Taurus: Then and Now

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Dense Cores in Dark Clouds LXV
for Phil Myers
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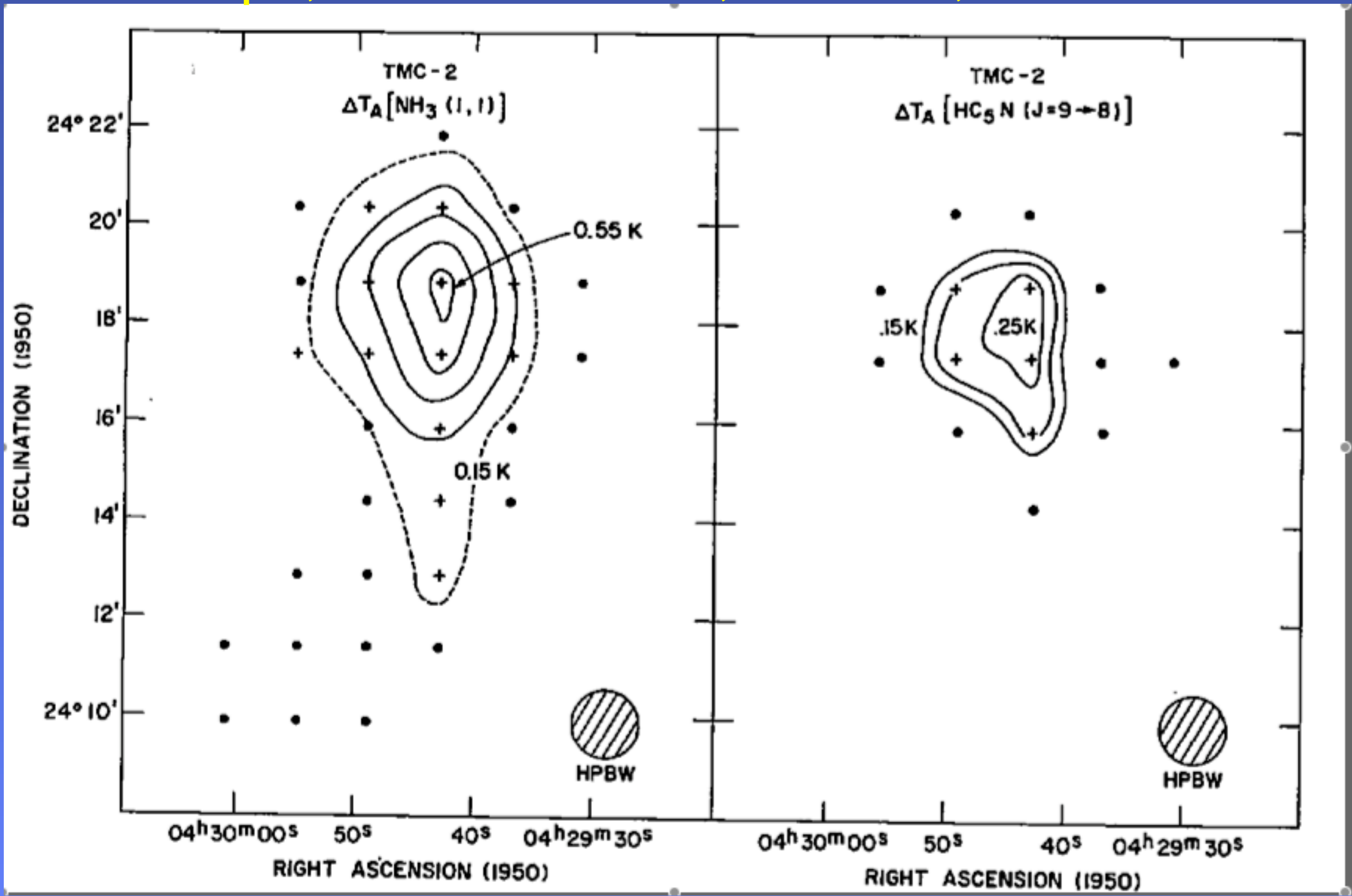
Taurus - poster child for star formation

- Interplay of observations and theory in Taurus greatly advanced star formation theory

- Understanding the structure of Taurus was key. Phil led the way by relating optical obscuration in filaments to dense cores, and relating dense cores to star formation

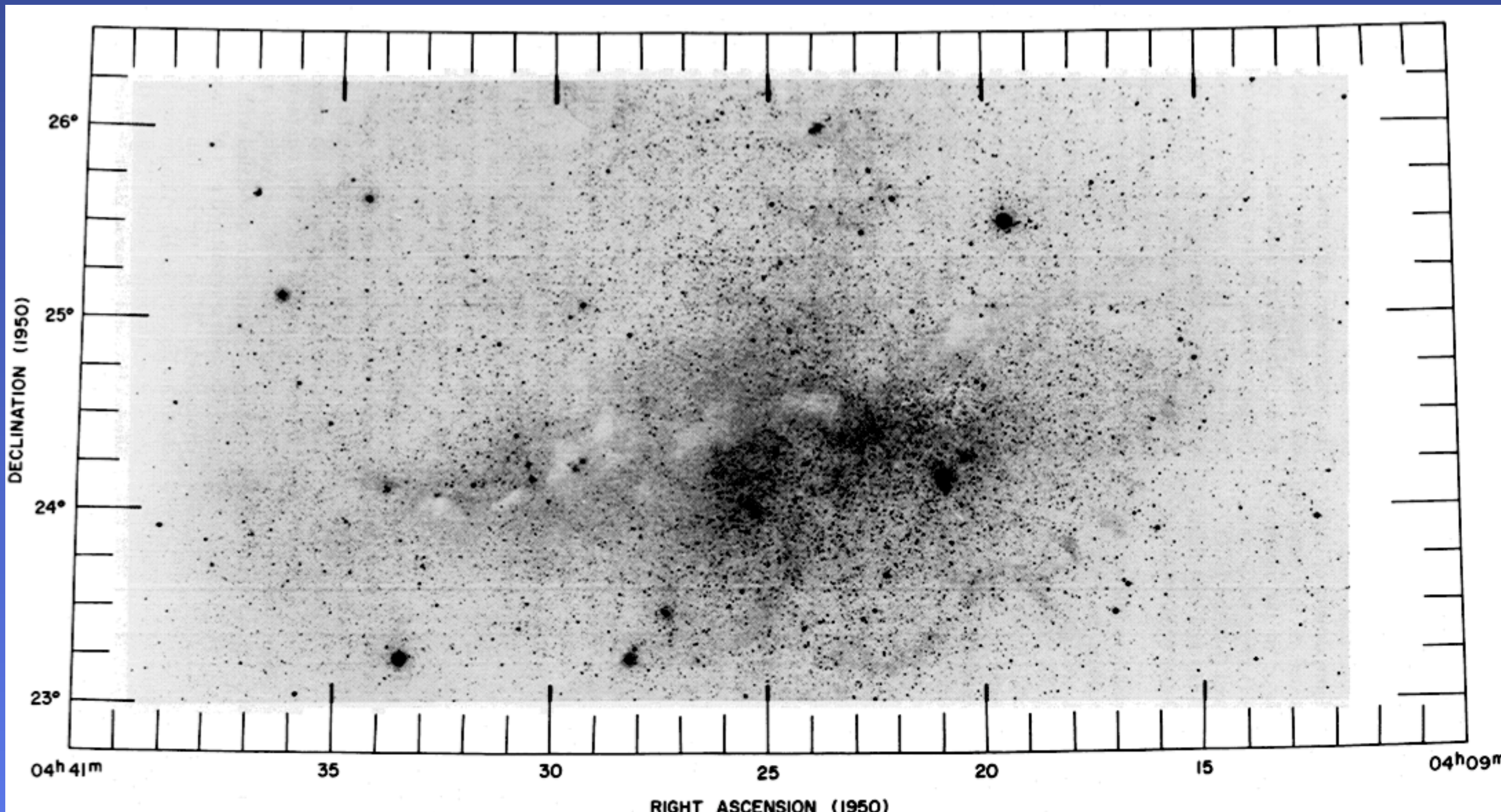
Early steps in opaque filaments &cores

Survey a dozen `opaque' points along the B18 filament for dense gas tracers NH3 and HC5N. Below is map of 'fragment' TMC-2 L~0.1pc, N~4x10^4 cm^{-3} , M~1Mo, dv=0.2 km/s



Myers, Ho, & Benson 1979 ApJ, 233, 141

Cylinder model of B18 filament



2 cylinders, Less dense outer cyl (2x5pc, $n<700/cm^3$) and denser inner cyl ($3000/cm^3$) with 9 T Tauri stars.

