Magnetic field structure in star-forming regions by polarization observations

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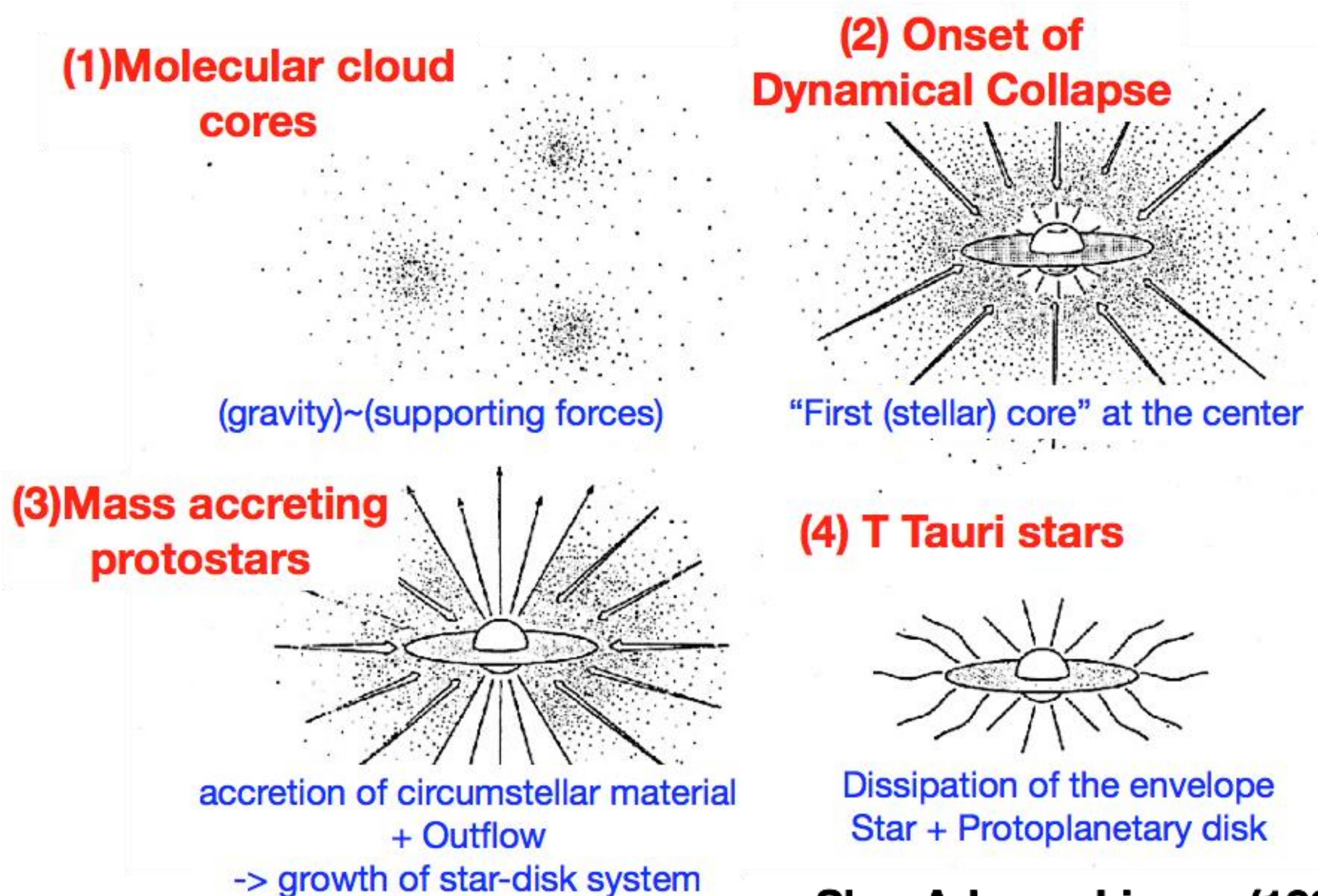
Summary of this talk

- 星・惑星形成における磁場が果たす役割の解明は観測的に未開拓かつ重要テーマの1つ
- 星・円盤形成時の磁場の役割やダスト整列に関し，予言能力・検証可能な理論が登場したことに加え，近年の観測進展（SCUPOL, PLANCK, ALMA）
- 地上サブミリ波望遠鏡は，コア構造を分解(≲ 10”)しつつながら高感度な広域観測が可能で，このテーマにとってユニークな装置能力を持たせうる

Introduction:
Star-formation & magnetic fields

Formation of low-mass stars



Shu, Adams, Lizano (1987)

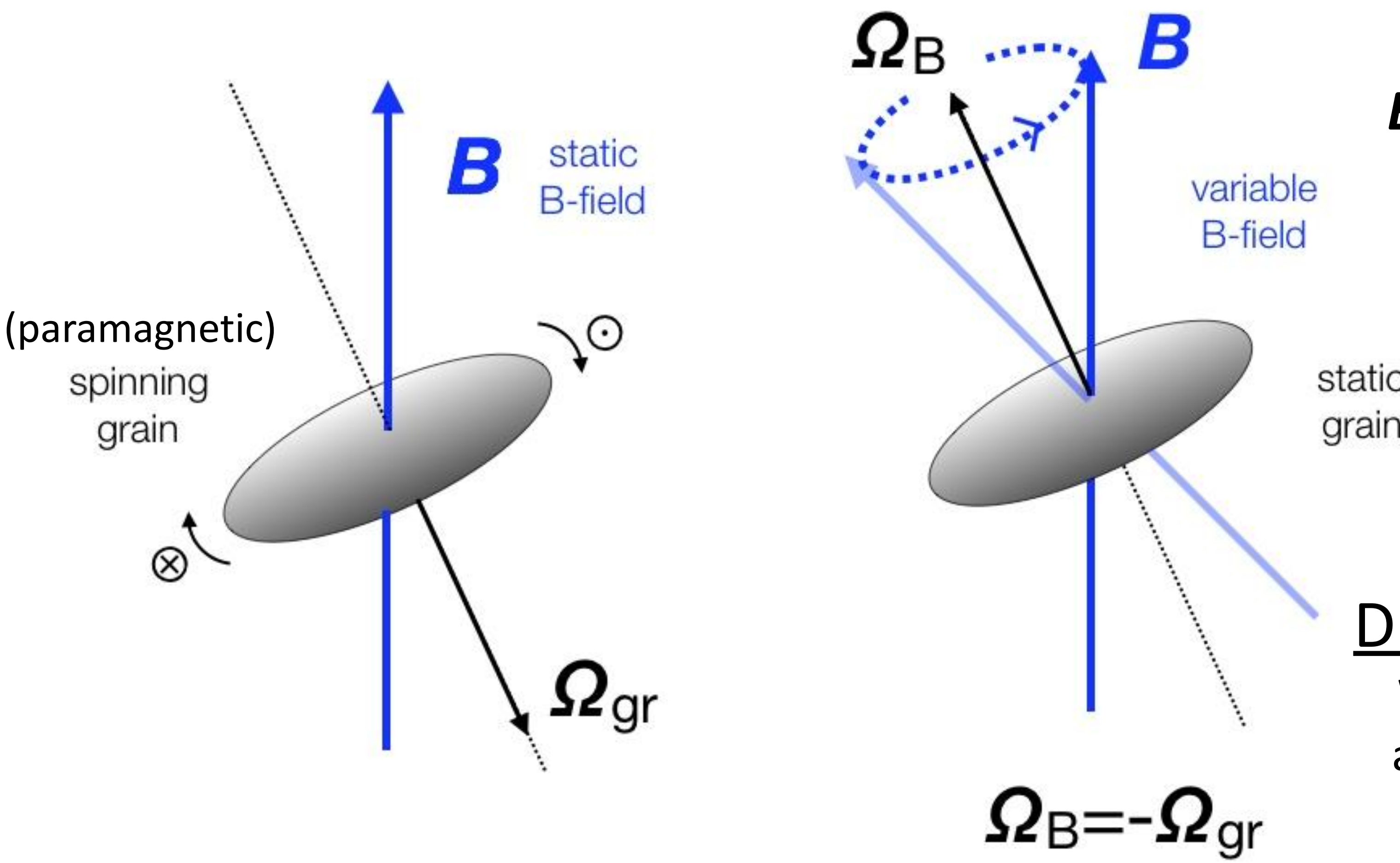
Importance of magnetic (**B-**)field in formation of stars and planets

