SPICA Meeting in 2017 (ISAS/JAXA, 22Nov. 2017)

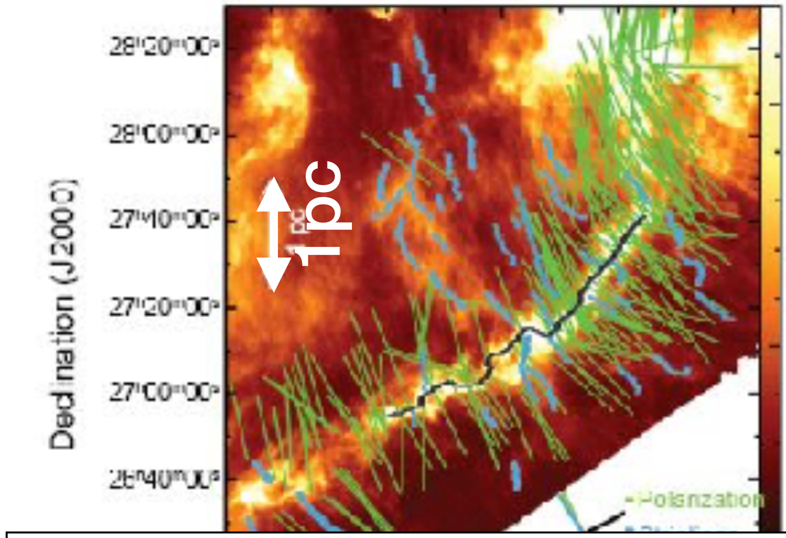
Observations of disks around young stellar objects

Recent progresses and Prospects of polarization observations with SPICA

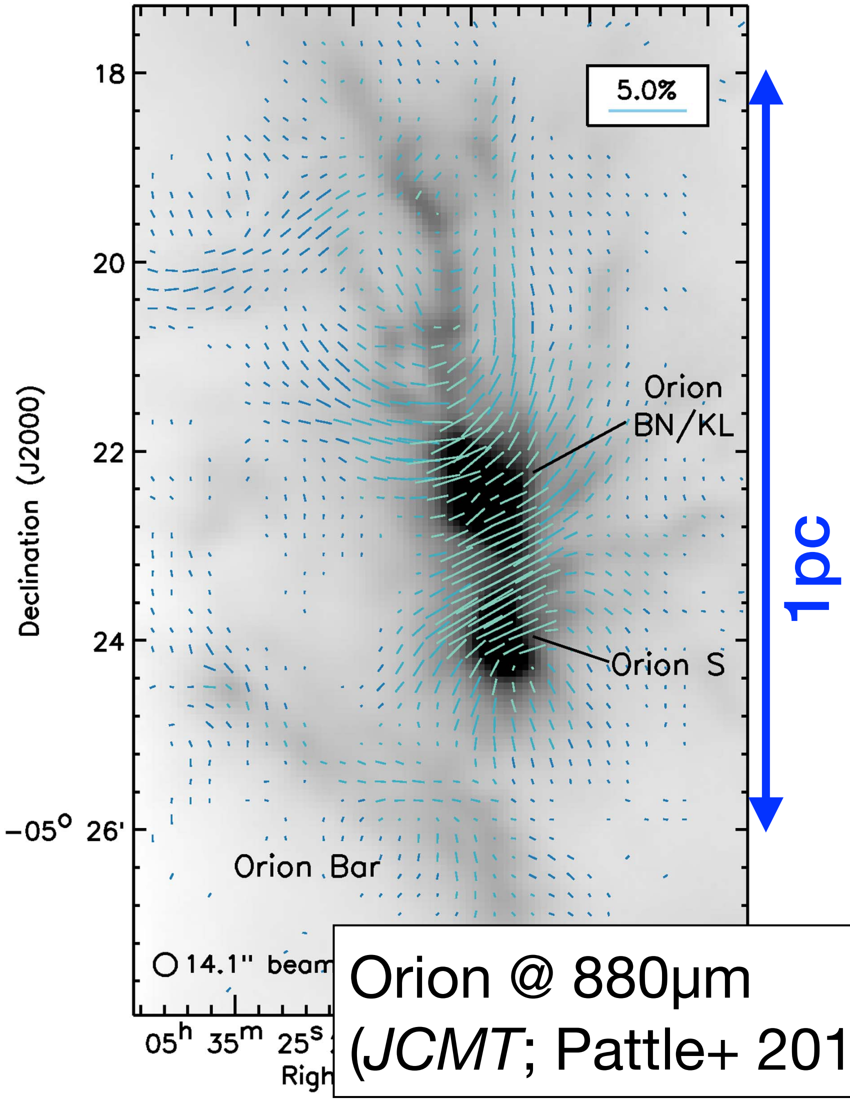
Munetake MOMOSE (Ibaraki University)

~ 0.1pc

B-field



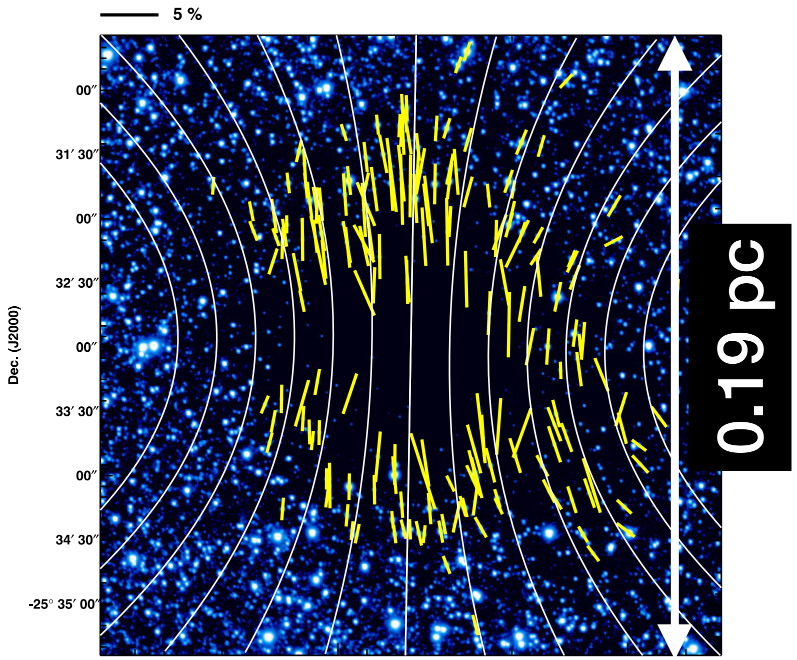
Taurus@250μm + Optical/IR Pol.
(Palmeirim+ 2013; Heyer+ 2008)



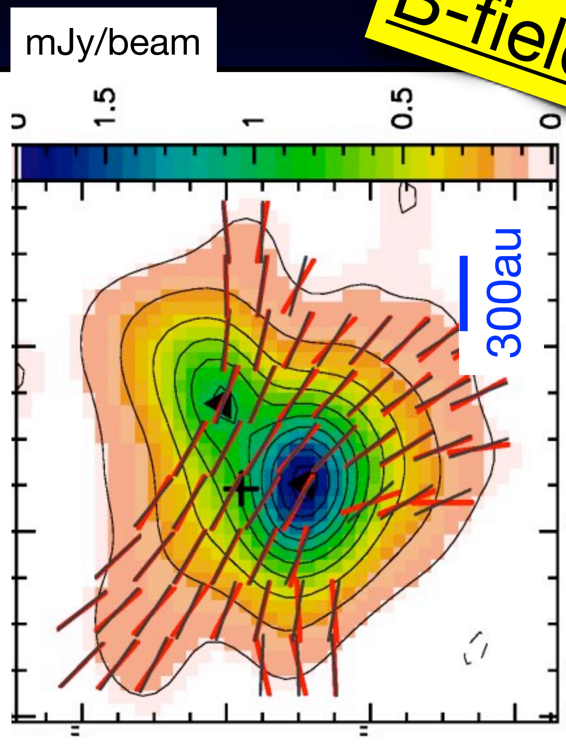
Orion @ 880μm
(*JCMT*; Pattle+ 2017)

~ 0.01pc (2000au)

B-field



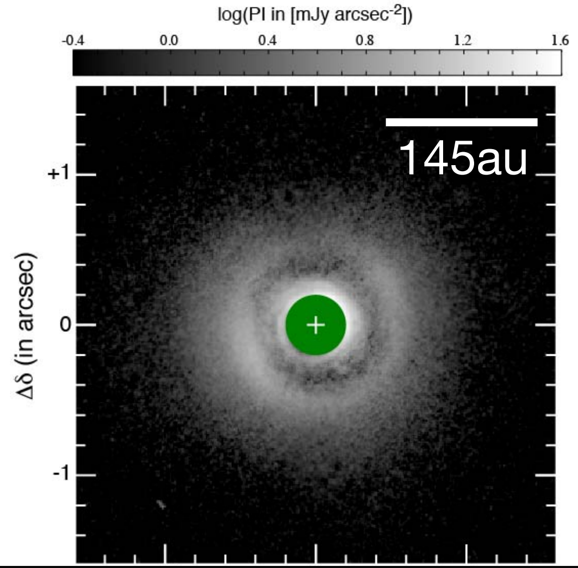
Prestellar Core, FeSt1-457
@1.6μm(*IRSF*; Kandori+2017)



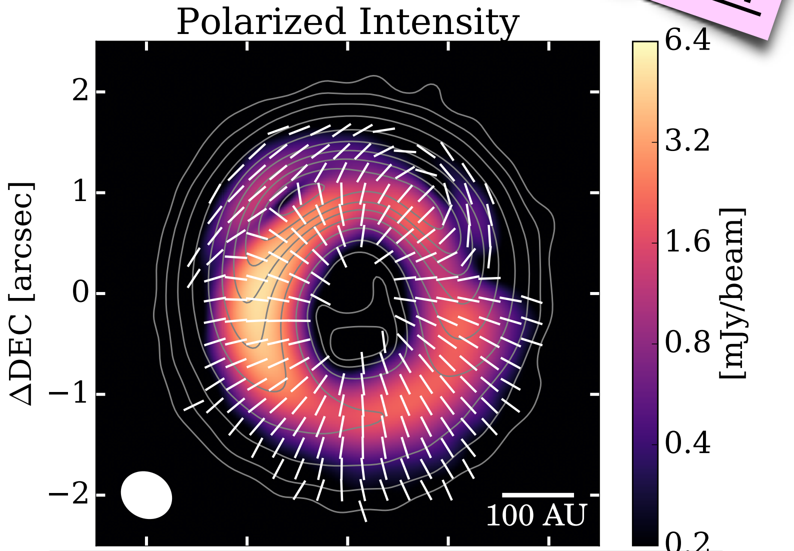
Protobinary, L1333 IRS4A
@880μm(*SMA*; Girart+2006)

~ 0.001pc (200au)