Myers 1982, ApJ, 257, 620

Other SF news in late 70's
L1551 bipolar outflow in Taurus

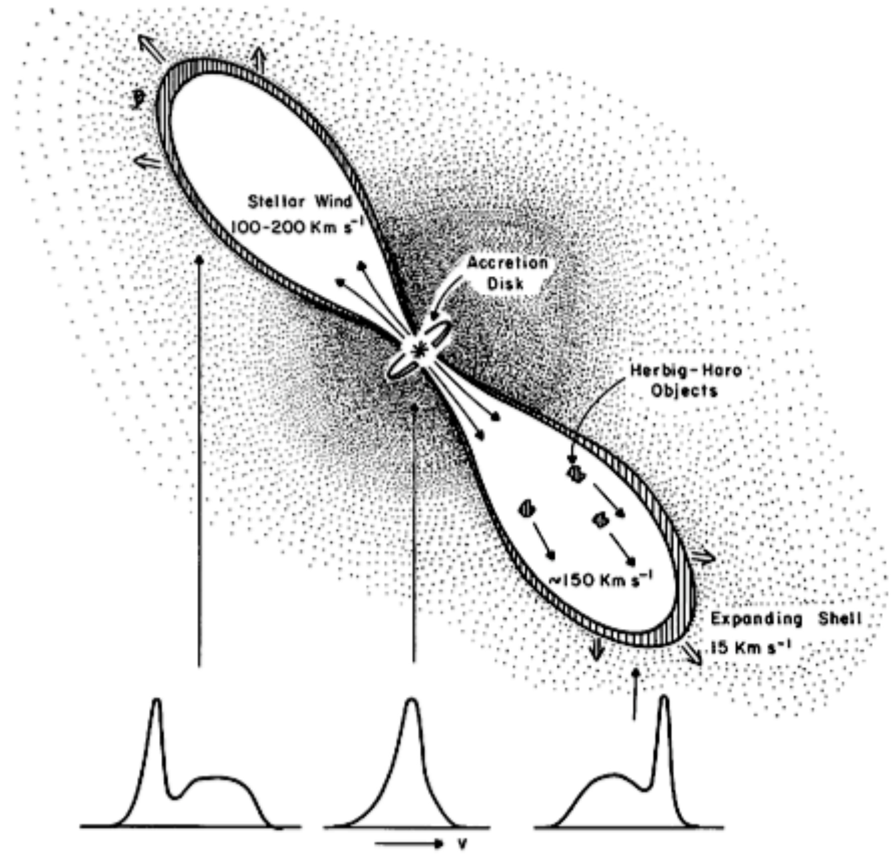


FIG. 5.—A schematic picture of the stellar wind driven shock model for L1551, indicating the CO line profiles which would be expected at different positions across the source. The Herbig-Haro objects are not necessarily located inside the shell; because of their high velocities, they may have been ejected through the shell and into the surrounding medium.

Snell, Loren, & Plambeck 1980, ApJ, 239, 17

Collapse models/ initial conditions

- Before Phil,
  - typical theory starting state

    n = constant, unstable cloud,

    1Mo cloud forms 1Mo star

- Phil's work greatly influenced our theory (Frank Shu, me) in setting better initial conditions
  - Thermal (T~10K) 0.2 km/s,
  - in near equilibrium with gravity $n \sim 1/r^2$.
  - Mcloud > Mstar

Collapse models with rotation

Terebey, Shu, & Cassen 1984, ApJ, 286, 529

THE COLLAPSE OF THE CORES OF SLOWLY ROTATING ISOTHERMAL CLOUDS

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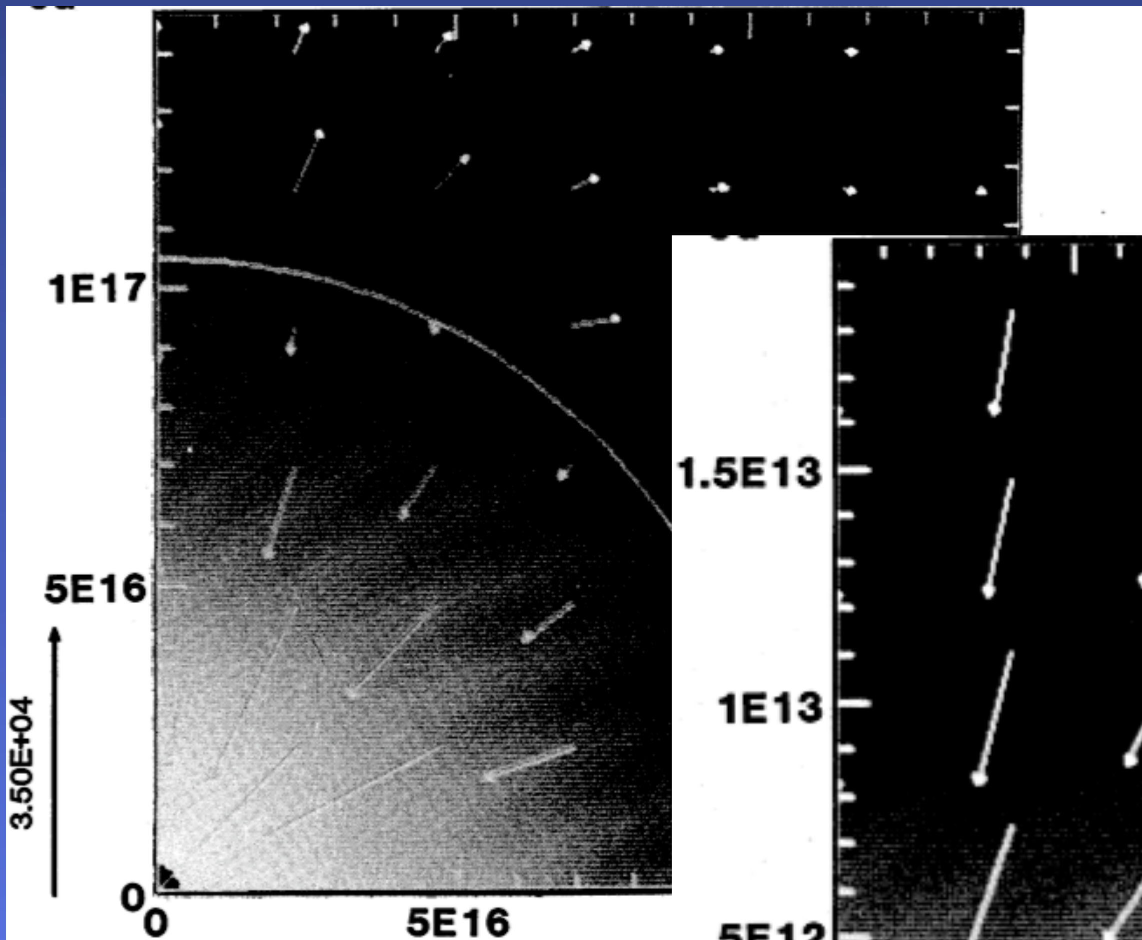
ABSTRACT

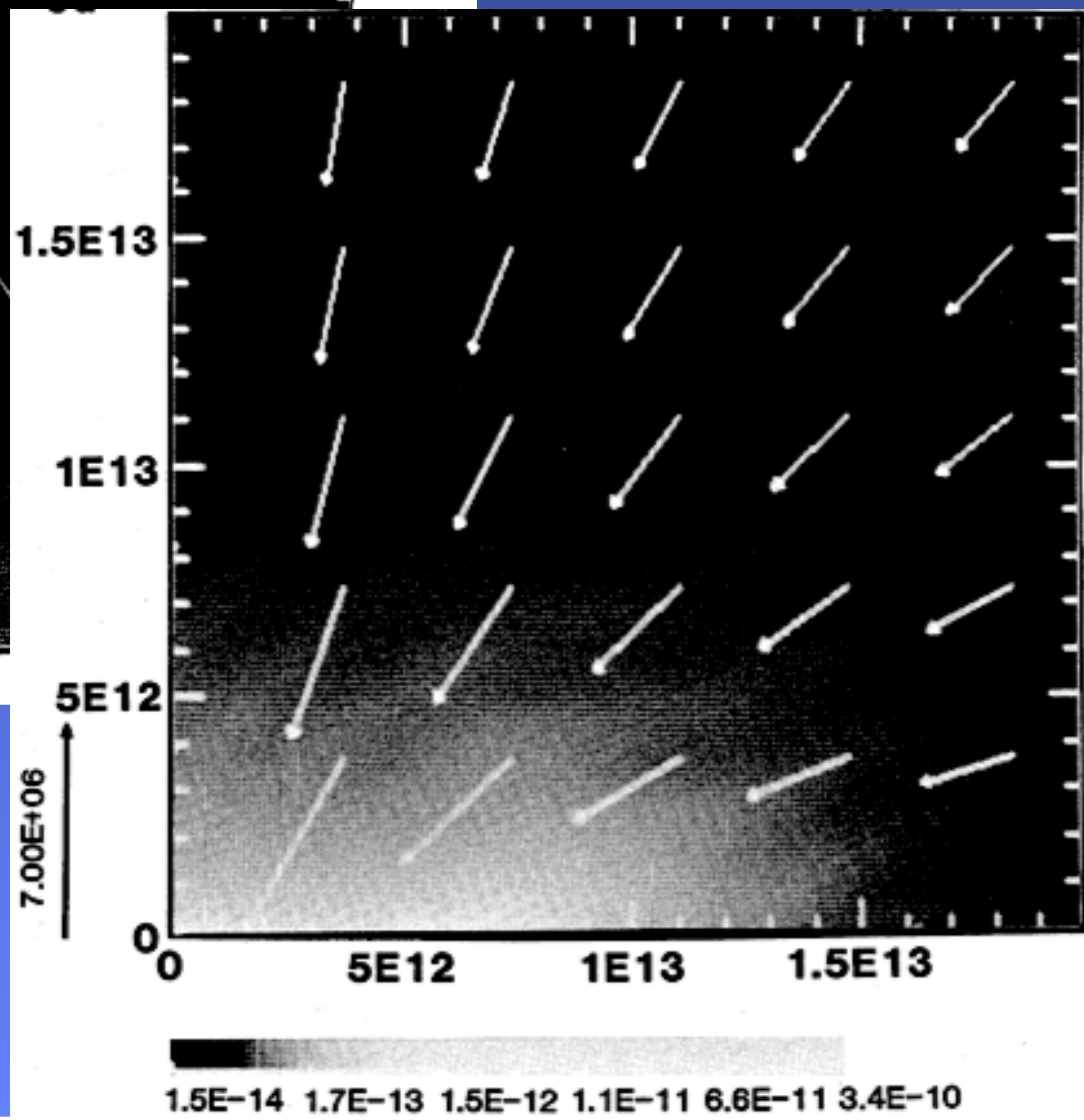
Rotation plays an important role in the formation of stars and planetary systems, but detailed calculations of its effects have been limited by the difficulty of following the collapse from interstellar dimensions to those characteristic of the solar system or binary stars. We present here a semianalytic perturbational solution for

$$\rho(r) = \frac{a^2}{2\pi G r^2}, \tag{1}$$

$$\bar{\rho}(R) = \frac{3}{4\pi R^3}\int_0^R \rho(r) 4\pi r^2 dr = \frac{3a^2}{2\pi G R^2}. \tag{2}$$

Myers and Benson (1983) quote mean values of temperature $T = 10.5$ K and ammonia linewidth (FWHM) = 0.32 km s^{-1}, which correspond to an equivalent sound speed (in a cosmic molecular gas including turbulence) $a = 0.22$ km s^{-1}. On the other hand, if we





Snapshot of collapse (~0.1pc) looks radial on outside. L (ang. mom.) conserved leads to disk on AU scales.

