Polarimetry with SOFIA

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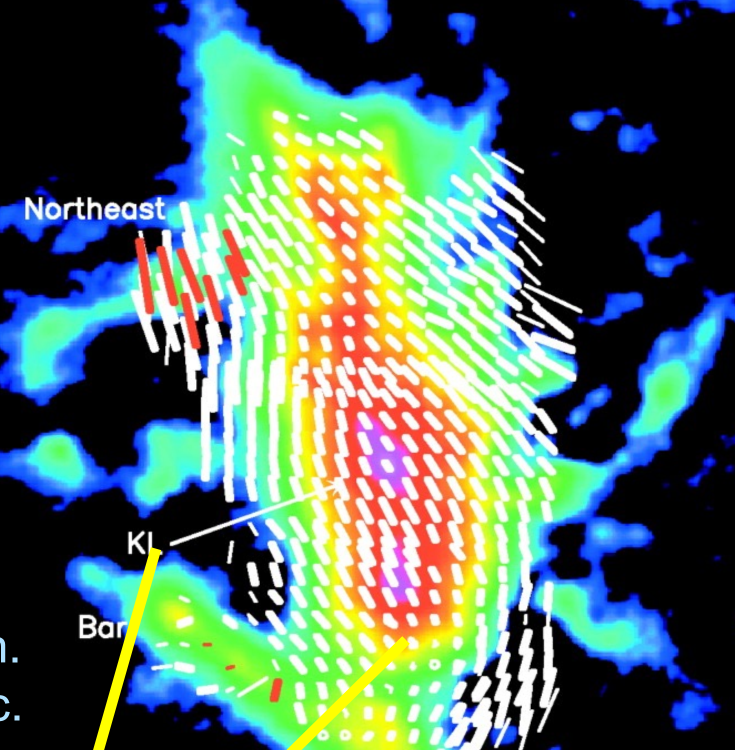
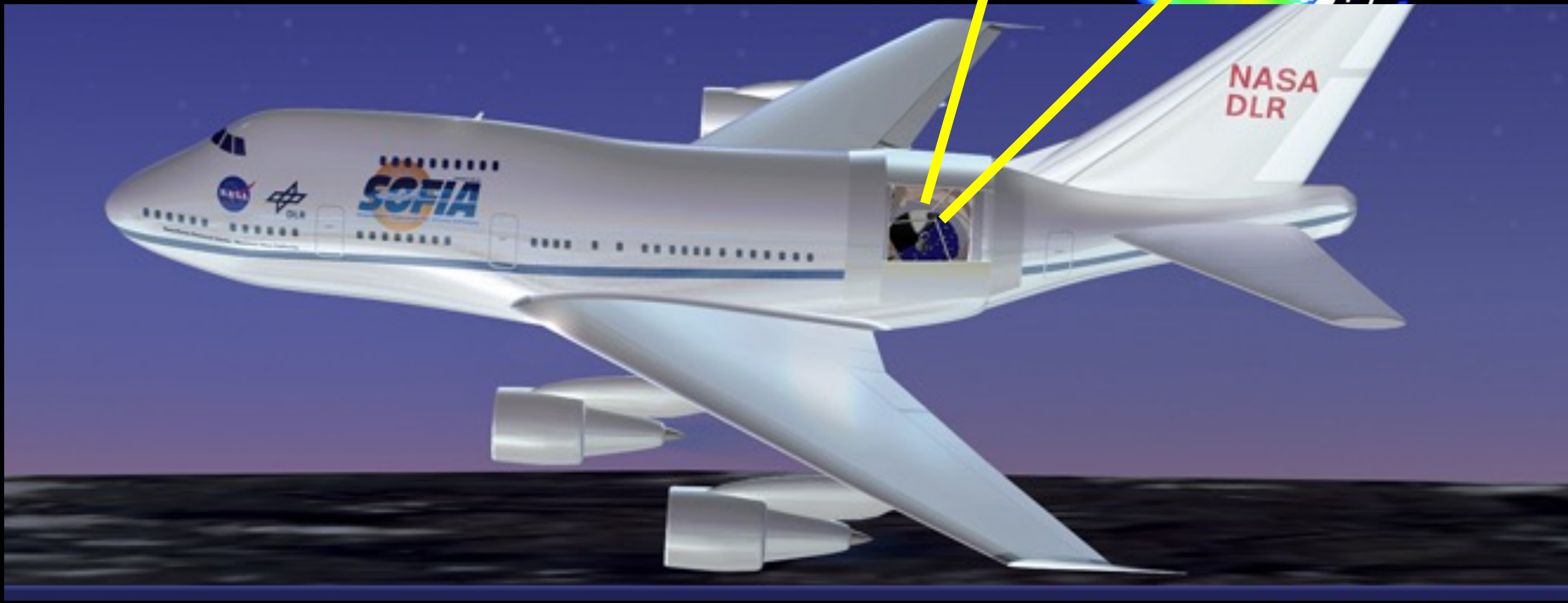




Outline

-- using far-IR/submm polarimetry to study star formation

-- 3 examples from recent past

-- capabilities of SOFIA

B-fields may strongly influence star formation

-- *mechanical support by strong B-fields may explain the low overall efficiency of the star forming process*

(e.g., Shu et al. ‘87; Mouschovias & Ciolek ‘99; Basu & Ciolek ’04)

-- *B-fields may solve the “angular momentum problem”*

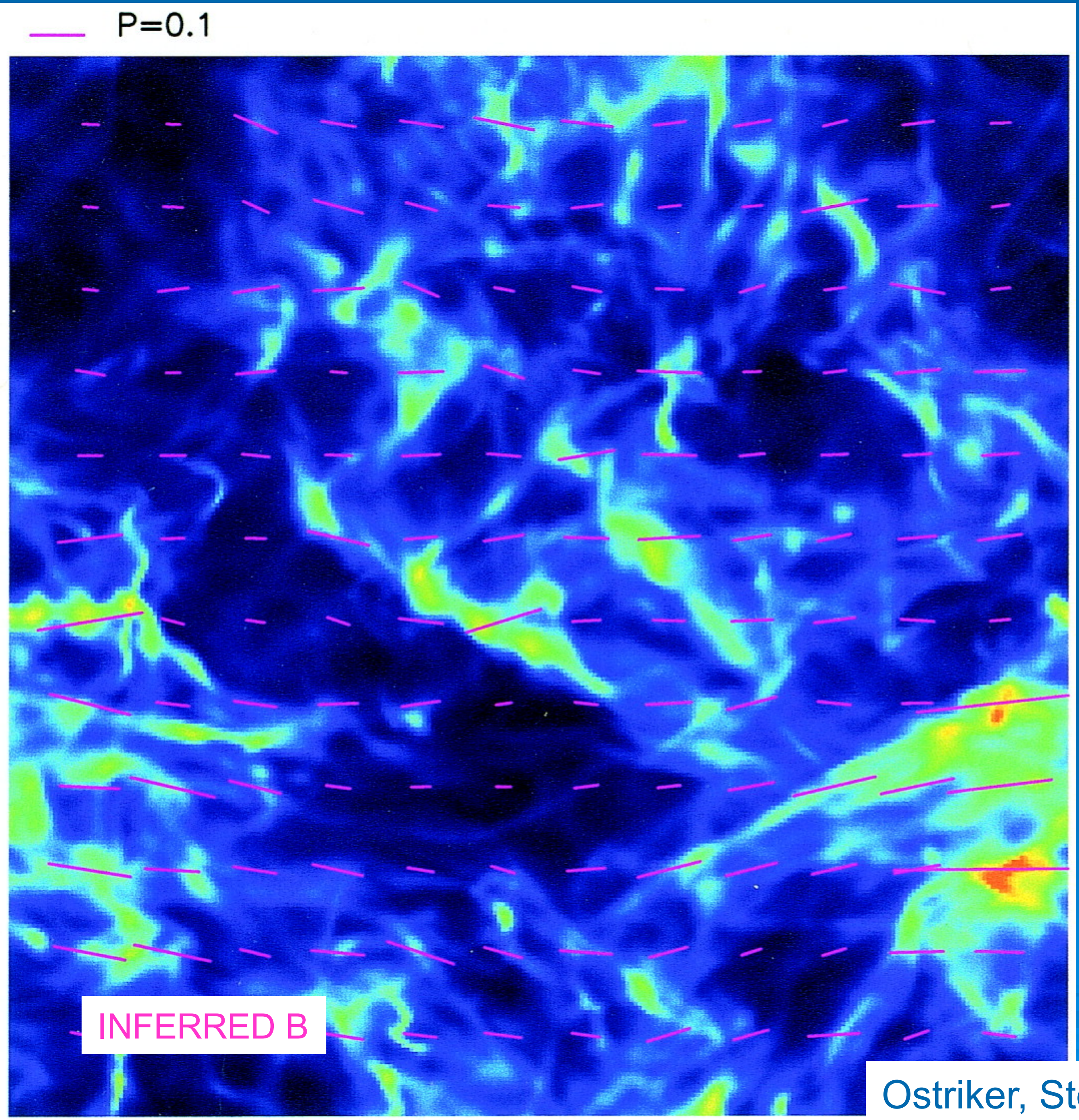
(e.g., Allen et al. ’03, Shu et al. ‘04)