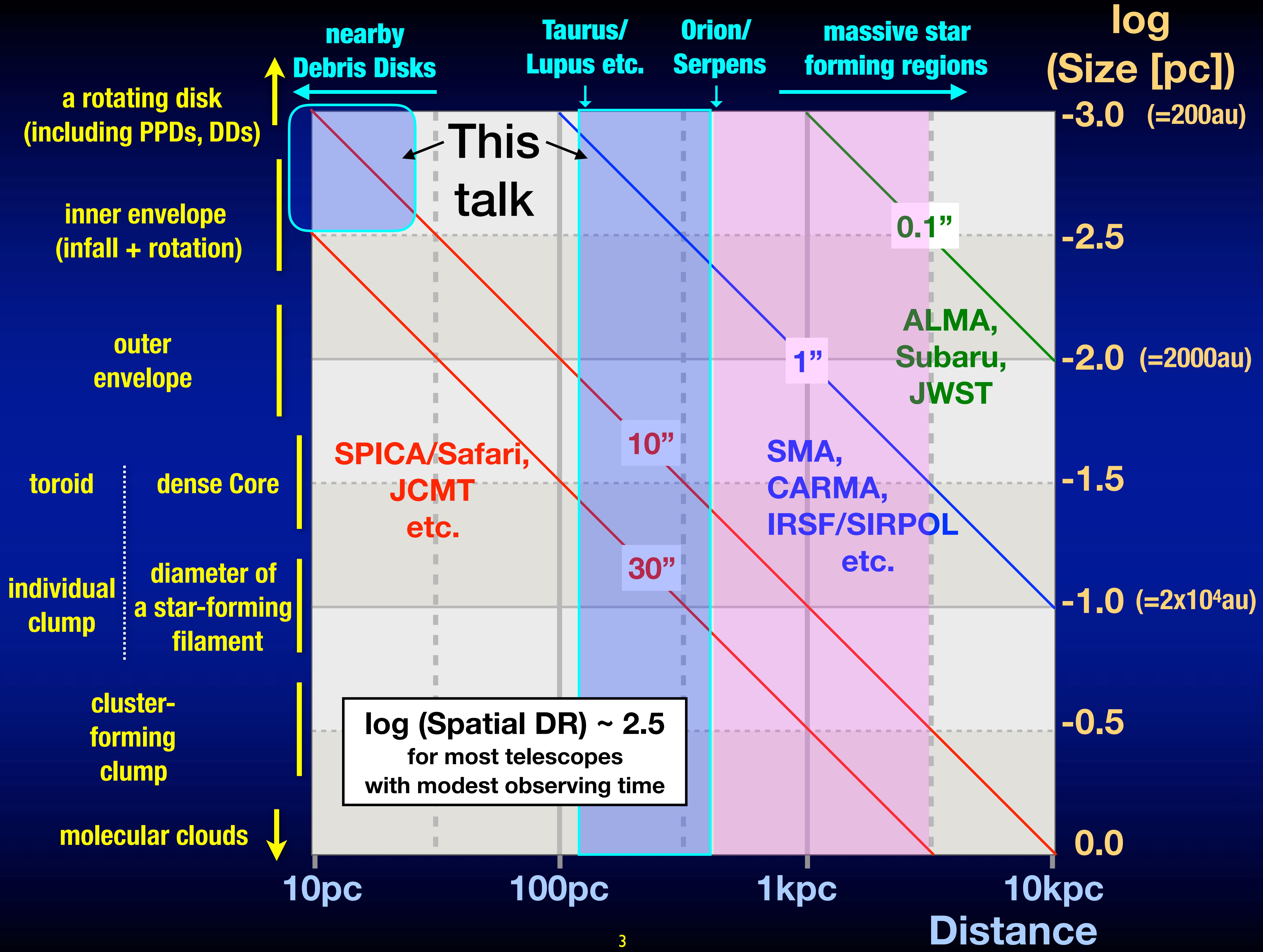
E-vector



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



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



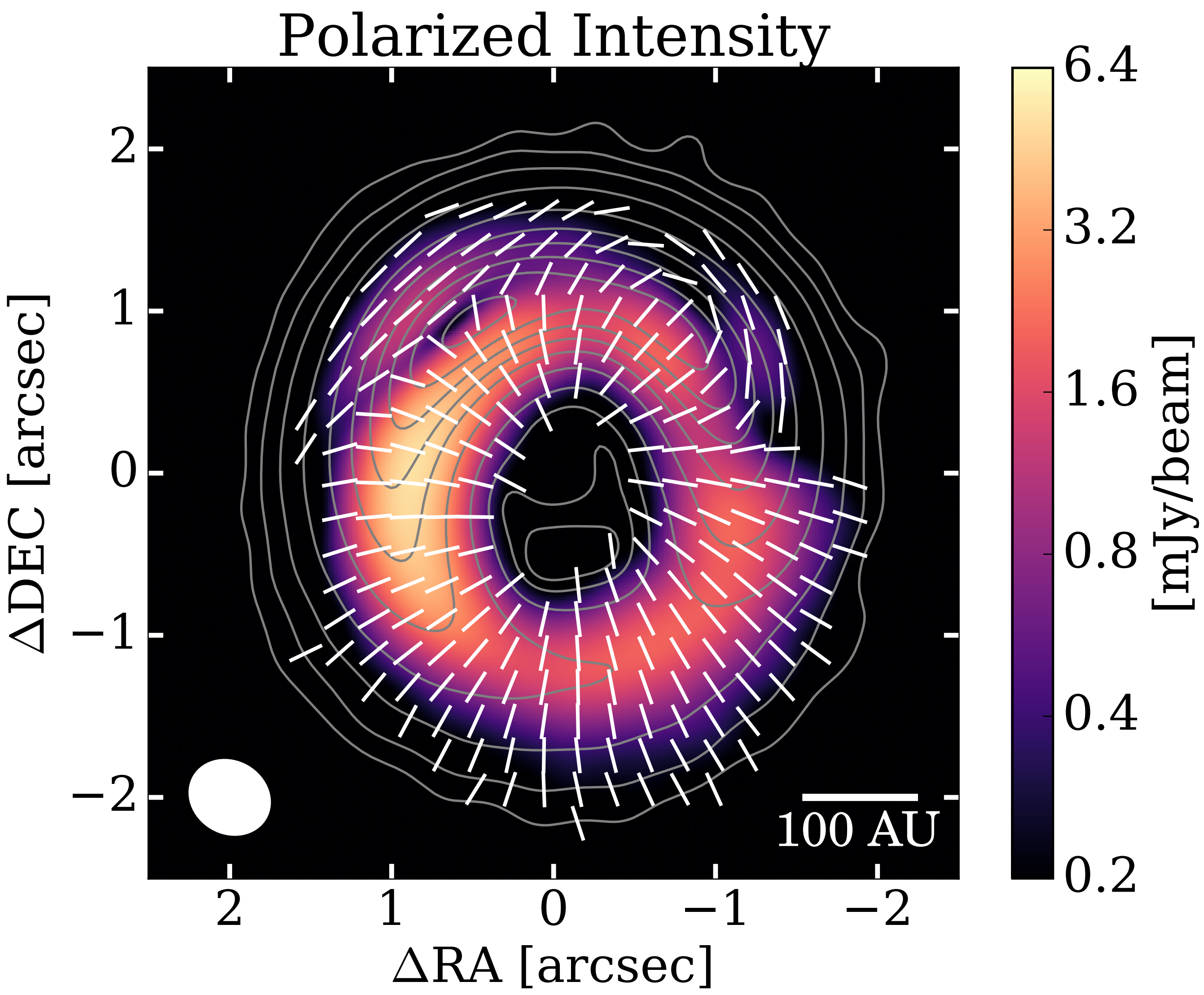
log (Spatial DR) ~ 2.5
for most telescopes
with modest observing time

(1) Polarization observations of Protoplanetary & Debris Disks

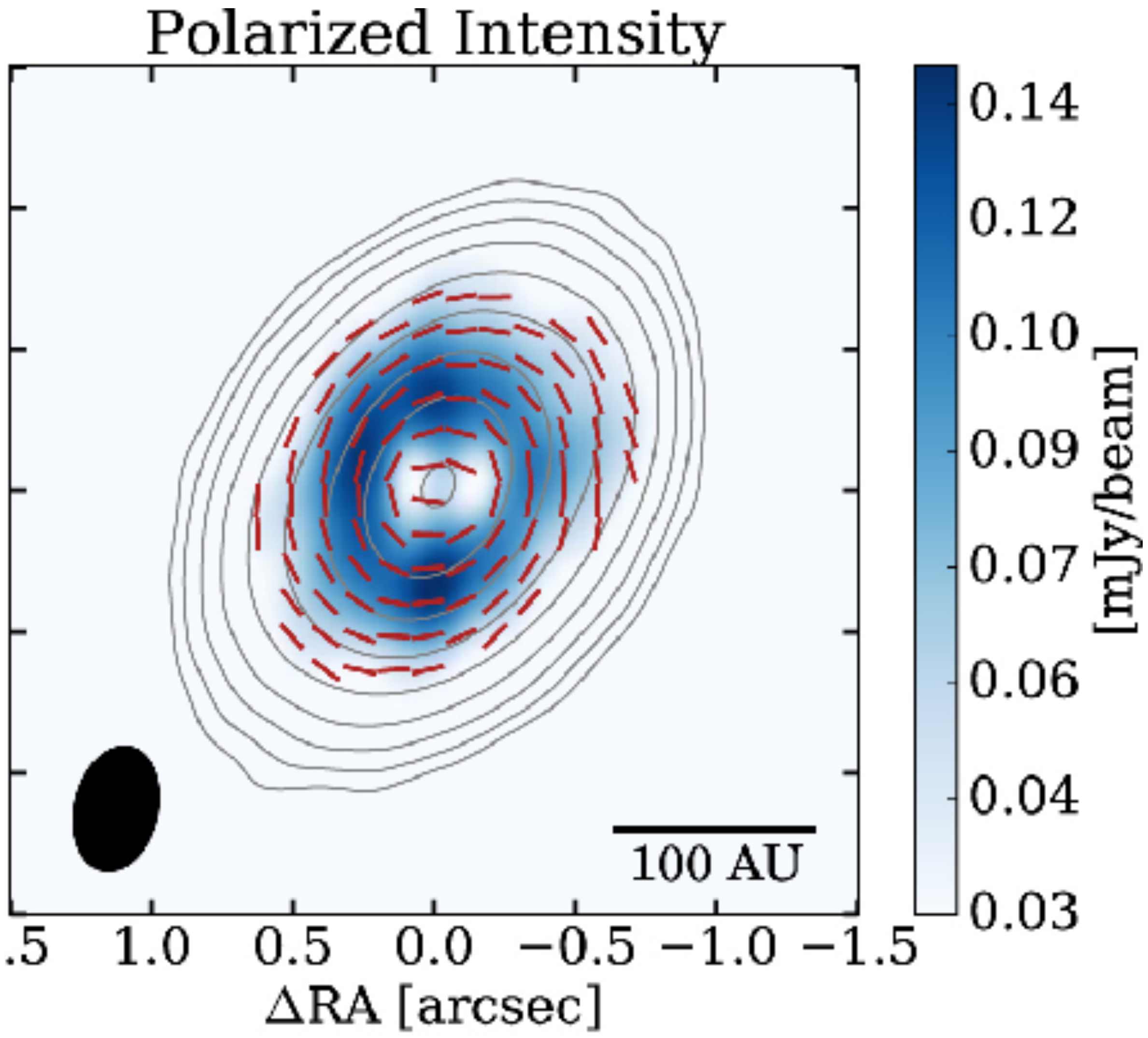
Polarization in a protoplanetary disk

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
     1. ***J // B*** **:** Larmor precession (***B:*** magnetic field)
     2. ***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 !