Are they Protostars? adventures with Phil

Terebey, Vogel, & Myers 1989, ApJ, 340, 472

1992, ApJ, 390, 181

- Snapshot survey of 25 IRAS-Dense cores in CO for circumstellar emission with Owens Valley interferometer. 64% show CO outflow structure on small (~1000 AU) scales. H2O masers seen on 100AU scales.

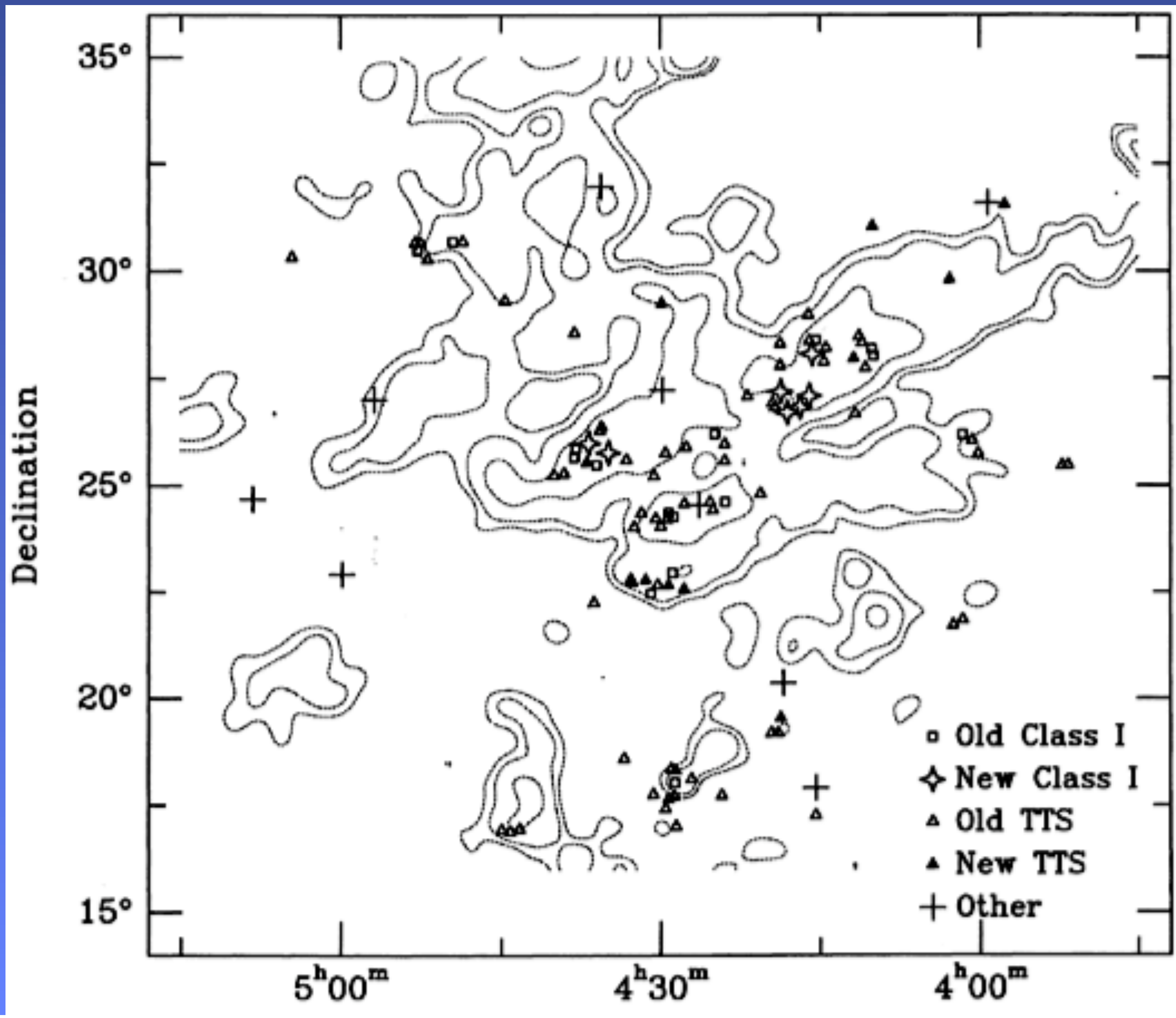
TABLE 1

CO OUTFLOW PROPERTIES OF *IRAS*-DENSE CORES

No.	*IRAS*	Core	R.A.(1950)	Decl.(1950)	V_{lsr} [a] km s^{-1}	D (pc)	L_{IR} [b] ($L_\odot$)	OVRO Snapshot	FCRAO	Ref. FCRAO CO outflow
1..........	03445+3242	B5	$03^h44^m31^s.8$	32°42′34″	10.1[c]	350	5.8	d hvg	of	1
2..........	04016+2610	L1489	04 01 40.6	26 10 49	7.0[c]	140	2.9	d hvg	of	2
3..........	04108+2803	L1495	04 10 49.3	28 03 57	6.8[c]	140	0.6	...	...	3
4..........	04263+2426[d]	L1524	04 26 22.0	24 26 30	6.5[c]	140	5.0	d hvg	...	2, 3
5..........	04325+2402	L1535	04 32 31.5	24 02 07	5.7[c]	140	0.6	d	of	2, 3
6..........	04365+2535	TMC1A	04 36 31.2	25 35 56	6.4[c]	140	1.9	d hvg	...	2, 3
7..........	04368+2557	L1527	04 36 49.3	25 57 16	6.0[c]	140	1.0	d hvg	...	2, 3
8..........	04381+2540	TMC1	04 38 08.5	25 40 53	5.5[c]	140	0.6	d hvg	...	2, 3
9..........	05417+0907	B35	05 41 45.3	09 07 40	11.7	460	15.	d hvg	of	2

Global view: IRAS sources in Taurus

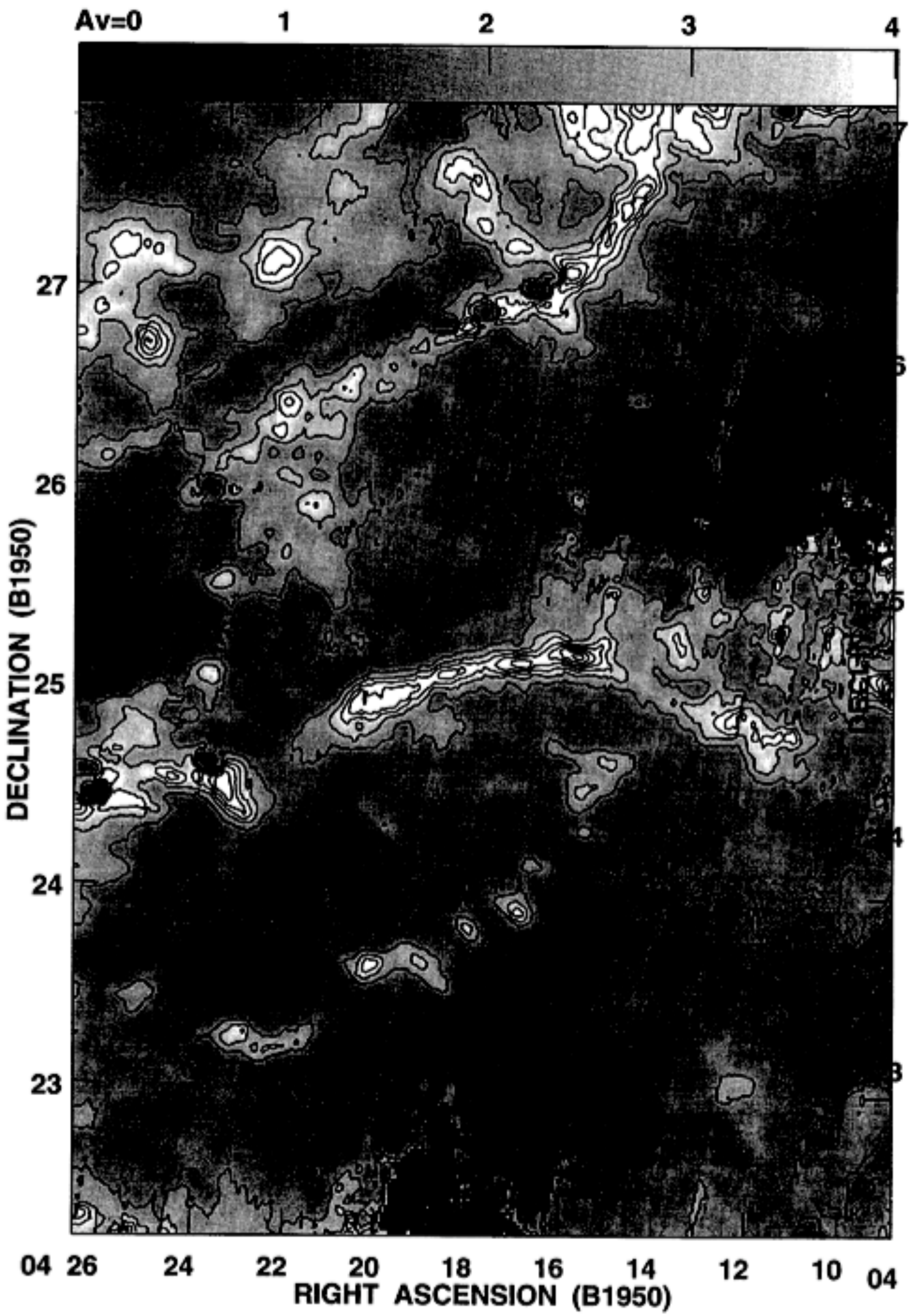
Kenyon, Hartmann, Strom, & Strom 1990, AJ, 99, 869