-- *“…supersonic turbulent flows rather than static magnetic fields control star formation.”* … Mac Low & Klessen 2004

(see also, e.g., Hartmann et al. `01; Elmegreen & Scalo `04)

-- *Zeeman molecular line observations provide for direct measurement of magnetic field strength*

(e.g., Crutcher ‘99; Bourke et al. ’01; Crutcher et al. ‘09)



simulated GMC

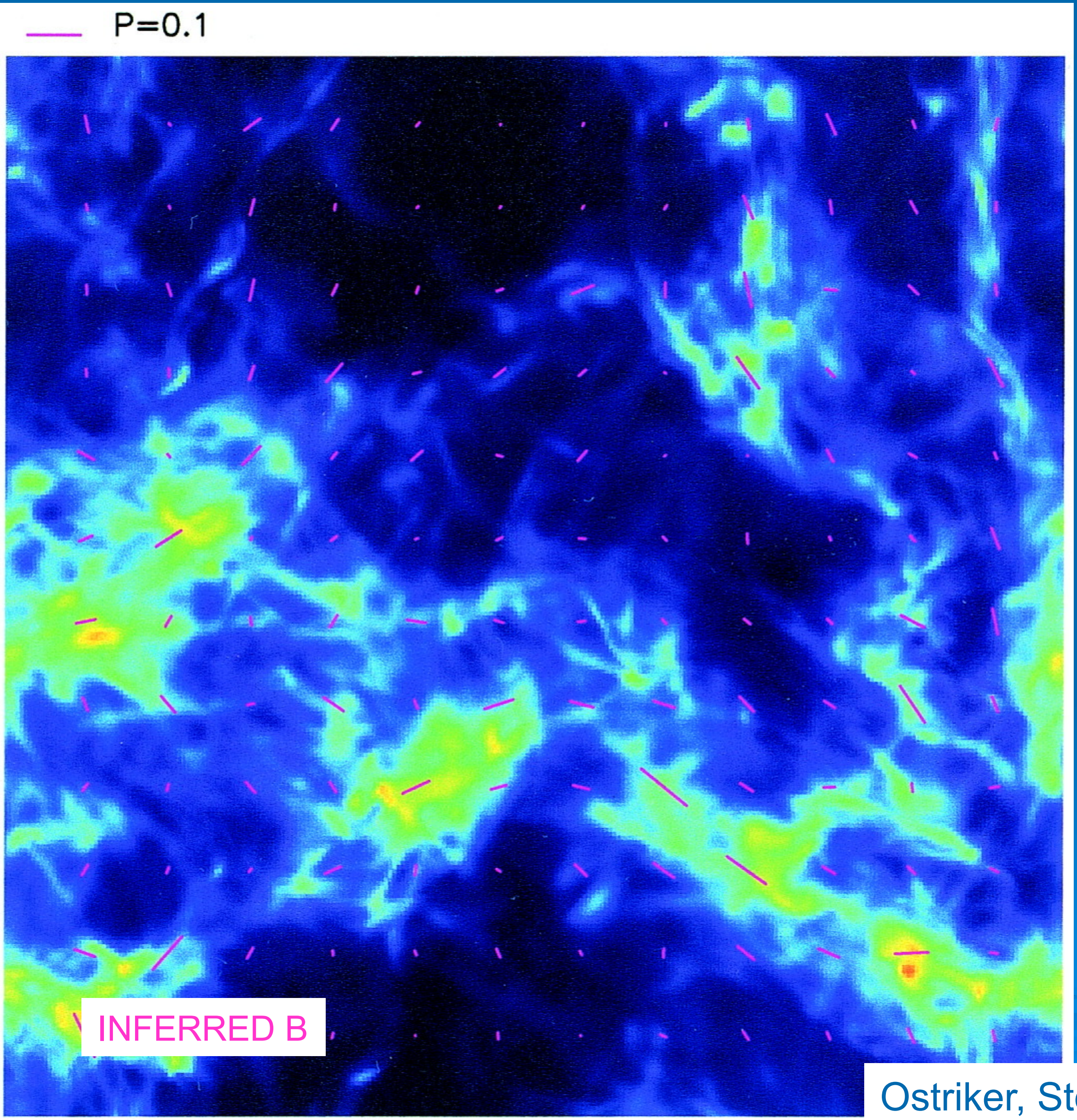
3-dimensional simulation of magnetohydro-dynamic (MHD) turbulence;

- compressible
- high Mach #
- incl. self-gravity
- isothermal

strong B-field

σ_{ϕ} = 9.6 °

Ostriker, Stone, & Gammie (2001)



Ostriker, Stone, & Gammie (2001)