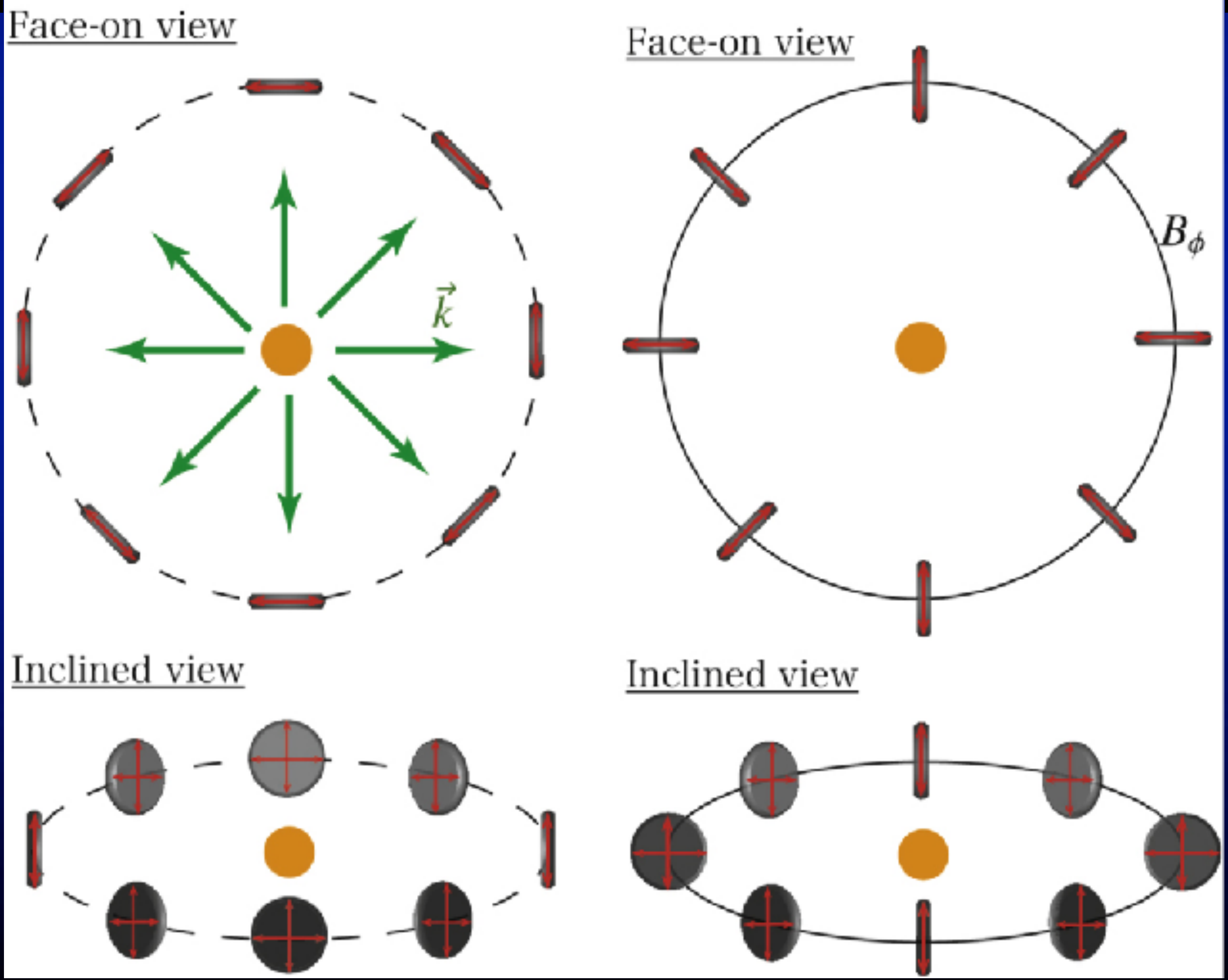
Two external alignment mechanisms

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

with radiation flux

with toroidal B-field

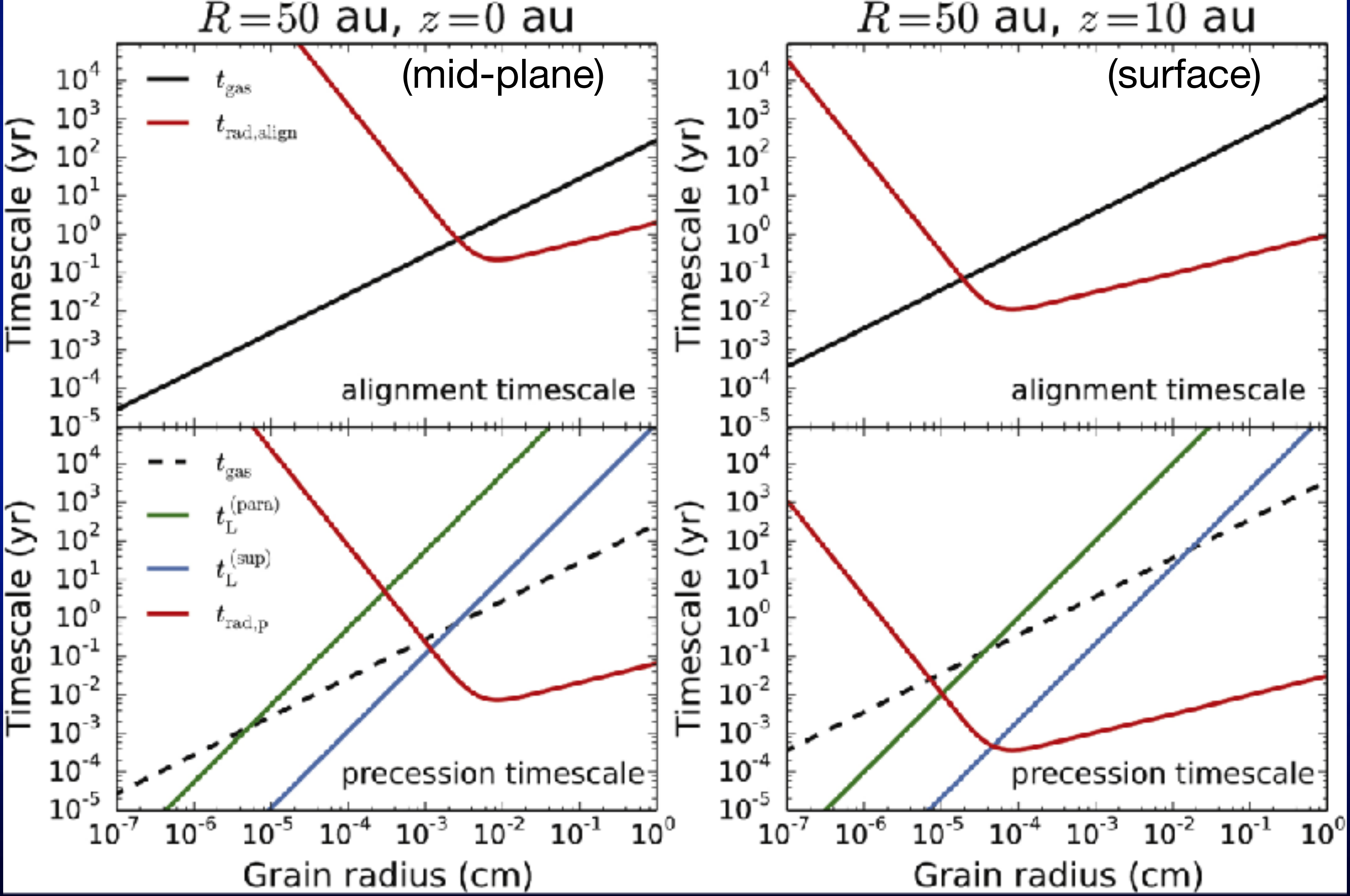
$\vec{J} \parallel \vec{B}$



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

Origin of dust polarization at mm-submm

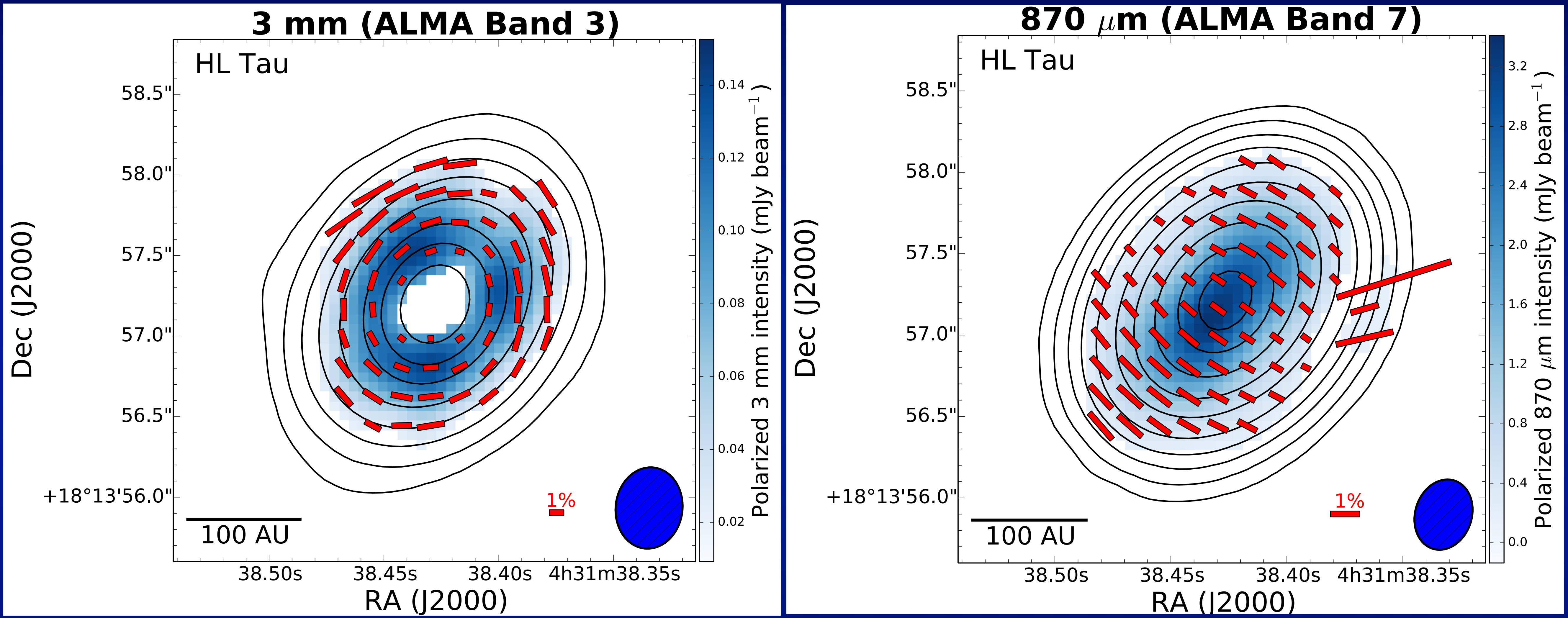
1. Thermal emission of “aligned” grains (Tazaki+ 2017)
   - Two alignment mechanisms
     A. ***J // B* :** Larmor precession (***B*:** magnetic field)
     B. ***J // k* :** Radiative precession (***k*:** net radiation flux)
   - Radiative alignment (***J // k***) seems dominant for a large grains ($a > 100\mu$m) 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 !