More phil-aments in Taurus

Wood, Myers, & Daugherty 1994, ApJS, 95,457

Interpret filaments using IRAS 60um/100um at 5' resolution

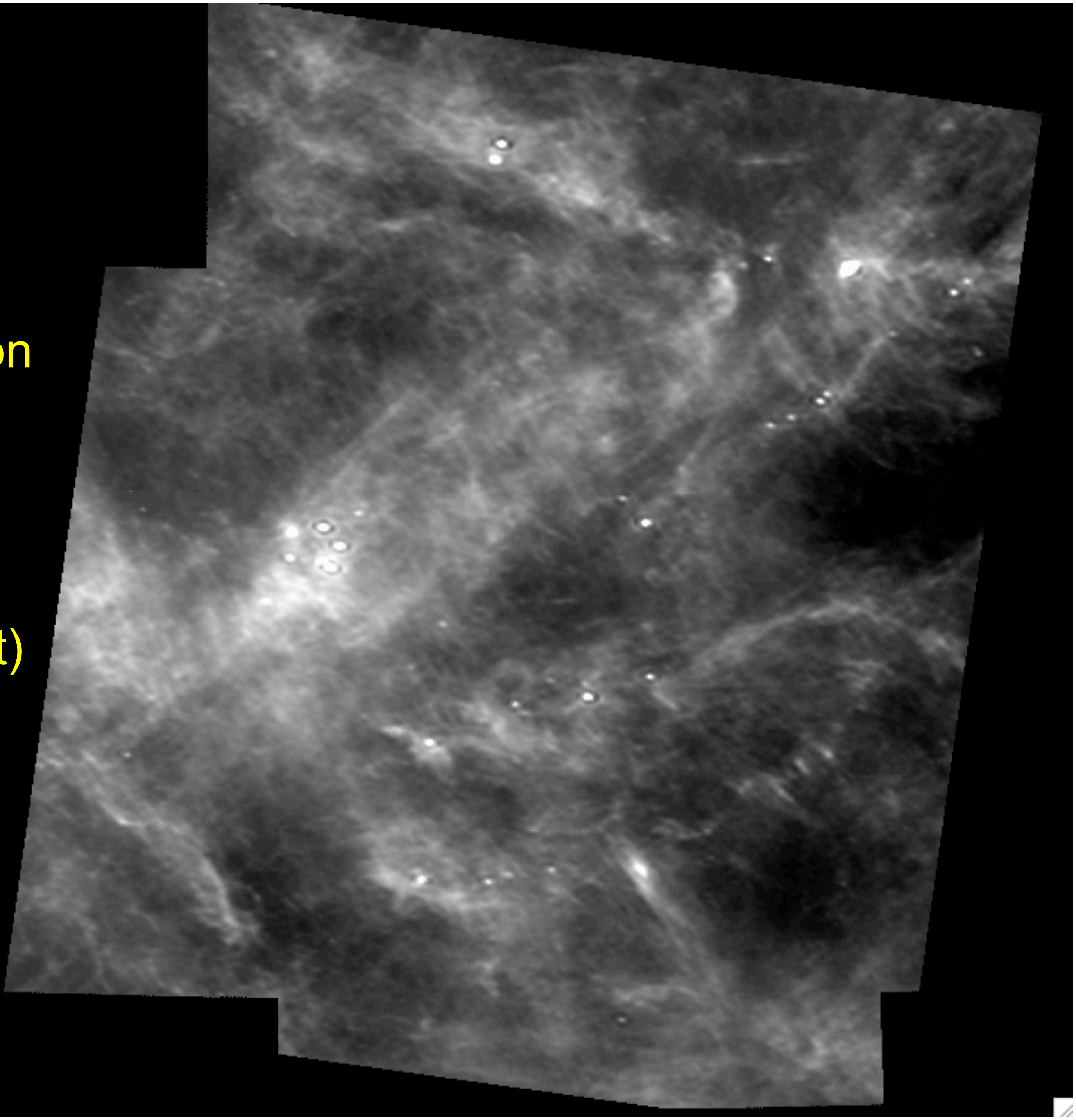


Taurus

IRAS 100um
HIRES 2’ resolution
(see my poster)

100um point sources (youngest) are embedded in the filaments

Looking forward: want a complete survey of dense gas



Taurus: Now
….with Spitzer

- Taurus Legacy Survey
  - 44 sq deg

  Padgett et al 2009
  - overview

  Rebull et al 2009
  - census of old & new YSOs

  Terebey et al 2009, ApJ, 696, 1918
  - analysis of 160um emission
  - (see my poster)

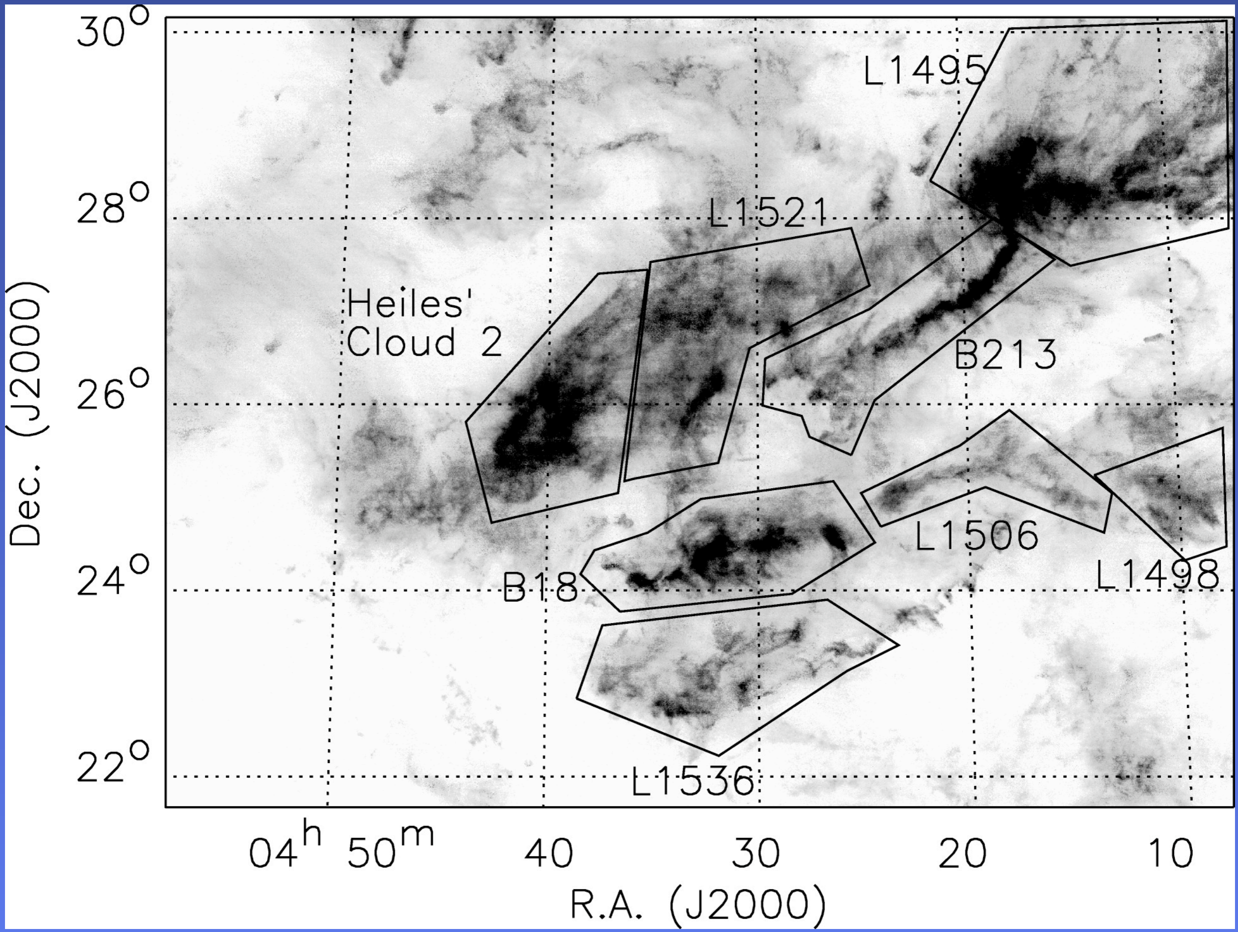
Synergies of Multiple Surveys

- *Spitzer Space Telescope*: MIR/FIR survey determines the state of circumstellar material for all stellar and substellar members including edge-on disks too faint for IRAS.