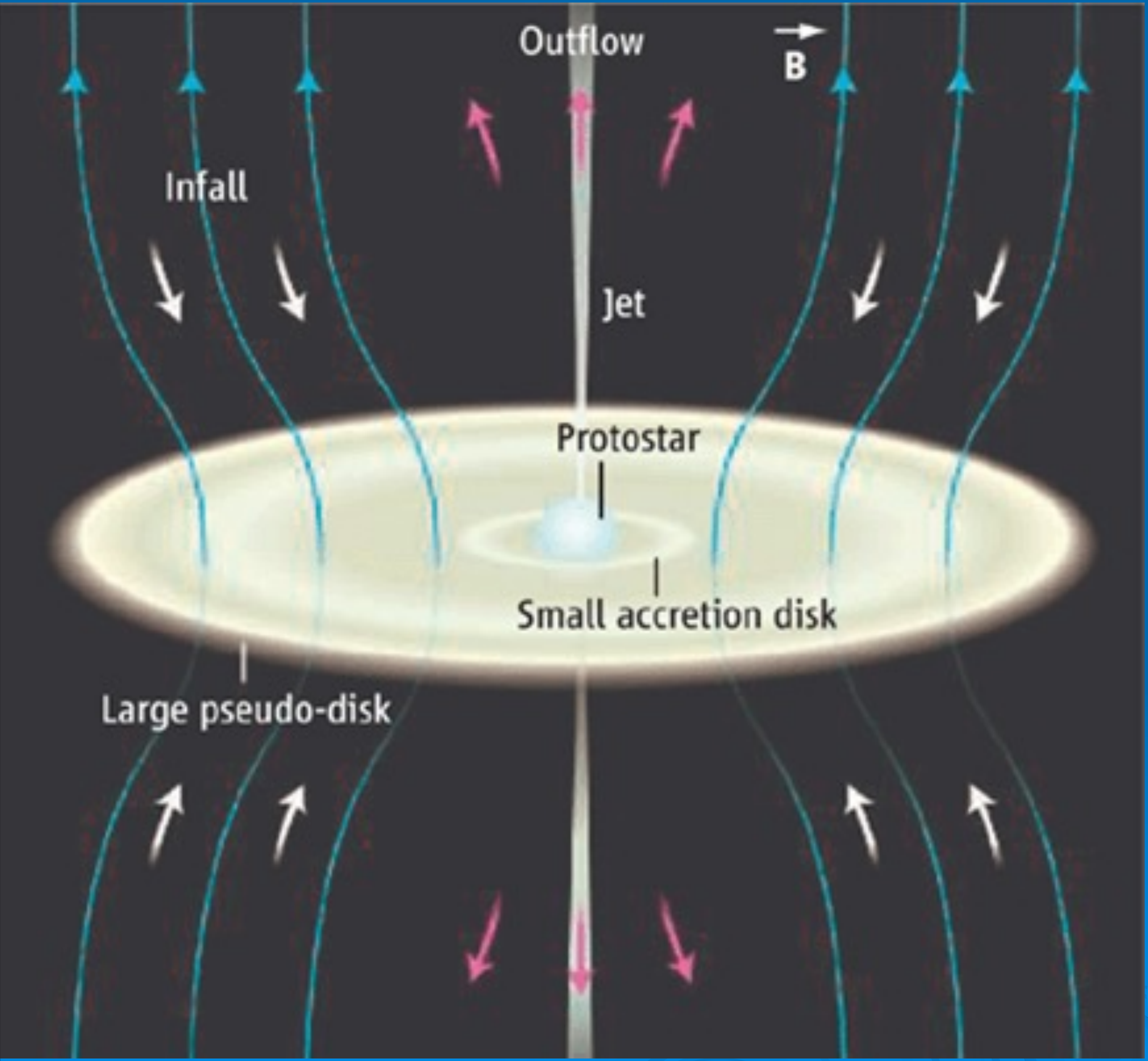
simulated GMC

weak B-field

σ_{ϕ} = 45.3 °

can determine |B| from σ_{ϕ}

(Chandrasekhar & Fermi 1951)



cartoon from Crutcher '06

shows the idea behind "laminar" models of …

-Galli & Shu '93

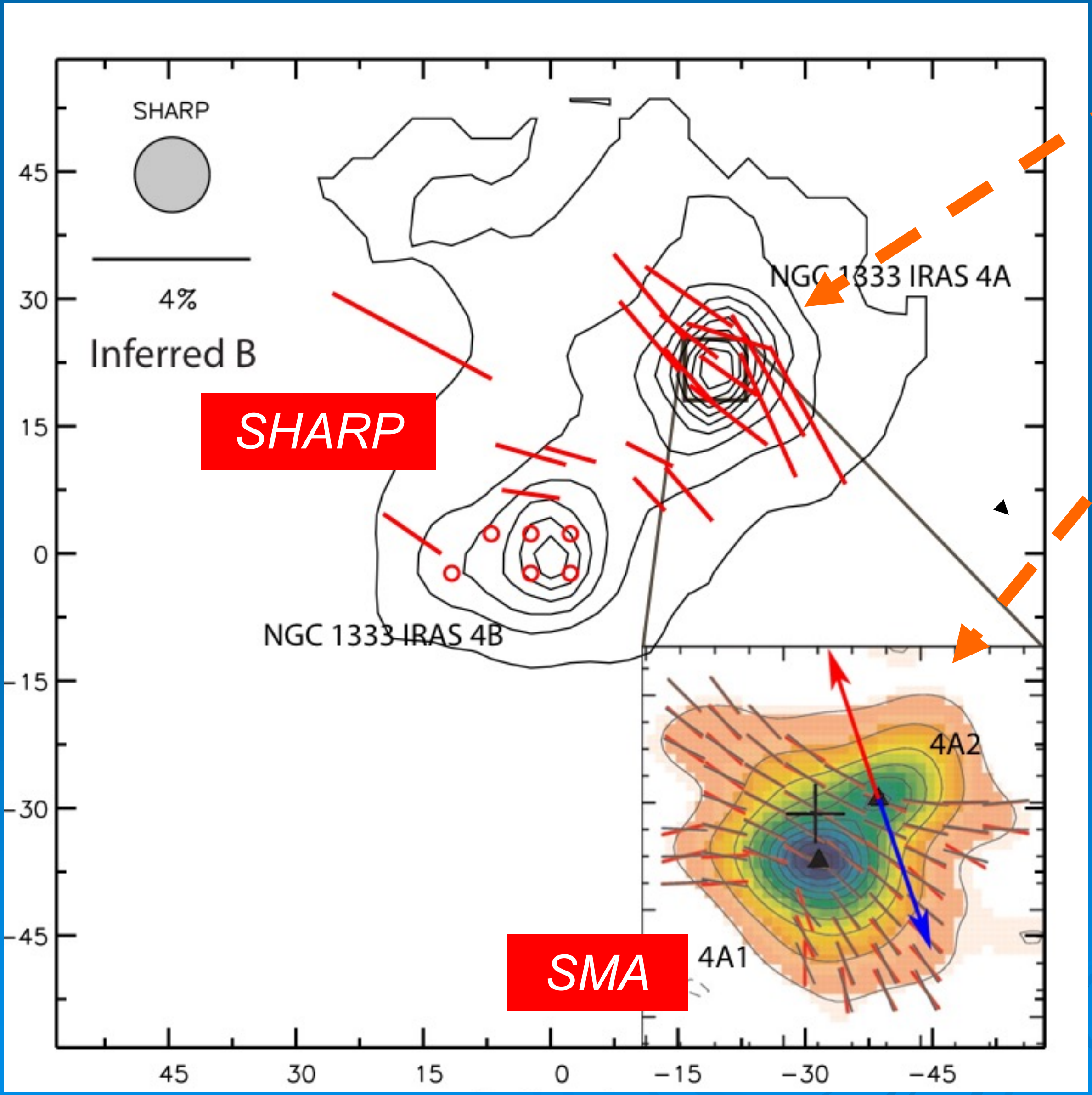
-Fieldler & Mouschovias '93

-Allen et al '03

-Shu et al '04

… etc.

first observation of a *magnetic hourglass* in a low-mass star forming region (NGC 1333 IRAS 4A)



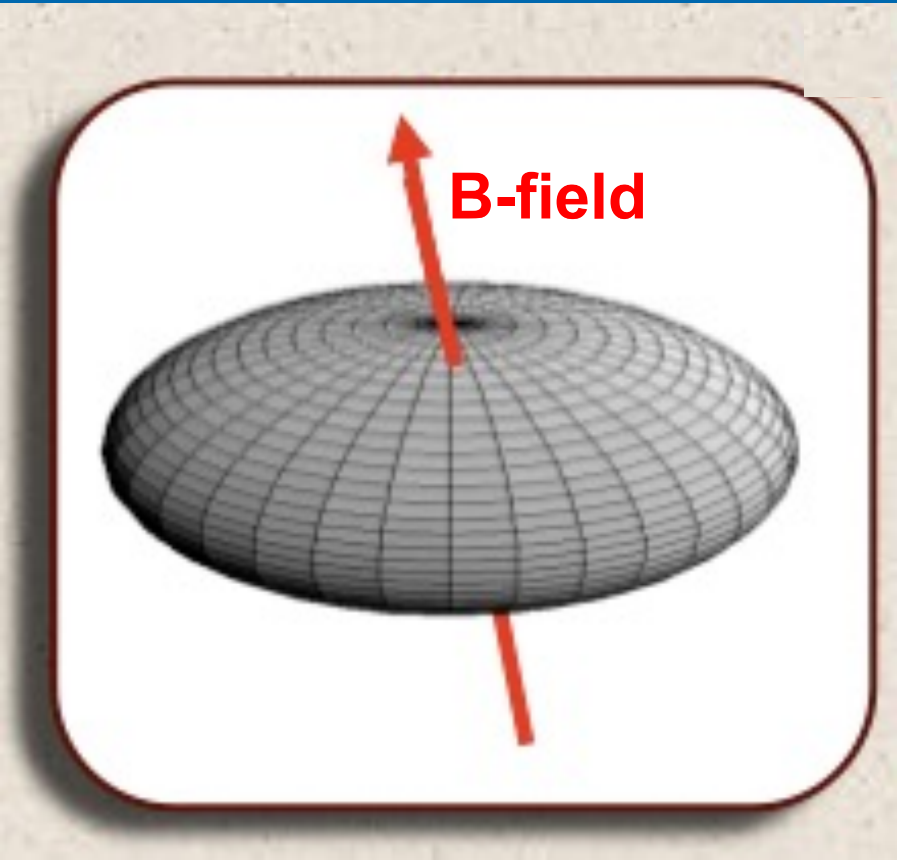
straight part of the hourglass seen by SHARP *(Attard et al. '09)*