- Transportation of angular momentum in a core
  - inevitable during star formation (∵ $L_{core}/M_{core} \gg L_*/M_*$)
  - magnetic breaking catastrophe !?
  - 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 (∵ $B_{core}R_{core}^2 \gg B_*R_*^2$); when, where and how ?
  - Ambipolar diffusion → Ohmic dissipation in a disk ?
  - Reconnection diffusion in a core ? (González-Casanova+ 2016)

Observational studies on B-field

- **B**-strength: Zeeman effect, (Faraday rotation)
    - OH, CN, (HI)
    - CCS with large SDs and ALMA, mainly at 40 GHz
- **B**-direction: Polarization due to dust extinction/emission
    - Polarization seen in background stars at optical & near-IR (*extinction*; B   E-vector): mainly on large scales (> 1pc)
    - Polarization in *emission* at far-IR & sub-mm (B ⍰ E-vector) : various size scales (shown later)
- Millimeter & sub-millimeter wavelengths are unique :
    - B-field in densest & coldest regions
    - Ground-based telescope → high resolution + wide field

Davis-Greenstein mechanism:
--- a “classical” theory (1951) ---



$B \nparallel M$ (or H) due to delayed induction

↓

Torque

↓

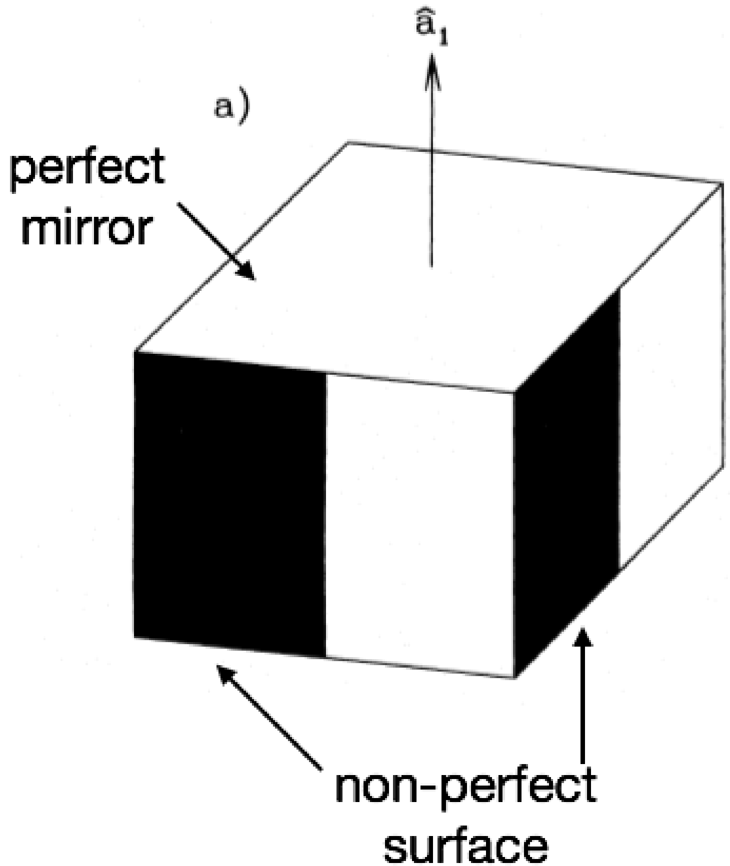
Ω_{gr} B

<u>Dust alignment !?</u>

What is the origin of a fast (suprathermal) spinning velocity ?

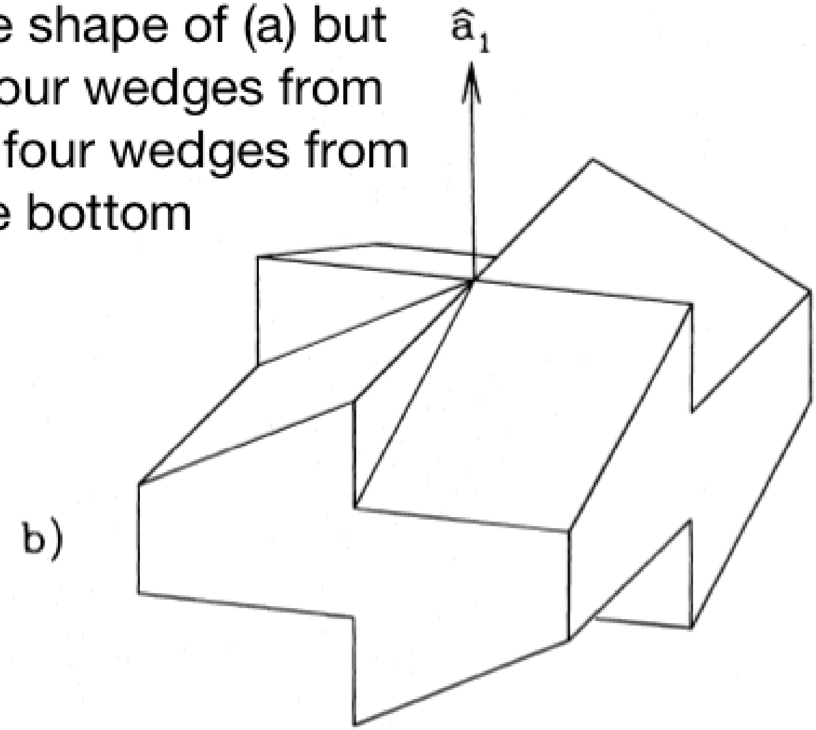
Induction of M in a spinning grain ⟺ Induction of M by time-variable B

Radiative torques + grain "helicity"



Isotropic radiation field would exert a torque along axis a_1

Starting the shape of (a) but removing four wedges from the top and four wedges from the bottom



Radiation antiparallel to a_1 would exert a torque along axis a_1

Figures by Draine & Weingartner (1996); Andersson+ (2015) for the review

Polarization images: extinction vs. emission

Polarization (l,b) map by ***extinction*** (optical & nIR)

o the equation:

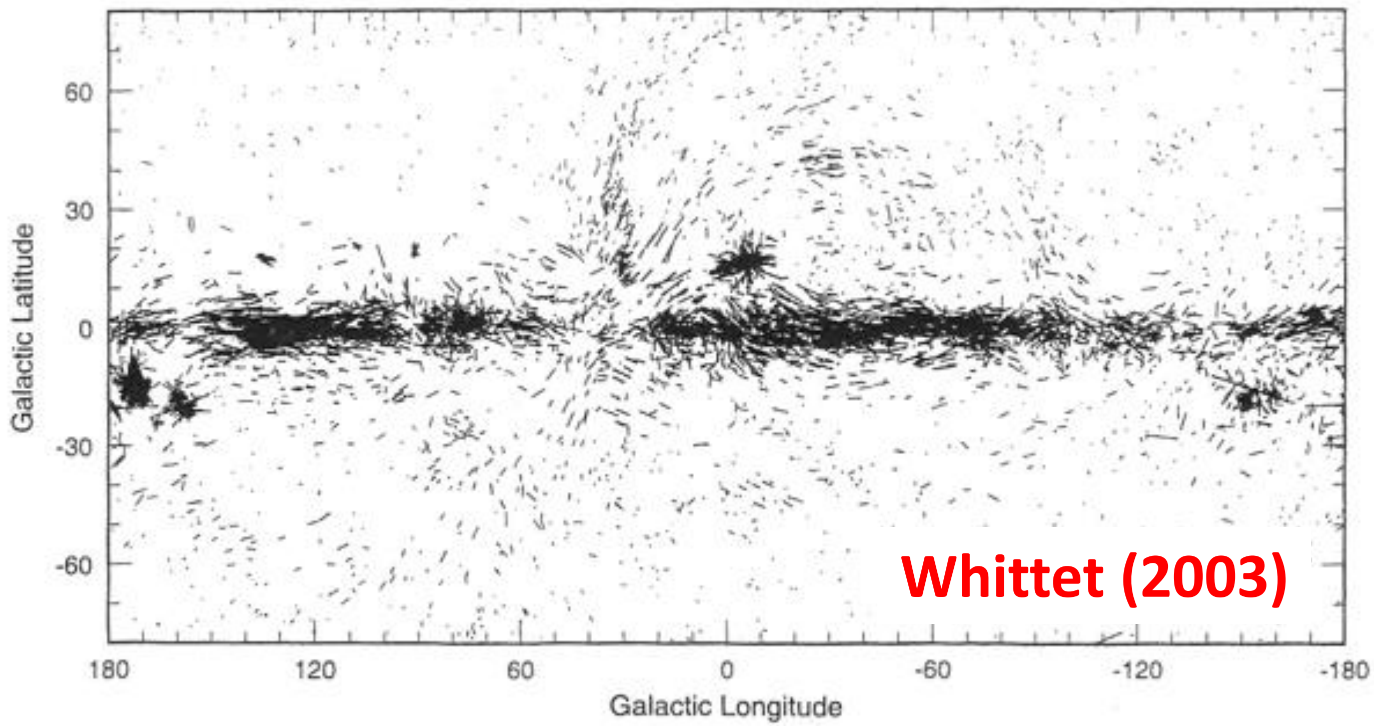
$$\kappa = \frac{2\sqrt{2}\lambda^2 n^2 e^6}{3\sqrt{\pi}\mu c^3 (mkT)^{3/2}} \log_e \left(\frac{4kT}{e^2 \sqrt[3]{2n}}\right)^2,$$