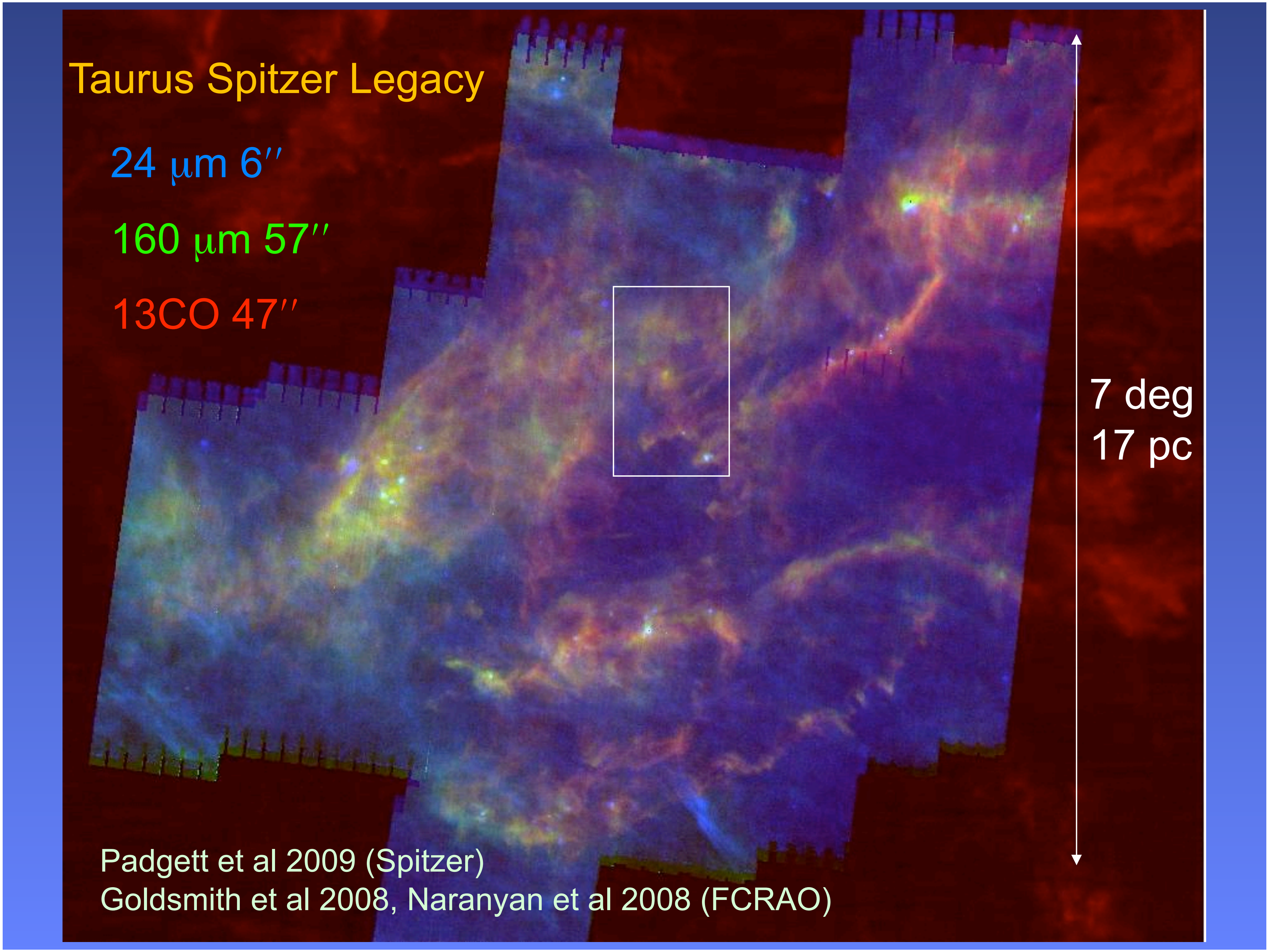
	IRAC	MIPS				
						44 deg^2
λ	3.6, 4.5, 5.8, 8.0	24	70	160	μm	
θ	1.7”	6”	18”	40”		

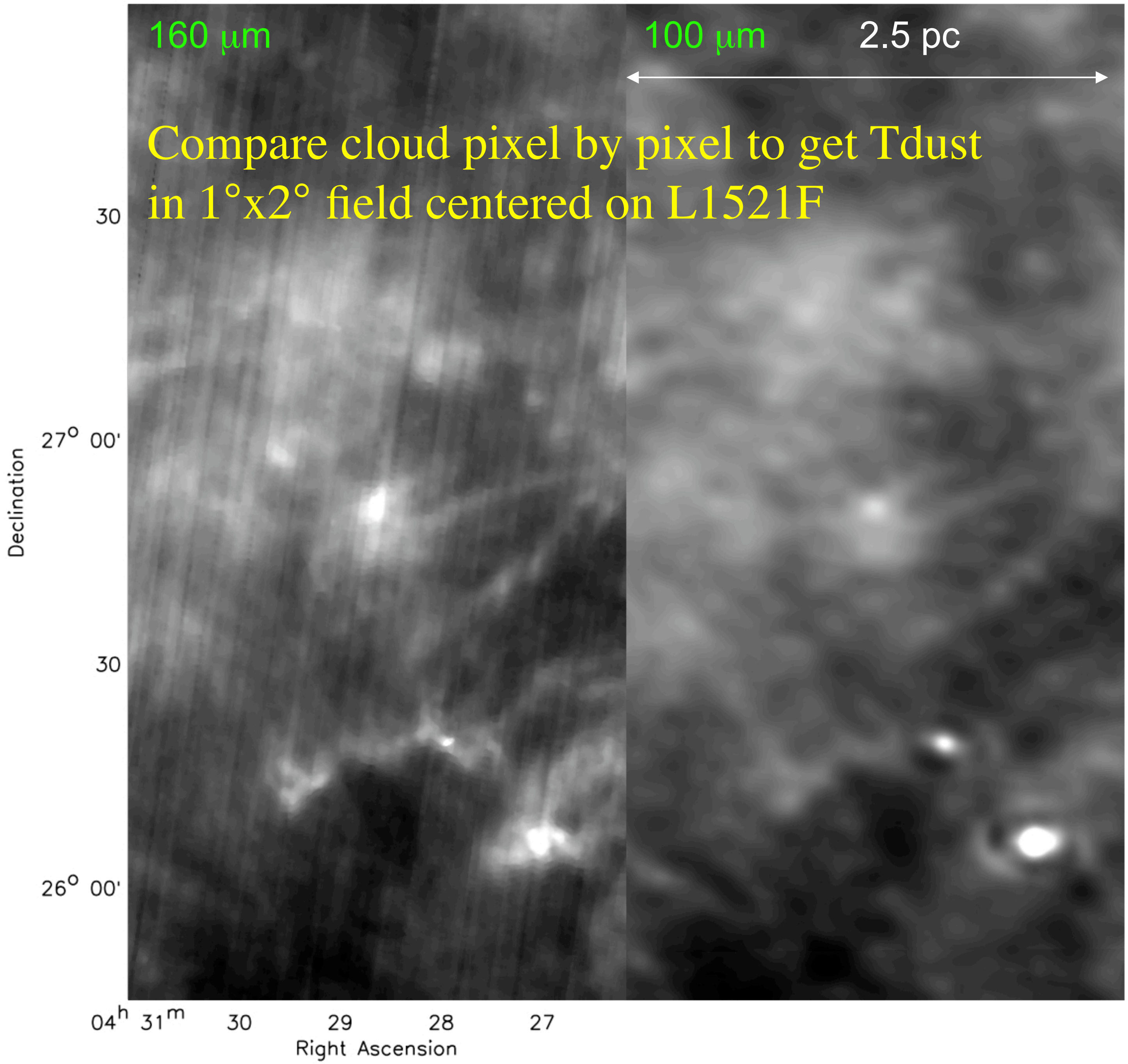
- CFHT and SDSS: Optical surveys identify very low mass stellar members and brown dwarfs and provide accurate griz & I, z band photometry with better than 1“ resolution; SDSS spectral scans as well
- *XMM-Newton*: X-ray survey penetrates tens of magnitudes of visual extinction, identifies potential WTTS, measures effect of stellar activity on circumstellar environment
- FCRAO: Millimeter survey of ^{12}CO and ^{13}CO at resolution of 45” and unsurpassed sensitivity provides molecular cloud context for point sources