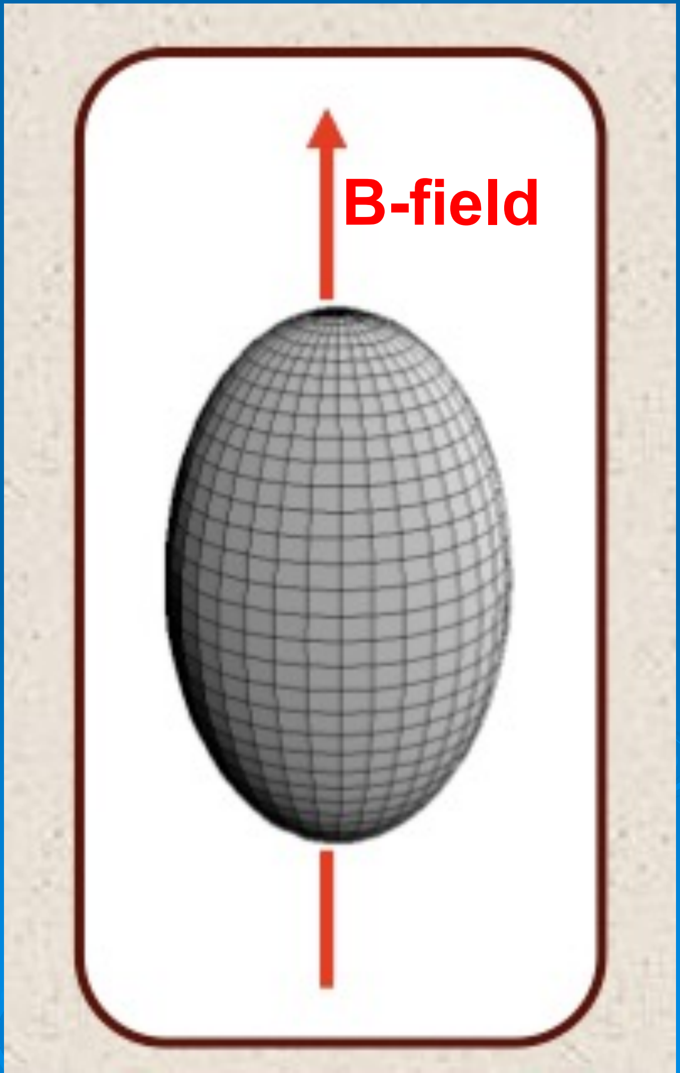
"waist" of the hourglass seen by SMA *(Girart et al. '06)*

"…at [the Class 0 phase] magnetic fields dominate over turbulence as the key parameter to control the star formation process."

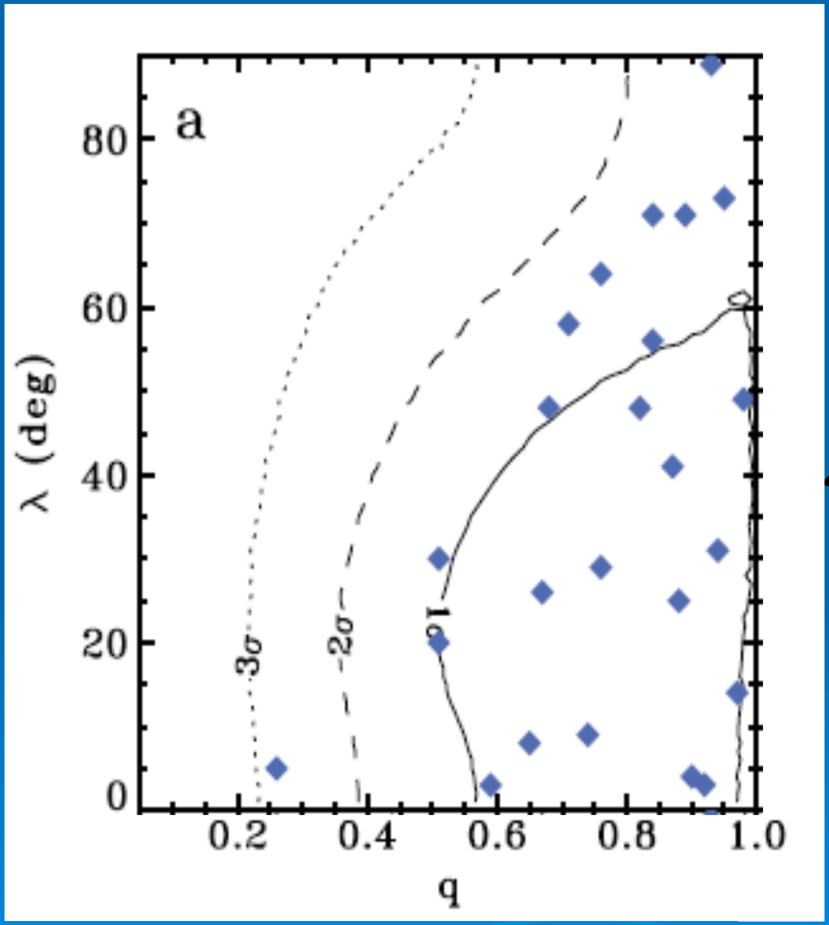
Example #1: The laminar models assume oblate cores, with B-field parallel to axis of symmetry ...

submm polarimetry can check this…
(Tassis et al. '09; data from Hertz)





Angle (λ) between ***observed B-field*** and ***observed short axis*** *vs.* ***observed* aspect ratio (q)**



more elongated ← → rounder

The data are reasonably well fit by **oblate cores with B-field parallel to axis of symmetry**

… but the very best fit has a 24° misalignment between B-field and sym. axis

Example #2: *dispersion of large-scale GMC B-fields*: comparing observations with turbulence simulations

Ostriker et al. '01 provided three models, of varying field strength; in the following papers *we show that the weak field model is inconsistent with the observations:*

Li et al. '06 – SPARO
Novak et al. '09 – SPARO + Hertz
Li et al. '09 – Hertz + SCUBA-POL + optical polarimetry

McKee & Ostriker paper on "Theory of Star Formation" (Ann. Rev. Astron. Astrophys.) :

"GMC magnetic fields are not too weak, however: 450 micron polarimetry of four GMCs shows that the orientation of the field appears to be preserved during the formation of the GMCs and that the energy in the field is comparable to the turbulent energy (Li et al. 2006)."

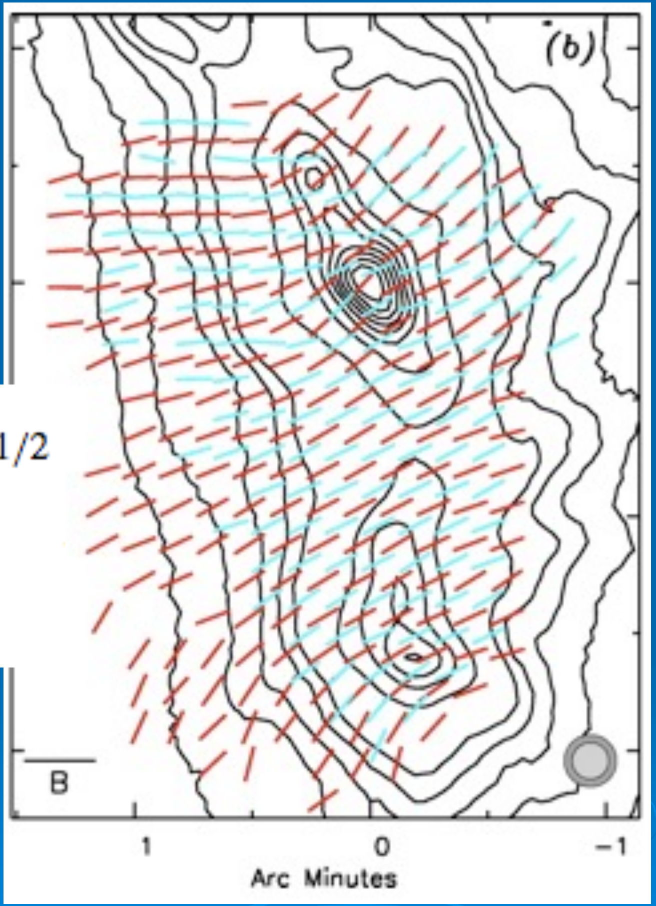
Example #3: use of polarization angle structure functions to study magnetized turbulence