where κ is the absorption coefficient, λ the wave length, n the electron density, e the charge on the electron, c the velocity of light, μ the refrac-

10,000° at a height of 10,000 km and then to rise exponentially to a maximum temperature of 10^6 degrees at a height of 25,000 km. This set of conditions in the solar atmosphere adequately explains the behavior of the quiet sun at short radio wave lengths.

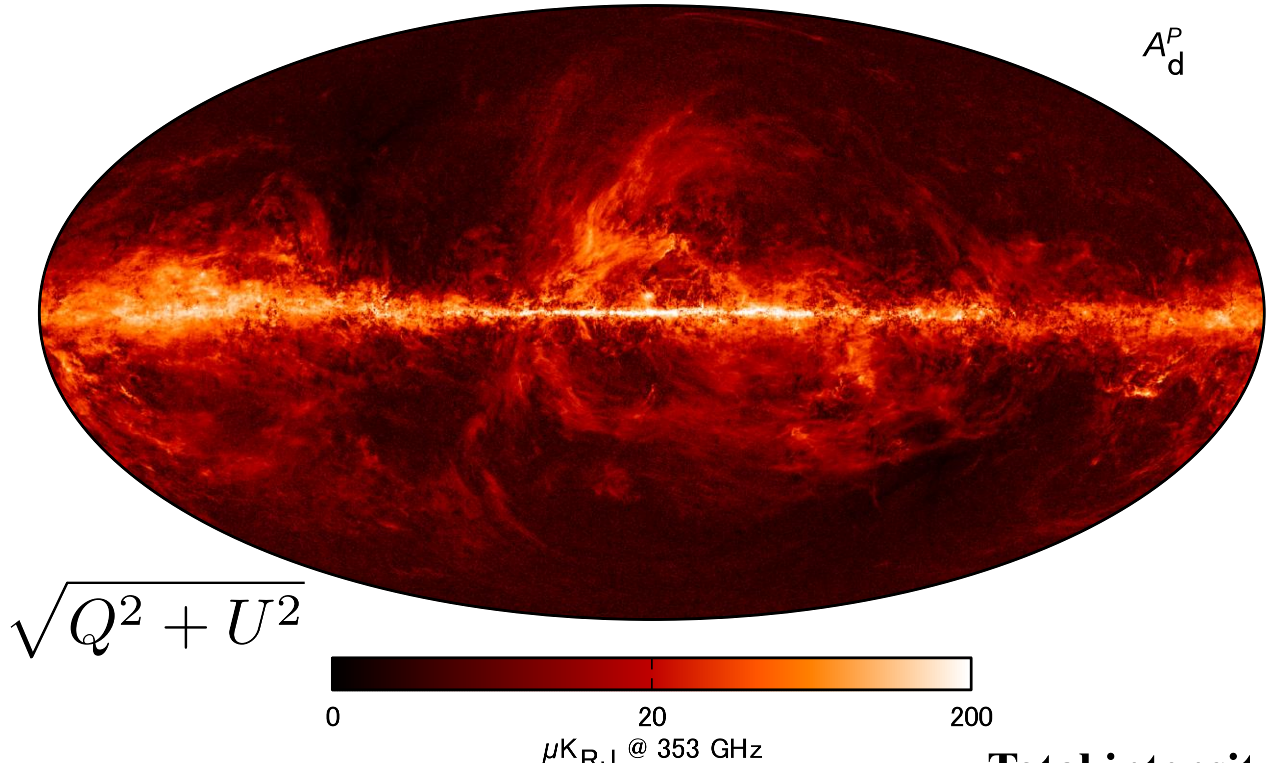
1. *Proc. Roy. Soc.* A, 193, 44–59, 1948.

Hall & Mikesell (1949)

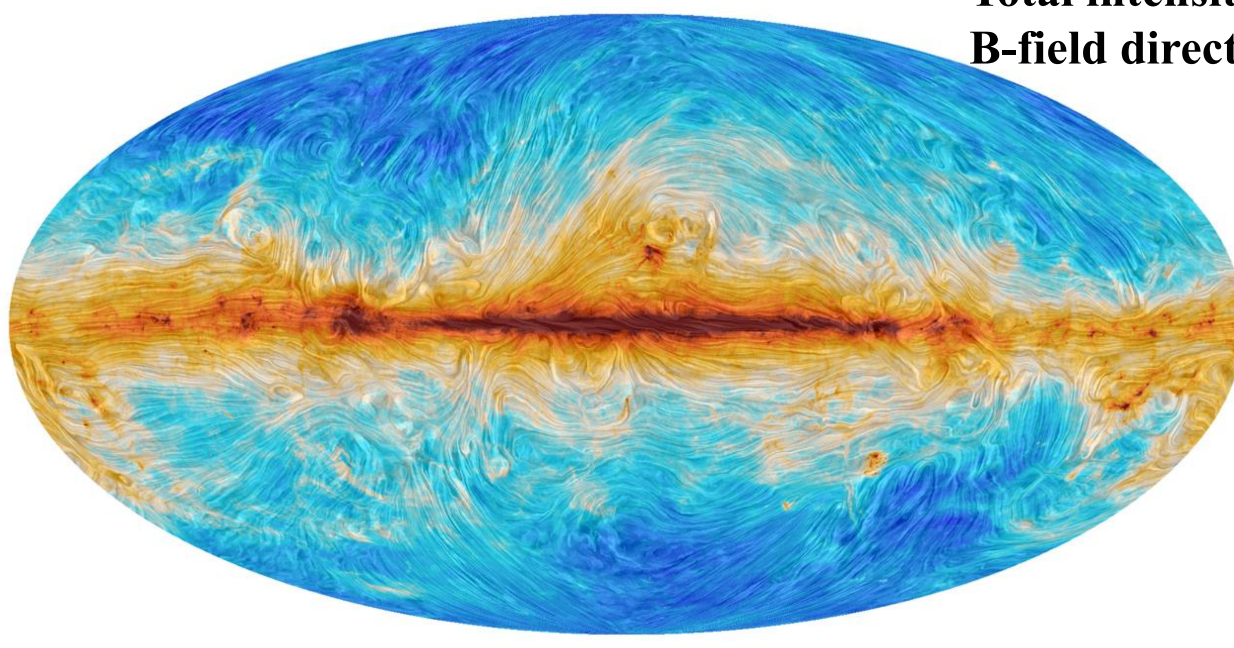


***B* || pol. E-vector**

Polarization (*l*,*b*) map by ***emission*** at 353GHz



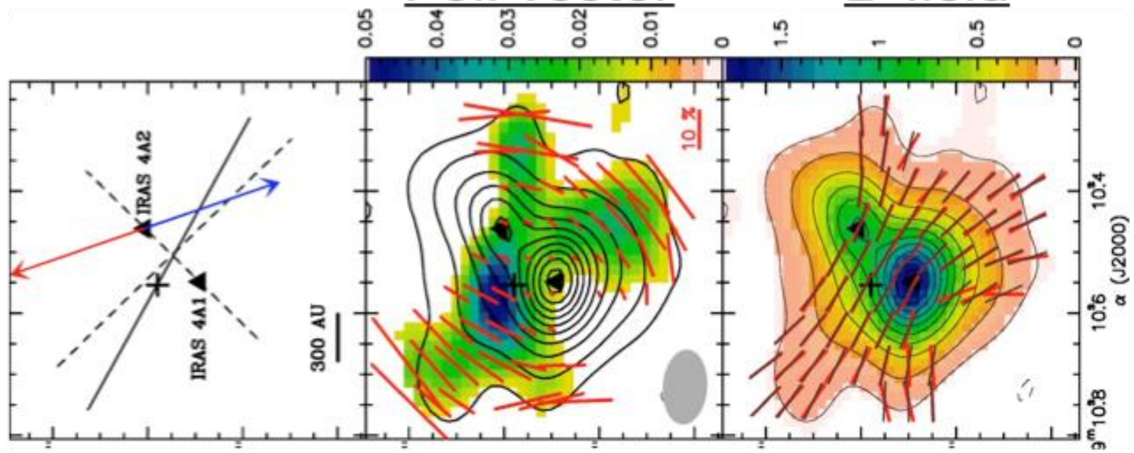
Total intensity & B-field direction



Planck Collaboration (2015)