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 $n(a) \propto a^{-3.5}$

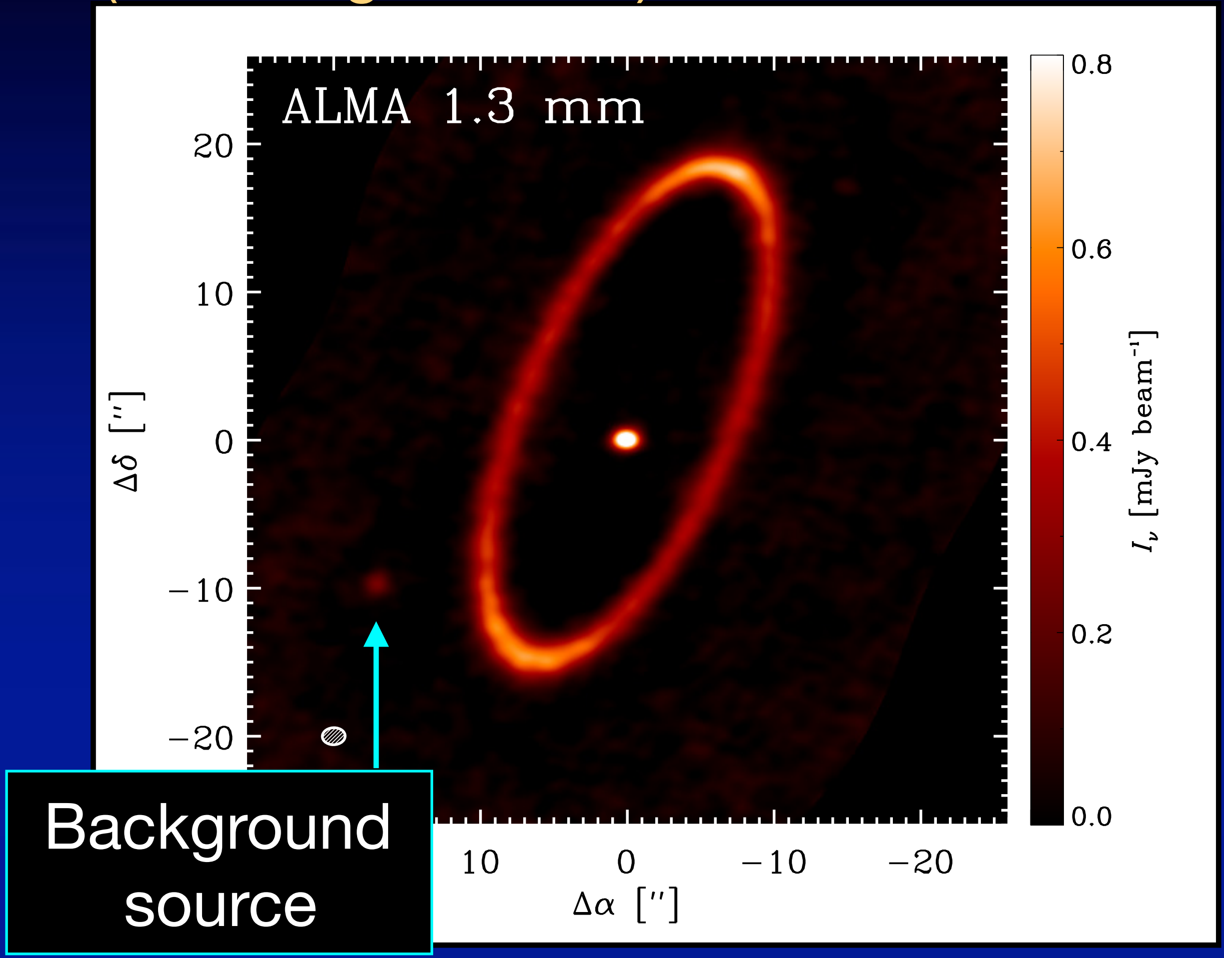
Protoplanetary Disks/Debris Disks with SPICA/SAFARI

- protoplanetary disks are very bright at λ=160μm
  - 89.1 Jy (HL Tau) & 4.1 Jy (TW Hya) : “filled” T Tauri disks
  - 1.9 Jy (V1094 Sco) & 1.8 Jy (Sz 91) : “transitional” disks
- will not be able to spatially resolve them…
  - polarization will be detected only when the polarization directions in the disk are rather uniform
  - λ-dependence of polarization detection — scattering ? (Kataoka-san’s talk)
- can detect & resolve POL in nearby debris disks
  - β Pic, Fomalhaut, ε Eri, Vega : “The Fabulous Four”
  - τ Cet : 120 mJy at λ=170μm (ISO) r_{out} = 52au at d=3.65 pc
  - Alignment mechanism, constraint on dust size, etc.

Fohmalhaut

(MacGregor+ 2017)

age = 0.44 Gyr;
d=7.66 pc; A4V

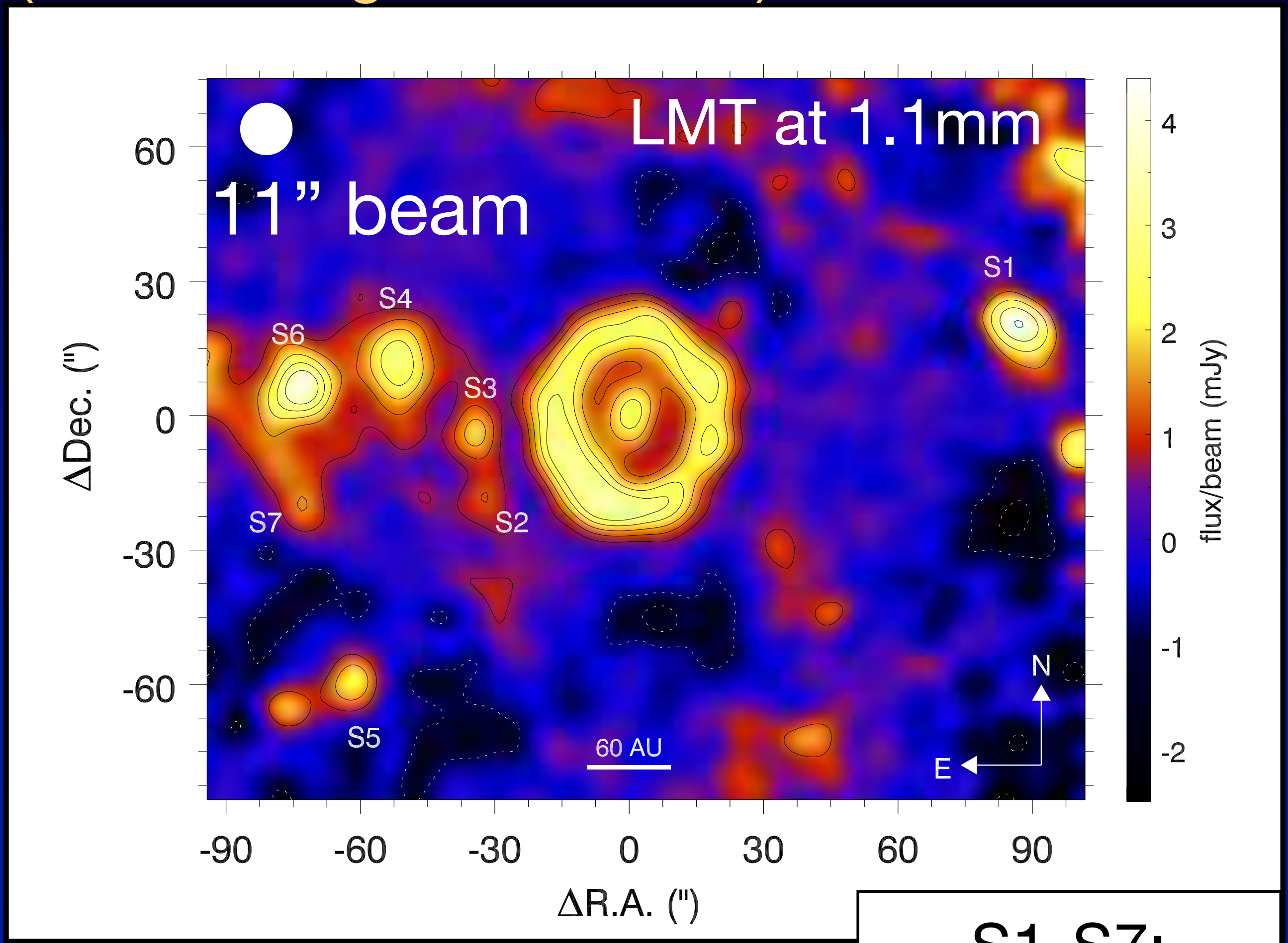


Background source

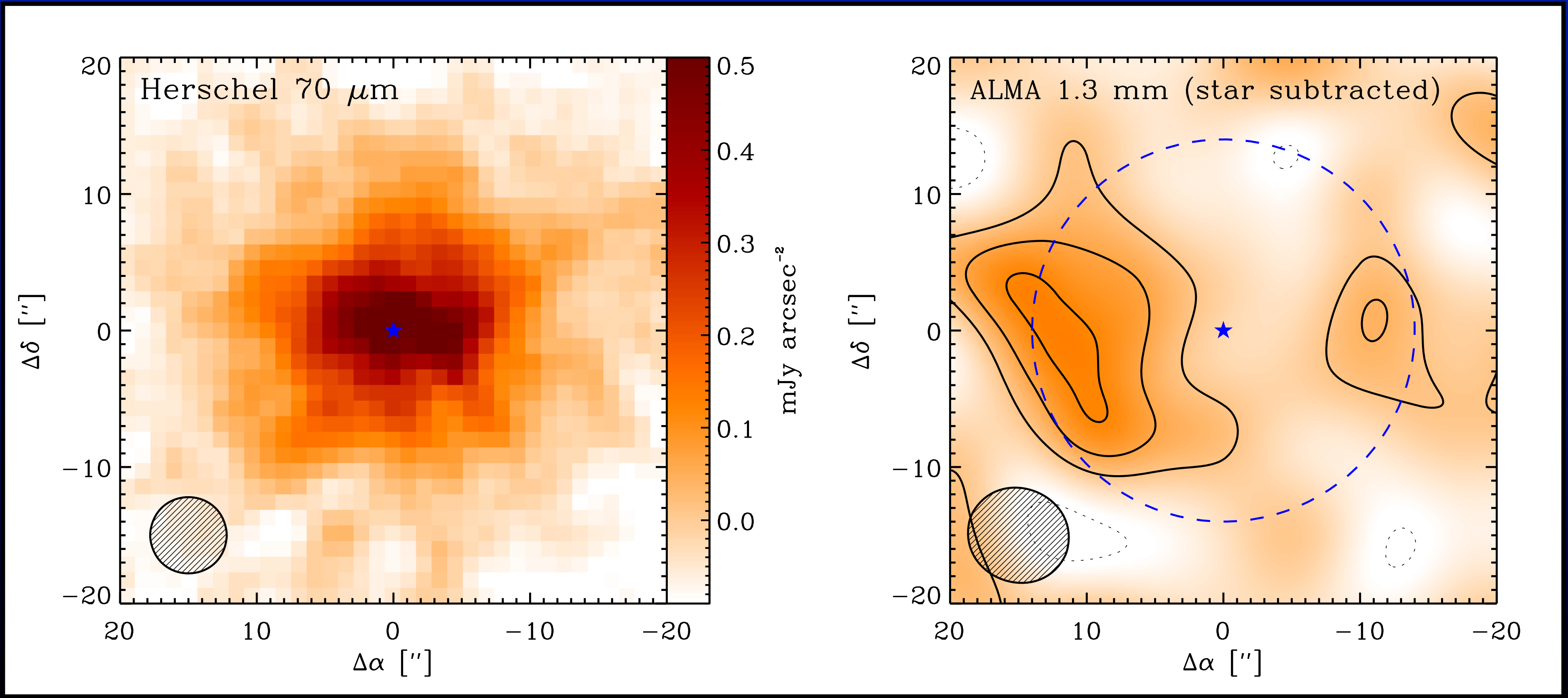
ε Eri

(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

Protoplanetary Disks/Debris Disks with SPICA/SAFARI

- protoplanetary disks are very bright at λ=160μm
  - 89.1 Jy (HL Tau) & 4.1 Jy (TW Hya) : "filled" T Tauri disks
  - 1.9 Jy (V1094 Sco) & 1.8 Jy (Sz 91) : "transitional" disks
- will not be able to spatially resolve them…
  - polarization will be detected only when the polarization directions in the disk are rather uniform
  - λ-dependence of polarization detection — scattering ? (Kataoka-san's talk)
- can detect & resolve POL in nearby debris disks
  - β Pic, Fomalhaut, ε Eri, Vega : "The Fabulous Four"
  - τ Cet : 120 mJy at λ=170μm (ISO) r_{out} = 52au at d=3.65 pc
  - Alignment mechanism, constraint on dust size, etc.