Hildebrand et al. '09; Houde et al. '09

angle $\Phi(\mathbf{x})$

$$\Delta\Phi(\ell) \equiv \Phi(\mathbf{x}) - \Phi(\mathbf{x}+\boldsymbol{\ell})$$

$$\langle \Delta\Phi^2(\ell)\rangle^{1/2} \equiv \left\{ \frac{1}{N(\ell)} \sum_{i=1}^{N(\ell)} [\Phi(\mathbf{x}) - \Phi(\mathbf{x}+\boldsymbol{\ell})]^2 \right\}^{1/2}$$



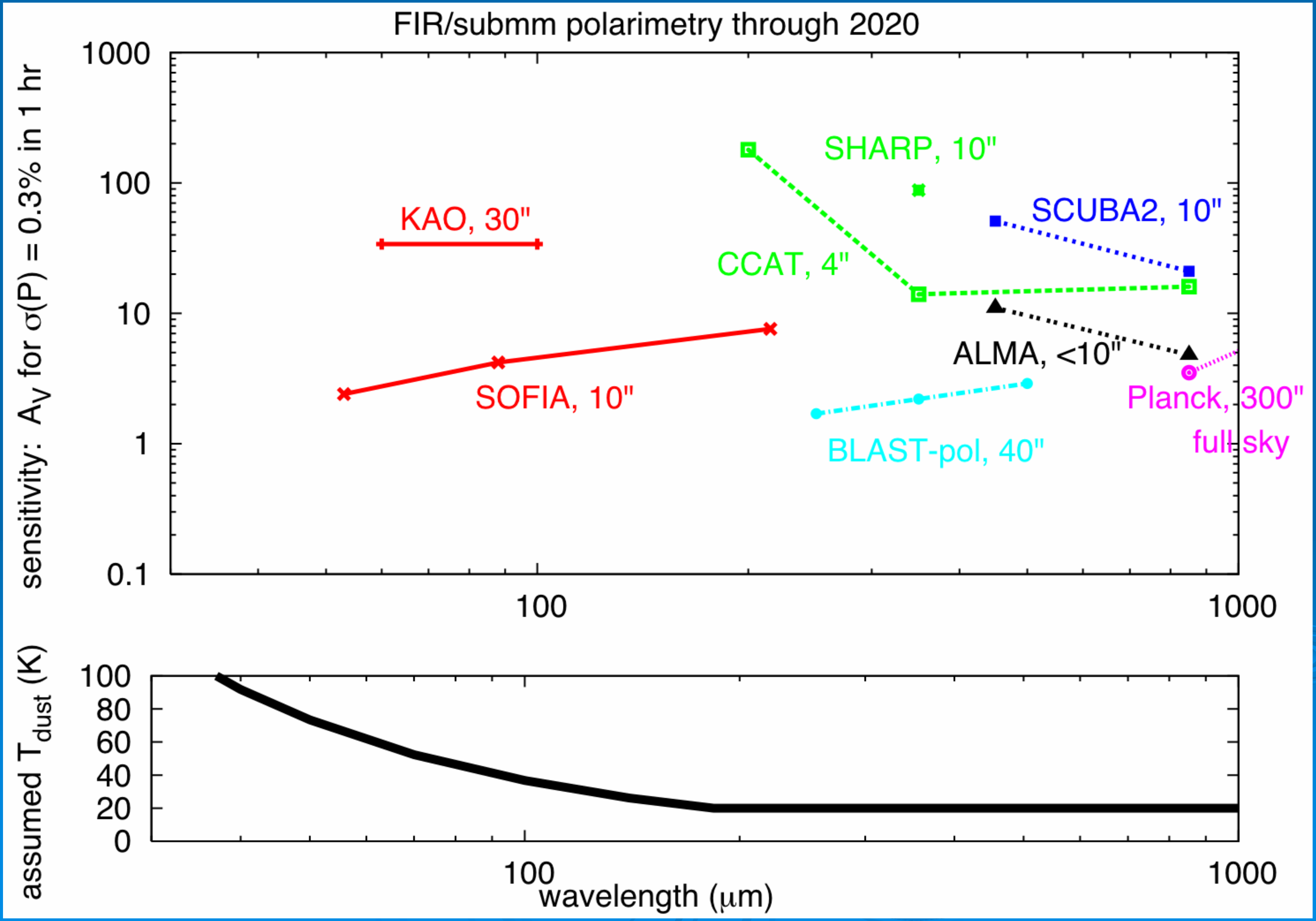
OMC-1 (SHARP)

- *turbulent correlation length: 16 mpc*
- *magnetic field strength: 0.8 mG*

- *new analysis including SMA data finds high-frequency cutoff in the power spectrum at 6 mpc*

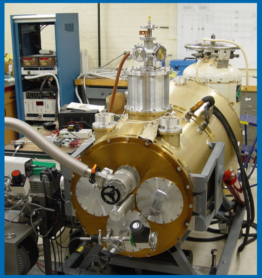
(Houde et al., in prep.)

SOFIA is a significant step forward in sensitivity to extended dust emission.

