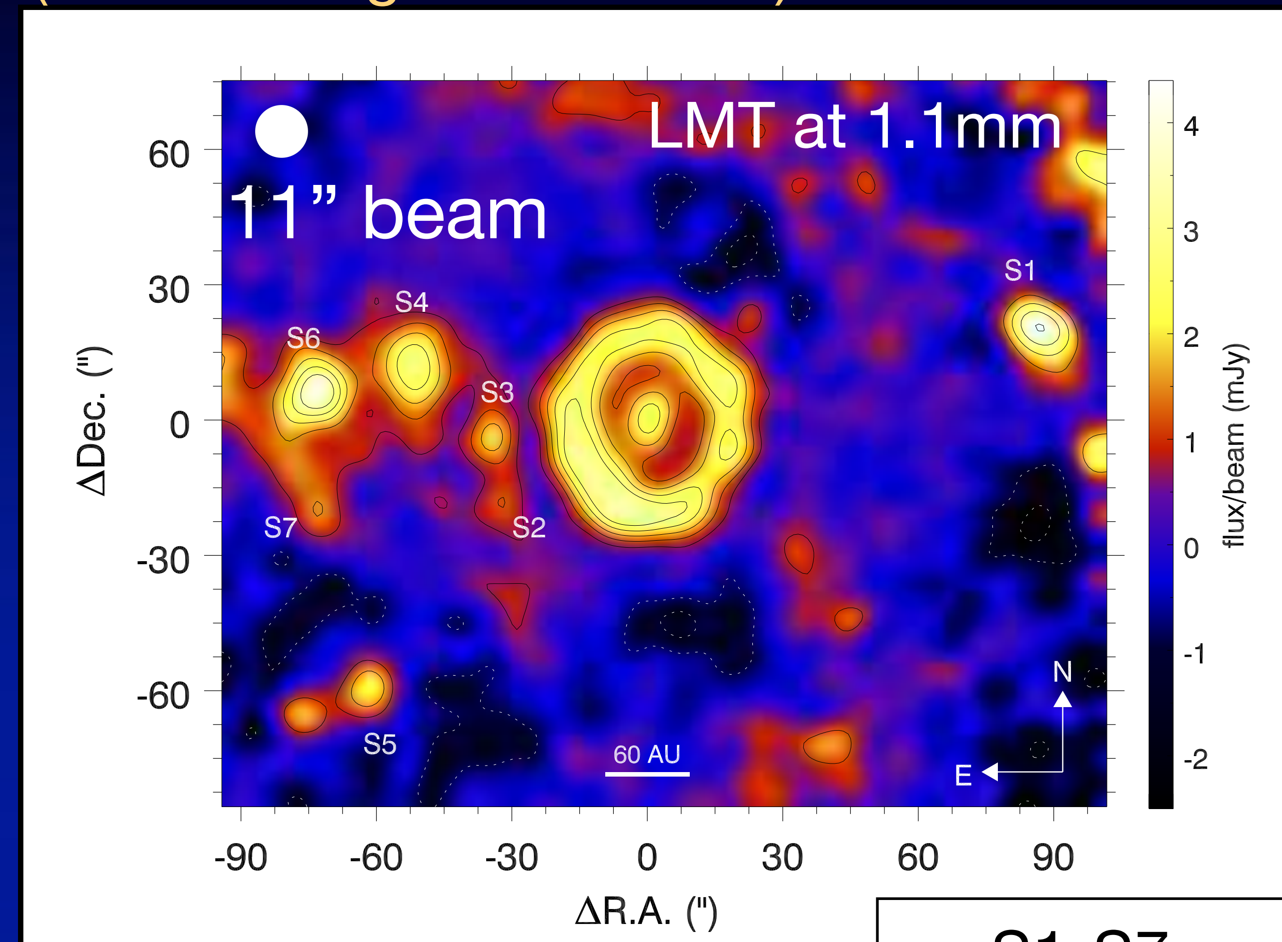
age = 0.44 Gyr; d=7.66 pc; A4V



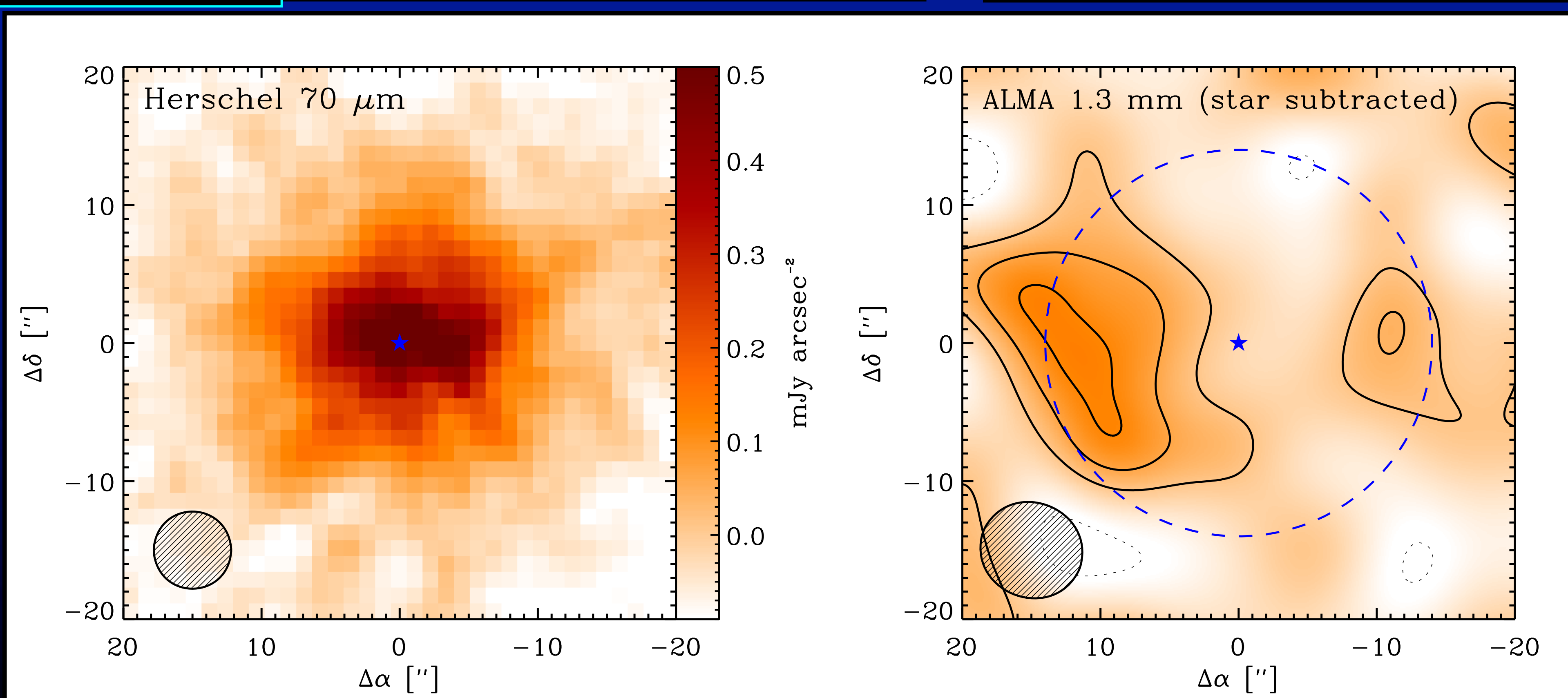
ε Eri

(Chavez-Dagostino+ 2016)

age = 0.8-1.4Gyr; d=3.22 pc; K2V



S1-S7: Background sources



τ Cet

(MacGregor+ 2016)

age = 7.24 Gyr; d=3.65 pc; G8V

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Summary

- Large vs. small scale B-fields and their connection with disk/outflow structure and their evolution
  - B-Field's directions & strengths at various size-scales
  - wavelength dependence of polarization efficiency
- Small-scale structure of polarization in protoplanetary disks has been detected by ALMA
  - no B-field alignment ? … but, wavelength dependence for a large sample -> dust size
- Nearby protoplanetary & debris disks may be important targets for the Single Disk in South Pole regions