***B* ⊥ pol. E-vector**

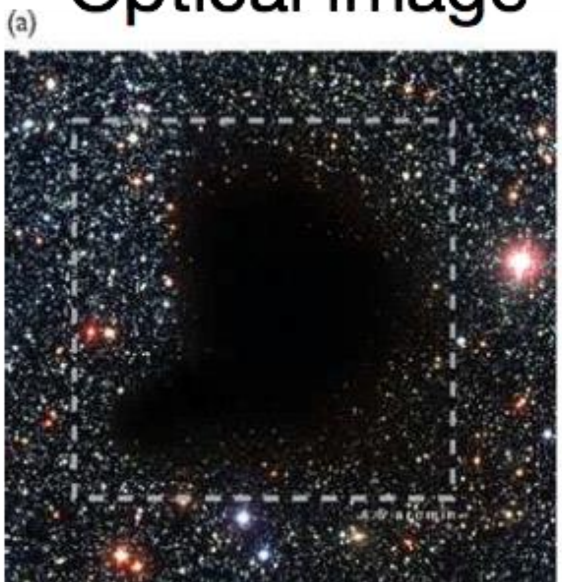
Pol-images in dense cores



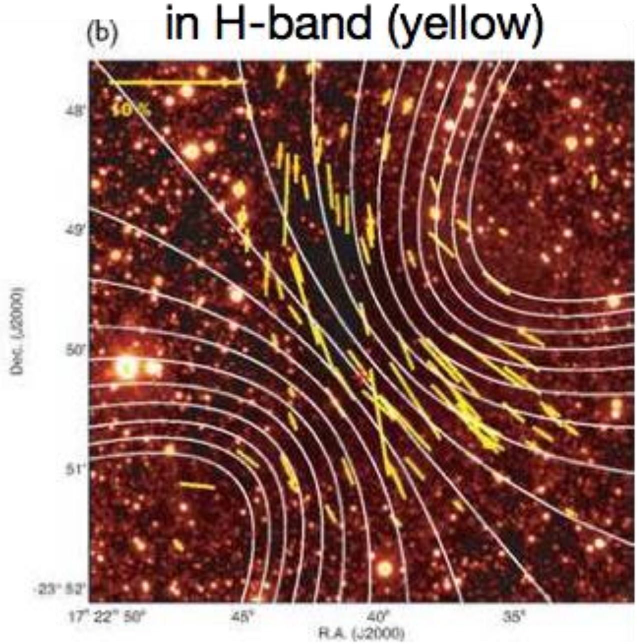
Pol. in 230GHz with SMA Girart+ (2006)

B68

Optical image



Pol. vector of 125 background stars in H-band (yellow)



Kandori+ (2009)

Polarization at mm-submm in star-forming regions

SCUBA-POL at λ=850μm

(Results in 1997-2005 by Matthews+, ApJS, 182, 2009)

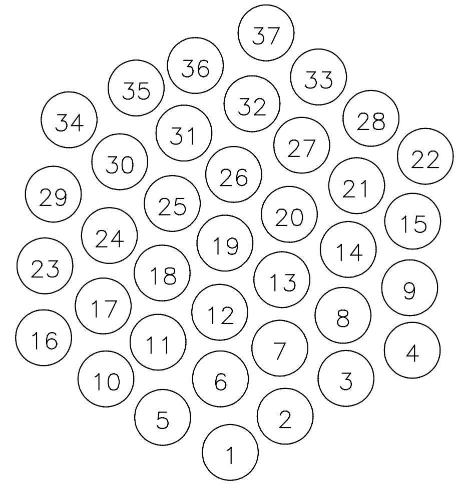
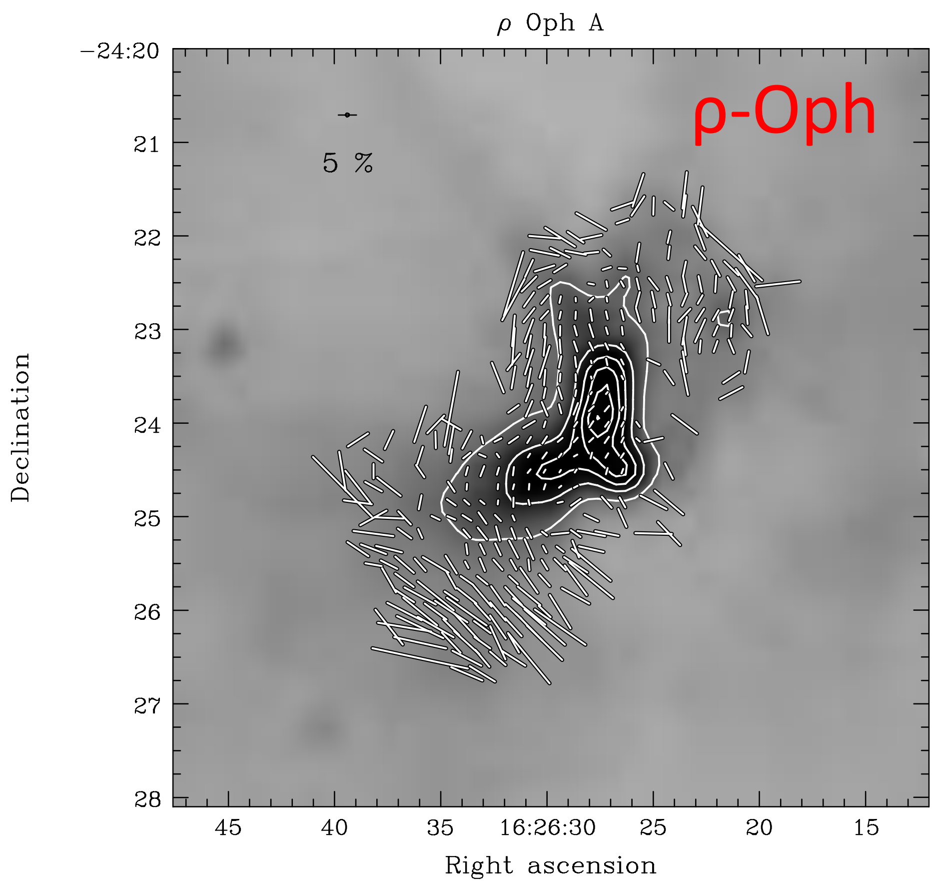
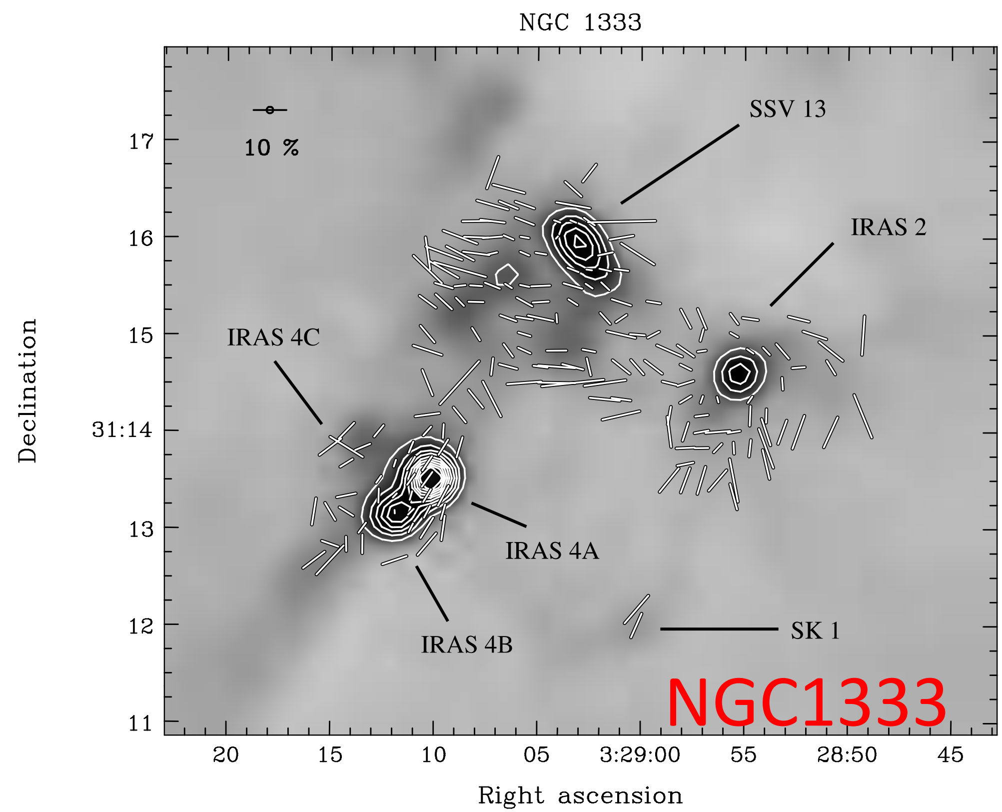