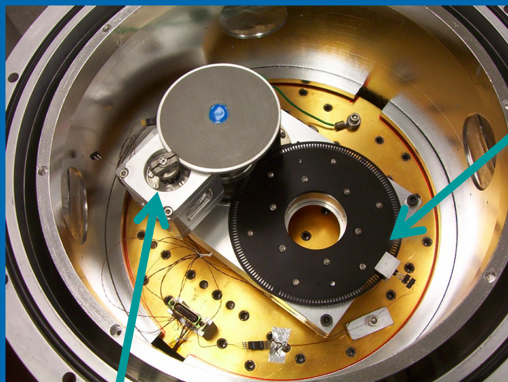


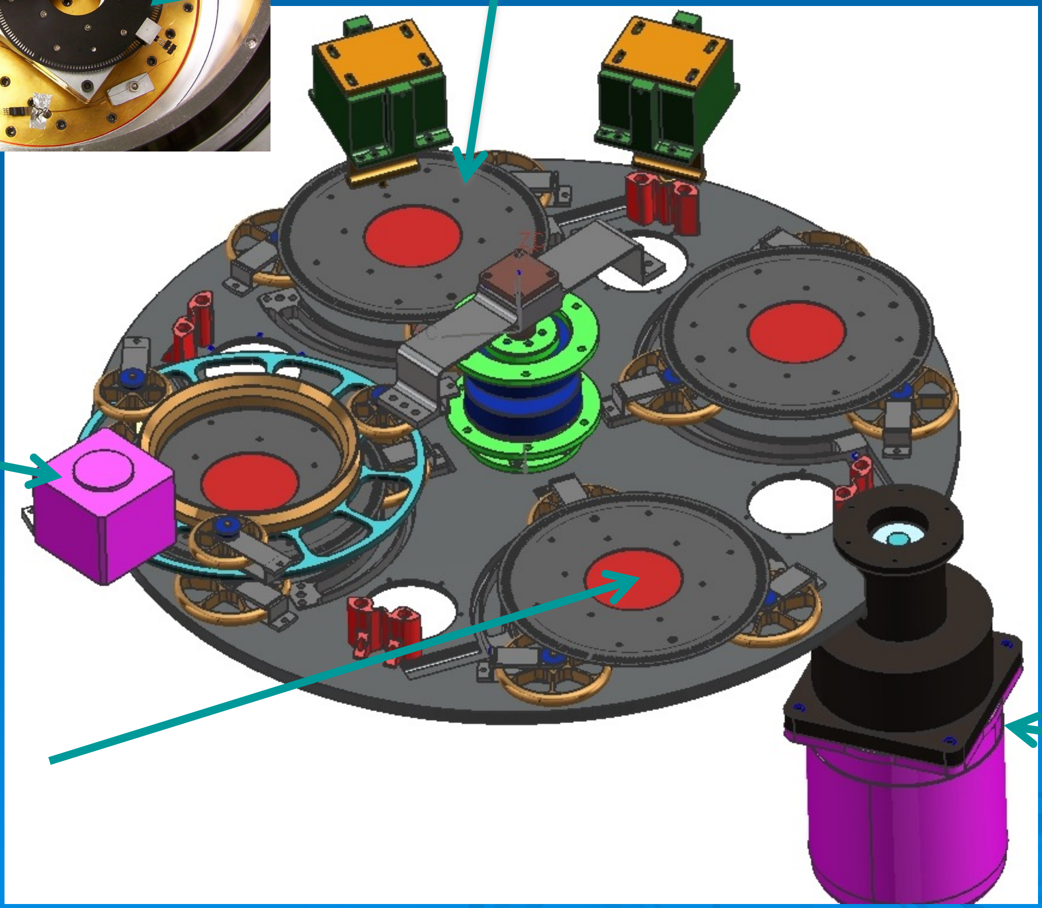
JPL Polarimeter for SOFIA/HAWC

SOFIA (NASA photo)



HAWC





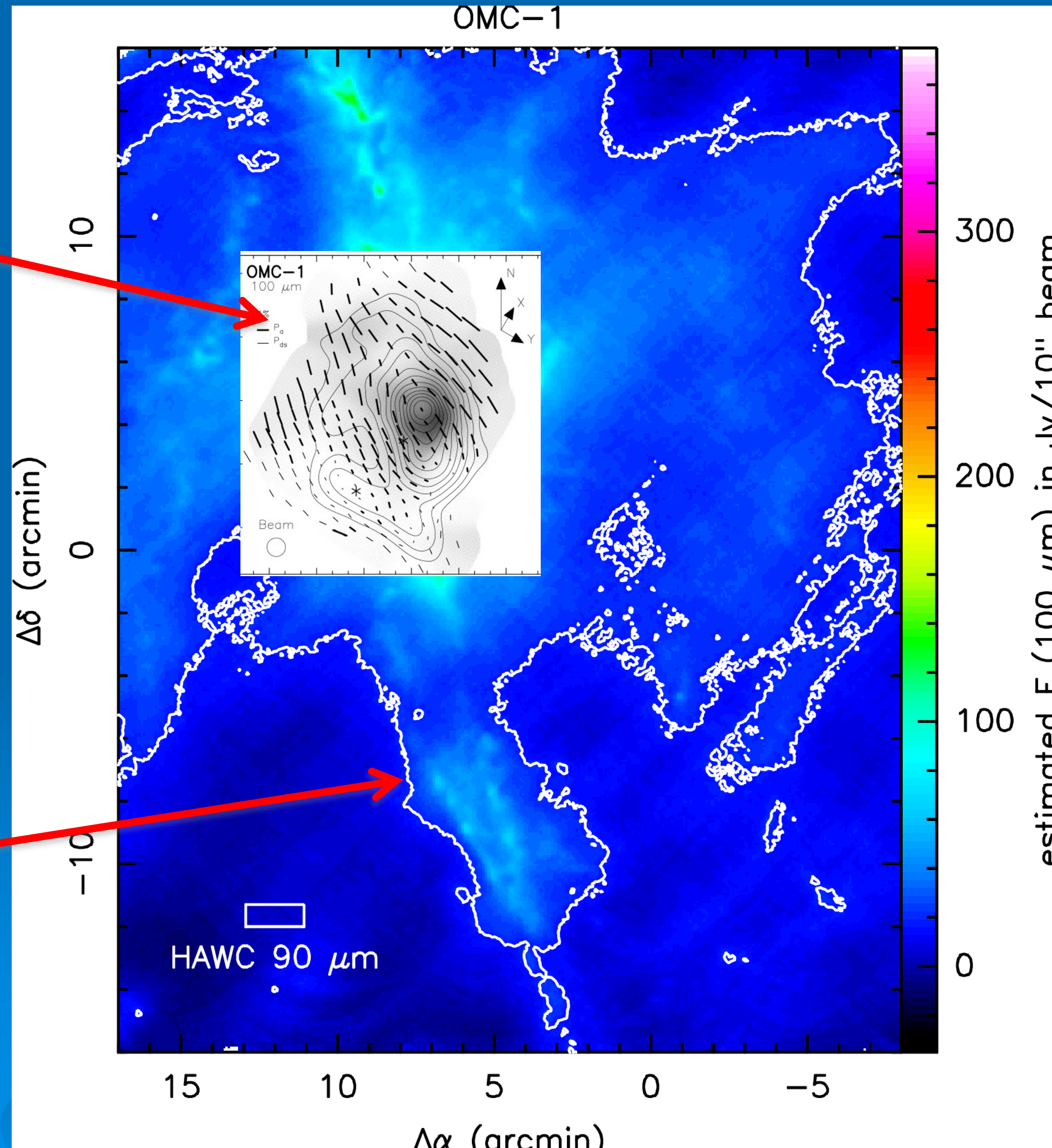
mechanical design for four-band far-IR polarimeter

- Project goals:
  - Complete polarimeter hardware via JPL R&D funds.
  - Apply to NASA SOFIA program in 2011 for integration, commissioning, data analysis.

Example SOFIA Coverage: Orion

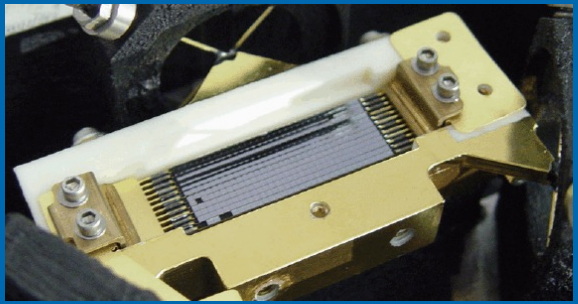
KAO polarization map:
Schleuning (1998)

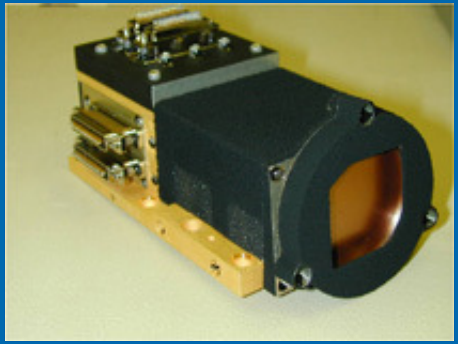
contour: pointings where
$\sigma(P) < 0.3\%$ in 4 minutes
with SOFIA



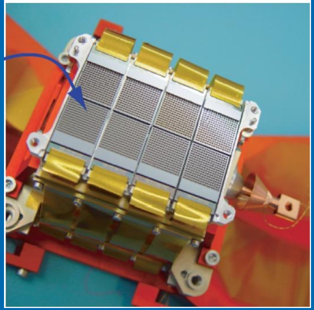
Present and Future Detectors

HAWC has a modest, but sensitive, array of 384 detectors:

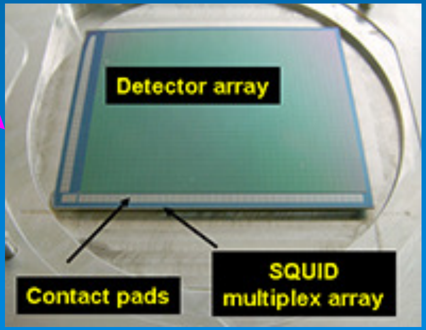




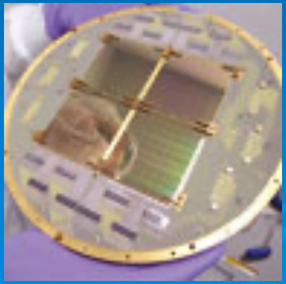
Spitzer/MIPS used a 1000-element array at 70 μm.