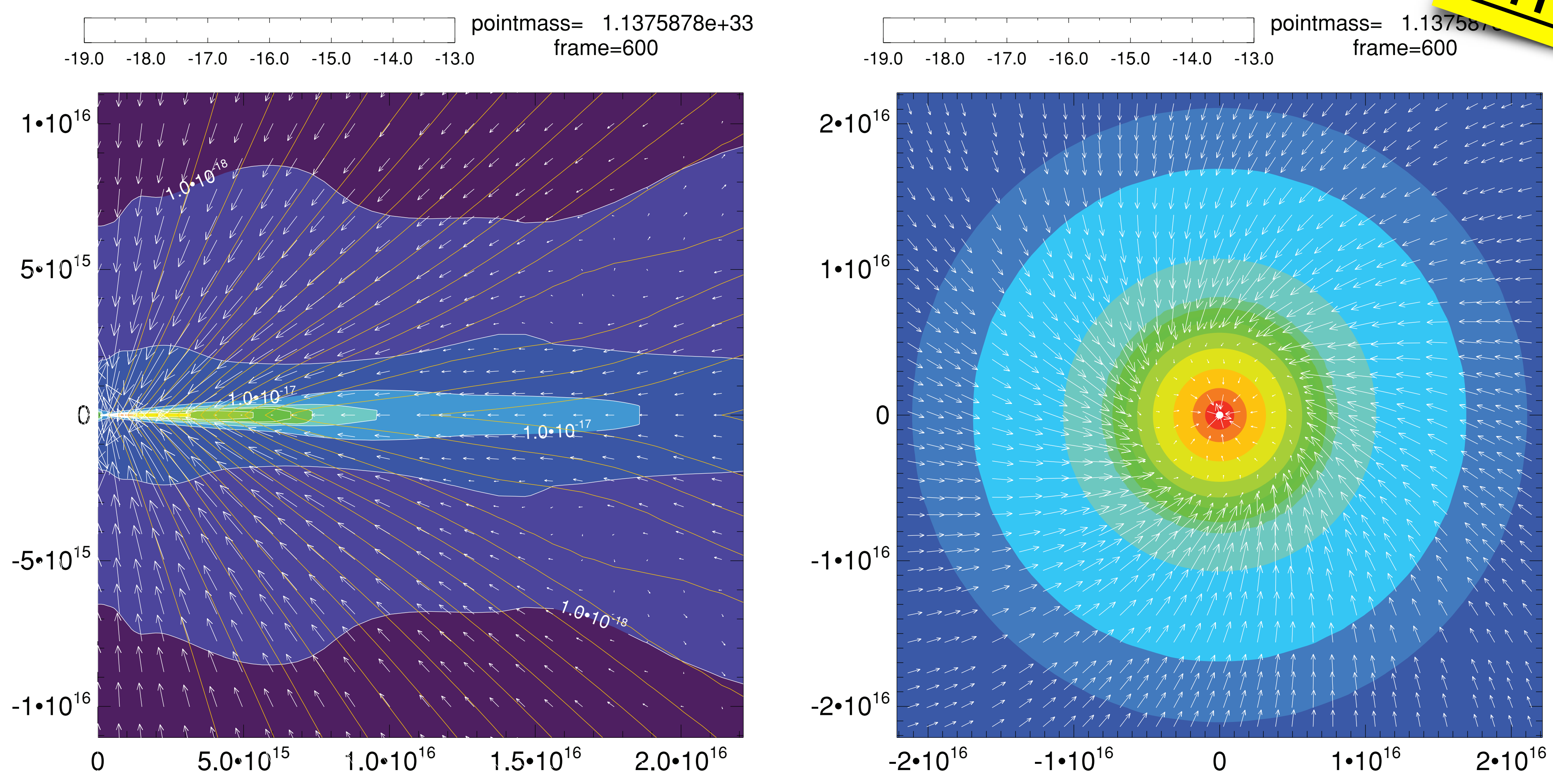
(2) The role of magnetic fields in protostellar phase : disk formation, outflow ejection

…

Magnetic braking catastrophe ?

Li et al. (2011); see also Machida et al. (2014)

MHD simulation including Ohmic dissipation & Ambipolar diffusion,
B // Angular Momentum (AM), sink cell = 6.7au
No disk forms due to very efficient removal of AM
by magnetic braking ??



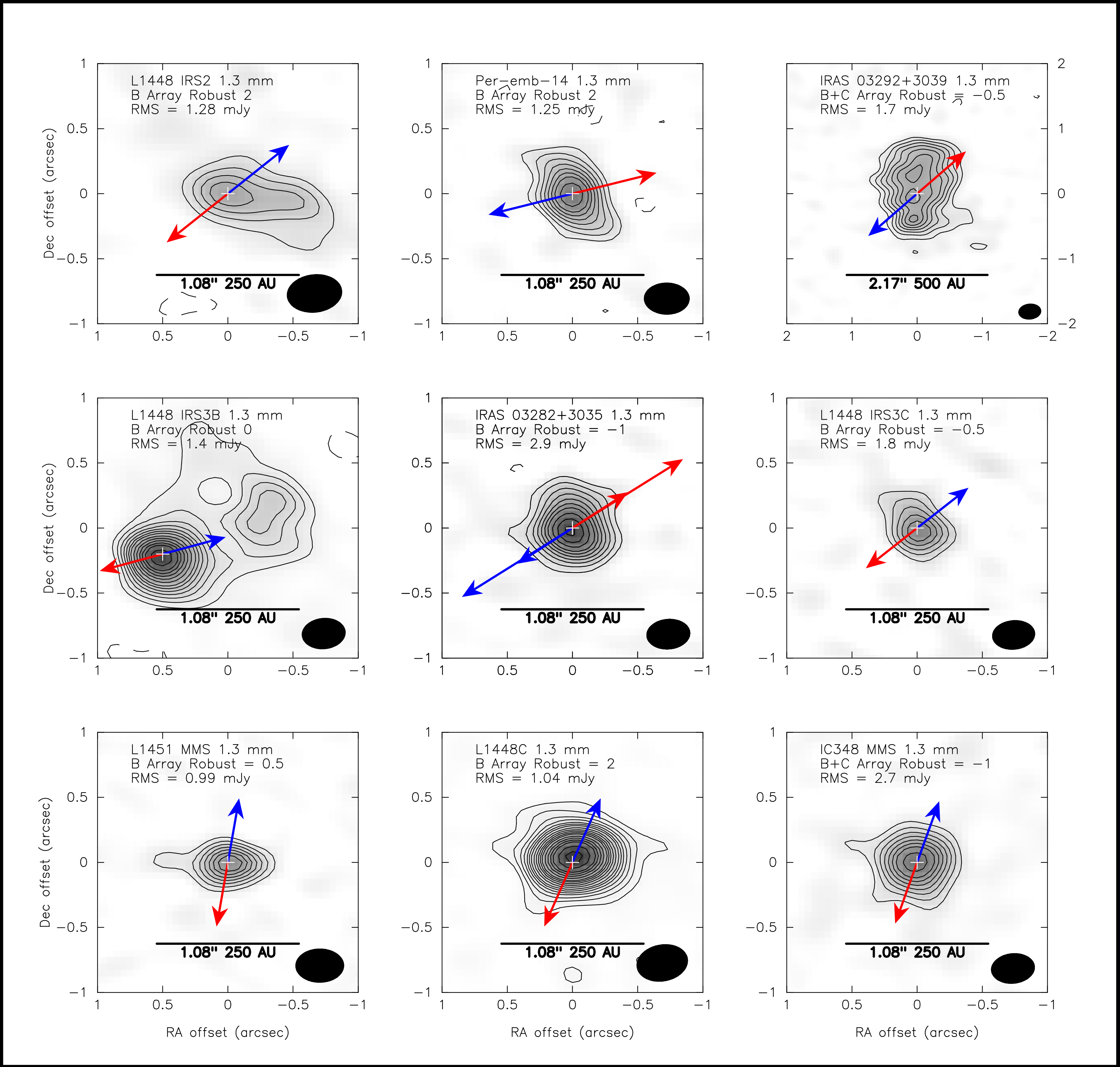
simulation

Figure 4. Density distribution (color map) and velocity field (white arrows) of the reference model (Model REF) in the meridian (left panel) and equatorial (right panel) planes, at a representative time $t = 6 \times 10^{12}$ s. The highly flattened, dense equatorial structure is not a rotationally supported disk, but rather a magnetically supported, nearly non-rotating pseudodisk. Also plotted in the left panel are poloidal field lines, with the same magnetic flux between adjacent lines. The color bars above the panels are for log(ρ), with g cm^{-3} and cm as the units for ρ and length.

CARMA Survey of Protostars in Perseus

Tobin et al. (2015)

observations



<u>1.3mm dust continuum</u>

There <u>ARE</u> protostars accompanied by circumstellar disks

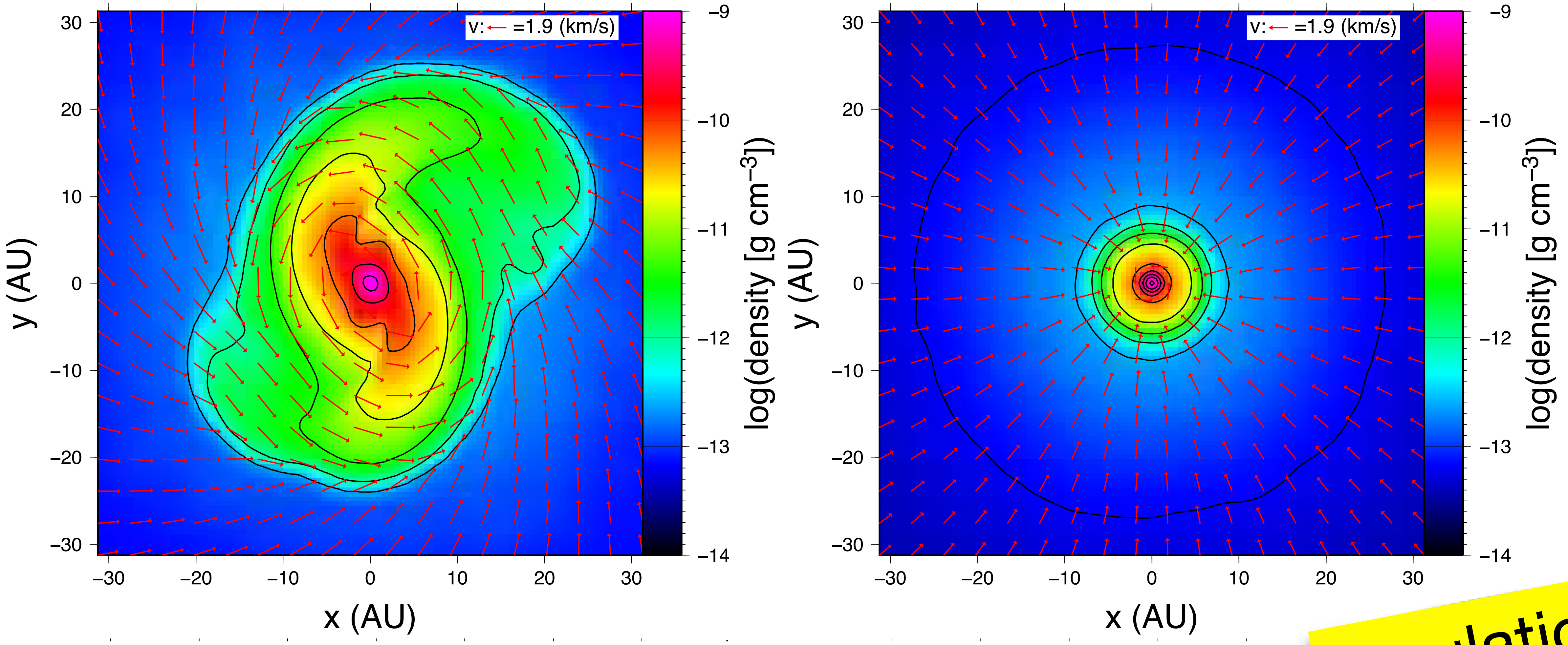
2 having r >100au disk
(L1448 IRS2; Per-emb-14)

3 marginally resolved
(L1448 IRS3B, I03282, L1448C)

3D-Simulation including Hall current

Tsukamoto et al. (2015)

- non-ideal MHD (Ohmic dissipation, Ambipolar diffusion & Hall current)
- Initial configuration of ***AM*** & ***B*** in core-scales affects the disk evolution