Figure 1. Arrangement of bolometers across the 850 μm SCUBA detector array.

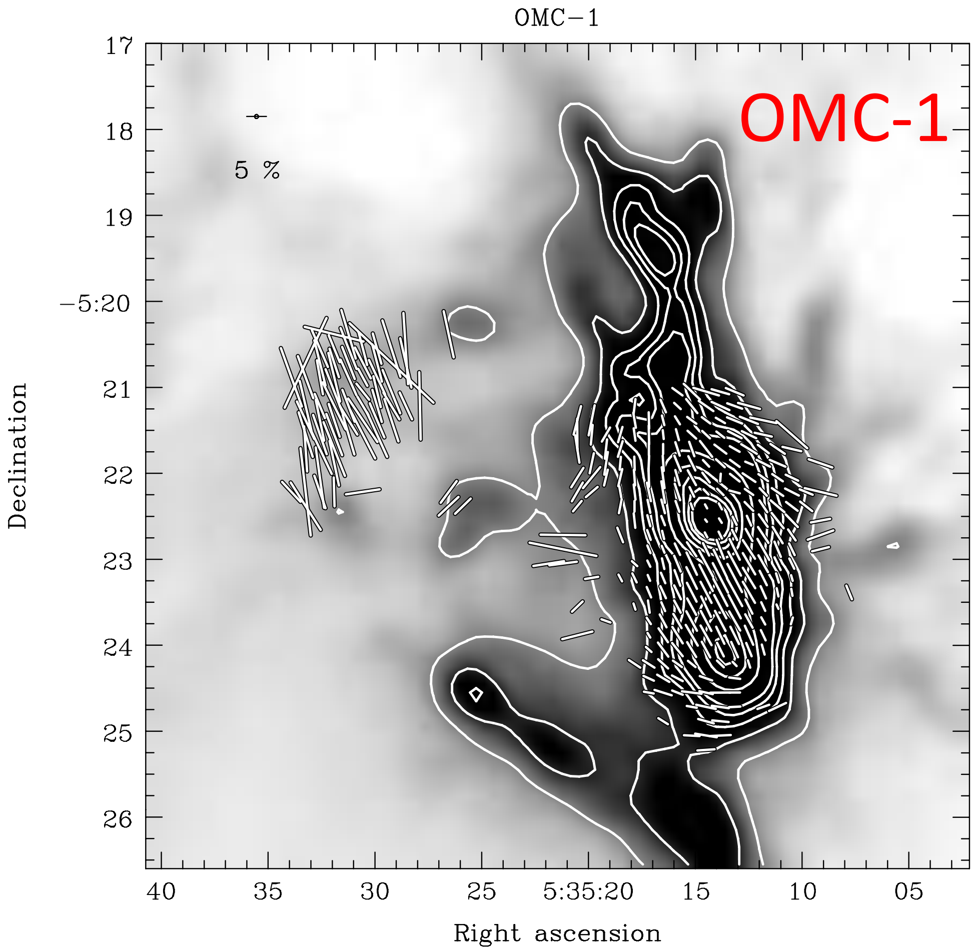


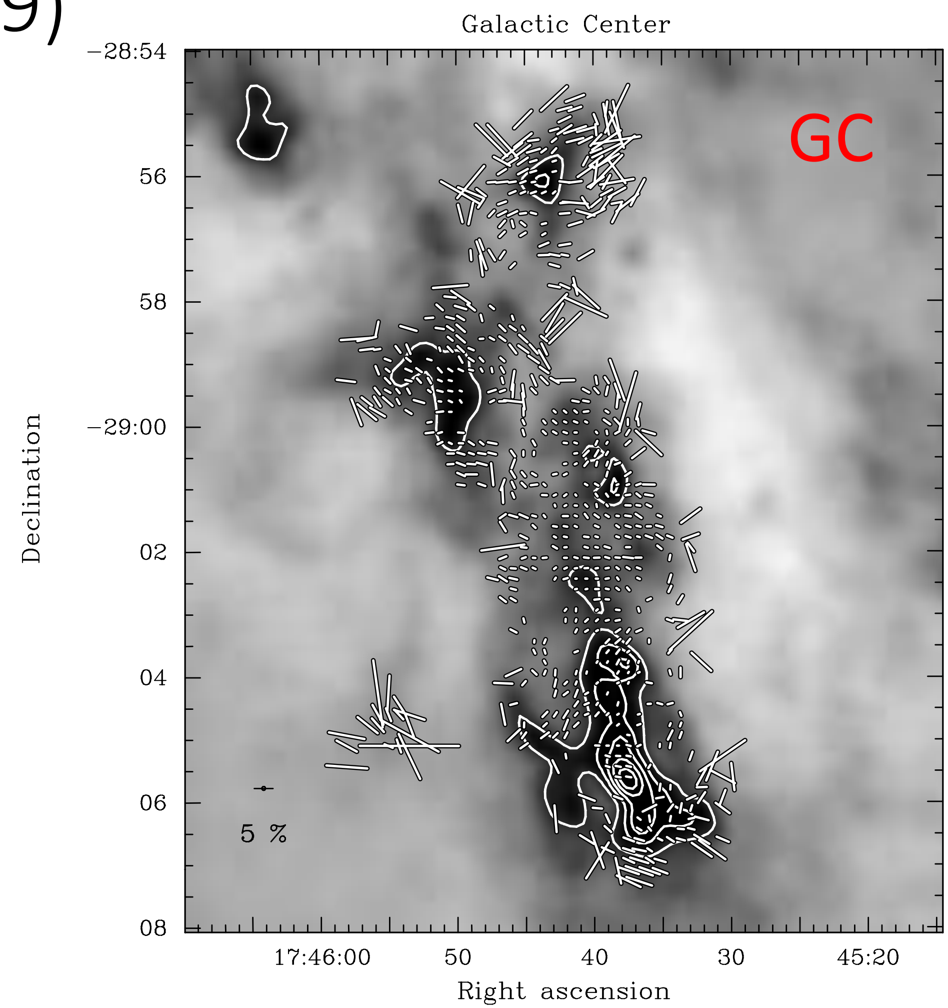


SCUBA-POL at λ=850μm

(Results in 1997-2005 by Matthews+, ApJS, 182, 2009)