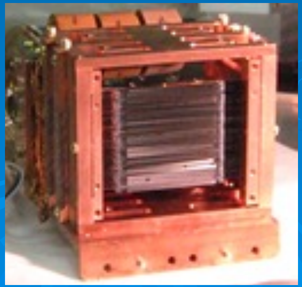


Herschel/PACS is using a 2000-element detector array in its 60-130 μm camera.



SCUBA2, which started shared-risk science last week, plans to field ***10,000*** detectors total at 450 and 850 μm.





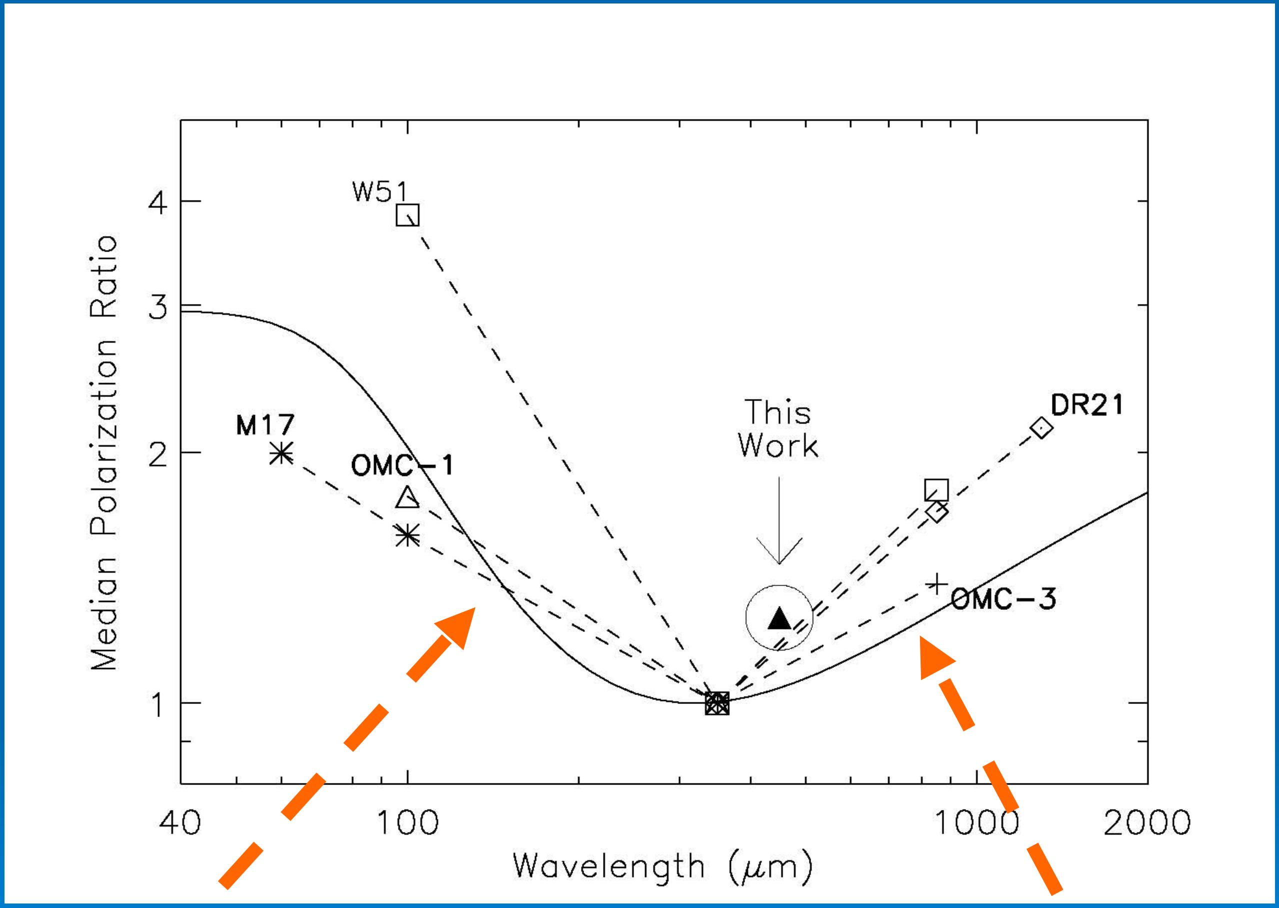
NIST, JPL/Caltech, and Goddard are working on FIR-mm arrays with 1000-10,000 detectors.

Why SOFIA?

-- **signal-to-noise**: *observe at peak of GMC spectrum; e.g., SOFIA Design Reference Mission Case Study by Novak et al. 2005 estimates 100,000 vectors in nine fields during 113 hours of observation*

-- **angular resolution**: *5 arcsec at 53 μm; 3 mpc at ρ Oph*

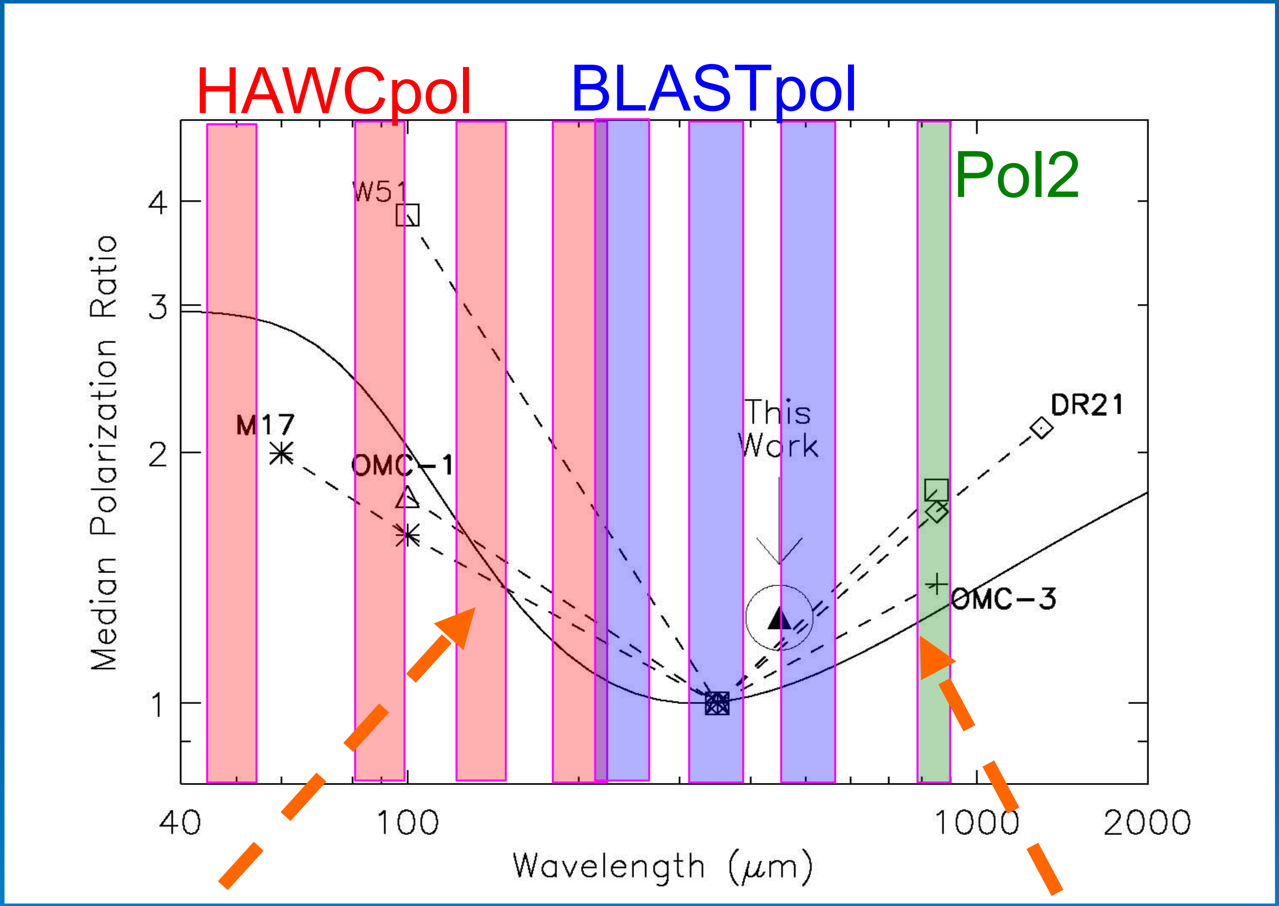
-- **polarization spectrum**: Grain alignment prescription is a key input for any cloud/core polarization model. Many experiments provide access to "*submm rise*", but SOFIA will provide the only access to *"far-IR drop"* polarization spectrum of GMC envelopes *(Vaillancourt et al. '08)*



far-IR drop:
alignment enhanced by IR radiation from embedded sources?