AM & ***B*** **are anti-parallel**

formation of a large (r>20au) disk

AM & ***B*** **are parallel**

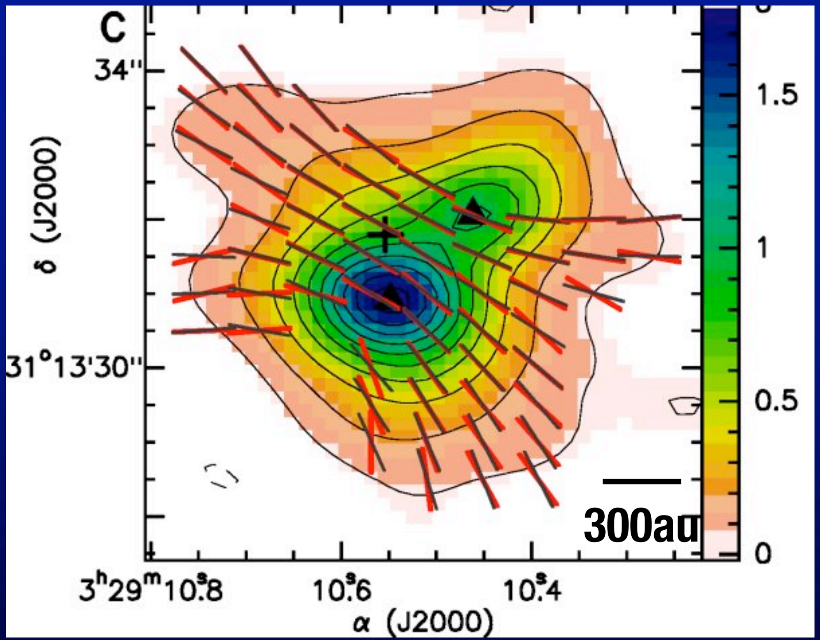
formation of a small (r~1au) disk

simulation

1.3mm Survey of Dust Polarization by CARMA

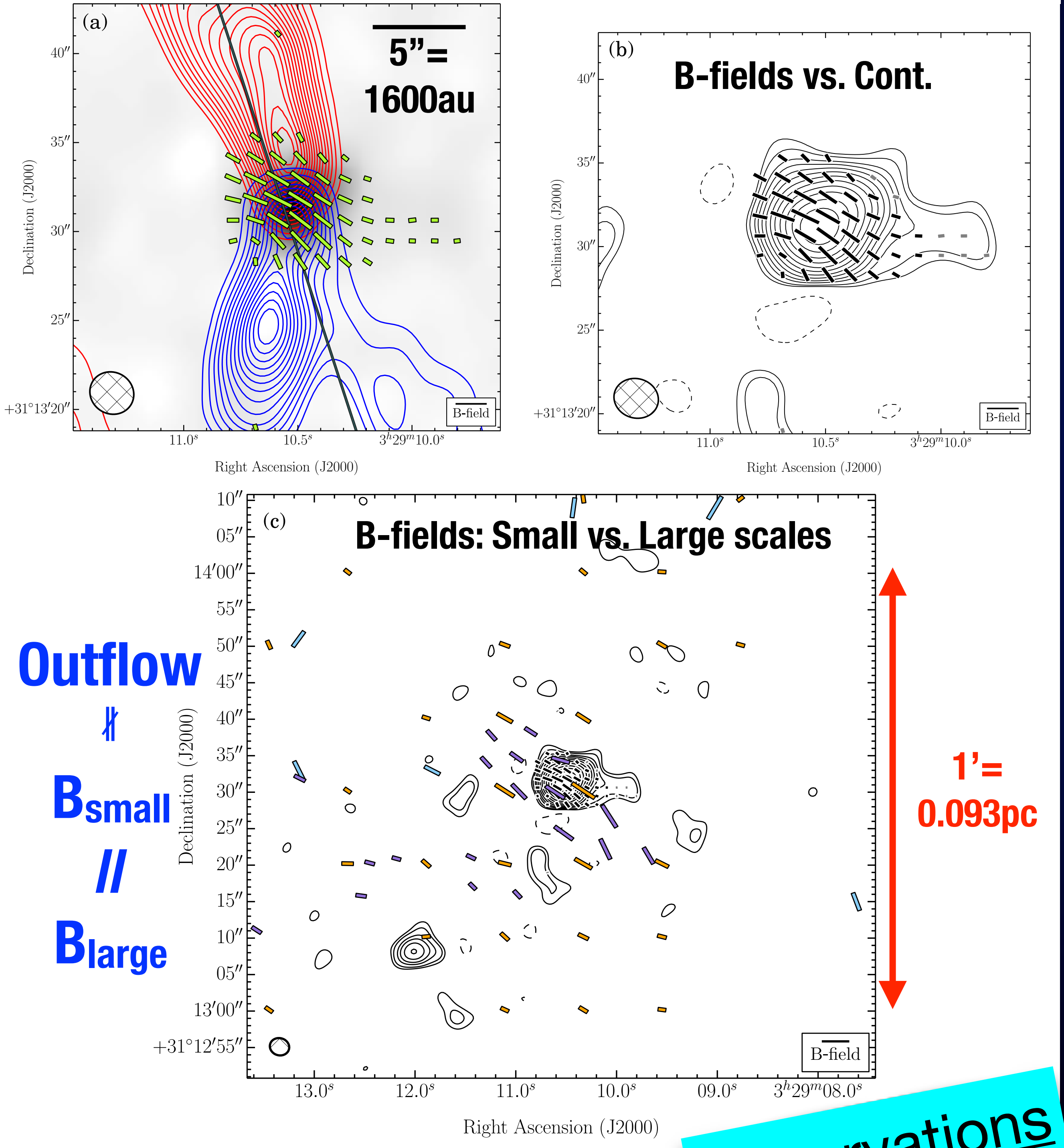
Hull et al. (2014); “TADPOL”-survey

- 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

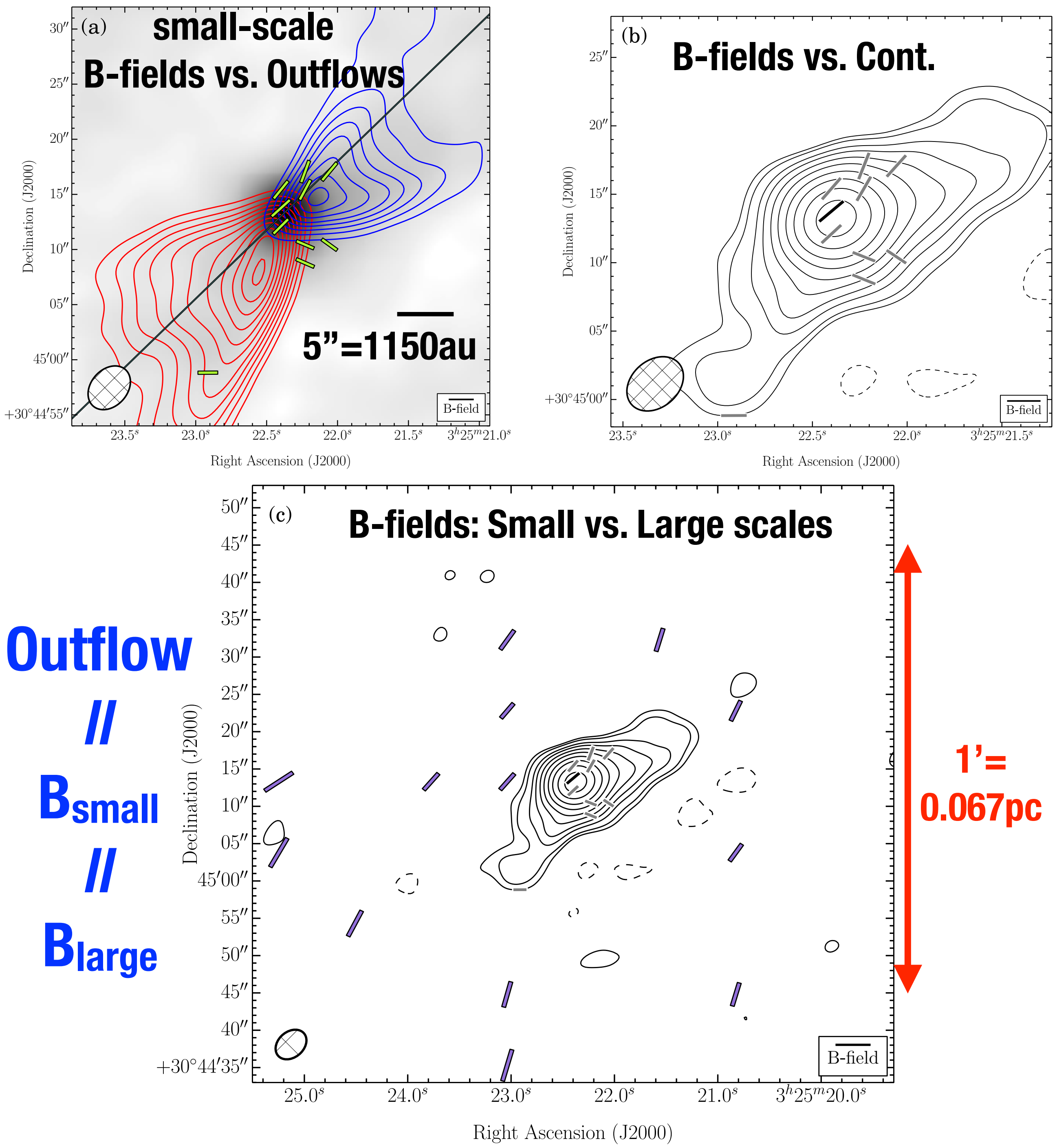


Observations

1.3mm Survey of Dust Polarization by CARMA

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

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



Outflow

//

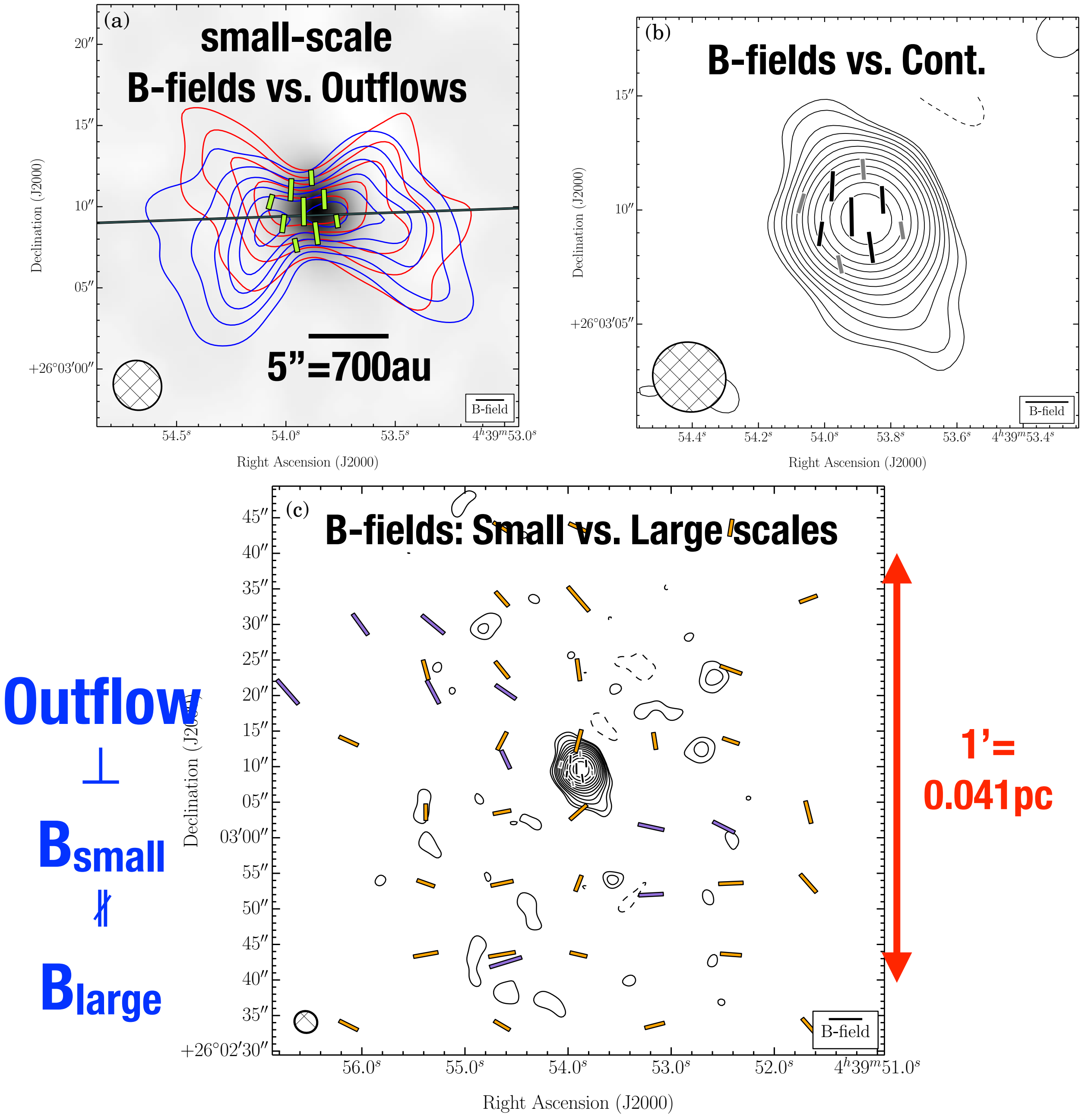
B_{small}

//

B_{large}

1'= 0.067pc

L1527 (Class 0); d=140pc



Outflow

⊥