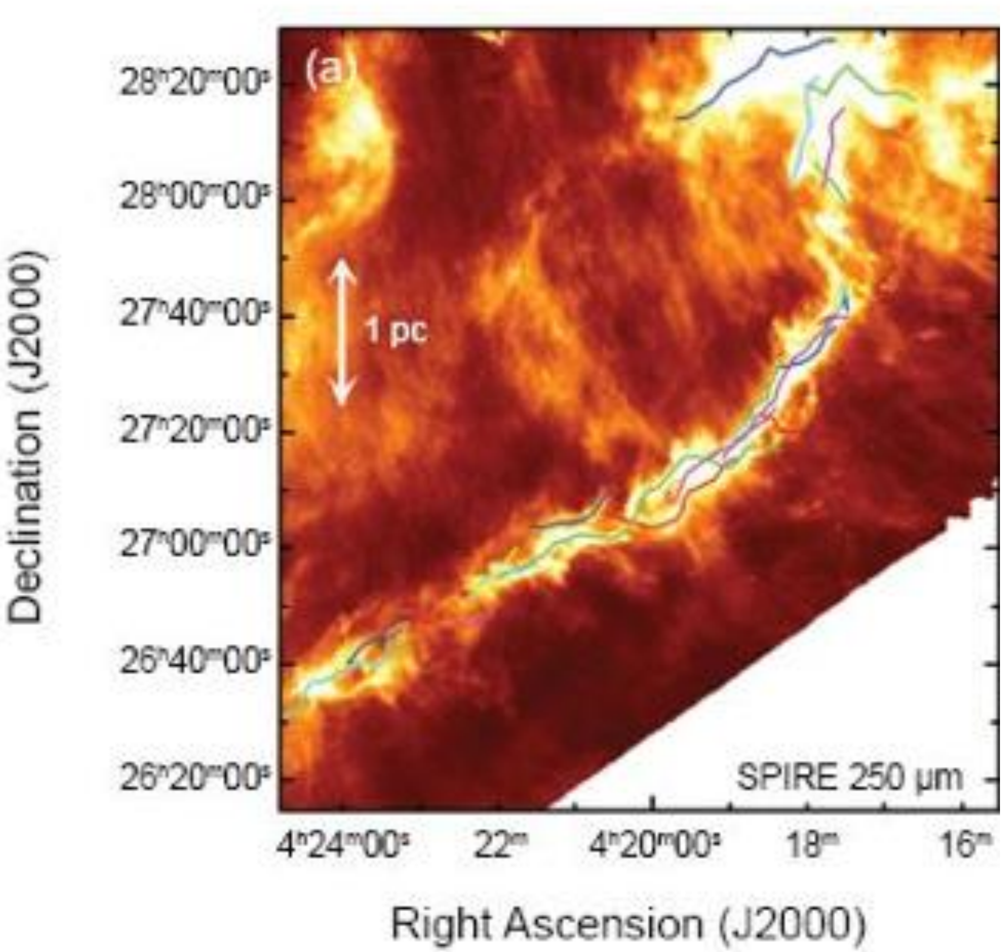
83 SF-regions, AGB stars, SNRs, ...





Star formation occurs in a filament

--- Herschel studies ---



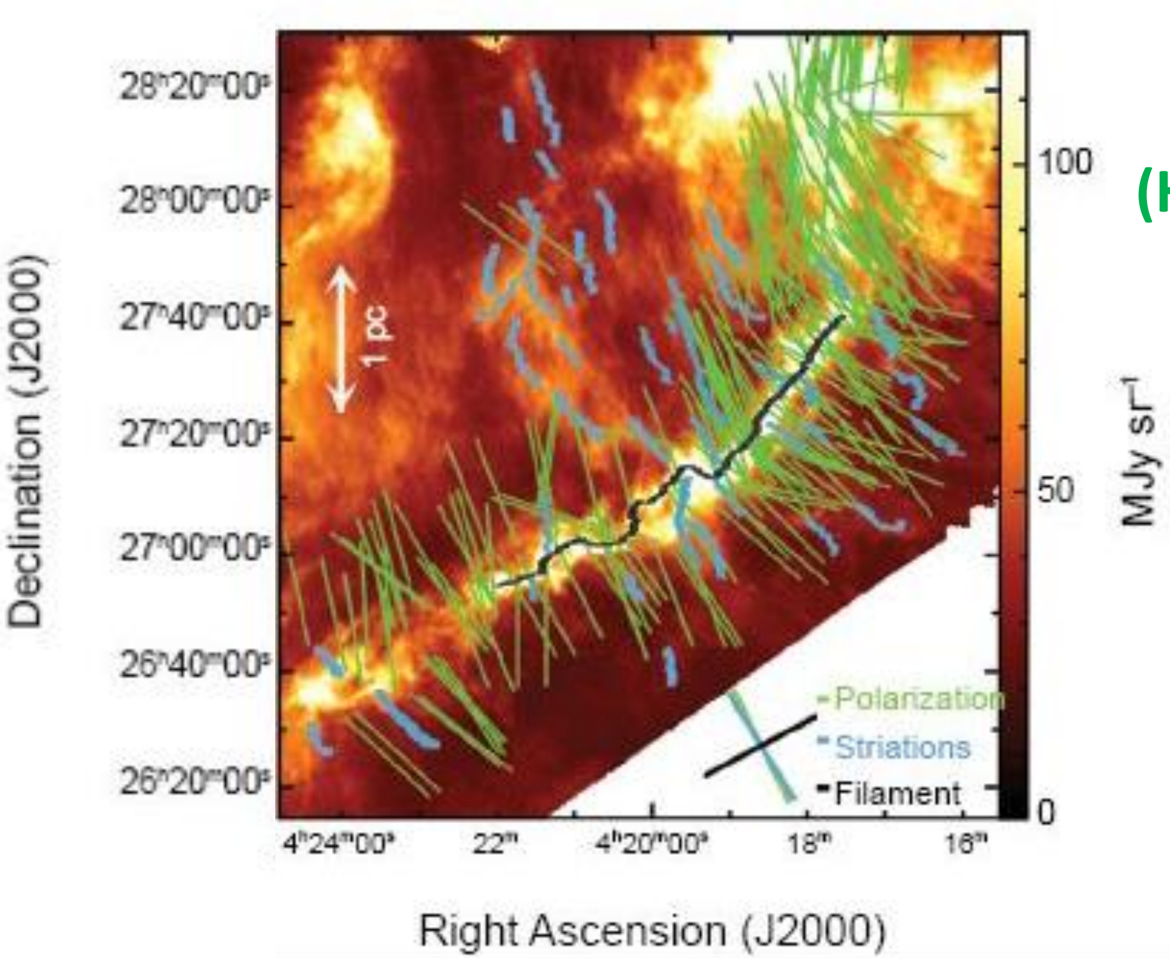
Herschel/SPIRE
250μm dust continuum image of B211/B213/L1495 in Taurus
(Palmeirim+ 2013)

&

"Fibers" in the filament identified in $C^{18}O$(J=1-0)
(Hacor+ 2013)

"Striations" ? filaments, consisting of "fibers"

Comparisons with B-field from near-IR



(figure from PPVI, Andre+ 2014)

Green: B-field suggested by dust polarization in near IR (Heyer+ 2008; Chapman+ 2011)