submm rise:
Draine & Fraisse '08
Bethell et al. '07

polarization spectrum of GMC envelopes *(Vaillancourt et al. '08)*



far-IR drop:
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submm rise:
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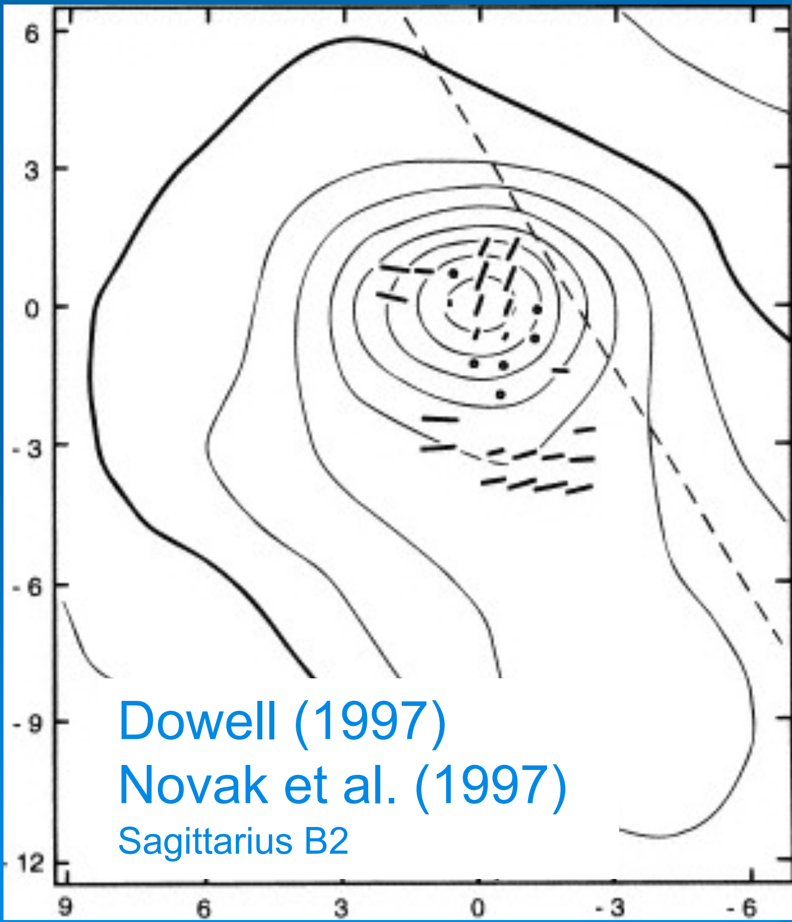
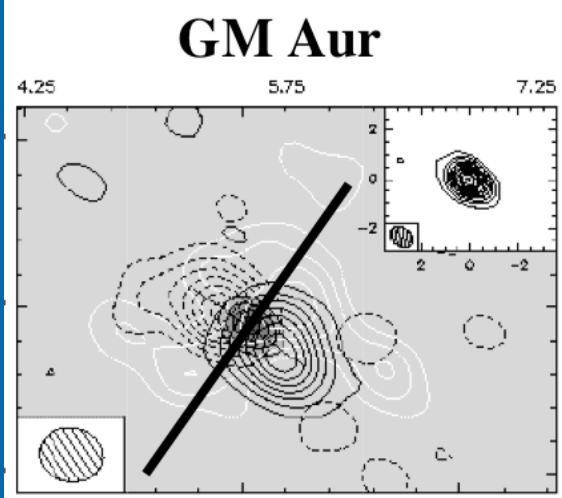
a further advantage of far-IR polarimetry:

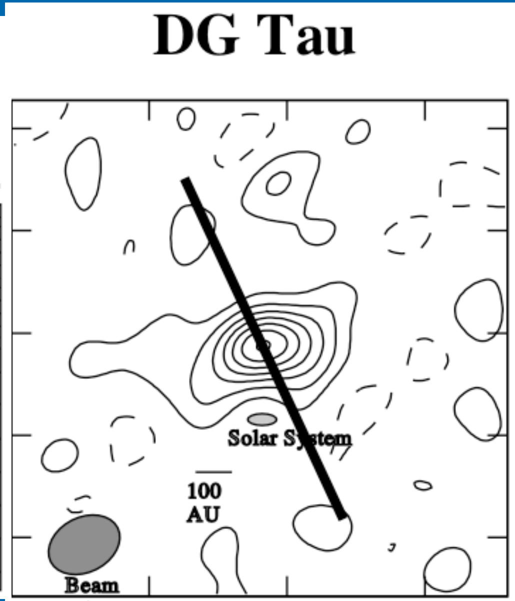
there can be more than one polarization mechanism

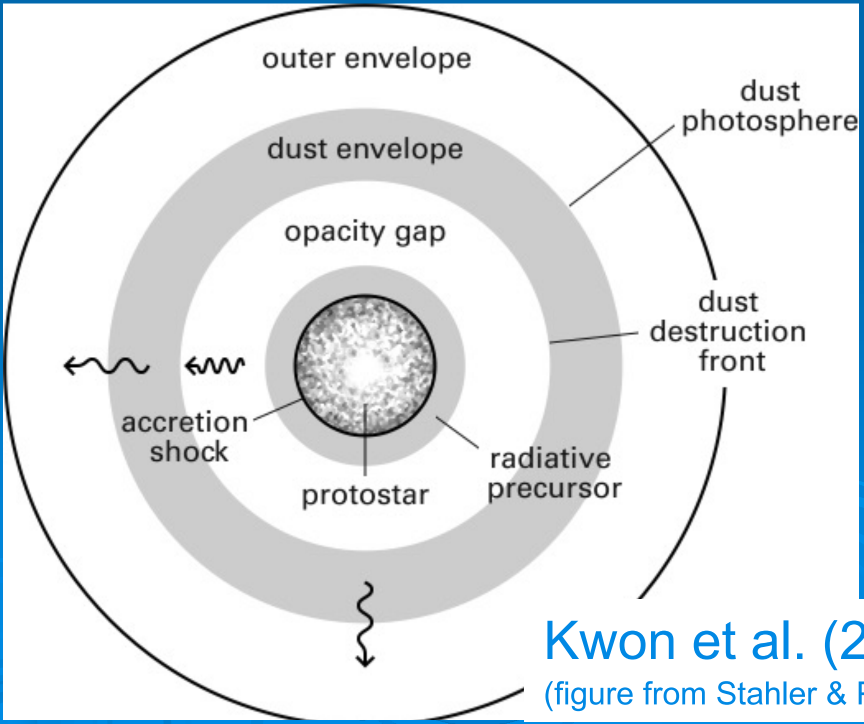


Dowell (1997)
Novak et al. (1997)
Sagittarius B2

Tamura et al. (1999)







Kwon et al. (2009)
(figure from Stahler & Palla 2004)

Summary

polarimetry of dust emission is allowing direct comparisons with theoretical models – both laminar and turbulent. key question: *what role do interstellar magnetic fields play in star formation?*

SOFIA will uniquely access the “far-IR drop”

polarimetry of disks and infall envelopes with SOFIA may provide a *new window on grain properties* in these sources; probing grain coagulation and planet formation

first-light SOFIA far-IR polarimetry can be attained reasonably quickly and inexpensively via HAWC-POL