B_{small}

∦

B_{large}

1'= 0.041pc

Observations

1.3mm Survey of Dust Polarization by CARMA

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

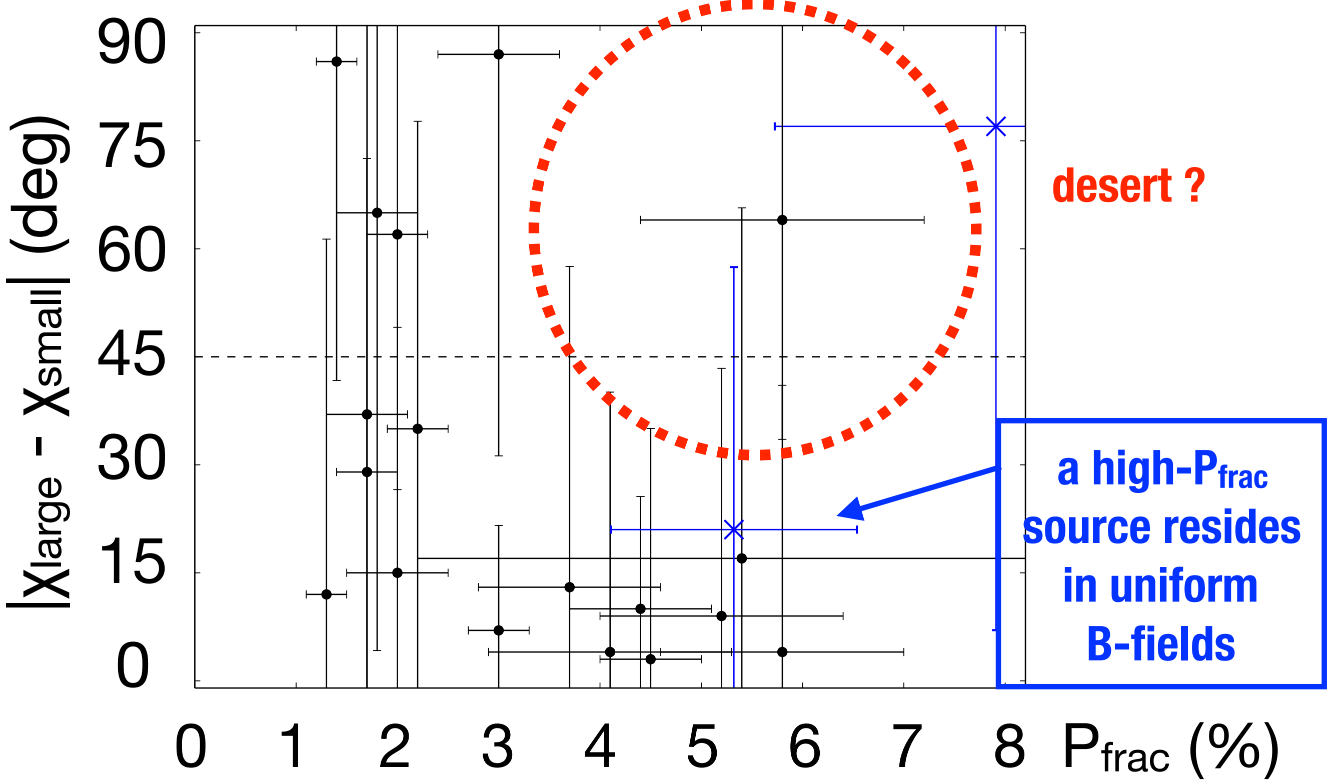
(Results)

- 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

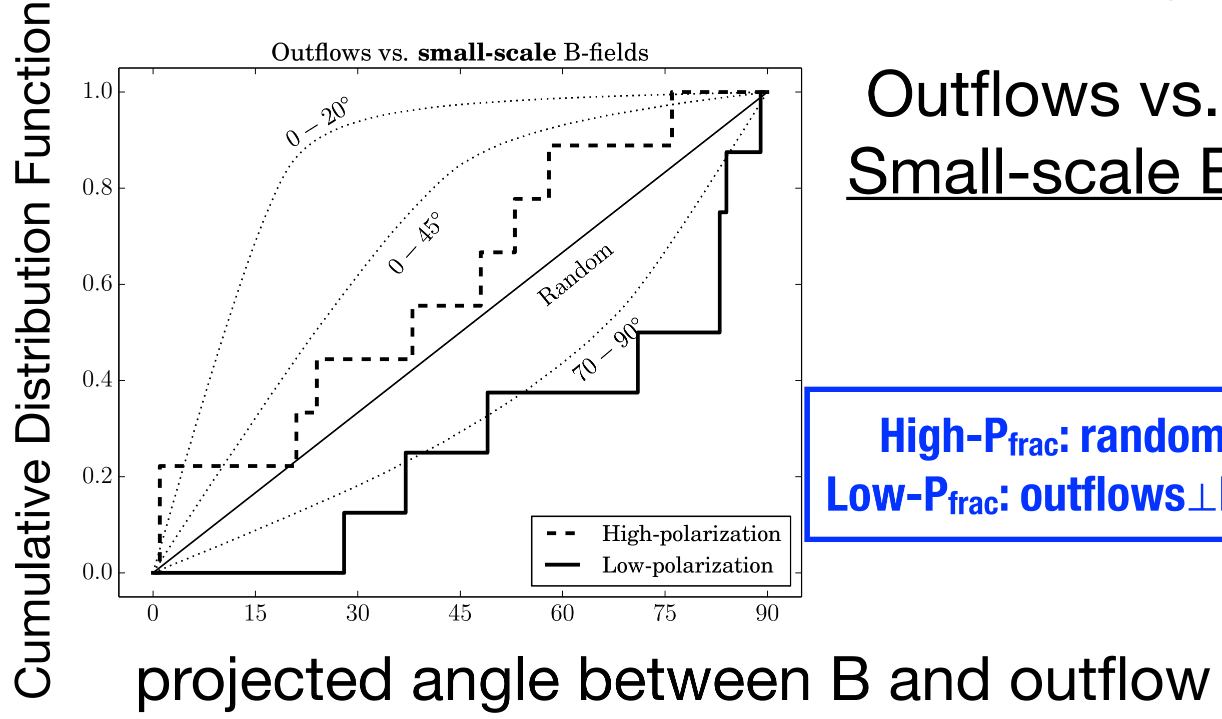
• B-directions (small & large)
• Outflows
• AM (the axis of rotating disk)
are not always parallel

Δ(B-field angles) vs. Pol. fraction



desert ?

a high-P_{frac} source resides in uniform B-fields



Outflows vs. Small-scale B

High-P_{frac}: random
Low-P_{frac}: outflows⊥B ?

Recent progress (1): New large-scale maps

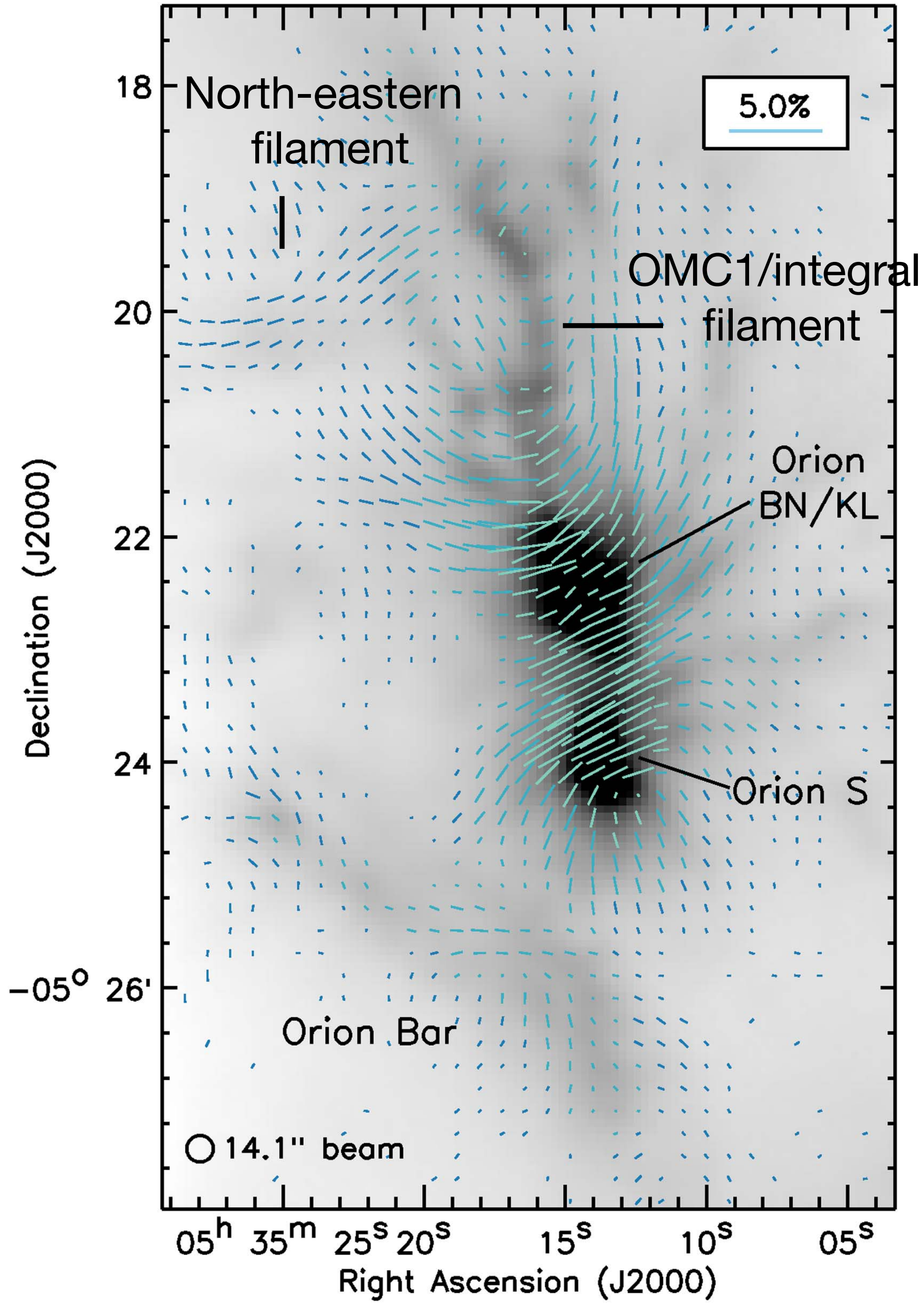
Ward-Thompson+ (2017); Pattle+ (2017); “BISTRO”-team