Taurus by name

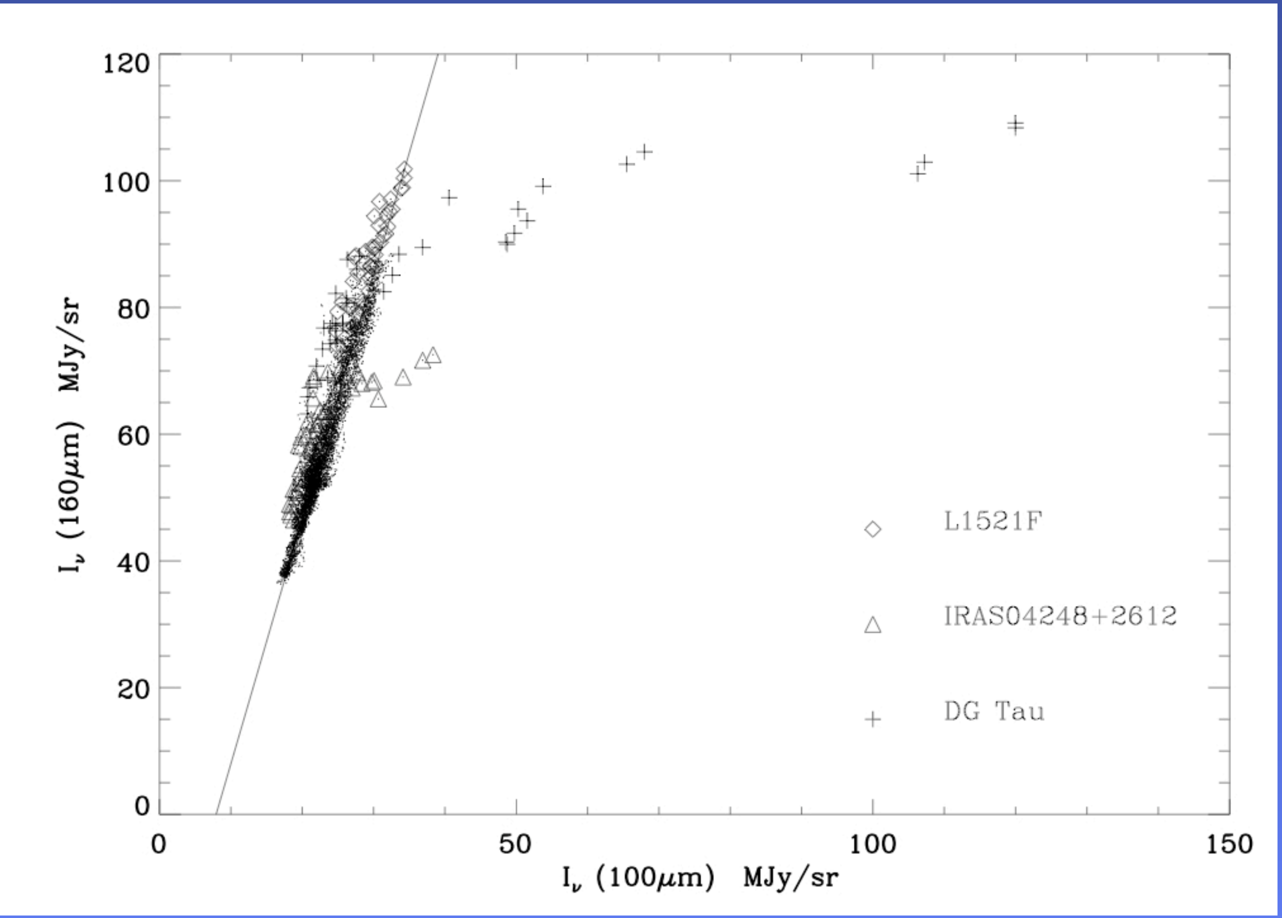


From FCRAO 12CO/13CO survey
Goldsmith et al, 2008, ApJ, 680, 428


Taurus Spitzer Legacy
24 μm 6″
160 μm 57″
13CO 47″
7 deg
17 pc
Padgett et al 2009 (Spitzer)
Goldsmith et al 2008, Naranyan et al 2008 (FCRAO)

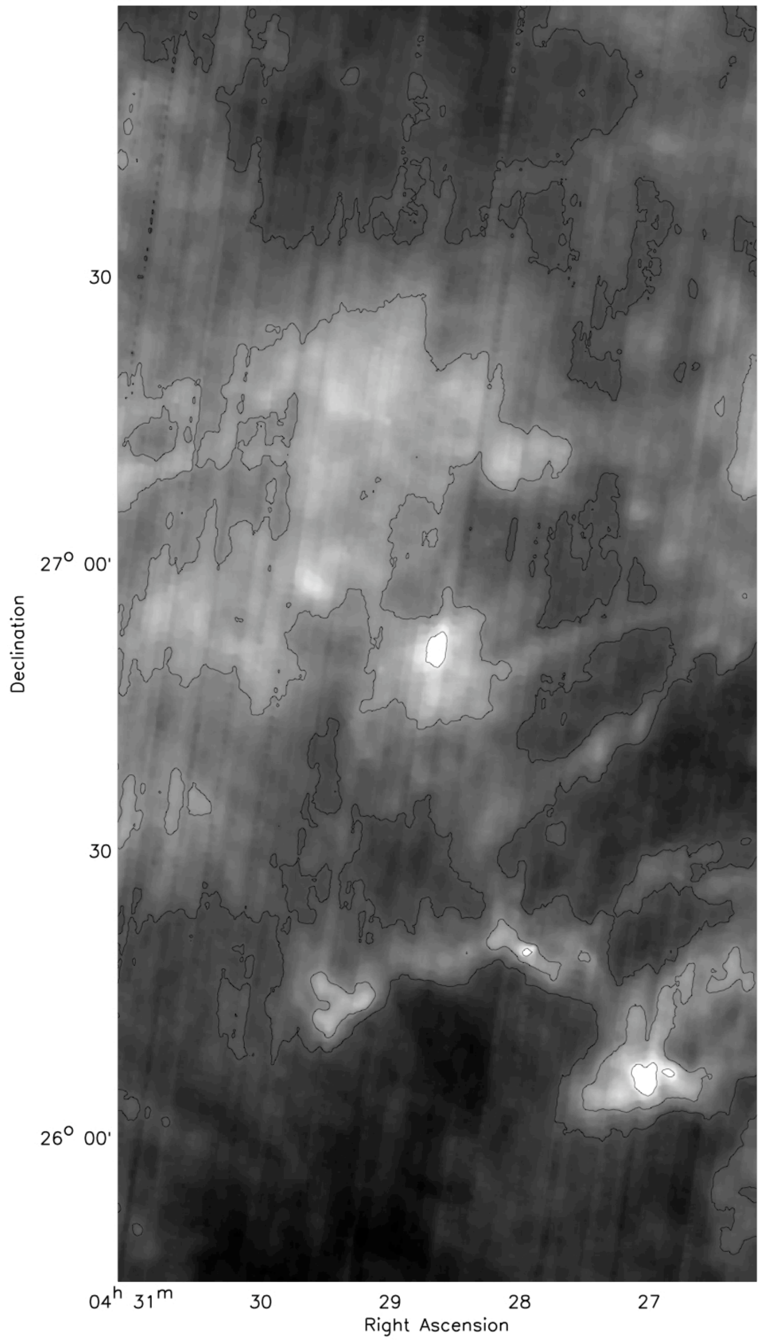

160 μm
100 μm
2.5 pc
Compare cloud pixel by pixel to get Tdust
in 1°x2° field centered on L1521F
30
27° 00'
30
26° 00'
Declination
04h 31m
30
29
28
27
Right Ascension

Dust temperature



1.1’ matched spatial resolution

Td = 14.2 K from linear fit



Given Tdust now get optical depth at 160 μm

$$I_\nu = \tau_\nu B_\nu(T)$$

Use image data I_{160}

Use T from slope I_{160}/I_{100}

=> τ_{160}

$$\delta A_V = 1, 2, 4$$

160 μm opacity

$$\tau_\nu = \kappa_\nu \rho L$$

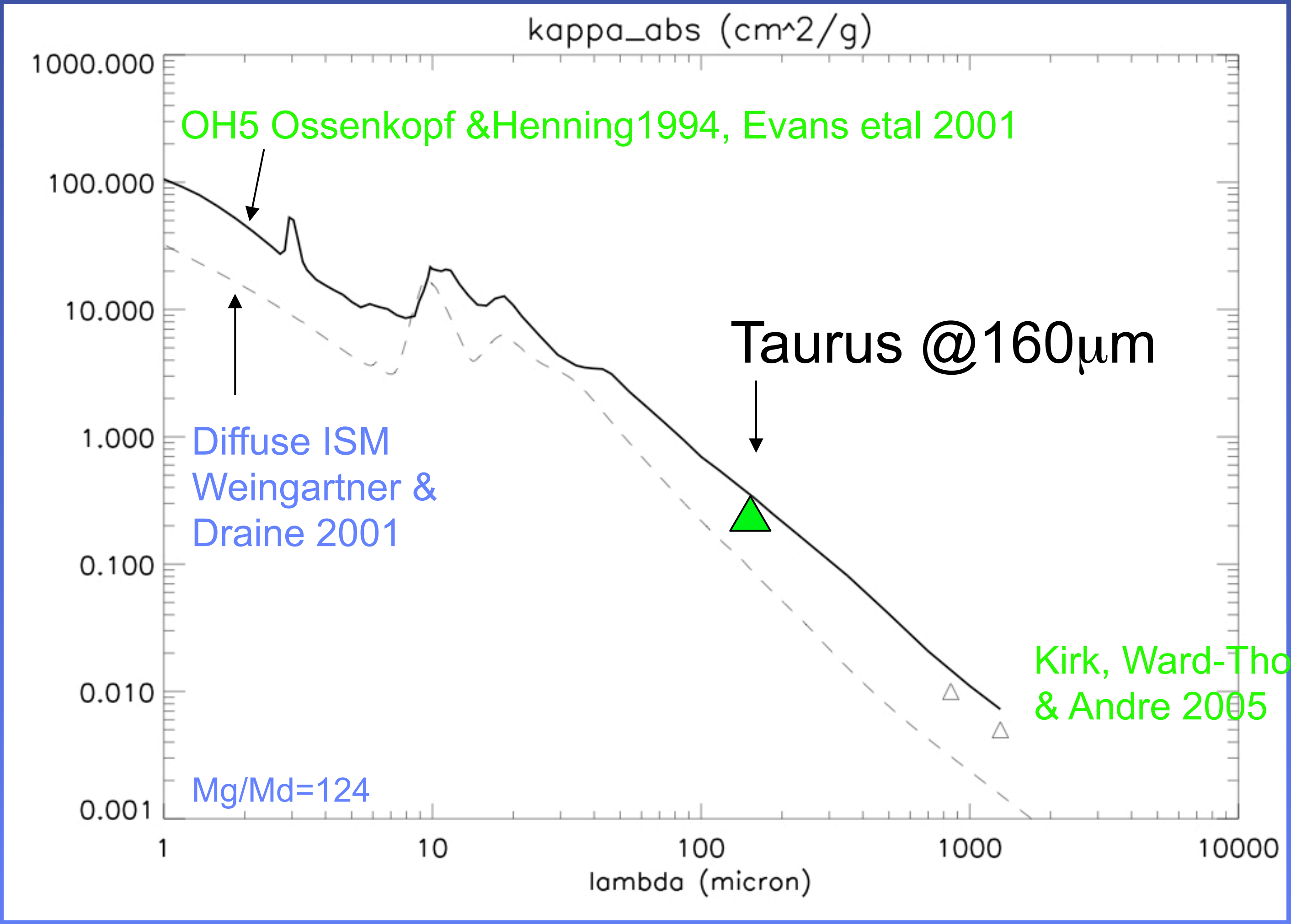
Use ratio at 2 wavelengths A_v/A_{160} to get κ_{160}