Black: Filaments

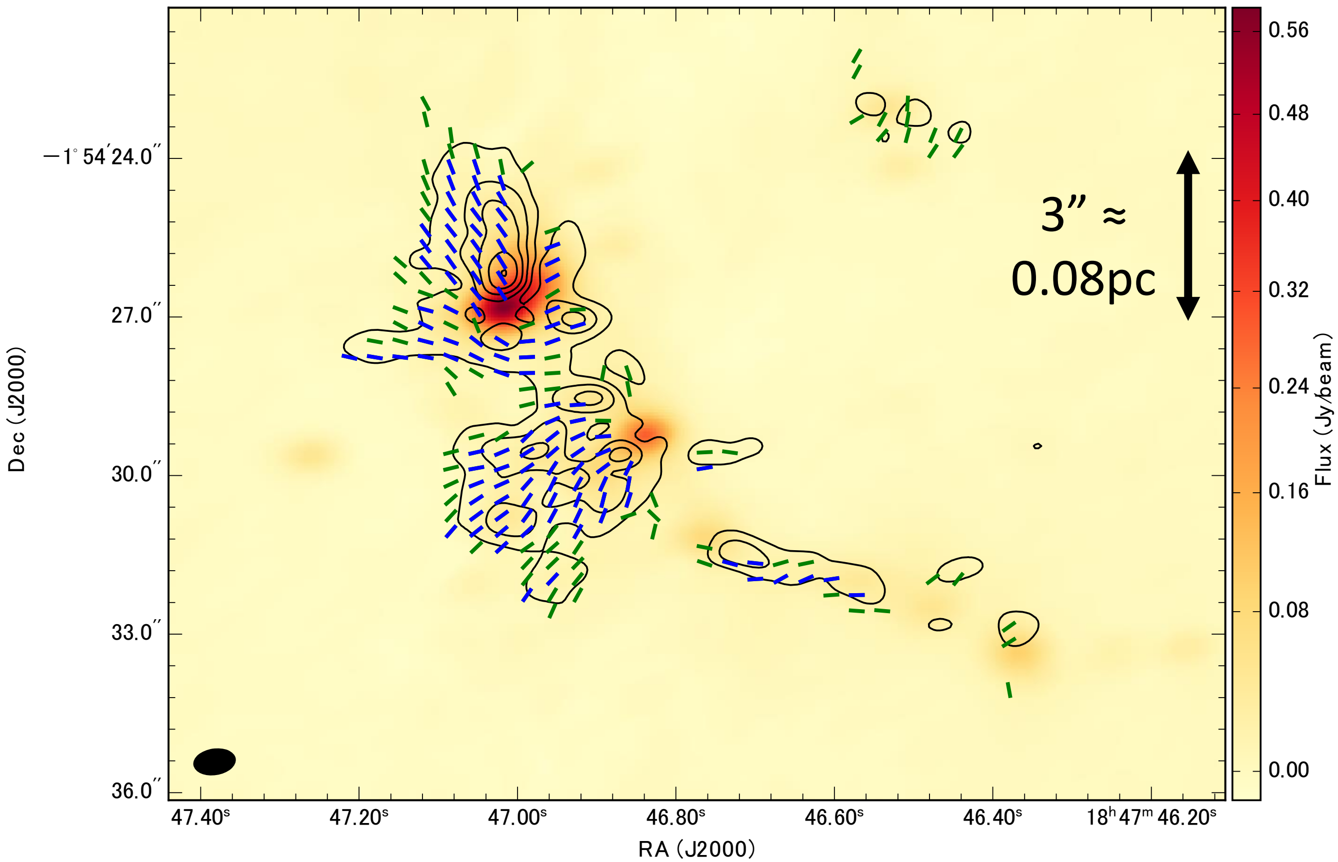
Blue: Striations

<u>Star-forming Filaments</u>

$$\text{elongation} \perp \boldsymbol{B}$$

$$\text{line mass density} \geq \frac{2c_s^2}{G}$$

Dust polarization seen by ALMA (1):
--- massive SF clumps (Cortes+ 2016) ---



Color + contour image : Stokes I at λ=1mm;
pseudo-vectors: B-fields (blue > 5σ; green > 3σ)

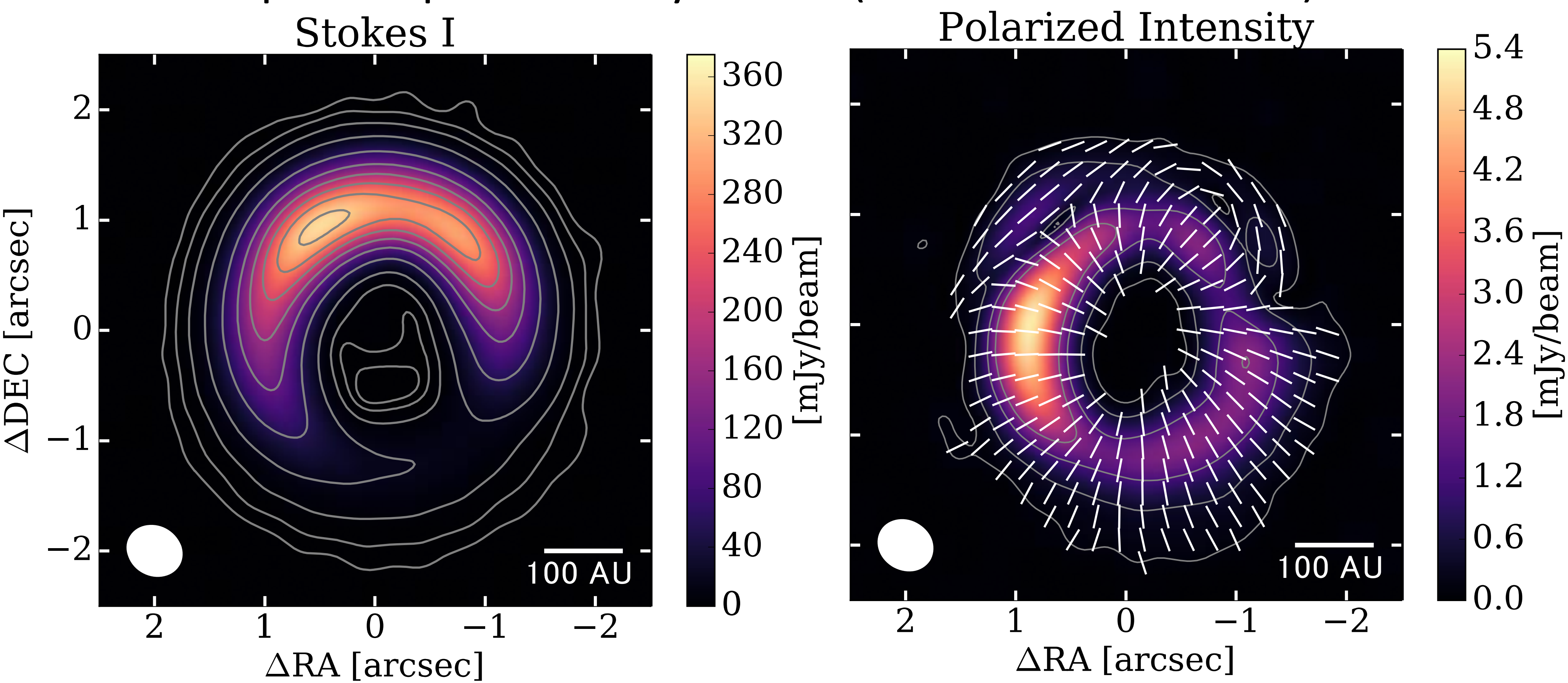
<u>W43-MM1 (d=5.5kpc)</u>

A fragmented filament, containing ~ 15 clumps (14- 312$M_\odot$)

<u>B strength in clumps</u>
0.2-9 mG, estimated from $\Delta v(C^{18}O)$, $n(H_2)$ & $\delta\phi$

(Chandrasekhar & Fermi method)

Dust polarization seen by ALMA (2):
--- a protoplanetary disk (Kataoka+ 2016) ---



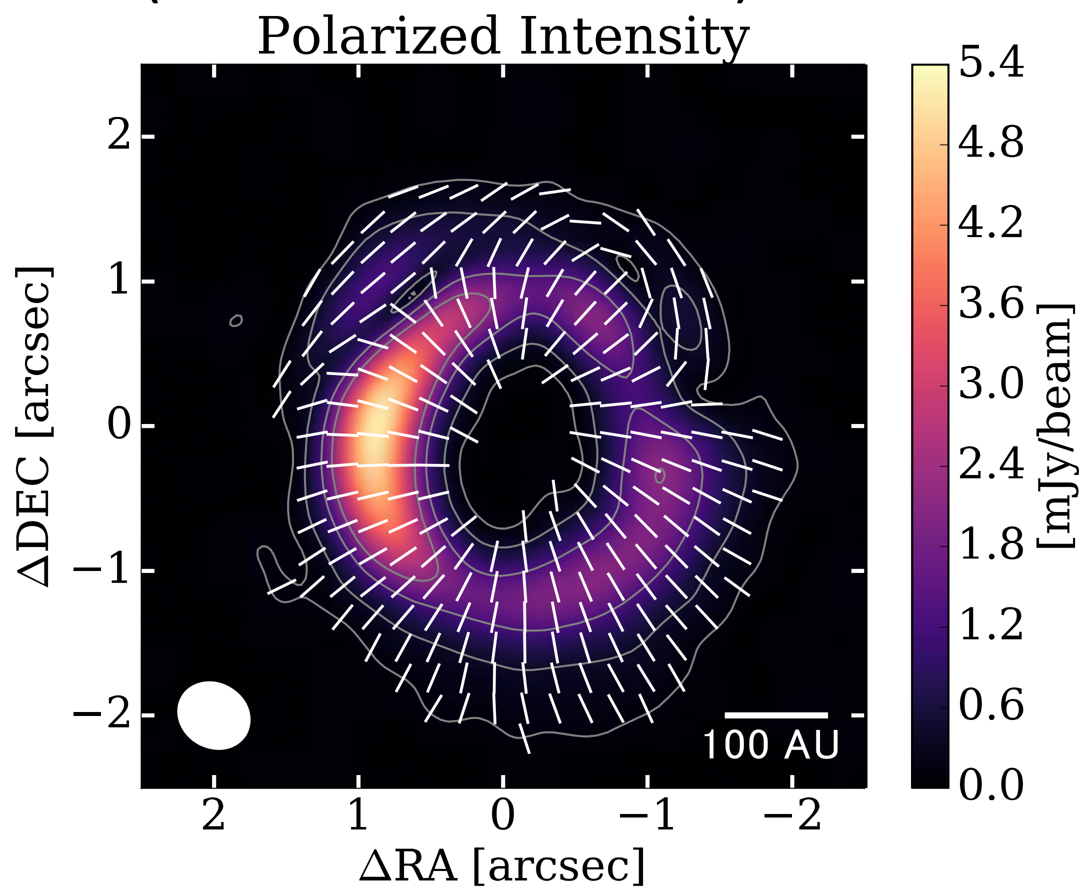
Stokes I at λ=0.9mm; PI & E-vectors (> 3σ) by pseudo-vectors