- 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

$$B_{\mathrm{pos}} \propto \frac{\sqrt{n_{\mathrm{H}_2}}\Delta V_{\mathrm{turb}}}{\langle\sigma_\theta\rangle}$$

  - a systematic method to derive <σθ> is also employed (Hildebrand+2009; Pattle+ 2017)

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



Recent progress (2): ALMA Pol. maps

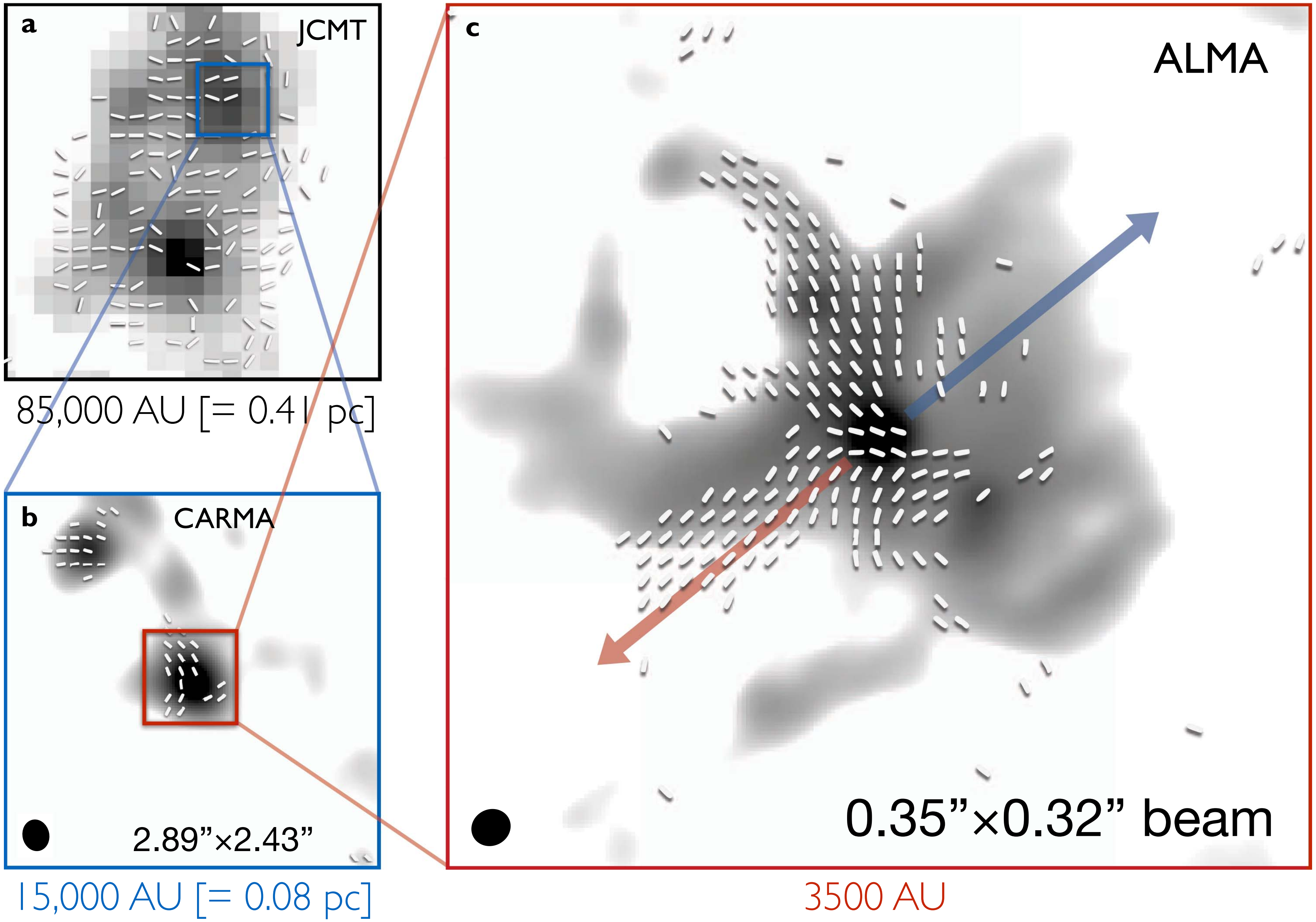
Hull+ (2017)

B-fields around Ser-emb8

d=436±9pc

λ=
870μm

λ=
1.3mm

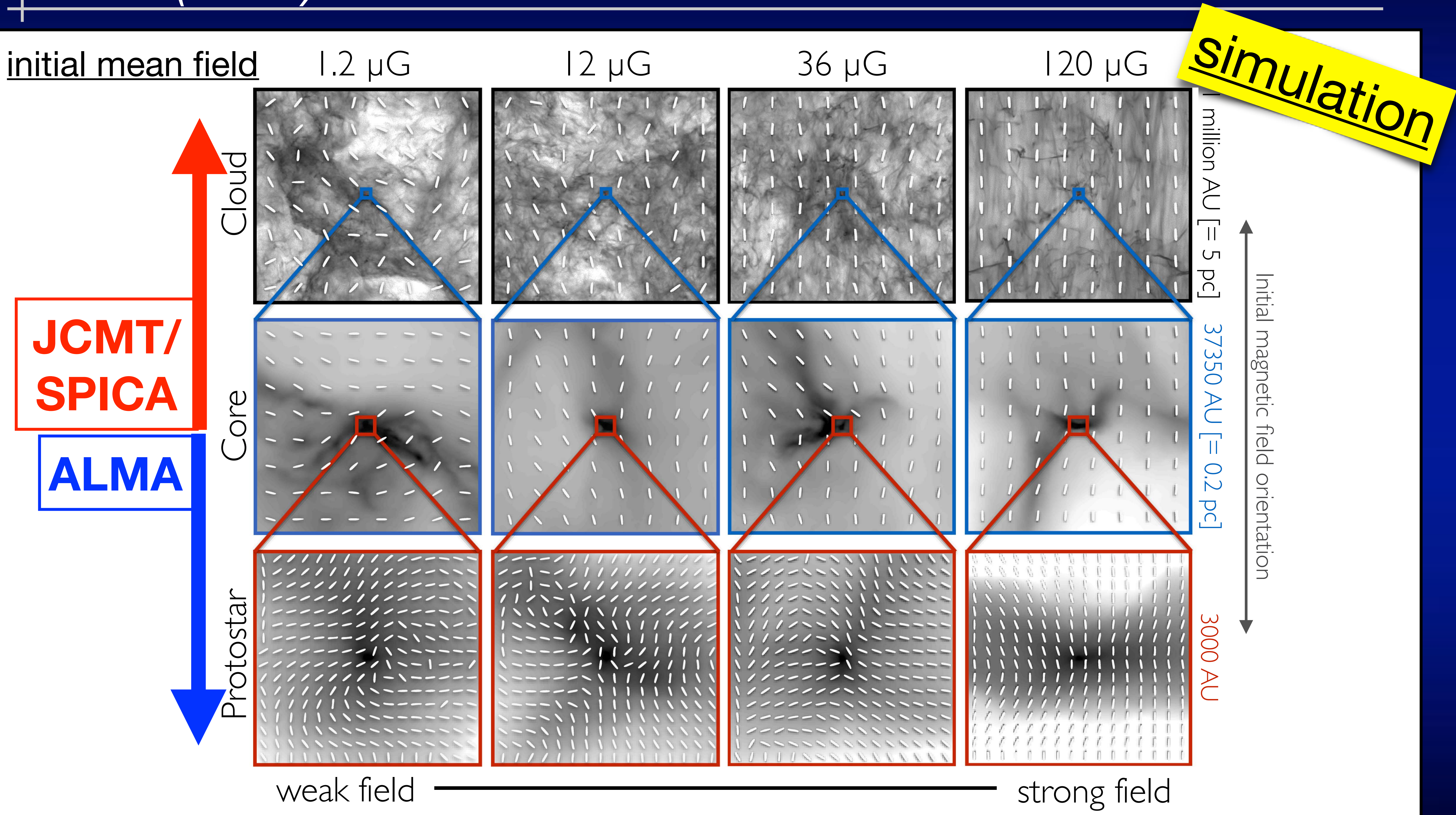


λ=
870μm

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 SPICA/SAFARI

- 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. Submm Single Dishes
  - wavelength dependence
    - dust characterization,
    - alignment mechanism (environmental effects, etc.)

misalignment between B & AM may produce

Two types of outflows ? (Matsumoto+ 2017)

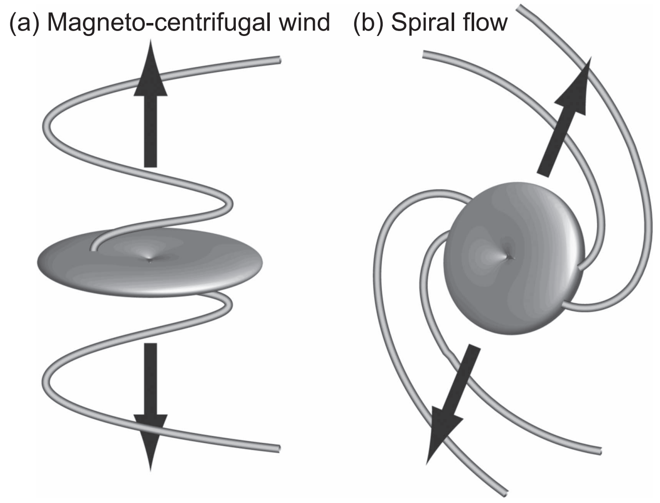
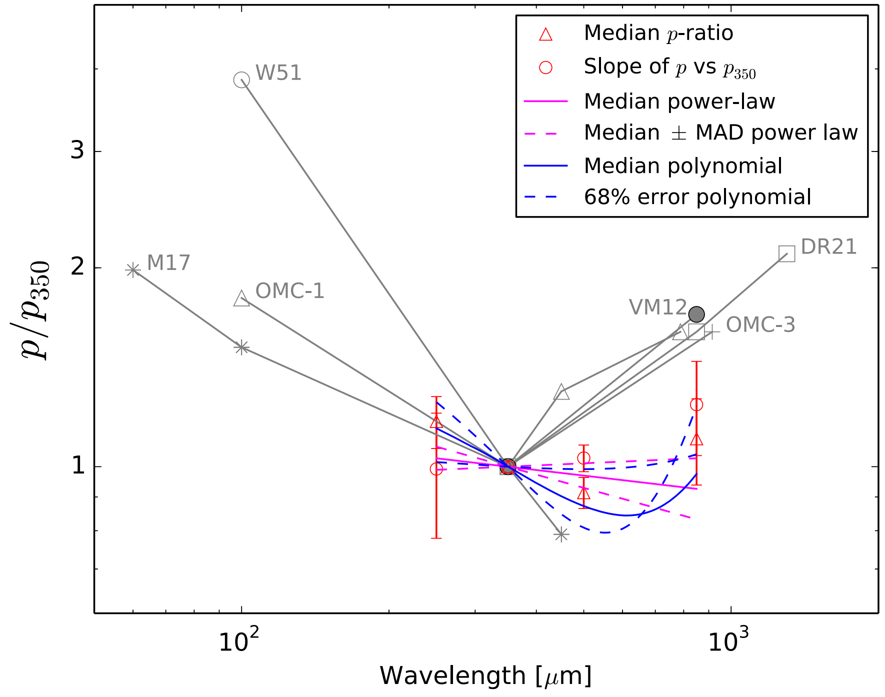


Figure 15. Schematic diagram of two types of outflows: (a) magnetocentrifugal wind, and (b) spiral flow. The surfaces represent isodensity surfaces, and the tubes denote the magnetic field lines. The arrows indicate the direction of the outflow.

λ-dependence

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



Summary

- Small-scale structure of polarization in protoplanetary disks has been detected by ALMA
  - self-scattering and alignment (next talk)
- Nearby debris disks will be important targets for SPICA/SAFARI
  - dust characterization
  - most of them are difficult to detect pol. even by ALMA
- 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