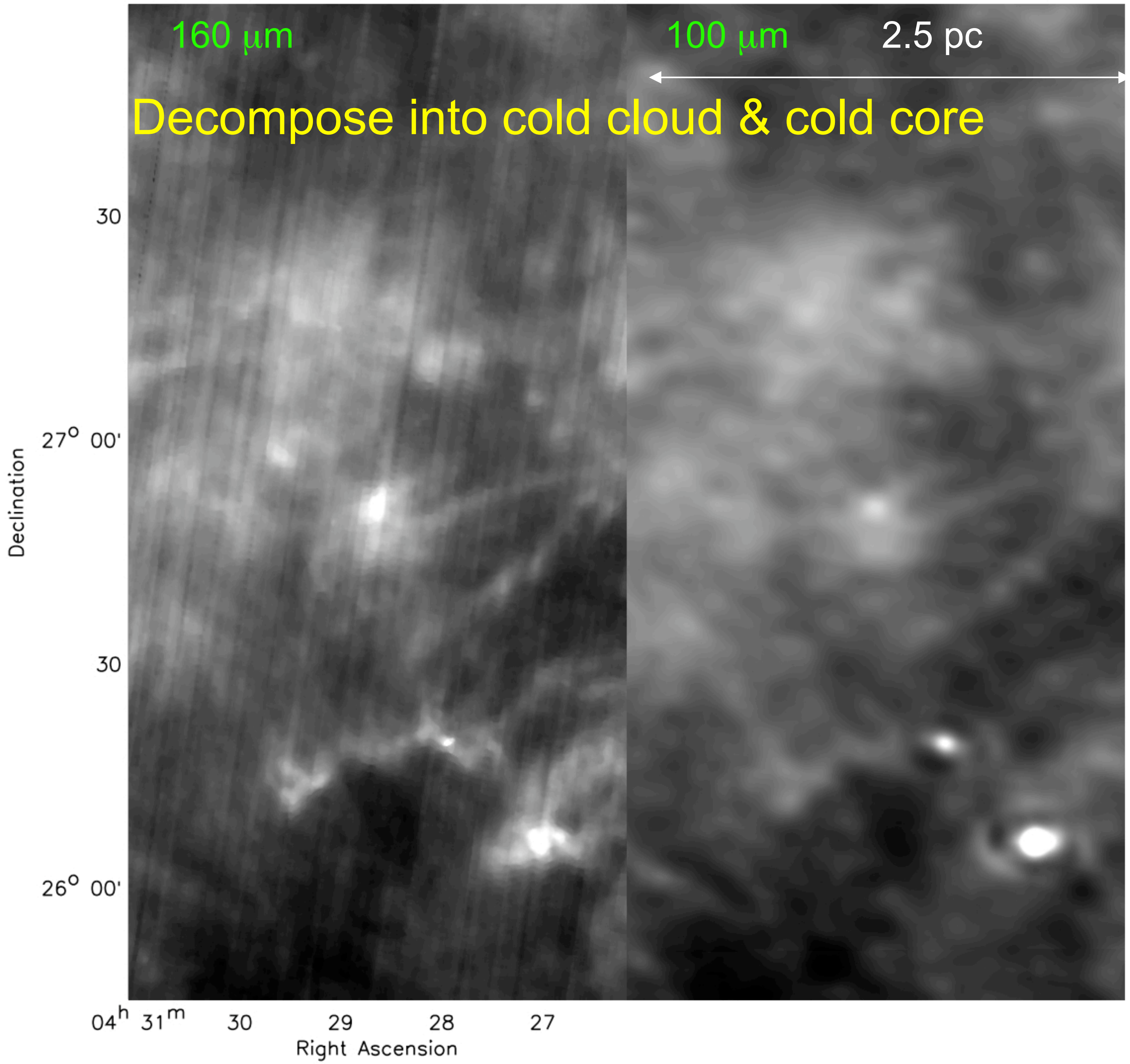
$$\kappa_{160} = 0.23\ cm^2\ g^{-1}$$

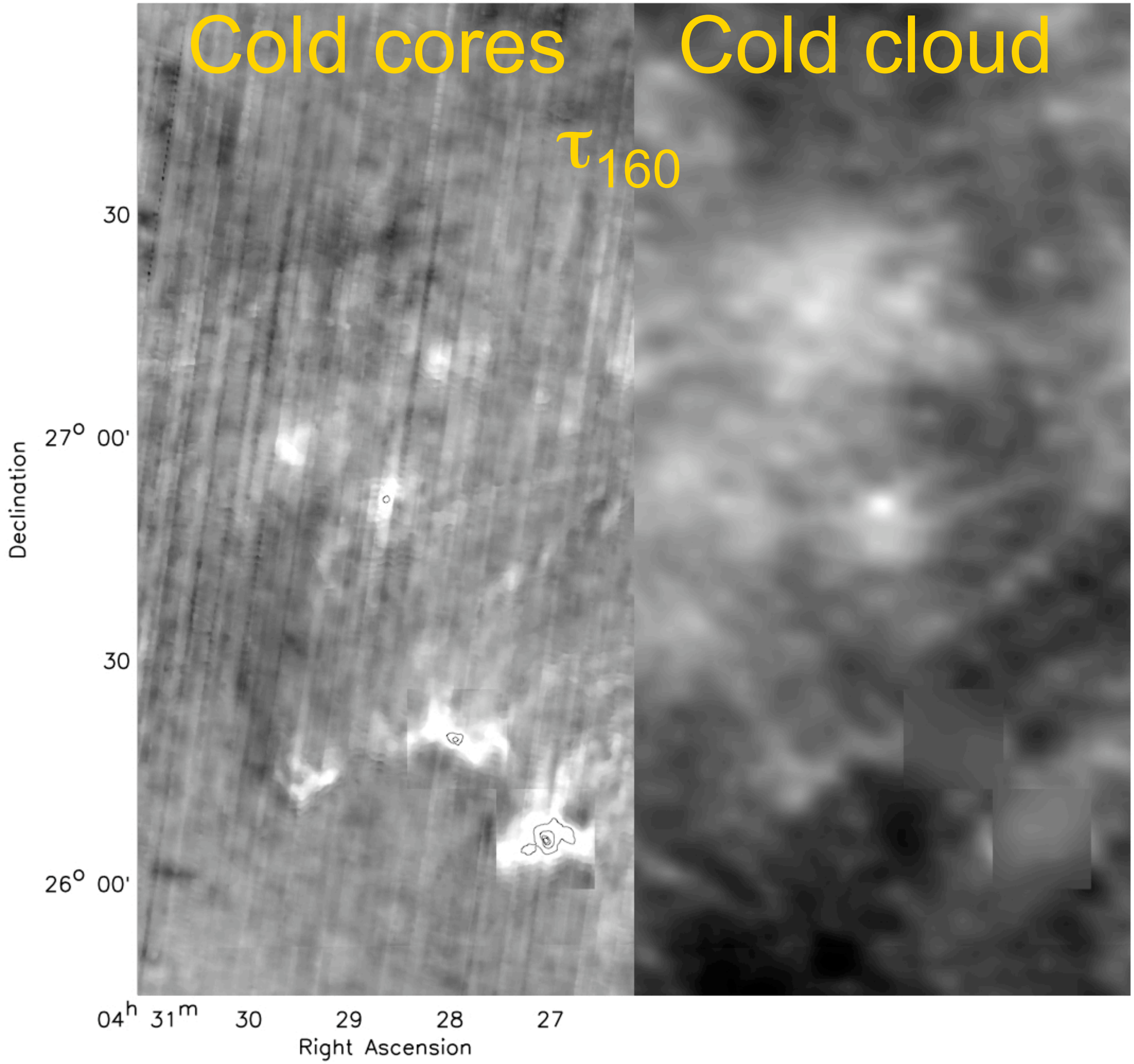
Consistent with commonly assumed values for submm opacity in dense cores for β = 2.