Dust polarization seen by ALMA (2):
--- a protoplanetary disk (Kataoka+ 2016) ---

<u>HD142527 (d=140 pc)</u>

“Polarization flip” in NE, due to **<u>self-scattering</u>** by large (size ~ 150μm) grains ?
(see also Kataoka+ 2015)

Radiative grain alignment is more efficient than B-field ? (Tazaki, Lazarian & Nomura 2017)



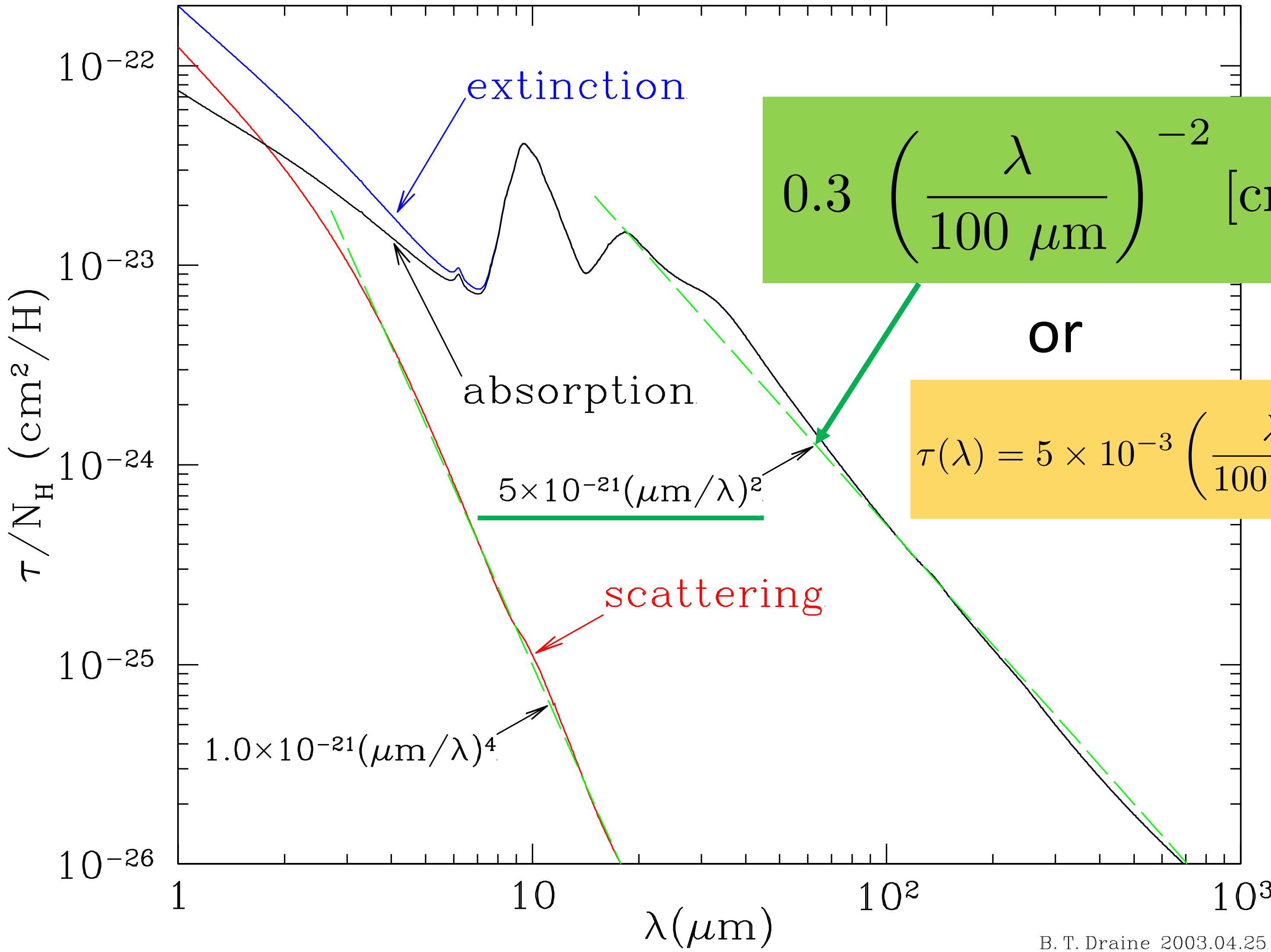
PI & E-vectors (> 3σ) by pseudo-vectors

Summary of the current status

- Large scale (> 1pc) B-fields and corresponding filaments
- ALMA is accumulating new Pol. Data at smaller scale
  - Pol. does not always trace B-fields in protoplanetary disks
  - Good laboratories for studies on alignment mechanism
- Progress in theories of dust alignment mechanisms
  - "Quantitative" predictive power
- Connection btw large-scale and cores/clumps; unknown
  - BISTRO with JCMT/SCUPOL 2 ?
  - Wide-field imaging with $\lesssim$ 10" resolution is essential
  - ALMA will not be the best instrument for this purpose … (probably)

Technical considerations

Draine (2003)



$$0.3\left(\frac{\lambda}{100\ \mu\mathrm{m}}\right)^{-2}\ [\mathrm{cm}^2\ \mathrm{g}^{-1}]$$

or

$$\tau(\lambda) = 5\times10^{-3}\left(\frac{\lambda}{100\ \mu\mathrm{m}}\right)^{-2}\left(\frac{N(\mathrm{H})}{10^{22}\ \mathrm{cm}^{-2}}\right).$$

Weingartner & Draine (2001) model
for our Milky-way galaxy

Targets

- Any frequency will do (350 GHz & > 800 GHz ?)
- $A_v \gtrsim 20$mag., or N(H) $\gtrsim 3.7 \times 10^{22}$ cm^{-2} & cold ($T \approx$ 15K) regions (see Draine (2003); to be complimentary to nIR and SPICA)
- Polarization degree $\gtrsim$ 5% (1σ = 1% of total intensity)
  - Systematic errors, loss in optics (e.g., transparency of HWP) & depolarization in the beam are for further studies
  - Advantage: Very stable condition in polar nights !?
- Suppressing other systematics
  - Differential imaging (frequent pol. switching) will be the key (c.f. Subaru HiCIAO)
  - Status of BISTRO with JCMT/SCUBA2-POL ?

Av > 20mag, T=15K, 5%-pol.deg (5σ)

	D=10m		D=30m	
Frequency [GHz]	Beamsize [asec]	Required sensitivity of 1% Total I (1σ) [mJy/beam]	Beamsize [asec]	Required sensitivity of 1% Total I (1σ) [mJy/beam]
400	18.6	1.11	6.2	0.123
850	8.7	1.95	2.9	0.216

※ 観測時間の見積もりは，(1)偏光成分取得，(2)半波長板透過率などの考慮もさらに必要。

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