& 2.6 times higher than diffuse ISM opacity

Similar to dense core opacity adopted by other groups



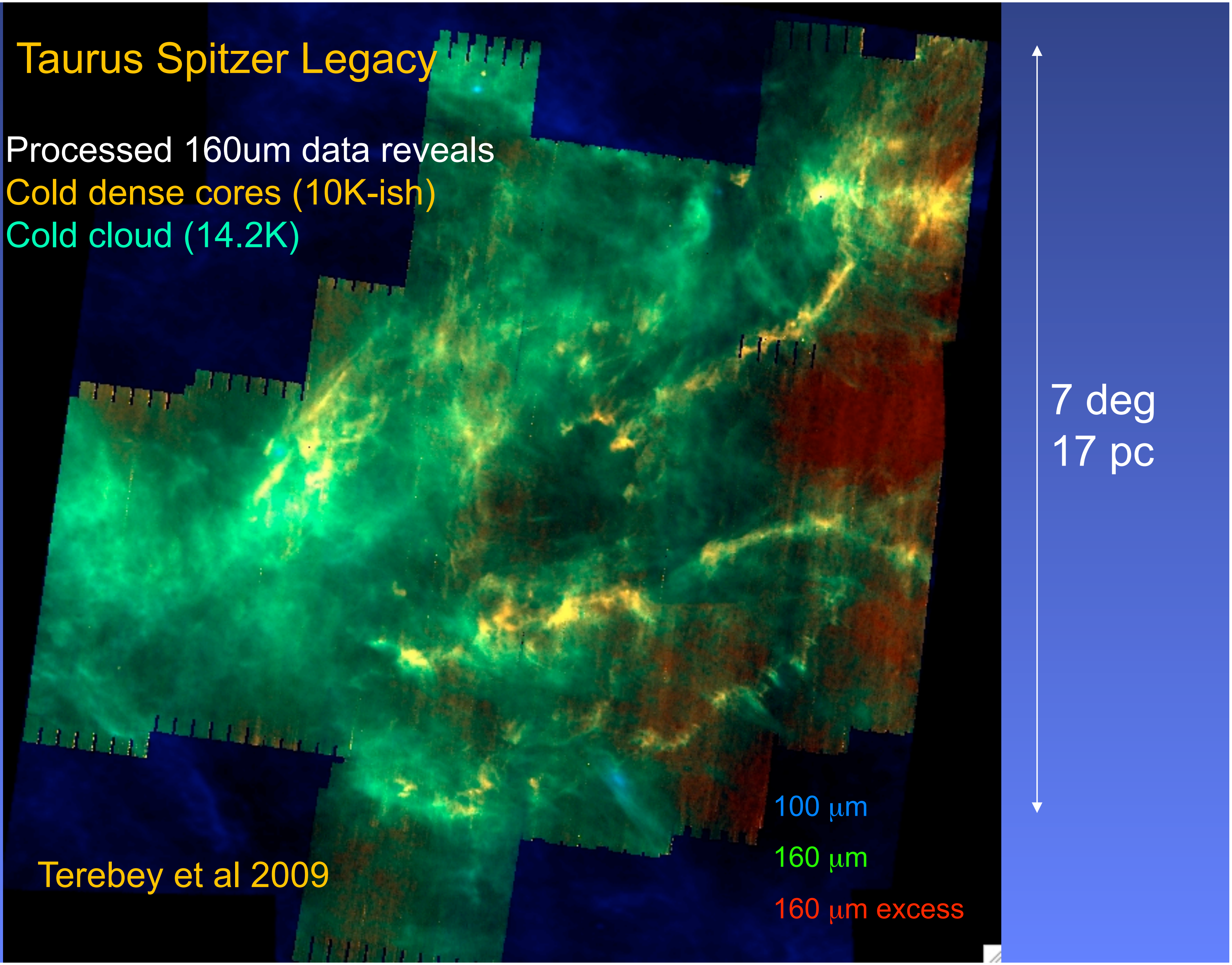

160 μm
100 μm
2.5 pc
Decompose into cold cloud & cold core
30
27° 00'
30
26° 00'
Declination
04h 31m
30
29
28
27
Right Ascension



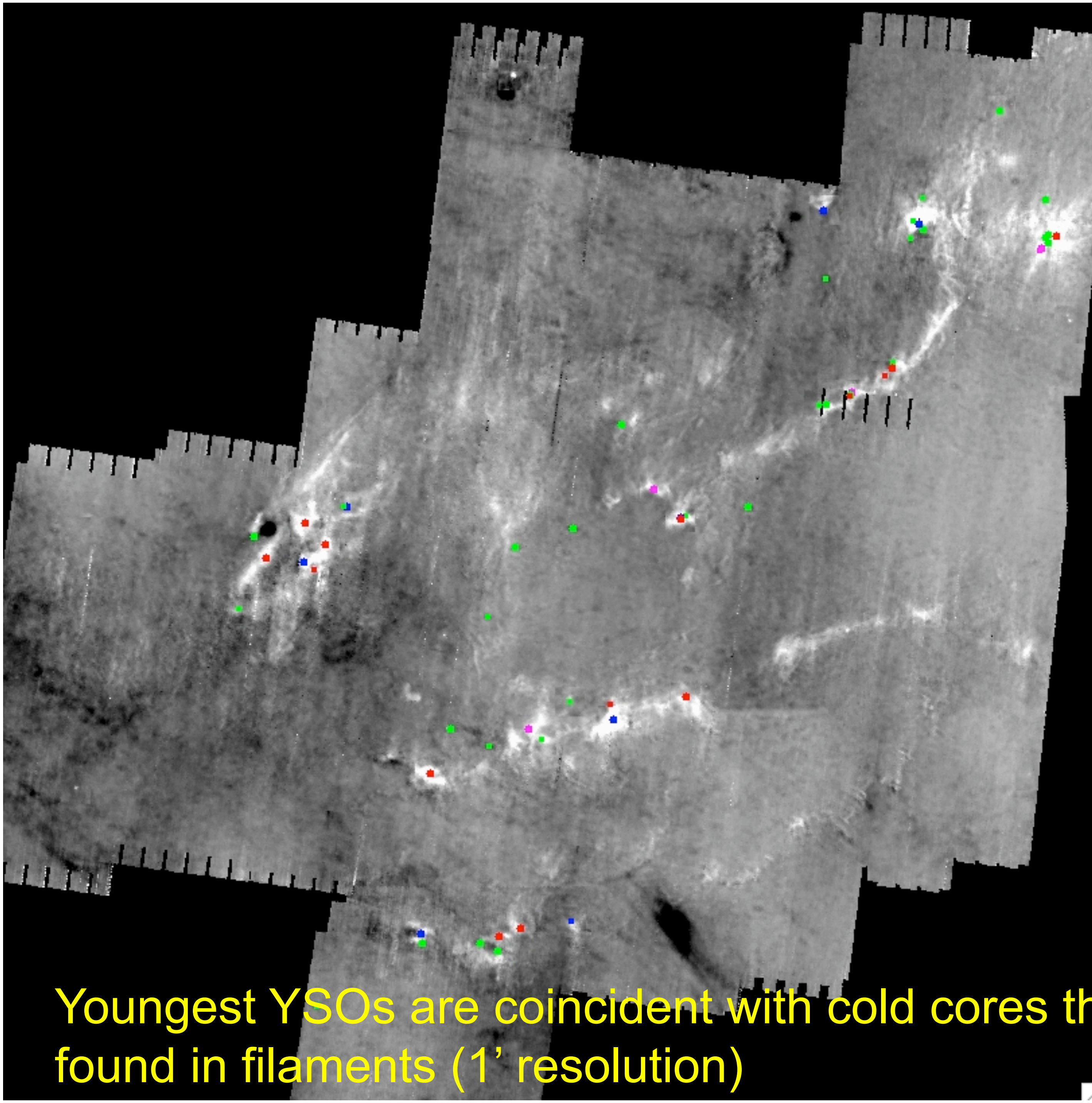
Cold cores
Cold cloud
τ160
30
27° 00'
30
26° 00'
Declination
04h 31m
30
29
28
27
Right Ascension

Taurus Spitzer Legacy

Processed 160um data reveals
Cold dense cores (10K-ish)
Cold cloud (14.2K)



Terebey et al 2009



Taurus
160um
cold cores

white= ~10K
cold dust

youngest
YSOs
class I =red
flat =magenta
class II =blue
fainter @ 70um
= green

Youngest YSOs are coincident with cold cores that are found in filaments (1’ resolution)

Closing remarks

Taurus continues to shed light on star formation

and…Thank you Phil

For being a great scientist

And a genuinely nice guy

There couldn't be a better combination

160um cold cores have counterparts

Table 7. Cross Identification of Spitzer 160 μm Cold Cores.

R.A. (deg)	Dec. (deg)	l (deg)	b (deg)	A_V Clump[1] Name	$C^{18}O$ Core[2] Number
66.76	26.10	171.84	-15.68	1211 P17	21
66.98	26.32	171.81	-15.38	1211 P22	22
67.03	27.18	171.17	-14.78	1211 P32	...
67.16	26.86	171.50	-14.91	1211 P16	20
67.30	26.24	172.07	-15.23	1211 P24	...
67.40	26.96	171.57	-14.69	1211 P21	...

Av clumps - Dobashi et al. 2005

C18O cores - Onishi et al. 1998